

Event Reconstruction at the LHC II



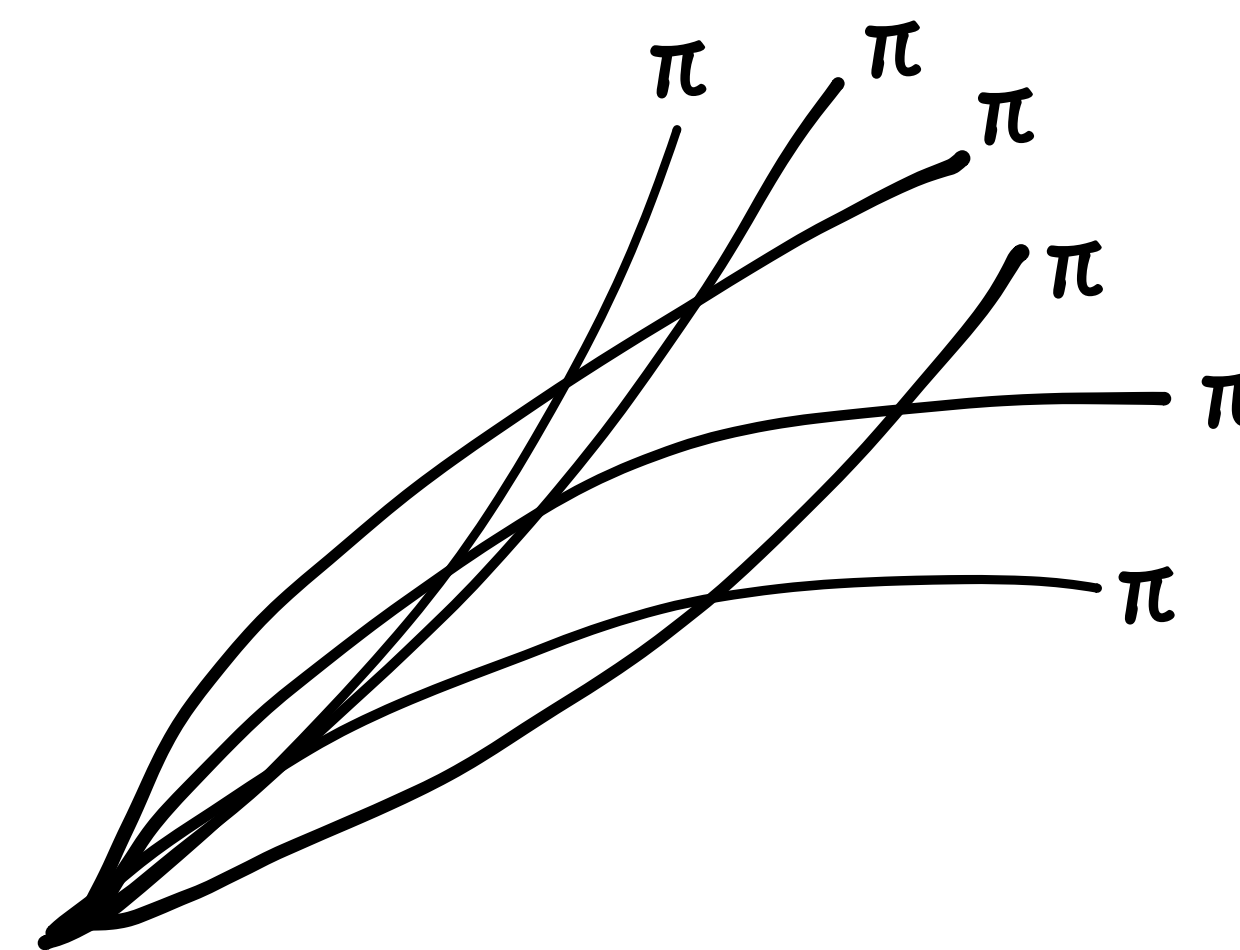
Recall: Jet Composition

Recall: Jet Composition

- Charged Particles: ~60%

Recall: Jet Composition

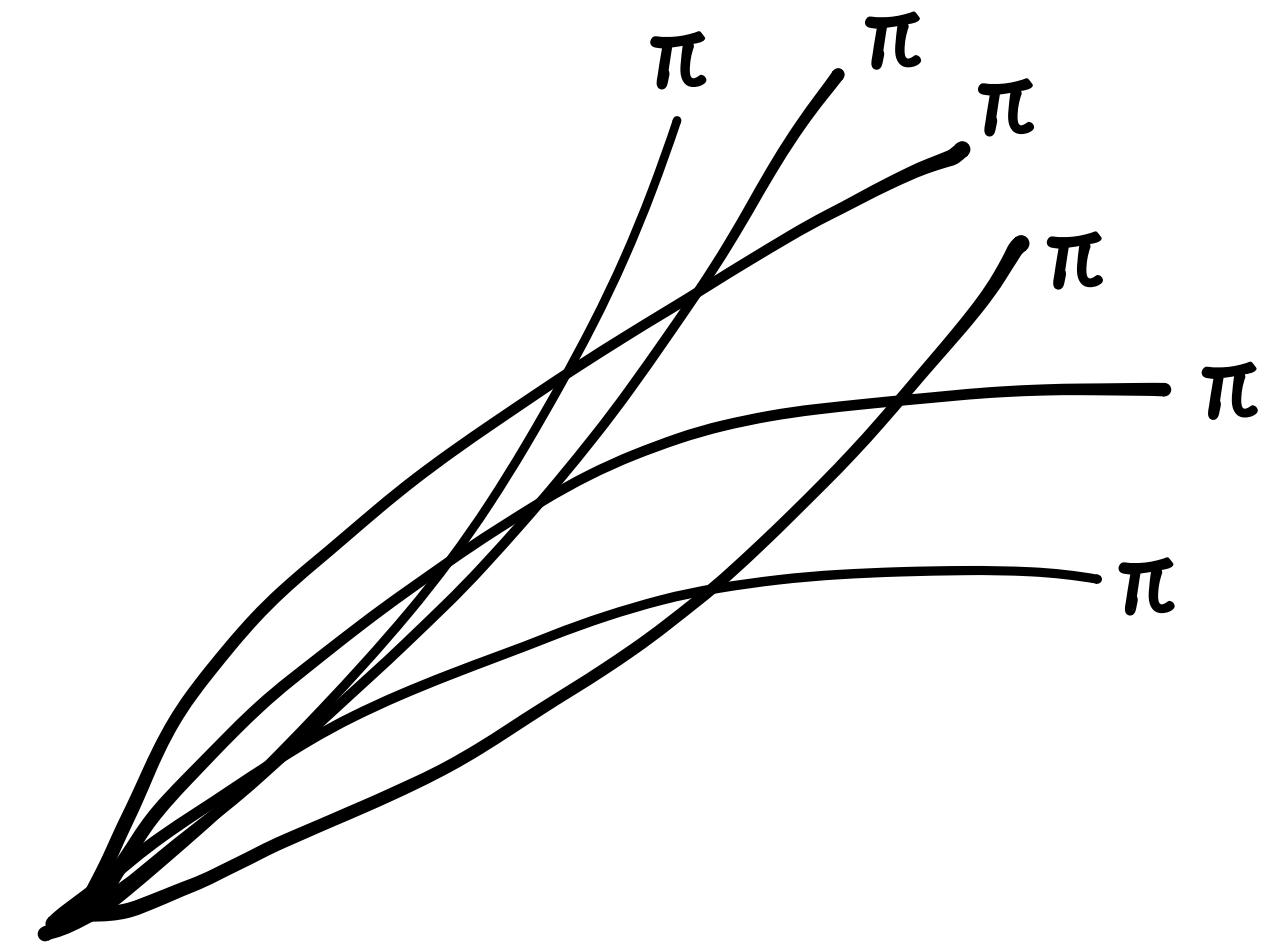
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Tracking Detectors

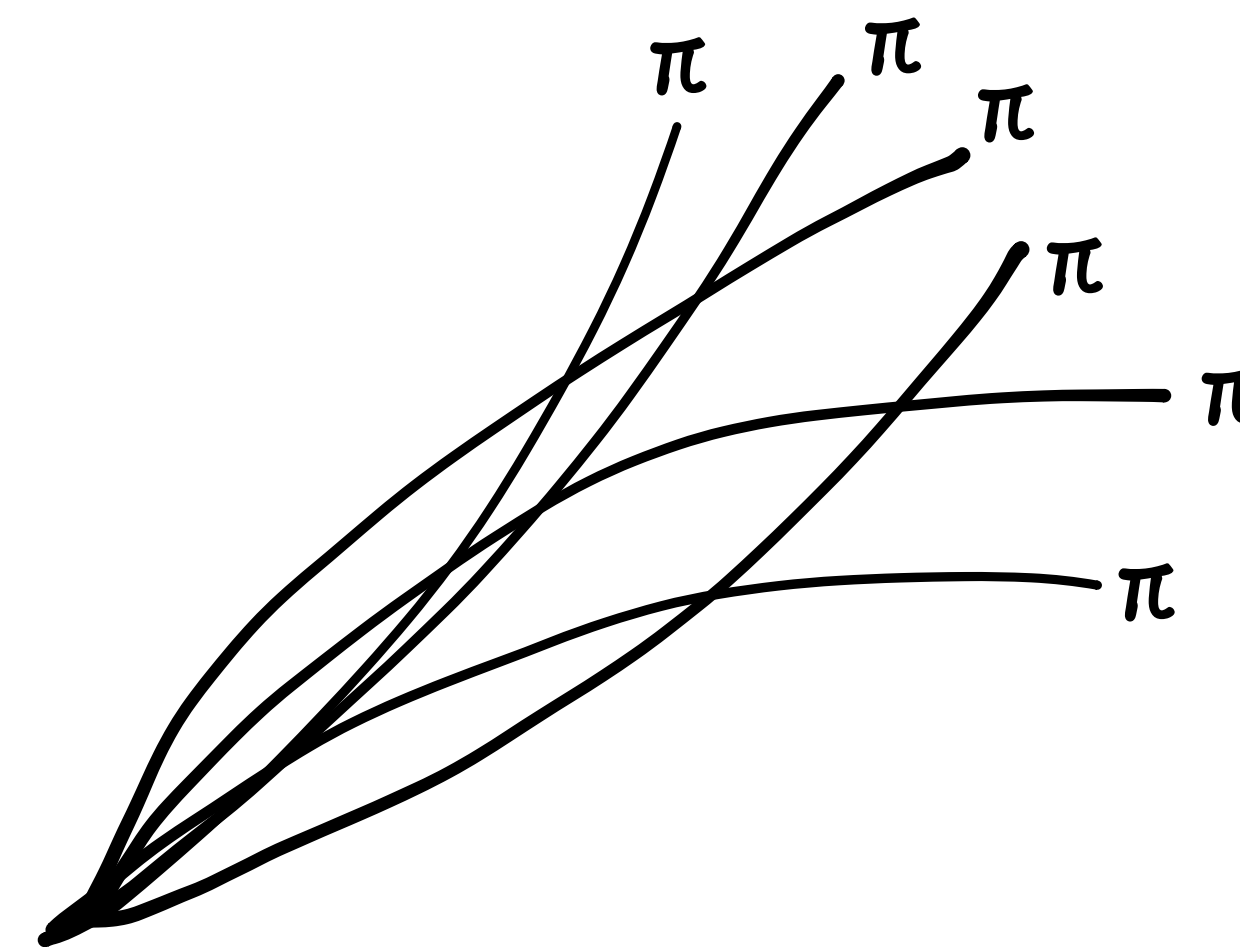


Recall: Jet Composition

- Charged Particles: ~60%

Tracking Detectors

- Photons: ~25%



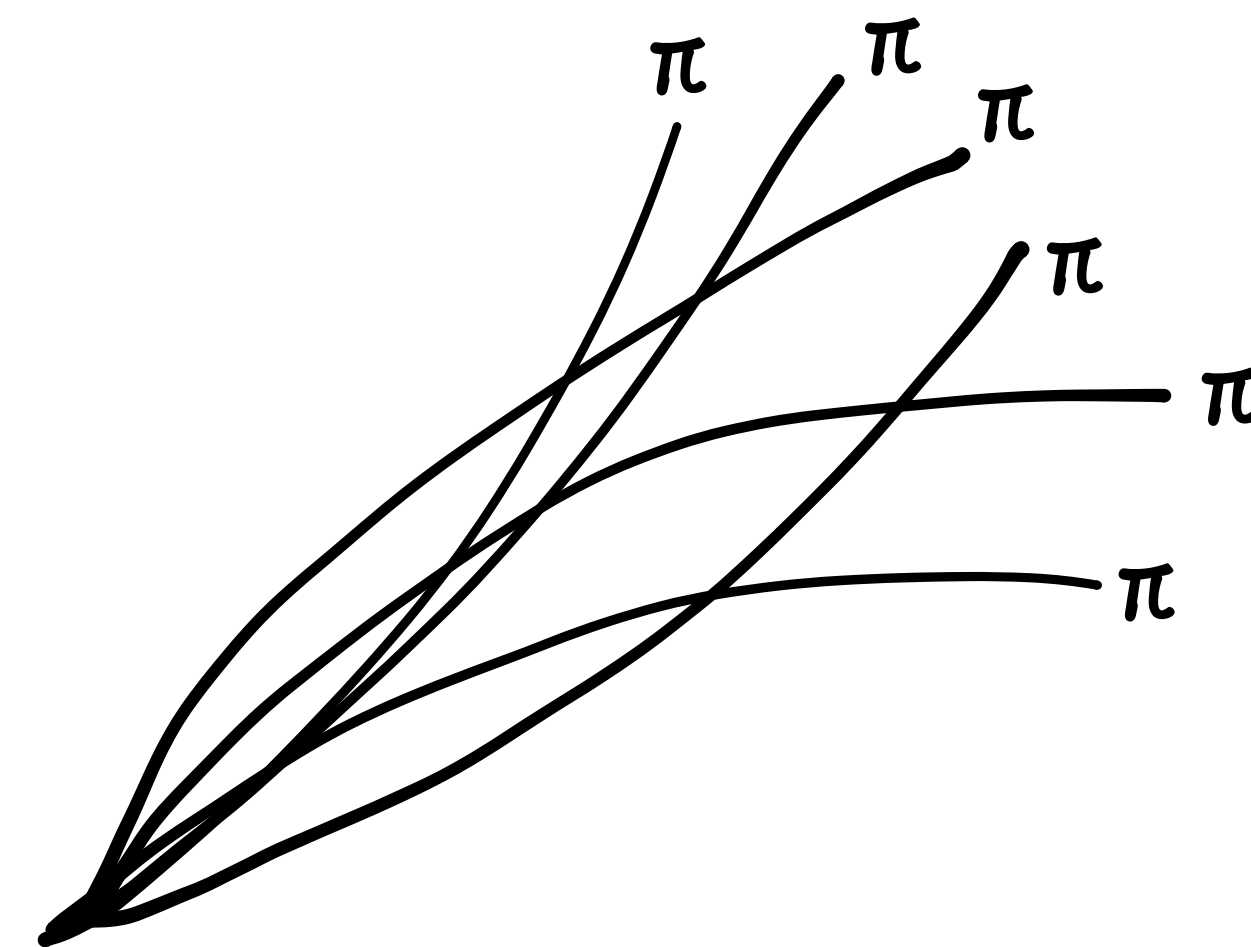
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EM Calorimeters



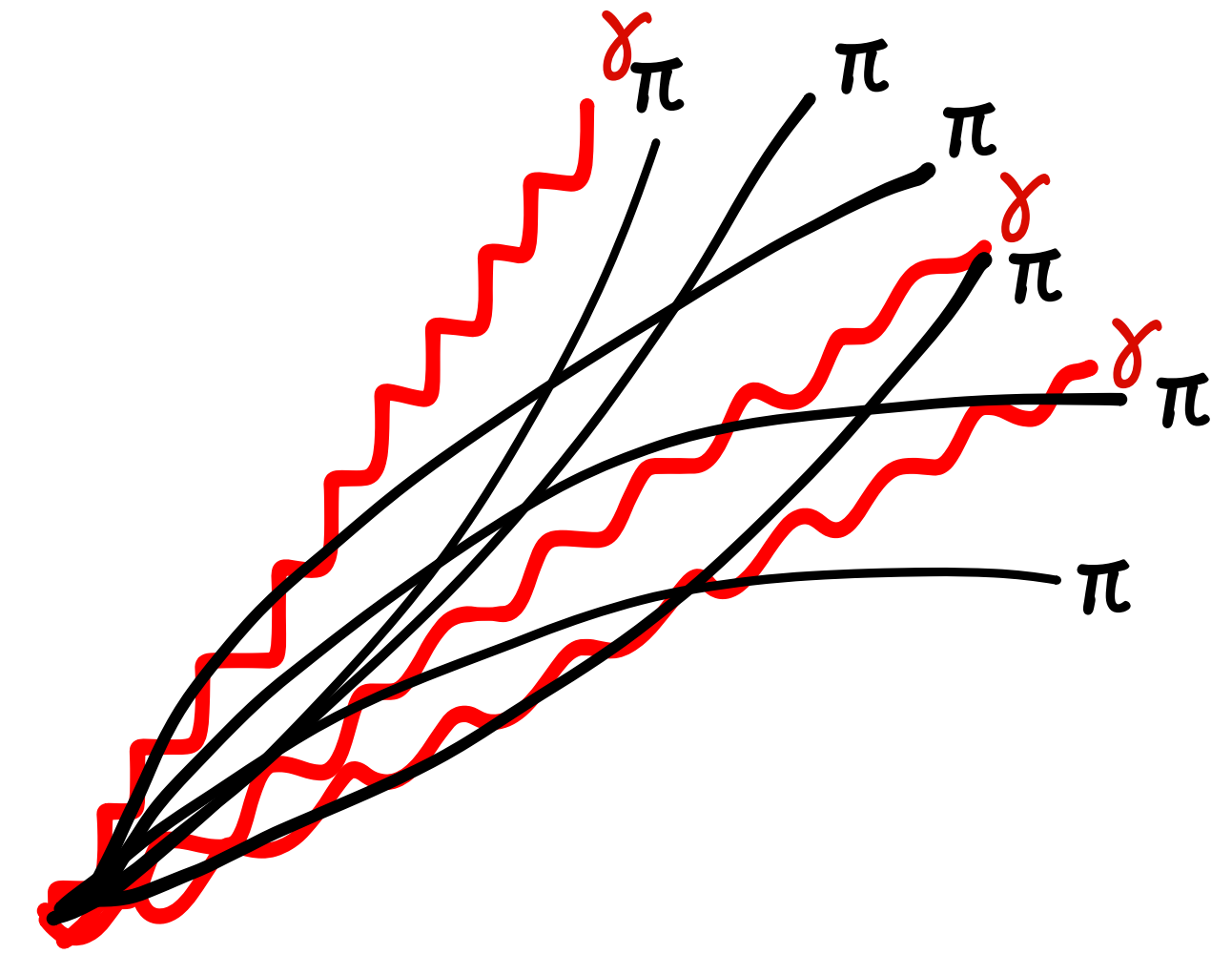
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EM Calorimeters



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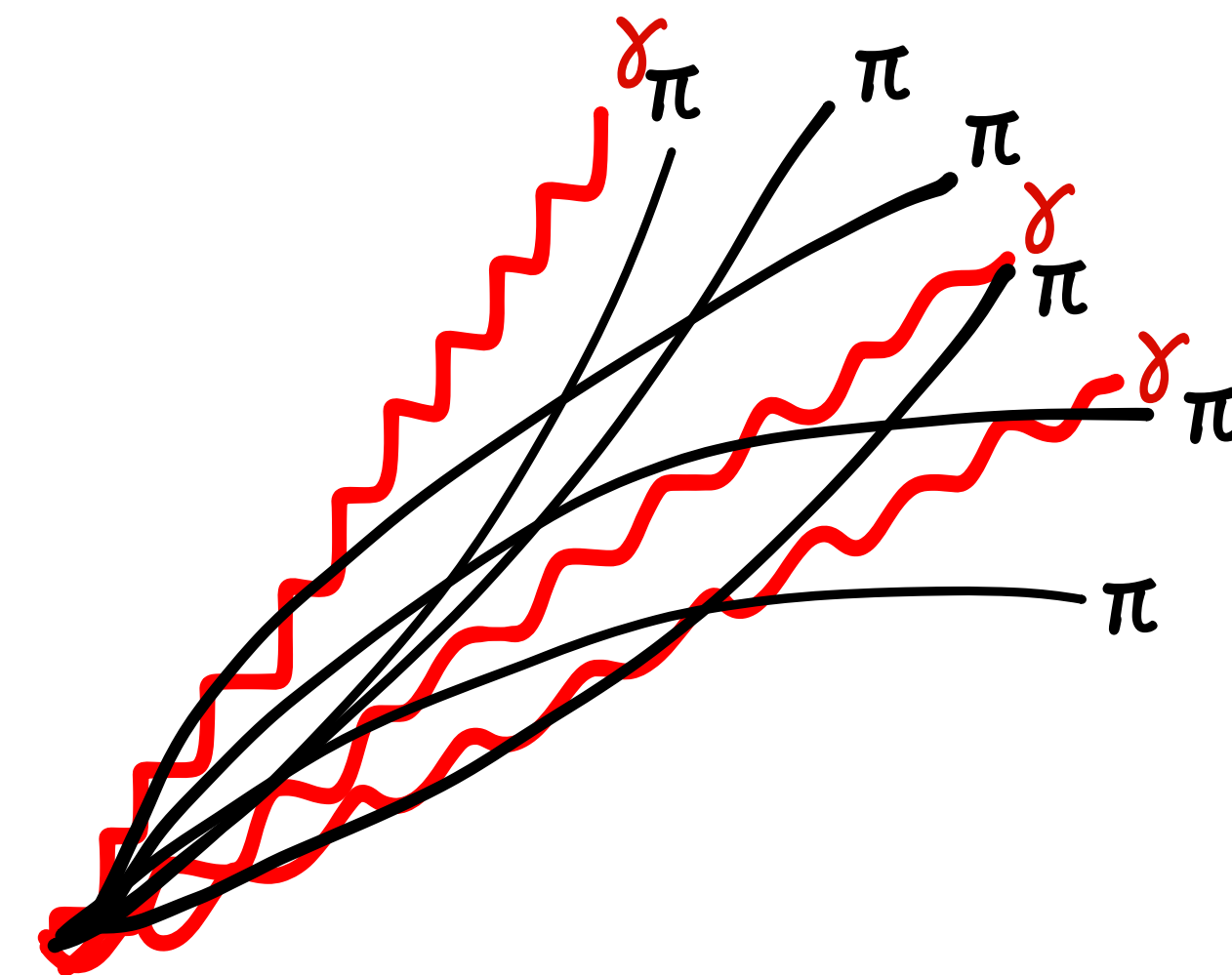
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EM Calorimeters

- Long-lived Neutral Hadrons: ~10%



Recall: Jet Composition

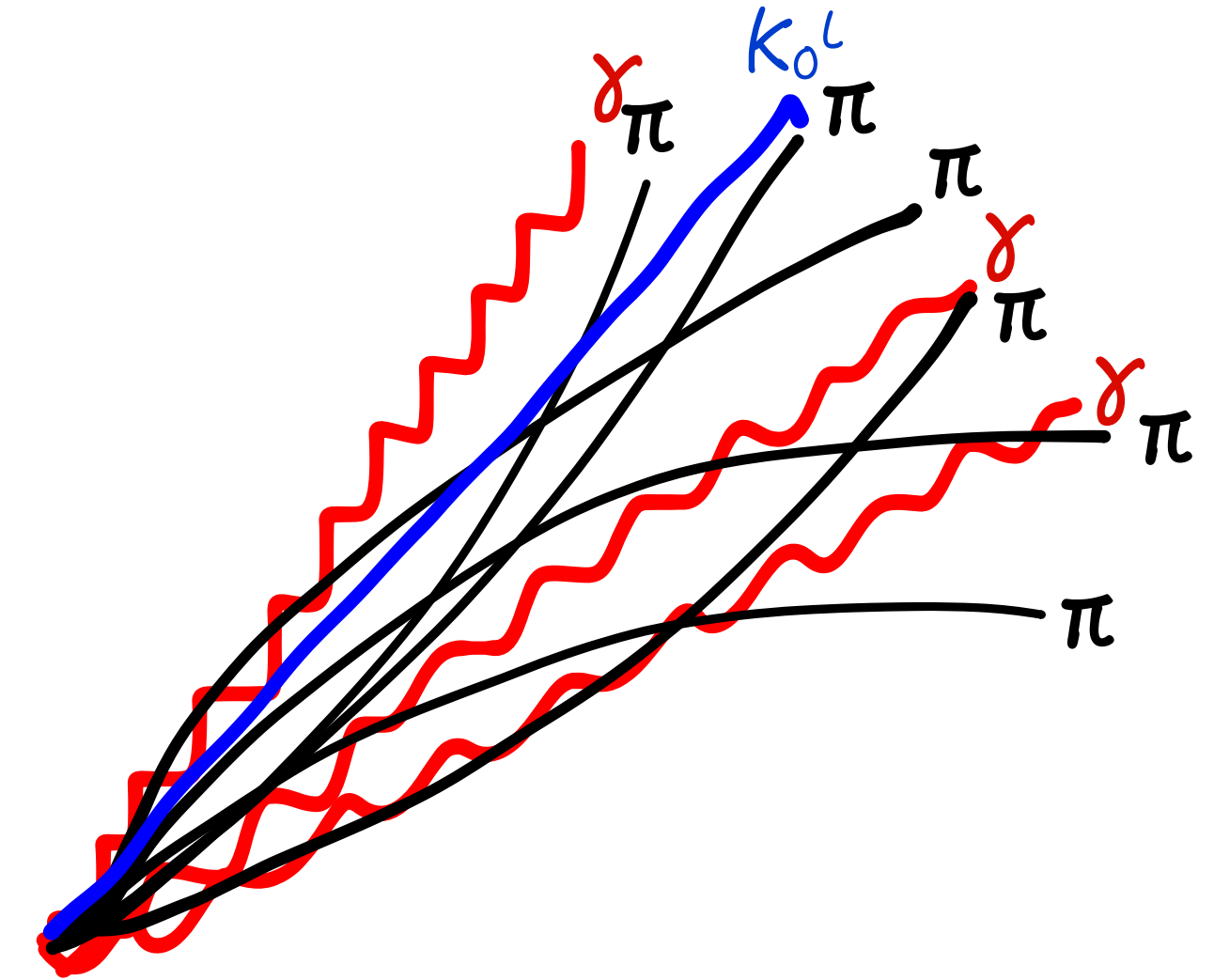
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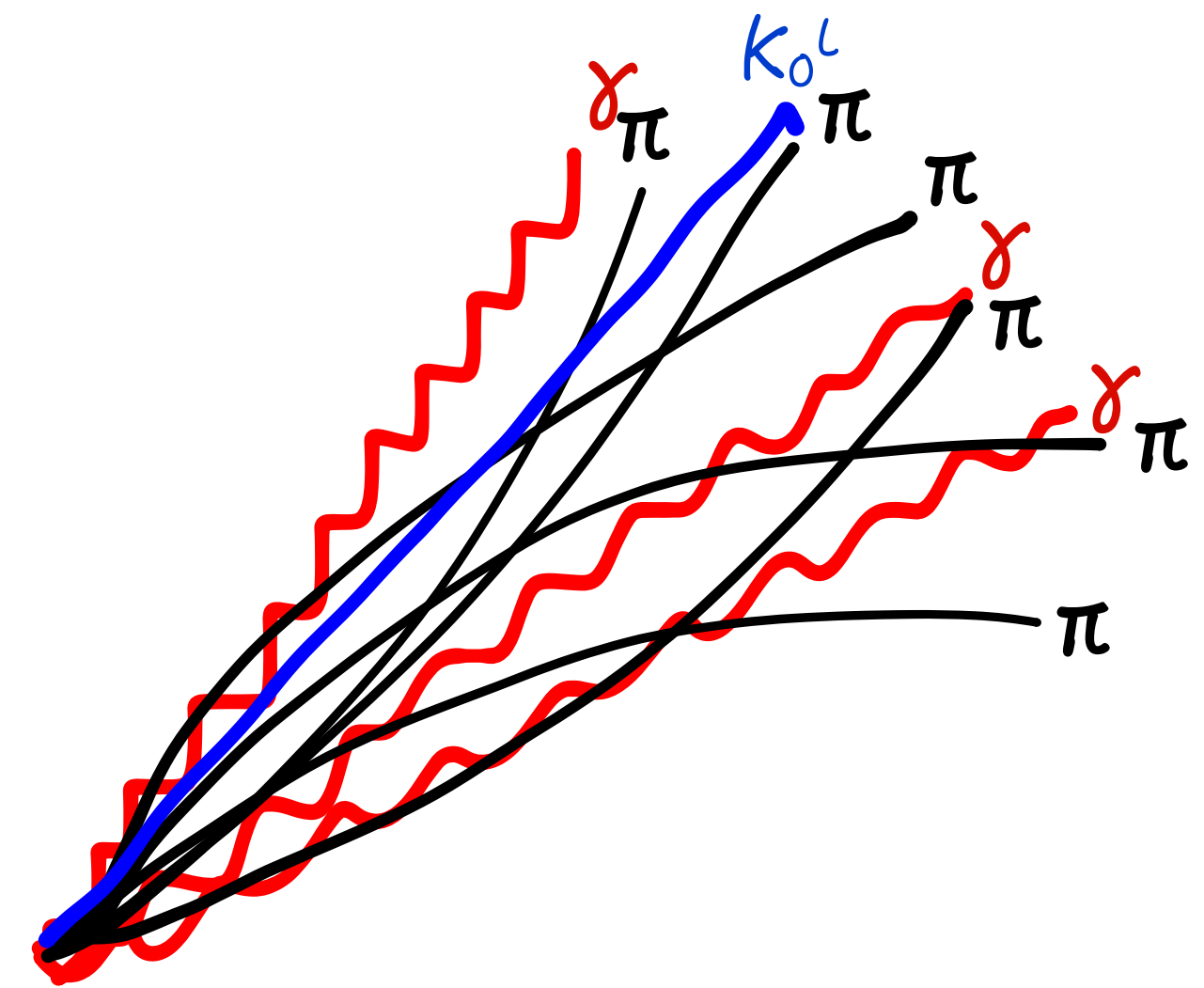
Tracking Detectors

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HAD Calorimeters



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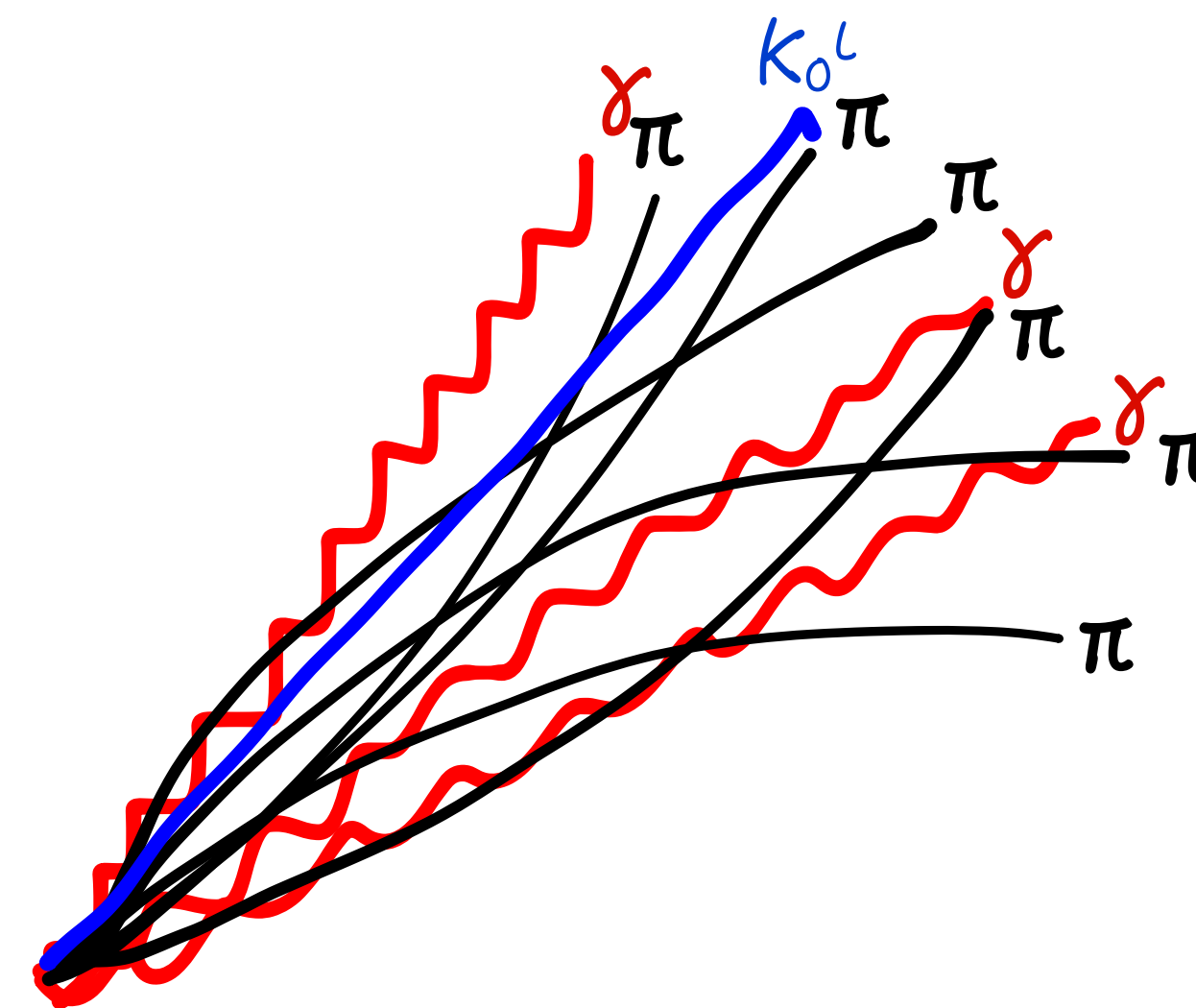
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HAD Calorimeters

- Short-lived Neutral Hadrons: ~5%



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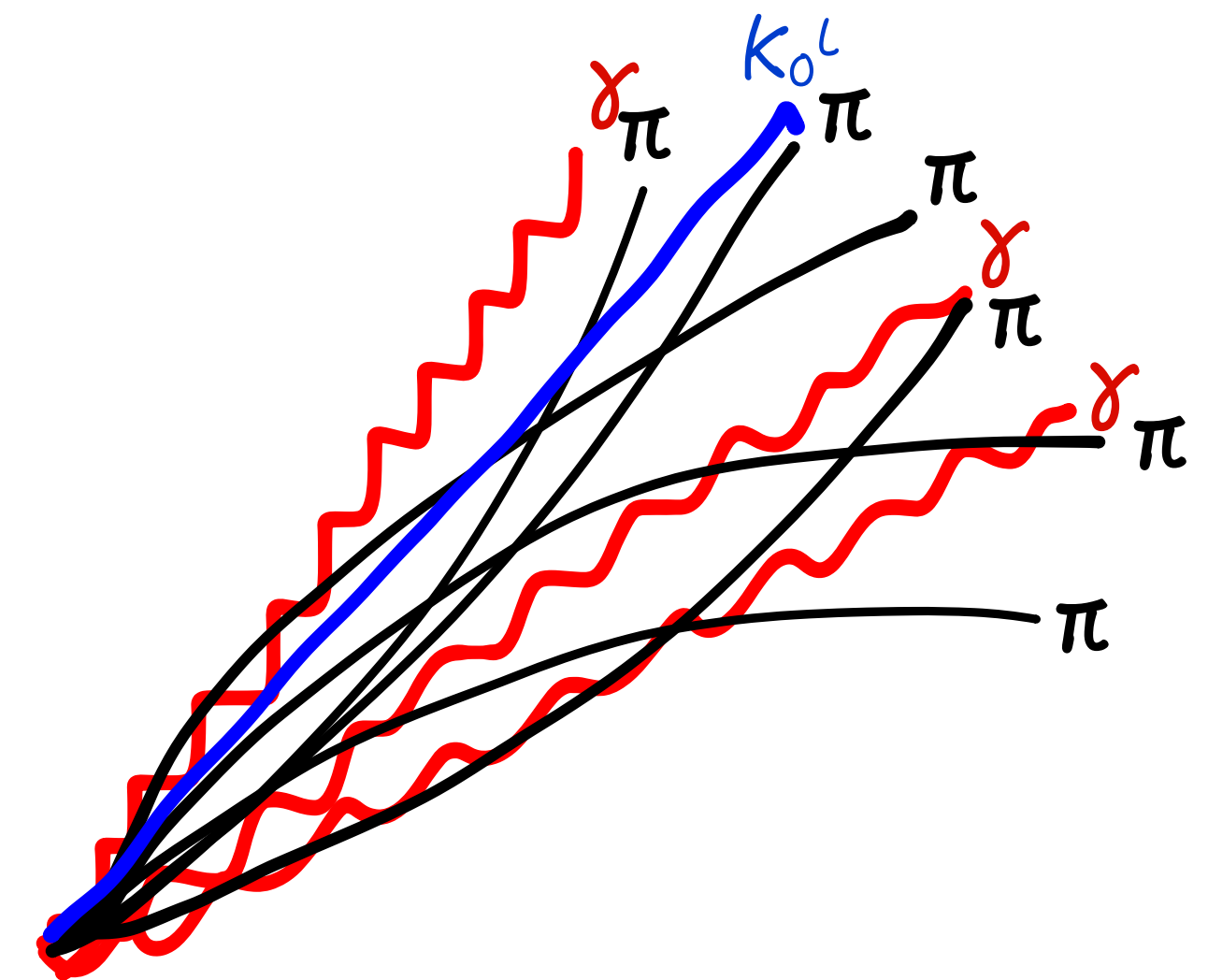
EM Calorimeters

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HAD Calorimeters

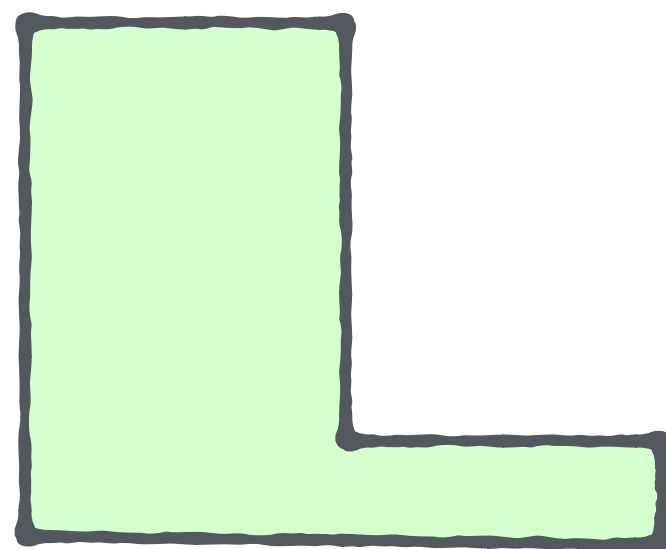
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Tracking Detectors



Recall: Associate hits within each detector

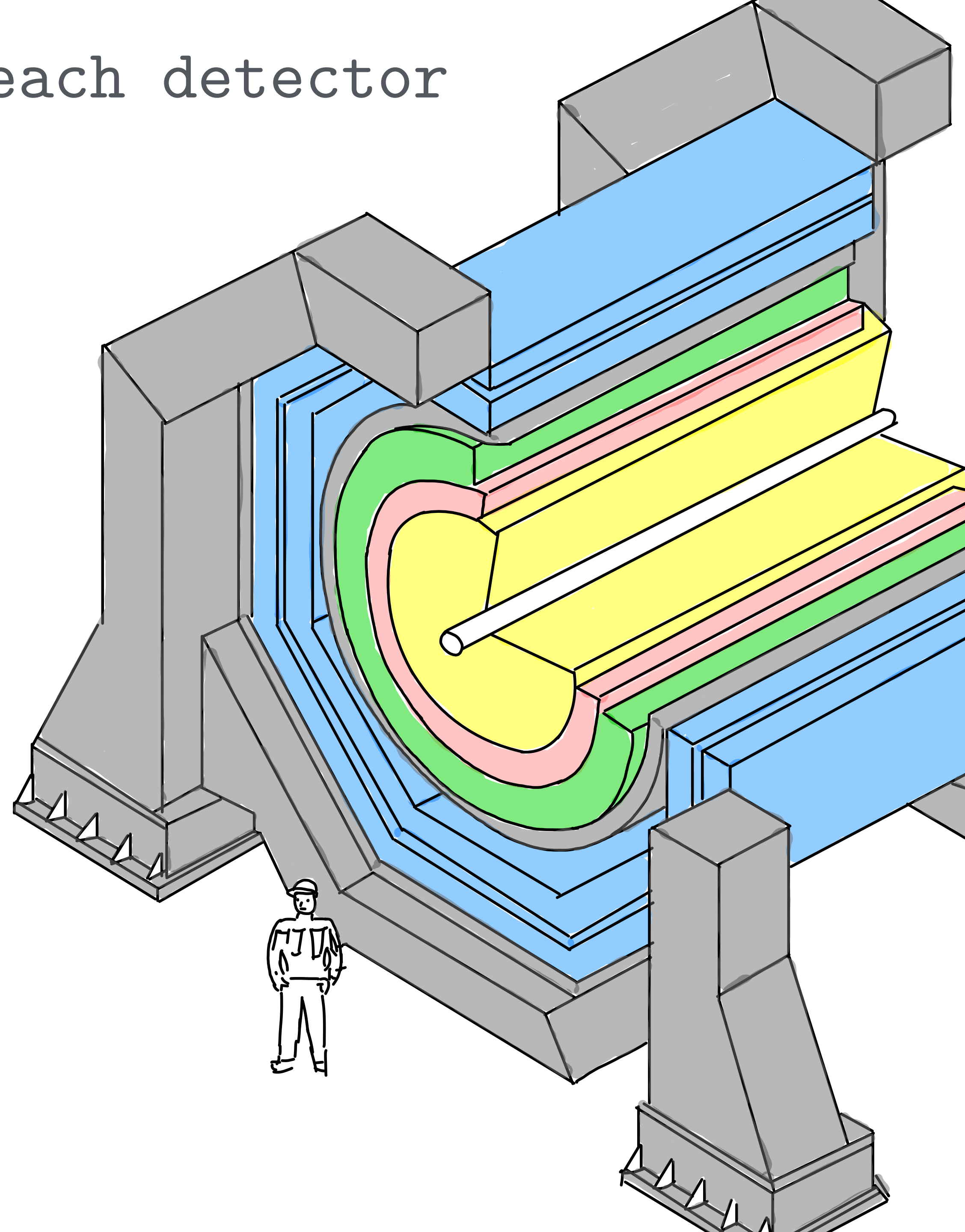
HCAL Clusters



ECAL Clusters

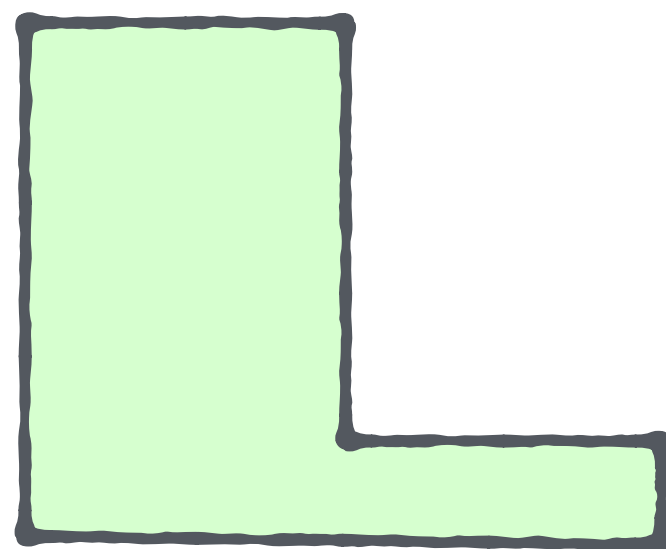


Tracks



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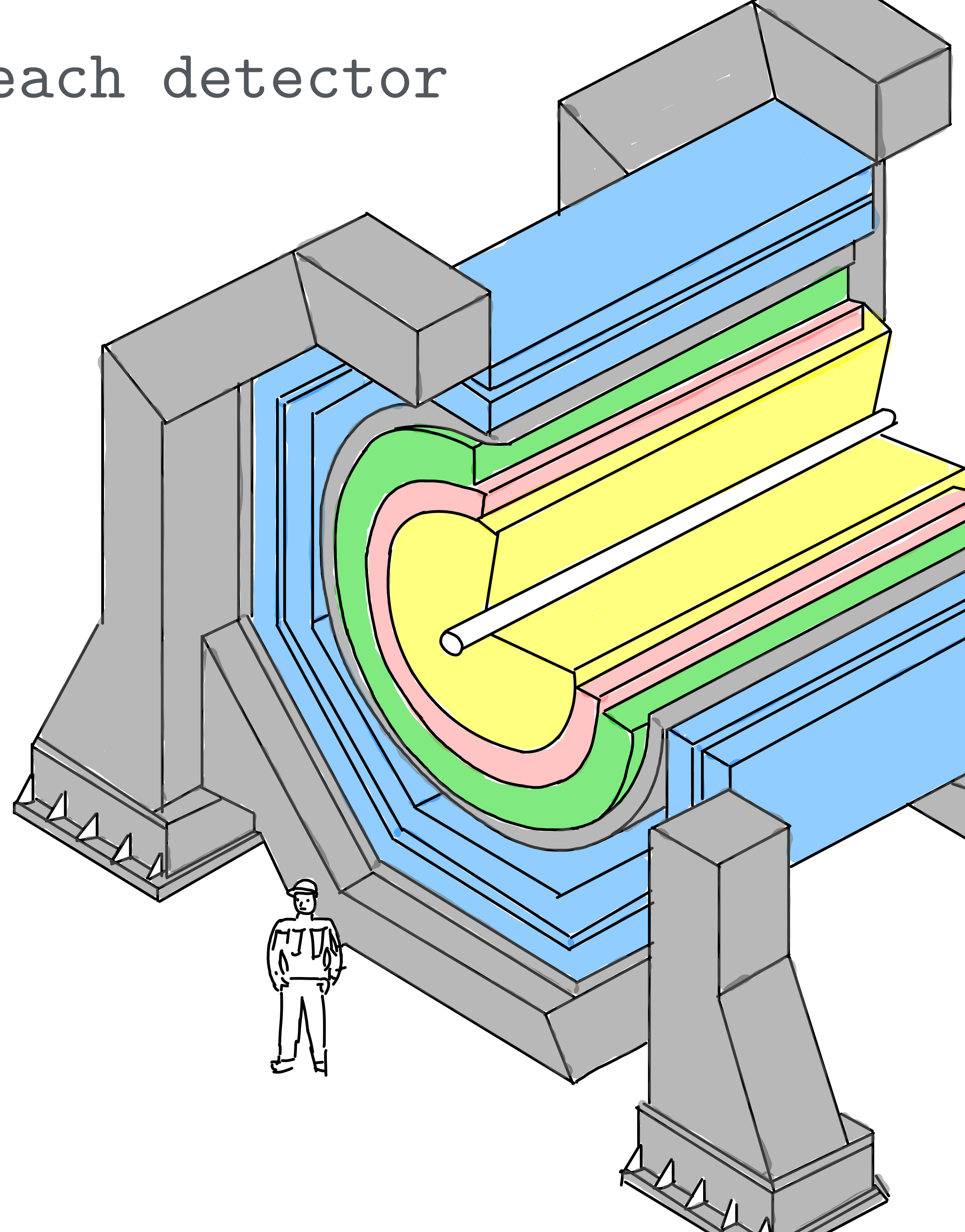


ECAL Clusters

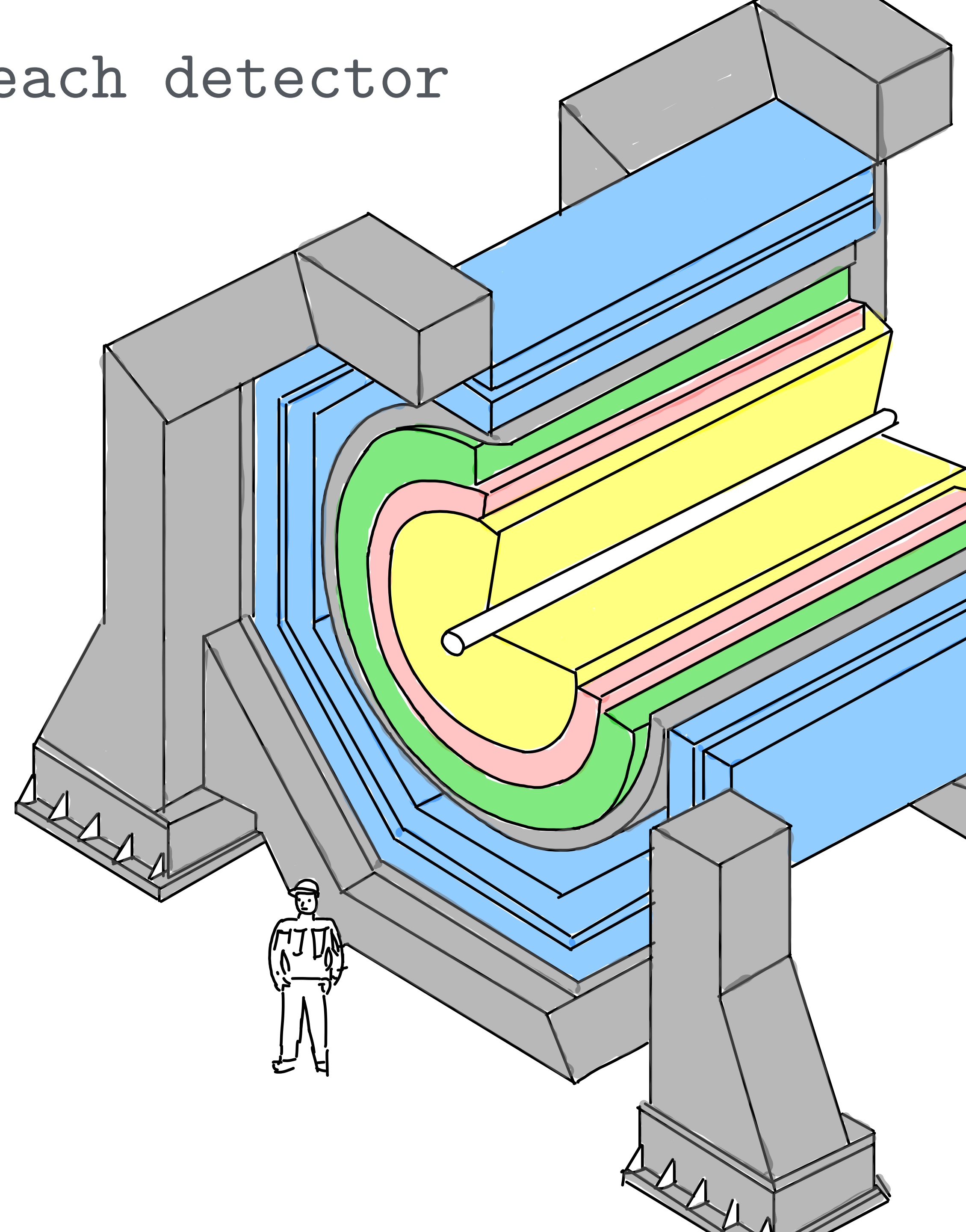
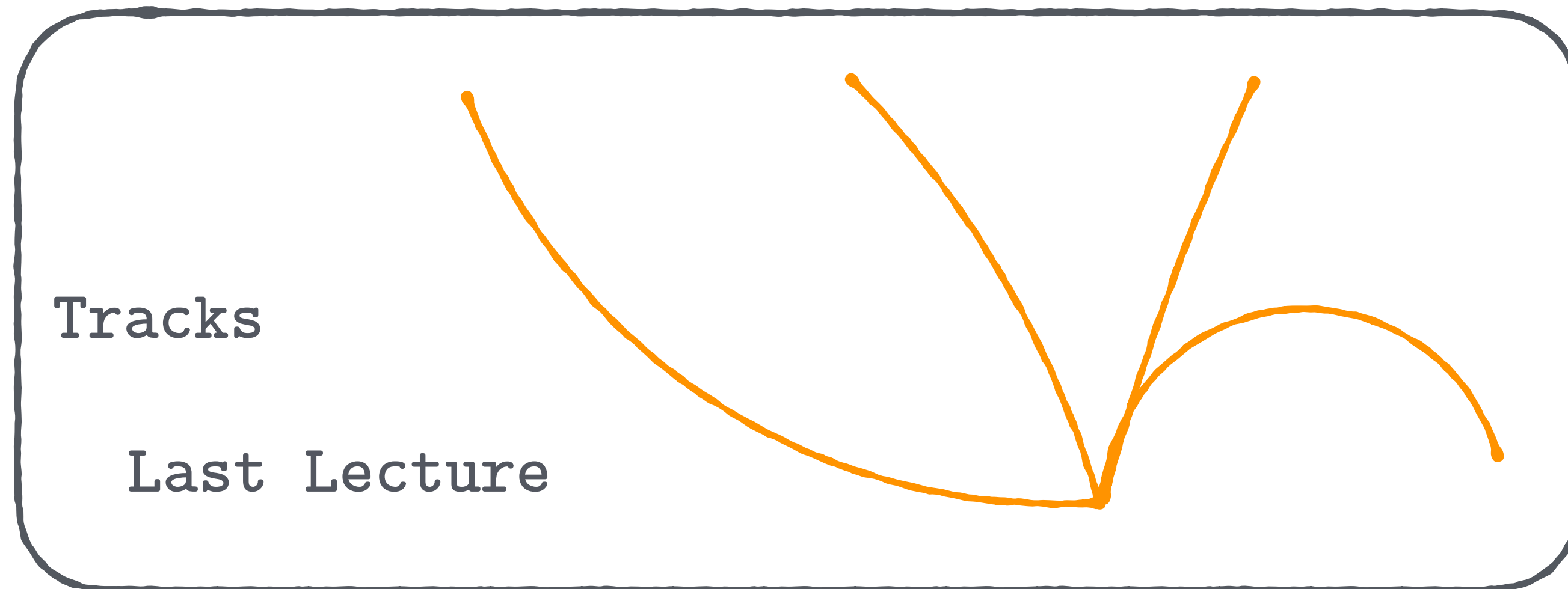
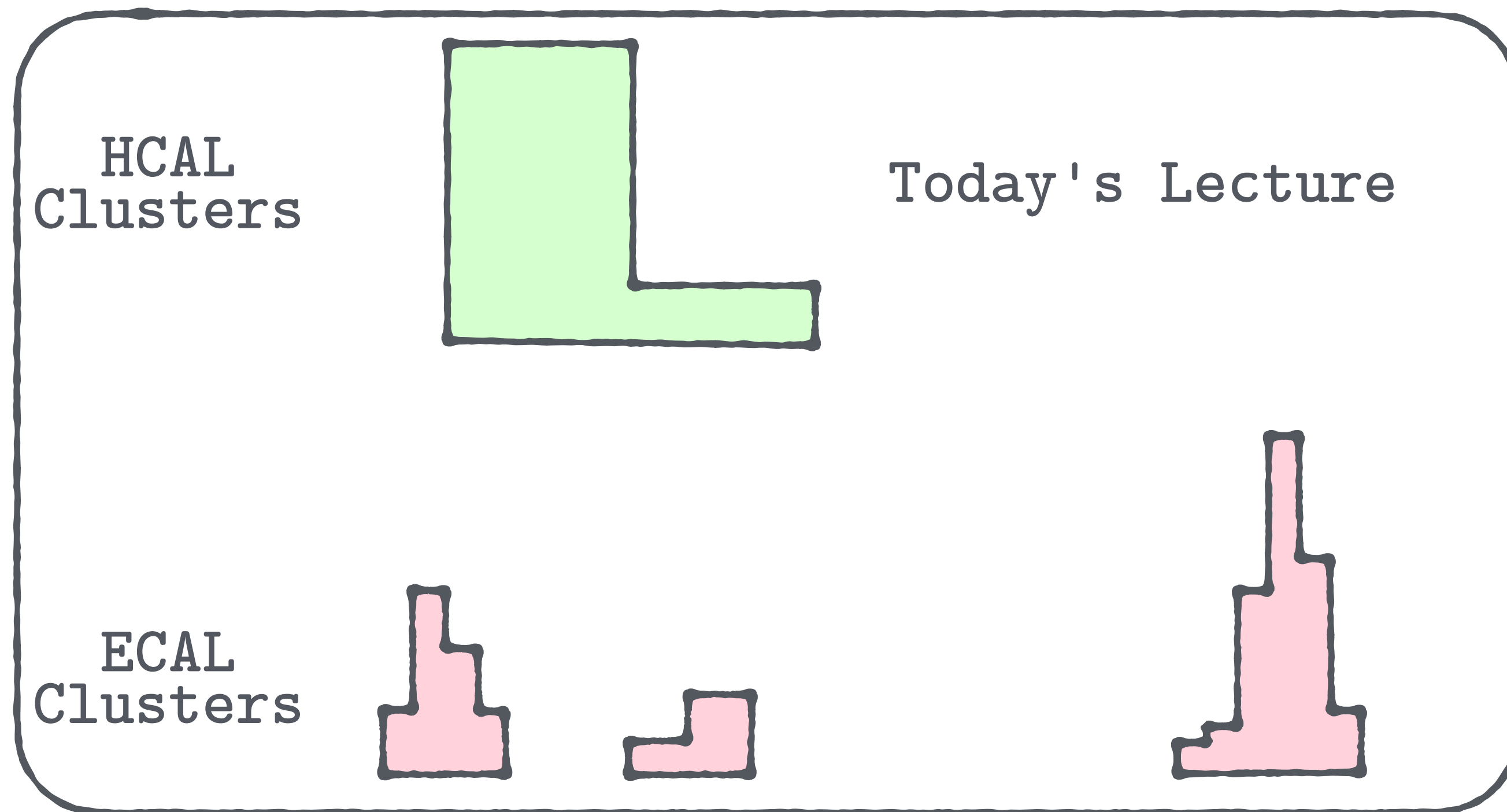


Tracks

Last Lecture

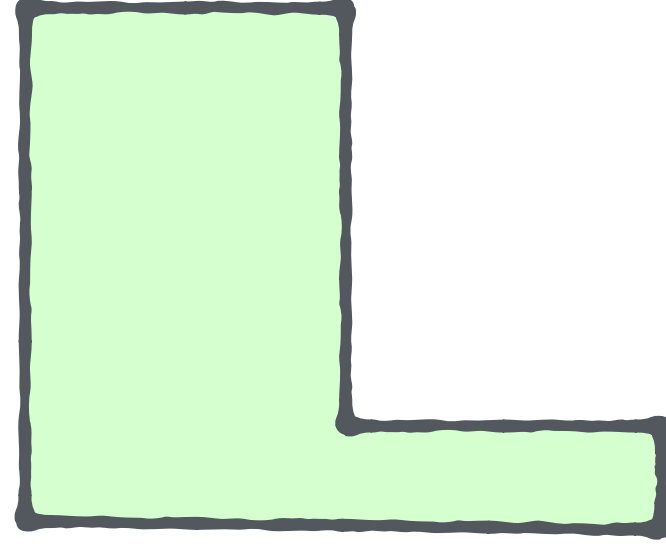


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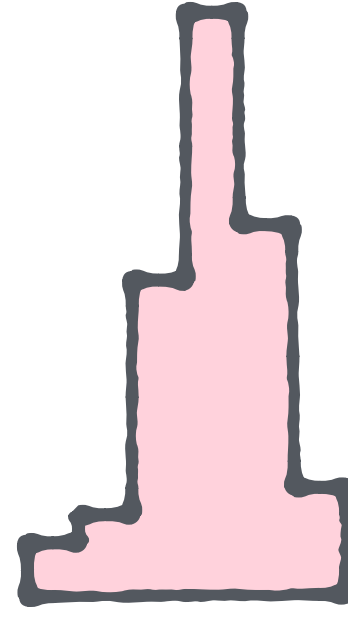
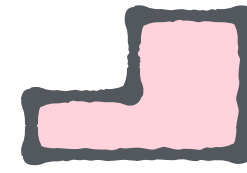
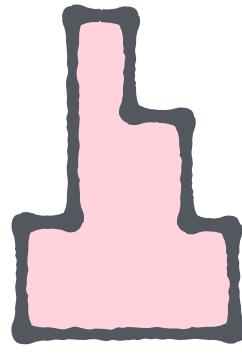


Calorimeter Clustering

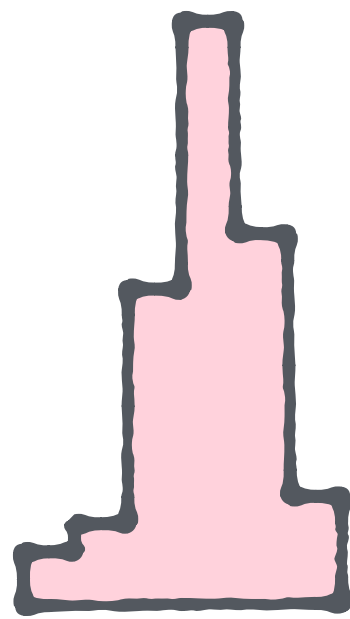
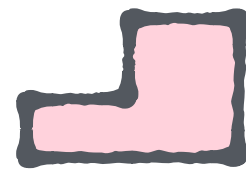
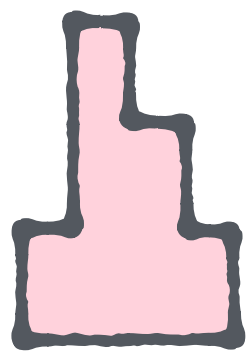
HCAL
Clusters



ECAL
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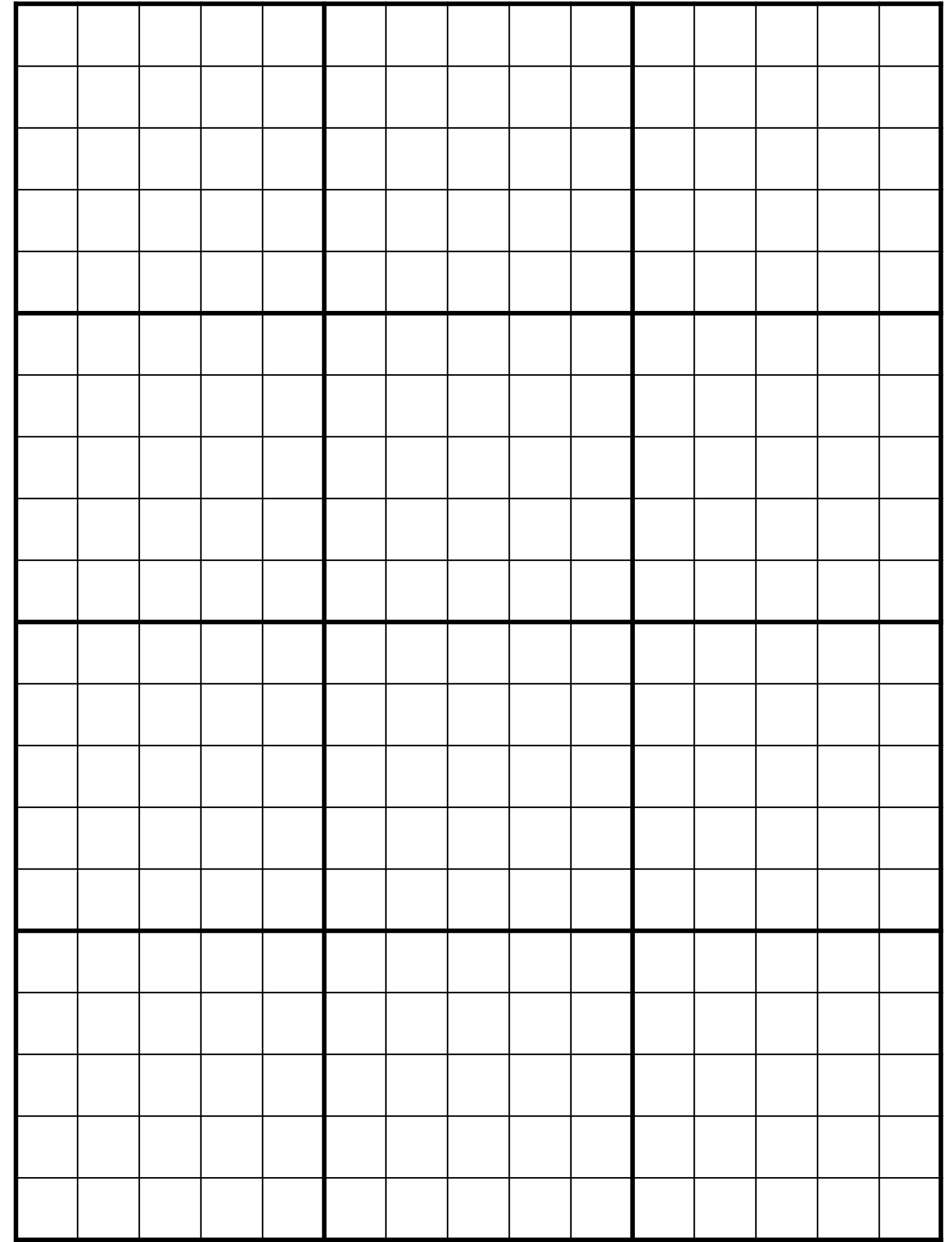


ECAL
Clusters



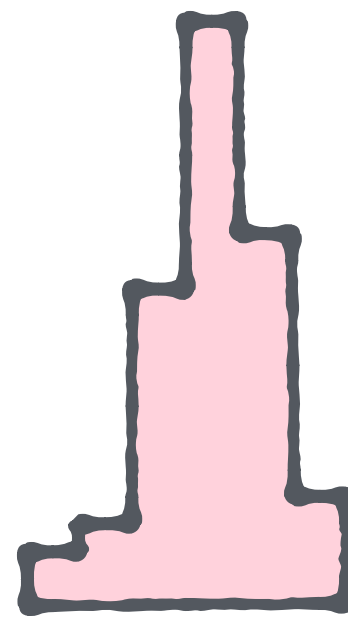
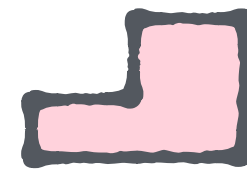
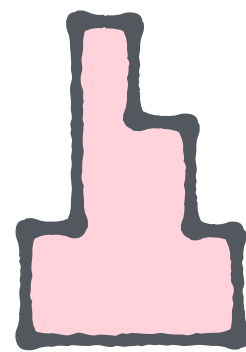
Calorimeter Clustering

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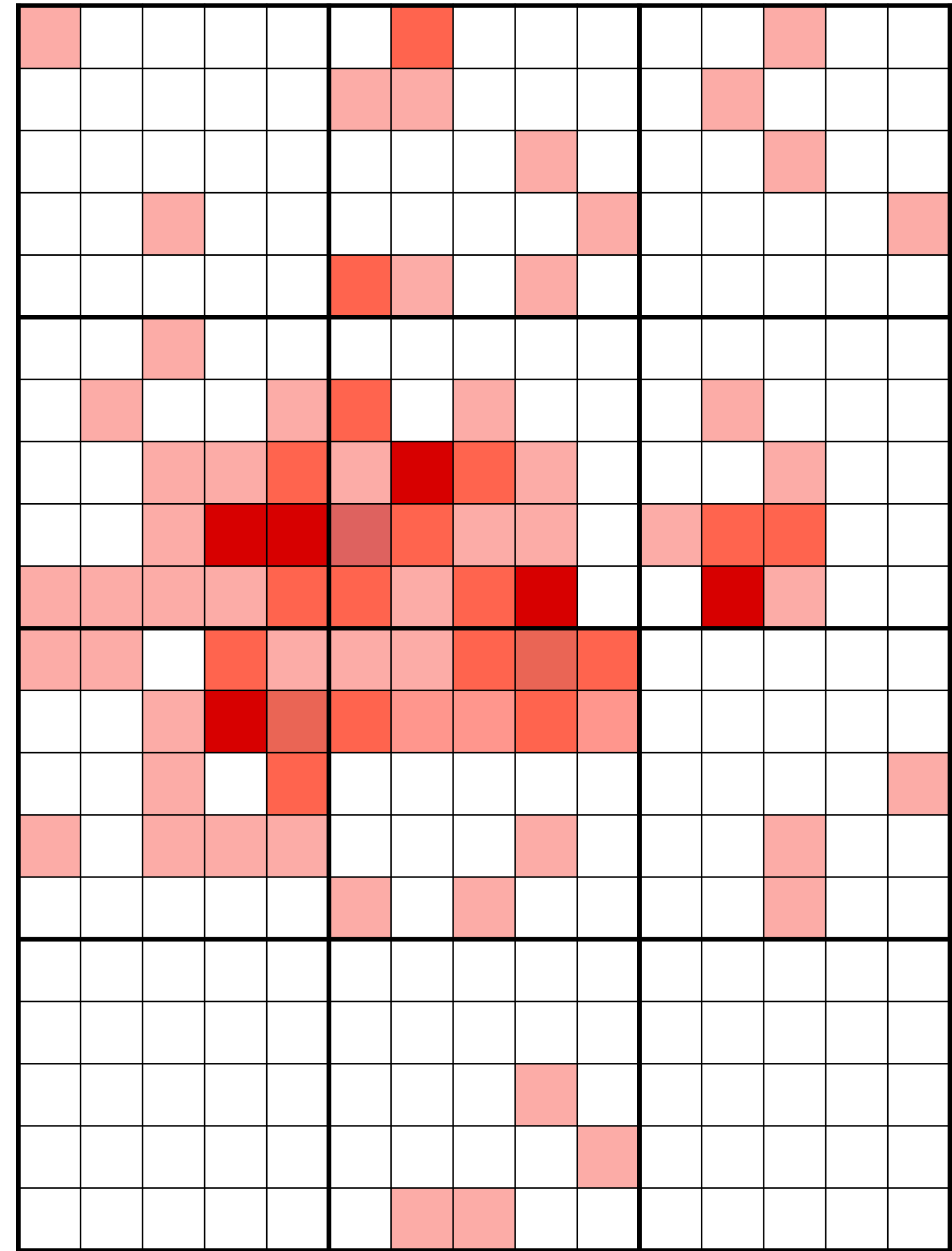
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ECAL
Clusters



Calorimeter Clustering

ϕ

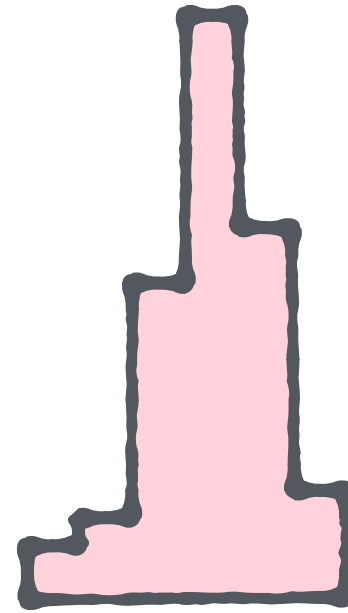
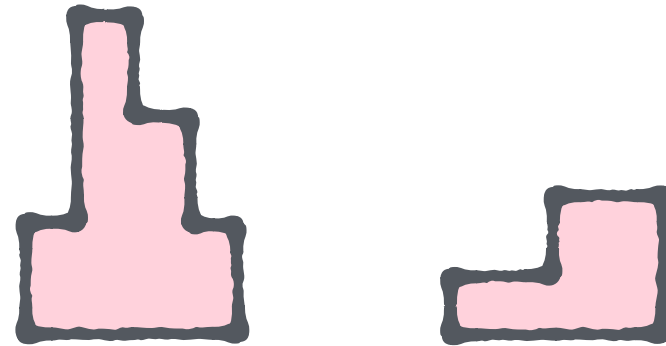


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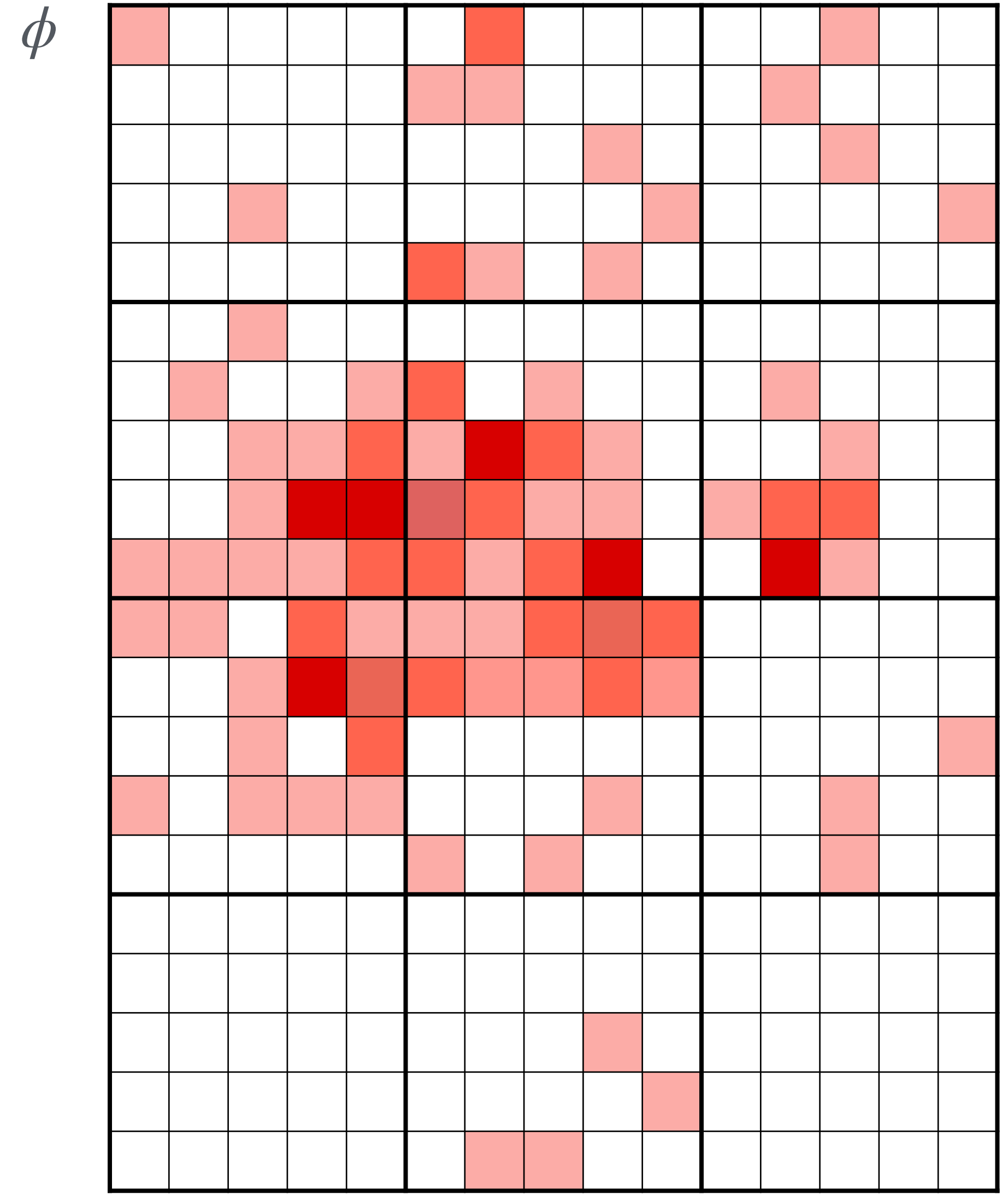
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- Any cell that is above some energy threshold
- Local maximum: energy larger than all neighbouring cells

ECAL Clusters



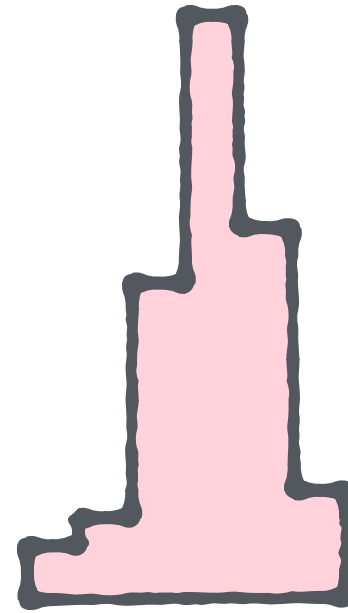
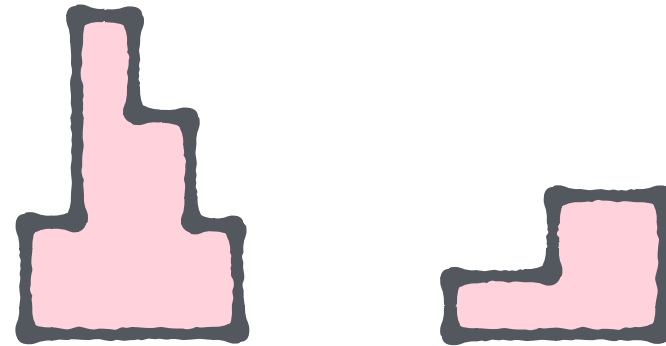
Calorimeter Clustering



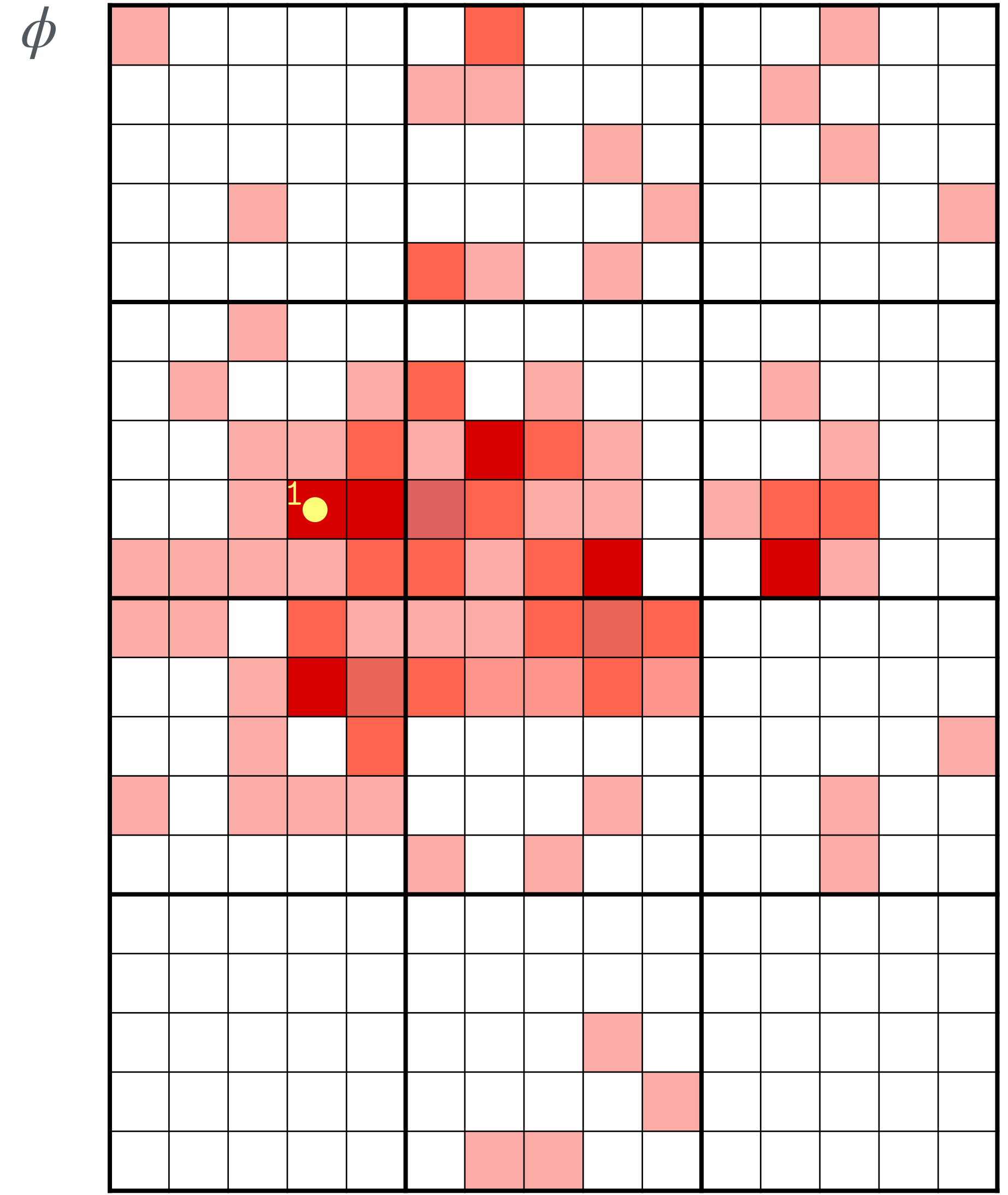
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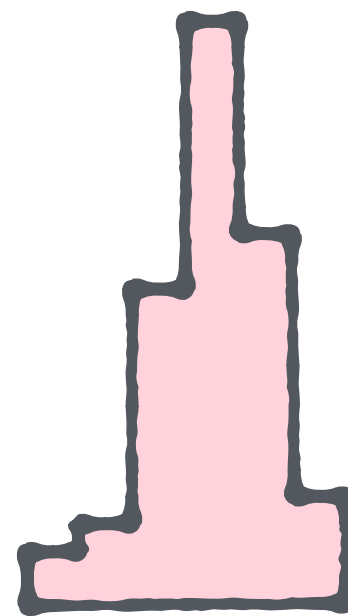
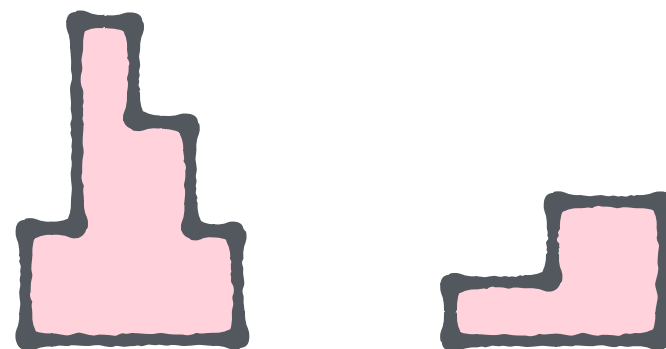
Calorimeter Clustering



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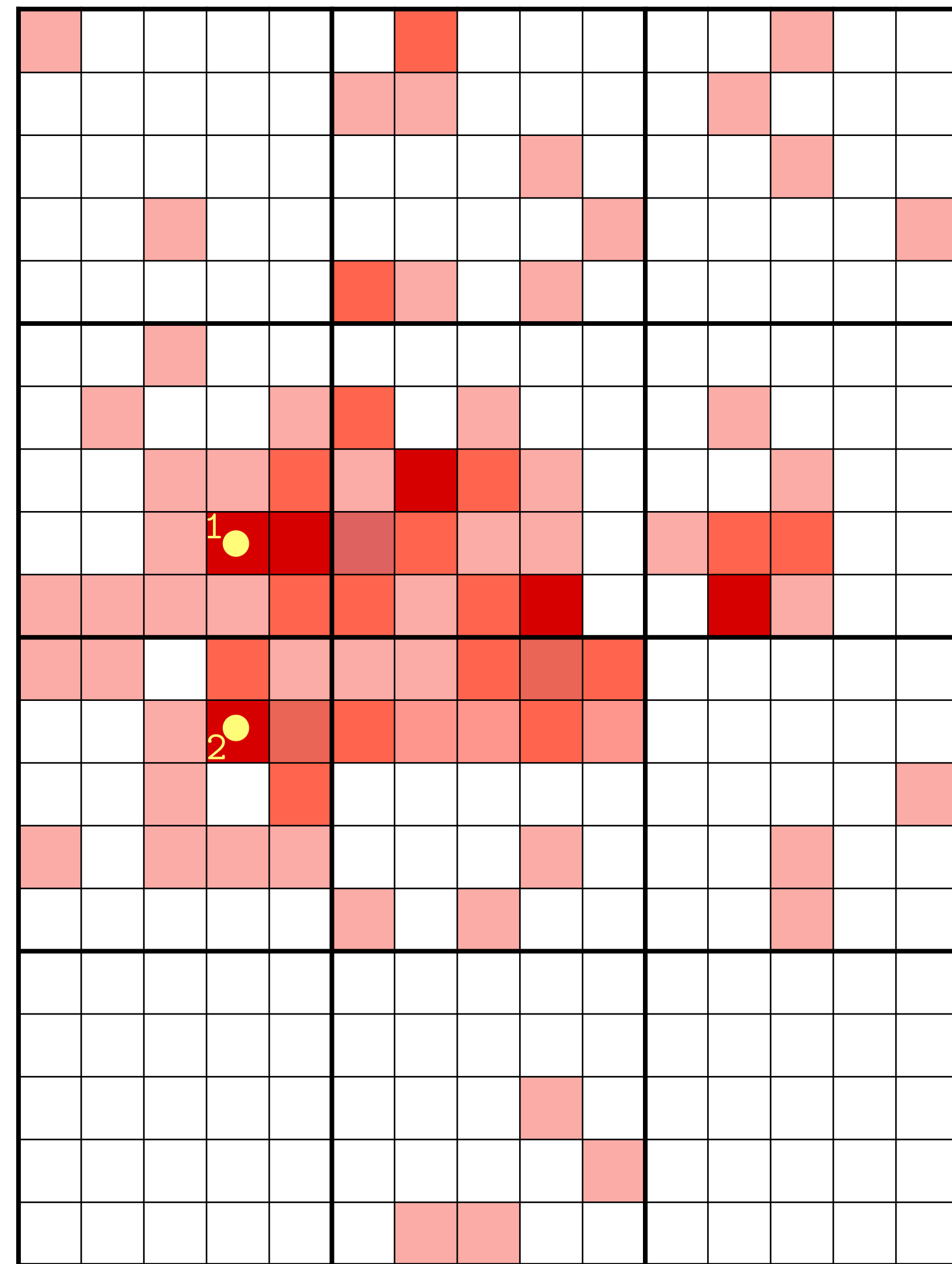
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Calorimeter Clustering

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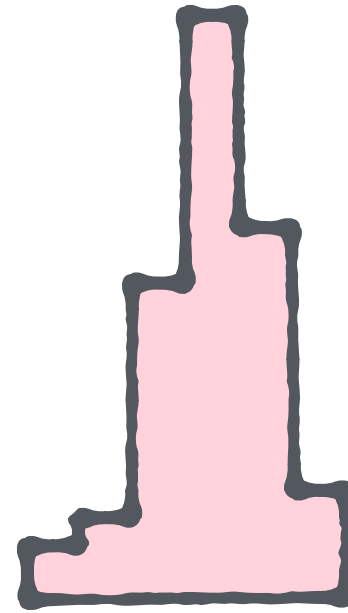
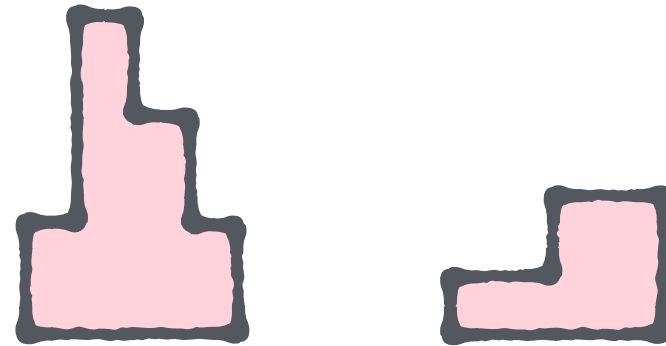


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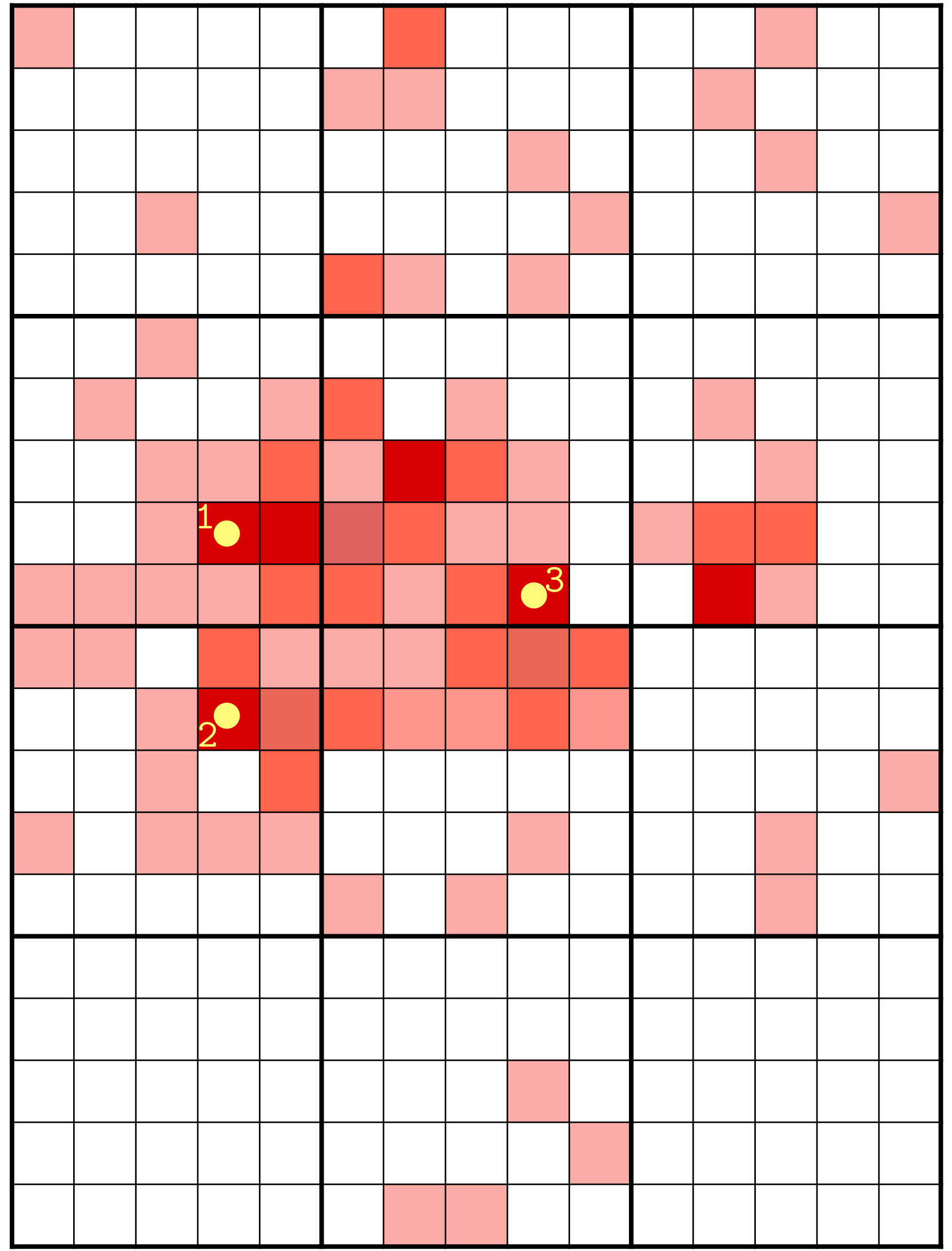
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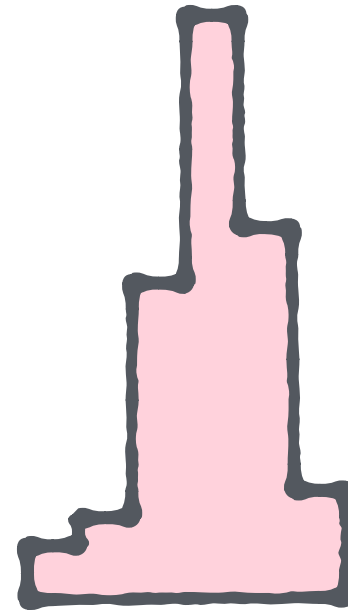
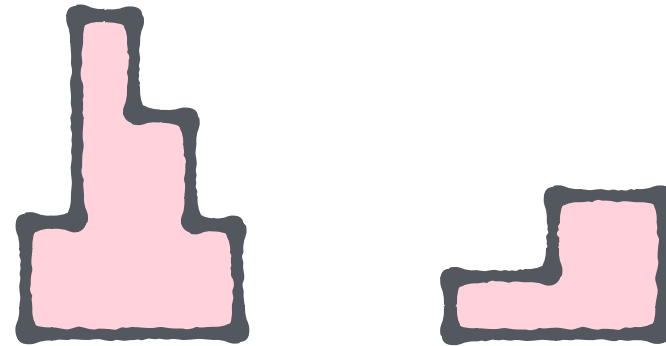


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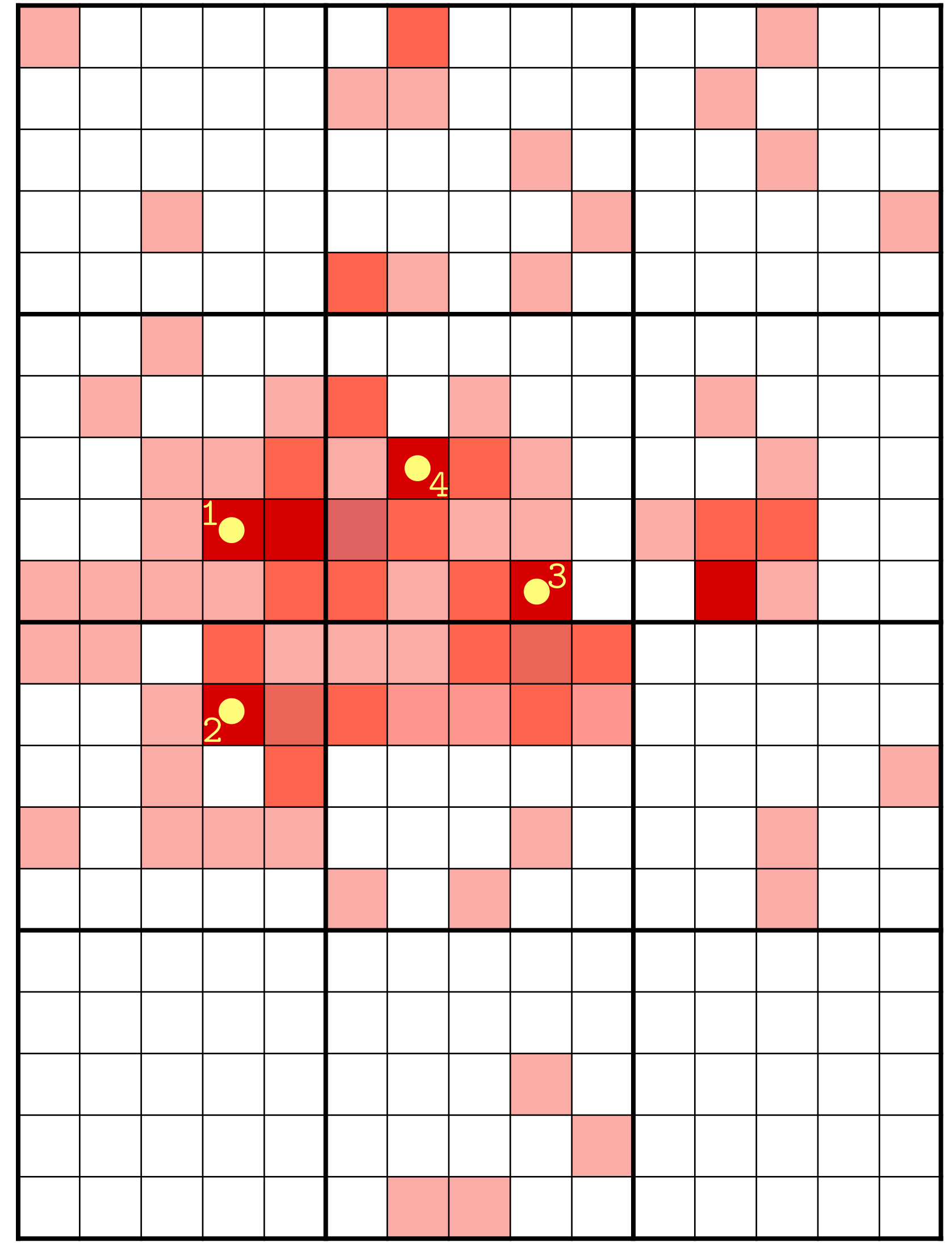
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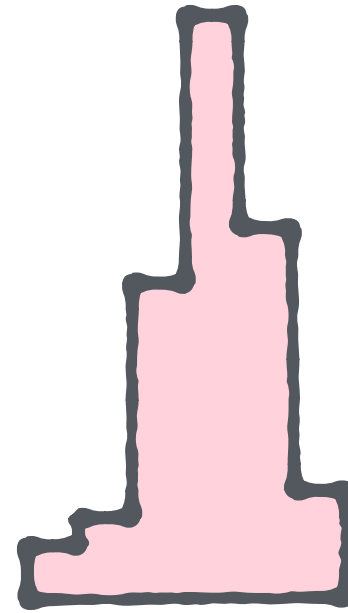
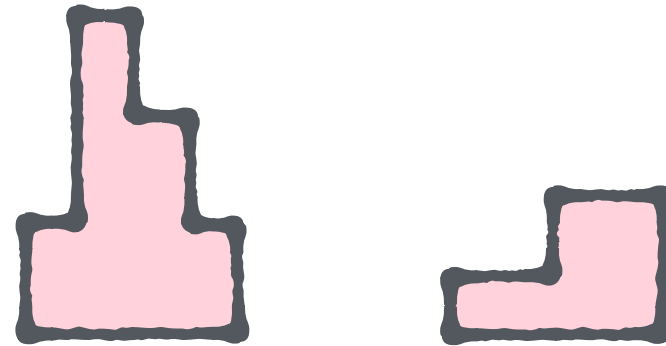


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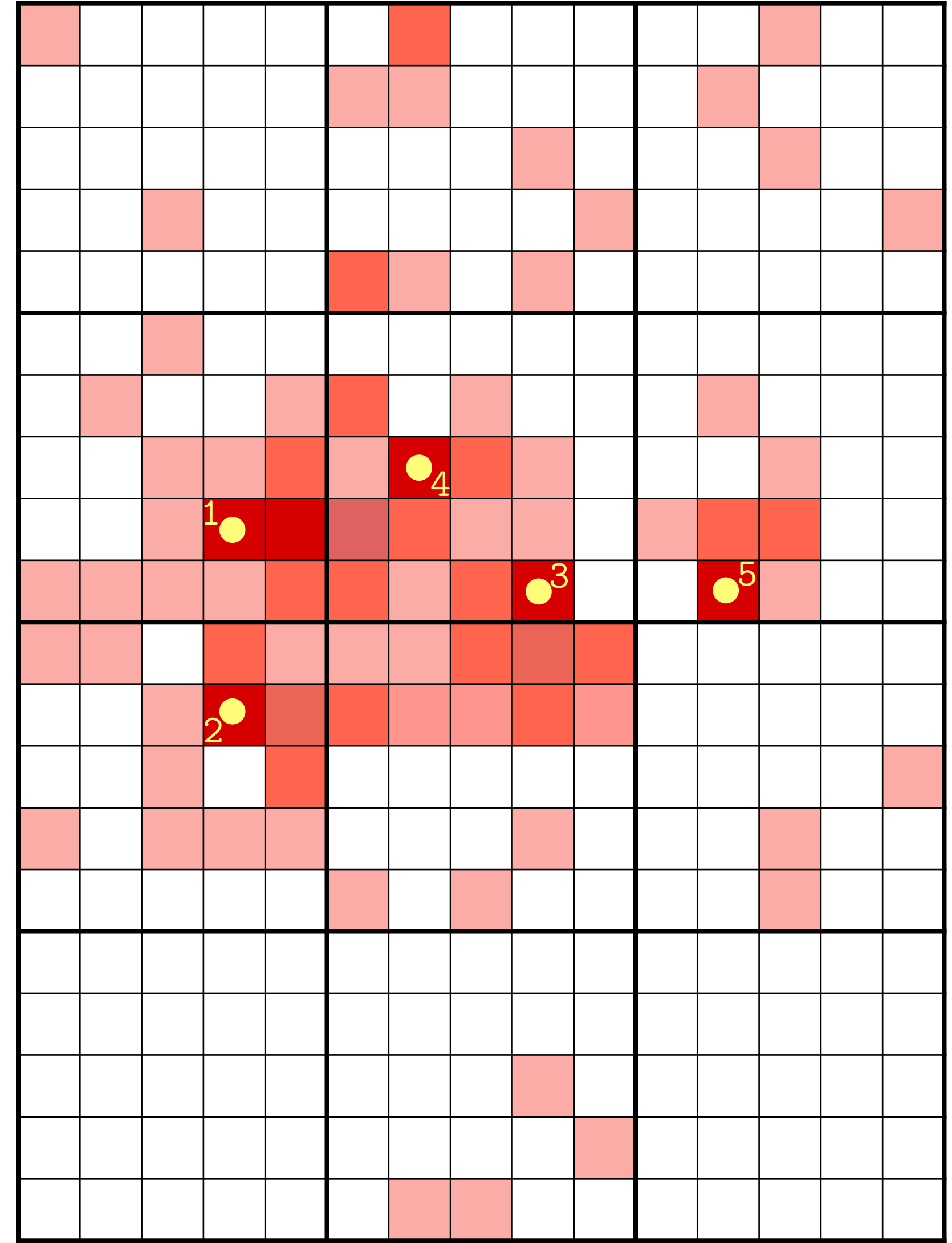
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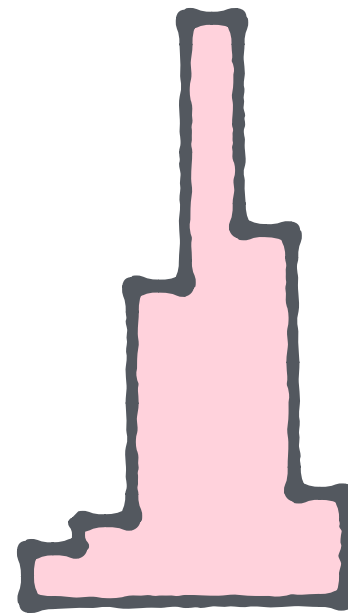
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Step 2: Form Topological Clusters

- Grown from seeds
- Consider only cells with energy above:

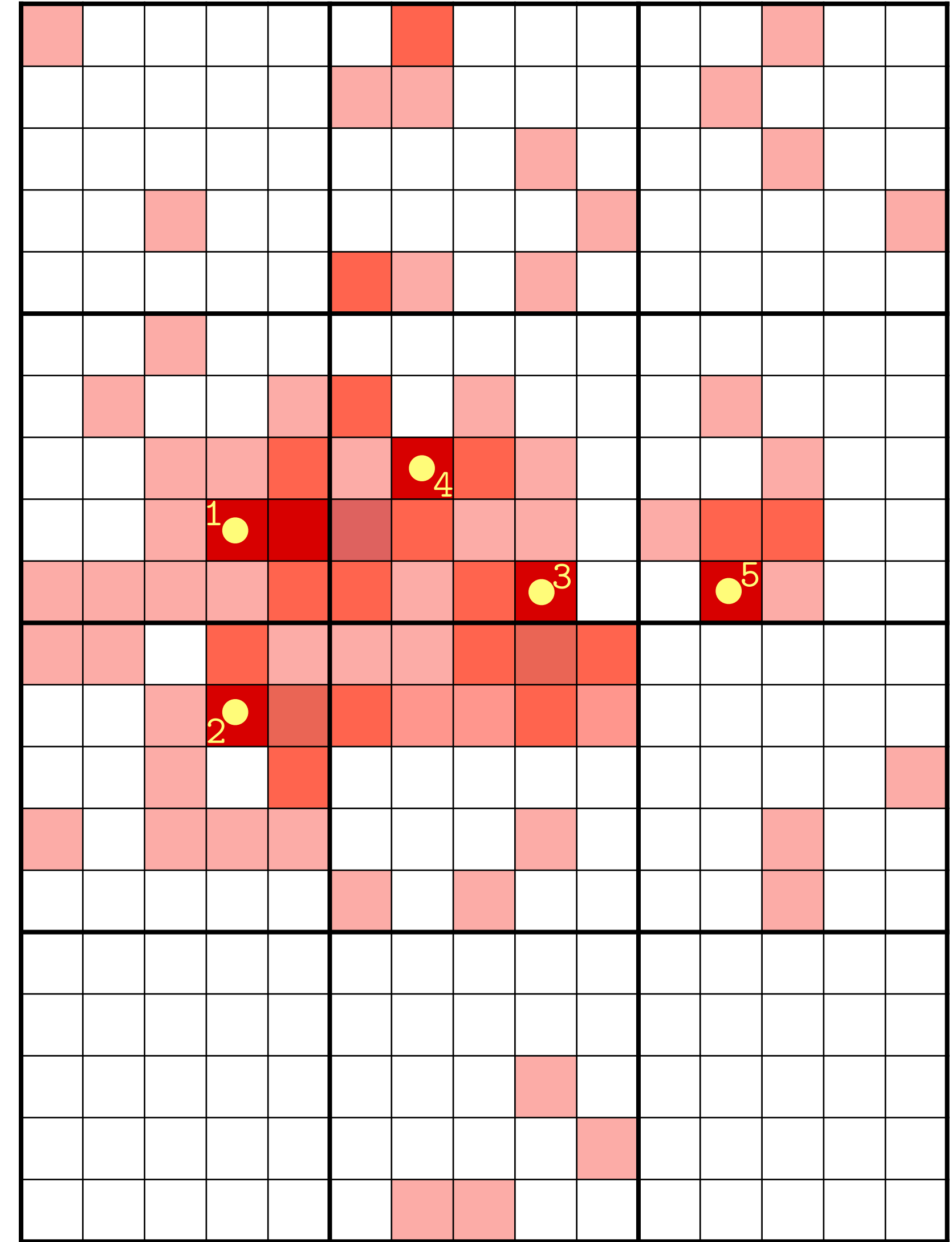
$$E + 2 \sigma_{\text{noise}}(E)$$

- Aggregate all cells with at least a corner in common with cell already in cluster



Calorimeter Clustering

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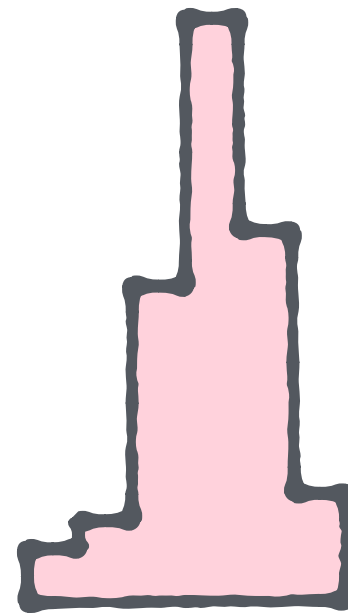
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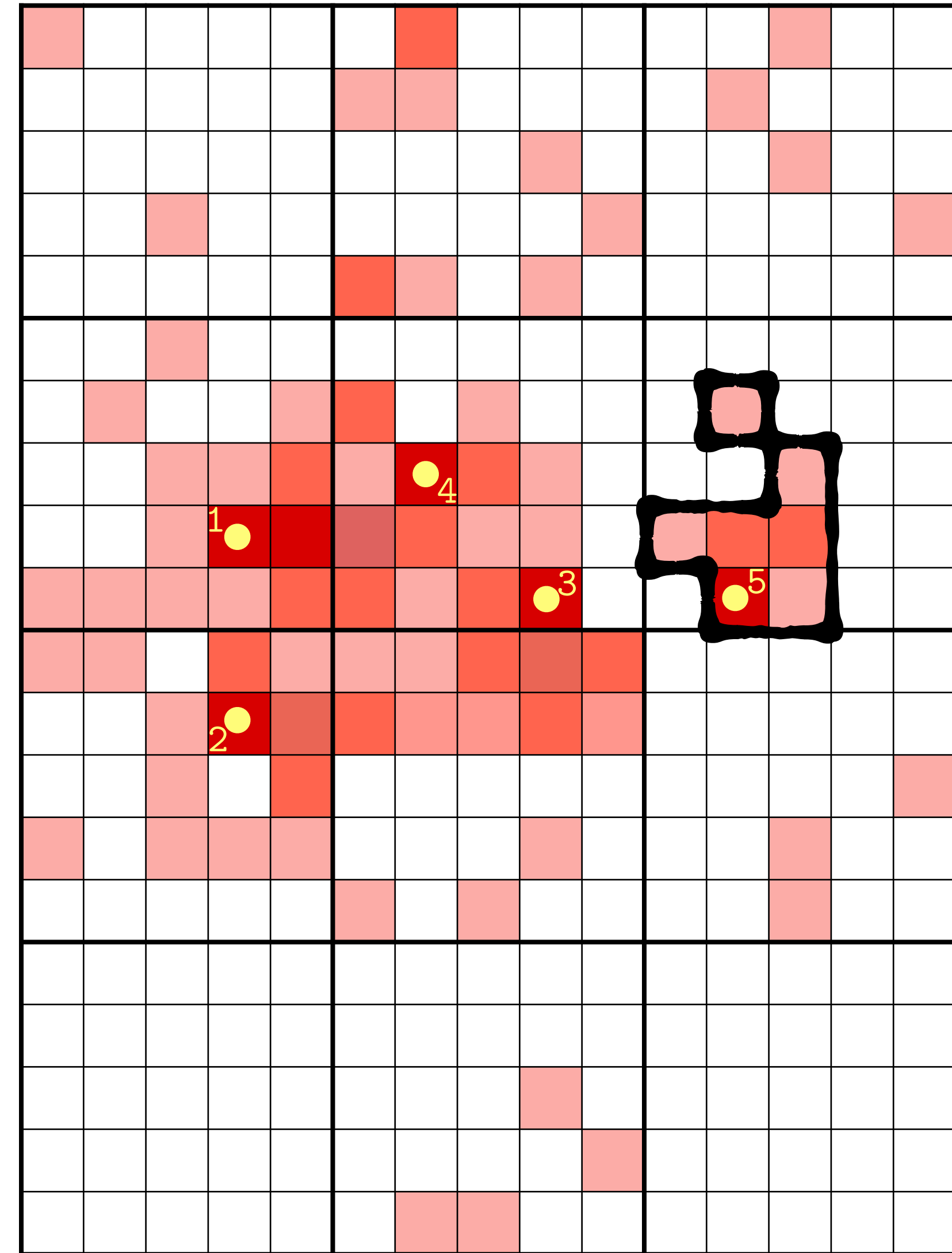
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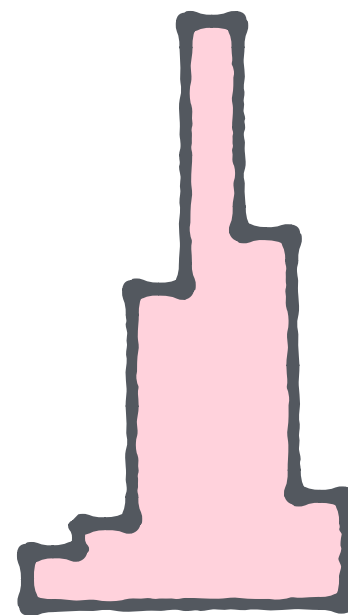
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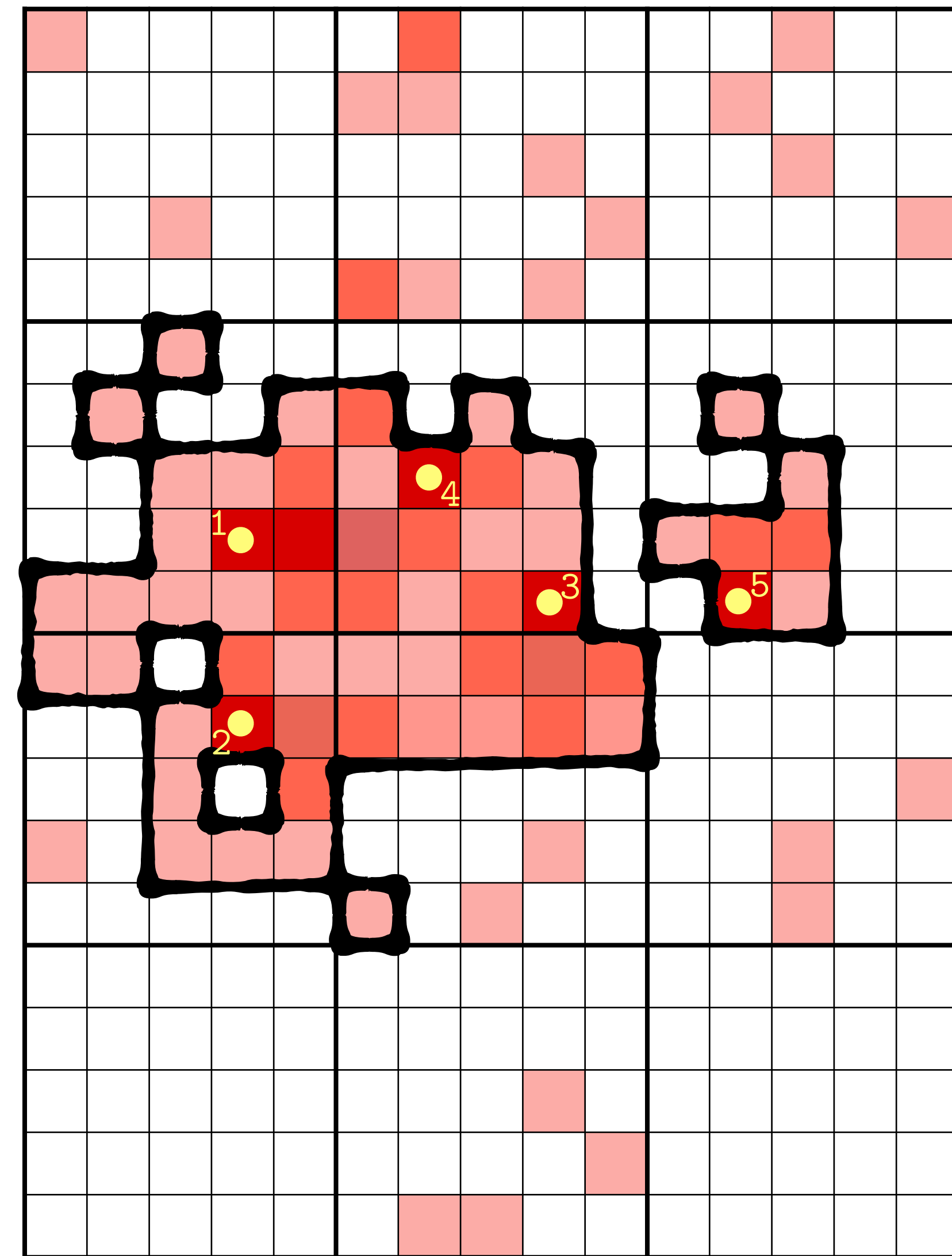
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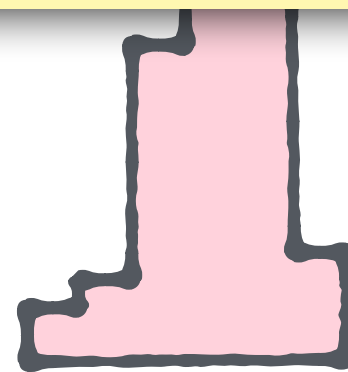
Step 3: Share energy in Topological Cluster

- Single seed clusters with N cells:
- Energy is sum over all cells:

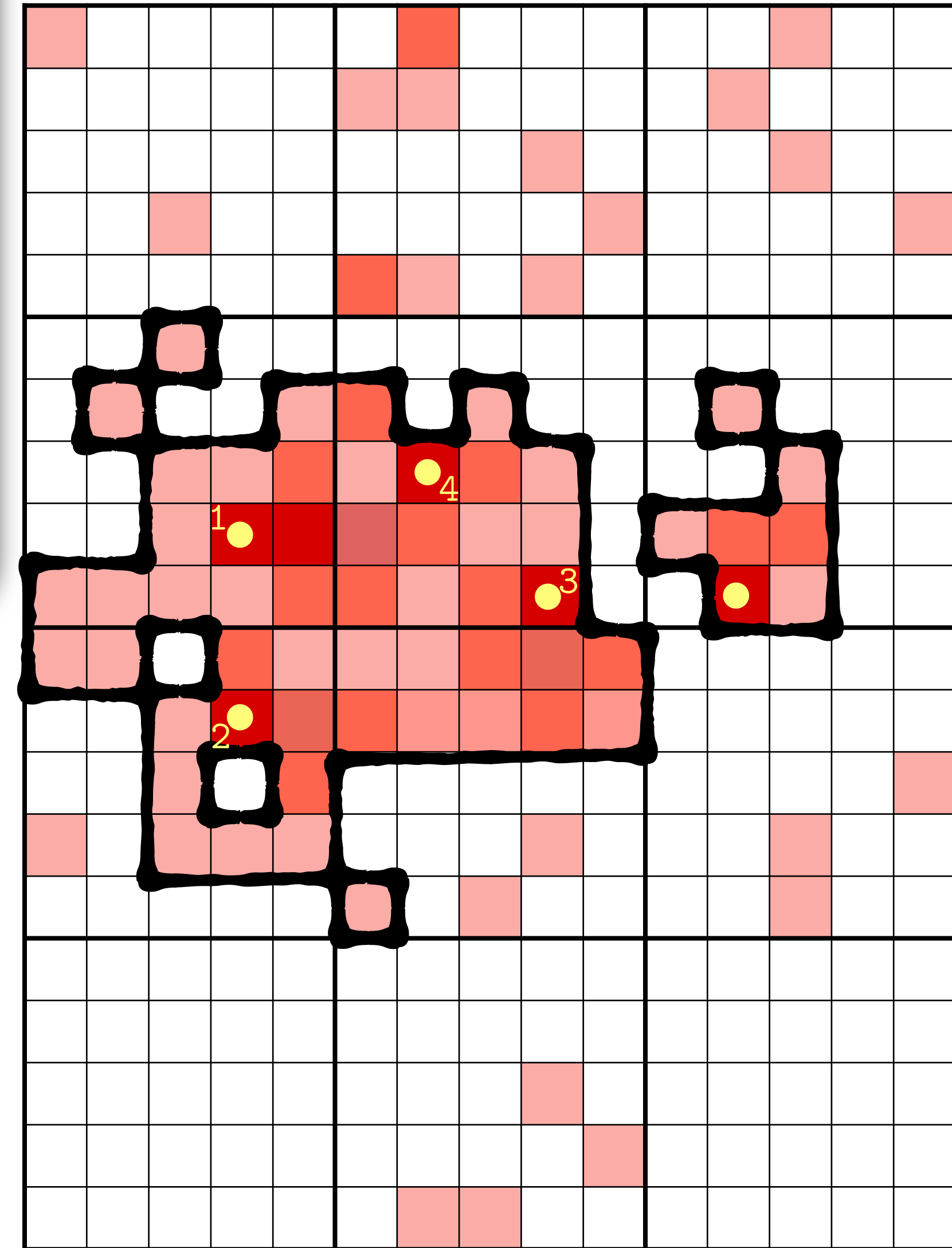
$$E = \sum_i^N E_i$$

- Position is energy weighted sum:

$$\vec{\mu} = \frac{1}{E_{\text{tot}}} \sum_i^N E_i \vec{x}_i$$



Calorimeter Clustering



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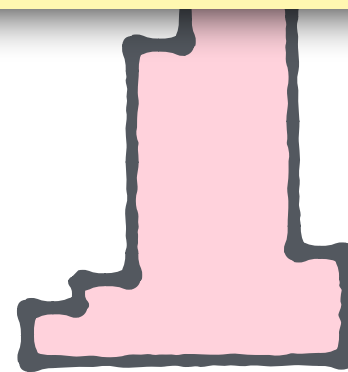
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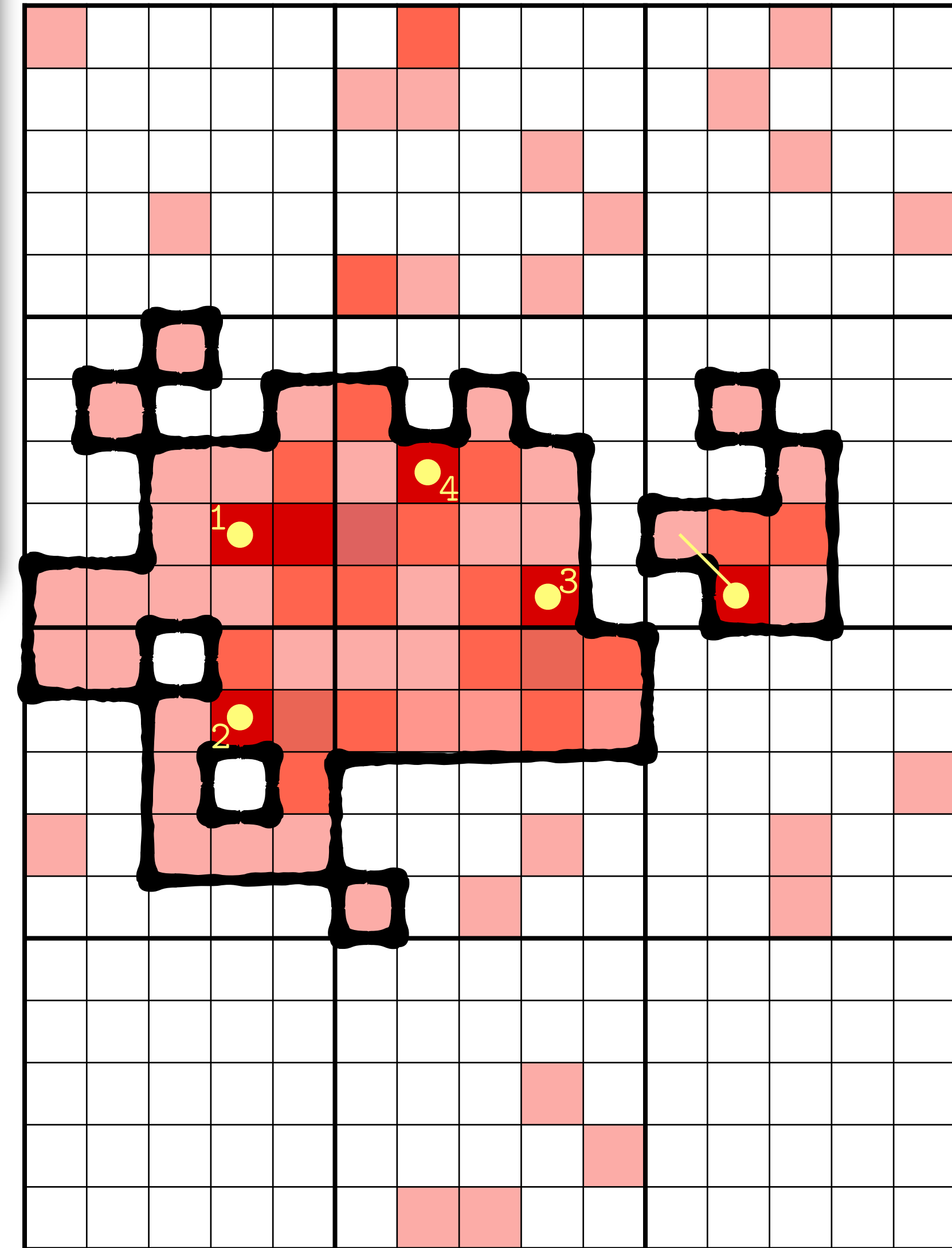
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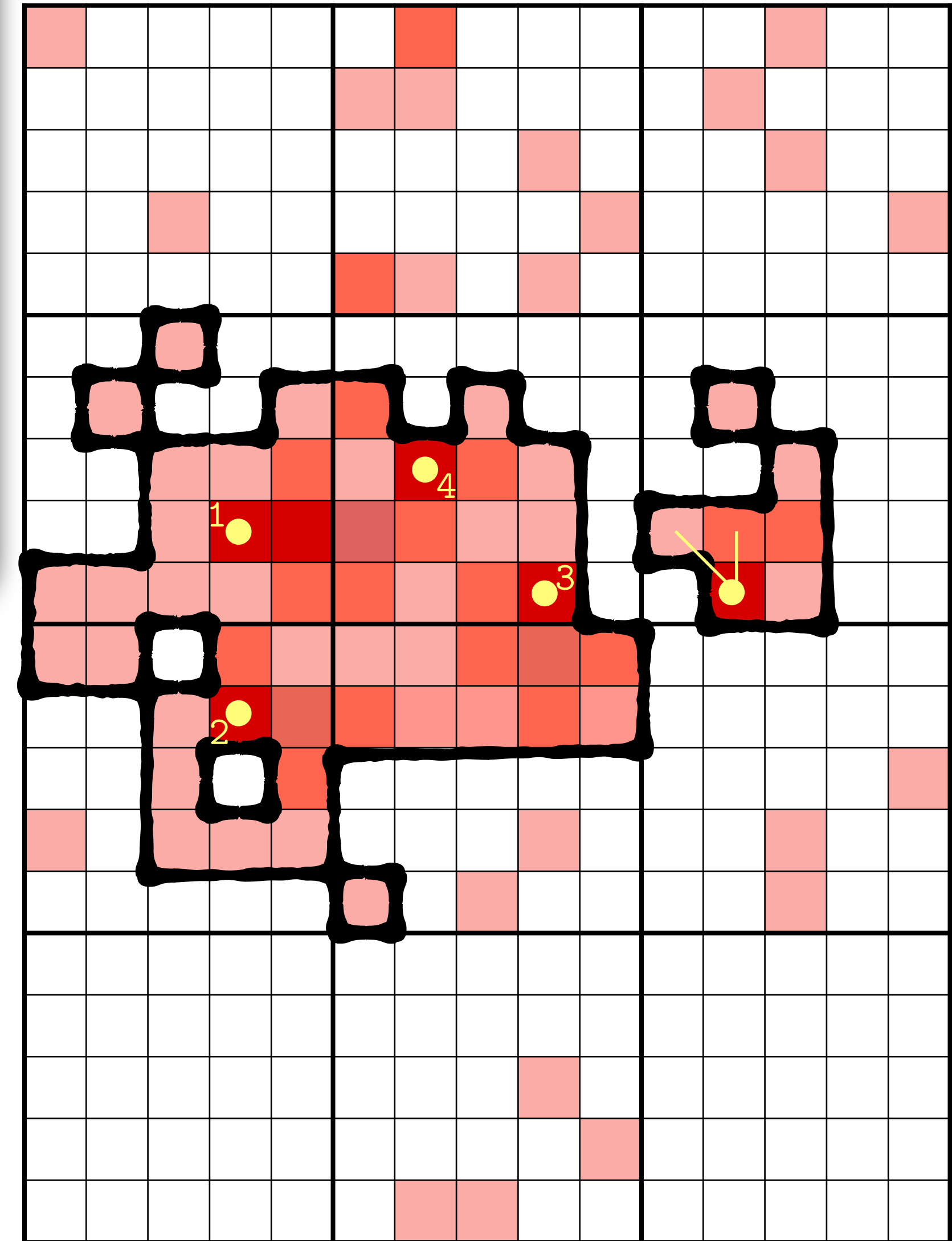
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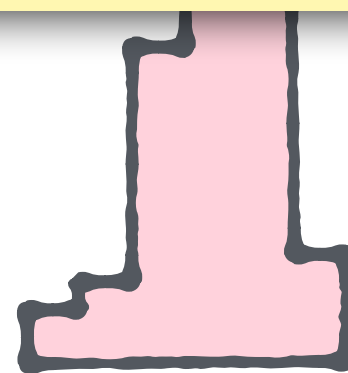
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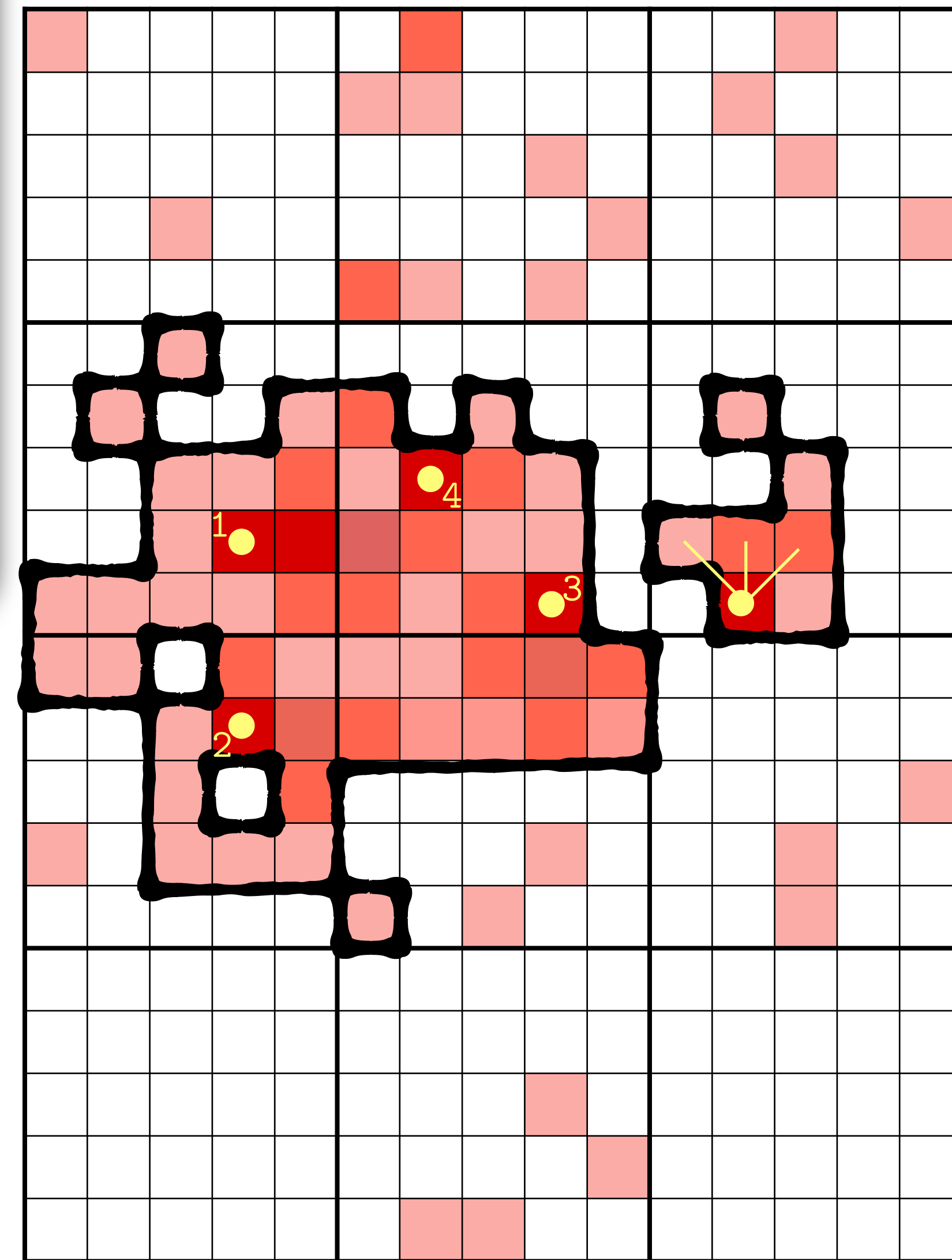
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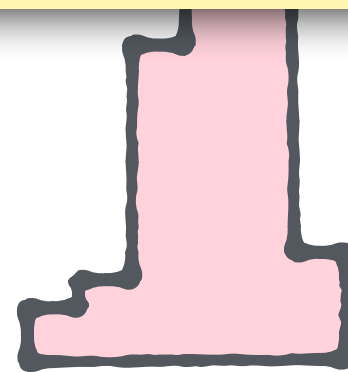
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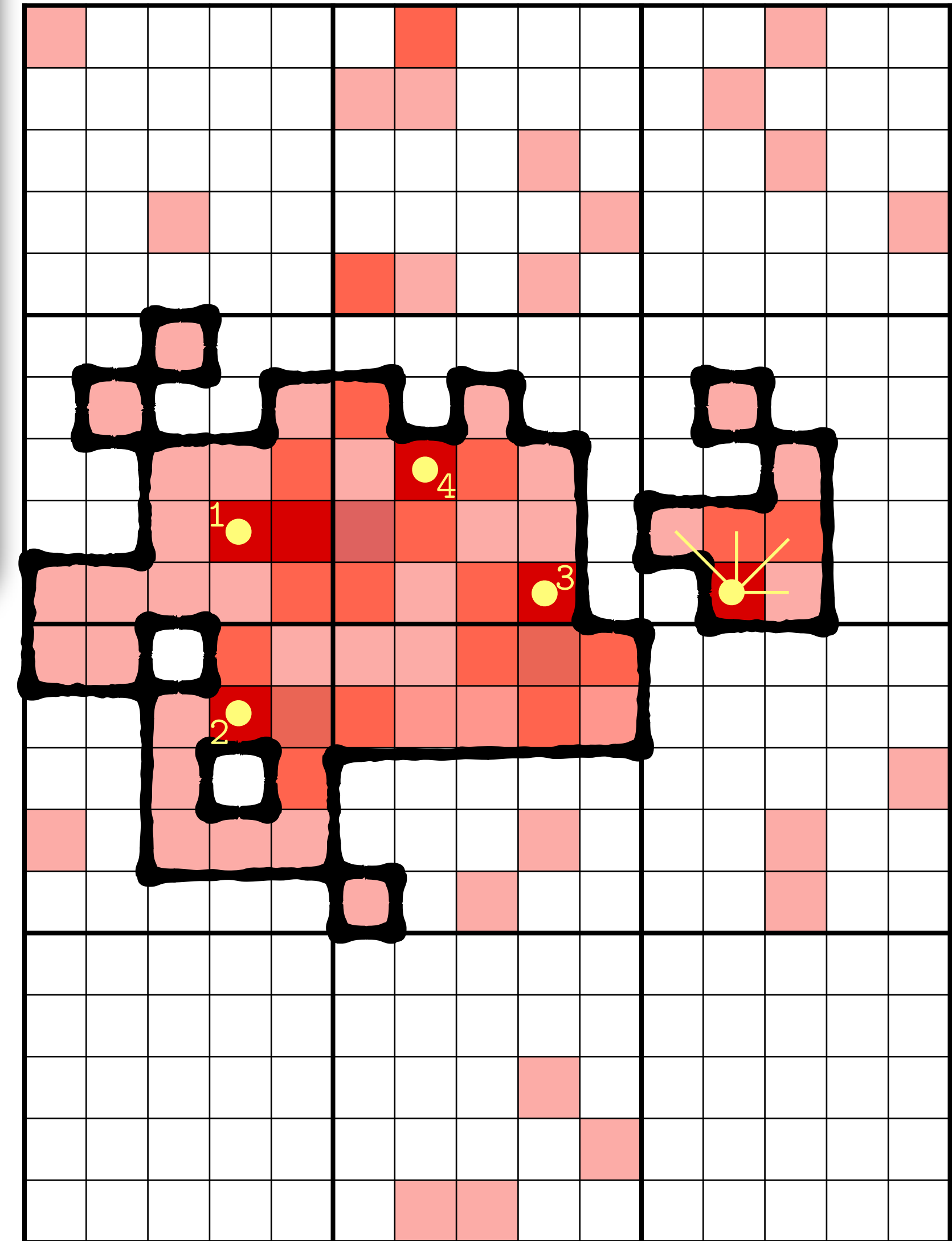
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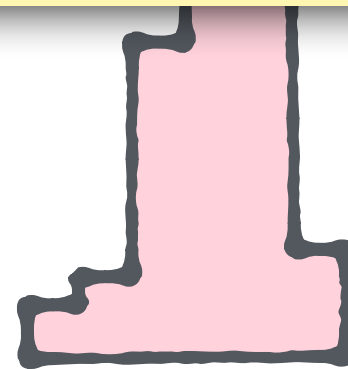
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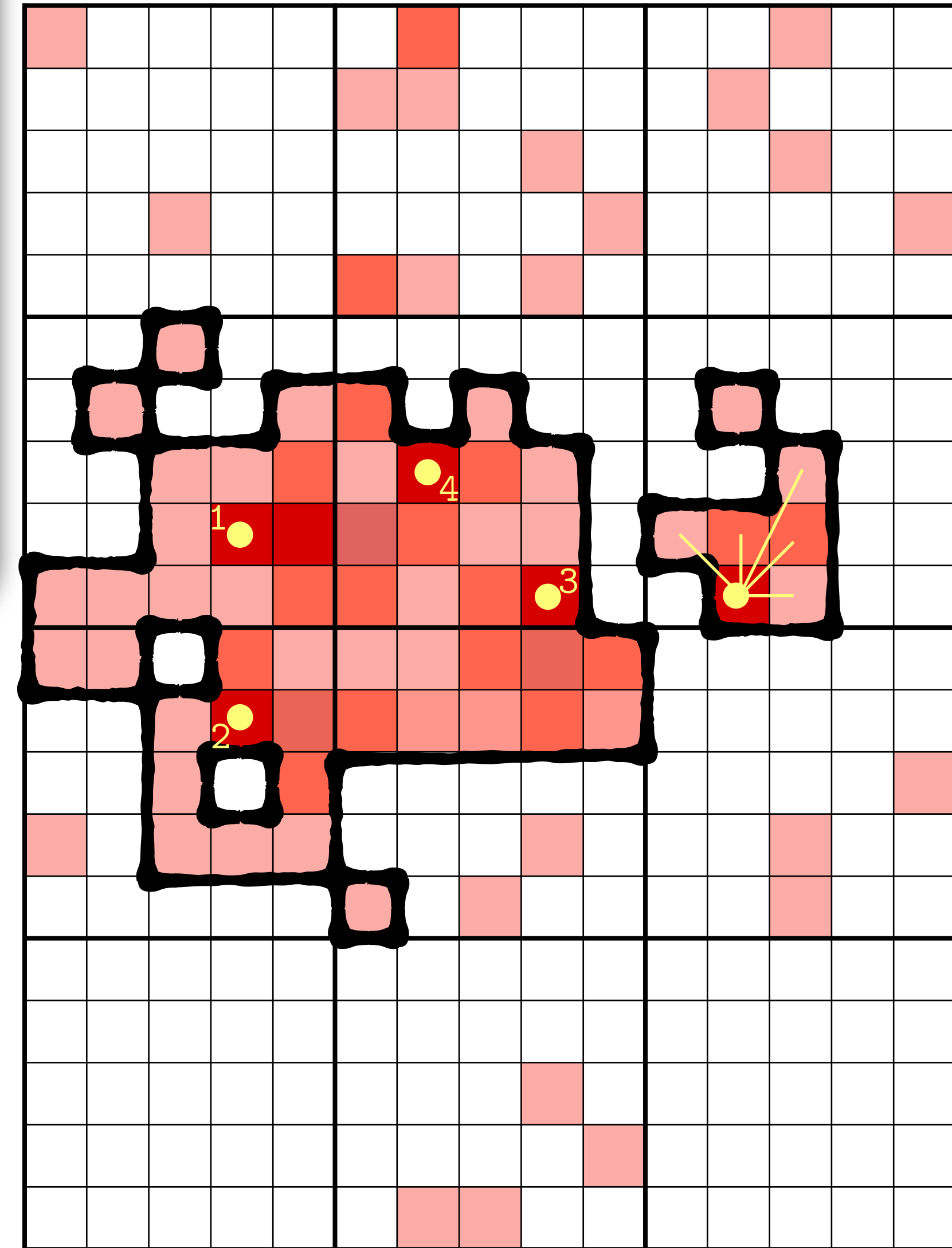
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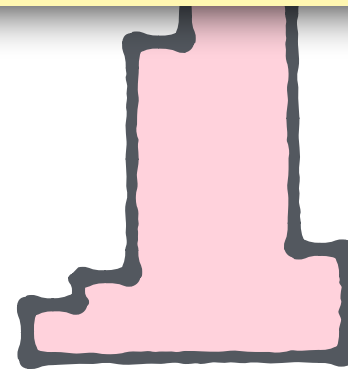
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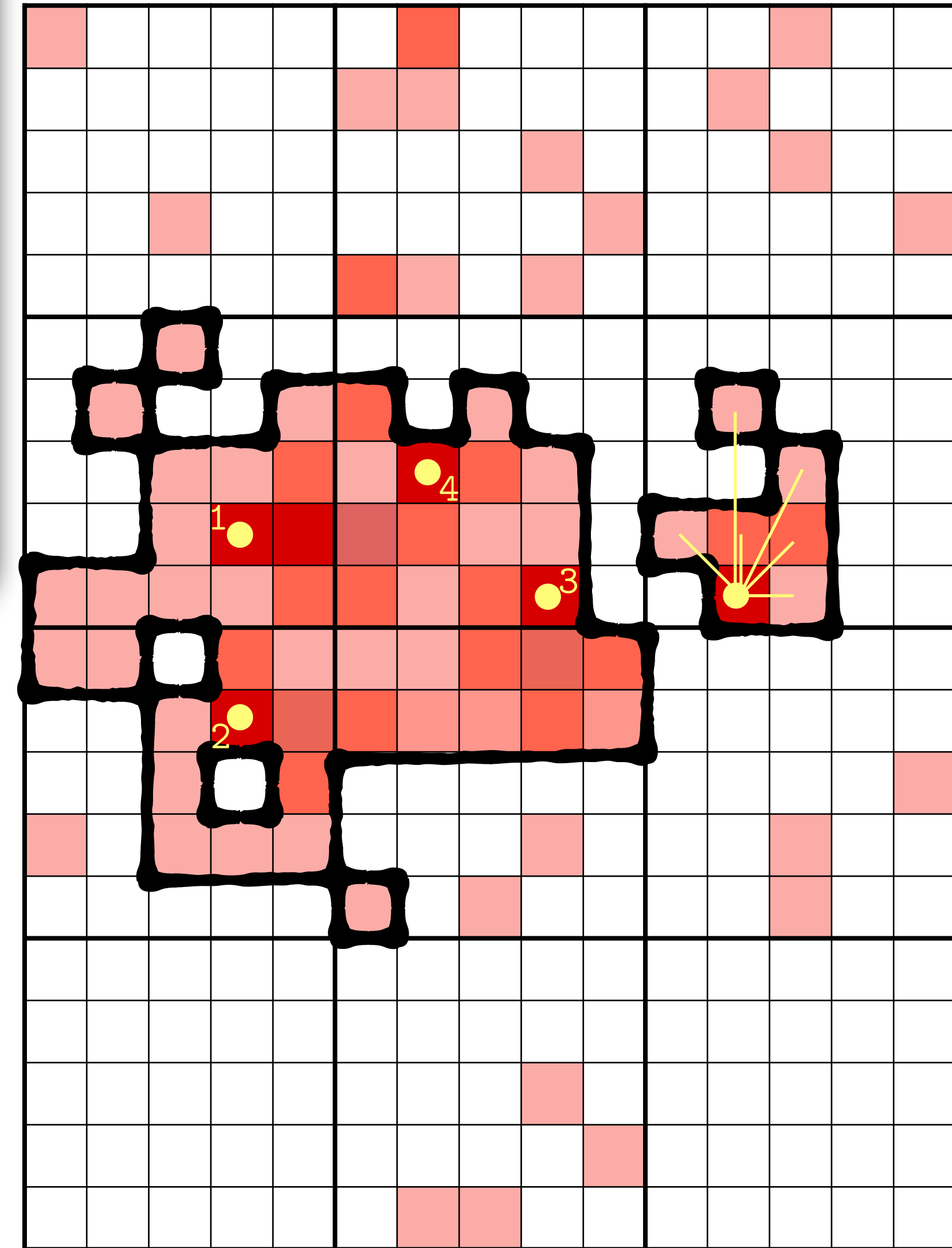
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- Aggregate all cells with at least a corner in common with cell already in cluster

Step 3: Share energy in Topological Cluster

- Single seed clusters with N cells:
- Energy is sum over all cells:

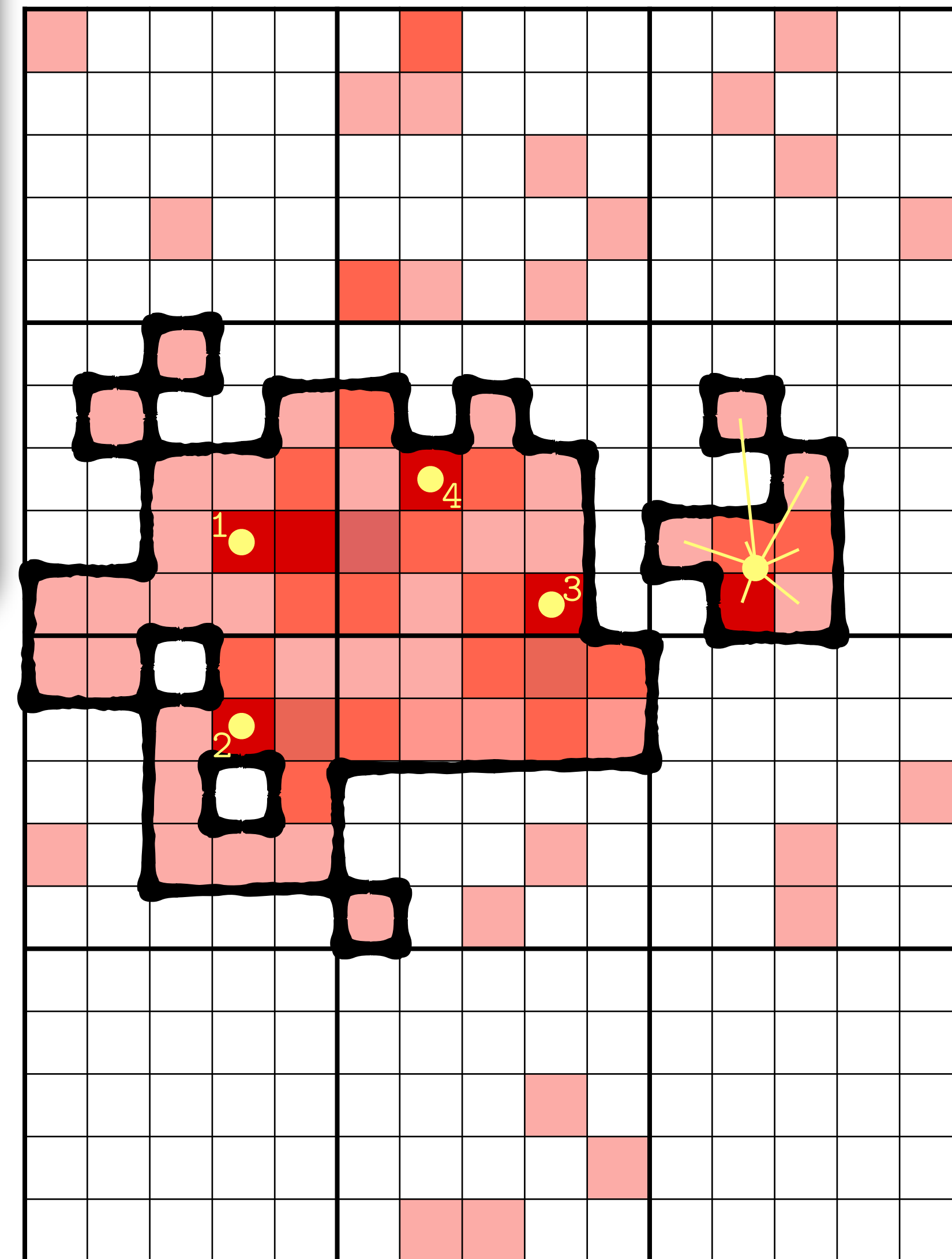
$$E = \sum_i^N E_i$$

- Position is energy weighted sum:

$$\vec{\mu} = \frac{1}{E_{\text{tot}}} \sum_i^N E_i \vec{x}_i$$



Calorimeter Clustering



Step 1: Identify Seeds

- Any cell that is above some energy threshold
- Local maximum: energy larger than all neighbouring cells

Step 2: Form Topological Clusters

- Grown from seeds
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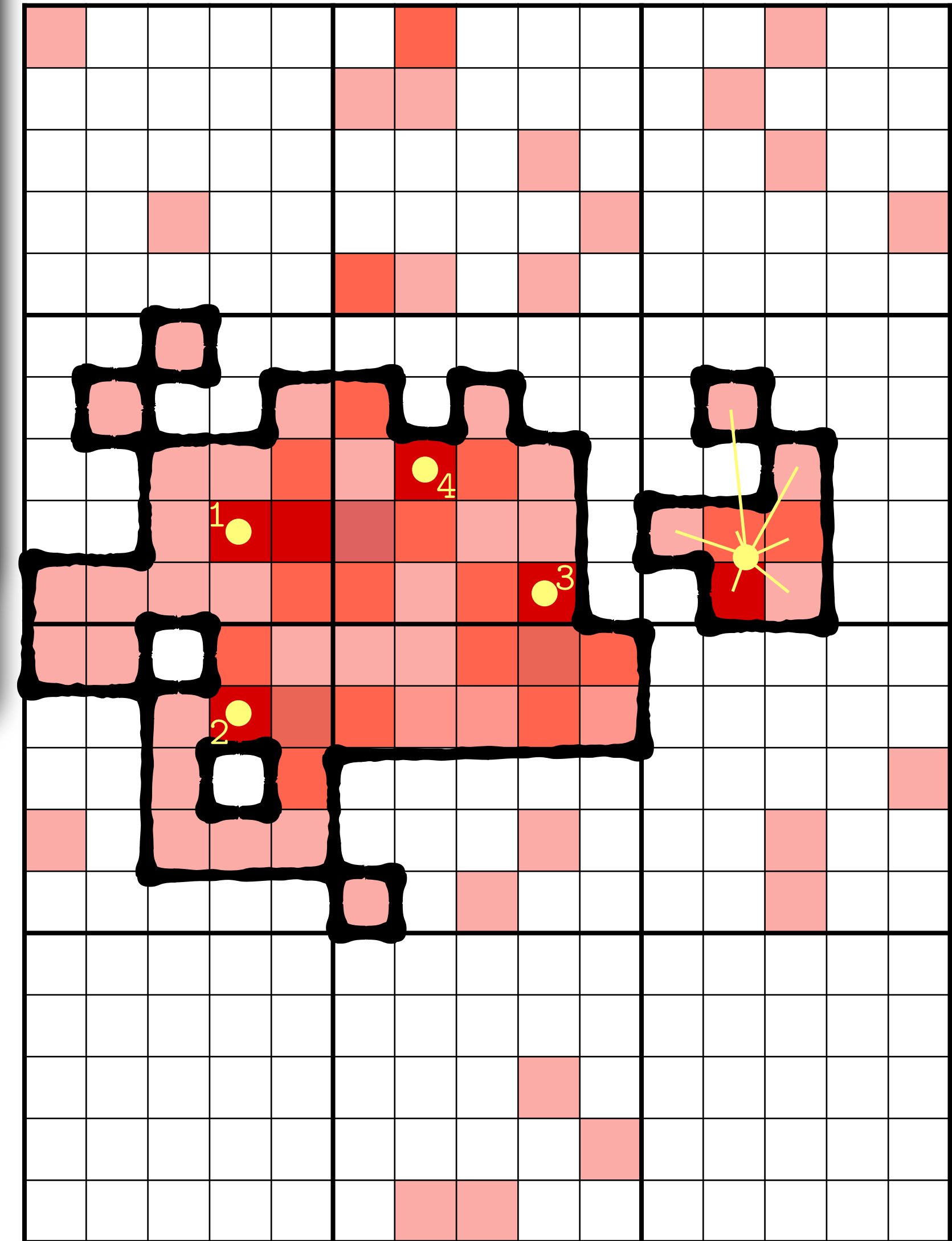
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 - less than 10^{-8} or 50 steps



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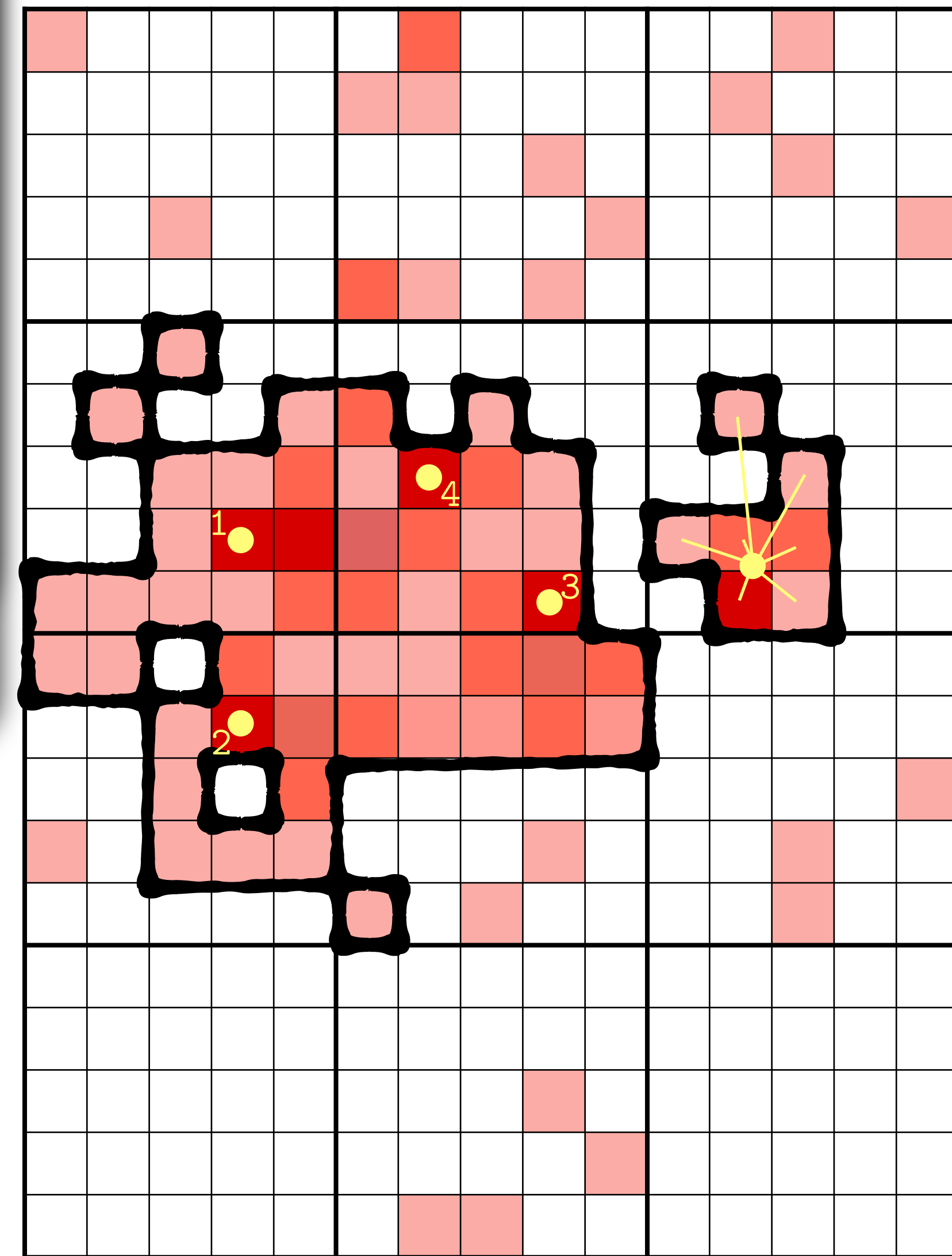
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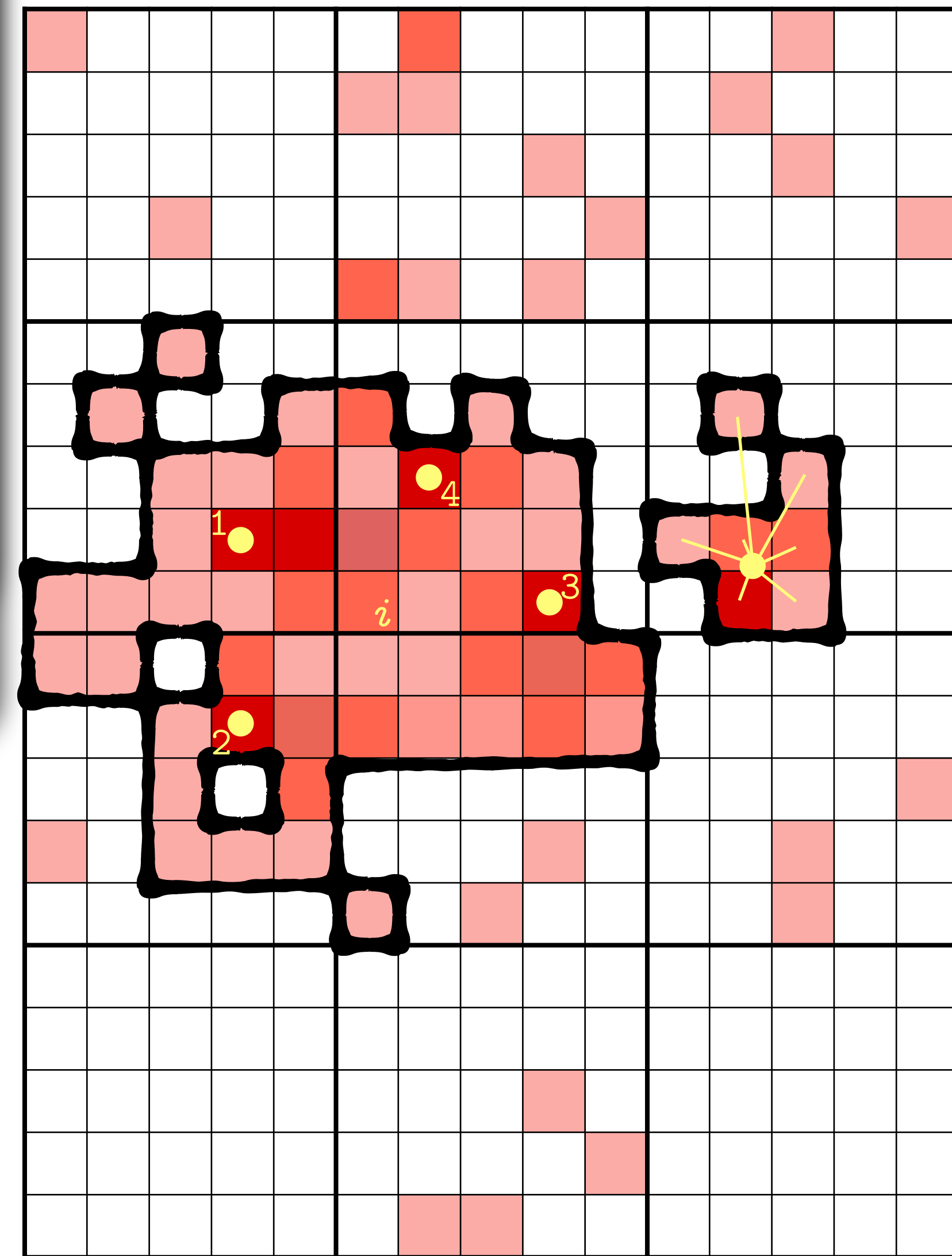
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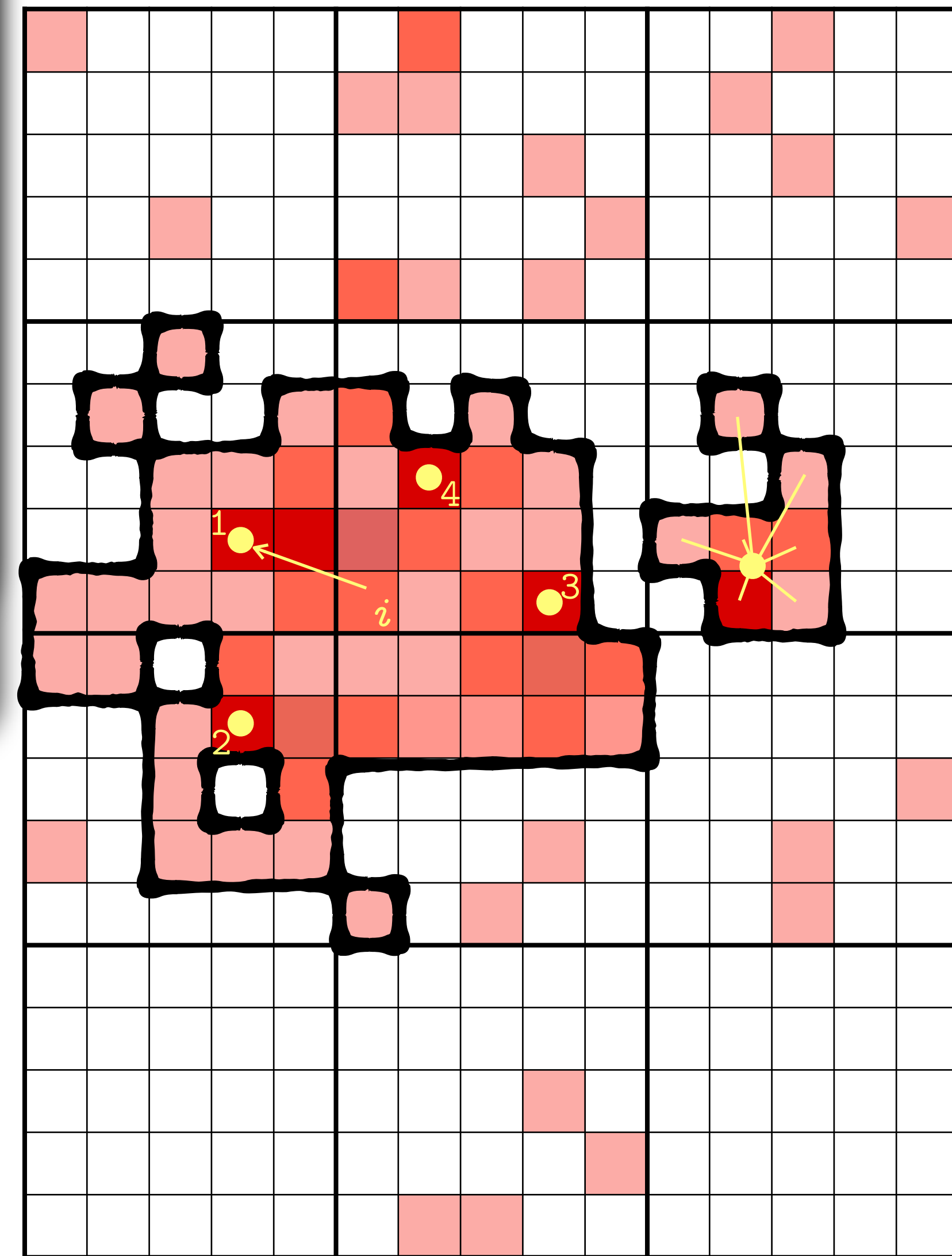
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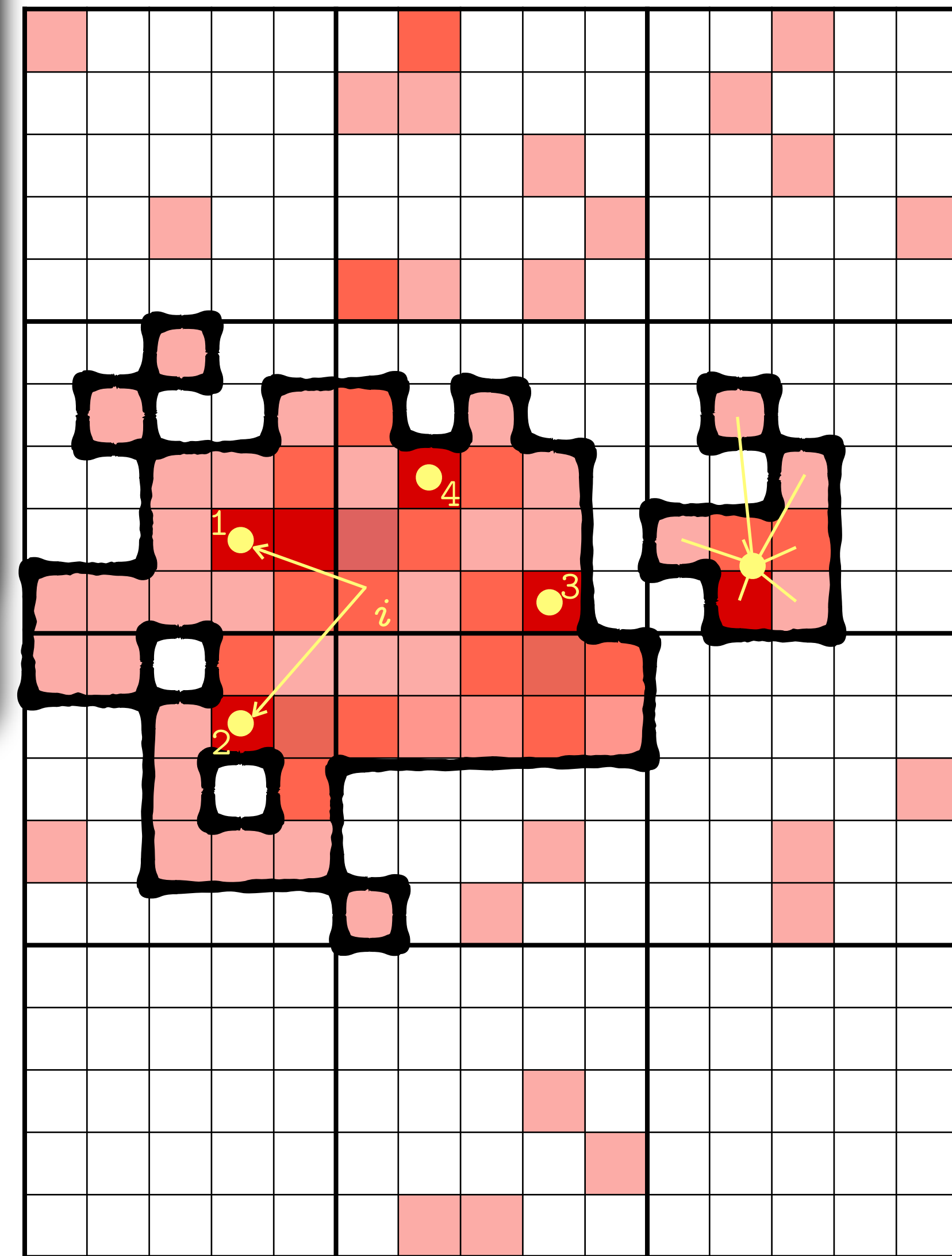
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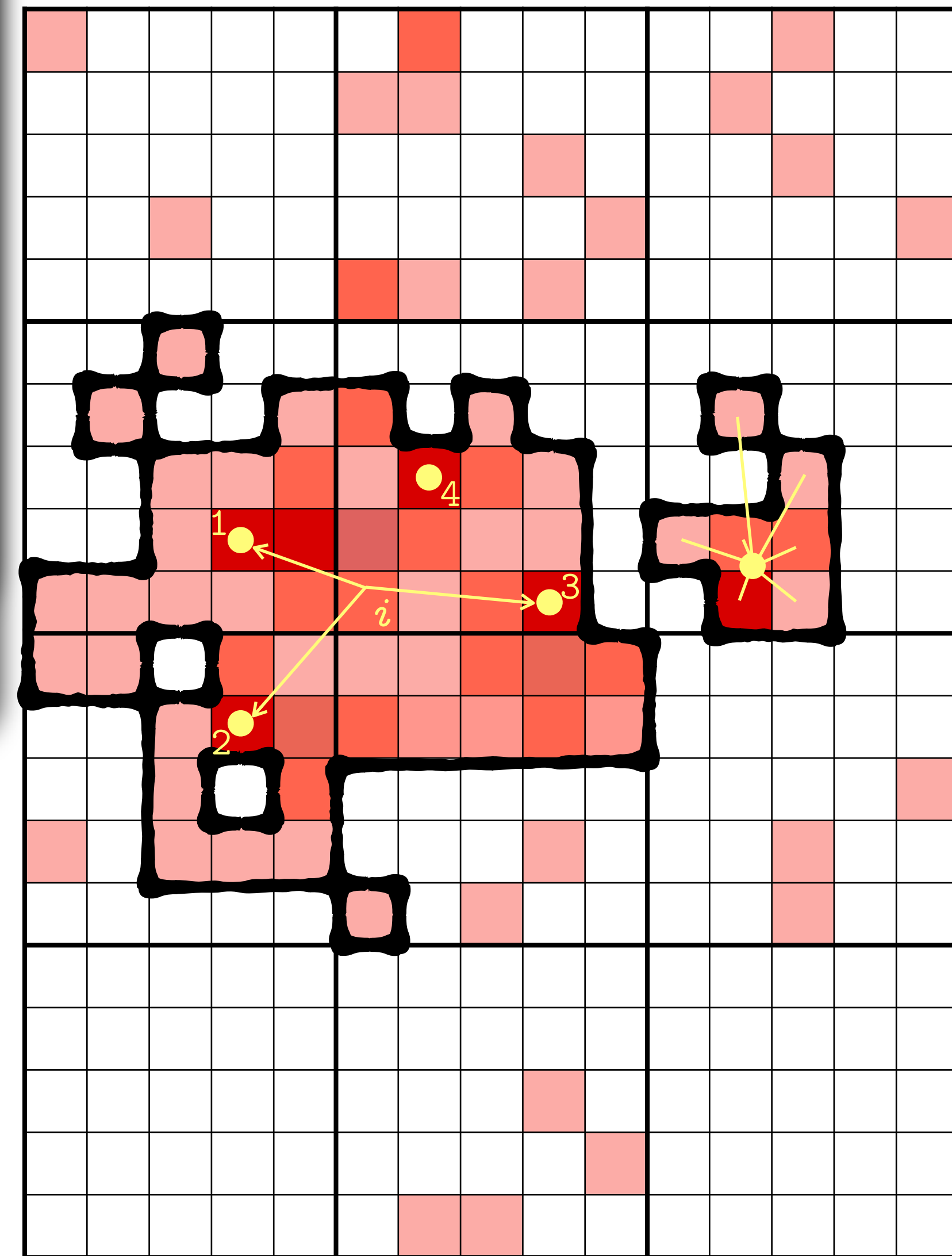
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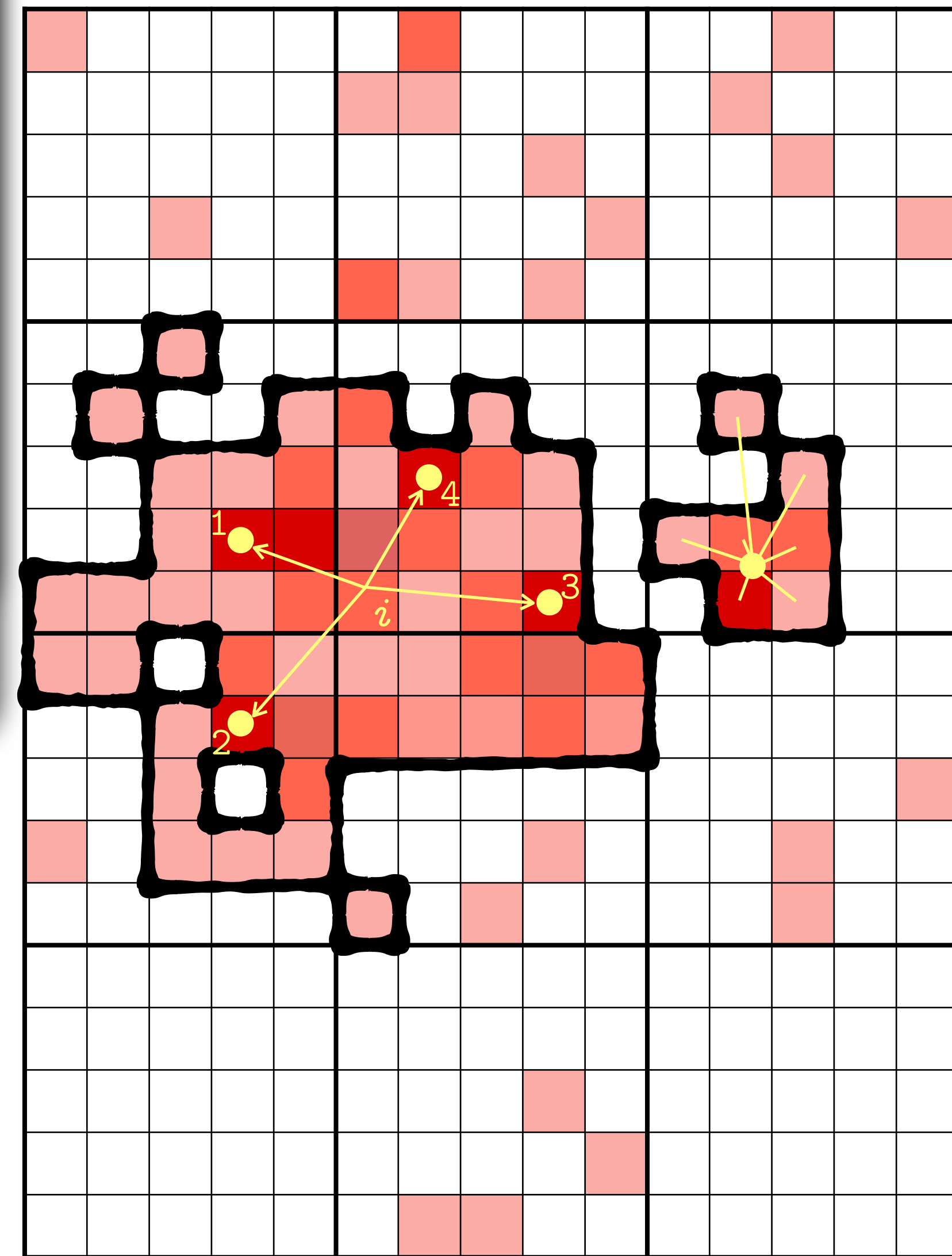
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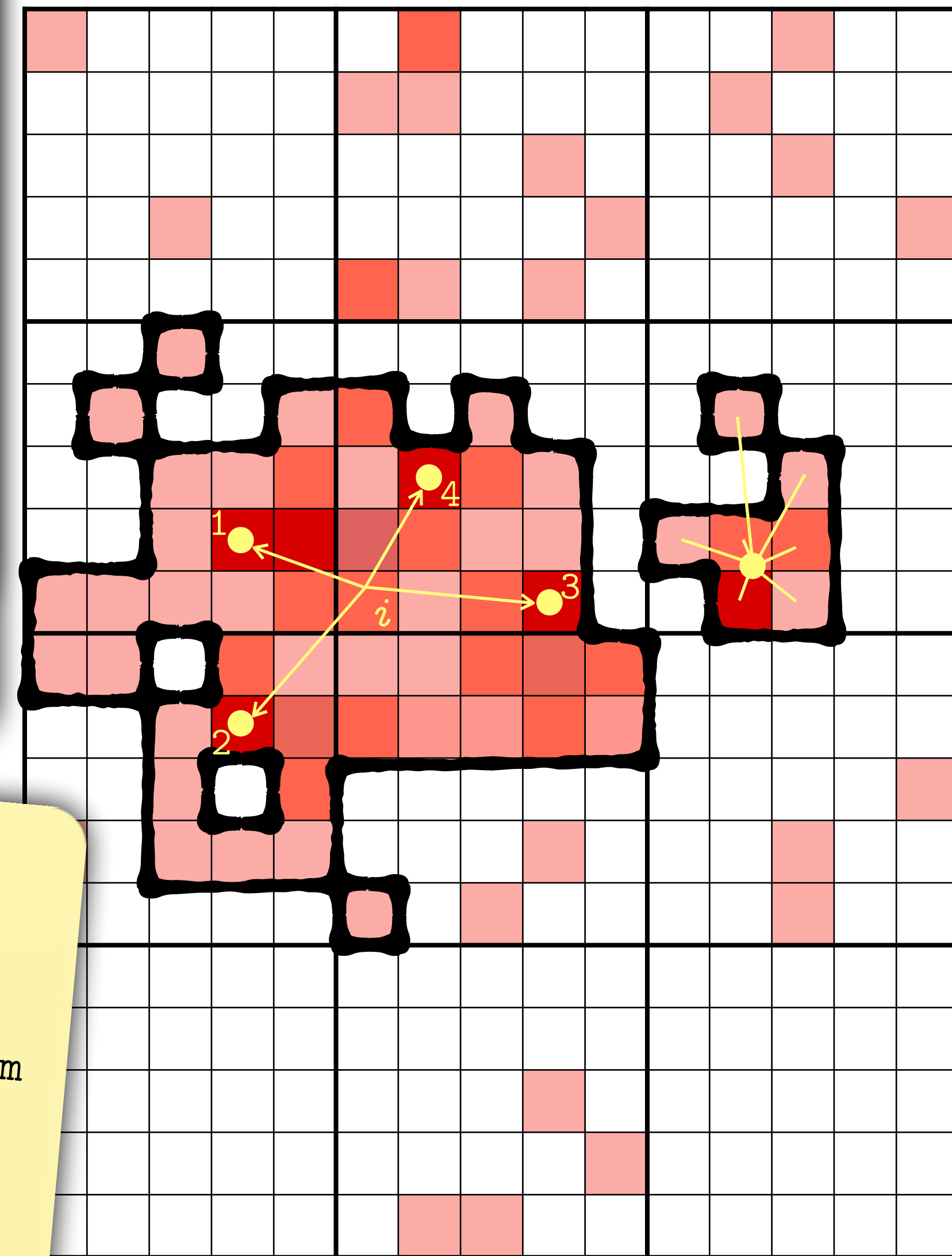
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$$A_i = \sum_j^M f_{ij} E_j$$

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$$\vec{d}_i^{\text{new}} = \sum_k^M f_{ik} \vec{d}_k^{\text{old}}$$

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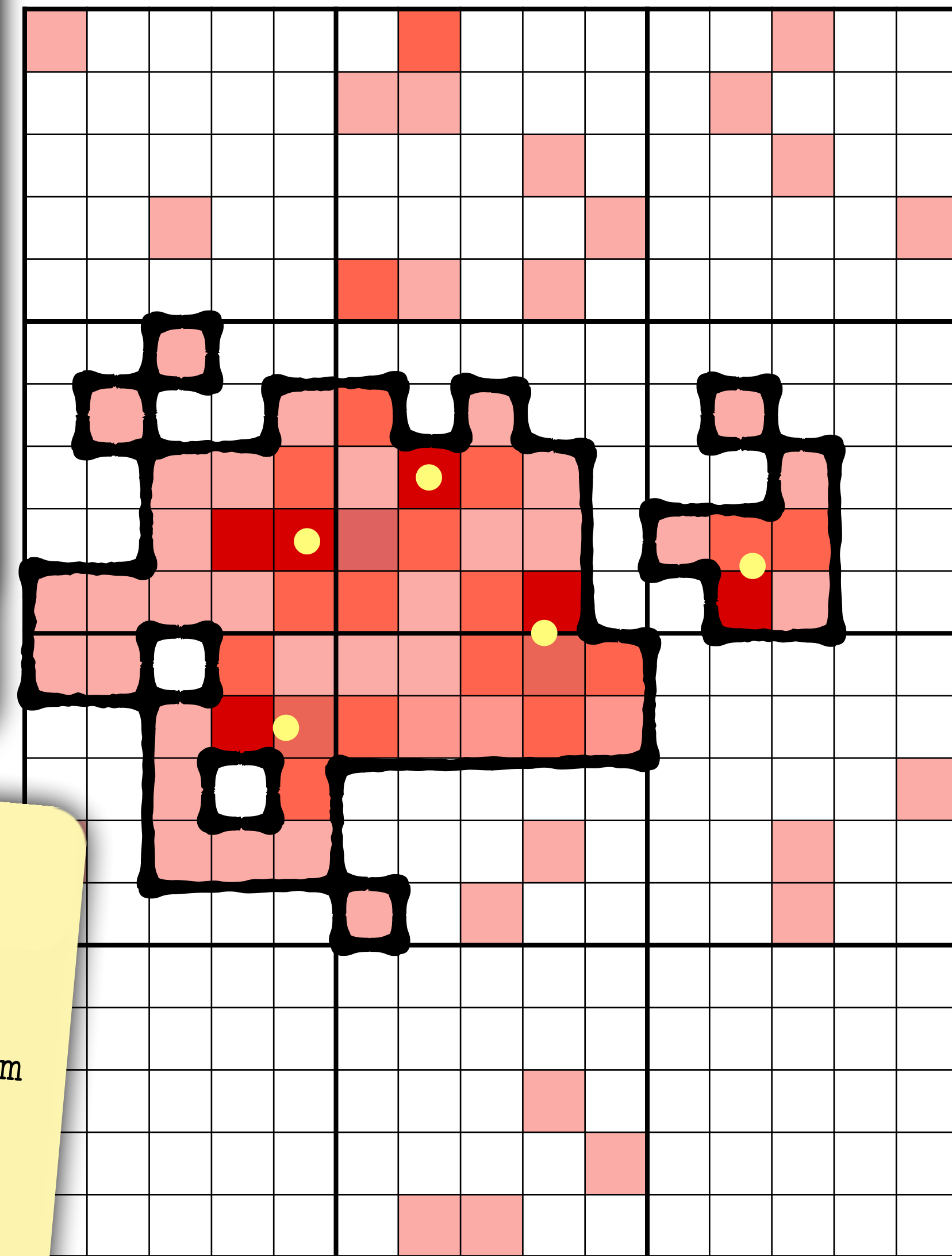
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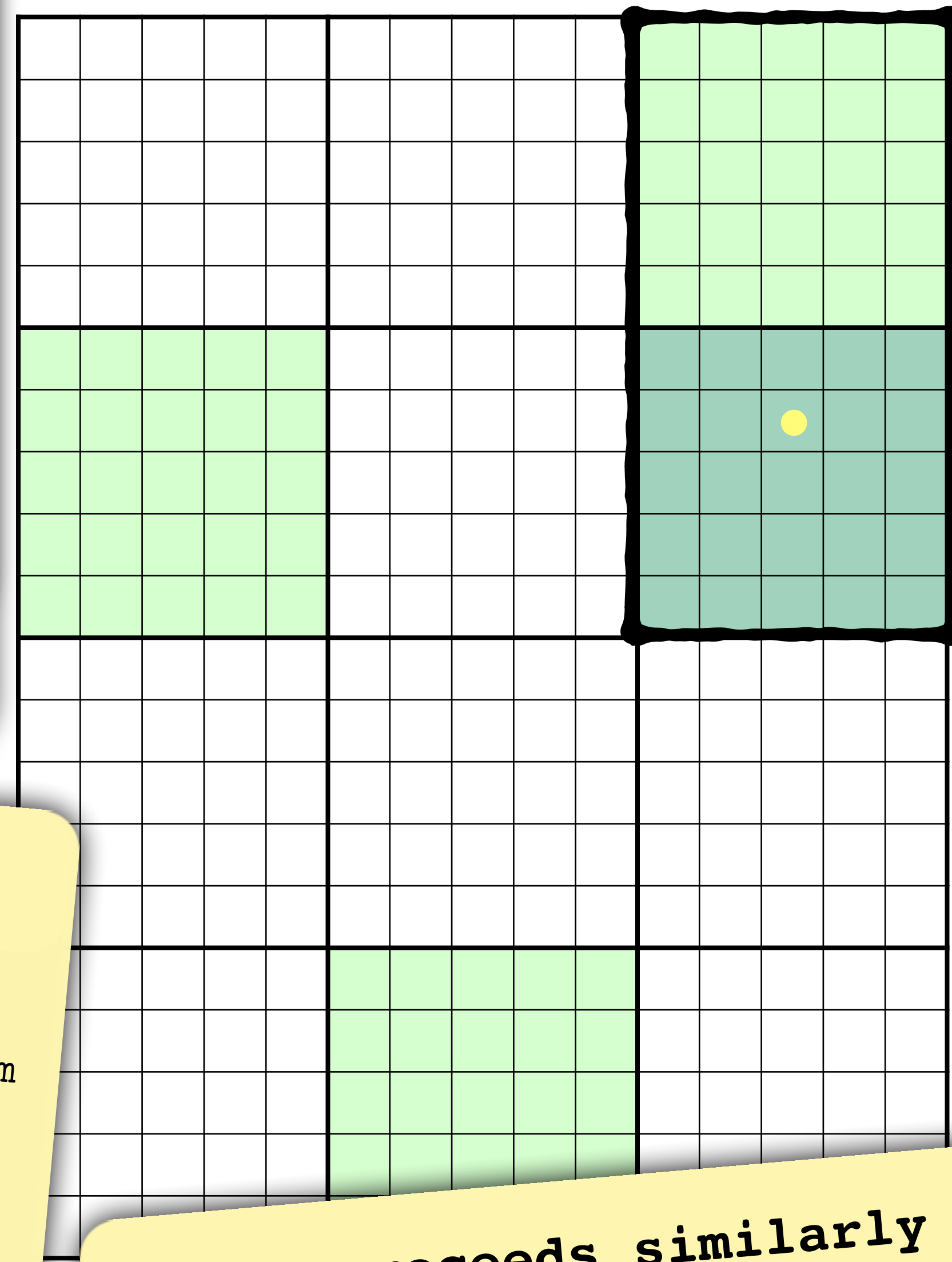
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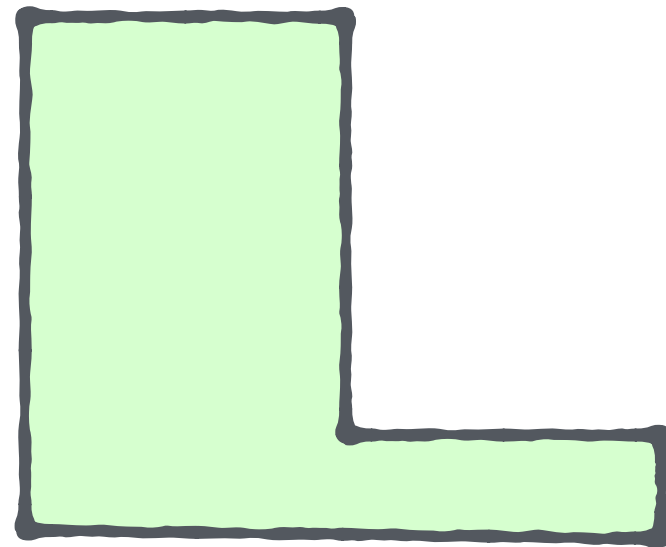


HCAL proceeds similarly

Just less granularity and different parameters

Next: Link across detectors

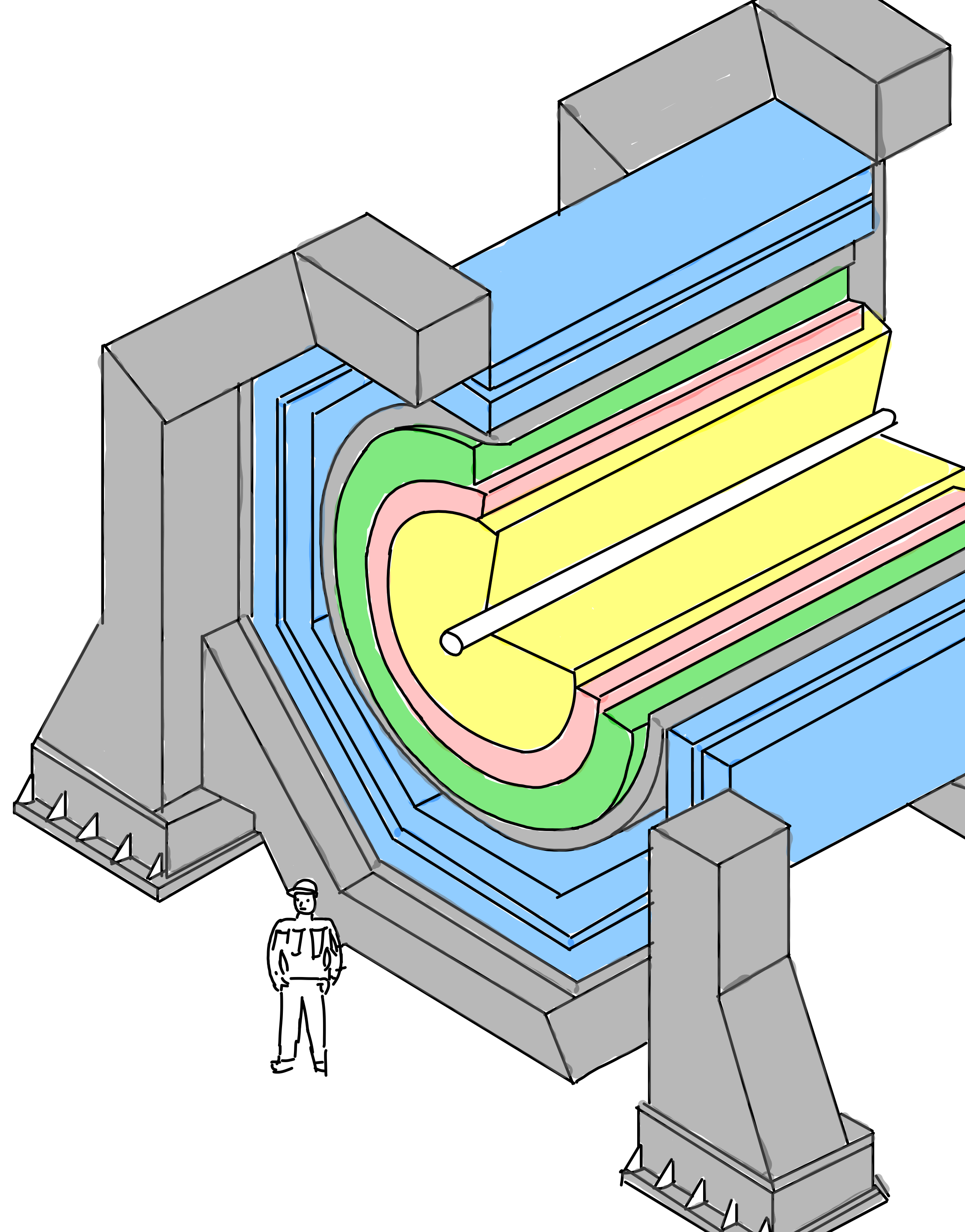
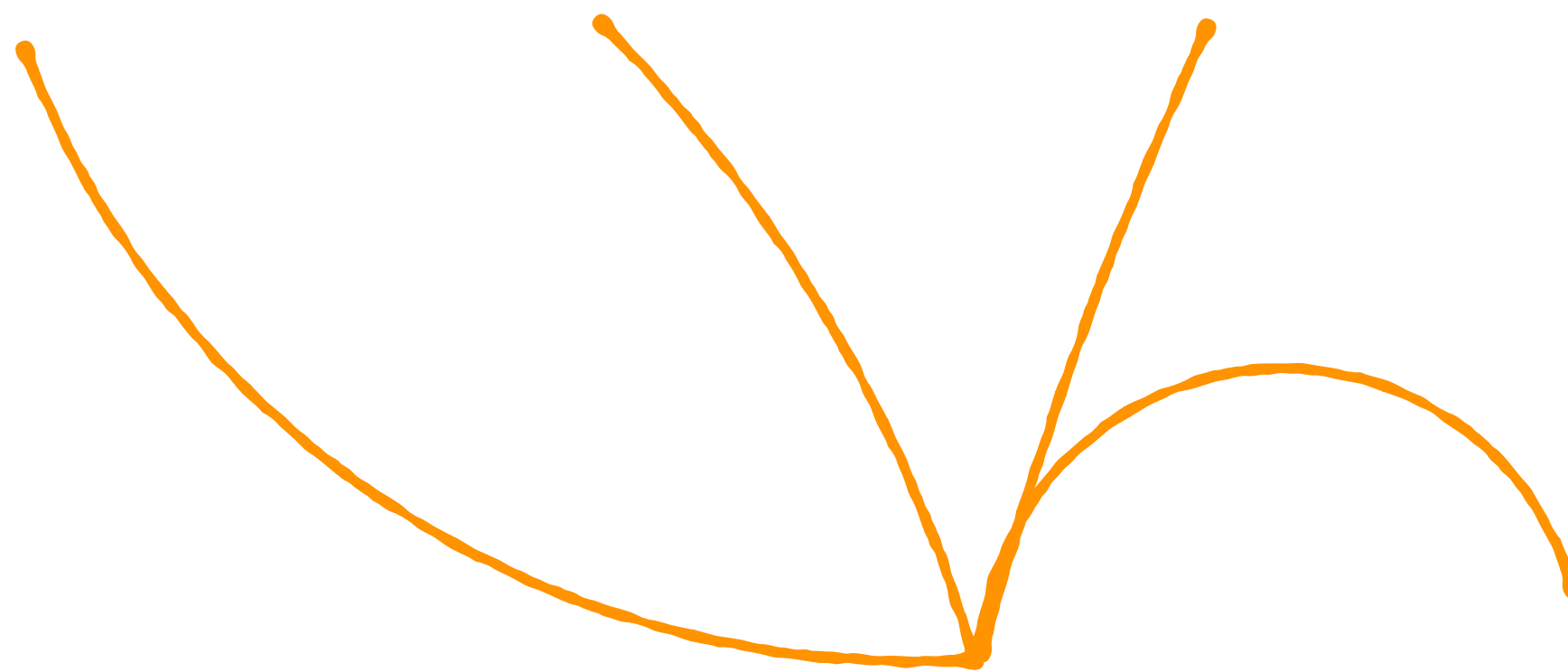
HCAL Clusters



ECAL Clusters

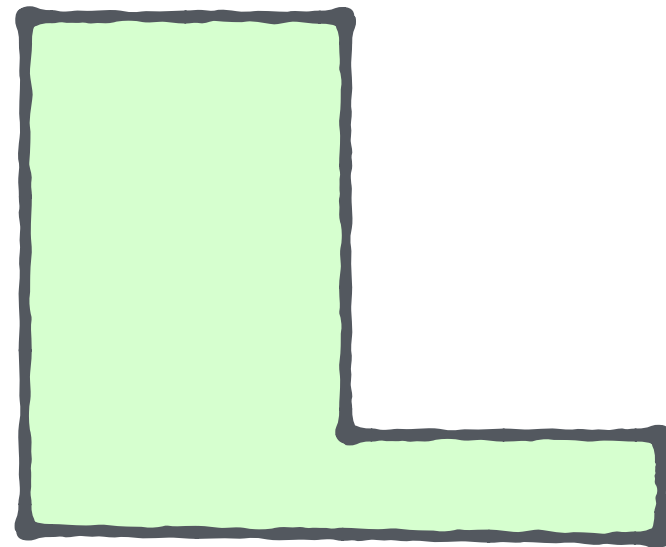


Tracks



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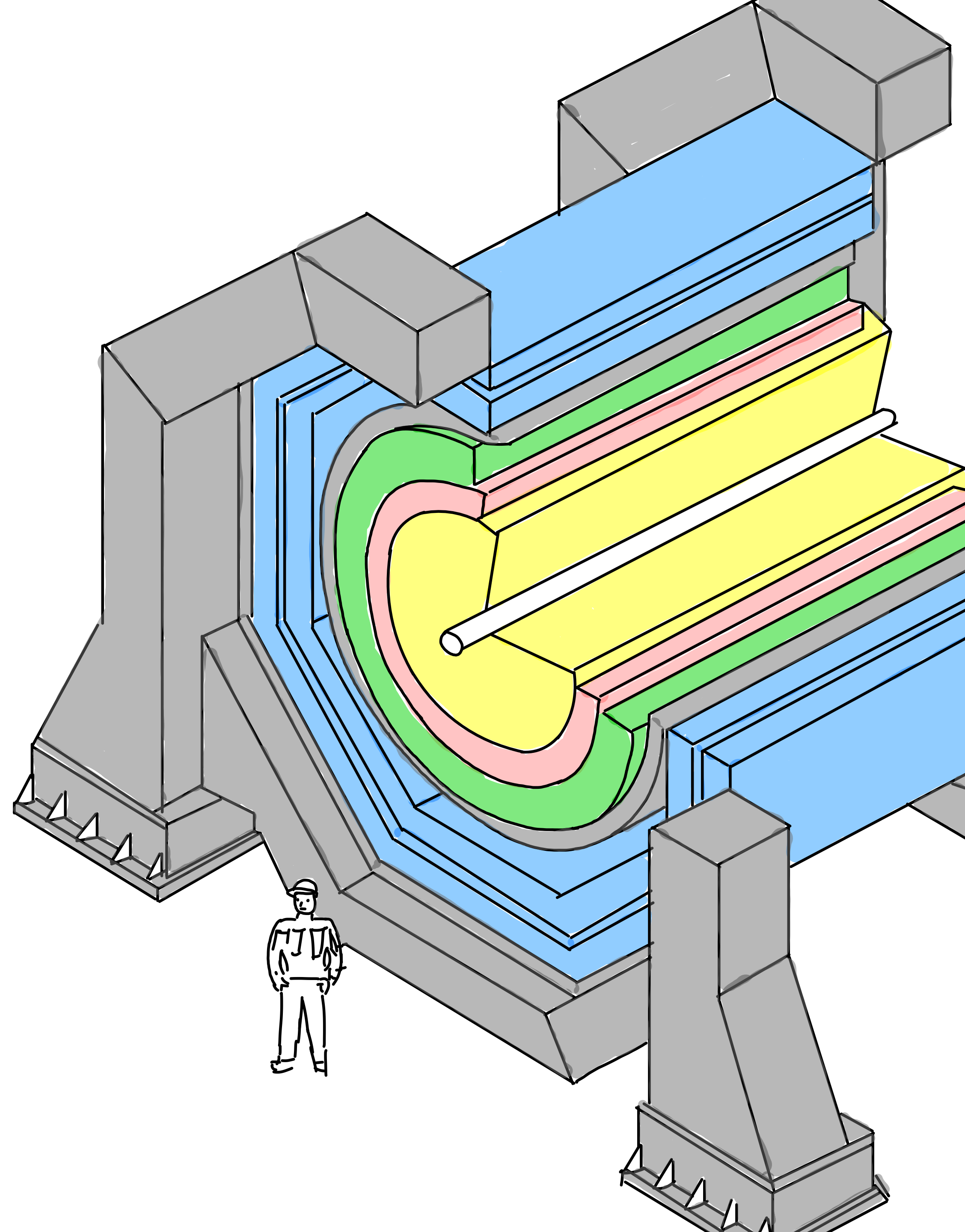
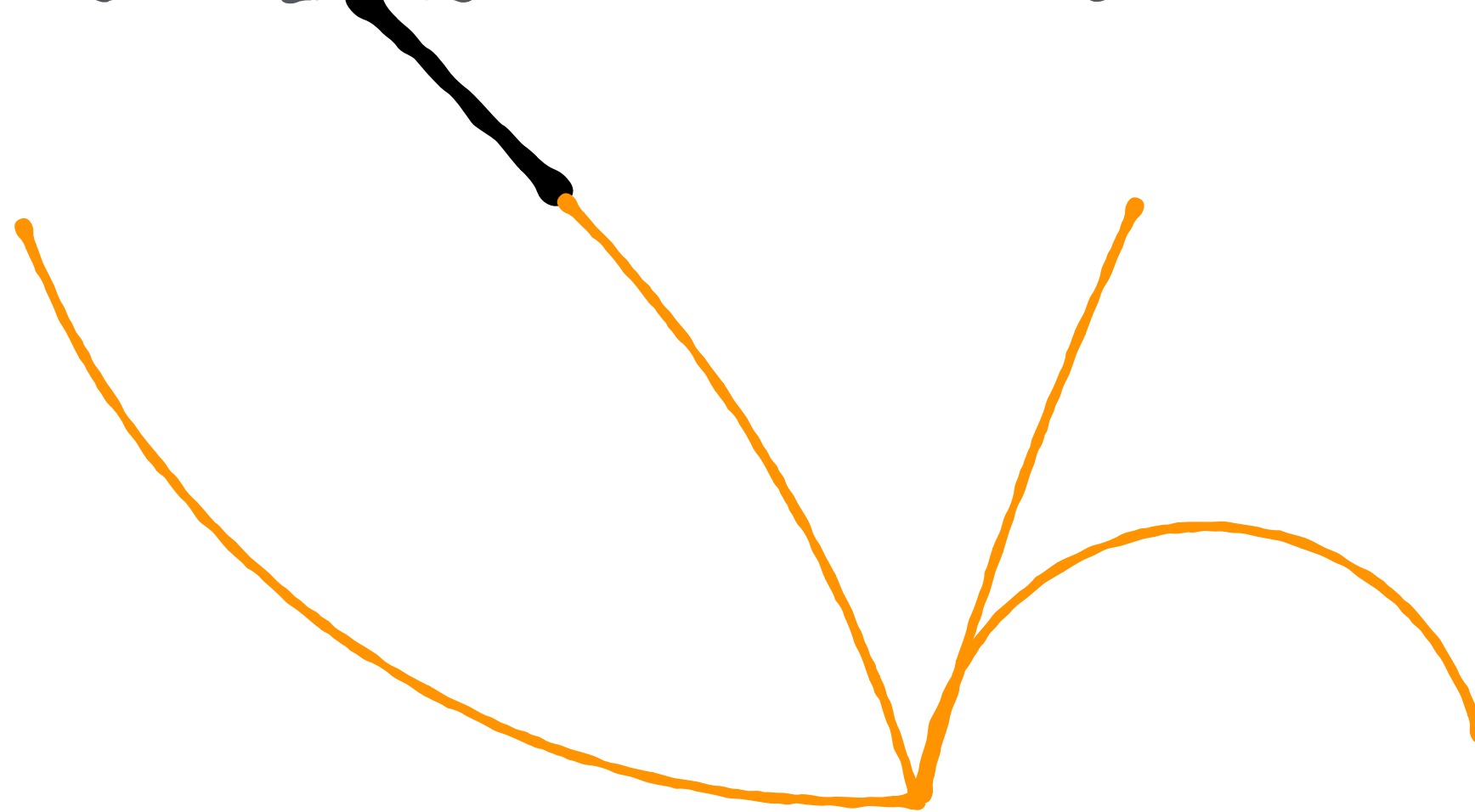
HCAL Clusters



ECAL Clusters

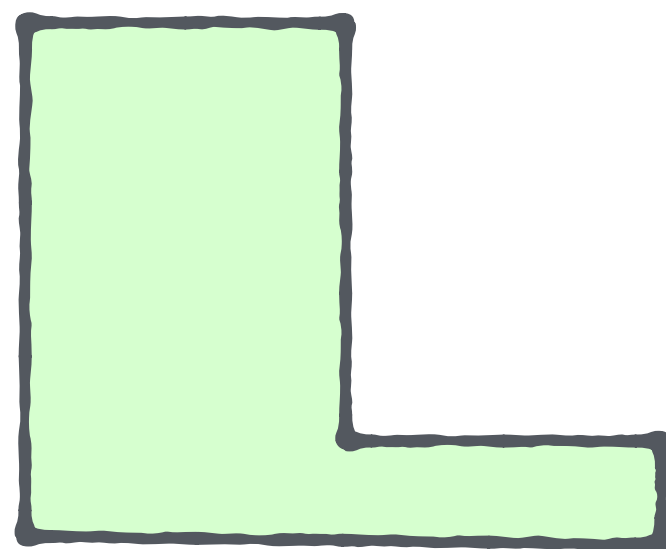


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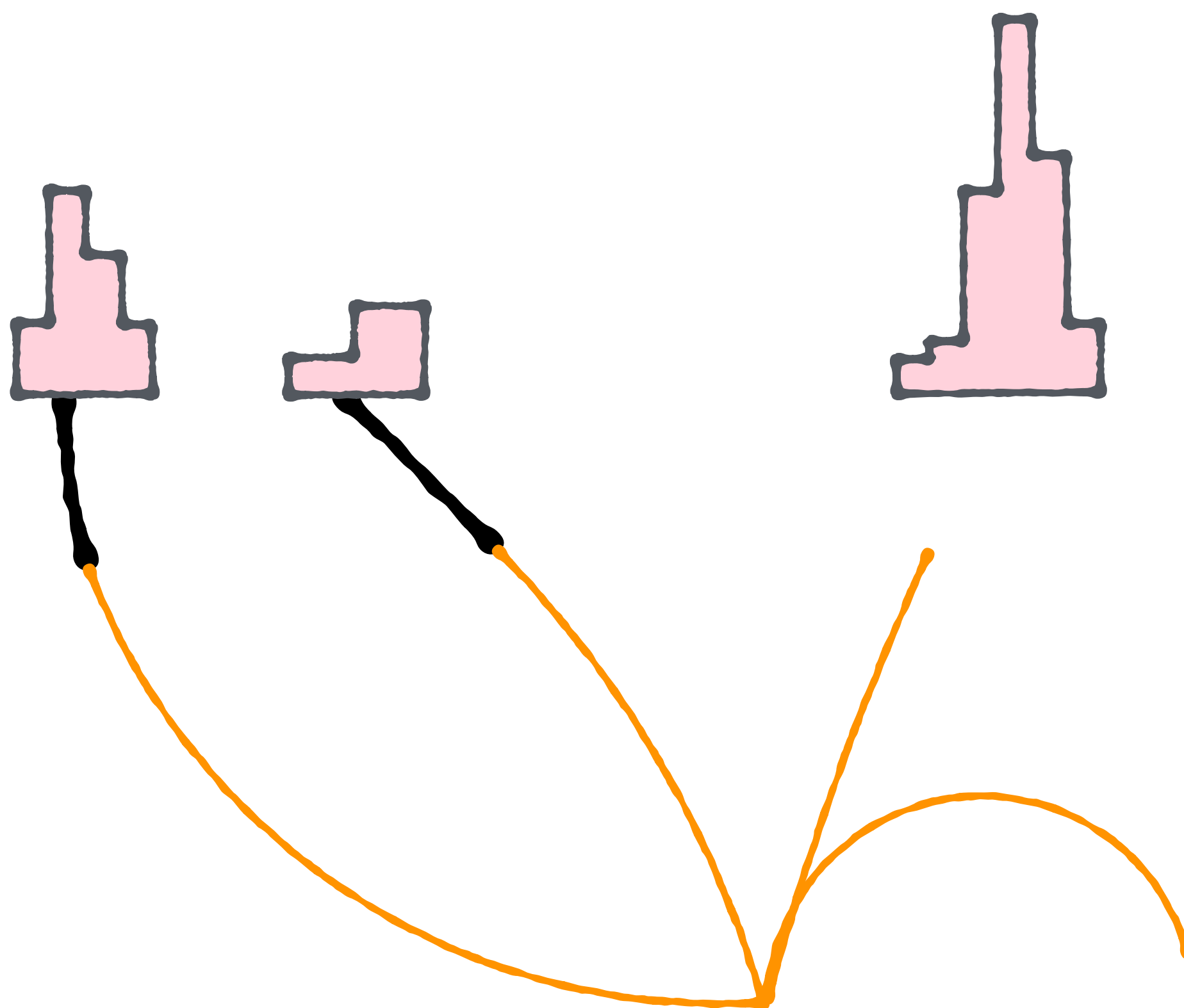


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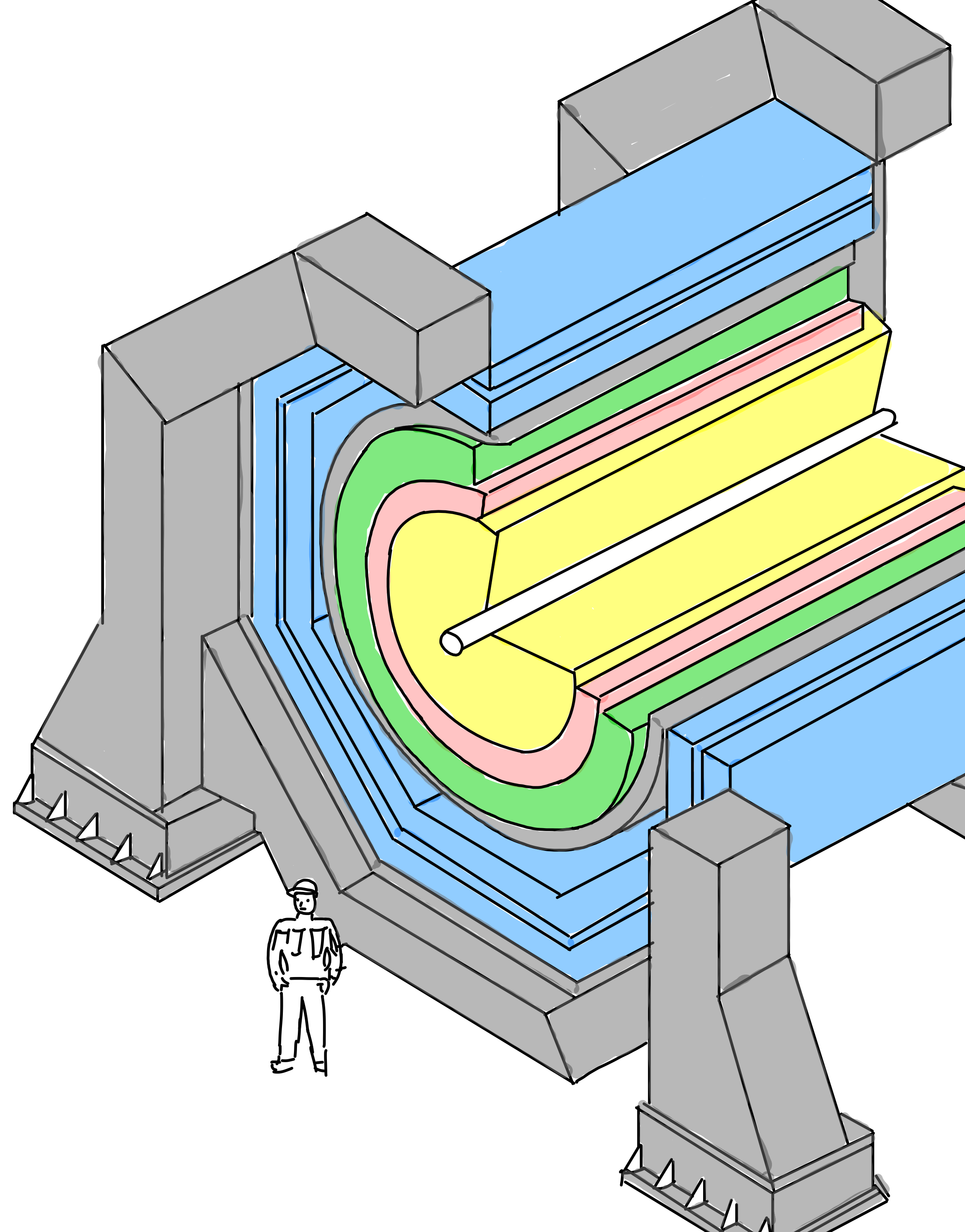
HCAL Clusters



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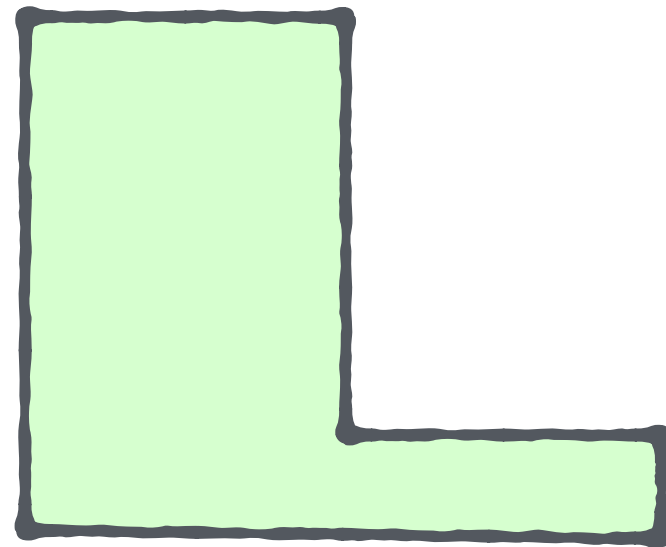


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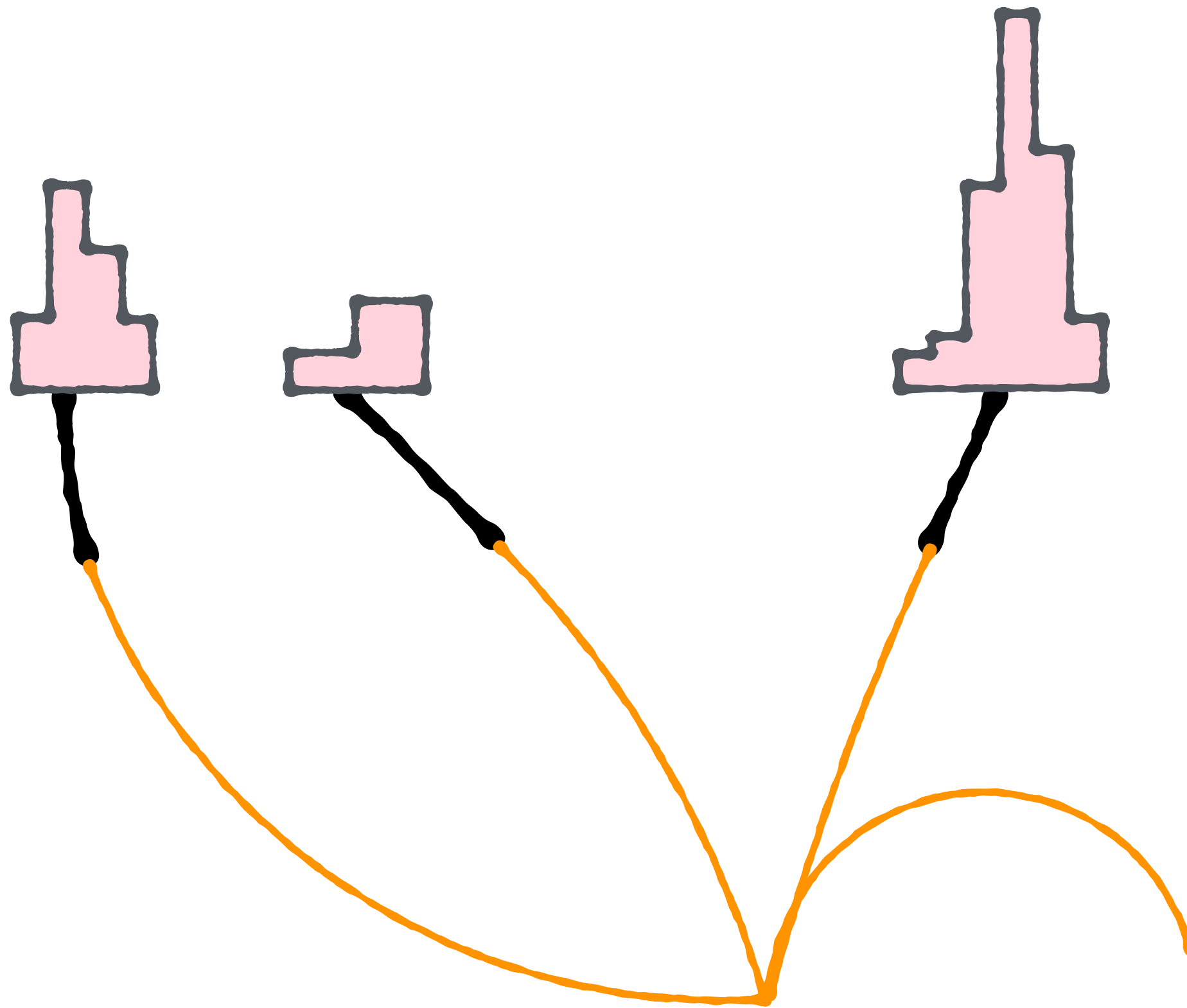


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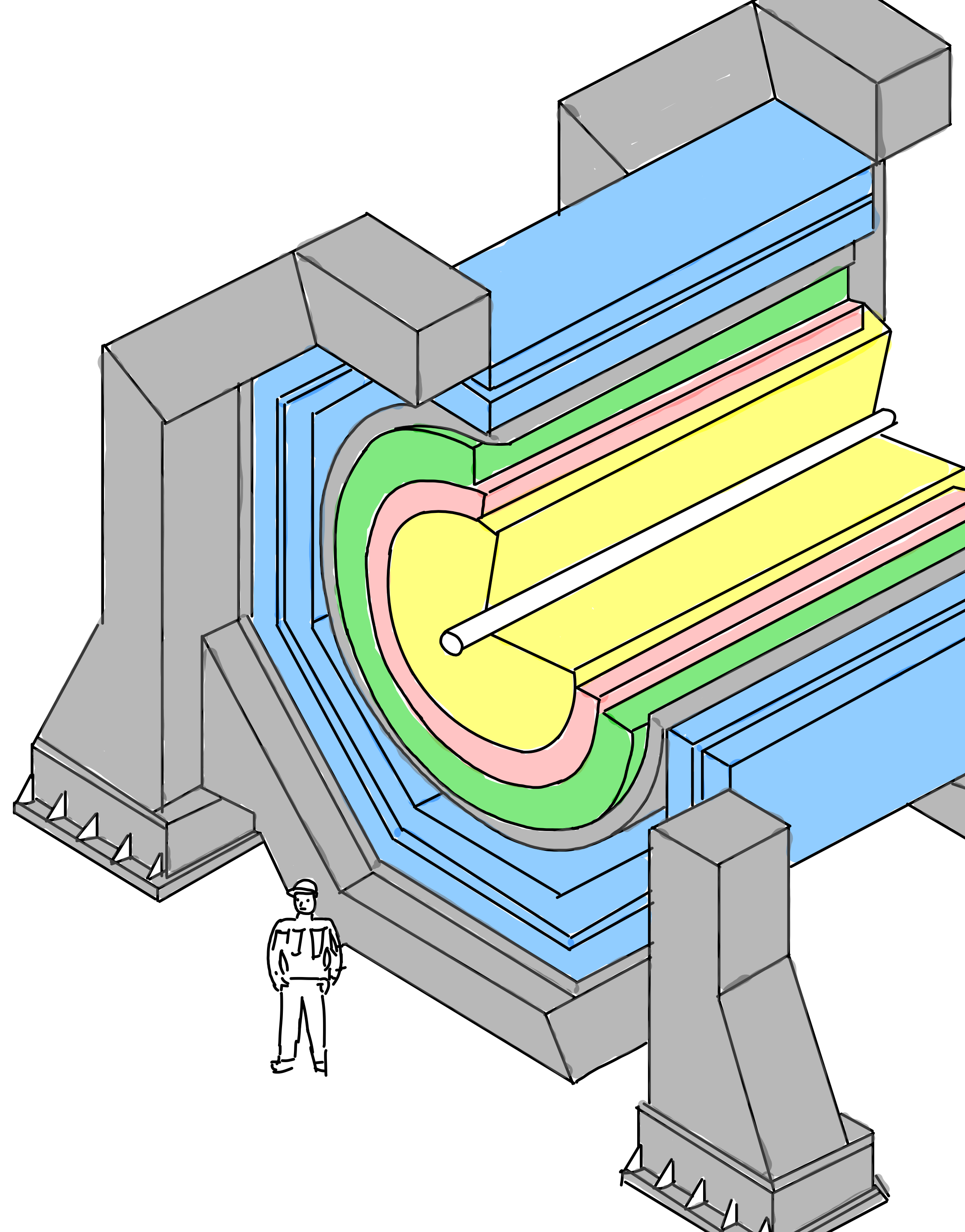
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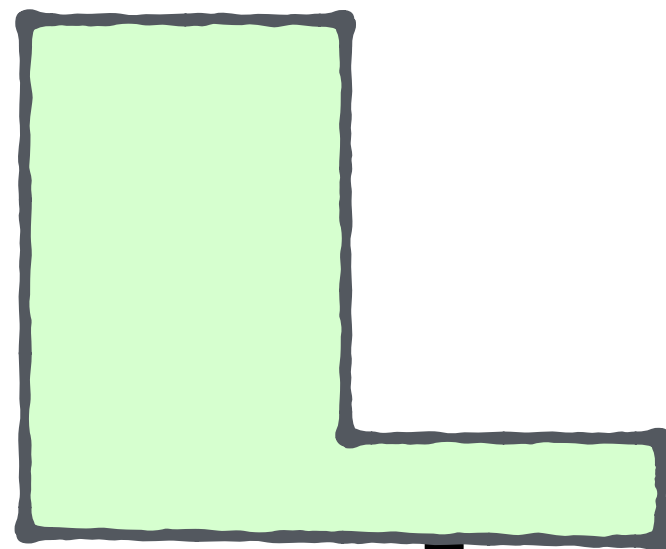


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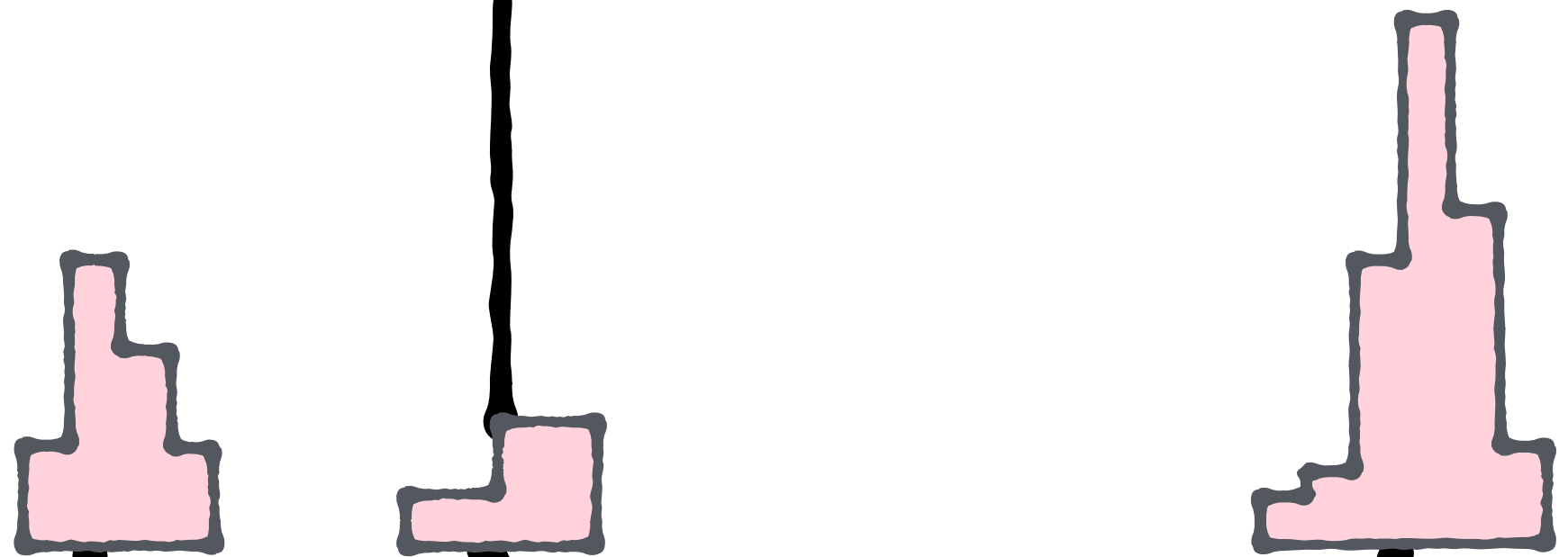


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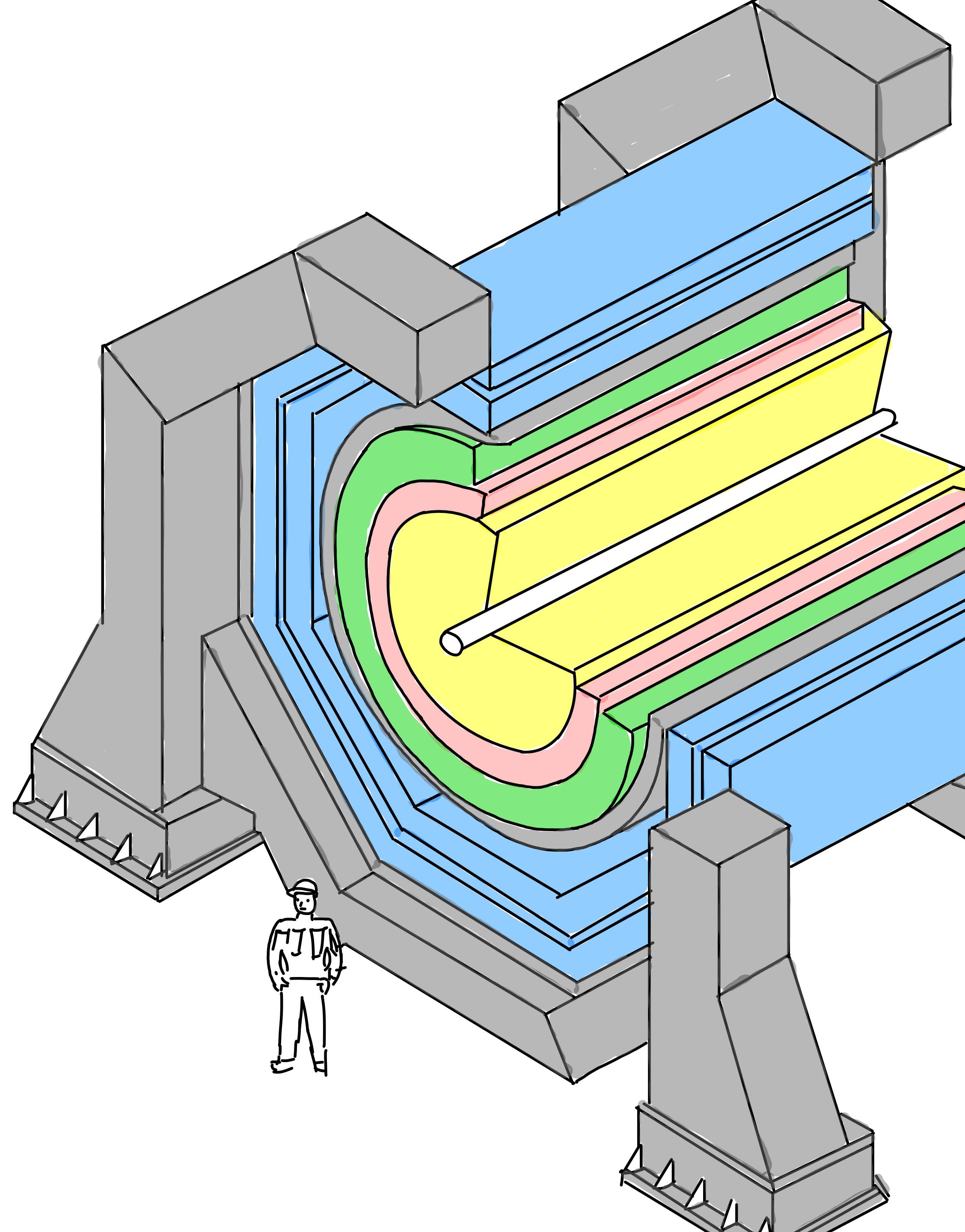
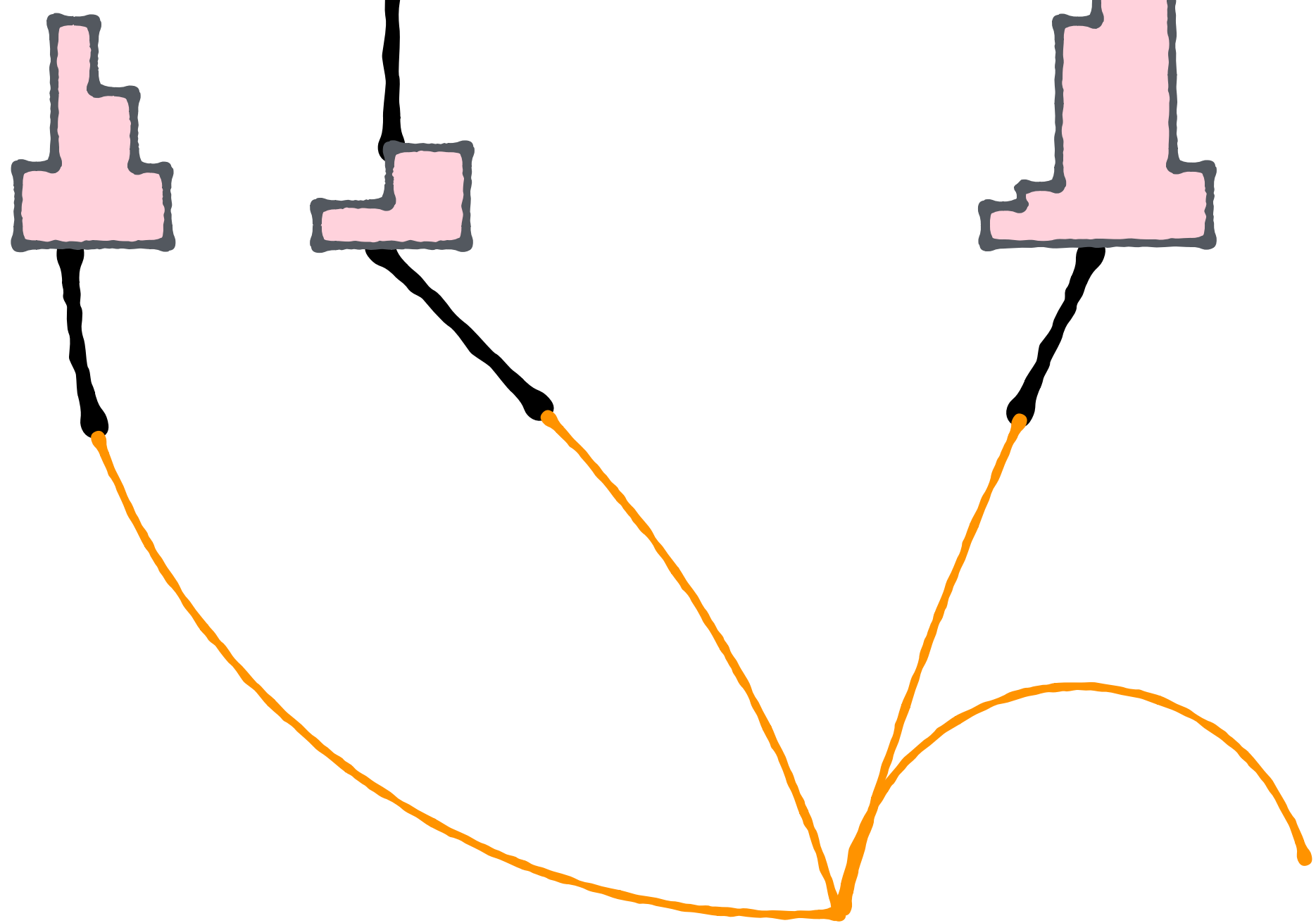
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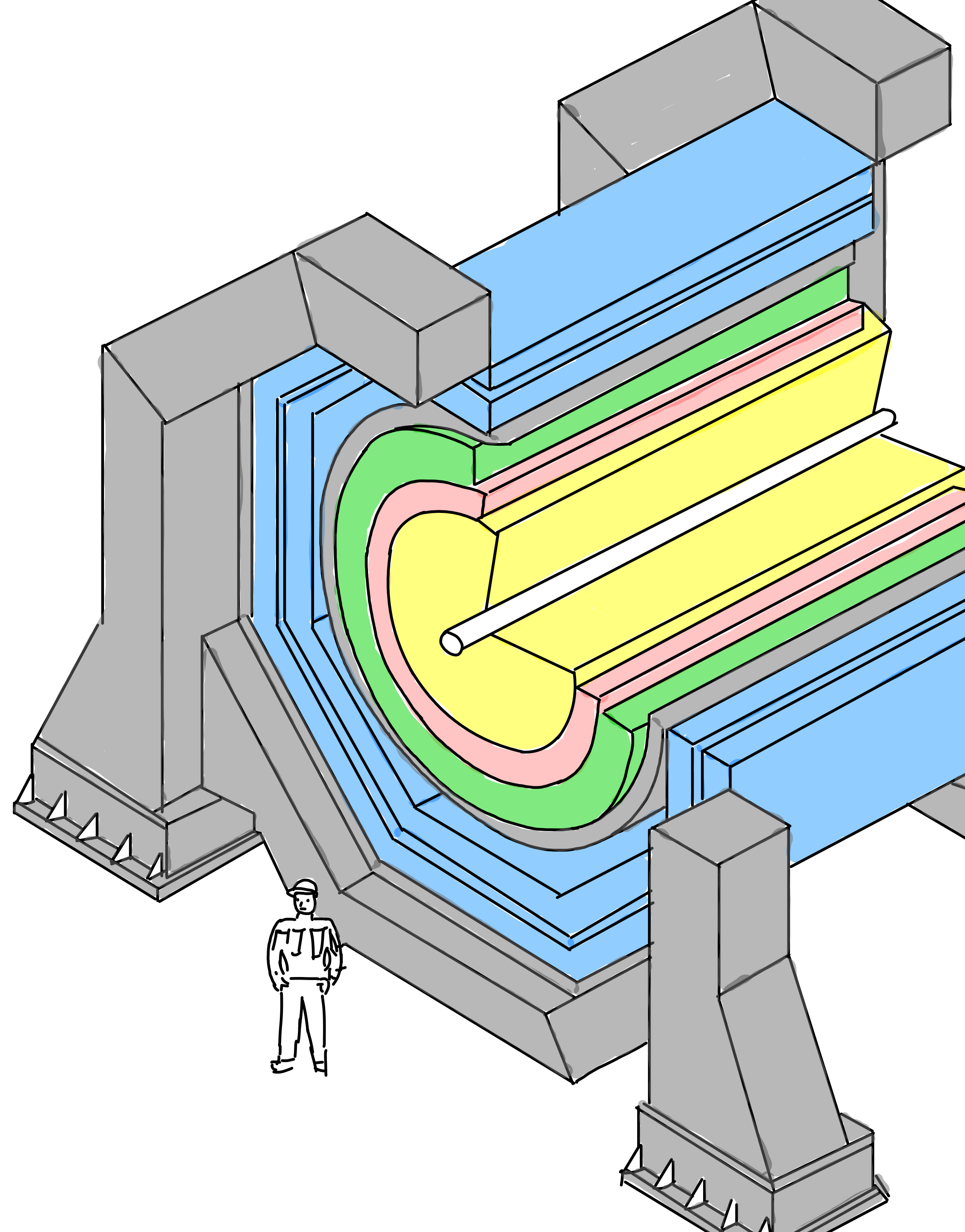
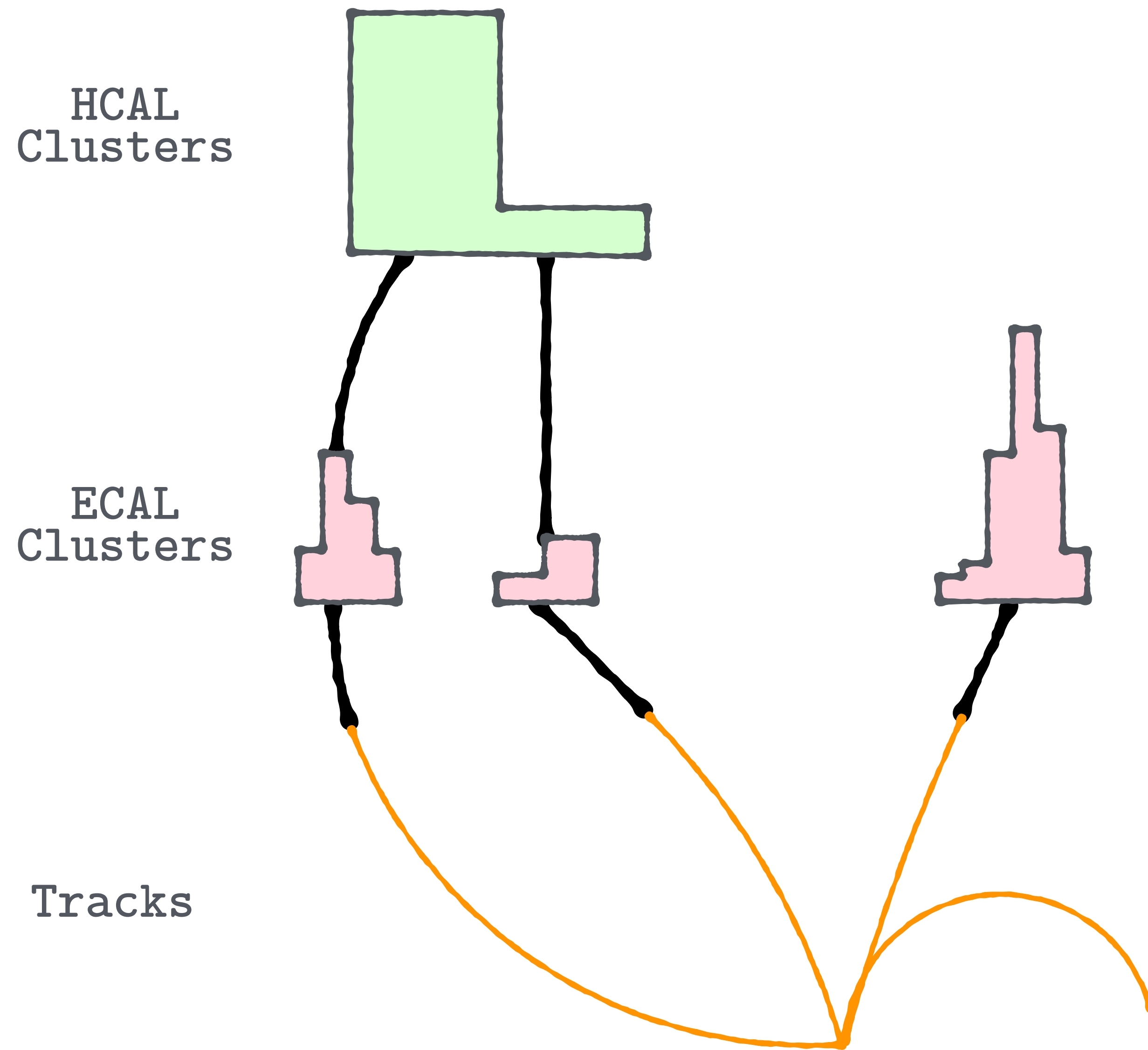
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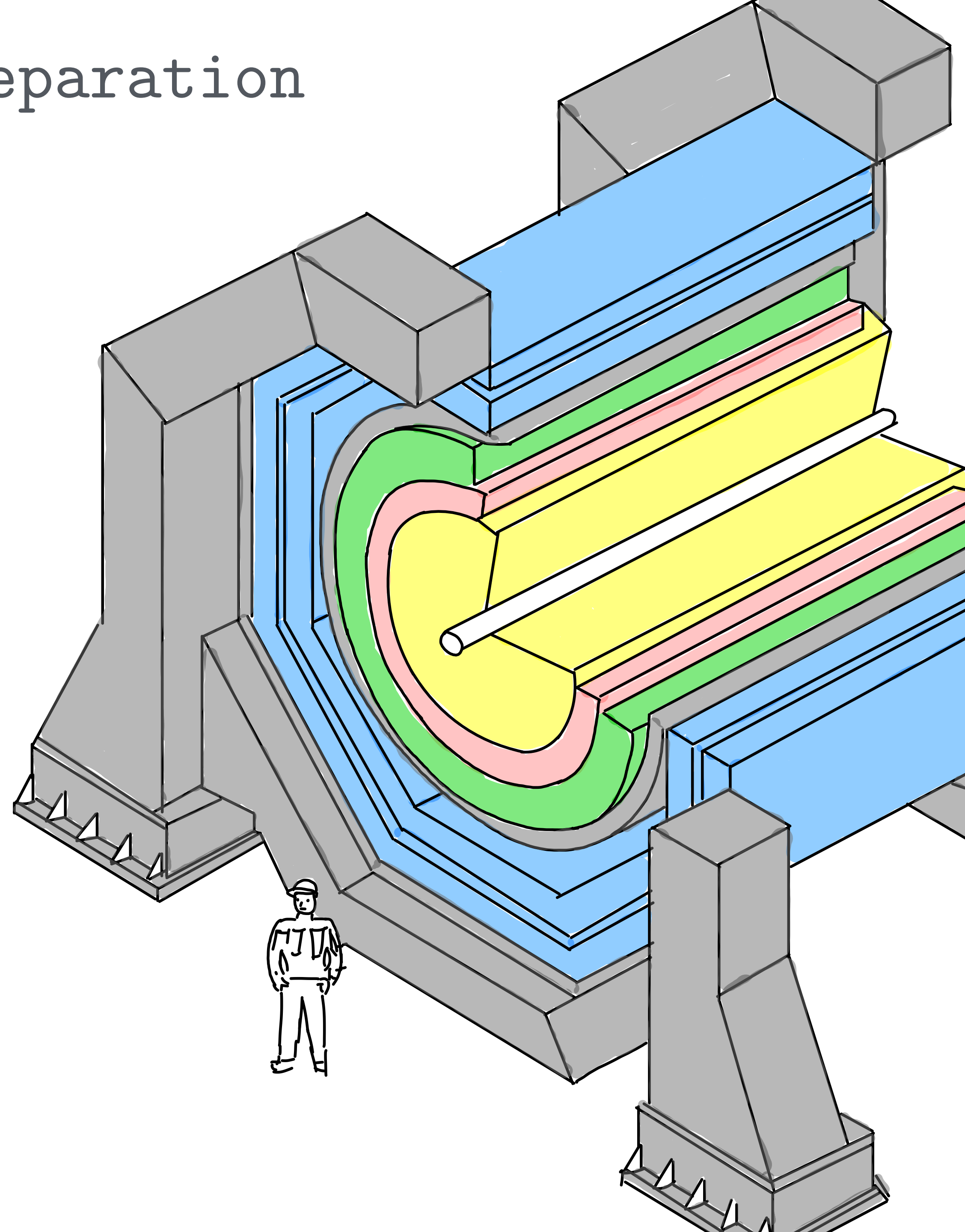
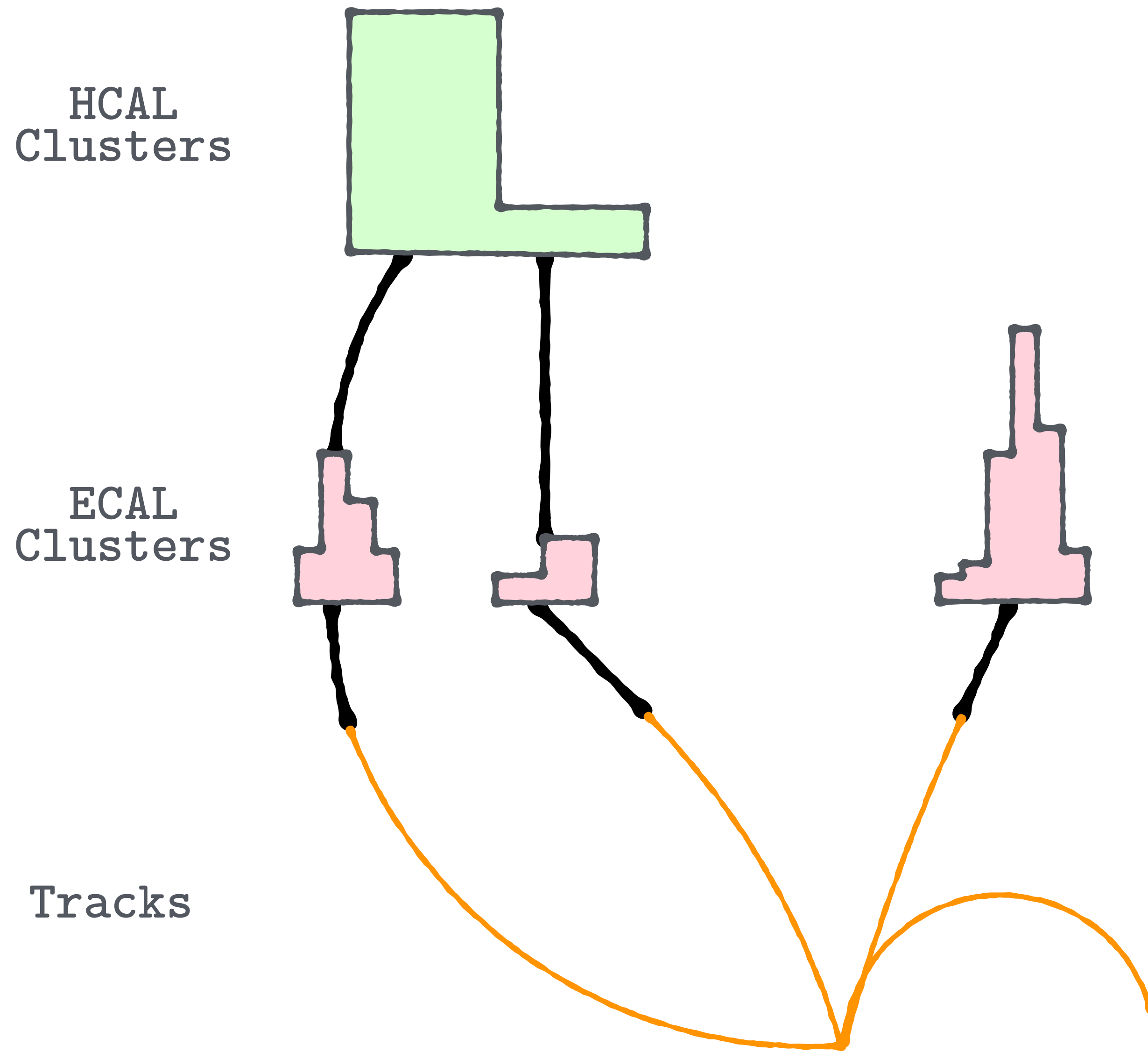
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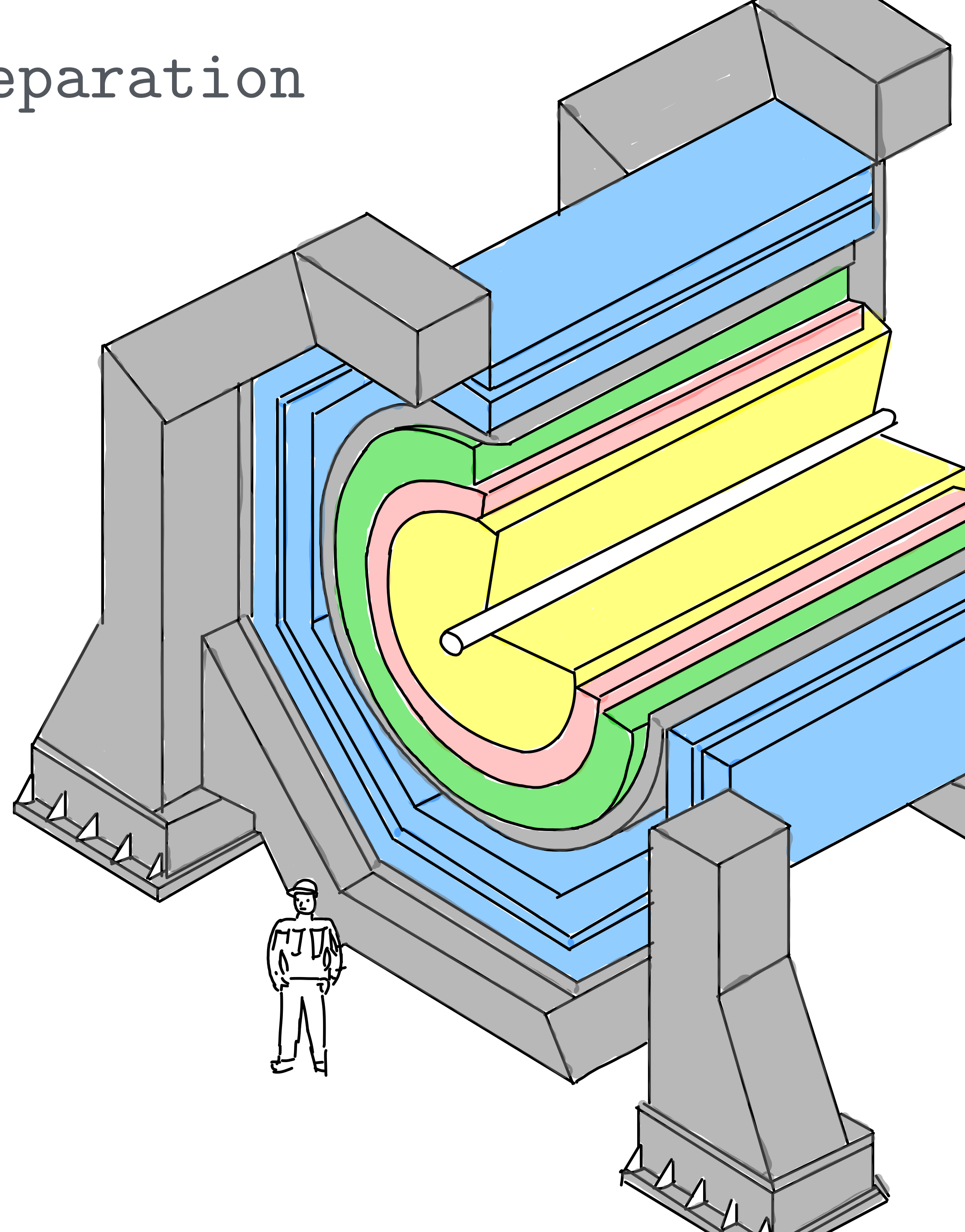
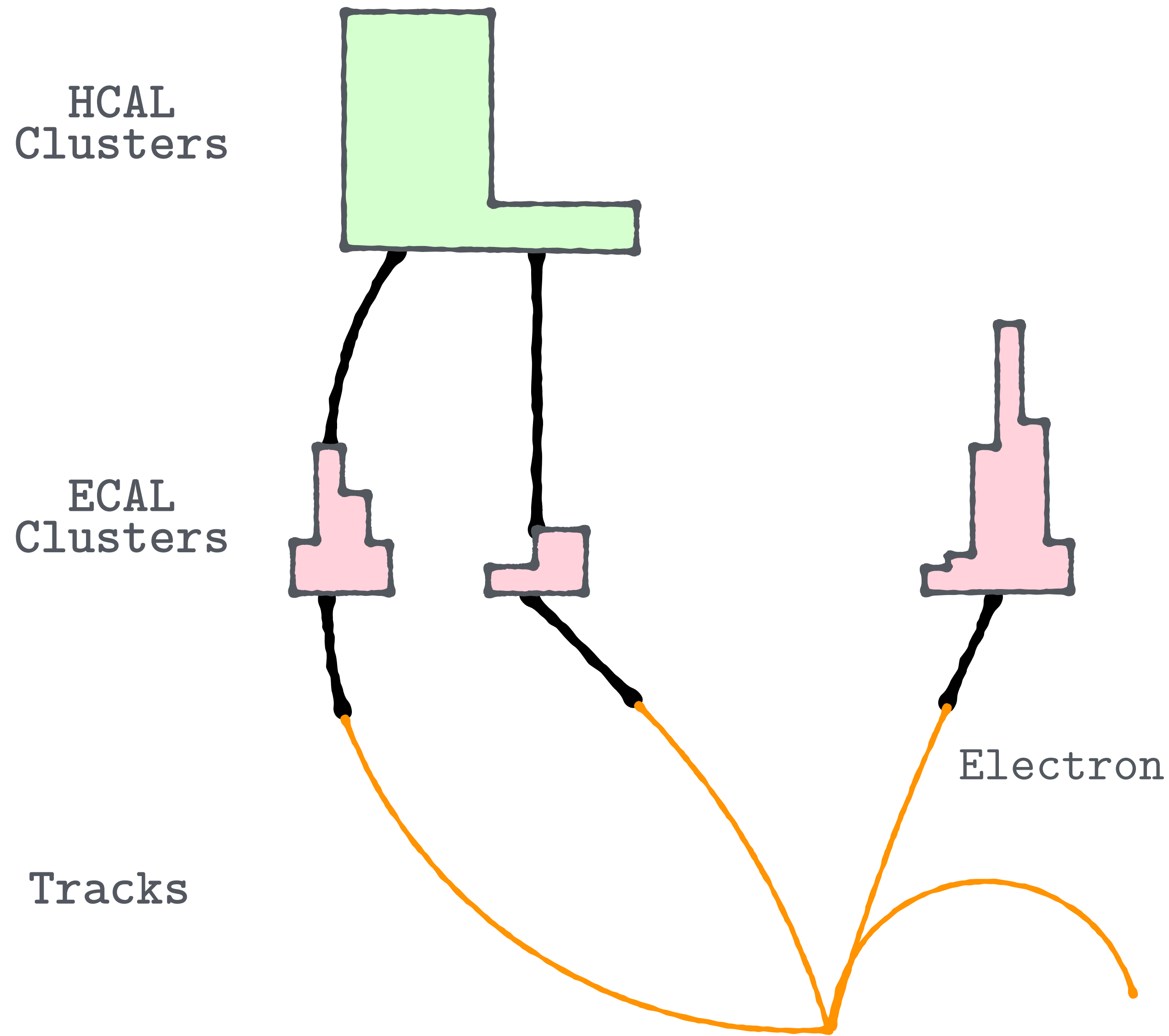
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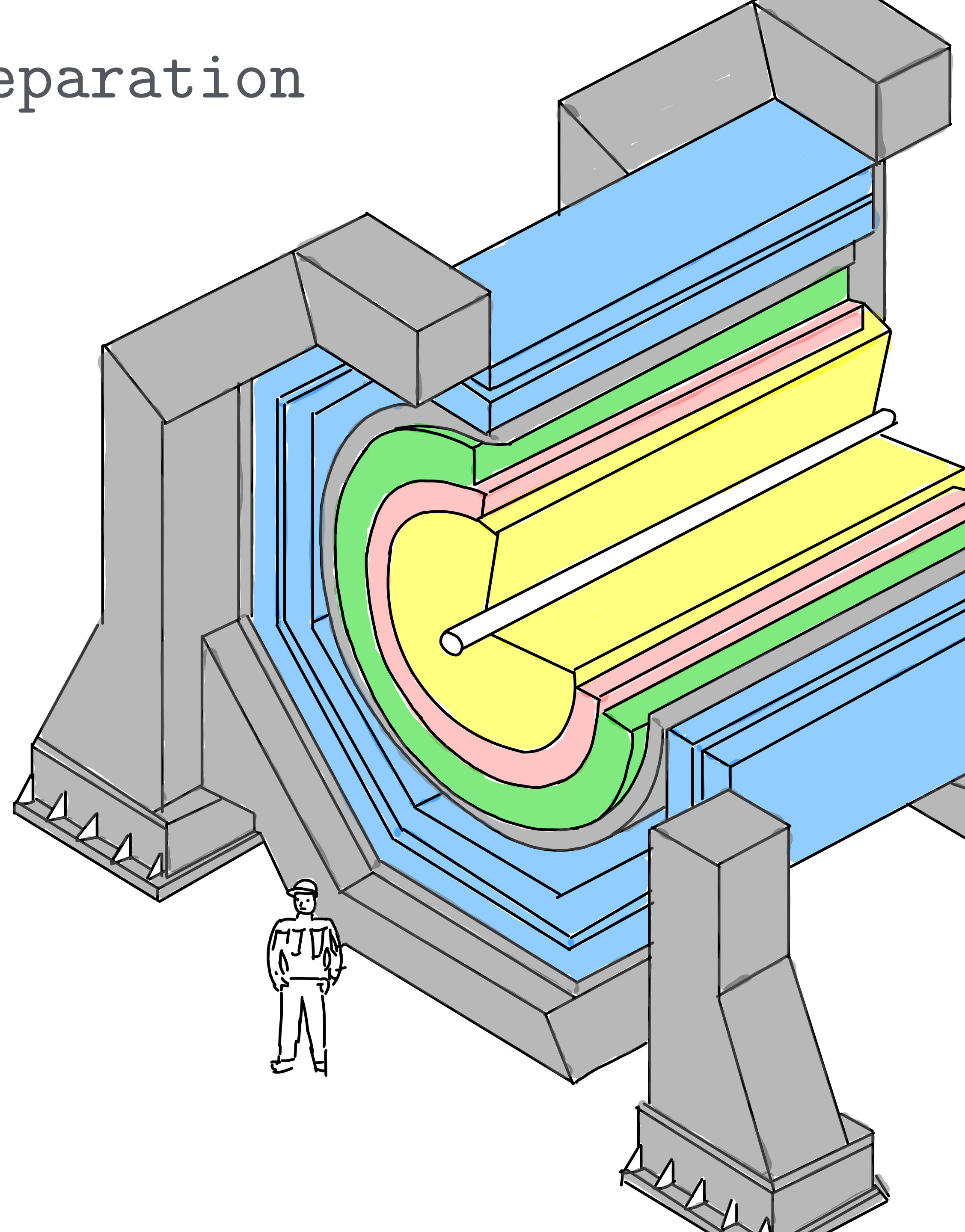
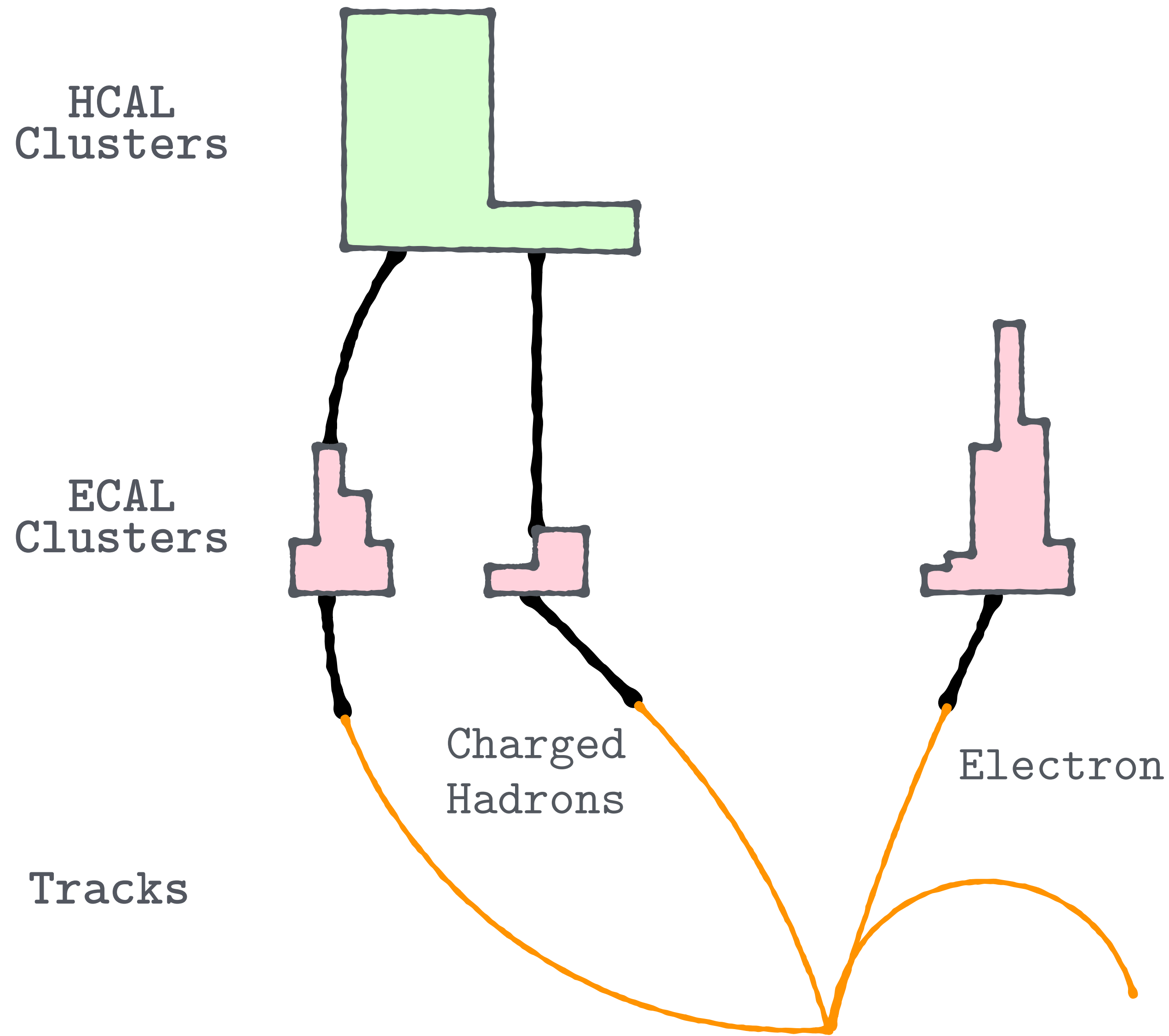
Finally: Apply Particle ID & Separation



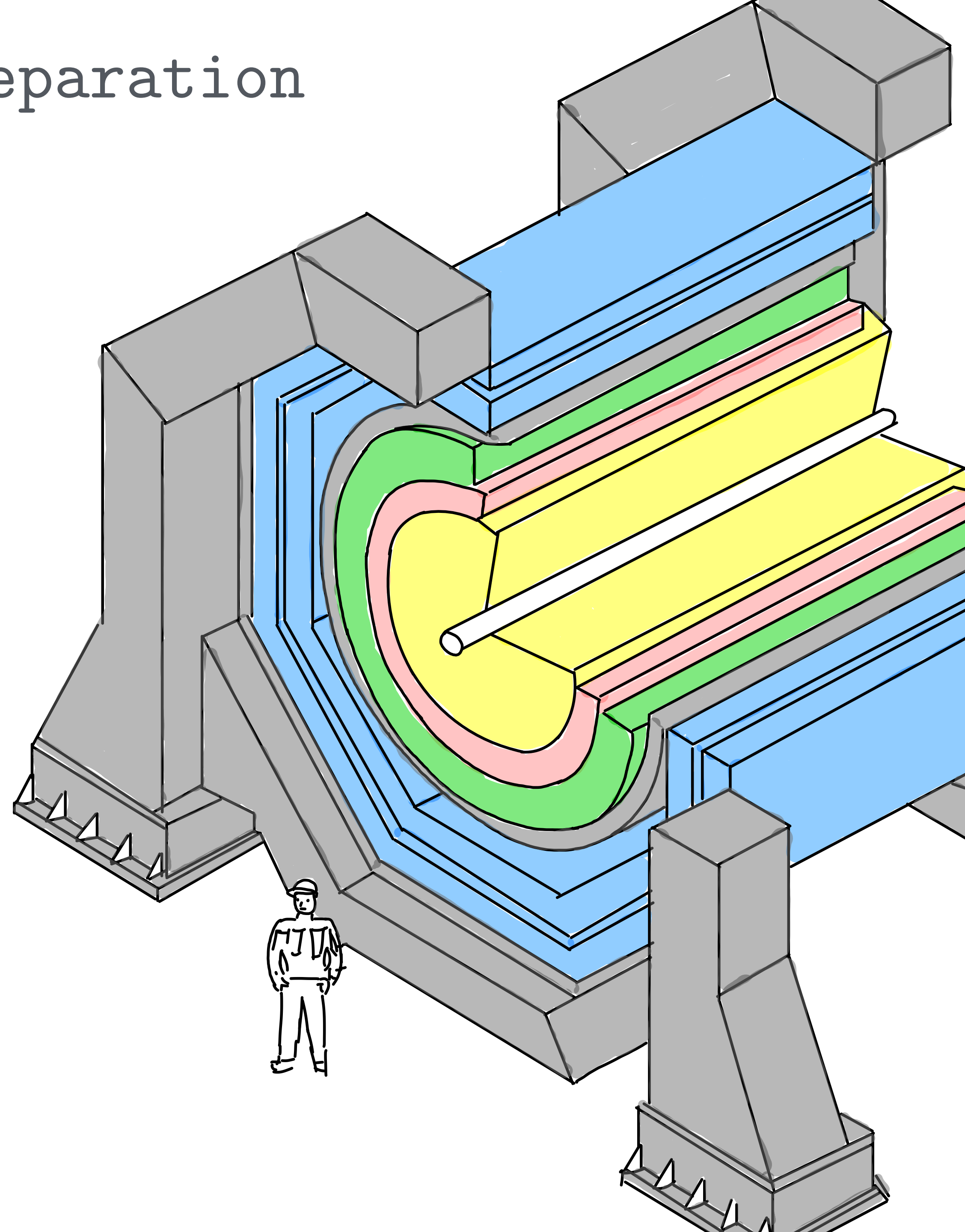
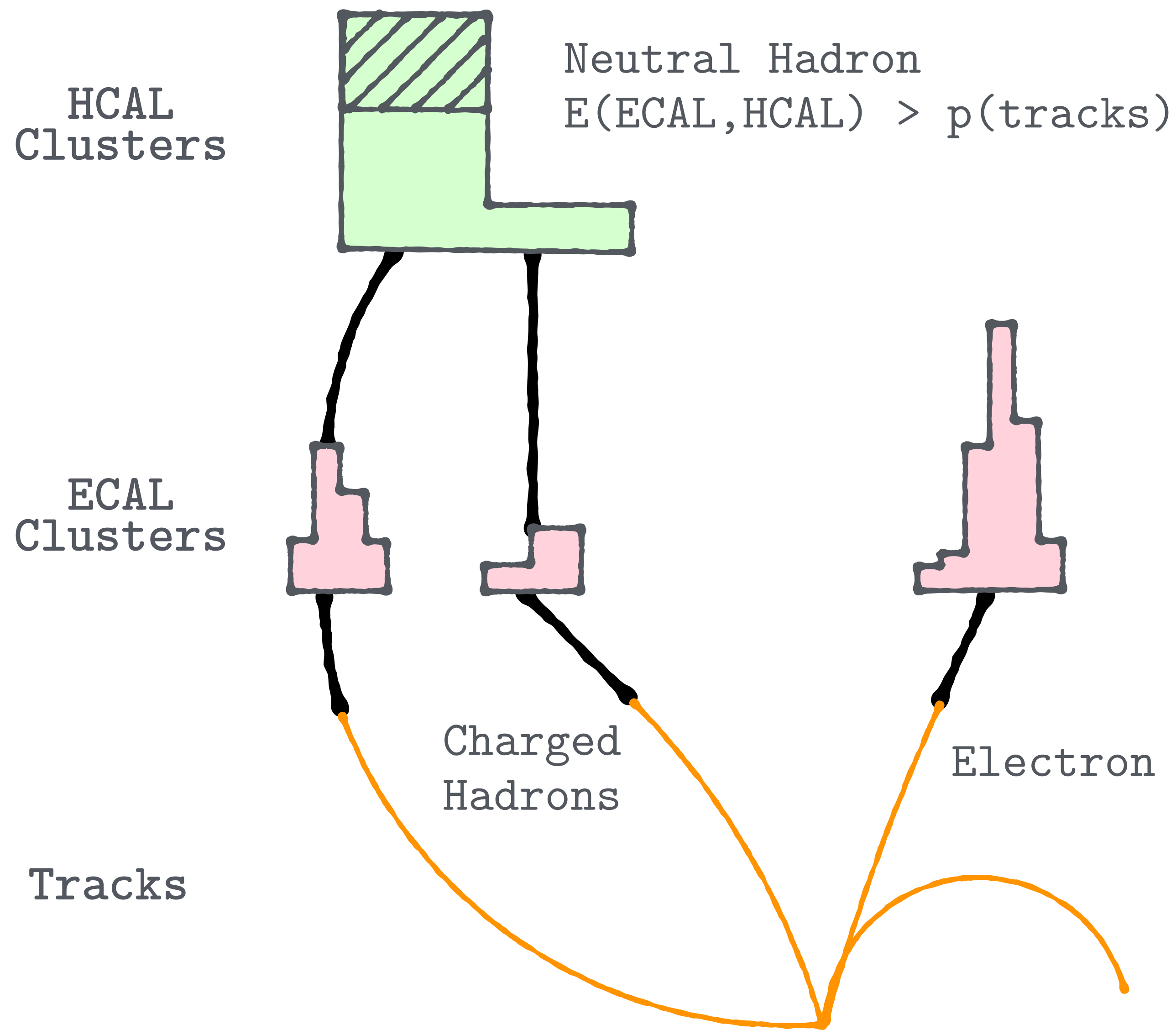
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- Find and “remove” muons

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σ_{track}

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- Find and “remove” electrons

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$\min[\sigma_{\text{track}}, \sigma_{\text{ECAL}}]$

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- Find and “remove” muons
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- Find and “remove” charged hadrons

σ_{track}

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- Find and “remove” converted photons

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- Find and “remove” V0's σ_{track}
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- Find and “remove” V0's σ_{track}
- Find and “remove” photons σ_{ECAL}
- Left with neutral hadrons (10%)

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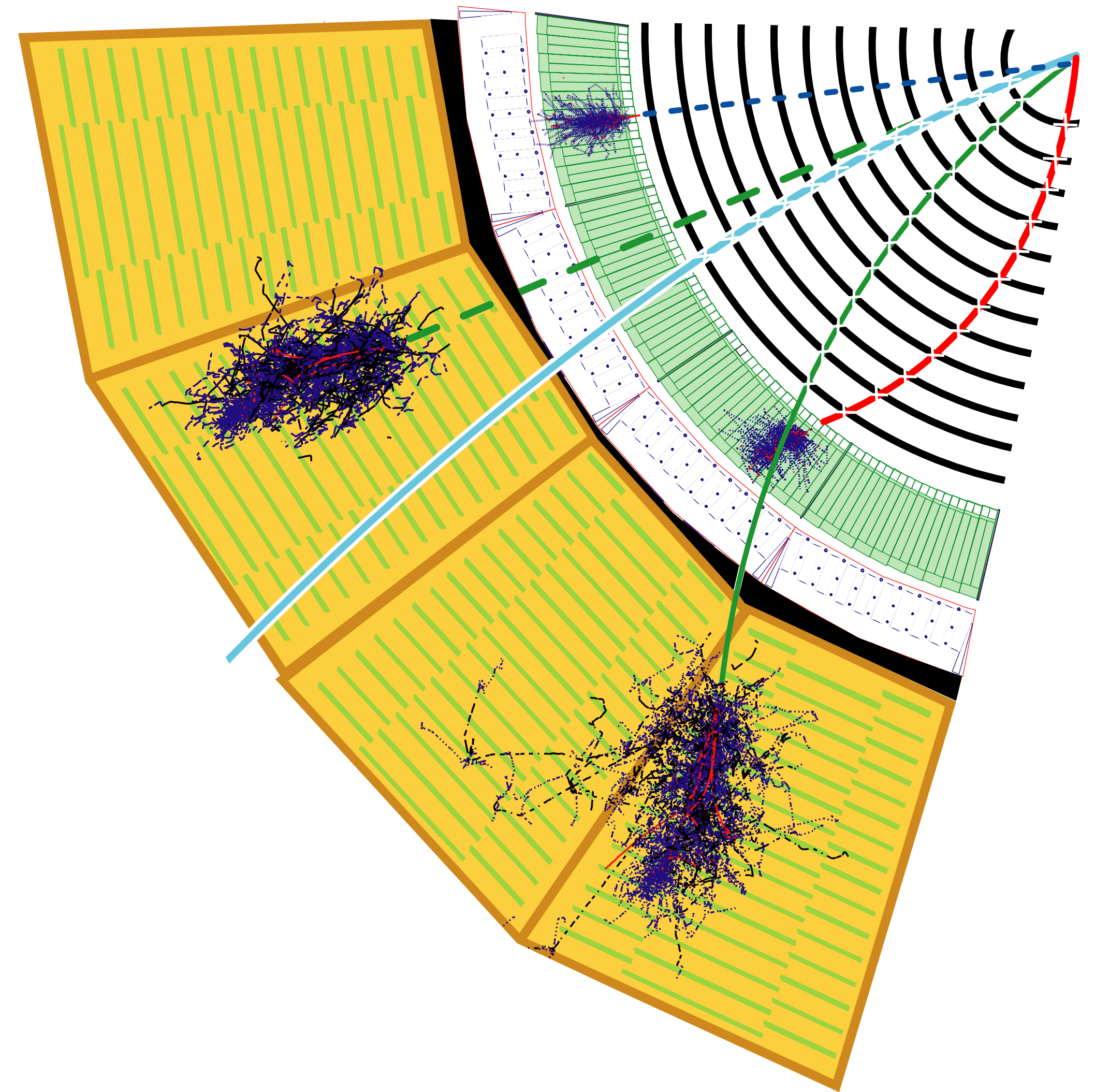
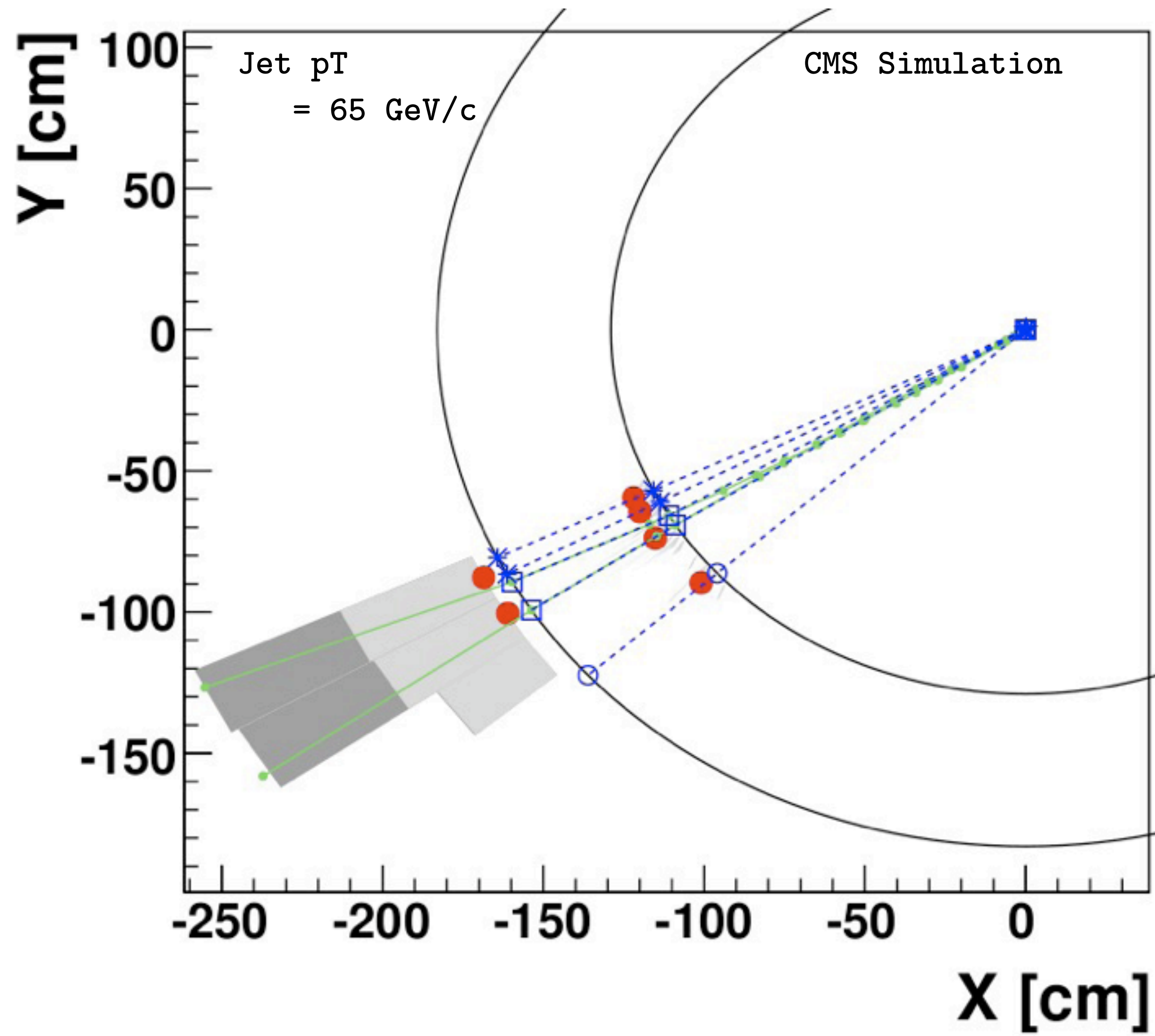
- Use above list of Particles to describe entire event!

Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

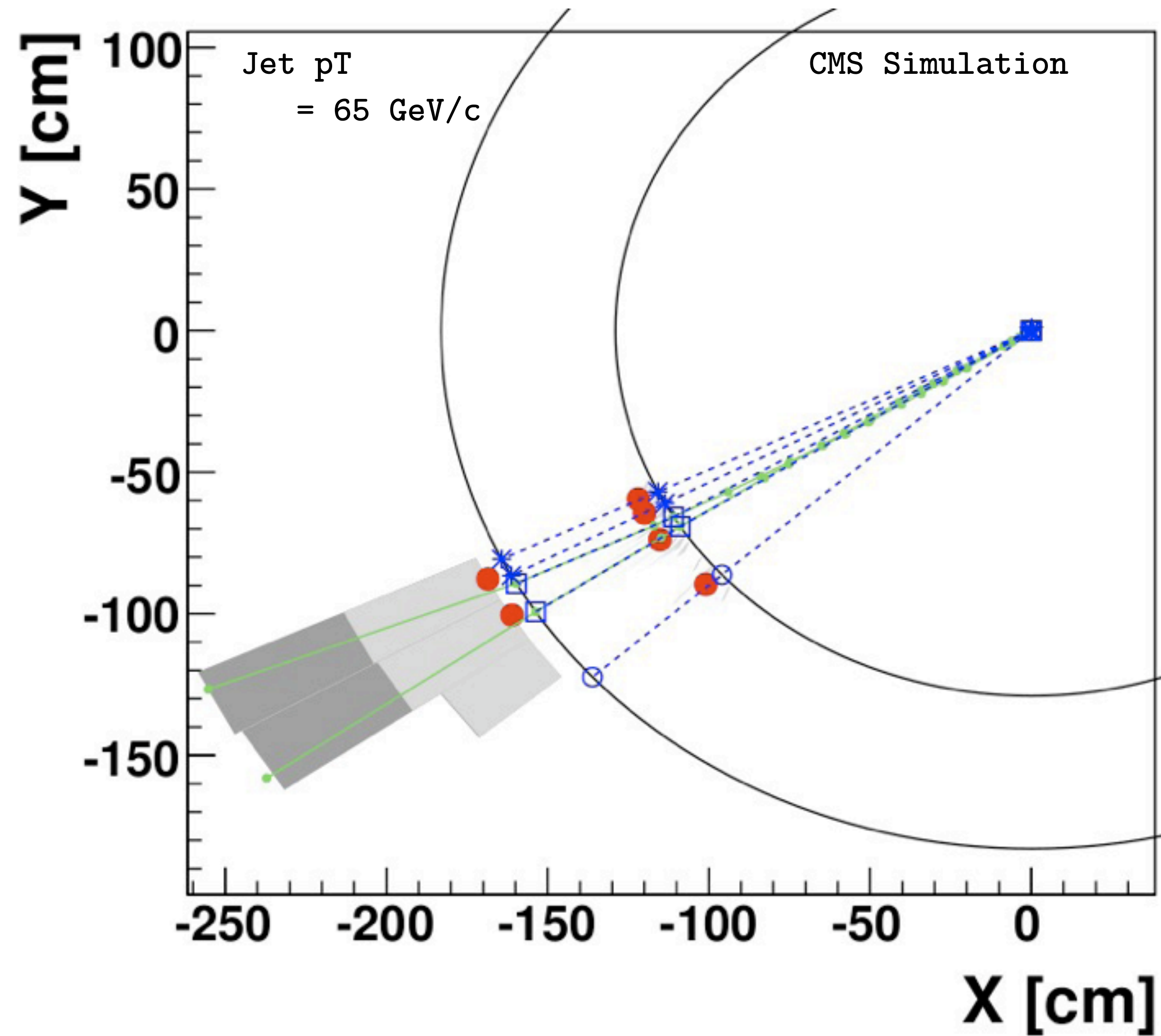
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



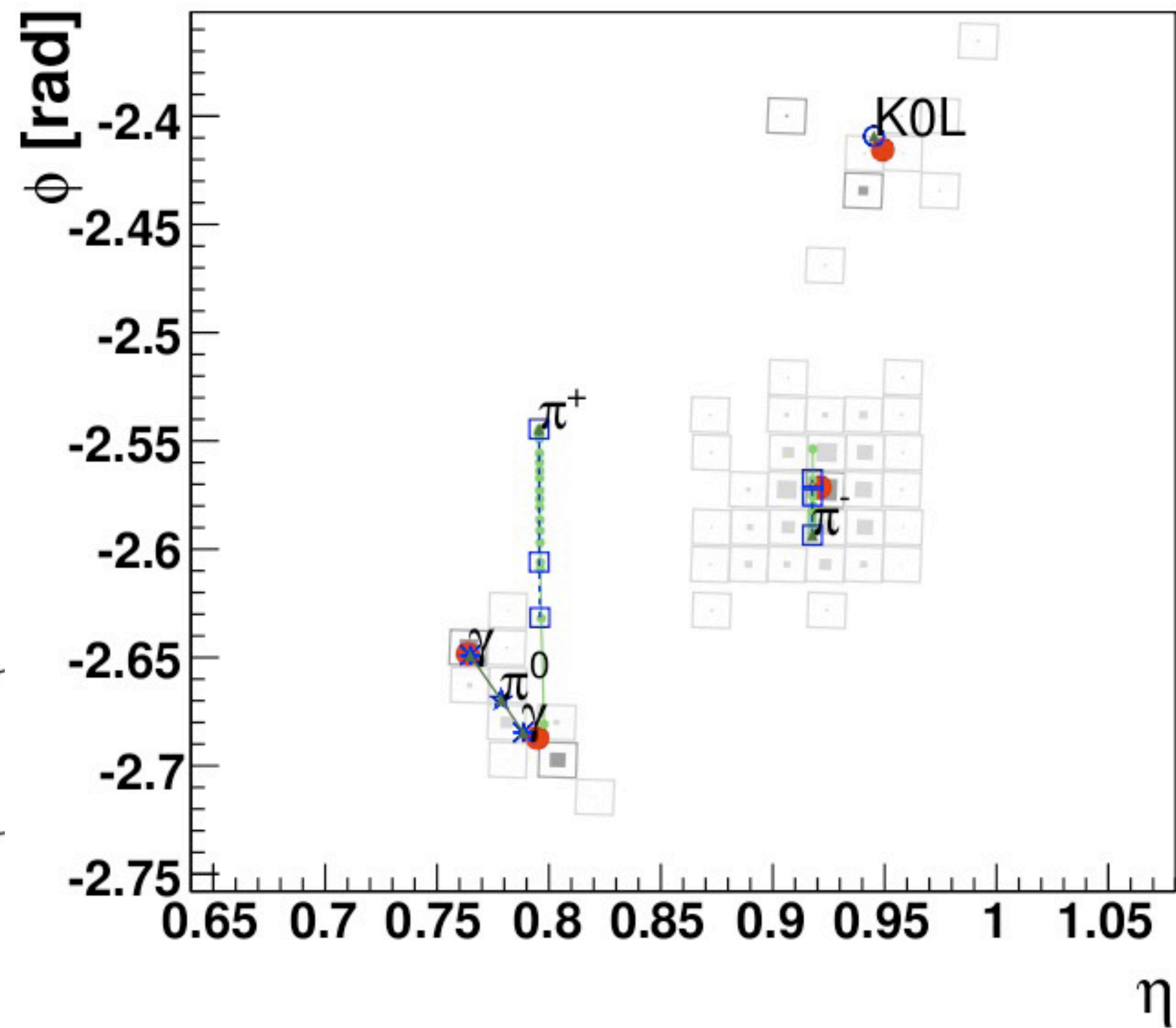
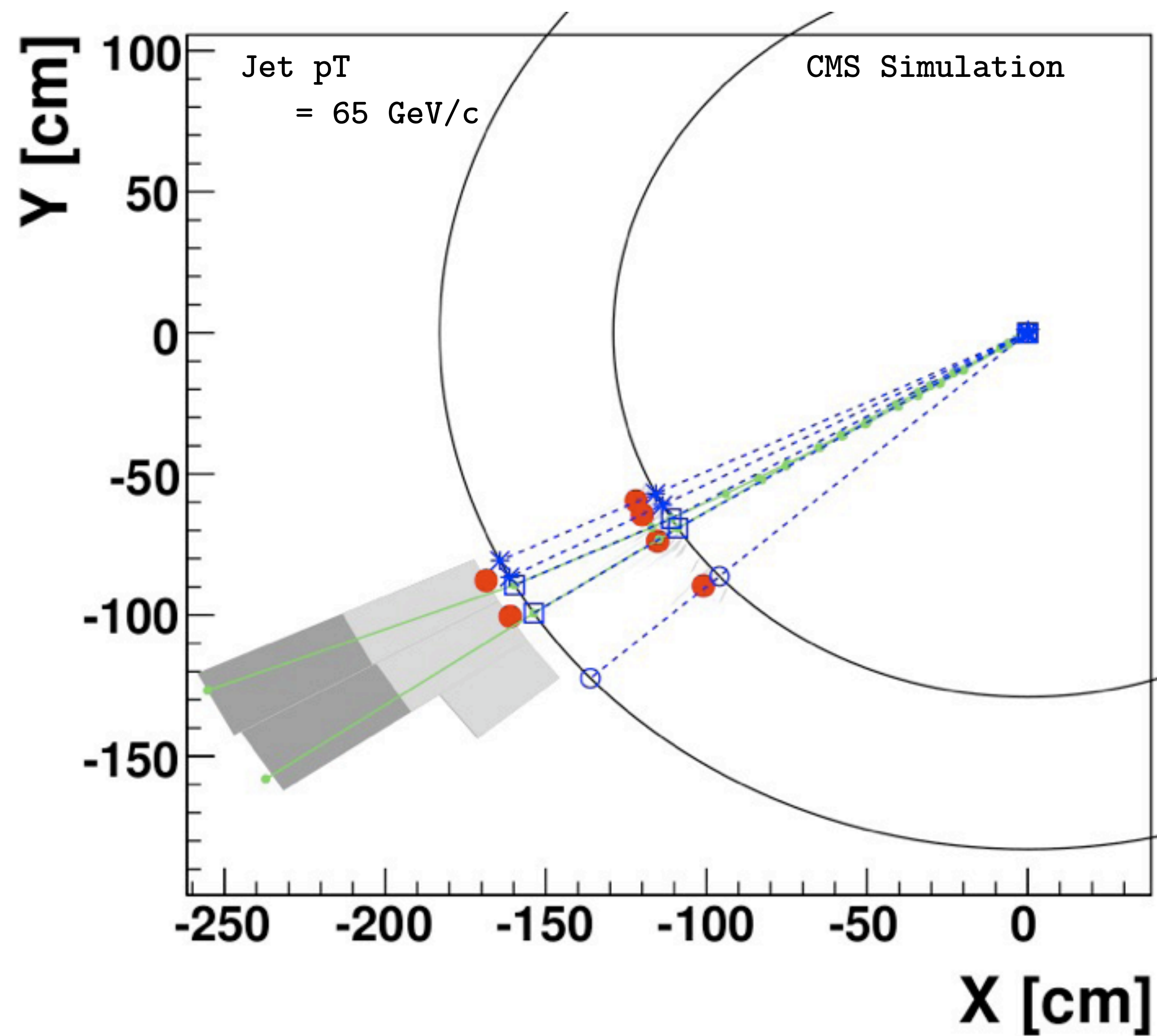
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



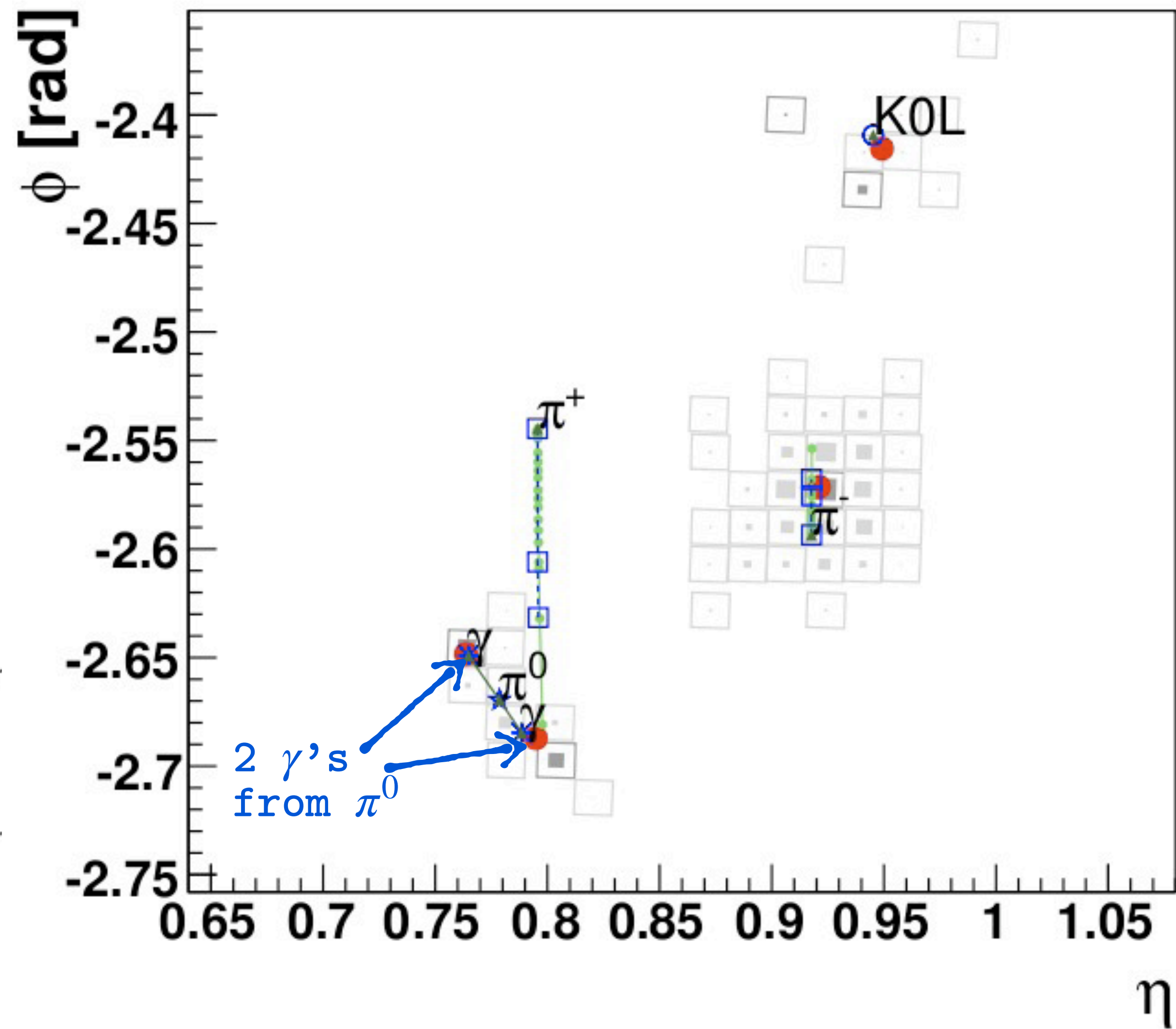
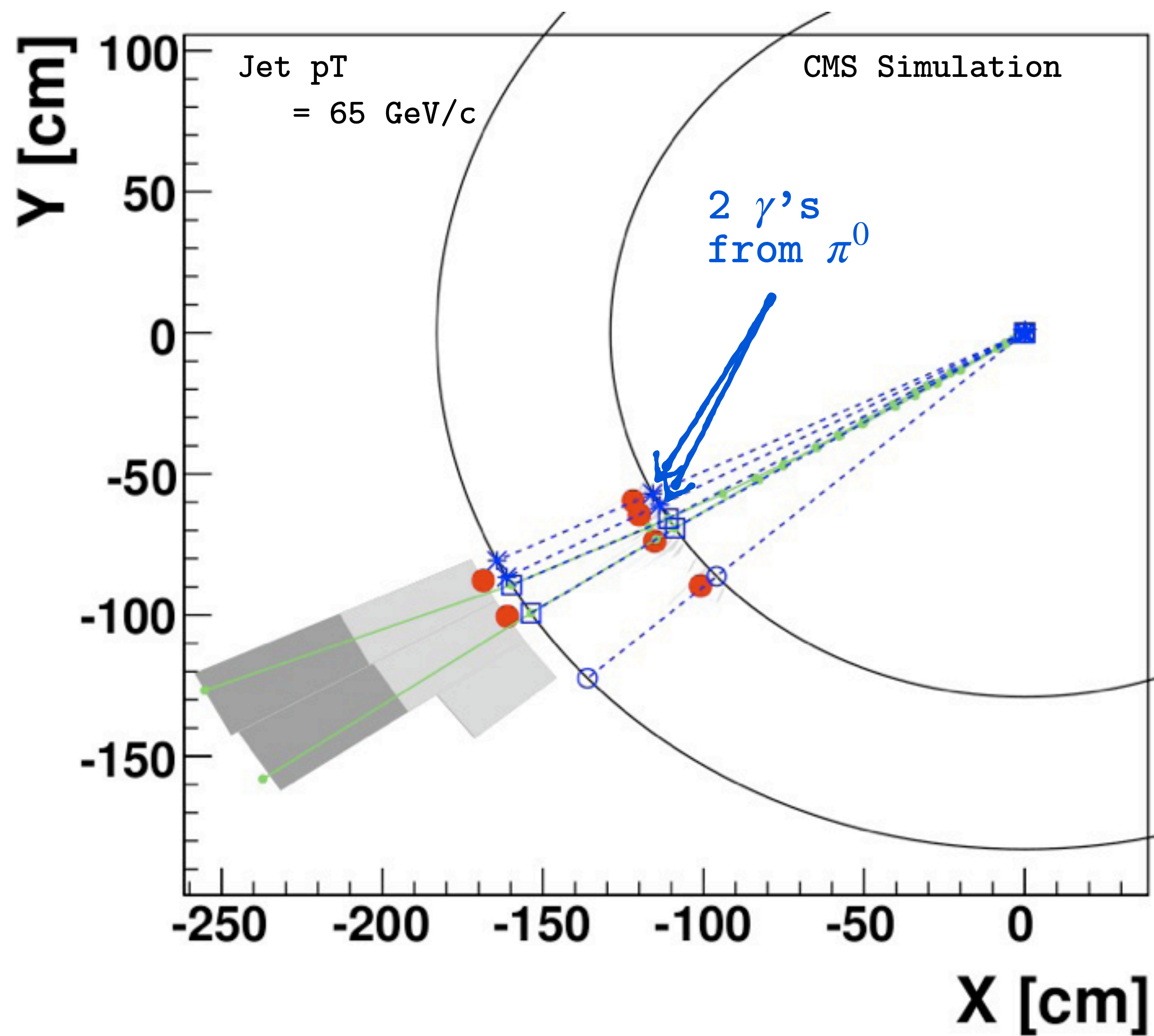
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



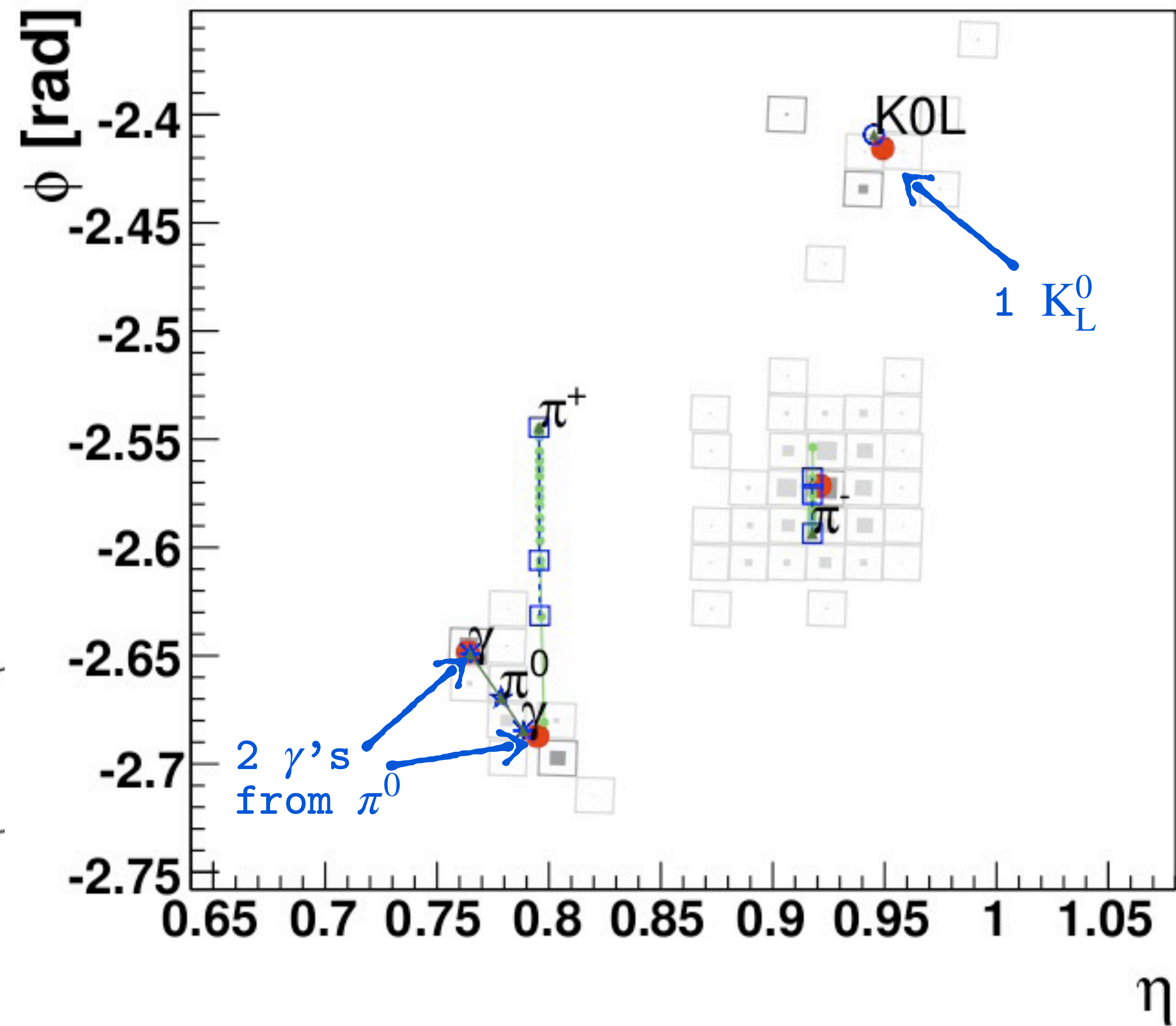
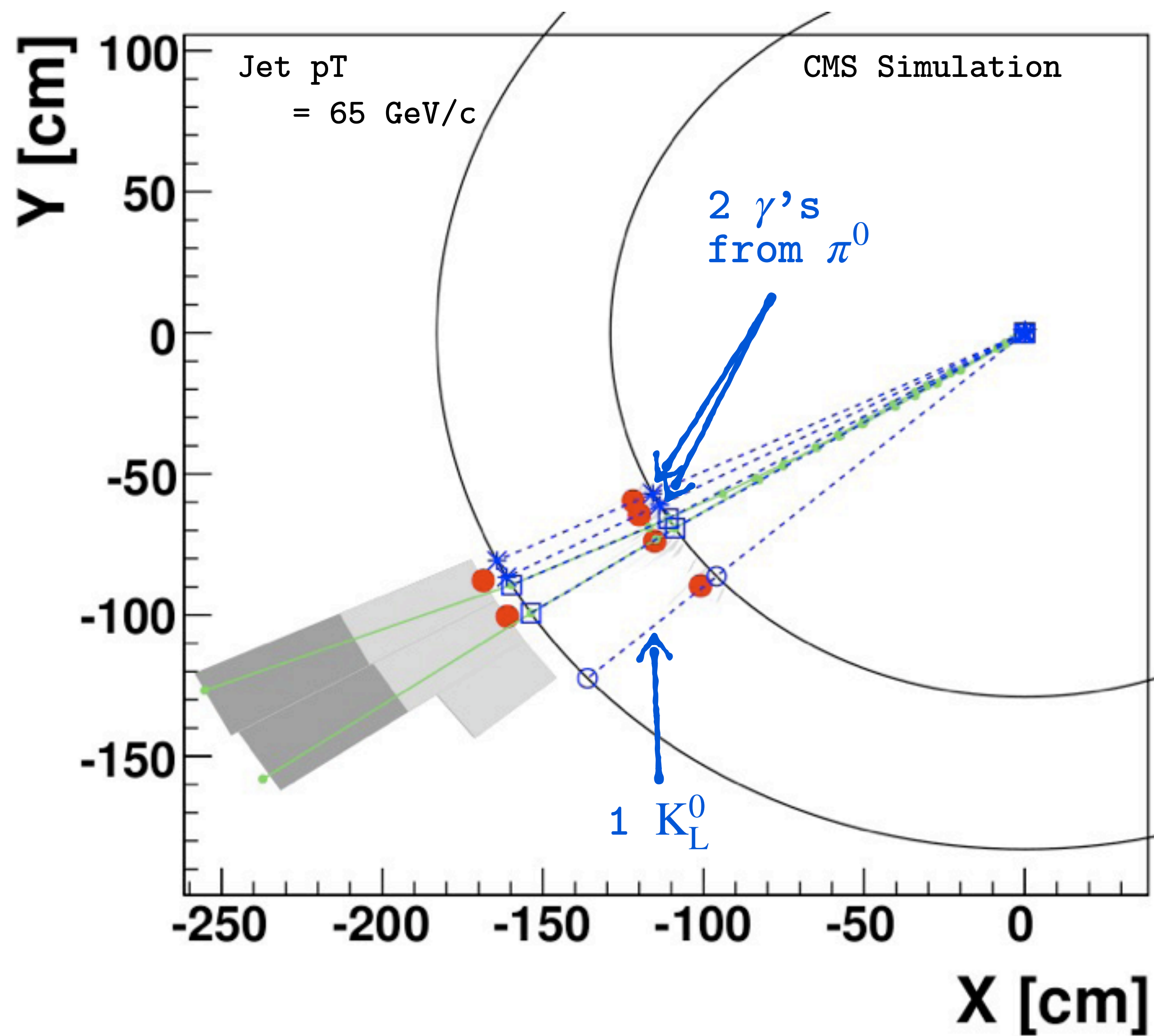
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



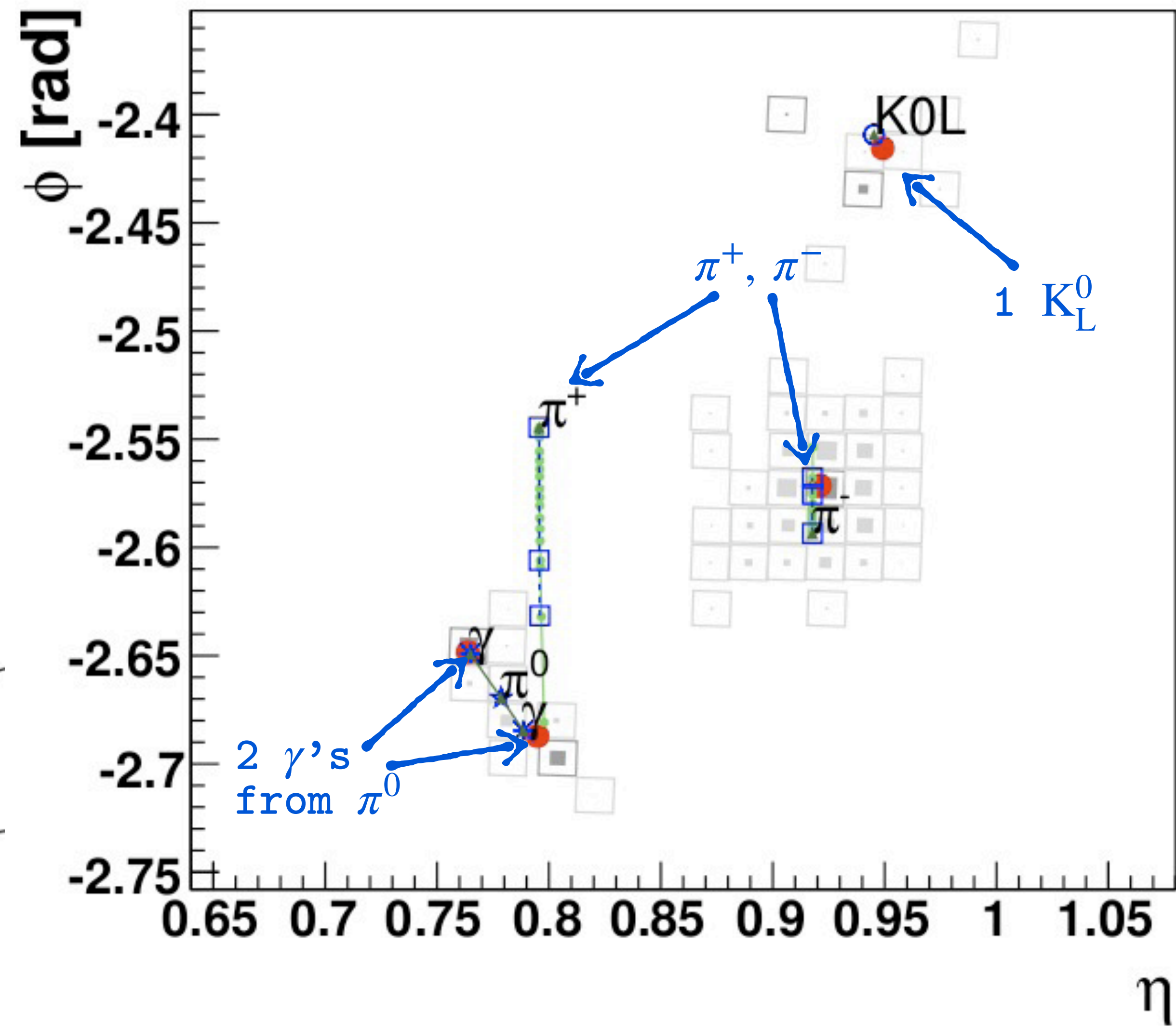
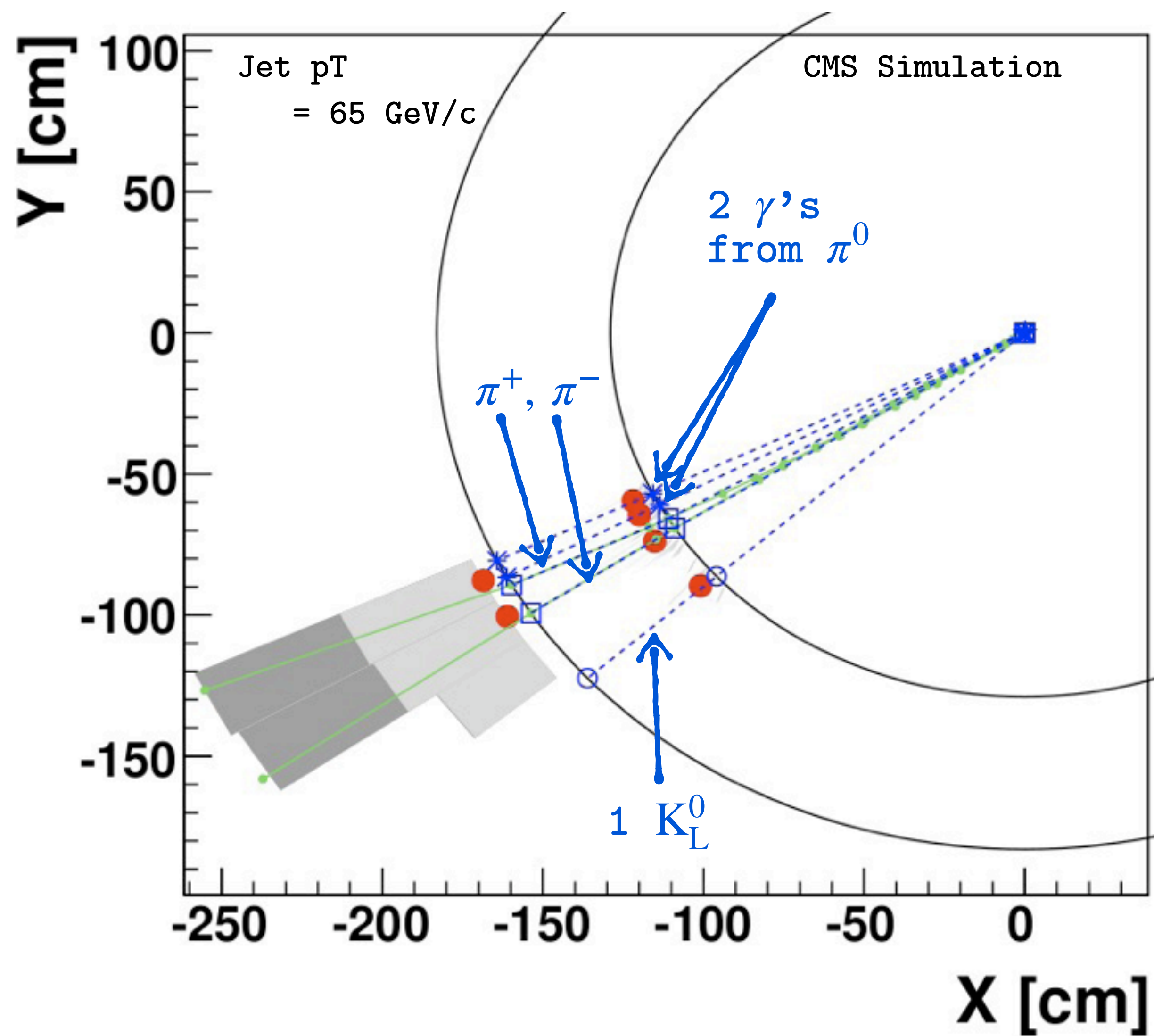
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



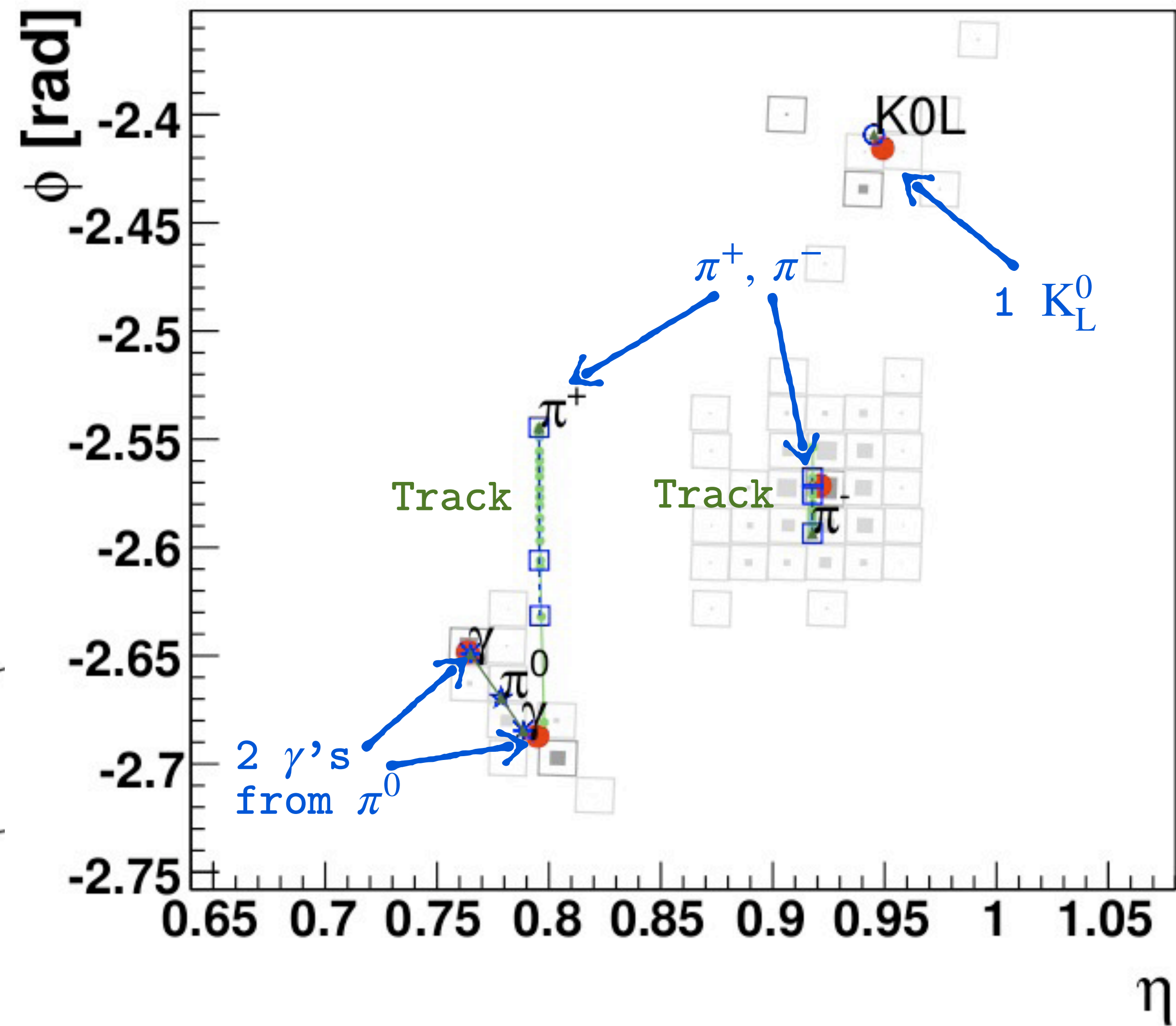
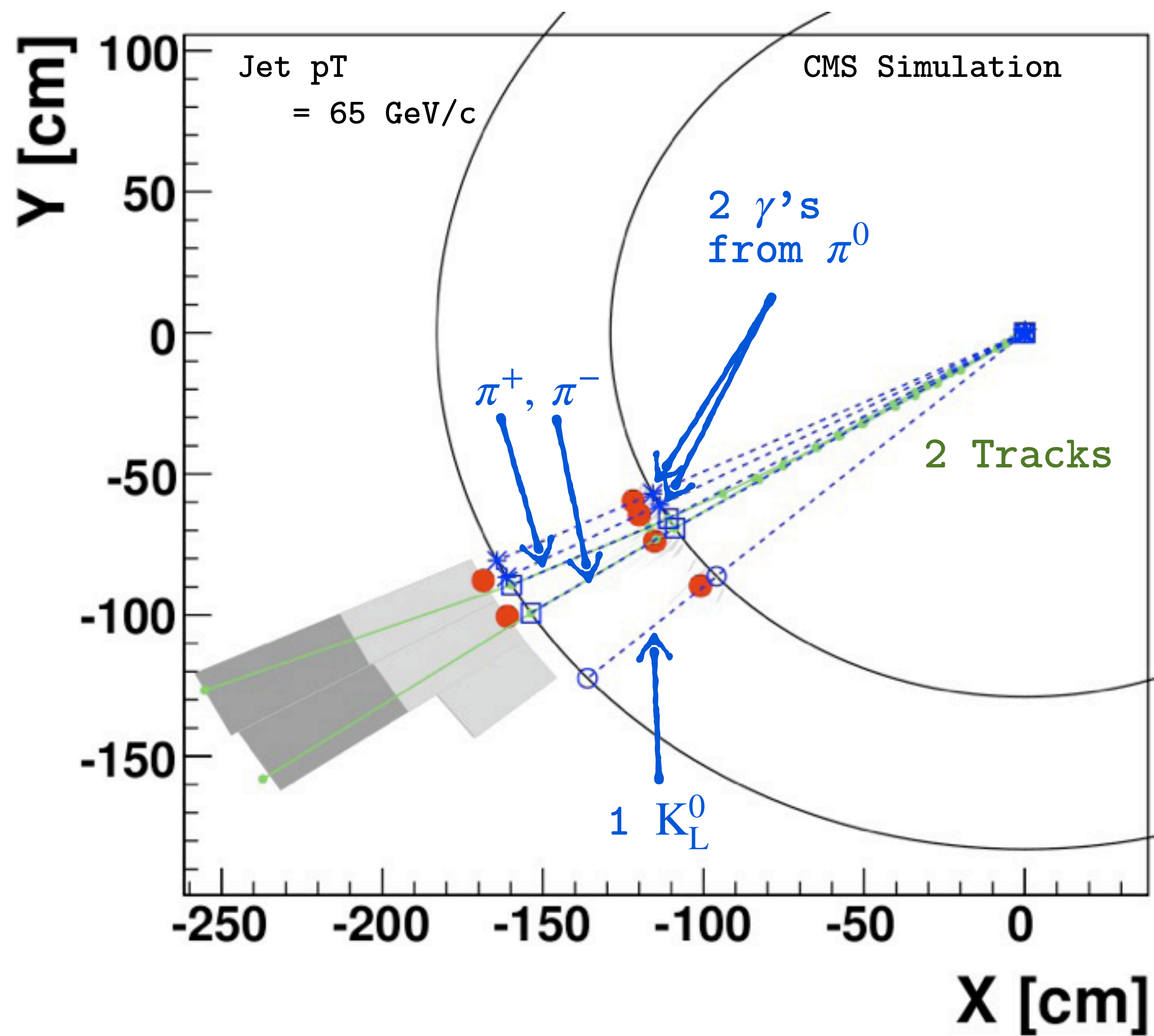
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



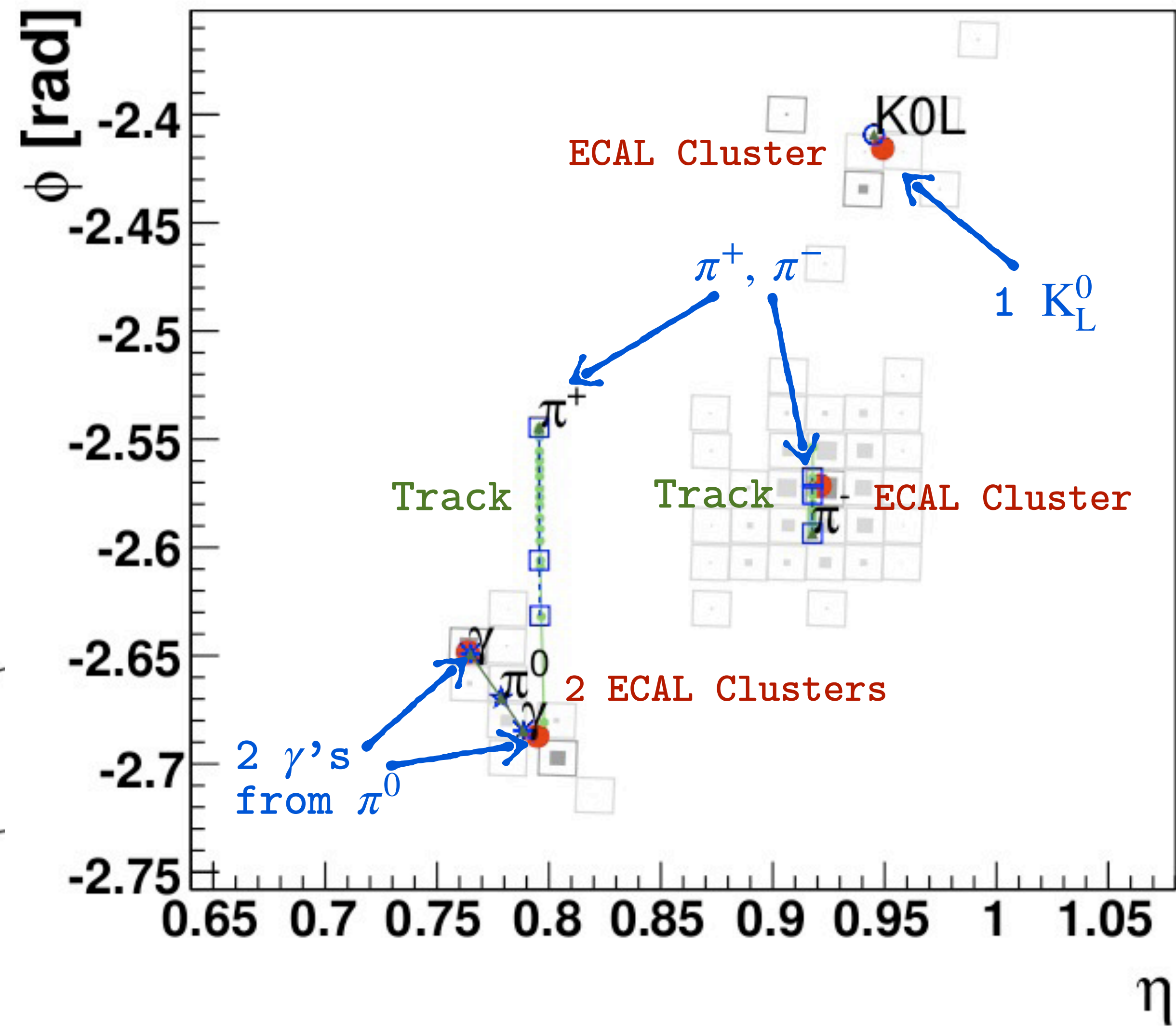
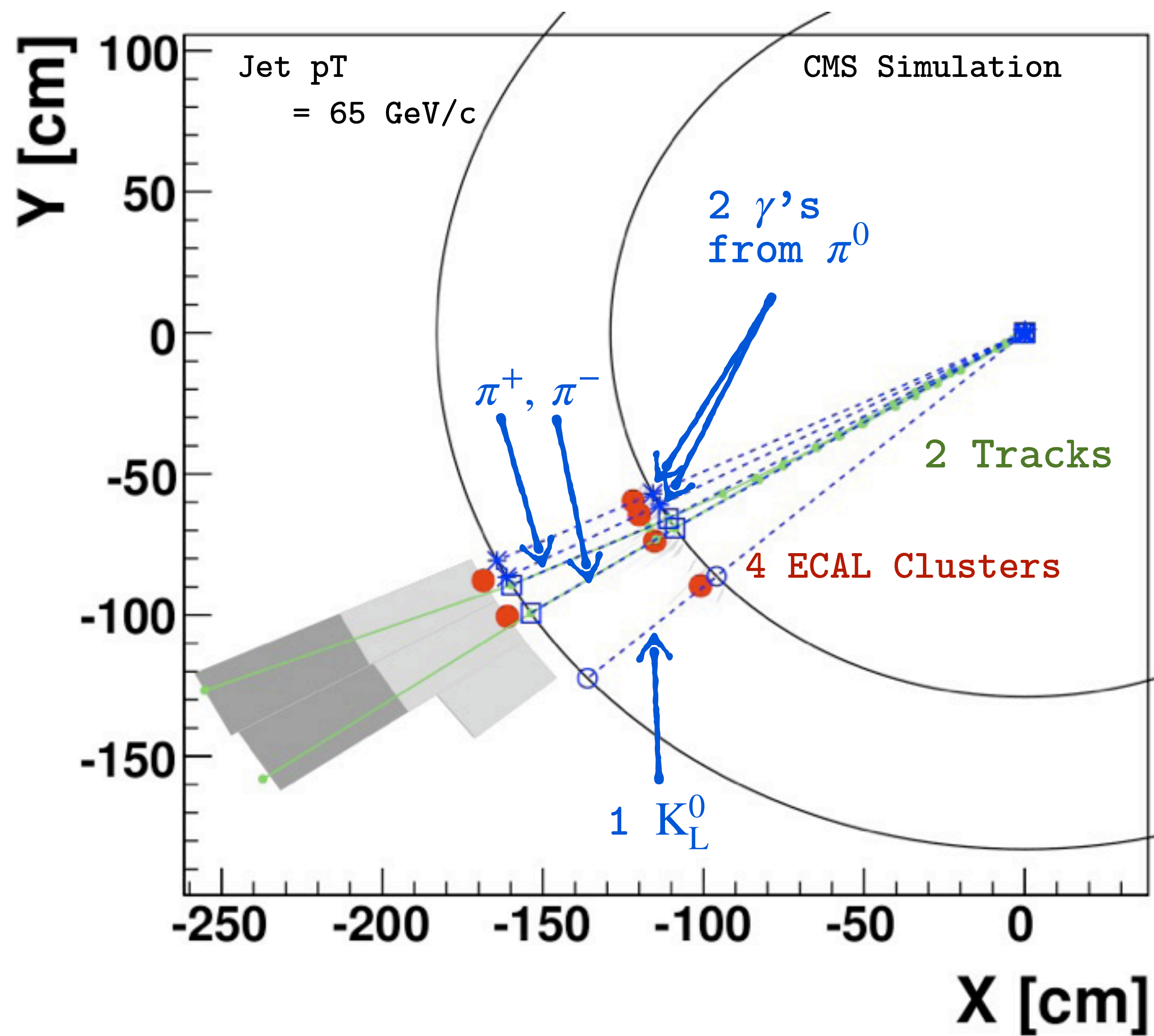
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



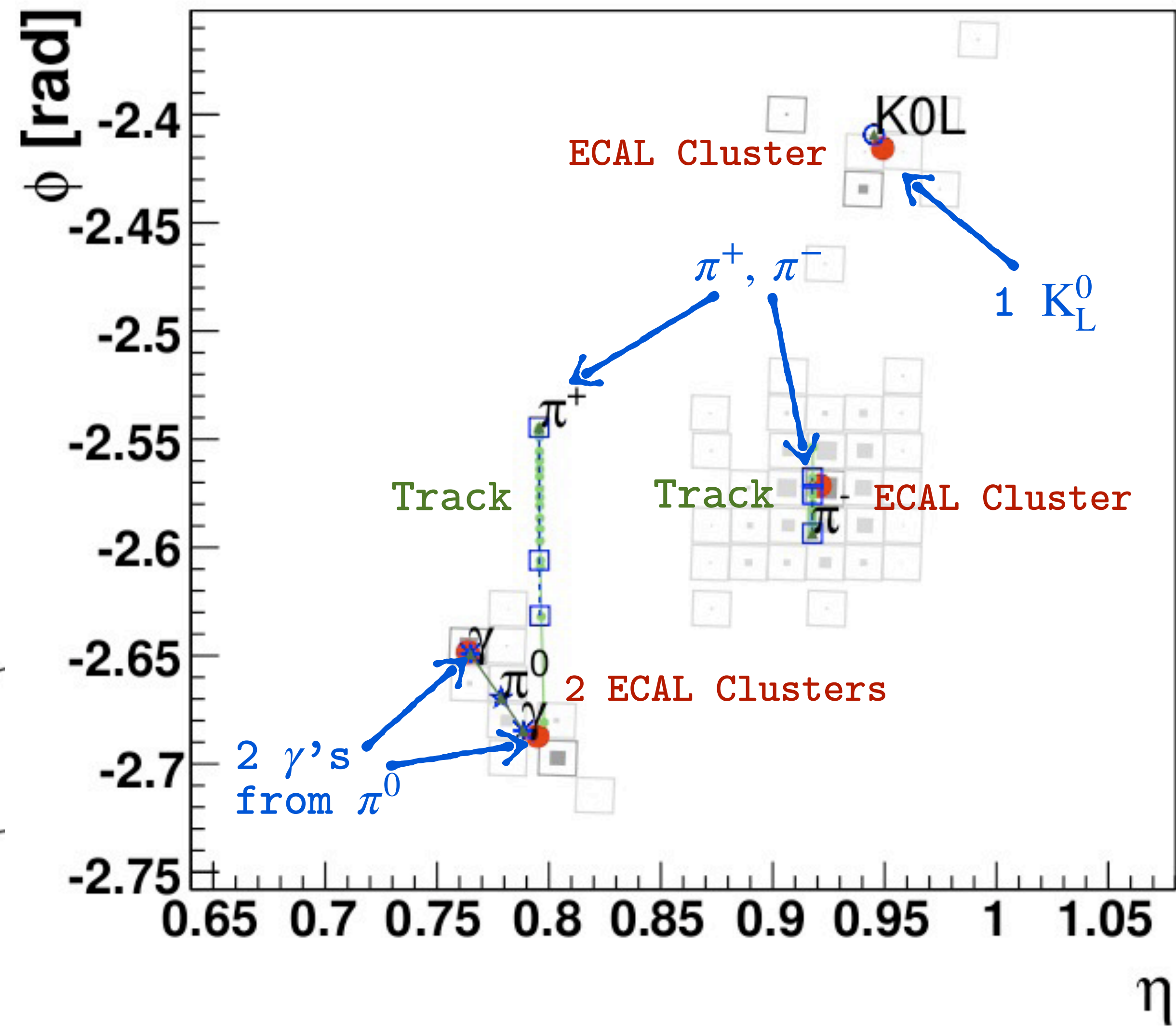
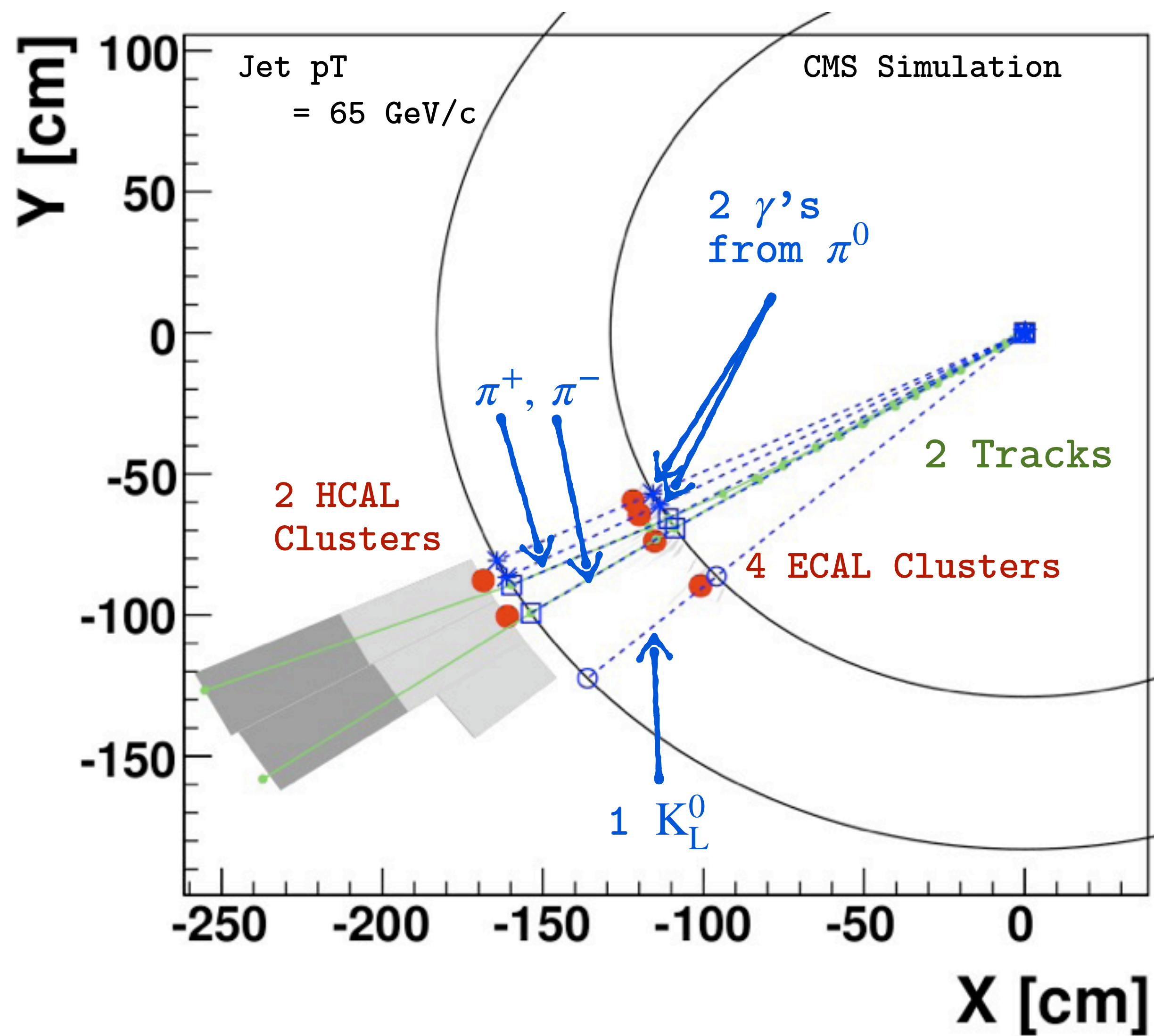
Four true particles:

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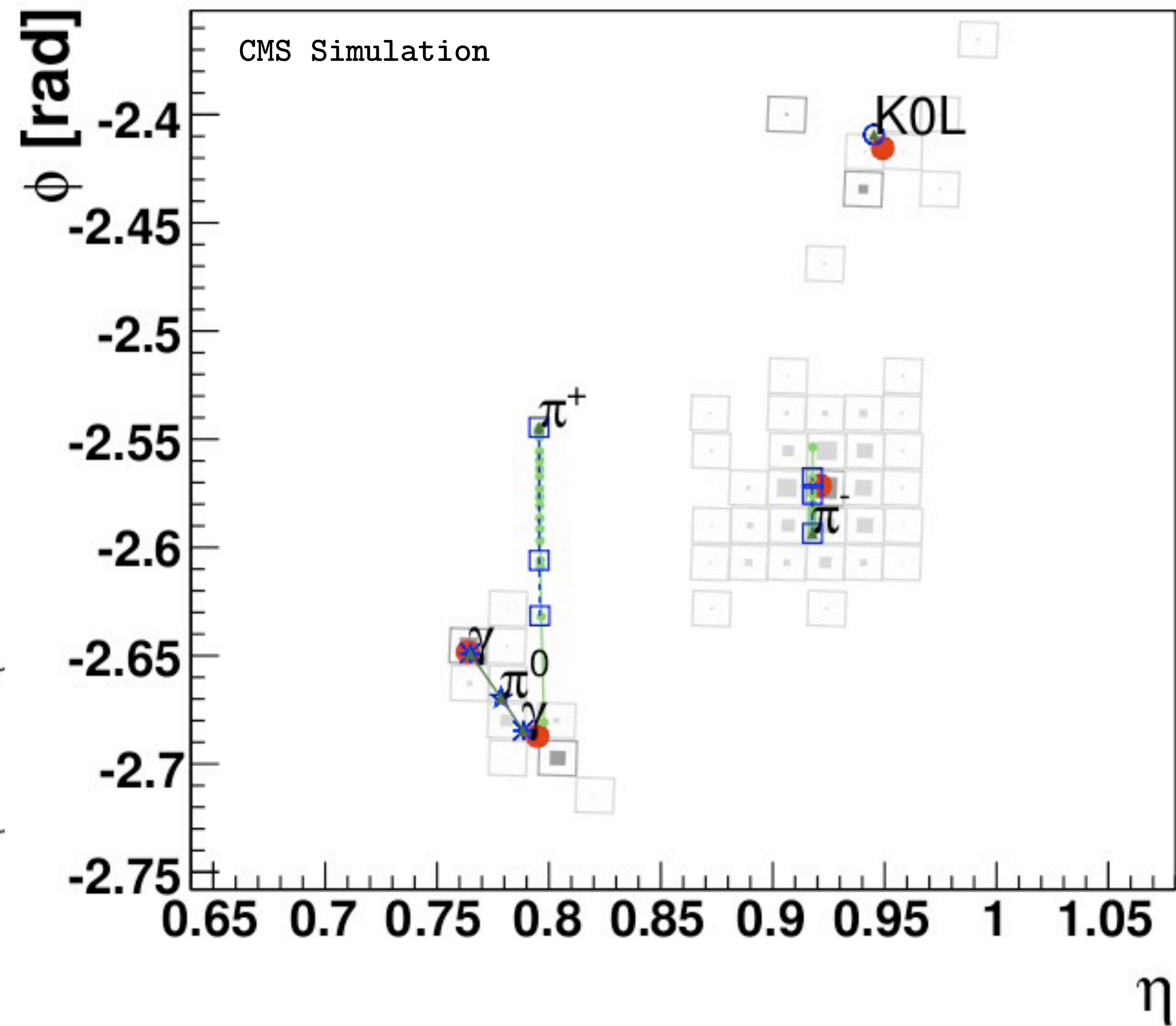
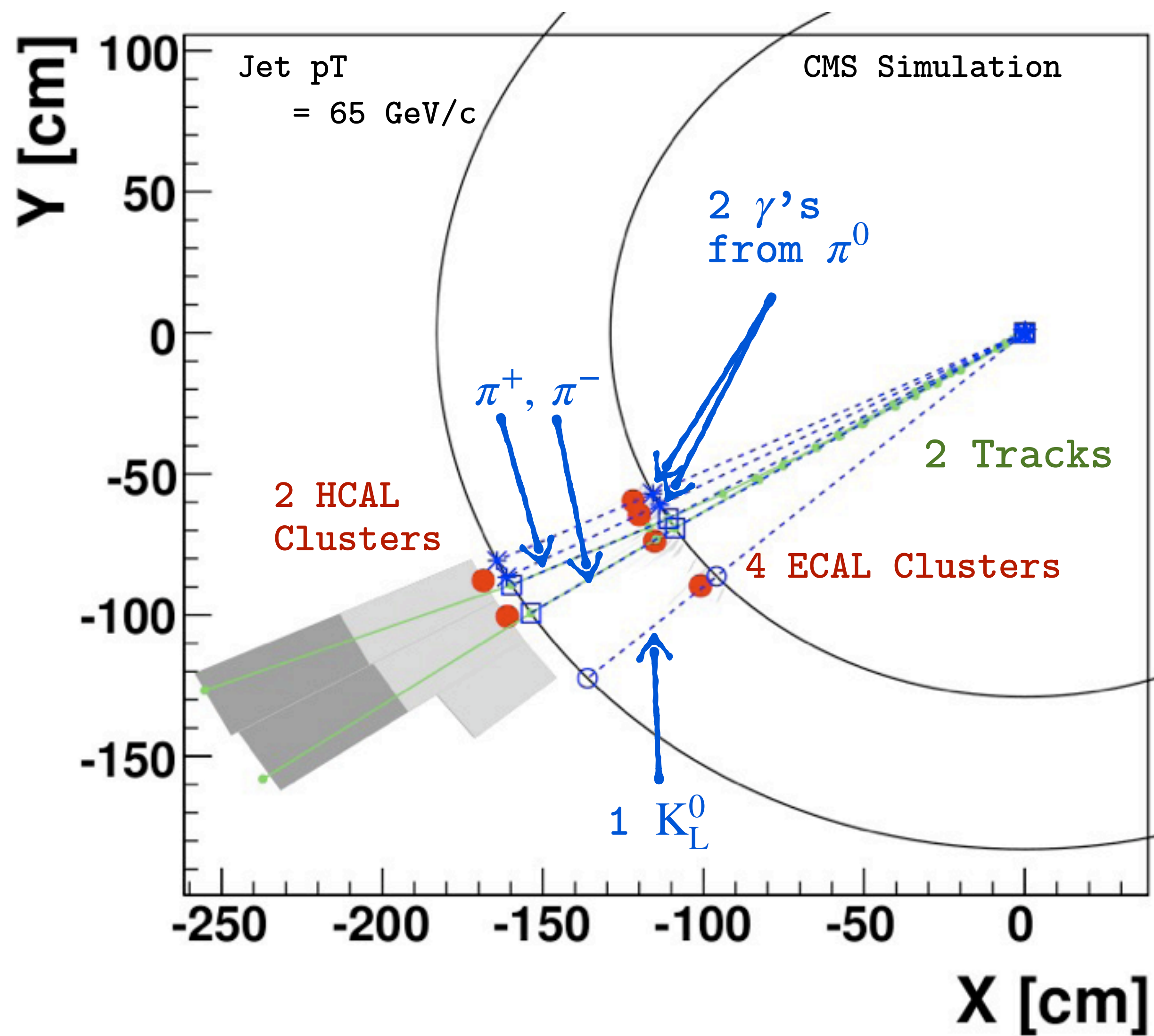
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



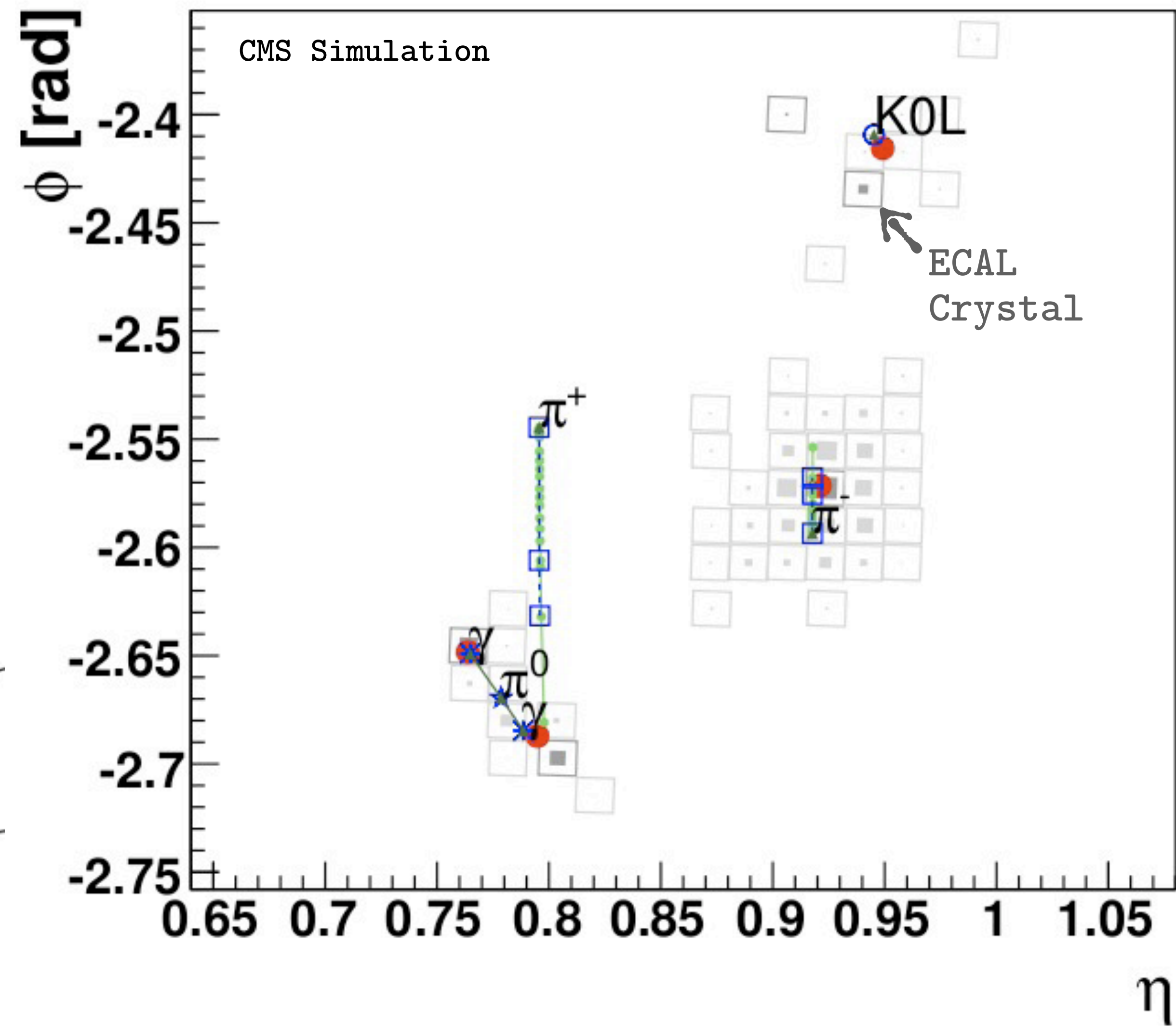
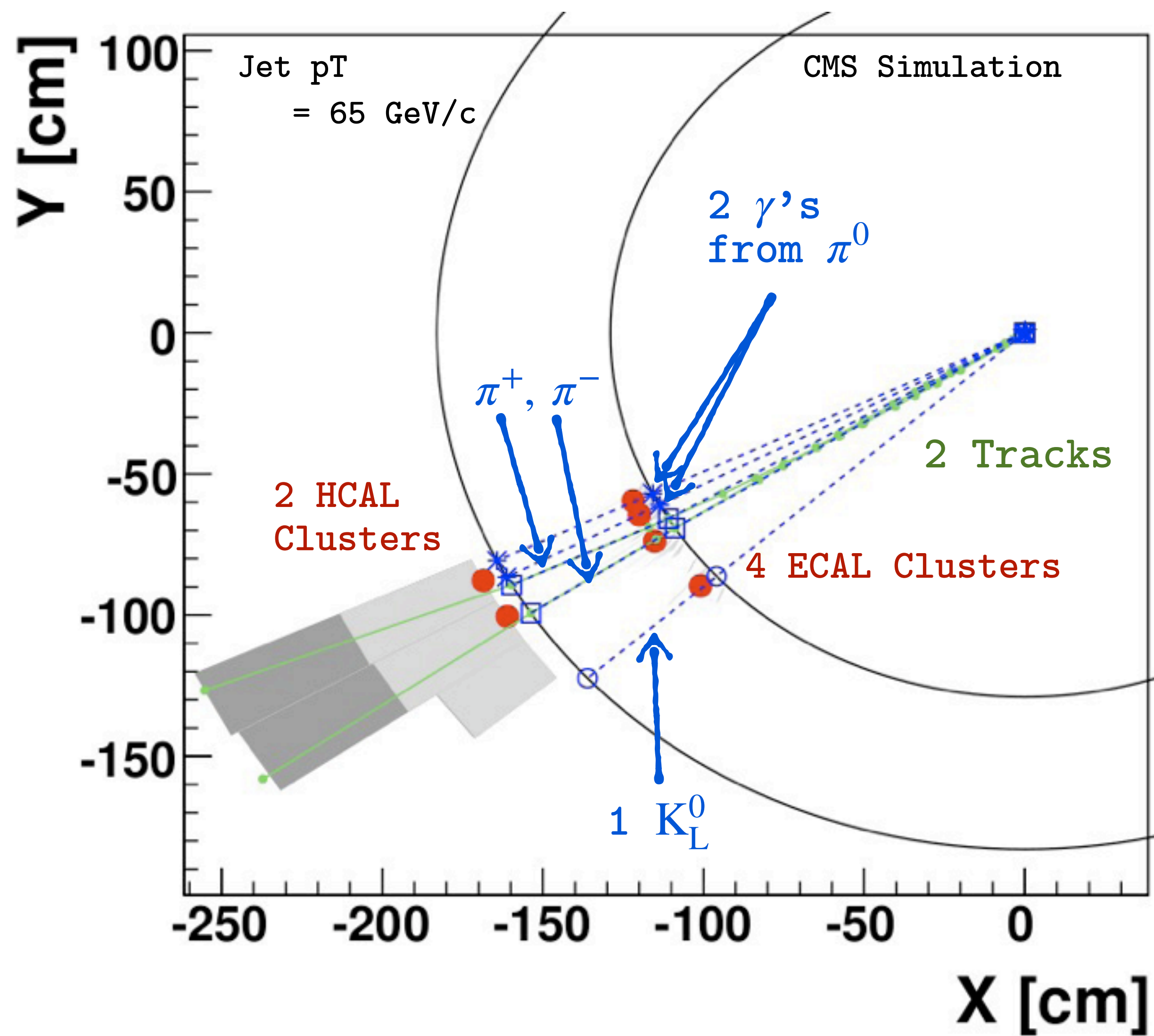
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



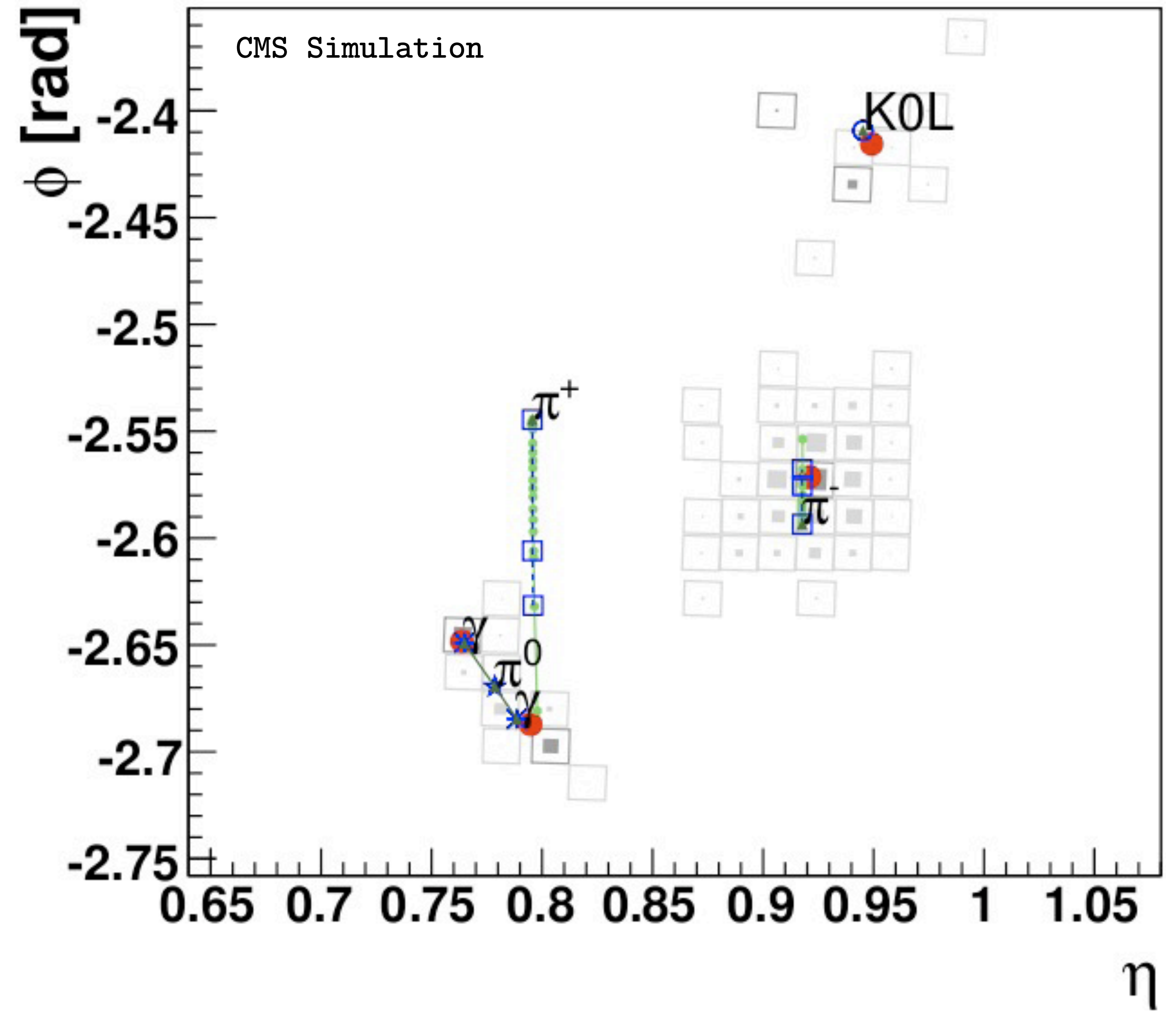
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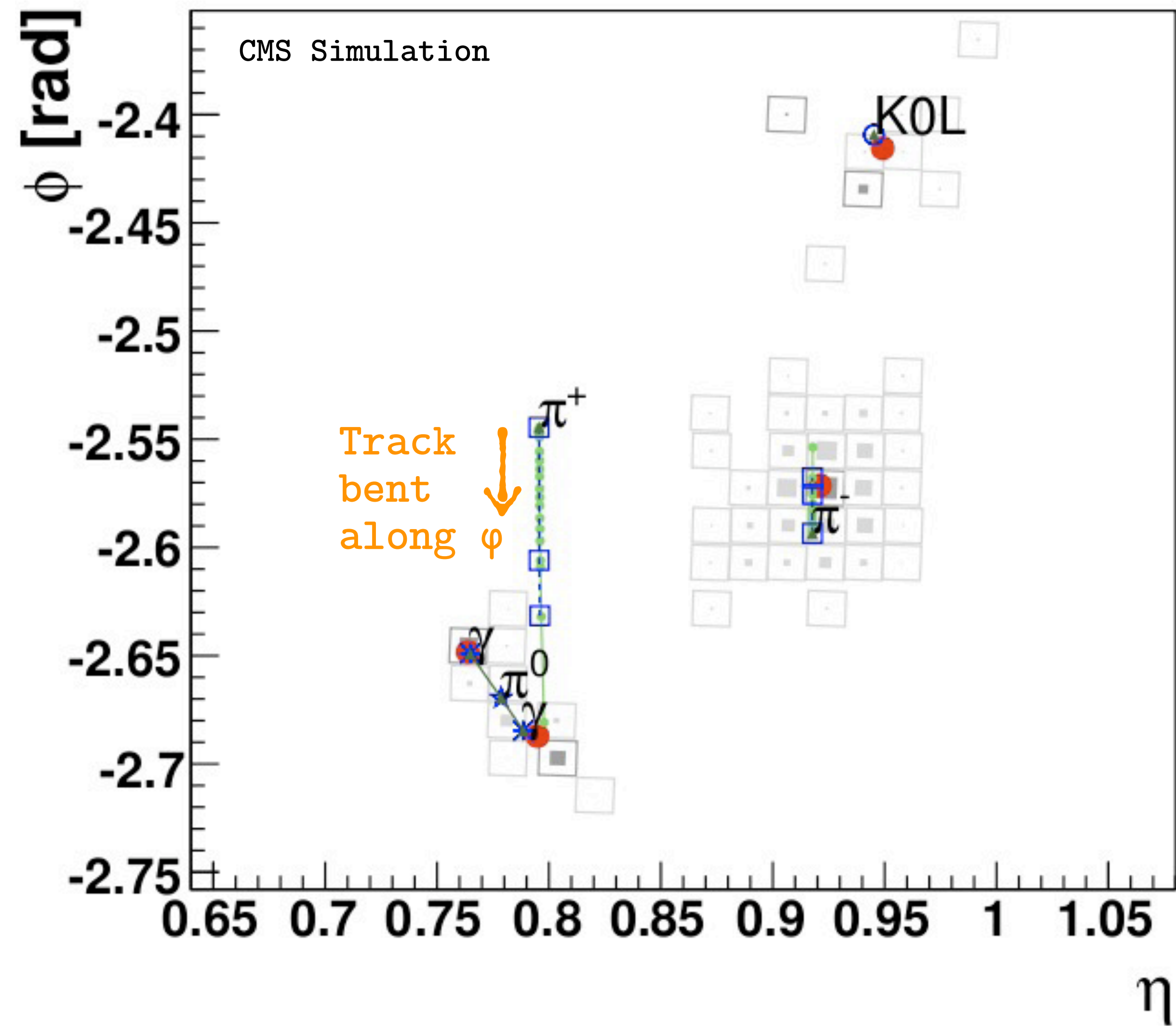
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



Four true particles:

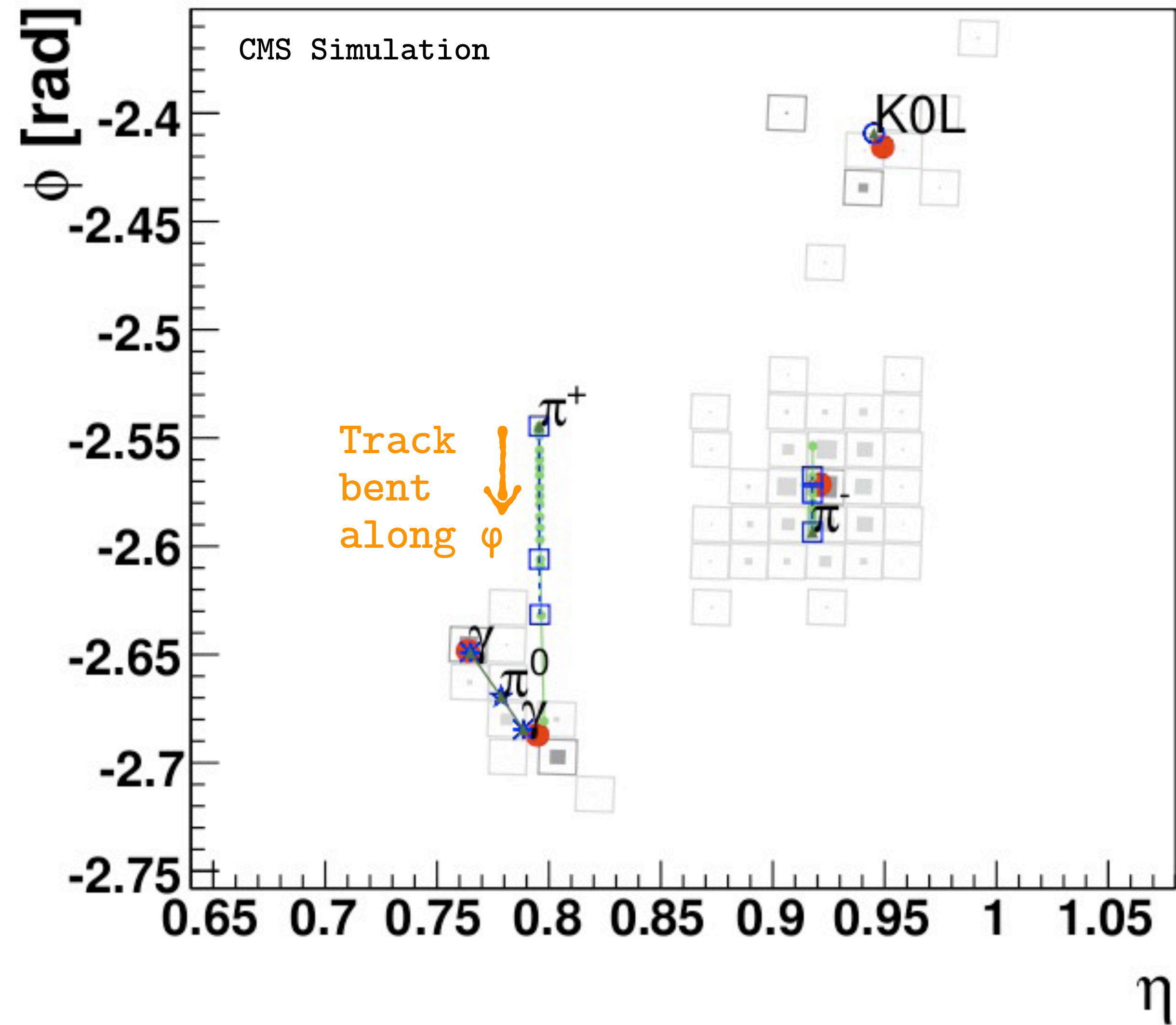
$$\pi^+, \pi^-, \pi^0, K_L^0$$



Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

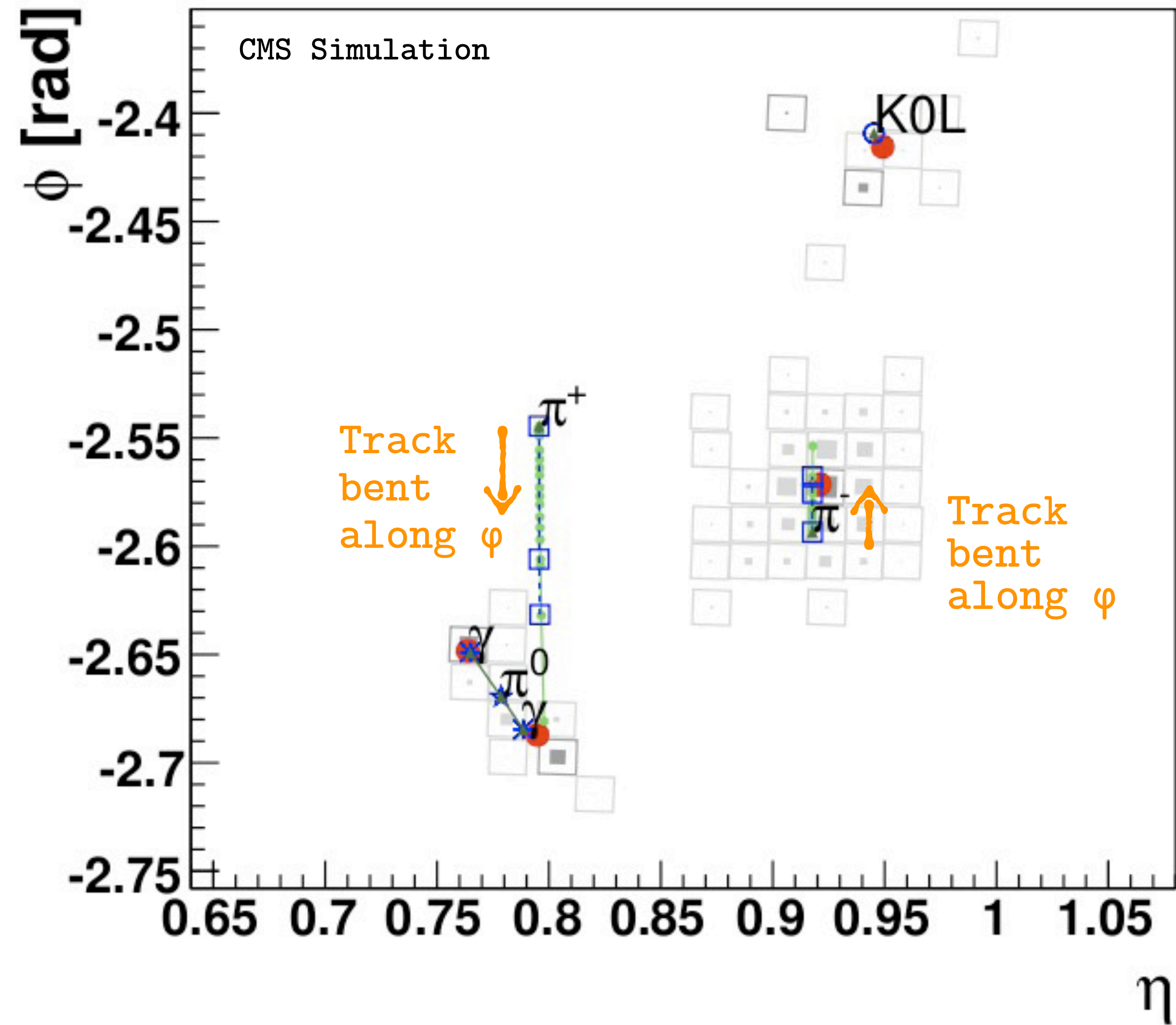
Track



Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

Track

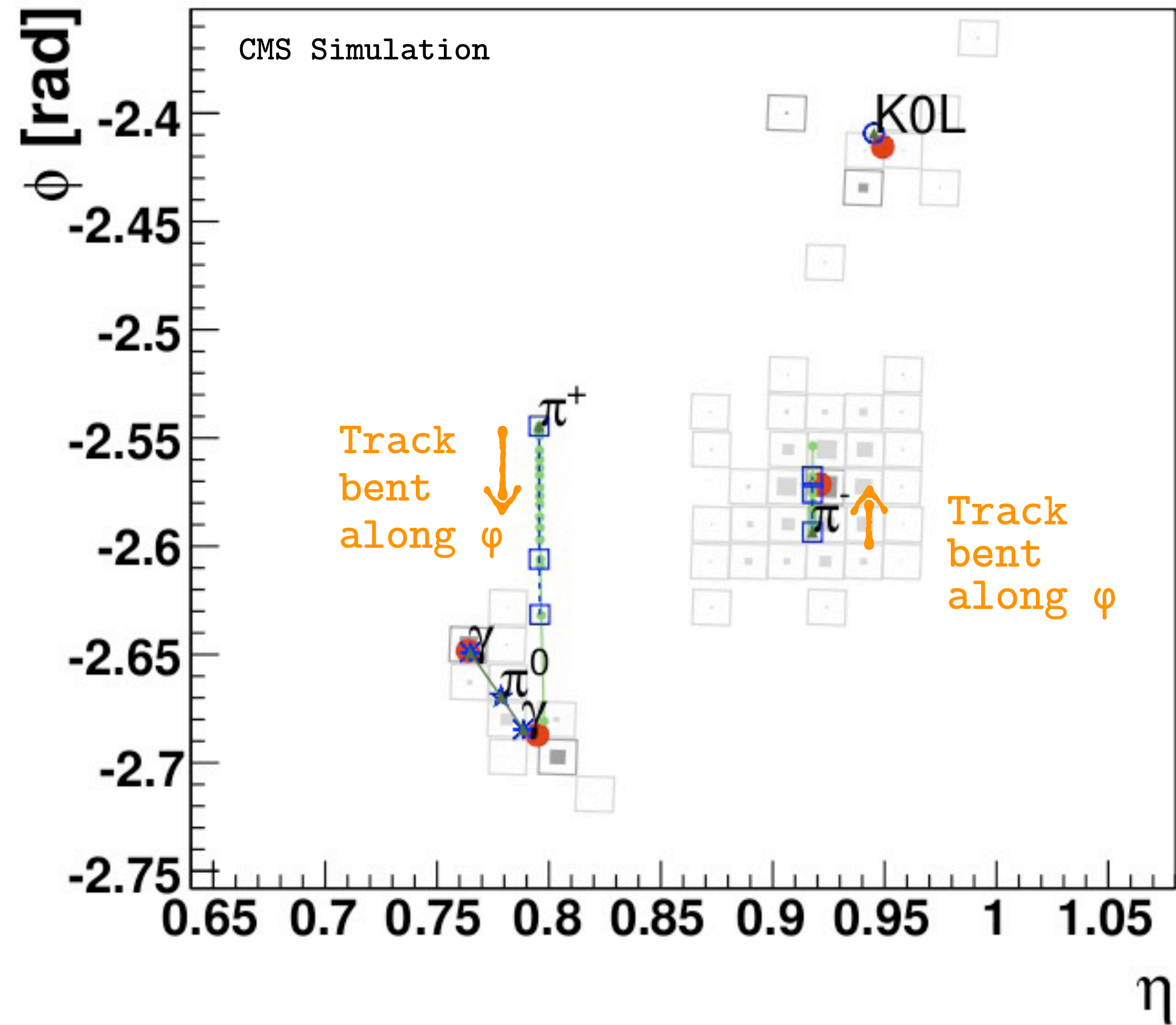


Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

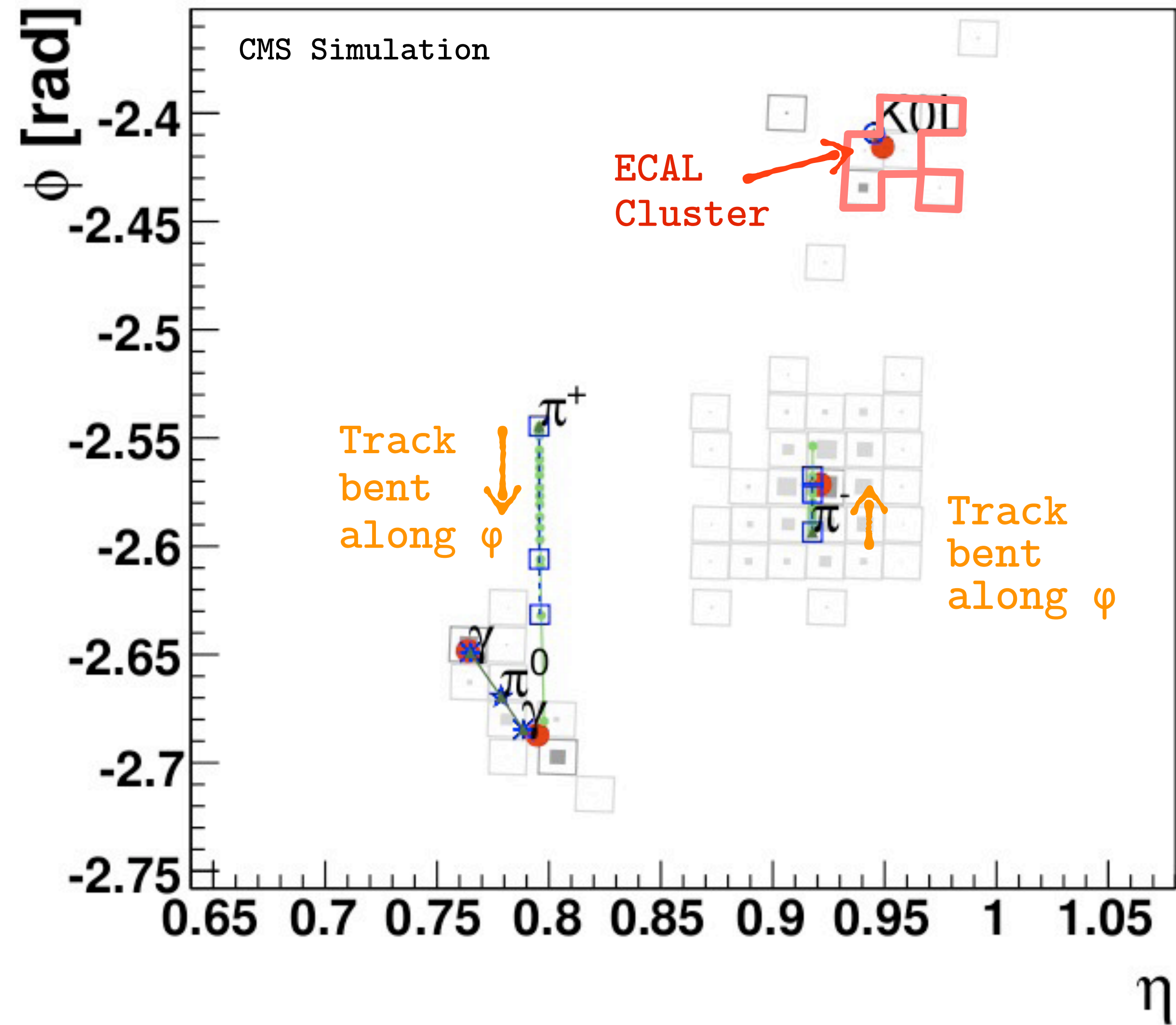
Track

Track



Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



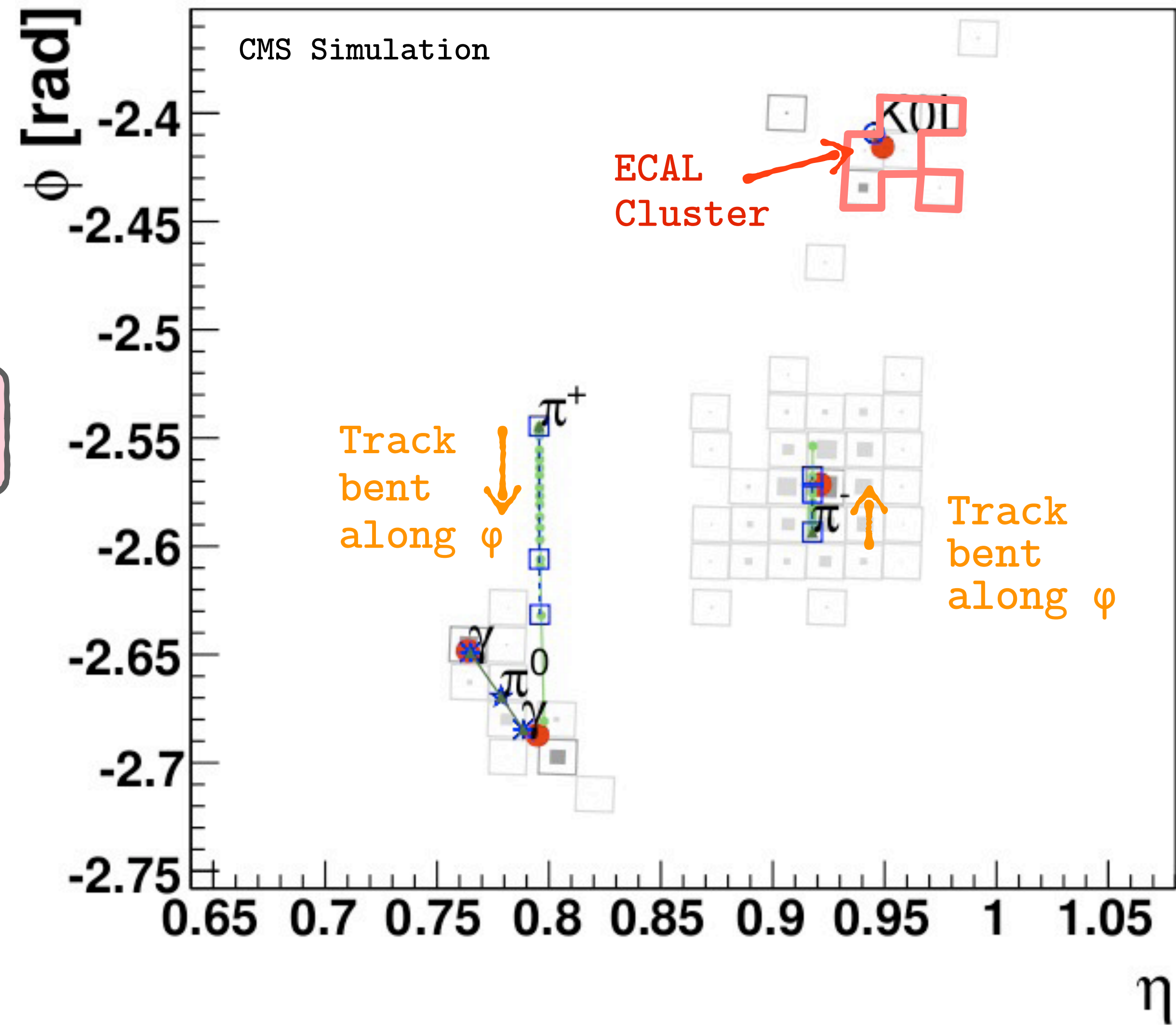
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

Track

Track

ECAL



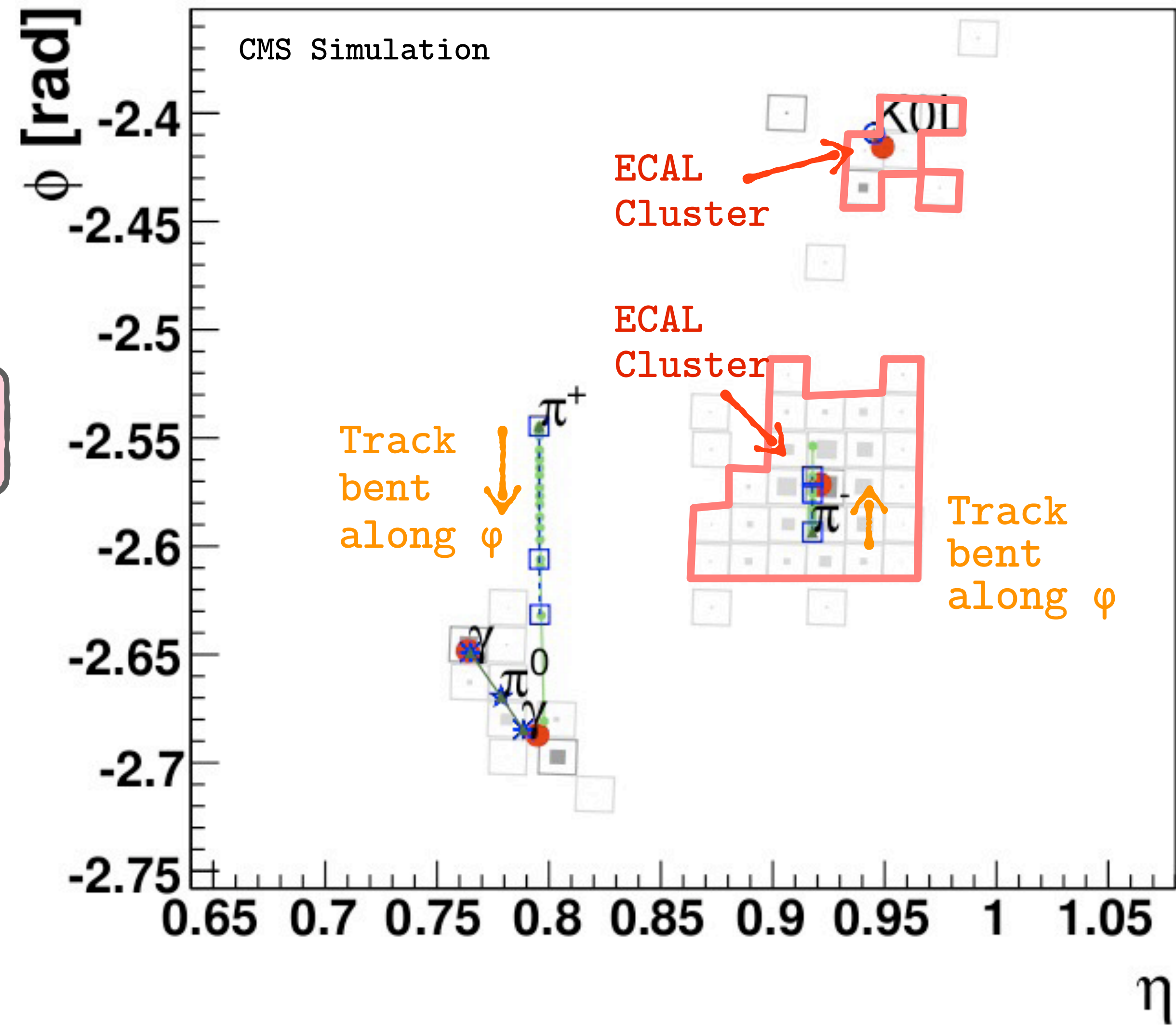
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

Track

Track

ECAL



Four true particles:

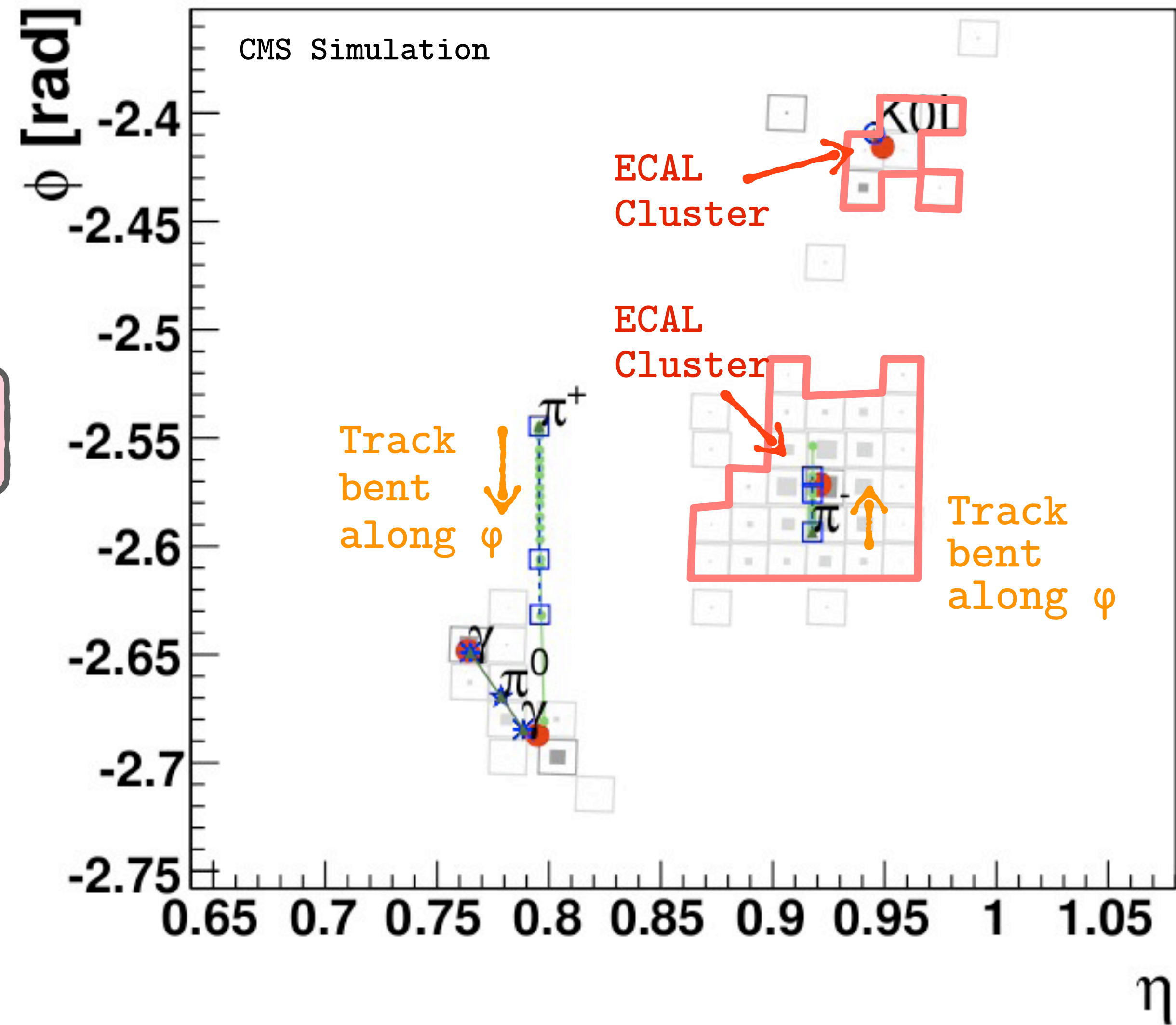
$$\pi^+, \pi^-, \pi^0, K_L^0$$

ECAL

Track

Track

ECAL



Four true particles:

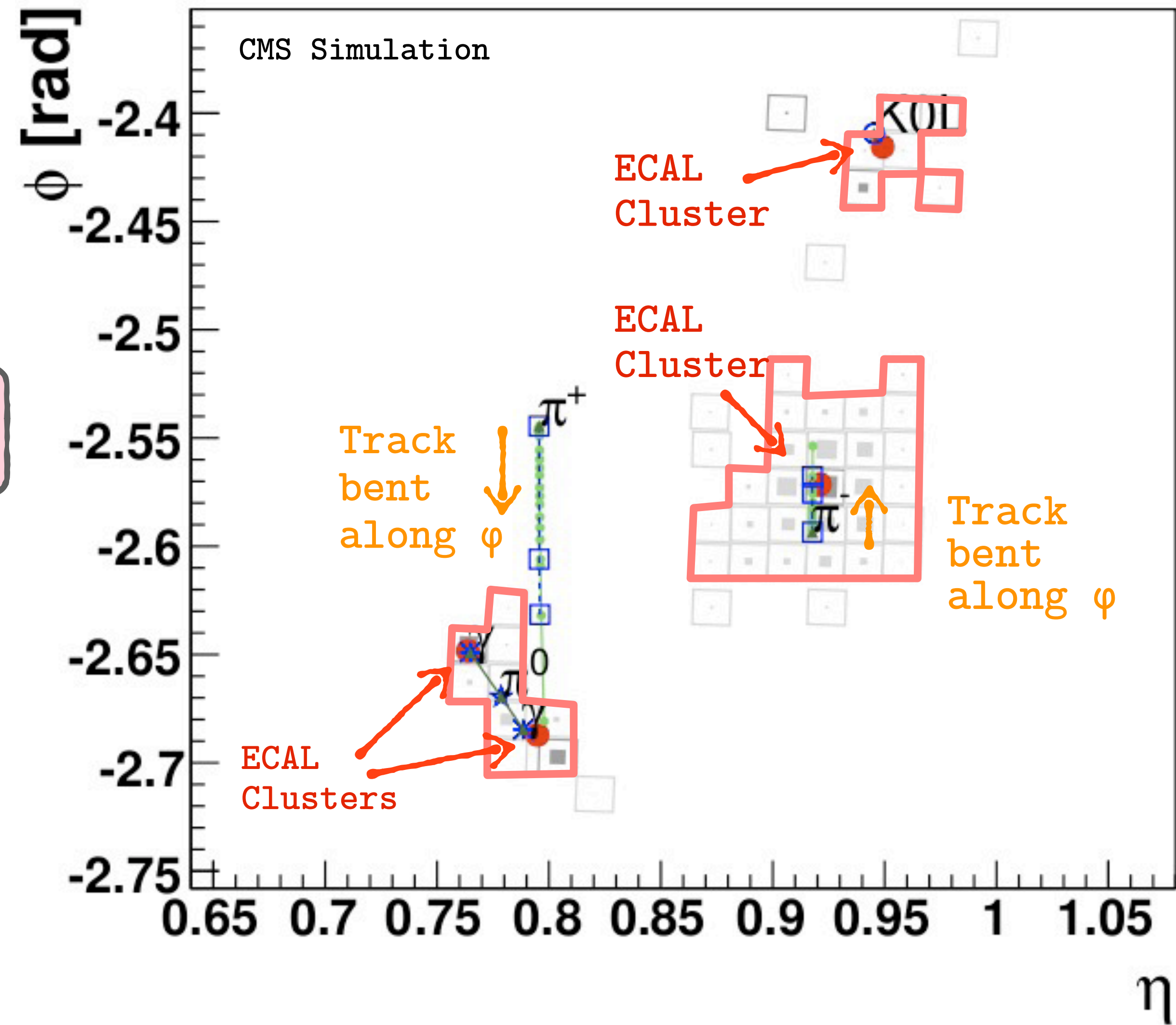
$$\pi^+, \pi^-, \pi^0, K_L^0$$

ECAL

Track

Track

ECAL



Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

ECAL

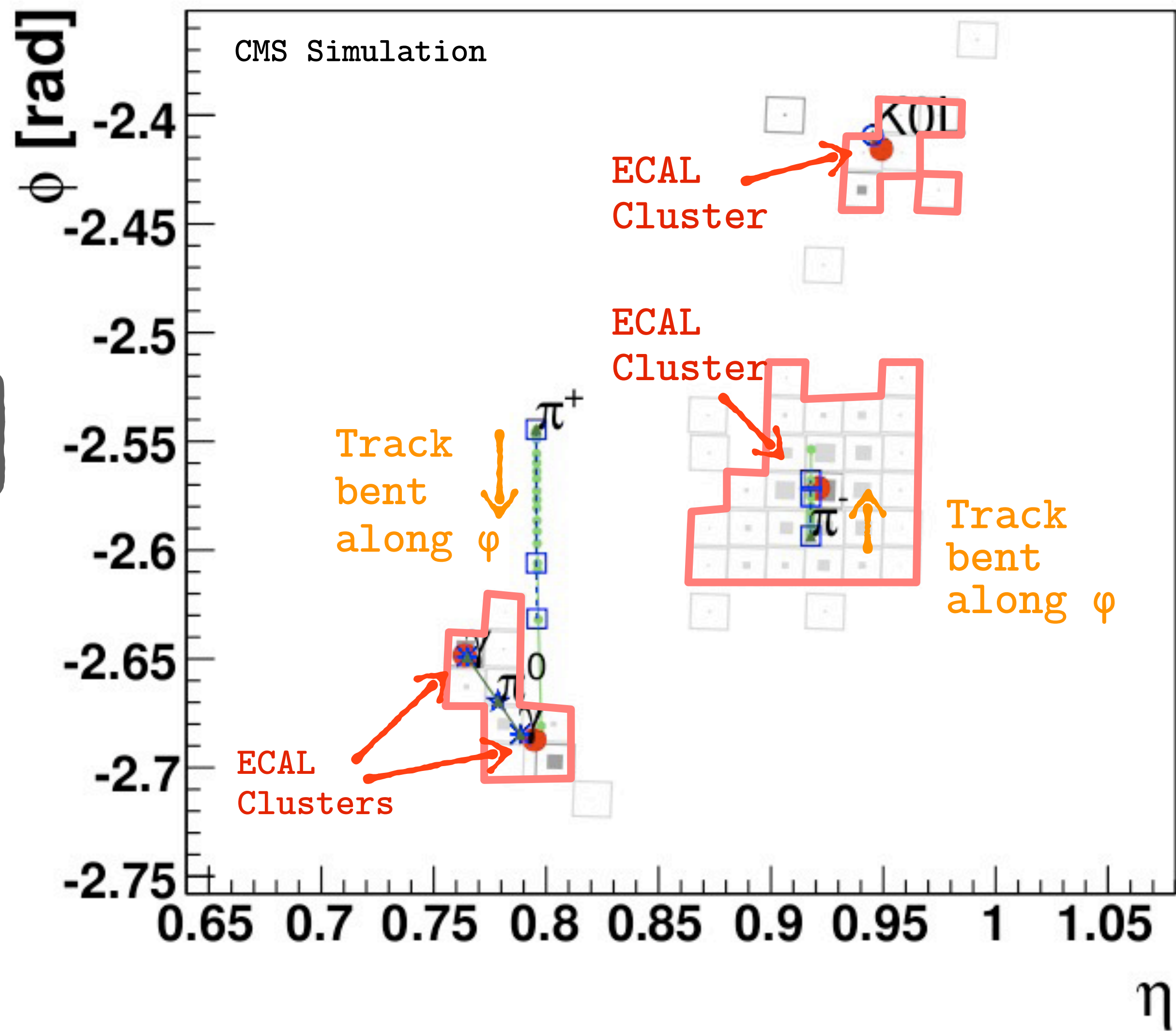
Track

ECAL

Track

ECAL

ECAL



Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

ECAL

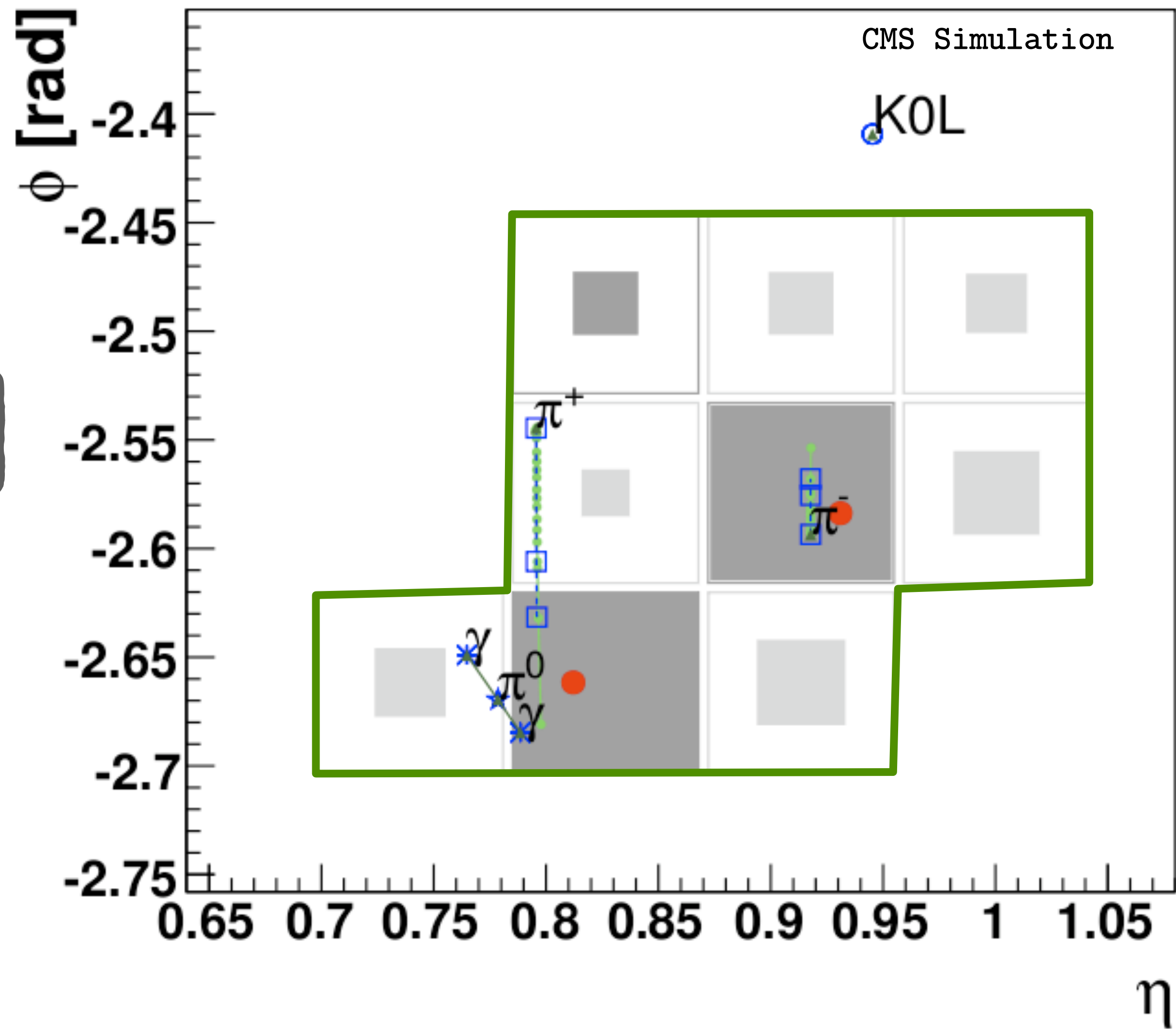
Track

Track

ECAL

ECAL

ECAL



Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

ECAL

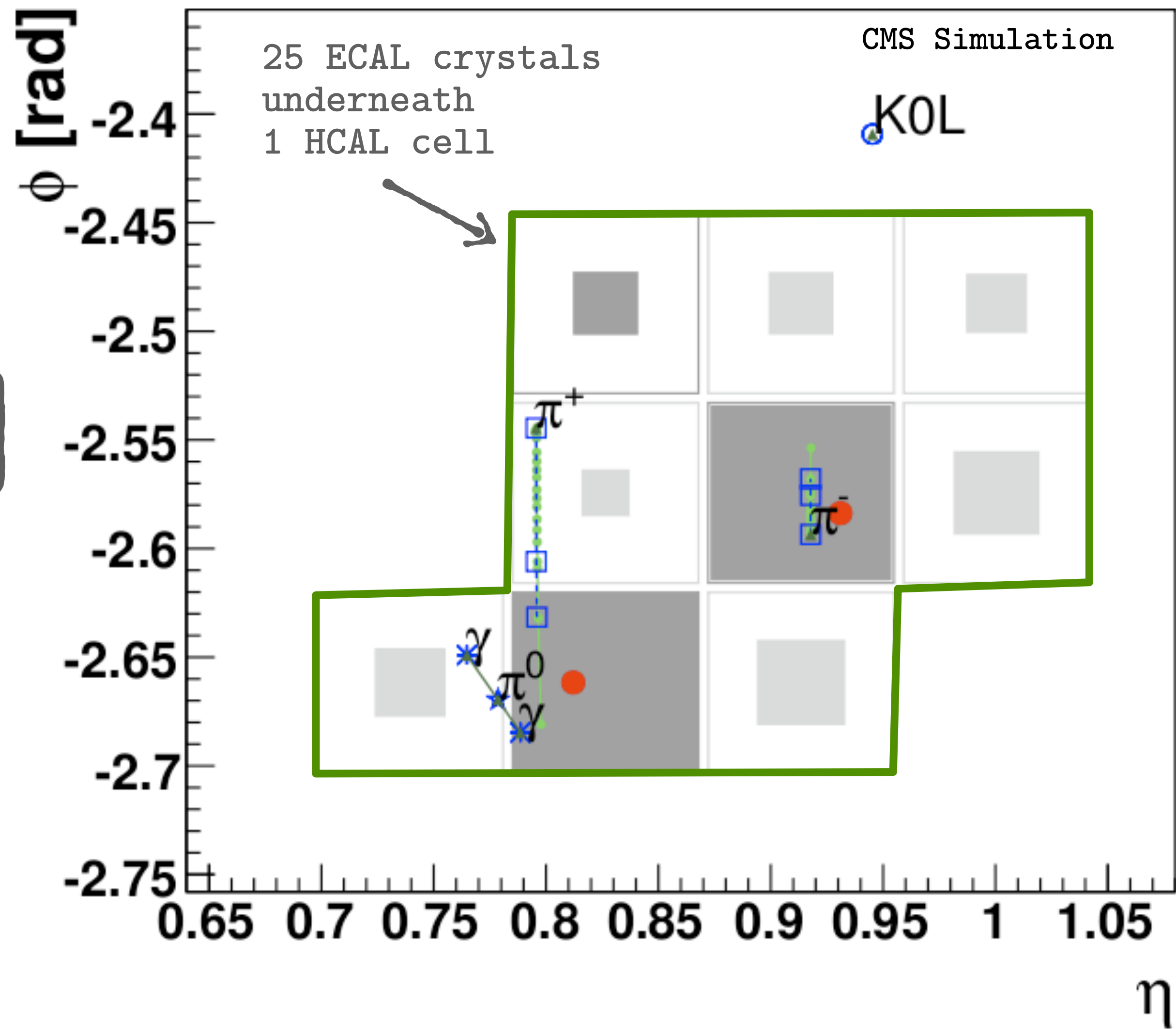
Track

Track

ECAL

ECAL

ECAL



Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

ECAL

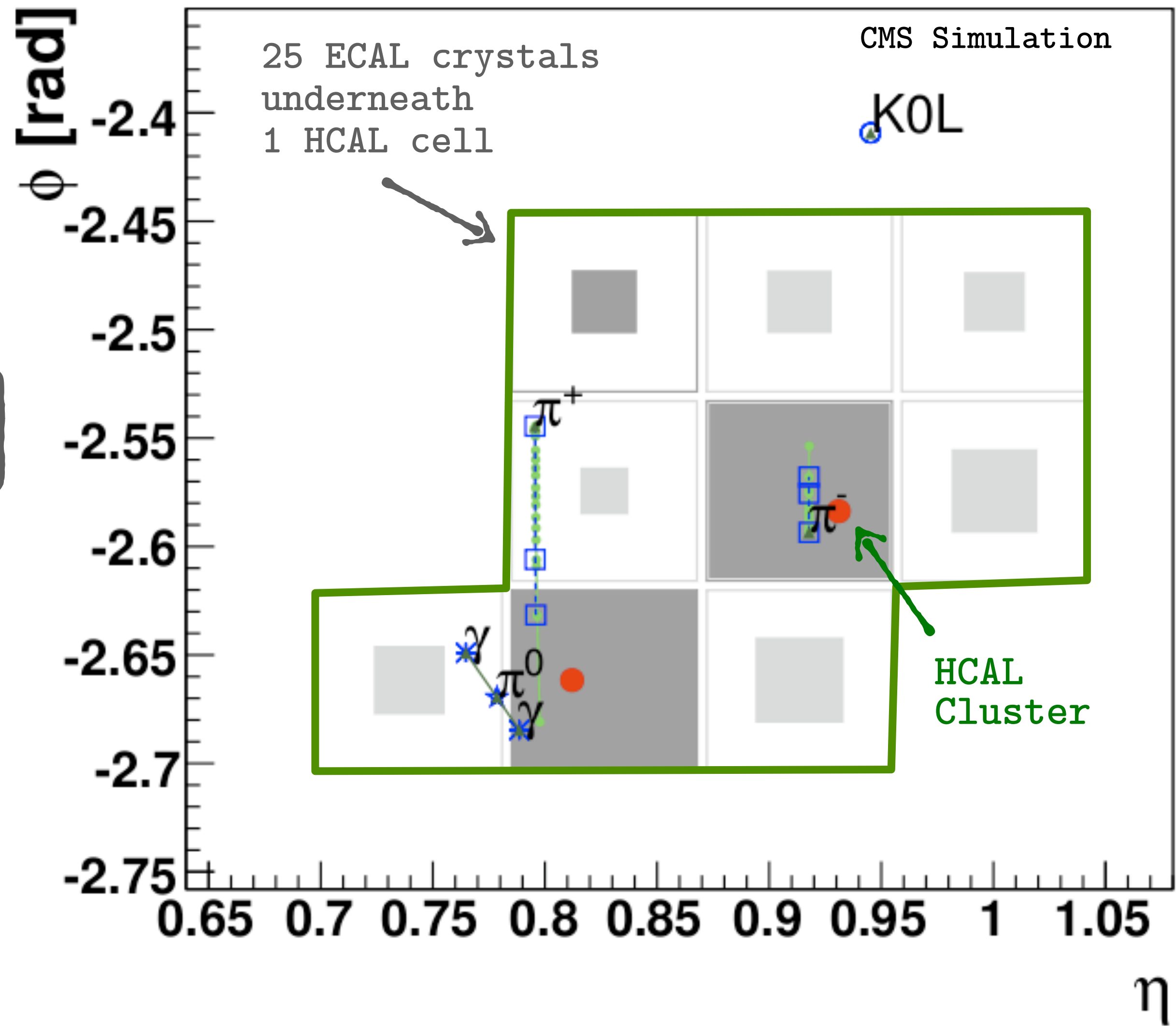
Track

Track

ECAL

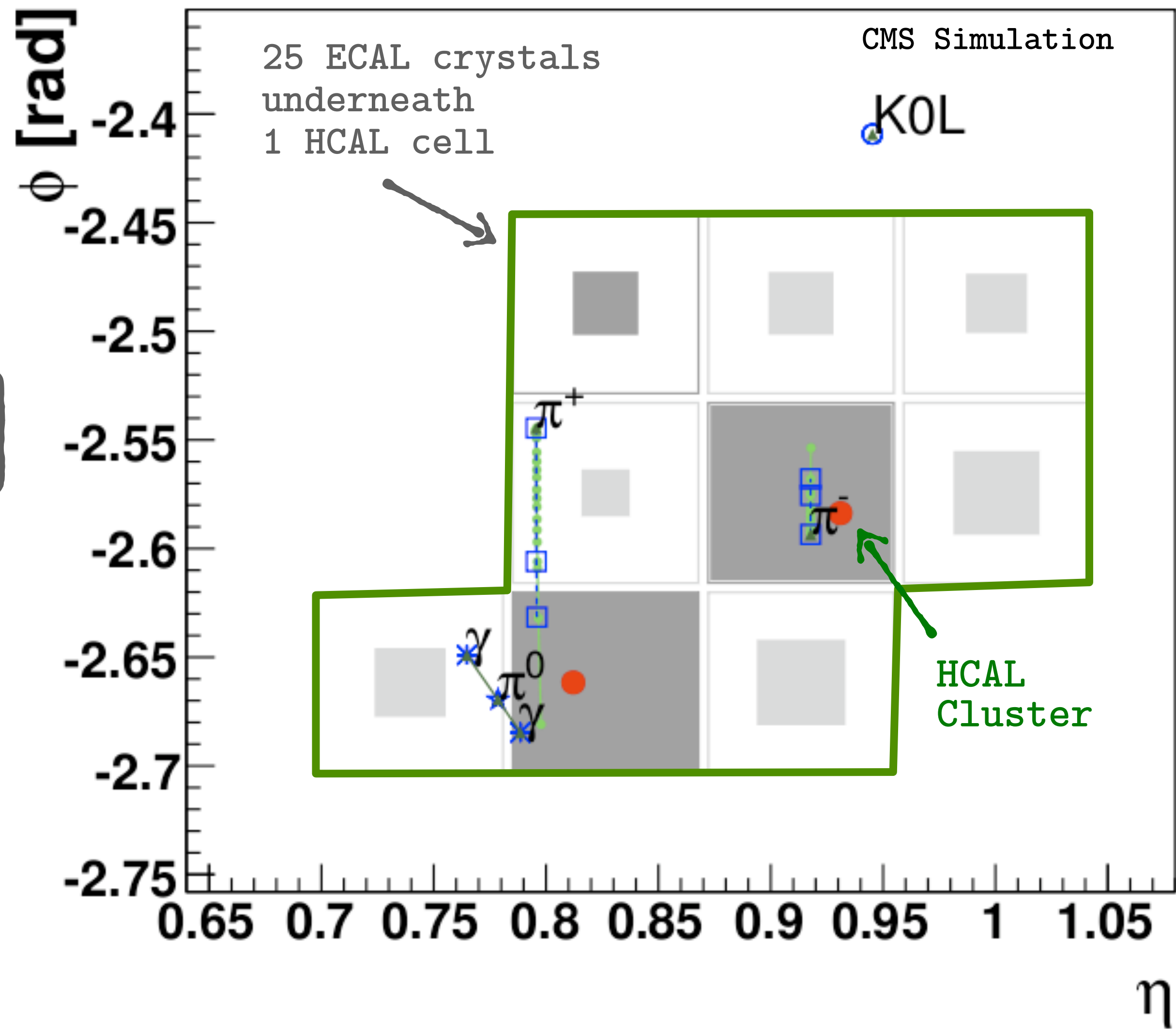
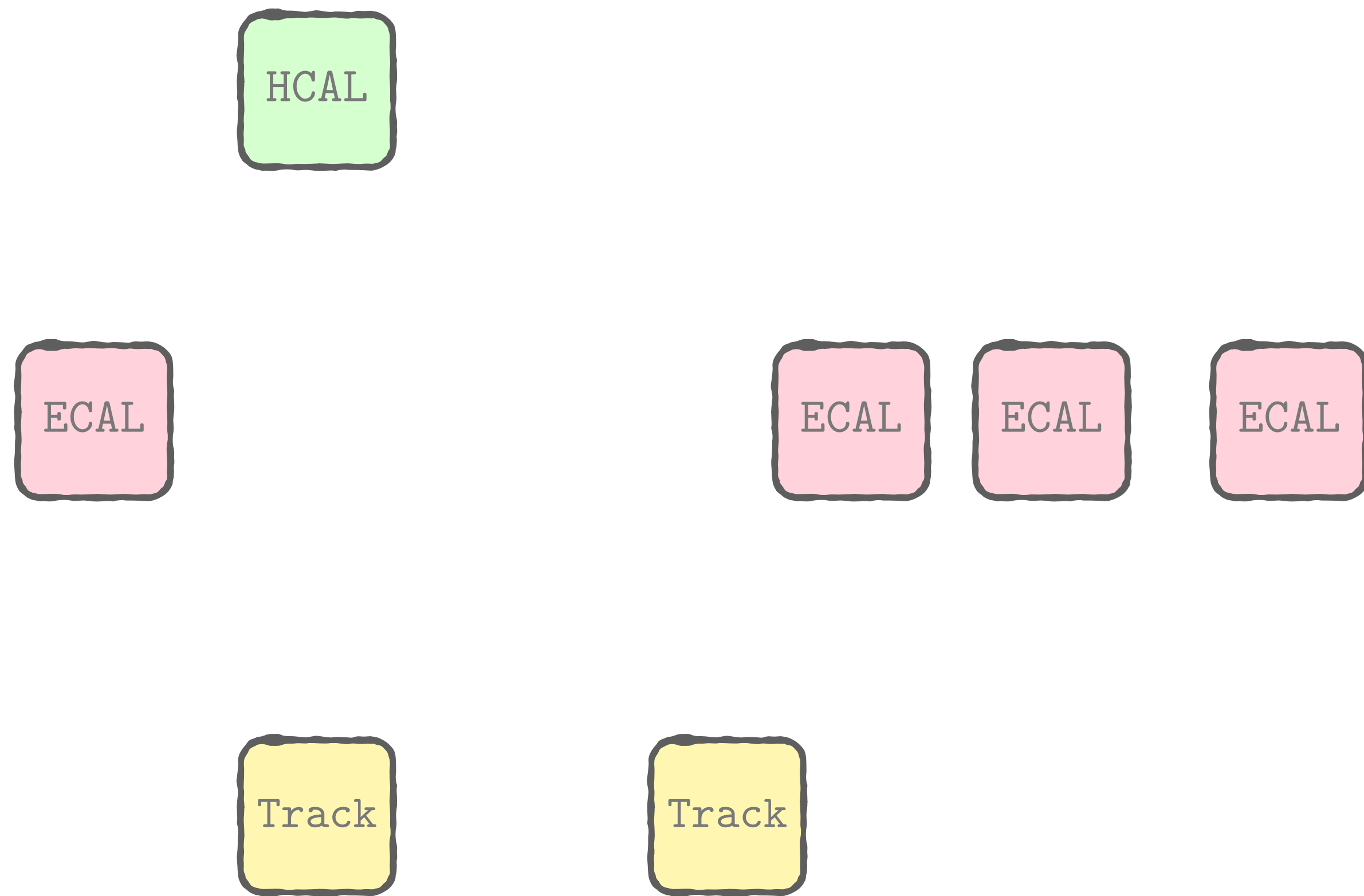
ECAL

ECAL



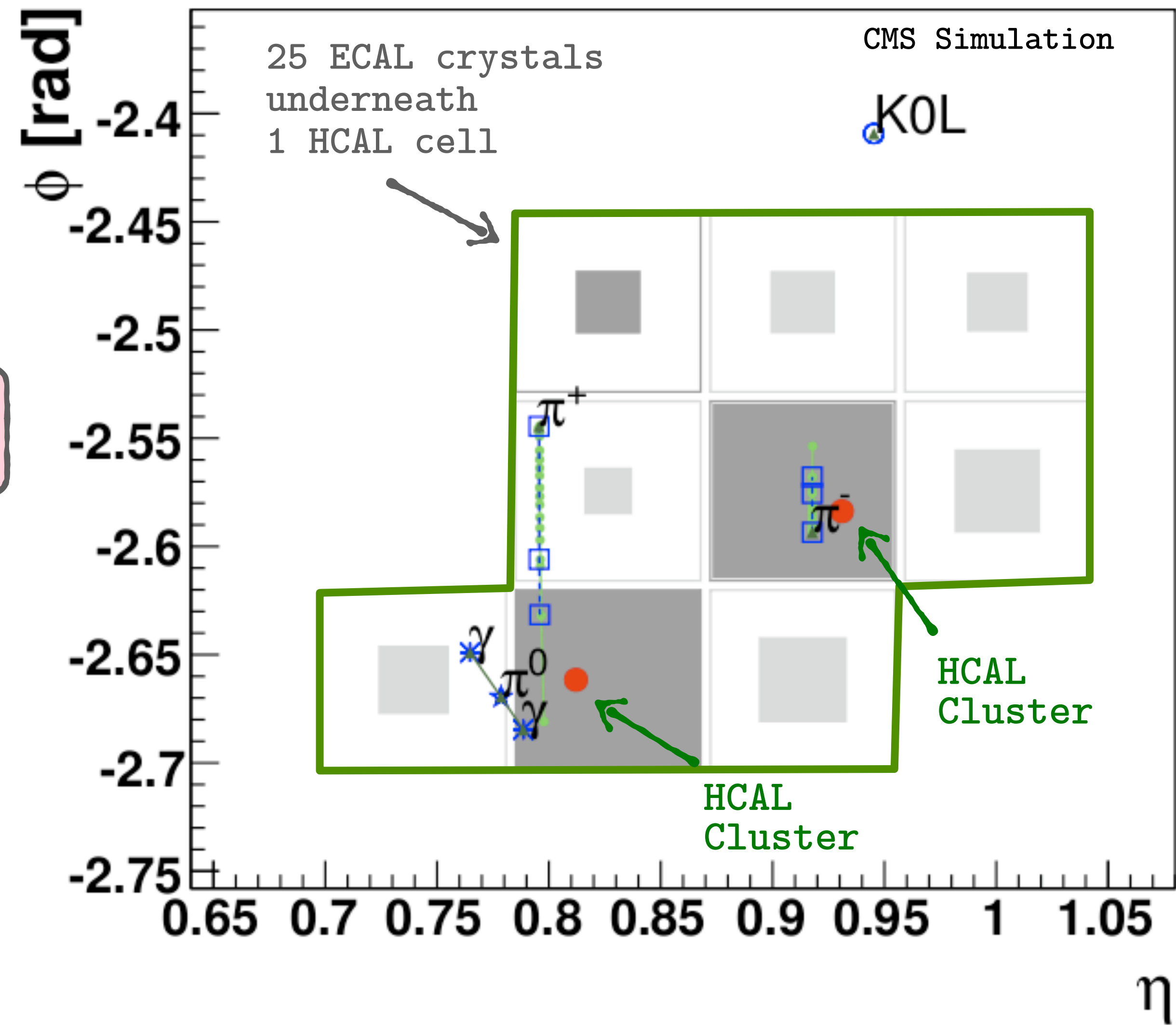
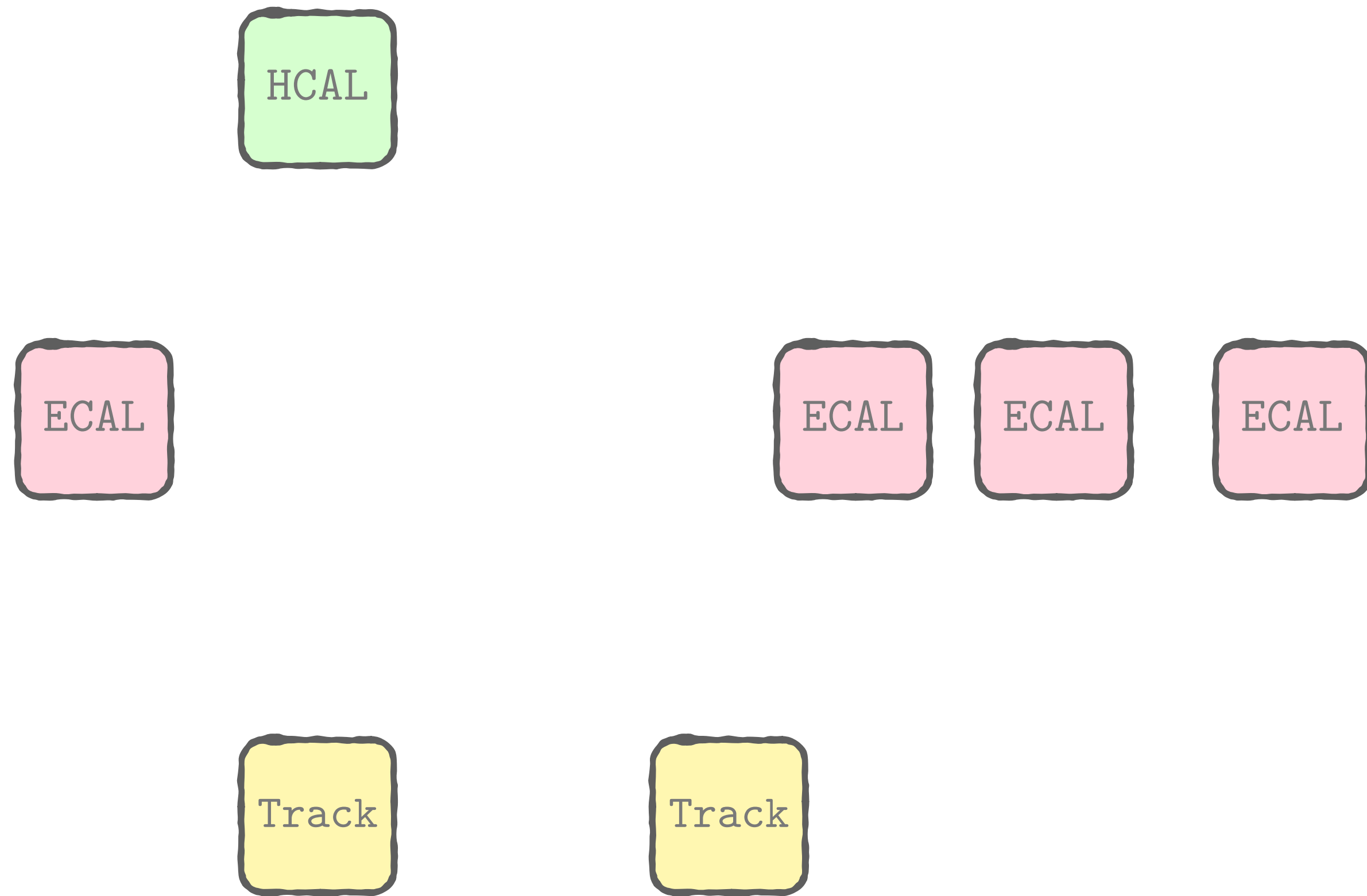
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



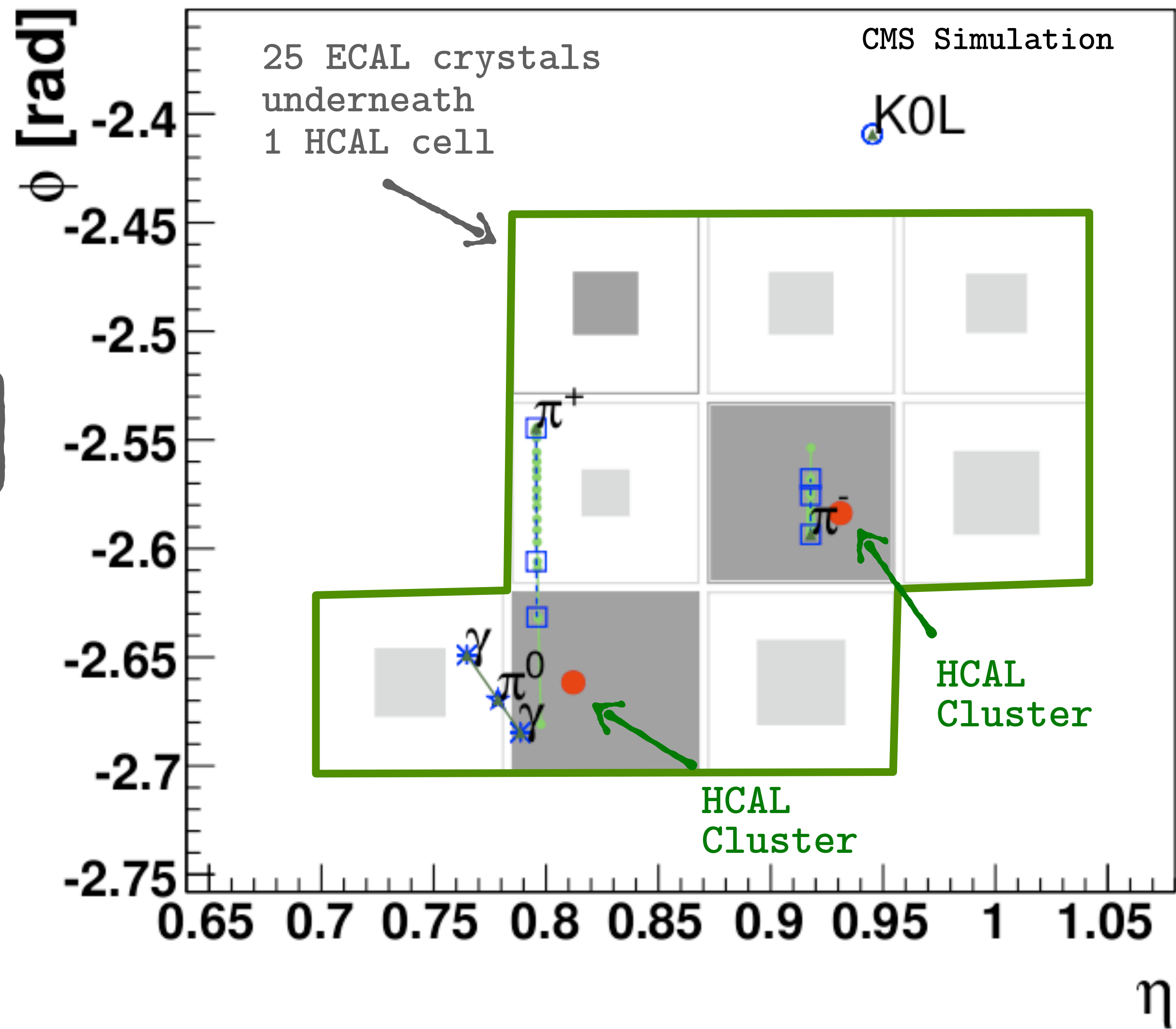
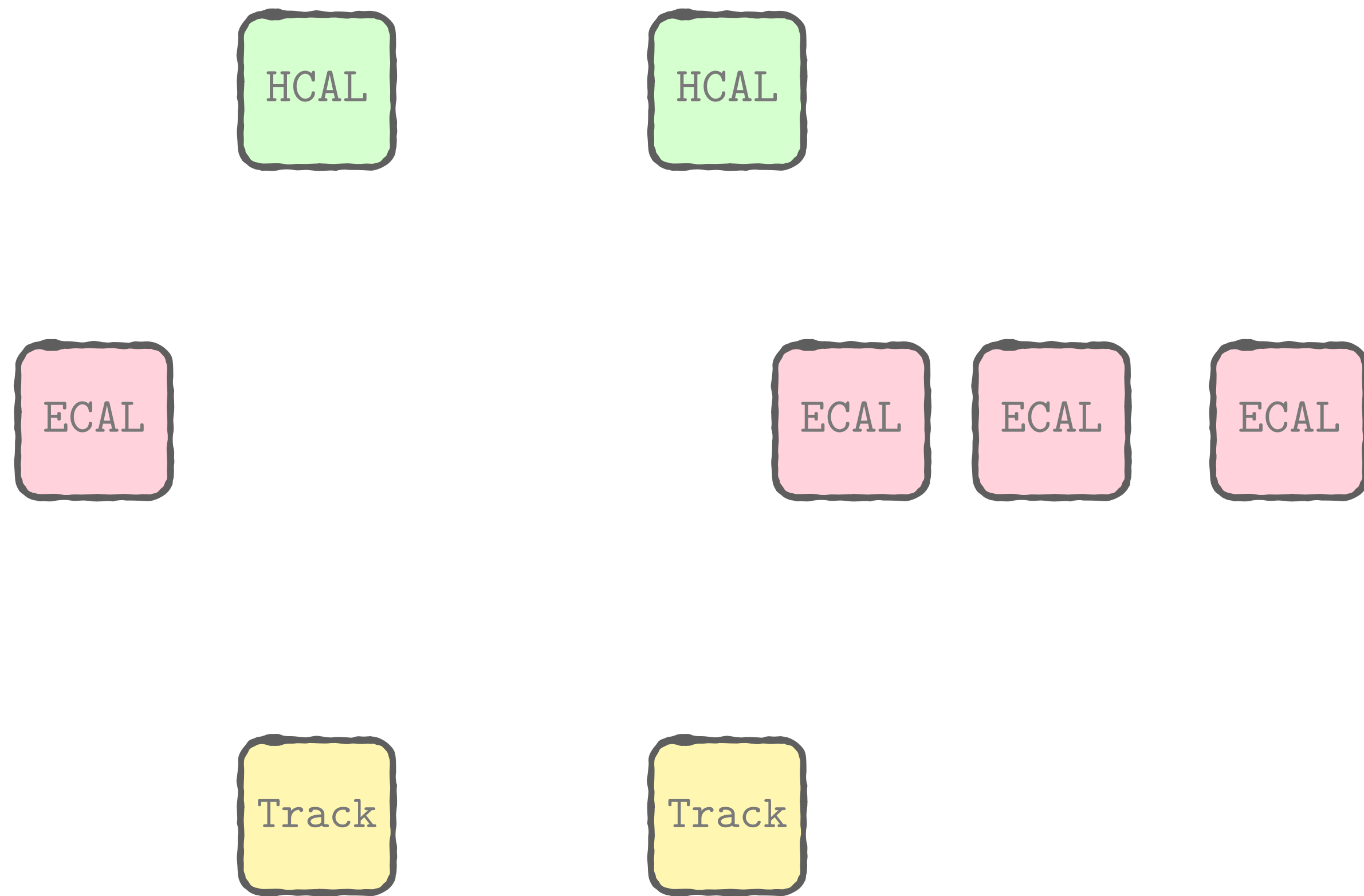
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



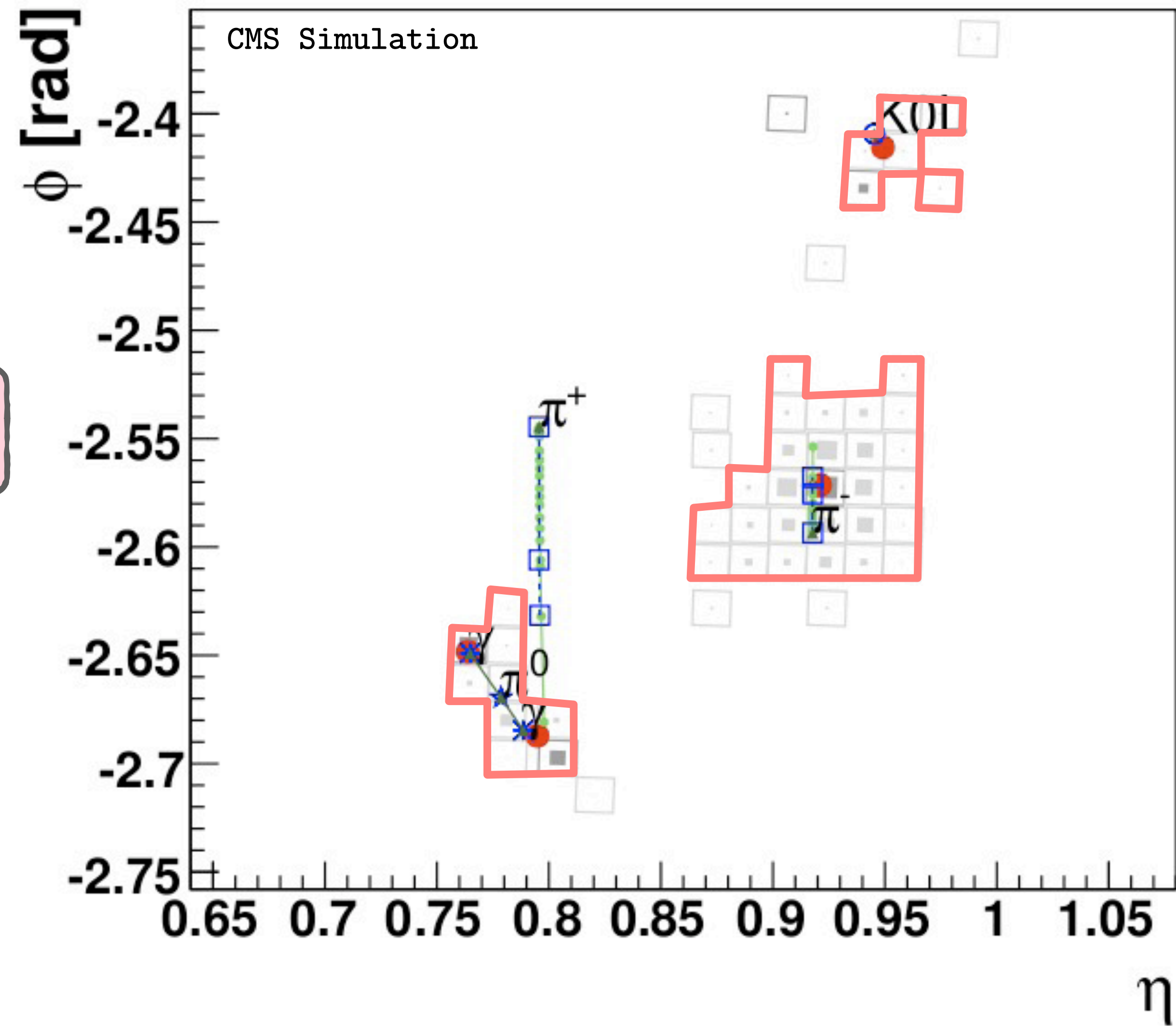
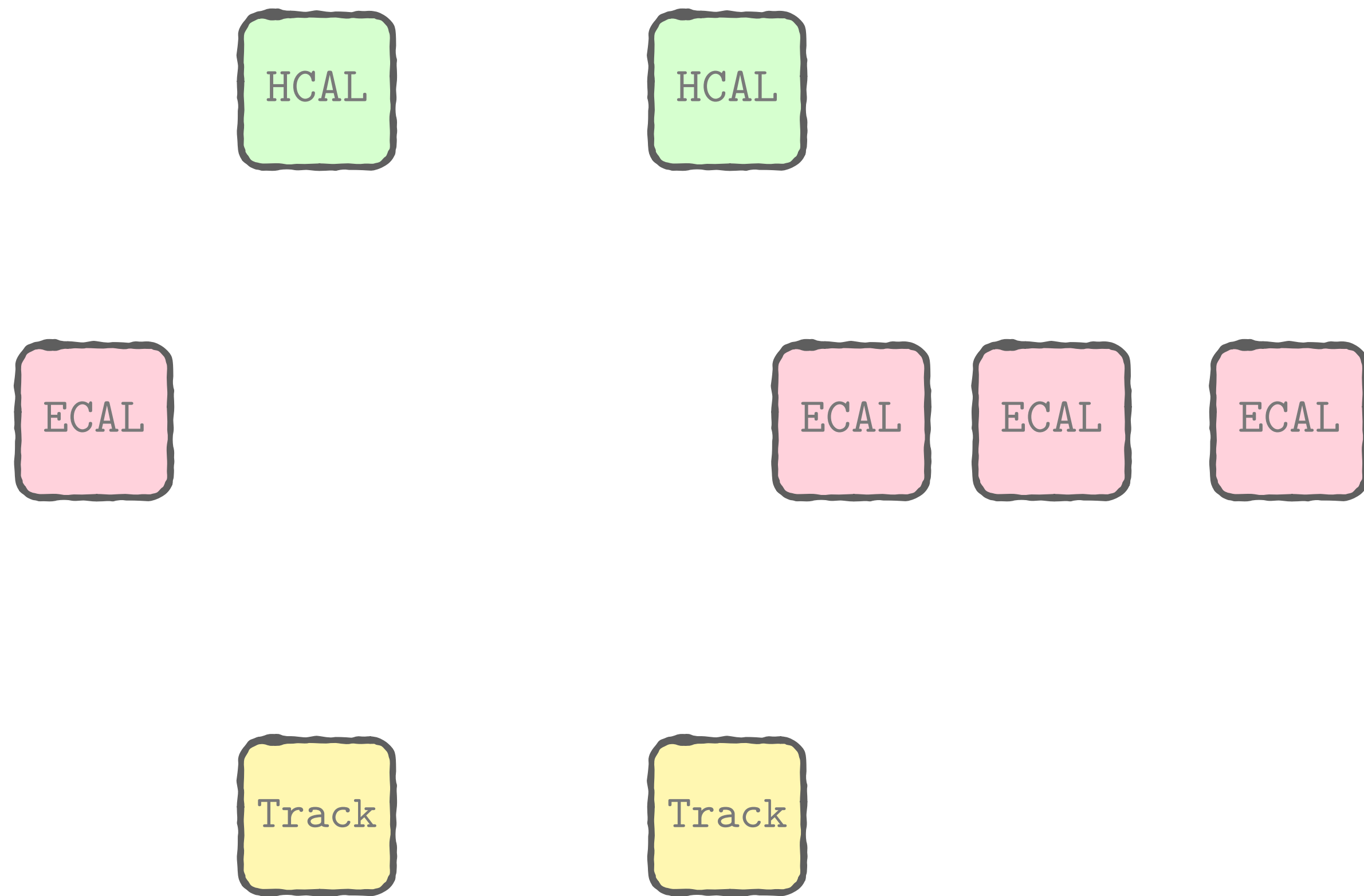
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



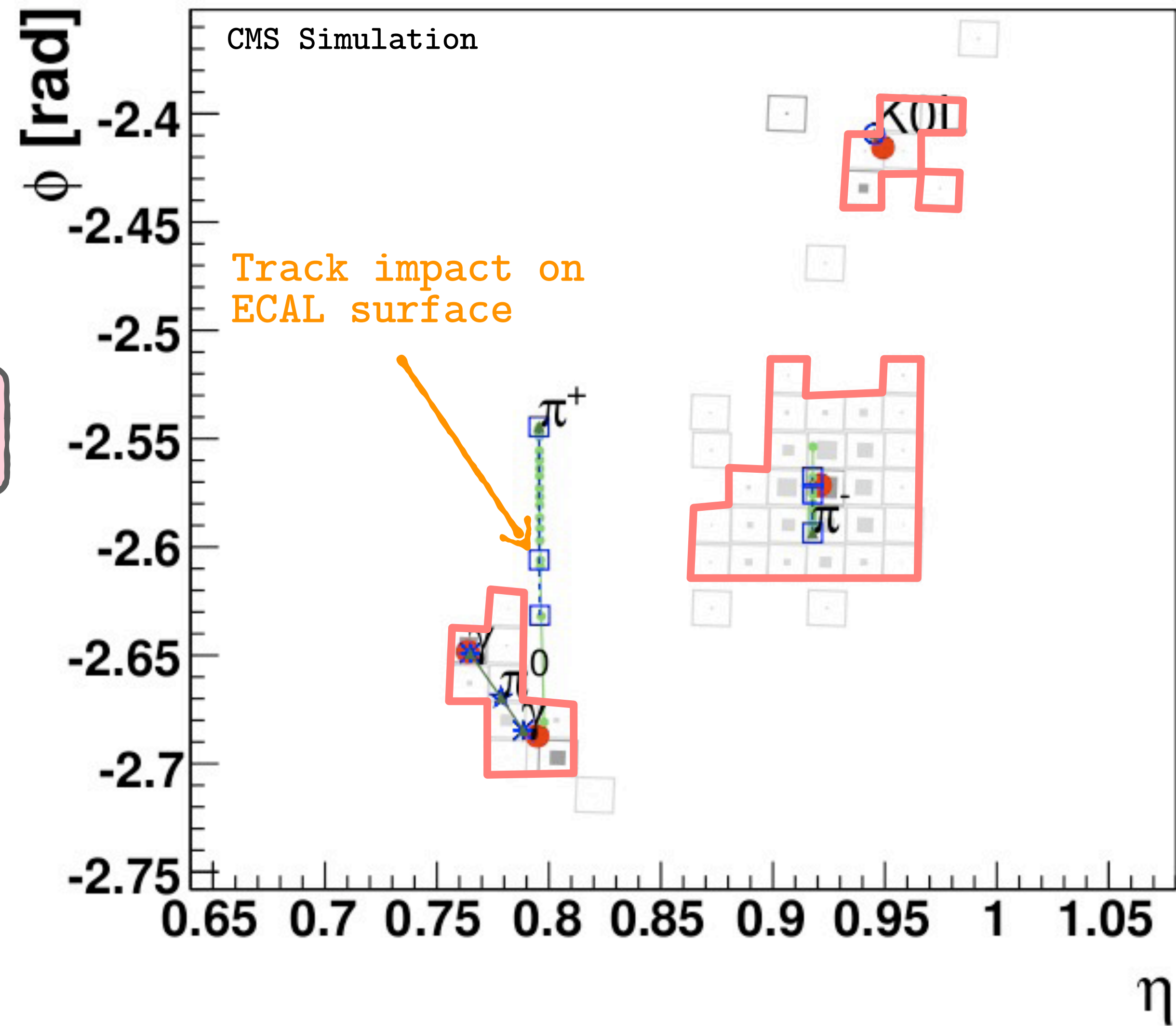
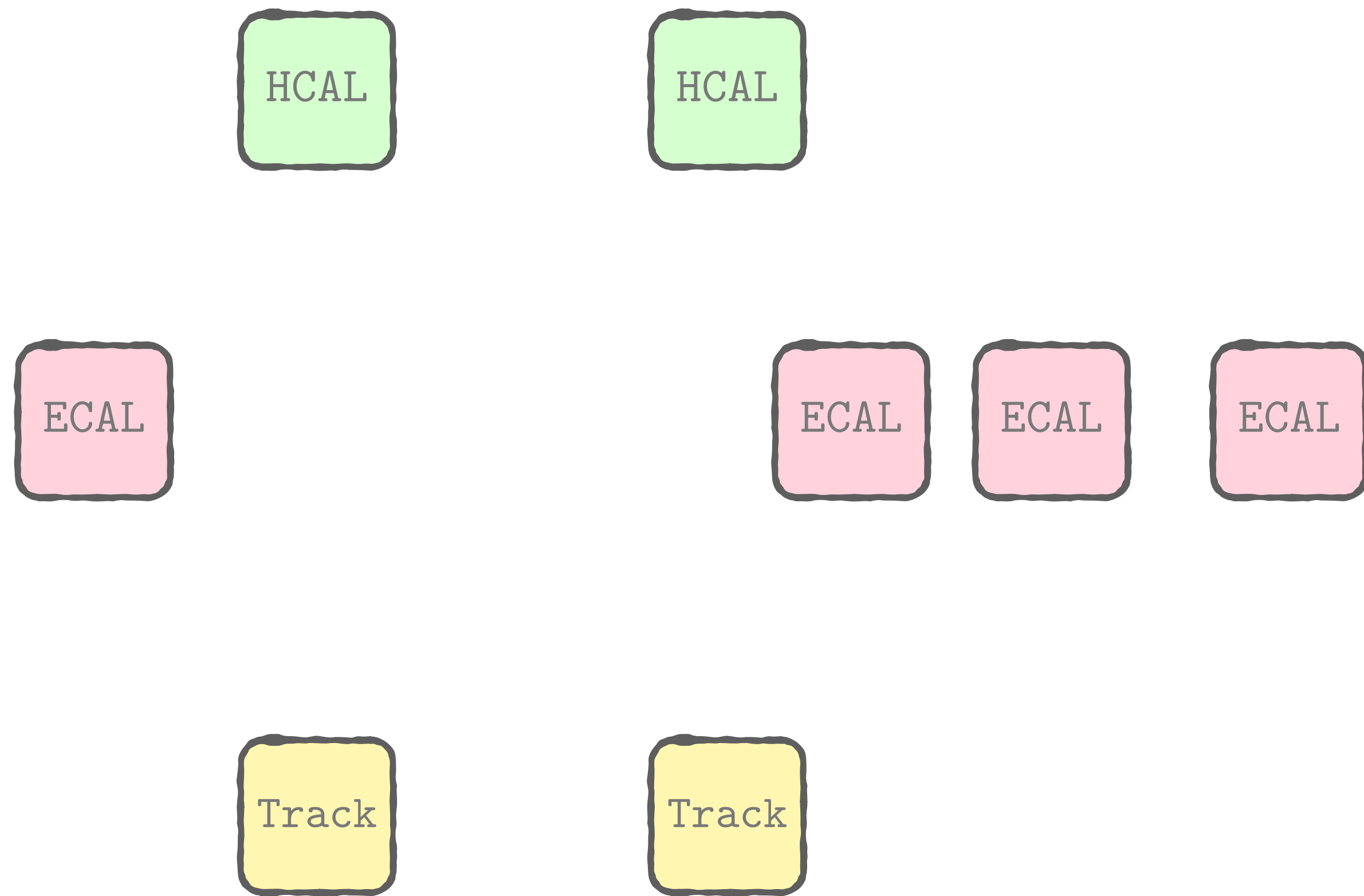
Four true particles:

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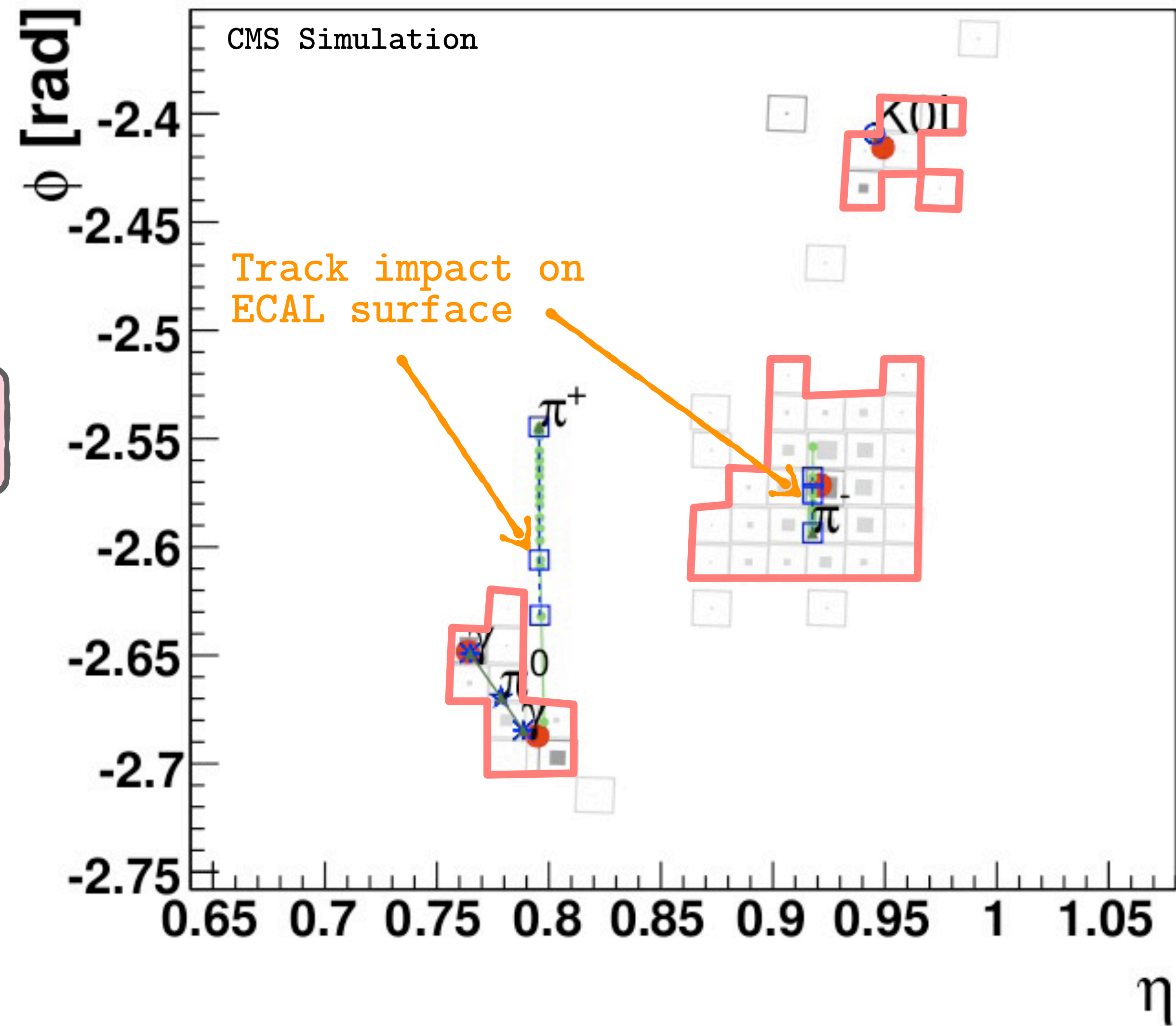
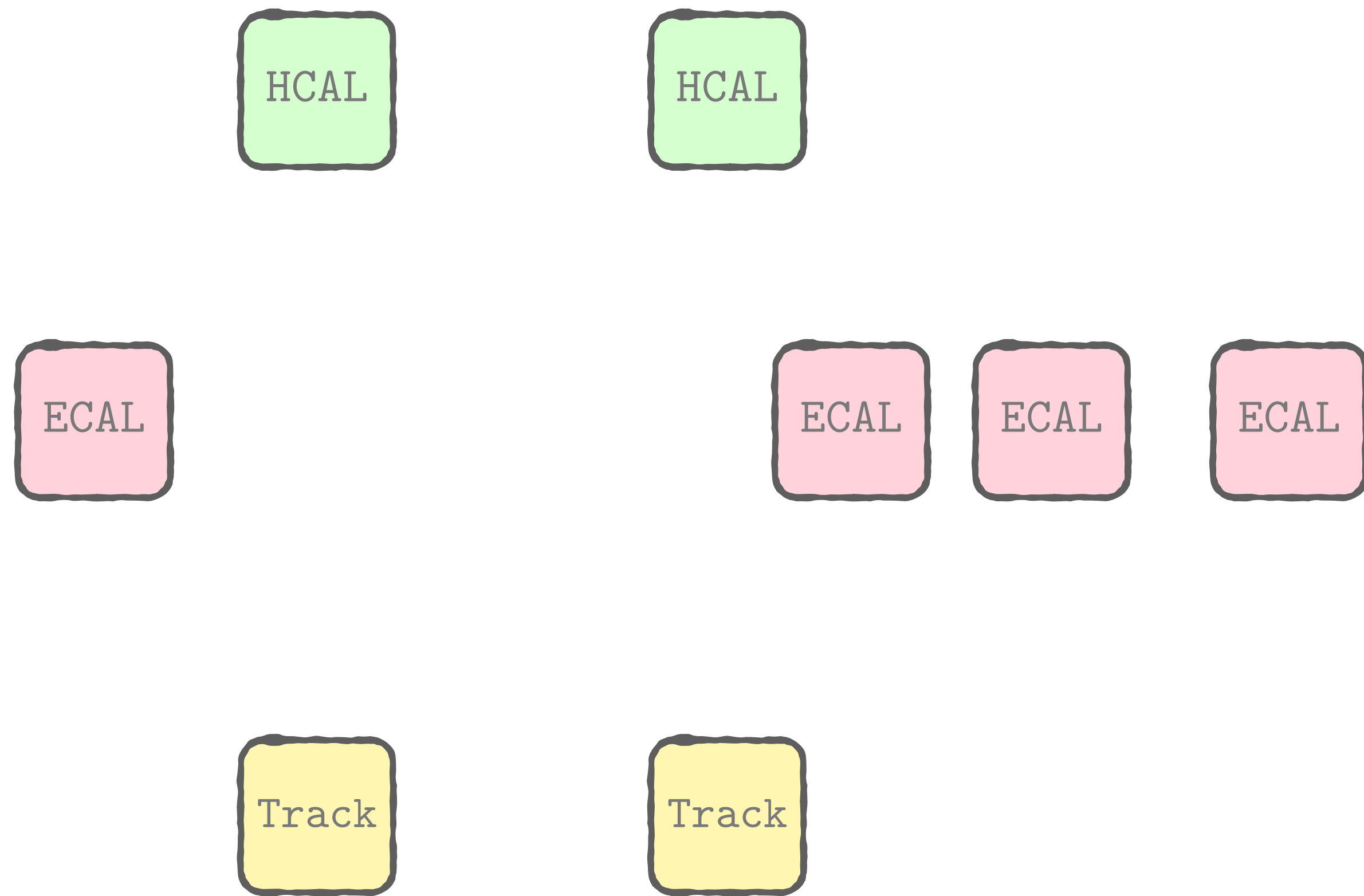
Four true particles:

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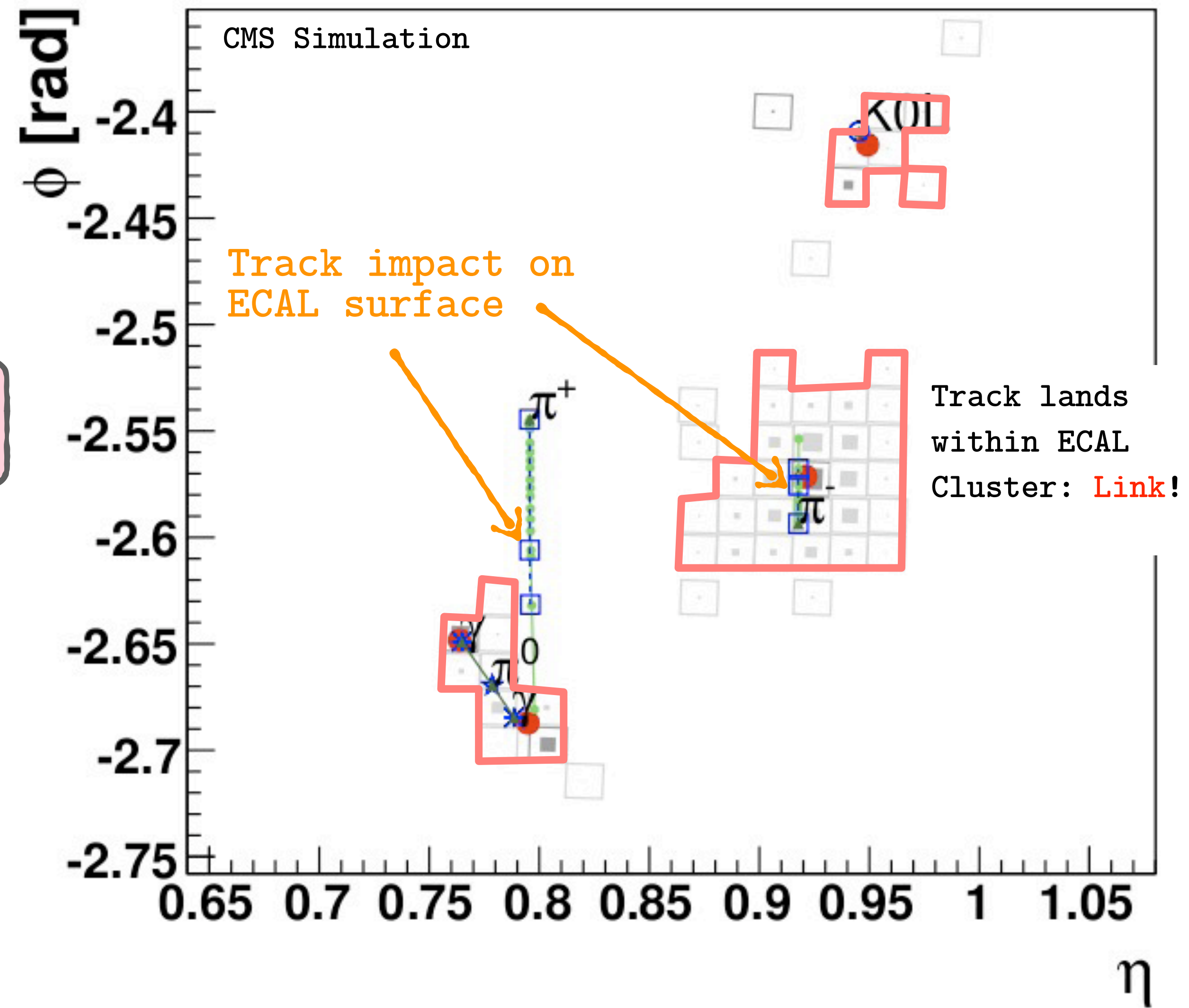
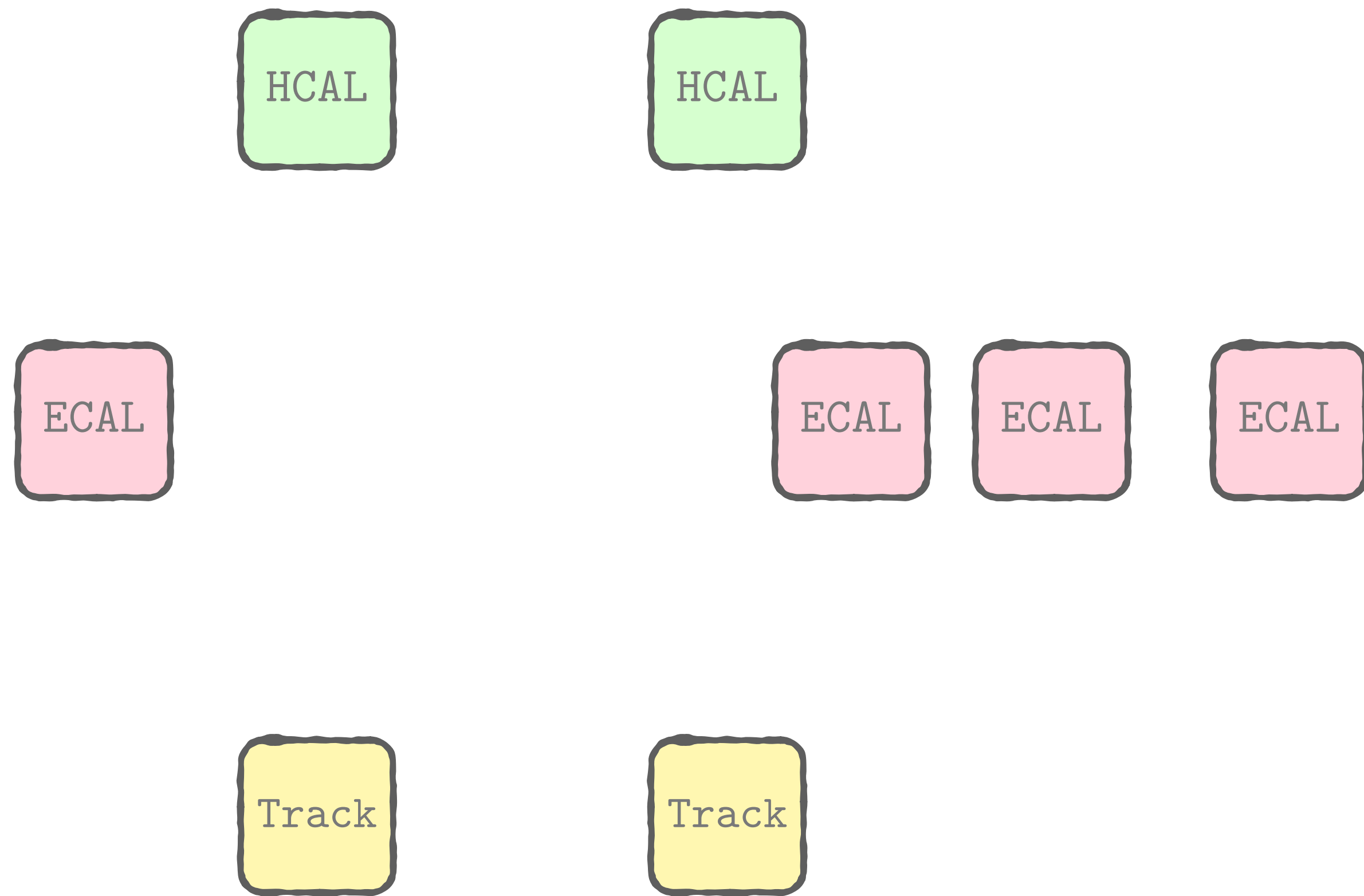
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



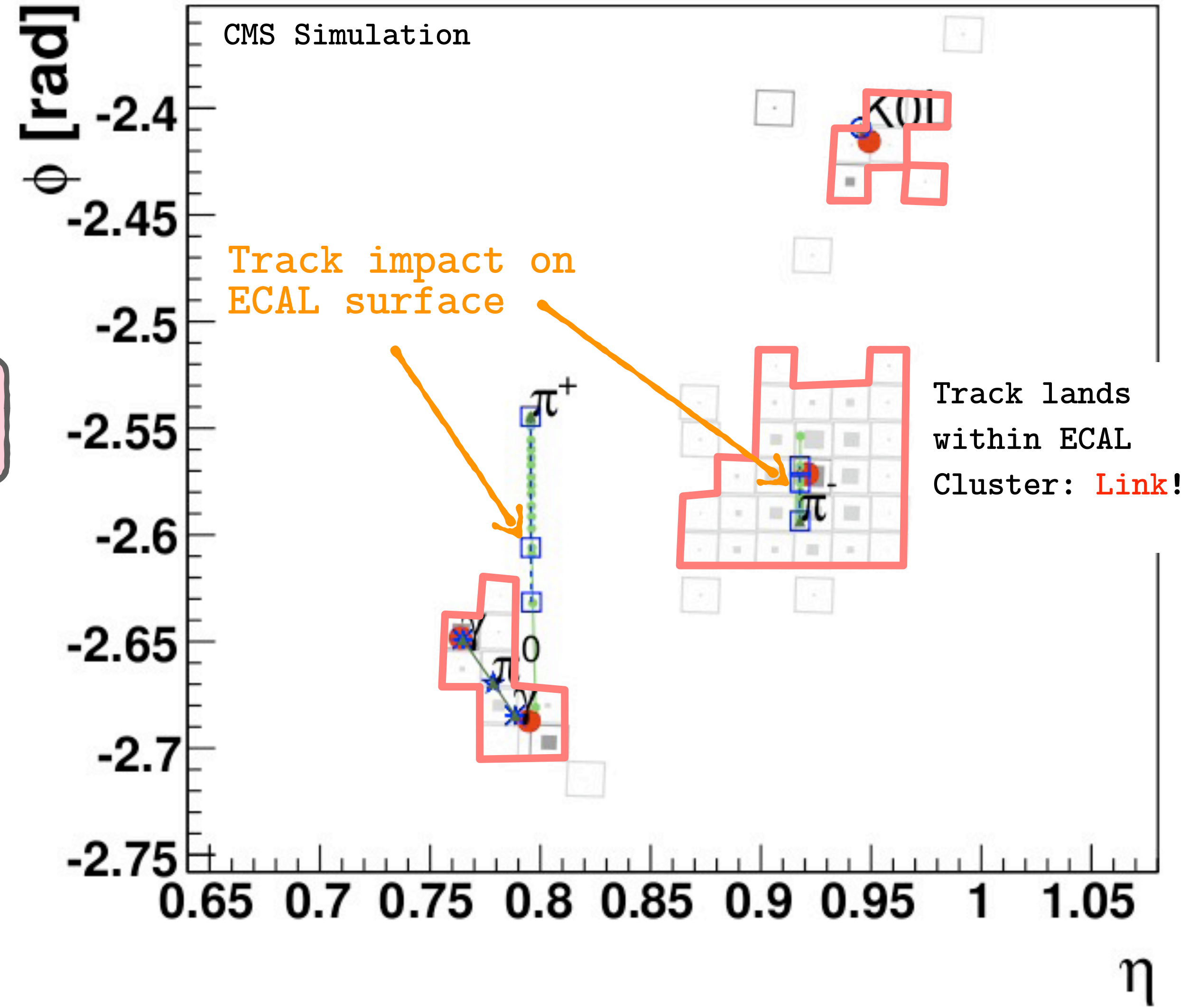
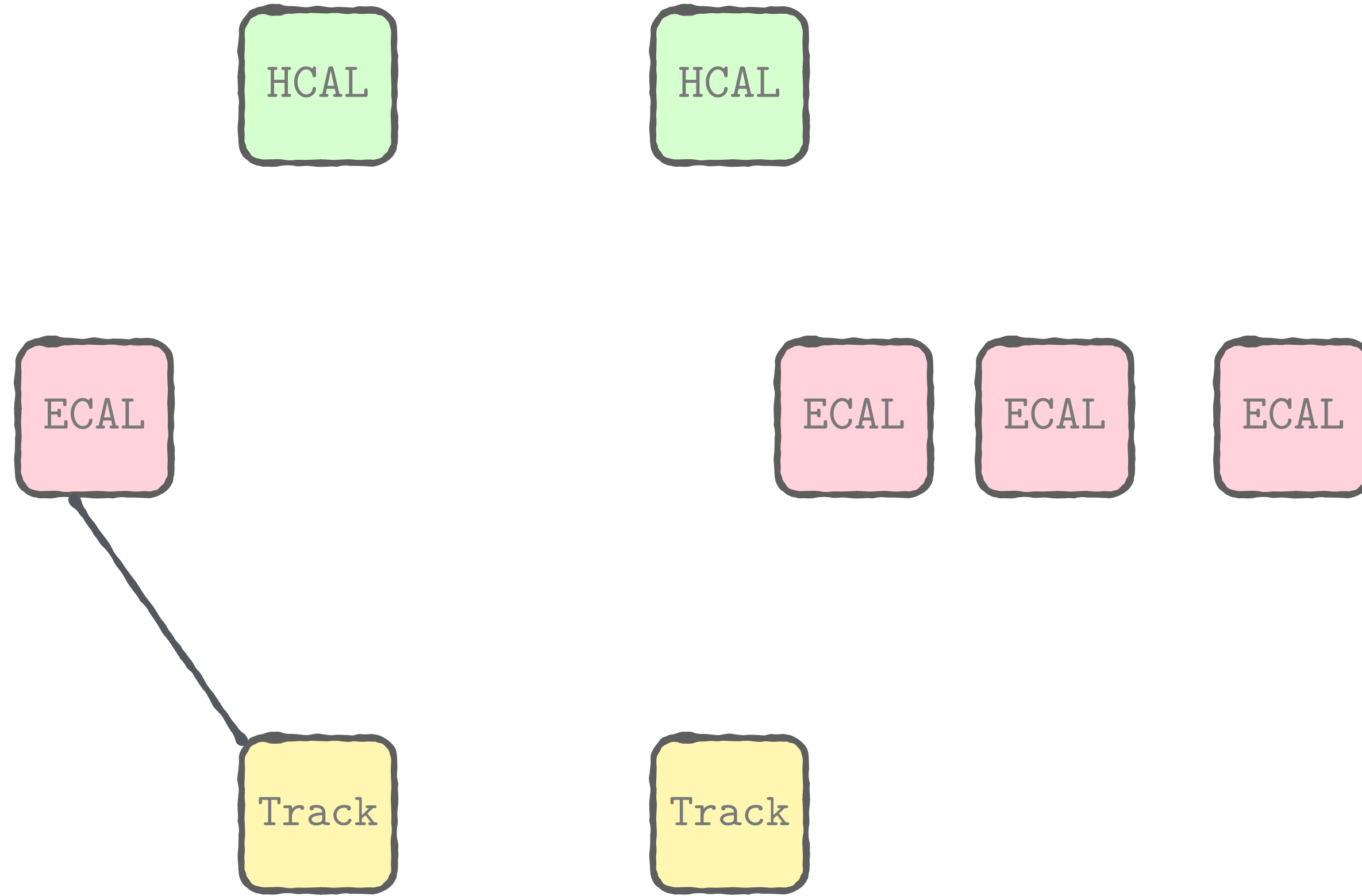
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



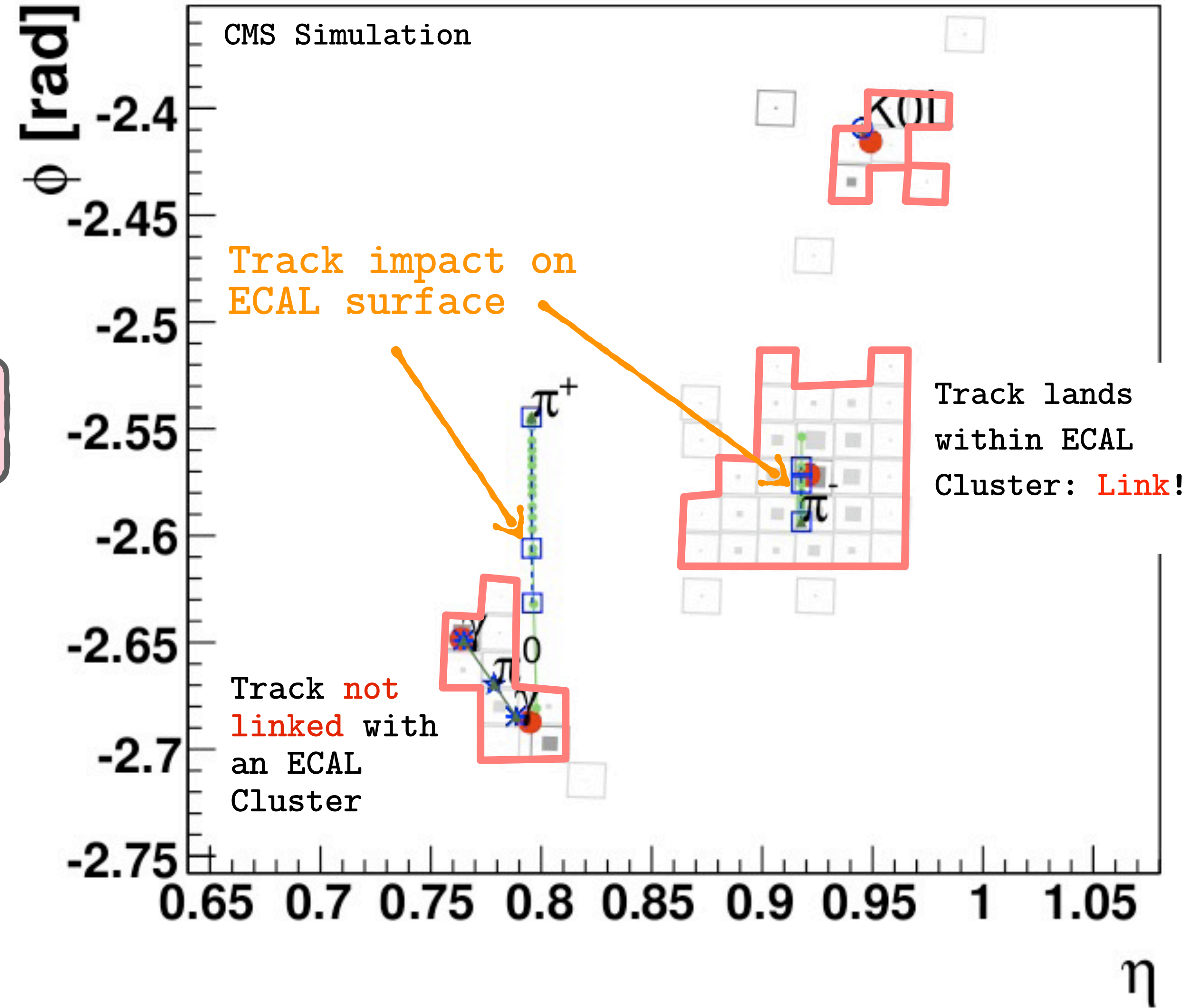
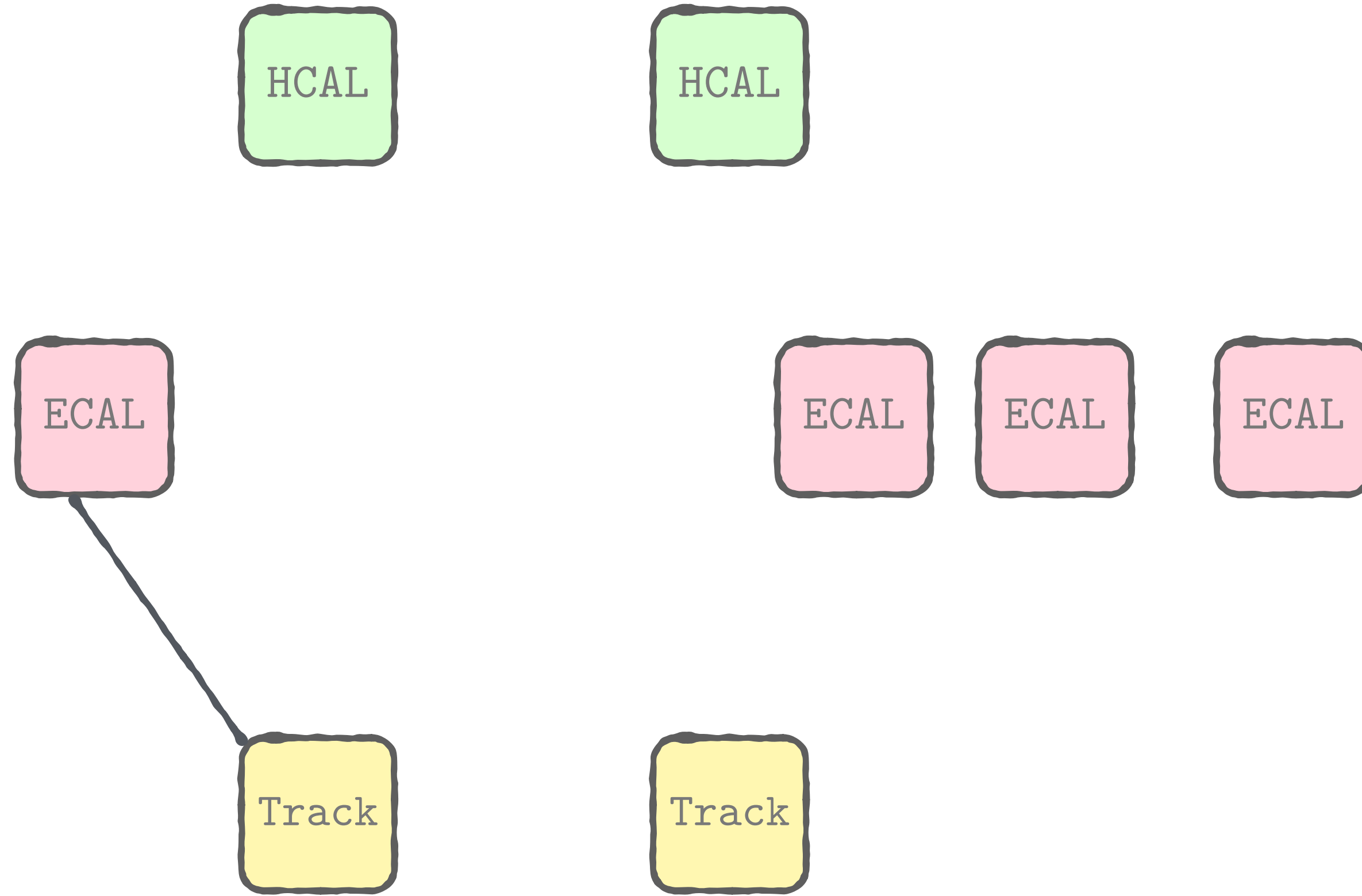
Four true particles:

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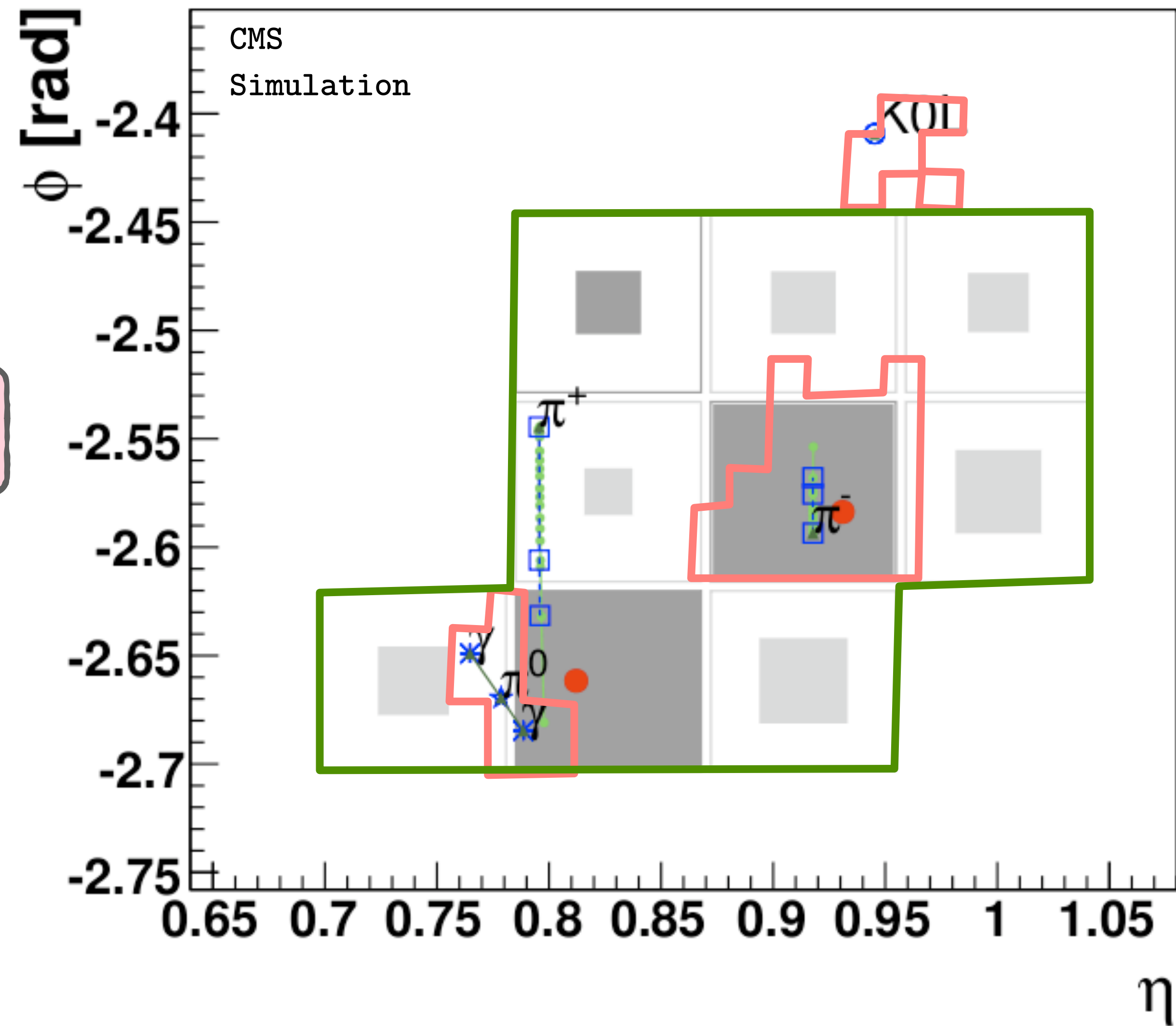
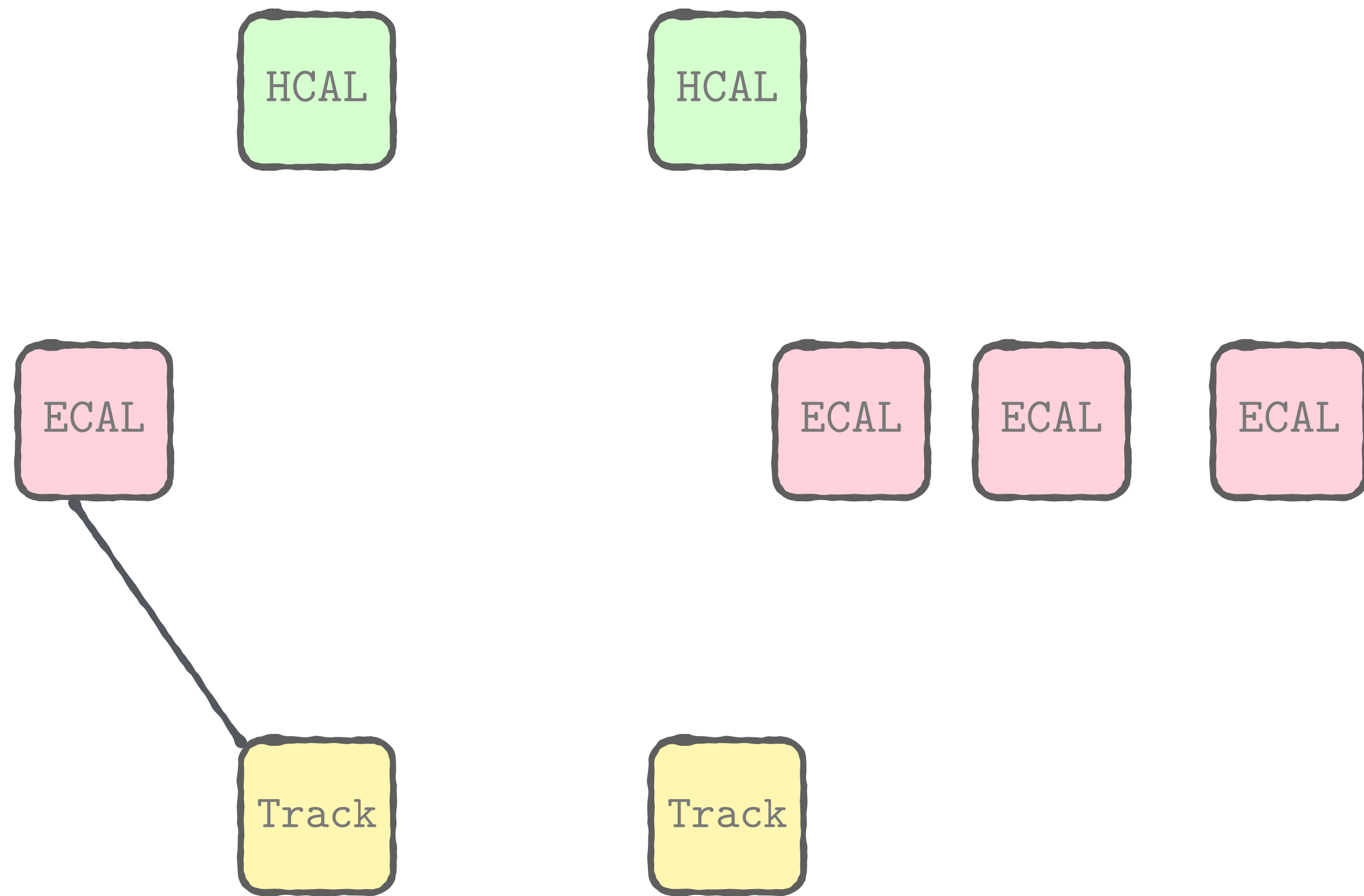
Four true particles:

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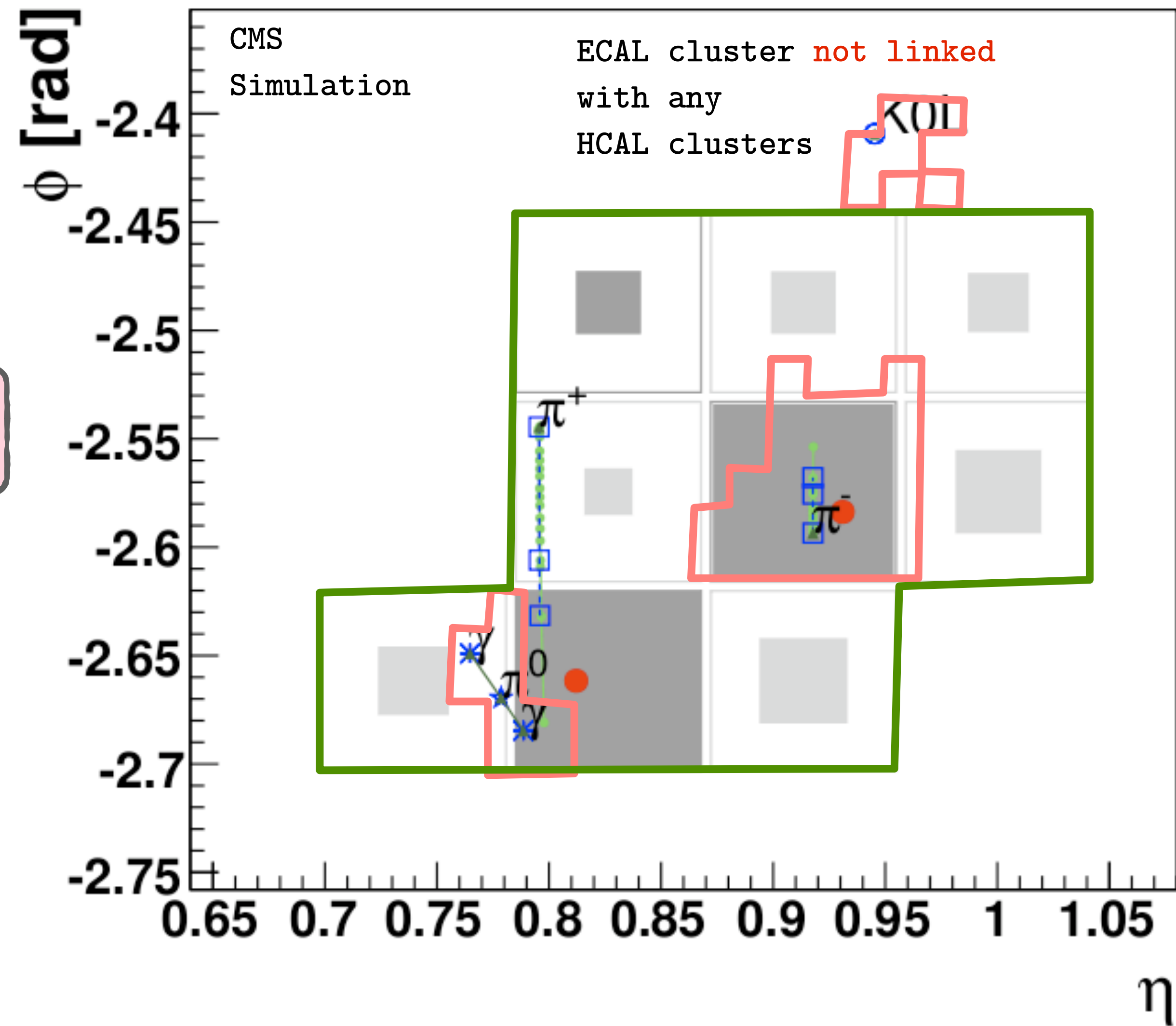
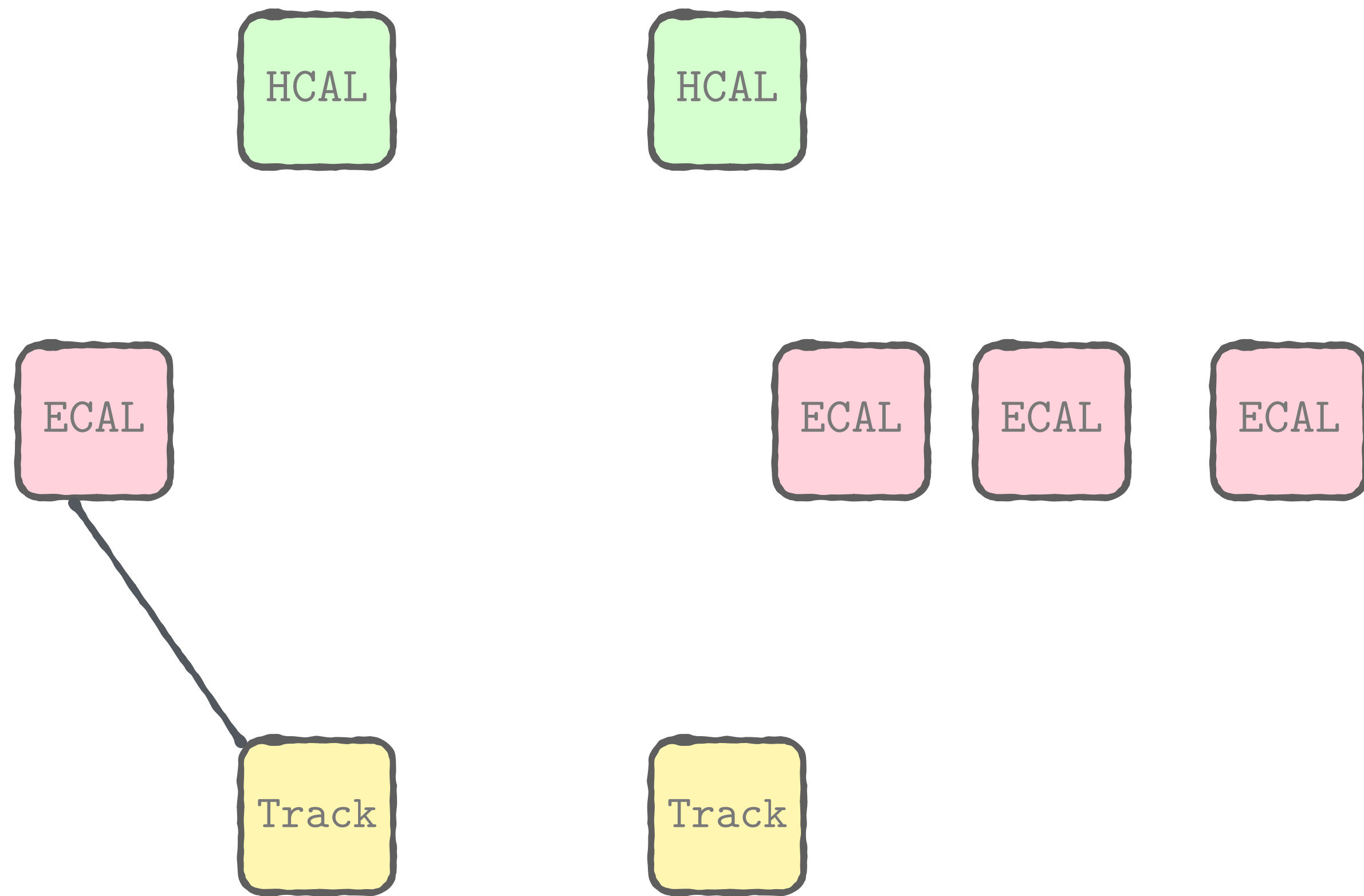
Four true particles:

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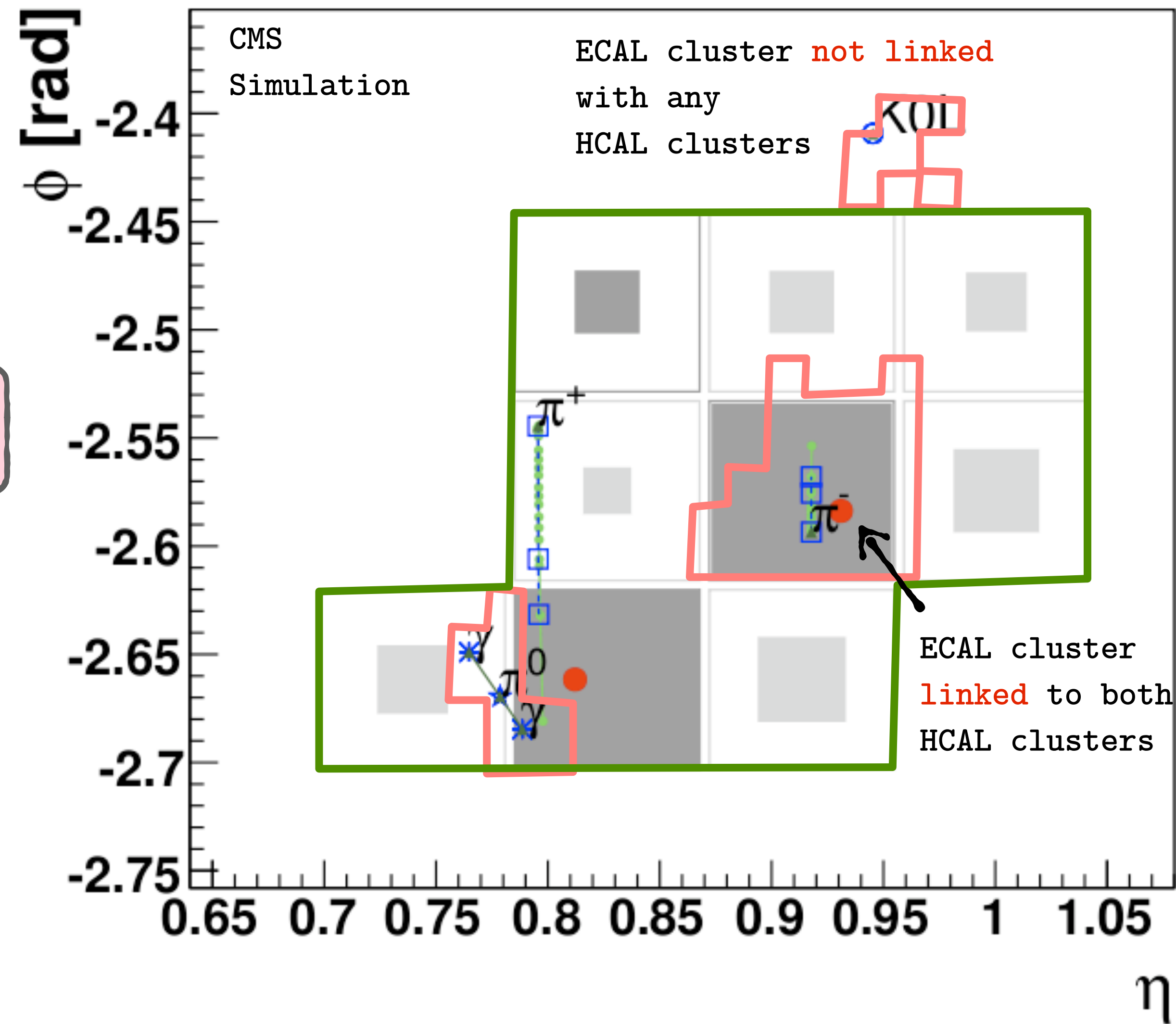
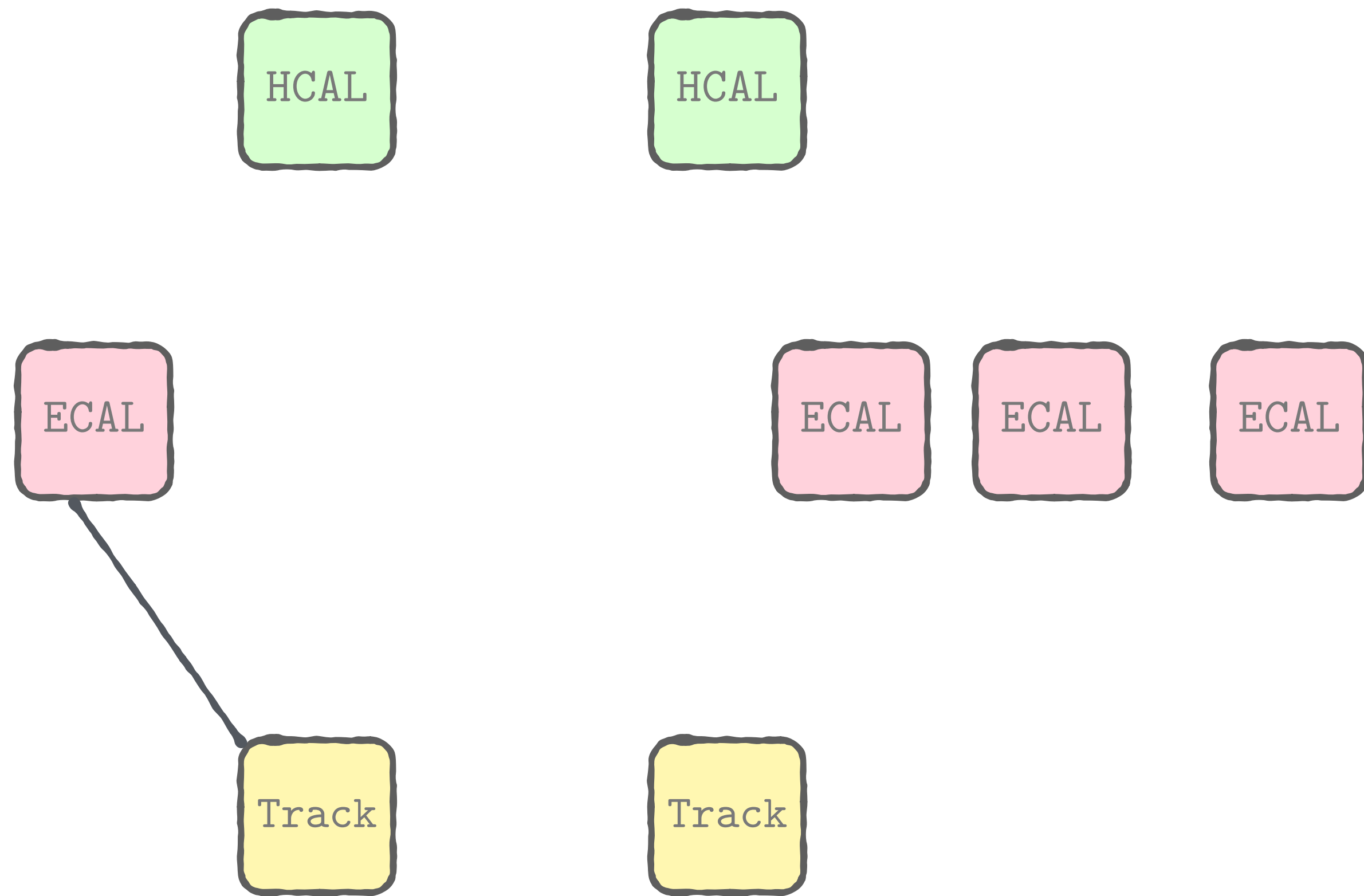
Four true particles:

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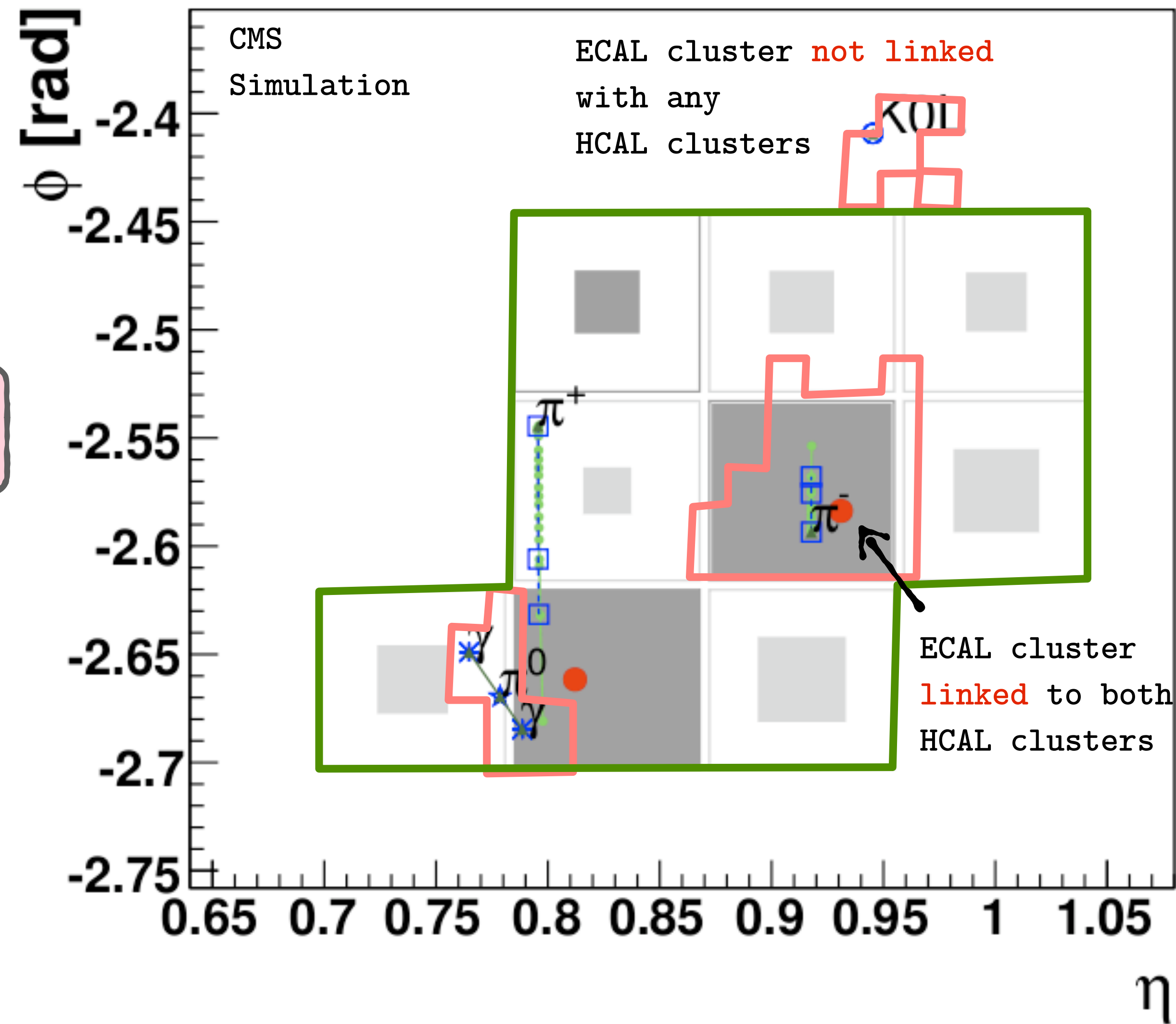
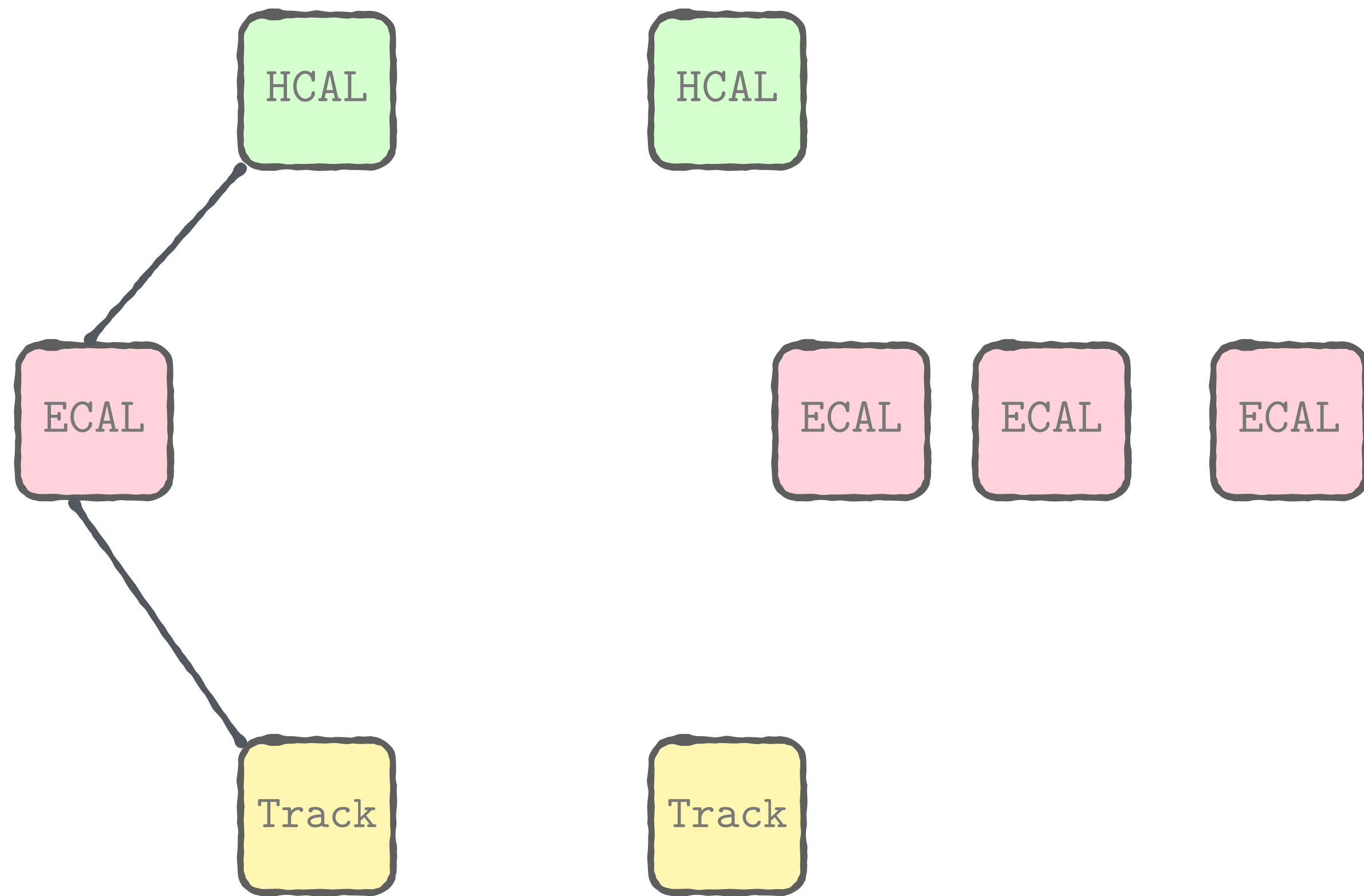
Four true particles:

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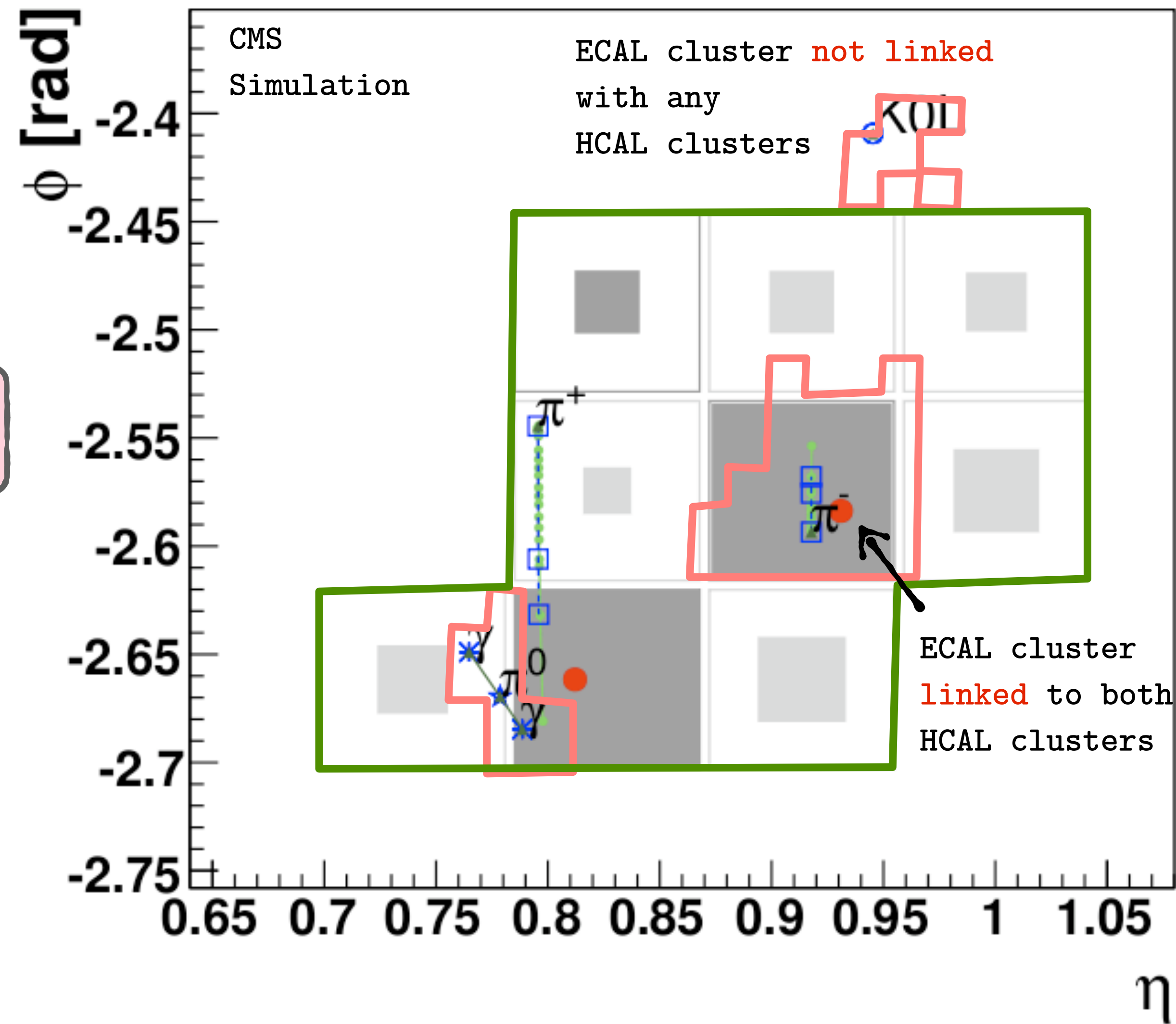
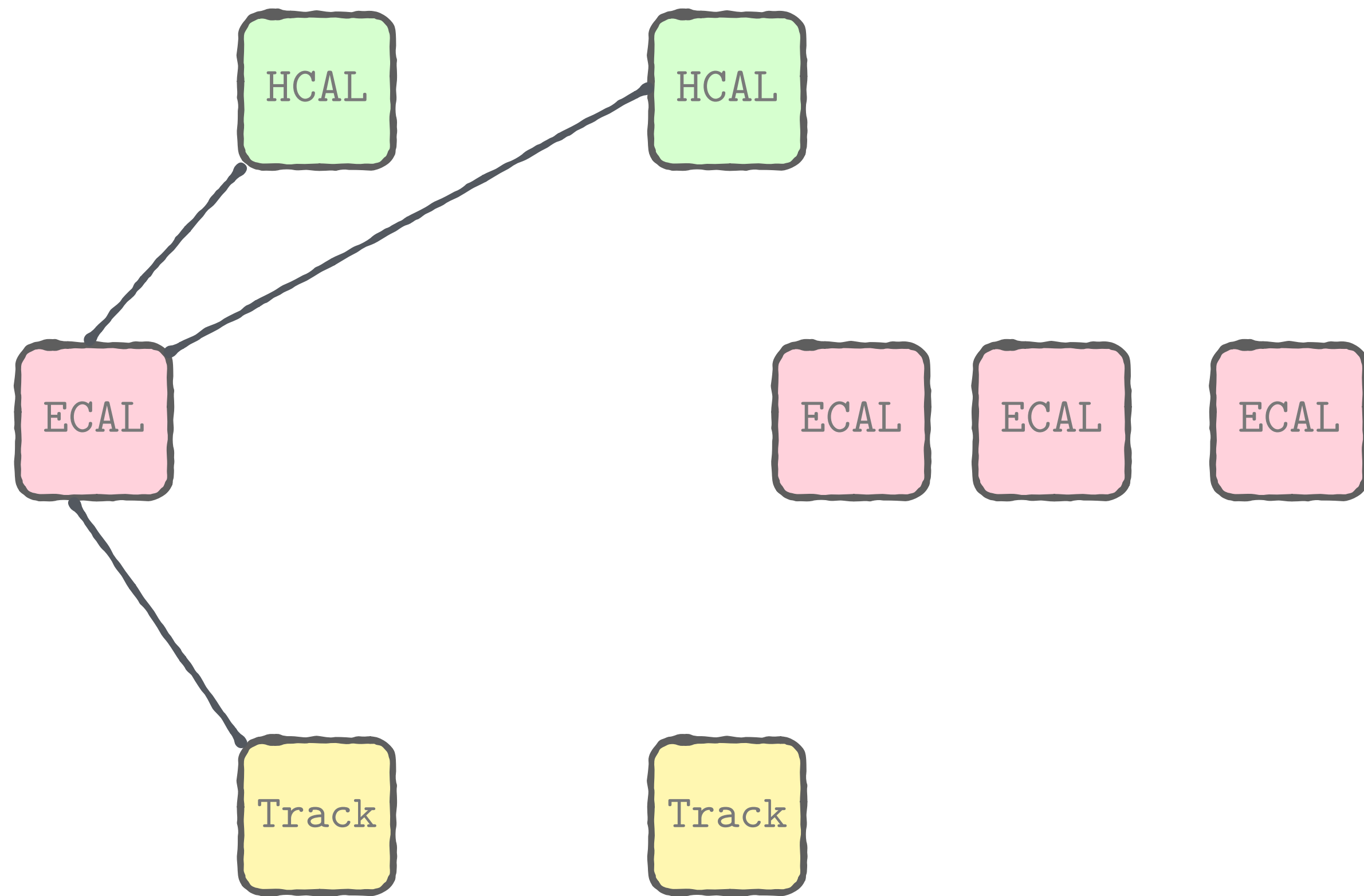
Four true particles:

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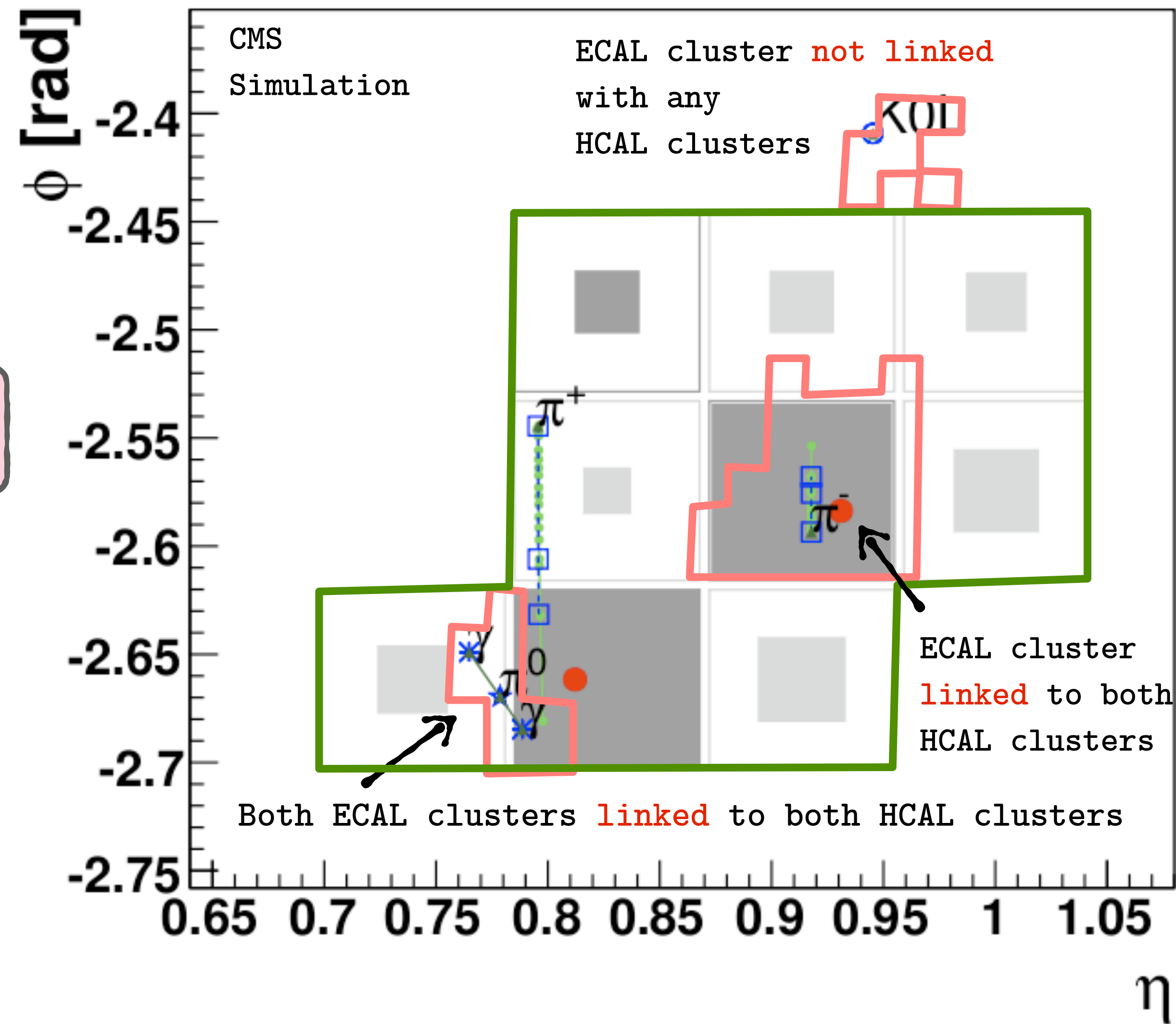
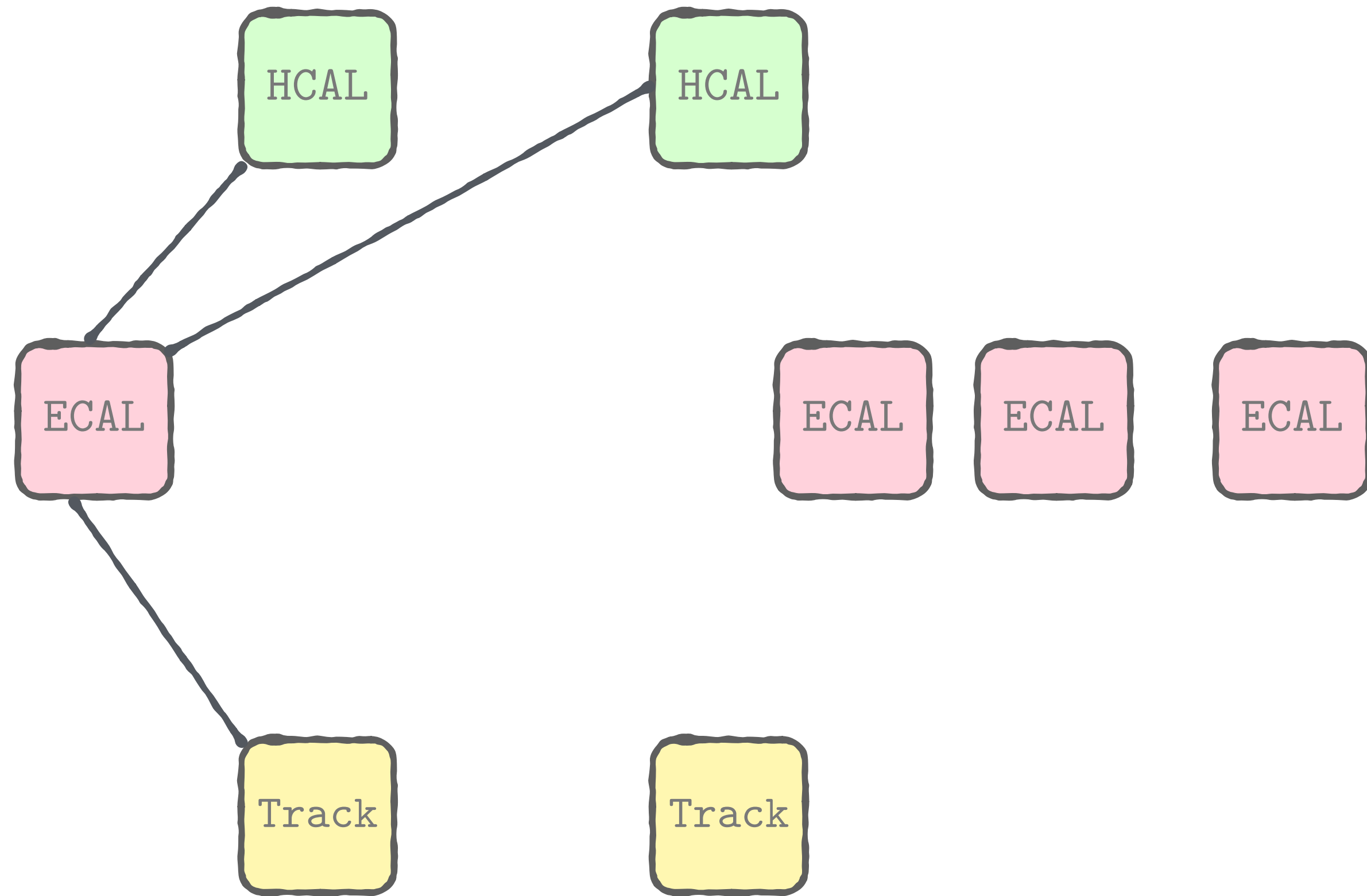
Four true particles:

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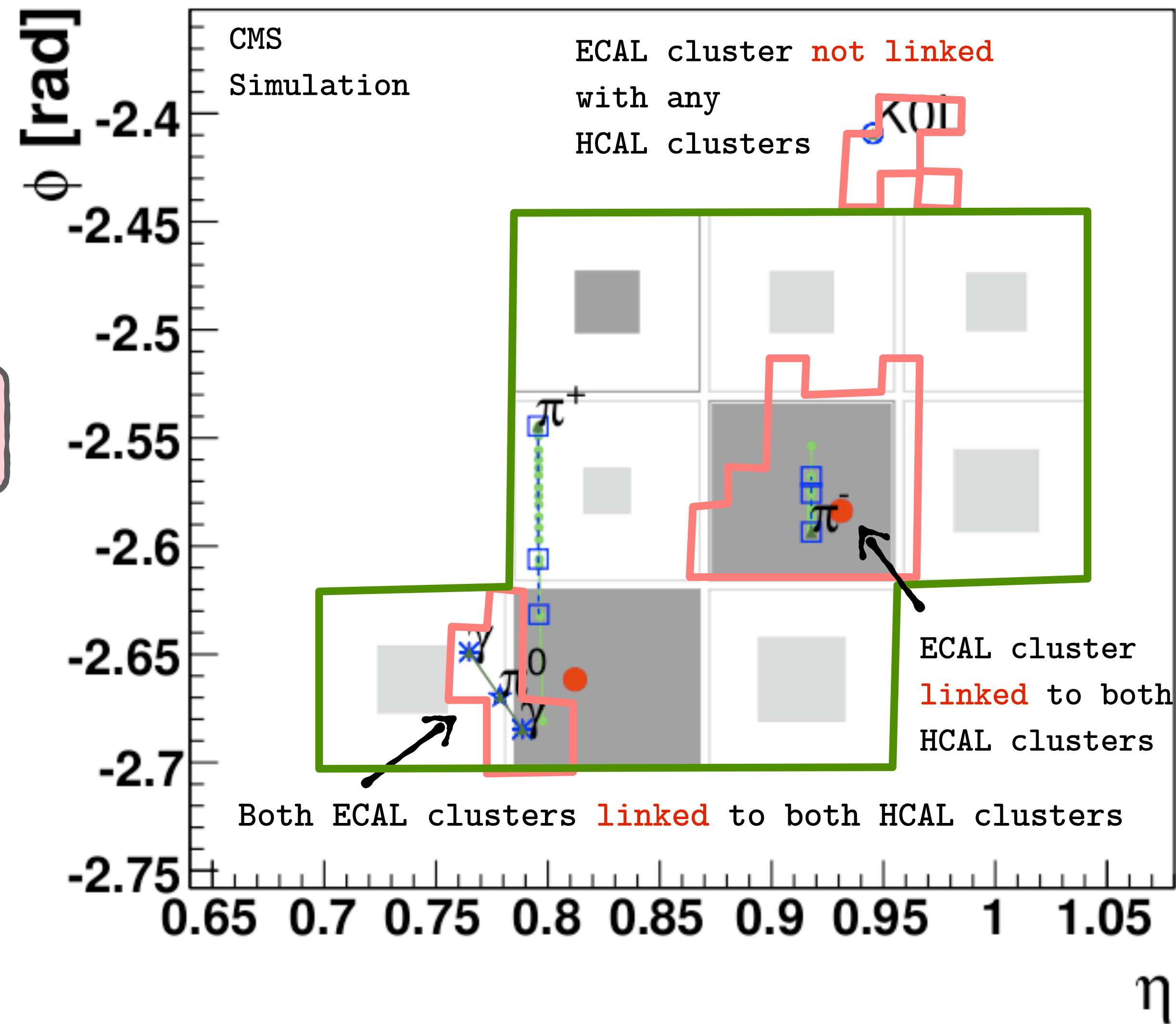
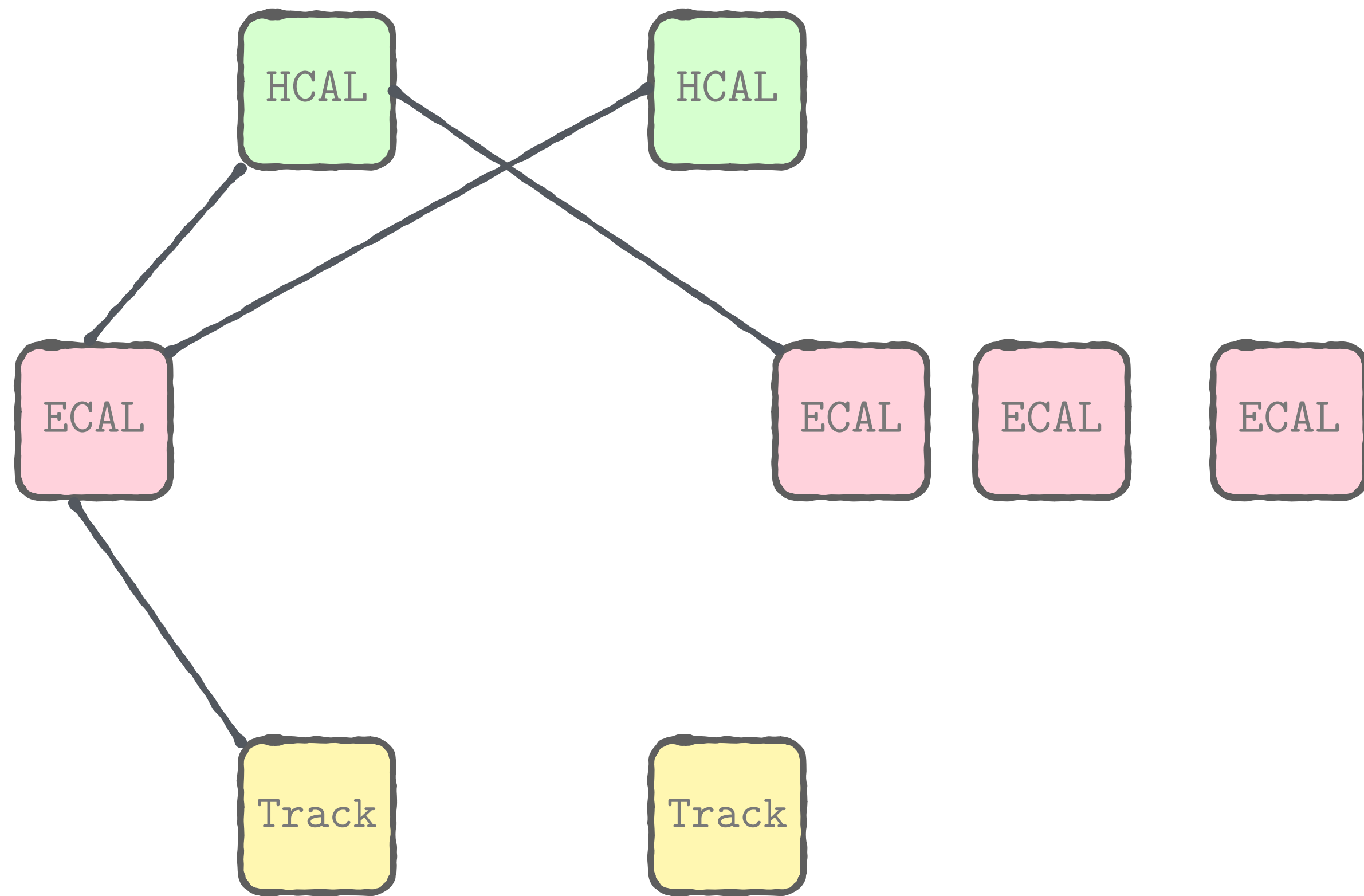
Four true particles:

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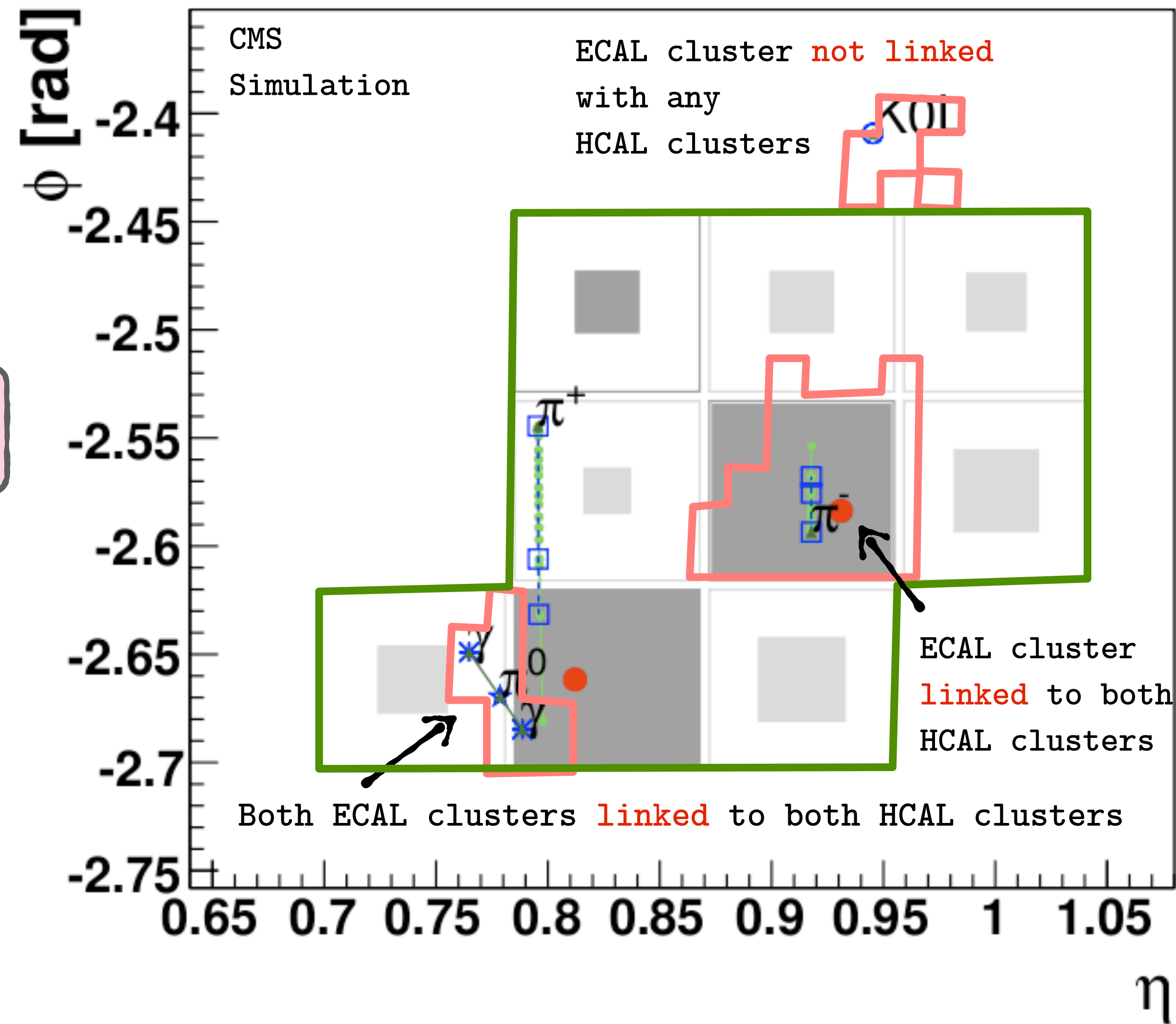
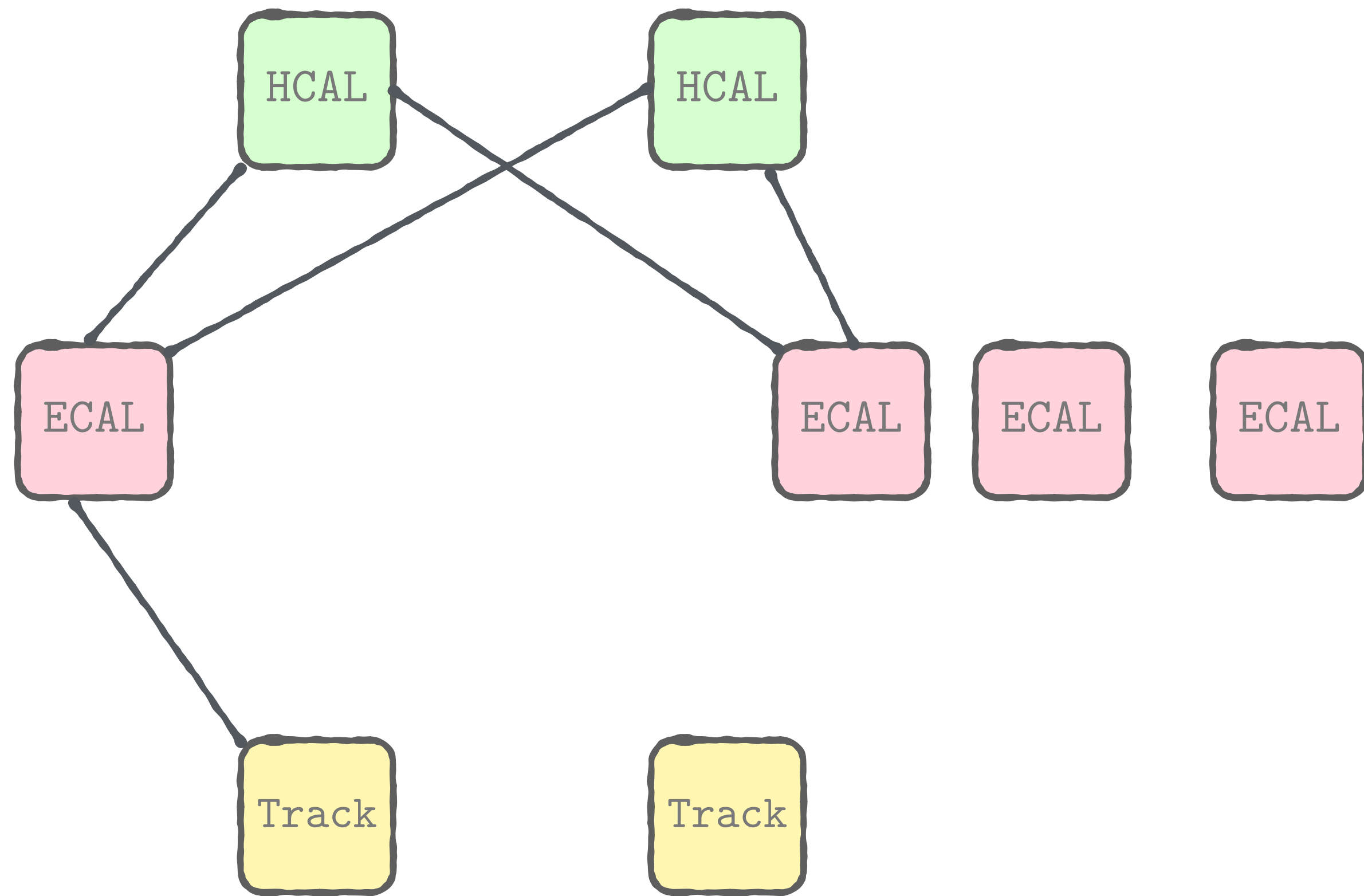
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



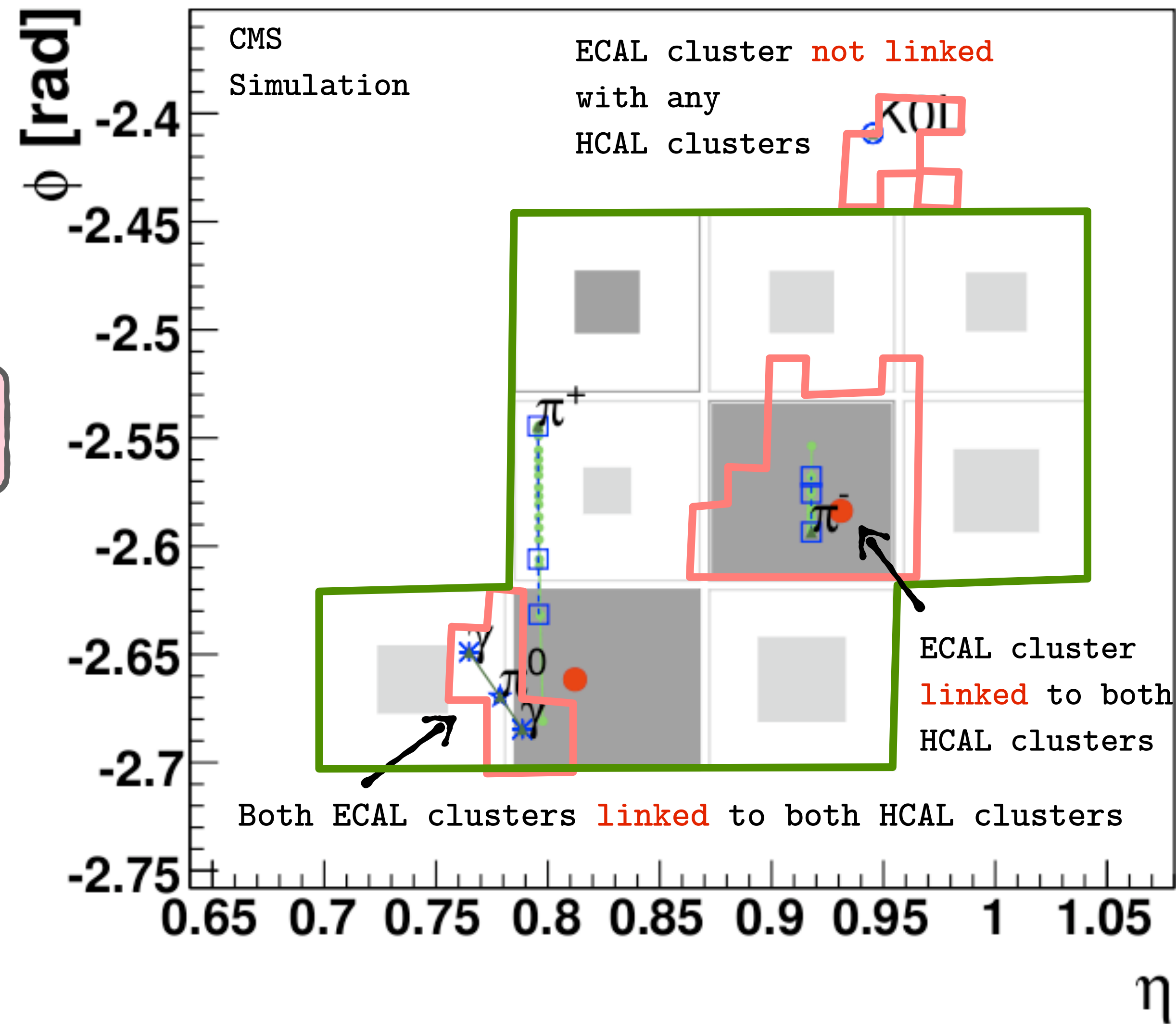
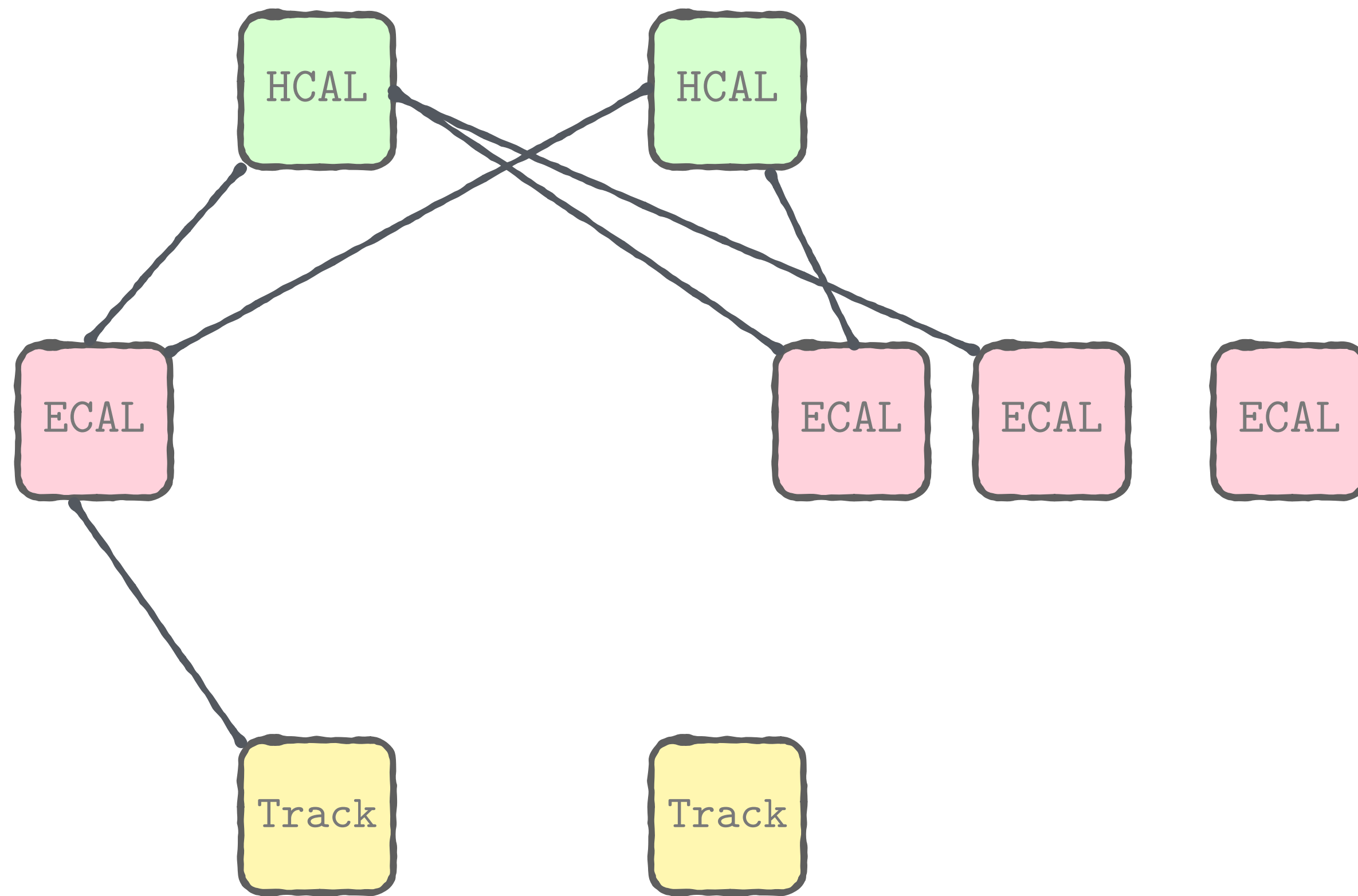
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



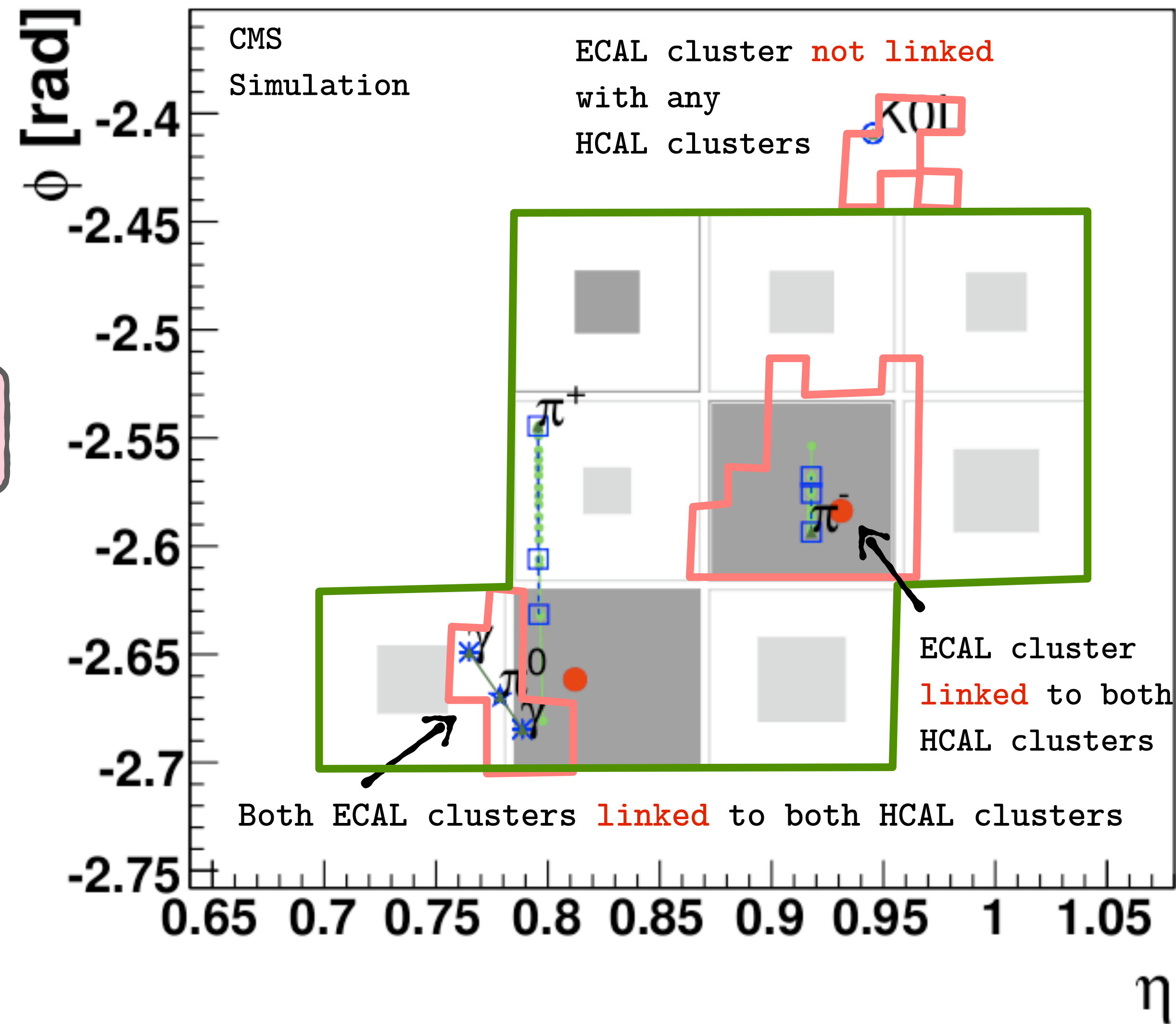
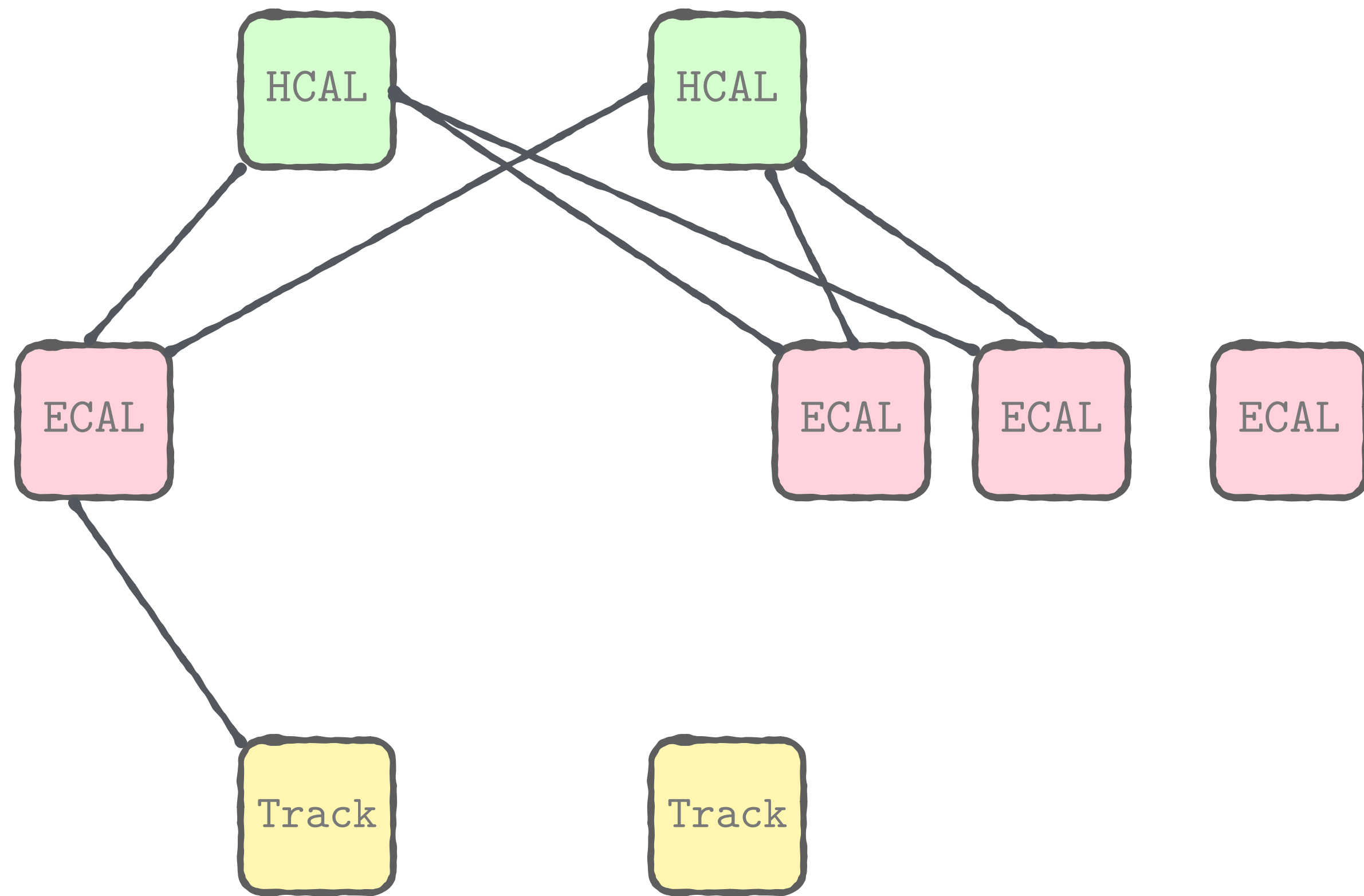
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



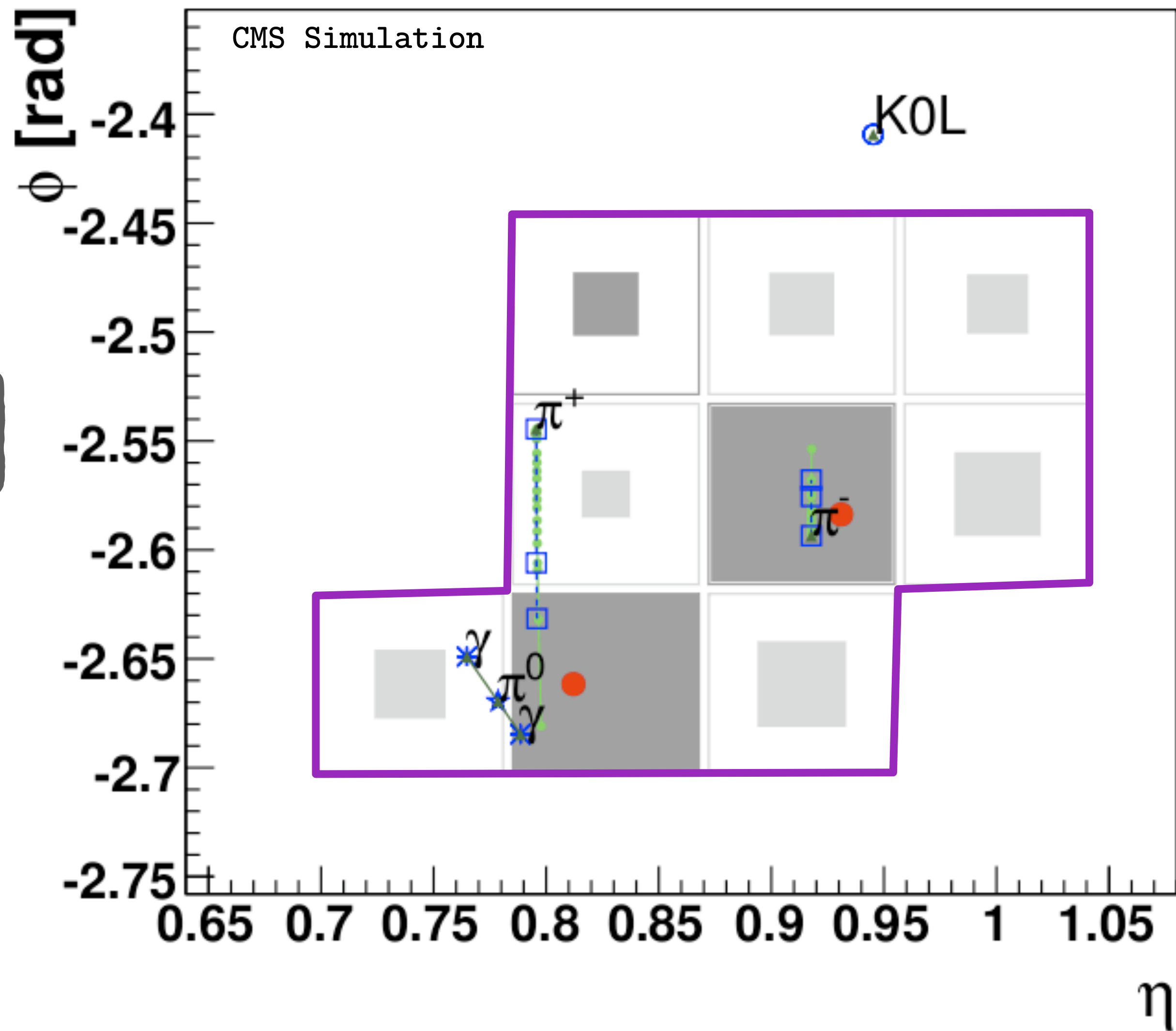
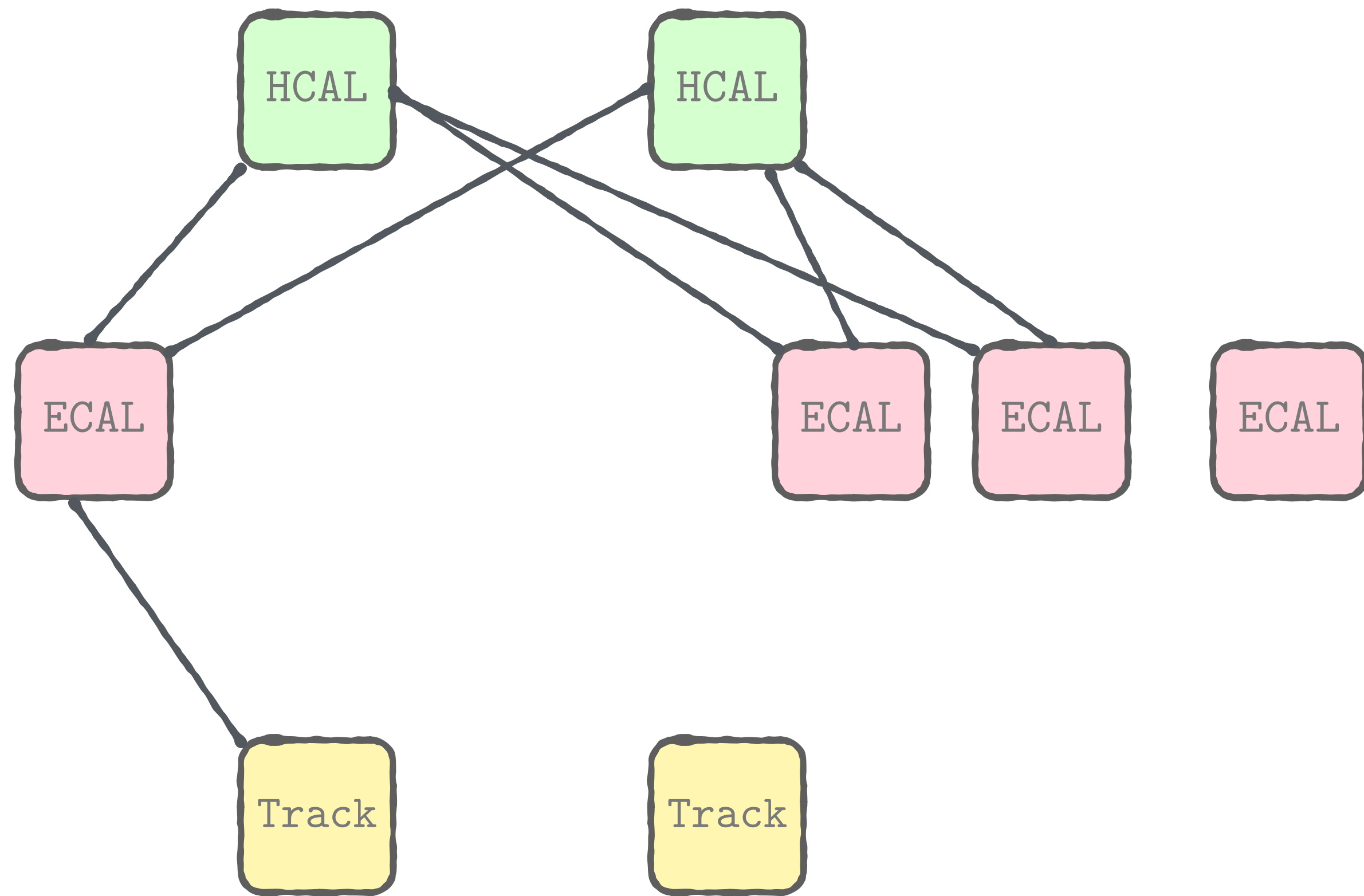
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



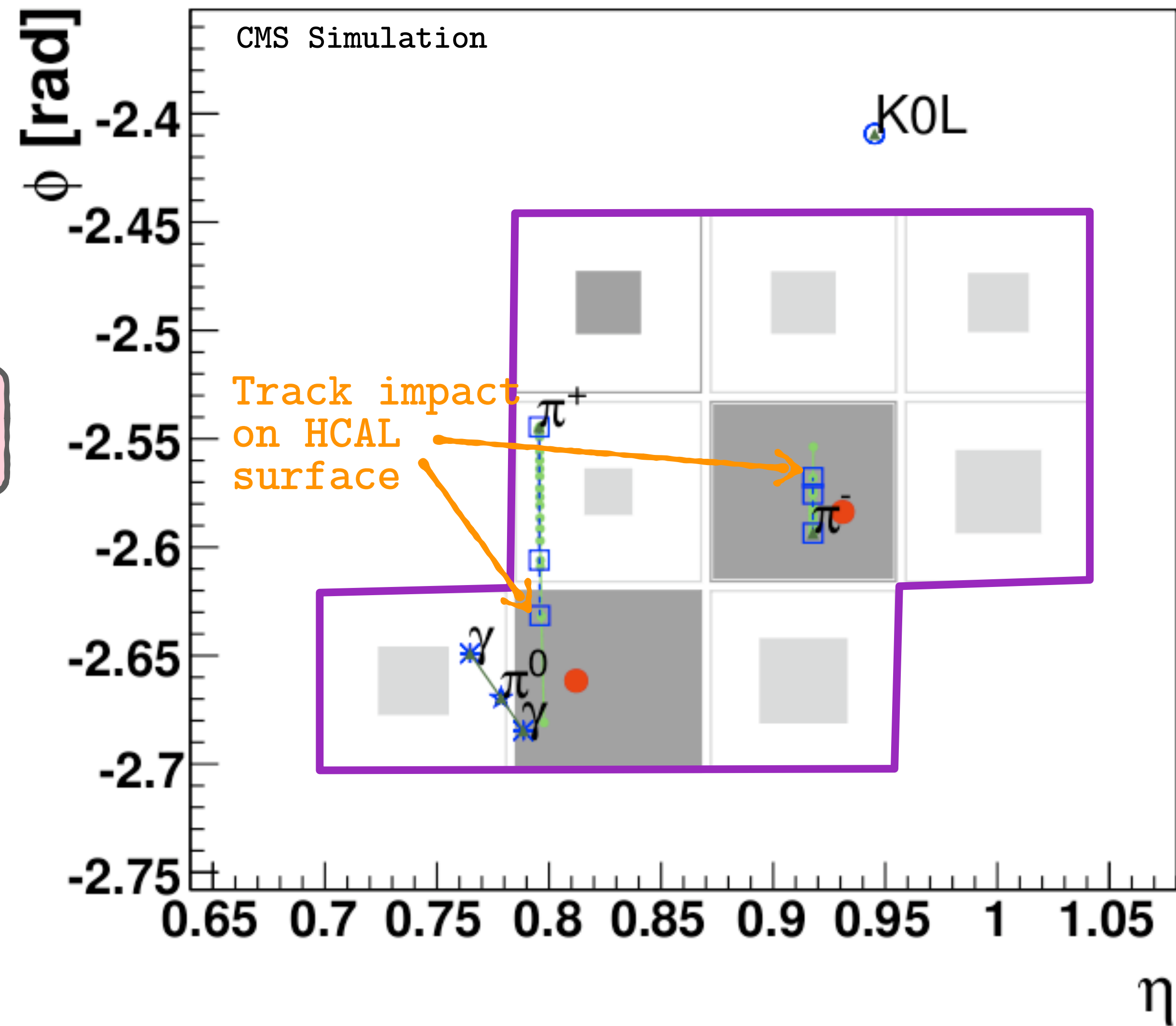
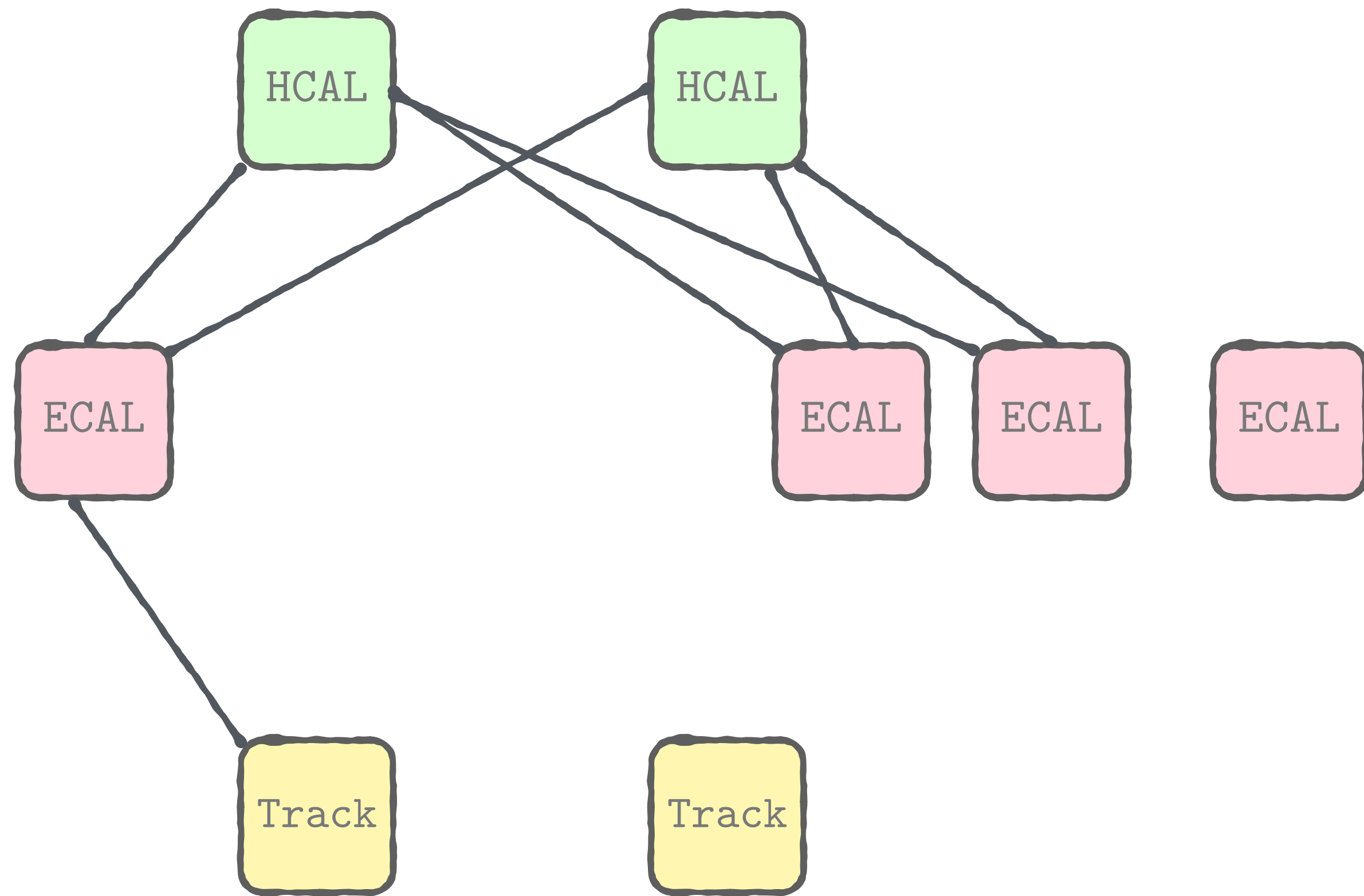
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



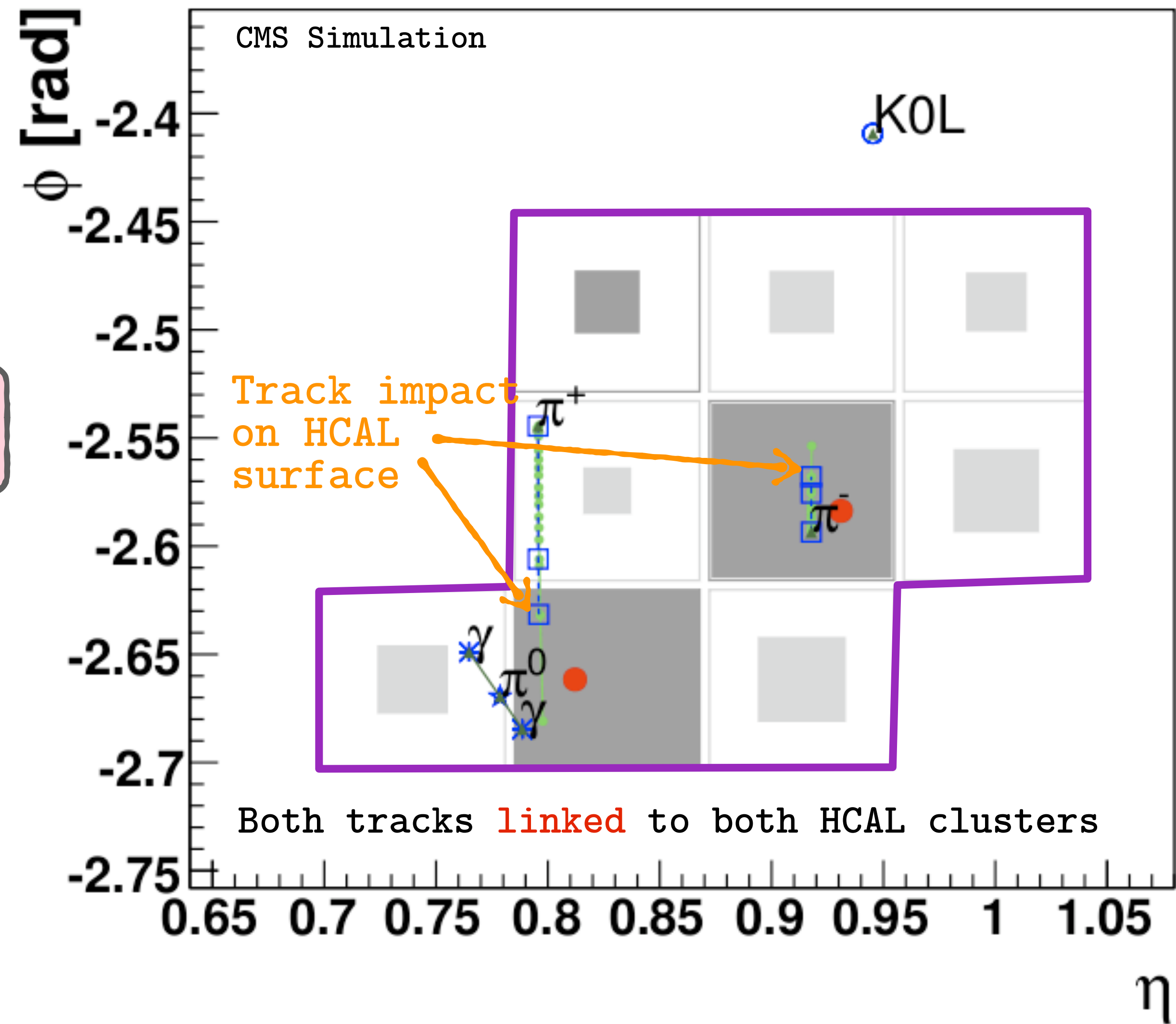
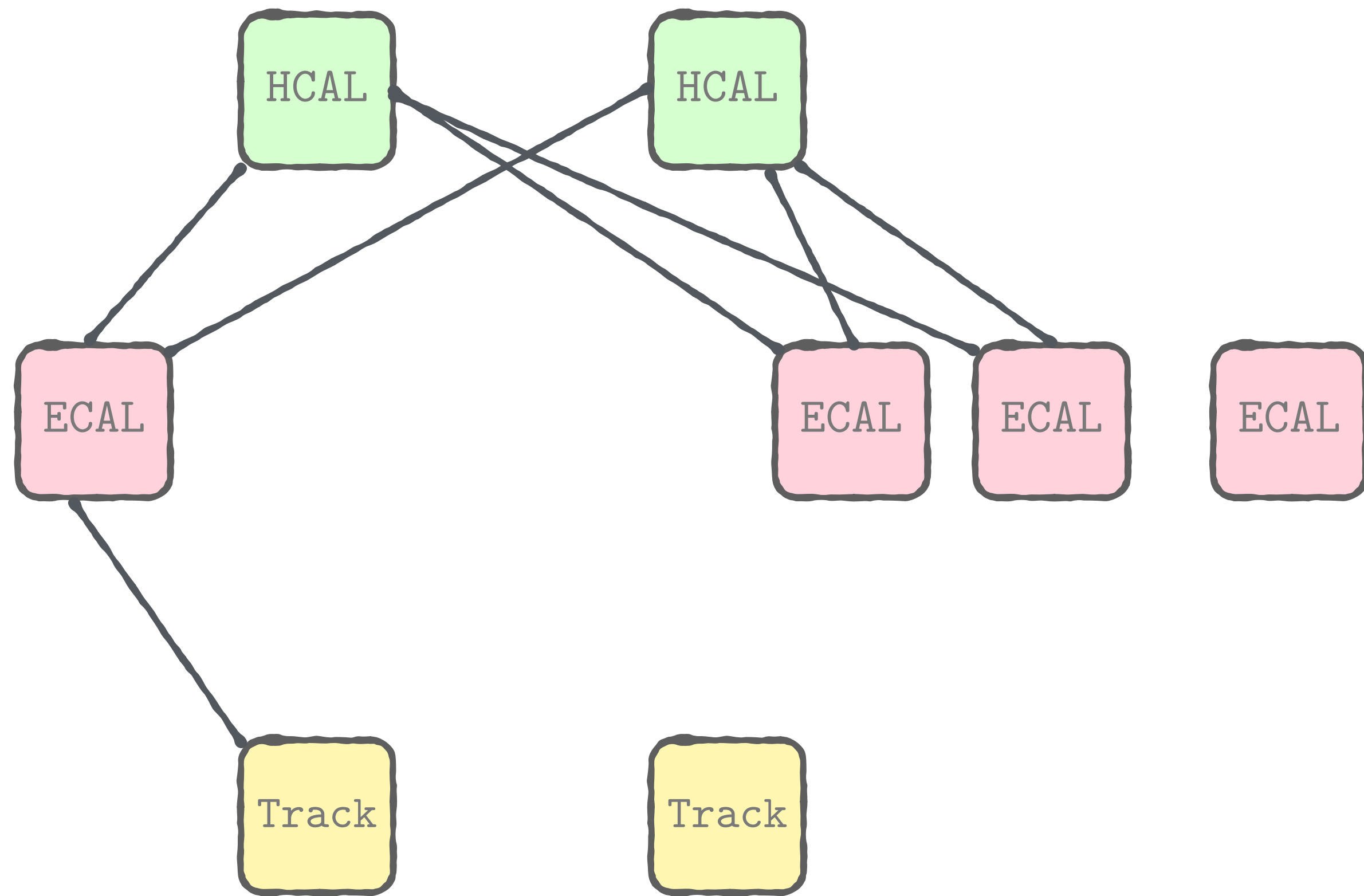
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



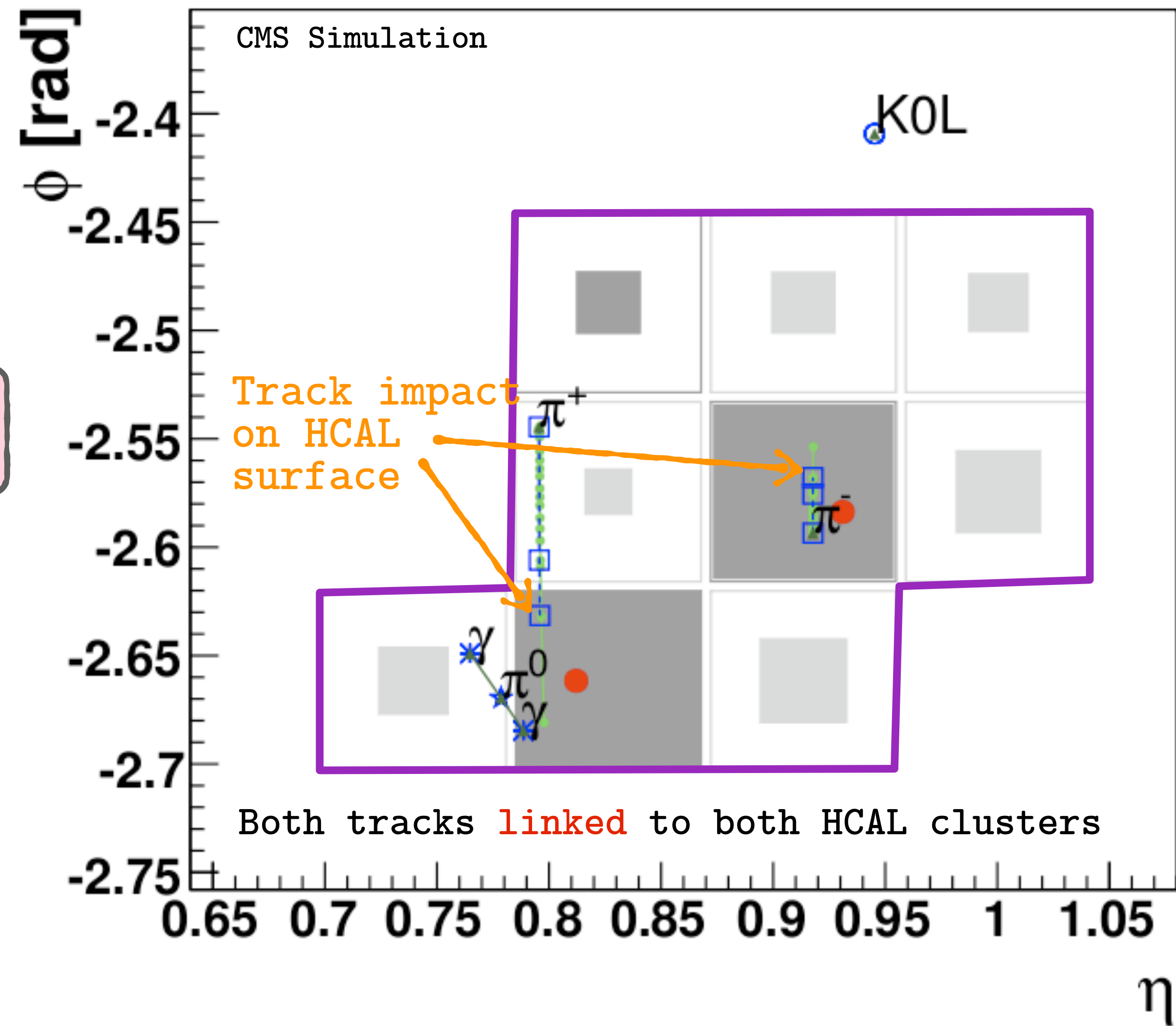
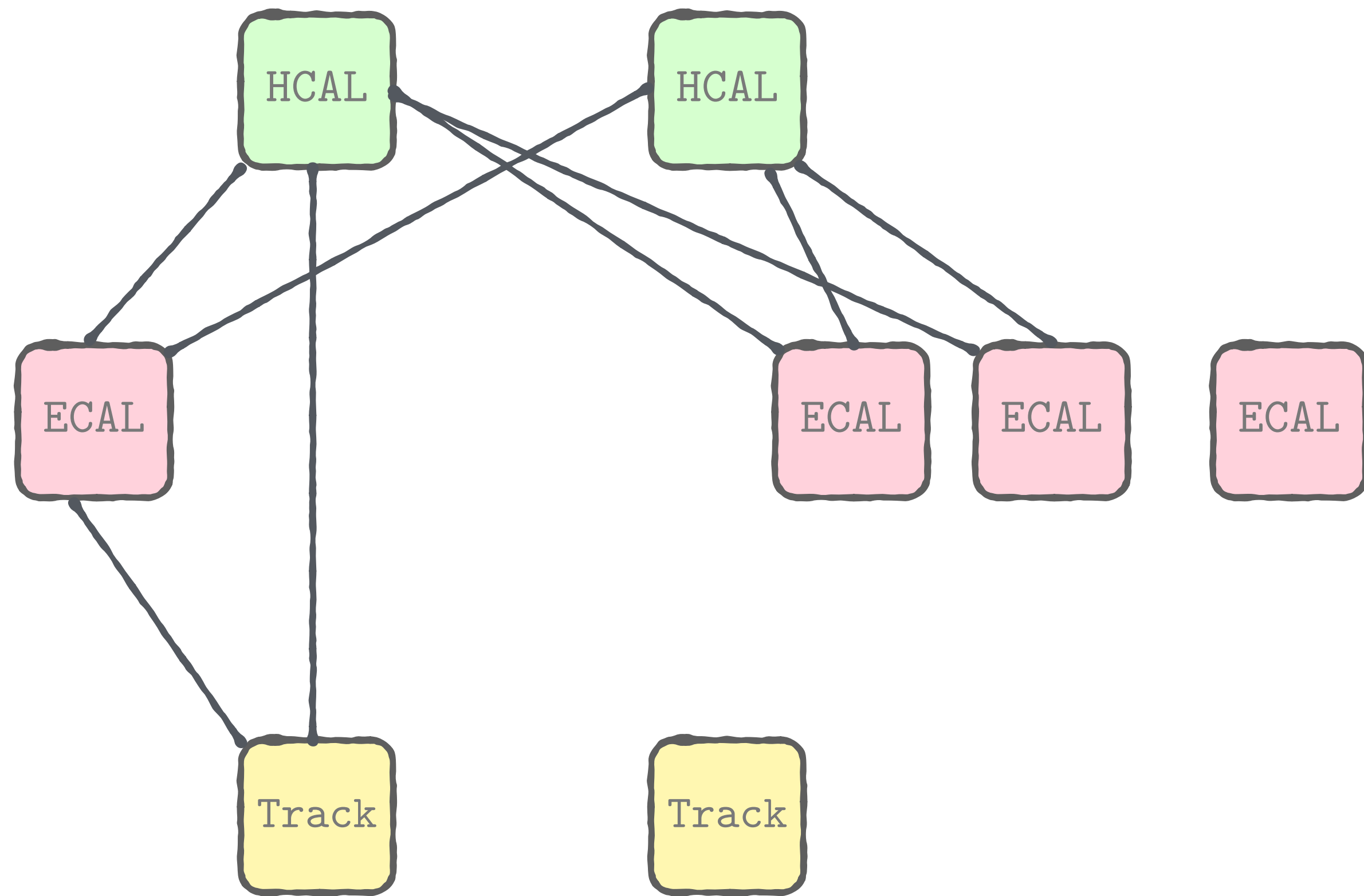
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



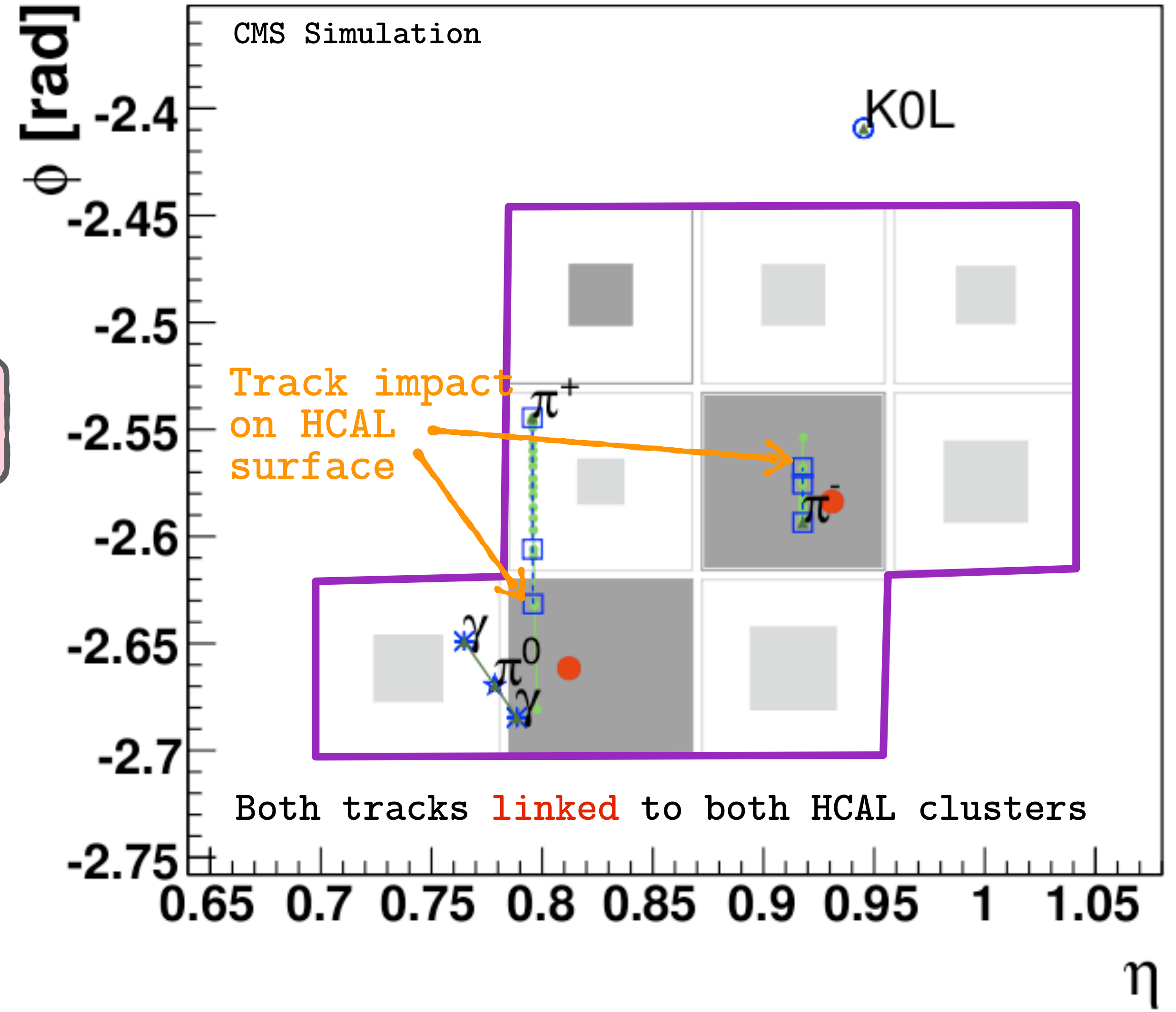
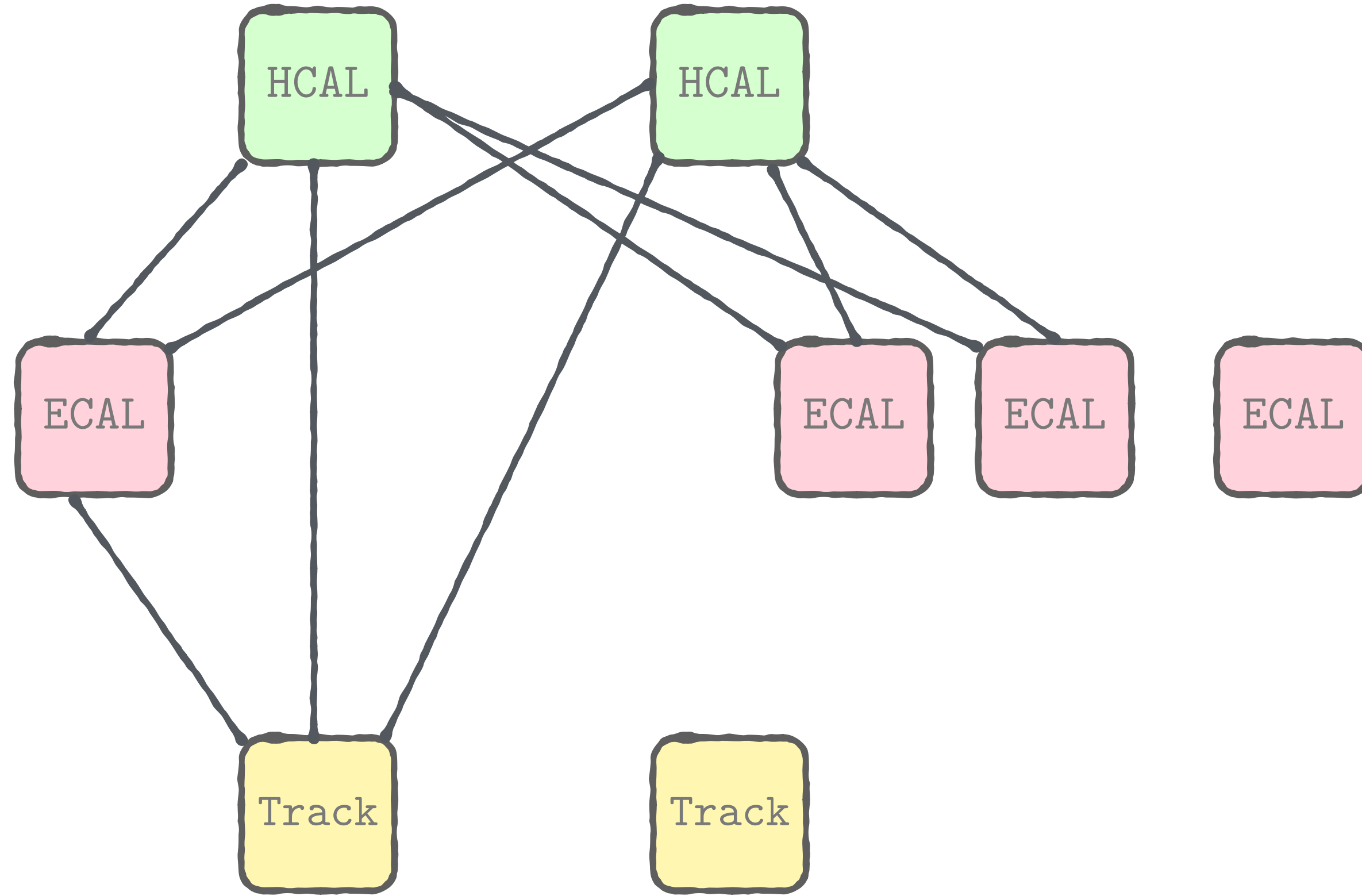
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



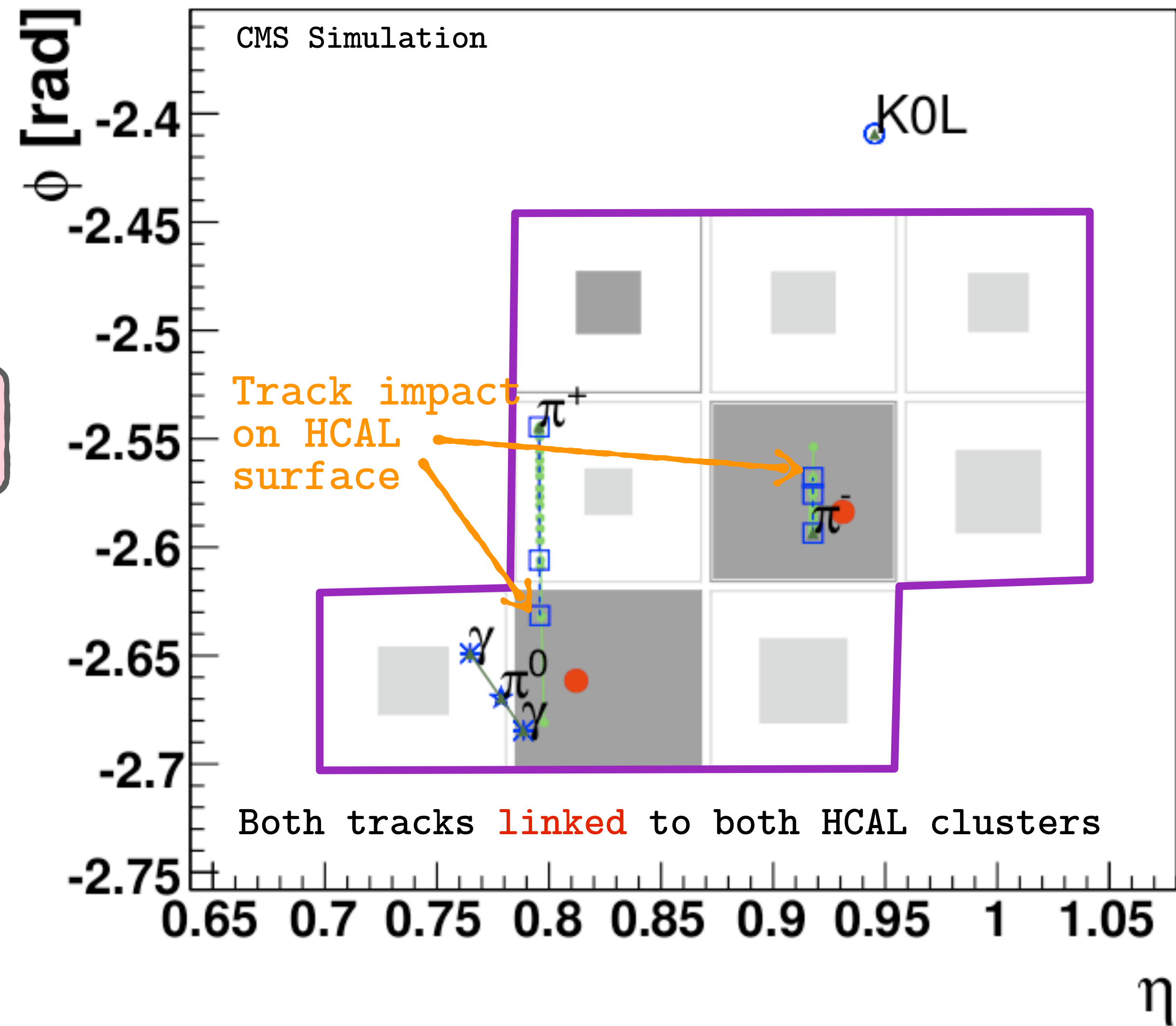
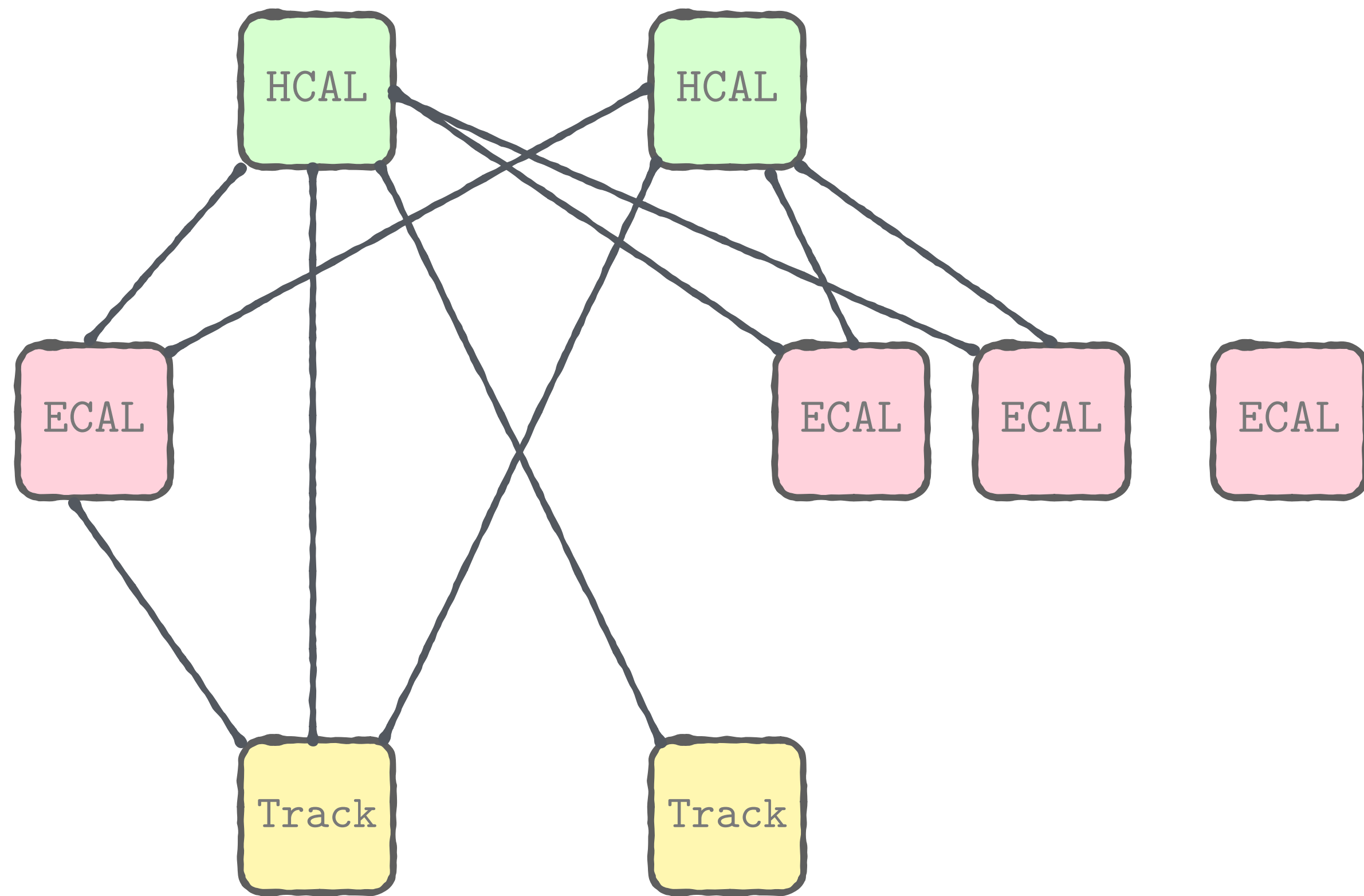
Four true particles:

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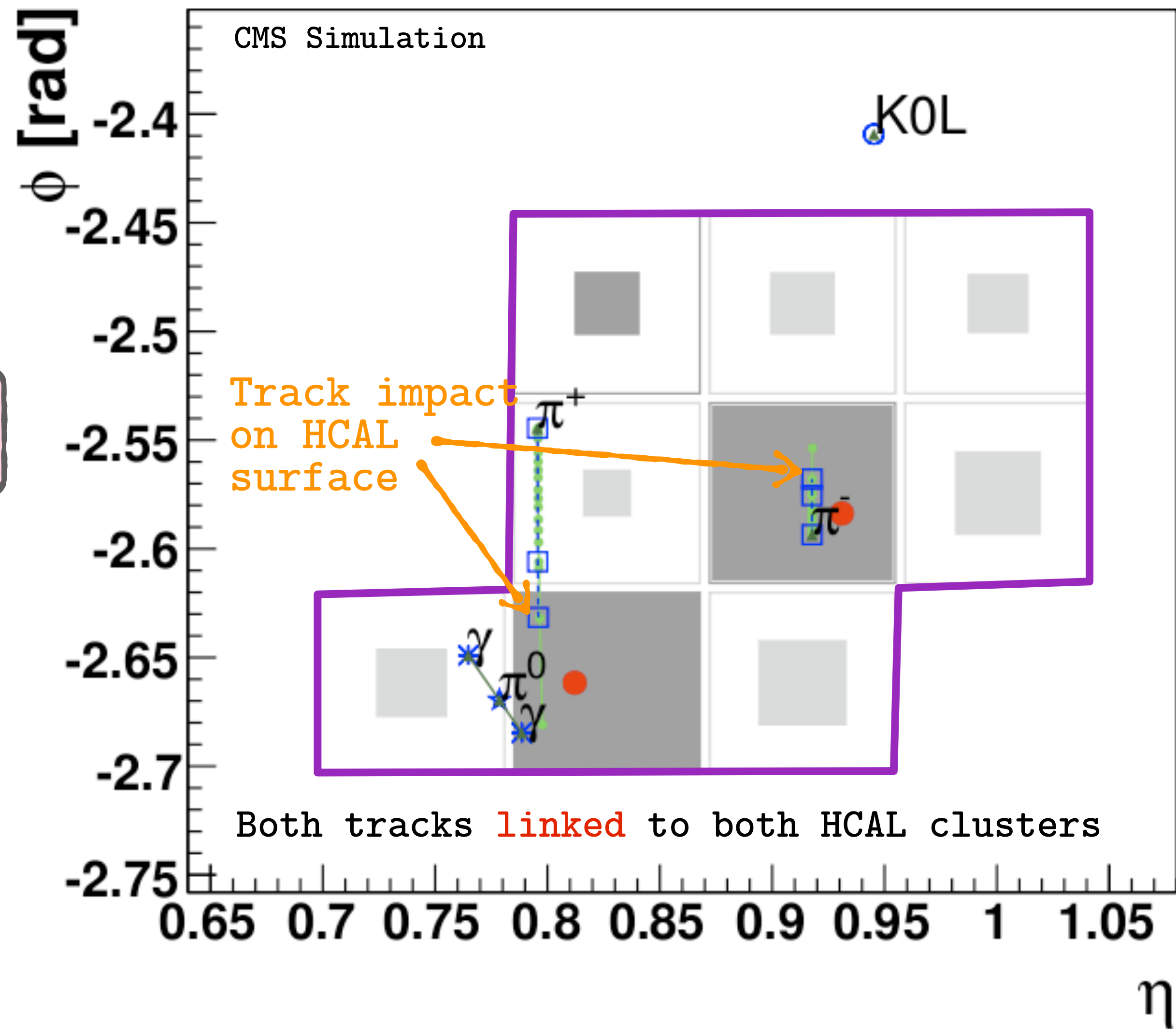
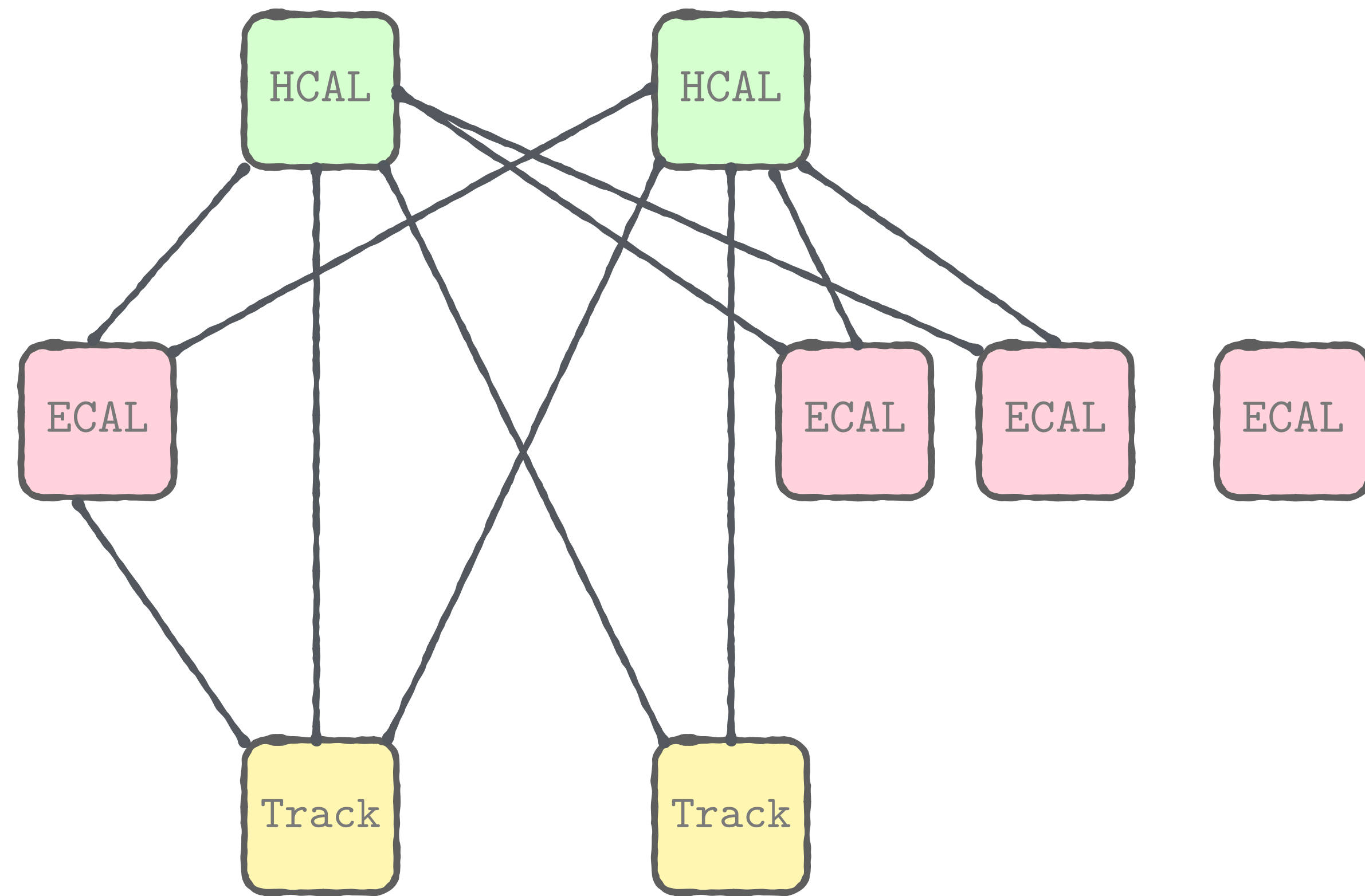
Four true particles:

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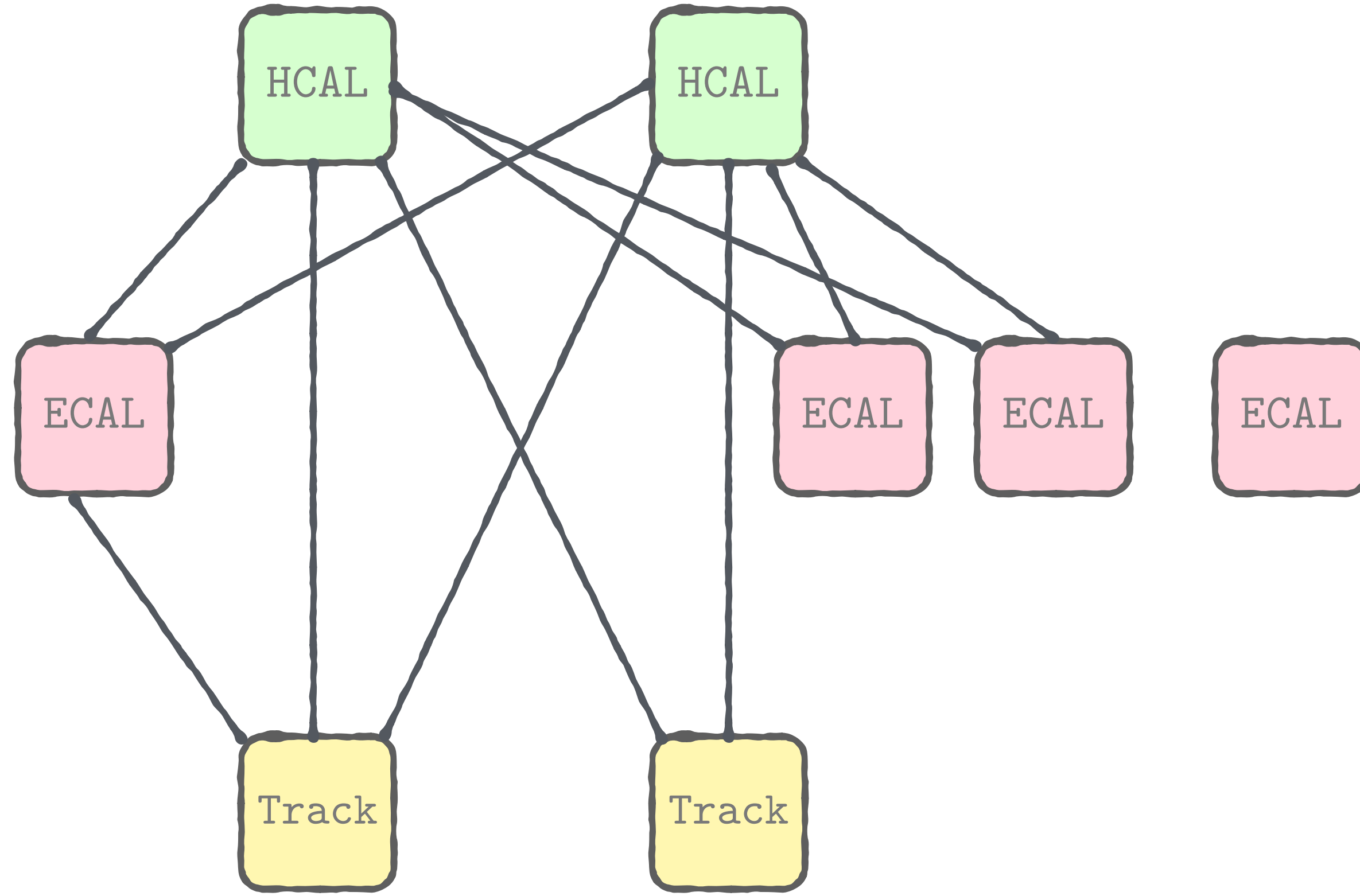
Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



Four true particles:

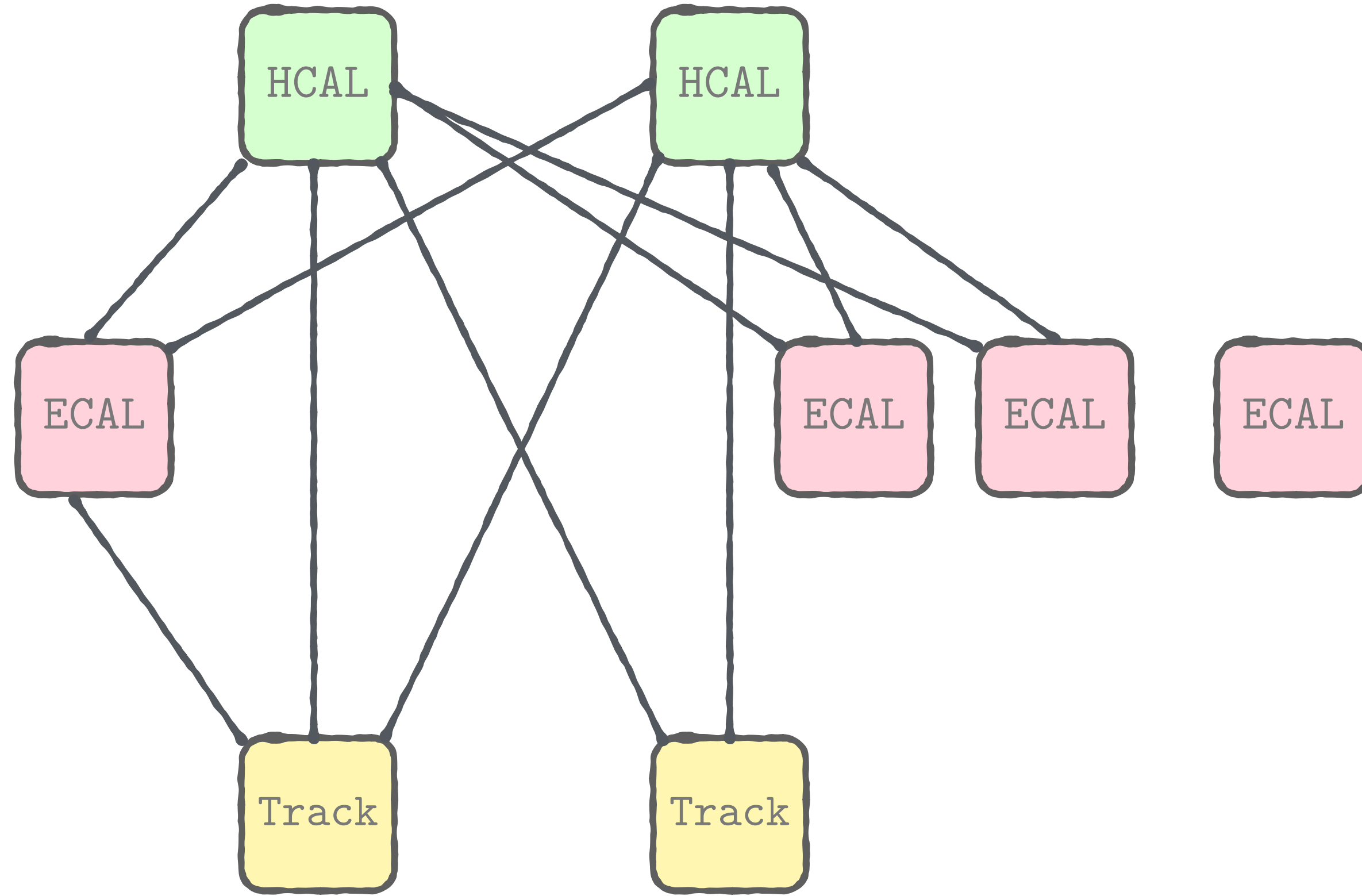
π^+ , π^- , π^0 , K_L^0



Four true particles:

π^+ , π^- , π^0 , K_L^0

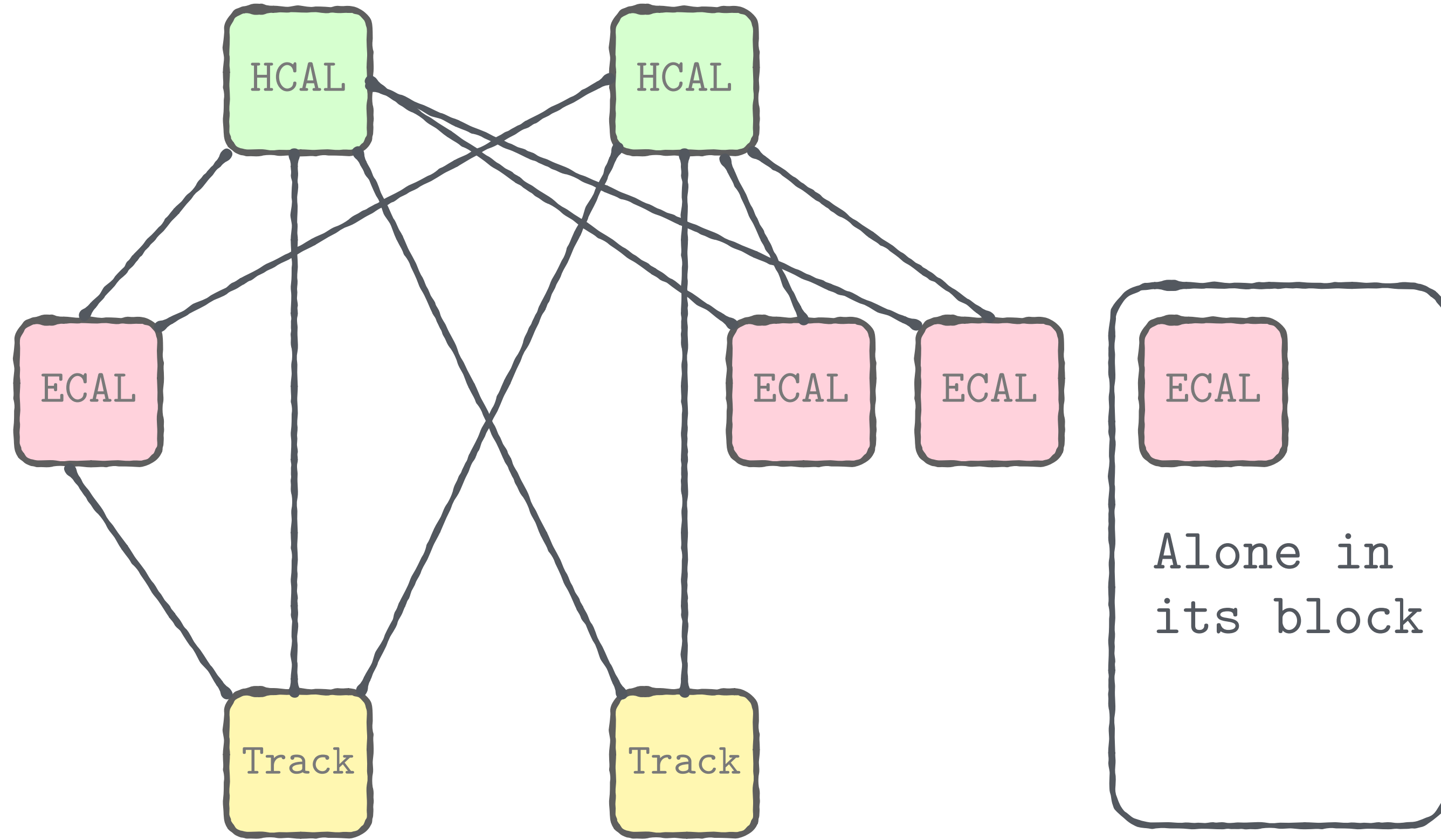
Build "blocks" of linked elements



Four true particles:

π^+ , π^- , π^0 , K_L^0

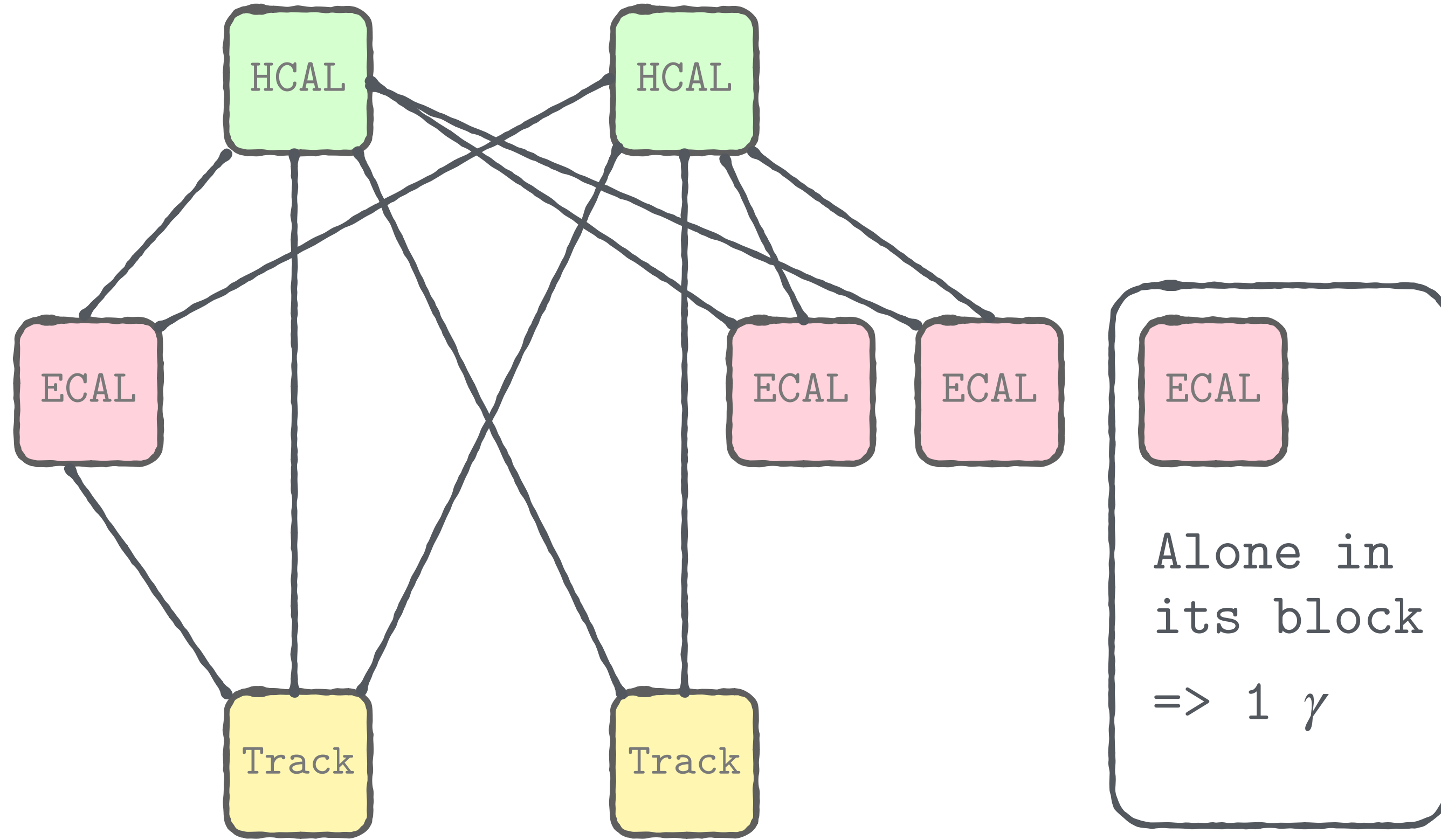
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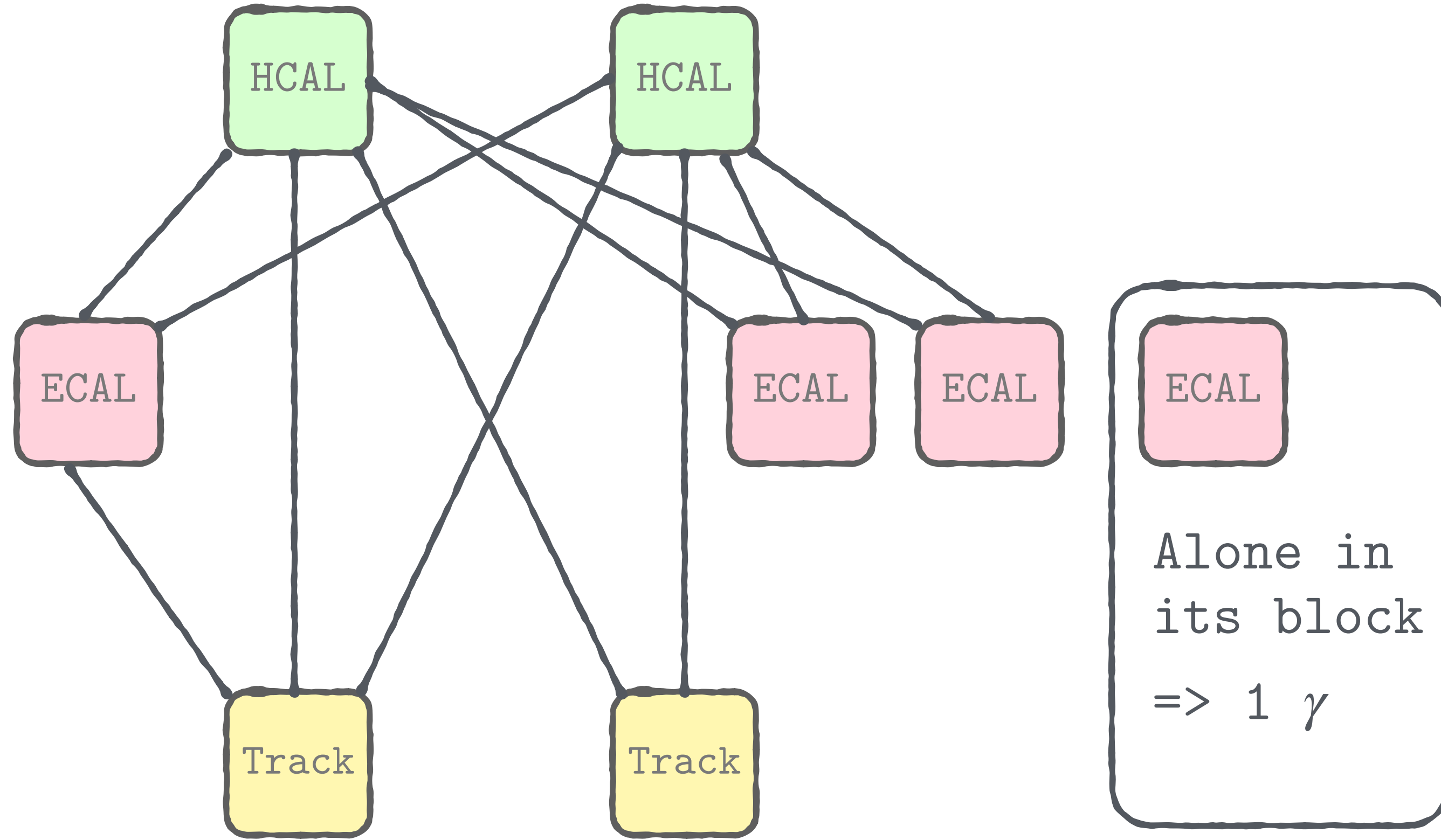
Build "blocks" of linked elements



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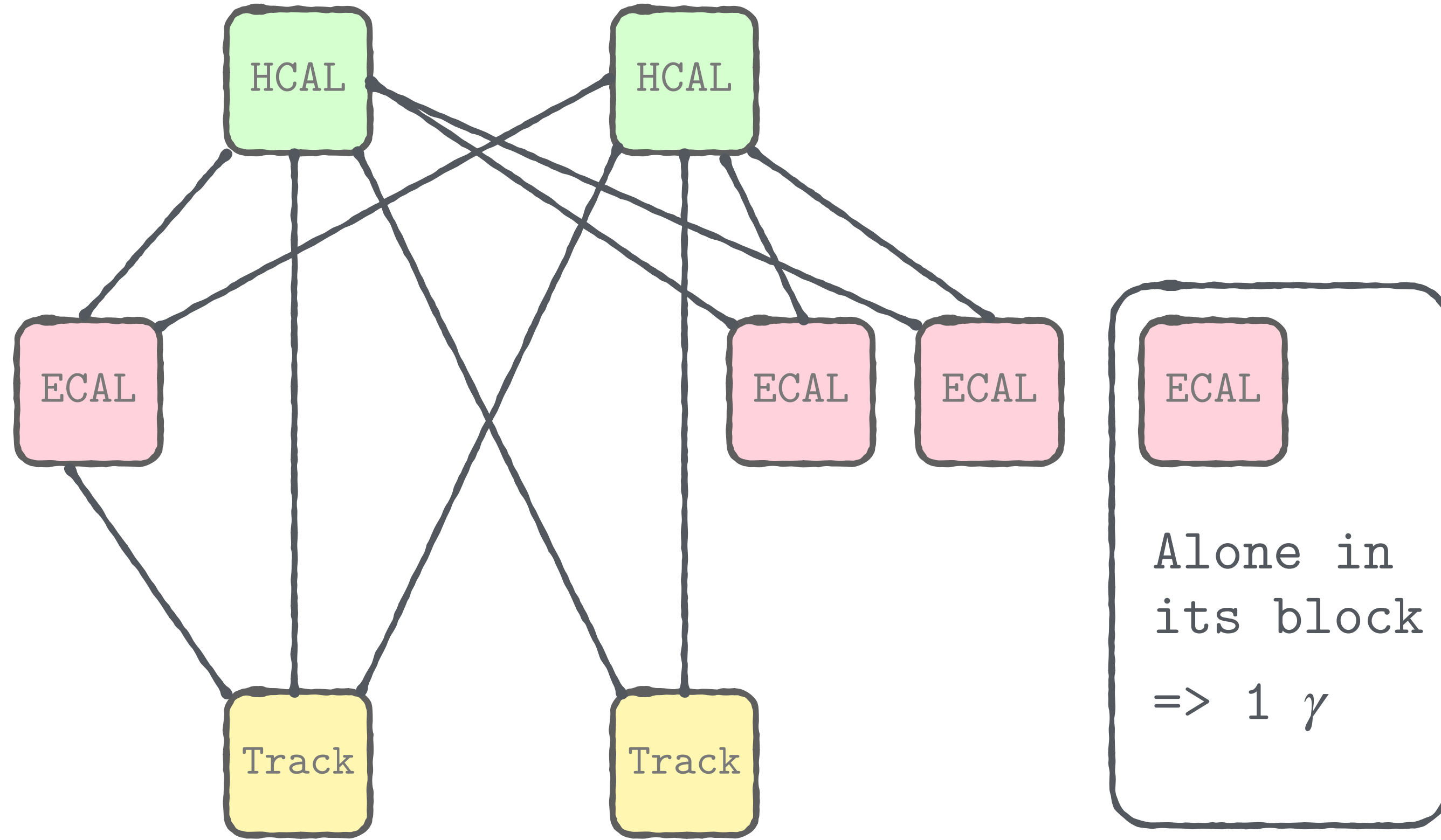


List of reconstructed (candidate) particles

Four true particles:

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Build "blocks" of linked elements



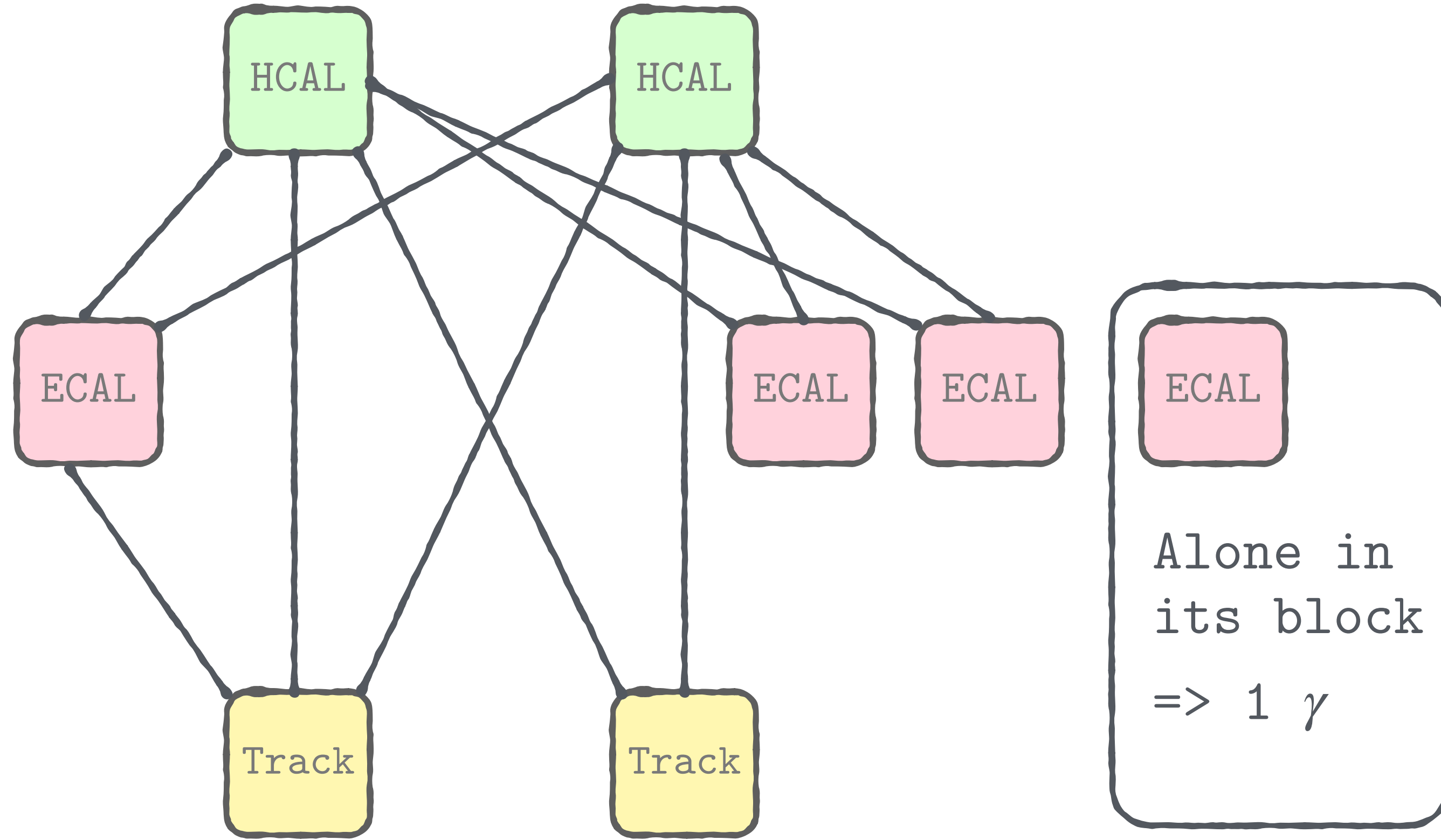
List of reconstructed (candidate) particles

{

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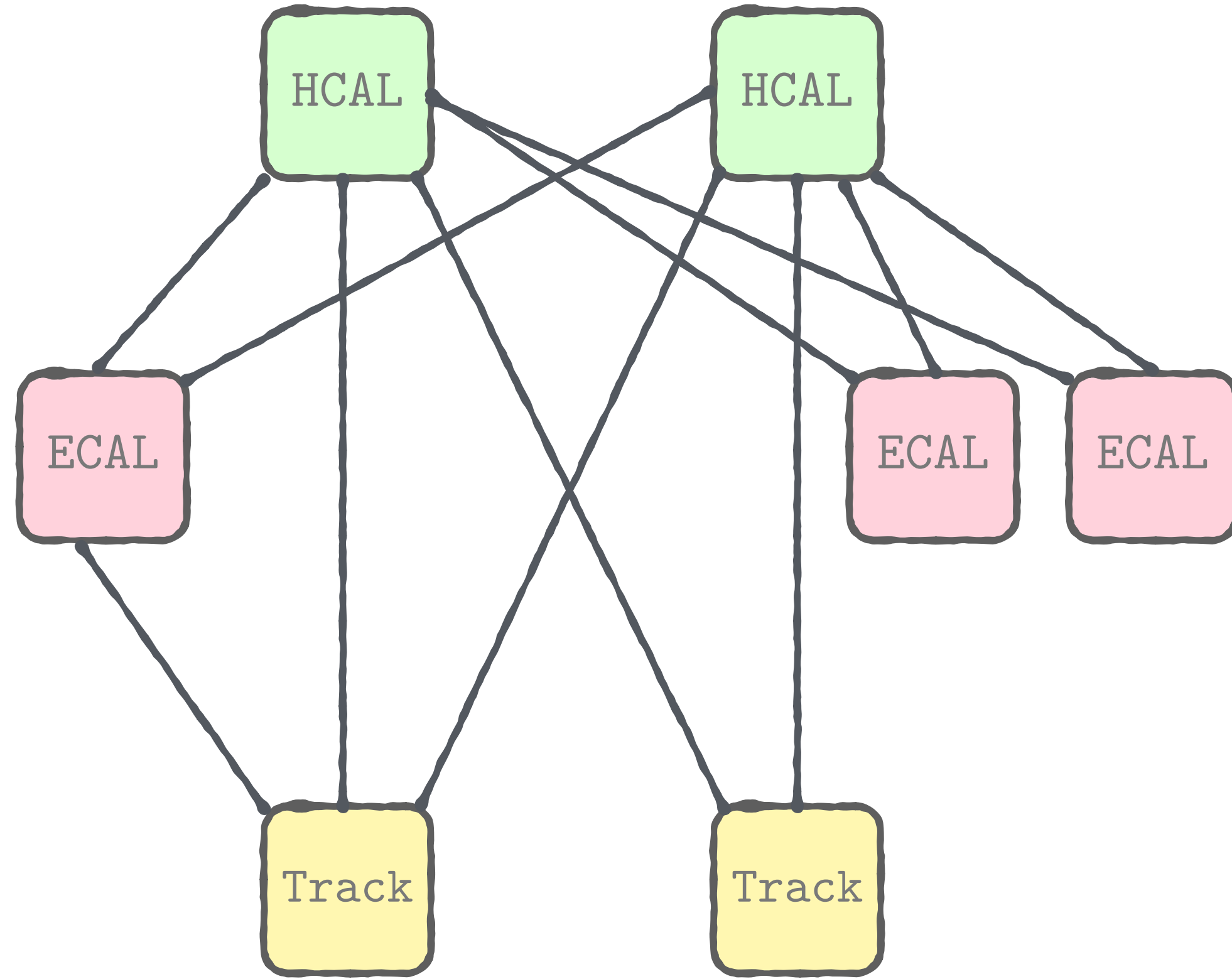


List of reconstructed (candidate) particles

{ γ

Four true particles:

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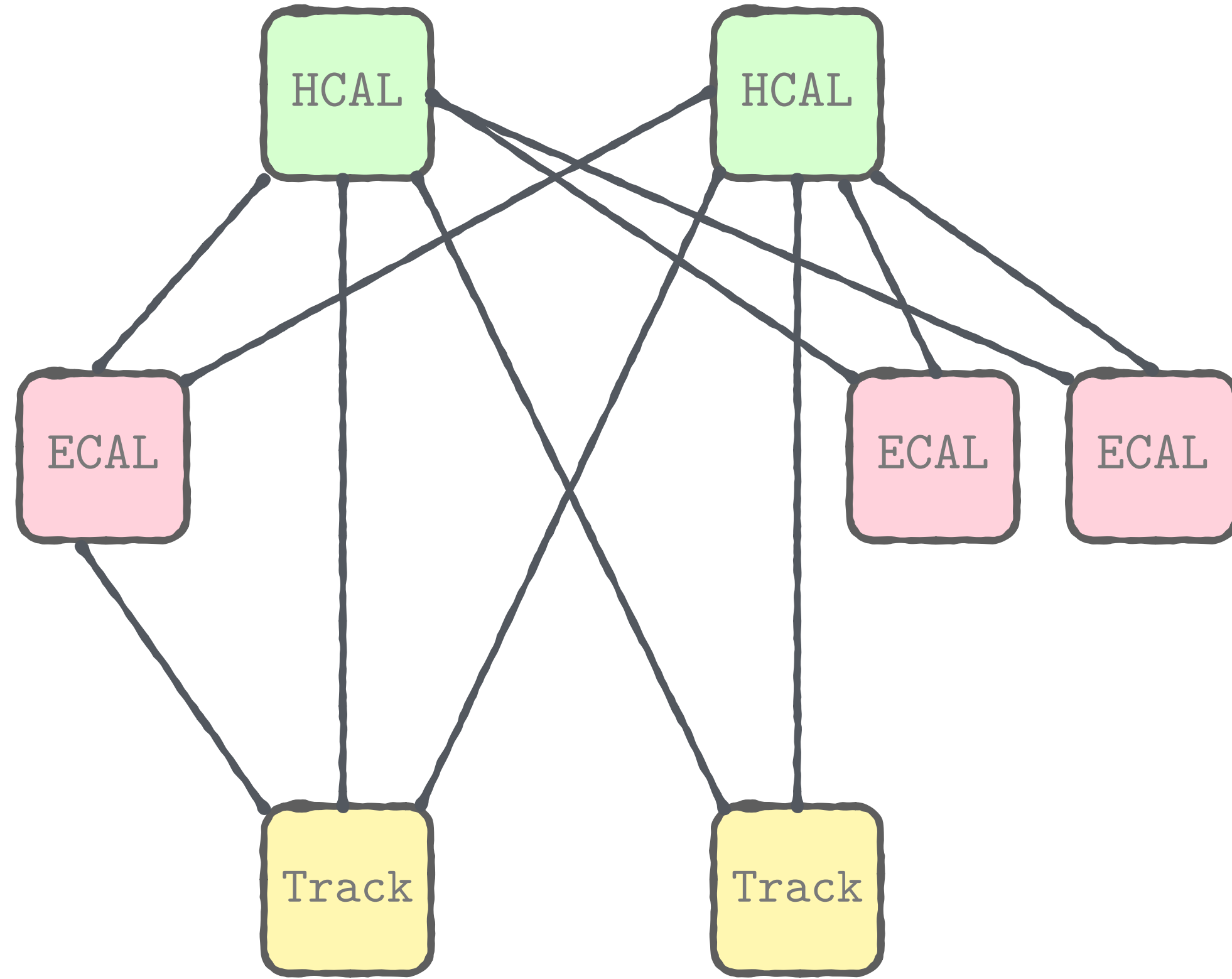
List of reconstructed (candidate) particles

$\{\gamma\}$

Four true particles:

$\pi^+, \pi^-, \pi^0, K_L^0$

Find photons in the blocks



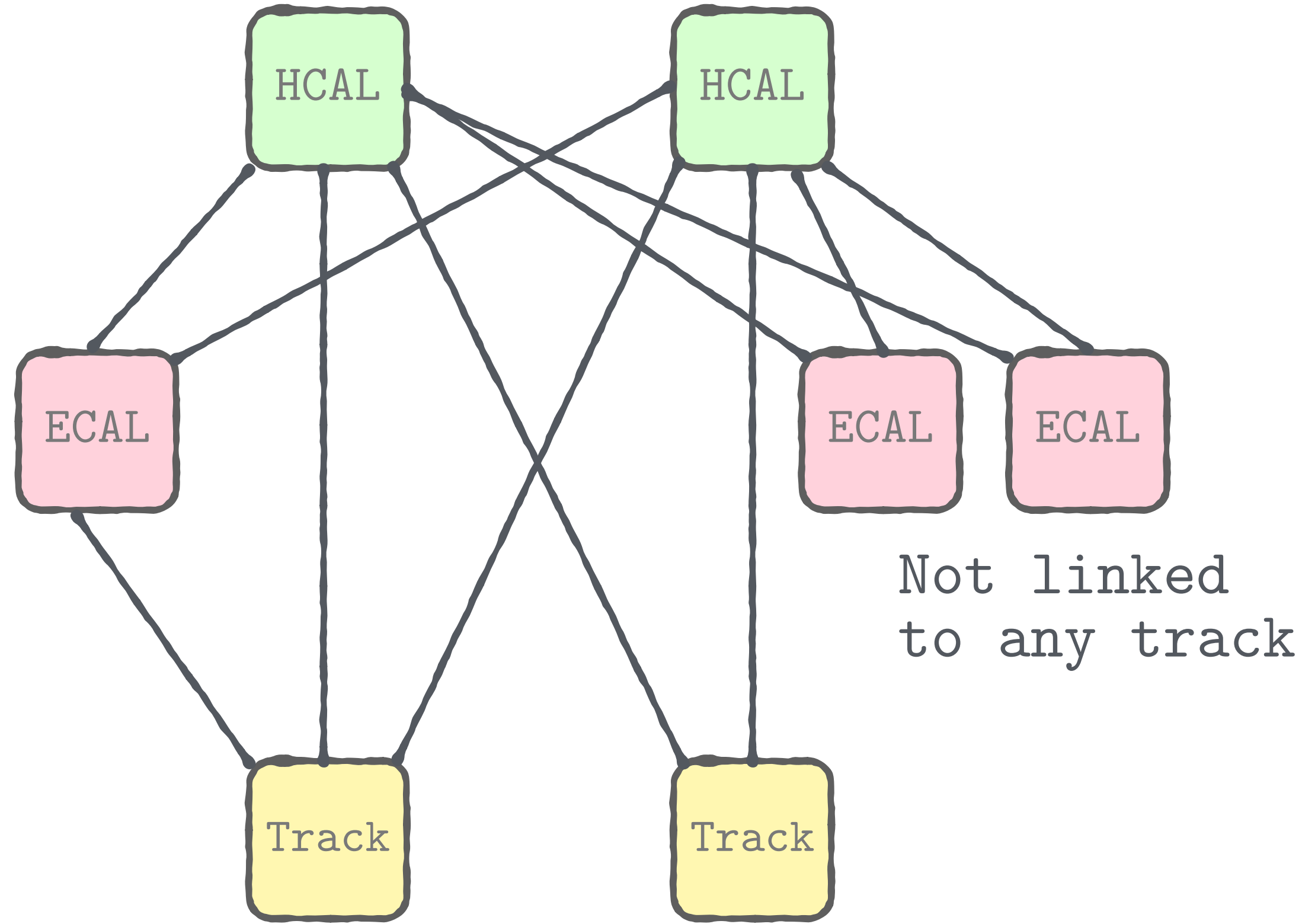
List of reconstructed (candidate) particles

$\{ \gamma \}$

Four true particles:

π^+ , π^- , π^0 , K_L^0

Find photons in the blocks



Not linked
to any track

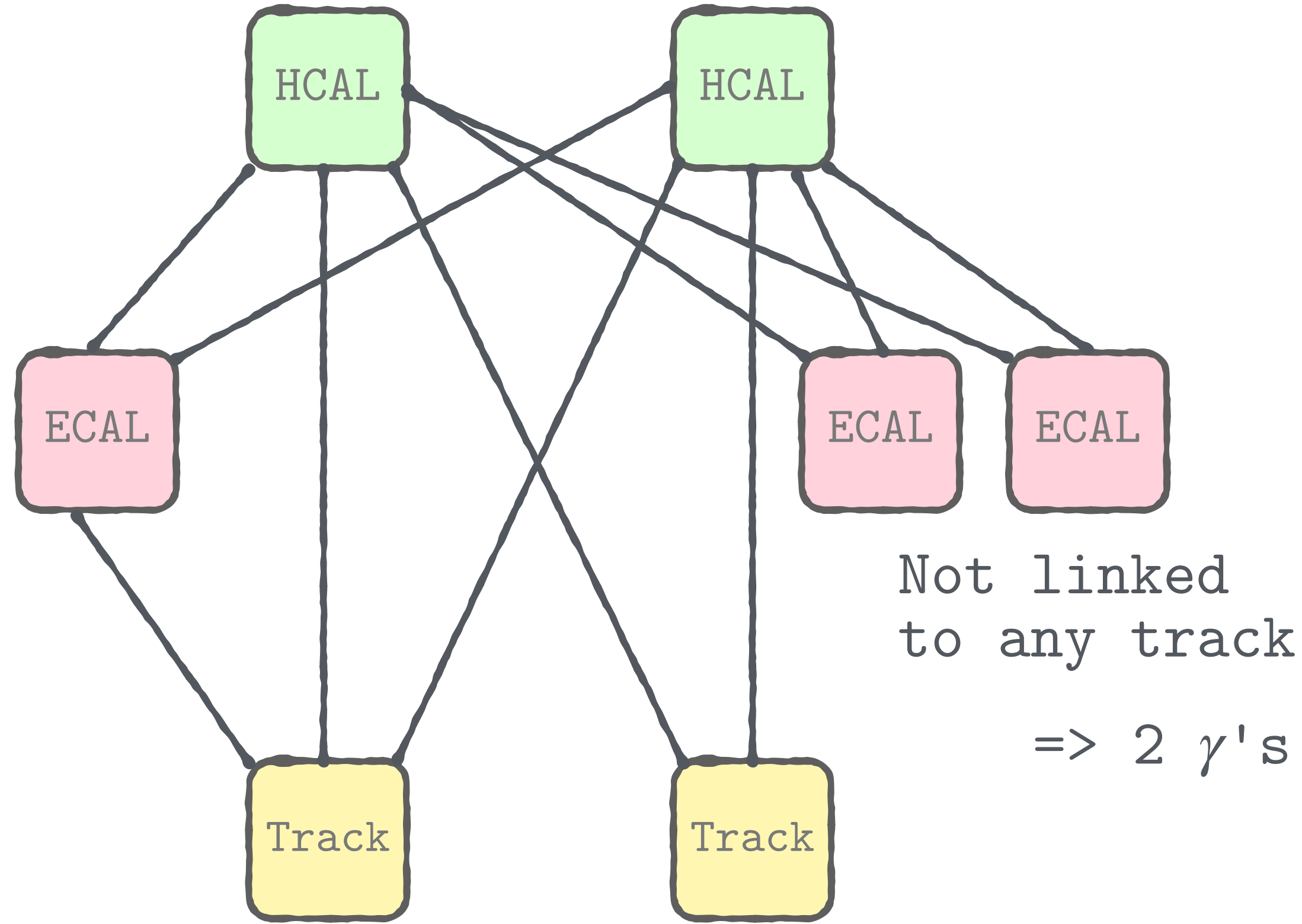
List of reconstructed (candidate) particles

{ γ

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Find photons in the blocks



Not linked
to any track
=> 2 γ 's

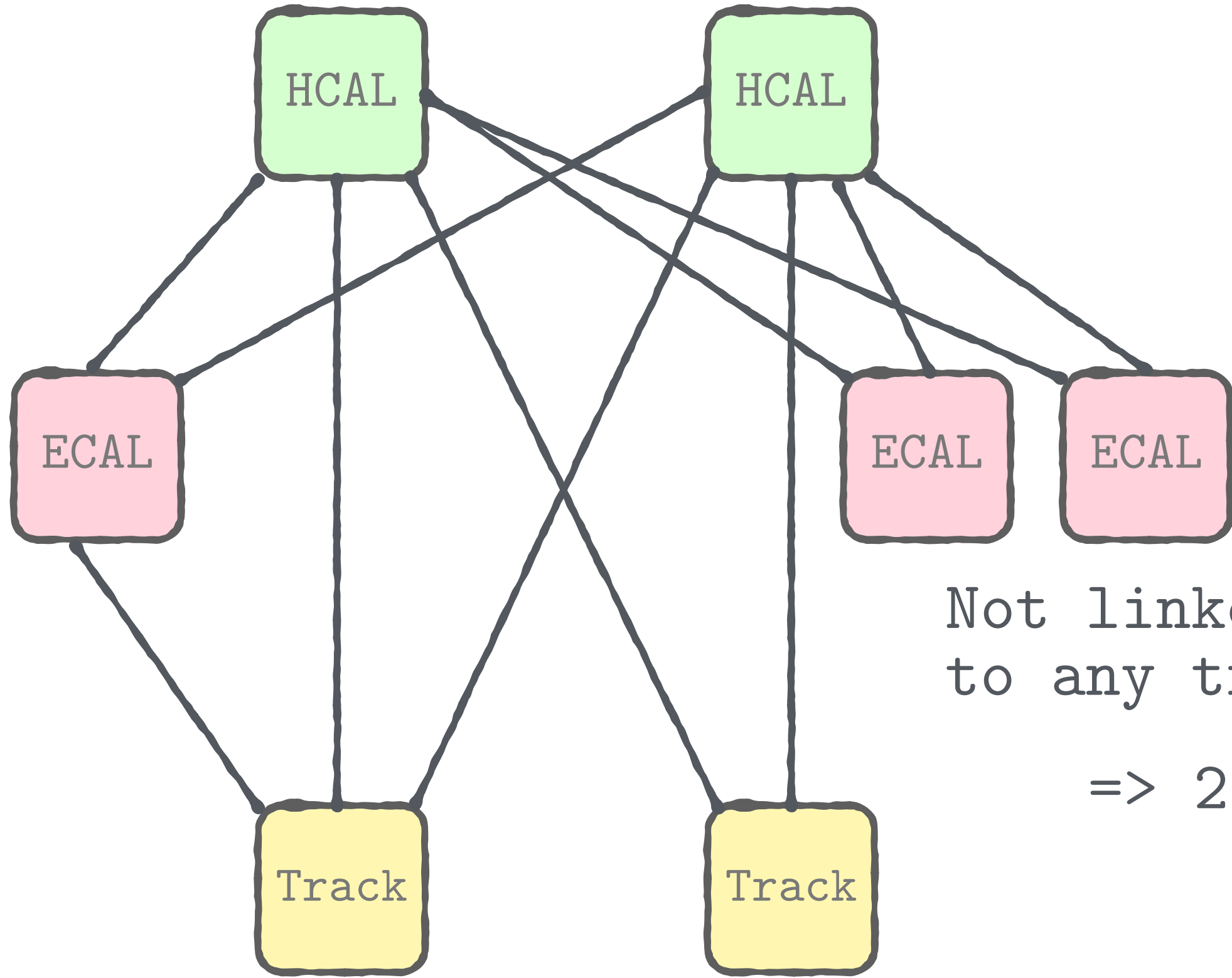
List of reconstructed (candidate) particles

{ γ

Four true particles:

$\pi^+, \pi^-, \pi^0, K_L^0$

Find photons in the blocks



Please ask: Why not neutral hadrons???

Not linked to any track

=> 2 γ 's

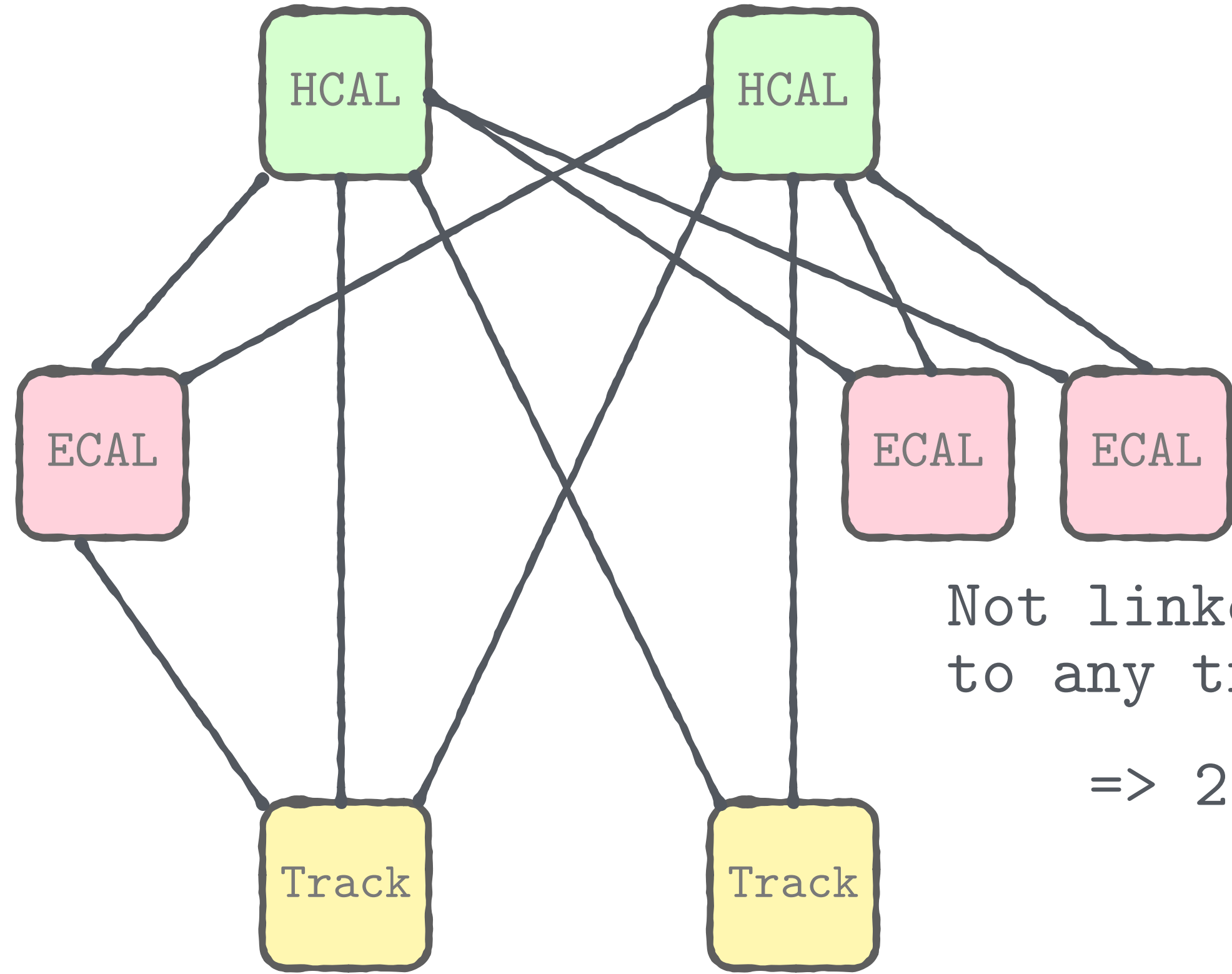
List of reconstructed (candidate) particles

{ γ

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Find photons in the blocks



Please ask: Why not neutral hadrons???

Quick A: Give precedence to photons!
Jet: 0(25%) photons, 0(10%) neutral hadrons

Not linked to any track
=> 2 γ 's

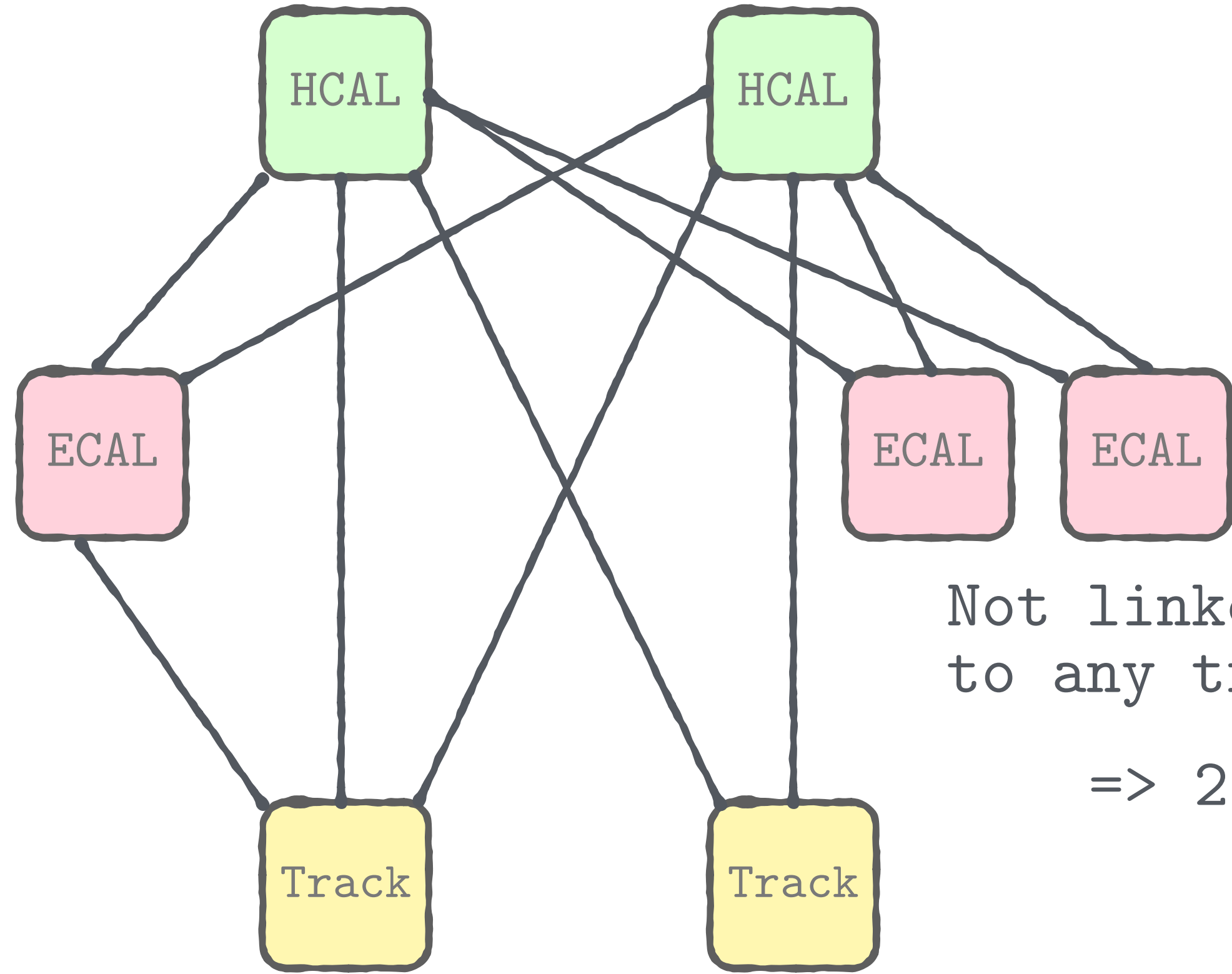
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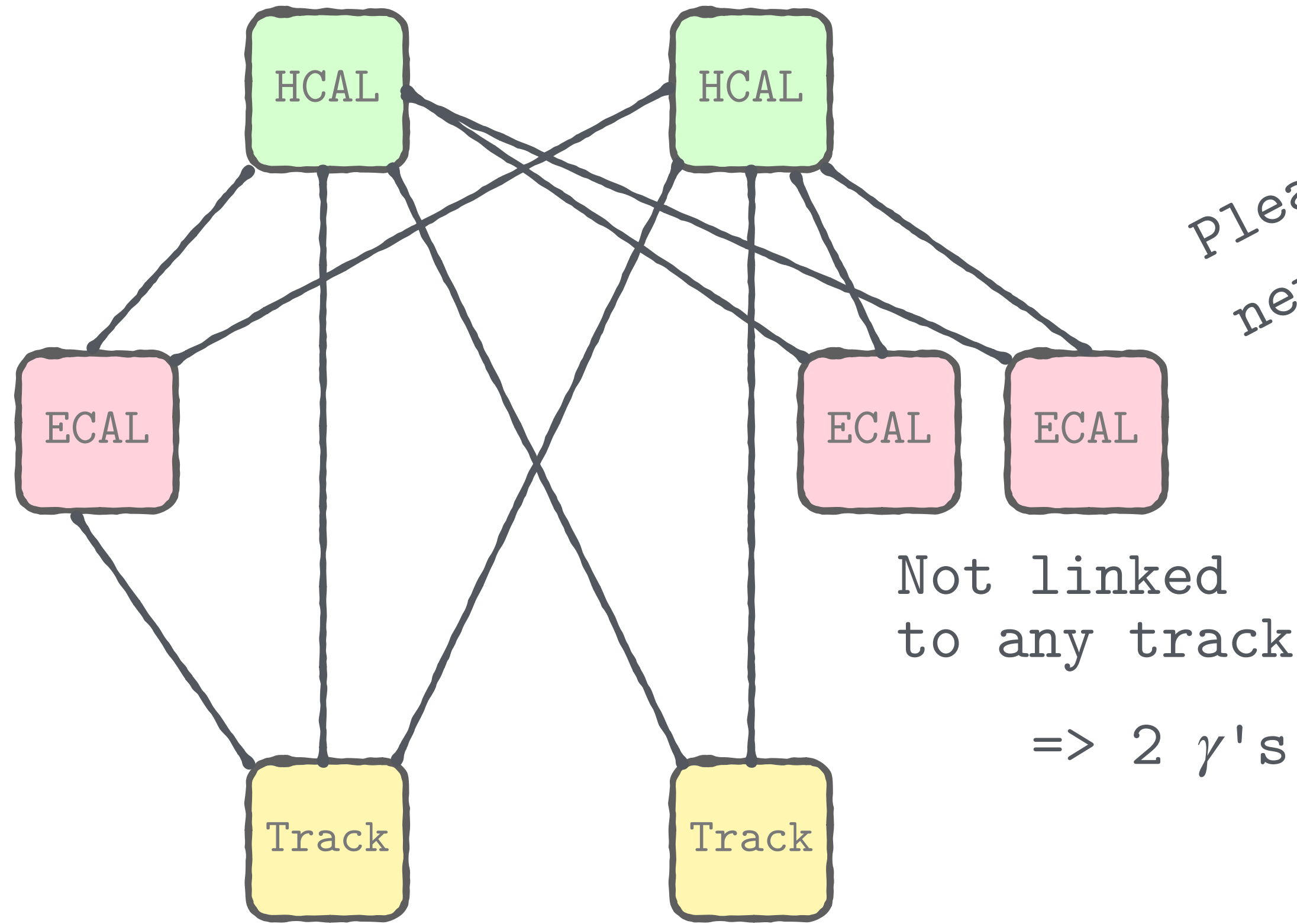
List of reconstructed (candidate) particles

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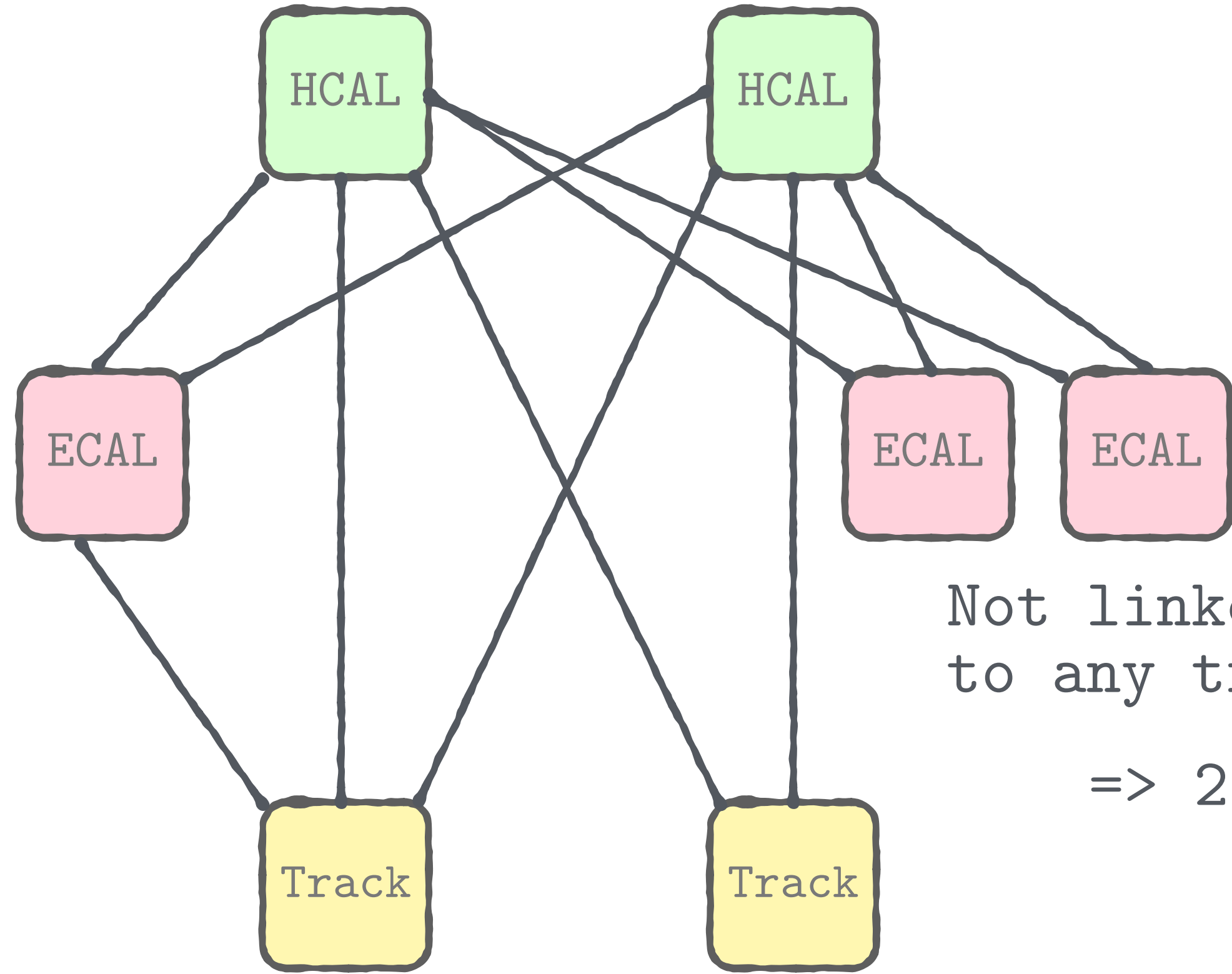
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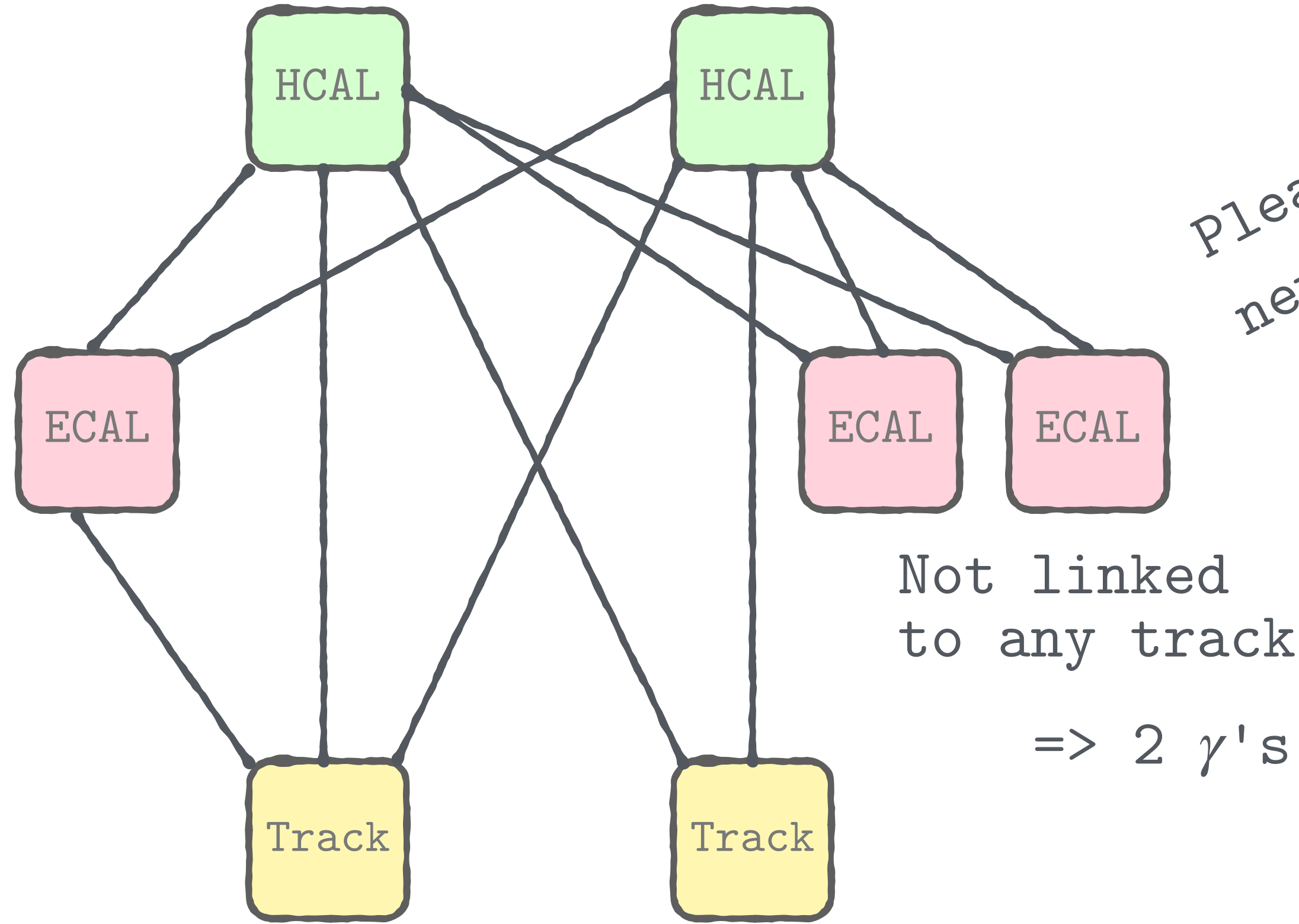
List of reconstructed (candidate) particles

{ $\gamma, \gamma,$

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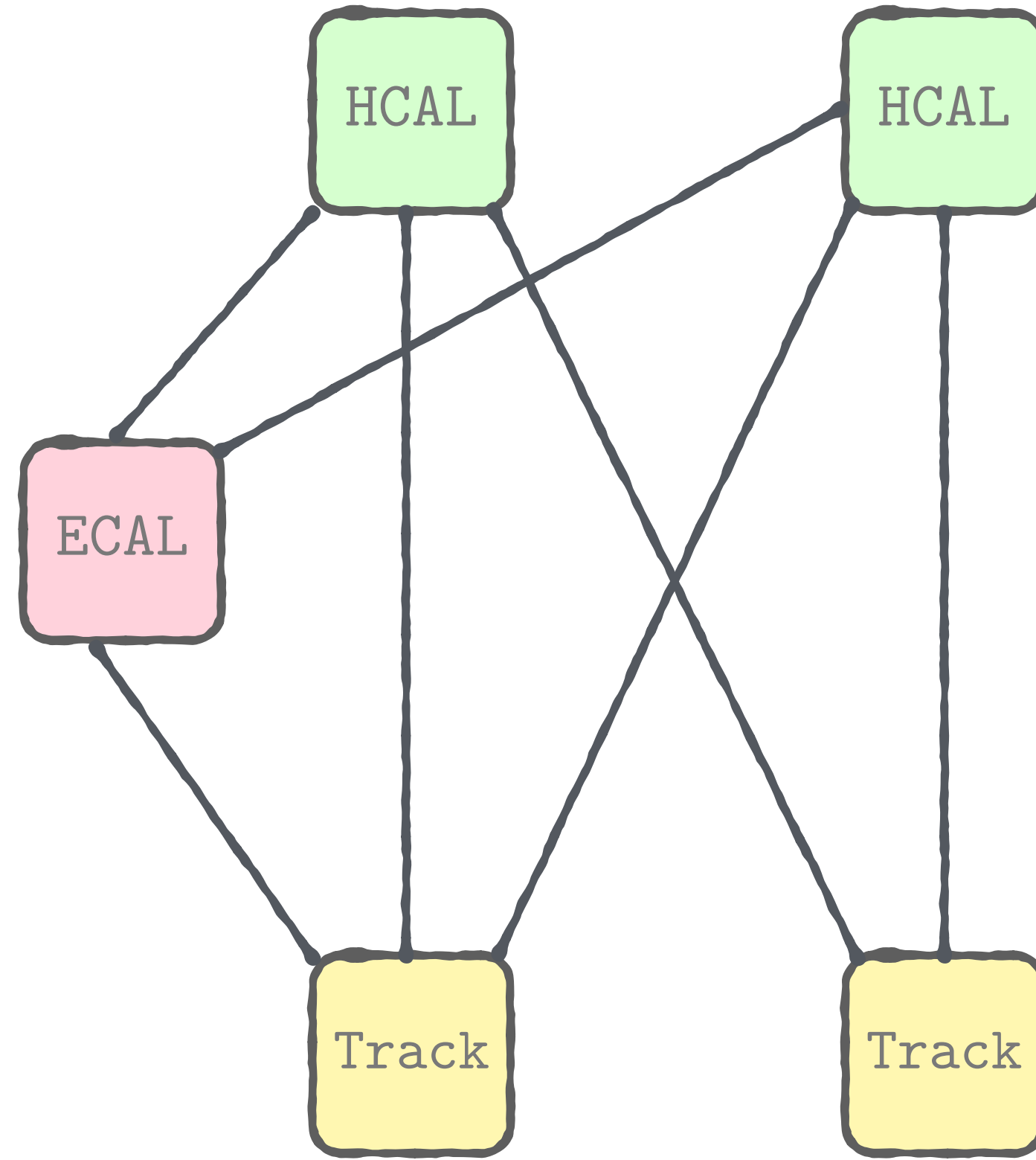
Not linked to any track
=> 2 γ 's

List of reconstructed (candidate) particles

$\{\gamma, \gamma, \gamma\}$

Four true particles:

$\pi^+, \pi^-, \pi^0, K_L^0$



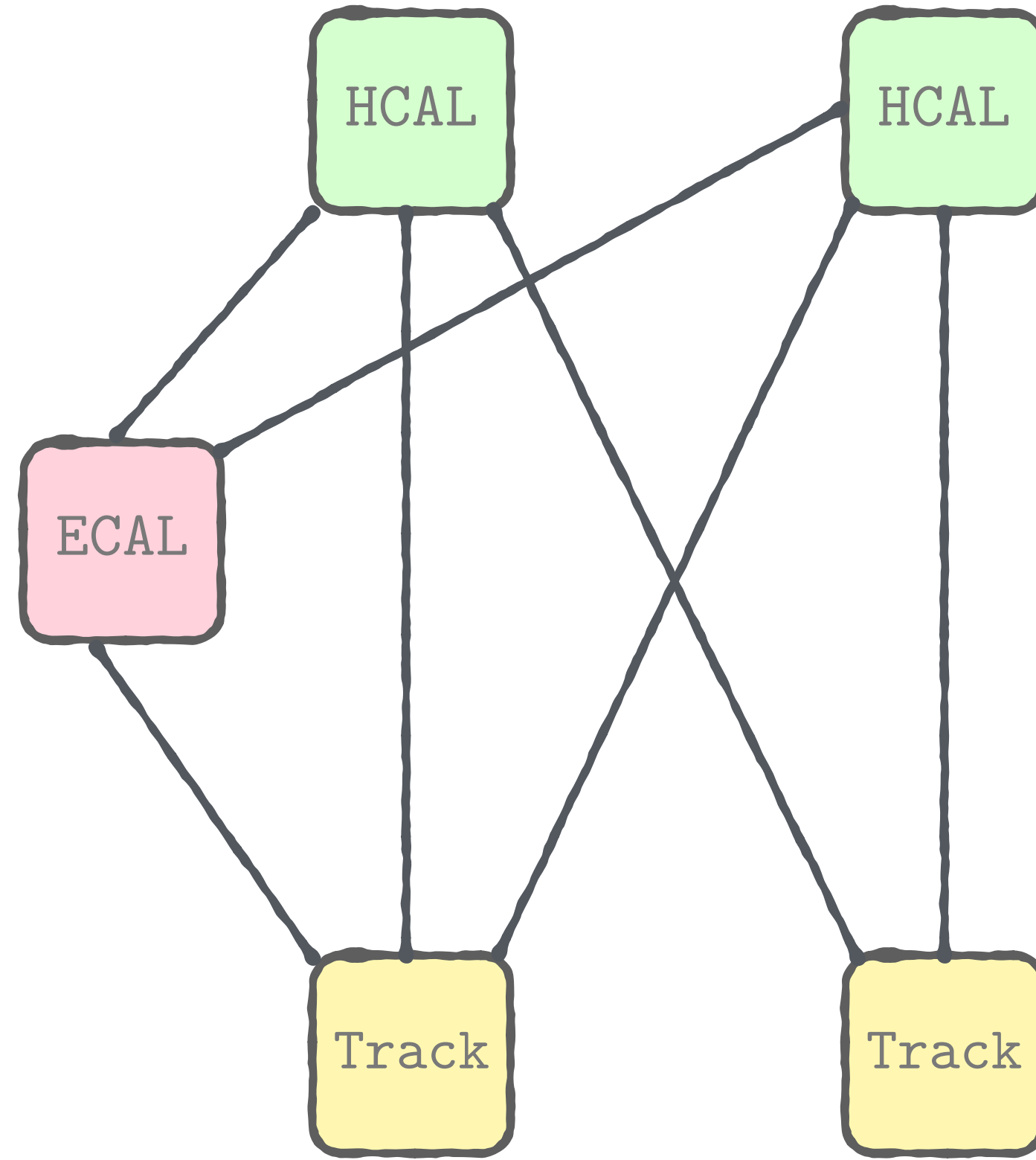
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$\{\gamma, \gamma, \gamma\}$

Four true particles:

$\pi^+, \pi^-, \pi^0, K_L^0$

Simplified block (1st step)



List of reconstructed (candidate) particles

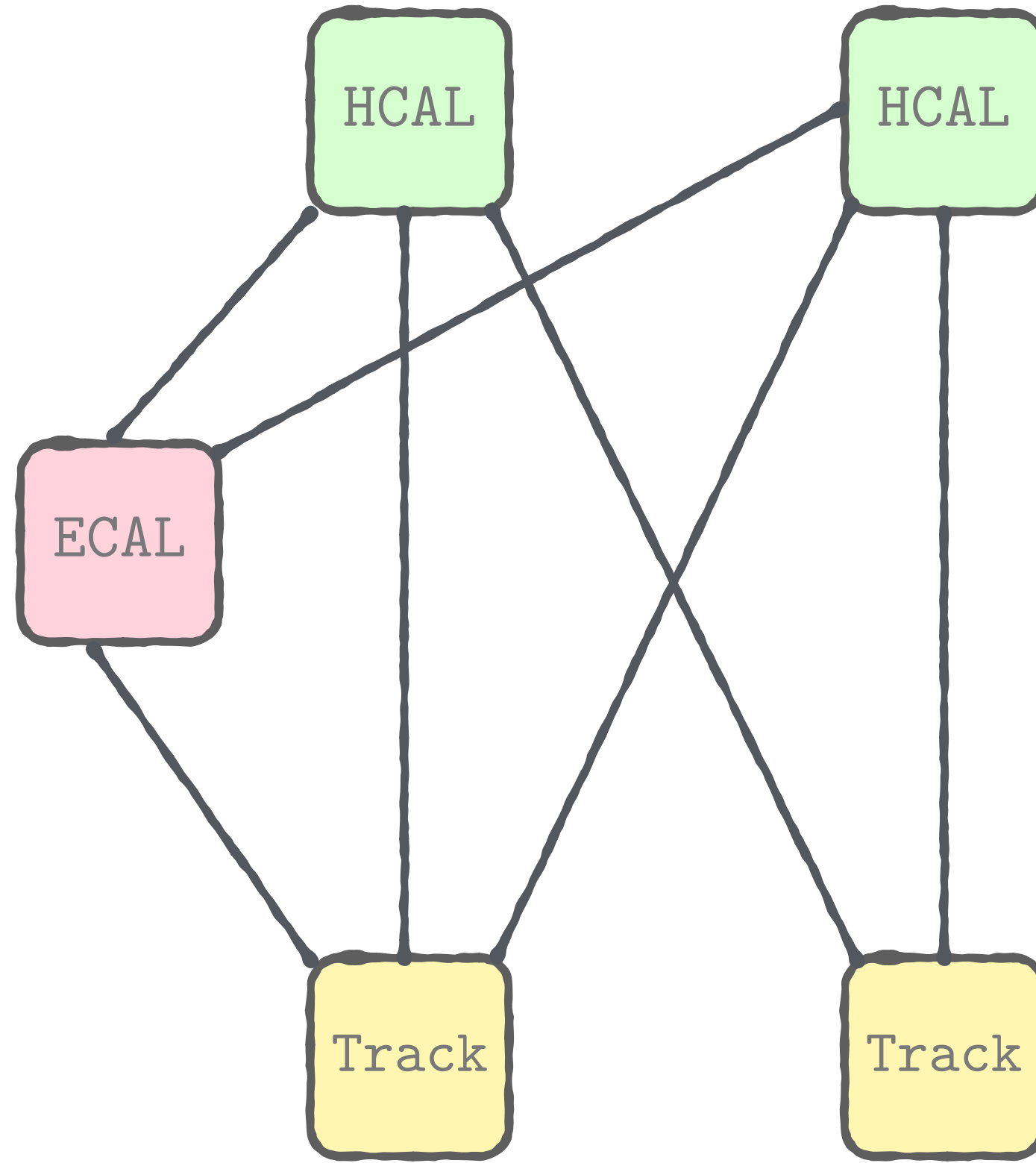
$\{\gamma, \gamma, \gamma\}$

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Simplified block (1st step)

Optimise the use of HCAL granularity



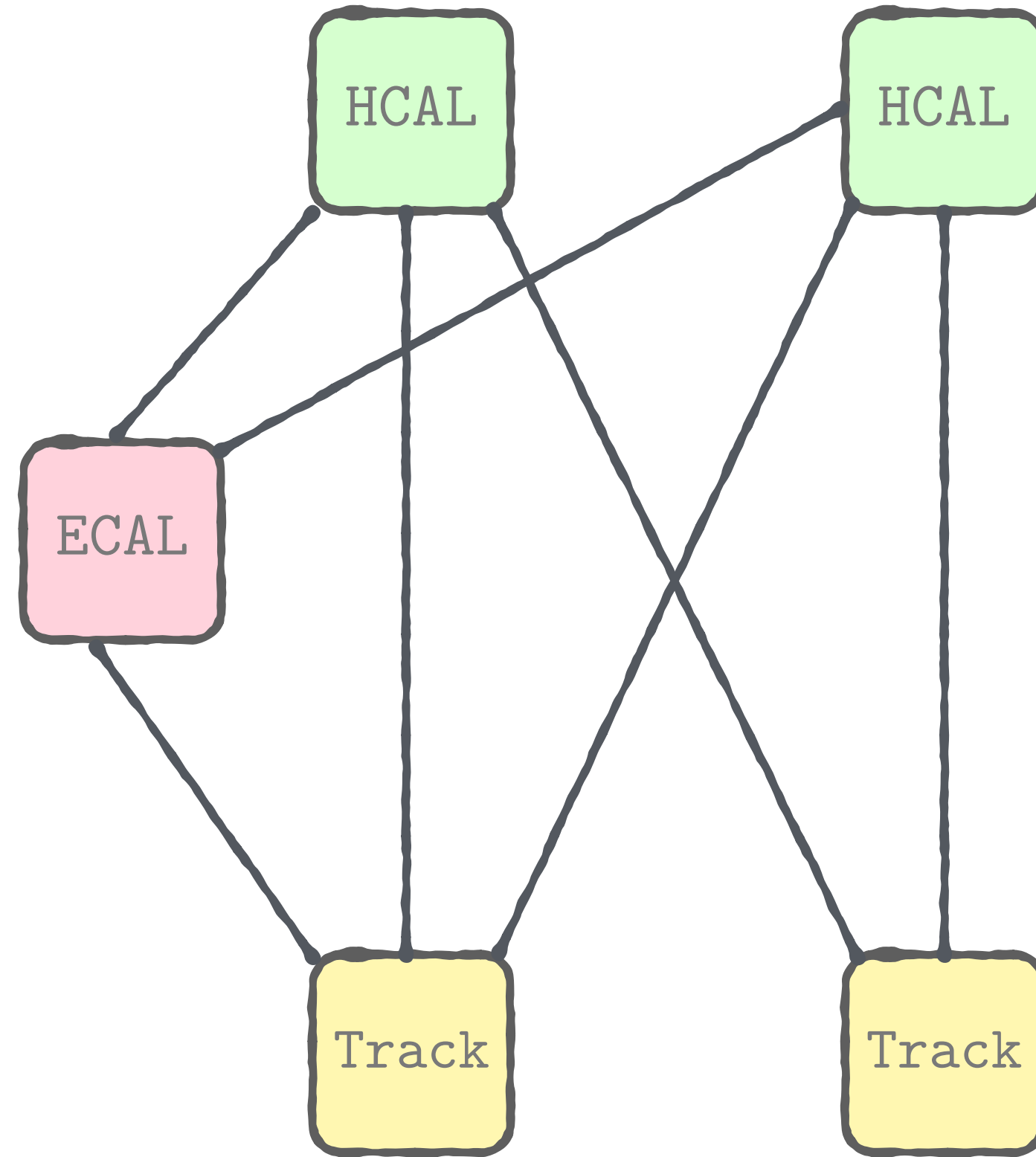
List of reconstructed (candidate) particles

$\{\gamma, \gamma, \gamma\}$

Four true particles:

$\pi^+, \pi^-, \pi^0, K_L^0$

Simplified block (1st step)



Optimise the use of HCAL granularity

Keep only the link to the closest cluster

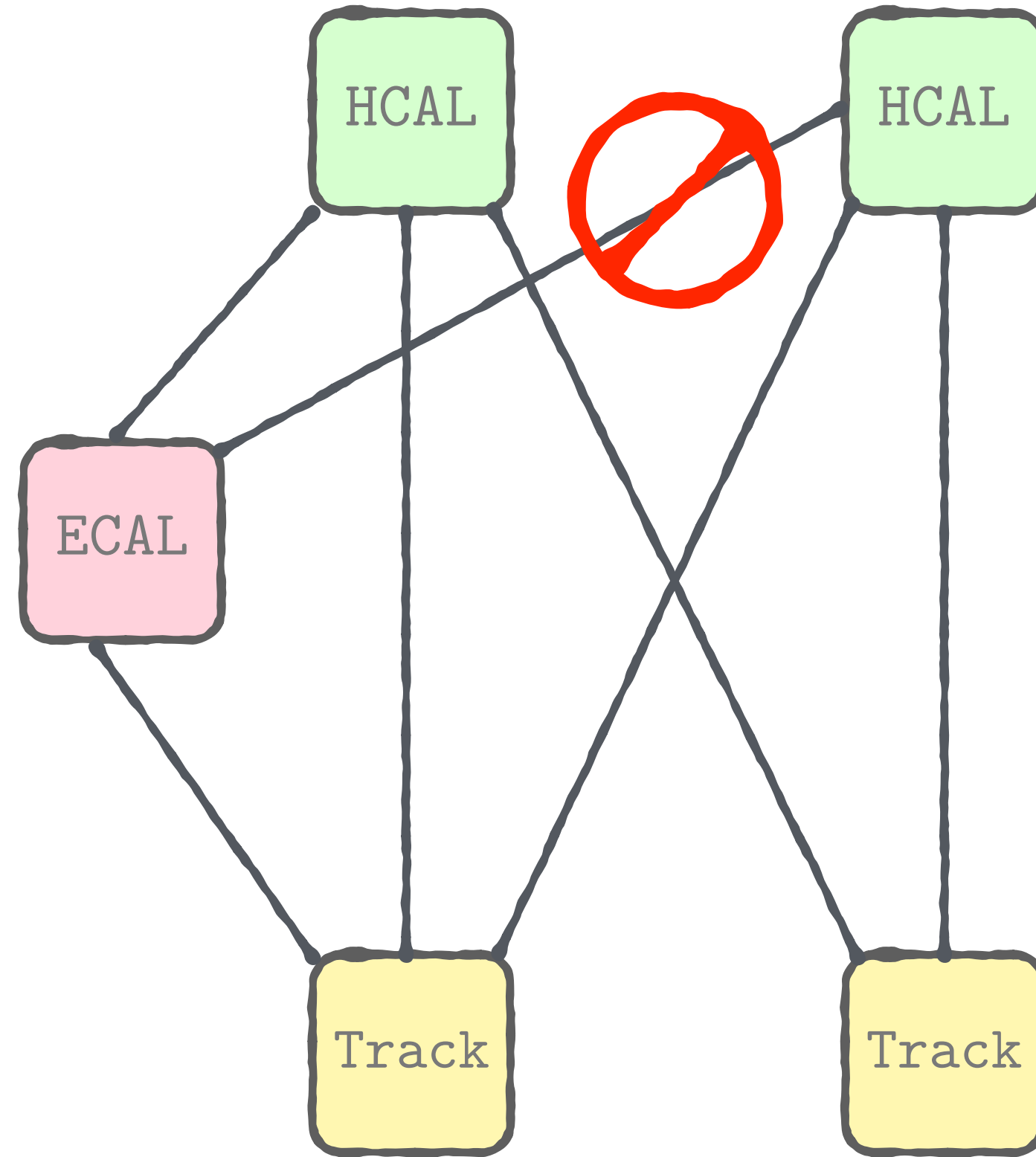
List of reconstructed (candidate) particles

$\{\gamma, \gamma, \gamma\}$

Four true particles:

$\pi^+, \pi^-, \pi^0, K_L^0$

Simplified block (1st step)



Optimise the use of HCAL granularity

Keep only the link to the closest cluster

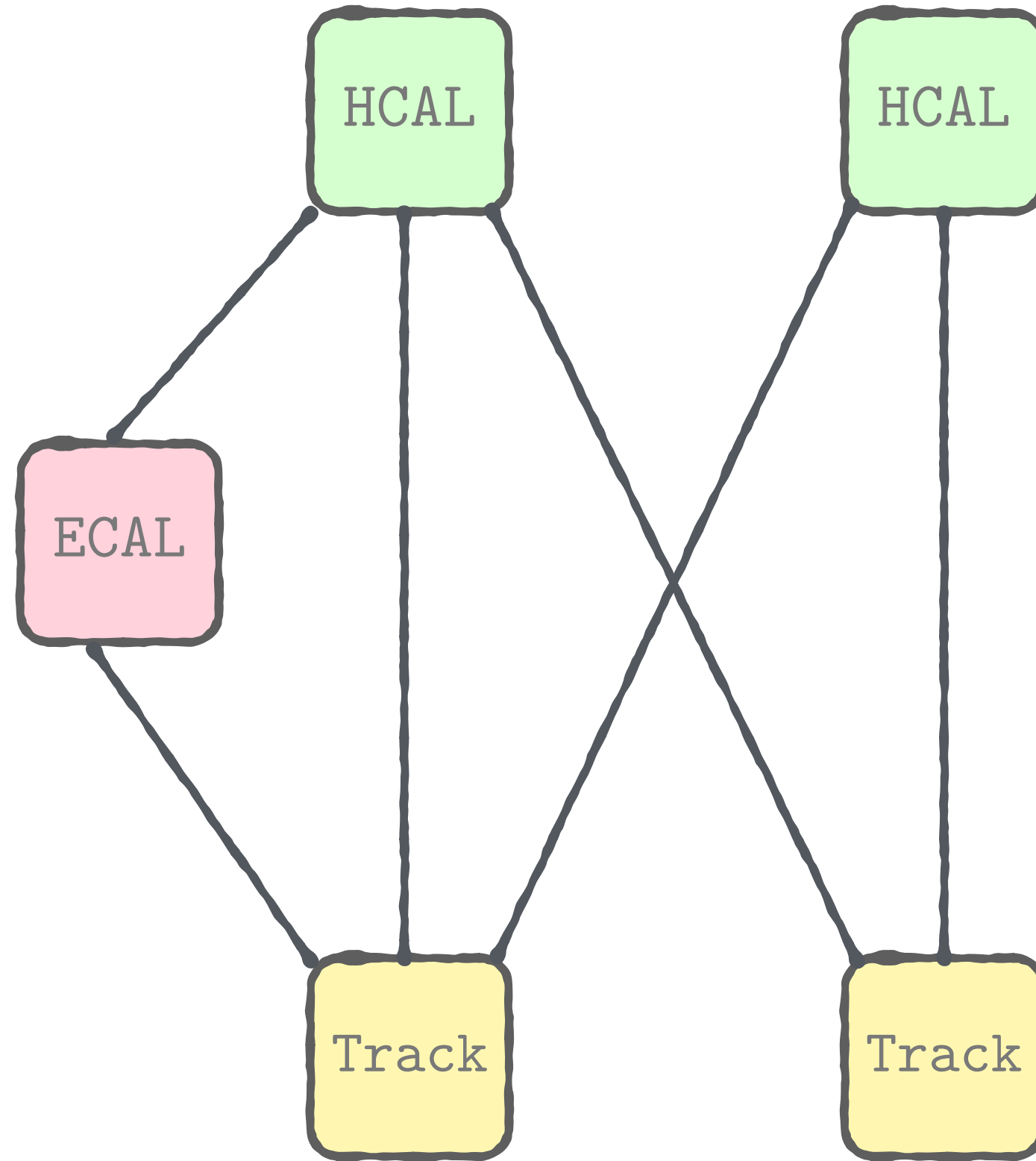
List of reconstructed (candidate) particles

$\{\gamma, \gamma, \gamma\}$

Four true particles:

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Simplified block (1st step)



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Keep only the link to the closest cluster

List of reconstructed (candidate) particles

$\{\gamma, \gamma, \gamma\}$

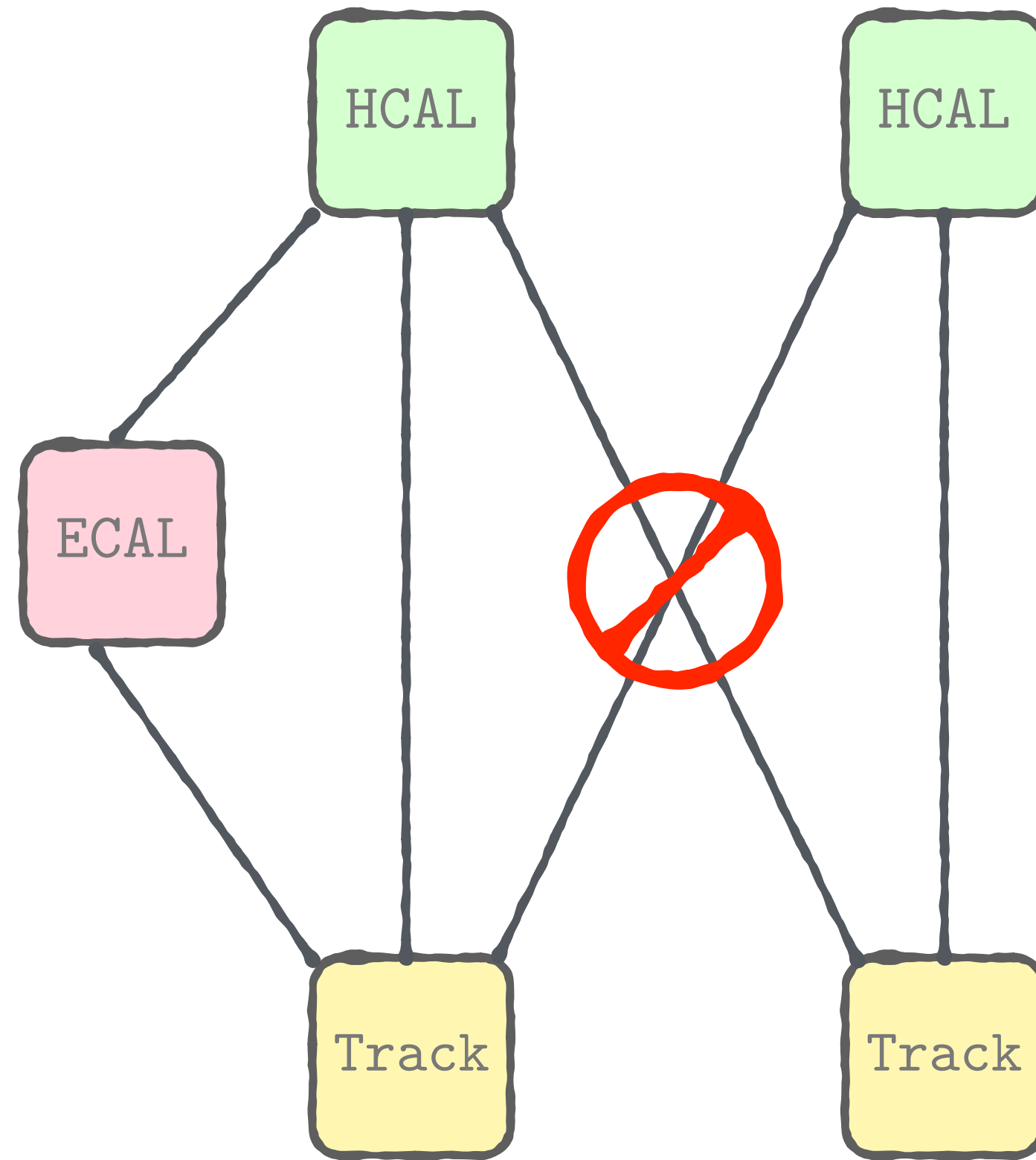
Four true particles:

$\pi^+, \pi^-, \pi^0, K_L^0$

Simplified block (1st step)

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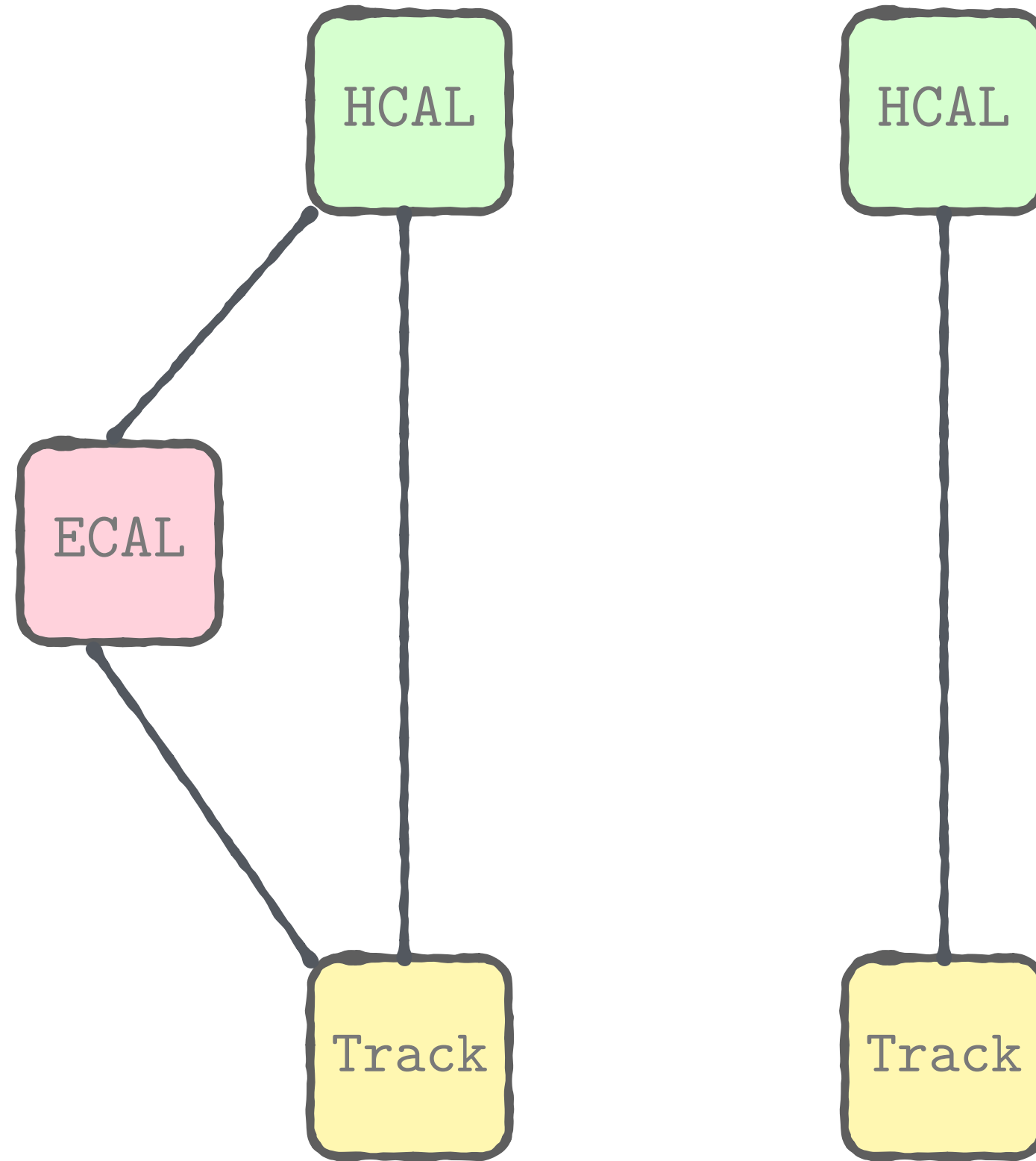
List of reconstructed (candidate) particles

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Simplified block (1st step)



Optimise the use of HCAL granularity

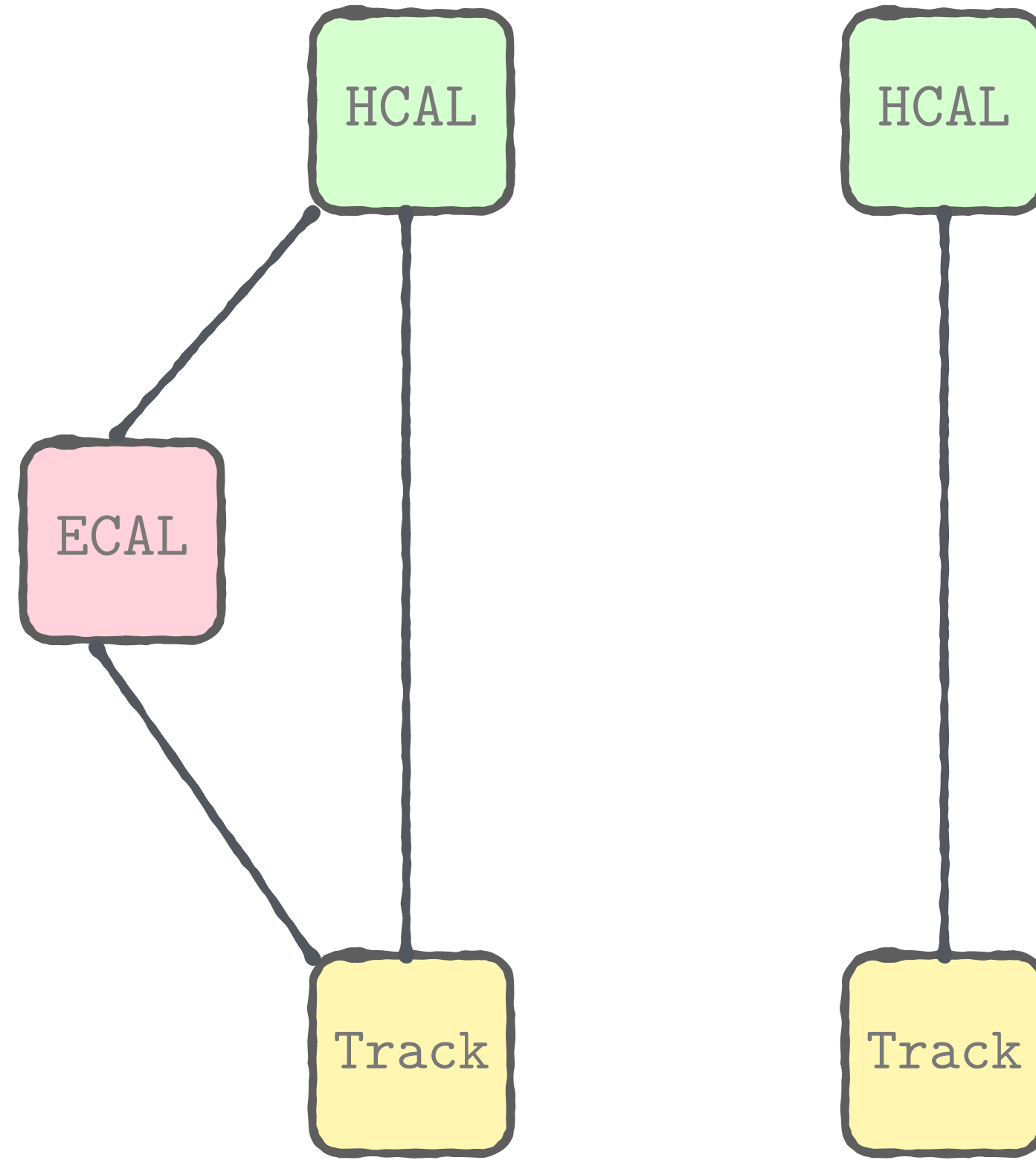
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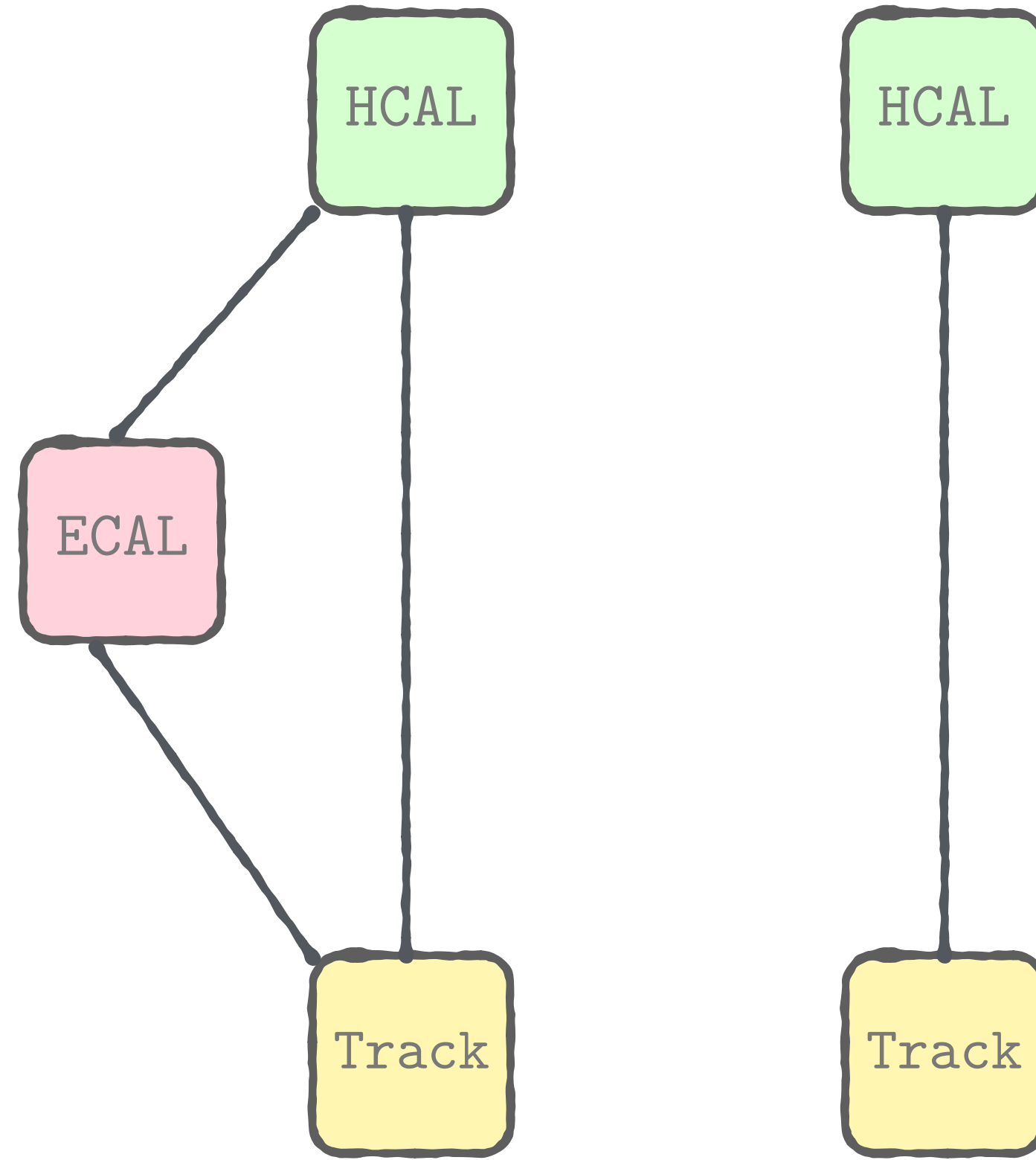
List of reconstructed (candidate) particles

$\{\gamma, \gamma, \gamma\}$

Four true particles:

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Simplified block (2nd step)



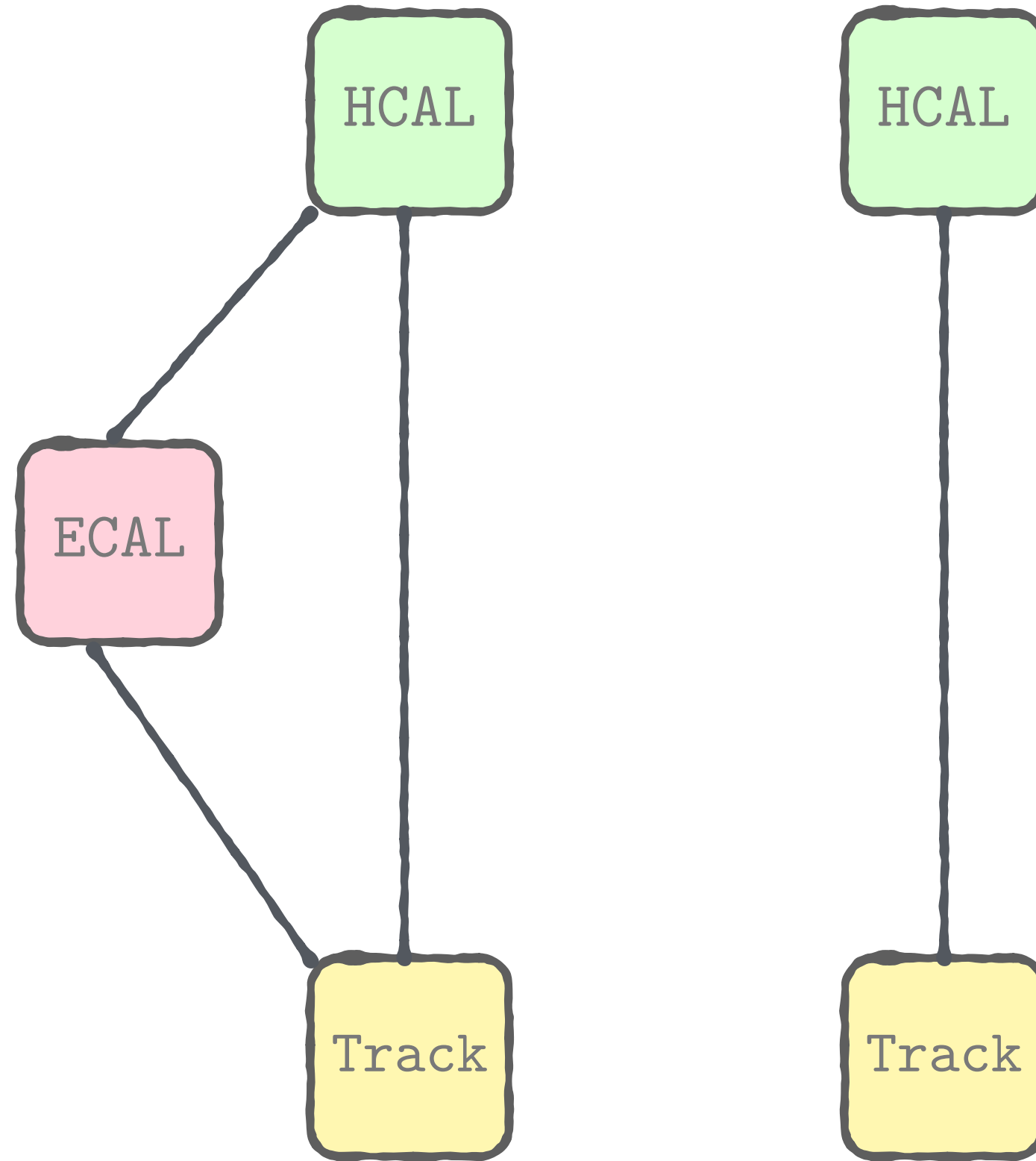
List of reconstructed (candidate) particles

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Simplified block (2nd step)



List of reconstructed (candidate) particles

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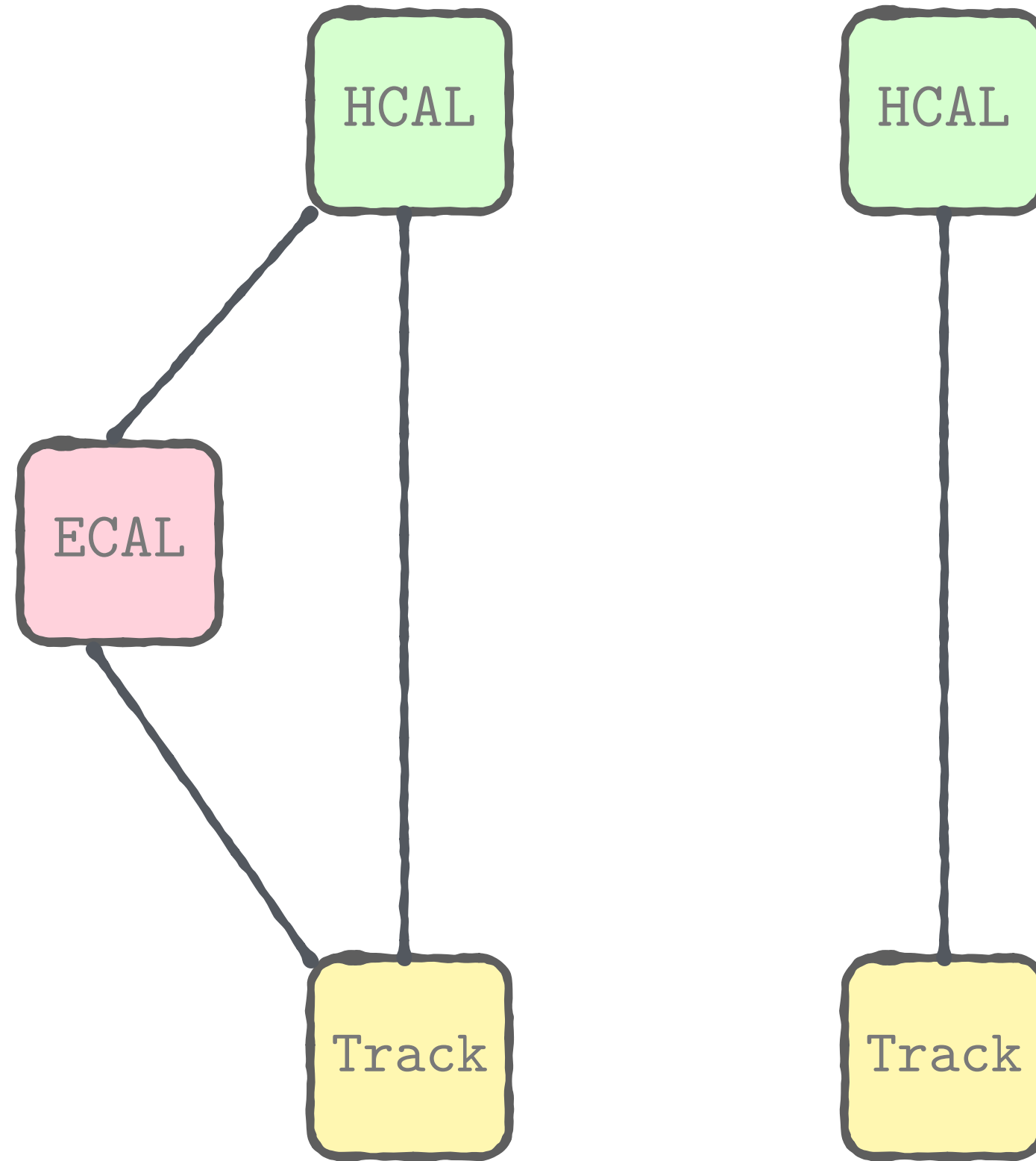
(blocks are usually very small)

Four true particles:

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Simplified block (2nd step)

Find charged hadrons & merged photons / neutral hadrons



List of reconstructed (candidate) particles

$\{\gamma, \gamma, \gamma\}$

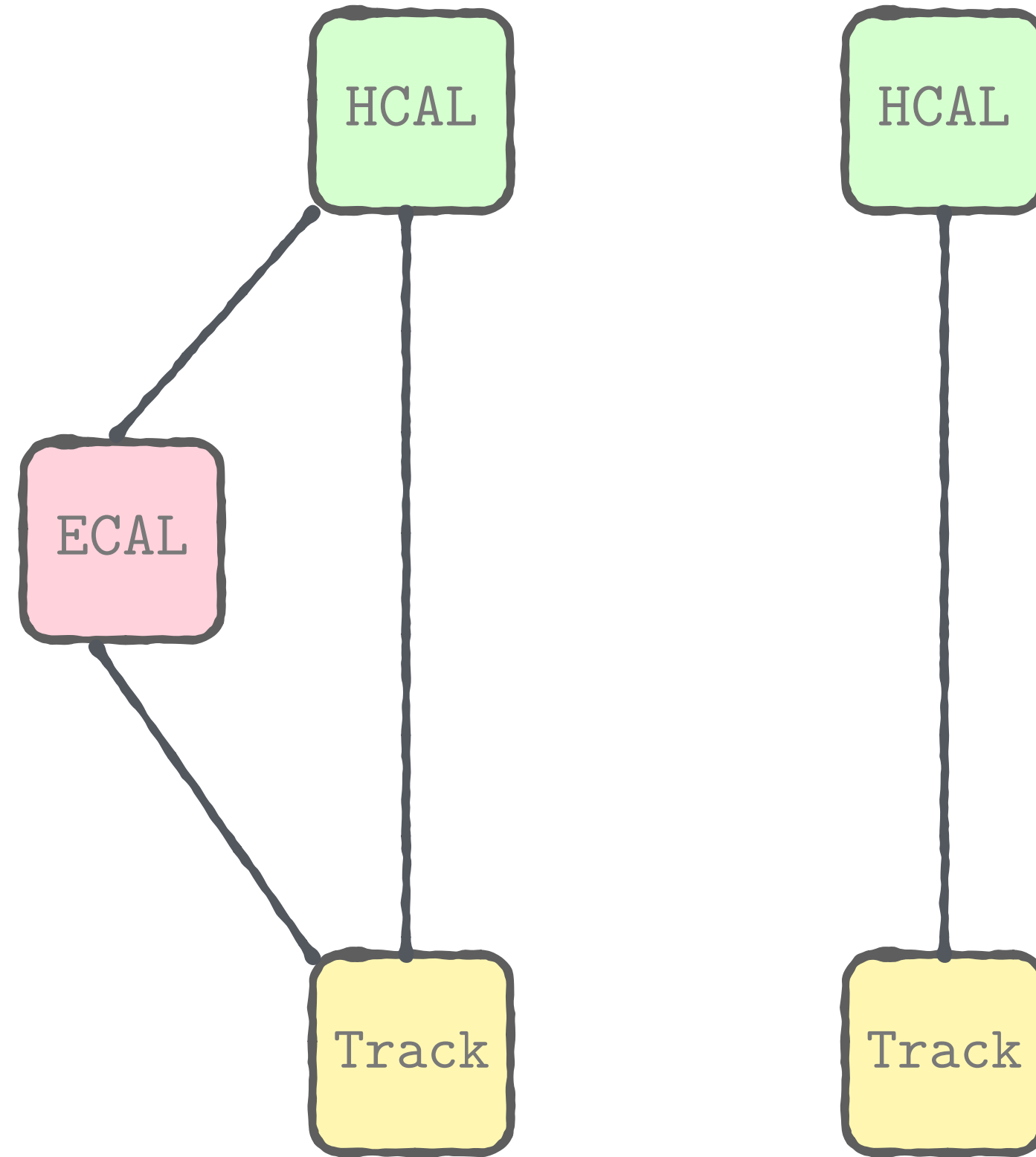
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Simplified block (2nd step)

Find charged hadrons & merged photons / neutral hadrons



For each HCAL Cluster compare:

- Sum of track momenta p
- Sum of cluster energies E
- linked to the tracks in ECAL & in HCAL "hadron calibrated" (see later)

List of reconstructed (candidate) particles

$$\{\gamma, \gamma, \gamma\}$$

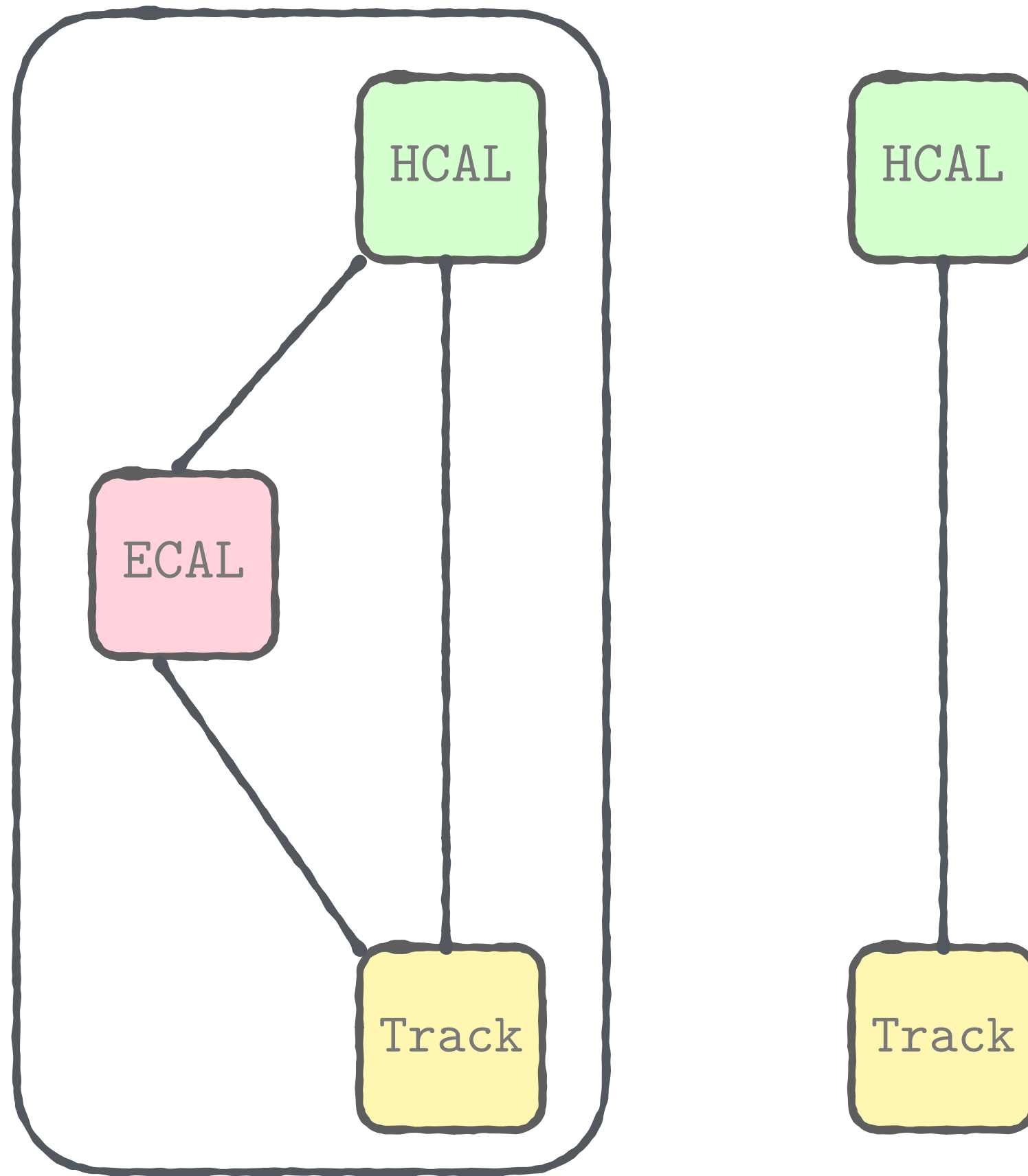
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Simplified block (2nd step)

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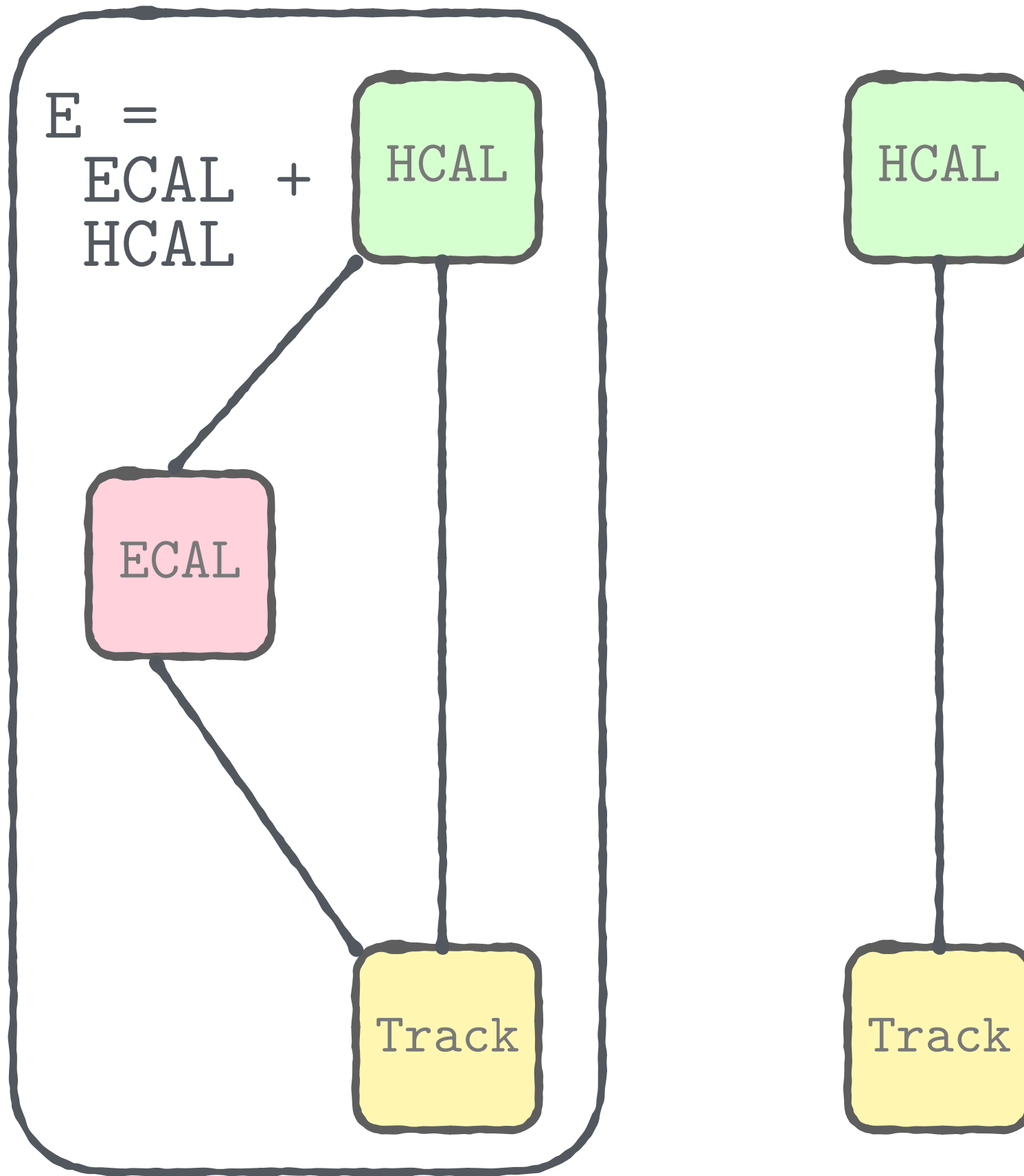
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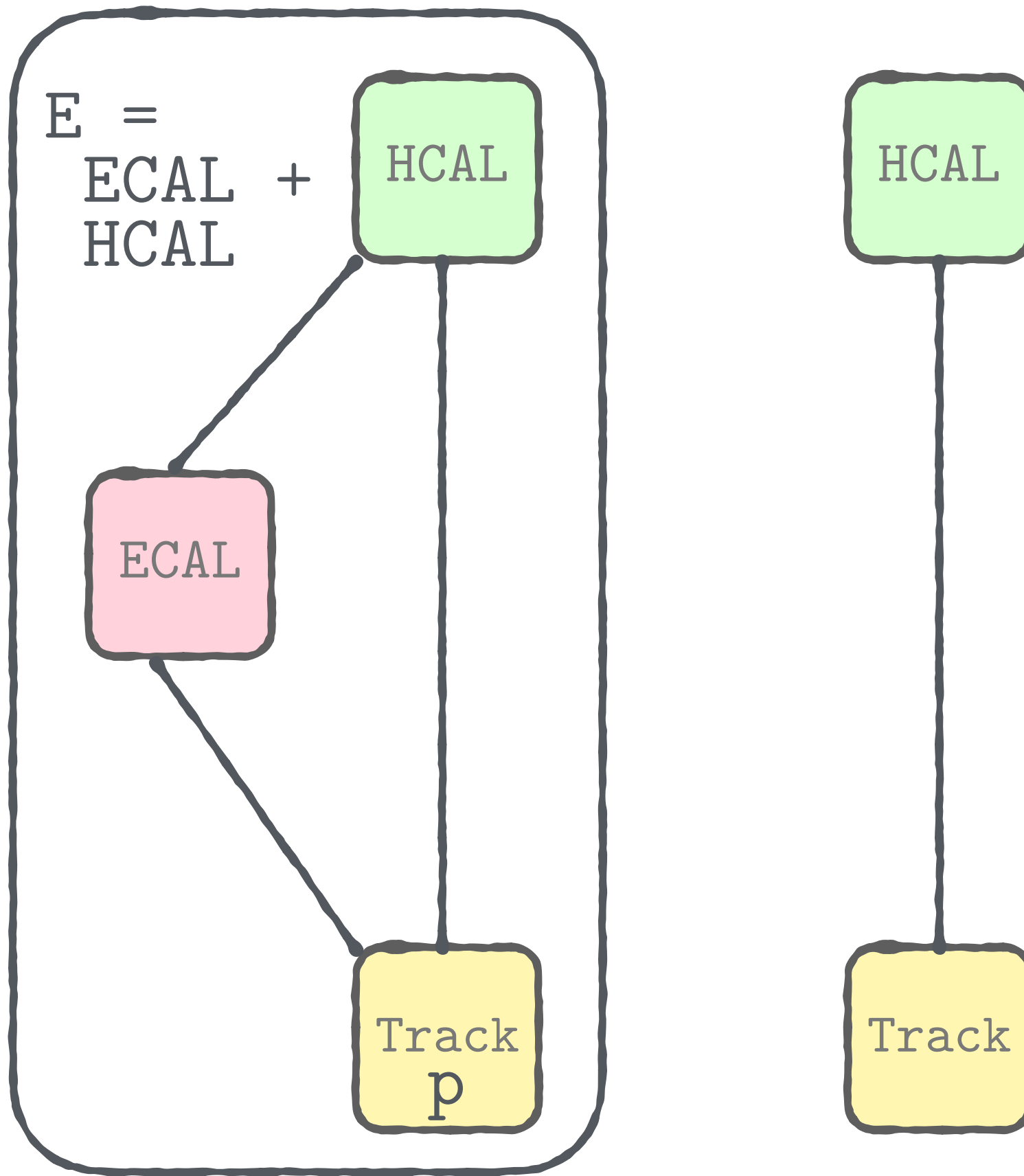
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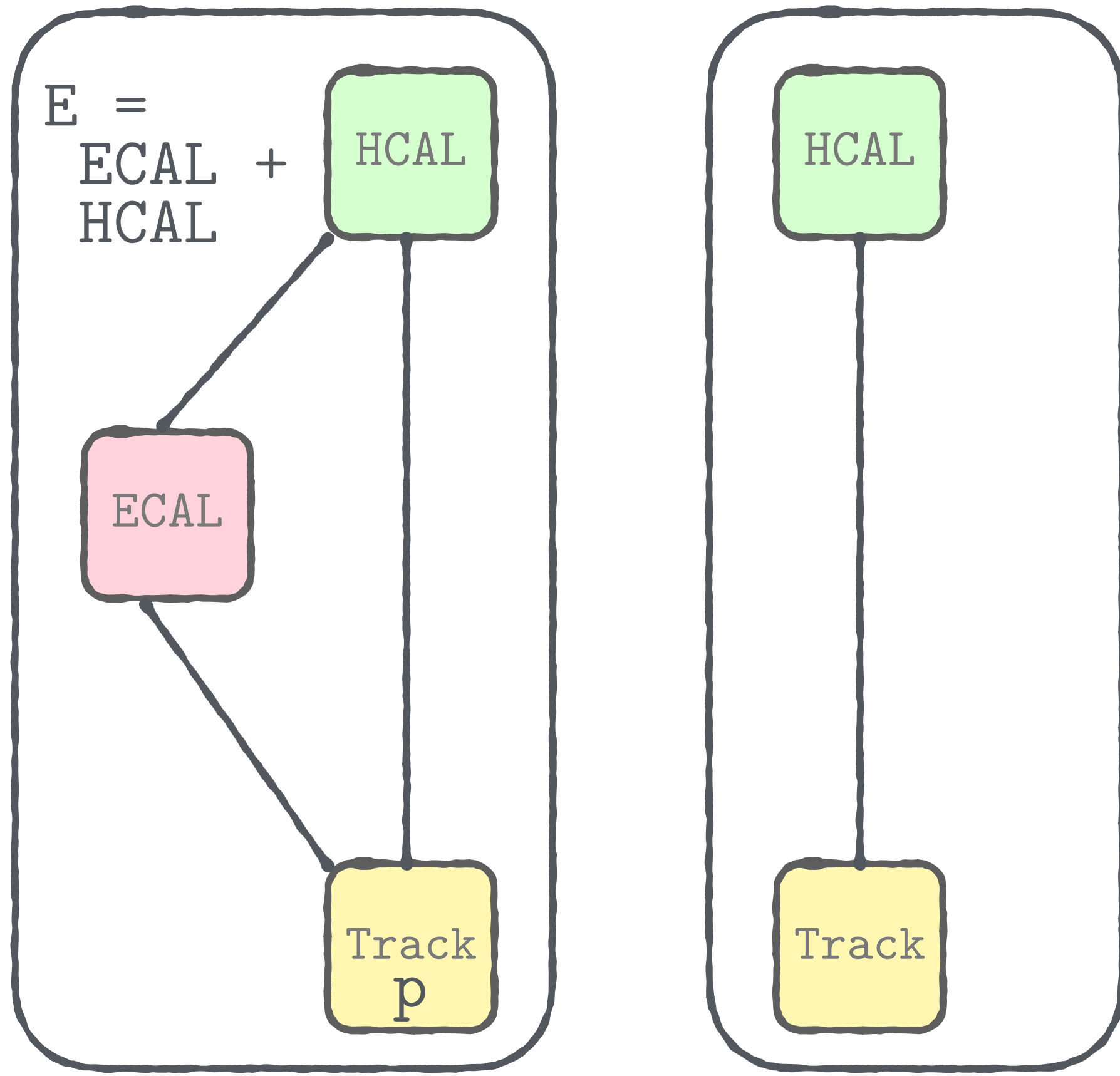
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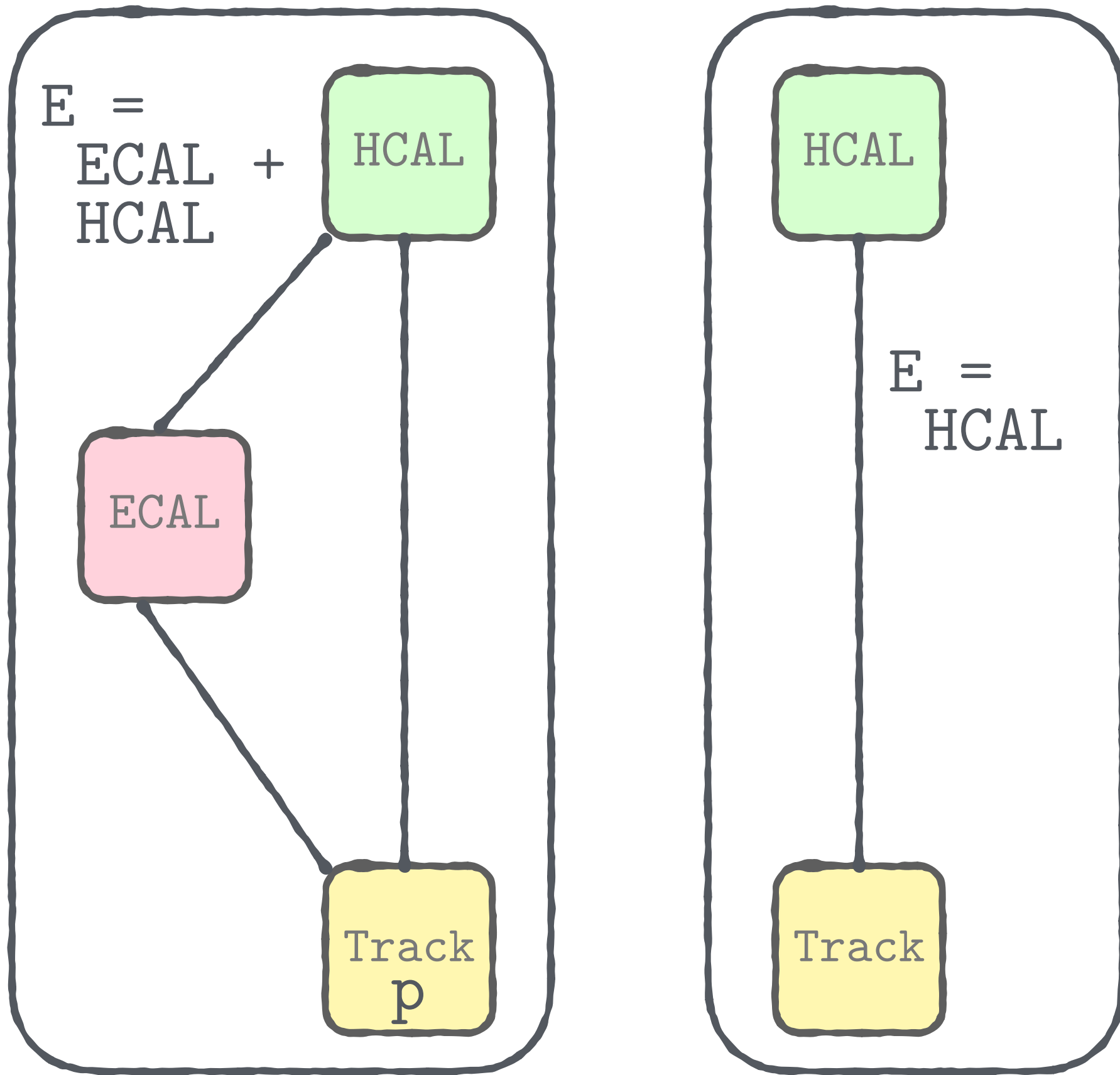
(blocks are usually very small)

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Find charged hadrons & merged photons / neutral hadrons



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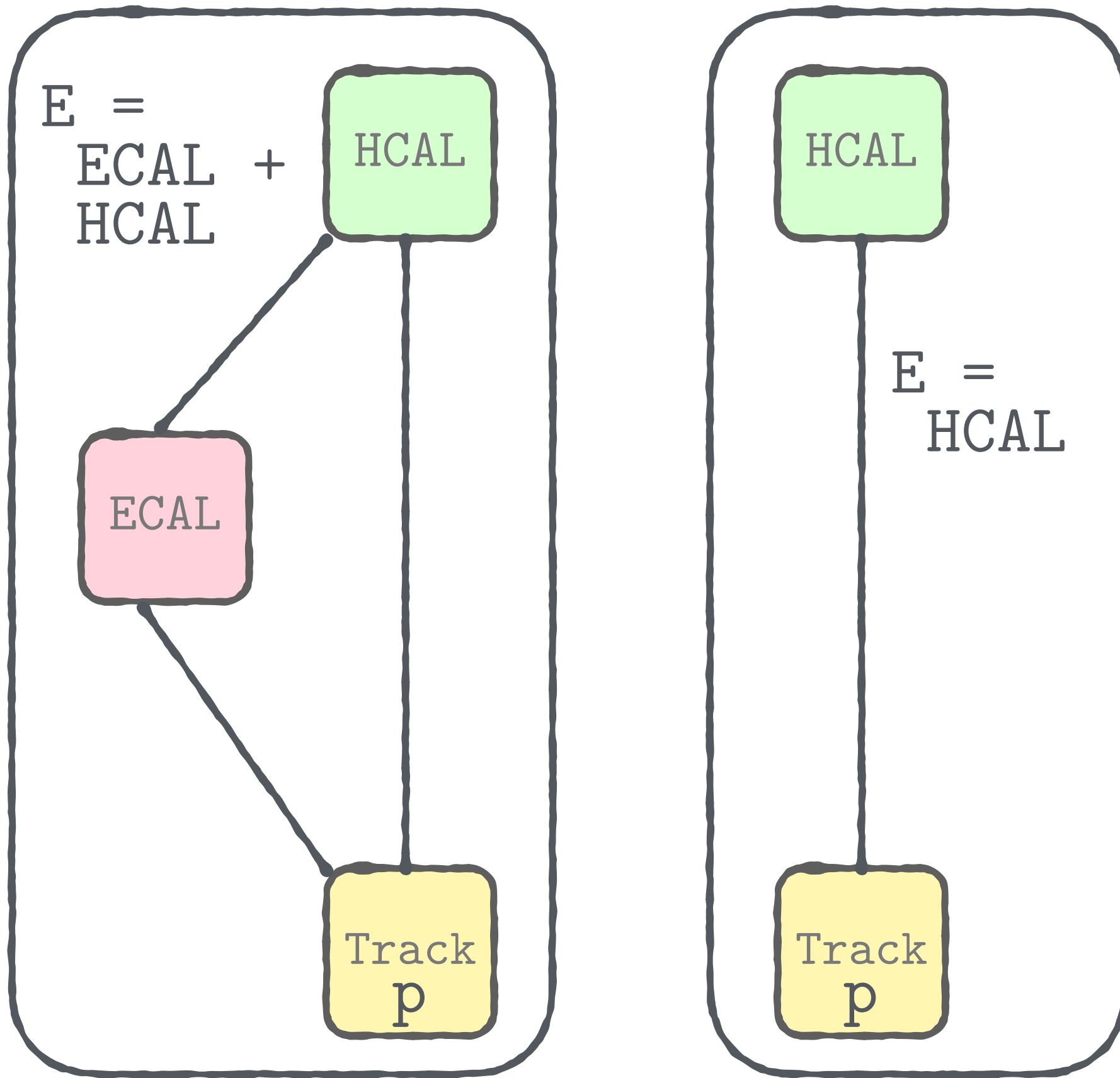
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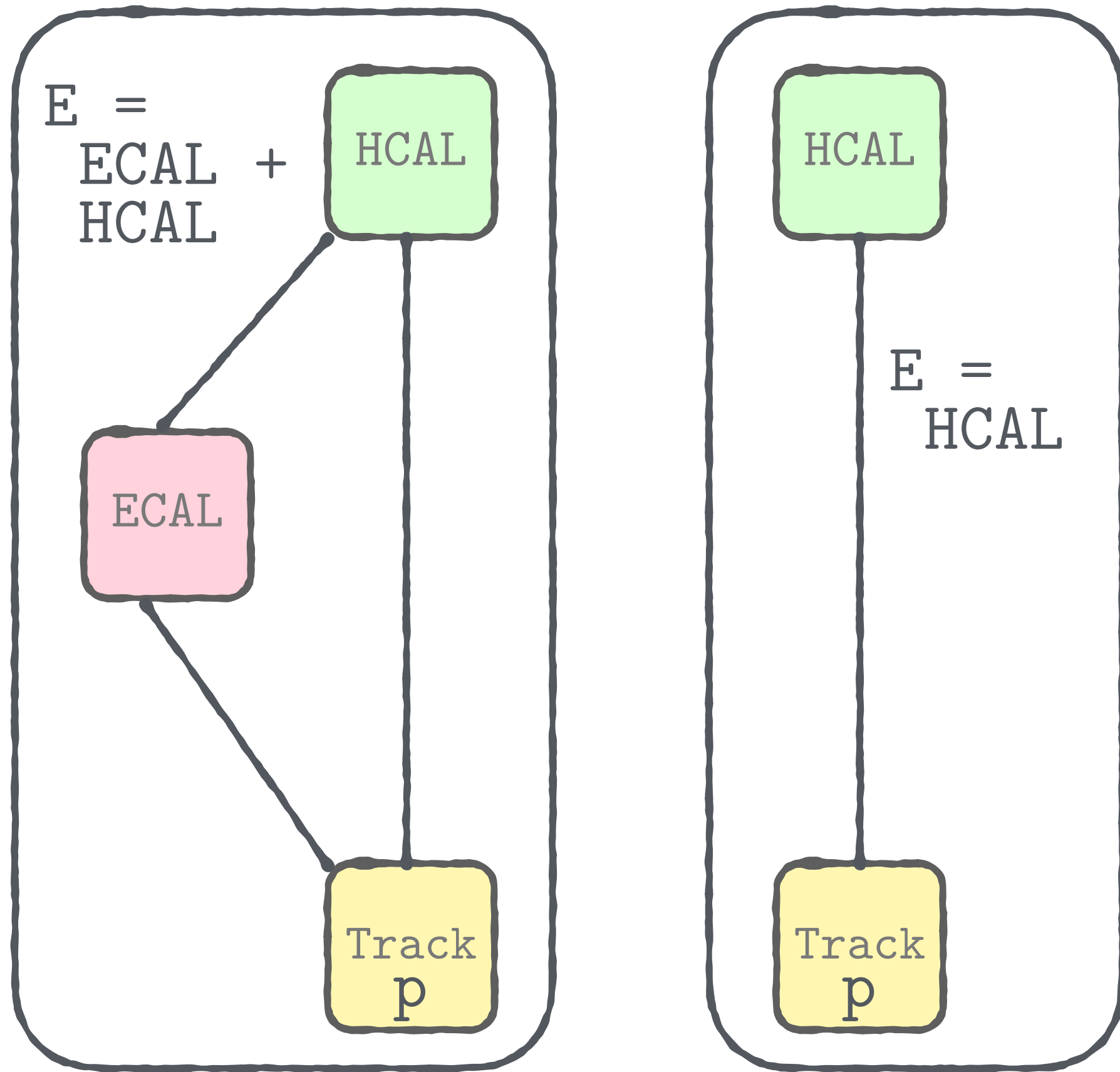
(blocks are usually very small)

Four true particles:

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Simplified block (2nd step)

Find charged hadrons & merged photons / neutral hadrons



List of reconstructed (candidate) particles

$$\{\gamma, \gamma, \gamma\}$$

For each HCAL Cluster compare:

- Sum of track
- Sum

If p and E are compatible

- Identify charged hadrons only
- one per track

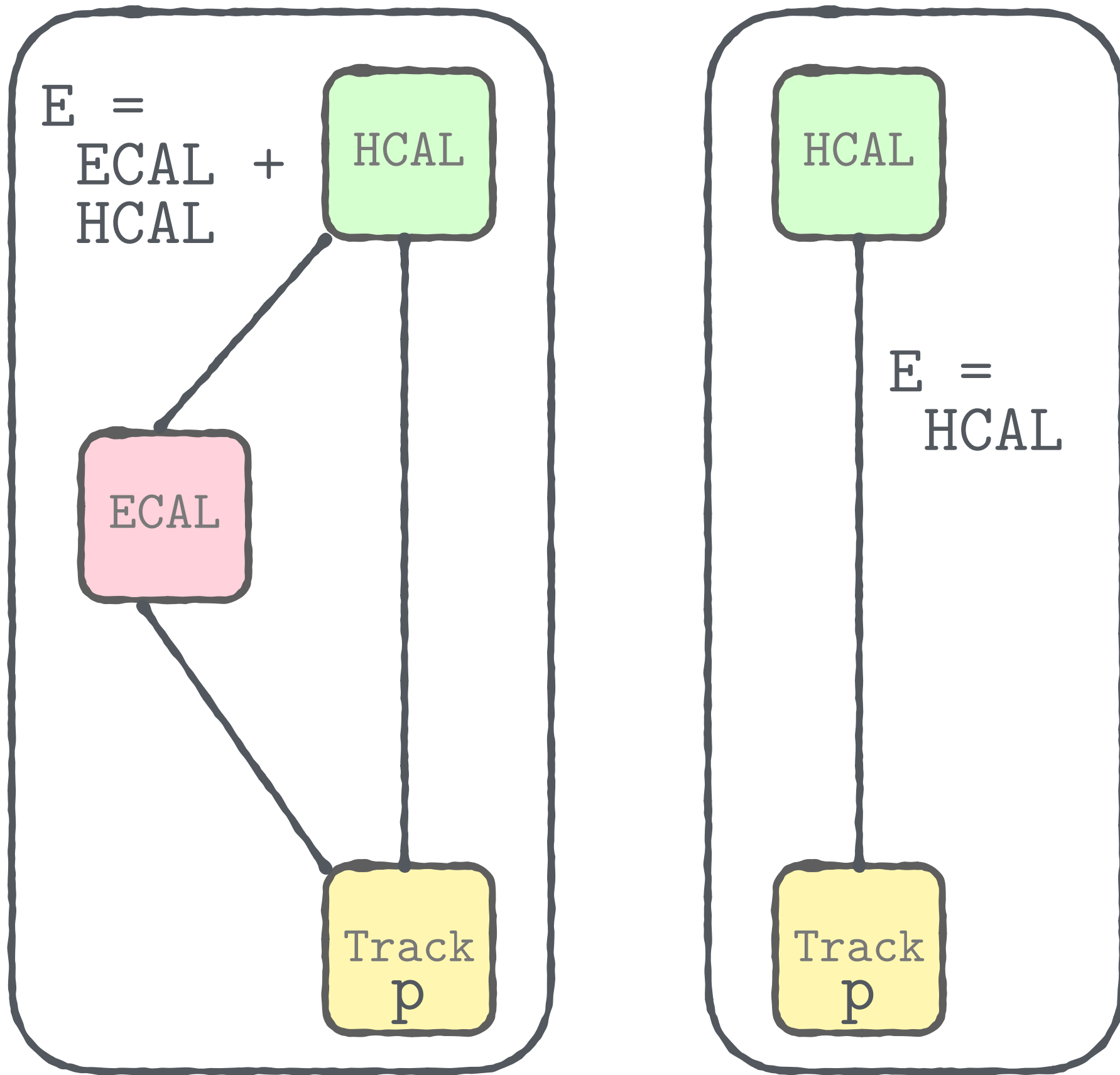
(blocks are usually very small)

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Simplified block (2nd step)

Find charged hadrons & merged photons / neutral hadrons



List of reconstructed (candidate) particles

$$\{\gamma, \gamma, \gamma\}$$

For each HCAL Cluster compare:

- Sum of track
- Sum

If p and E are compatible

- Identify charged hadrons only
- one per track

If $E > p + \sigma(E)$

- Identify charged hadrons + photons / neutral hadrons

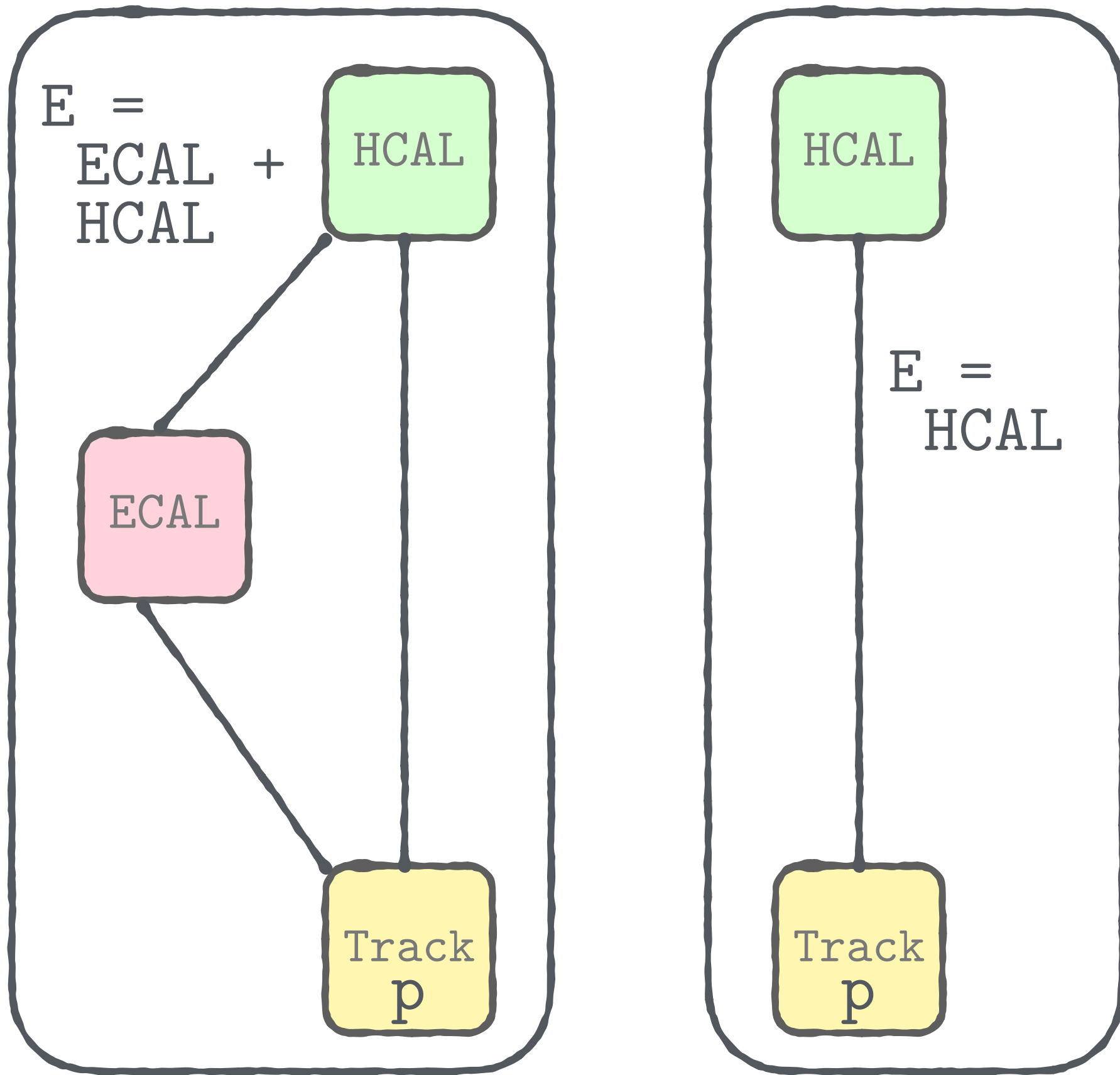
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Find charged hadrons & merged photons / neutral hadrons



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- Sum

If p and E are compatible

- Identify charged hadrons only
- one per track

If $E > p + \sigma(E)$

- Identify charged hadrons + photons / neutral hadrons

If $E \ll p$

- Something odd going on...needs attention (doesn't happen often)

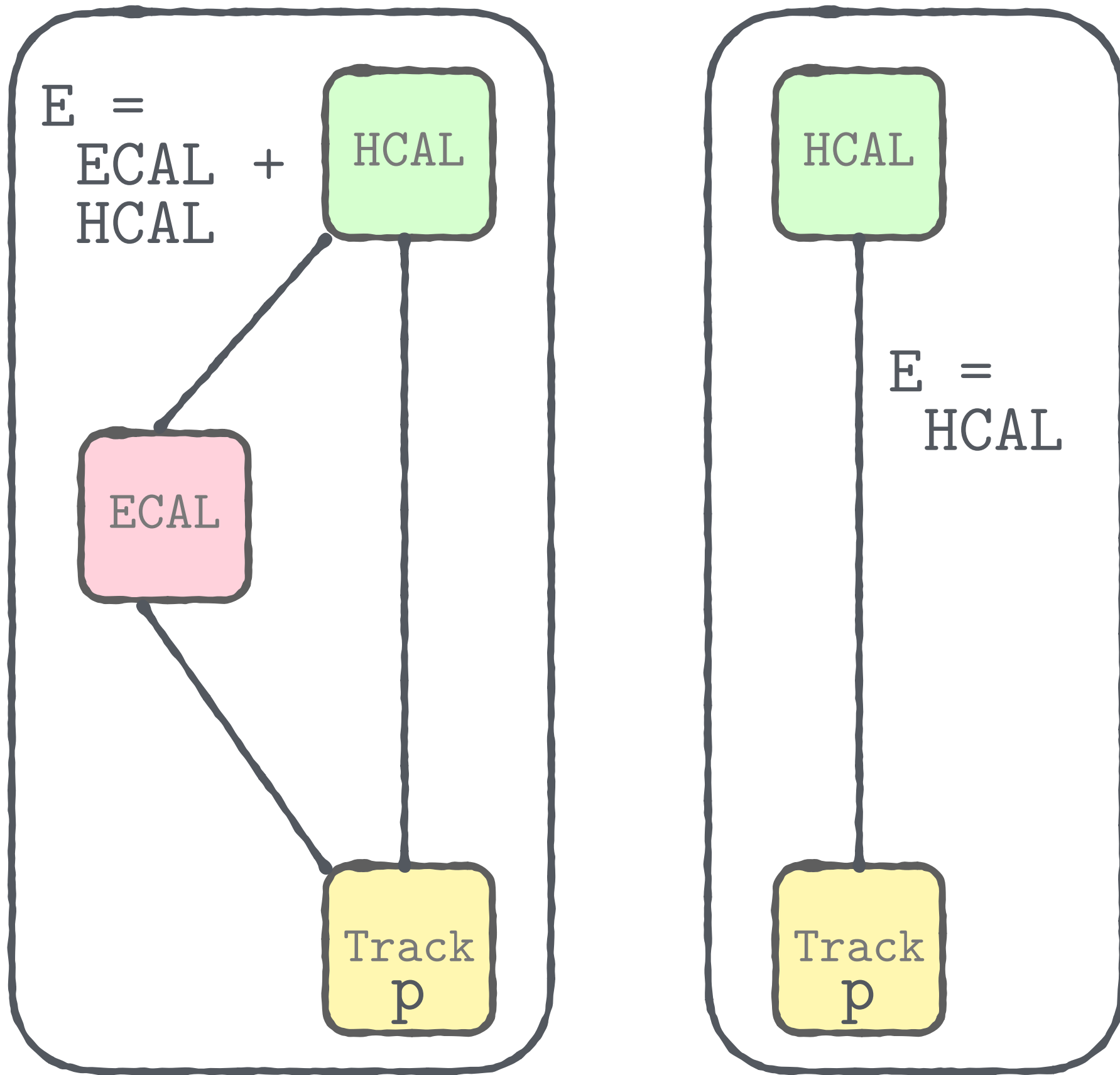
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Find charged hadrons & merged photons / neutral hadrons



List of reconstructed (candidate) particles

$\{\gamma, \gamma, \gamma,$

For each HCAL Cluster compare:

- Sum of track
- Sum

If p and E are compatible

- Identify charged hadrons only
- one per track

If E << p

- Something odd going on...needs attention (doesn't happen often)

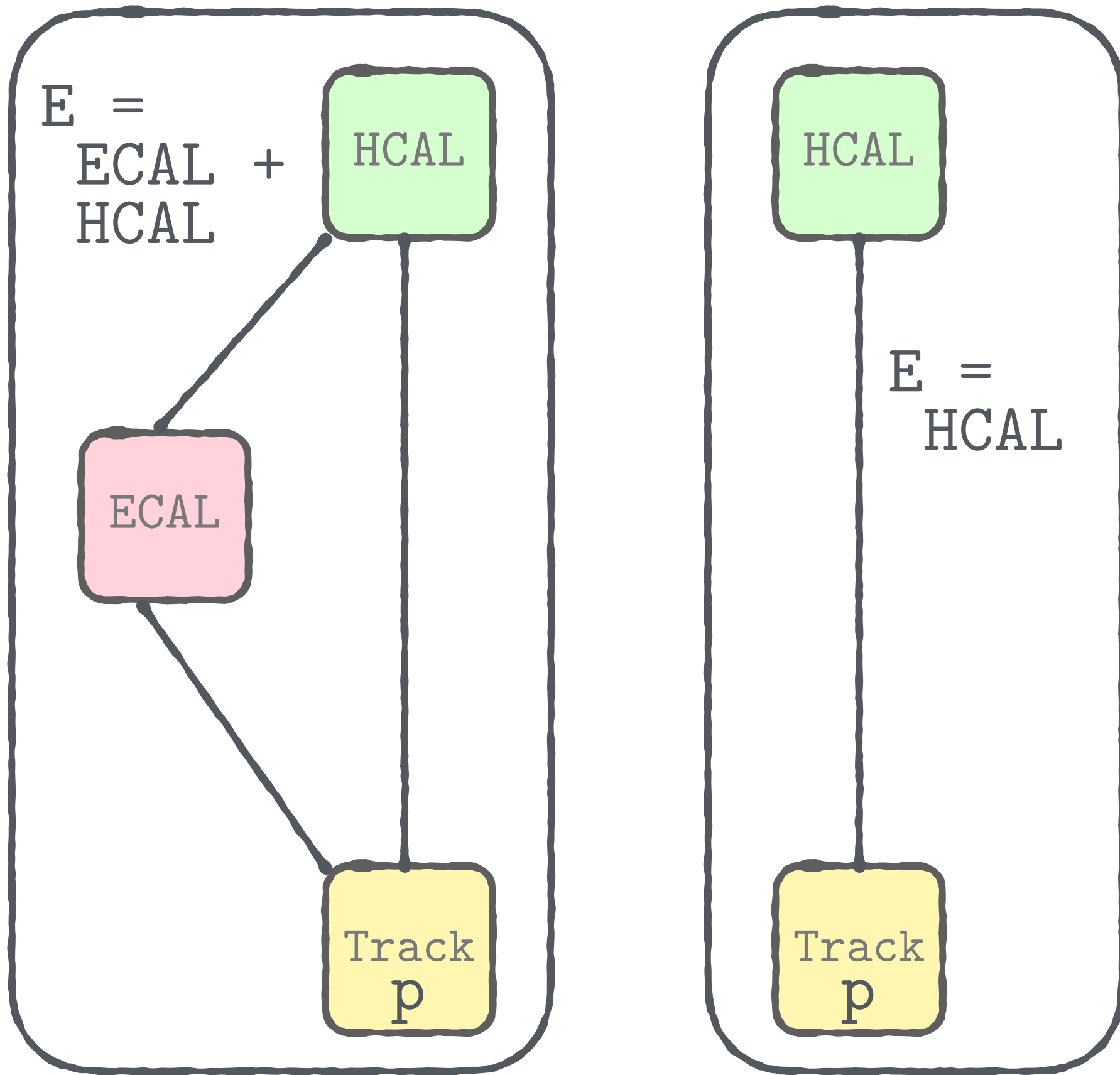
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Simplified block (2nd step)

Find charged hadrons & merged photons / neutral hadrons



List of reconstructed (candidate) particles

$$\{\gamma, \gamma, \gamma,$$

For each HCAL Cluster compare:

If p and

- Identify
- one pe

If $E > p + \sigma(E)$

- If E is just ECAL or just HCAL
 - ECAL: photon (E-p)
 - HCAL: neutral hadron (E-p)
- If E from both ECAL and HCAL
 - if (E-p) > ECAL then photon (ECAL) + neutral hadron (HCAL - p)
 - otherwise photon (E-p)/b

attention (doesn't happen often)

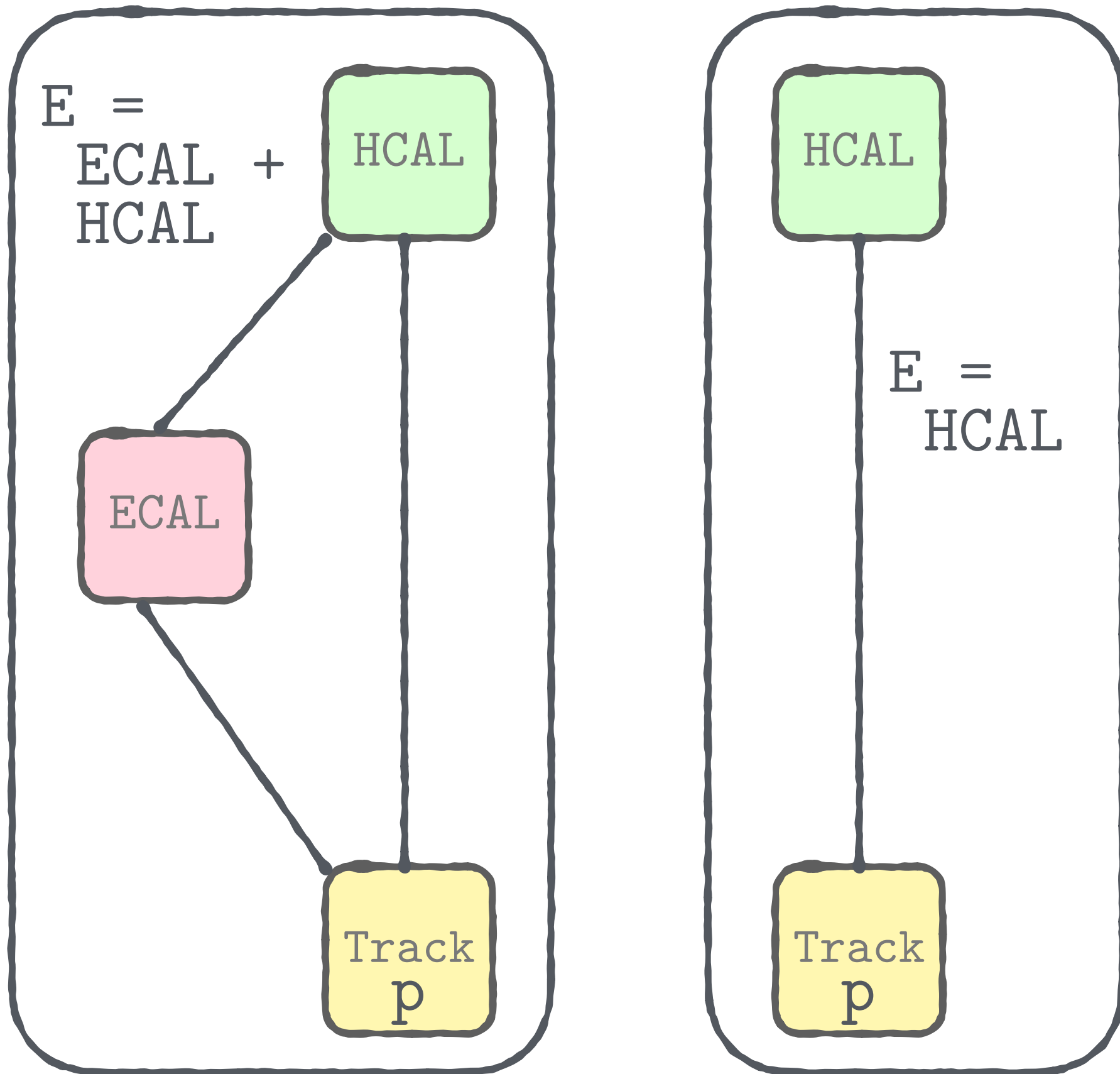
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Simplified block (2nd step)

Find charged hadrons & merged photons / neutral hadrons



List of reconstructed (candidate) particles

$\{\gamma, \gamma, \gamma,$

For each HCAL Cluster compare:

- Sum
- Sum

If p and

- Identify
- one pe

If $E > p + \sigma(E)$

- If E is just ECAL or just HCAL
 - ECAL: photon (E-p)
 - HCAL: neutral hadron (E-p)
- If E from both ECAL and HCAL
 - if (E-p) > ECAL then photon (ECAL) + neutral hadron (HCAL - p)
- otherwise photon (E-p)/b

attention (doesn't happen often) ...going on...needs

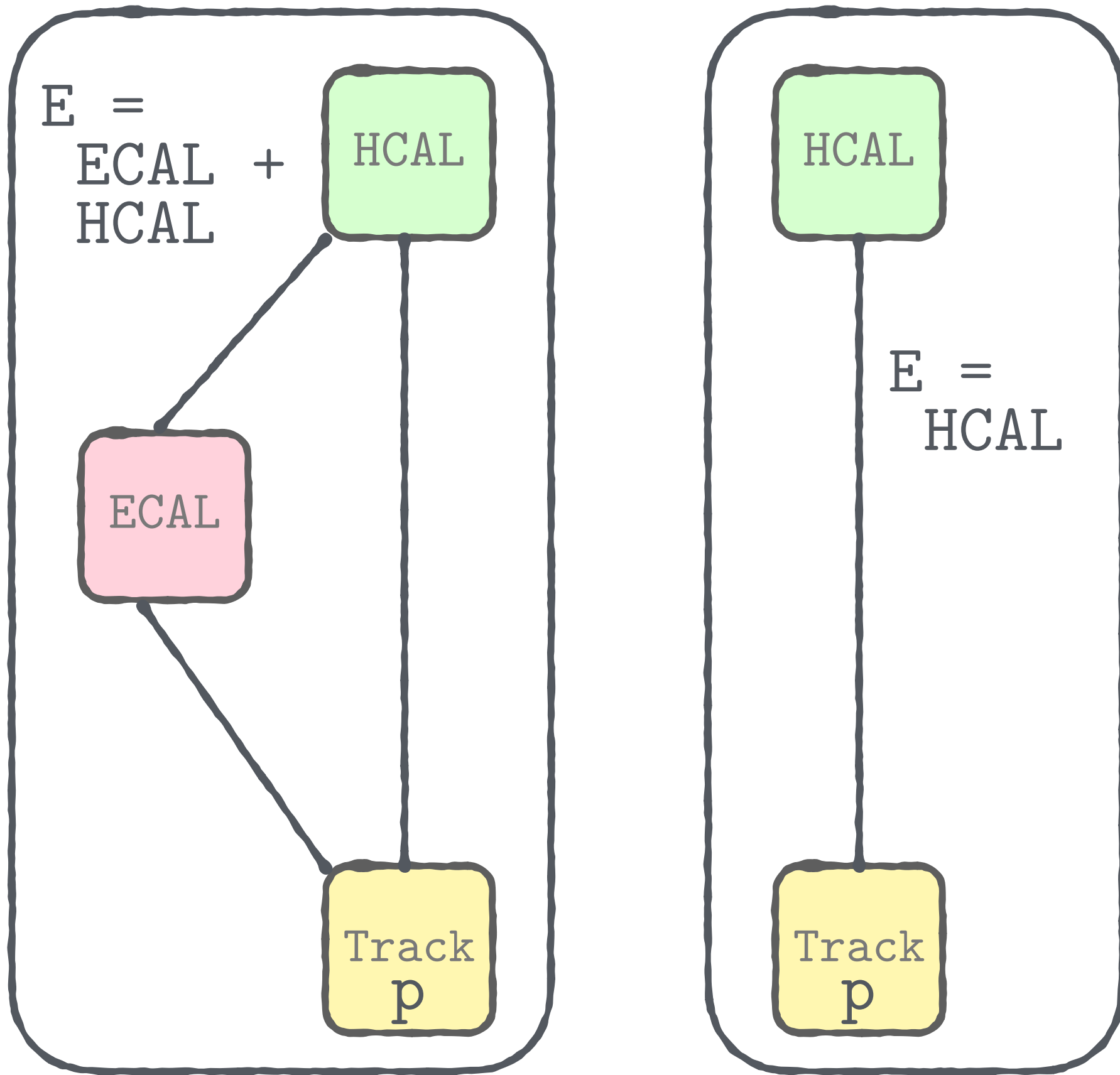
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List of reconstructed (candidate) particles

$$\{\gamma, \gamma, \gamma,$$

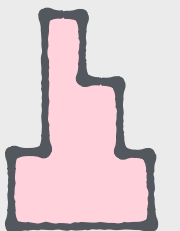
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If p and

- Identify
- one pe

If $E > p + \sigma(E)$

- If E is just ECAL or just HCAL
 - ECAL: photon (E-p)
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- If E from both ECAL and HCAL
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attention (doesn't happen often)

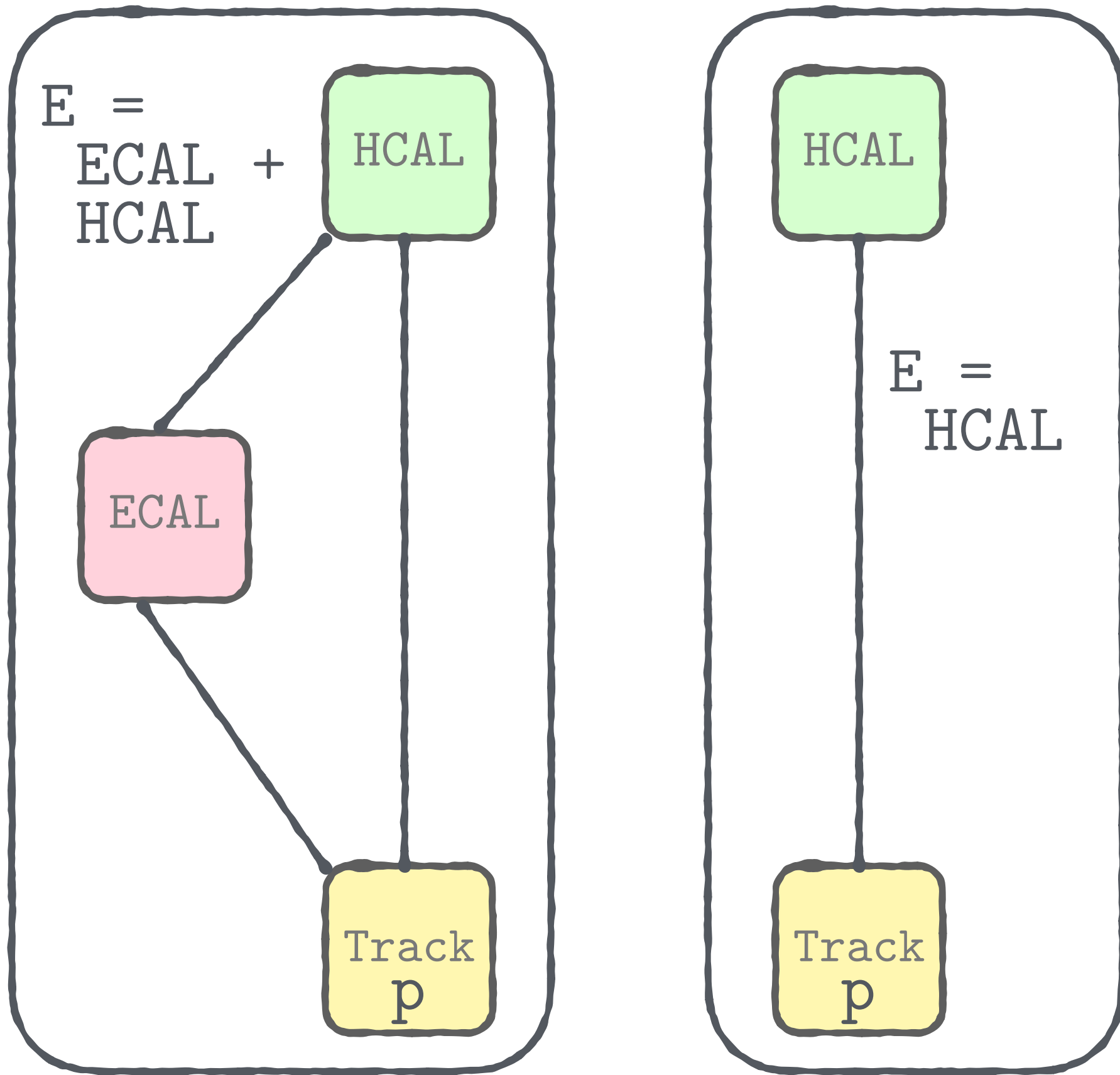
(blocks are usually very small)

Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

Simplified block (2nd step)

Find charged hadrons & merged photons / neutral hadrons



List of reconstructed (candidate) particles

$$\{\gamma, \gamma, \gamma,$$

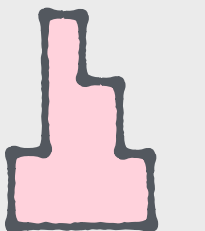
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p

attention (doesn't happen often)

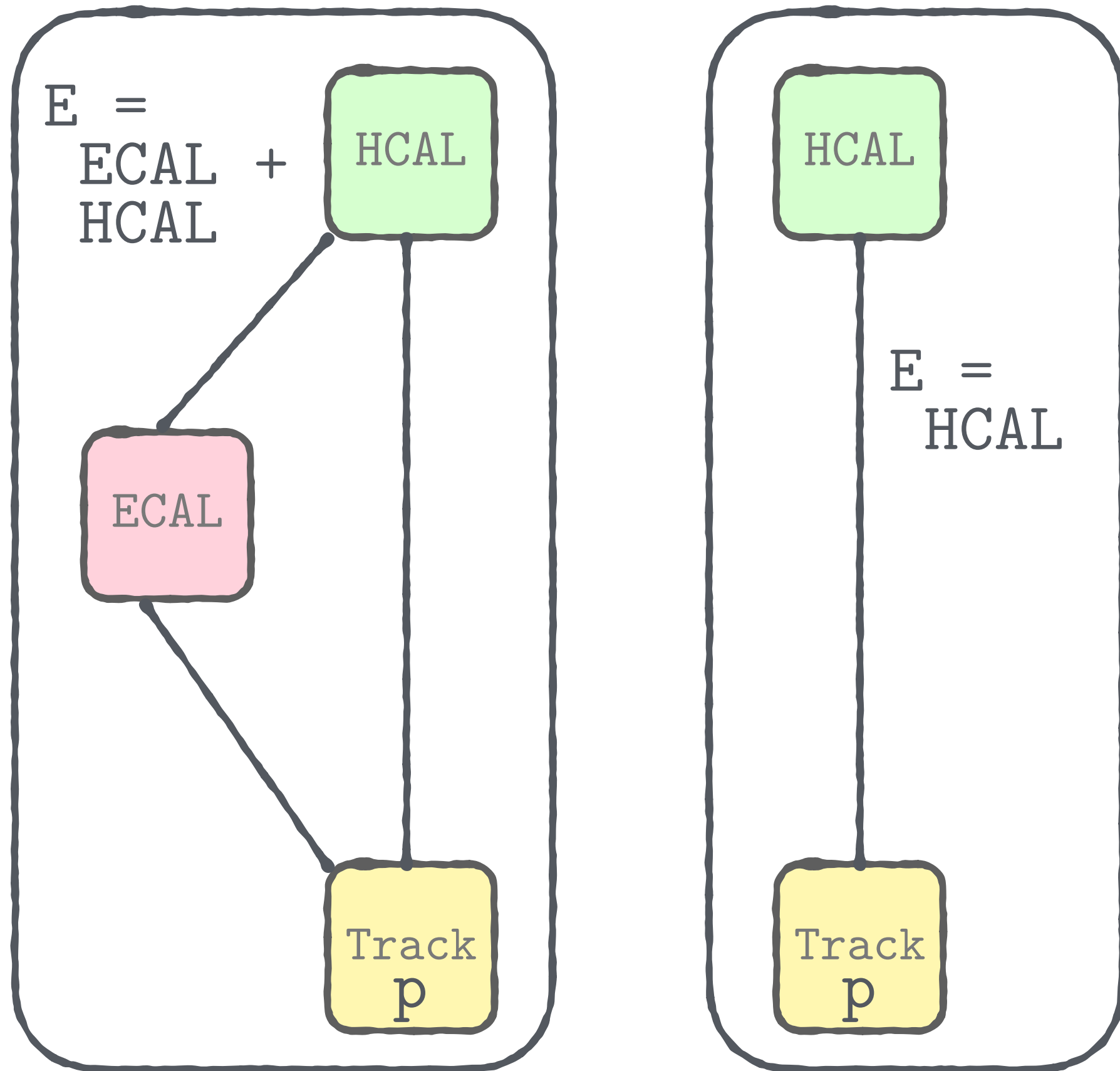
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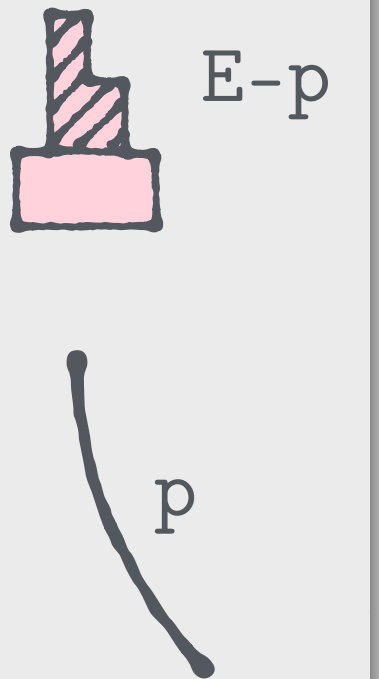
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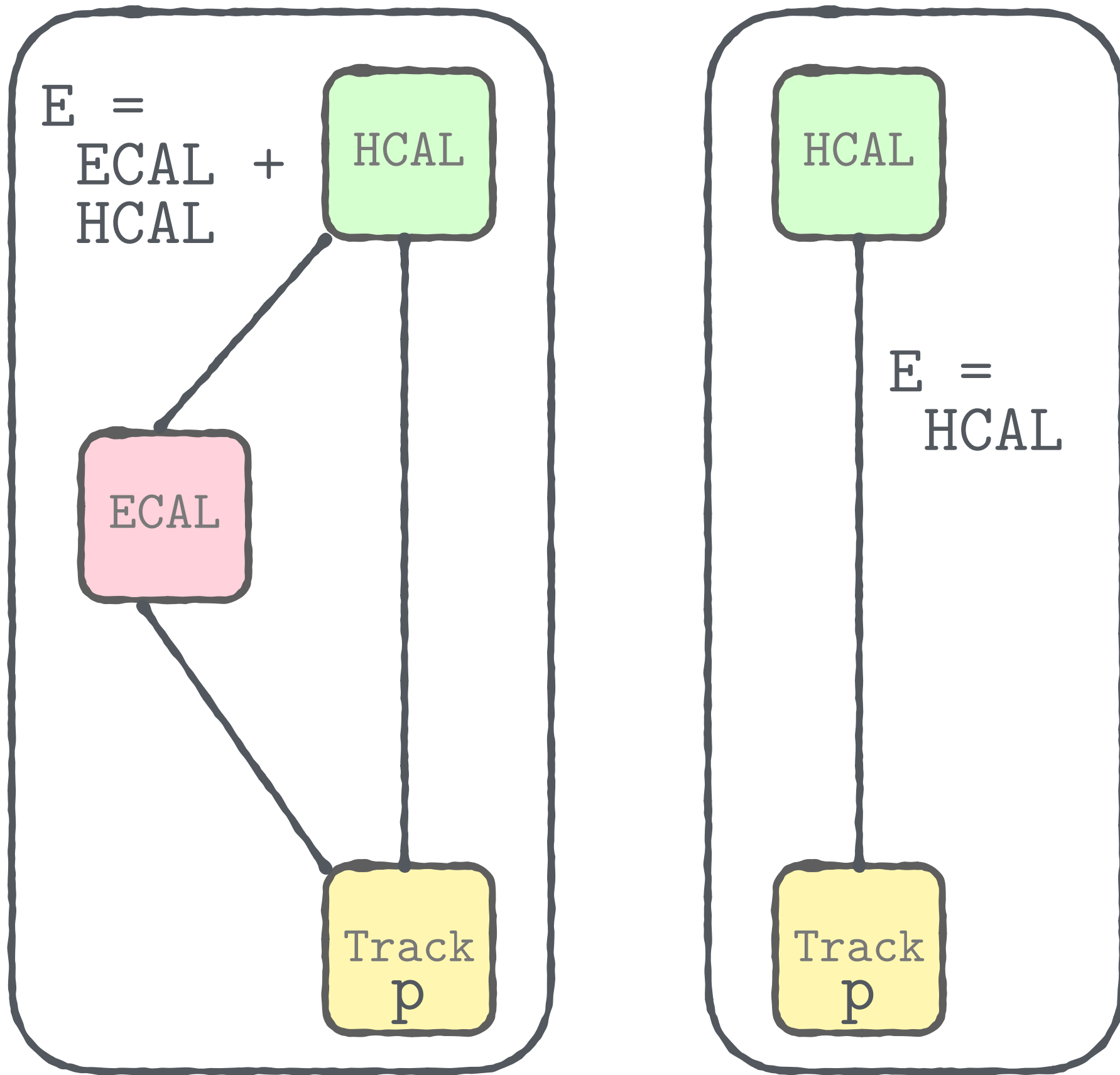
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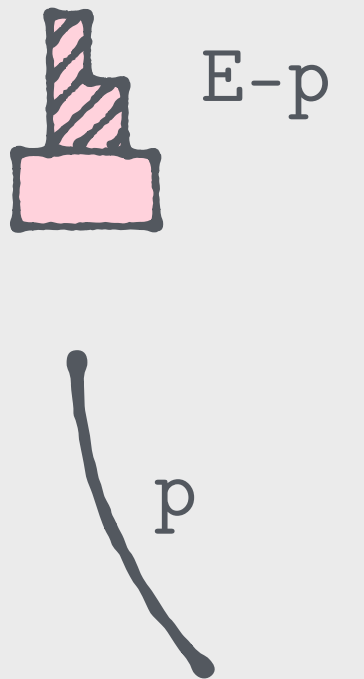
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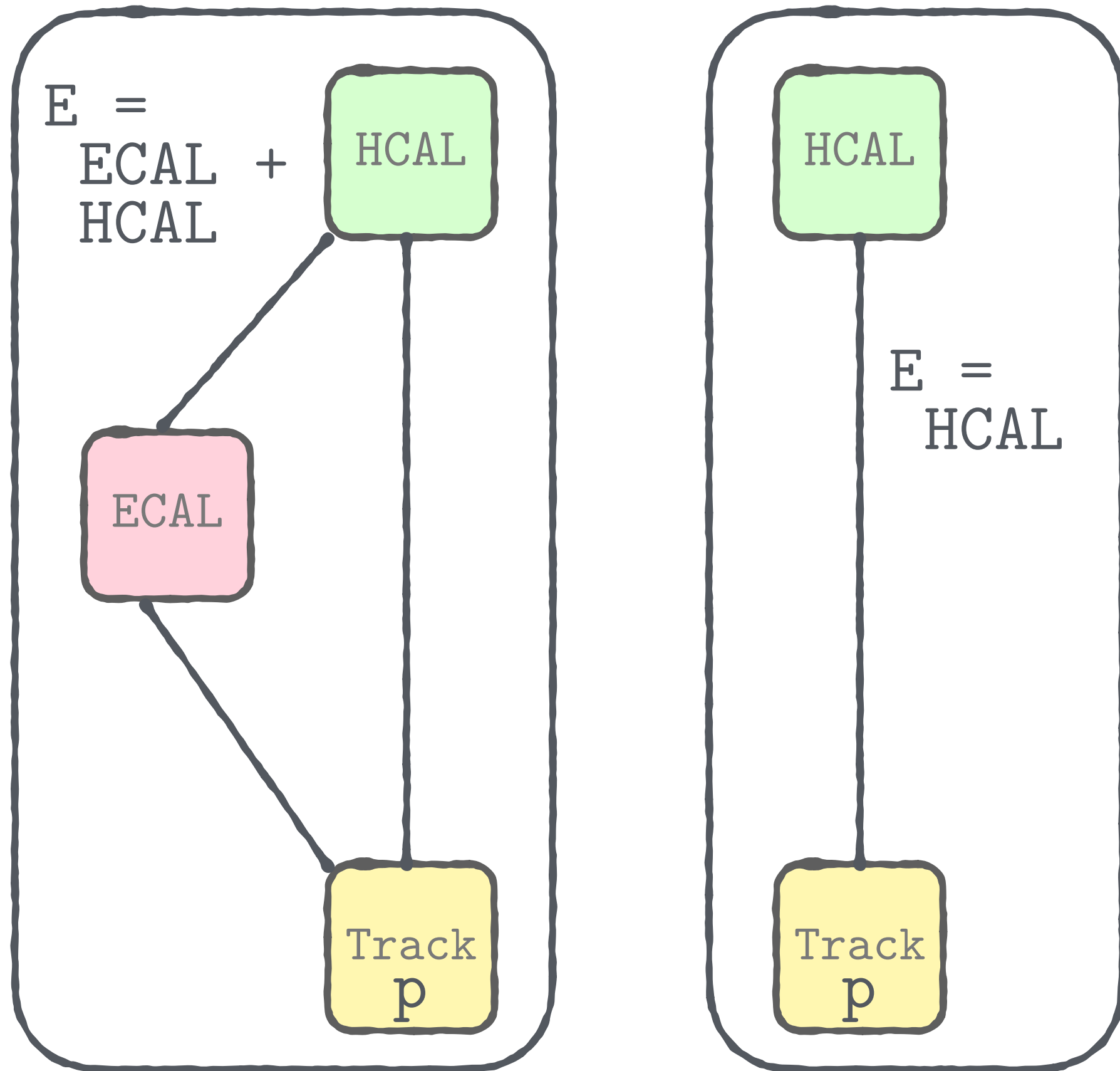
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The diagram shows a pink rectangular bar with diagonal hatching on top, labeled 'E-p'. Below it is a curved line labeled 'p'.

attention (doesn't happen often) ... going on...needs

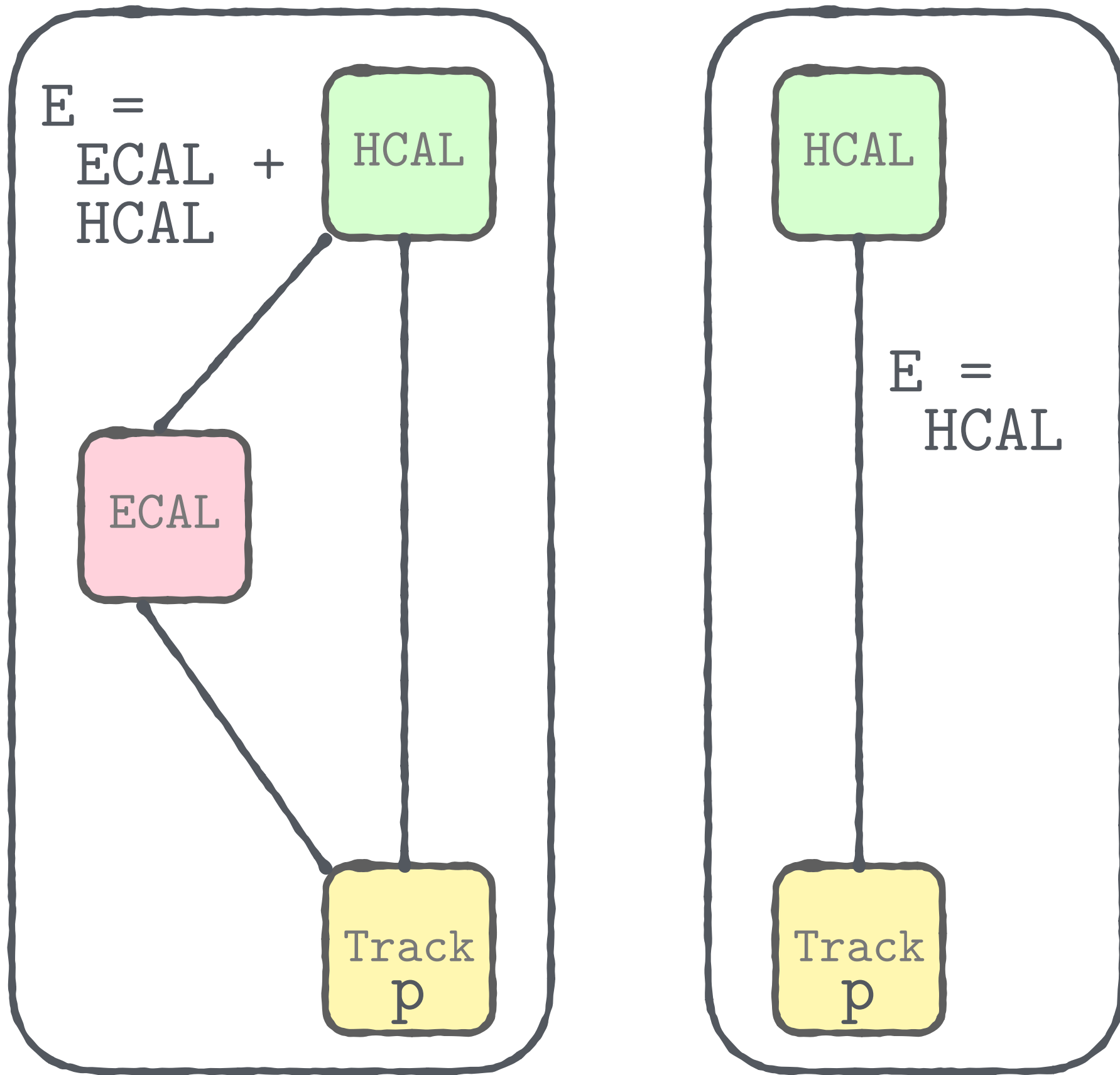
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Simplified block (2nd step)

Find charged hadrons & merged photons / neutral hadrons



List of reconstructed (candidate) particles

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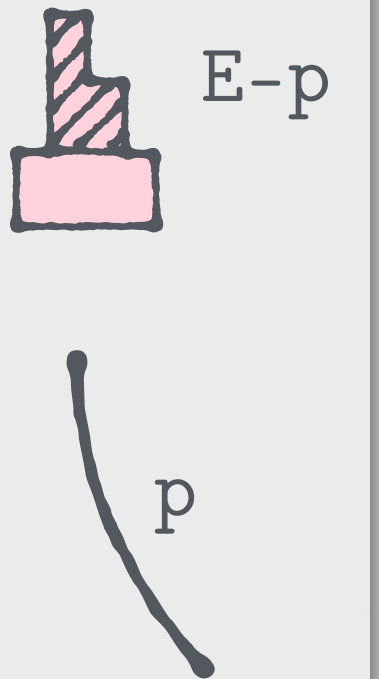
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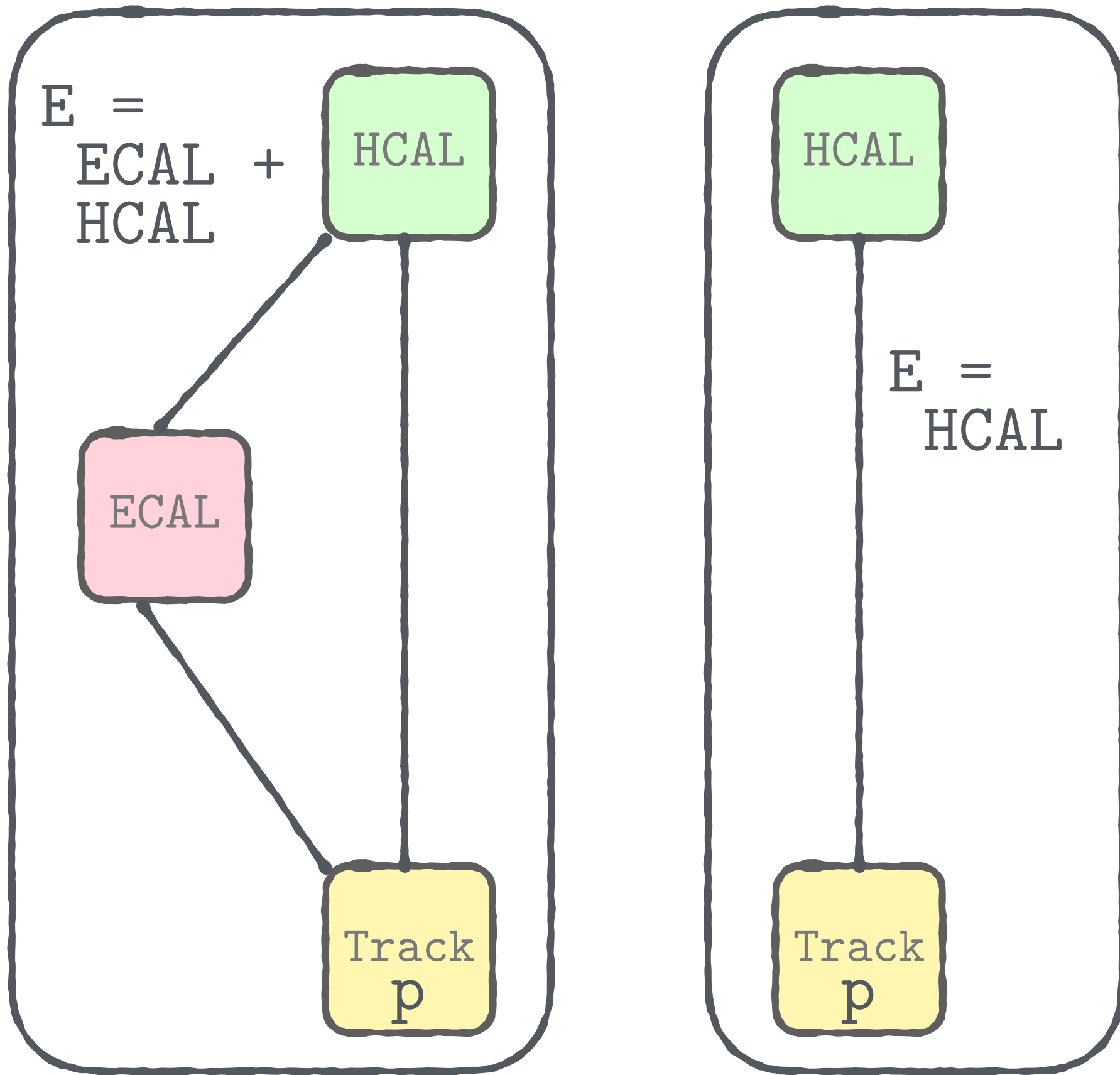
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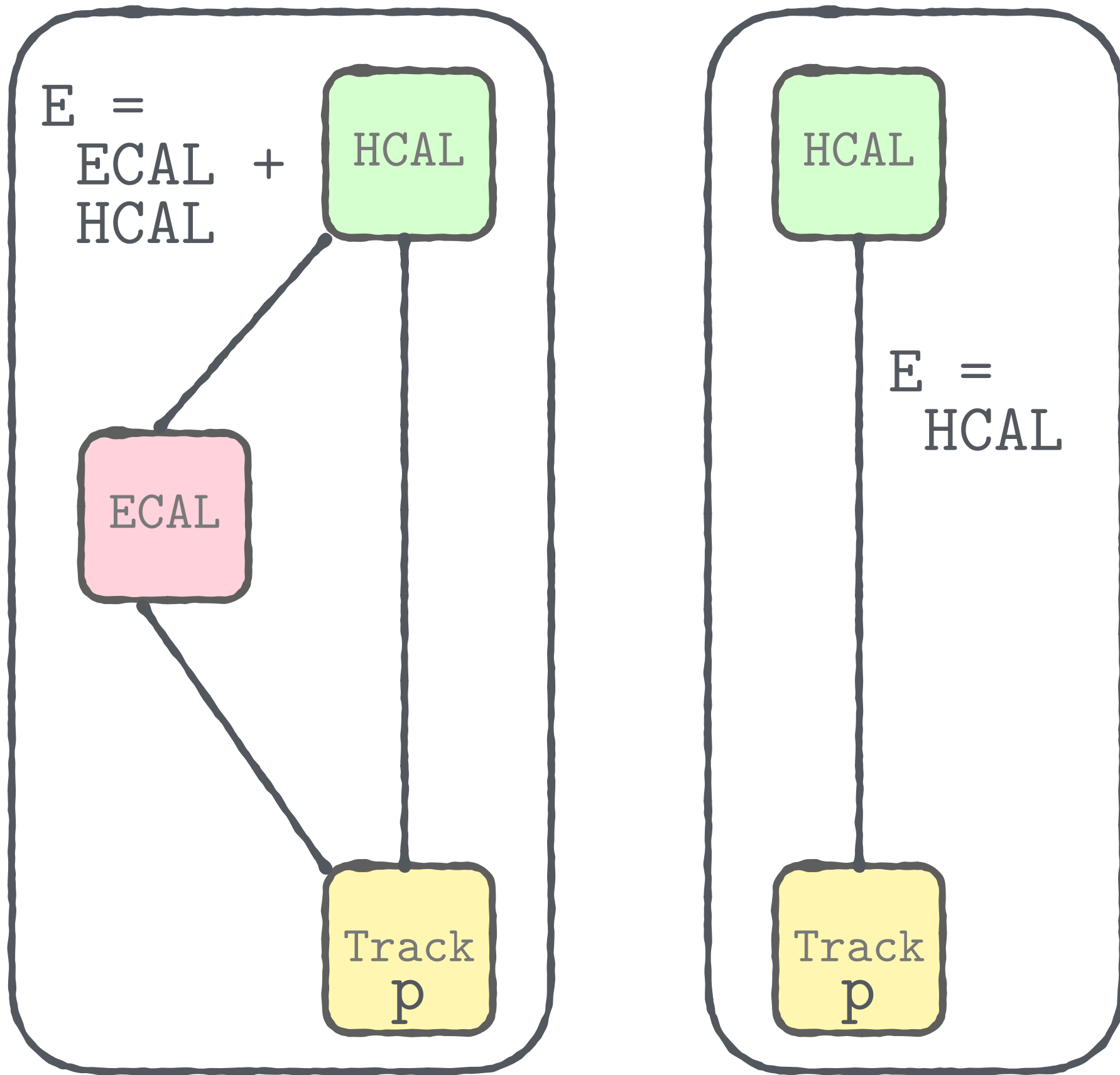
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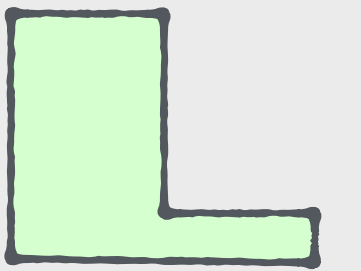
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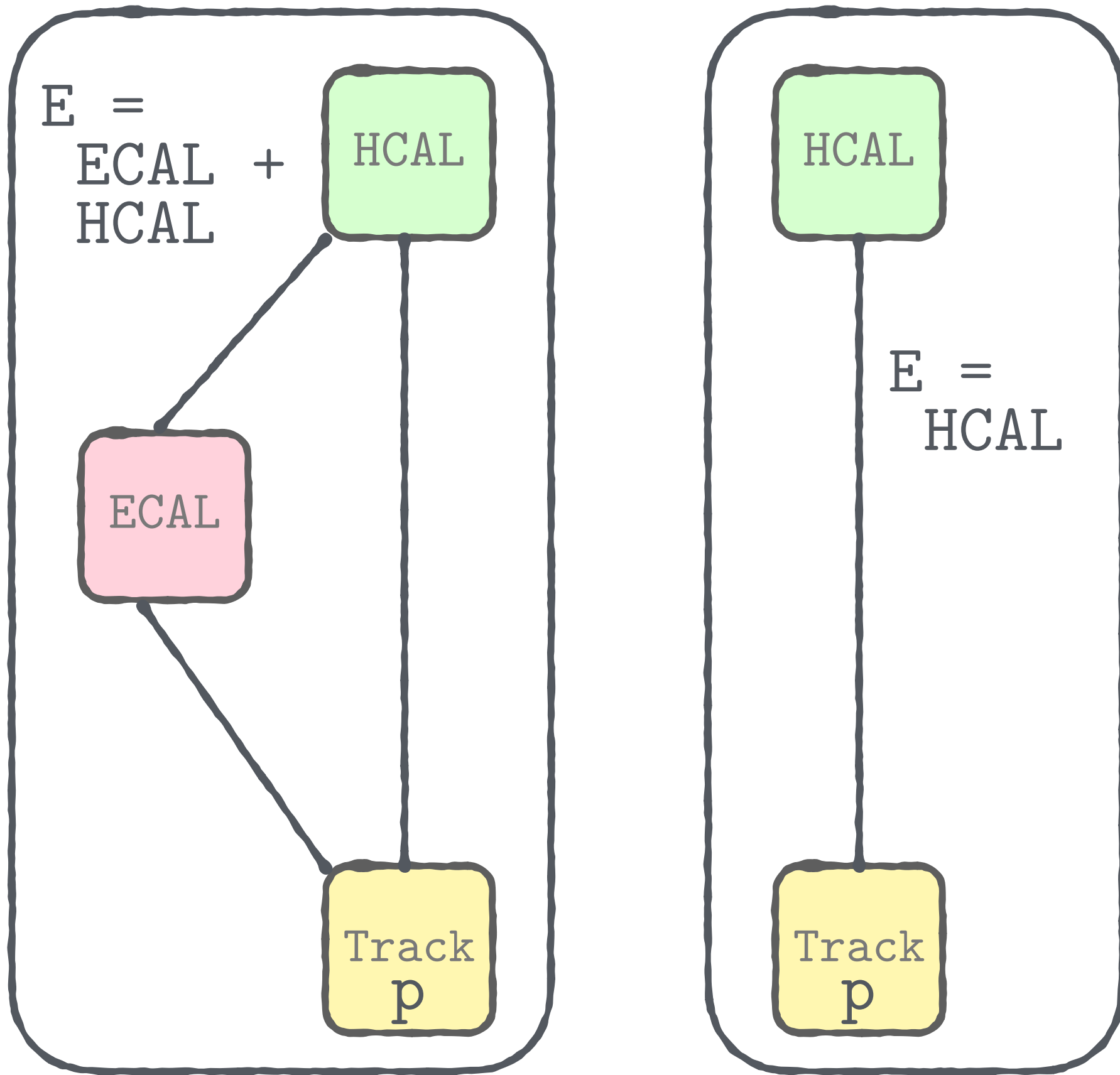
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The diagram shows an L-shaped region. The top-left corner is filled with diagonal hatching and labeled 'E-p'. The rest of the L-shape is light green. To the right, a curved line is labeled 'p'.

attention (doesn't happen often) ...going on...needs

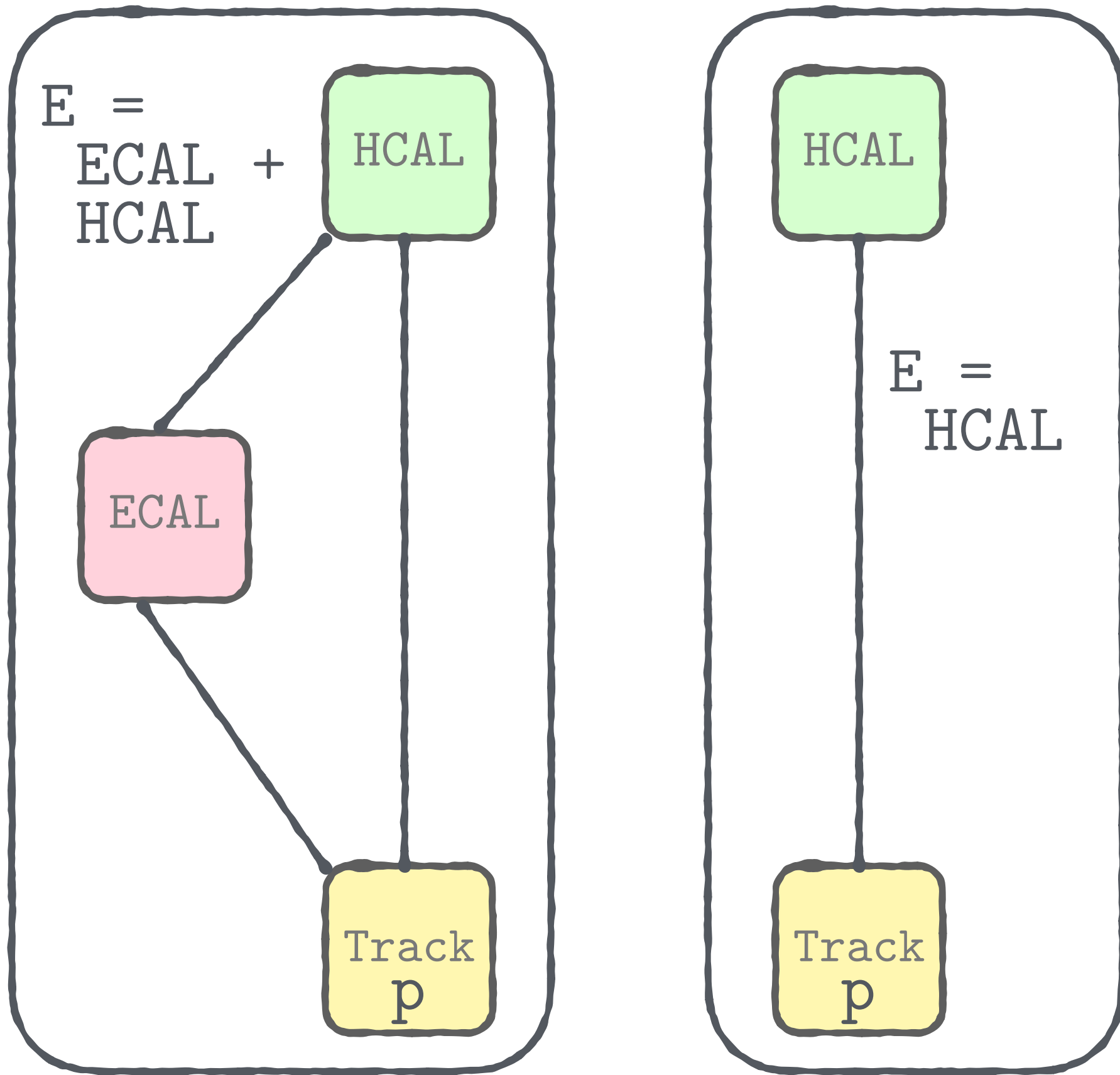
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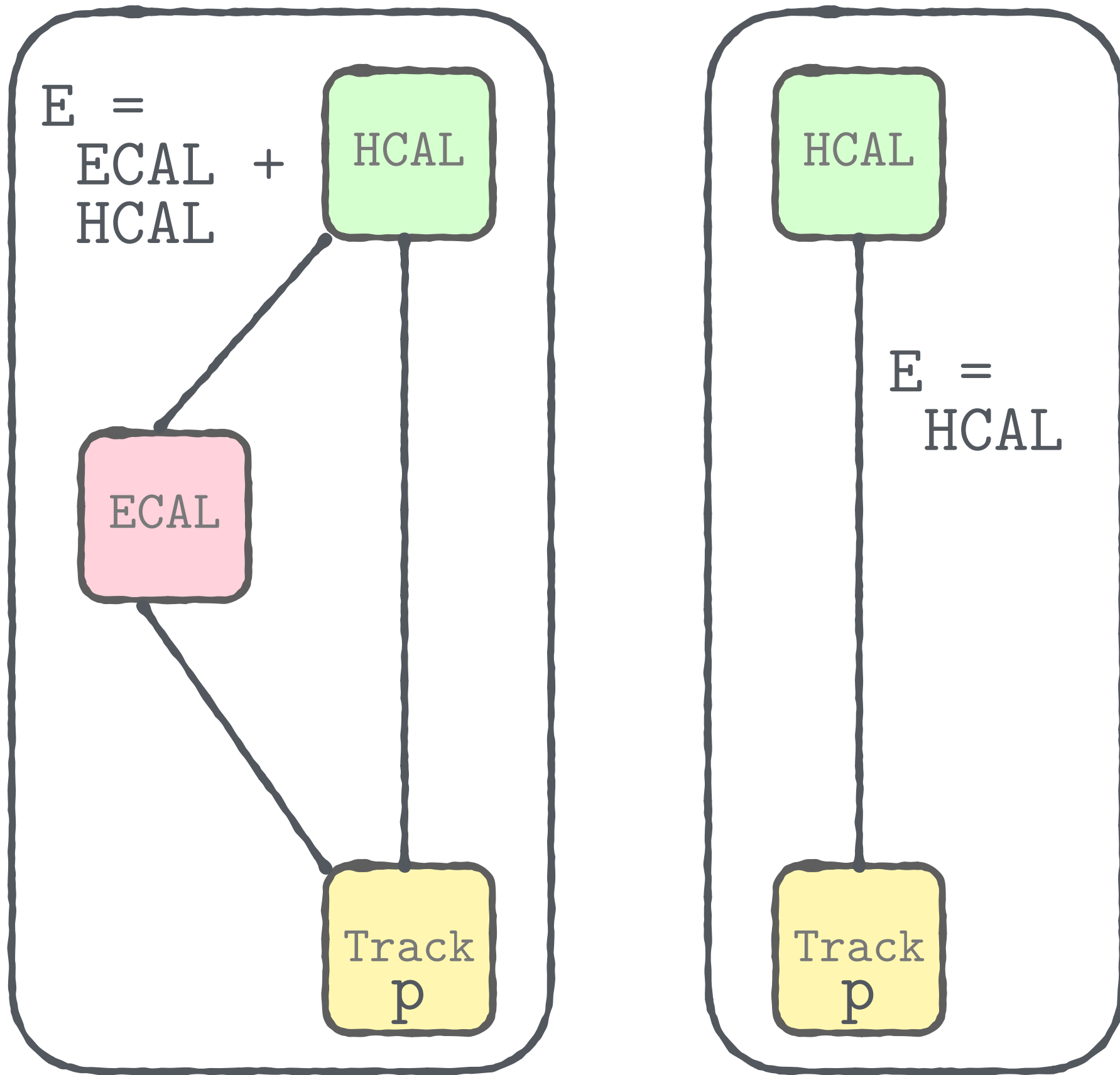
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The diagram shows an L-shaped cluster. The top-left corner is hatched and labeled 'E-p'. The rest of the L-shape is green. A curved line labeled 'p' is shown below the cluster.

attention (doesn't happen often) ...going on...needs

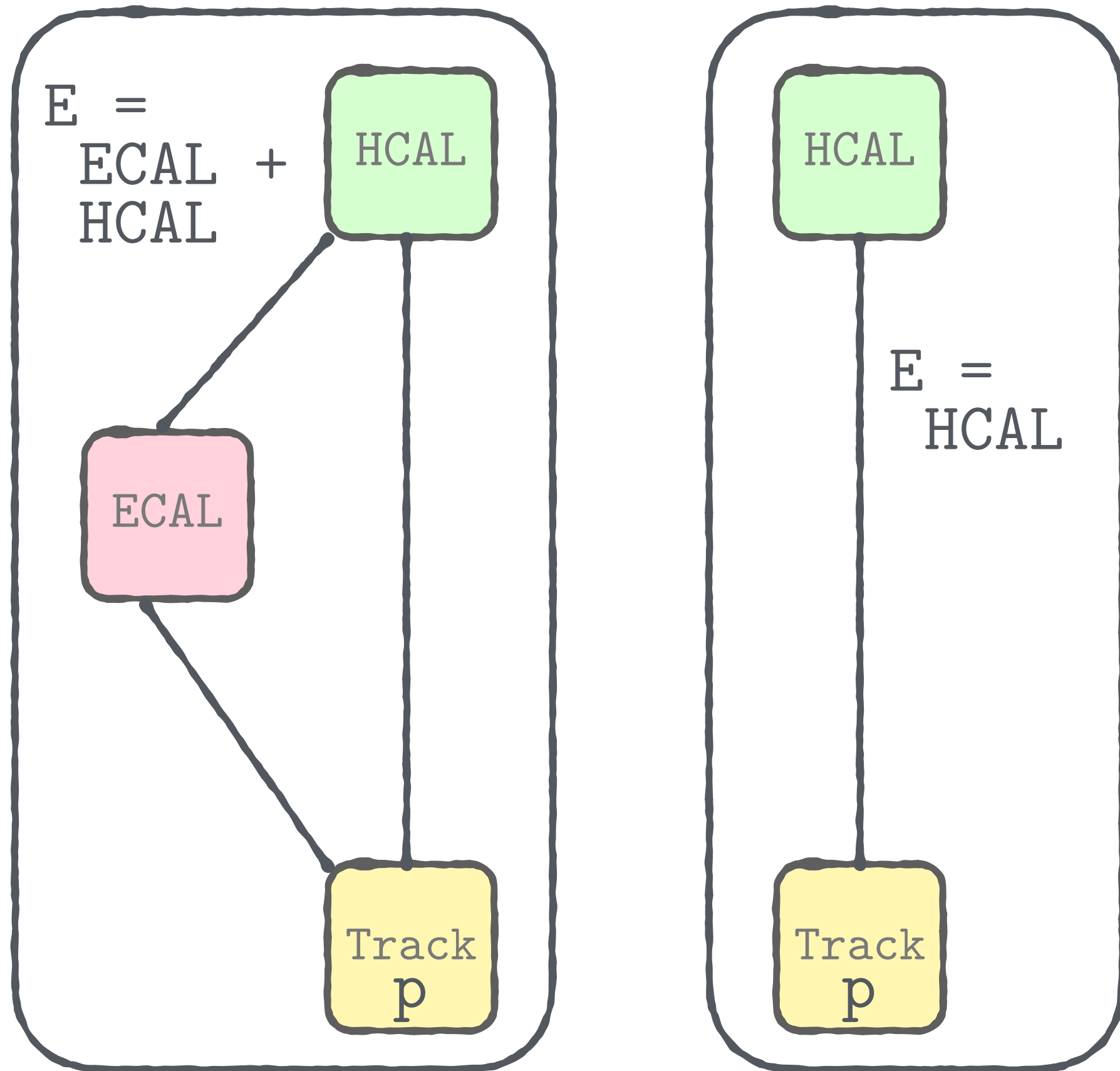
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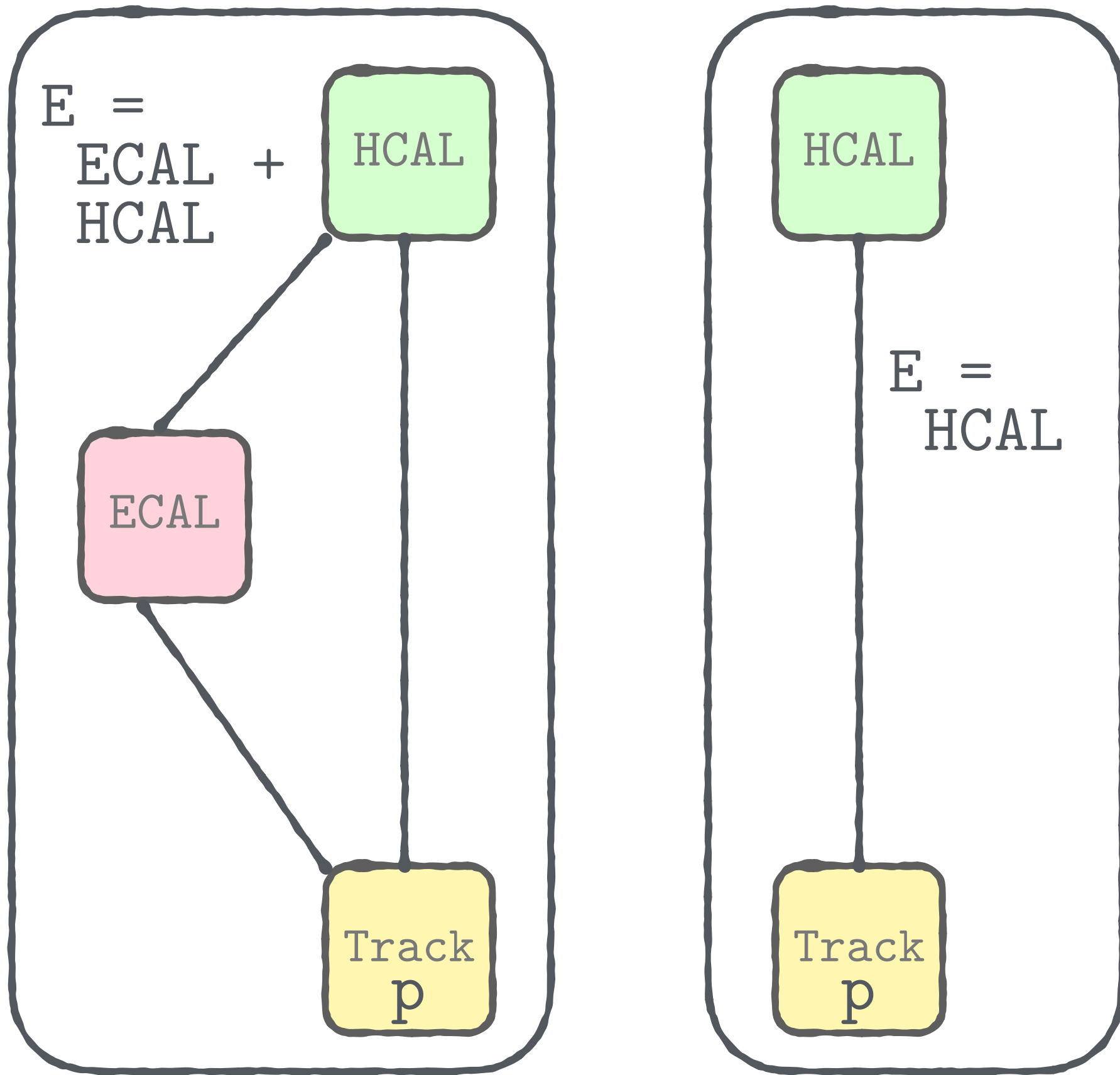
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p

attention (doesn't happen often)

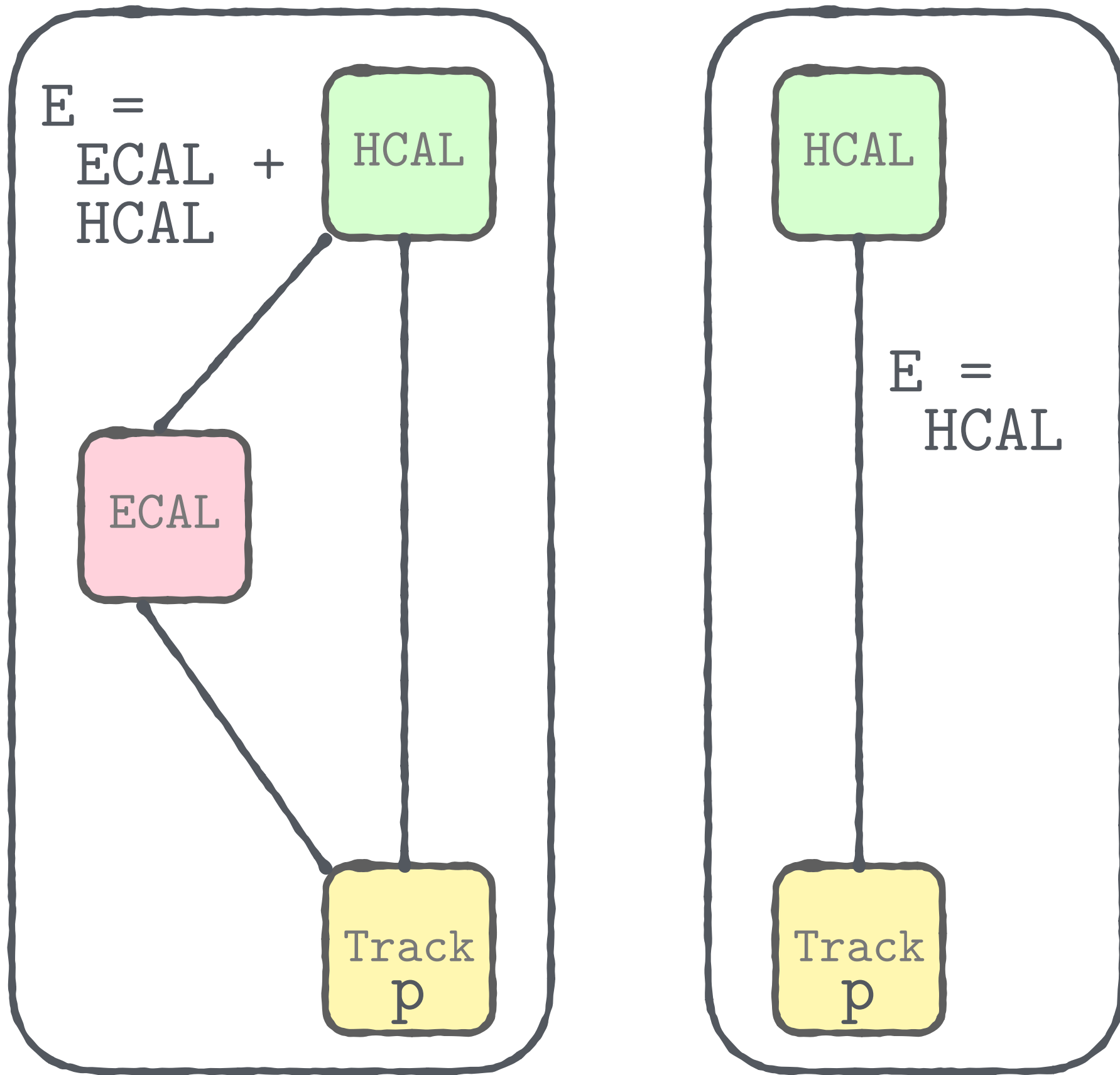
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The complex block contains several overlapping cards with text and diagrams. The top card has the heading 'For each HCAL Cluster compare:' followed by two bullet points '• Sum'. Below it is another card with 'If p and' followed by two bullet points '• Identify' and '• one pe'. The main card features the condition 'If E > p + sigma(E)' followed by three bullet points describing logic for identifying photons and neutral hadrons based on energy (E) and momentum (p) from ECAL and HCAL. To the right of the text are a small pink histogram and a curved line labeled 'p'. At the bottom, a partially visible card says 'attention (doesn't happen often)'. The text '(blocks are usually very small)' is located at the bottom right of the entire image.

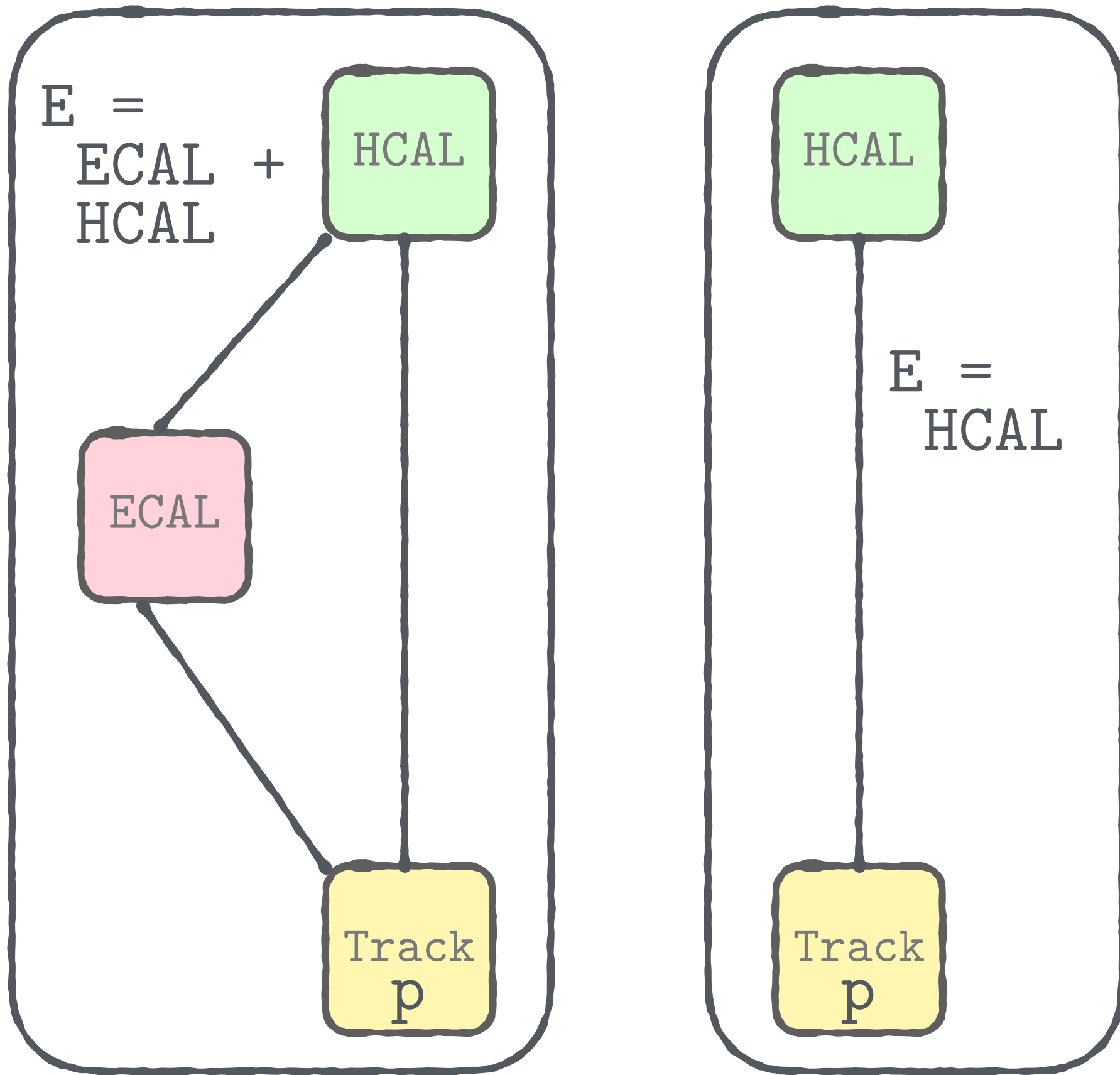
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The complex block contains several overlapping cards with text and diagrams. The top card has the heading 'For each HCAL Cluster compare:' and two bullet points '• Sum'. Below it is another card with 'If p and' and two bullet points '• Identify' and '• one pe'. The main card has the heading 'If $E > p + \sigma(E)$ ' and a list of conditions. To the right of the text are three small diagrams: a green L-shaped cluster, a pink T-shaped cluster, and a yellow curved track labeled 'p'. At the bottom of the cards, there is a note: 'attention (doesn't happen often) ... going on...needs'.

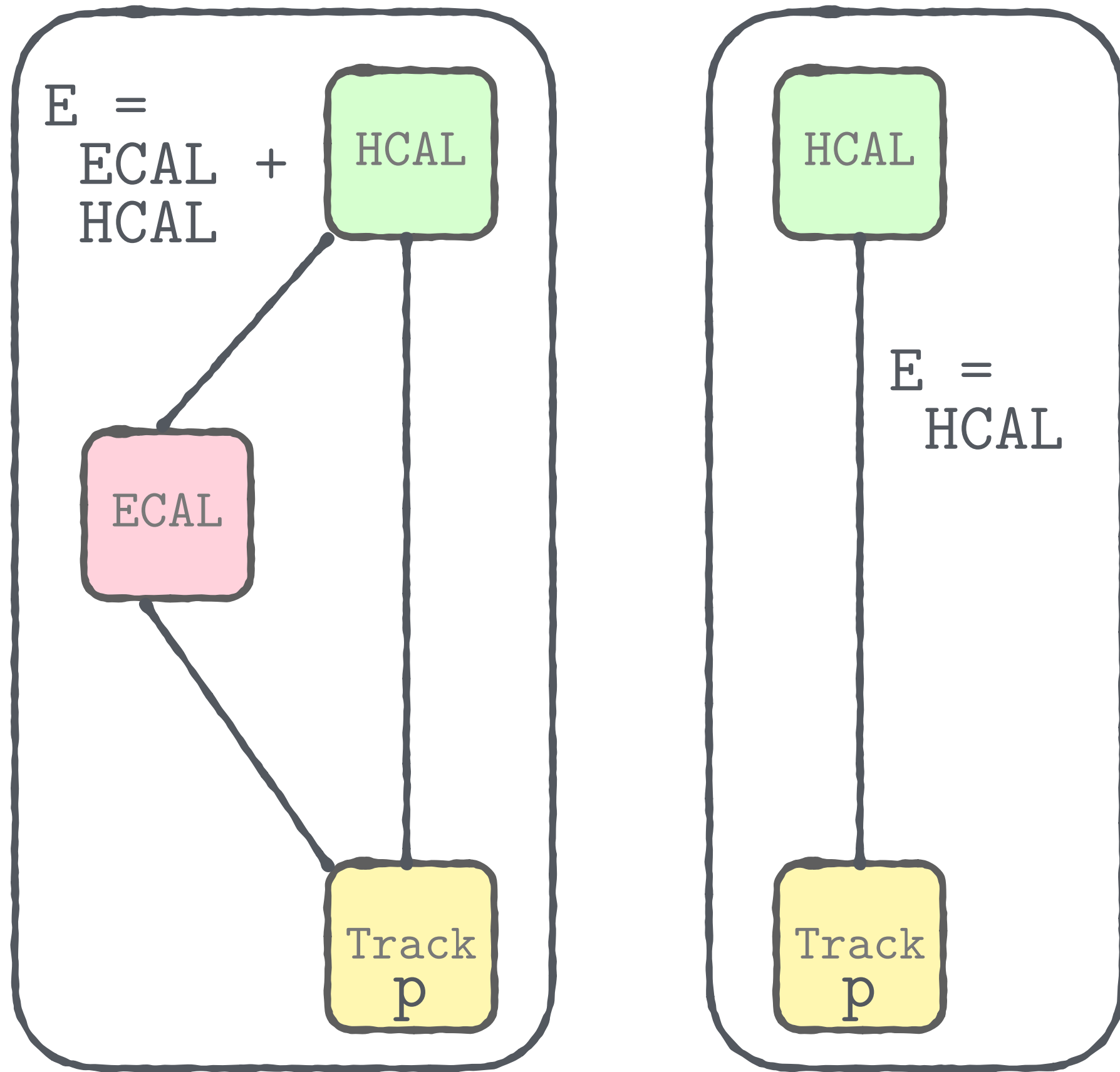
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The complex block contains several diagrams. On the right side, there are three distinct shapes: a light green L-shaped block, a red hatched block with the label 'ECAL' to its right, and a curved black line with the label 'p' to its right.

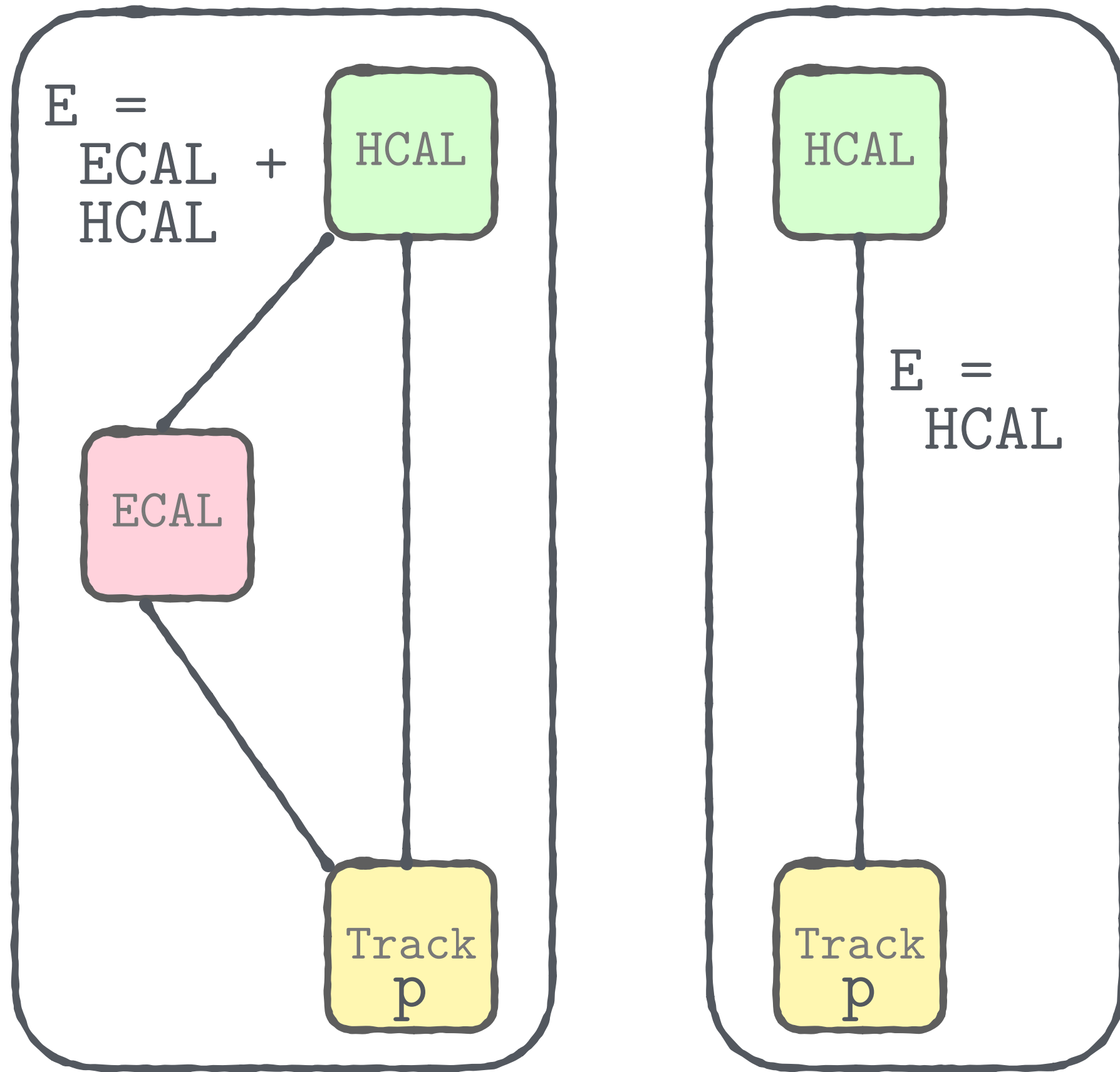
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The diagrams show three energy distributions: 1) 'HCAL-p' represented by a light green L-shaped area with a hatched top-left corner; 2) 'ECAL' represented by a red hatched L-shaped area; 3) 'p' represented by a curved line.

attention (doesn't happen often) ... needs

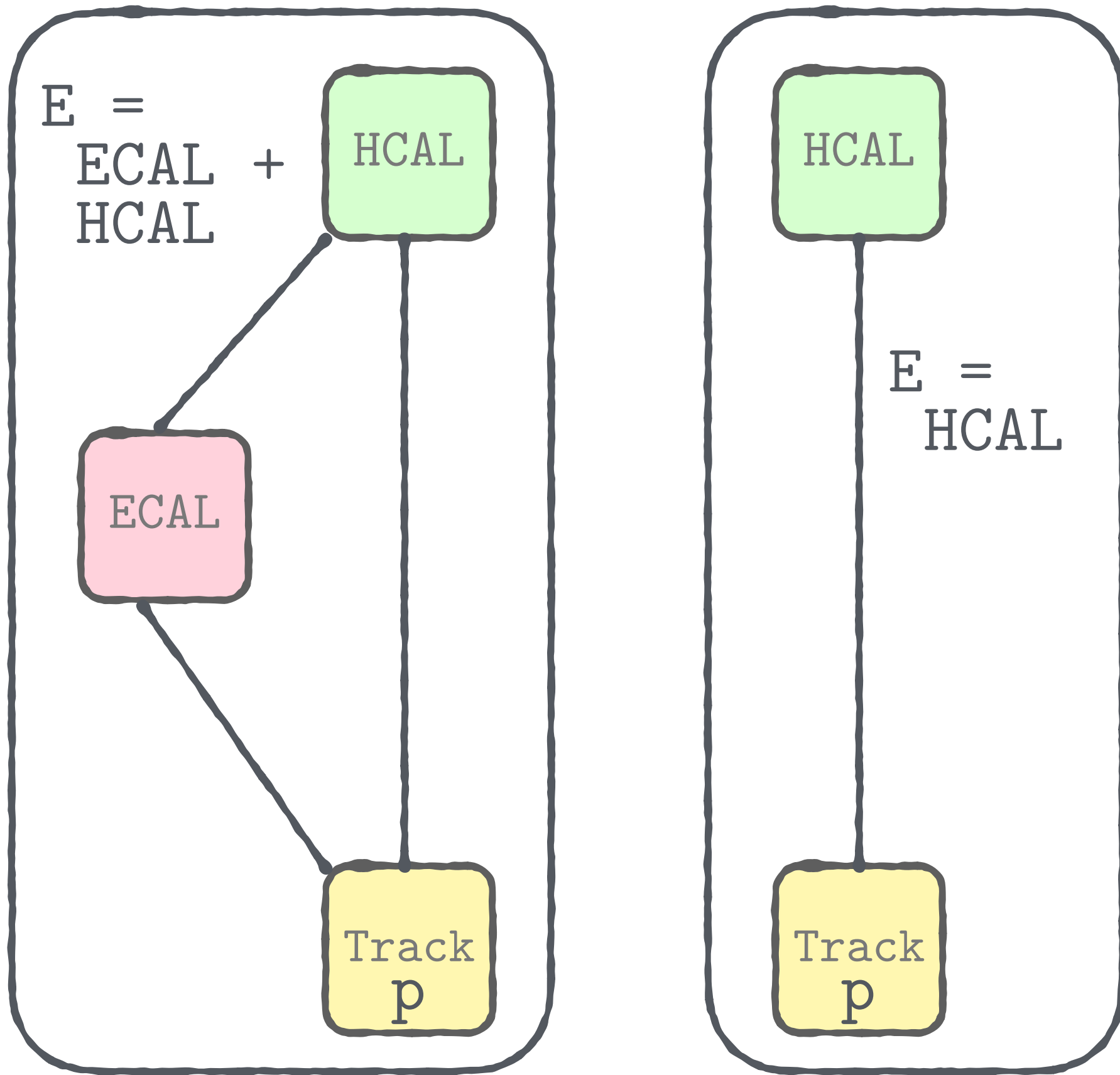
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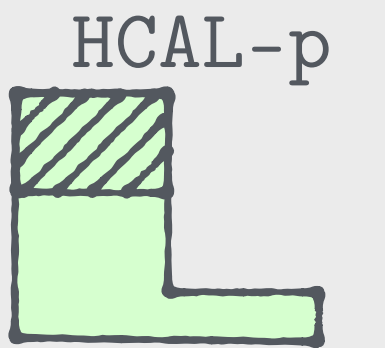
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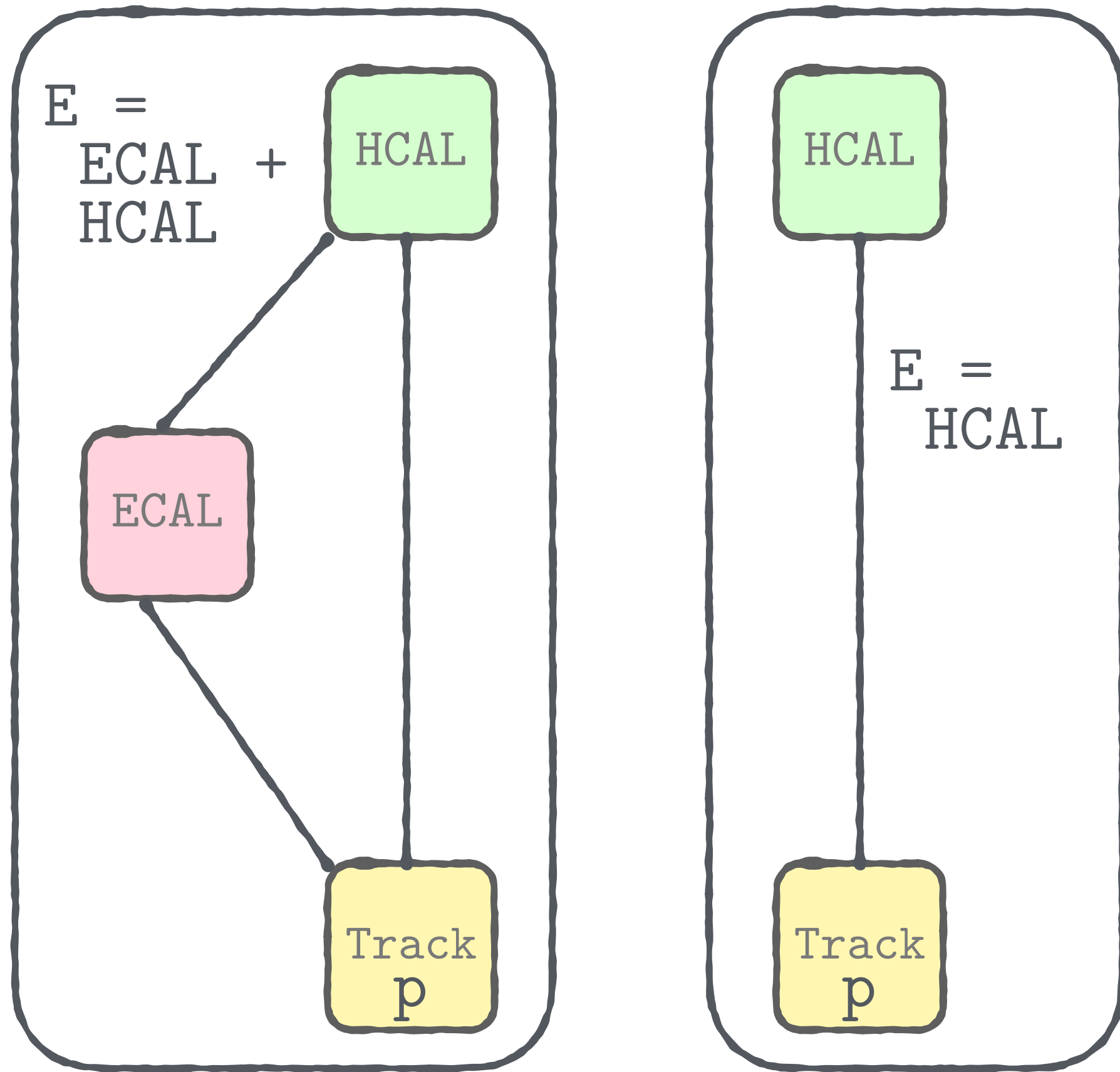
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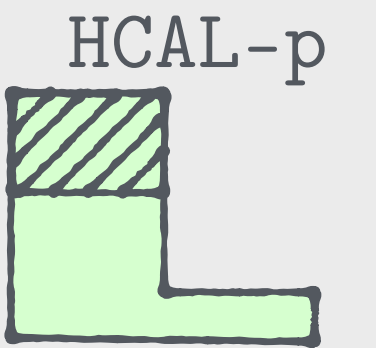
- Sum
- Sum

If p and

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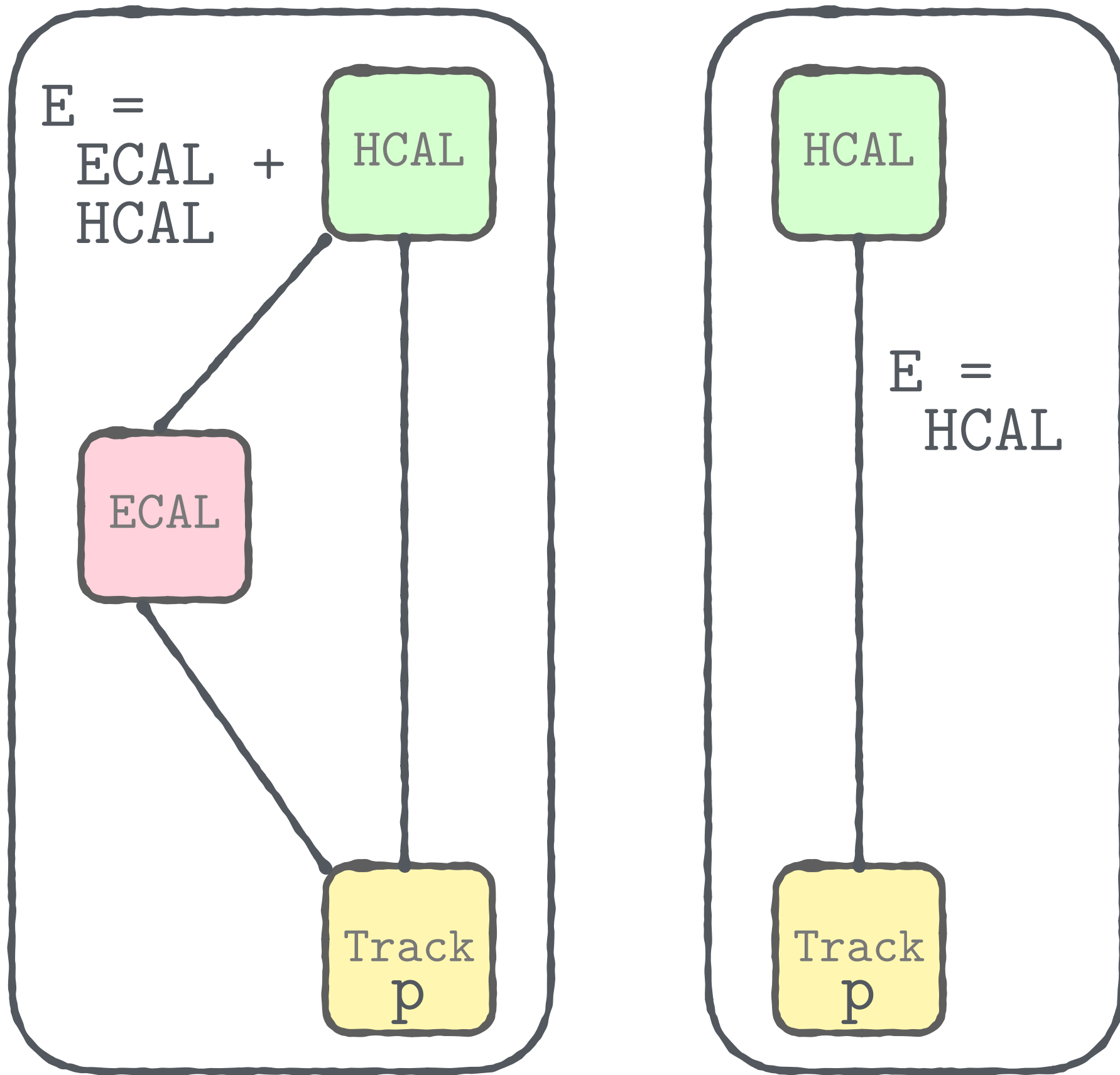
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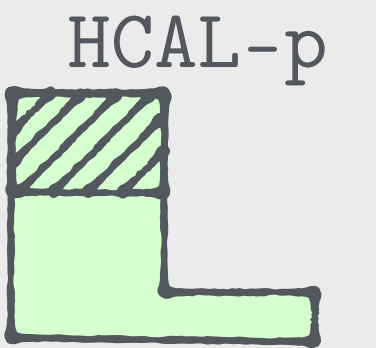
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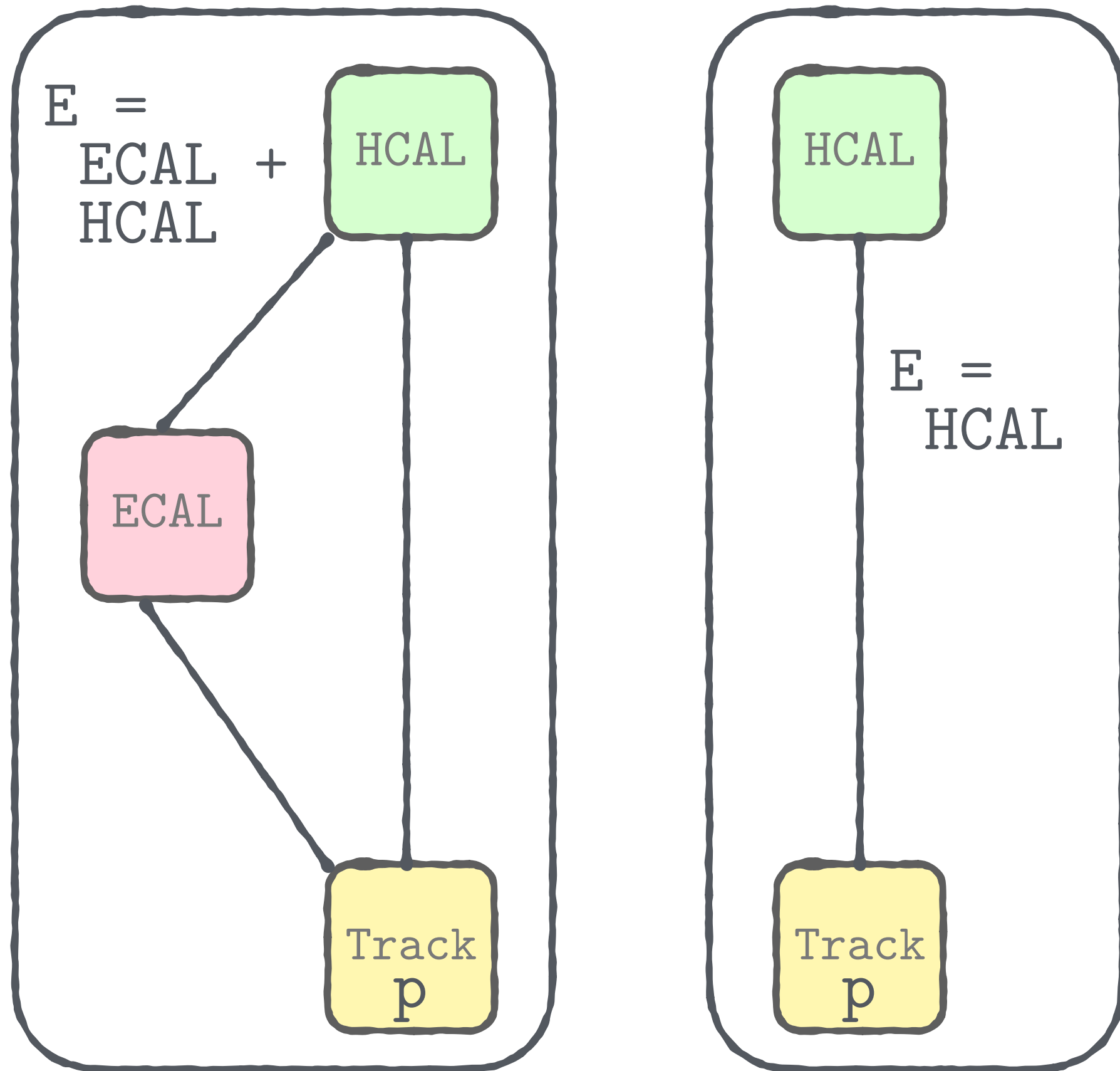
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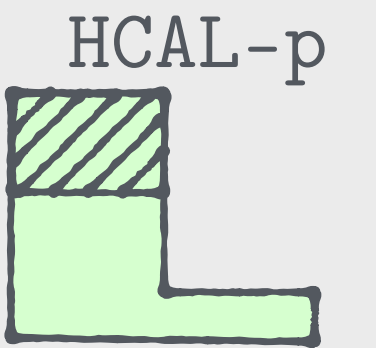
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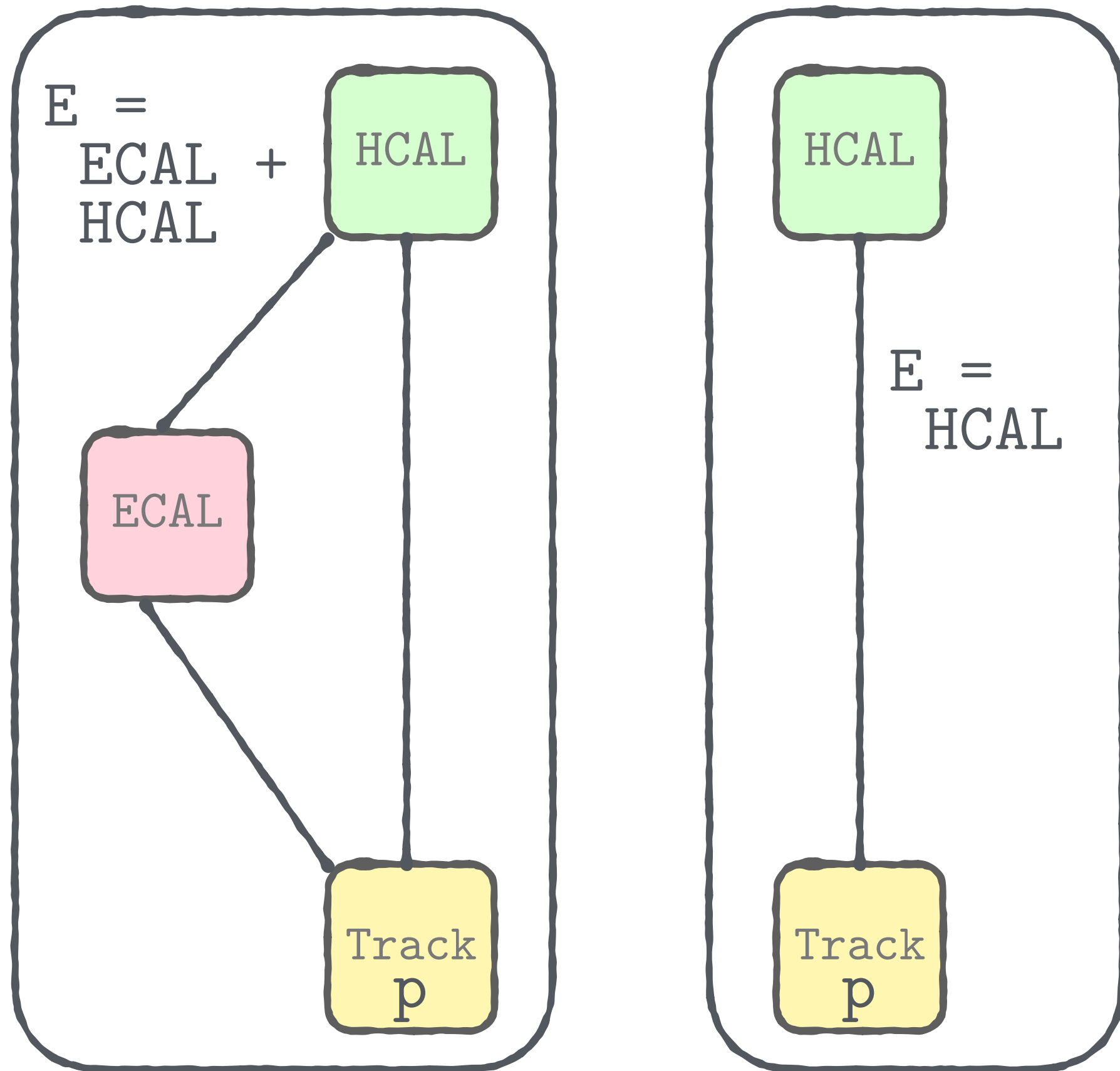
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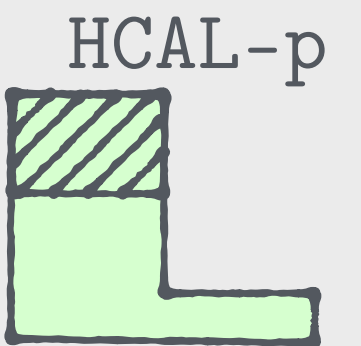
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If $E > p + \sigma(E)$

- If E is just ECAL or just HCAL
 - ECAL: photon (E-p)
 - HCAL: neutral hadron (E-p)
- If E from both ECAL and HCAL
 - if (E-p) > ECAL then photon (ECAL) + neutral hadron (HCAL - p)
 - otherwise photon (E-p)/b



attention (doesn't happen often)

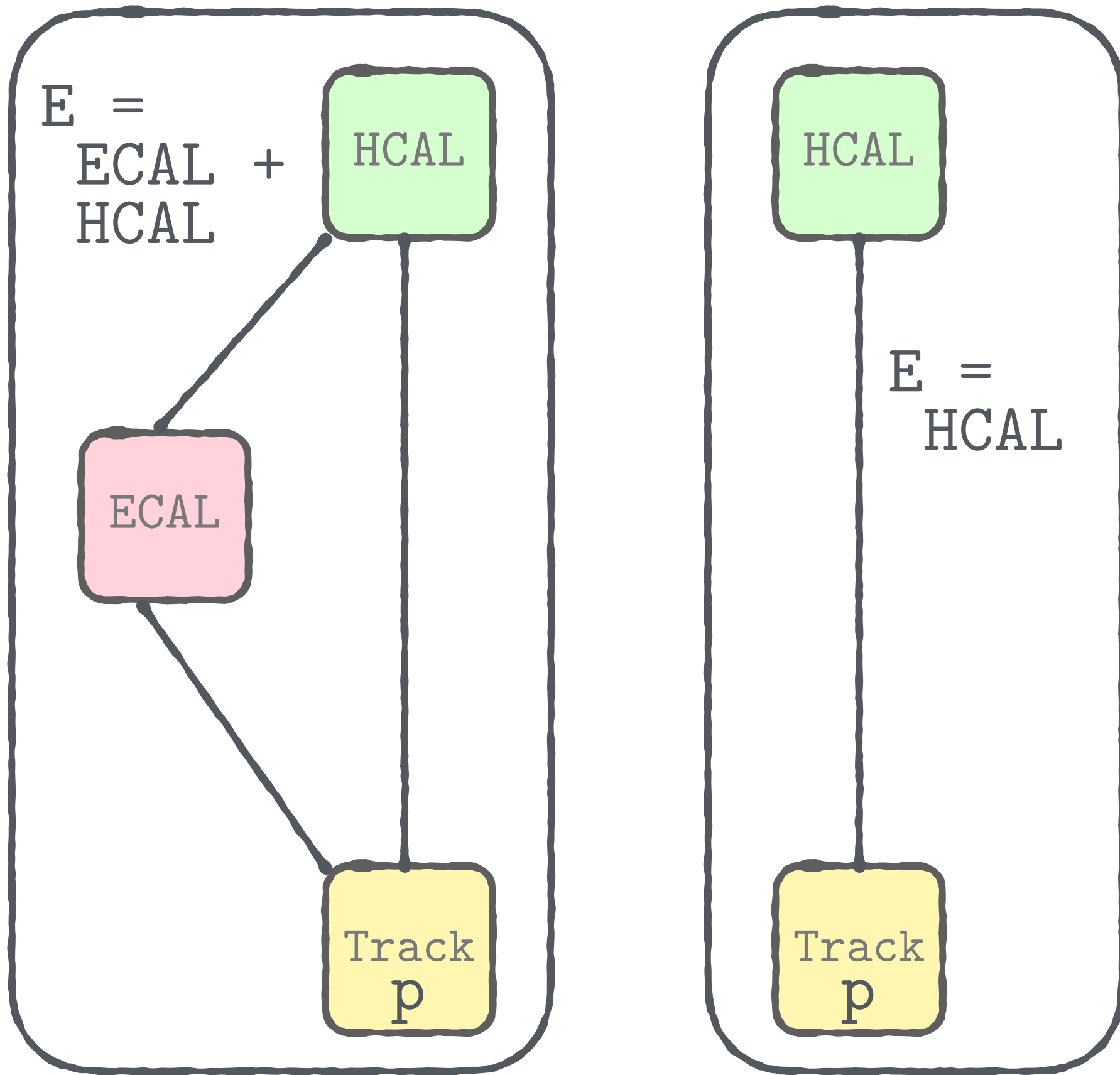
(blocks are usually very small)

Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

Simplified block (2nd step)

Find charged hadrons & merged photons / neutral hadrons



List of reconstructed (candidate) particles

$$\{\gamma, \gamma, \gamma,$$

For each HCAL Cluster compare:

- Sum
- Sum

If p and

- Identify
- one pe

If $E > p + \sigma(E)$

- If E is just ECAL or just HCAL
 - ECAL: photon (E-p)
 - HCAL: neutral hadron (E-p)
- If E from both ECAL and HCAL
 - if (E-p) > ECAL then photon (ECAL) + neutral hadron (HCAL - p)
 - otherwise photon (E-p)/b

The complex block contains several overlapping cards with text and diagrams. The top card has the heading 'For each HCAL Cluster compare:' and two bullet points. The middle card has the heading 'If p and' and two bullet points. The bottom card has the heading 'If E > p + sigma(E)' and a list of conditions. To the right of the text are three small diagrams: a green L-shaped cluster, a pink T-shaped cluster, and a curved line labeled 'p'.

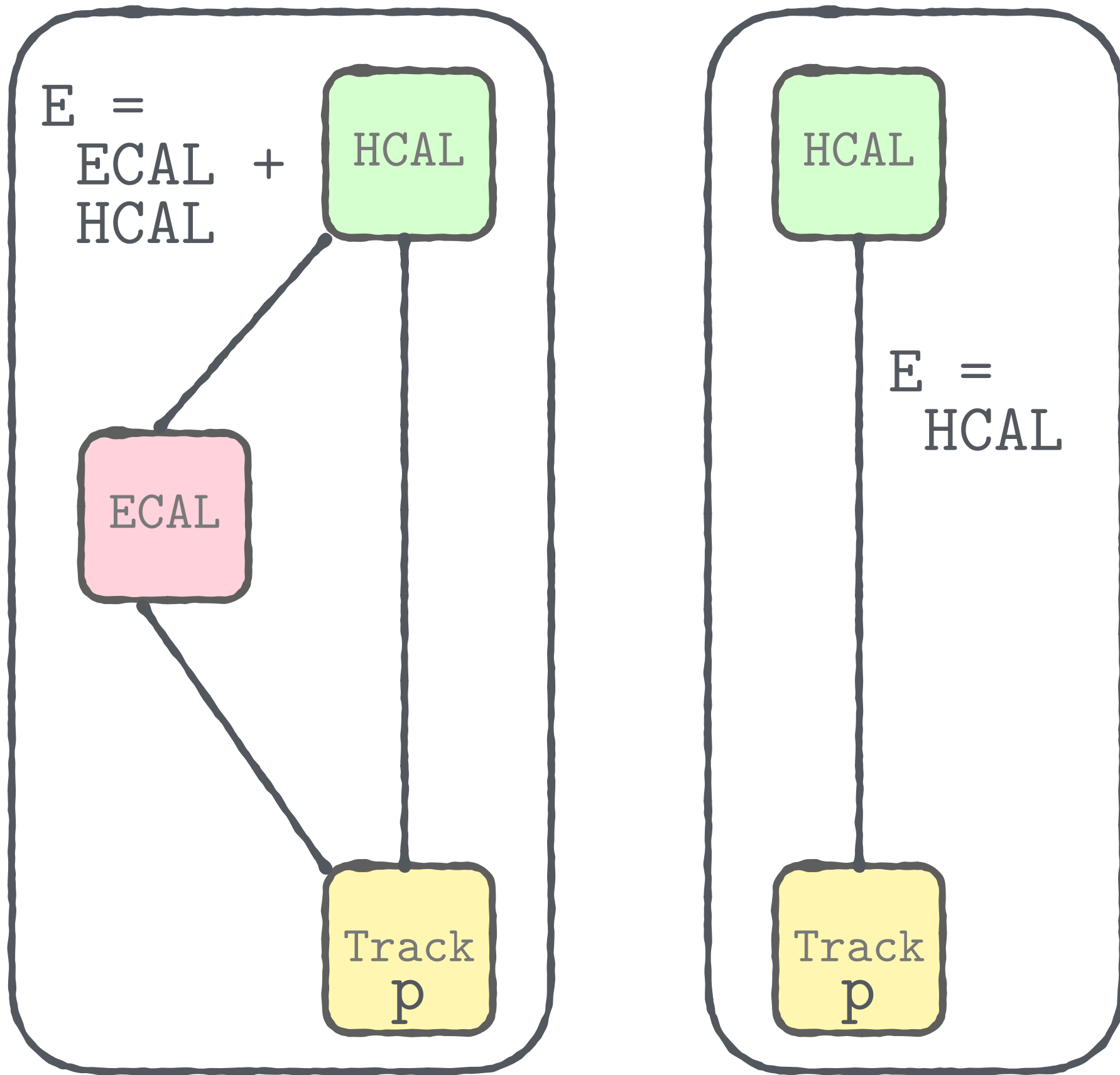
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Simplified block (2nd step)

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 - HCAL: neutral hadron $(E-p)$
- If E from both ECAL and HCAL
 - if $(E-p) > \text{ECAL}$ then photon $(\text{ECAL}) +$ neutral hadron $(\text{HCAL} - p)$
 - otherwise photon $(E-p)/b$

The complex block contains three diagrams. The top diagram is a light green L-shaped block representing HCAL. The middle diagram shows a pink ECAL block and a light green HCAL block stacked vertically, with a hatched top section on the ECAL block and the label $\frac{E-p}{b}$ next to it. The bottom diagram is a yellow curved line representing a track, labeled 'p'.

attention (doesn't happen often)

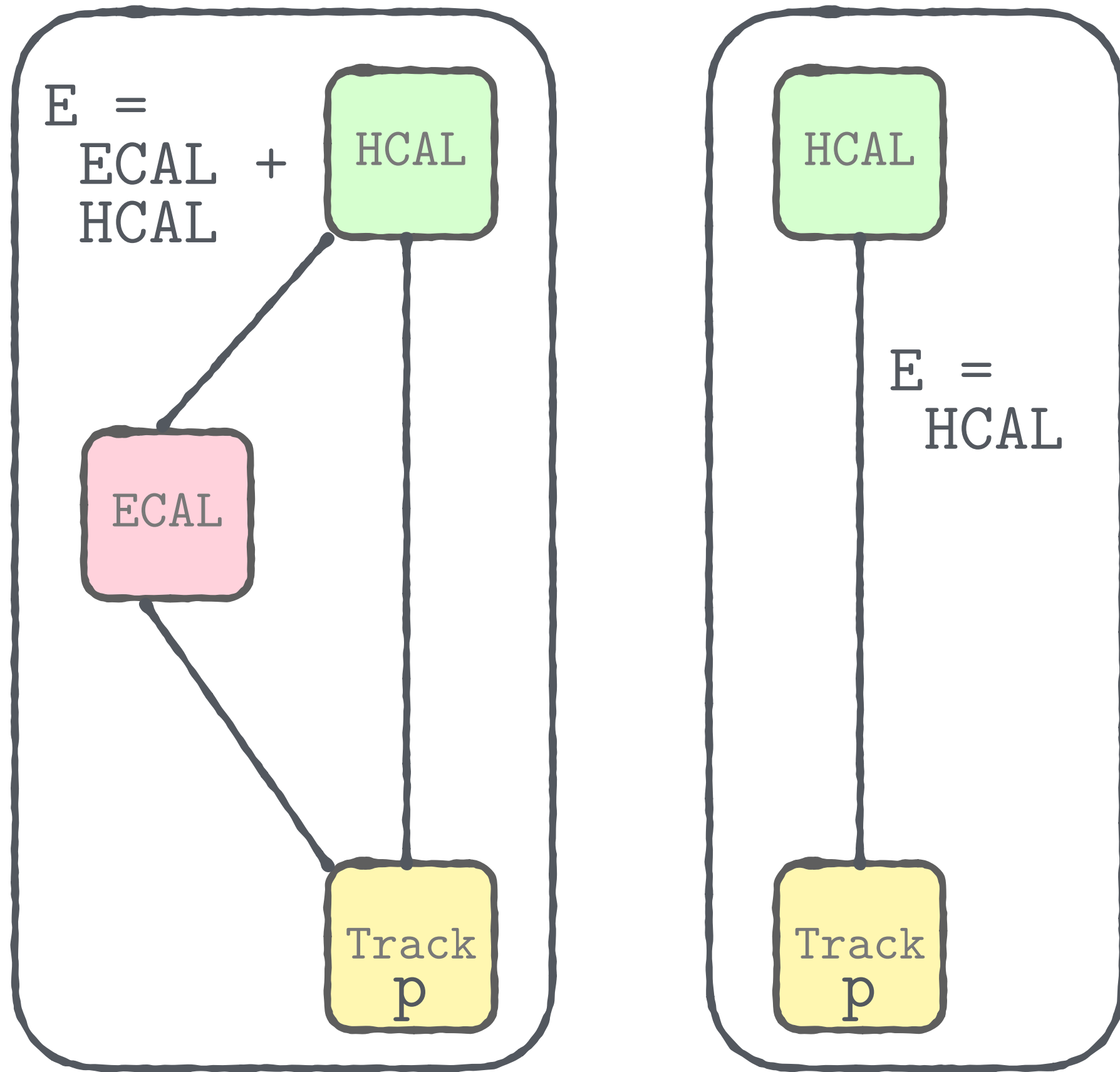
(blocks are usually very small)

Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

Simplified block (2nd step)

Find charged hadrons & merged photons / neutral hadrons



List of reconstructed (candidate) particles

$$\{\gamma, \gamma, \gamma, \pi^-\}$$

For each HCAL Cluster compare:

- Sum
- Sum

If p and

- Identify
- one pe

If $E > p + \sigma(E)$

- If E is just ECAL or just HCAL
 - ECAL: photon $(E-p)$
 - HCAL: neutral hadron $(E-p)$
- If E from both ECAL and HCAL
 - if $(E-p) > \text{ECAL}$ then photon $(\text{ECAL}) +$ neutral hadron $(\text{HCAL} - p)$
 - otherwise photon $(E-p)/b$

The diagrams show: 1) A light green L-shaped block representing HCAL. 2) A pink block (ECAL) on top of a light green block (HCAL), with a hatched top section and the label $\frac{E-p}{b}$ to its right. 3) A yellow curved block representing a track with momentum p.

attention (doesn't happen often)

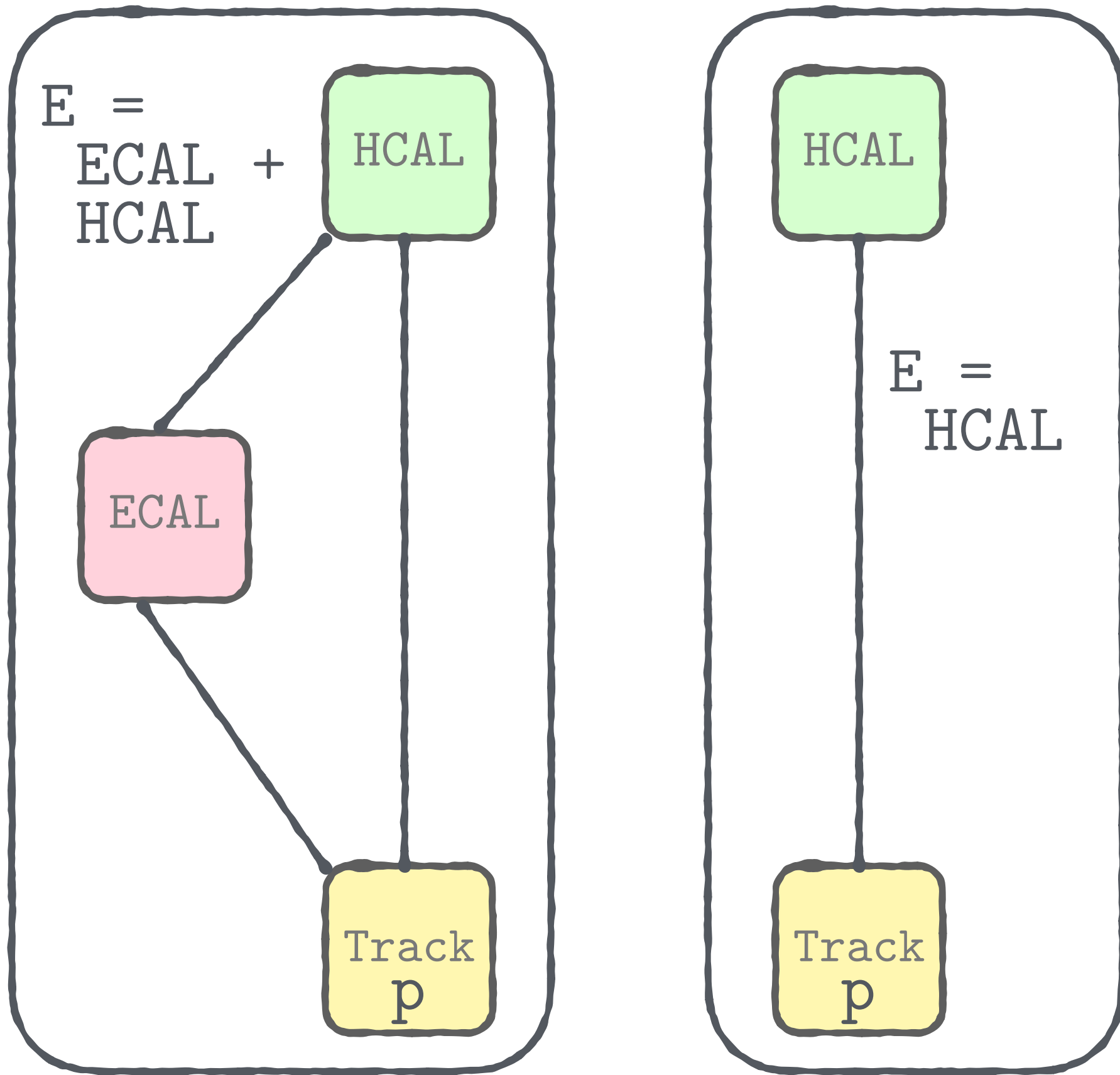
(blocks are usually very small)

Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

Simplified block (2nd step)

Find charged hadrons & merged photons / neutral hadrons



List of reconstructed (candidate) particles

$$\{\gamma, \gamma, \gamma, \pi^-,$$

For each HCAL Cluster compare:

- Sum
- Sum

If p and

- Identify
- one pe

If $E > p + \sigma(E)$

- If E is just ECAL or just HCAL
 - ECAL: photon $(E-p)$
 - HCAL: neutral hadron $(E-p)$
- If E from both ECAL and HCAL
 - if $(E-p) > \text{ECAL}$ then photon $(\text{ECAL}) +$ neutral hadron $(\text{HCAL} - p)$
 - otherwise photon $(E-p)/b$

The complex block contains three diagrams on the right side. The top one is an L-shaped light green block. The middle one is a pink block with a hatched top section, with the fraction $\frac{E-p}{b}$ next to it. The bottom one is a curved line labeled 'p'.

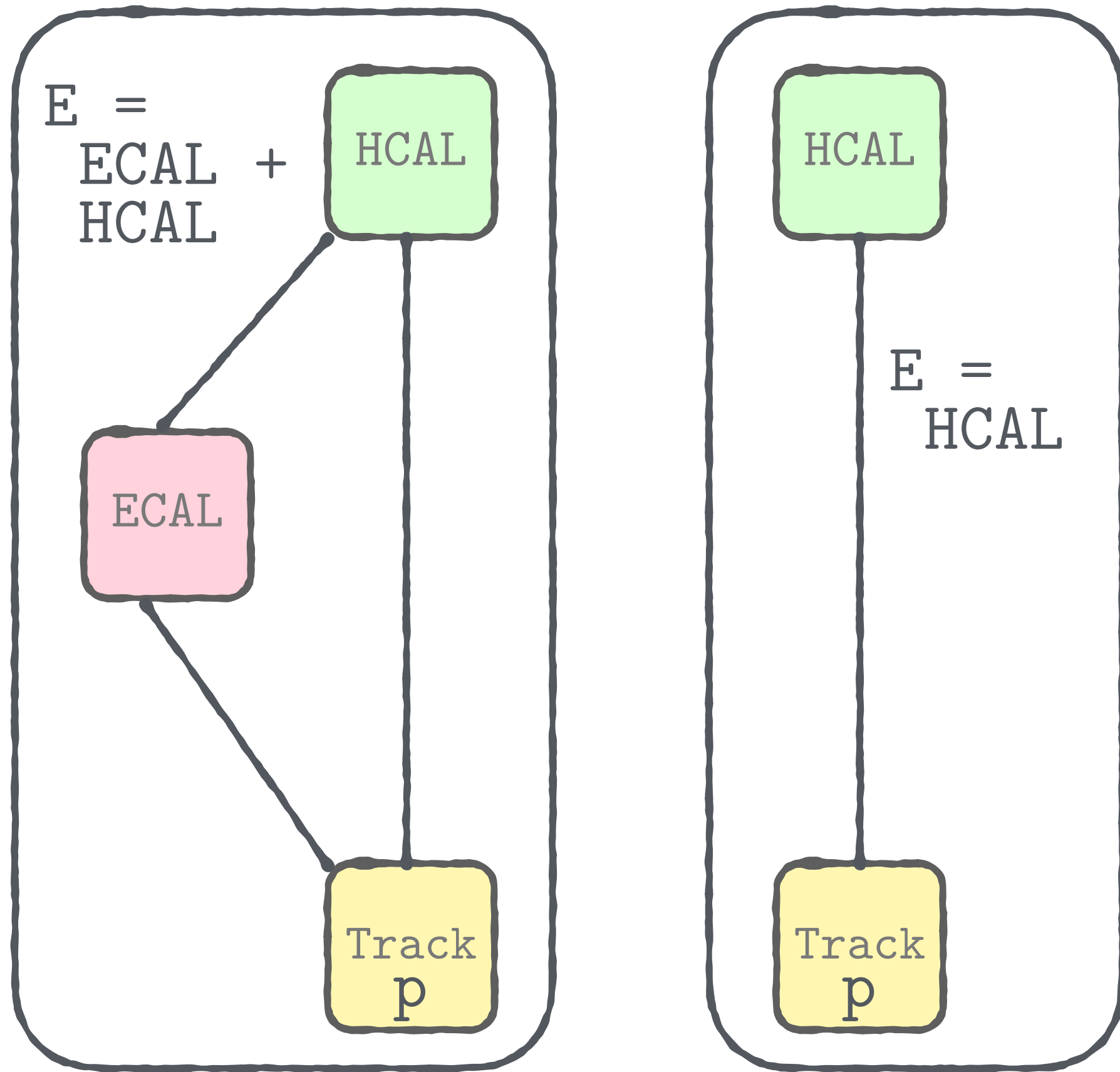
(blocks are usually very small)

Four true particles:

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Simplified block (2nd step)

Find charged hadrons & merged photons / neutral hadrons



List of reconstructed (candidate) particles

$$\{\gamma, \gamma, \gamma, \pi^-, \gamma\}$$

For each HCAL Cluster compare:

- Sum
- Sum

If p and

- Identify
- one pe

If $E > p + \sigma(E)$

- If E is just ECAL or just HCAL
 - ECAL: photon (E-p)
 - HCAL: neutral hadron (E-p)
- If E from both ECAL and HCAL
 - if (E-p) > ECAL then photon (ECAL) + neutral hadron (HCAL - p)
 - otherwise photon (E-p)/b

The complex block contains several diagrams. On the right, there is a light green L-shaped cluster. Below it is a pink T-shaped cluster with a hatched top bar. To the right of the T-shaped cluster is the label $\frac{E-p}{b}$. Below the T-shaped cluster is a yellow curved line labeled 'p'. At the bottom of the block, there is a note: 'attention (doesn't happen often) ... going on...needs'.

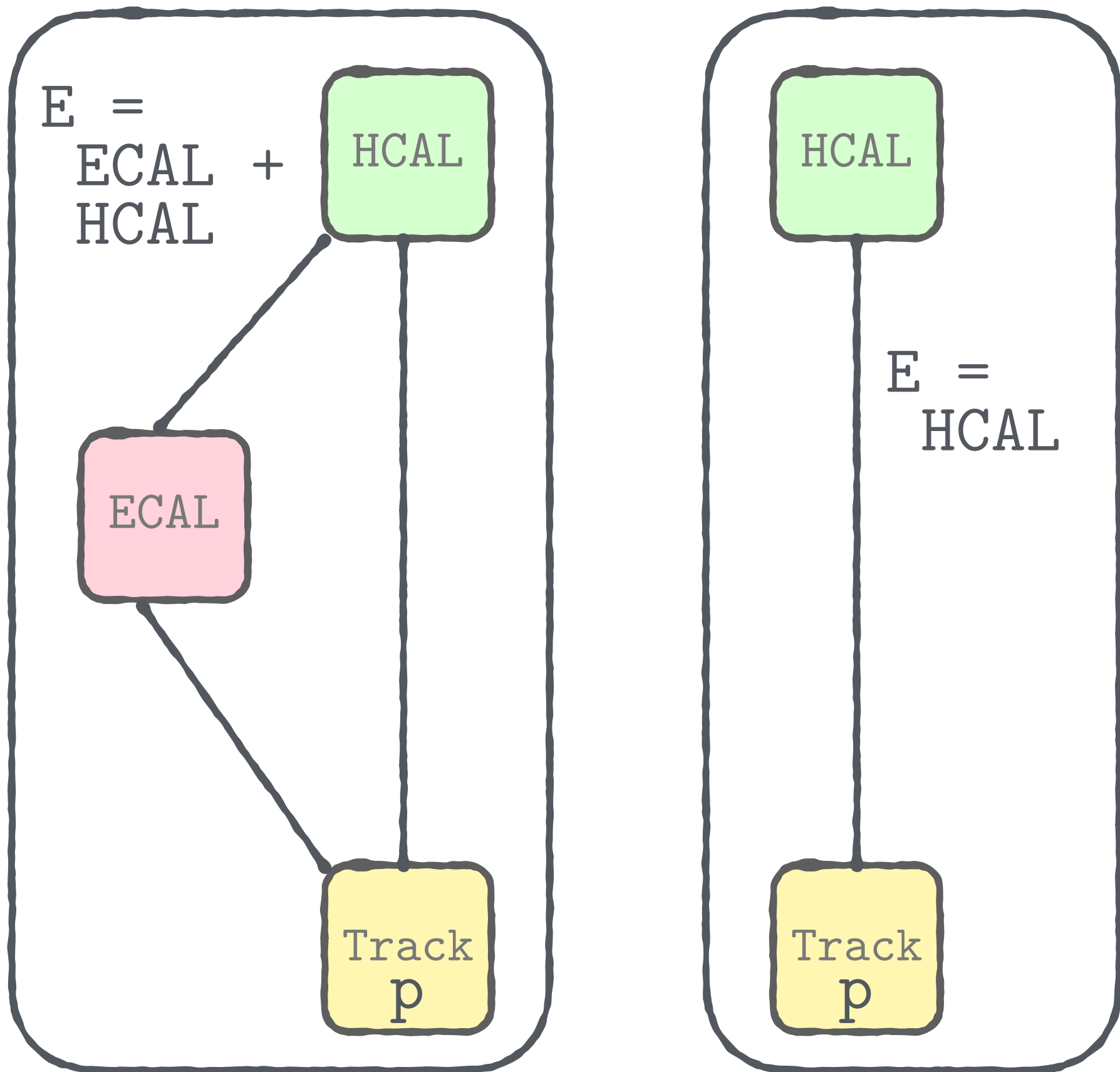
(blocks are usually very small)

Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

Simplified block (2nd step)

Find charged hadrons & merged photons / neutral hadrons



For each HCAL Cluster compare:

- Sum
- Sum

If p and

- Identify
- one pe

If $E > p + \sigma(E)$

- If E is just ECAL or just HCAL
 - ECAL: photon $(E-p)$
 - HCAL: neutral hadron $(E-p)$
- If E from both ECAL and HCAL
 - if $(E-p) > \text{ECAL}$ then photon $(\text{ECAL}) +$ neutral hadron $(\text{HCAL} - p)$
 - otherwise photon $(E-p)/b$

The complex block contains three diagrams on the right side. The top one is an L-shaped light green block. The middle one is a pink block with a hatched top, labeled with the fraction $\frac{E-p}{b}$. The bottom one is a curved line labeled 'p'.

List of reconstructed (candidate) particles

$$\{\gamma, \gamma, \gamma, \pi^-, \gamma\}$$

Always give precedence to photons in ECAL

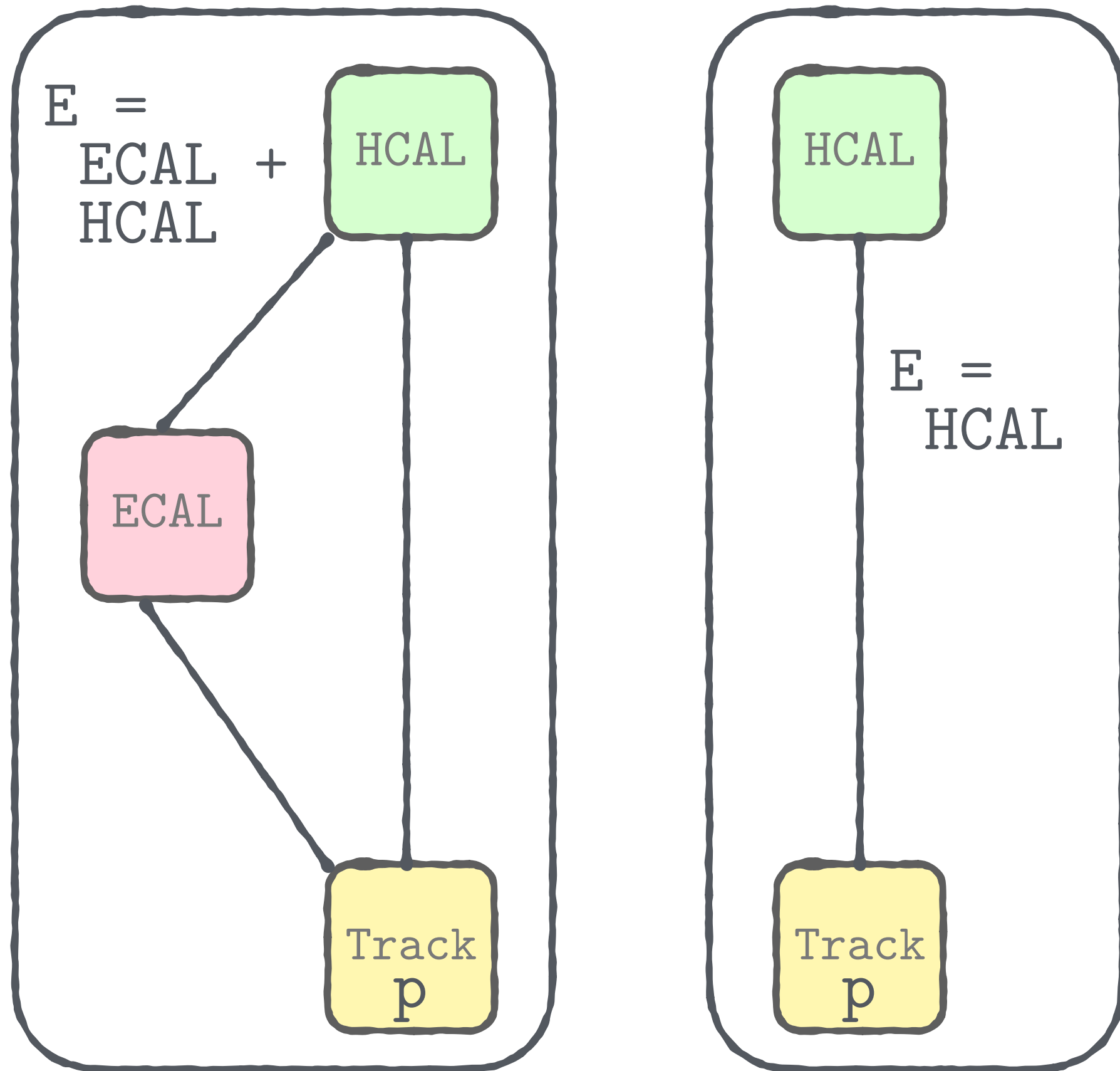
(blocks are usually very small)

Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

Simplified block (2nd step)

Find charged hadrons & merged photons / neutral hadrons



For each HCAL Cluster compare:

- Sum
- Sum
- lin in "had"

If $E > p + \sigma(E)$

- If E is just ECAL or just HCAL
 - ECAL: photon (E-p)
 - HCAL: neutral hadron (E-p)
- If E from both ECAL and HCAL
 - if (E-p) > ECAL then photon (ECAL) + neutral hadron (HCAL - p)
- otherwise photon (E-p)/b

The complex block contains three diagrams. The first is a light green L-shaped block. The second is a pink block with a hatched top section, with the label $\frac{E-p}{b}$ to its right. The third is a curved line labeled 'p'.

List of reconstructed (candidate) particles

$$\{\gamma, \gamma, \gamma,$$

Always give precedence to photons in ECAL

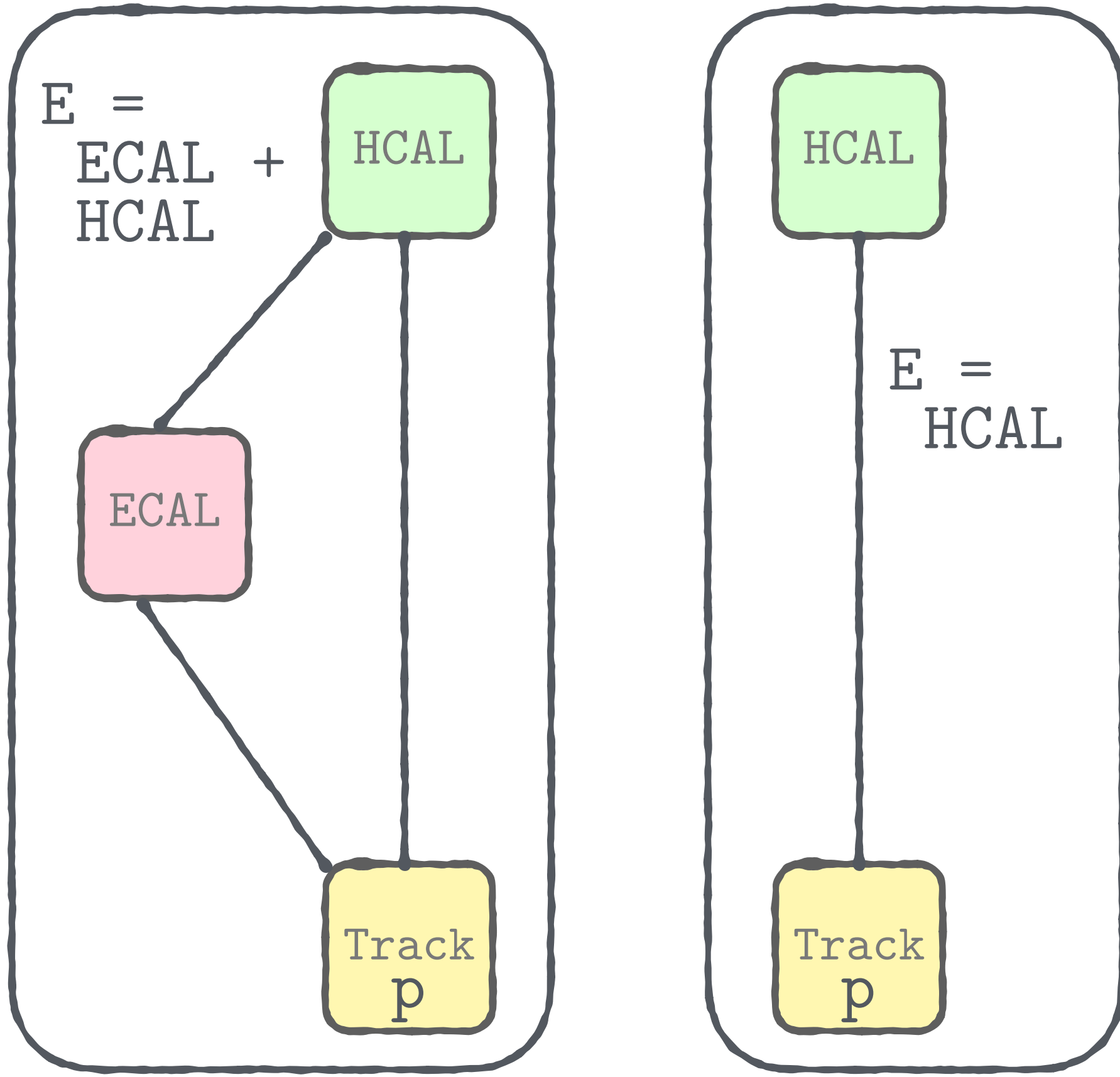
(blocks are usually very small)

Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

Simplified block (2nd step)

Find charged hadrons & merged photons / neutral hadrons



List of reconstructed (candidate) p

$\{\gamma, \gamma, \gamma,$

Always give precedence to photons in ECAL

(blocks are usually very small)

For each HCAL Cluster compare:

- Sum
- Sum

If p and E are compatible

- Fit p_i and E according to $\sigma(E, p_i)$
- uncertainty weighted average

The graph plots $\sigma(E)/E$ on the y-axis against p_T on the x-axis. It features three data series: a red line with downward-pointing triangles labeled 'ECAL', a green line with upward-pointing triangles labeled 'Tracker', and a blue line with dots labeled 'Combined'. The 'ECAL' curve starts high and decreases as p_T increases. The 'Tracker' curve starts low and increases as p_T increases. The 'Combined' curve is the lowest and flattest, representing the uncertainty-weighted average of the other two.

...needs
en often)

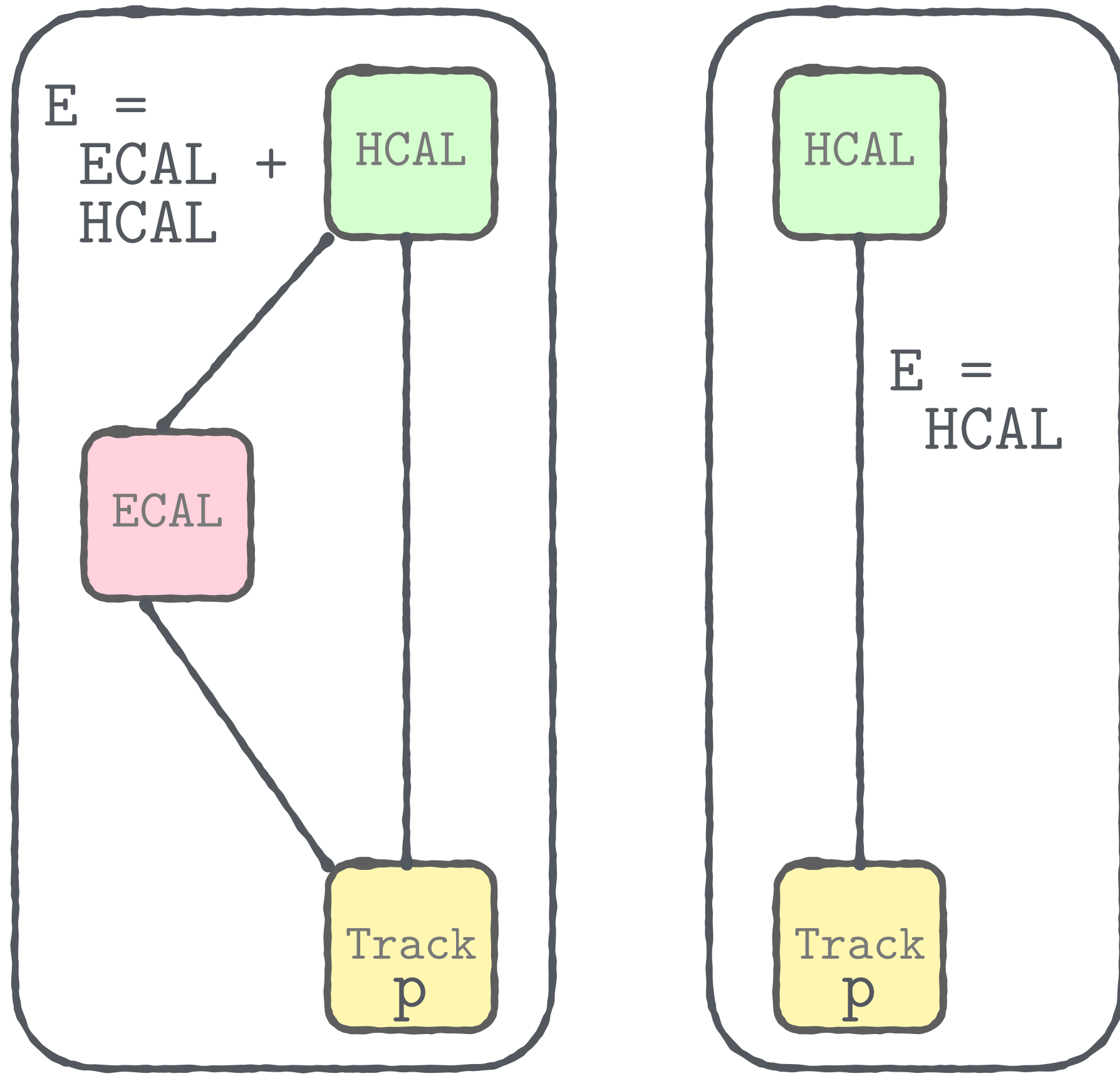
The diagram shows an L-shaped green box representing an HCAL cluster. Below it is a pink box with a hatched top section, representing a particle track. To the right of the track is the equation $\frac{E-p}{b}$. Below the track is a curved line labeled 'p'.

Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

Simplified block (2nd step)

Find charged hadrons & merged photons / neutral hadrons



List of reconstructed (candidate) p

$$\{\gamma, \gamma, \gamma, \pi^+\}$$

Always give precedence to photons in ECAL

(blocks are usually very small)

For each HCAL Cluster compare:

- Sum
- Sum

If p and E are compatible

- Fit p_i and E according to $\sigma(E, p_i)$
- uncertainty weighted average

The plot shows $\sigma(E)/E$ on the y-axis and p_T on the x-axis. Three curves are shown: a red line with downward-pointing triangles labeled 'ECAL', a green line with upward-pointing triangles labeled 'Tracker', and a blue line with dots labeled 'Combined'. The red curve starts high and decreases as p_T increases. The green curve starts low and increases as p_T increases. The blue curve is the lowest and flattest, representing the combined uncertainty.

...needs
en often)

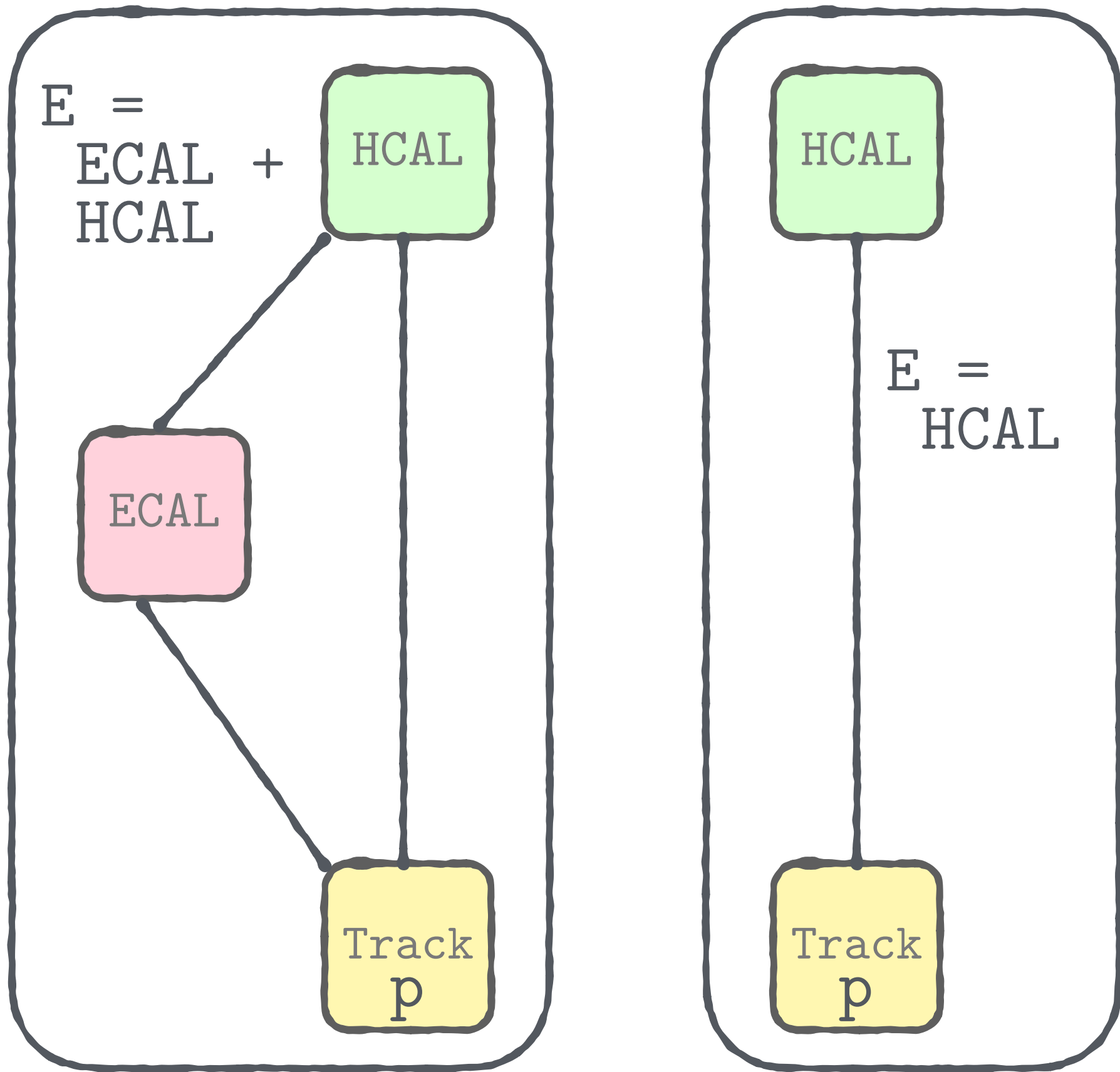
The diagram shows an L-shaped light green box representing an HCAL cluster. Below it is a pink box with a hatched top section, representing a particle track. To the right of the pink box is the equation $\frac{E-p}{b}$. Below the pink box is a curved line labeled 'p' representing a particle track.

Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

Simplified block (2nd step)

Find charged hadrons & merged photons / neutral hadrons



List of reconstructed (candidate) p

$$\{\gamma, \gamma, \gamma, \pi^+,$$

Always give precedence to photons in ECAL

(blocks are usually very small)

For each HCAL Cluster compare:

- Sum
- Sum

If p and E are compatible

- Fit p_i and E according to $\sigma(E, p_i)$
- uncertainty weighted average

The graph plots $\sigma(E)/E$ on the y-axis against p_T on the x-axis. It features three data series: a red line with downward-pointing triangles labeled 'ECAL', a green line with upward-pointing triangles labeled 'Tracker', and a blue line with dots labeled 'Combined'. The ECAL curve starts high and decreases as p_T increases. The Tracker curve starts low and increases as p_T increases. The Combined curve follows the Tracker curve at low p_T and the ECAL curve at high p_T .

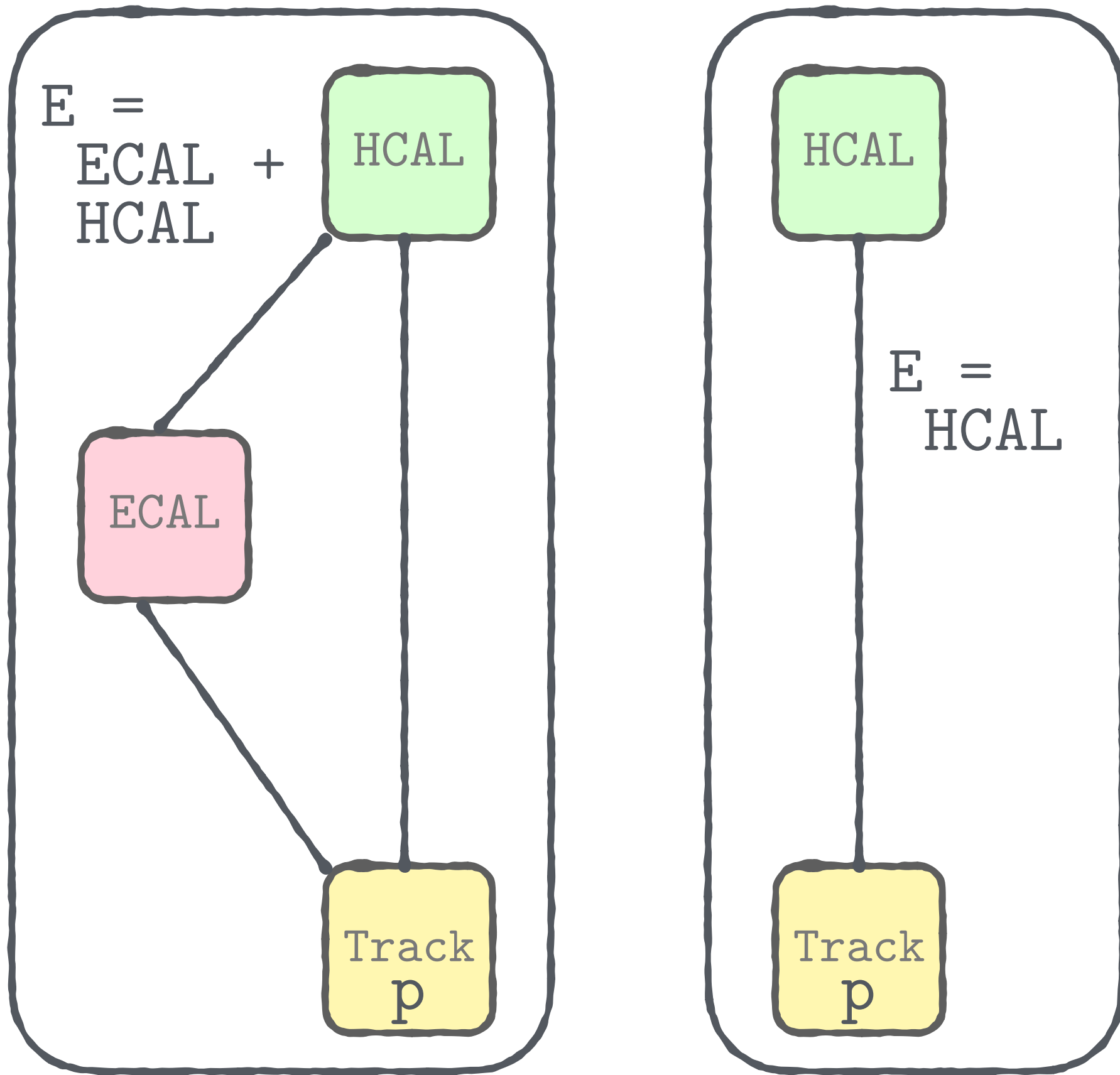
Below the graph, there is a diagram of an L-shaped HCAL cluster (green) and a curved line representing a particle track (p). To the right of the track, the text $\frac{E-p}{b}$ is visible. Below the track, the text "...needs en often)" is partially visible.

Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

Simplified block (2nd step)

Find charged hadrons & merged photons / neutral hadrons



List of reconstructed (candidate) p

$$\{\gamma, \gamma, \gamma, \pi^+, \pi^-\}$$

Always give precedence to photons in ECAL

(blocks are usually very small)

For each HCAL Cluster compare:

- Sum
- Sum

If p and E are compatible

- Fit p_i and E according to $\sigma(E, p_i)$
- uncertainty weighted average

The graph plots $\sigma(E)/E$ on the y-axis against p_T on the x-axis. It features three data series: a red line with downward-pointing triangles labeled 'ECAL', a green line with upward-pointing triangles labeled 'Tracker', and a blue line with dots labeled 'Combined'. The ECAL curve starts high and decreases as p_T increases. The Tracker curve starts low and increases as p_T increases. The Combined curve follows the Tracker curve at low p_T and the ECAL curve at high p_T .

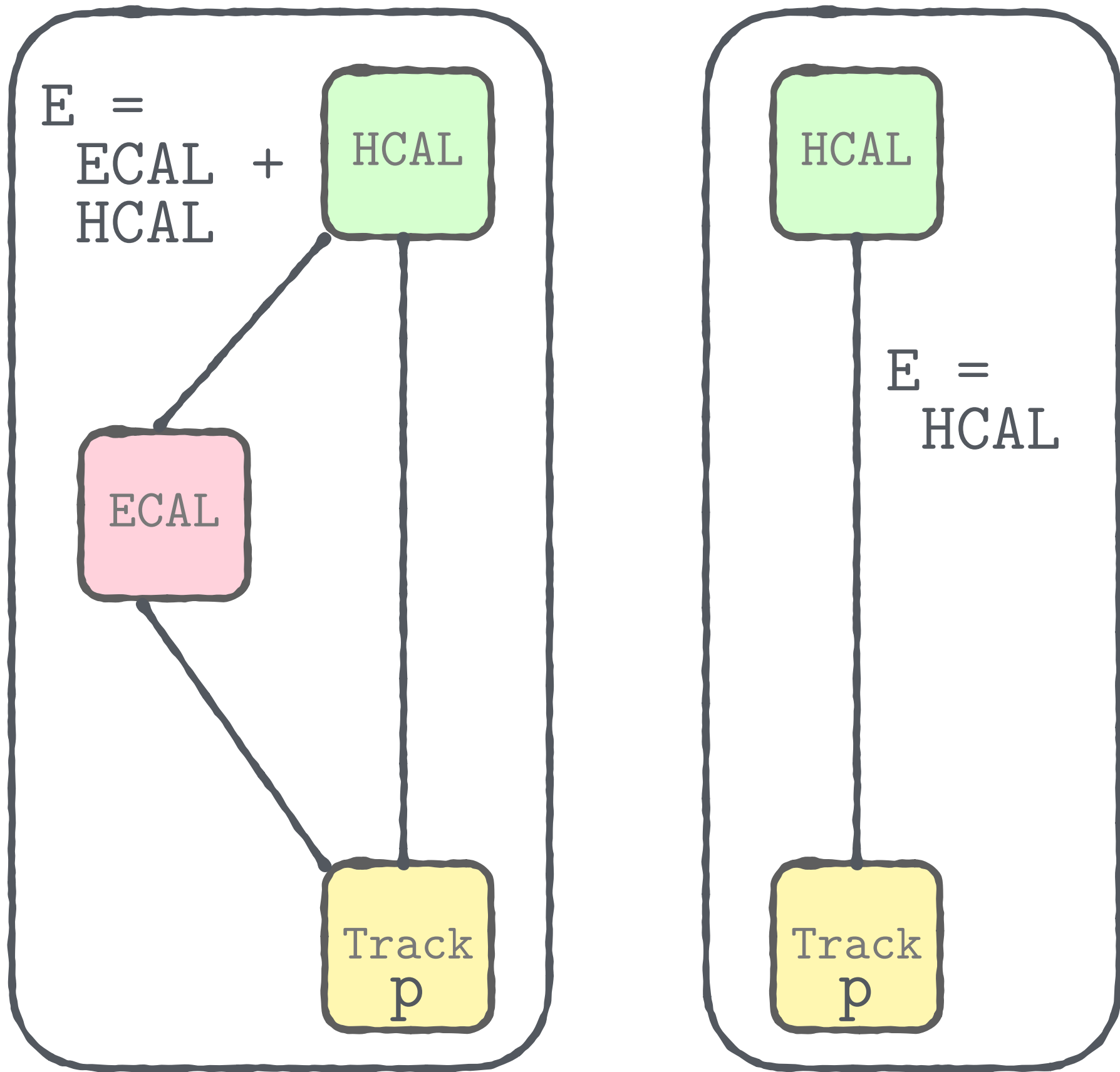
Below the graph, there is a diagram of an L-shaped HCAL cluster (green) and a curved line representing a particle track (p). To the right of the track is the formula $\frac{E-p}{b}$. Below this is another diagram showing a pink rectangular block with a hatched top section, and the text "...needs en often)".

Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

Simplified block (2nd step)

Find charged hadrons & merged photons / neutral hadrons



List of reconstructed (candidate) p

$$\{ \gamma, \gamma, \gamma, \pi^+, \pi^- \}$$

Always give precedence to photons in ECAL

(blocks are usually very small)

For each HCAL Cluster compare:

- Sum
- Sum

If p and E are compatible

- Fit p_i and E according to $\sigma(E, p_i)$
- uncertainty weighted average

The plot shows $\sigma(E)/E$ on the y-axis and p_T on the x-axis. Three curves are shown: a red curve with downward-pointing triangles labeled 'ECAL', a green curve with upward-pointing triangles labeled 'Tracker', and a blue curve with dots labeled 'Combined'. The ECAL curve starts high and decreases as p_T increases. The Tracker curve starts low and increases as p_T increases. The Combined curve is the lowest and flattest.

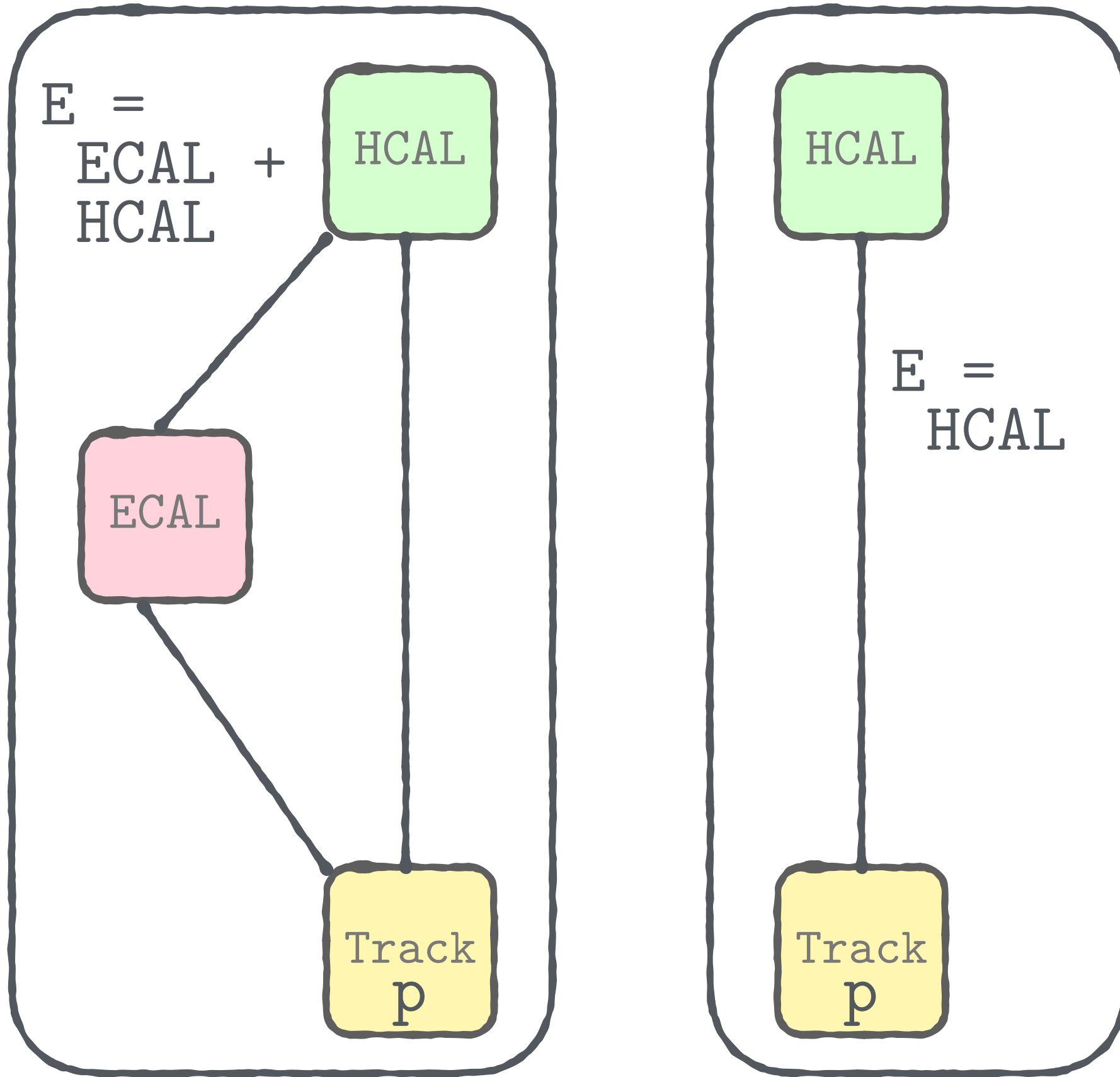
Additional diagrams on the right show an L-shaped HCAL cluster, a diagram with a pink box and a hatched box labeled $\frac{E-p}{b}$, and a curved line labeled 'p'.

...needs
en often)

Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

Conclusion from this simple Example



List of reconstructed (candidate) particles

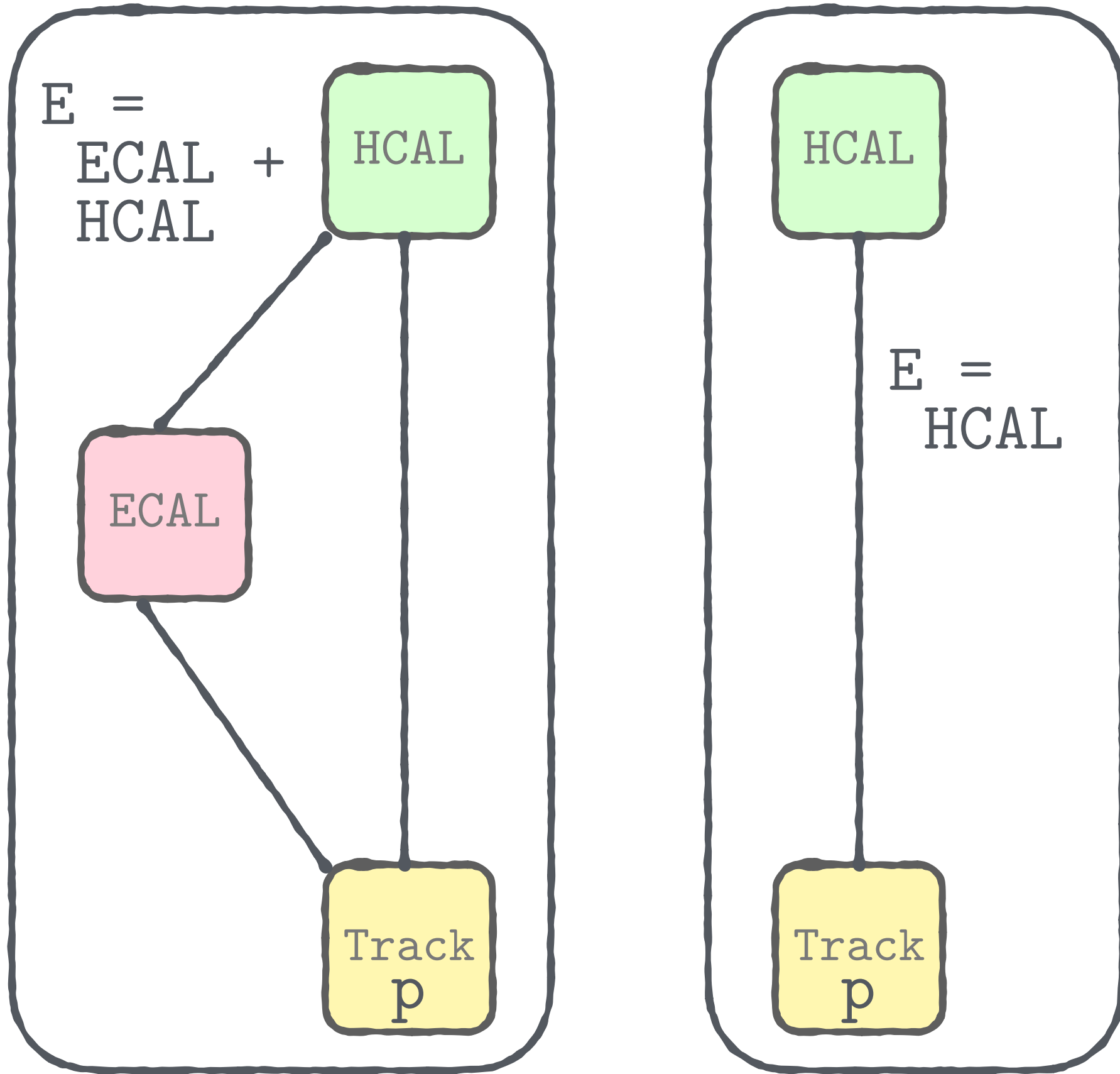
$$\{ \gamma, \gamma, \gamma, \pi^+, \pi^- \}$$

Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

Conclusion from this simple Example

- Five particles reconstructed



List of reconstructed (candidate) particles

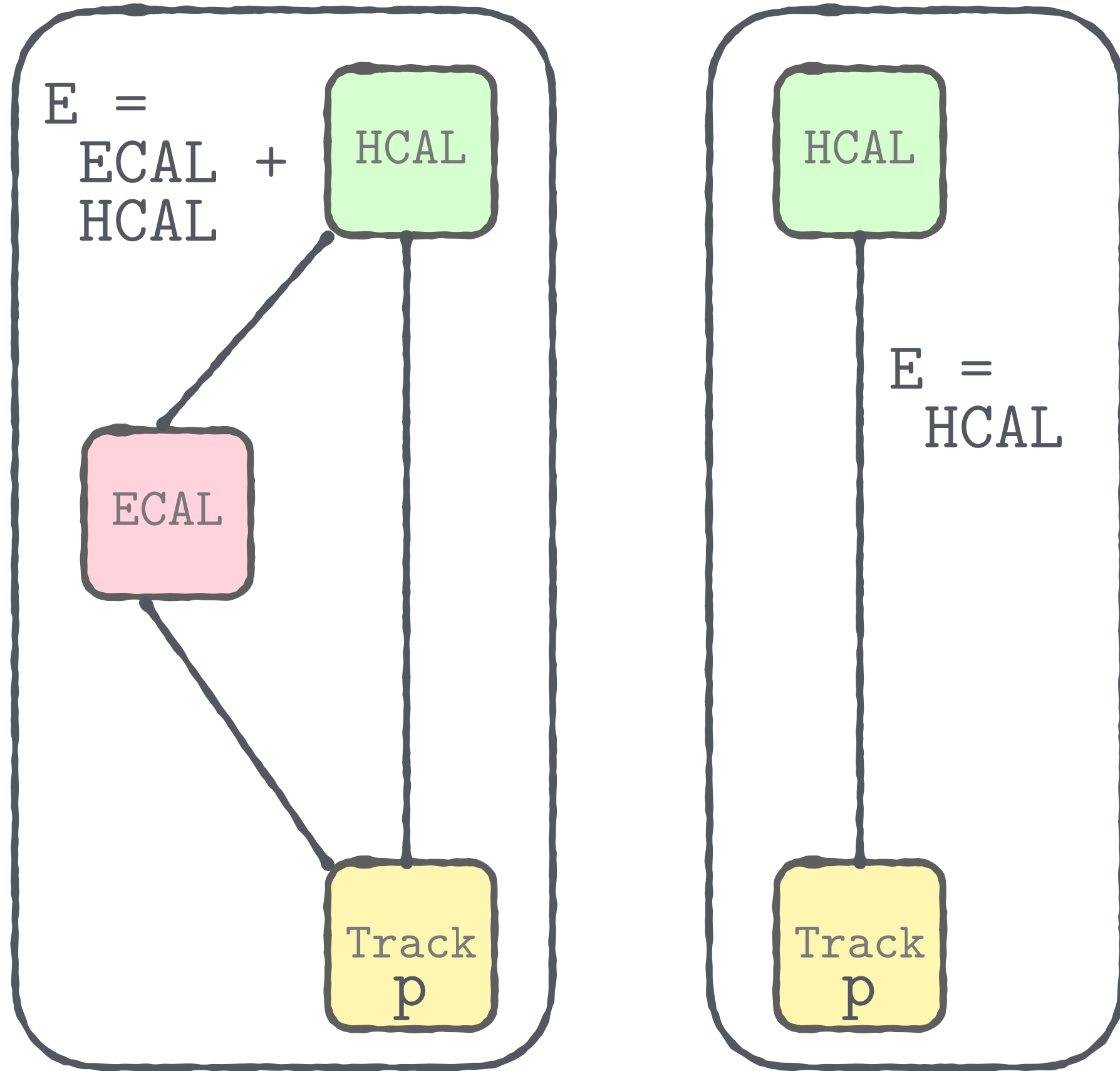
$$\{ \gamma, \gamma, \gamma, \pi^+, \pi^- \}$$

Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

Conclusion from this simple Example

- Five particles reconstructed
- two oppositely charged hadrons (π^+ and π^-)



List of reconstructed (candidate) particles

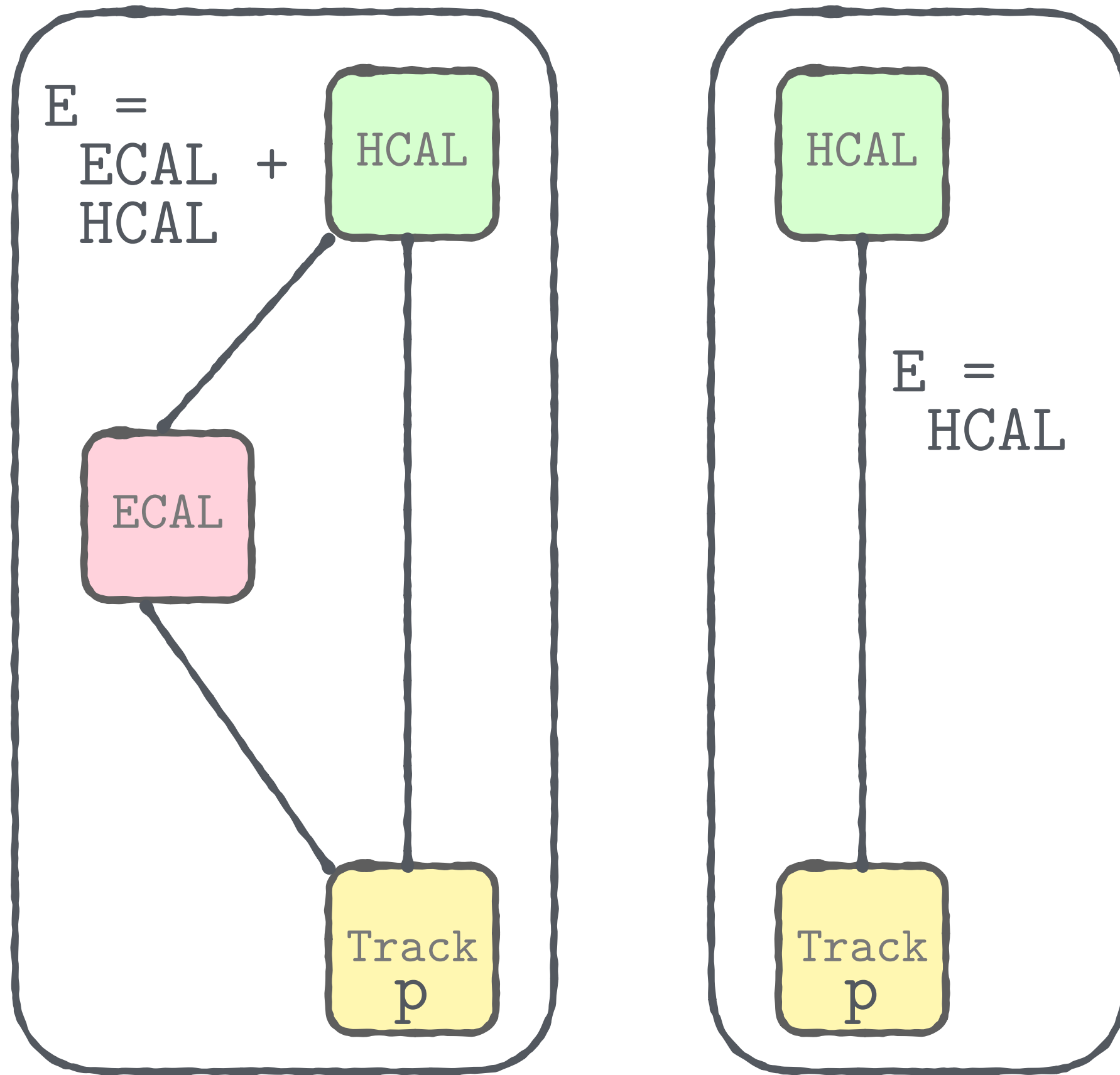
$$\{ \gamma, \gamma, \gamma, \pi^+, \pi^- \}$$

Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

Conclusion from this simple Example

- Five particles reconstructed
- two oppositely charged hadrons (π^+ and π^-)
- three photons



List of reconstructed (candidate) particles

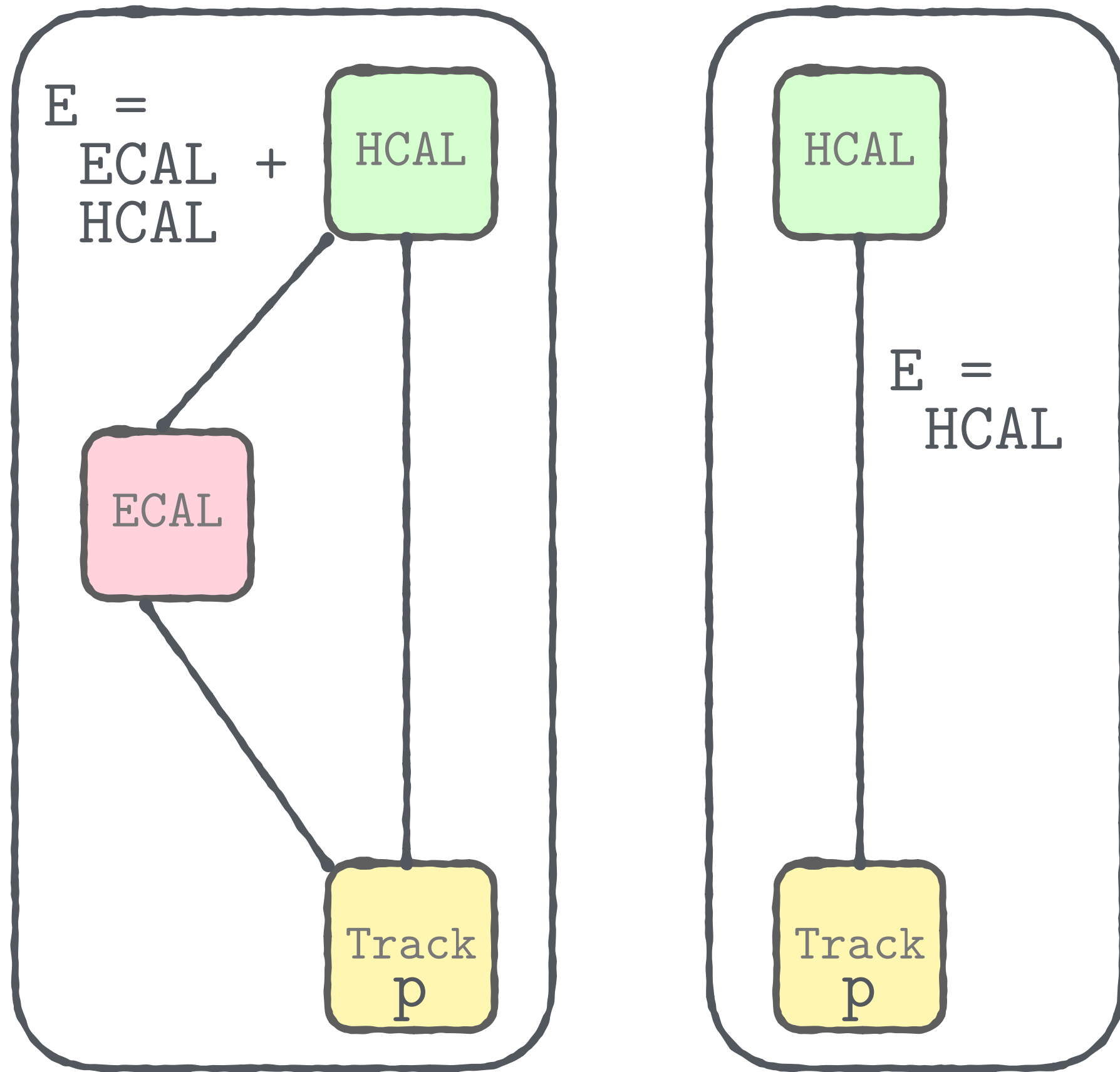
$$\{ \gamma, \gamma, \gamma, \pi^+, \pi^- \}$$

Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

Conclusion from this simple Example

- Five particles reconstructed
- two oppositely charged hadrons (π^+ and π^-)
- three photons
 - two from π^0 decay and one from K_L^0 energy deposit



List of reconstructed (candidate) particles

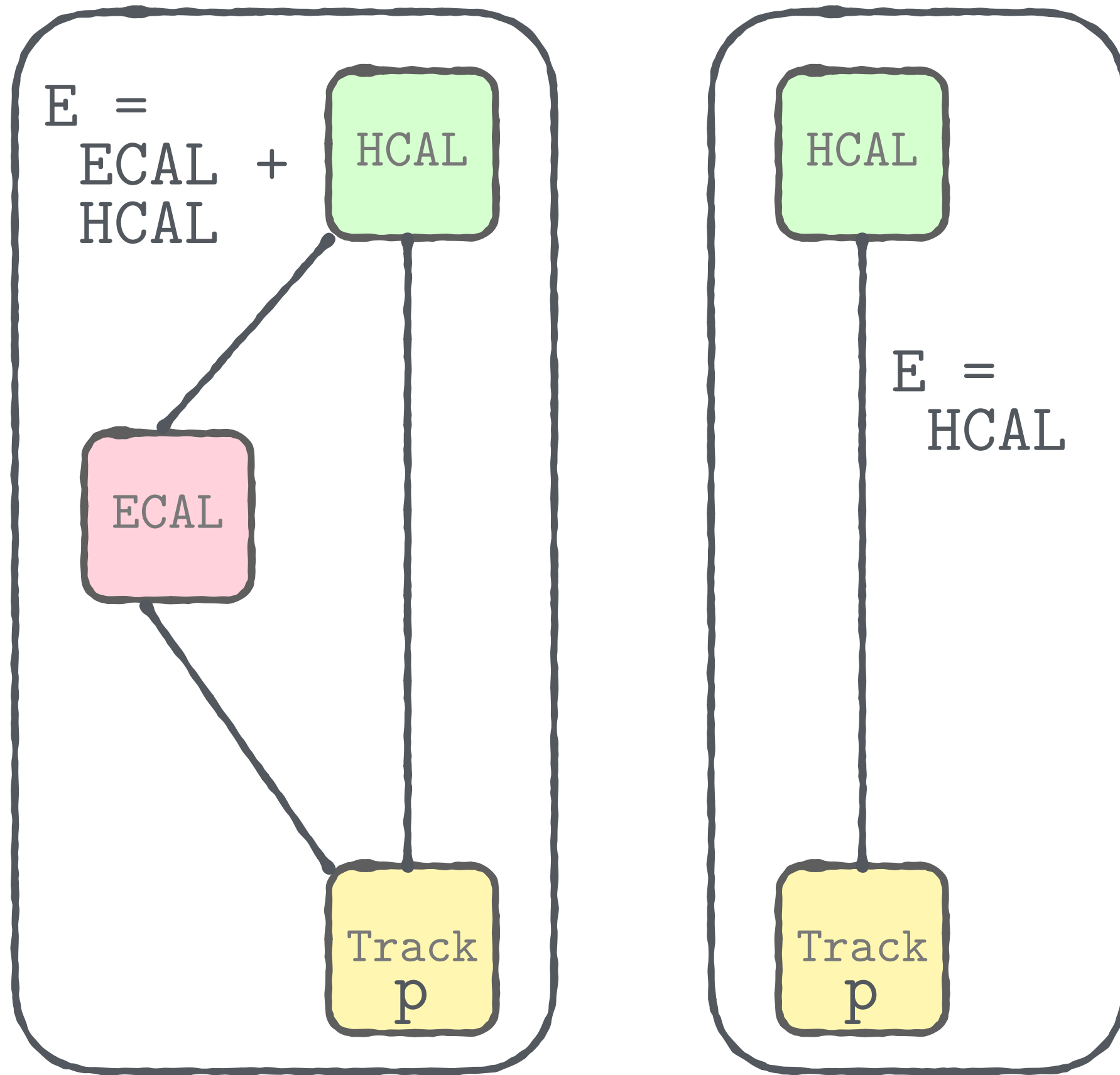
$$\{ \gamma, \gamma, \gamma, \pi^+, \pi^- \}$$

Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

Conclusion from this simple Example

- Five particles reconstructed
 - two oppositely charged hadrons (π^+ and π^-)
 - three photons
 - two from π^0 decay and one from K_L^0 energy deposit
 - no neutral hadron



List of reconstructed (candidate) particles

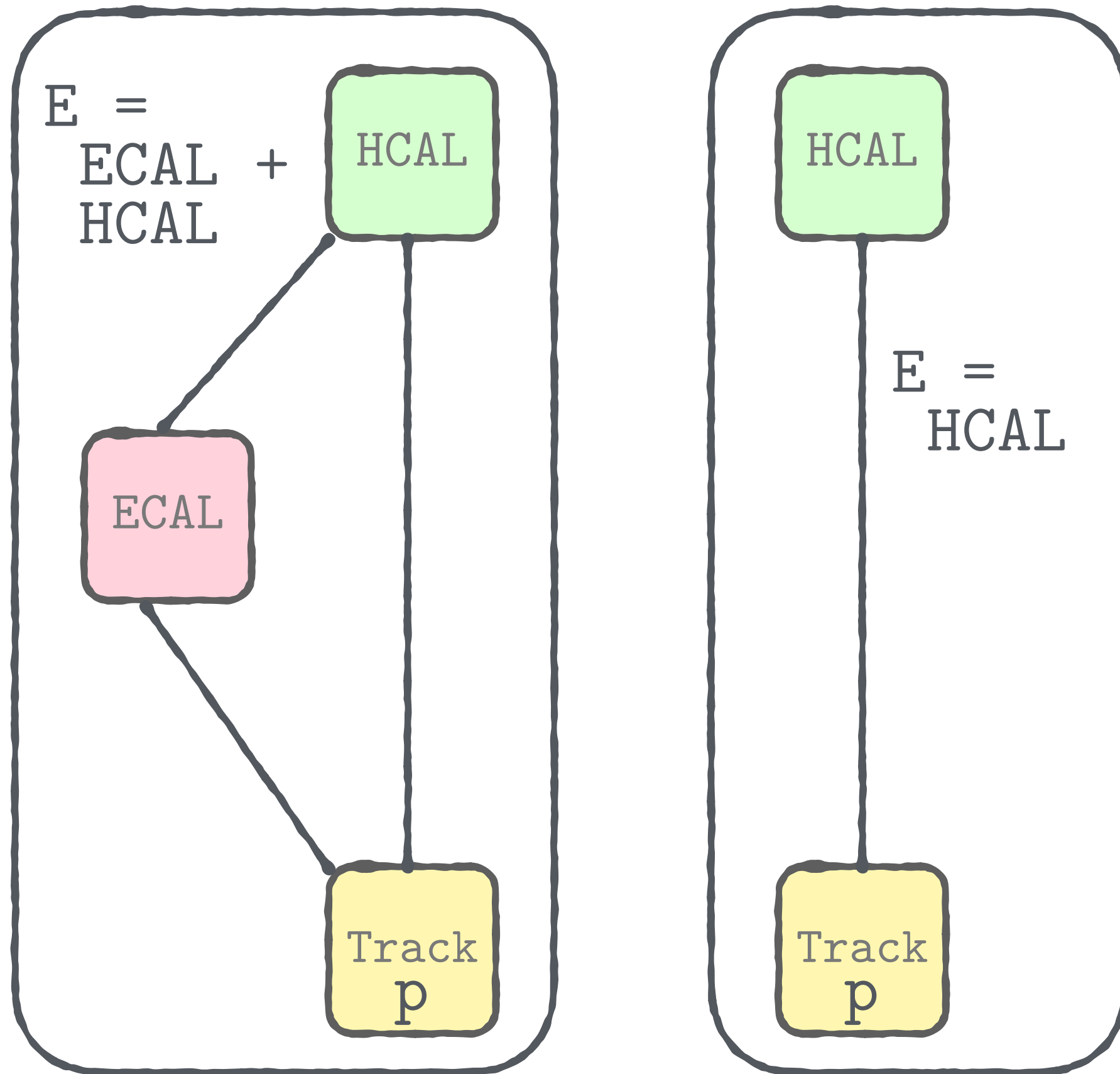
$$\{ \gamma, \gamma, \gamma, \pi^+, \pi^- \}$$

Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$

Conclusion from this simple Example

- Five particles reconstructed
 - two oppositely charged hadrons (π^+ and π^-)
 - three photons
 - two from π^0 decay and one from K_L^0 energy deposit
 - no neutral hadron
 - because for both tracks, E compatible with p

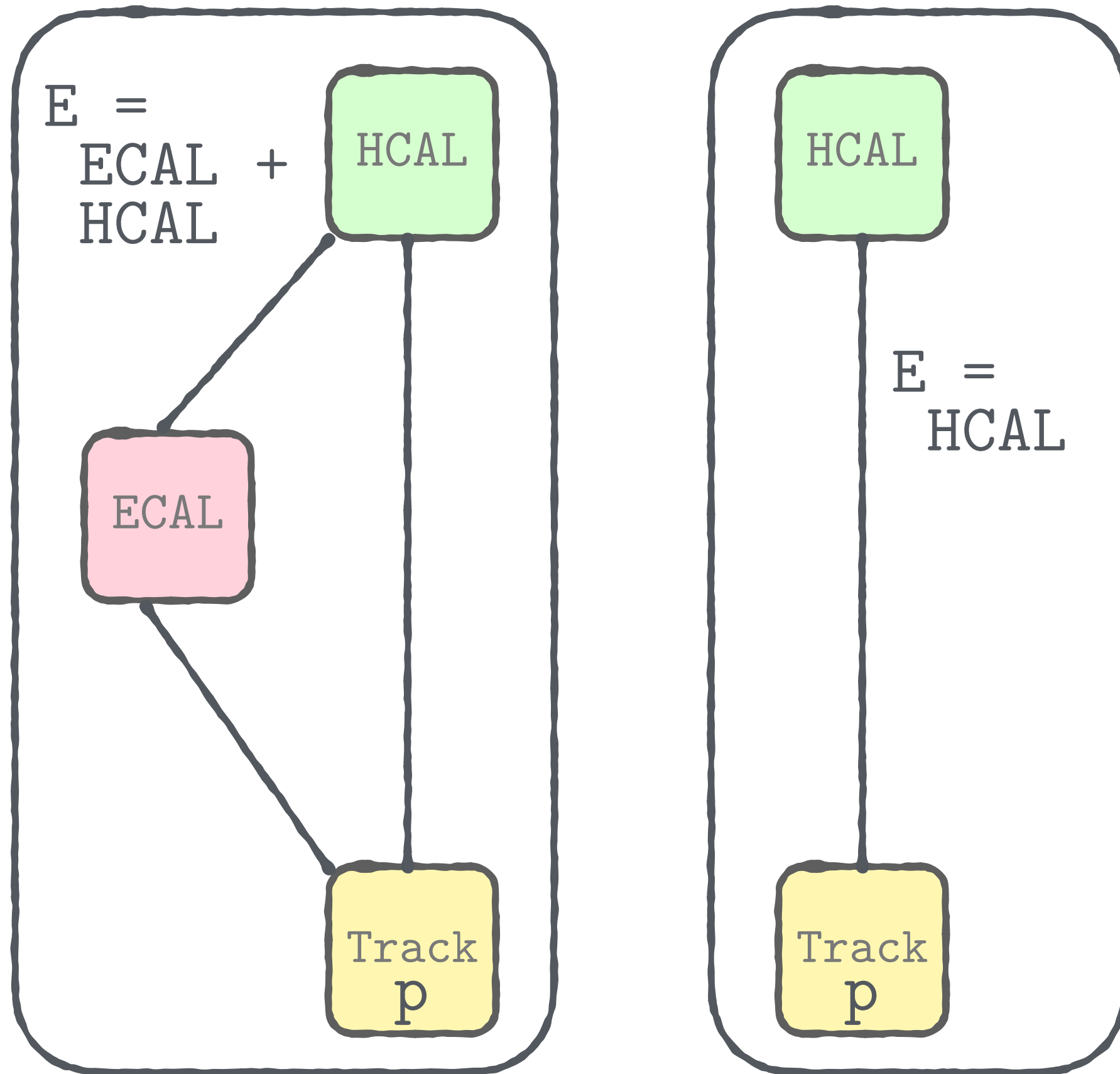


List of reconstructed (candidate) particles

$$\{ \gamma, \gamma, \gamma, \pi^+, \pi^- \}$$

Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



Conclusion from this simple Example

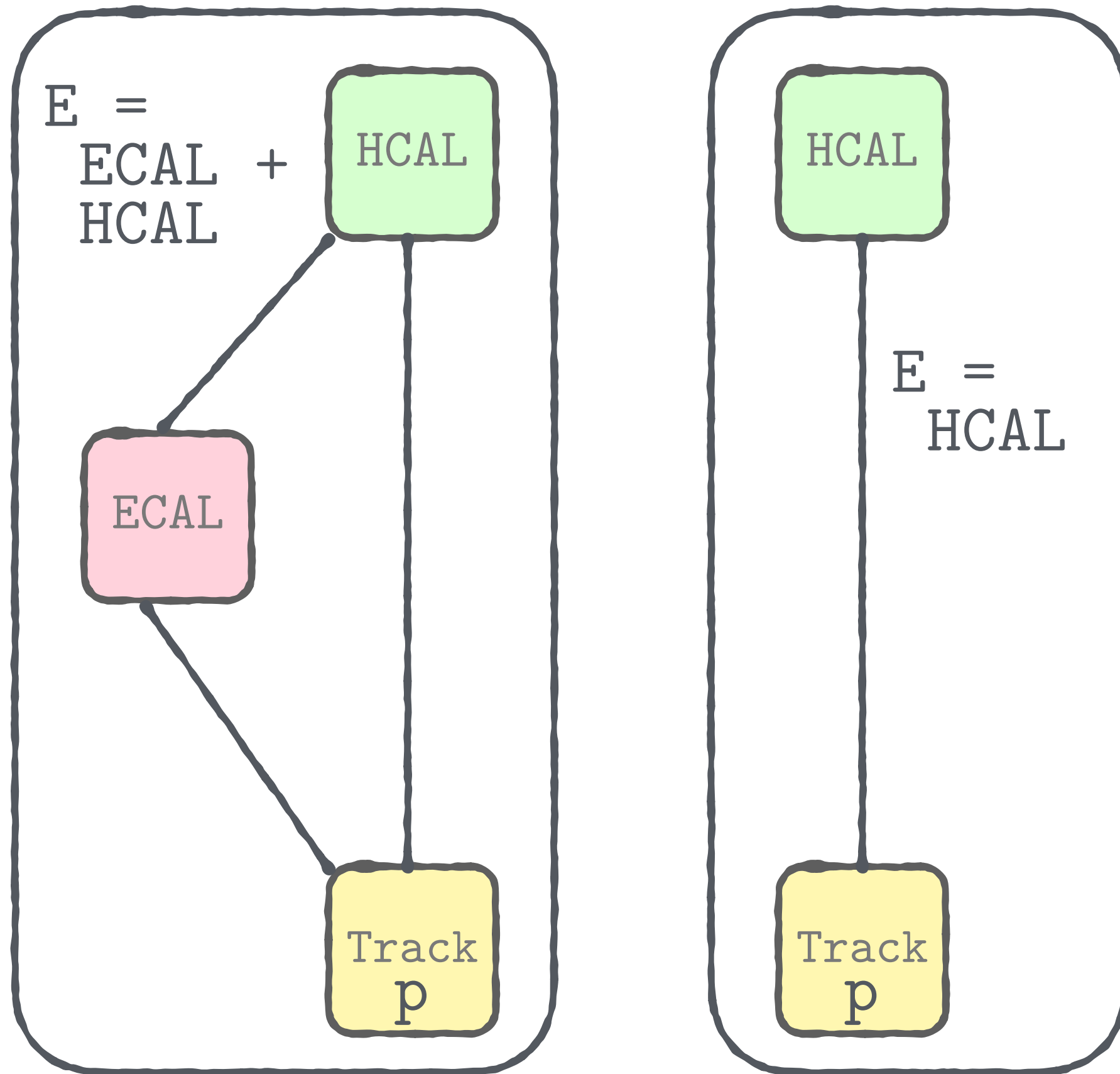
- Five particles reconstructed
- two oppositely charged hadrons (π^+ and π^-)
- three photons
 - two from π^0 decay and one from K_L^0 energy deposit
- no neutral hadron
 - because for both tracks, E compatible with p
- Note: the precedence given to photon ID in ECAL

List of reconstructed (candidate) particles

$$\{ \gamma, \gamma, \gamma, \pi^+, \pi^- \}$$

Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



Conclusion from this simple Example

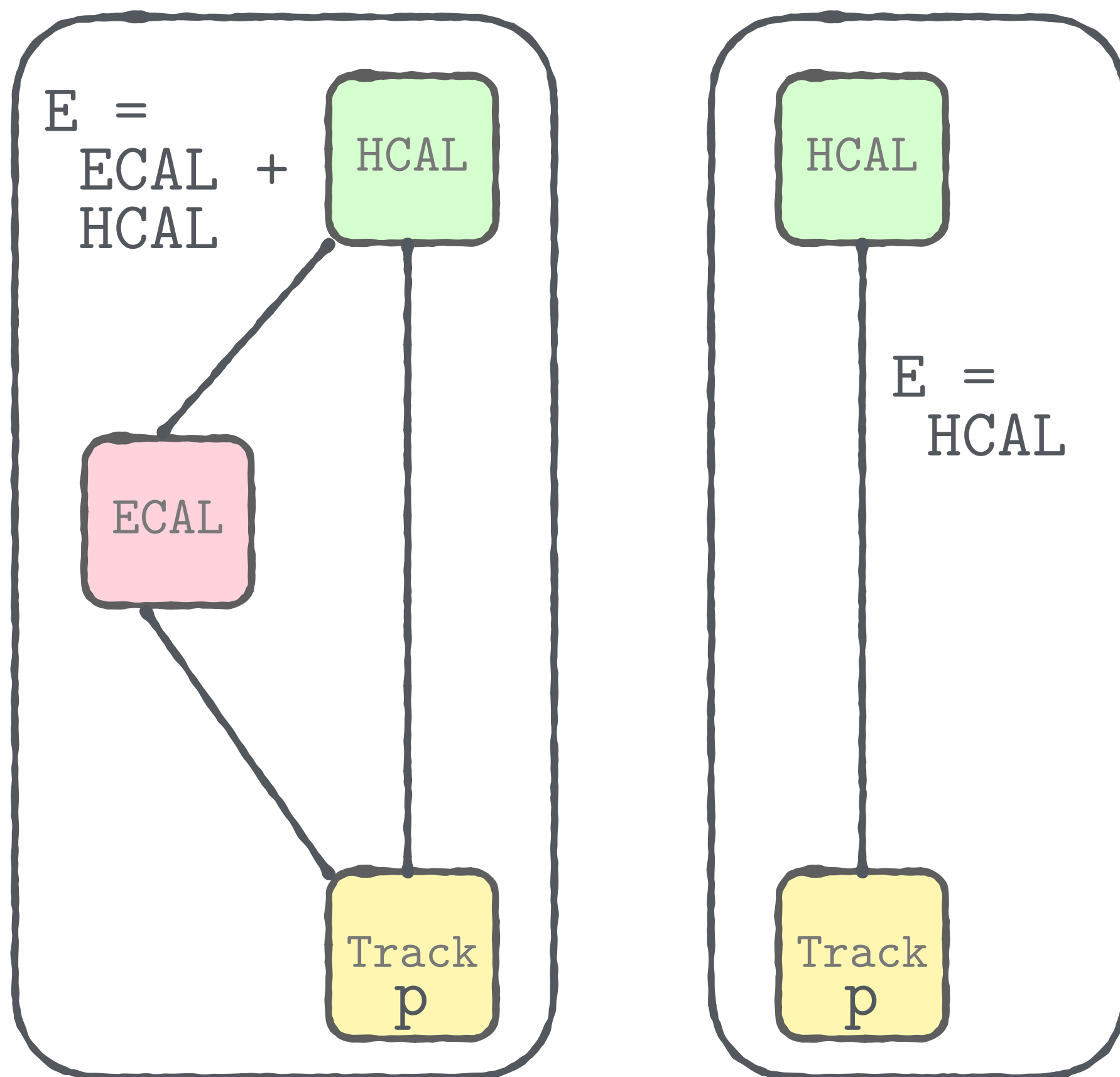
- Five particles reconstructed
 - two oppositely charged hadrons (π^+ and π^-)
 - three photons
 - two from π^0 decay and one from K_L^0 energy deposit
 - no neutral hadron
 - because for both tracks, E compatible with p
- Note: the precedence given to photon ID in ECAL
 - Could underestimate ECAL deposits of neutral hadrons

List of reconstructed (candidate) particles

$$\{ \gamma, \gamma, \gamma, \pi^+, \pi^- \}$$

Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



Conclusion from this simple Example

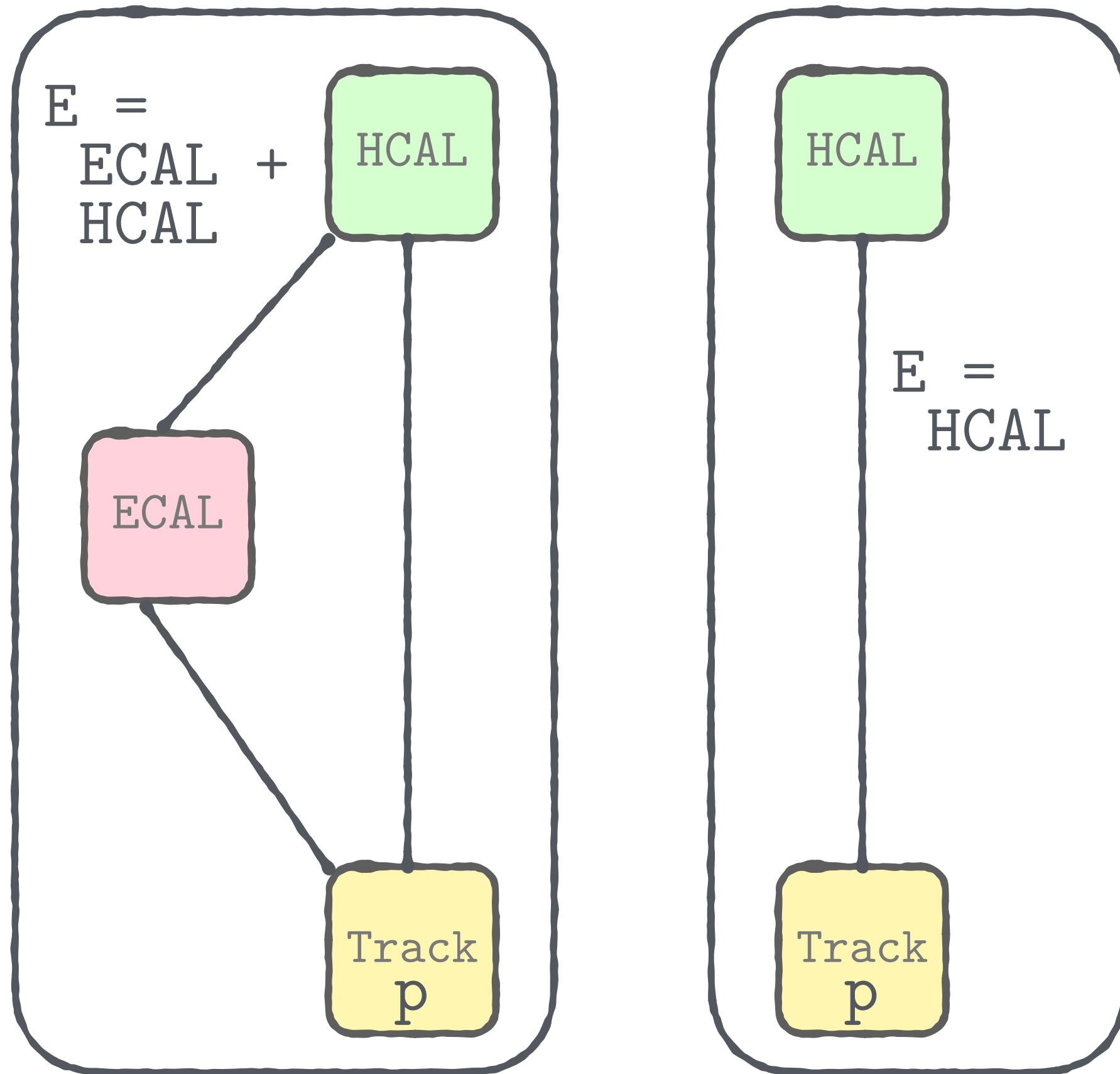
- Five particles reconstructed
 - two oppositely charged hadrons (π^+ and π^-)
 - three photons
 - two from π^0 decay and one from K_L^0 energy deposit
 - no neutral hadron
 - because for both tracks, E compatible with p
- Note: the precedence given to photon ID in ECAL
 - Could underestimate ECAL deposits of neutral hadrons
 - But neutral hadron energy deposited in ECAL is

List of reconstructed (candidate) particles

$$\{ \gamma, \gamma, \gamma, \pi^+, \pi^- \}$$

Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



Conclusion from this simple Example

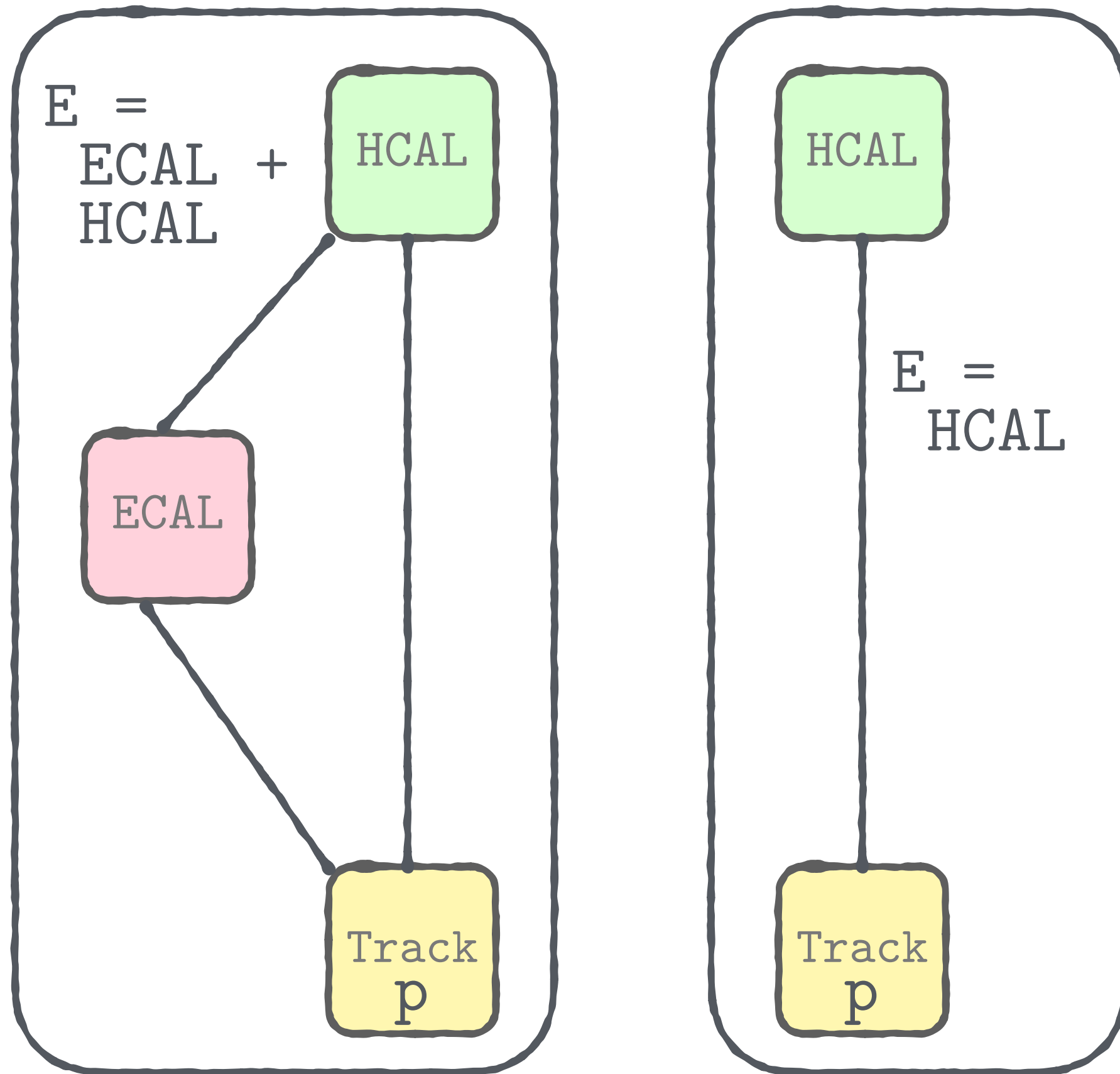
- Five particles reconstructed
 - two oppositely charged hadrons (π^+ and π^-)
 - three photons
 - two from π^0 decay and one from K_L^0 energy deposit
 - no neutral hadron
 - because for both tracks, E compatible with p
- Note: the precedence given to photon ID in ECAL
 - Could underestimate ECAL deposits of neutral hadrons
 - But neutral hadron energy deposited in ECAL is
 - (10% neutral hadron energy) x (30% ECAL fraction) = 3% of event energy

List of reconstructed (candidate) particles

$$\{ \gamma, \gamma, \gamma, \pi^+, \pi^- \}$$

Four true particles:

$$\pi^+, \pi^-, \pi^0, K_L^0$$



Conclusion from this simple Example

- Five particles reconstructed
 - two oppositely charged hadrons (π^+ and π^-)
 - three photons
 - two from π^0 decay and one from K_L^0 energy deposit
 - no neutral hadron
 - because for both tracks, E compatible with p
- Note: the precedence given to photon ID in ECAL
 - Could underestimate ECAL deposits of neutral hadrons
 - But neutral hadron energy deposited in ECAL is
 - (10% neutral hadron energy) x (30% ECAL fraction) = 3% of event energy
 - might loose < 0.5% of event energy due to this choice

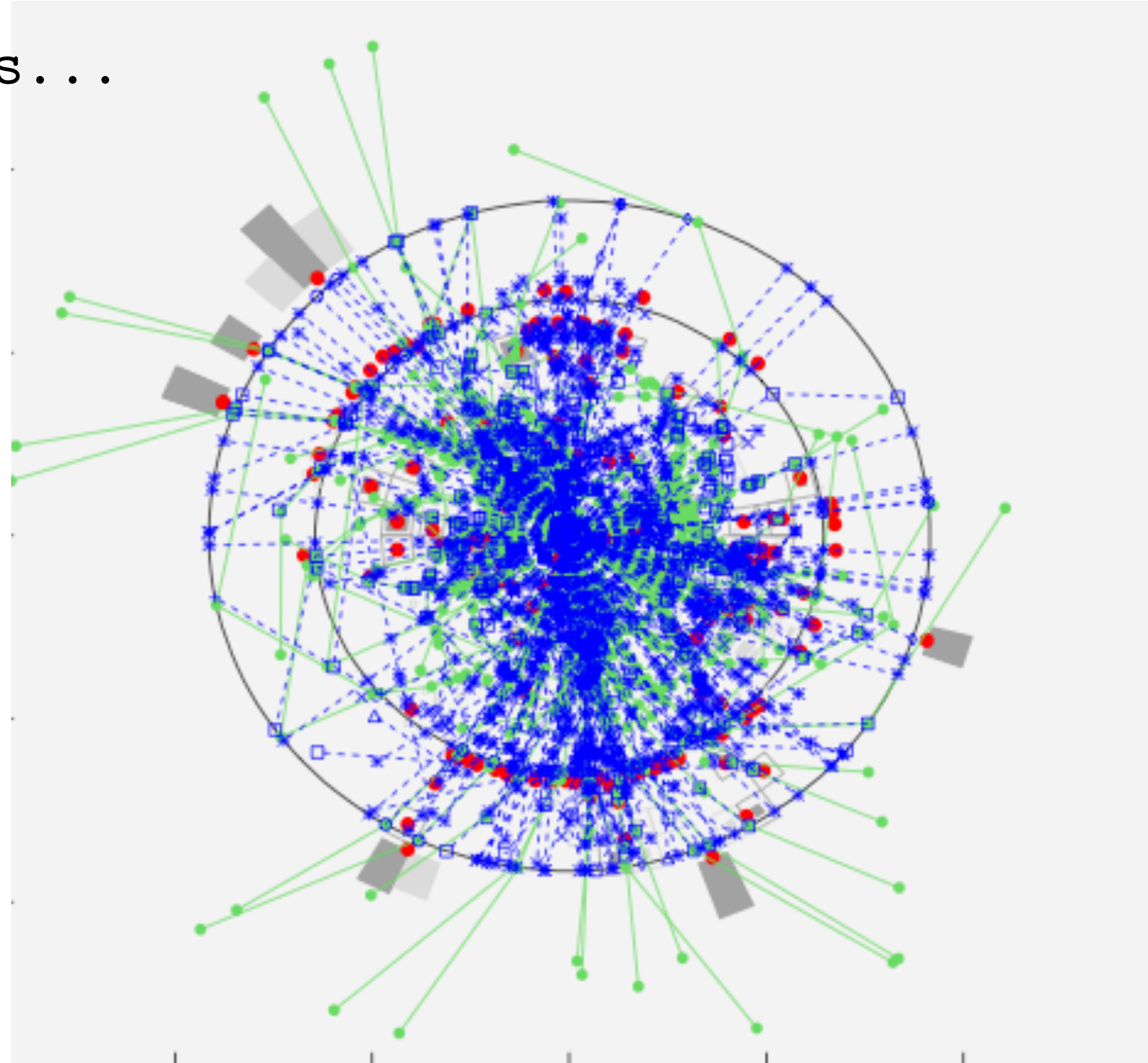
List of reconstructed (candidate) particles

$$\{ \gamma, \gamma, \gamma, \pi^+, \pi^- \}$$

That was a simple example, nevertheless...

...The Particle Flow algorithm scales to large particle multiplicities!

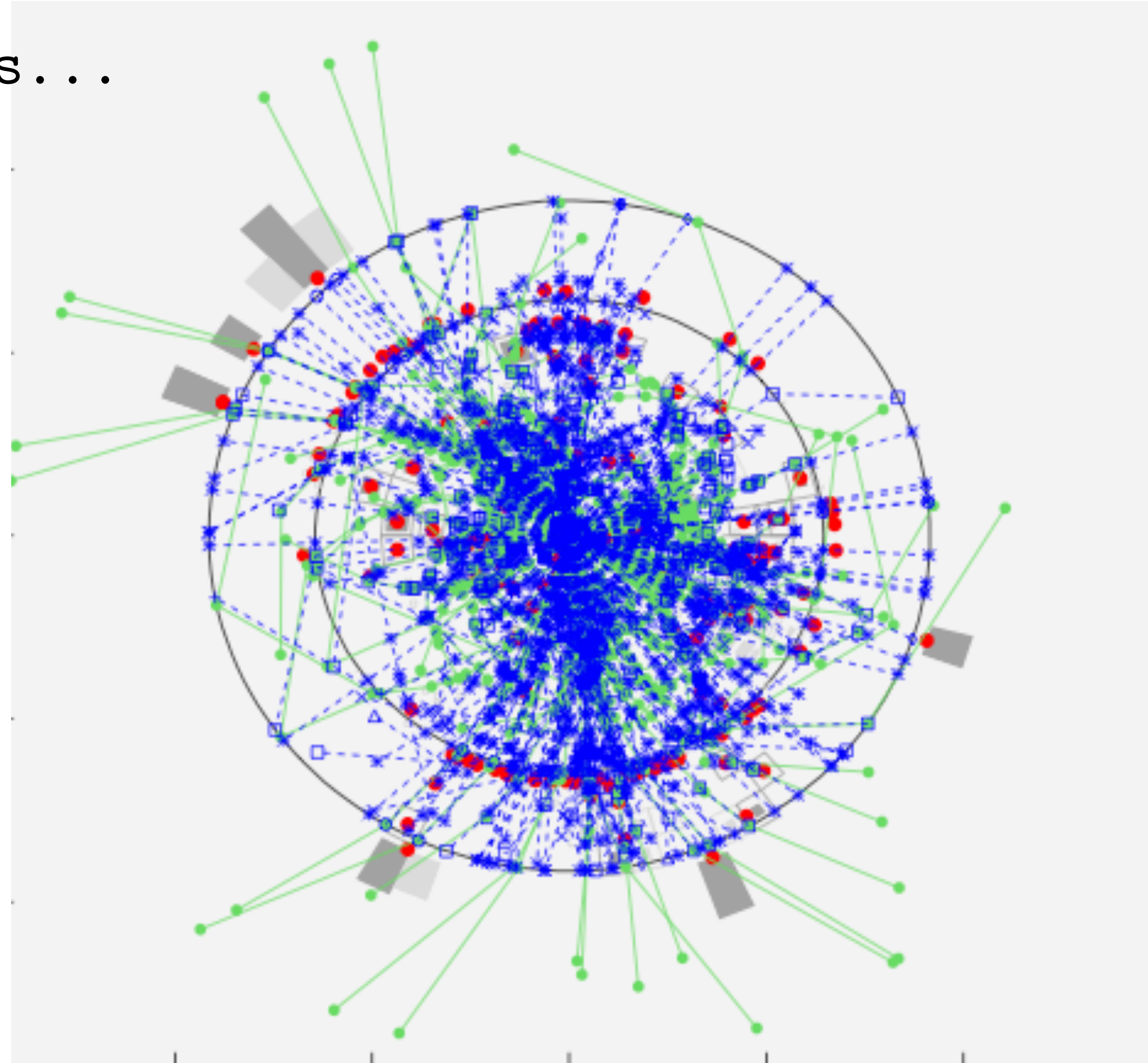
Analysis of the leading jet from simulated event of all-hadronic top-quark pairs:



That was a simple example, nevertheless...

...The Particle Flow algorithm scales to large particle multiplicities!

Analysis of the leading jet from simulated event of all-hadronic top-quark pairs:



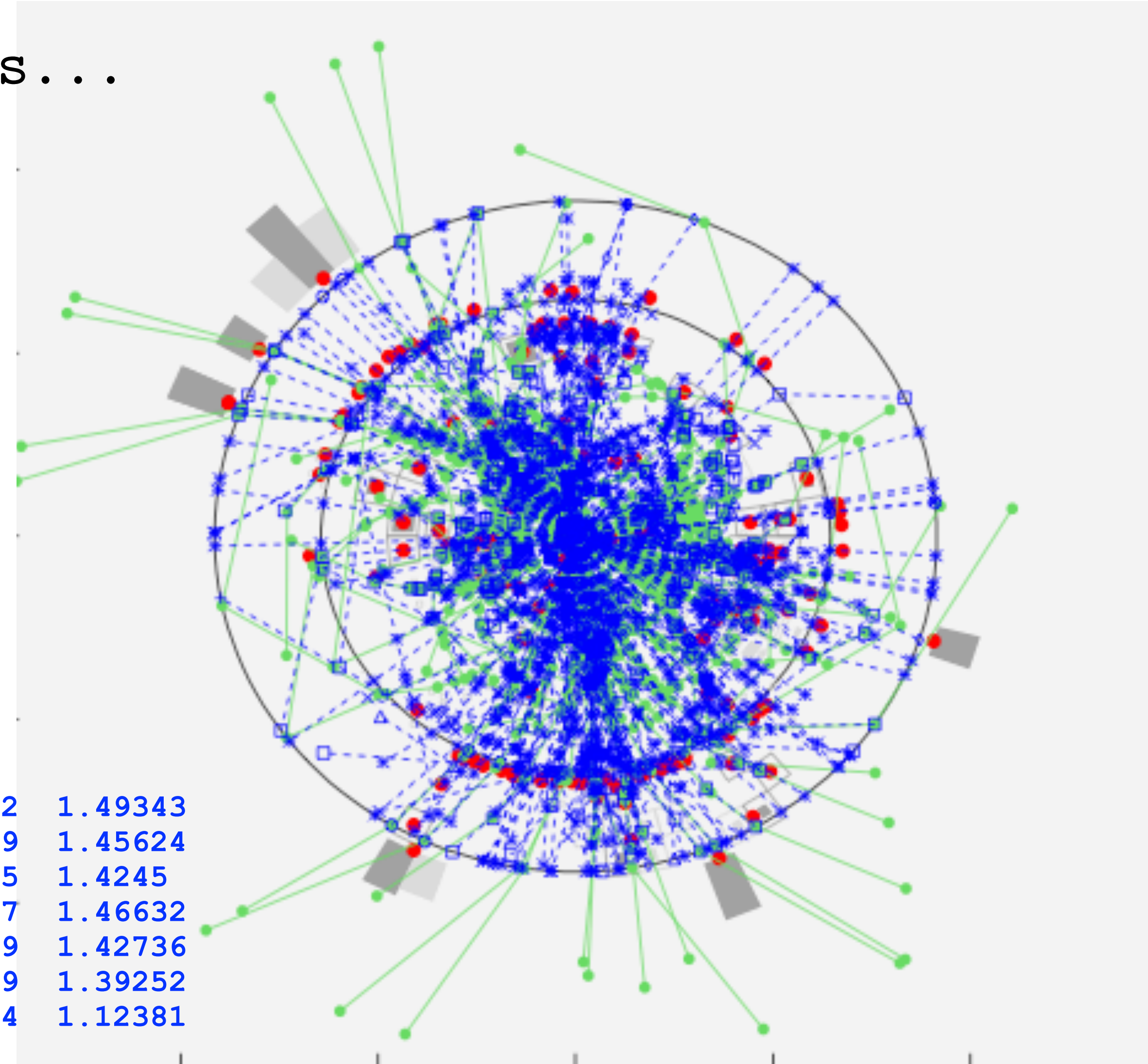
That was a simple example, nevertheless...

...The Particle Flow algorithm scales to large particle multiplicities!

Analysis of the leading jet from simulated event of all-hadronic top-quark pairs:

True Particles

#0	PDG code:130,	p/pt/eta/phi:	20.3845	16.7688	-0.645422	1.49343
#1	PDG code:211,	p/pt/eta/phi:	17.2954	15.0452	-0.540329	1.45624
#2	PDG code:211,	p/pt/eta/phi:	11.453	9.82512	-0.567975	1.4245
#3	PDG code:22,	p/pt/eta/phi:	7.75683	6.52999	-0.603777	1.46632
#4	PDG code:22,	p/pt/eta/phi:	7.26097	6.17551	-0.584549	1.42736
#5	PDG code:22,	p/pt/eta/phi:	6.56173	5.52903	-0.602059	1.39252
#6	PDG code:2212,	p/pt/eta/phi:	5.69095	5.14257	-0.457804	1.12381
...						

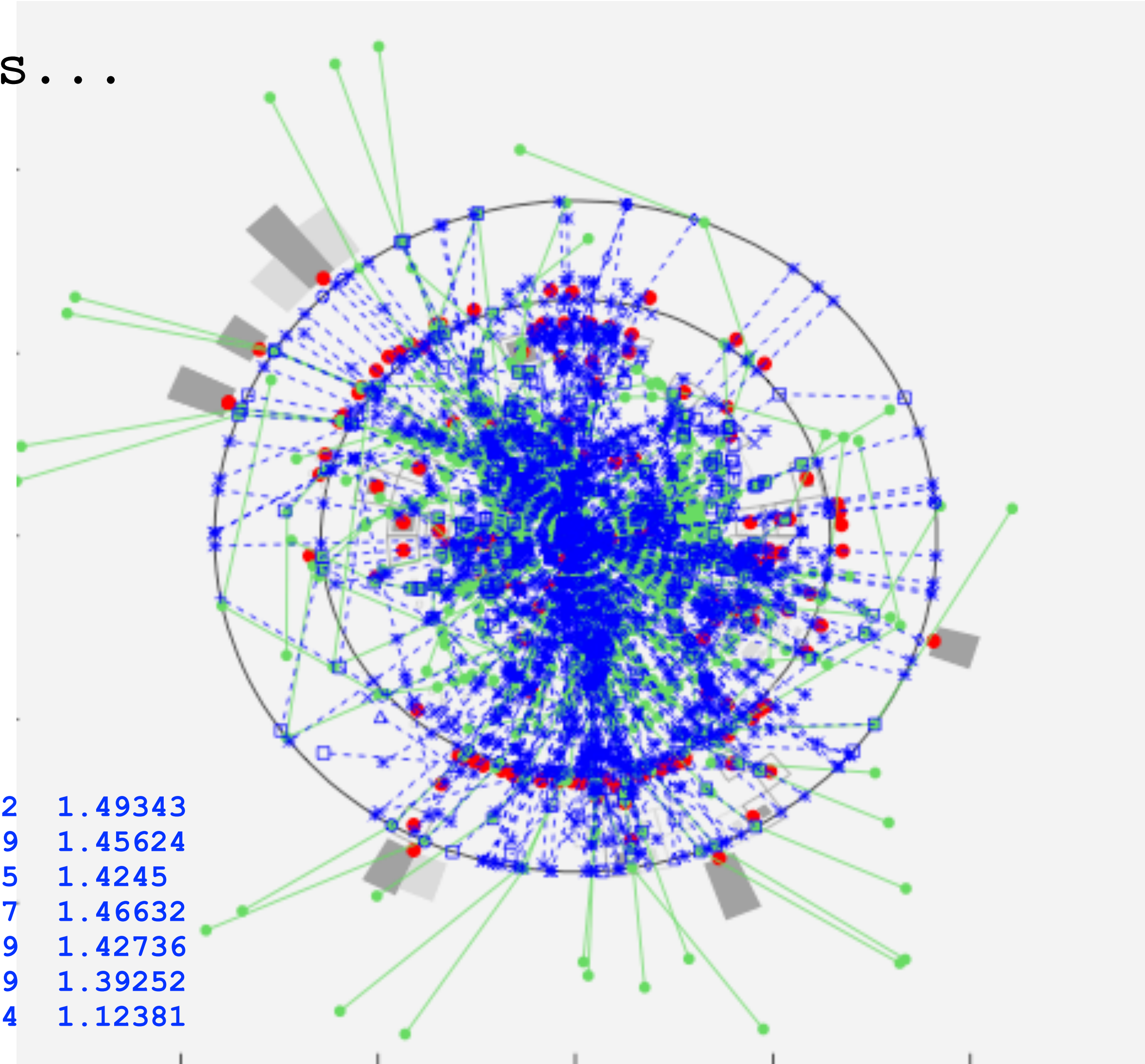


#0	PDG code:130,	p/pt/eta/phi:	20.3845	16.7688	-0.645422	1.49343
#1	PDG code:211,	p/pt/eta/phi:	17.2954	15.0452	-0.540329	1.45624
#2	PDG code:211,	p/pt/eta/phi:	11.453	9.82512	-0.567975	1.4245
#3	PDG code:22,	p/pt/eta/phi:	7.75683	6.52999	-0.603777	1.46632
#4	PDG code:22,	p/pt/eta/phi:	7.26097	6.17551	-0.584549	1.42736
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#6	PDG code:2212,	p/pt/eta/phi:	5.69095	5.14257	-0.457804	1.12381
...						

That was a simple example, nevertheless...

...The Particle Flow algorithm scales to large particle multiplicities!

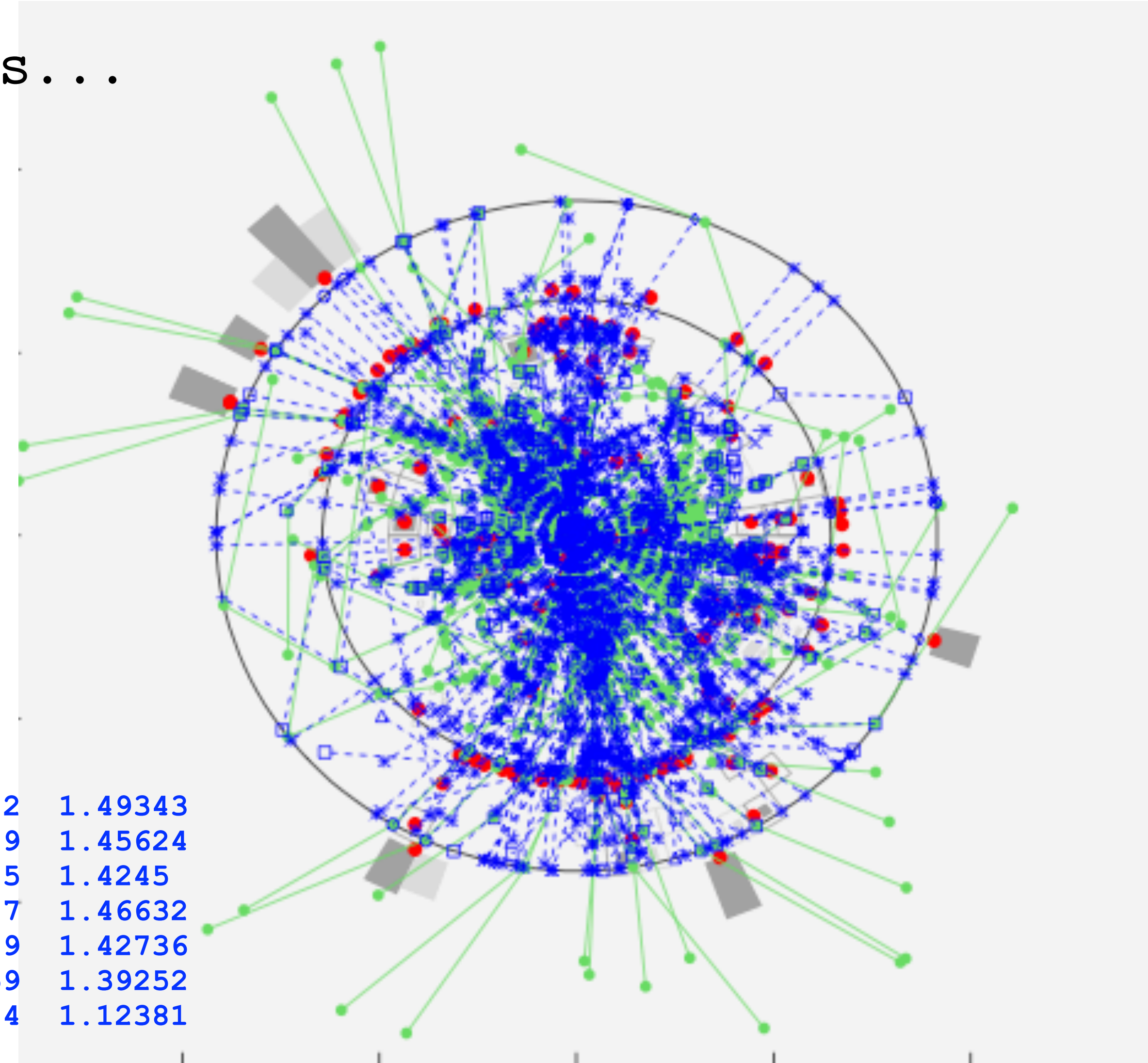
Analysis of the leading jet from simulated event of all-hadronic top-quark pairs:



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Analysis of the leading jet from simulated event of all-hadronic top-quark pairs:

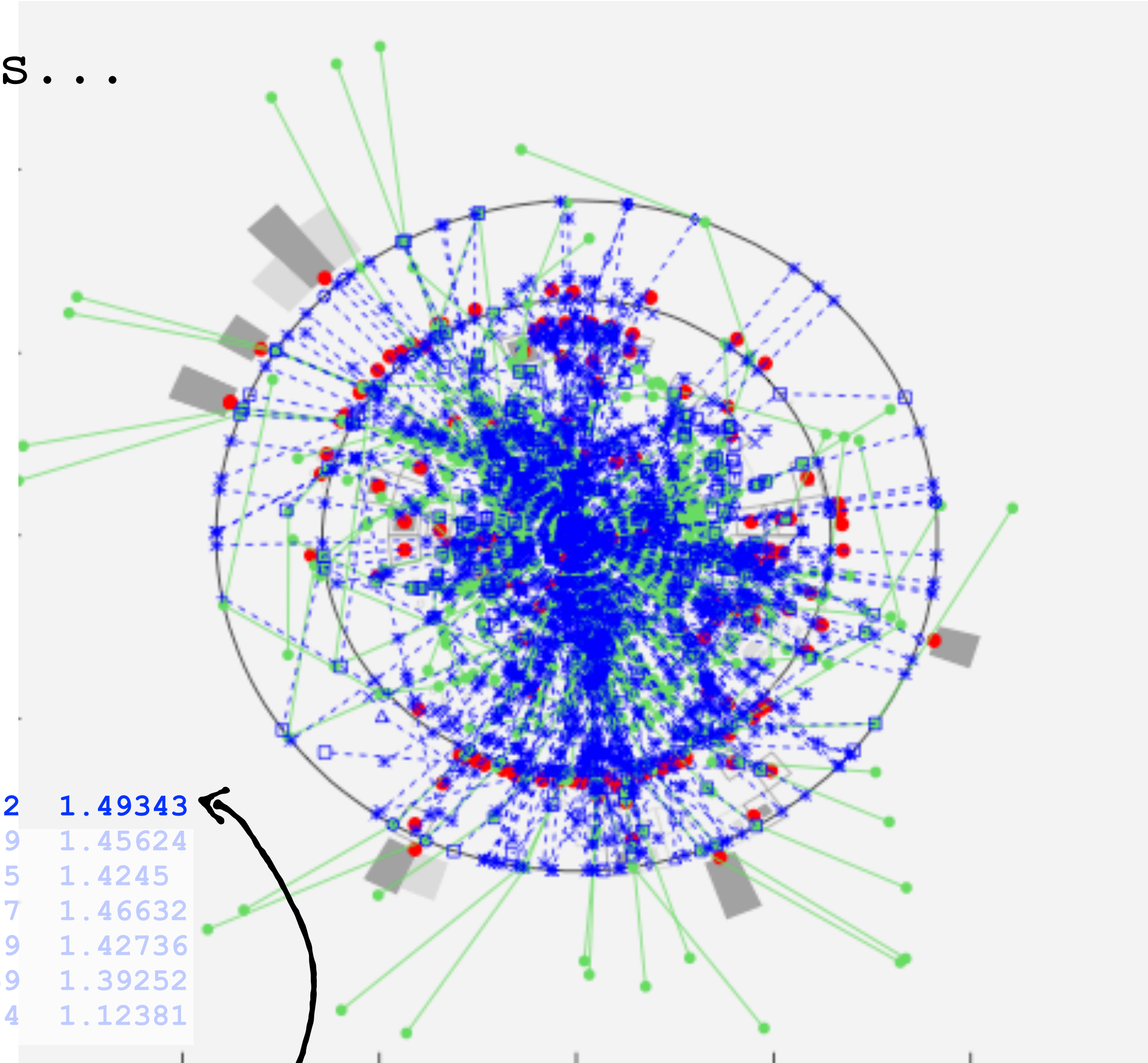


True Particles	PDG code:		p/pt/eta/phi:			
#0	130,		20.3845	16.7688	-0.645422	1.49343
#1	211,		17.2954	15.0452	-0.540329	1.45624
#2	211,		11.453	9.82512	-0.567975	1.4245
#3	22,		7.75683	6.52999	-0.603777	1.46632
#4	22,		7.26097	6.17551	-0.584549	1.42736
#5	22,		6.56173	5.52903	-0.602059	1.39252
#6	2212,		5.69095	5.14257	-0.457804	1.12381
...						
Reco Particles	PFCandidate type:	E/pT/eta/phi				
#0	5	31.929	26.176	-0.651	1.493,	
#1	1	17.237	14.994	-0.540	1.456,	
#2	1	11.540	9.900	-0.568	1.425,	
#3	4	9.684	8.195	-0.594	1.420,	
#4	4	6.663	5.602	-0.606	1.388,	
#5	1	5.720	5.170	-0.457	1.124,	
...						

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Analysis of the leading jet from simulated event of all-hadronic top-quark pairs:



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#0	PDG code:130,	p/pt/eta/phi:	20.3845	16.7688	-0.645422	1.49343
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#3	PDG code:22,	p/pt/eta/phi:	7.75683	6.52999	-0.603777	1.46632
#4	PDG code:22,	p/pt/eta/phi:	7.26097	6.17551	-0.584549	1.42736
#5	PDG code:22,	p/pt/eta/phi:	6.56173	5.52903	-0.602059	1.39252
#6	PDG code:2212,	p/pt/eta/phi:	5.69095	5.14257	-0.457804	1.12381
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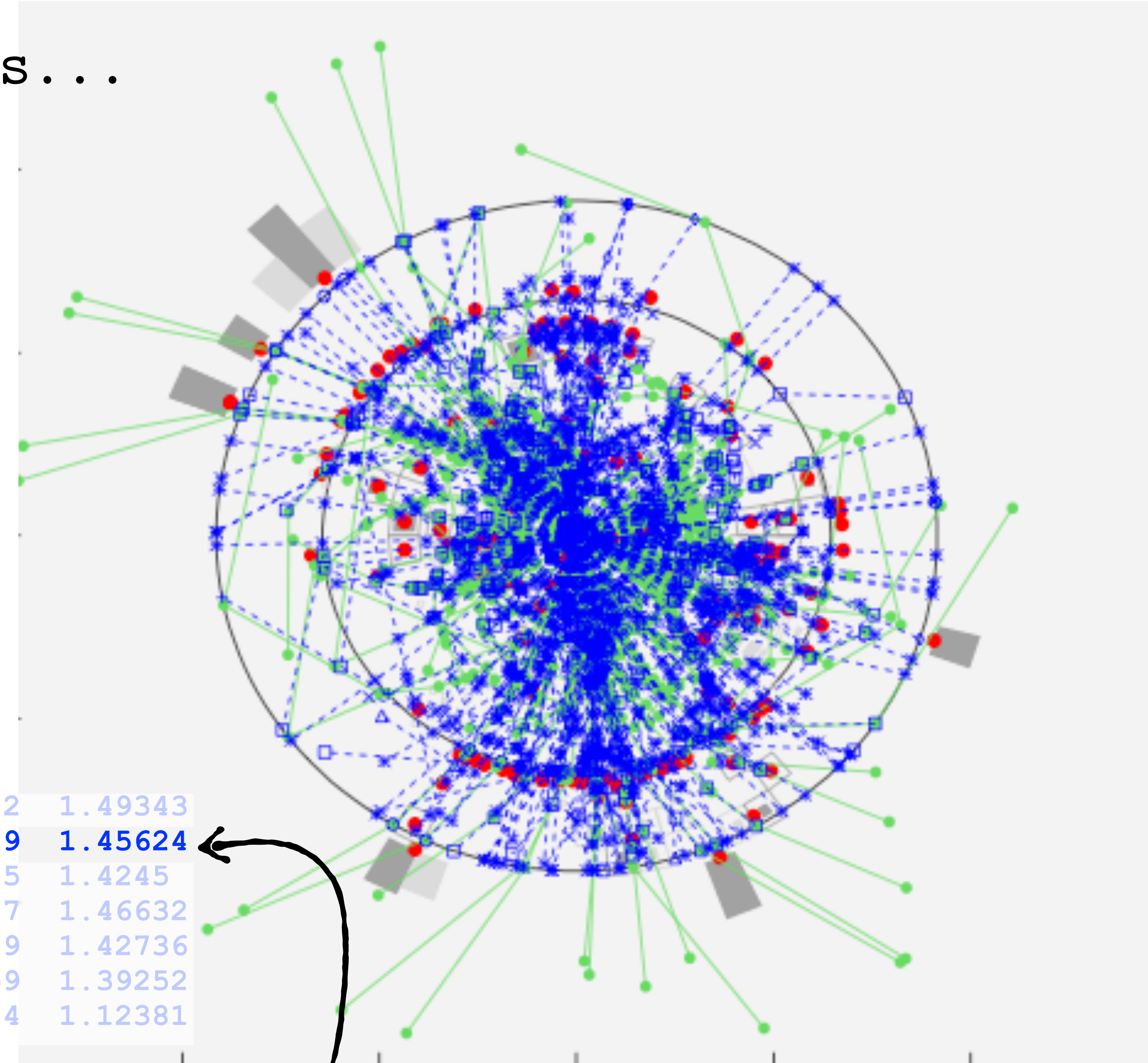
Reco Particles

#0	PFCandidate type: 5	E/pT/eta/phi	31.929	26.176	-0.651	1.493,
#1	PFCandidate type: 1	E/pT/eta/phi	17.237	14.994	-0.540	1.456,
#2	PFCandidate type: 1	E/pT/eta/phi	11.540	9.900	-0.568	1.425,
#3	PFCandidate type: 4	E/pT/eta/phi	9.684	8.195	-0.594	1.420,
#4	PFCandidate type: 4	E/pT/eta/phi	6.663	5.602	-0.606	1.388,
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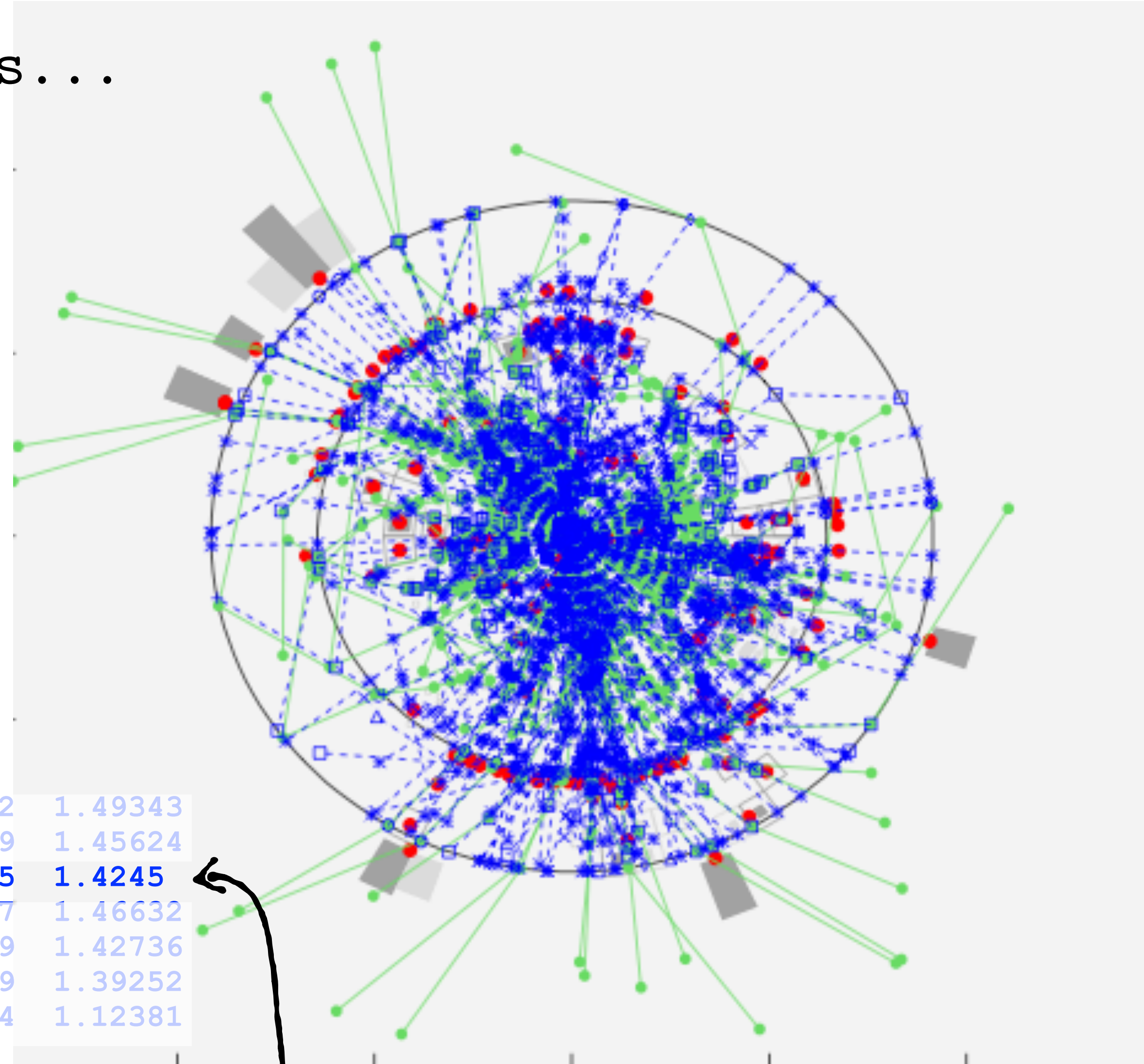


True Particles						
#0	PDG code:	130,	p/pt/eta/phi:	20.3845	16.7688	-0.645422 1.49343
#1	PDG code:	211,	p/pt/eta/phi:	17.2954	15.0452	-0.540329 1.45624
#2	PDG code:	211,	p/pt/eta/phi:	11.453	9.82512	-0.567975 1.4245
#3	PDG code:	22,	p/pt/eta/phi:	7.75683	6.52999	-0.603777 1.46632
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#1	PFCandidate type:	1	E/pT/eta/phi	17.237	14.994	-0.540 1.456,
#2	PFCandidate type:	1	E/pT/eta/phi	11.540	9.900	-0.568 1.425,
#3	PFCandidate type:	4	E/pT/eta/phi	9.684	8.195	-0.594 1.420,
#4	PFCandidate type:	4	E/pT/eta/phi	6.663	5.602	-0.606 1.388,
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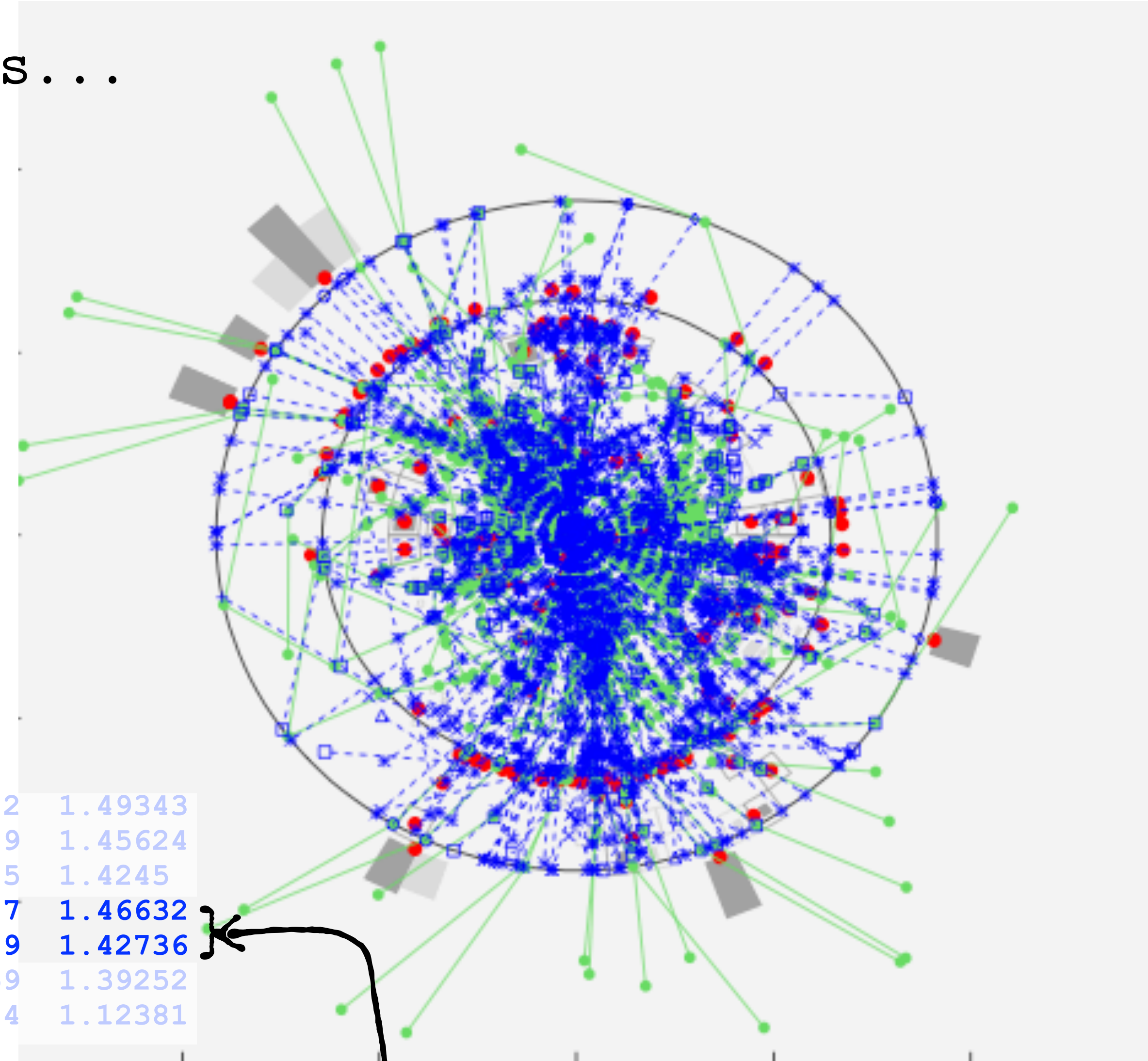
True Particles	Reco Particles
#0 PDG code:130,	#0 PFCandidate type: 5 E/pT/eta/phi 31.929
#1 PDG code:211,	#1 PFCandidate type: 1 E/pT/eta/phi 17.237
#2 PDG code:211,	#2 PFCandidate type: 1 E/pT/eta/phi 11.540
#3 PDG code:22,	#3 PFCandidate type: 4 E/pT/eta/phi 9.684
#4 PDG code:22,	#4 PFCandidate type: 4 E/pT/eta/phi 6.663
#5 PDG code:22,	#5 PFCandidate type: 1 E/pT/eta/phi 5.720
#6 PDG code:2212,	
...	...

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p/pt/eta/phi: 20.3845 16.7688 -0.645422 1.49343	E/pT/eta/phi 26.176 -0.651 1.493,
p/pt/eta/phi: 17.2954 15.0452 -0.540329 1.45624	E/pT/eta/phi 14.994 -0.540 1.456,
p/pt/eta/phi: 11.453 9.82512 -0.567975 1.4245	E/pT/eta/phi 9.900 -0.568 1.425,
p/pt/eta/phi: 7.75683 6.52999 -0.603777 1.46632	E/pT/eta/phi 8.195 -0.594 1.420,
p/pt/eta/phi: 7.26097 6.17551 -0.584549 1.42736	E/pT/eta/phi 6.602 -0.606 1.388,
p/pt/eta/phi: 6.56173 5.52903 -0.602059 1.39252	E/pT/eta/phi 5.170 -0.457 1.124,
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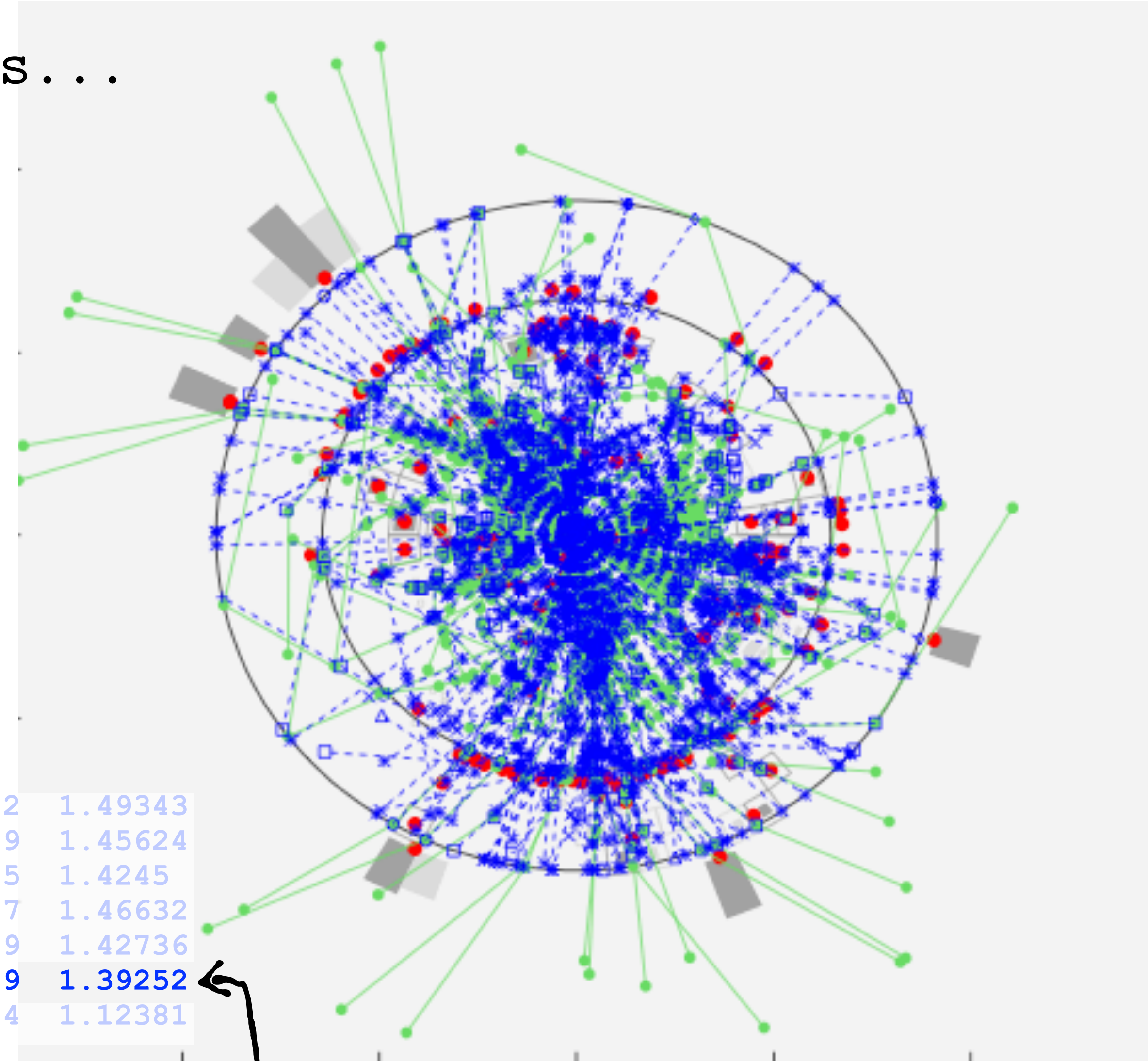


True Particles							
#0	PDG code:130,		p/pt/eta/phi:	20.3845	16.7688	-0.645422	1.49343
#1	PDG code:211,		p/pt/eta/phi:	17.2954	15.0452	-0.540329	1.45624
#2	PDG code:211,		p/pt/eta/phi:	11.453	9.82512	-0.567975	1.4245
#3	PDG code:22,		p/pt/eta/phi:	7.75683	6.52999	-0.603777	1.46632
#4	PDG code:22,		p/pt/eta/phi:	7.26097	6.17551	-0.584549	1.42736
#5	PDG code:22,		p/pt/eta/phi:	6.56173	5.52903	-0.602059	1.39252
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#2	PFCandidate type:	1	E/pT/eta/phi	11.540	9.900	-0.568	1.425,
#3	PFCandidate type:	4	E/pT/eta/phi	9.684	8.195	-0.594	1.420,
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#4	PDG code:22,	p/pt/eta/phi:	7.26097	6.17551	-0.584549	1.42736
#5	PDG code:22,	p/pt/eta/phi:	6.56173	5.52903	-0.602059	1.39252
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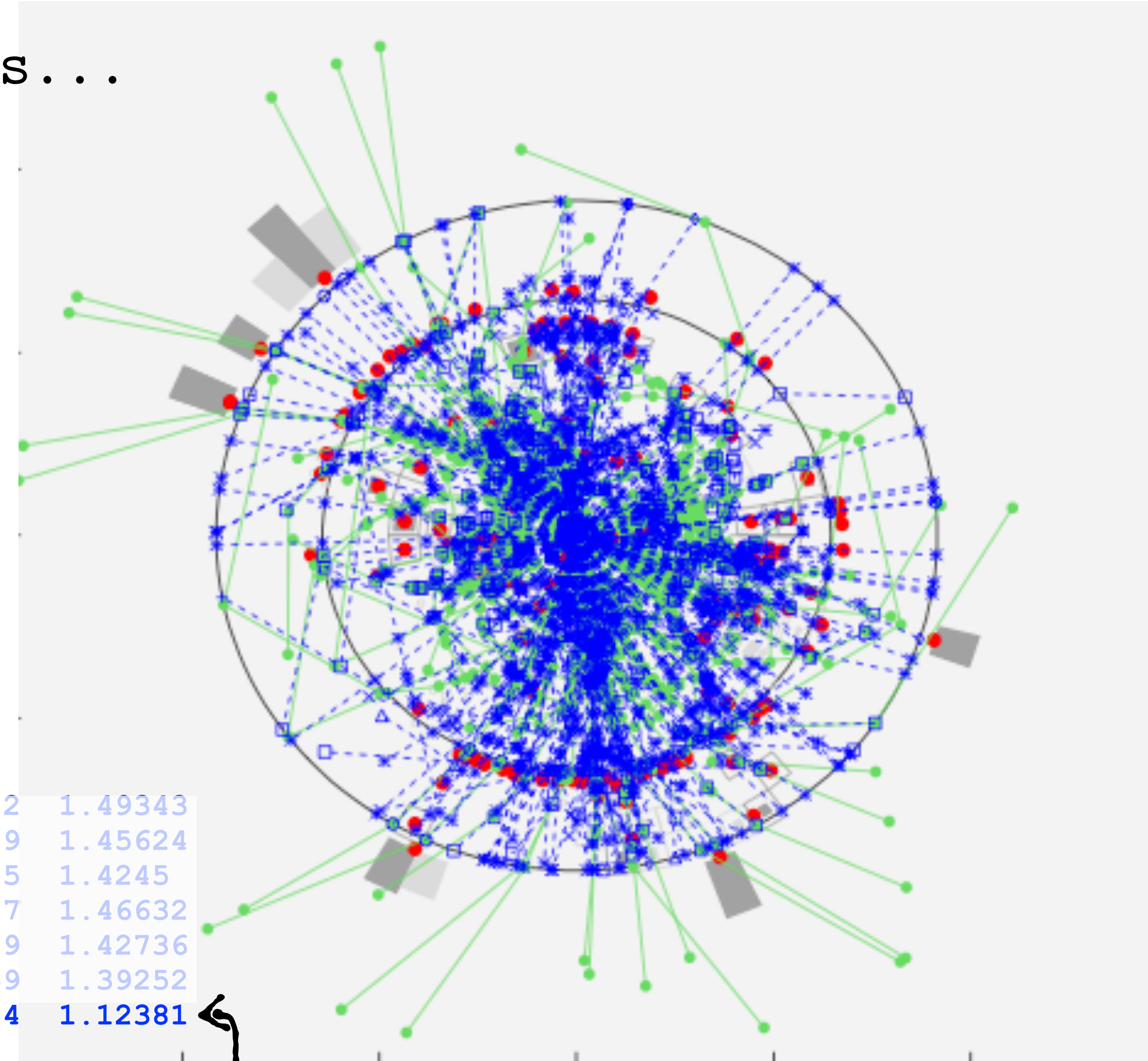
Reco Particles

#0	PFCandidate type: 5	E/pT/eta/phi	31.929	26.176	-0.651	1.493,
#1	PFCandidate type: 1	E/pT/eta/phi	17.237	14.994	-0.540	1.456,
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#3	PFCandidate type: 4	E/pT/eta/phi	9.684	8.195	-0.594	1.420,
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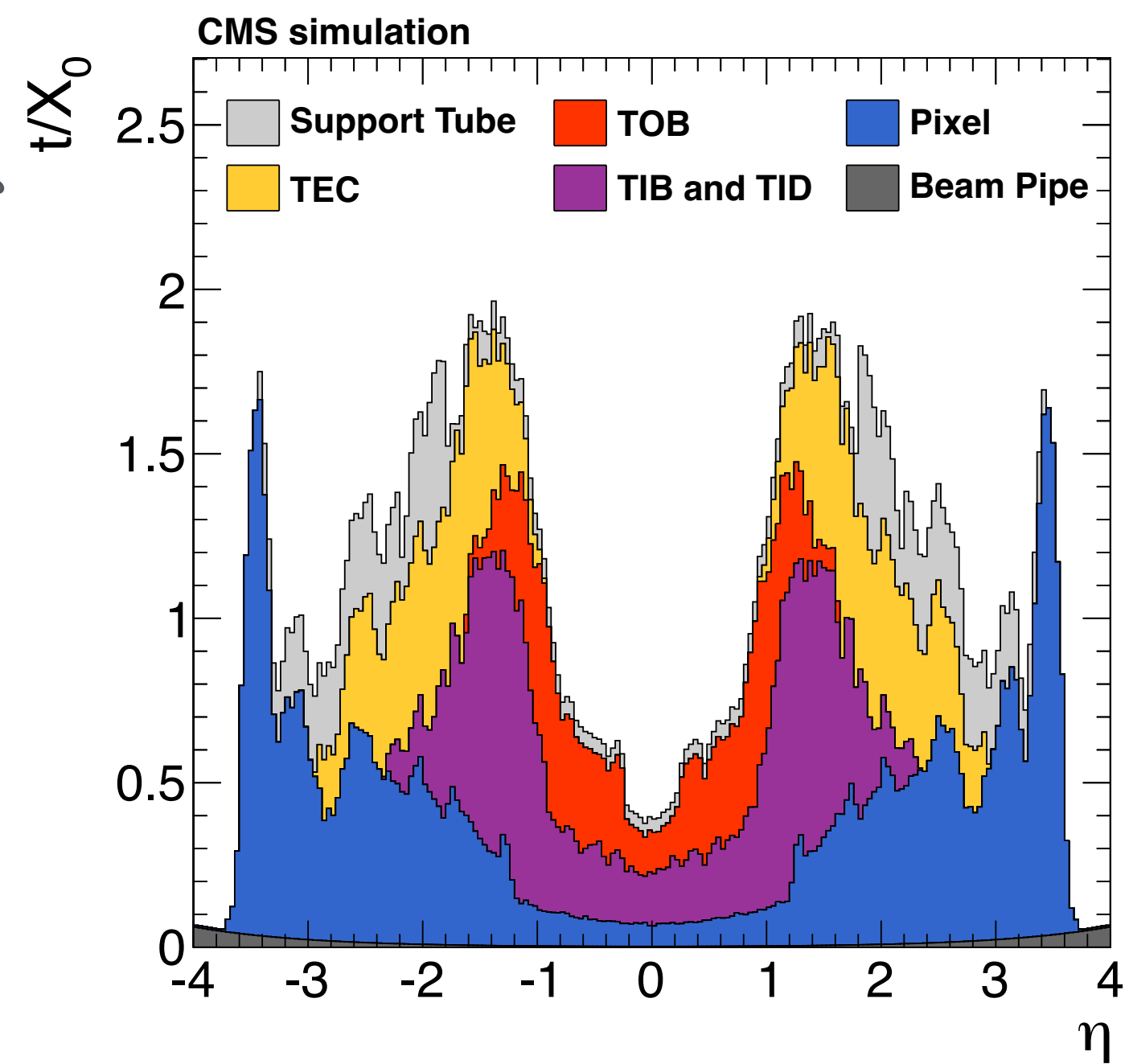
True Particles	Reco Particles
#0 PDG code:130,	#0 PFCandidate type: 5 E/pT/eta/phi 31.929
#1 PDG code:211,	#1 PFCandidate type: 1 E/pT/eta/phi 17.237
#2 PDG code:211,	#2 PFCandidate type: 1 E/pT/eta/phi 11.540
#3 PDG code:22,	#3 PFCandidate type: 4 E/pT/eta/phi 9.684
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...	...

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p/pt/eta/phi: 17.2954	15.0452	-0.540329	1.45624
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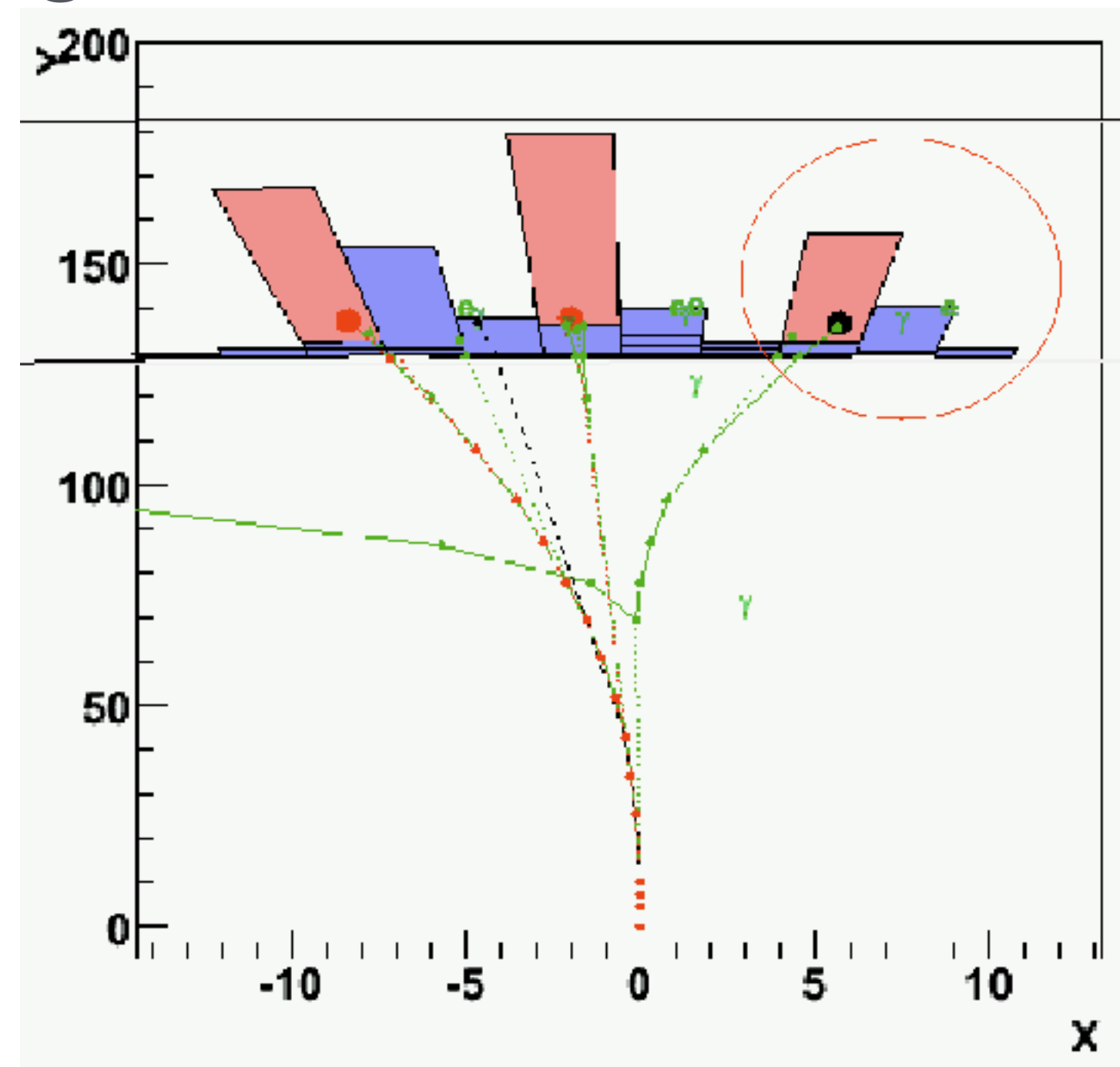
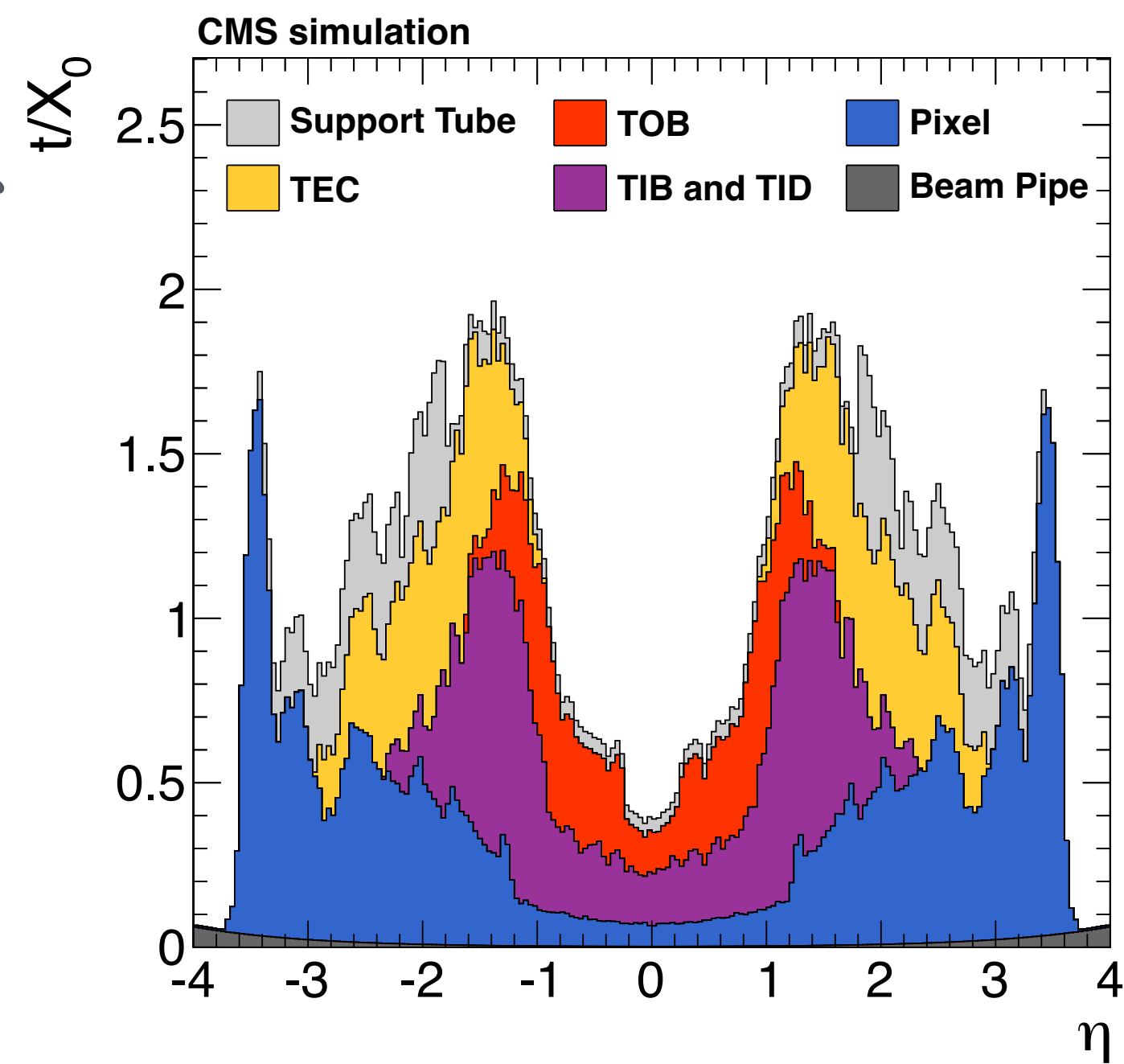
Important details (again!) Tracker Material Budget

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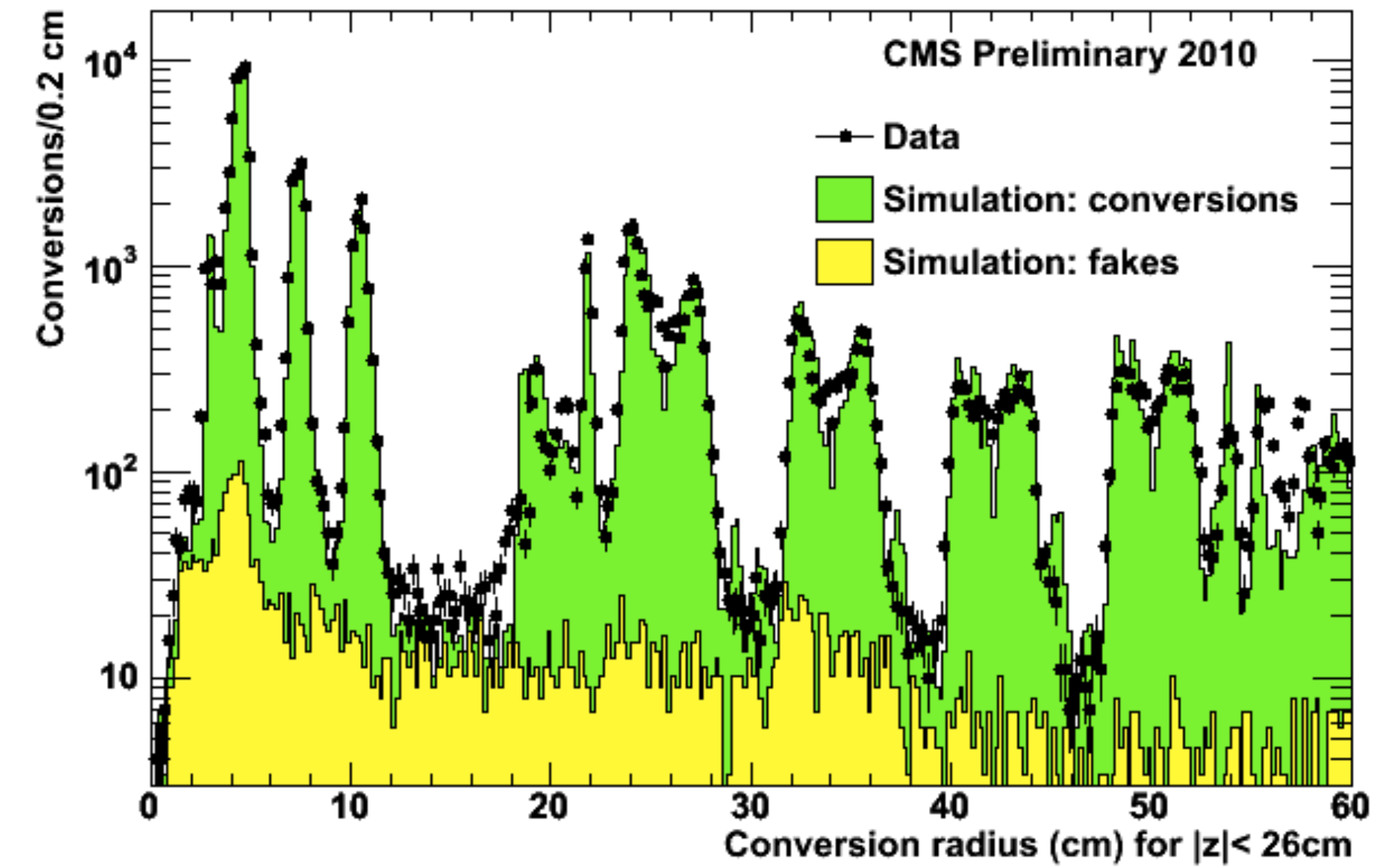
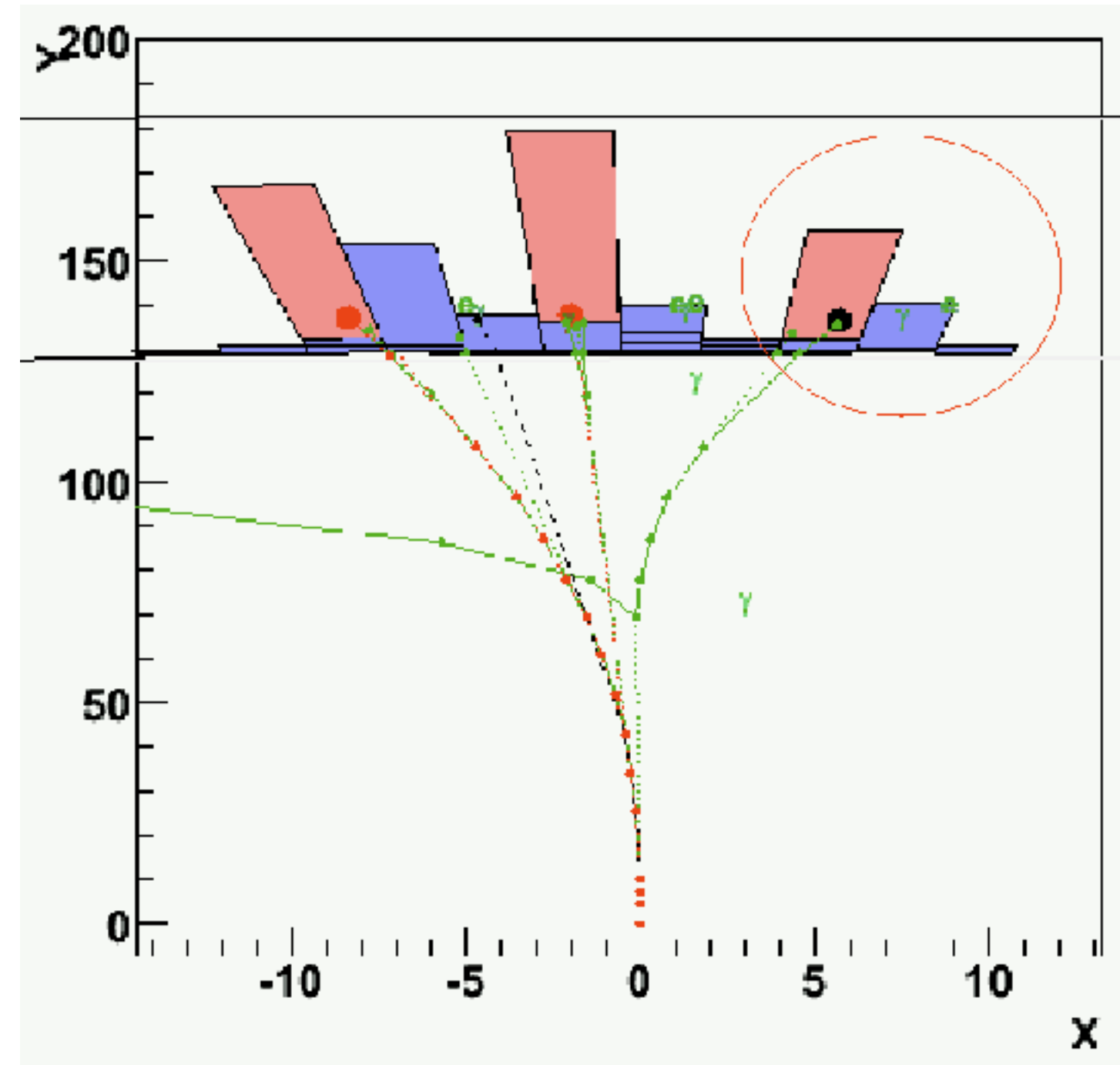
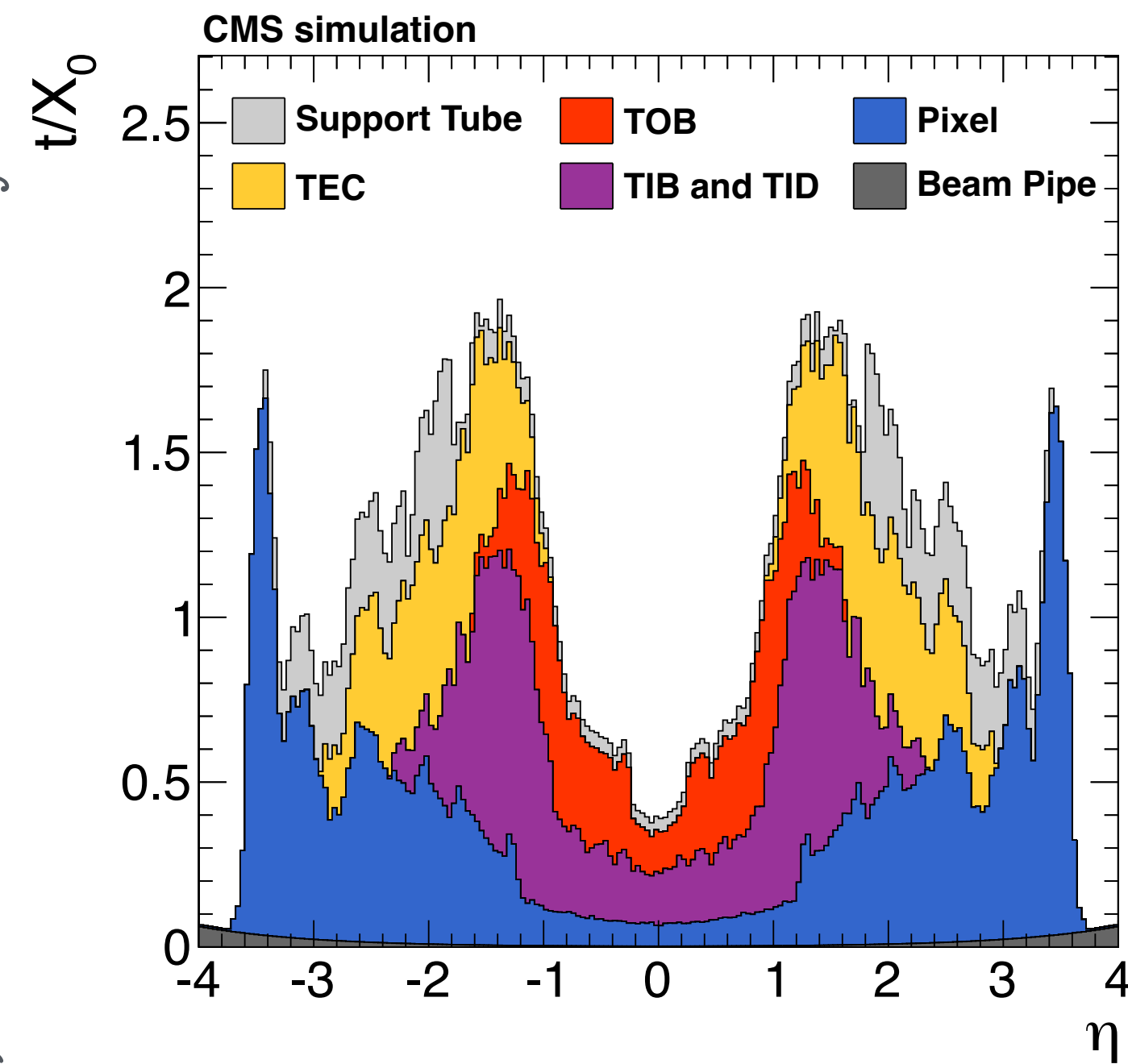
Richard Cavanaugh, Fermilab/UIC, HCP Summer School 31 July 2024



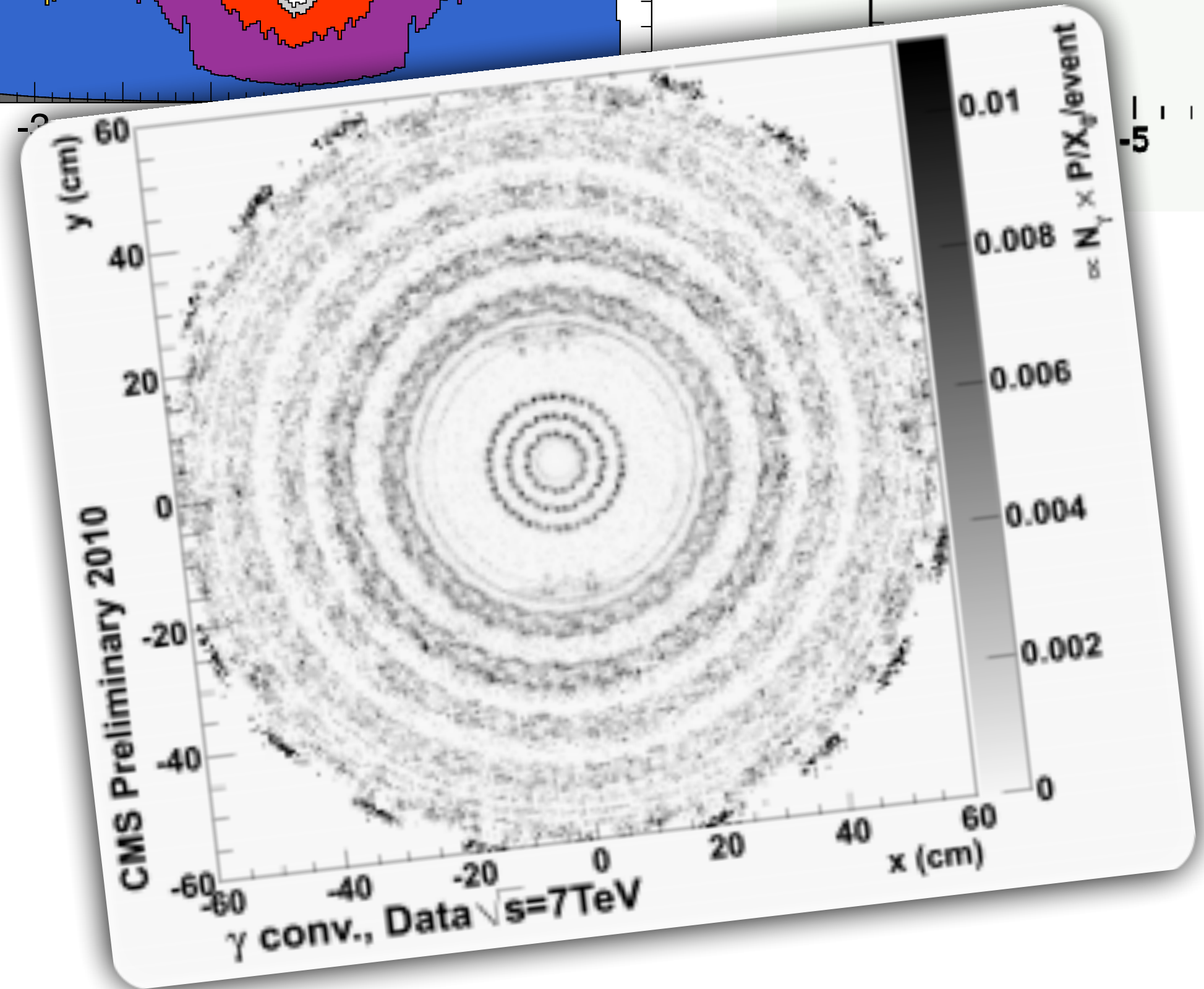
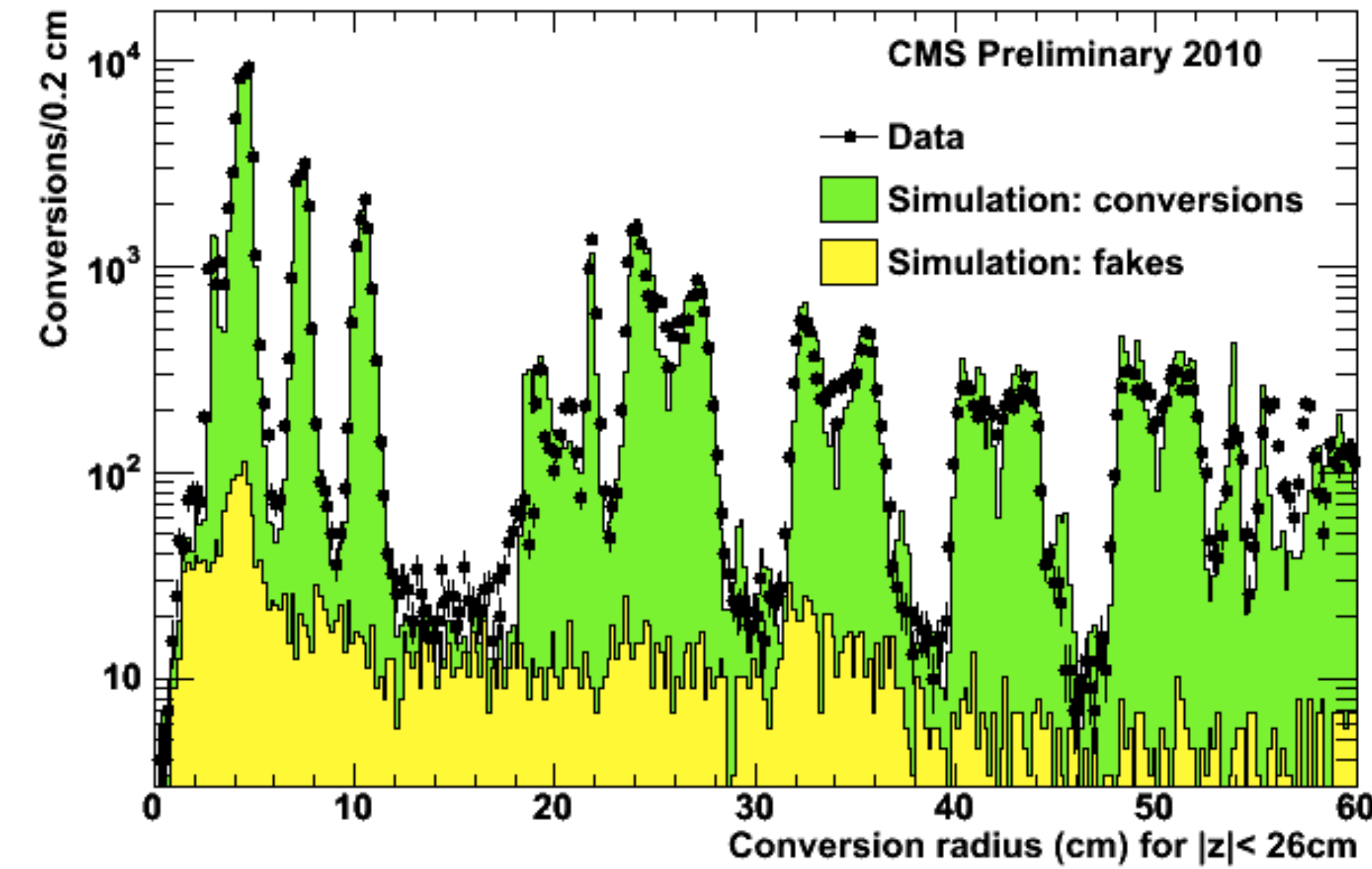
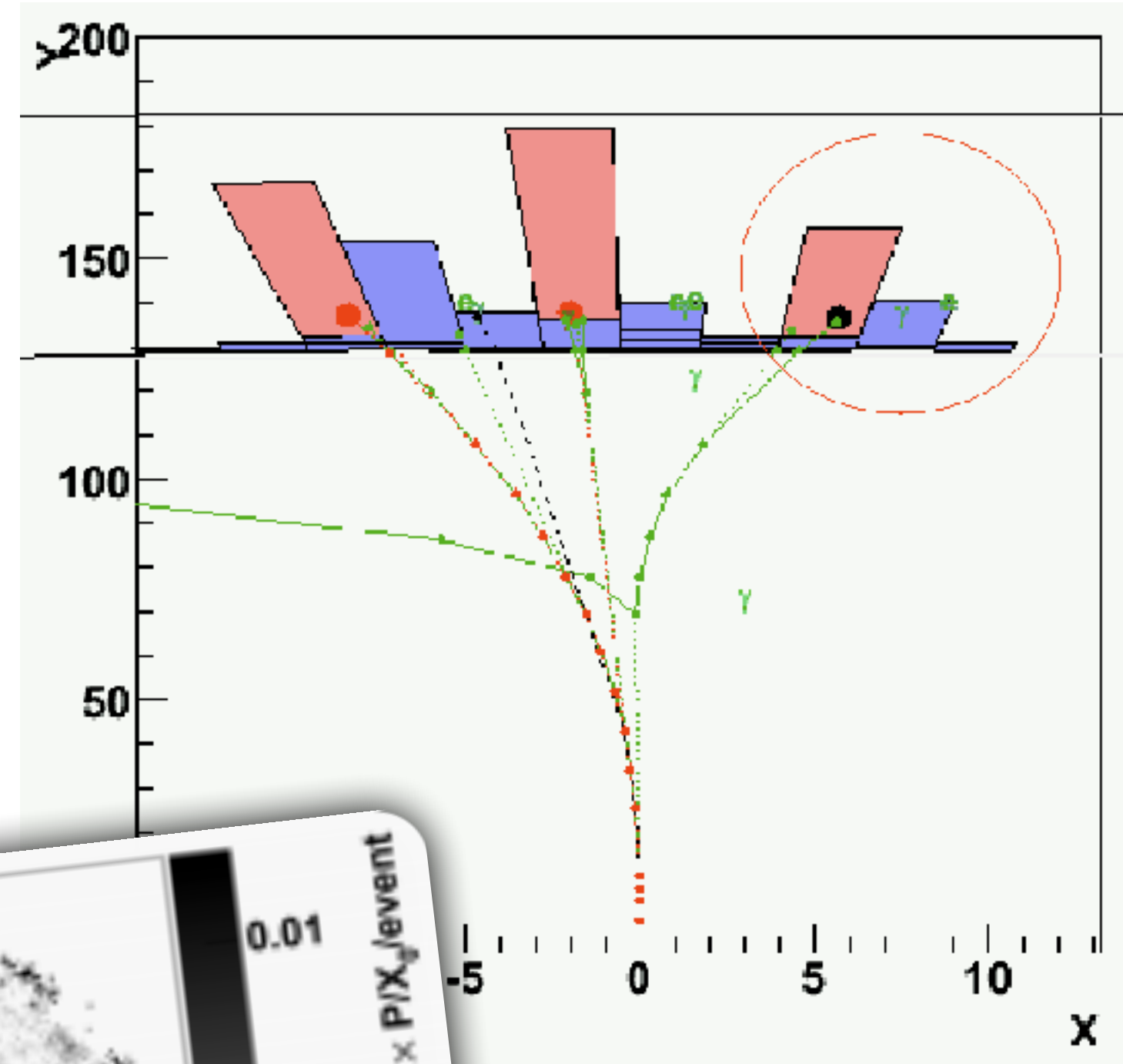
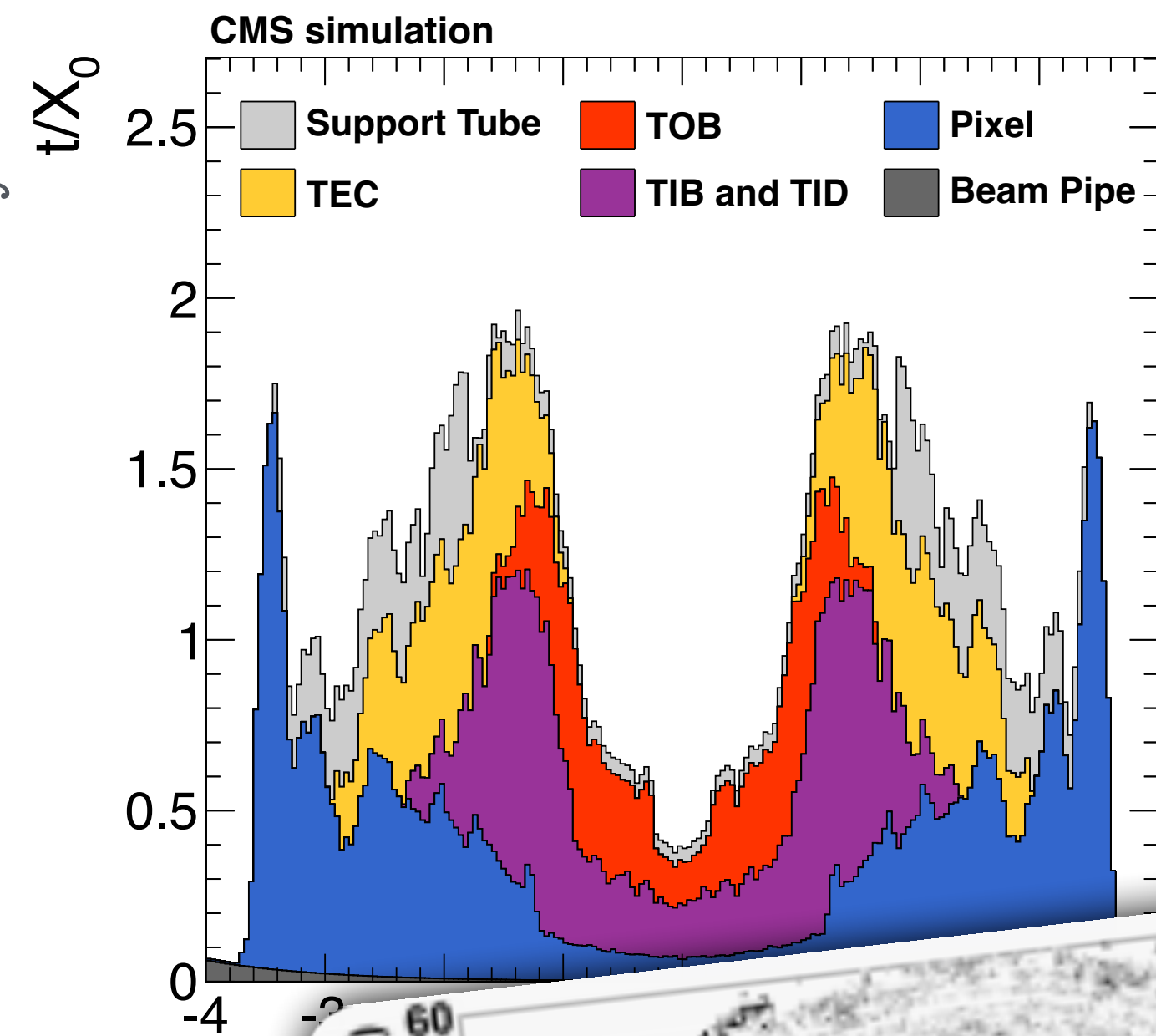
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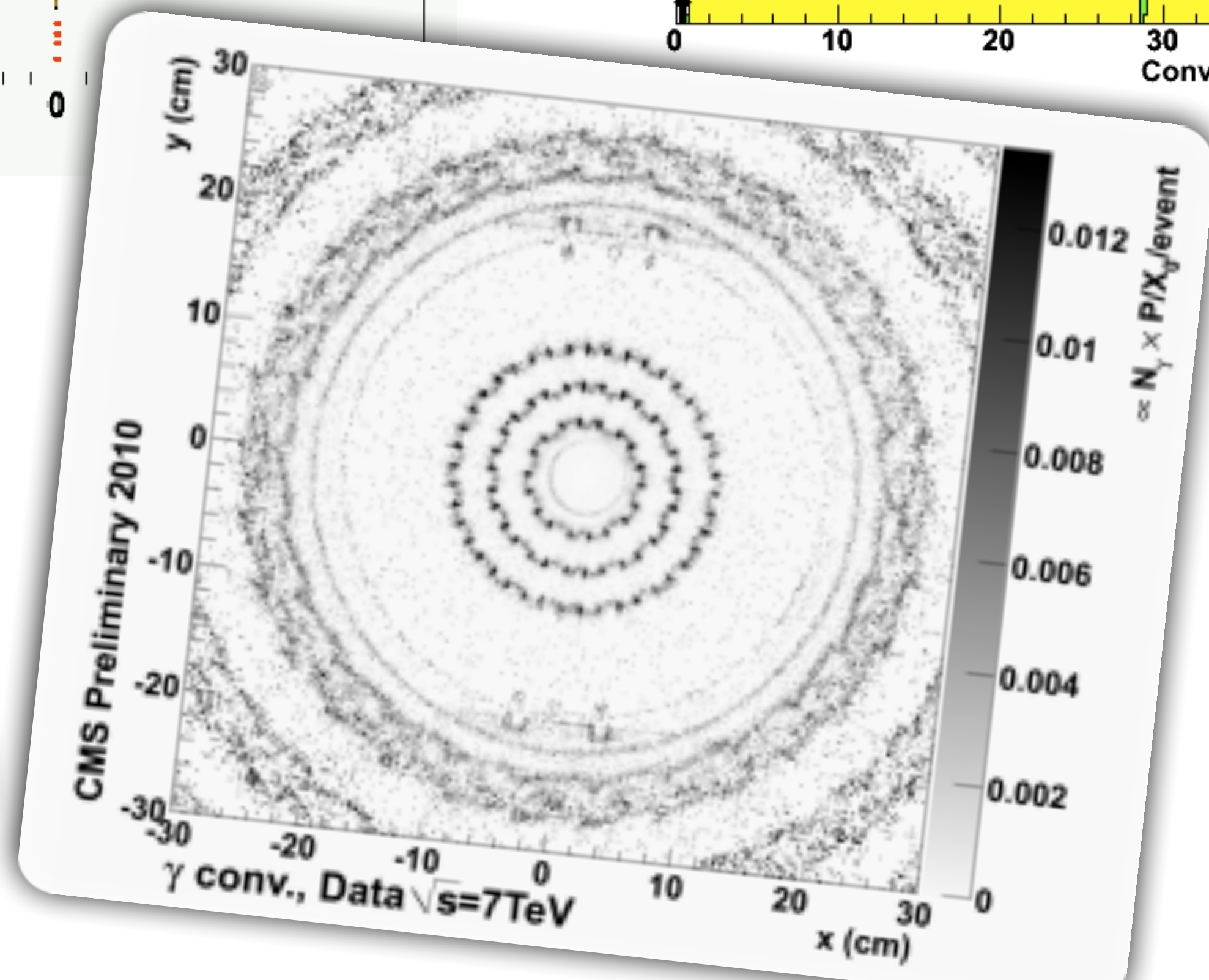
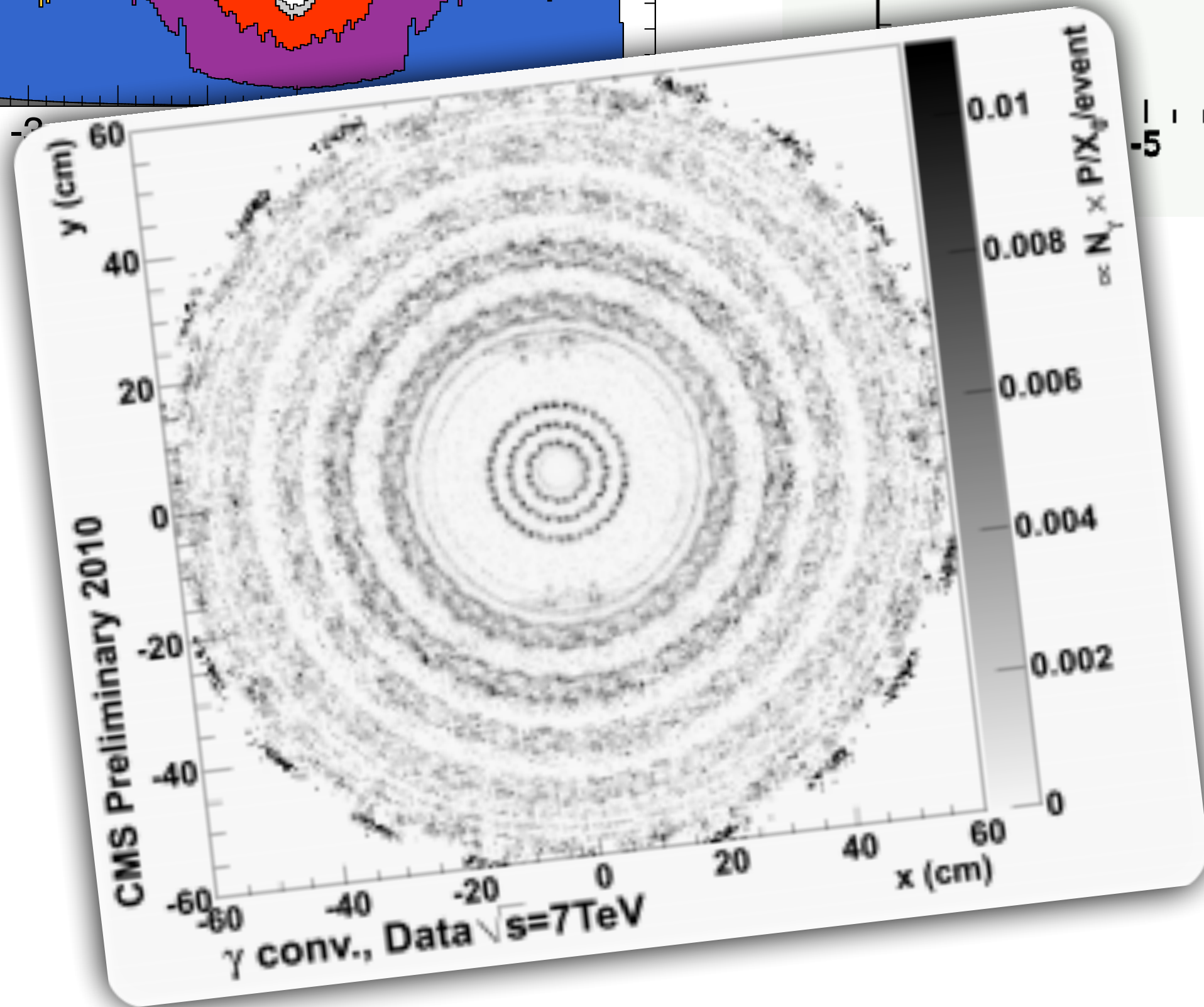
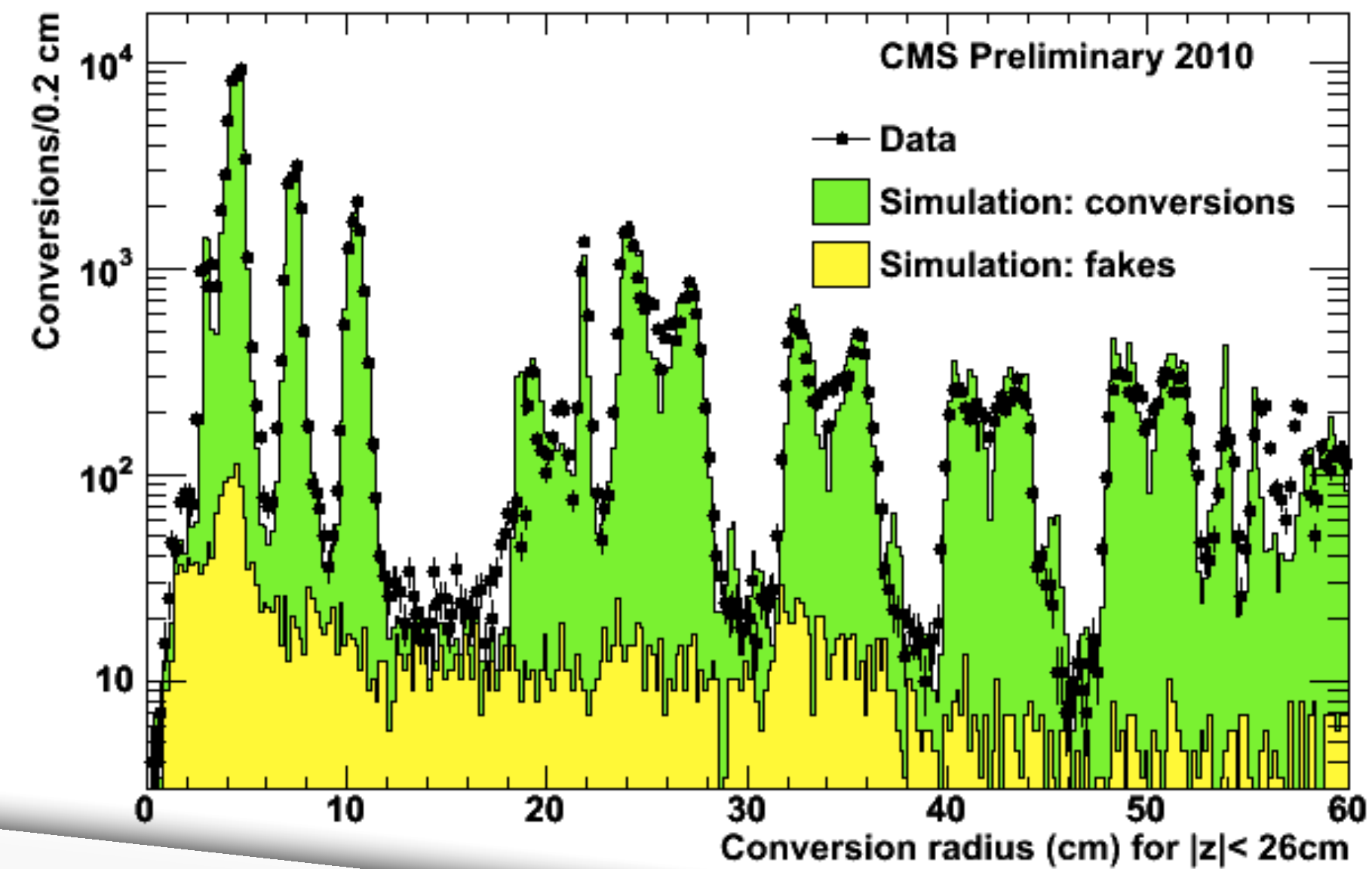
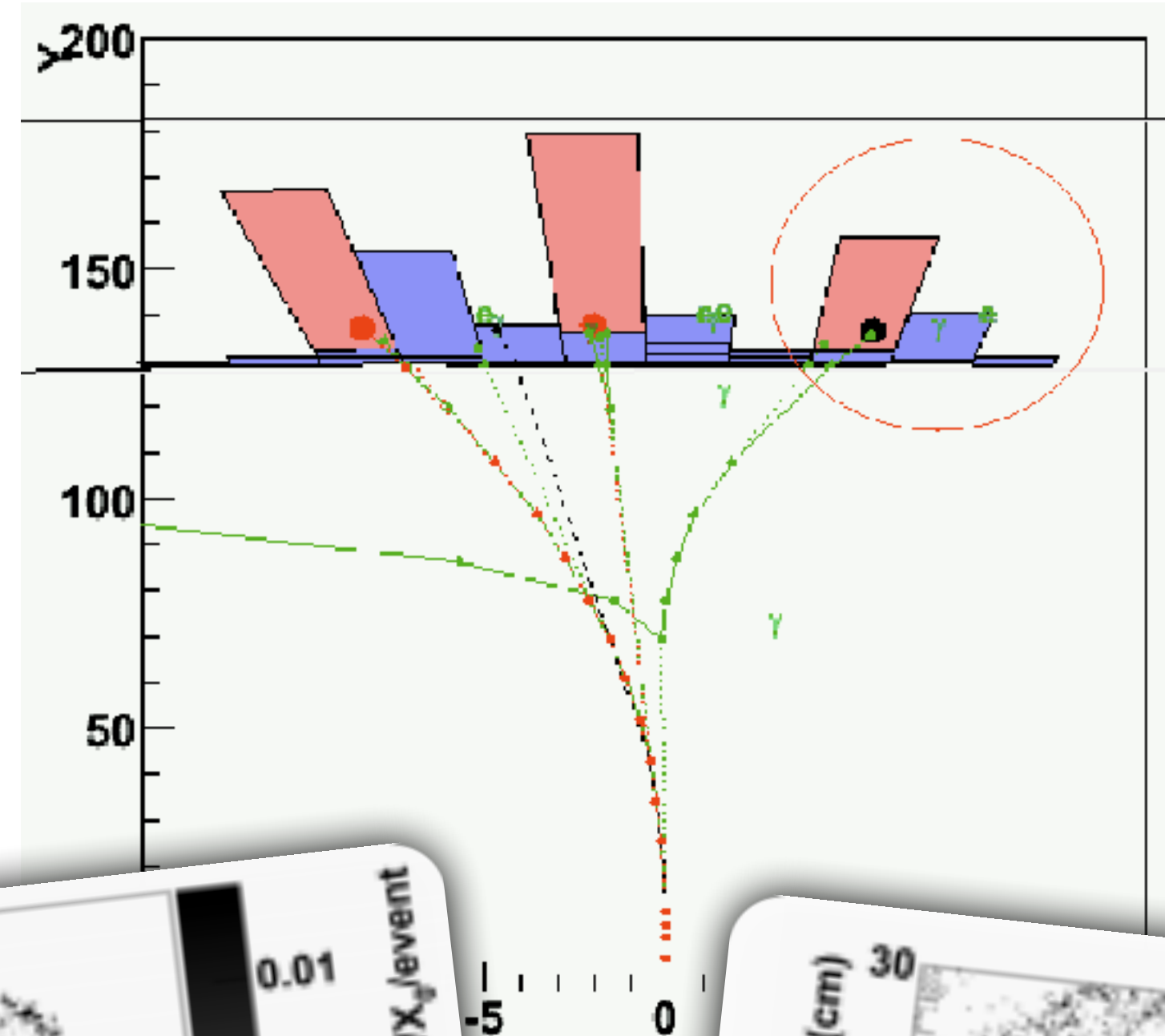
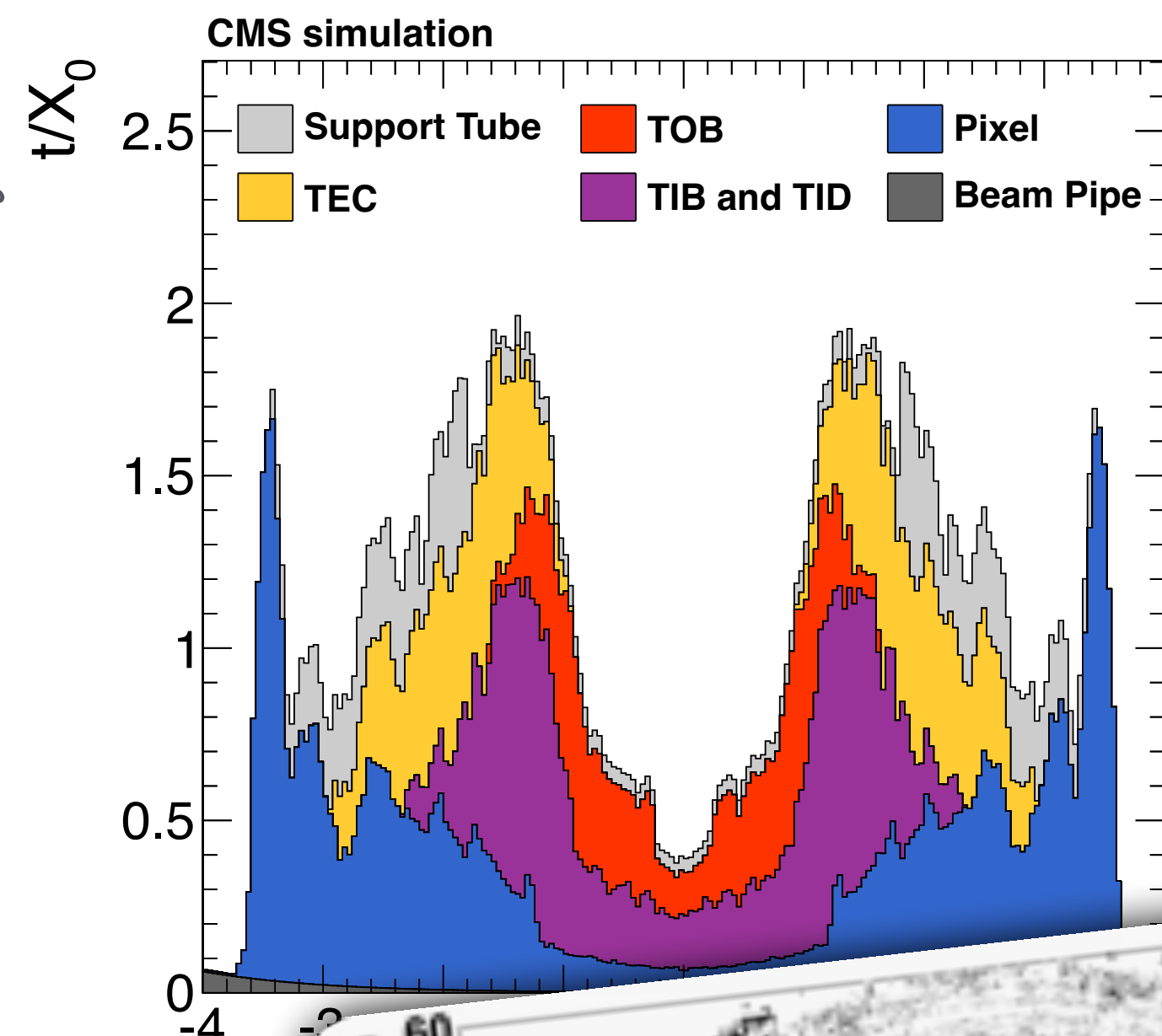
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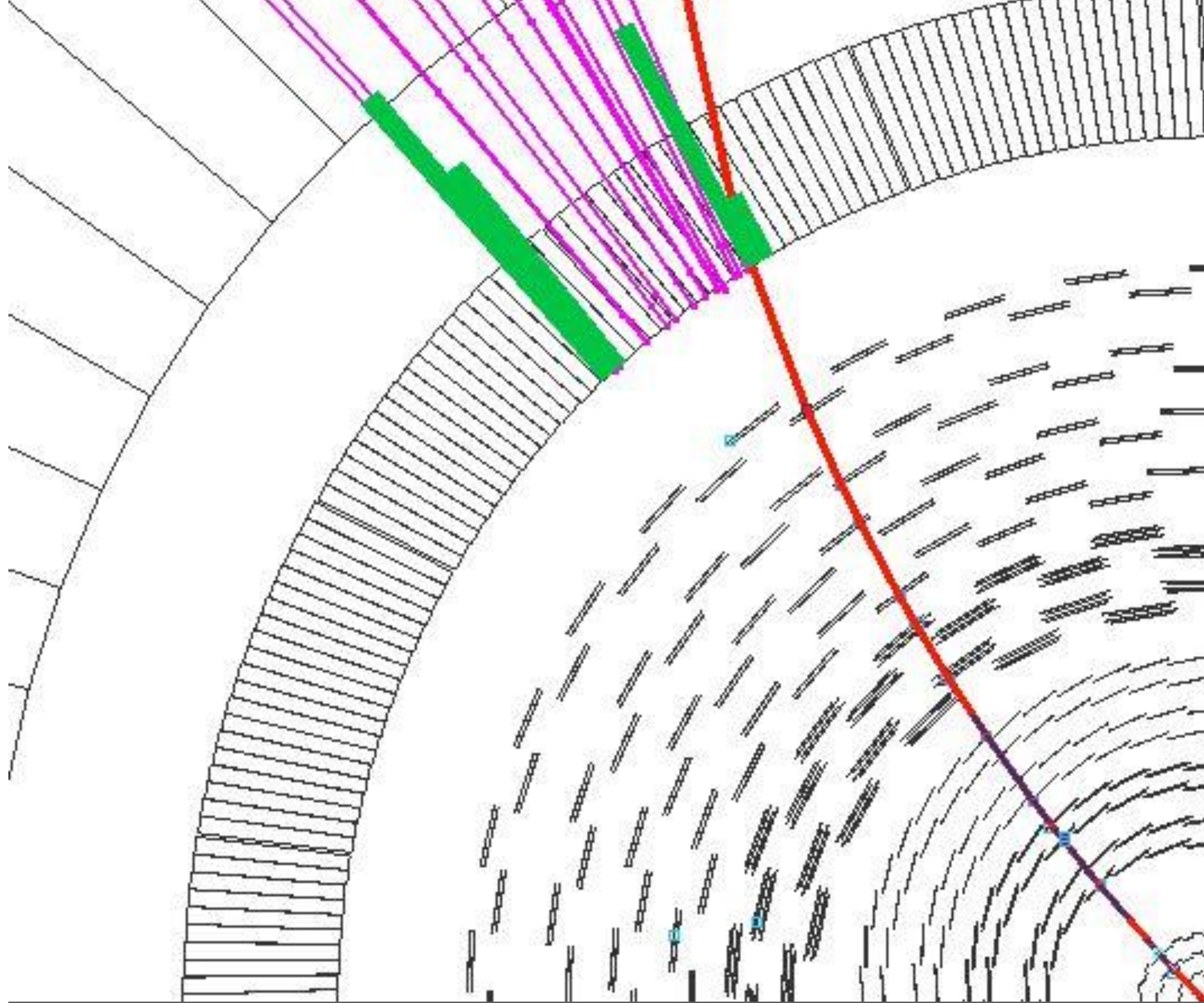
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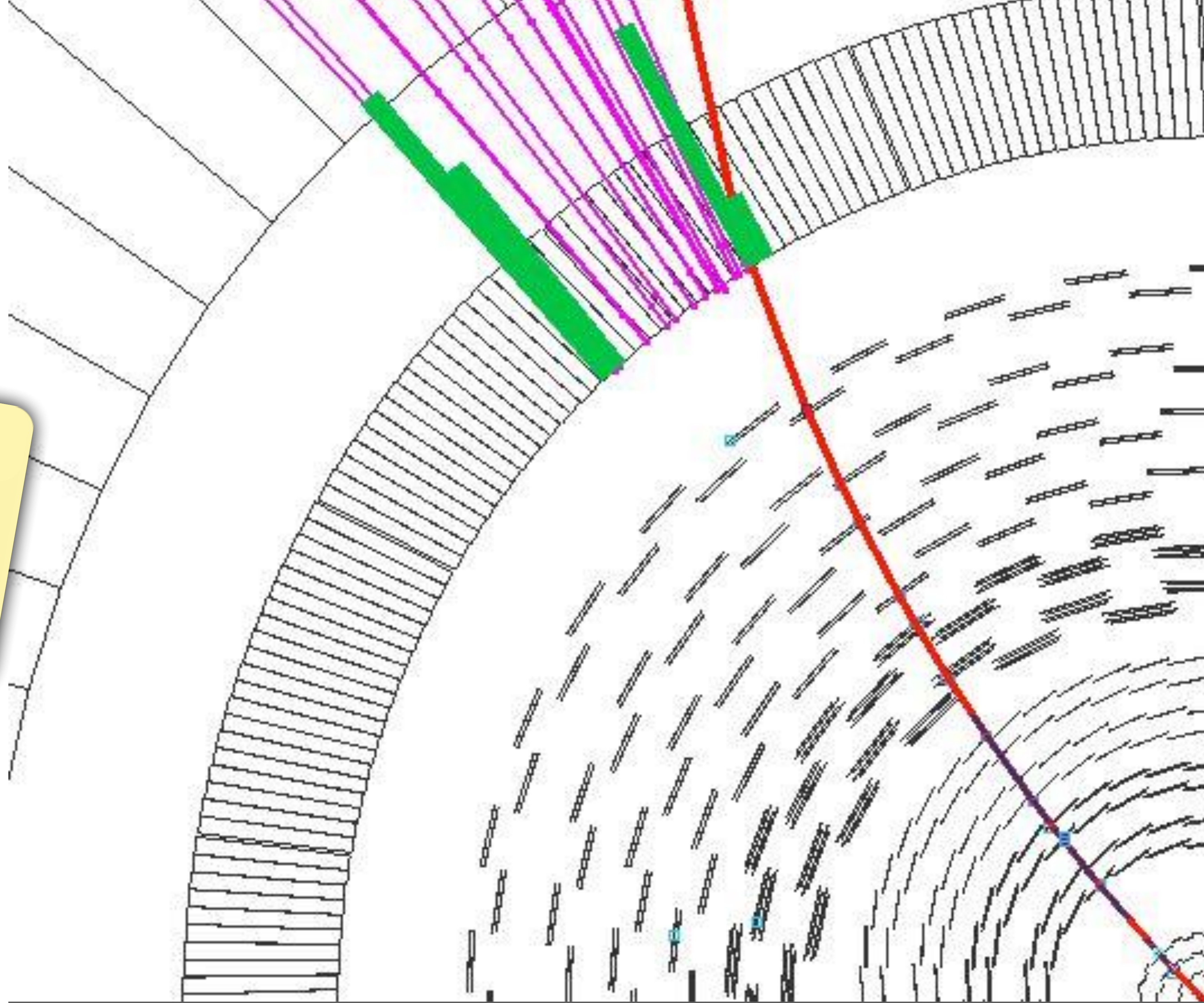
Electron ID



Electron ID

Huge Effect!

- Electrons radiate on average $\approx 70\%$ of their energy in the track by bremsstrahlung
- photons have $> 50\%$ probability to convert to e^+e^- pair
- energy spreads in ϕ due to B-field



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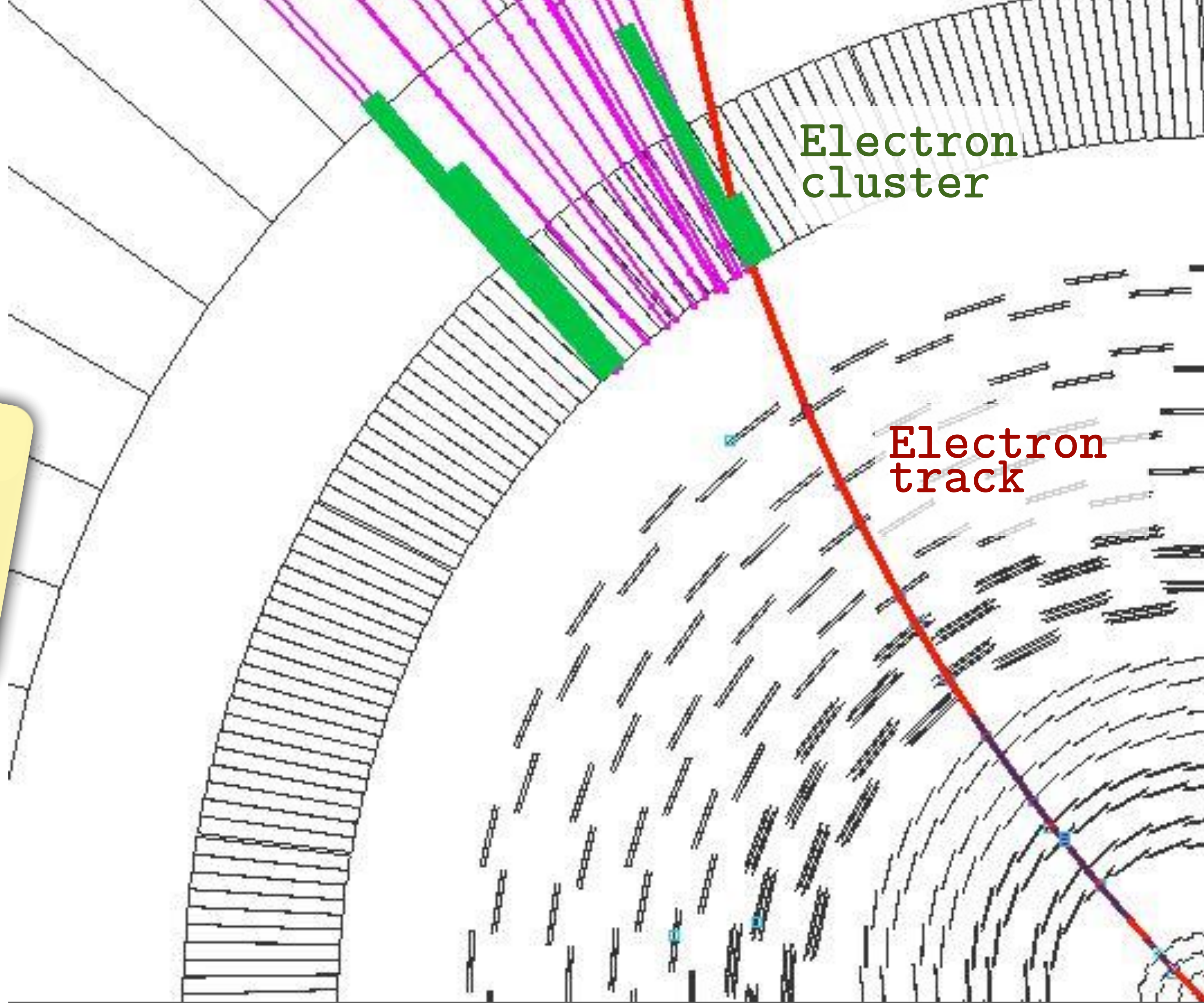


Electron track

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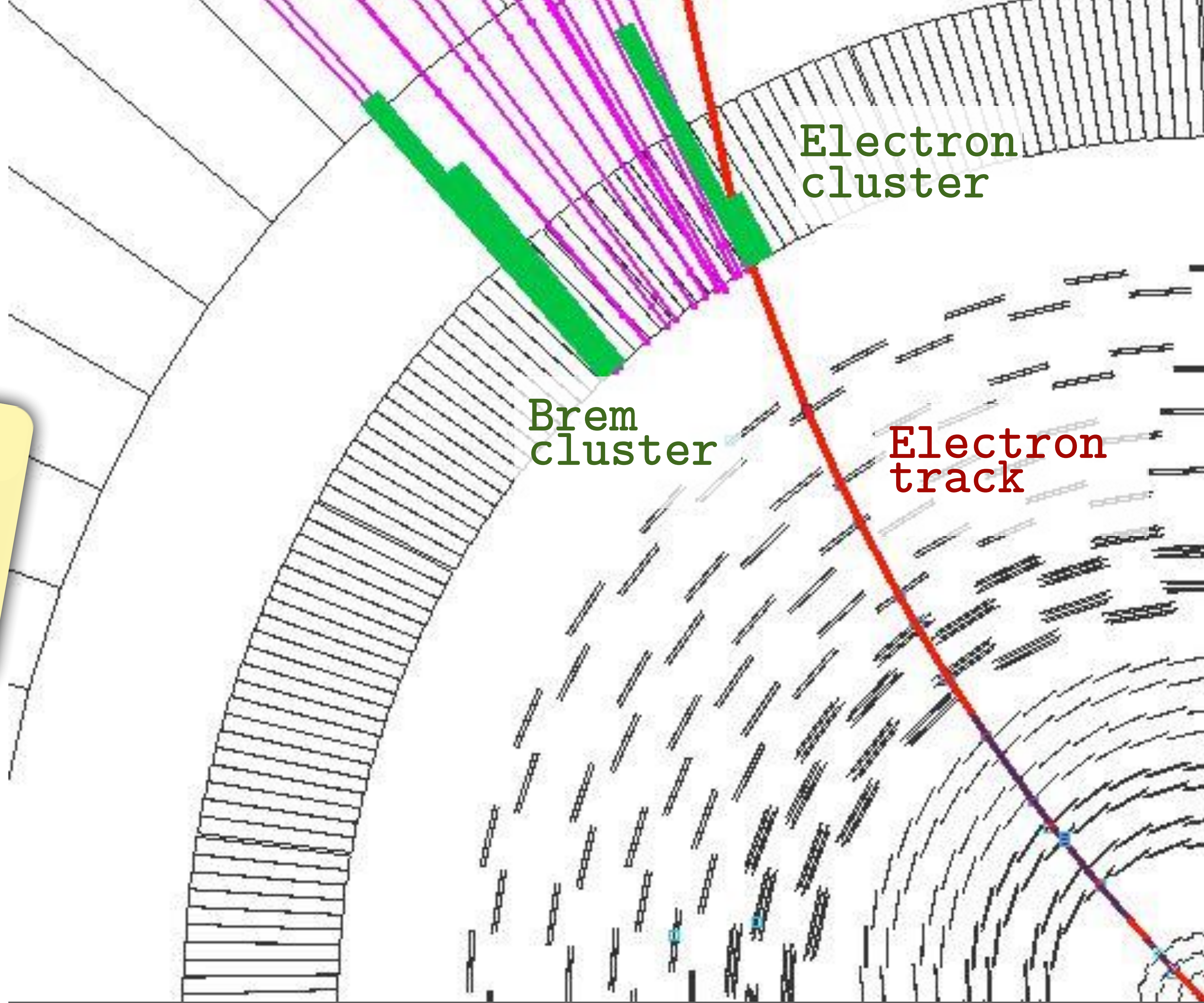
Electron cluster

Electron track

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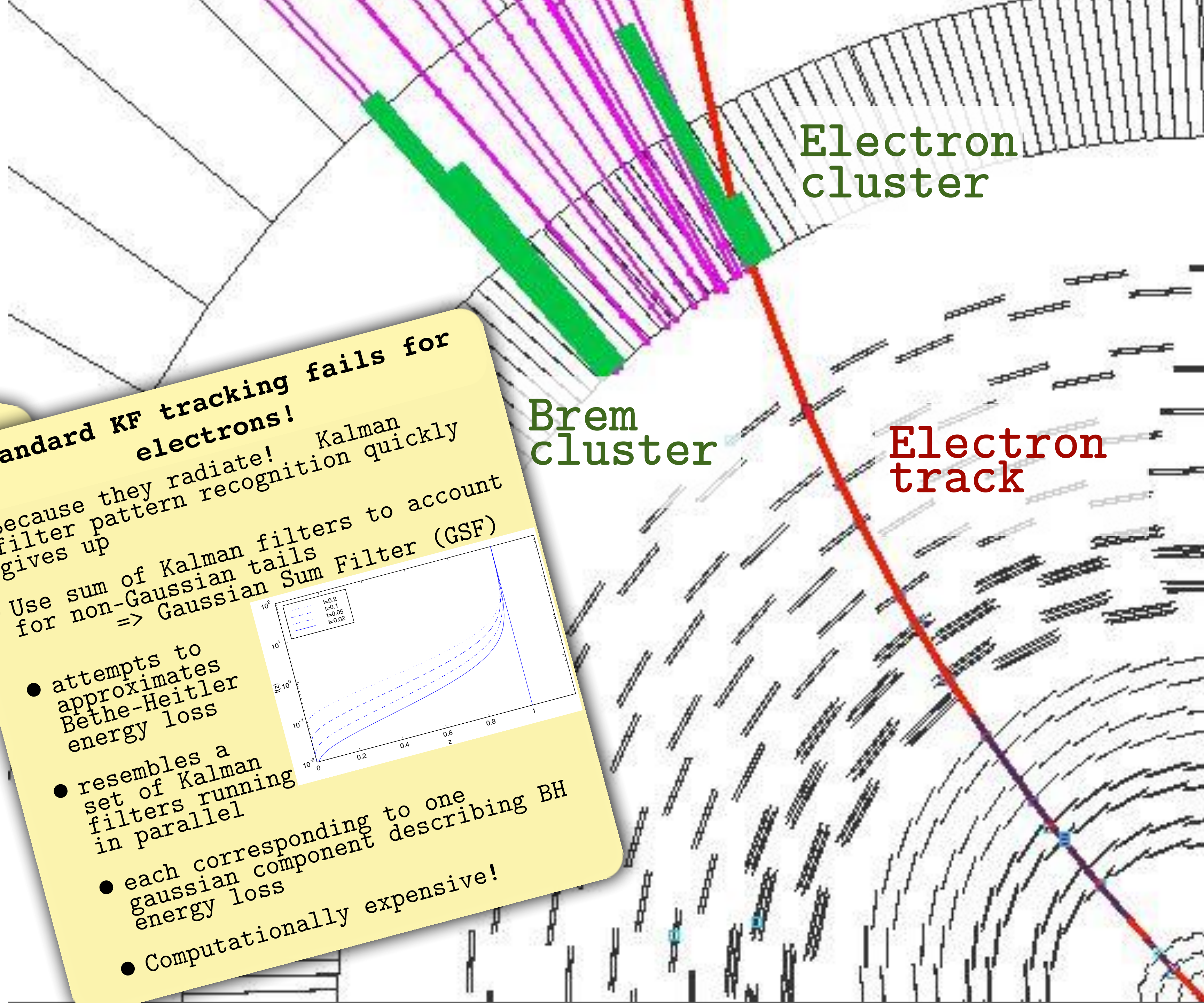


Electron cluster

Brem cluster

Electron track

Electron ID



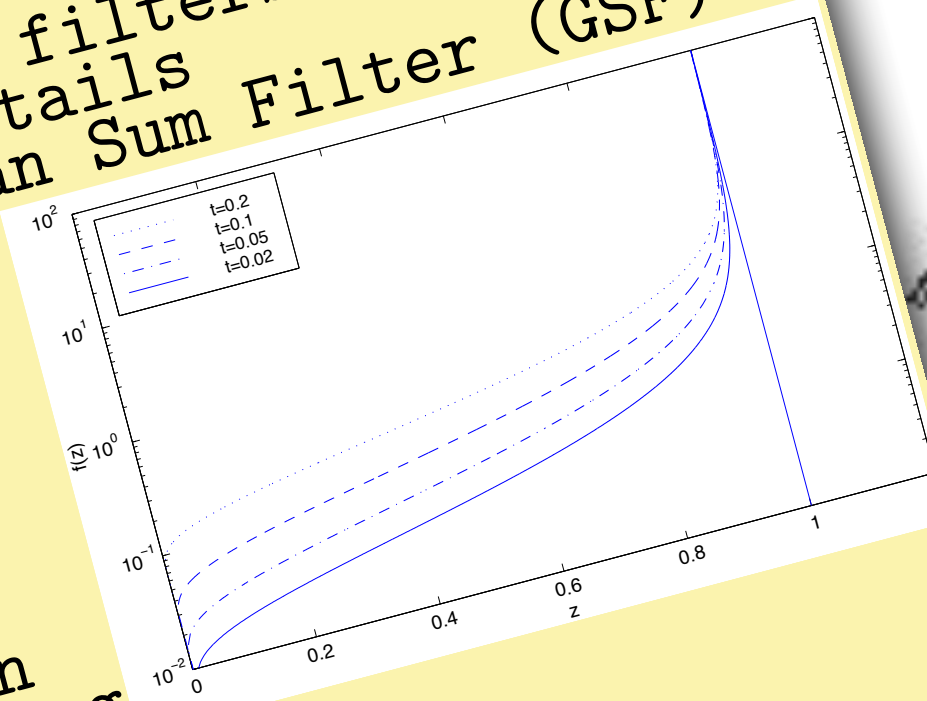
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Standard KF tracking fails for electrons!

- Because they radiate! Kalman filter pattern recognition quickly gives up
- Use sum of Kalman filters to account for non-Gaussian tails \Rightarrow Gaussian Sum Filter (GSF)

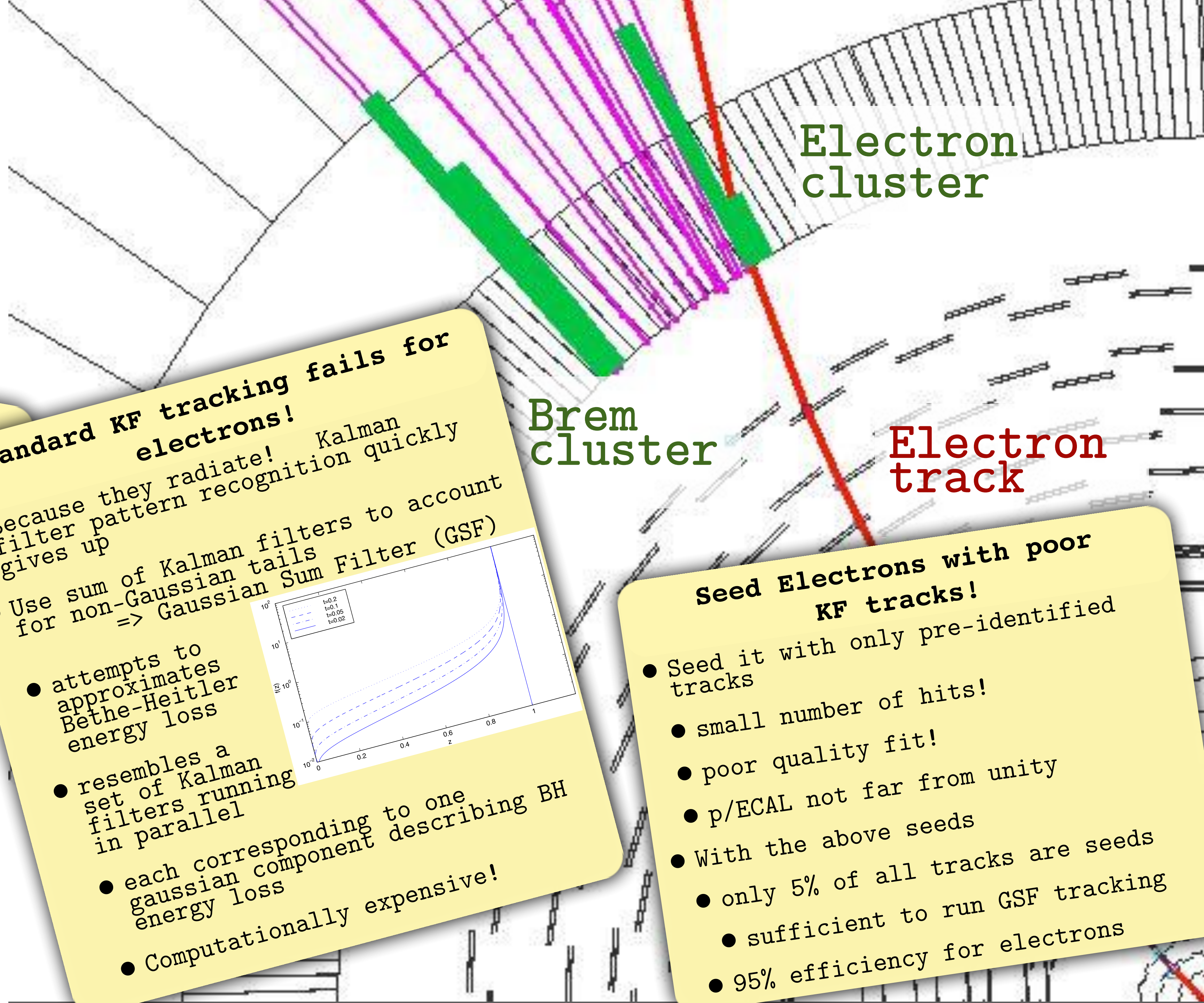
- attempts to approximate Bethe-Heitler energy loss



- resembles a set of Kalman filters running in parallel

- each corresponding to one gaussian component describing BH energy loss
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Electron ID



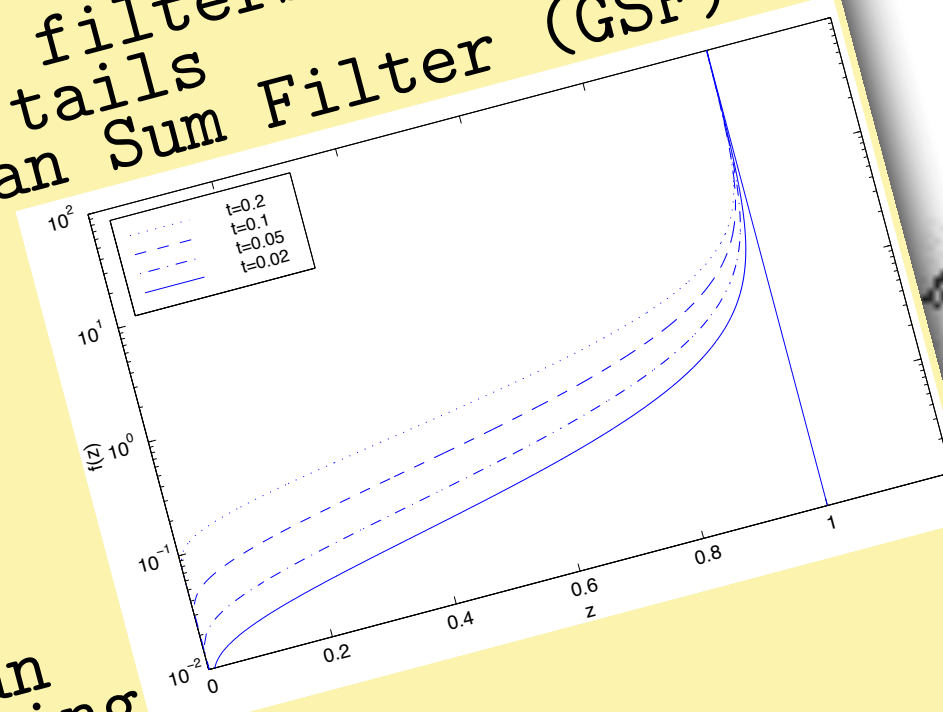
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Seed Electrons with poor KF tracks!

- Seed it with only pre-identified tracks
- small number of hits!
- poor quality fit!
- p/ECAL not far from unity
- With the above seeds
 - only 5% of all tracks are seeds
 - sufficient to run GSF tracking
 - 95% efficiency for electrons

Electron ID

New type of link: "by tangent"

- Violet lines are tangents to the GSF track
 - starting from each tracker layer
- If tangent points to a ECAL cluster
- link cluster to track
- Another possible handle
- test compatibility between ECAL cluster and $\Delta\phi$ along GSF track

Electron cluster

Brem cluster

Electron track

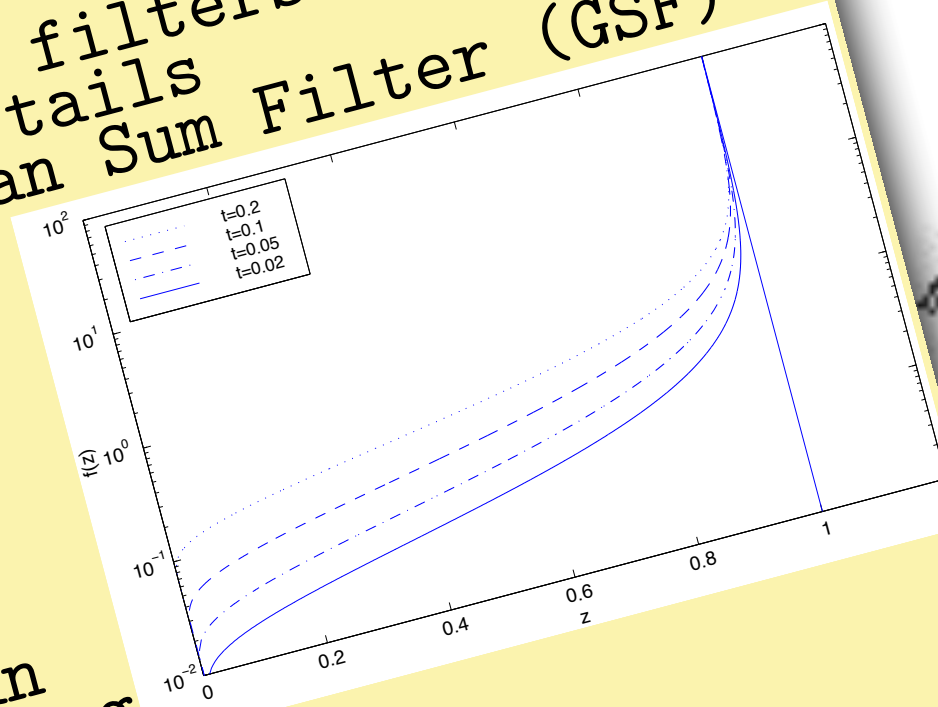
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Electron ID

Huge Effect!

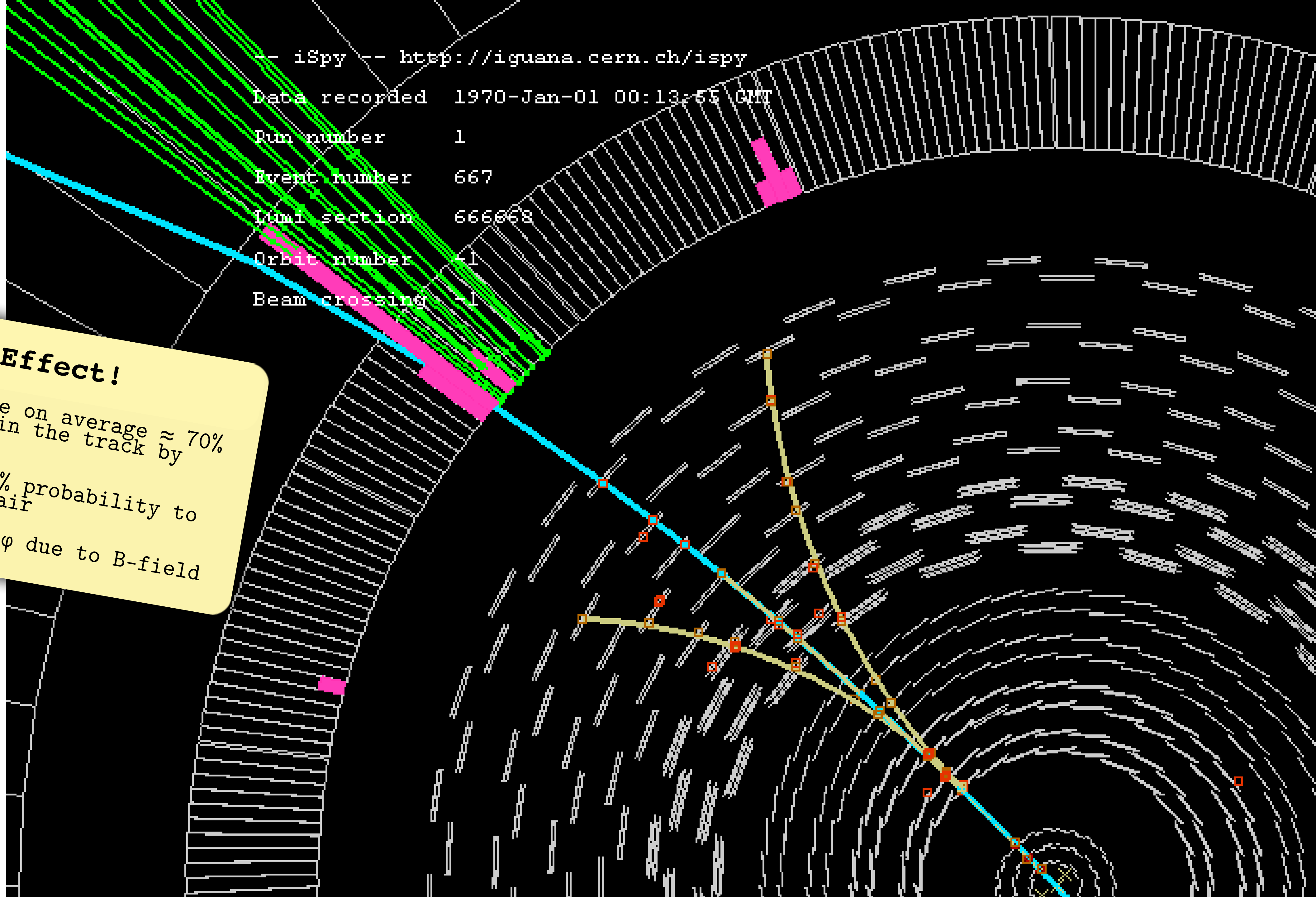
- Electrons radiate on average $\approx 70\%$ of their energy in the track by bremsstrahlung
- photons have $> 50\%$ probability to convert to e^+e^- pair
- energy spreads in φ due to B-field

Electron ID

```
-- iSpy -- http://iguana.cern.ch/ispy  
Data recorded 1970-Jan-01 00:13:55 GMT  
Run number 1  
Event number 667  
Lumi section 666668  
Orbit number -1  
Beam crossing -1
```

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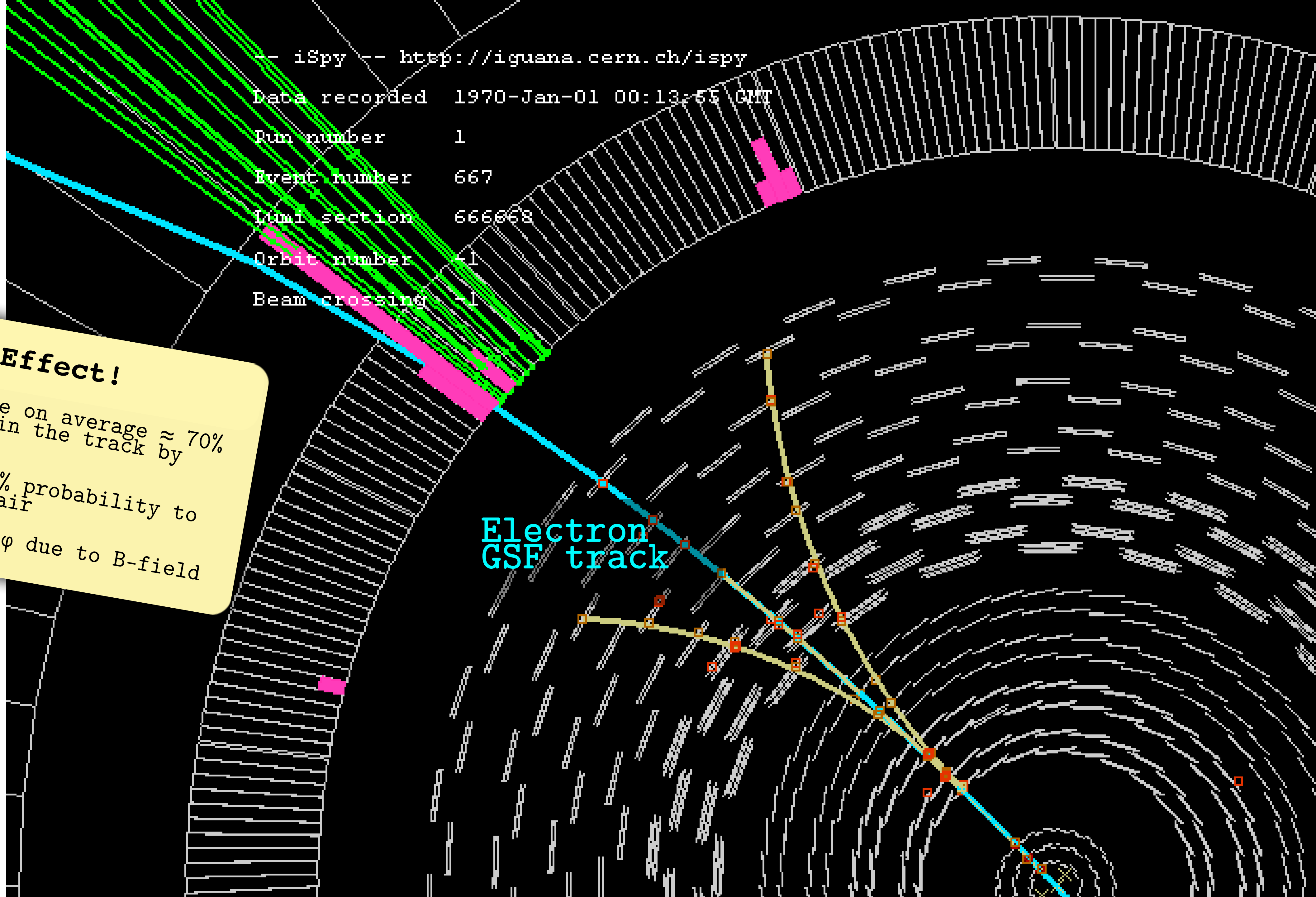
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Data recorded 1970-Jan-01 00:13:55 GMT  
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Electron
GSF track



Electron ID

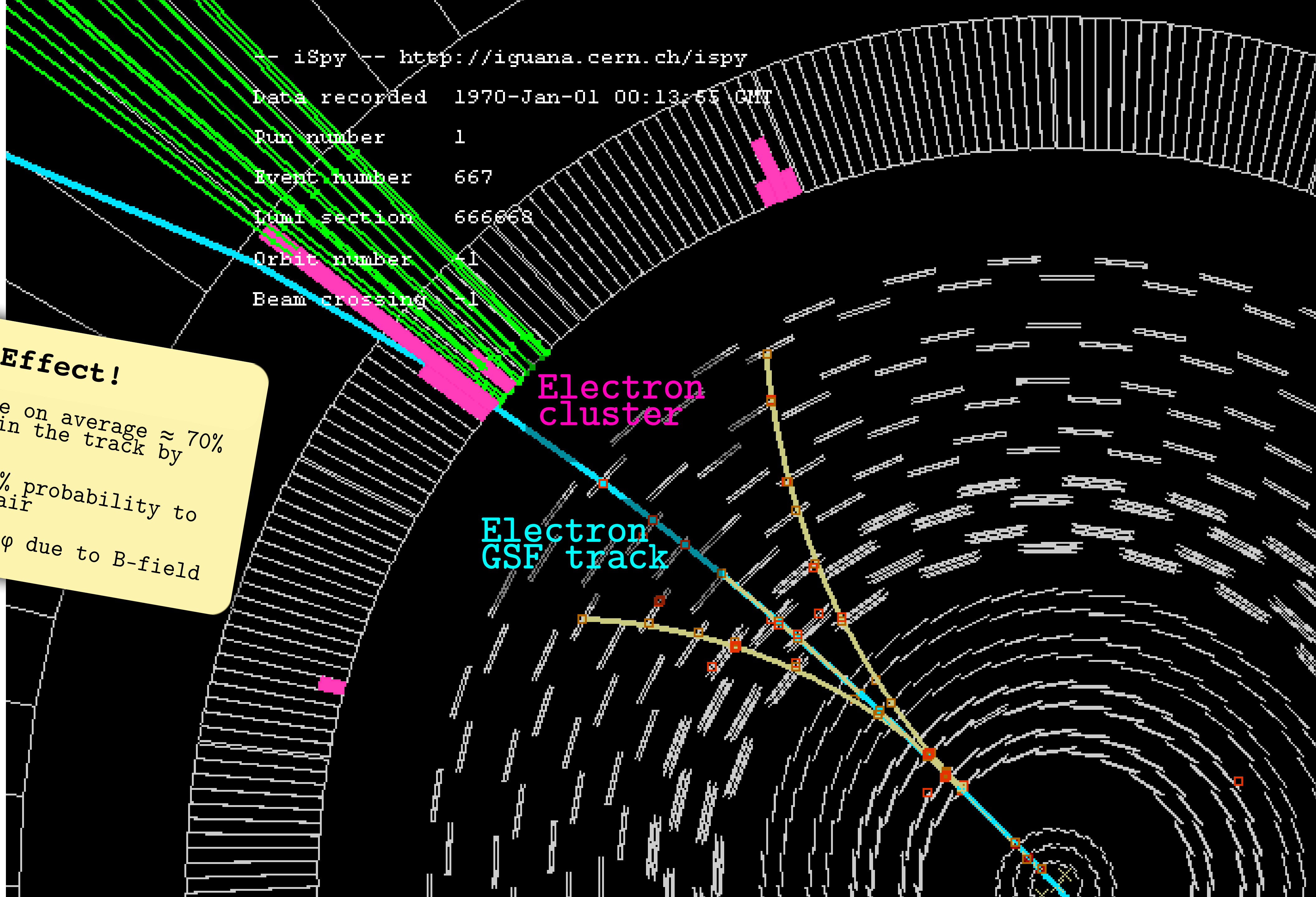
```
-- iSpy -- http://iguana.cern.ch/ispy
Data recorded 1970-Jan-01 00:13:55 GMT
Run number 1
Event number 667
Itmi section 666668
Orbit number -1
Beam crossing -1
```

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Electron cluster

Electron GSF track

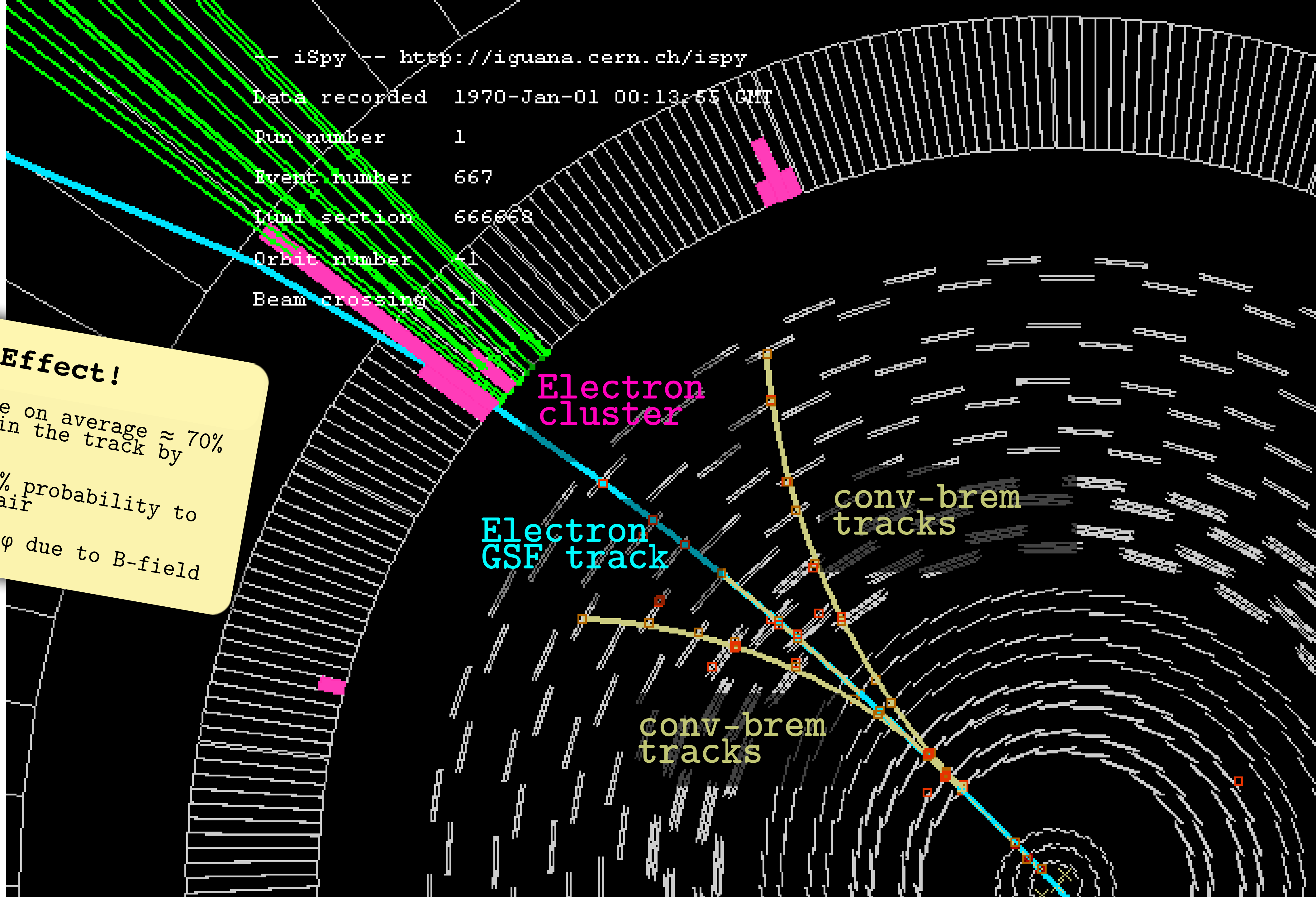


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-- iSpy -- http://iguana.cern.ch/ispy
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Run number 1
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Electron cluster

Electron GSF track

conv-brem tracks

conv-brem tracks

Electron ID

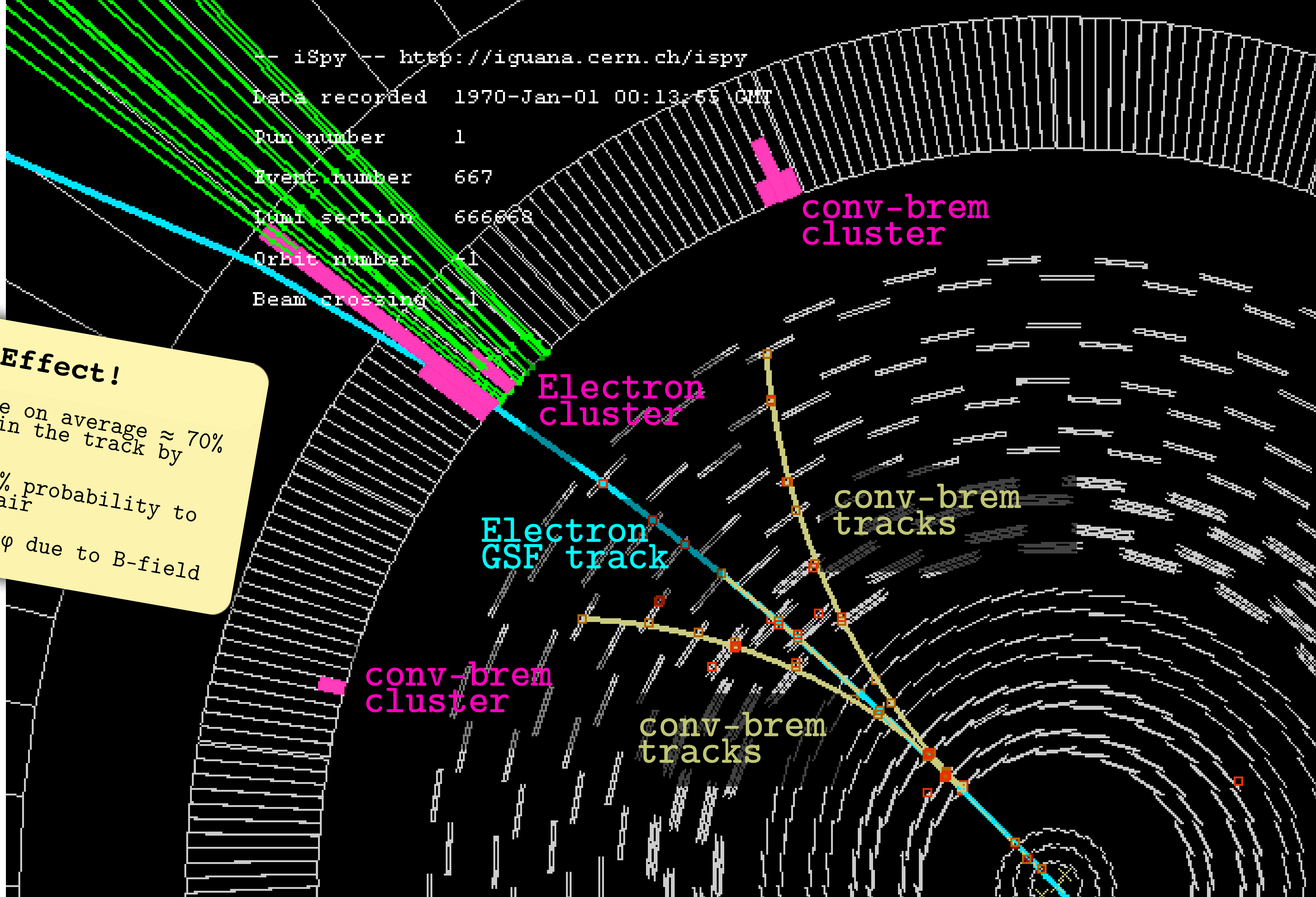
```

-- iSpy -- http://iguana.cern.ch/ispy
Data recorded 1970-Jan-01 00:13:55 GMT
Run number 1
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conv-brem cluster

Electron cluster

Electron GSF track

conv-brem tracks

conv-brem cluster

conv-brem tracks

Electron ID

```

-- iSp
Data
Run
Event
Ltm
Orbit num
Beam crossing -1
ch/isy

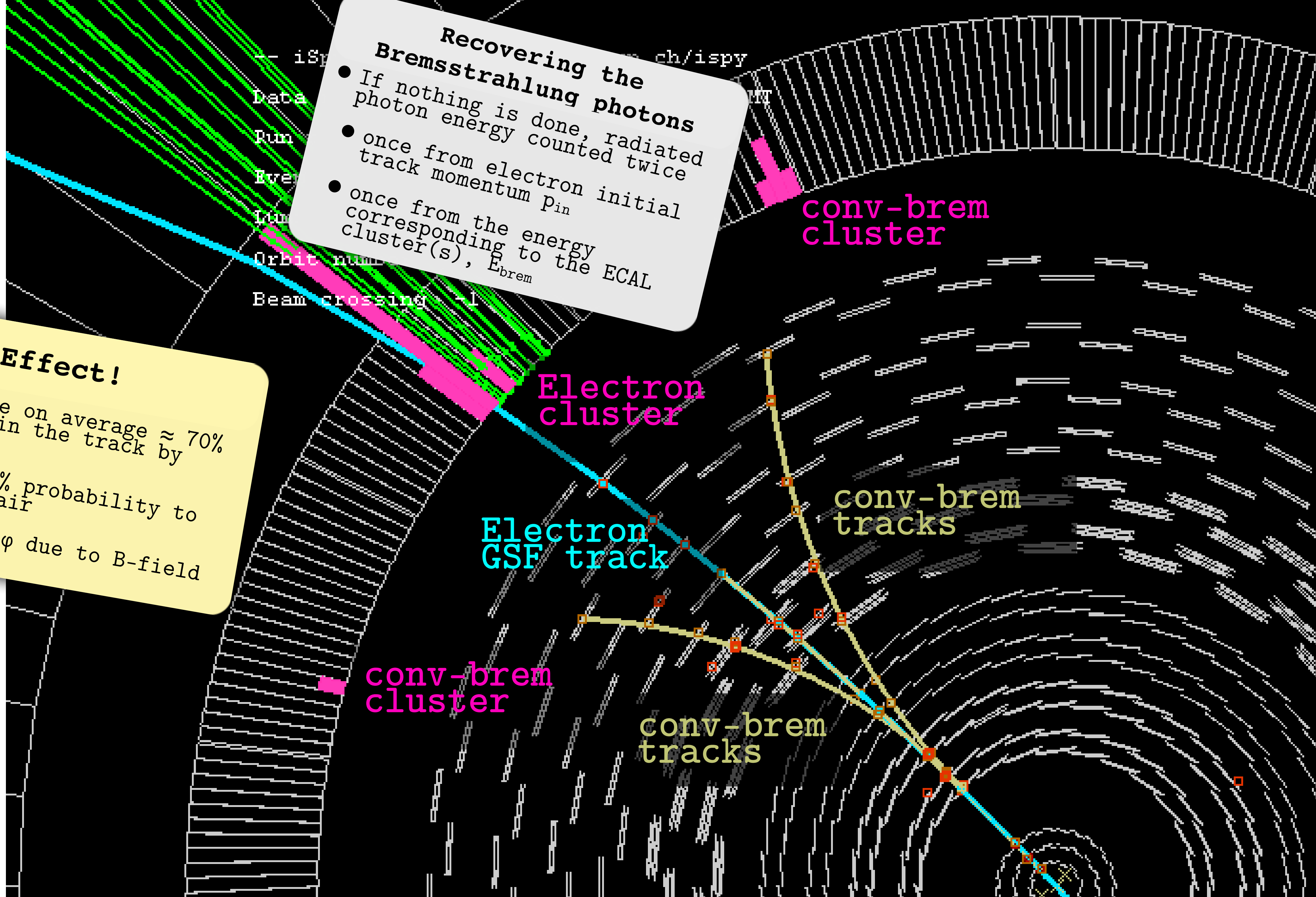
```

Recovering the Bremsstrahlung photons

- If nothing is done, radiated photon energy counted twice
- once from electron initial track momentum p_{in}
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conv-brem cluster

Electron cluster

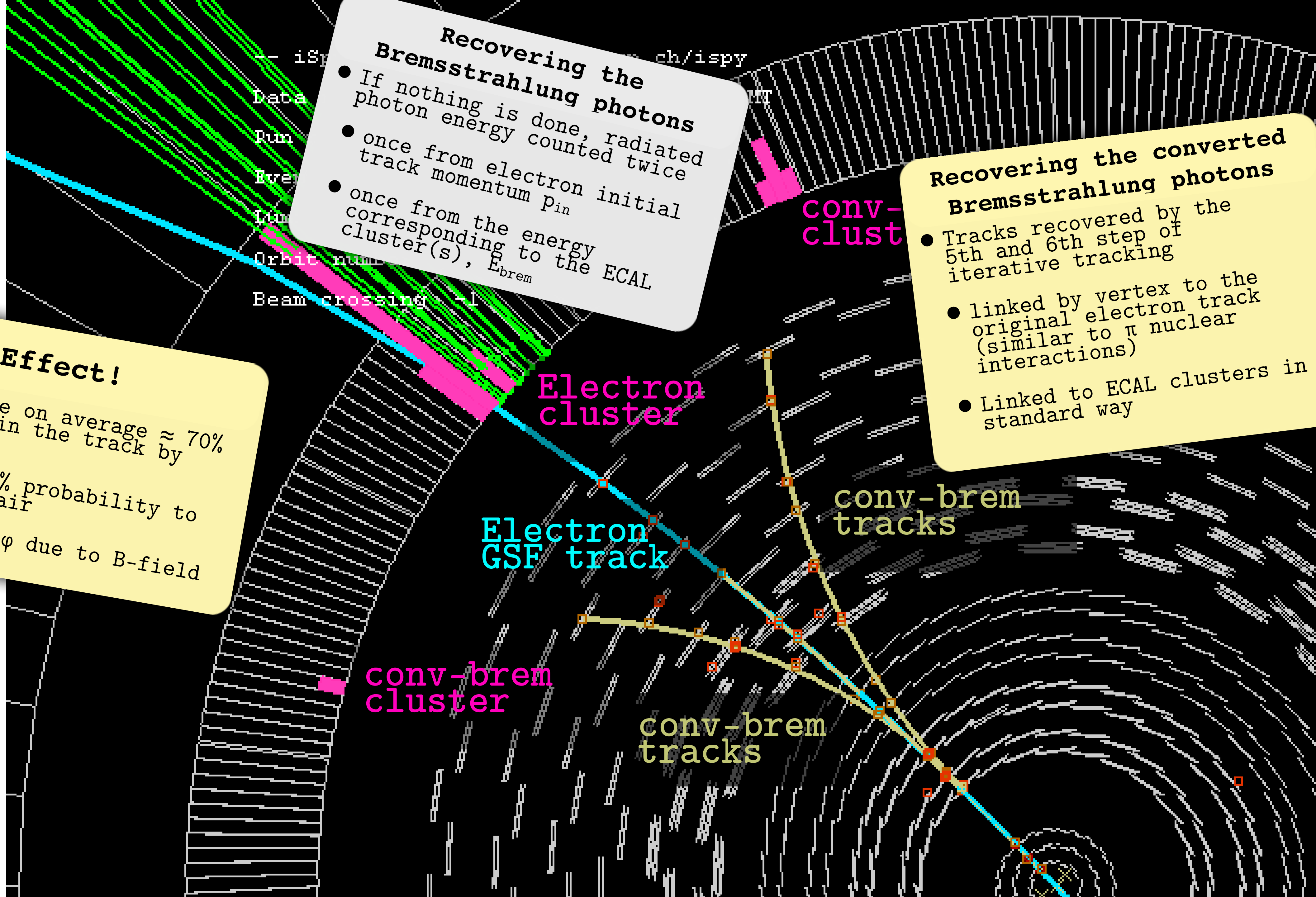
Electron GSF track

conv-brem tracks

conv-brem cluster

conv-brem tracks

Electron ID



Recovering the Bremsstrahlung photons

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Recovering the converted Bremsstrahlung photons

- Tracks recovered by the 5th and 6th step of iterative tracking
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-- iSp
Data
Run
Eve
ltn
Orbit num
Beam crossing -1

conv-clust

Electron cluster

Electron GSF track

conv-brem tracks

conv-brem tracks

conv-brem cluster

Electron ID

Question from Yesterday!

How to distinguish/calibrate between e's & π 's ?

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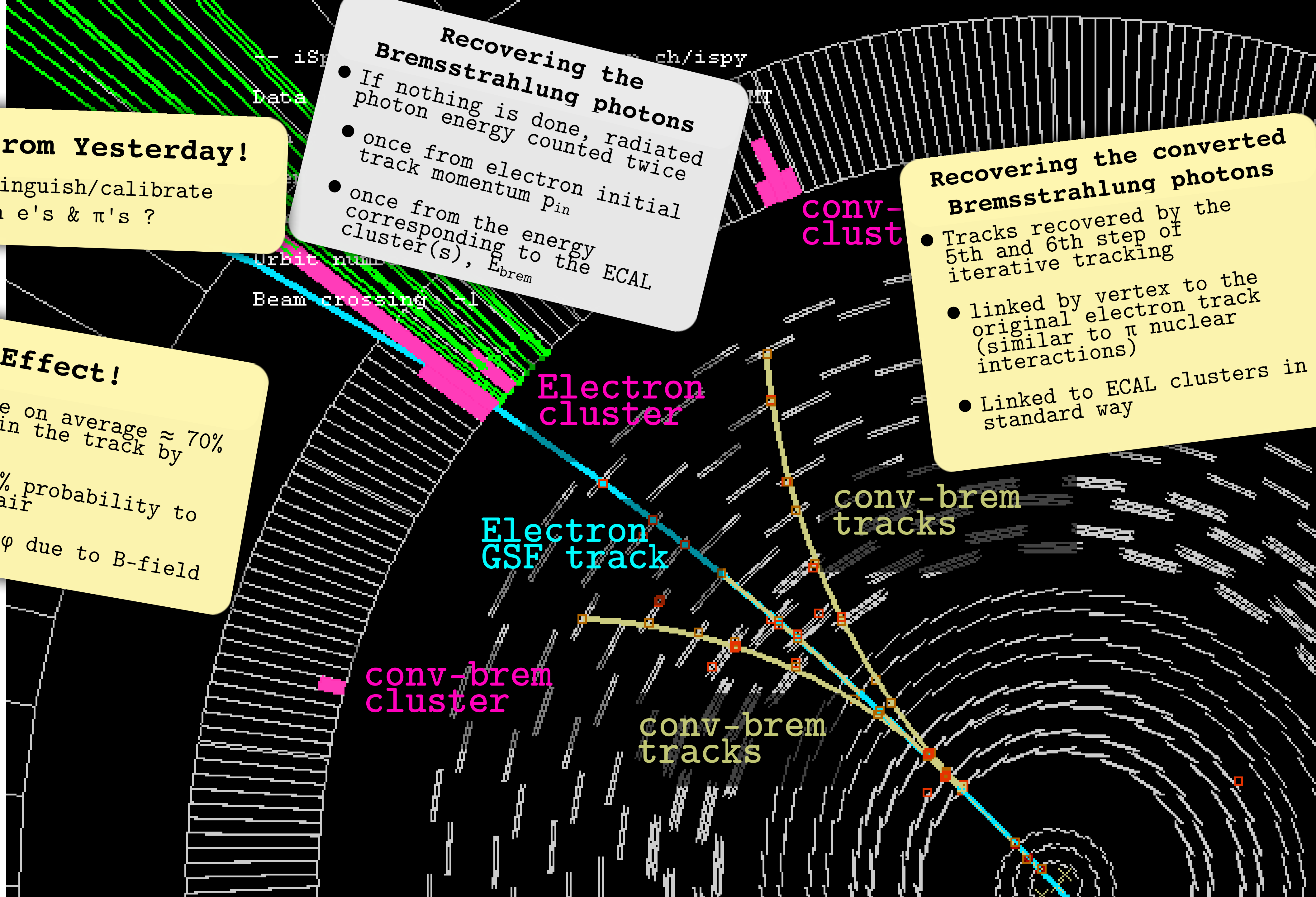
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conv-clust

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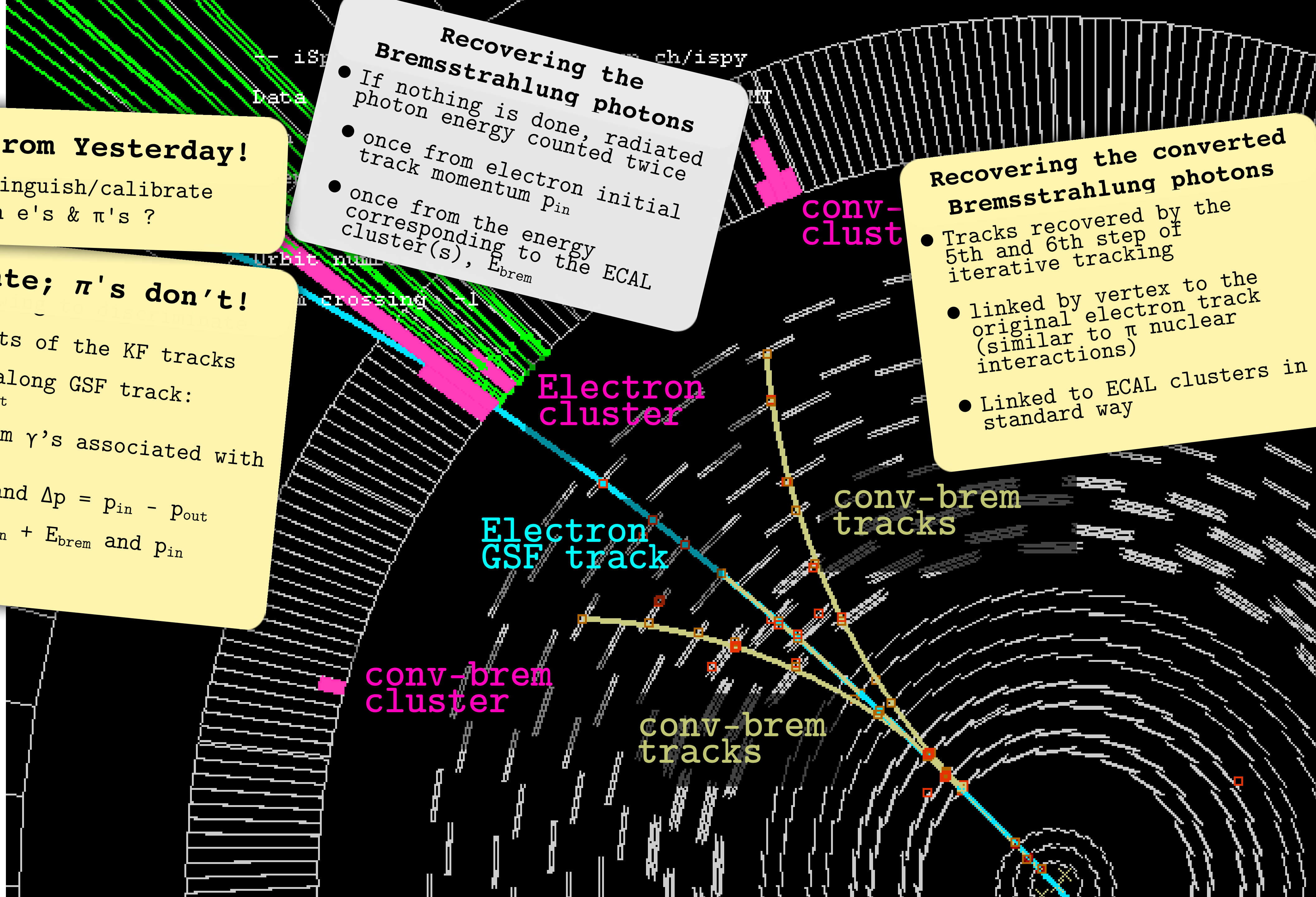
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Use cluster information!

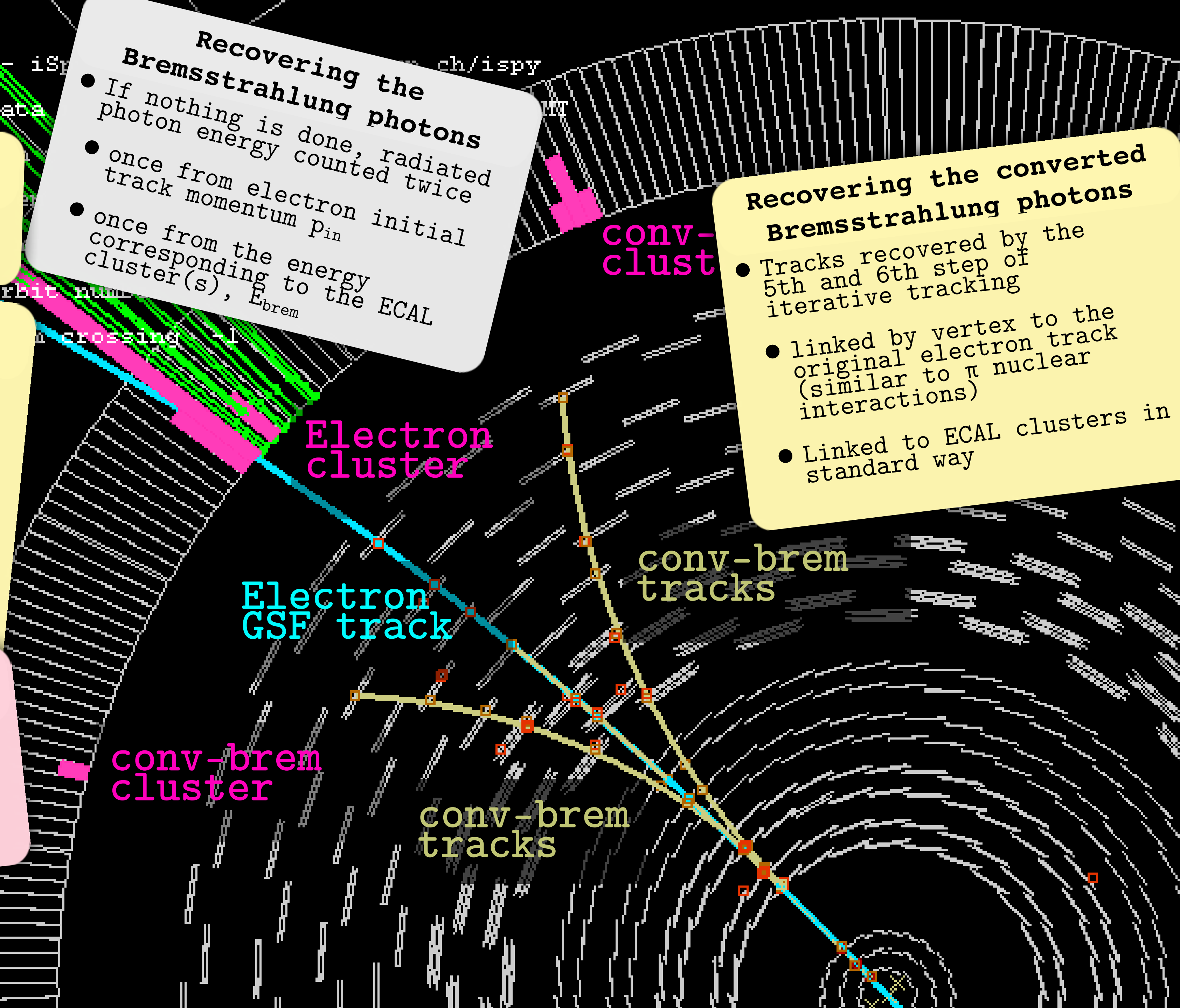
- Shower shape, such as width along η
- any possible linked HCAL energy
- etc

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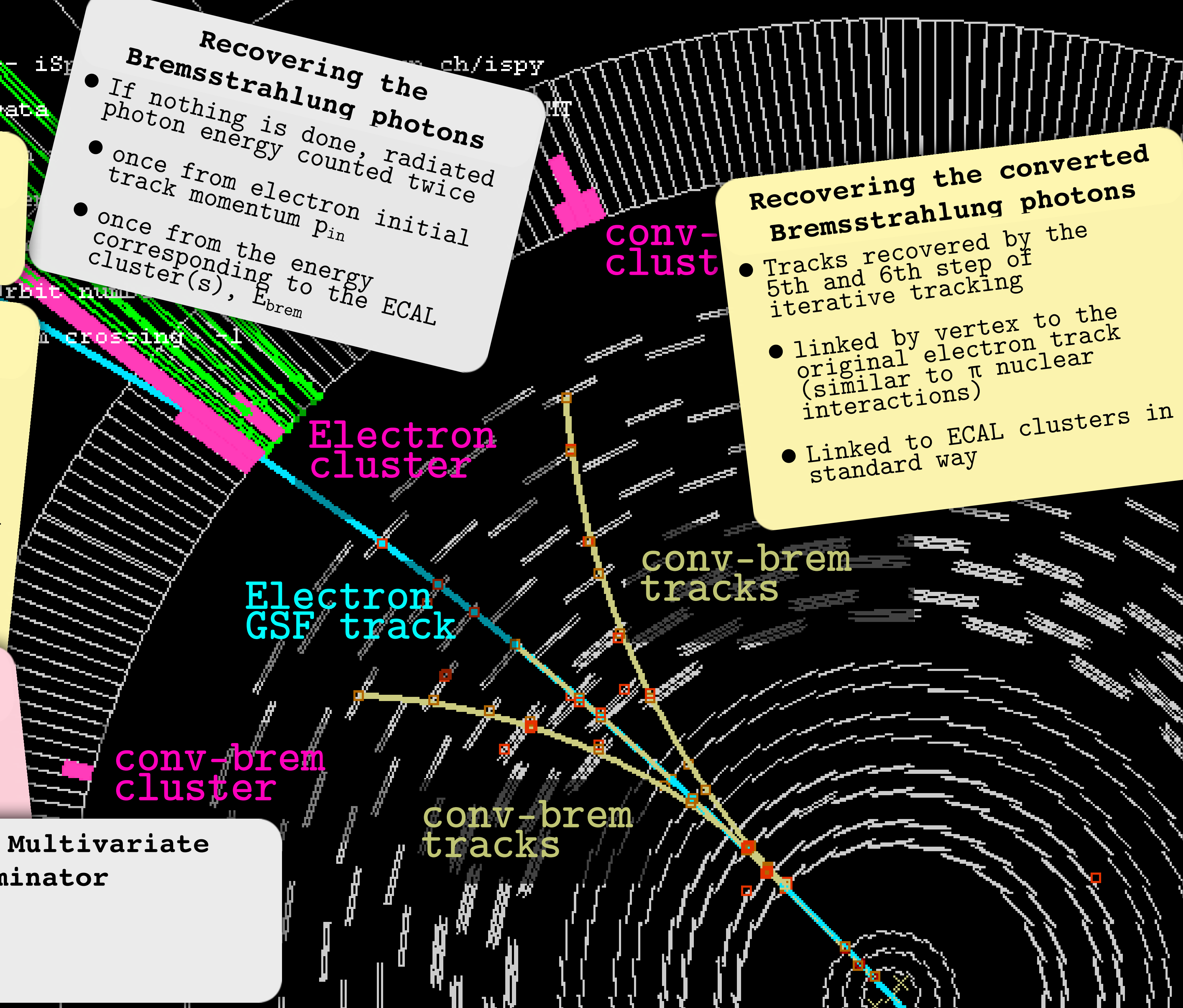
Combine into Multivariate Discriminator

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conv-clust

Electron cluster

Electron GSF track

conv-brem tracks

conv-brem tracks

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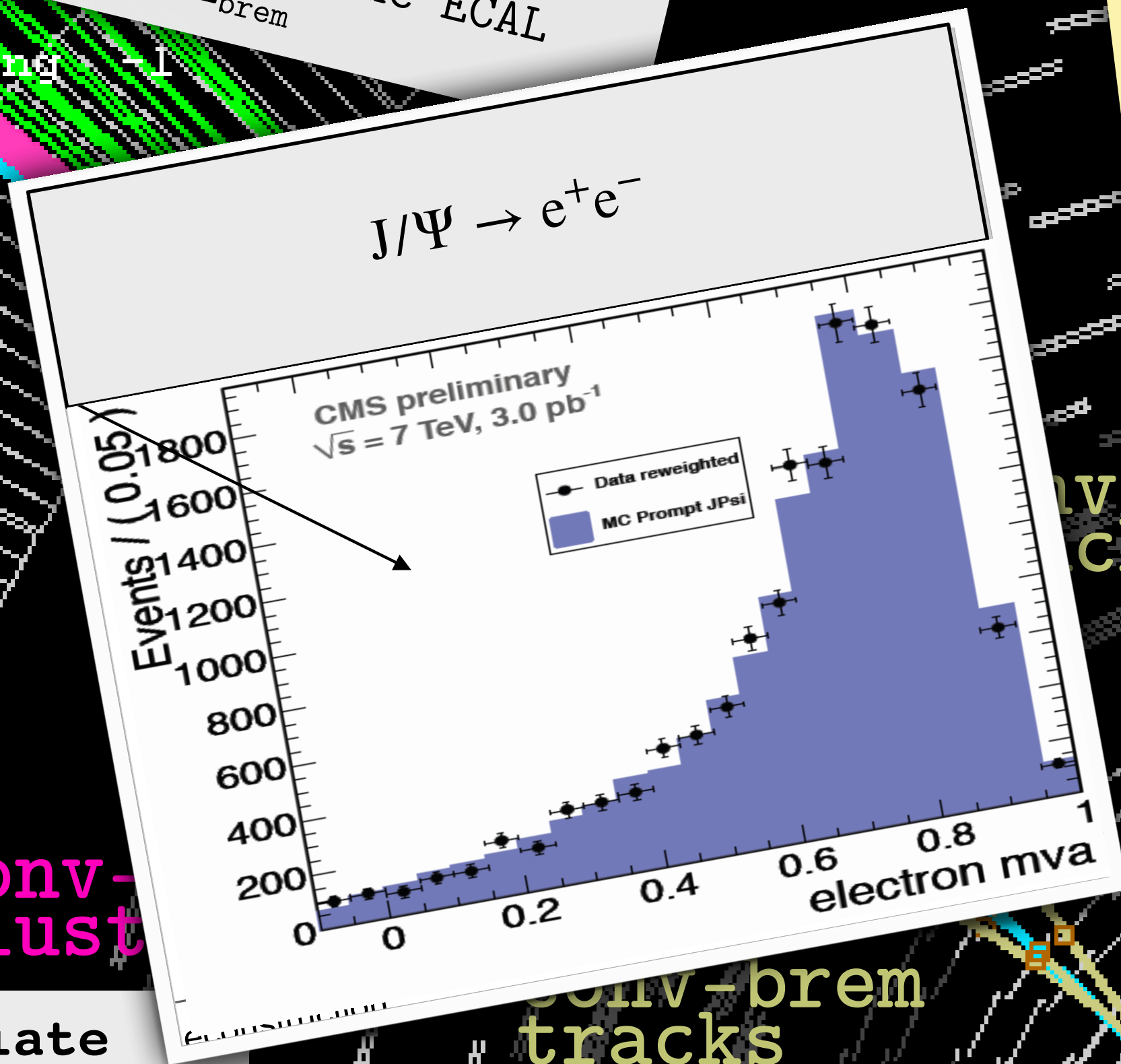
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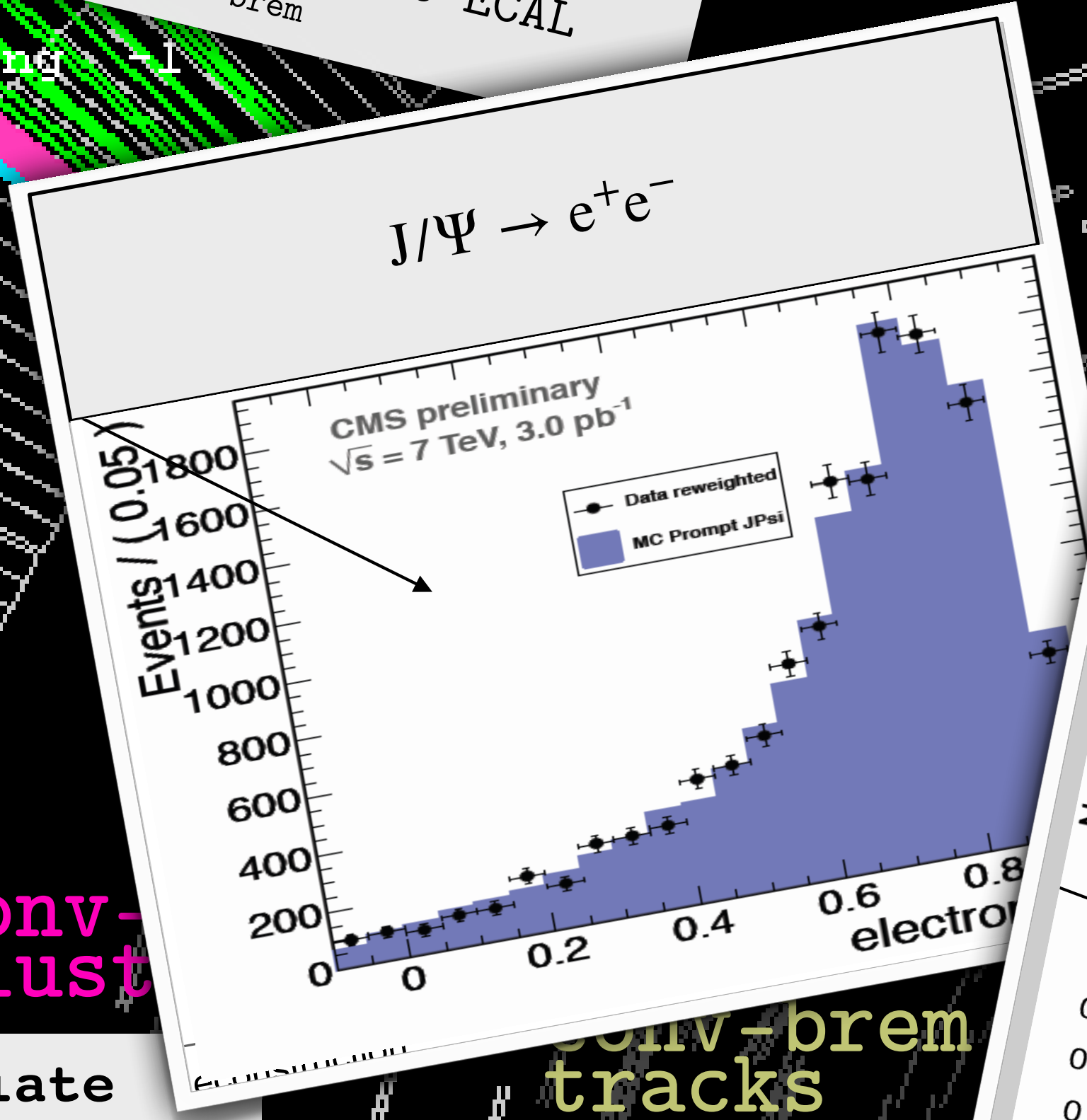
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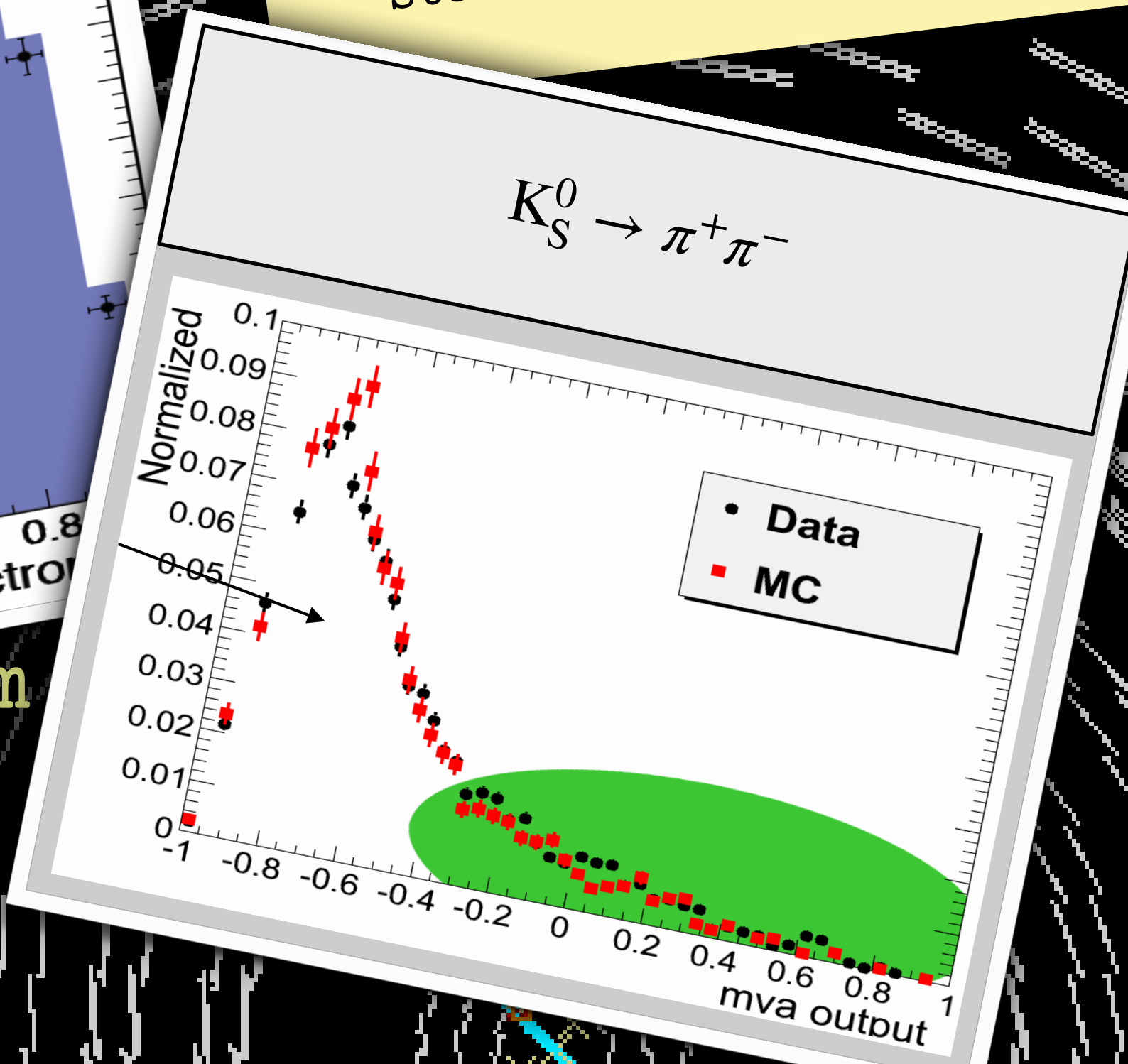
conv-clust

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Combine into Multivariate Discriminator

- 95% efficiency for isolated electrons
- 70-80% efficiency in jets

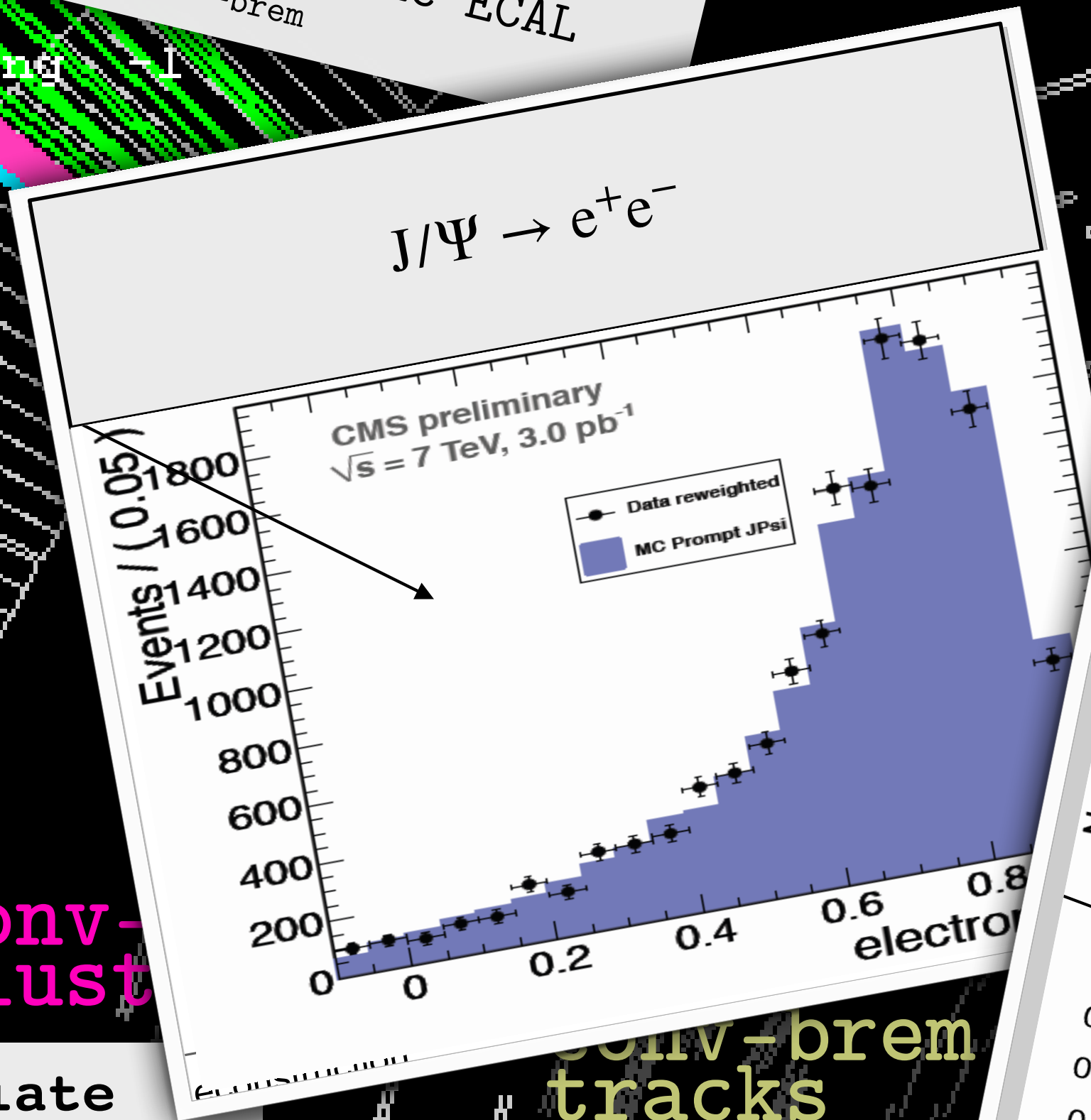
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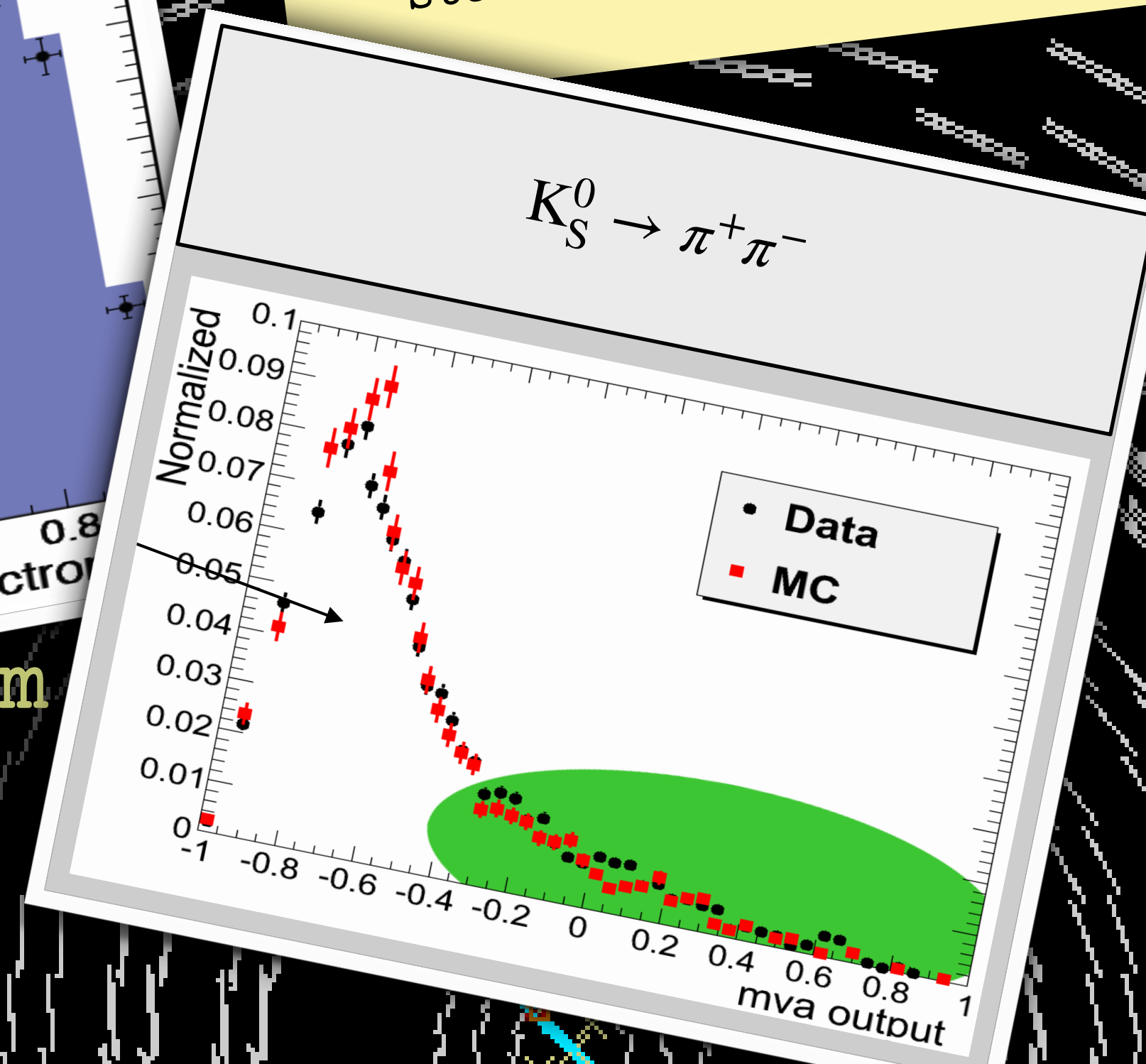
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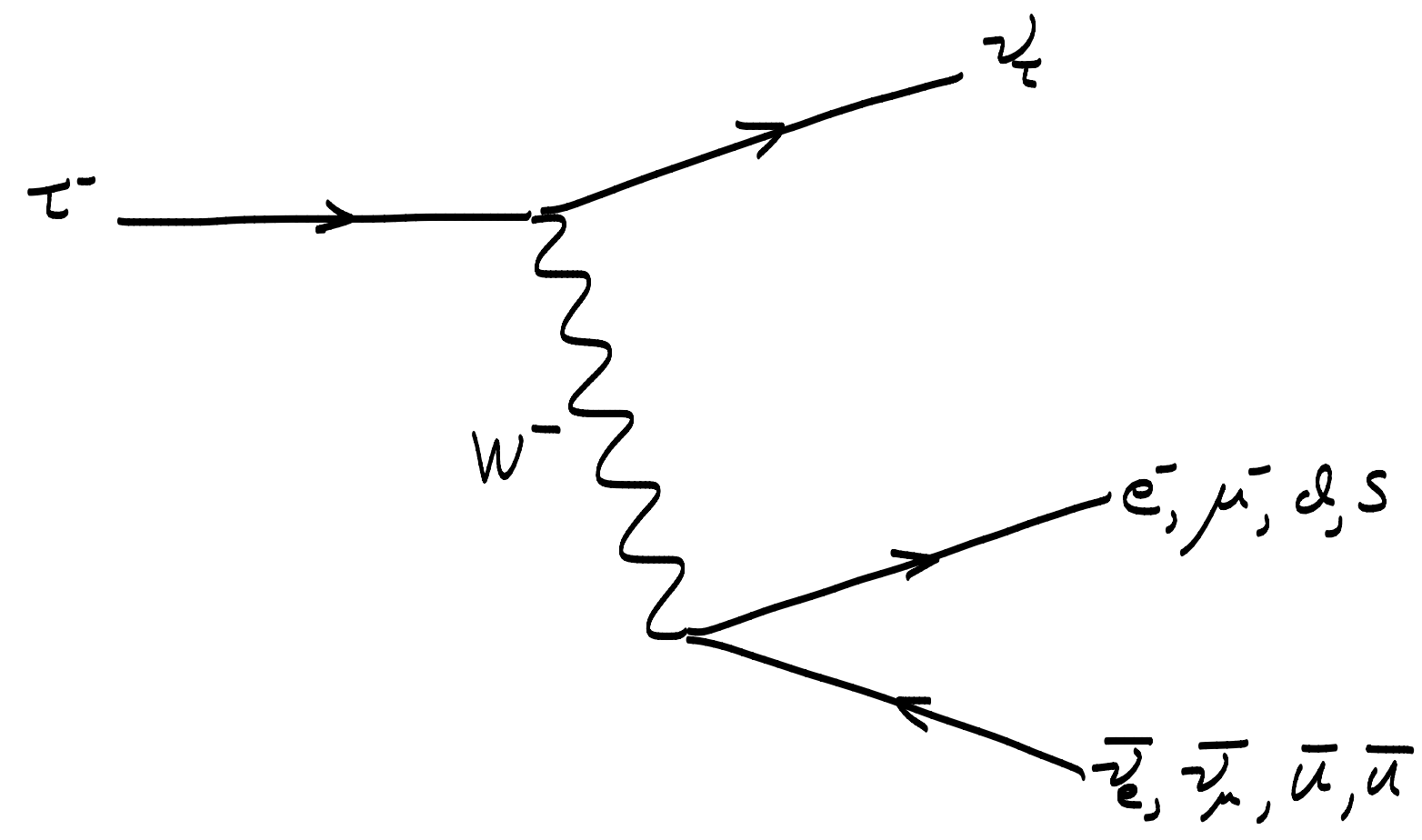


conv-brem tracks



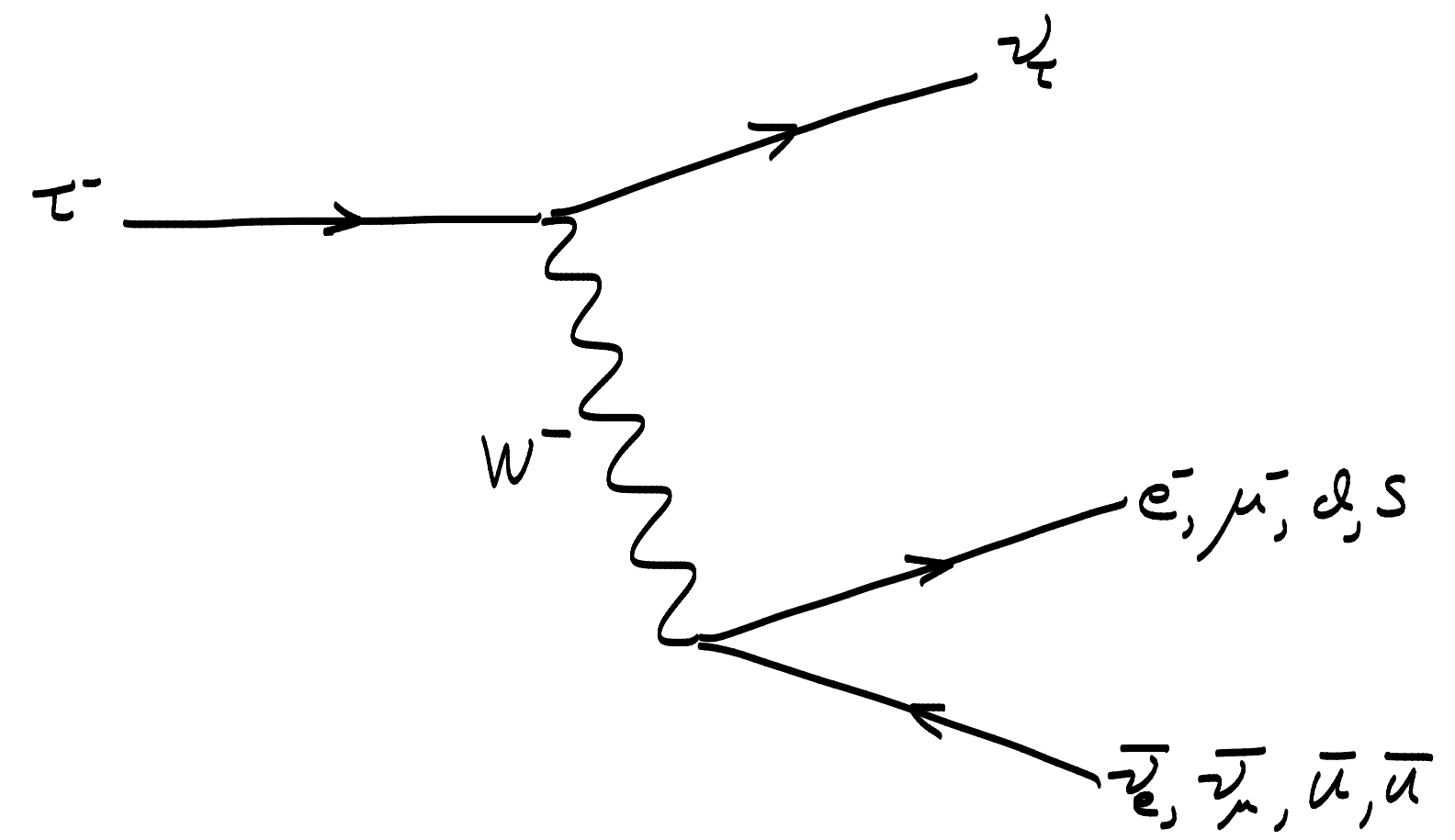
Tau ID & Reconstruction

Tau ID & Reconstruction



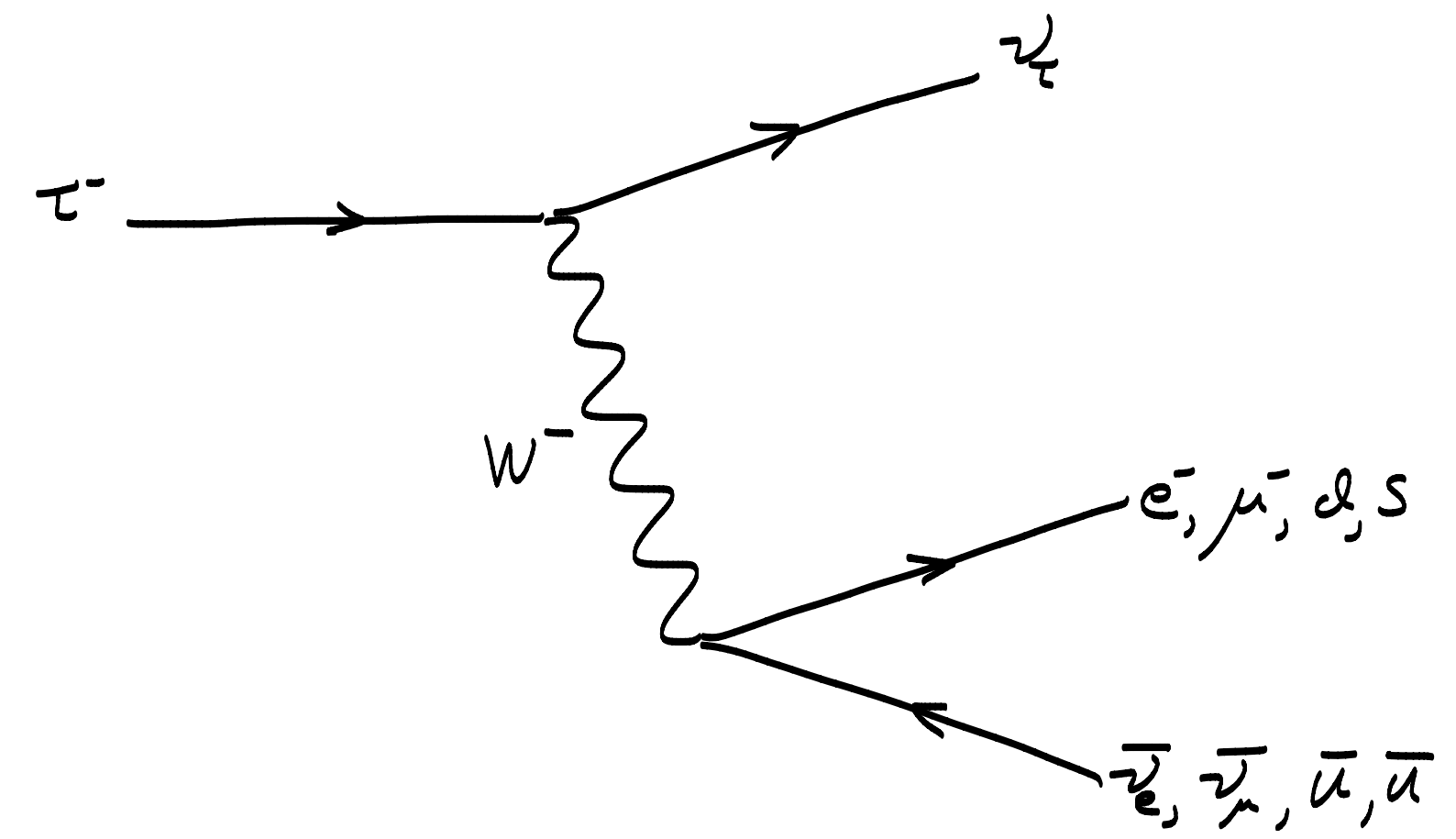
Tau ID & Reconstruction

- Massive, (relatively) long lived



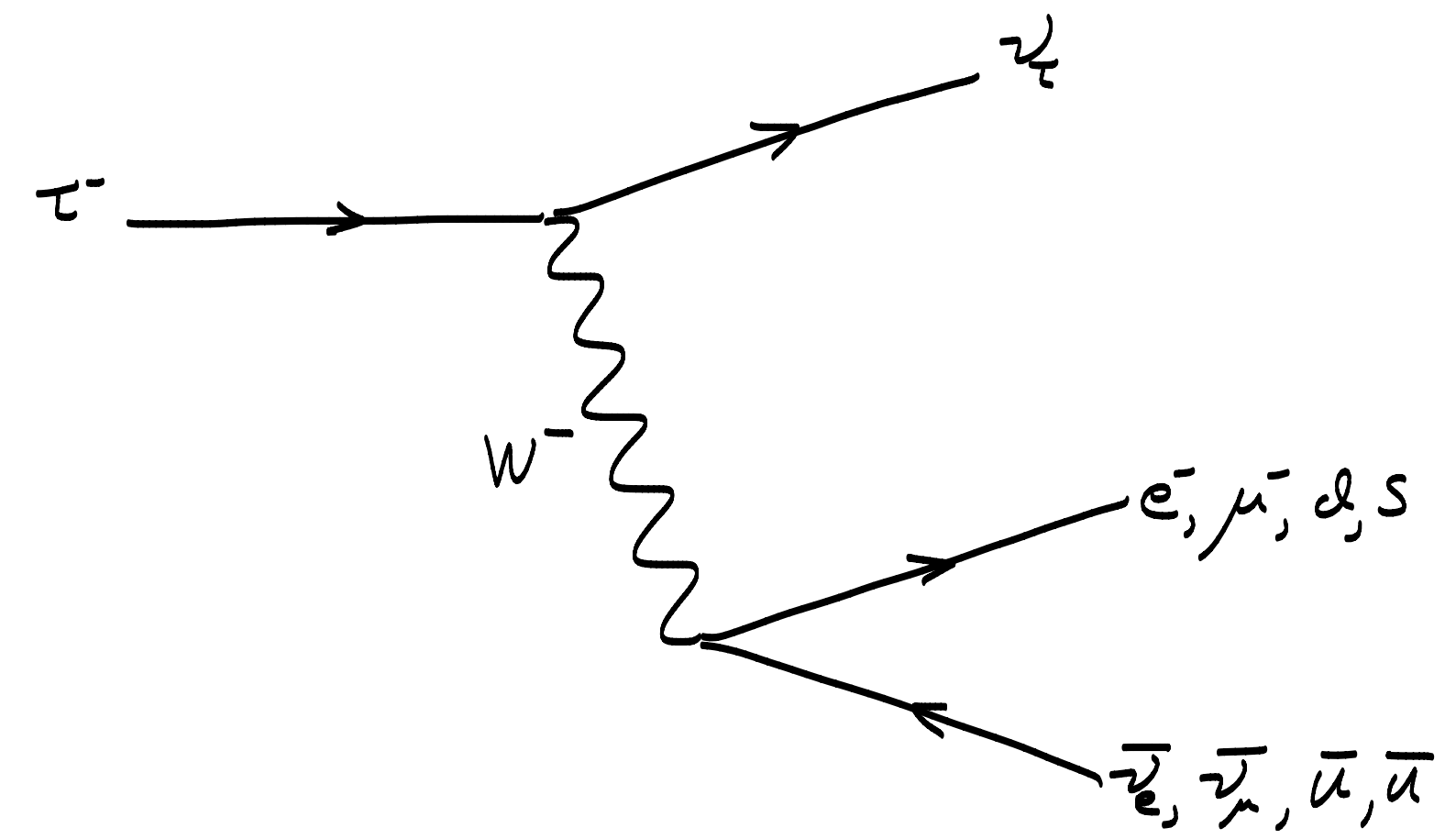
Tau ID & Reconstruction

- Massive, (relatively) long lived
 - $m(\tau^\pm) = 1.7 \text{ GeV}$



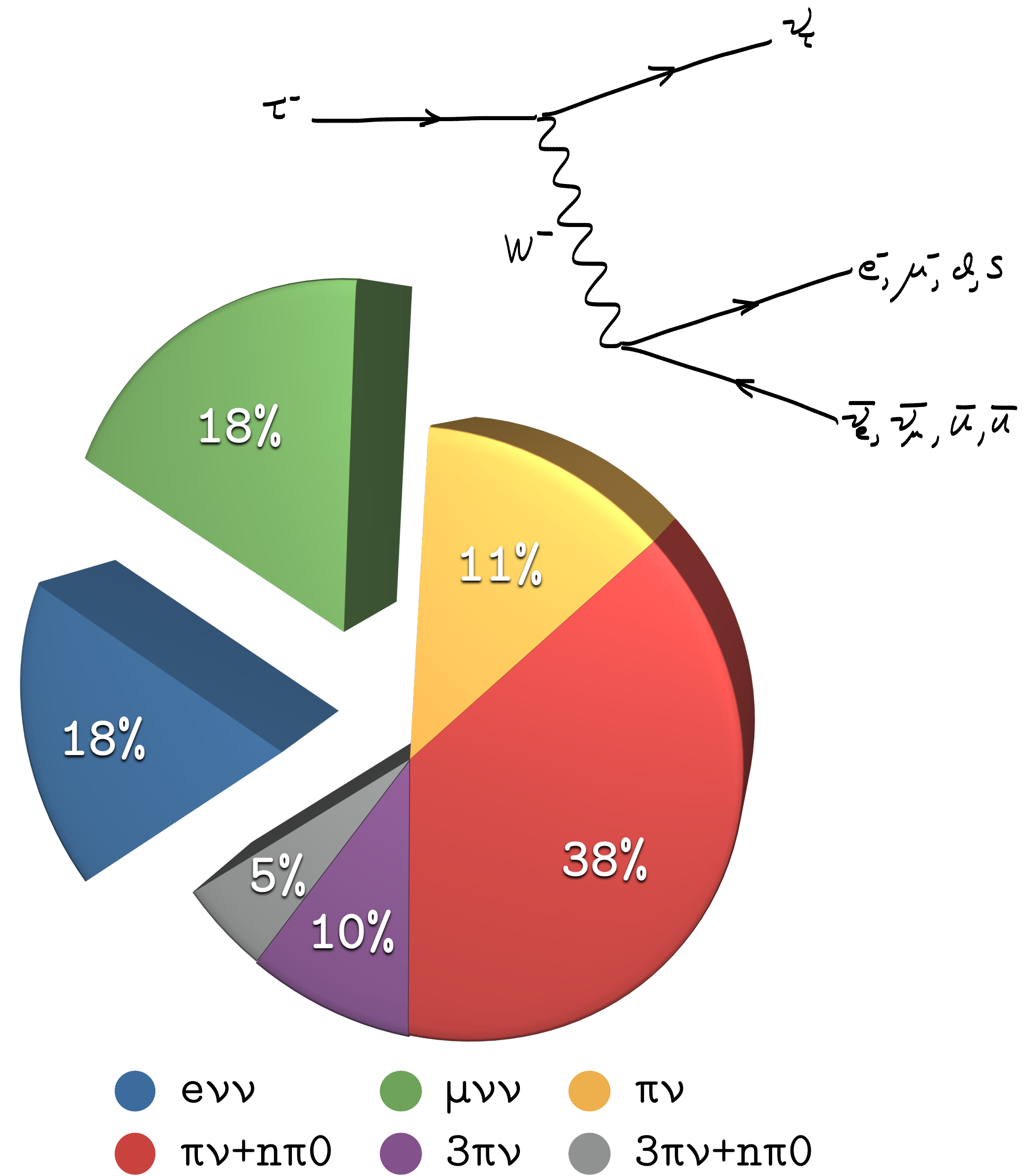
Tau ID & Reconstruction

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 - $c\tau = 87 \text{ }\mu\text{m}$



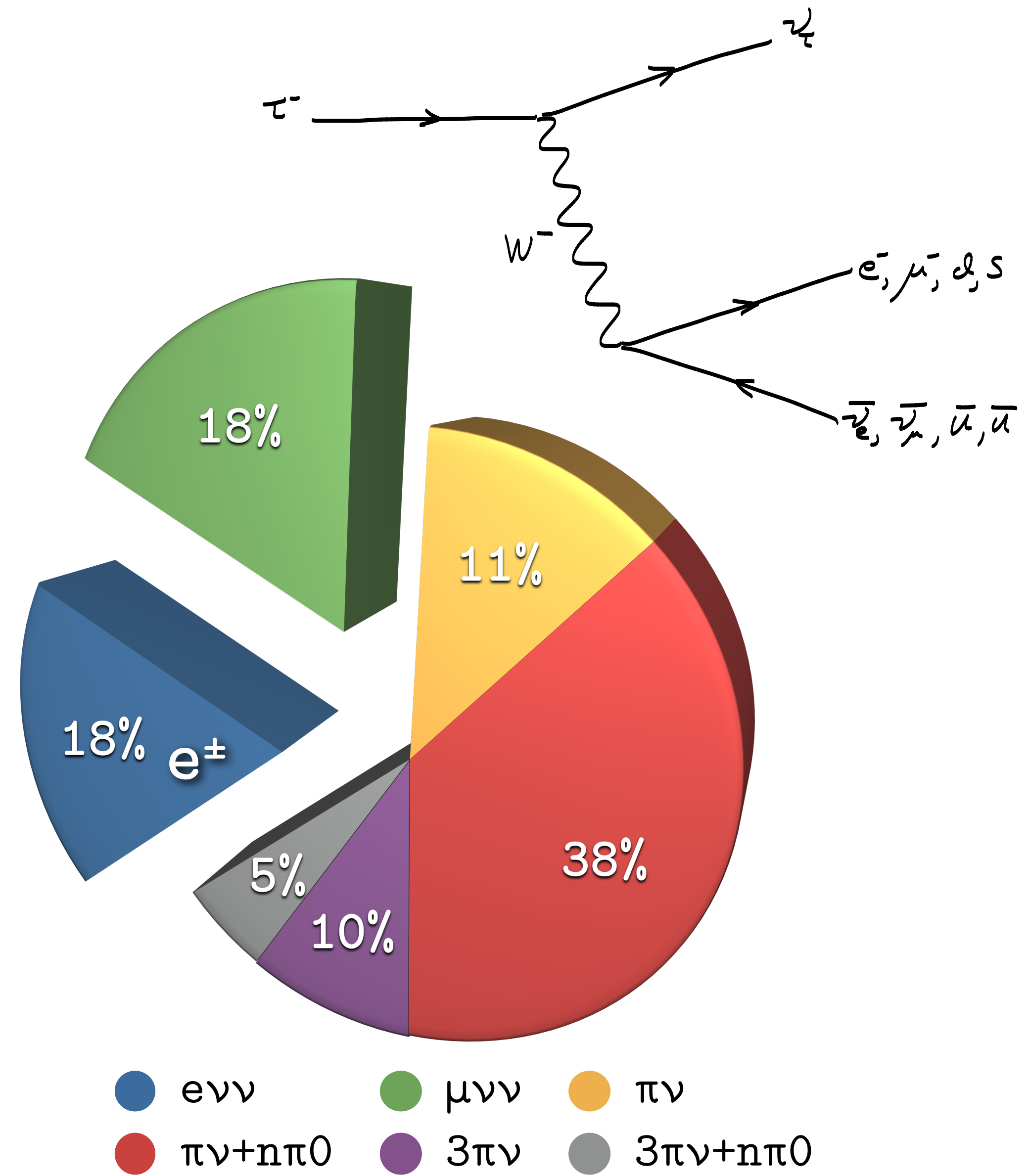
Tau ID & Reconstruction

- Massive, (relatively) long lived
 - $m(\tau^\pm) = 1.7 \text{ GeV}$
 - $c\tau = 87 \mu\text{m}$
- leptonic decays: 35%



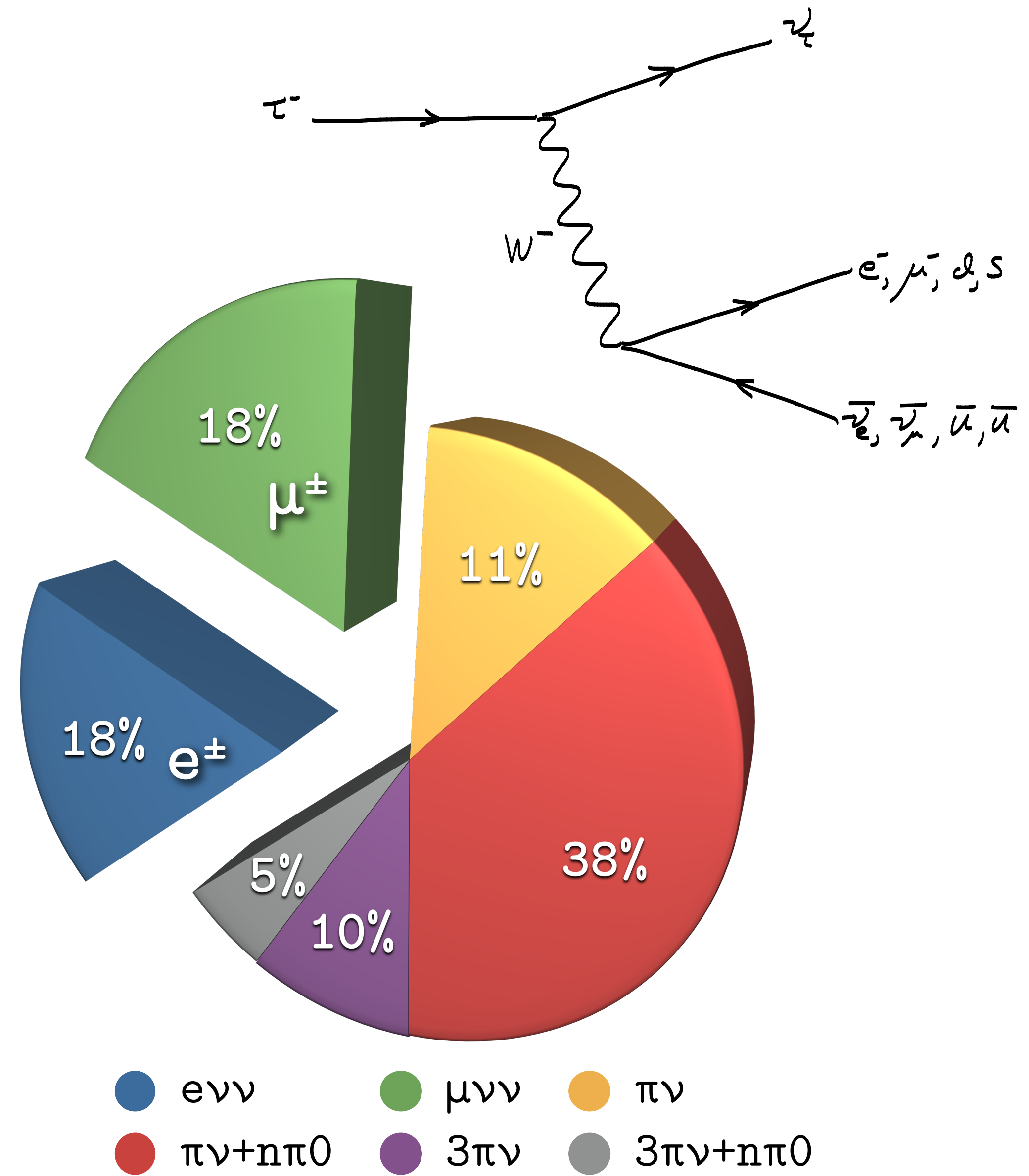
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 - electron: 17.5%



Tau ID & Reconstruction

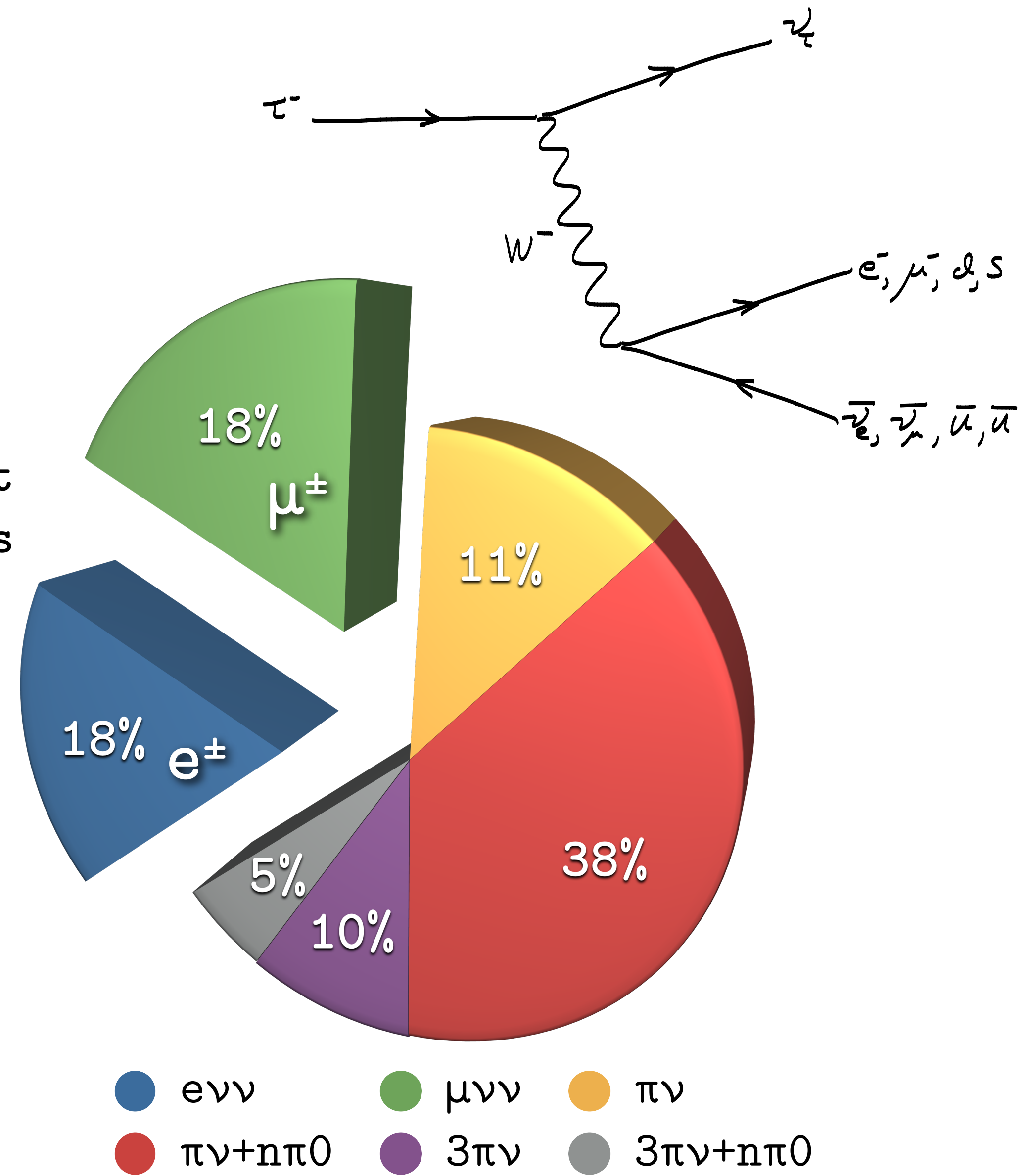
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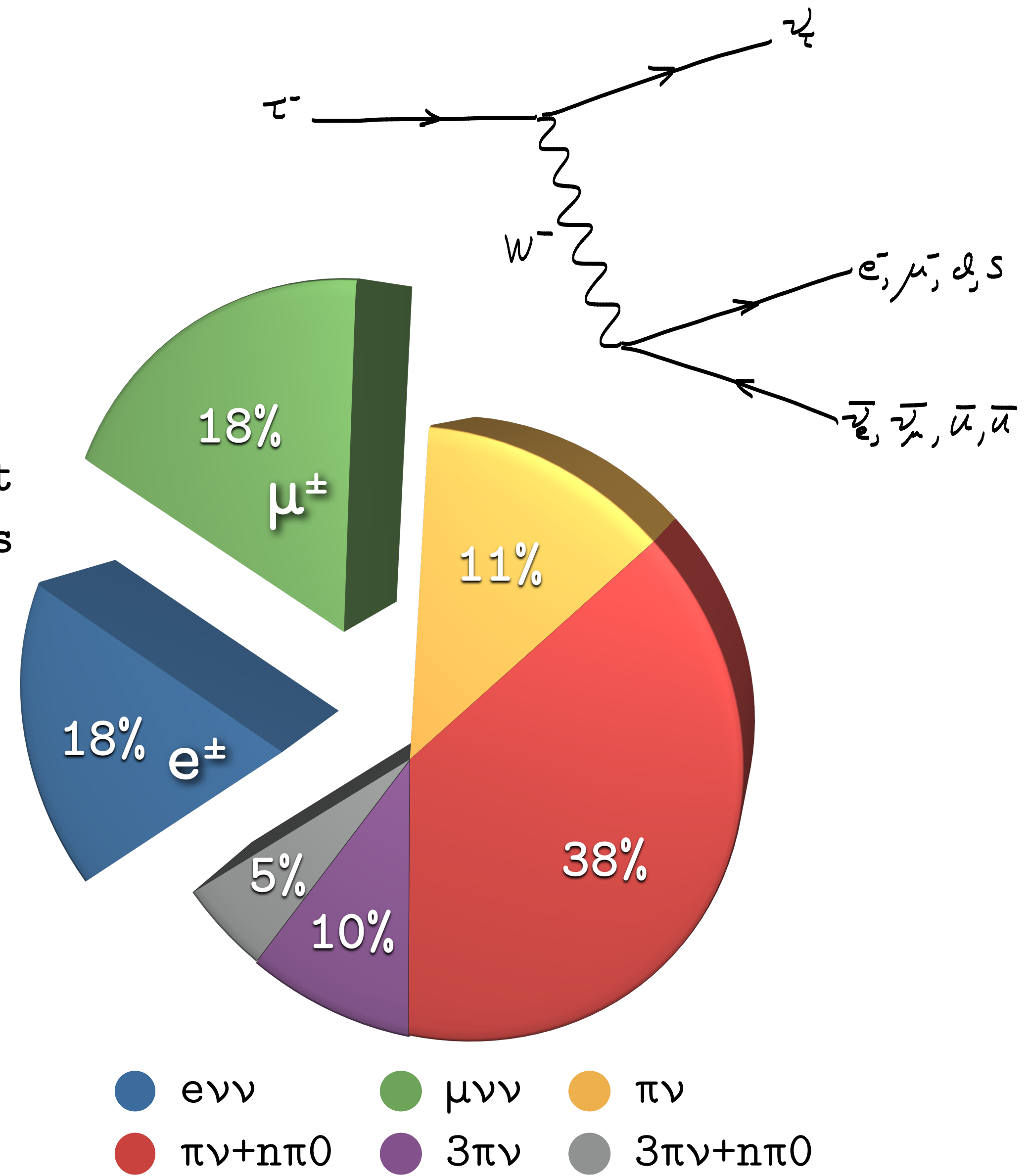
I won't talk about leptonic decays



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 - muon: 17.5%
- hadronic decays: 65%

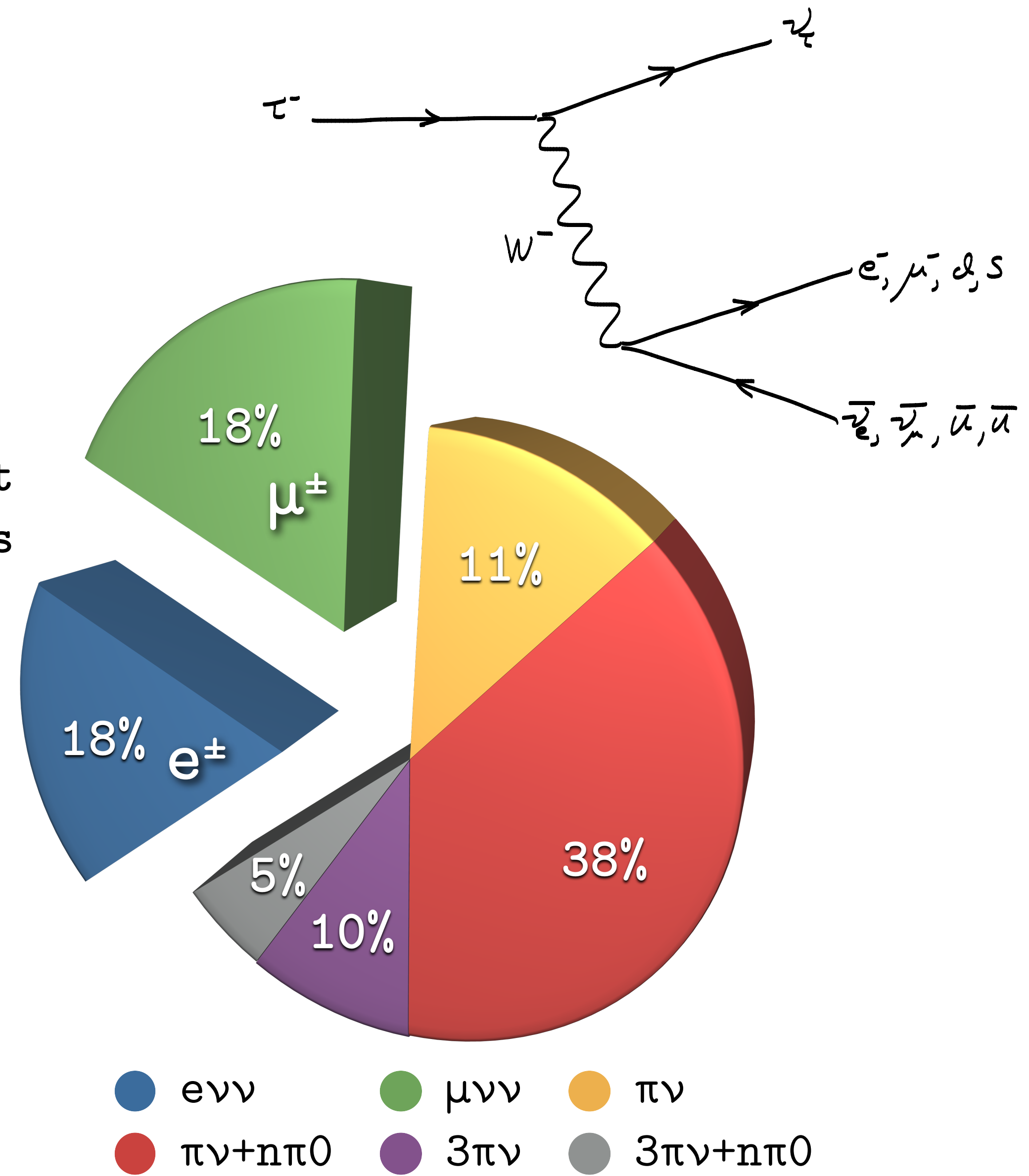
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 - muon: 17.5%
- hadronic decays: 65%
 - single prong: 49%

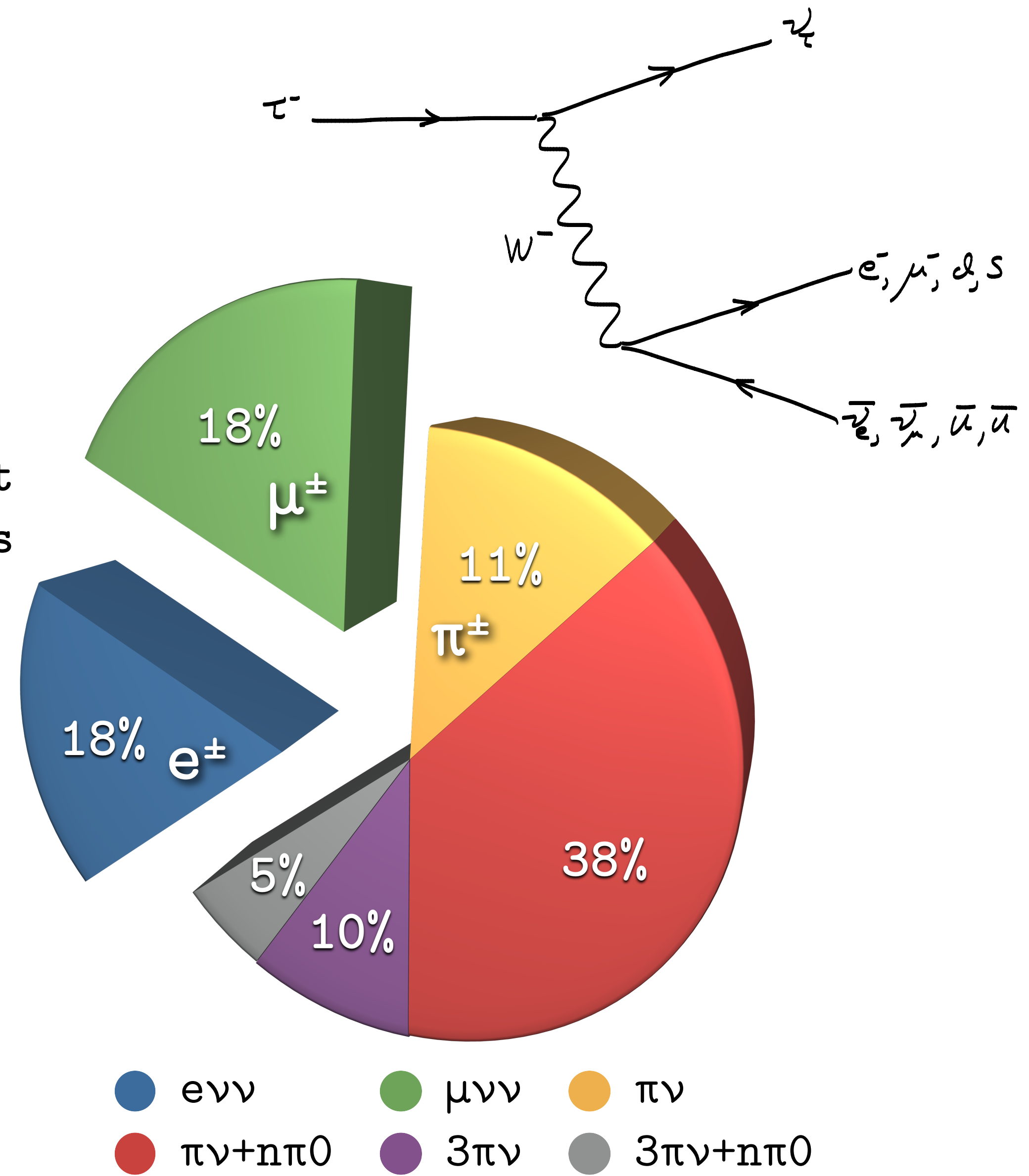
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 - single prong: 49%
 - 11% π^\pm

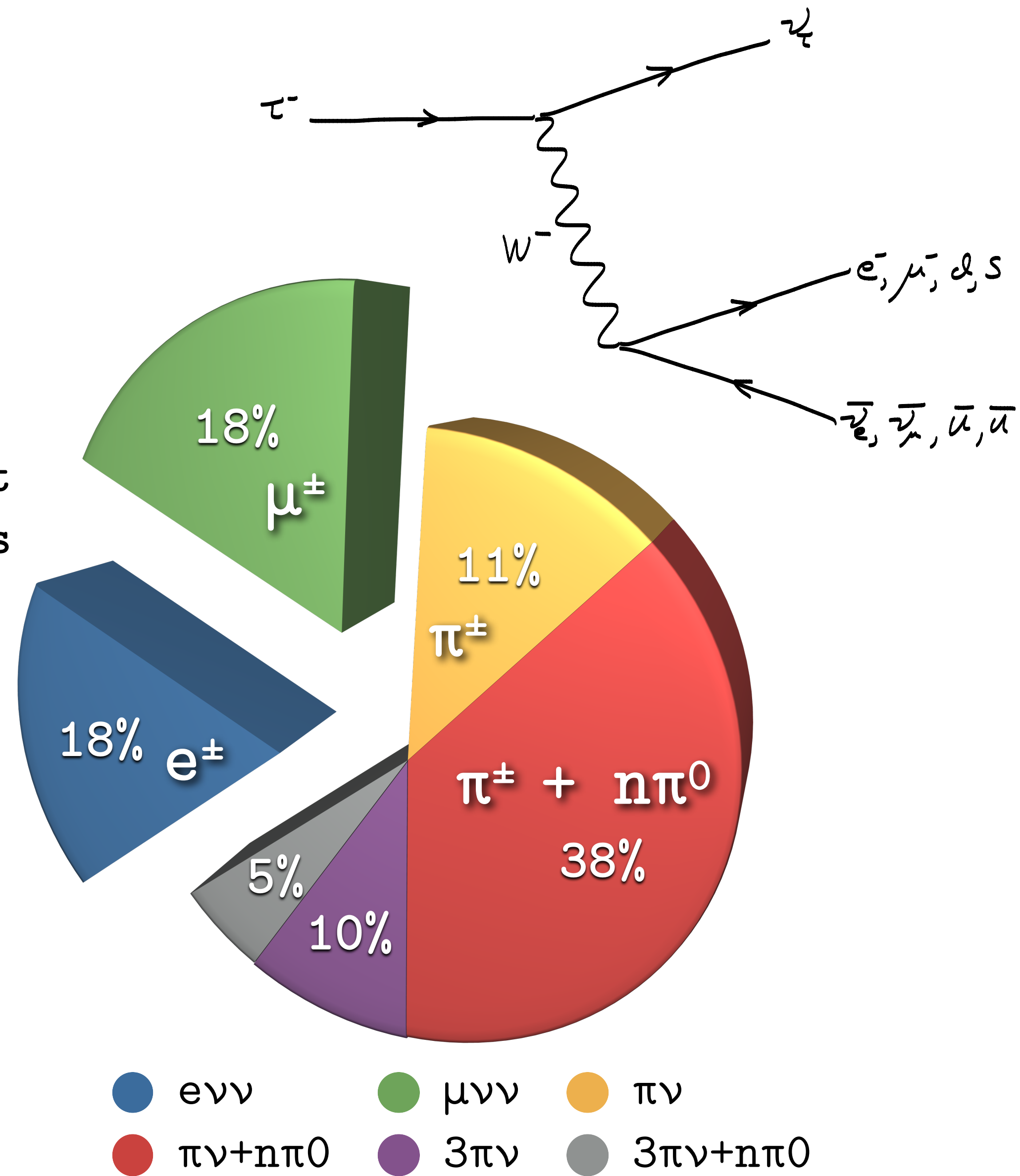
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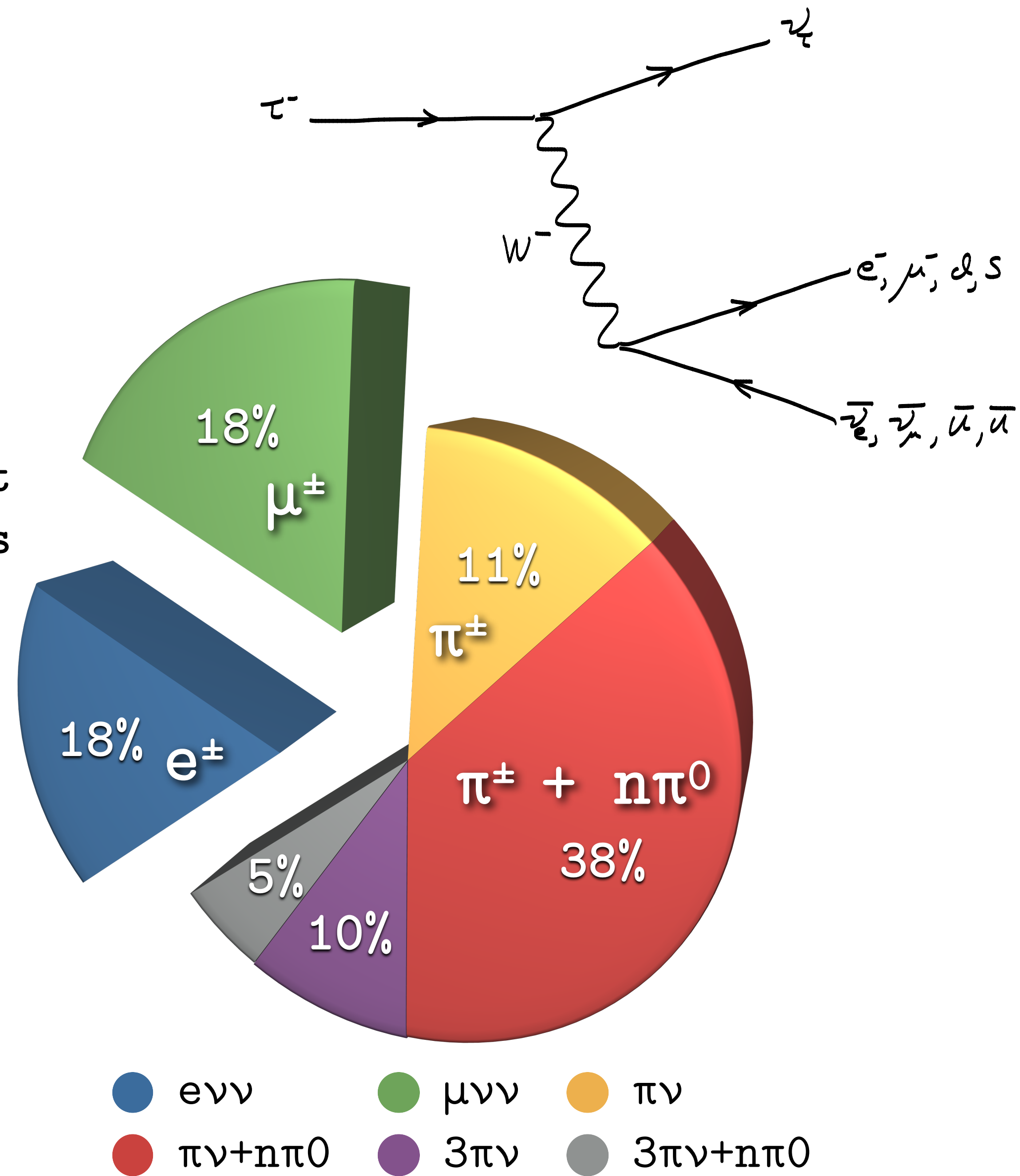
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 - three prong: 15%

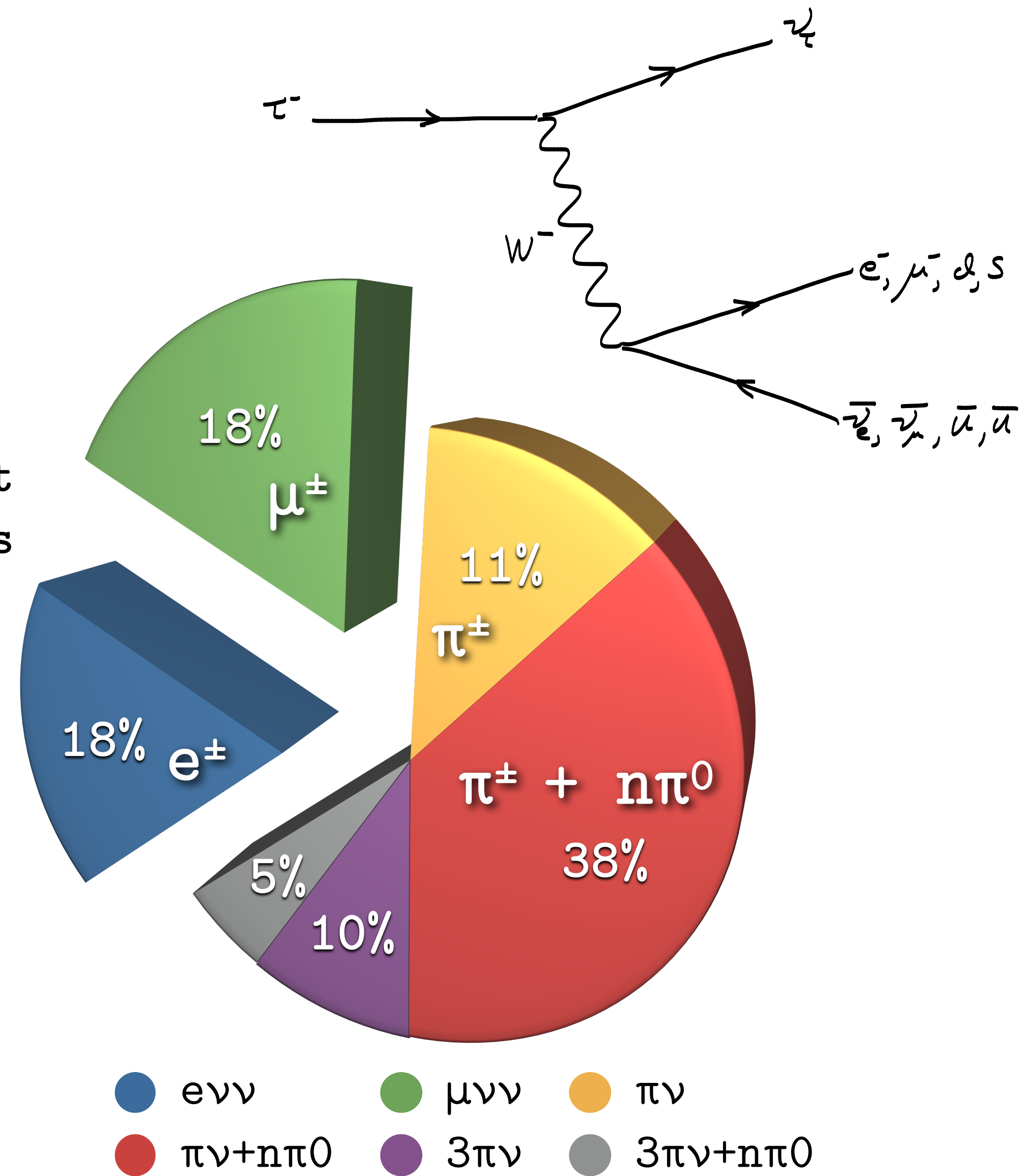
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 - 10% $\pi^\pm \pi^\pm \pi^\mp$

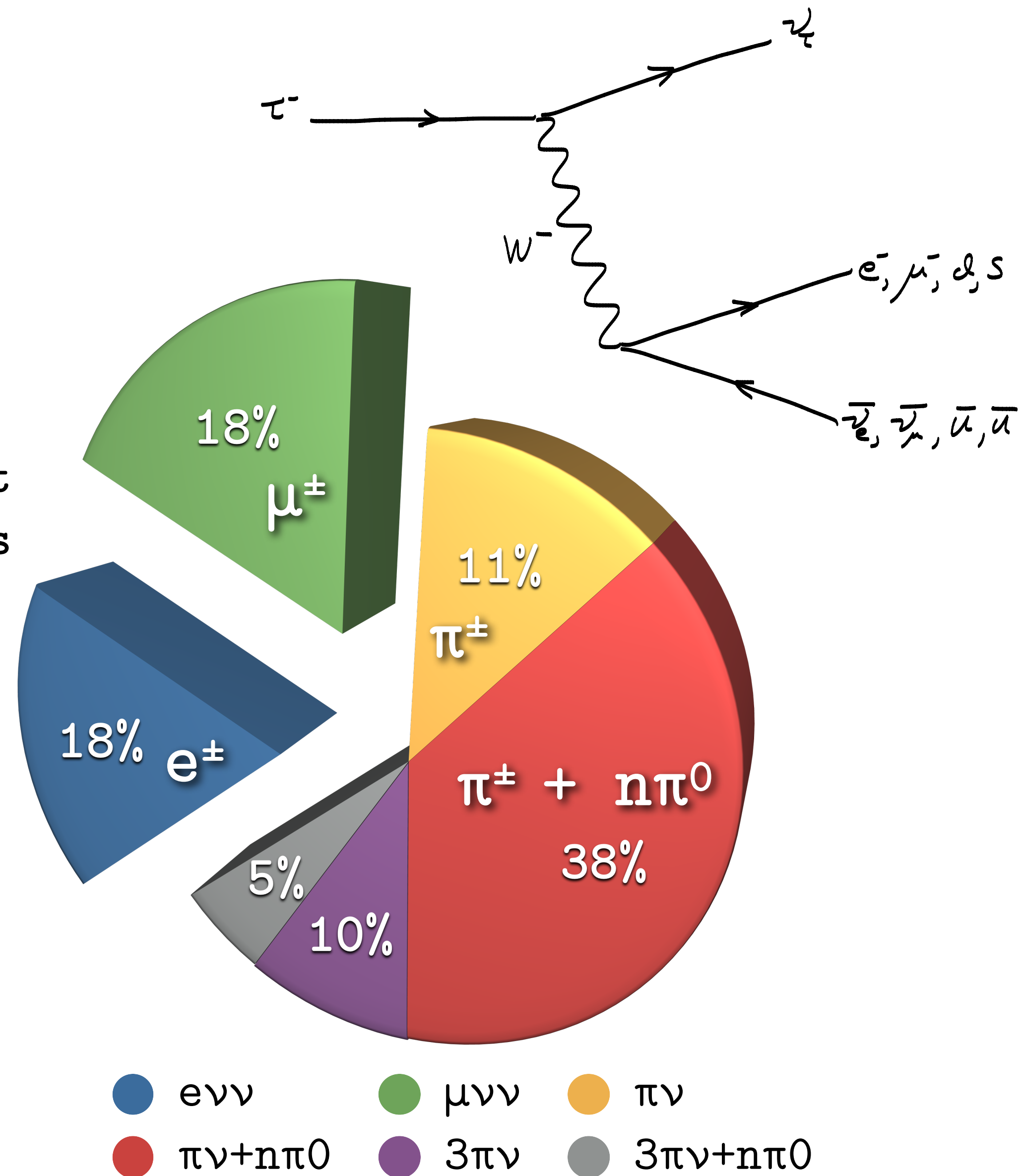
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 - 10% $\pi^\pm \pi^\pm \pi^\mp$
 - 5% $\pi^\pm \pi^\pm \pi^\mp + n\pi^0$

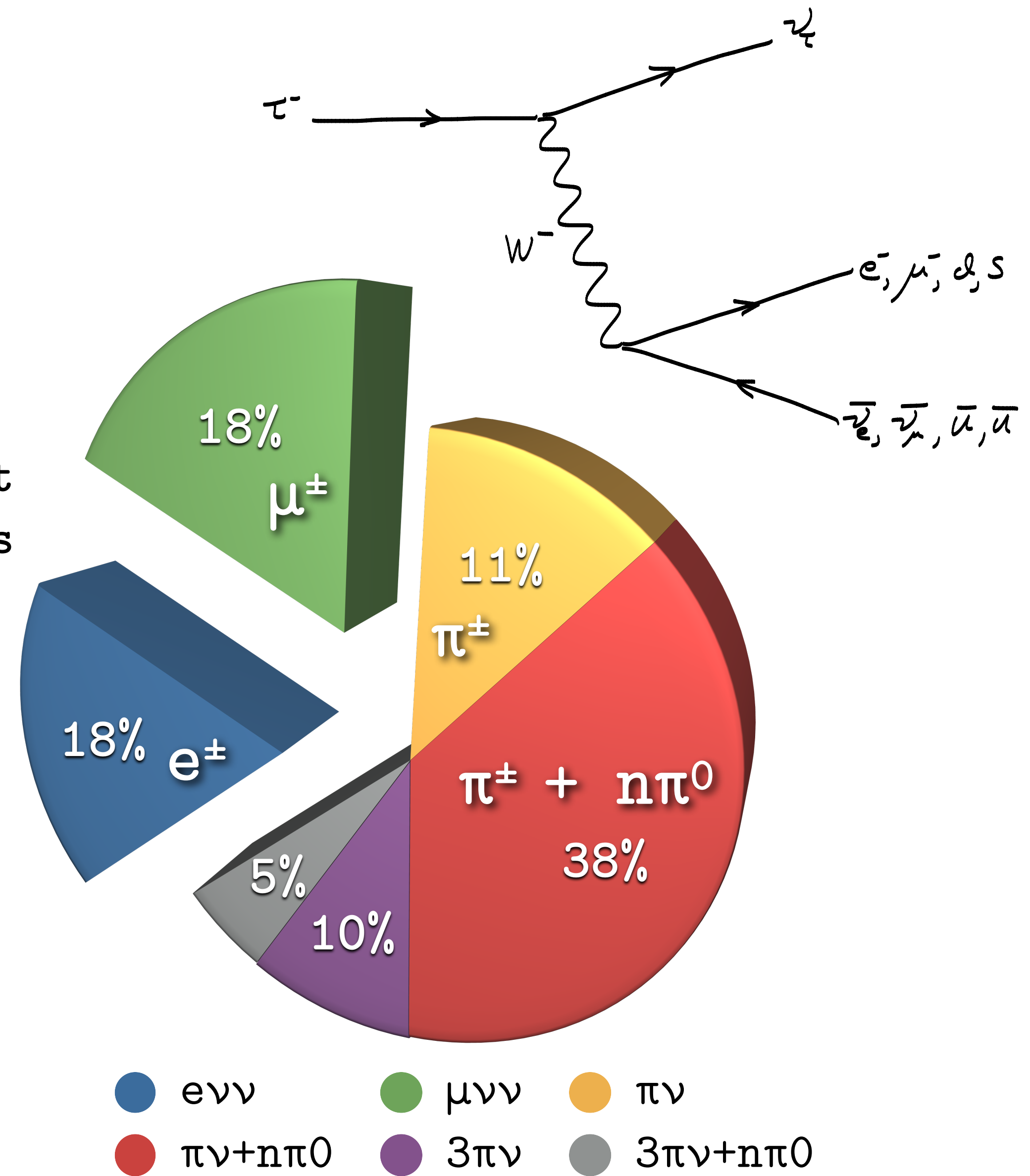
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- Experimental inefficiencies and fakes

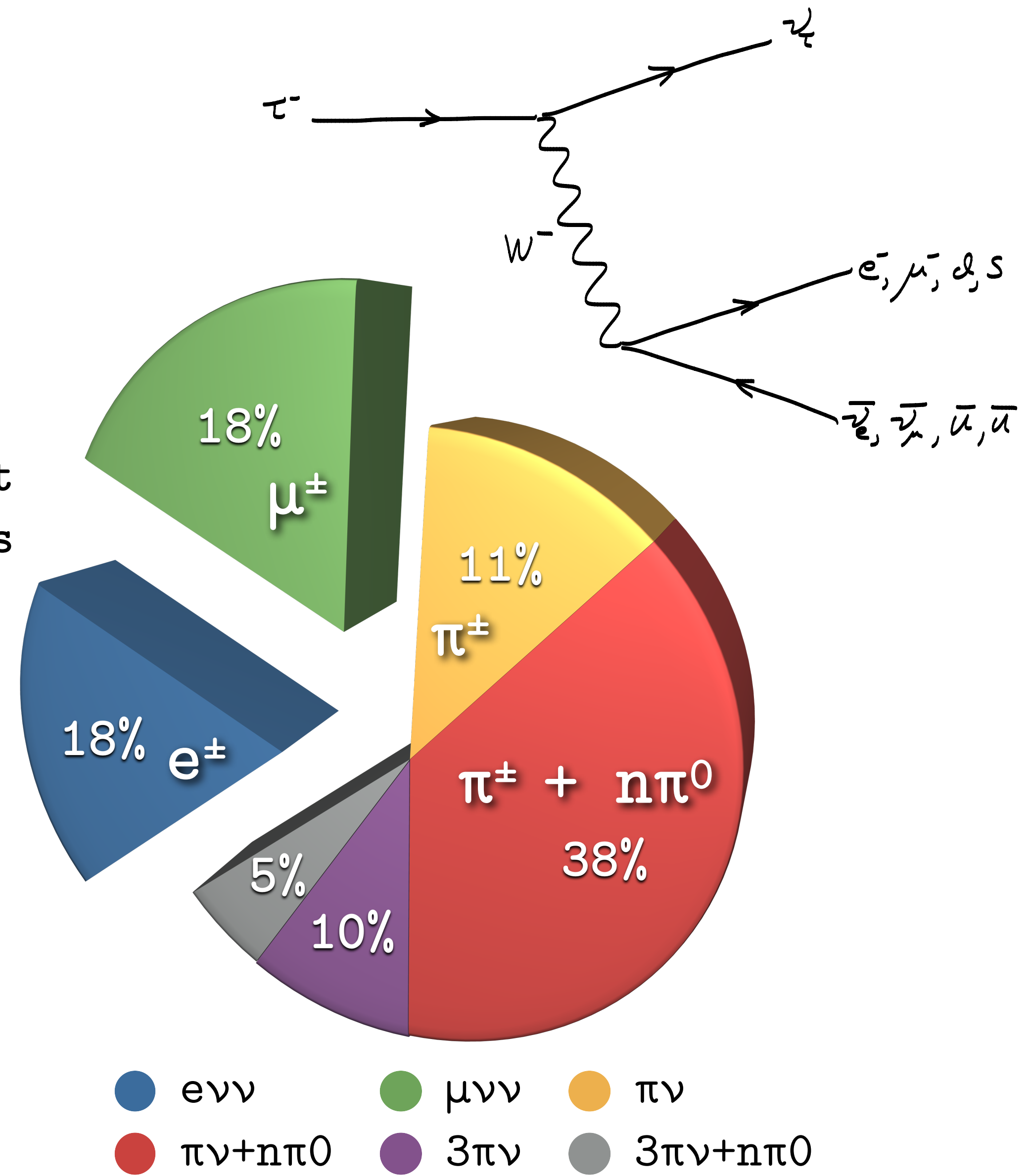
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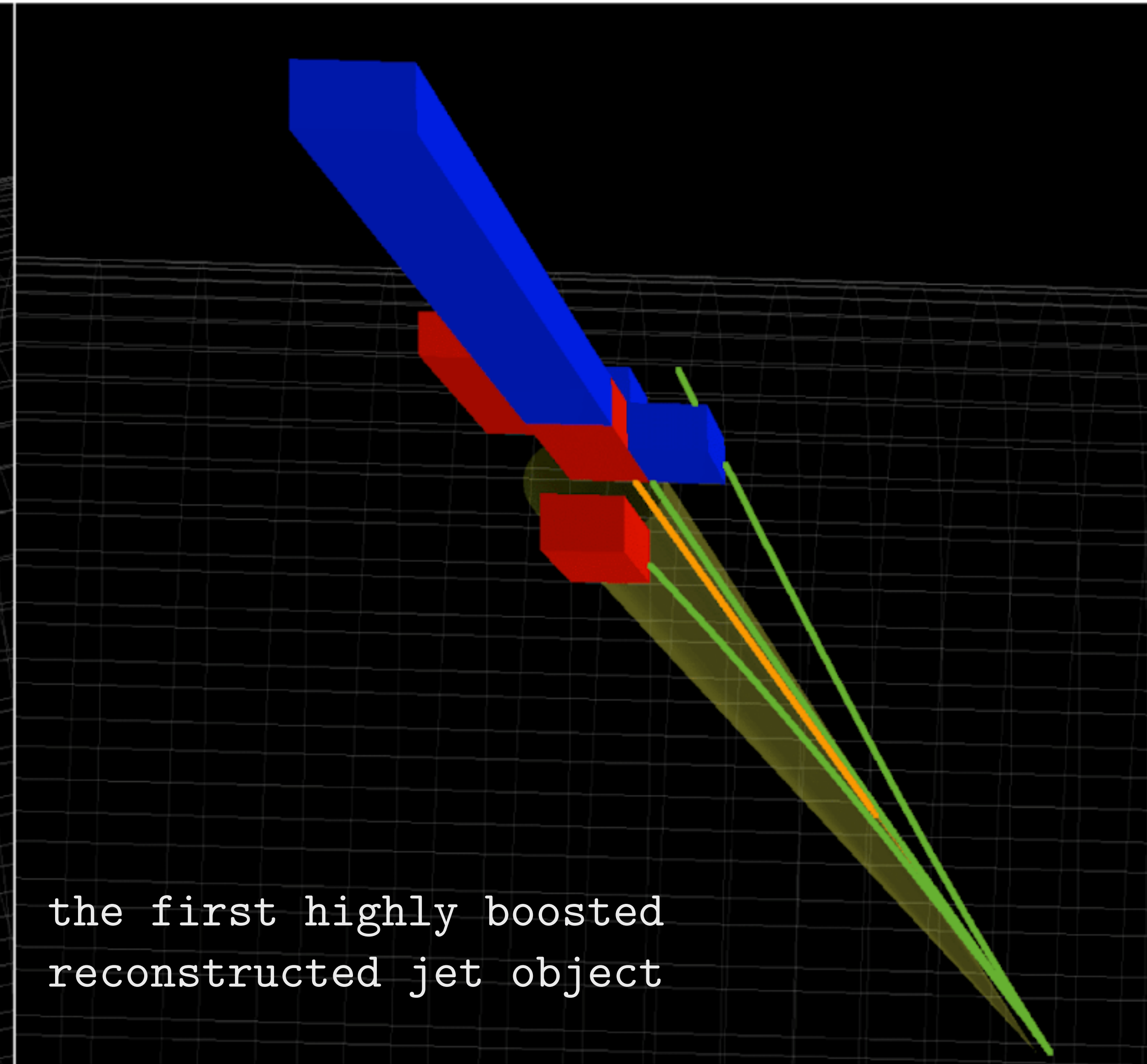
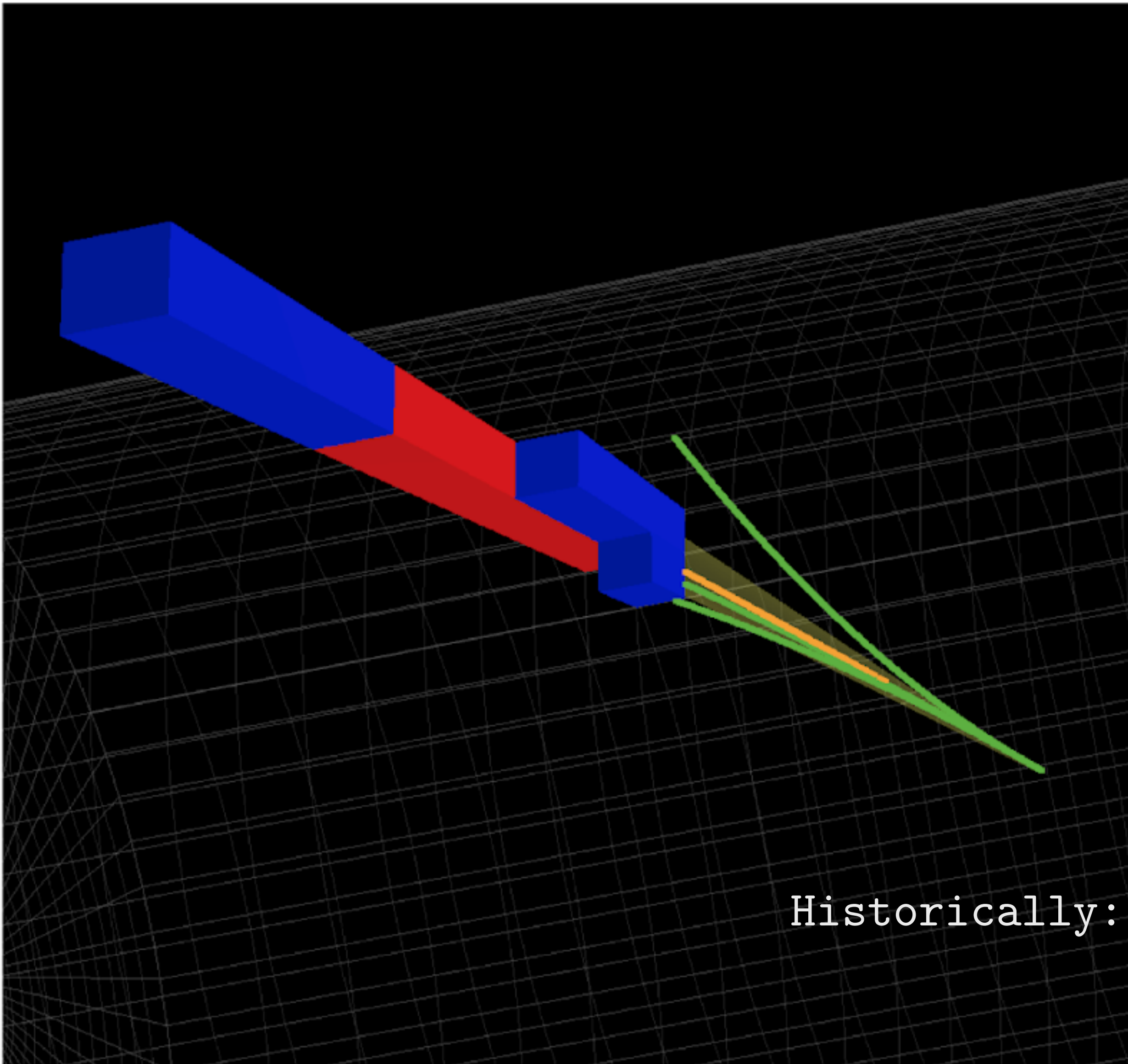
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 - 5% $\pi^\pm \pi^\pm \pi^\mp + n\pi^0$
- Experimental inefficiencies and fakes
 - reality: 0,1,2,3,4 pions + 0,1,2,3,4+ photons

I won't talk about leptonic decays

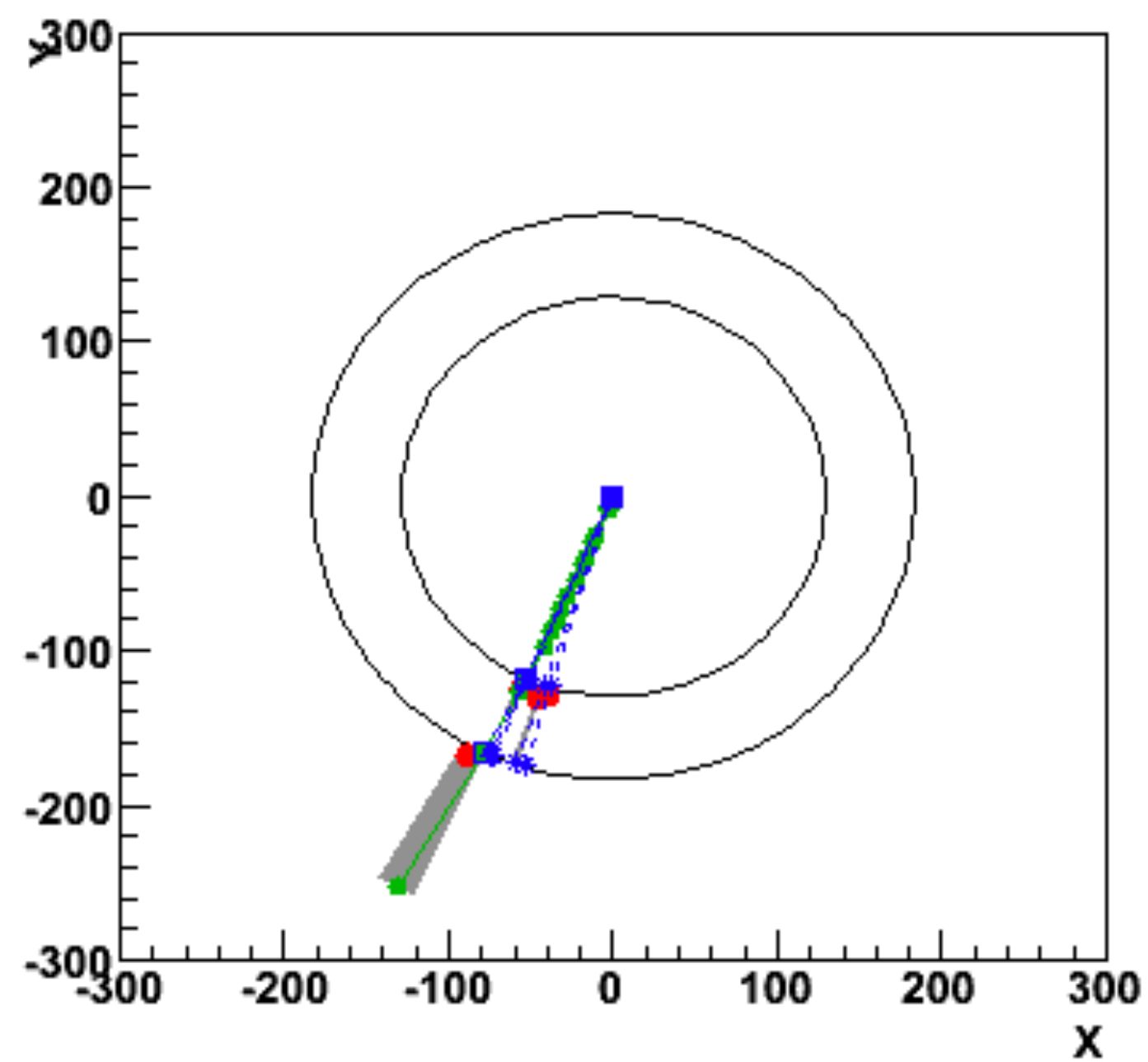


Tau ID & Reconstruction

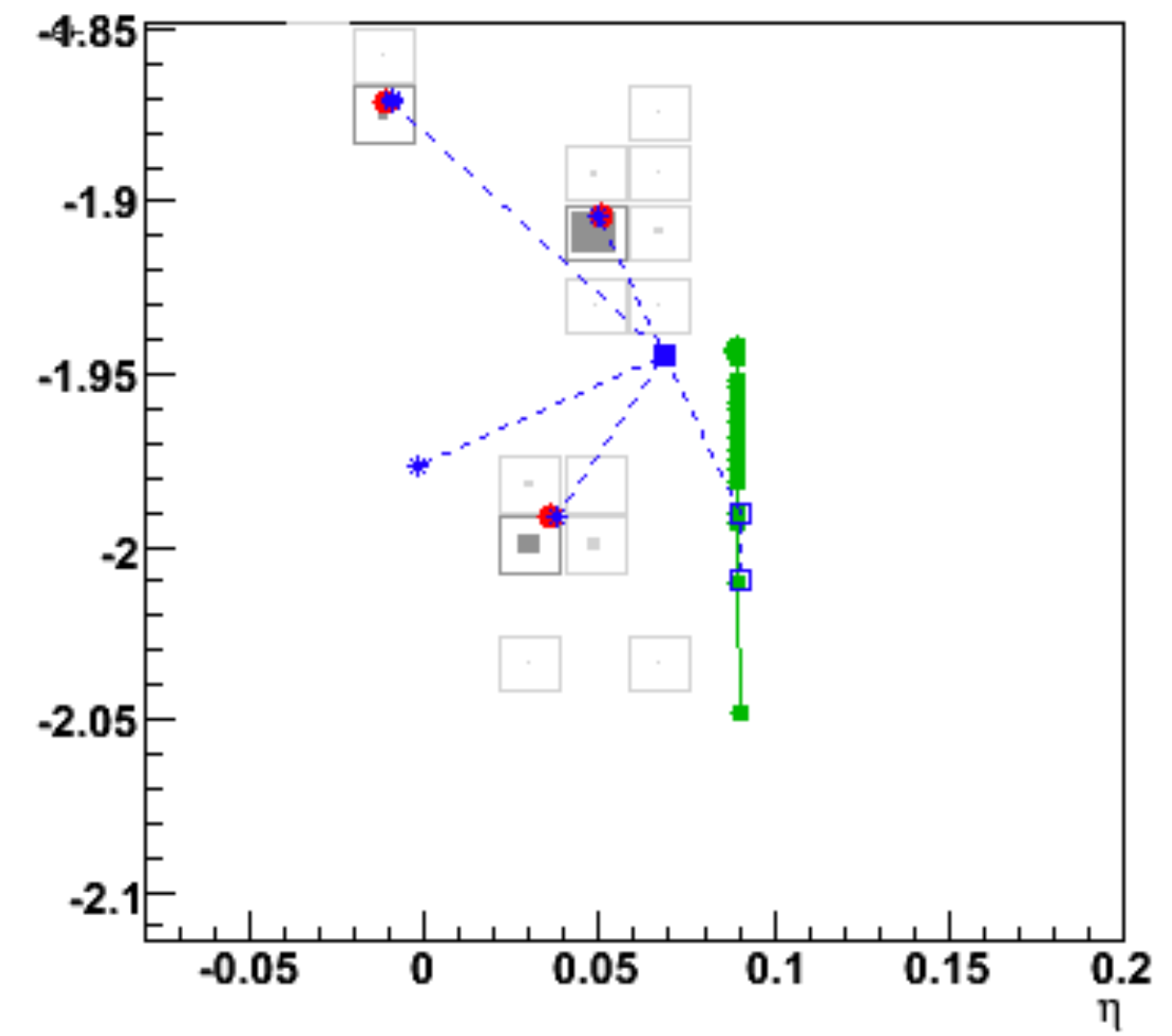
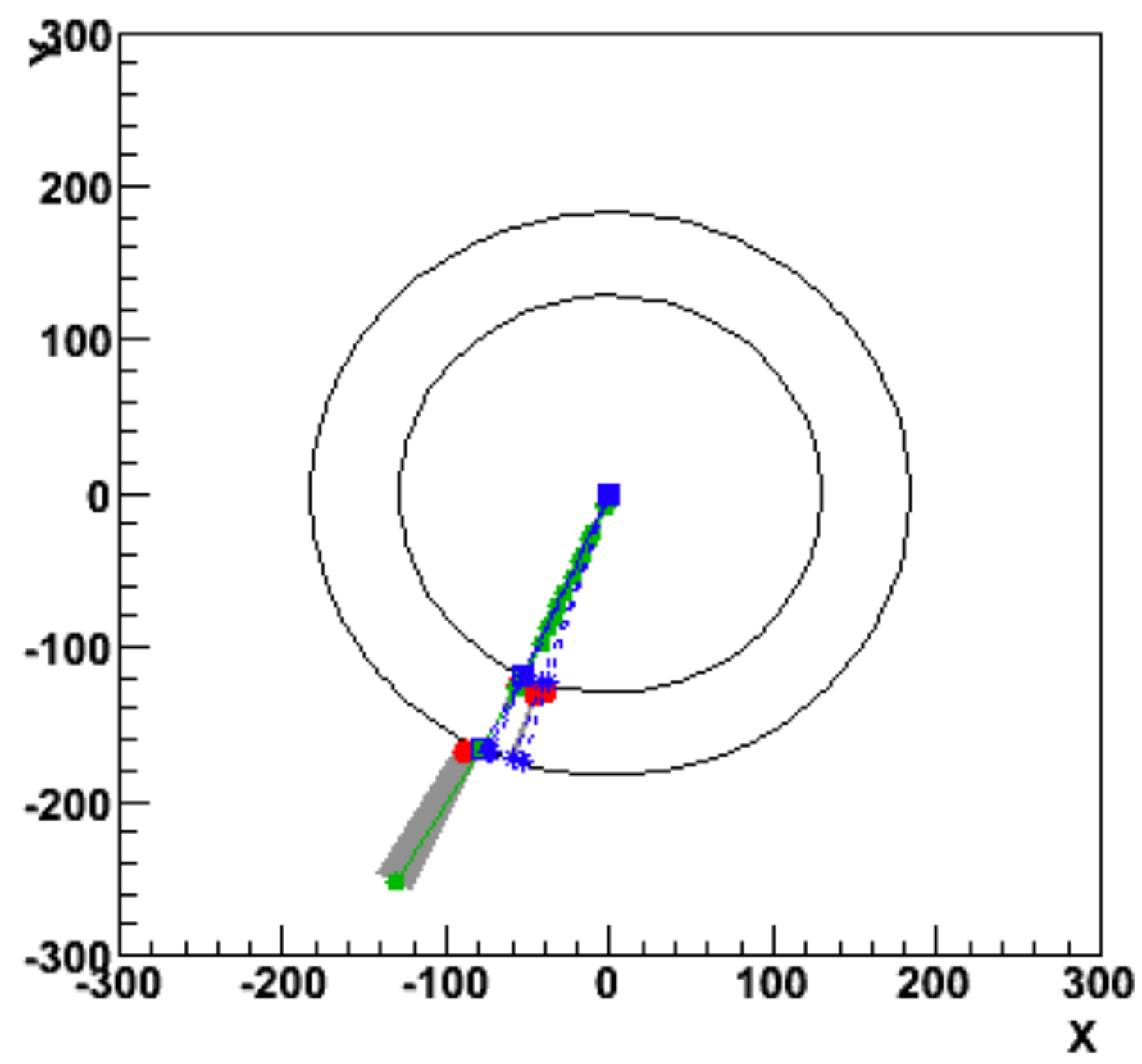


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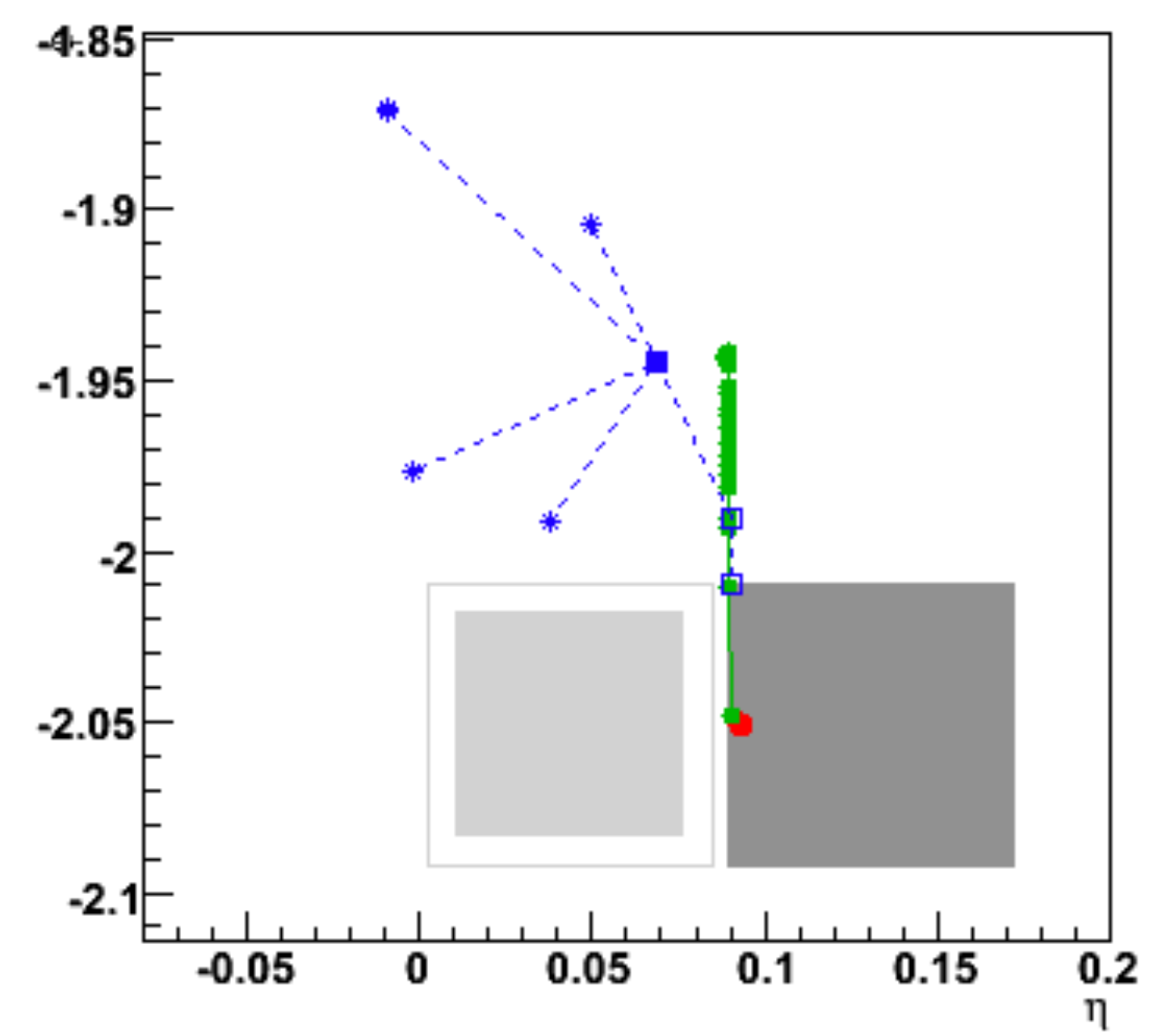
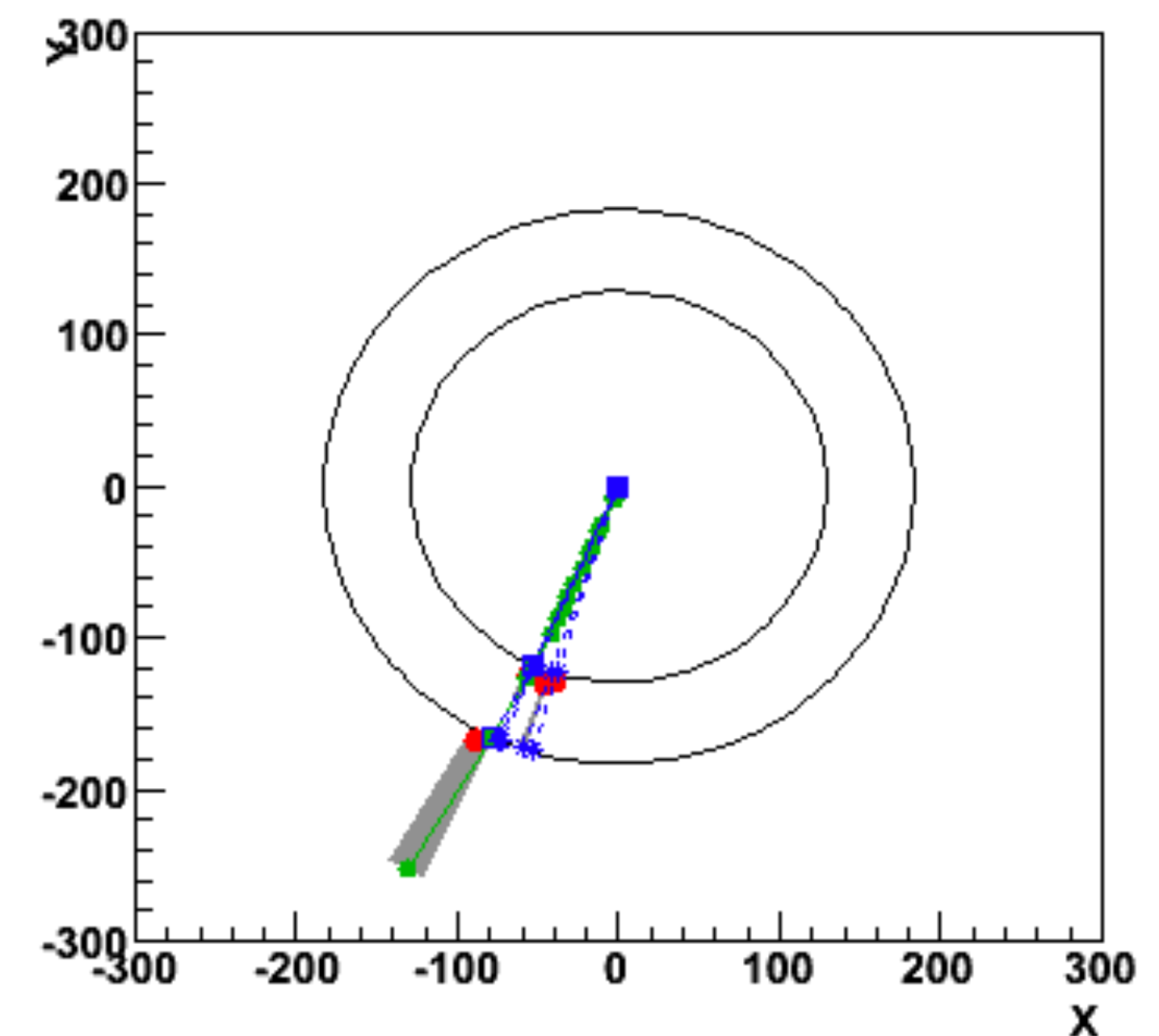
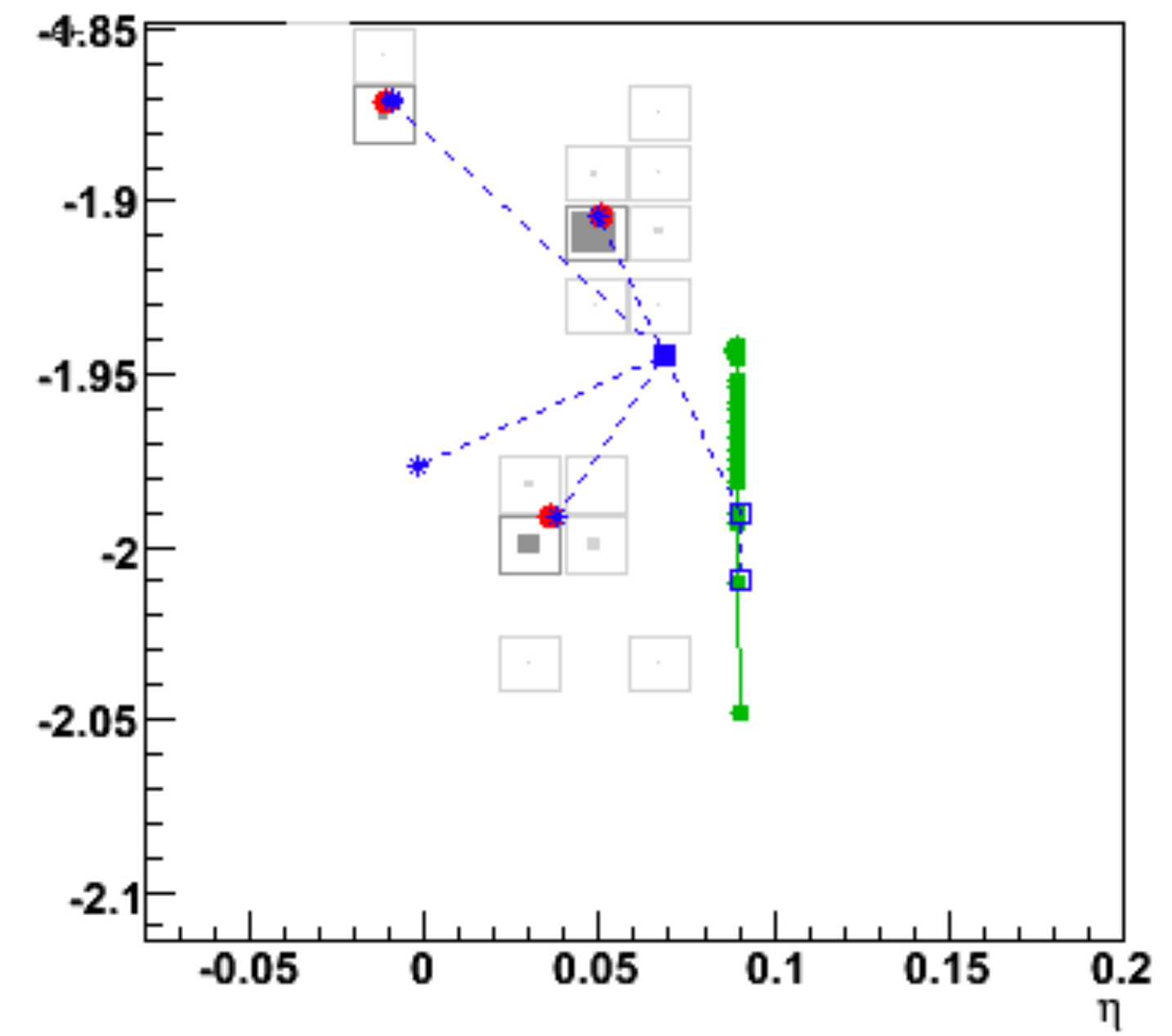
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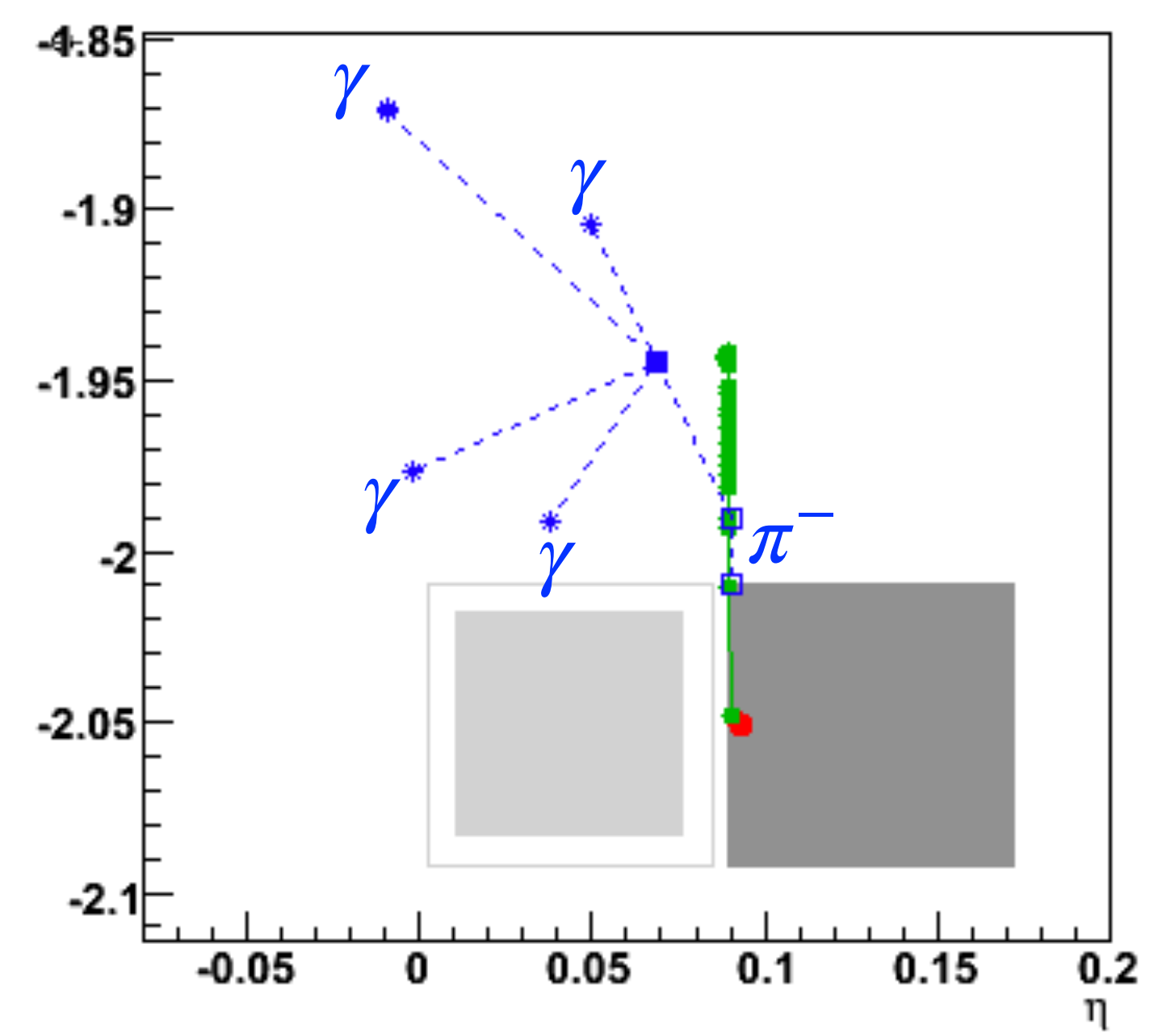
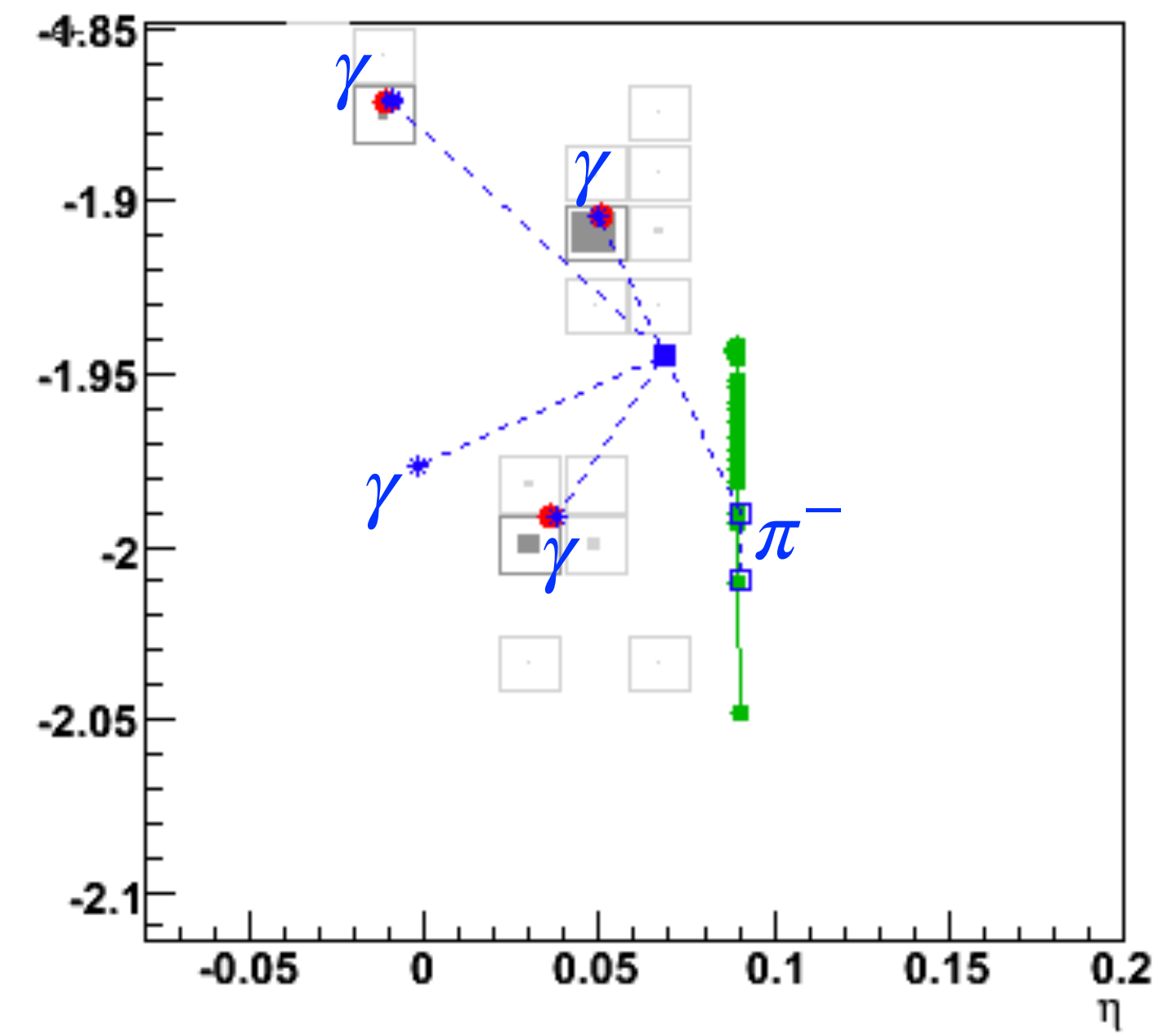
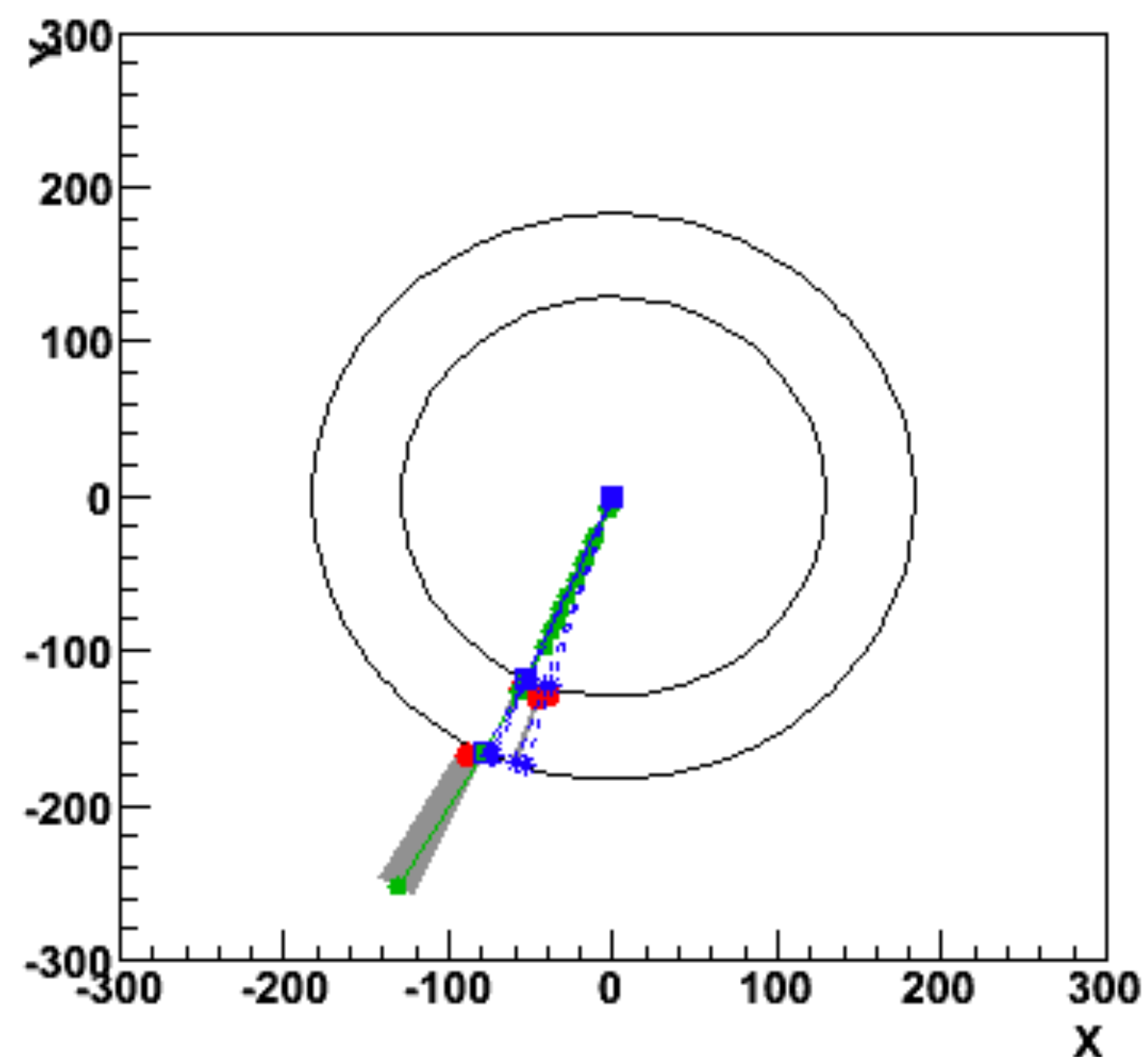
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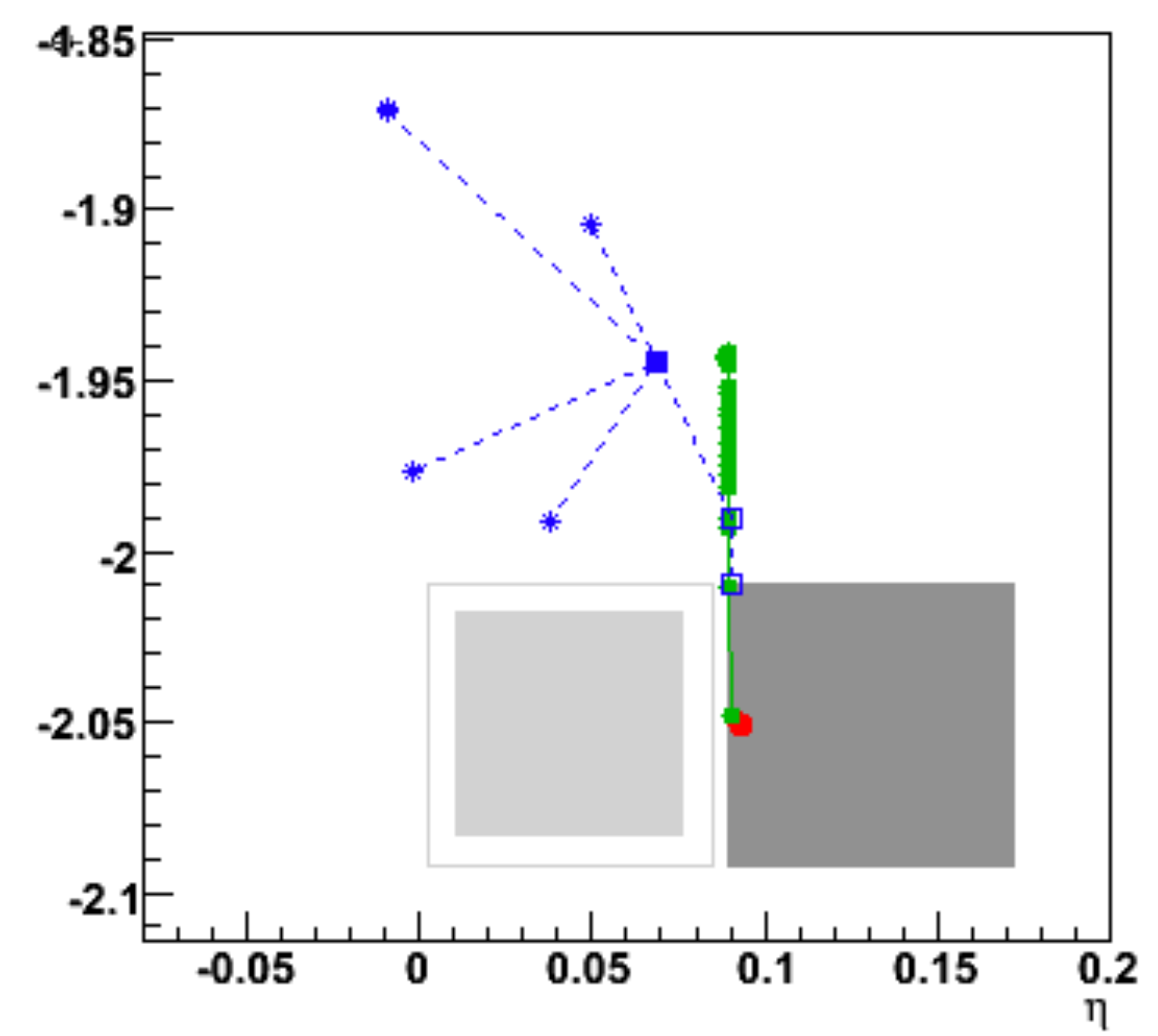
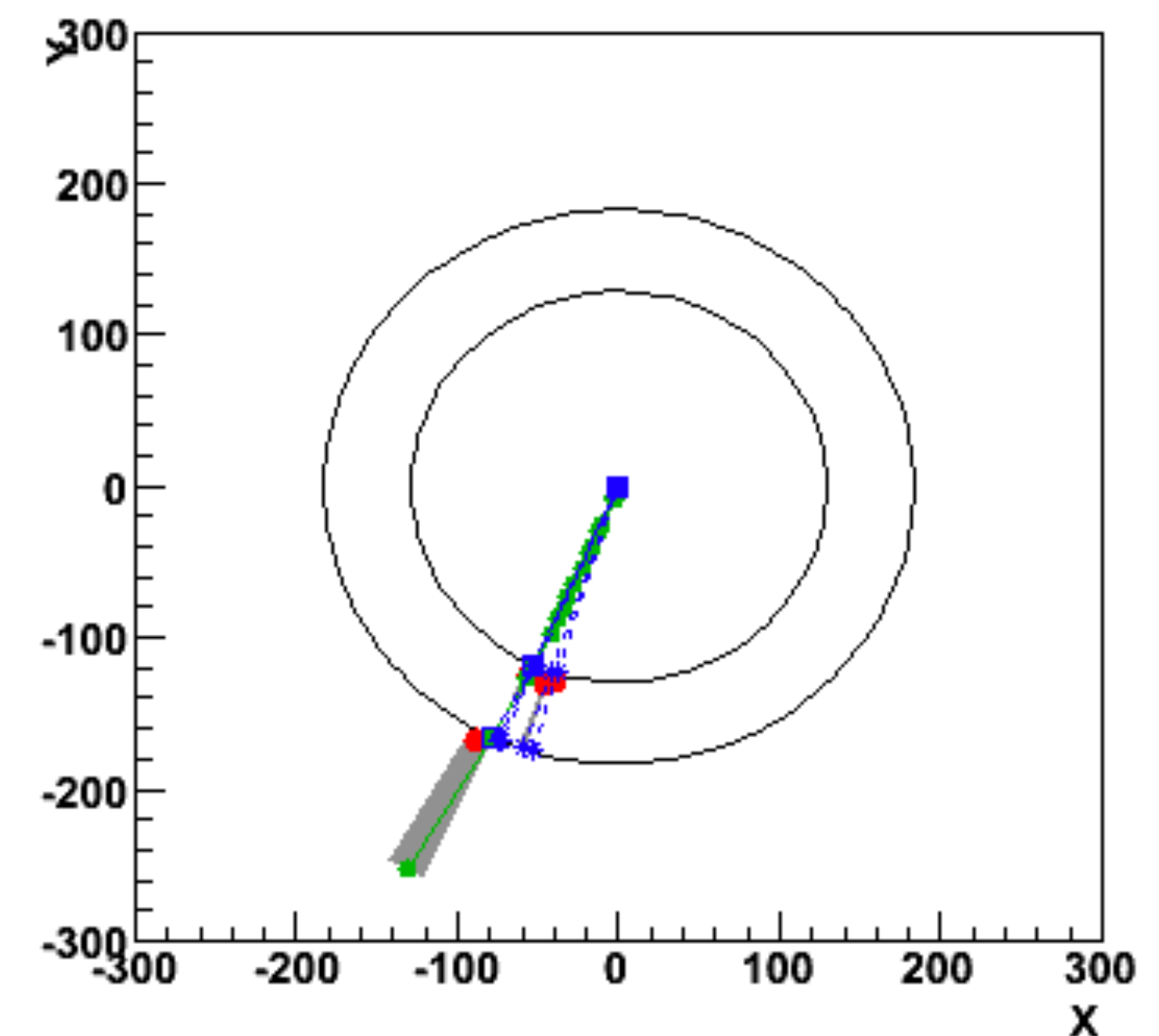
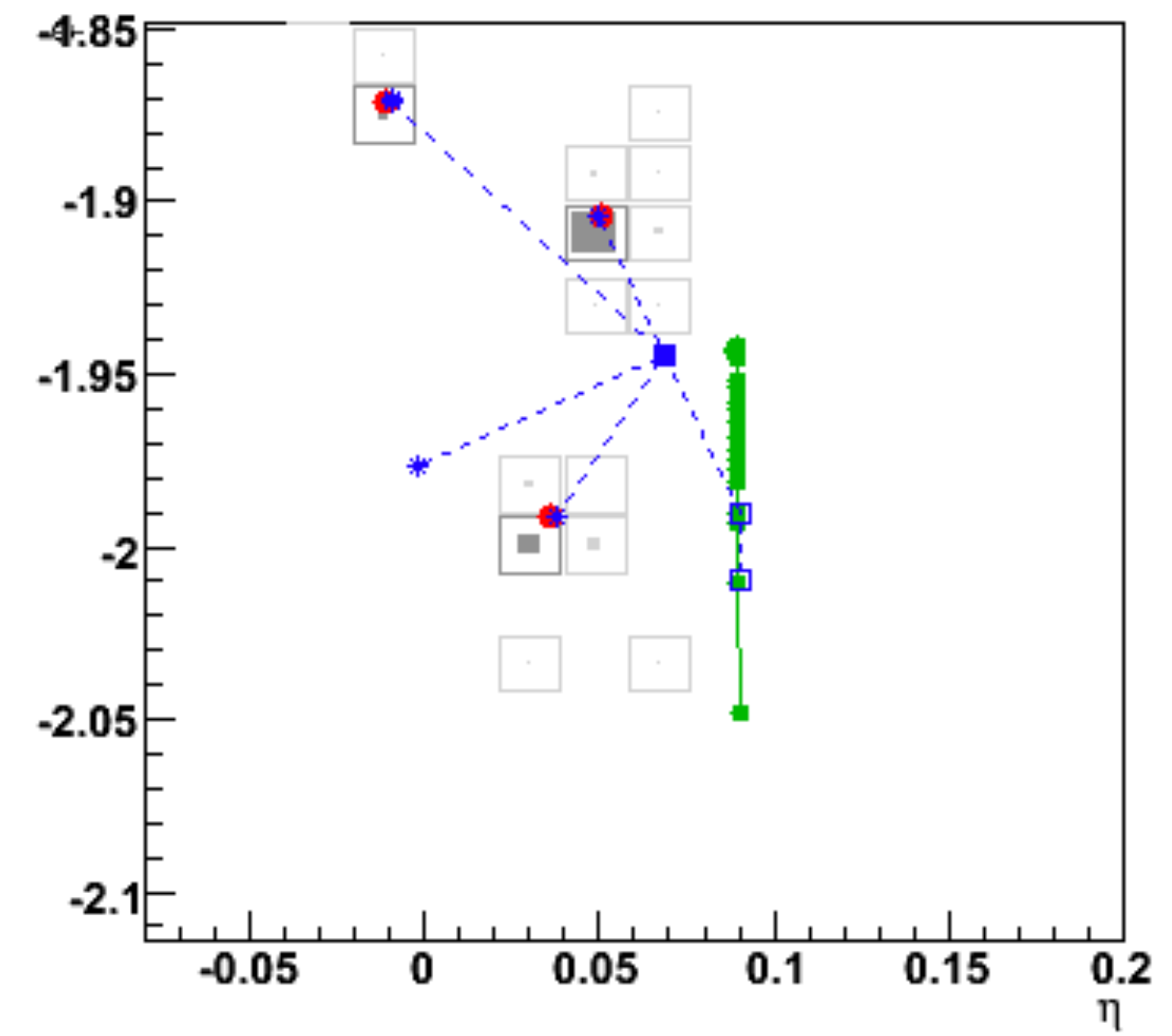
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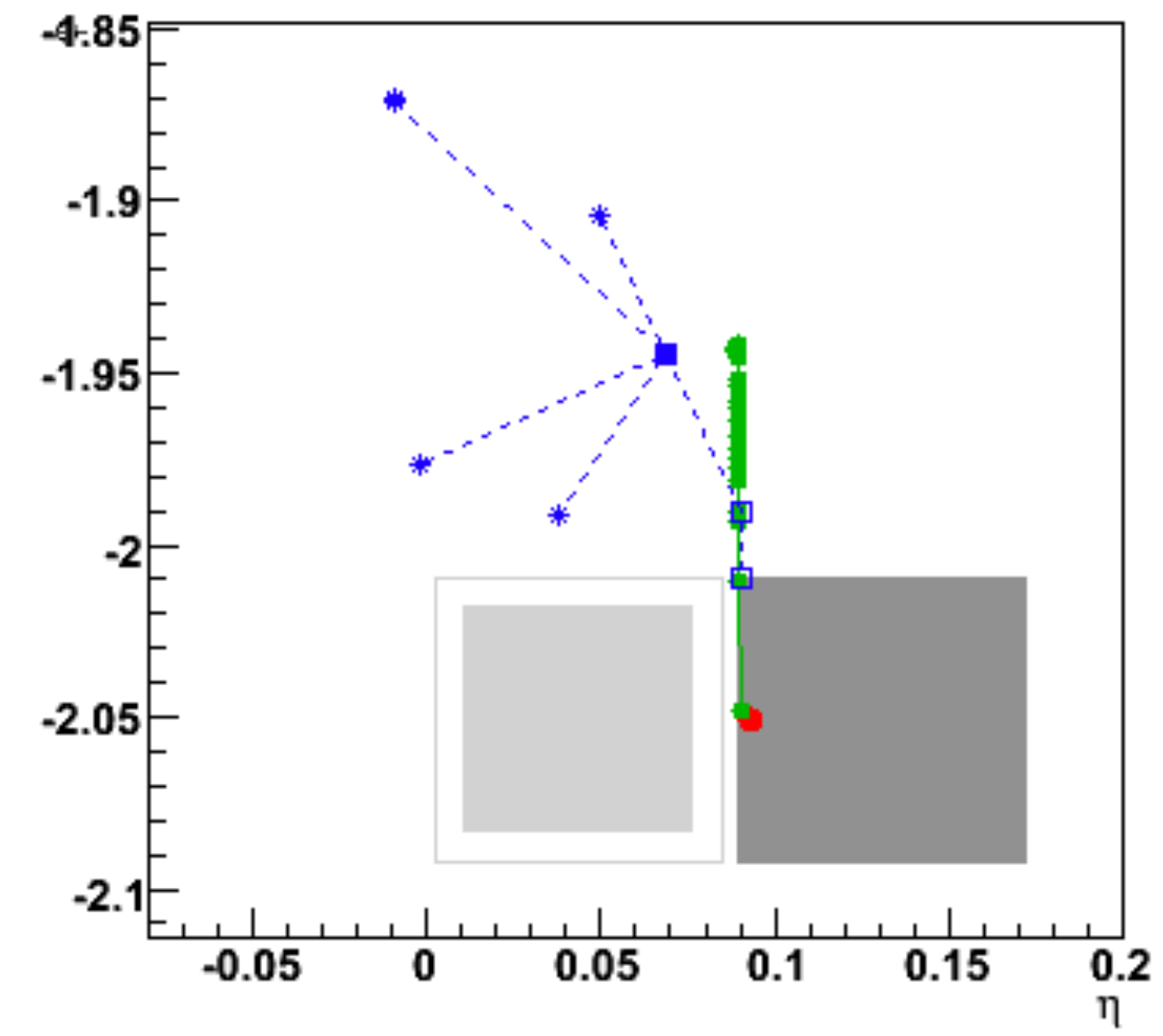
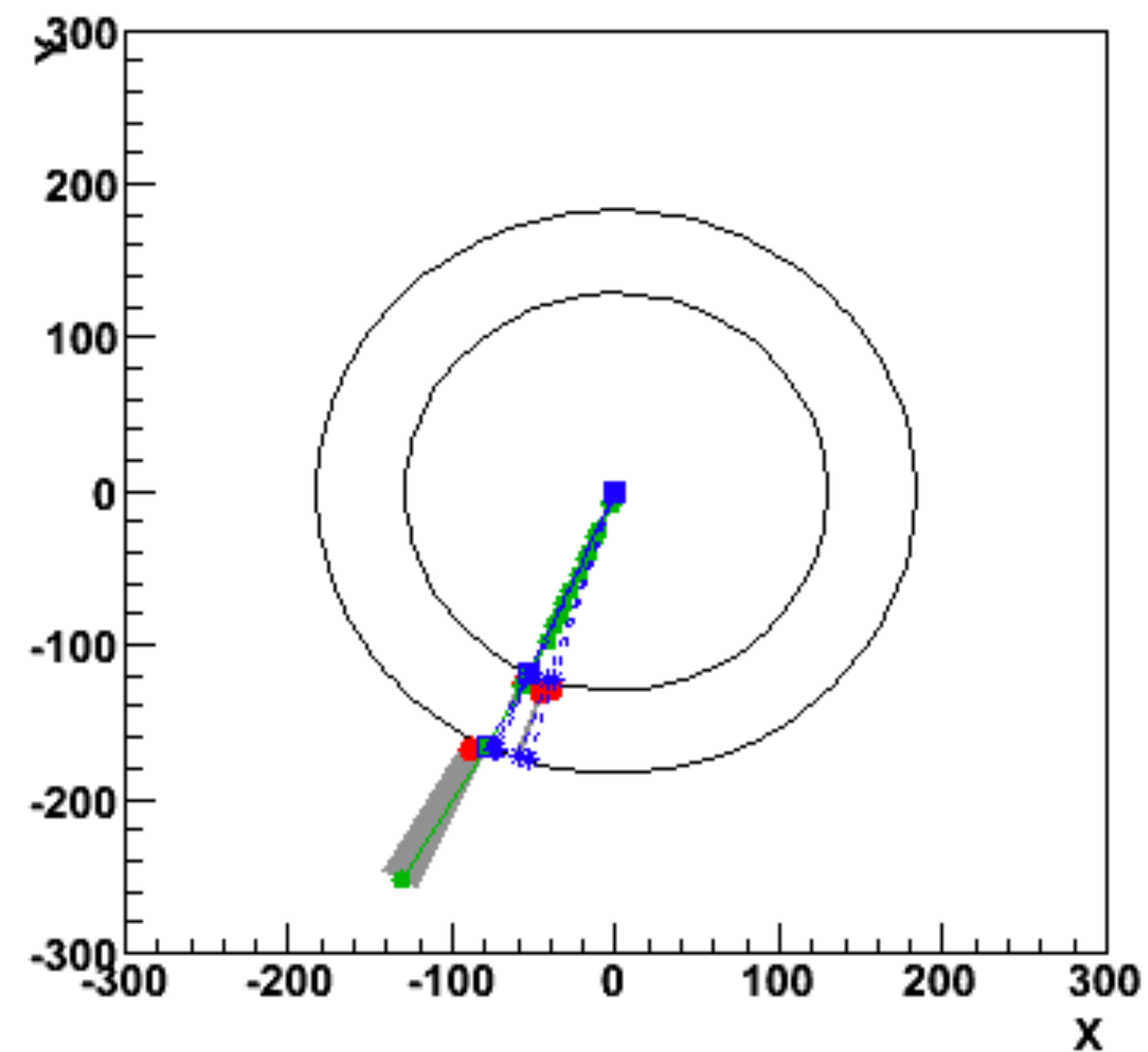
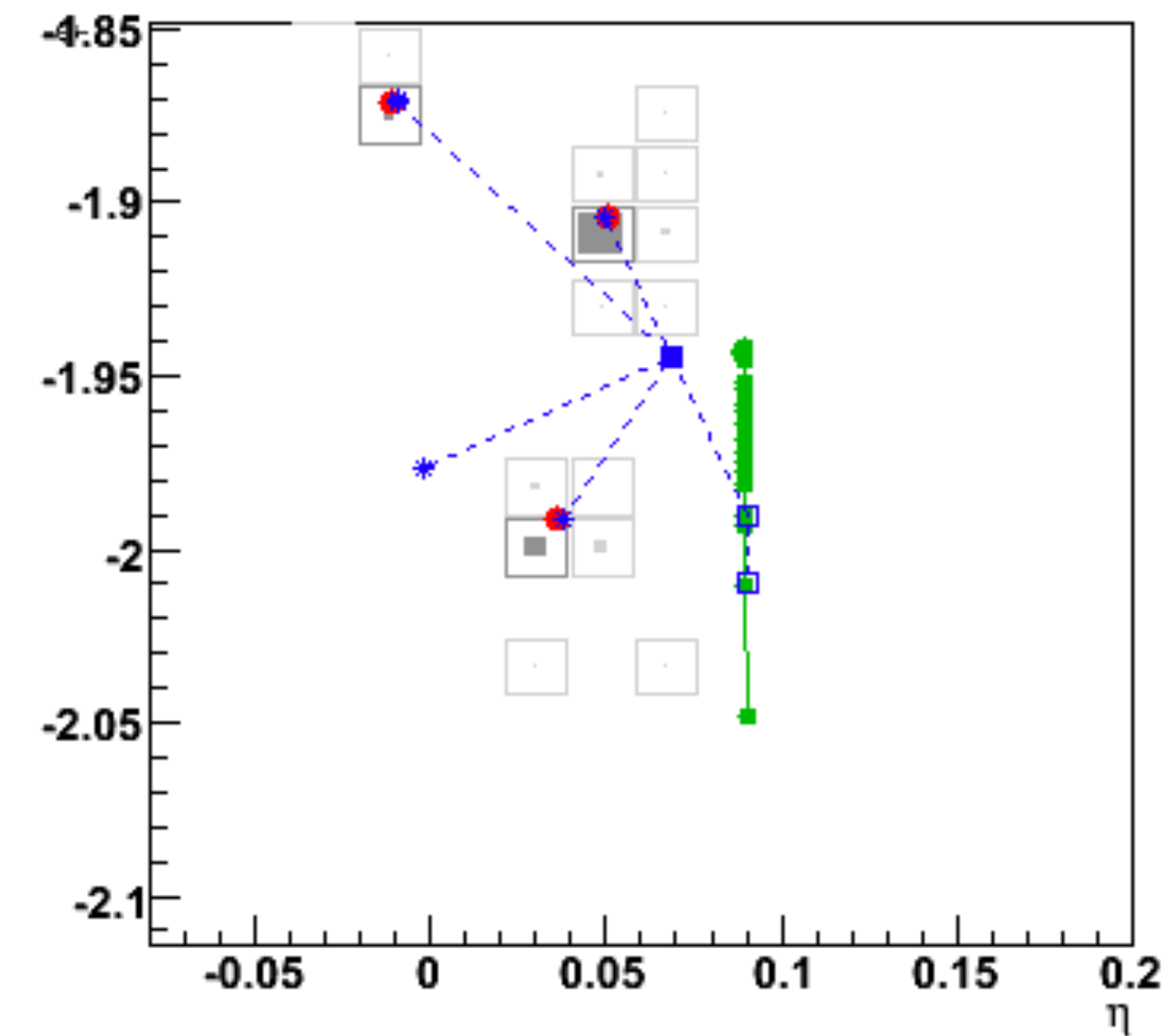
Tau ID & Reconstruction



Tau ID & Reconstruction

Basic Idea

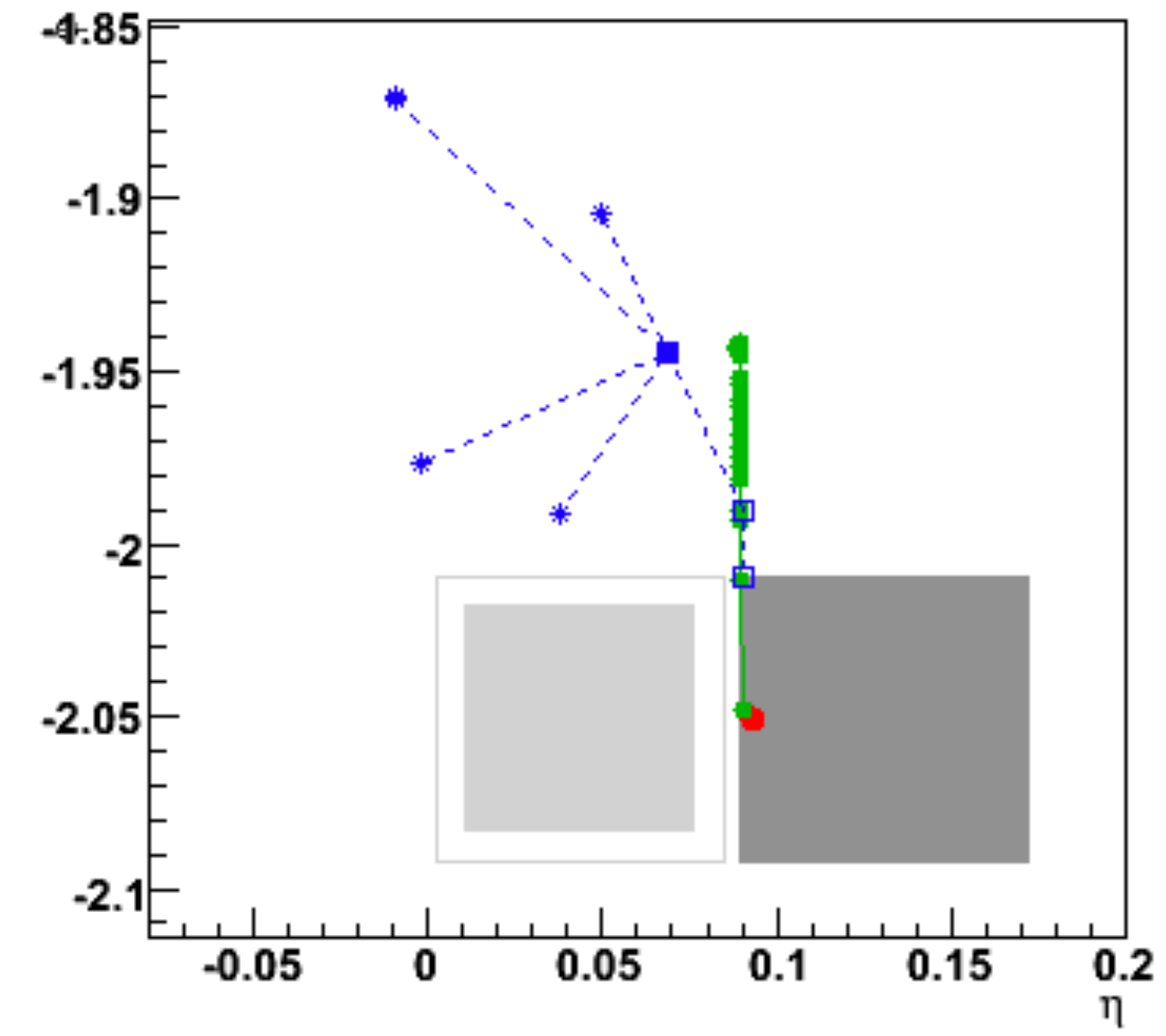
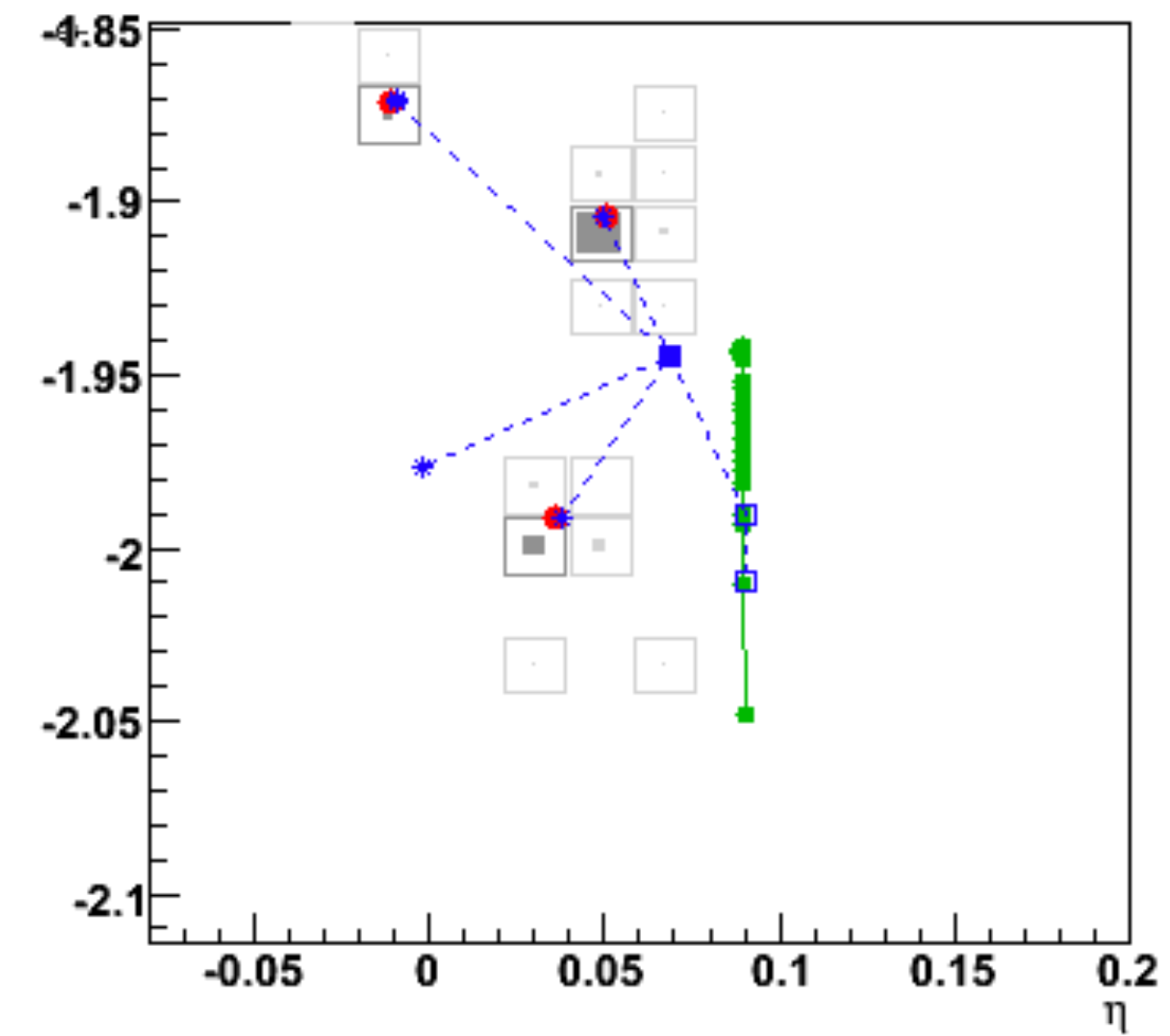
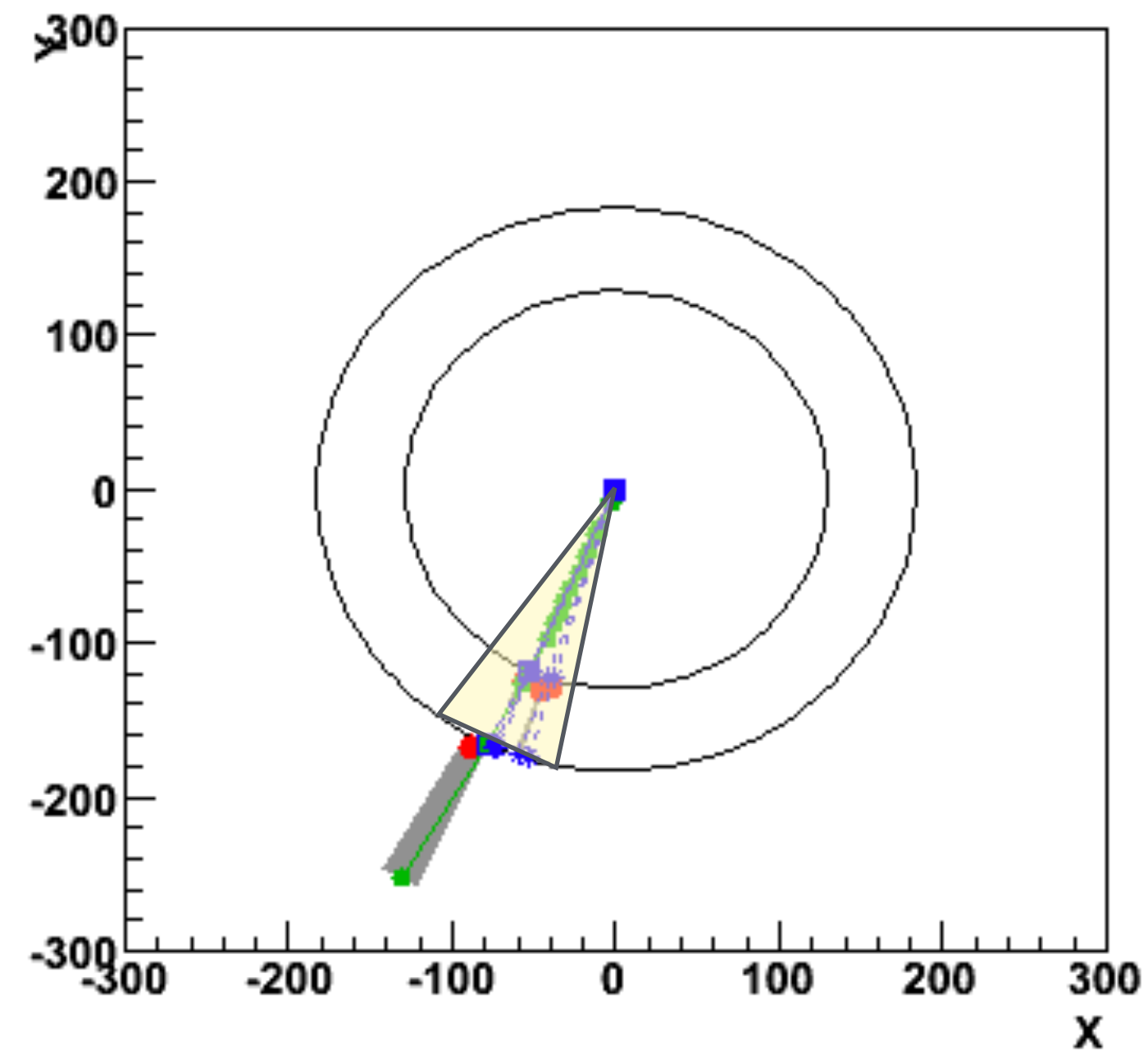
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Tau ID & Reconstruction

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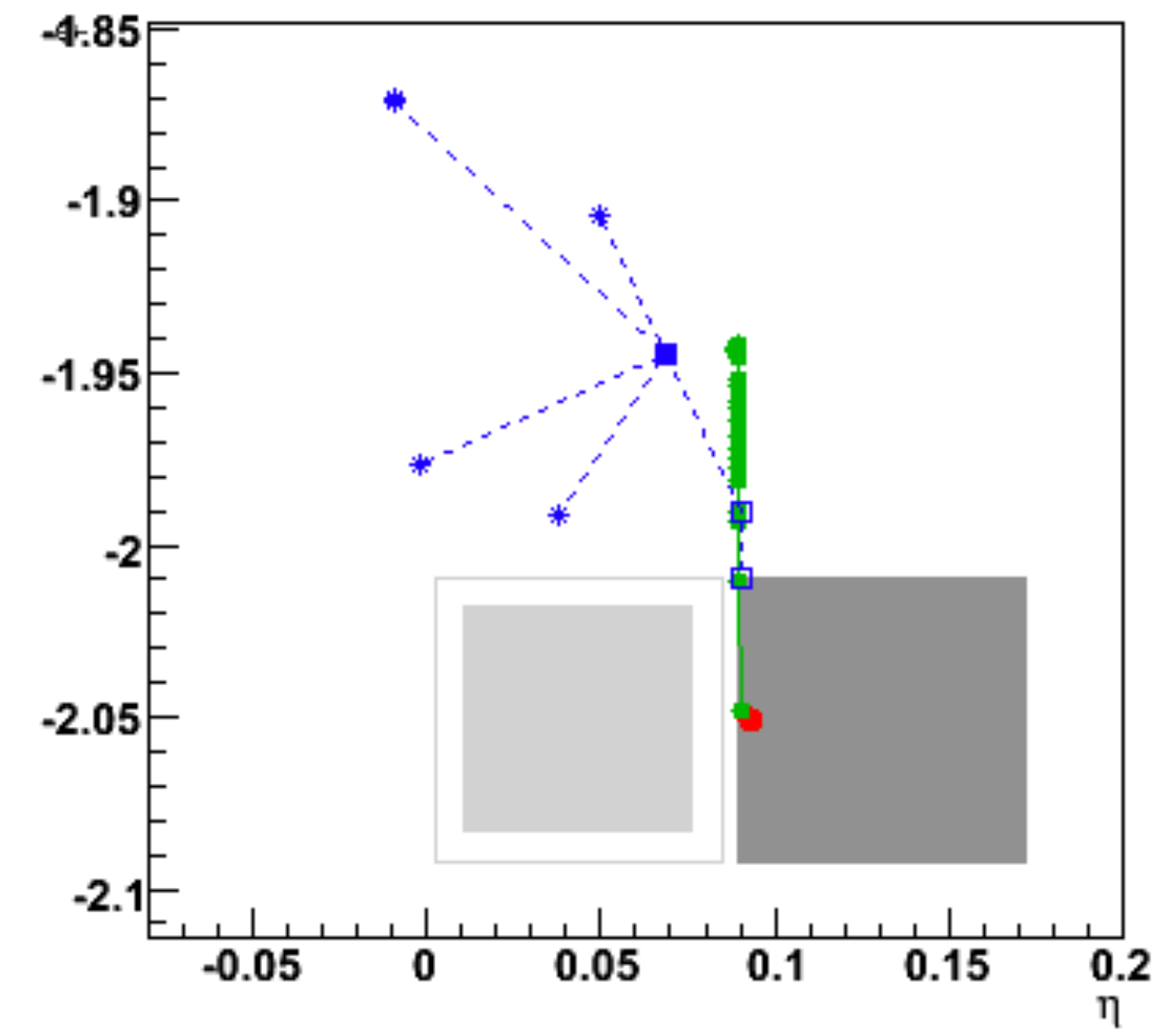
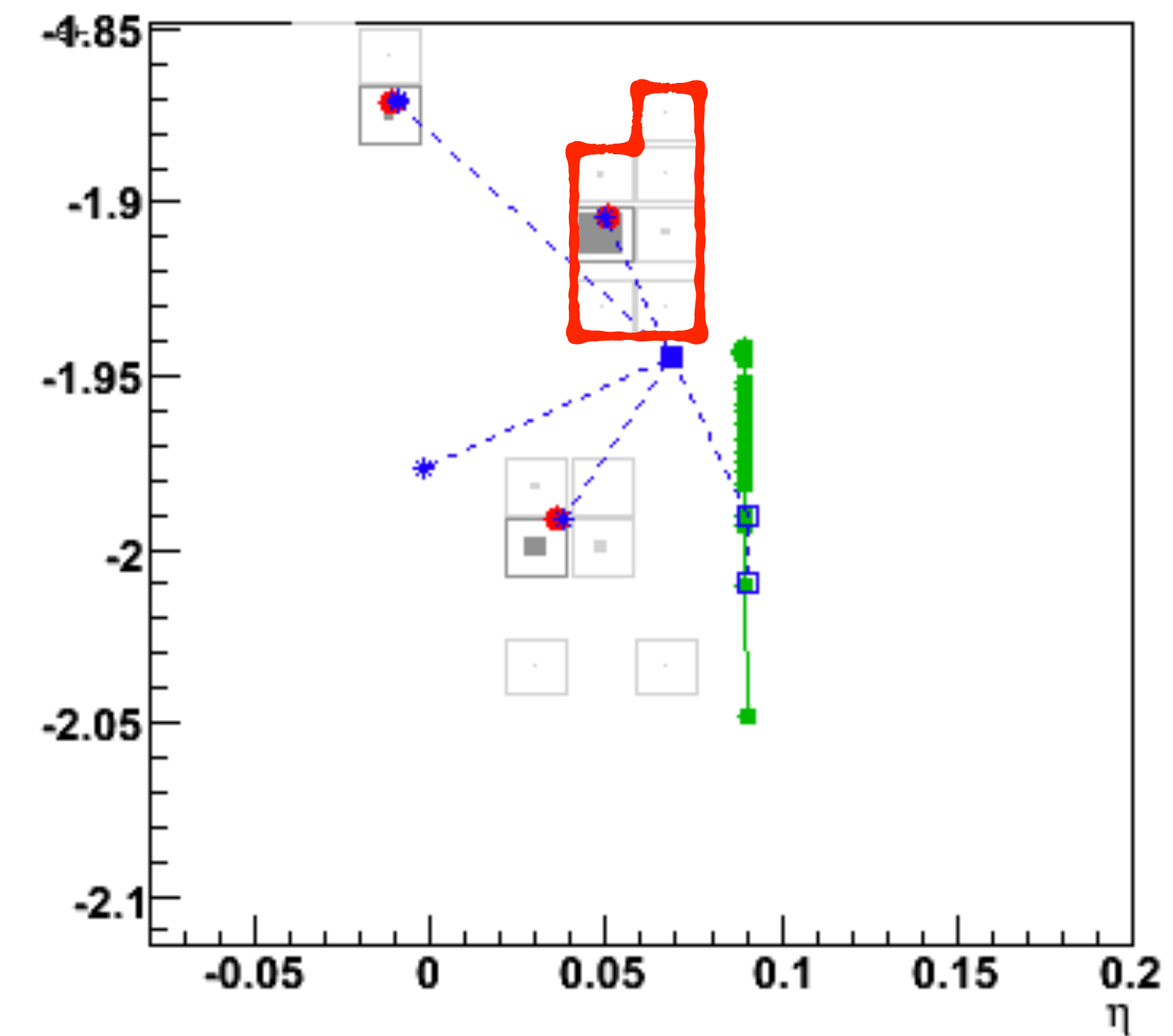
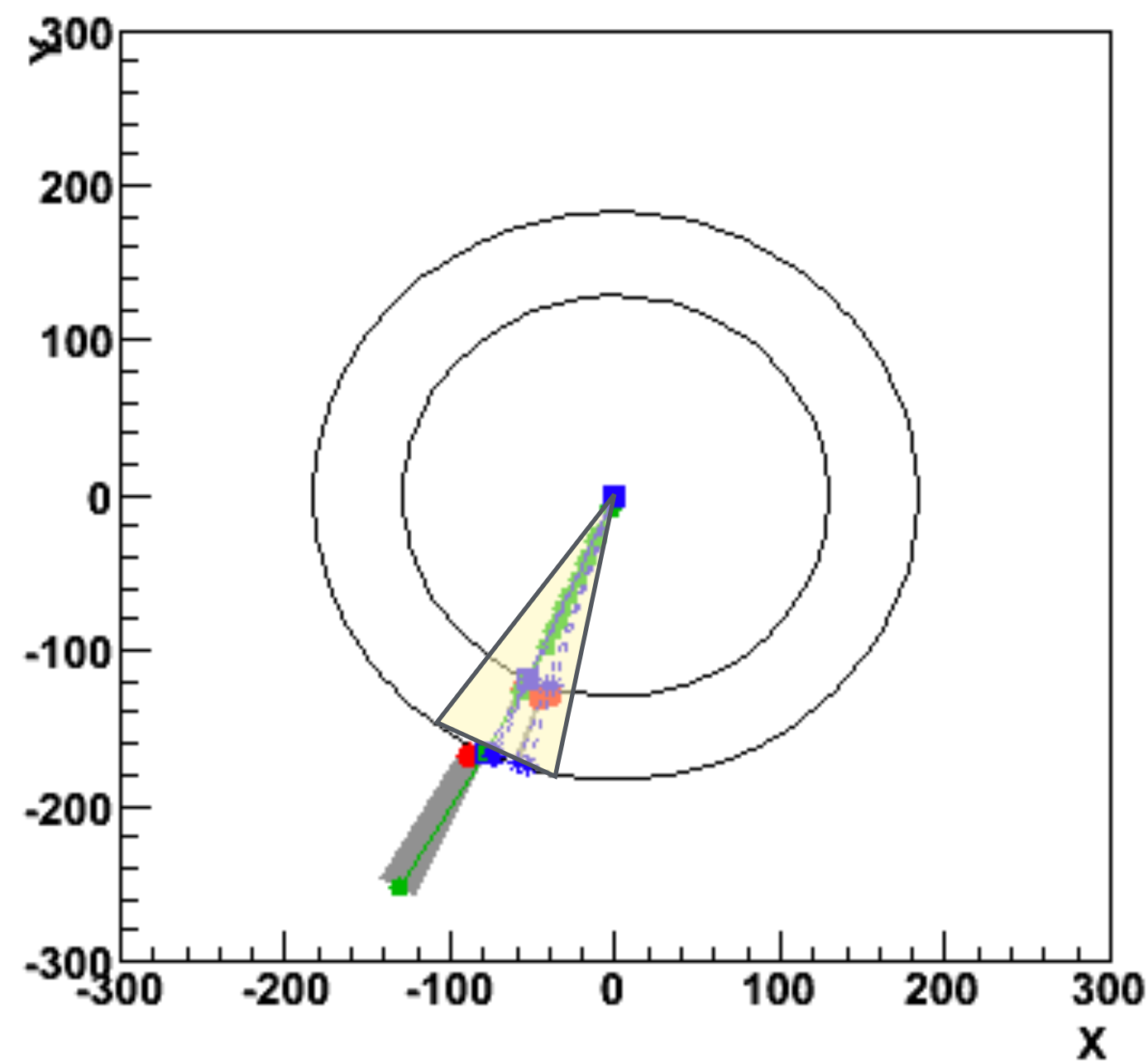
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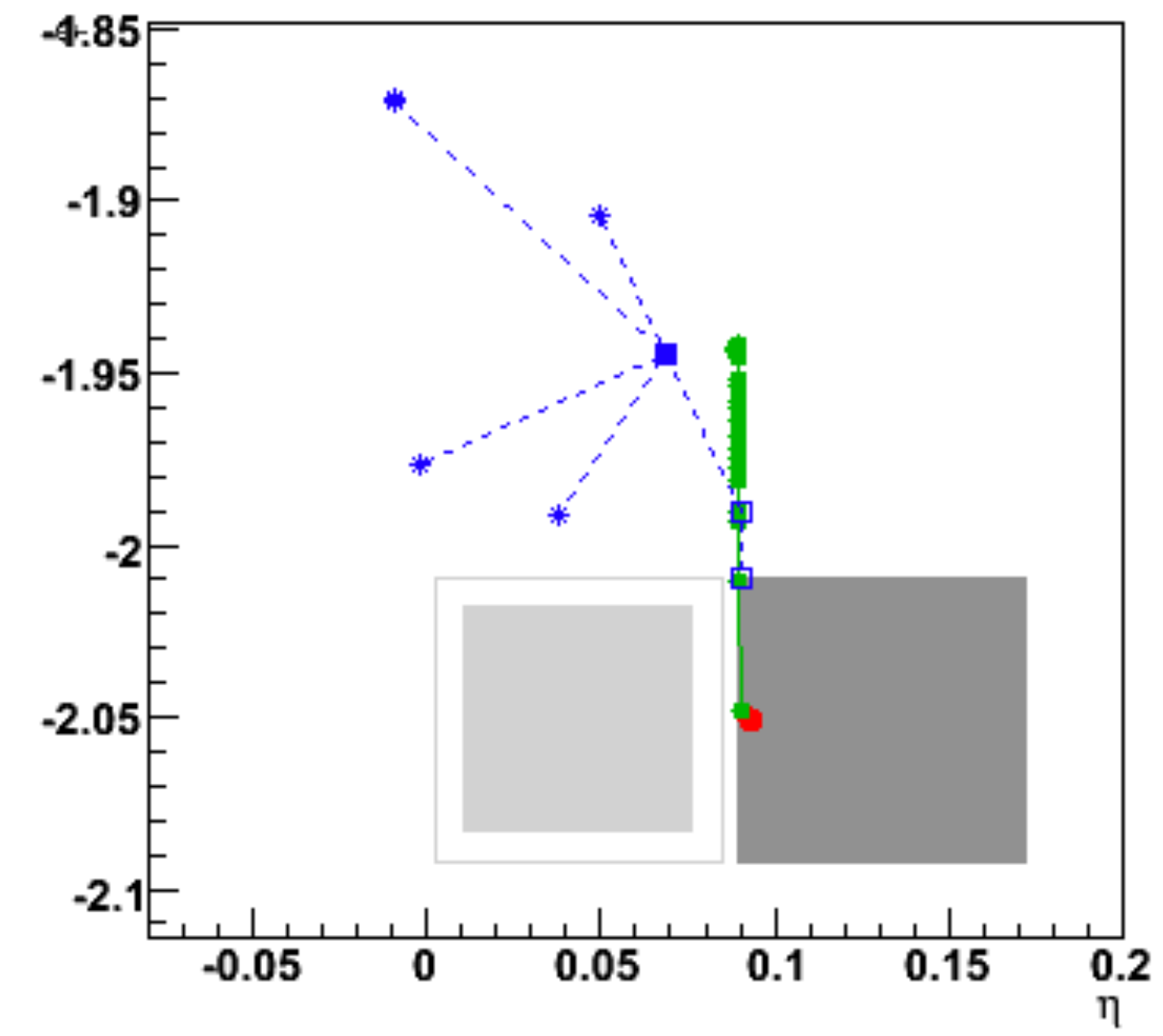
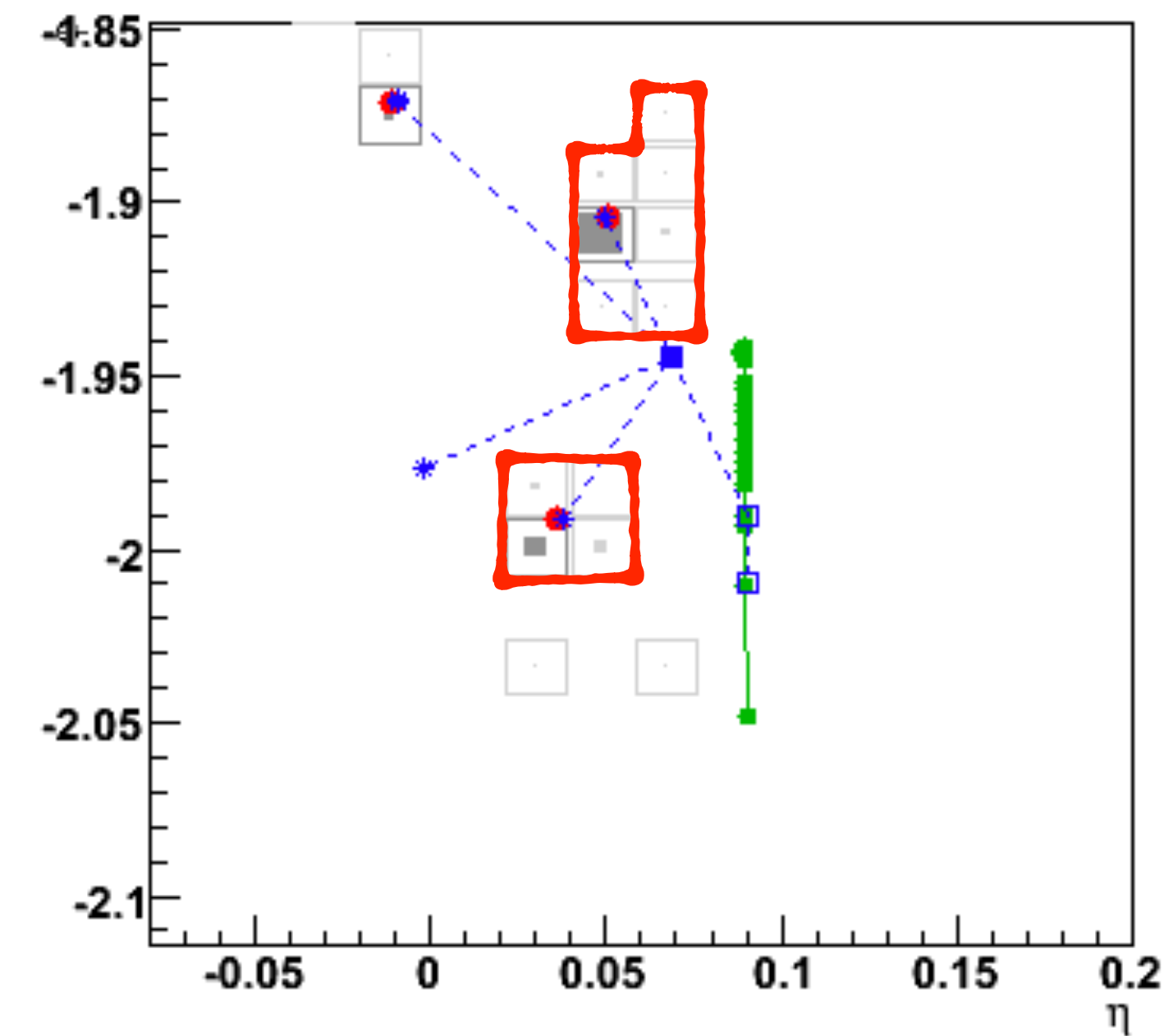
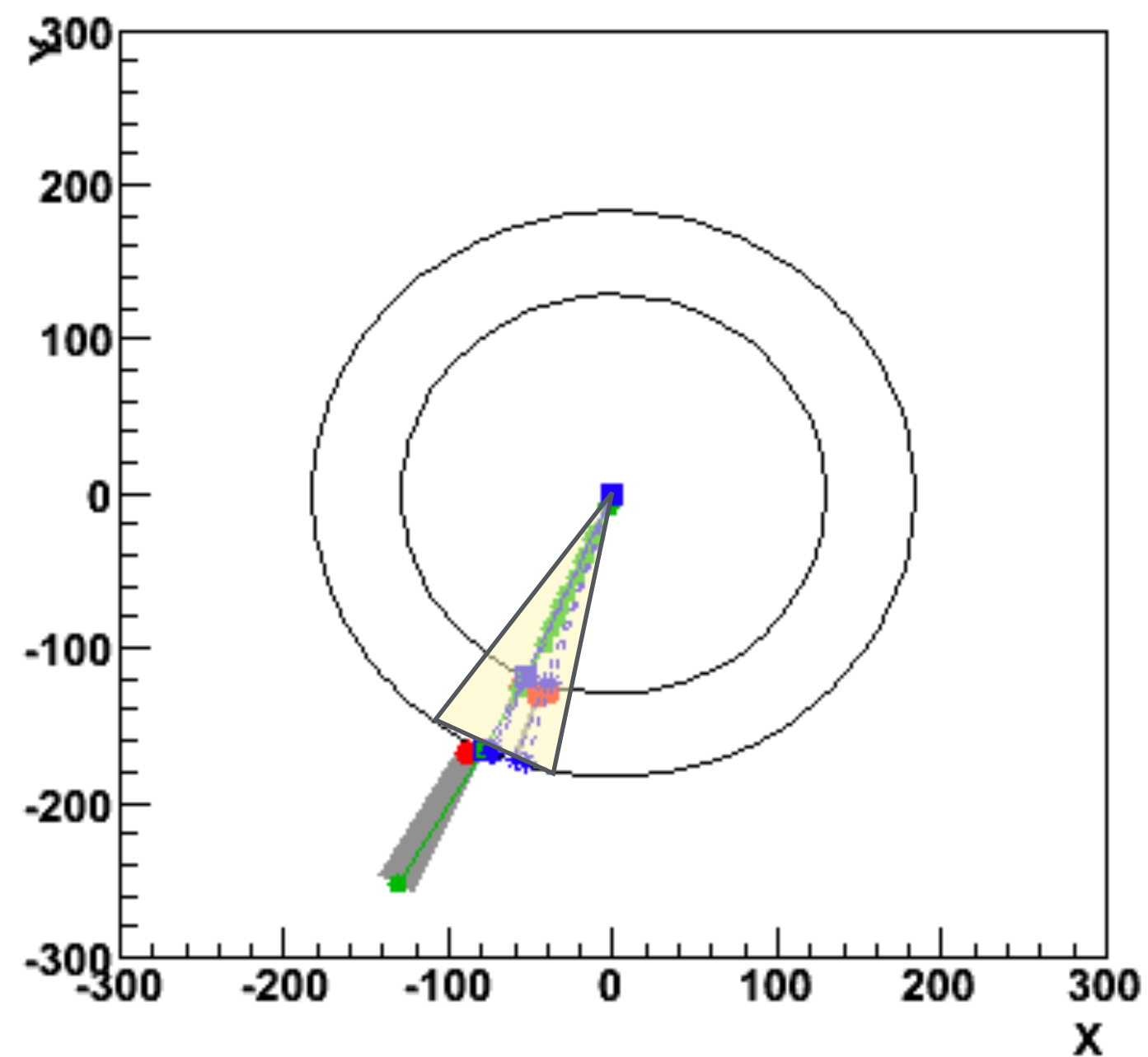
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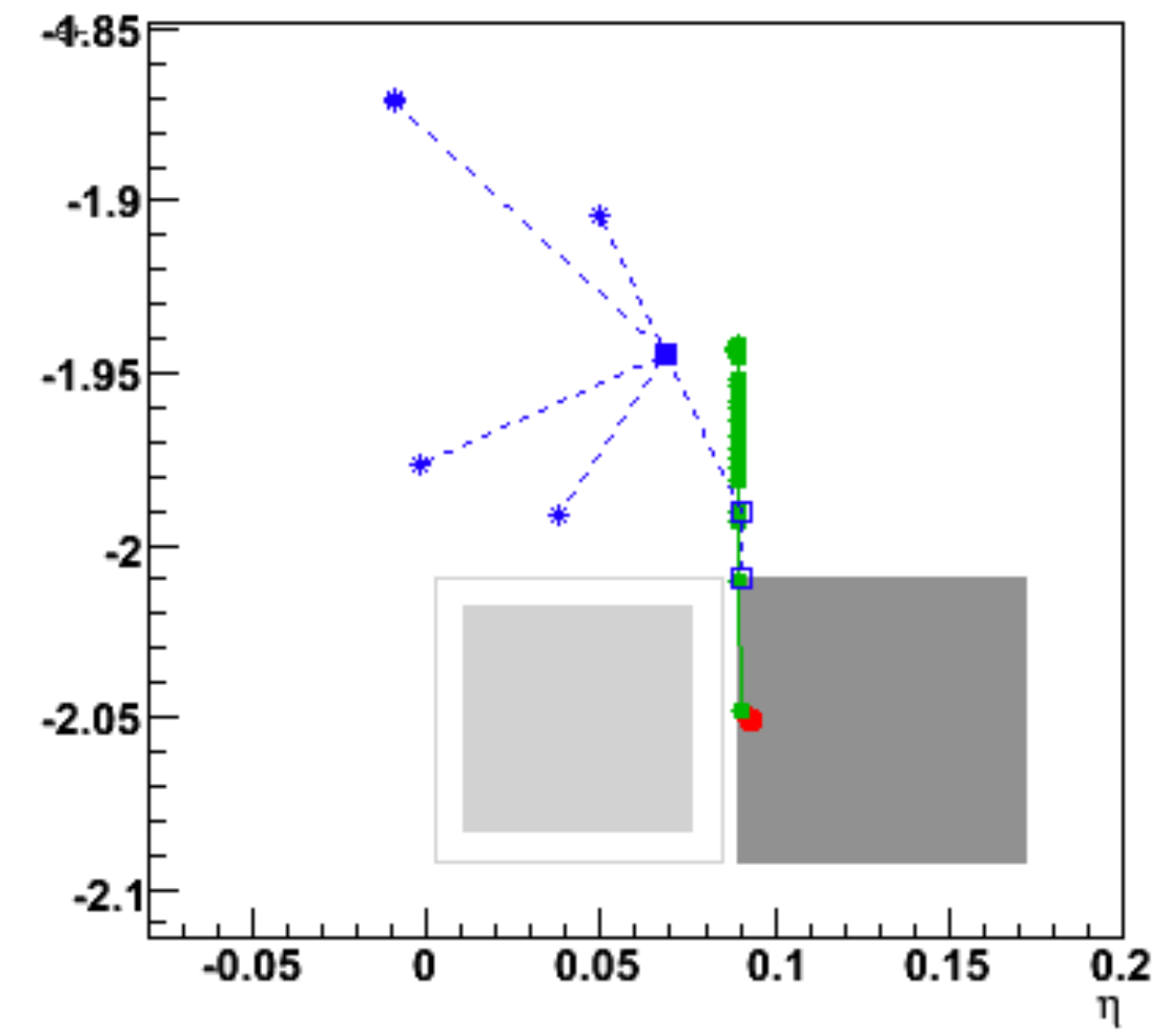
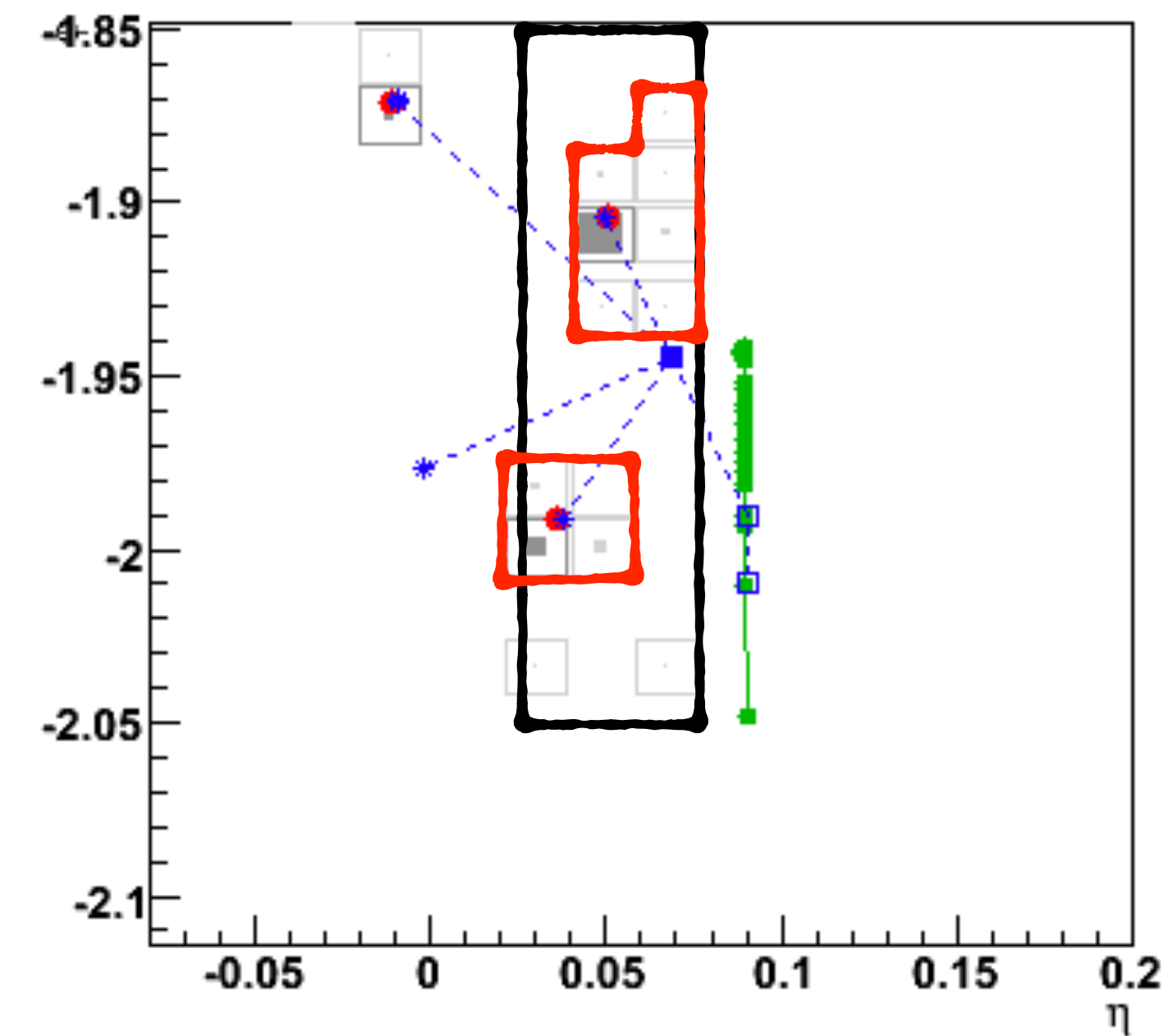
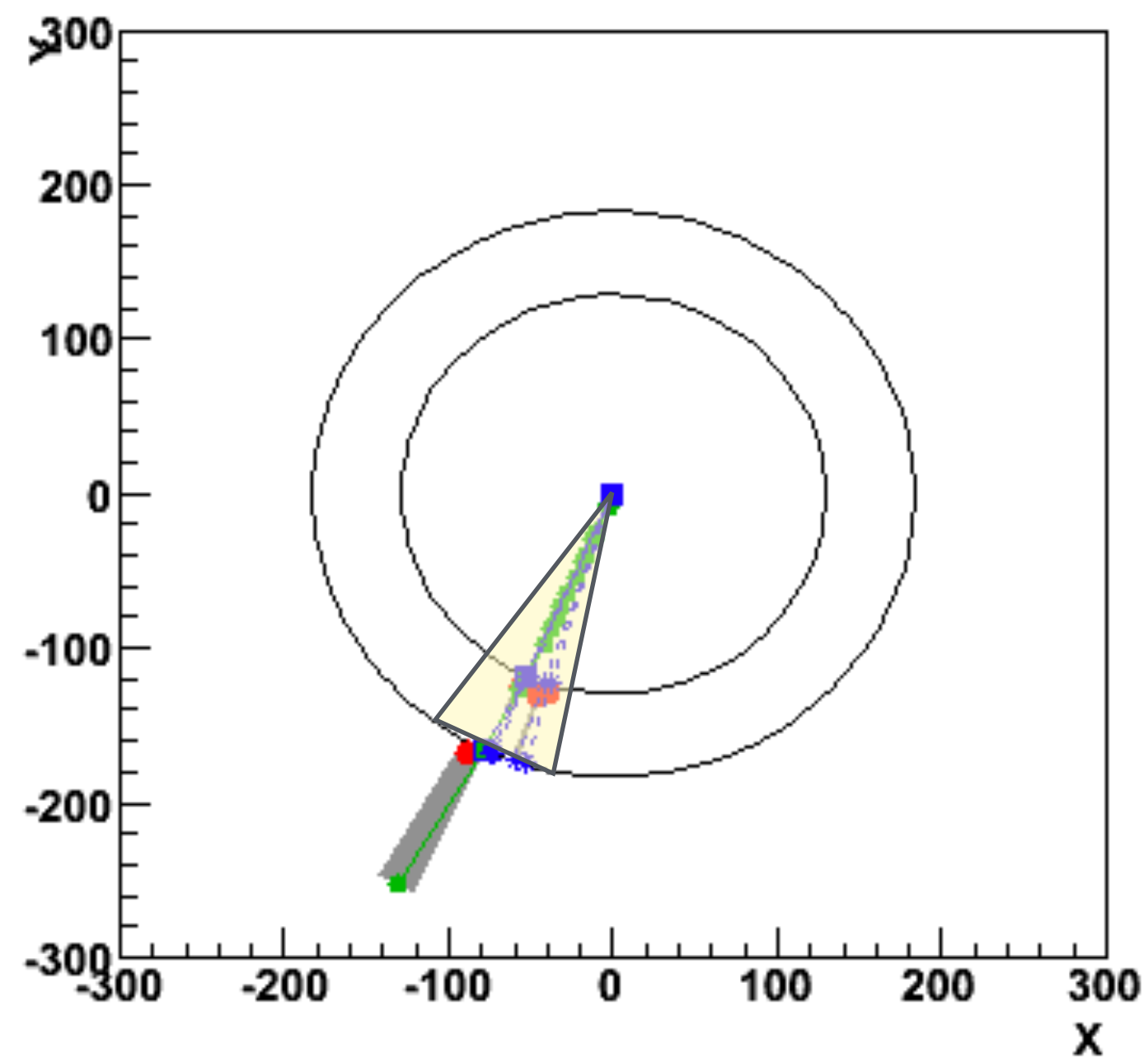
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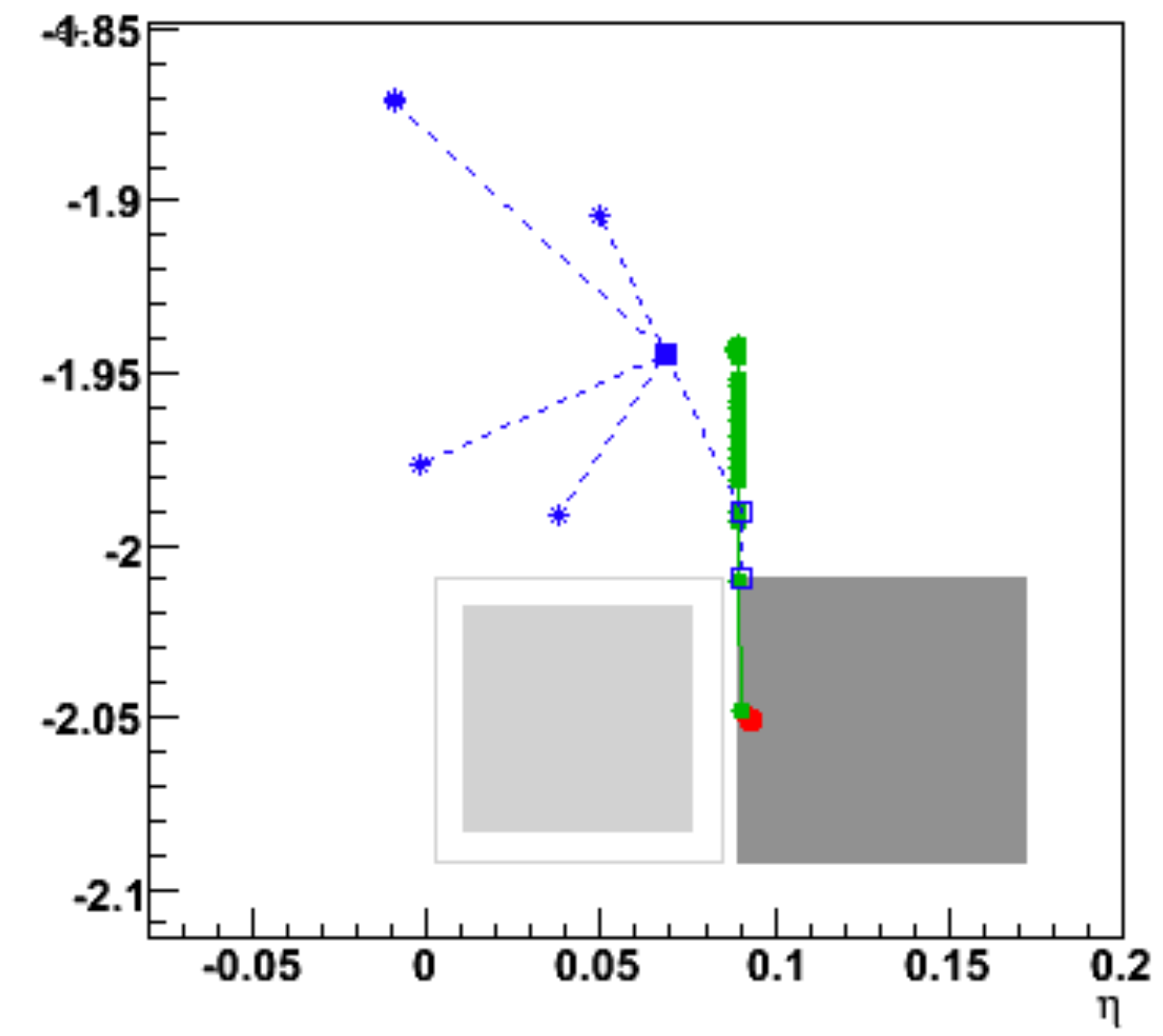
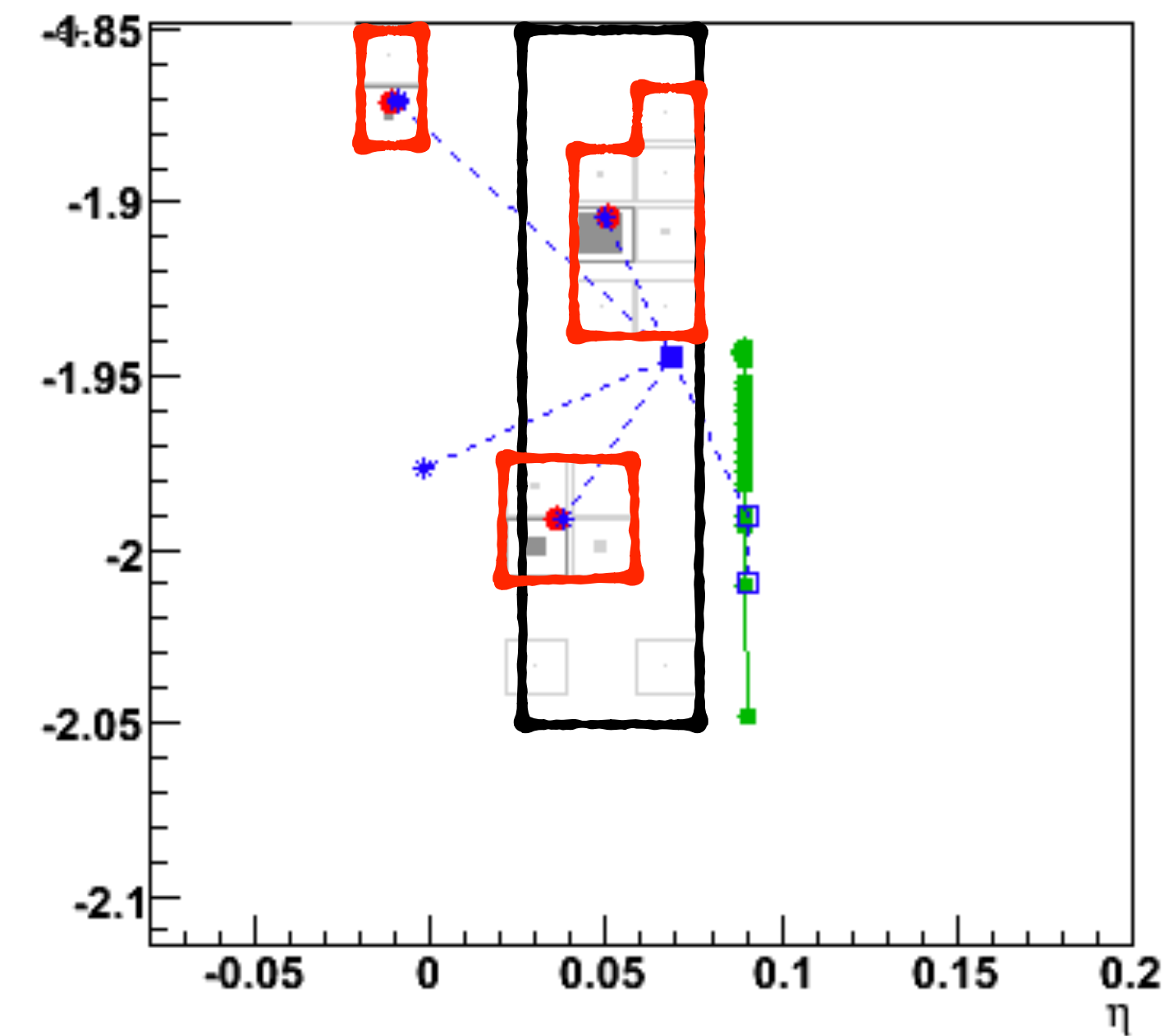
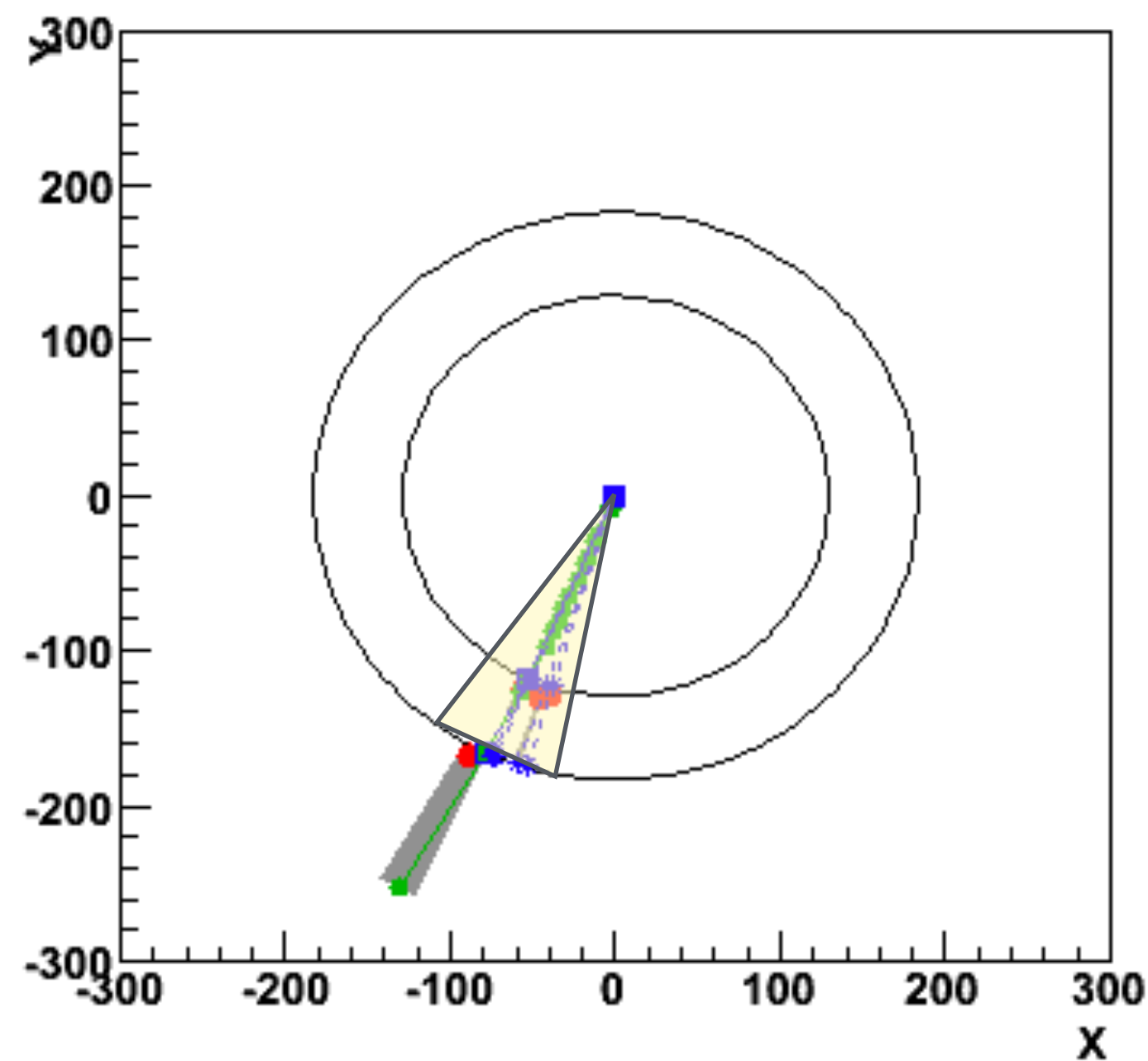
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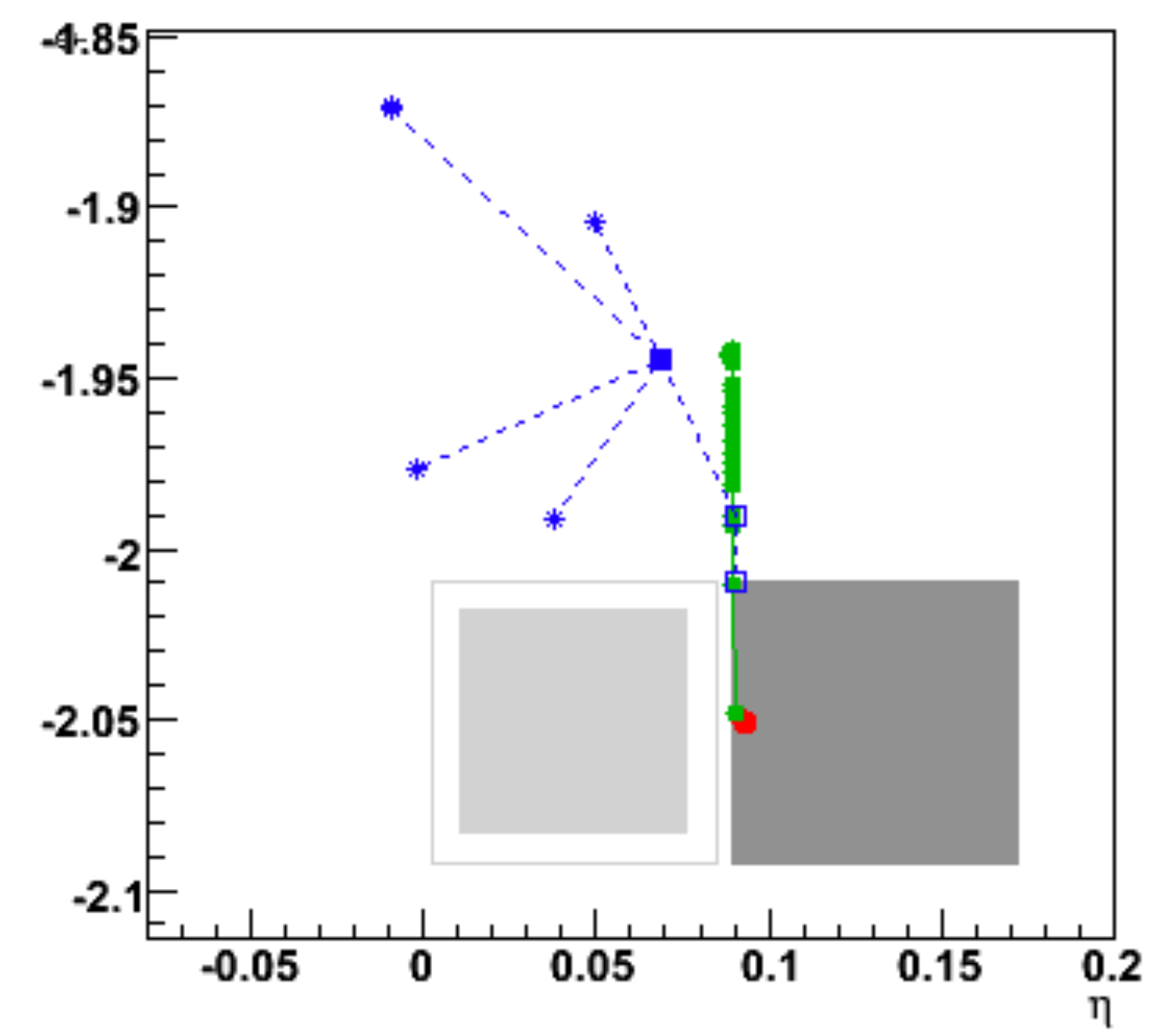
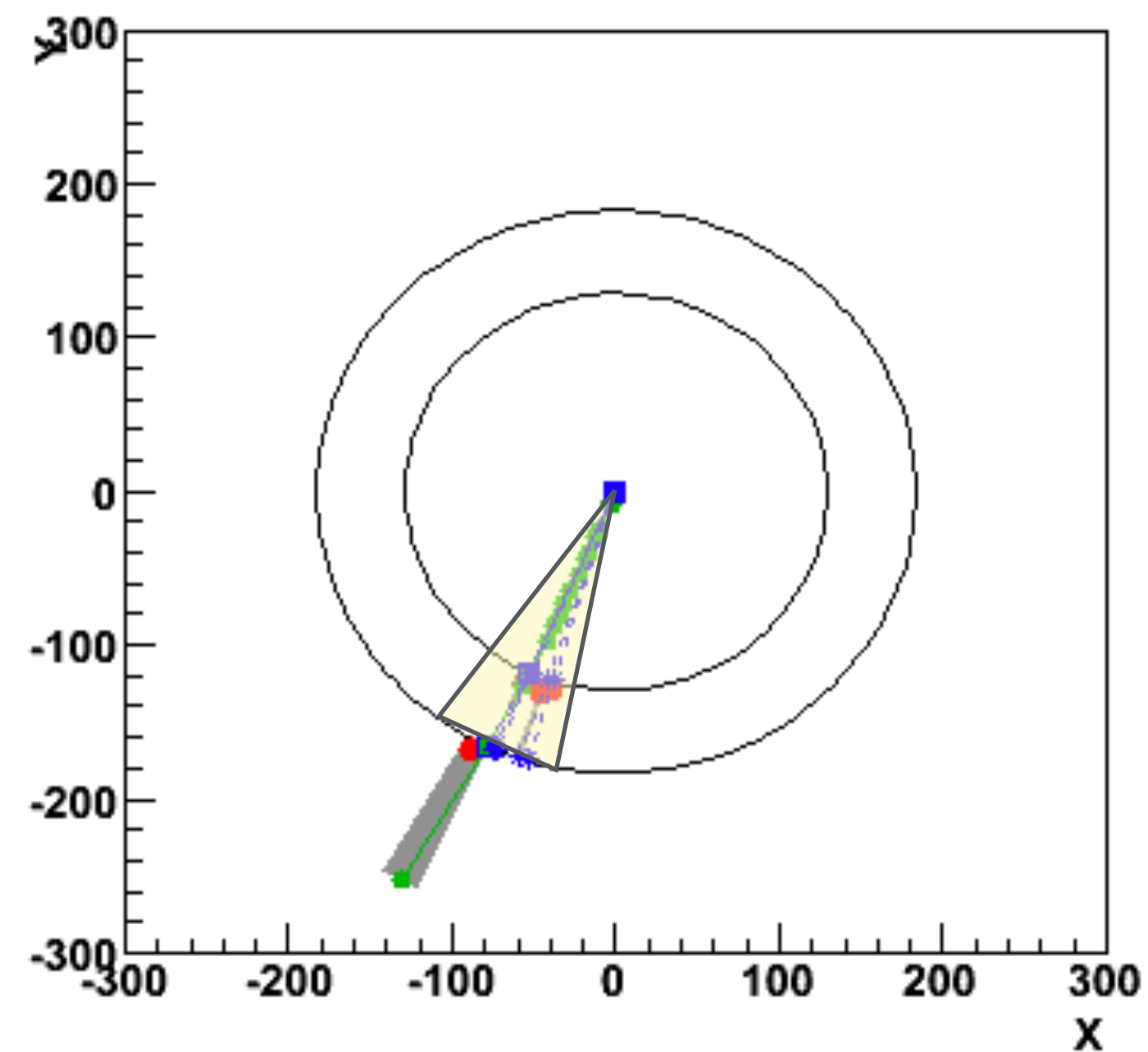
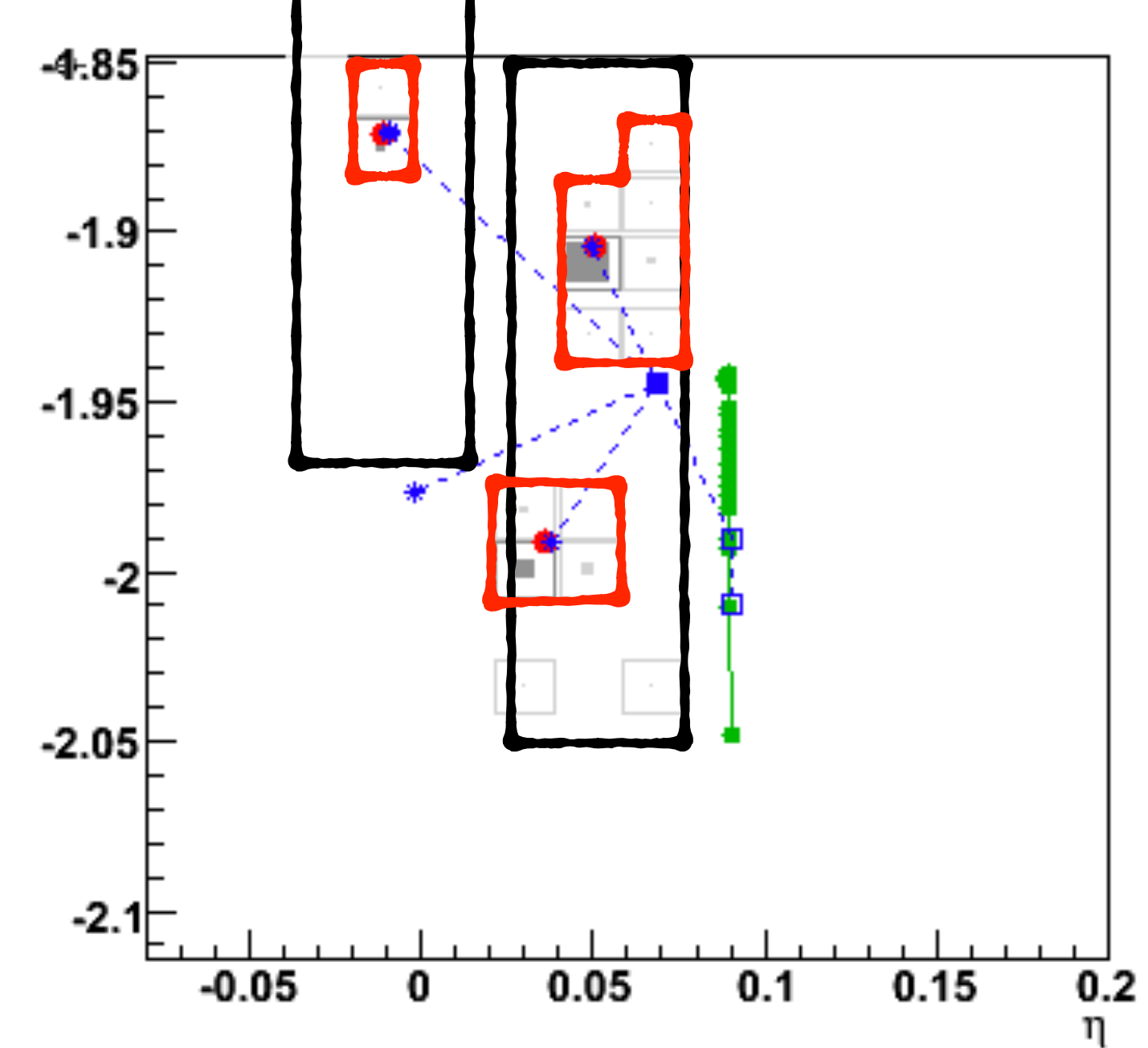
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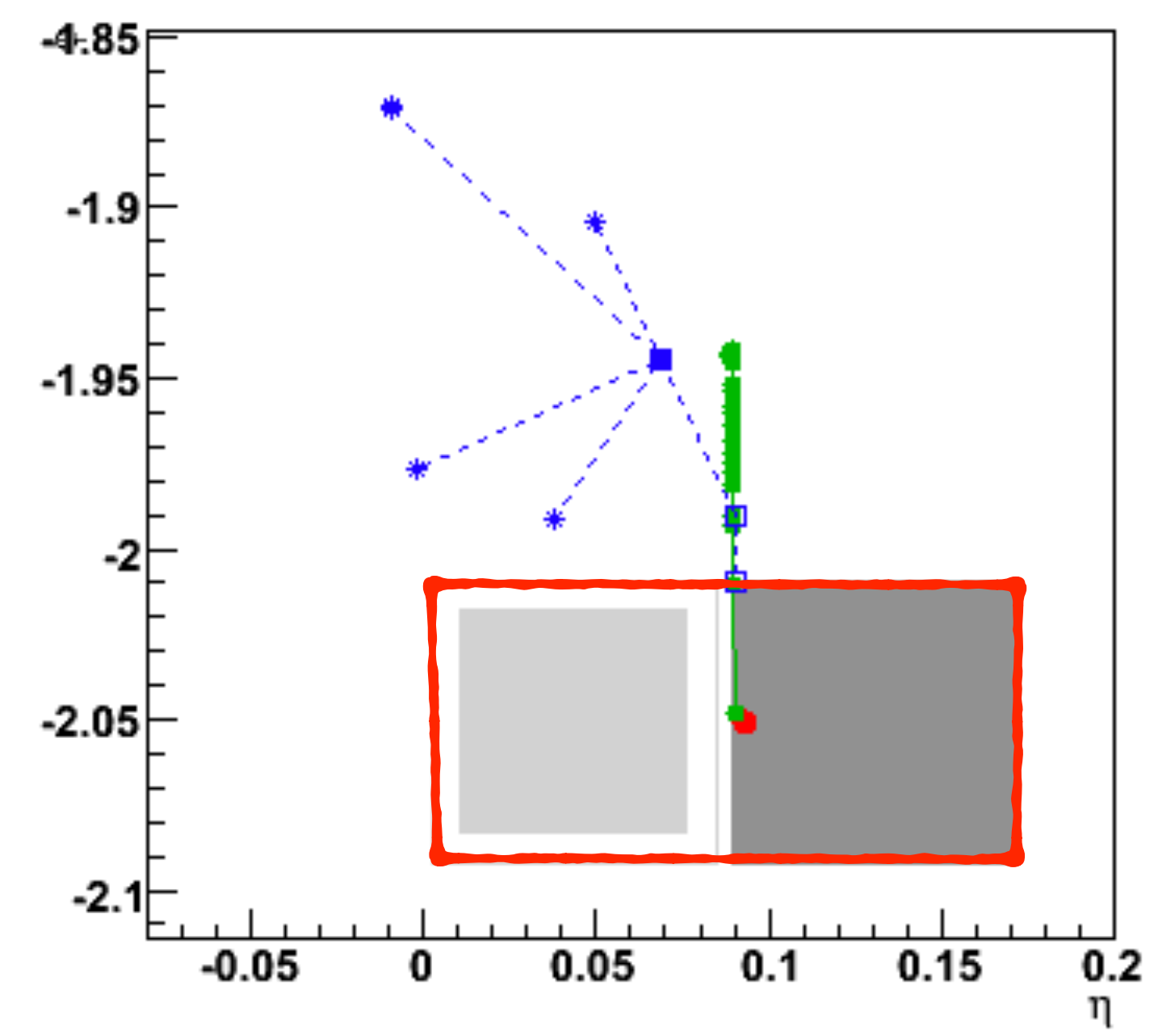
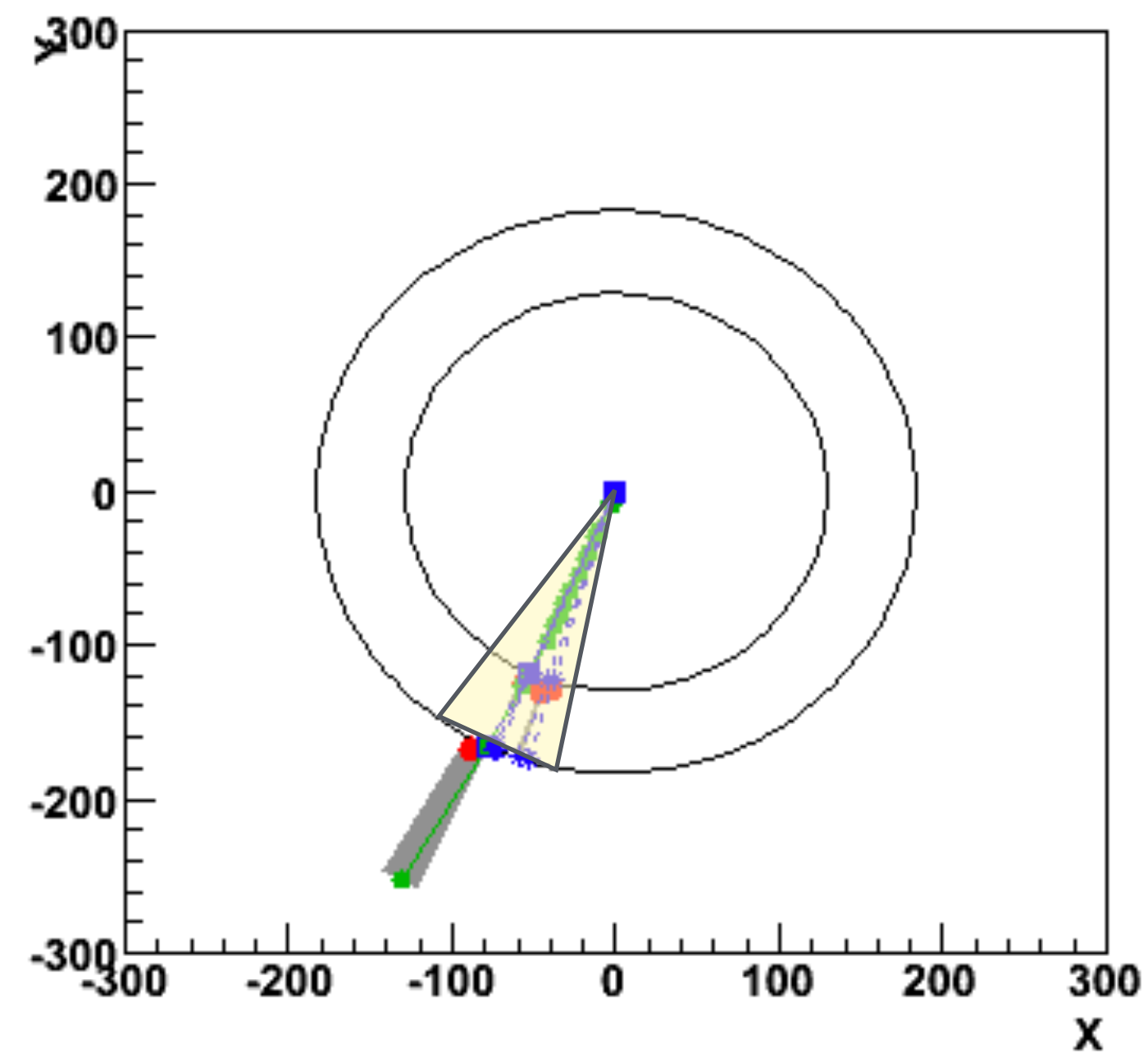
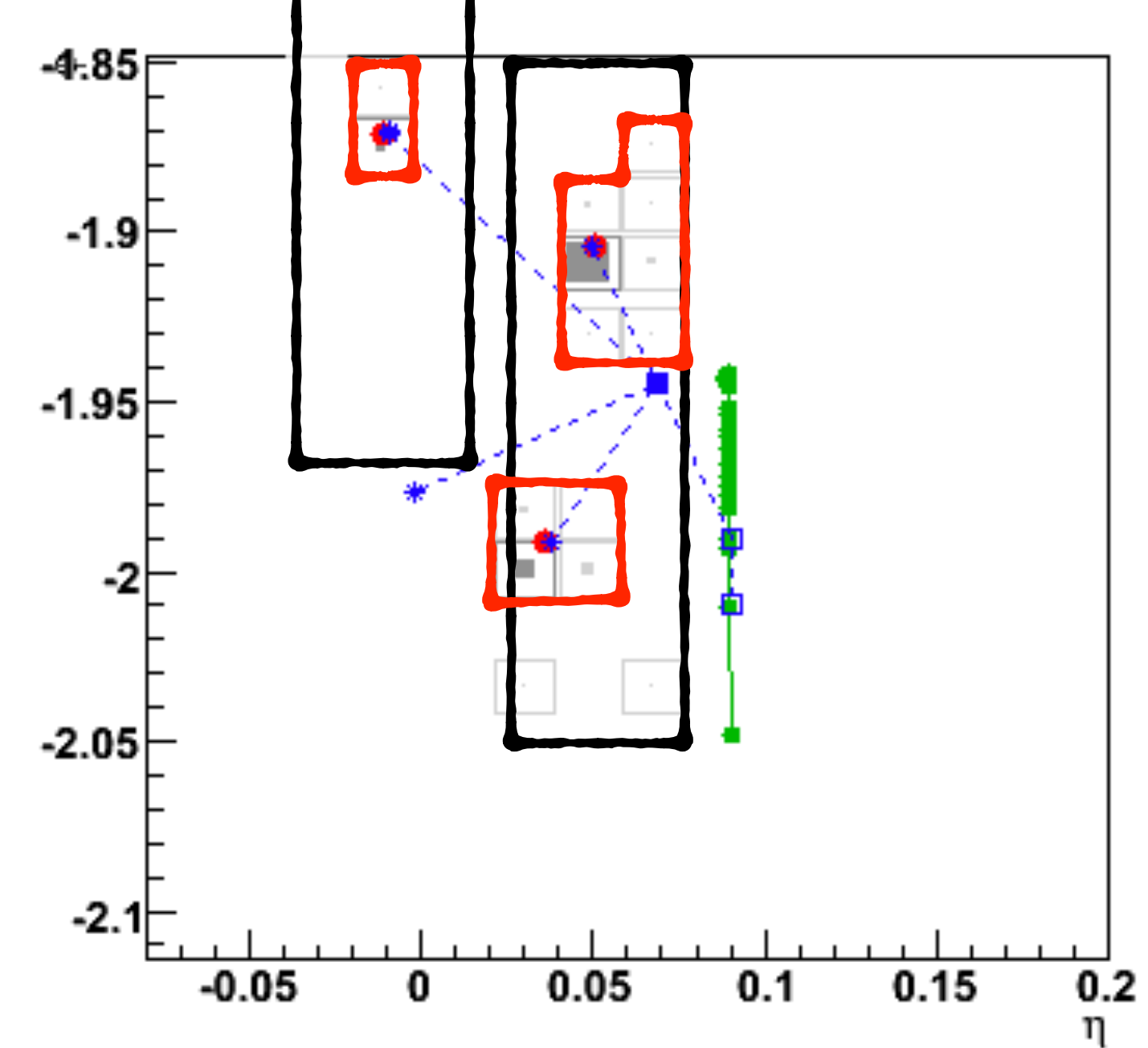
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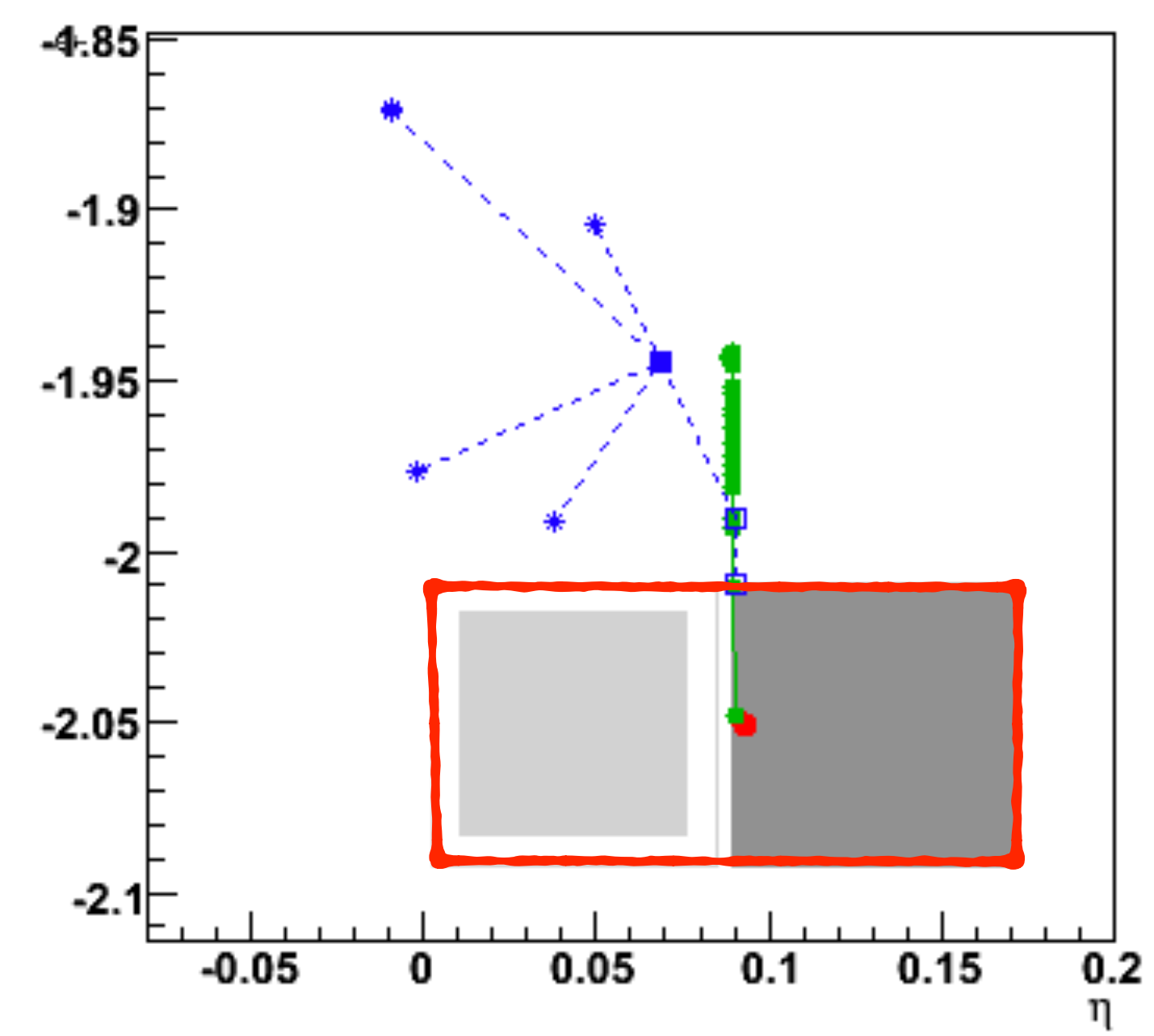
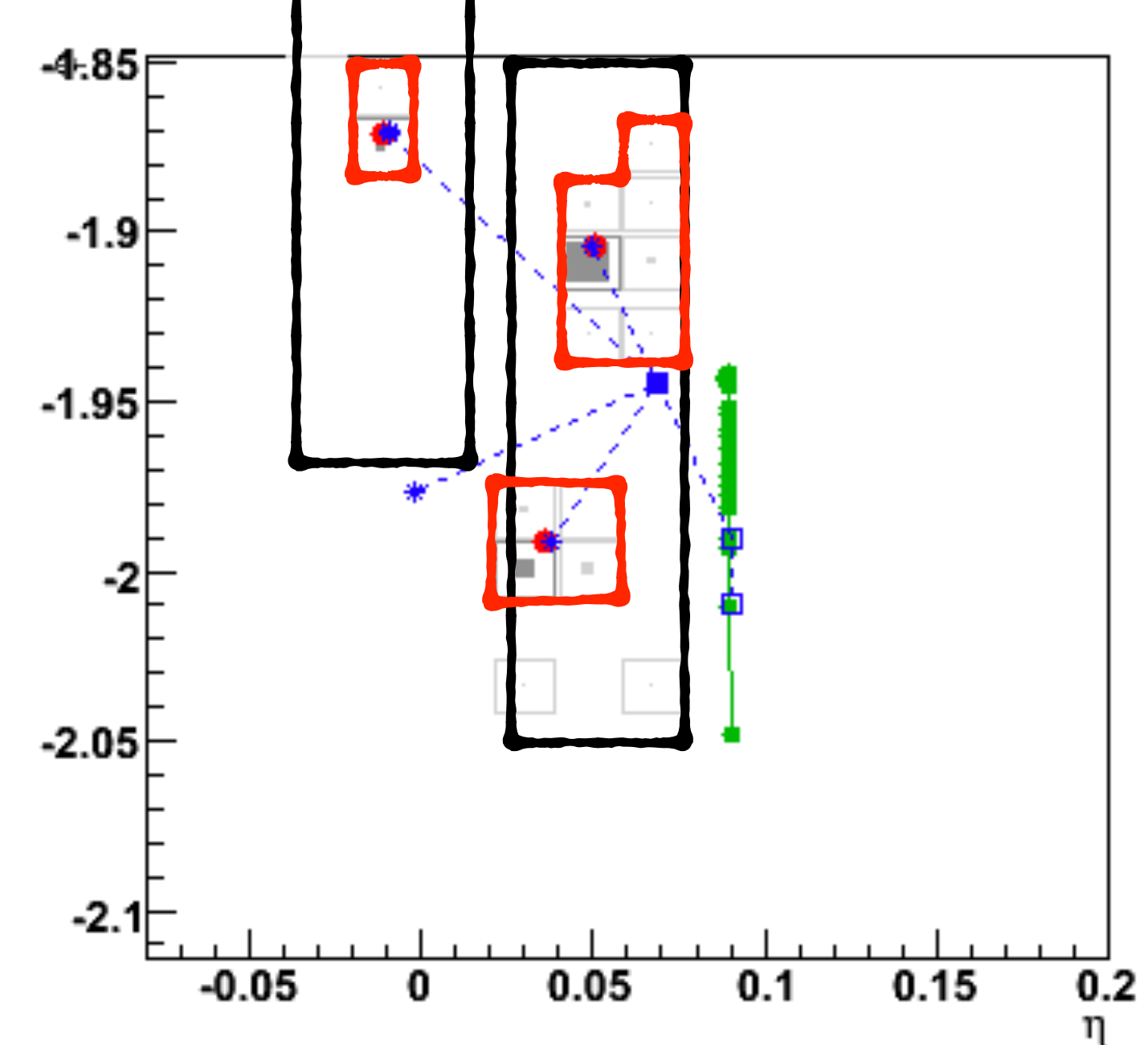
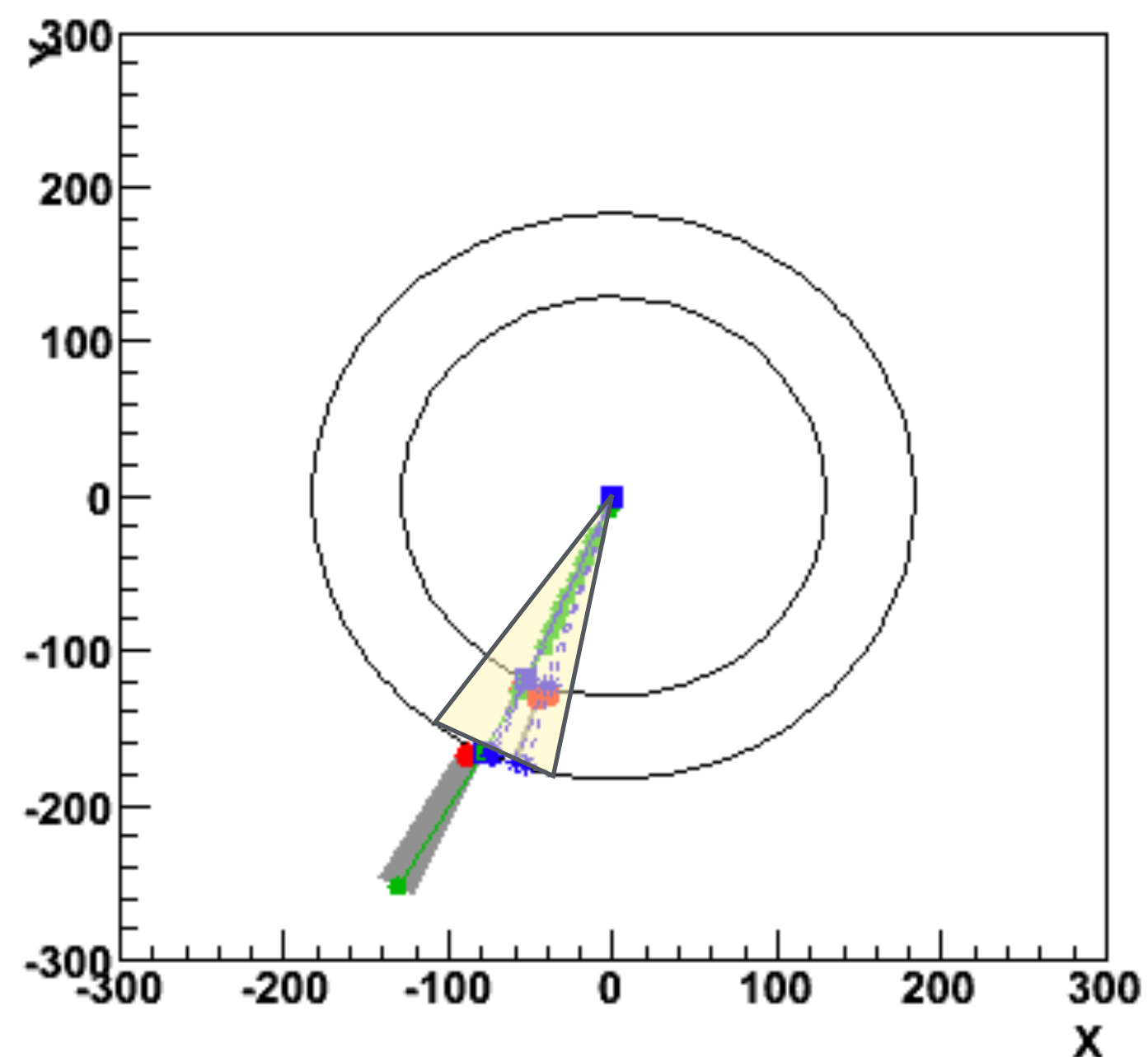
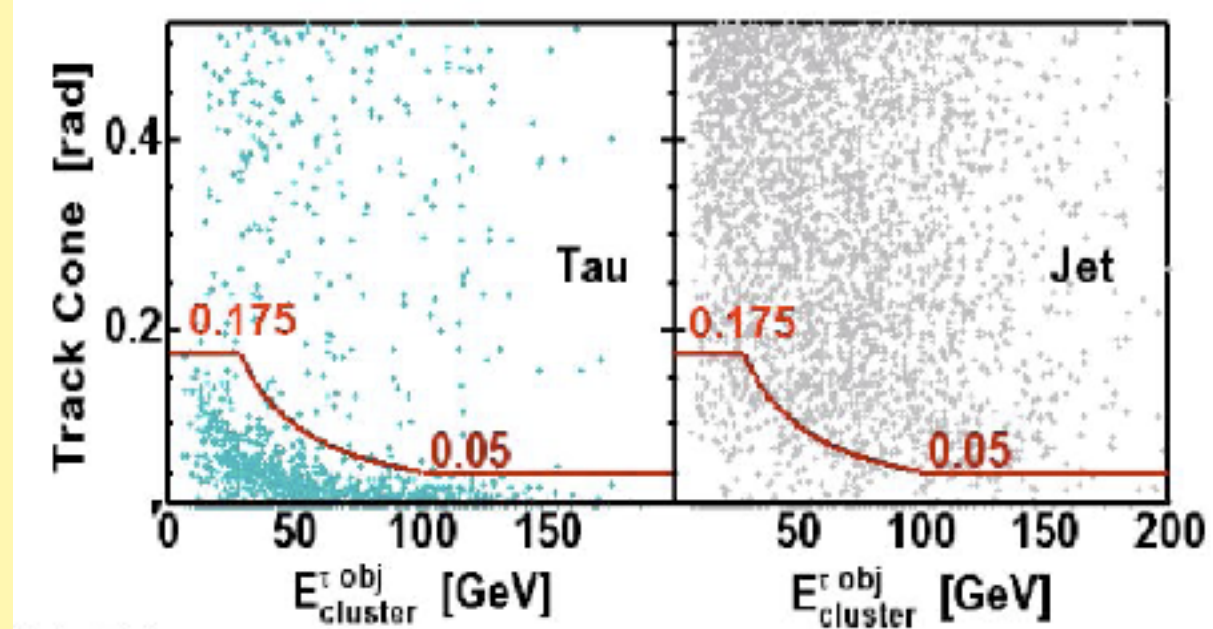
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Signal Cone

- Tau constituents must lie within a shrinking $\Delta R \leq 3 \text{ GeV} / p_T(\tau)$



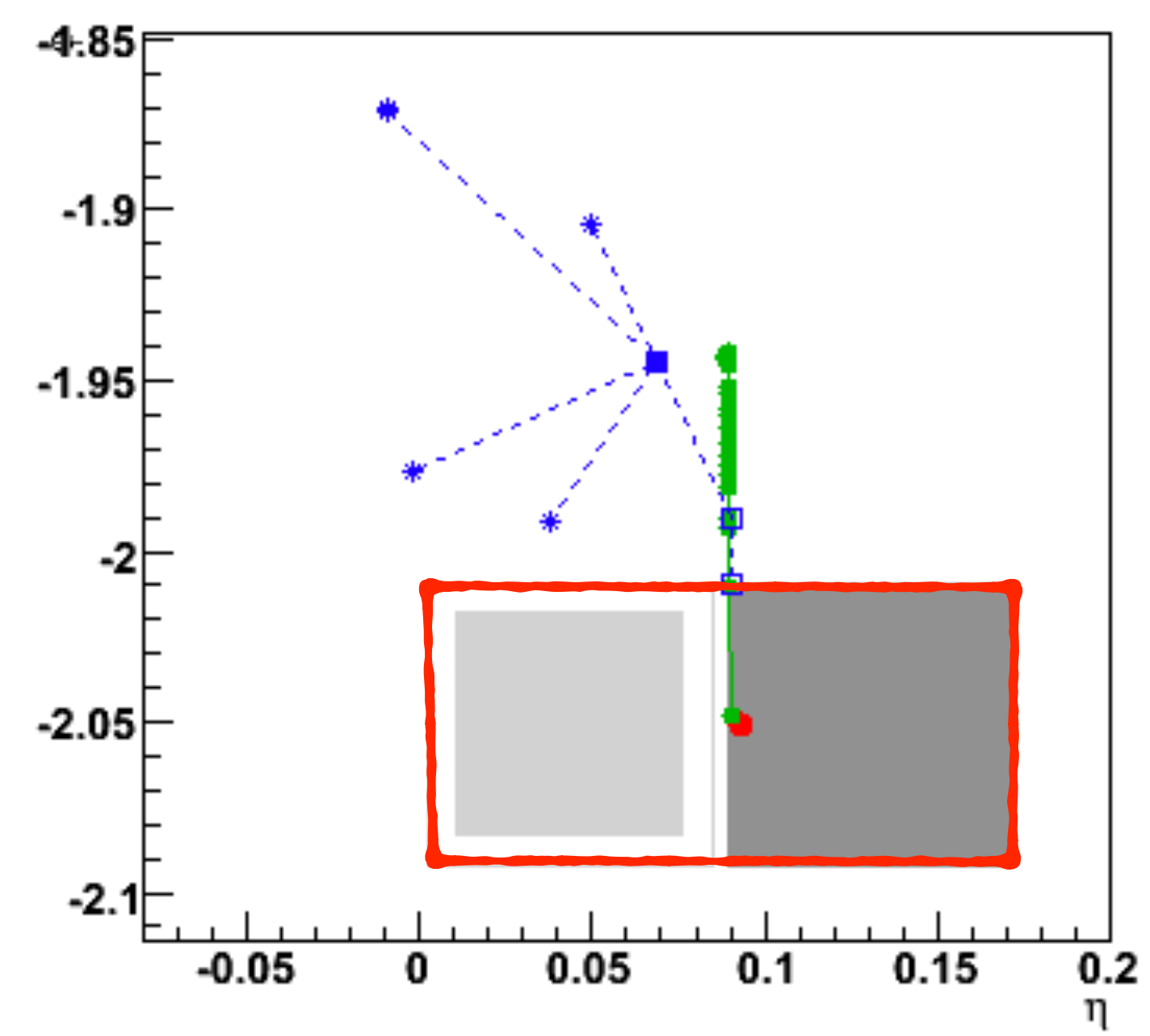
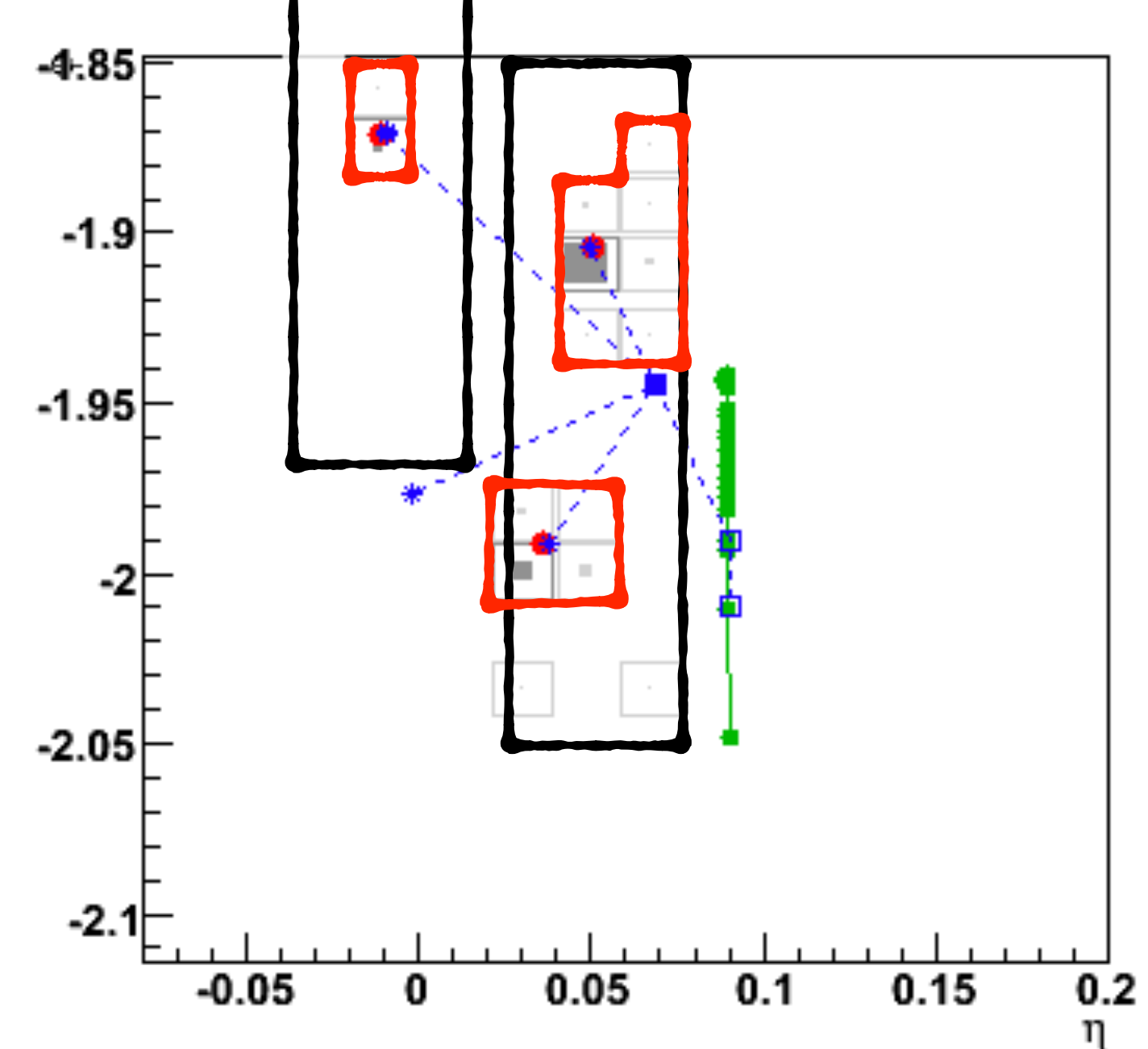
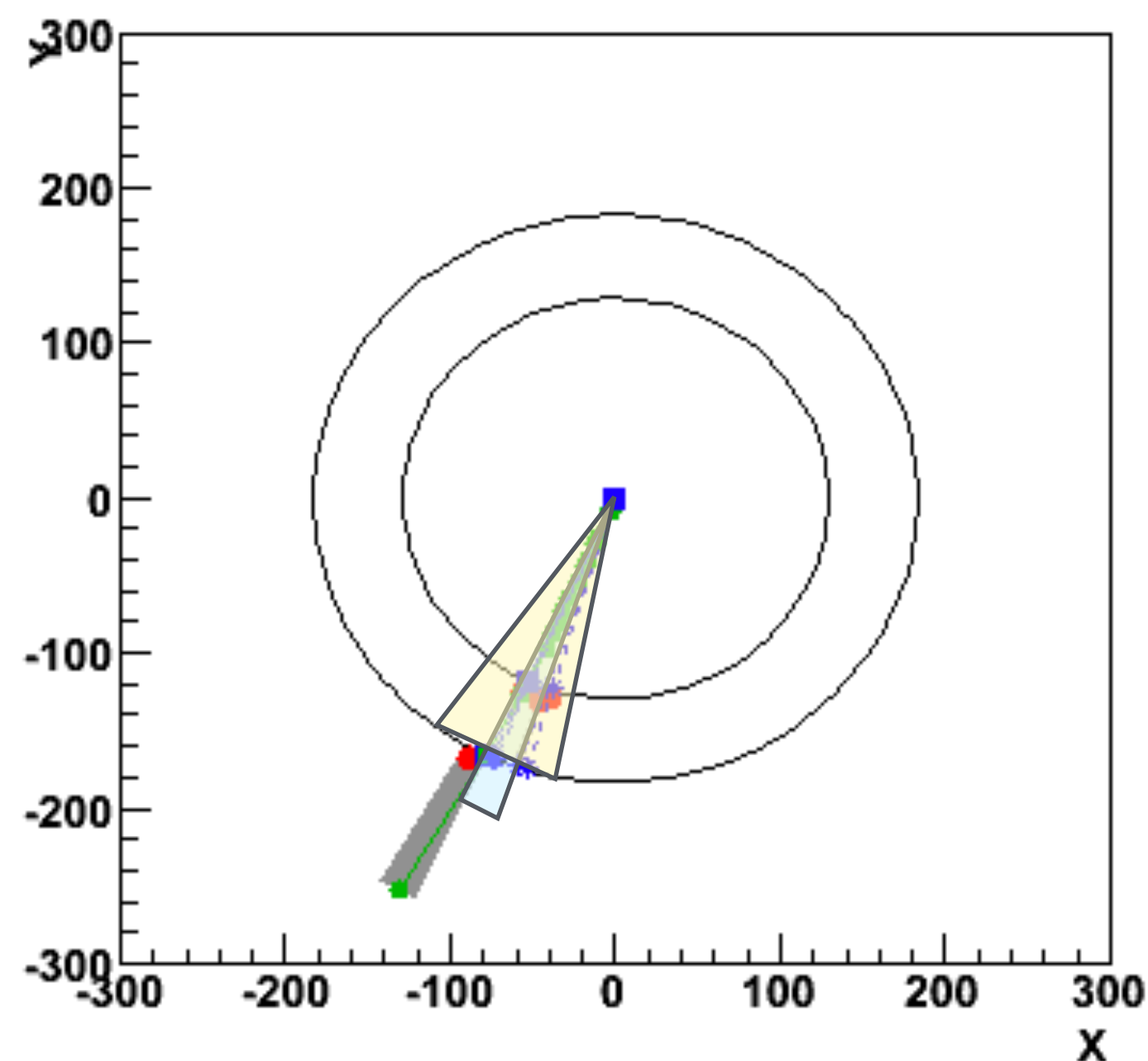
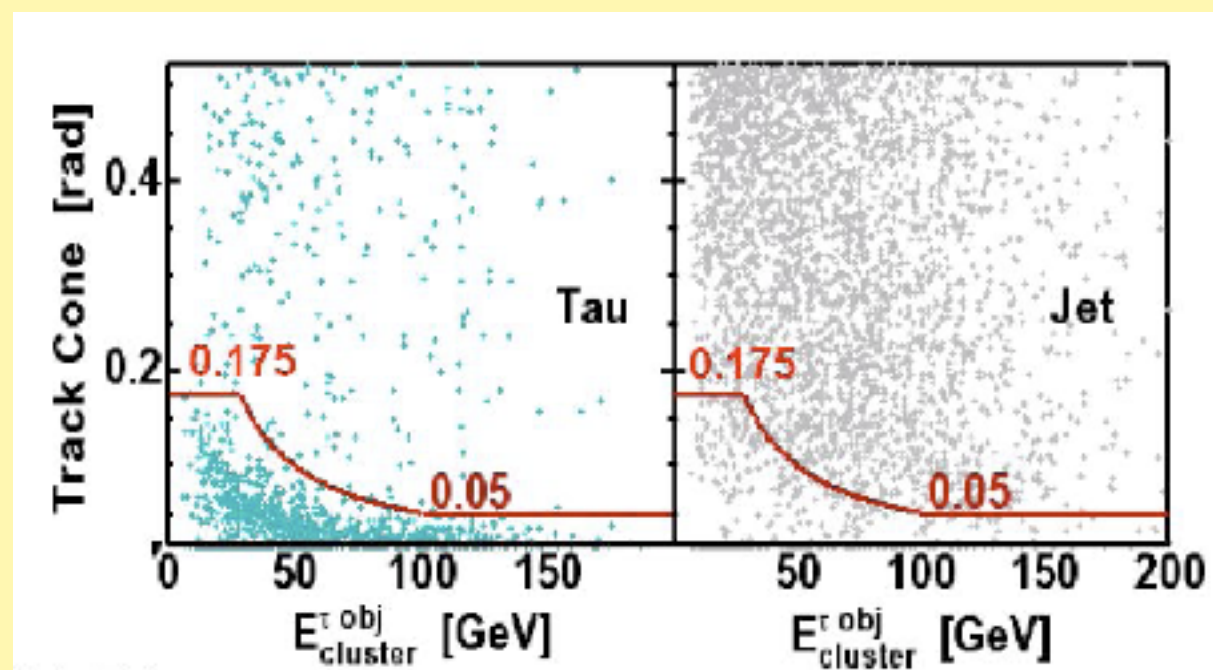
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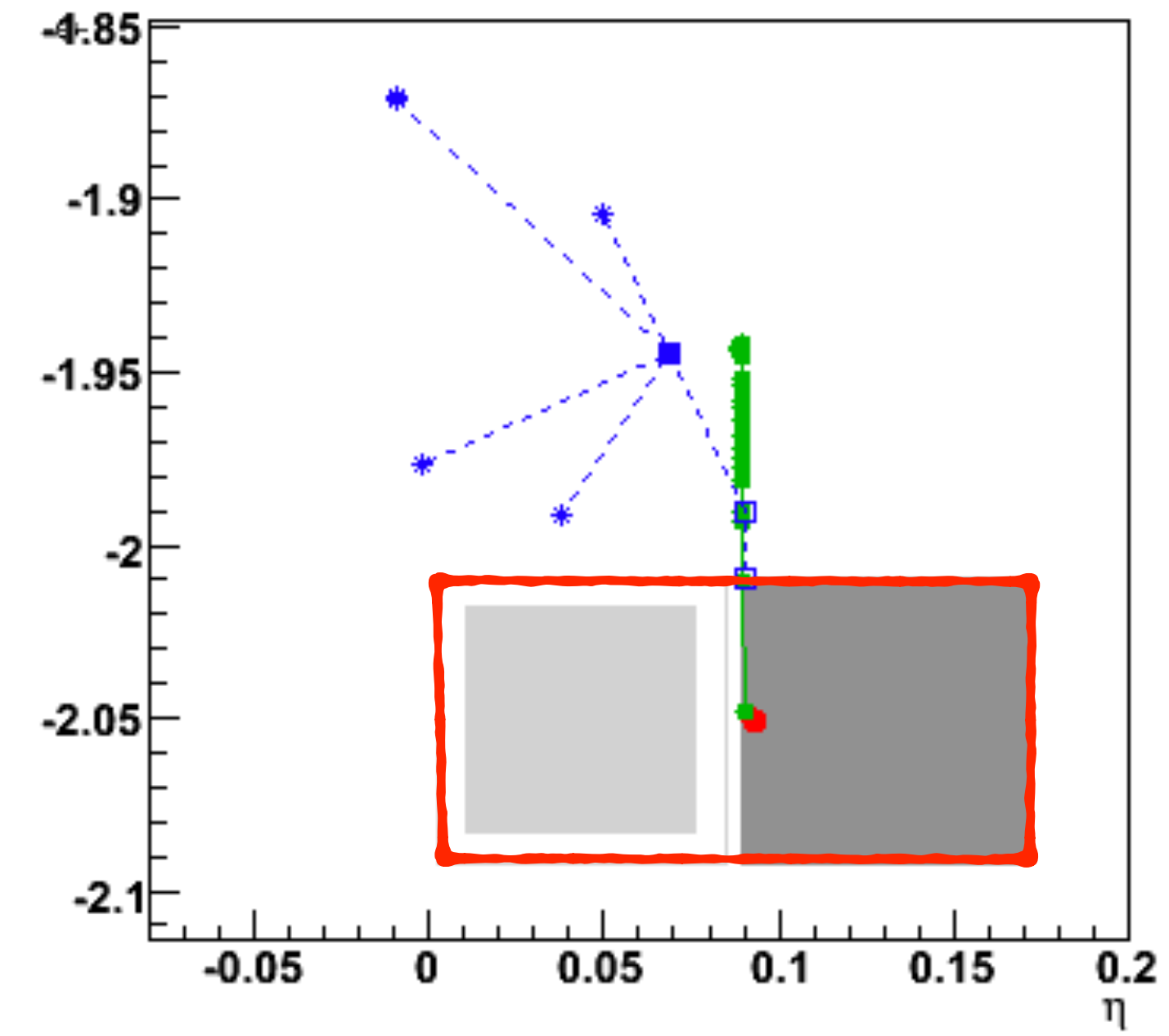
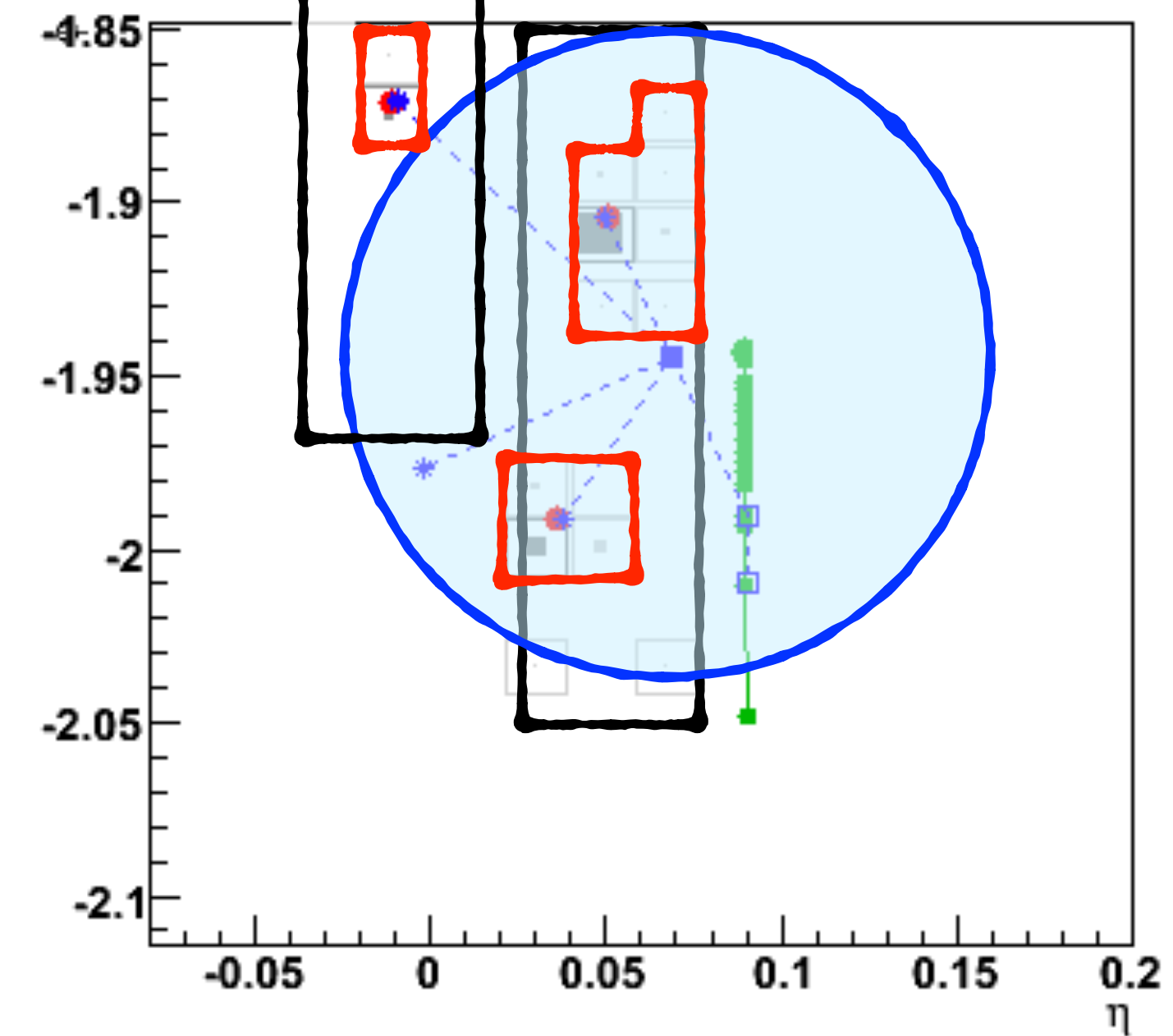
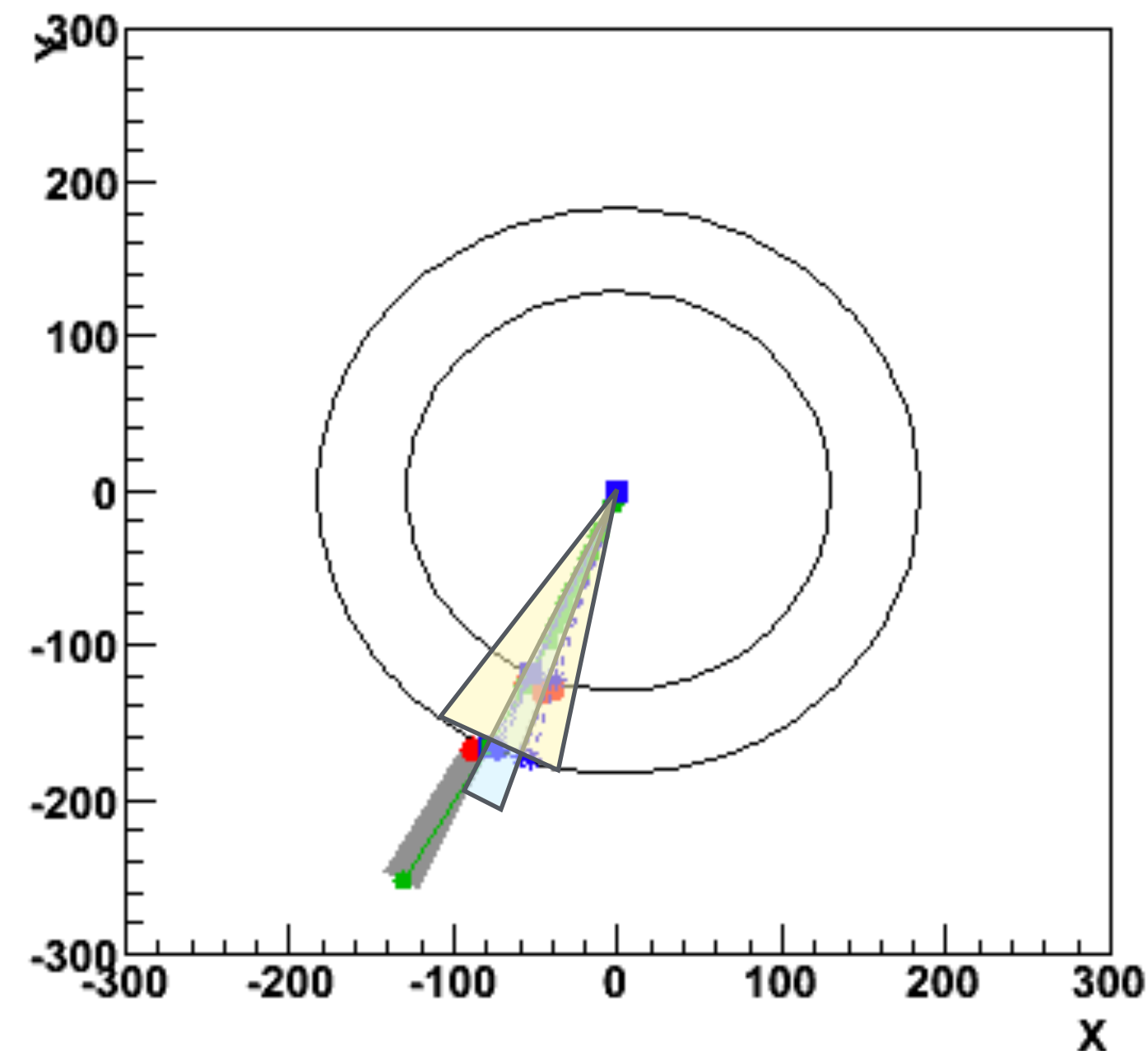
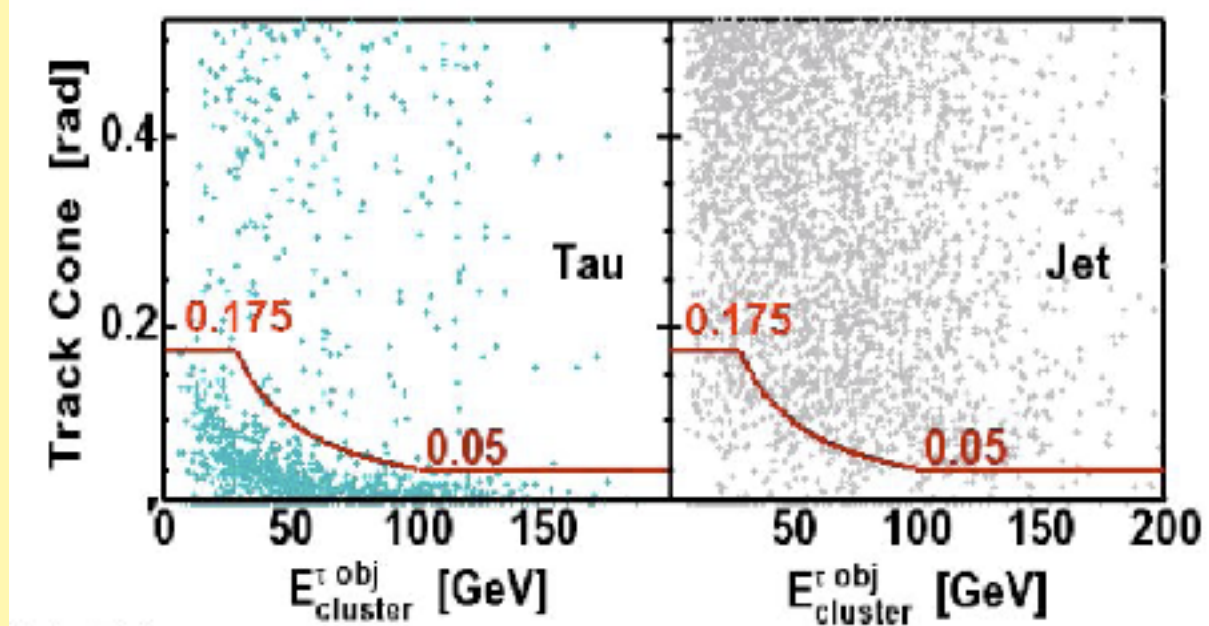
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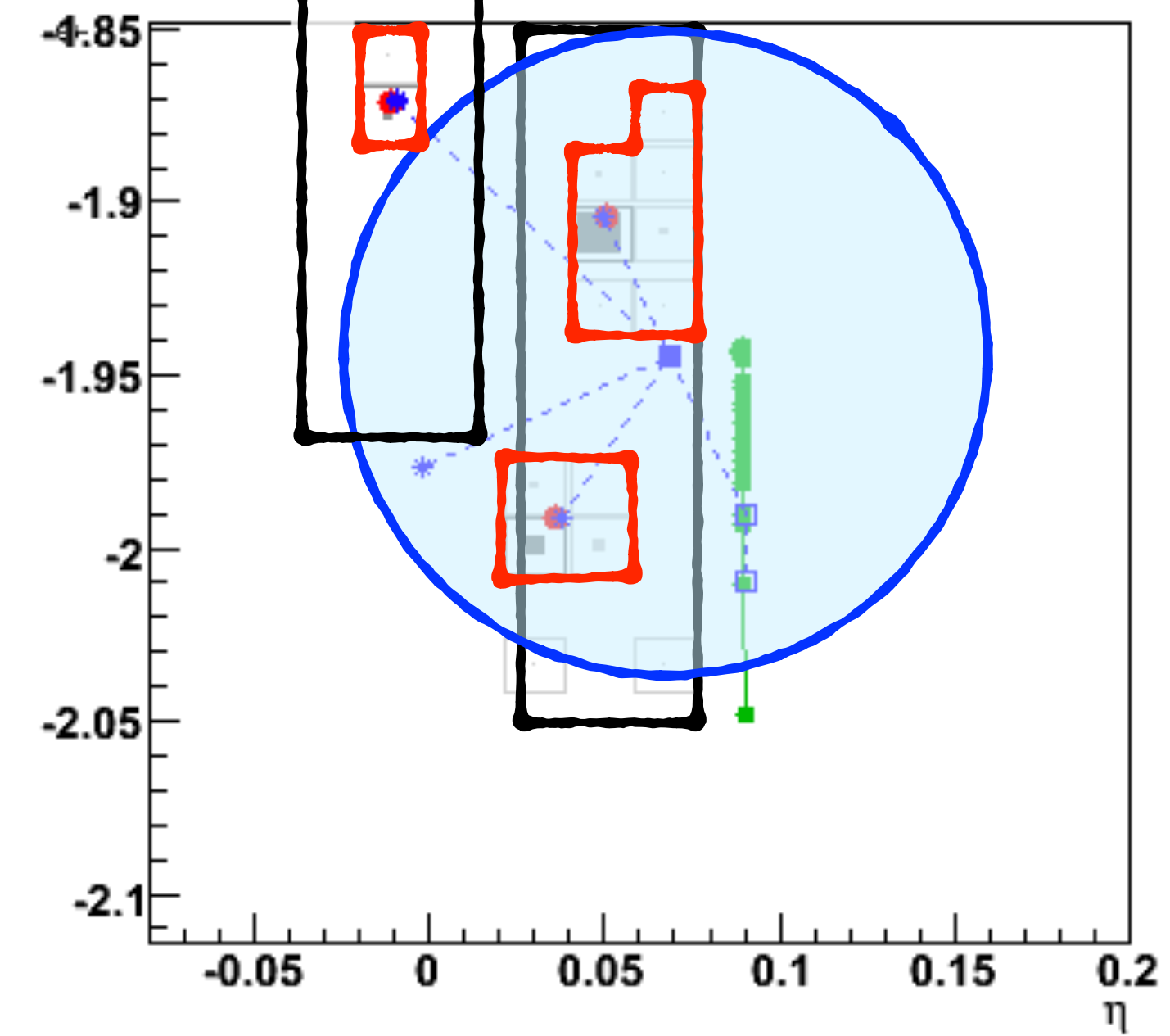
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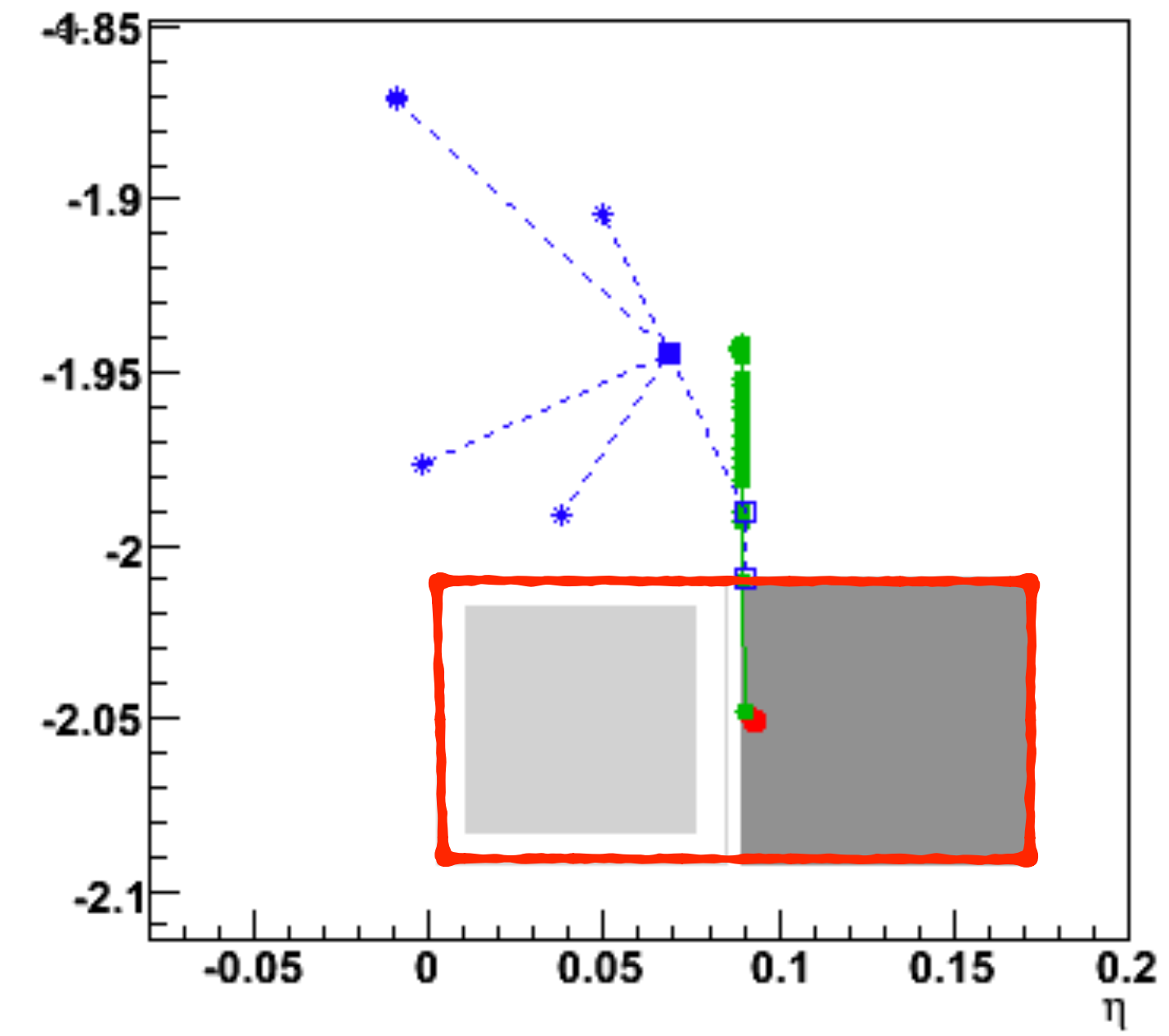
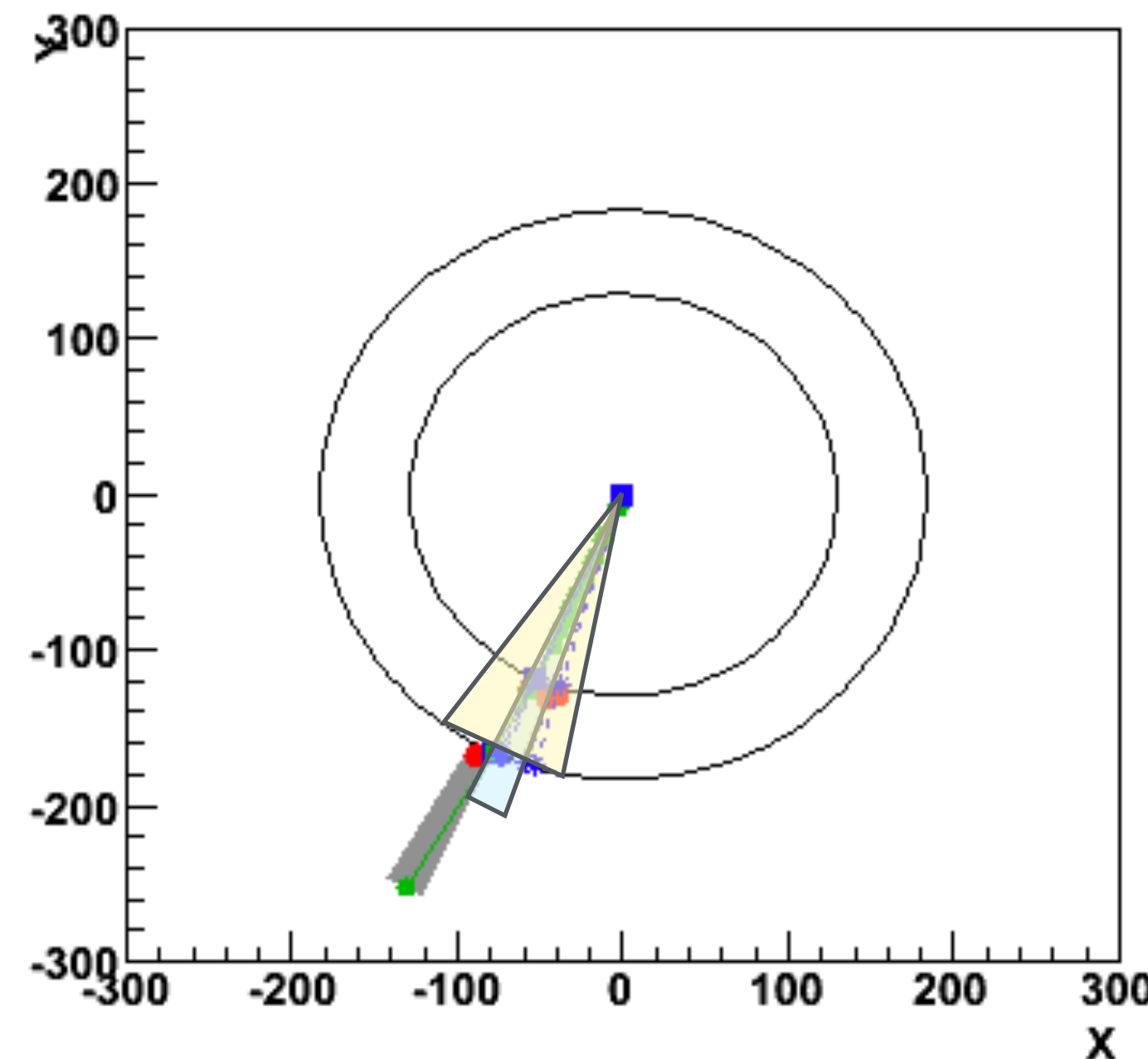
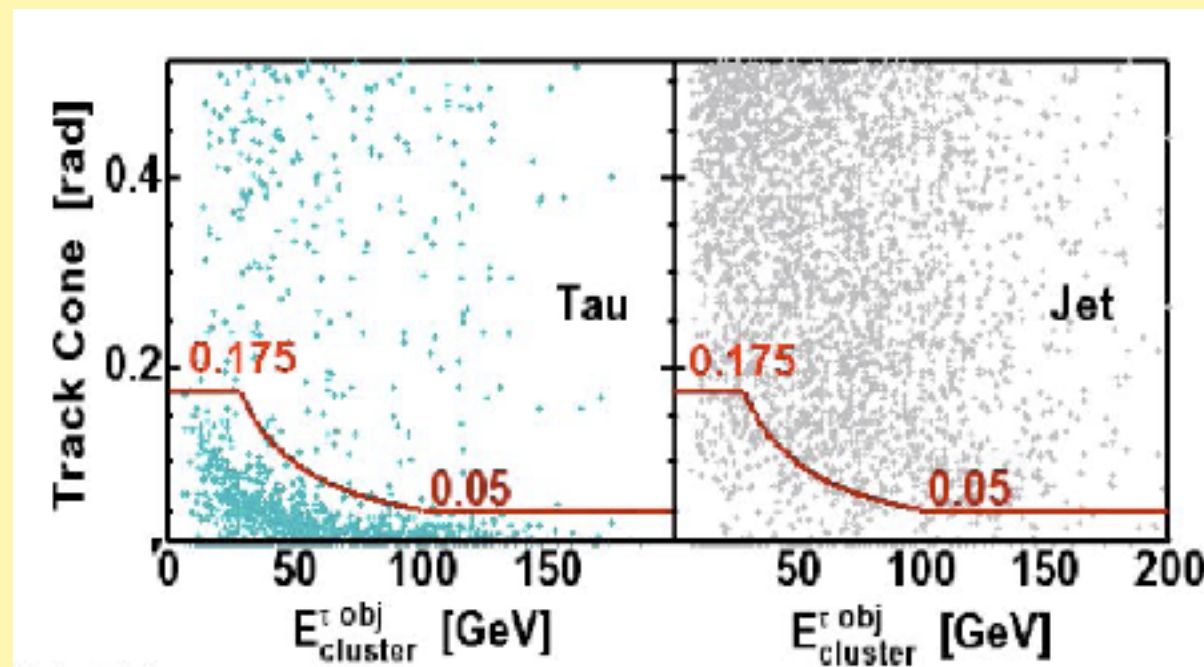
$1 \pi^\pm, 0 \pi^0$

- Branching Fraction: 11.6%
- Single isolated π^\pm



Signal Cone

- Tau constituents must lie within a shrinking $\Delta R \leq 3 \text{ GeV} / p_T(\tau)$



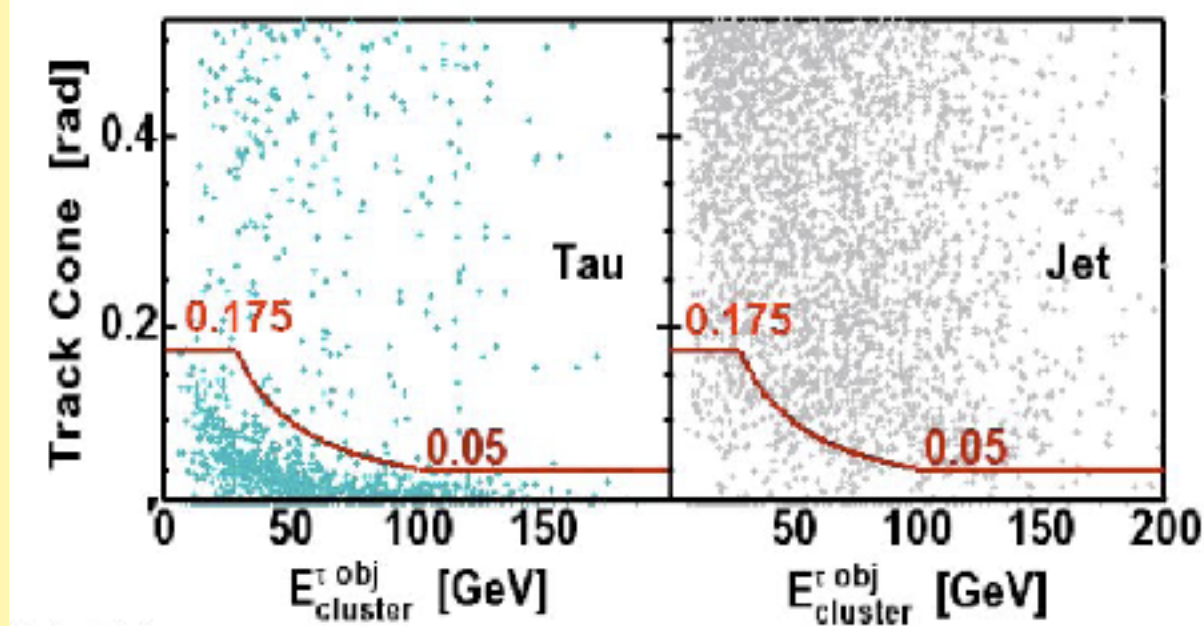
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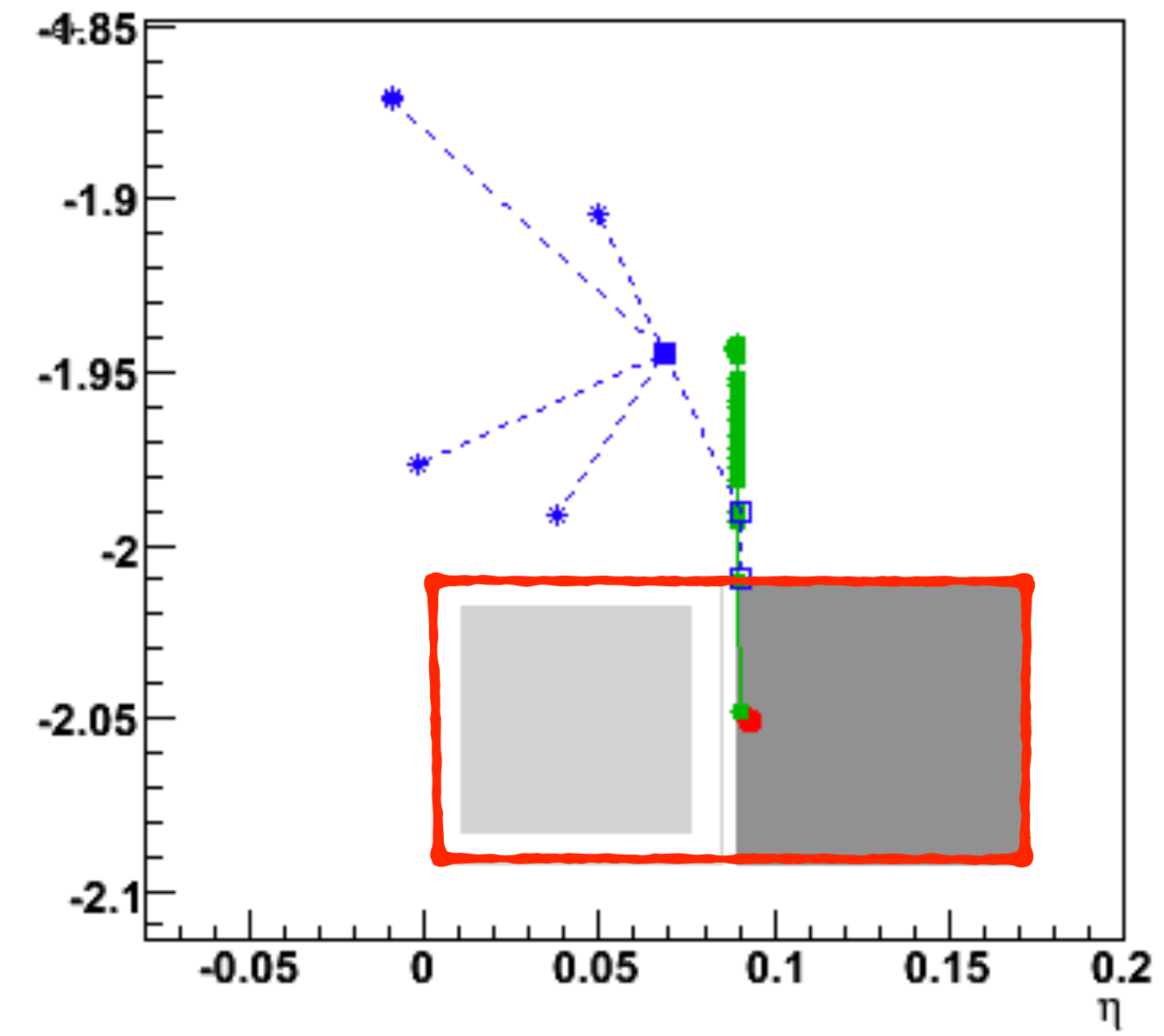
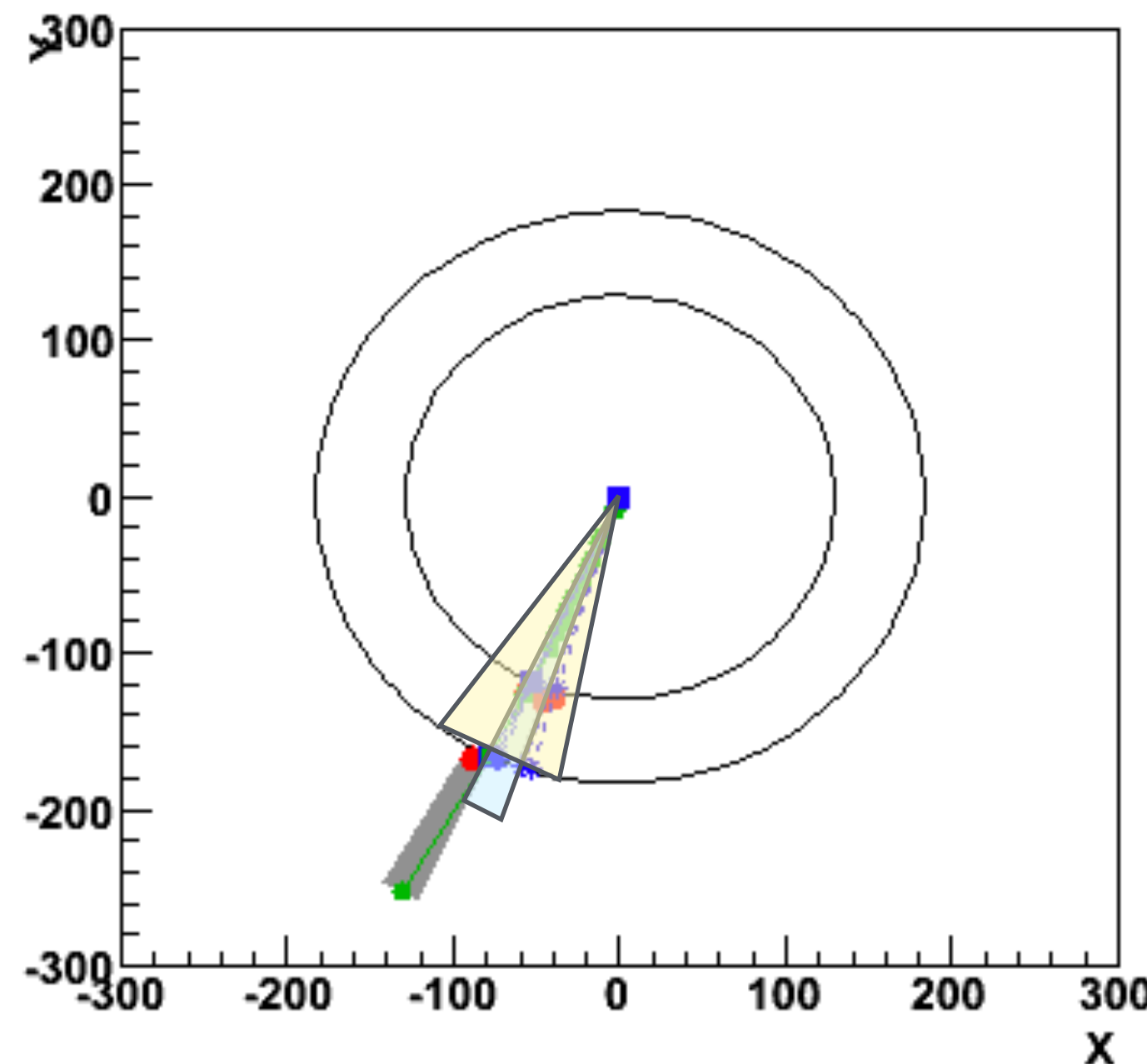
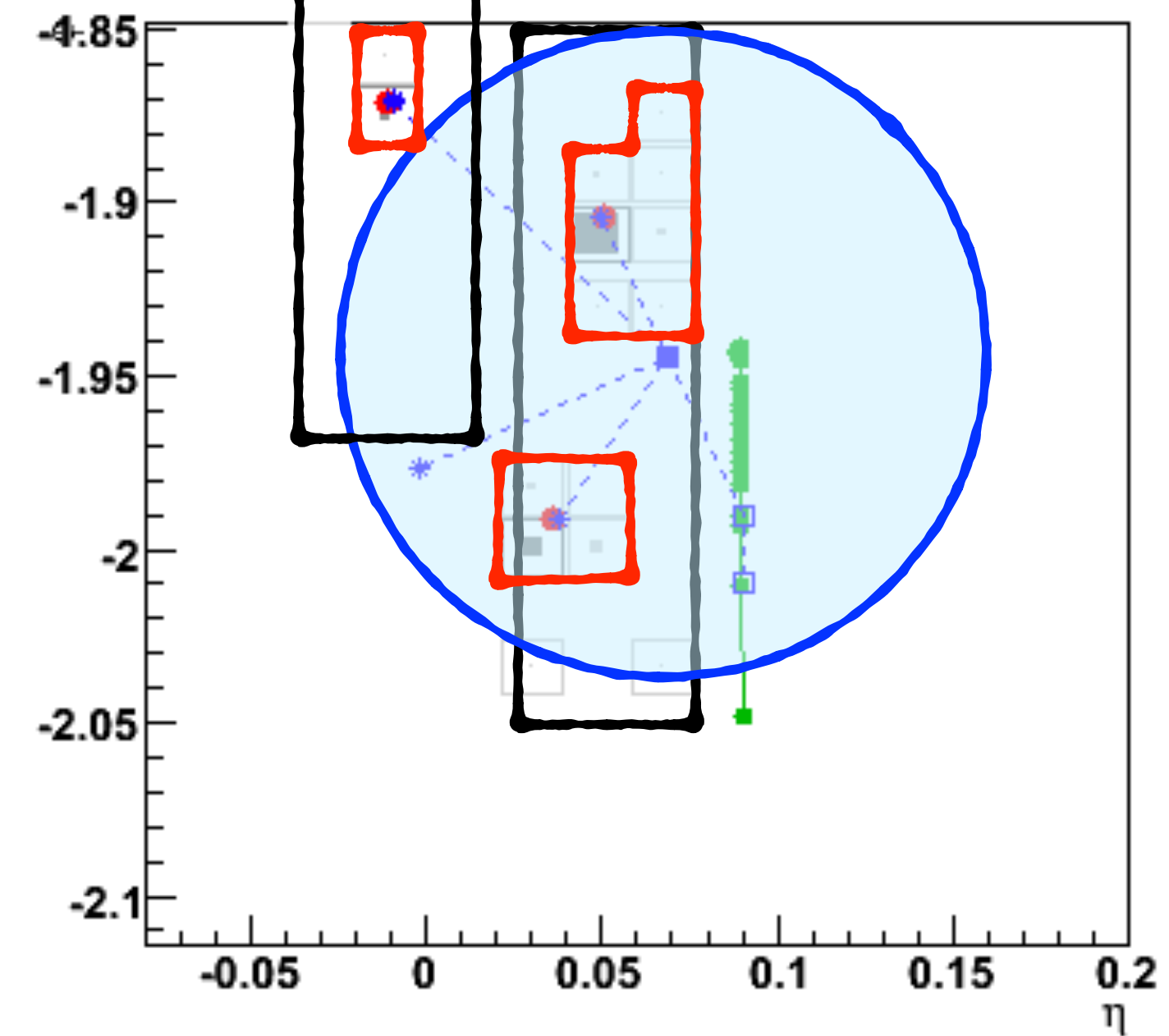


1 π^\pm , 0 π^0

- Branching Fraction: 11.6%
- S

3 π^\pm , 0 π^0

- Branching Fraction: 9.8%
- three $\pi^\pm \approx a_1$ mass



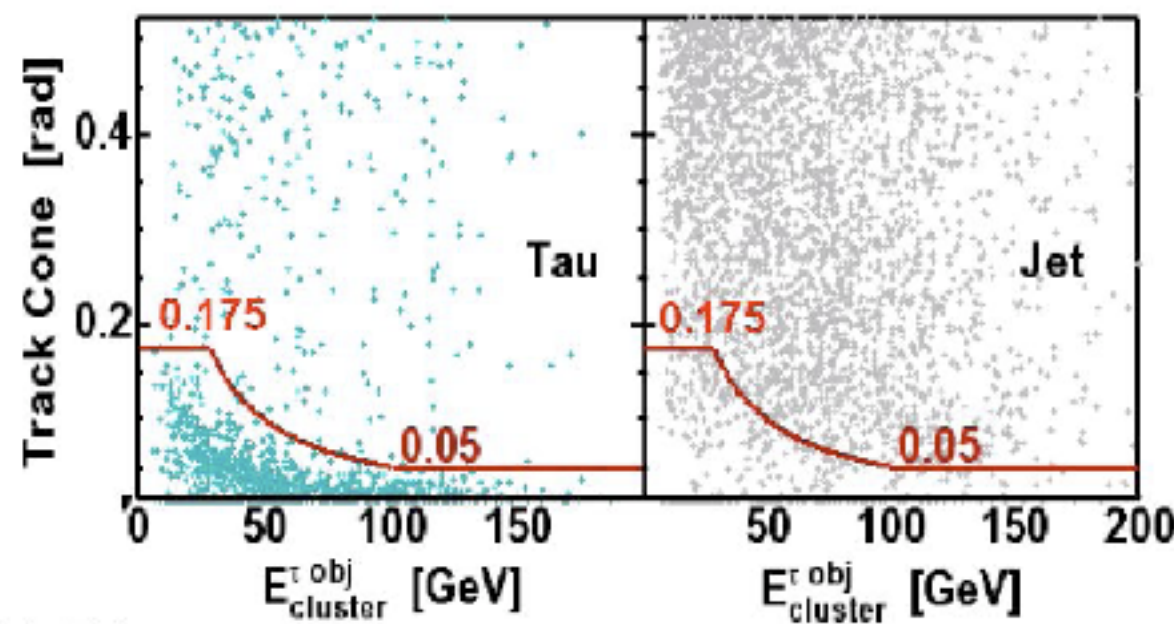
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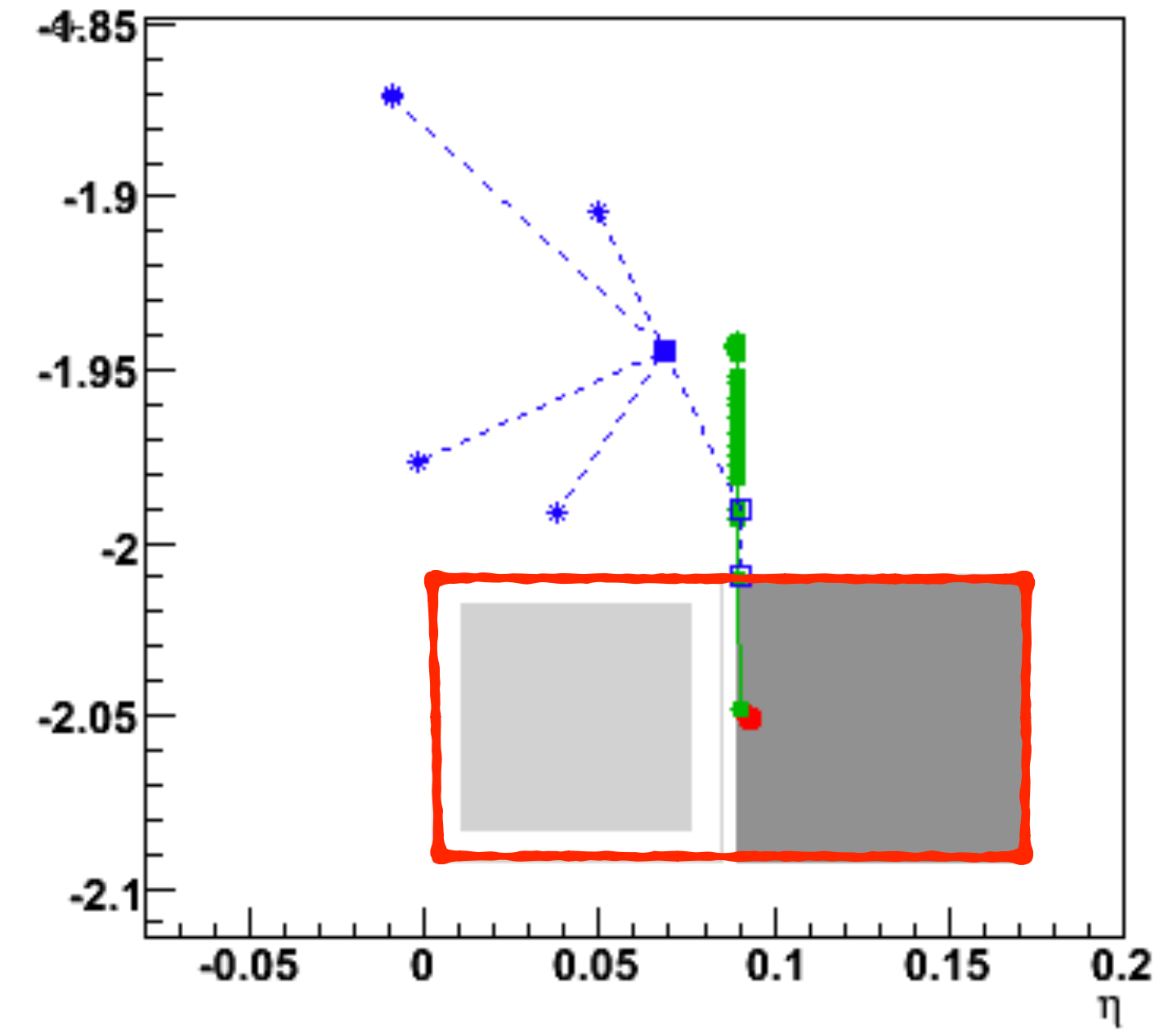
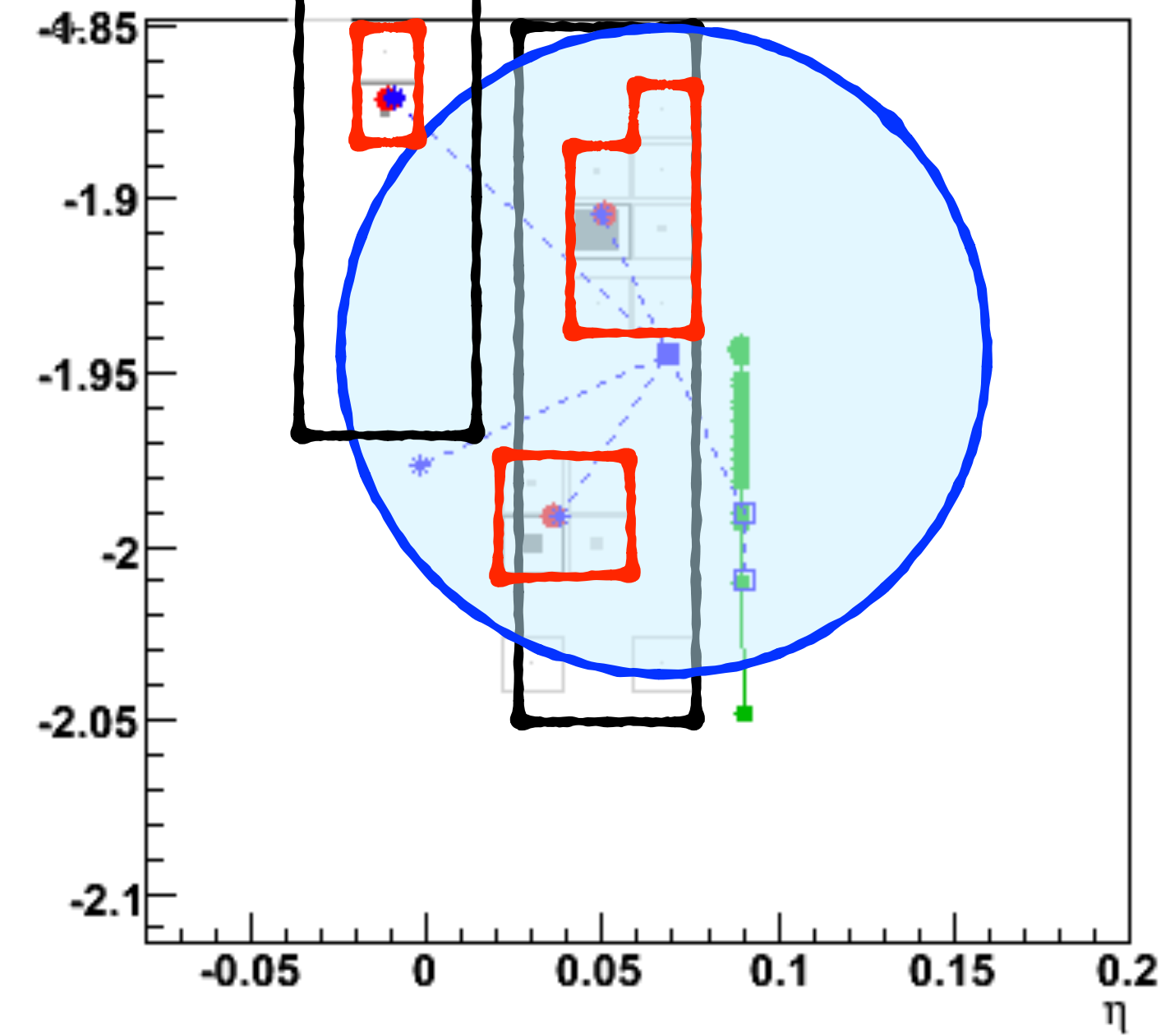
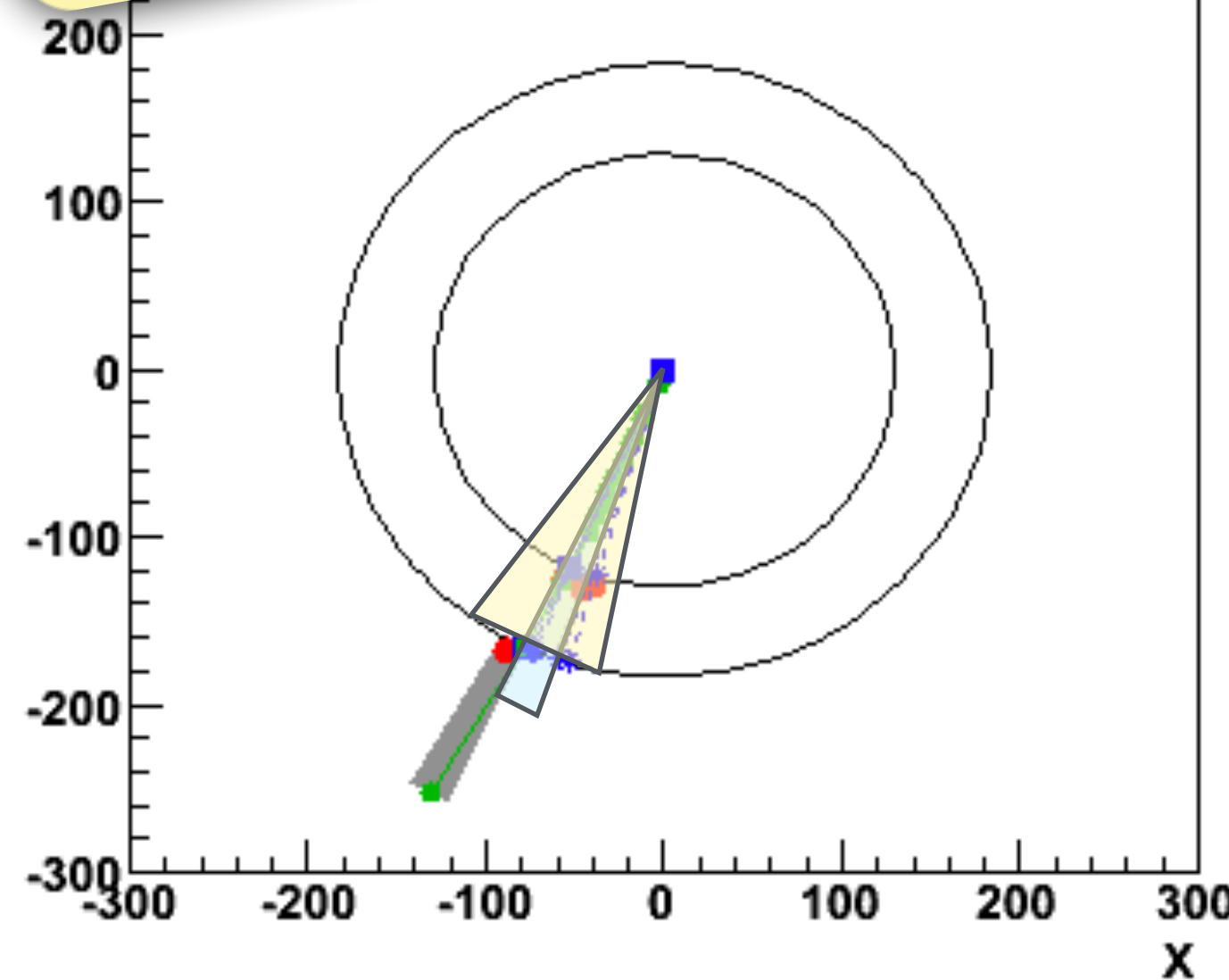
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1 π^\pm , 1 π^0 (merged $\gamma\gamma$)

- Branching Fraction: 26.0%
- single strip $\geq 1 \text{ GeV}$
- single π^\pm
- strip $\approx \pi^0$ mass
- strip + $\pi^\pm \approx \rho(770)$ mass



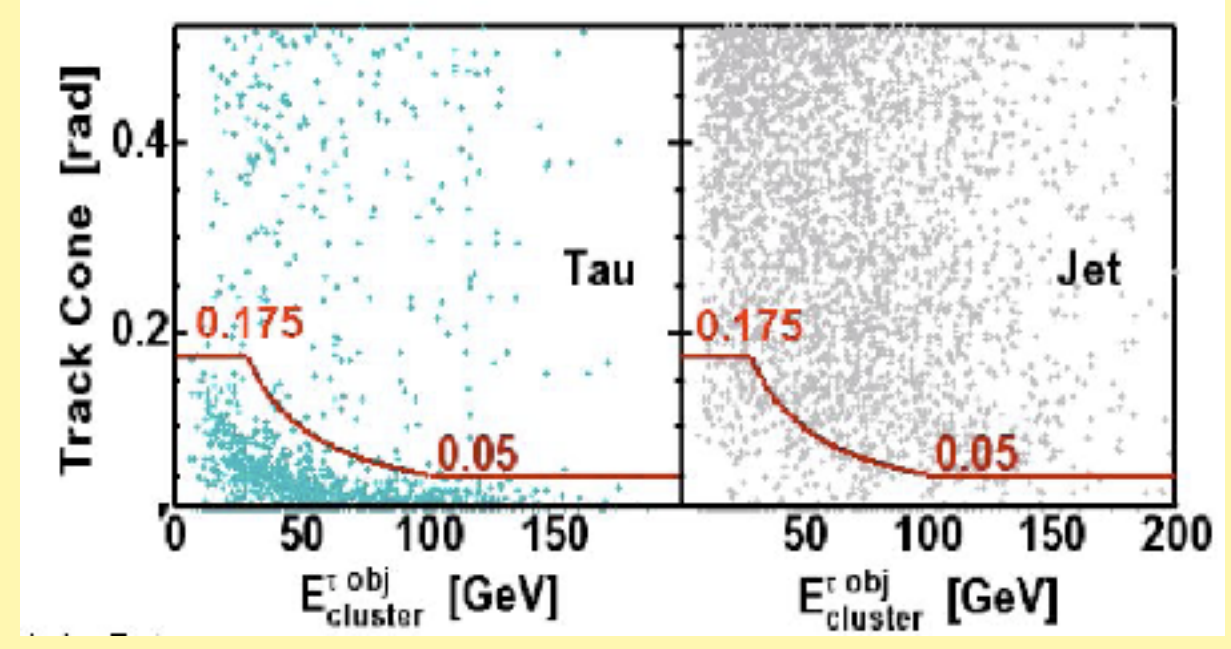
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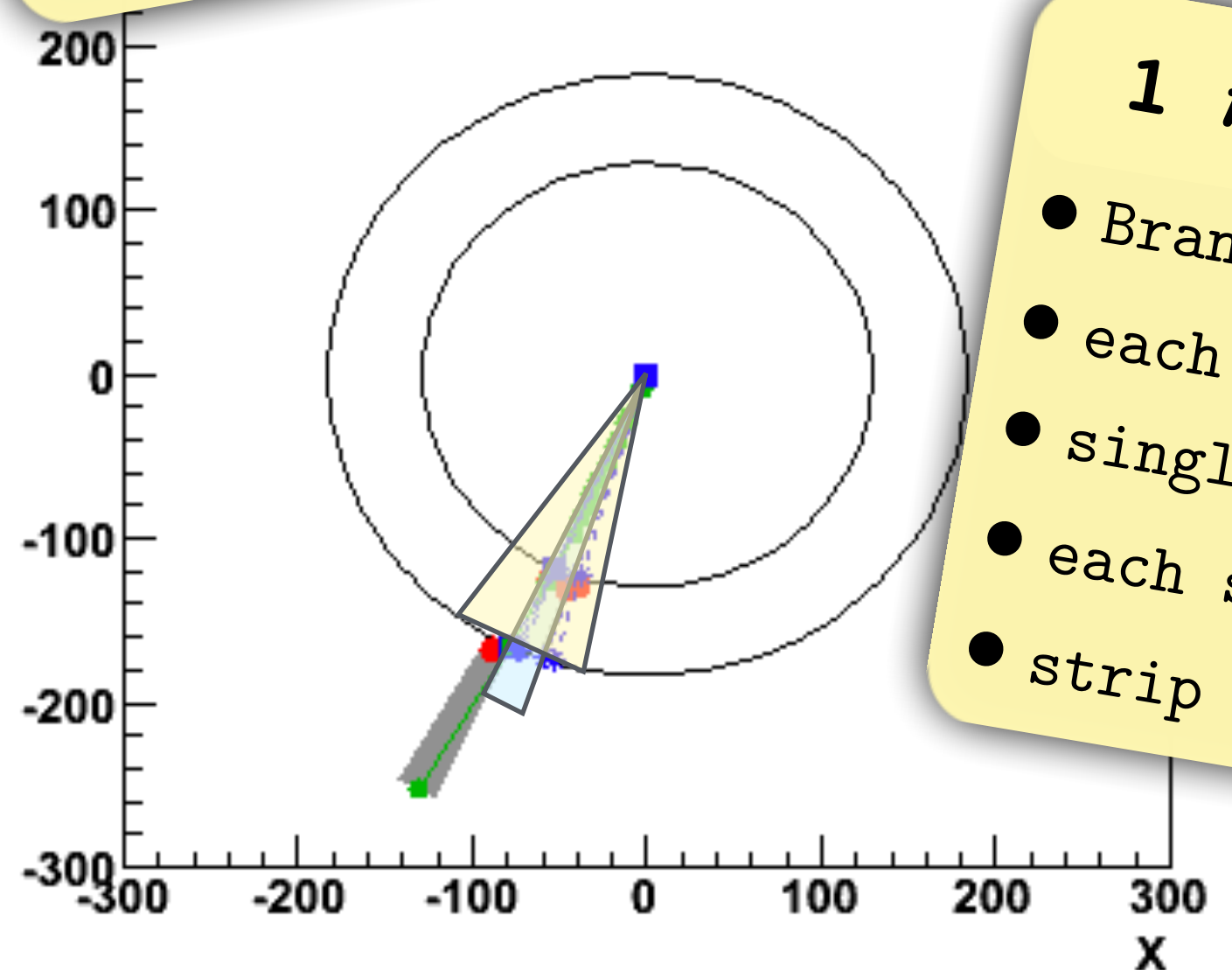
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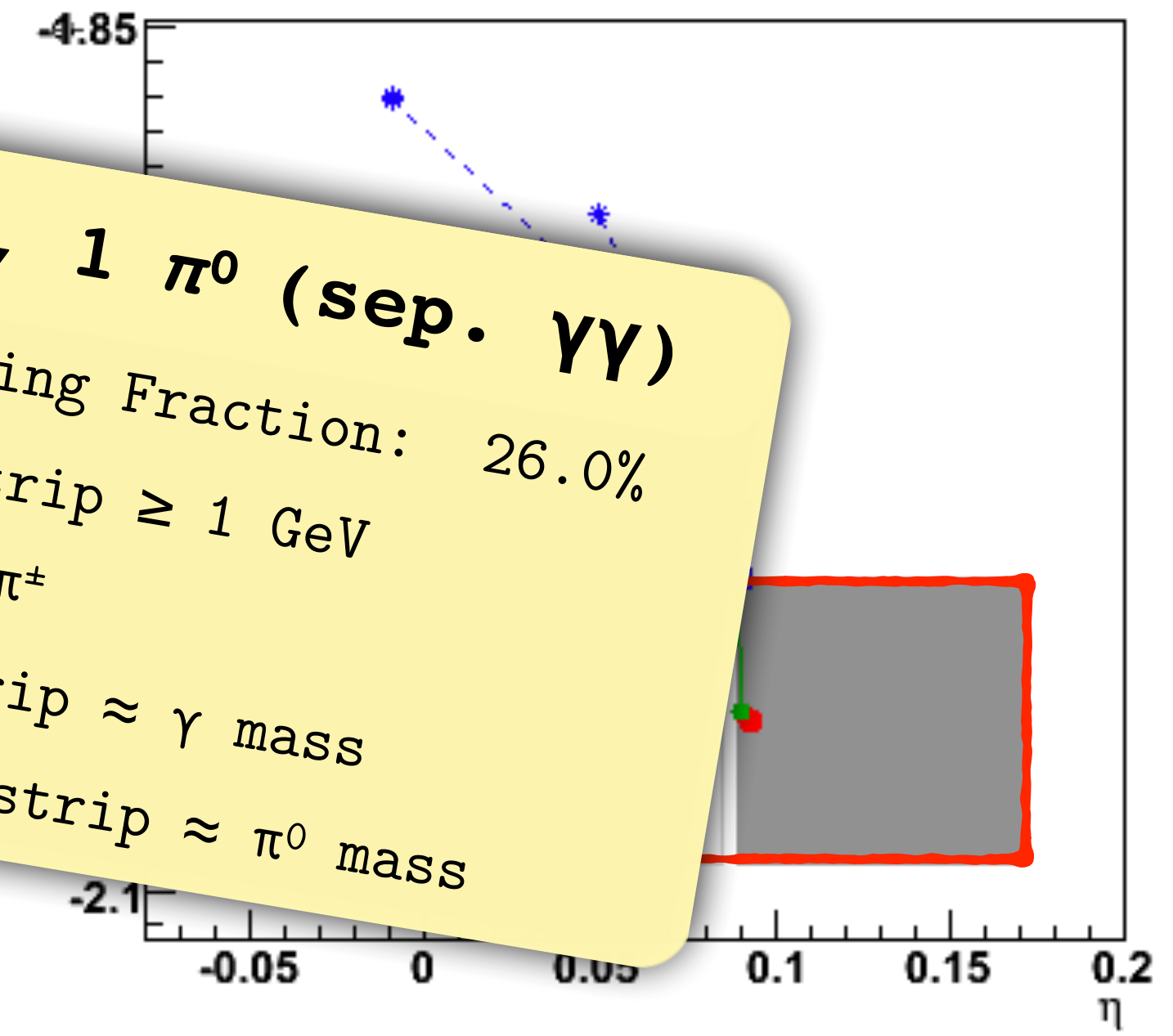
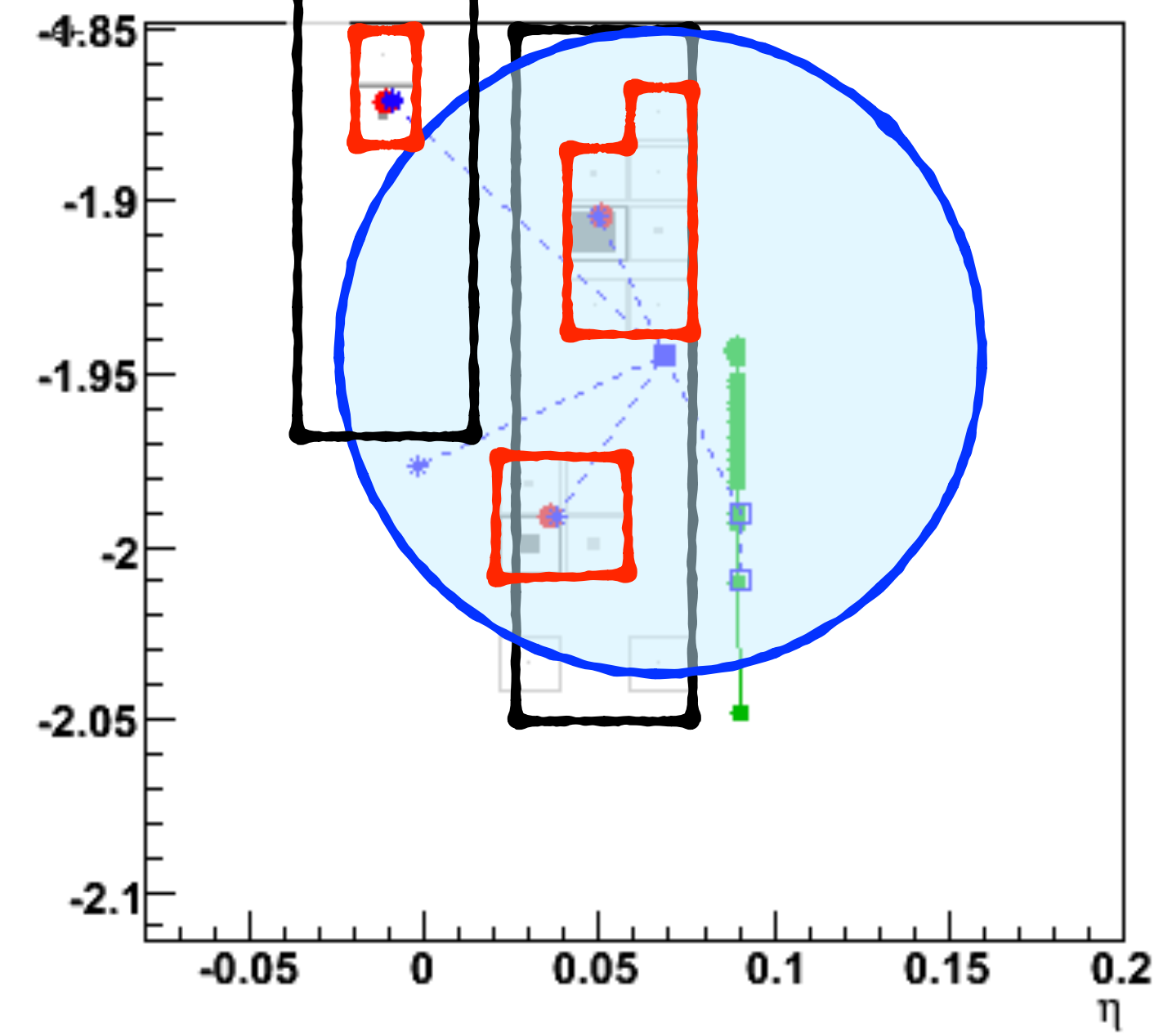
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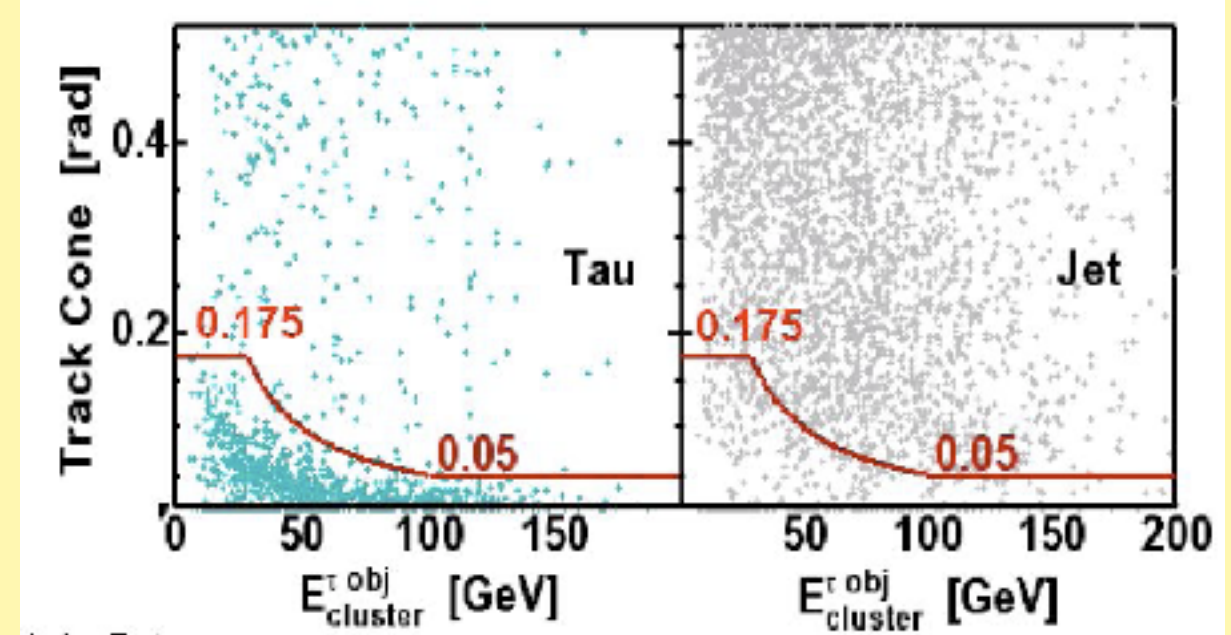
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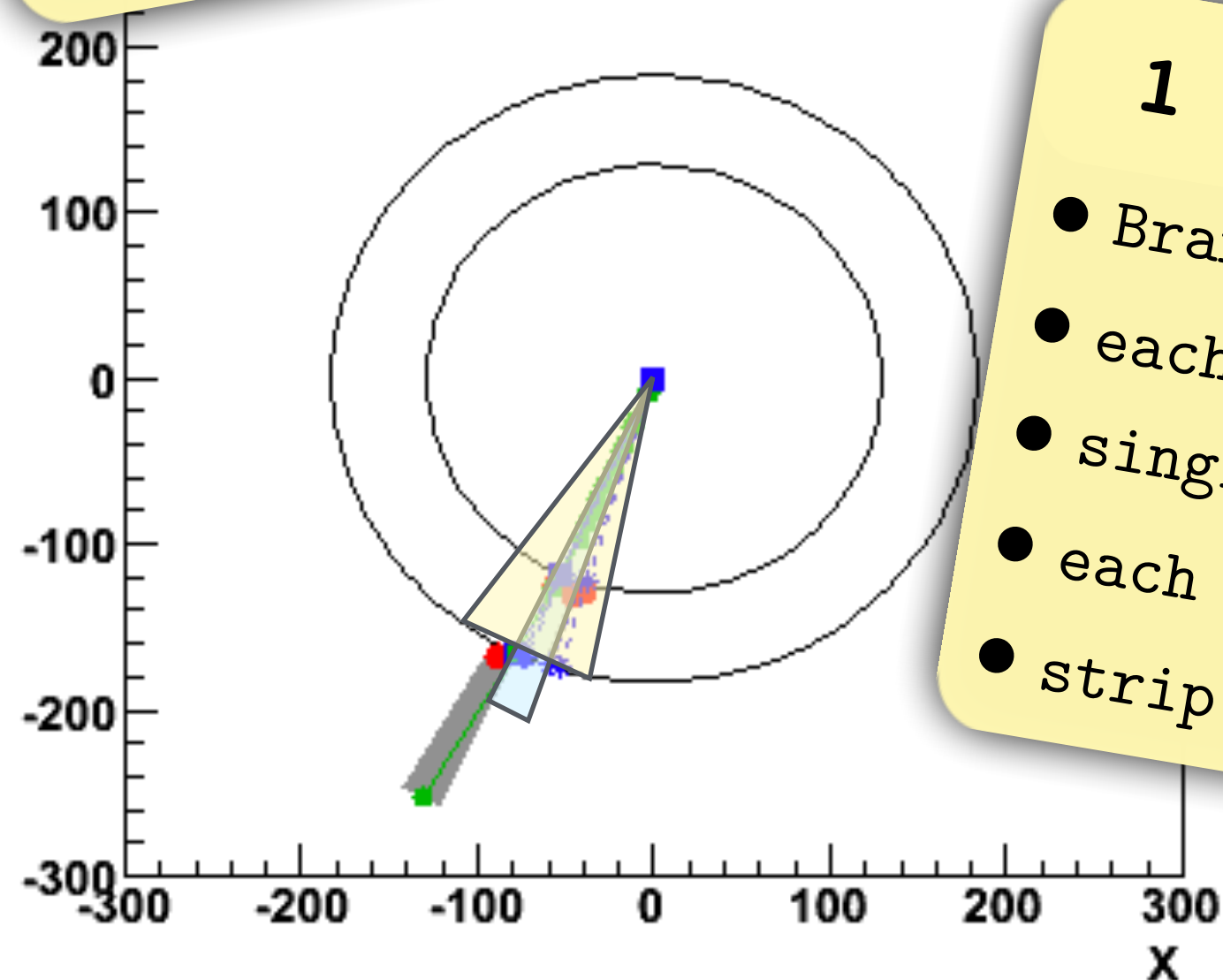
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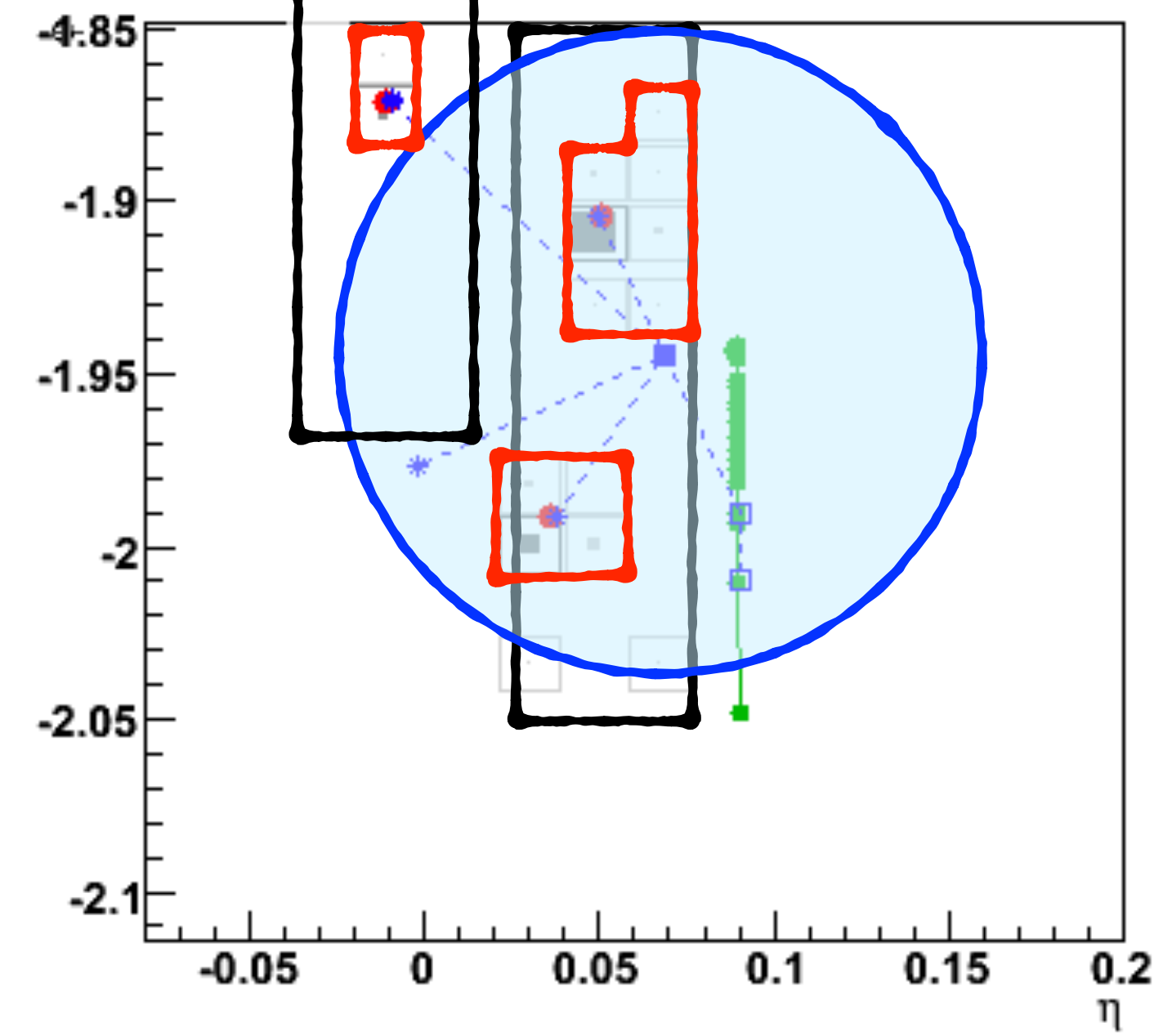
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- strip + $\pi^\pm \approx \rho(770)$ mass



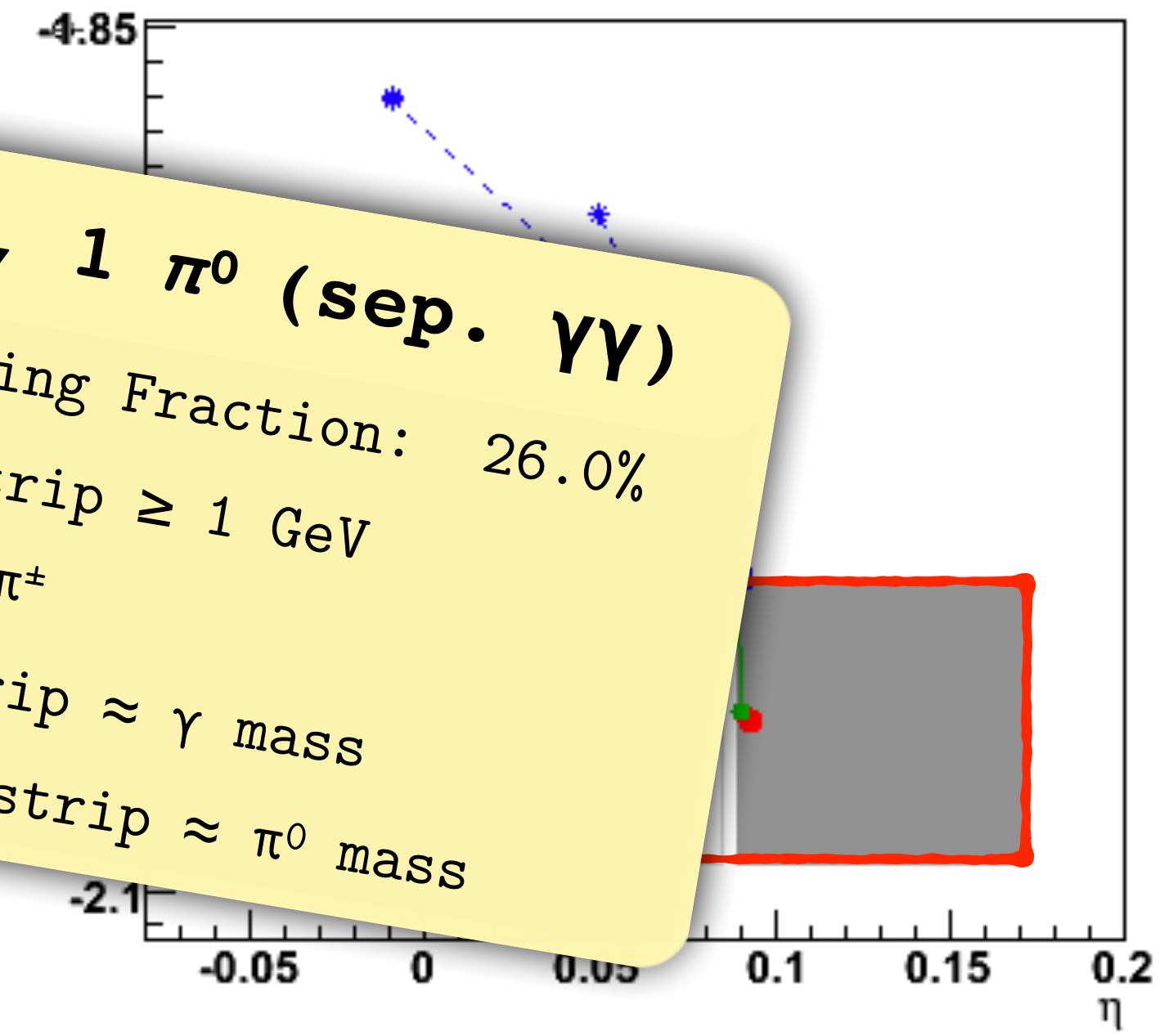
1 π^\pm , 1 π^0 (sep. $\gamma\gamma$)

- Branching Fraction: 26.0%
- each strip $\geq 1 \text{ GeV}$
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- each strip $\approx \gamma$ mass
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Could also do ID modes

1 π^\pm , 2 π^0 's or 3 π^\pm , 1 π^0



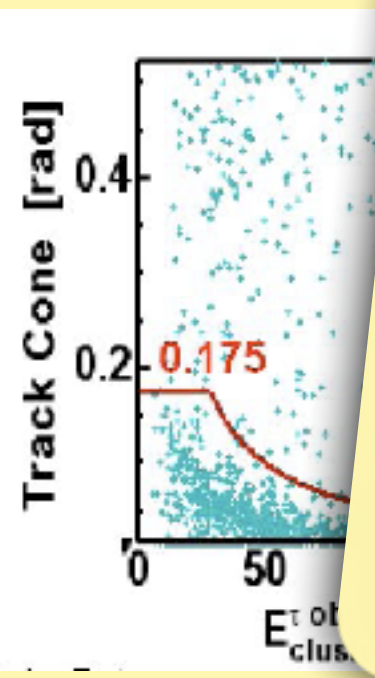
Tau ID & Reconstruction

Basic Idea

- Seed with R=0.4 anti-kt jet
- Start with highest p_T γ or e^\pm in jet
- Cluster all γ 's or e 's into strips
 - $\Delta\eta \times \Delta\phi = 0.05 \times 0.2$
 - to capture all conversions
- Combine with π^\pm 's to form tau candidates

Signature

- Tau constant within a cone of $\Delta R \leq 3$ GeV



Isolation

- Isolation cone of $\Delta R = 0.5$
- summed p_T of all particles, except constituents of tau-candidate
- loose: no π^\pm with $p_T > 1.0$ GeV; no γ with $p_T > 1.5$ GeV
- medium: no π^\pm with $p_T > 0.8$ GeV; no γ with $p_T > 0.8$ GeV
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1 π^\pm , 0 π^0

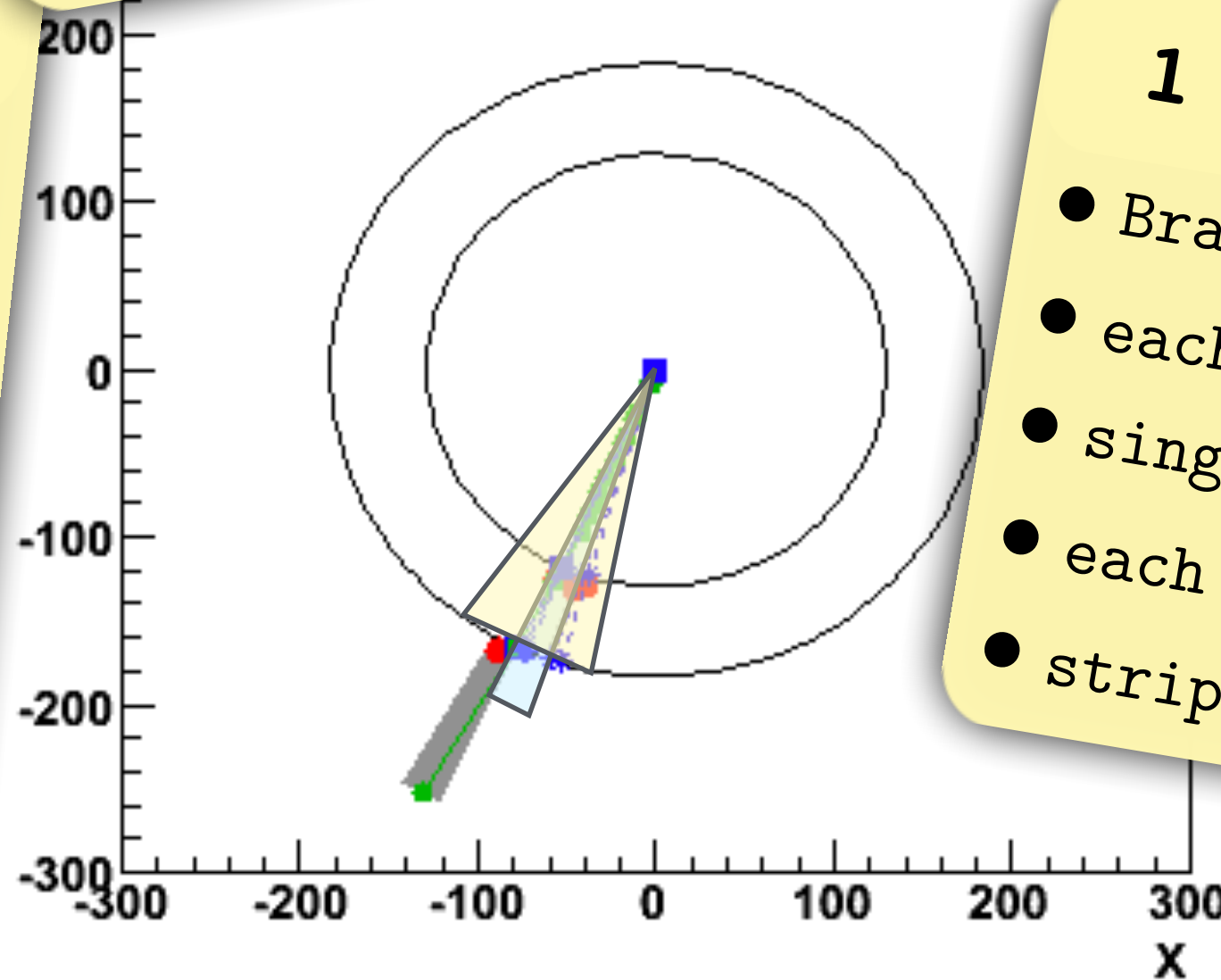
- Branching Fraction: 11.6%
- S...

3 π^\pm , 0 π^0

- Branching Fraction: 9.8%
- three $\pi^\pm \approx a_1$ mass

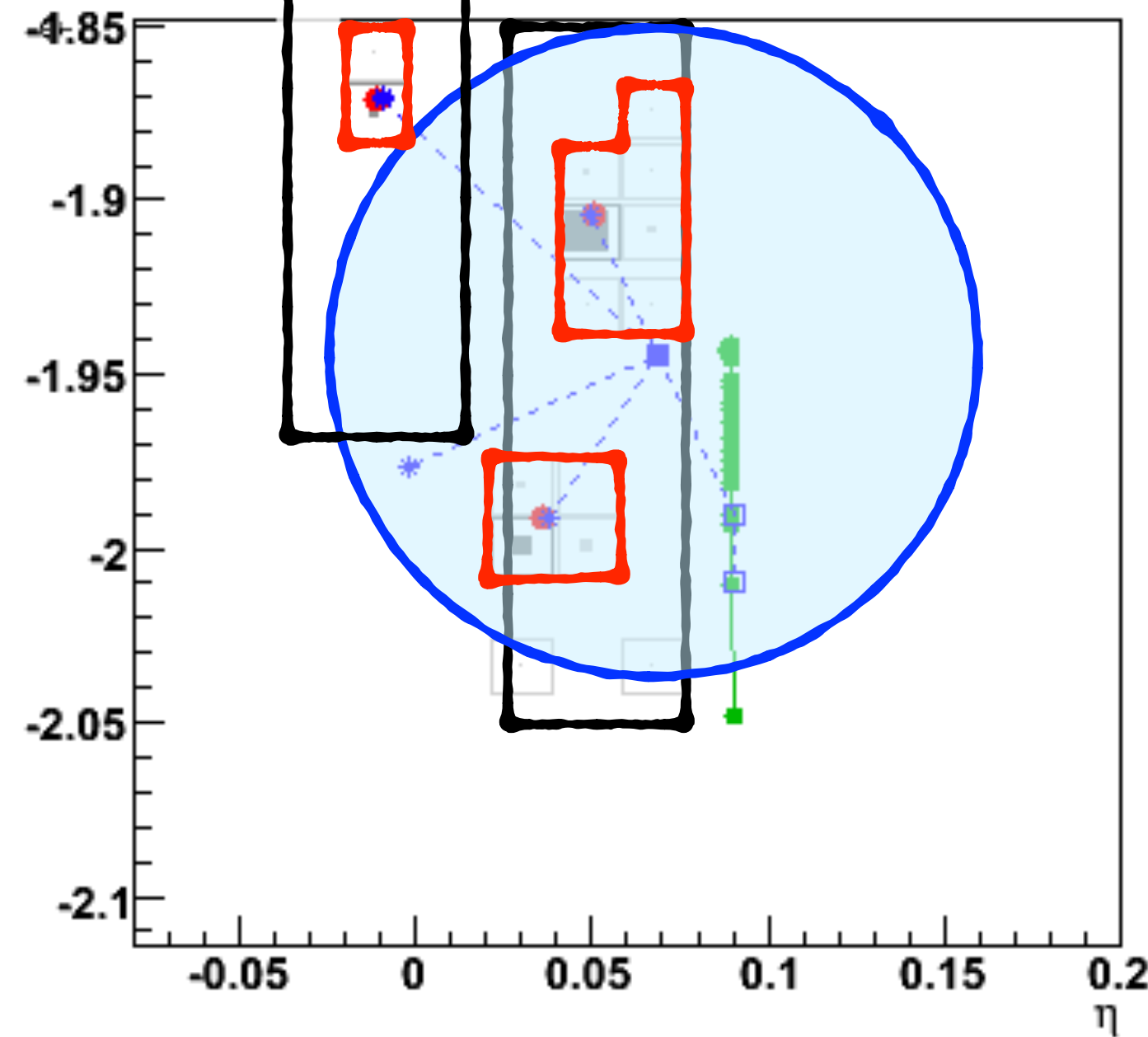
1 π^\pm , 1 π^0 (merged $\gamma\gamma$)

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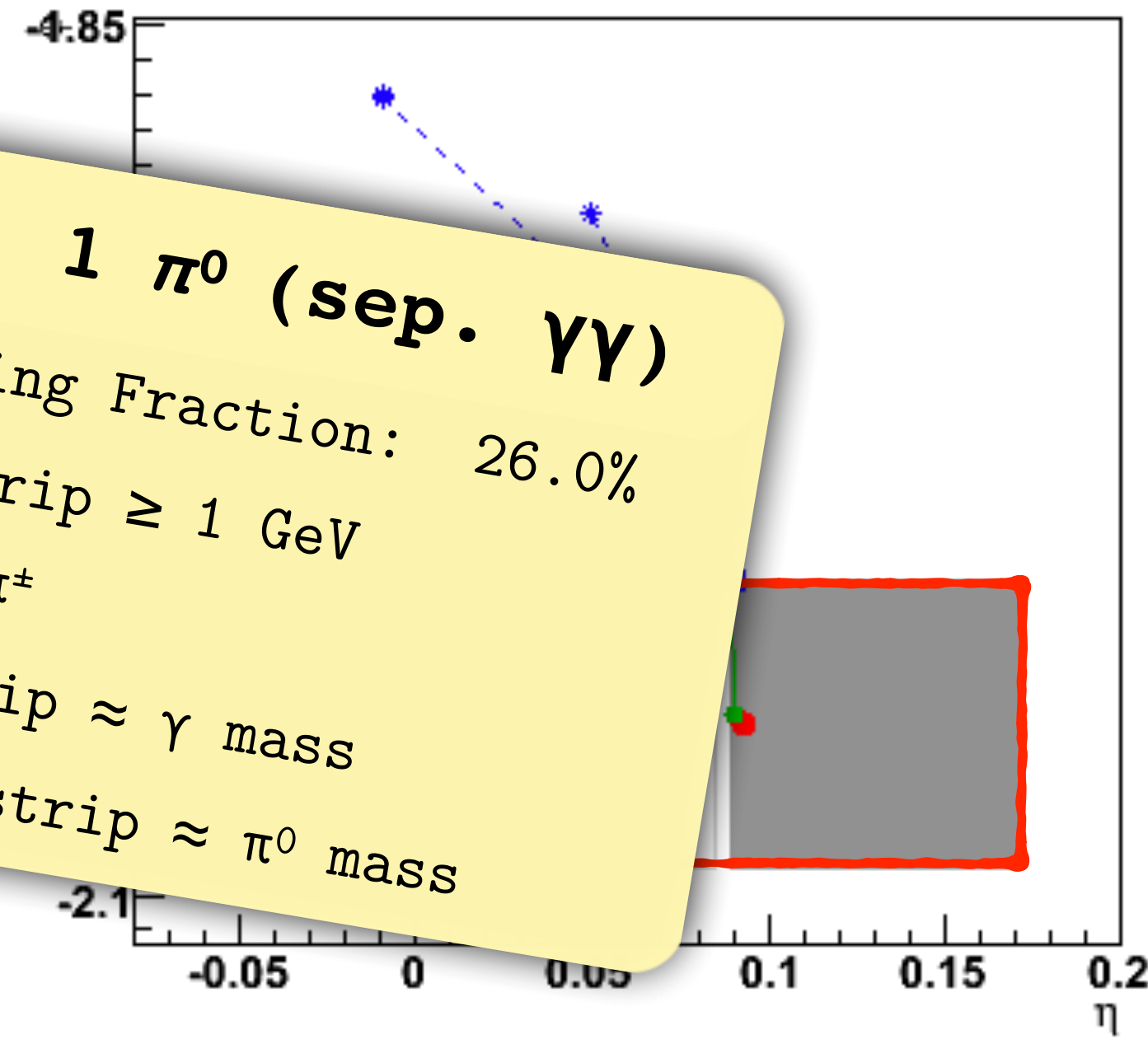
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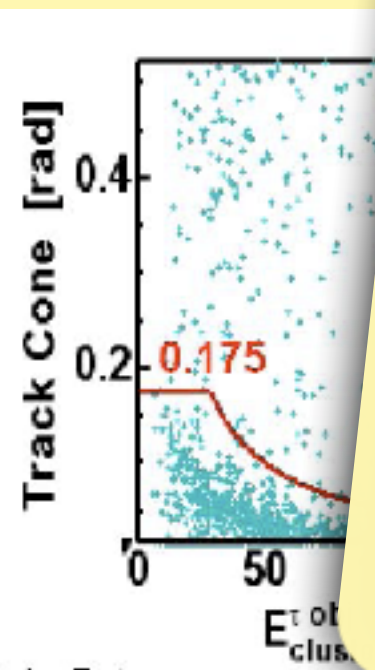
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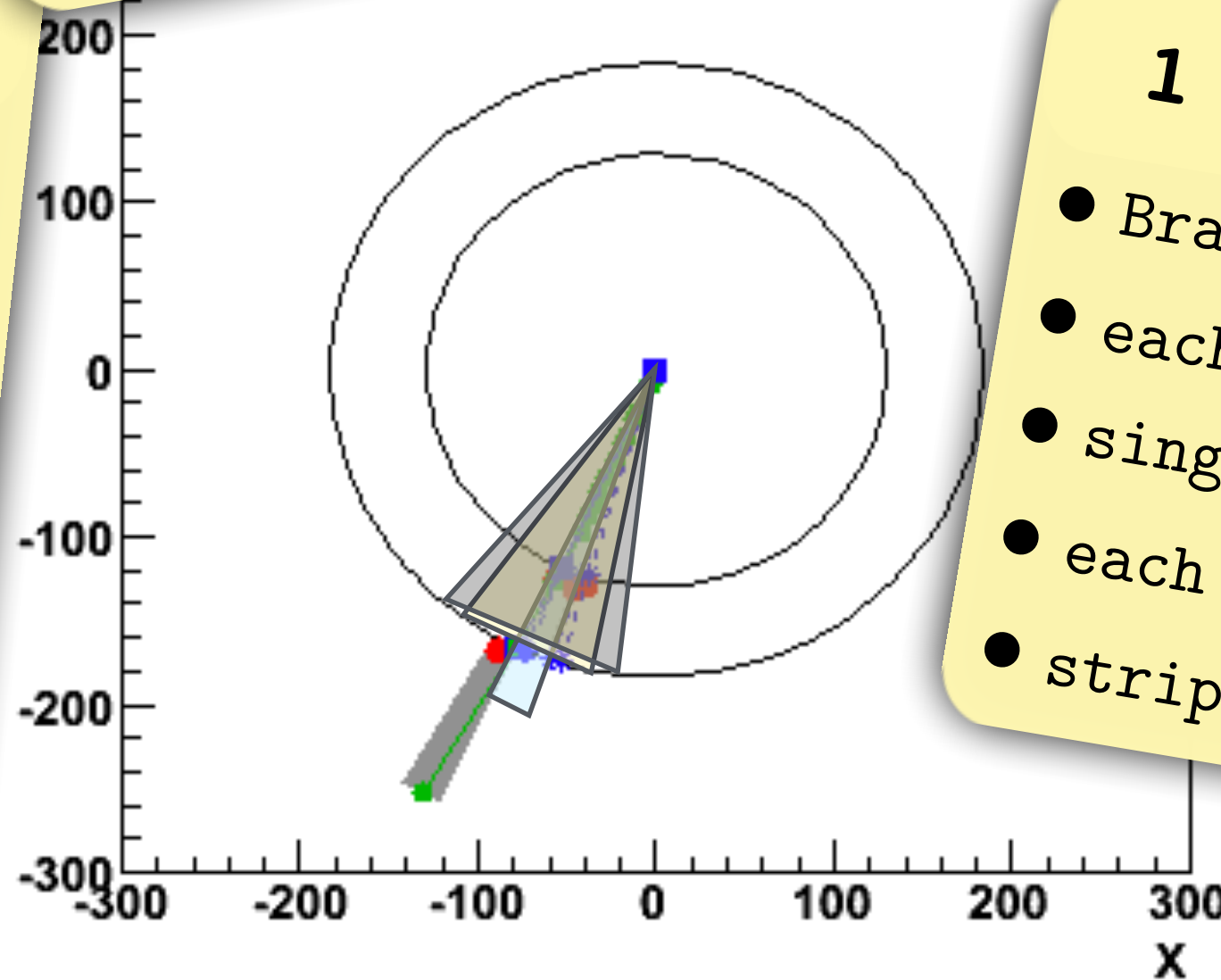
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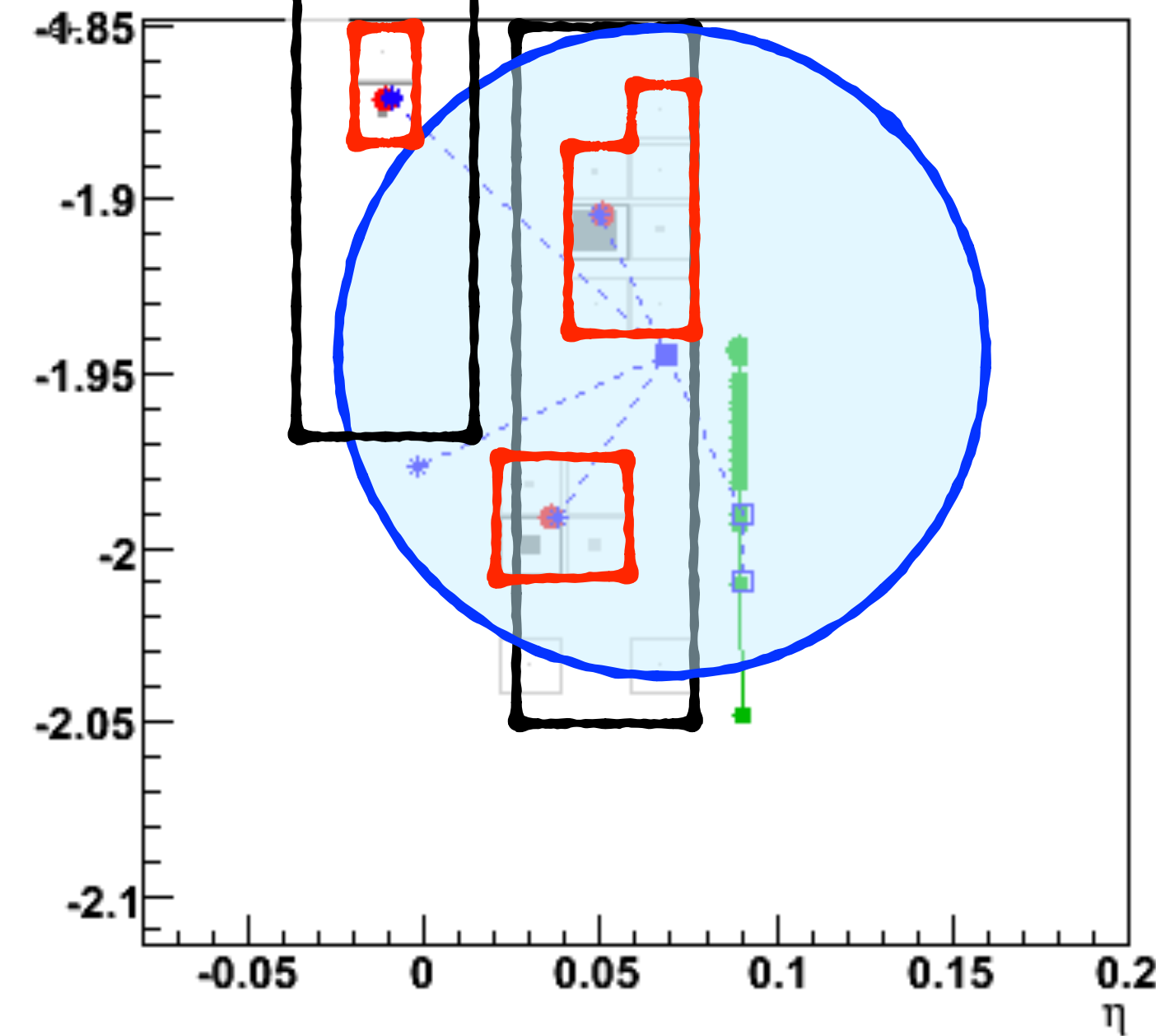
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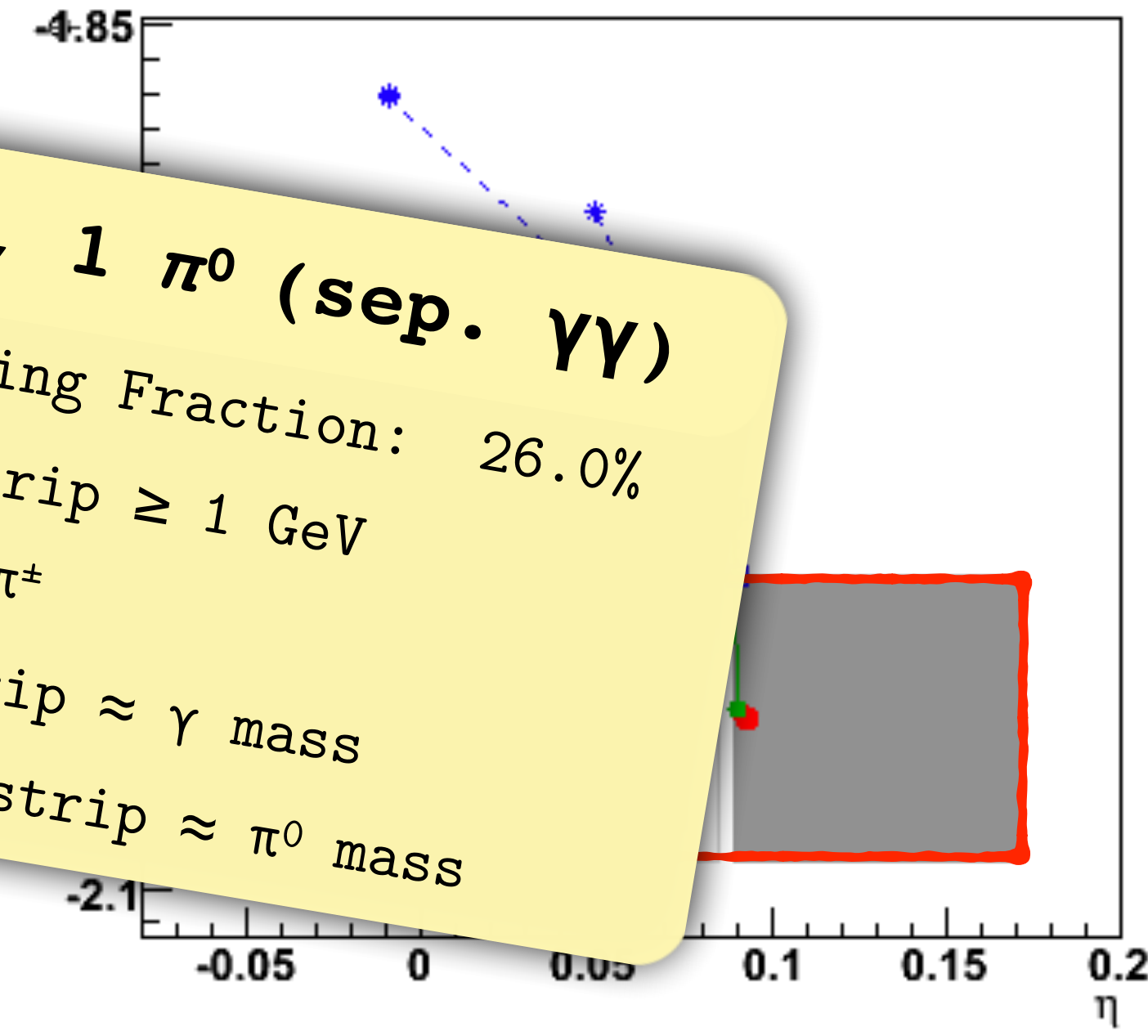
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Tau ID & Reconstruction

Basic Idea

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- Start with jet
- Cluster a strips
- $\Delta\eta \times \Delta\phi =$
- to capture
- Combine candidate

Typical Reconstruction Efficiencies

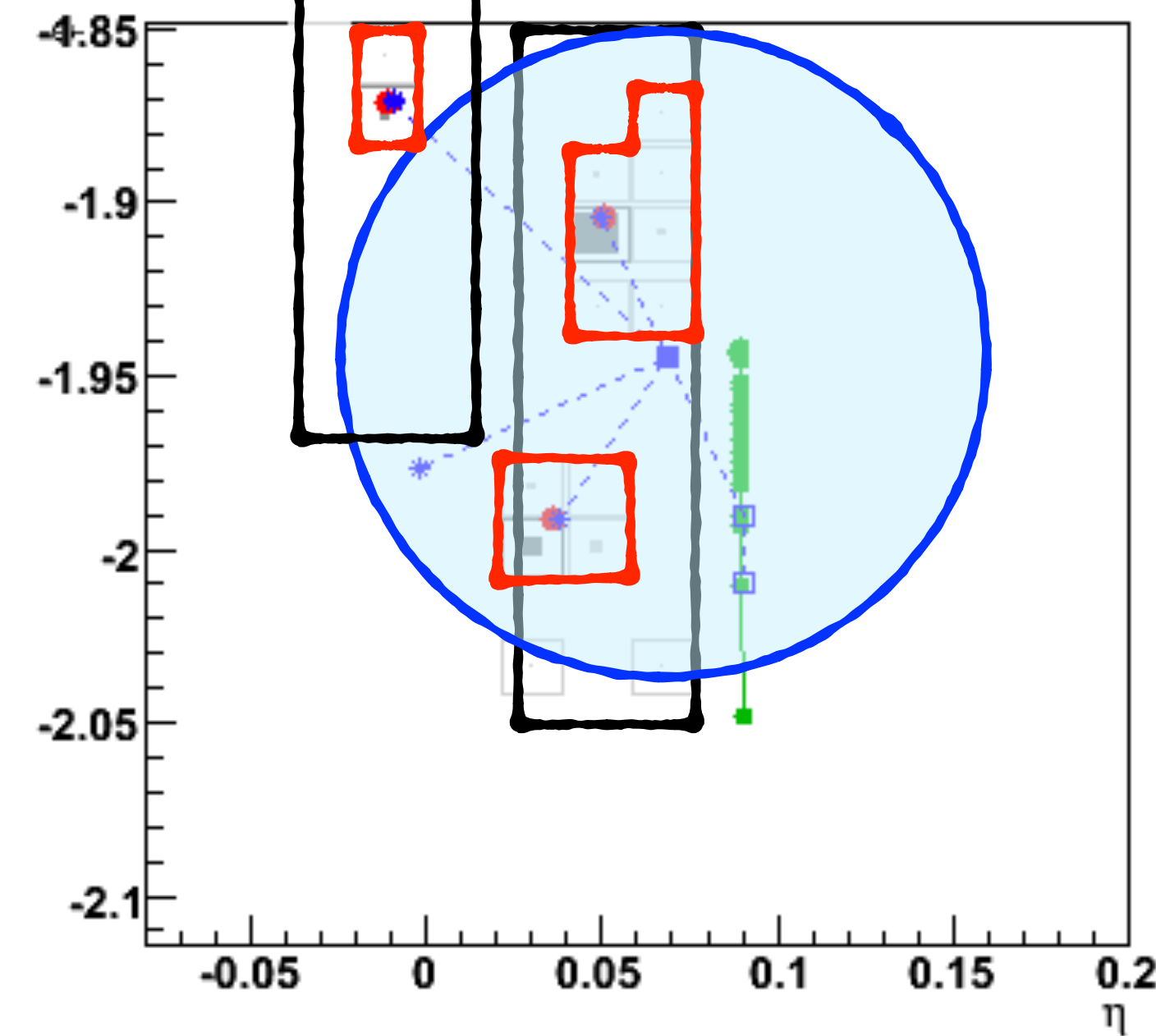
Reconstructed	Generated		
	$\tau^- \rightarrow h^- \nu_\tau$	$\tau^- \rightarrow h^- \geq 1\pi^0 \nu_\tau$	$\tau^- \rightarrow h^- h^+ h^- \nu_\tau$
$\tau^- \rightarrow h^- \nu_\tau$	0.89	0.16	0.01
$\tau^- \rightarrow h^- \geq 1\pi^0 \nu_\tau$	0.11	0.83	0.02
$\tau^- \rightarrow h^- h^+ h^- \nu_\tau$	0.00	0.01	0.97

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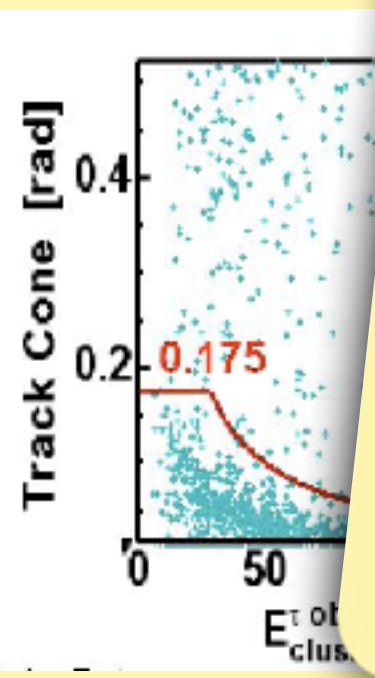


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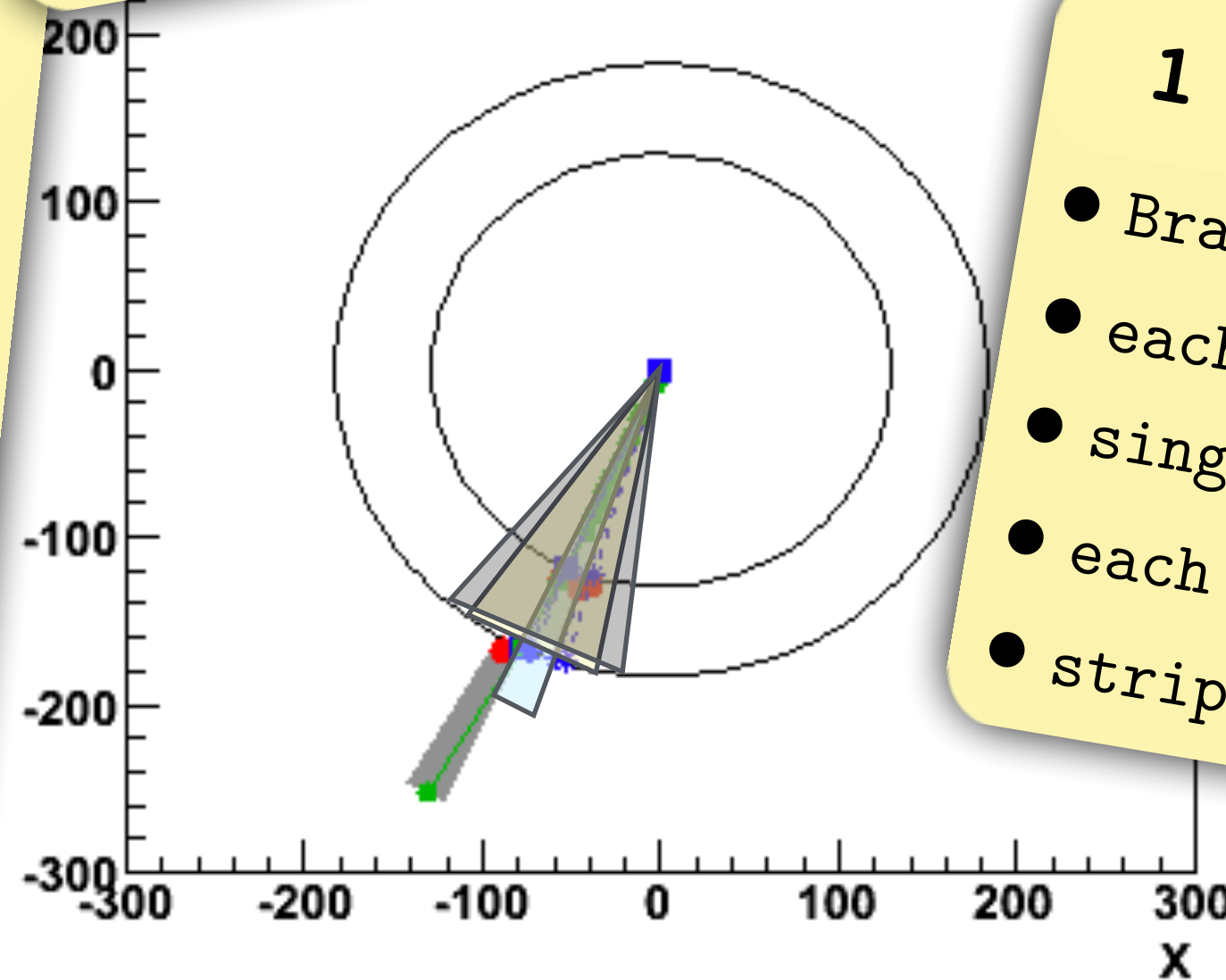
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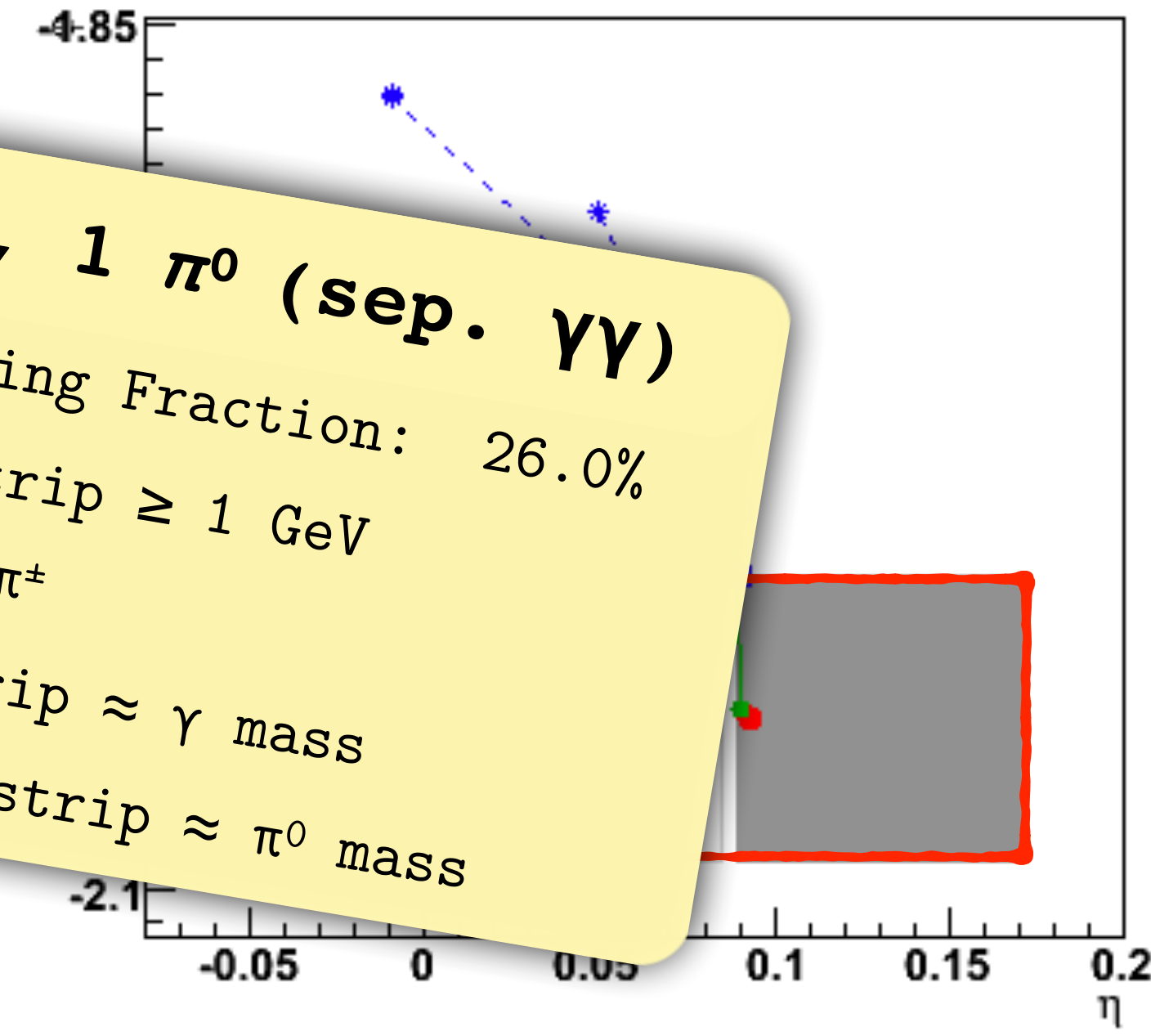
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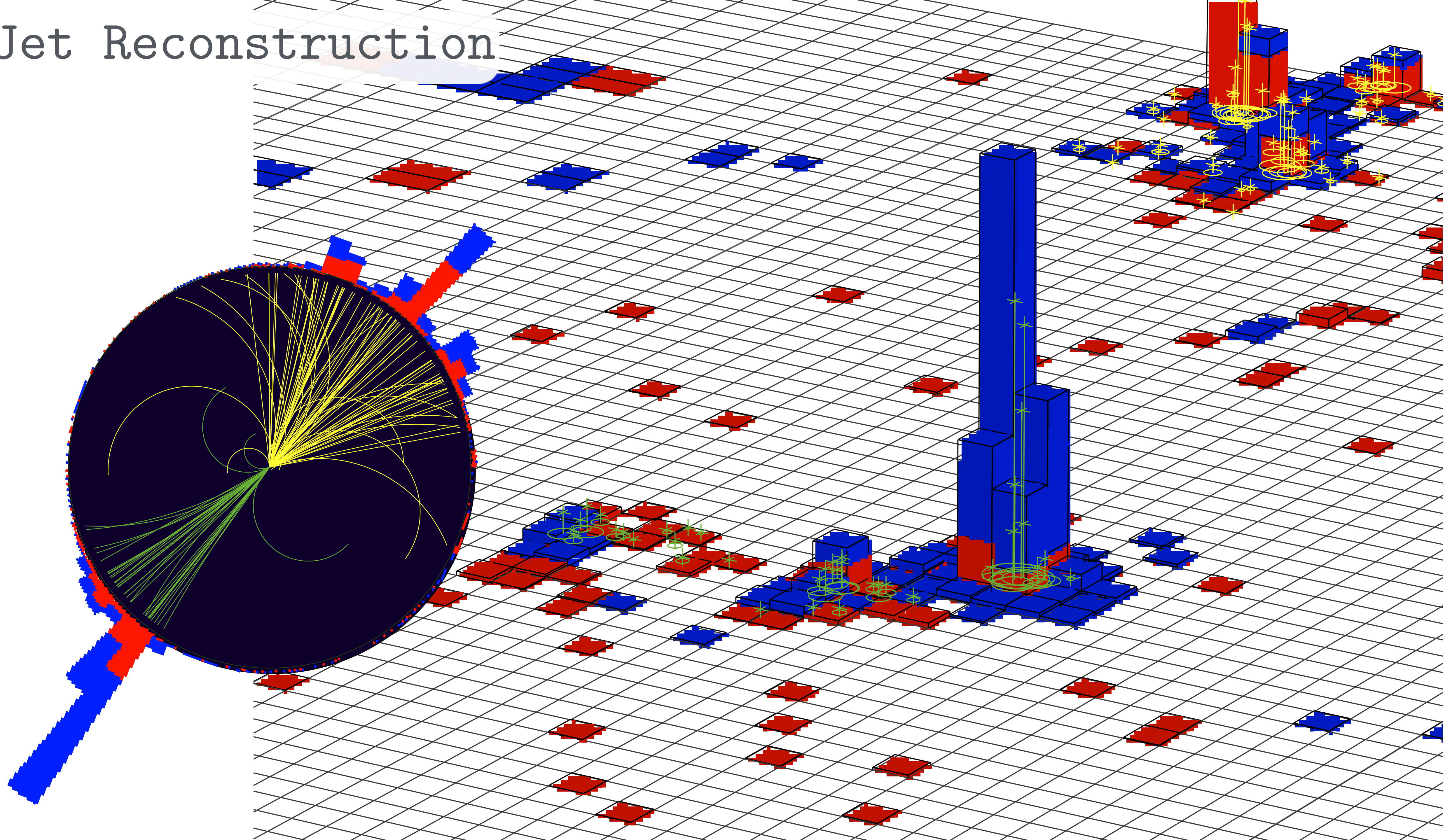


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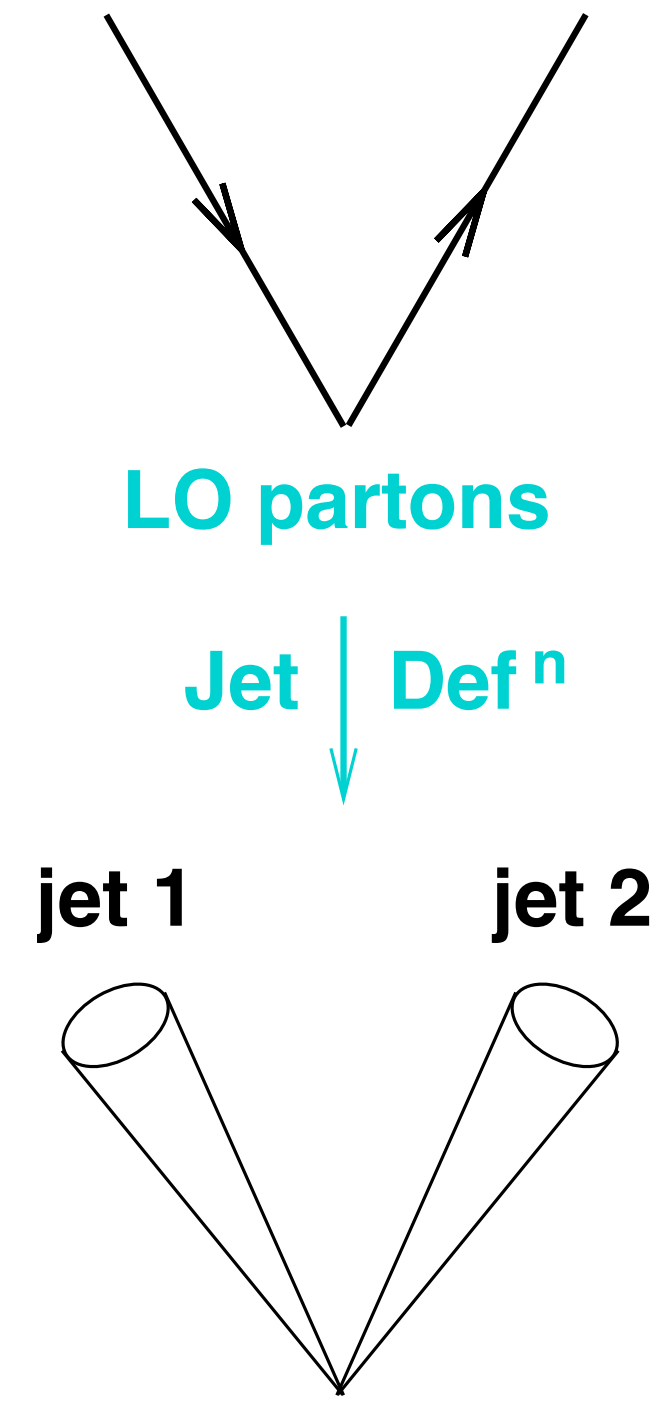
Jet Reconstruction



Jet Reconstruction

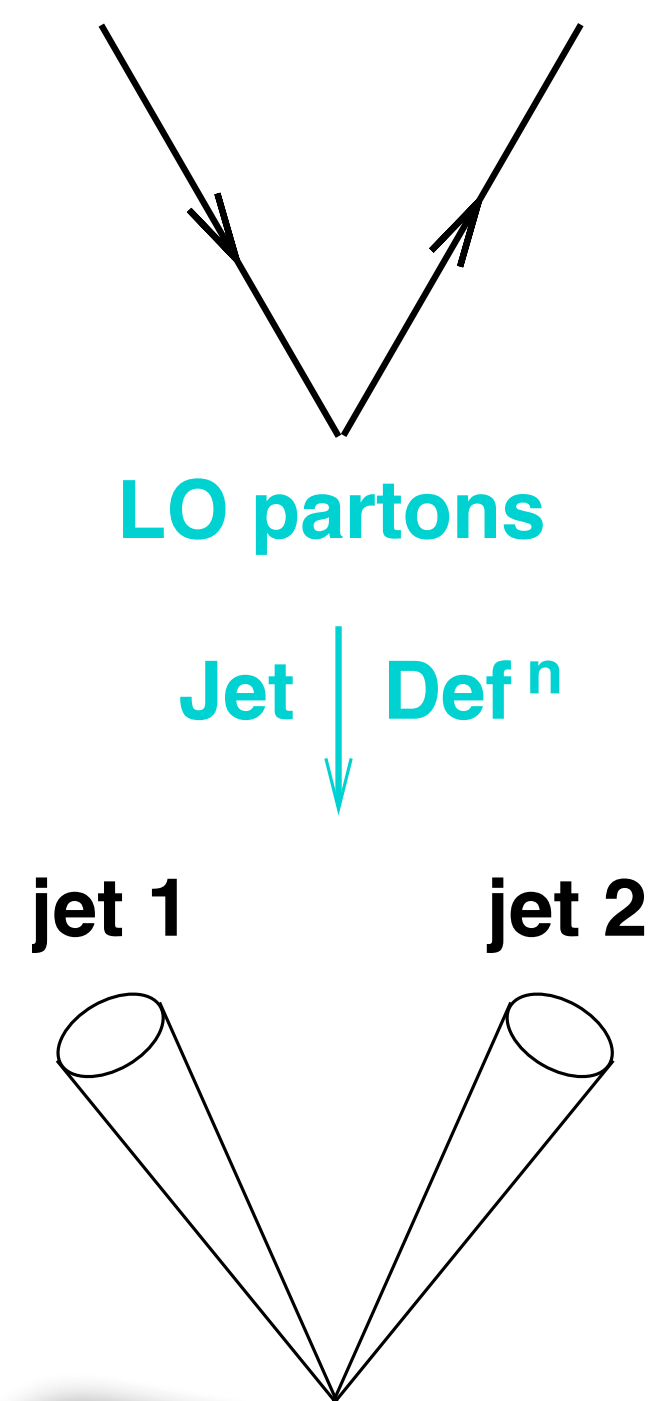
Jet Reconstruction

Diagram from Gavin Salam



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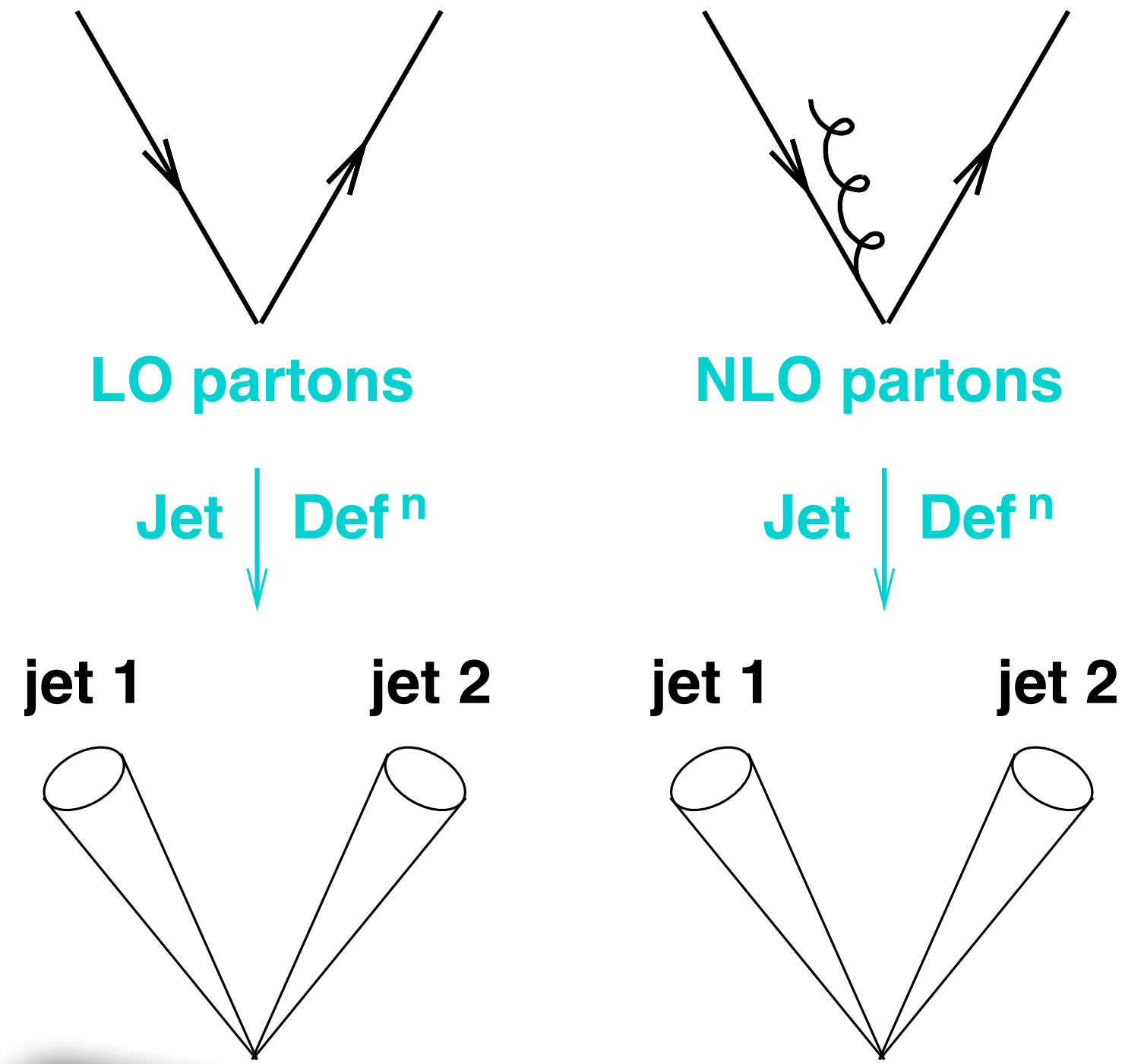


Coloured partons: quarks & gluons

- Central concepts of QCD
- Not directly observable (confinement)

Jet Reconstruction

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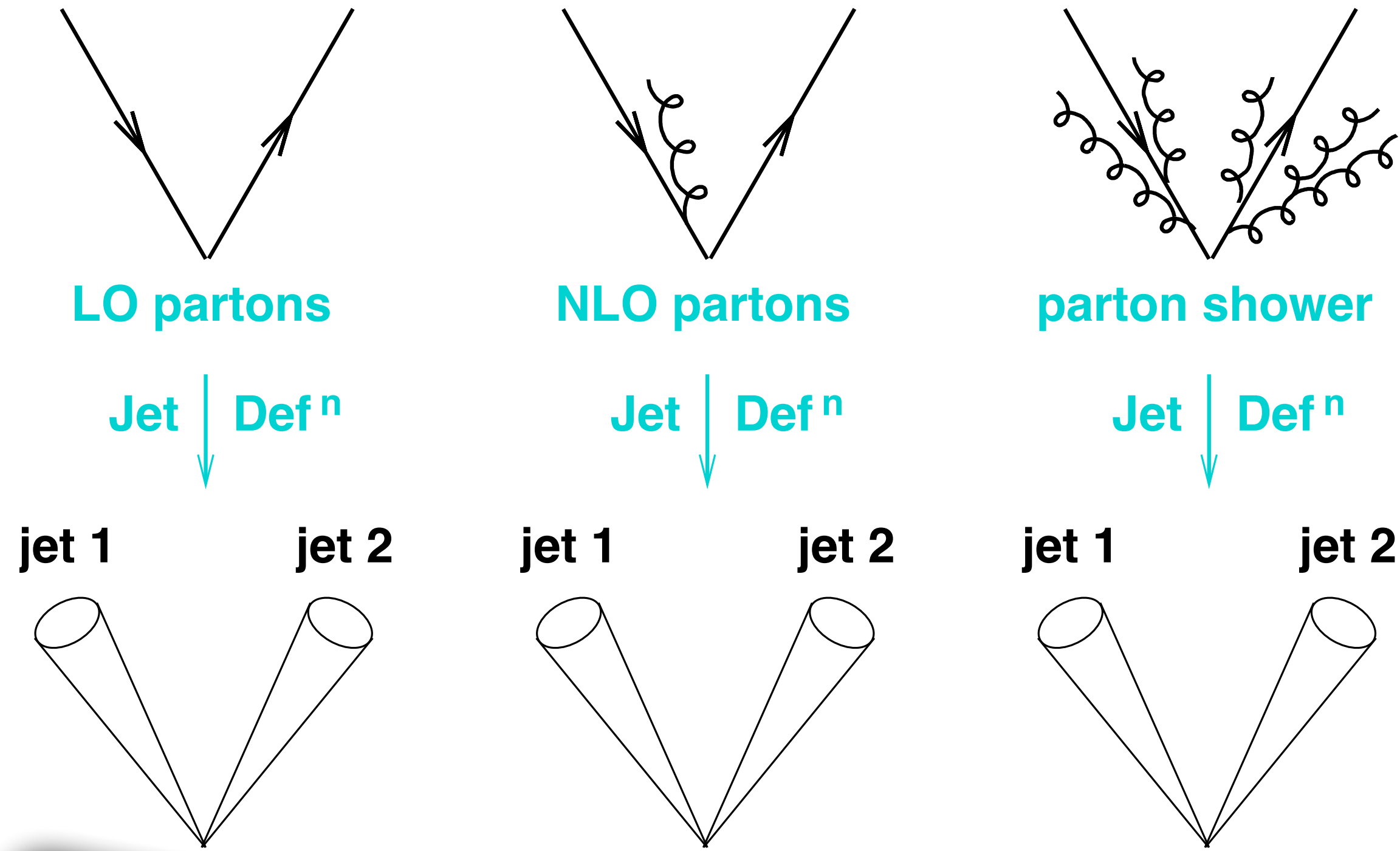


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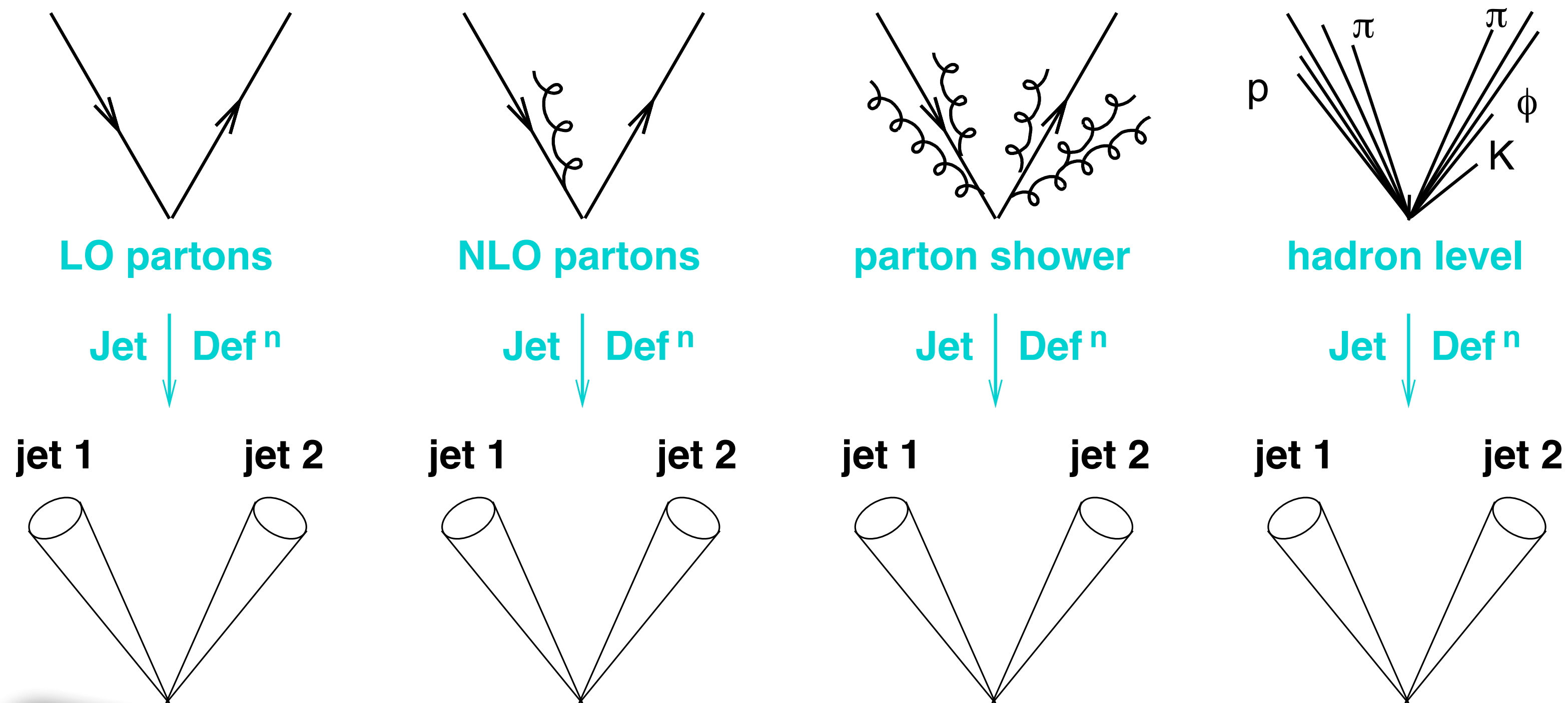


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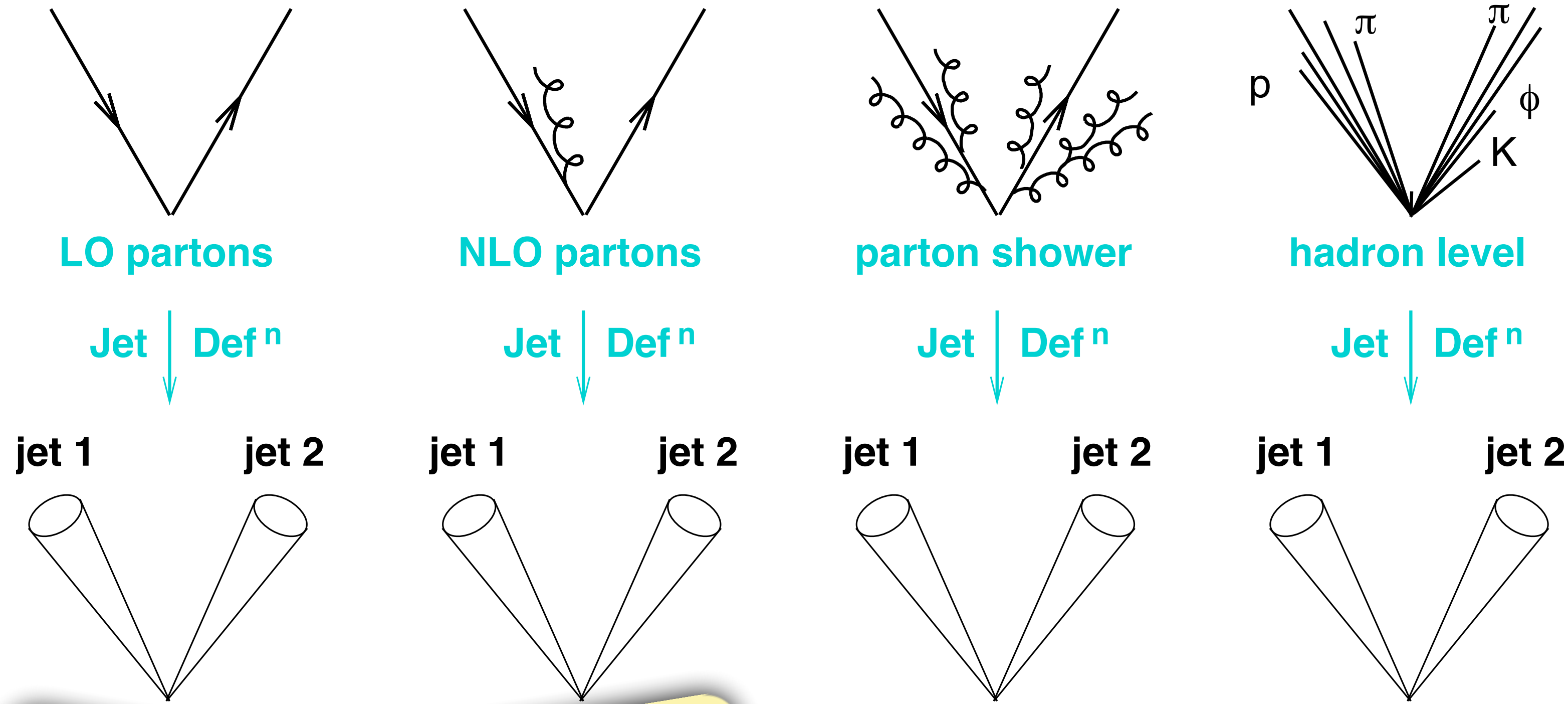


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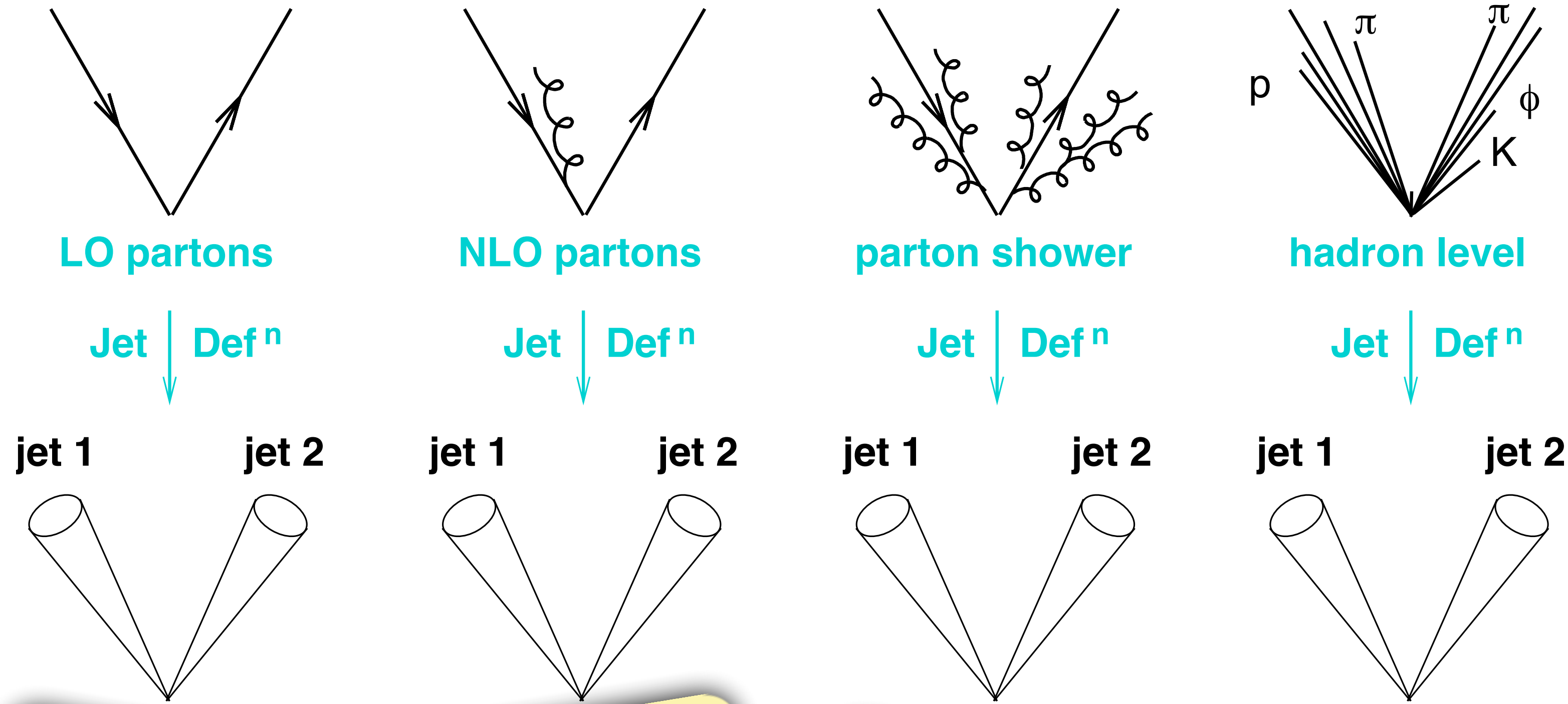
Co

Jets

- signatures of quarks & gluons from hard scattering processes
- result from fragmentation (perturbative) & hadronisation (non-perturbative) of original partons

Jet Reconstruction

Diagram from Gavin Salam



Jets

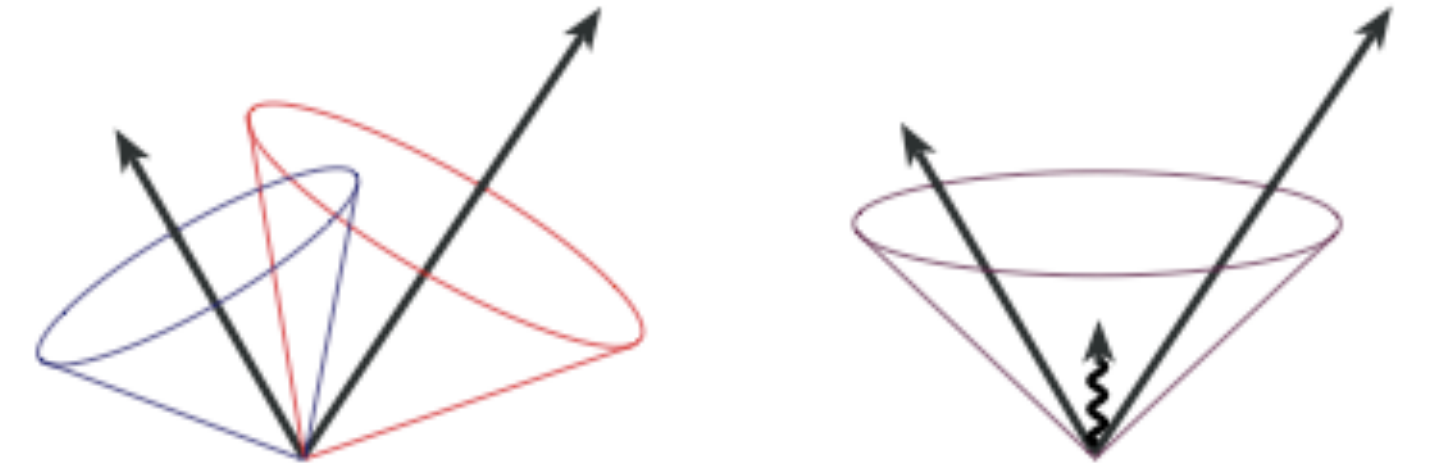
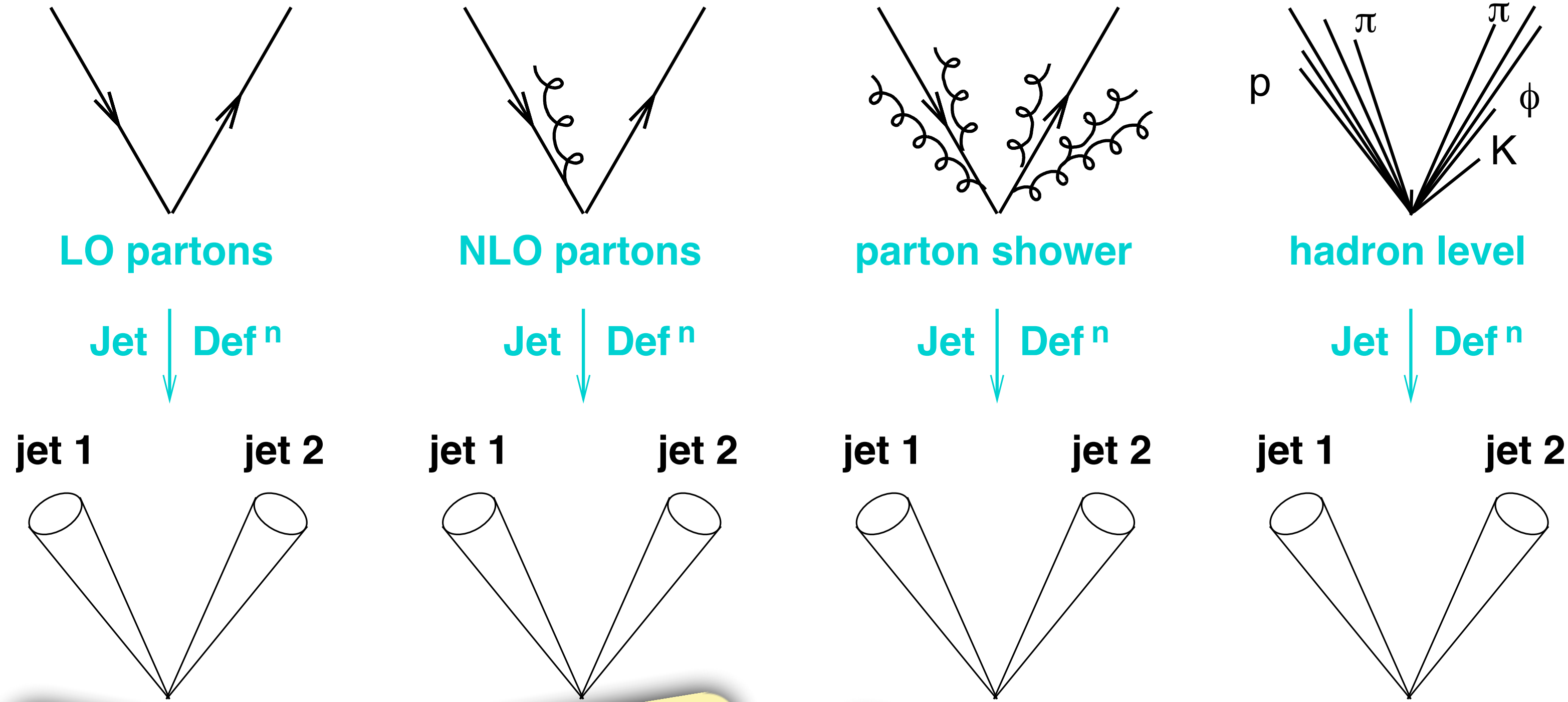
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Jets

- are collimated bunches (sprays) of particles
- reflect kinematics & topology of partons
- really are what the algorithm defines them to be!

Jet Reconstruction

Diagram from Gavin Salam



Jets

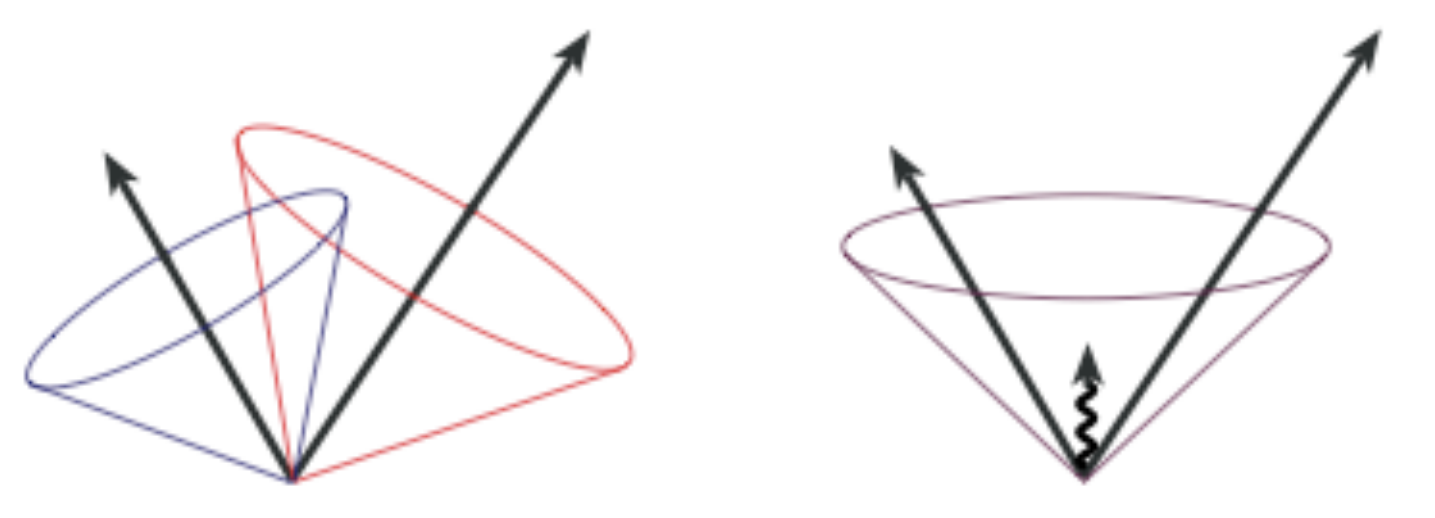
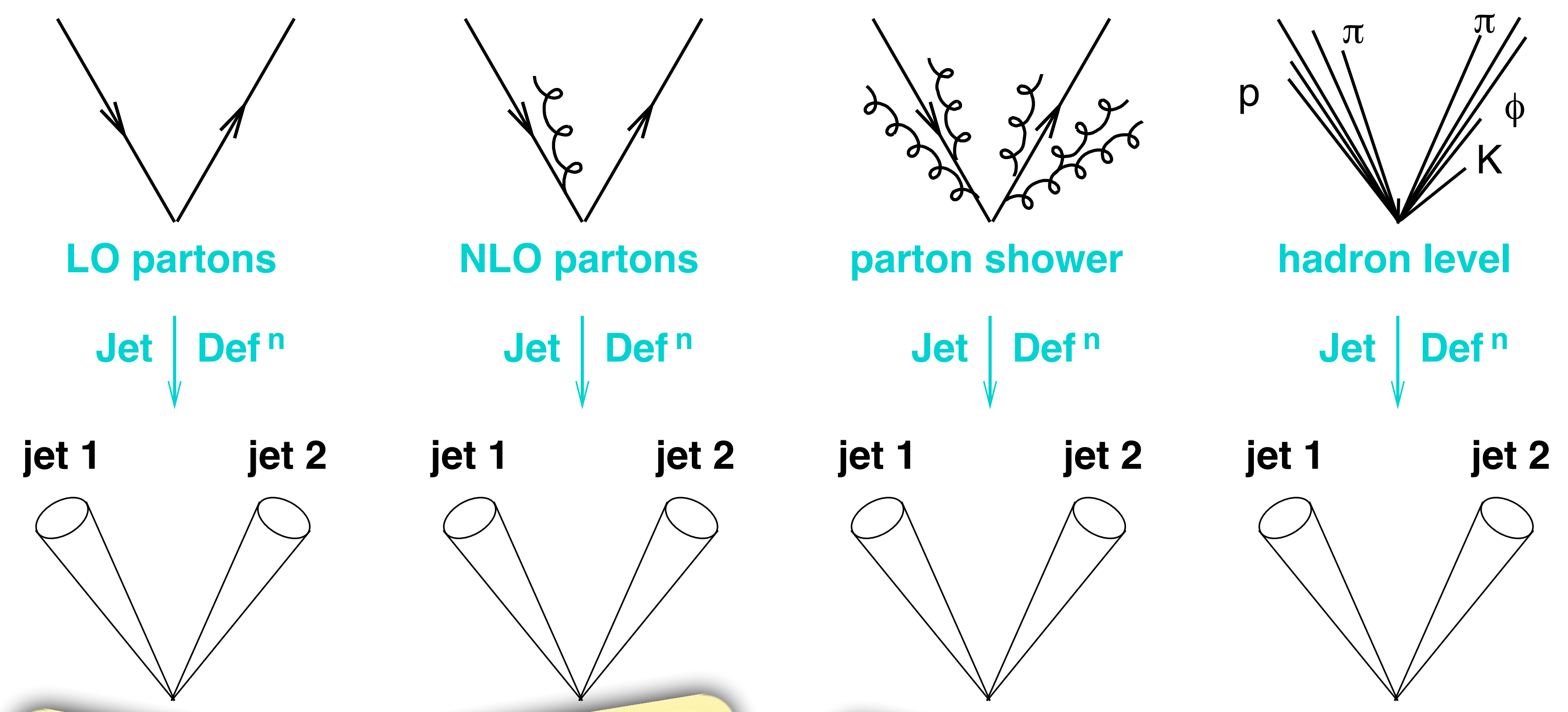
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Jet Reconstruction

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Infrared safety

- stable against adding soft parton emission

Jets

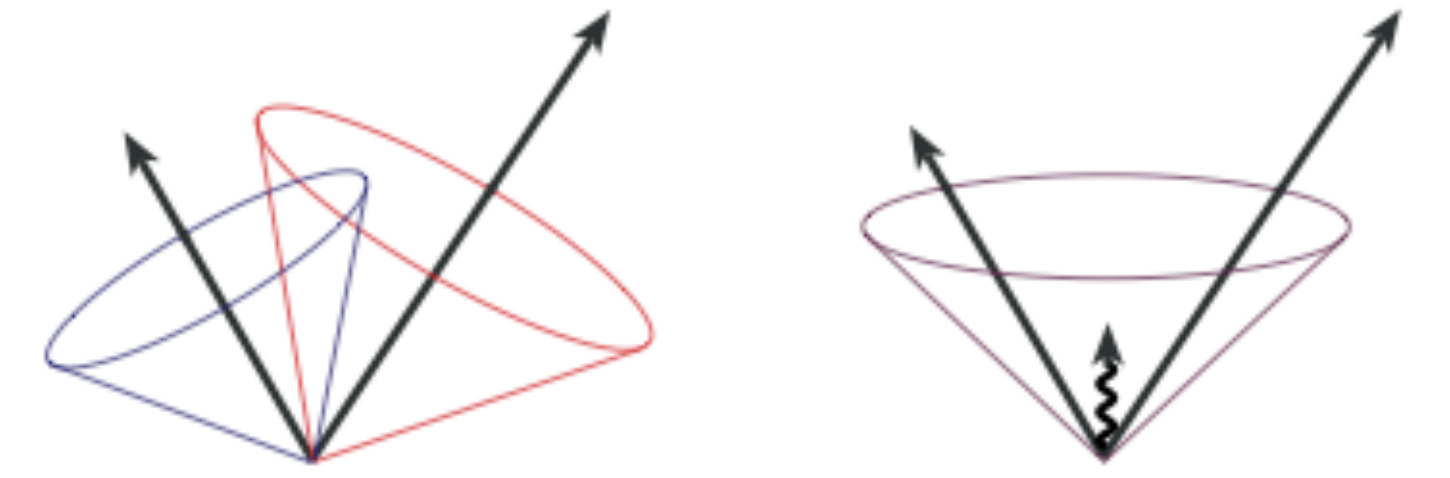
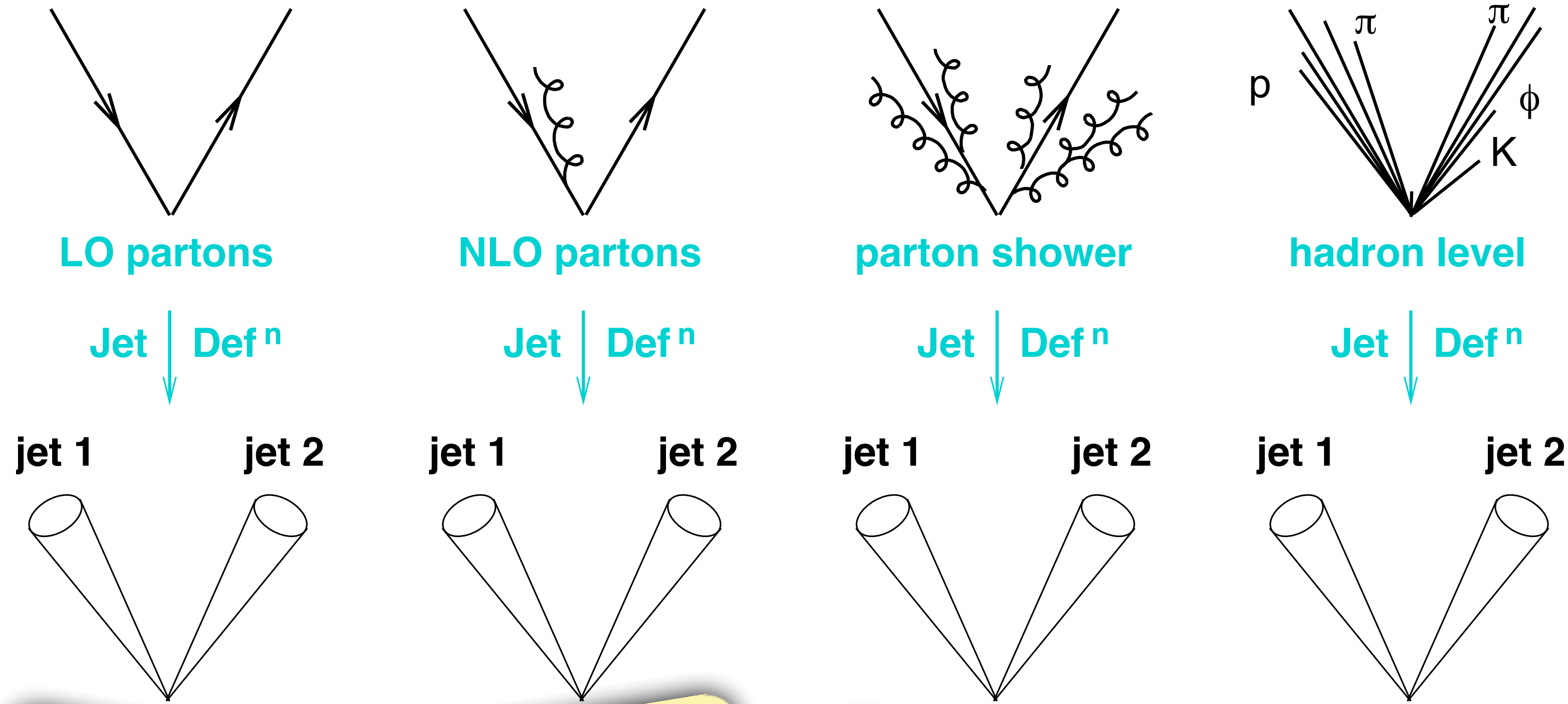
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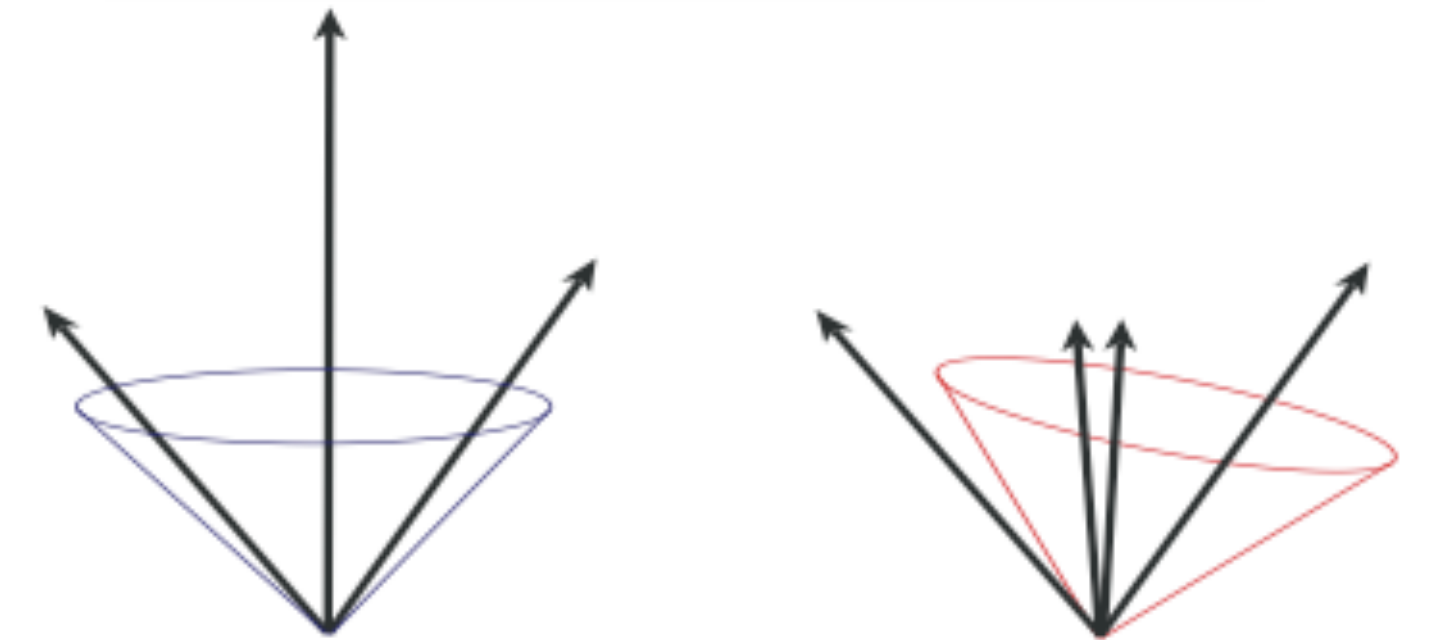
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Collimated

Jets

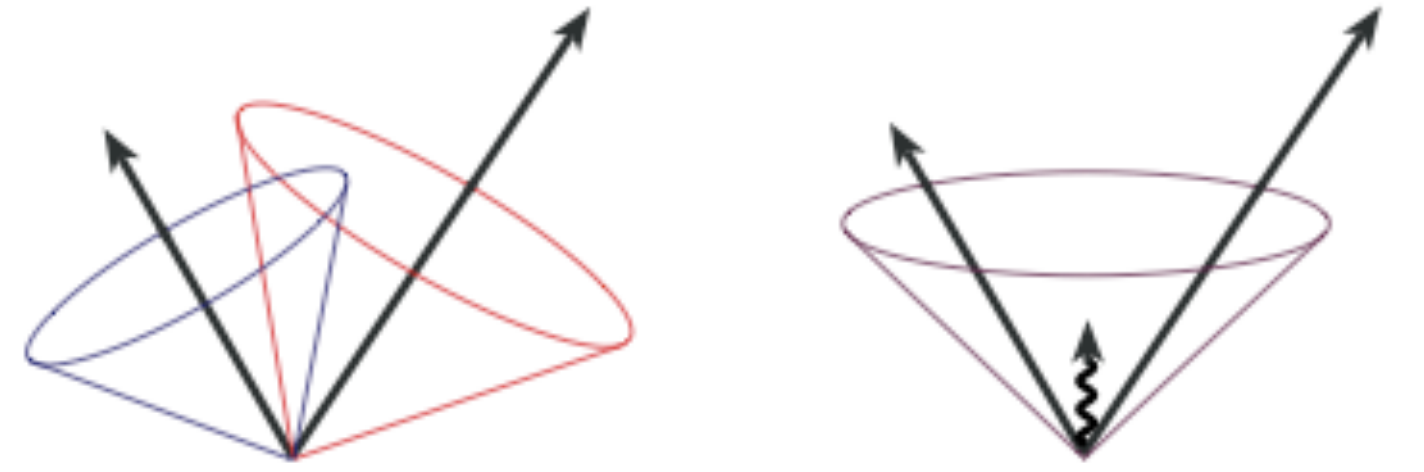
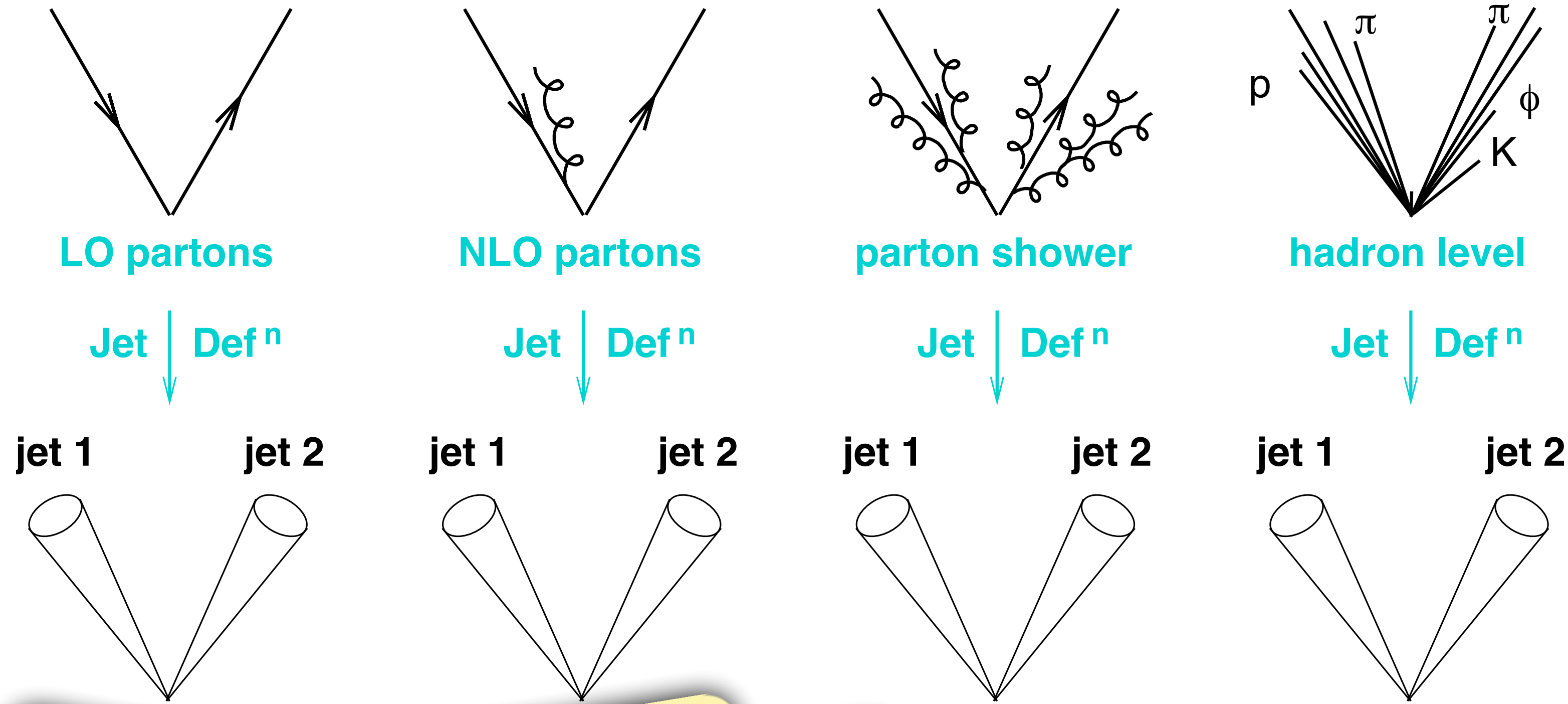
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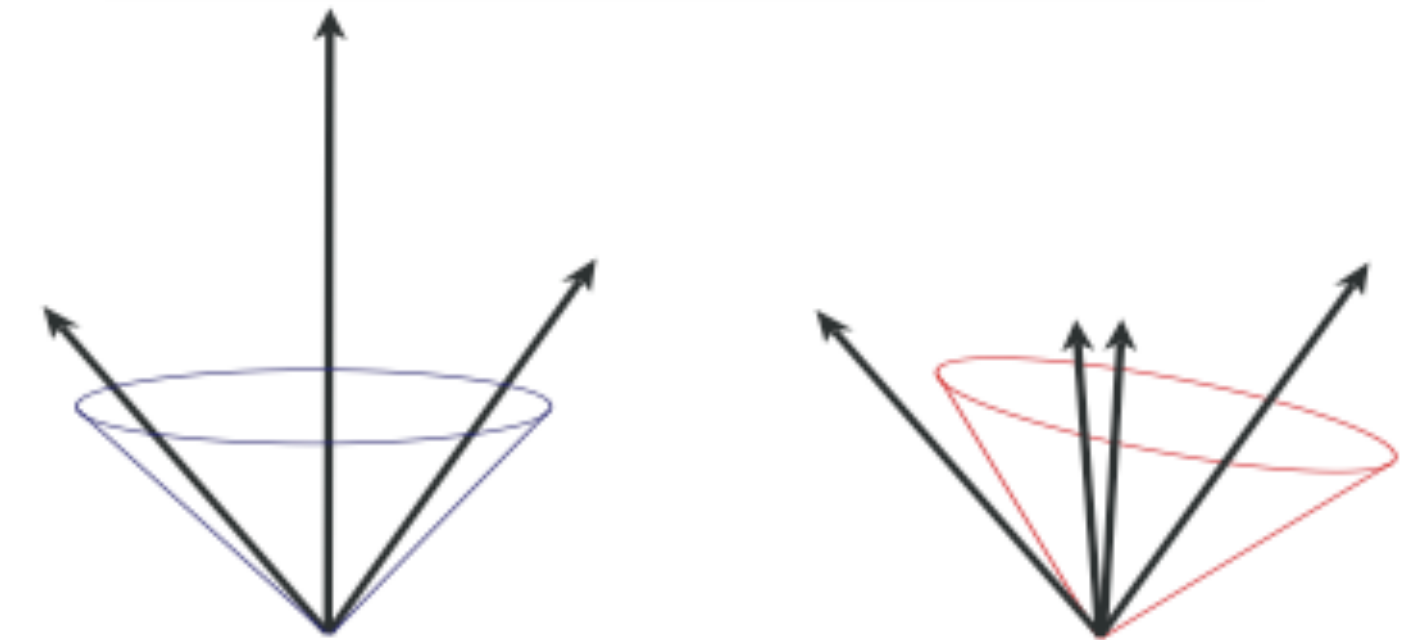
Jet Reconstruction

Diagram from Gavin Salam



Infrared safety

- stable against adding soft parton emission



Collinear safety

- stable against replacing any parton with collinear pair

Collinear safety

Jets

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Jets

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Jet Reconstruction

Jet Reconstruction

Iterative Cone Algorithms

- Historically used (before LHC) at hadron colliders
- But also tried at lepton colliders

Jet Reconstruction

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Sequential Clustering Algorithms

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- Now standard at LHC

Jet Reconstruction

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Sequential Clustering Algorithms

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Experimental Input

- Fundamentally, just a collection of 4-momenta, not more not less
- Historically
 - Reconstructed calo cells/clusters
 - Reconstructed tracks
- LHC (& LEP) Era(s)
 - Reconstructed particles $\{e^\pm, \gamma, \mu^\pm, h^\pm, h^0\}$

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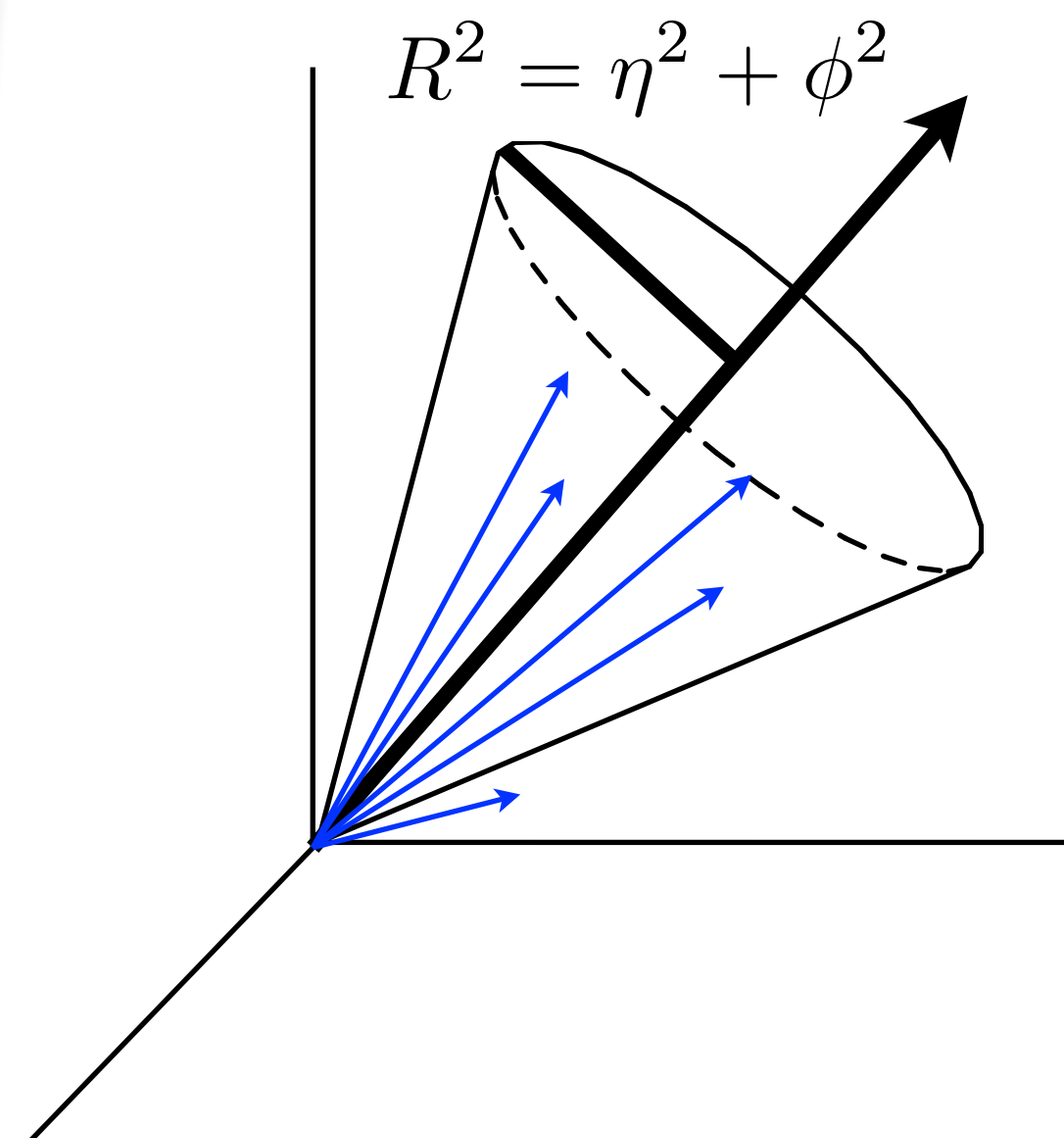
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Iterative Cone Algorithm

- Associate particles to jet if within a cone of radius R in (η, ϕ) space
 - Start with trial seed axis
 - calc centroid over all particles in cone
- $$\eta_C = \frac{\sum_i p_{T,i} \eta_i}{\sum_i p_{T,i}} ; \phi_C = \frac{\sum_i p_{T,i} \phi_i}{\sum_i p_{T,i}}$$
- Throw new trial cone about centroid
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Jet Reconstruction

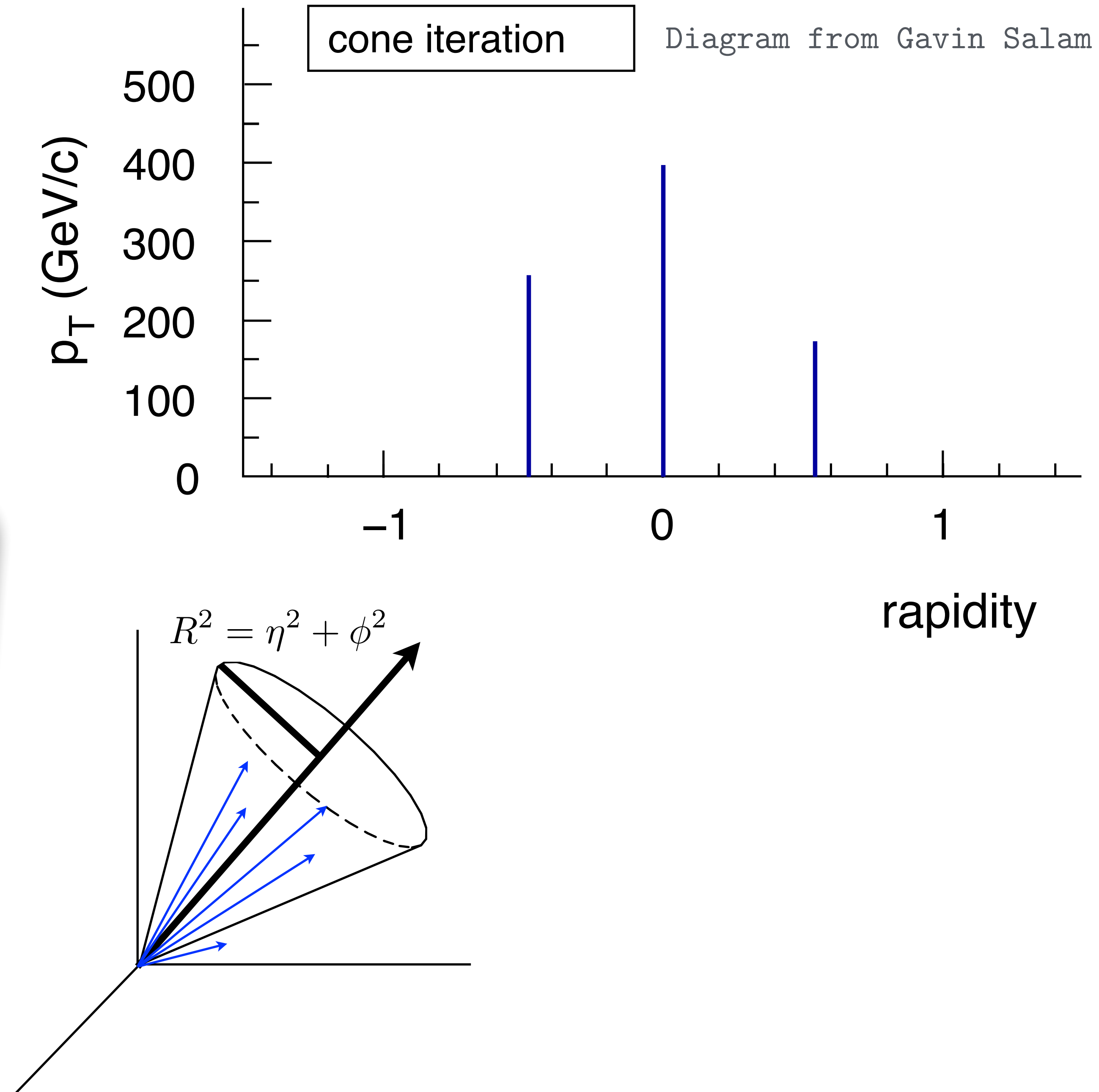
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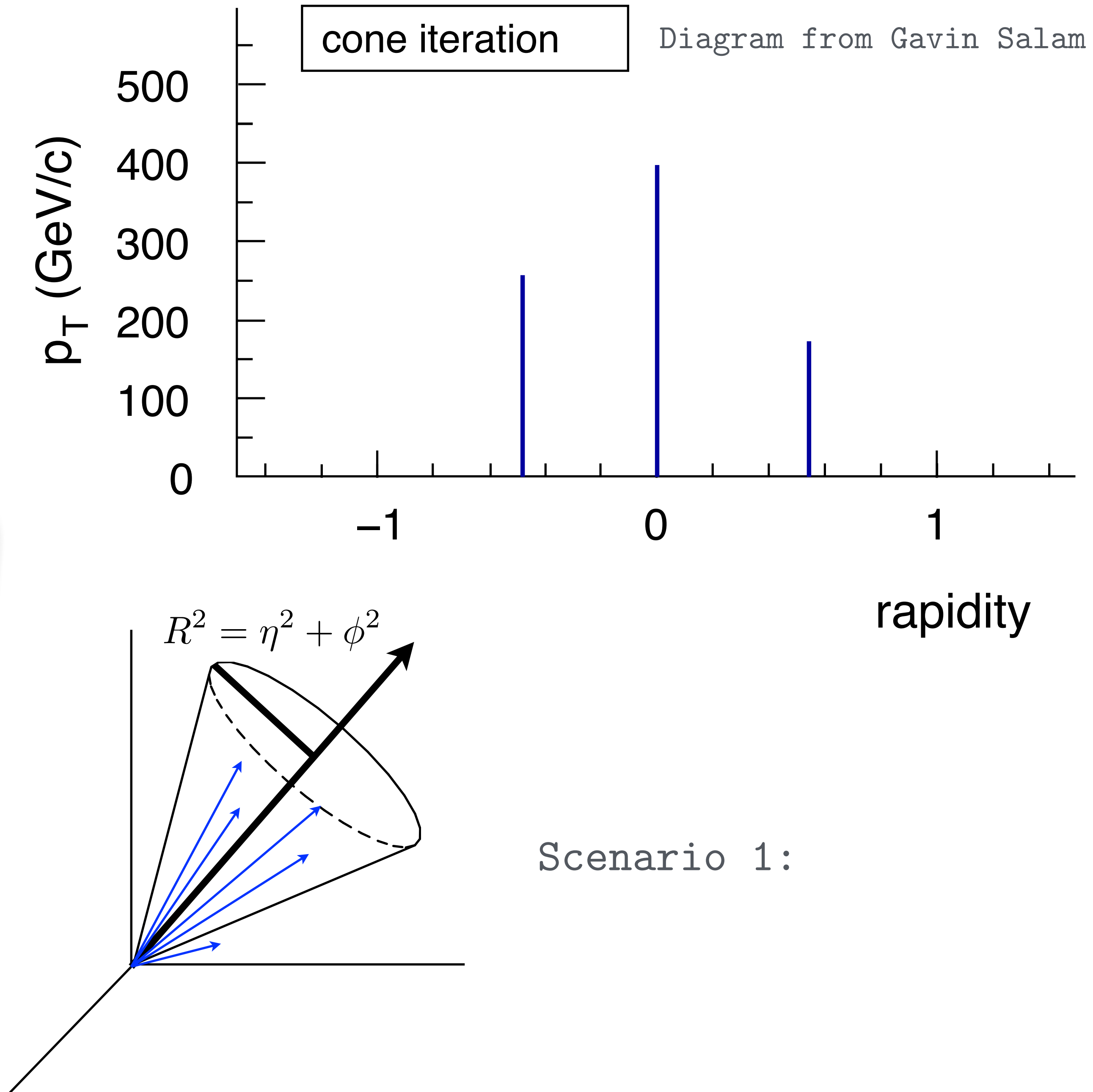
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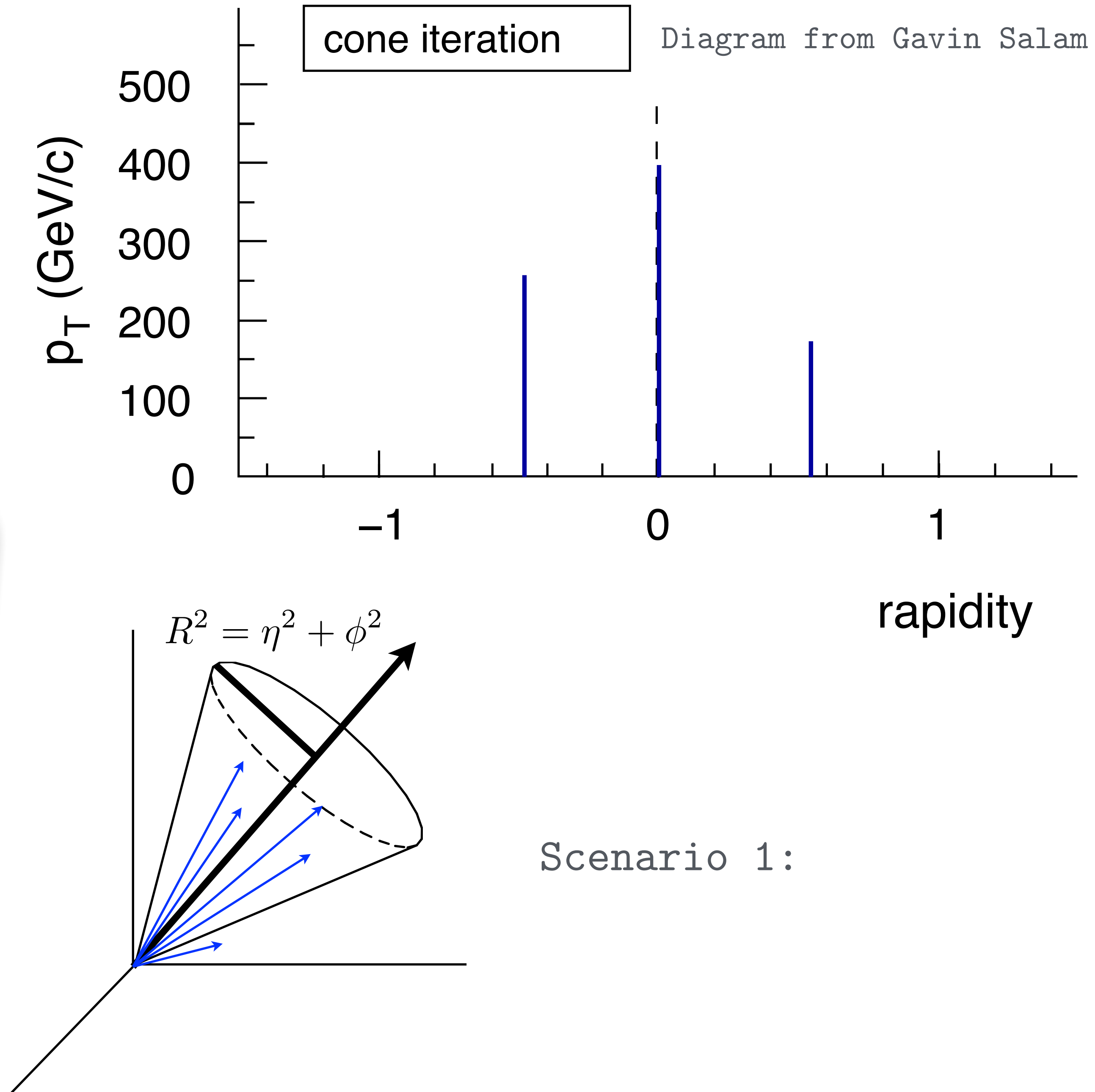
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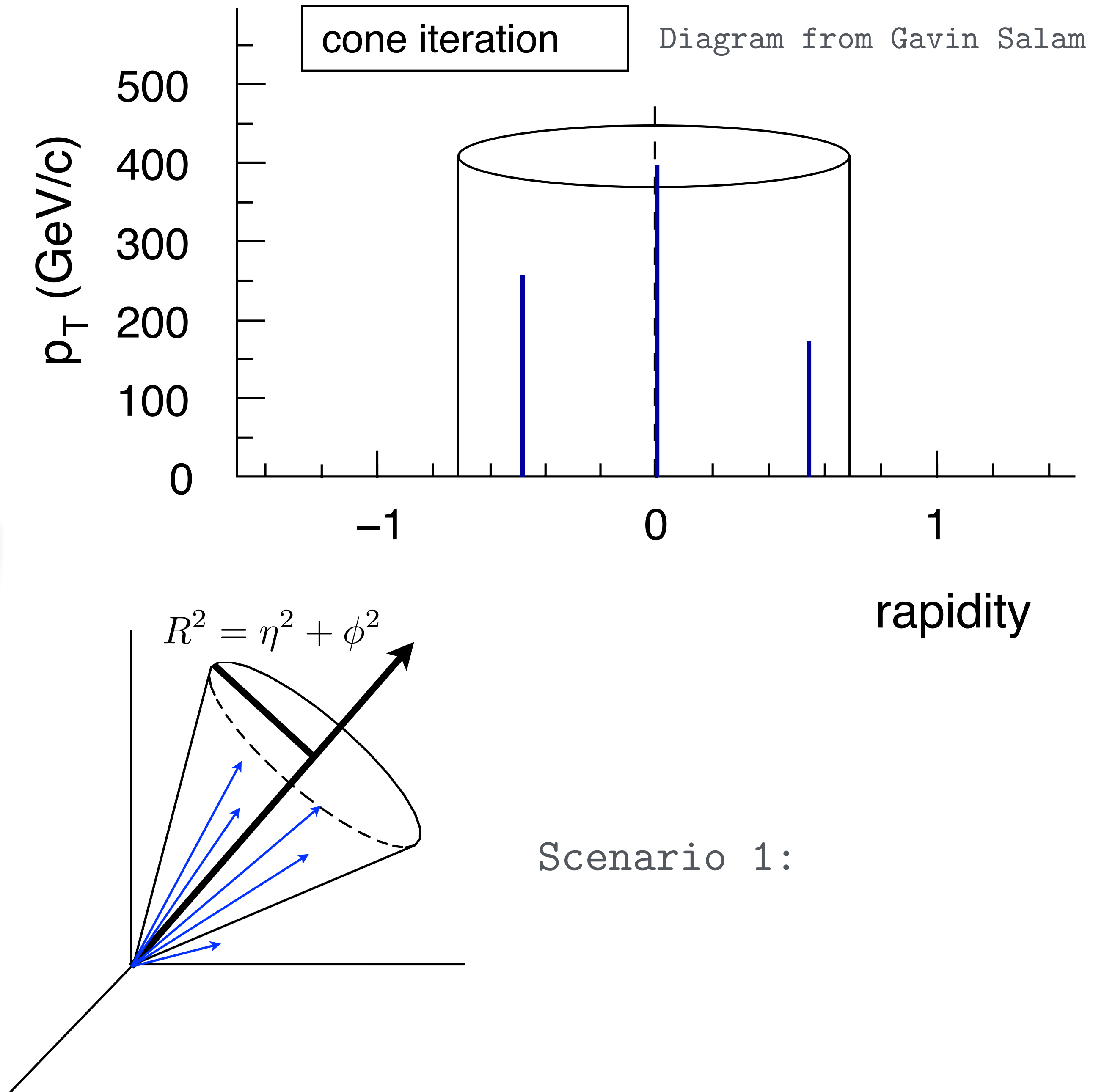
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Jet Reconstruction

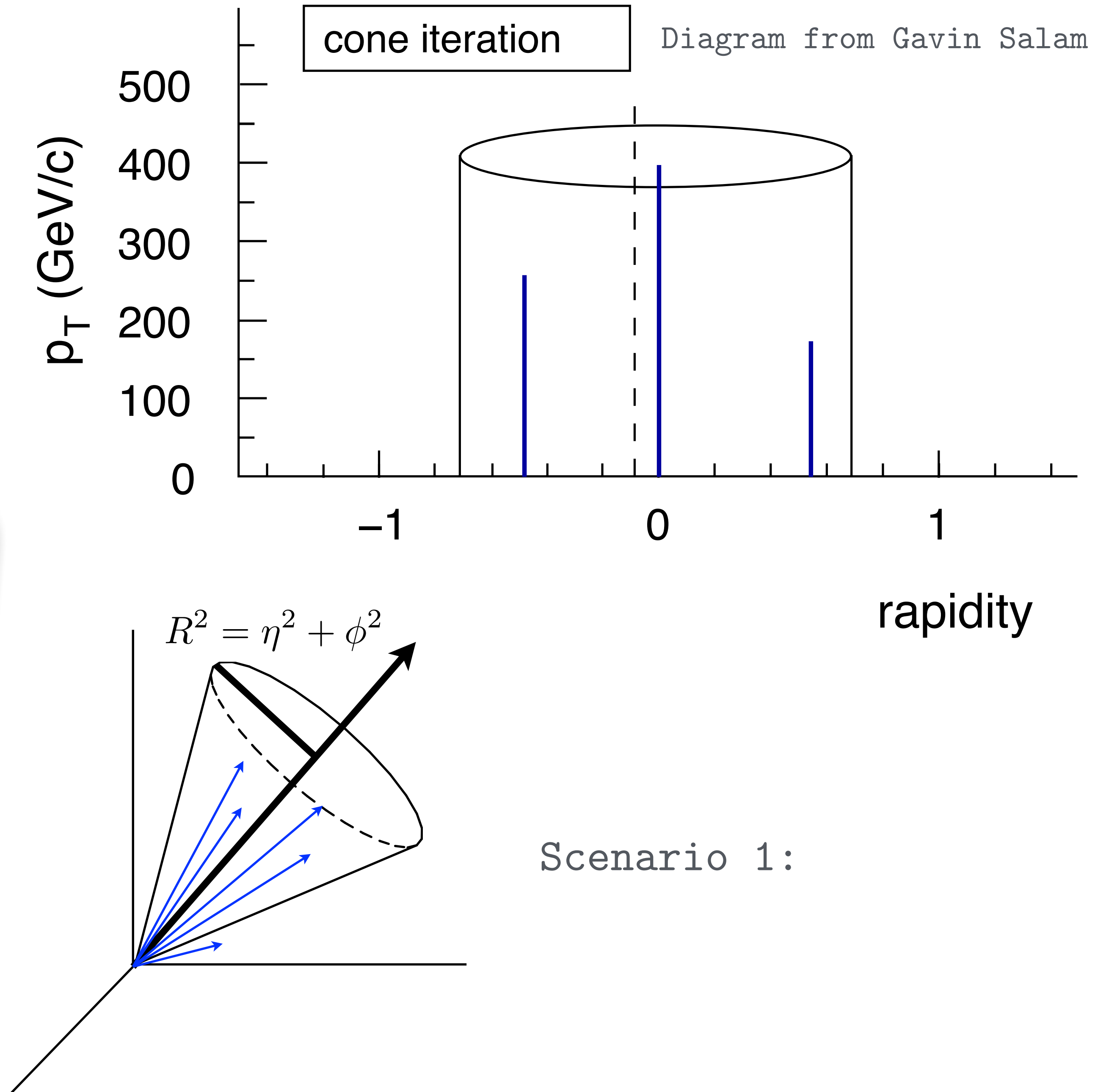
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Jet Reconstruction

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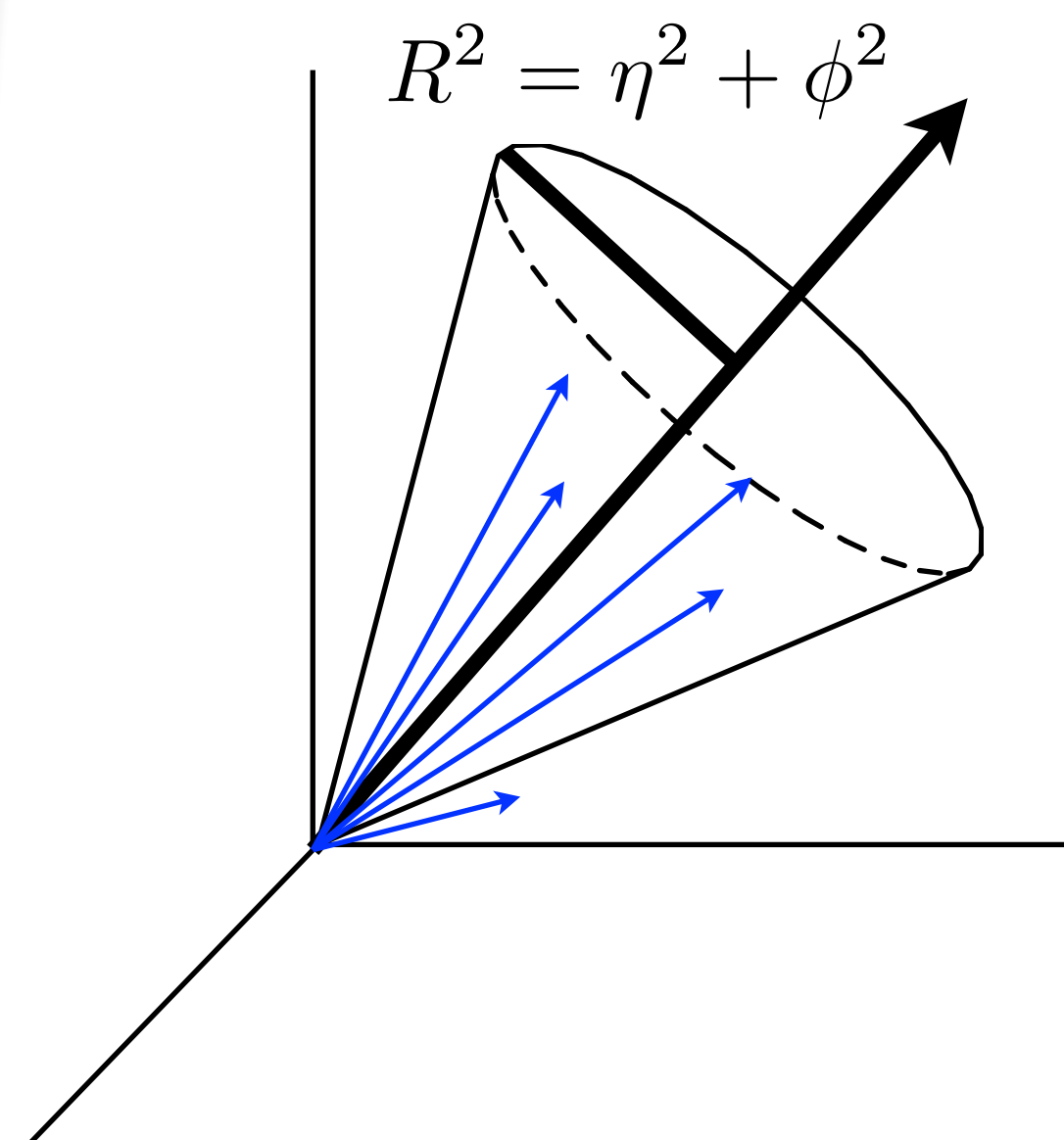
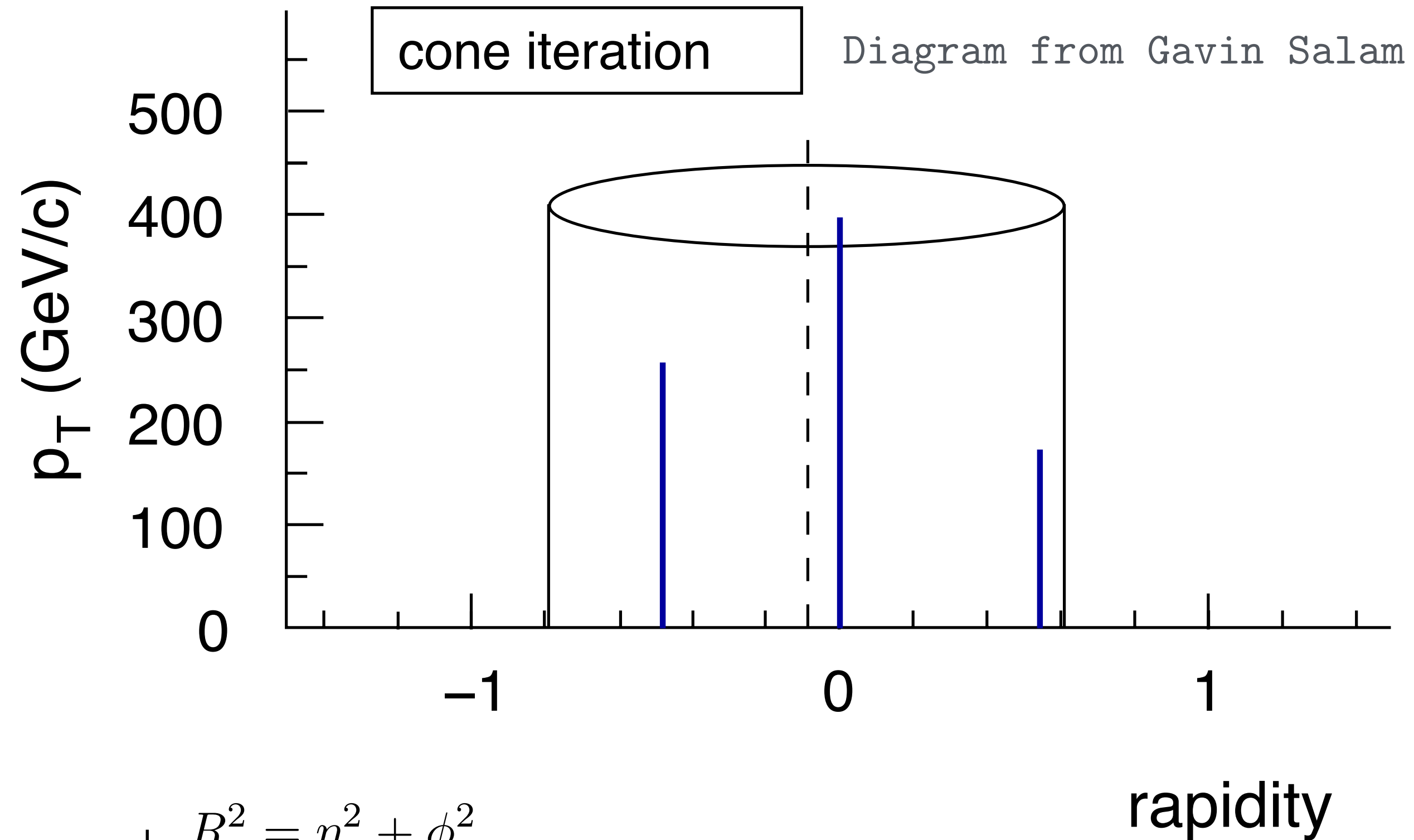
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Scenario 1:

Jet Reconstruction

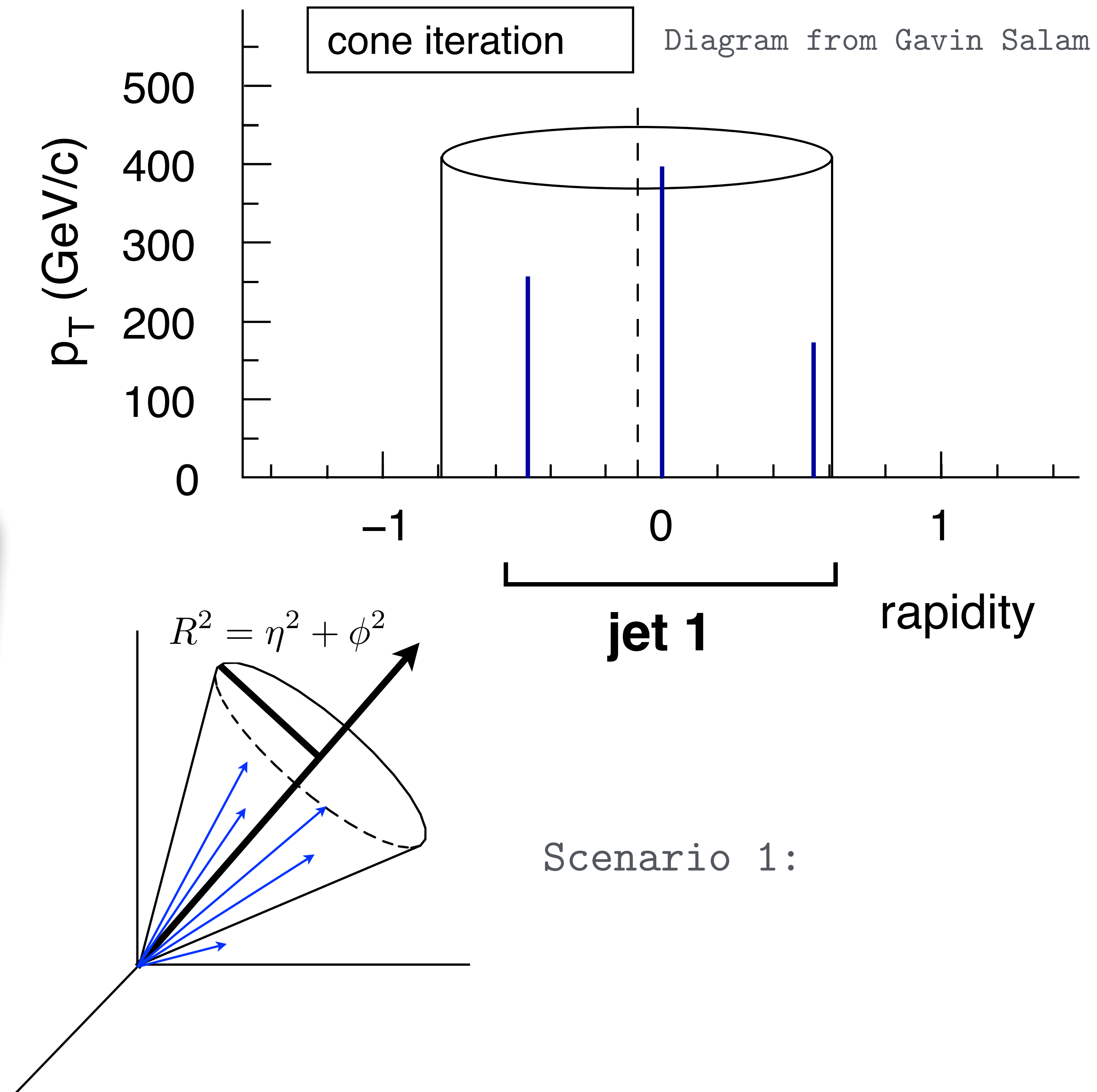
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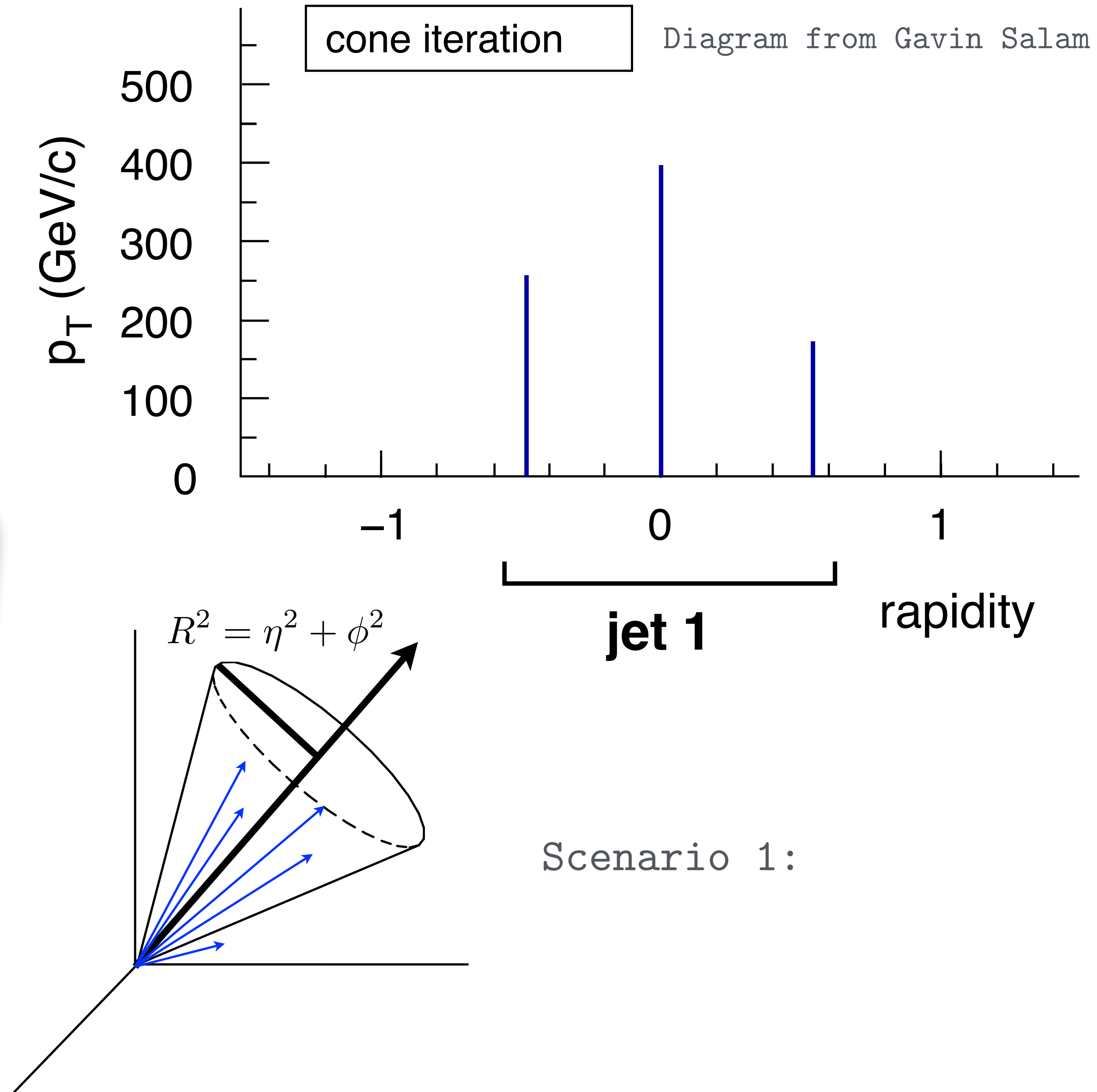
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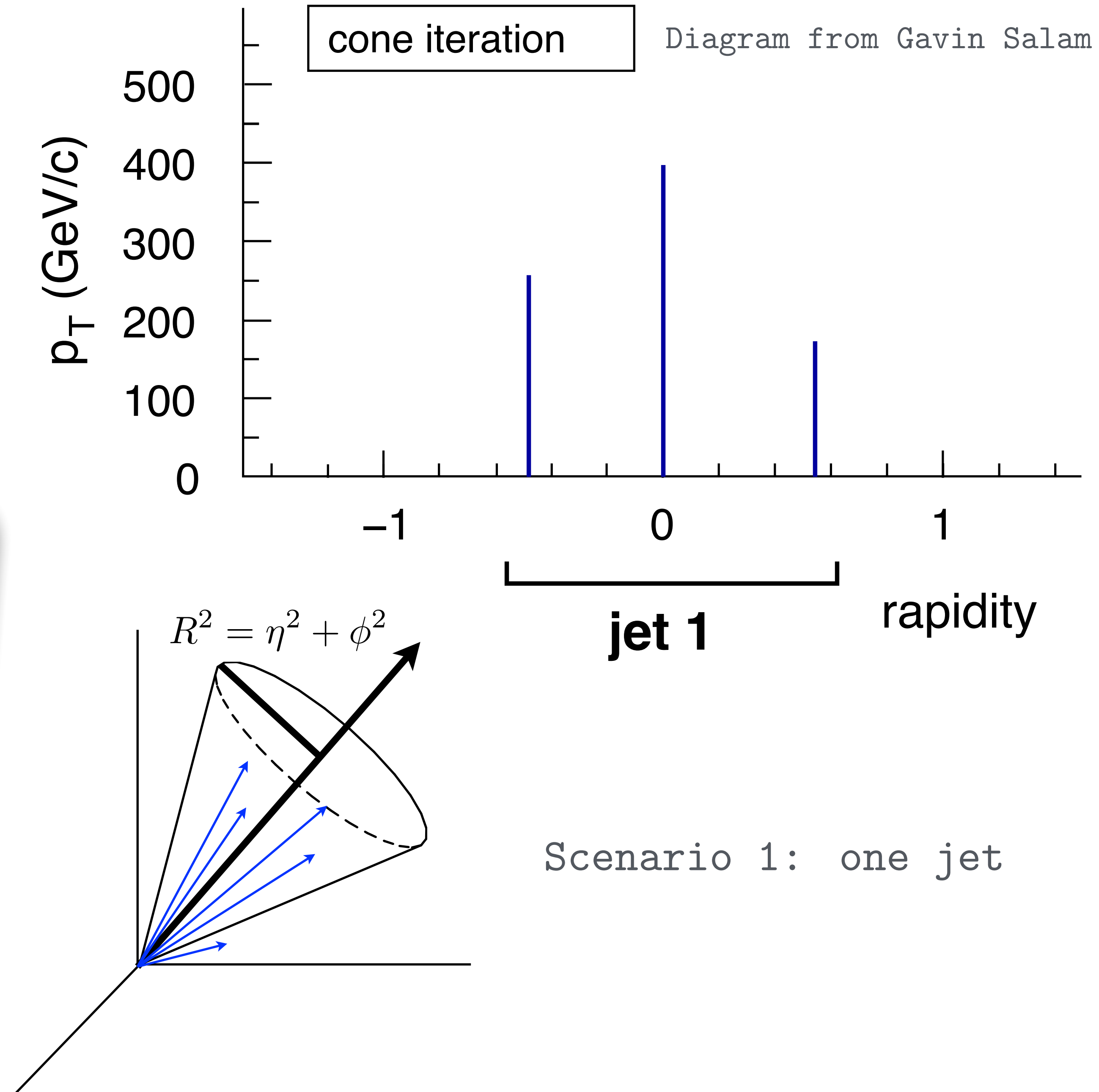
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Iterative Cone Algorithms

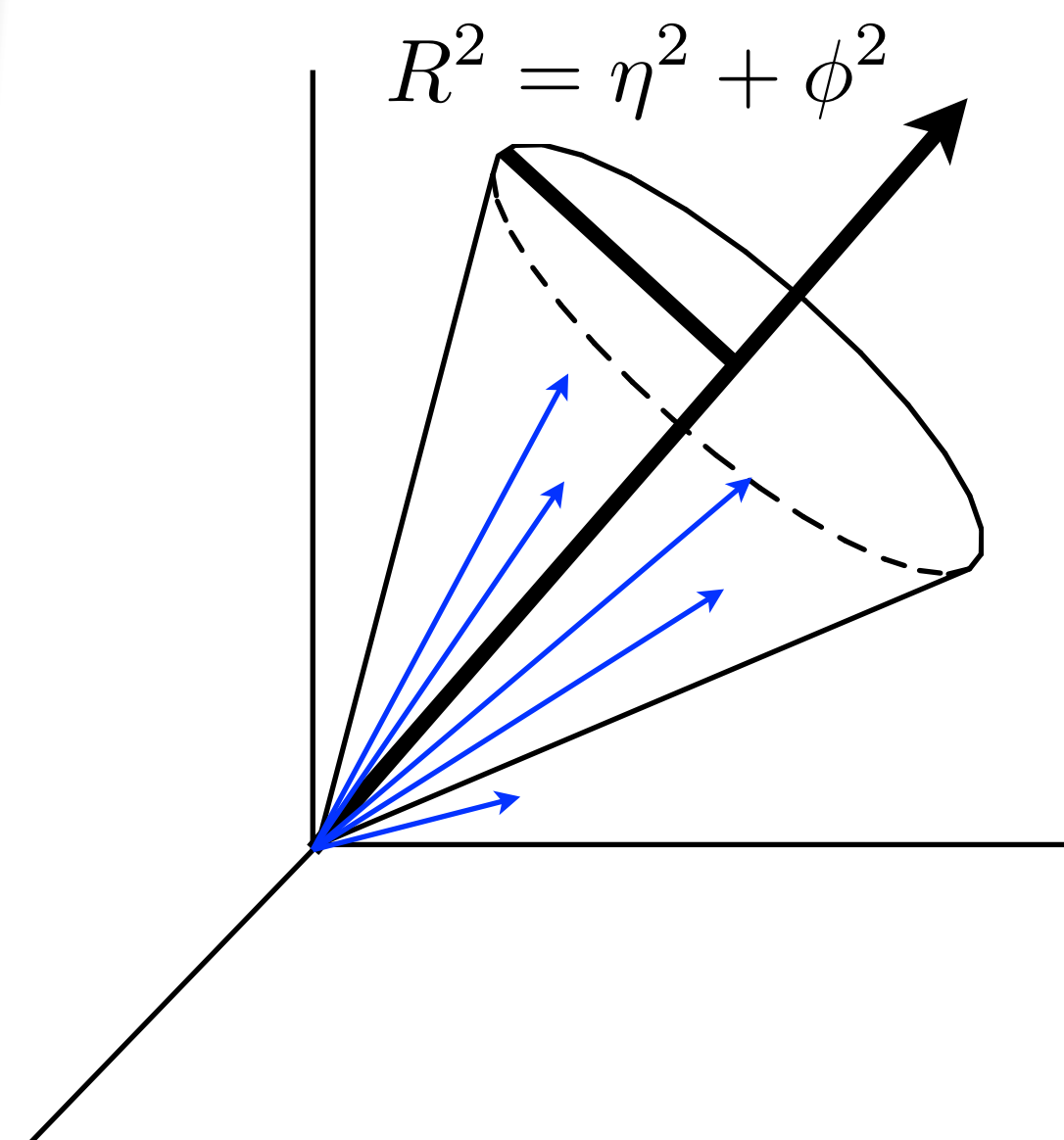
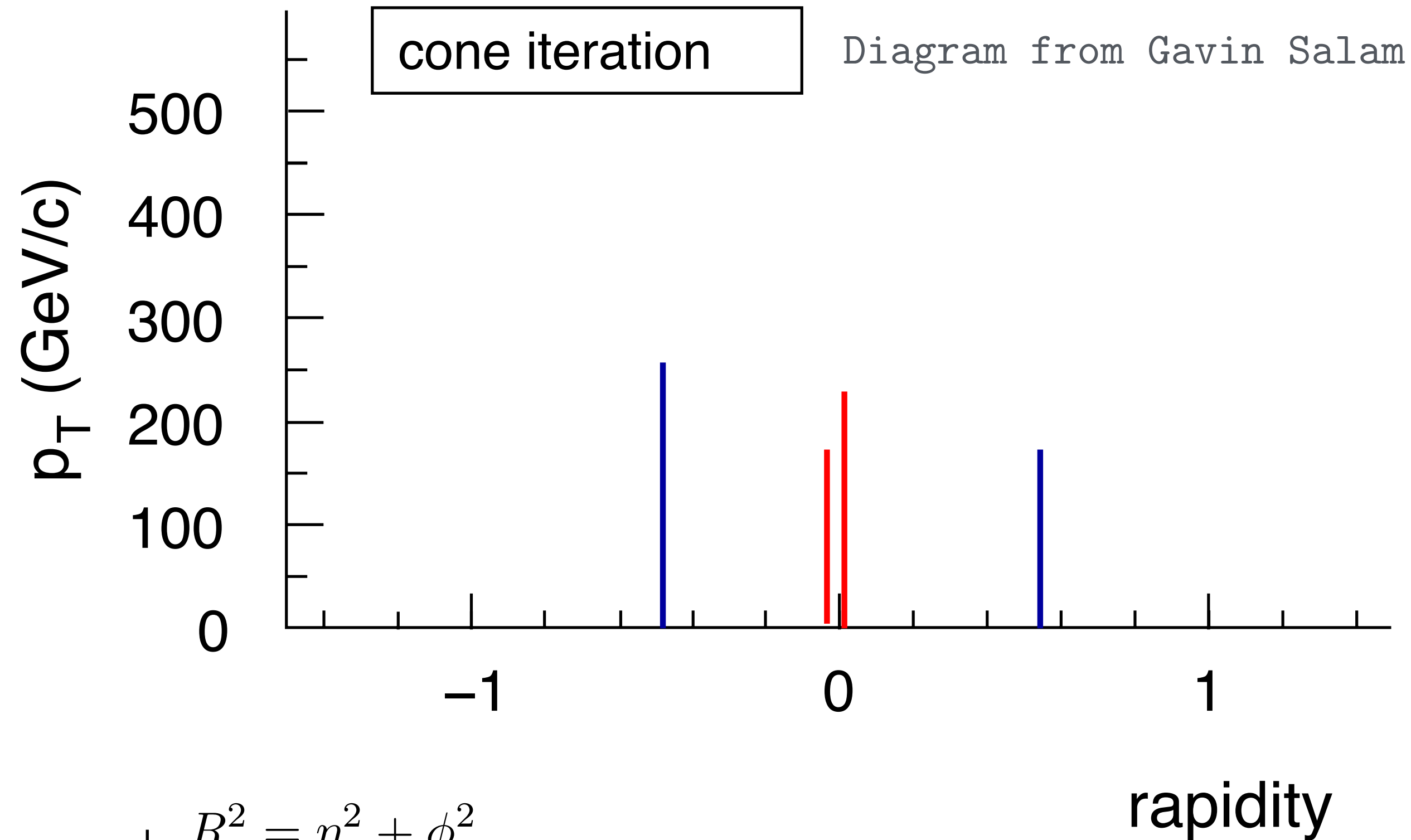
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Scenario 1: one jet

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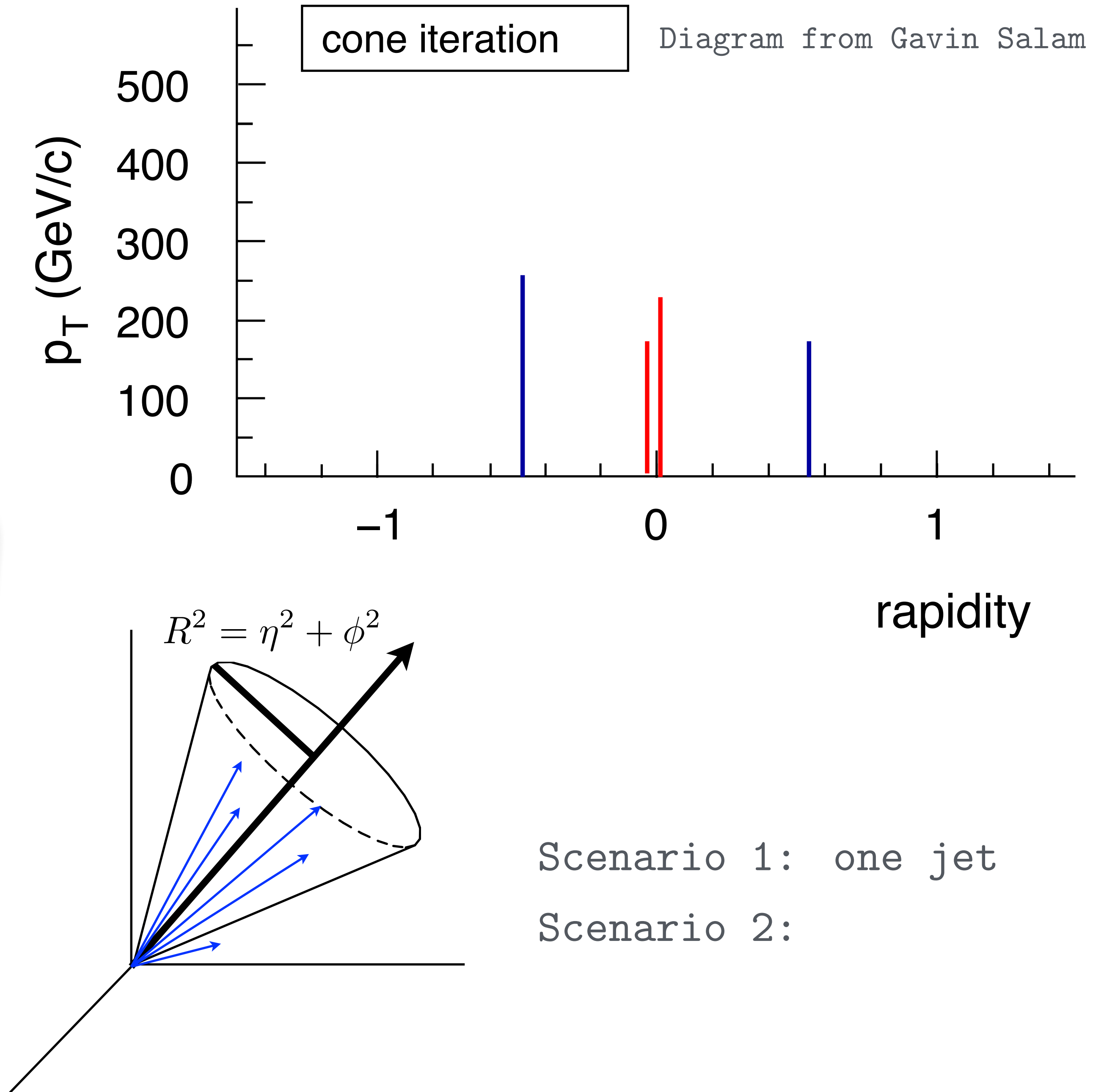
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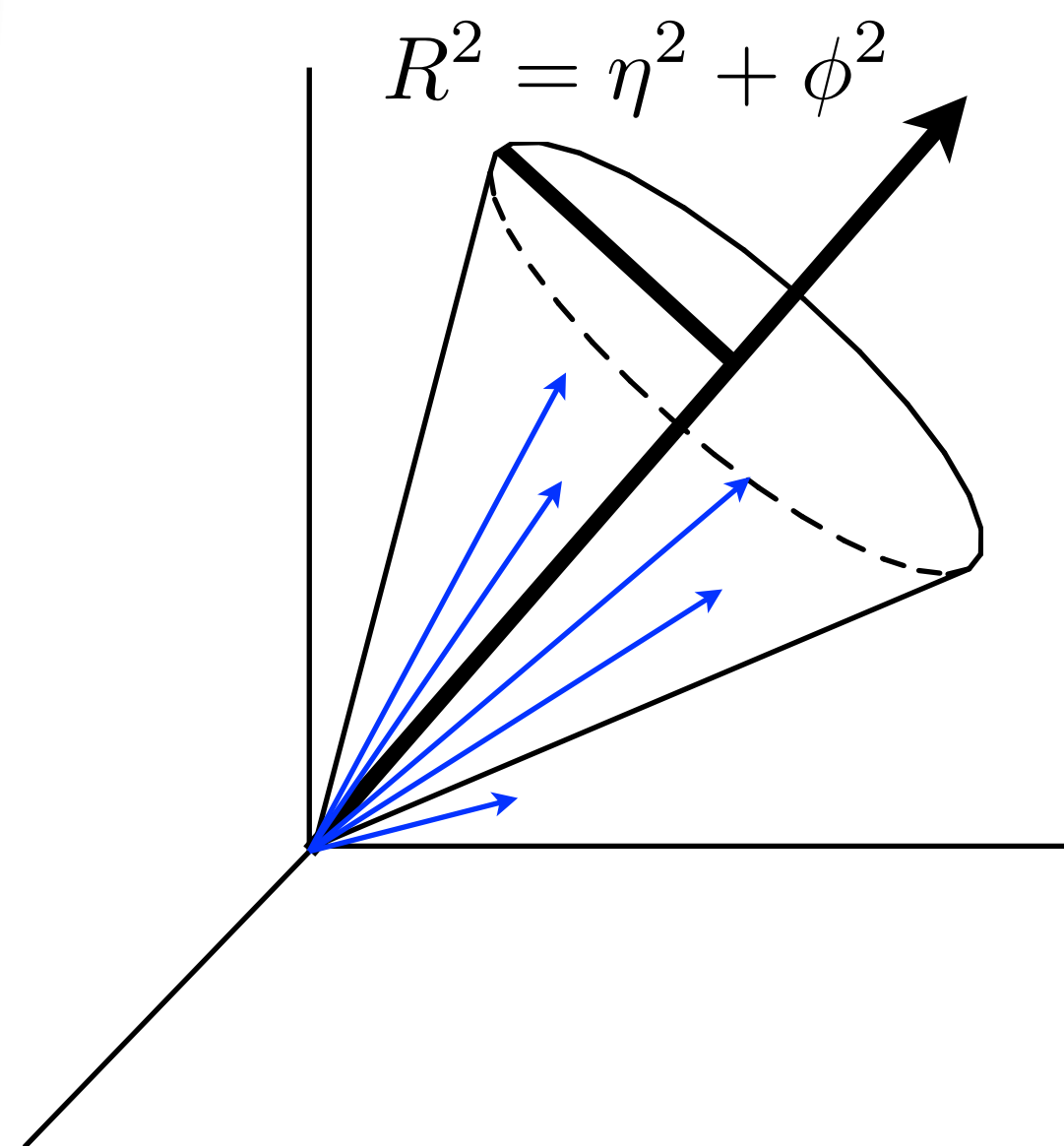
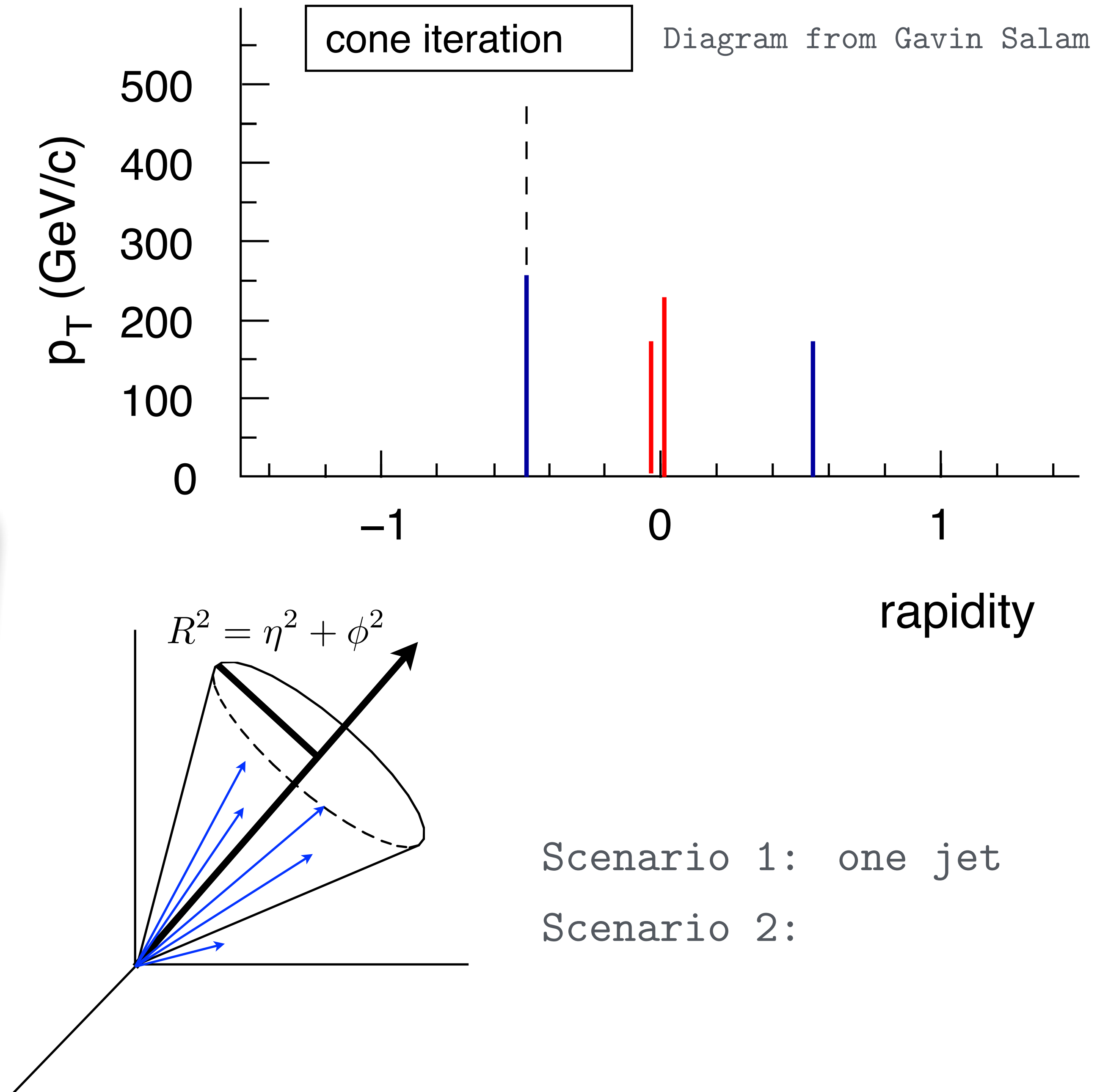
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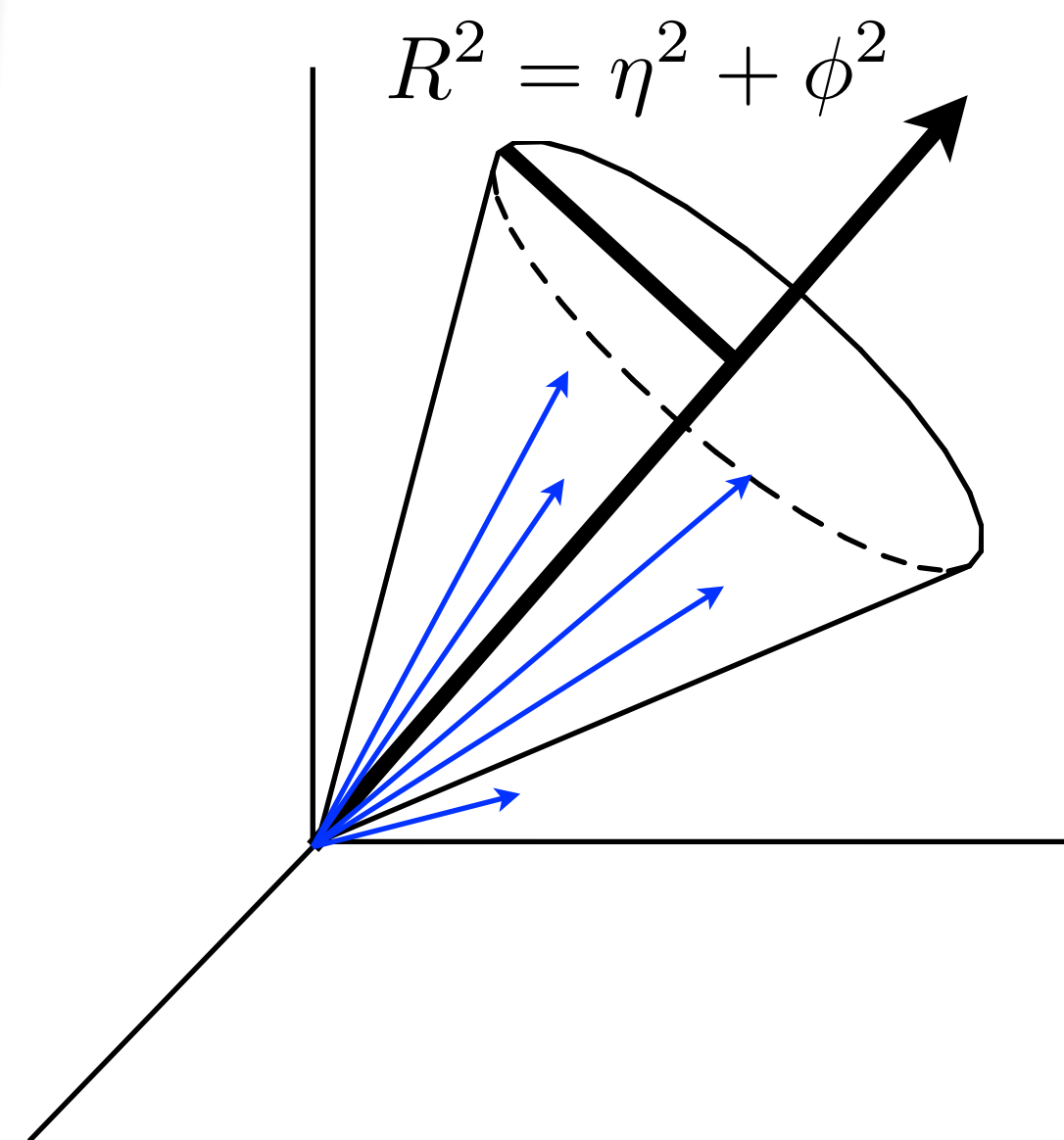
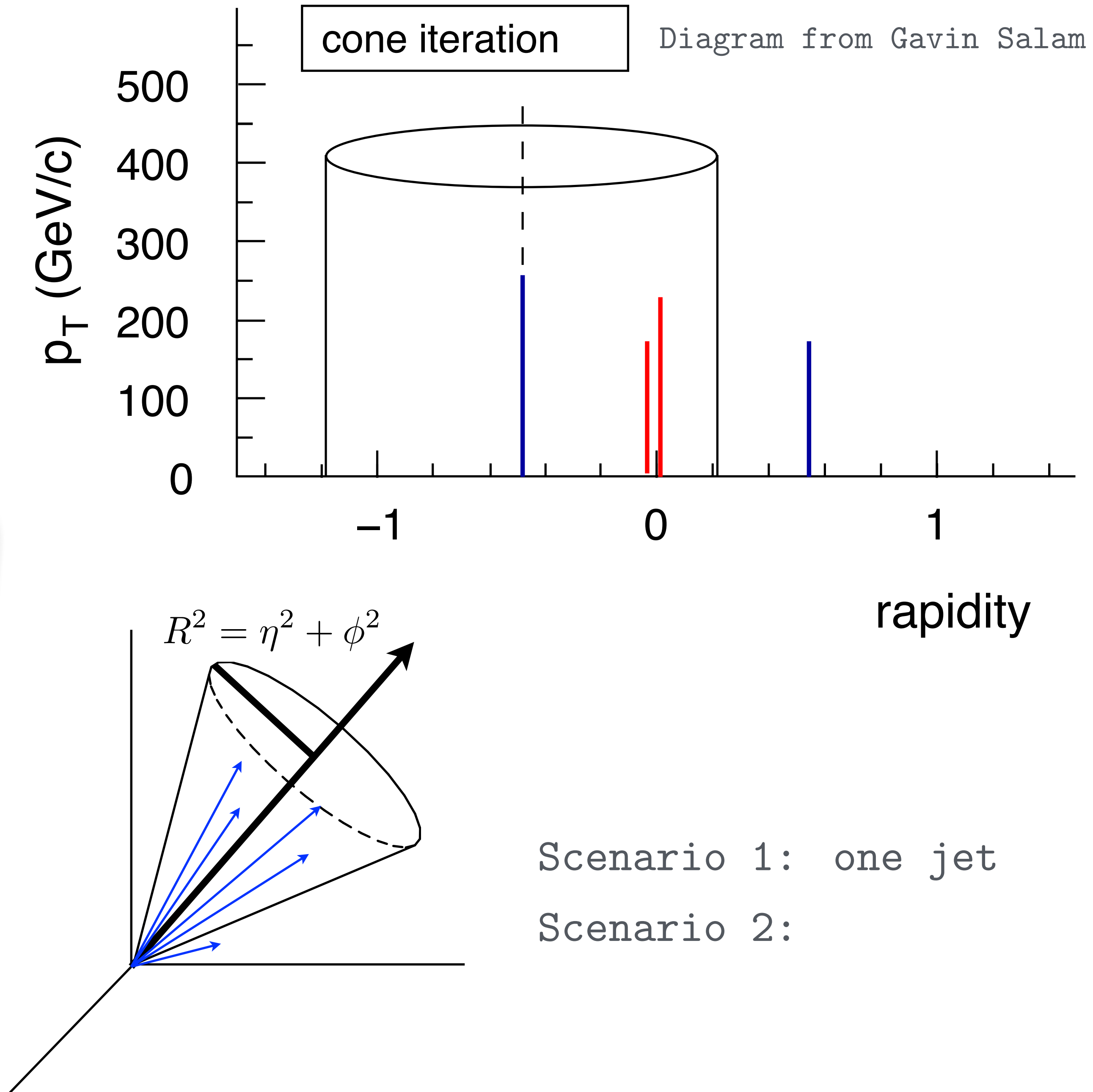
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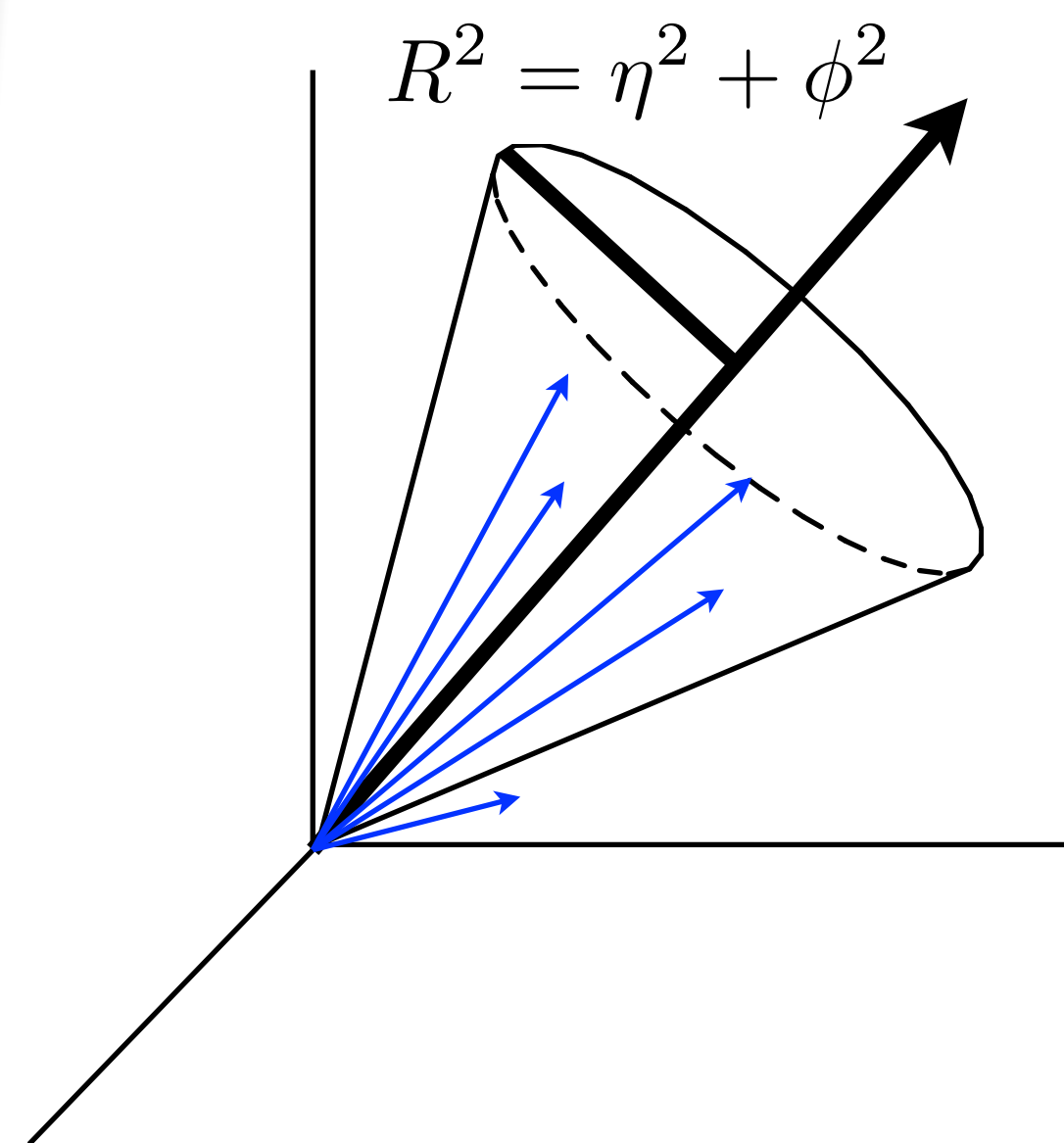
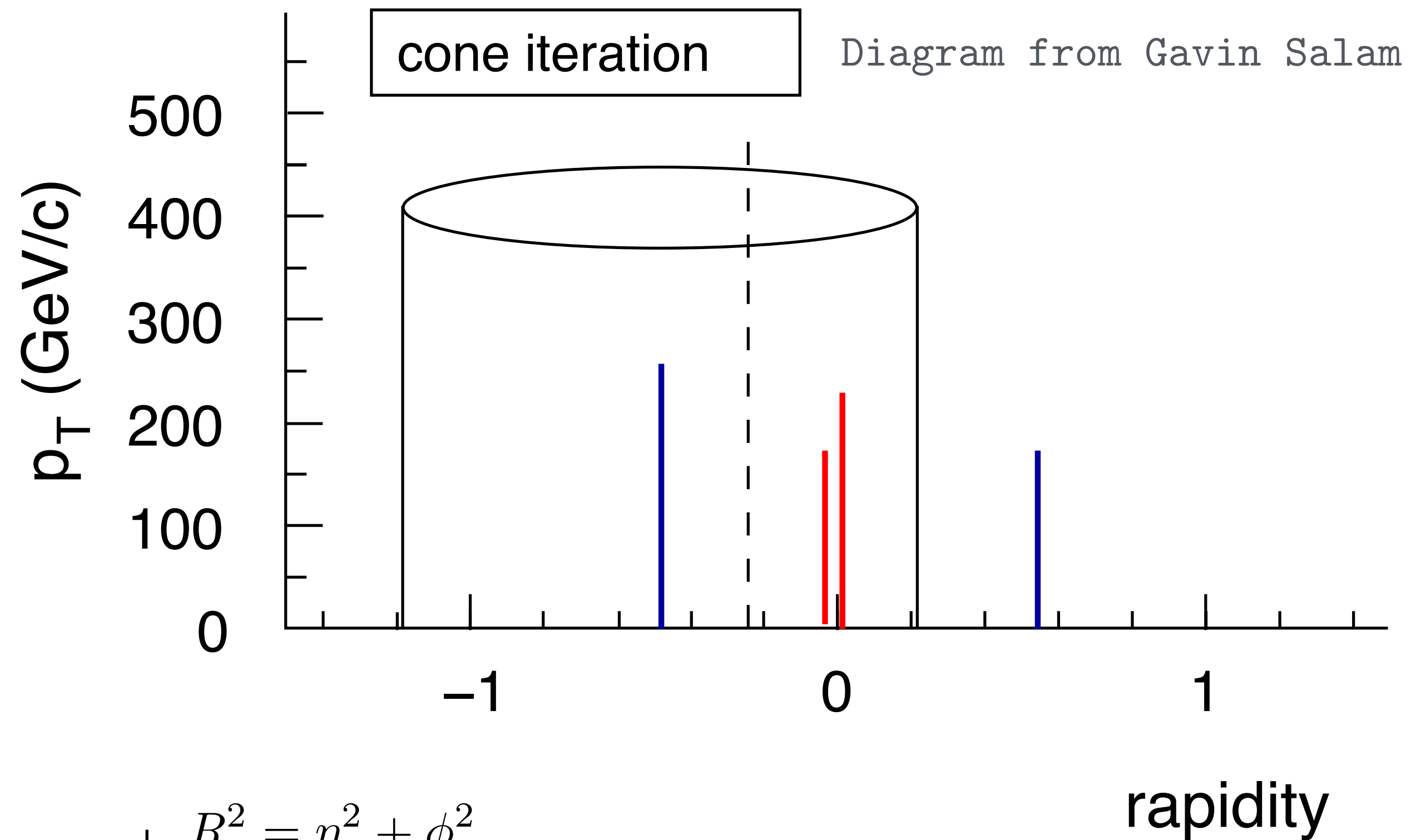
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Scenario 2:

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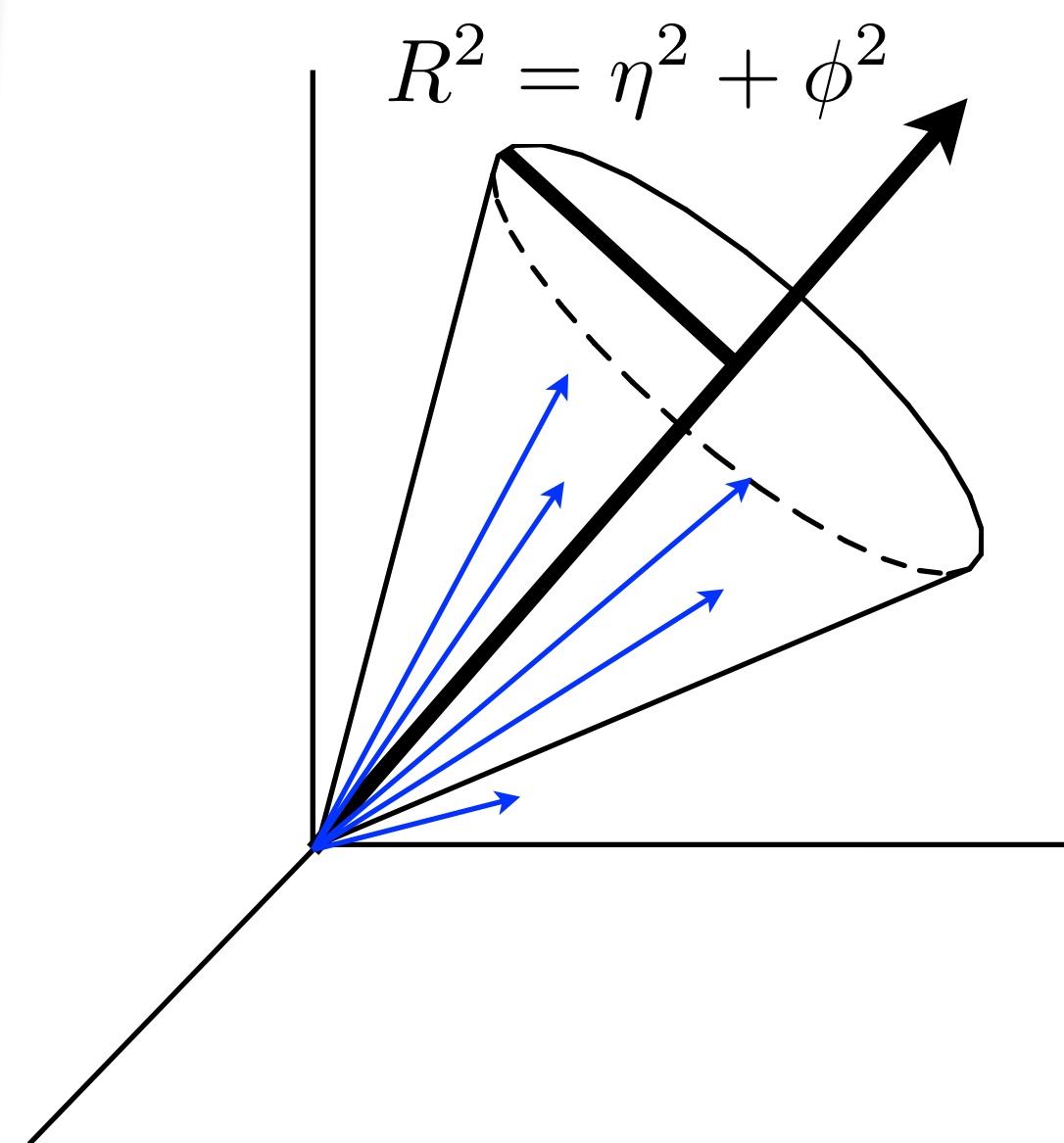
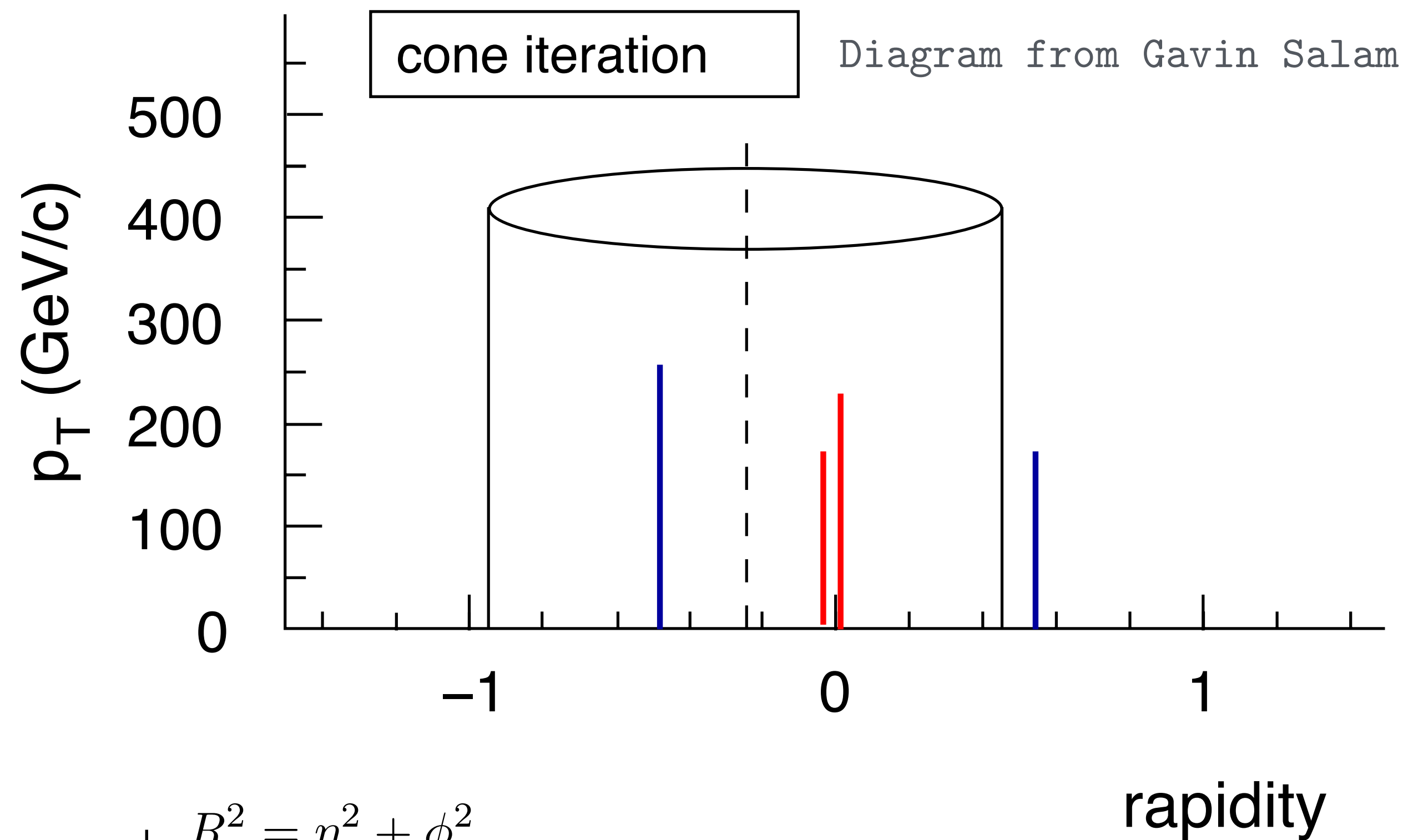
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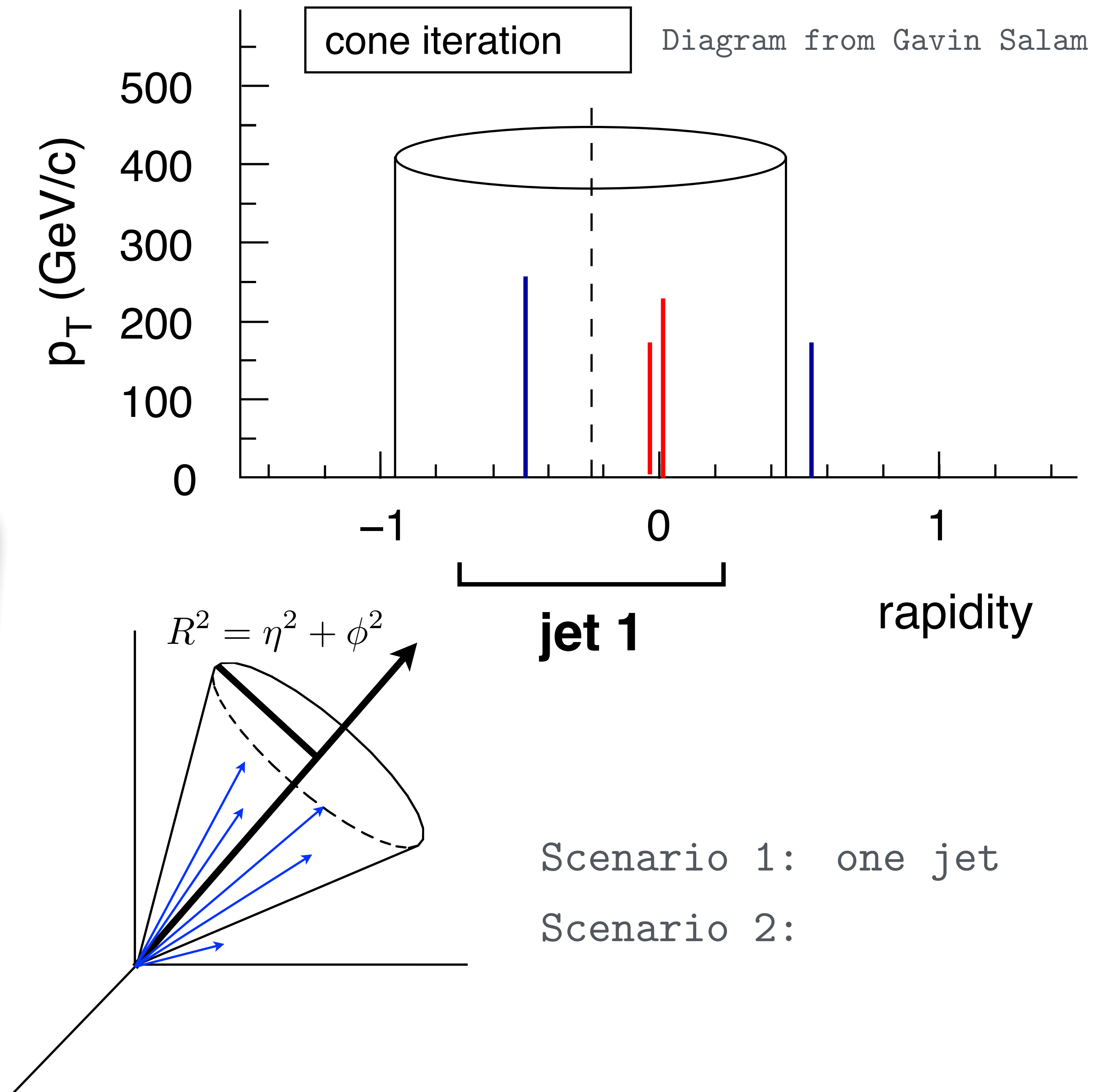
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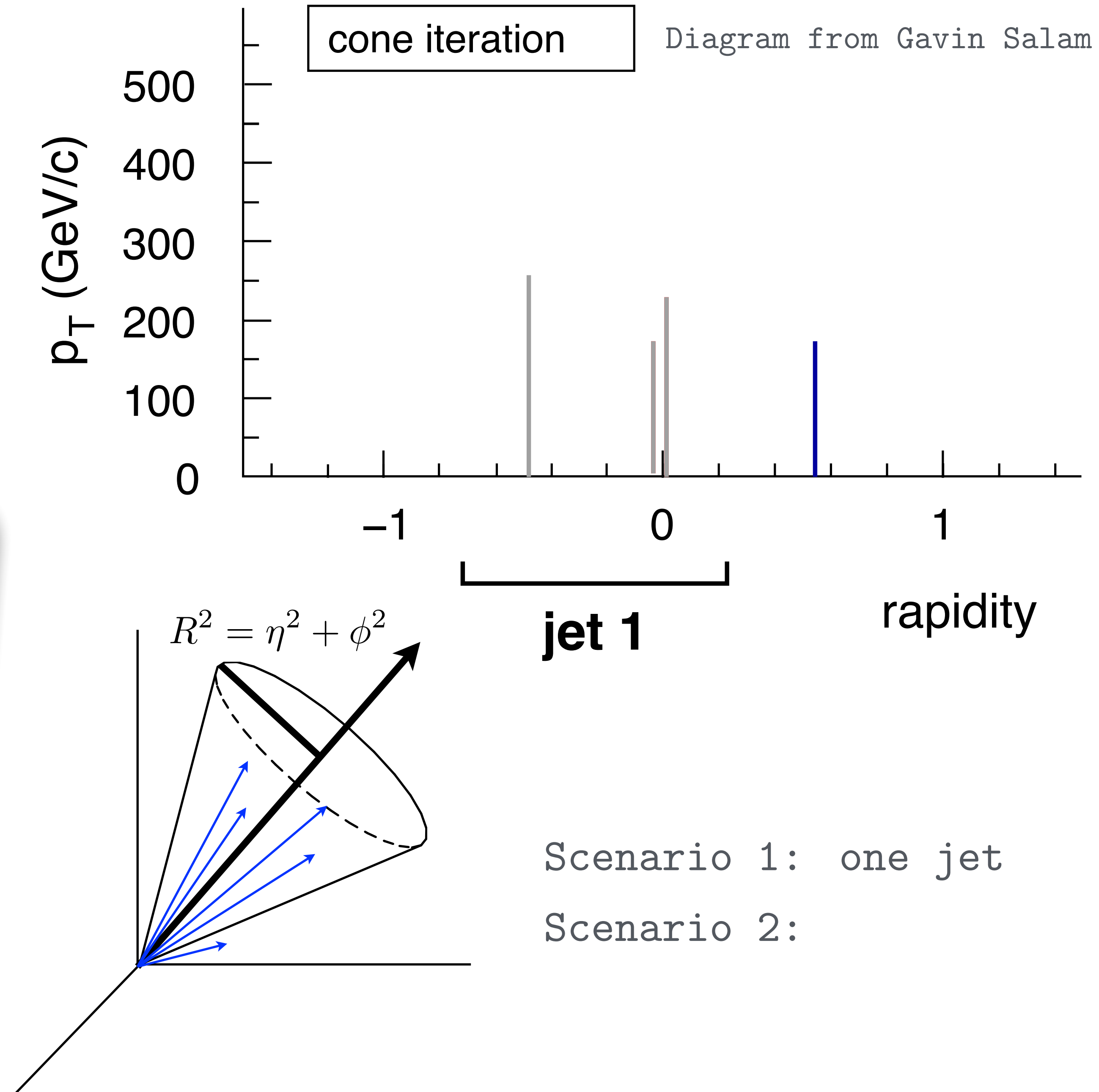
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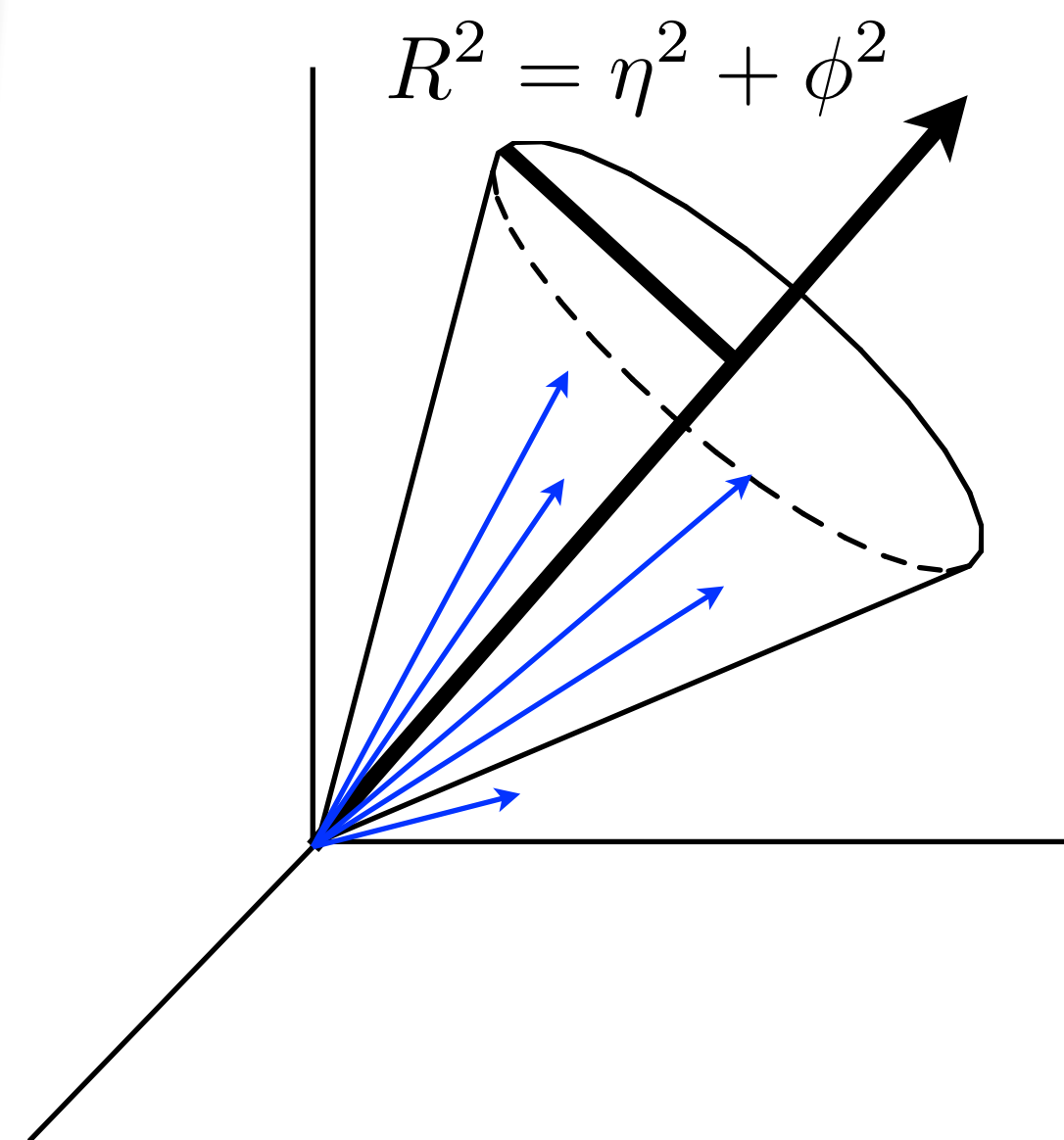
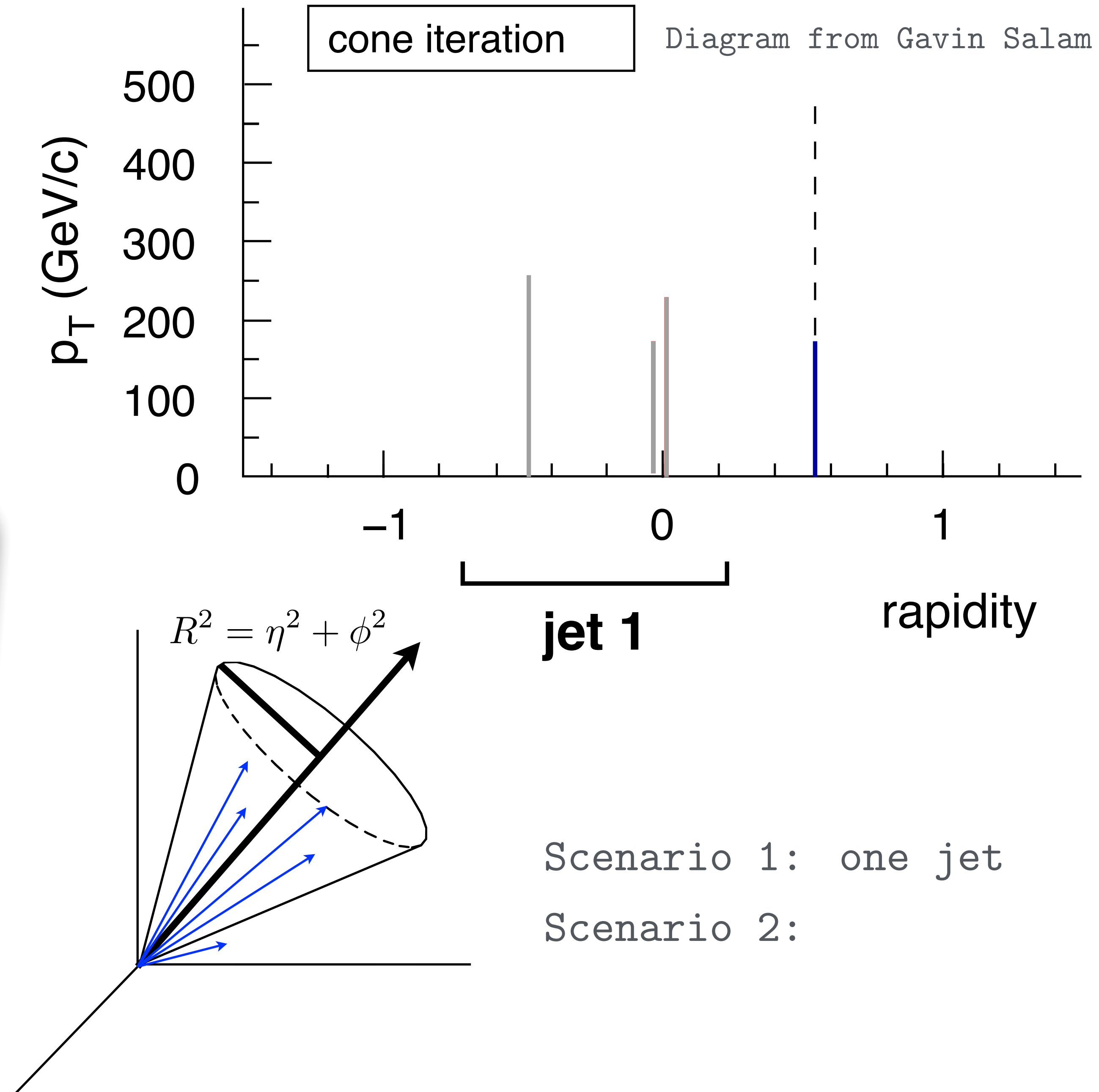
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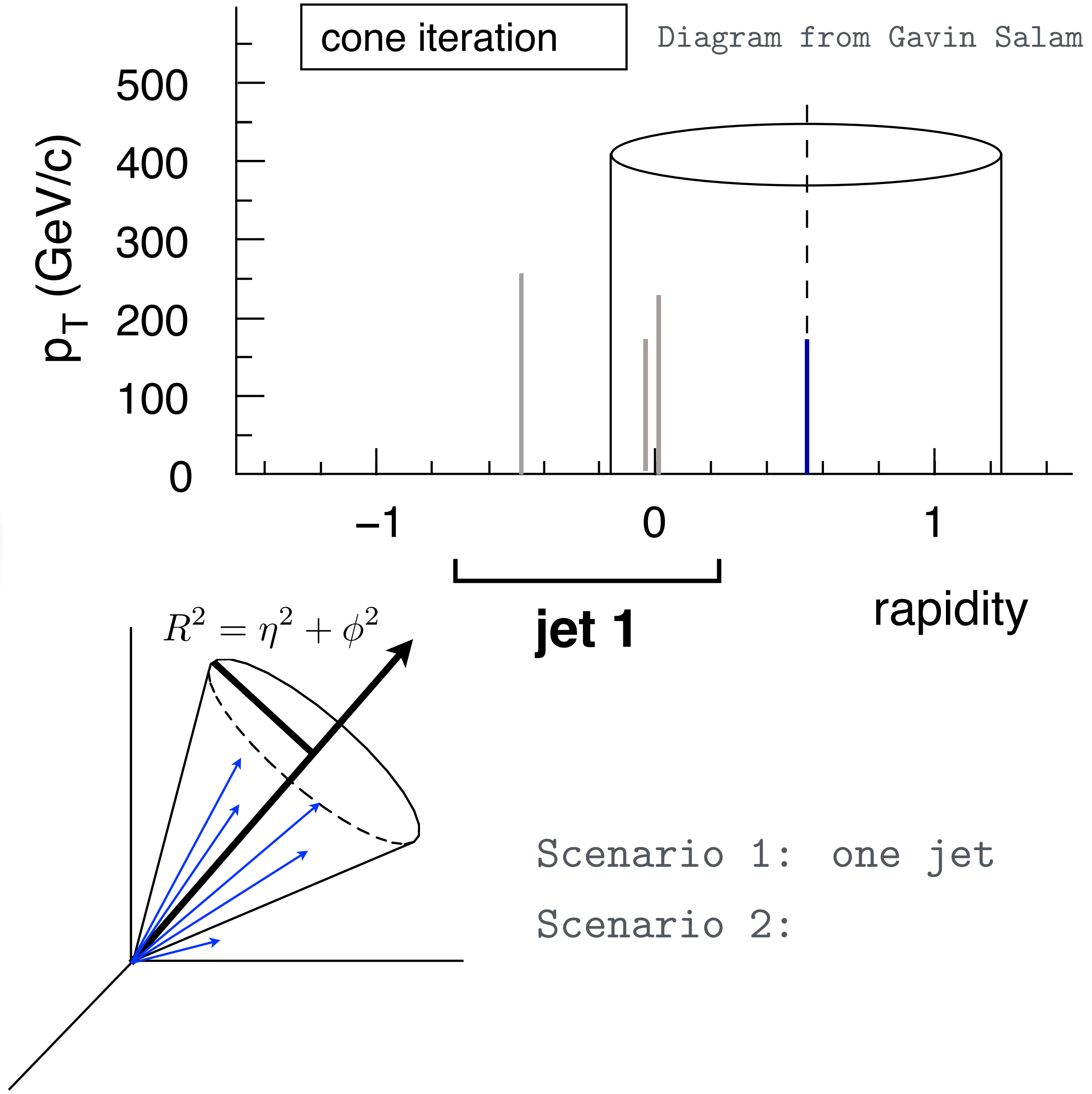
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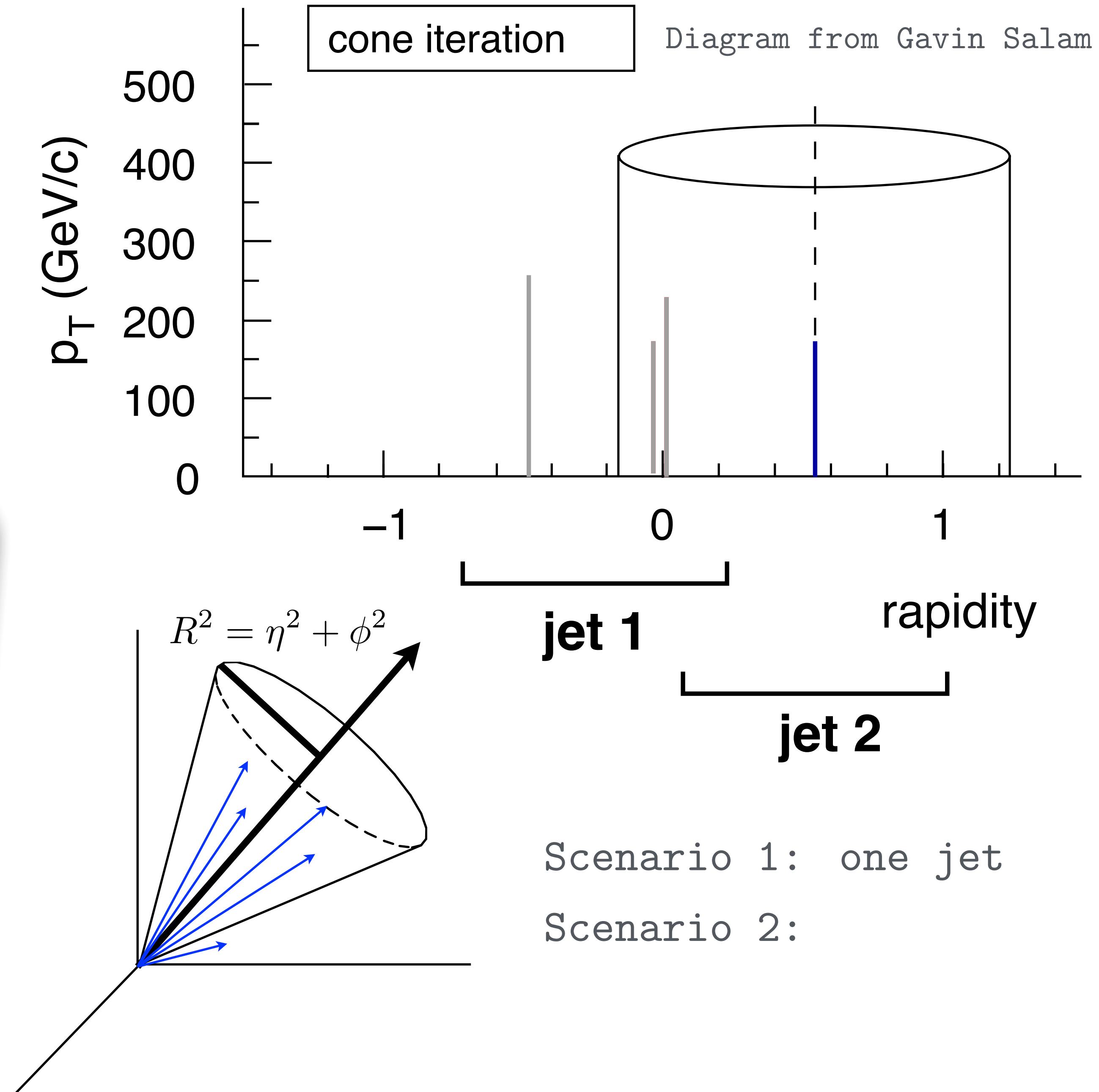
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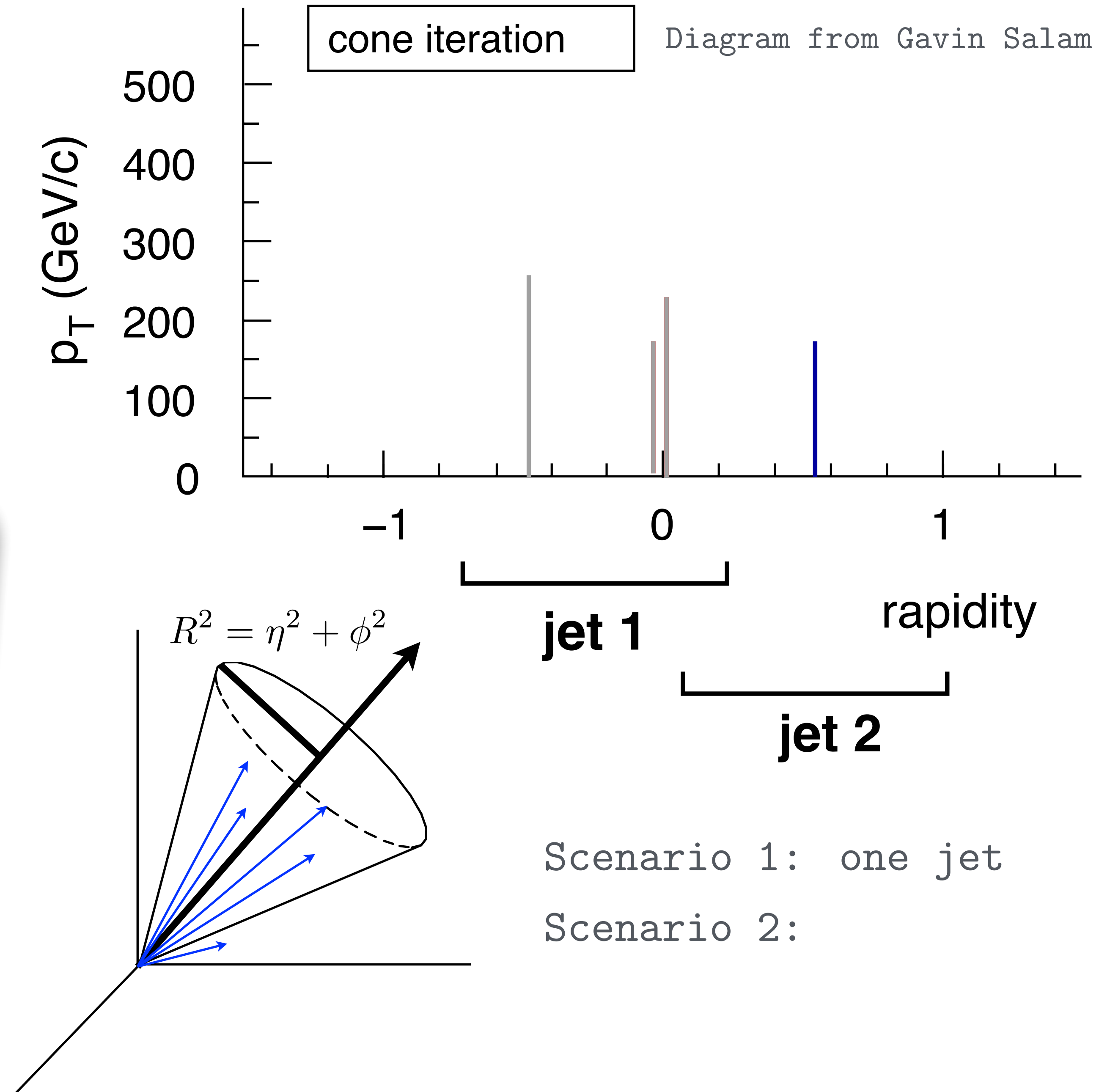
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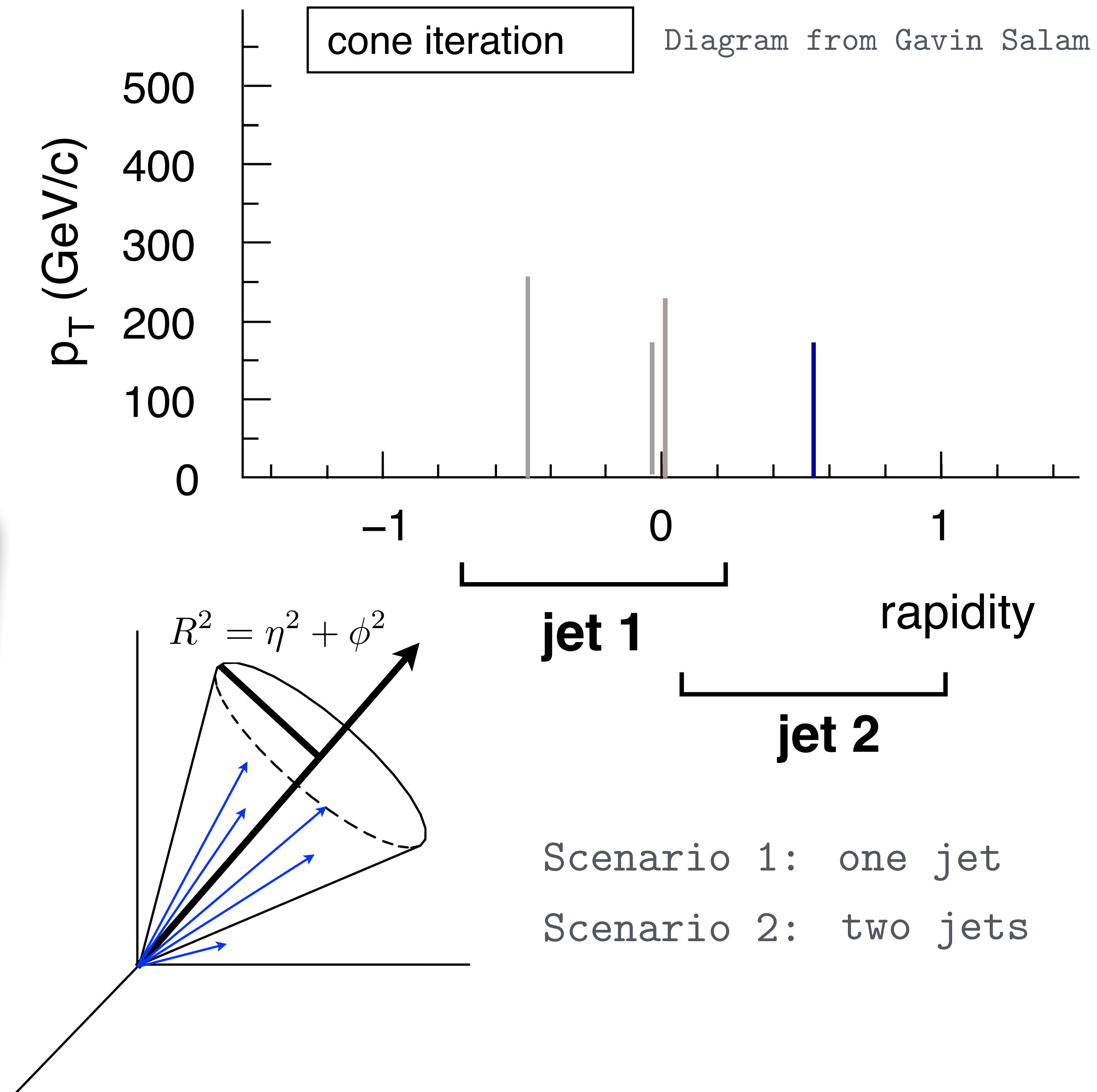
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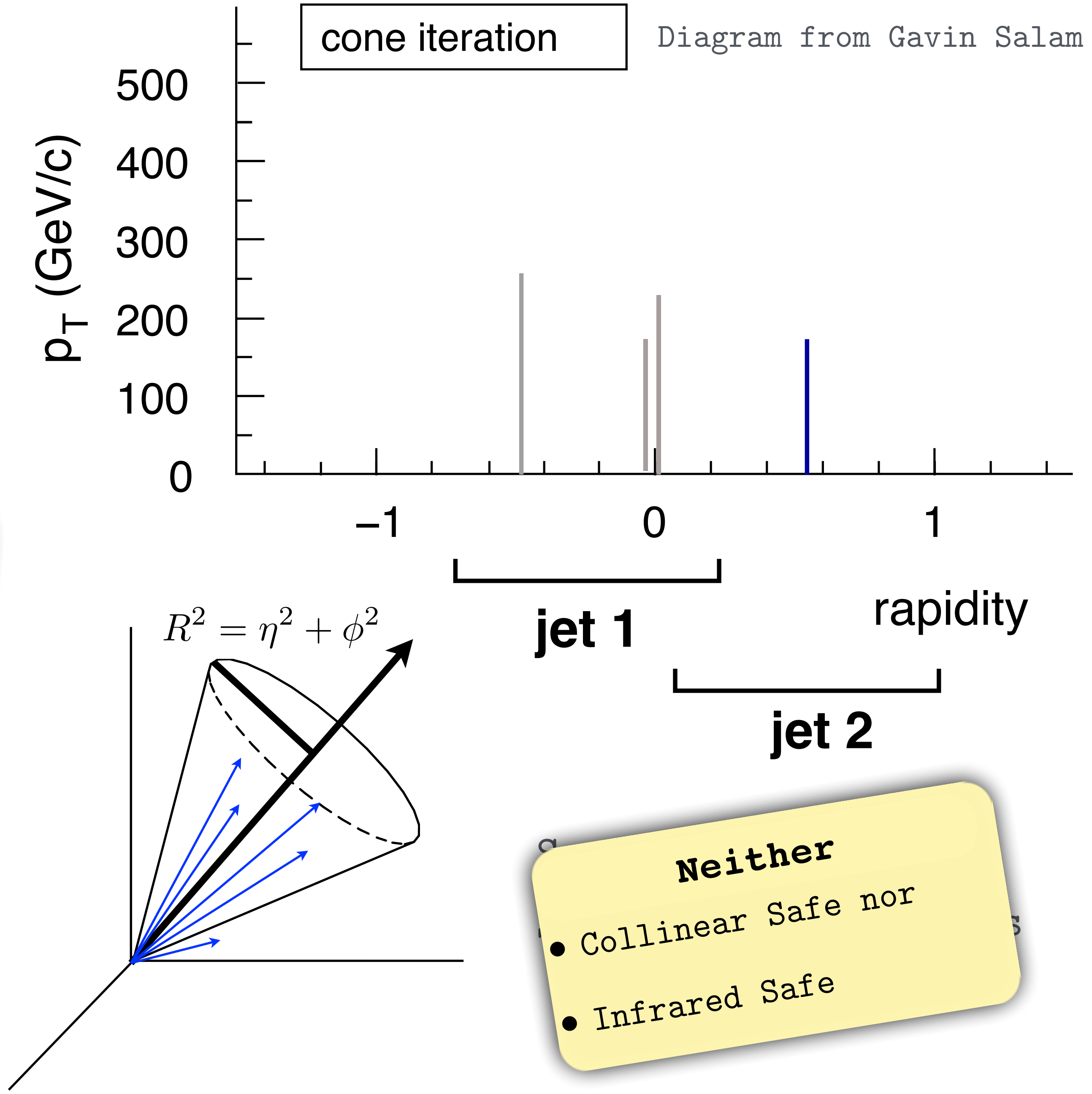


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Sequential Clustering Algorithms

- Historically used (before LHC) at lepton colliders
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Jet Reconstruction

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Advantages

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Jet Reconstruction

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Jet Reconstruction

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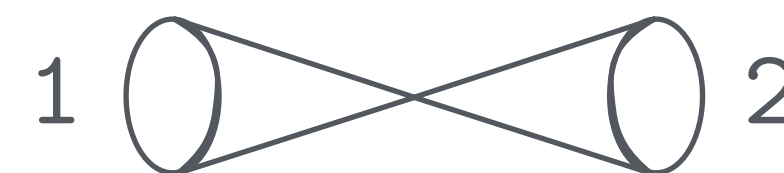
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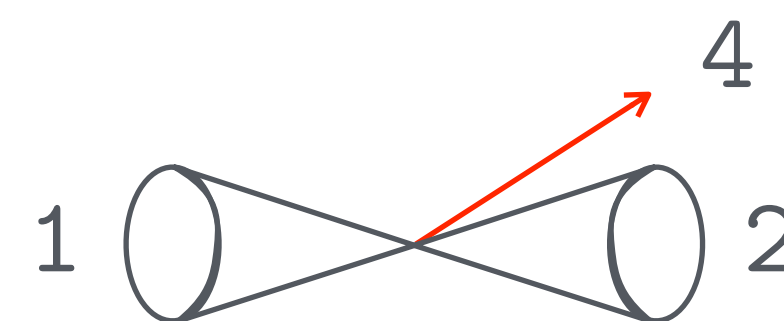
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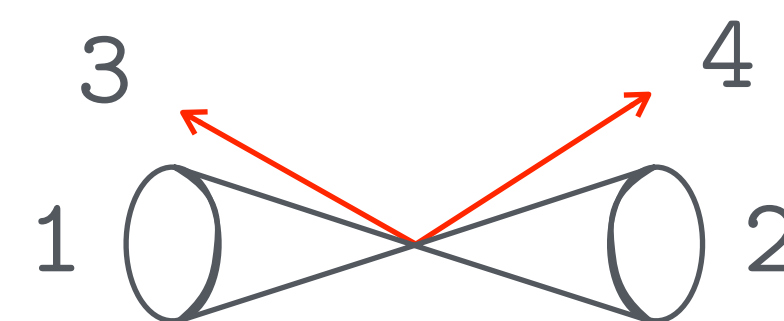
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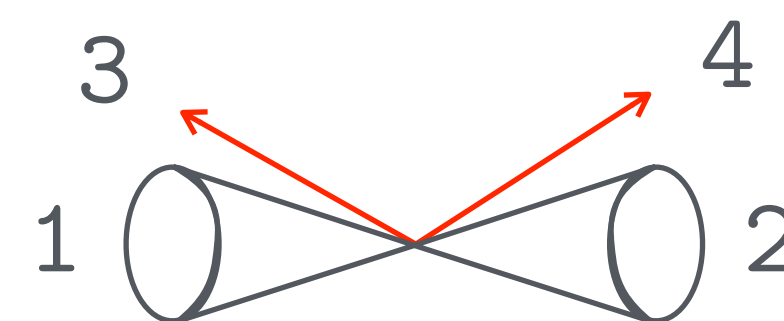
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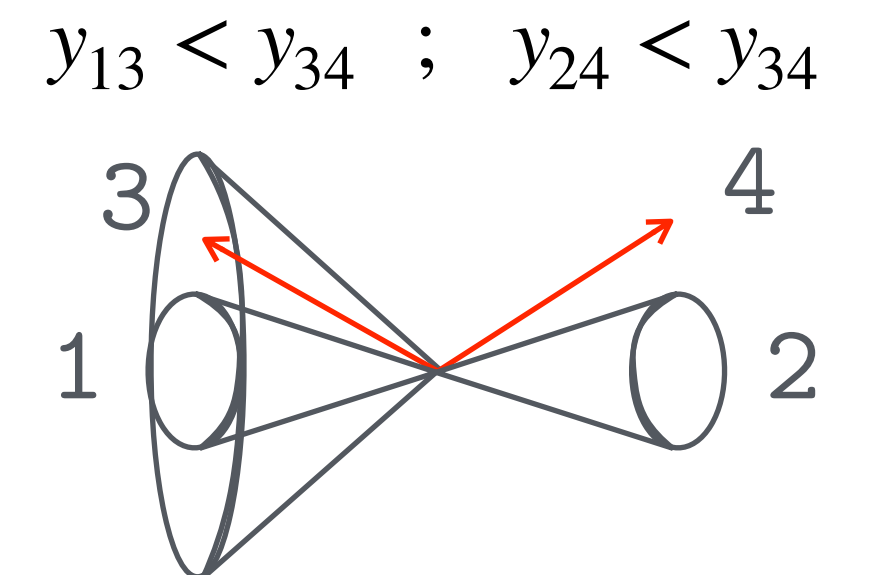
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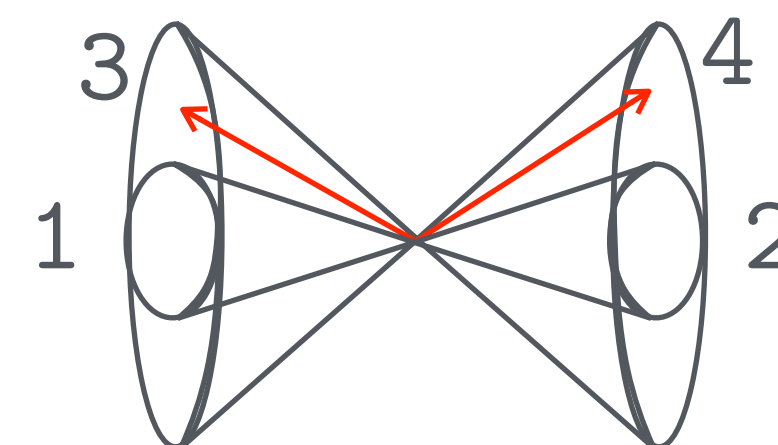
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Jet Reconstruction

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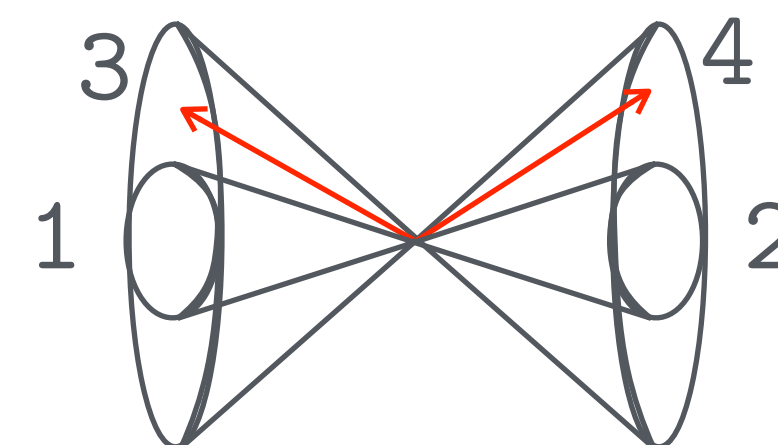
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JADE

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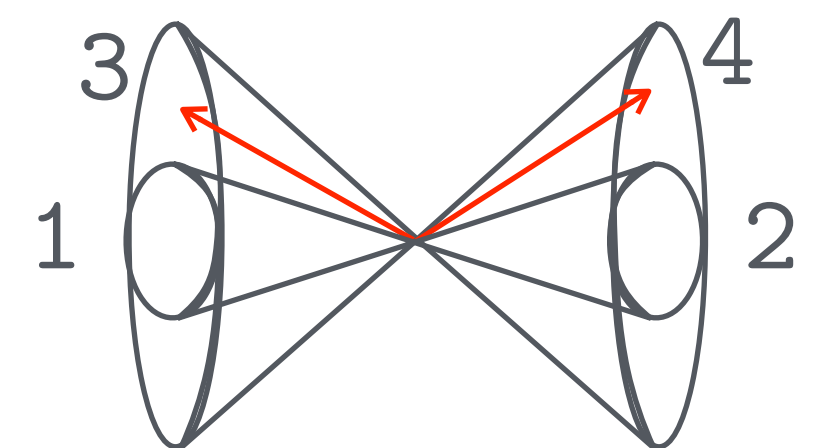
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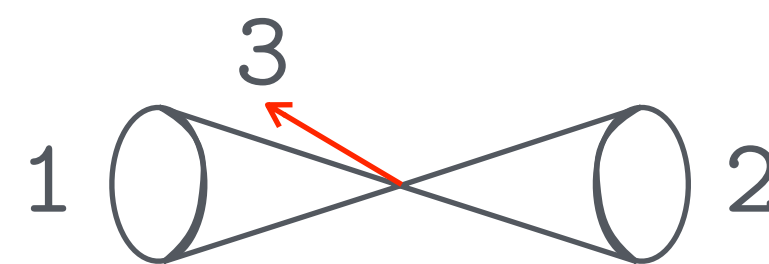
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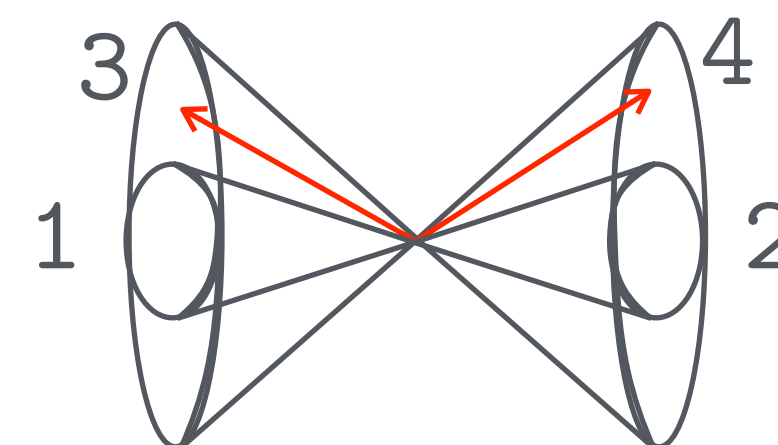
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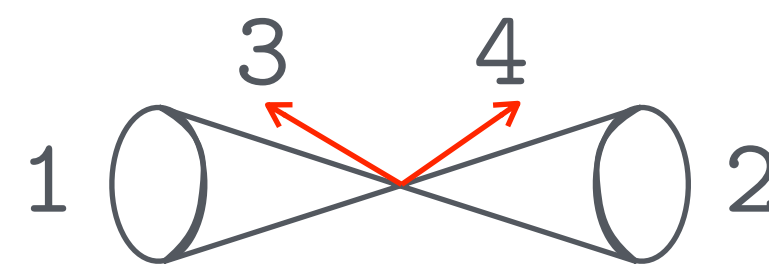
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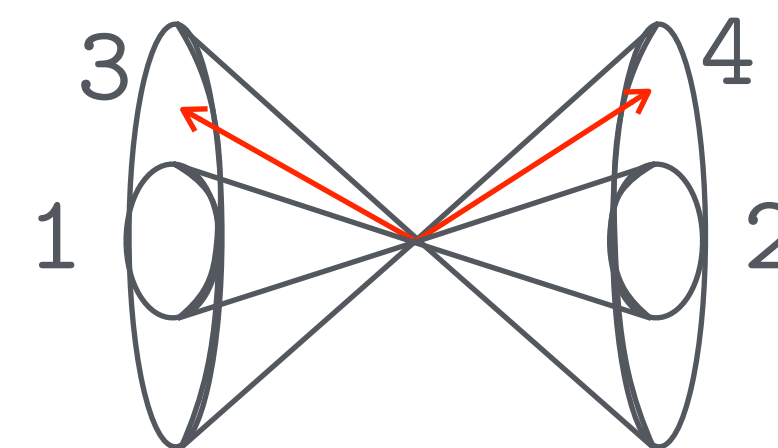
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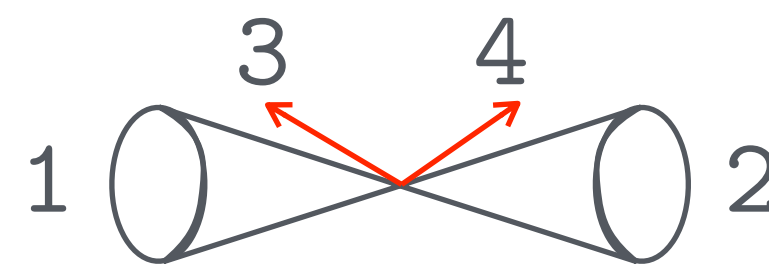
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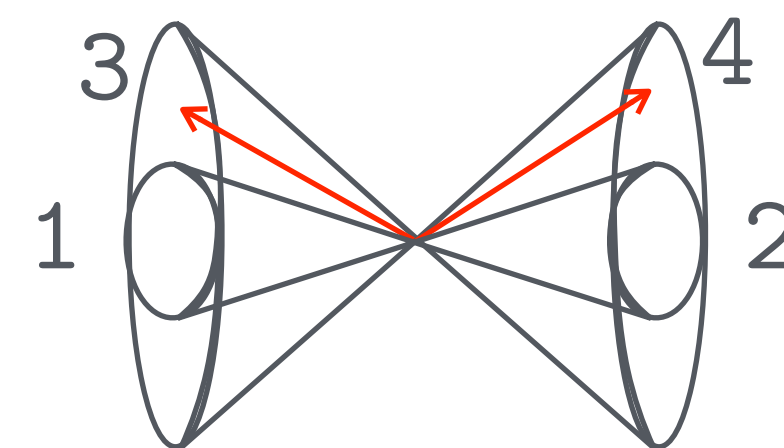
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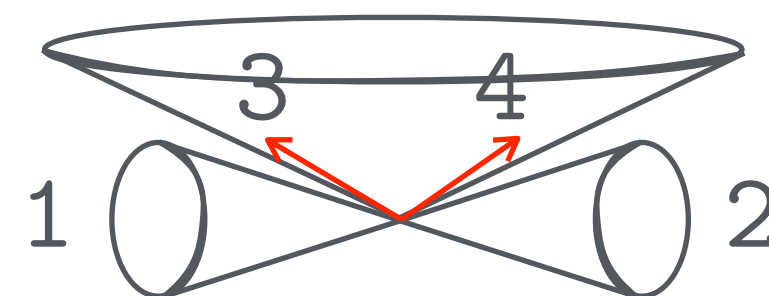
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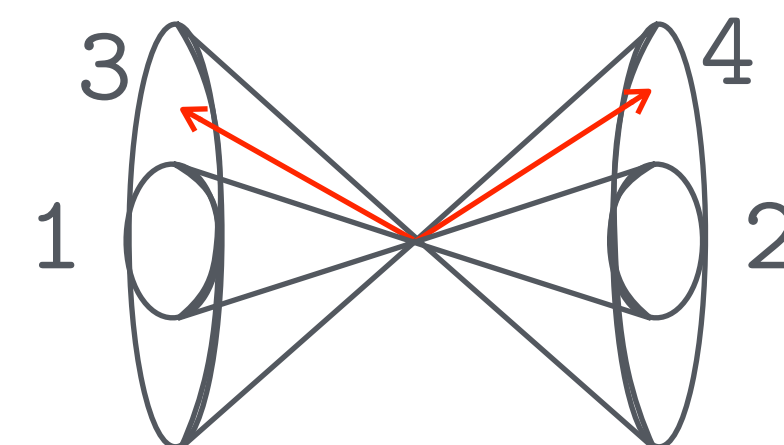
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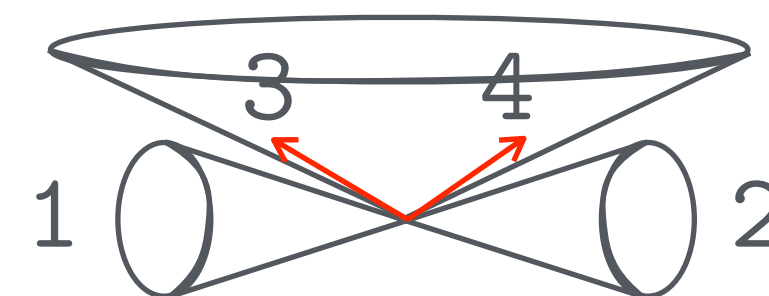
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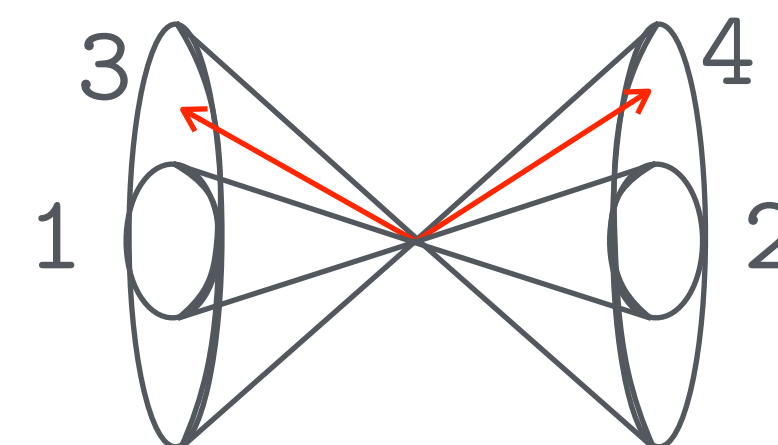
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3rd "ghost" jet

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DURHAM

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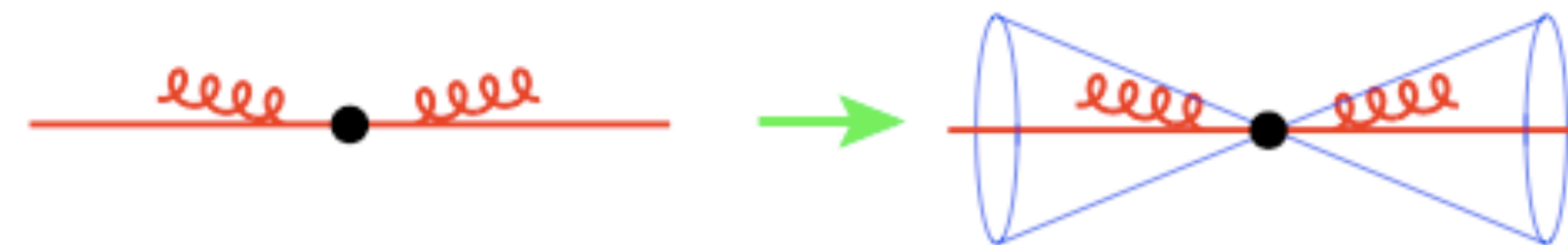
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Disadvantage

- Underlying beam remnant particles can obscure soft particles emitted from the hard scatter partons

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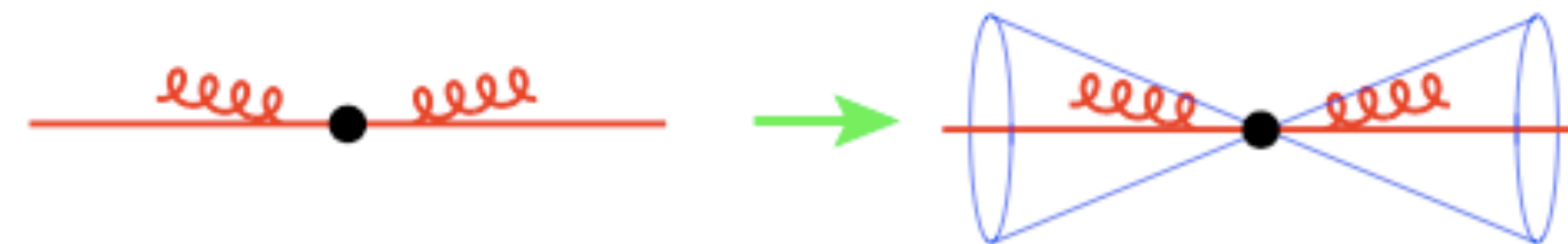
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kT Algorithm

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Jet Reconstruction

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Jet Reconstruction

kT Algorithm

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Jet Reconstruction

kT Algorithm

- List of particles with $k_T^2 = p_x^2 + p_y^2$ $y = \frac{1}{2} \ln \frac{E + p}{E - p}$
- For each particle, define the distance from the beam

Jet Reconstruction

kT Algorithm

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Typical values:
 $R = \{0.4, 0.8, 1.0\}$

Jet Reconstruction

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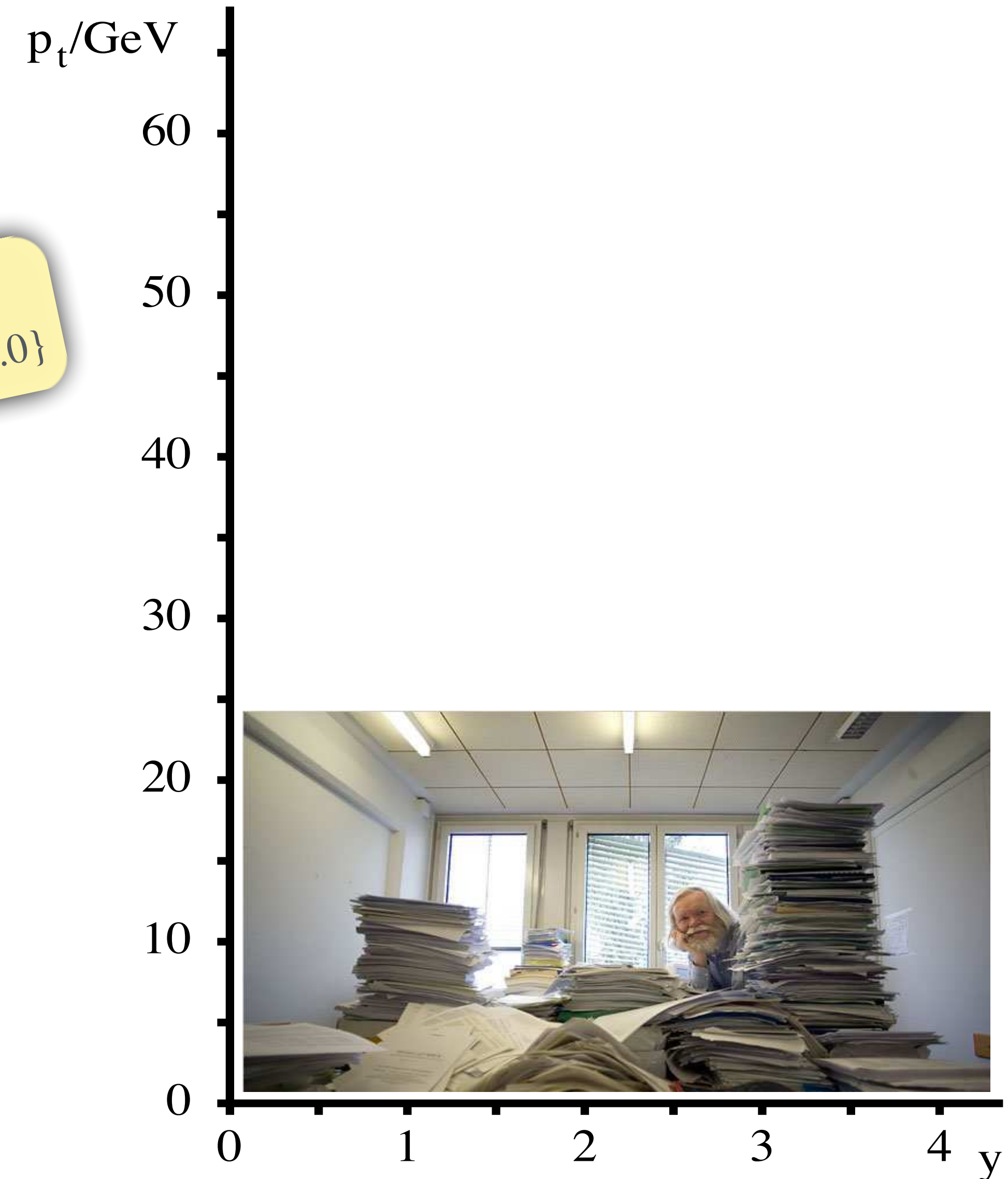
Jet Reconstruction

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kT Algorithm



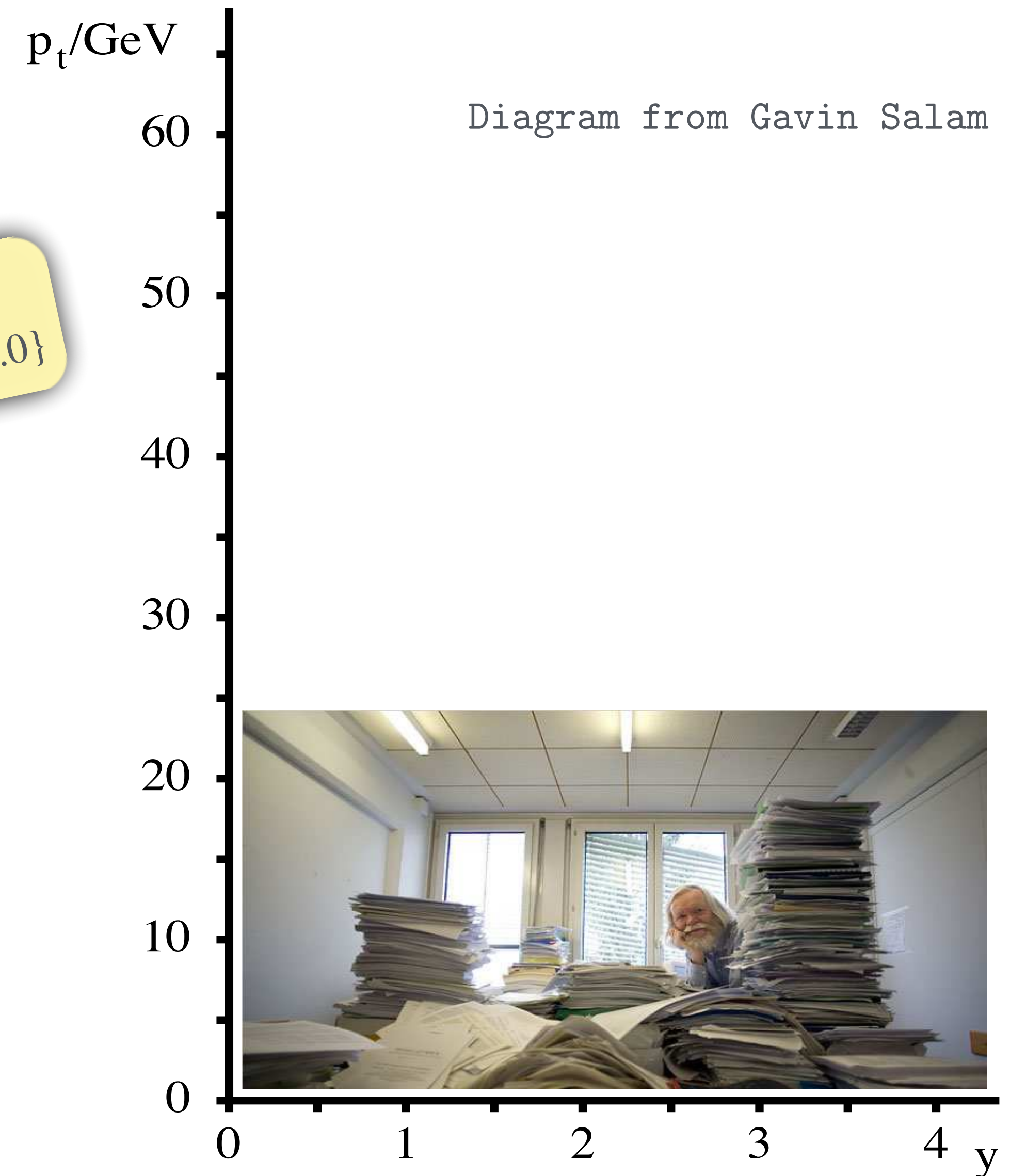
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kT Algorithm

p_t/GeV

60

50

40

30

20

10

0

0

1

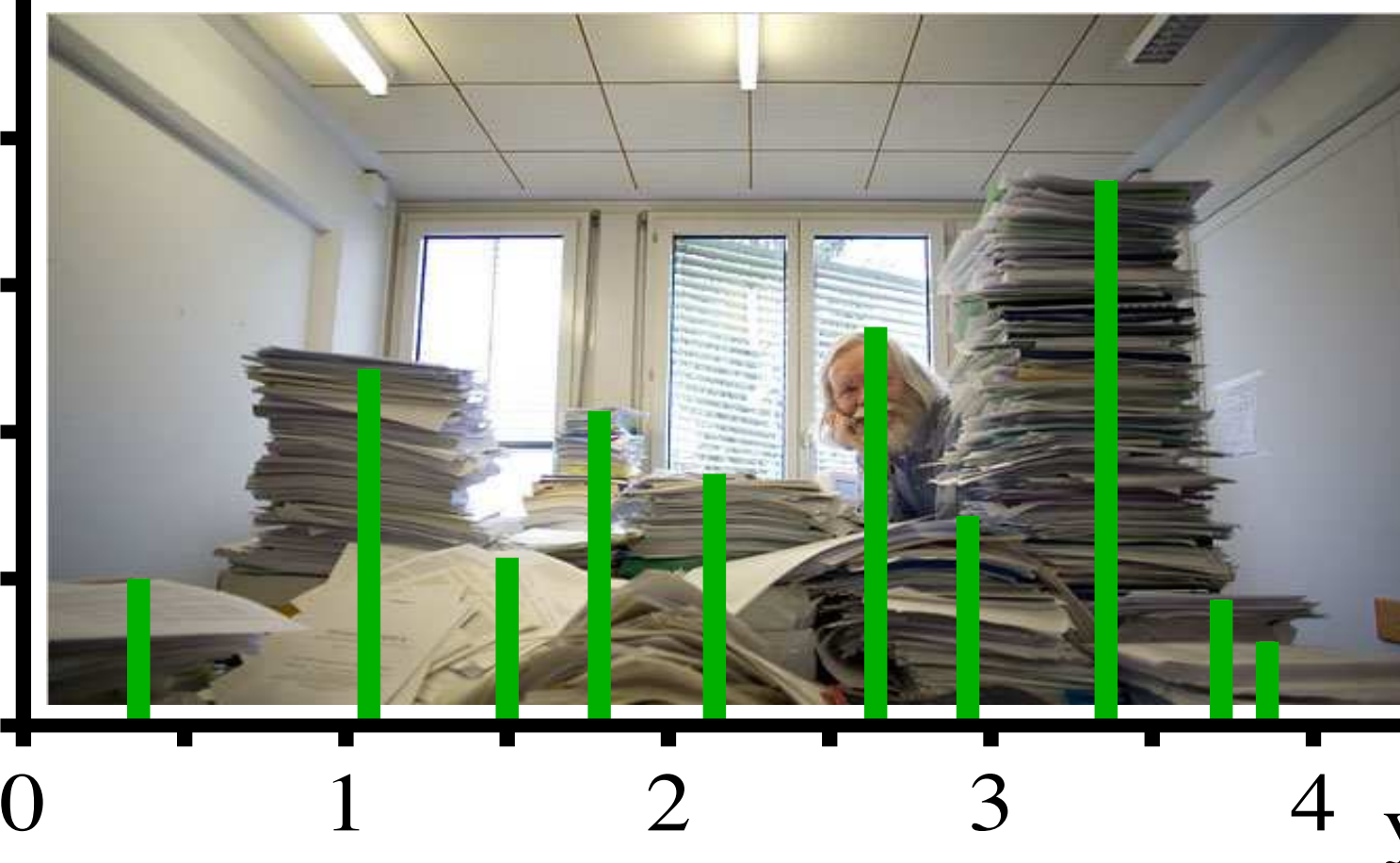
2

3

4

y

Diagram from Gavin Salam



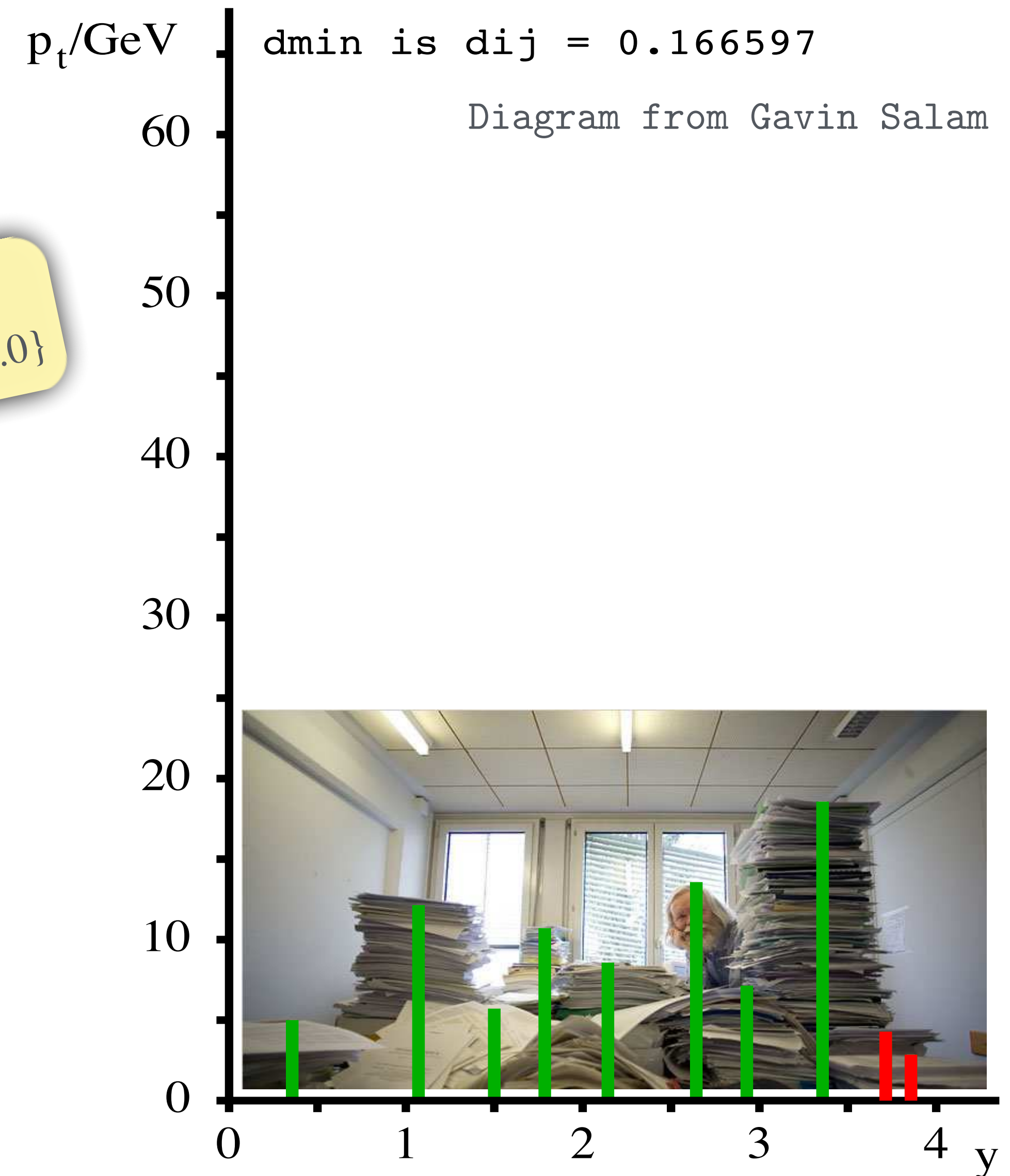
Jet Reconstruction

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kT Algorithm

p_t/GeV

60

50

40

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0

0

1

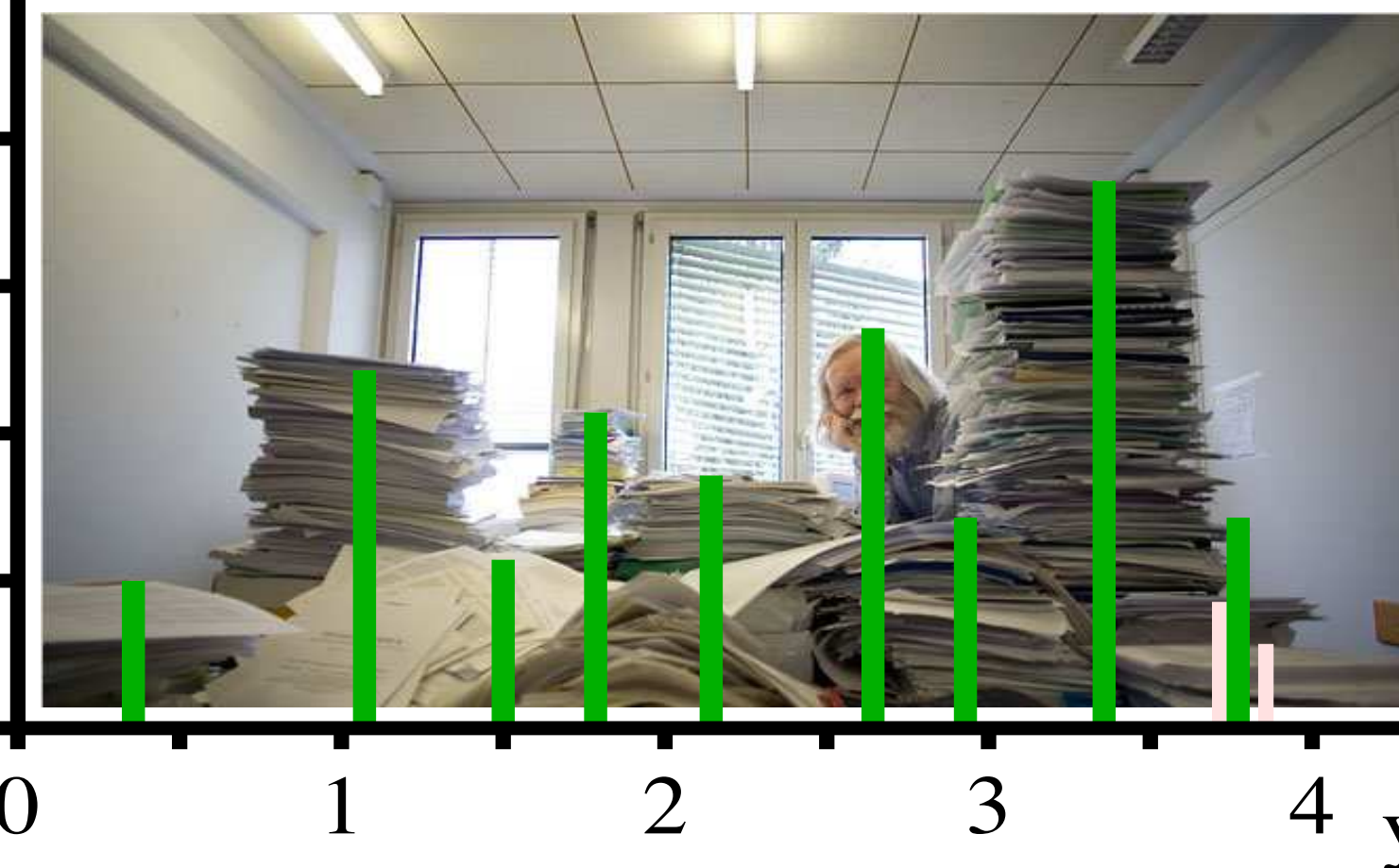
2

3

4

y

Diagram from Gavin Salam



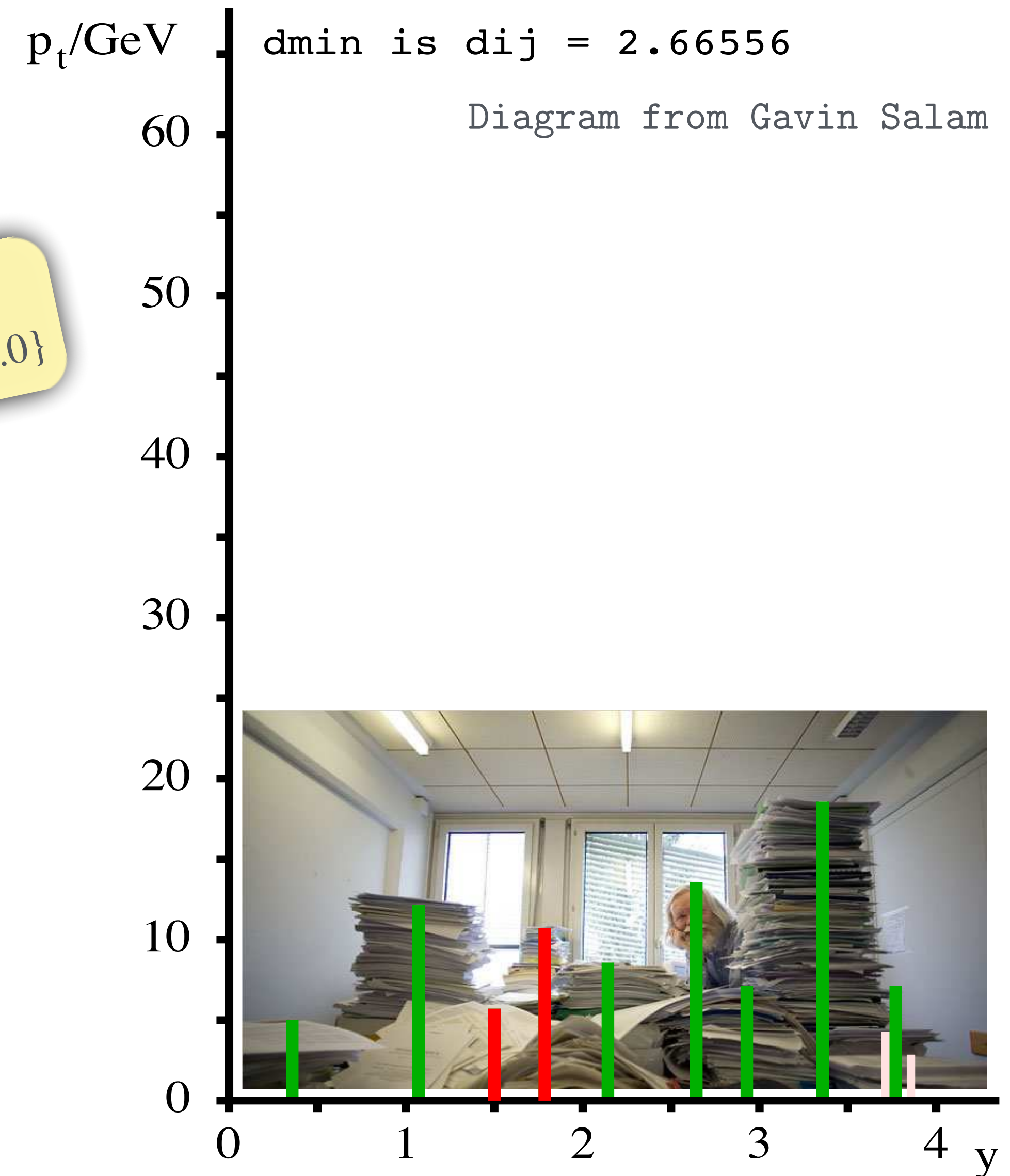
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kT Algorithm

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50

40

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20

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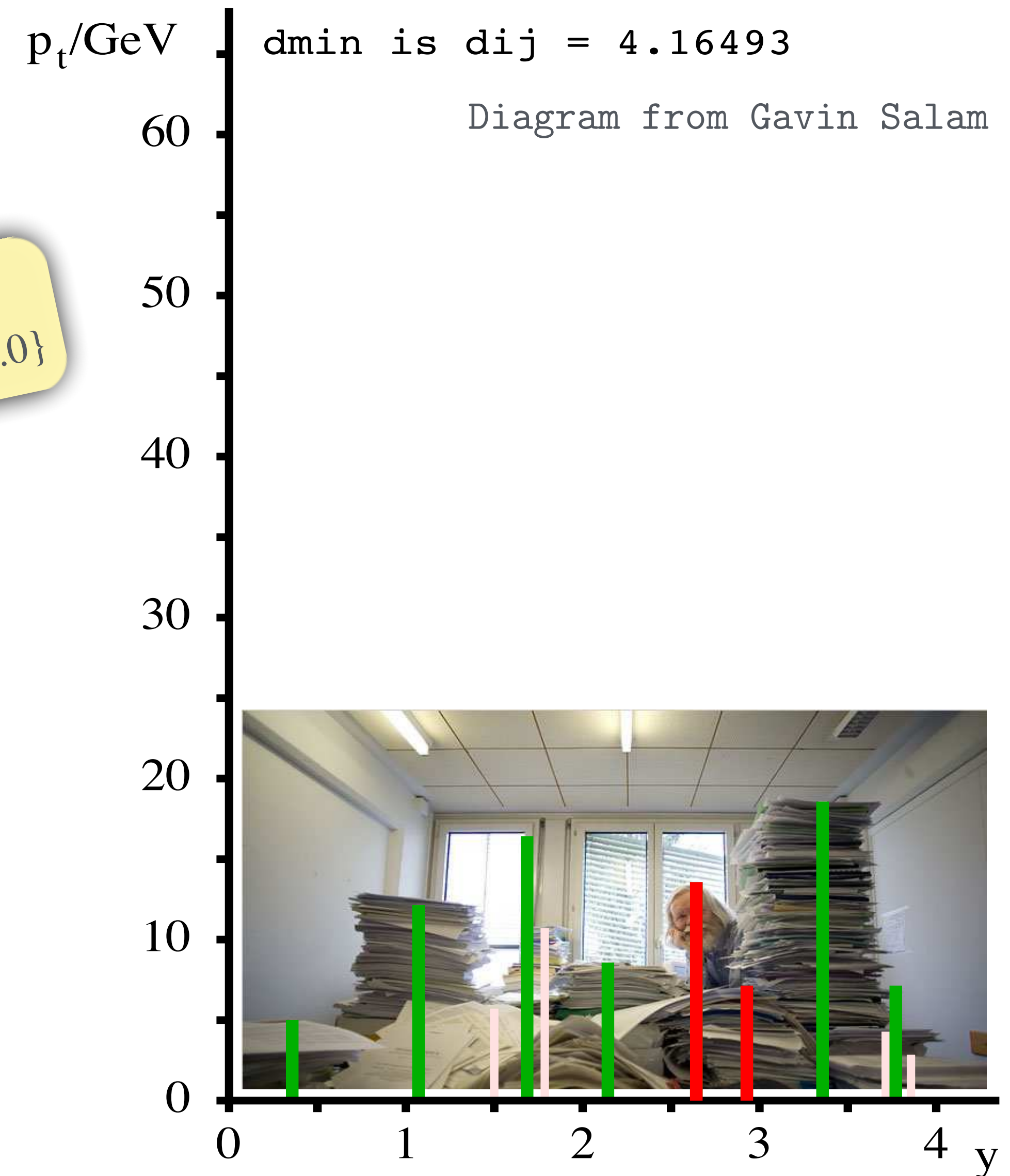
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p_t/GeV

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1

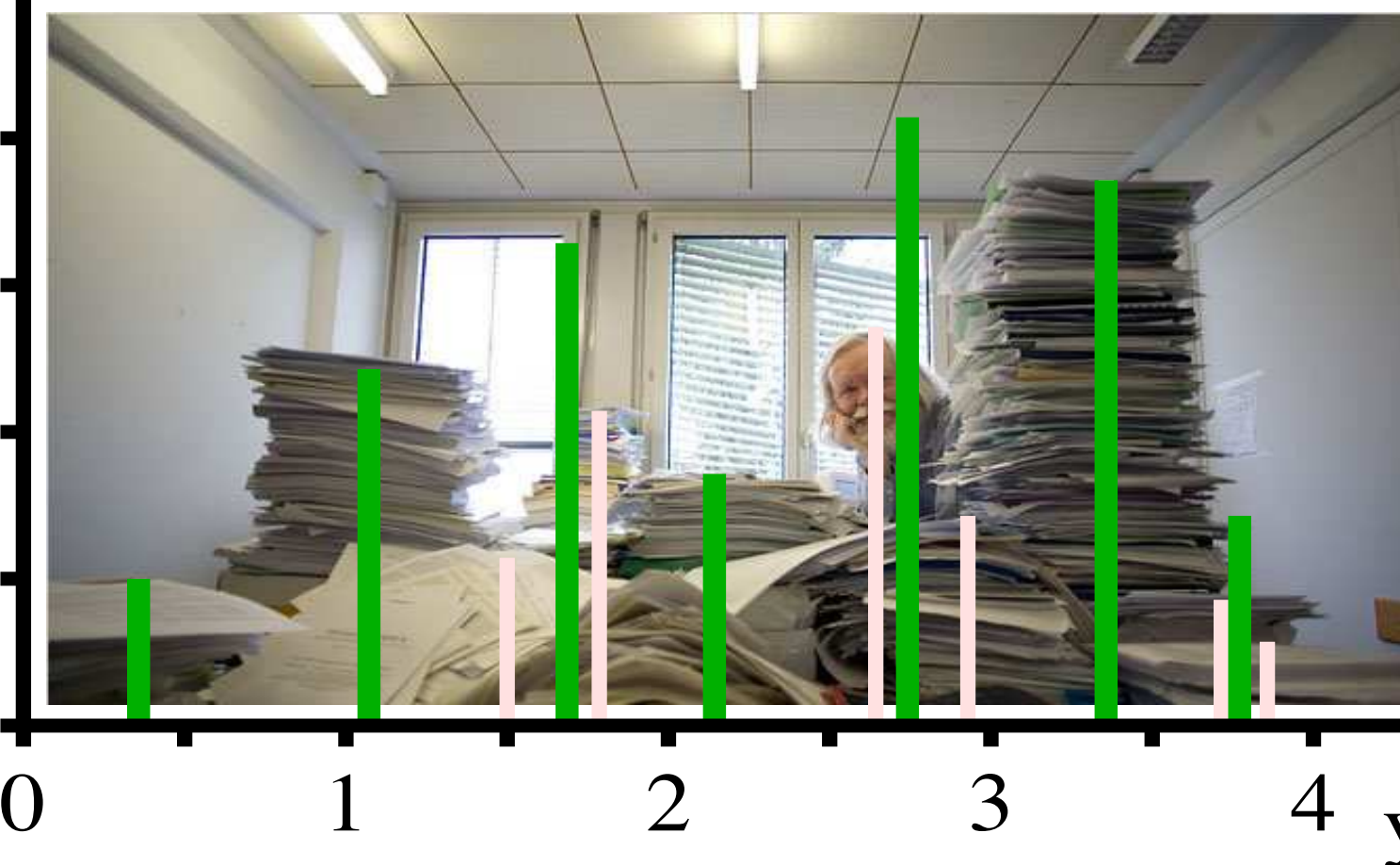
2

3

4

y

Diagram from Gavin Salam



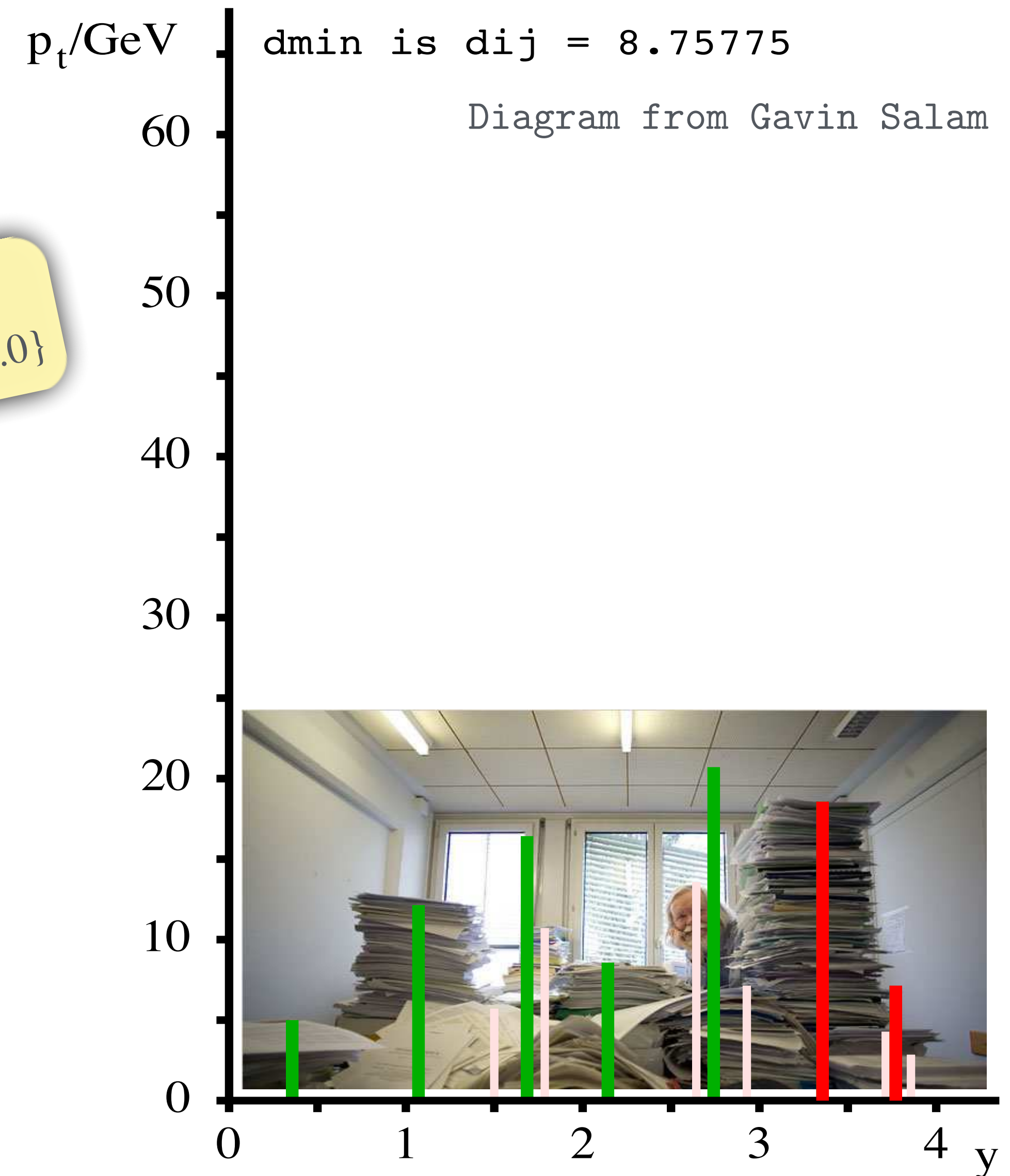
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kT Algorithm



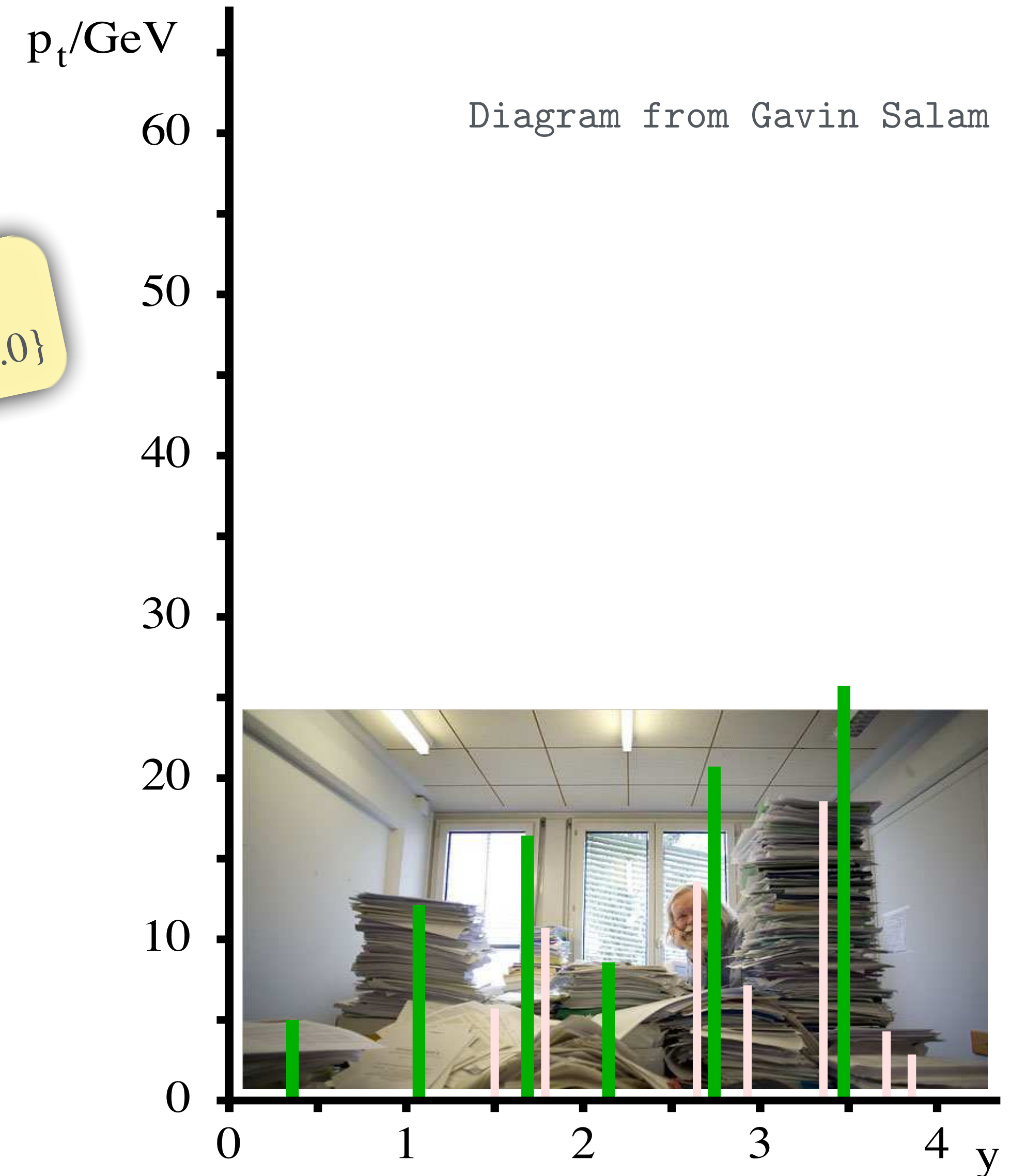
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kT Algorithm



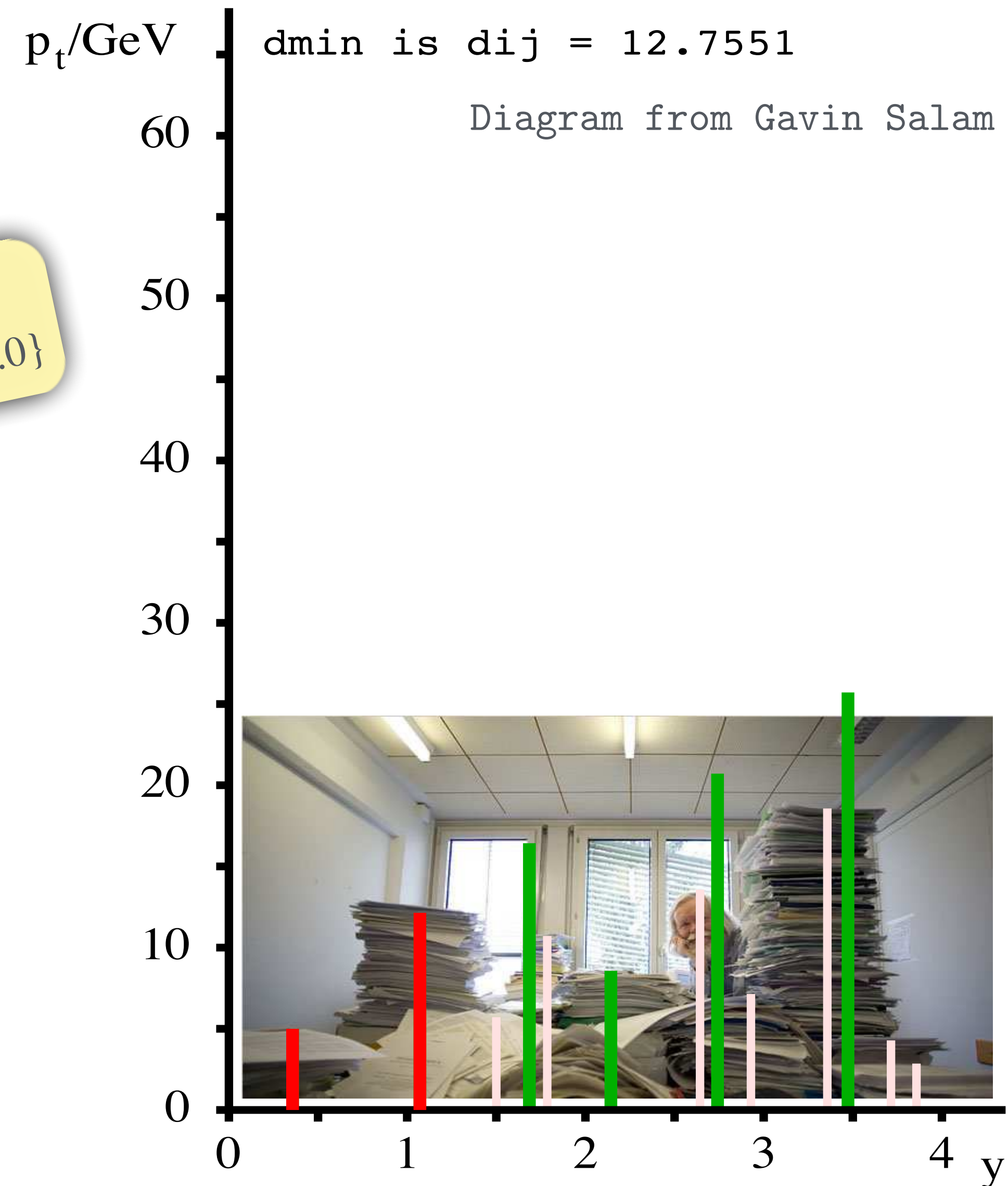
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kT Algorithm

p_t/GeV

60

50

40

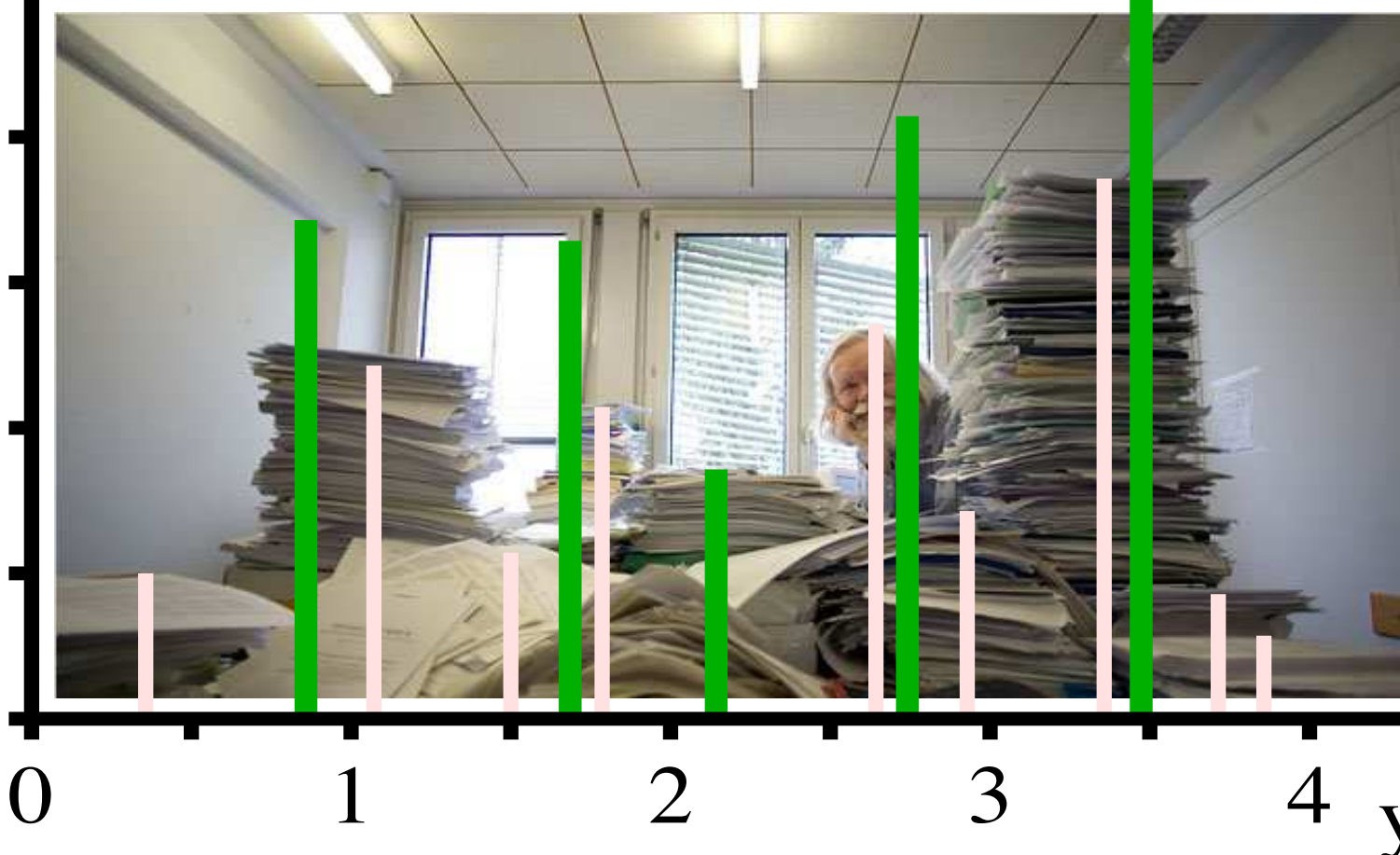
30

20

10

0

Diagram from Gavin Salam



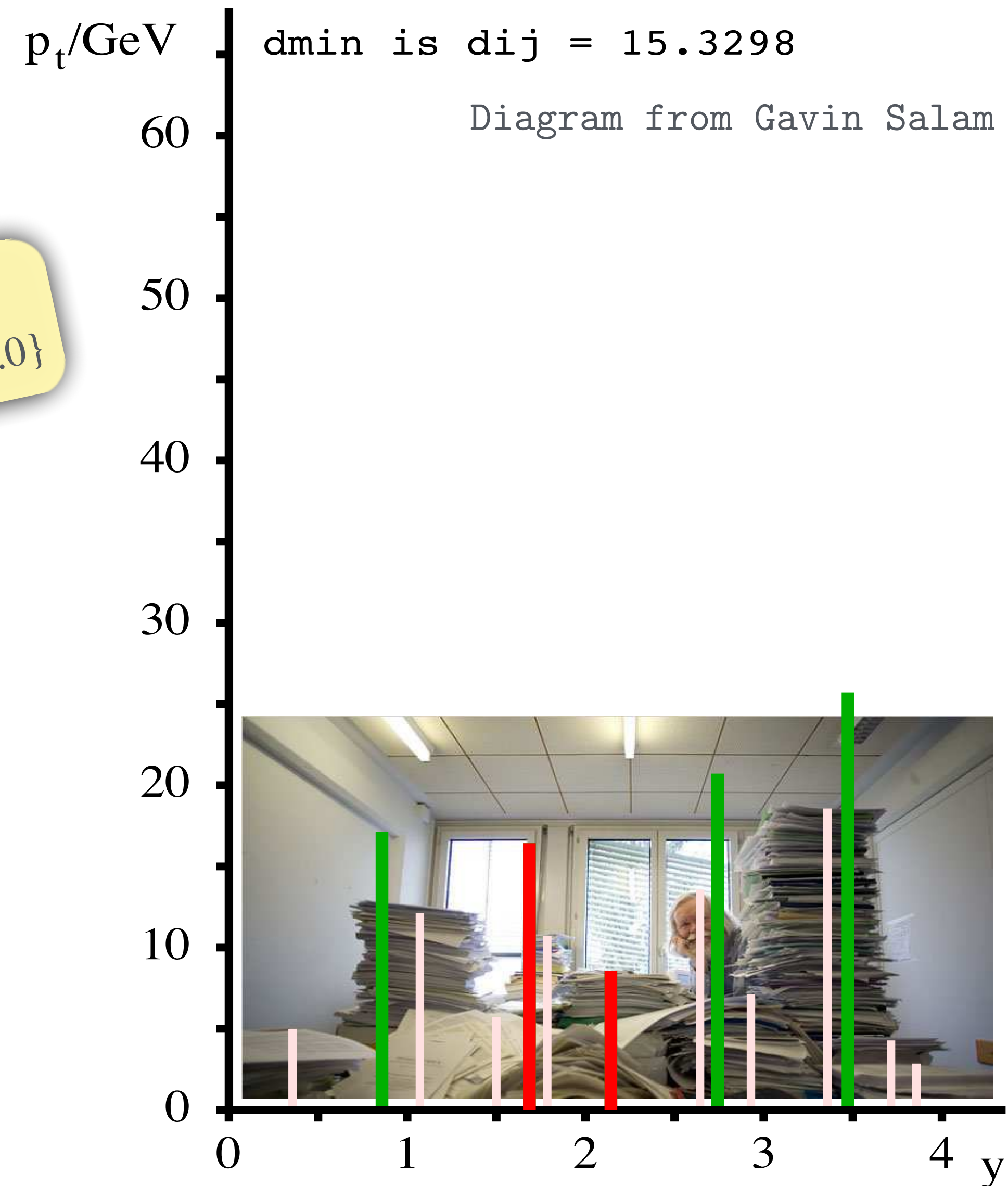
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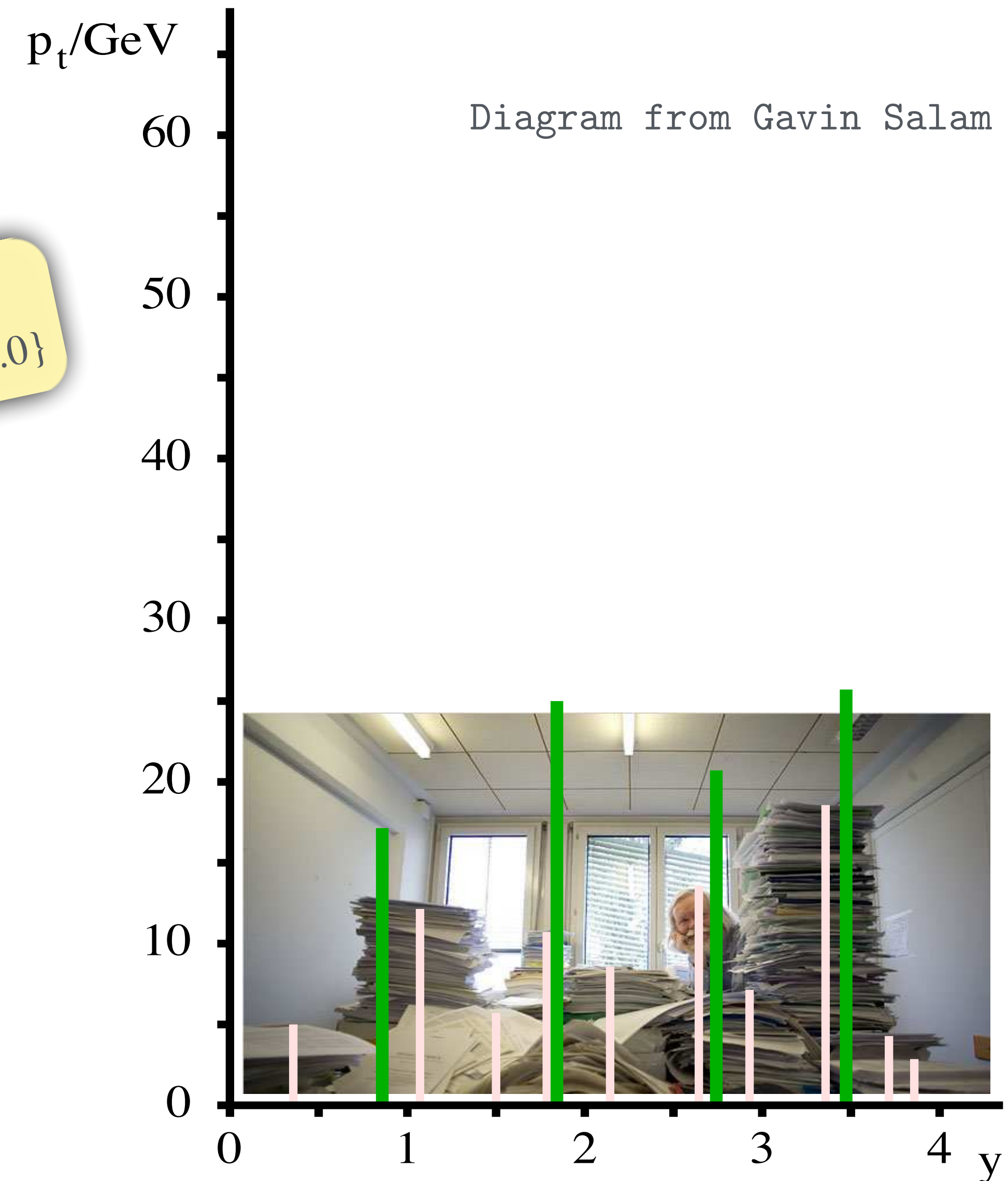
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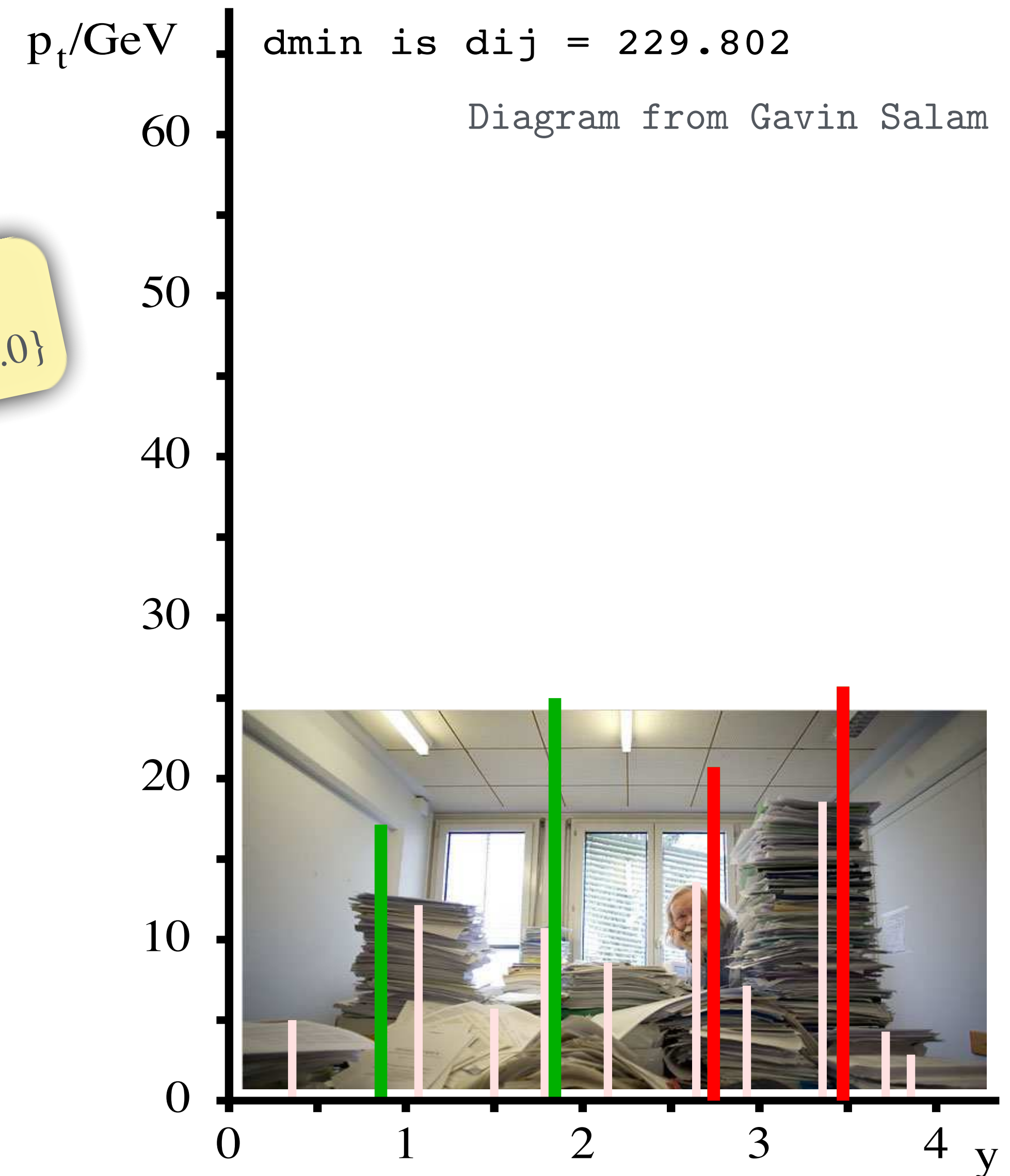
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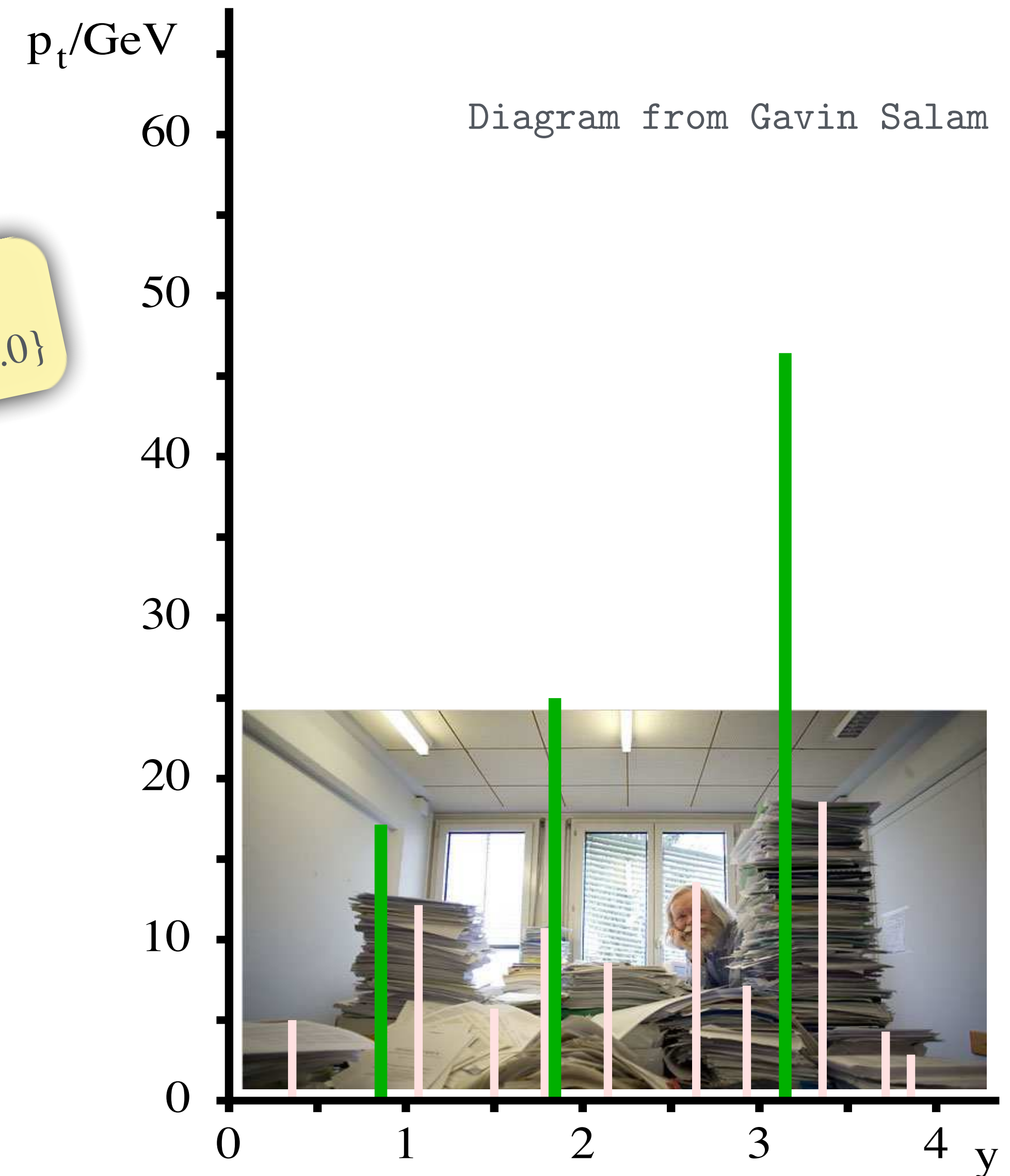
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kT Algorithm



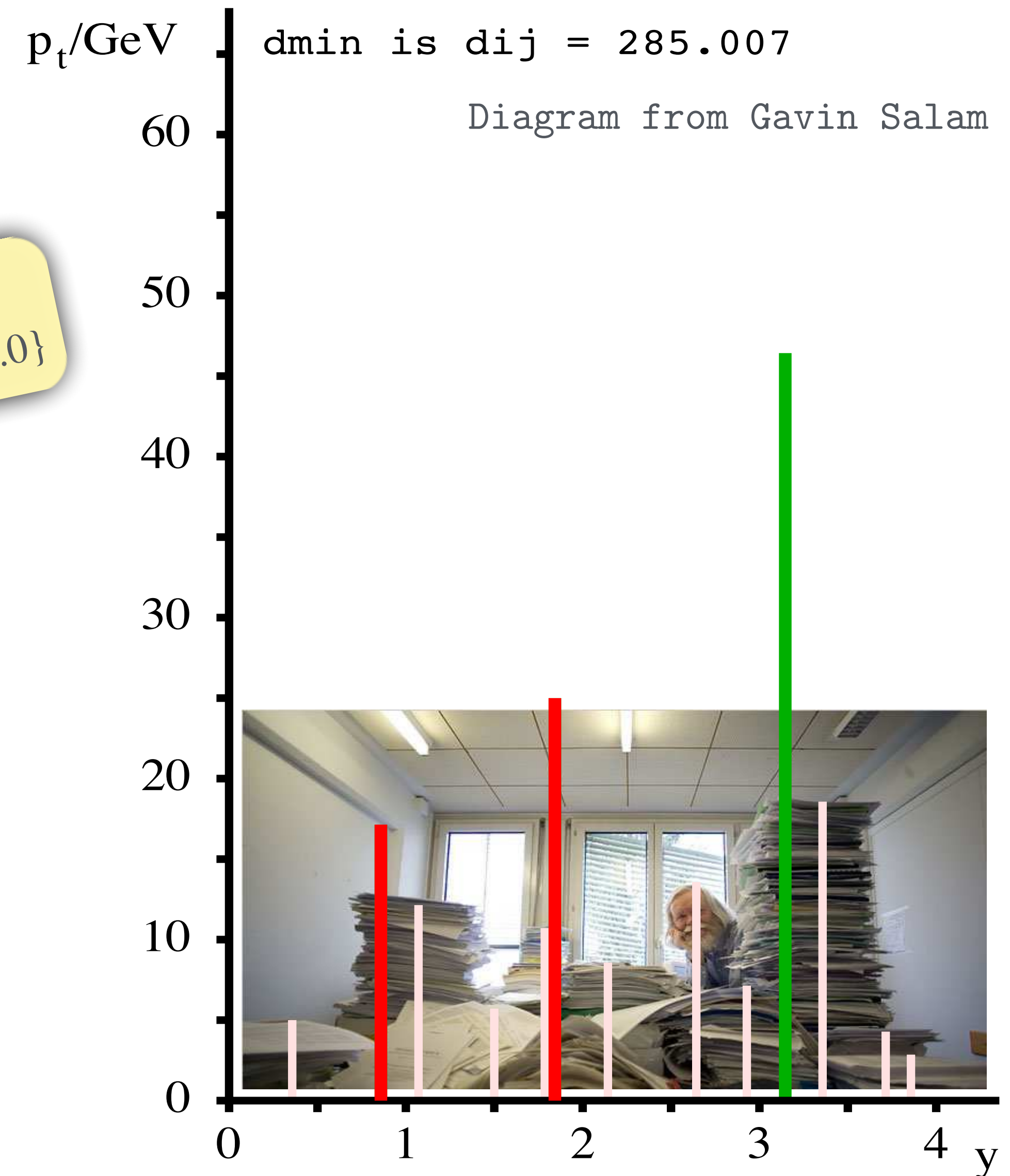
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kT Algorithm



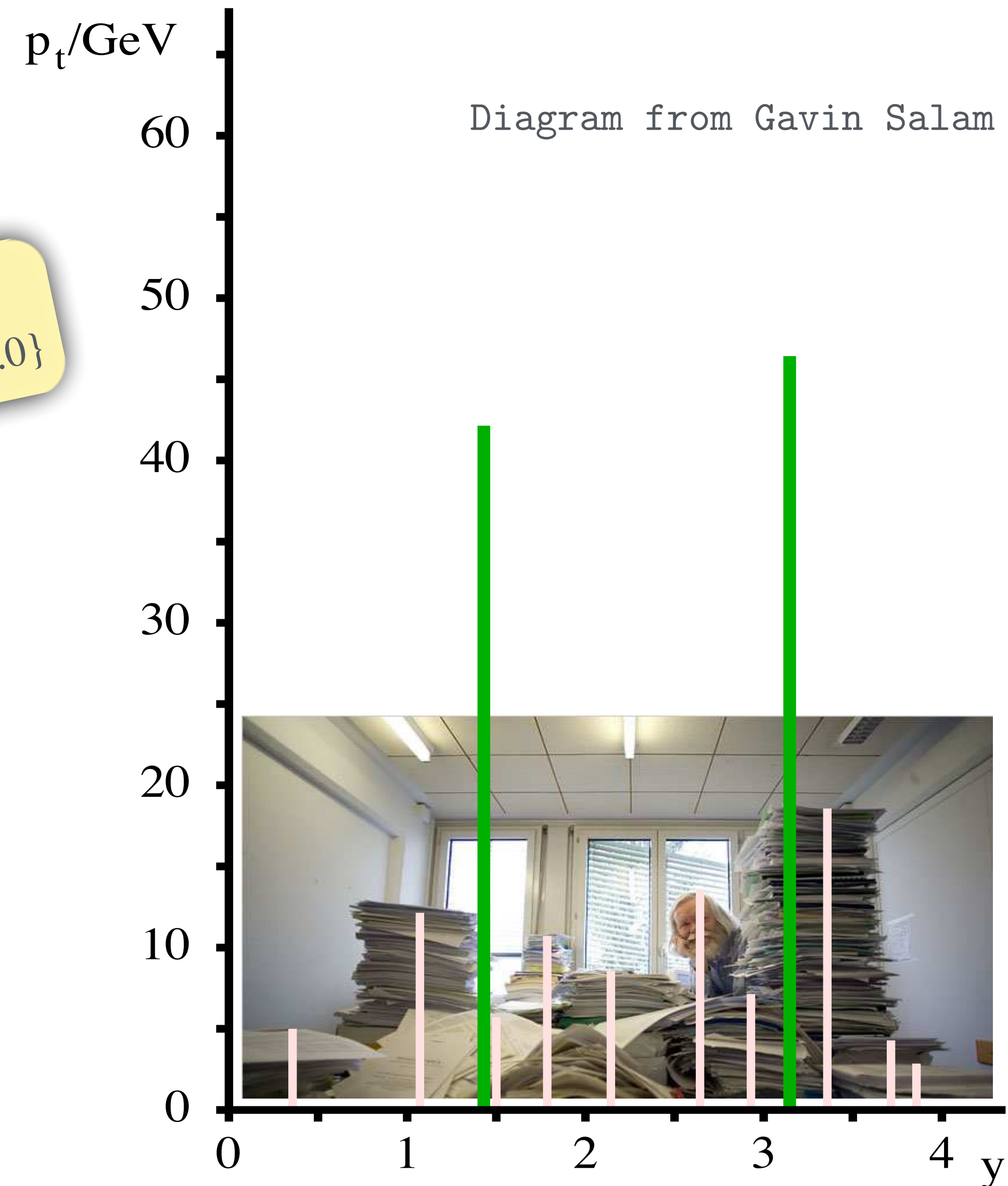
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kT Algorithm



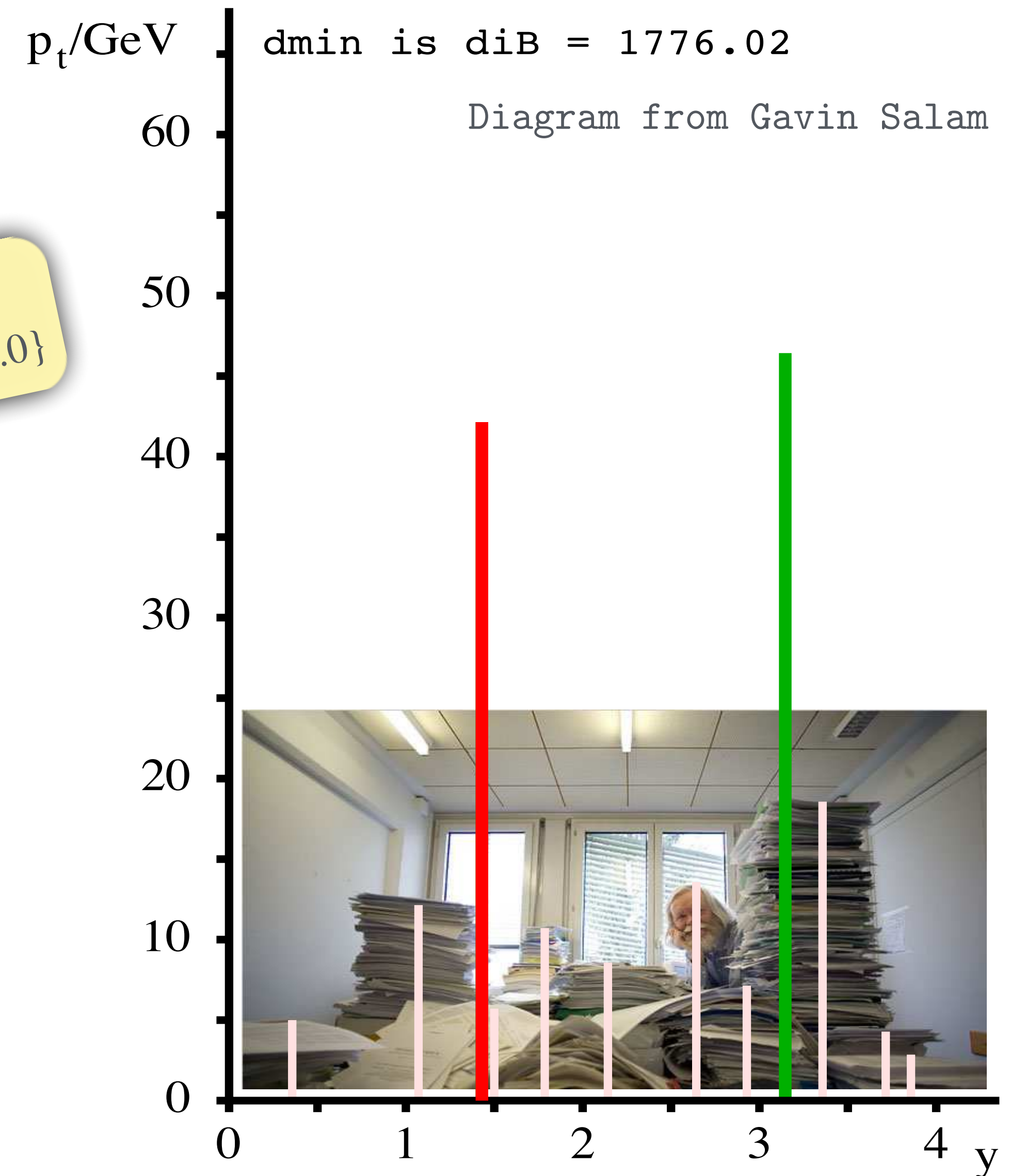
Jet Reconstruction

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kT Algorithm



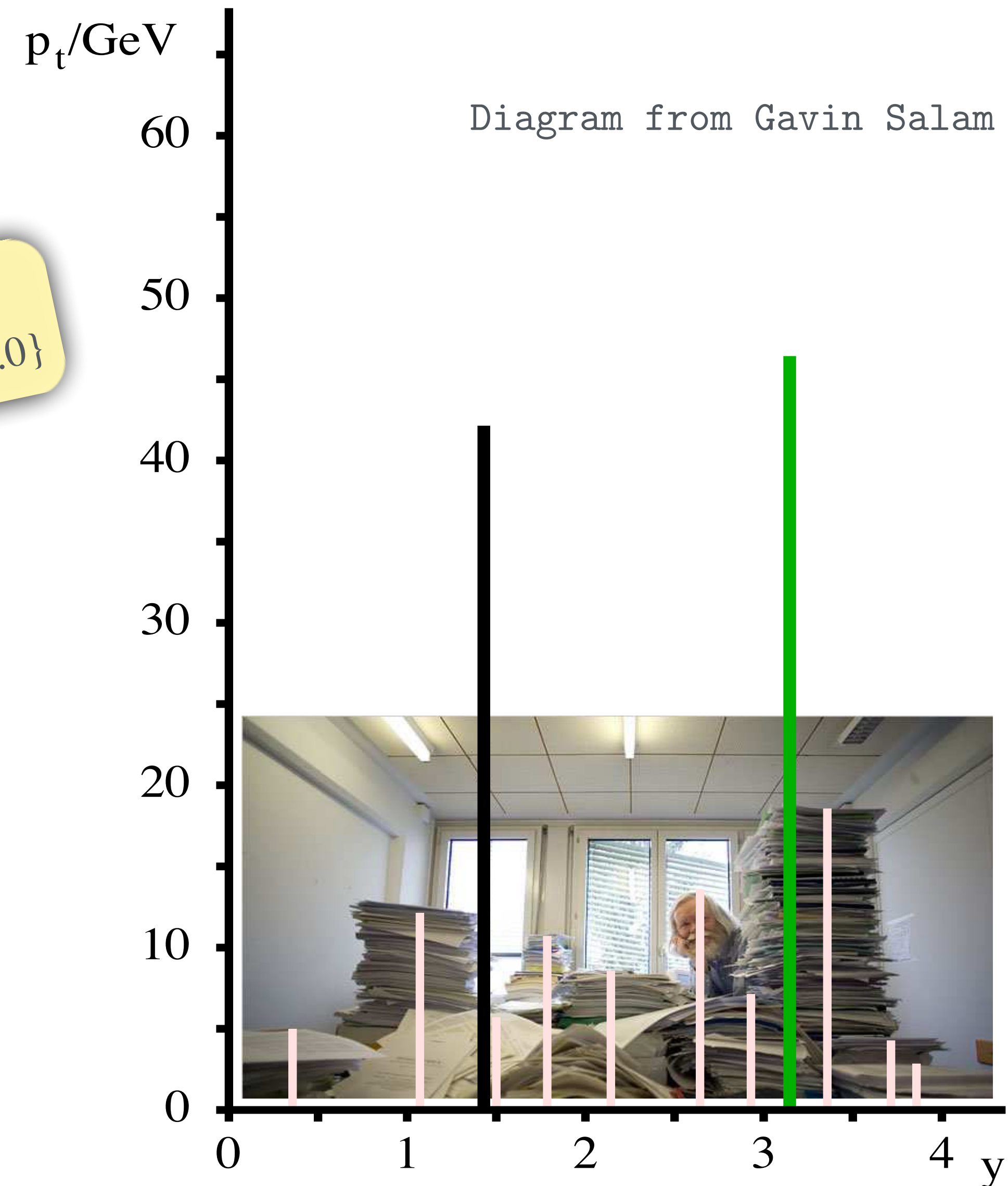
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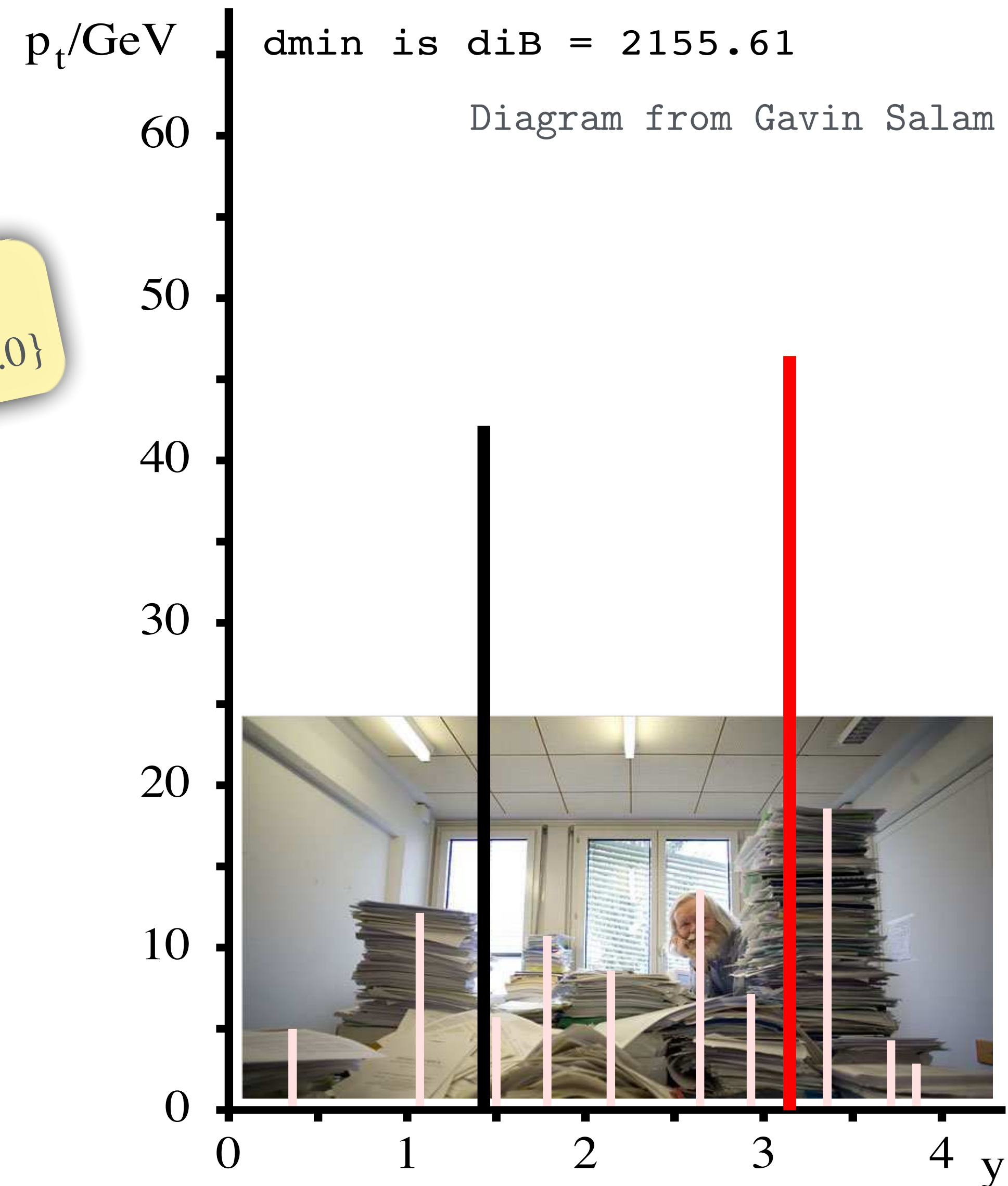
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kT Algorithm

p_t/GeV

60

50

40

30

20

10

0

0

1

2

3

4

y

Diagram from Gavin Salam



Jet Reconstruction

kT Algorithm

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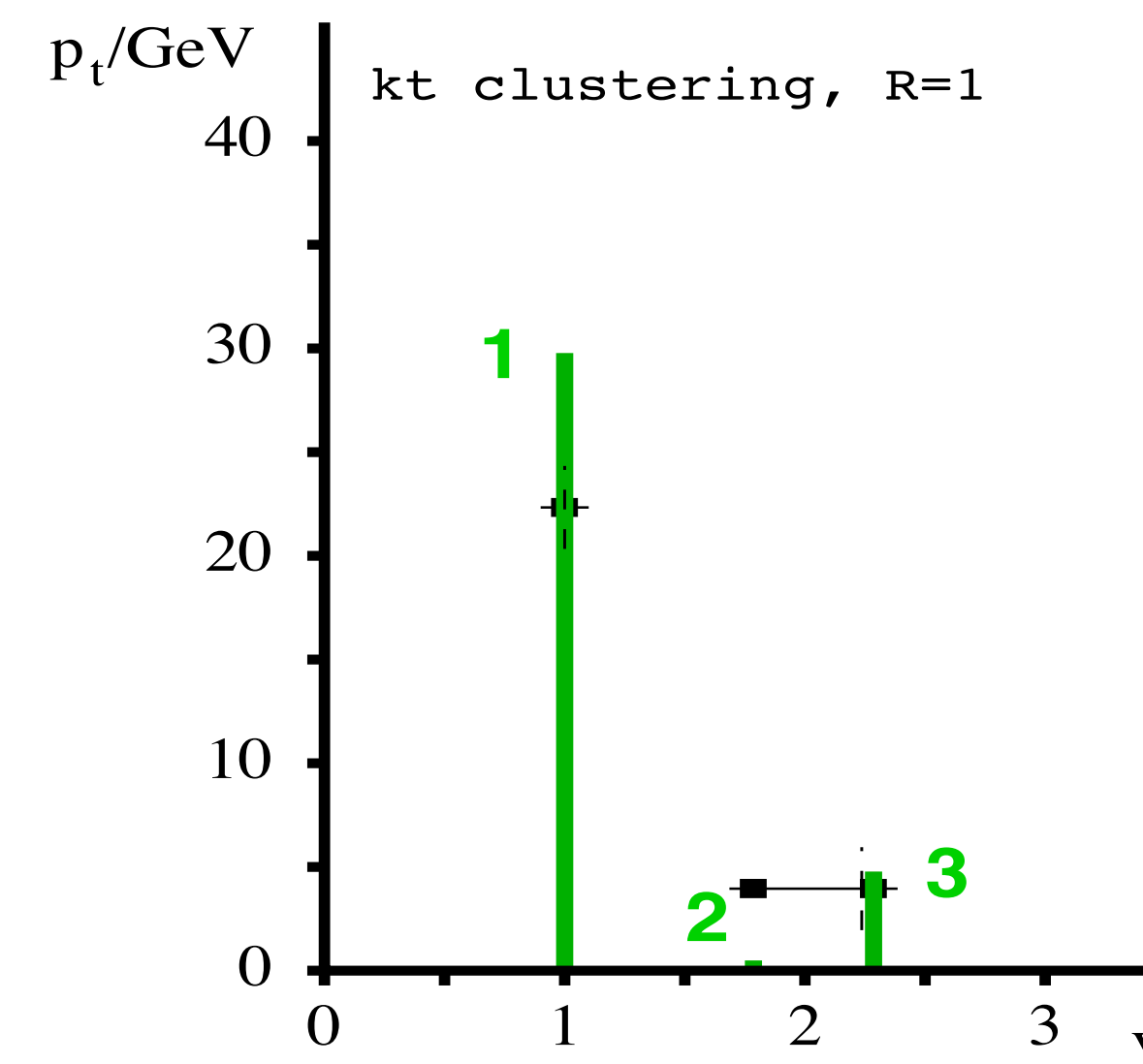
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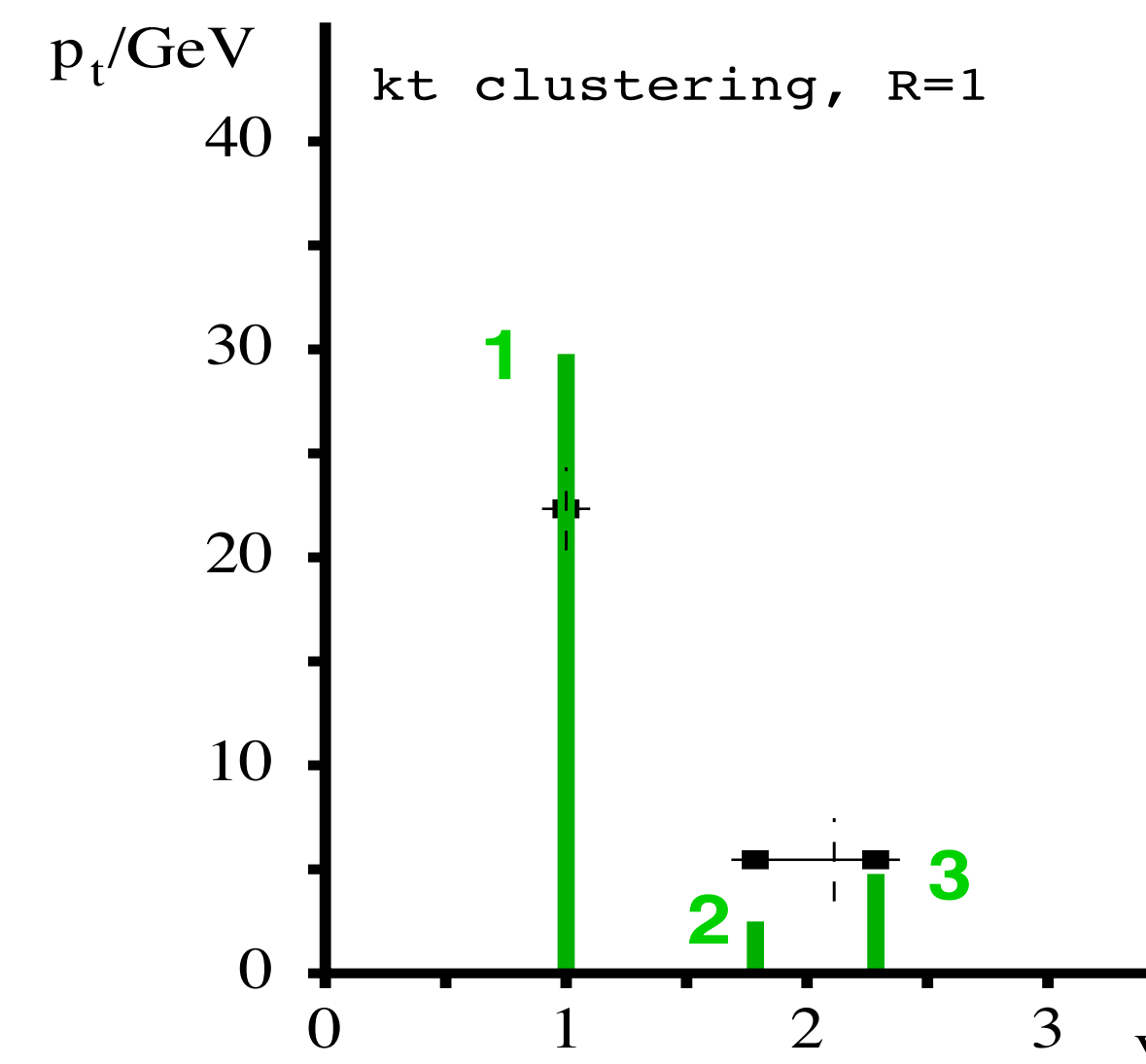
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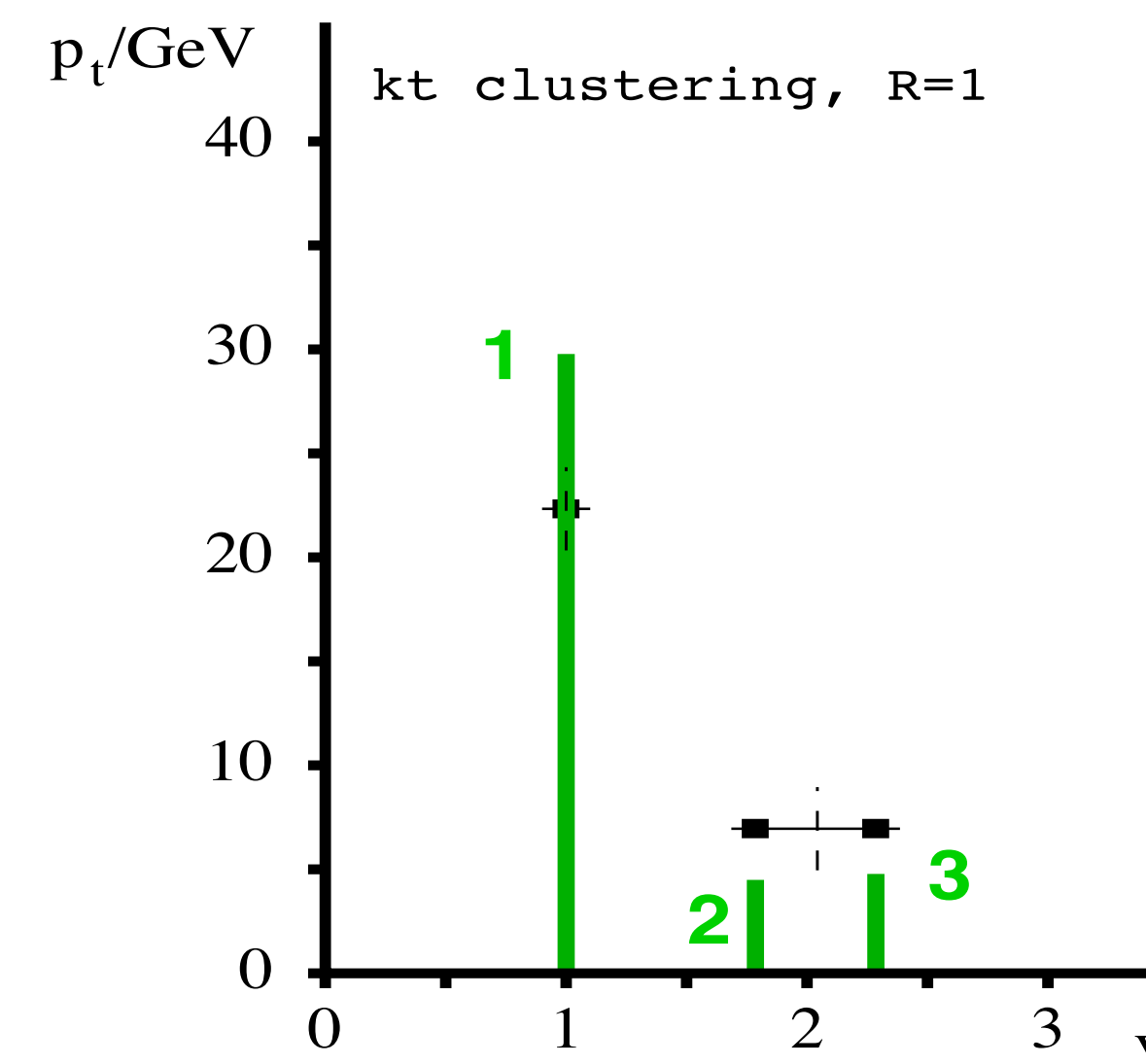
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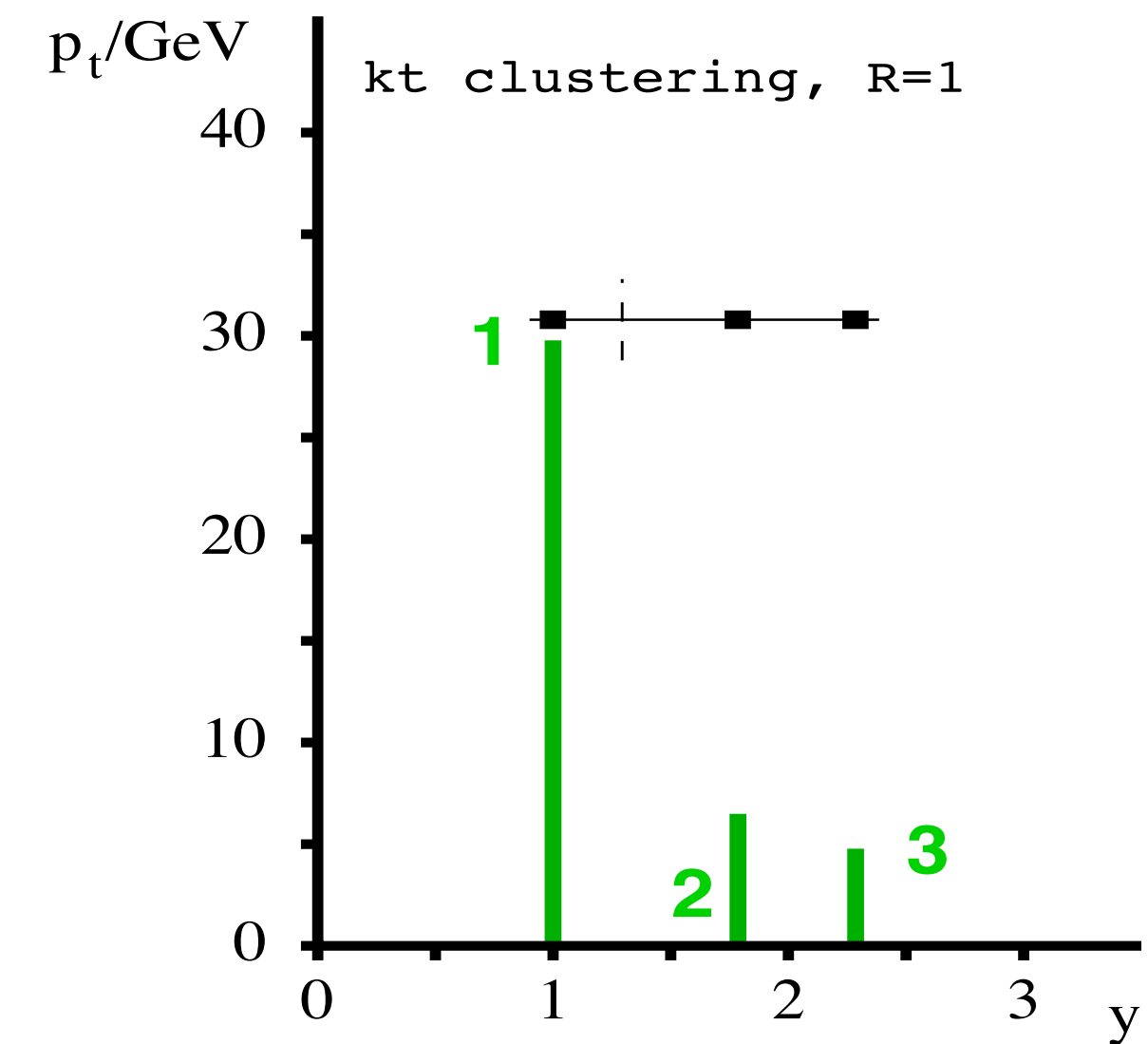
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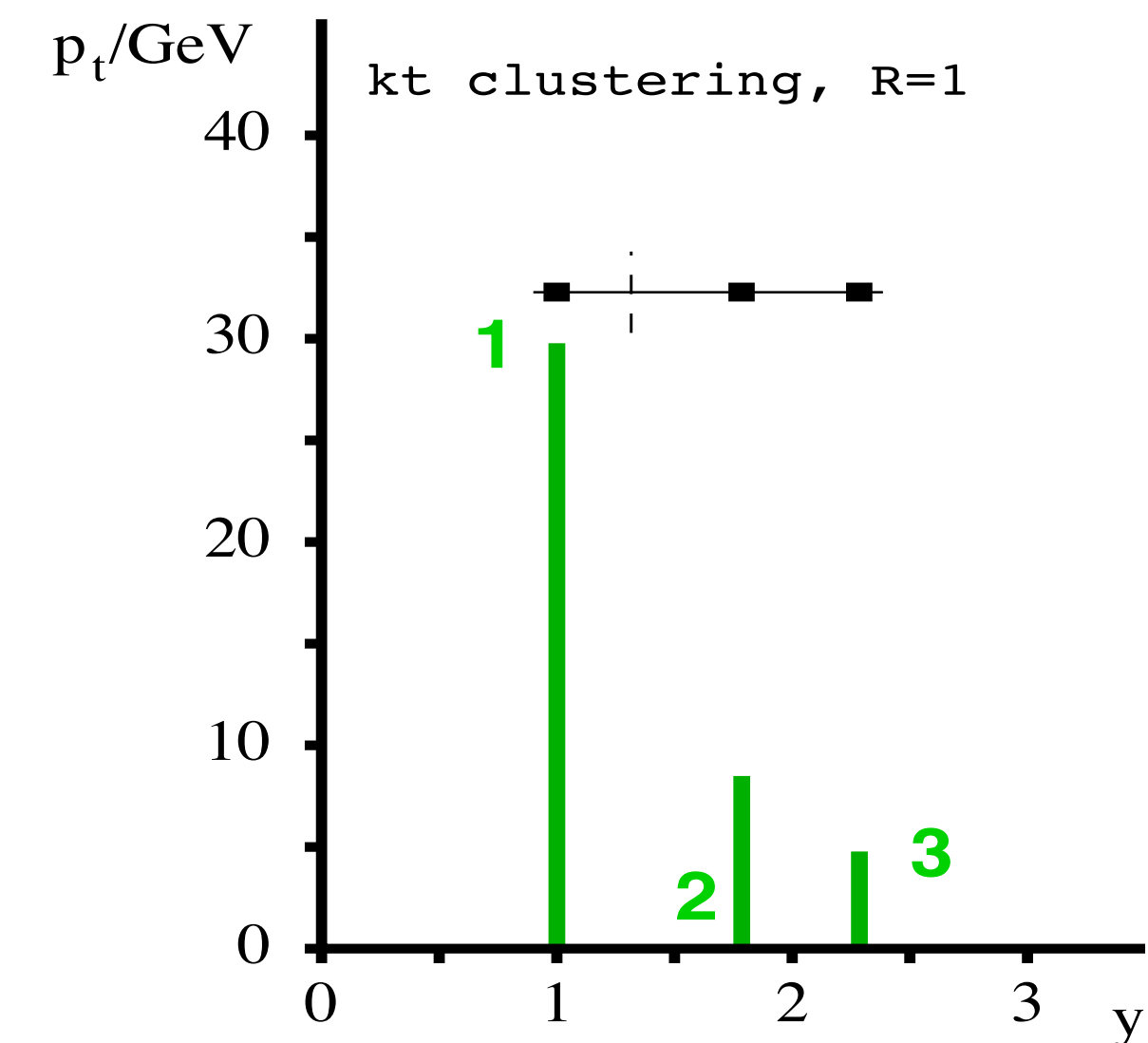
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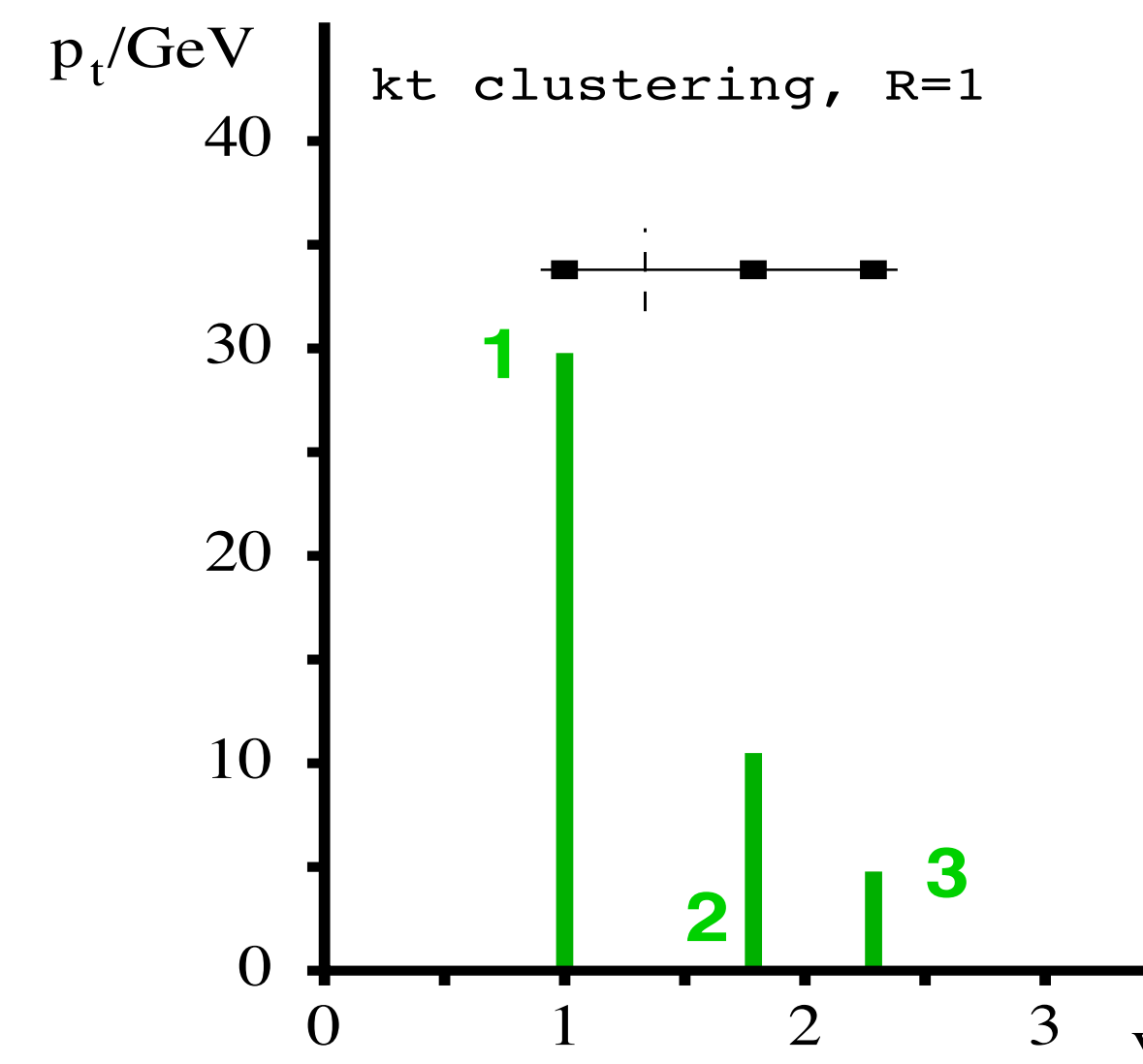
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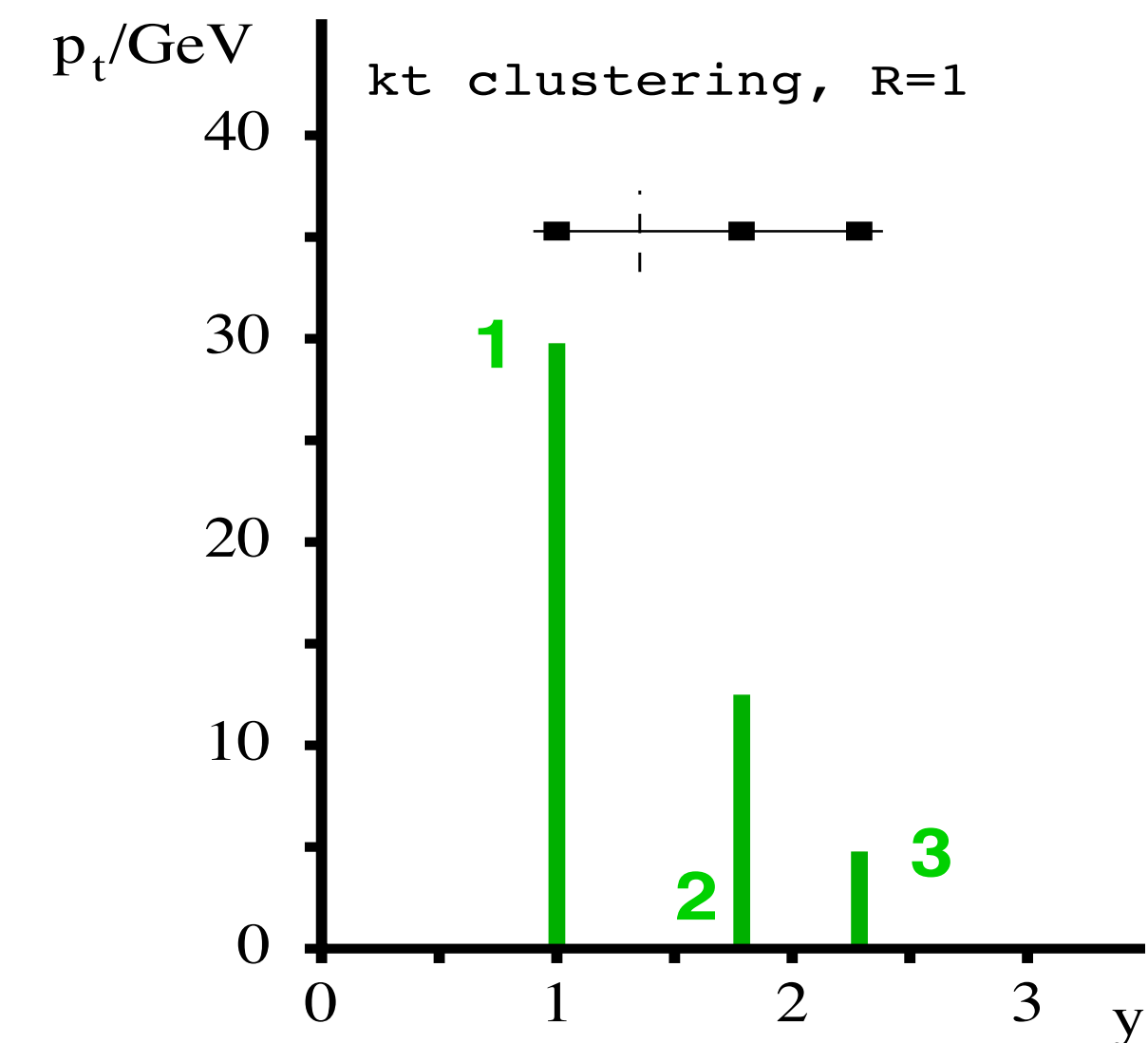
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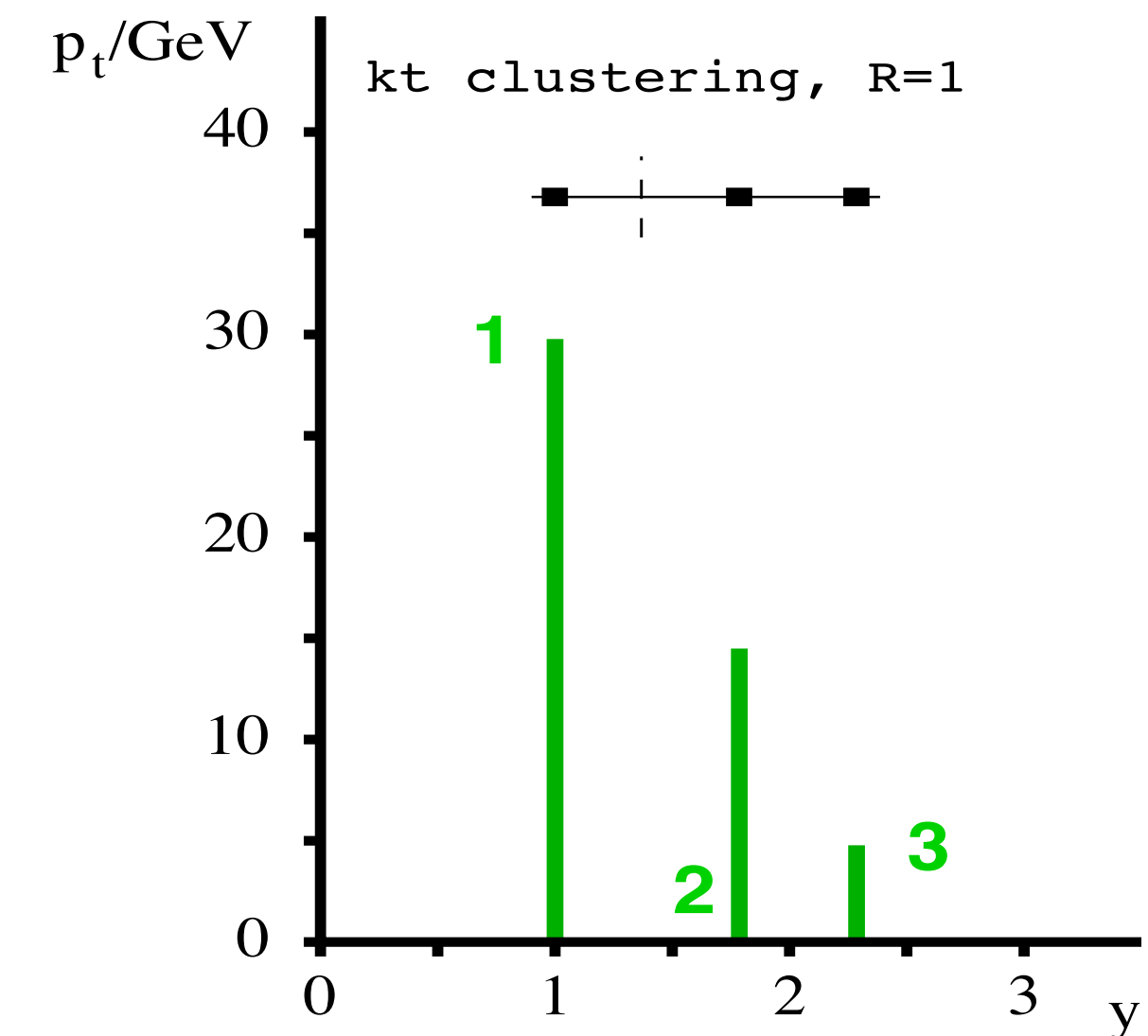
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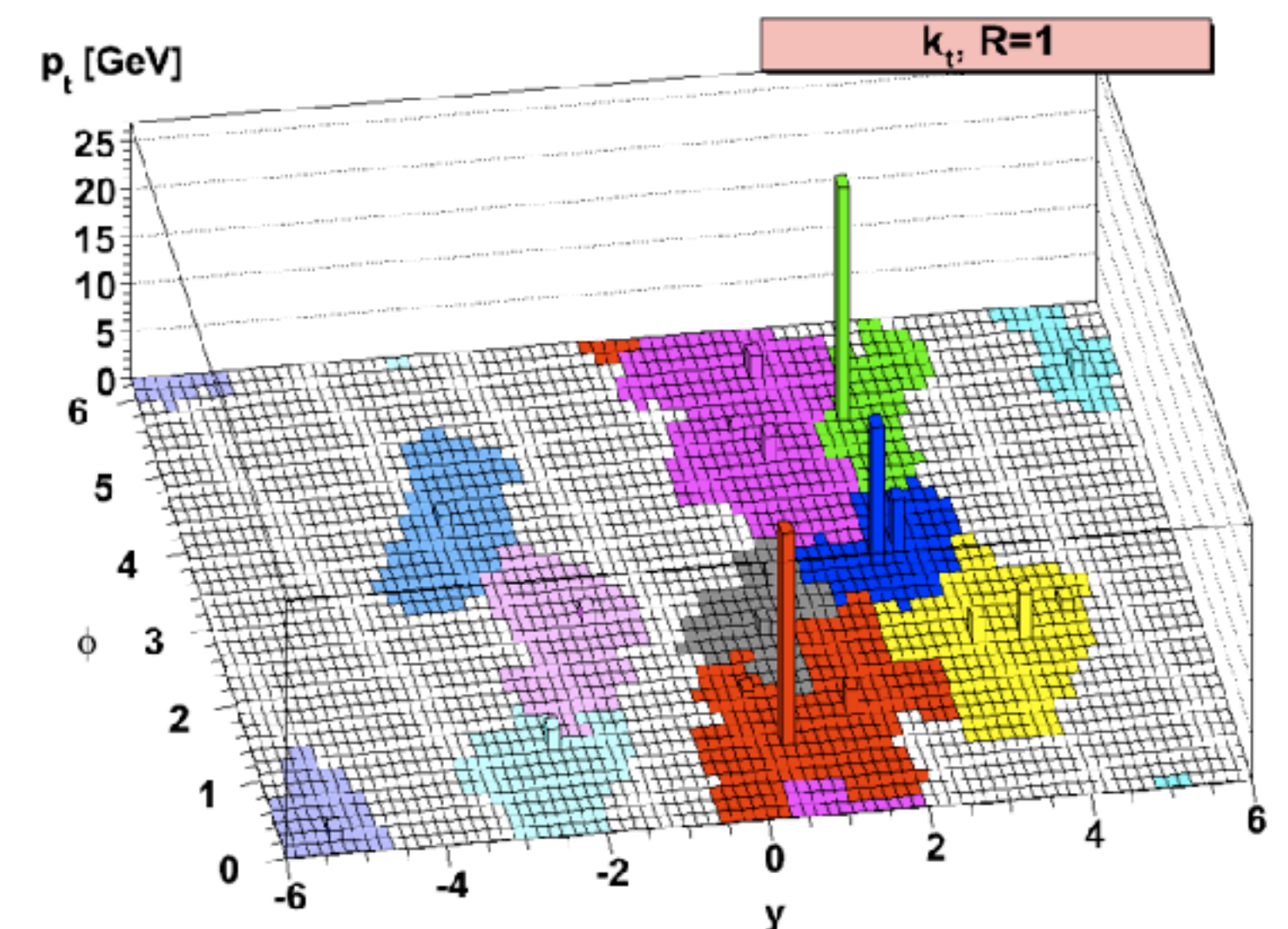
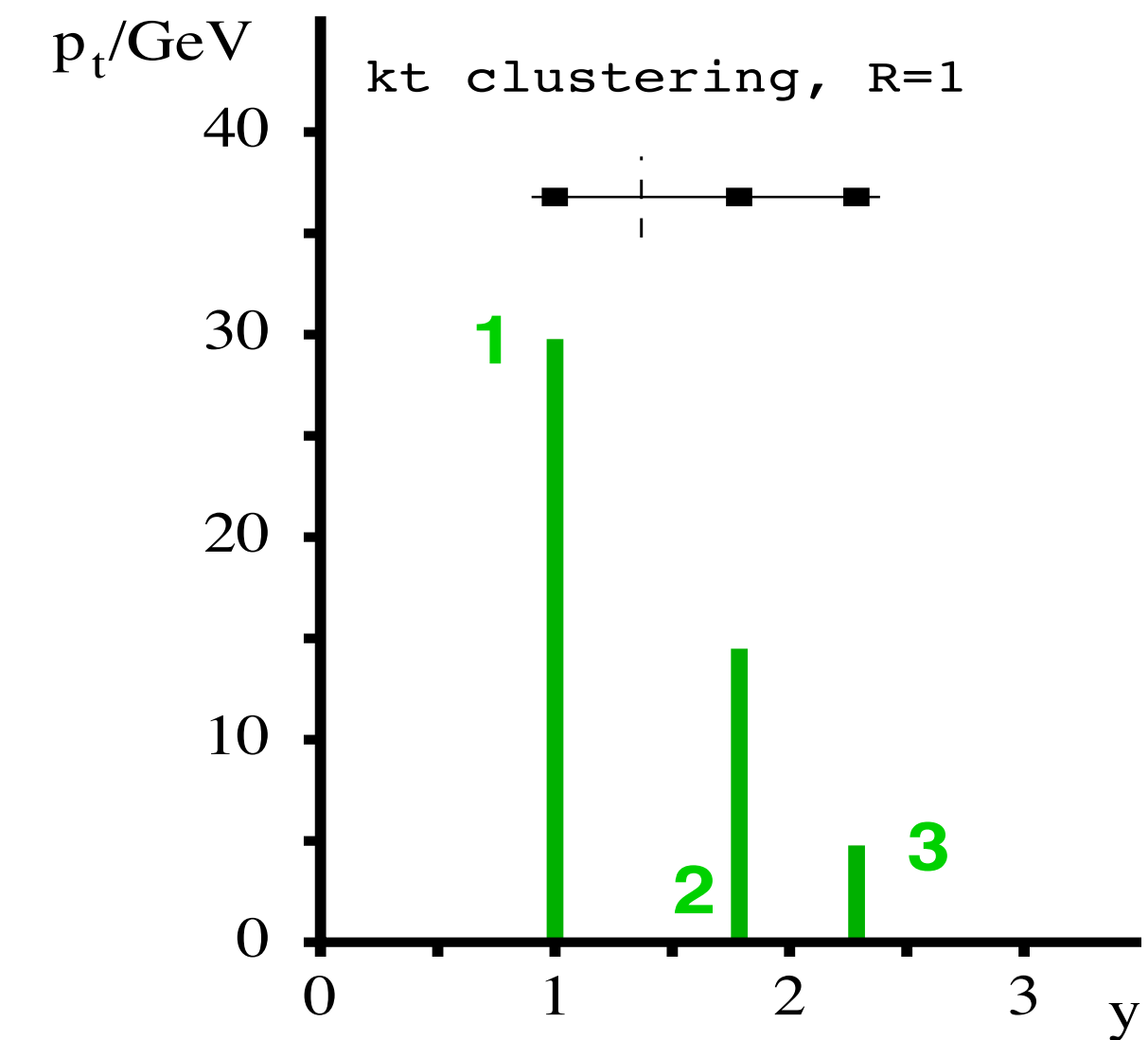
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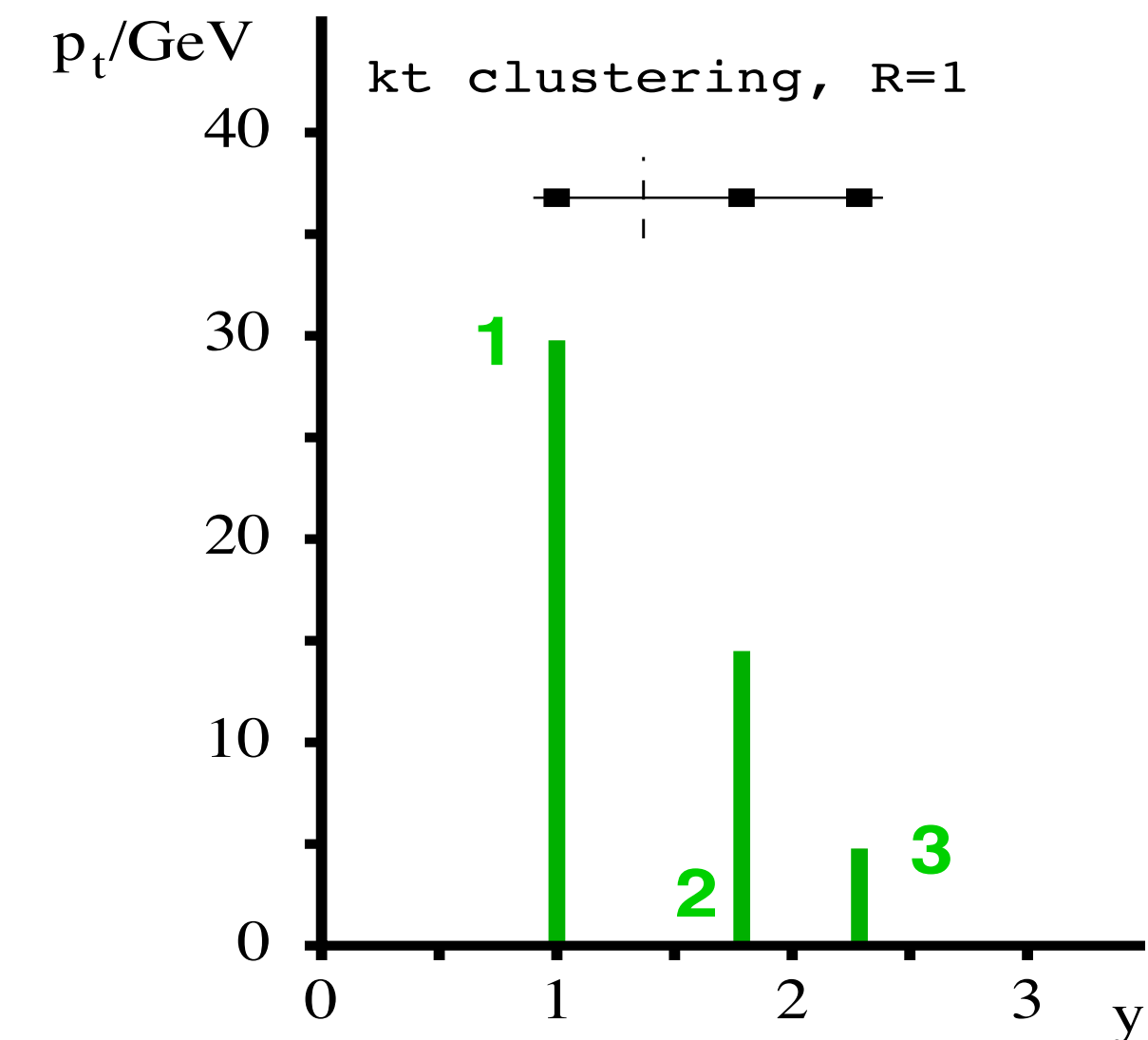
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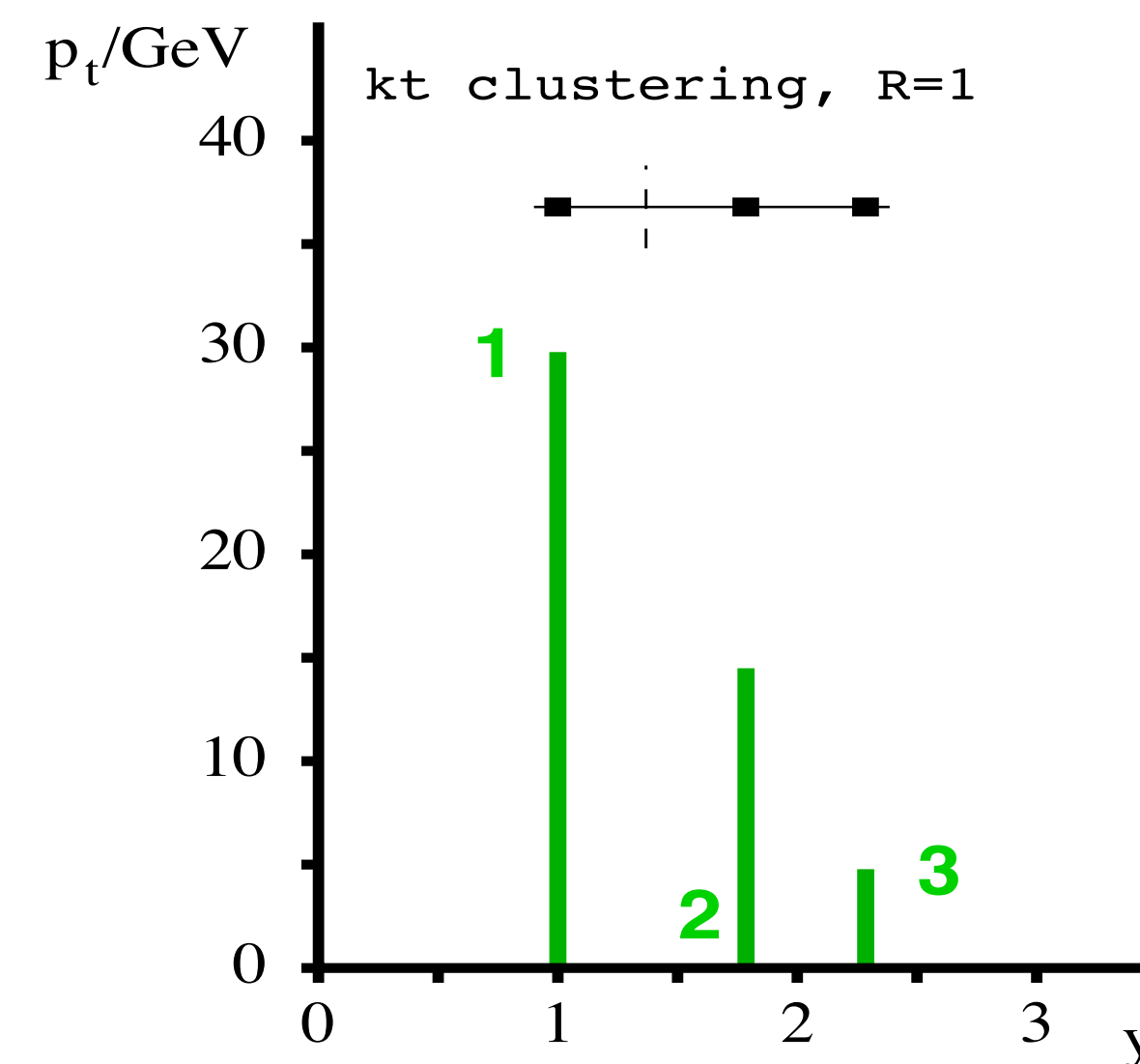
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anti-kT Algorithm



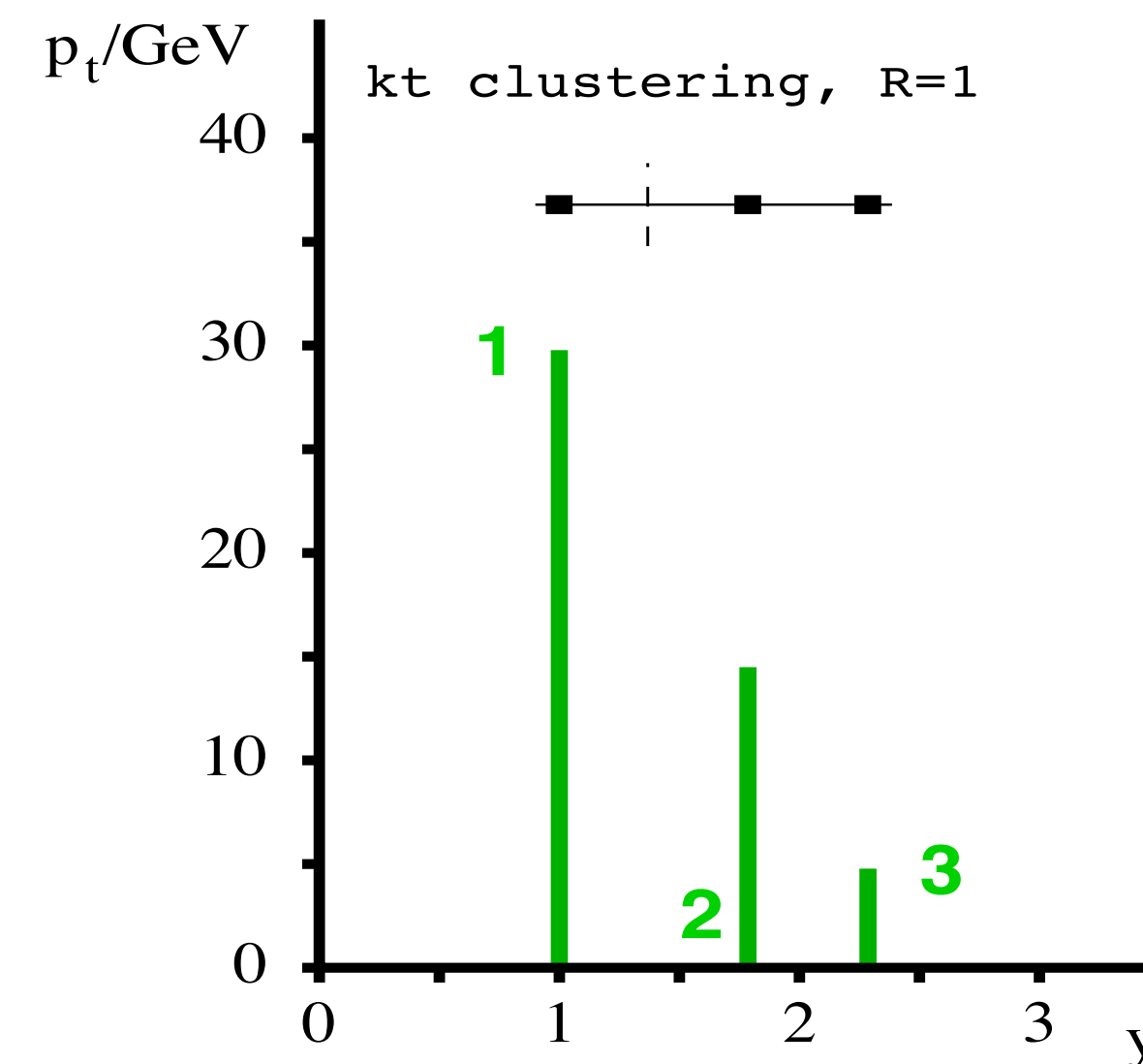
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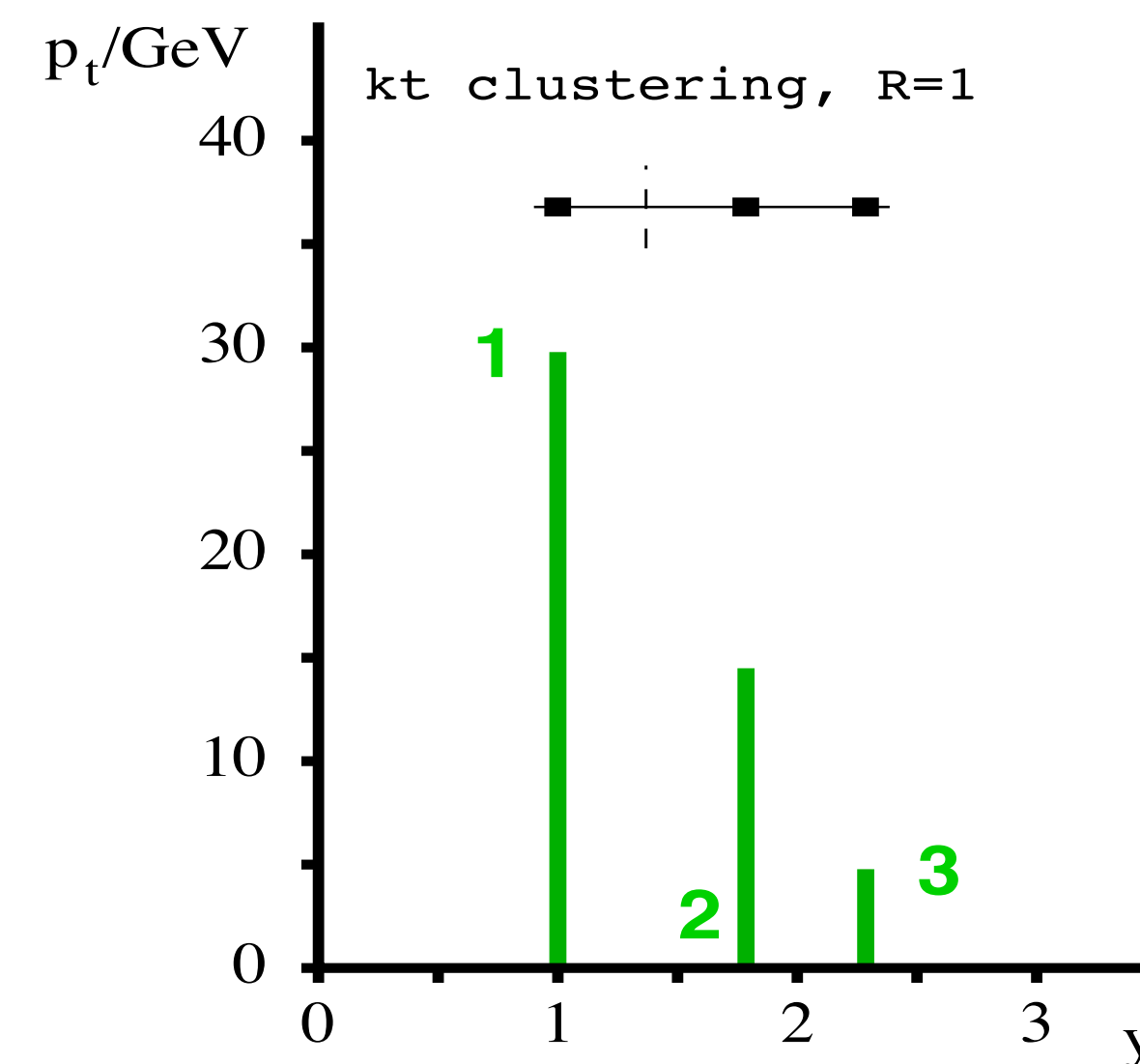
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anti-kT Algorithm



Jet Reconstruction

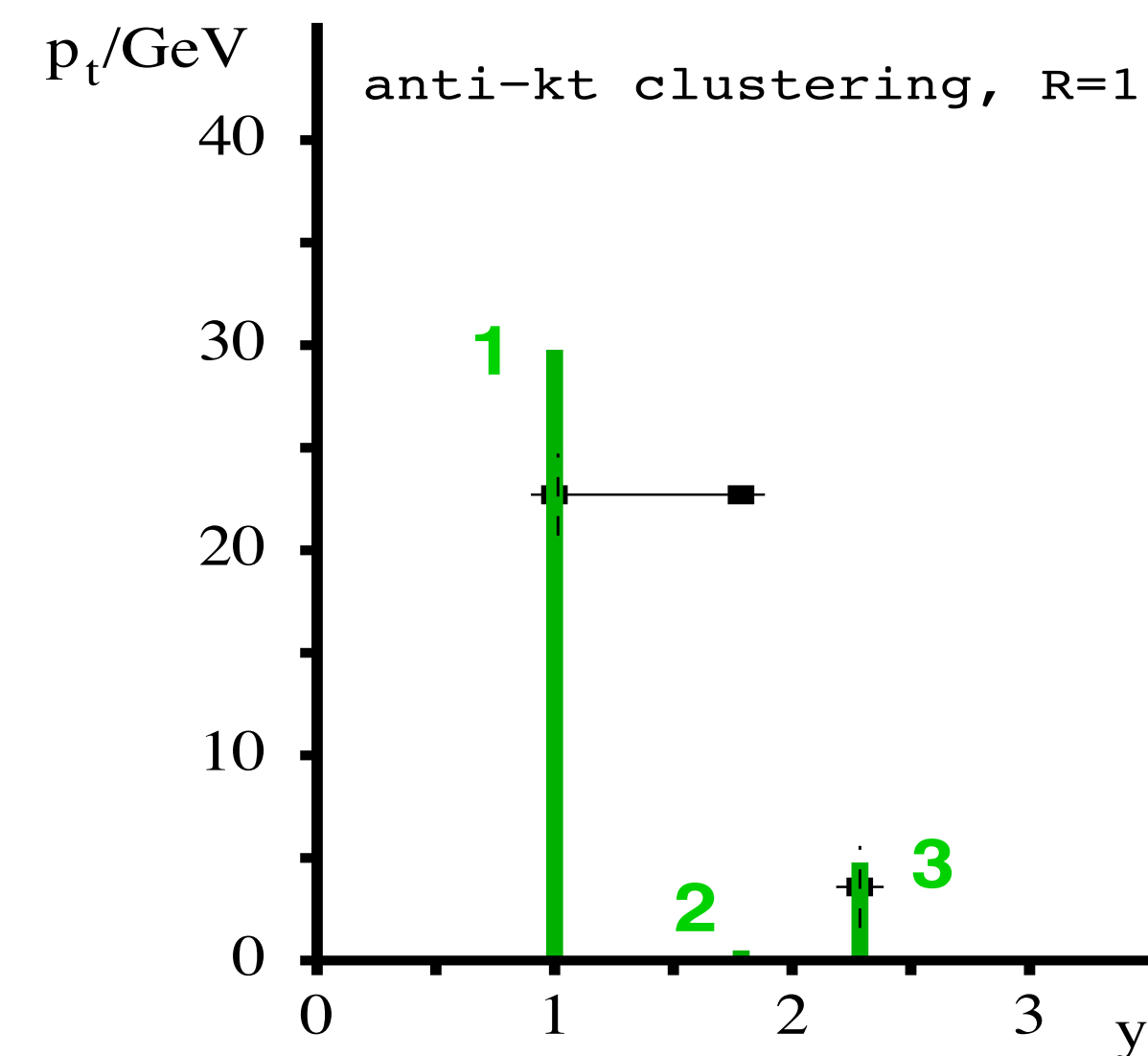
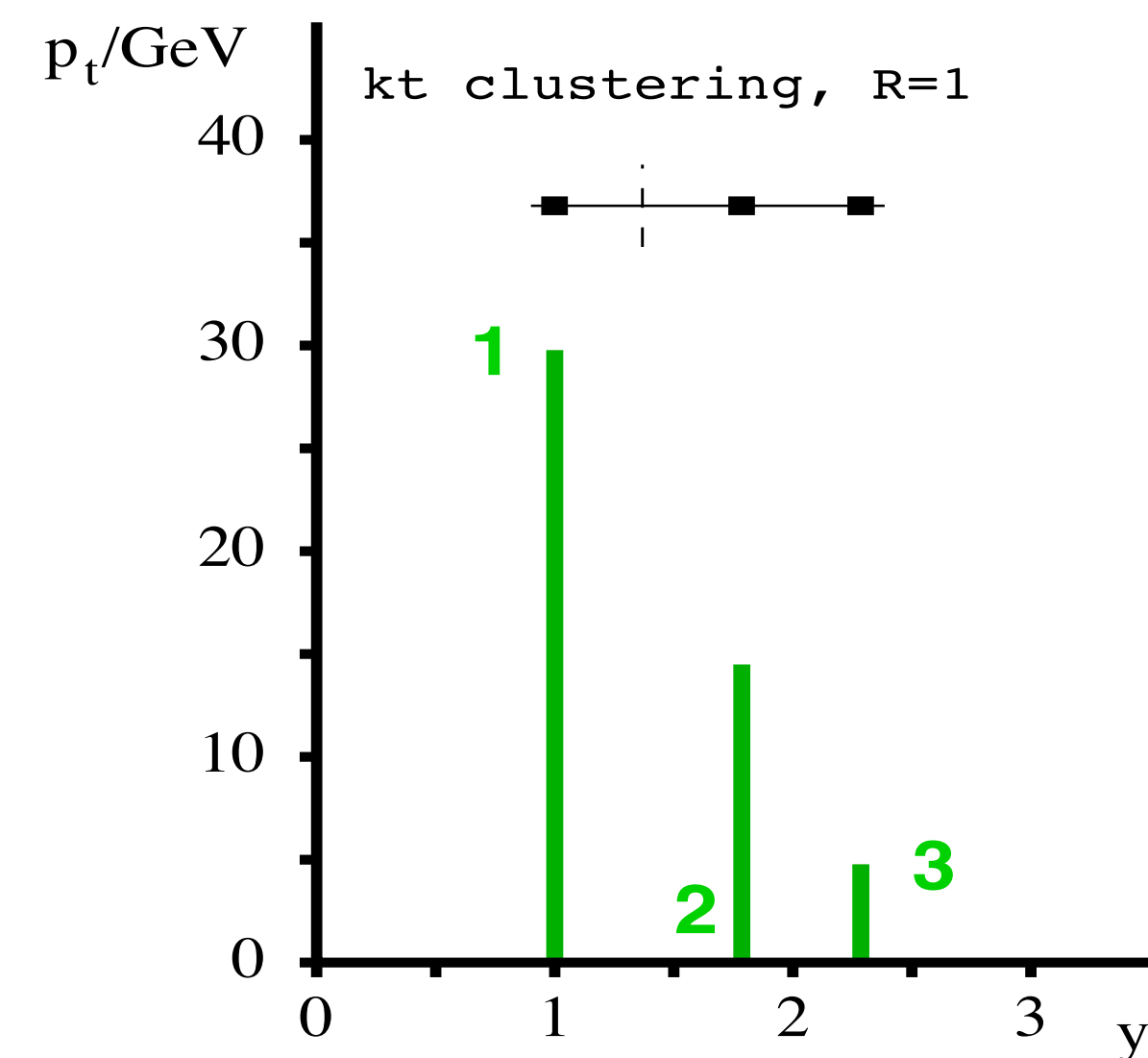
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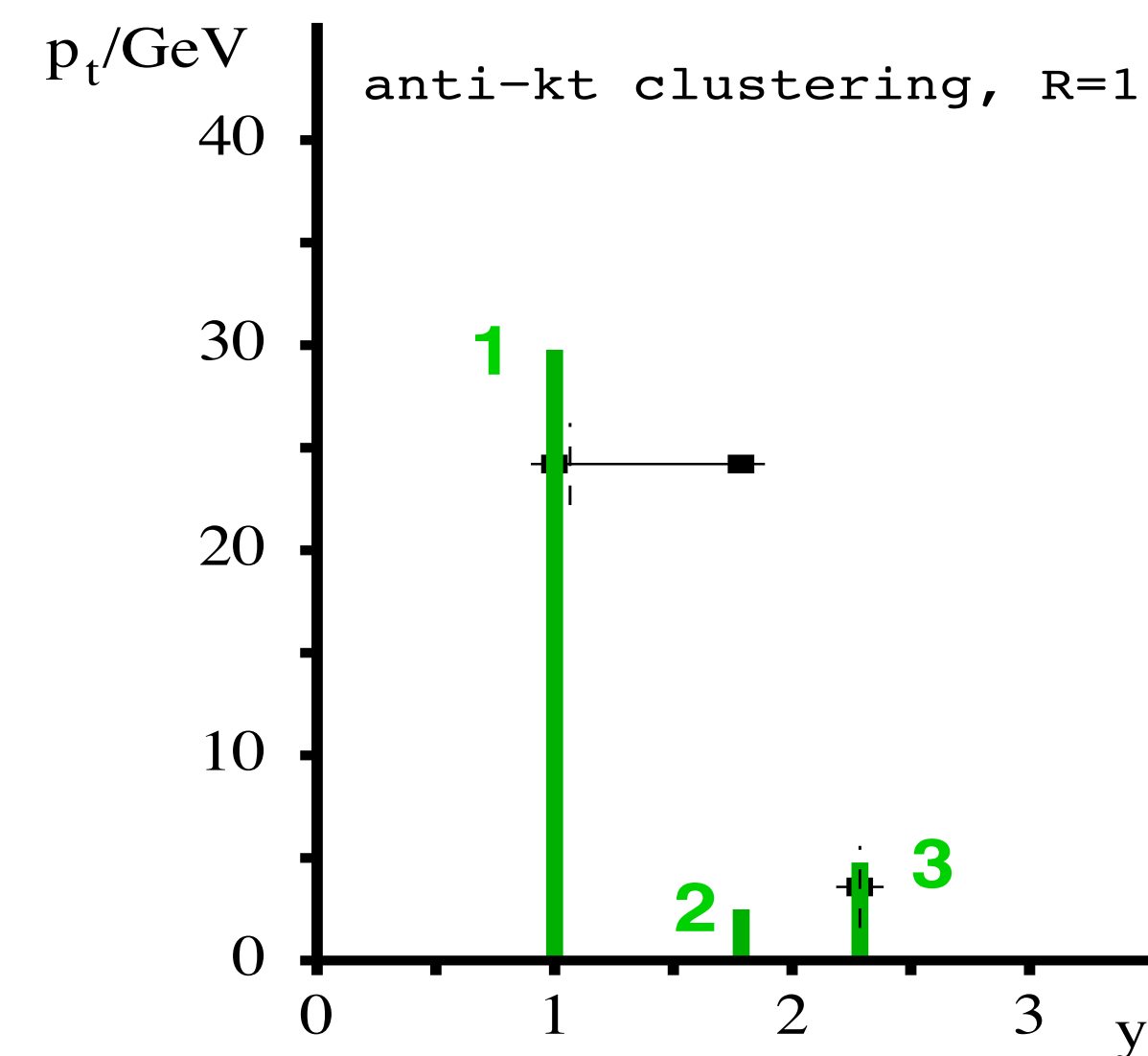
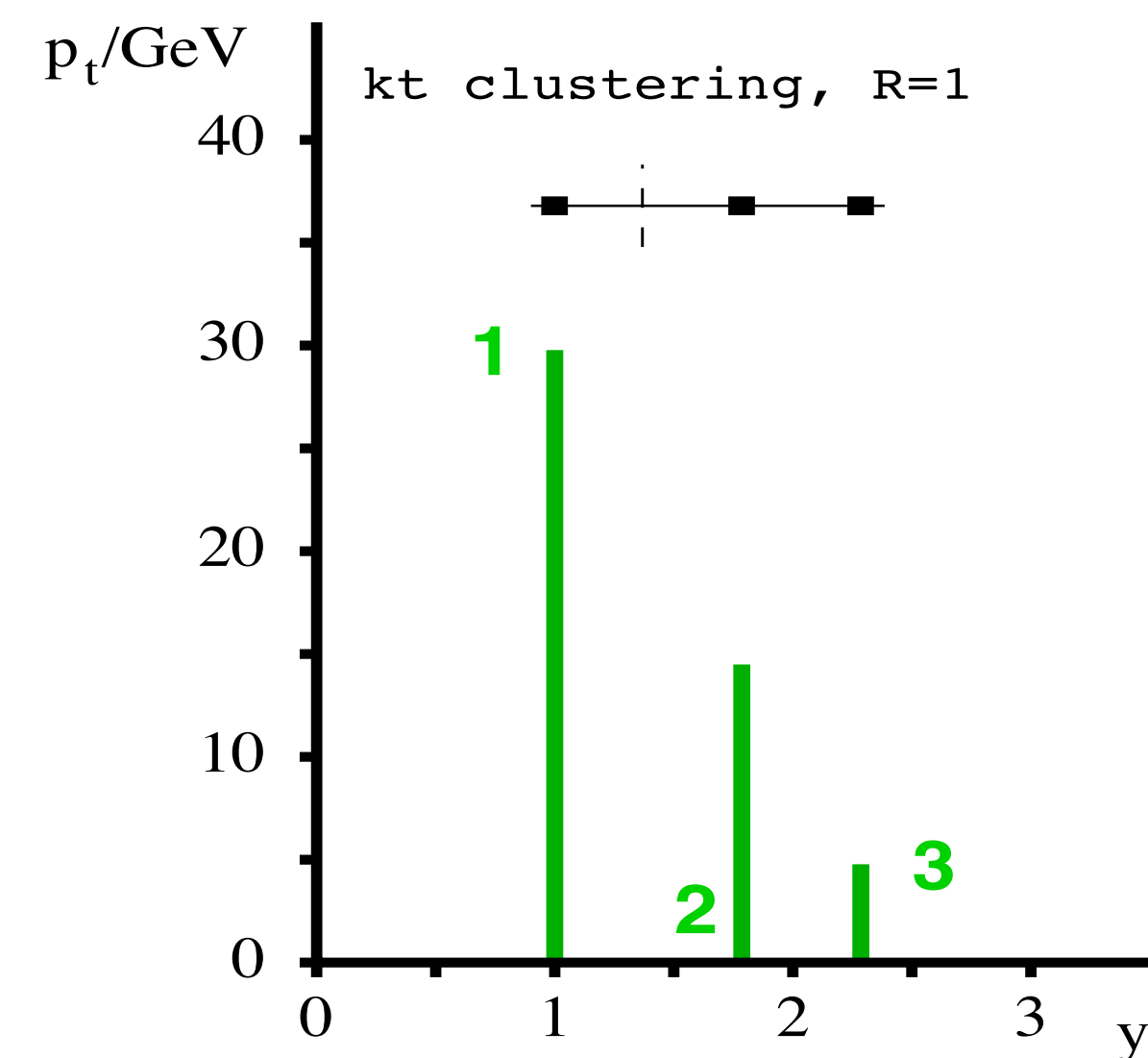
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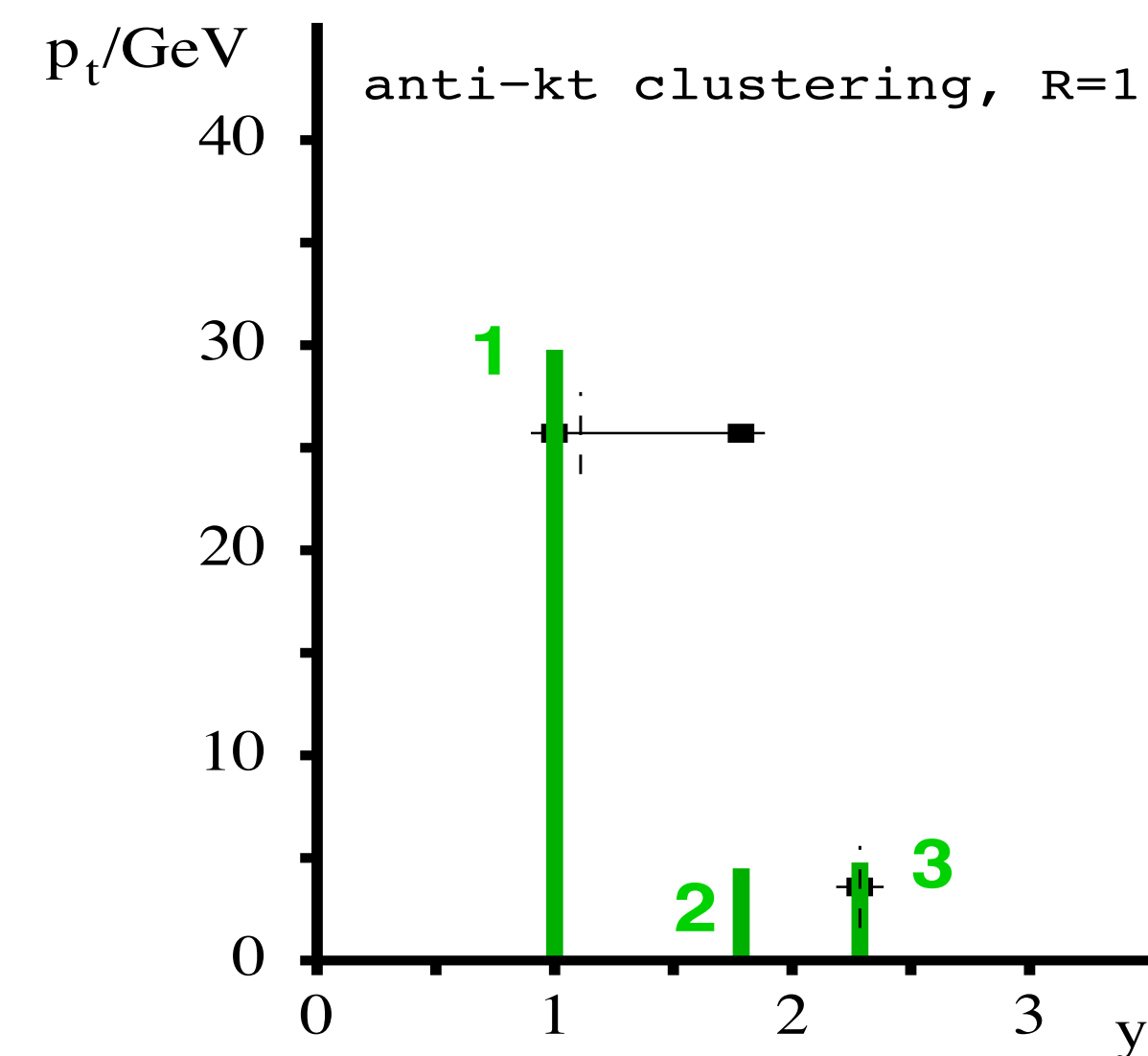
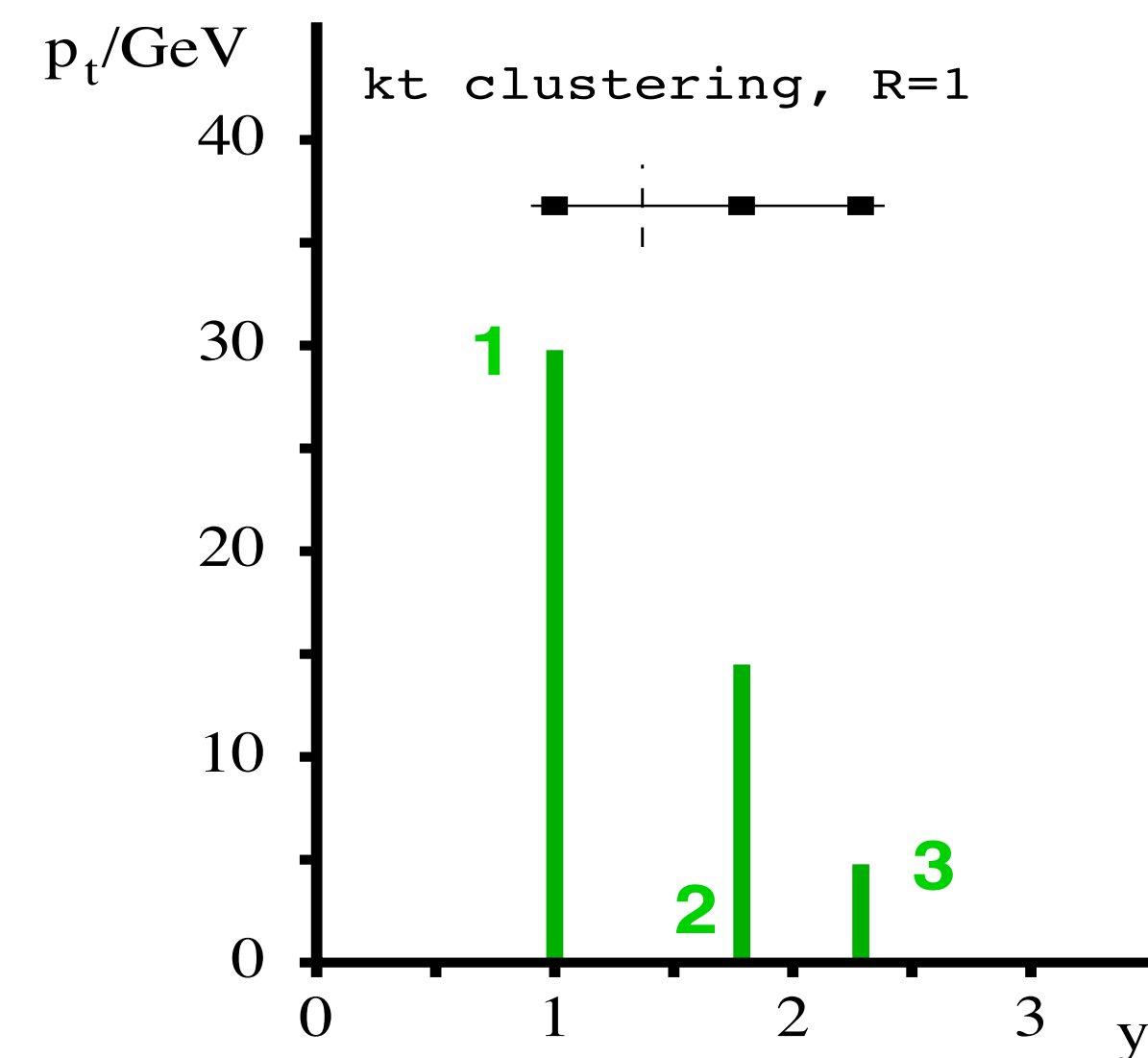
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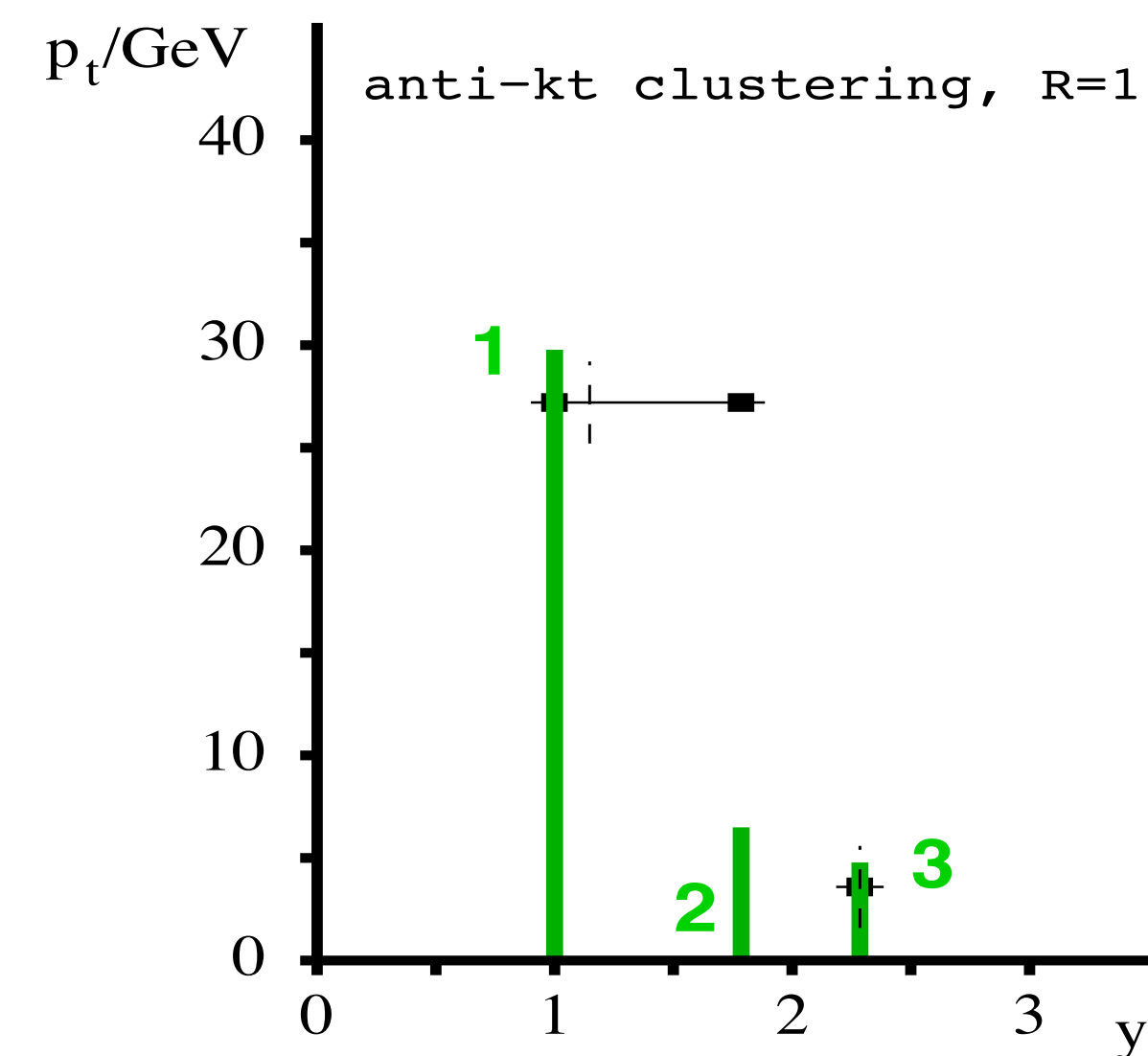
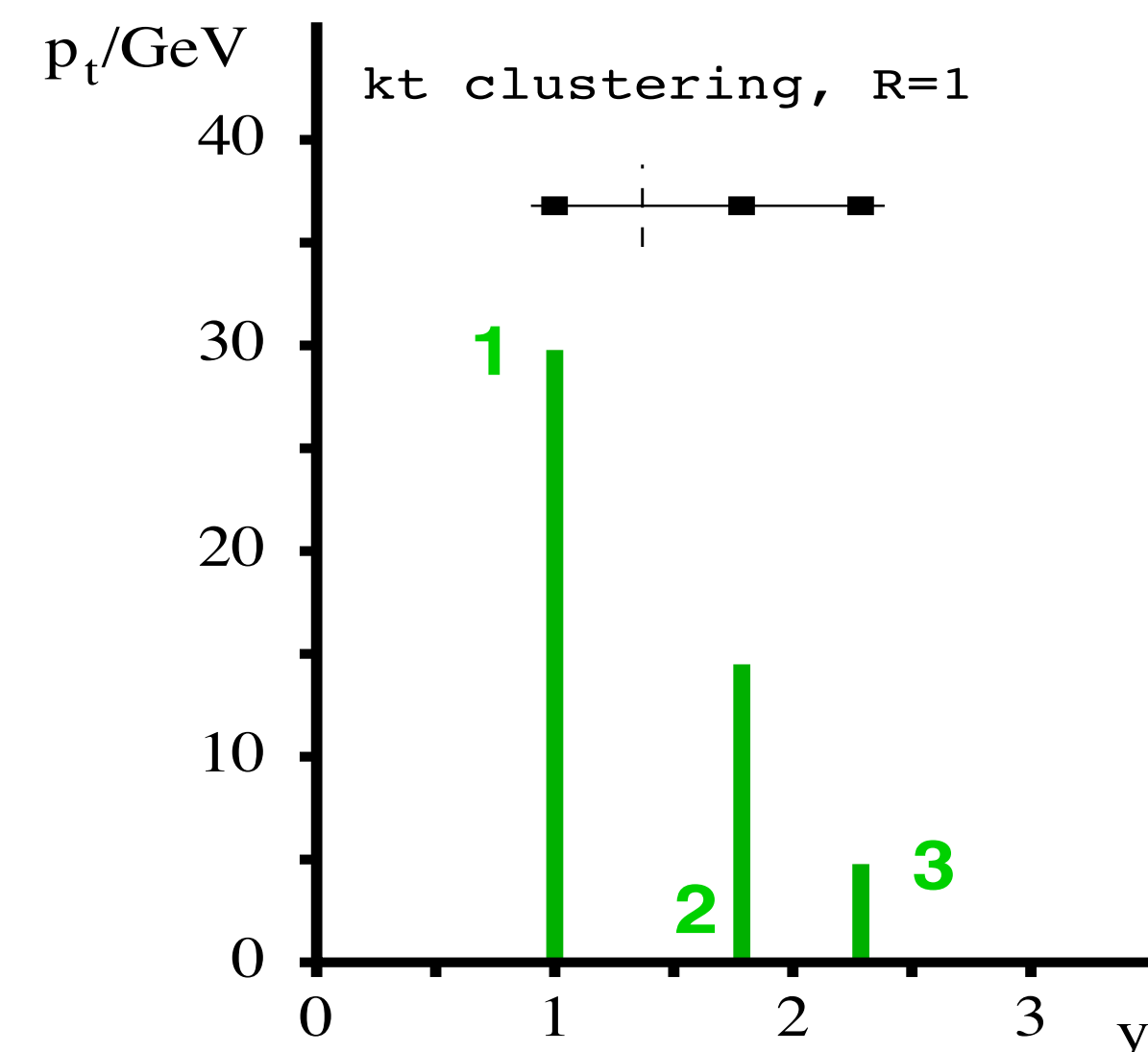
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anti-kT Algorithm



Jet Reconstruction

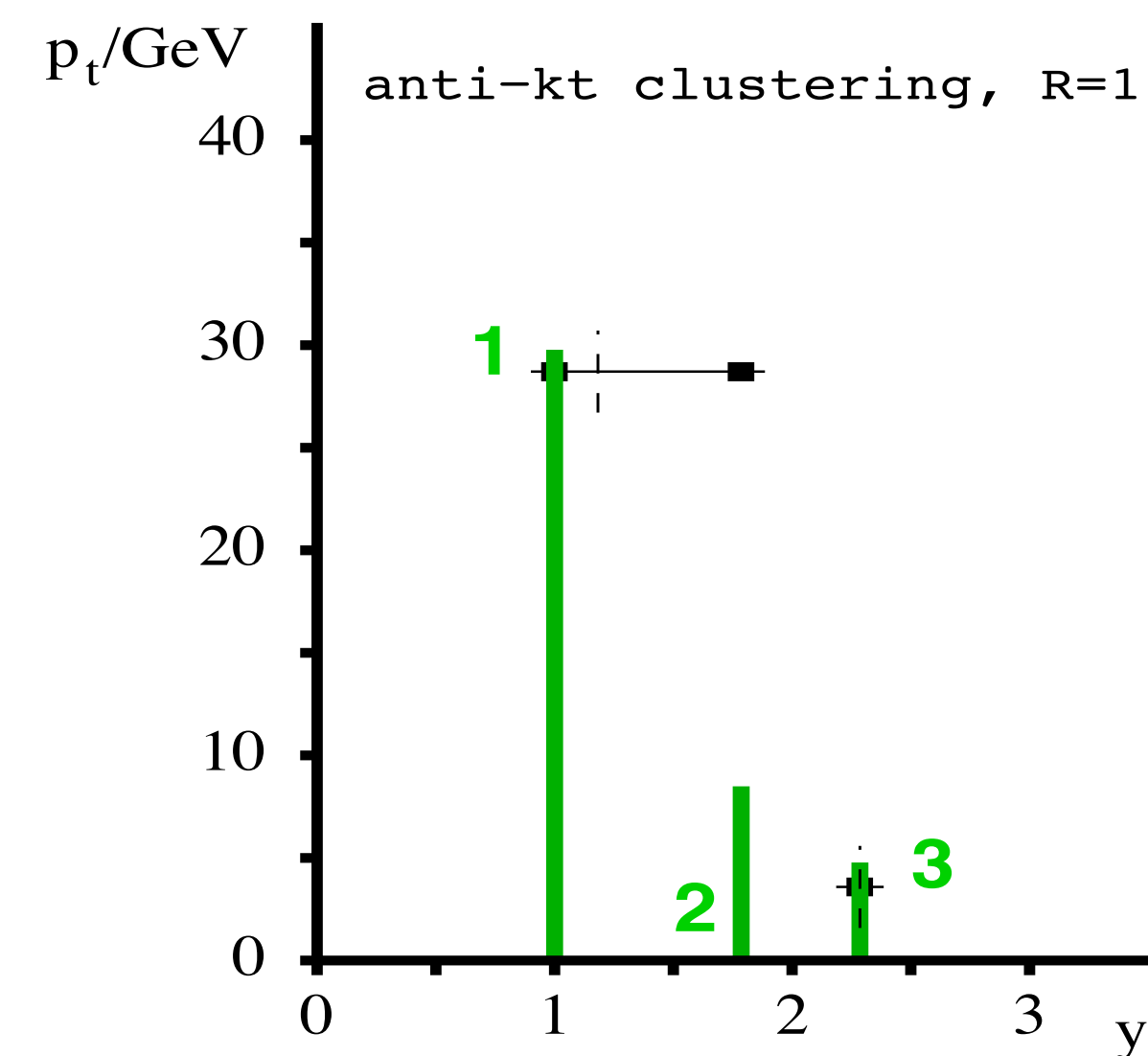
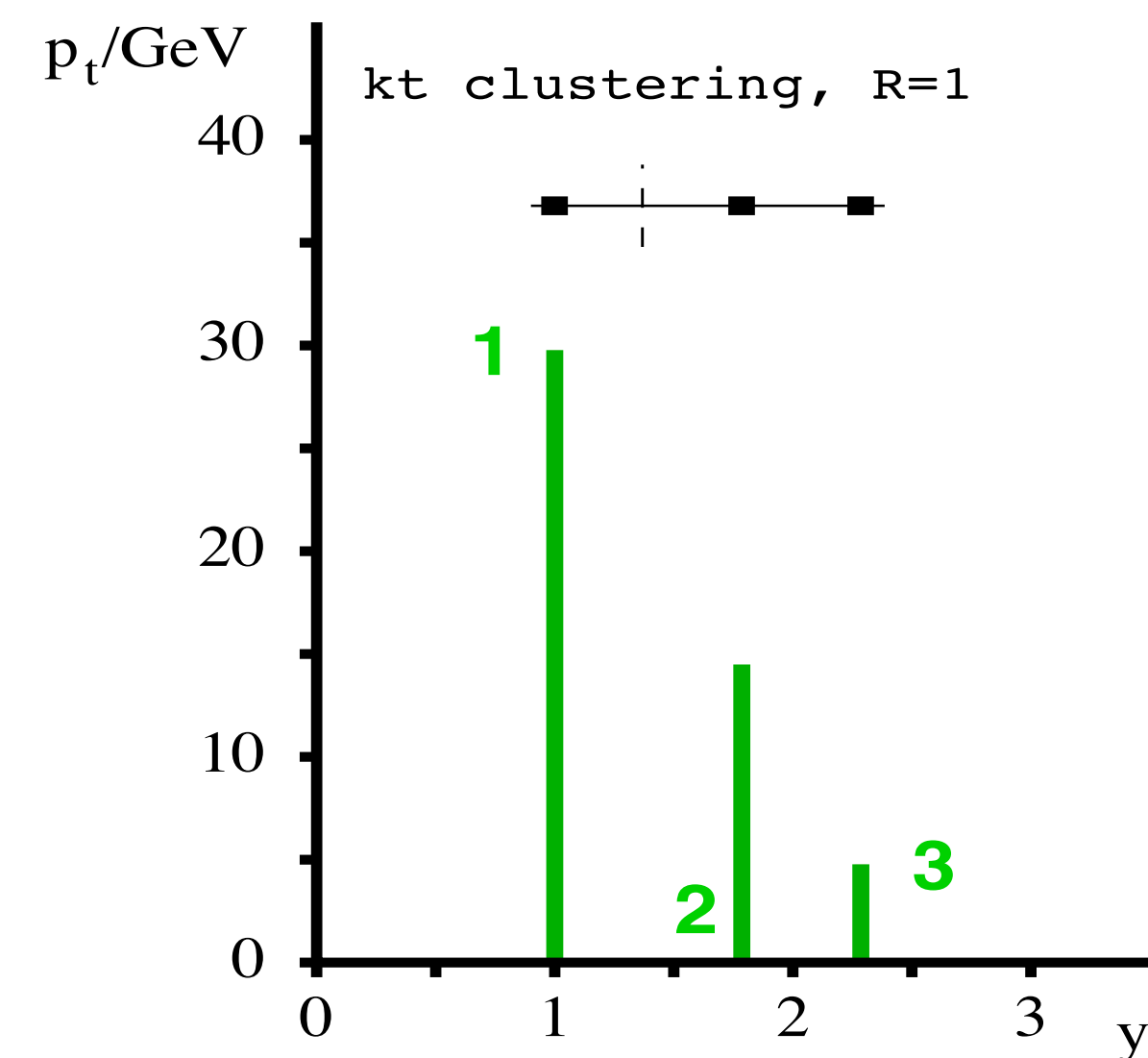
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Typical values:
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anti-kT Algorithm



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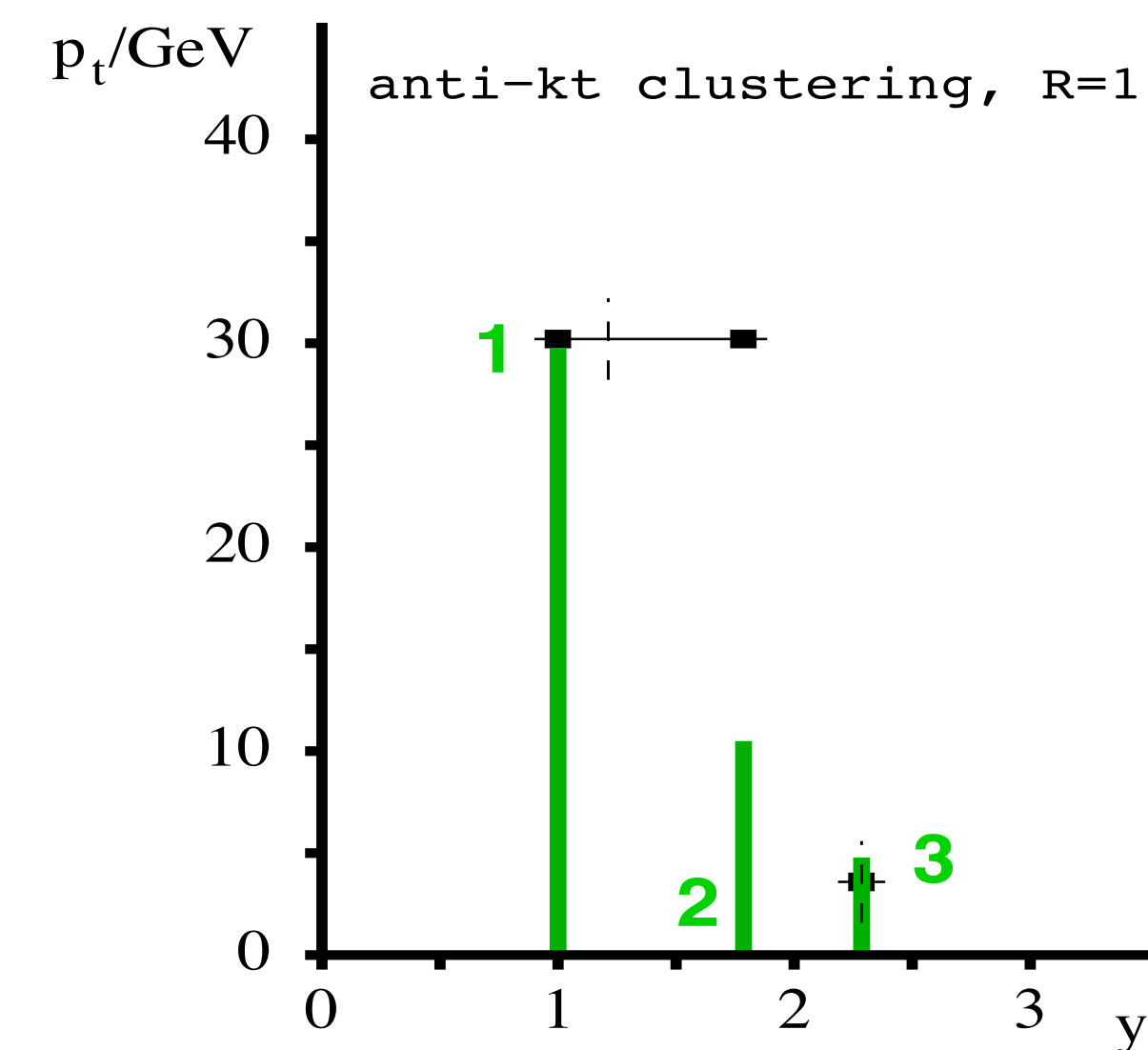
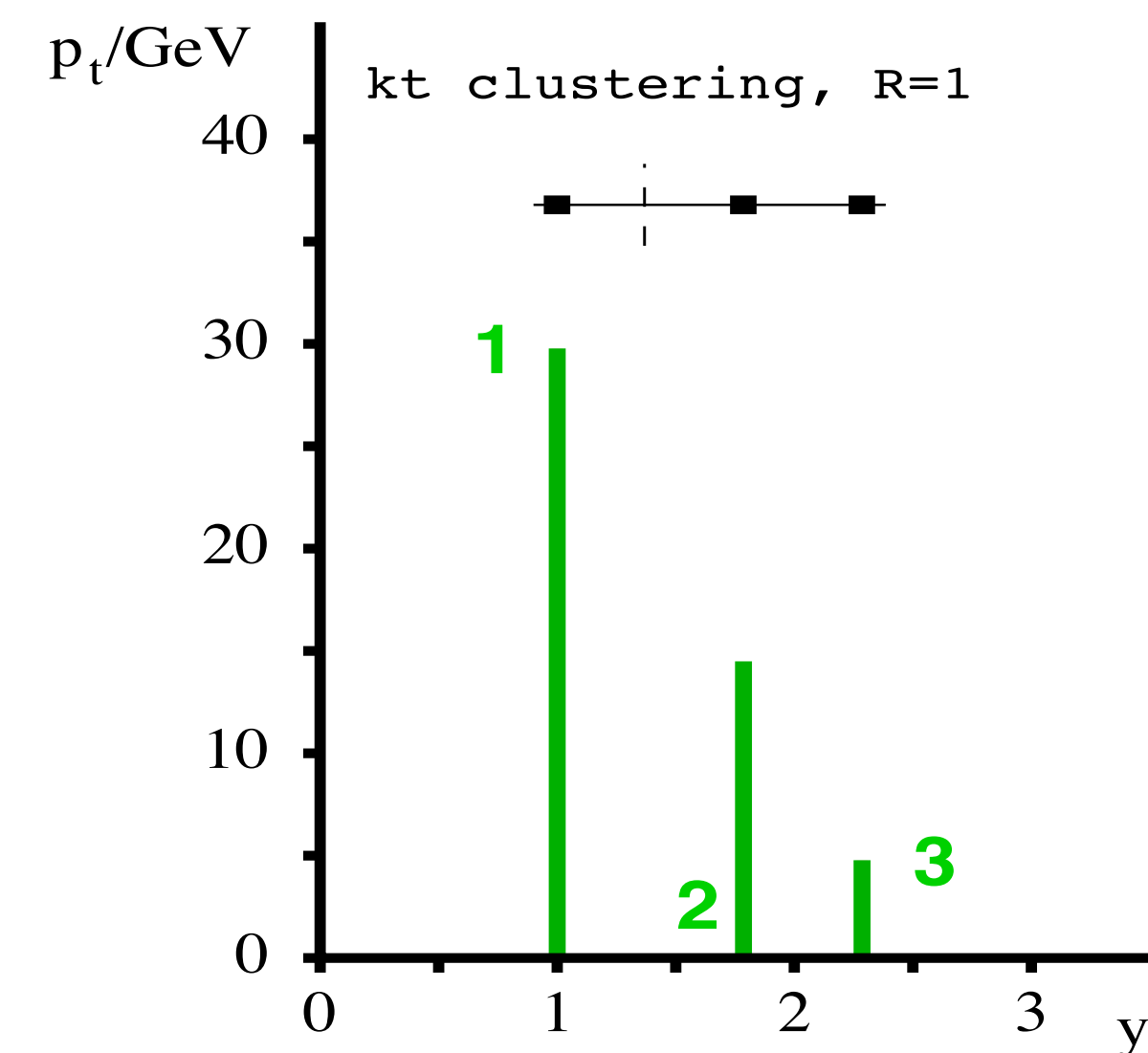
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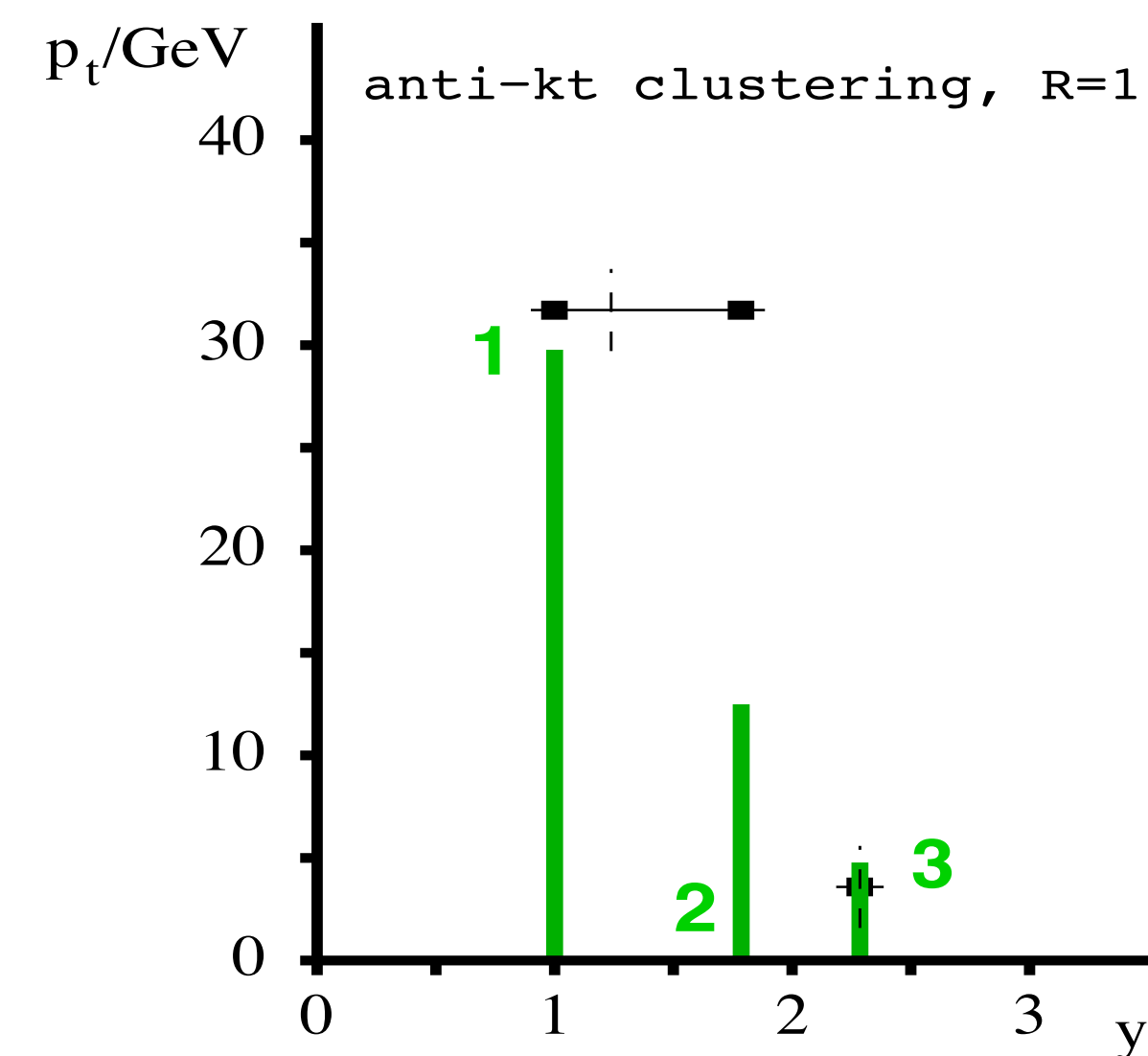
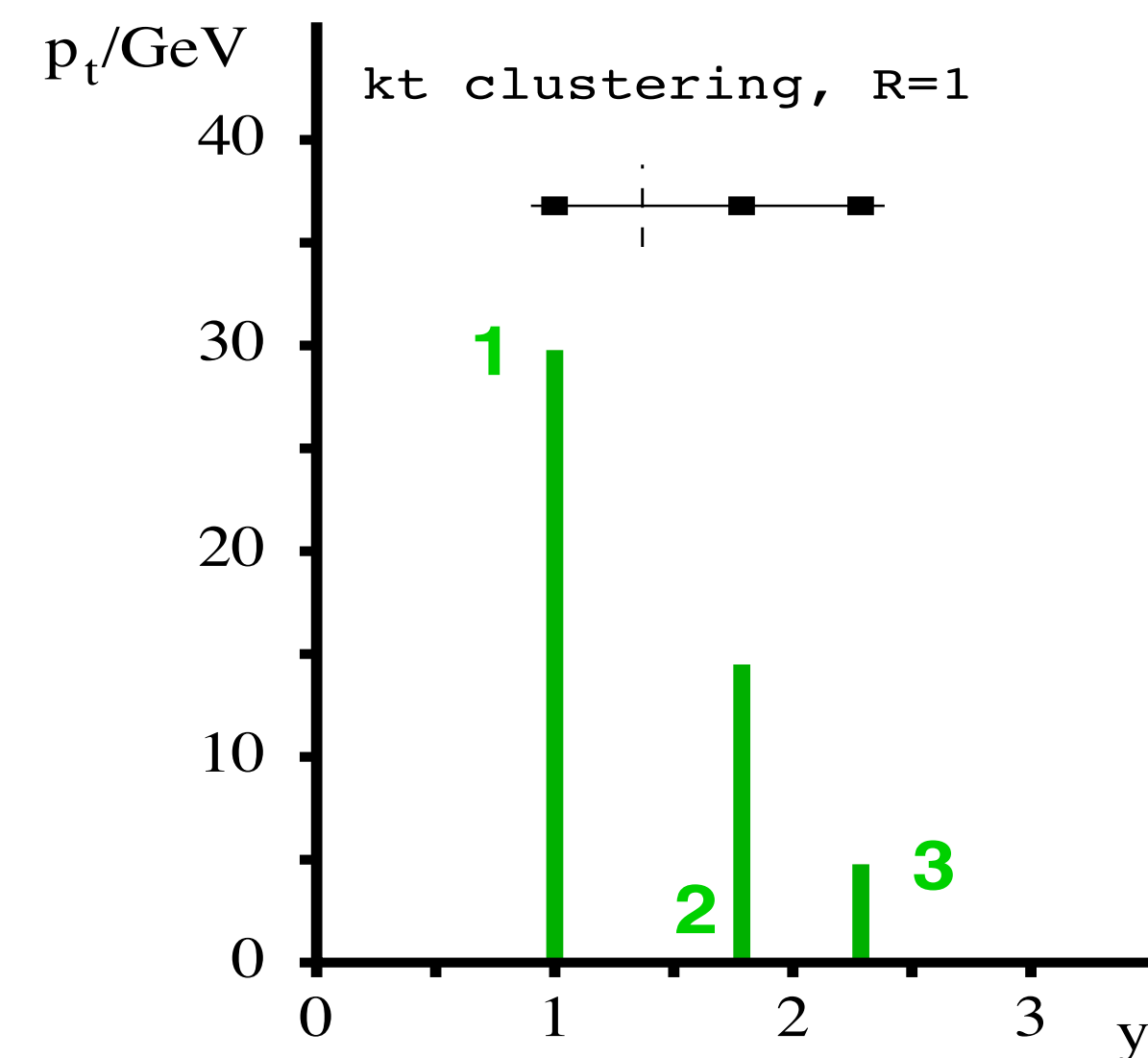
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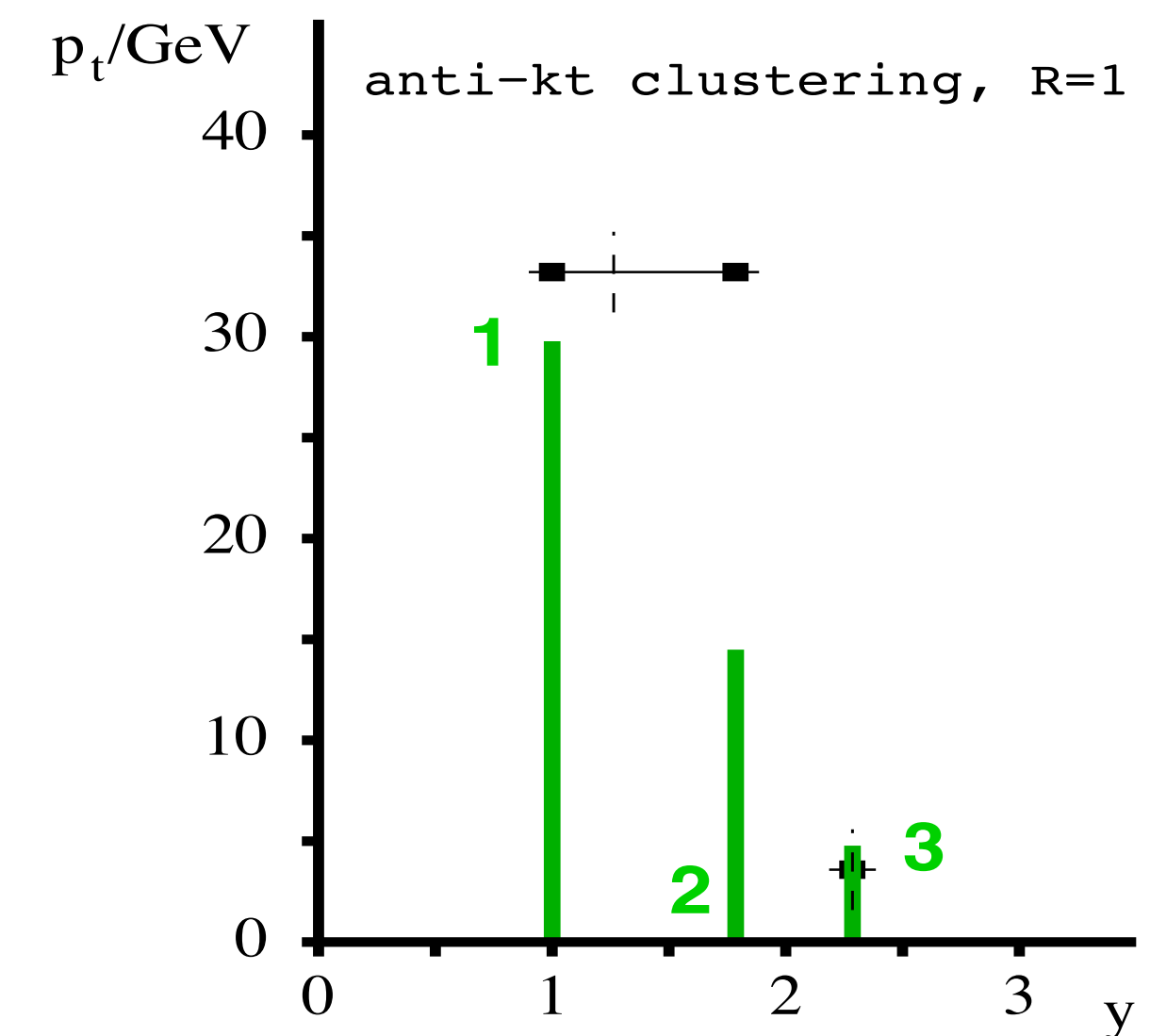
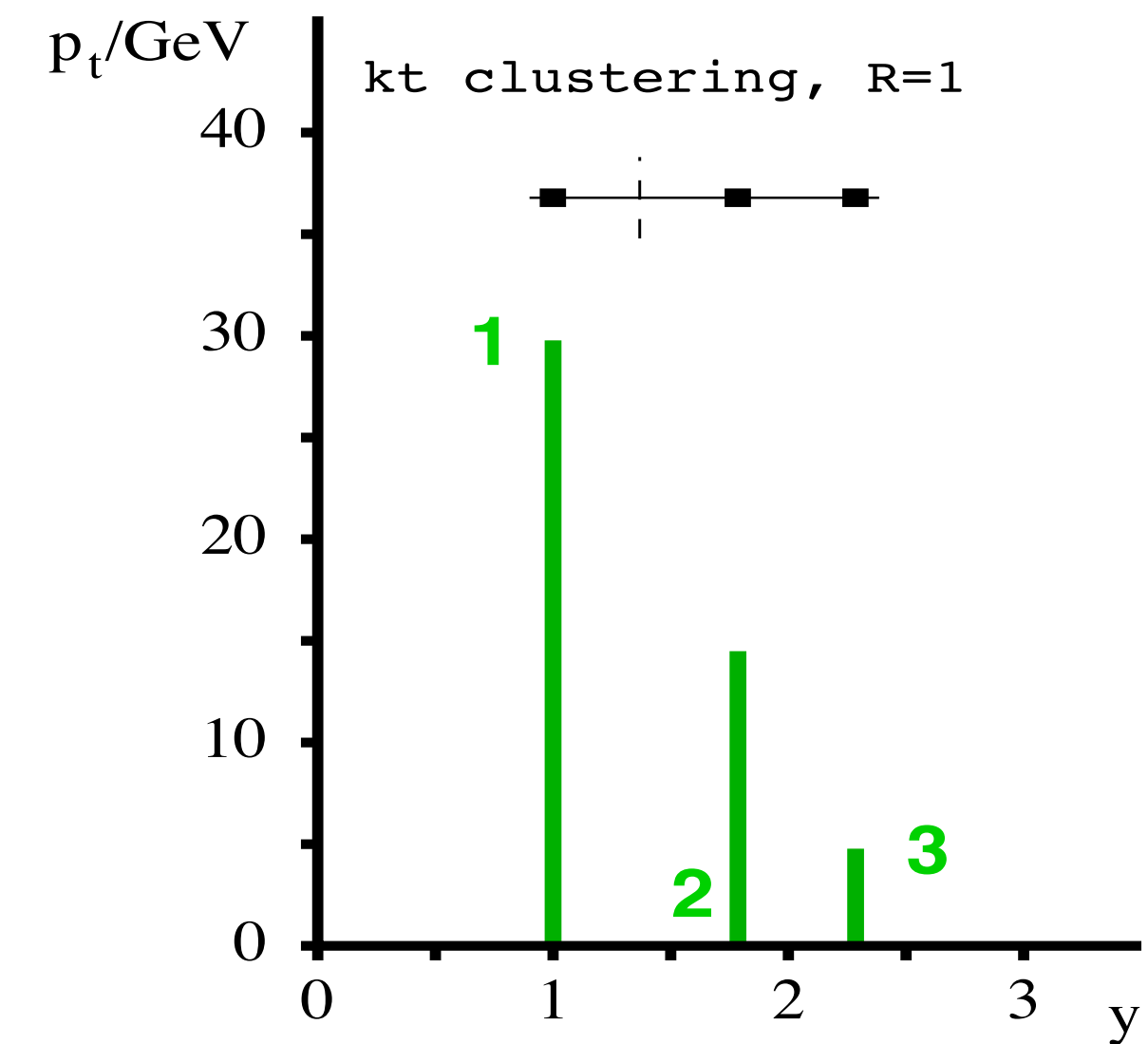
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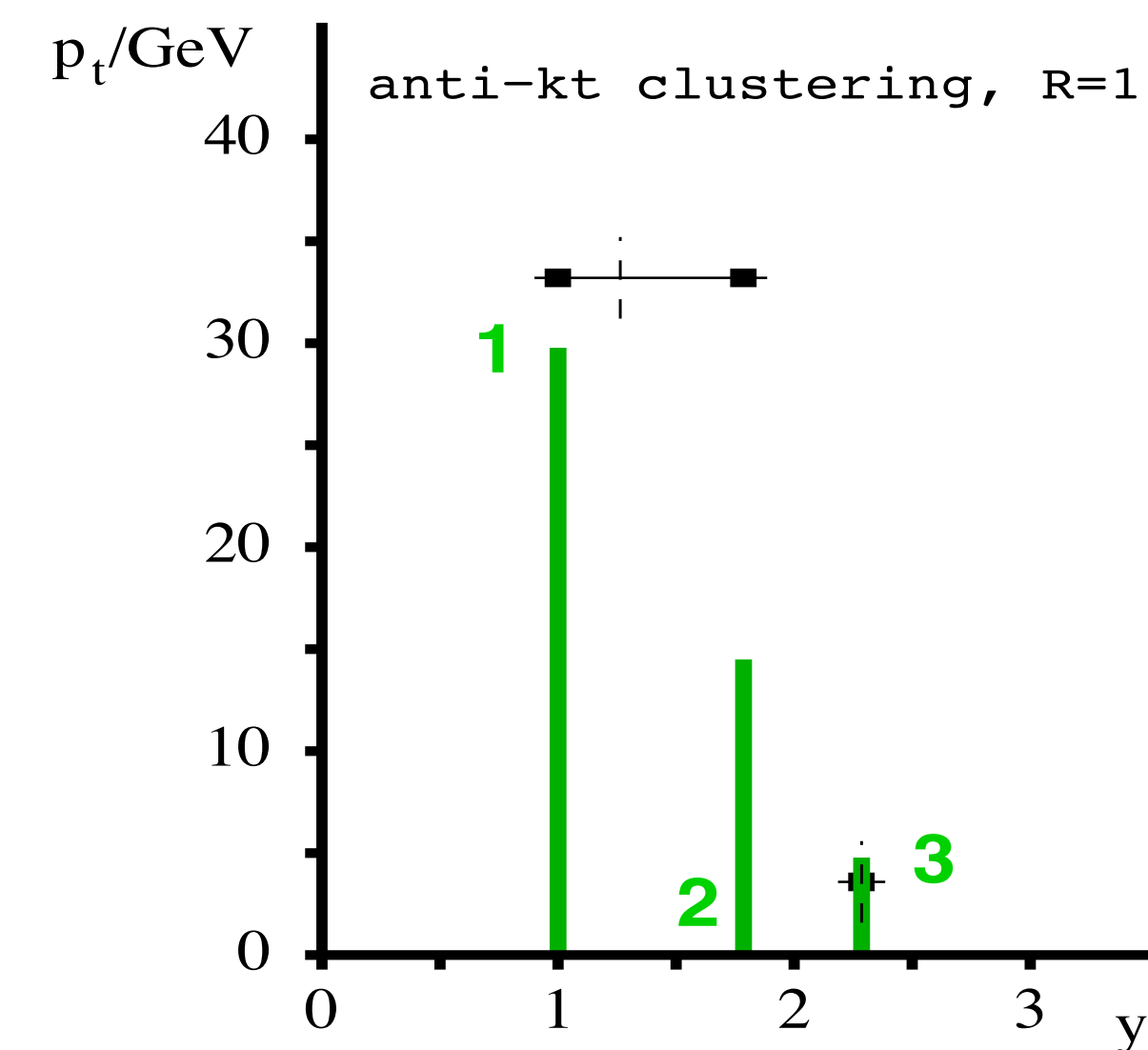
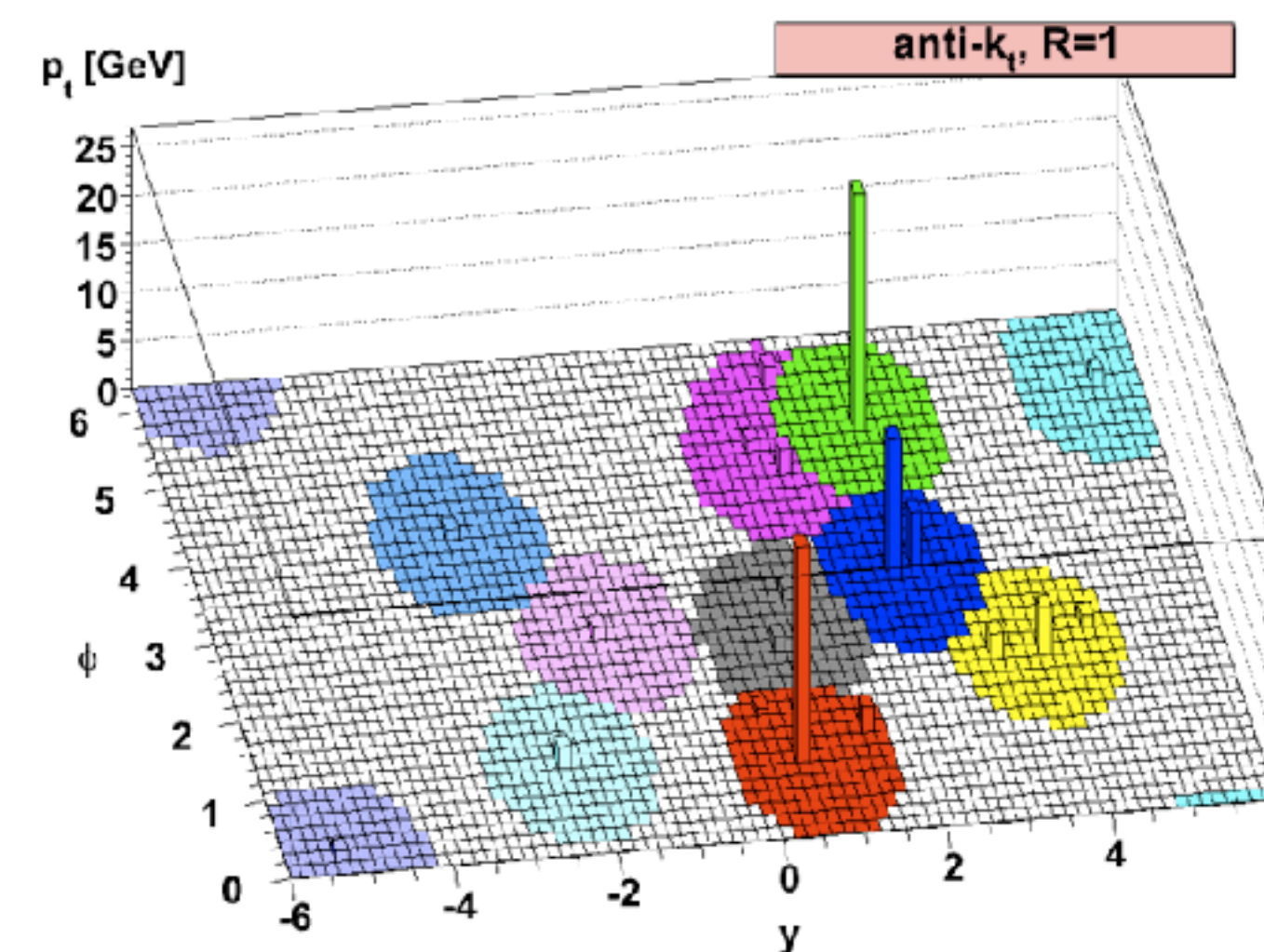
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CA Algorithm:
Often used in jet
sub-structure

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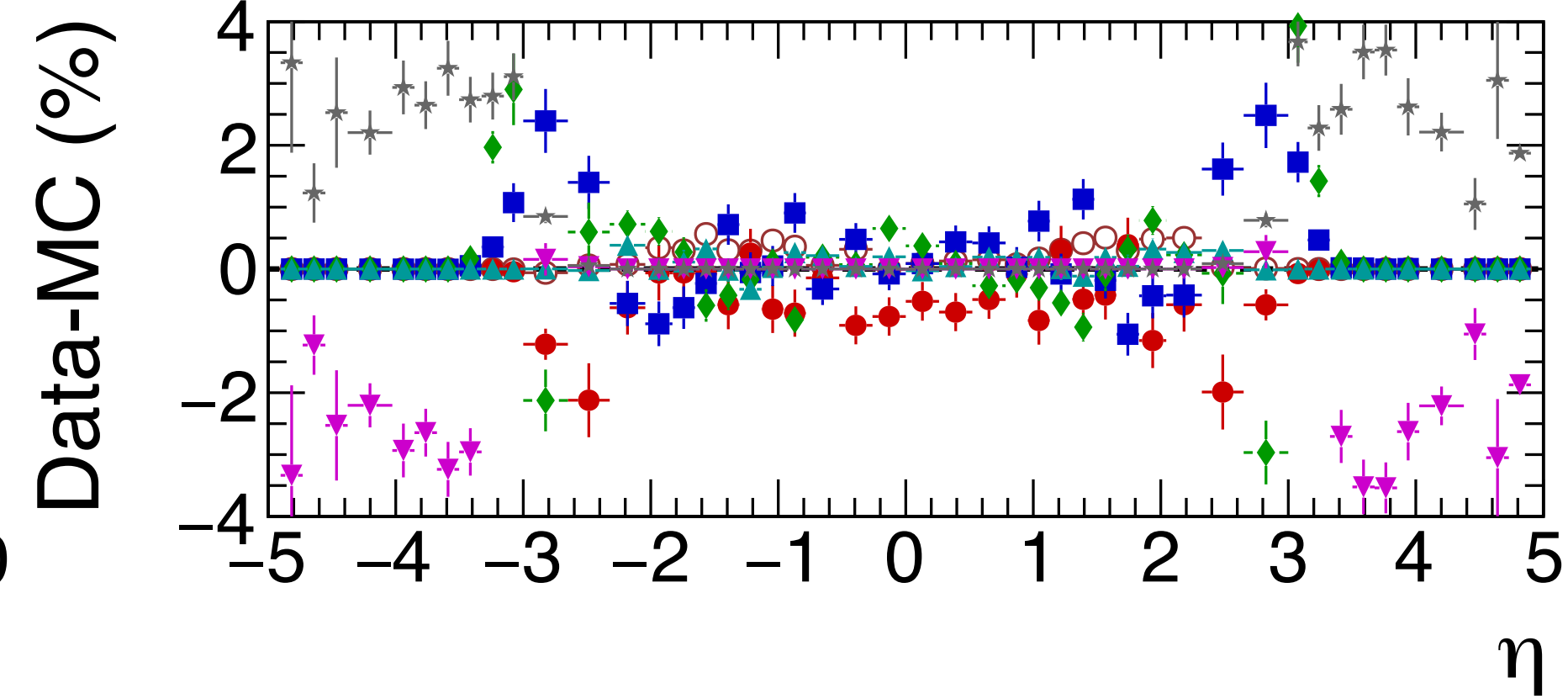
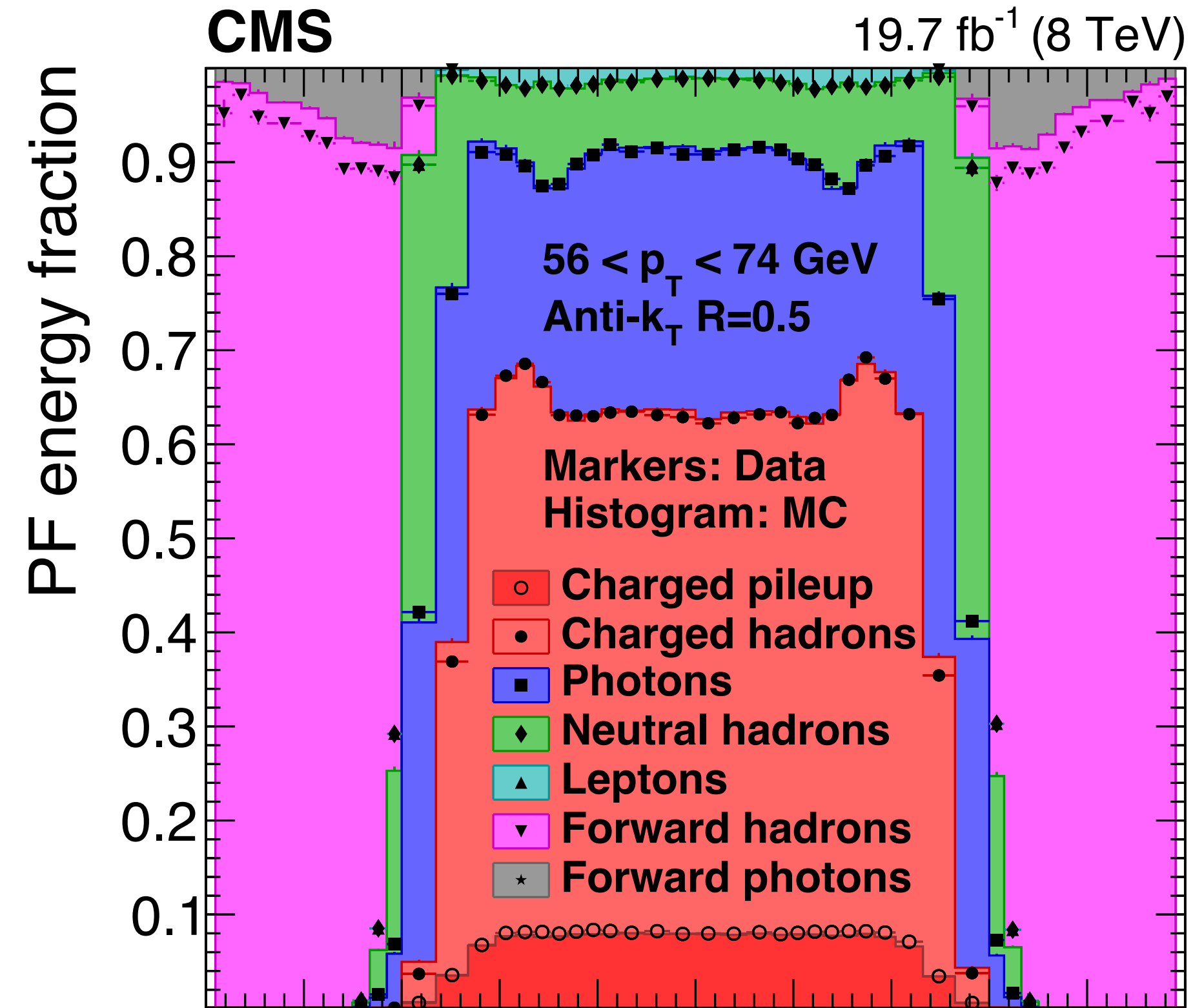
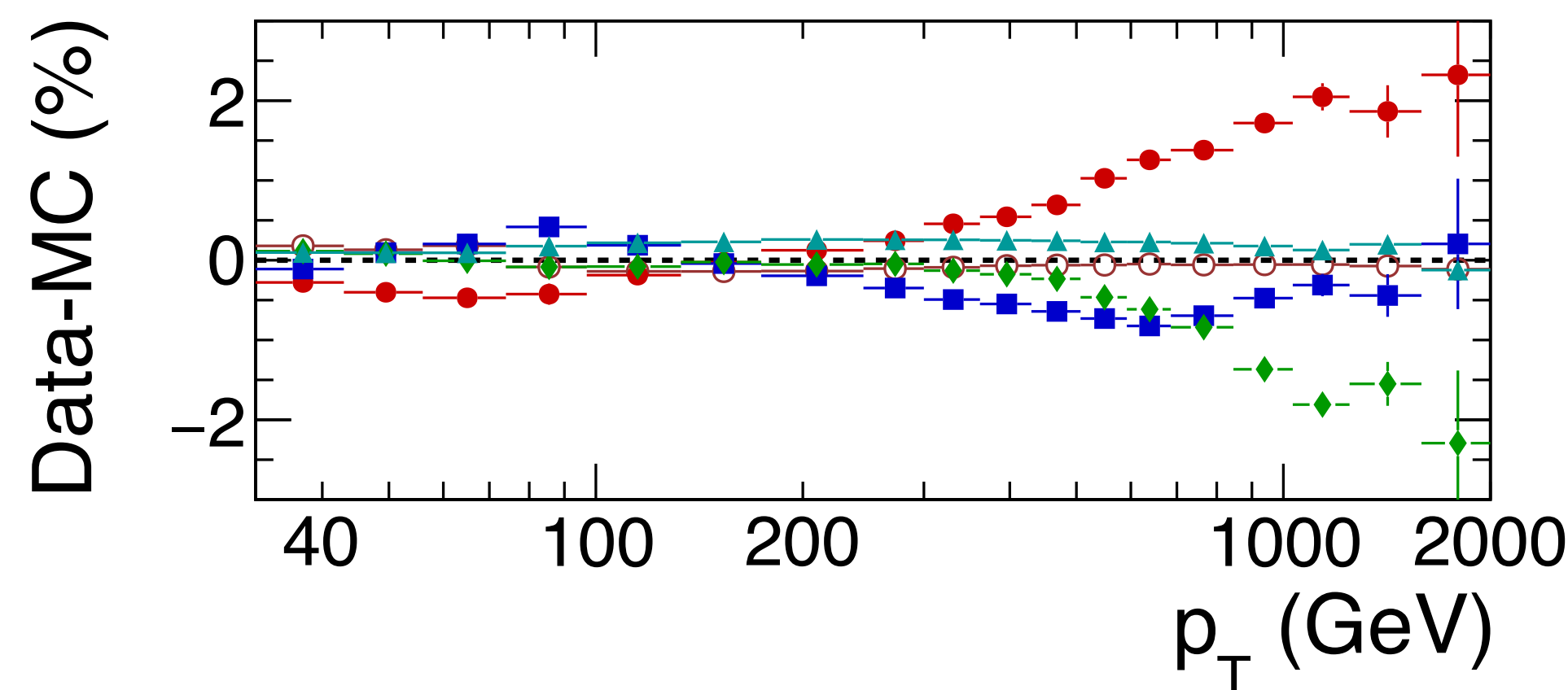
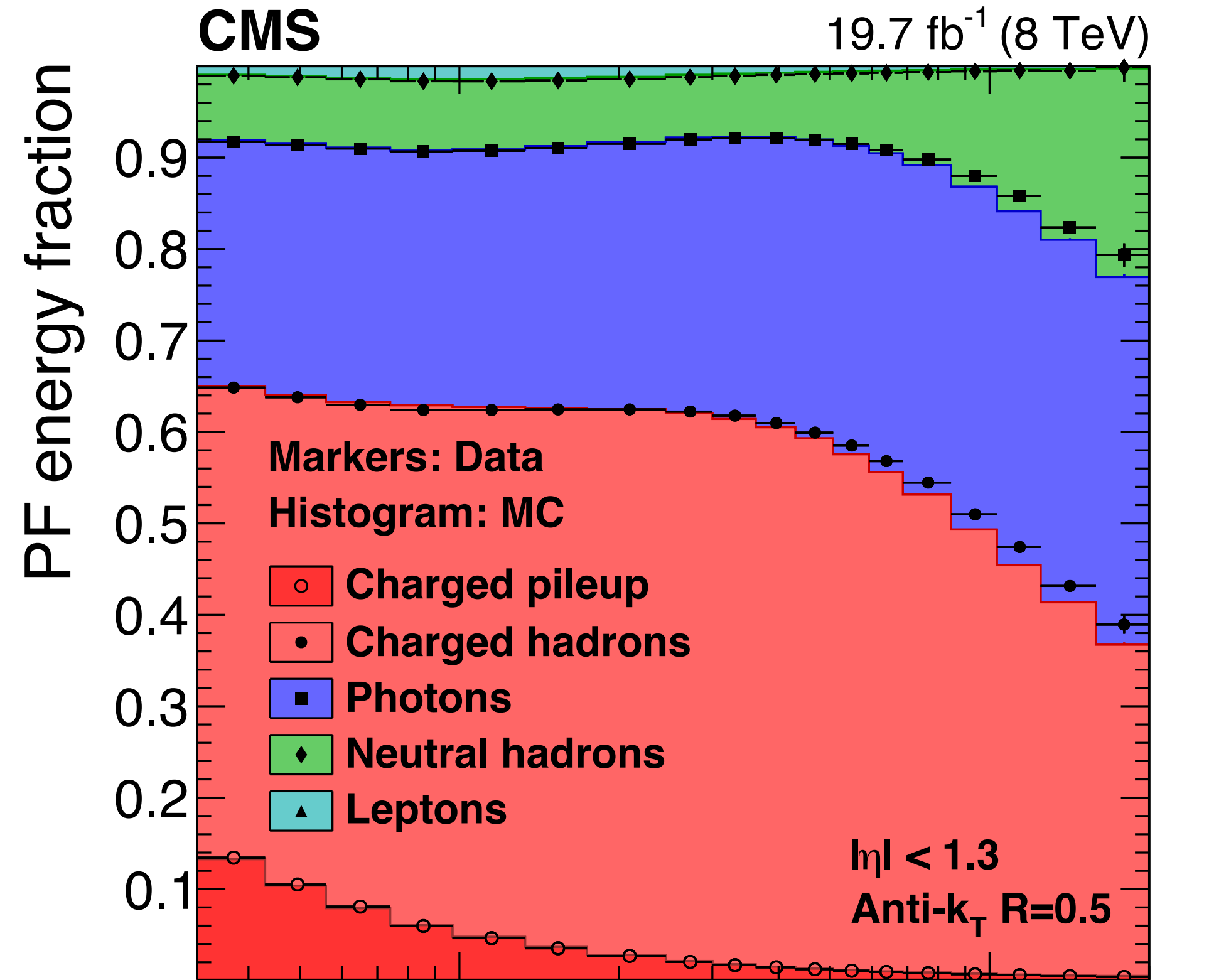
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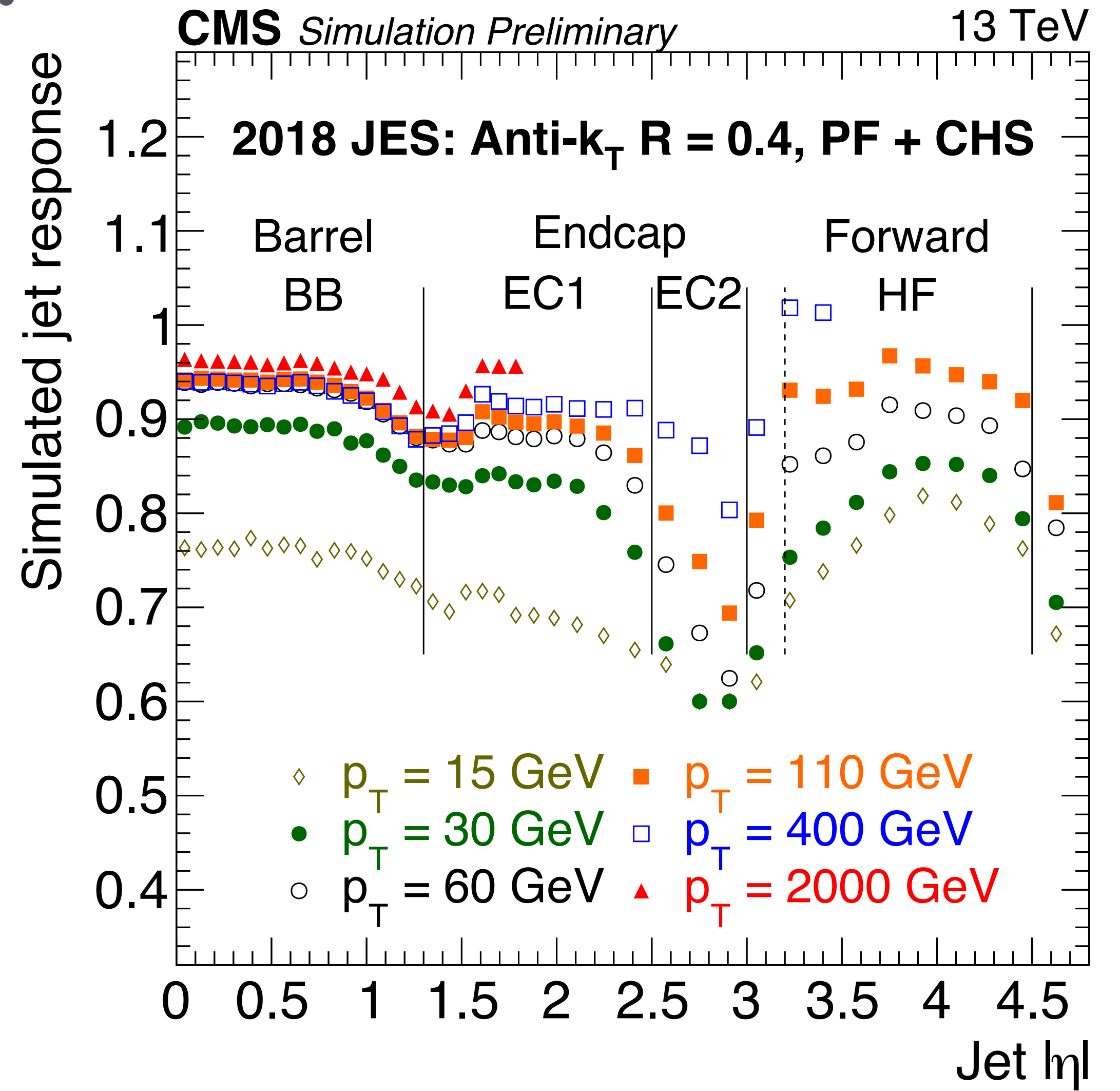
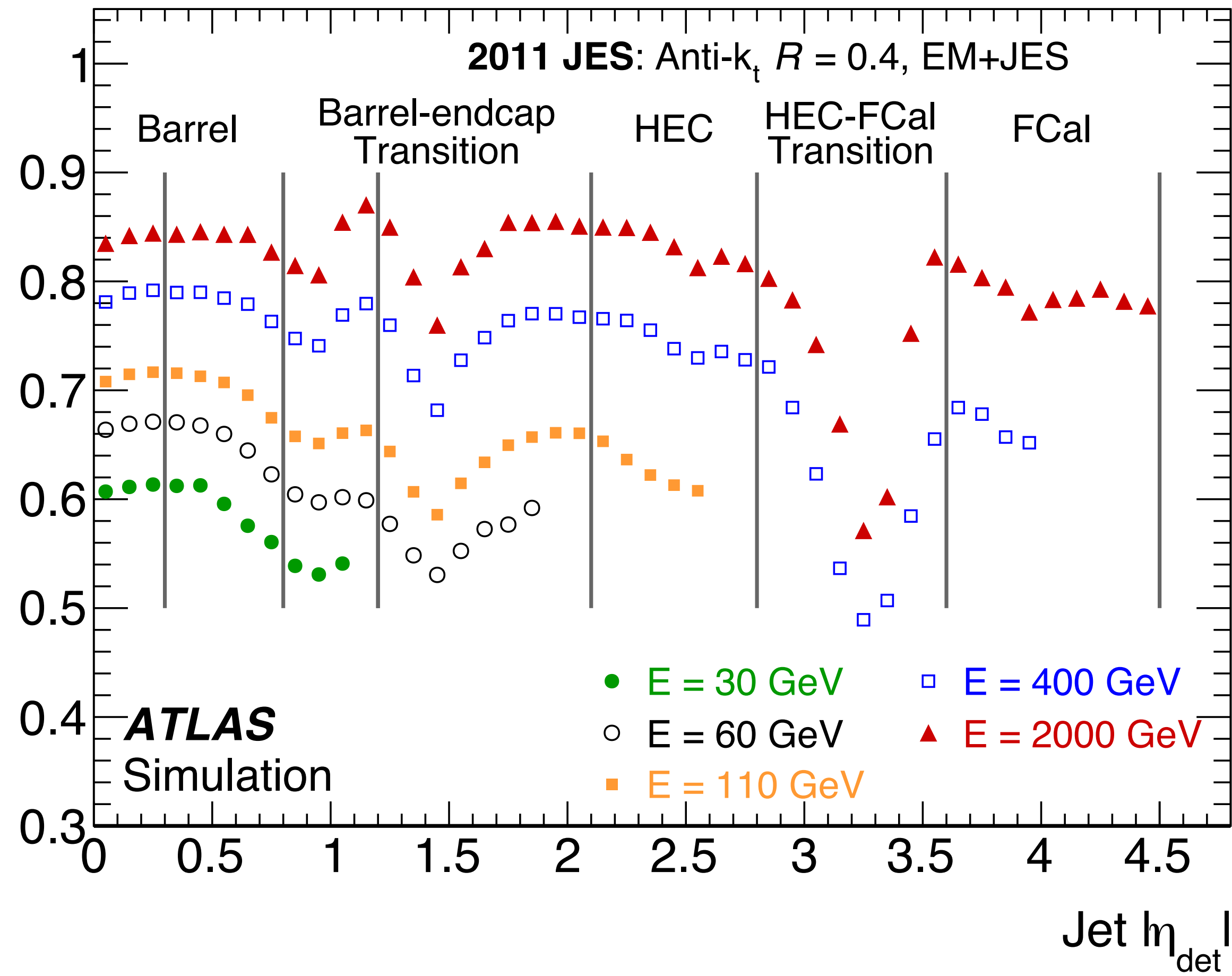
I am so very sorry!!
 Just not enough time to discuss jet sub-structure -- but wow is it interesting!

Actual particle composition of jets



Done finding jets...

Jet response at EM scale

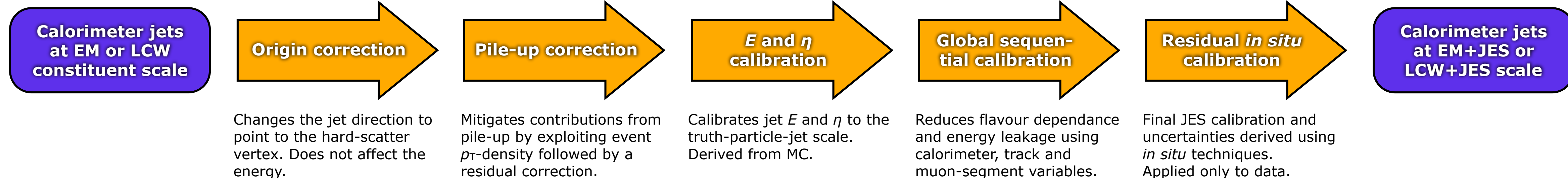


...must now calibrate !

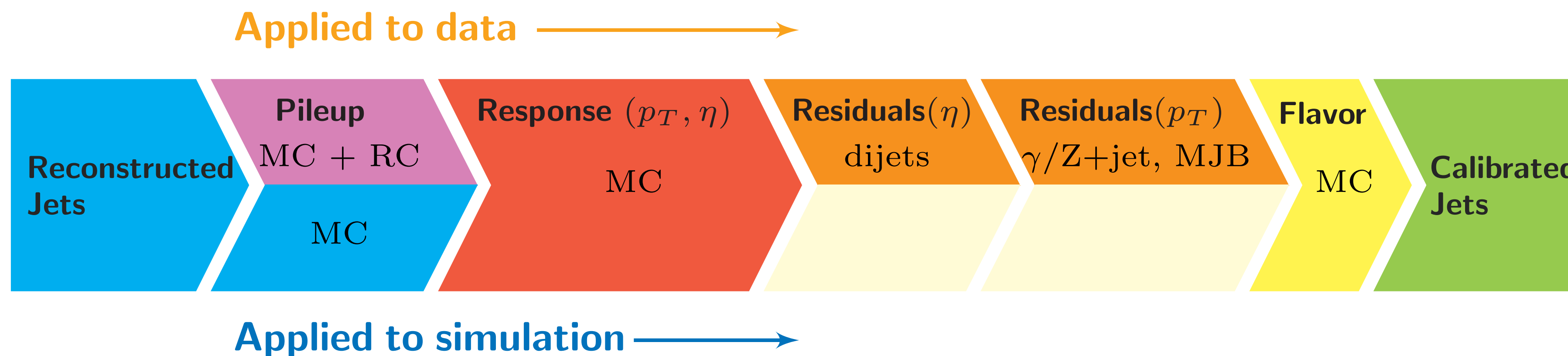
Jet Momentum Corrections

ATLAS

Anti- k_t $R = 0.4$ and $R = 0.6$



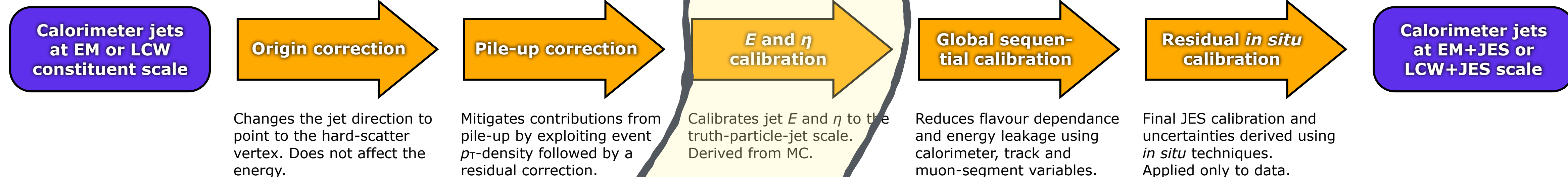
CMS



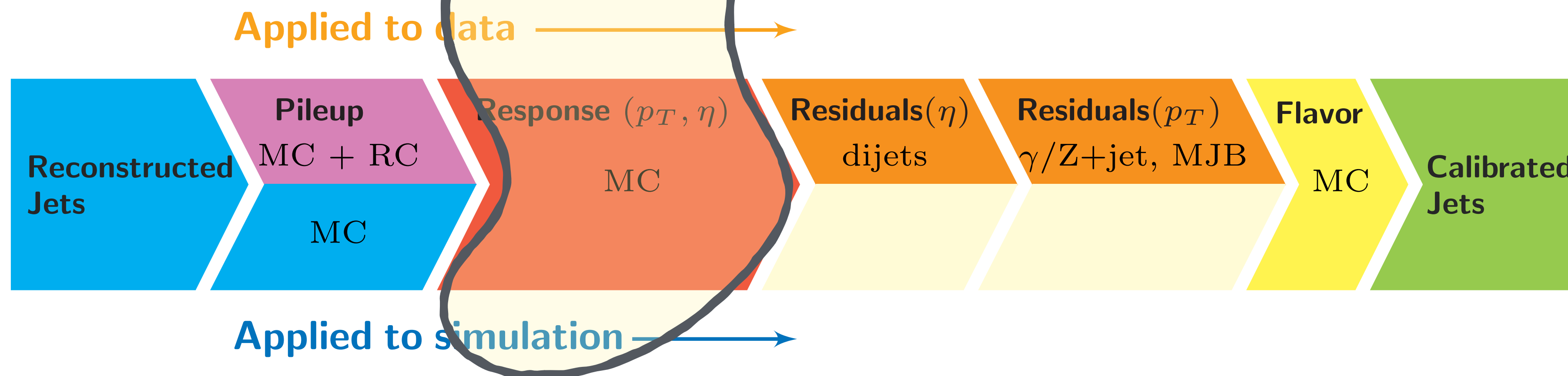
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Calorimeter jets at EM or LCW constituent scale

Origin correction

Changes the jet direction to point to the hard-scatter vertex. Does not affect the energy.

Pile-up correction

Mitigates contributions from pile-up by exploiting event p_T -density followed by a residual correction.

E and η calibration

Calibrates jet E and η to the truth-particle-jet scale. Derived from MC.

Global sequential calibration

Reduces flavour dependence and energy leakage using calorimeter, track and muon-segment variables.

Residual *in situ* calibration

Final JES calibration and uncertainties derived using *in situ* techniques. Applied only to data.

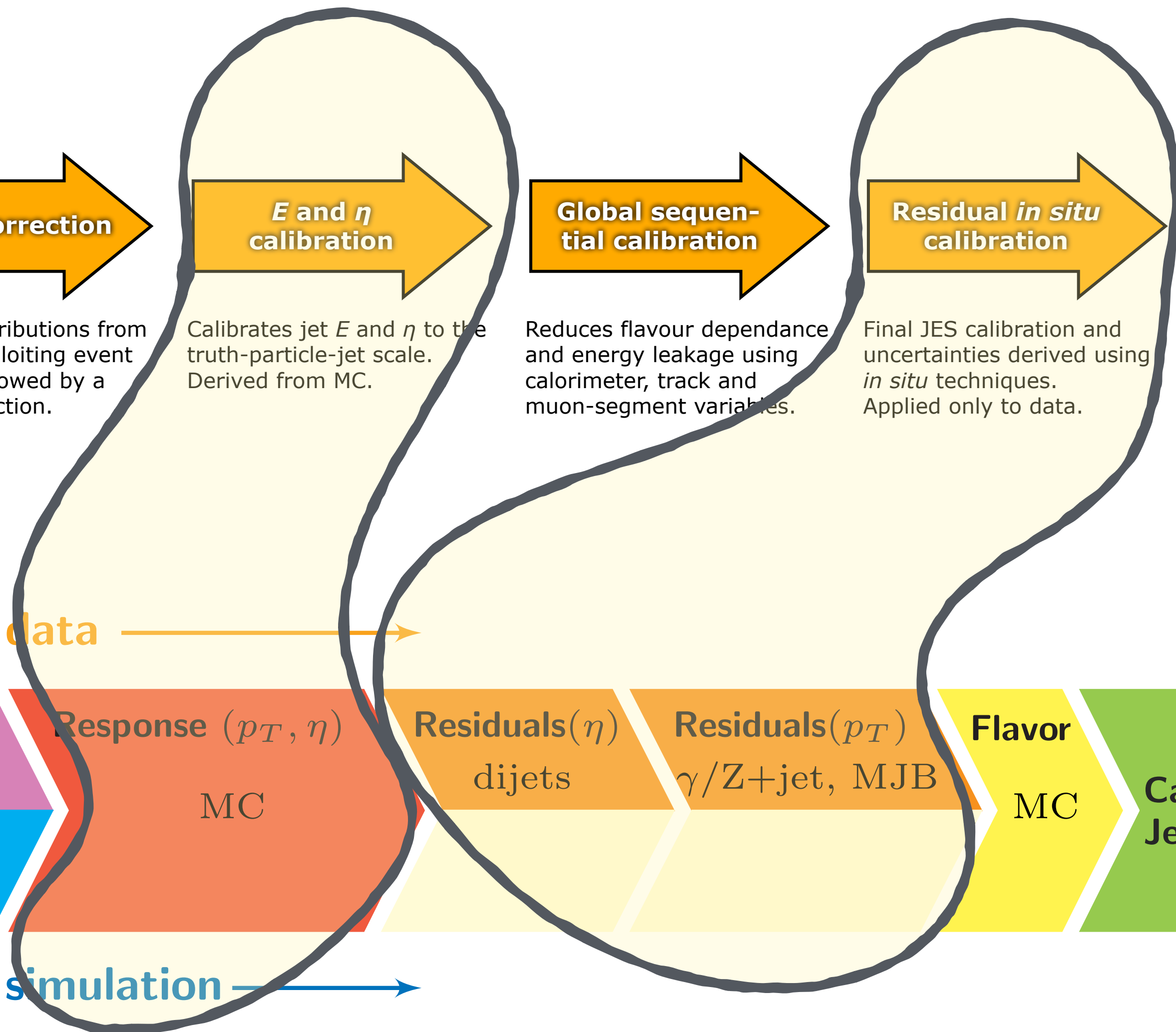
Calorimeter jets at EM+JES or LCW+JES scale

CMS



Applied to data

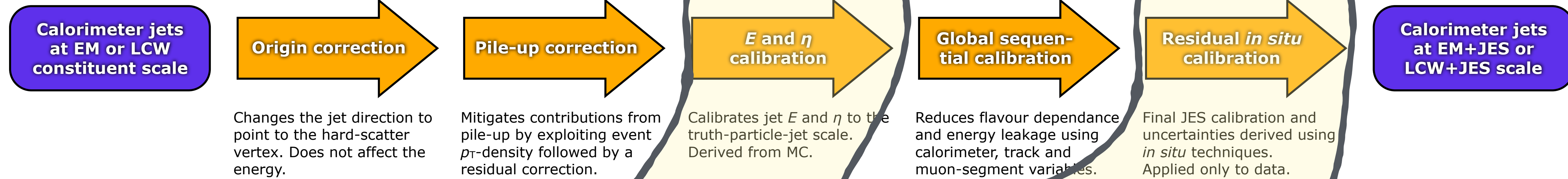
Applied to simulation



Jet Momentum Corrections

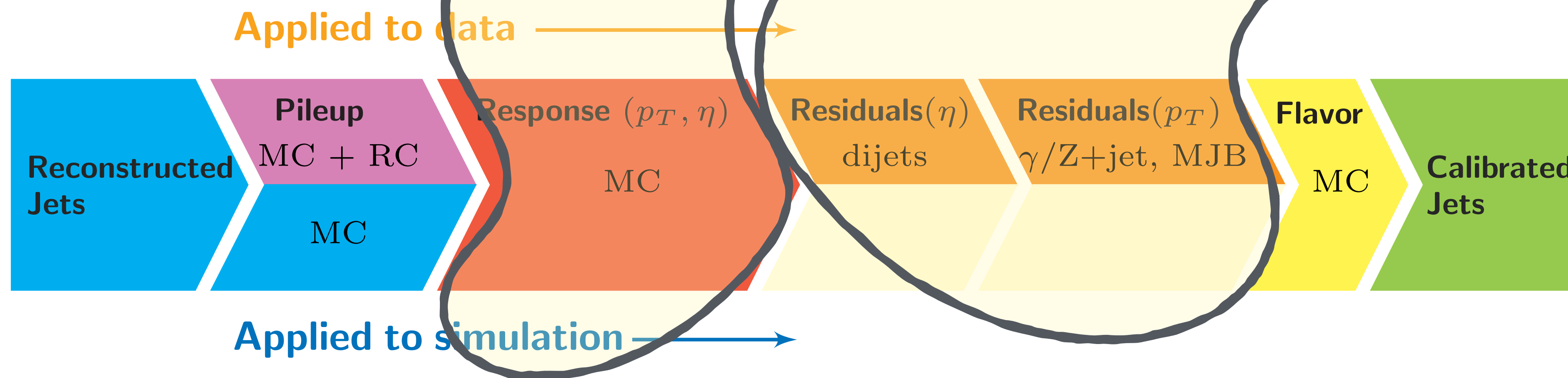
ATLAS

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Discuss these (briefly) first

CMS



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Applied to simulation

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Finish with
this

Discuss these
(briefly) first

Applied to data

CMS

Reconstructed
Jets

Pileup
MC + RC
MC

Response (p_T, η)
MC

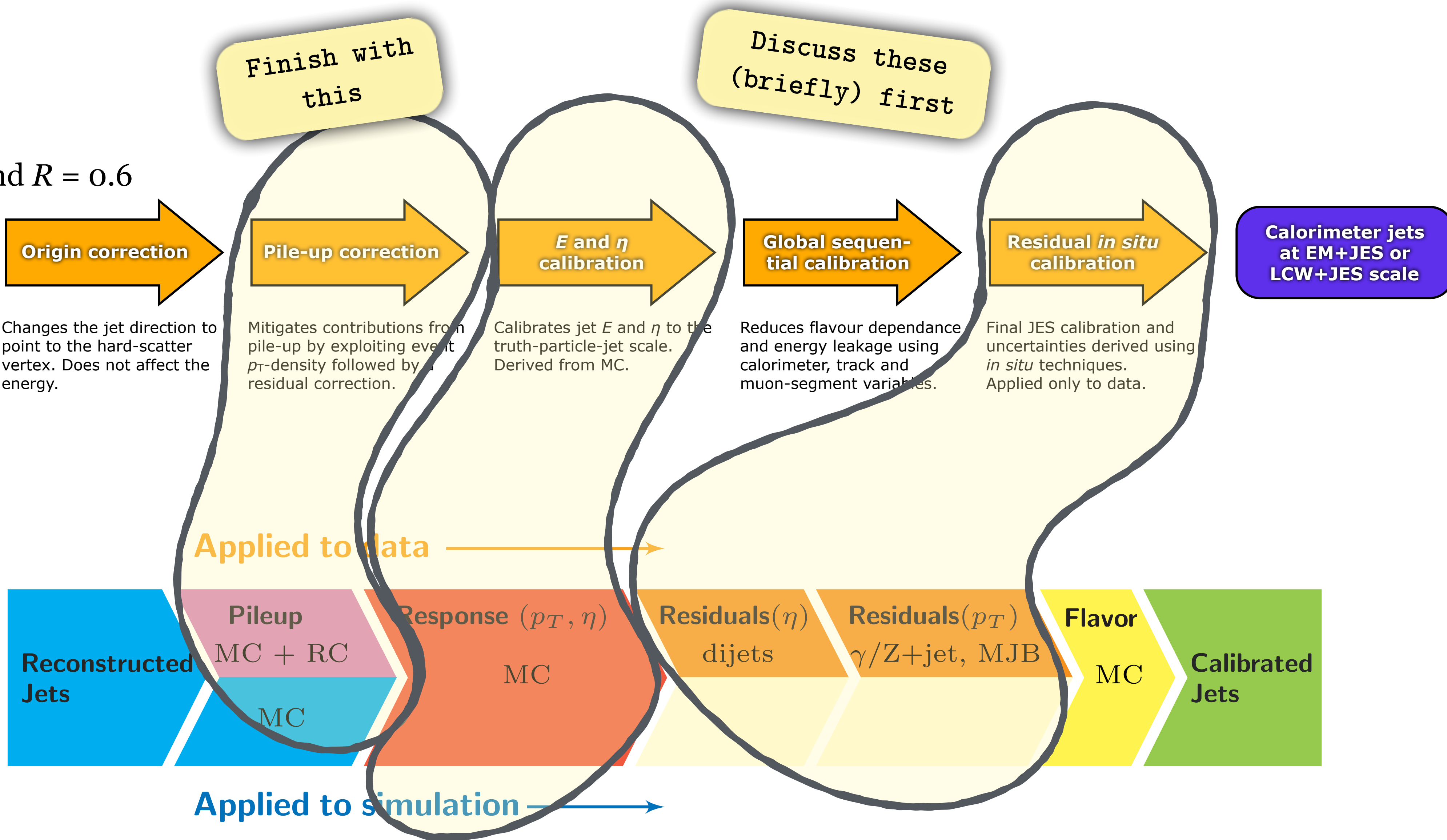
Residuals(η)
dijets

Residuals(p_T)
 γ/Z +jet, MJB

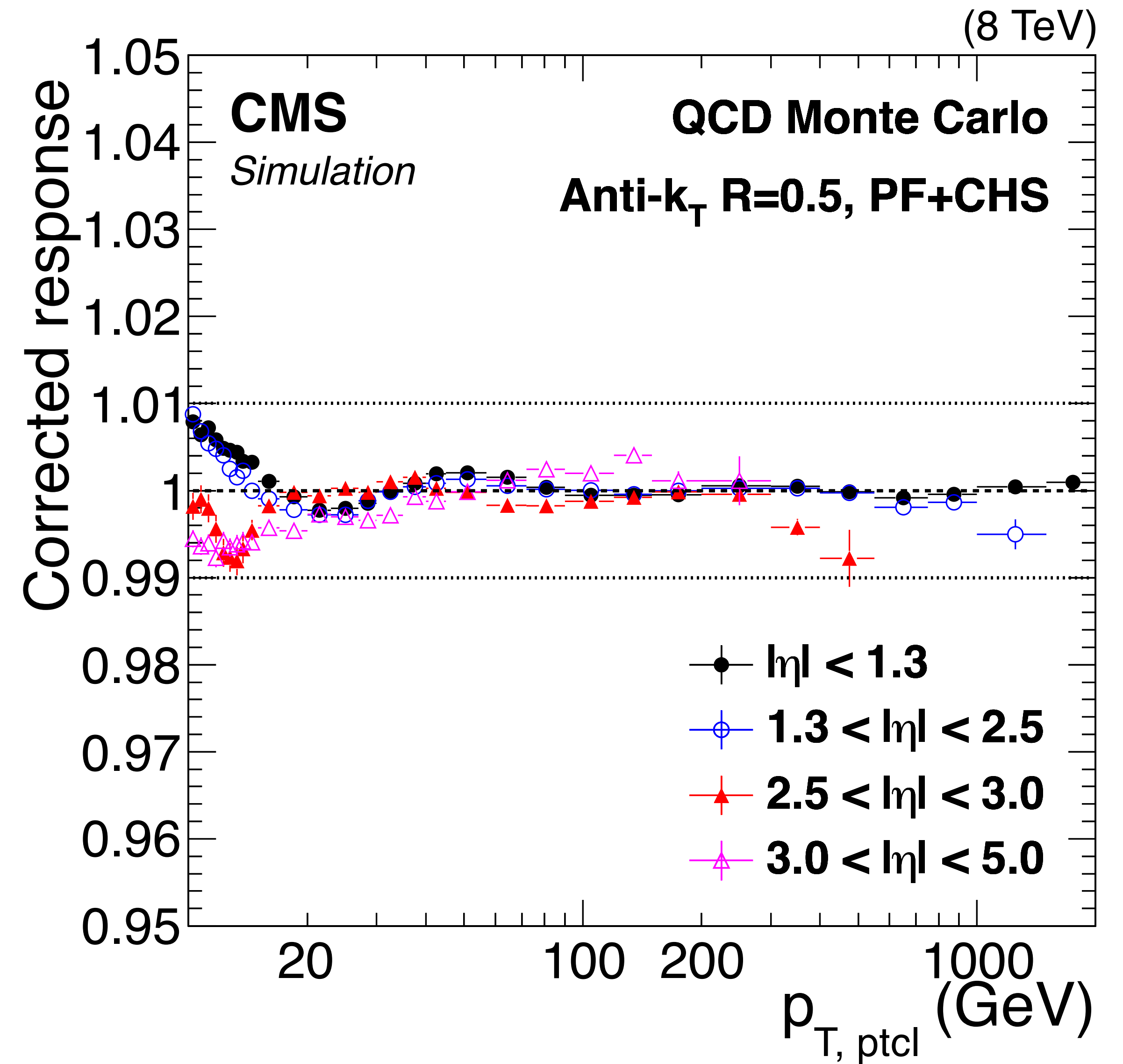
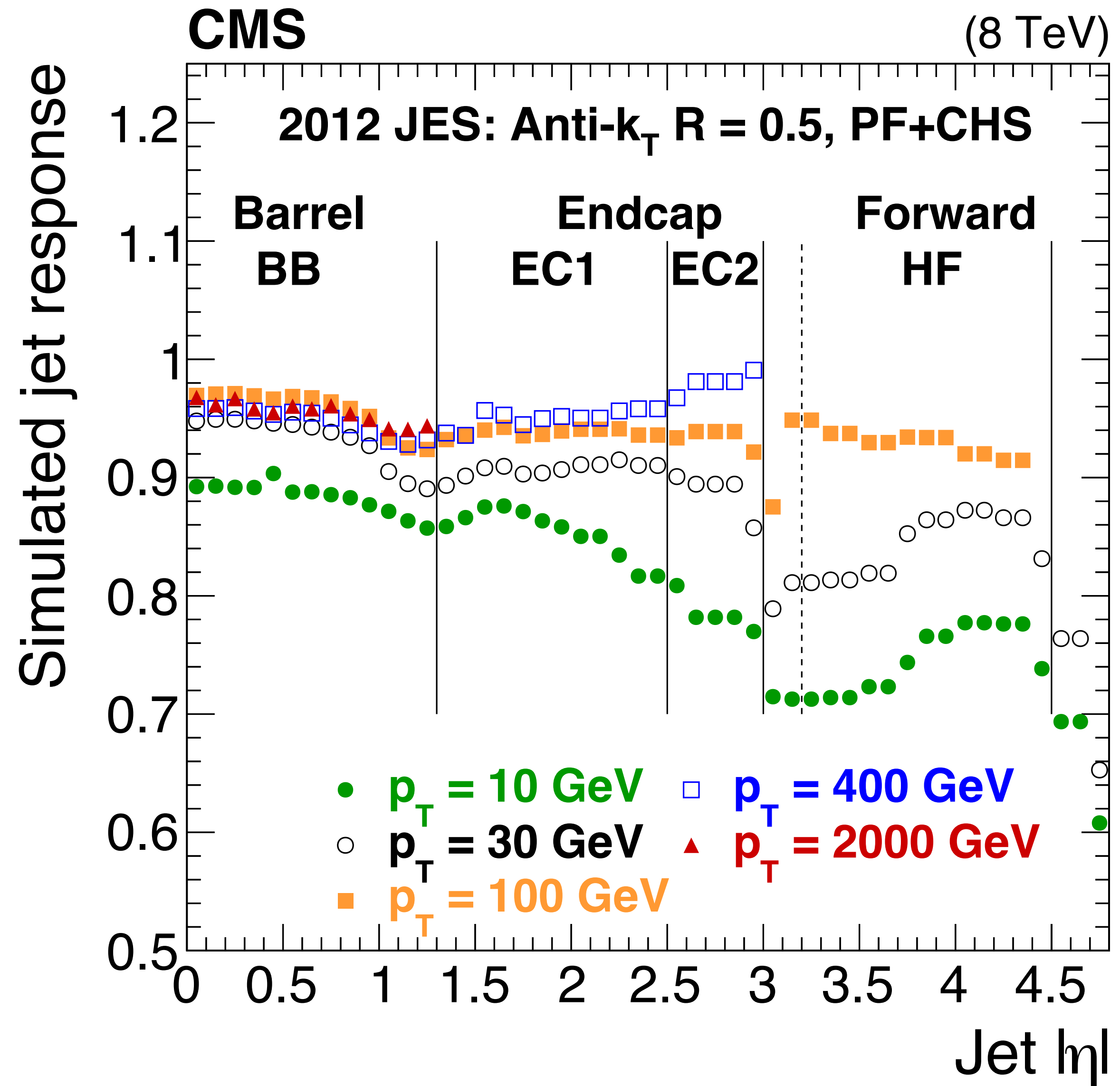
Flavor
MC

Calibrated
Jets

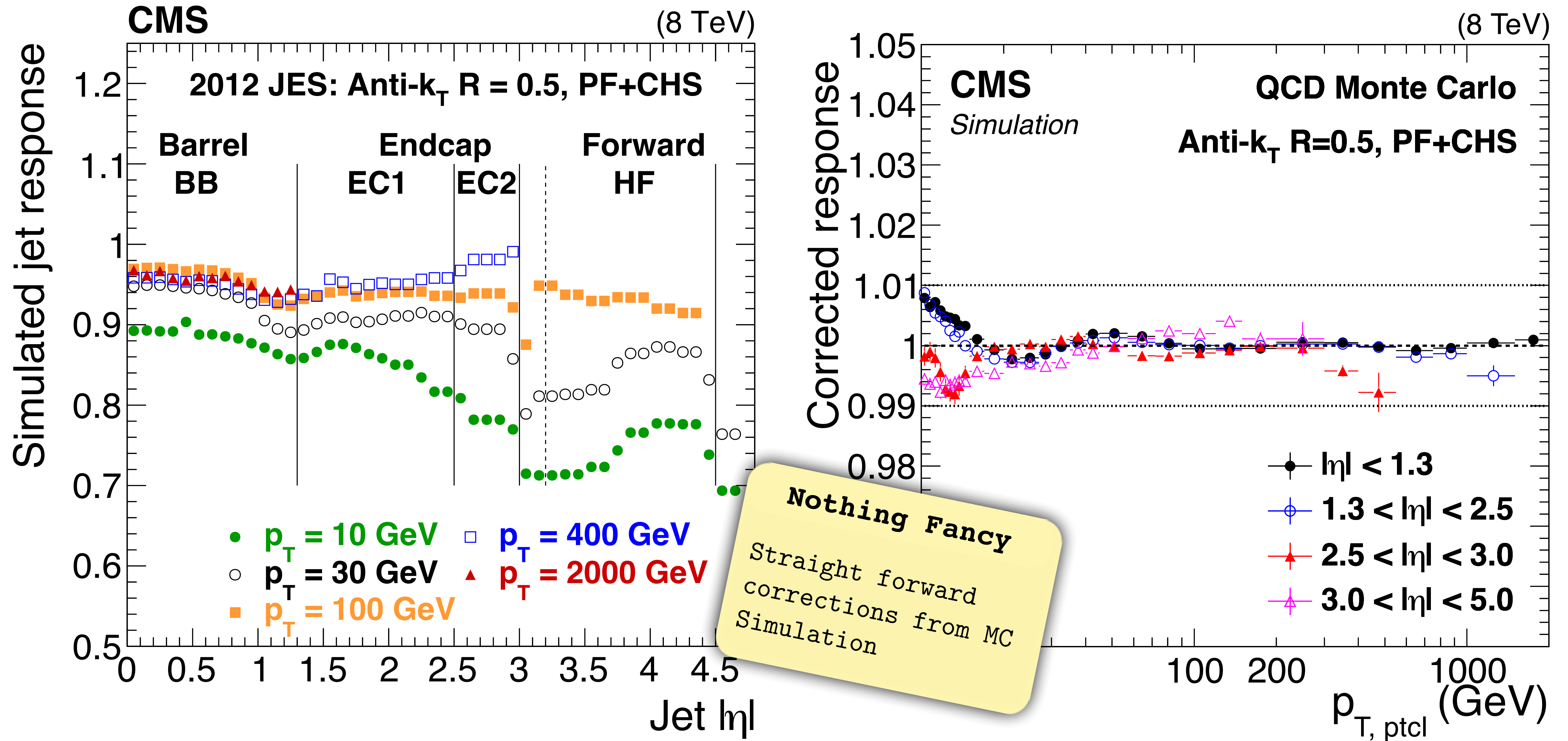
Applied to simulation



Step 1: Correct gross response using MC Simulation

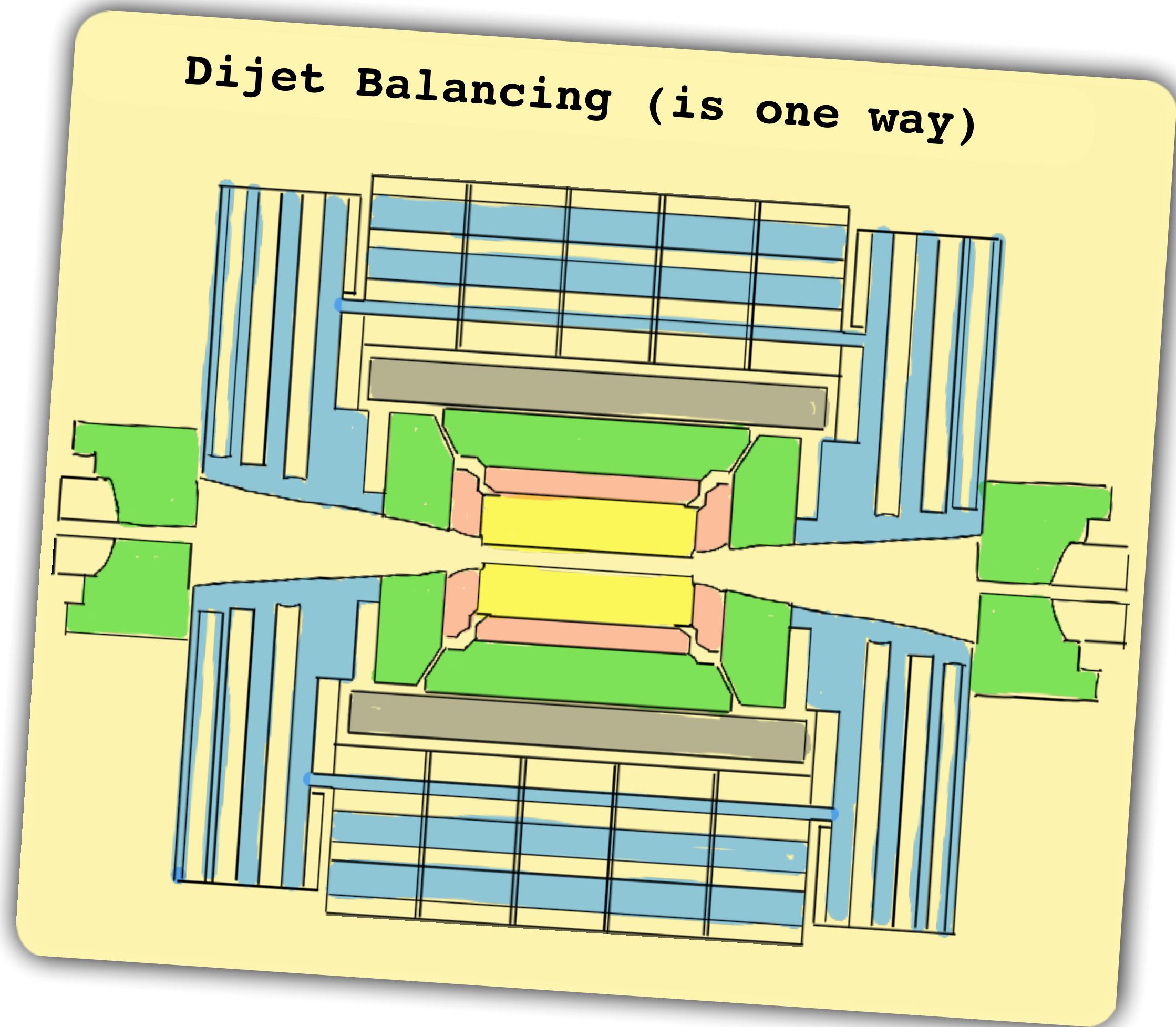


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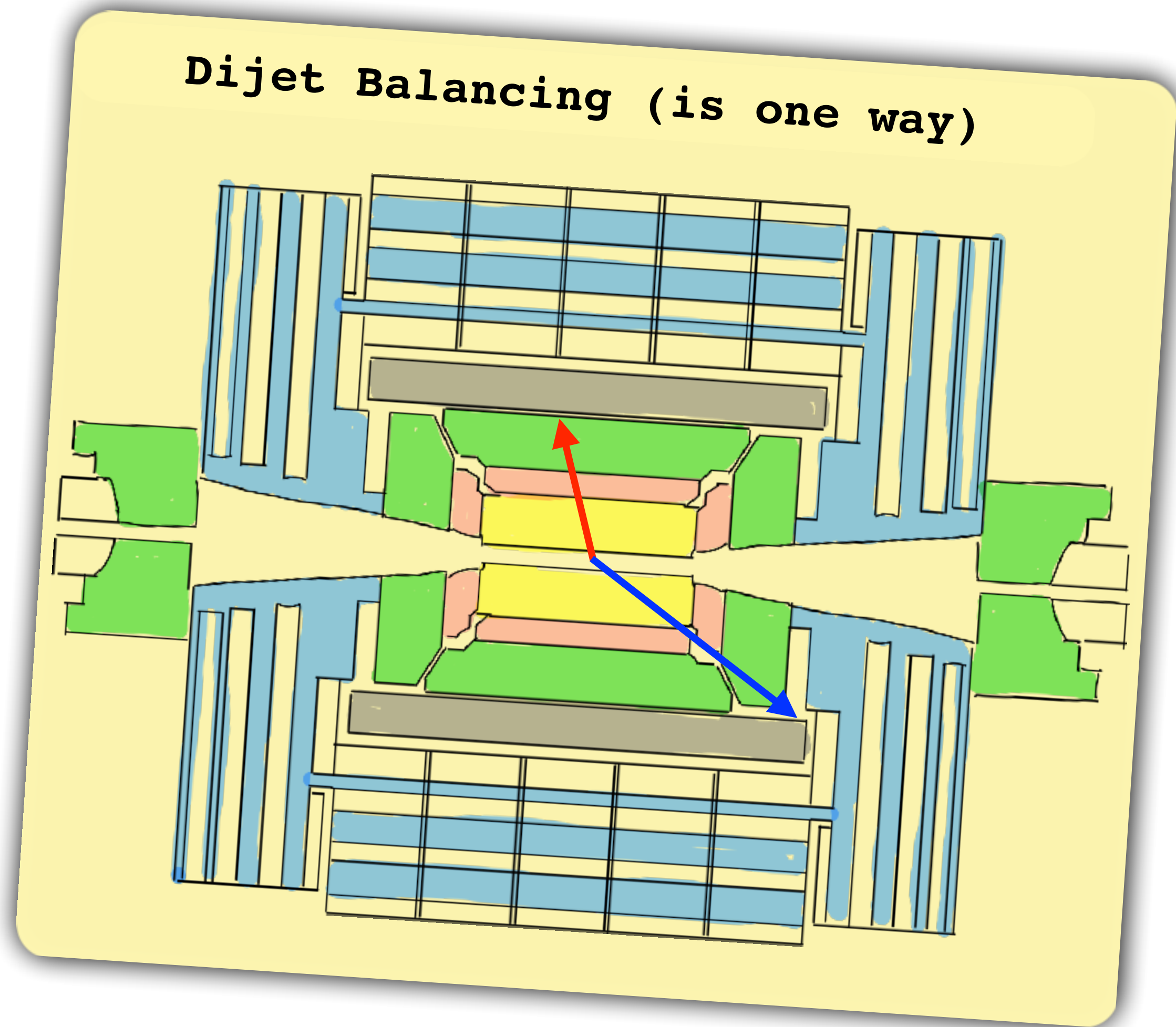


Step 2: Relative η Residual-Correction using data

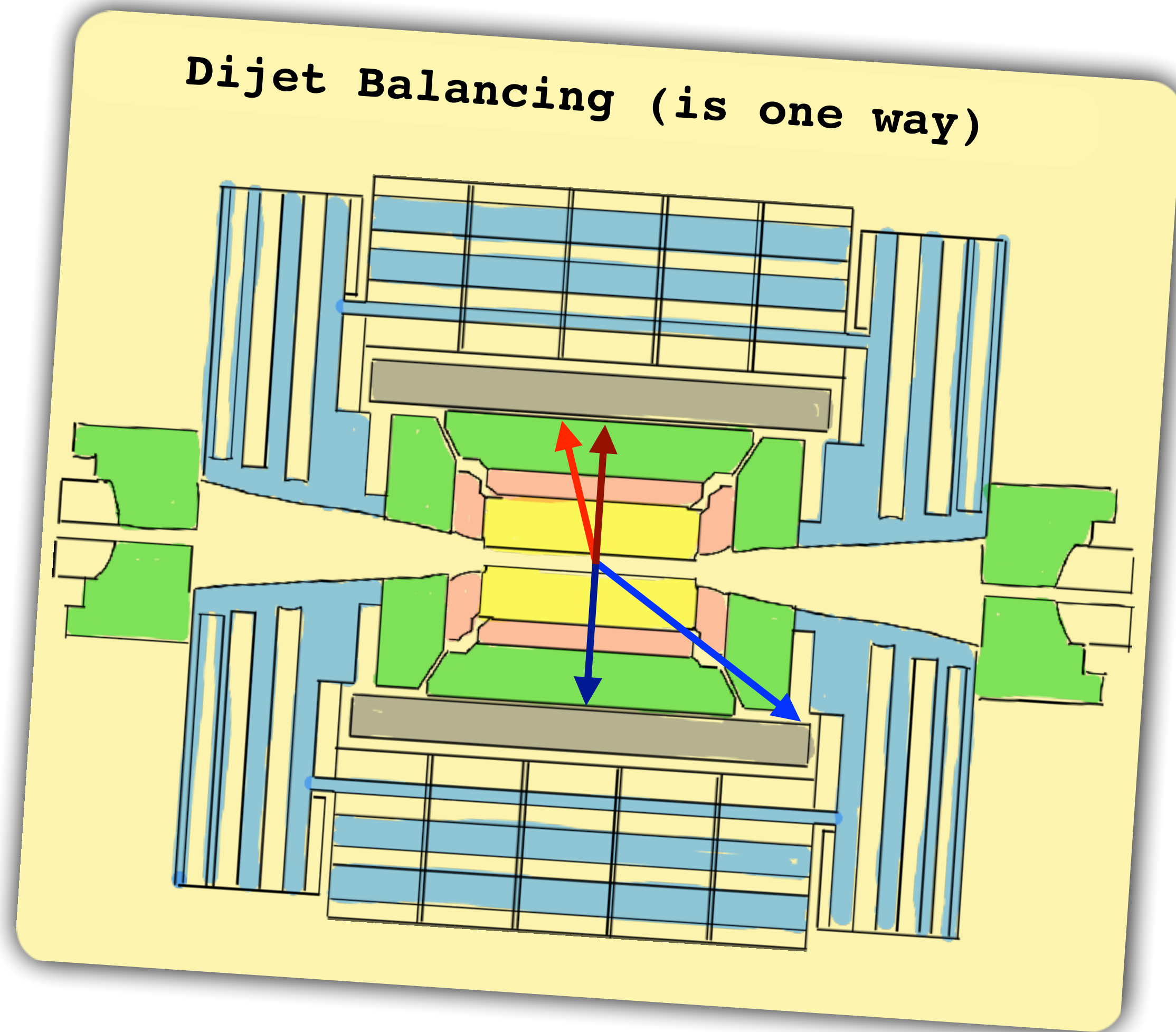
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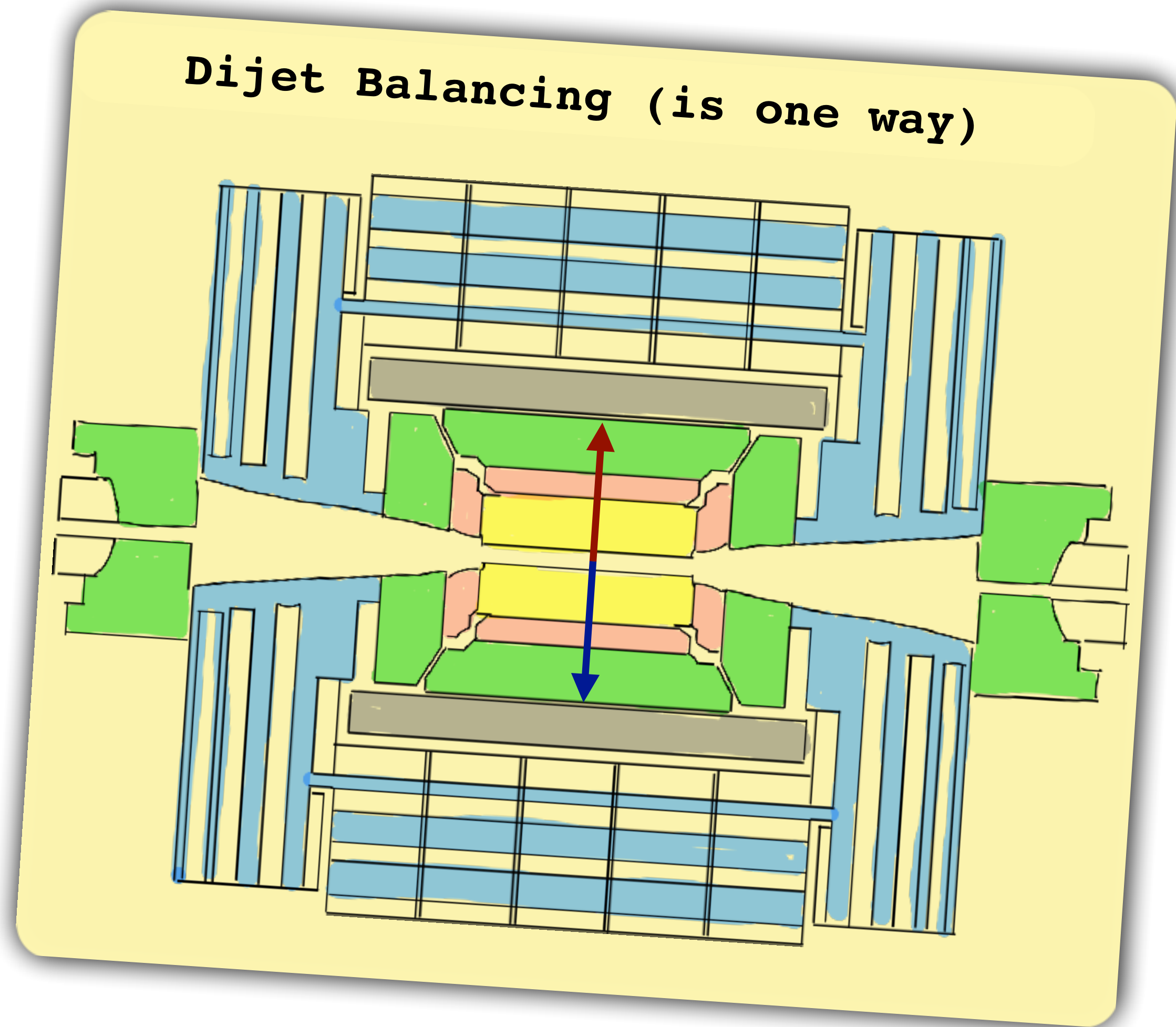
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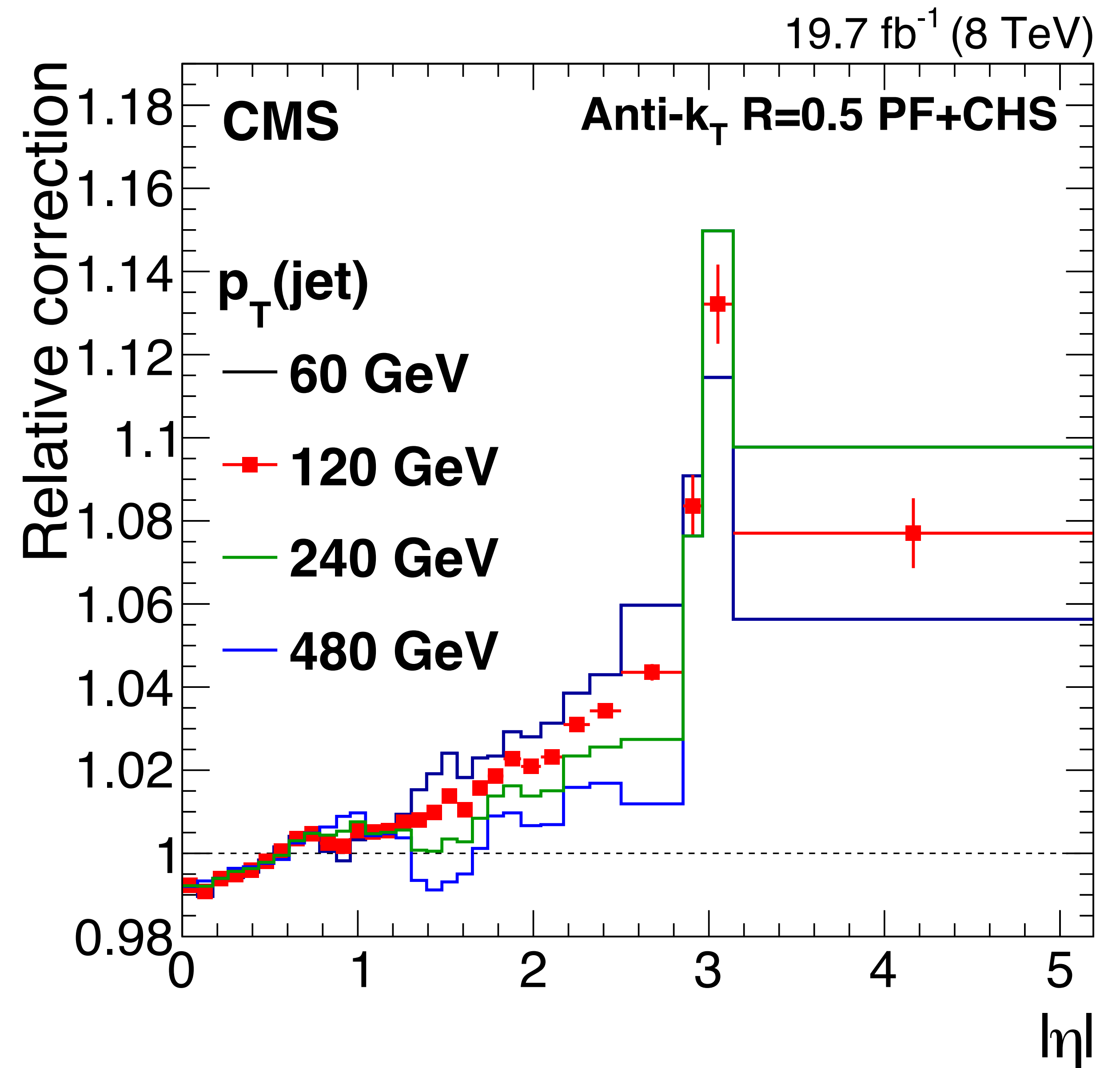
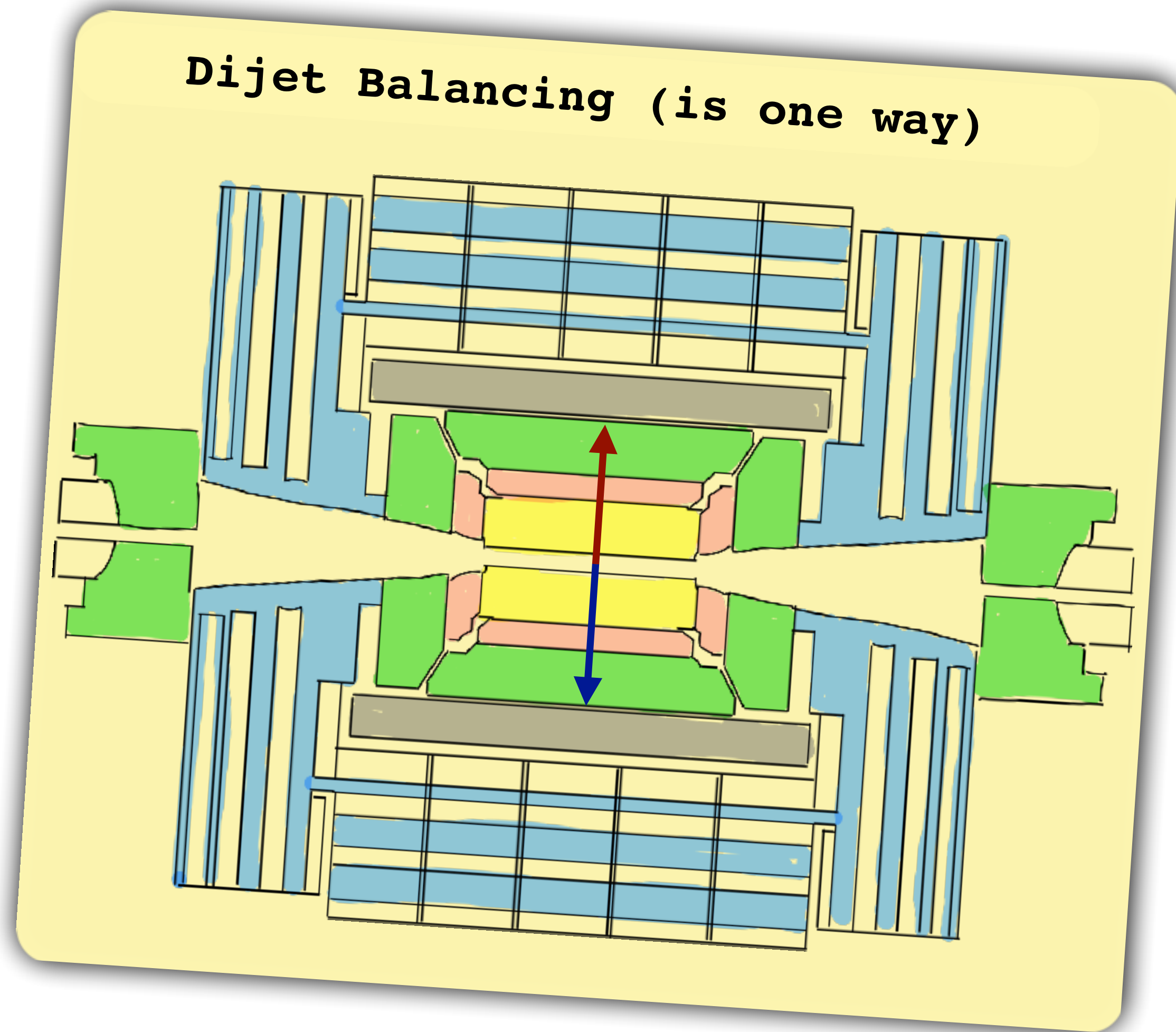
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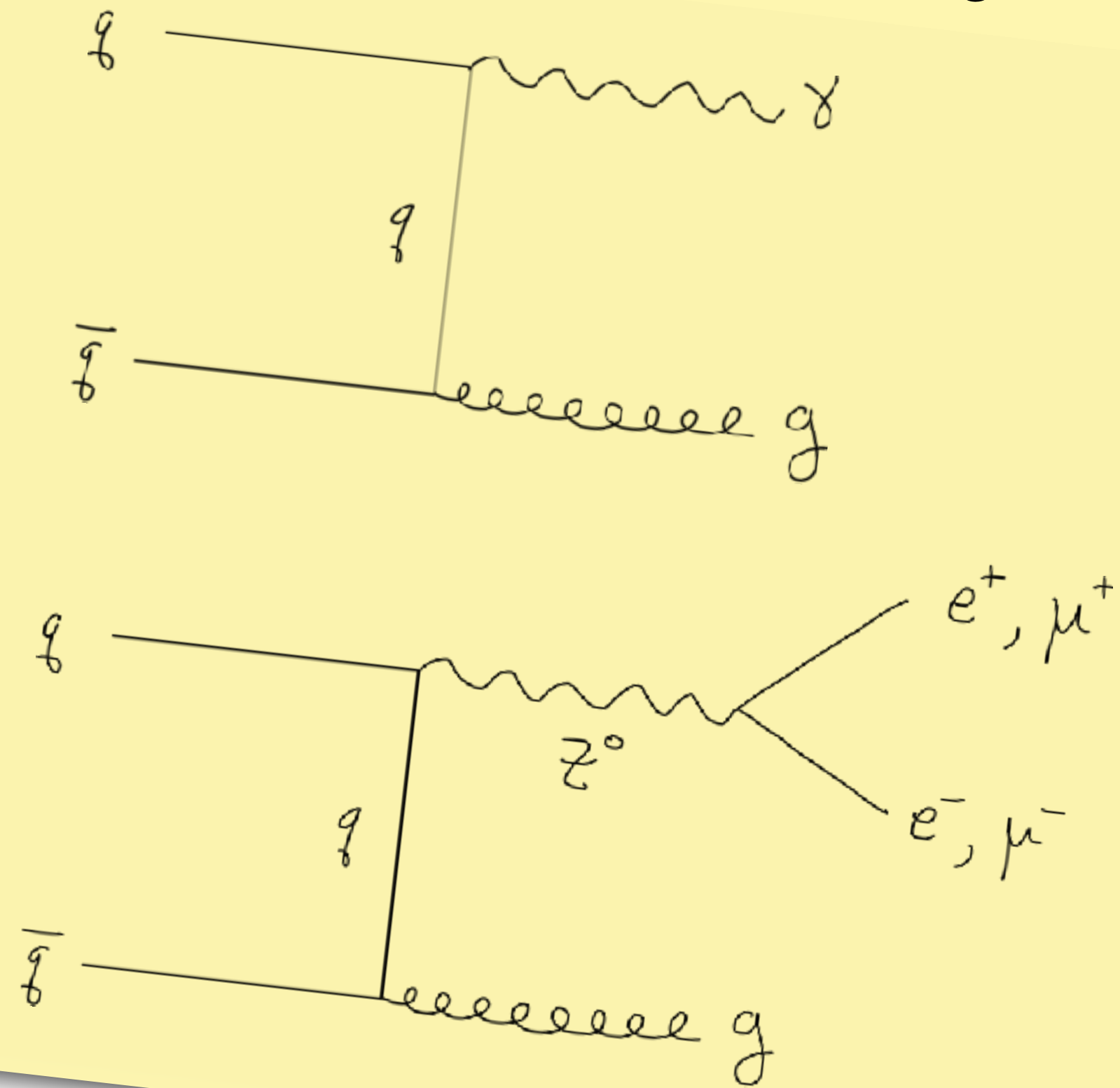
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Step 3: Absolute p_T Residual-Correction using data

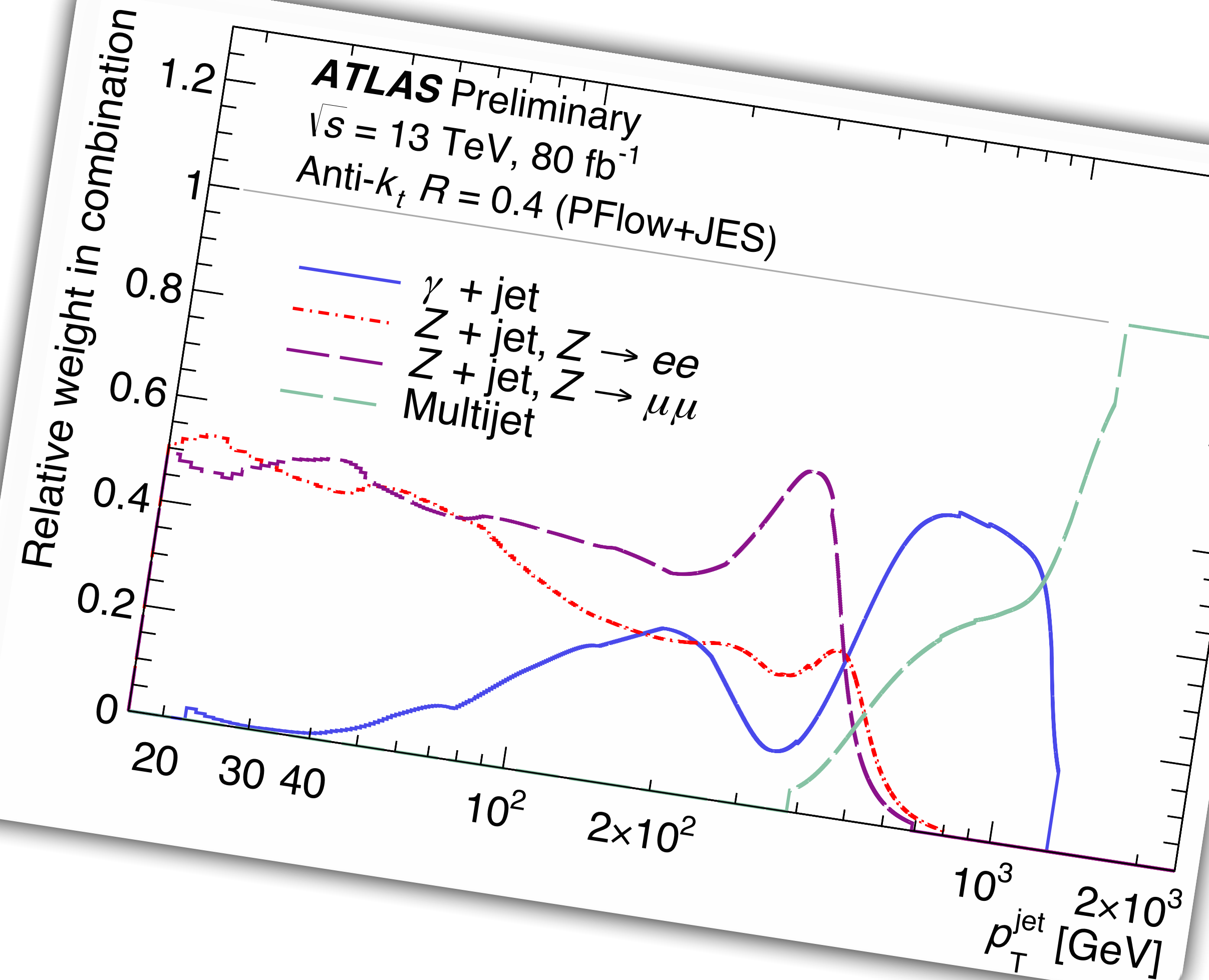
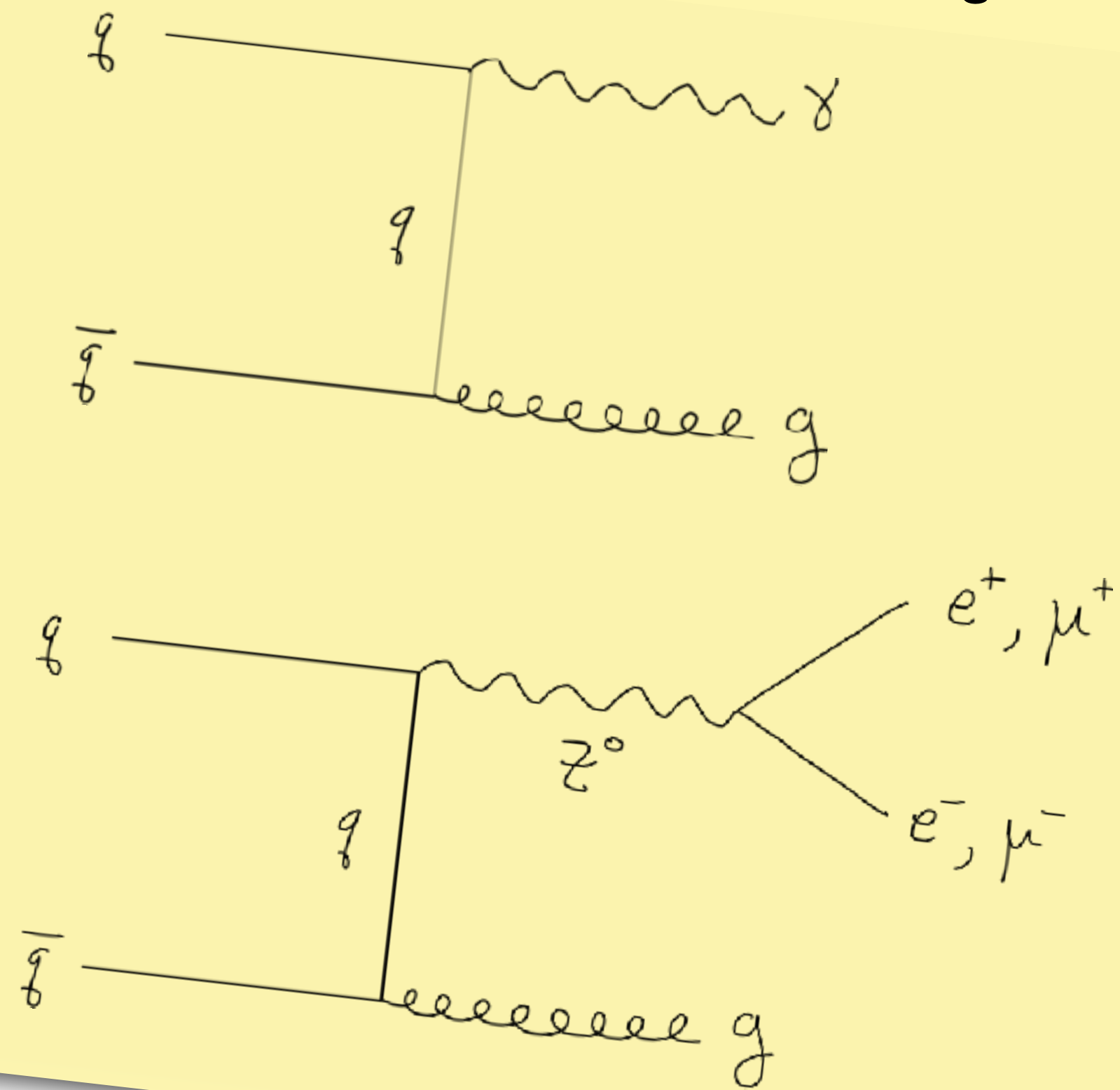
Step 3: Absolute p_T Residual-Correction using data

Photon or Z against 1 Jet



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Photon or Z against 1 Jet

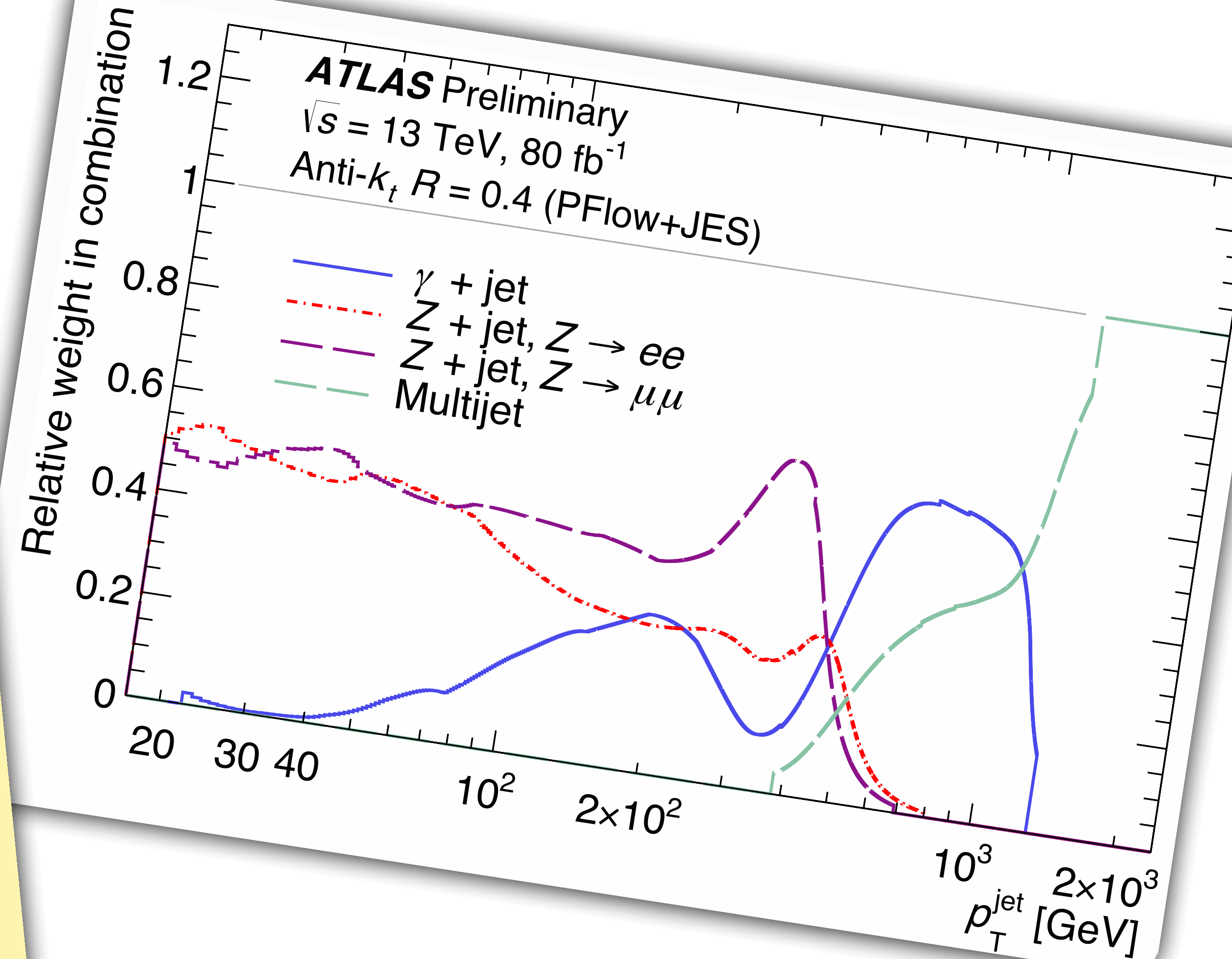
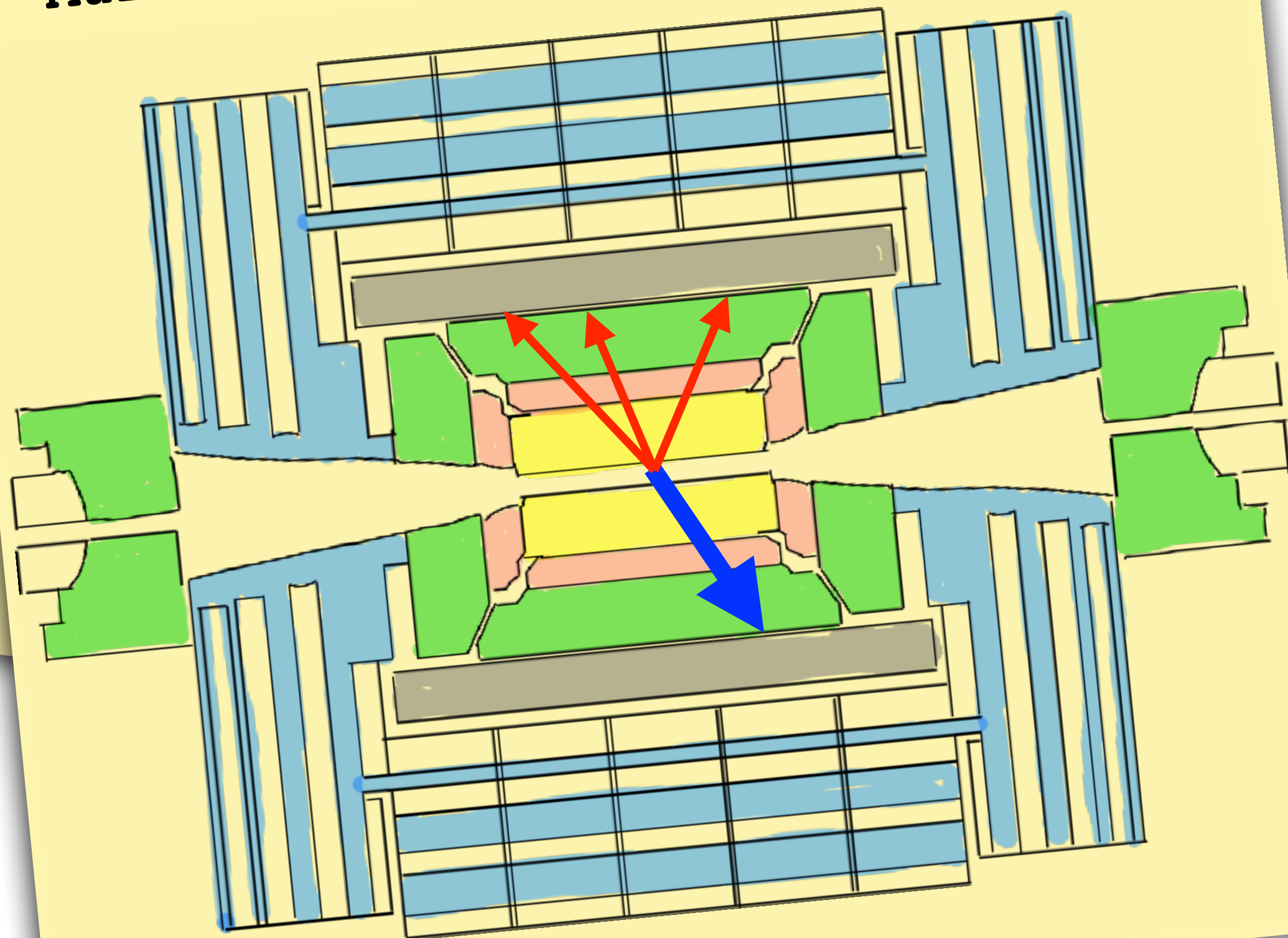


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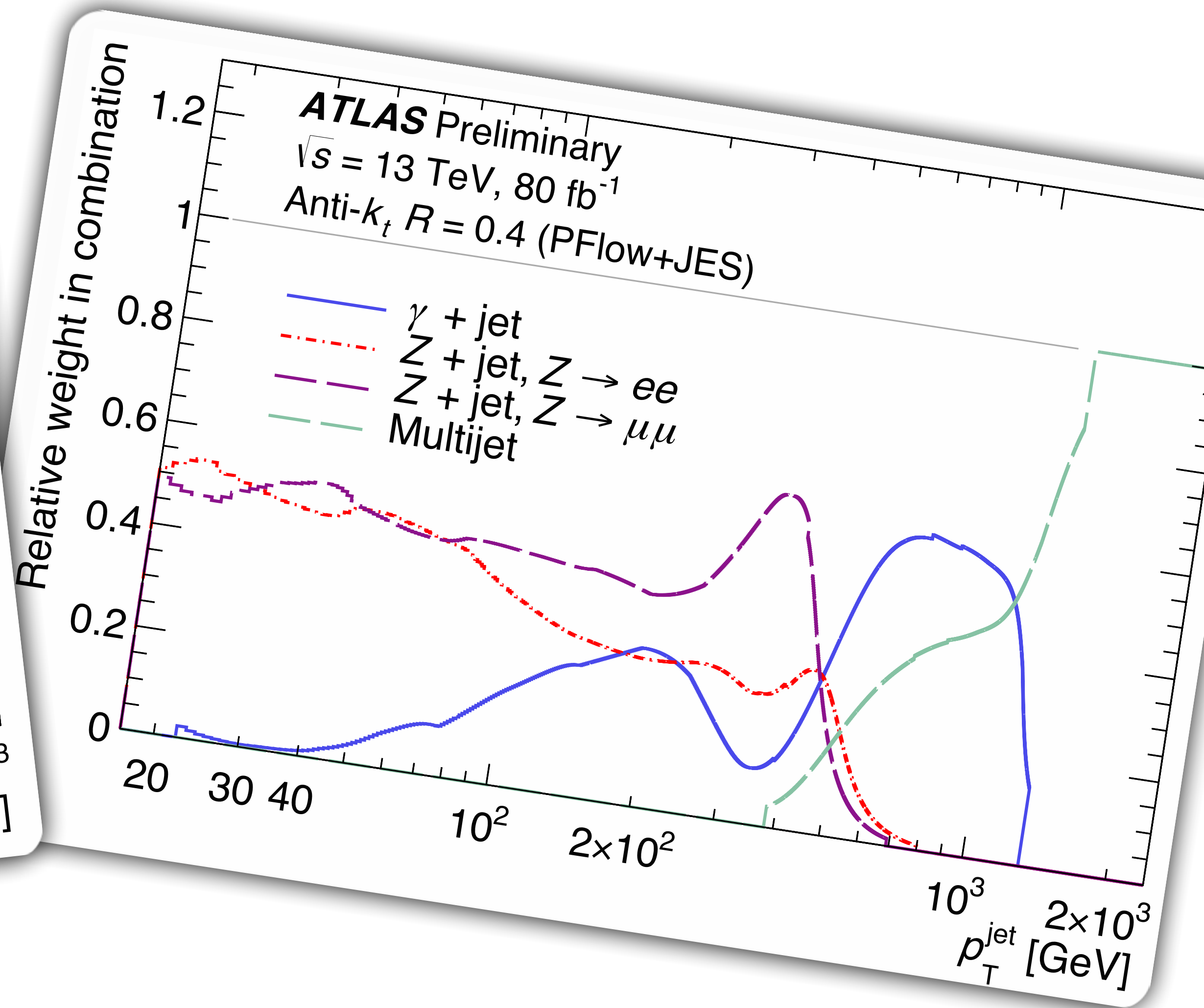
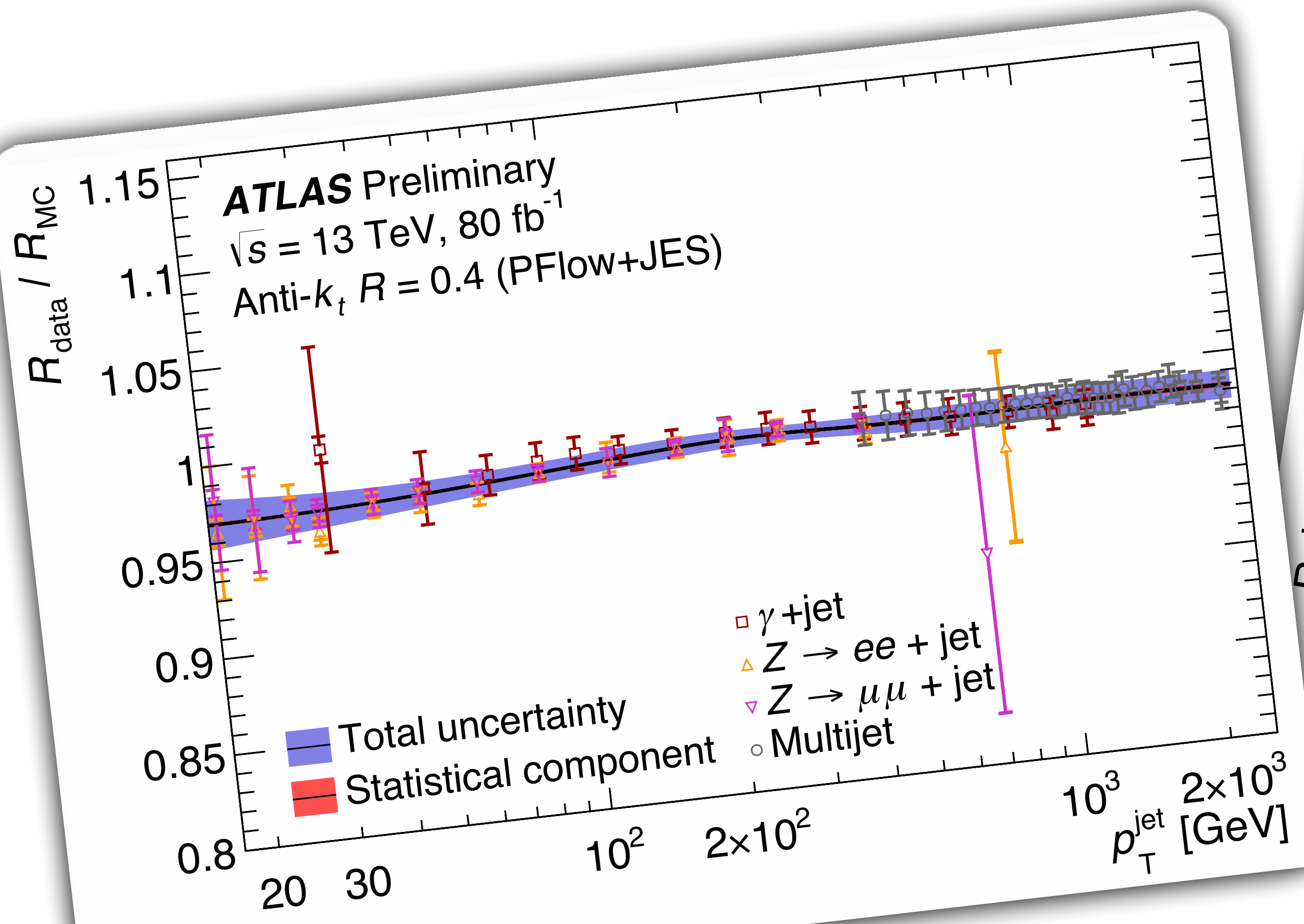
Photon or Z against 1 Jet



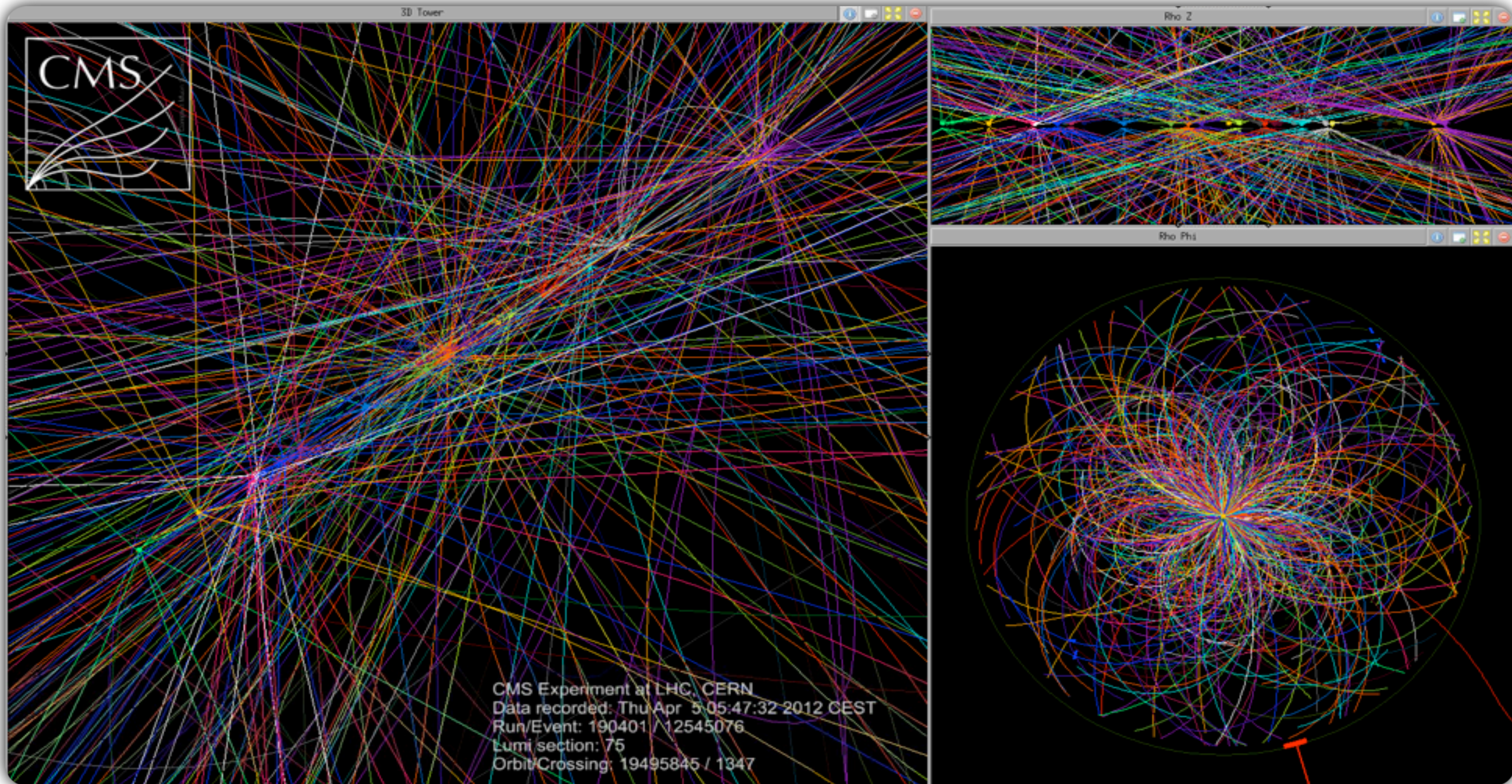
Multi-jets against high p_T Jet



Step 3: Absolute p_T Residual-Correction using data



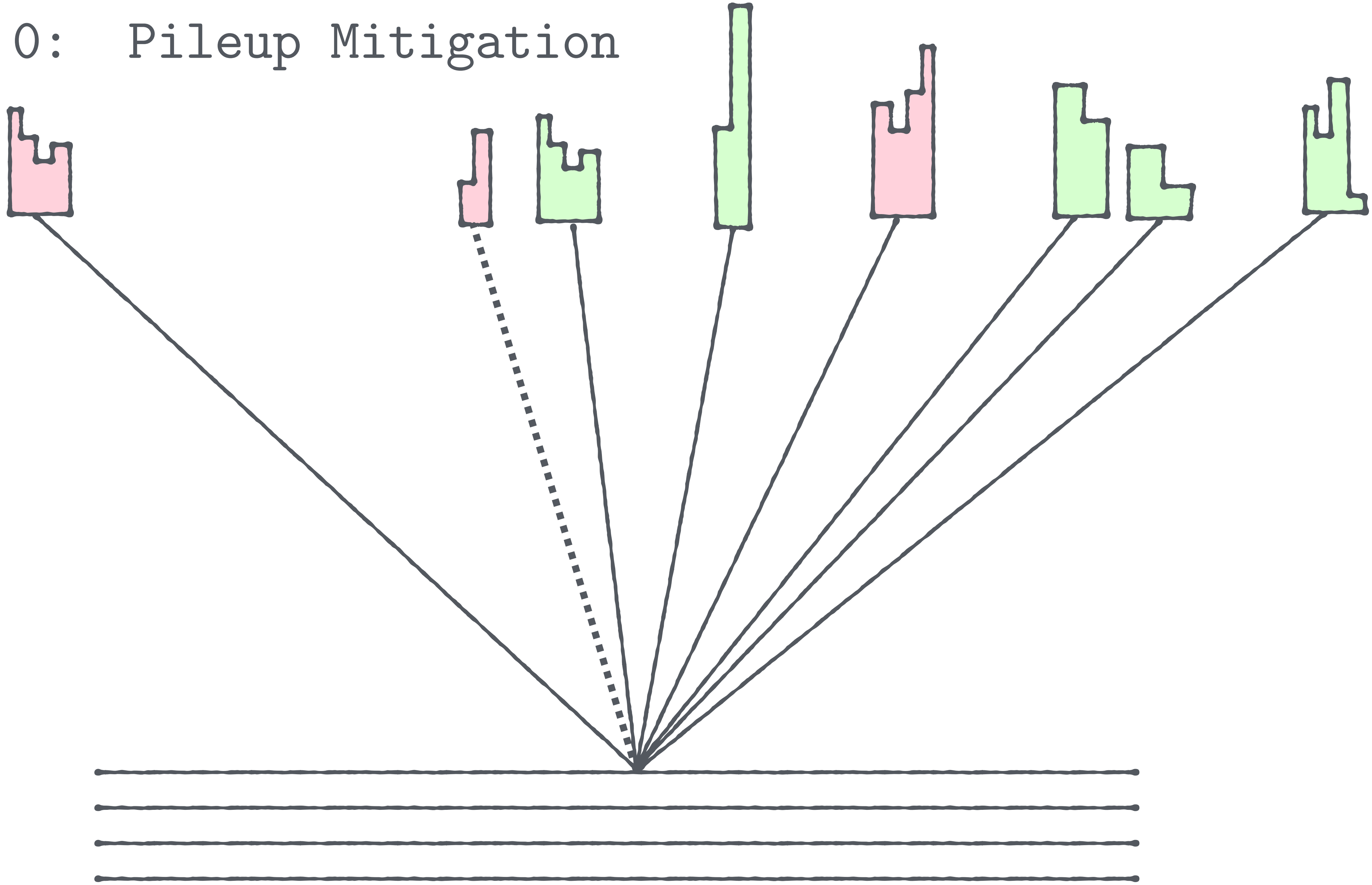
Step 0: Pileup Mitigation



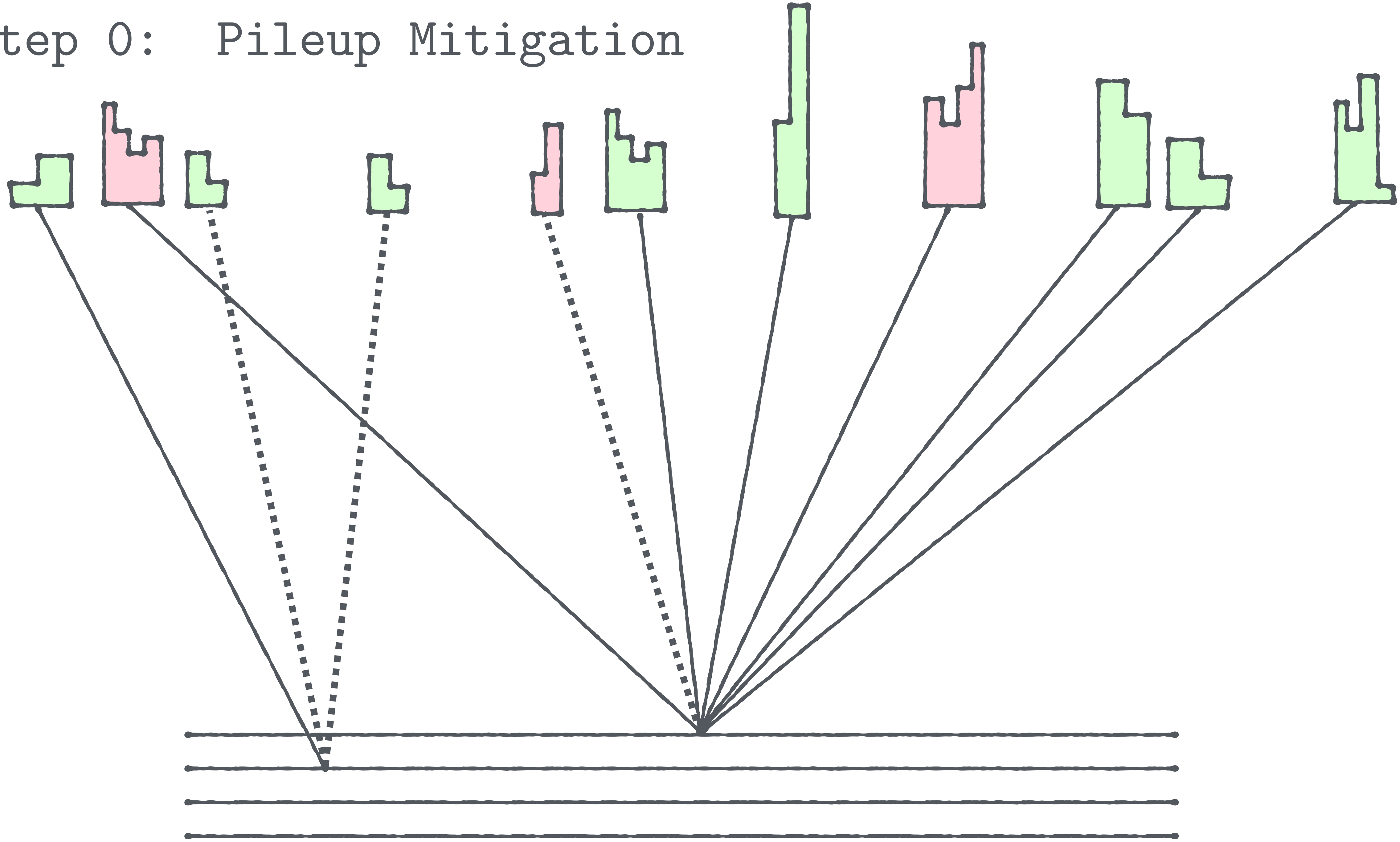
Step 0: Pileup Mitigation



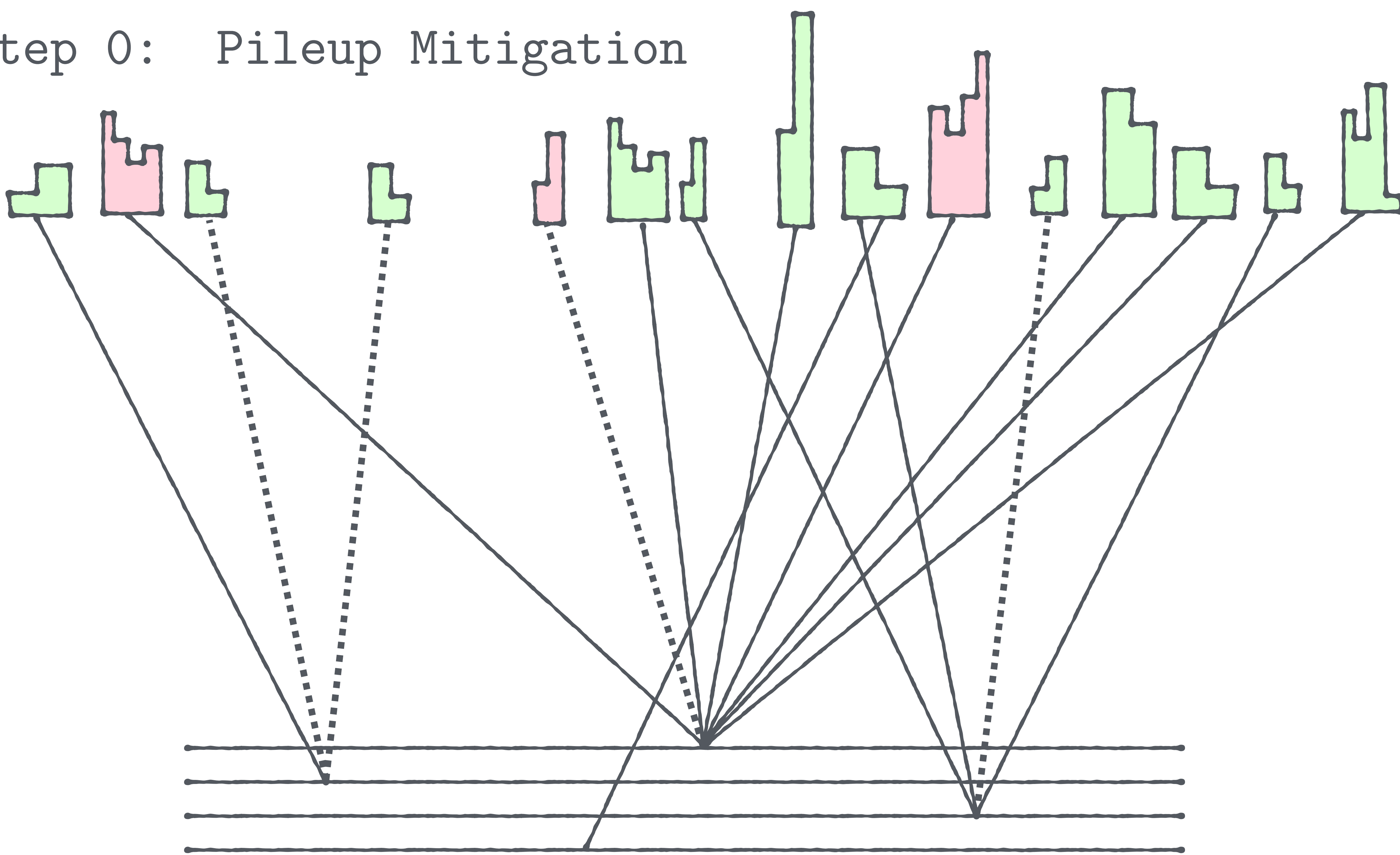
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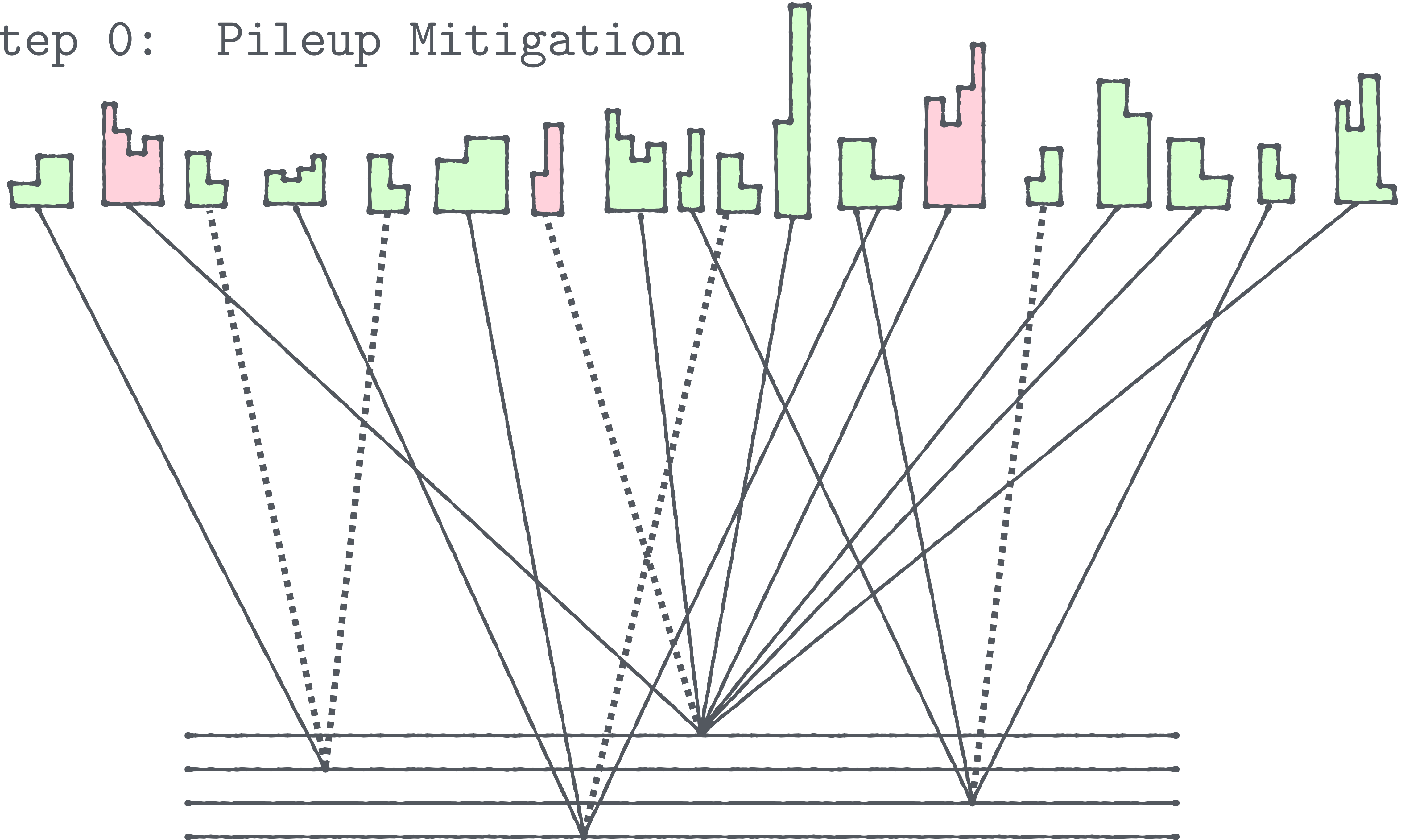
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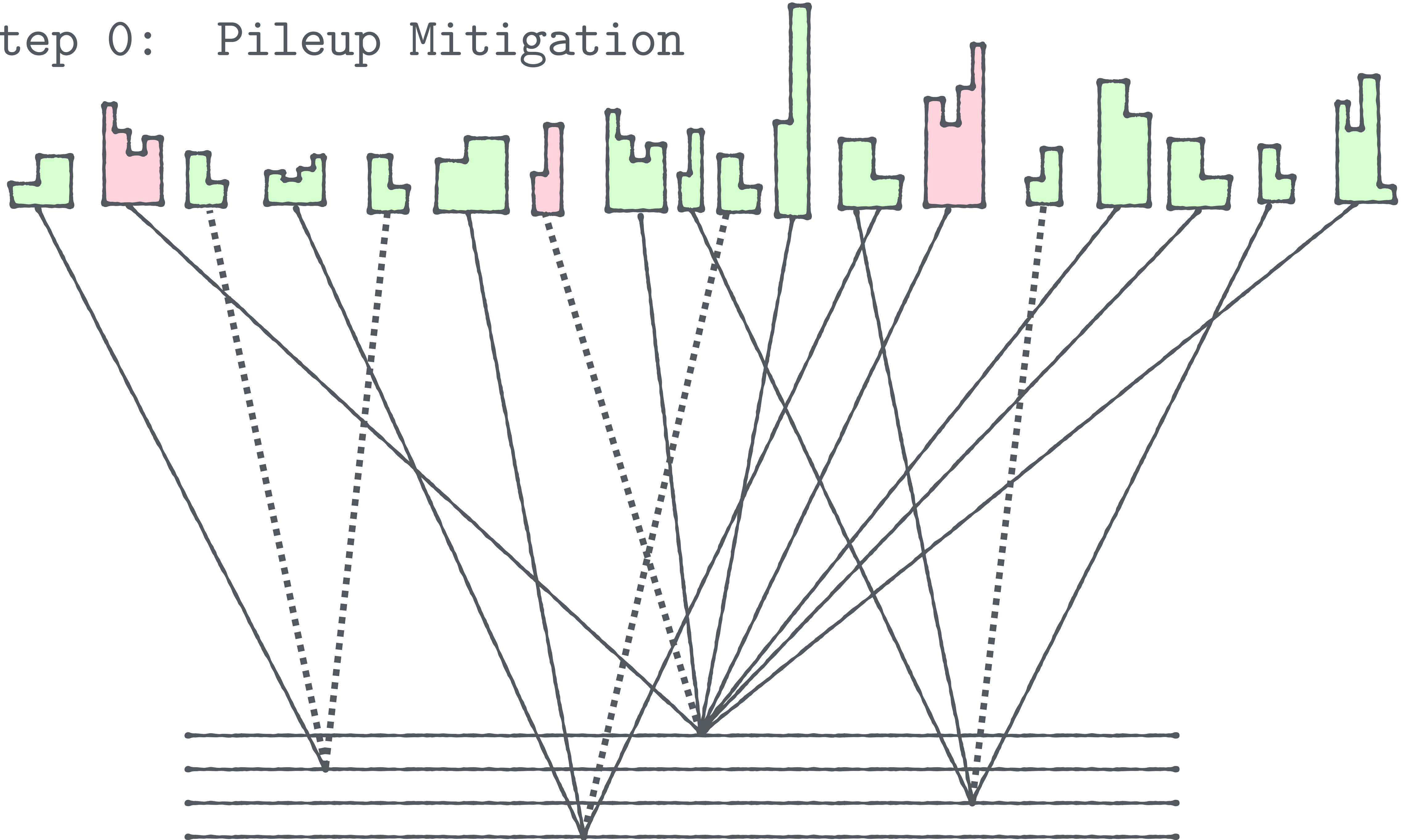
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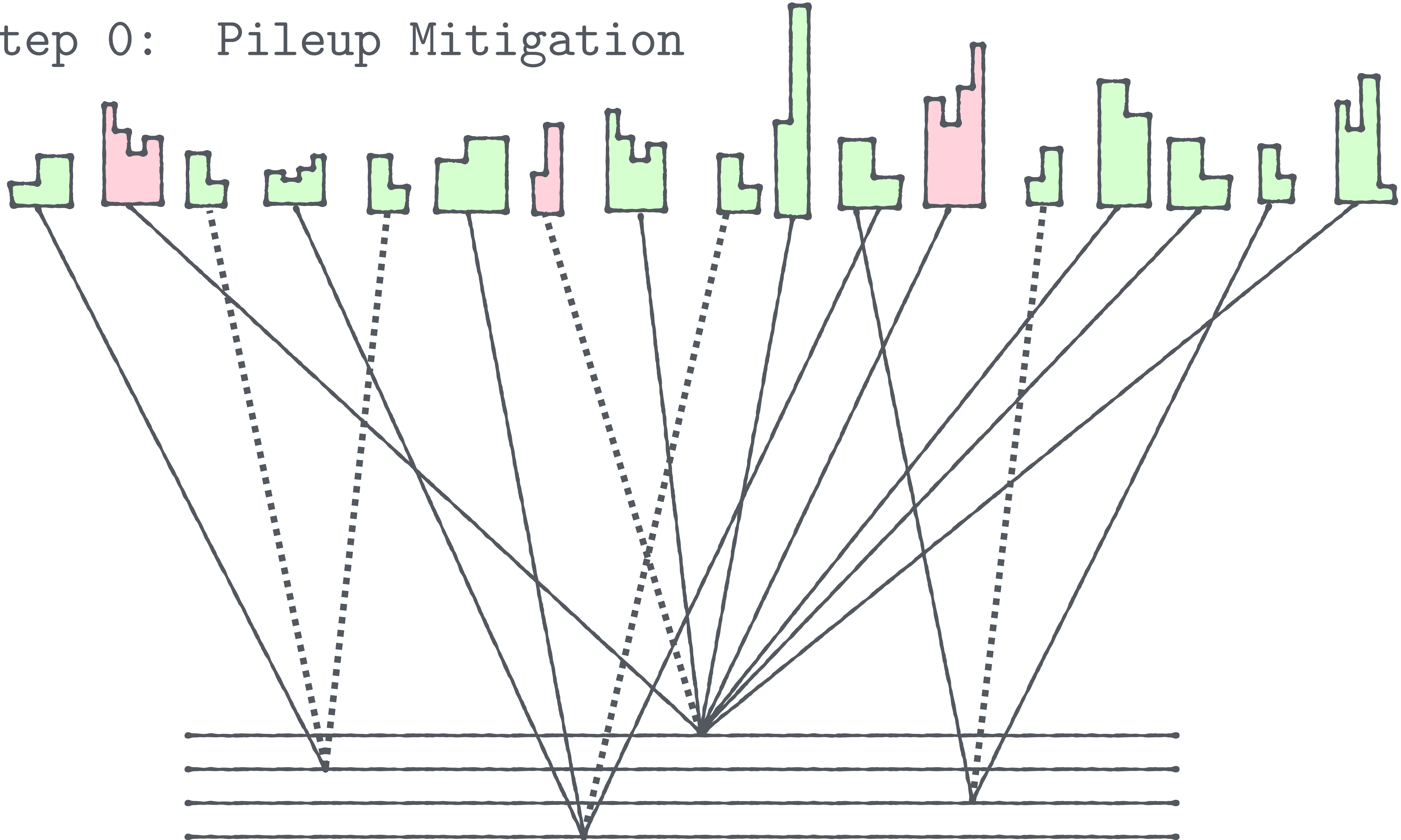
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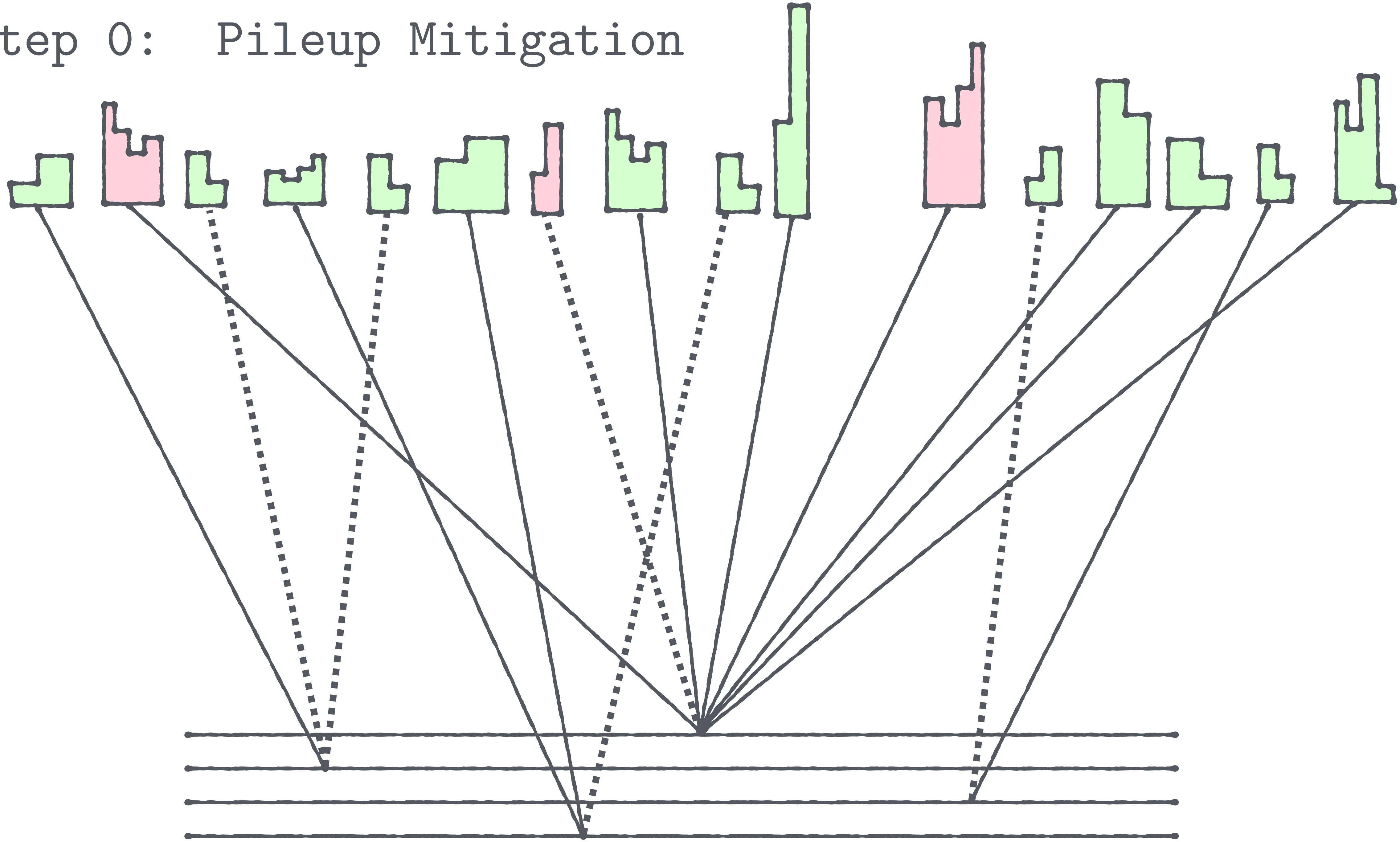
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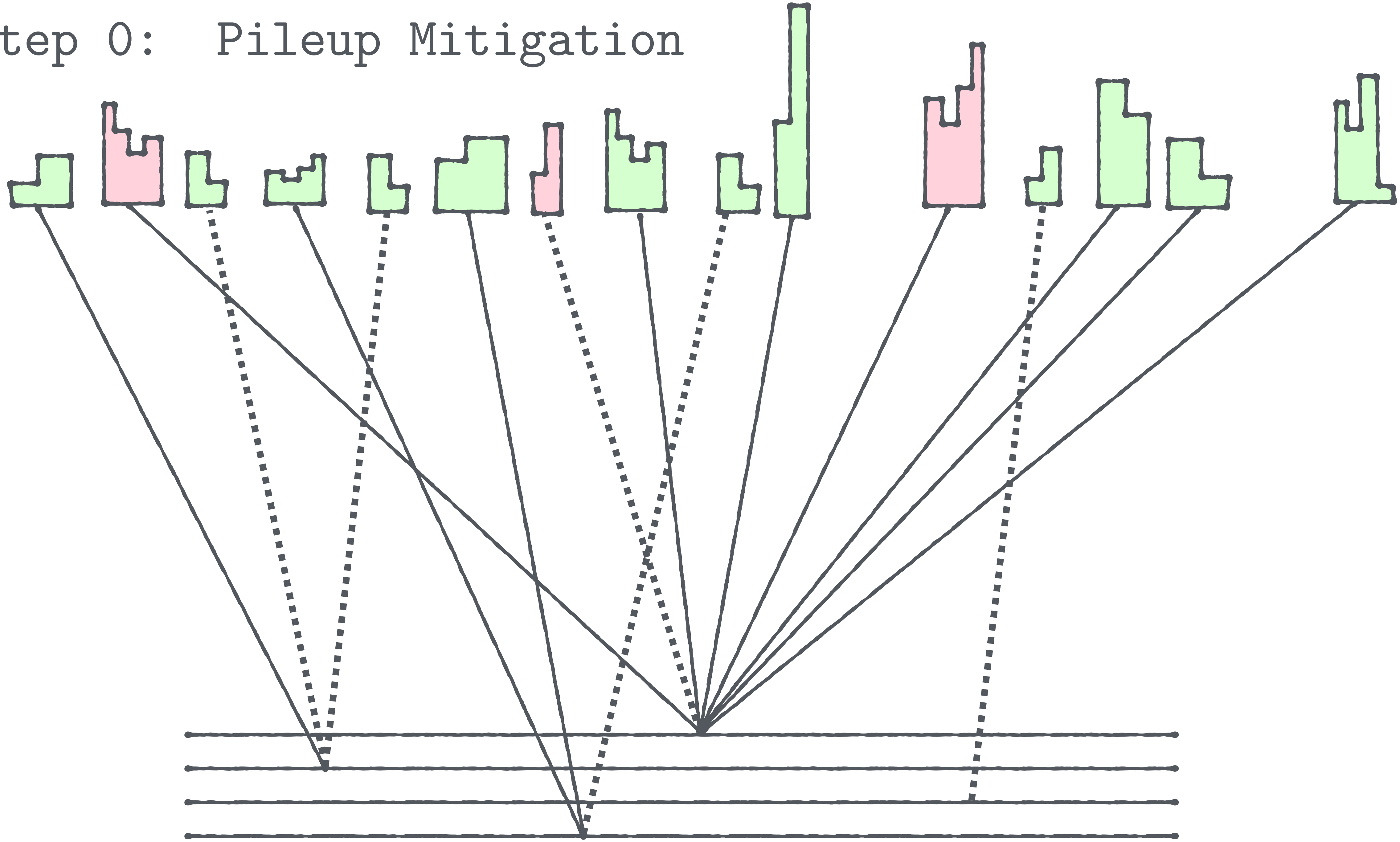
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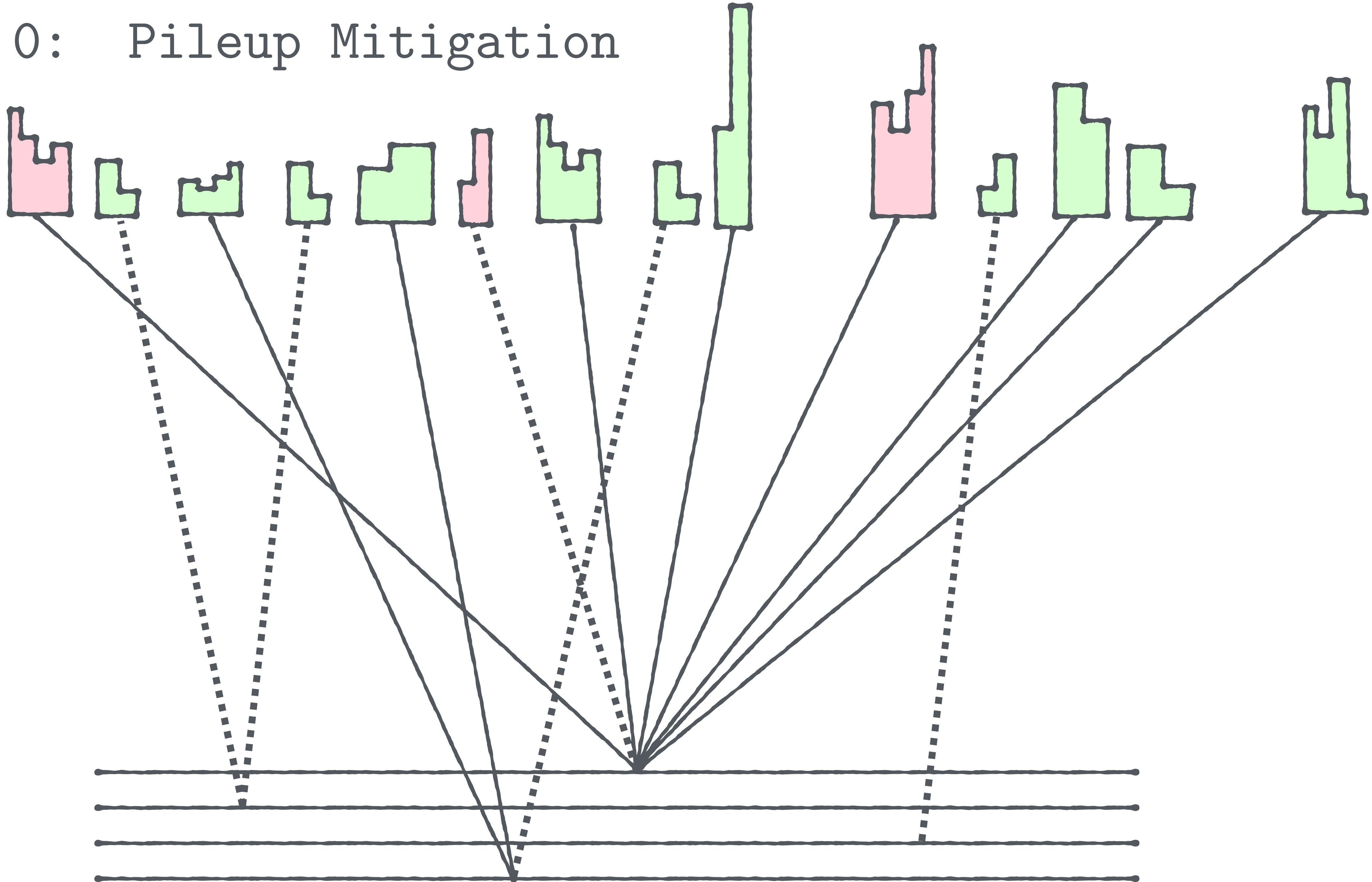
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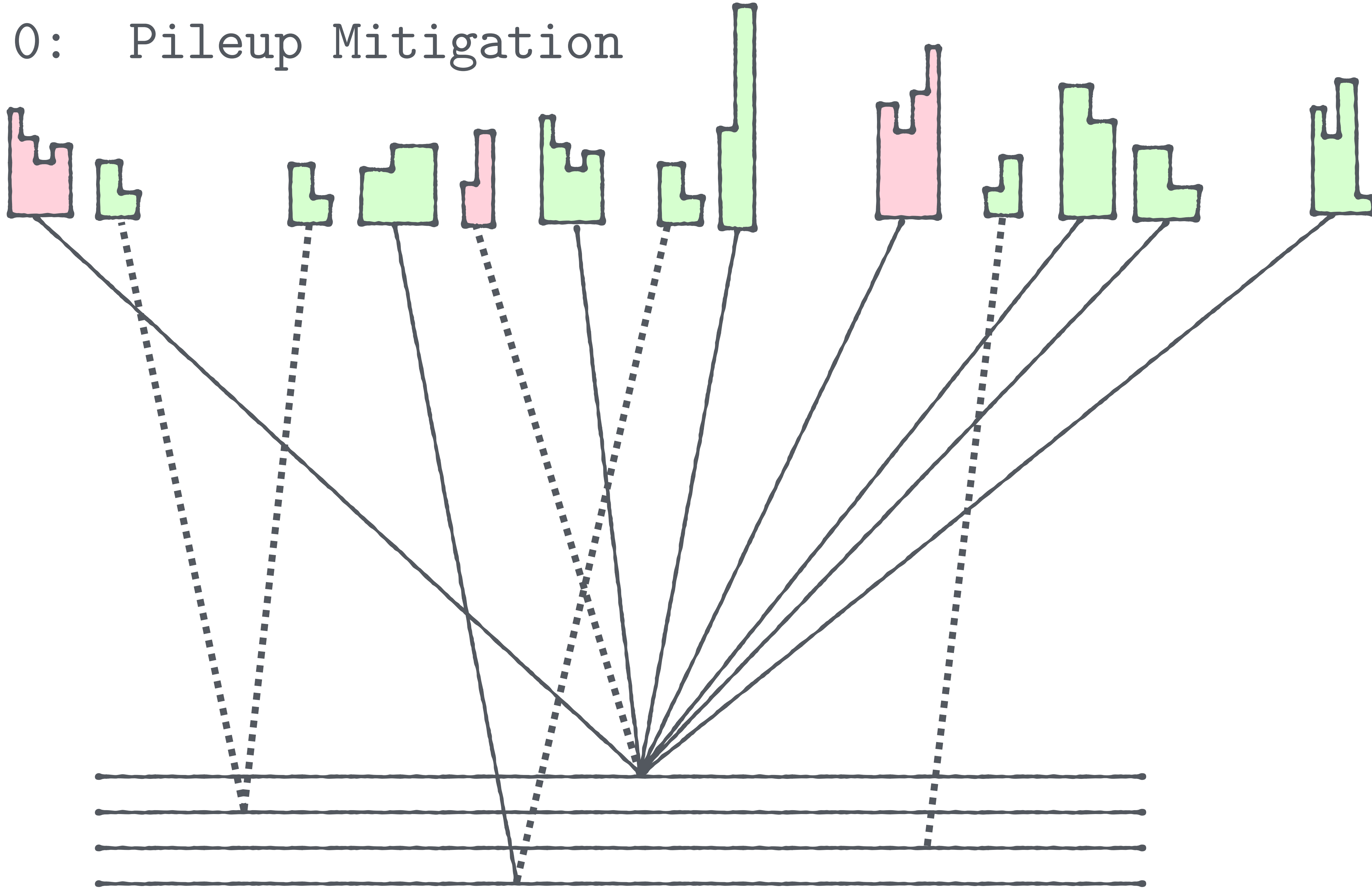
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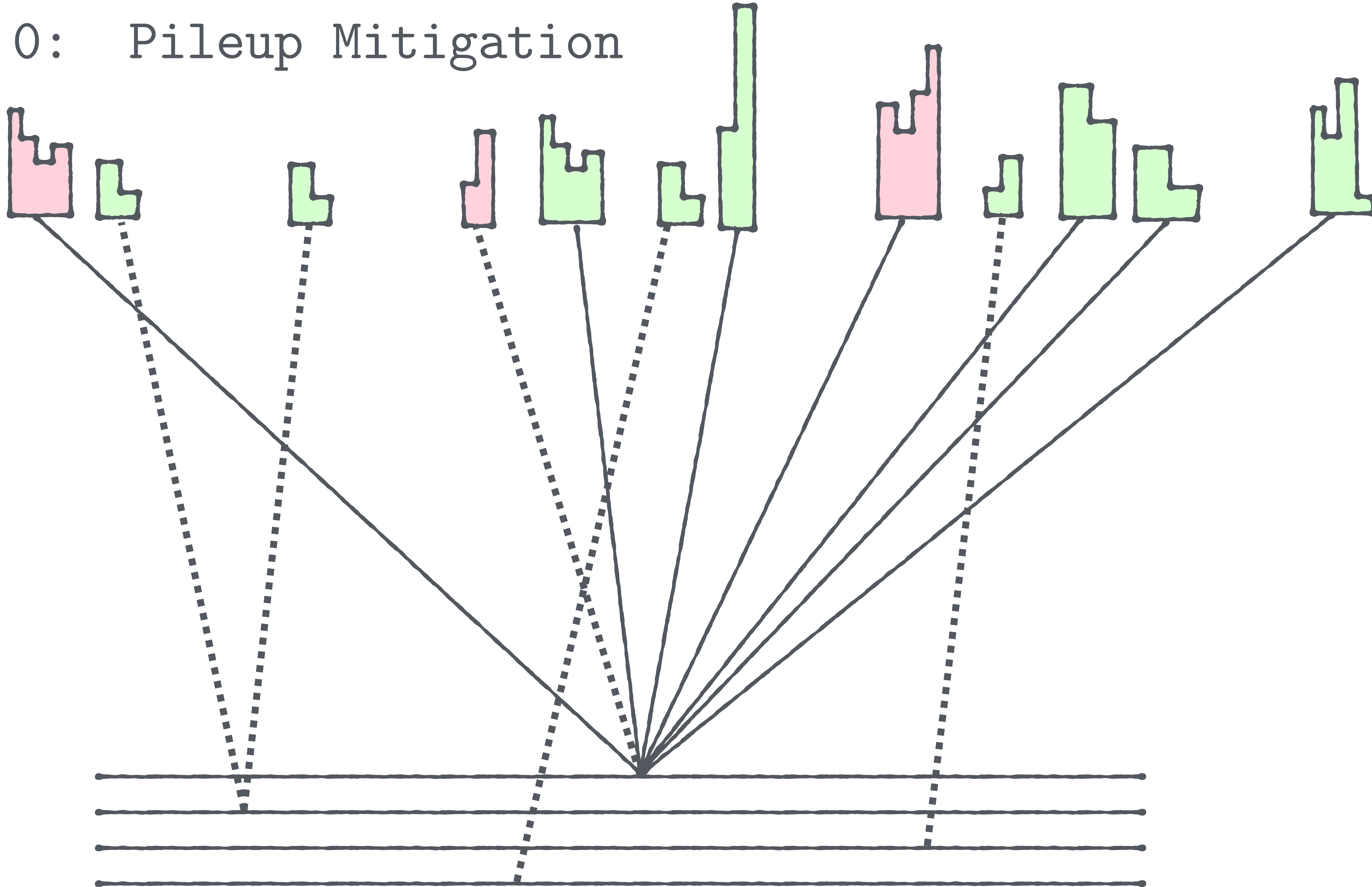
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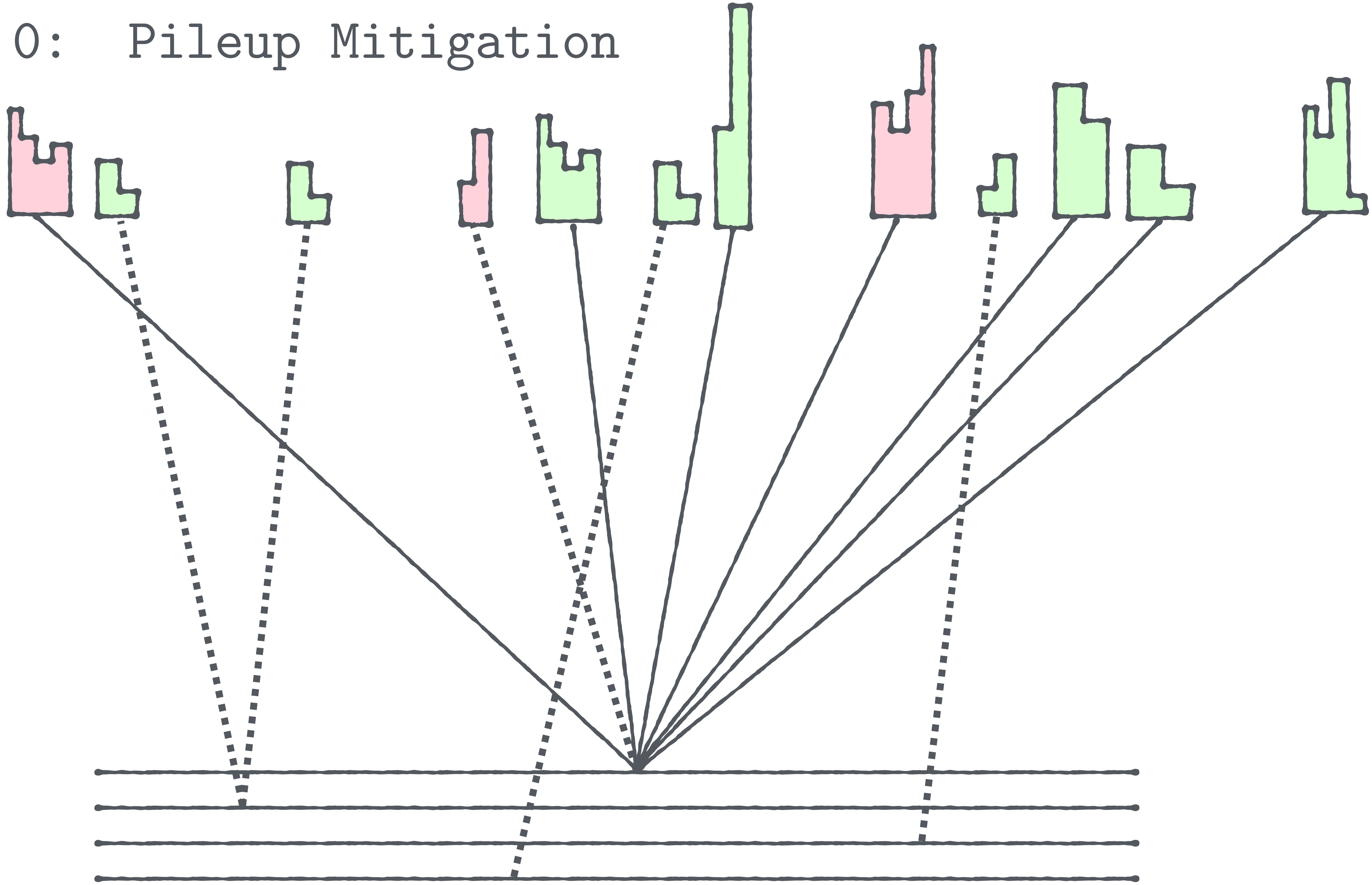
Step 0: Pileup Mitigation



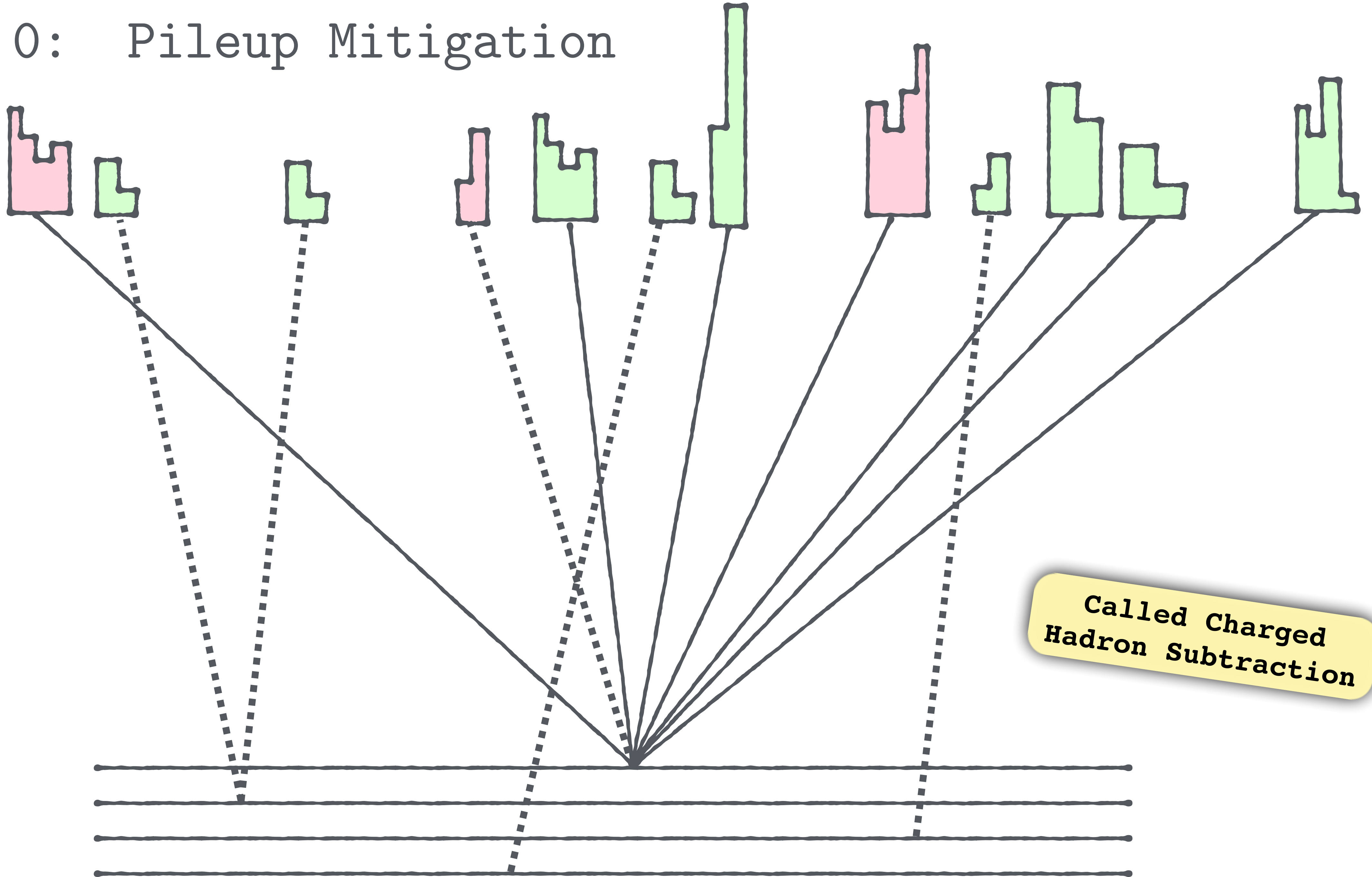
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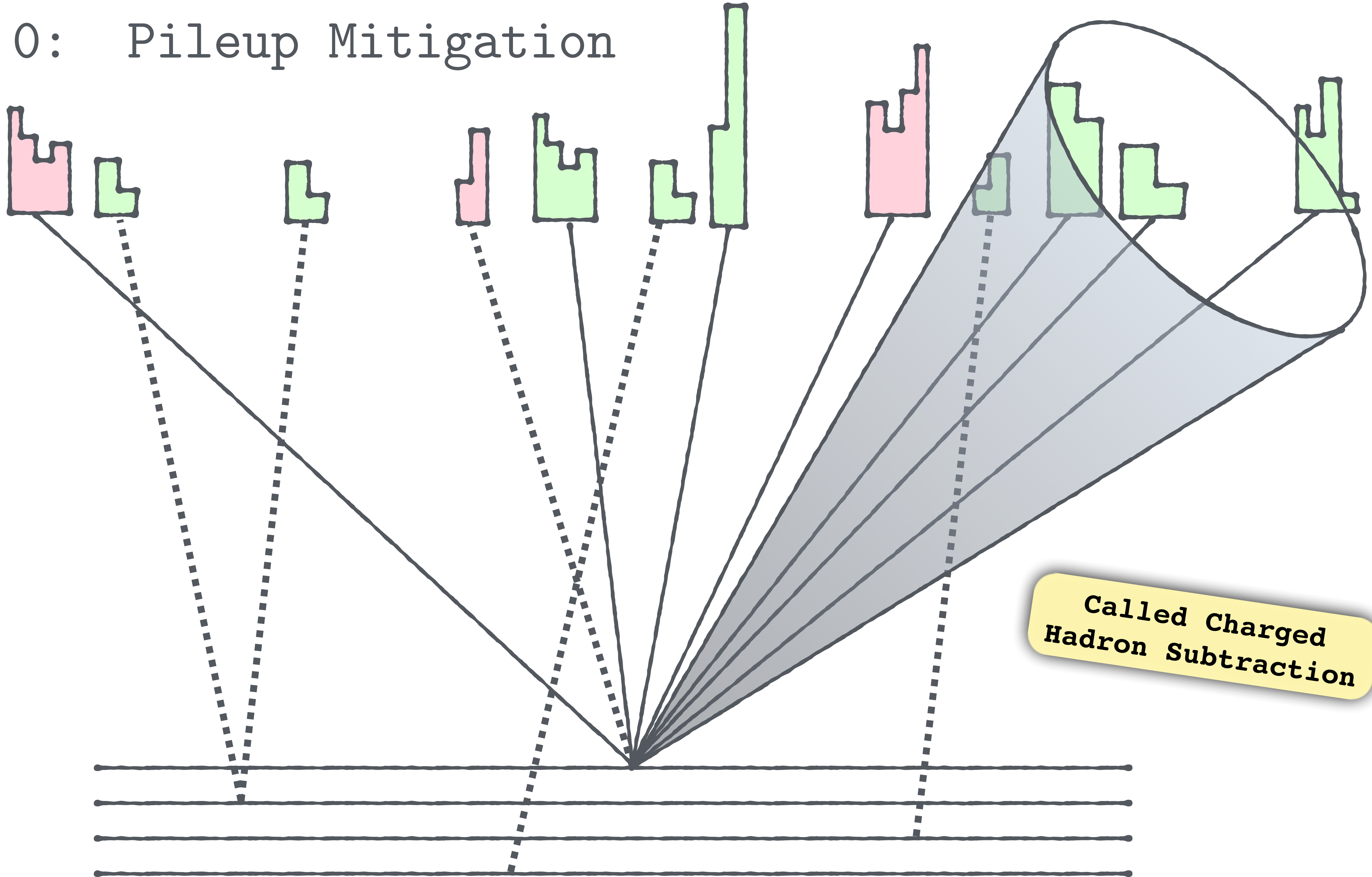


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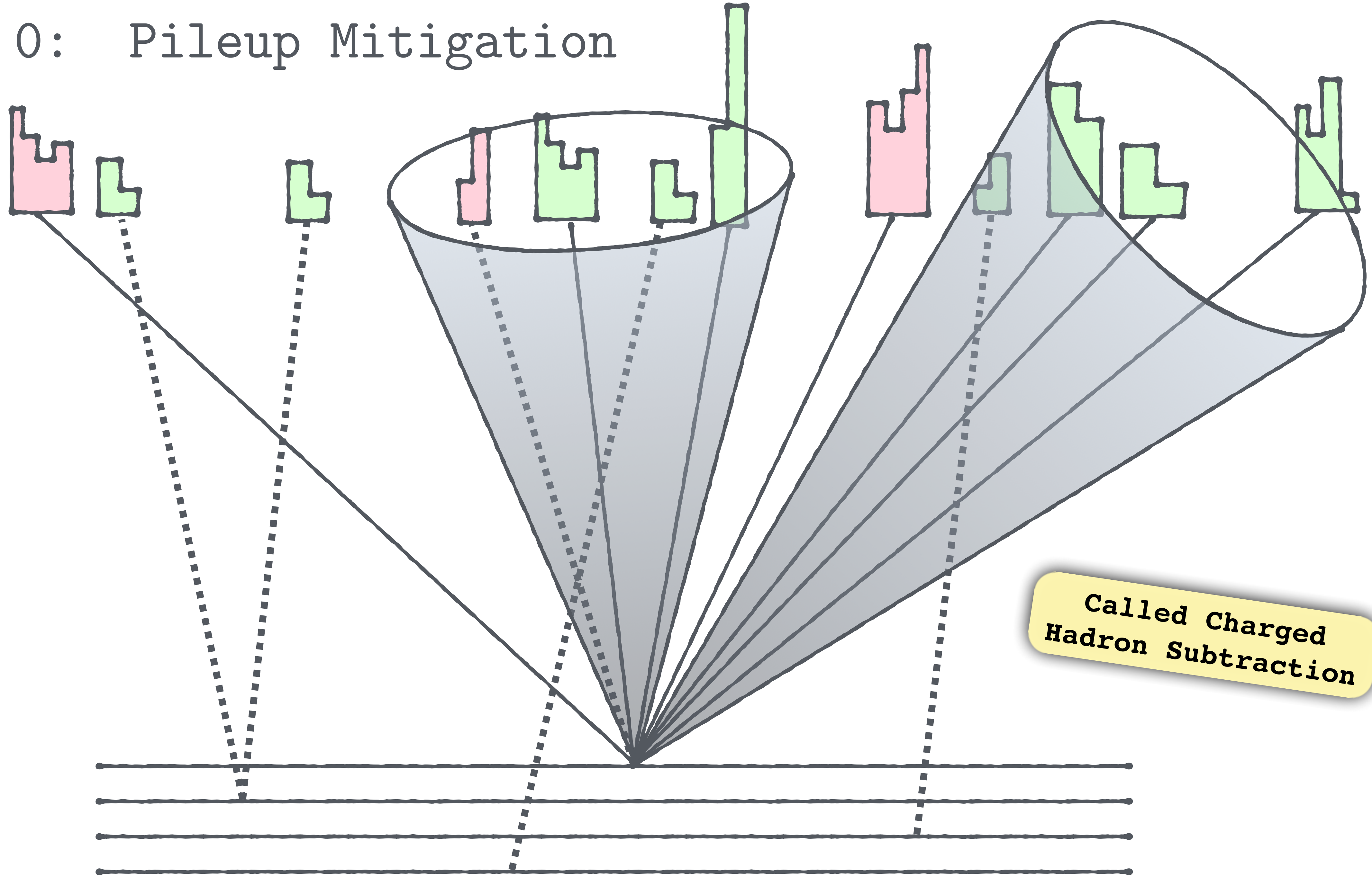
**Called Charged
Hadron Subtraction**

Step 0: Pileup Mitigation

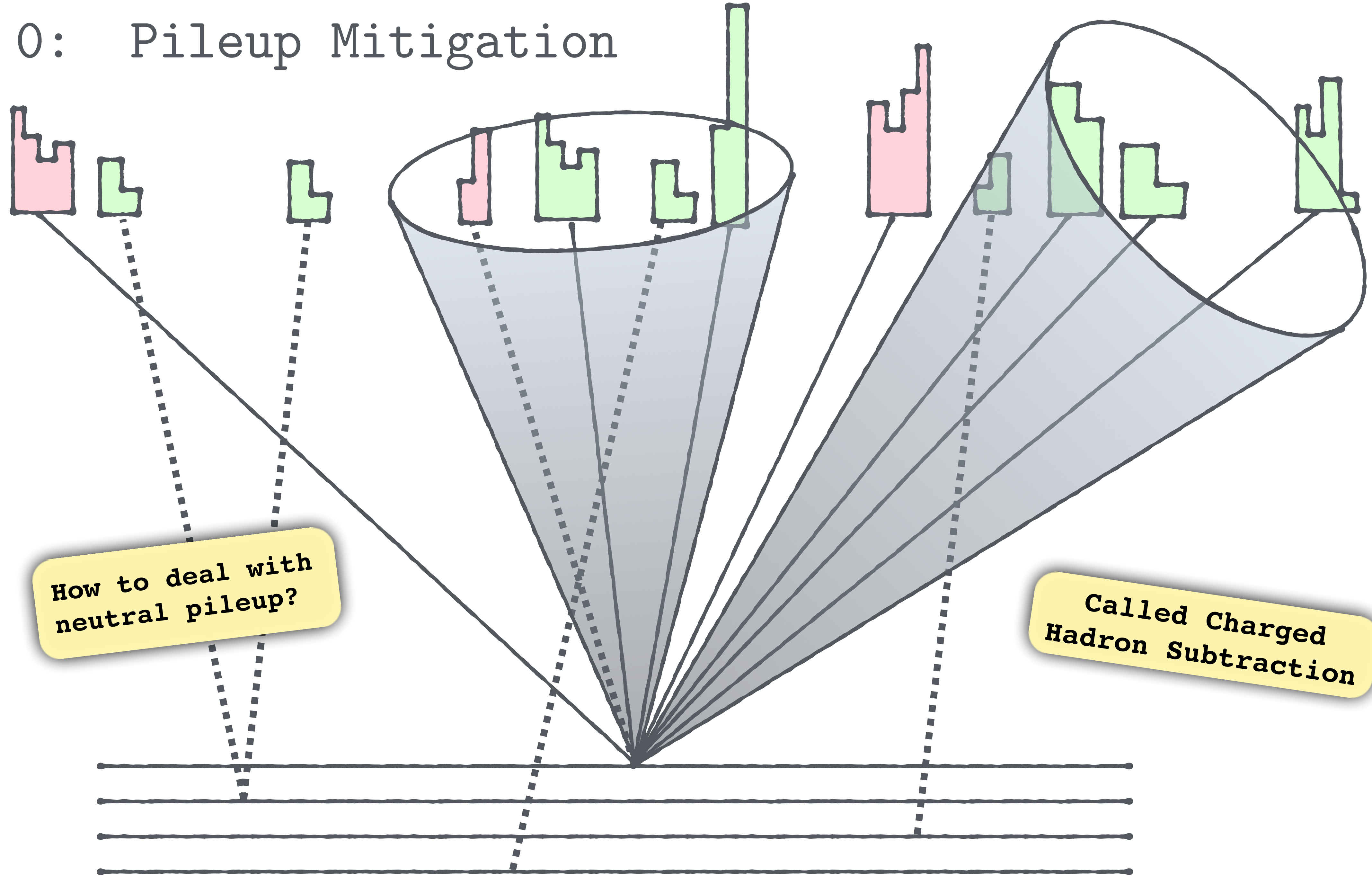


**Called Charged
Hadron Subtraction**

Step 0: Pileup Mitigation



Step 0: Pileup Mitigation



Pile Up Per Particle Identification

Pile Up Per Particle Identification

Idea in a nutshell

- Particles from the leading vertex originate from a hard scattering process
- QCD Confinement: hadrons are produced in jets, which are collimated
 - leading vertex hadrons tend to be hard and not isolated
- Particles from pileup are soft and uncorrelated with the leading vertex hard process
 - PU particles tend to be soft and isolated

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Consider the following

$$\epsilon_{ij} \equiv \frac{p_{T,i}}{\Delta R_{ij}}$$

Encapsulates the basic idea:

- (1) hard vs soft
- (2) nearby vs far-away

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Pile Up Per Particle Identification

Form a shape variable

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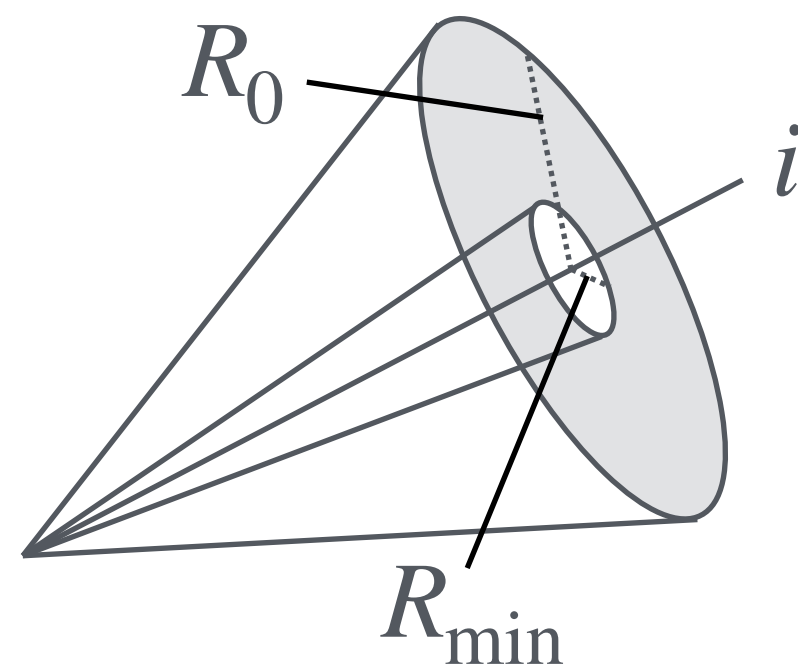
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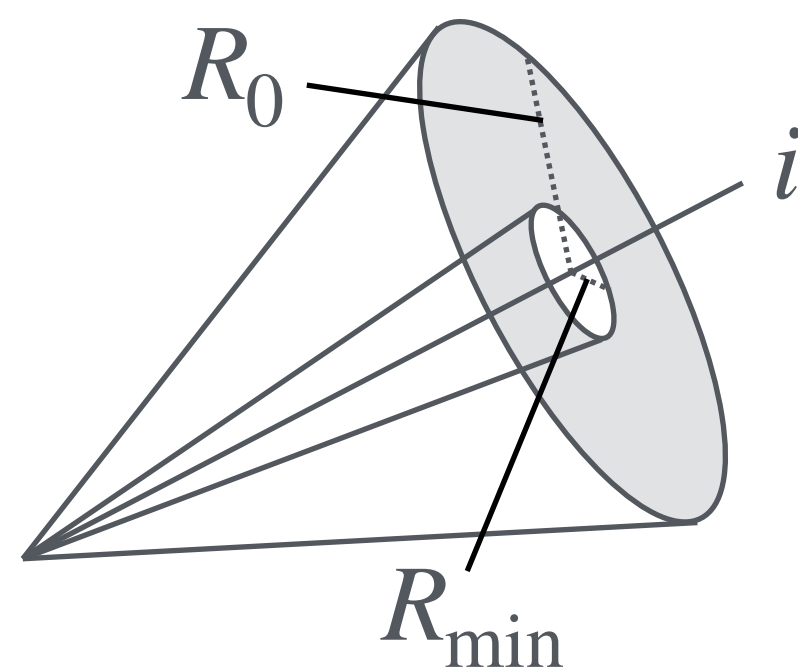
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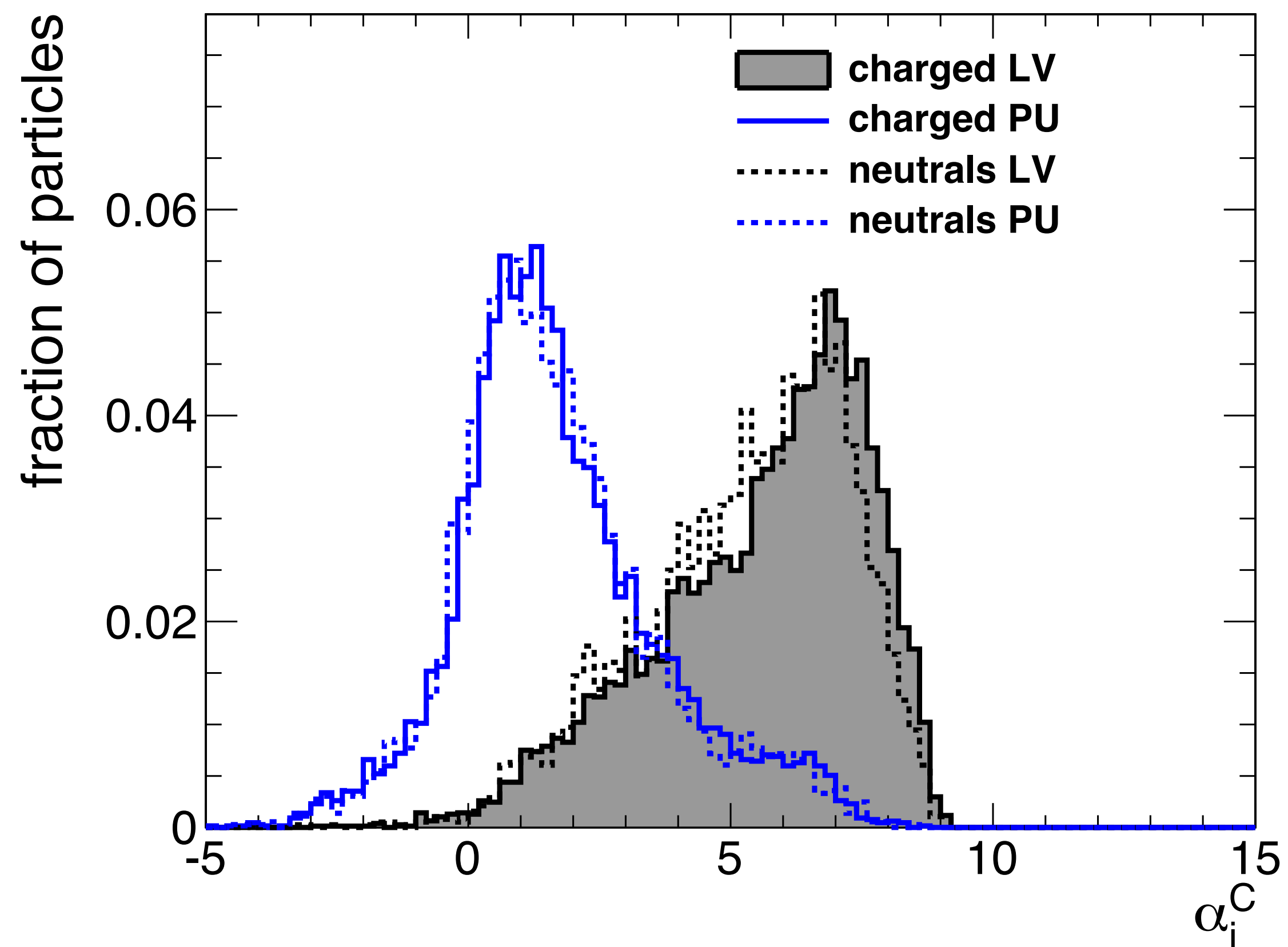


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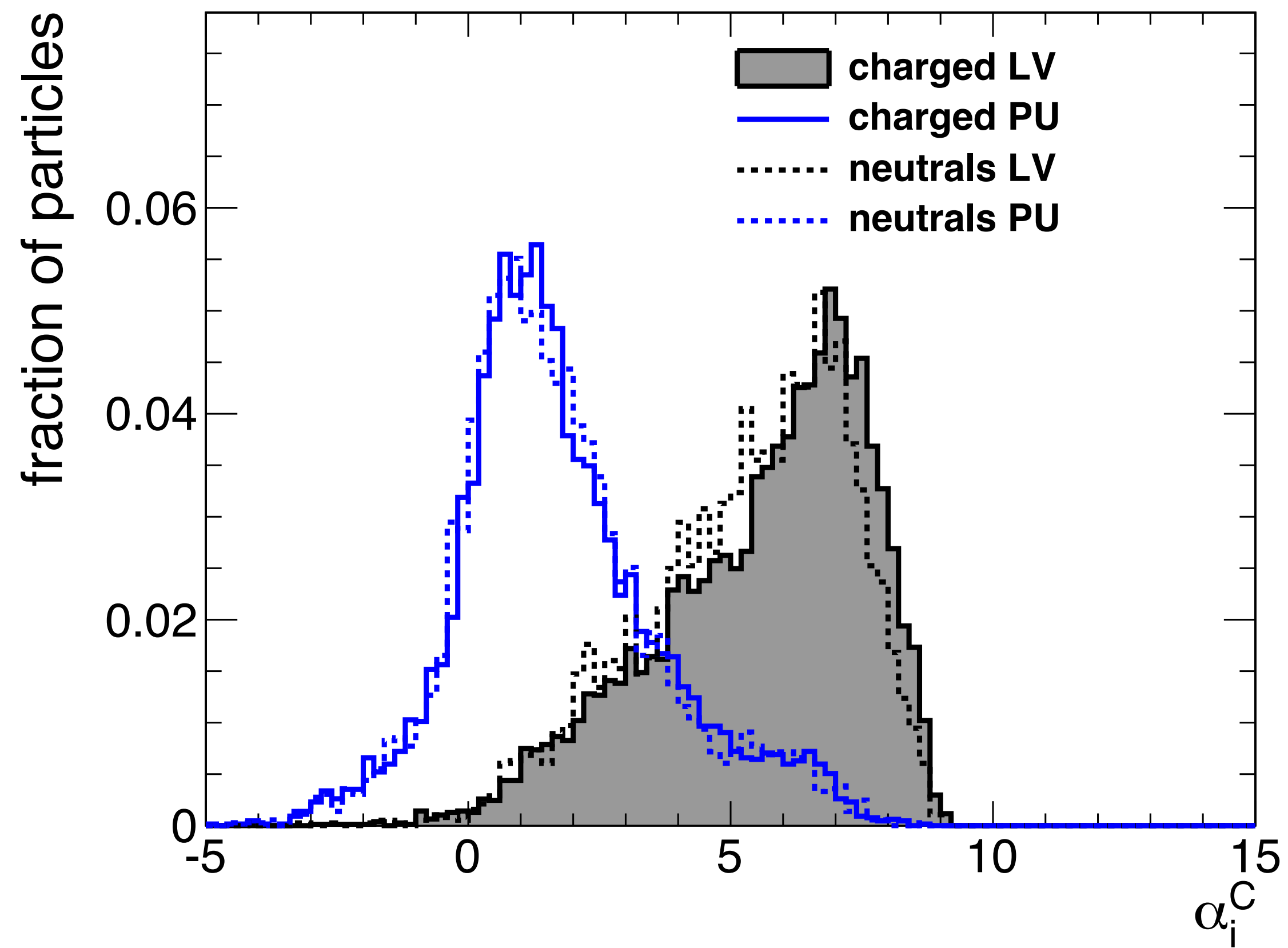
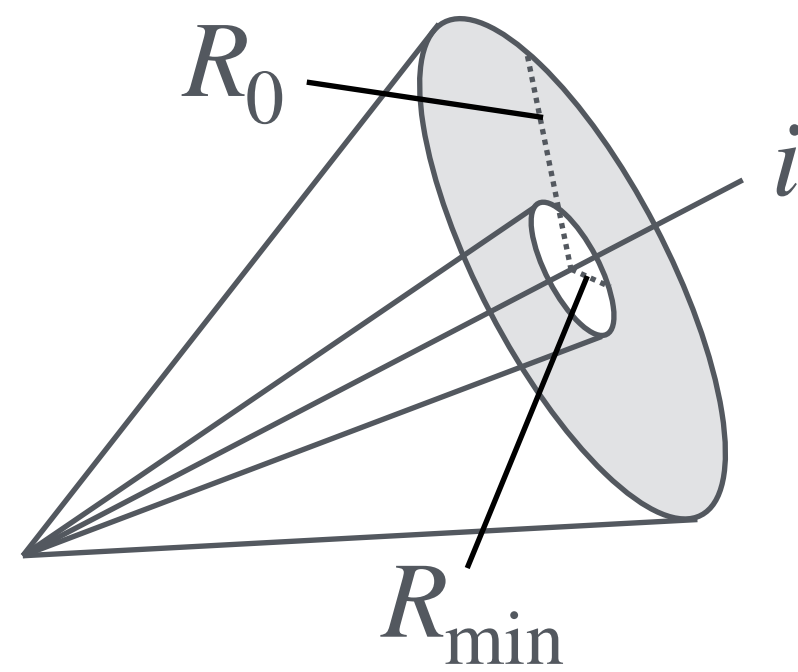
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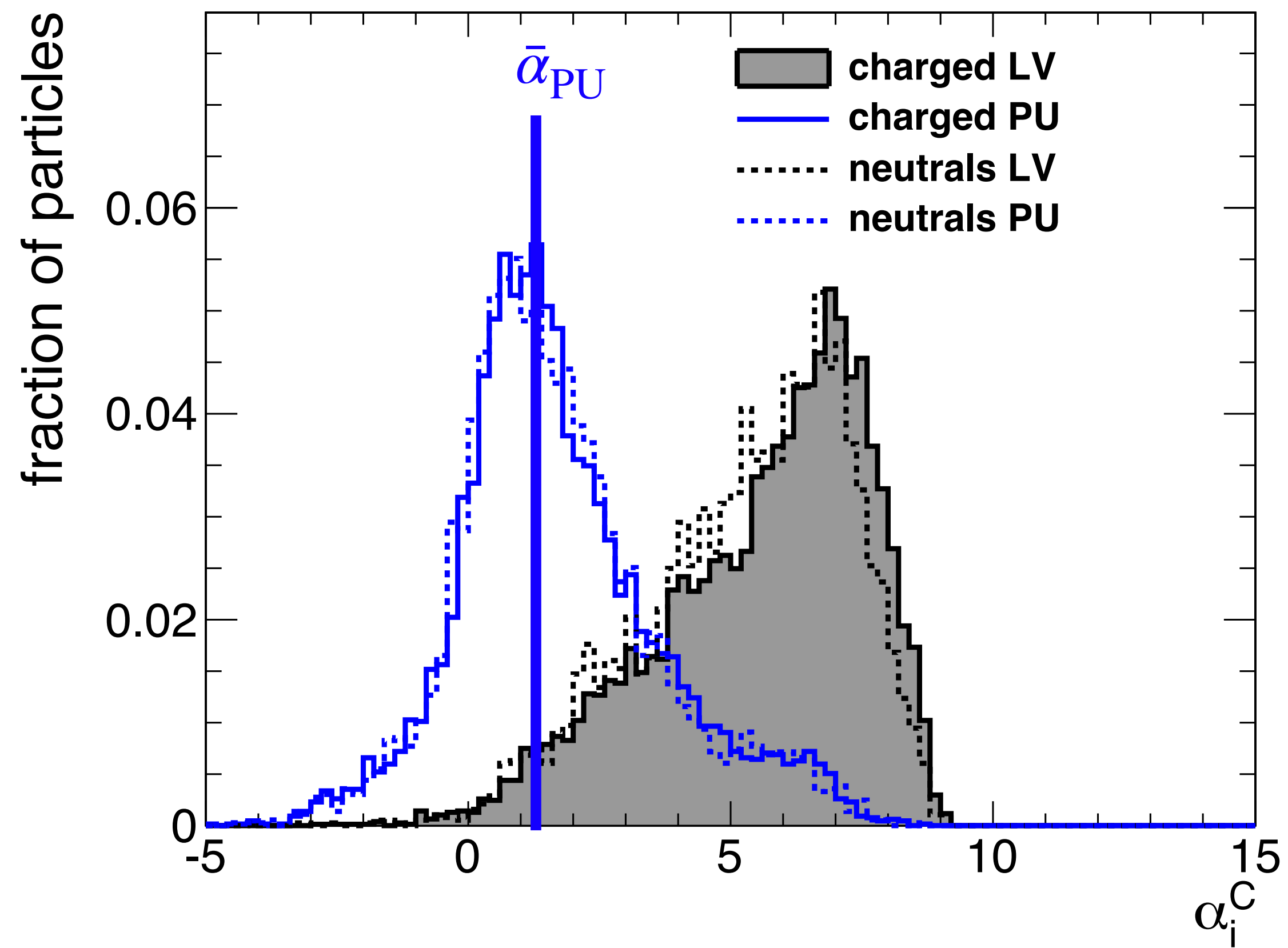
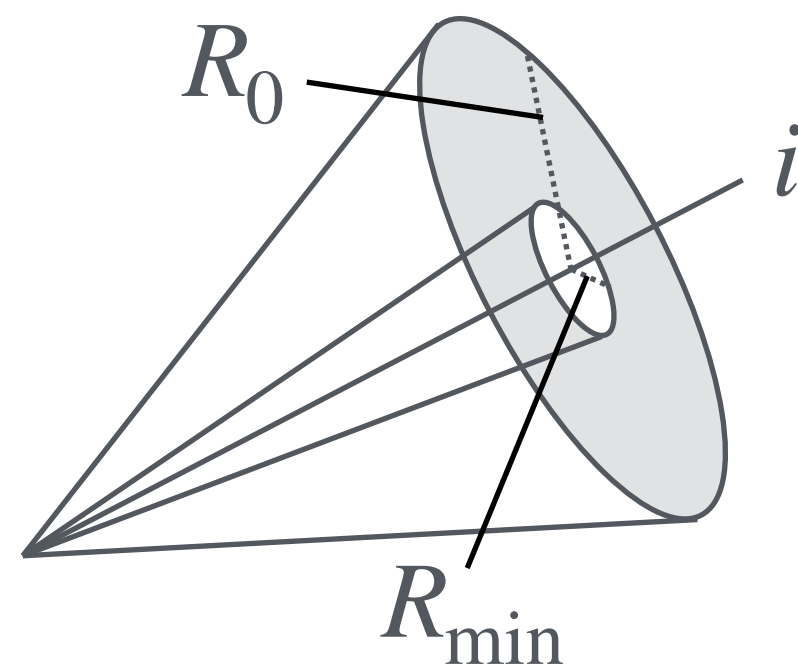
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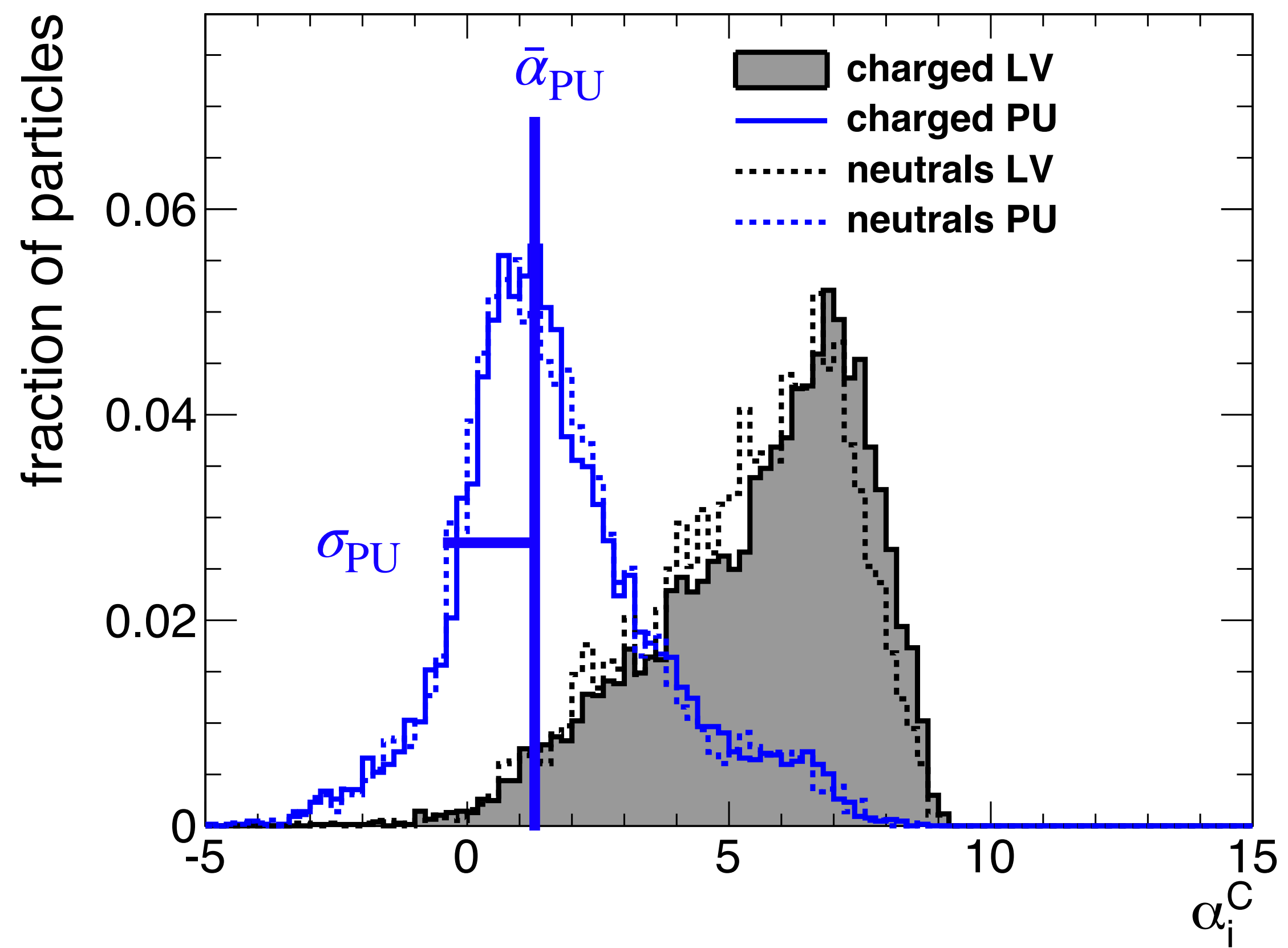
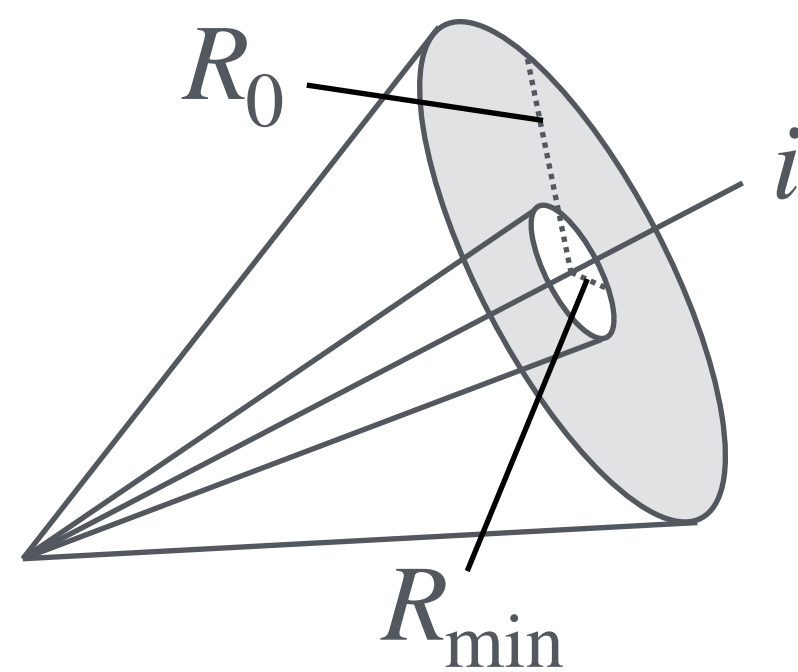
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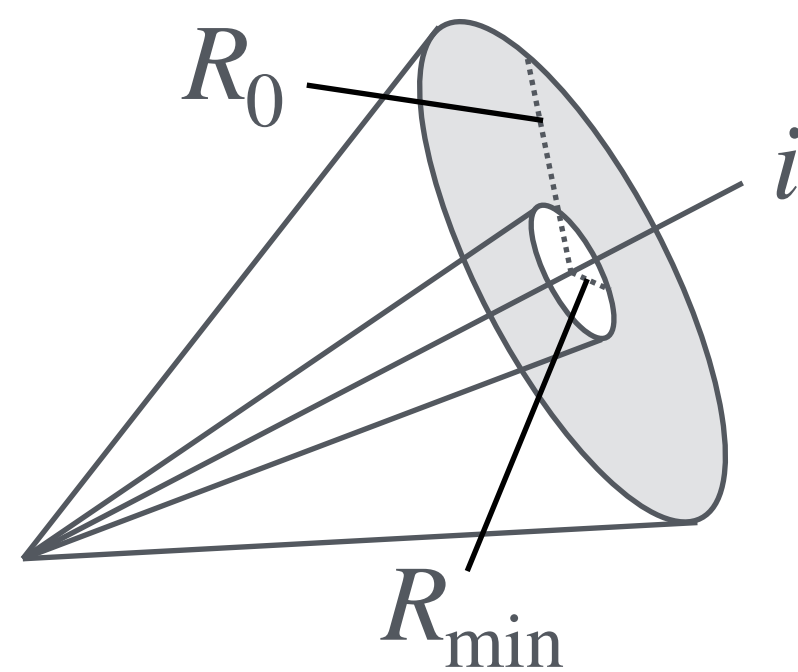
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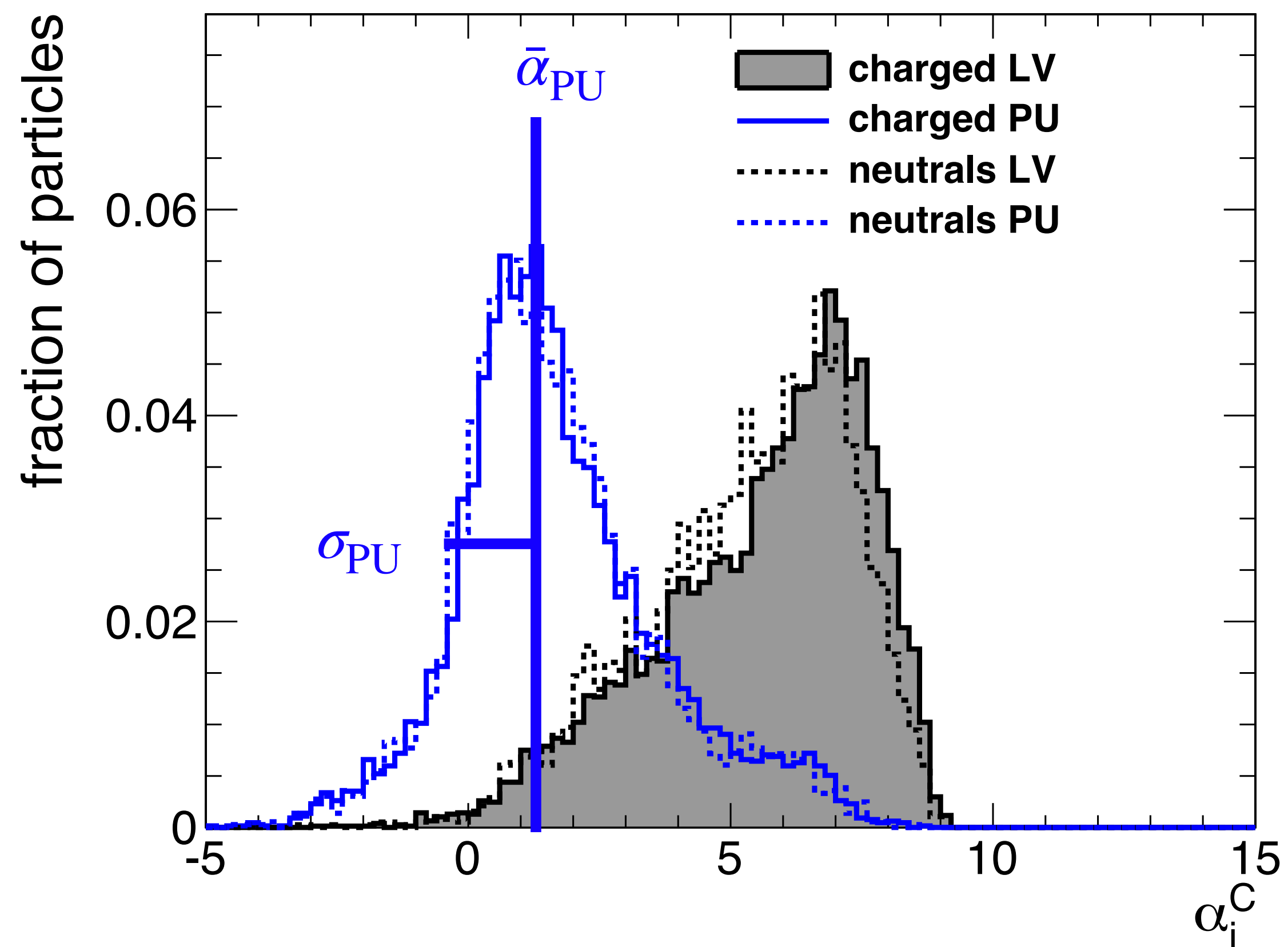


Now form a test statistic

$$\chi_i^2 \equiv \Theta(\alpha_i - \bar{\alpha}_{\text{PU}}) \frac{(\alpha_i - \bar{\alpha}_{\text{PU}})^2}{\sigma_{\text{PU}}^2}$$

and assign a weight as

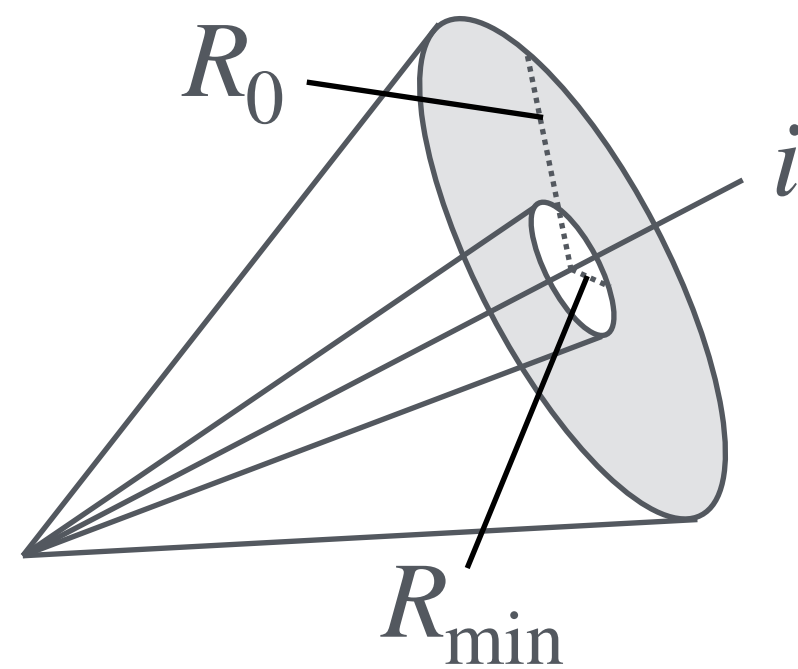
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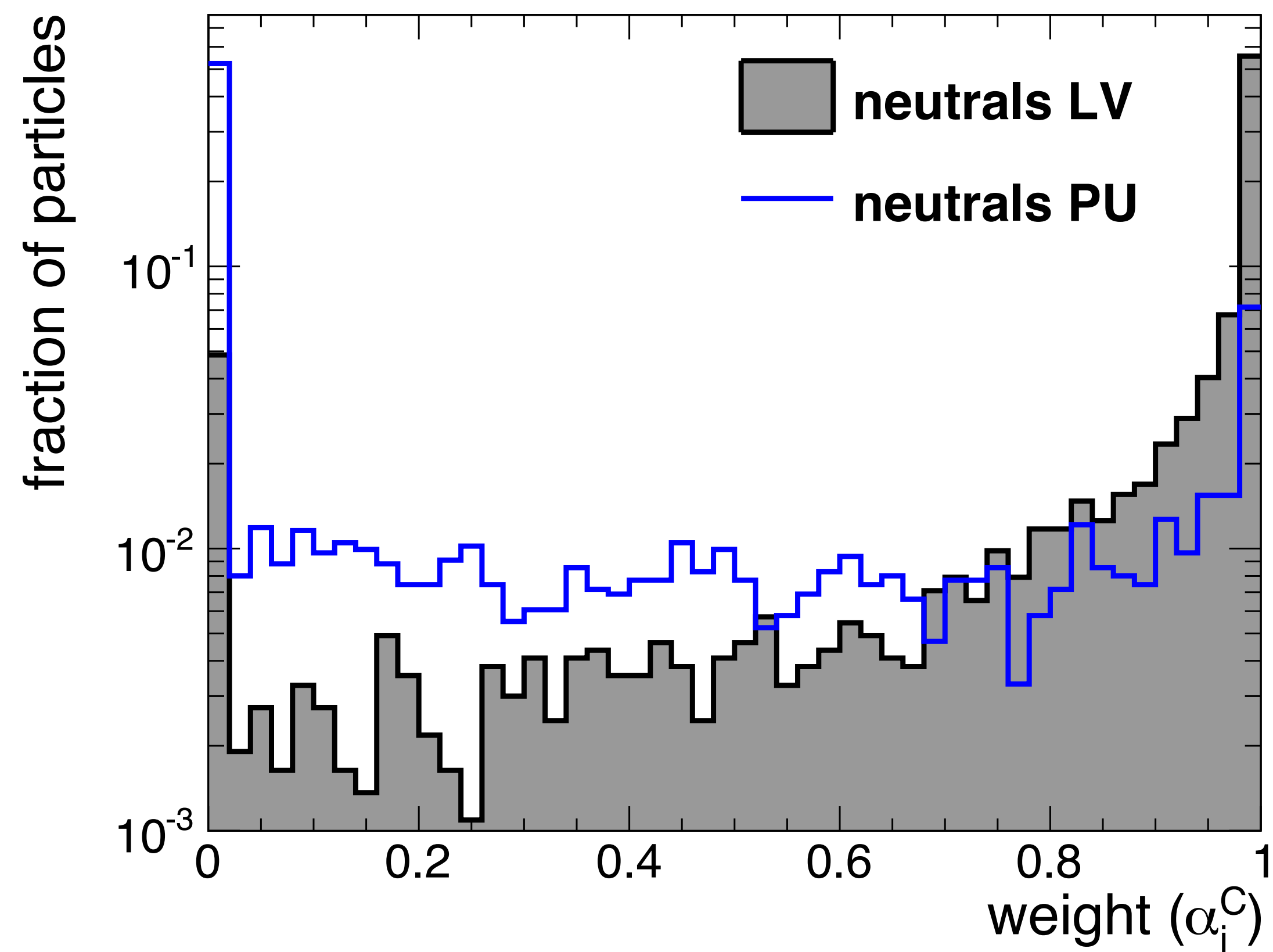
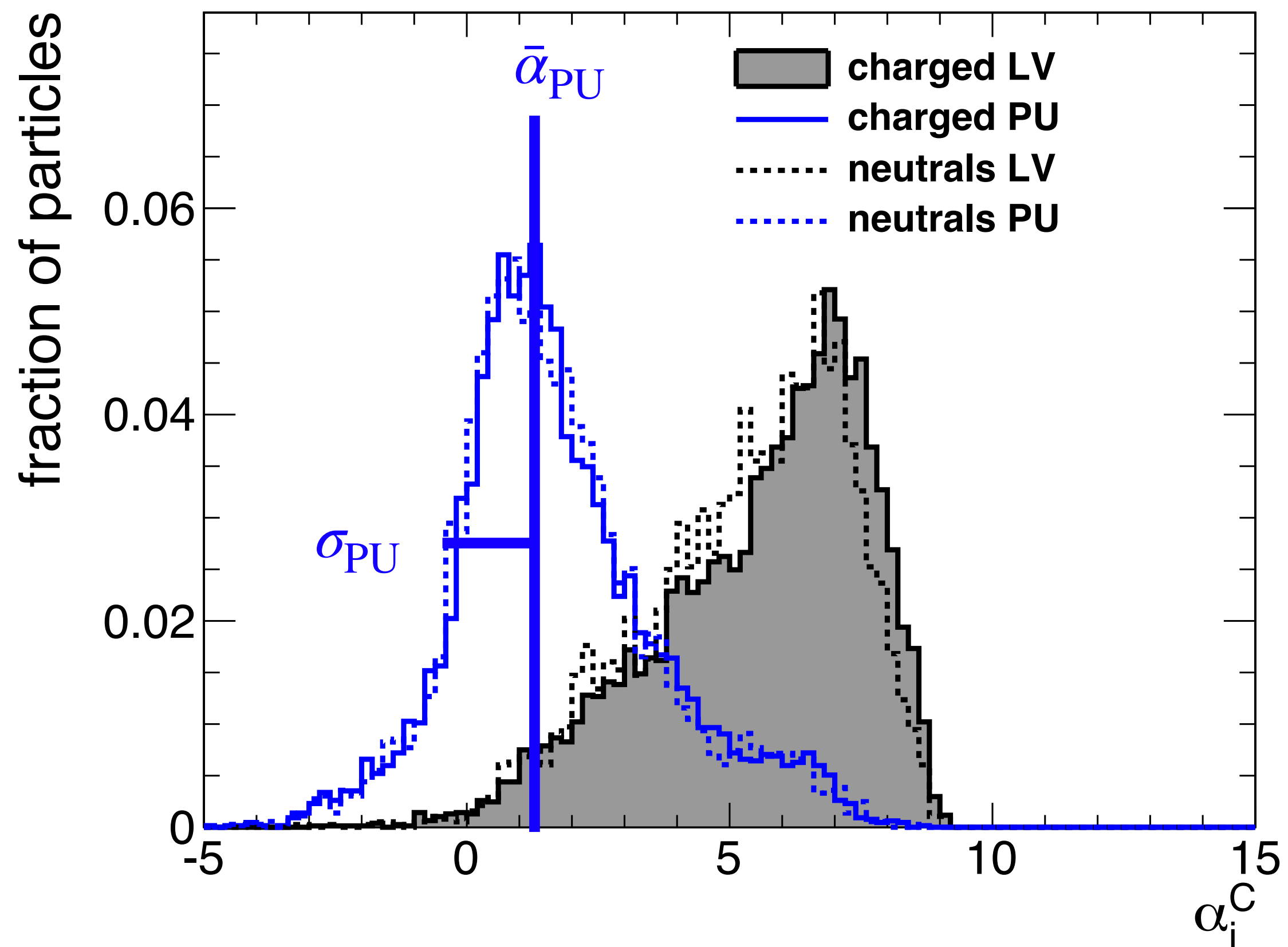


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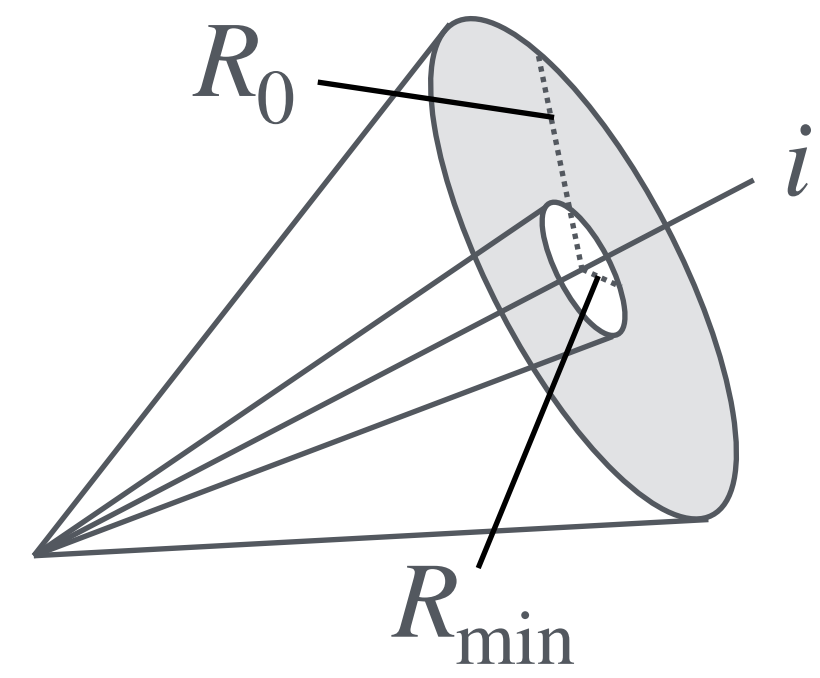
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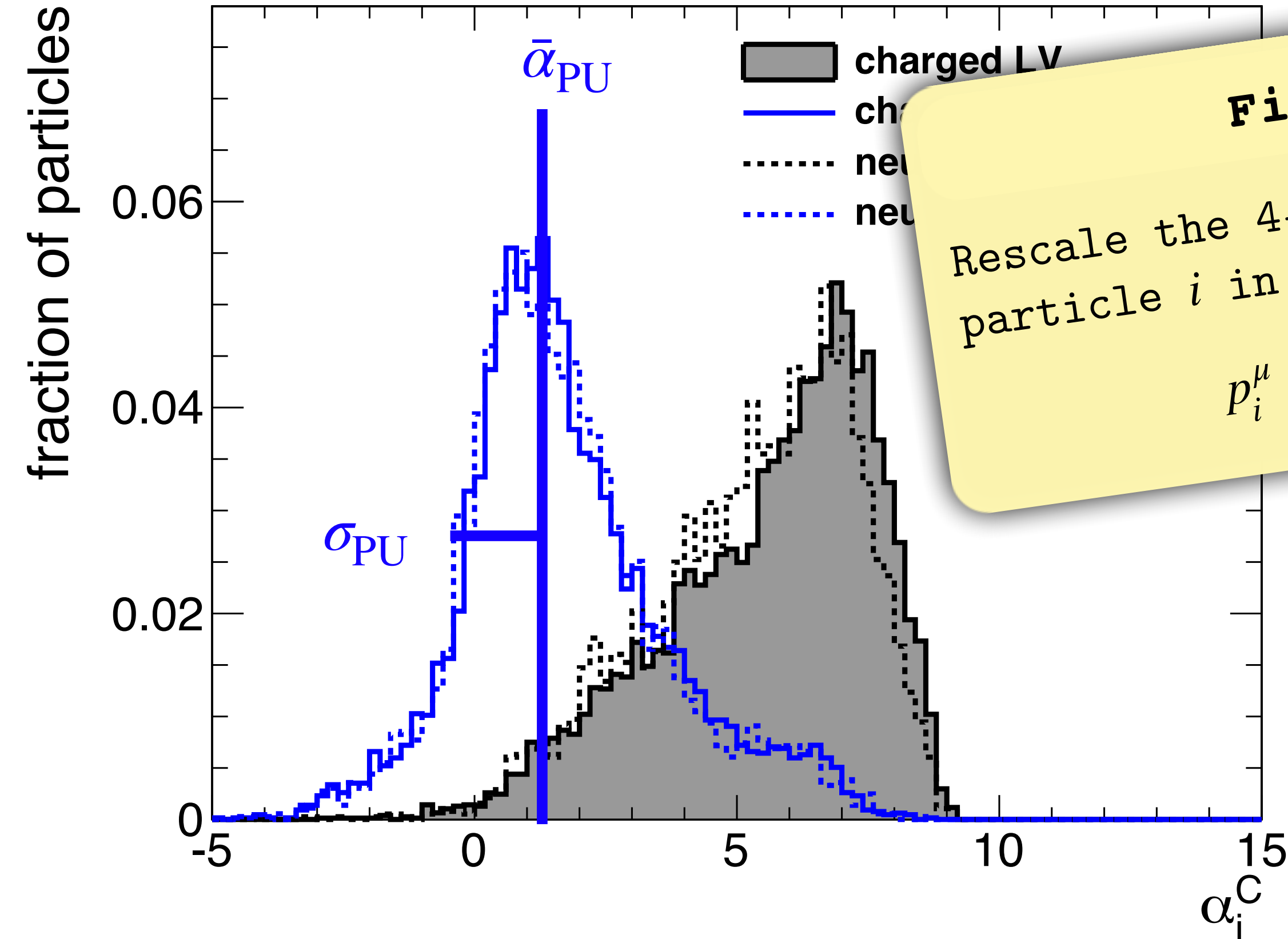
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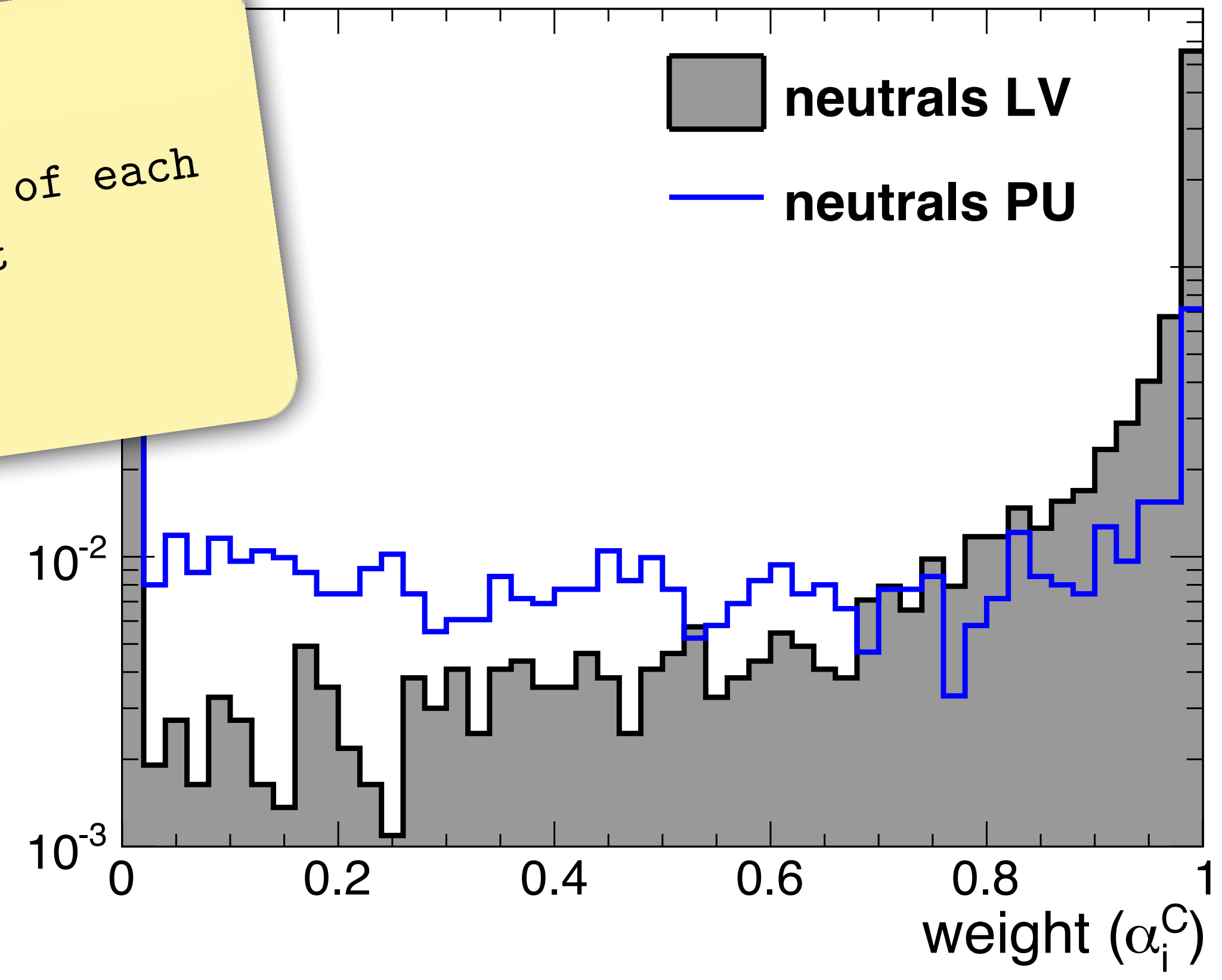
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Finally

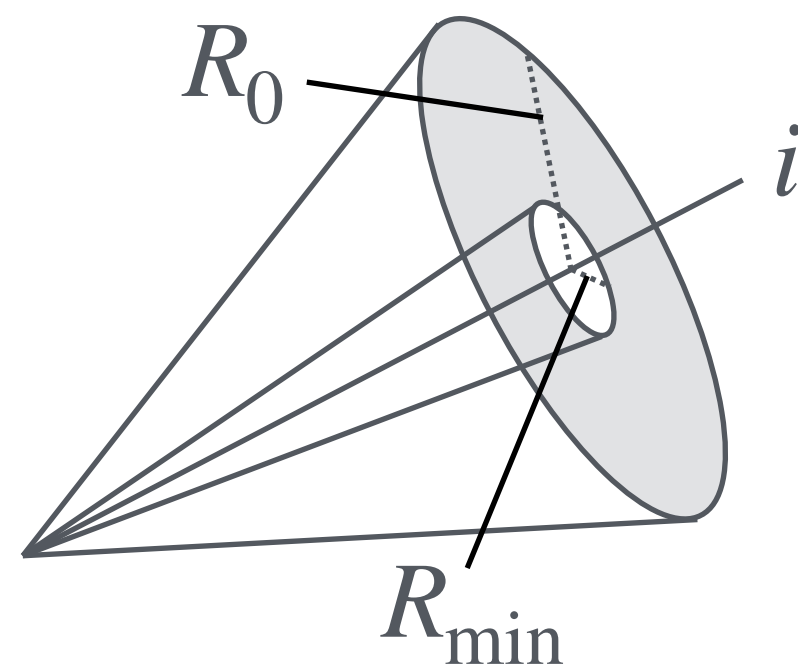
Rescale the 4-momentum of each particle i in the event

$$p_i^\mu \rightarrow w_i p_i^\mu$$


Pile Up Per Particle Identification

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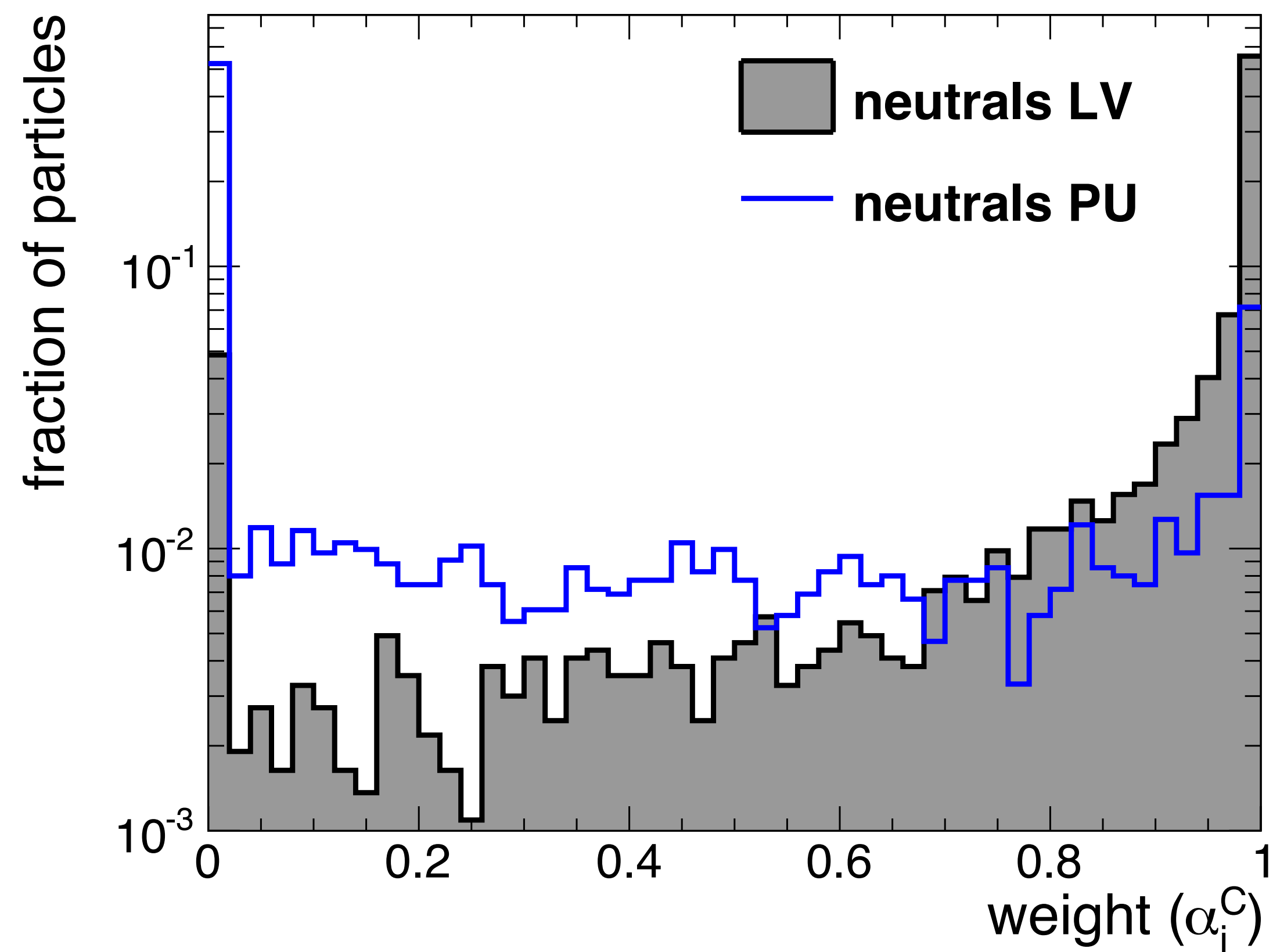
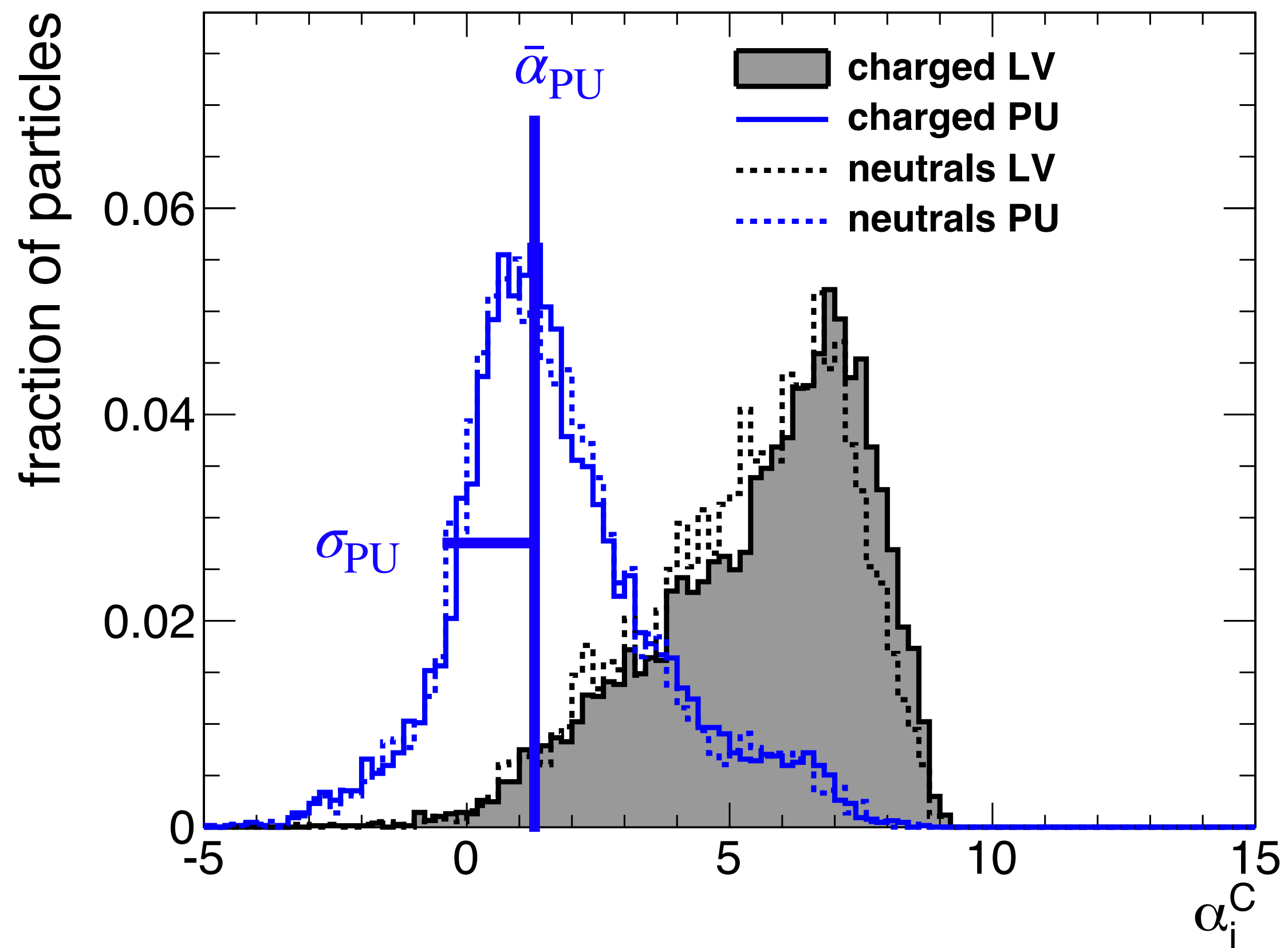


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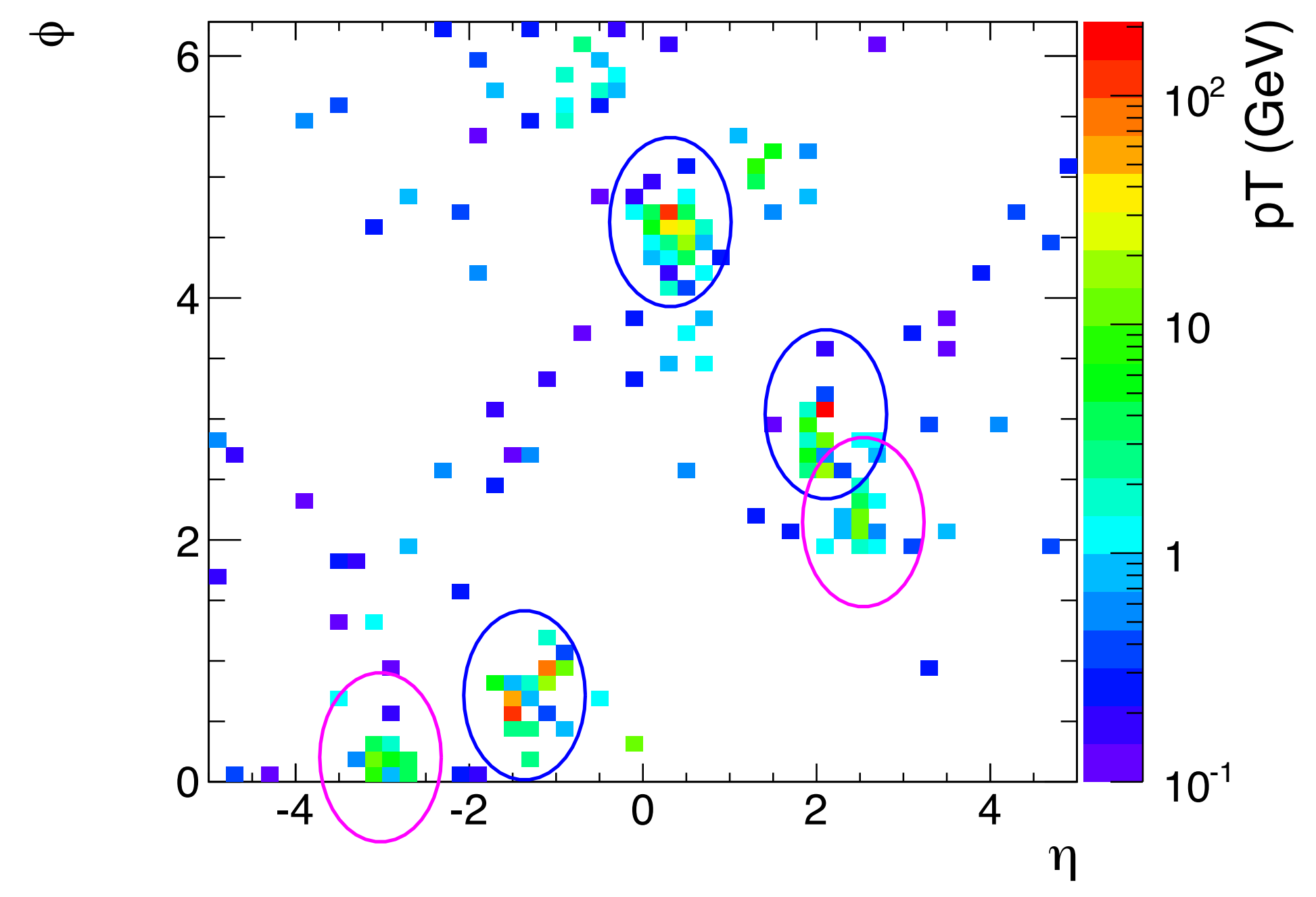
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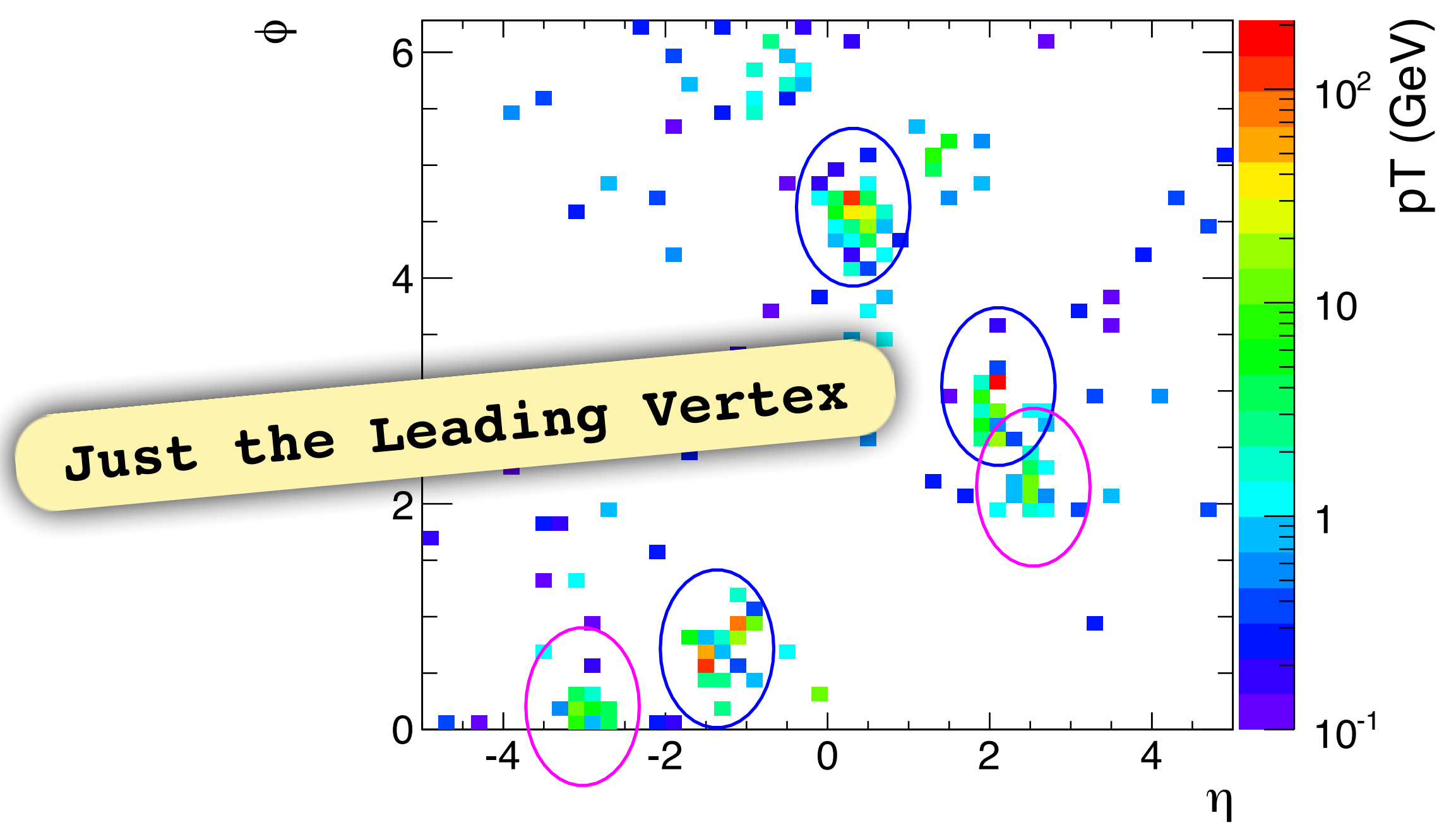


Pile Up Per Particle Identification

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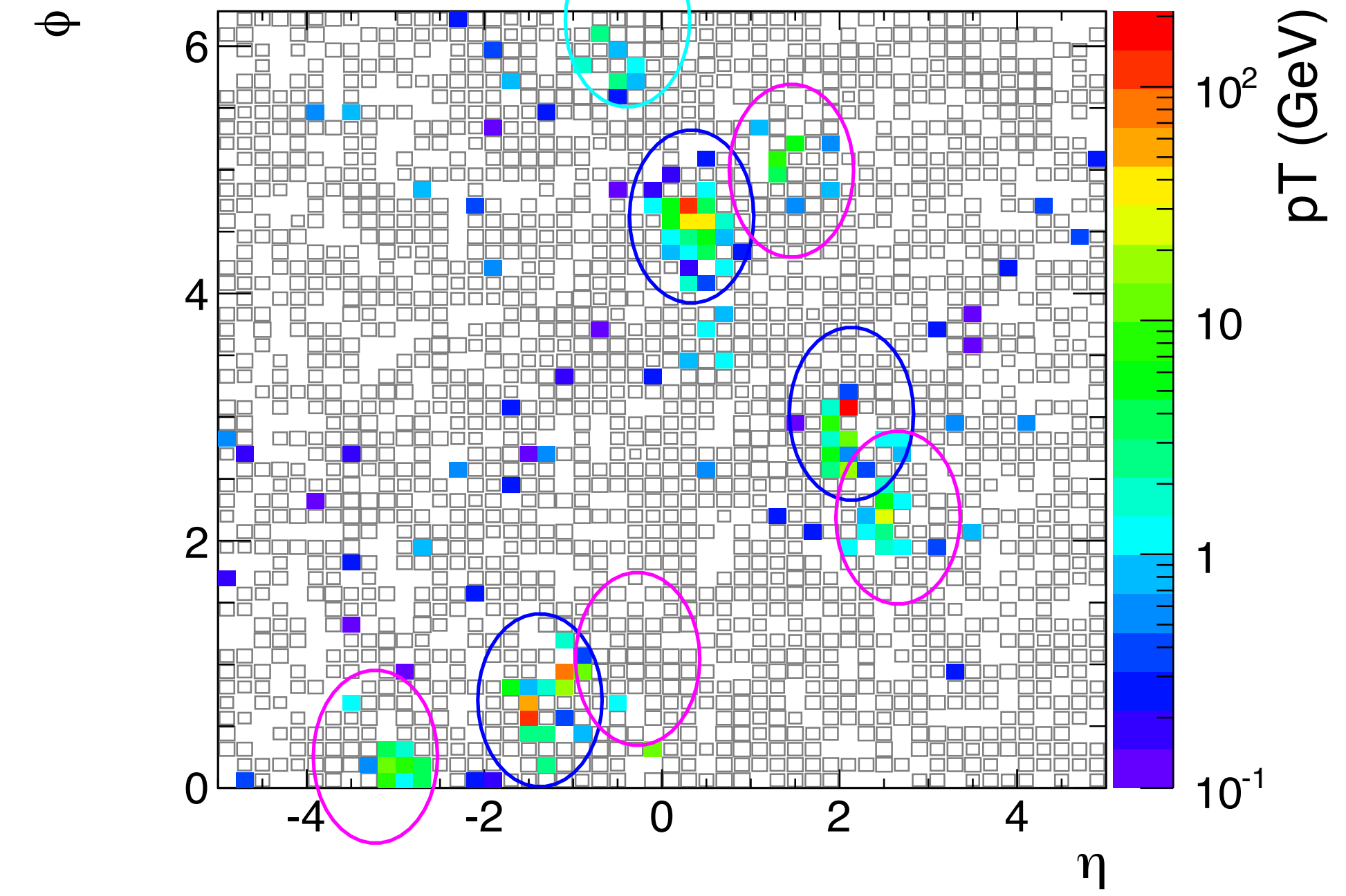
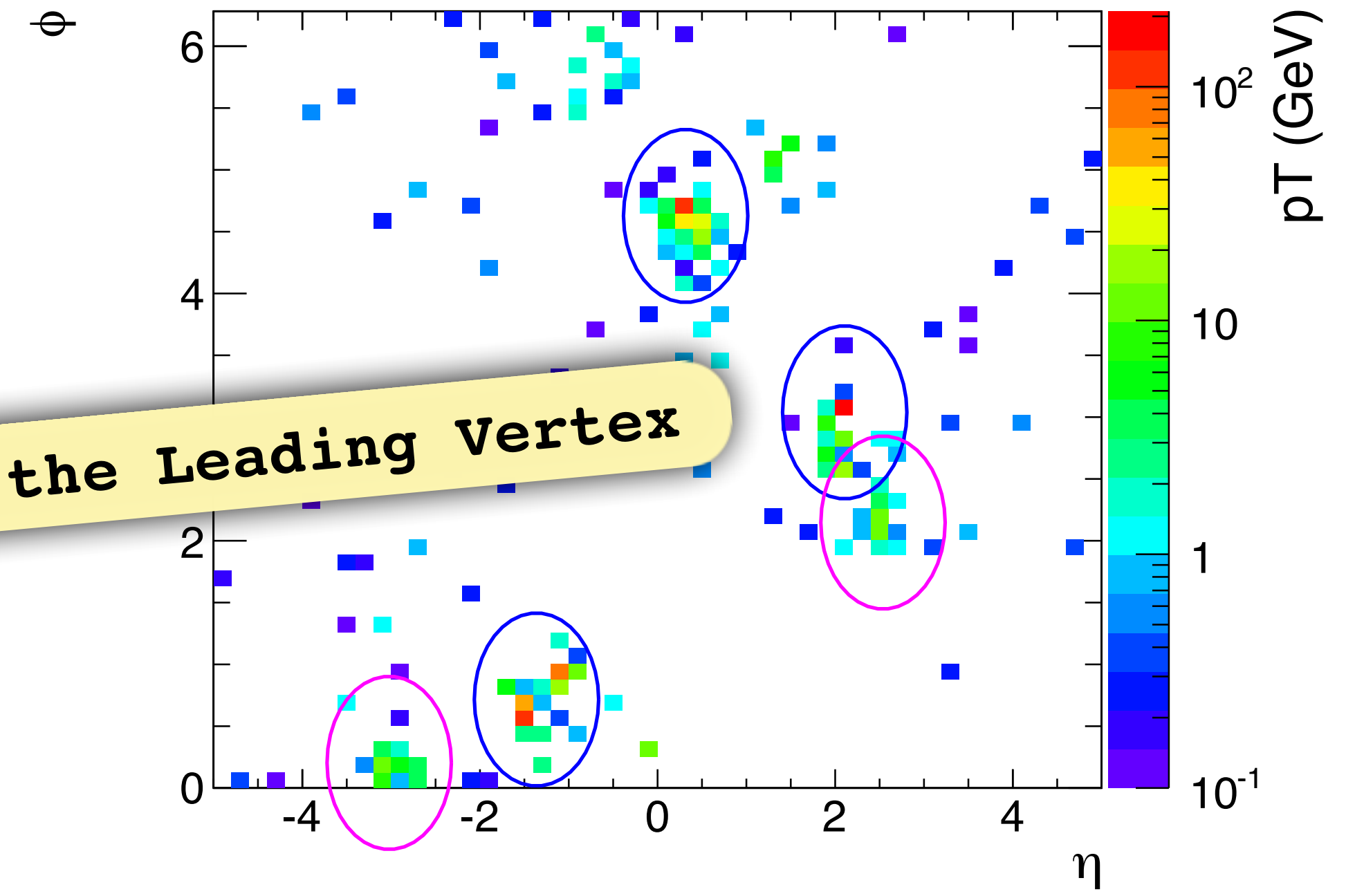


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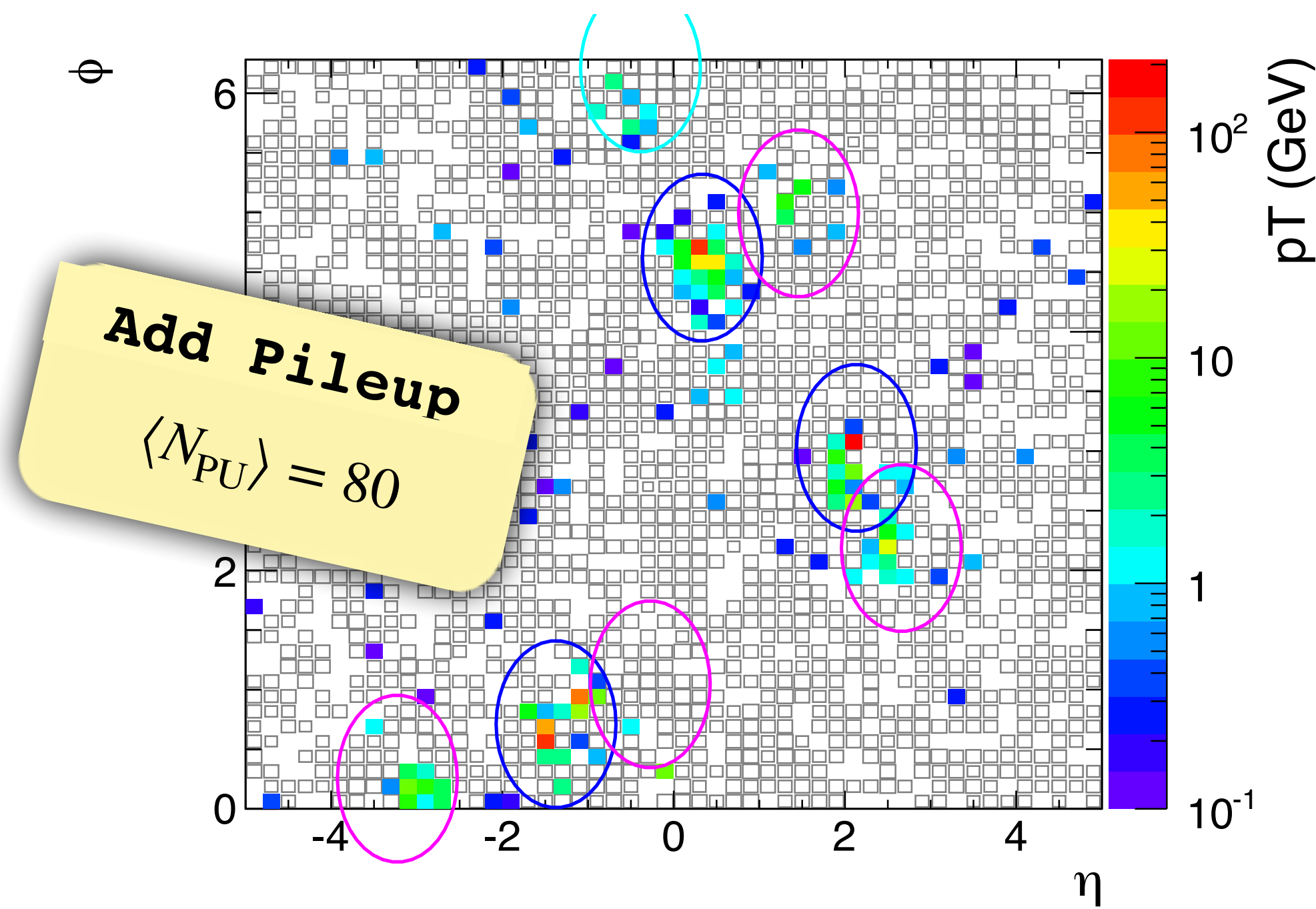
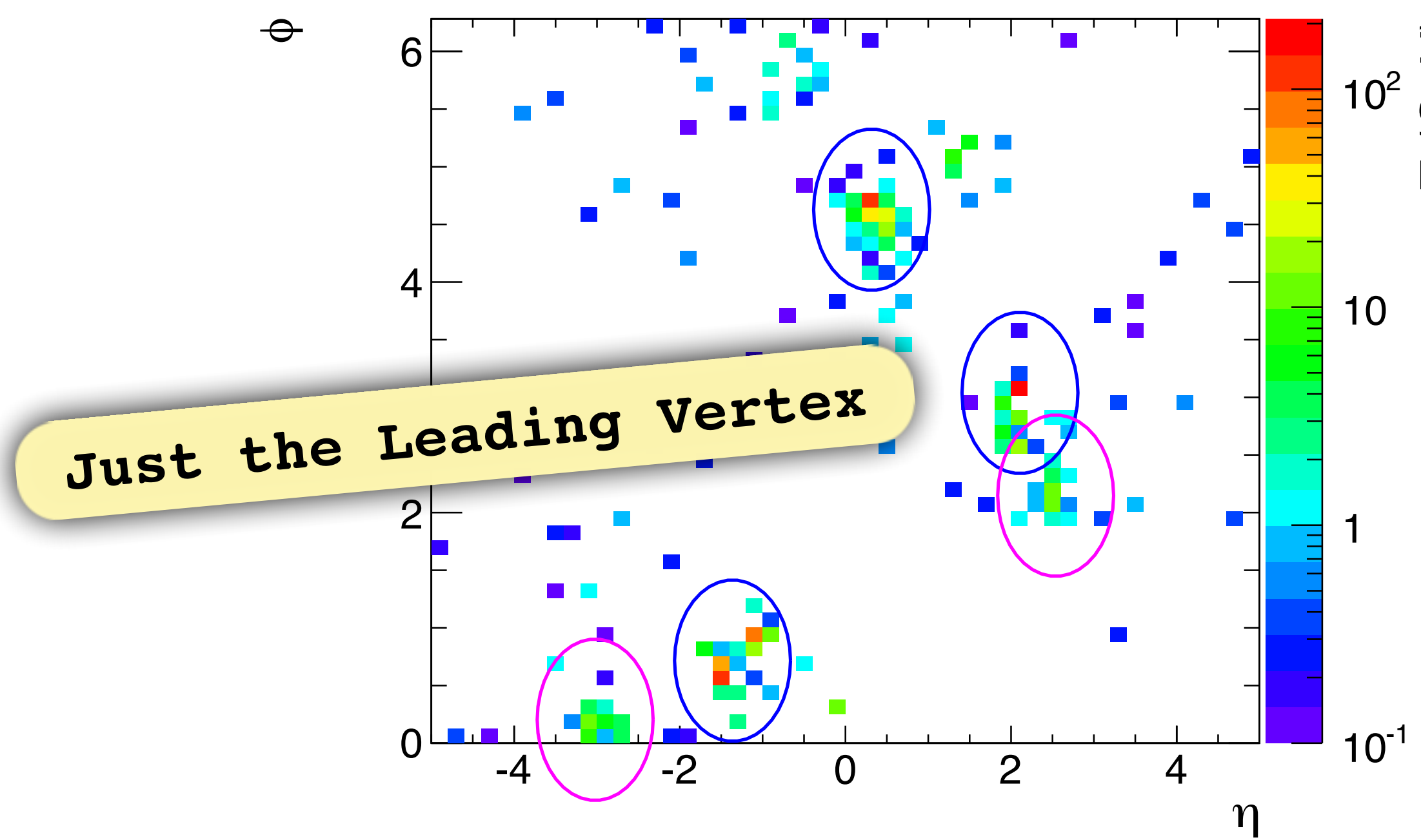


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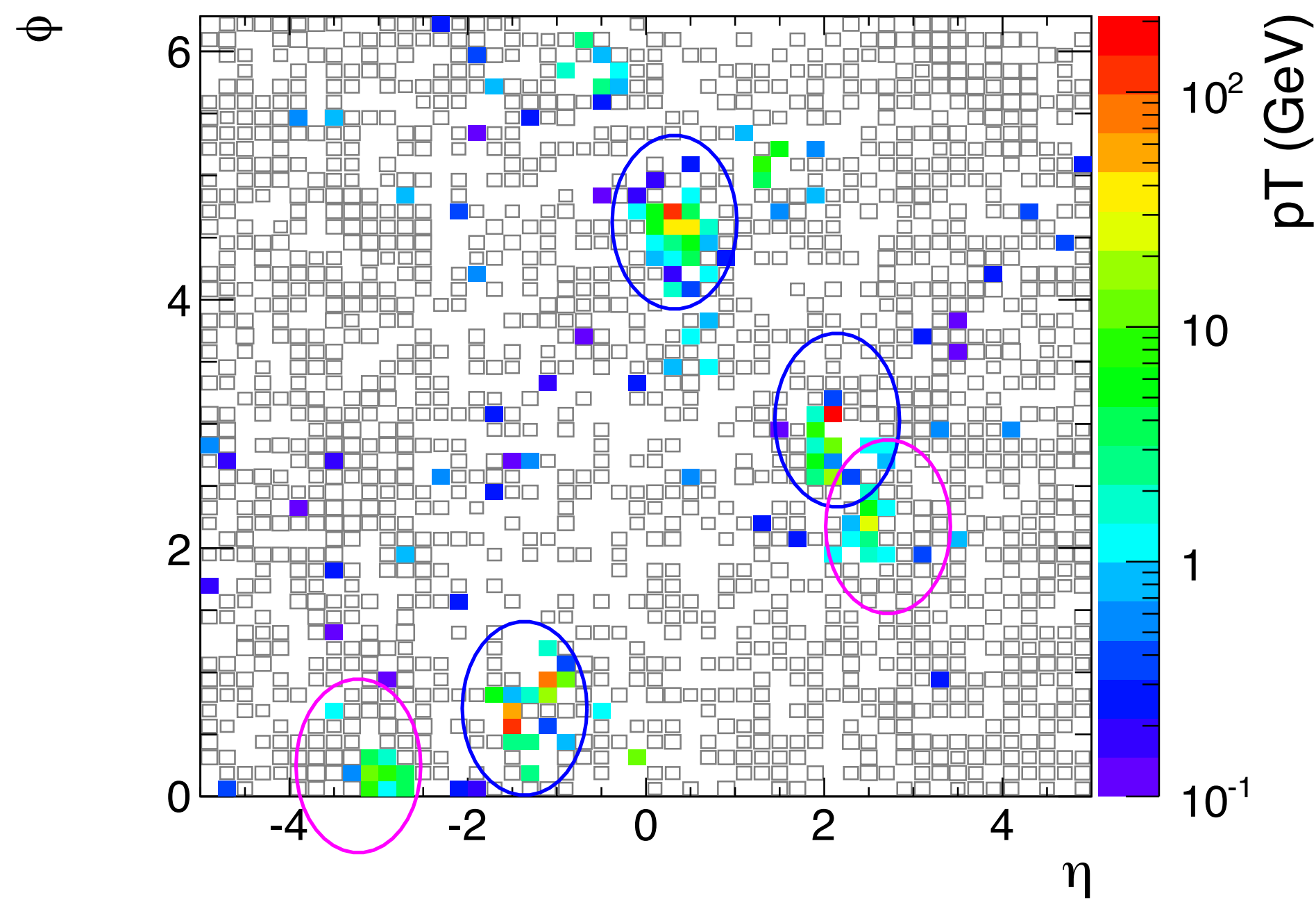
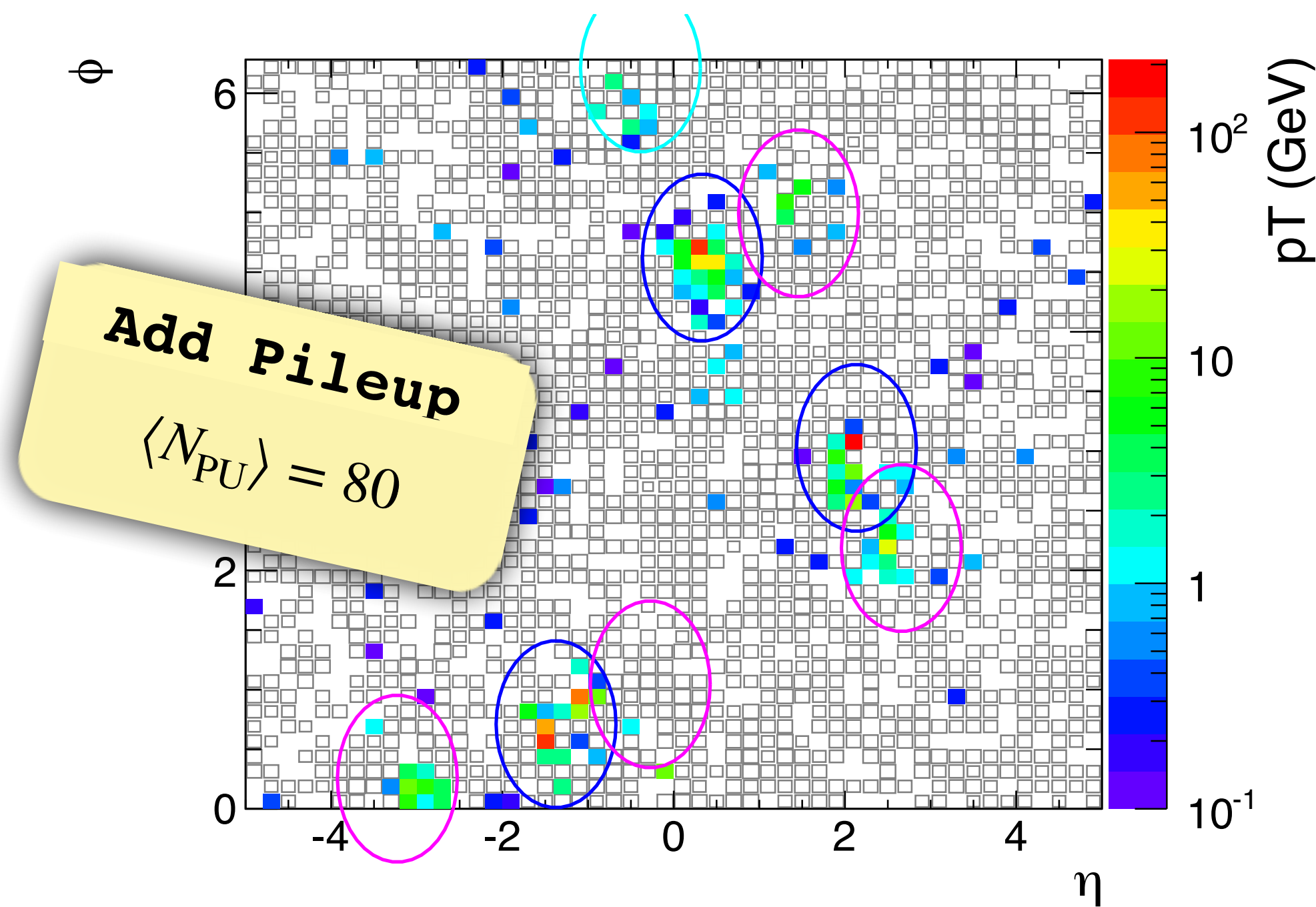
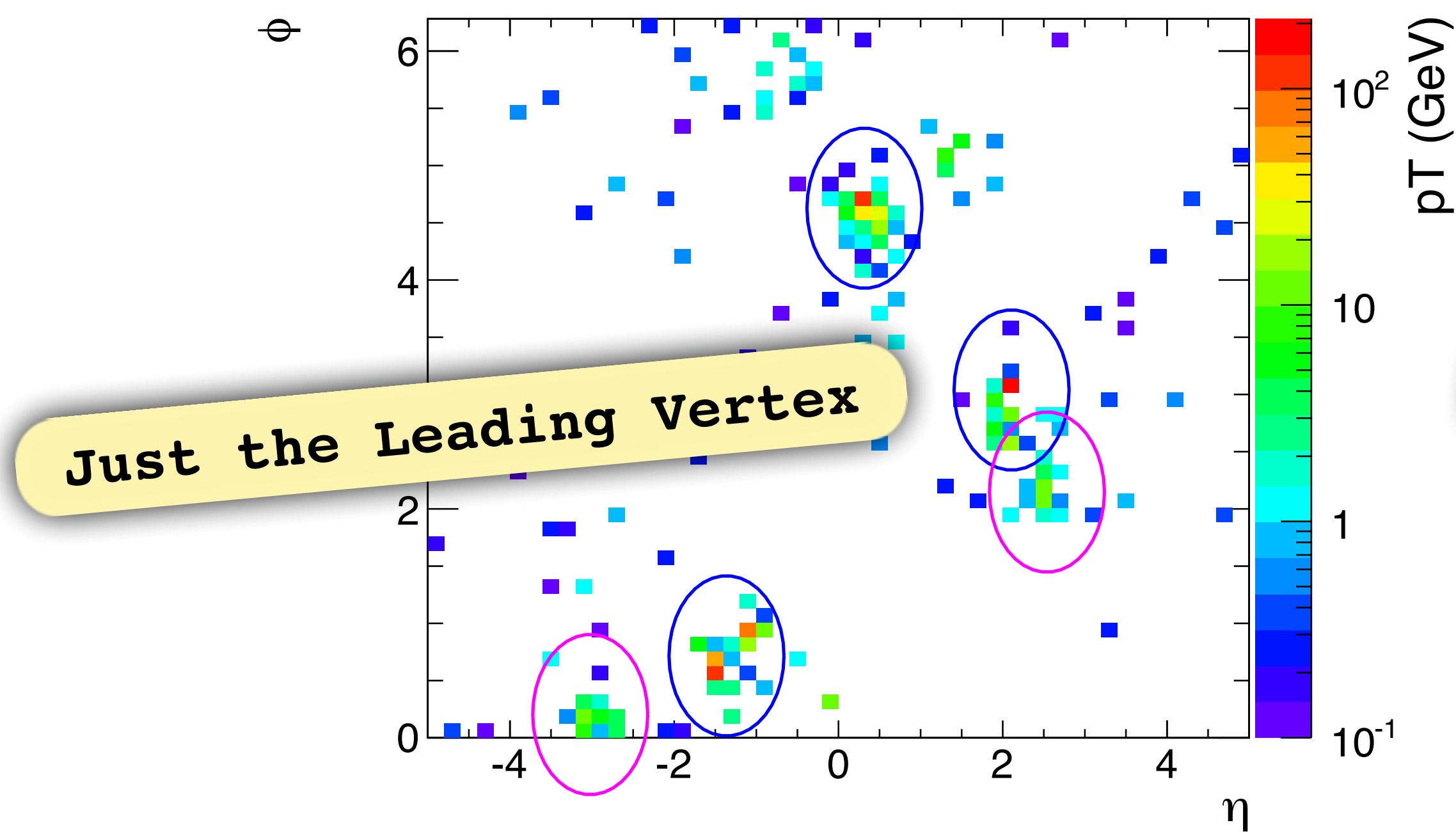
Just the Leading Vertex



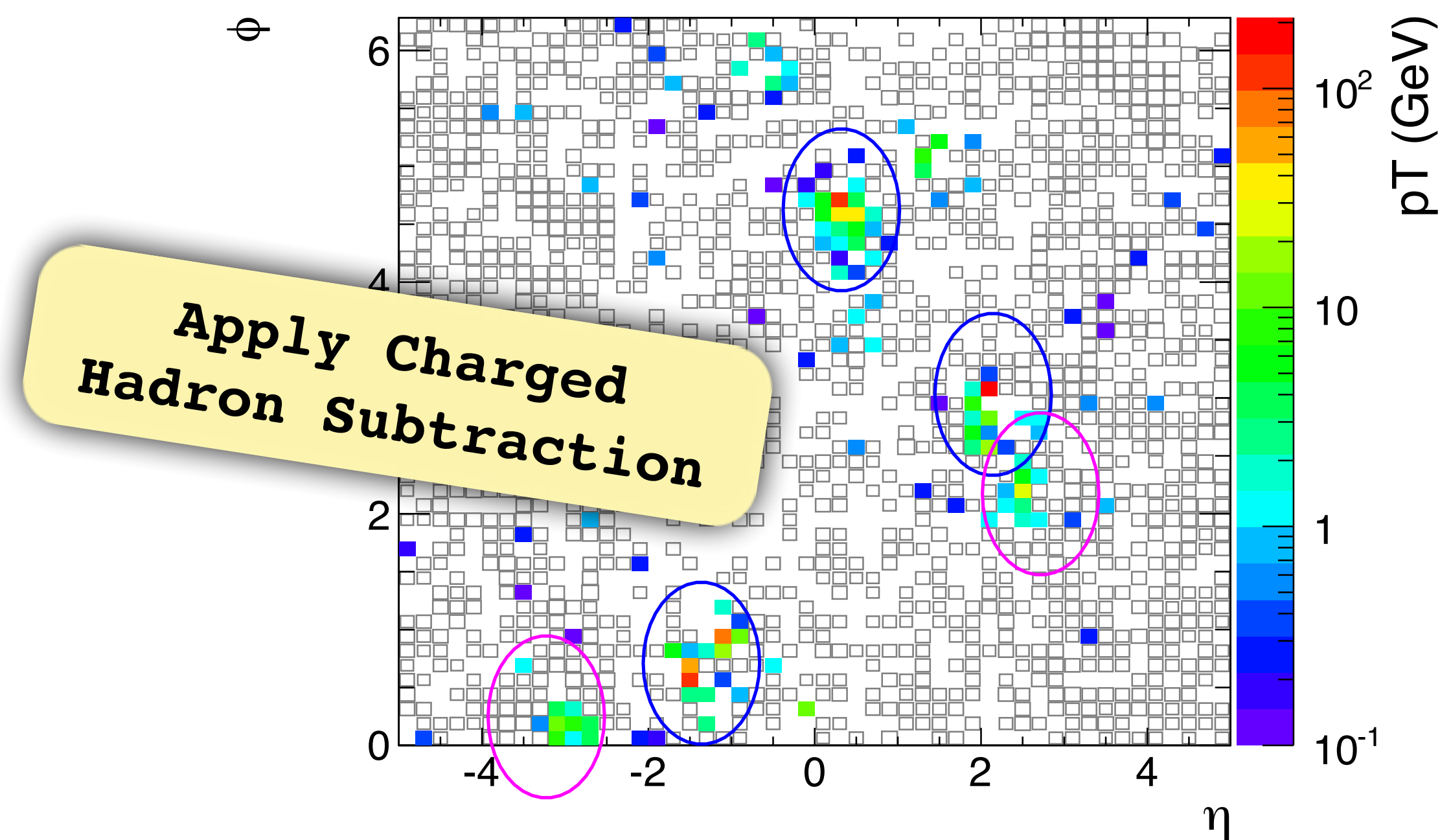
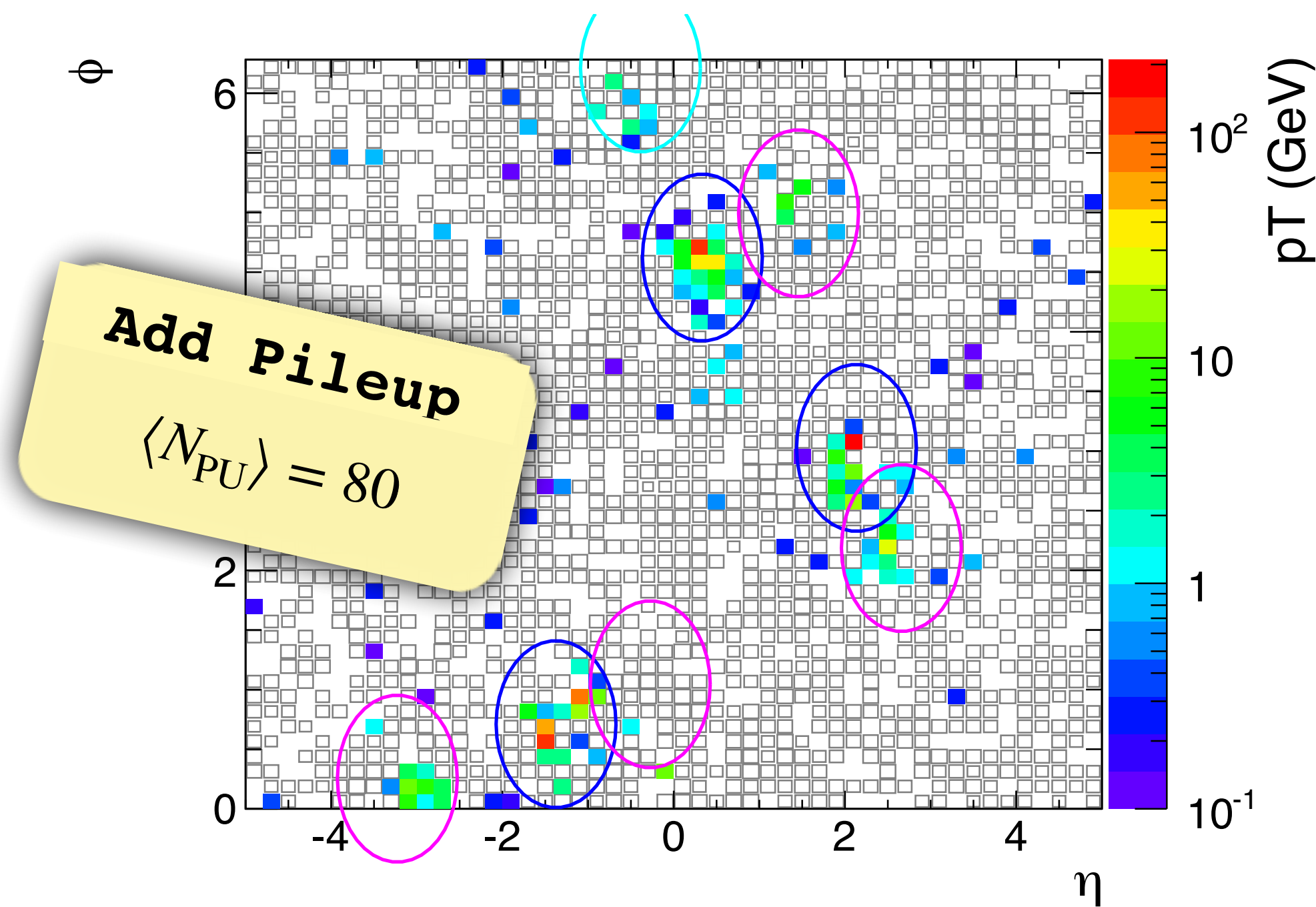
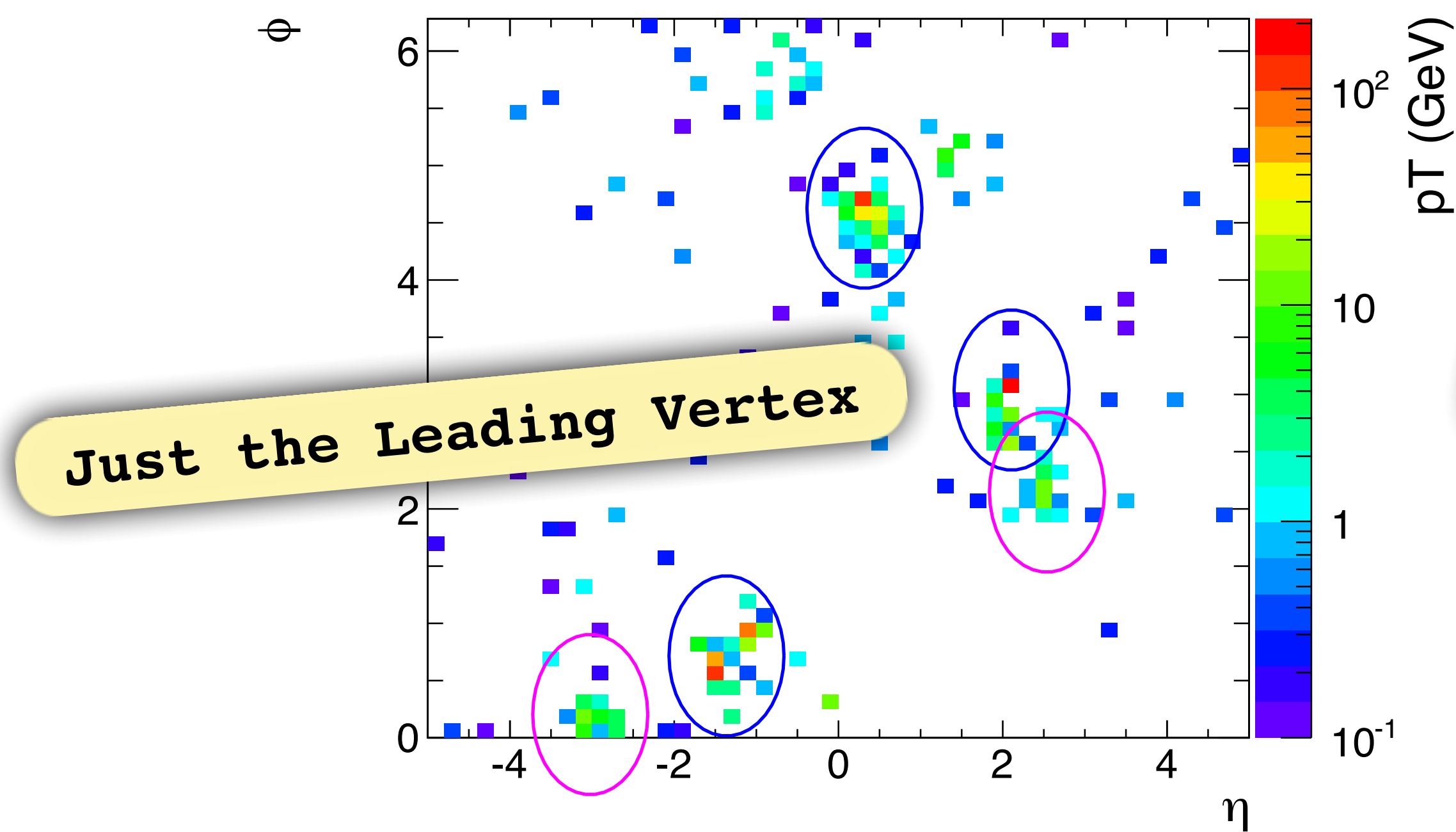
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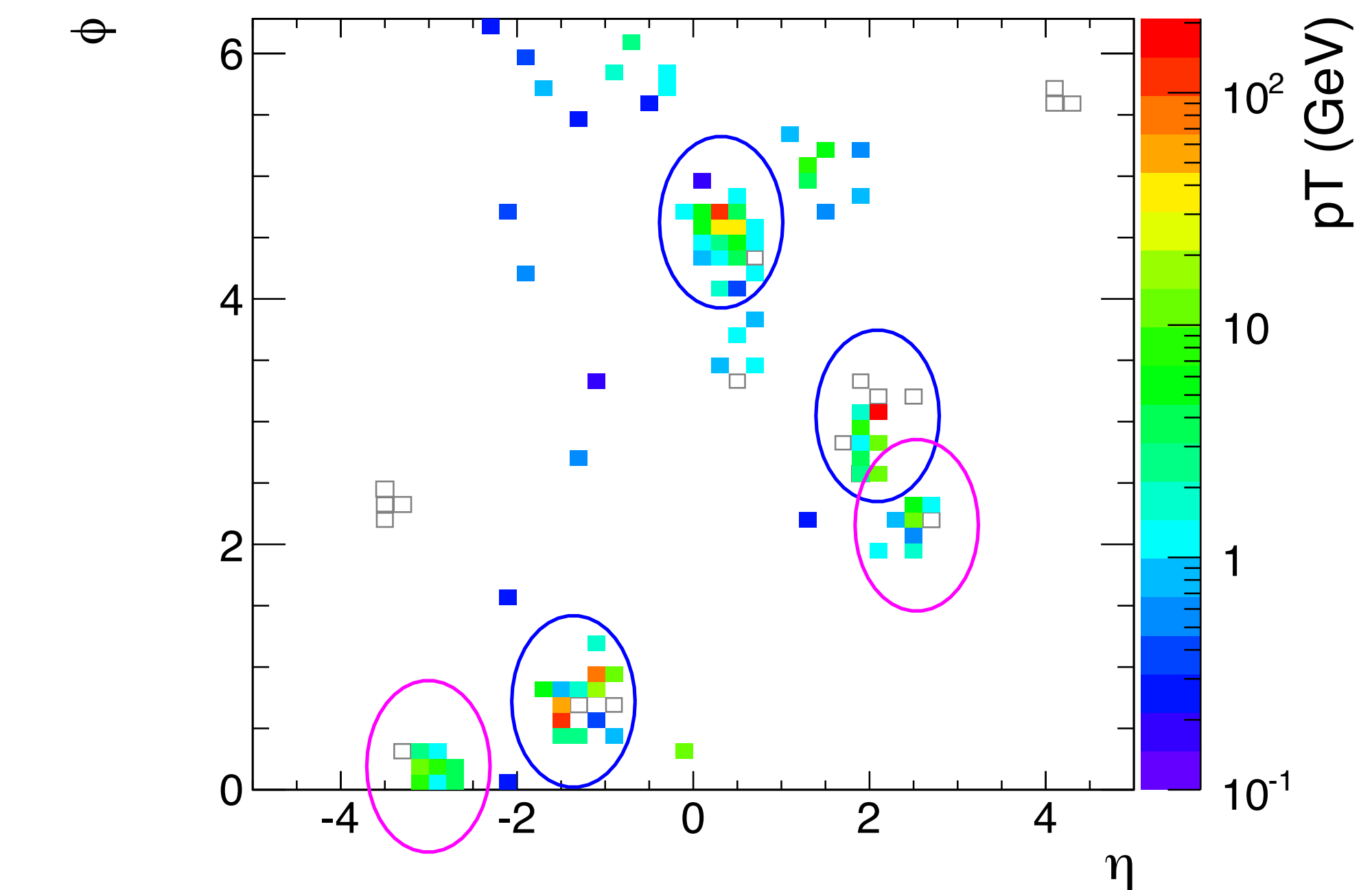
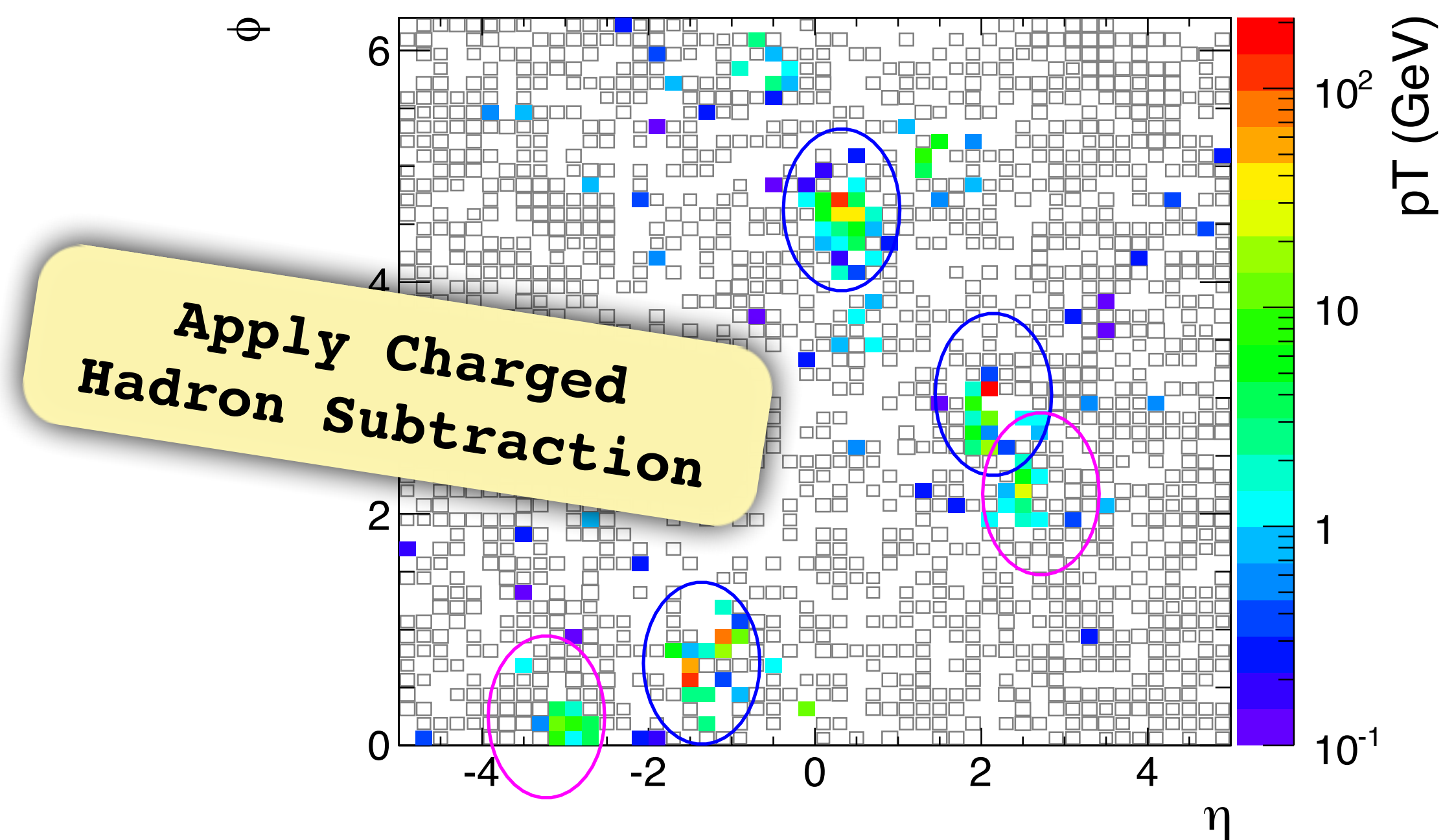
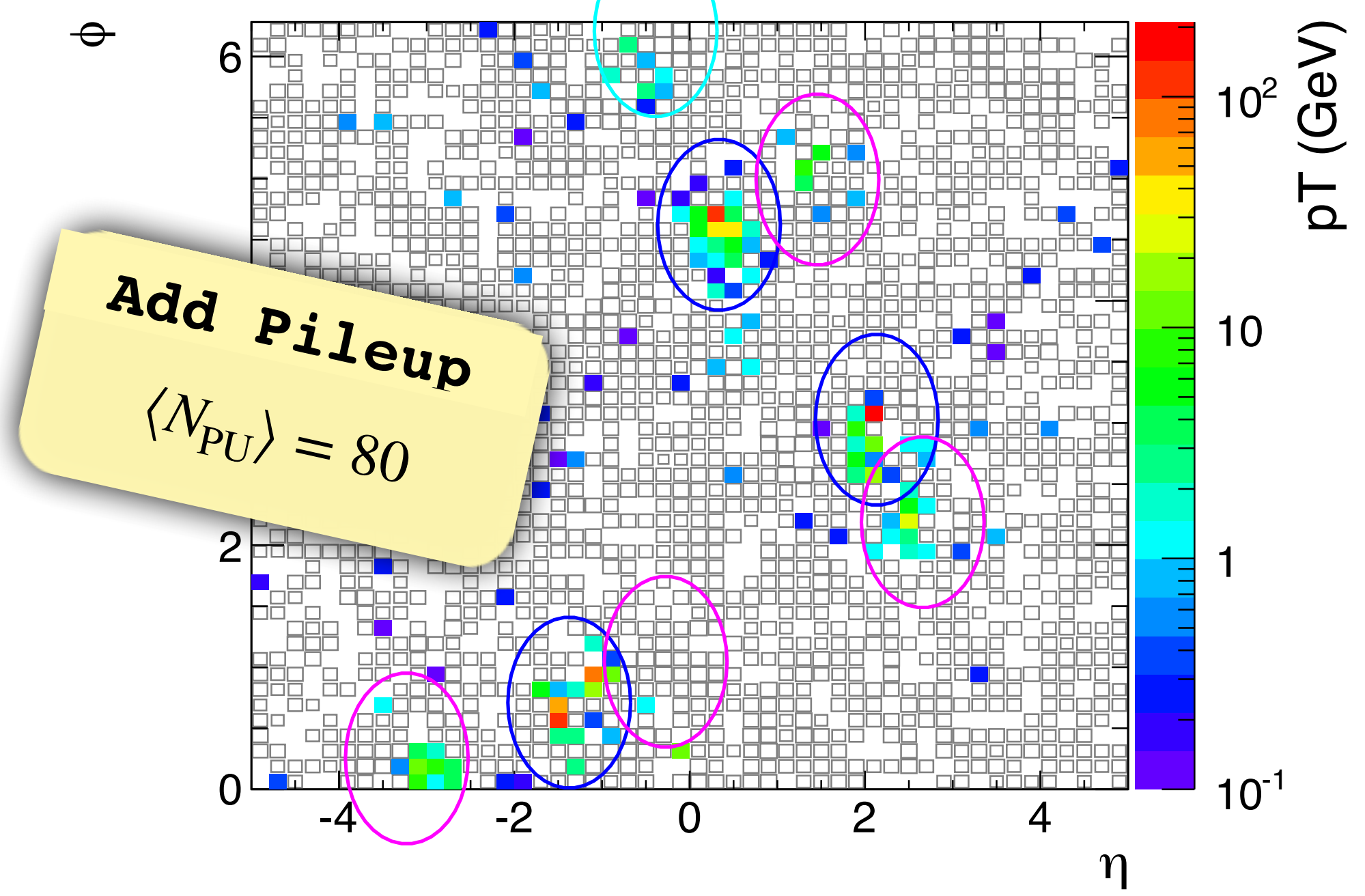
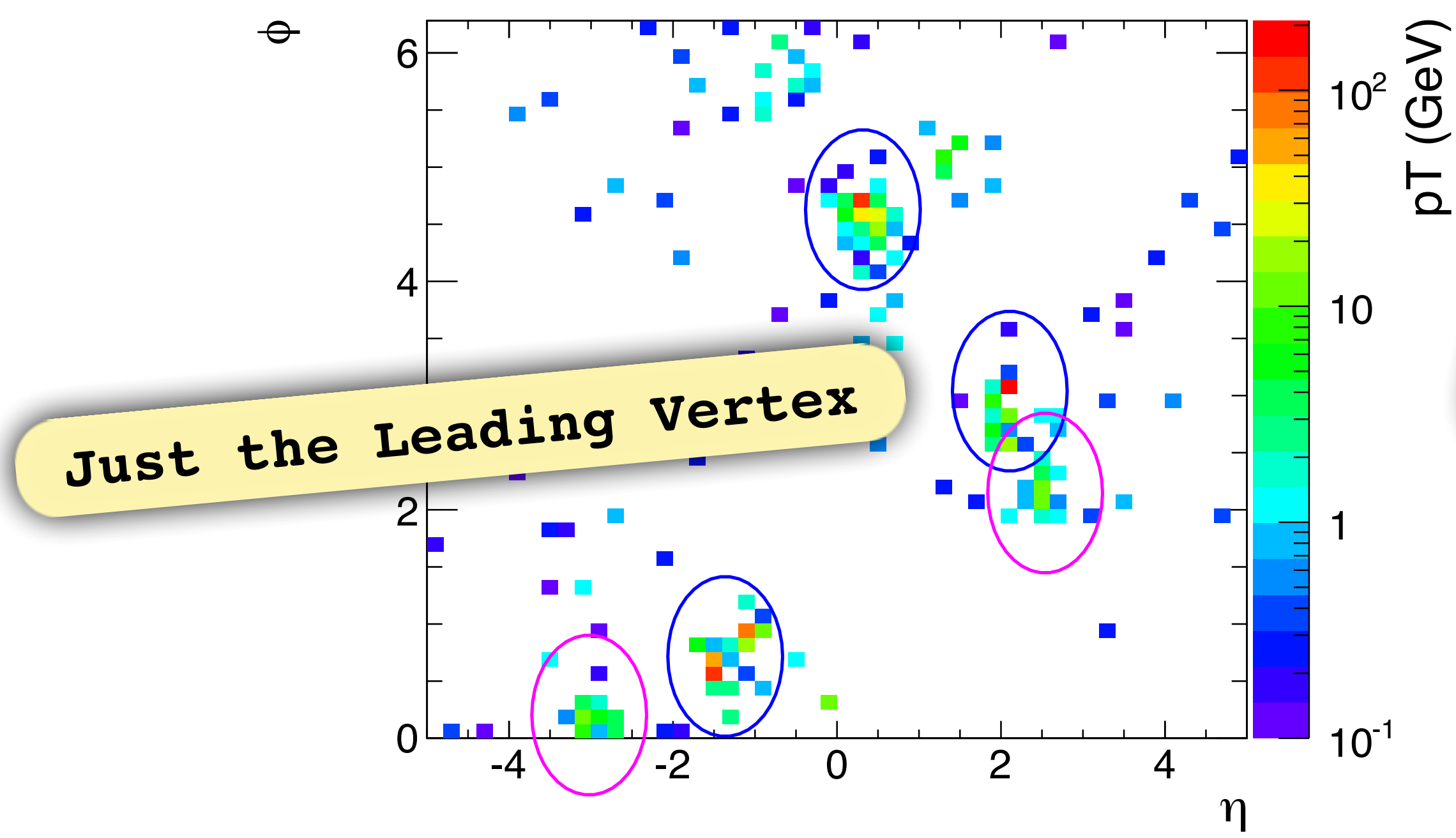
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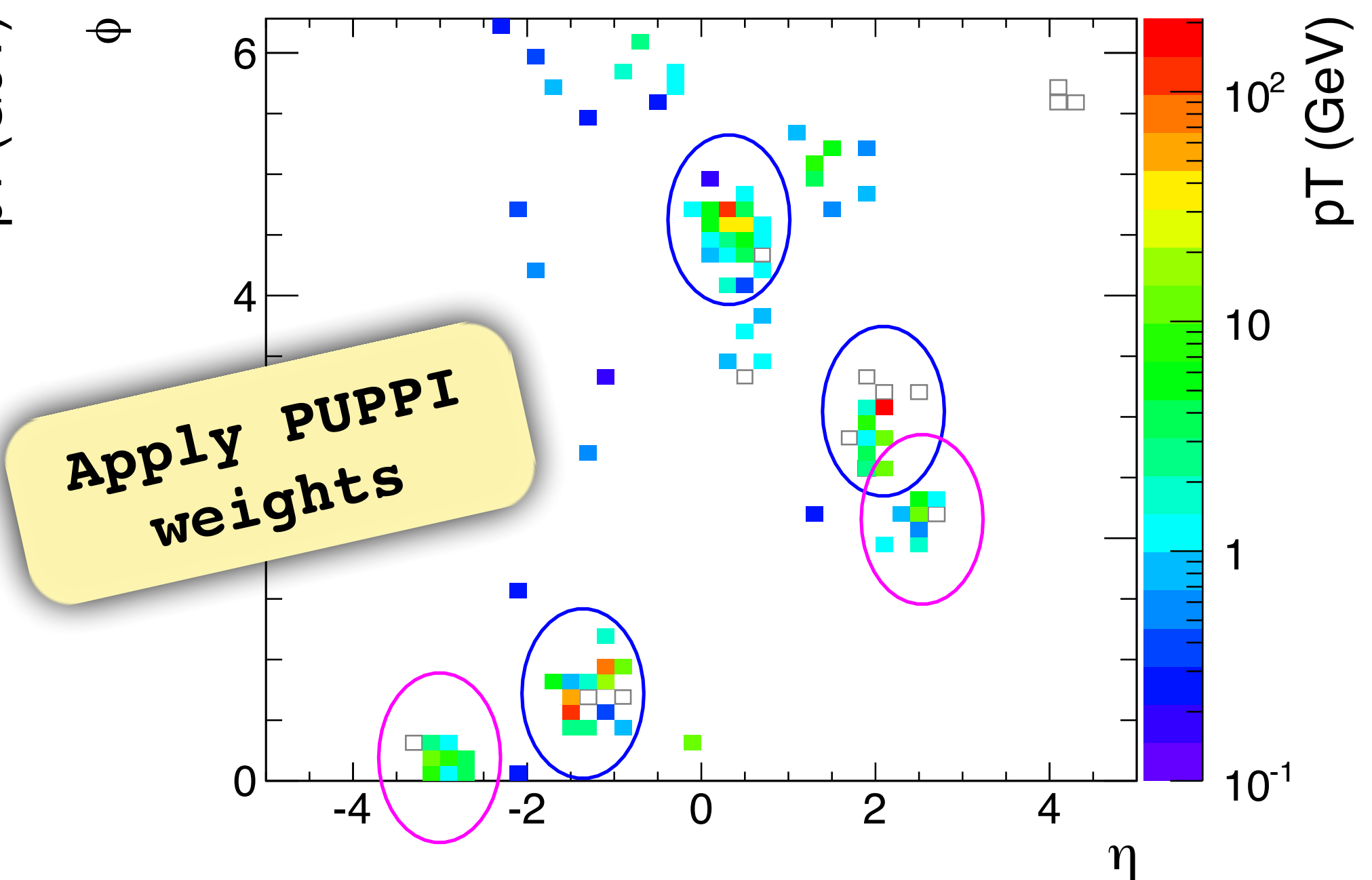
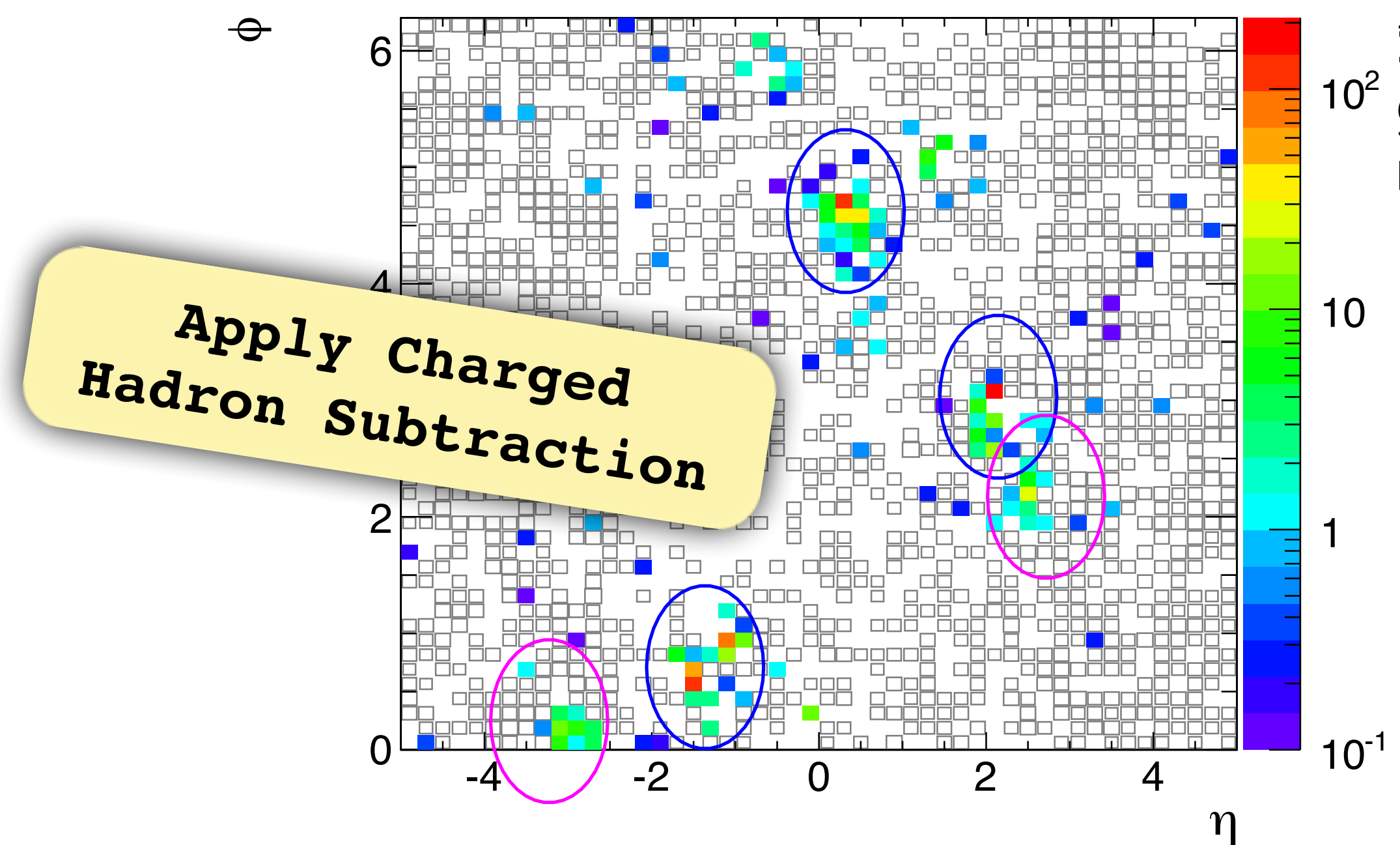
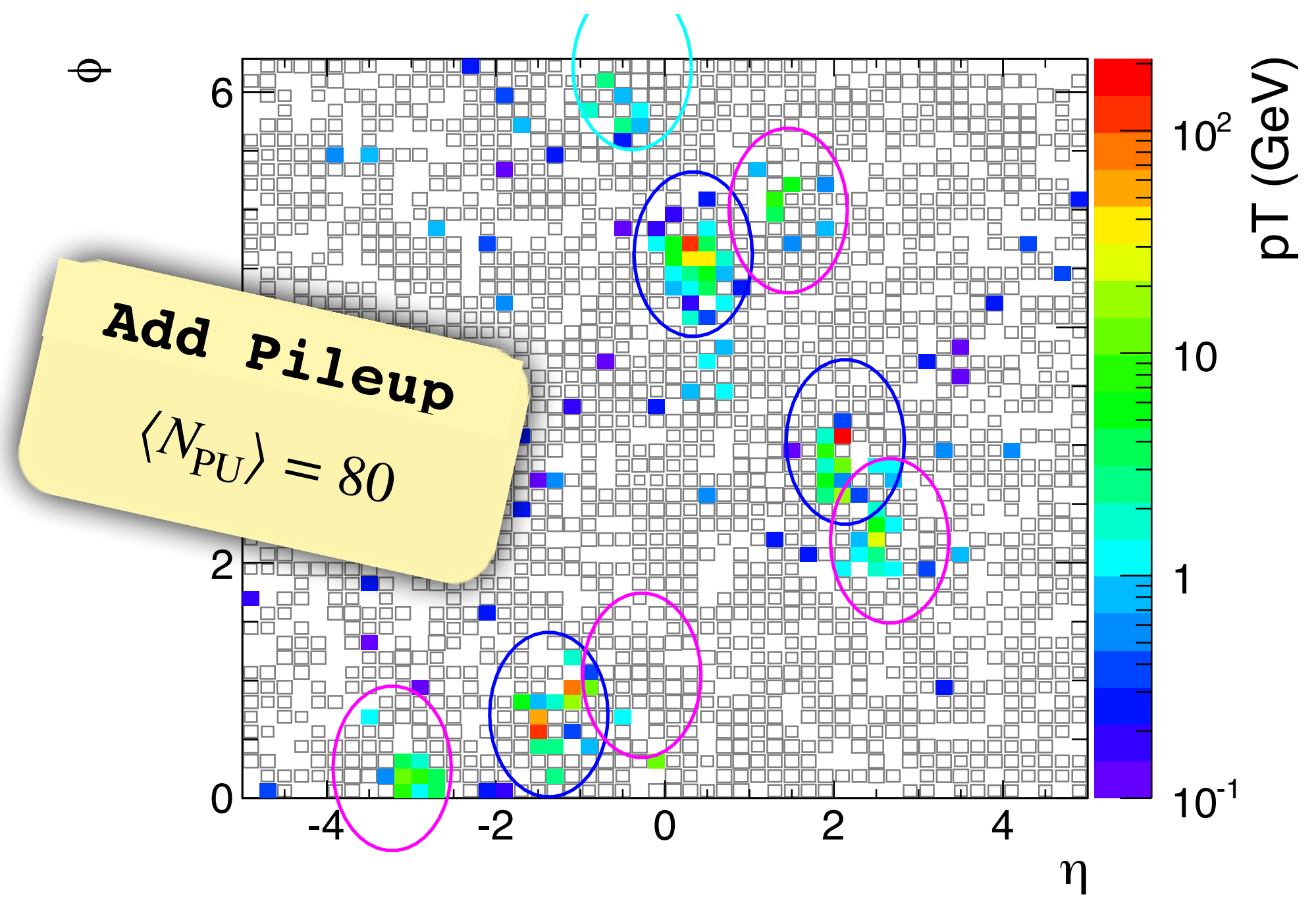
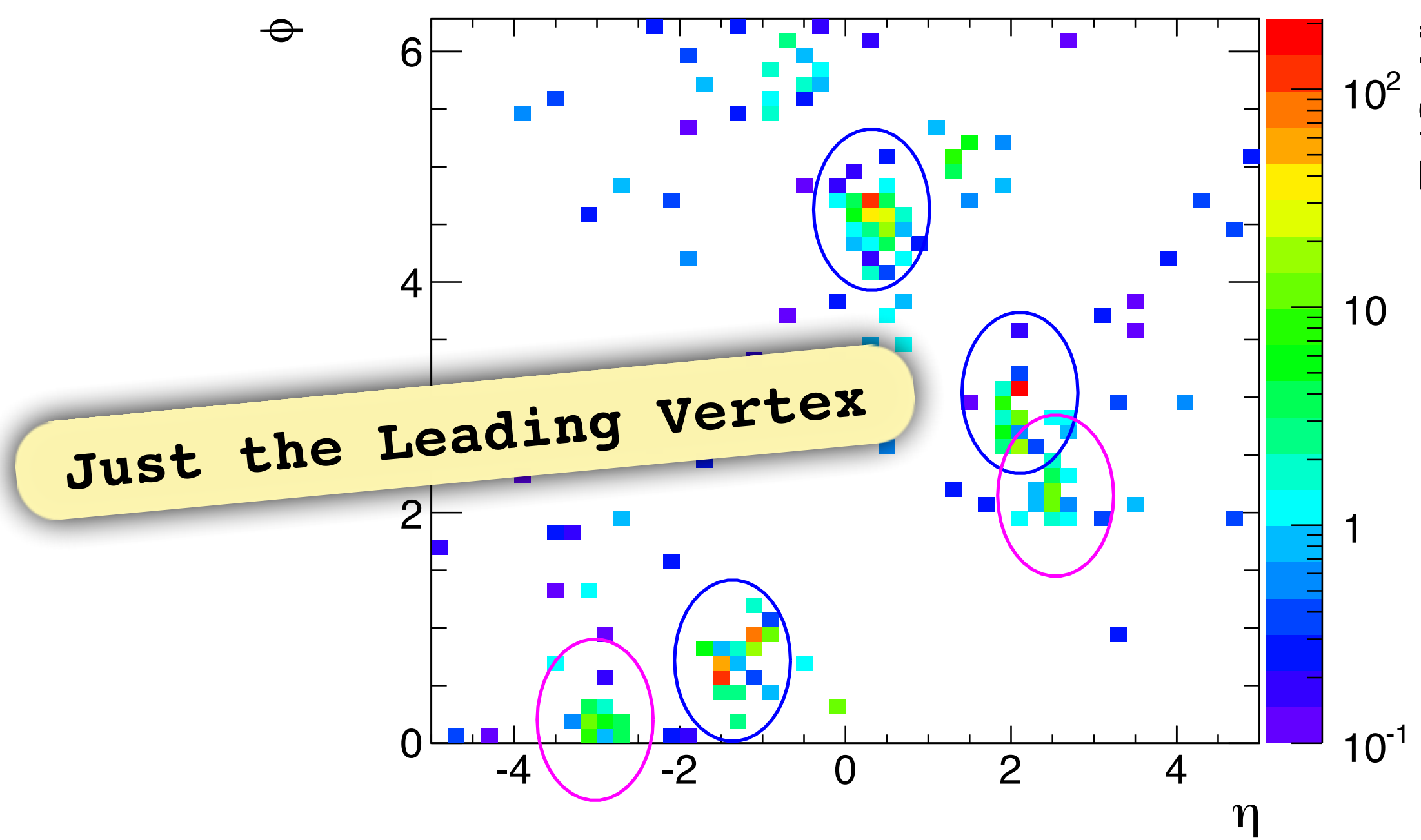
Pile Up Per Particle Identification



Pile Up Per Particle Identification



Pile Up Per Particle Identification



OK...I'll stop here