Event Reconstruction at the LHC II

FERMILAB-CERN
HADRON COLLIDER PHYSICS
SUMMER SCHOOL
2024

Richard Cavanaugh, Fermilab/UIC, HCPSS 31 July 2024

Recall: Jet Composition

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- Charged Particles: ~60%

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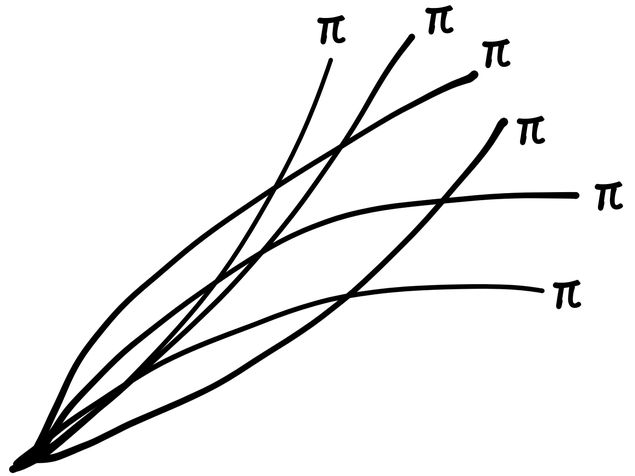
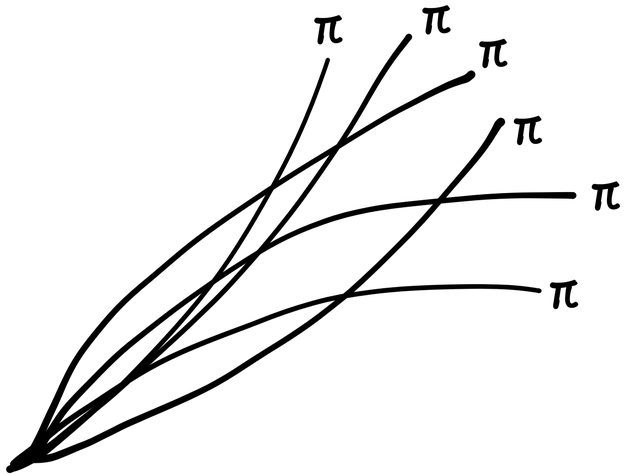


Recall: Jet Composition

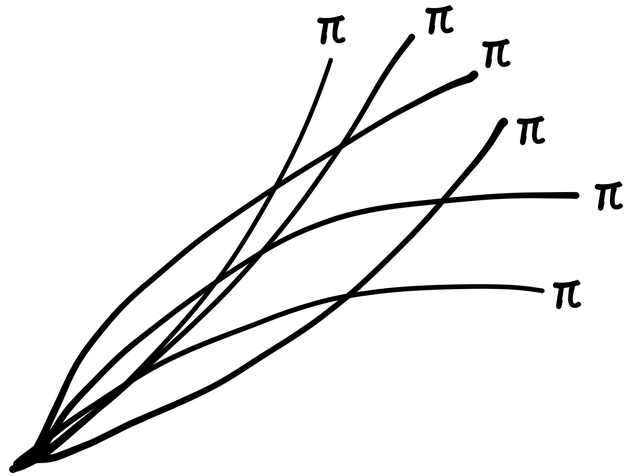
- Charged Particles: ~60% **Tracking Detectors**



Recall: Jet Composition

- Charged Particles: ~60% **Tracking Detectors**

- Photons: ~25%



Recall: Jet Composition

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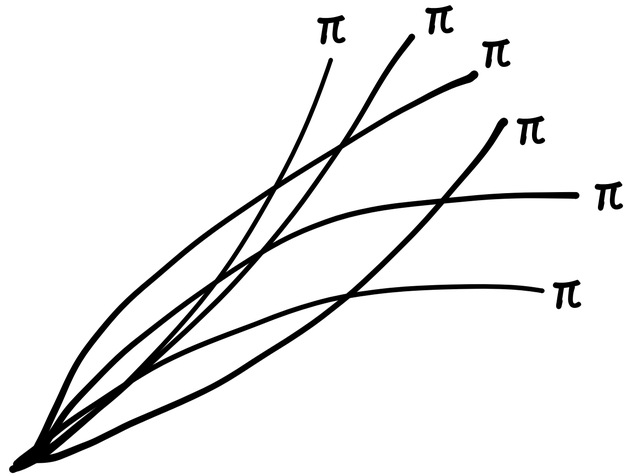

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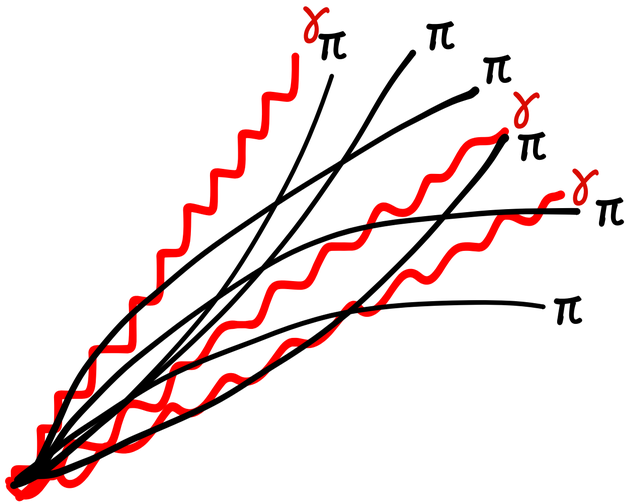

Recall: Jet Composition

- Charged Particles: ~60%

Tracking Detectors

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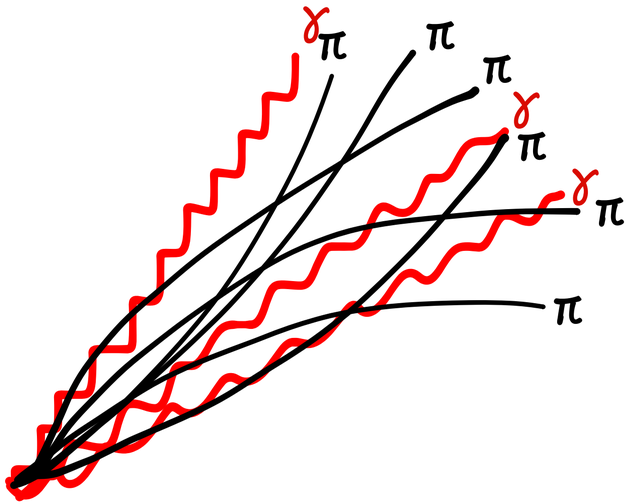
EM Calorimeters

- Long-lived Neutral Hadrons: ~10%



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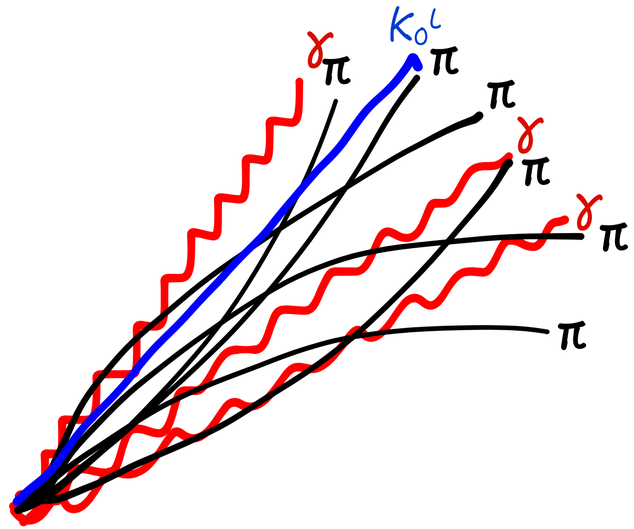

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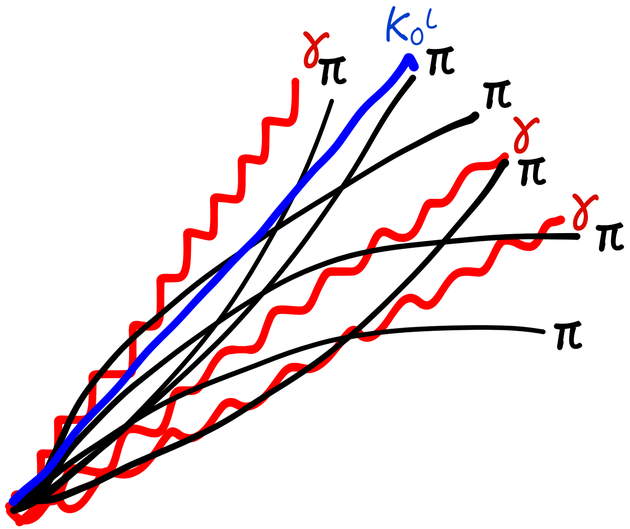
HAD Calorimeters



Recall: Jet Composition

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EM Calorimeters

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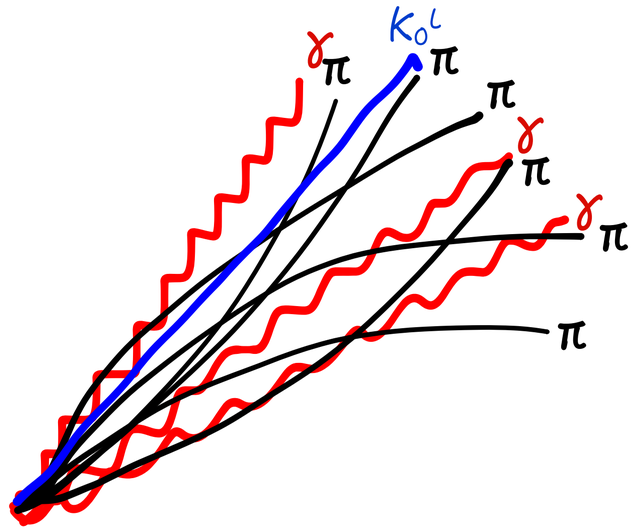
HAD Calorimeters

- Short-lived Neutral Hadrons: ~5%



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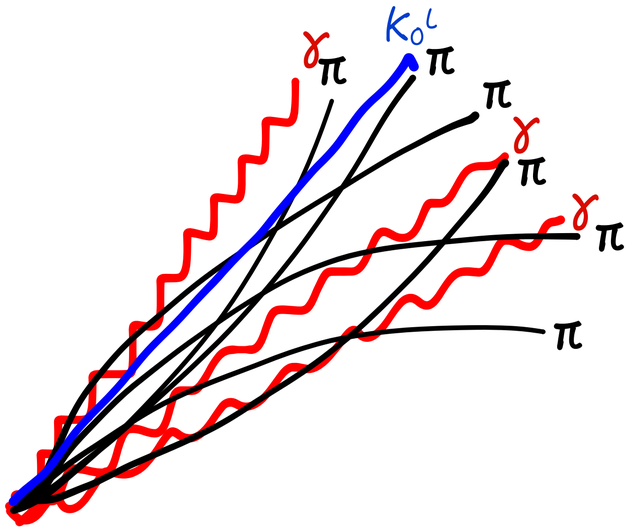
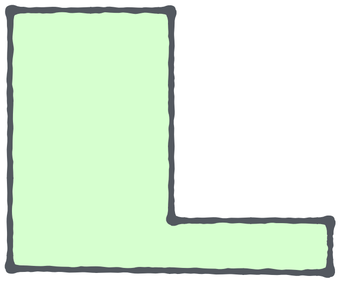


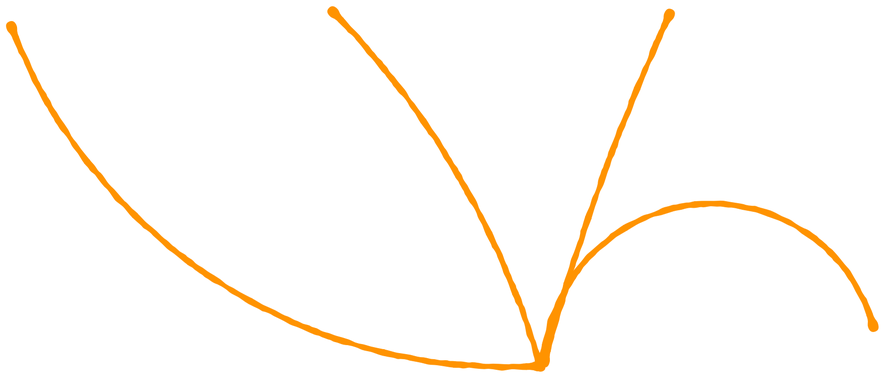
Recall: Associate hits within each detector

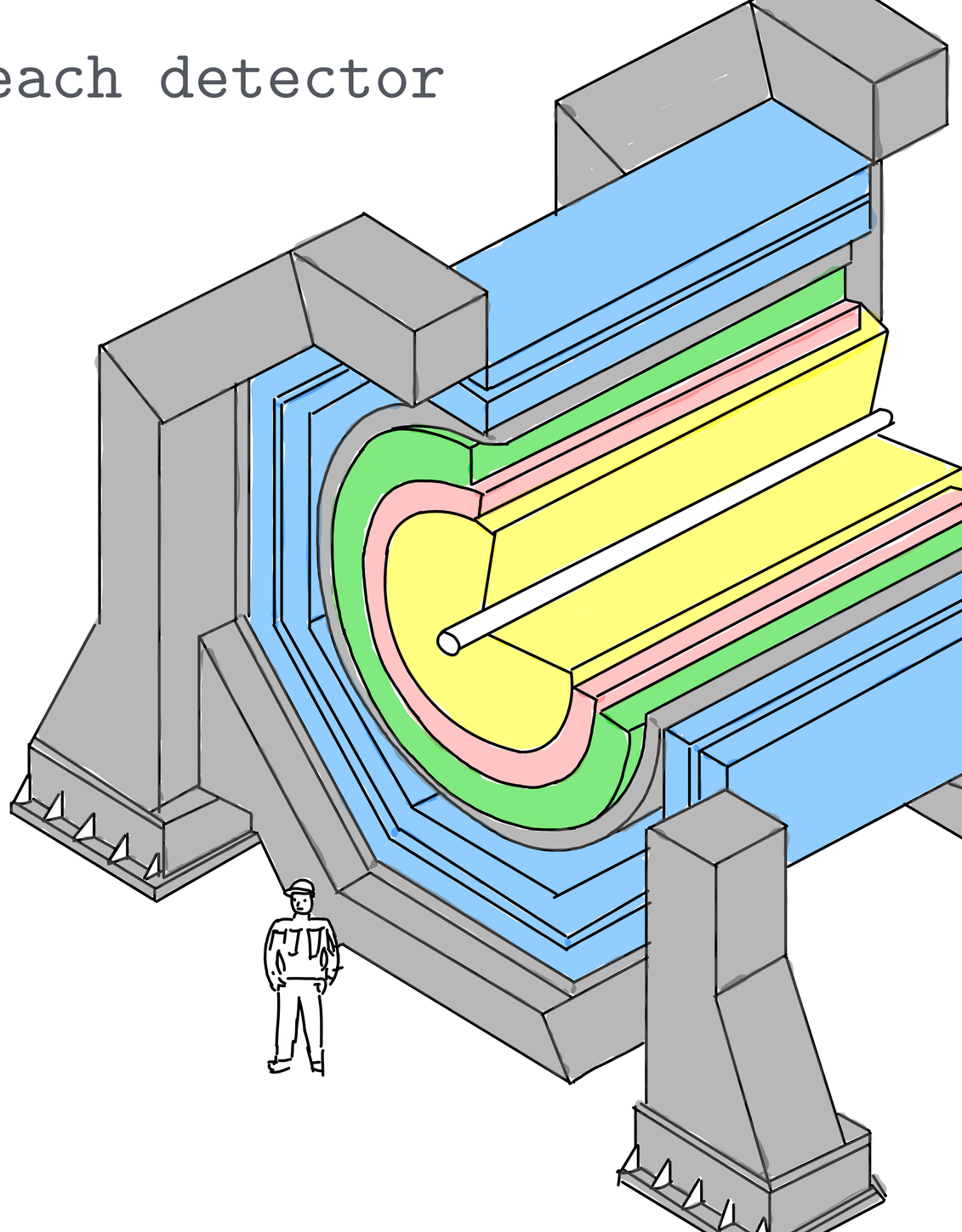
HCAL Clusters



ECAL Clusters

Tracks





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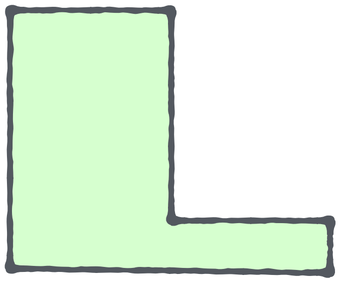

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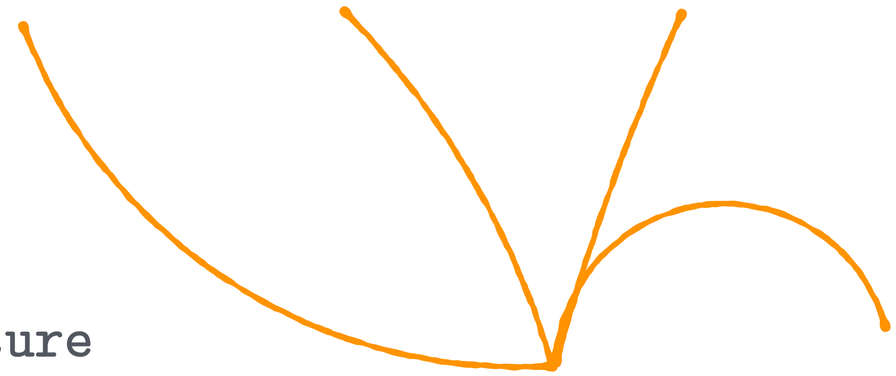
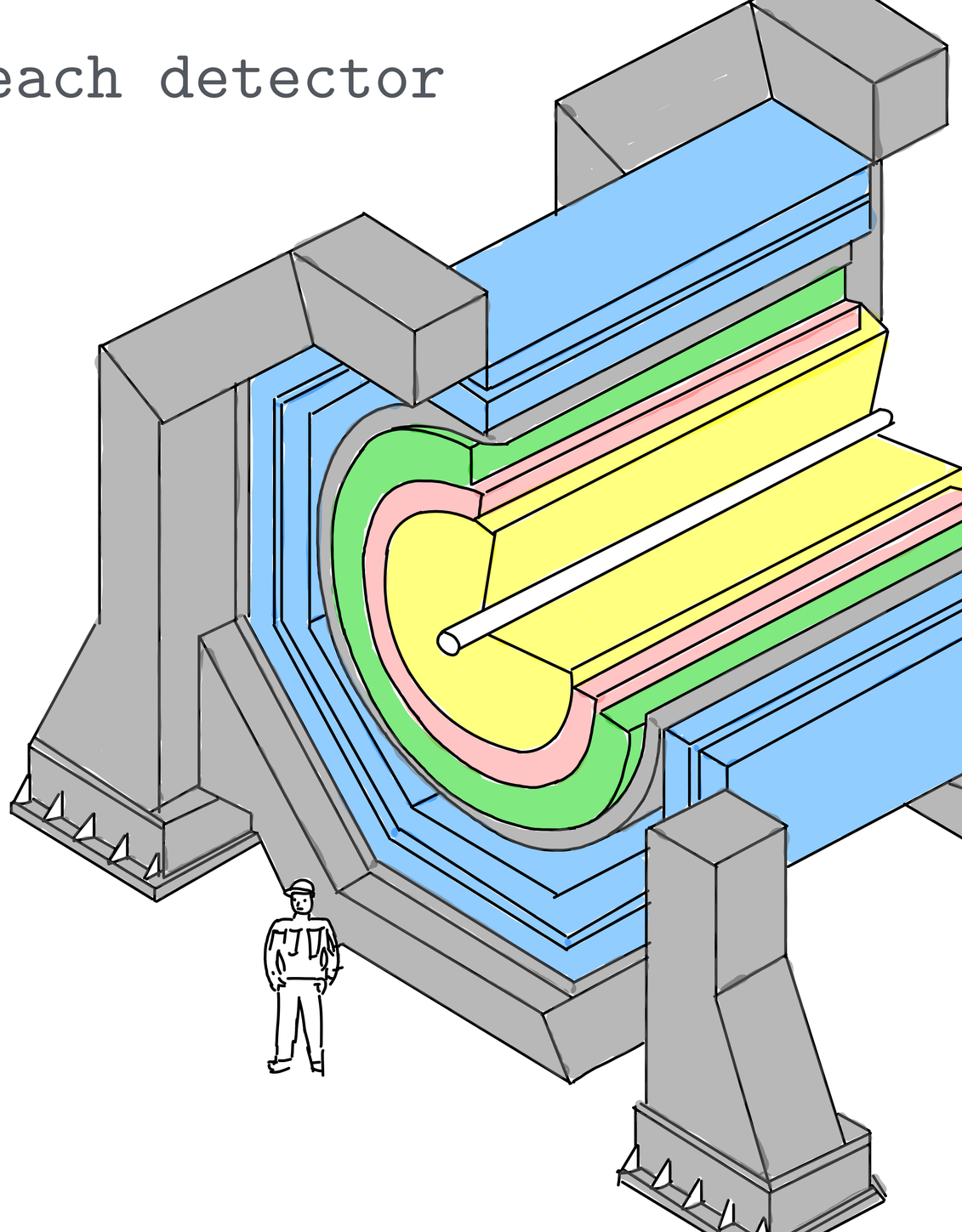


Last Lecture



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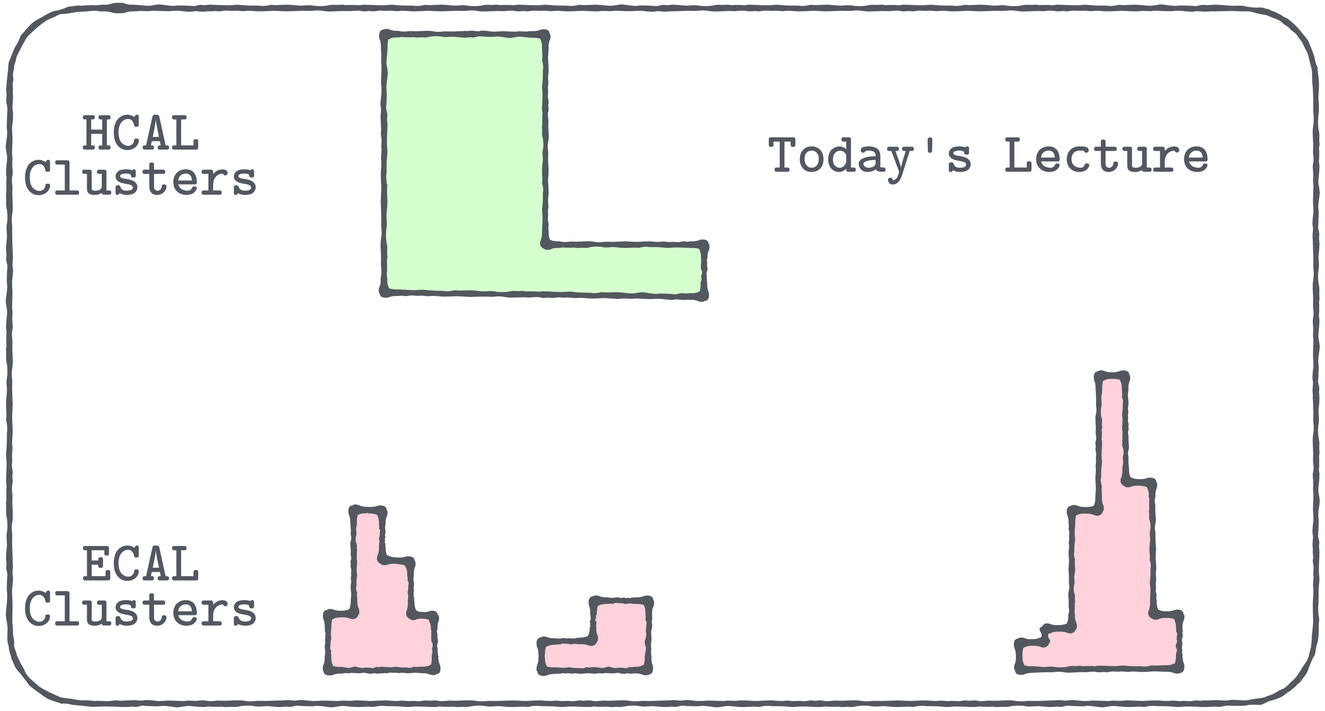
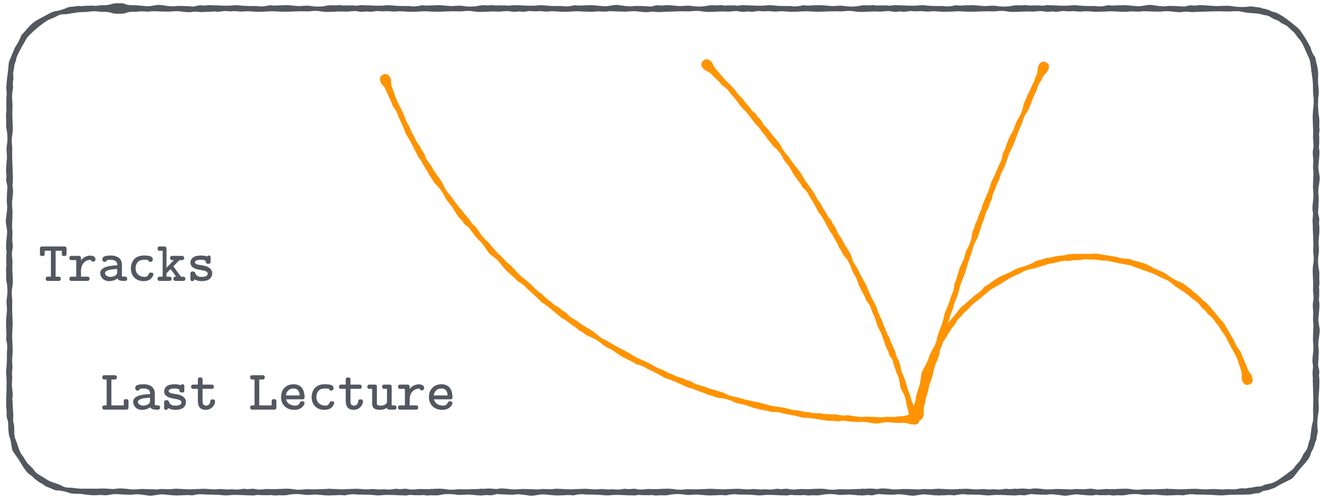
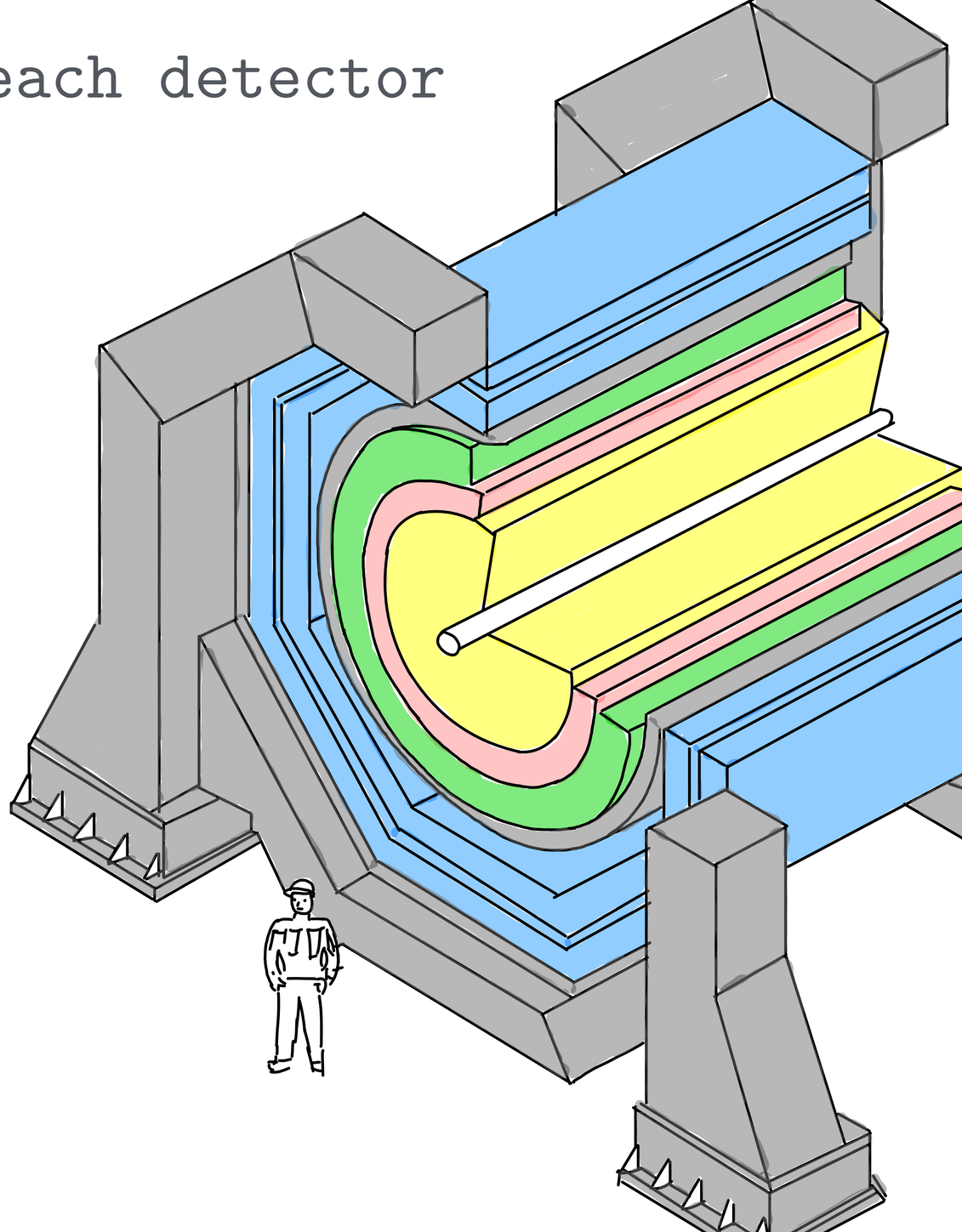
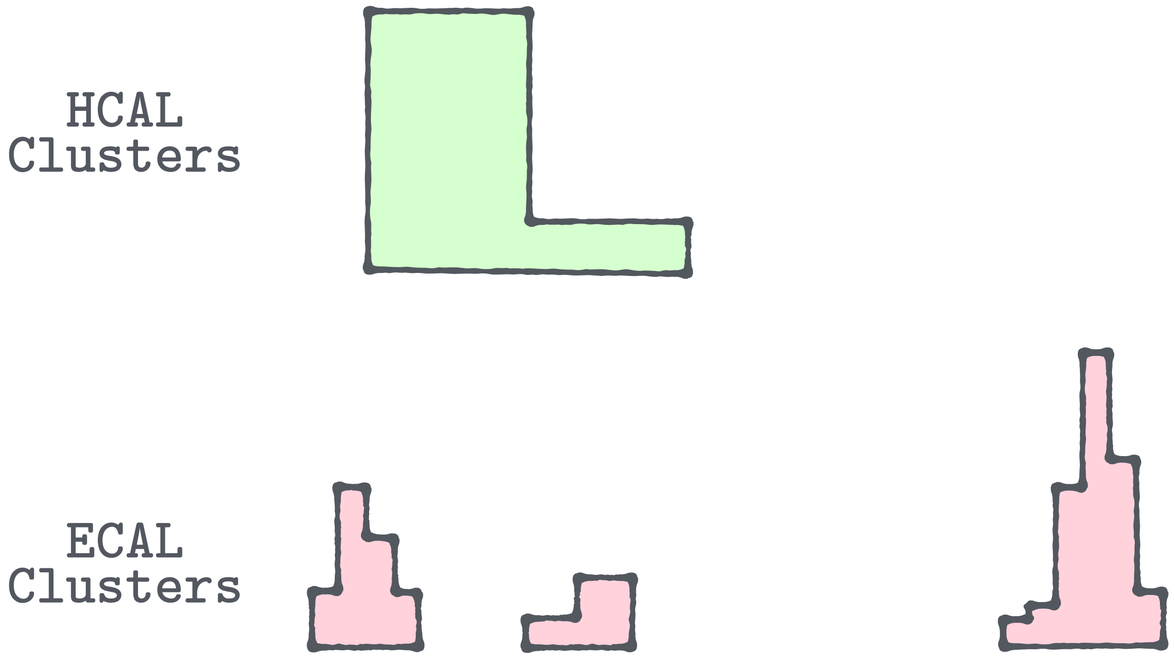






Calorimeter Clustering



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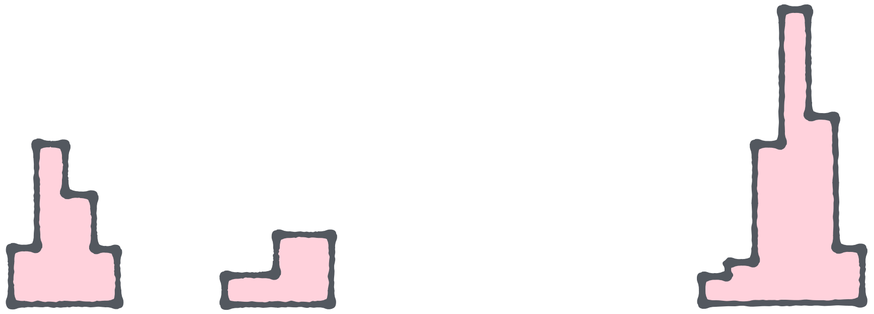

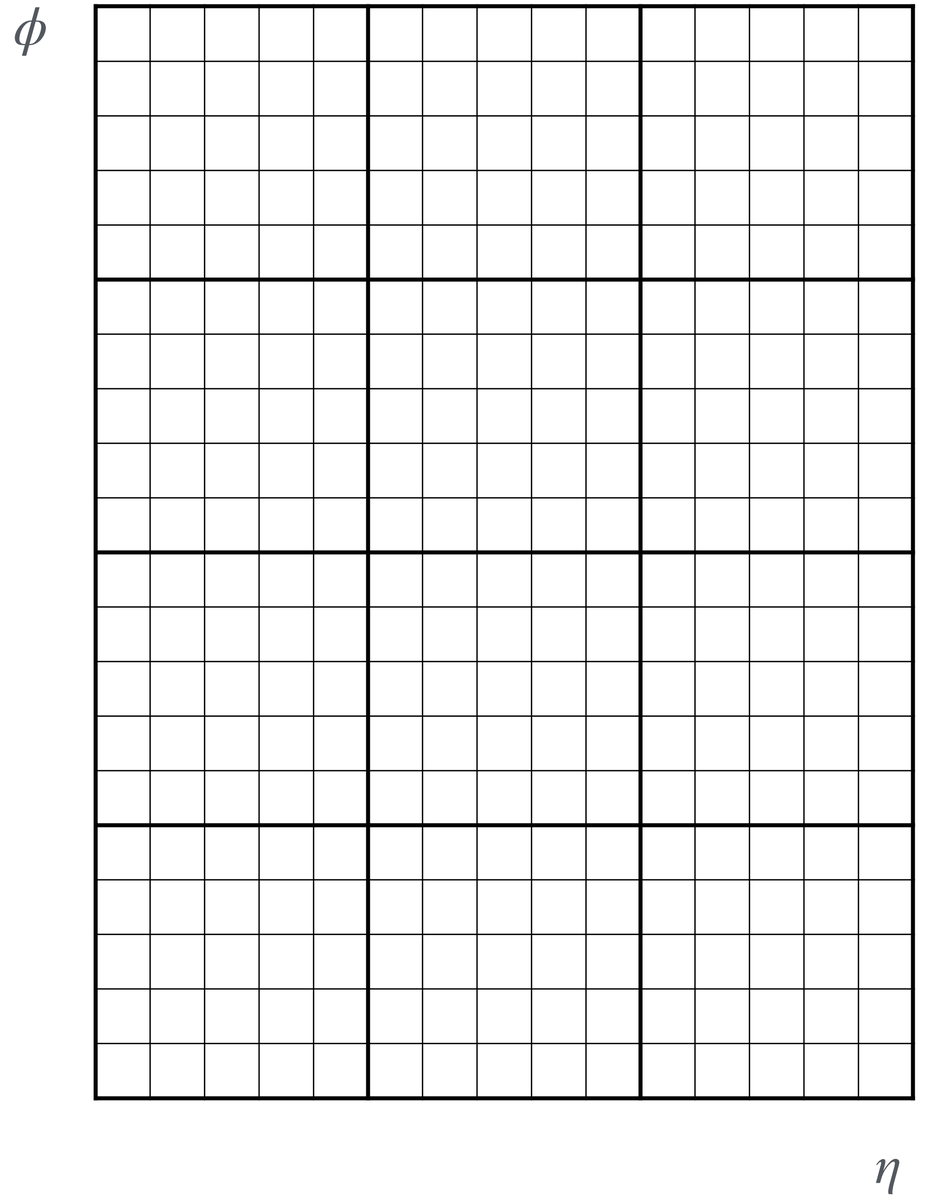

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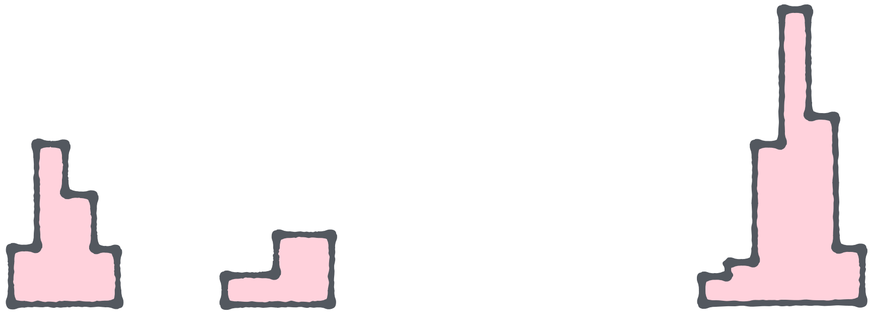

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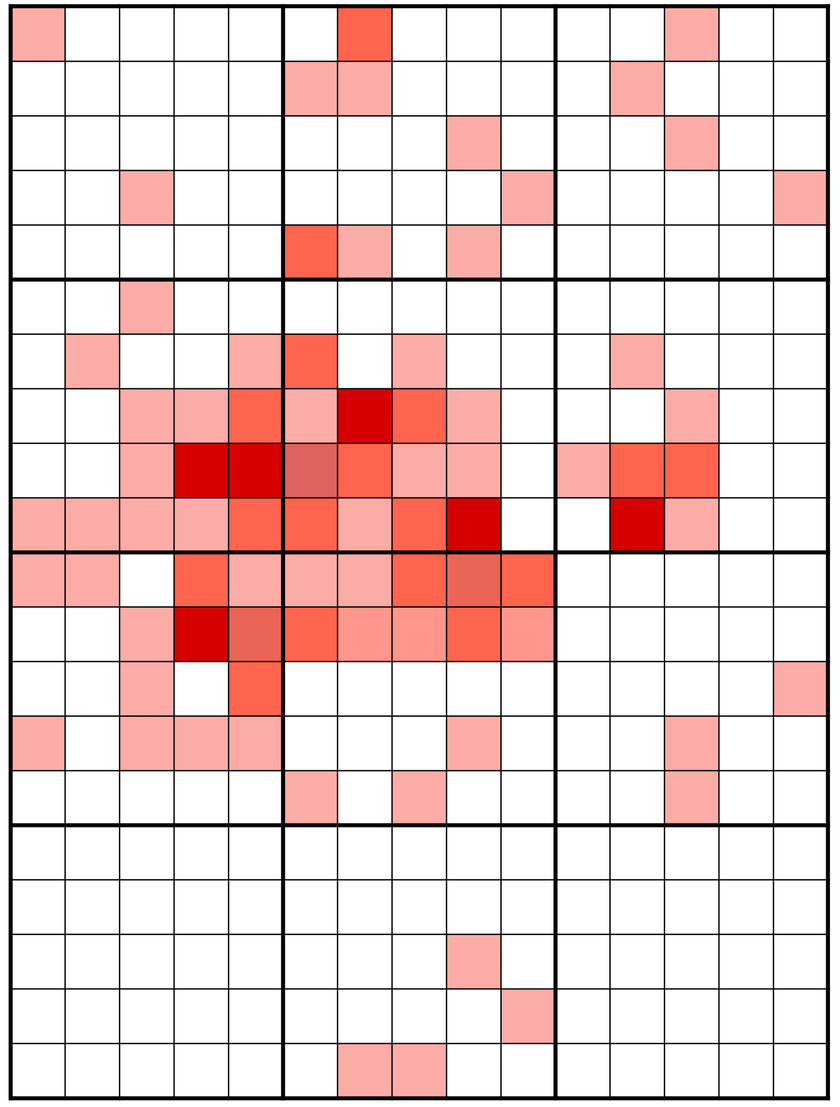

Calorimeter Clustering

Step 1: Identify Seeds

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

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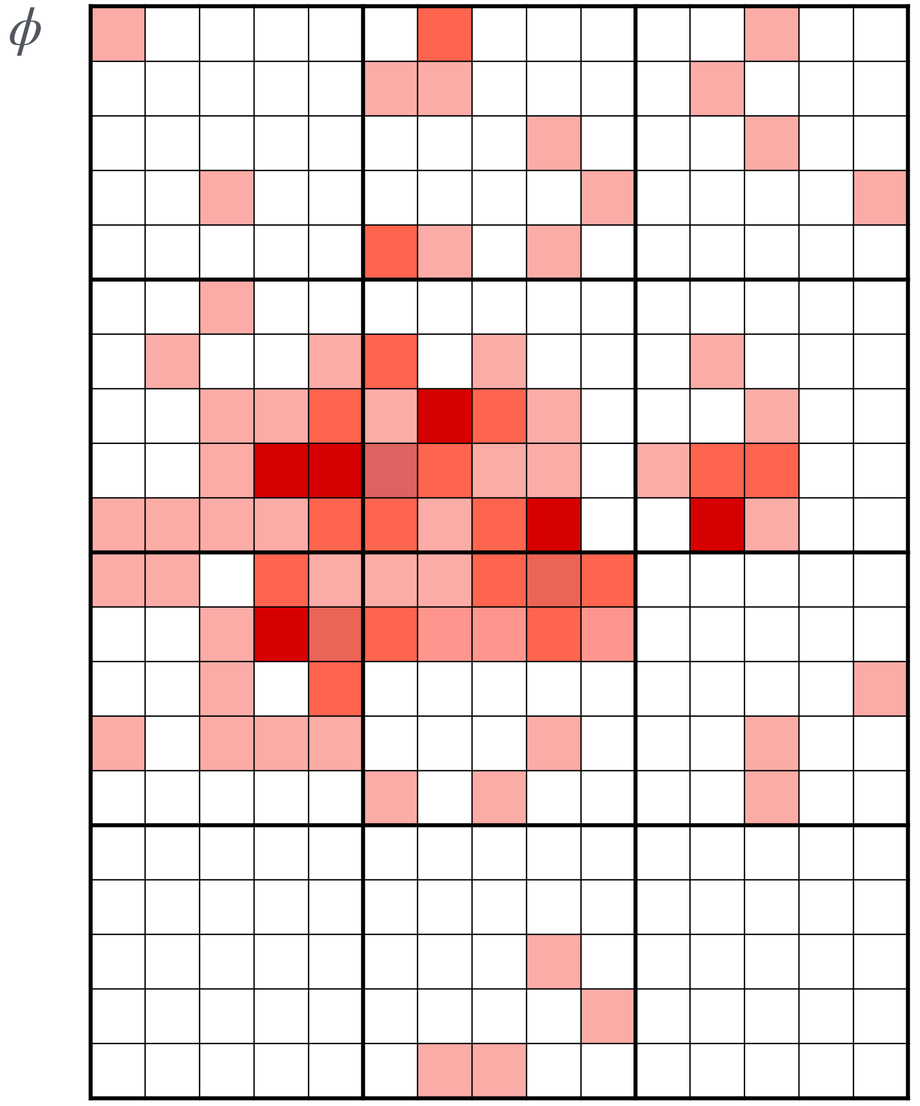

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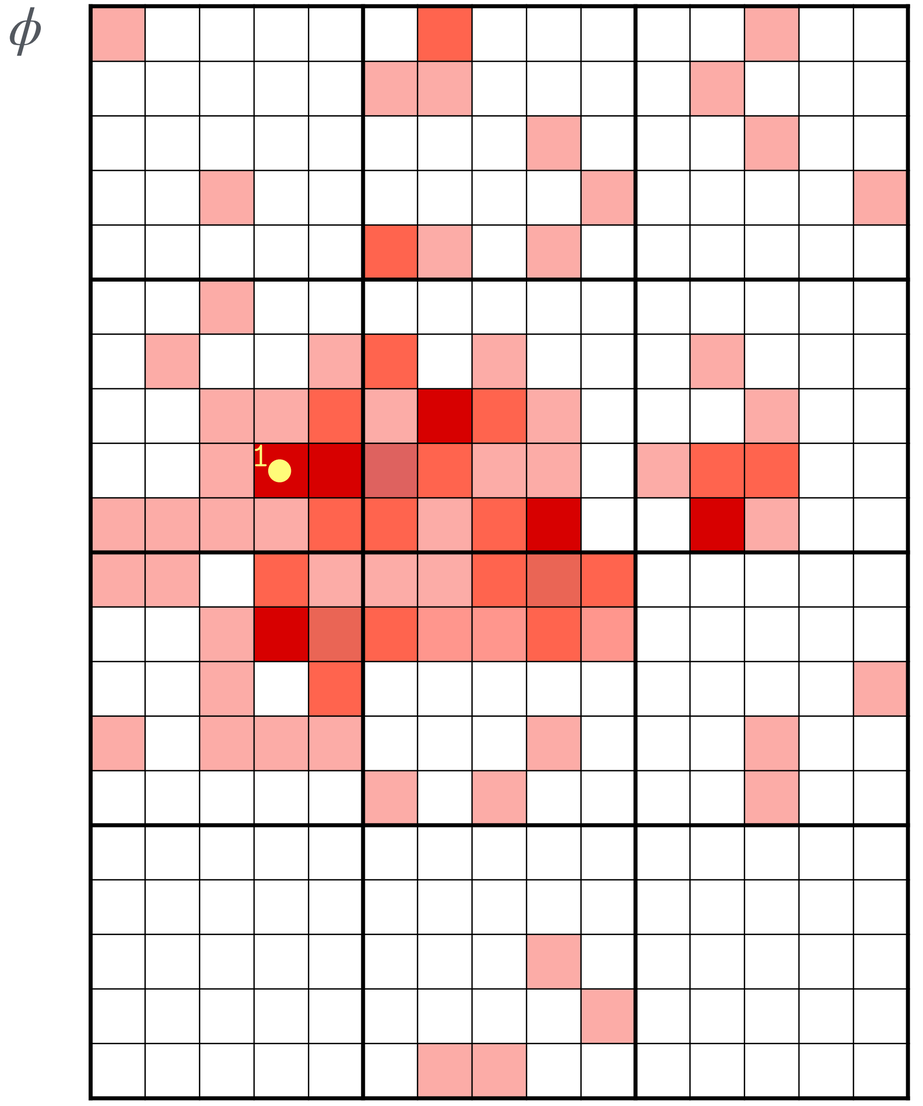

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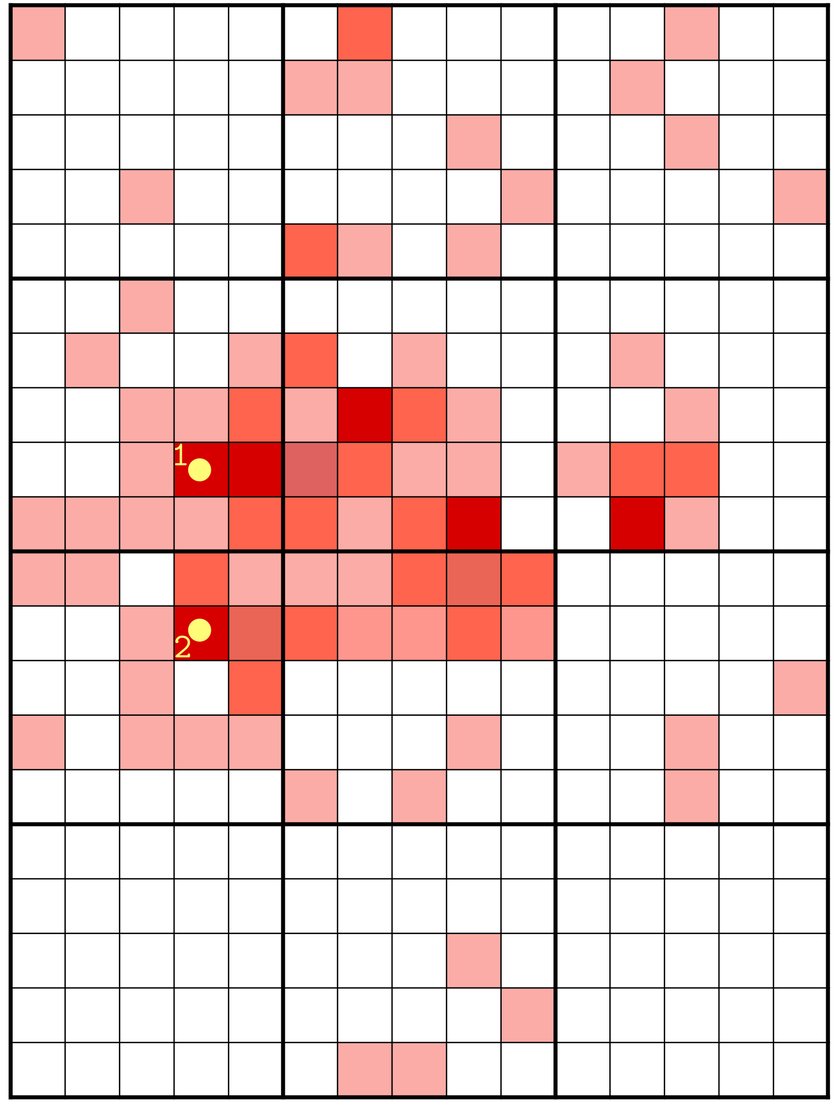

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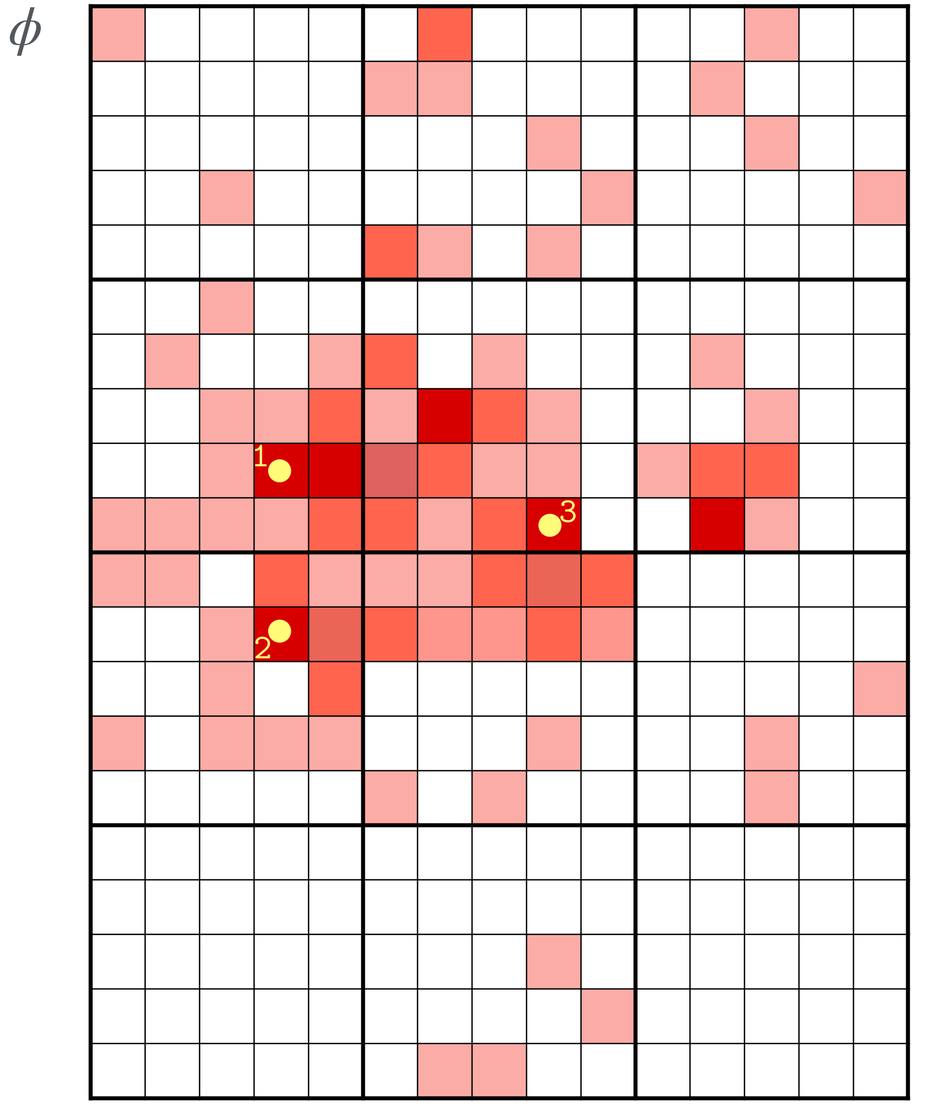

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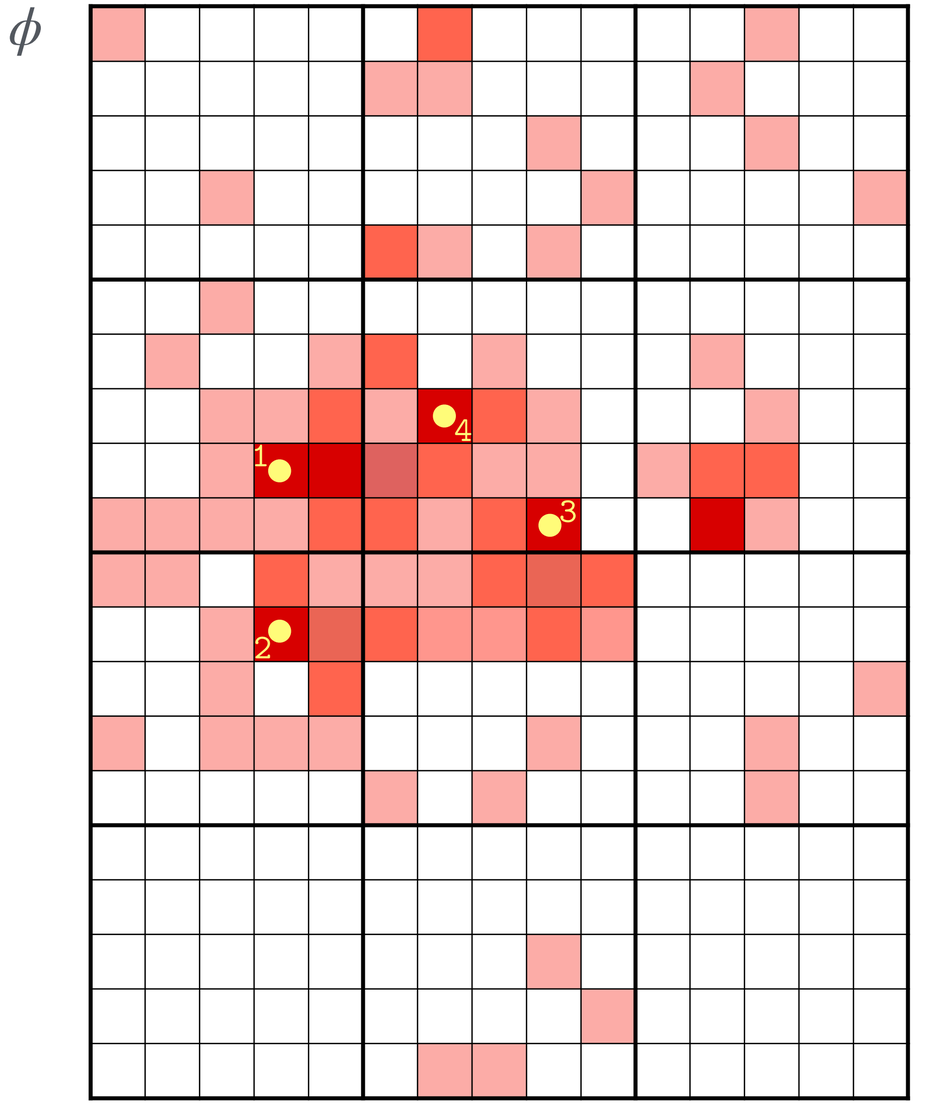

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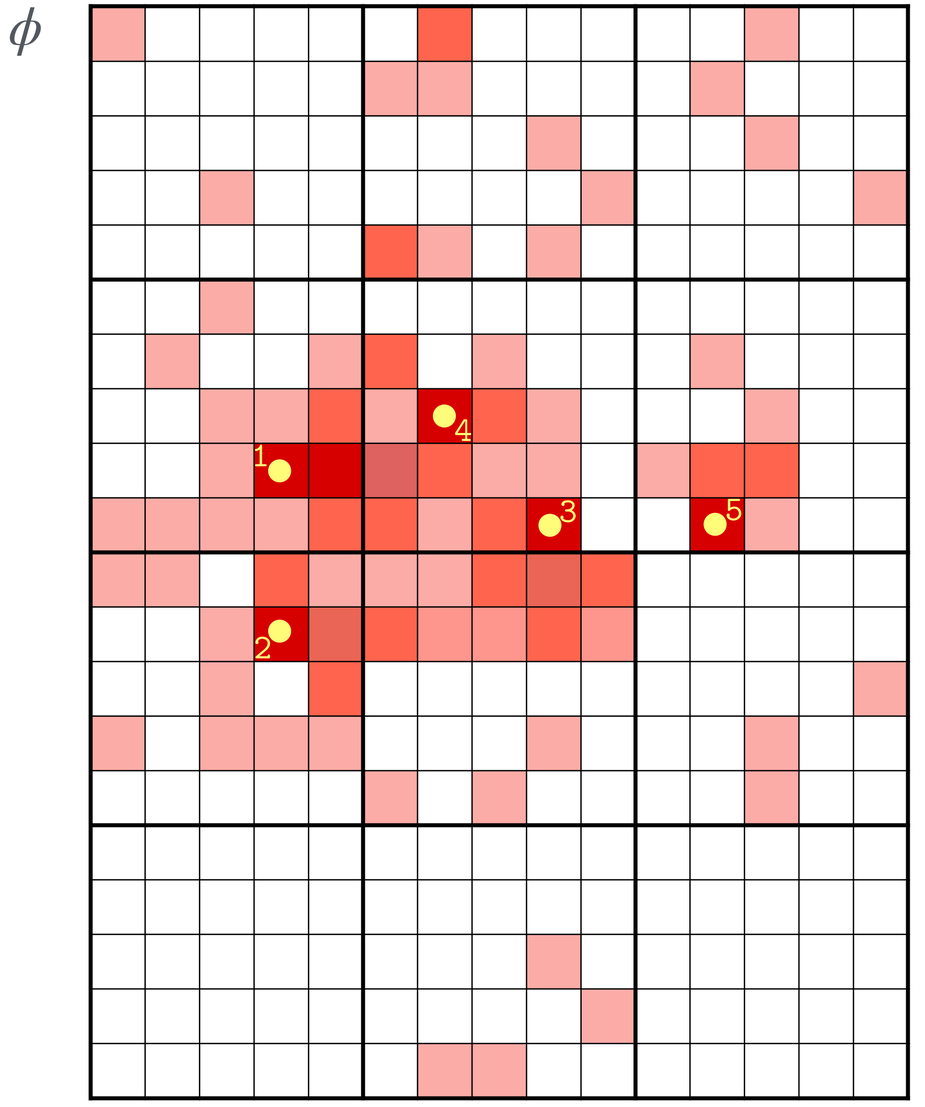

Calorimeter Clustering

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Step 2: Form Topological Clusters

- Grown from seeds
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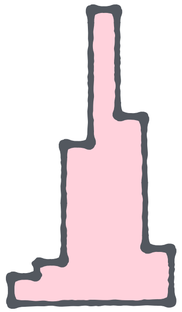
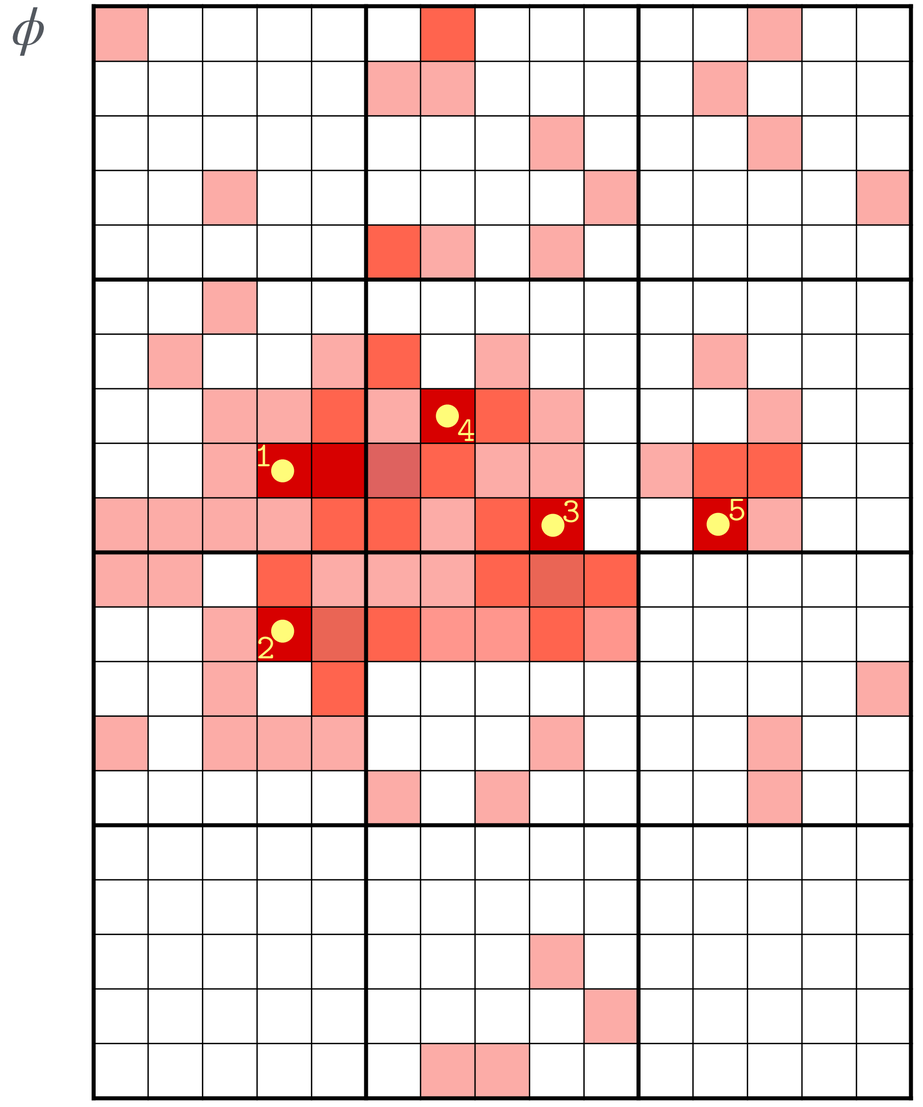
$$E + 2\,\sigma_{noise}(E)$$

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





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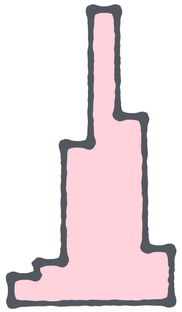

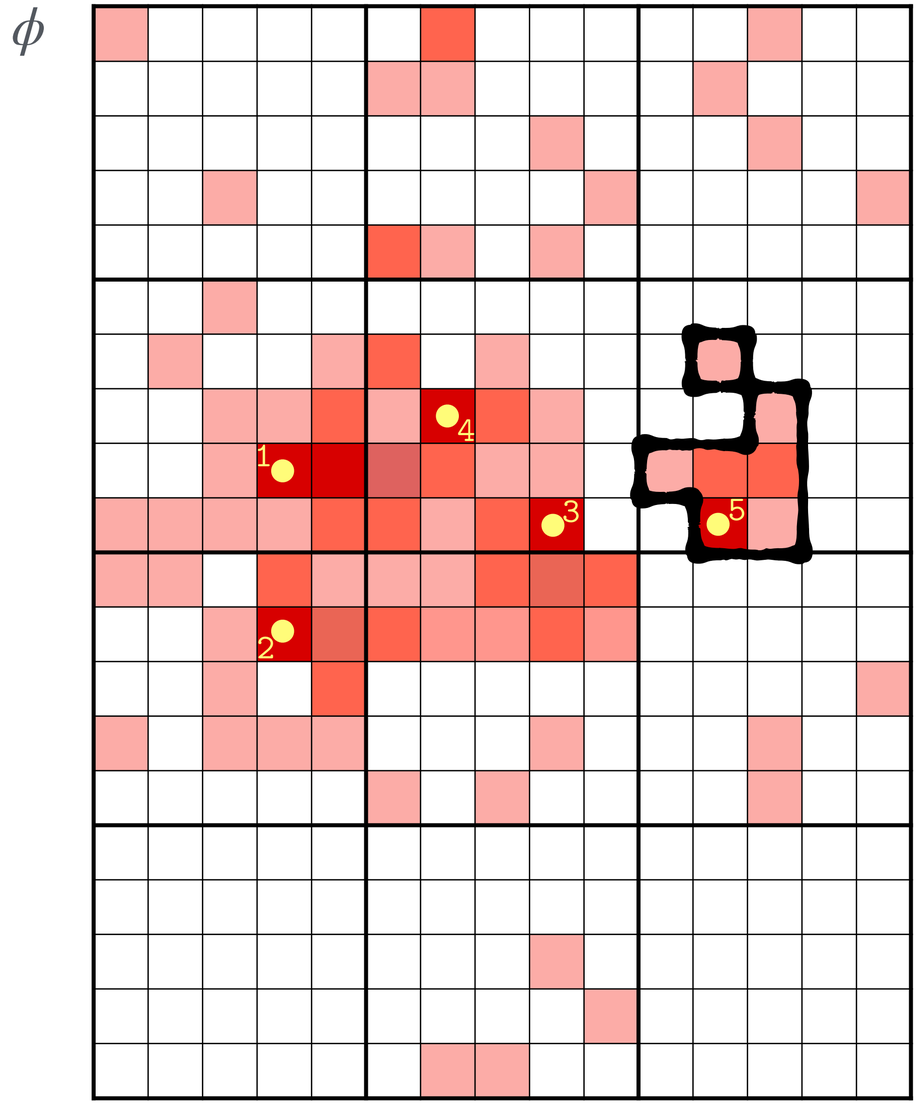

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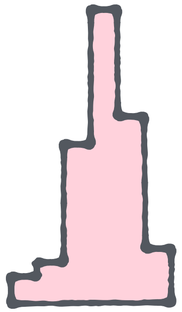

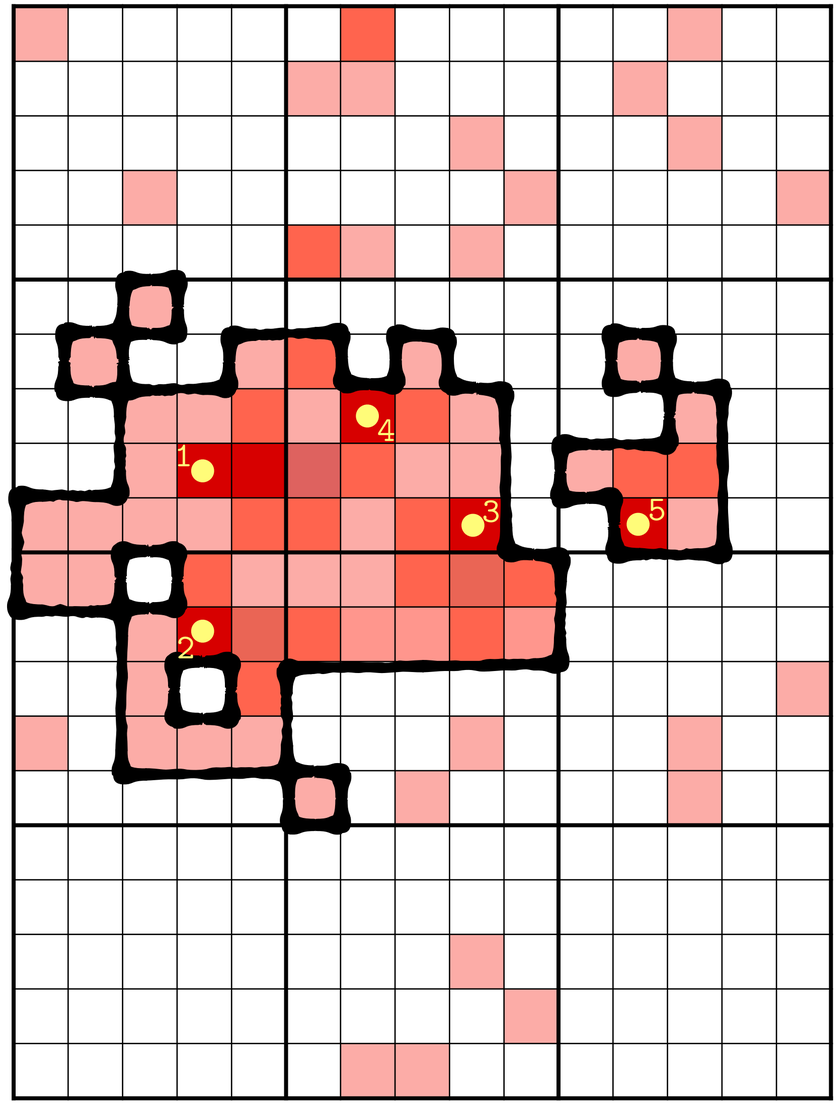

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Step 3: Share energy in Topological Cluster

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

$$E = \sum_{i}^{N} E_i$$

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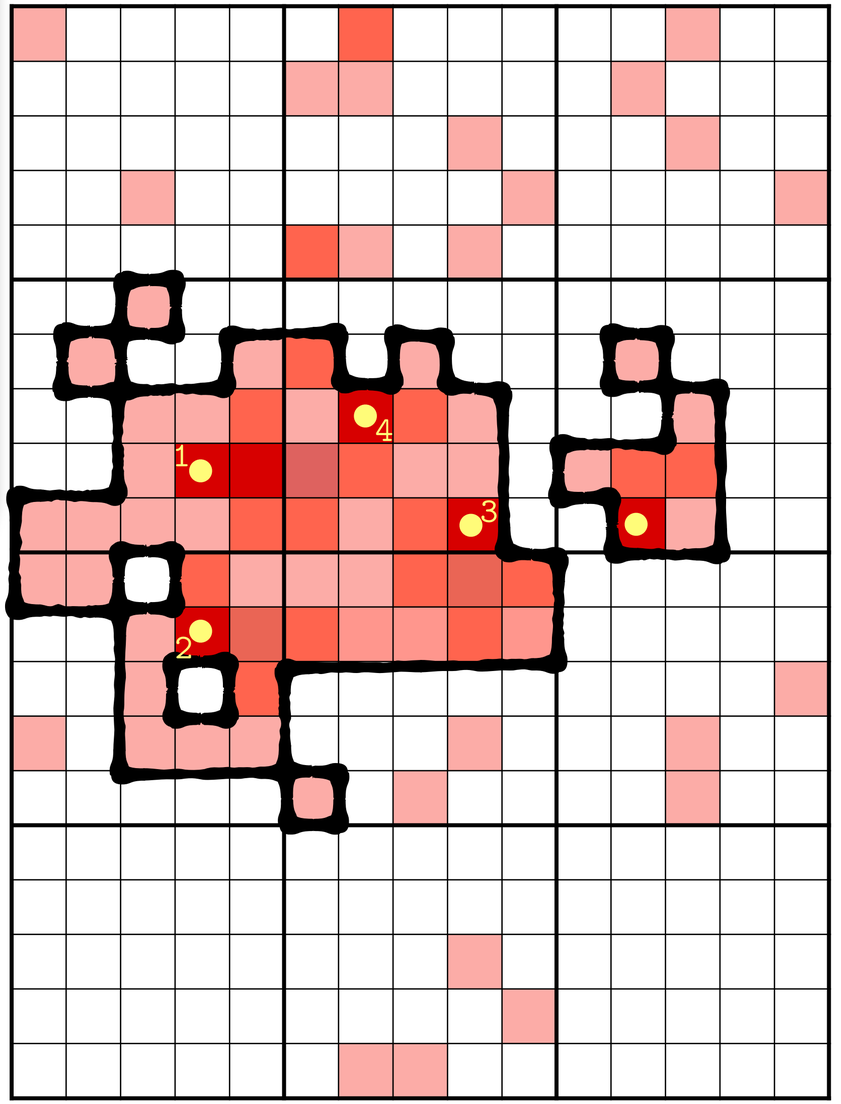

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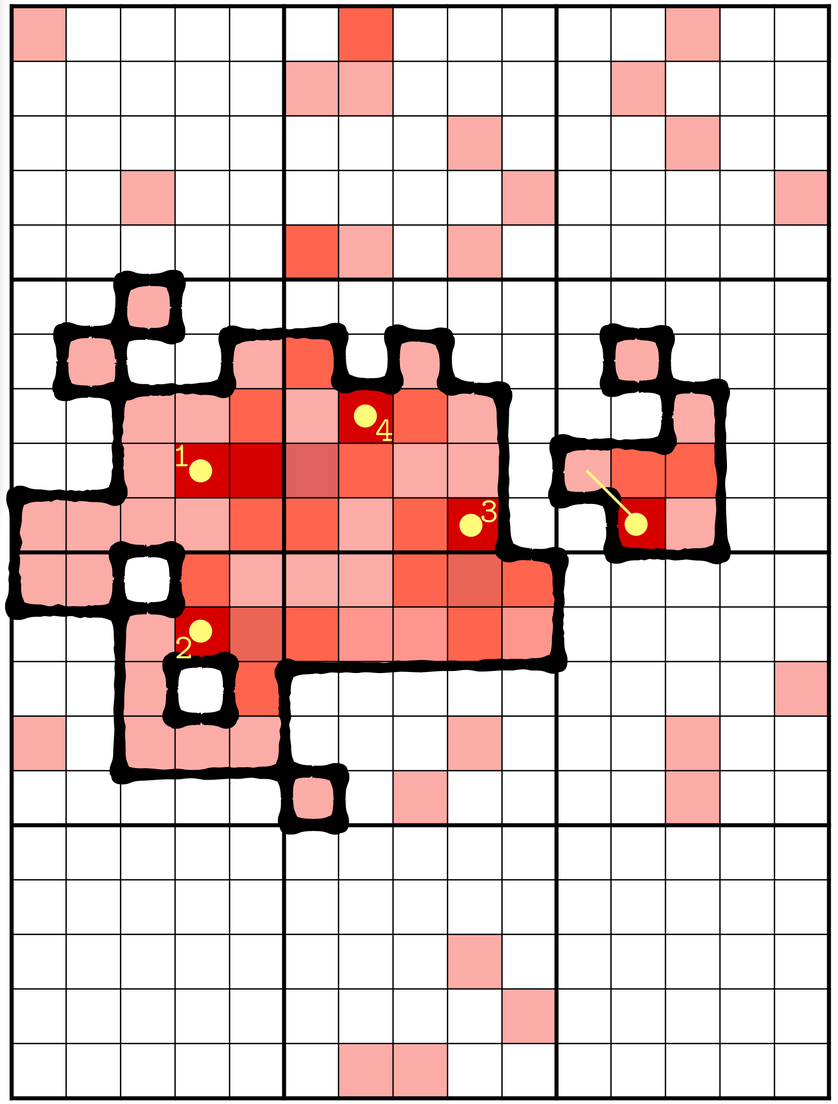

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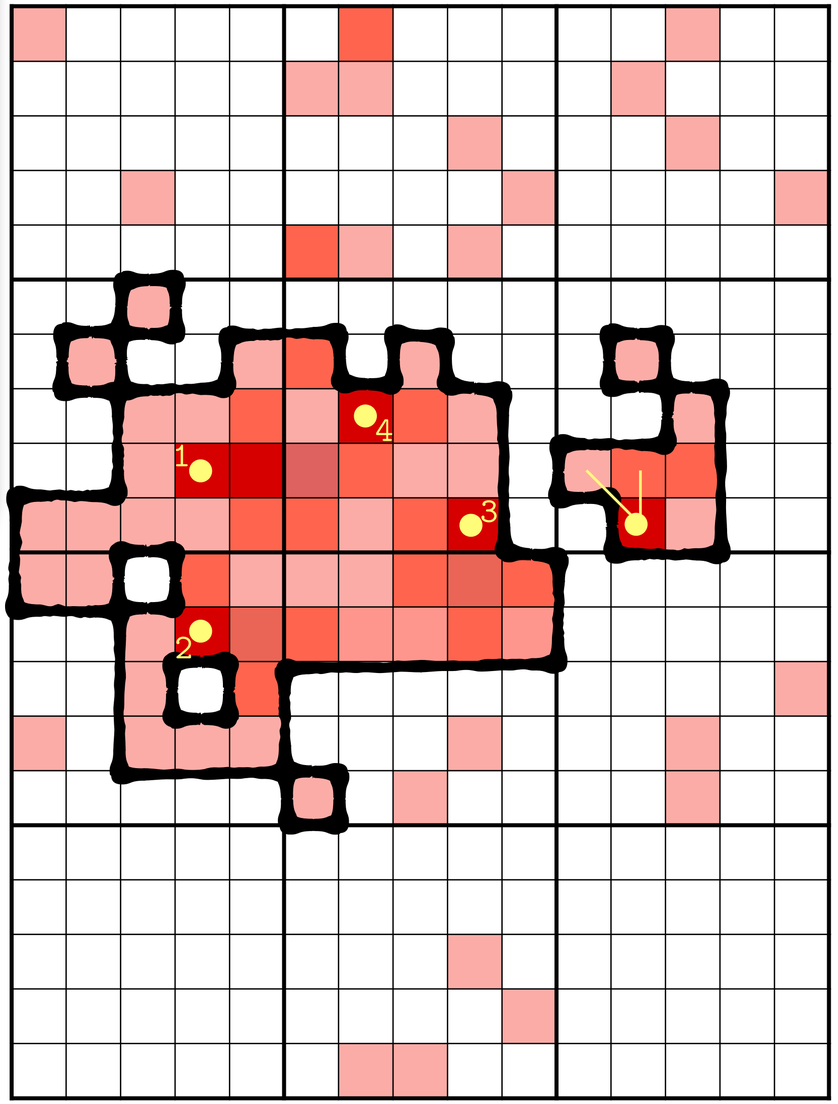

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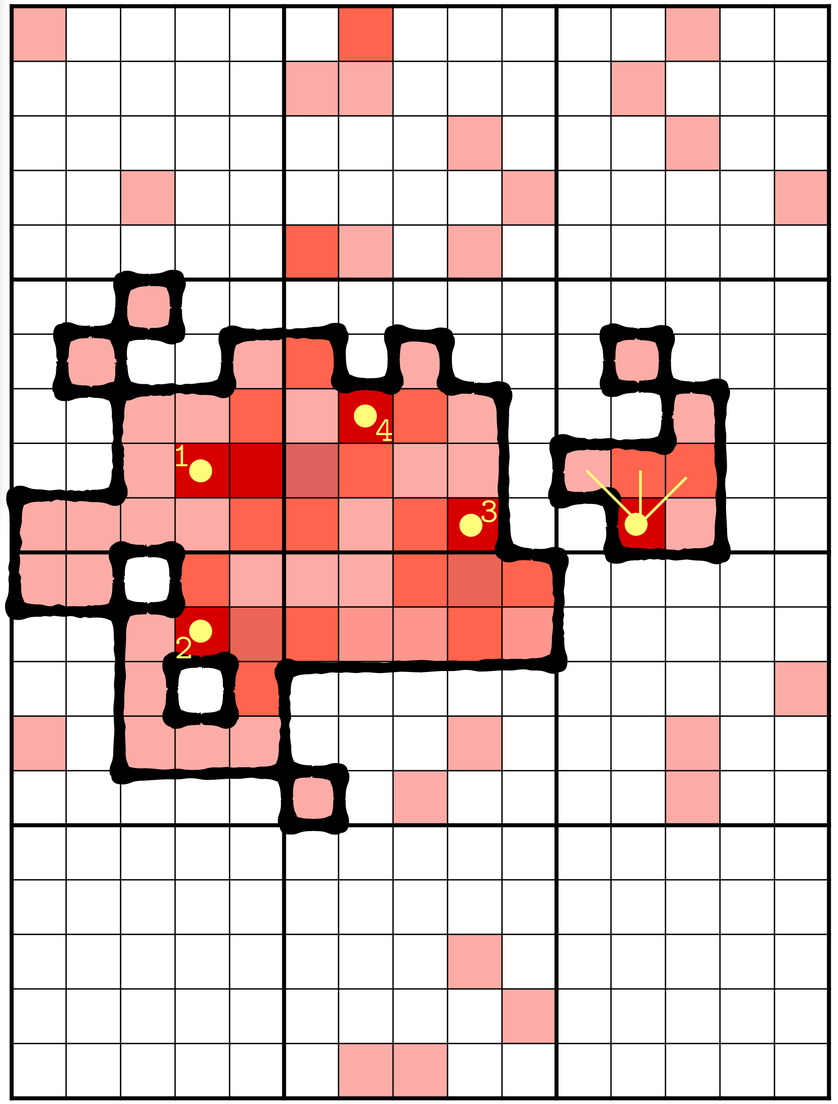

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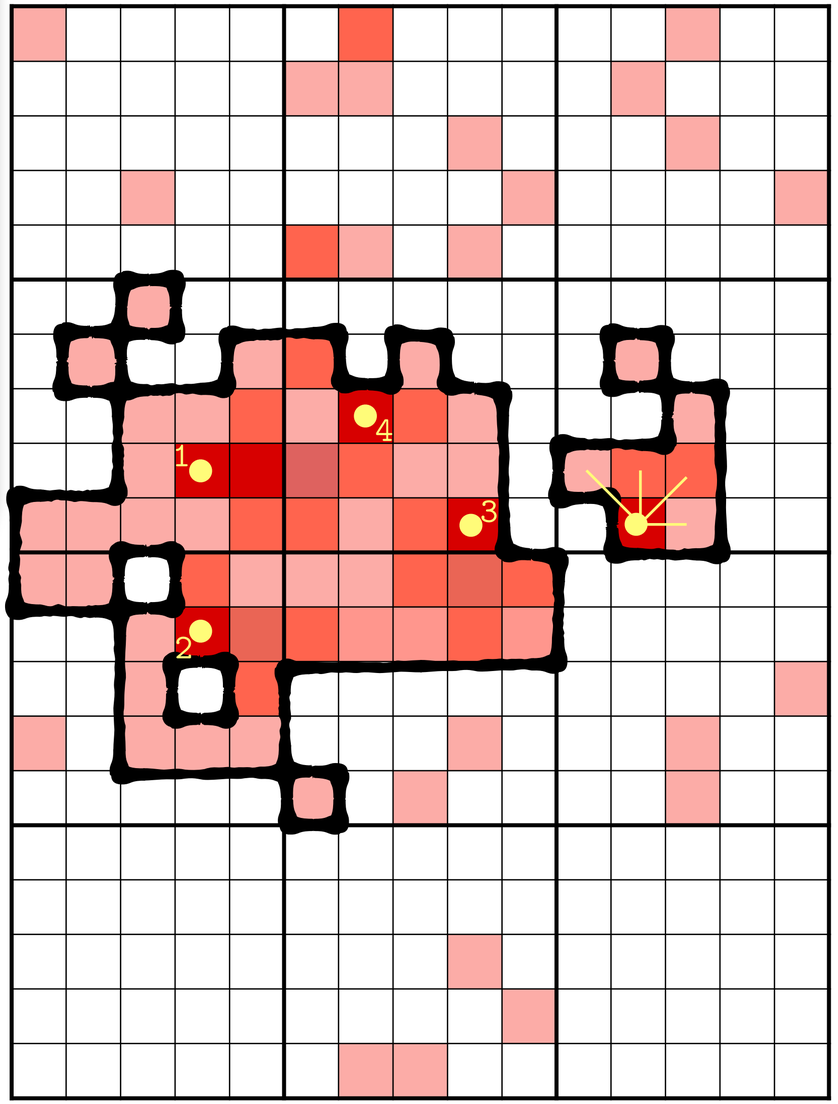

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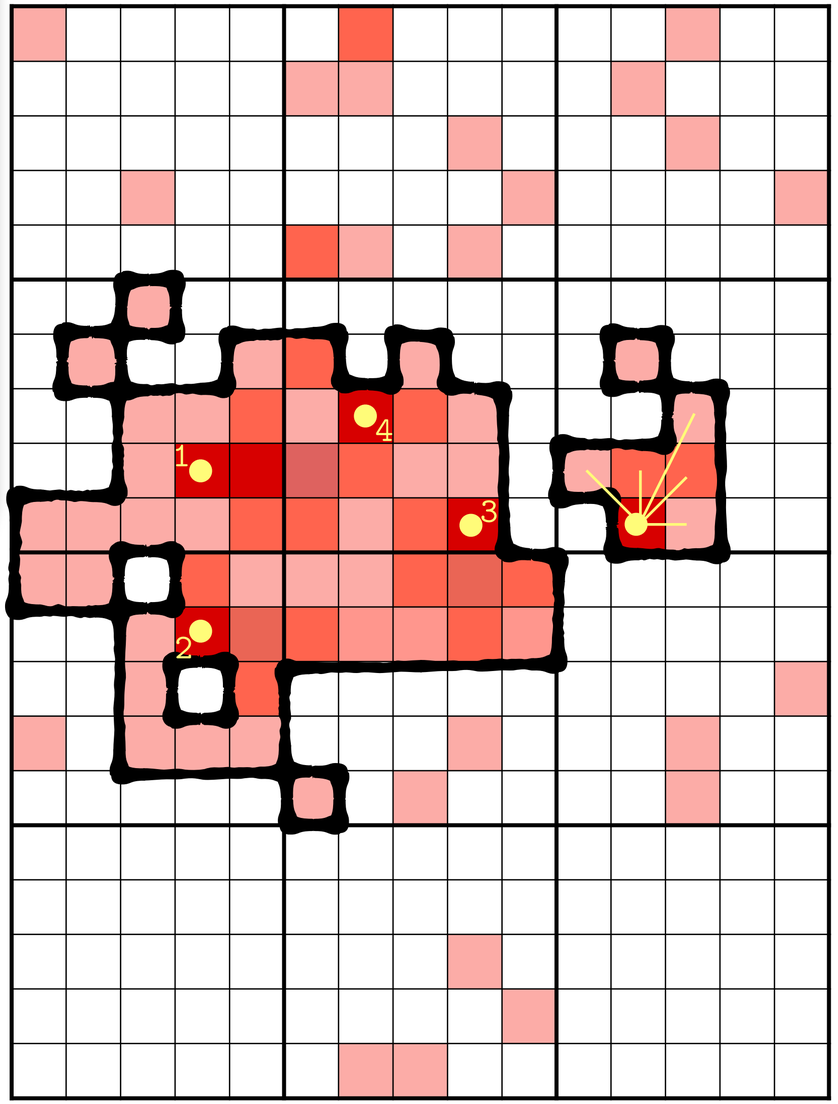

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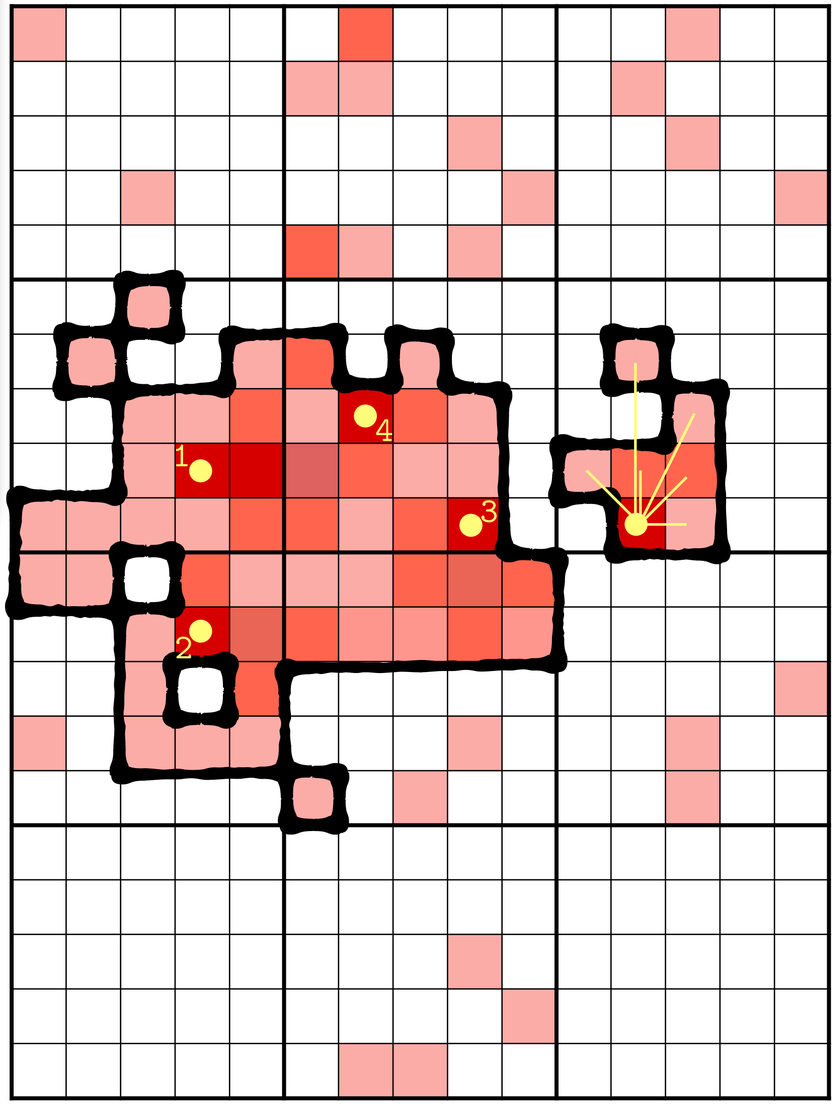

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- Aggregate all cells with at least a corner in common with cell already in cluster

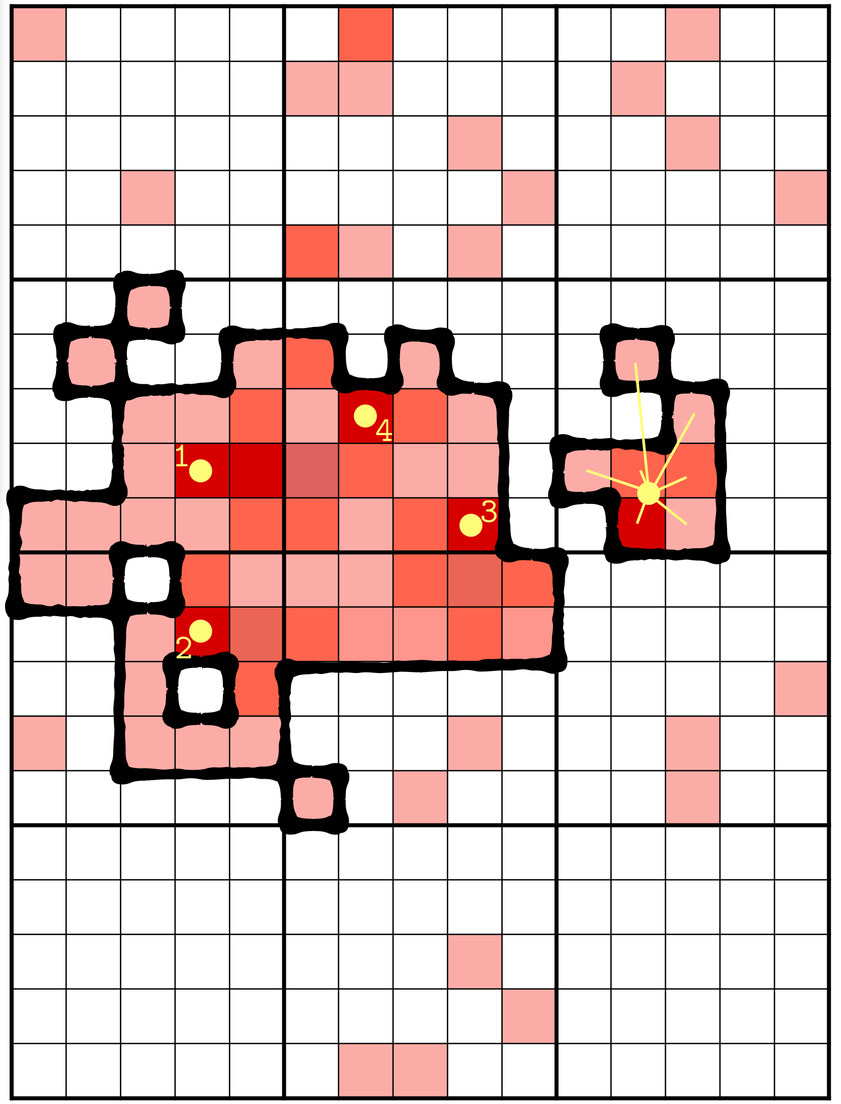
Step 3: Share energy in Topological Cluster

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

$$E = \sum_{i}^{N} E_i$$

  - Position is energy weighted sum:

$$\vec{\mu} = \frac{1}{E_{tot}} \sum_{i}^{N} E_I \vec{x}_i$$



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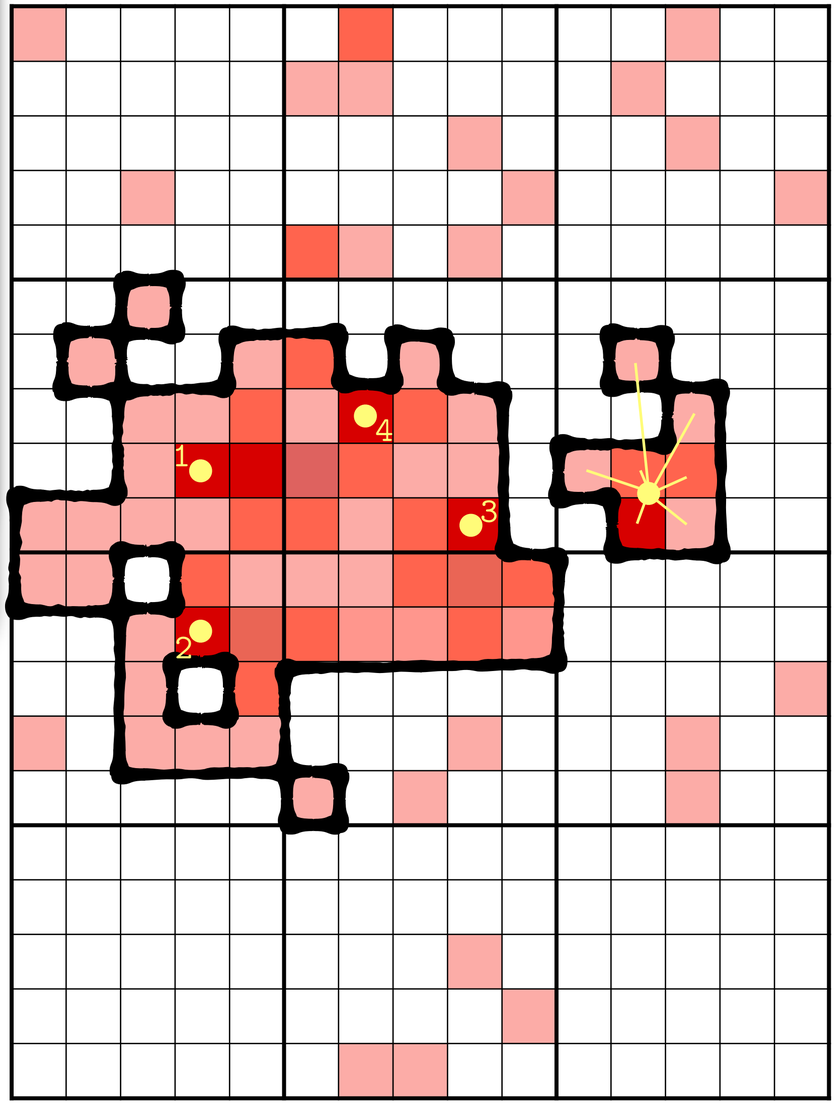

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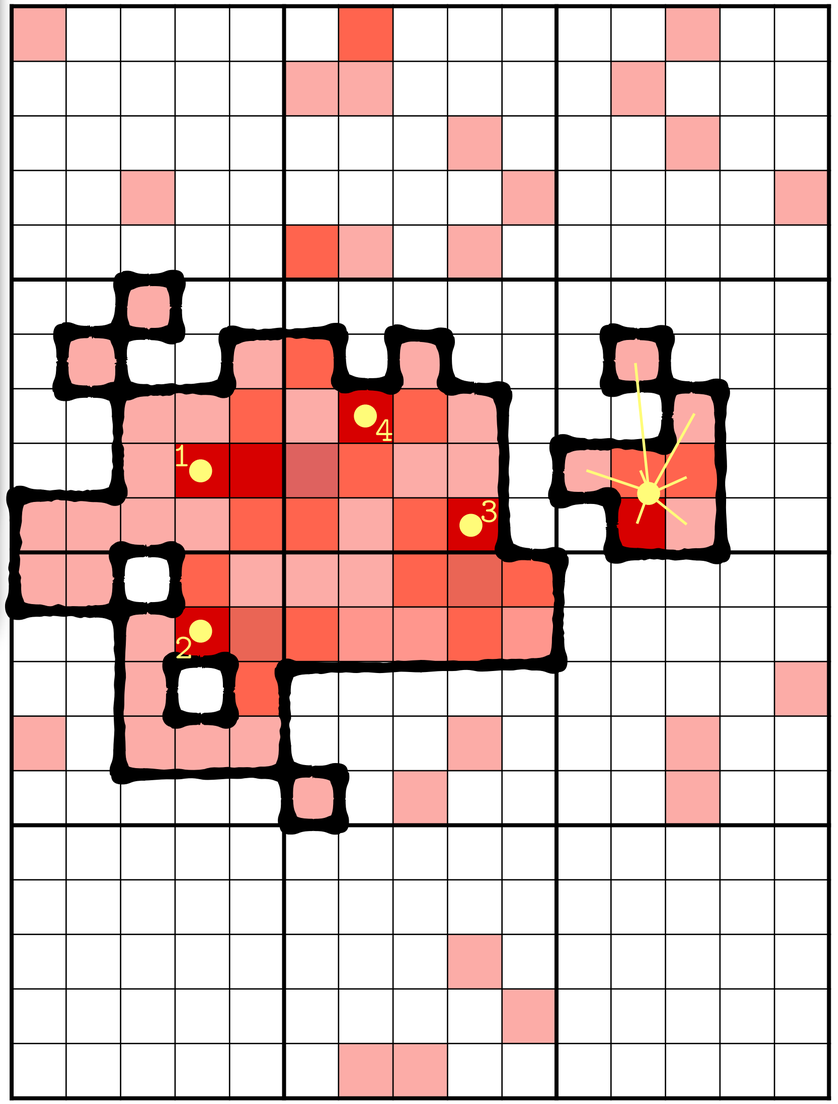

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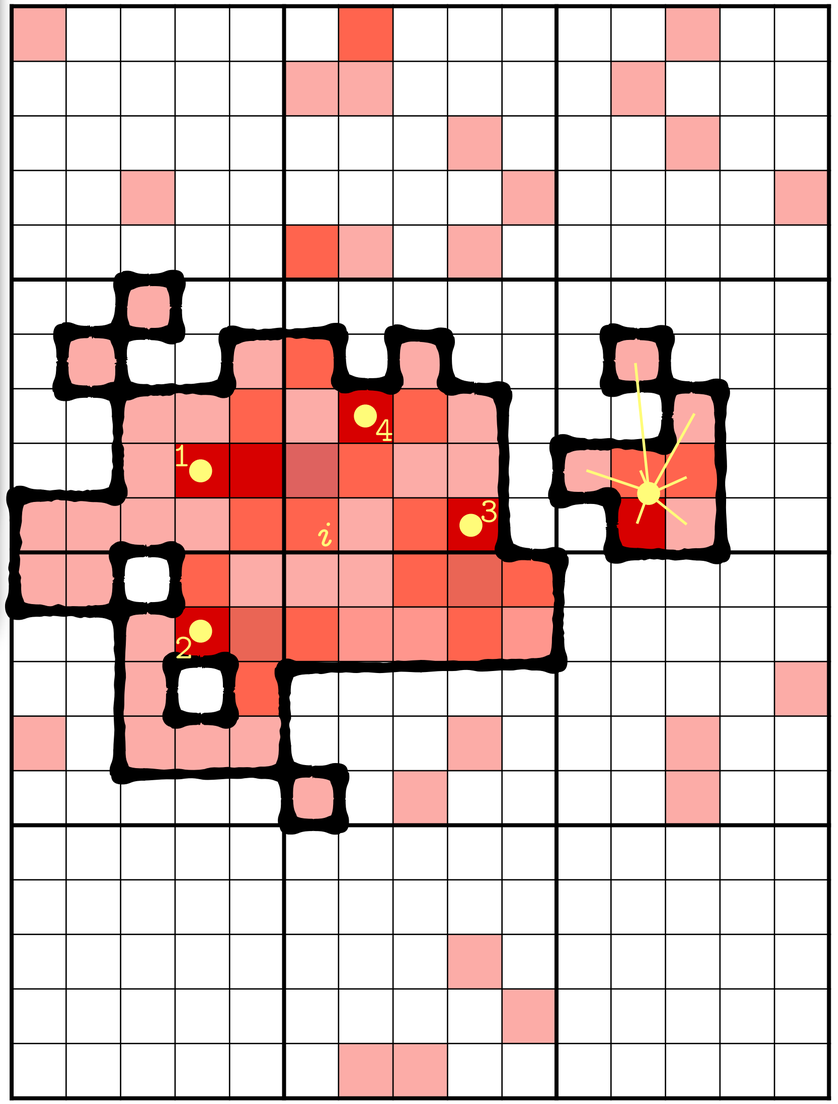

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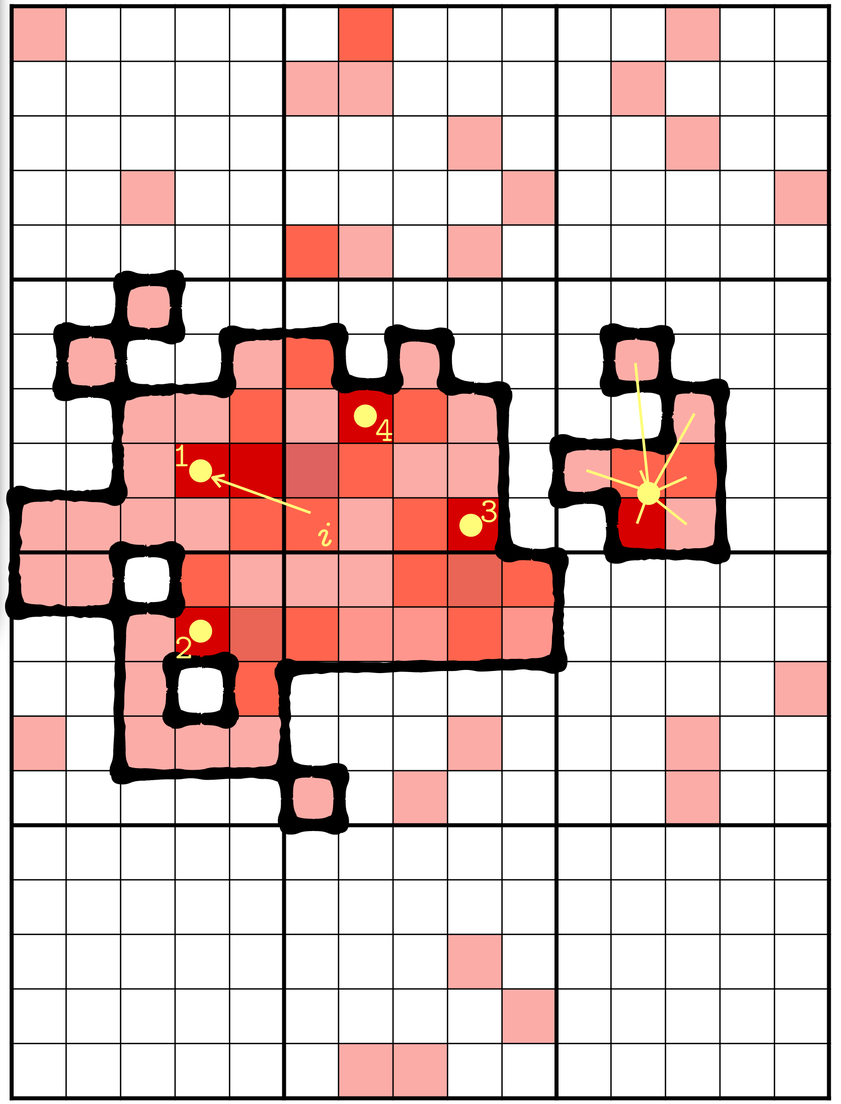

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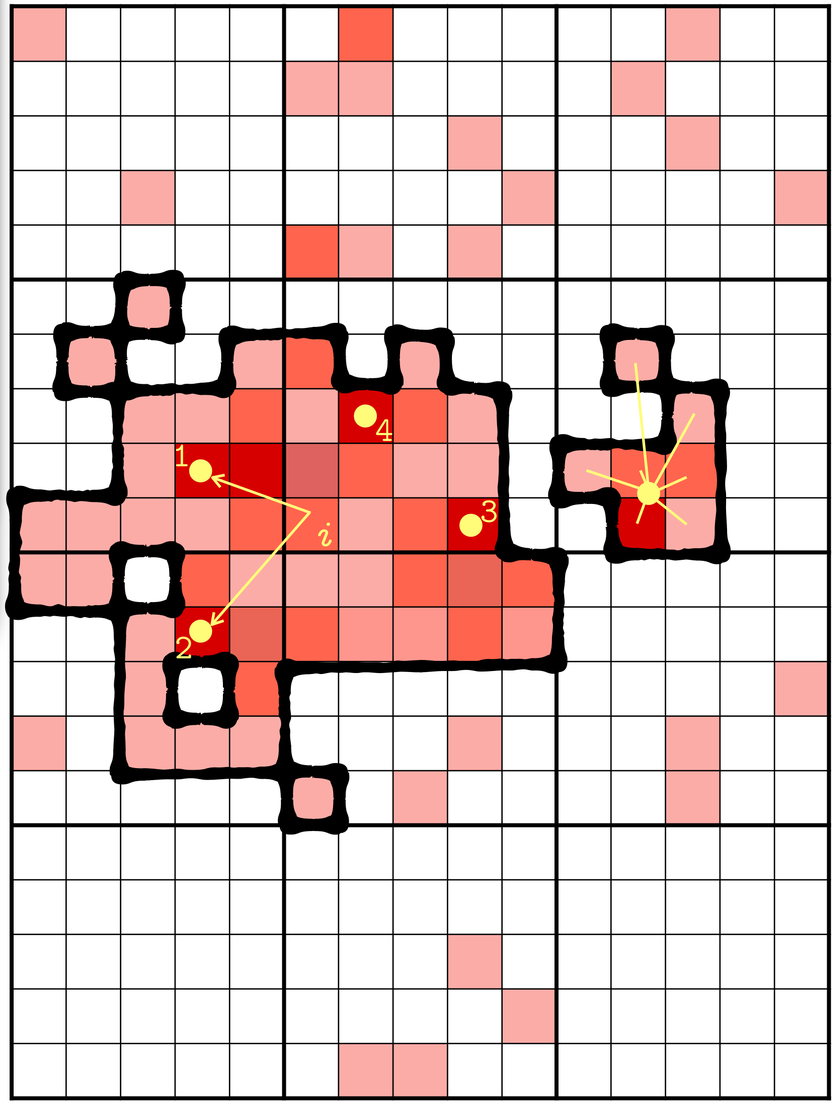

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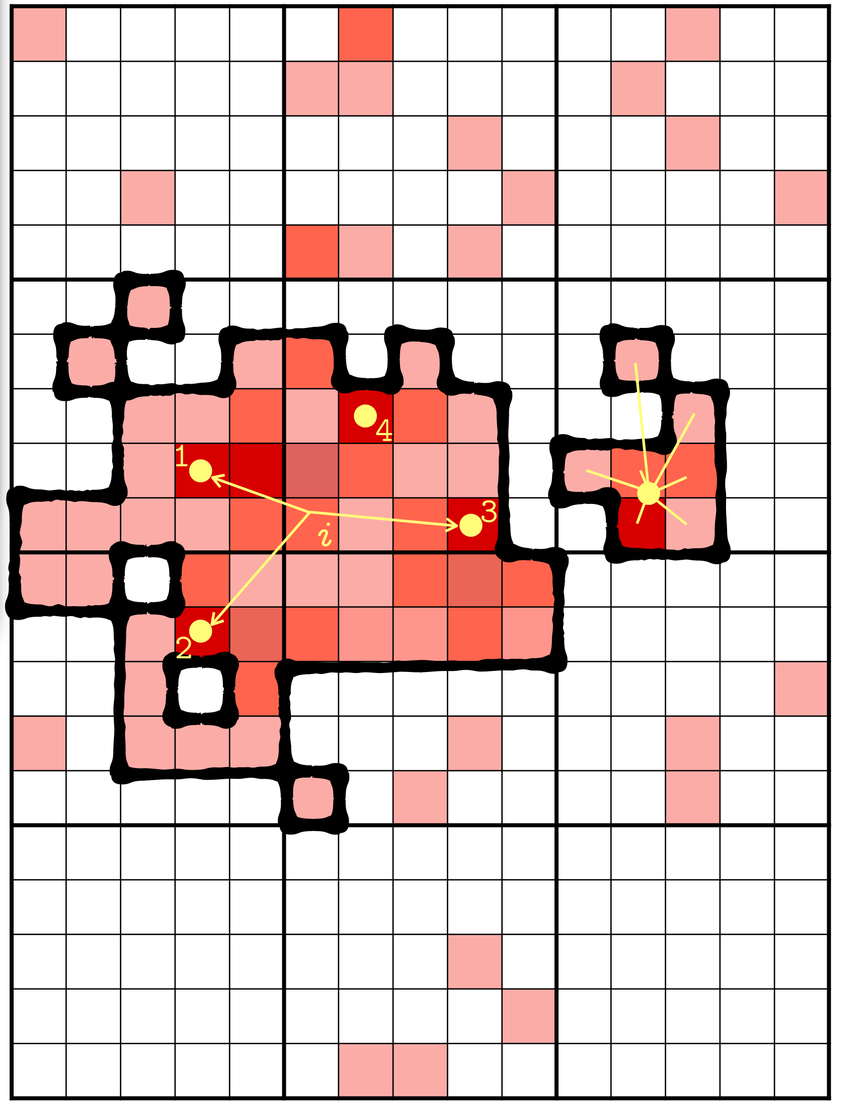

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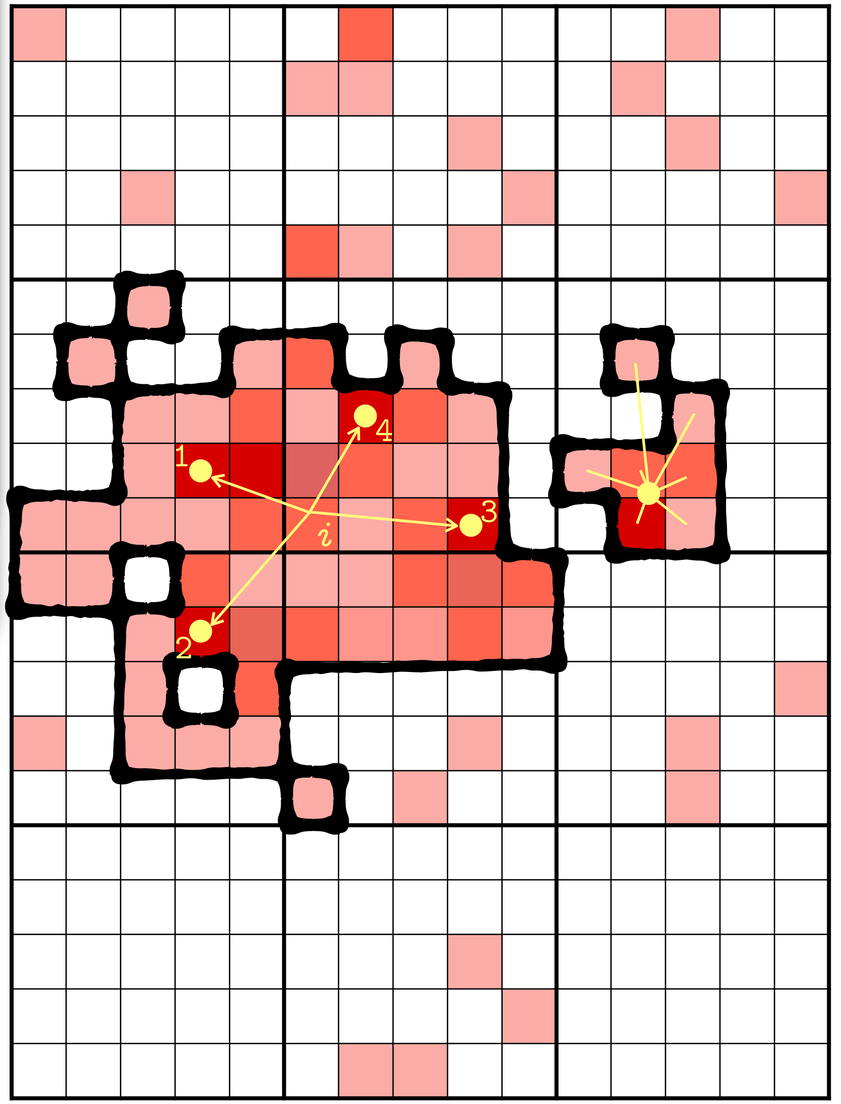

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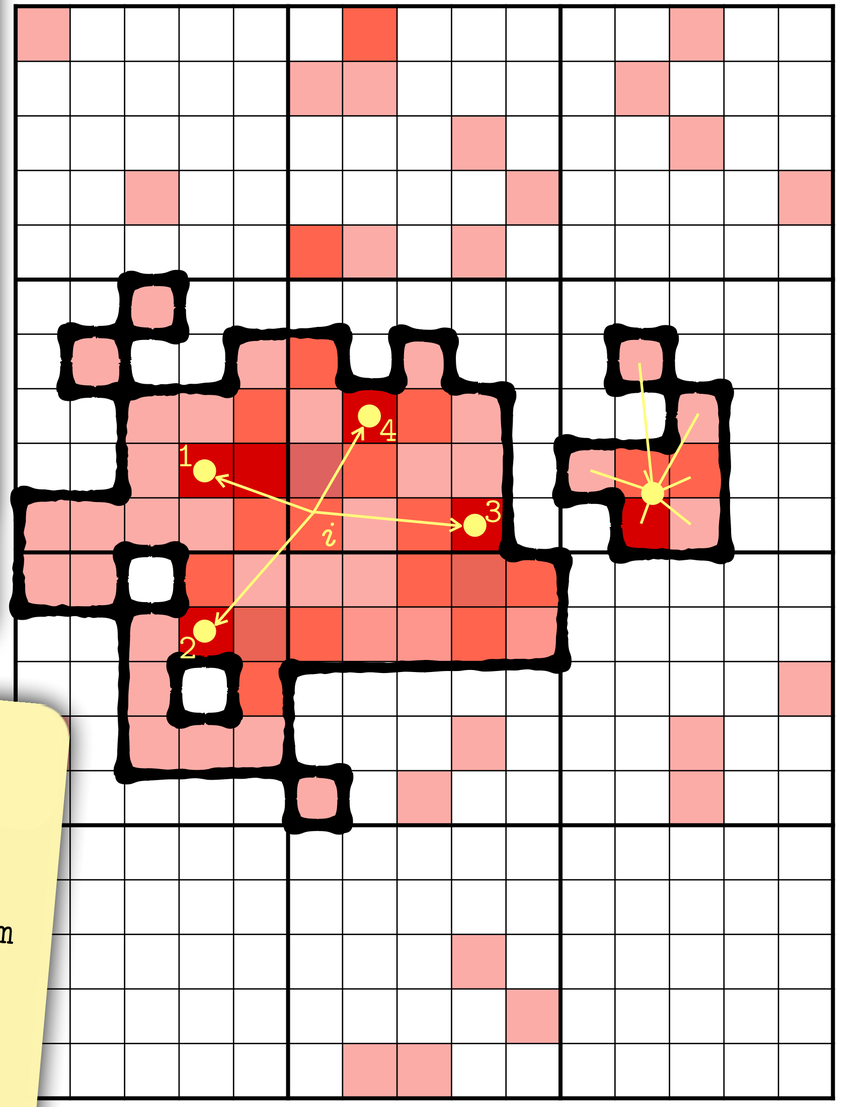

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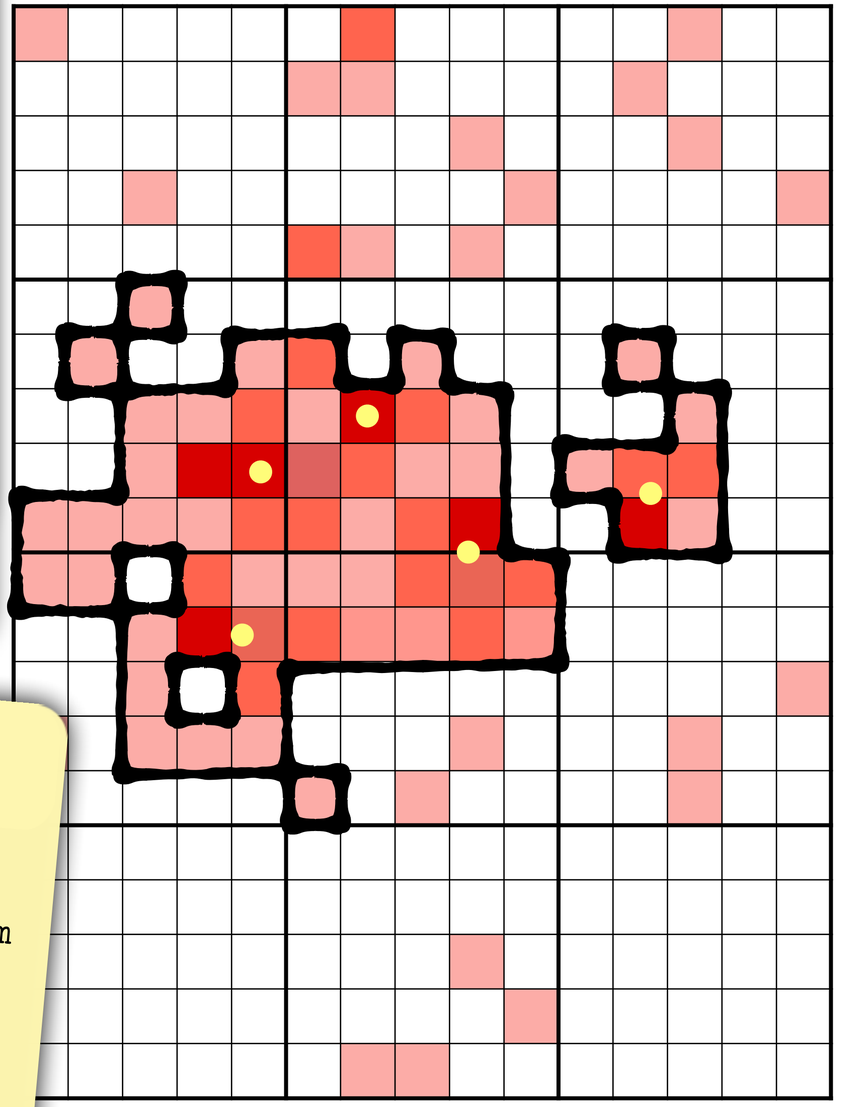

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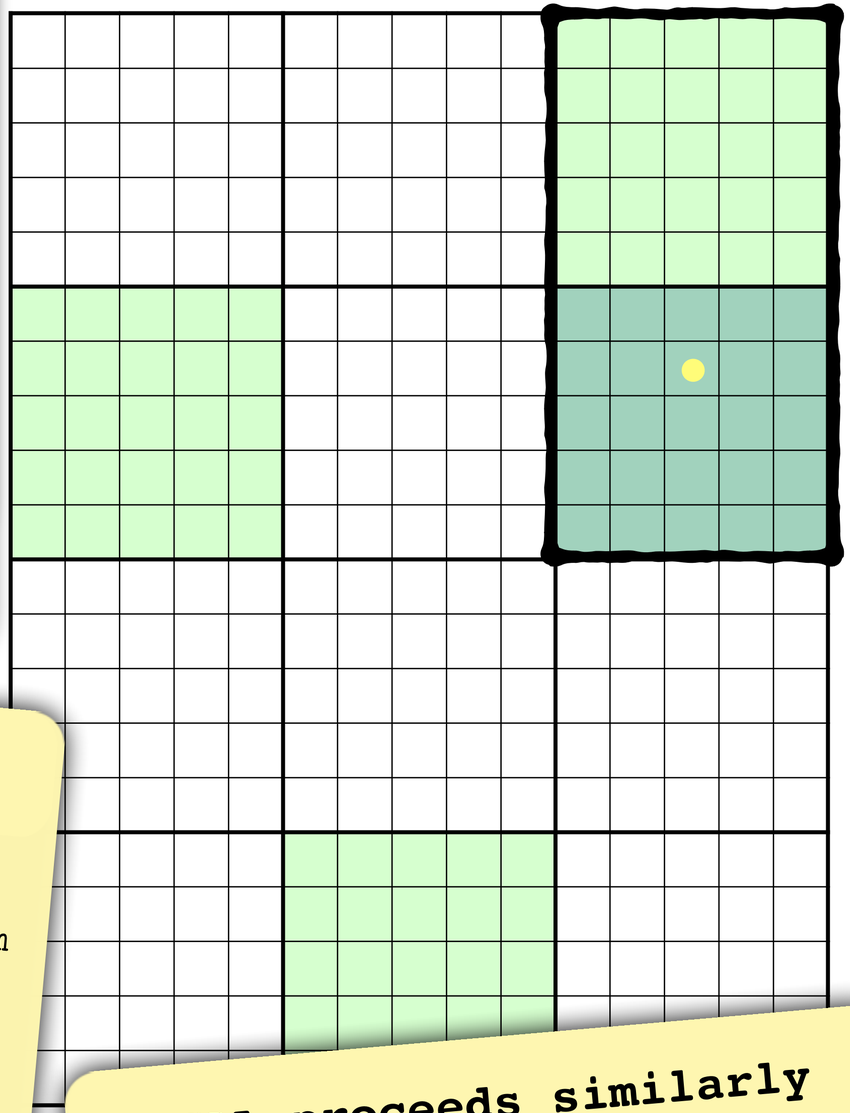

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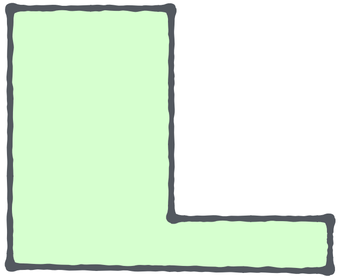
HCAL proceeds similarly

Just less granularity and different parameters

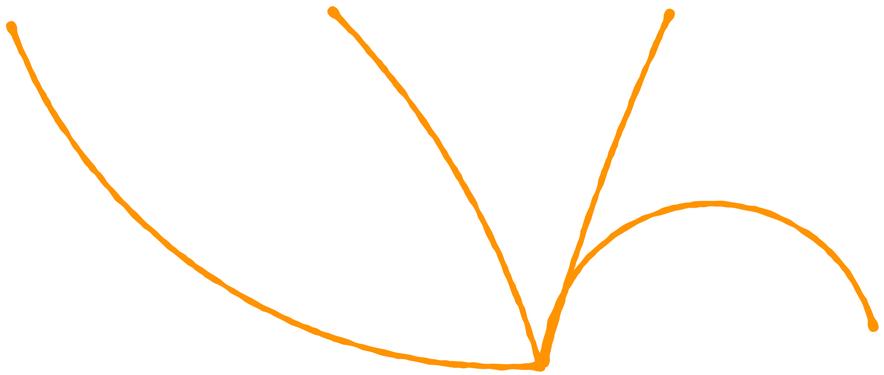
Next: Link across detectors

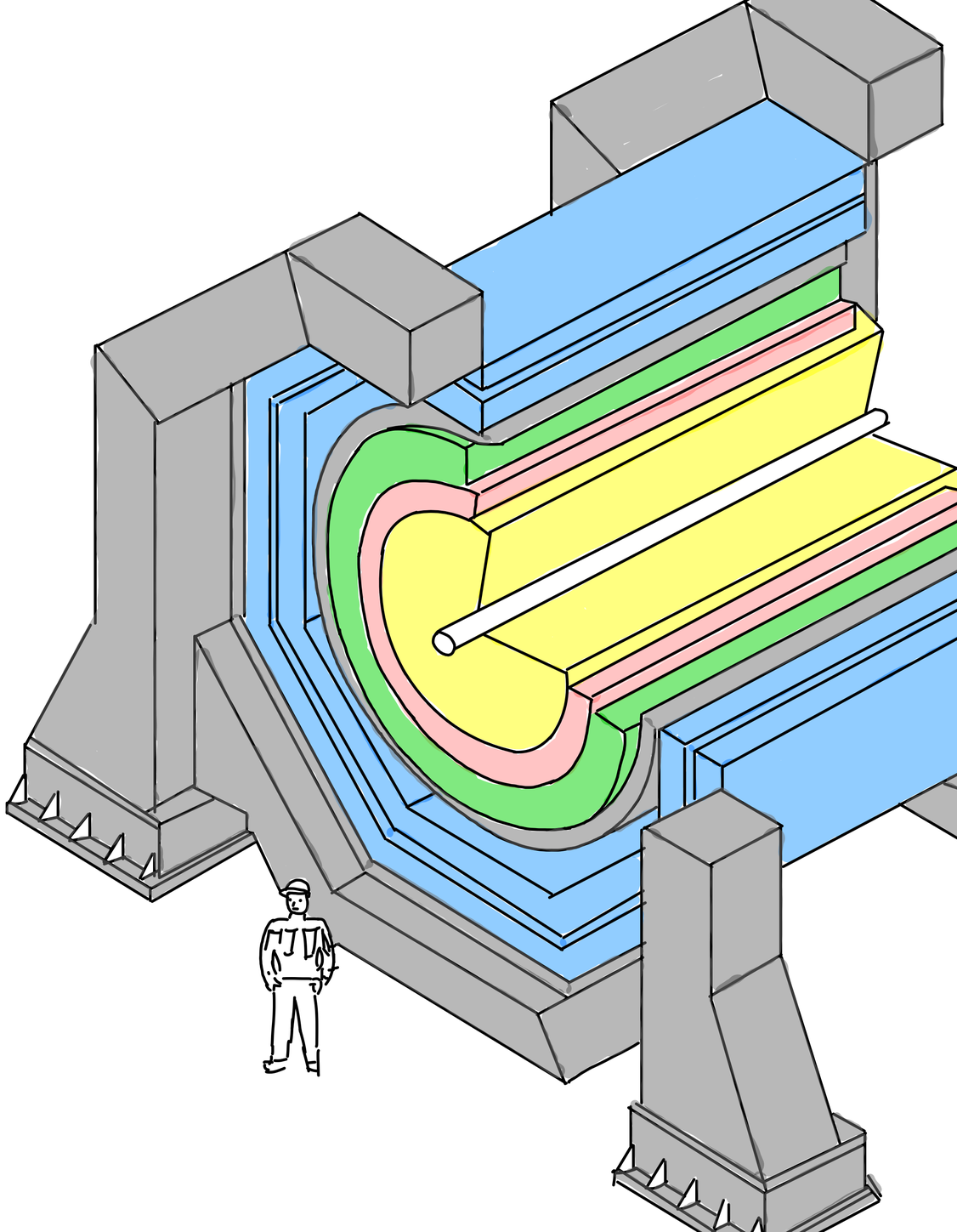
HCAL Clusters



ECAL Clusters

Tracks





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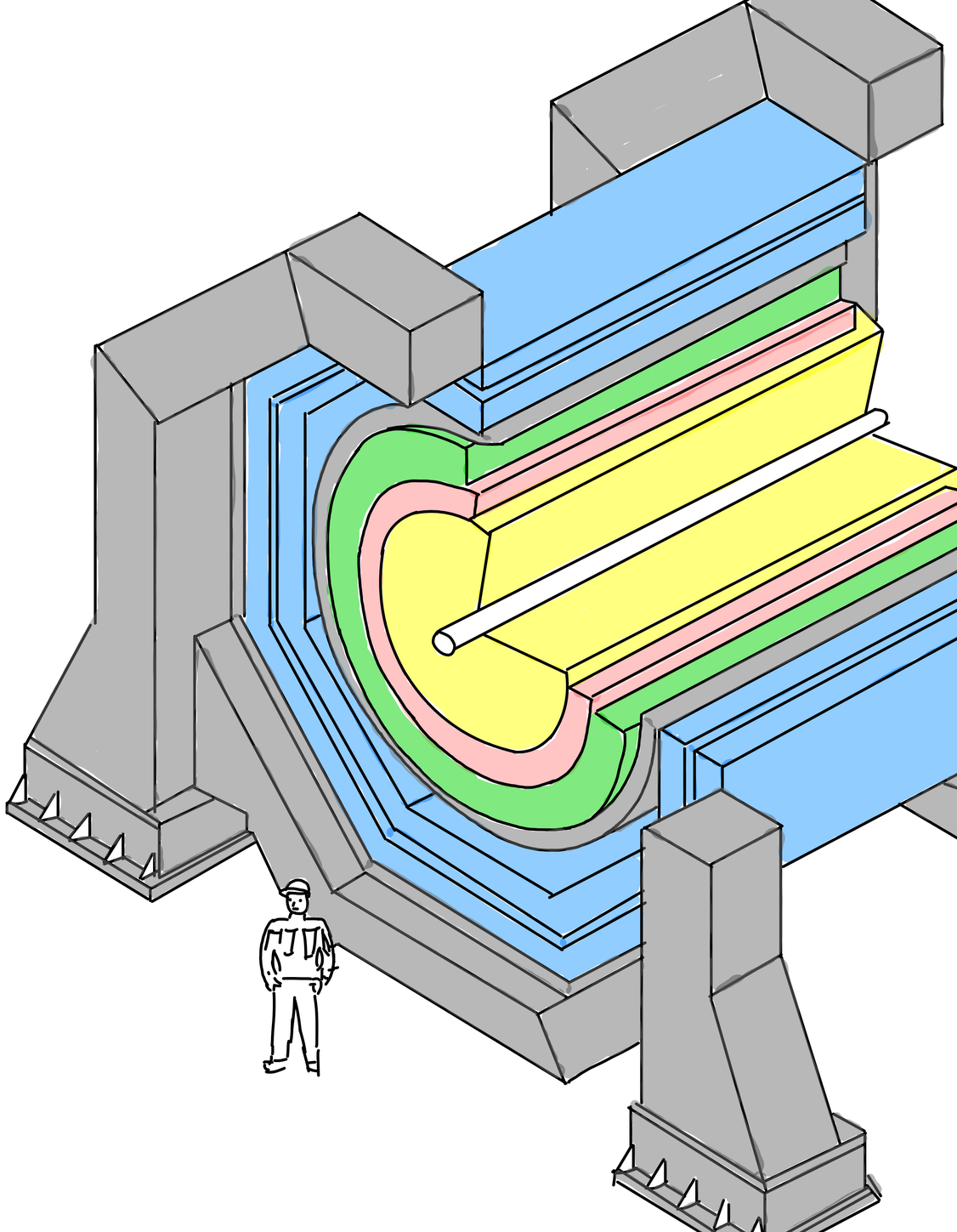

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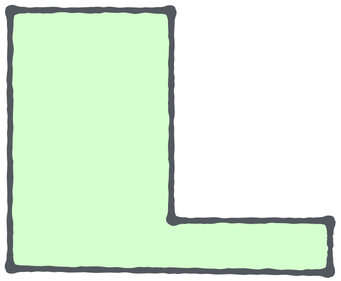

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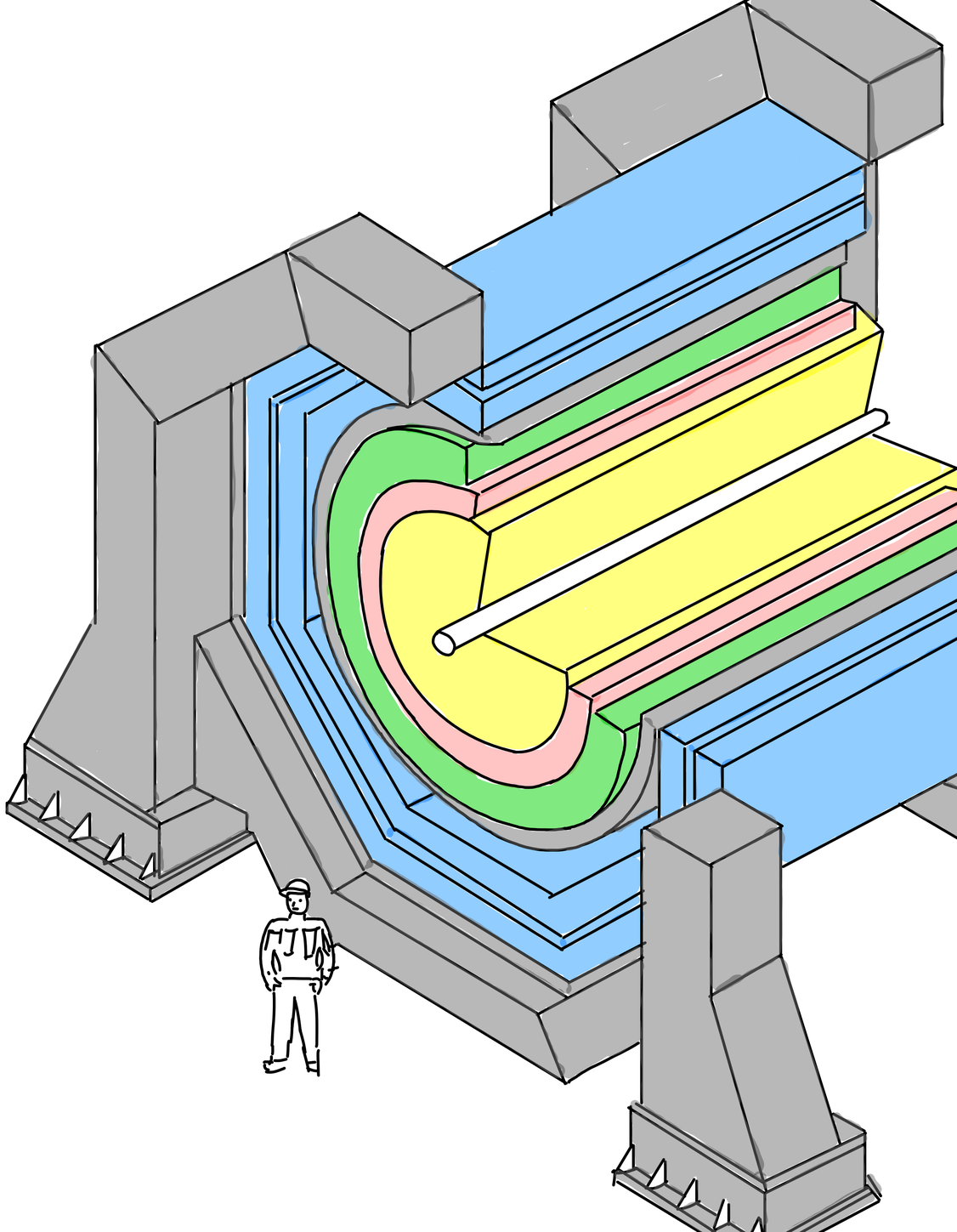

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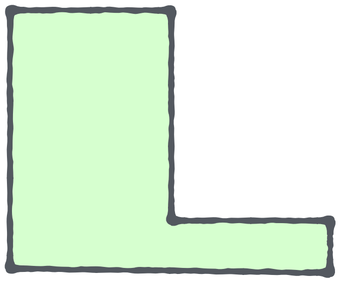

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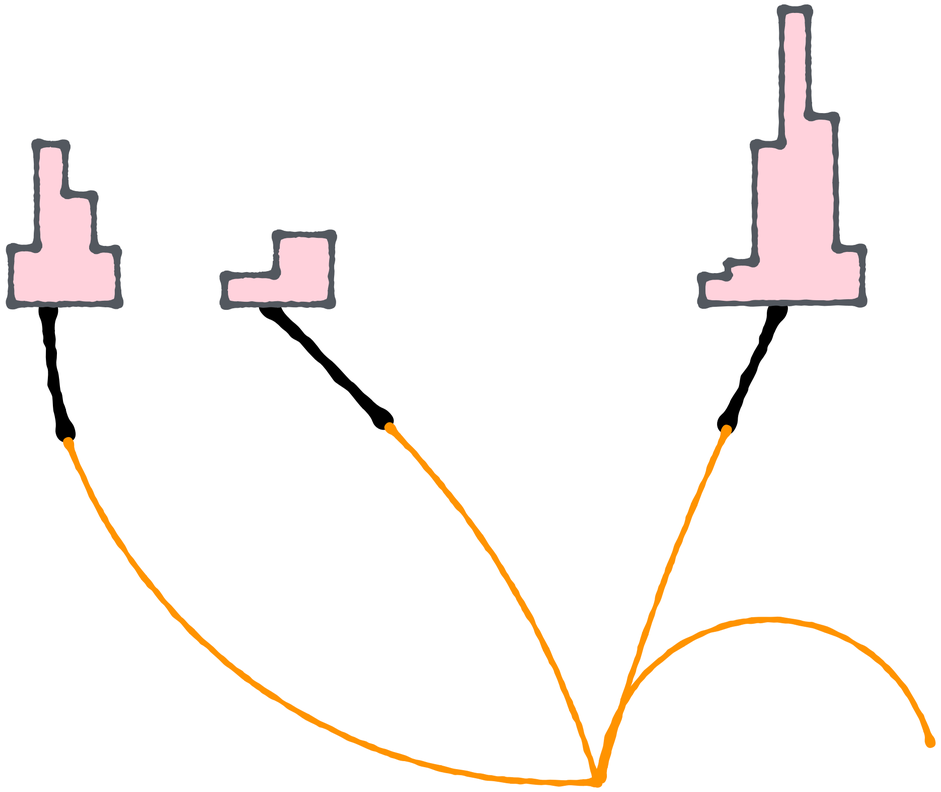

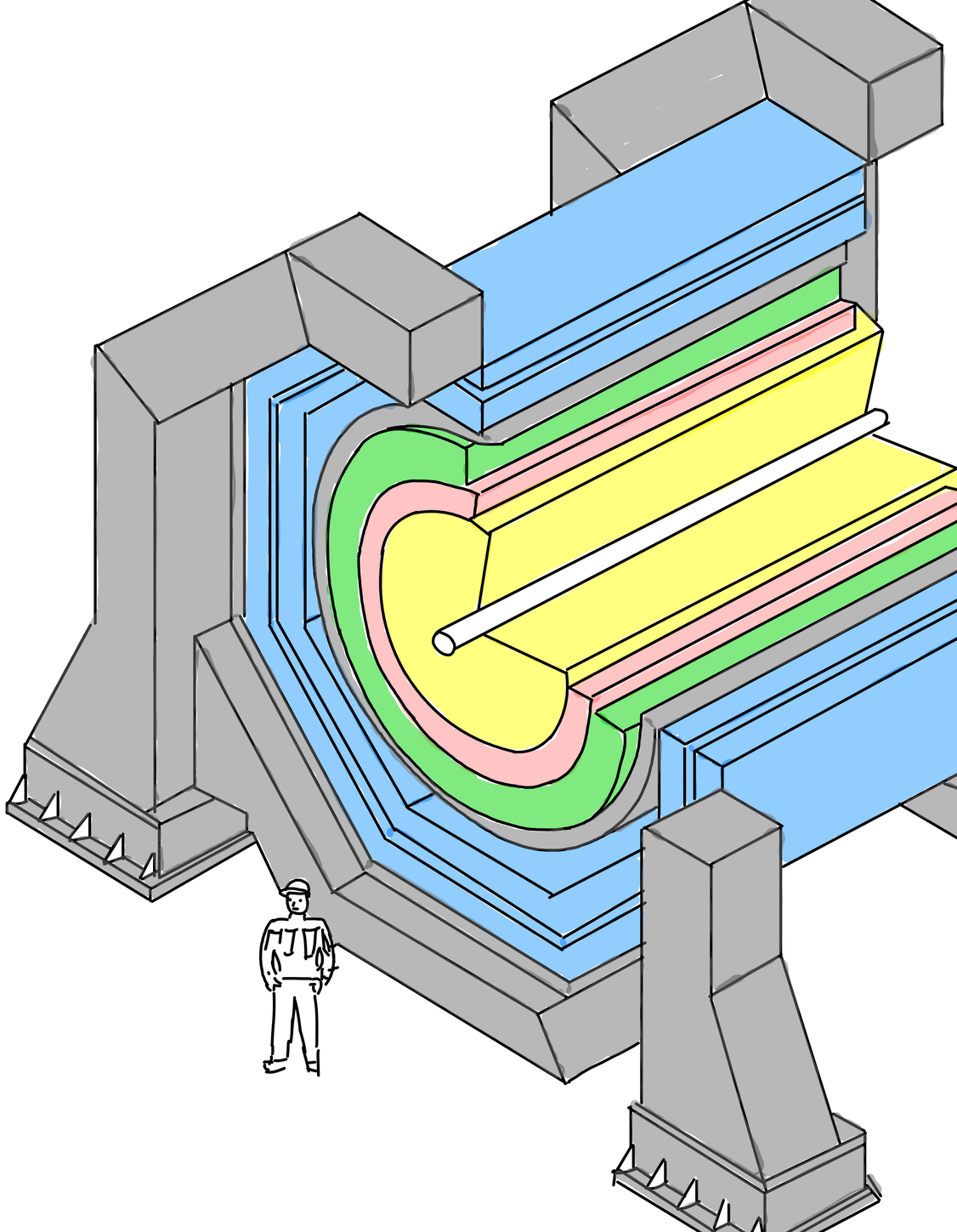

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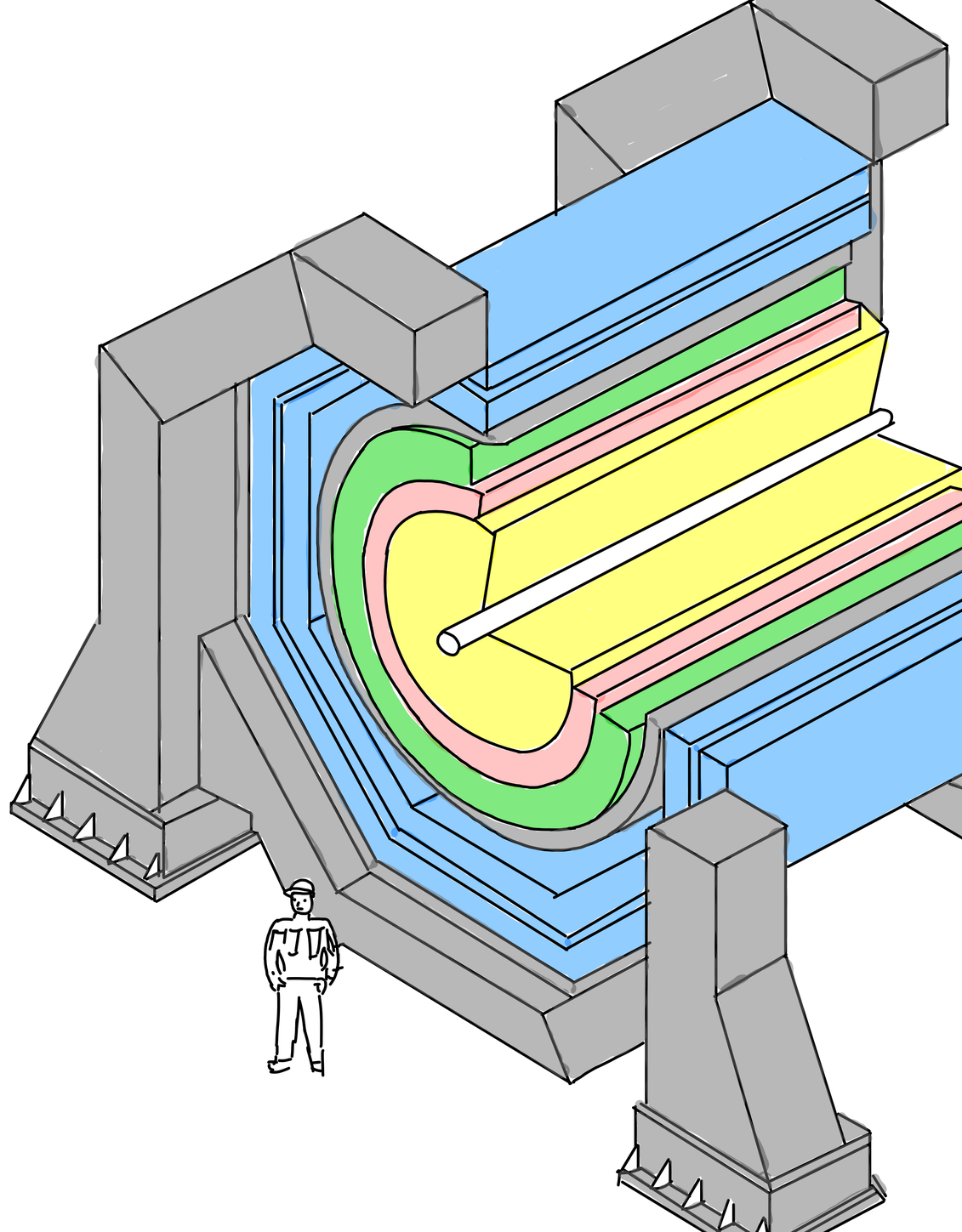

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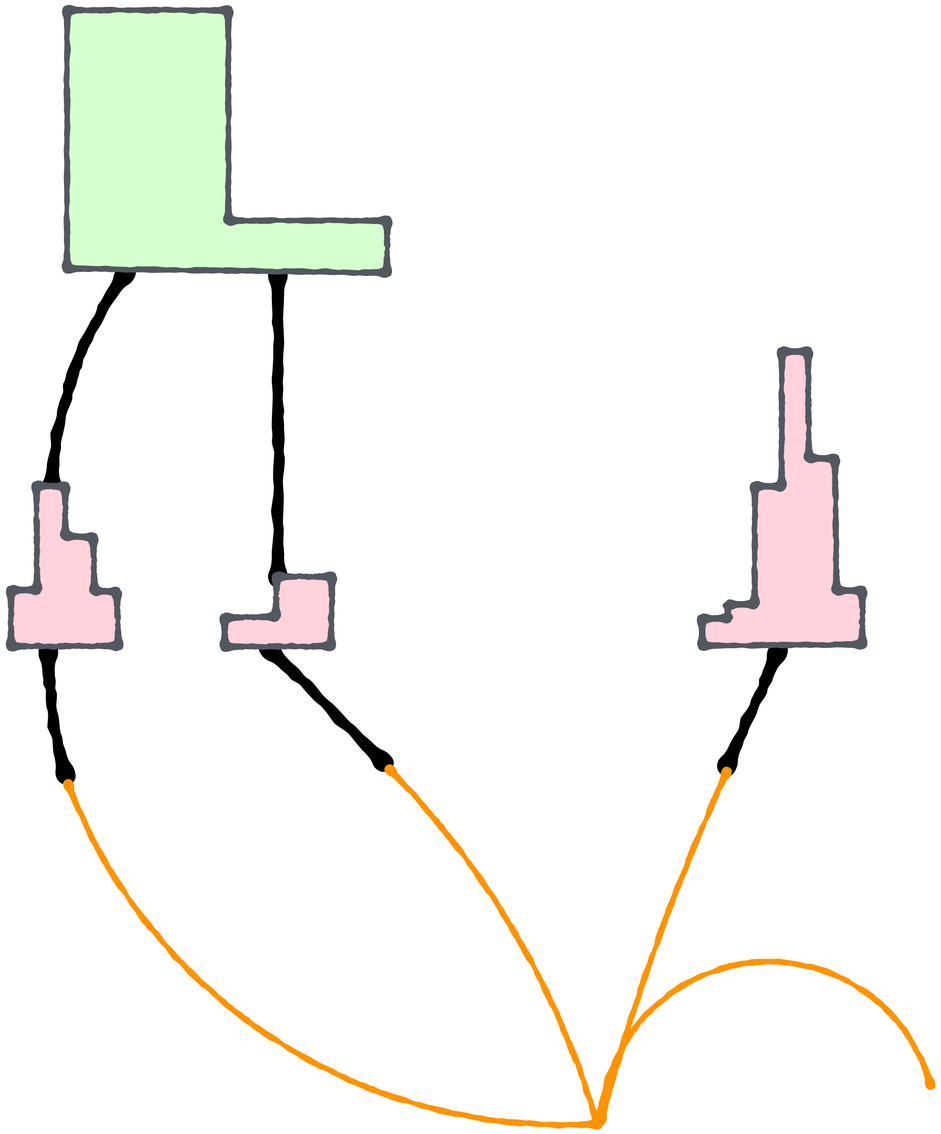

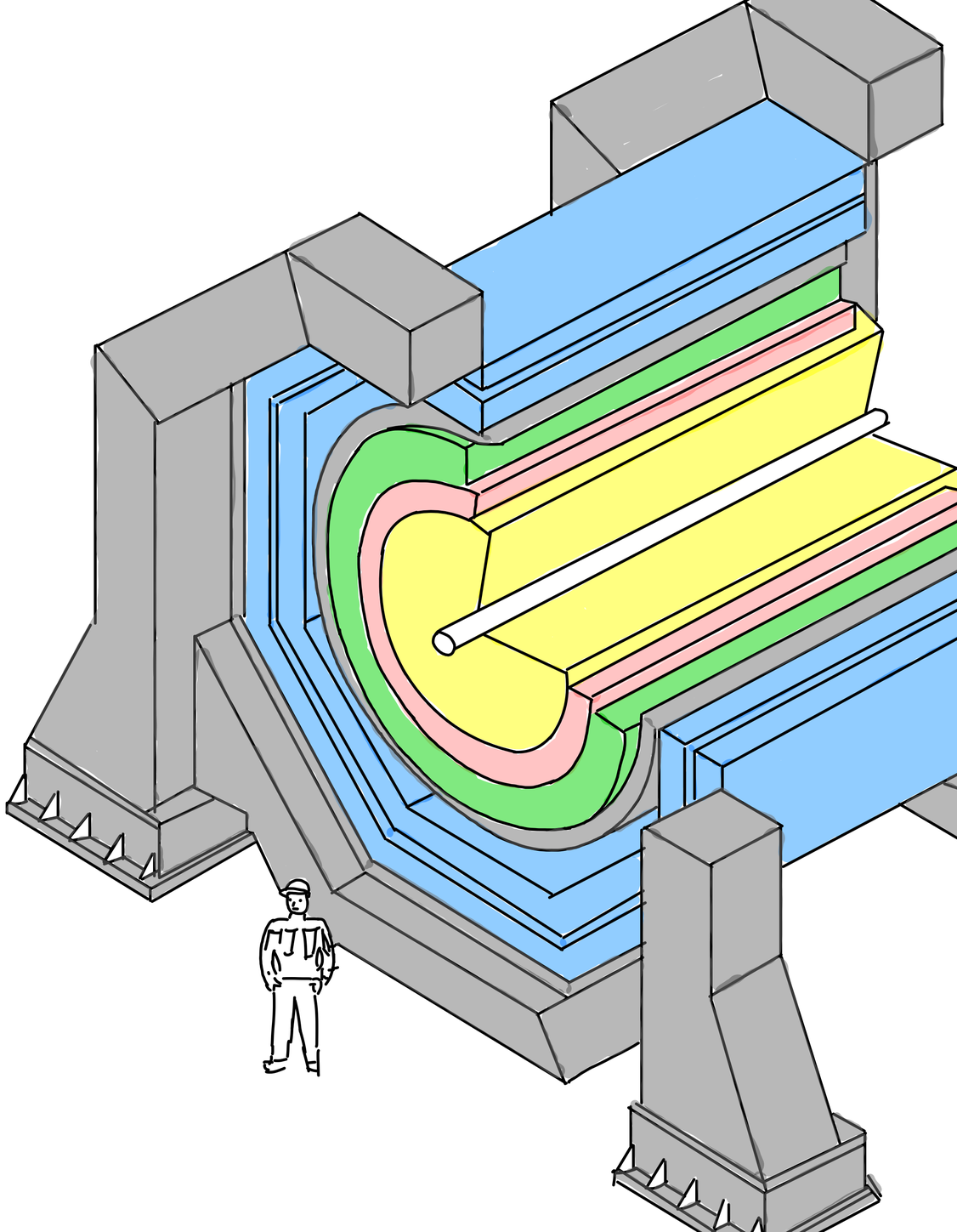

Finally: Apply Particle ID & Separation

HCAL Clusters

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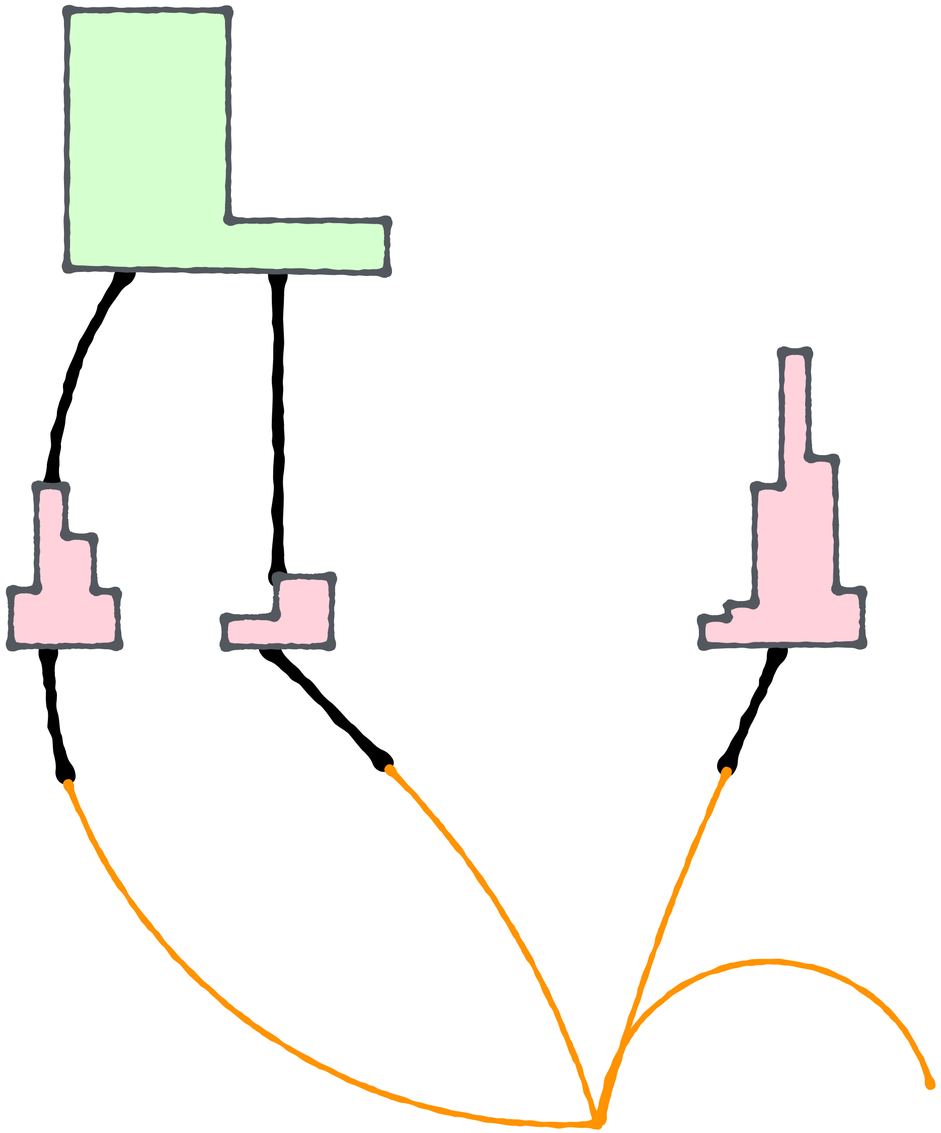

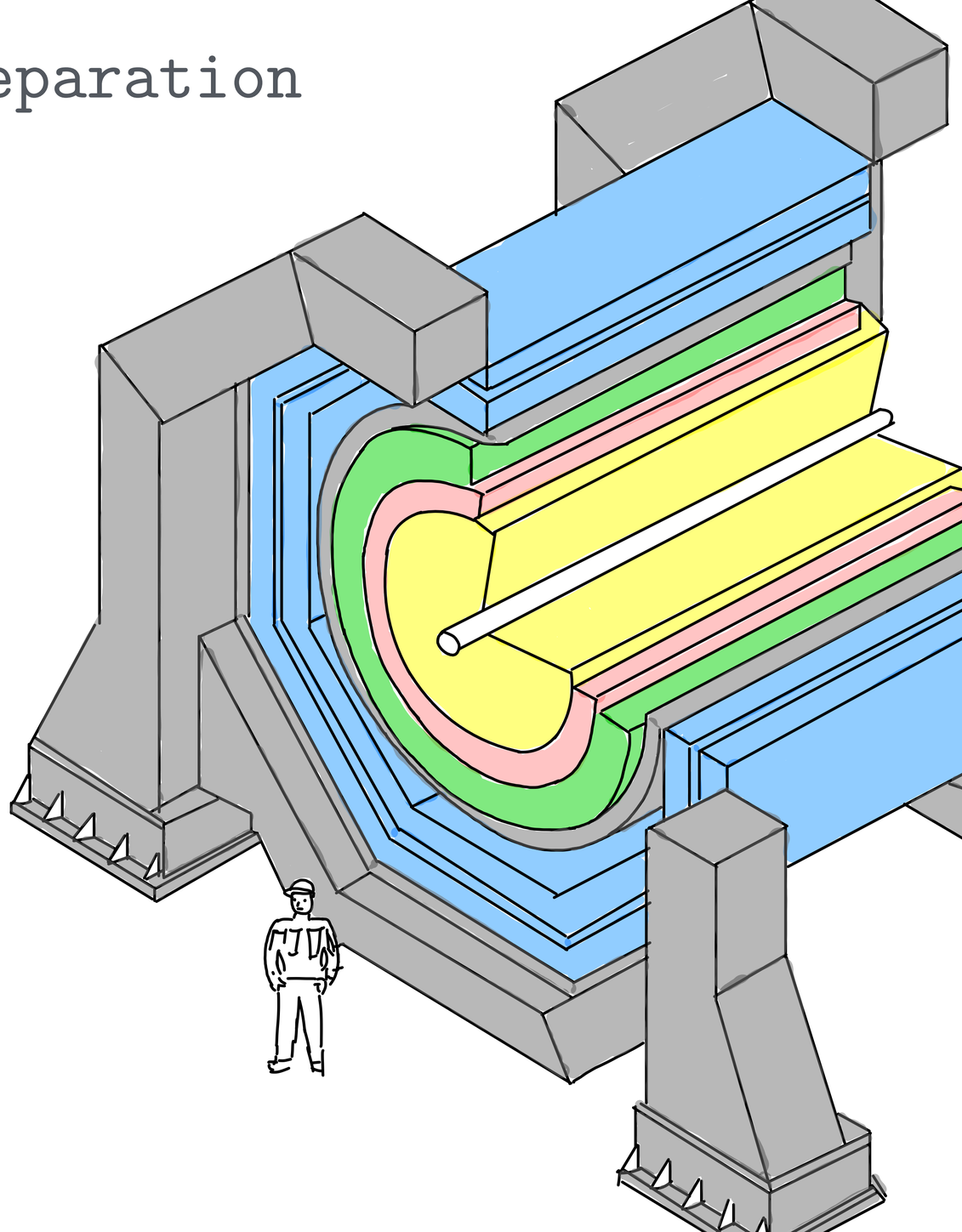

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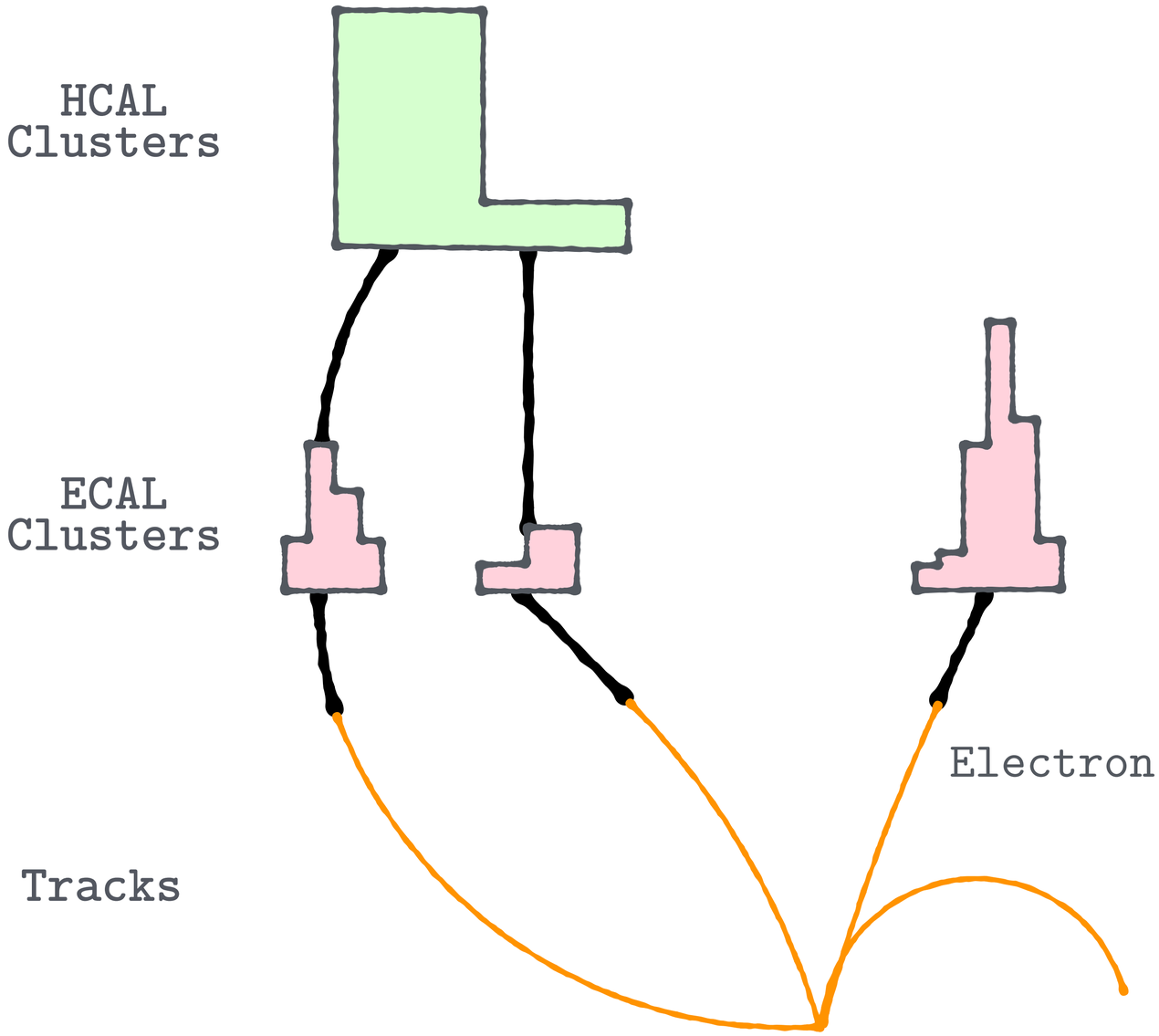

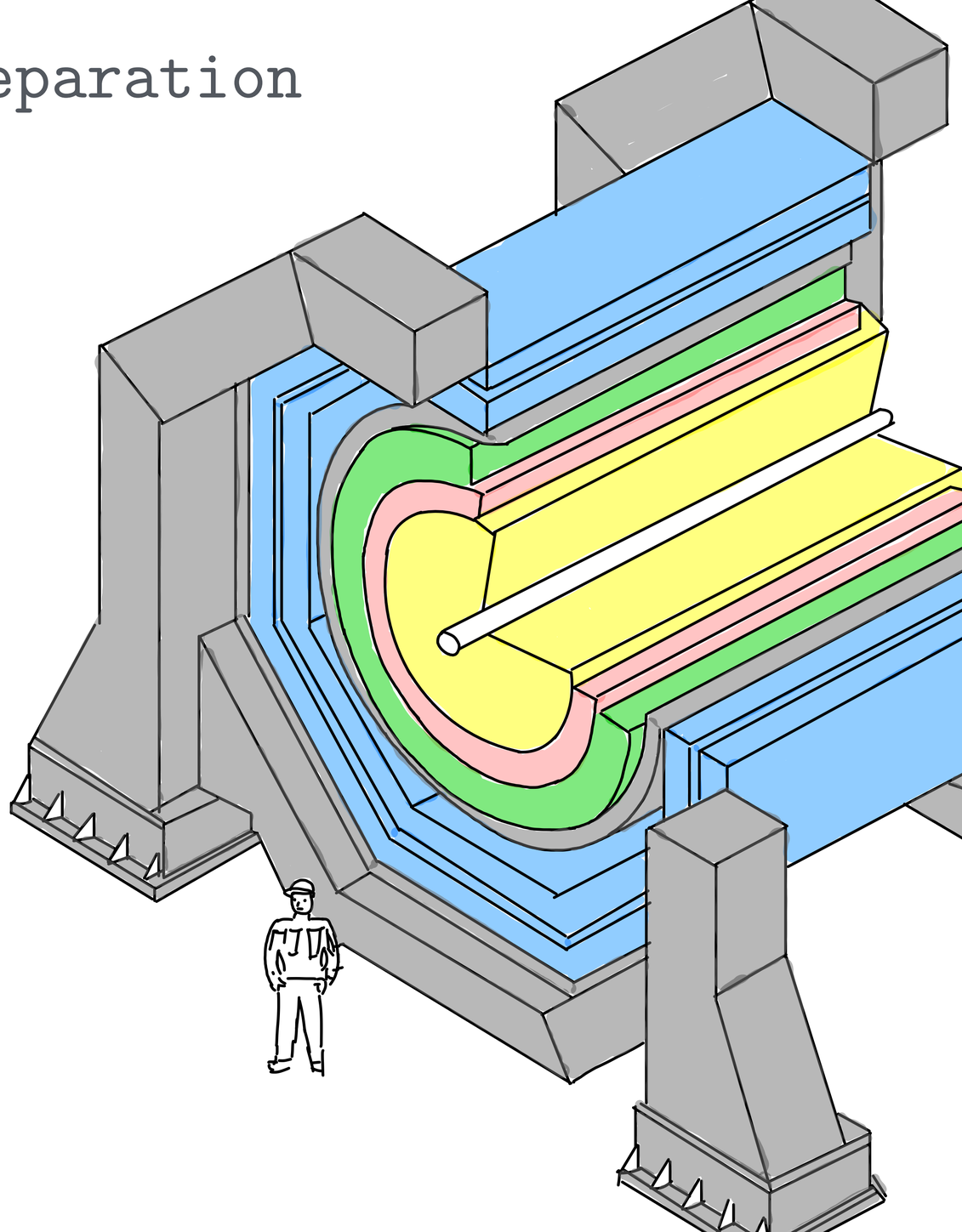

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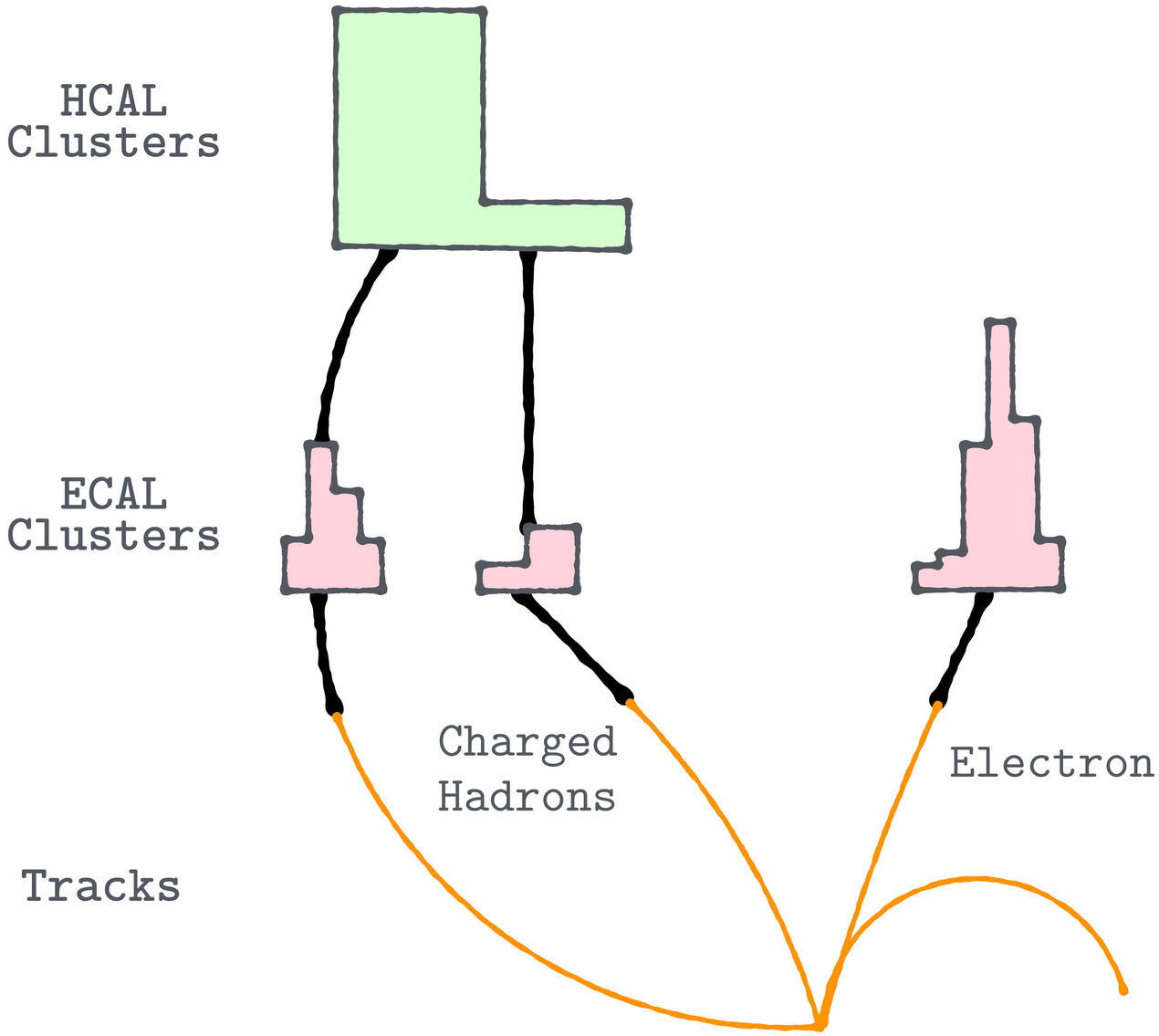

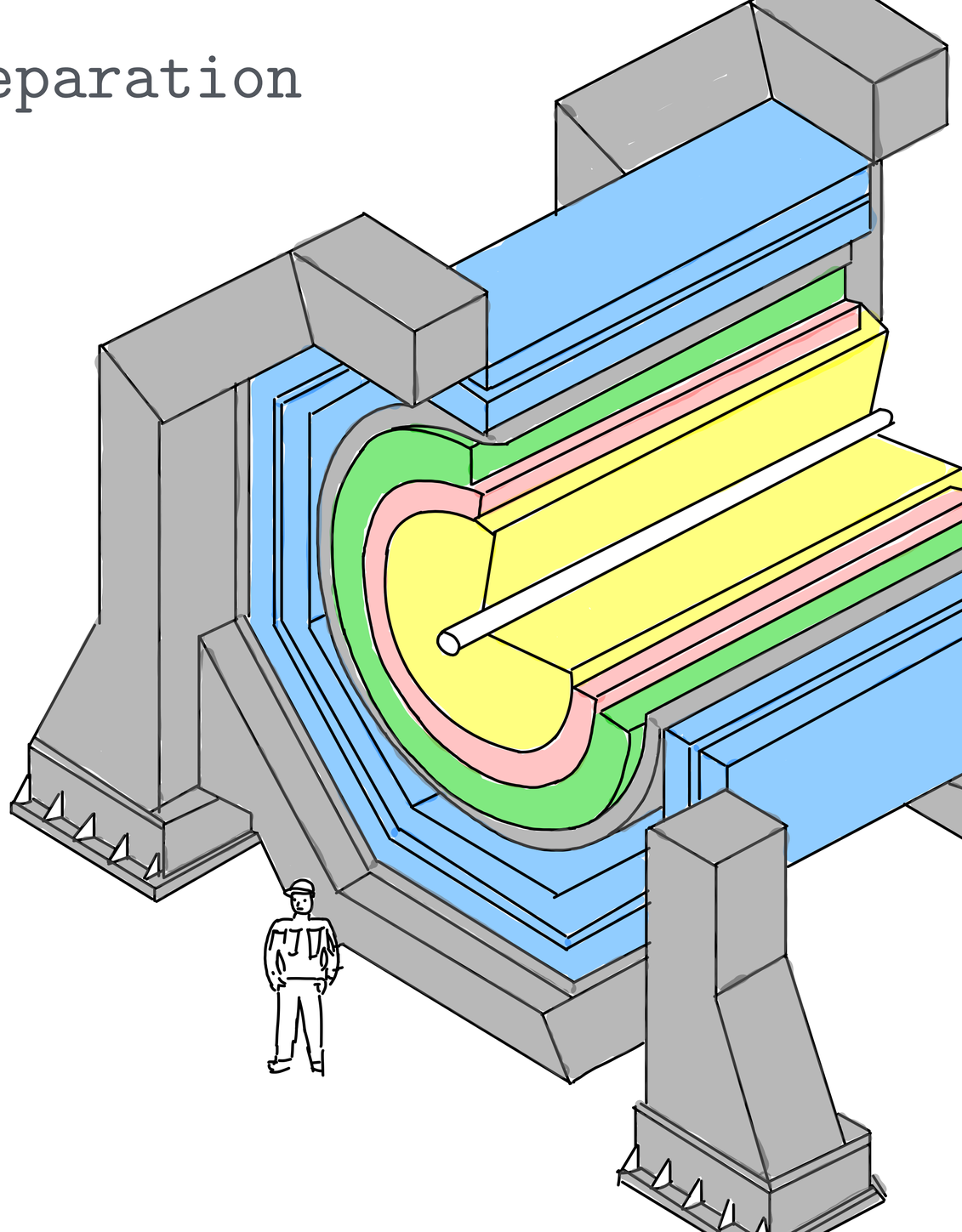

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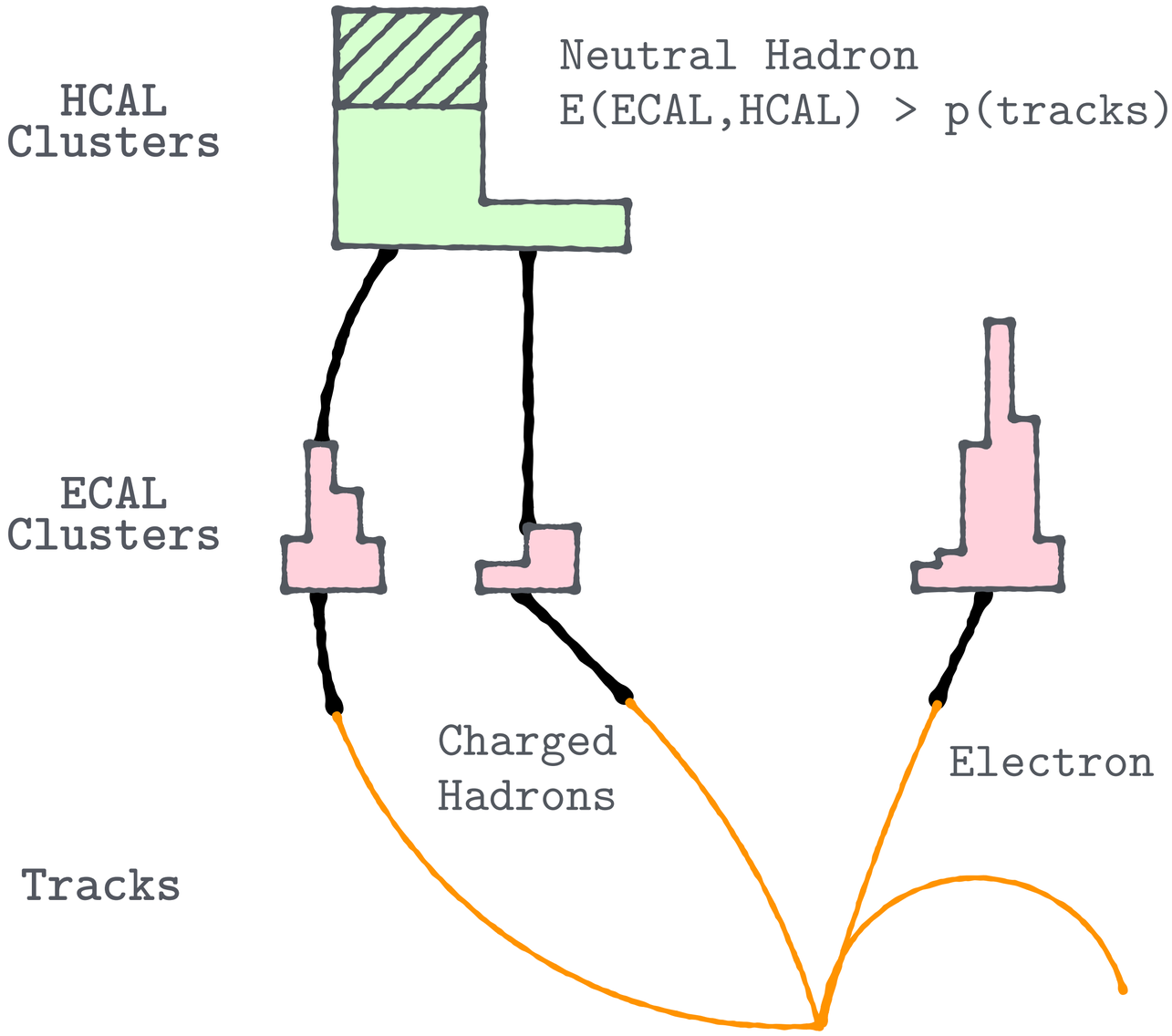

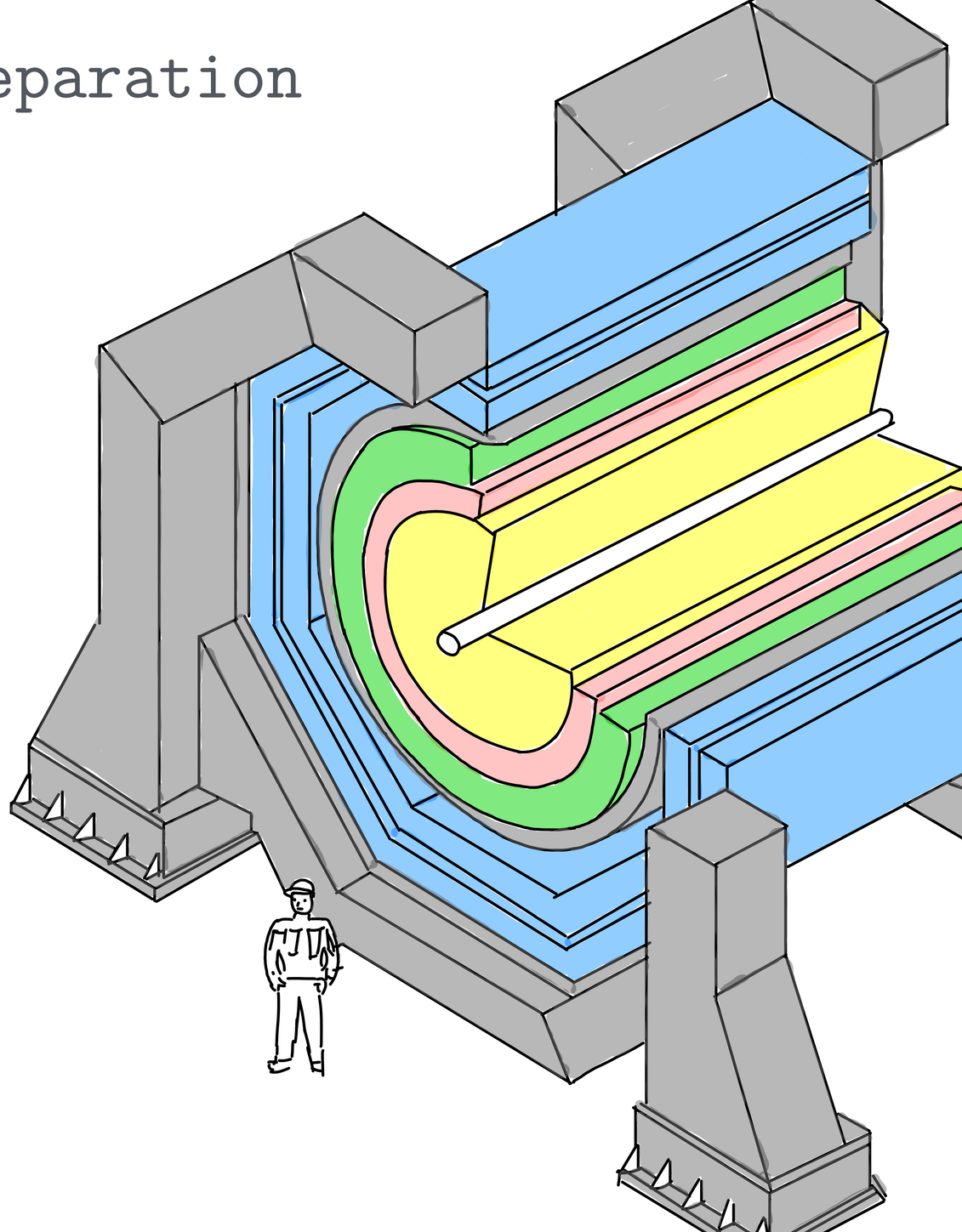

Clean the Event During Reconstruction

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- Find and “remove” muons

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σ_{track}

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- Find and “remove” muons
- Find and “remove” electrons

σ_{track}

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- Find and “remove” muons σ_{track}
- Find and “remove” electrons $\min[\ \sigma_{\text{track}}, \sigma_{\text{ECAL}}\ ]$

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σ_{track}

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- Find and “remove” charged hadrons $\min[\ \sigma_{\text{track}}, \sigma_{\text{HCAL}}\ ]$
- Find and “remove” converted photons σ_{track}

Clean the Event During Reconstruction

- Find and “remove” muons — σ_{track}
- Find and “remove” electrons — $\min[\ \sigma_{\text{track}}, \sigma_{\text{ECAL}}\ ]$
- Find and “remove” charged hadrons — $\min[\ \sigma_{\text{track}}, \sigma_{\text{HCAL}}\ ]$
- Find and “remove” converted photons — σ_{track}
- Find and “remove” V0’s

Clean the Event During Reconstruction

- Find and “remove” muons σ_{track}
- Find and “remove” electrons $\min[\ \sigma_{\text{track}}, \sigma_{\text{ECAL}}\ ]$
- Find and “remove” charged hadrons $\min[\ \sigma_{\text{track}}, \sigma_{\text{HCAL}}\ ]$
- Find and “remove” converted photons σ_{track}
- Find and “remove” V0’s σ_{track}

Clean the Event During Reconstruction

- Find and “remove” muons — σ_{track}
- Find and “remove” electrons — $\min[\ \sigma_{\text{track}}, \sigma_{\text{ECAL}}\ ]$
- Find and “remove” charged hadrons — $\min[\ \sigma_{\text{track}}, \sigma_{\text{HCAL}}\ ]$
- Find and “remove” converted photons — σ_{track}
- Find and “remove” V0’s — σ_{track}
- Find and “remove” photons

Clean the Event During Reconstruction

- Find and “remove” muons — σ_{track}
- Find and “remove” electrons — $\min[\ \sigma_{\text{track}}, \sigma_{\text{ECAL}}\ ]$
- Find and “remove” charged hadrons — $\min[\ \sigma_{\text{track}}, \sigma_{\text{HCAL}}\ ]$
- Find and “remove” converted photons — σ_{track}
- Find and “remove” V0’s — σ_{track}
- Find and “remove” photons — σ_{ECAL}

Clean the Event During Reconstruction

- Find and “remove” muons — σ_{track}
- Find and “remove” electrons — $\min[\ \sigma_{\text{track}}, \sigma_{\text{ECAL}}\ ]$
- Find and “remove” charged hadrons — $\min[\ \sigma_{\text{track}}, \sigma_{\text{HCAL}}\ ]$
- Find and “remove” converted photons — σ_{track}
- Find and “remove” V0’s — σ_{track}
- Find and “remove” photons — σ_{ECAL}
- Left with neutral hadrons (10%)

Clean the Event During Reconstruction

- Find and “remove” muons — σ_{track}
- Find and “remove” electrons — $\min[\ \sigma_{\text{track}}, \sigma_{\text{ECAL}}\ ]$
- Find and “remove” charged hadrons — $\min[\ \sigma_{\text{track}}, \sigma_{\text{HCAL}}\ ]$
- Find and “remove” converted photons — σ_{track}
- Find and “remove” V0’s — σ_{track}
- Find and “remove” photons — σ_{ECAL}
- Left with neutral hadrons (10%) — σ_{HCAL} + fakes

Clean the Event During Reconstruction

- Find and “remove” muons — σ_{track}
- Find and “remove” electrons — $\min[\ \sigma_{\text{track}}, \sigma_{\text{ECAL}}\ ]$
- Find and “remove” charged hadrons — $\min[\ \sigma_{\text{track}}, \sigma_{\text{HCAL}}\ ]$
- Find and “remove” converted photons — σ_{track}
- Find and “remove” V0’s — σ_{track}
- Find and “remove” photons — σ_{ECAL}
- Left with neutral hadrons (10%) — σ_{HCAL} **+ fakes**

- Use above list of Particles to describe entire event!

Four true particles:

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

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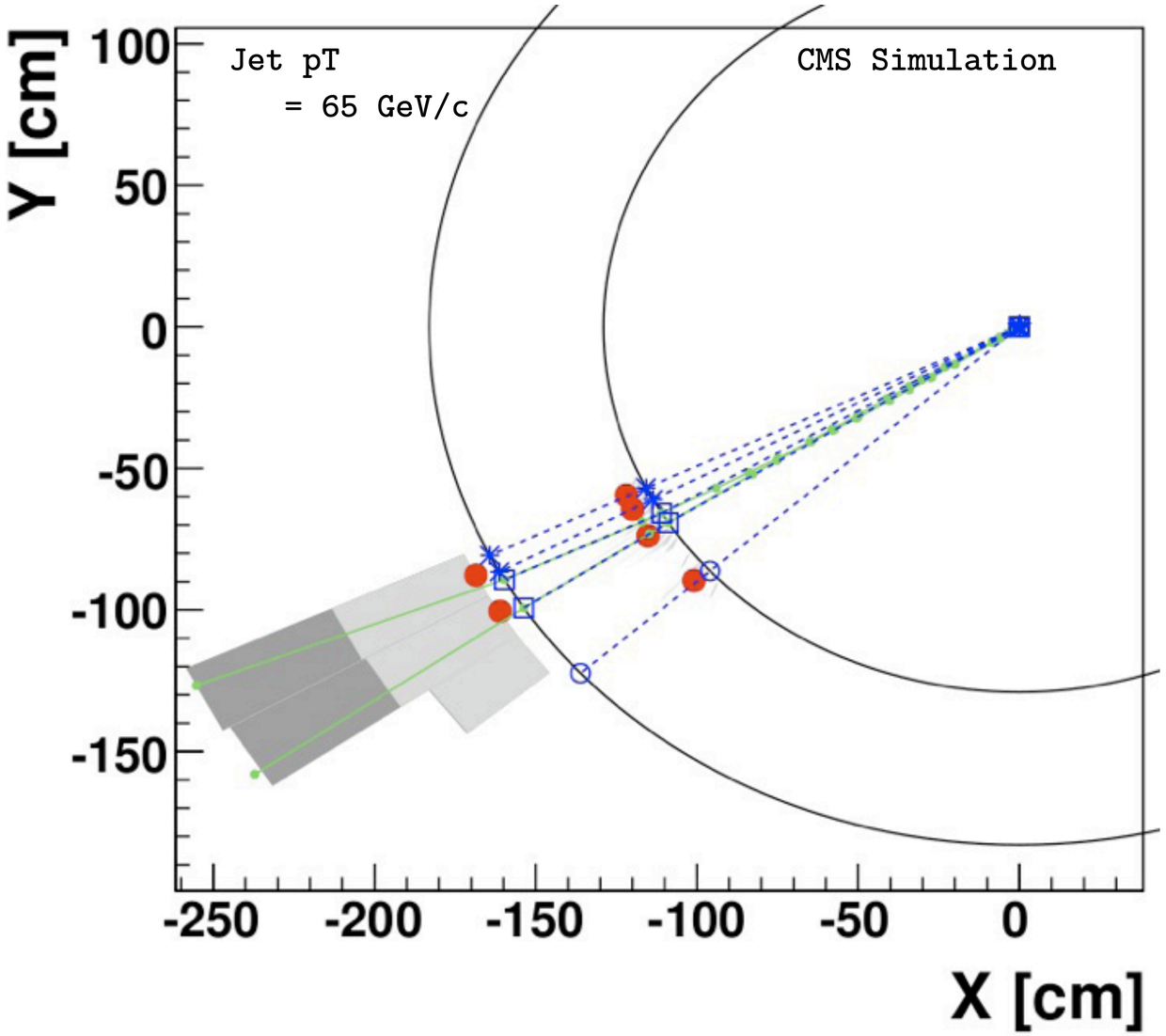
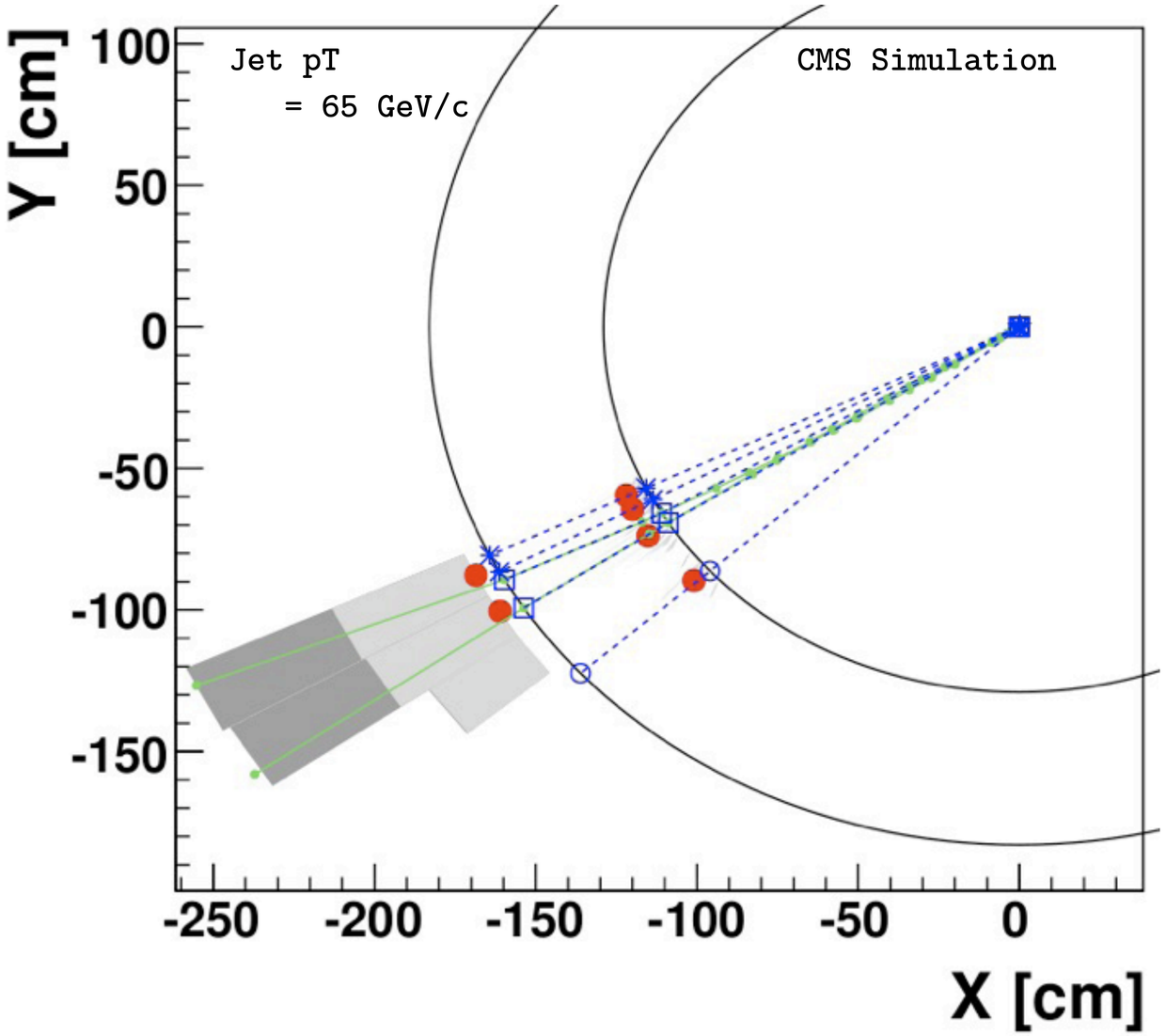
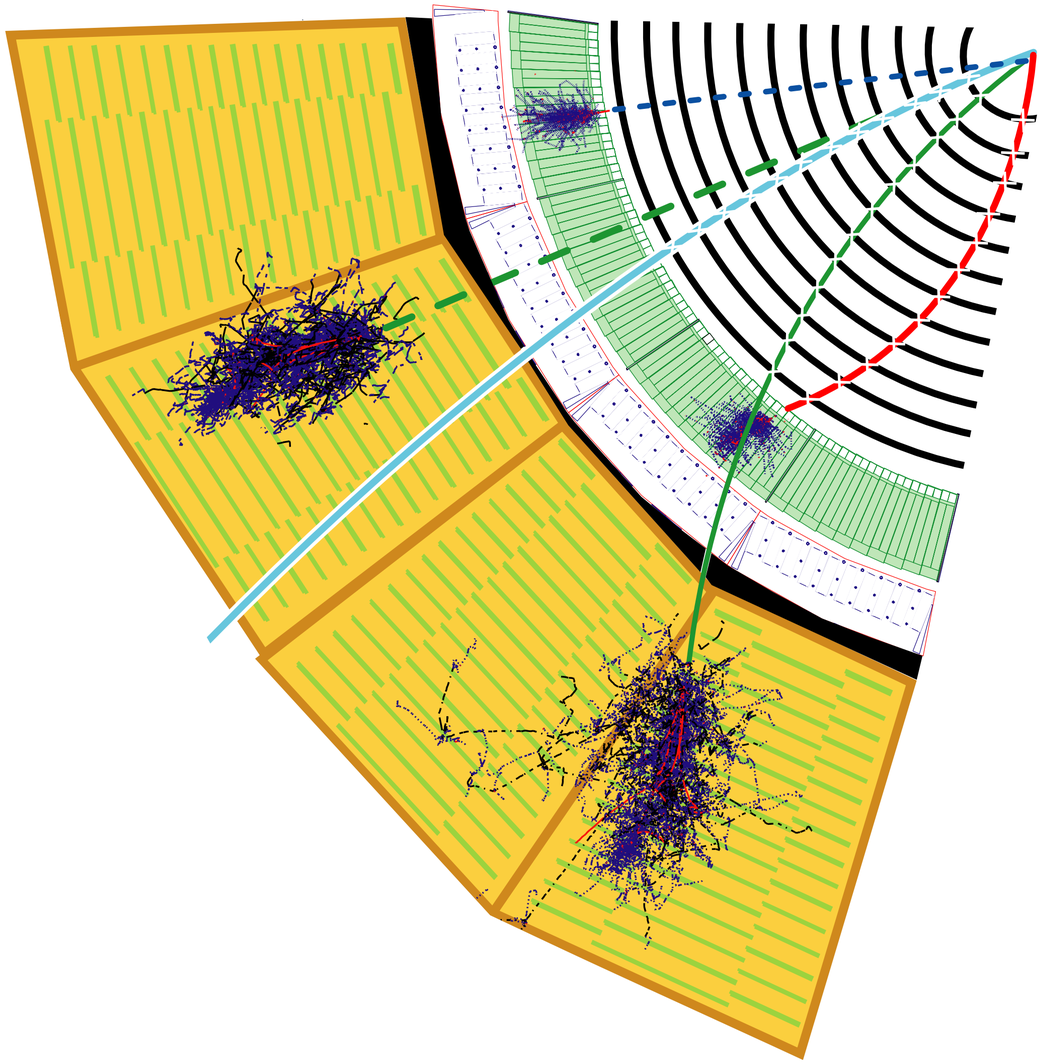
$\pi^+, \pi^-, \pi^0, K_L^0$



Four true particles:

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





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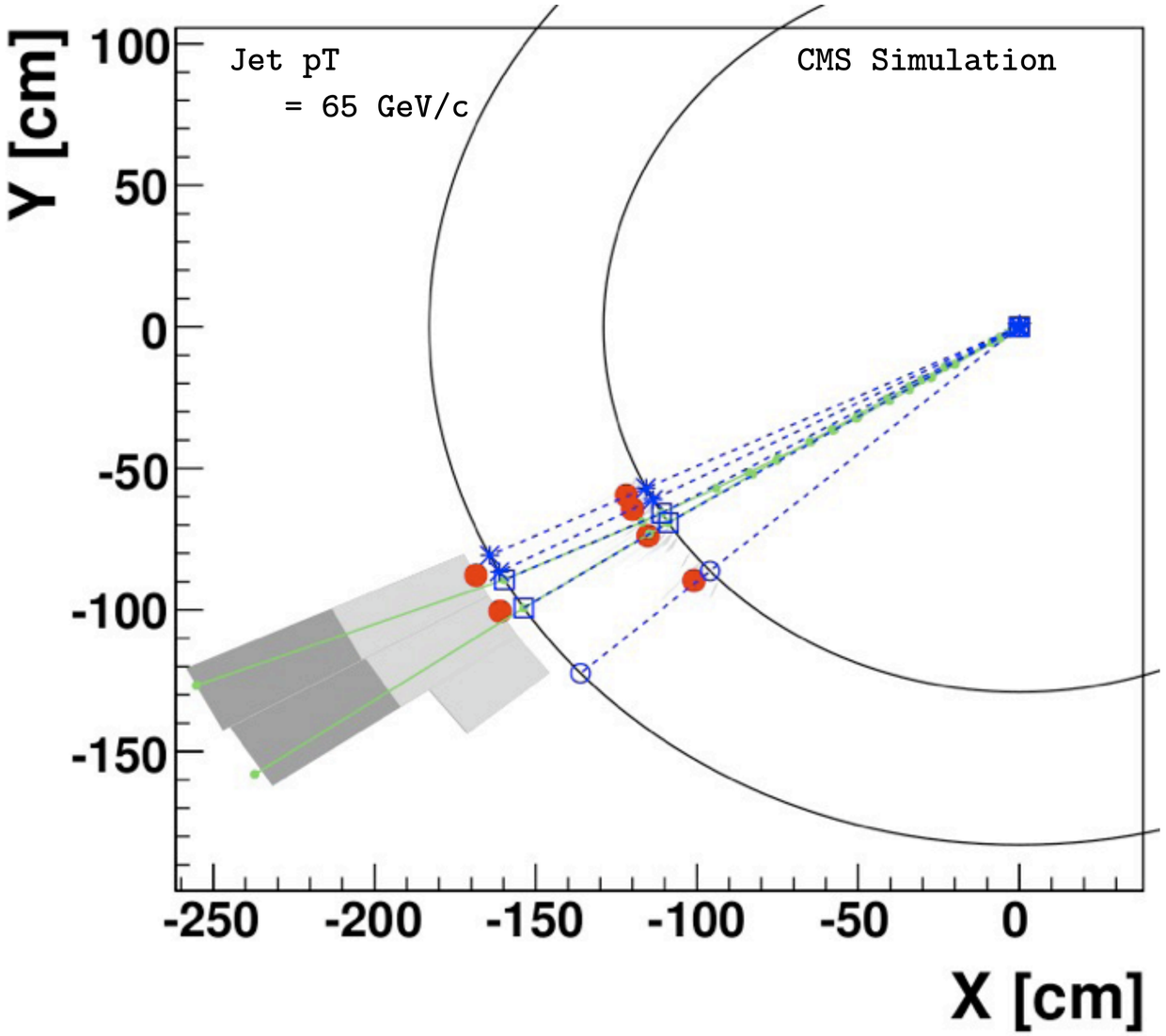

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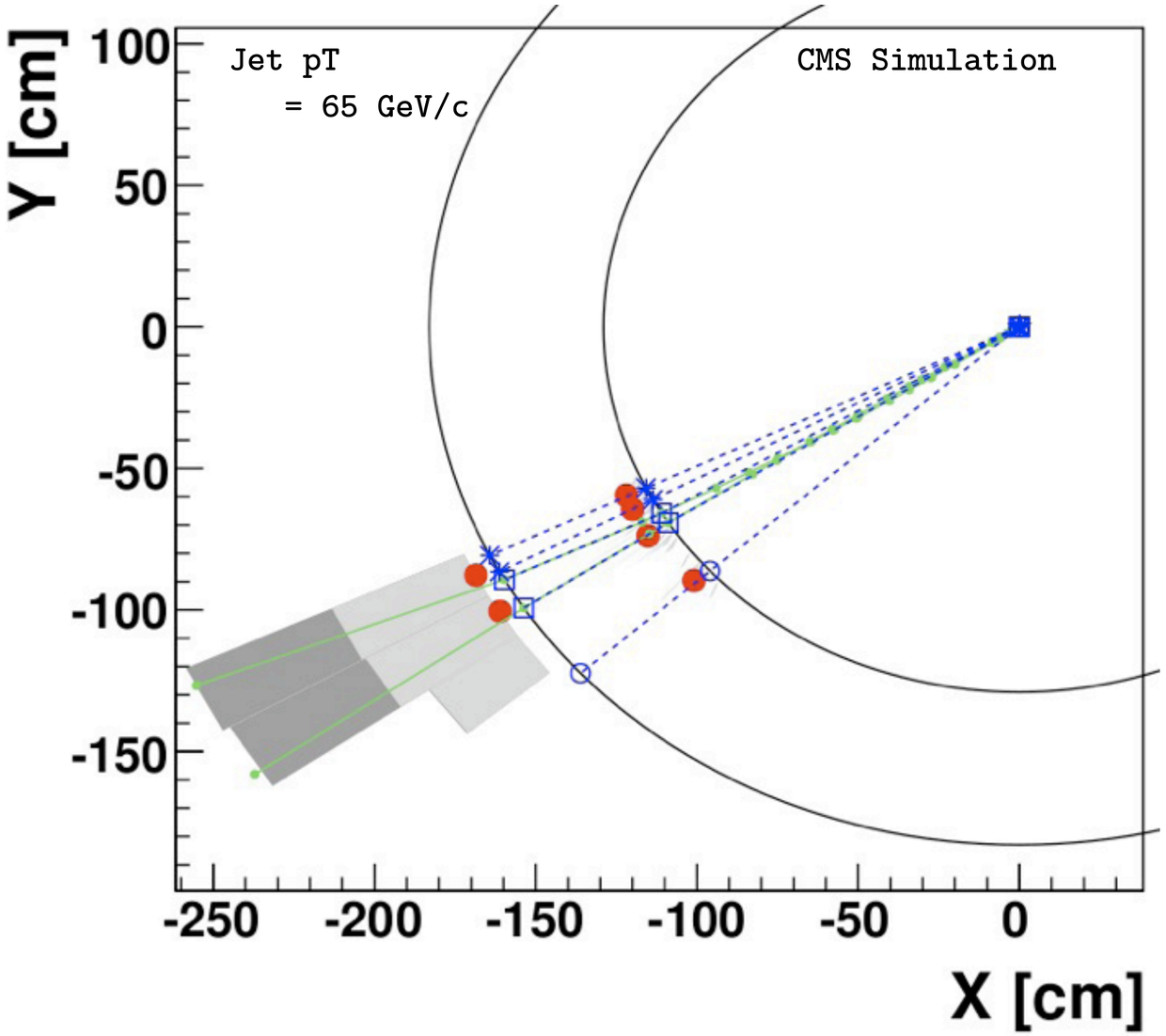

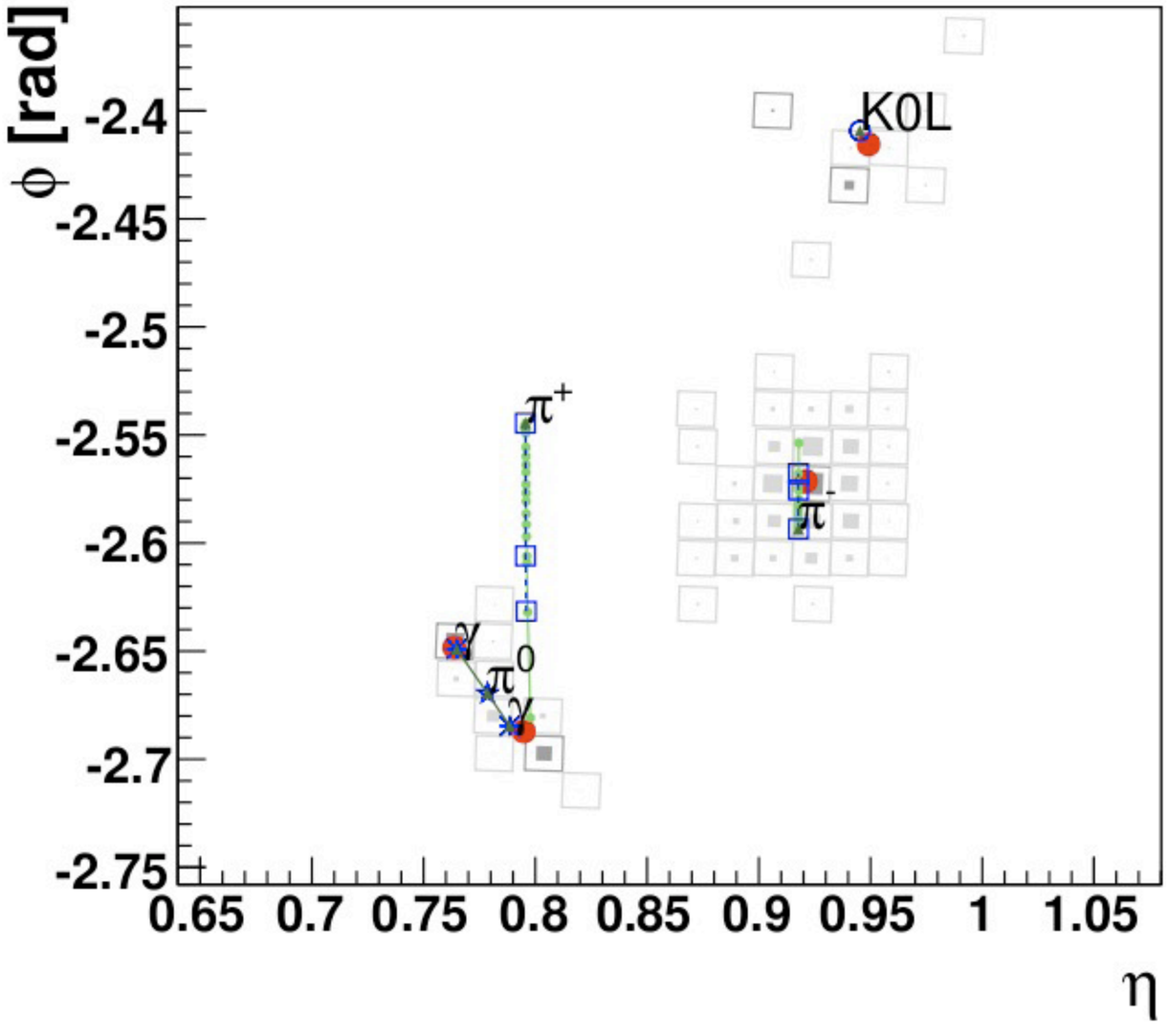

Four true particles:

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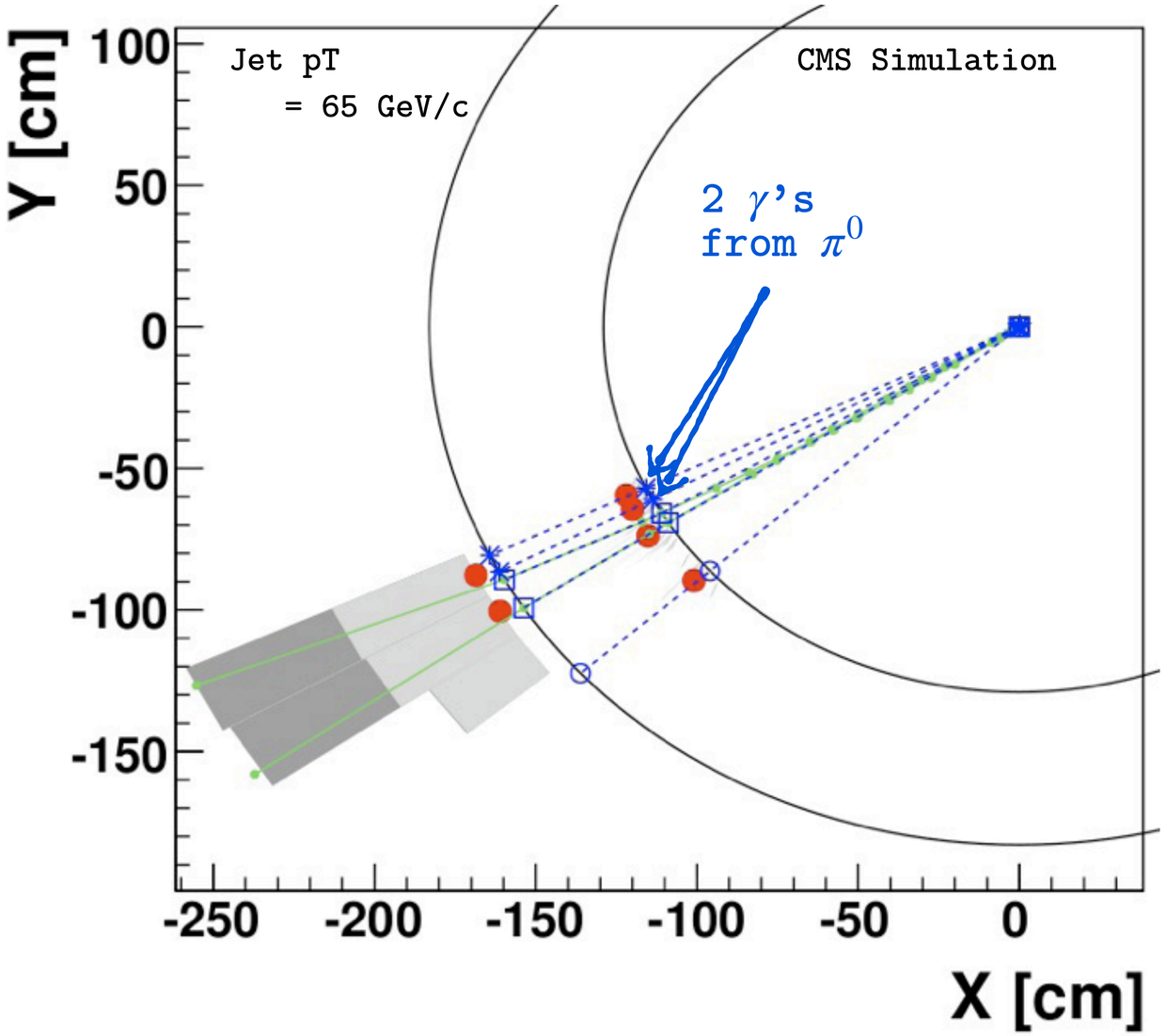

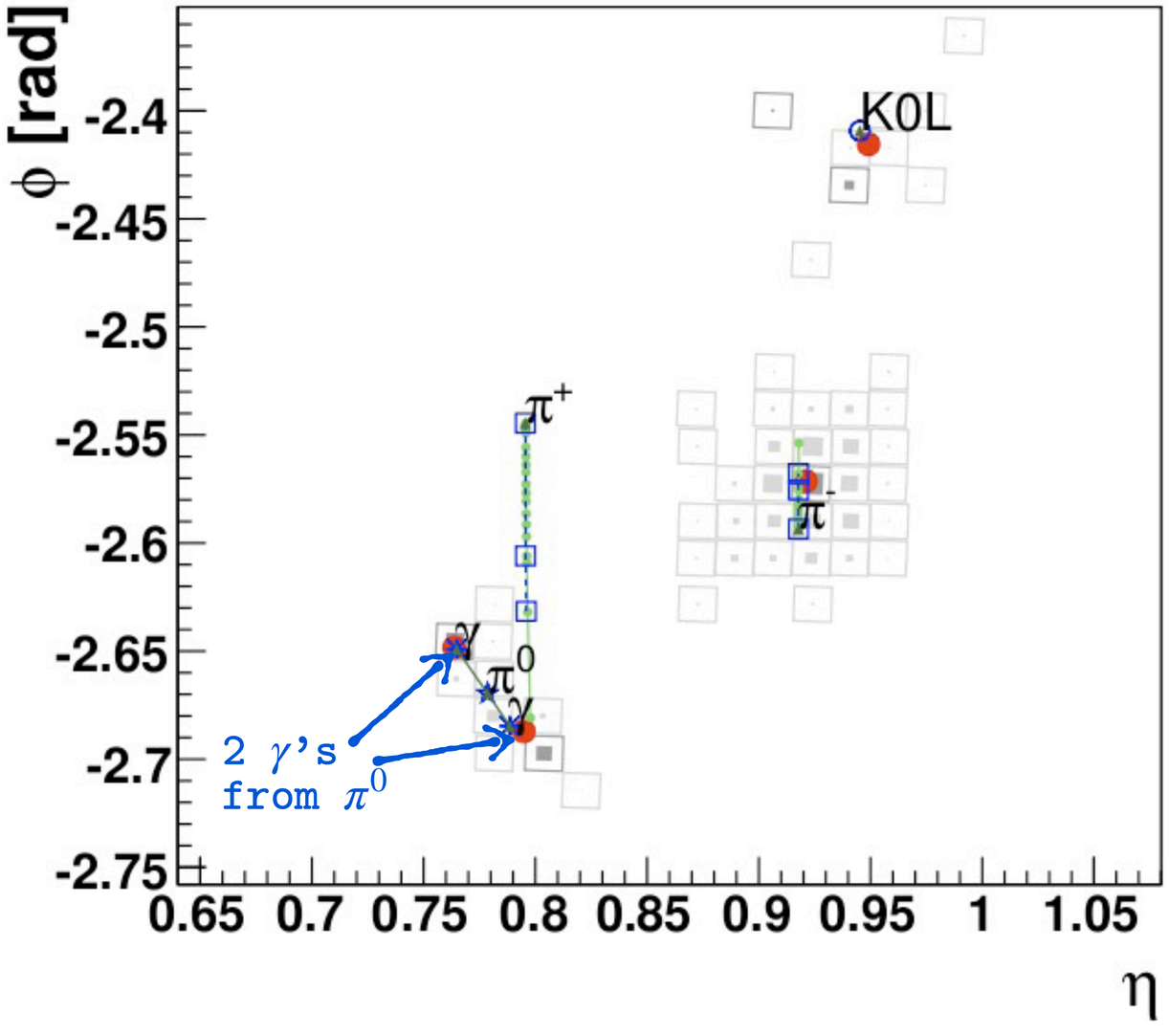

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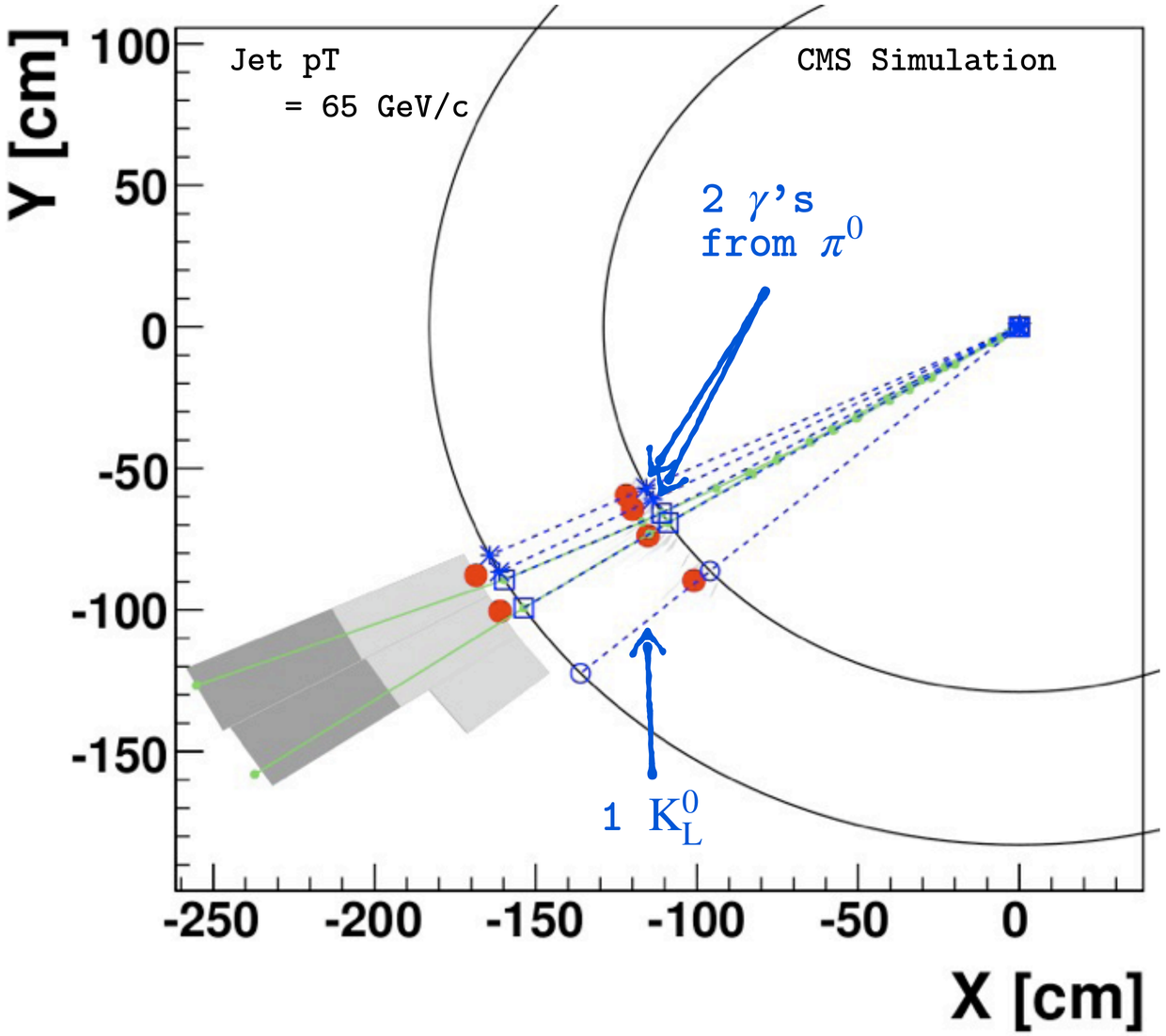

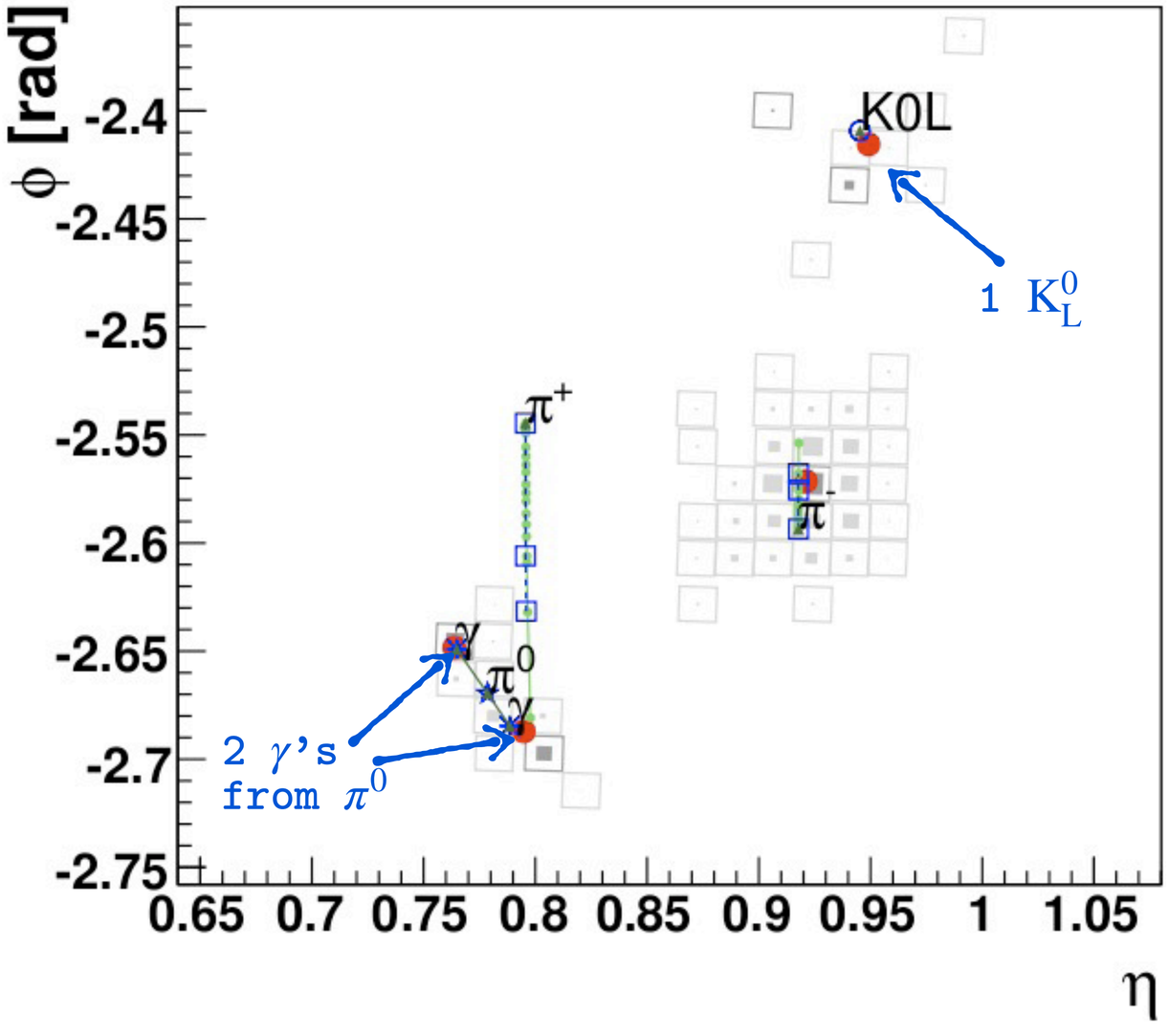

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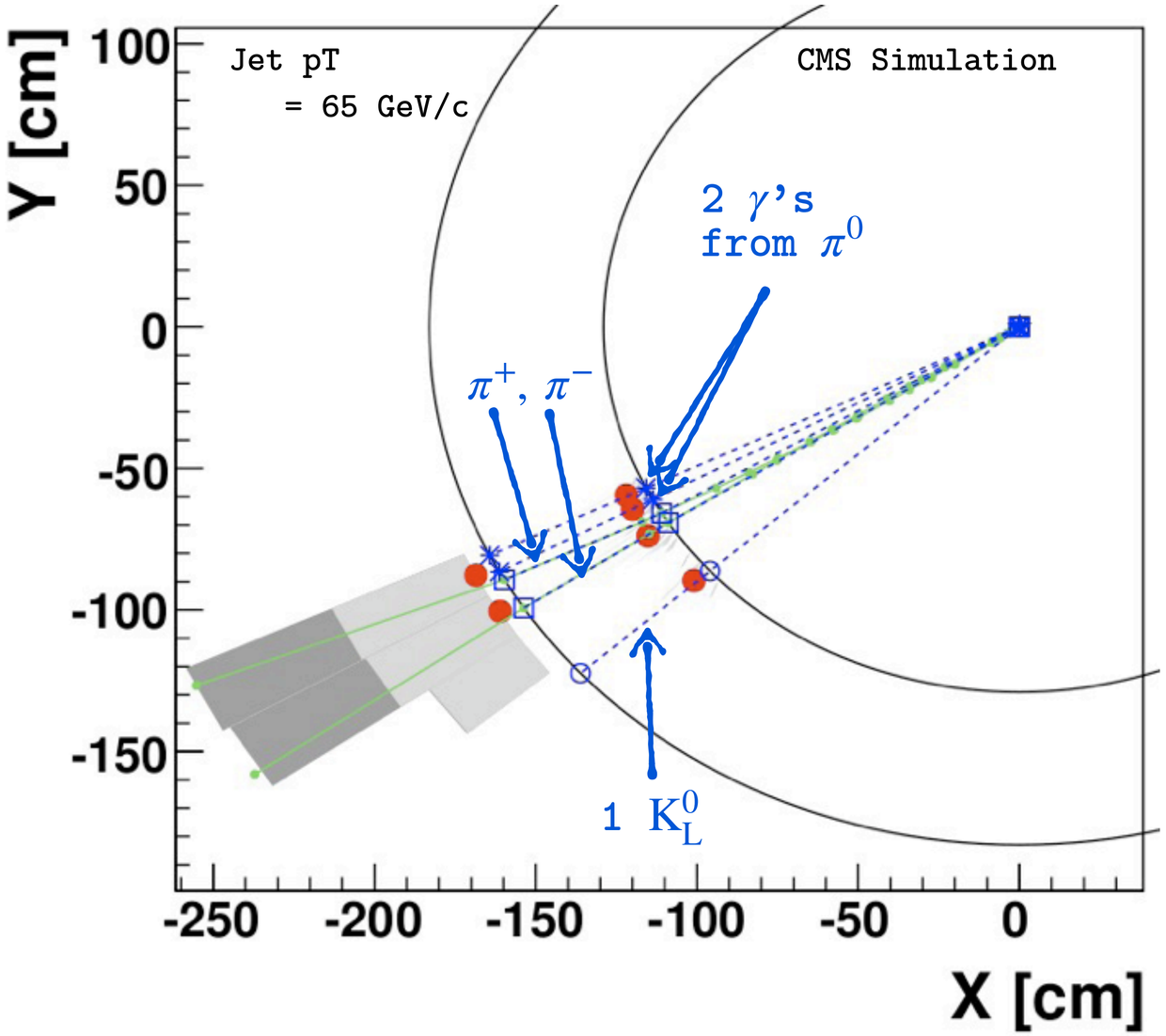

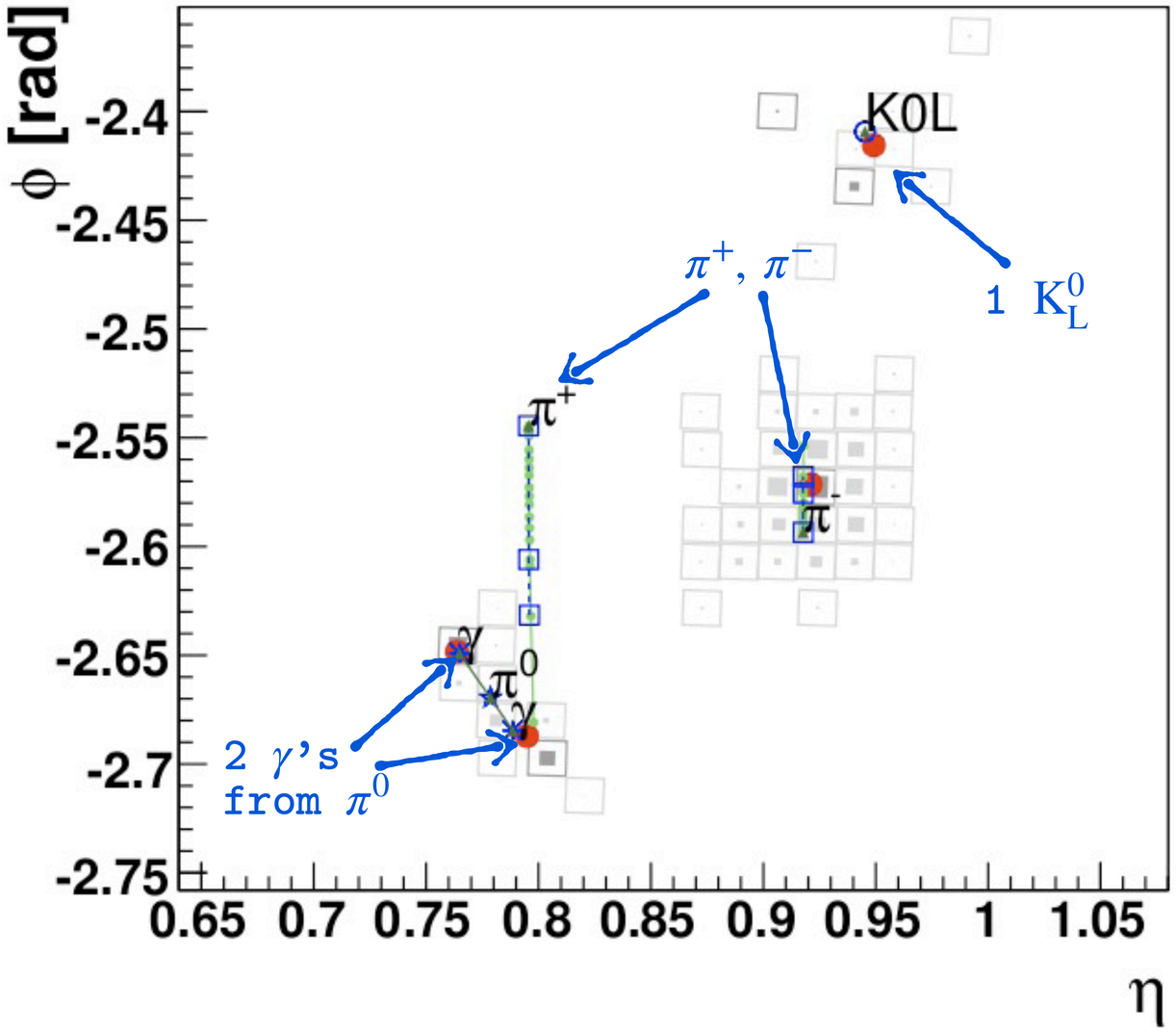

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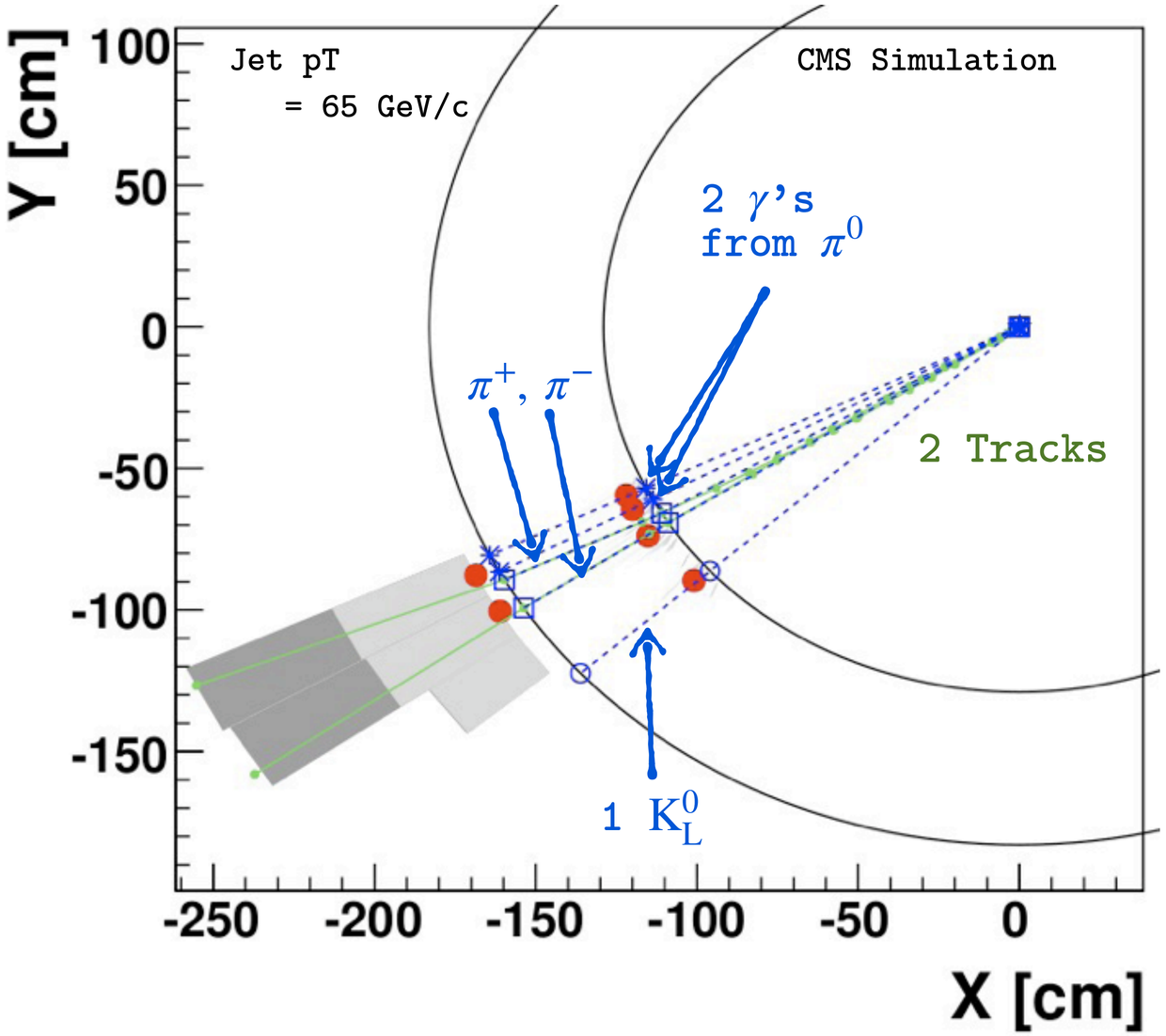

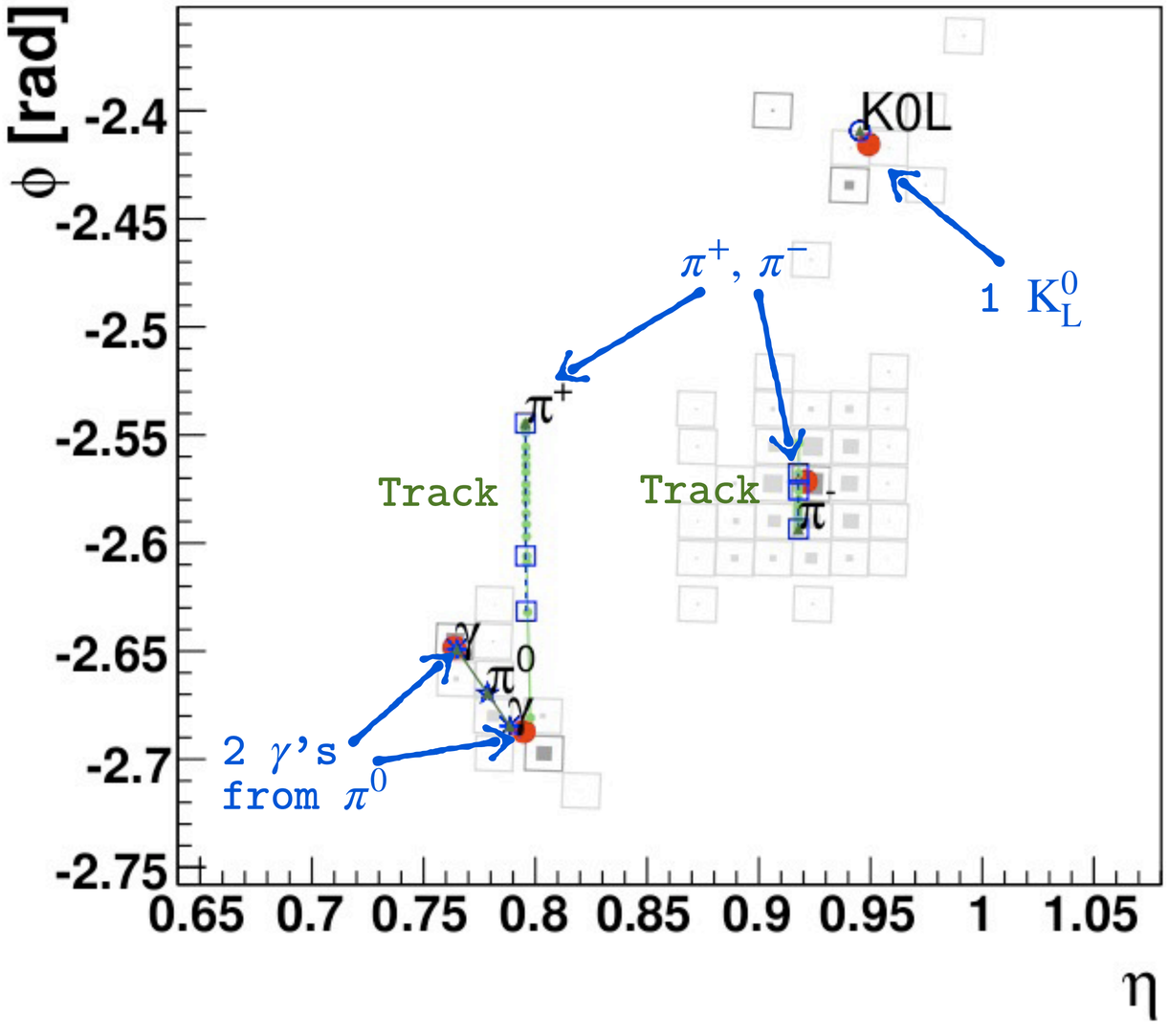

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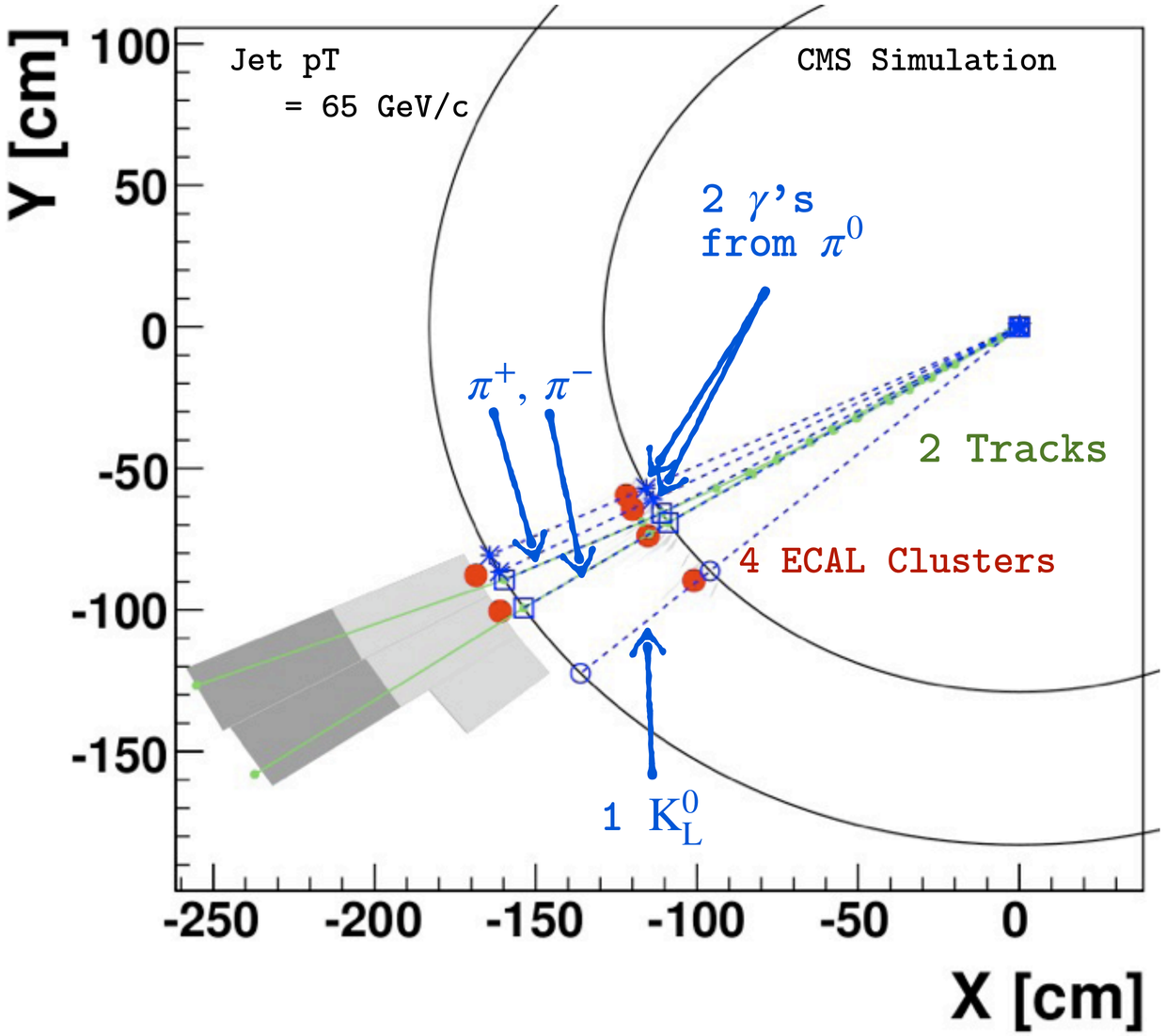

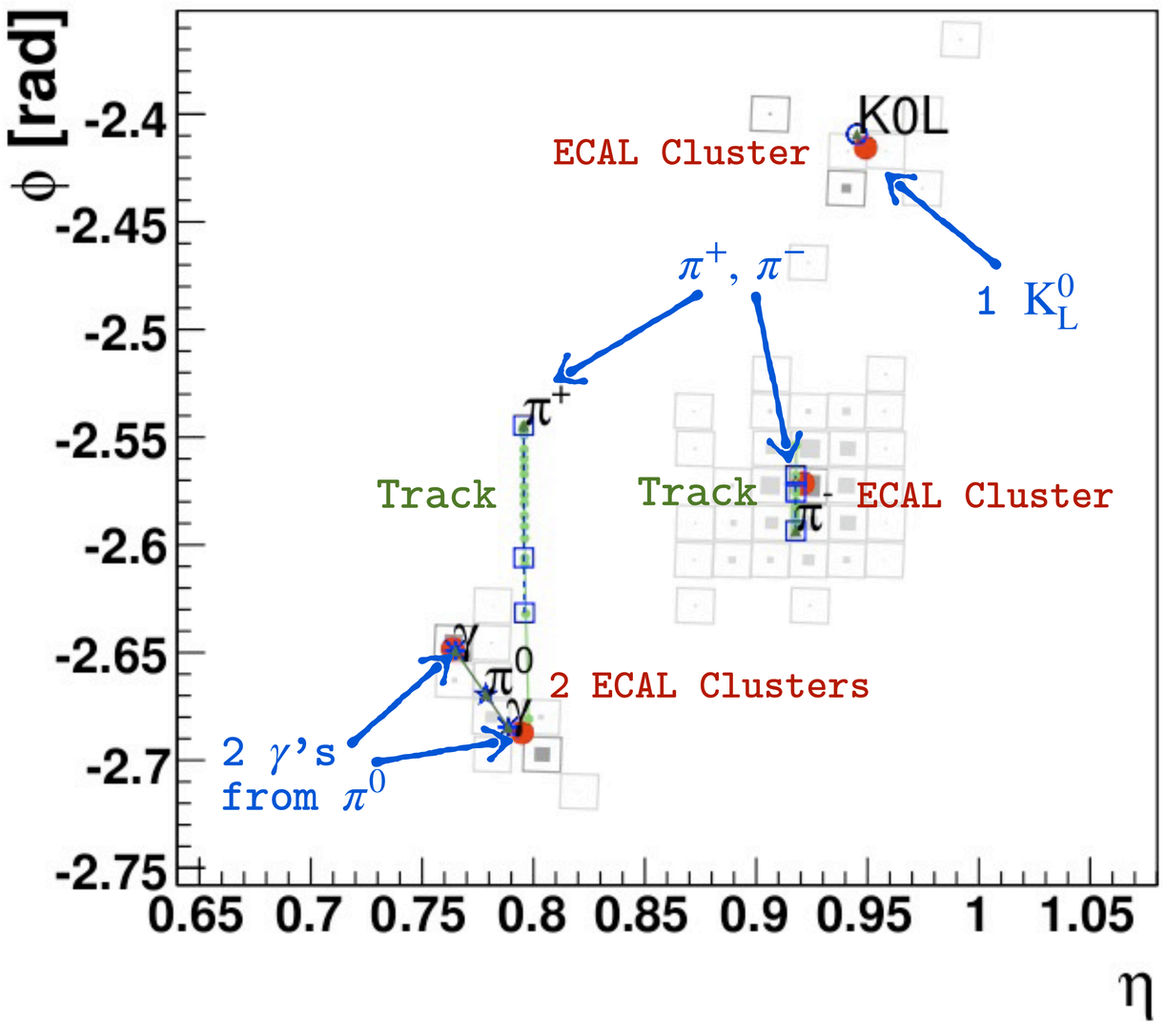

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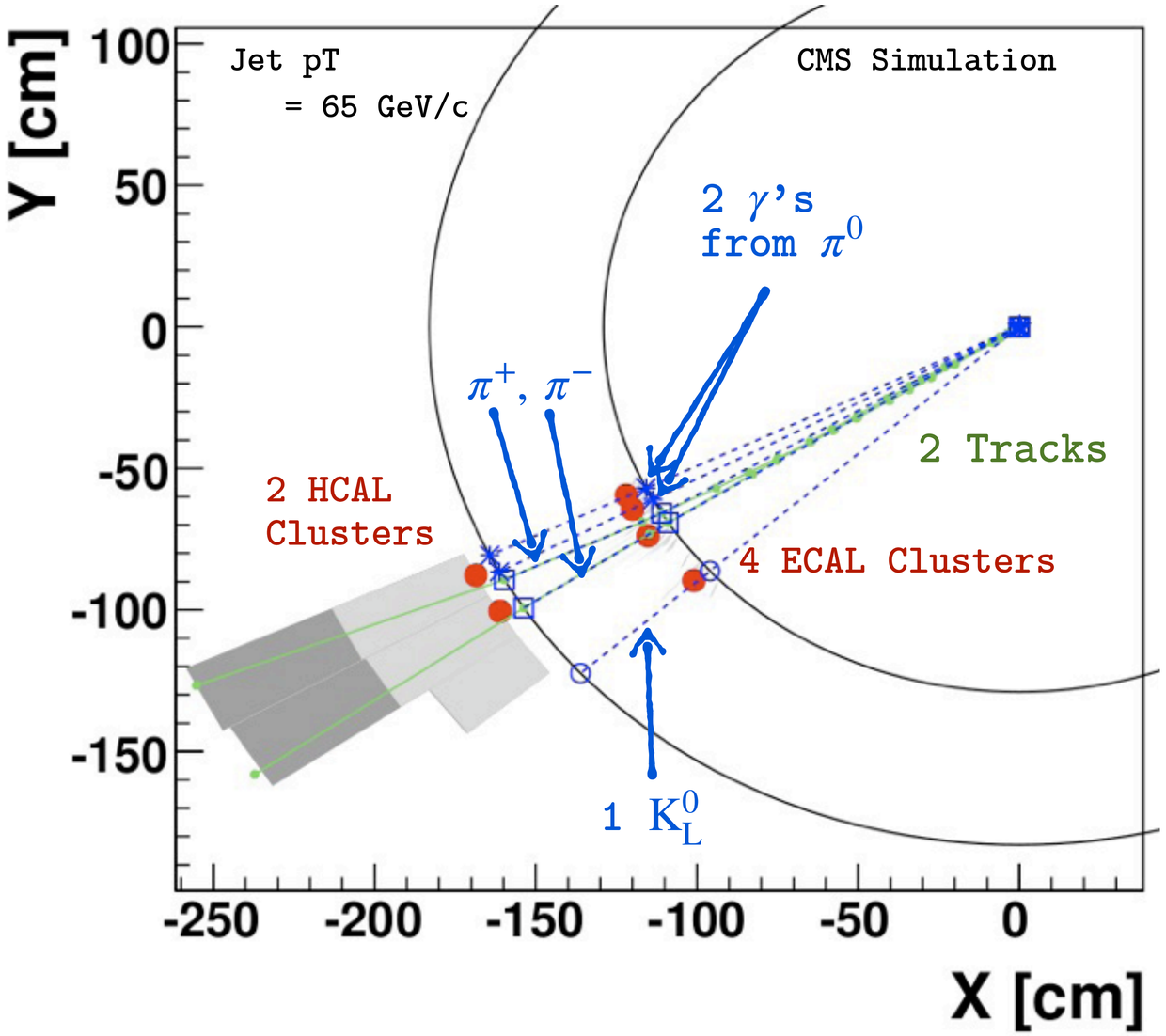

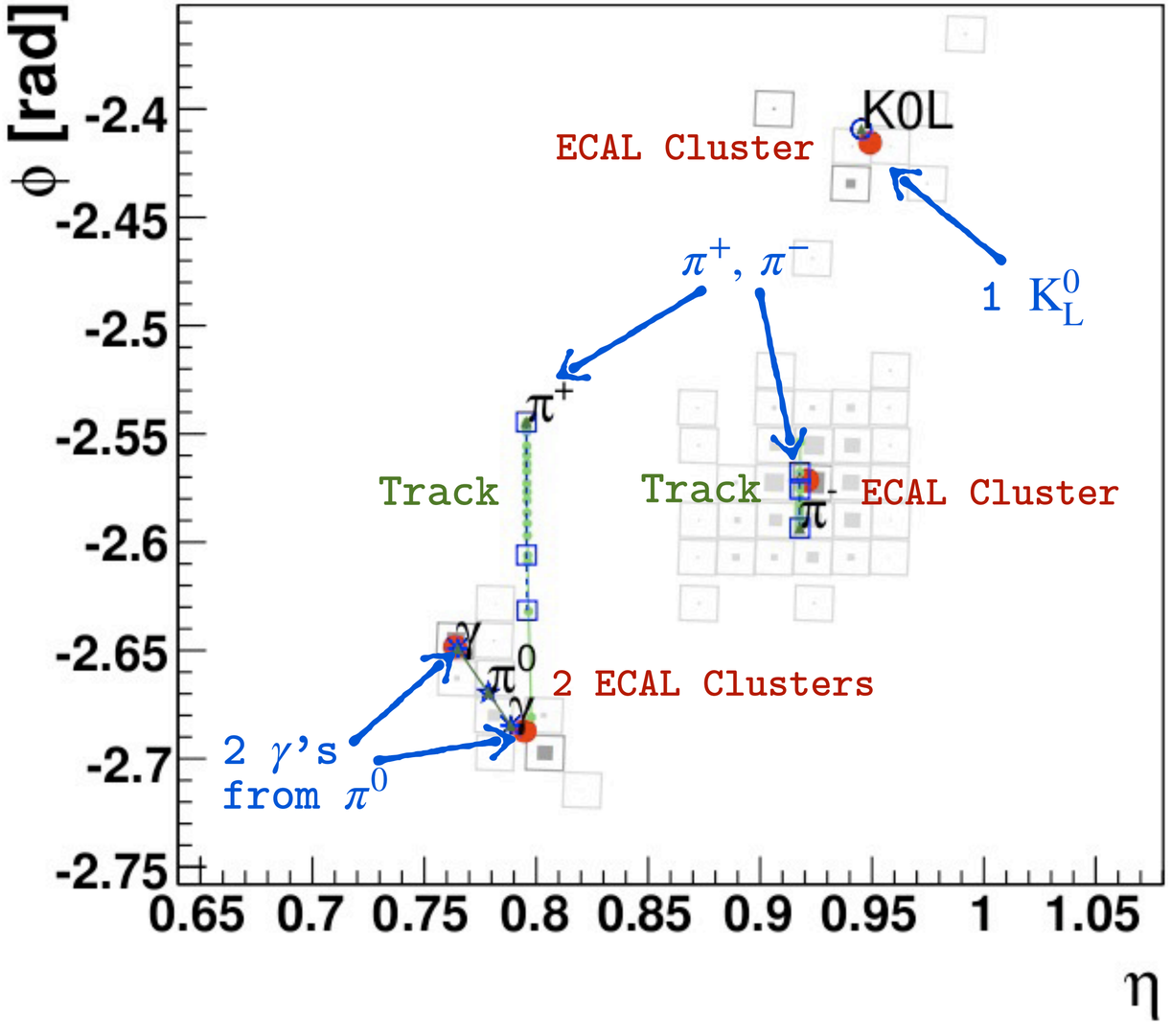

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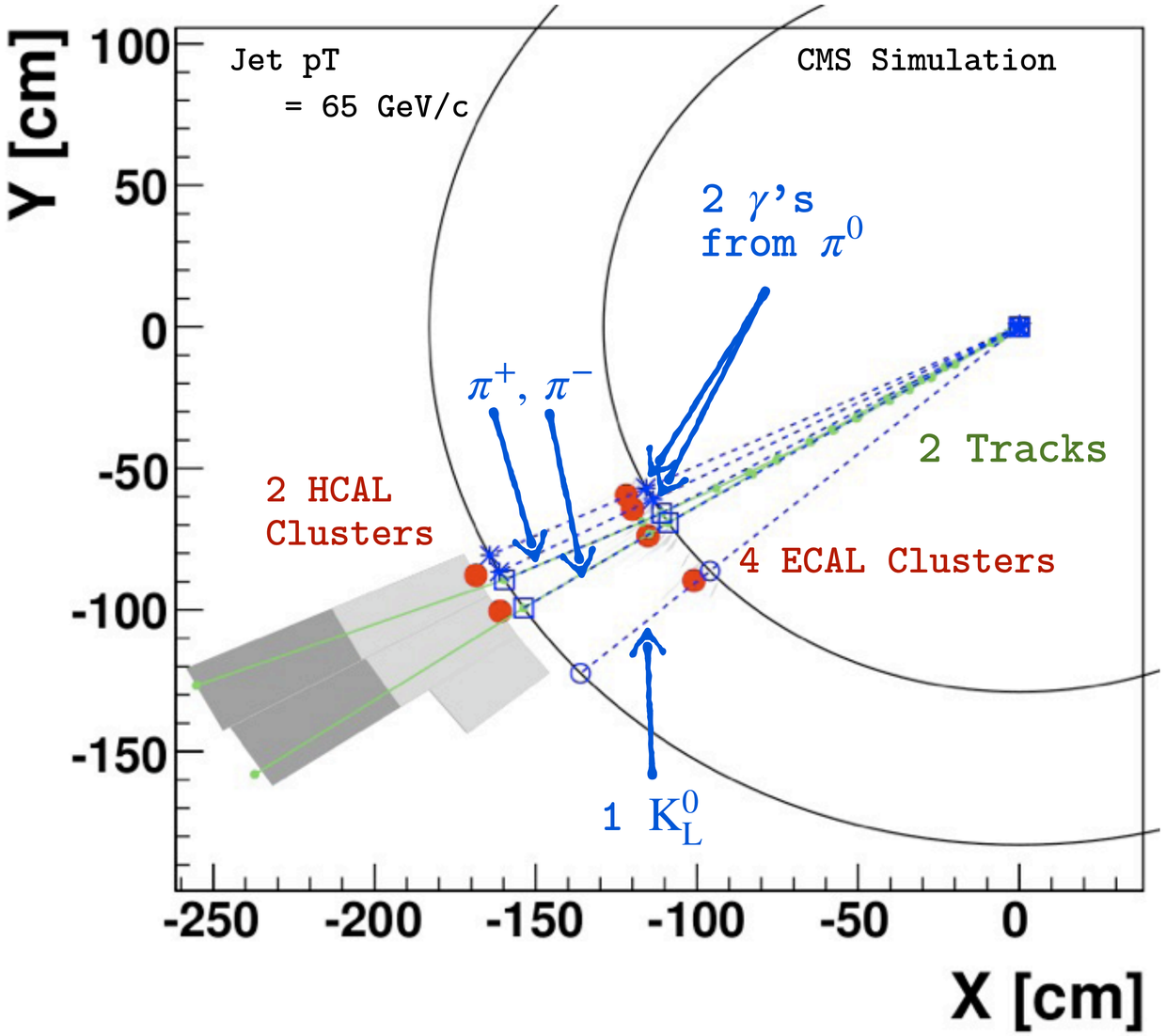

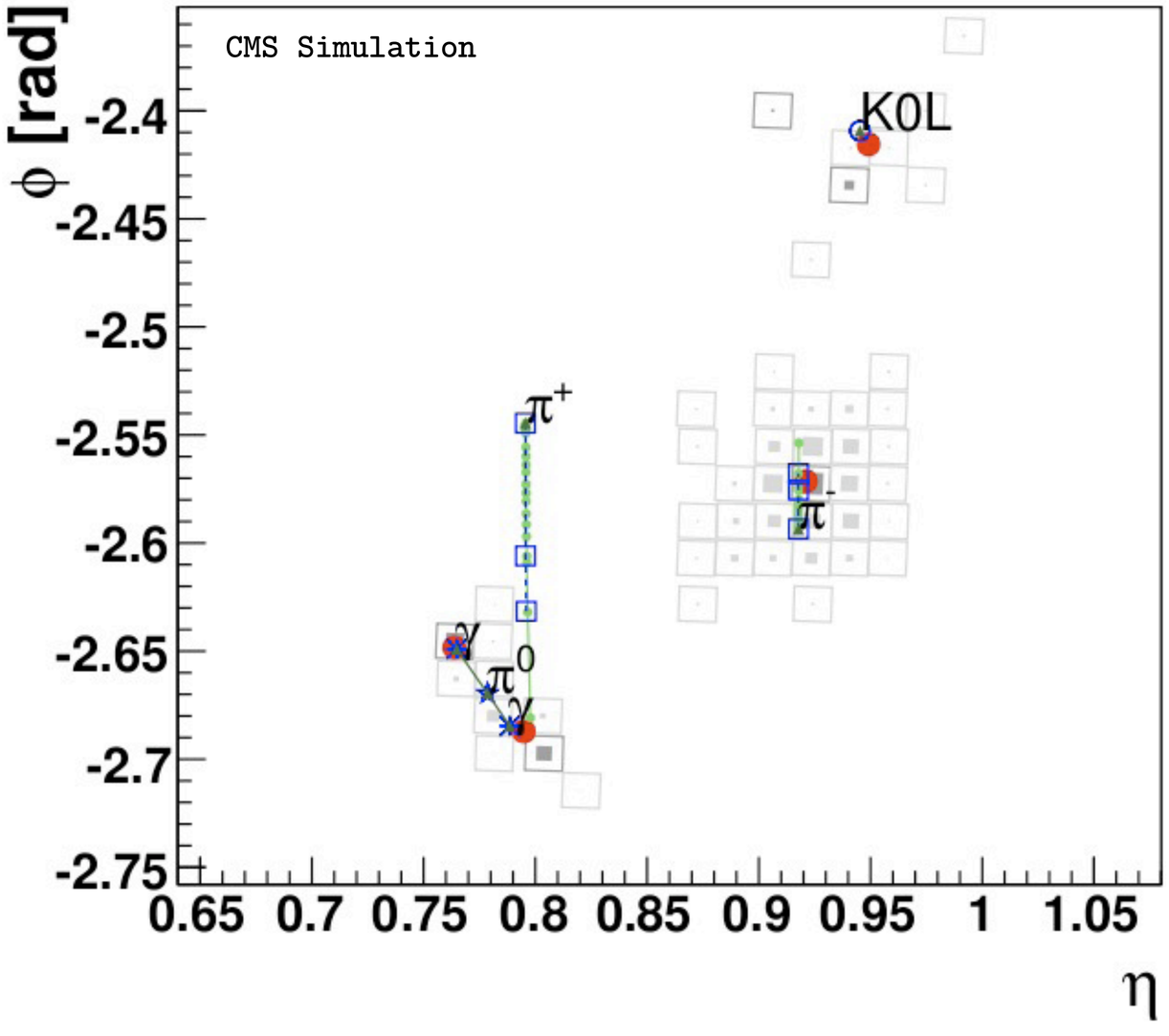

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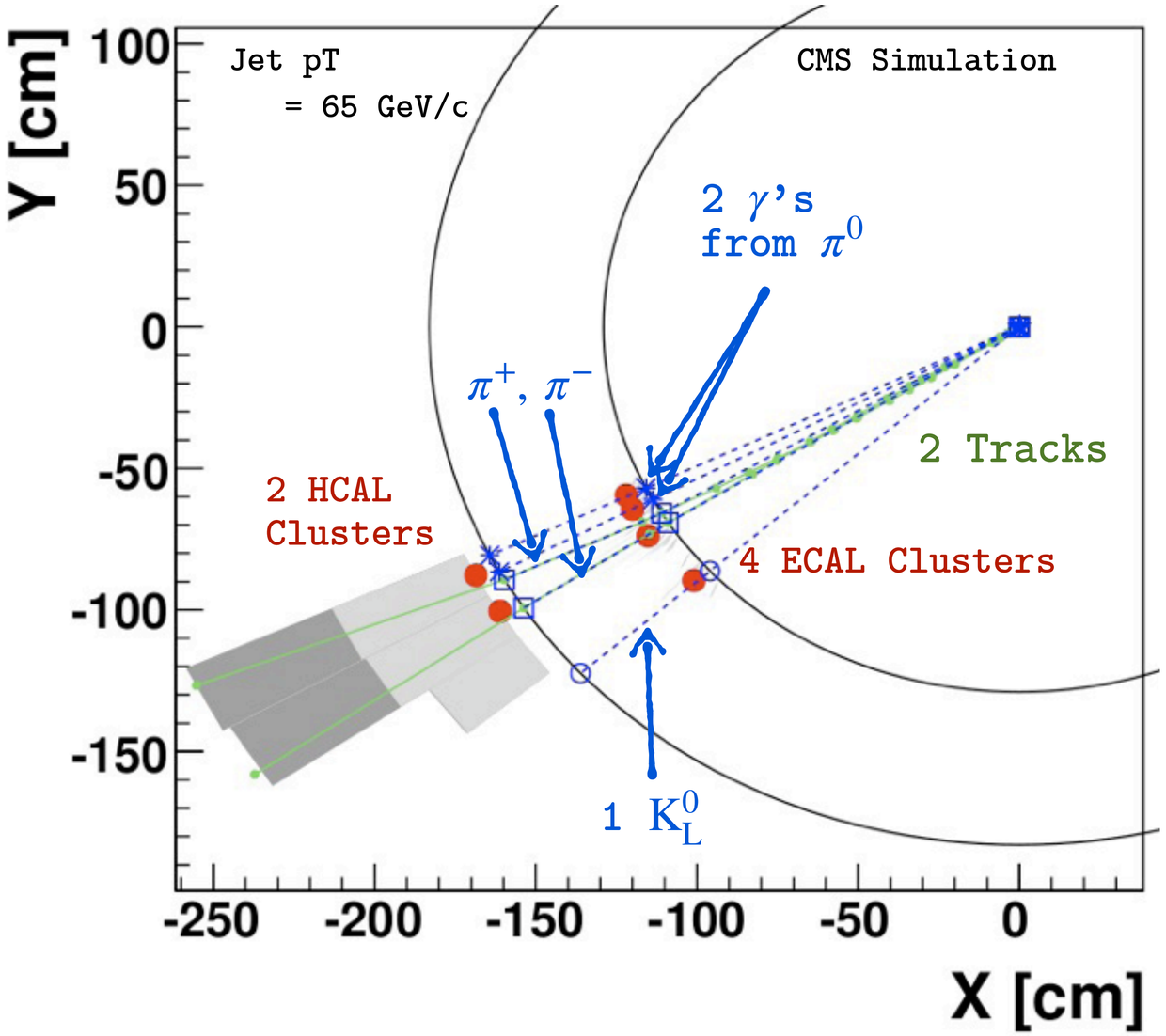

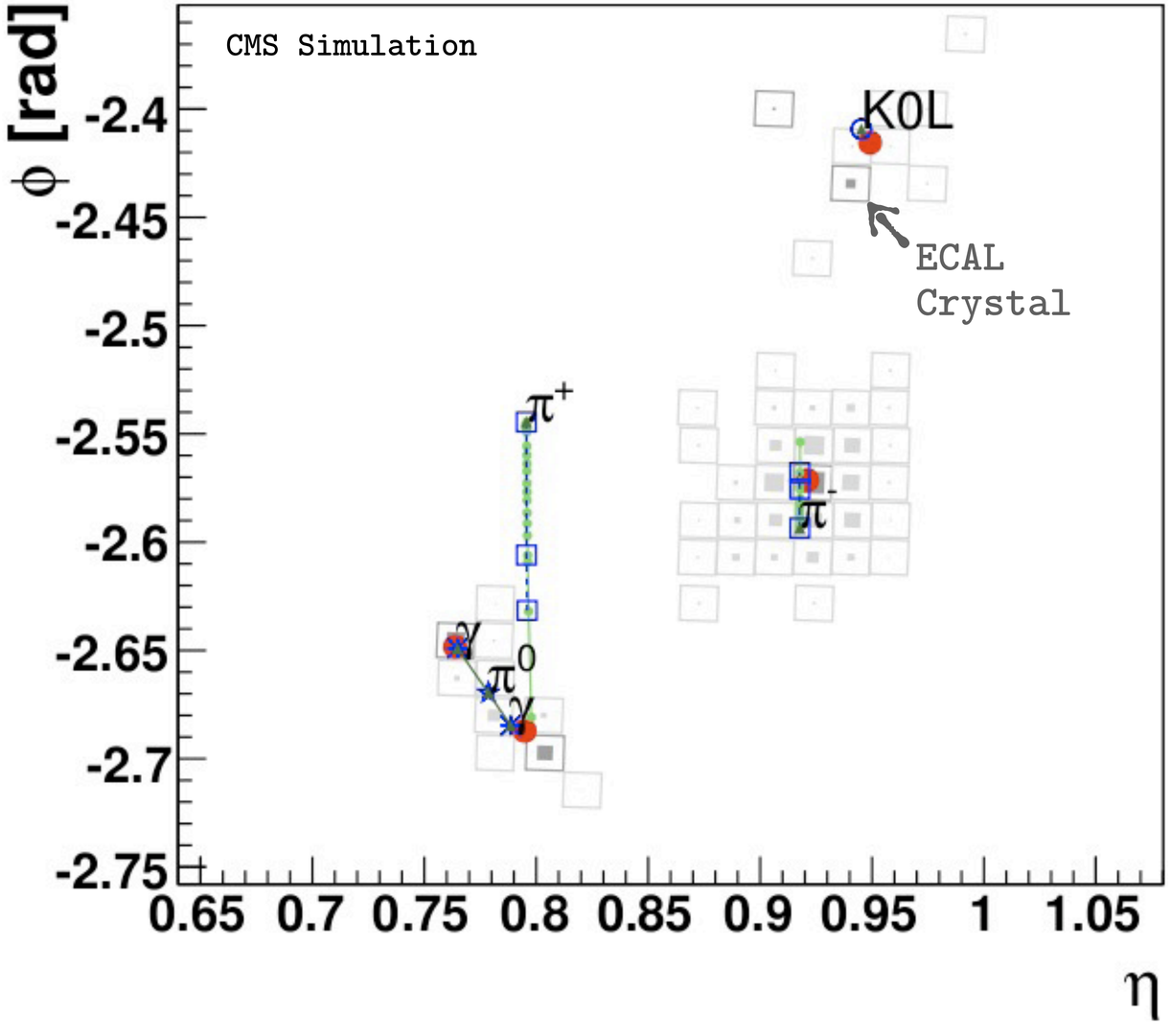

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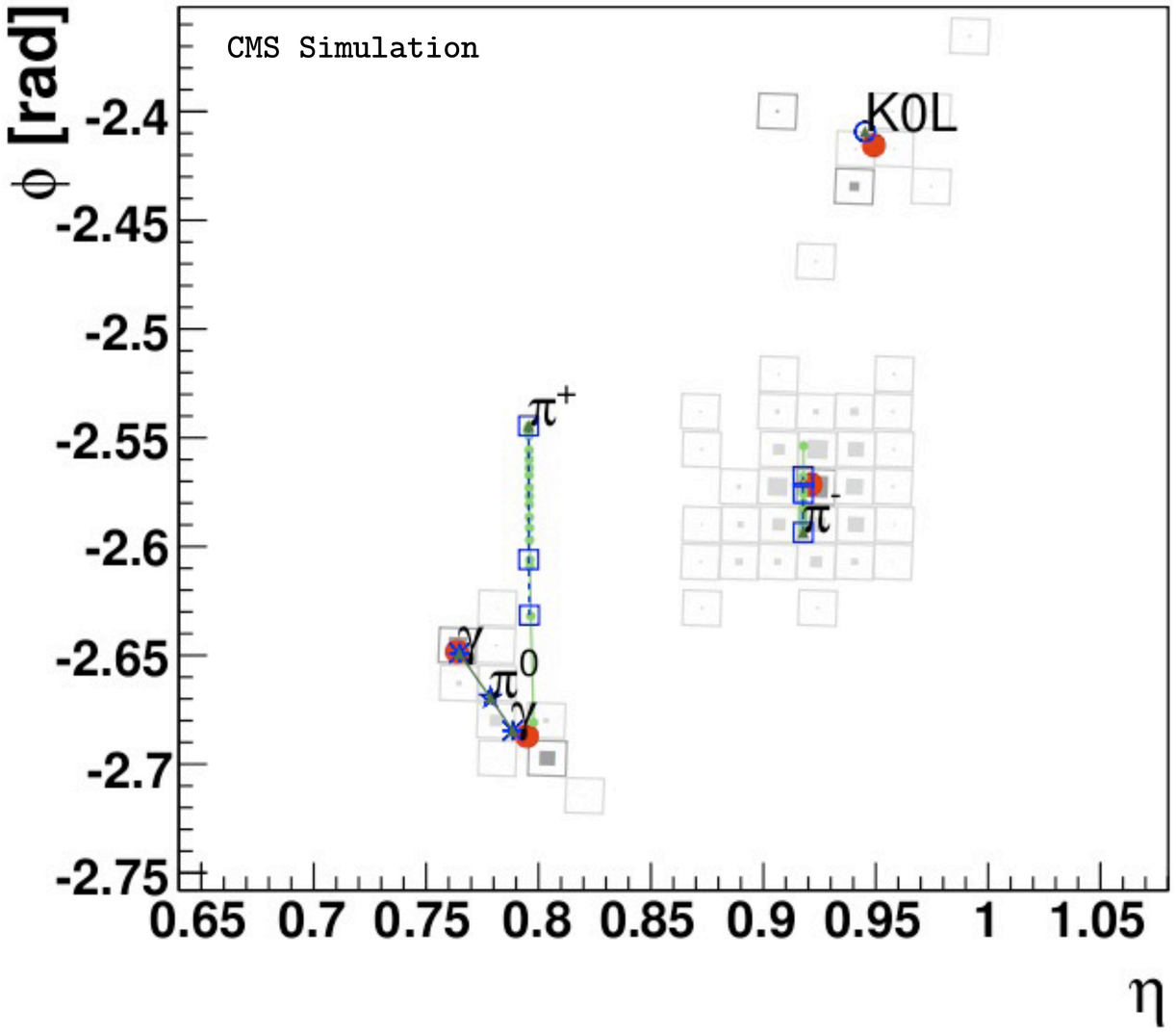

Four true particles:

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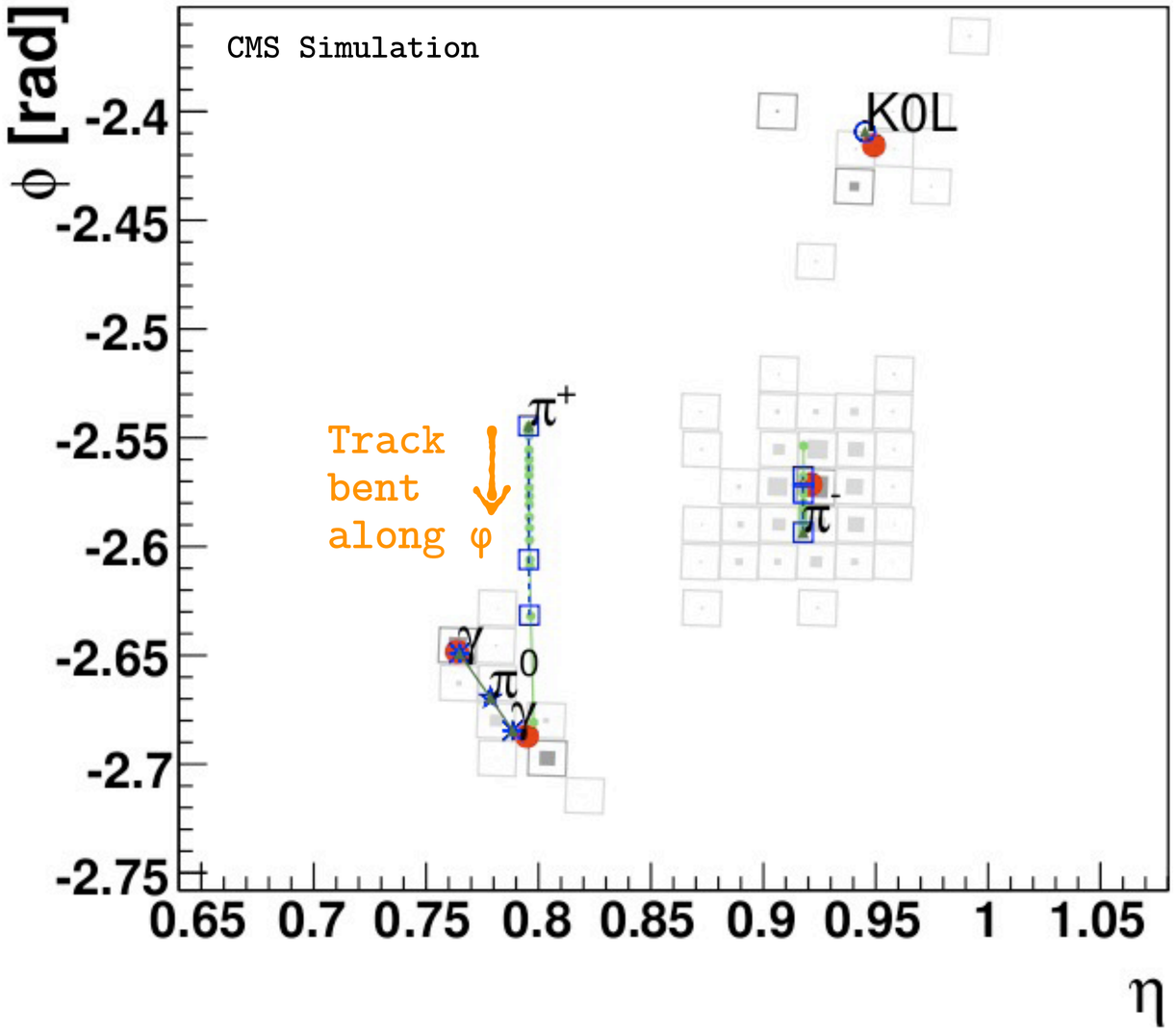
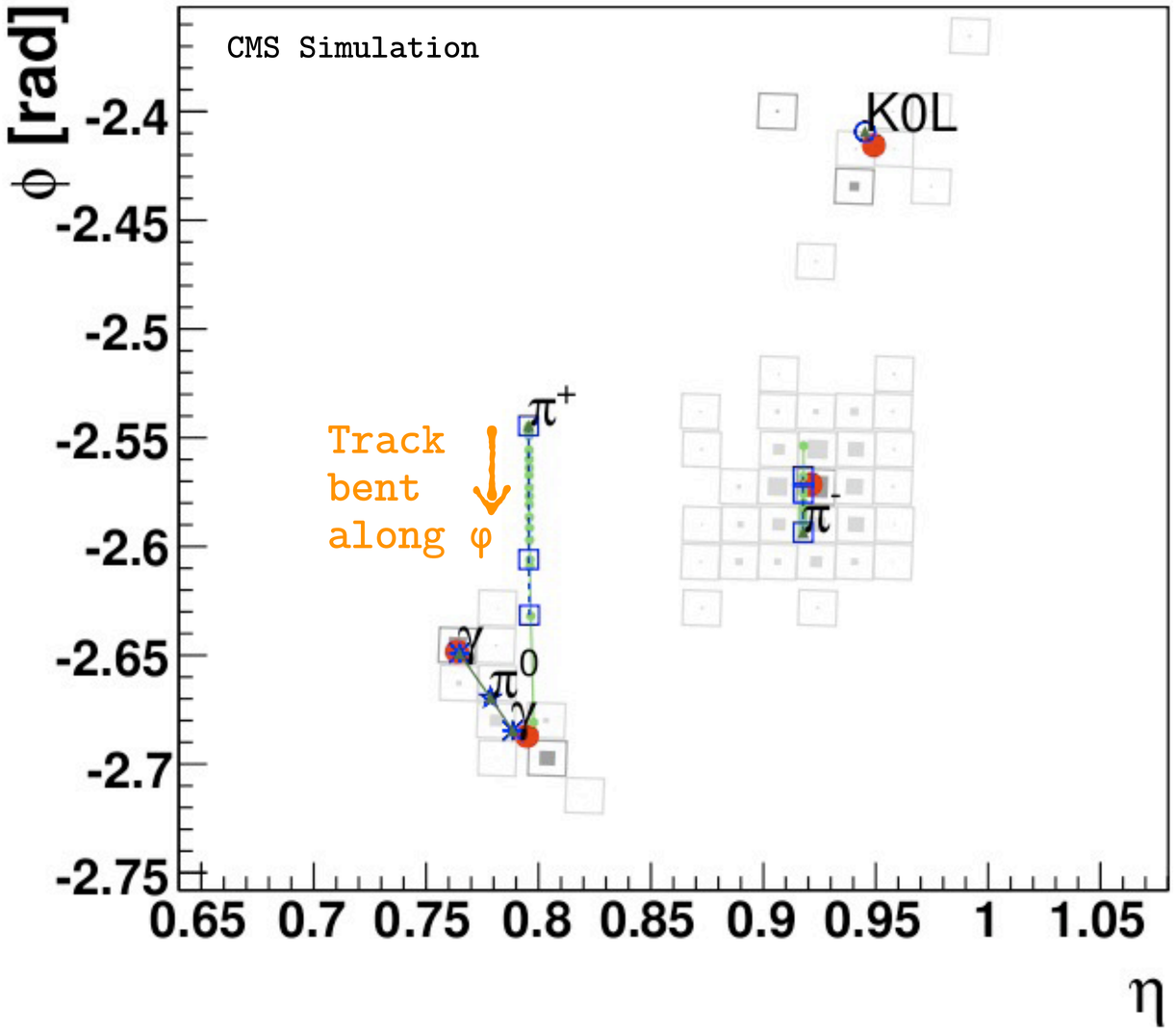


Four true particles:

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

Track



Four true particles:

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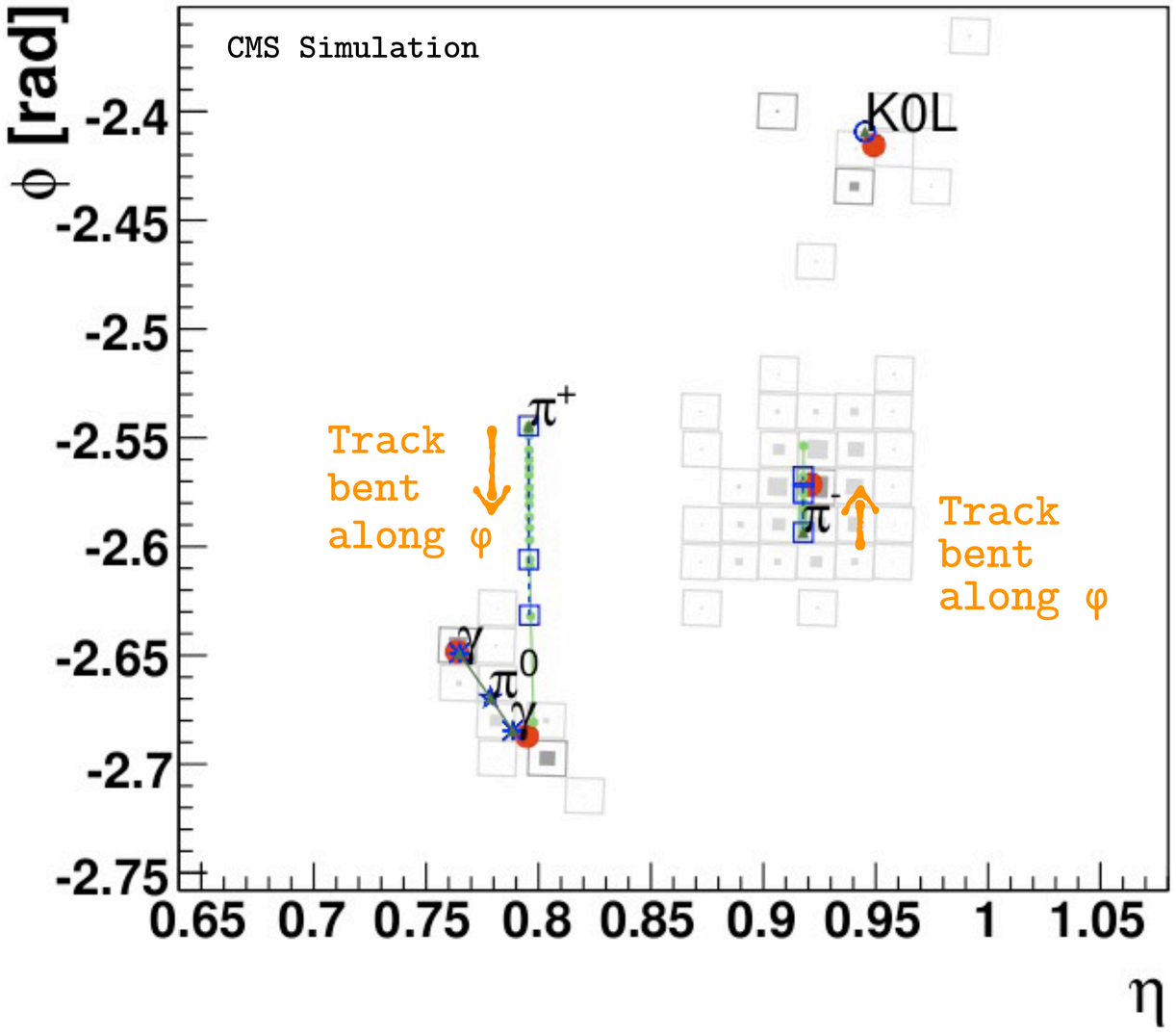
Track



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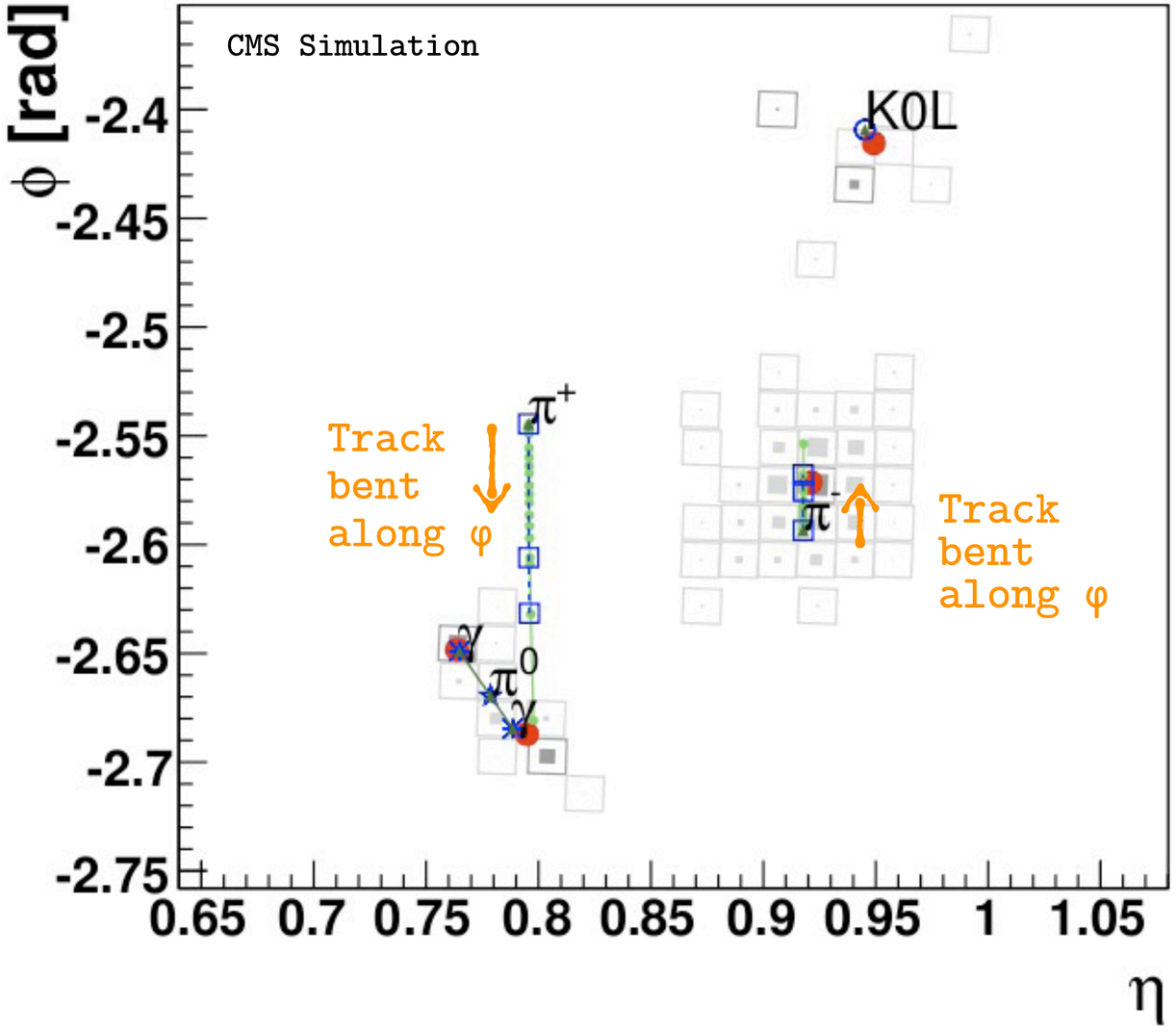
Track

Track



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Track

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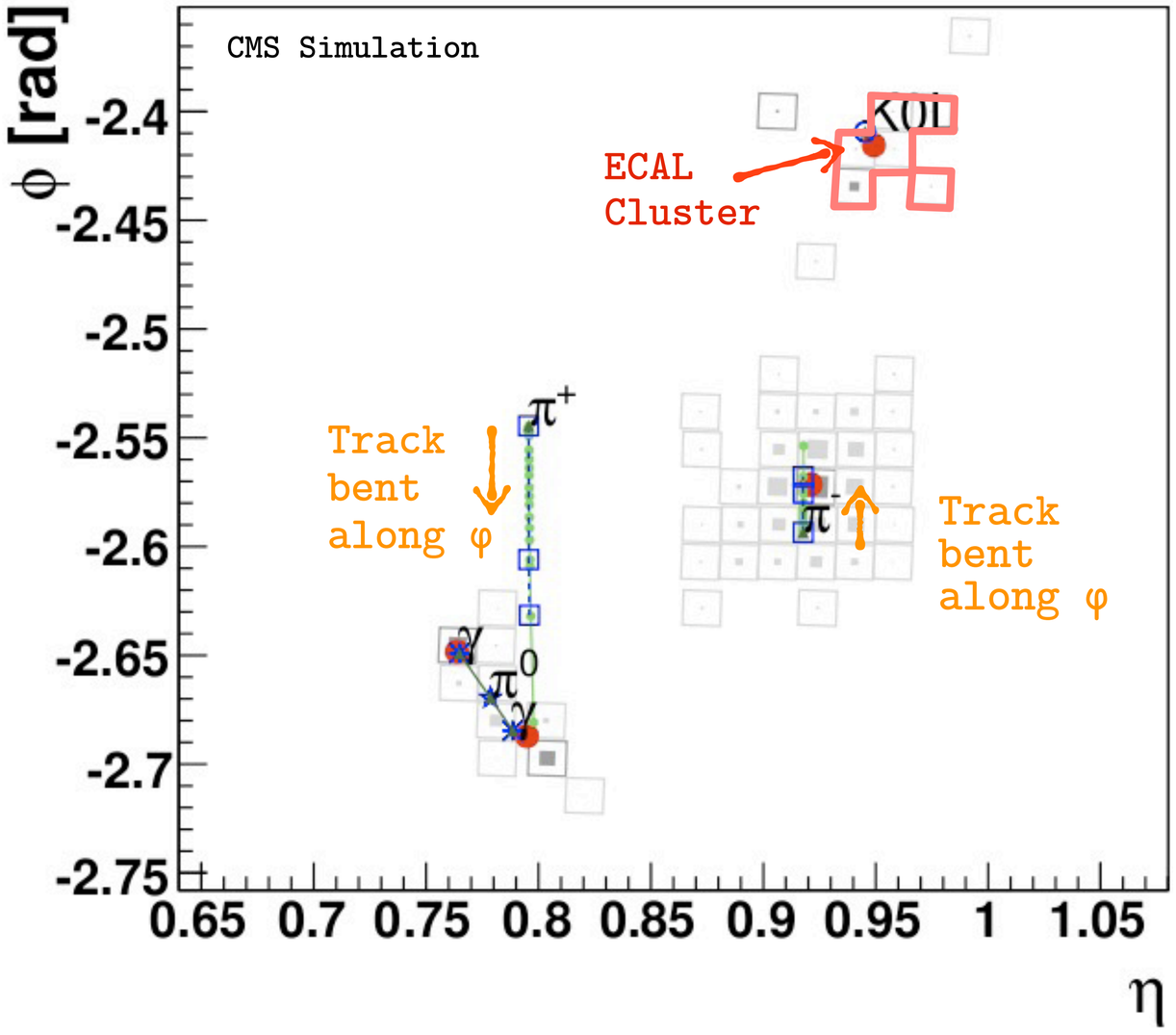
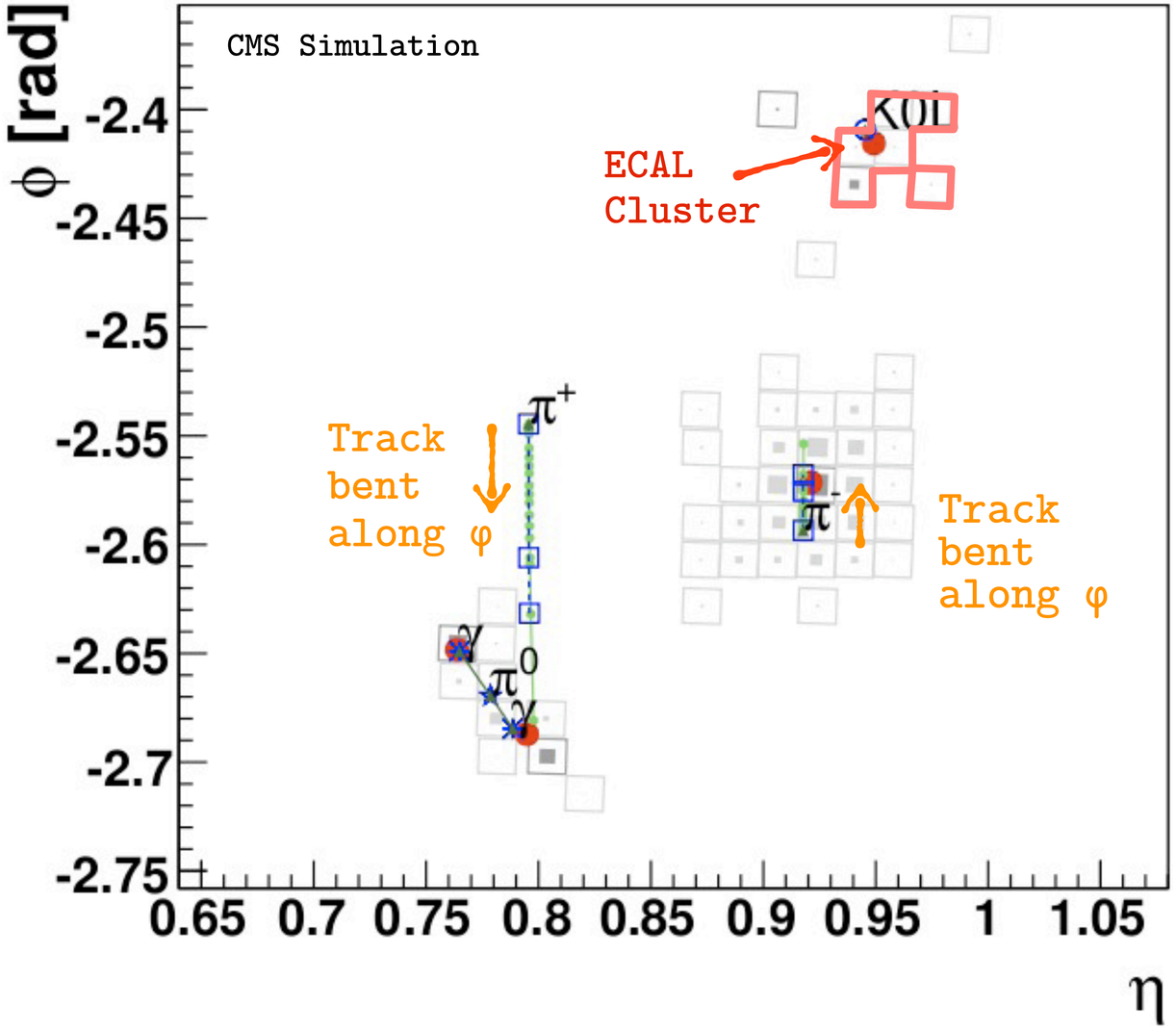


Four true particles:

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



Four true particles:

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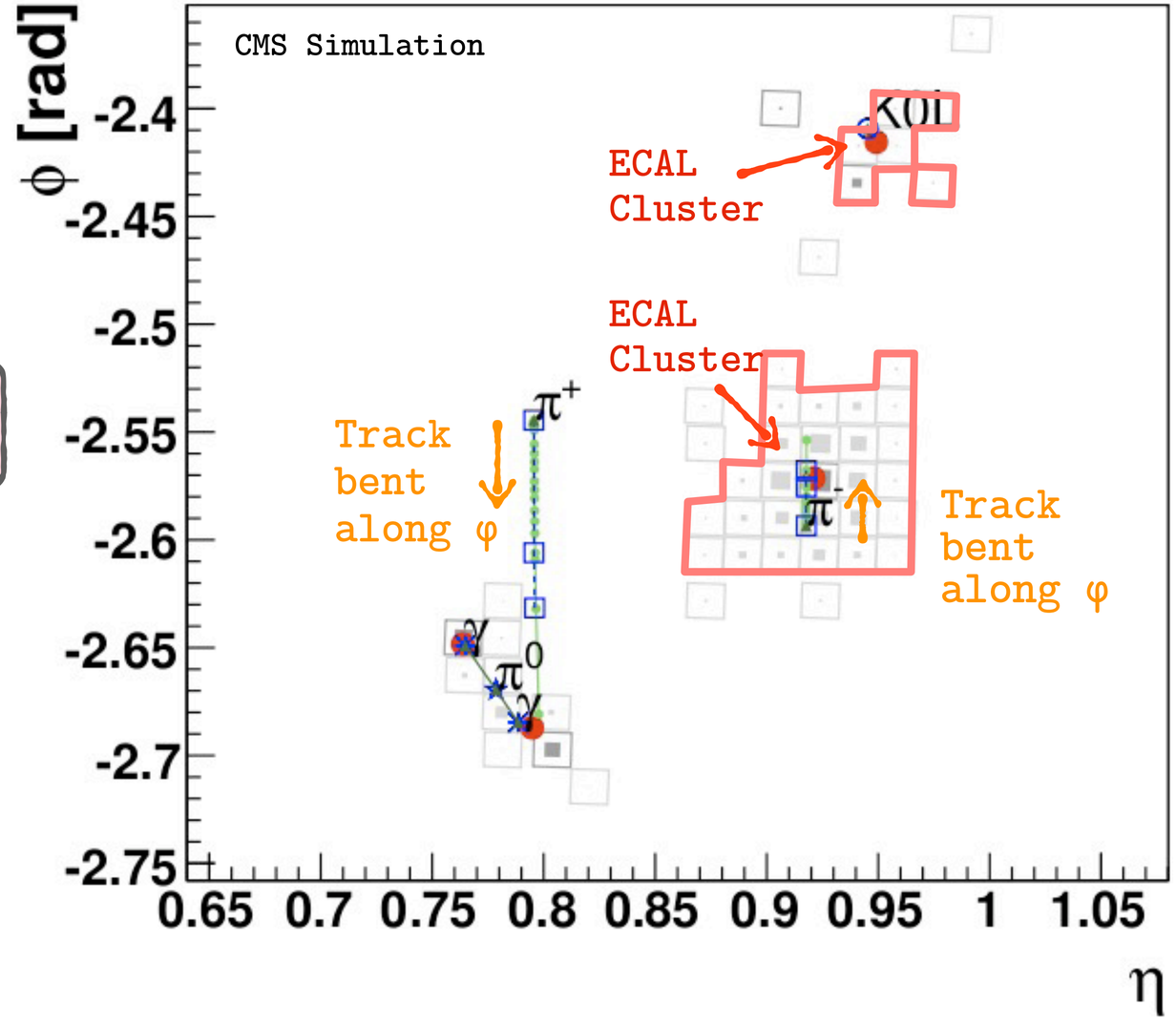
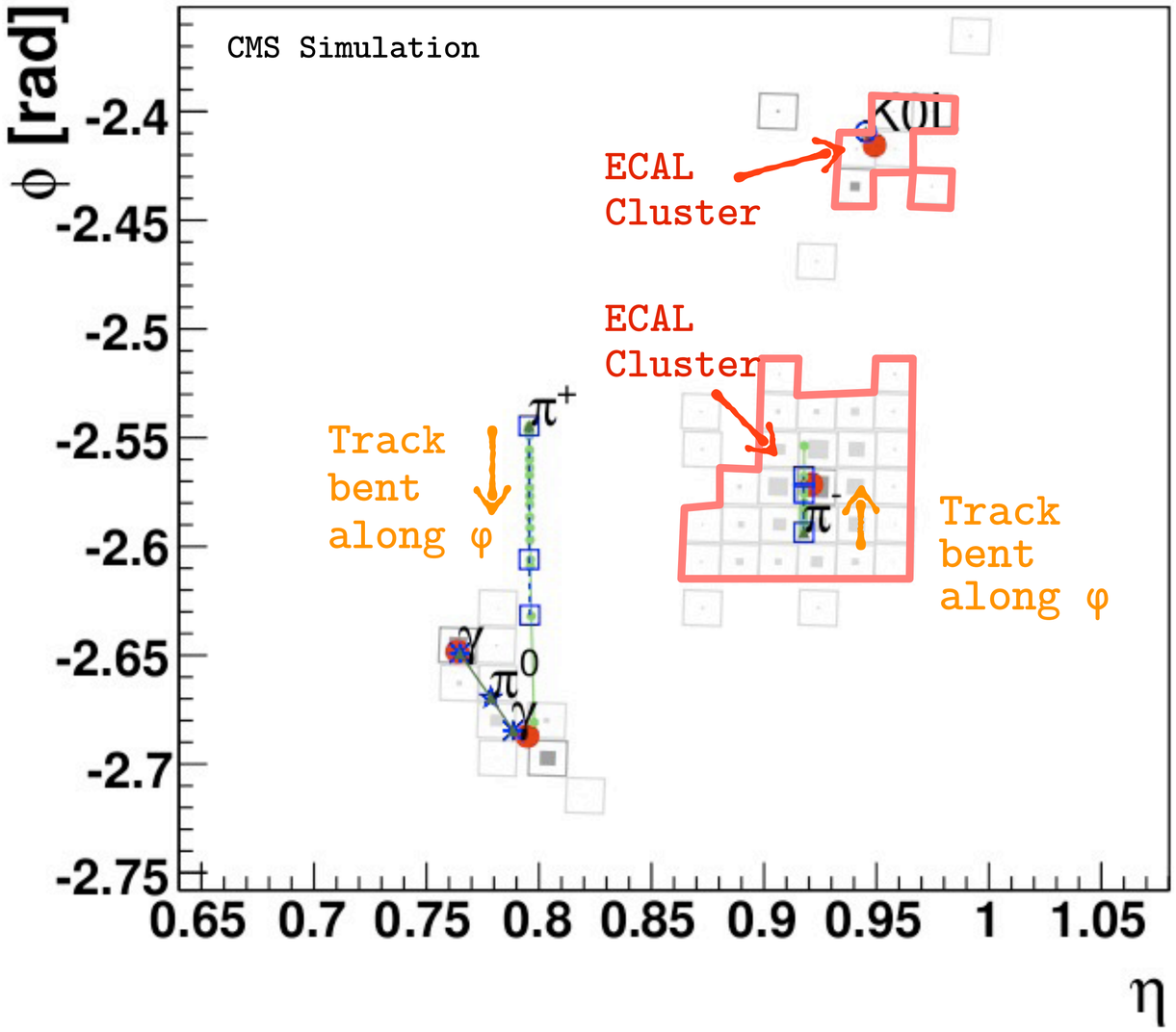


Four true particles:

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



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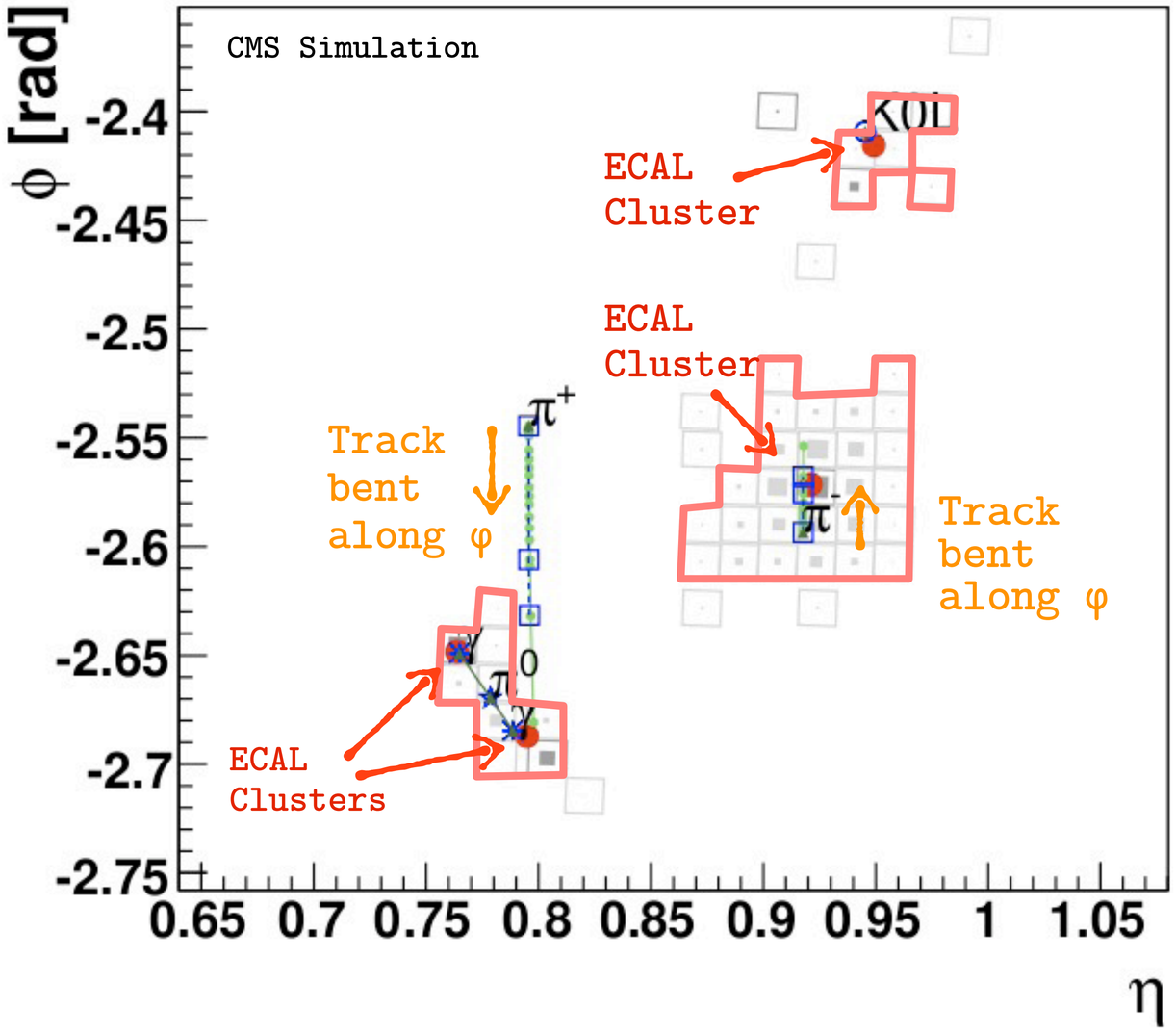

Four true particles:

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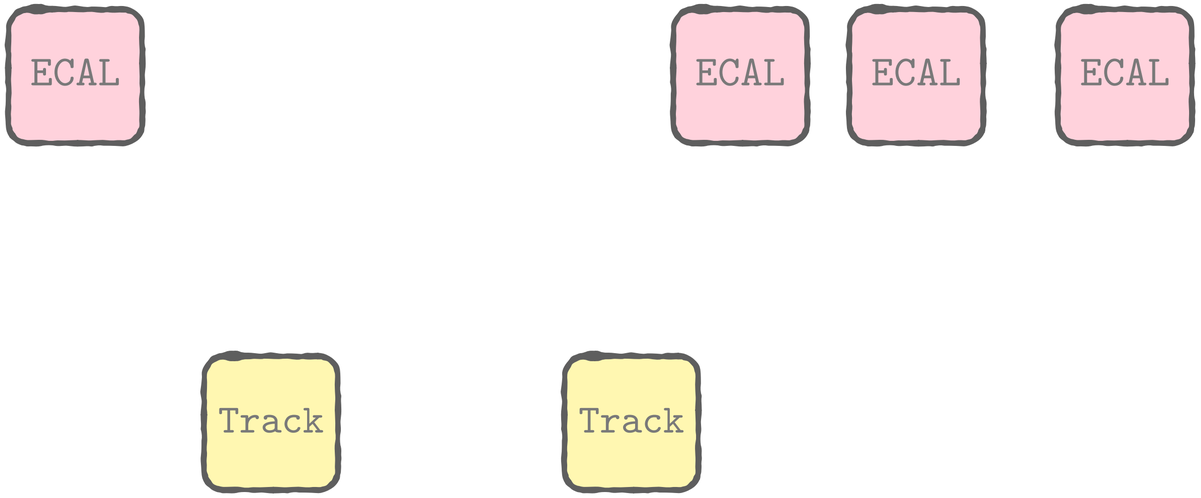

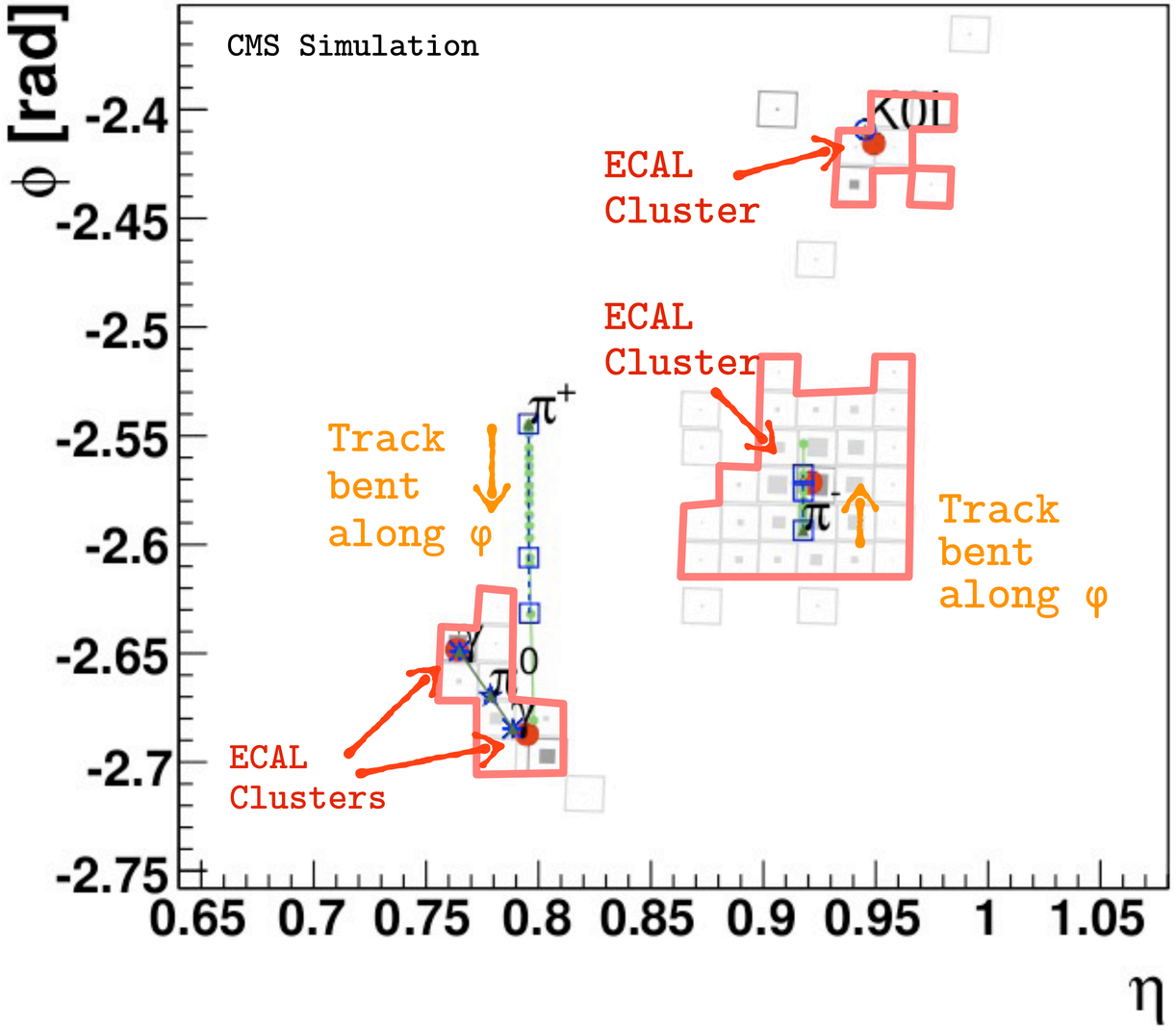

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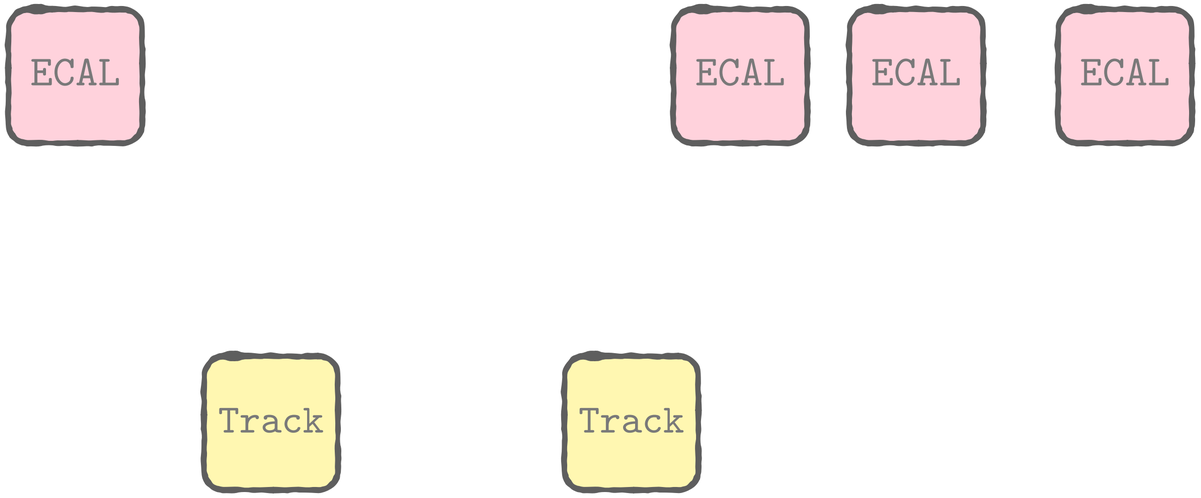

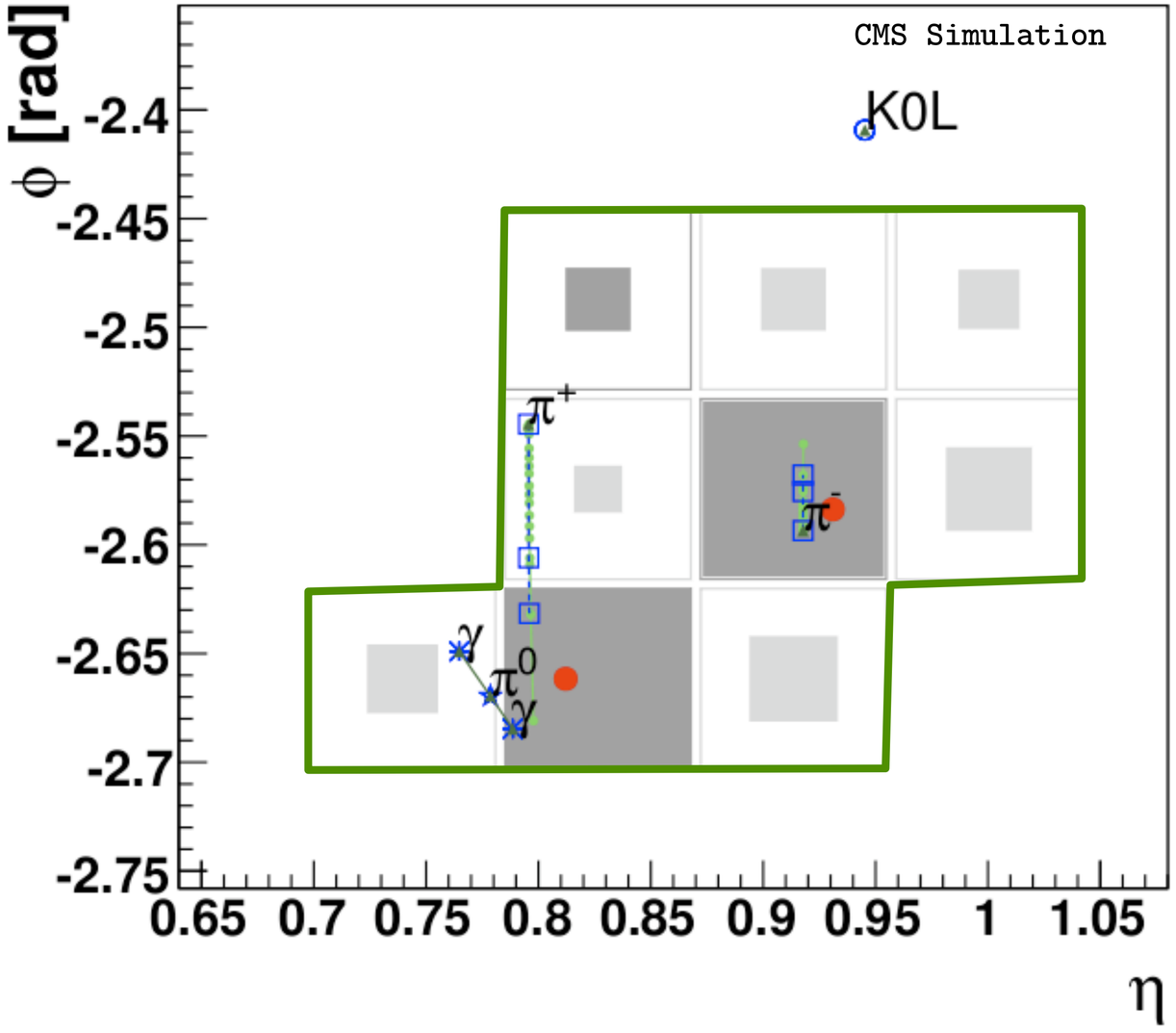

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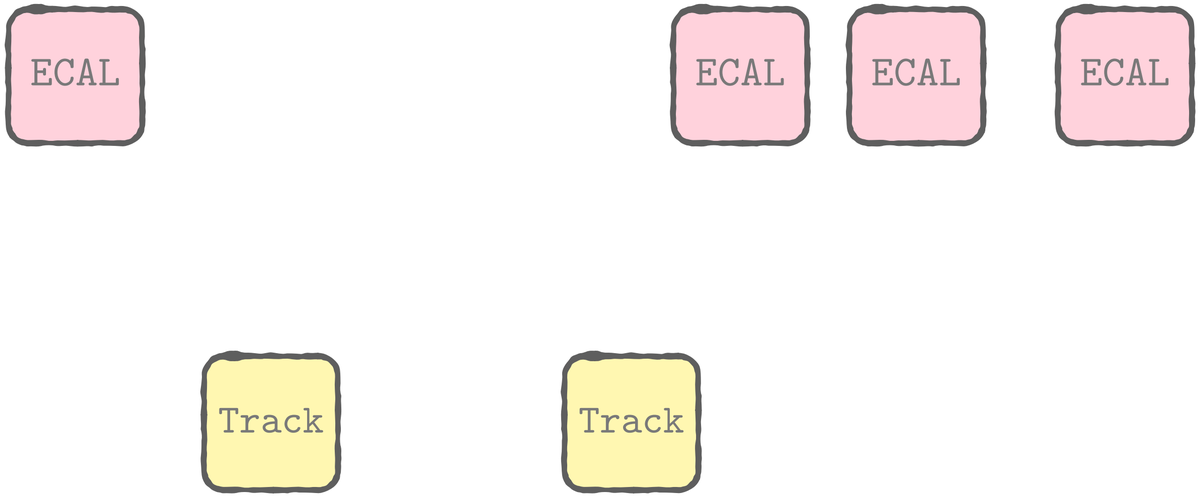

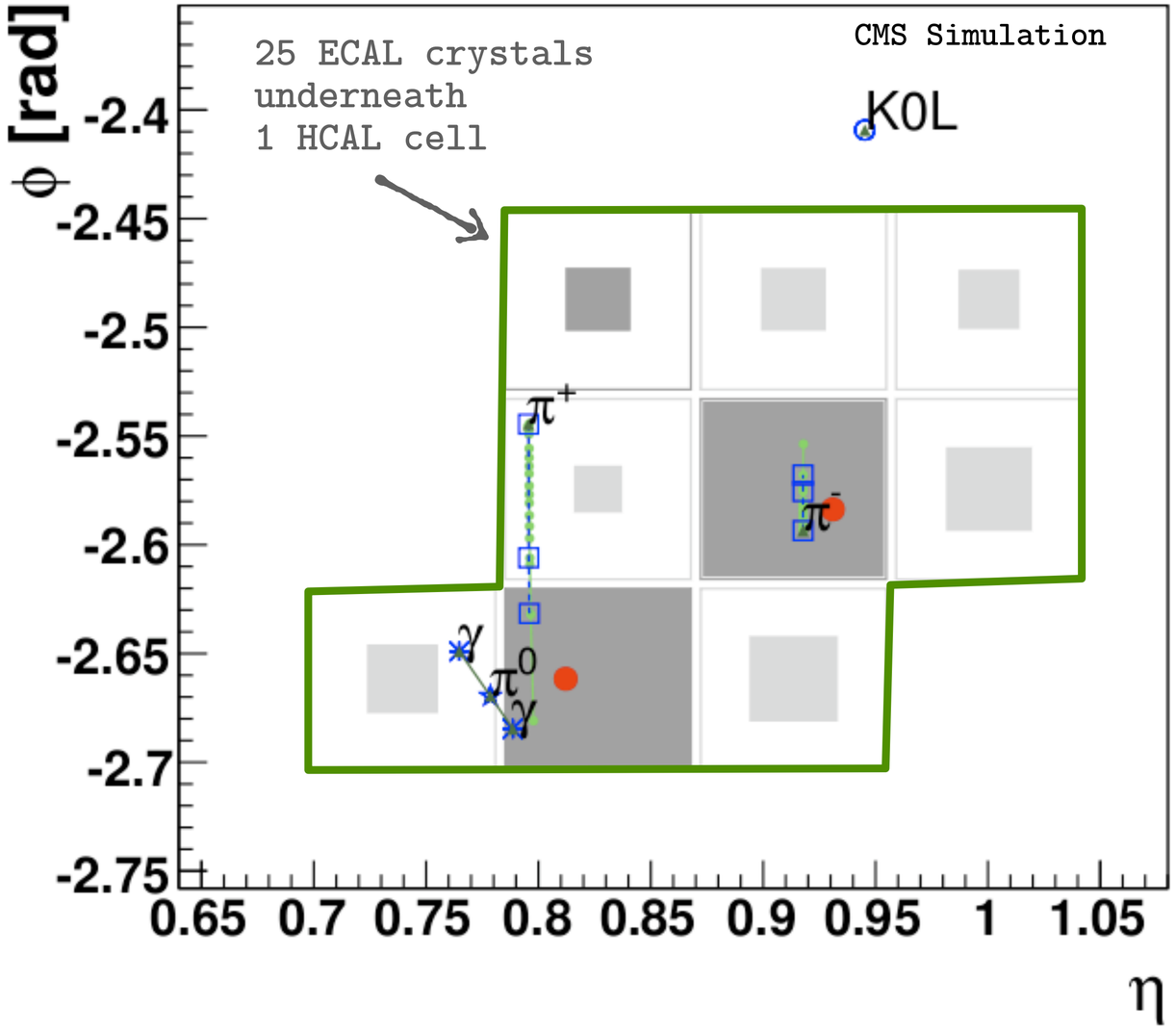

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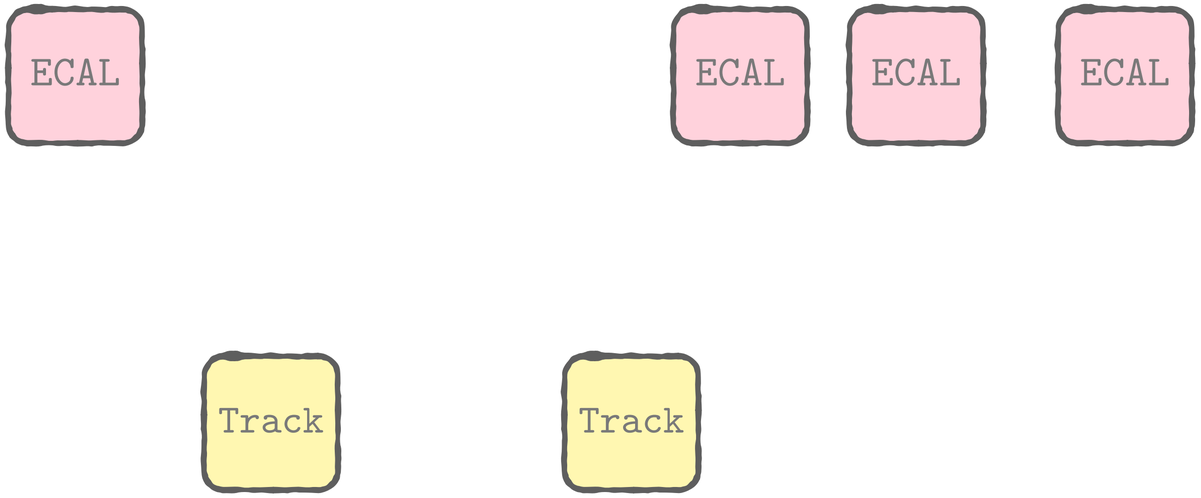

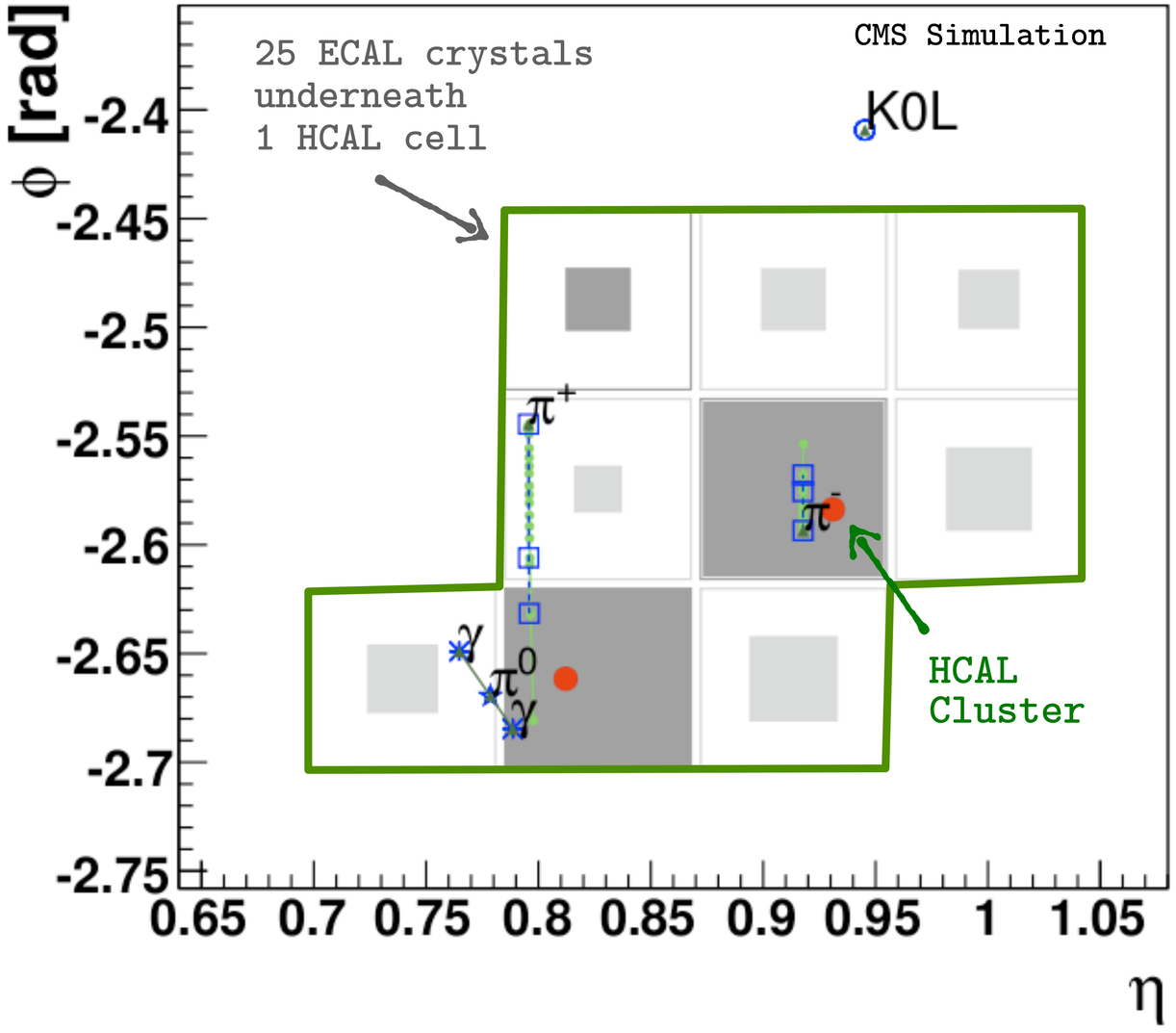

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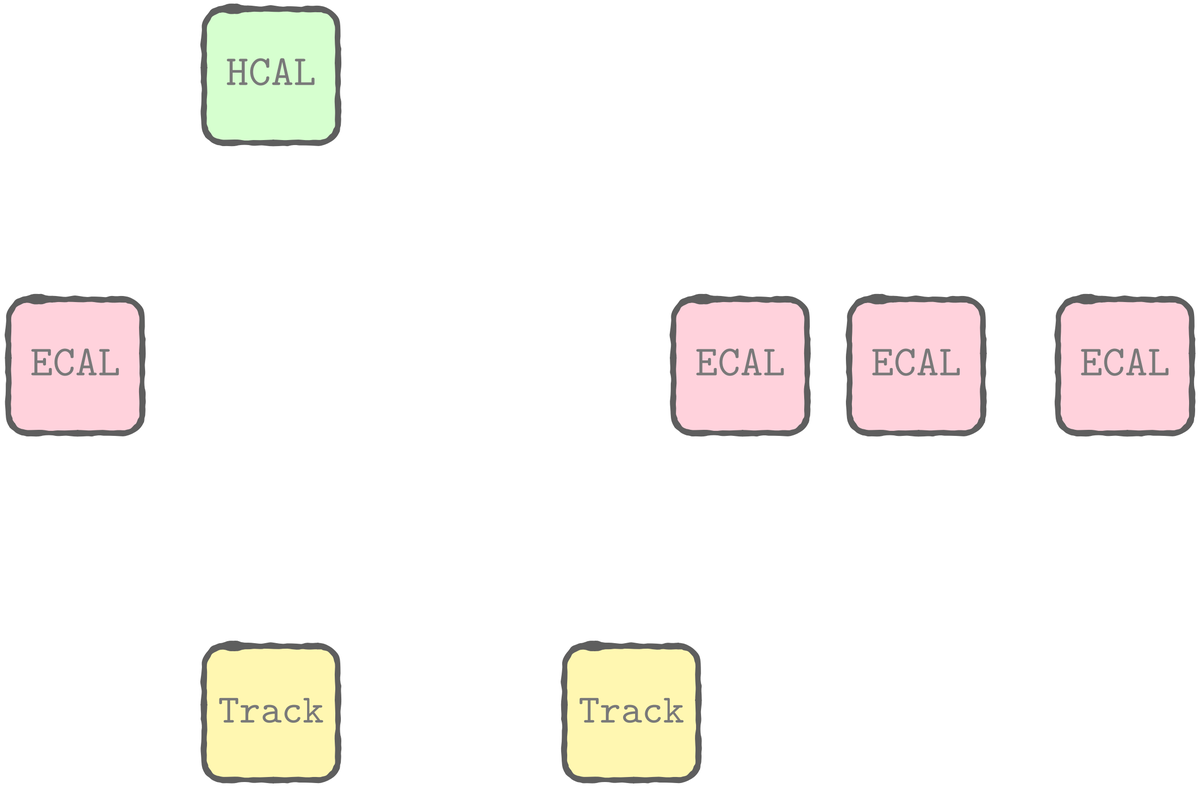

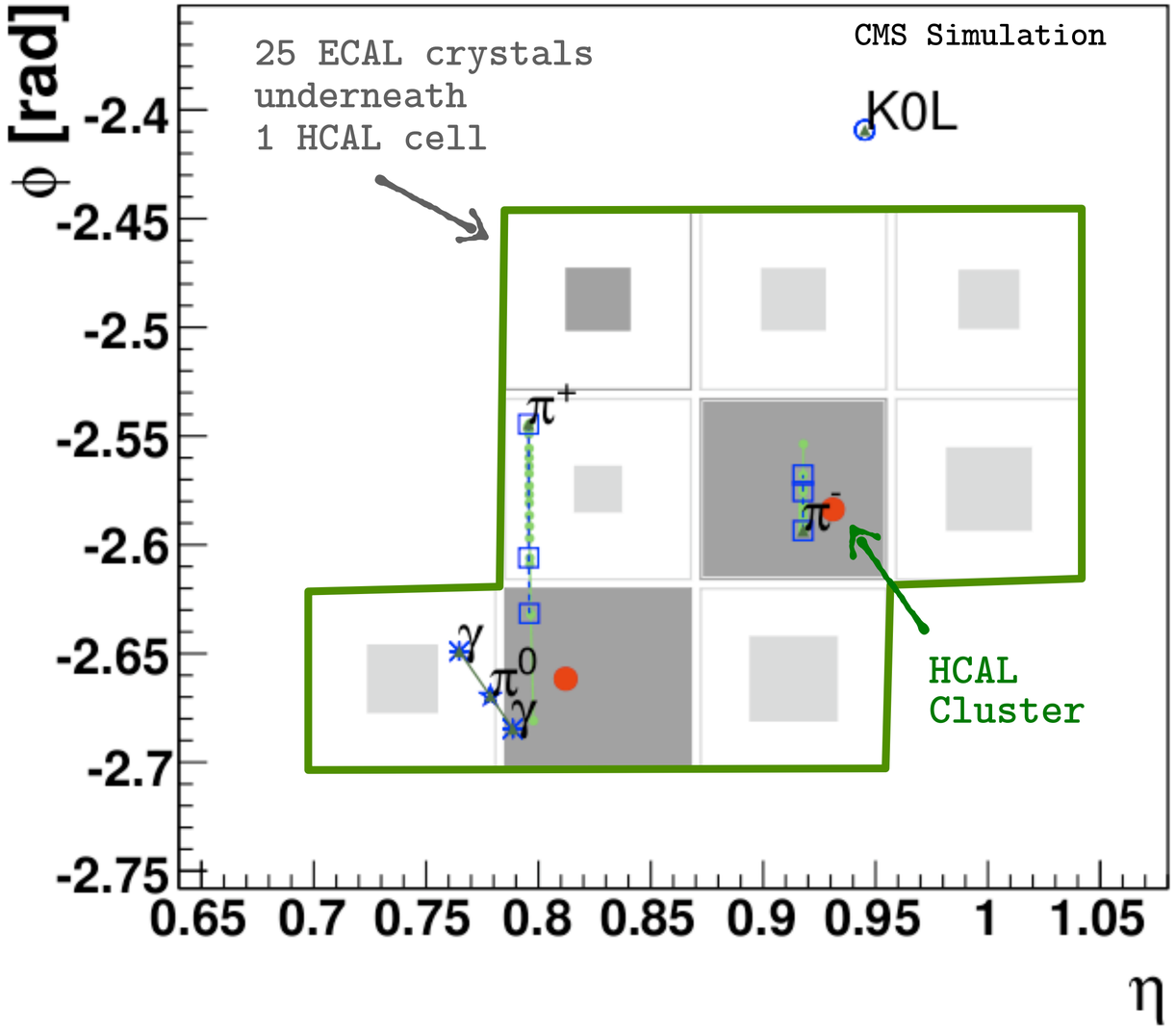

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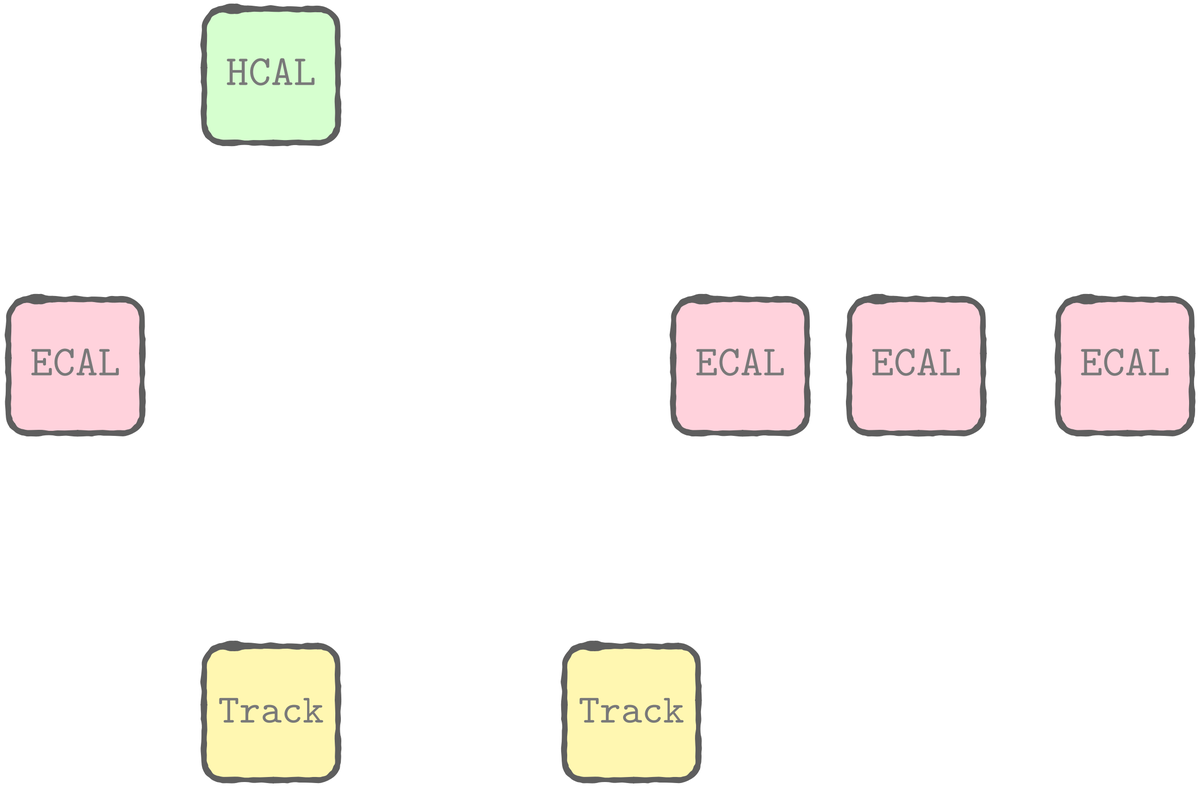

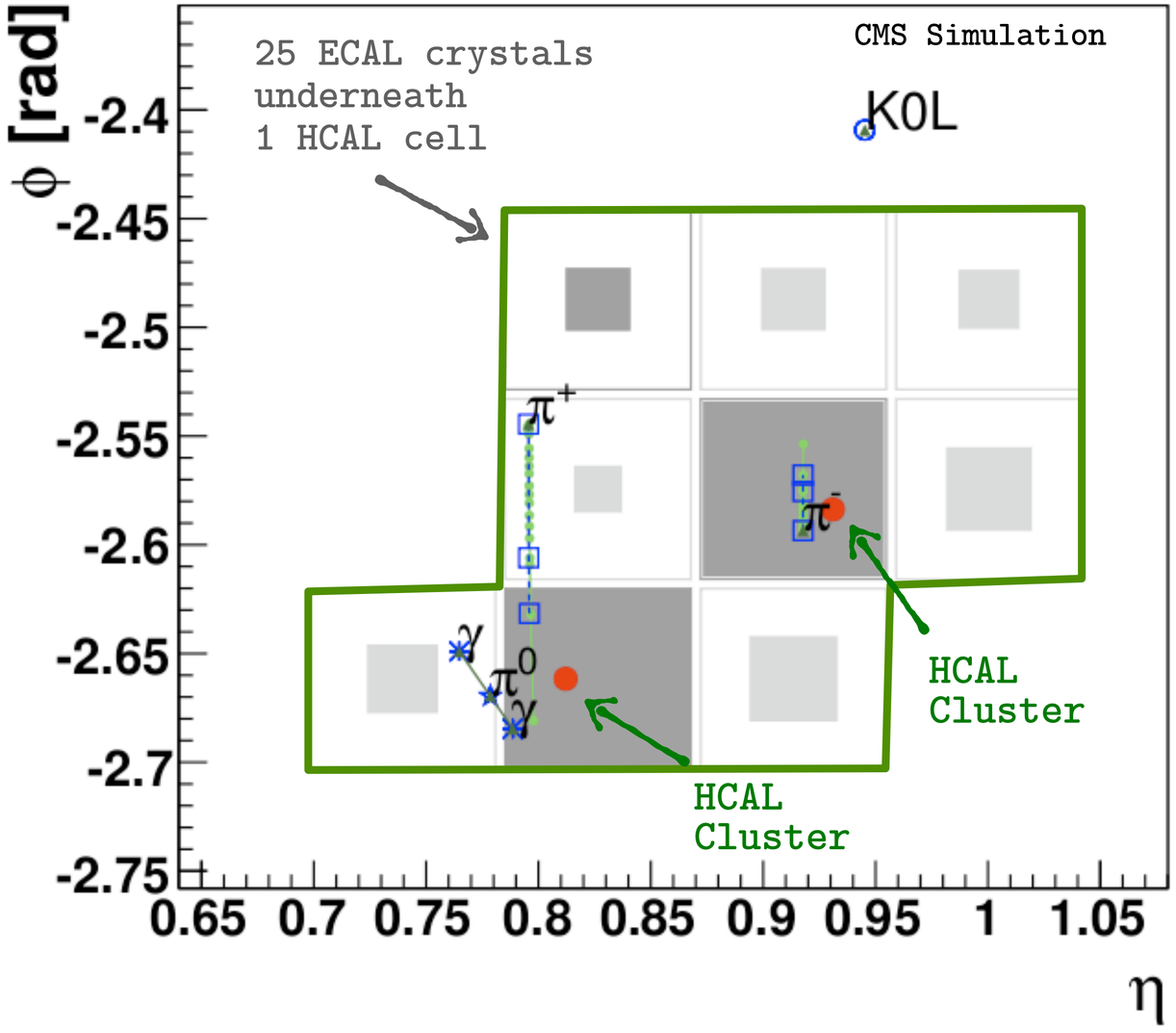

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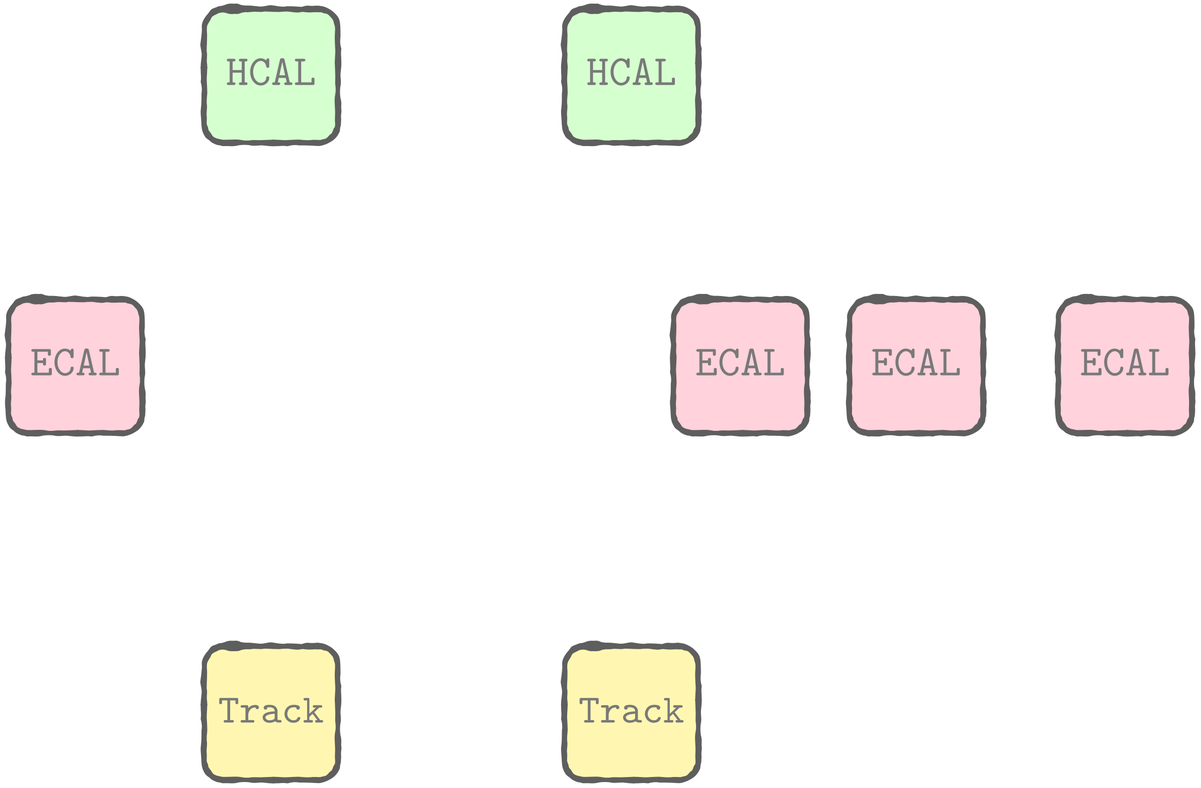

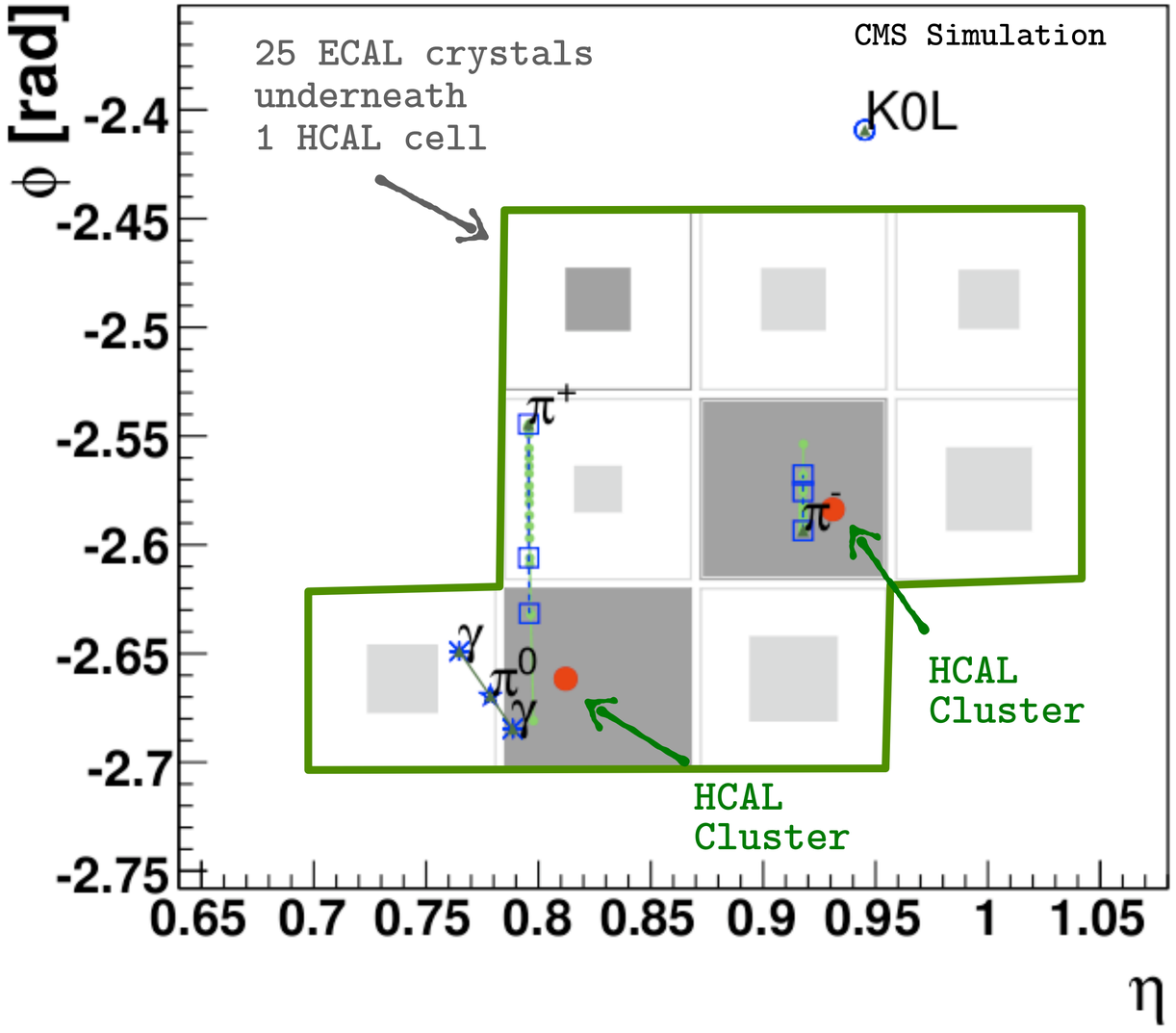

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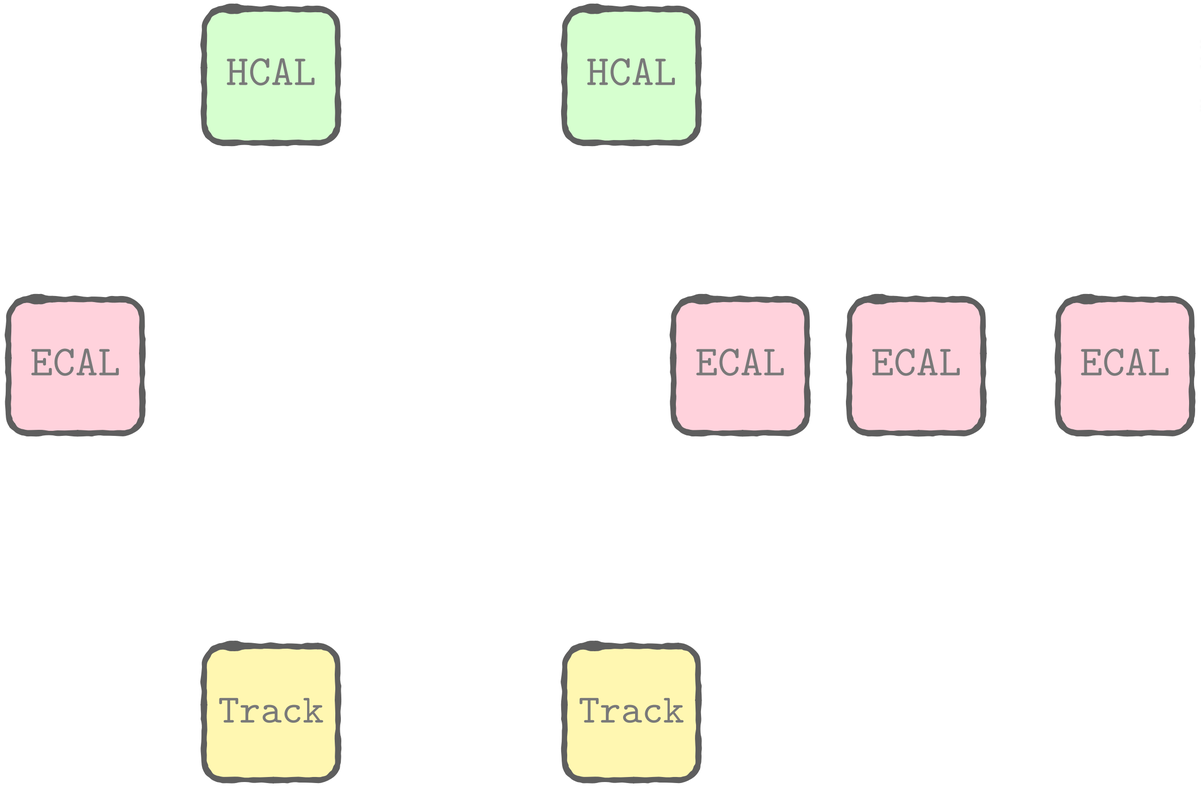

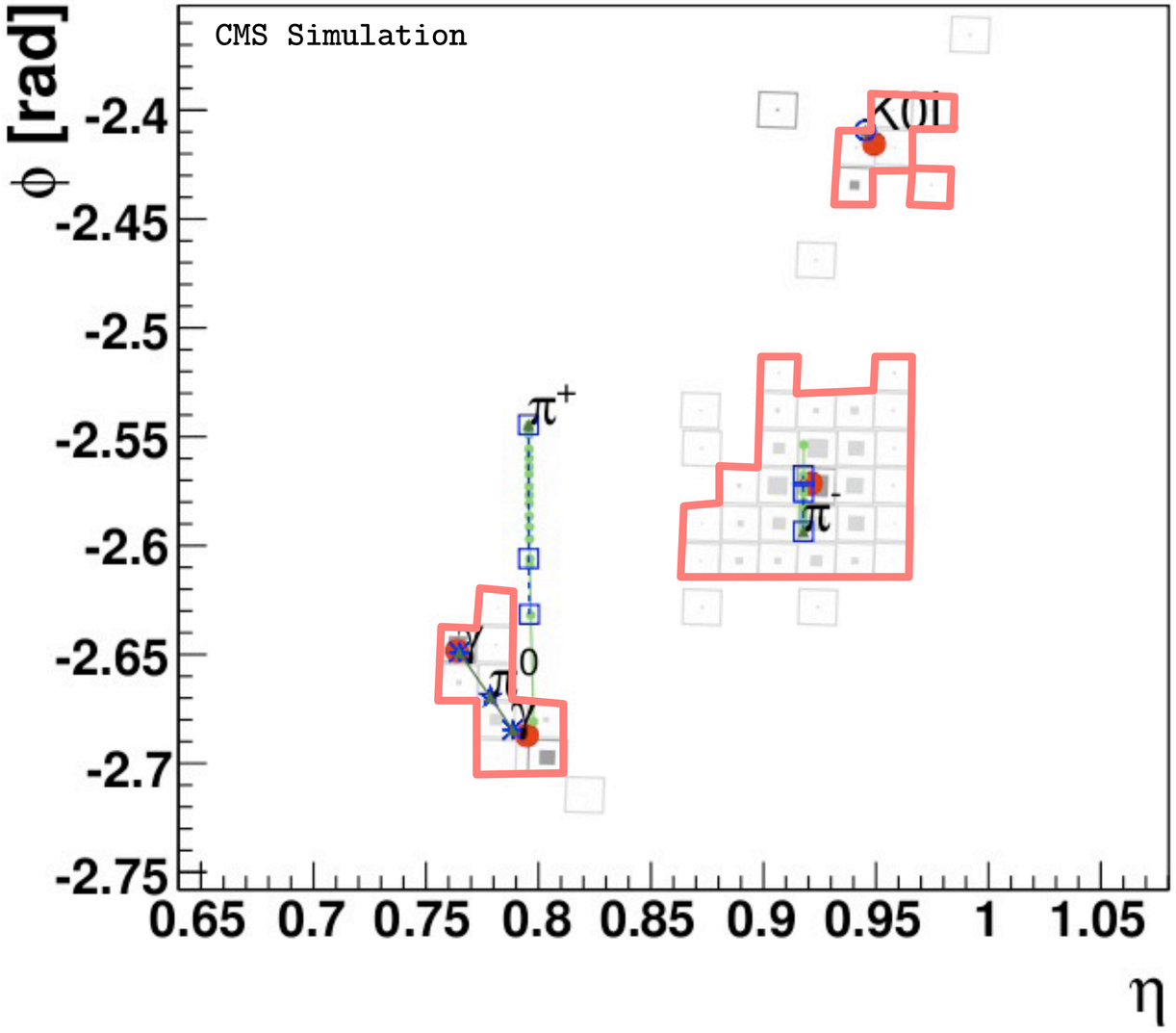

Four true particles:

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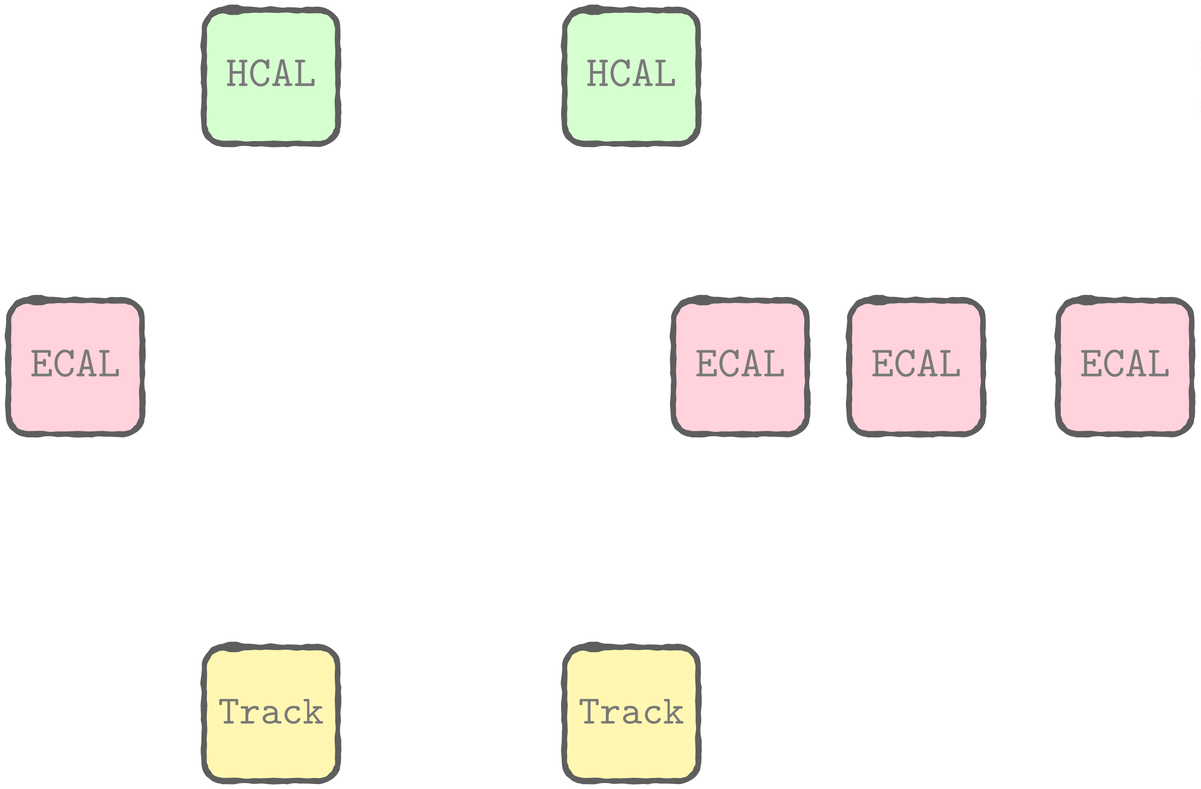

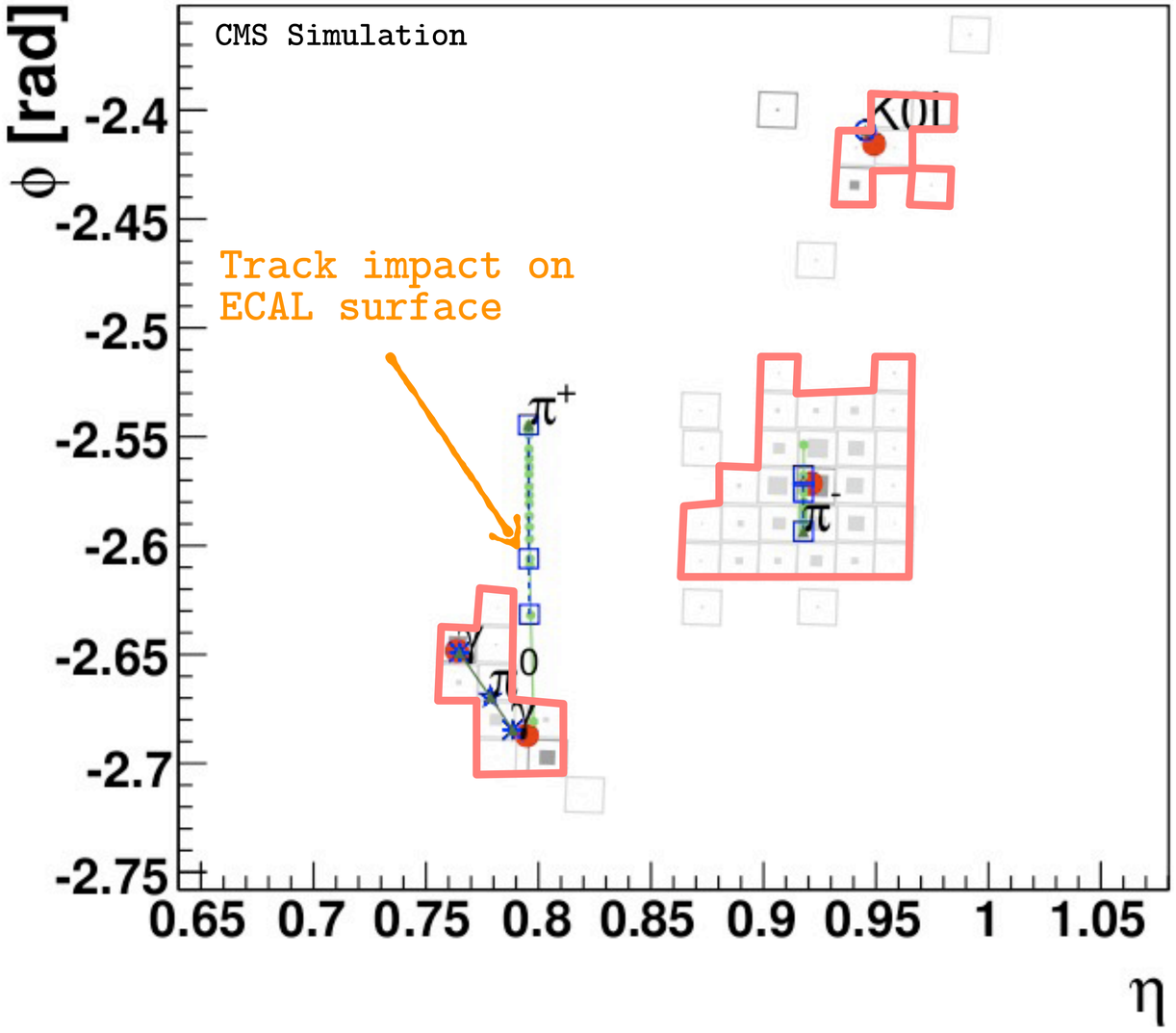

Four true particles:

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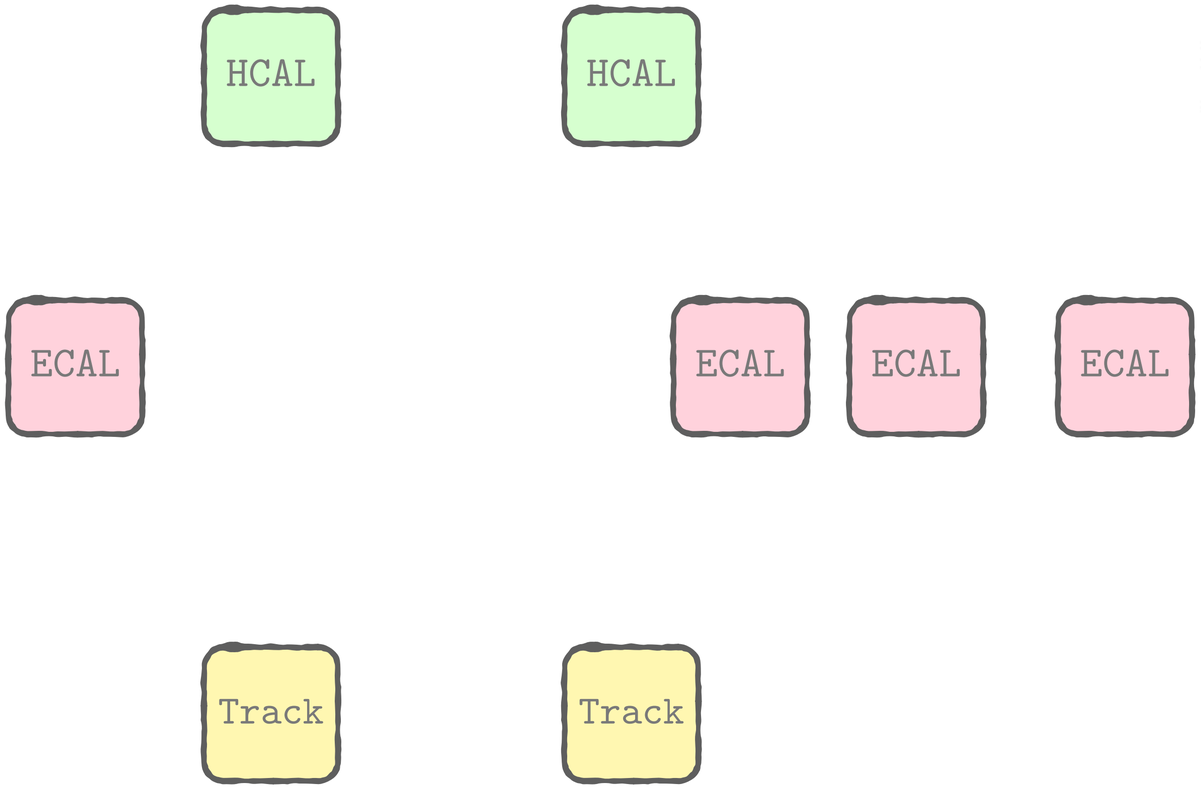

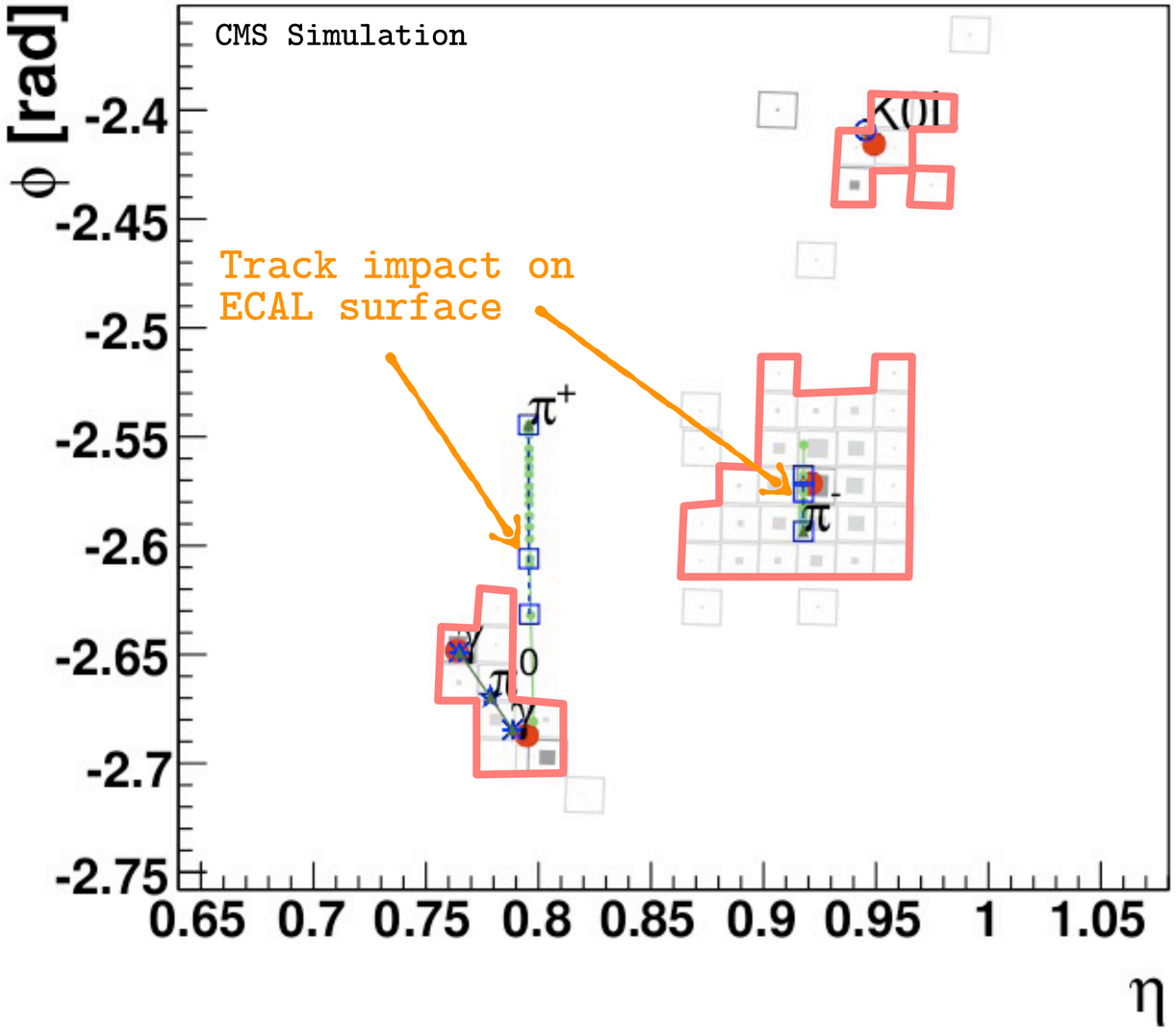

Four true particles:

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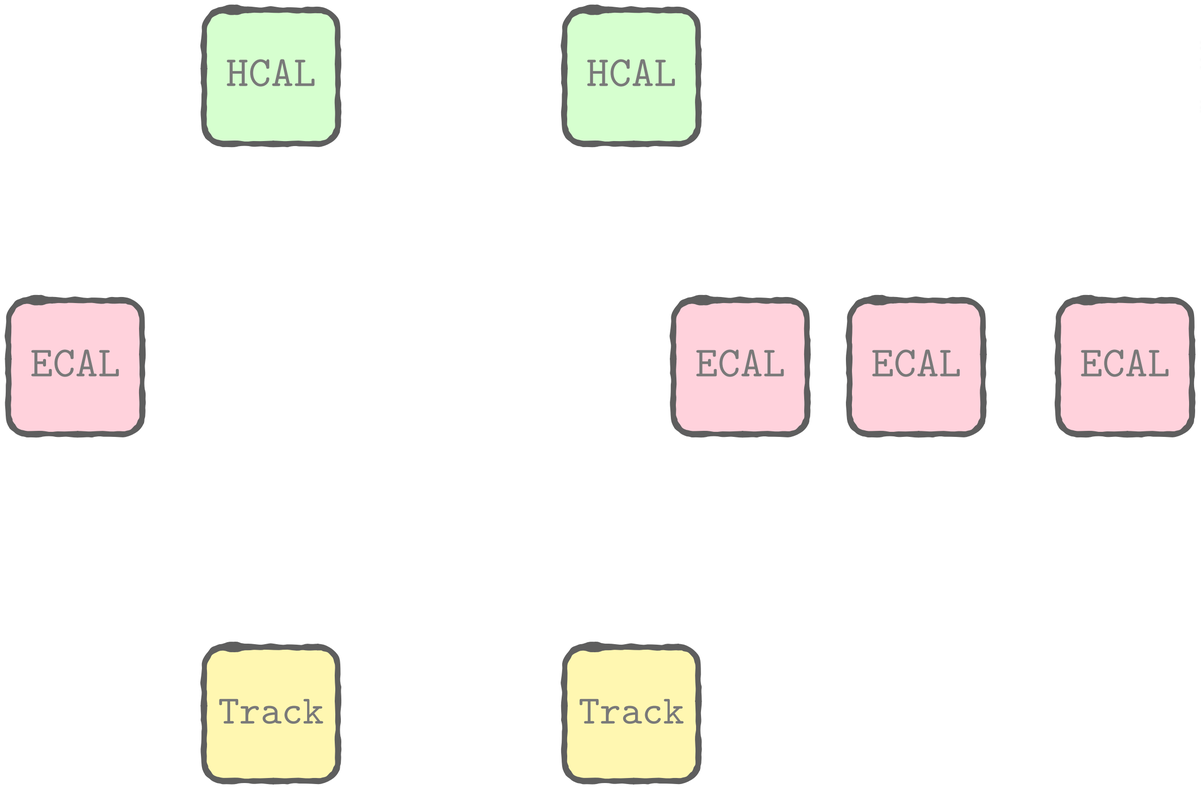

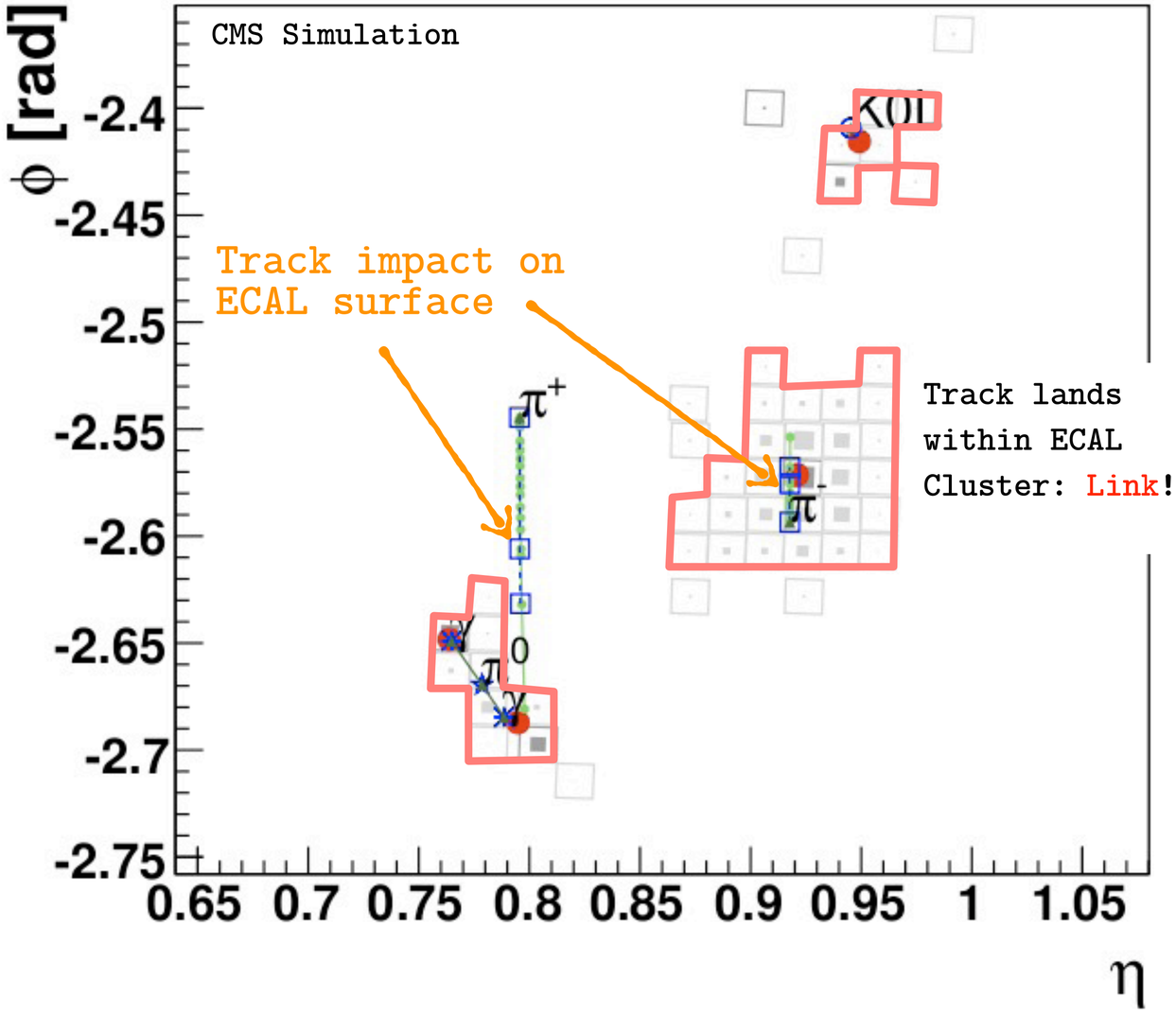

Four true particles:

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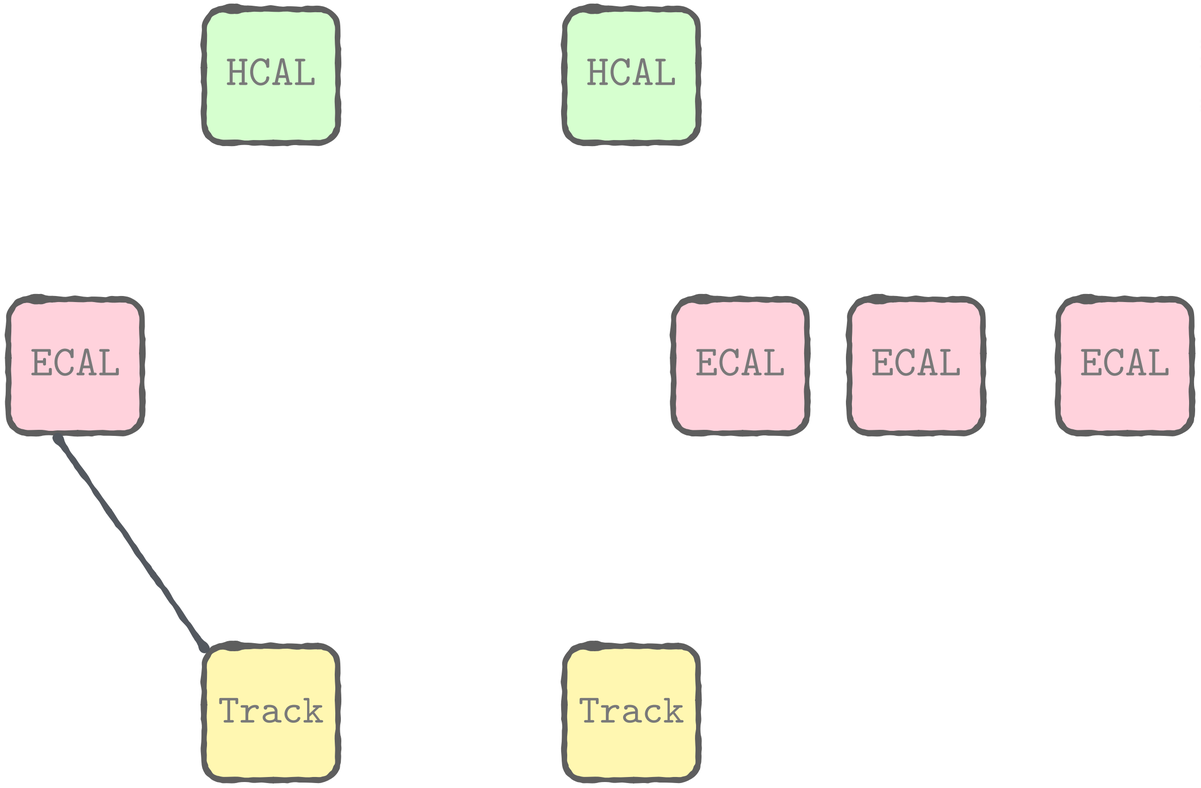

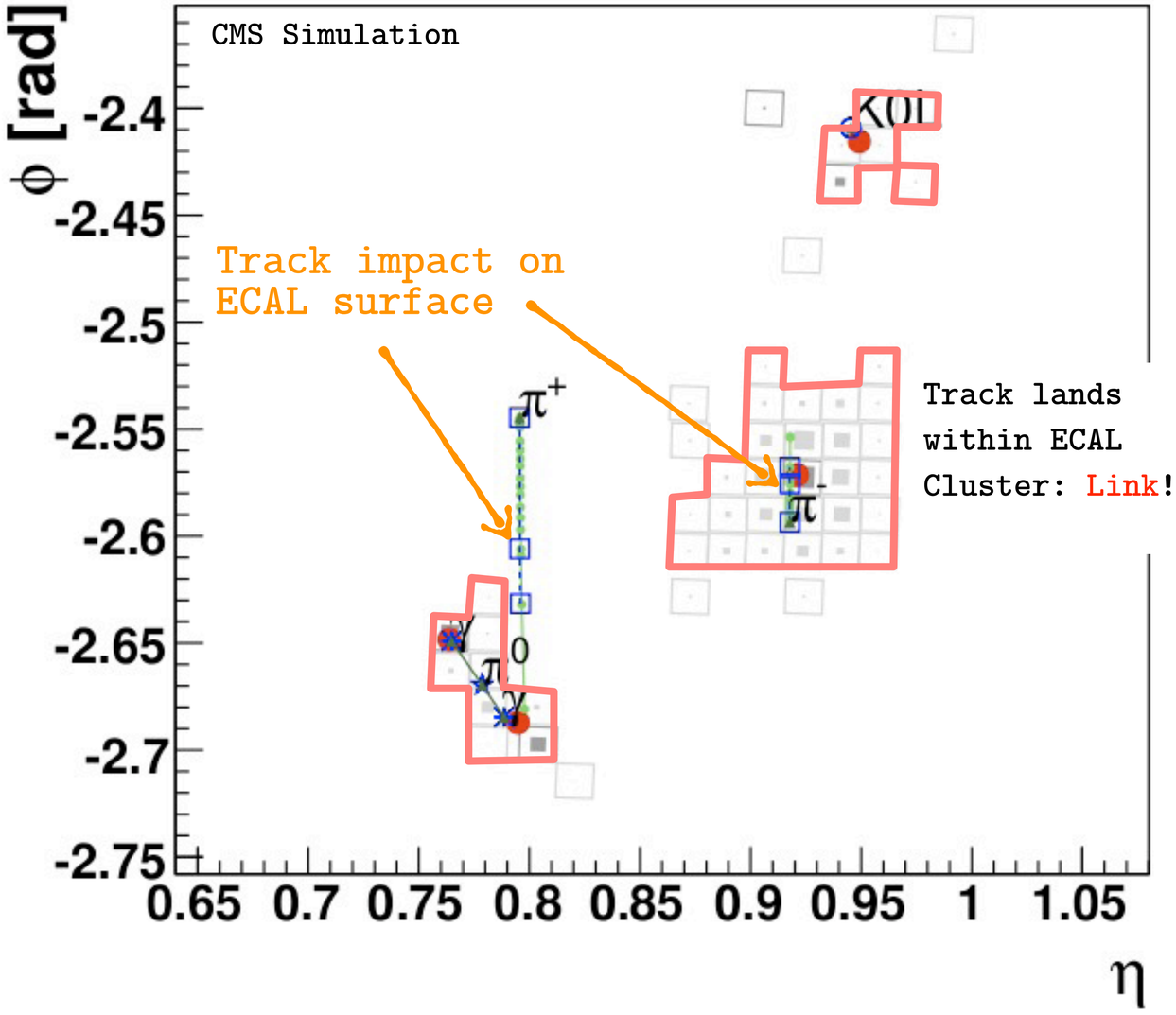

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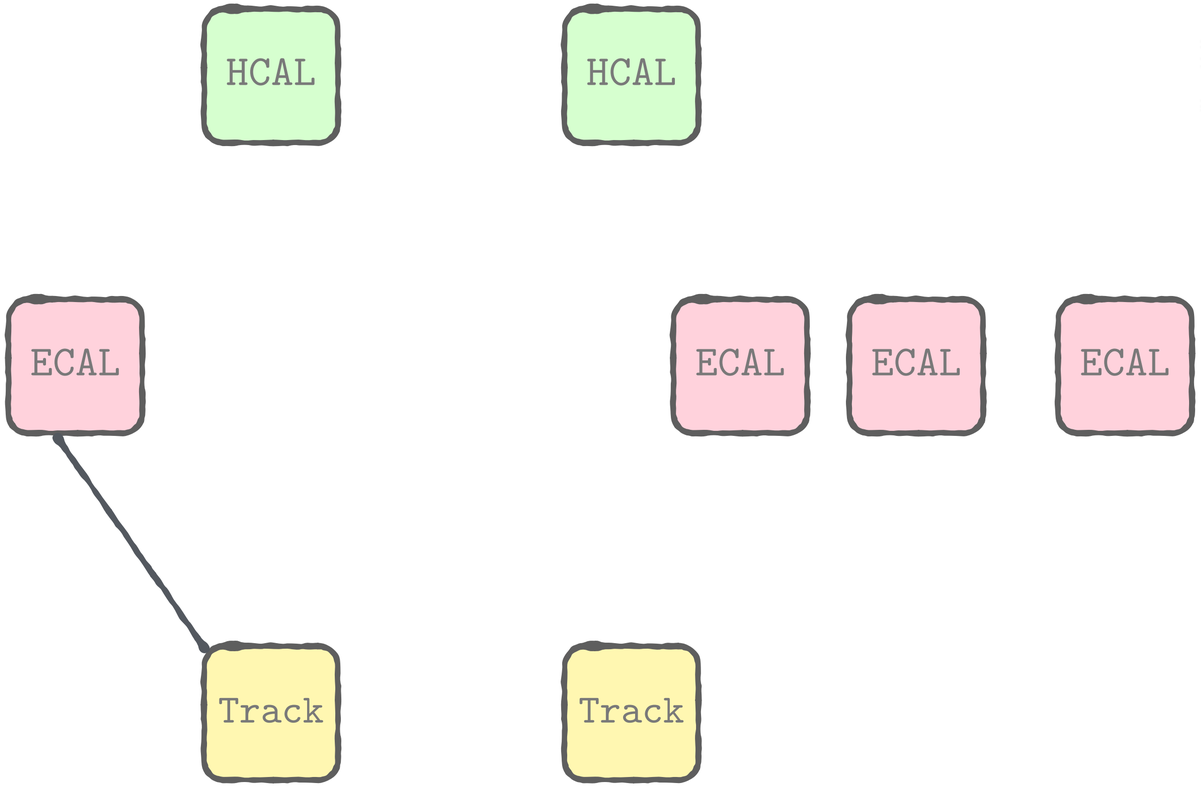

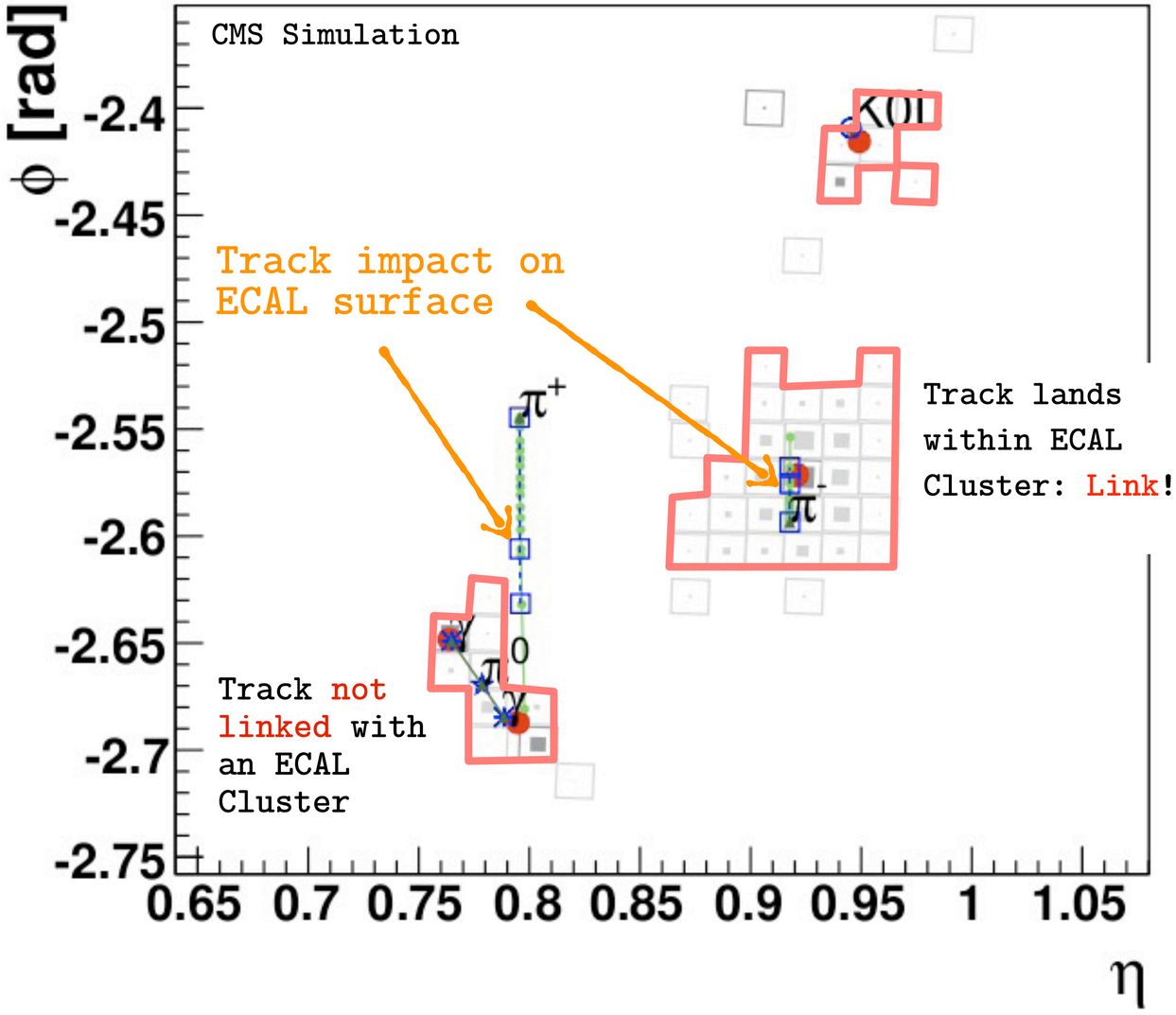

Four true particles:

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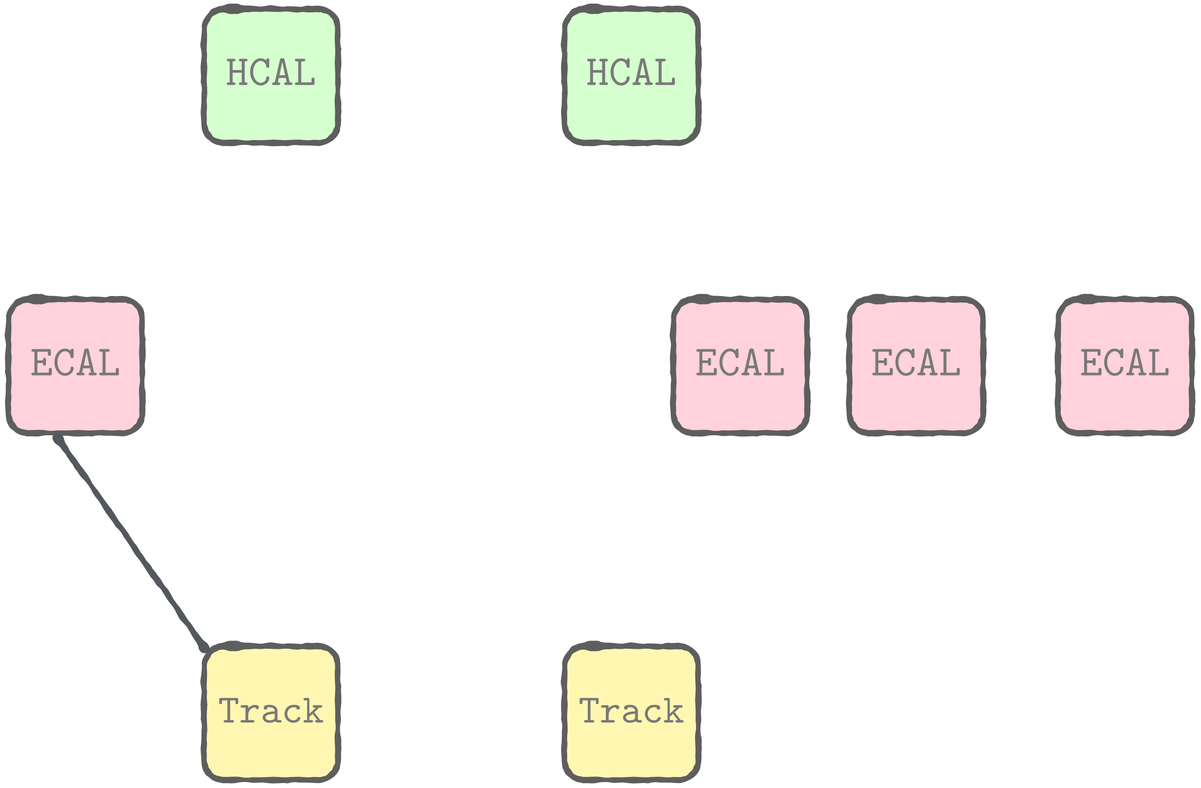

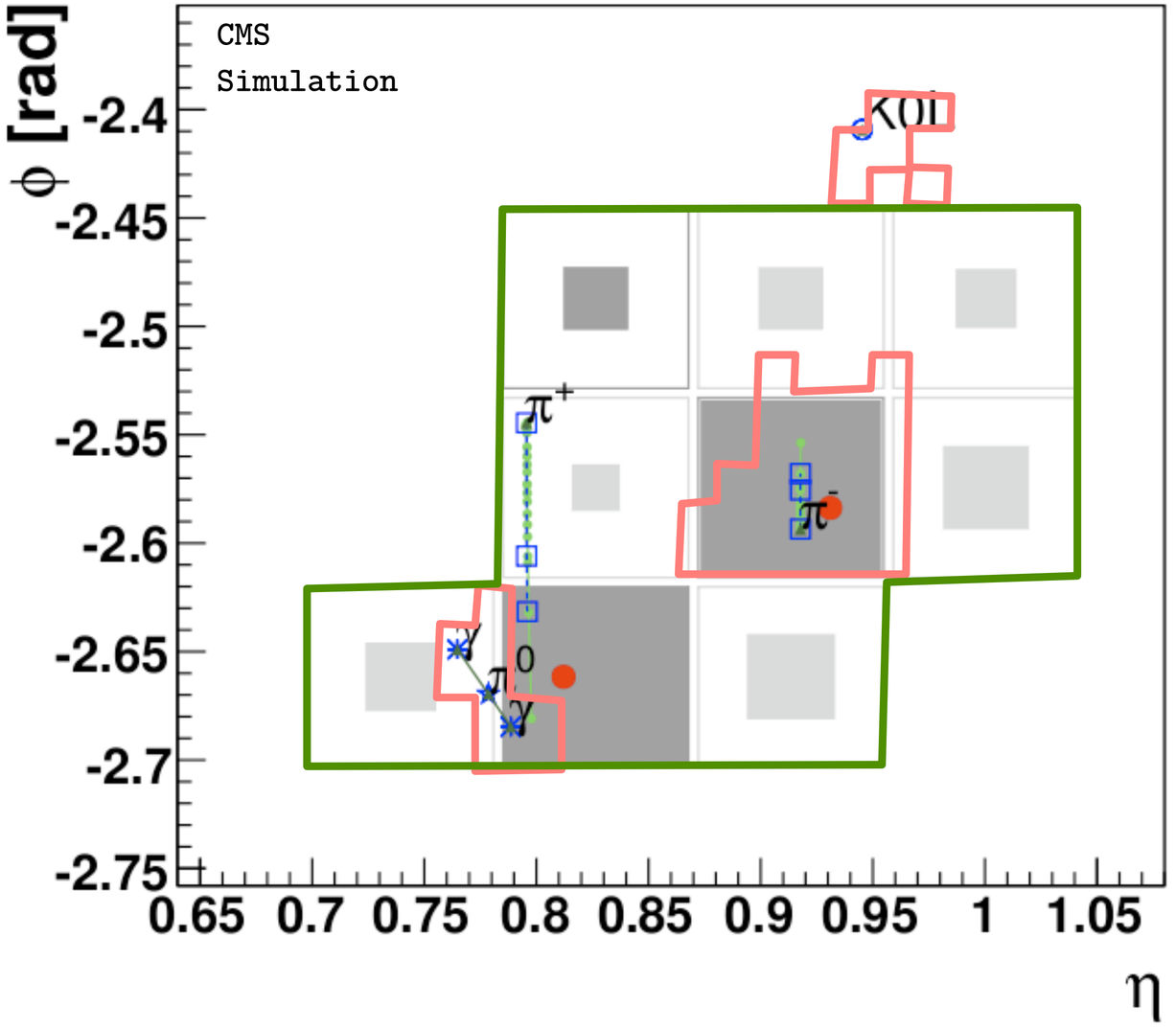

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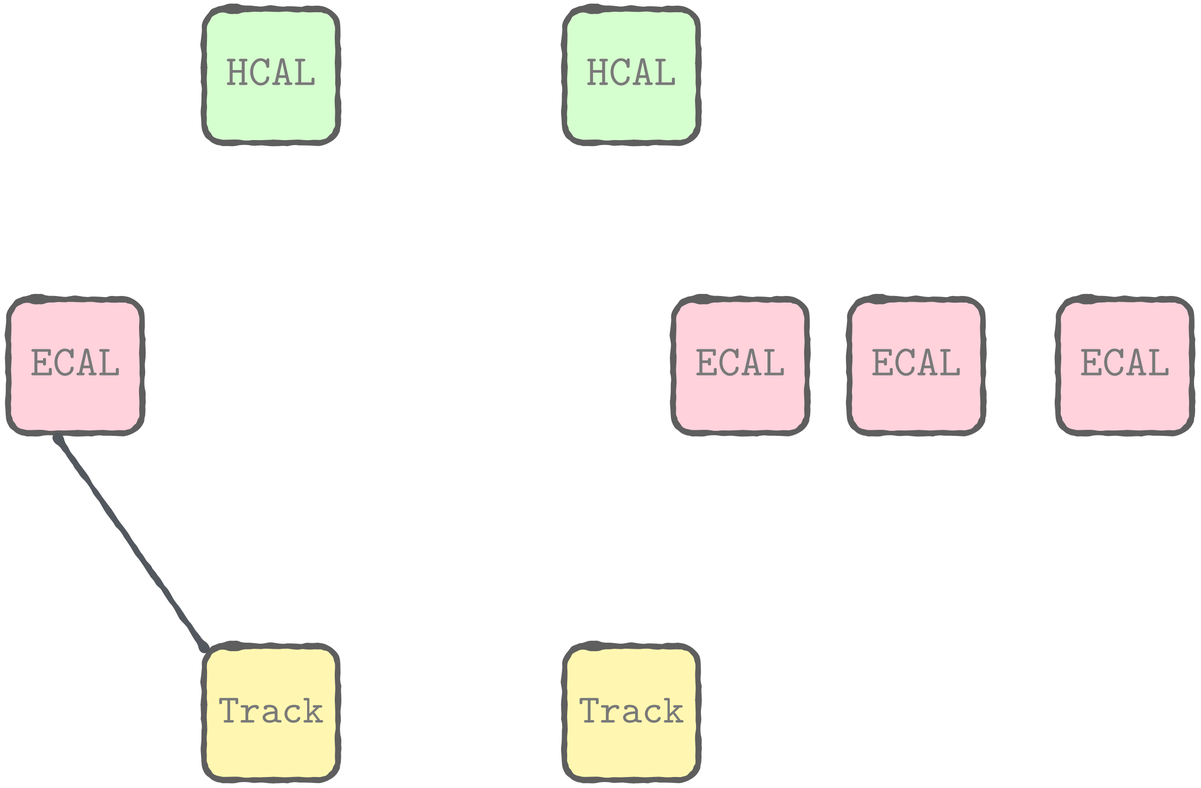

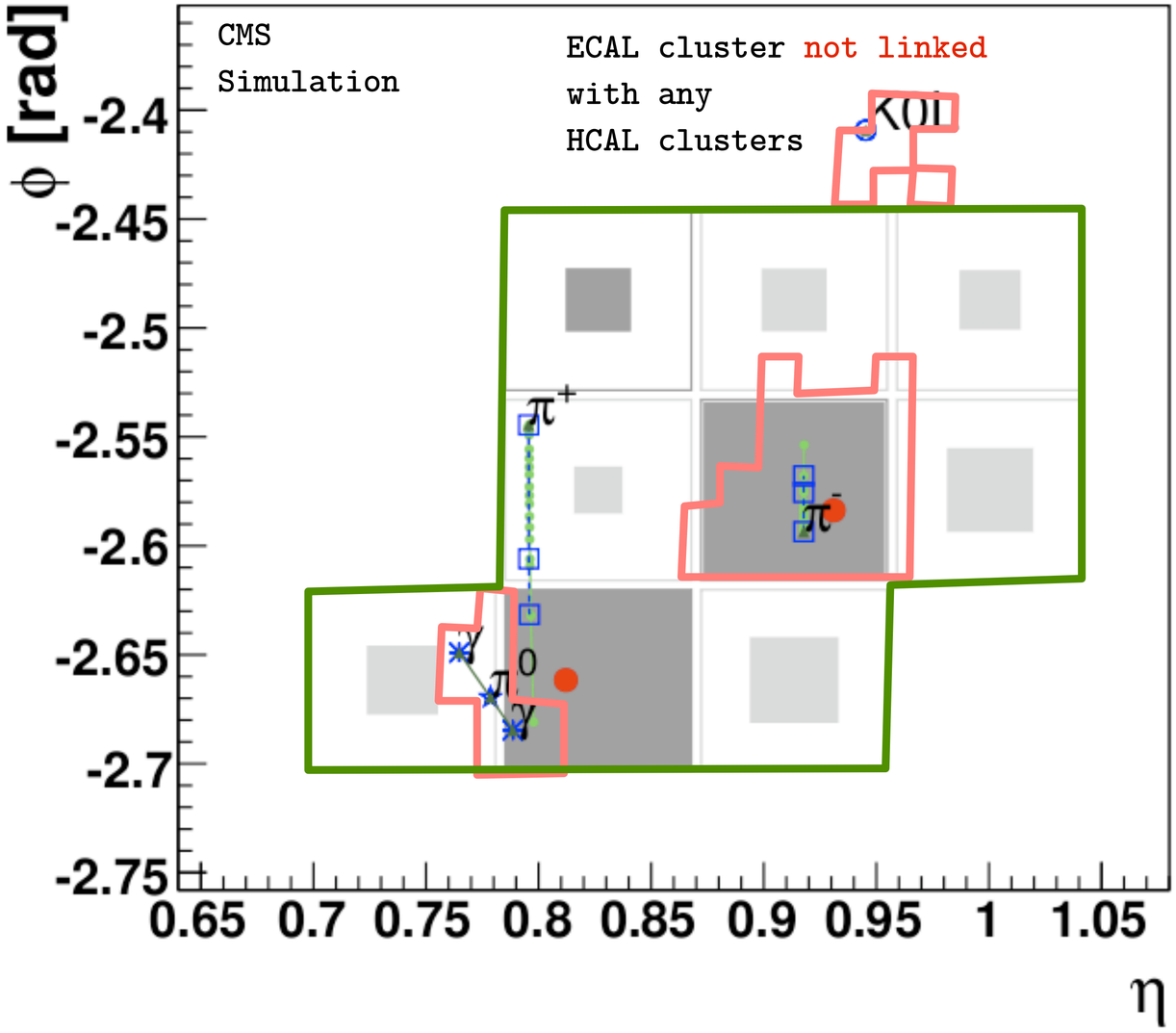

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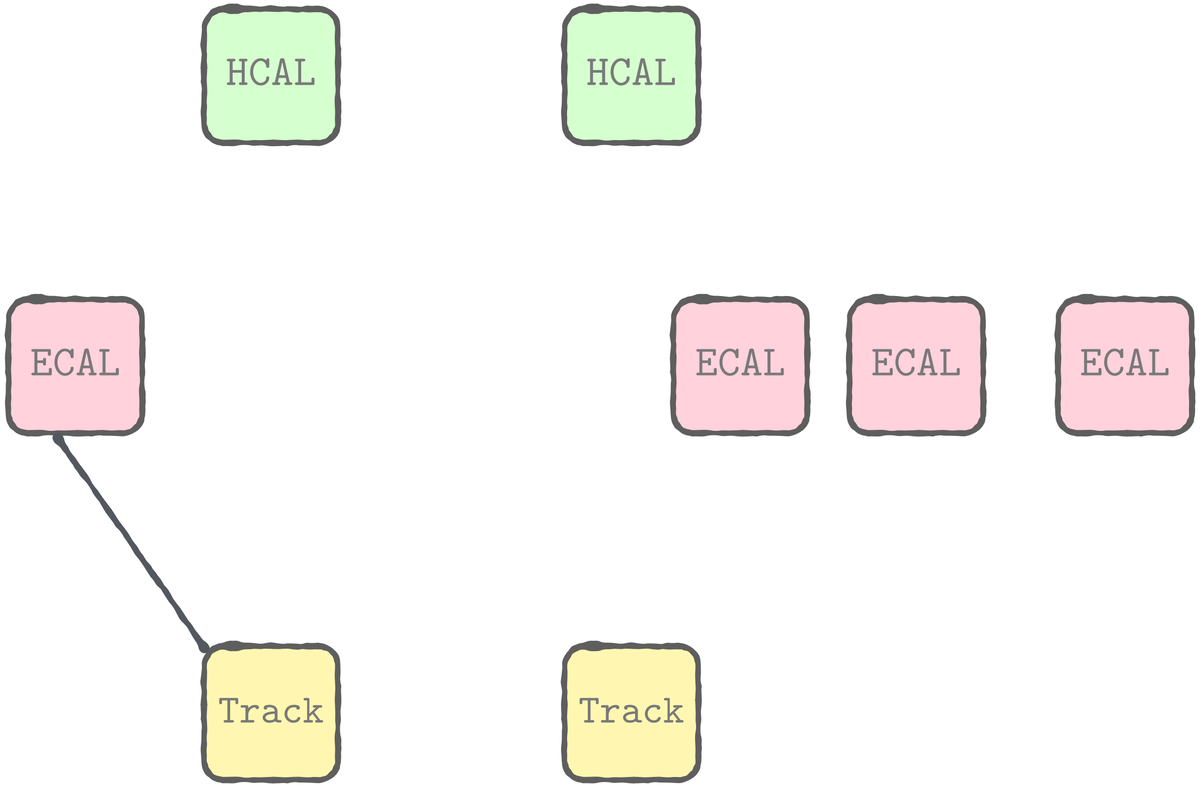

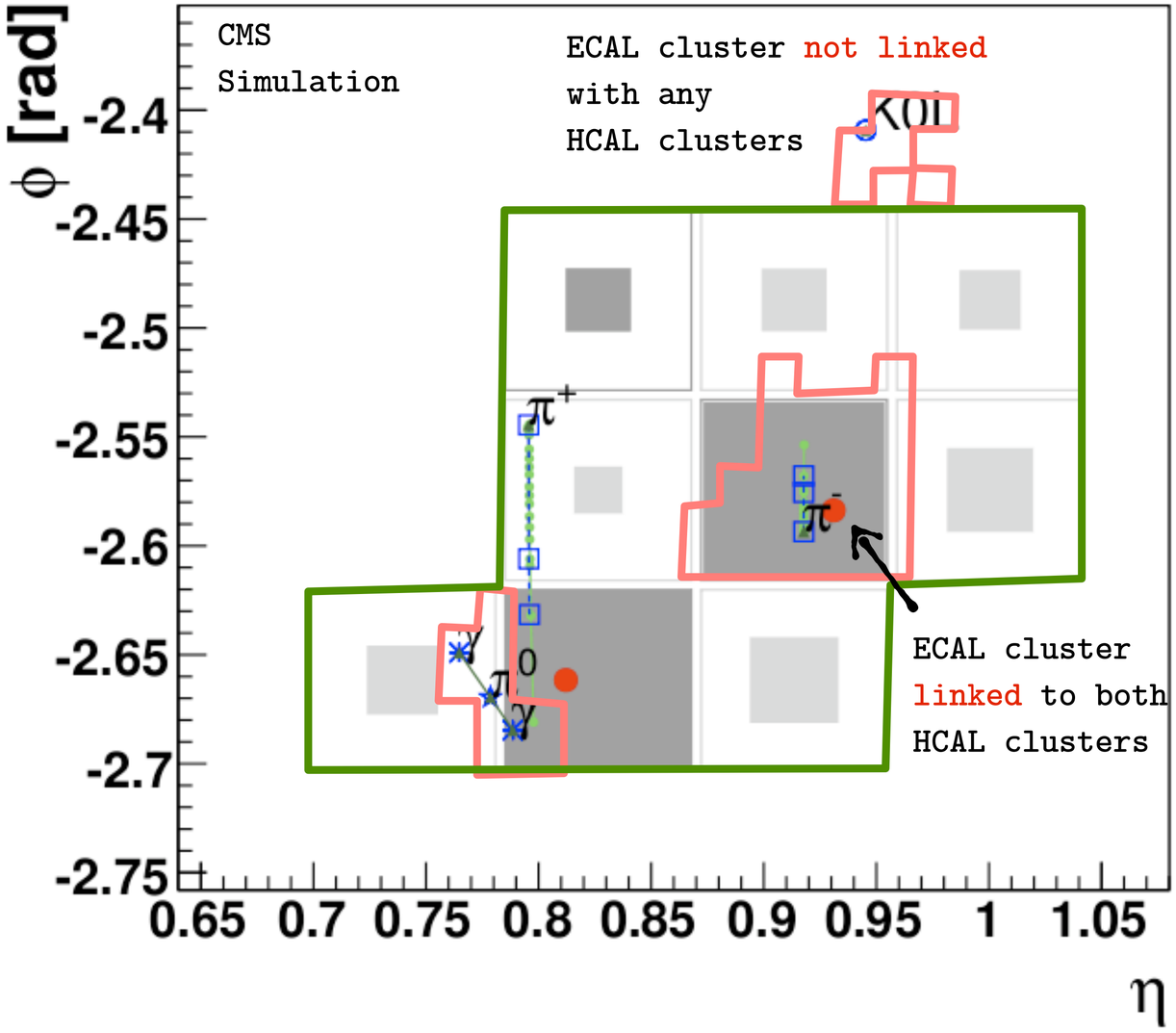

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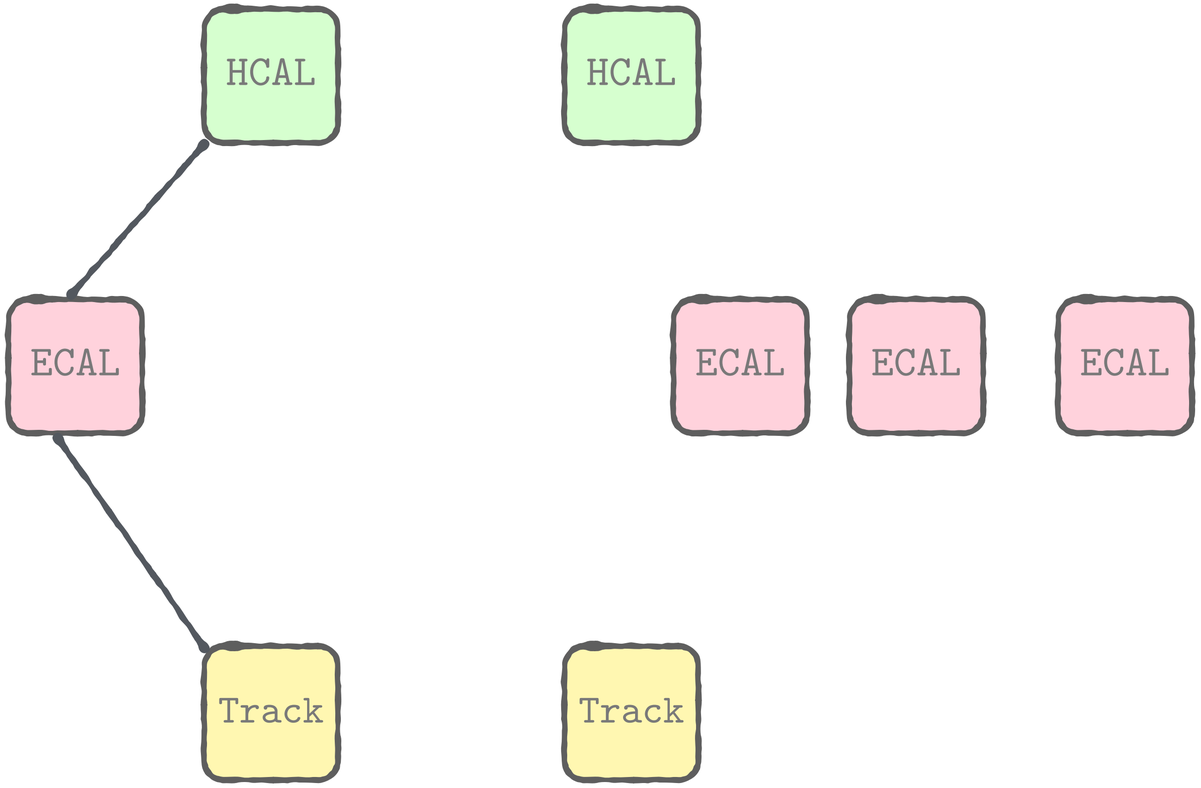

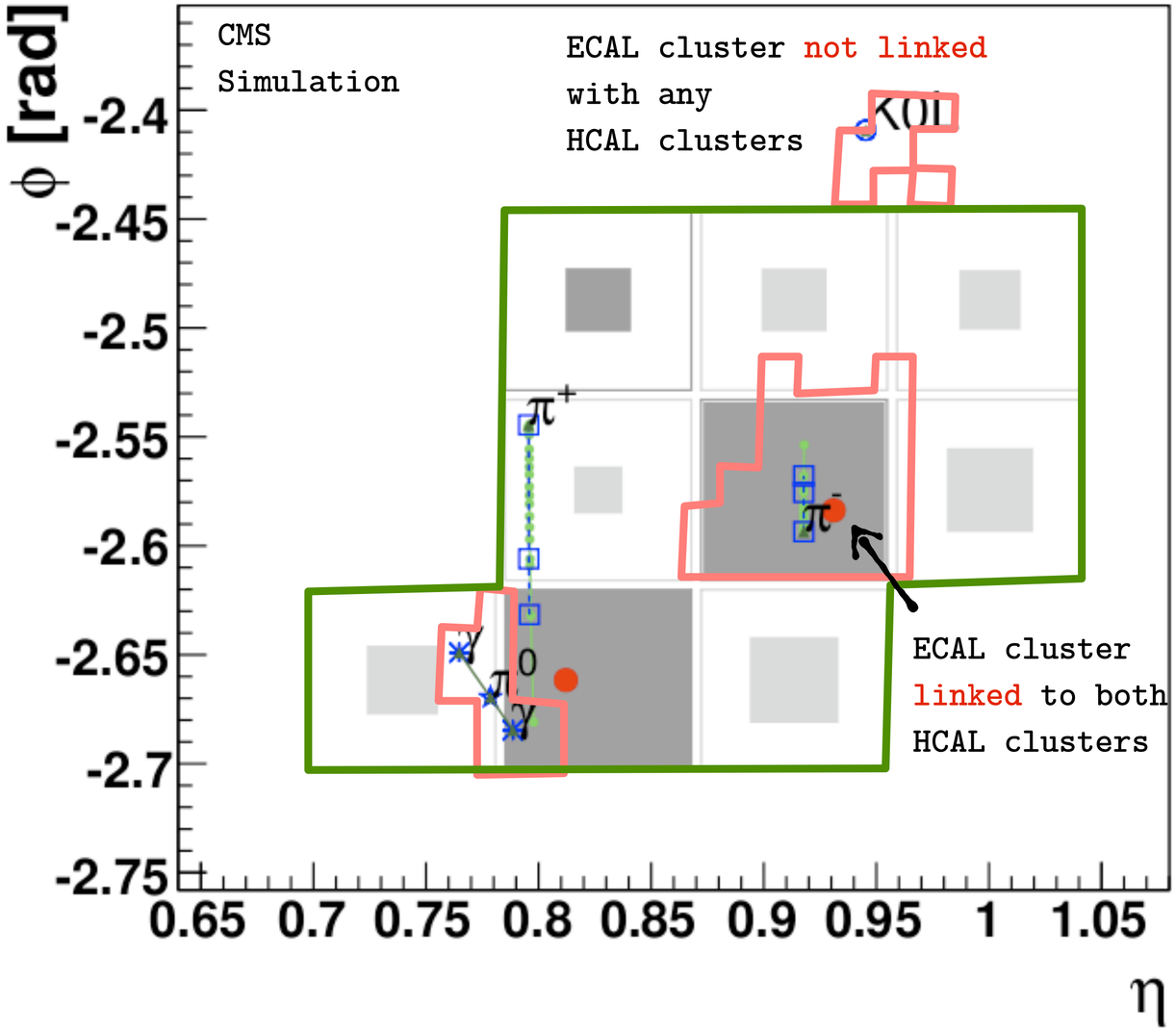

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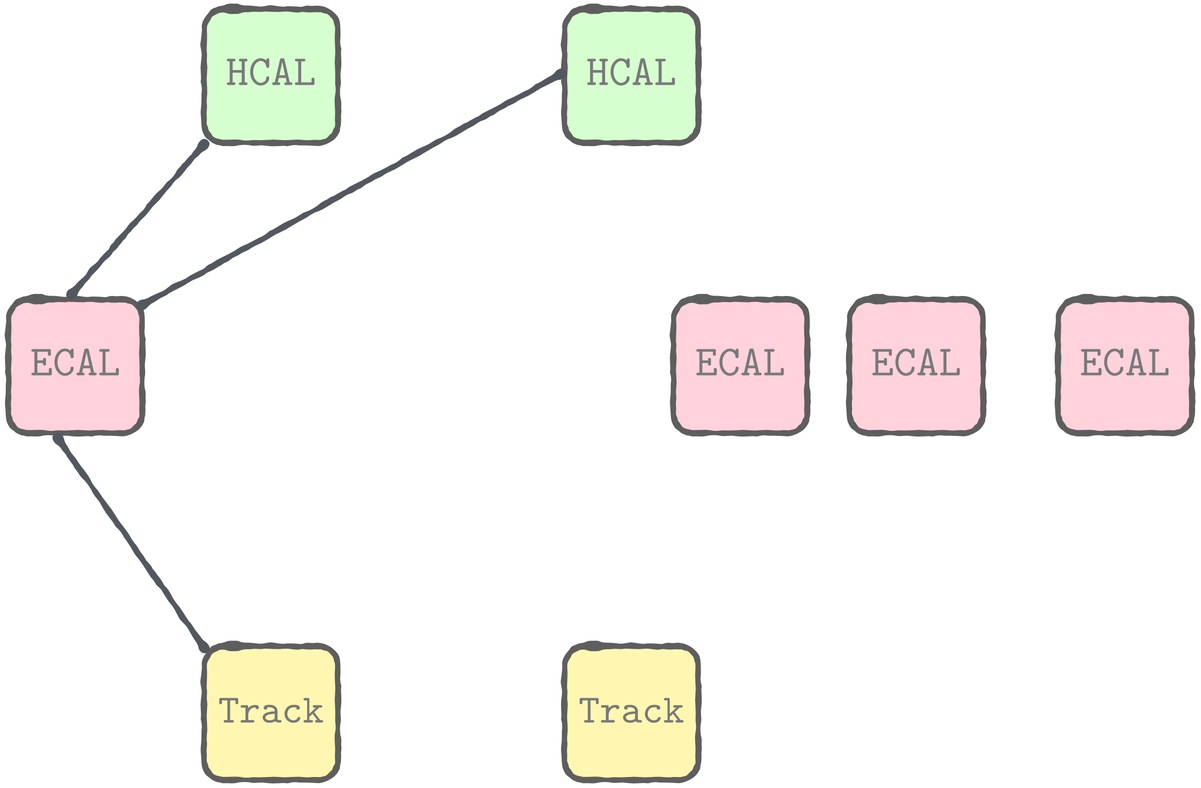

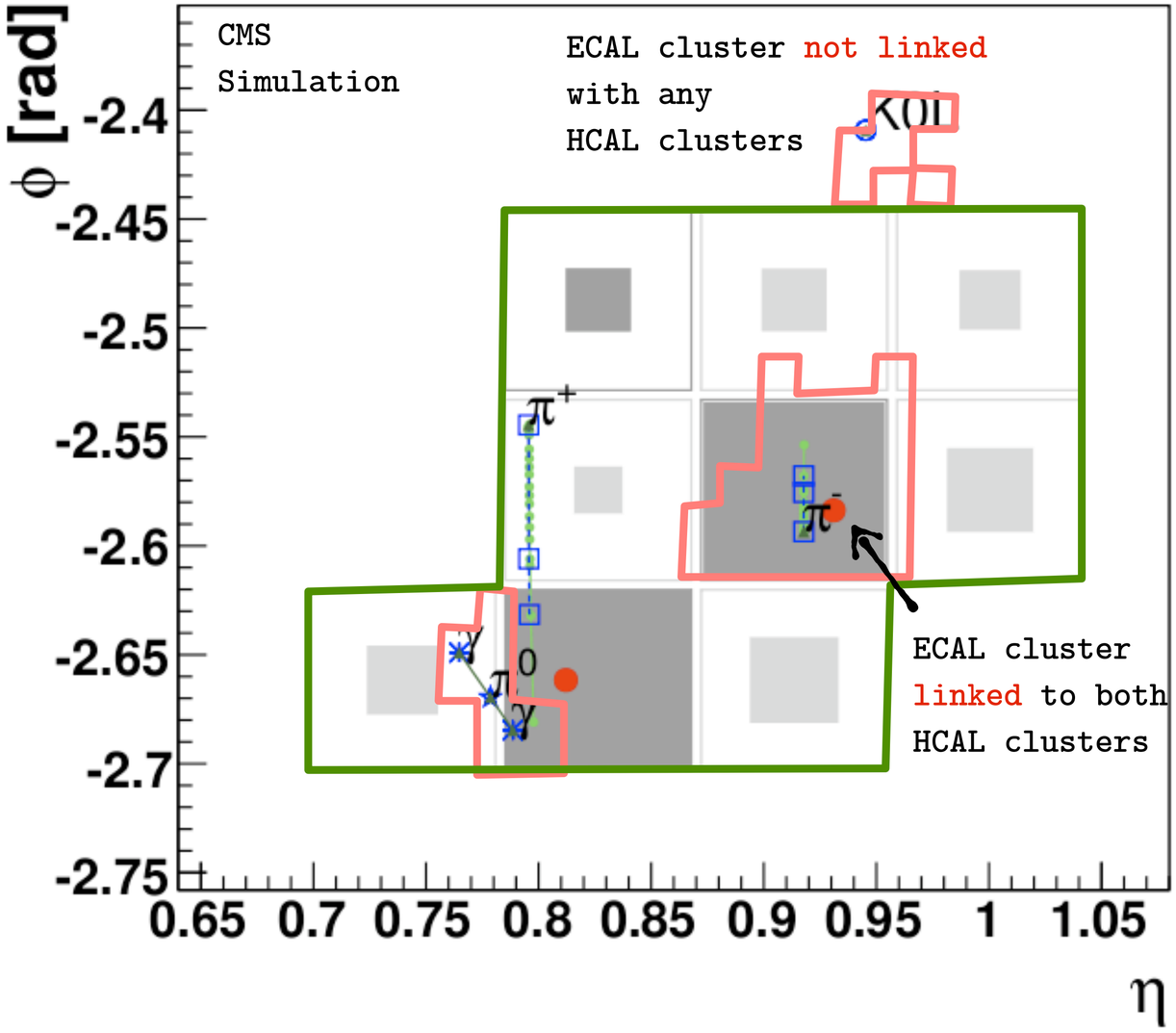

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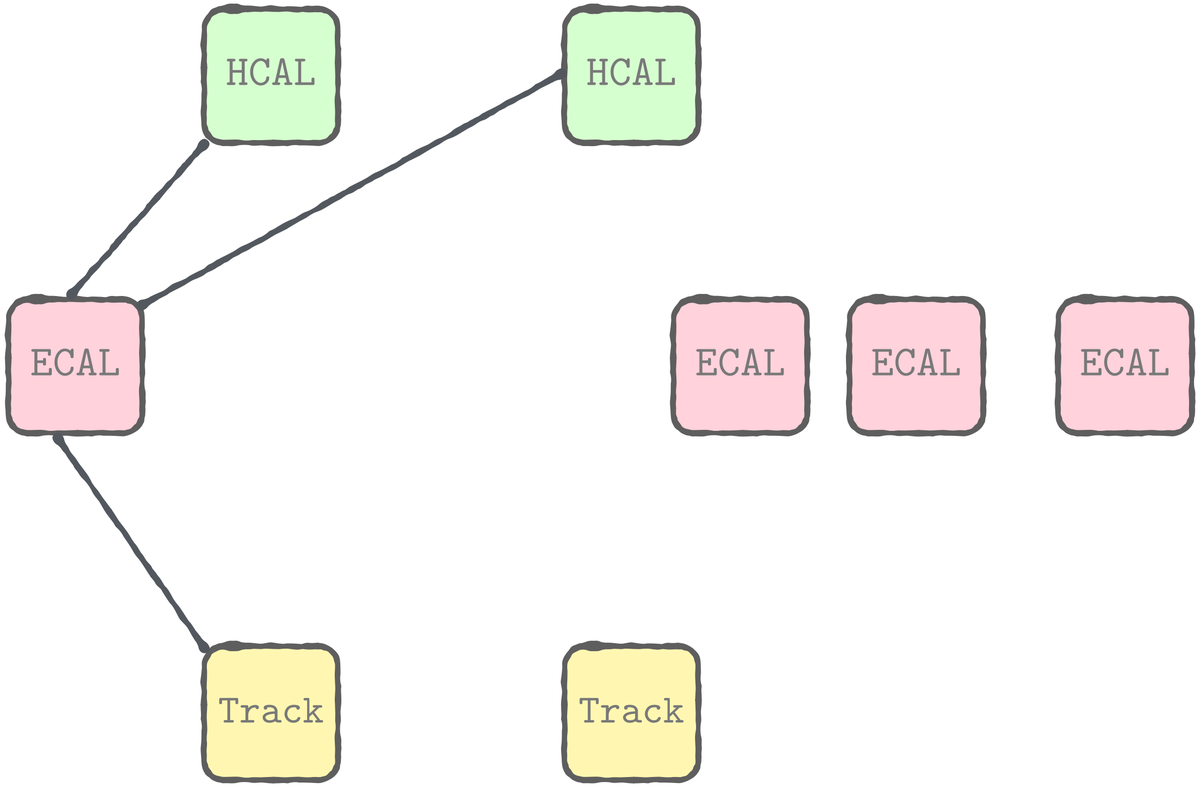

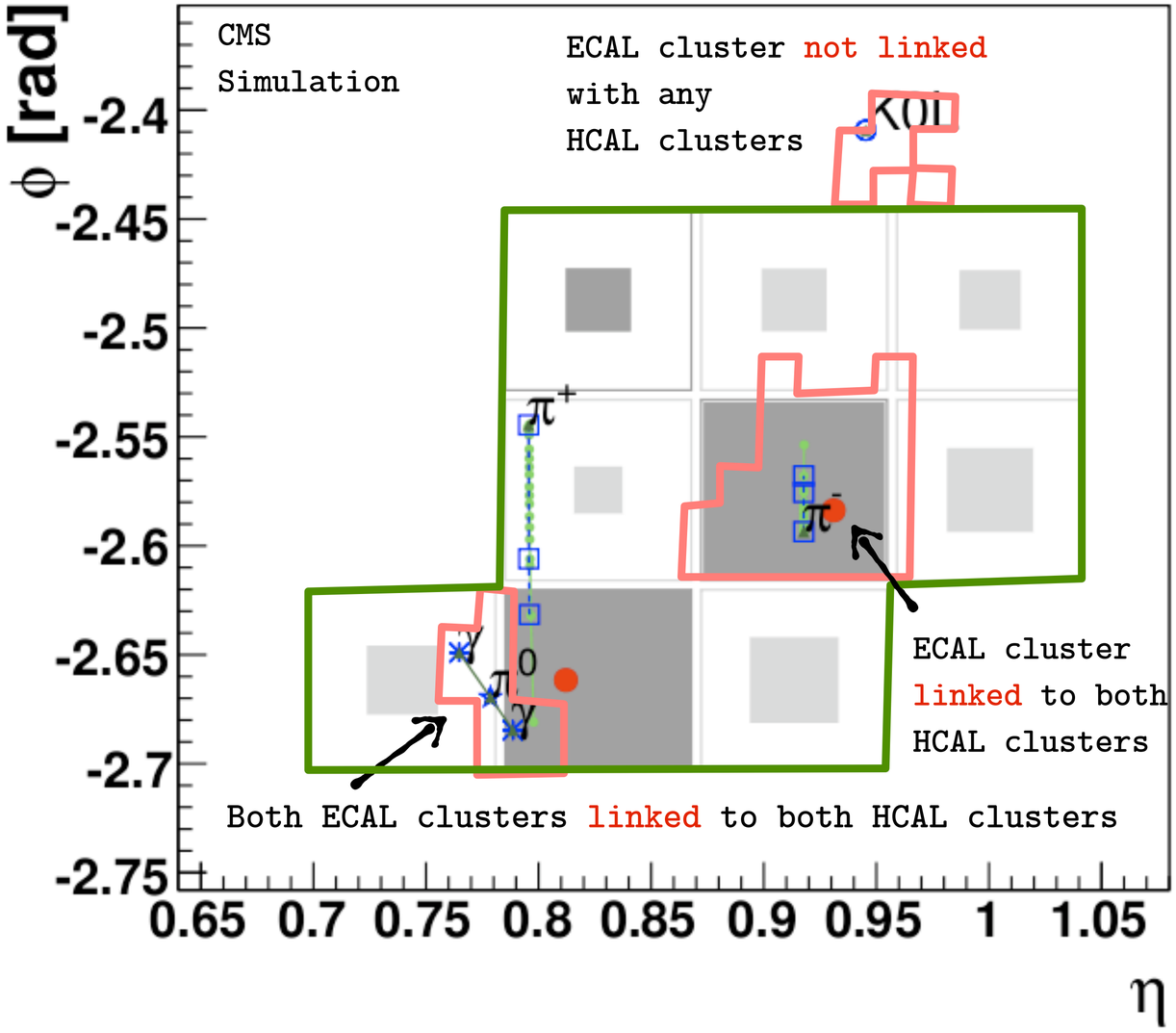

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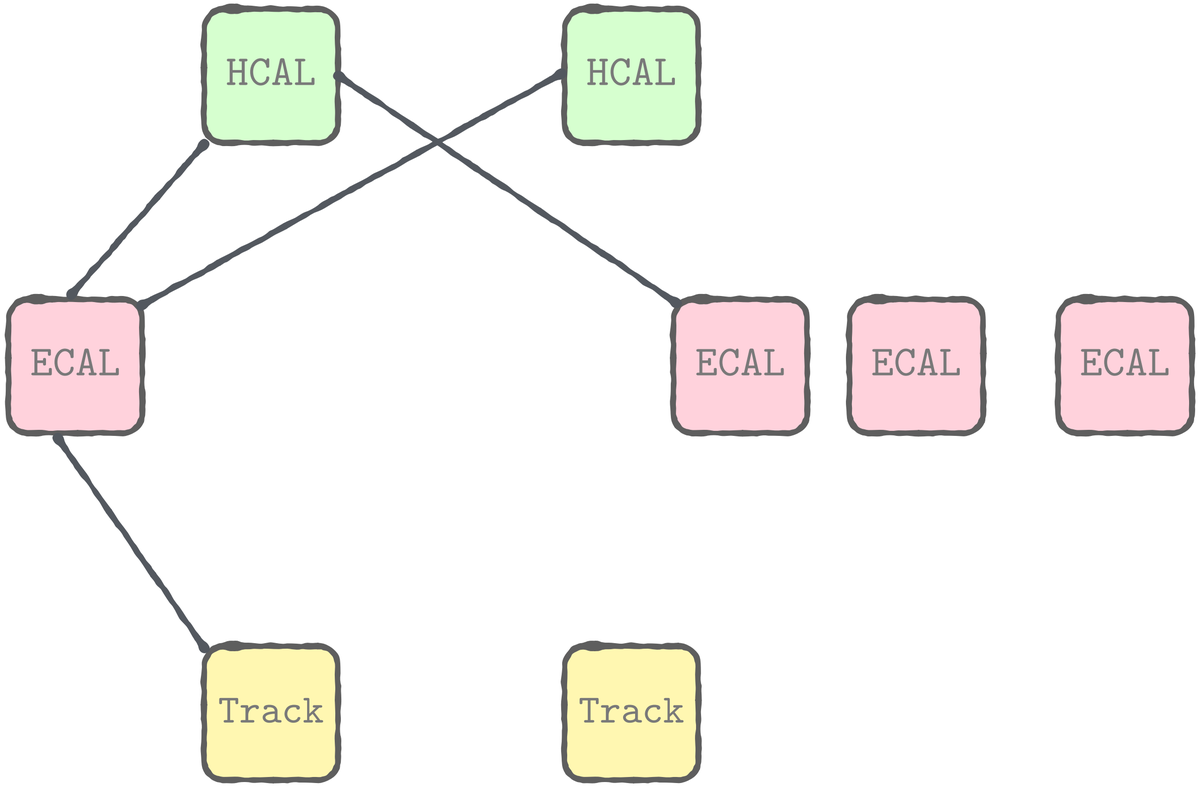

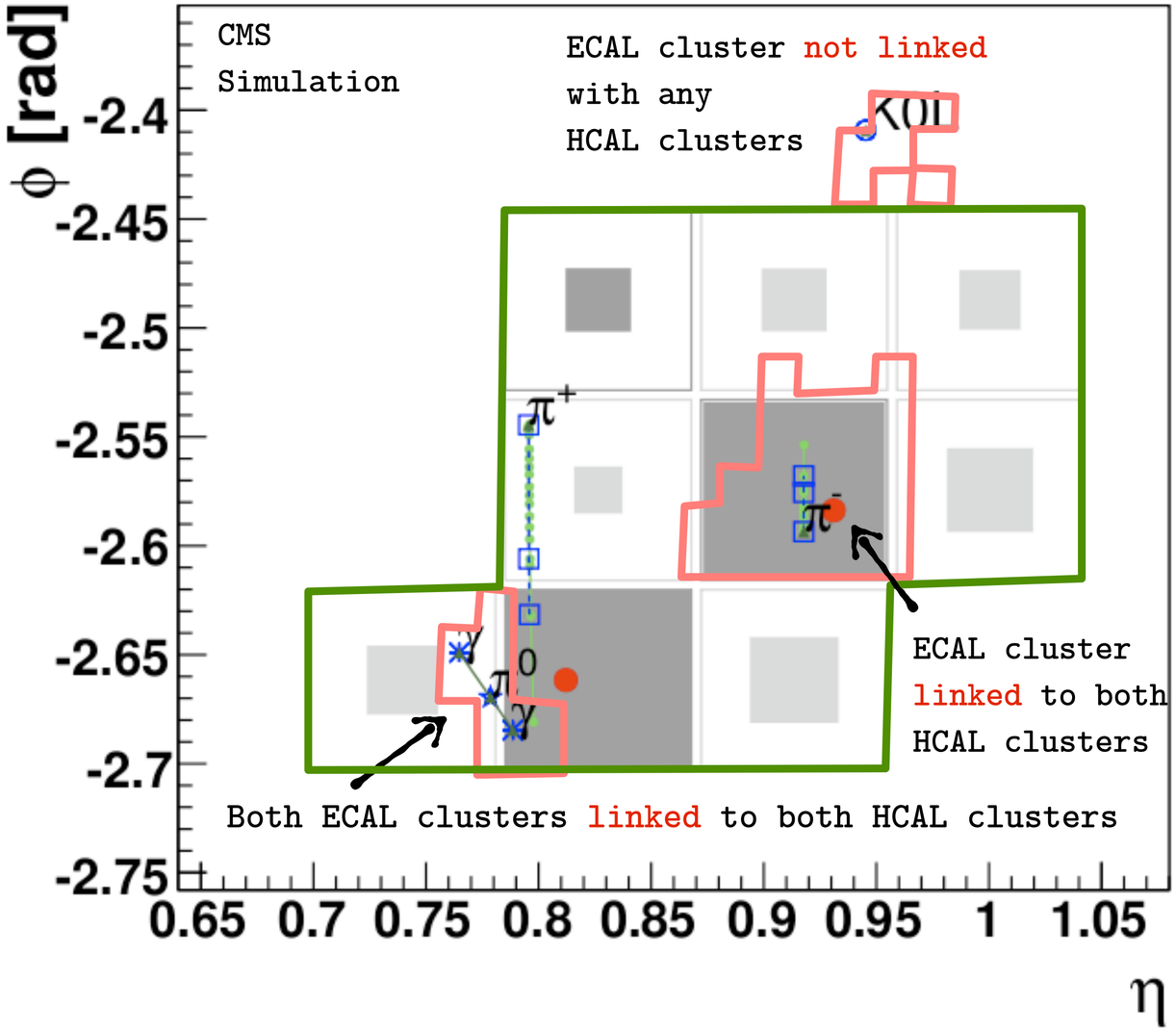

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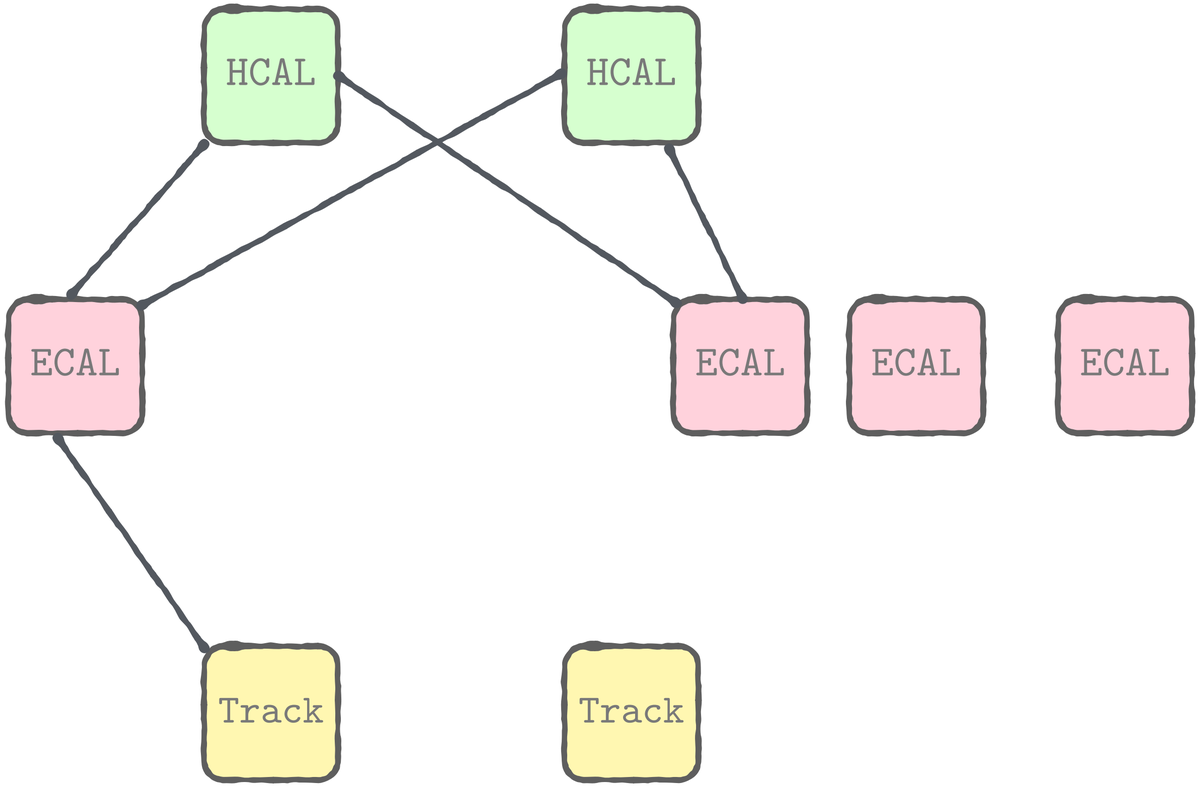

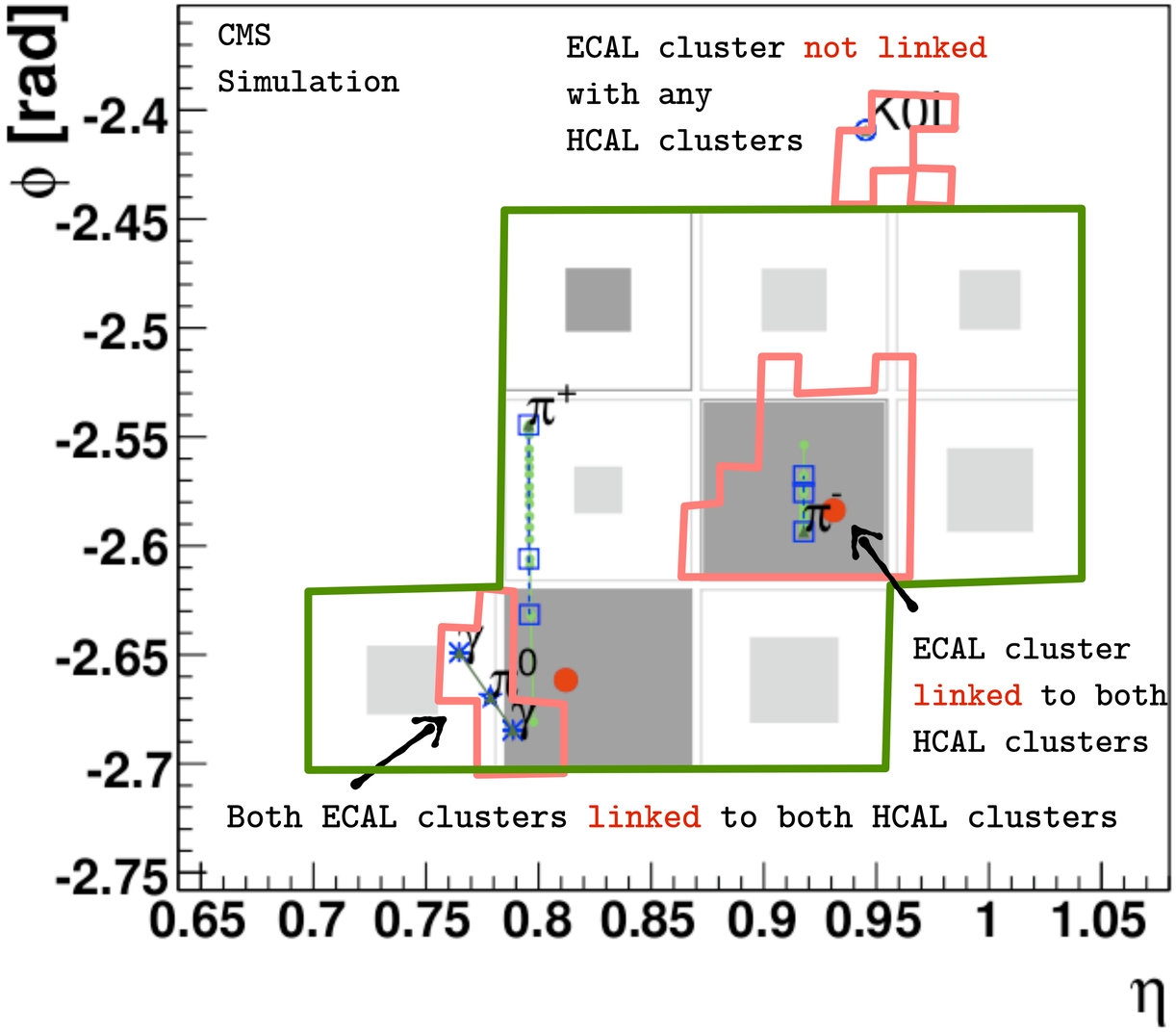

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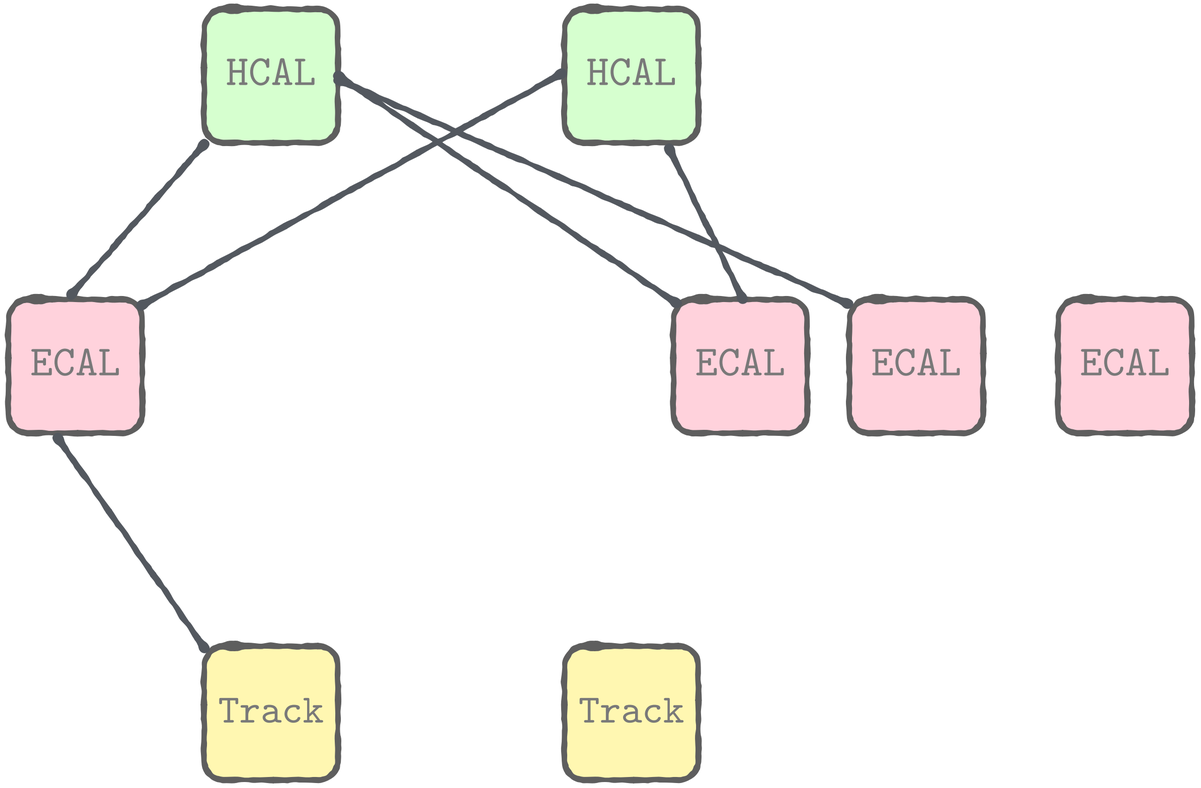

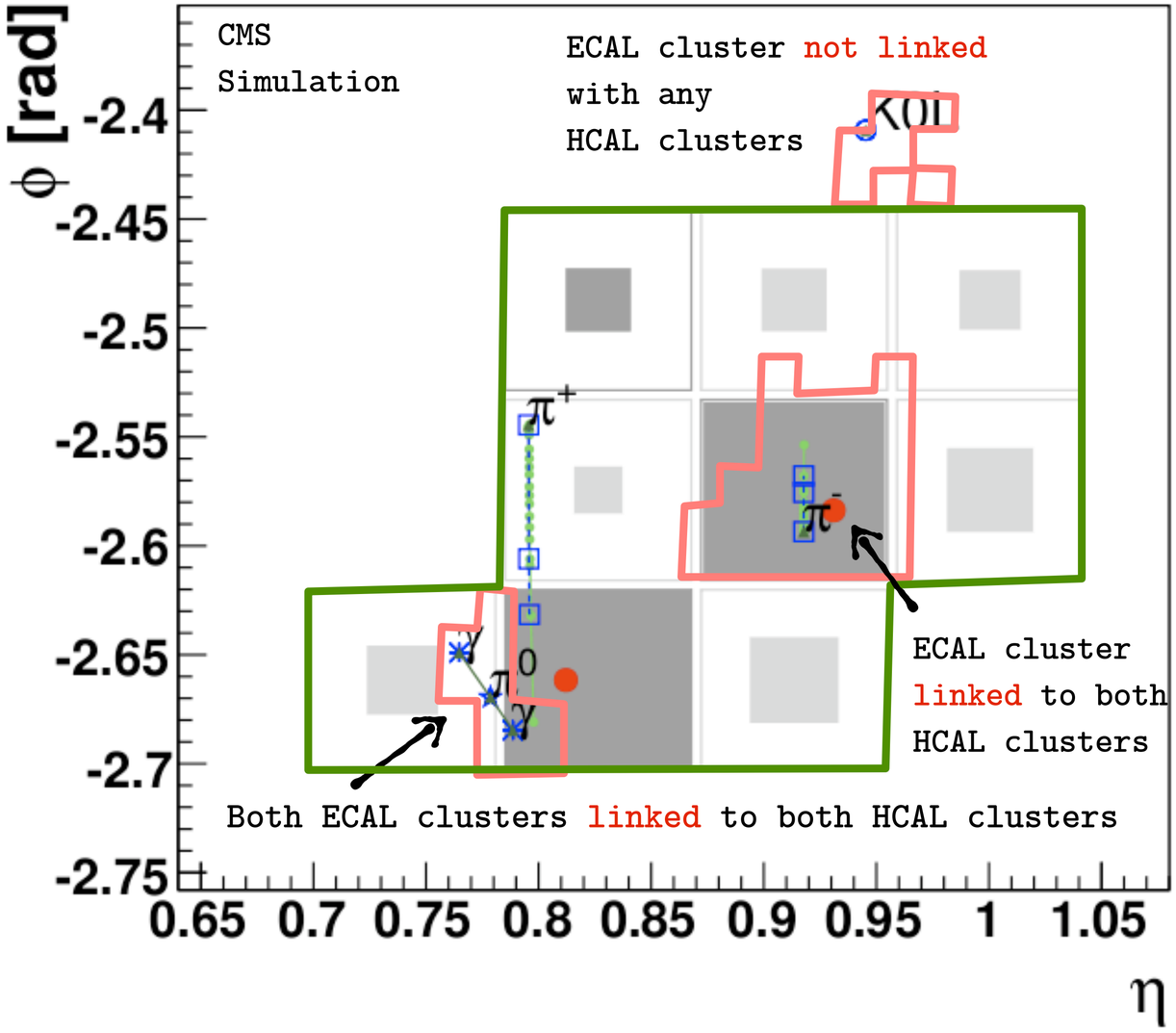

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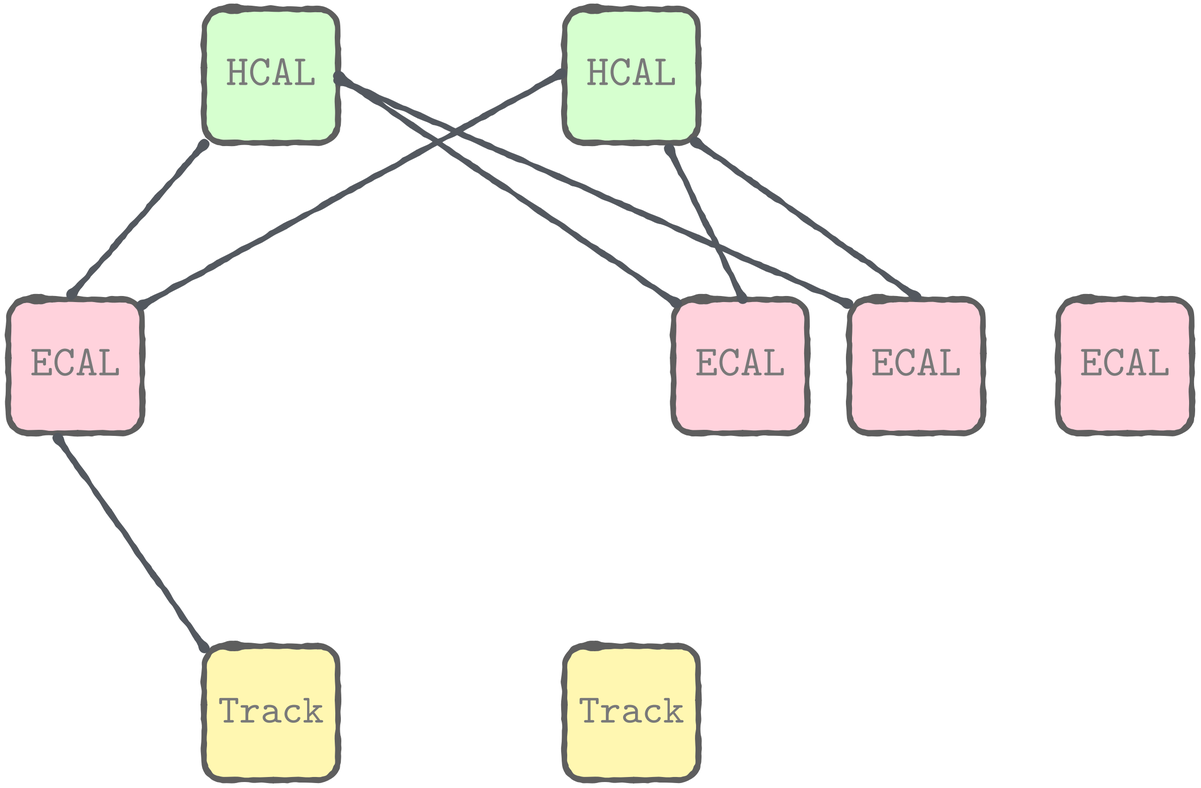

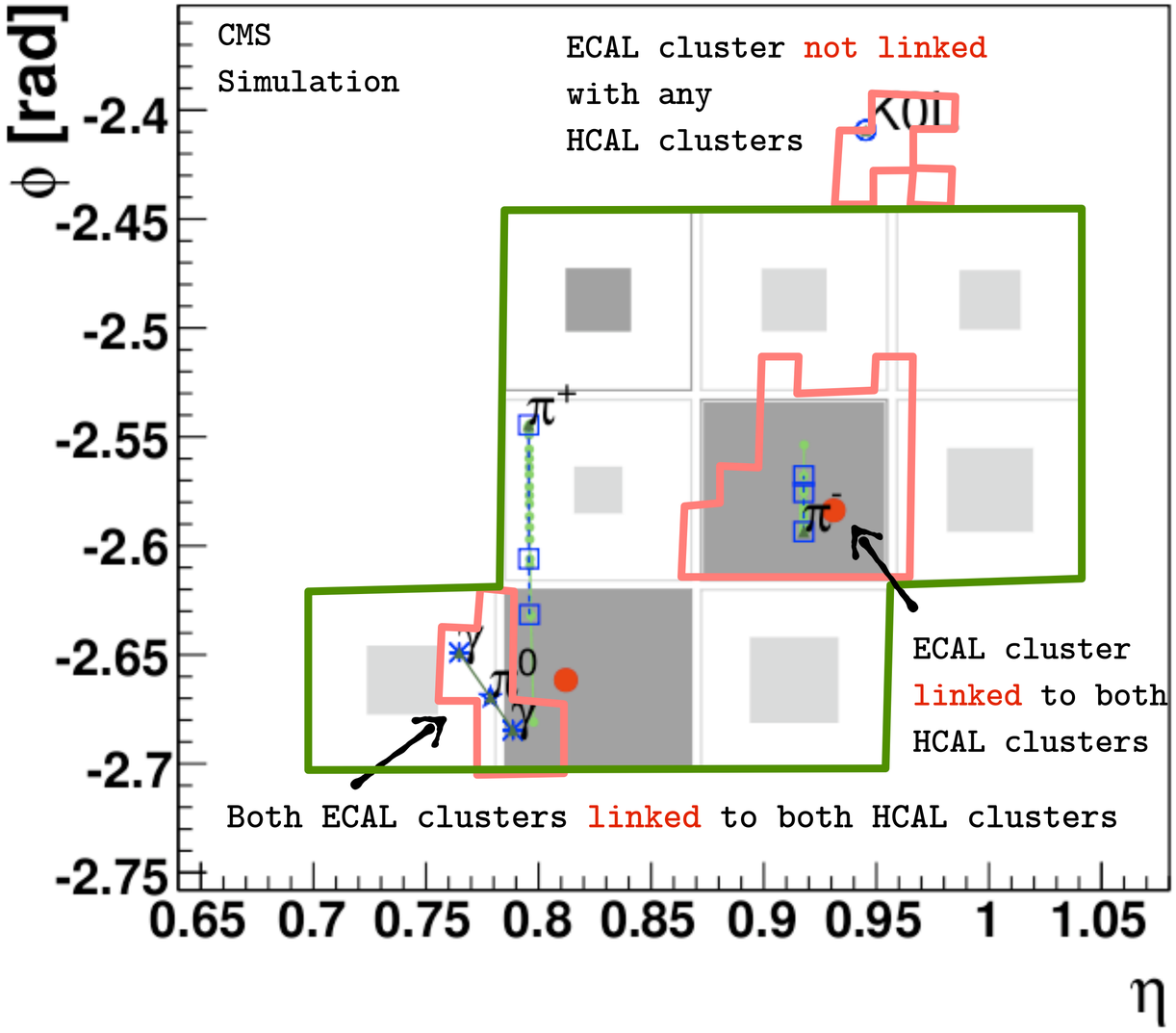

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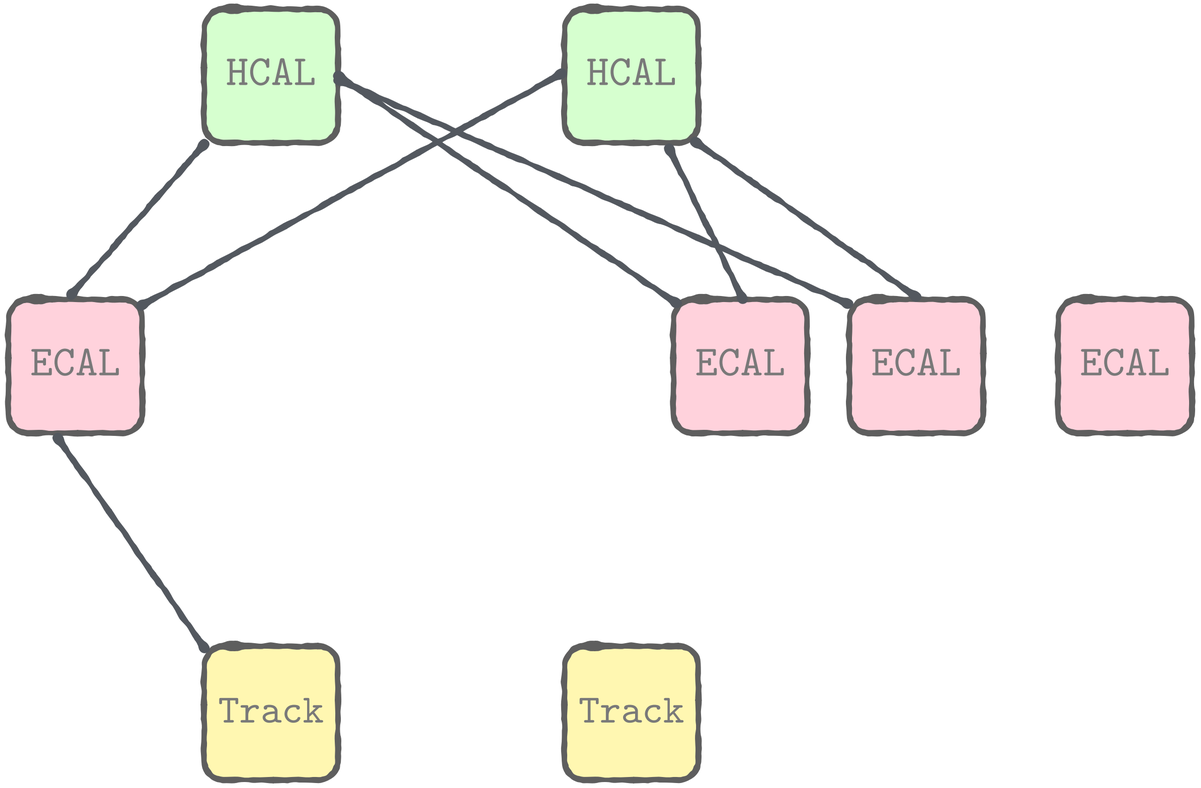

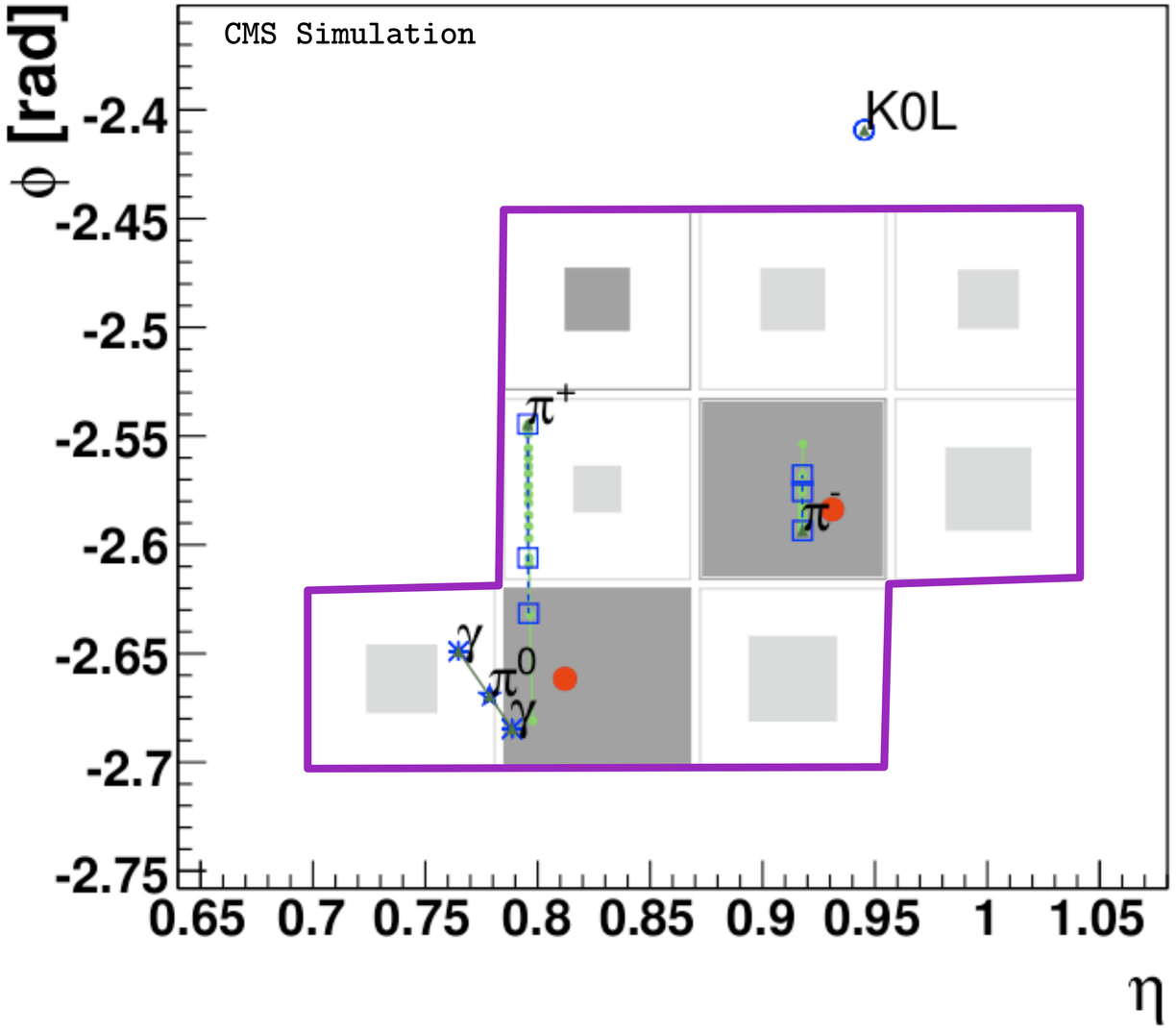

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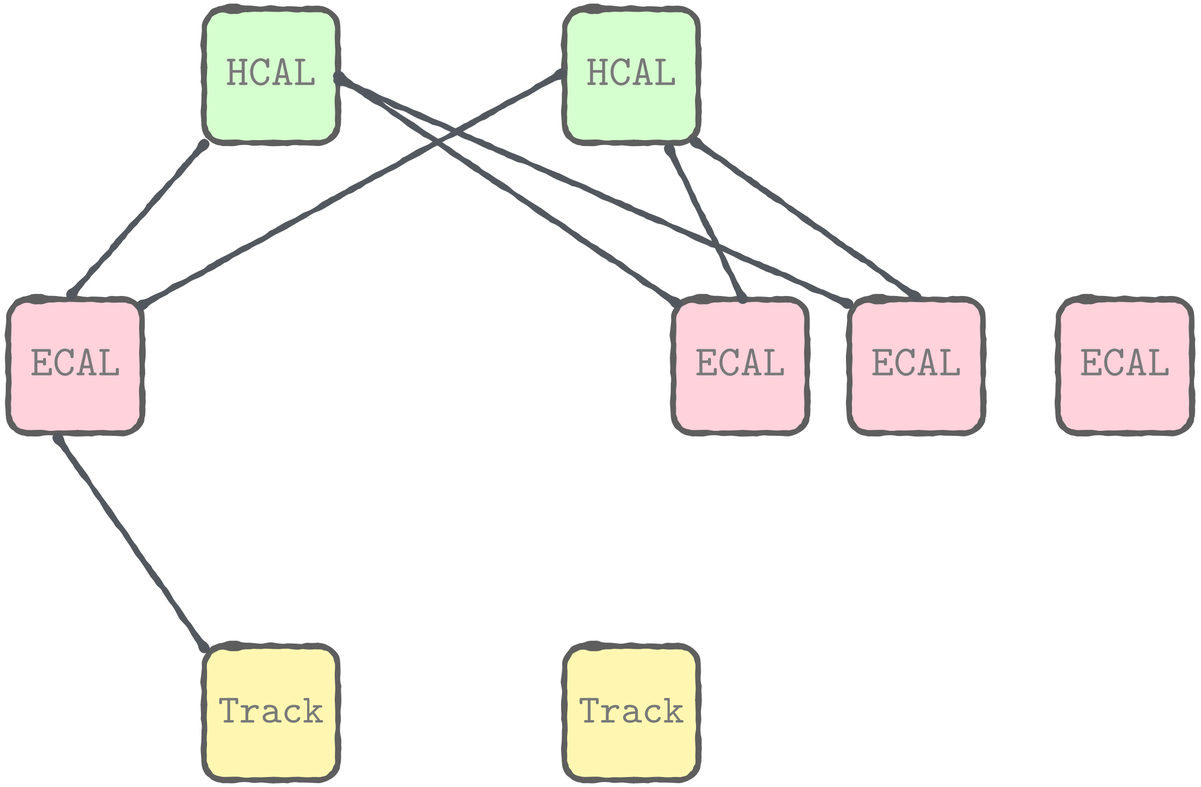

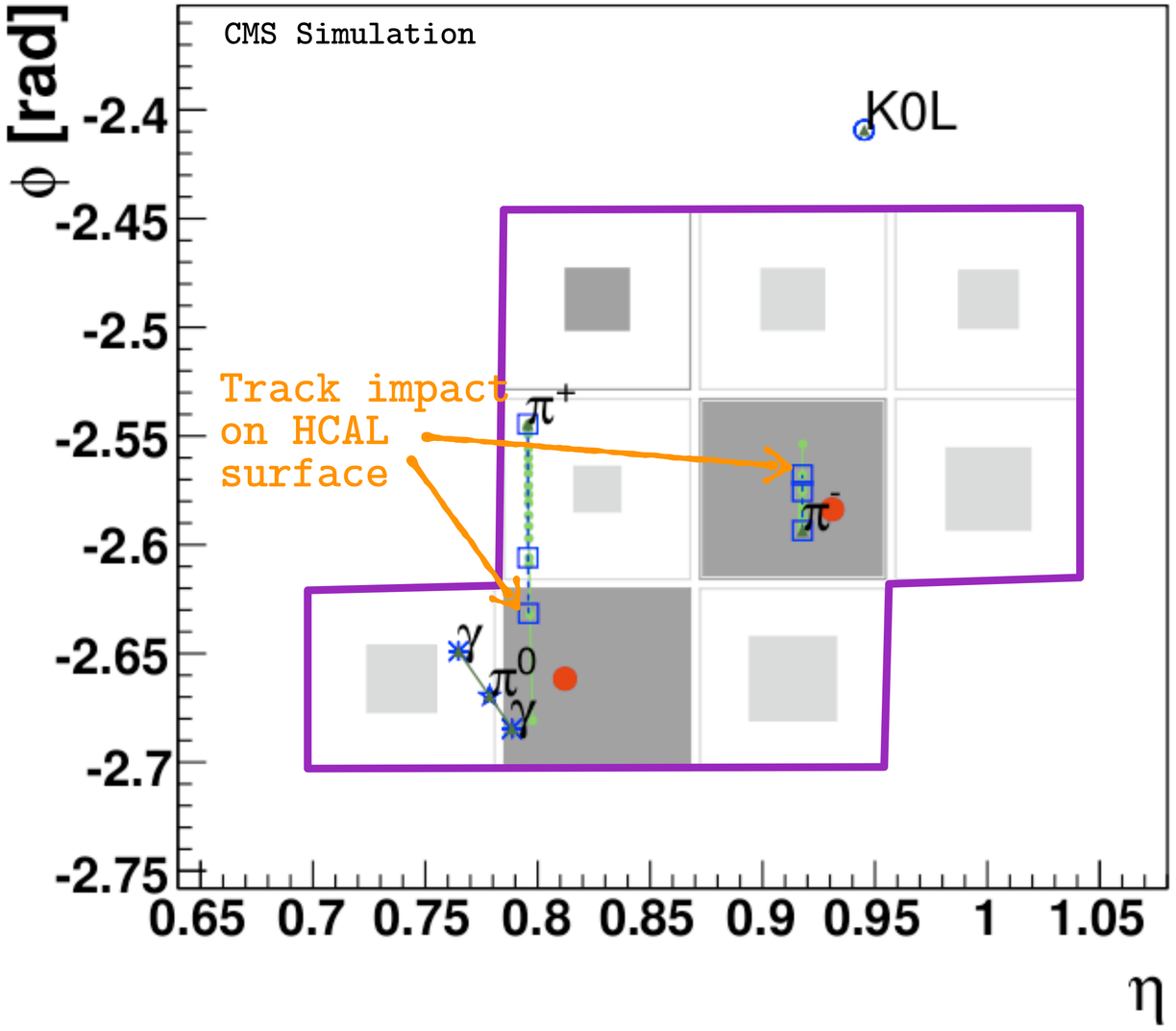

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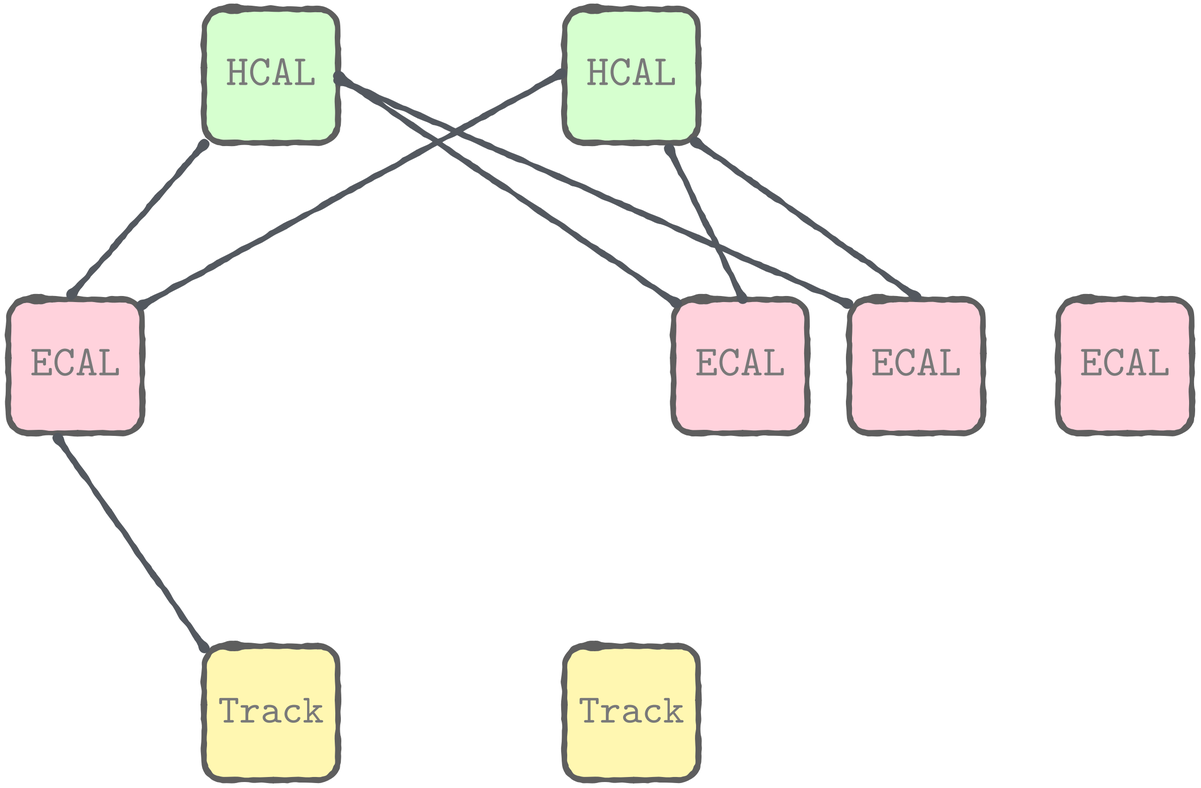

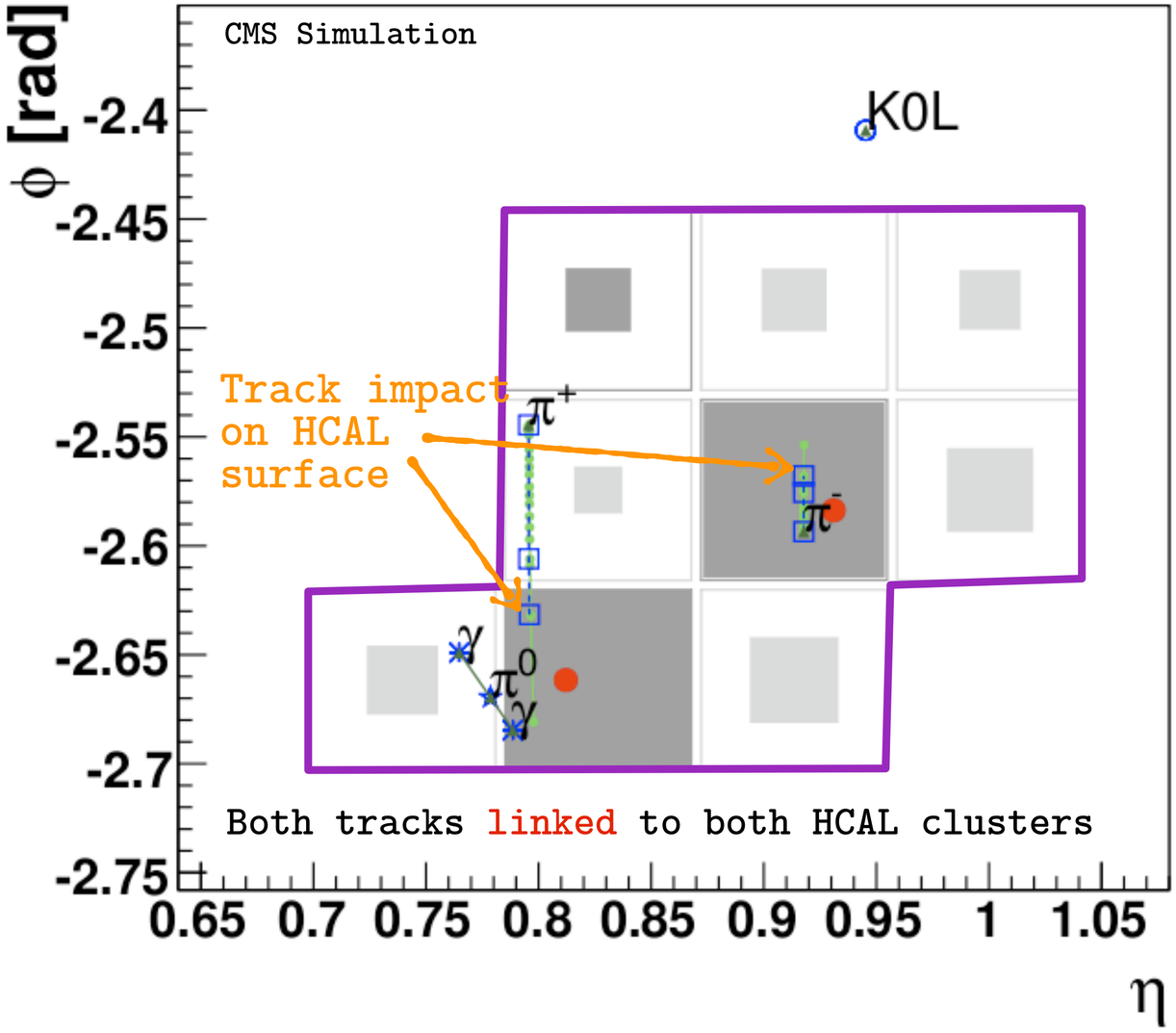

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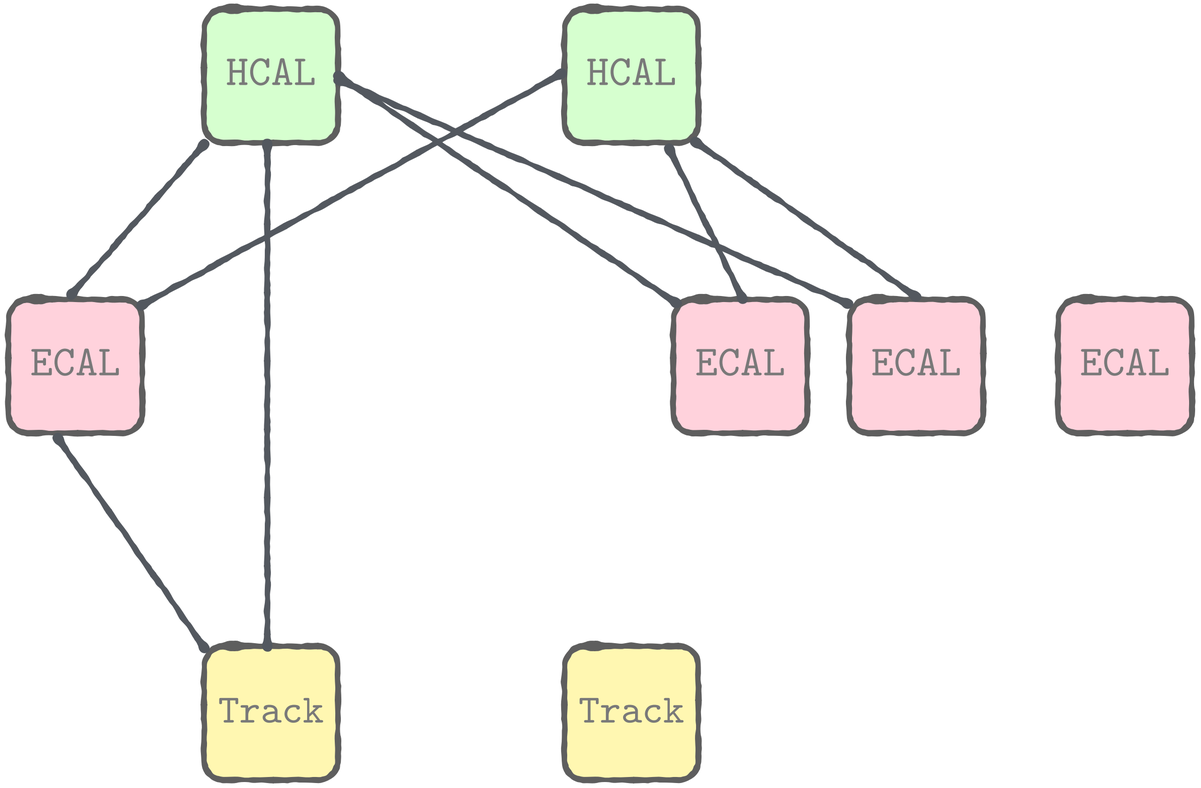

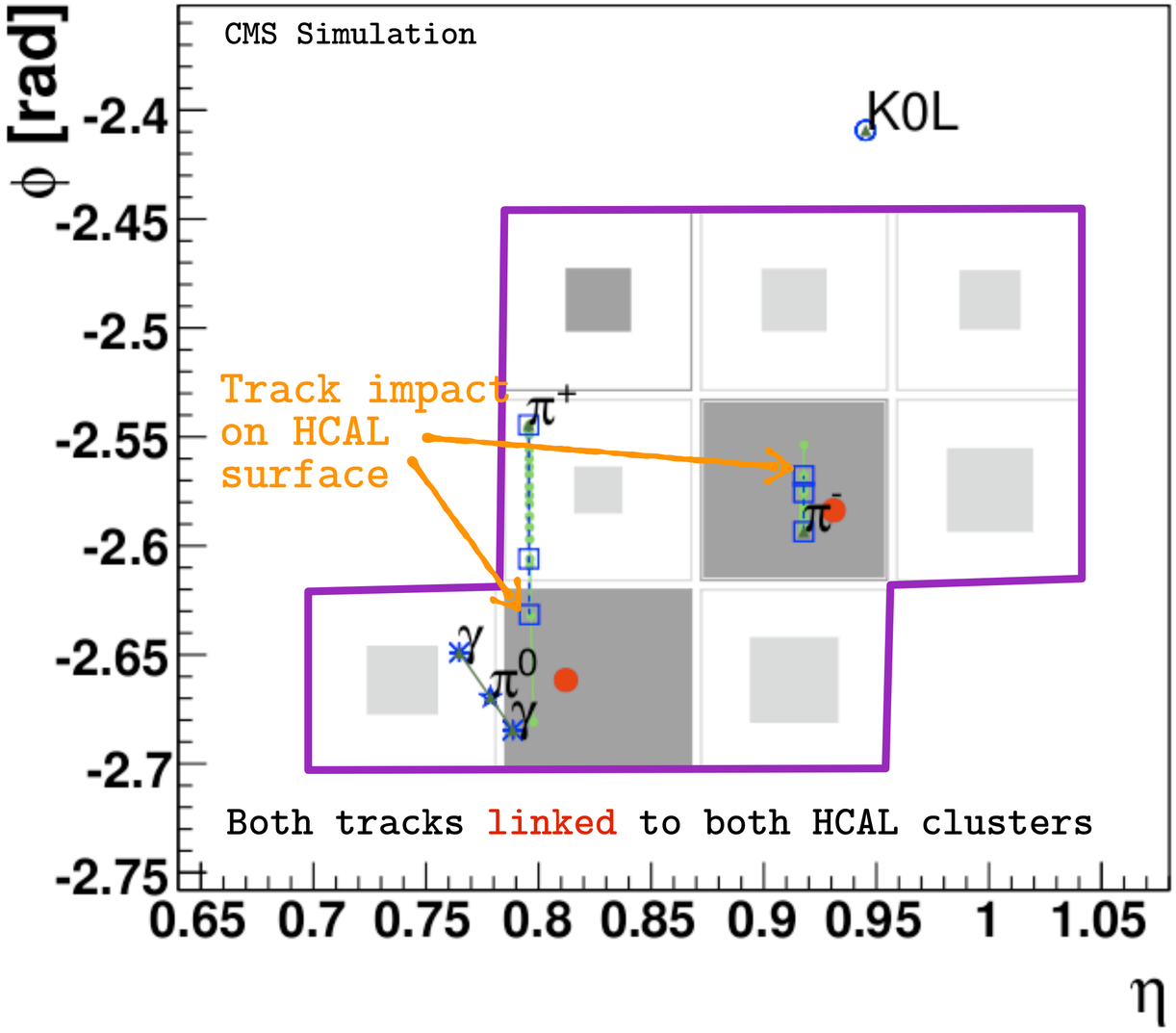

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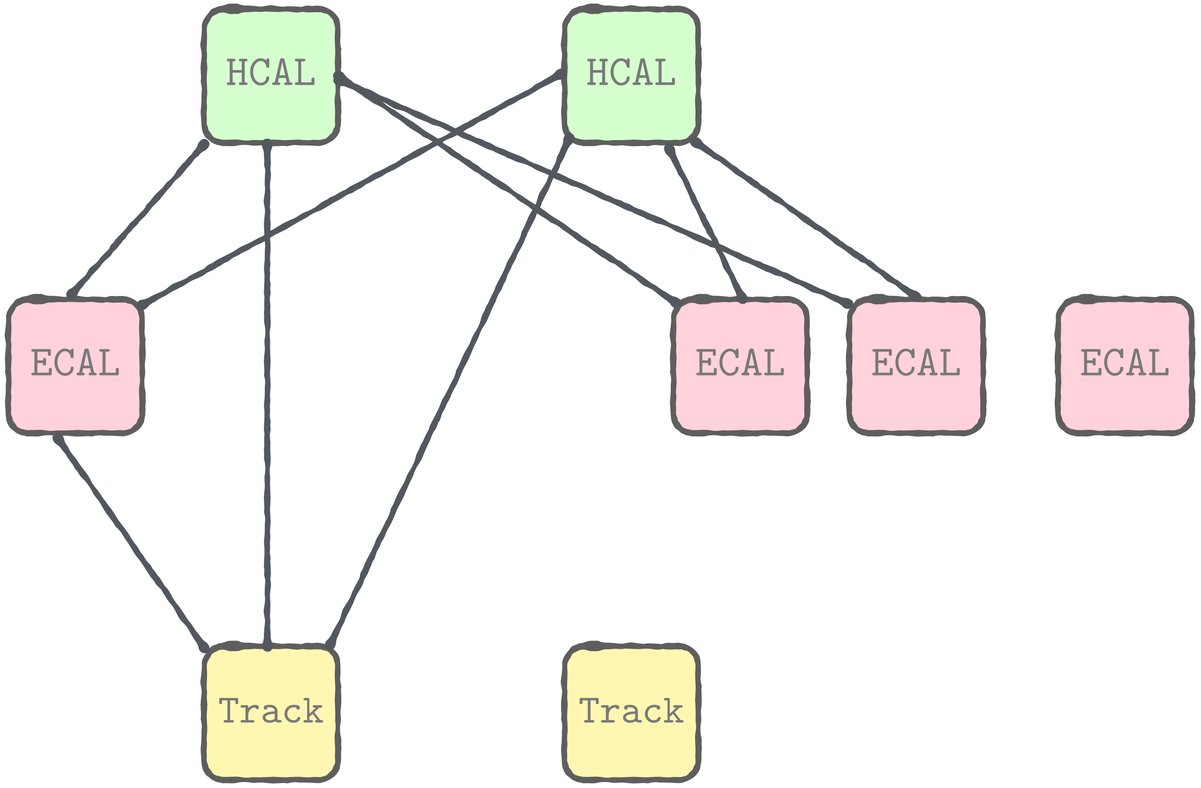

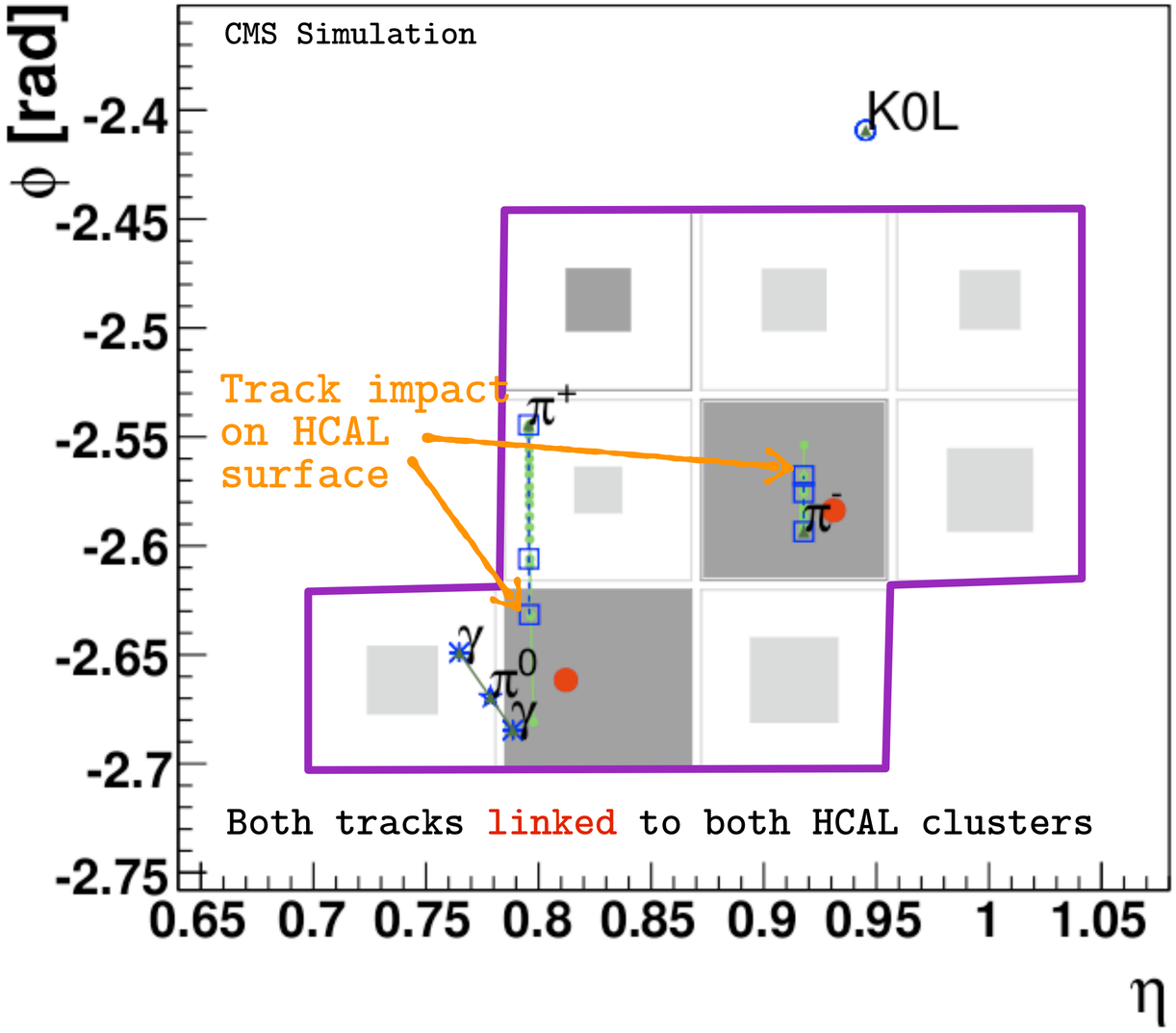

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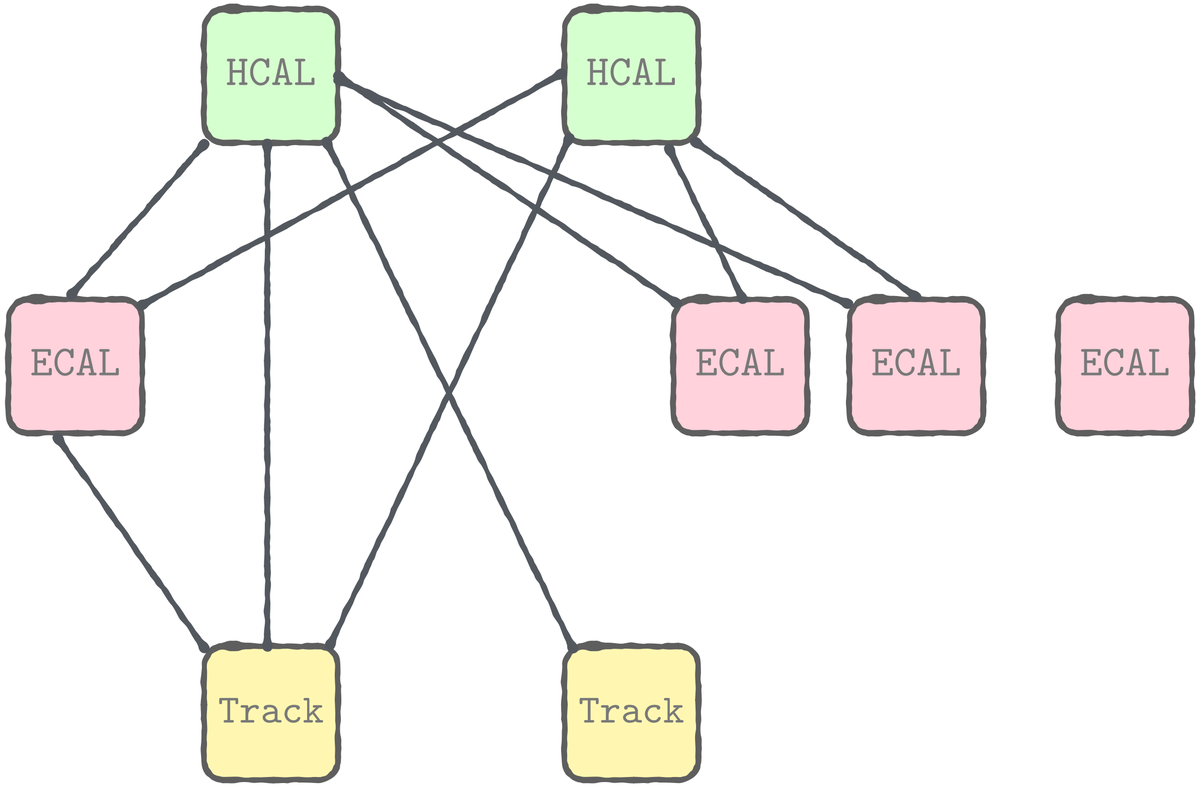

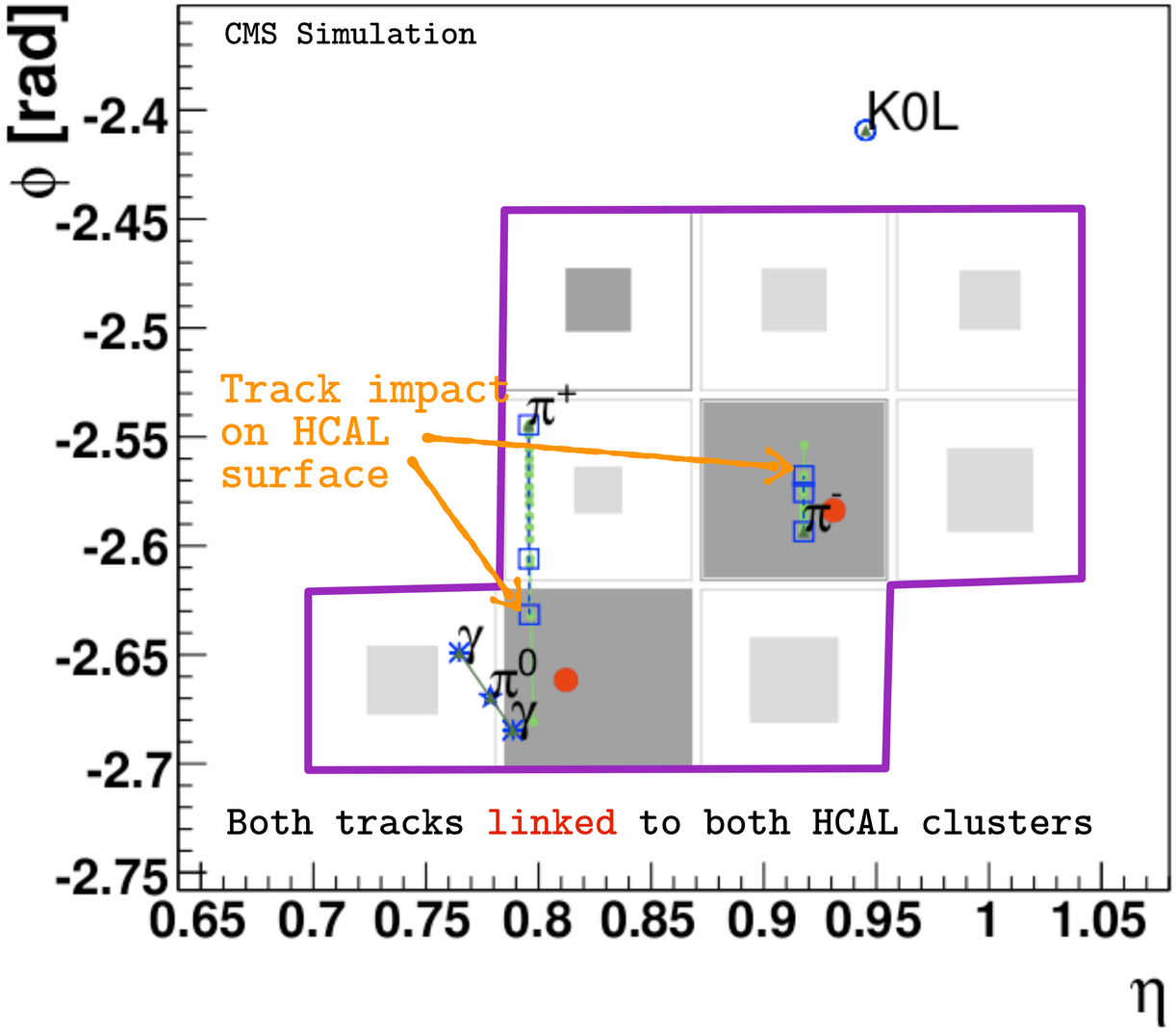

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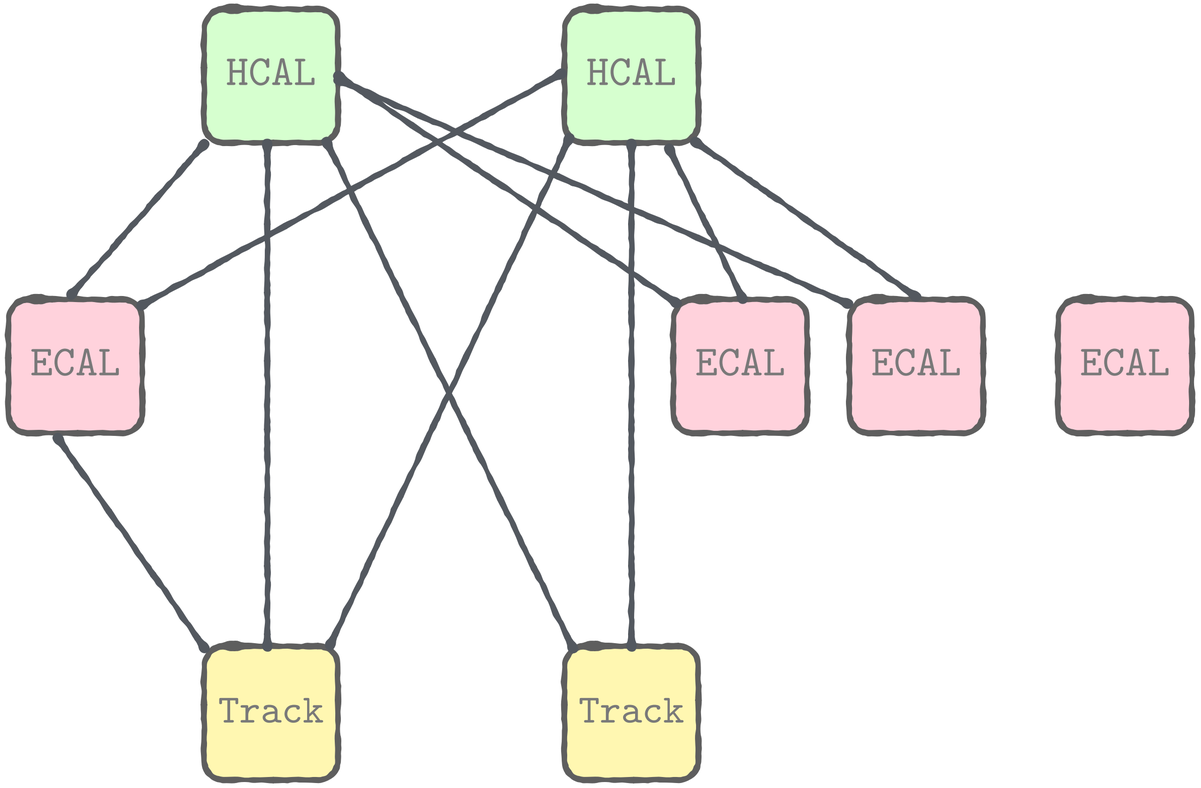

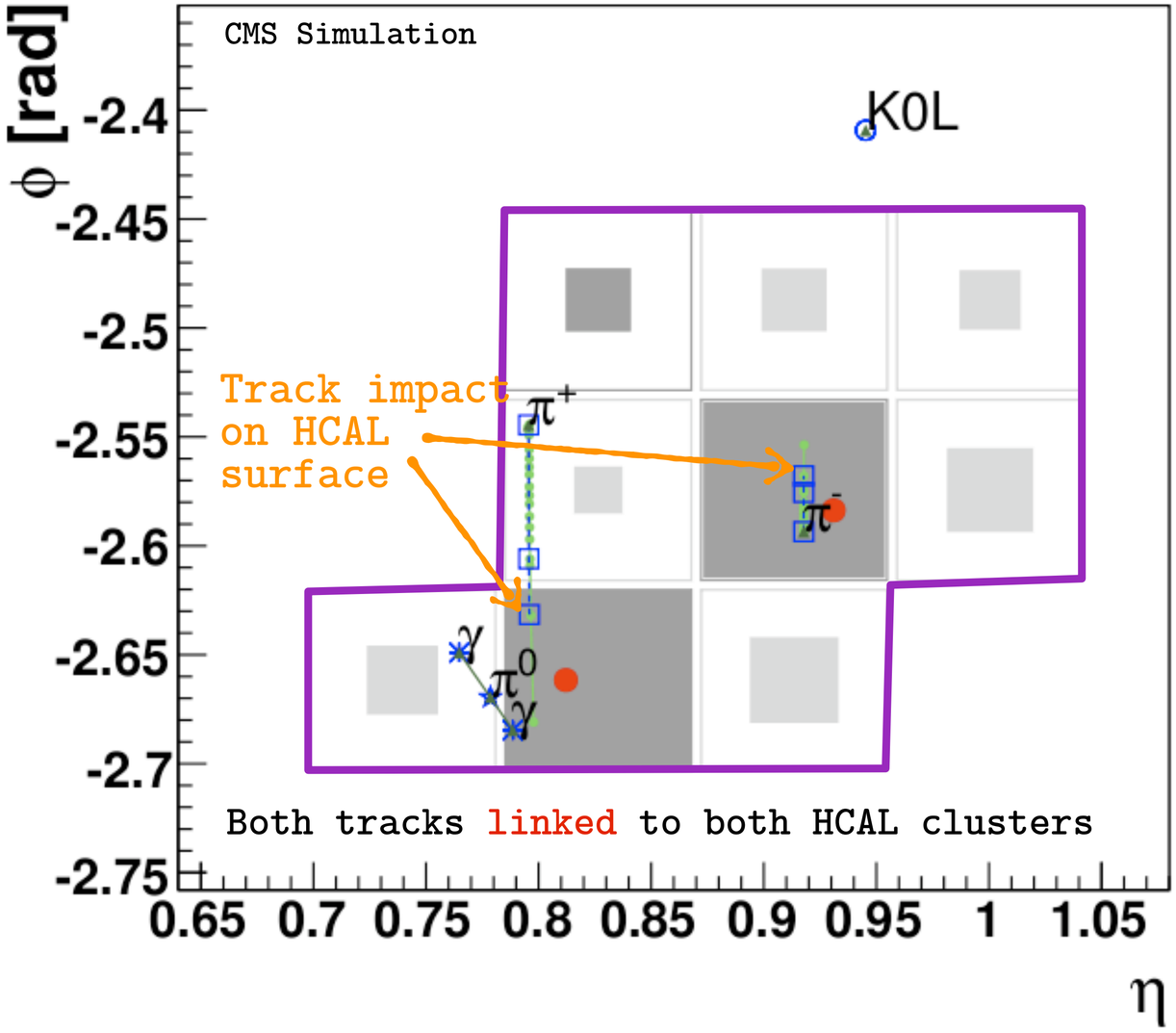

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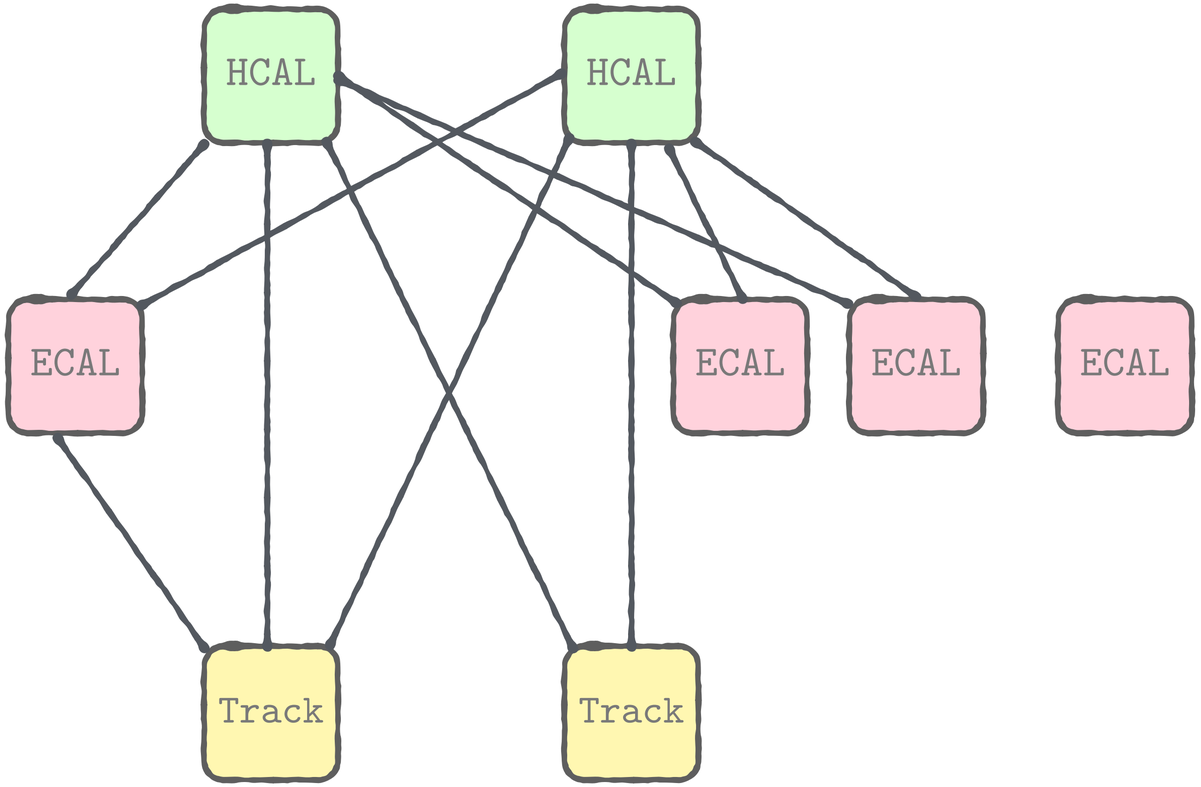

Four true particles:

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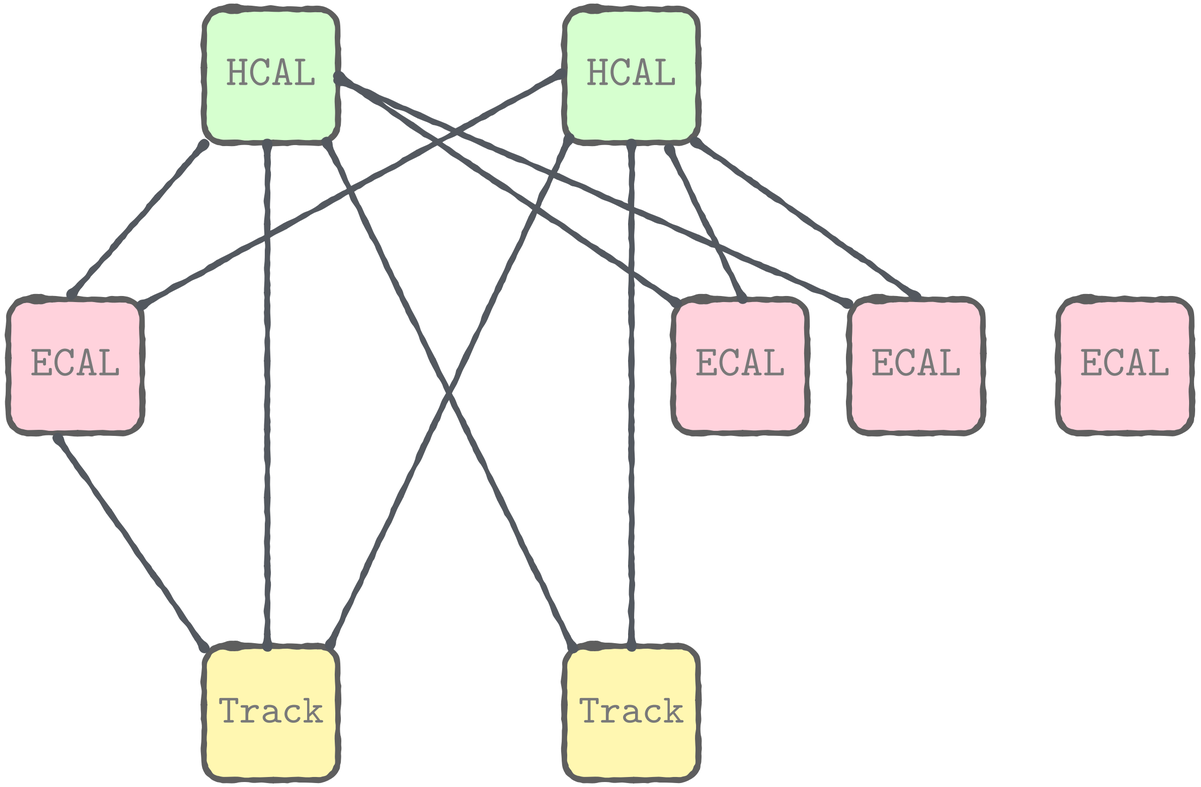
Build "blocks" of linked elements



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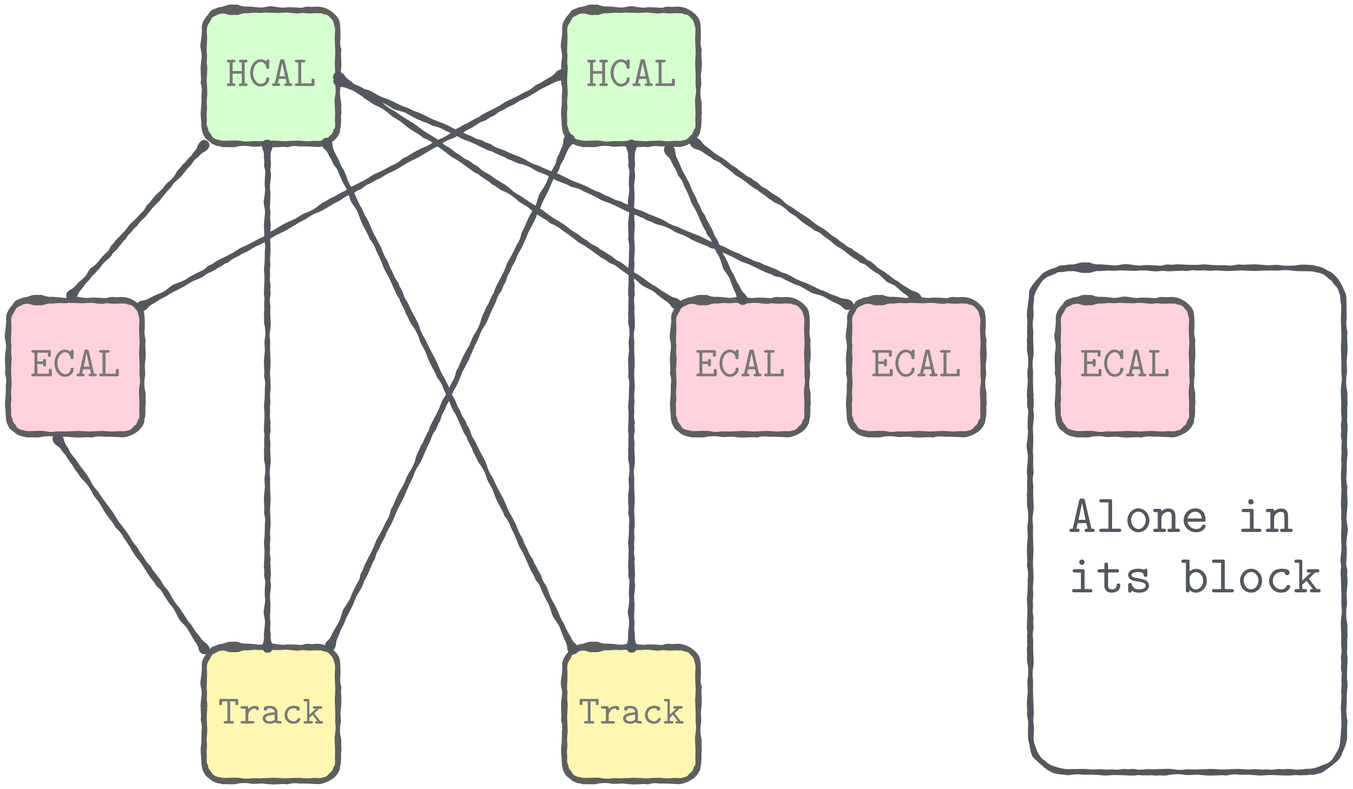

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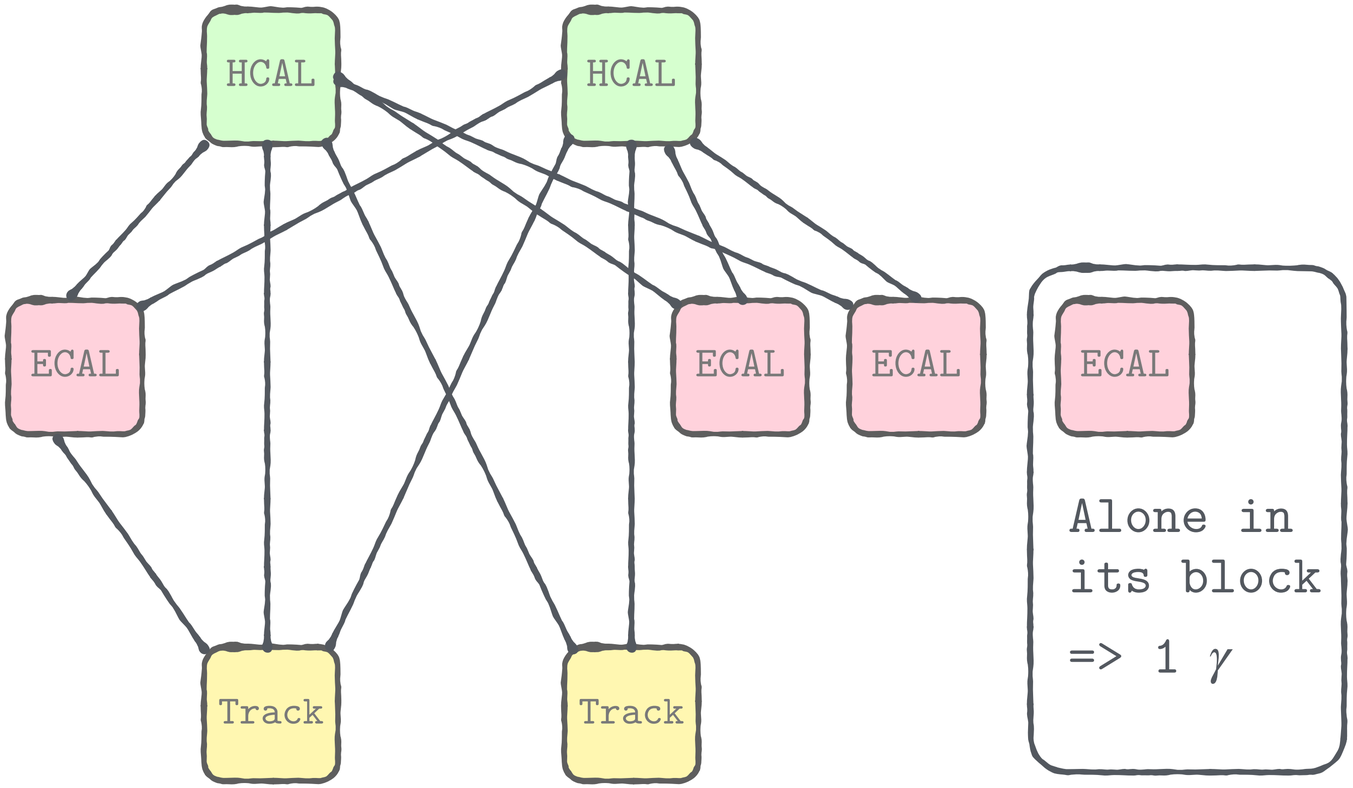

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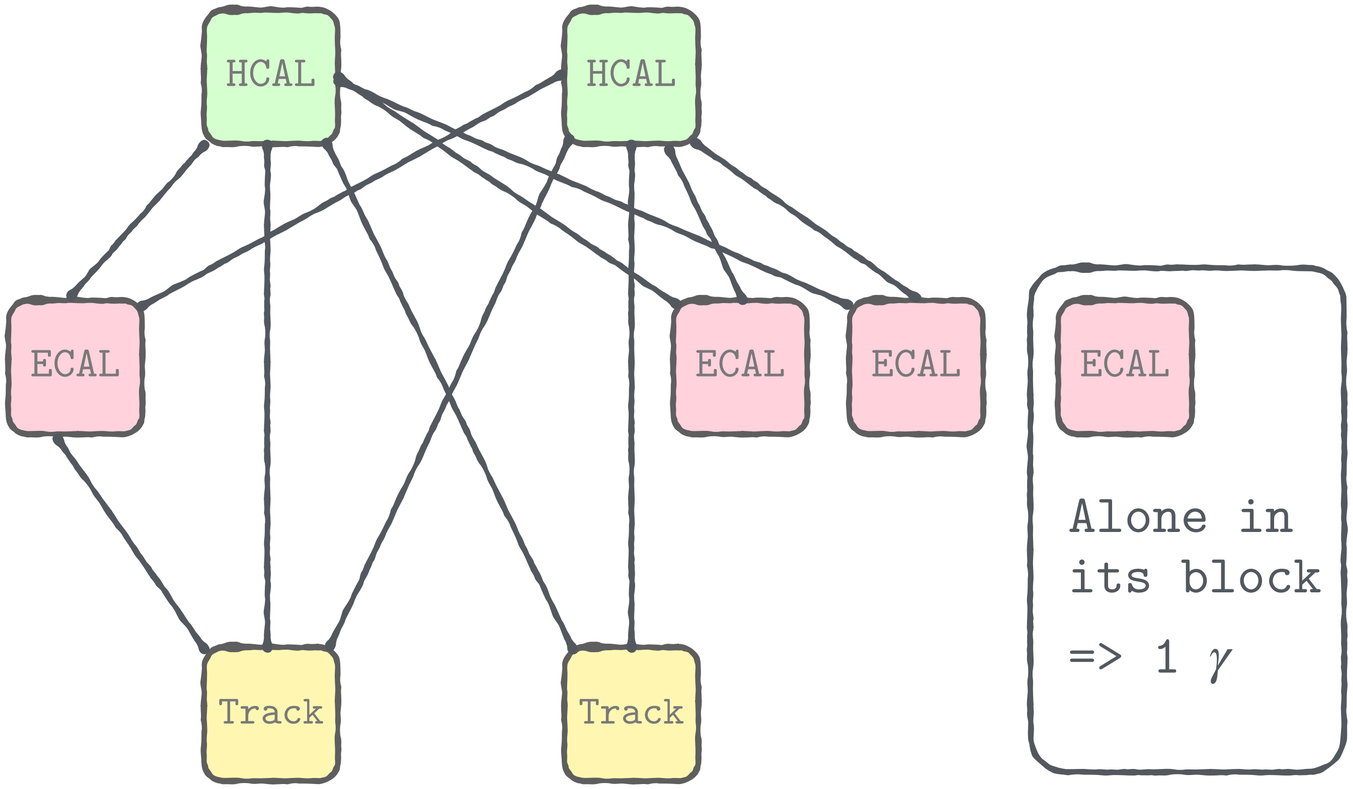
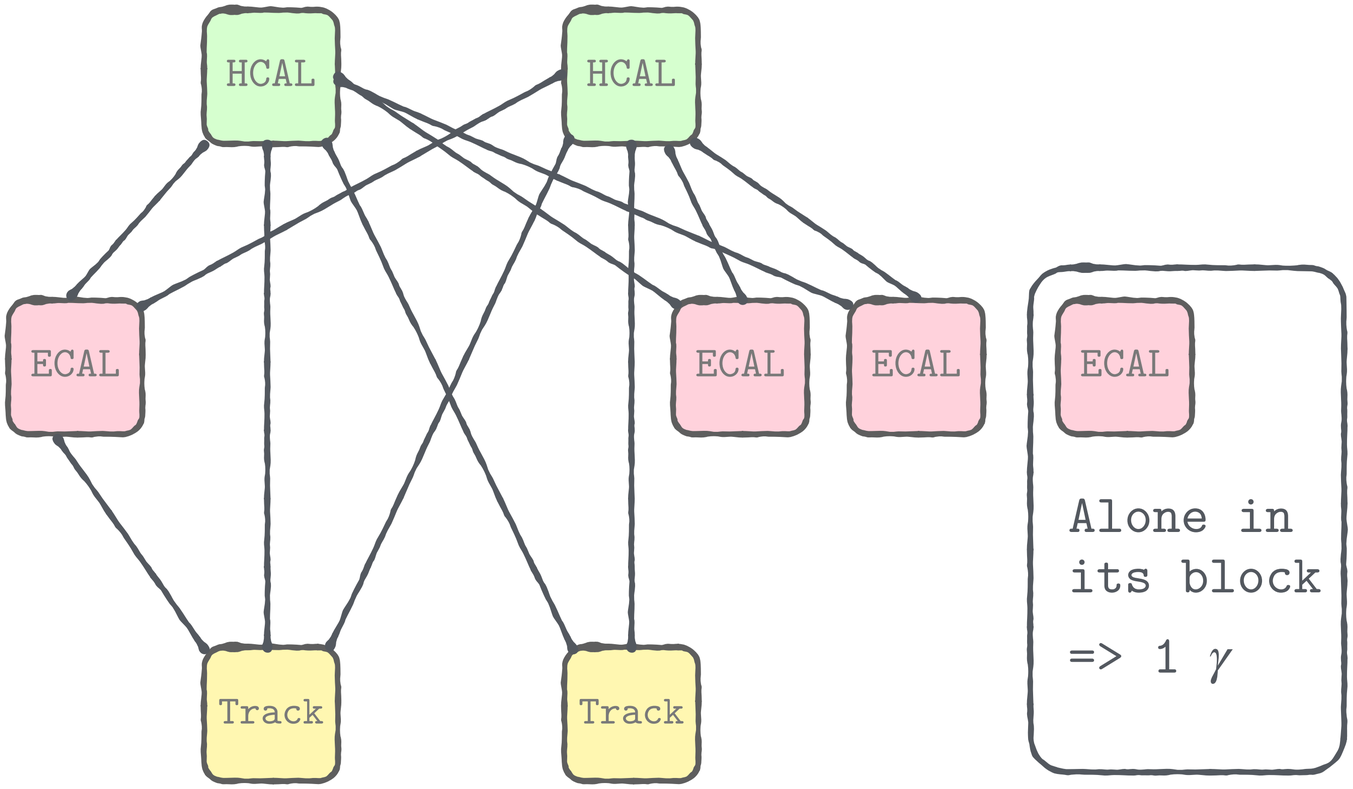


List of reconstructed (candidate) particles

Four true particles:

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

Build "blocks" of linked elements



List of reconstructed (candidate) particles

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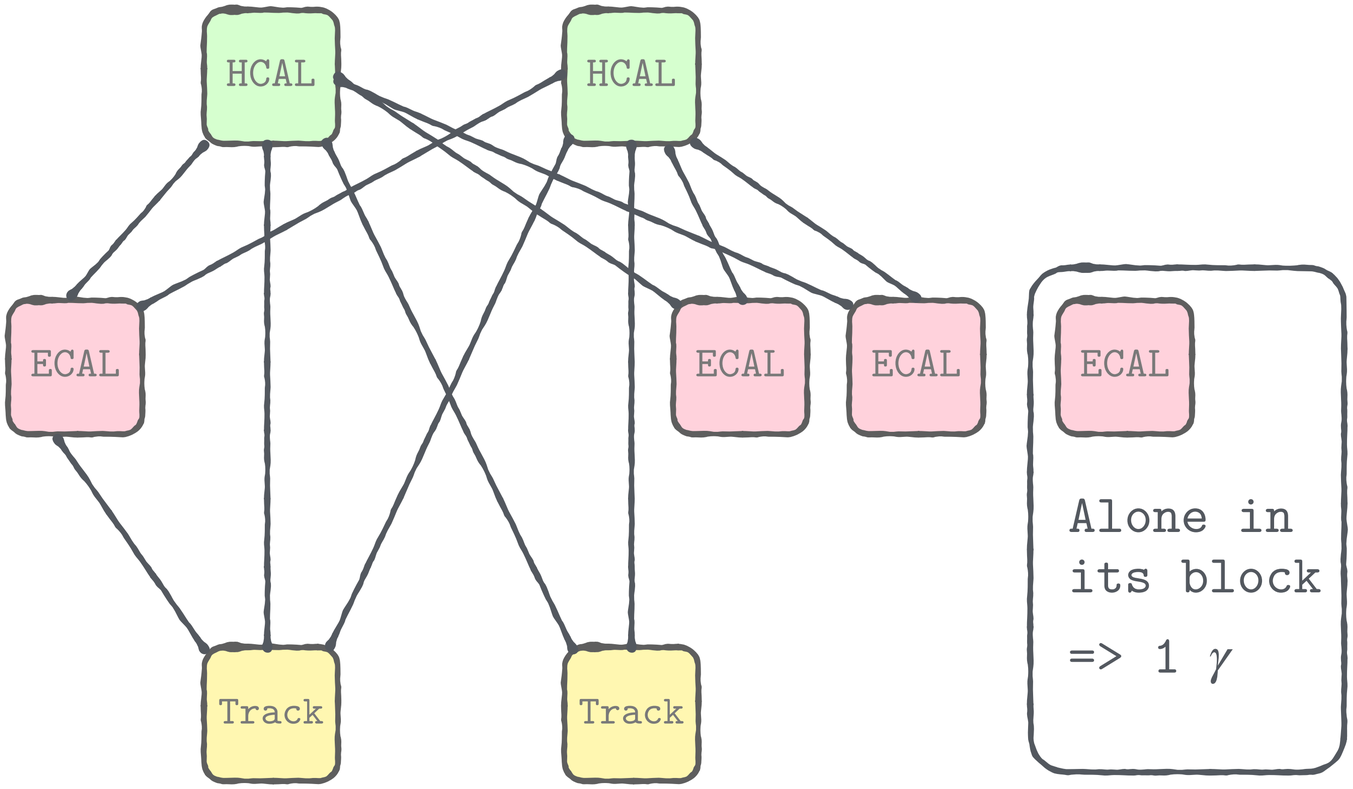

List of reconstructed (candidate) particles

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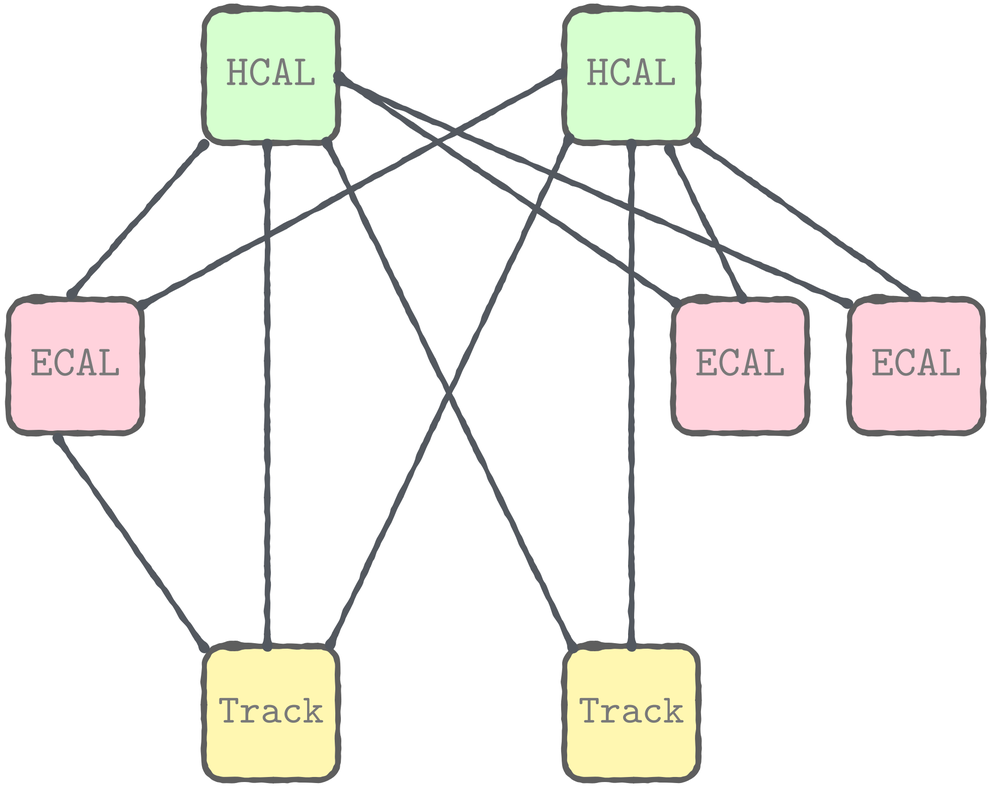

List of reconstructed (candidate) particles

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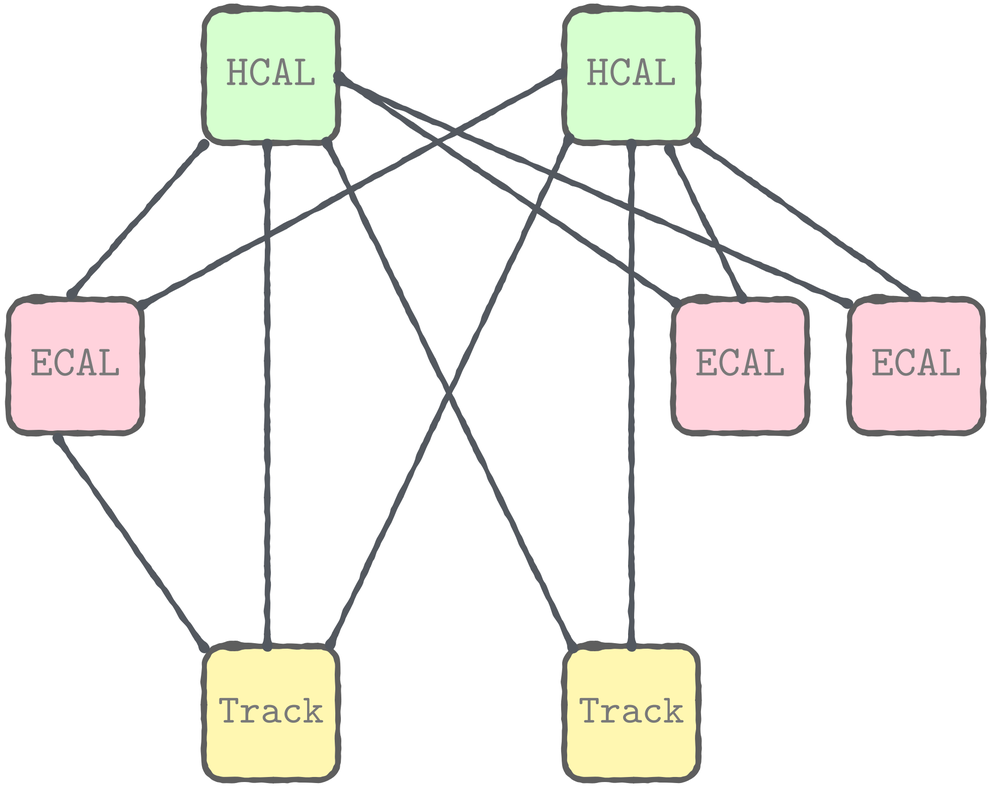
Find photons in the blocks



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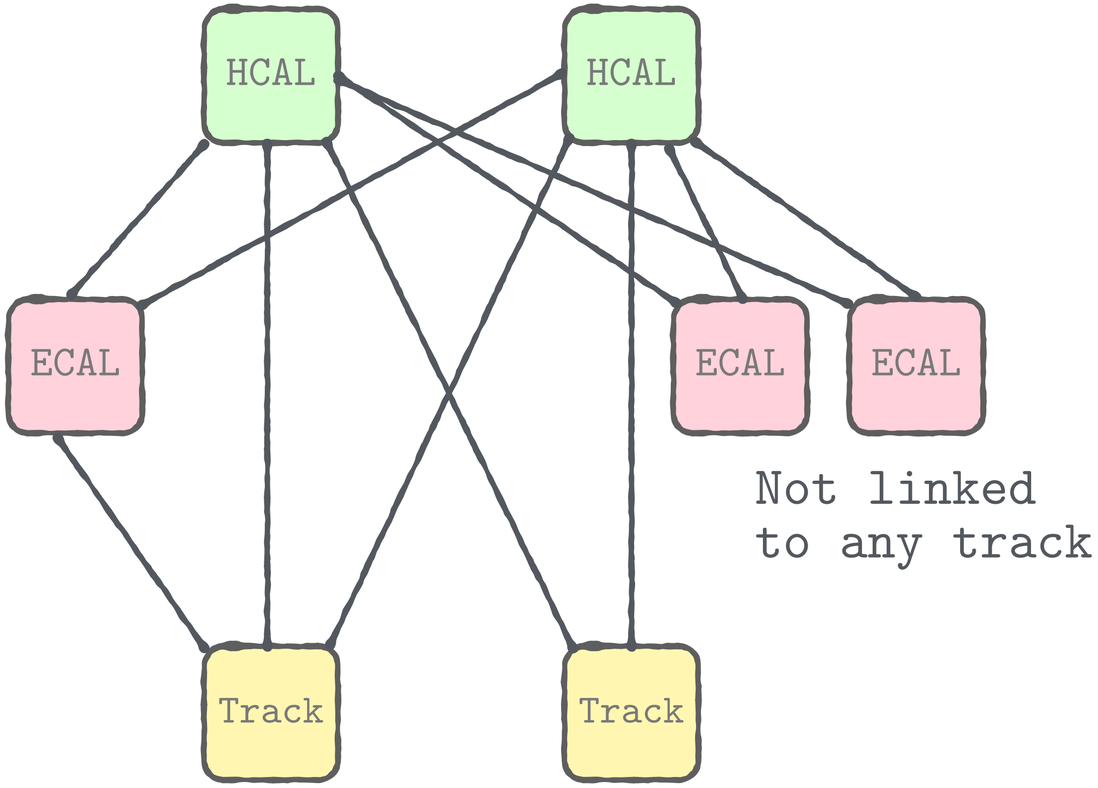

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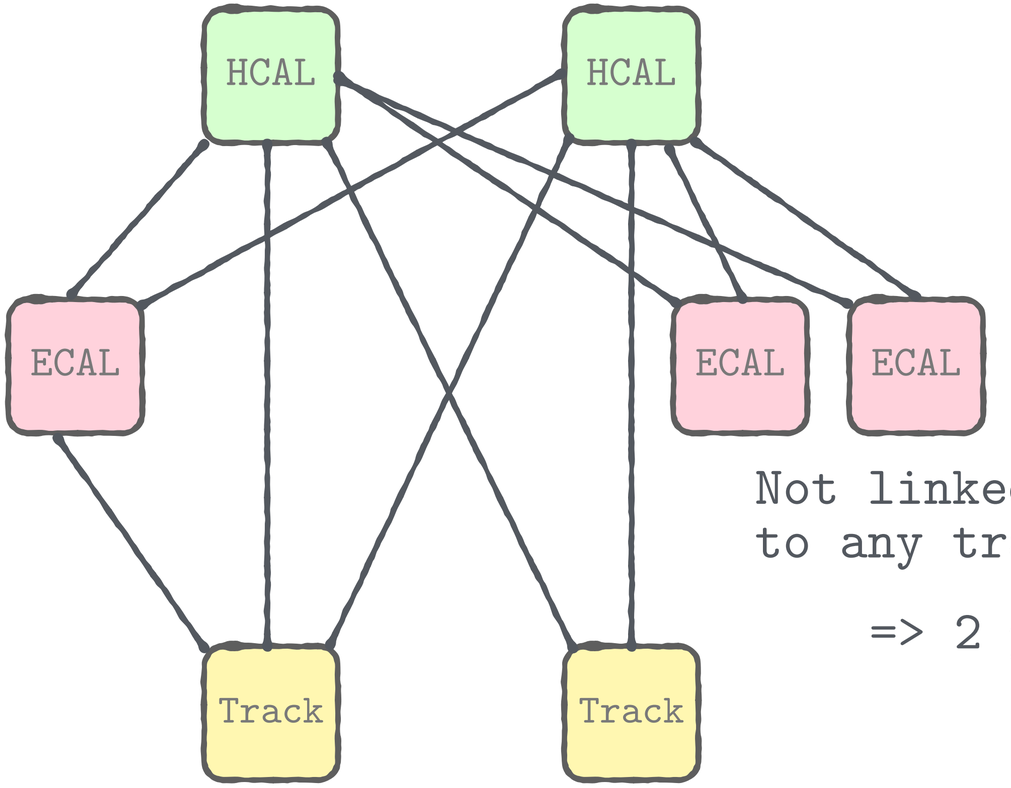
Find photons in the blocks



Not linked
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=> 2 γ's

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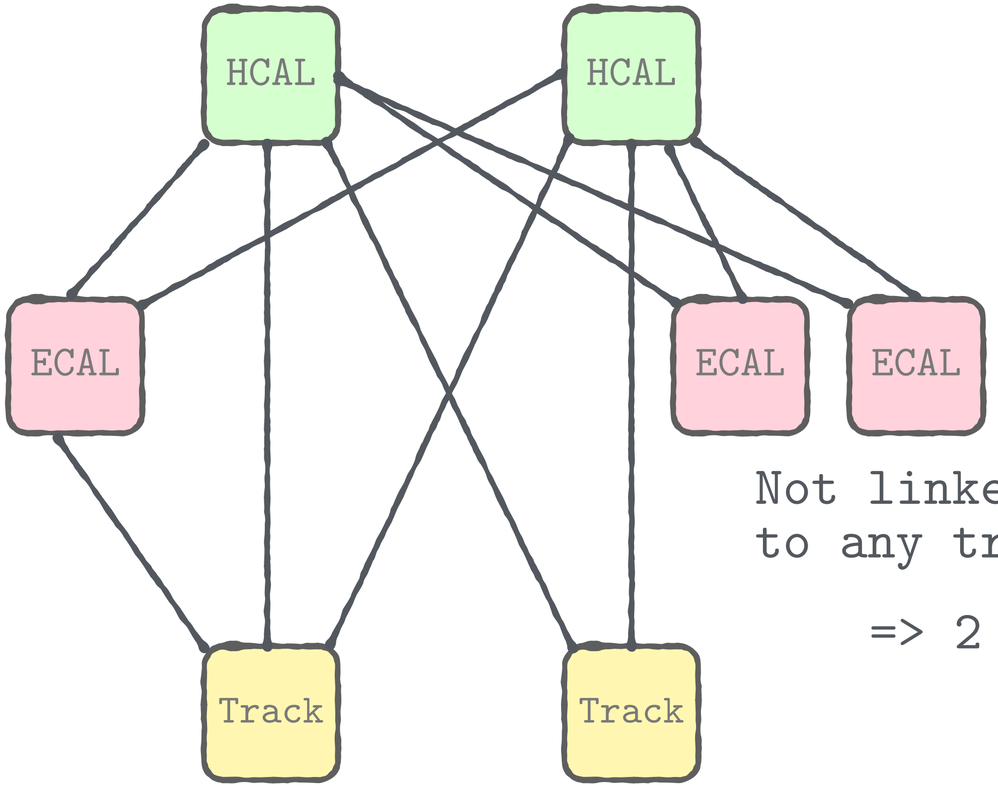

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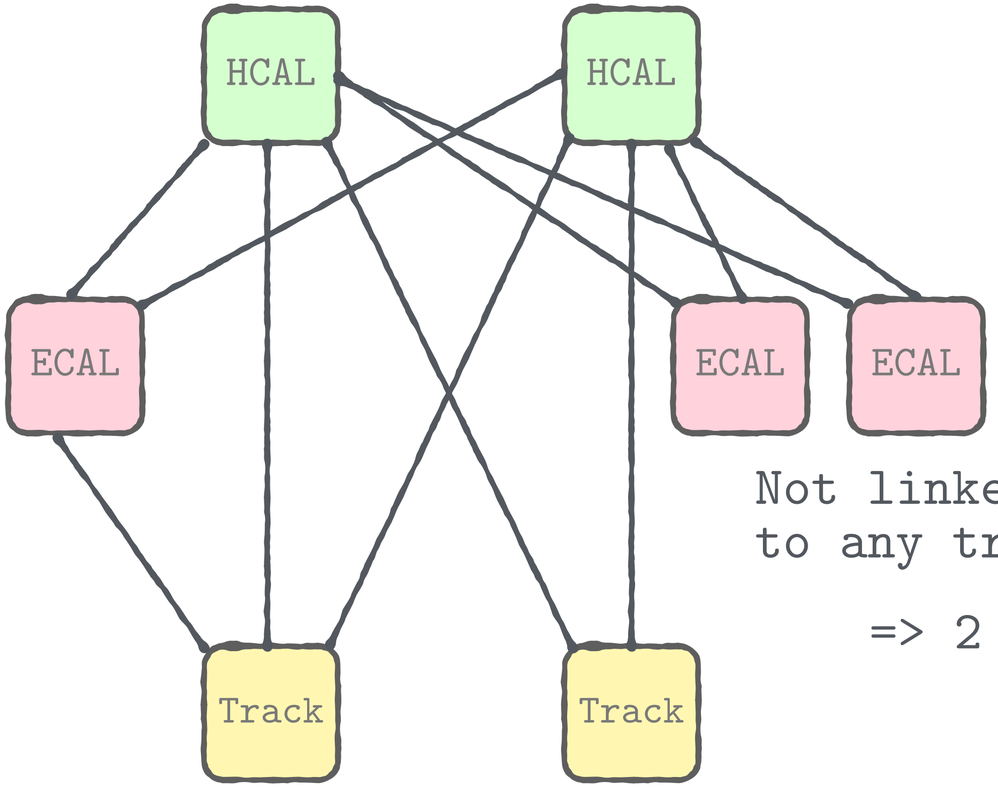

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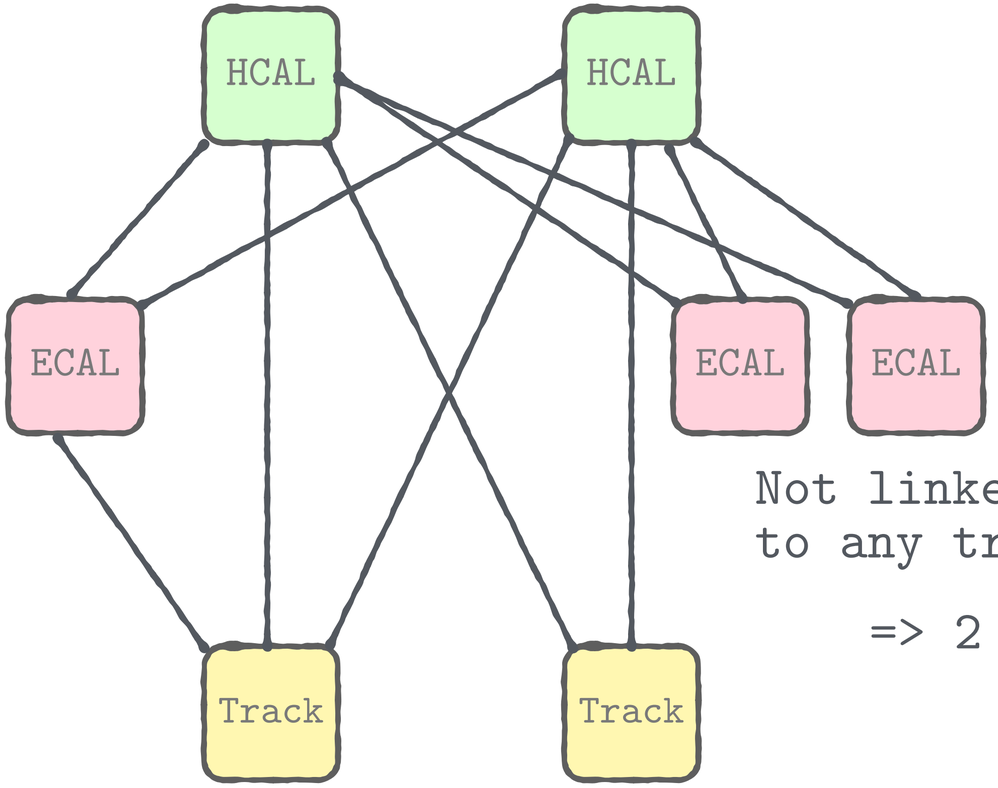

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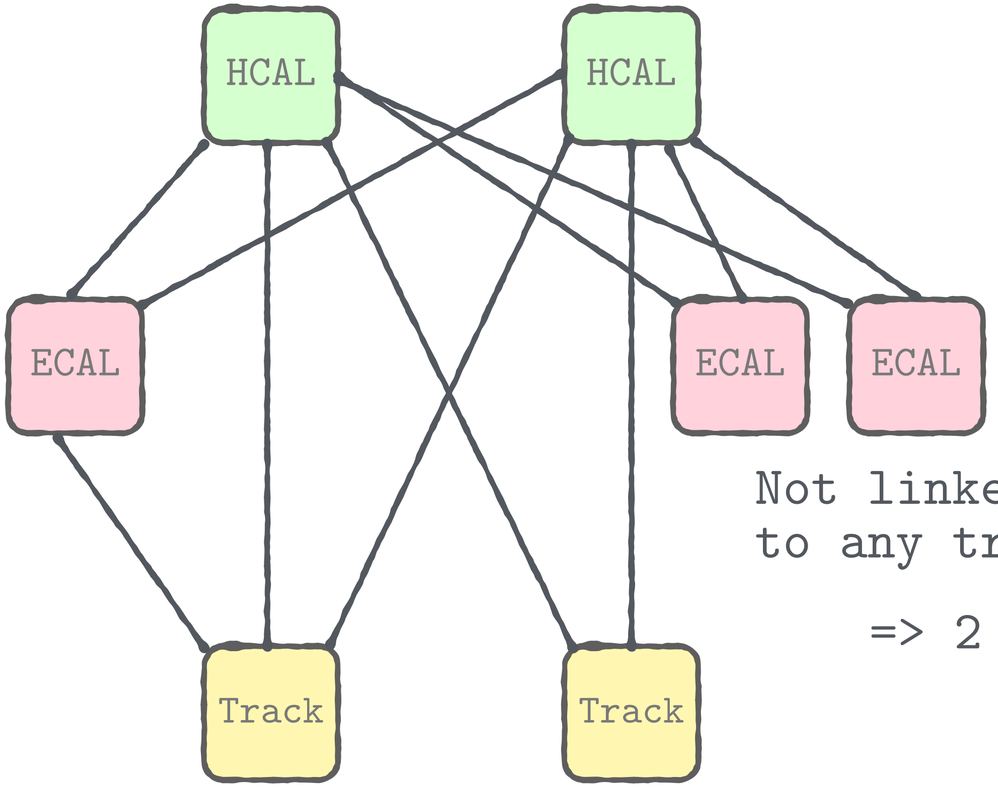

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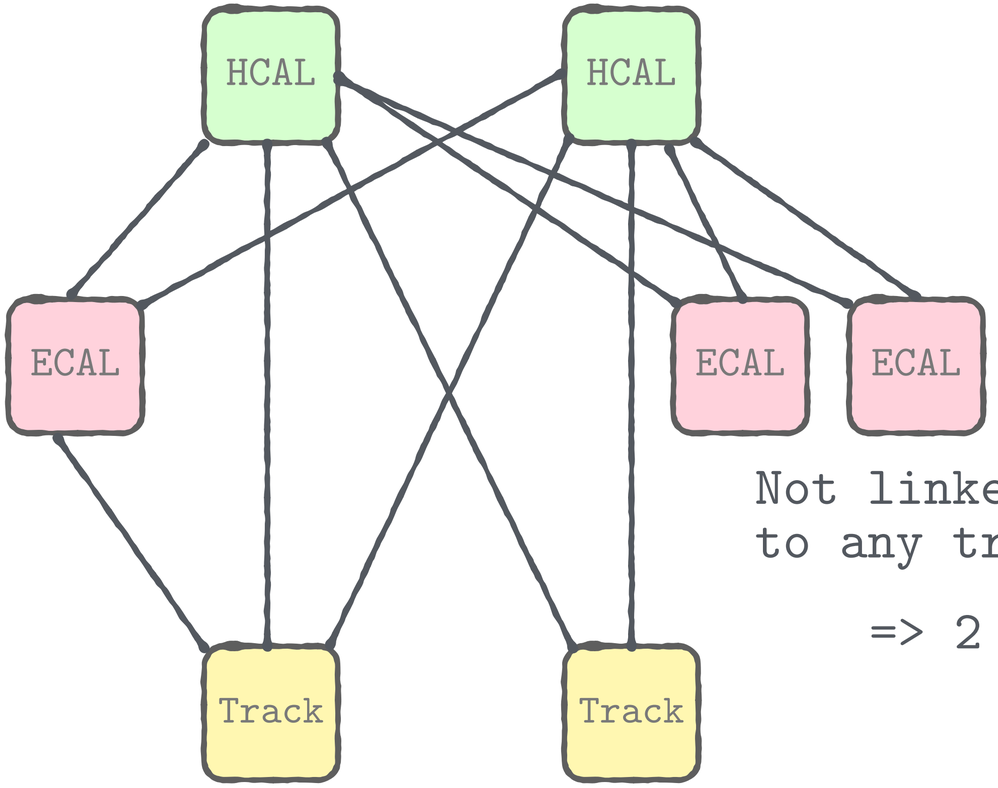

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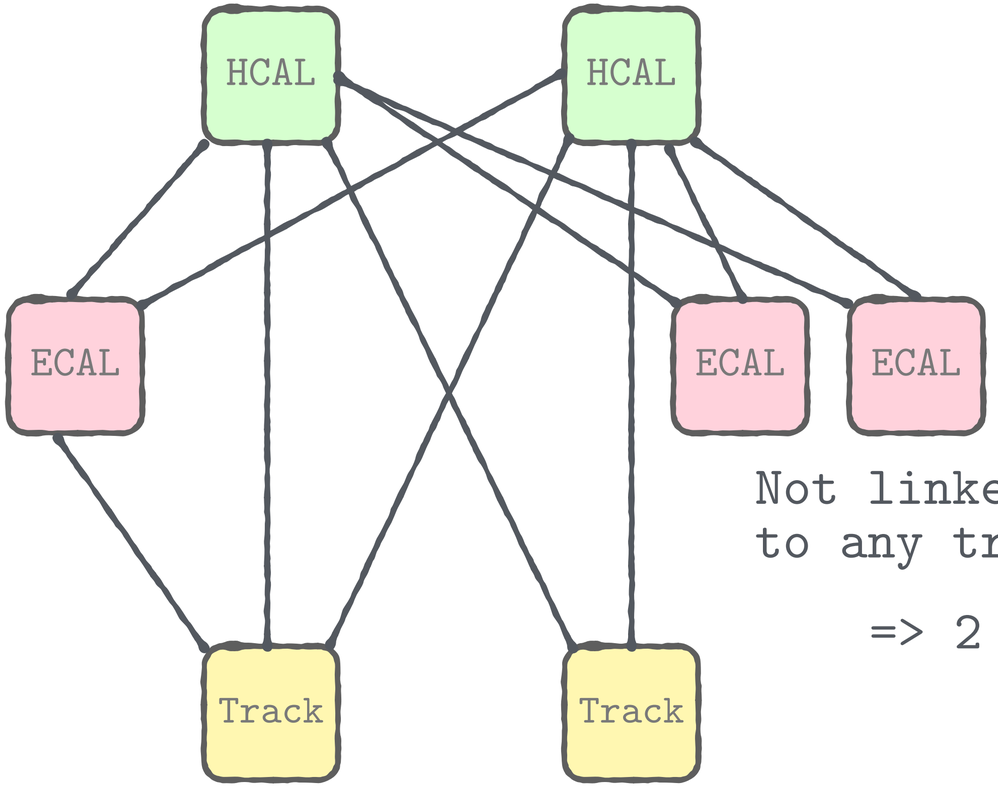

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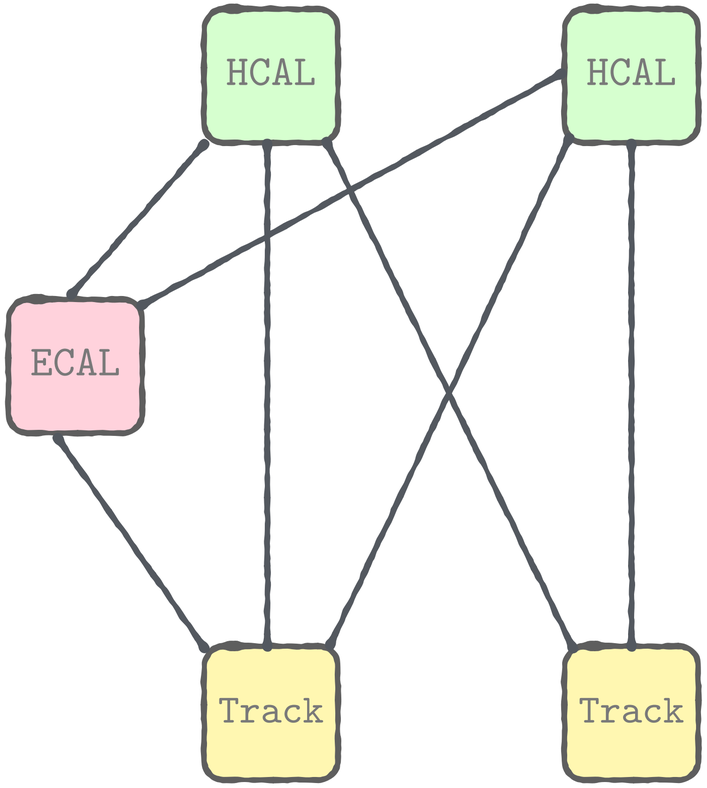

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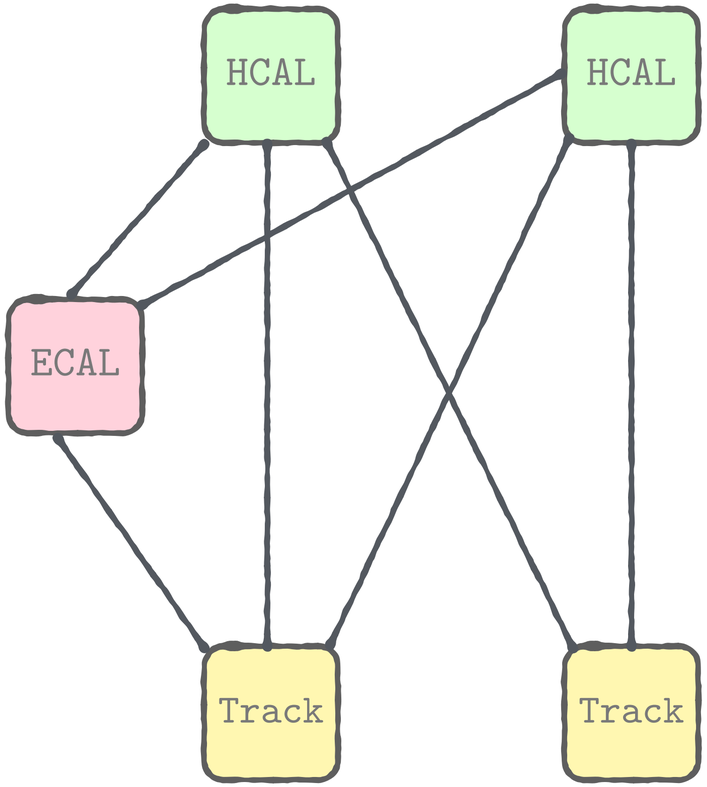

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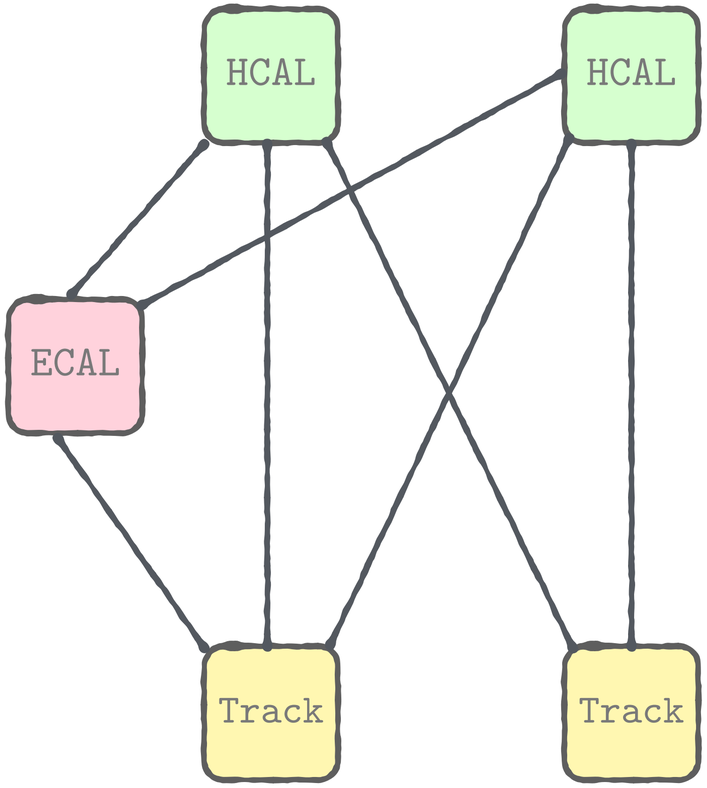

Optimise the use of HCAL granularity

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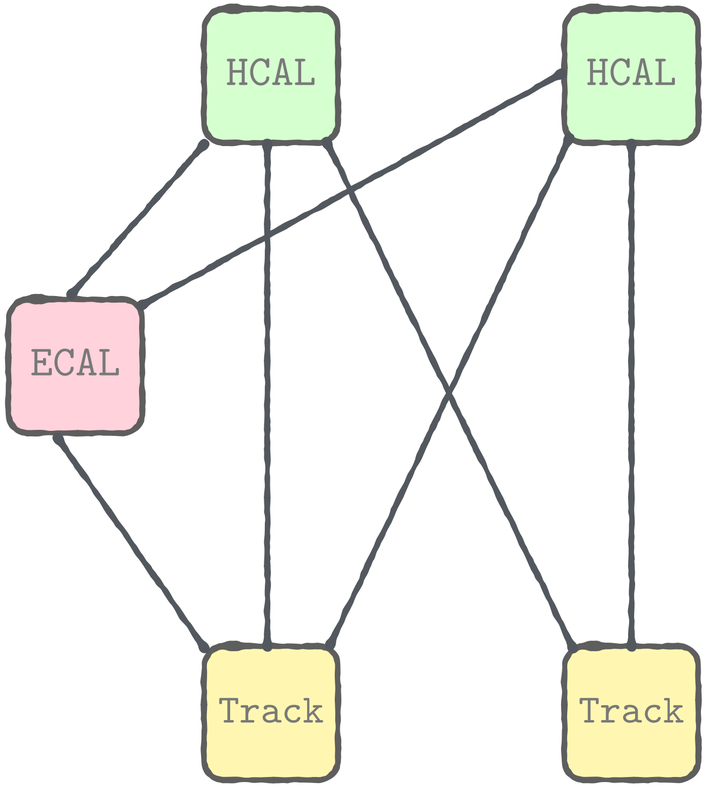

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Keep only the link to the closest cluster

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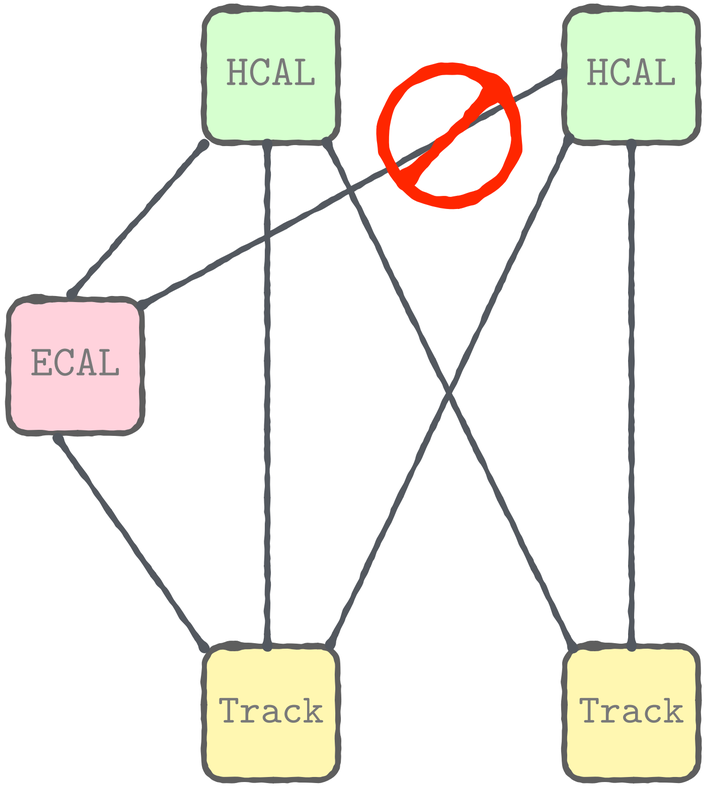

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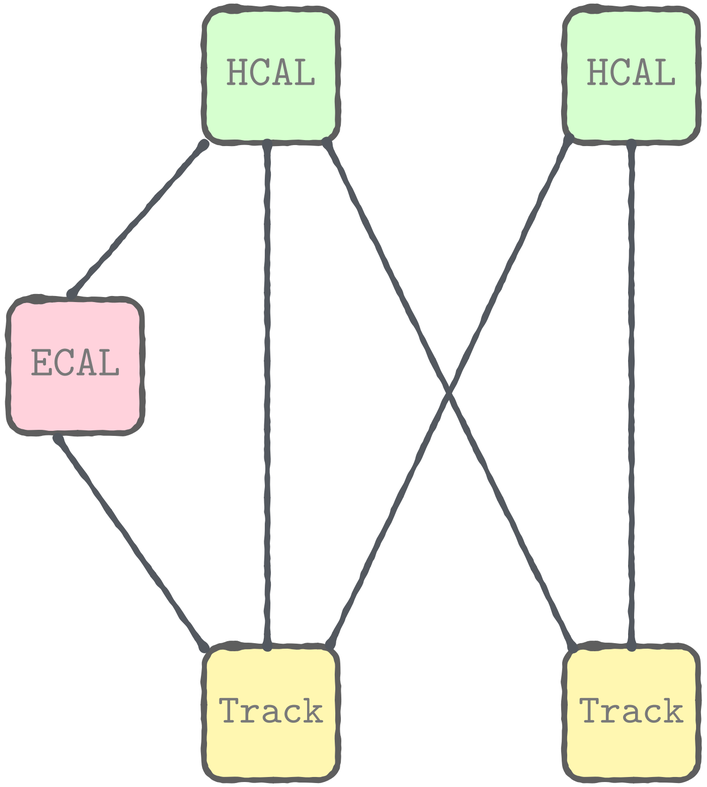

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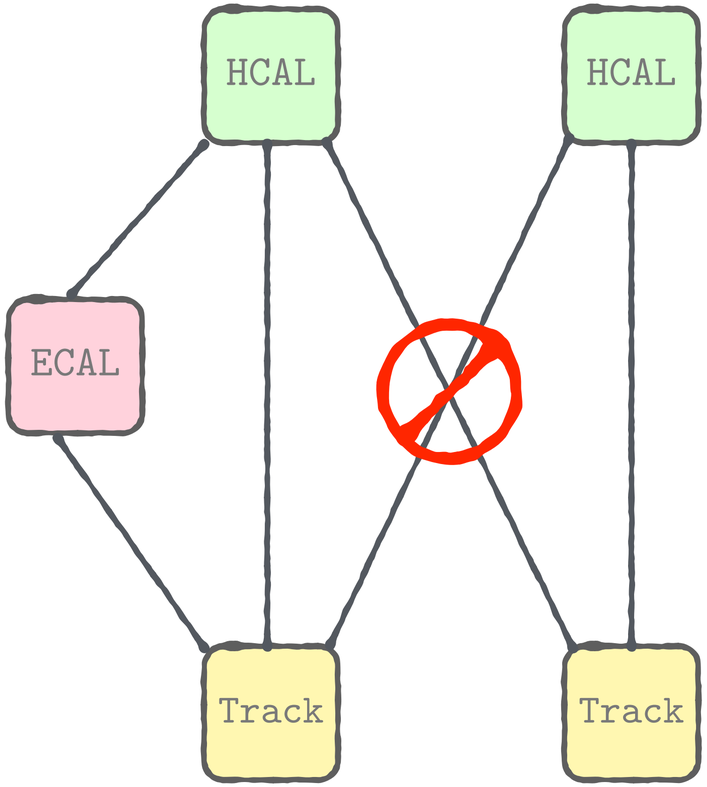

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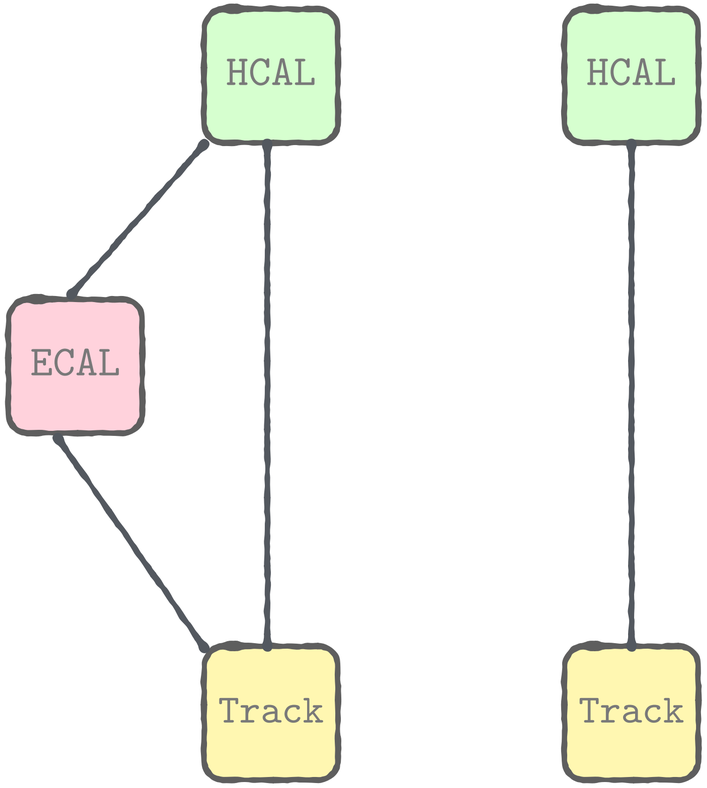

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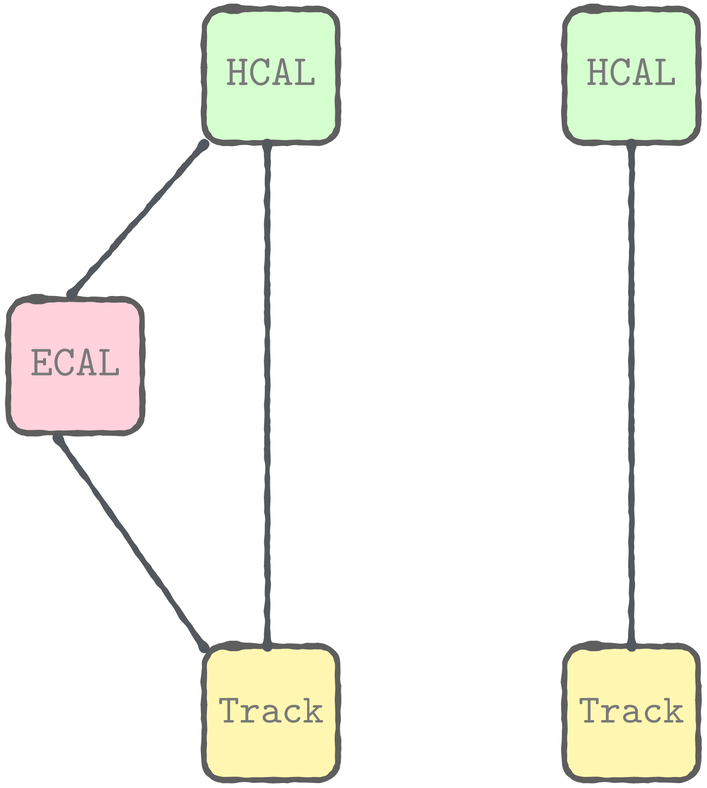

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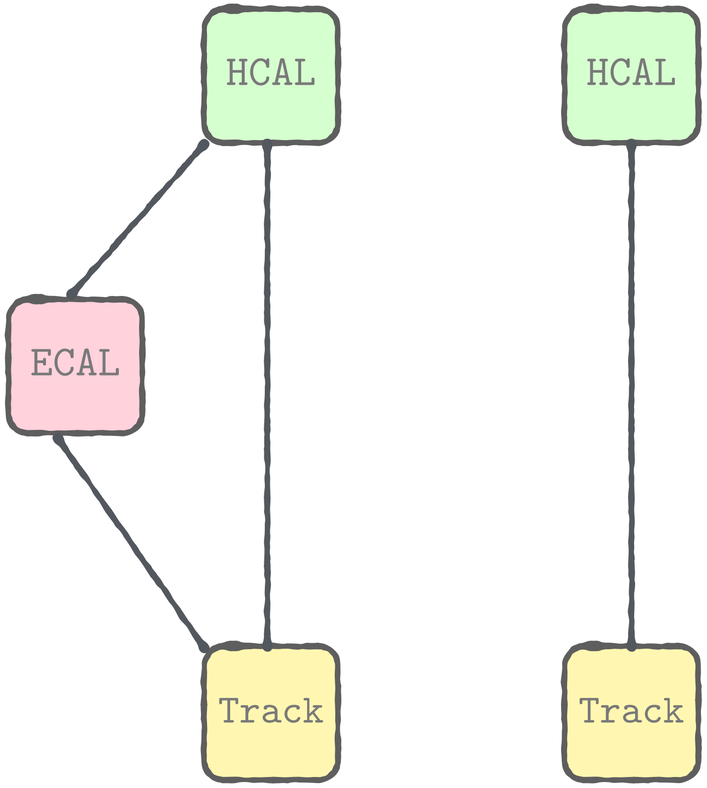

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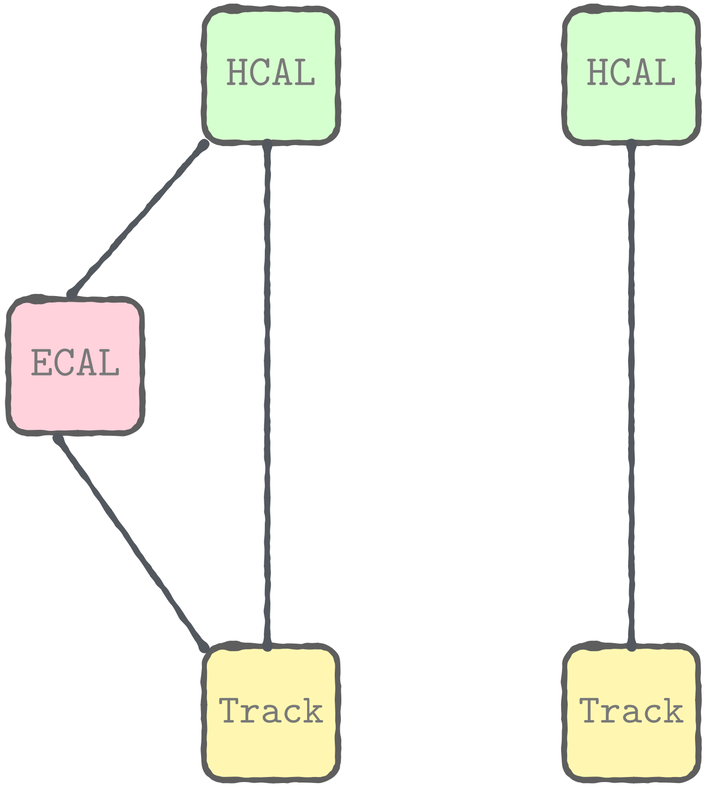

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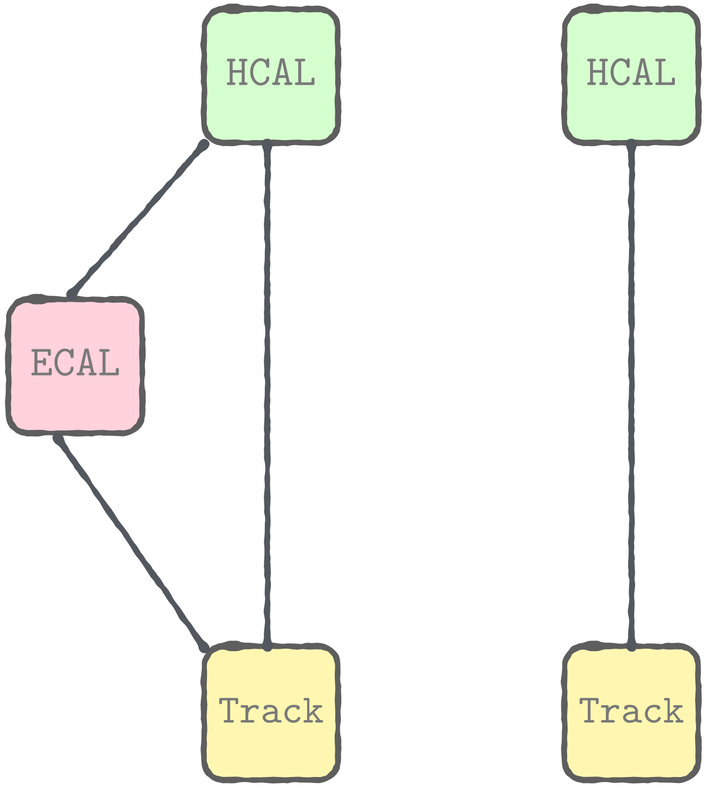
Find charged hadrons & merged photons / neutral hadrons



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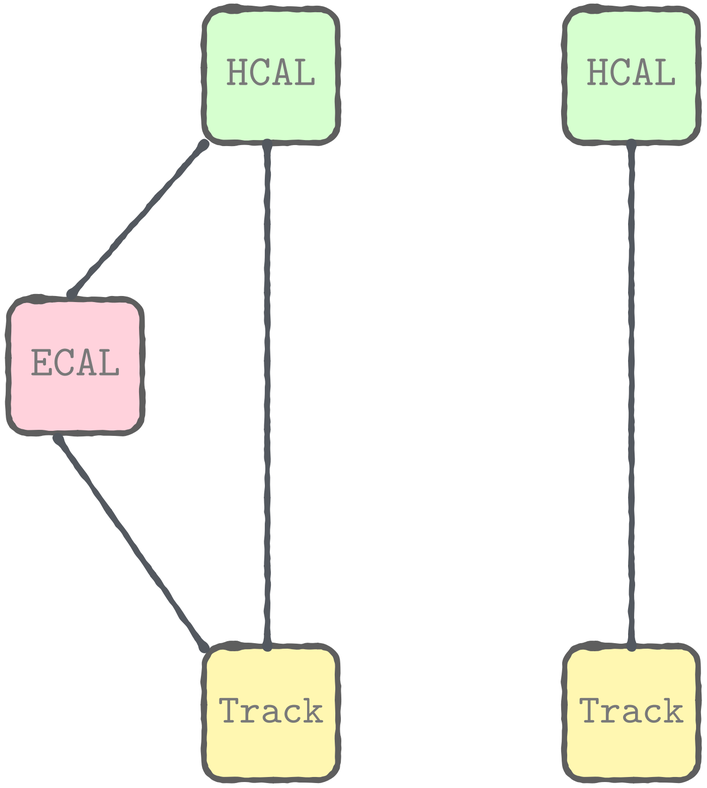

Simplified block (2nd step)

Find charged hadrons & merged photons / neutral hadrons

For each HCAL Cluster compare:

- Sum of track momenta p
- Sum of cluster energies E
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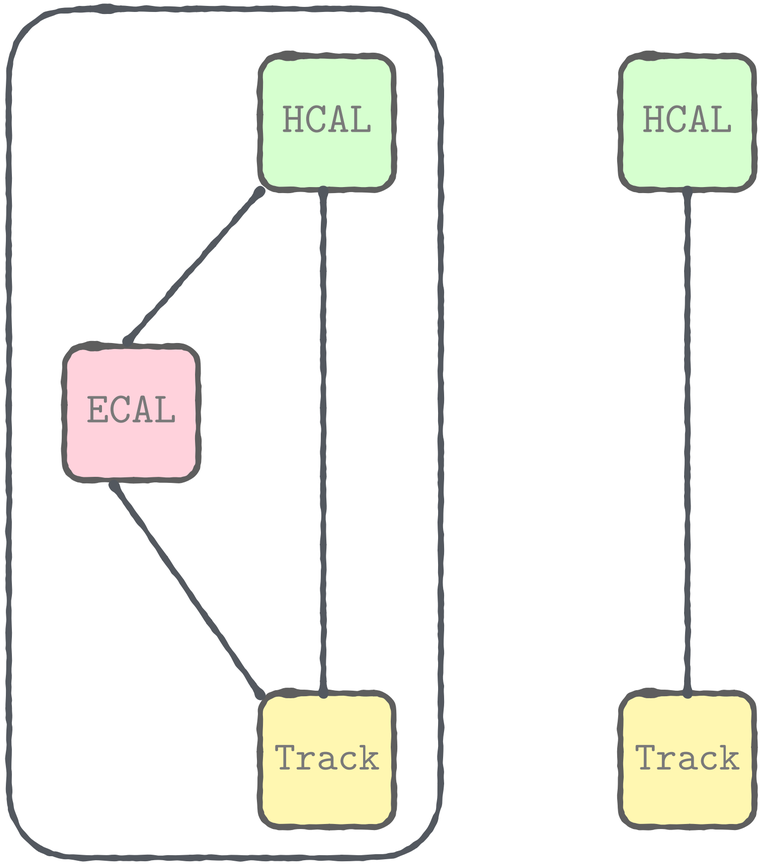

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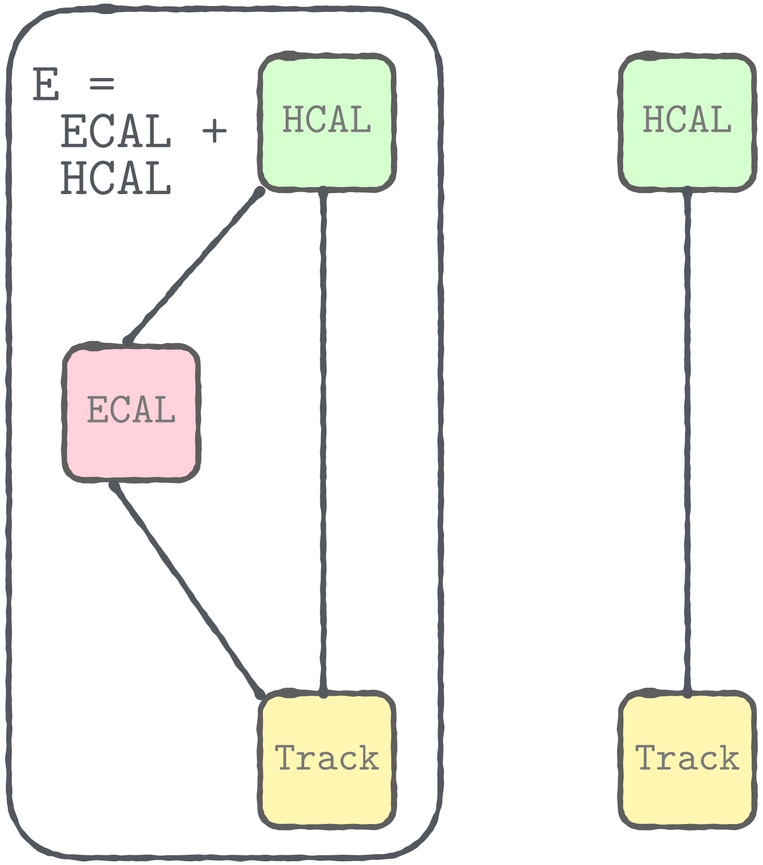

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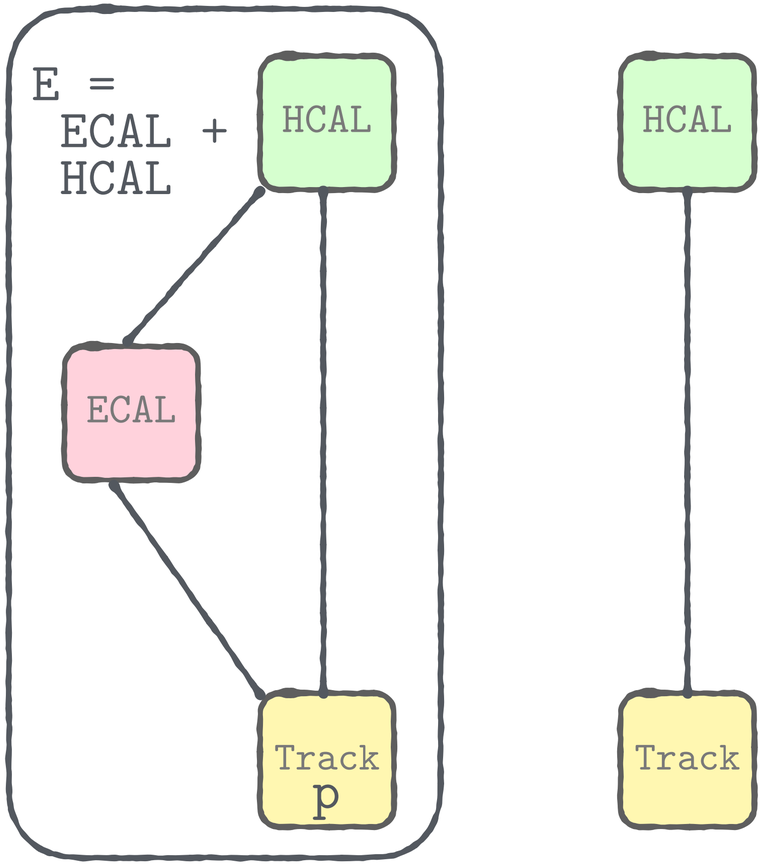

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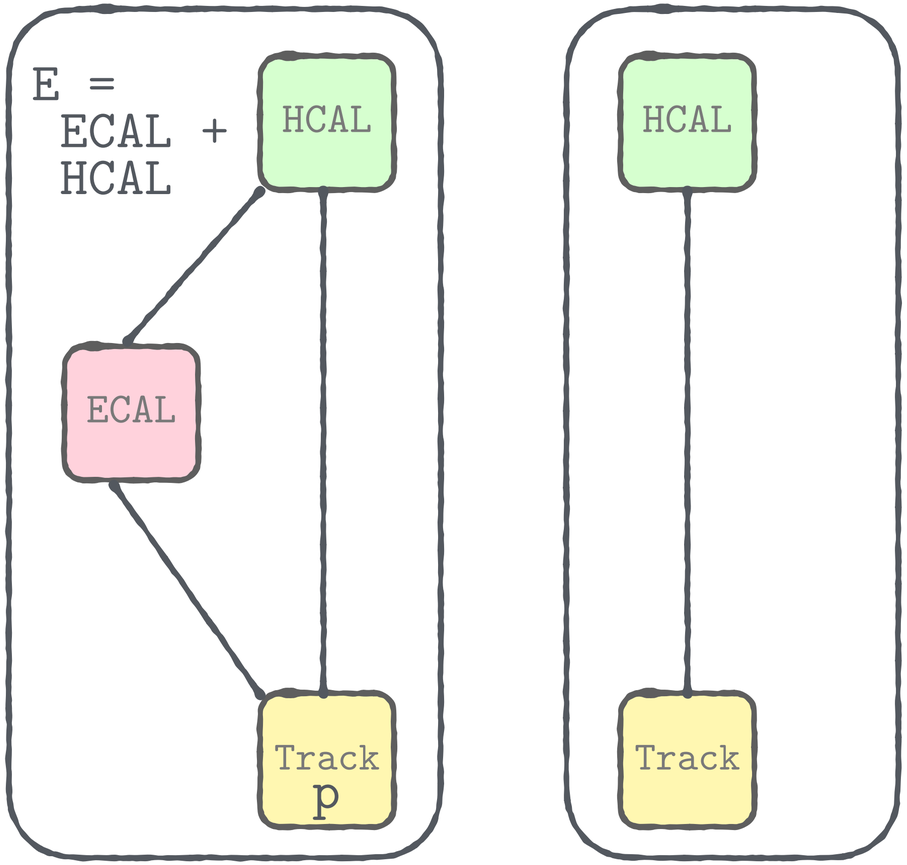

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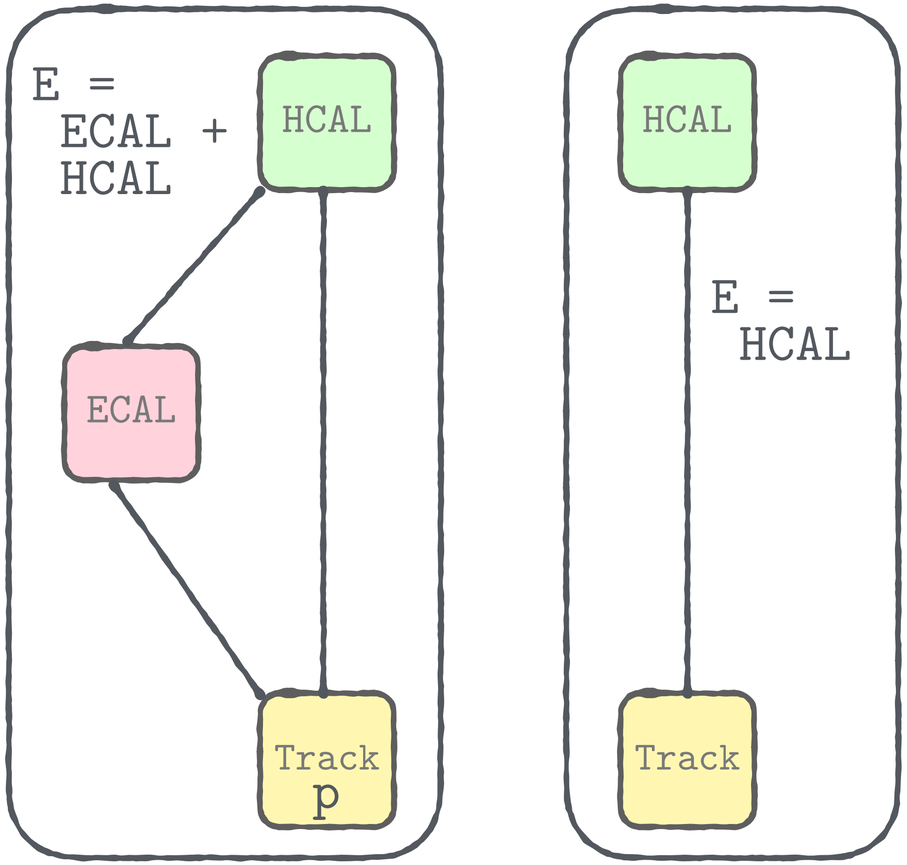

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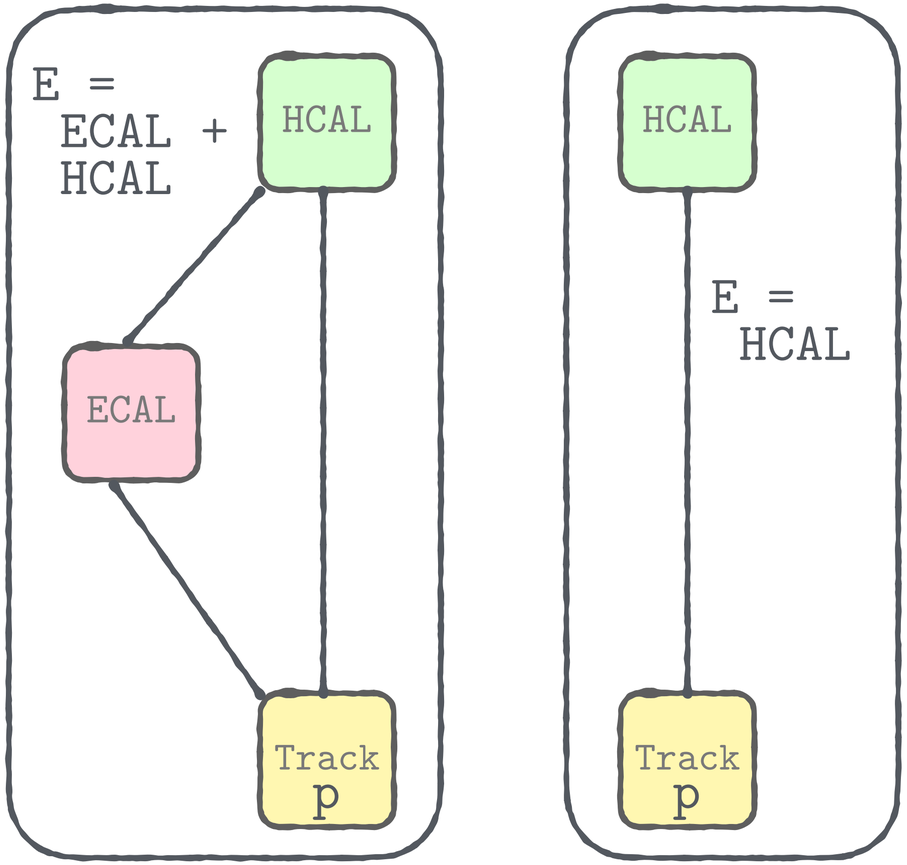

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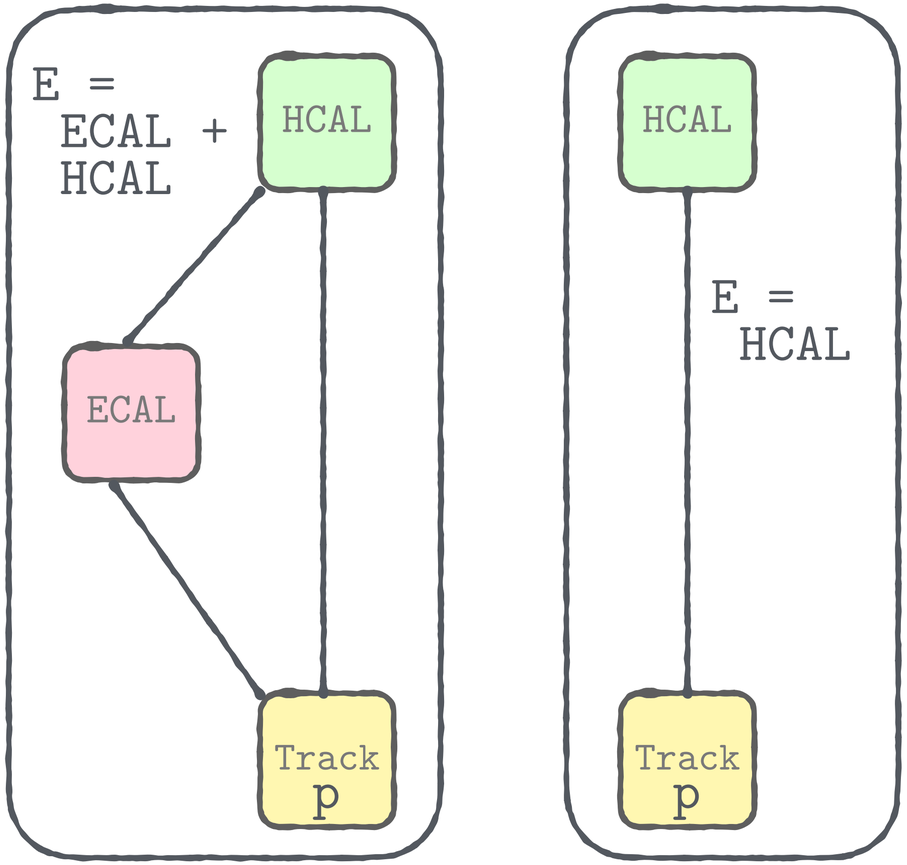

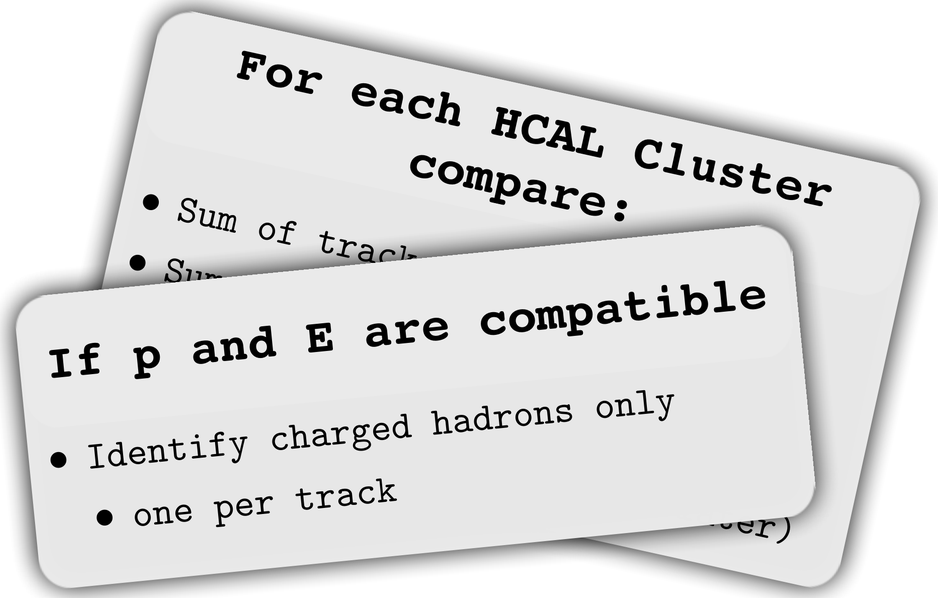

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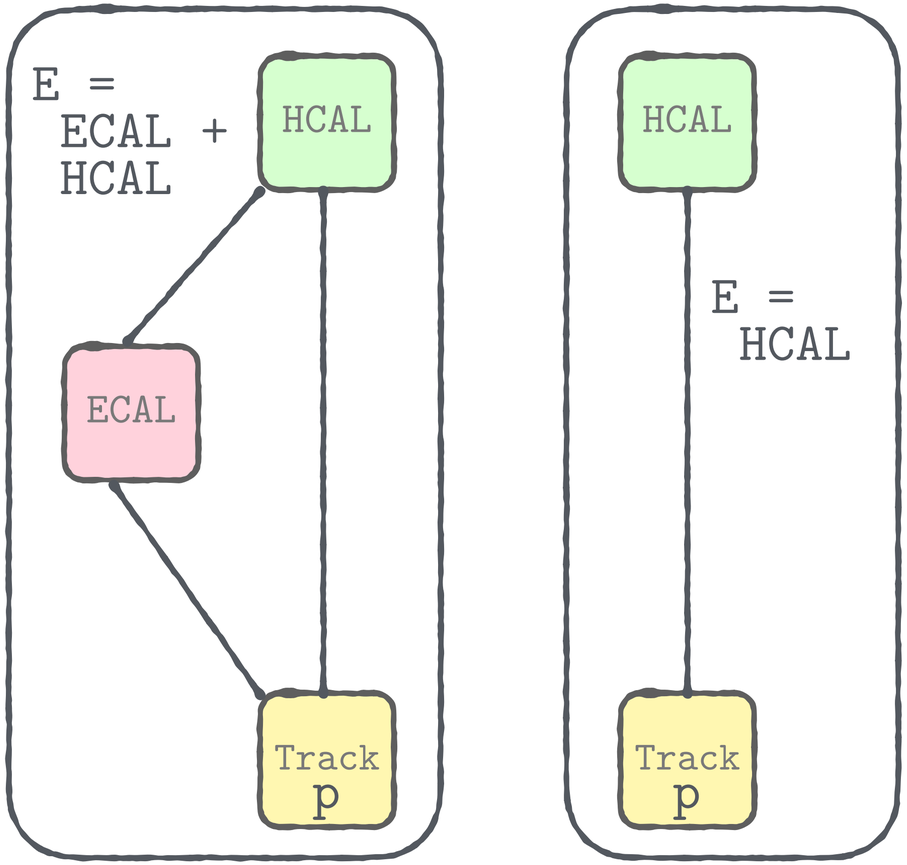

For each HCAL Cluster compare:

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If p and E are compatible

- Identify charged hadrons only
  - one per track

If E > p + σ(E)

- Identify charged hadrons + photons / neutral hadrons

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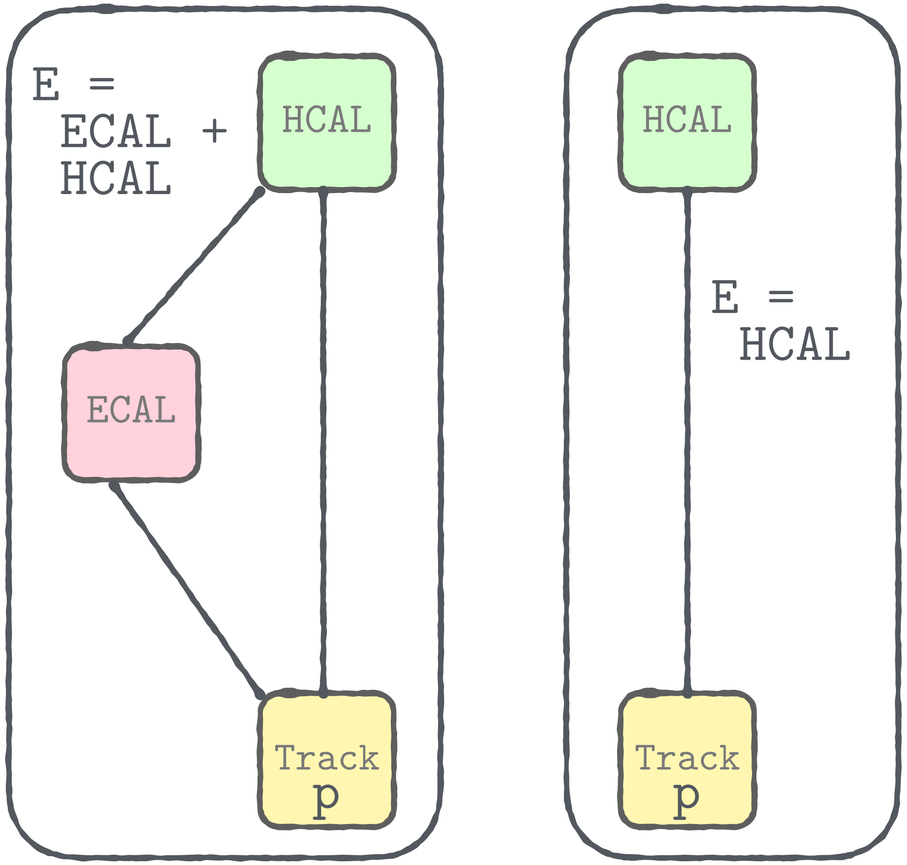

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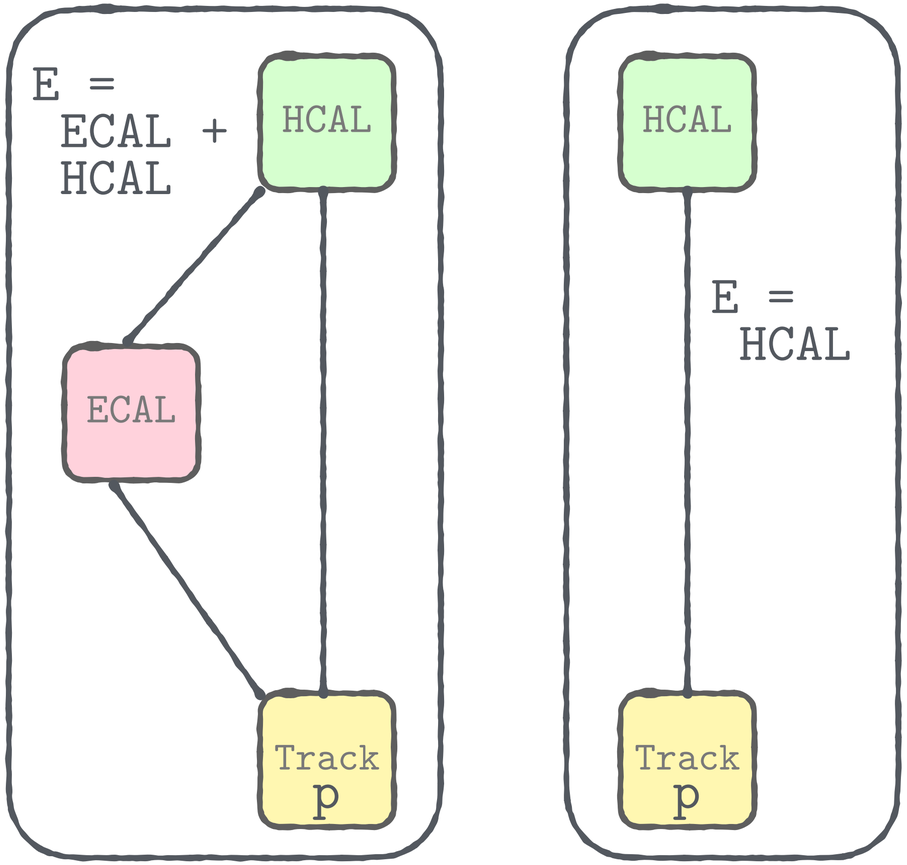

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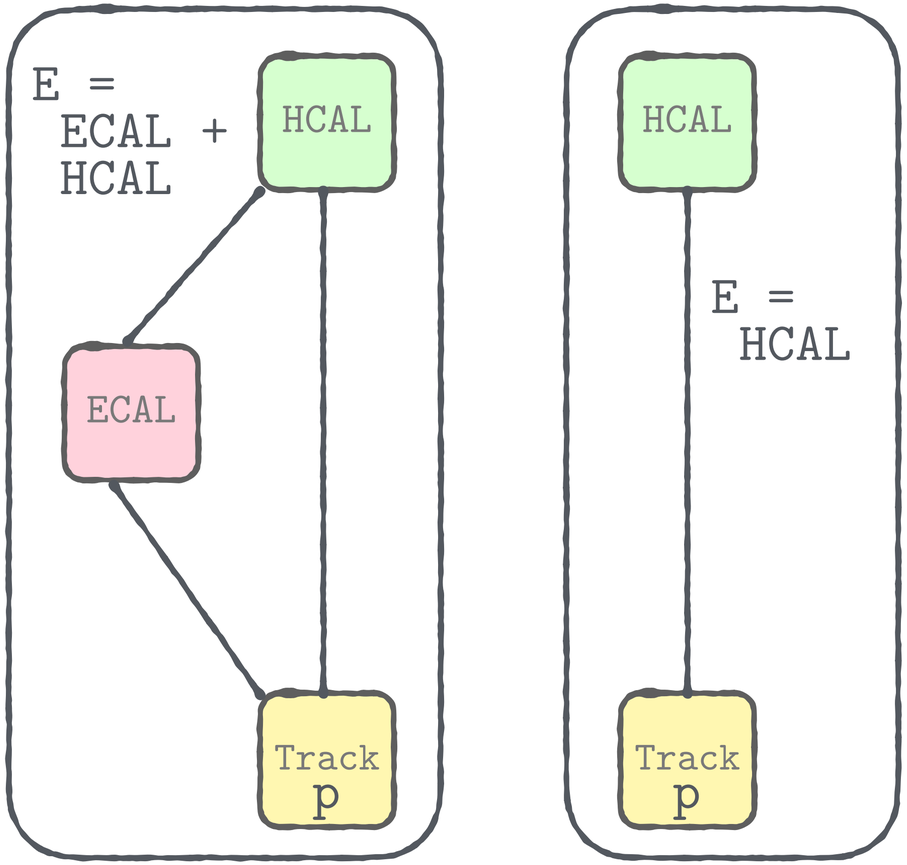

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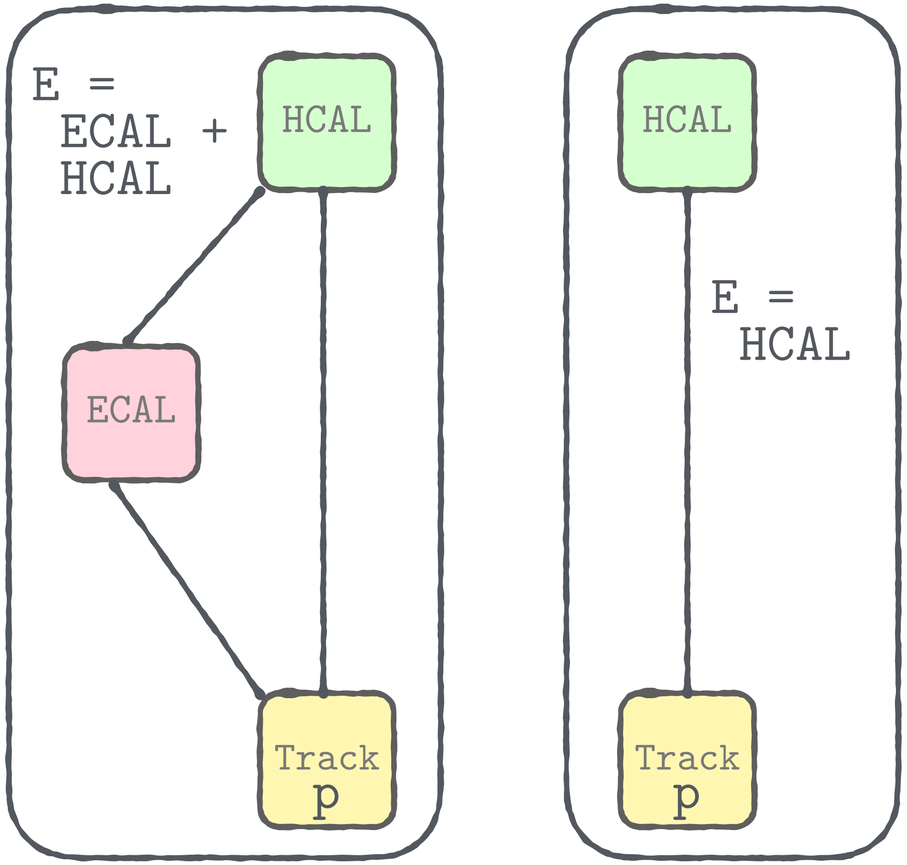

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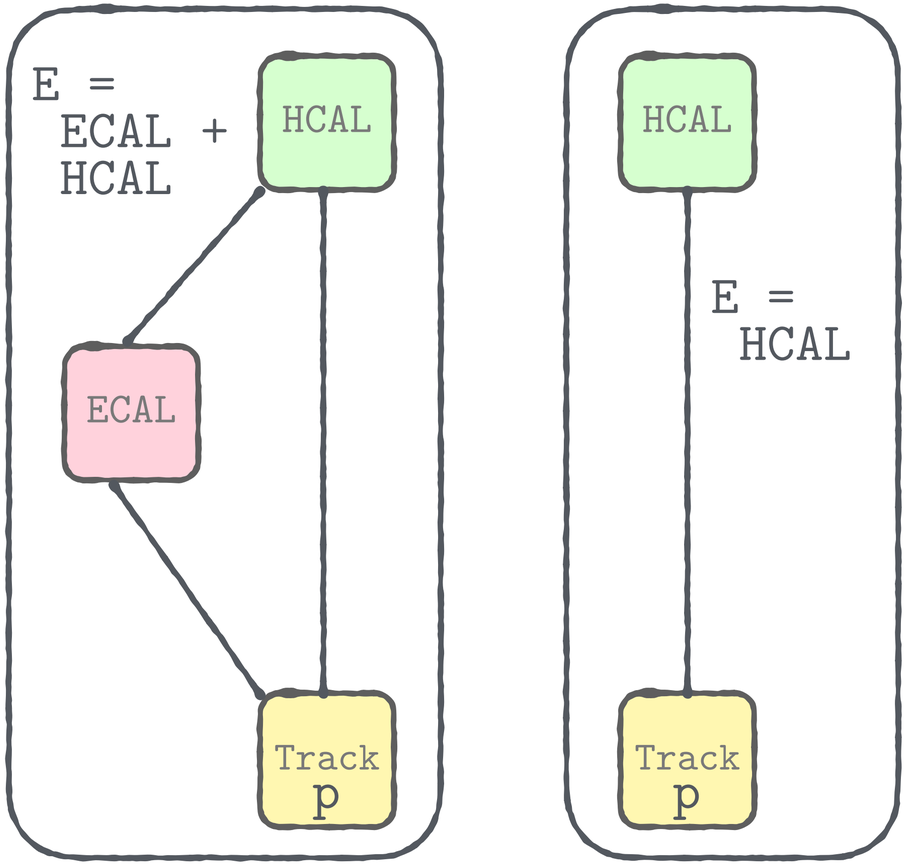

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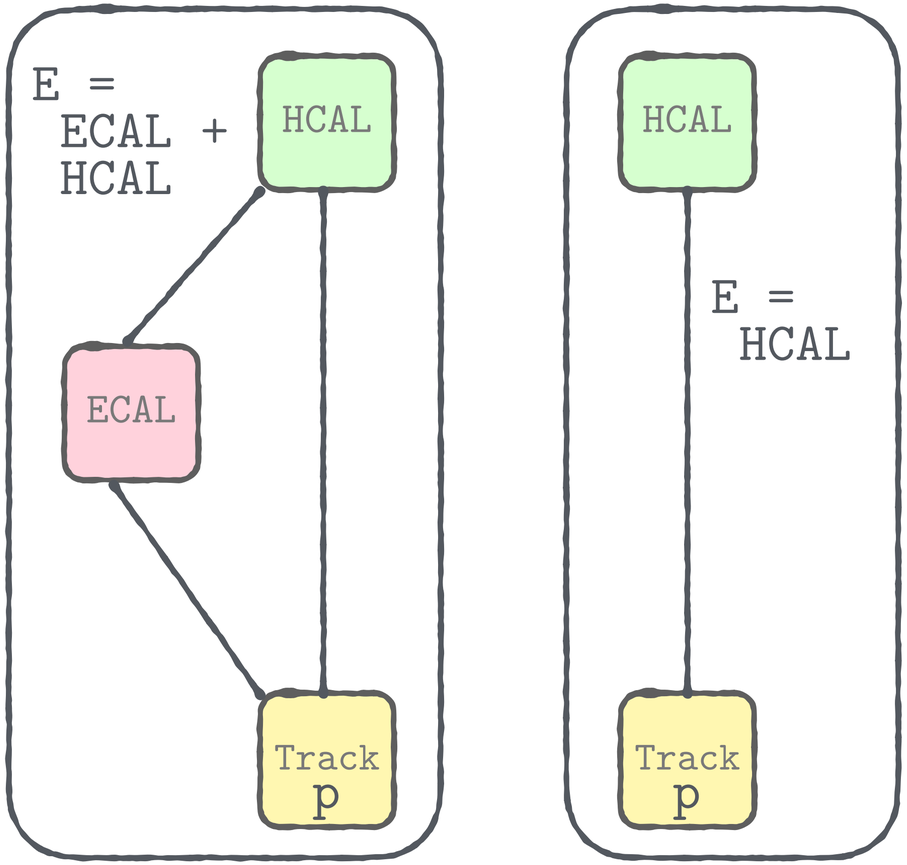

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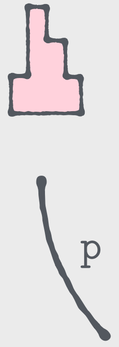

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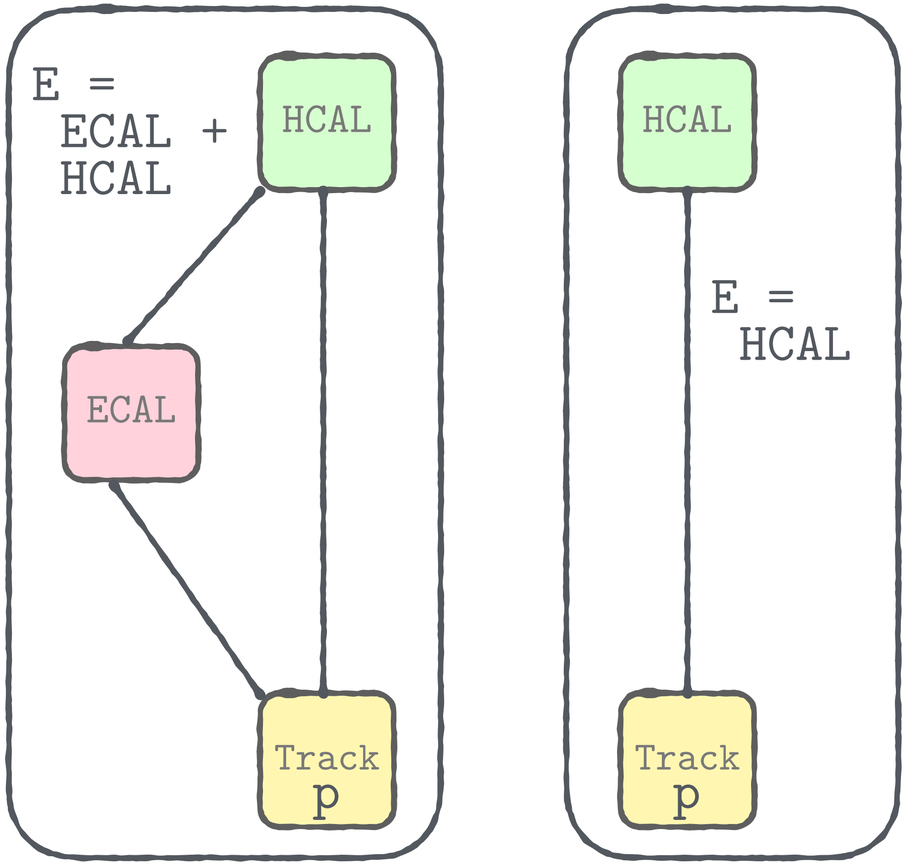

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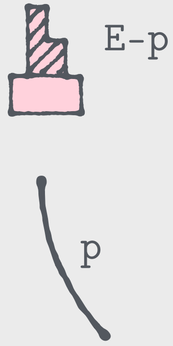

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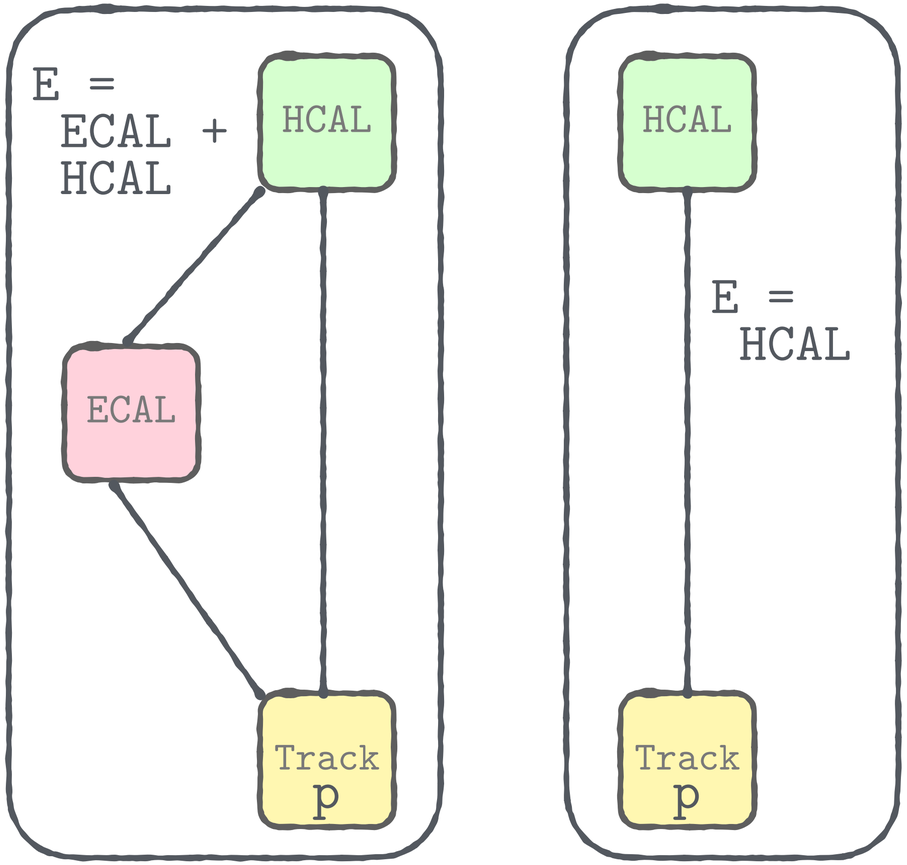

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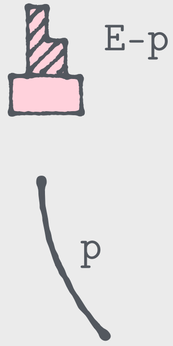

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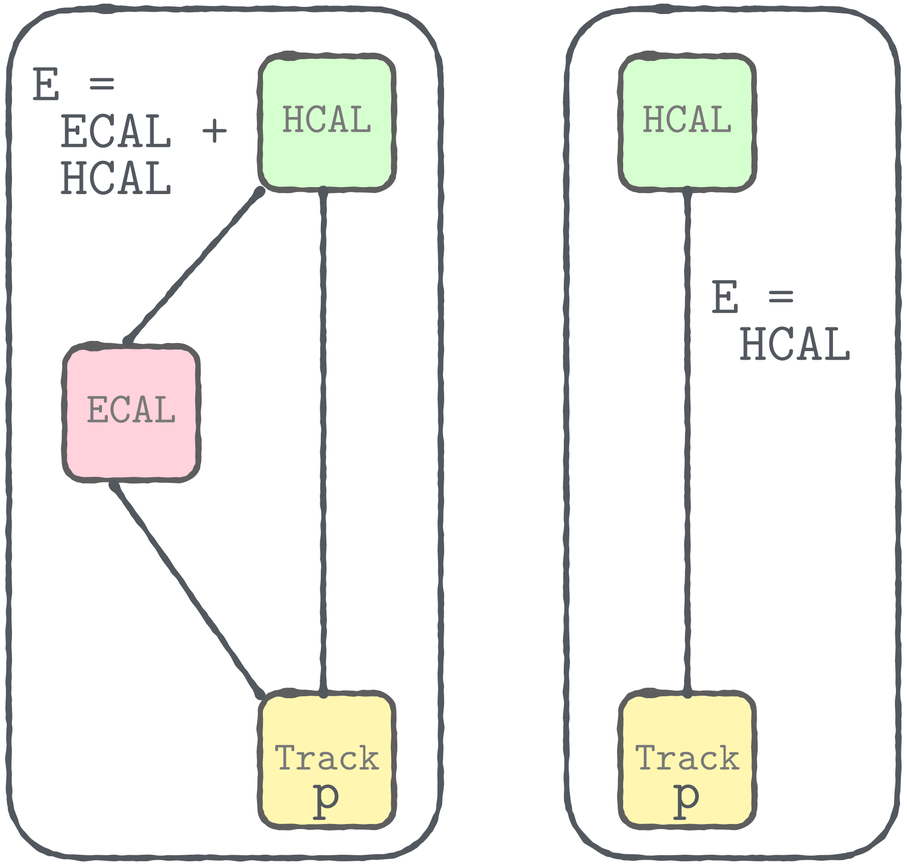

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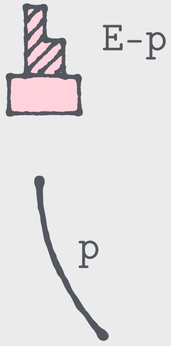

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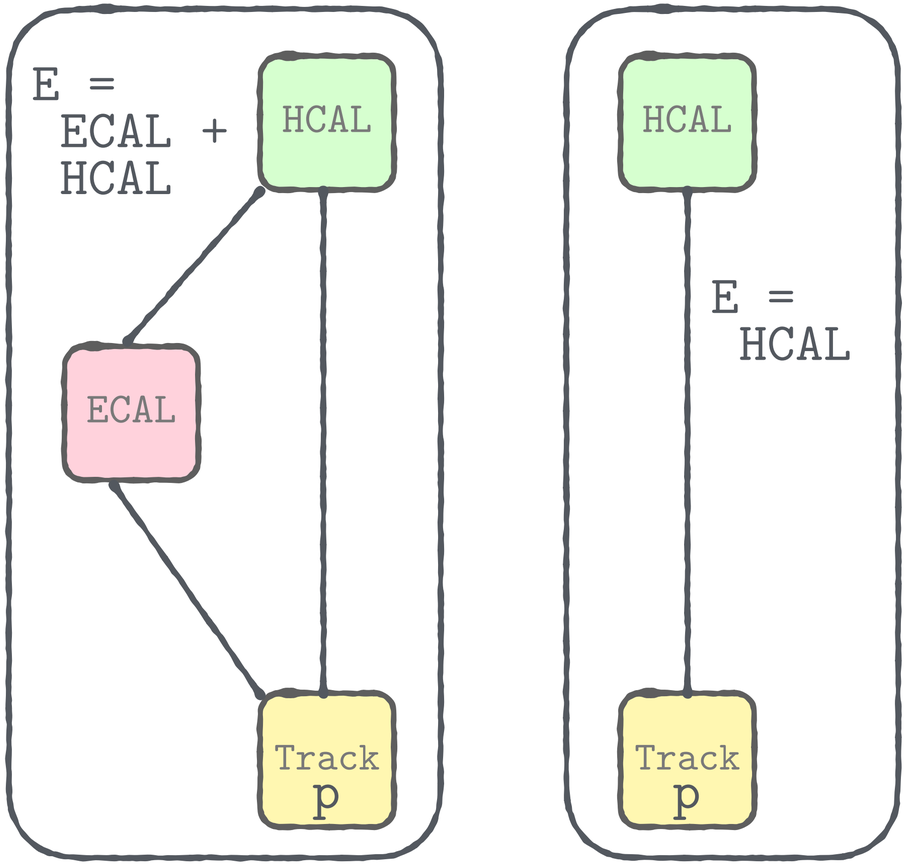

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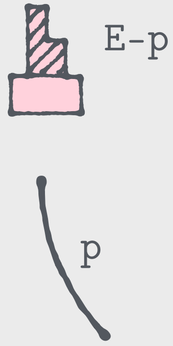

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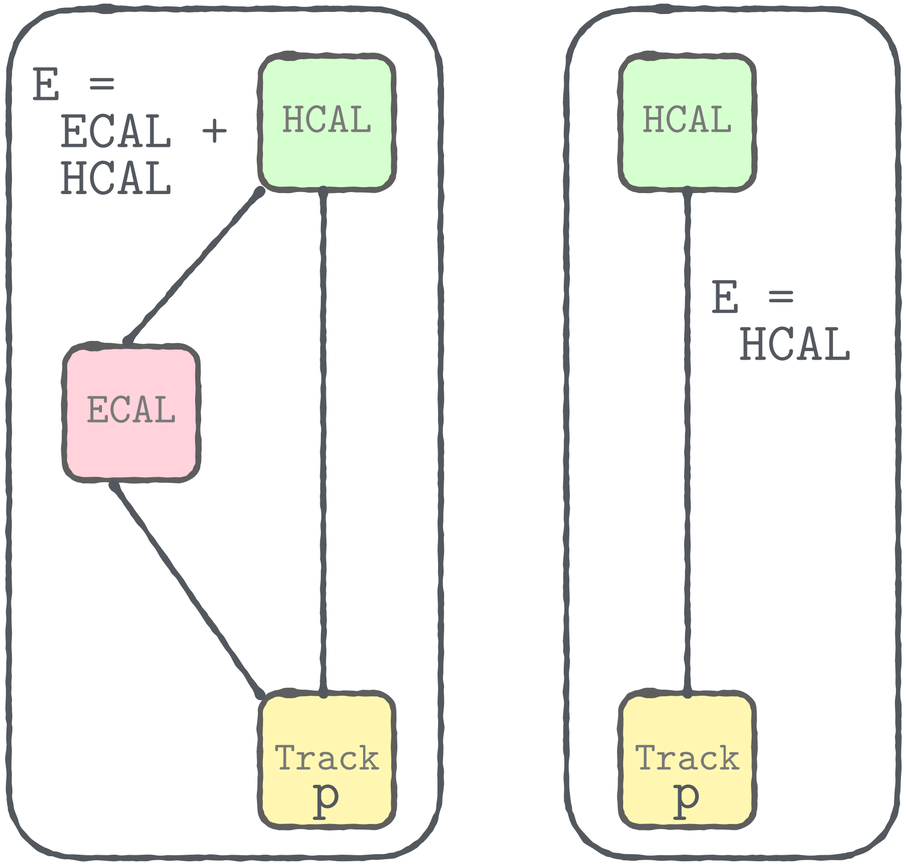

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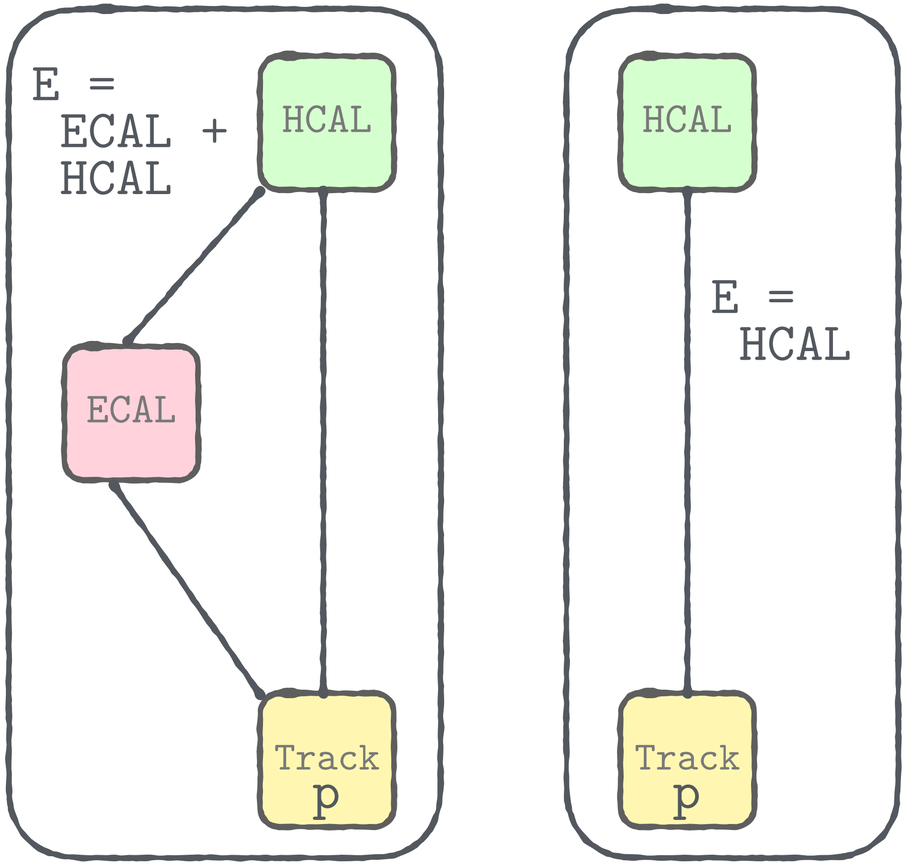

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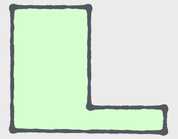

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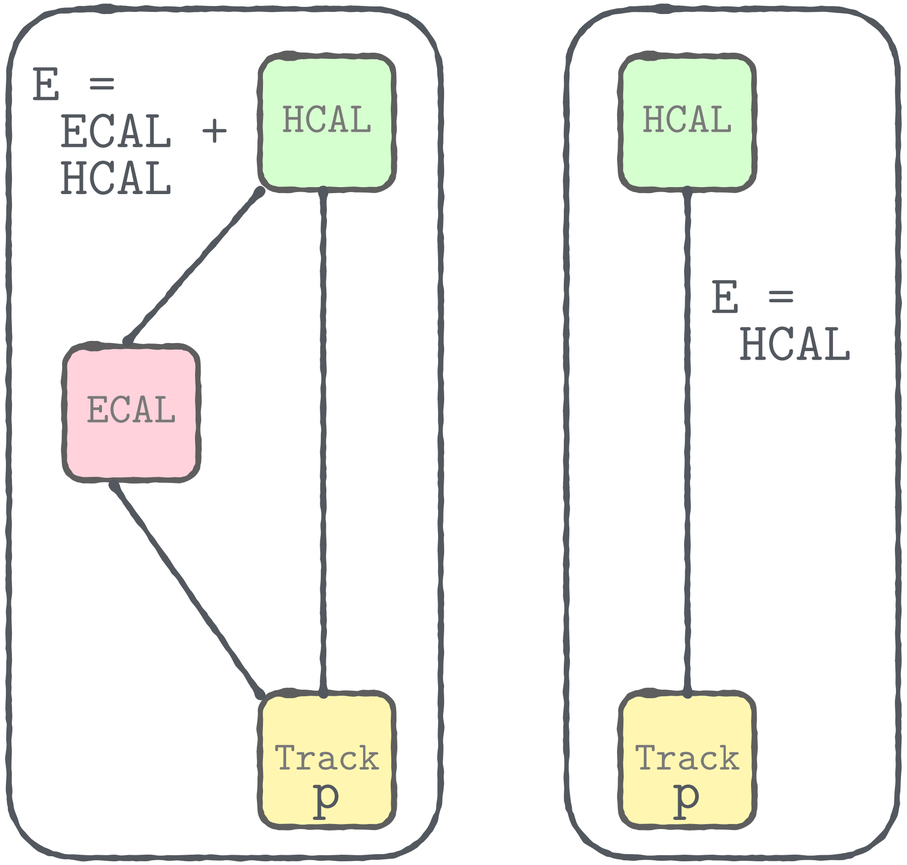

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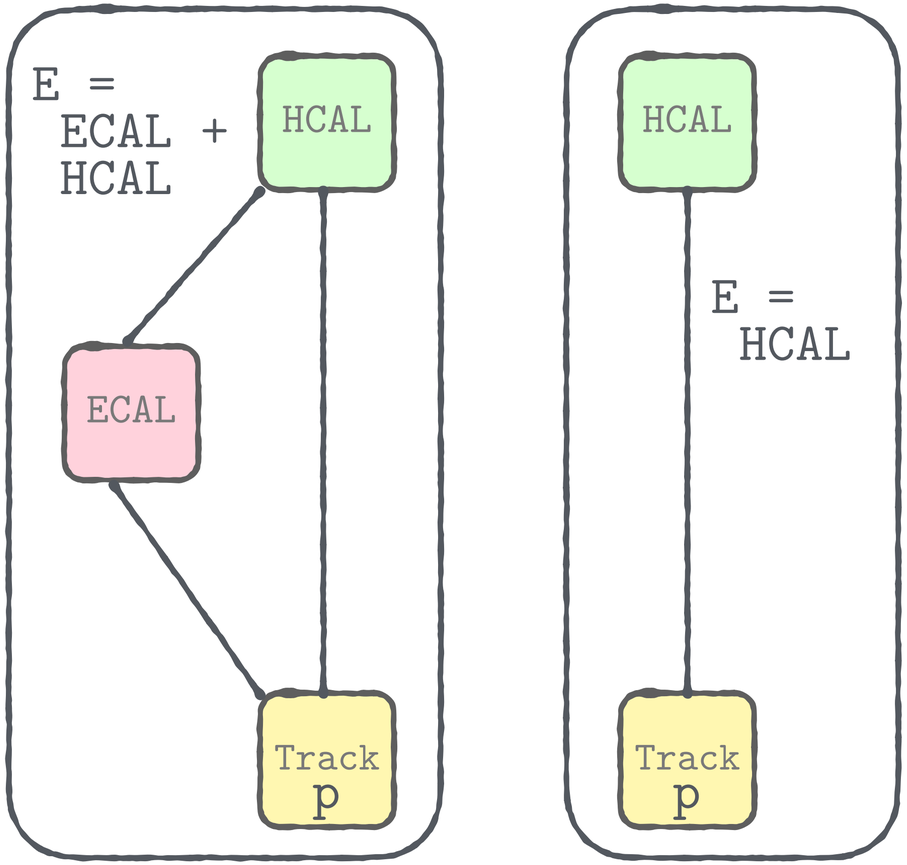

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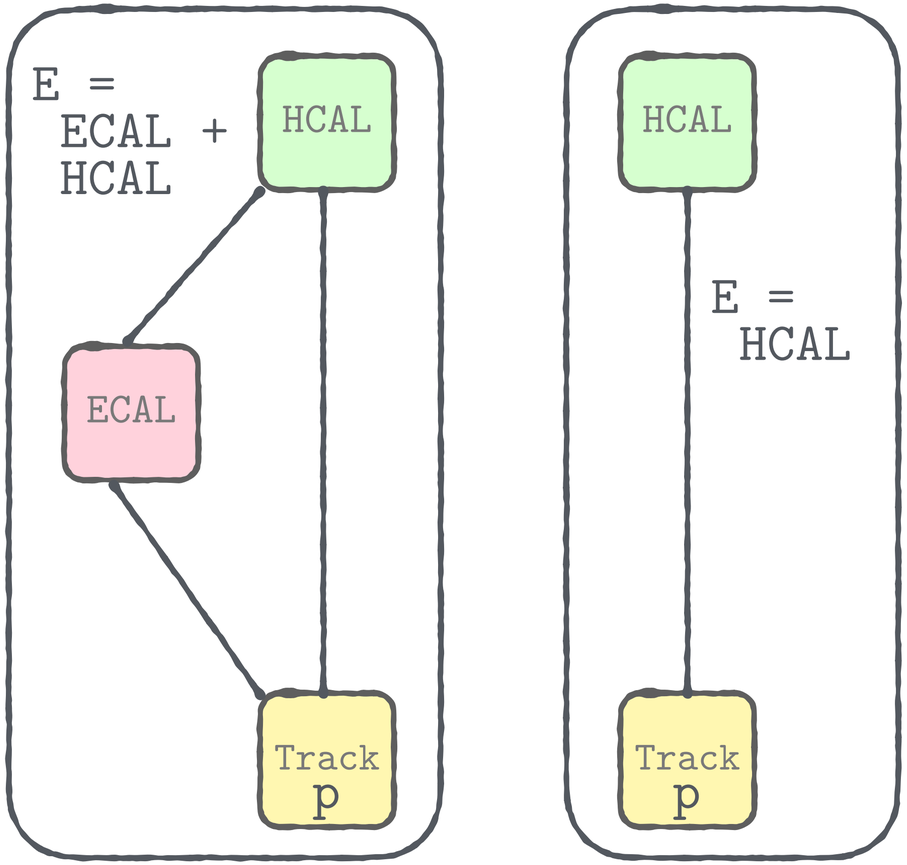

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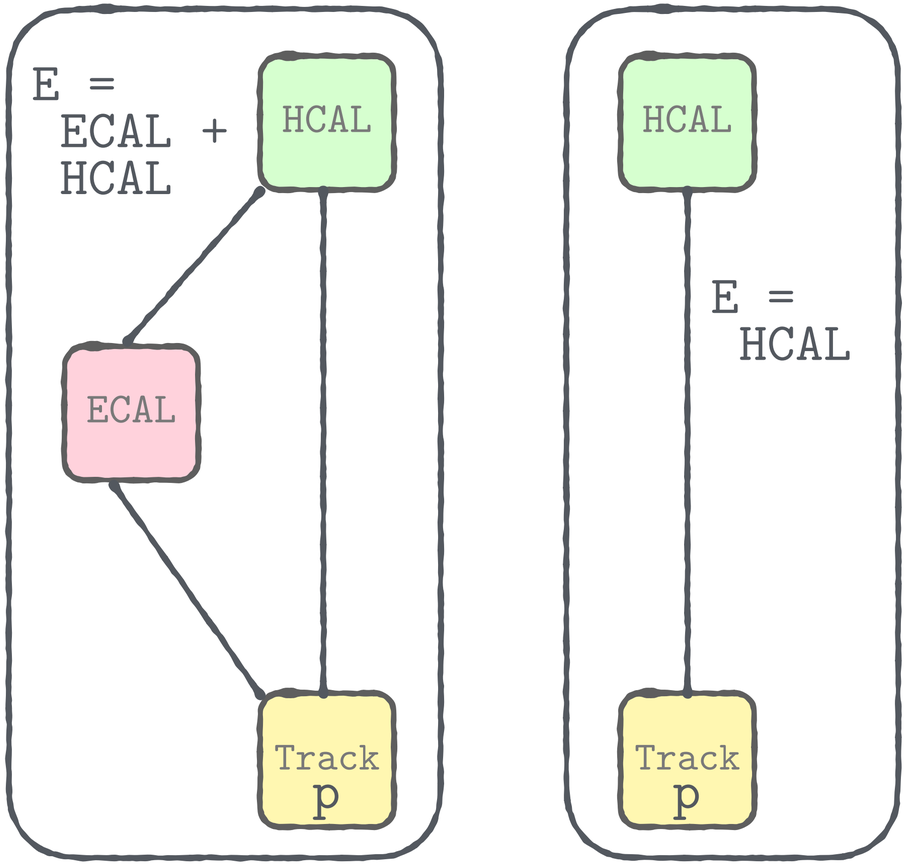

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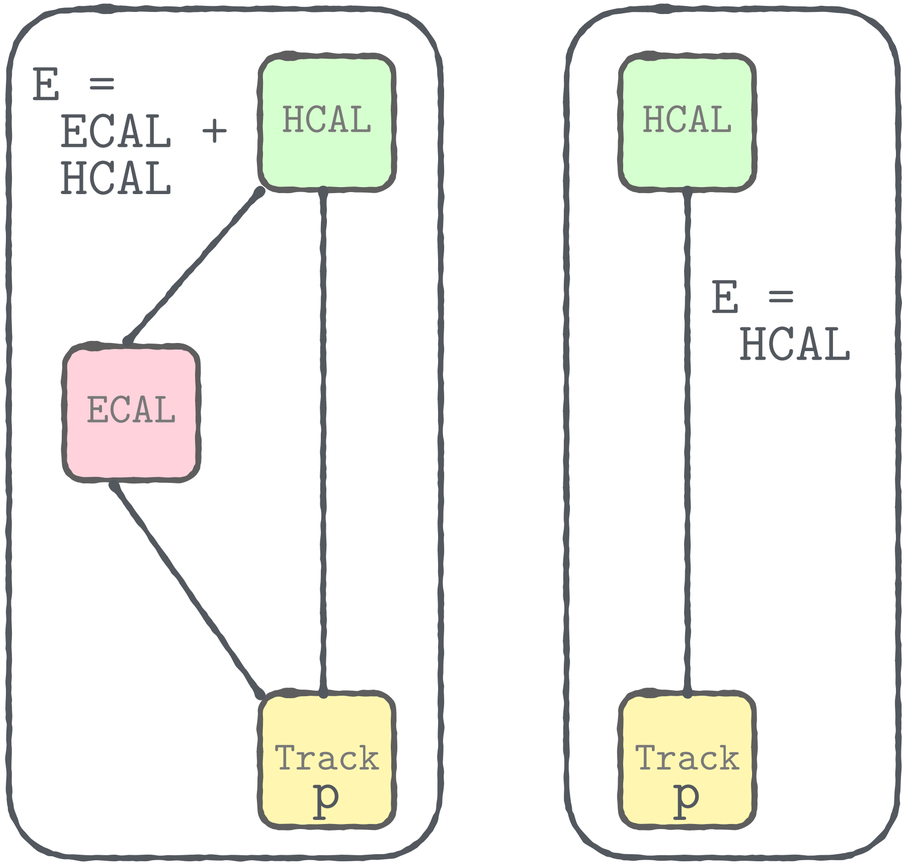

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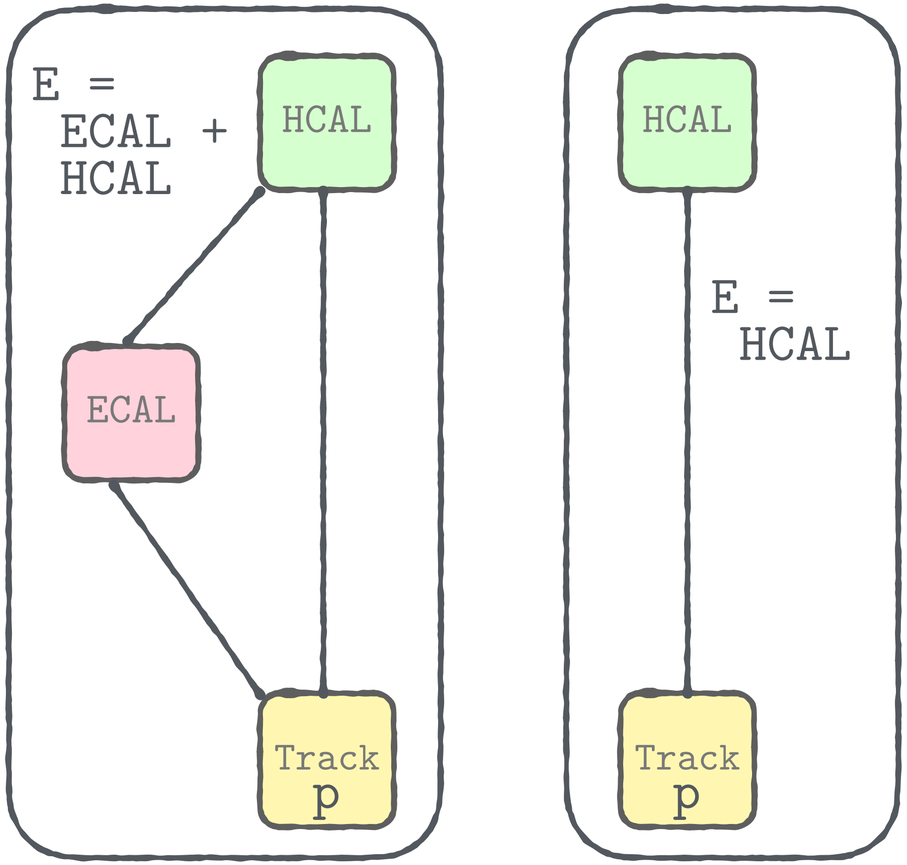

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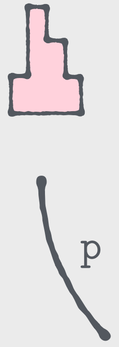

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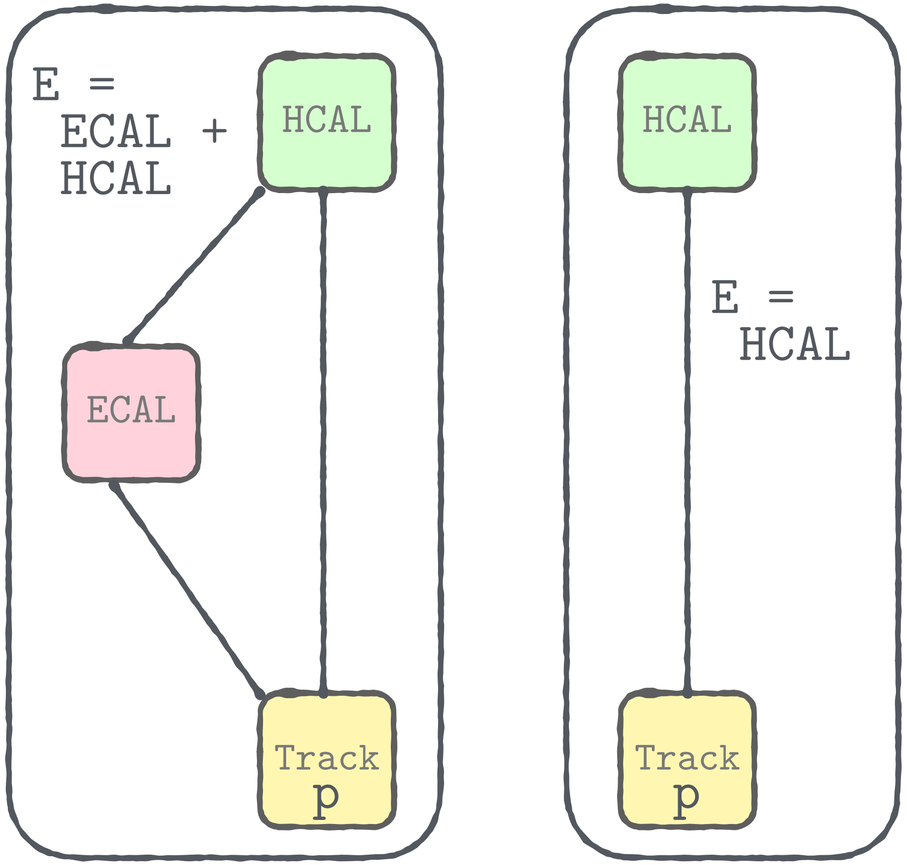

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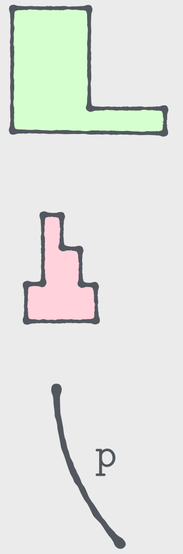

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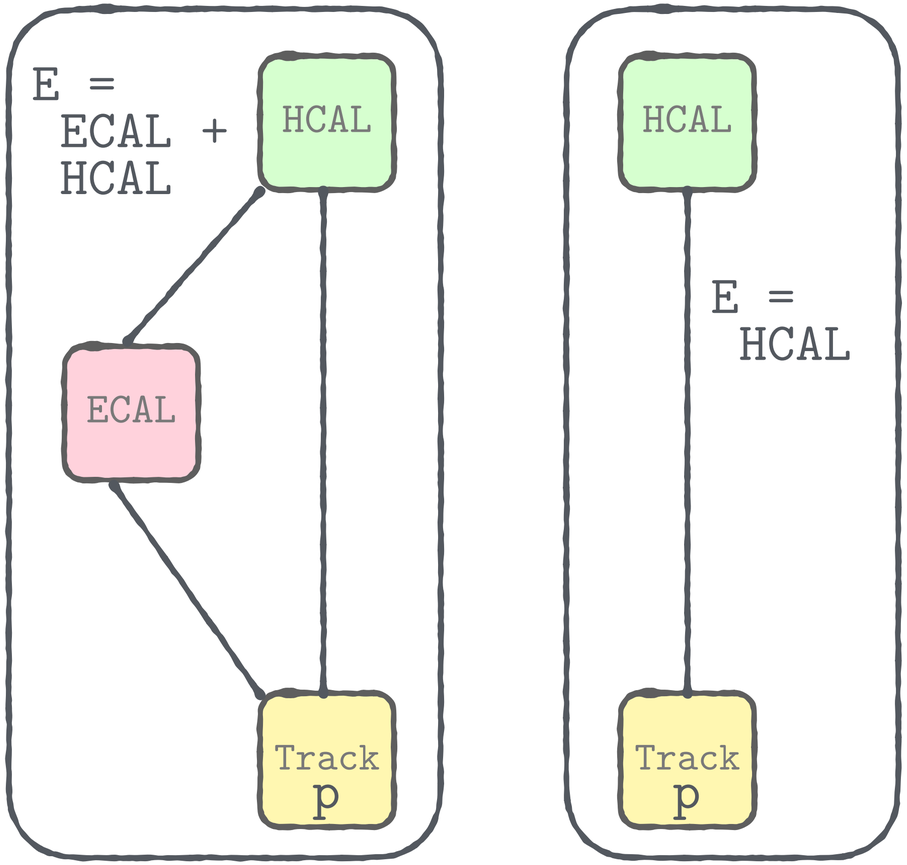

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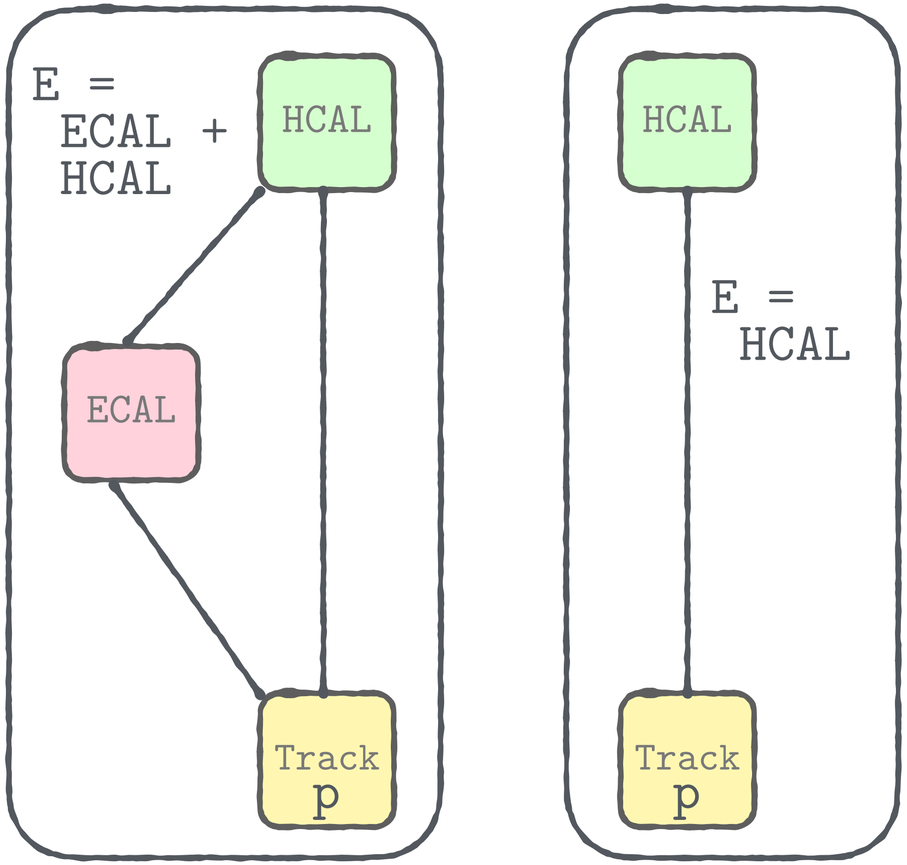

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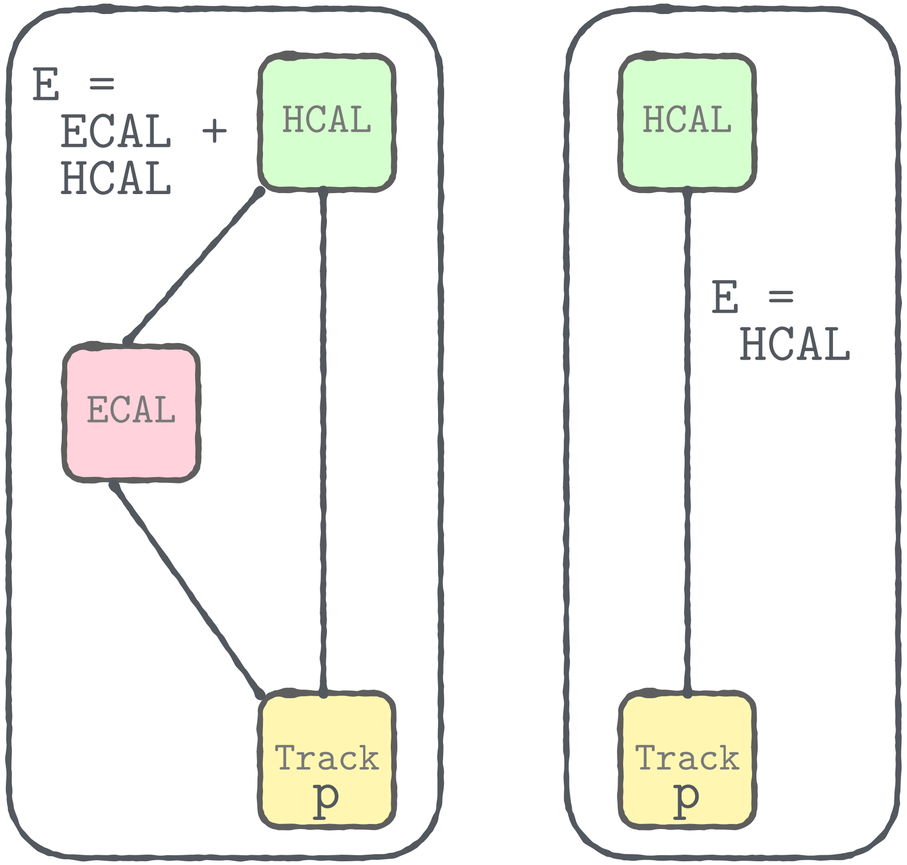

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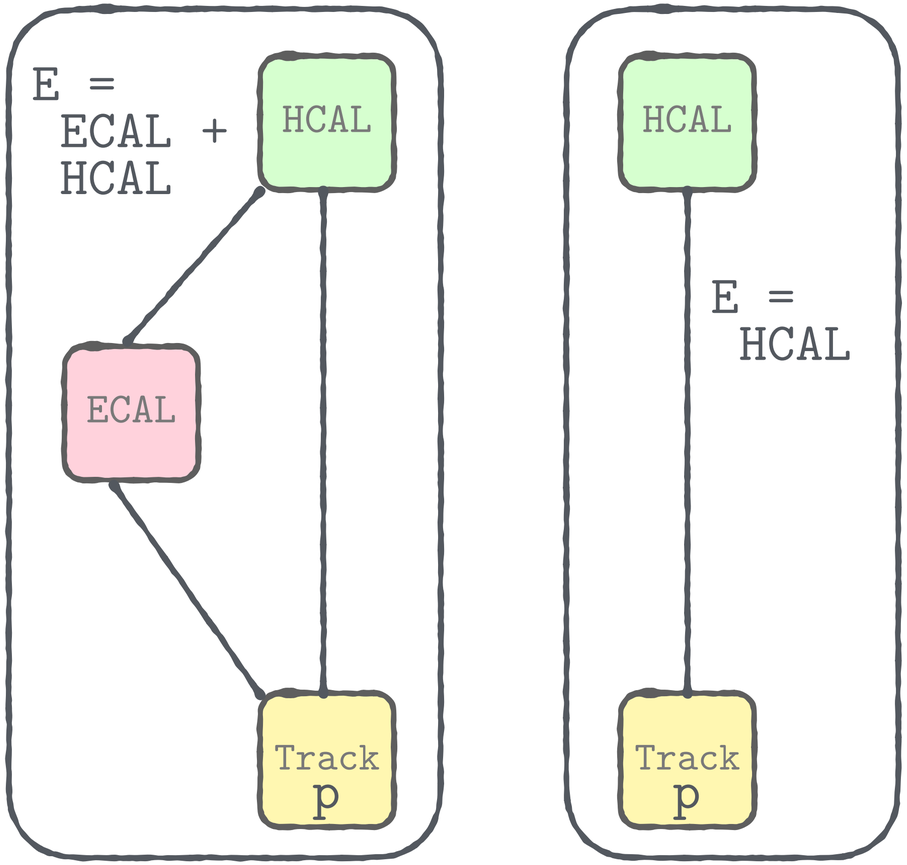

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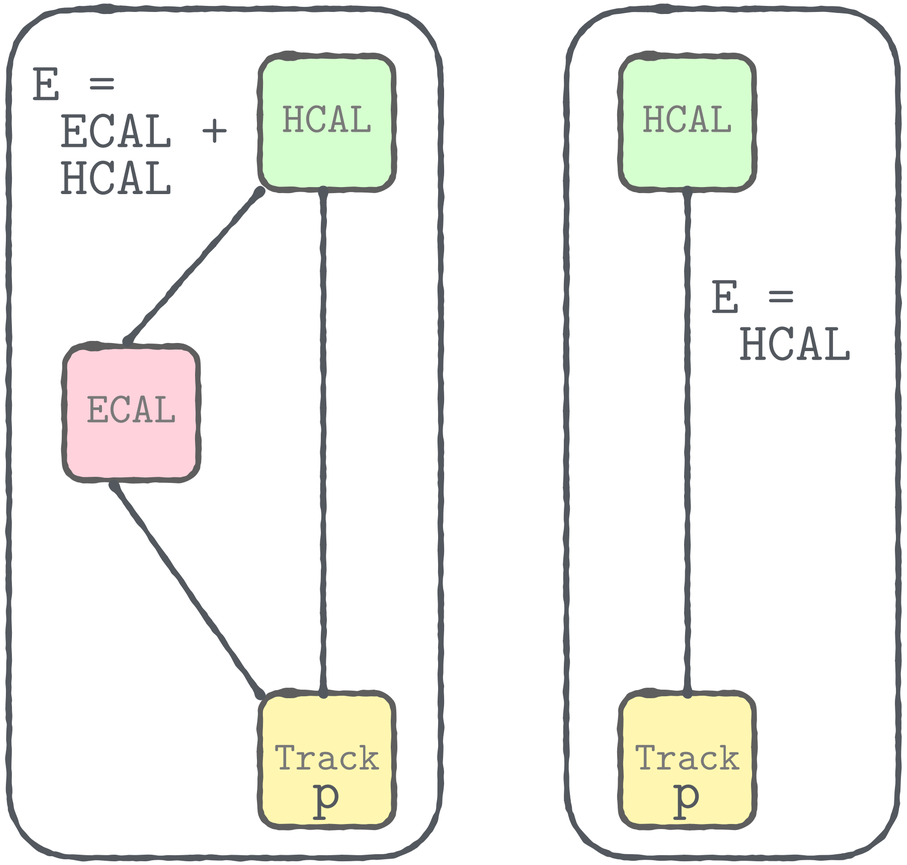

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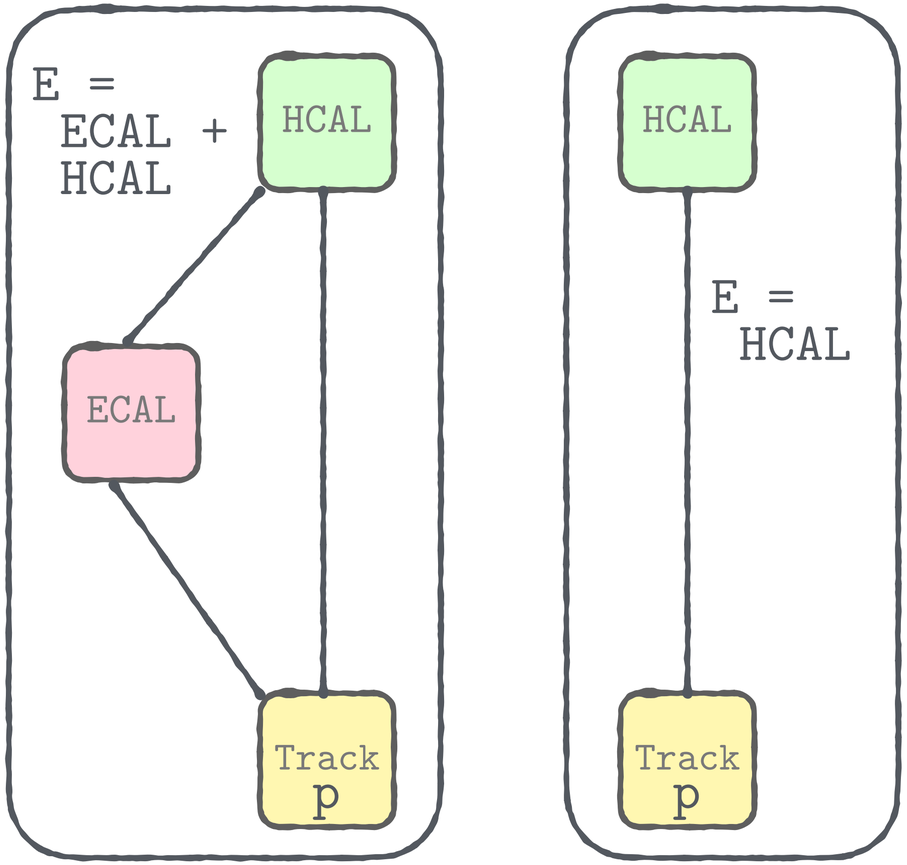
$\pi^+, \pi^-, \pi^0, K_L^0$

Simplified block (2nd step)

Find charged hadrons & merged photons / neutral hadrons



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- Sum
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If p an

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

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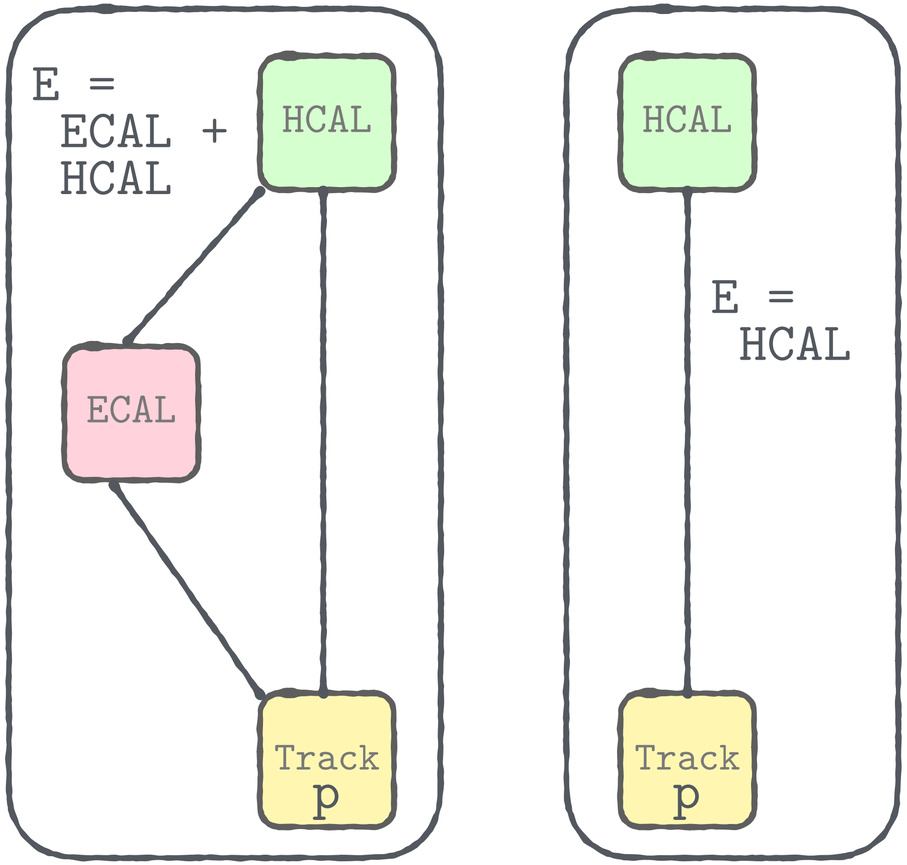

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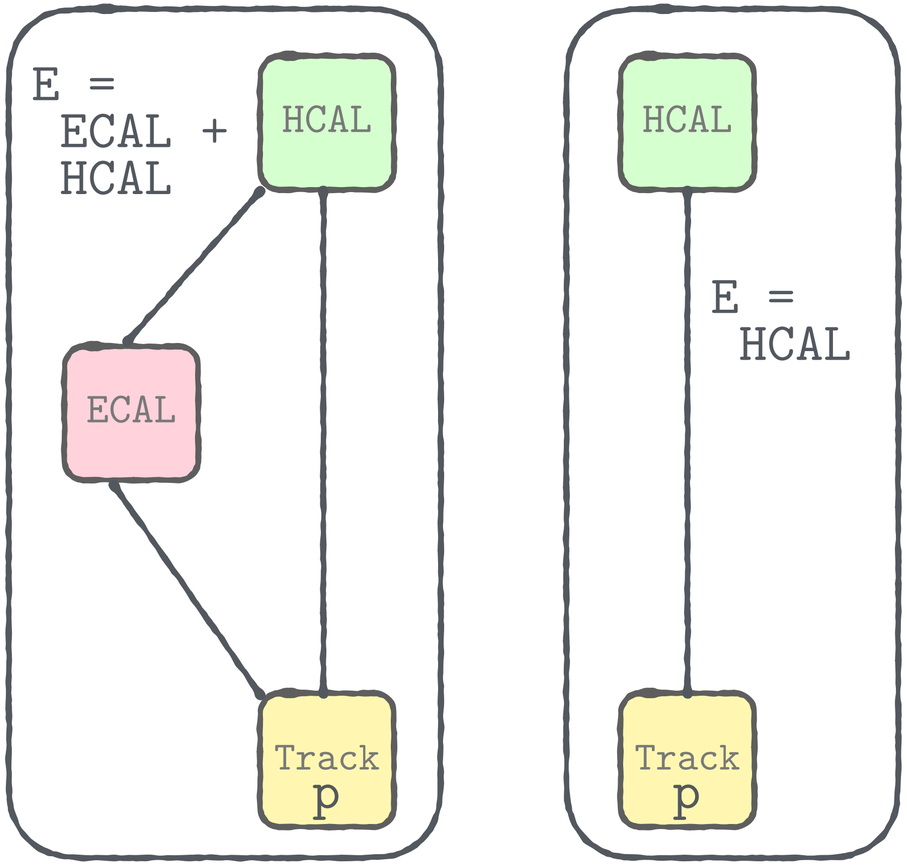

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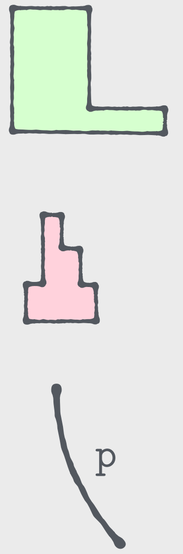

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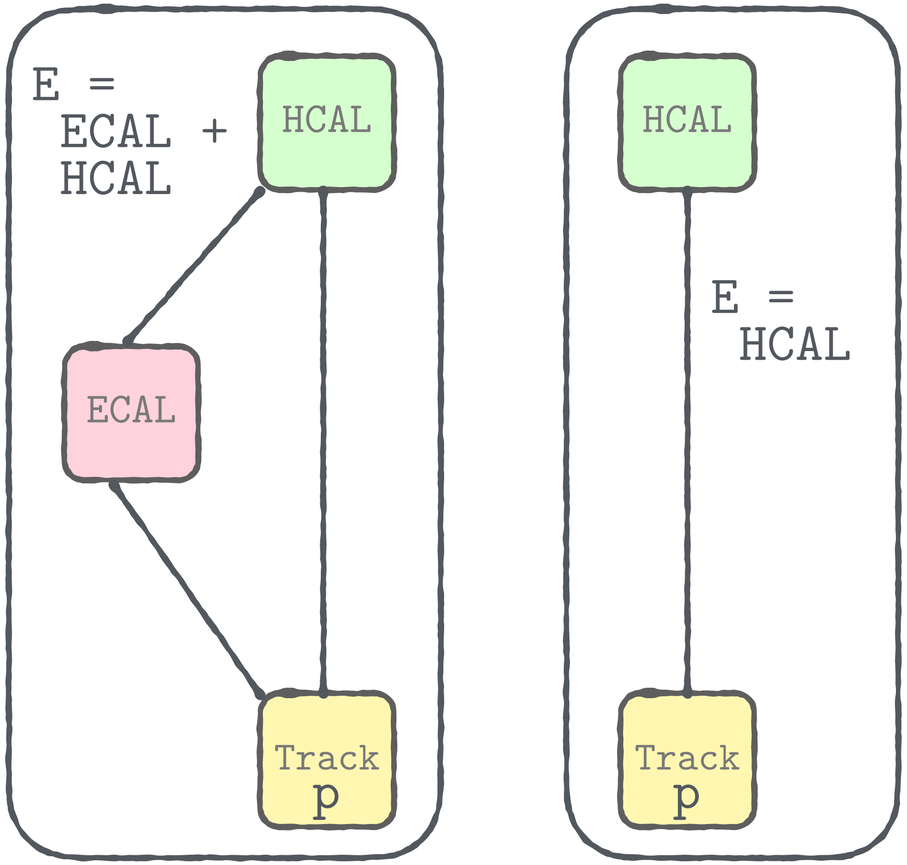

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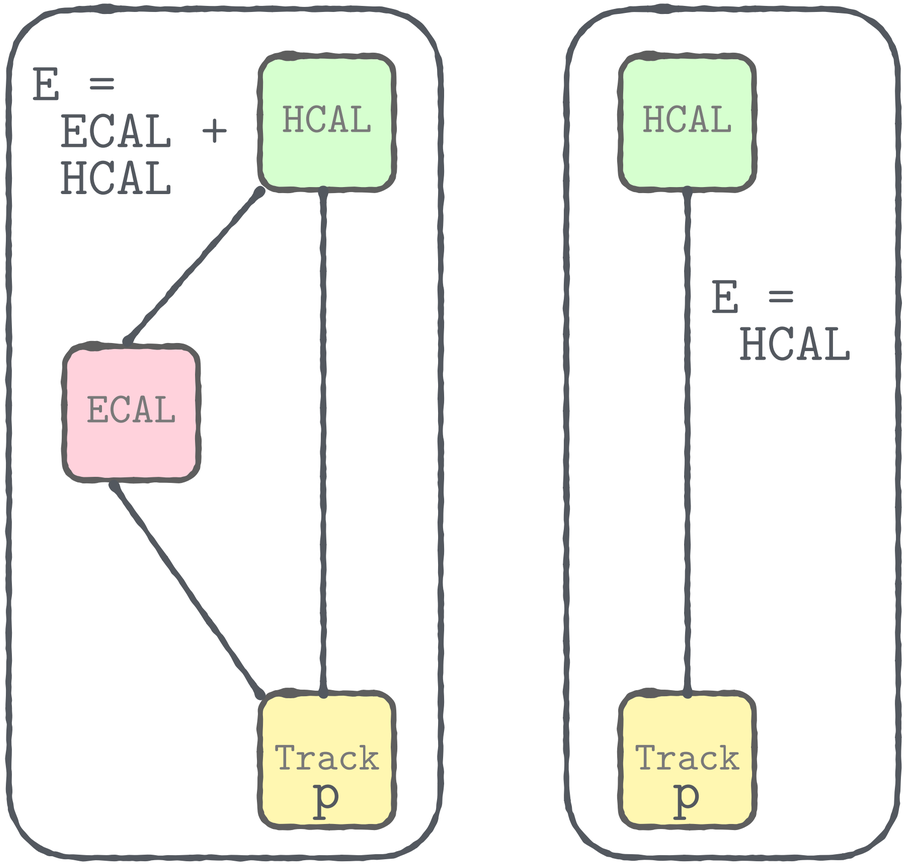

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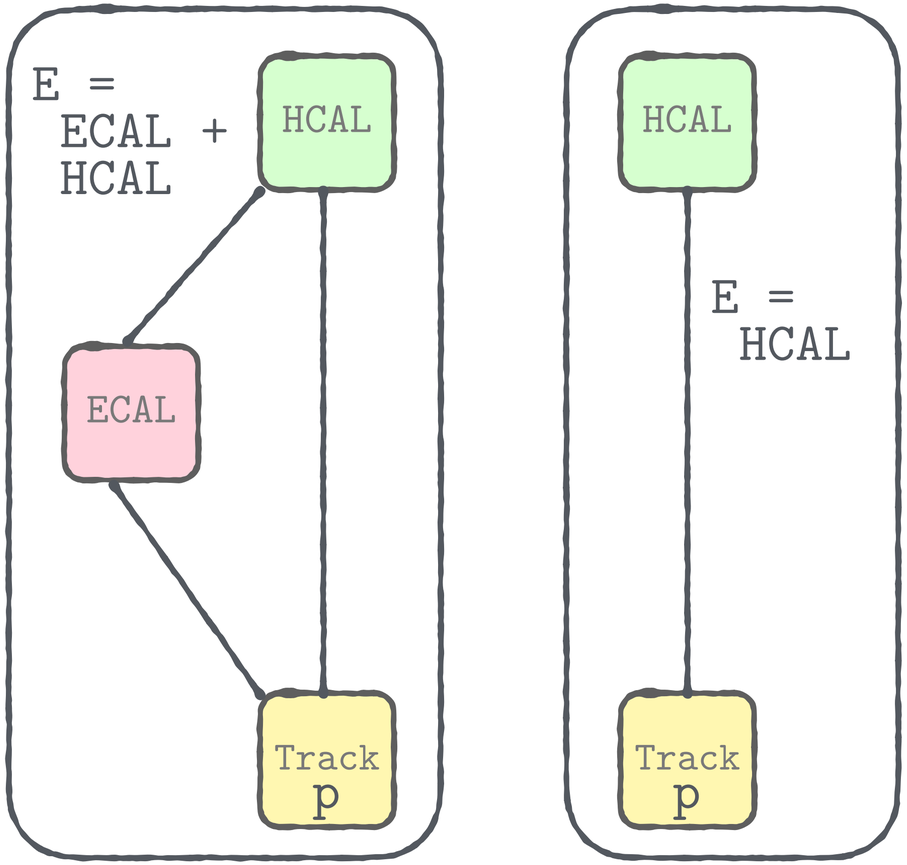

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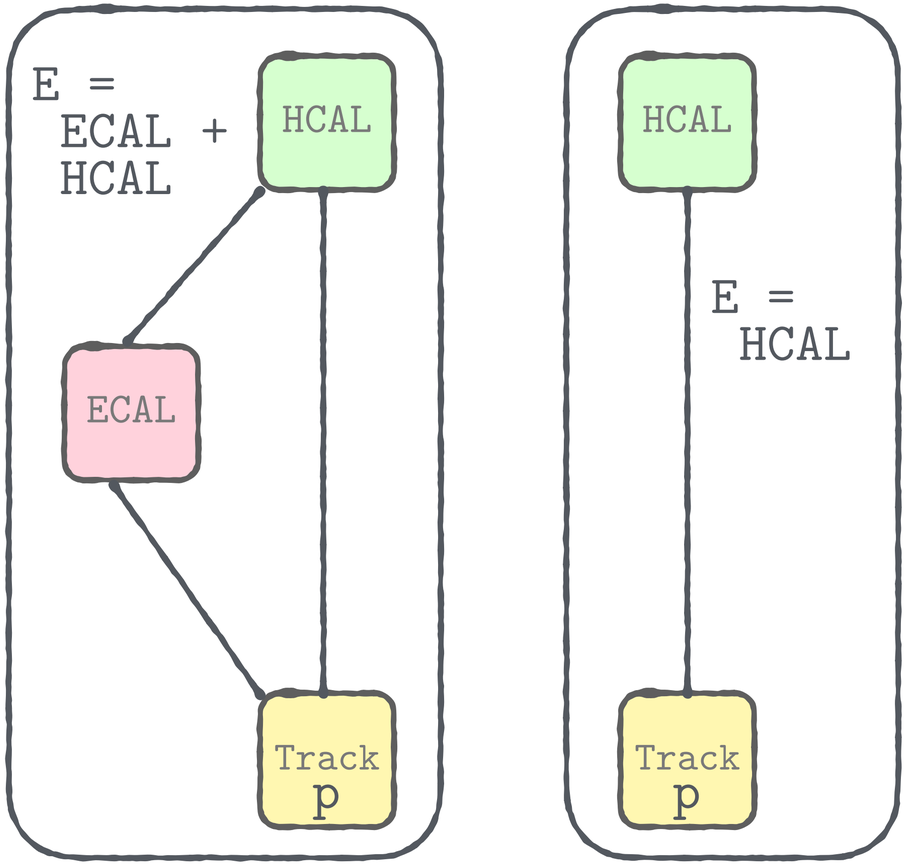

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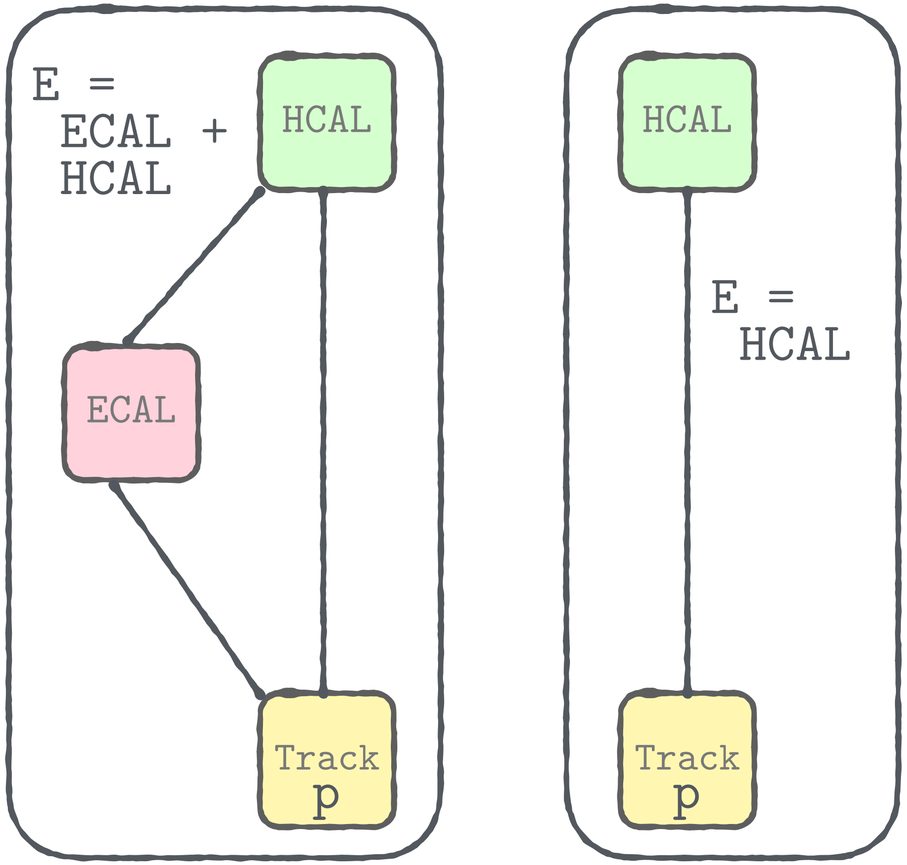

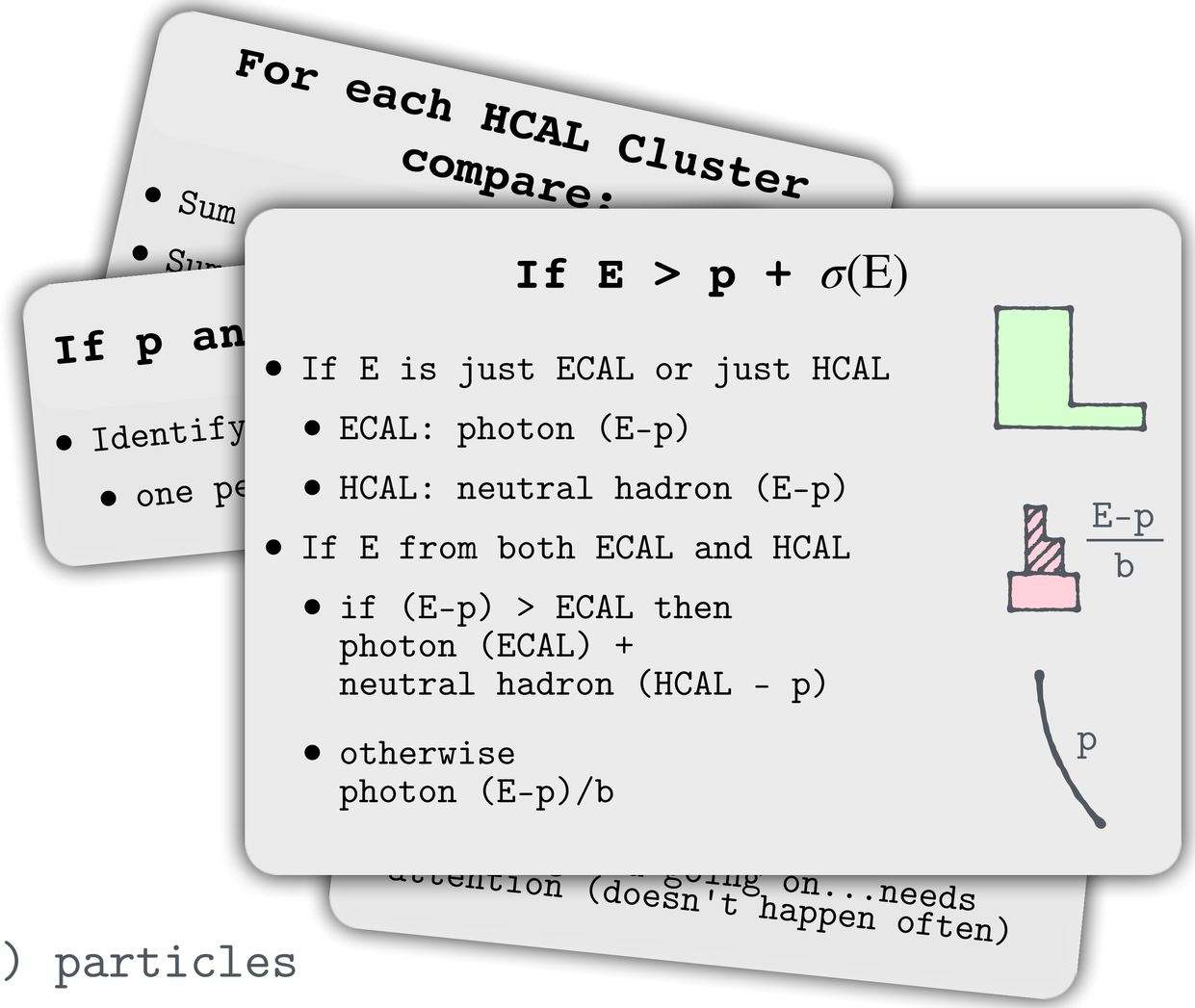

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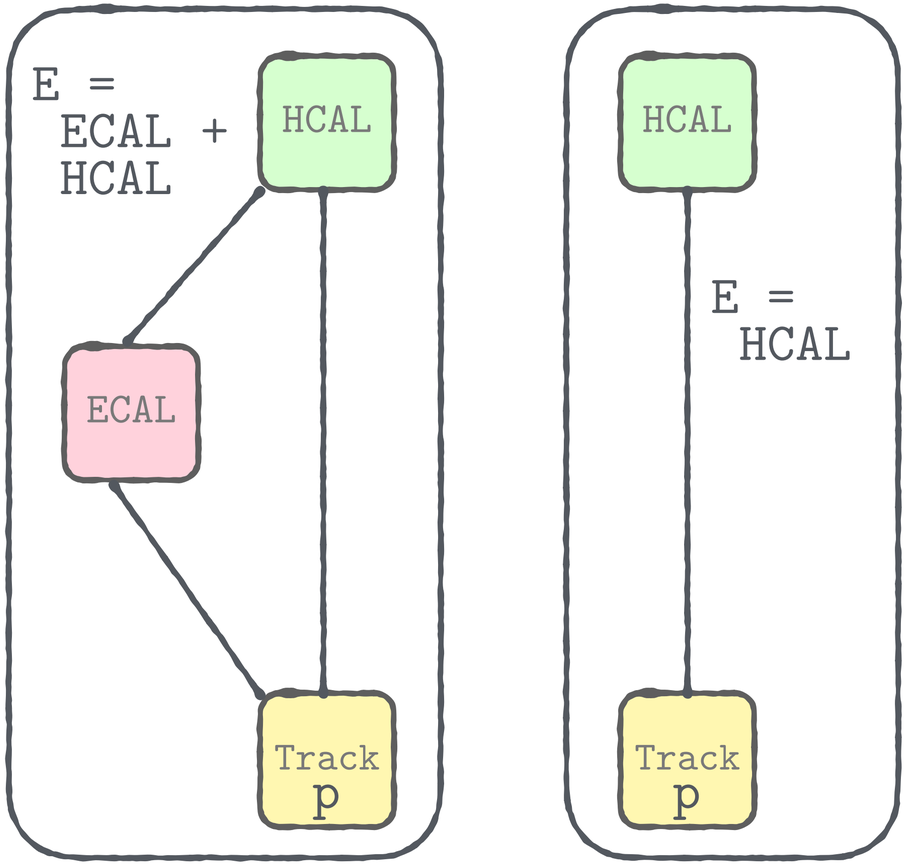

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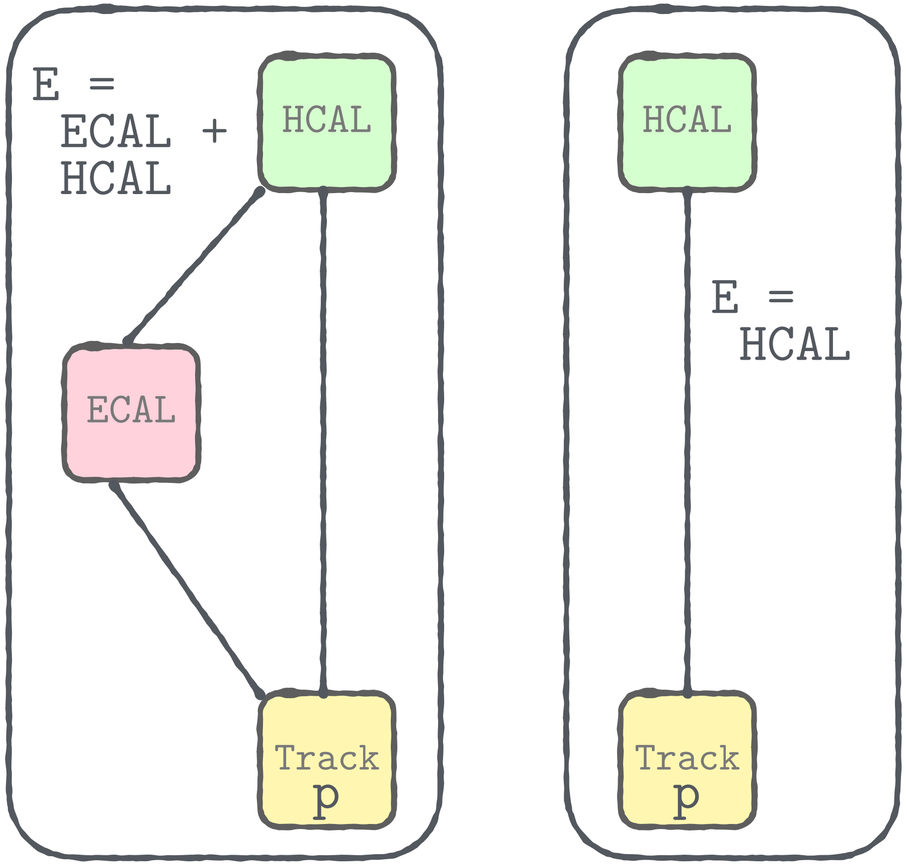

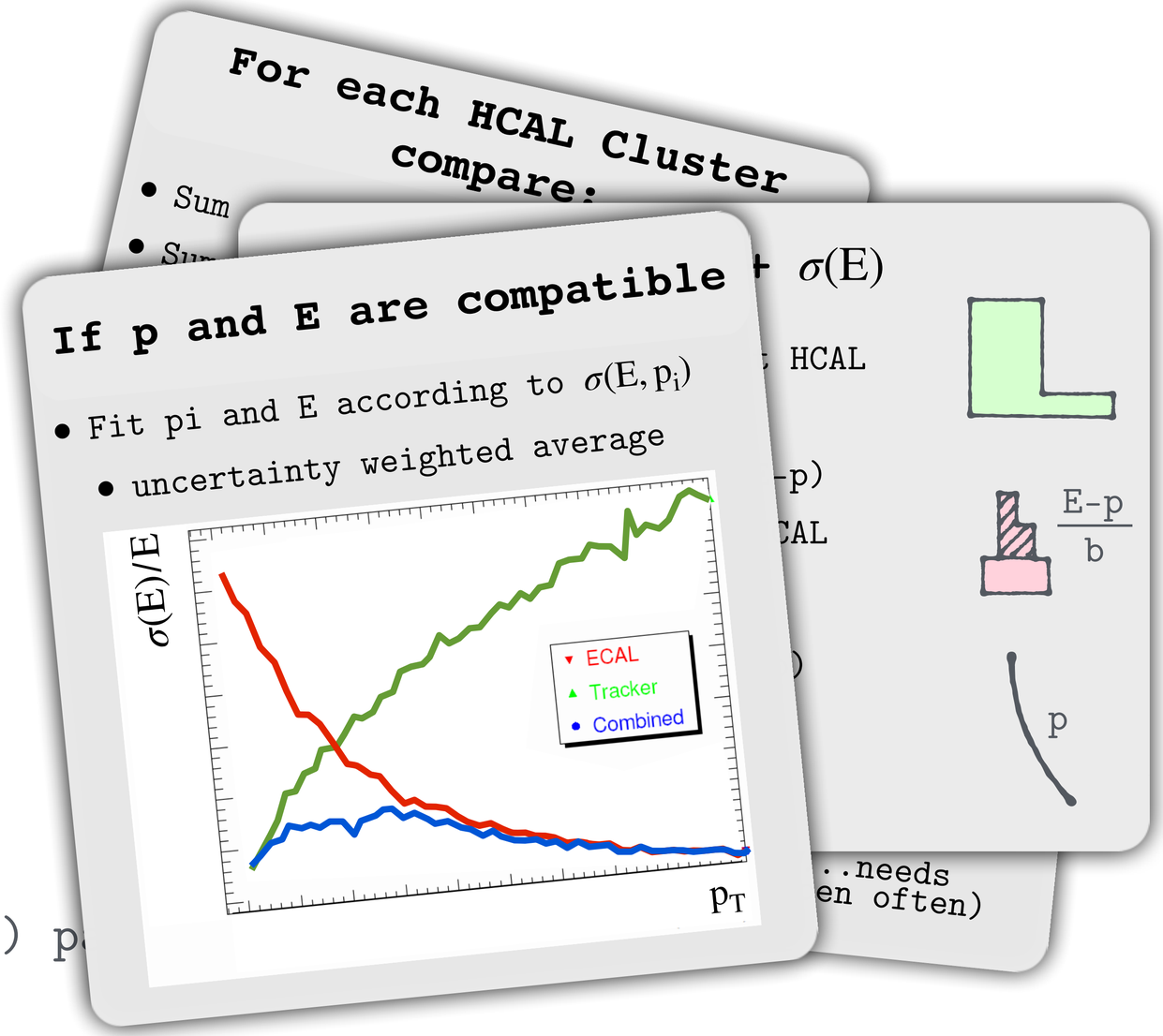

List of reconstructed (candidate) p

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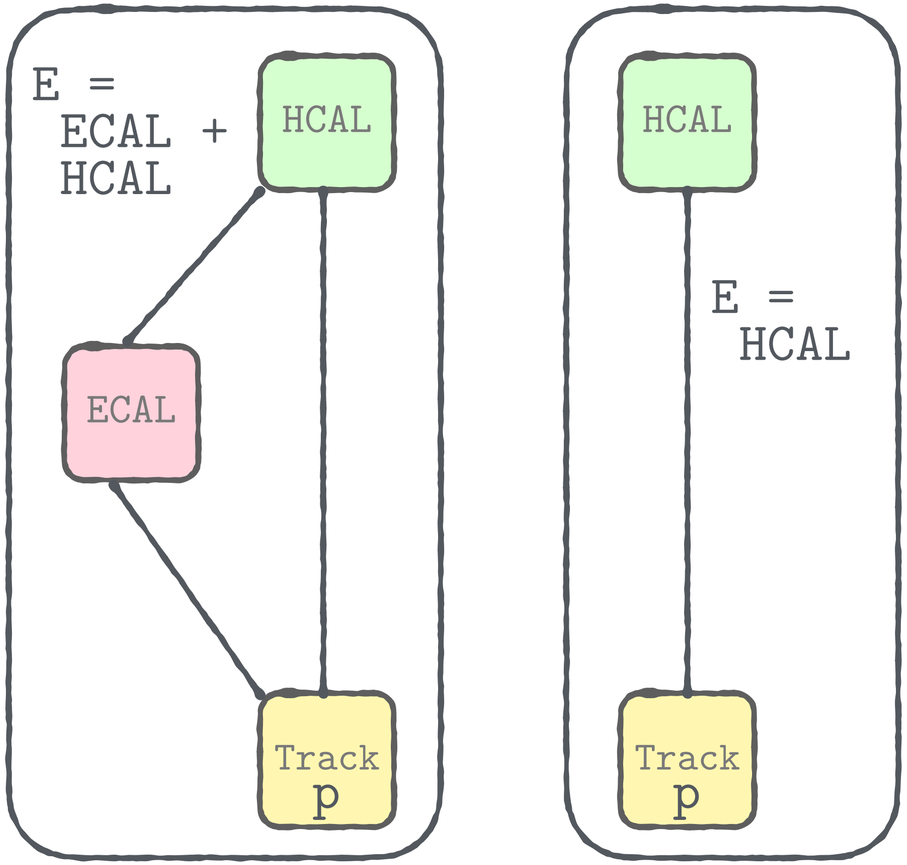

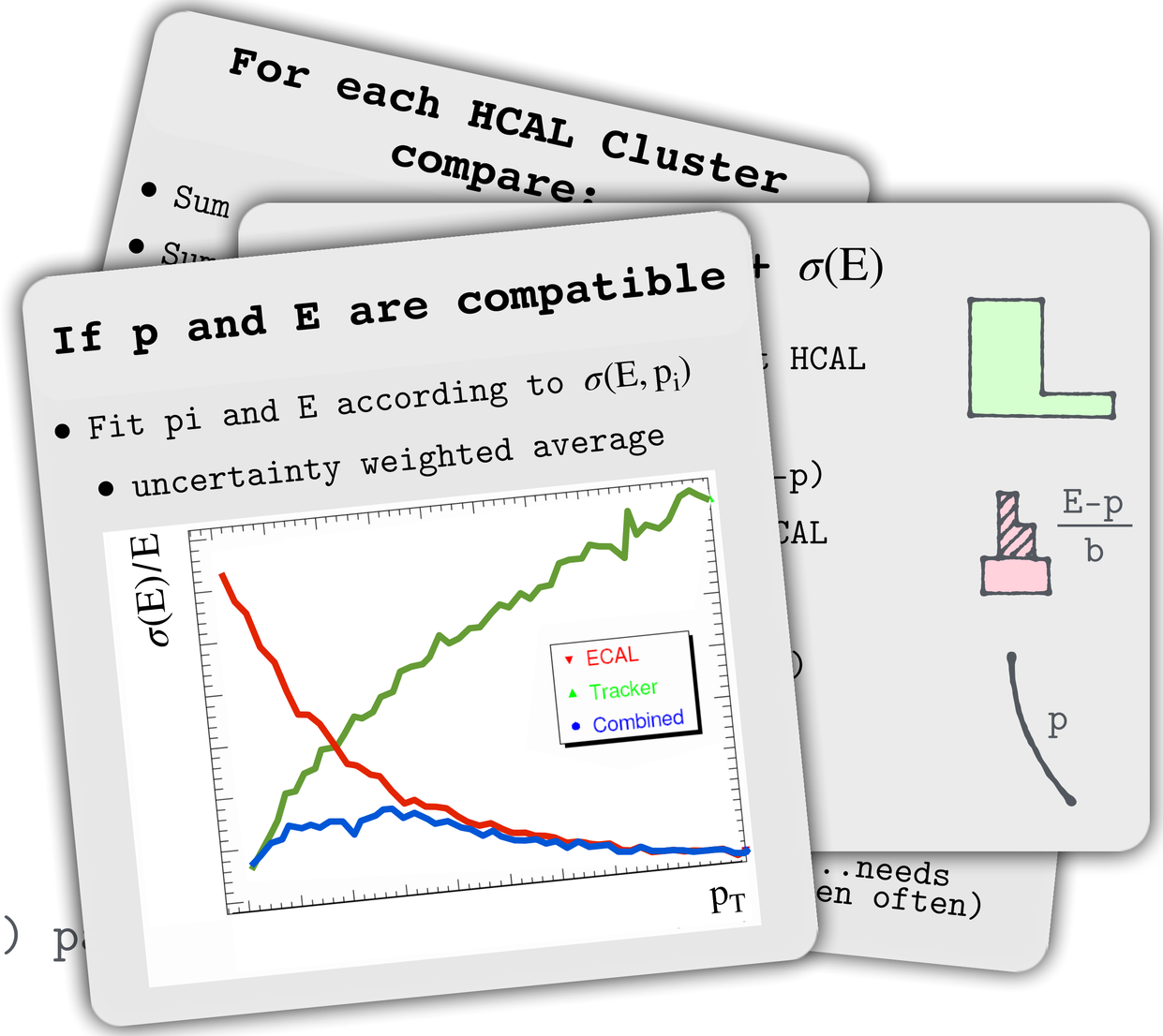

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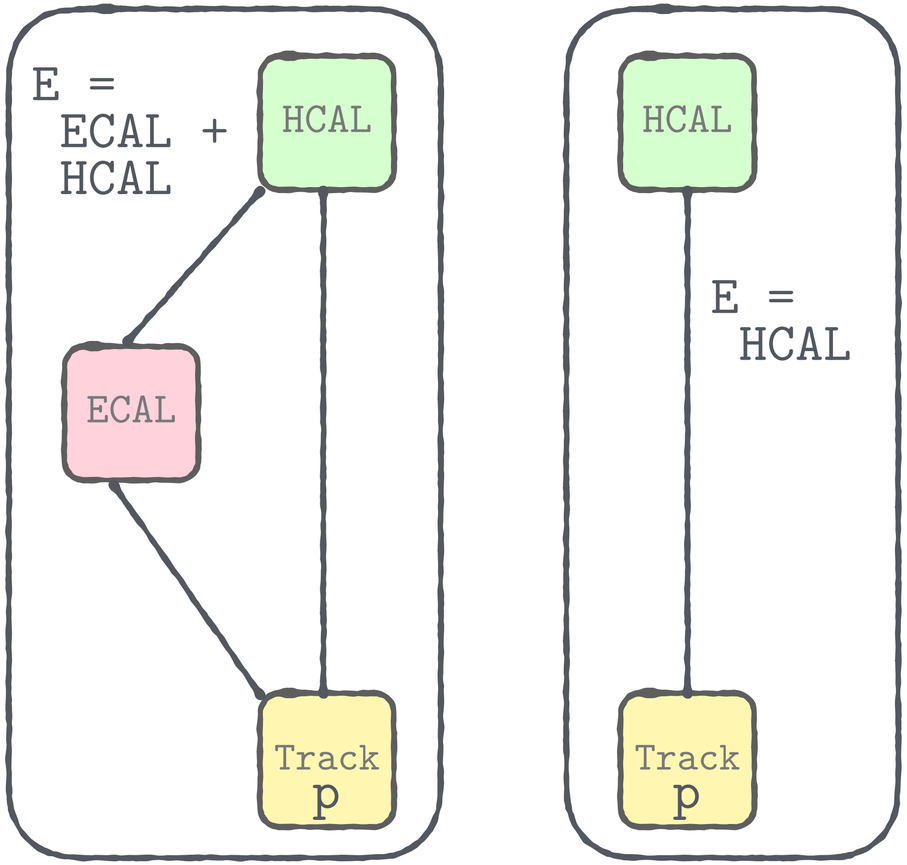

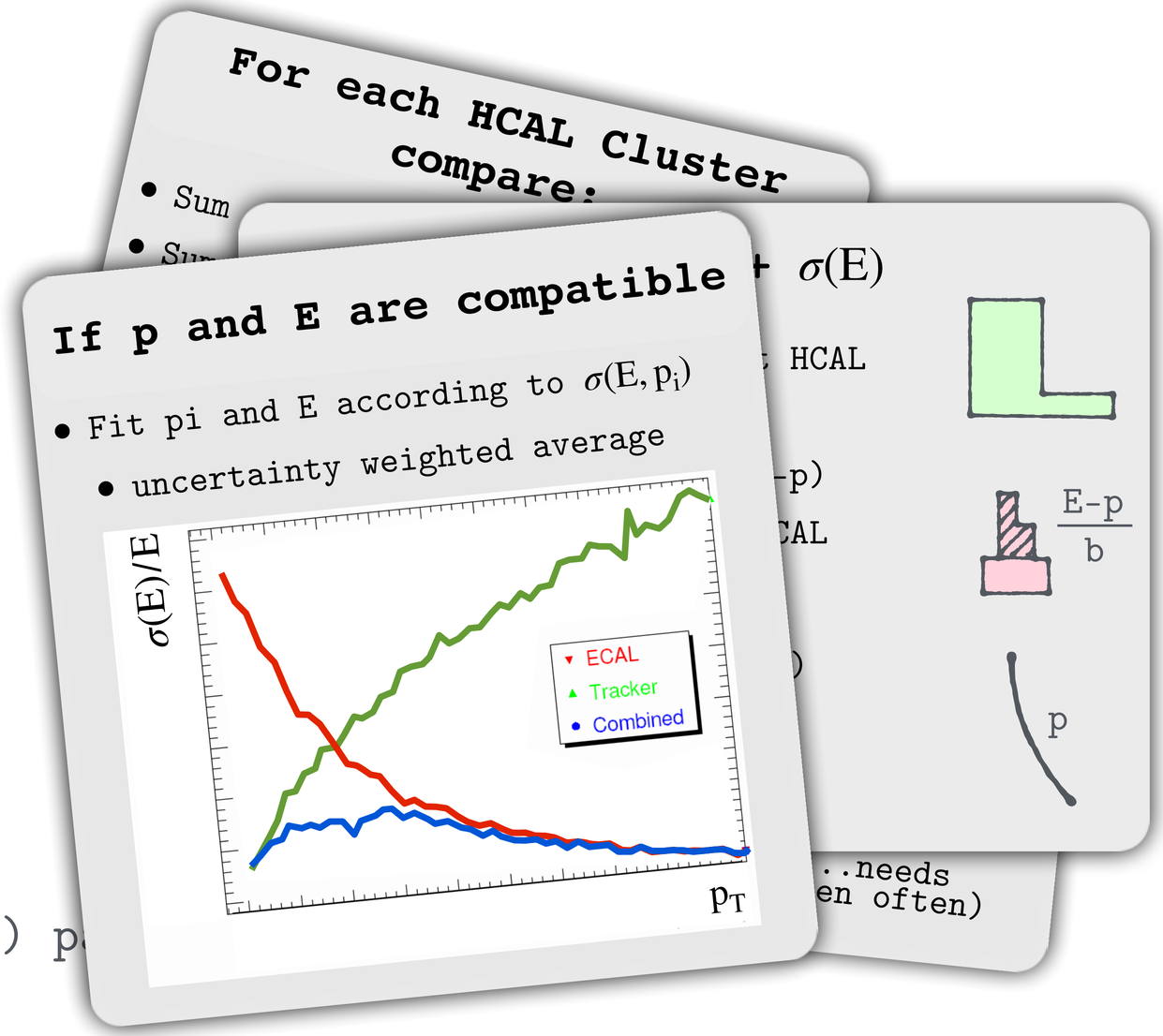

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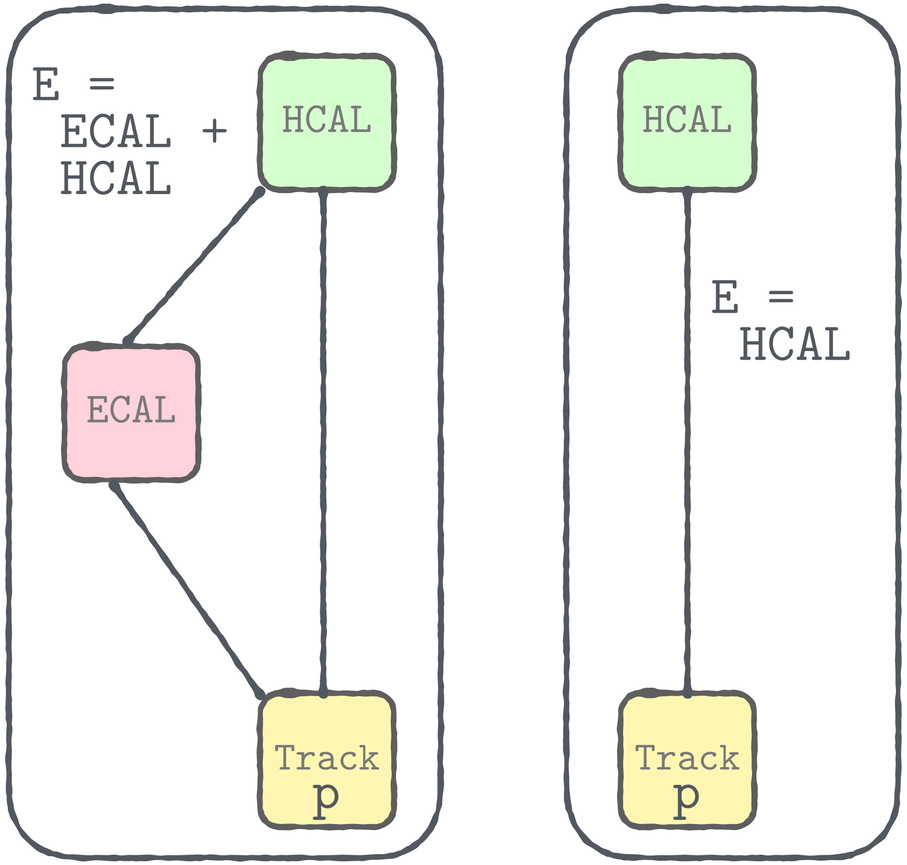

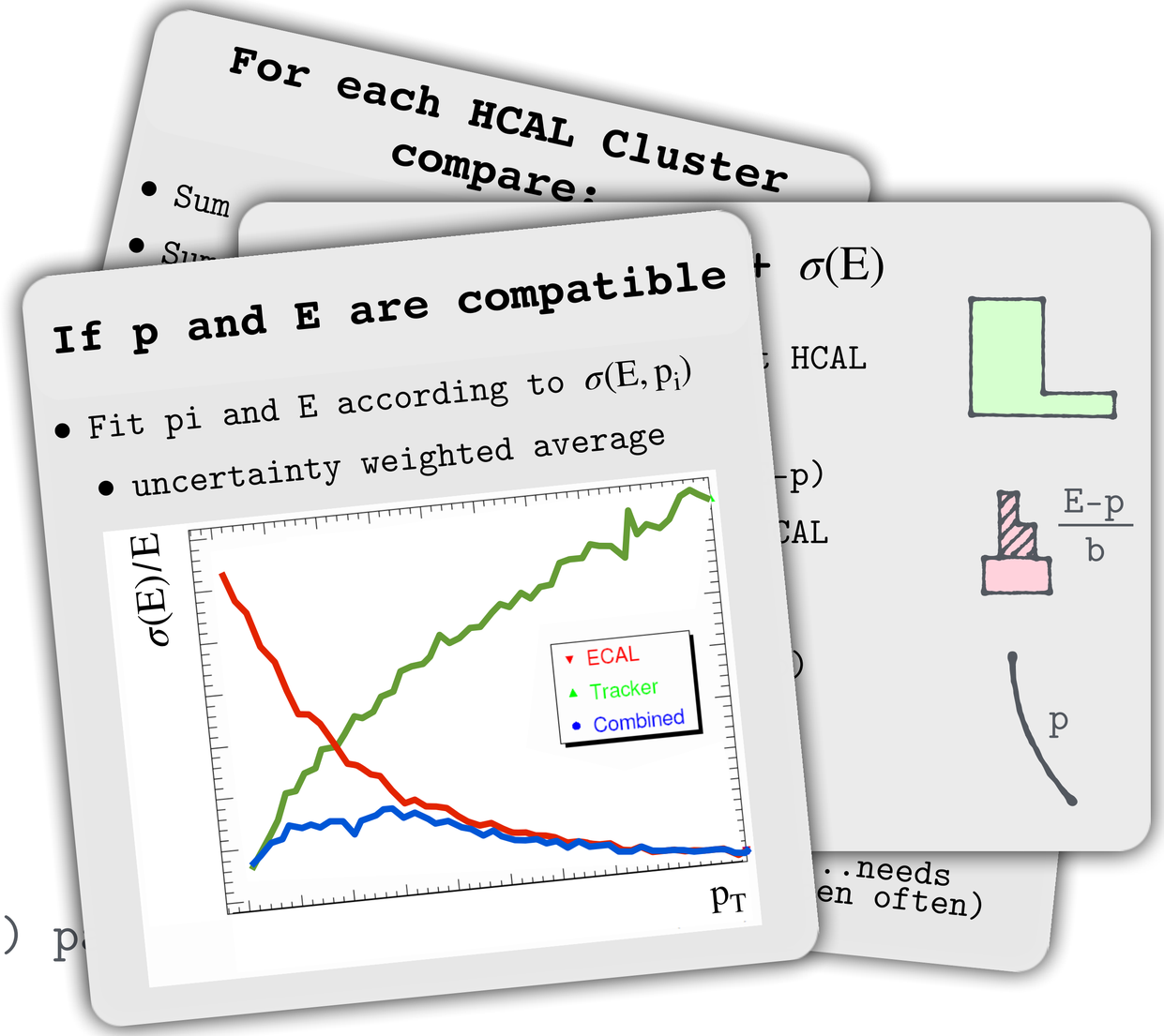

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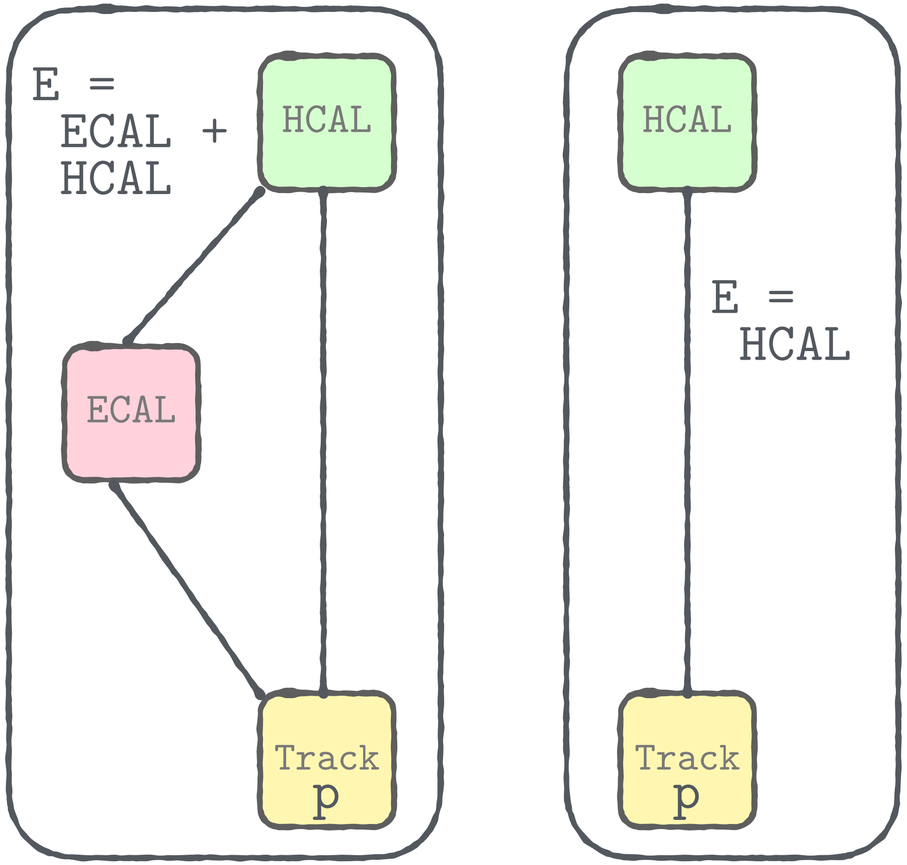

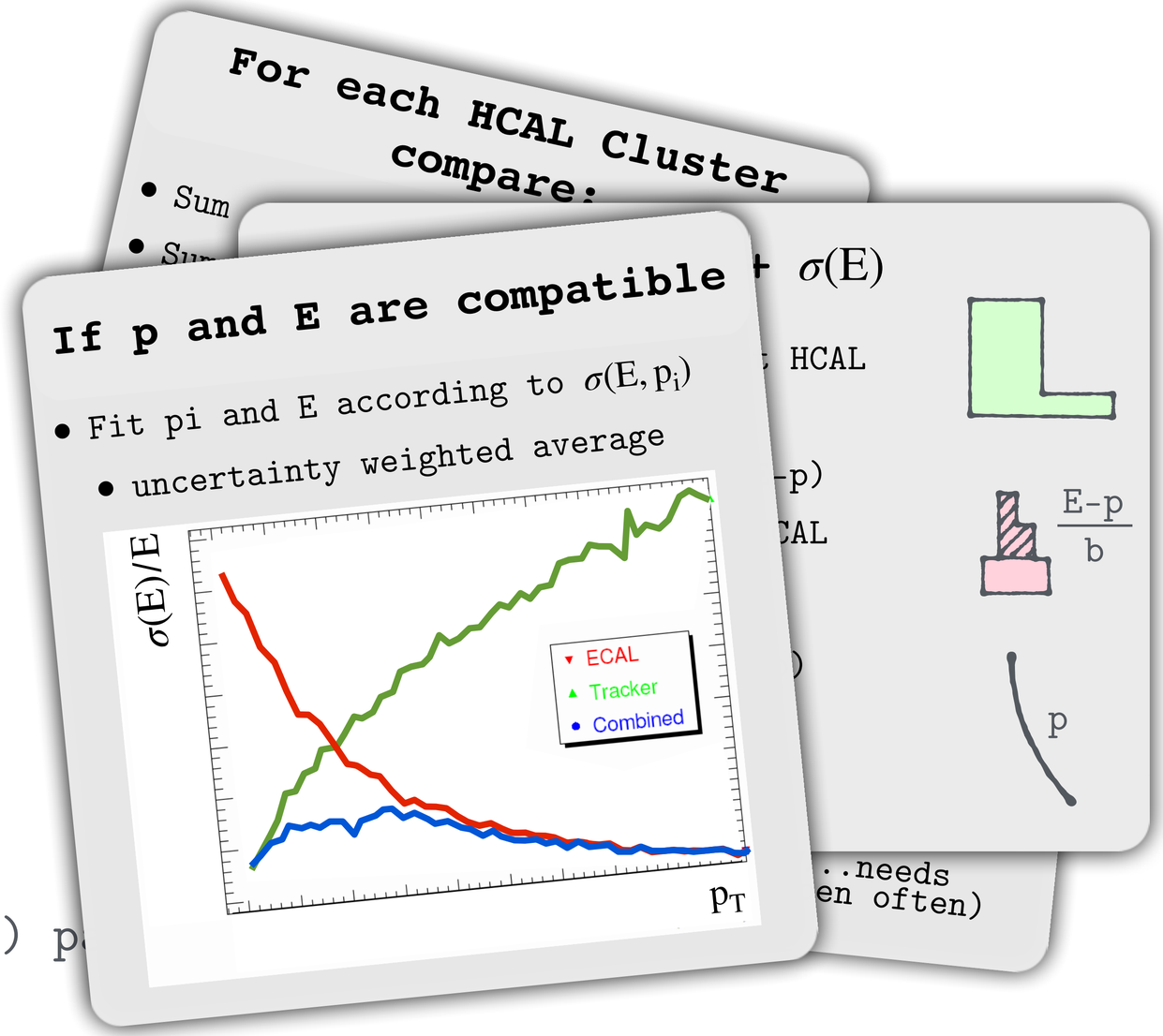

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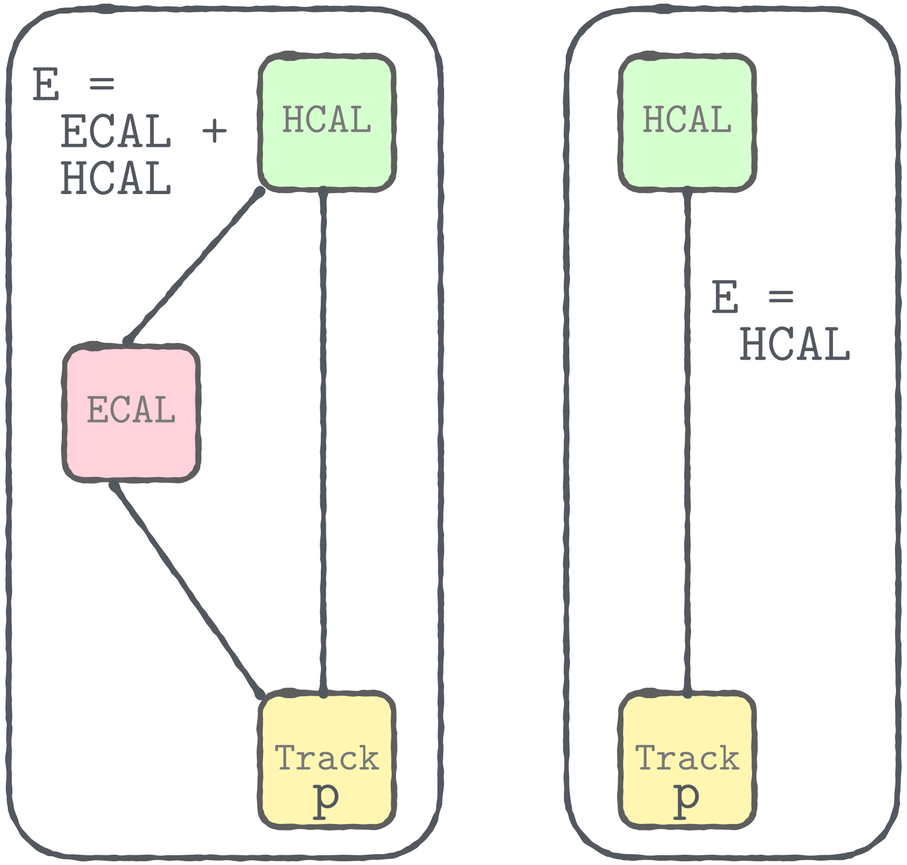

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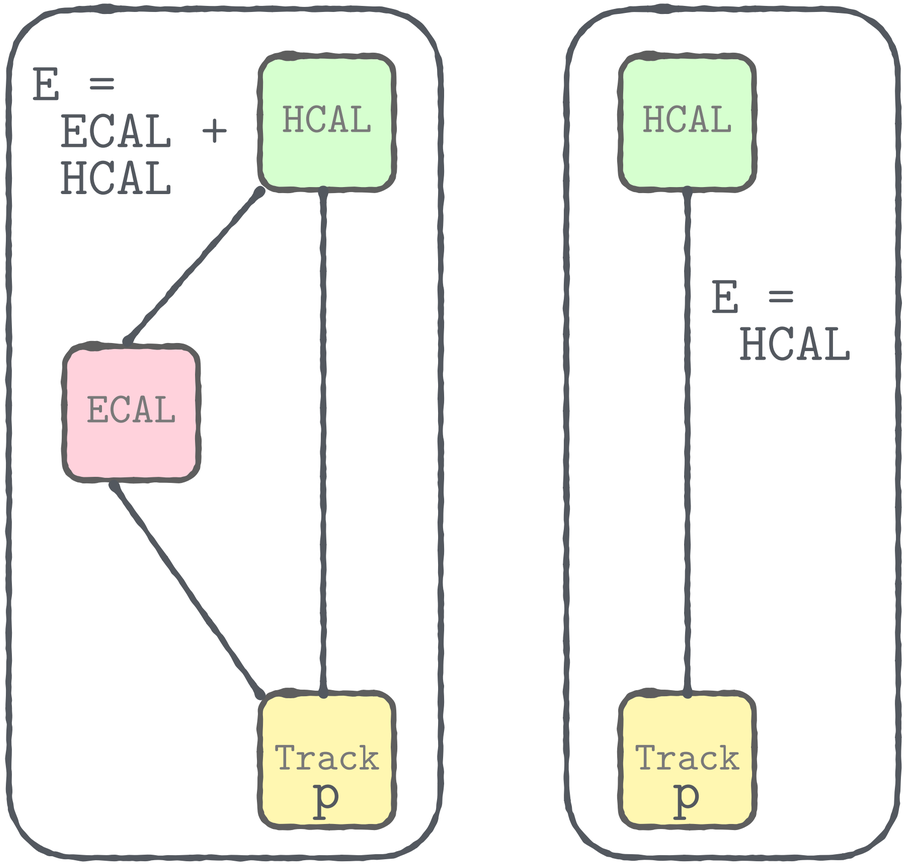

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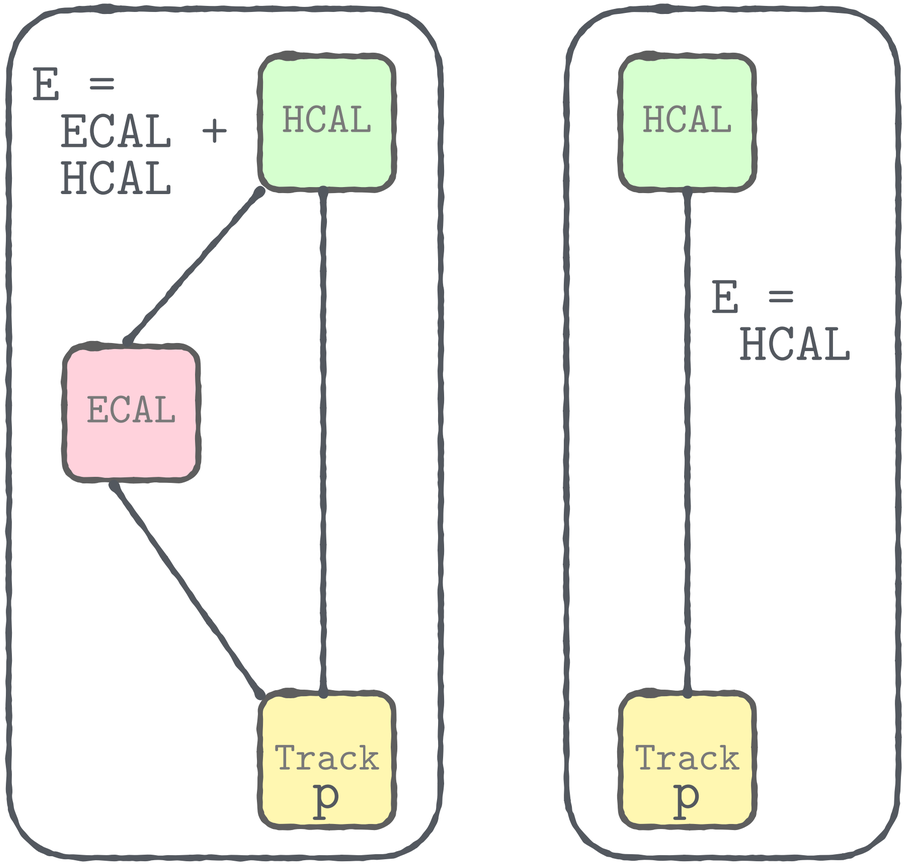

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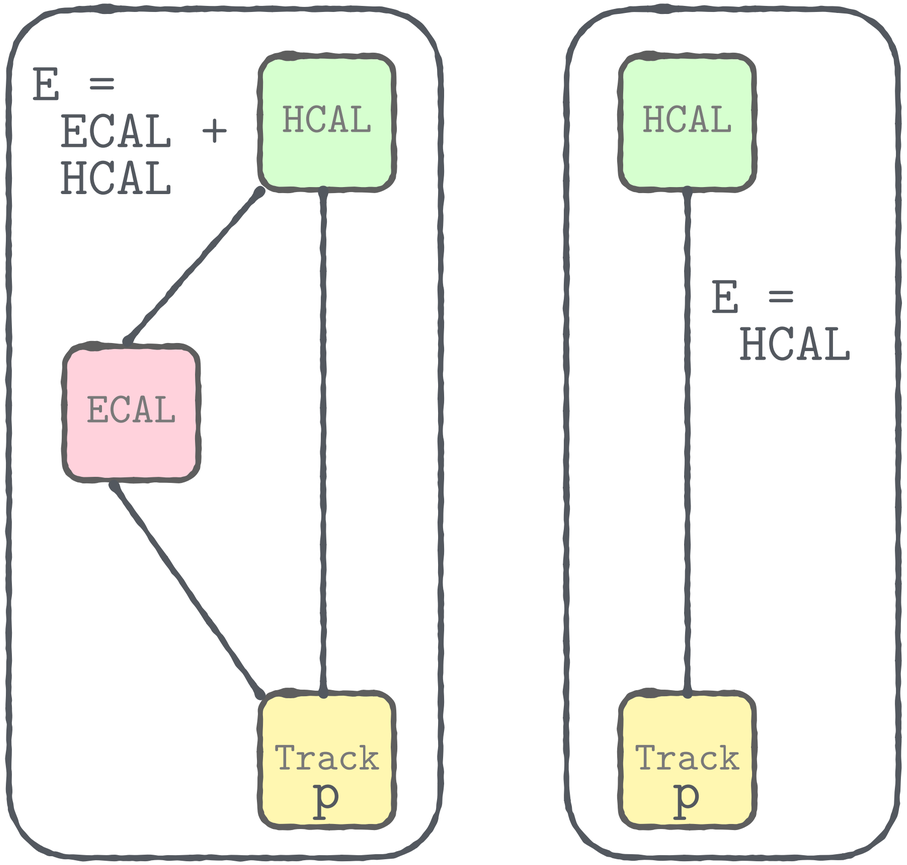

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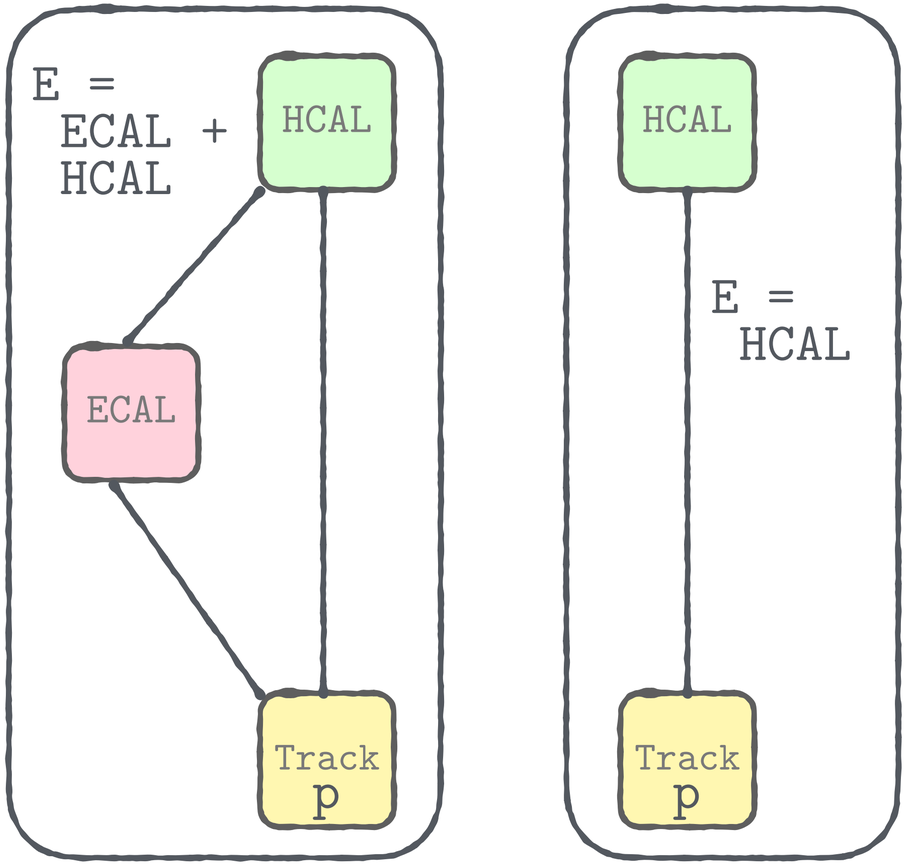

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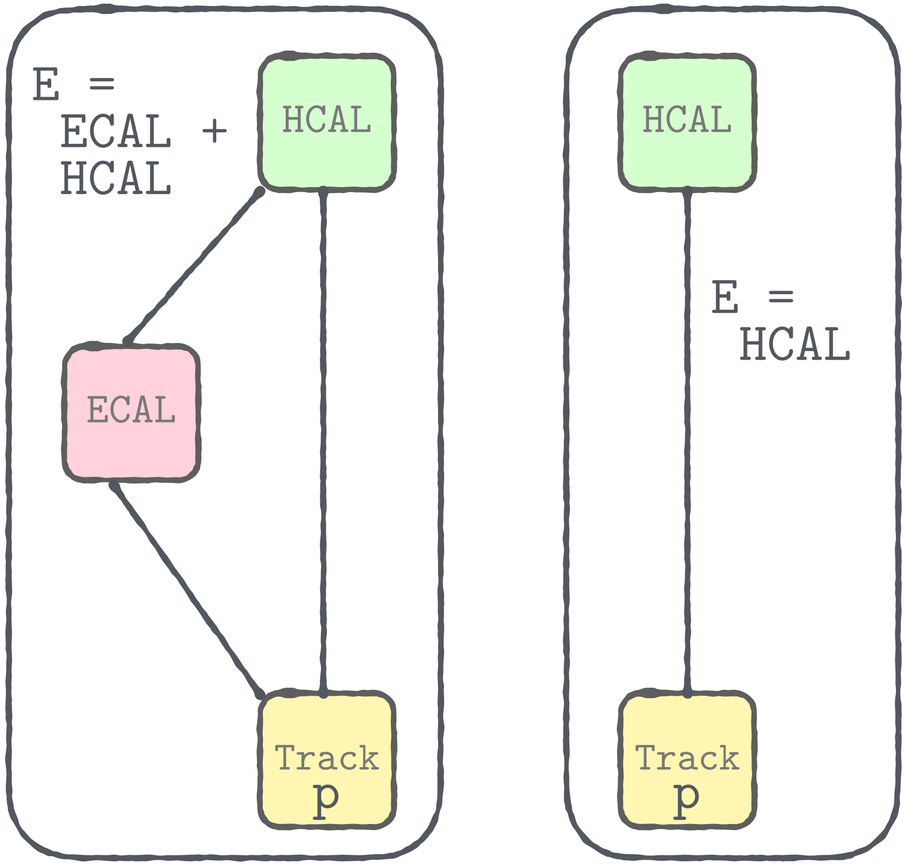

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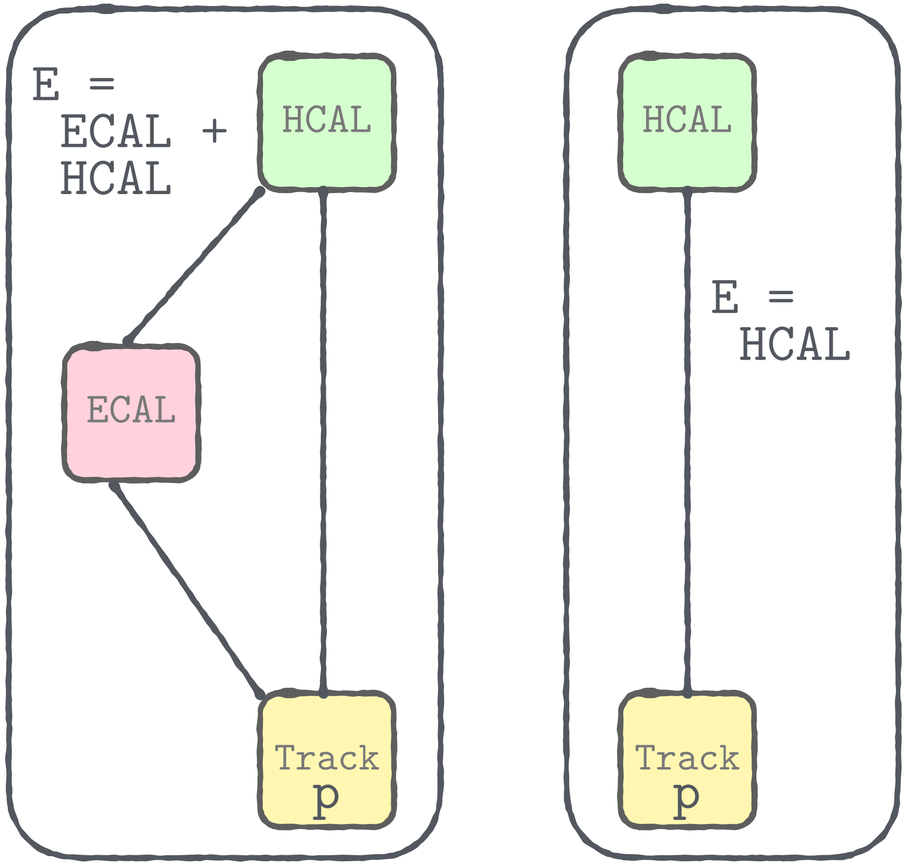

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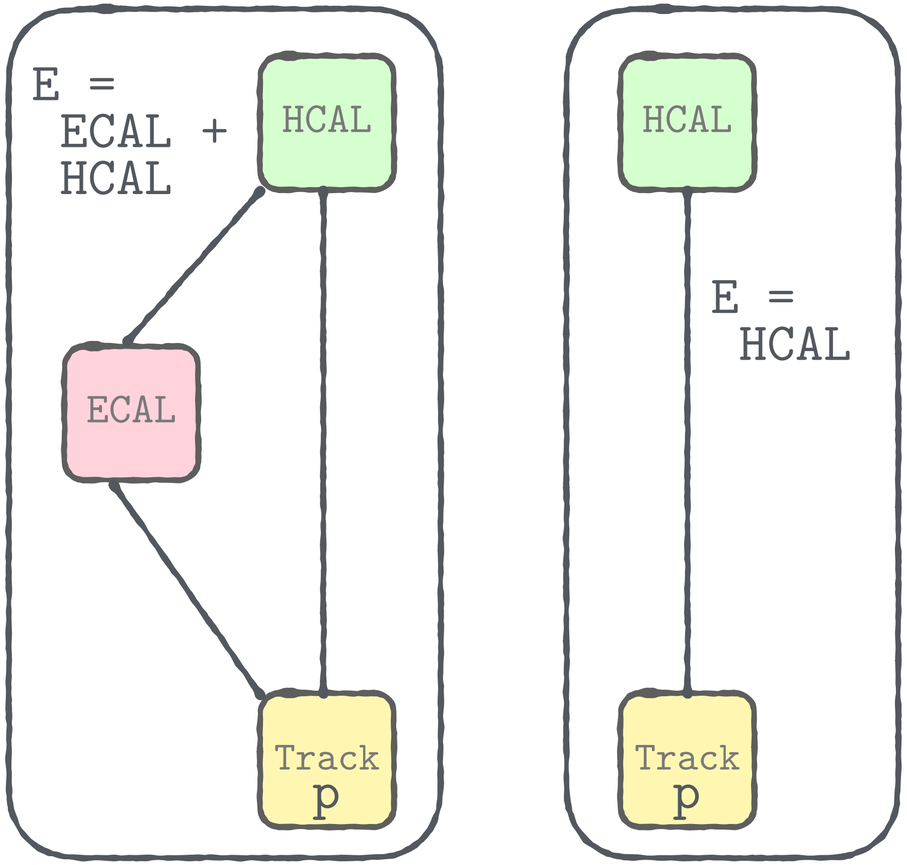

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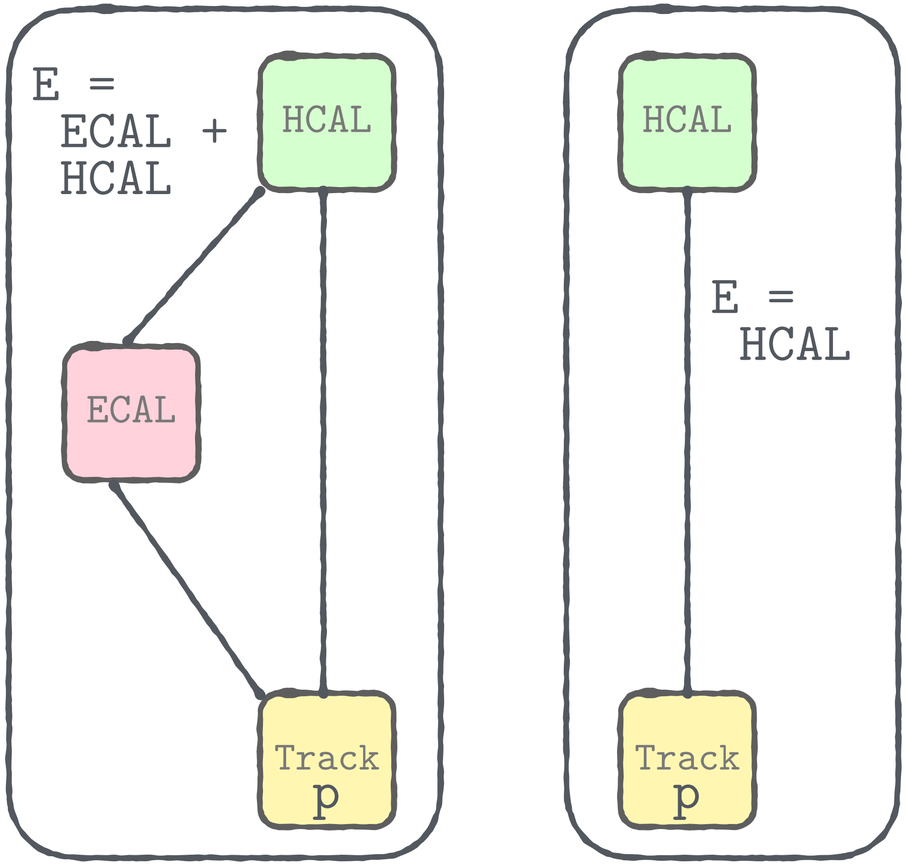

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  - Could underestimate ECAL deposits of neutral hadrons

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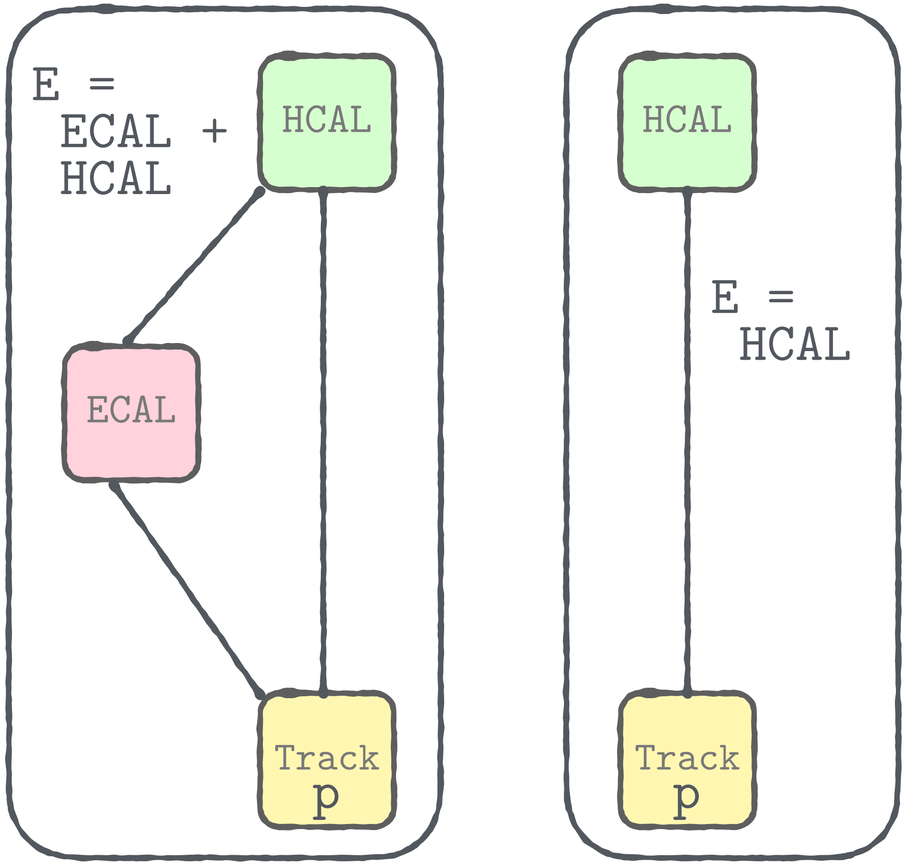

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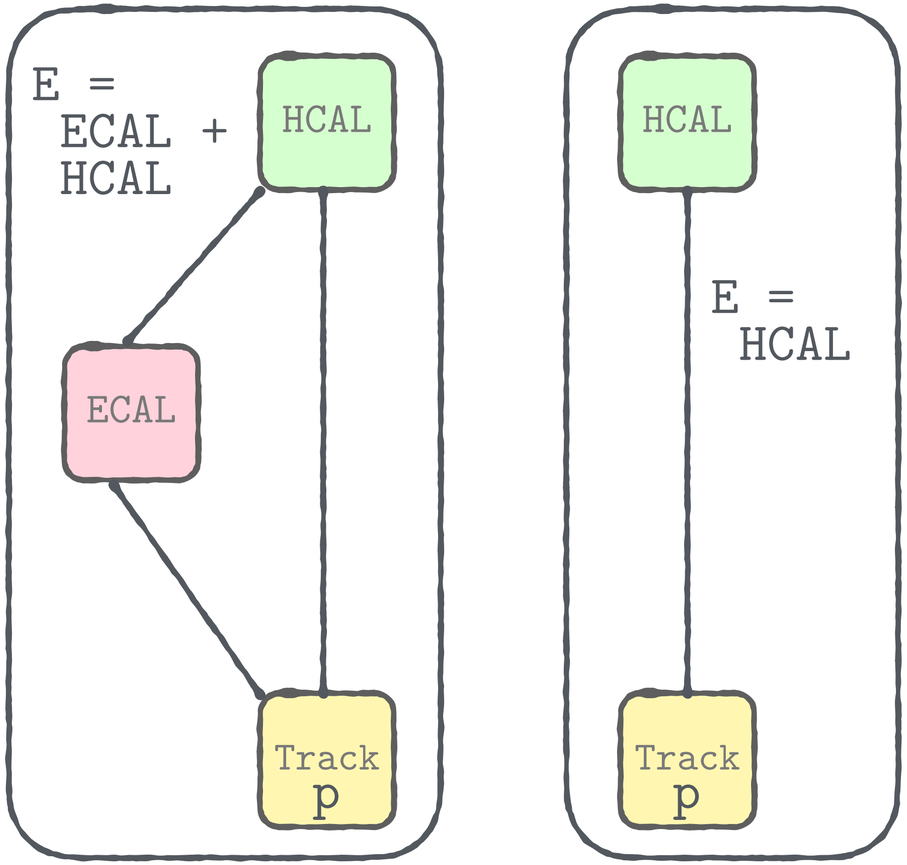

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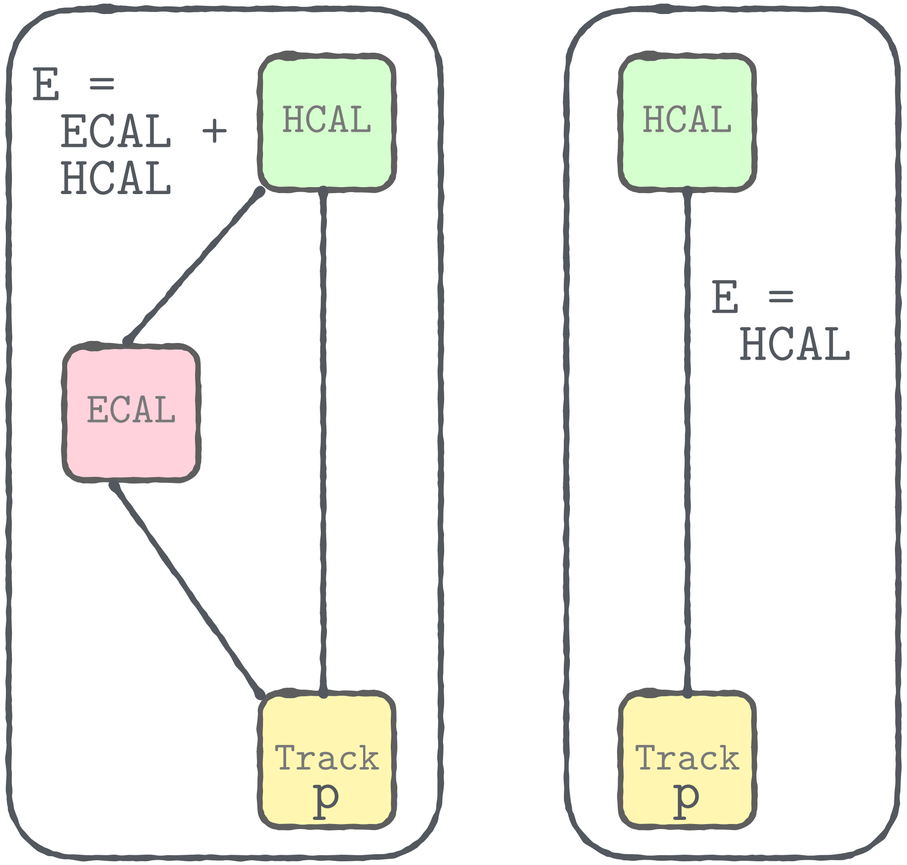
Four true particles:

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



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

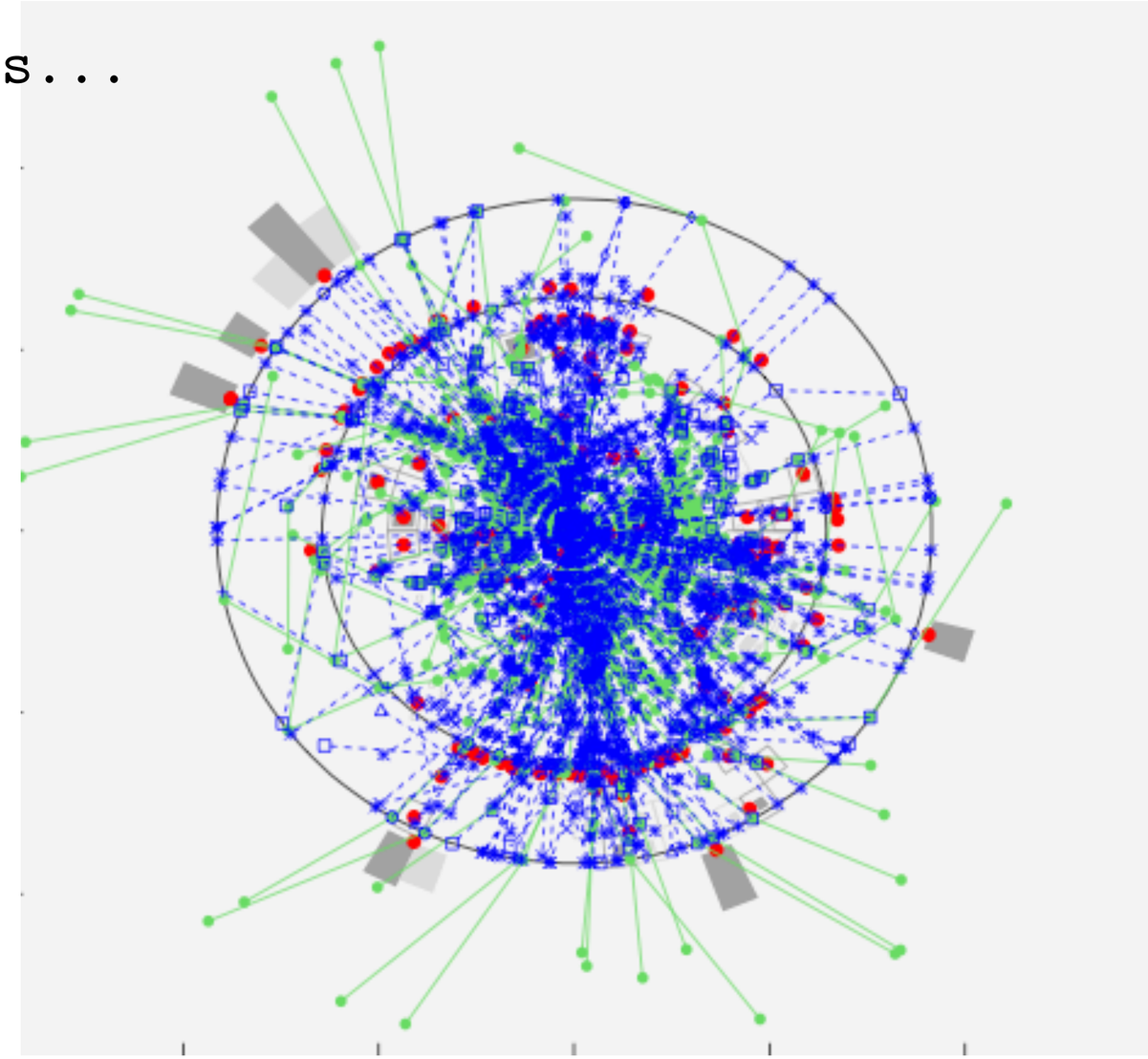
List of reconstructed (candidate) particles

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

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:



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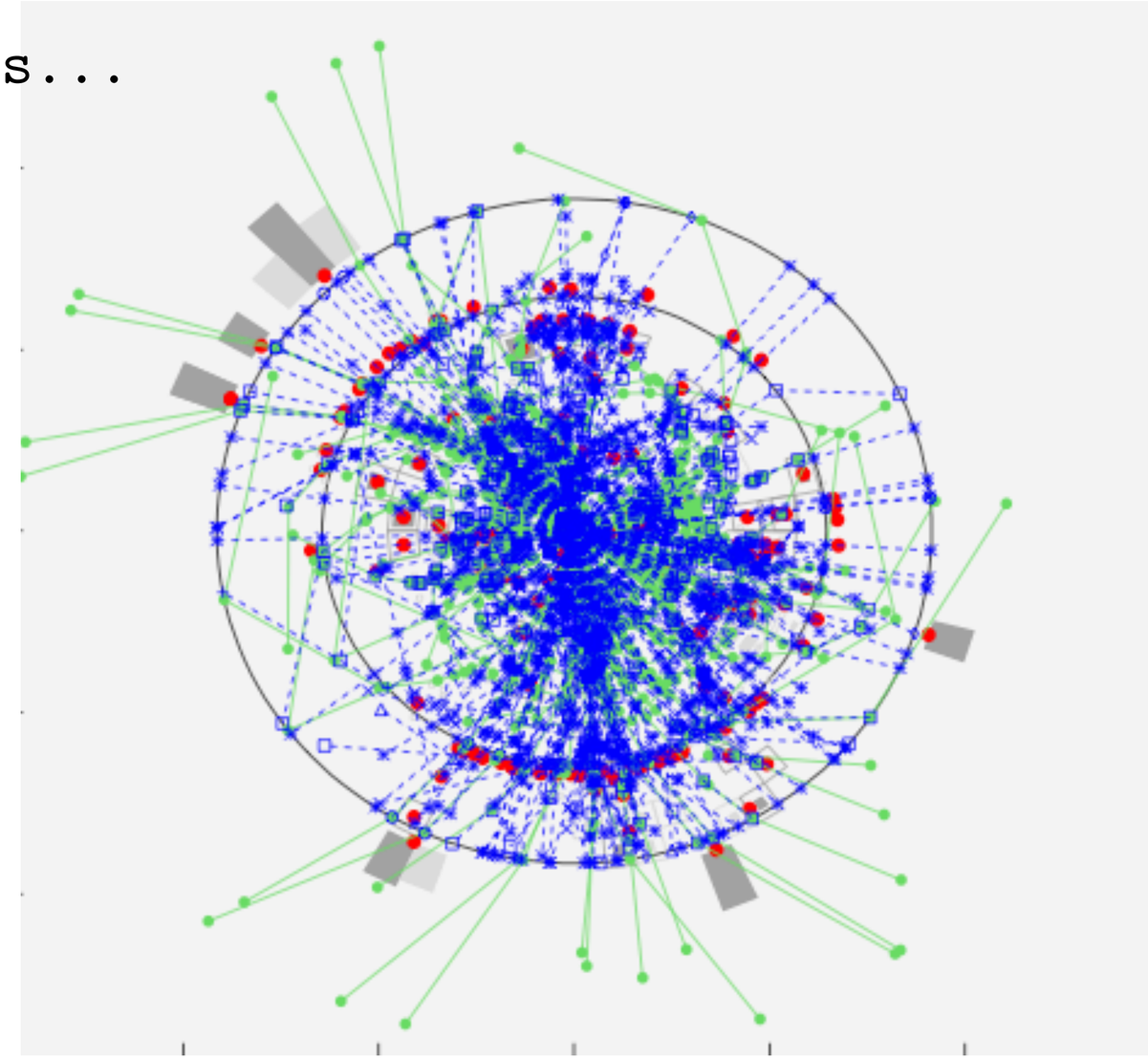

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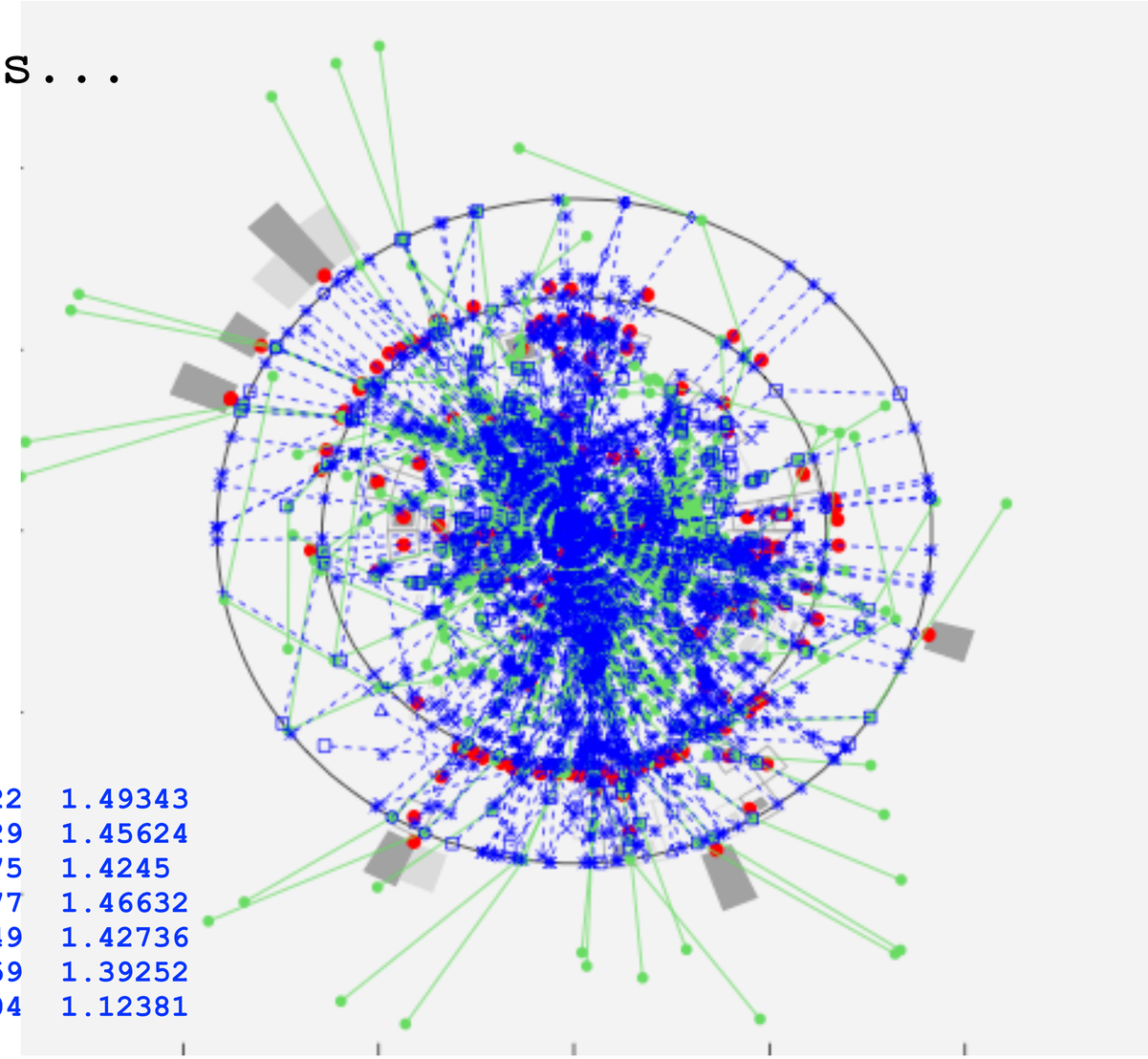

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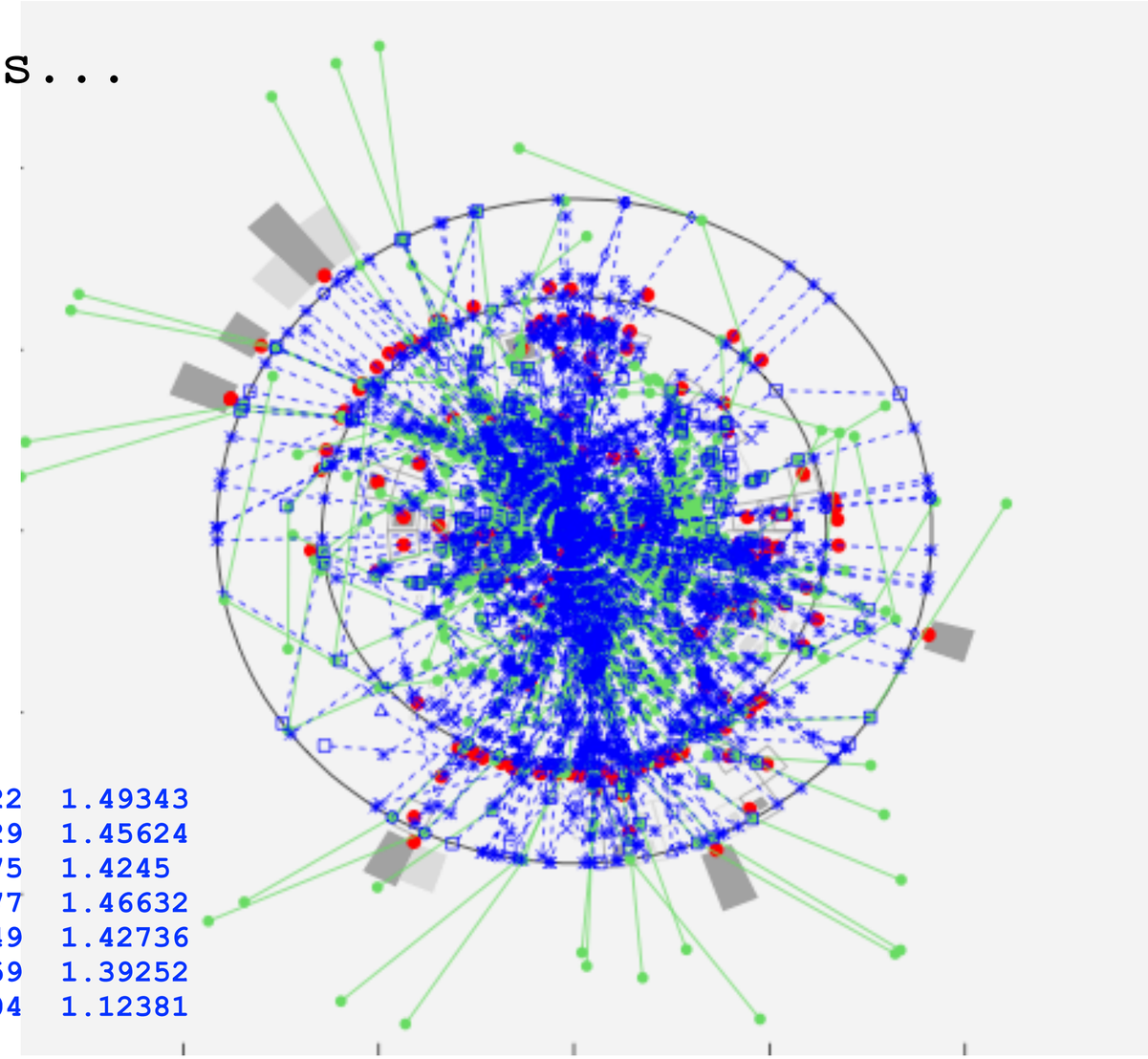

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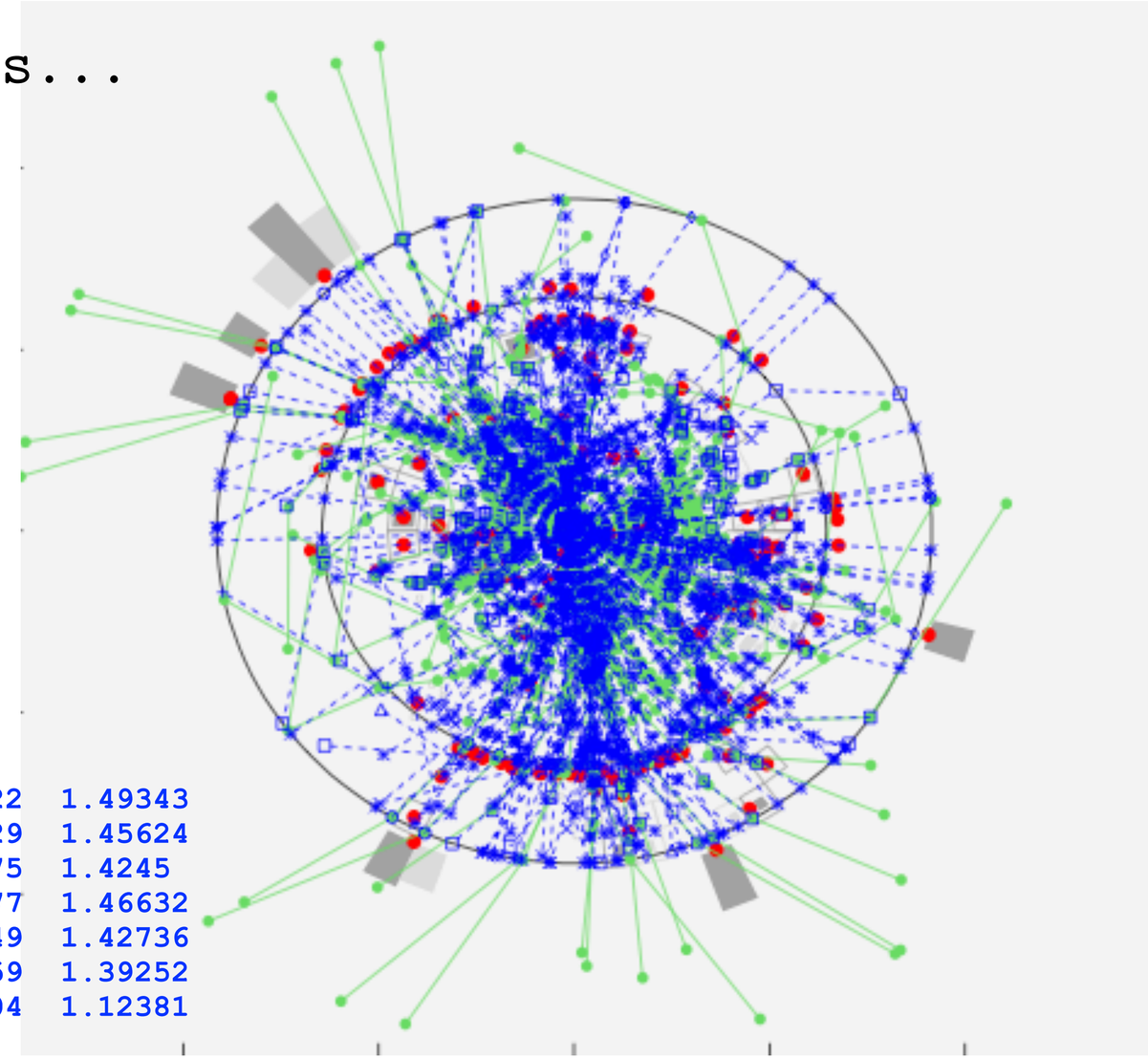

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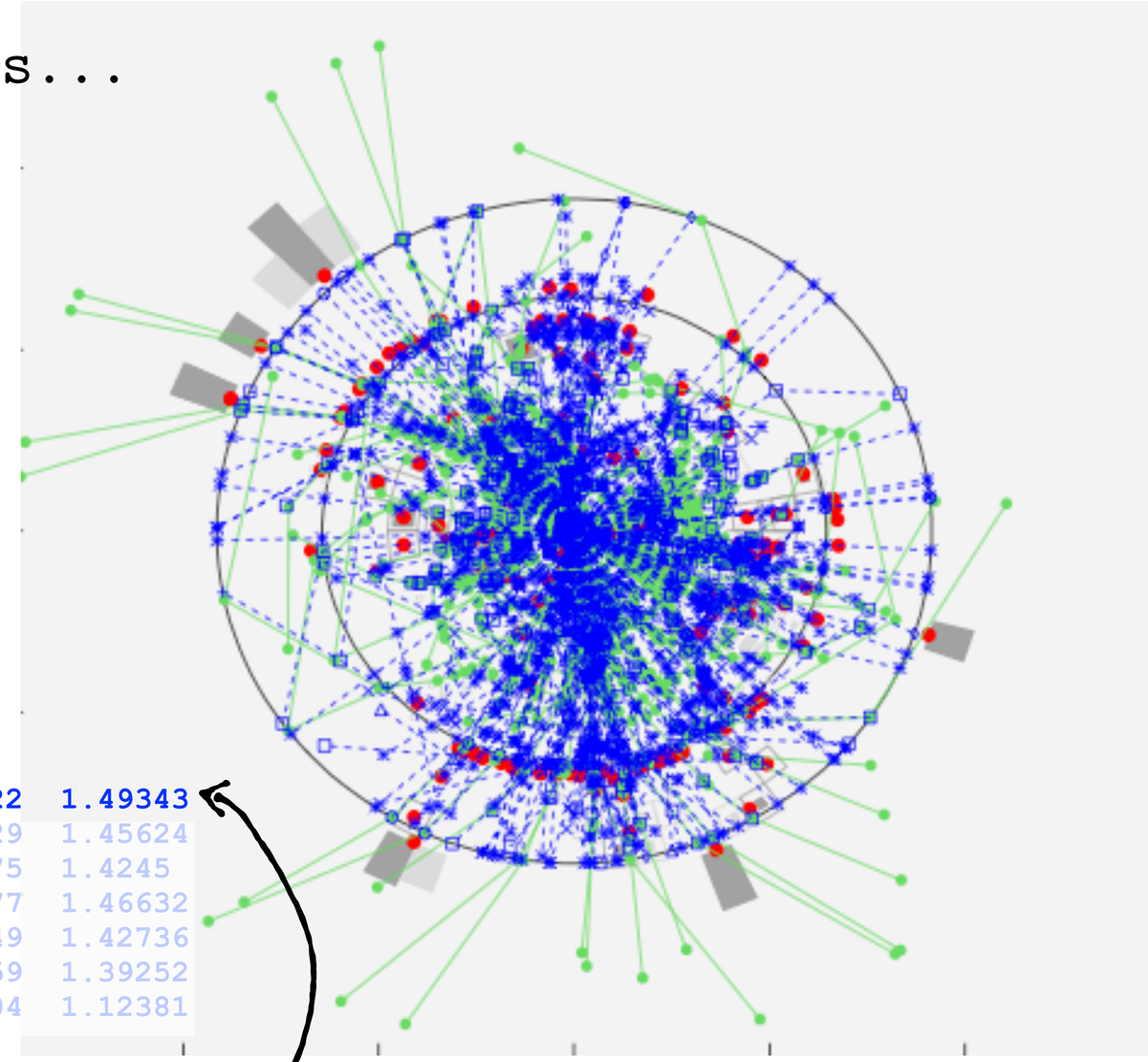

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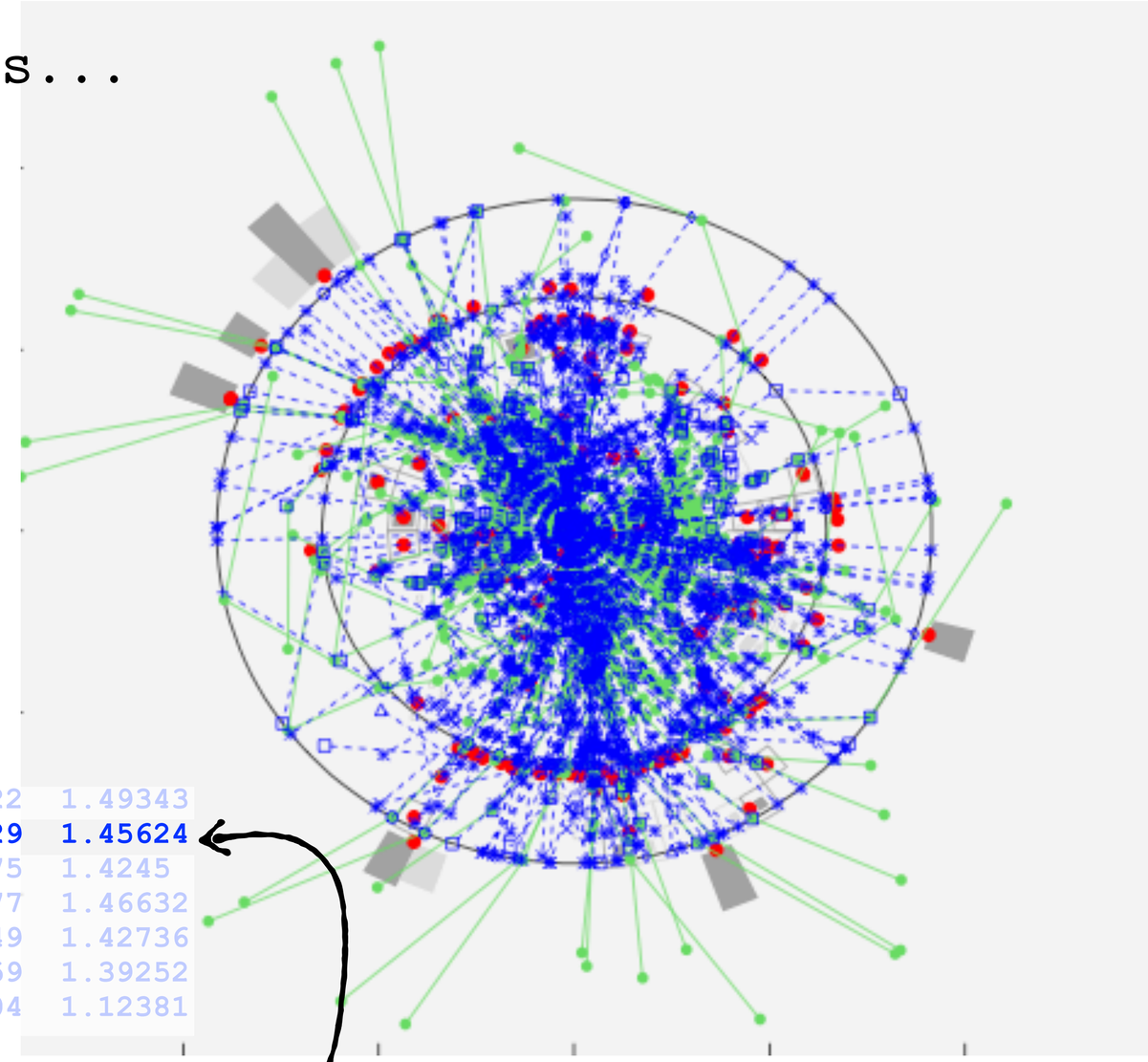

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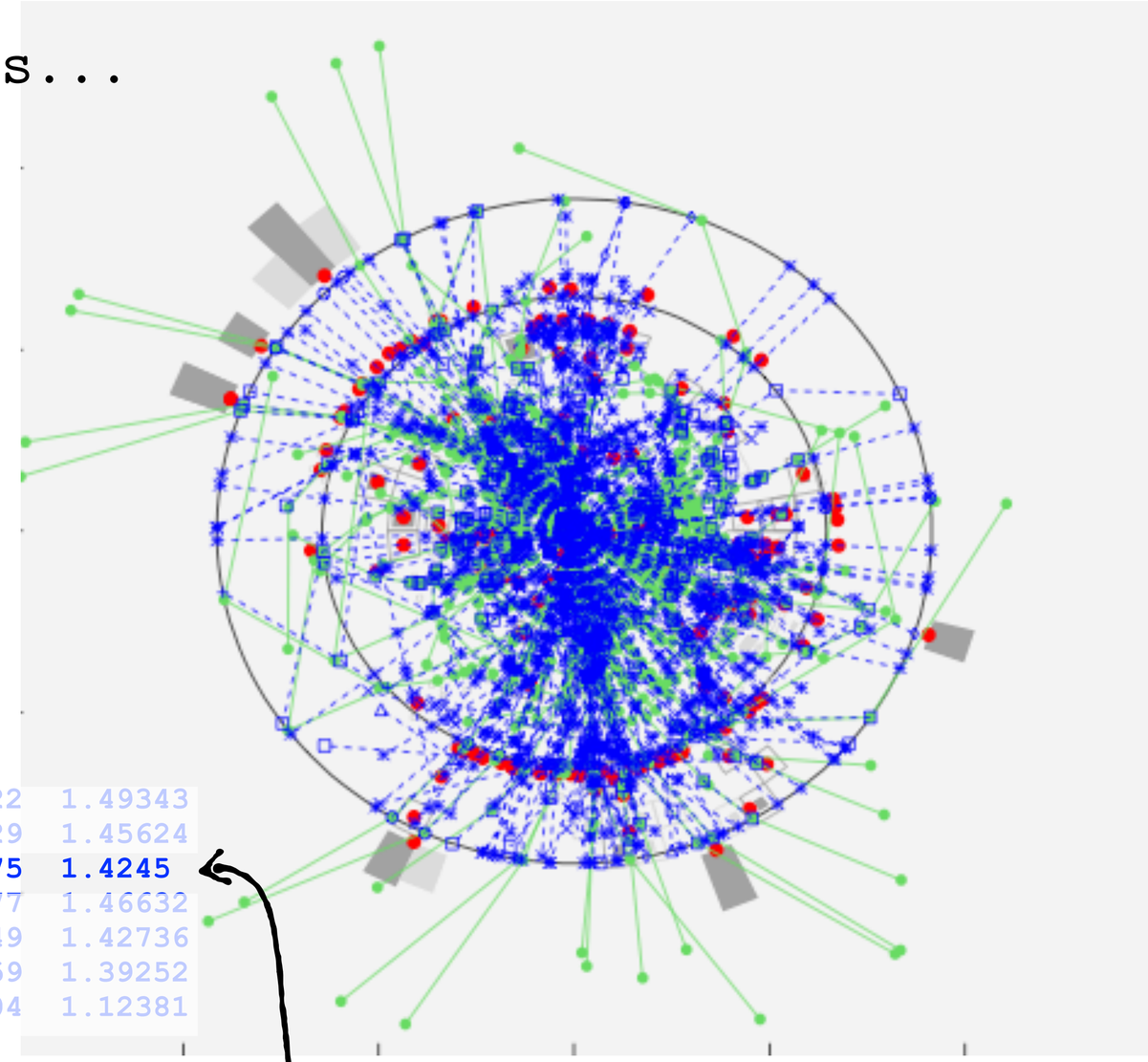

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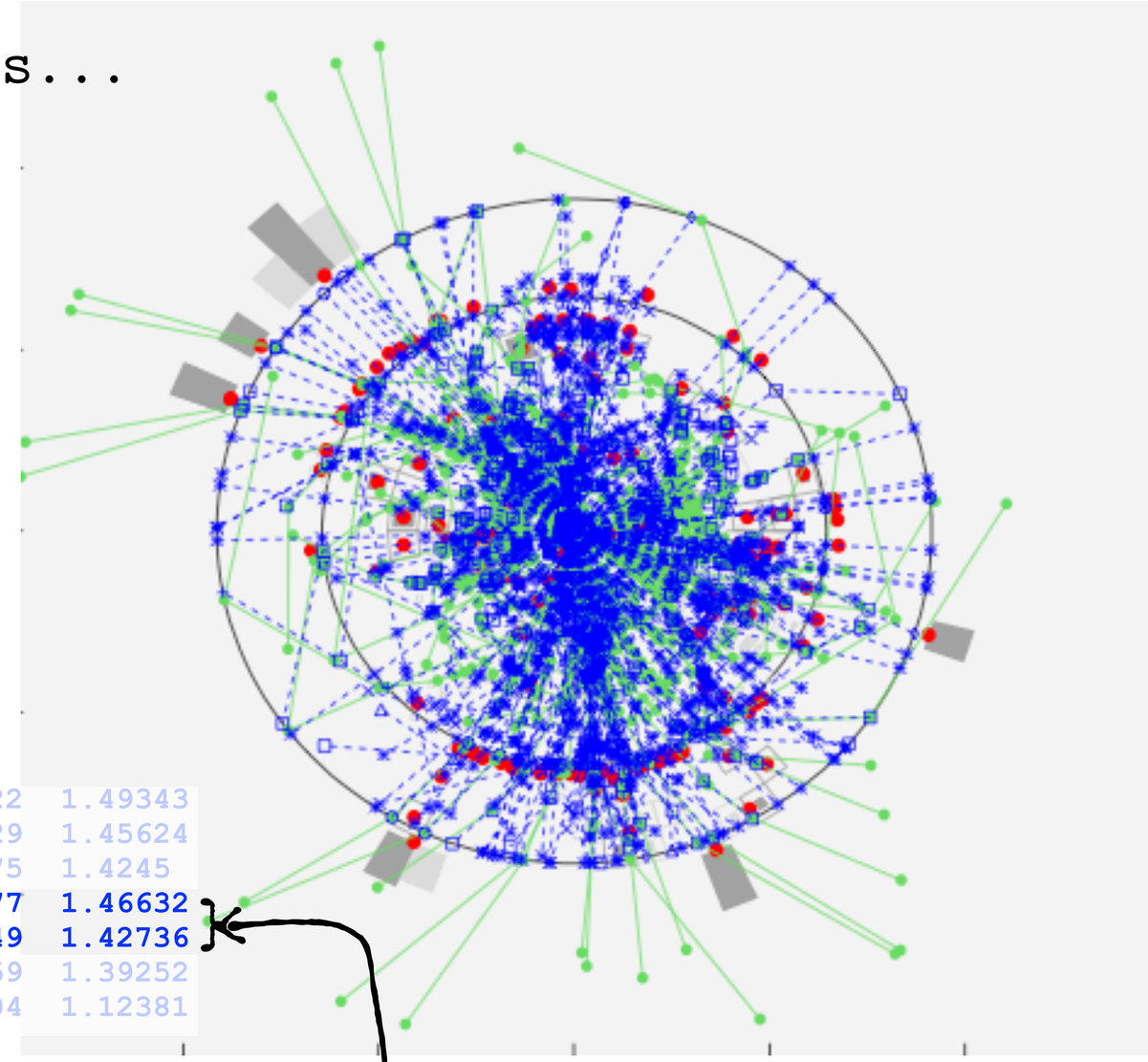

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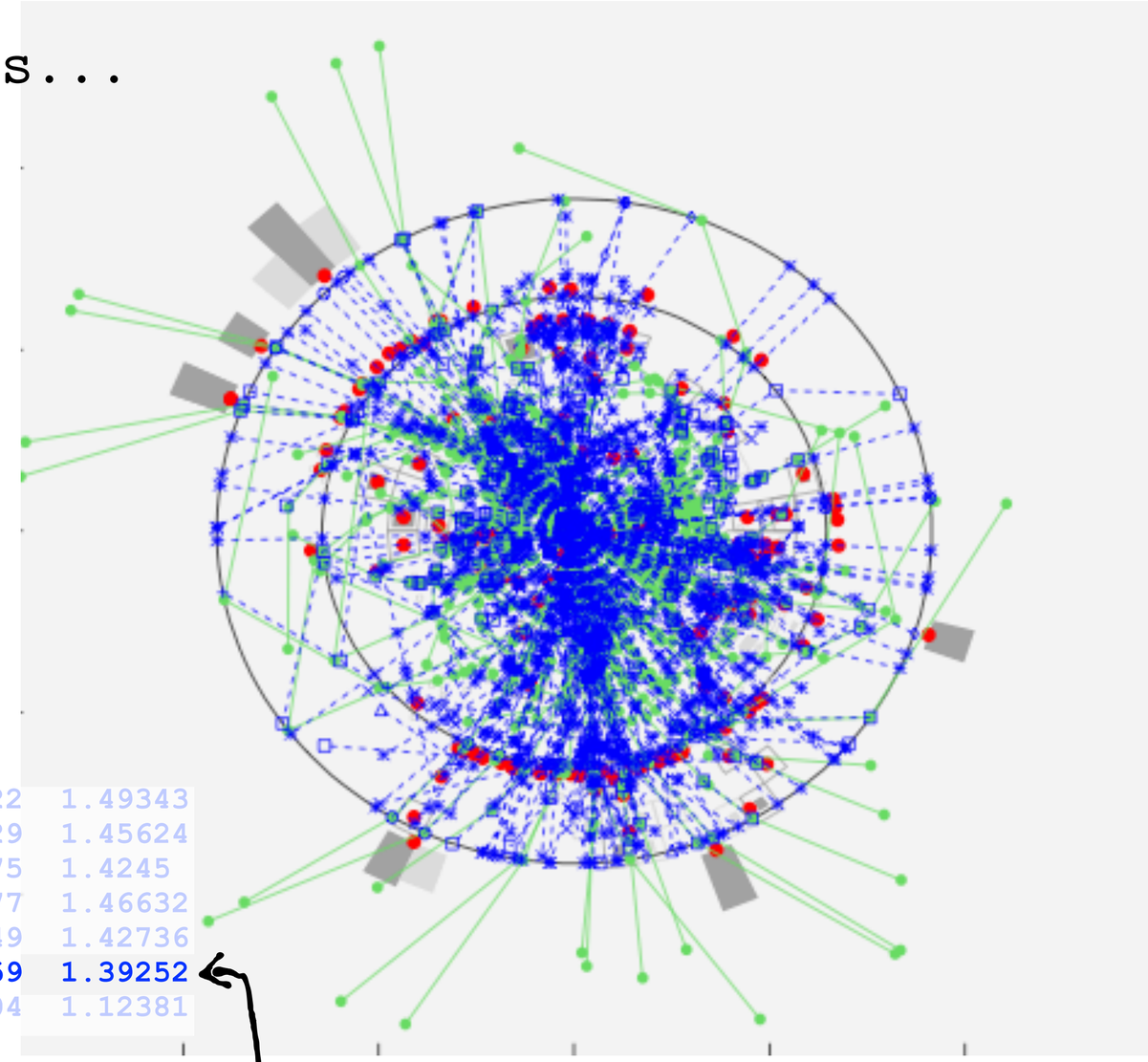

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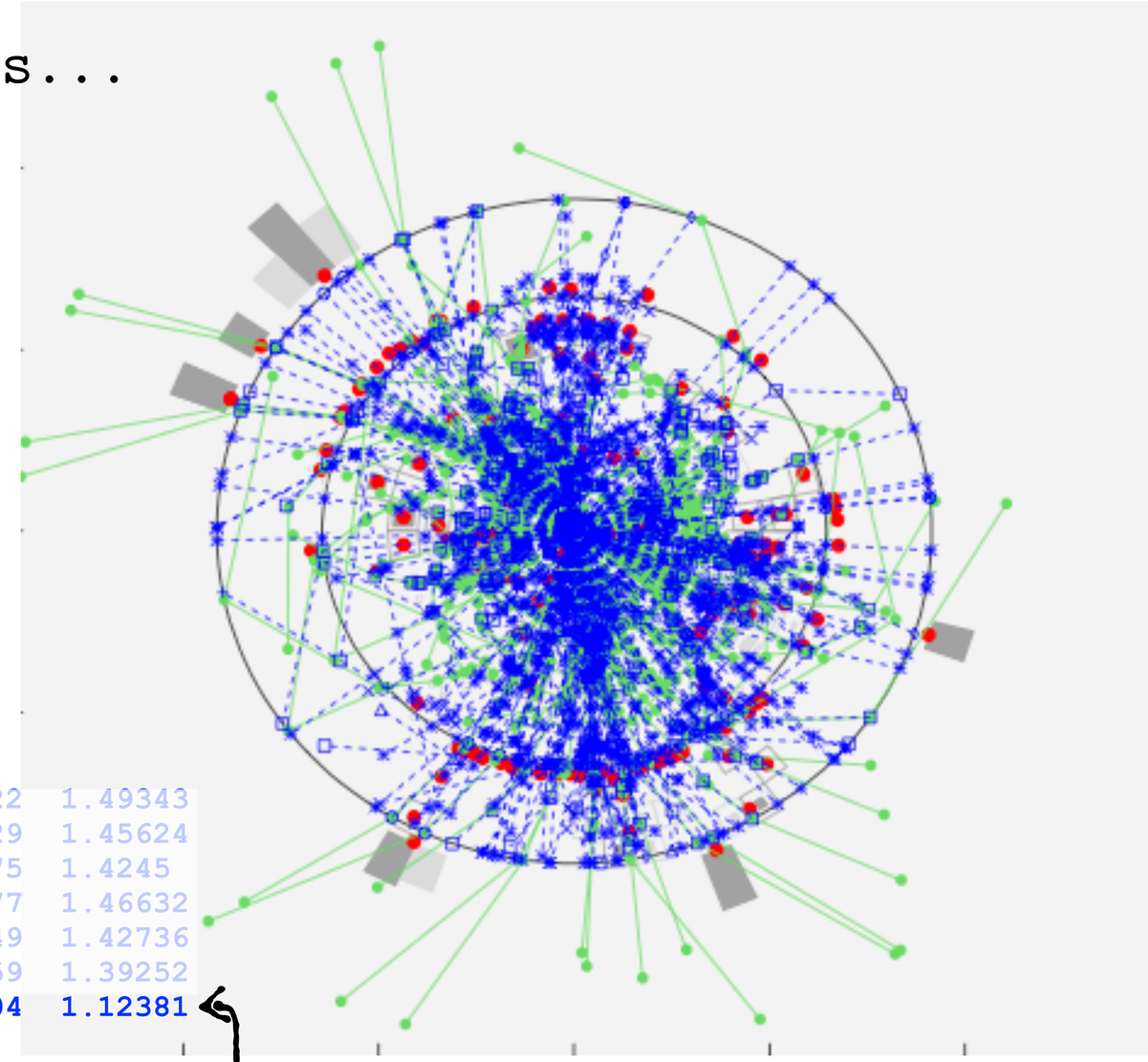

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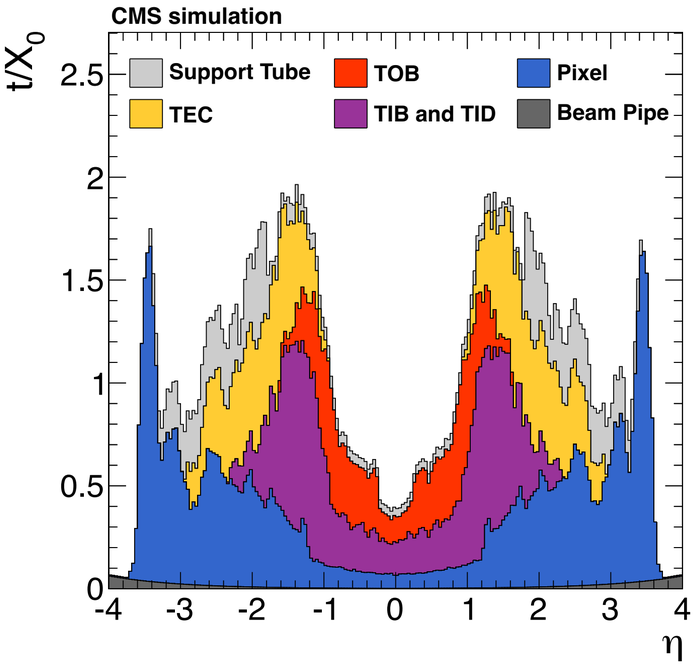

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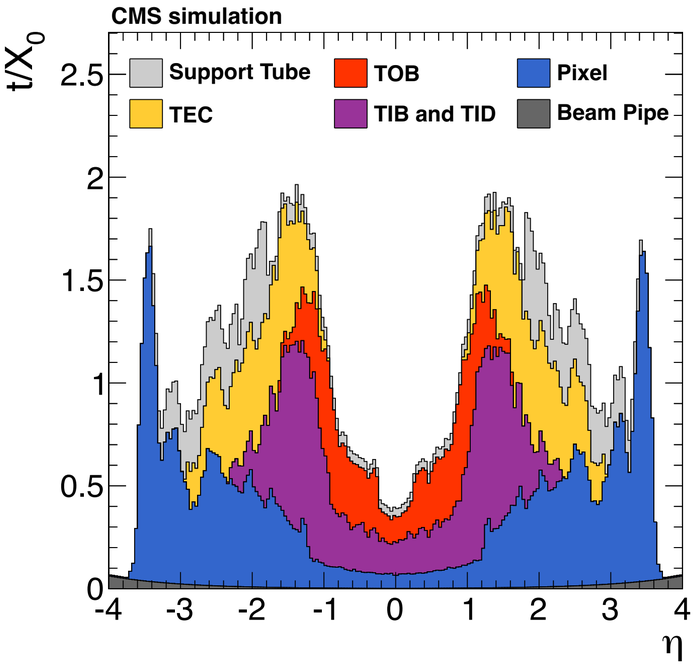

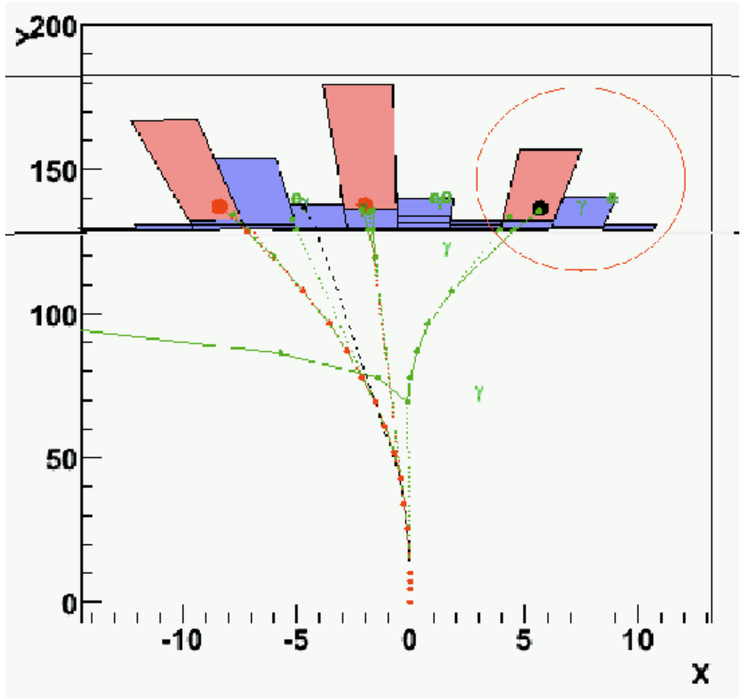

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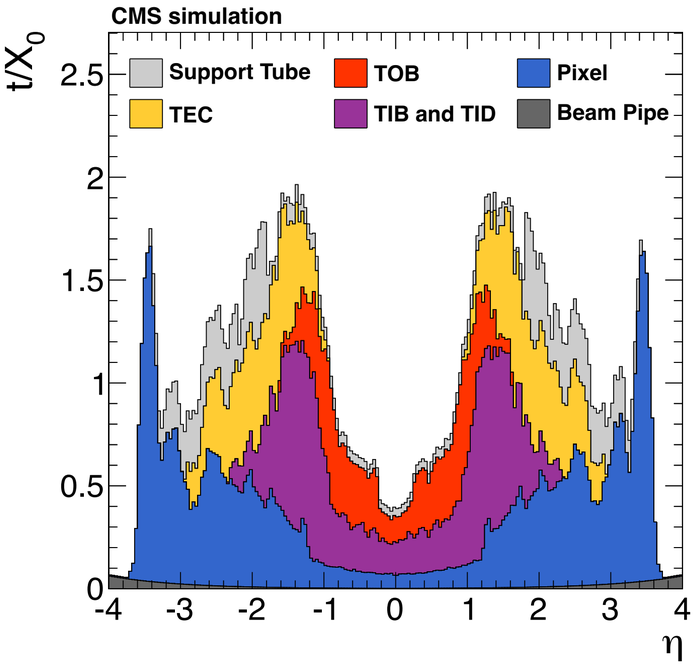

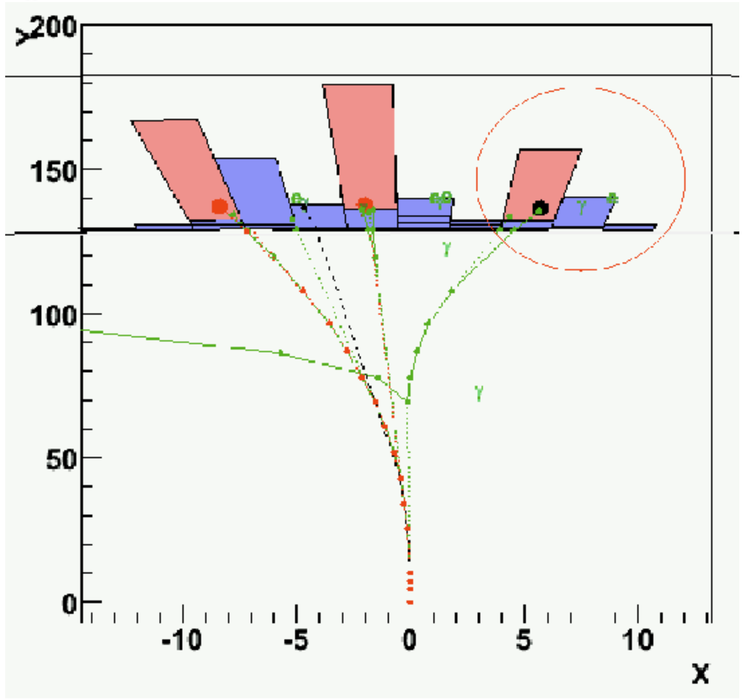

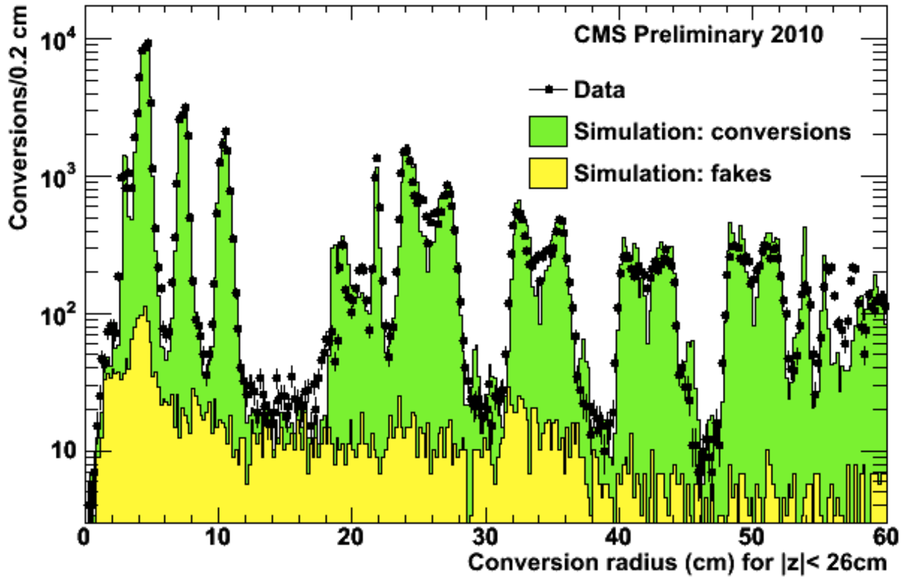

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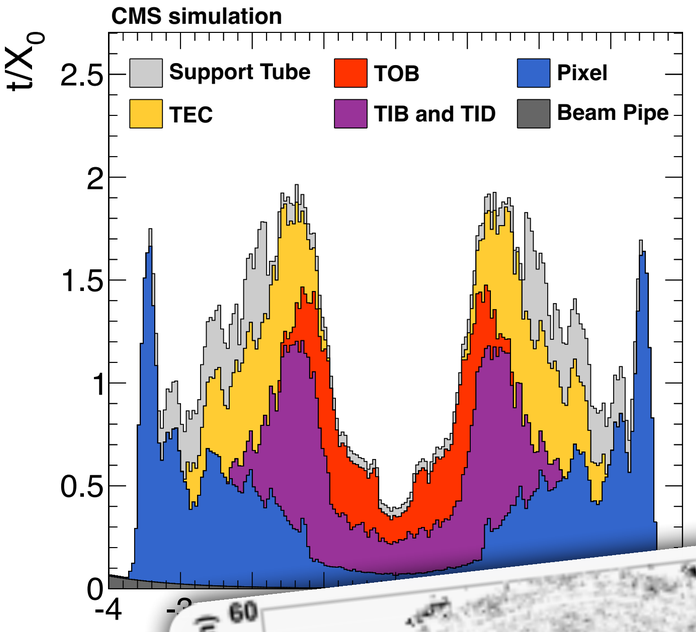
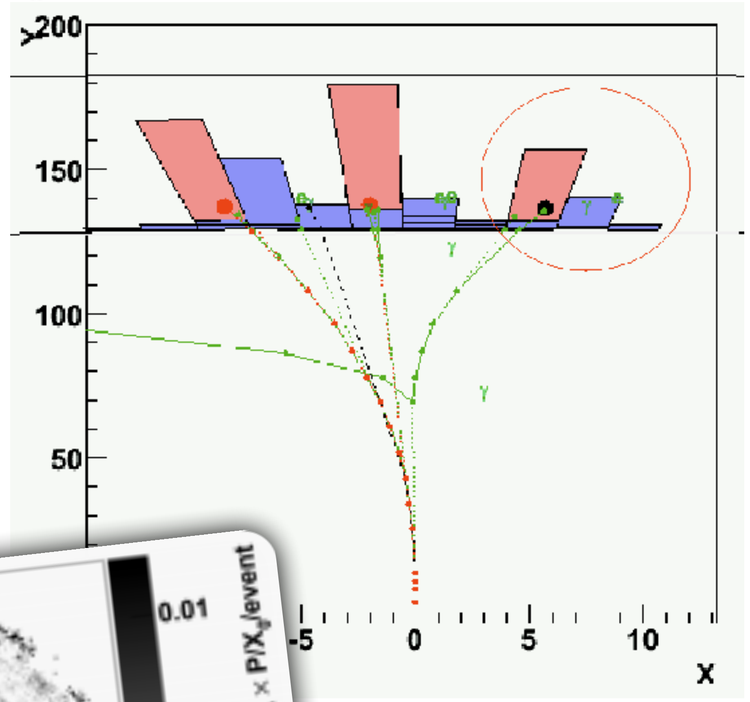
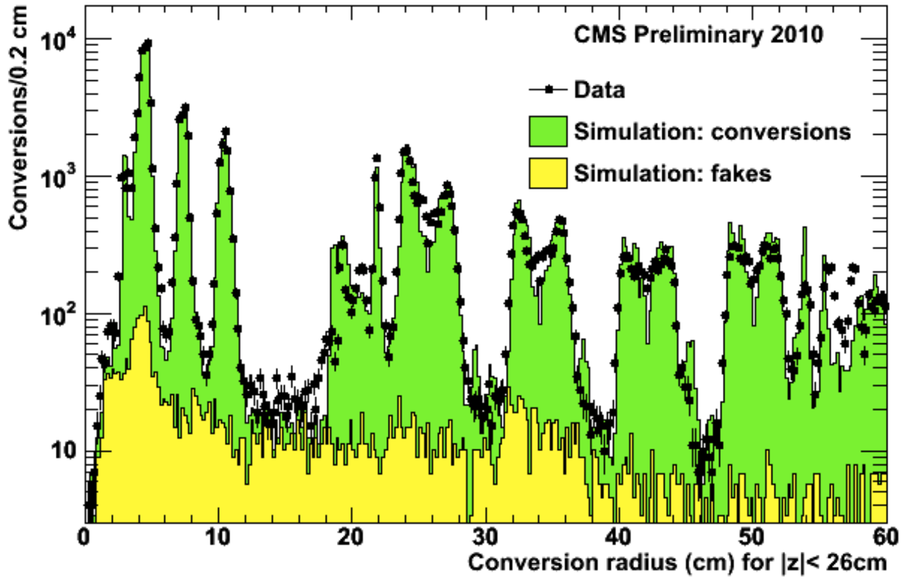
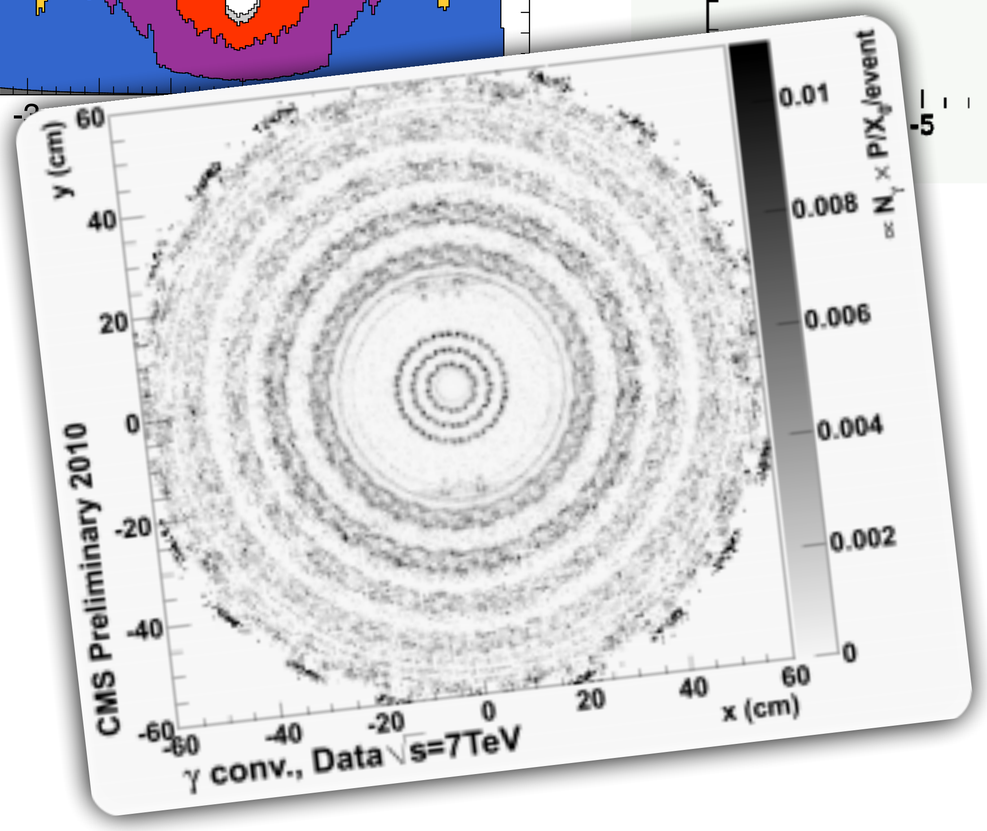
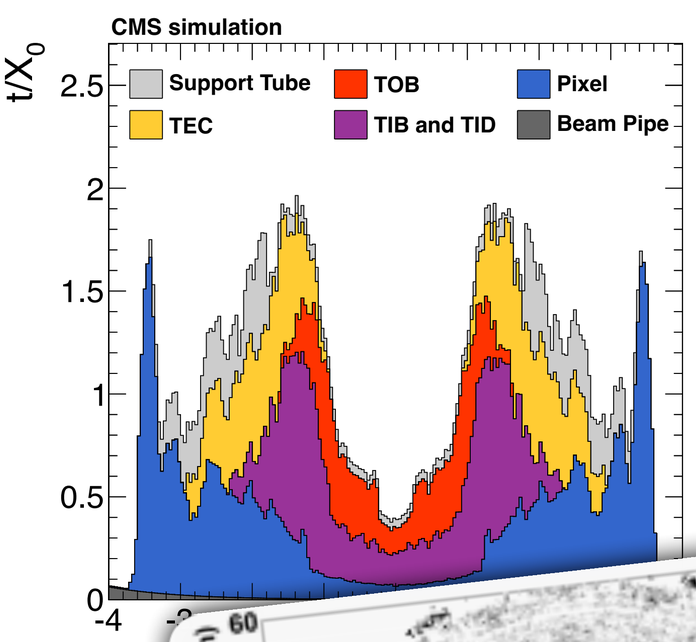


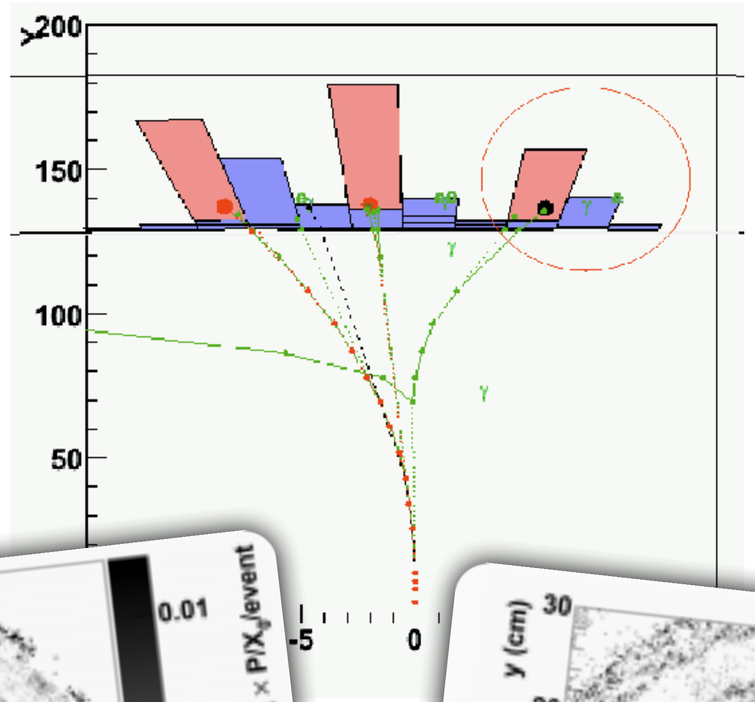


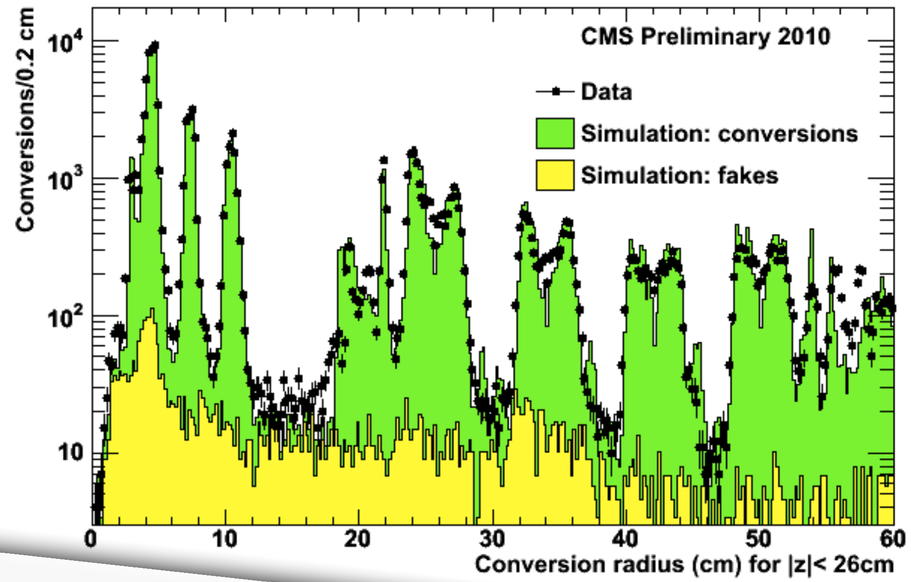


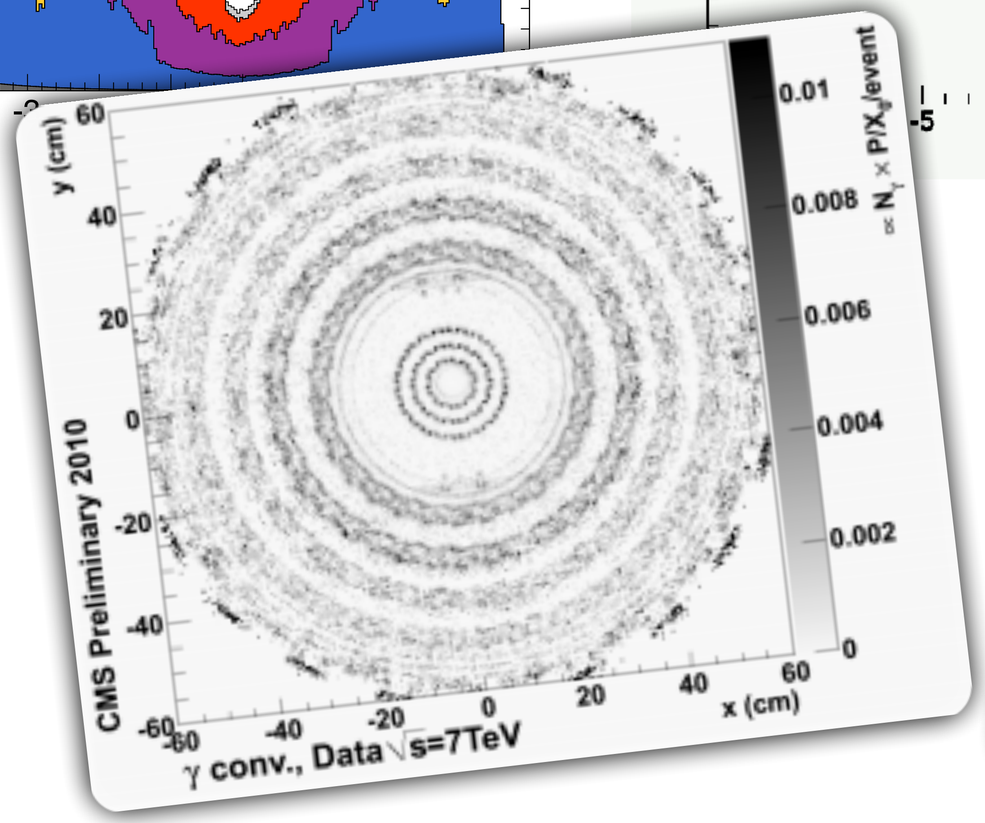


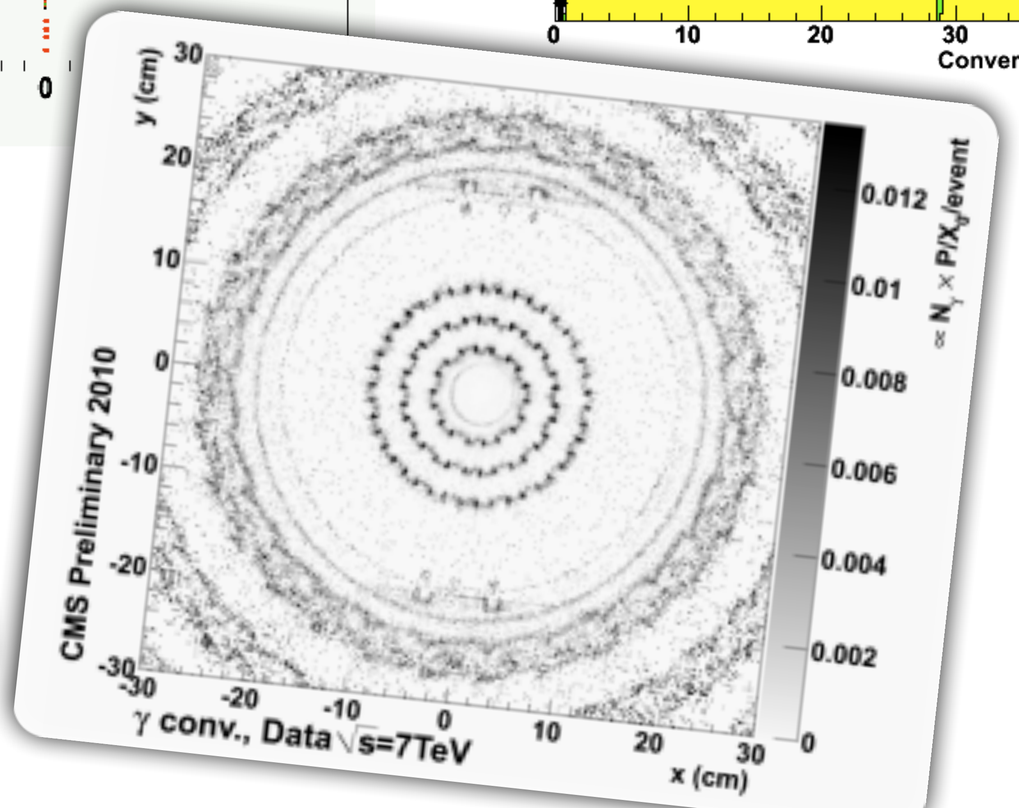
Important details (again!) Tracker Material Budget



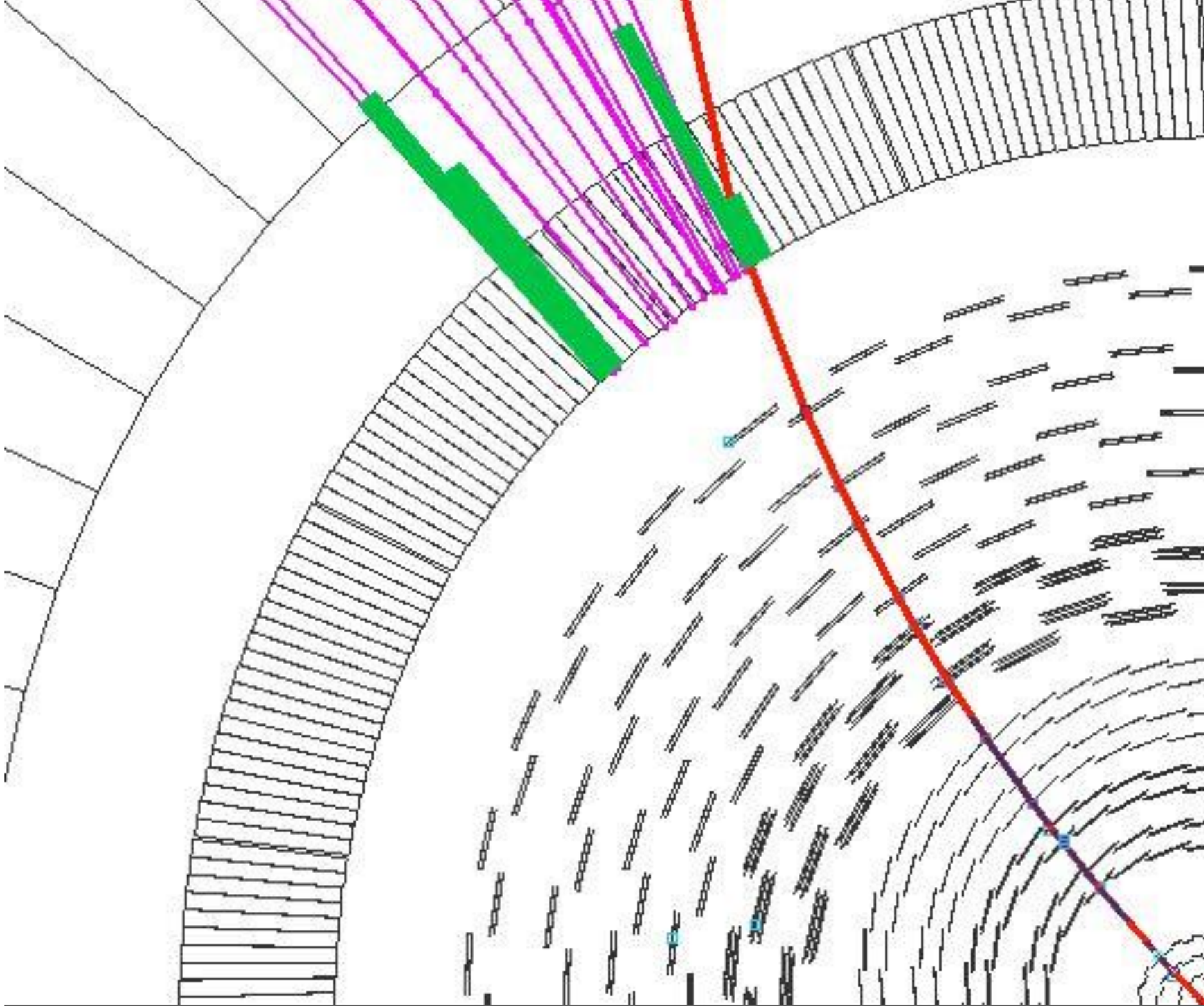








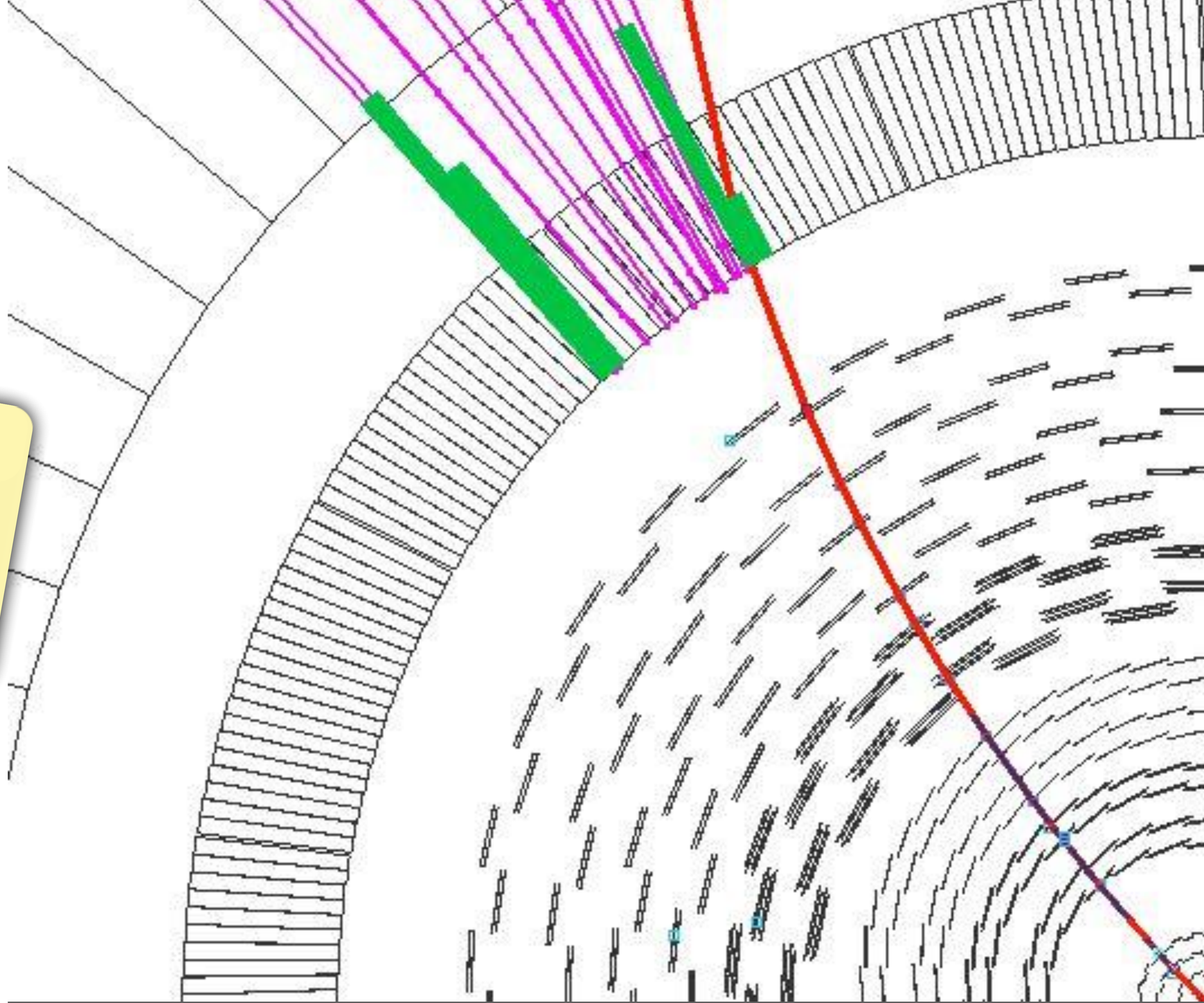
Electron ID



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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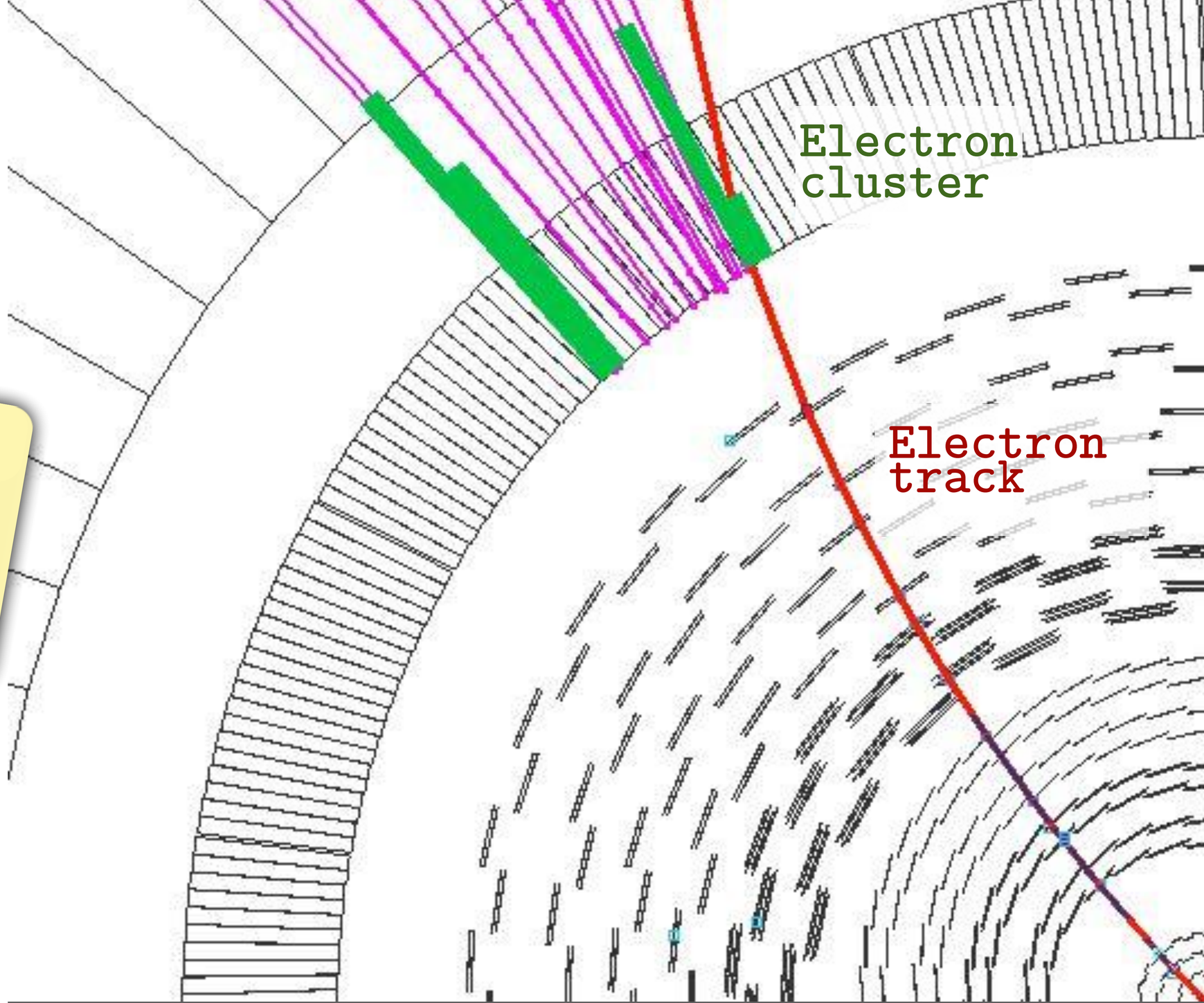

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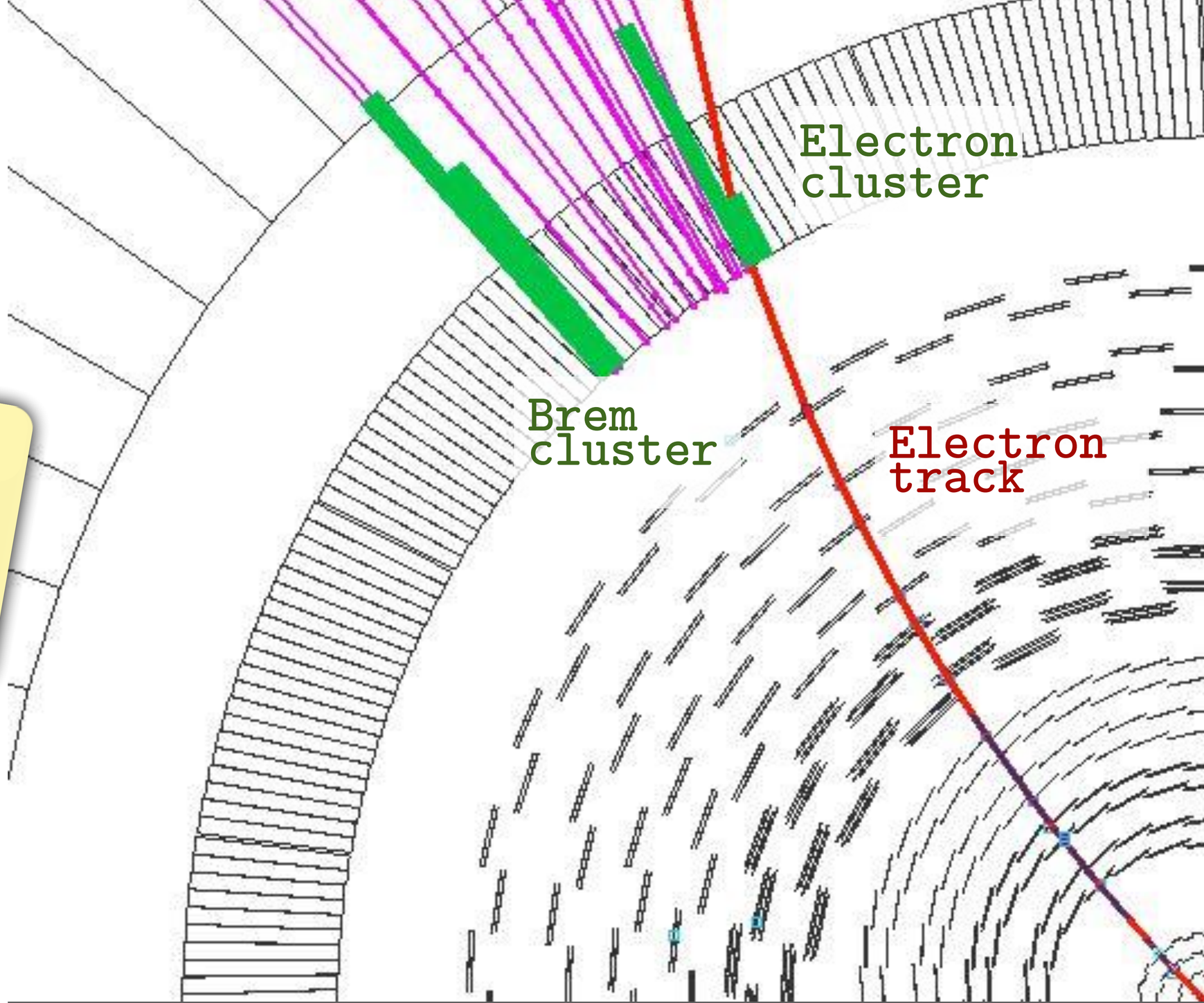

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- Electrons radiate on average $\approx \frac{2}{3}$ of their energy in the track by bremsstrahlung
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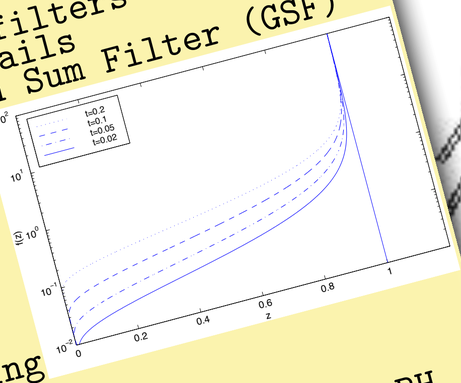
Standard KF tracking fails for electrons!

- Because they radiate! Kalman filter pattern recognition quickly gives up
- Use sum of Kalman filters to account for non-Gaussian tails
  => Gaussian Sum Filter (GSF)
  - attempts to approximates Bethe-Heitler energy loss
  - resembles a set of Kalman filters running in parallel
    - each corresponding to one gaussian component describing BH energy loss
    - Computationally expensive!

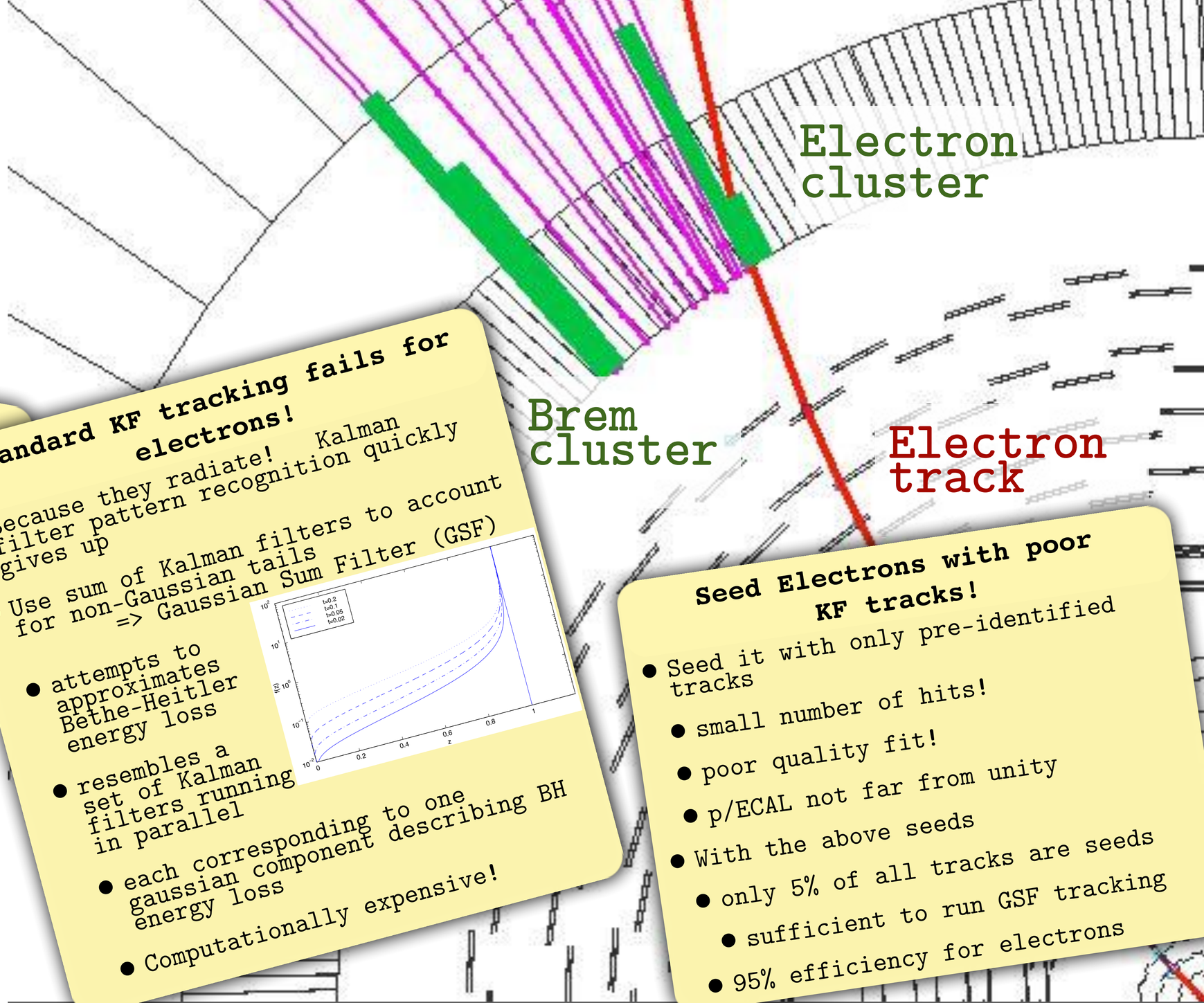


Electron cluster

Brem cluster

Electron track

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 Δp along GSF track

Huge Effect!

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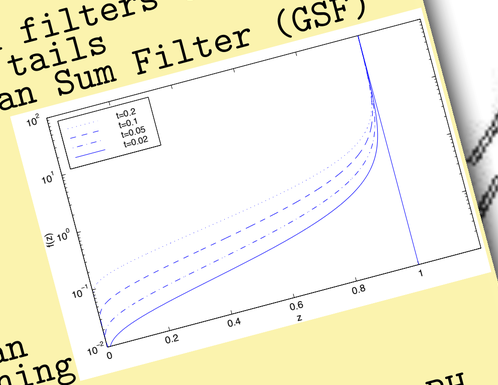

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Electron cluster

Brem cluster

Electron track

Electron ID

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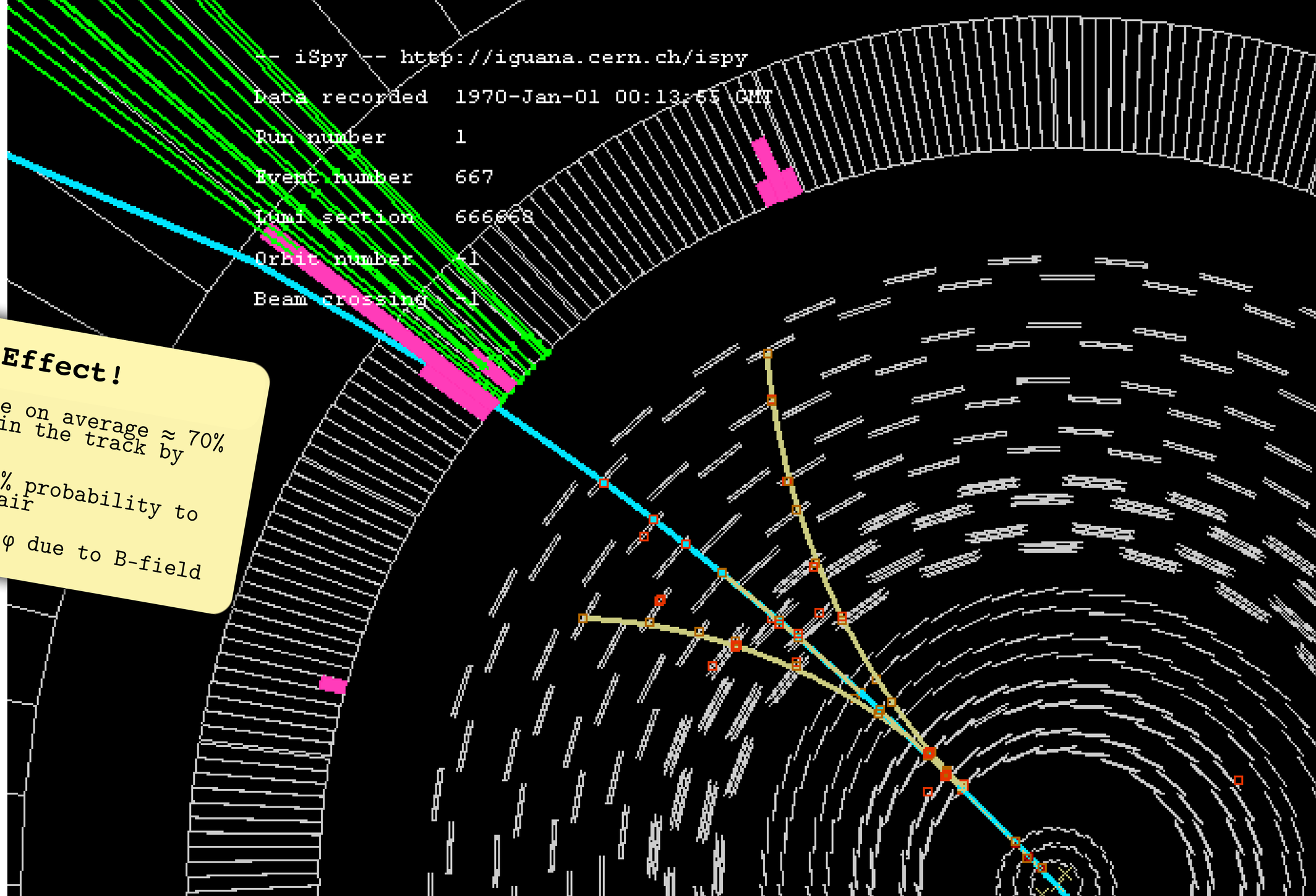

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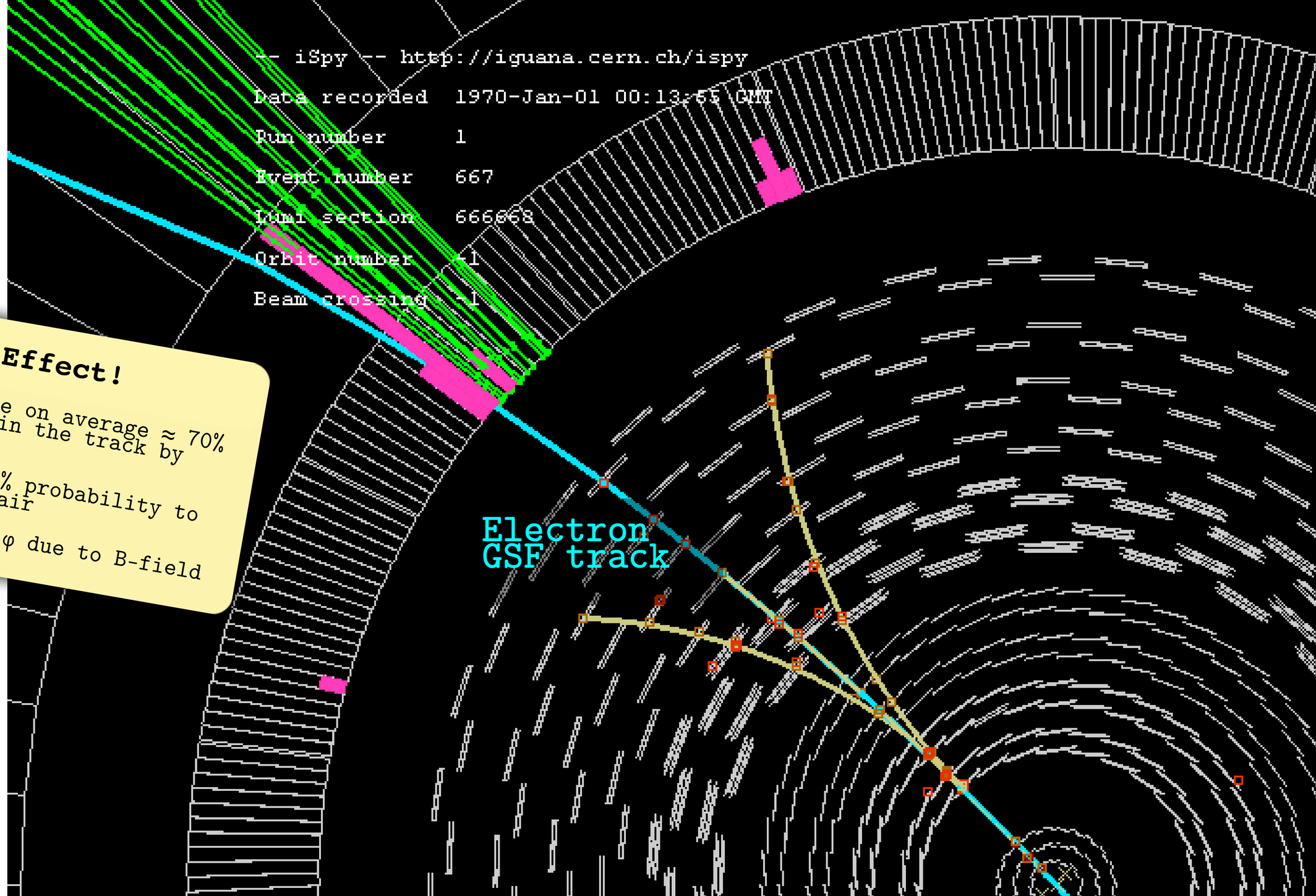

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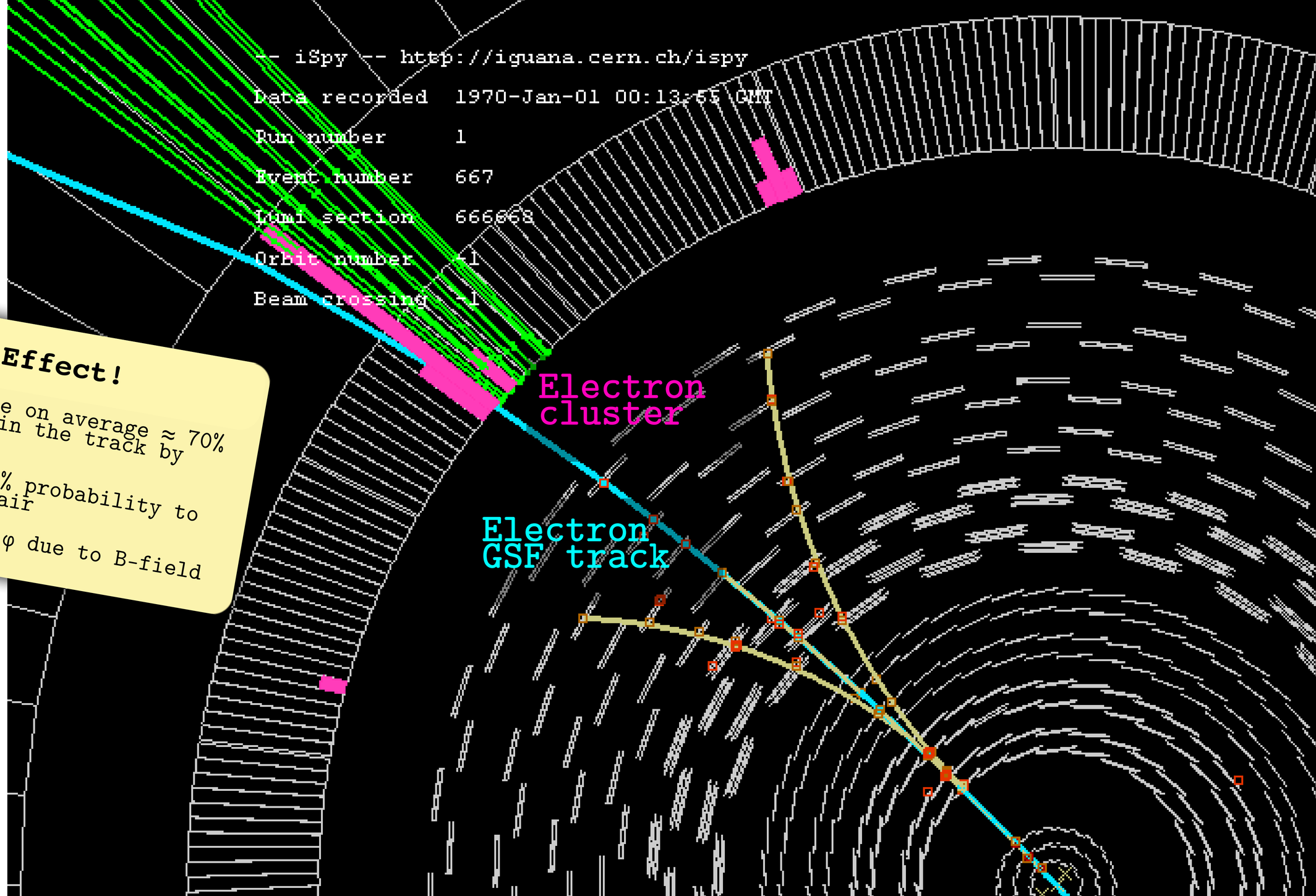

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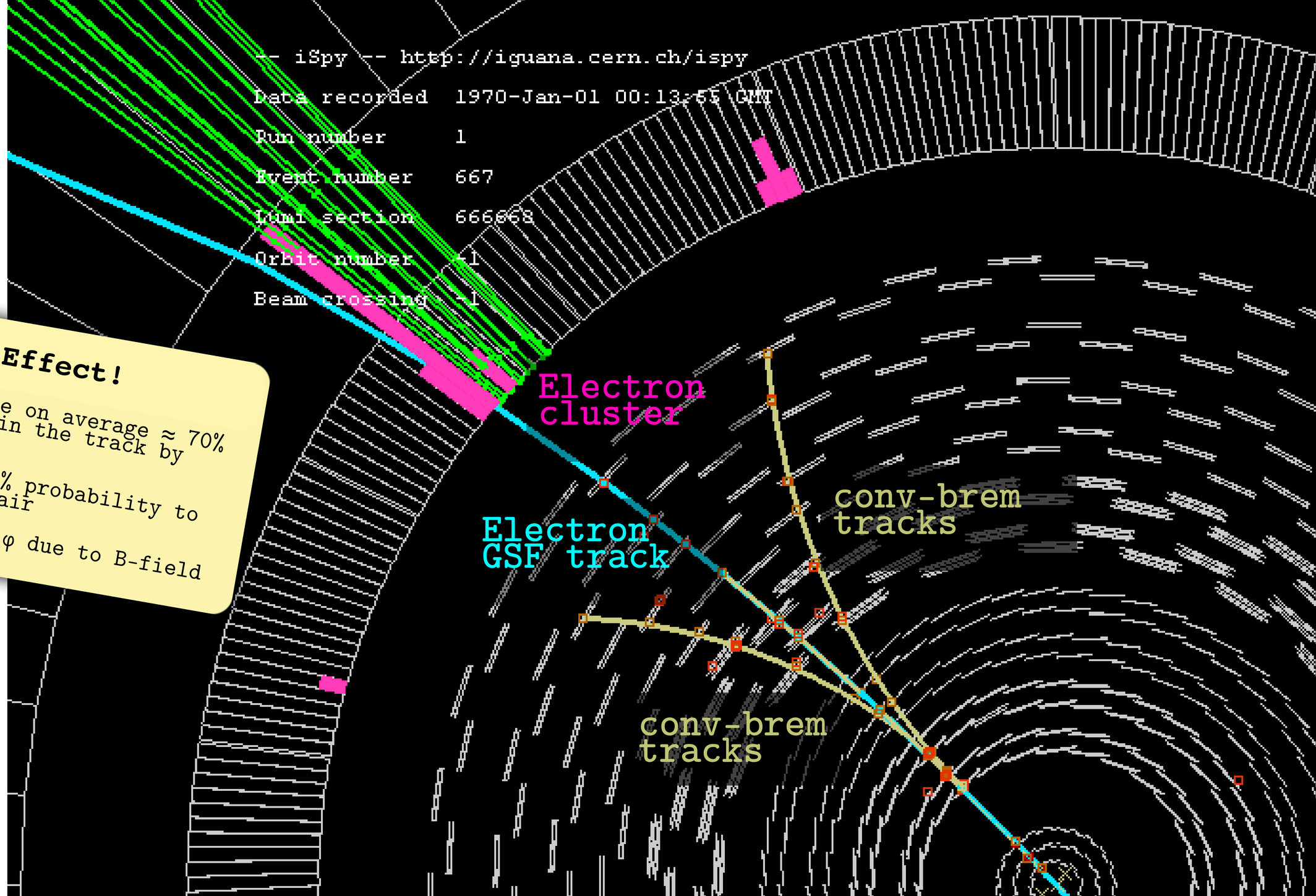

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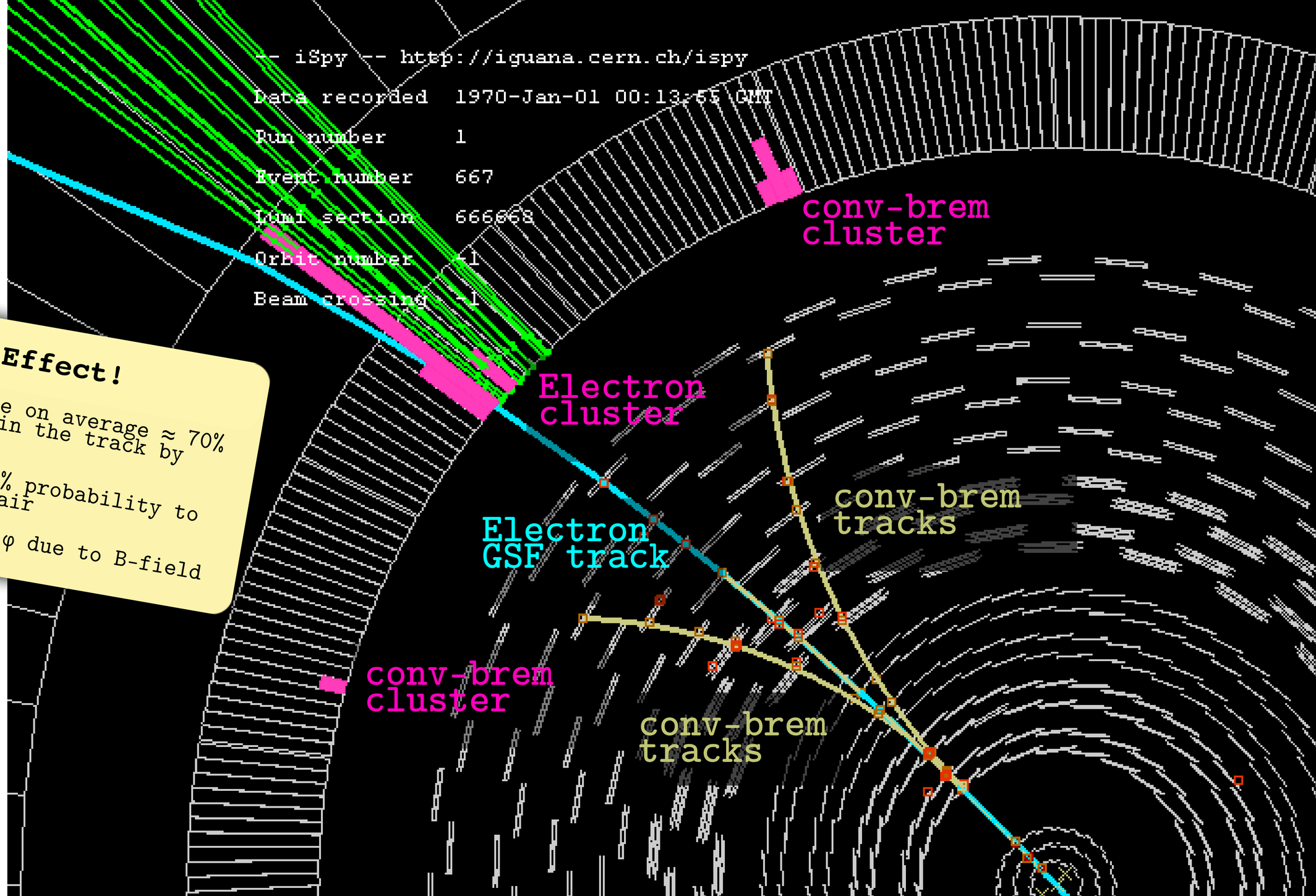

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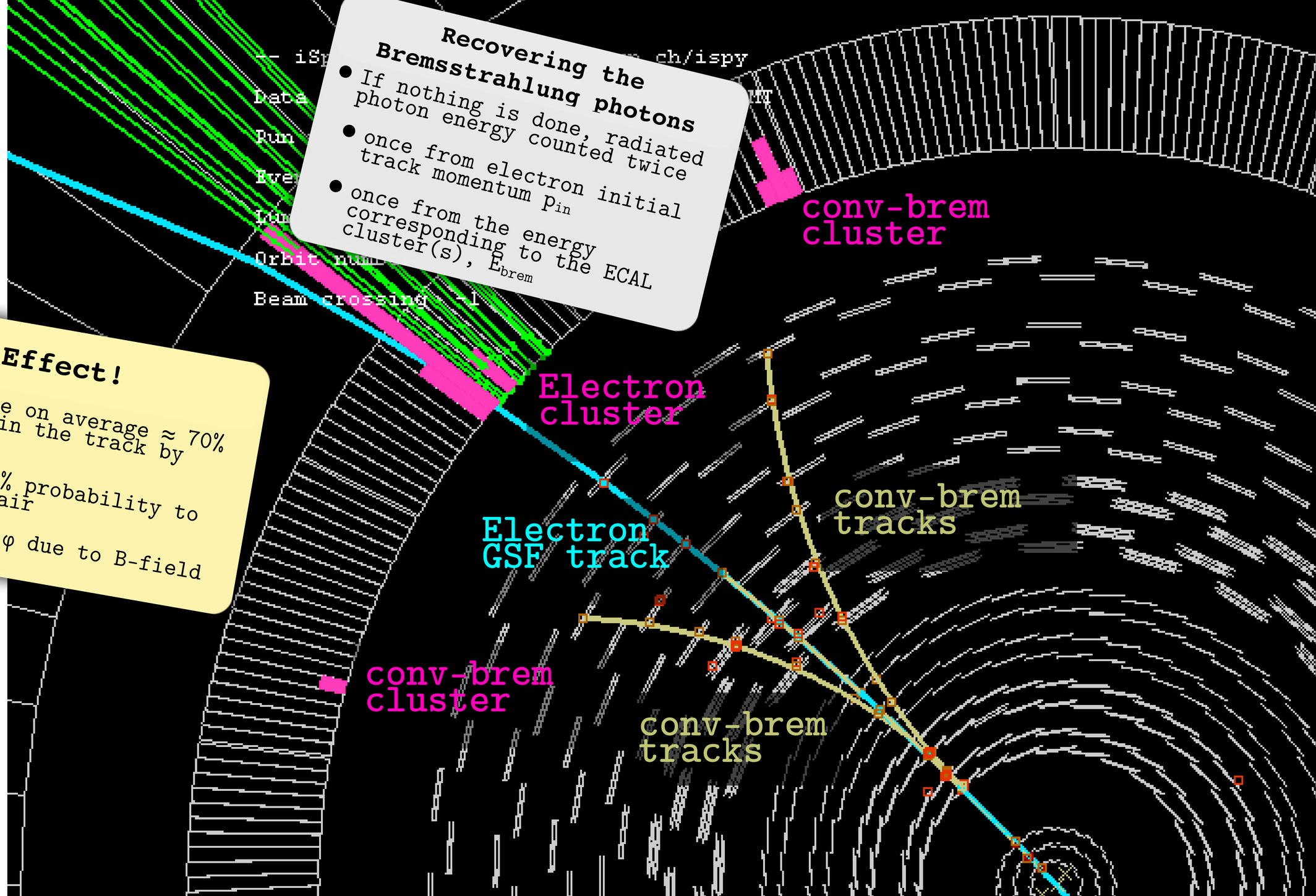
Recovering the Bremsstrahlung photons
If nothing is done, radiated photon energy counted twice
once from electron initial track momentum p_{in}
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conv-brem cluster
Electron cluster
Electron GSF track
conv-brem tracks
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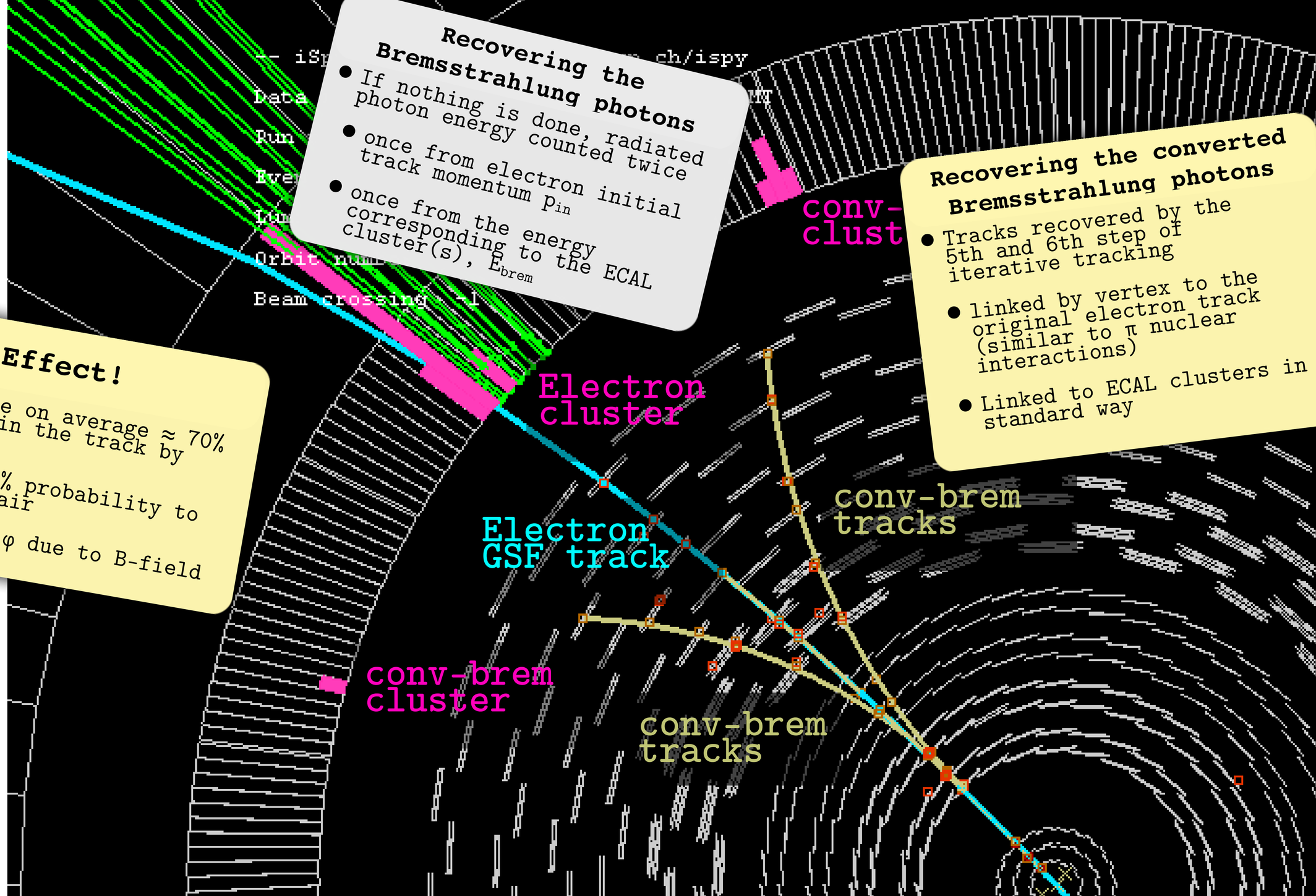

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- Tracks recovered by the 5th and 6th step of iterative tracking
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How to distinguish/calibrate between e's & π's ?

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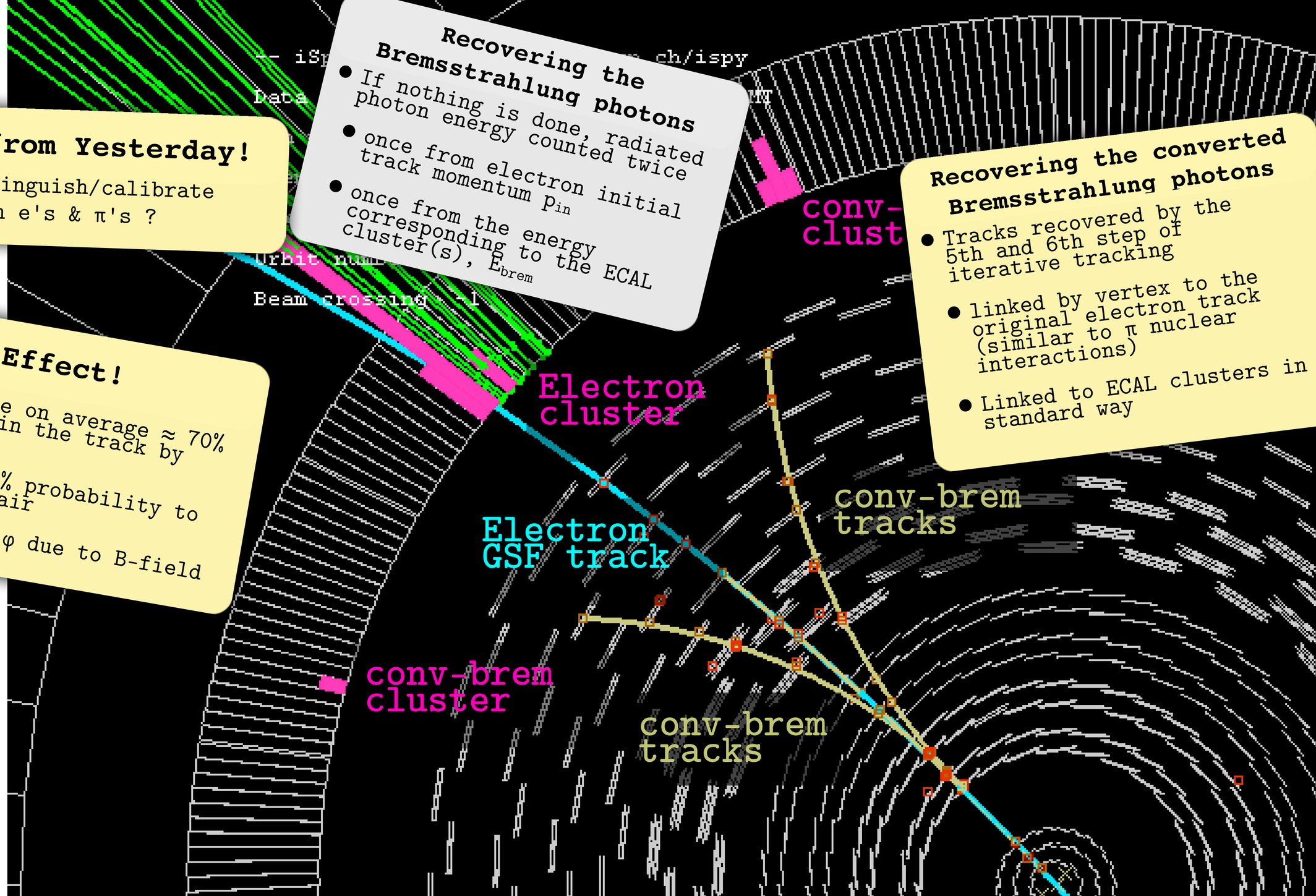

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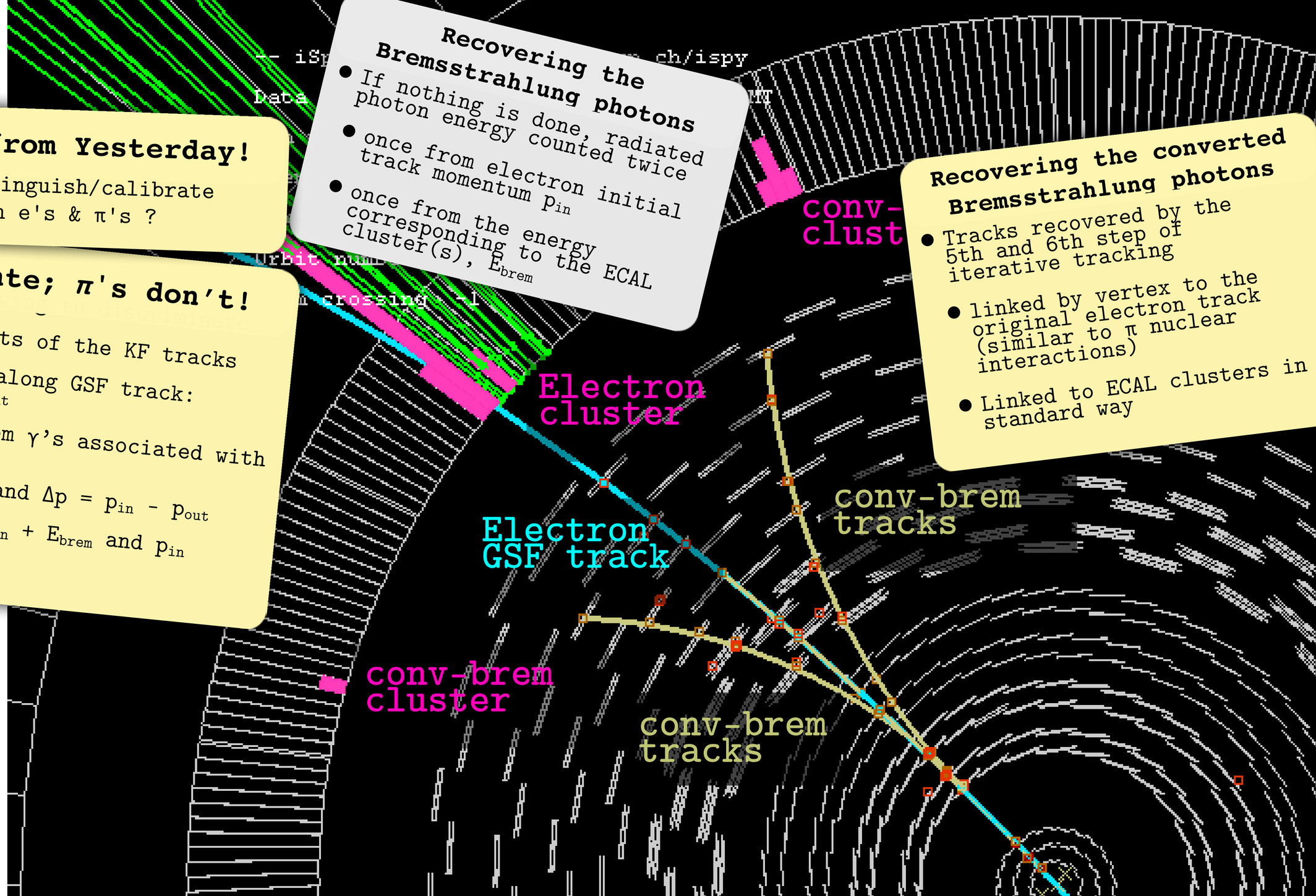

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Use cluster information!

- Shower shape, such as width along η
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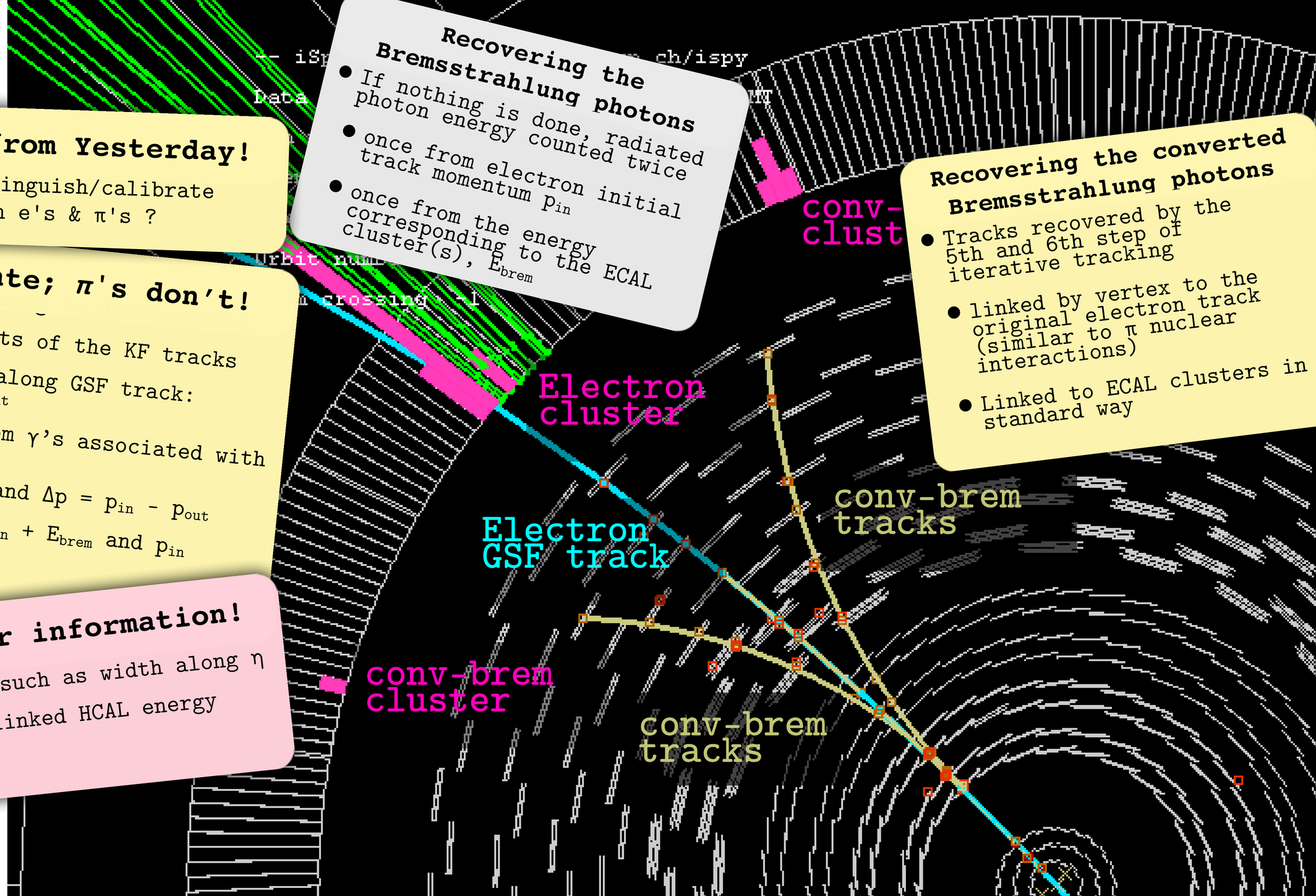

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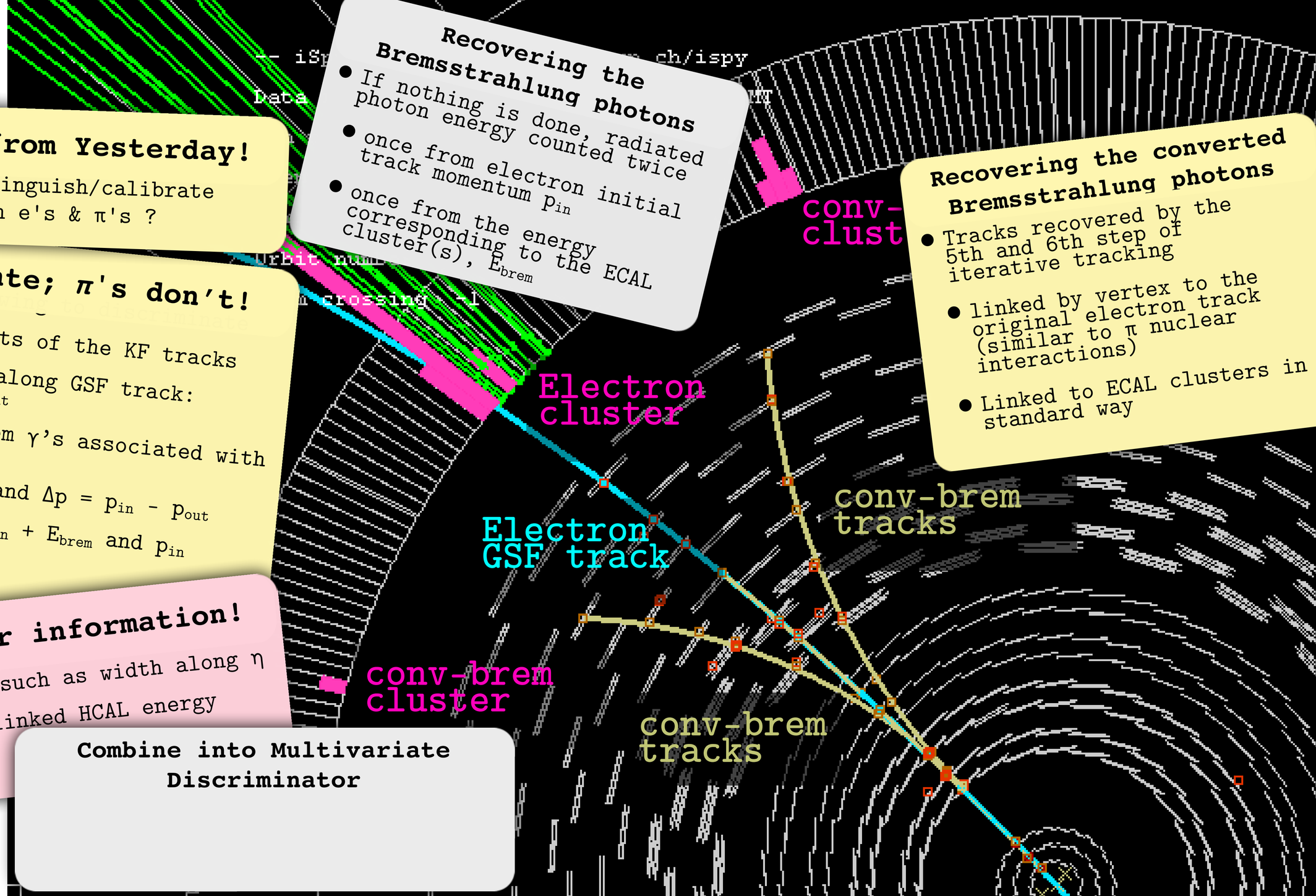

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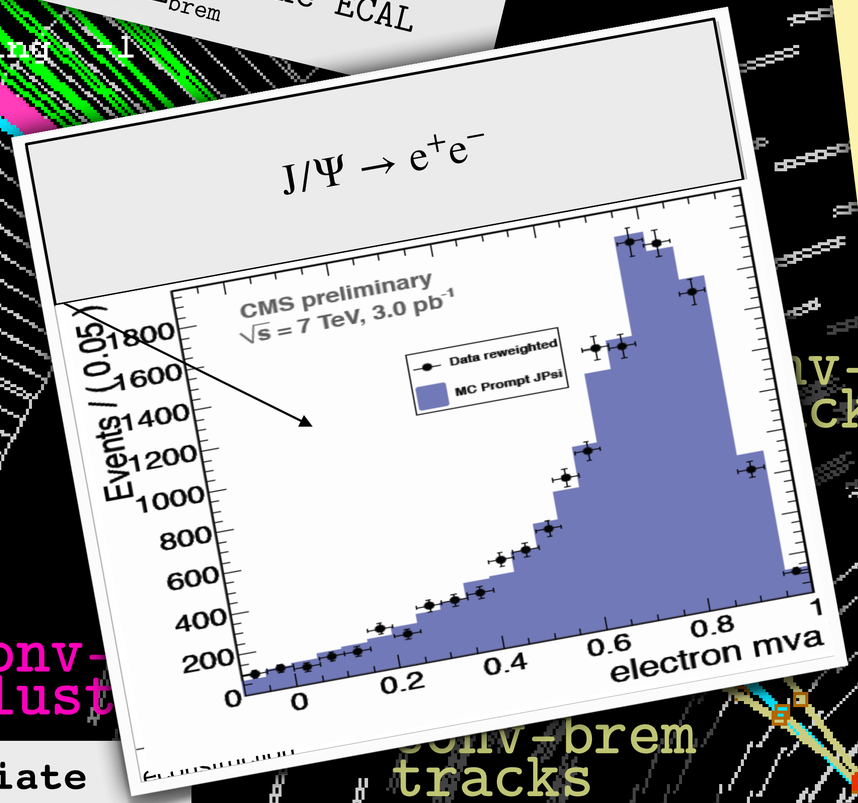

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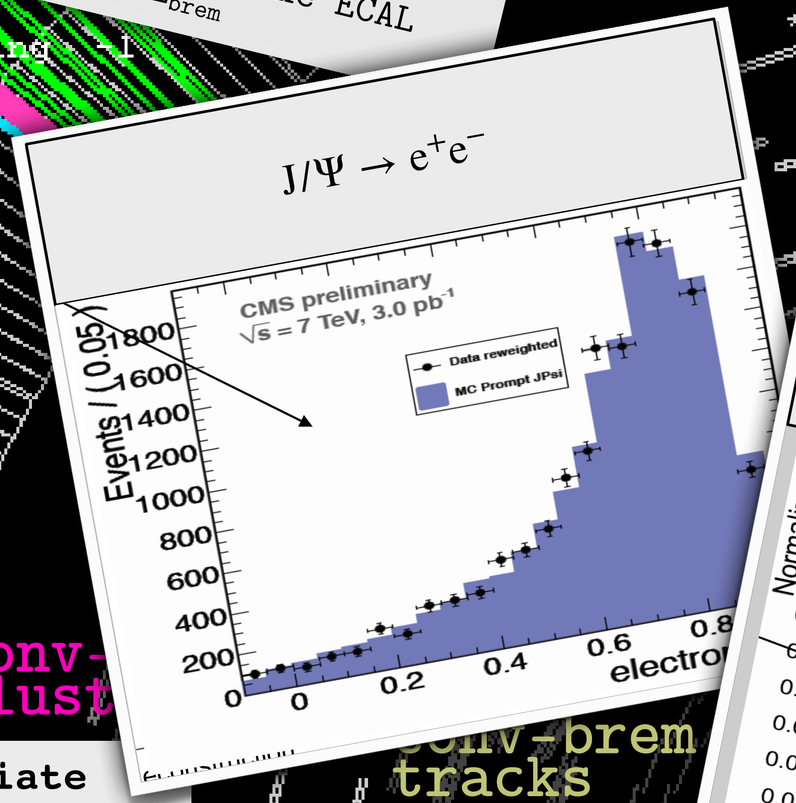

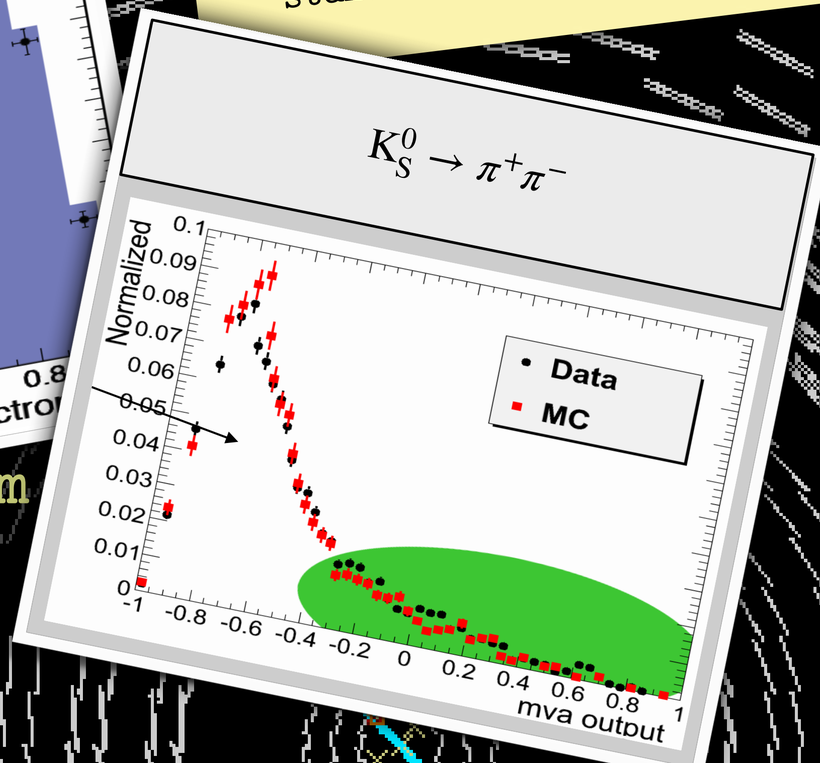

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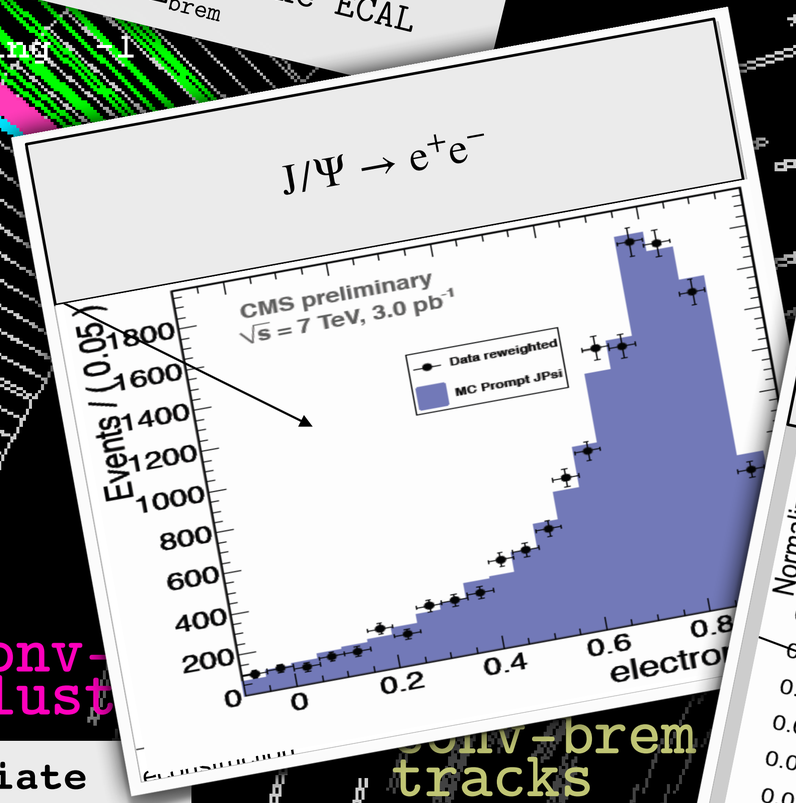
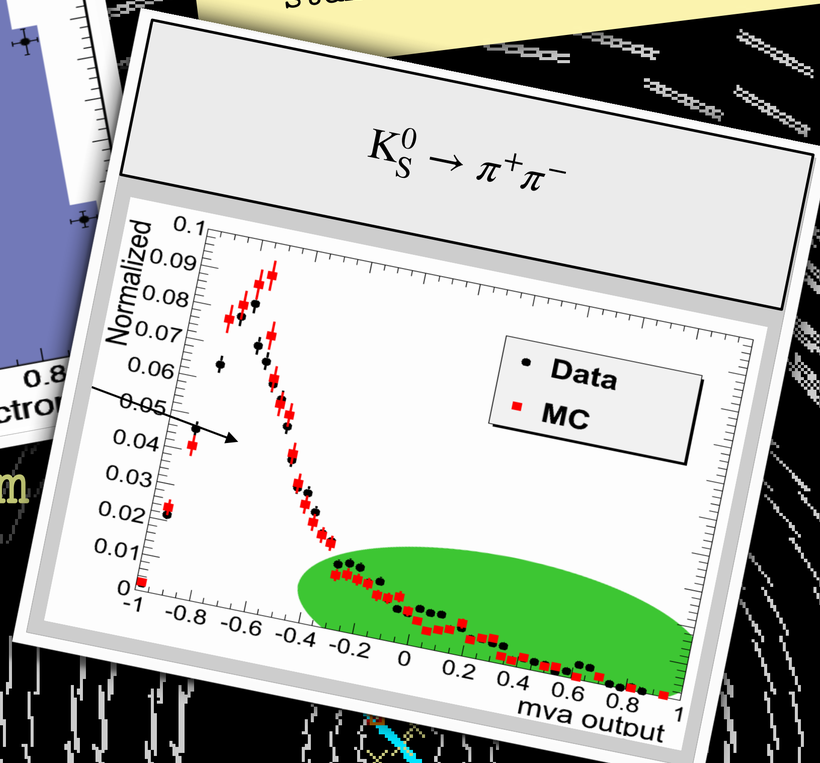
- 95% efficiency for isolated electrons
- 70-80% efficiency in jets





Tau ID & Reconstruction

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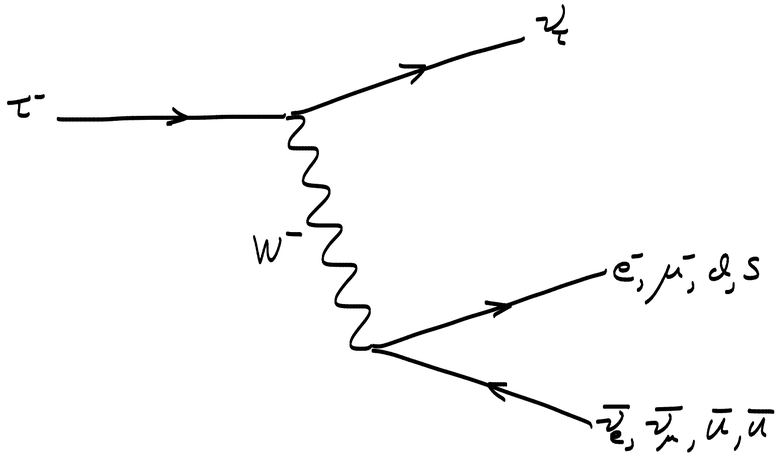
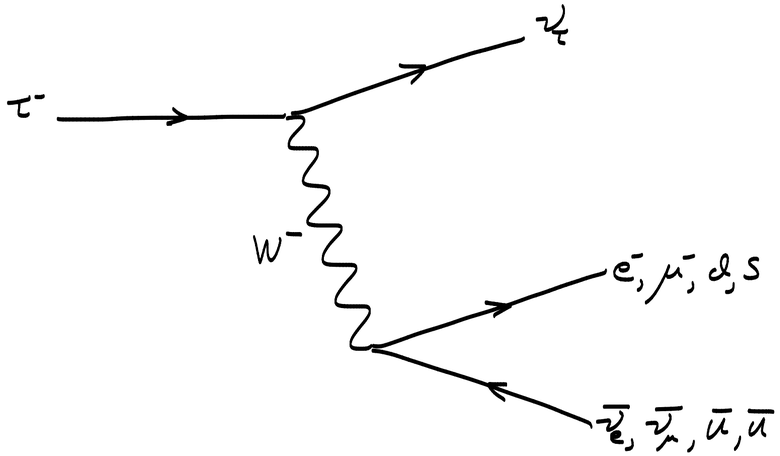


Tau ID & Reconstruction

- Massive, (relatively) long lived



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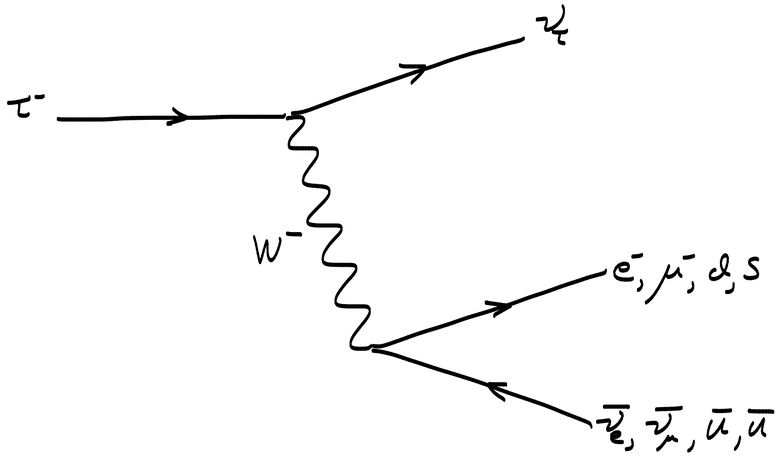

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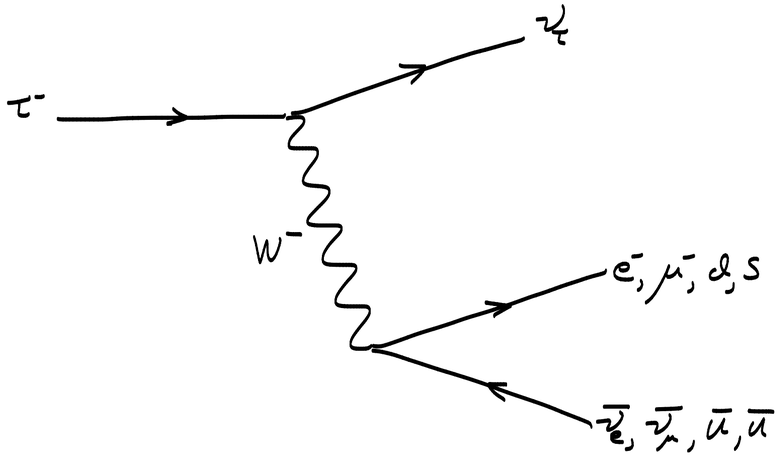

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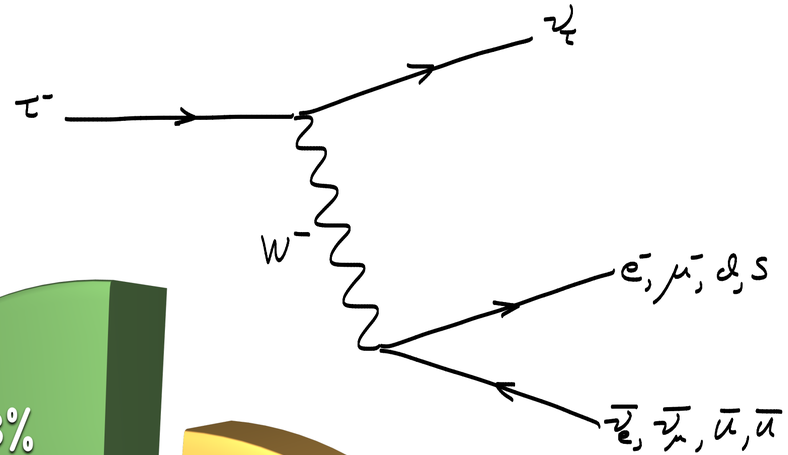
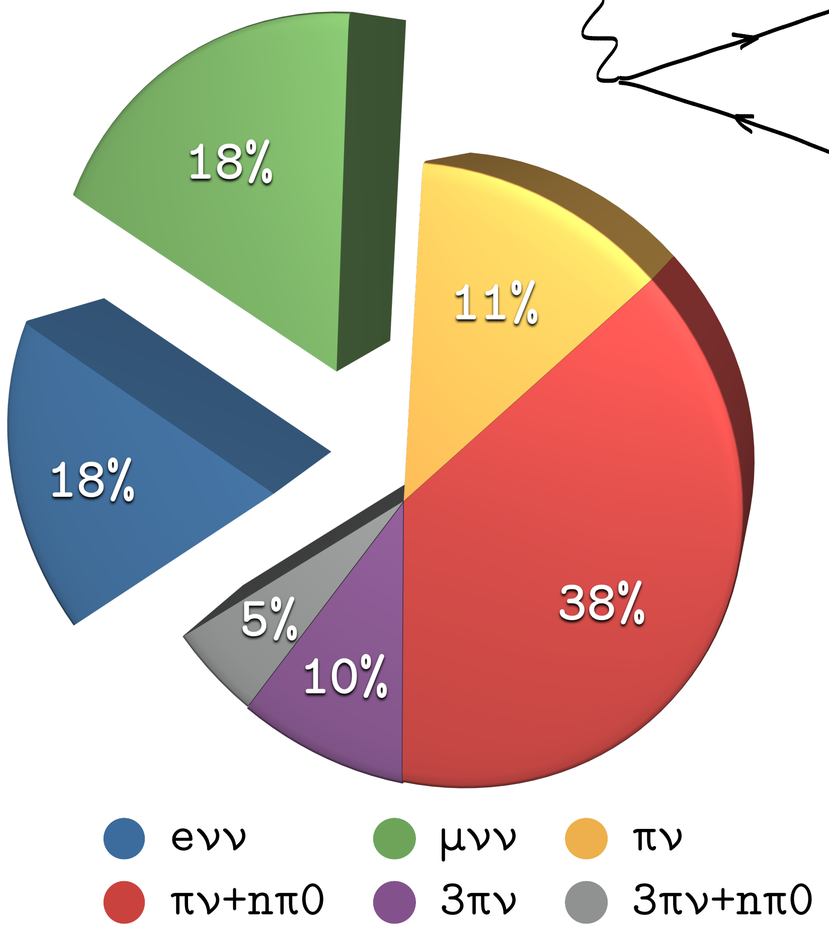
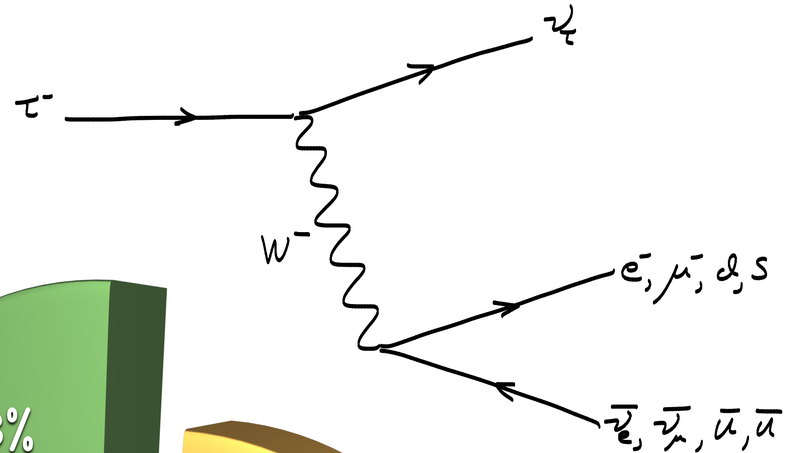
  - $c\tau = 87$ μm
- leptonic decays: 35%

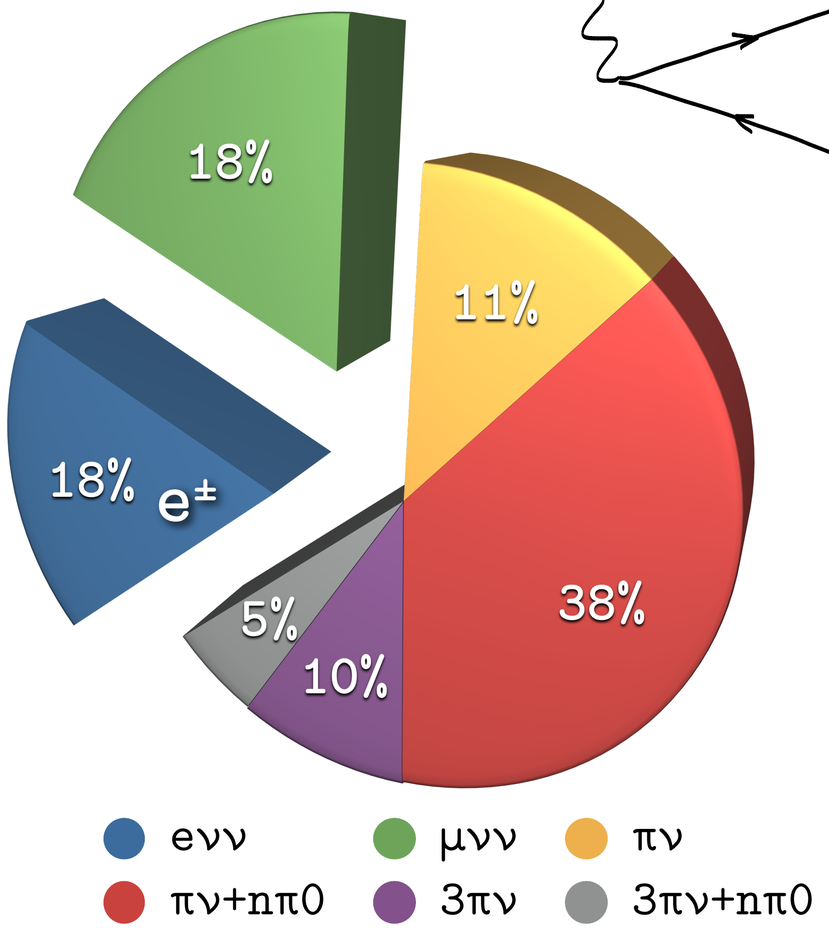




Tau ID & Reconstruction

- Massive, (relatively) long lived
  - $m(\tau^{\pm}) = 1.7$ GeV
  - $c\tau = 87$ μm
- leptonic decays: 35%
  - electron: 17.5%





Tau ID & Reconstruction

- Massive, (relatively) long lived
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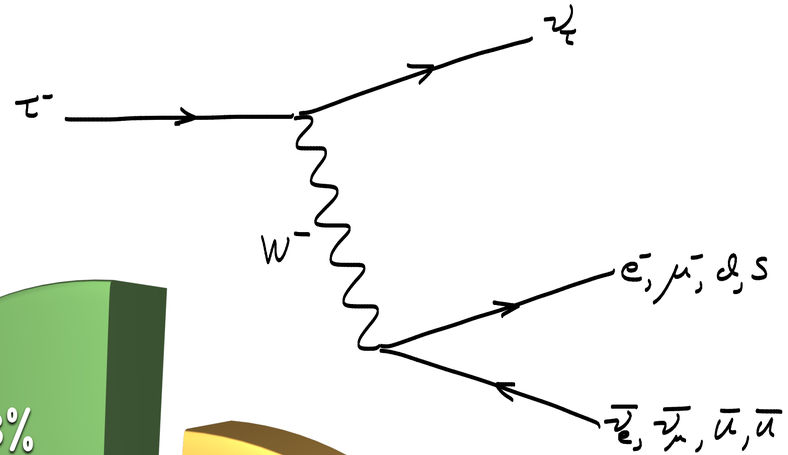
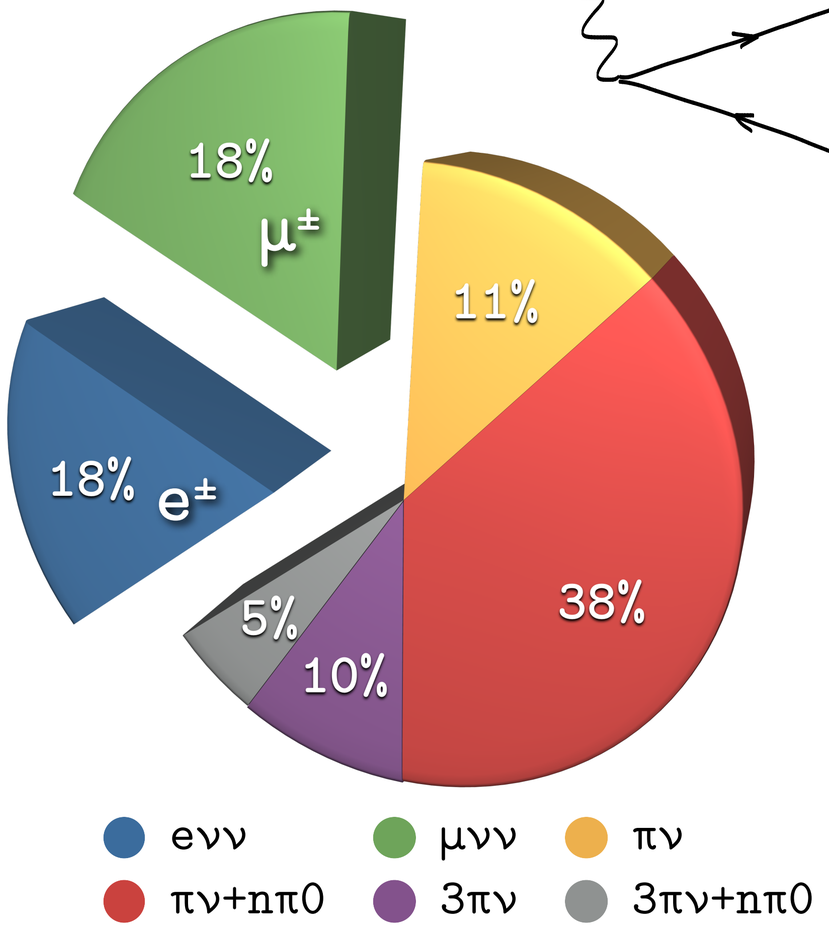
  - $c\tau = 87\ \mu m$
- leptonic decays: 35%
  - electron: 17.5%
  - muon: 17.5%





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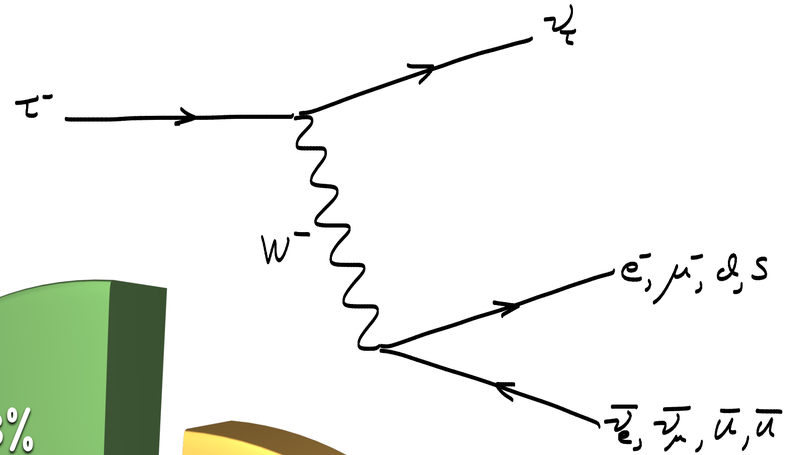
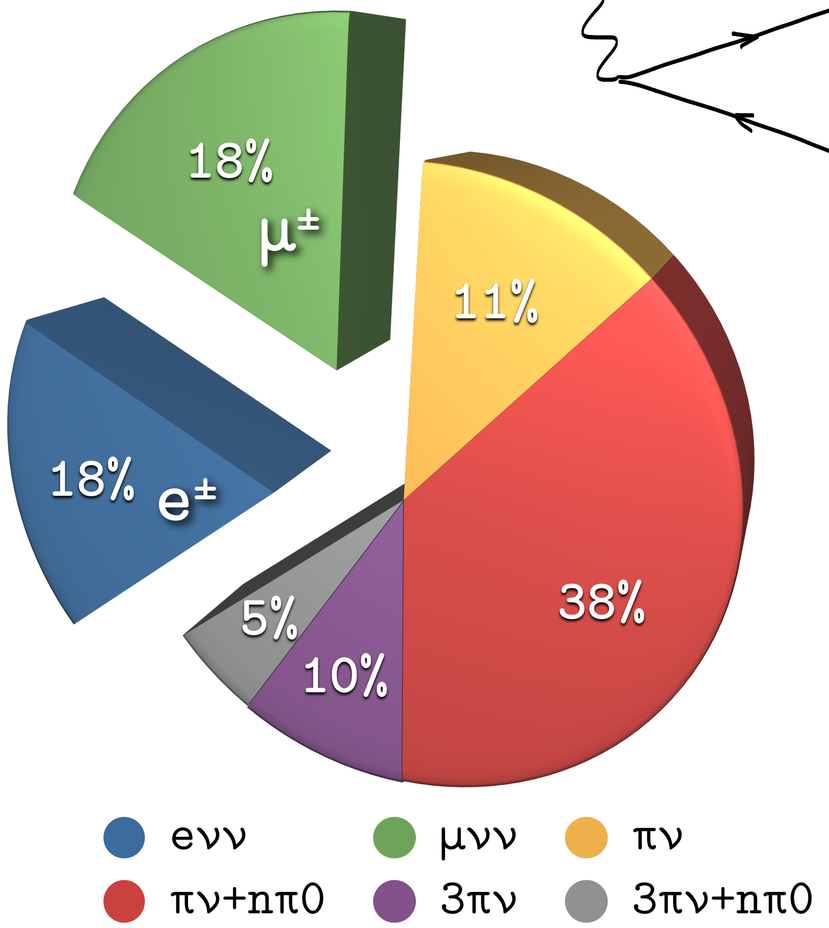
I won't talk about leptonic decays





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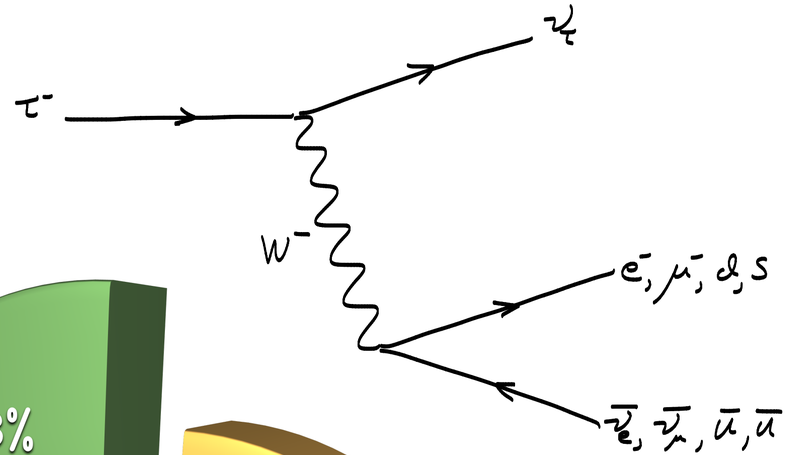
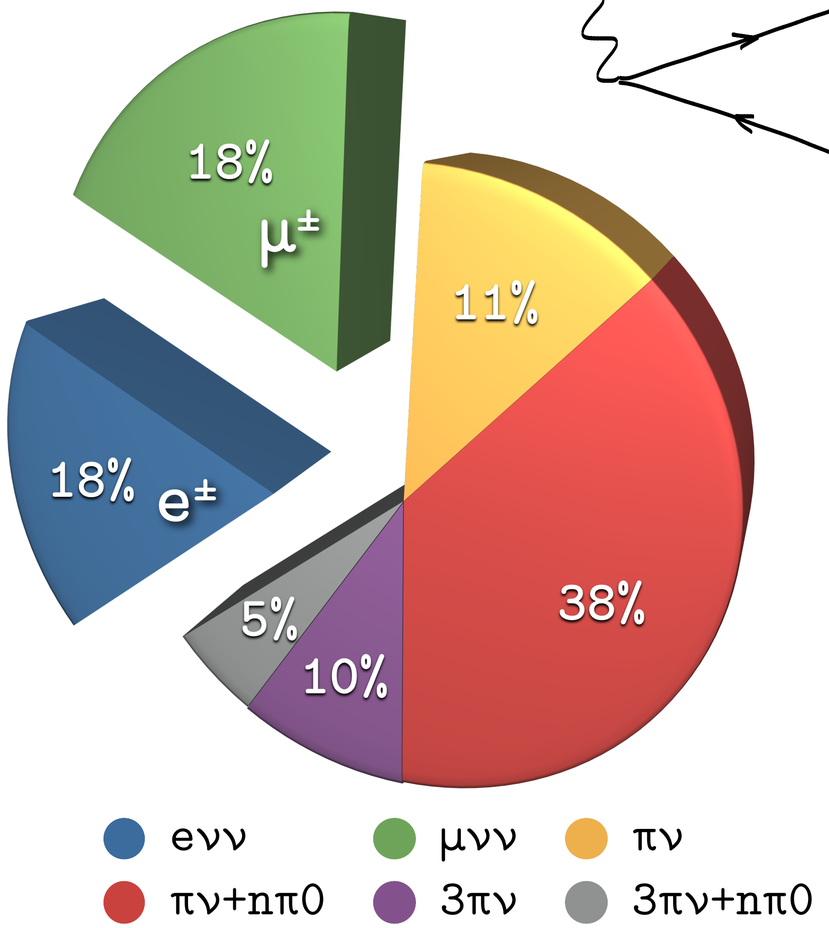
I won't talk about leptonic decays





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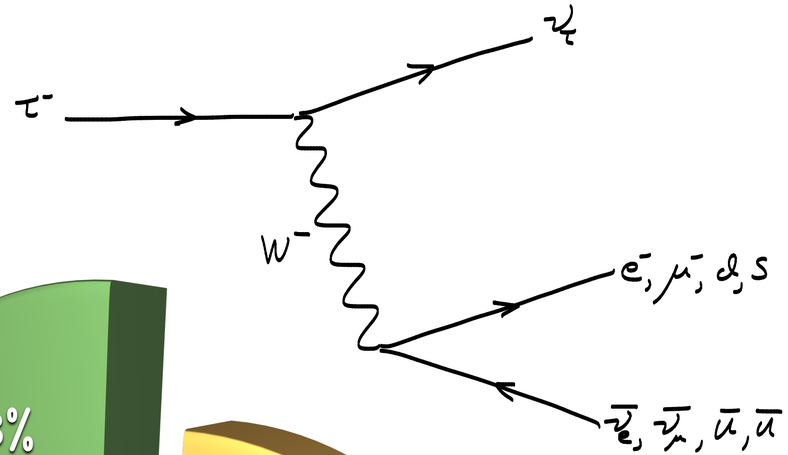
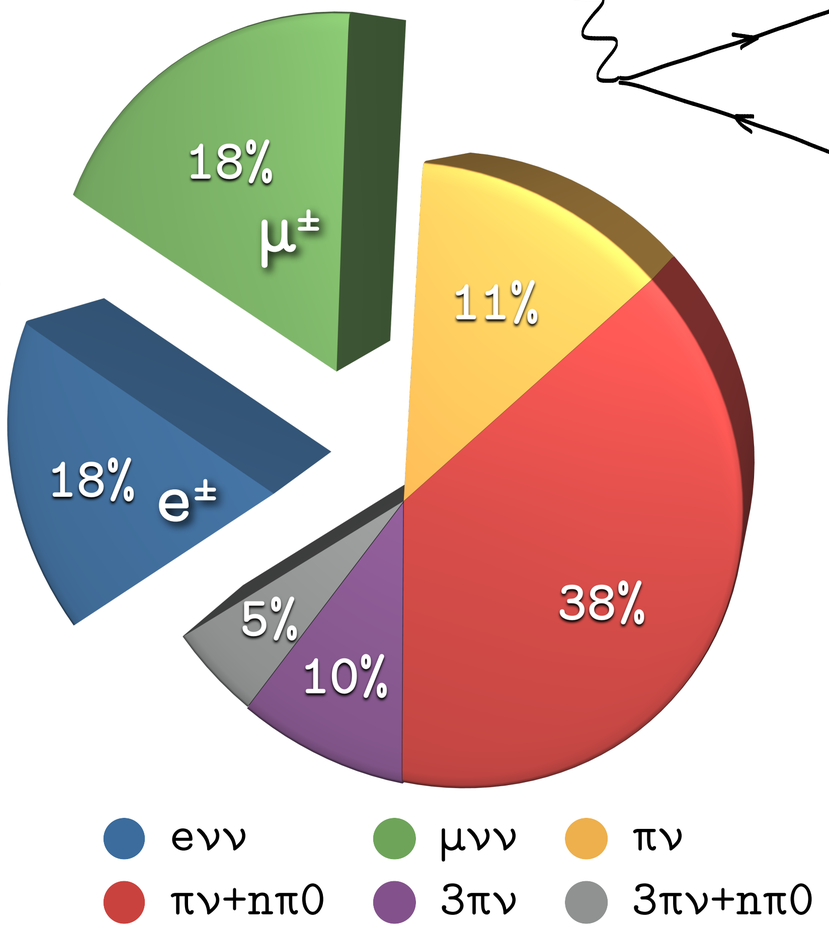
  - single prong: 49%

I won't talk about leptonic decays





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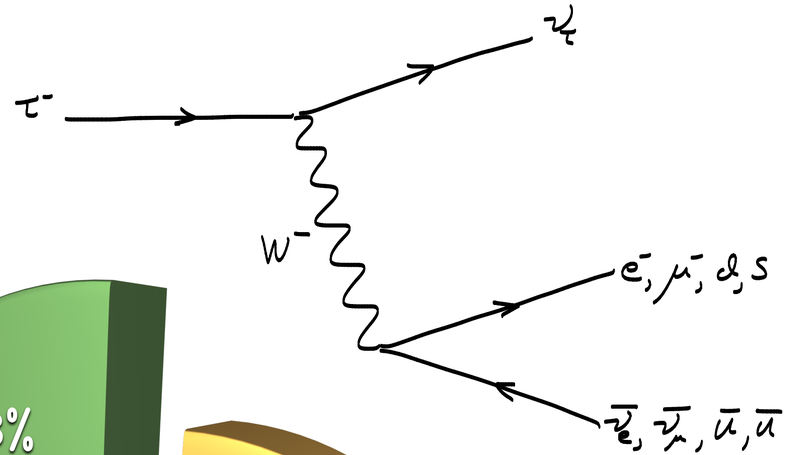

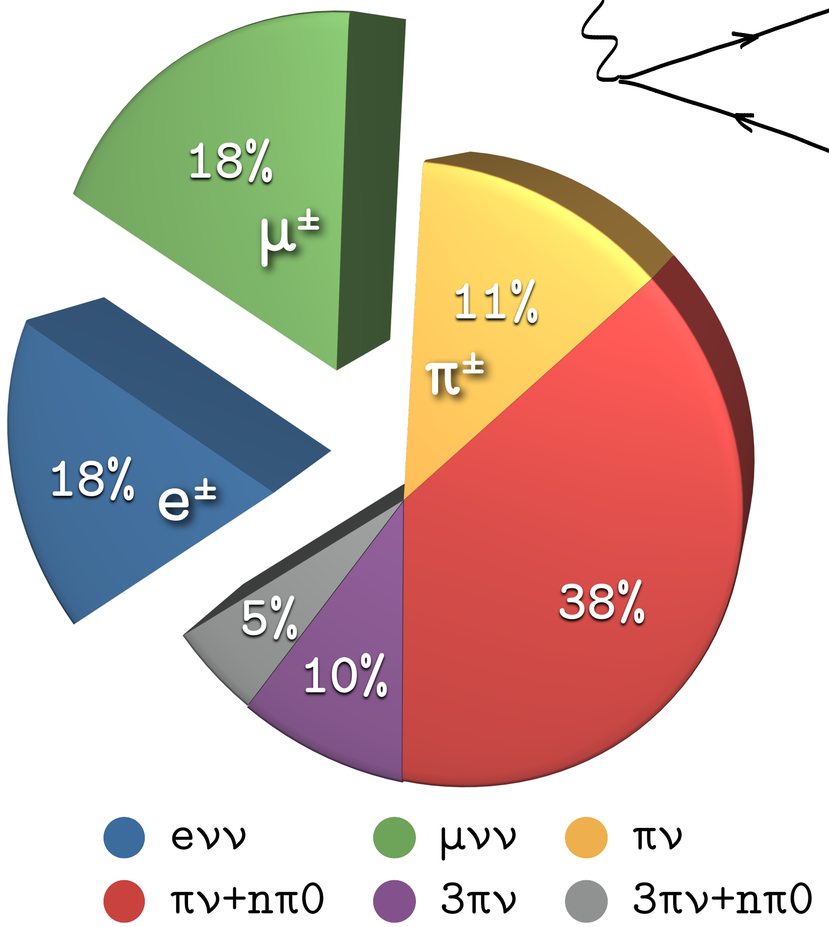

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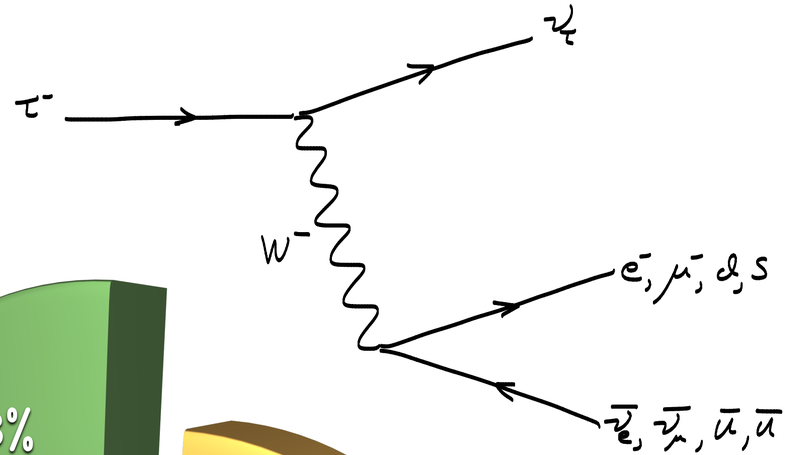

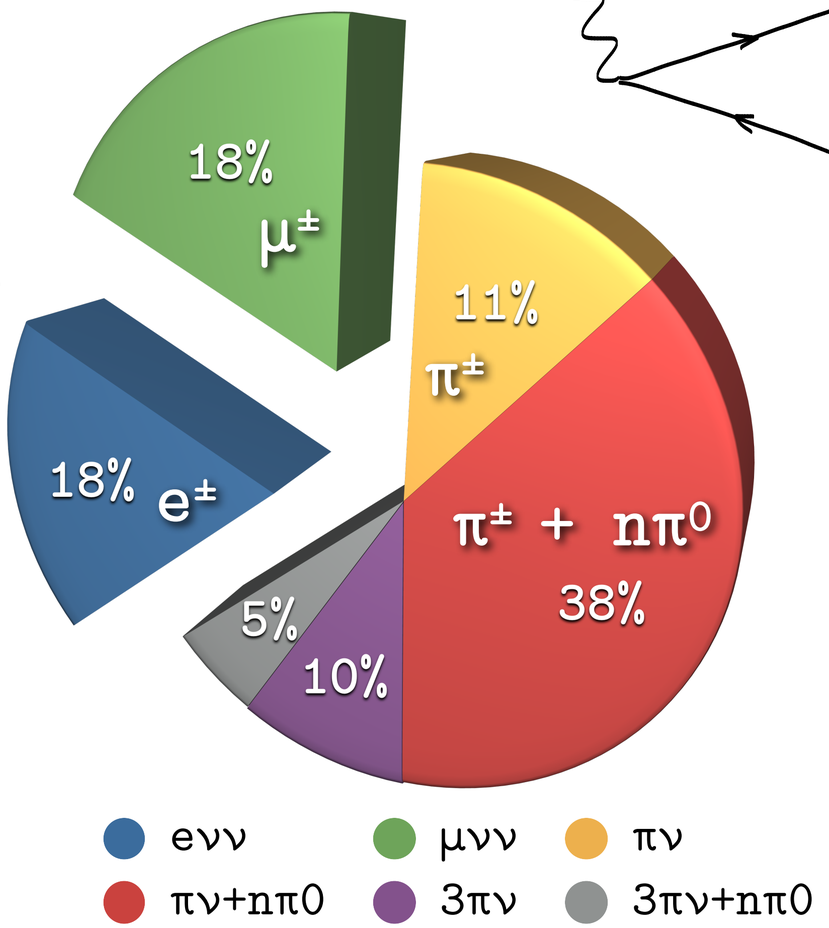

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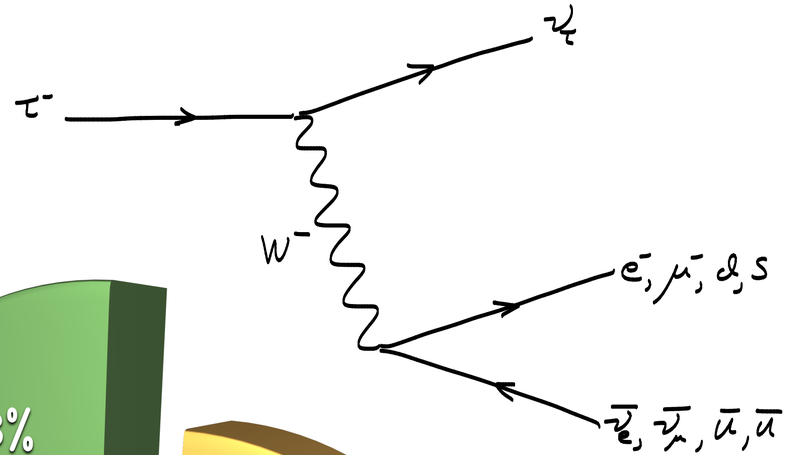

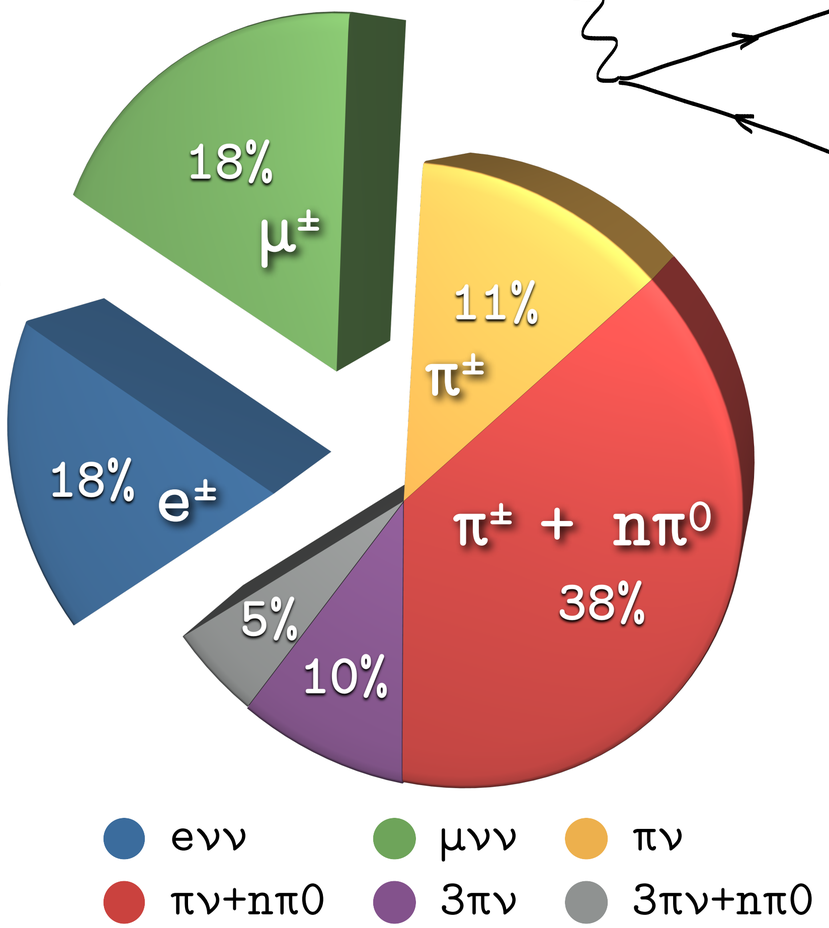

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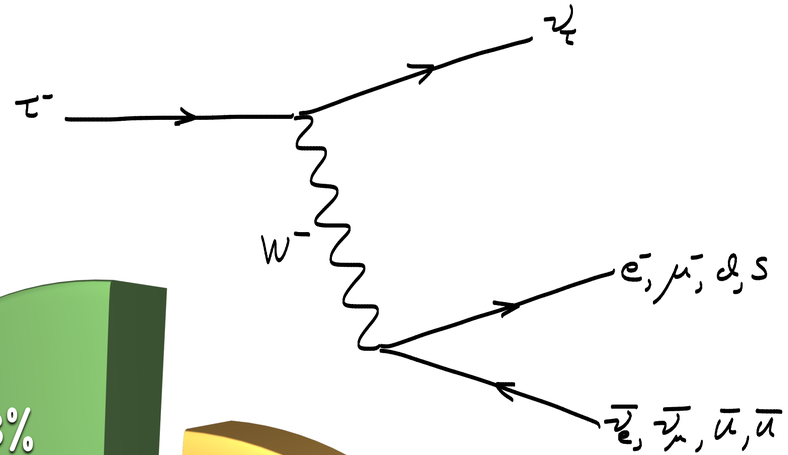

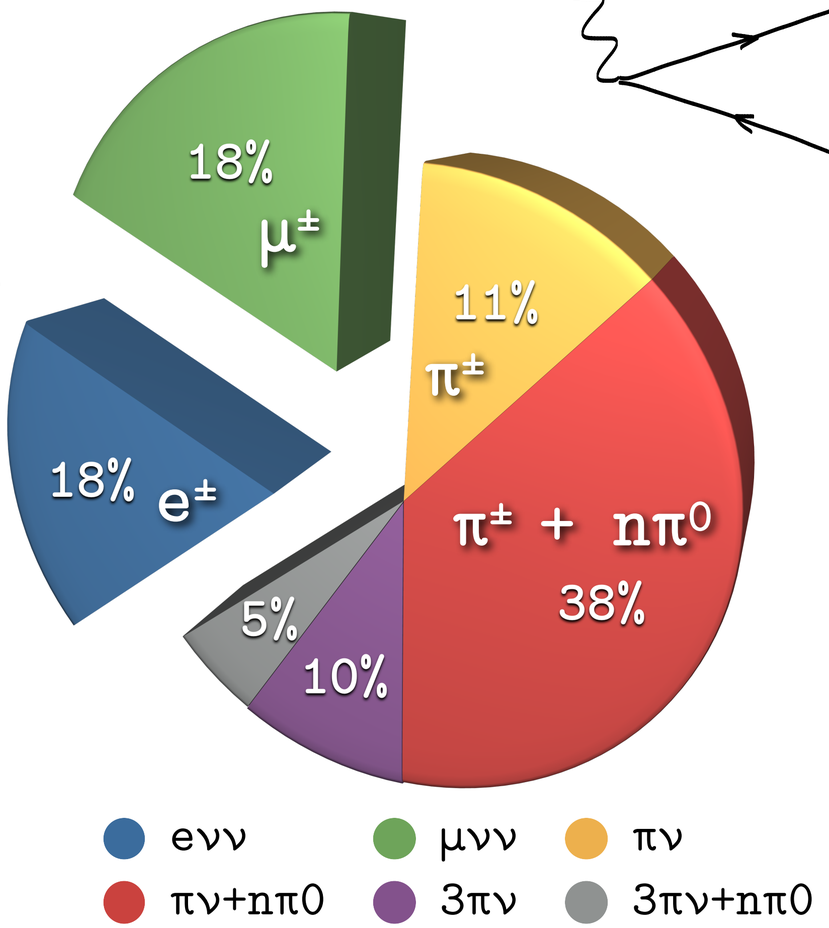

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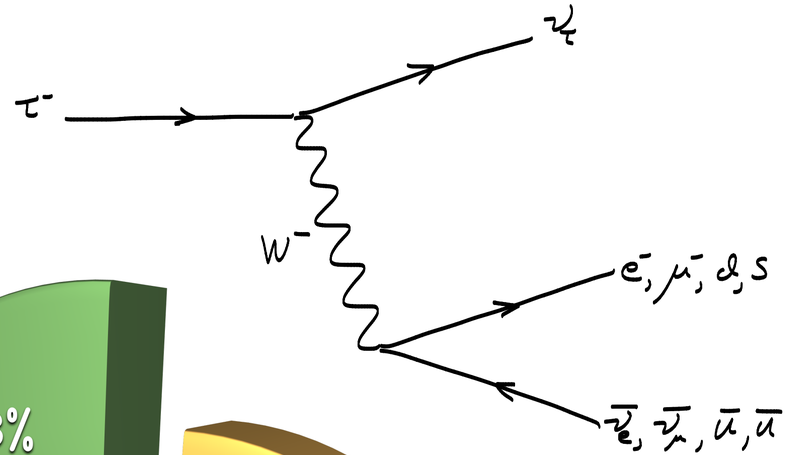

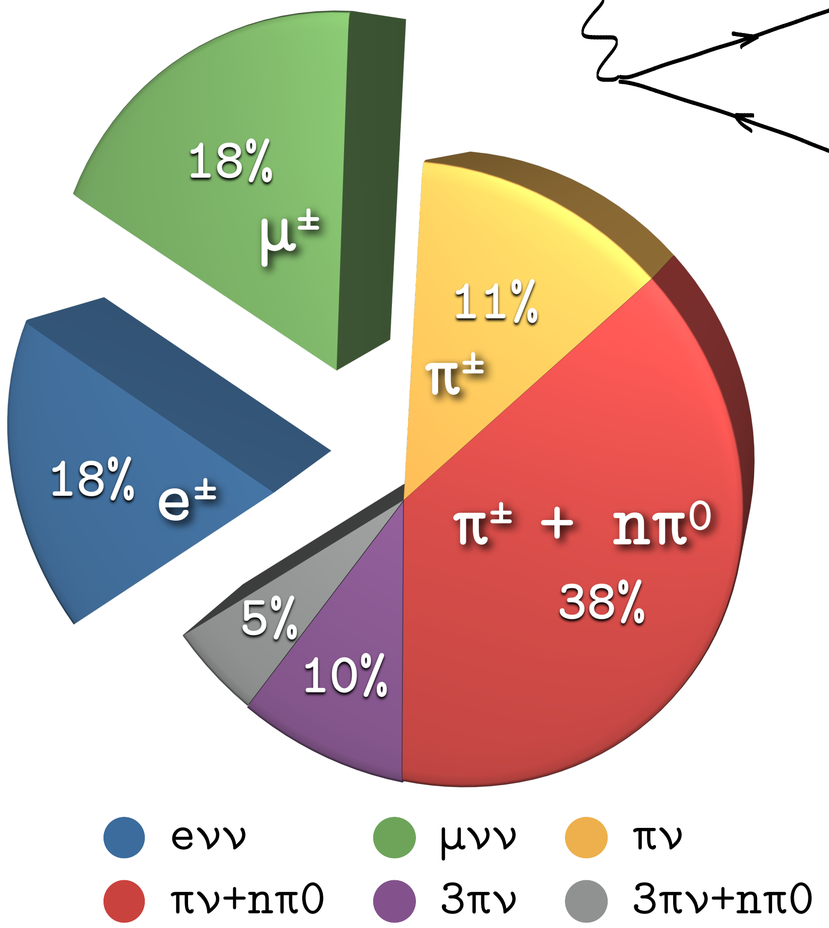

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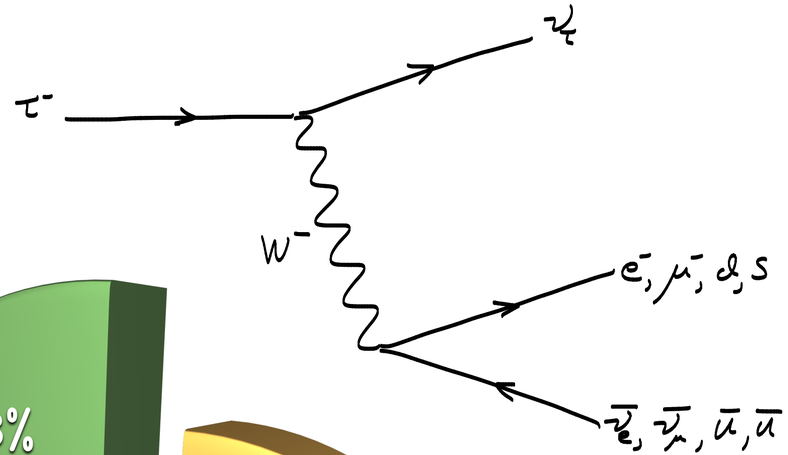
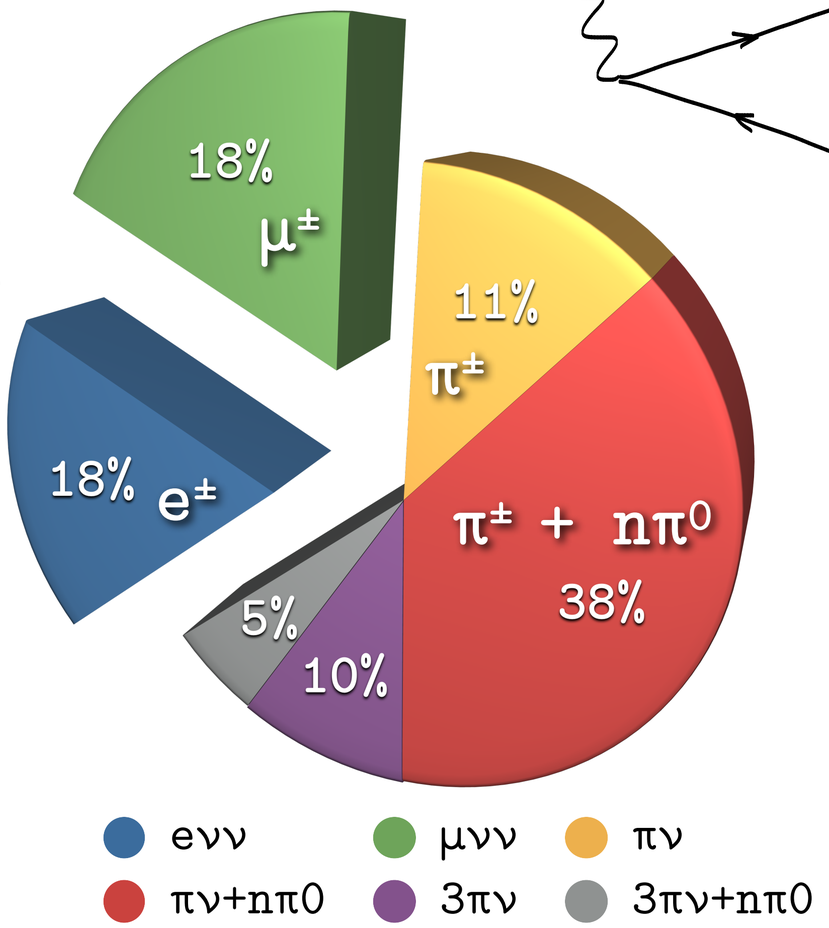
I won't talk about leptonic decays





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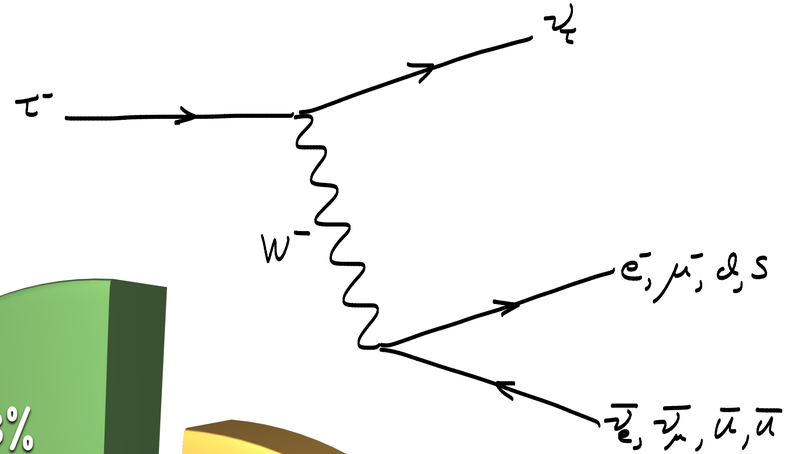
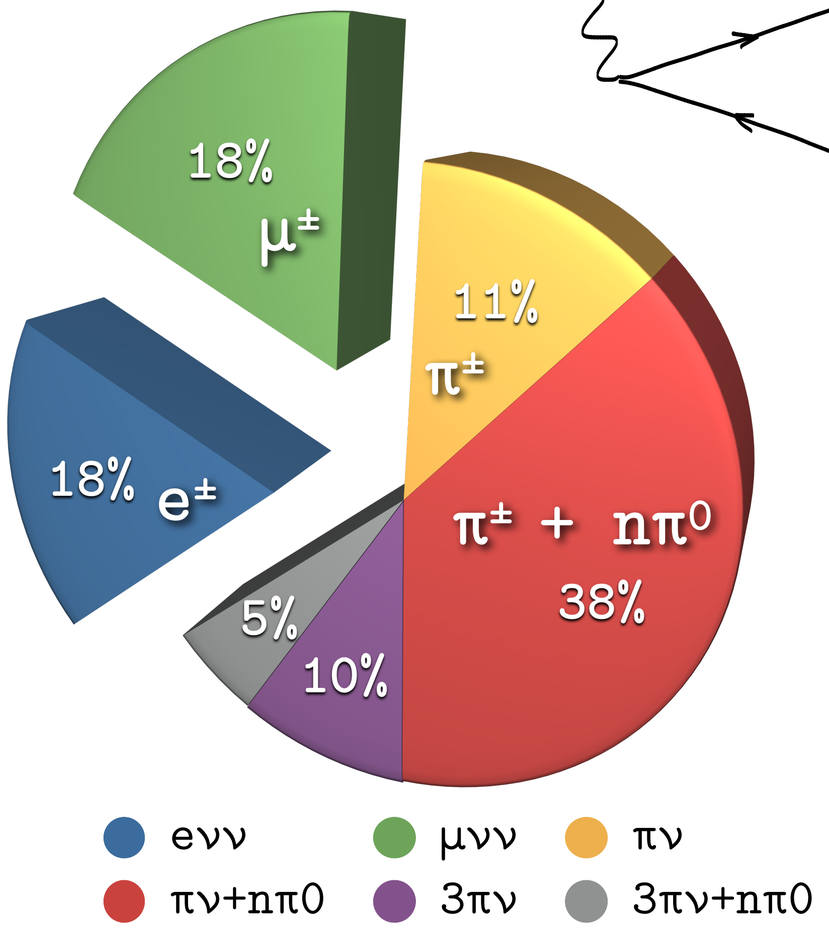
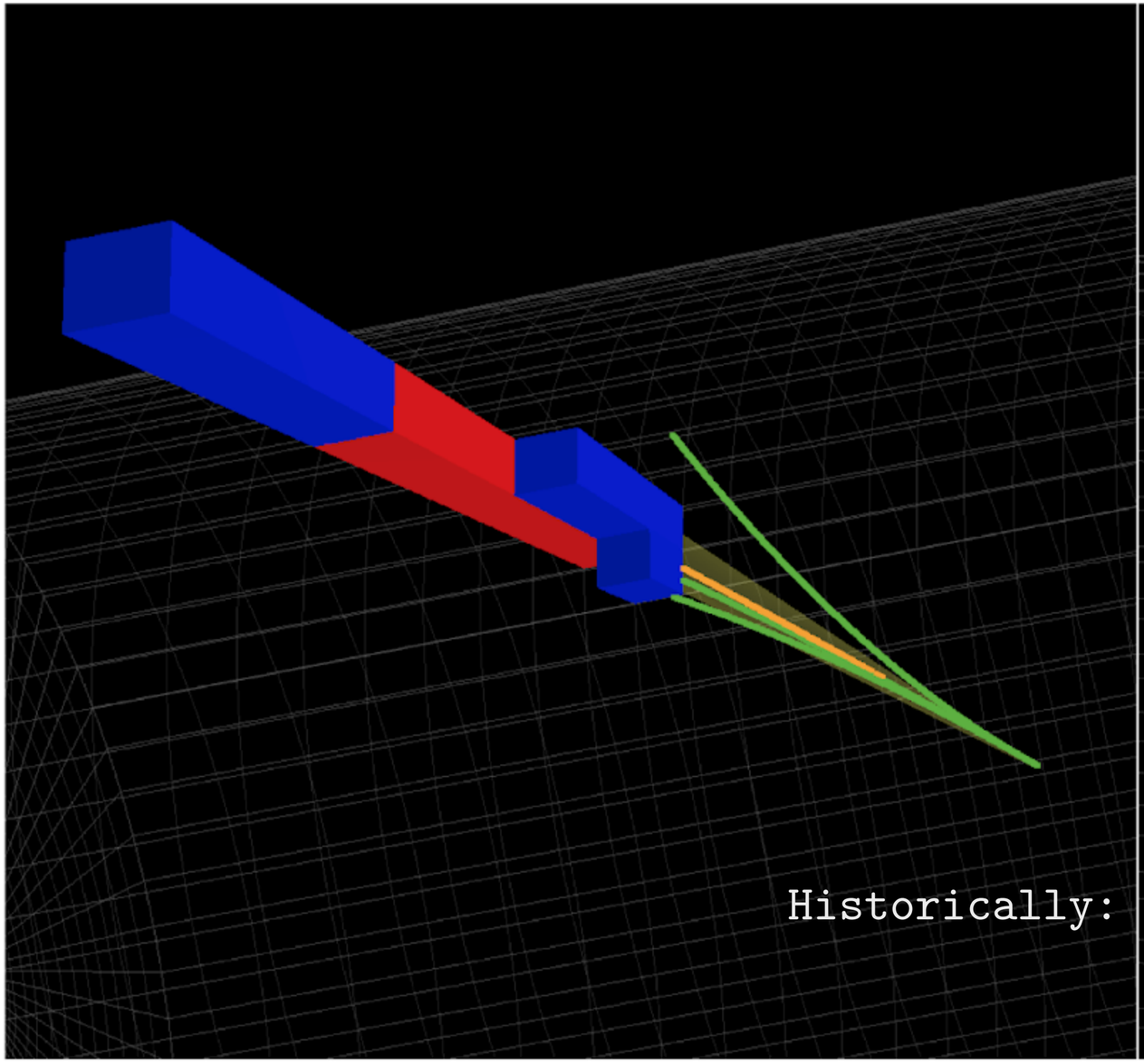
- Experimental inefficiencies and fakes
  - reality: 0,1,2,3,4 pions + 0,1,2,3,4+ photons

I won't talk about leptonic decays

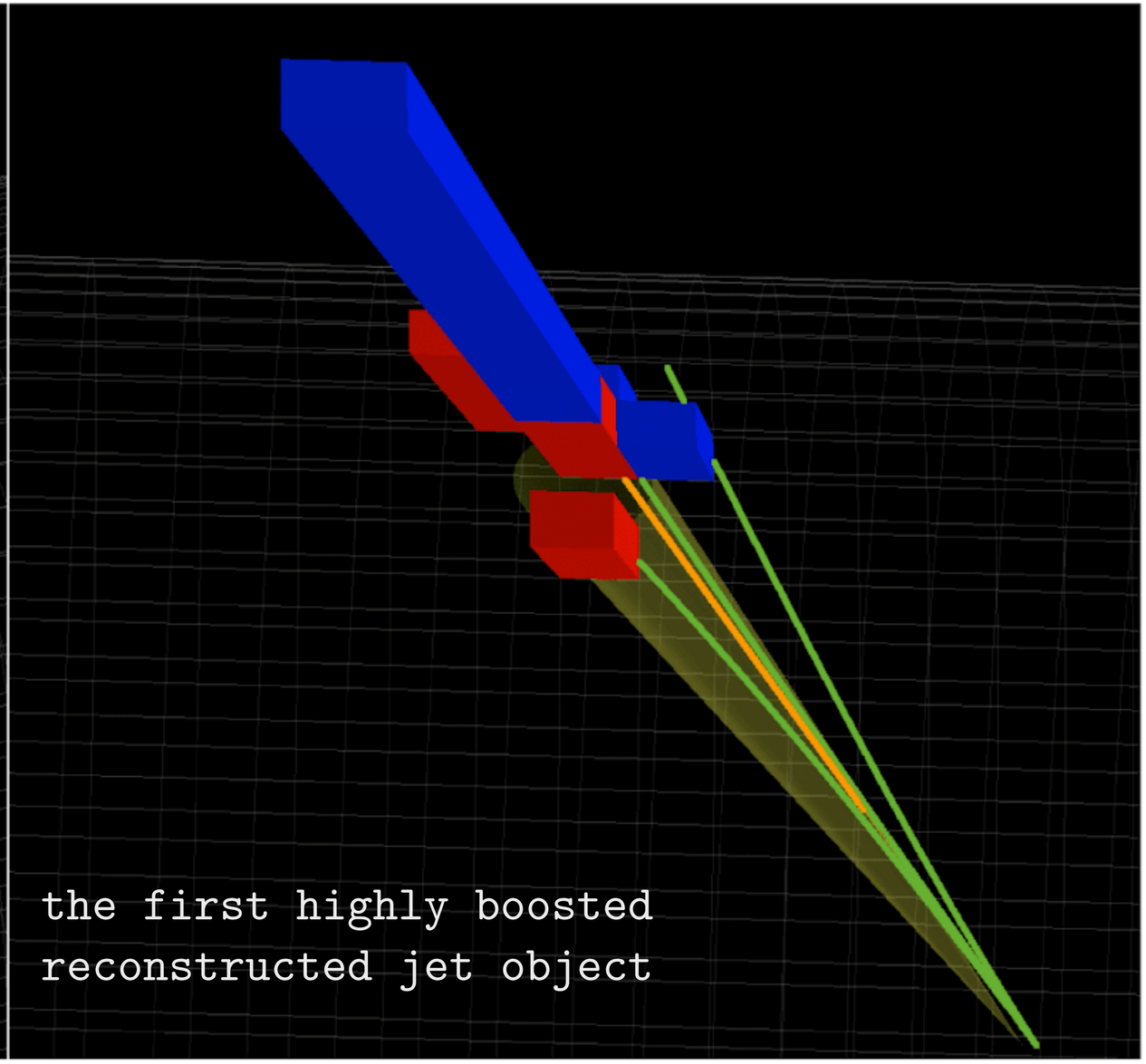




Tau ID & Reconstruction



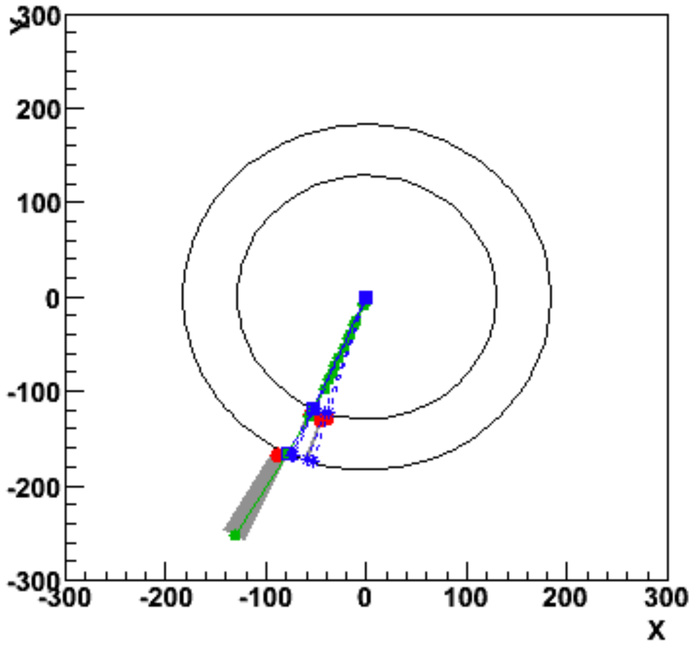
Historically:



the first highly boosted reconstructed jet object

Tau ID & Reconstruction

Tau ID & Reconstruction



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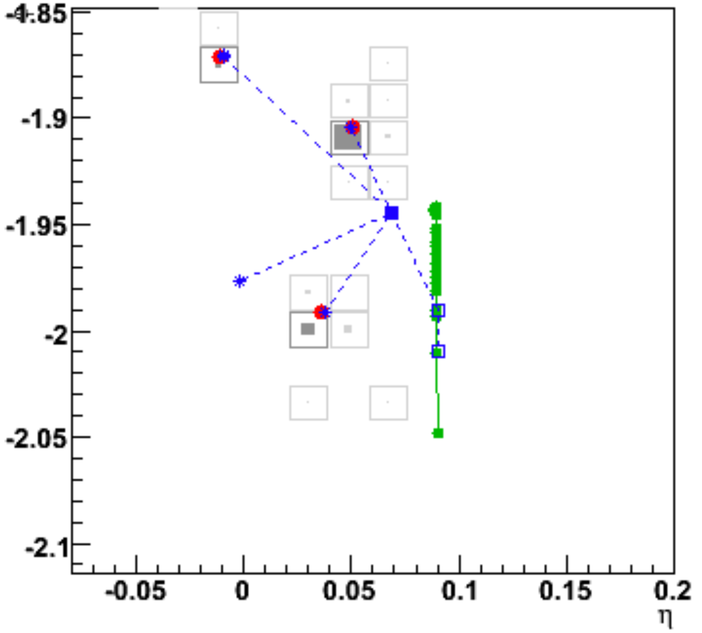

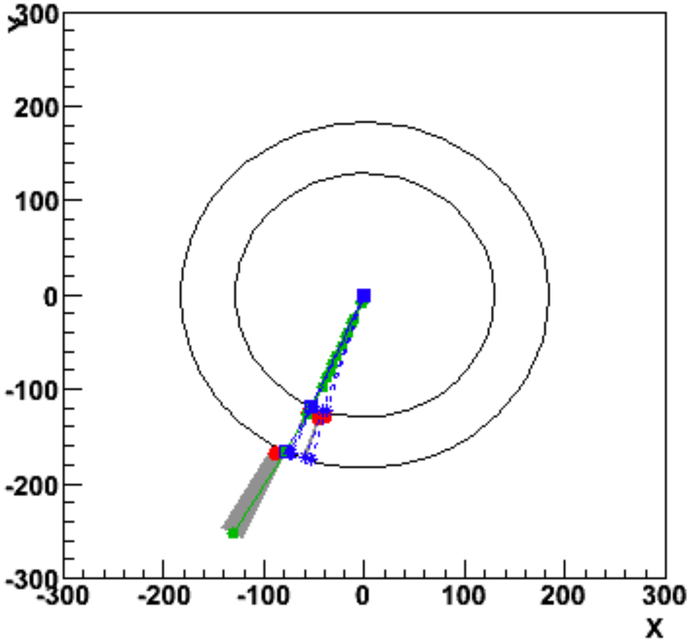

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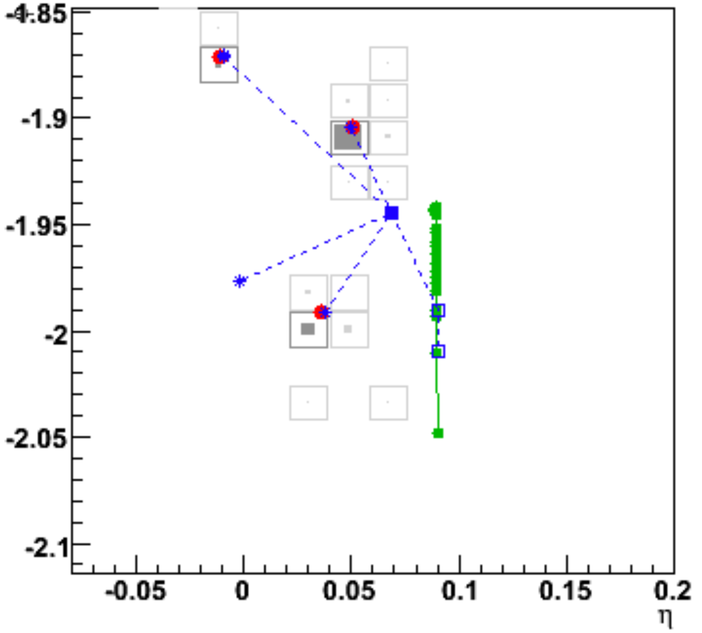

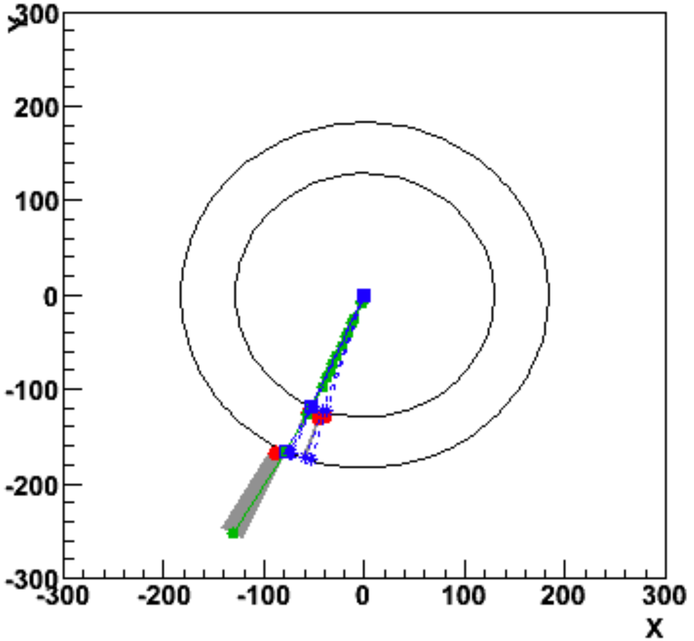

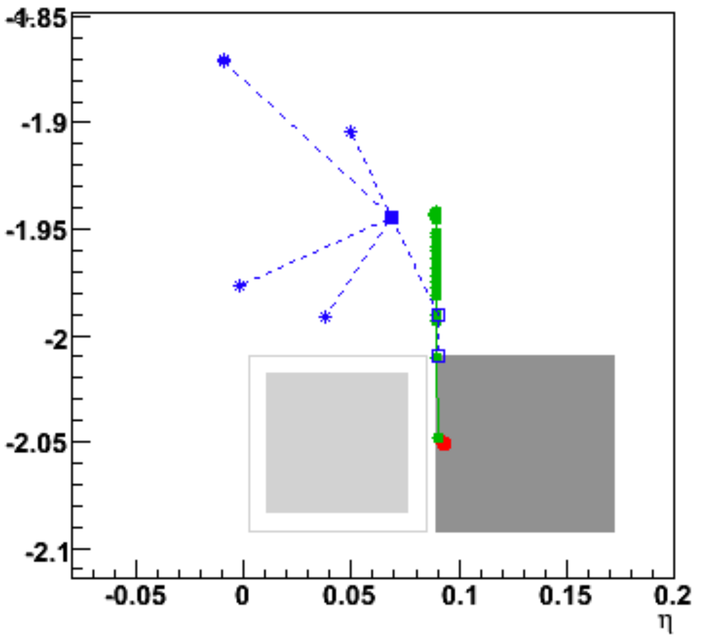

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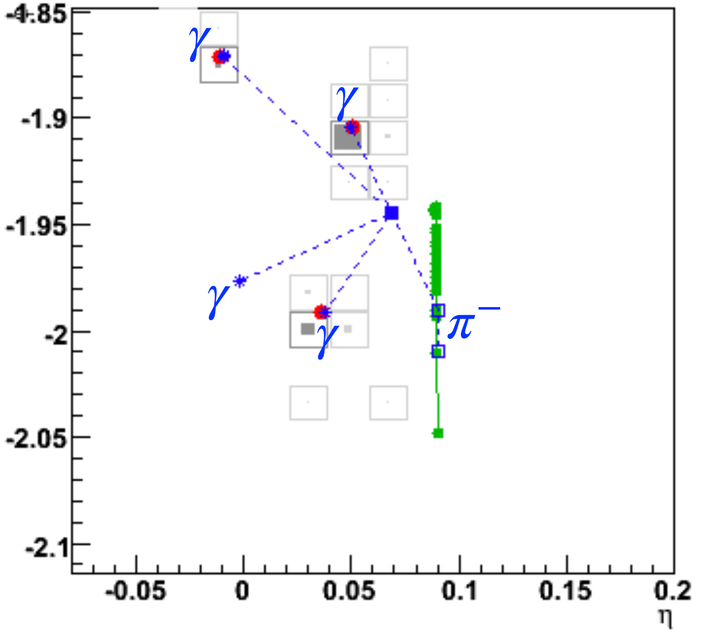

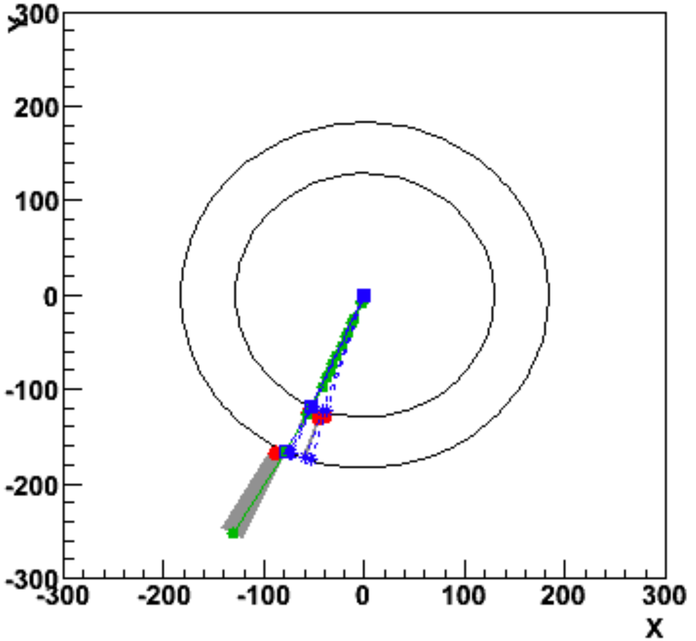

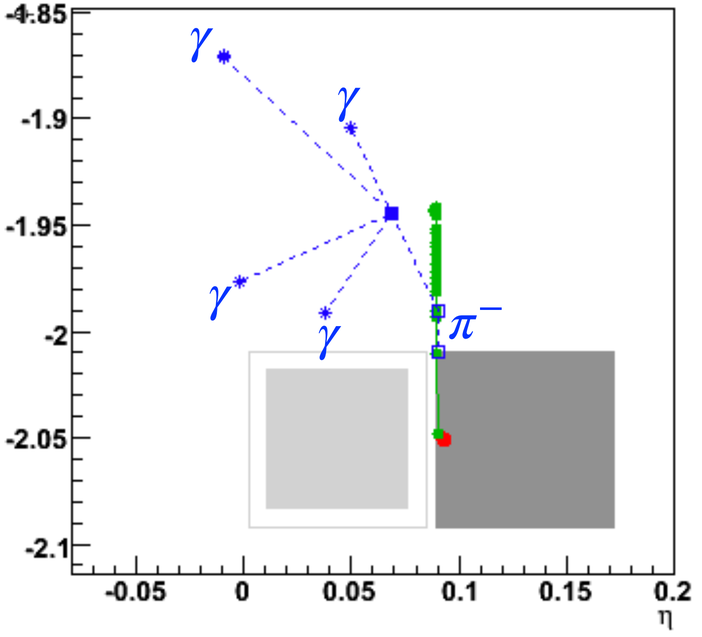

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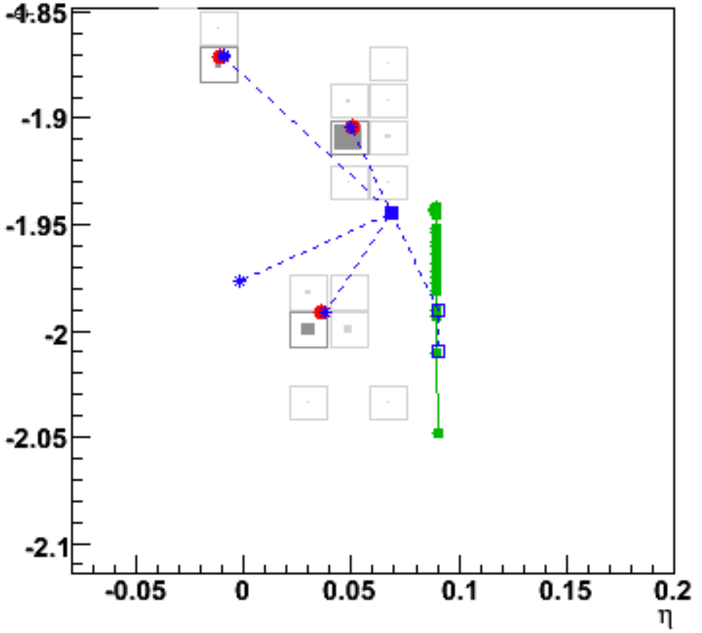
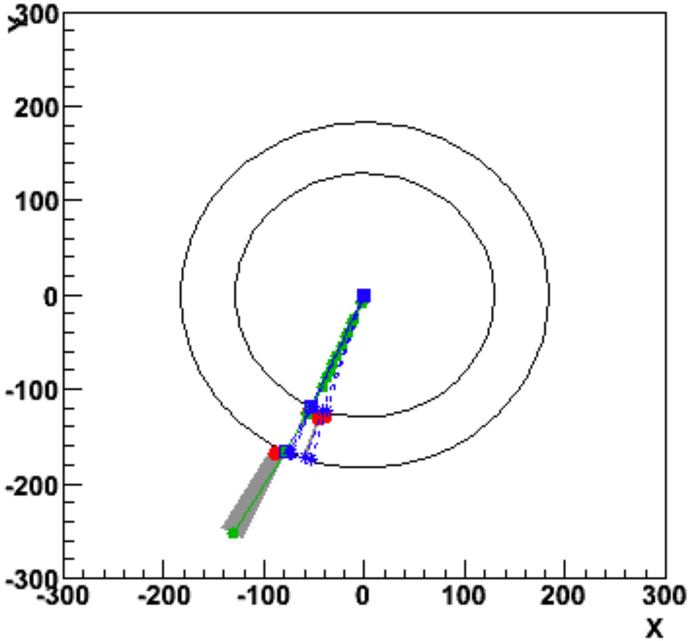
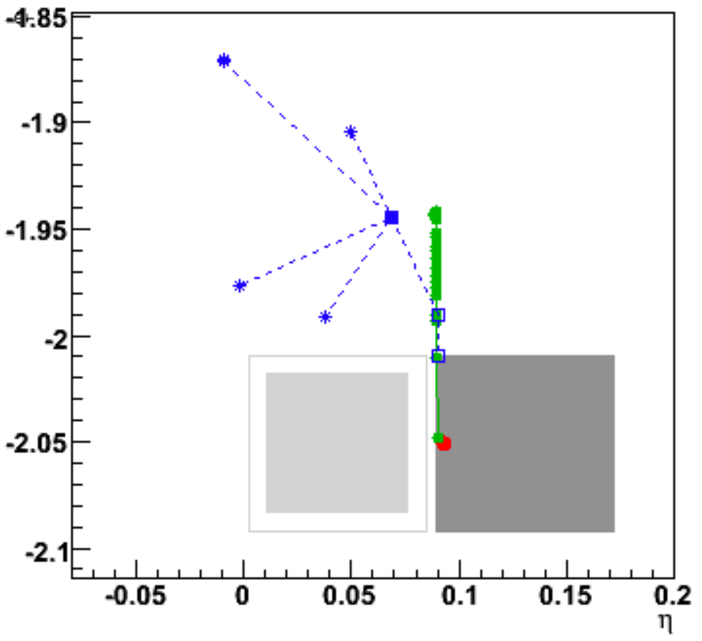


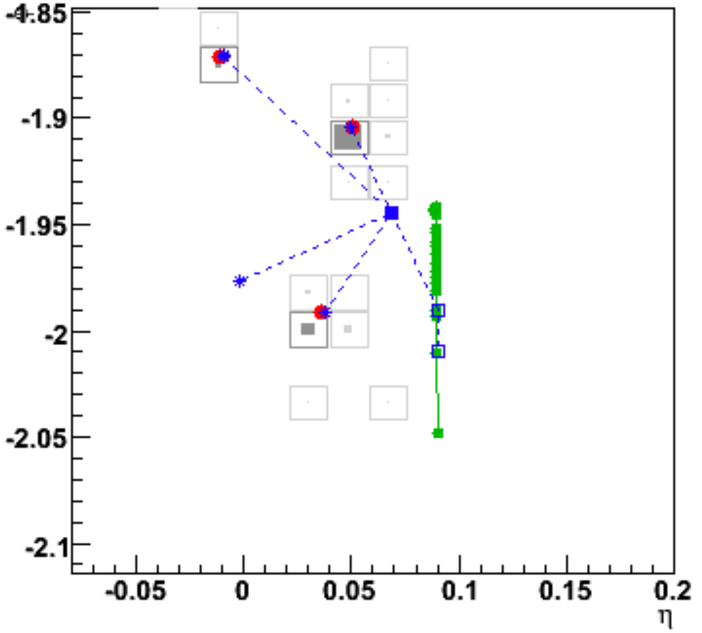


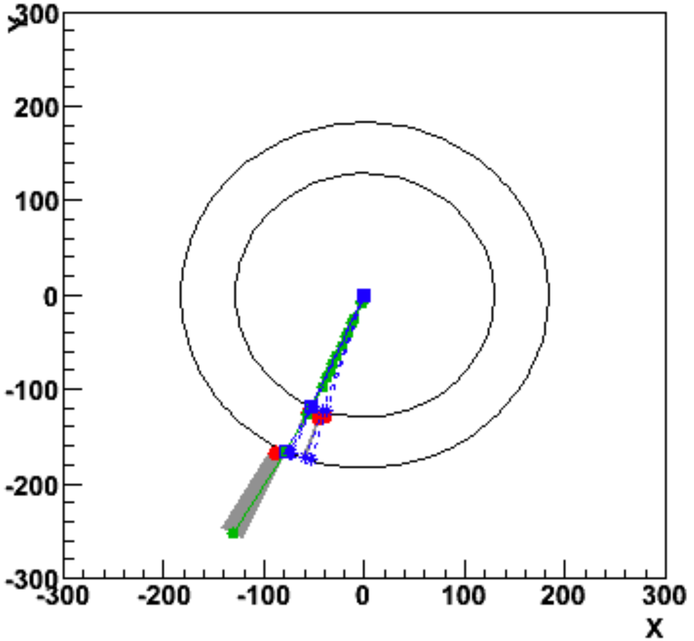


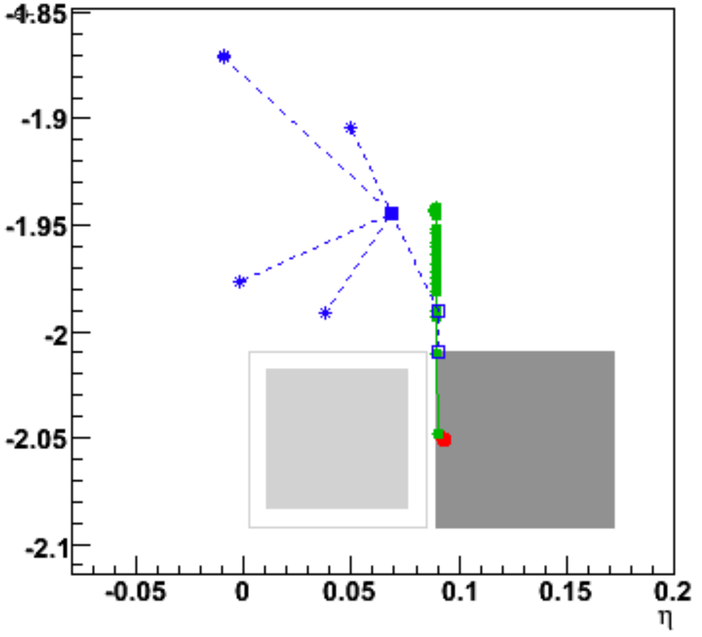
Tau ID & Reconstruction

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
  - $\Delta\eta \times \Delta\varphi$ = 0.05x0.2
  - to capture all conversions
- Combine with $\pi^{\pm}$'s to form tau candidates







Tau ID & Reconstruction

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

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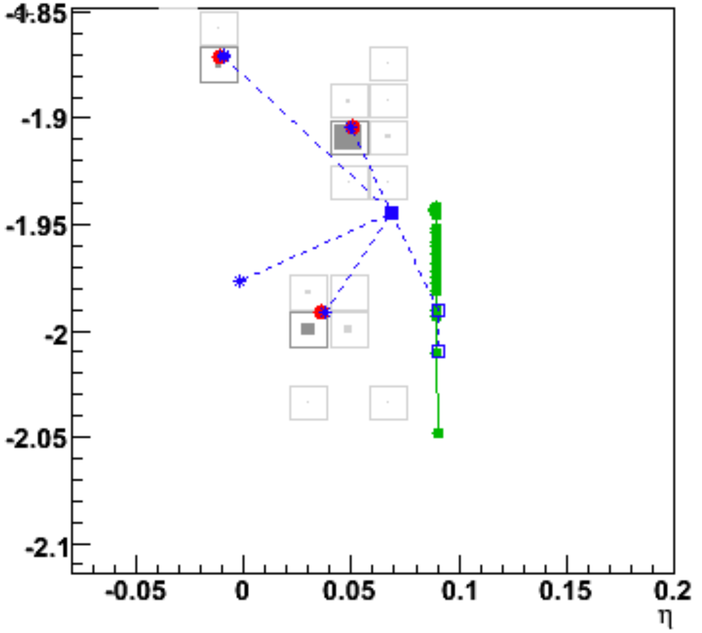

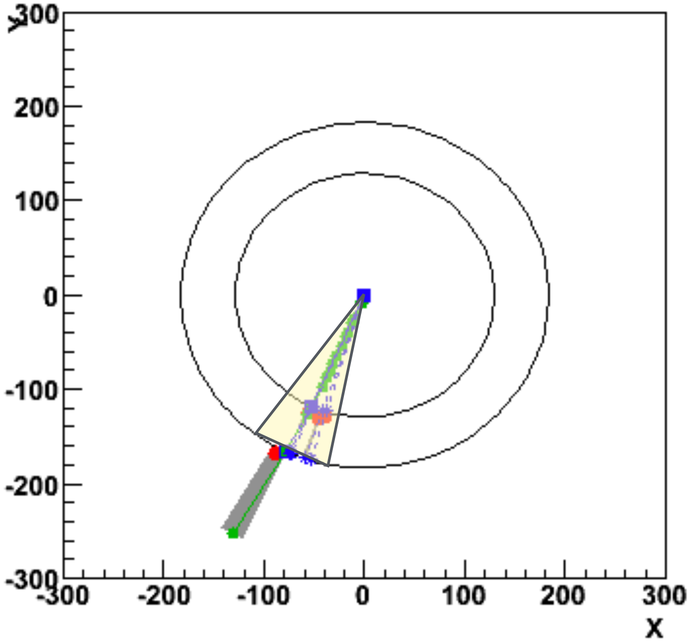

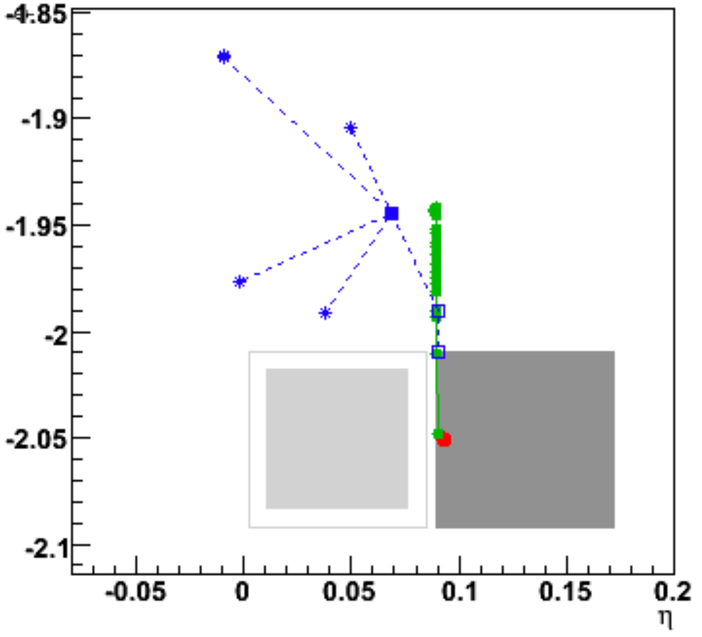

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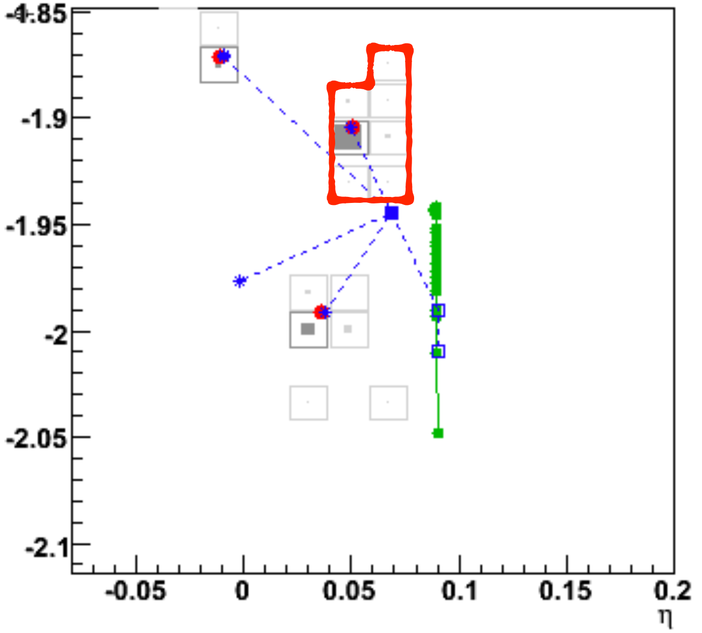

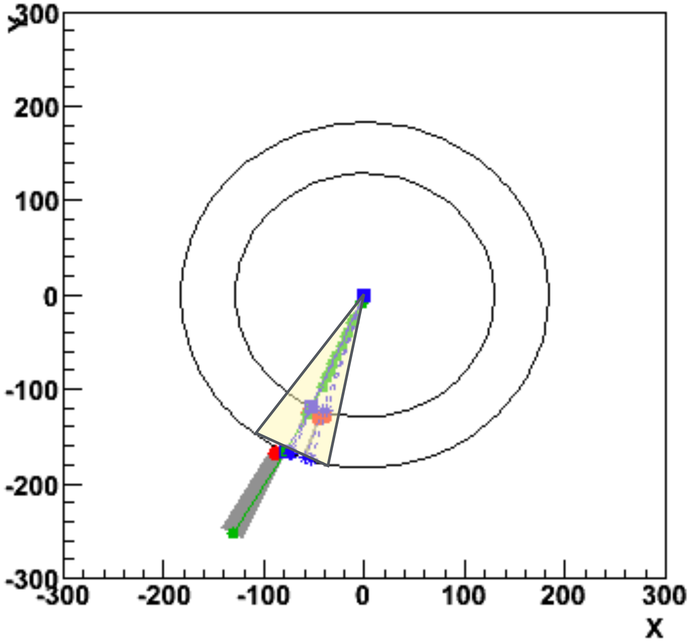

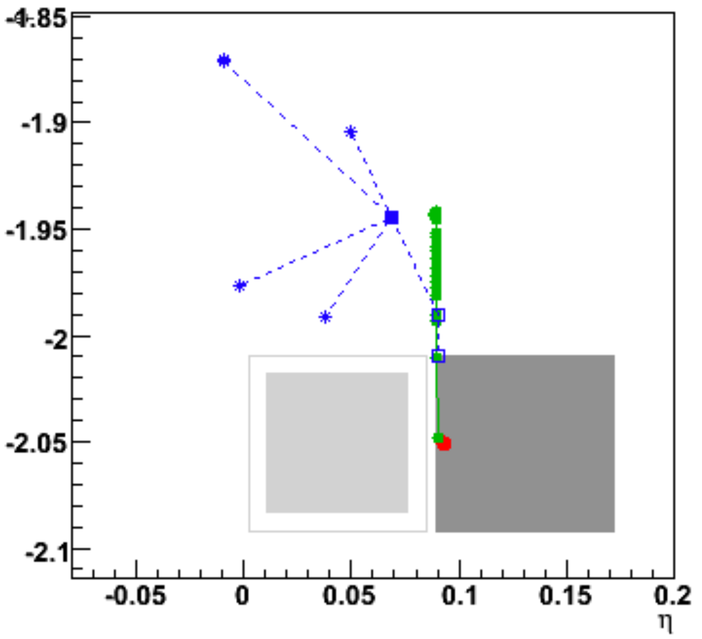

Tau ID & Reconstruction

Basic Idea

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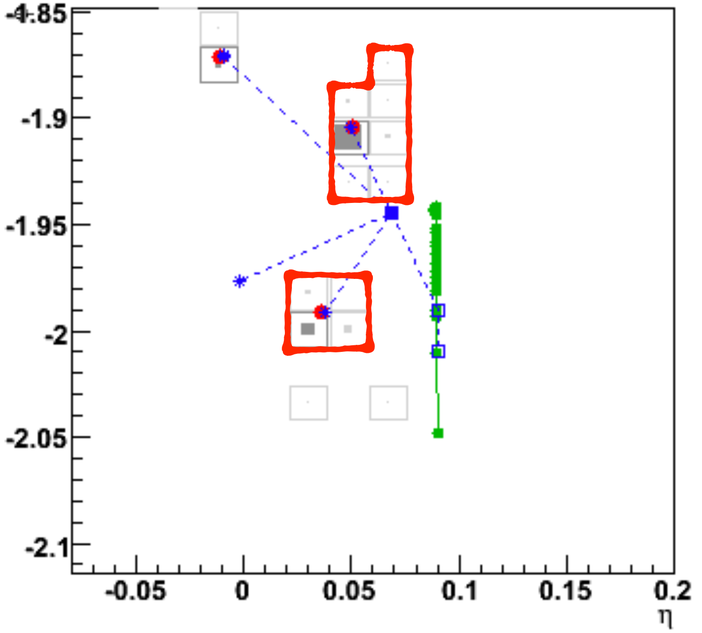

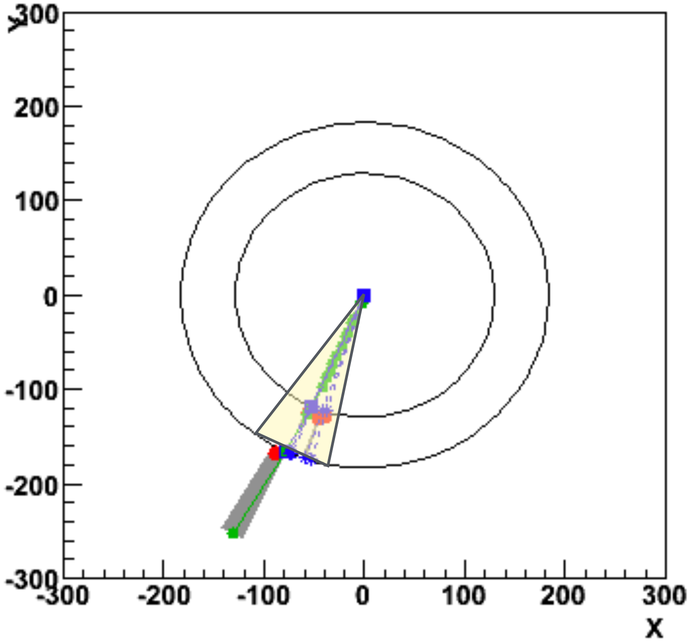

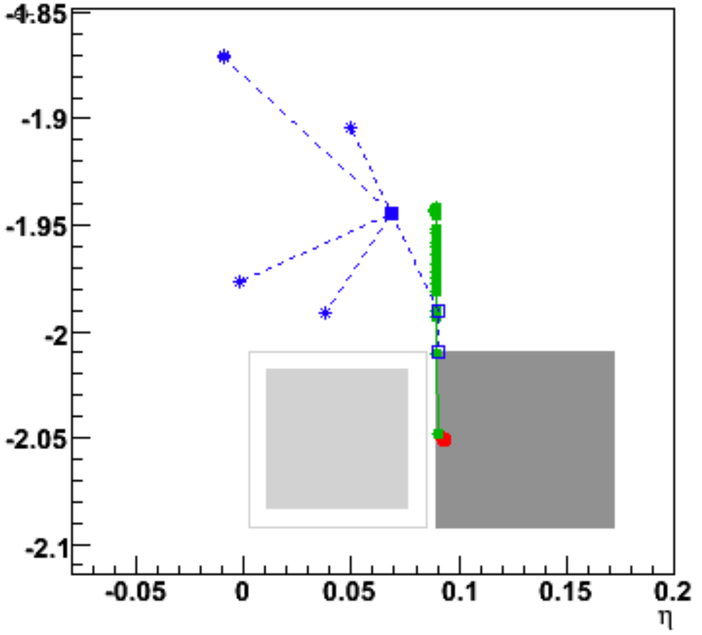

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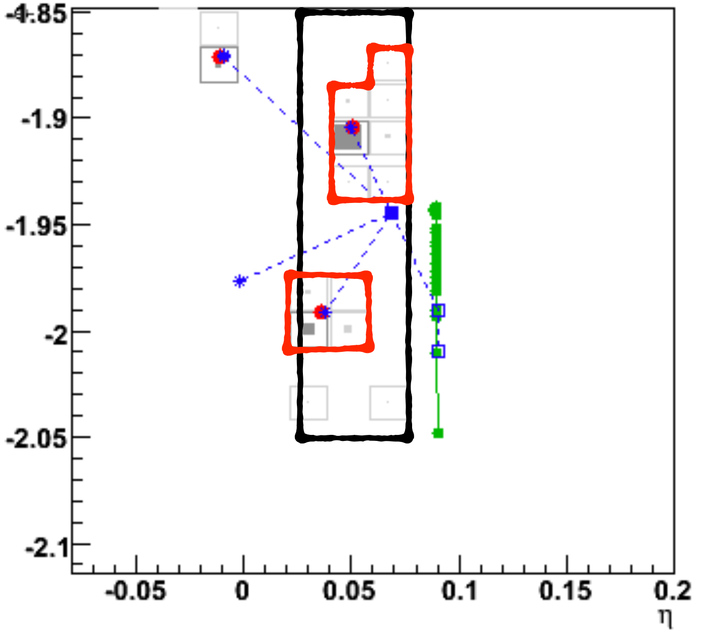

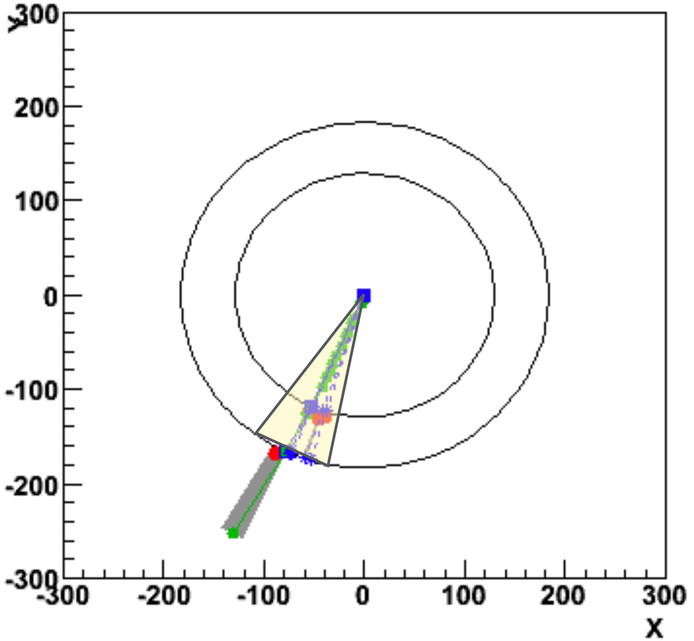

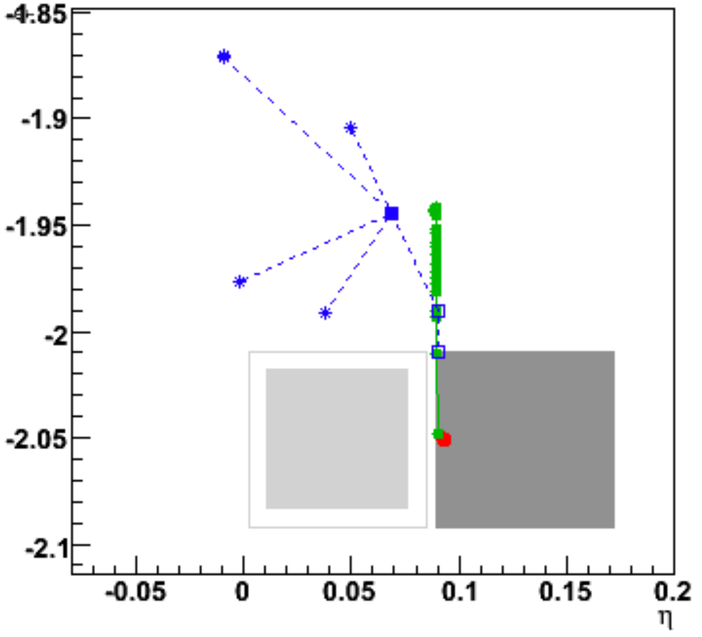

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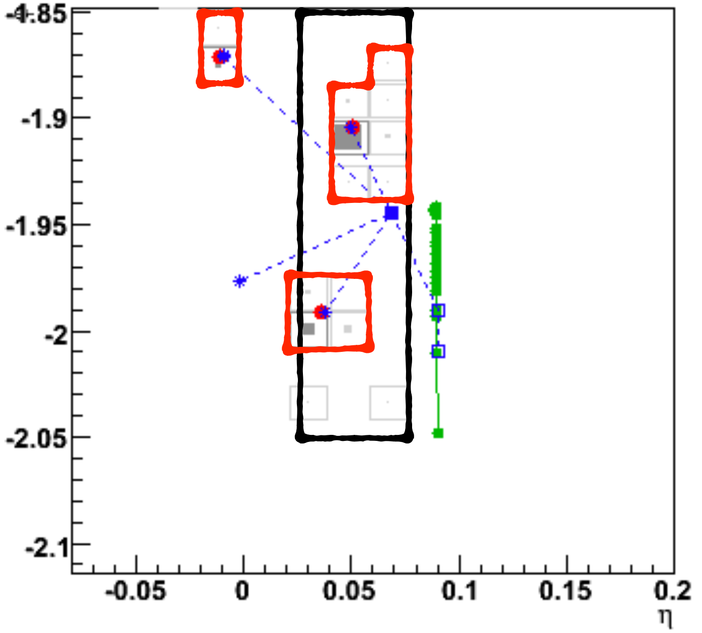

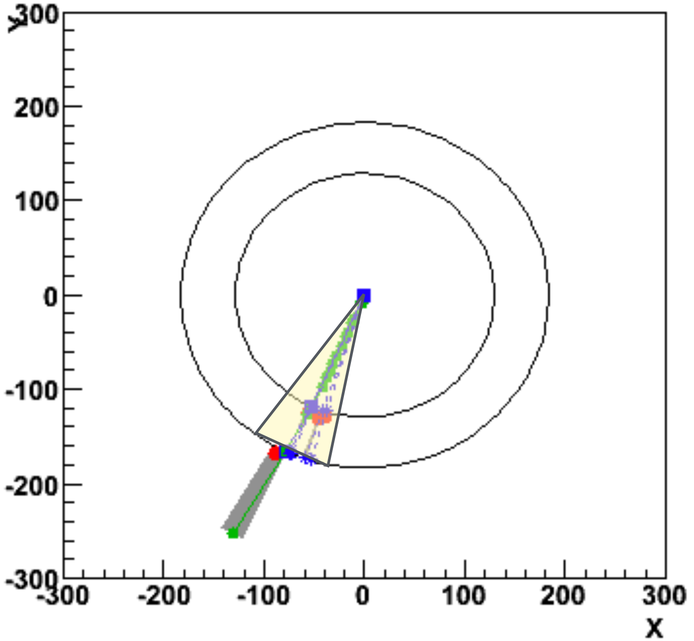

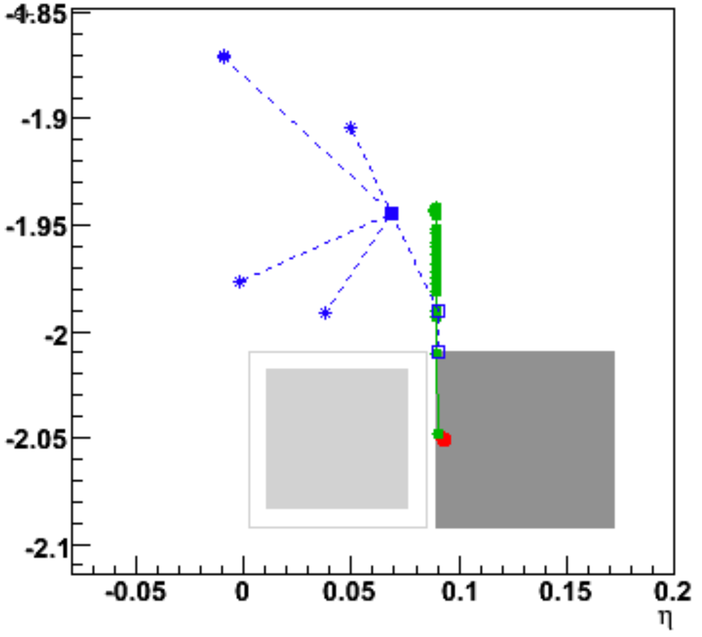

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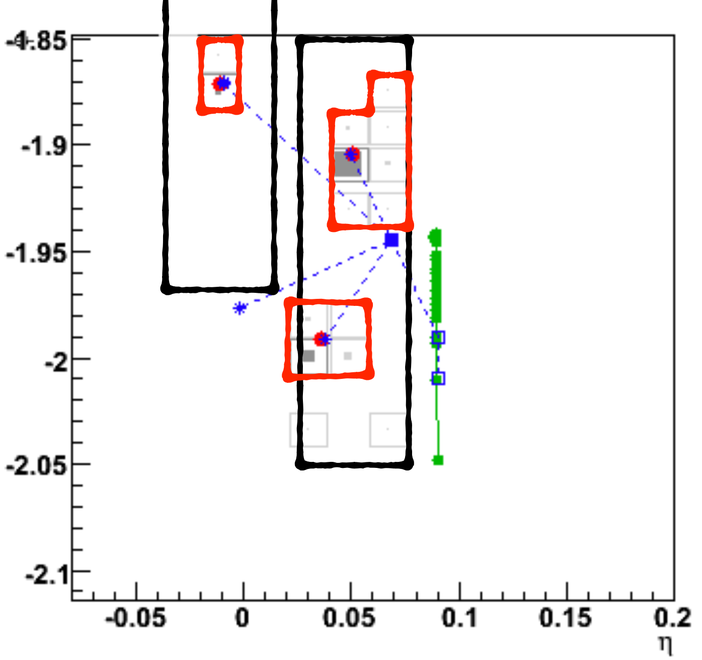

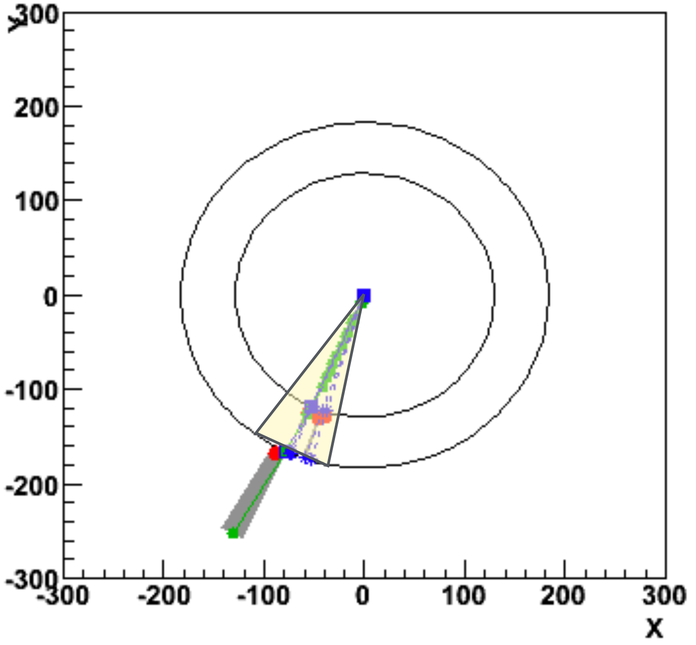

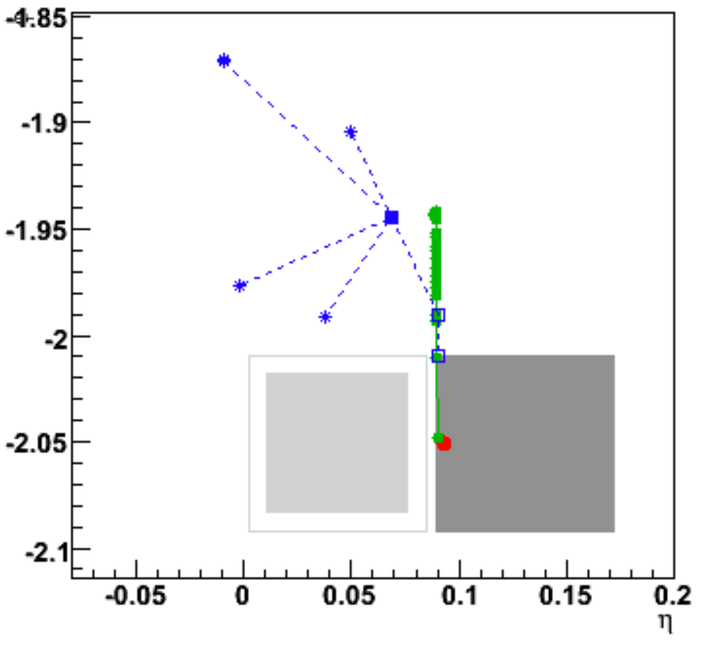

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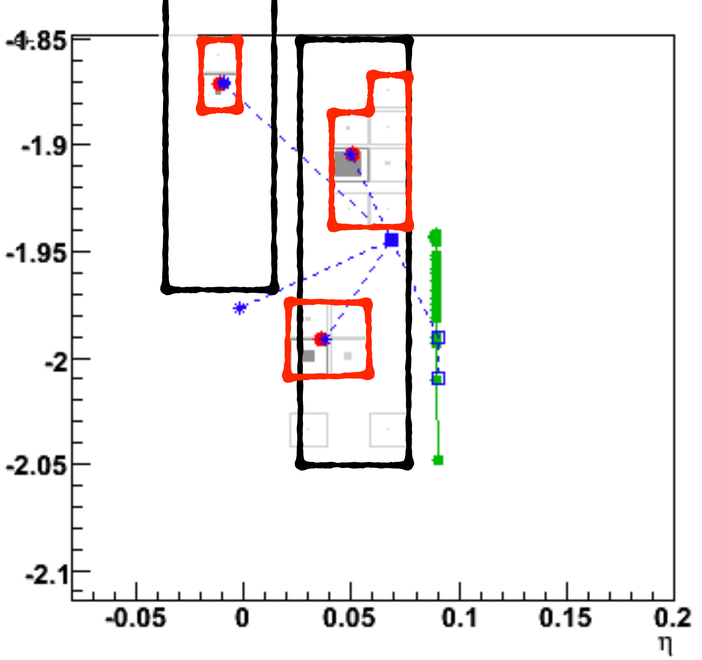

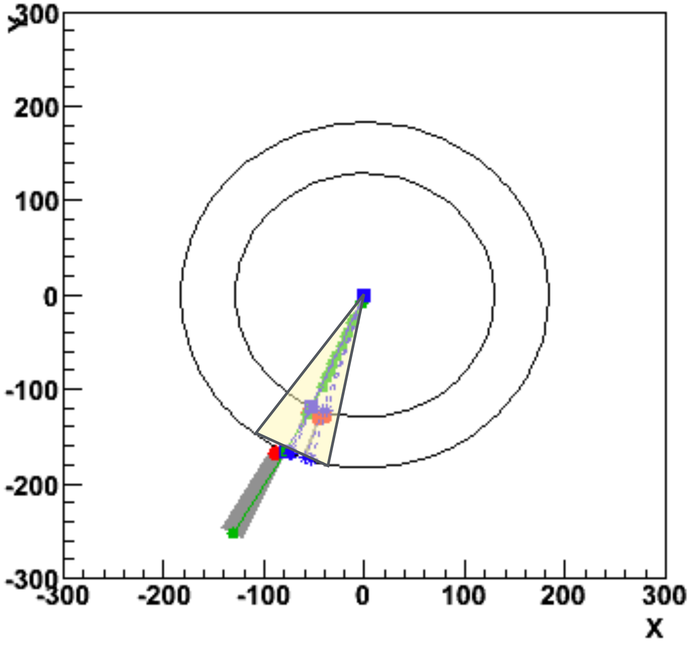

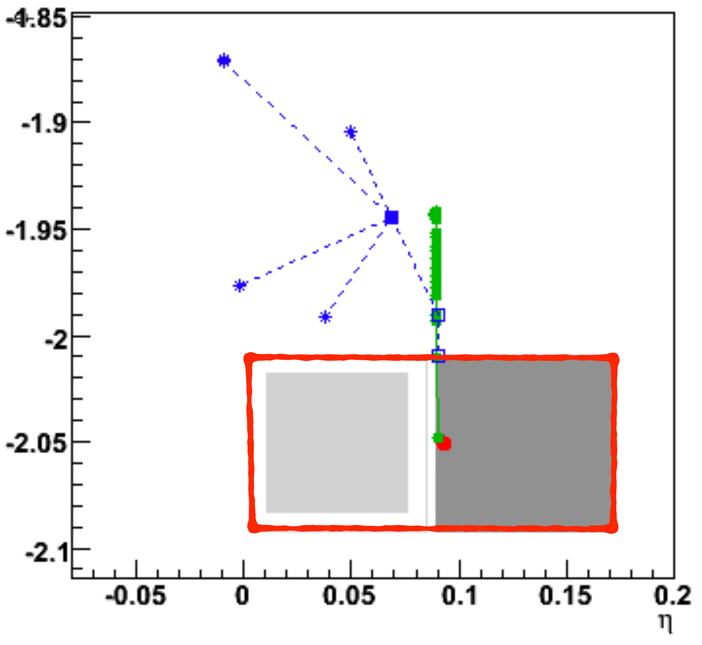

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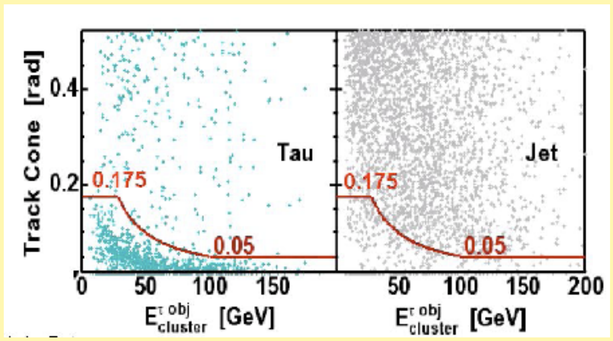

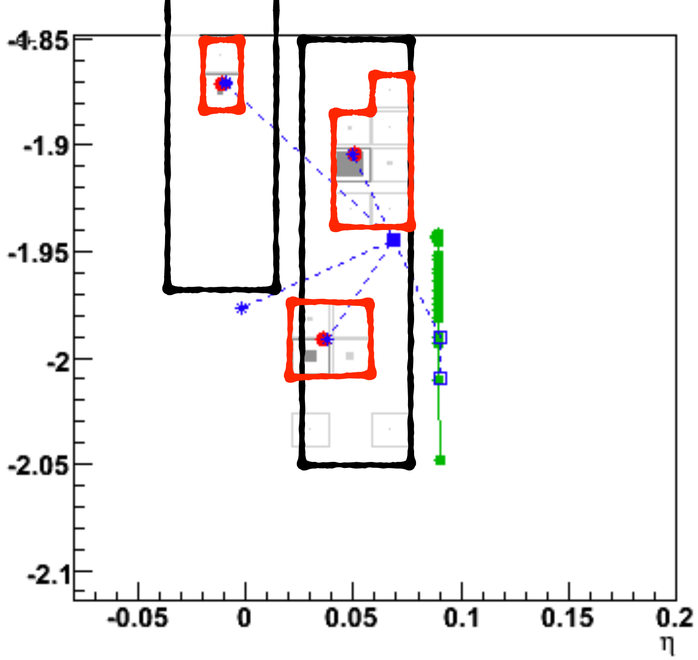

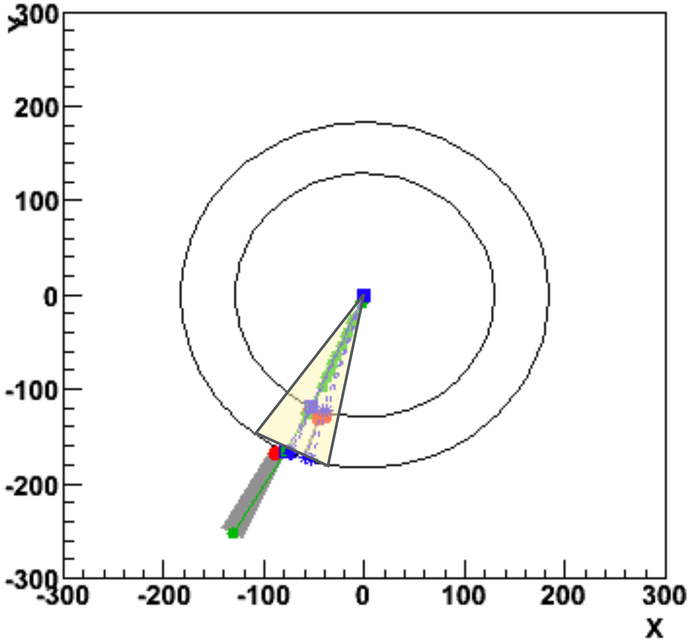

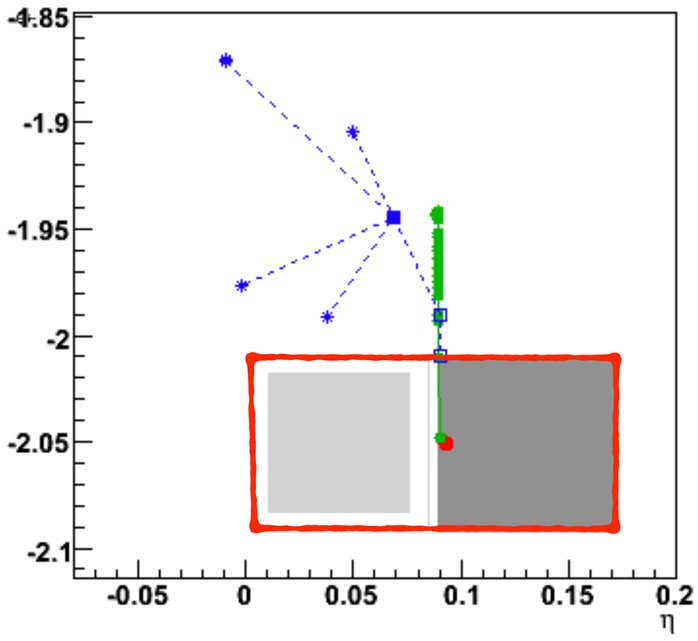

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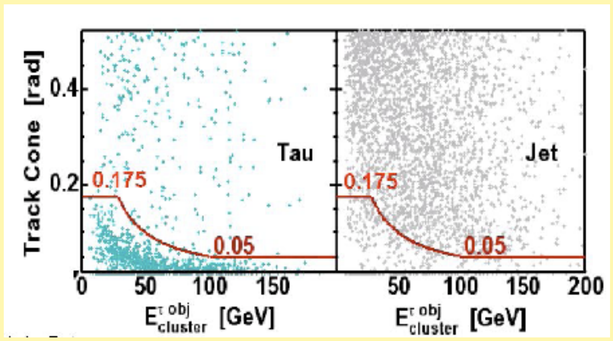

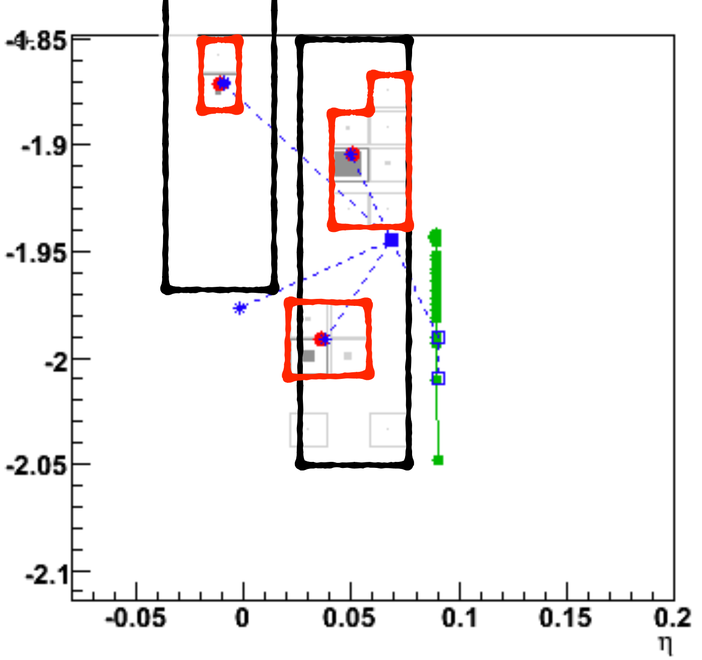

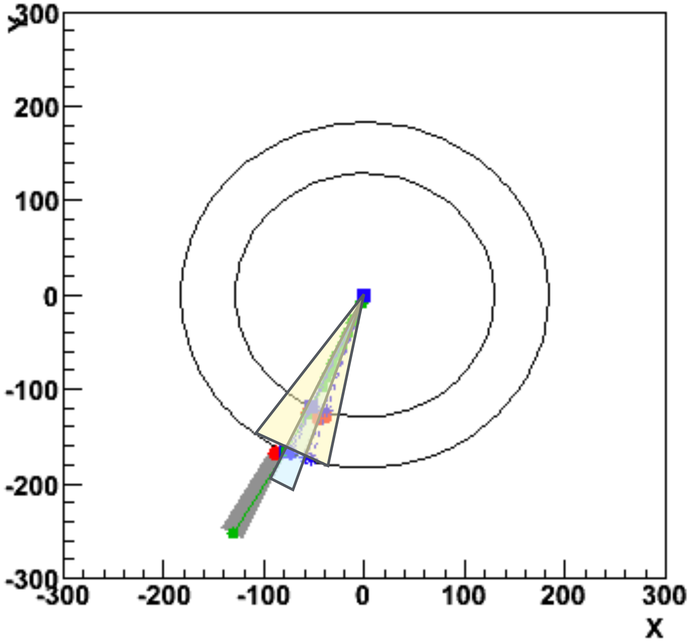

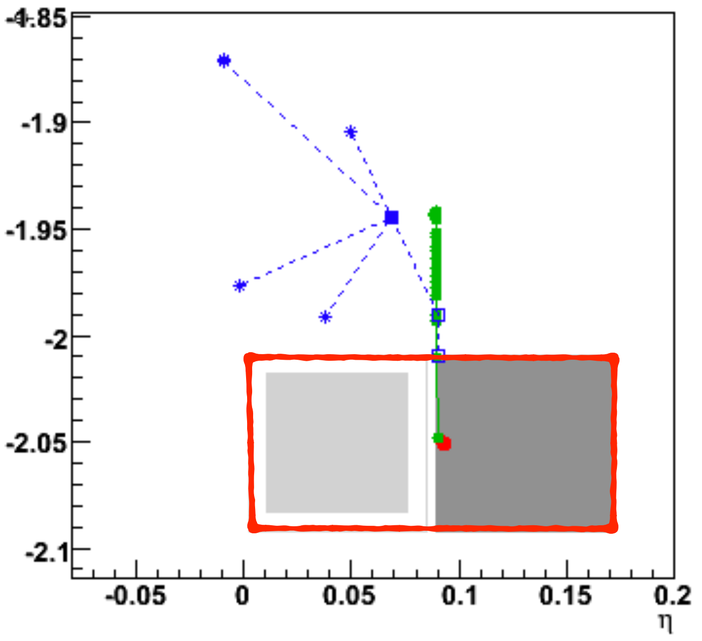

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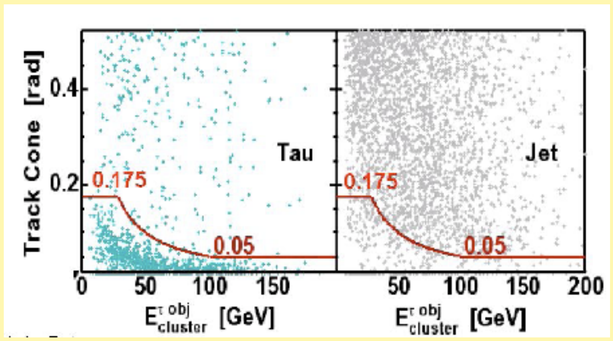

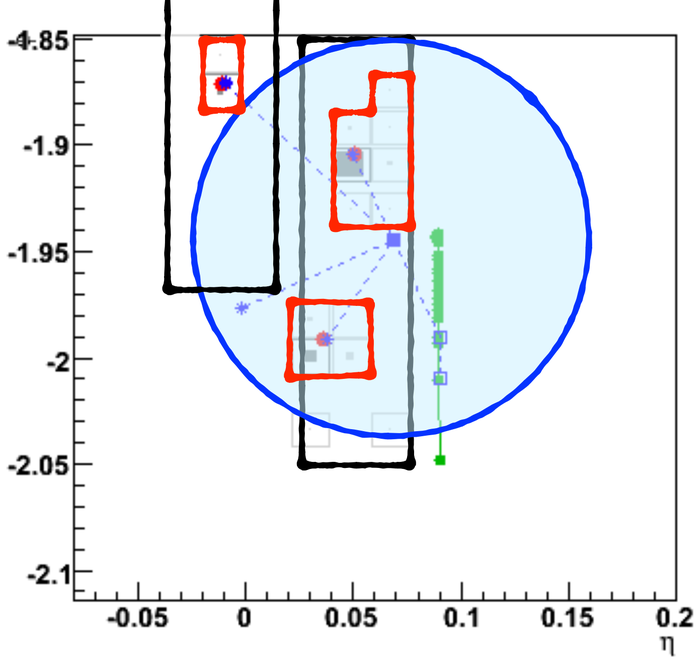

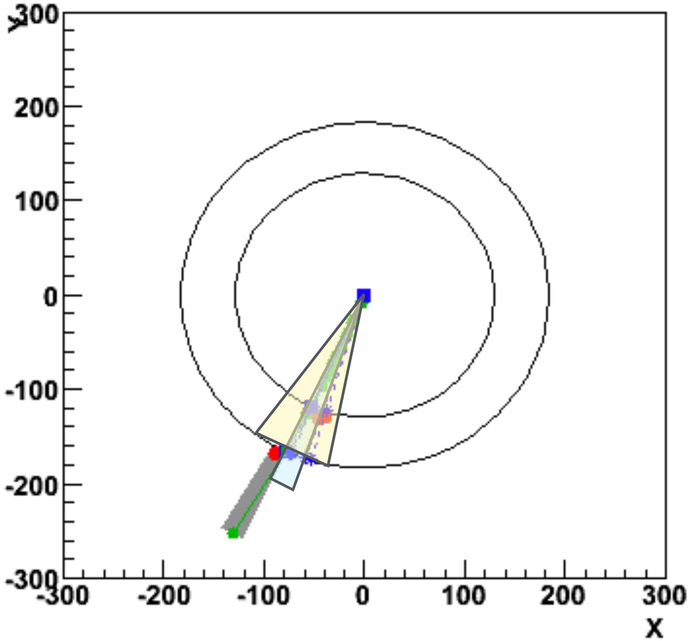

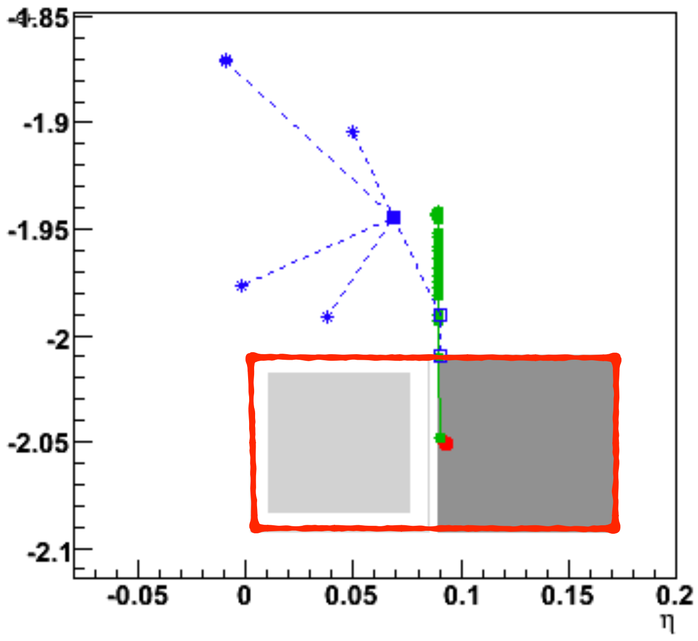

Tau ID & Reconstruc

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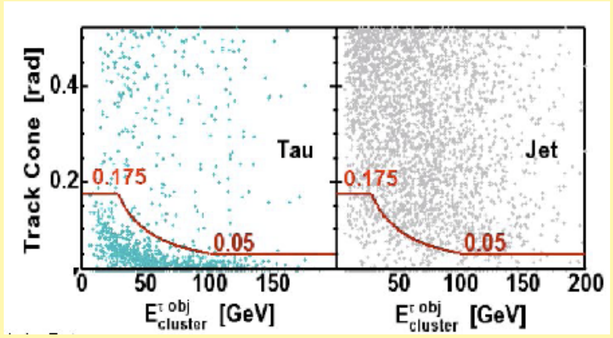
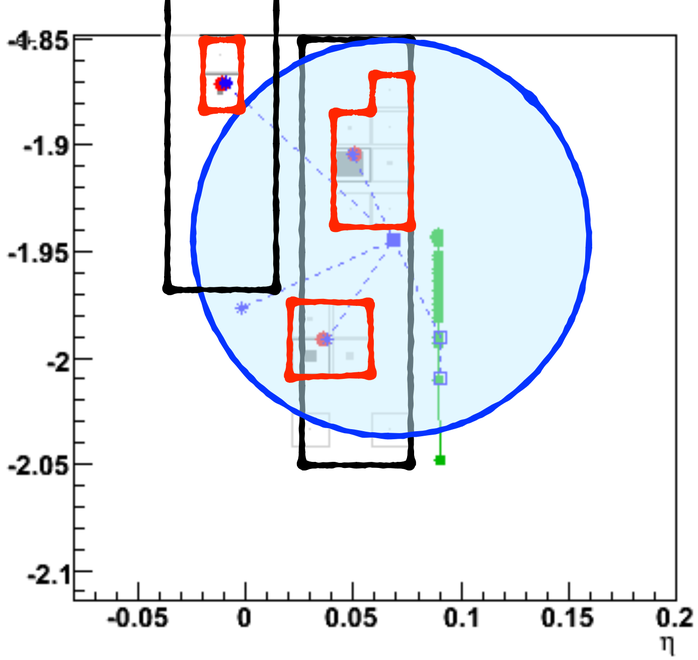
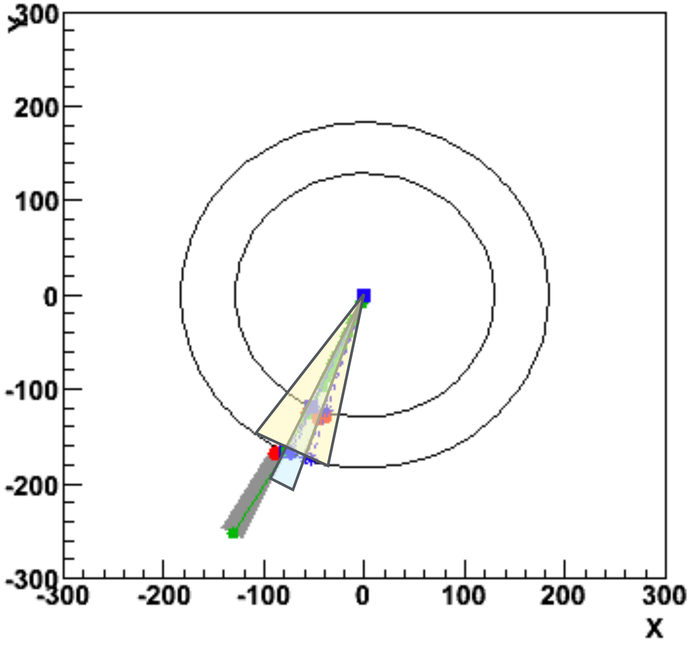
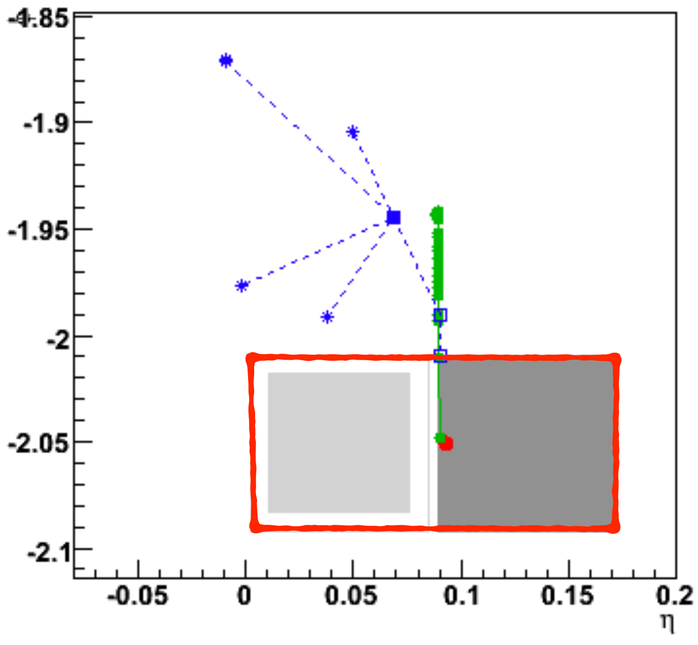


1 $\pi^{\pm}$, 0 π^0

- Branching Fraction: 11.6%
- Single isolated $\pi^{\pm}$







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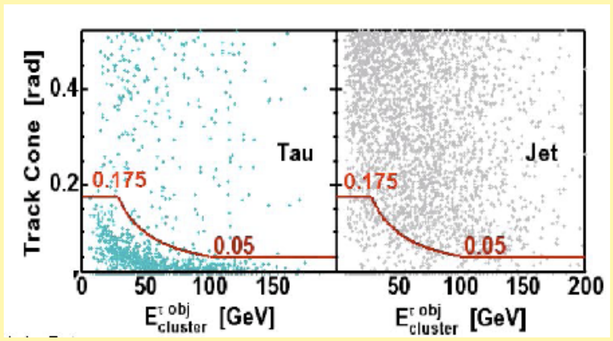
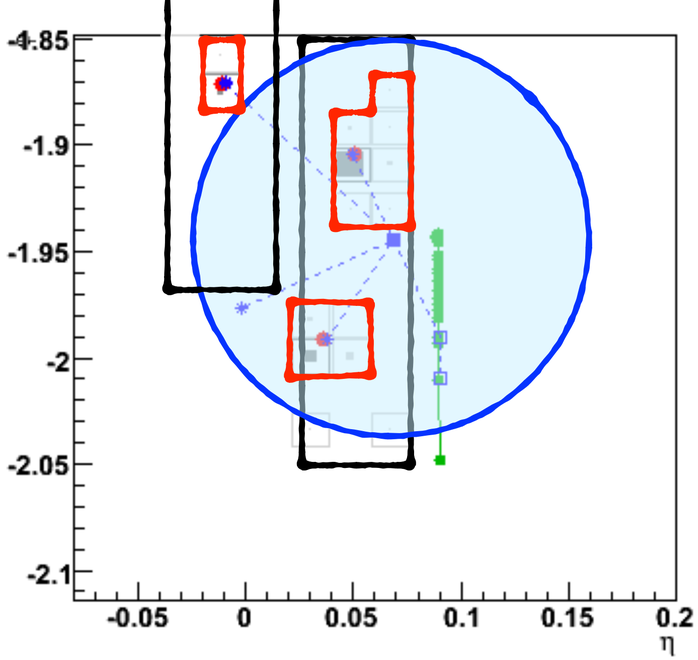


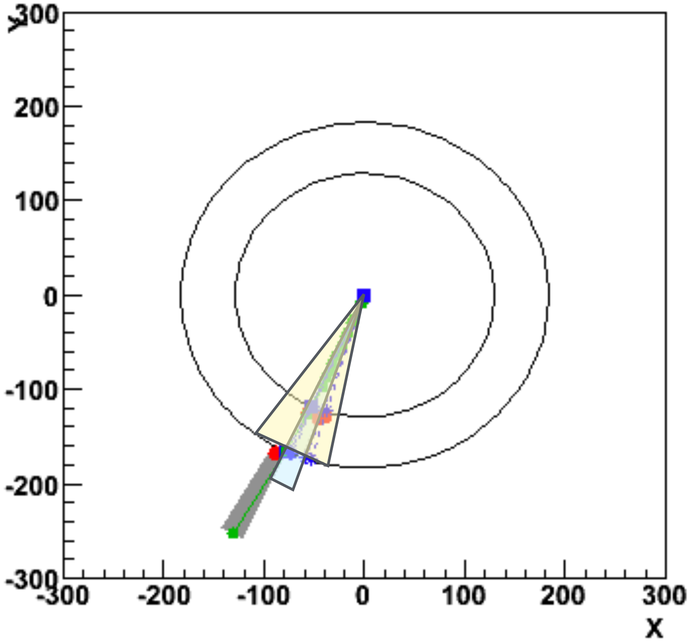
1 $\pi^{\pm}$, 0 π^0

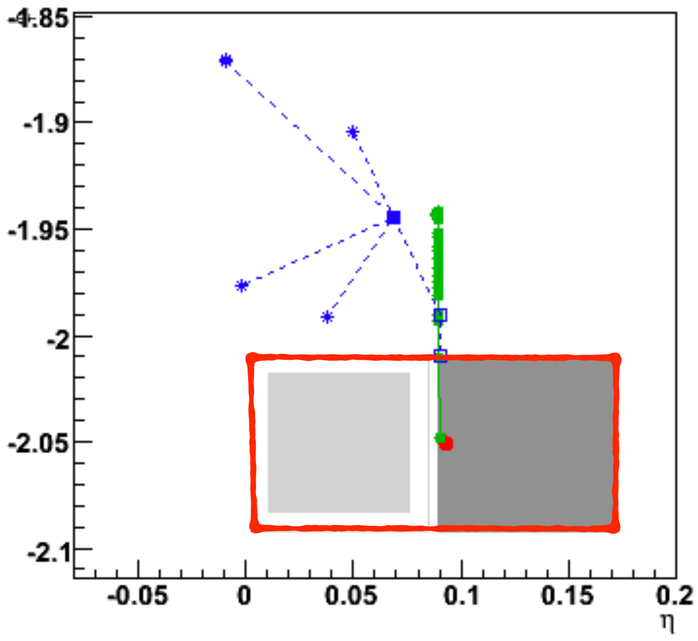
- Branching Fraction: 11.6%
- S

3 $\pi^{\pm}$, 0 π^0

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







Tau ID & Reconstru

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

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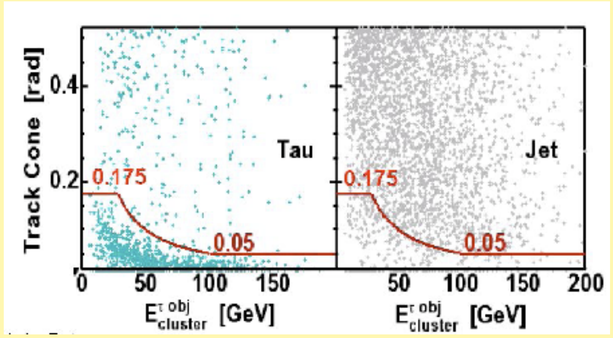

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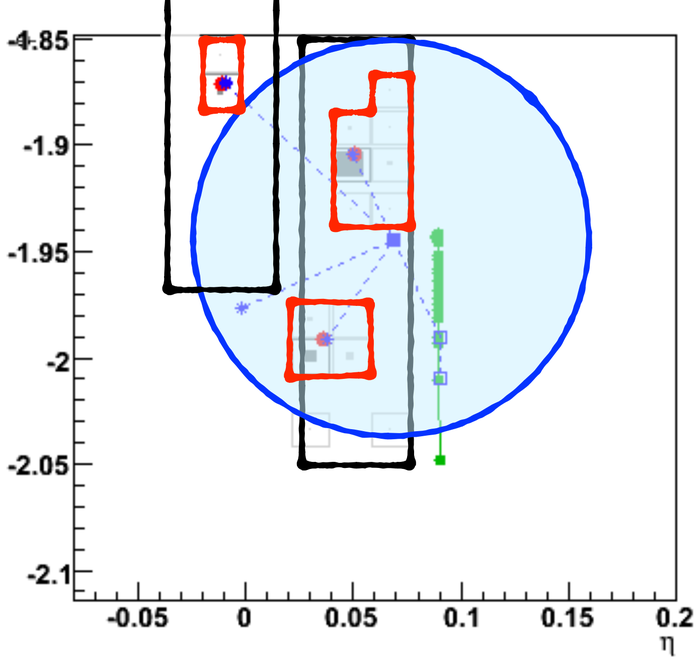
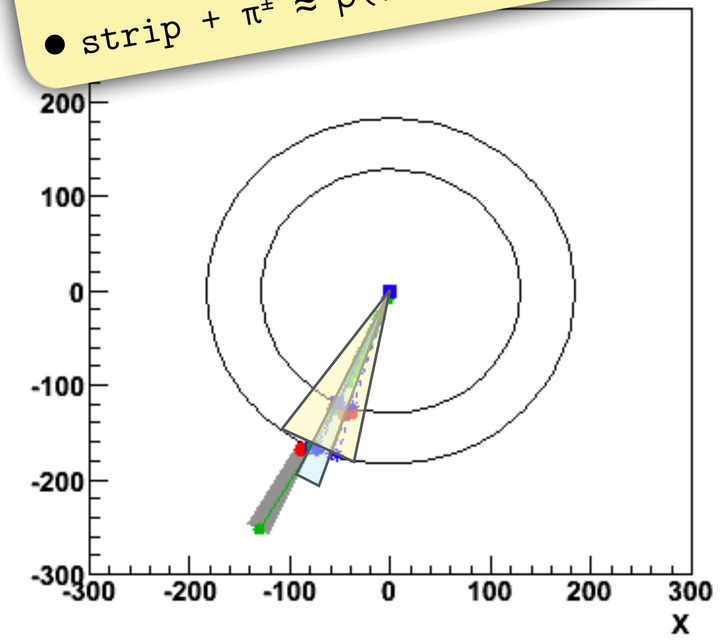
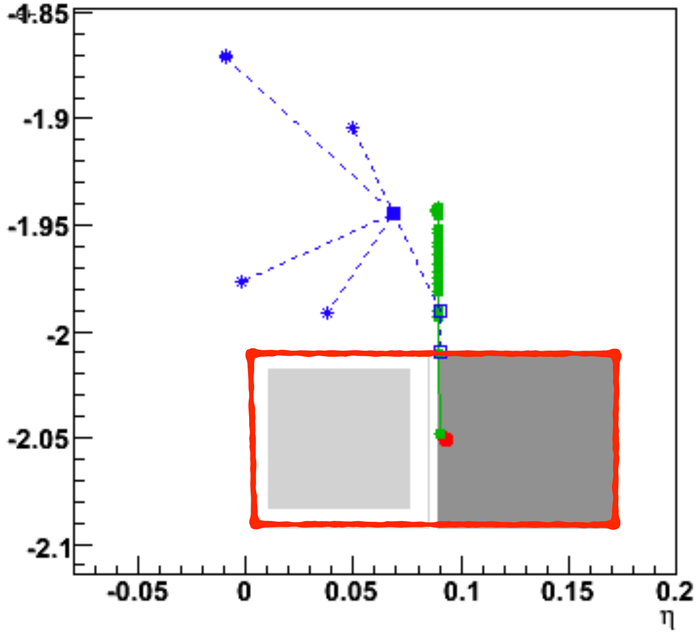
- three $\pi^{\pm} \approx a_1$ mass

1 $\pi^{\pm}$, 1 π^0 (merged γγ)

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







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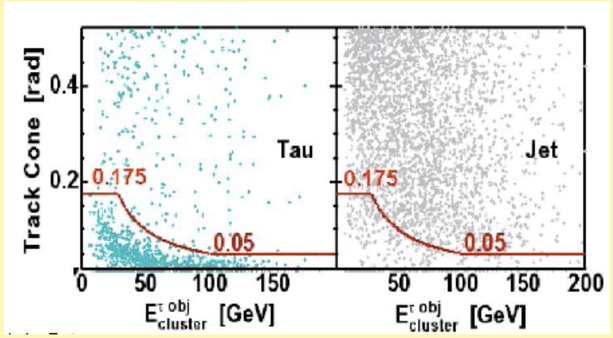

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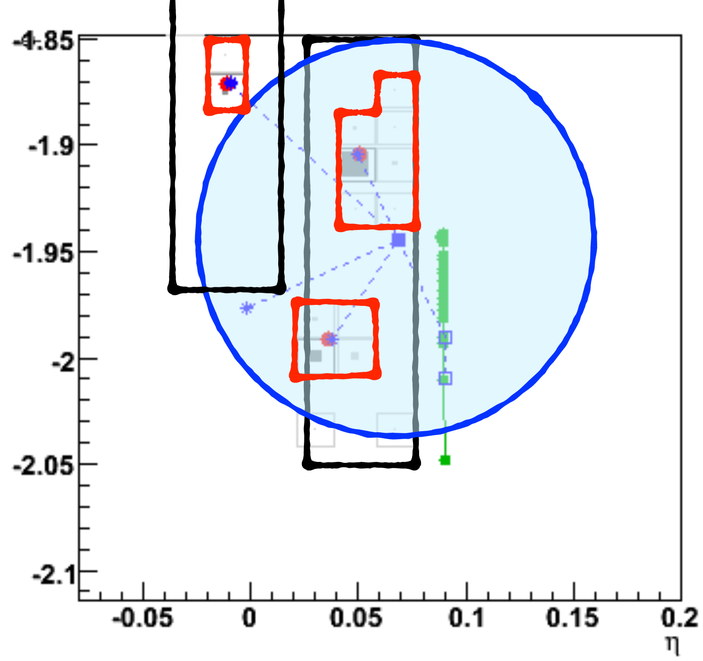

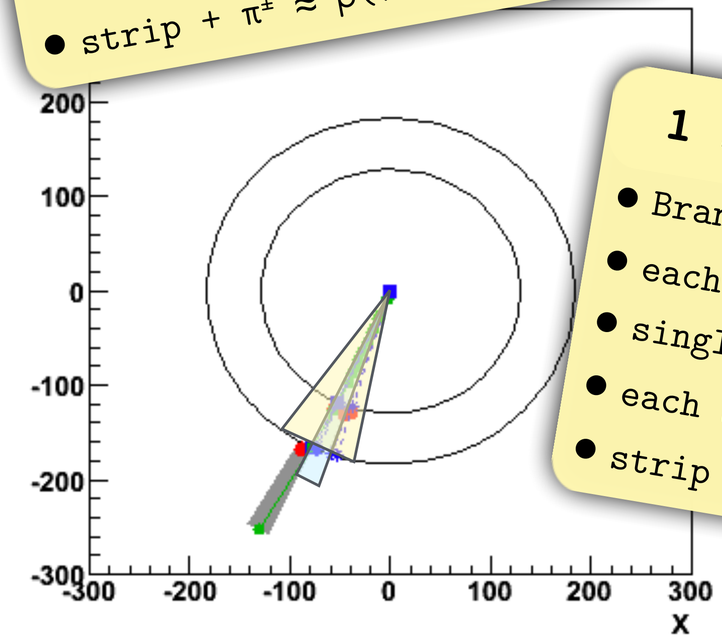

1 $\pi^{\pm}$, 1 π^0 (sep. γγ)

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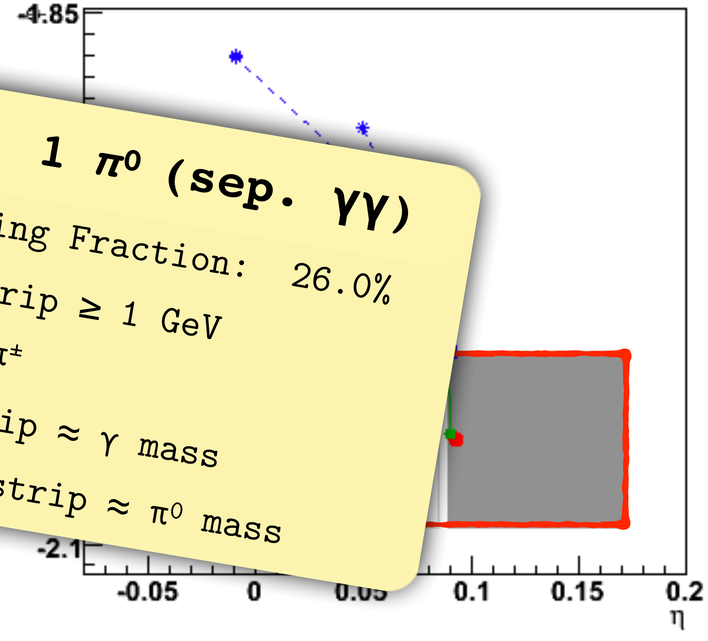
- each strip ≥ 1 GeV
- single $\pi^{\pm}$
- each strip ≈ γ mass
- strip + strip ≈ π^0 mass



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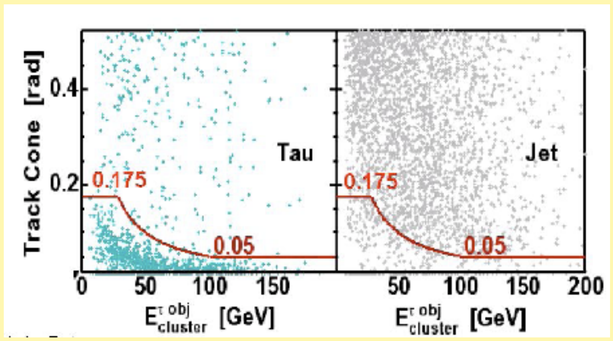

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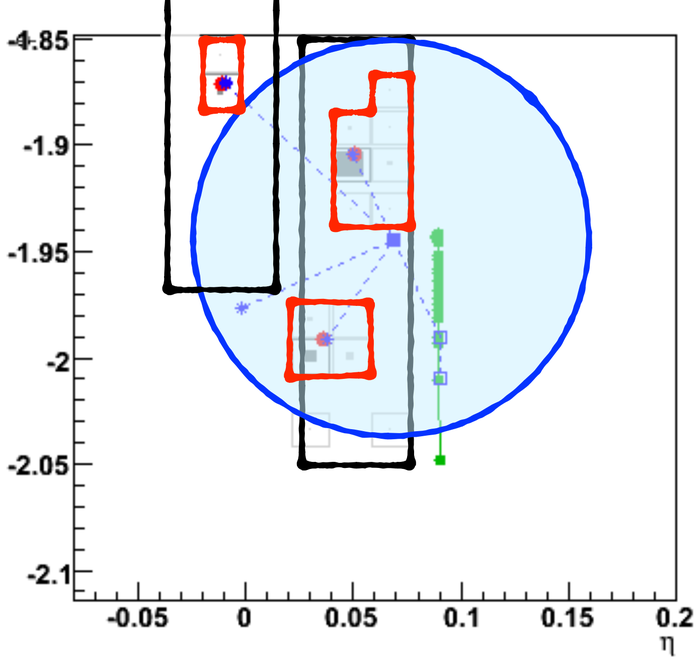

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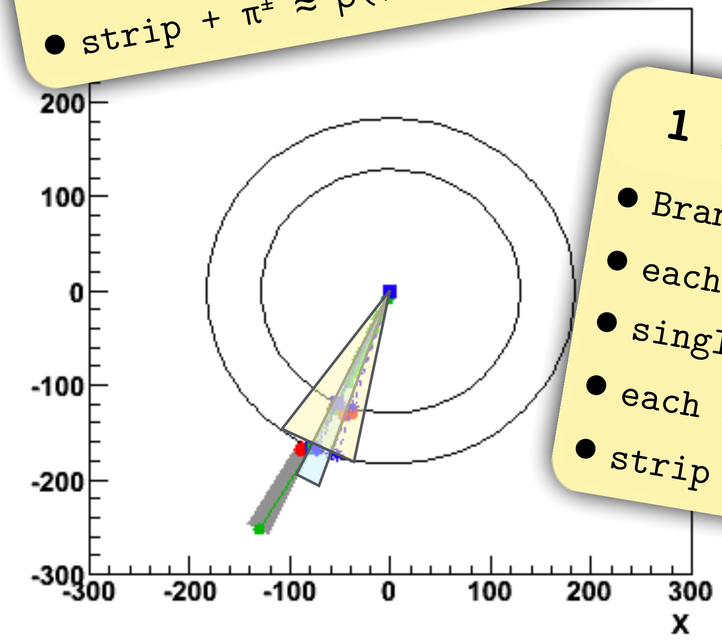

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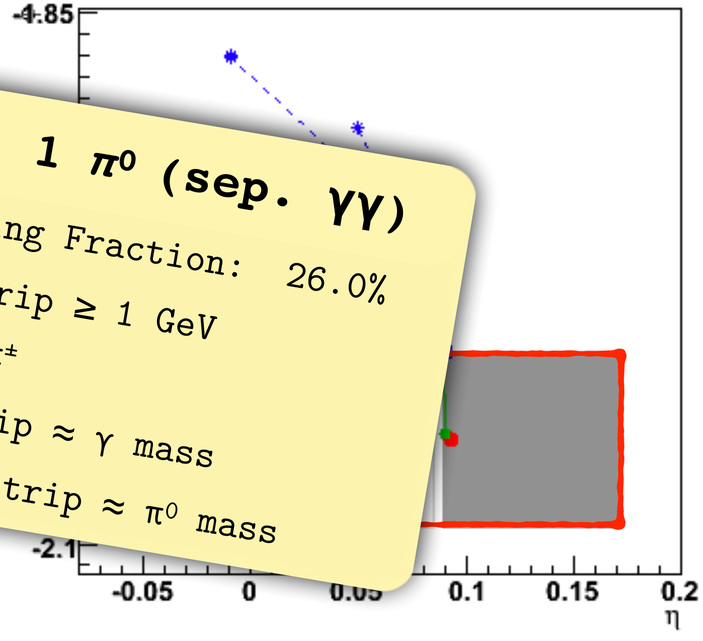

Tau ID & Reconstru

Basic Idea

- Seed with R=0.4 anti-kt jet
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- Cluster all γ's or e's into strips
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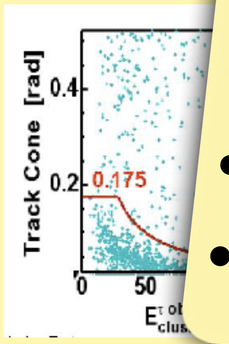

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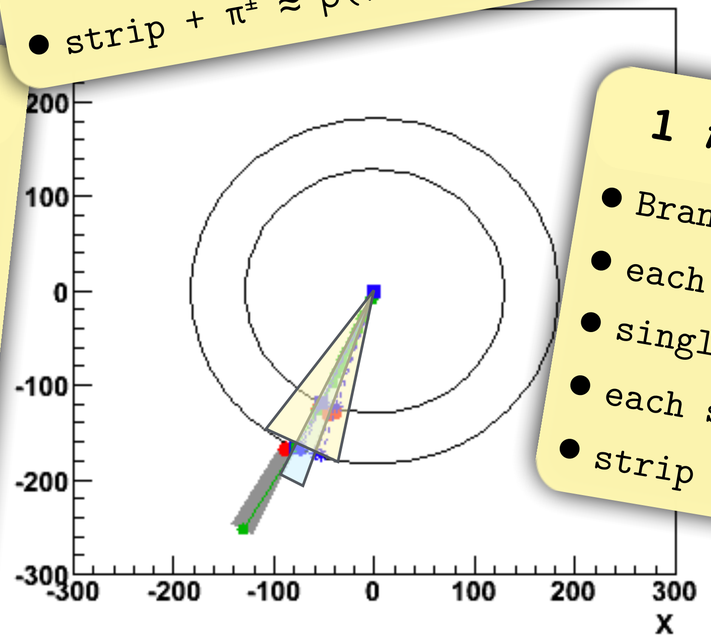

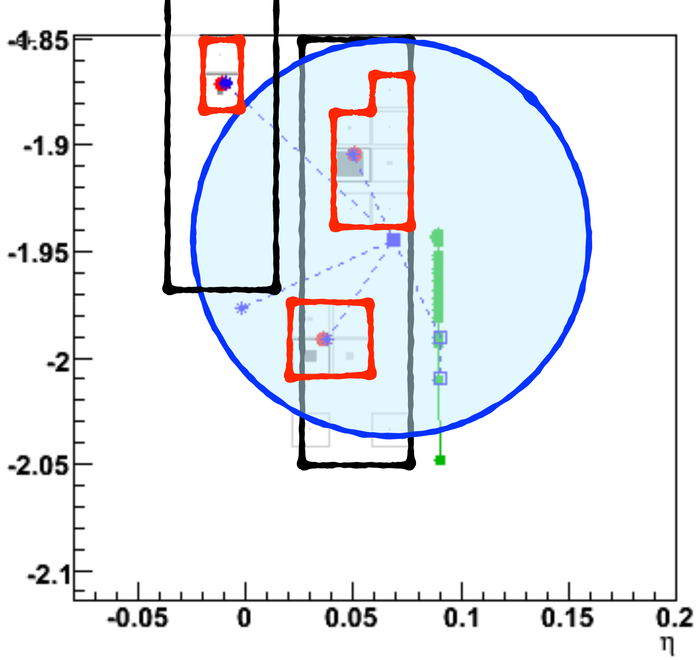

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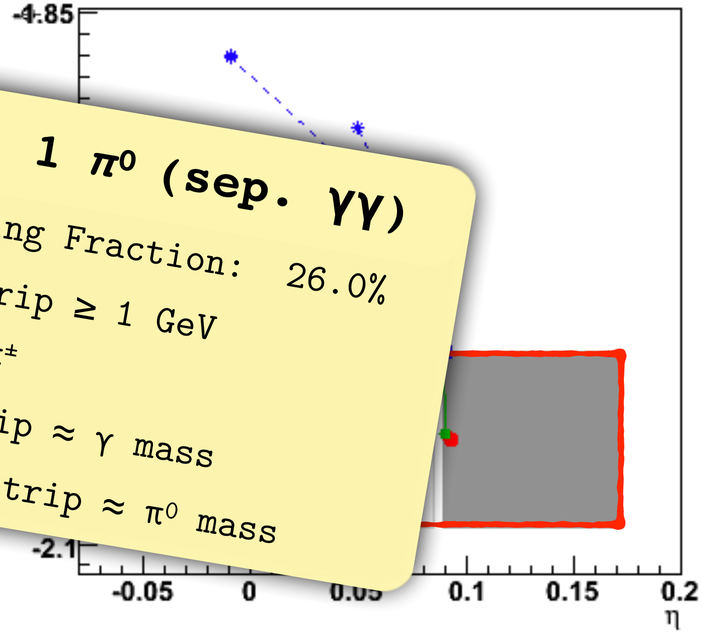

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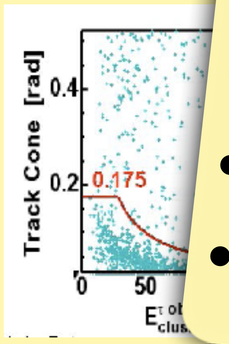

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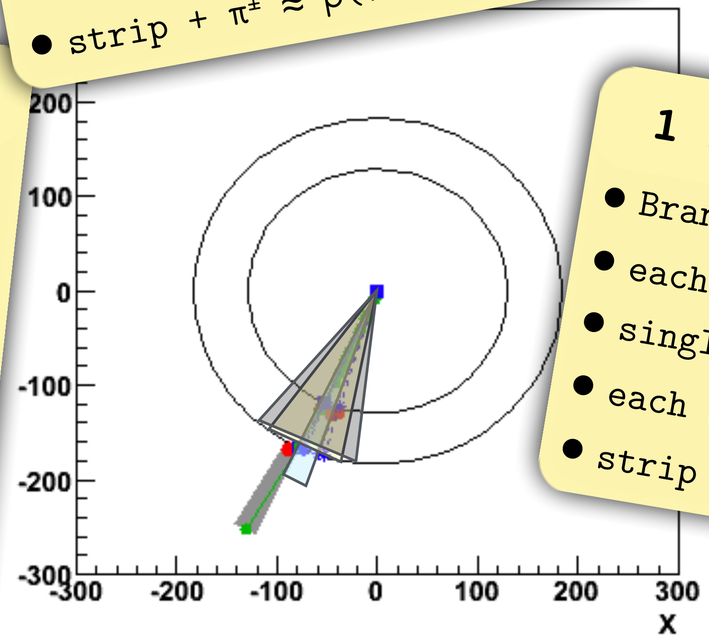

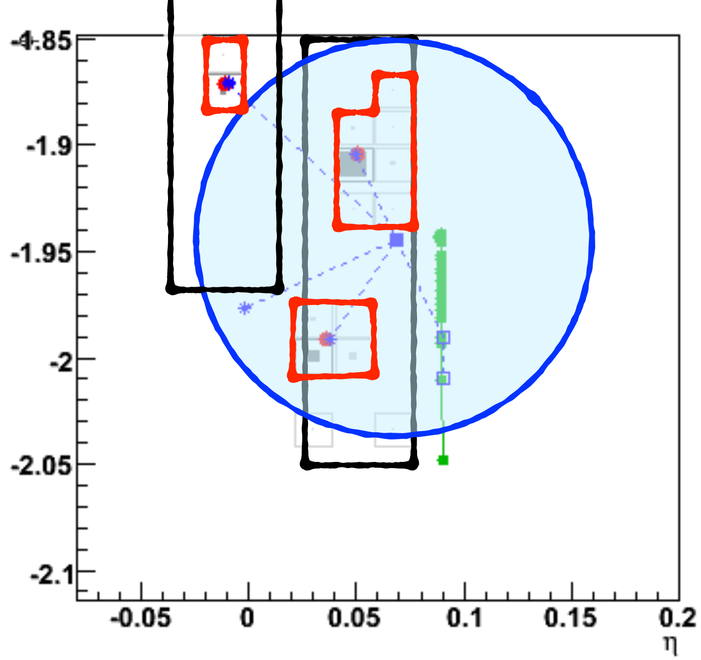

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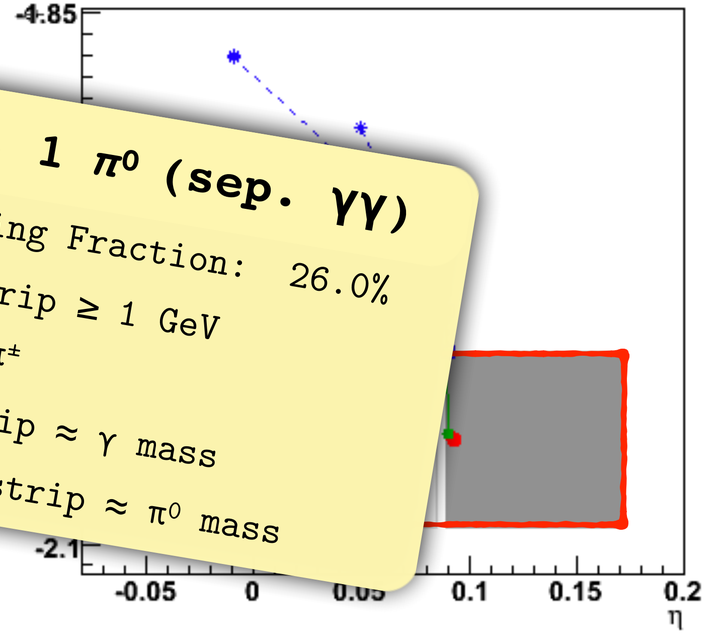

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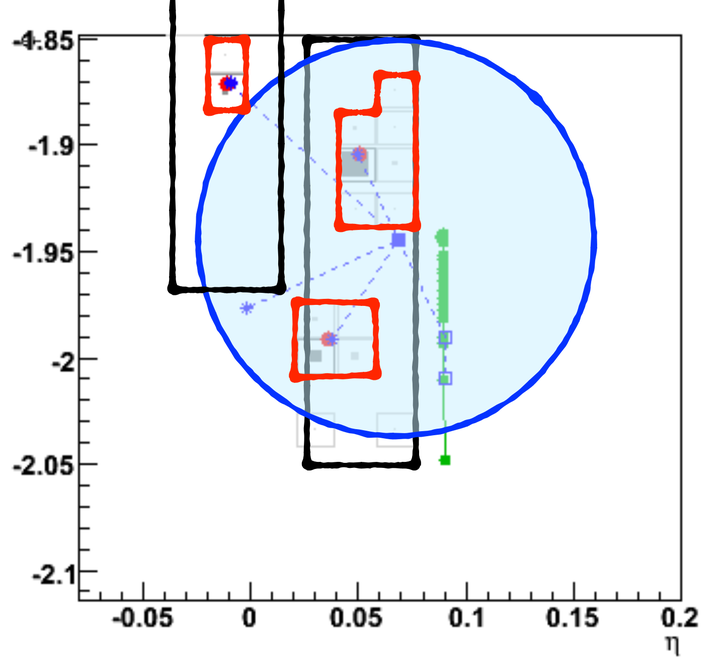
Typical Reconstruction Efficiencies

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



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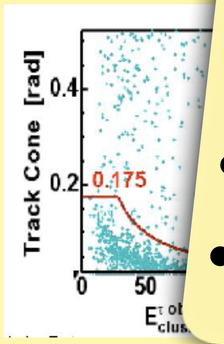

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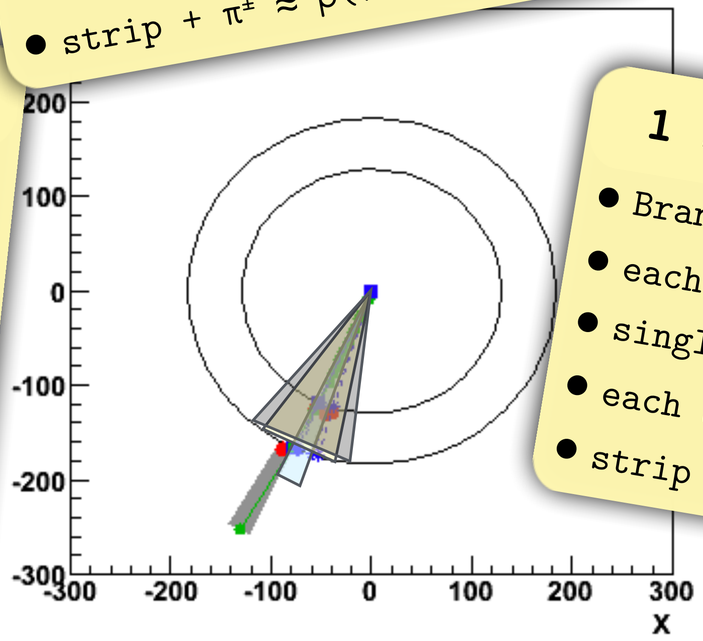

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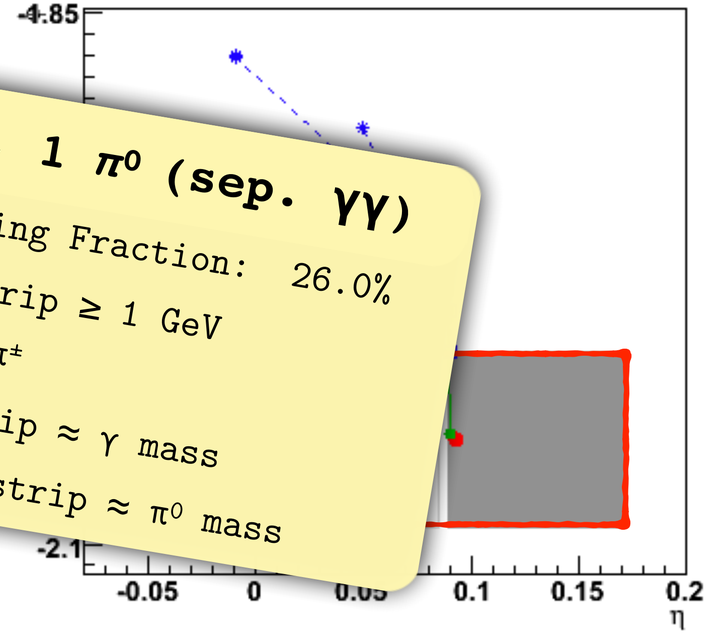
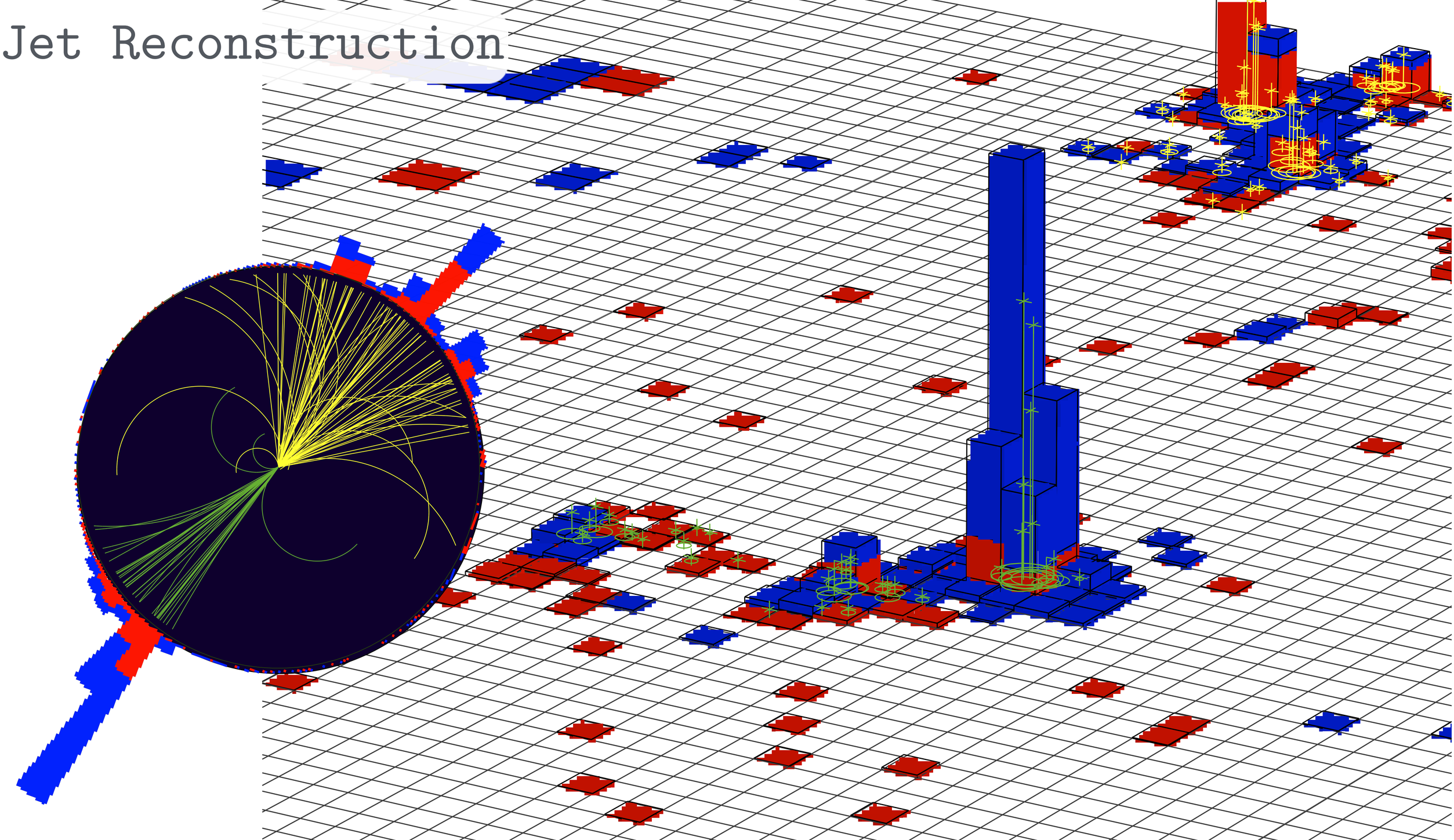


Jet Reconstruction



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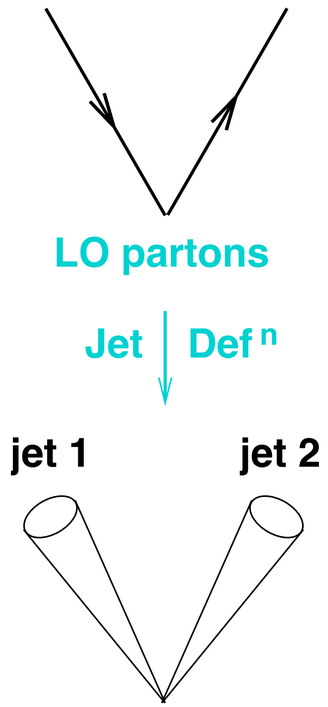

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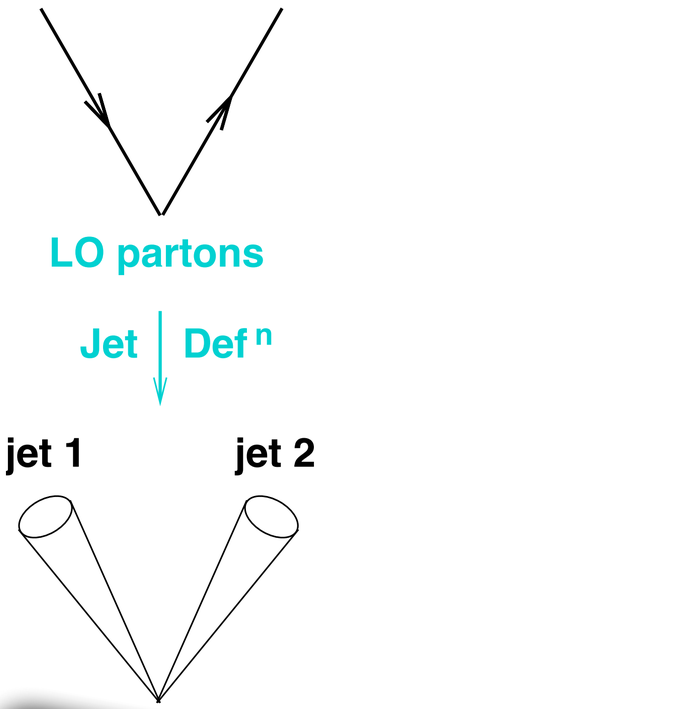

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- Central concepts of QCD
- Not directly observable (confinement)

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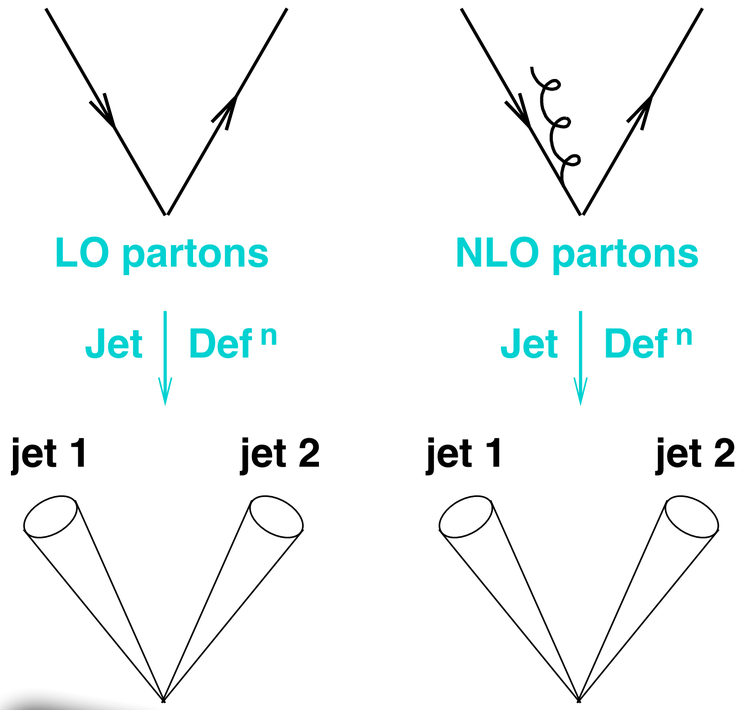

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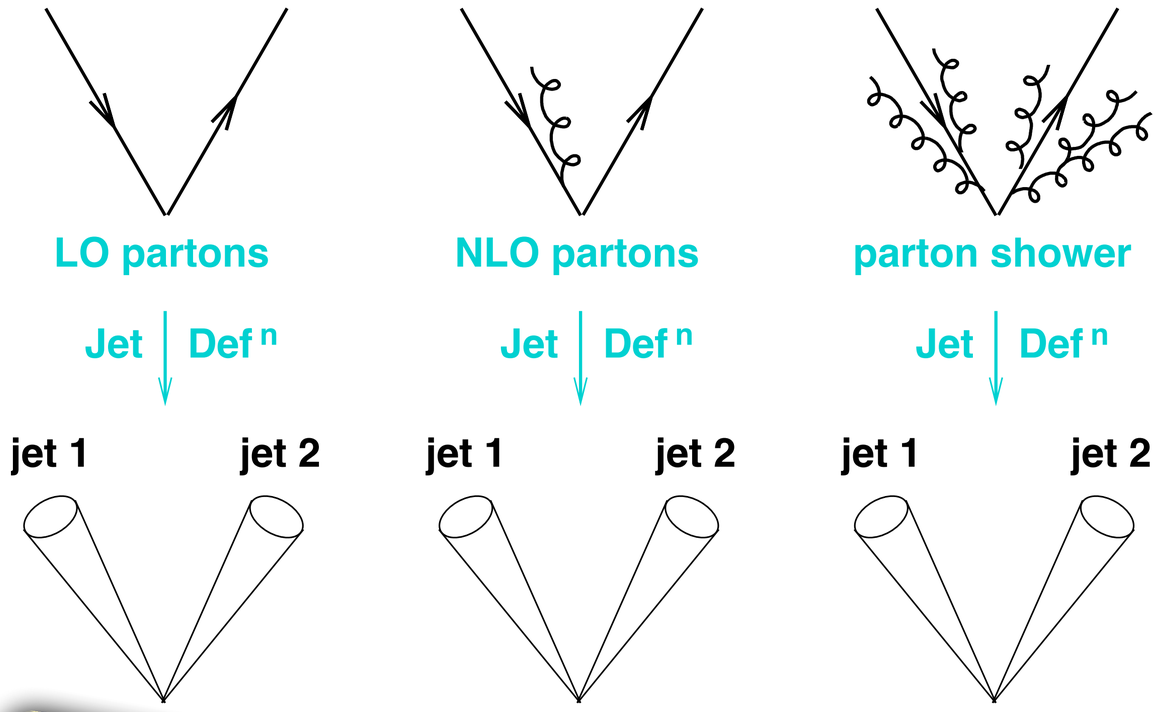

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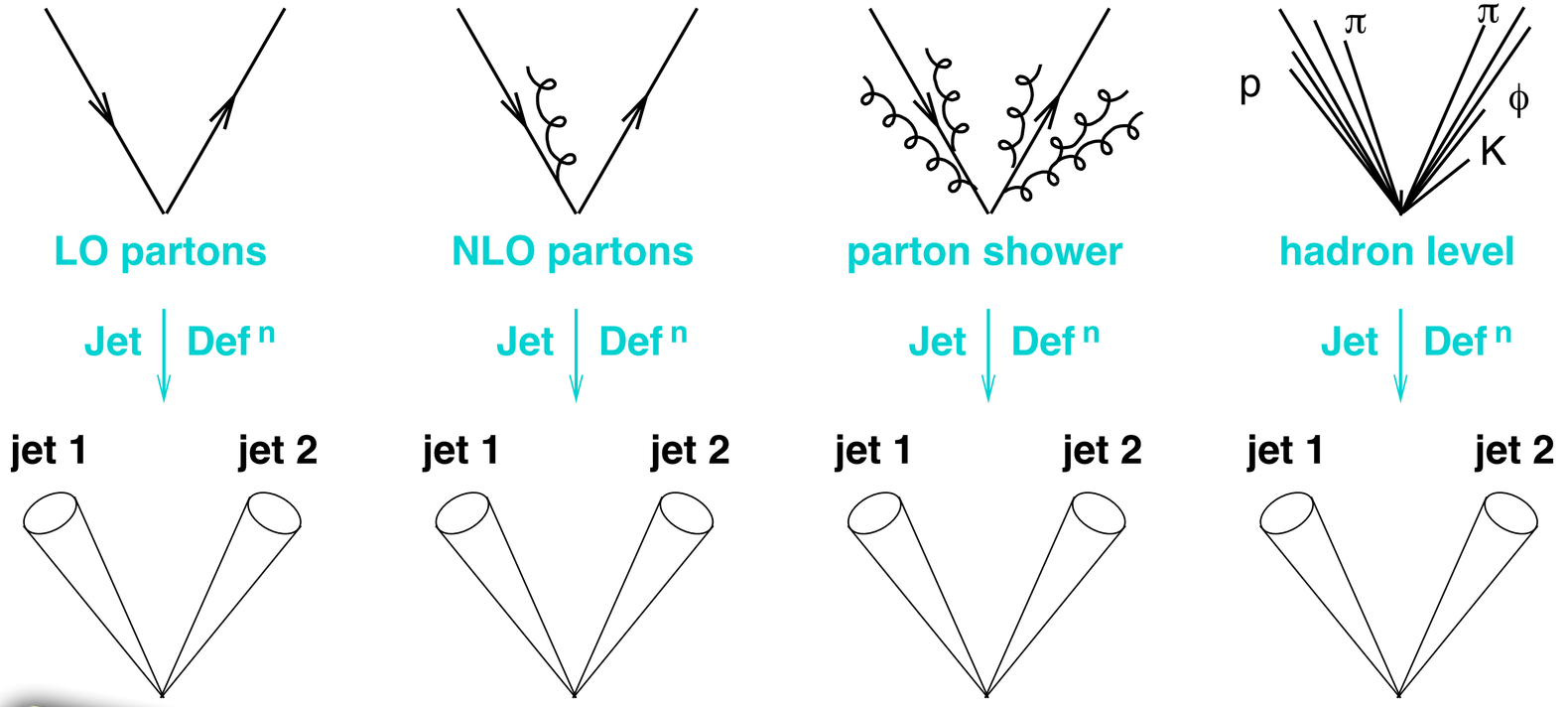

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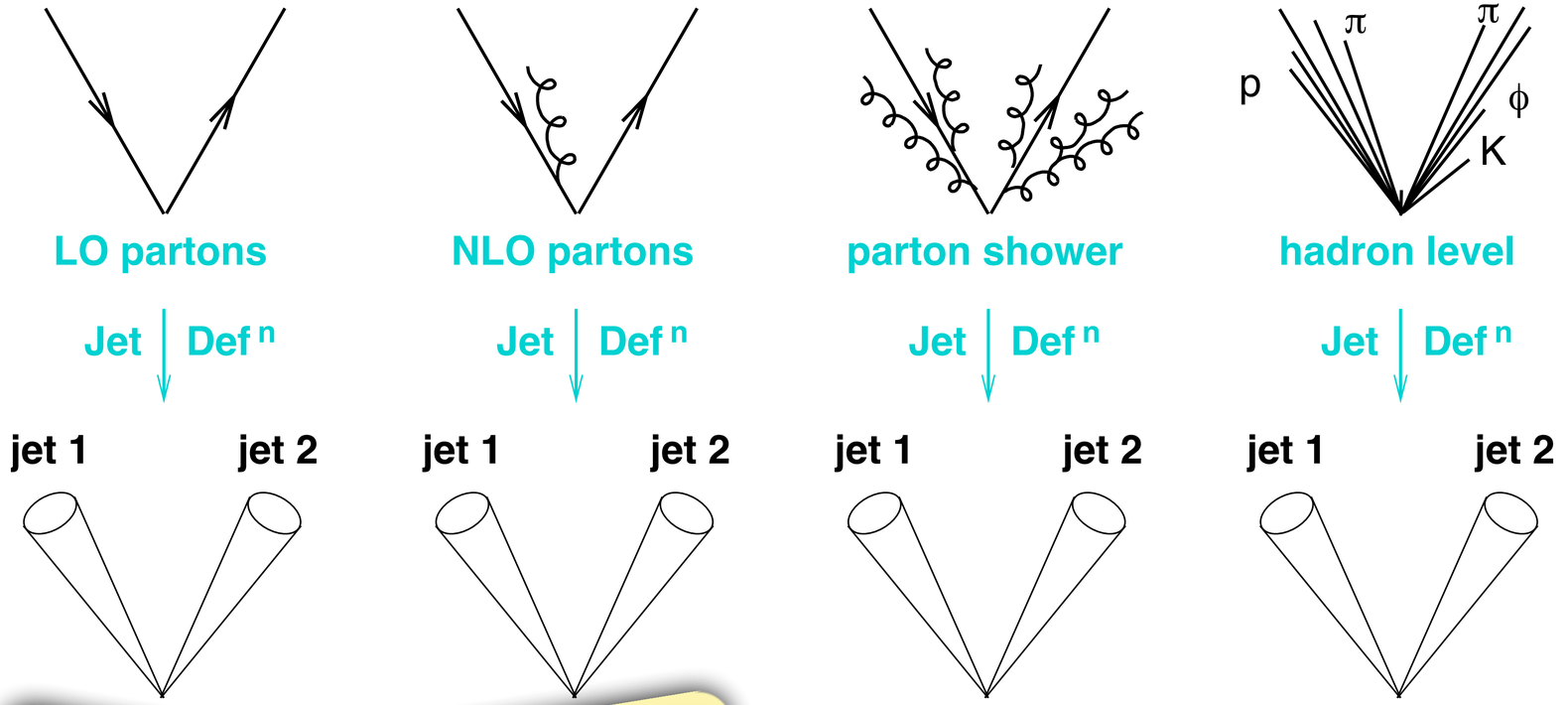

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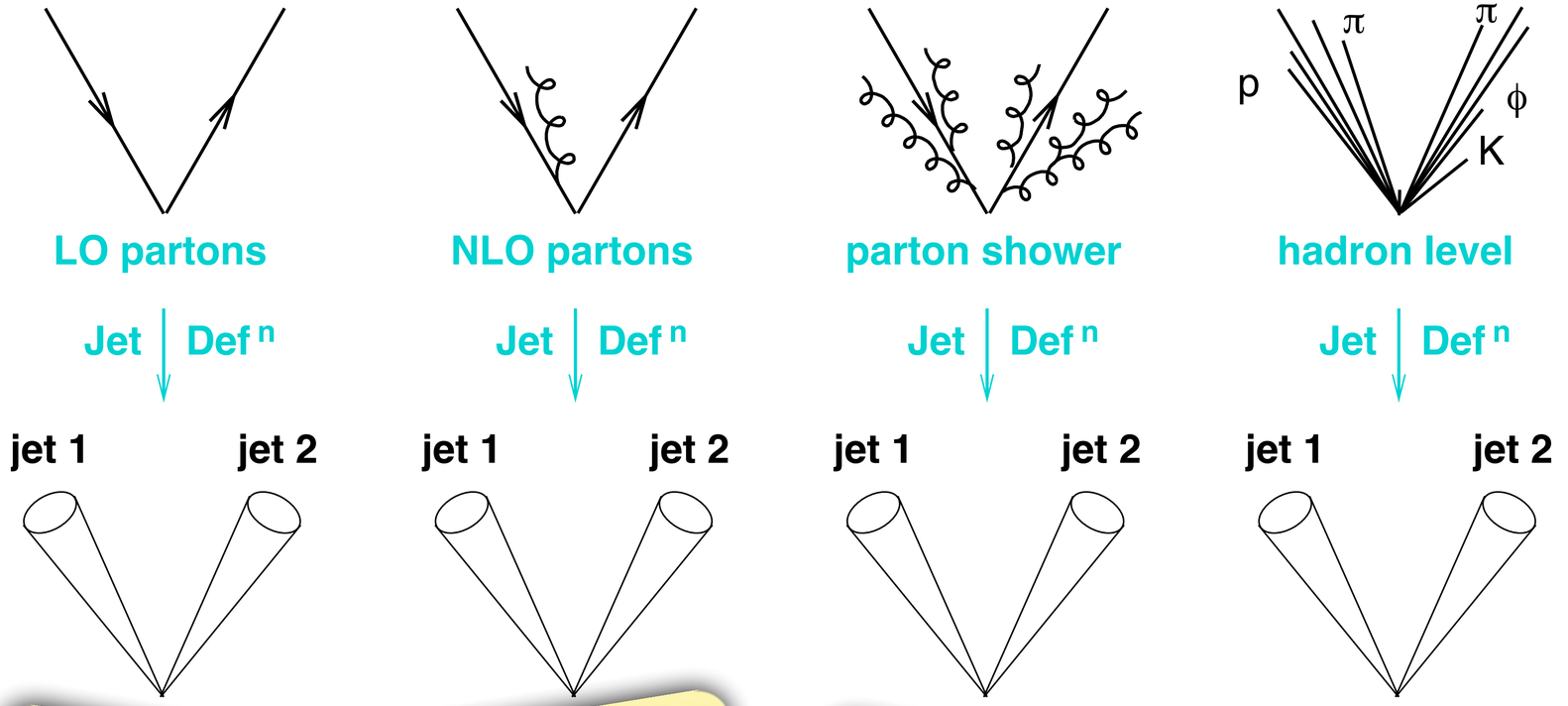

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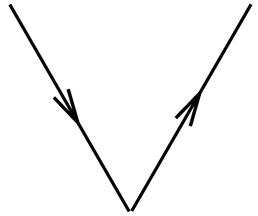

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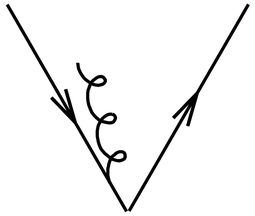

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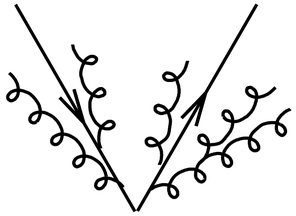
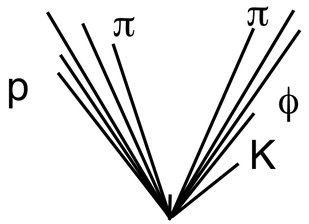
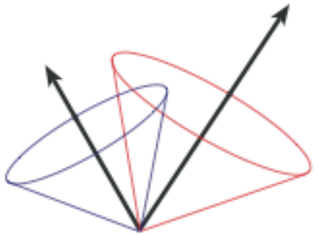
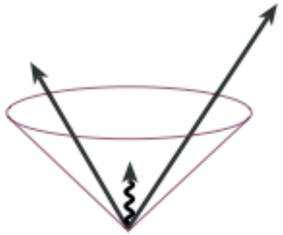


parton shower

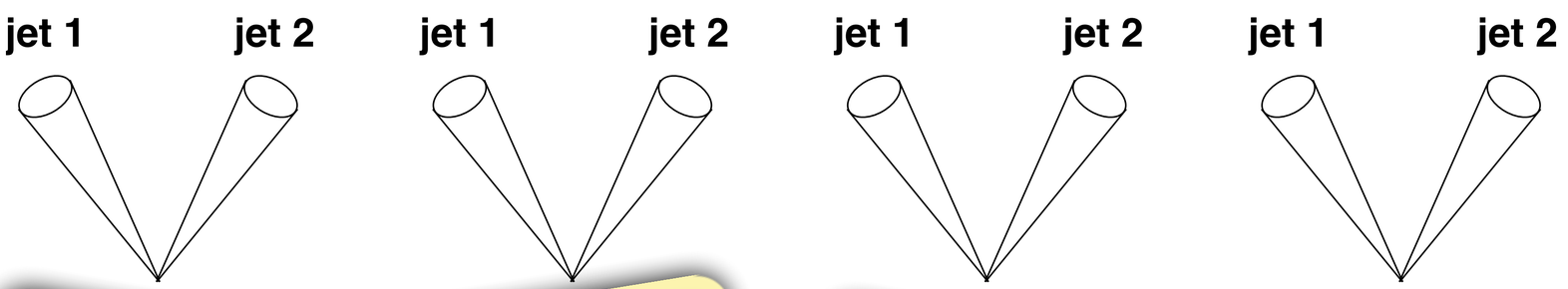


hadron level





Jet | Def^{n} Jet | Def^{n} Jet | Def^{n} Jet | Def^{n}



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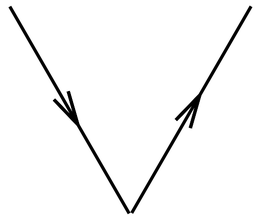

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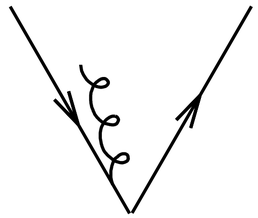

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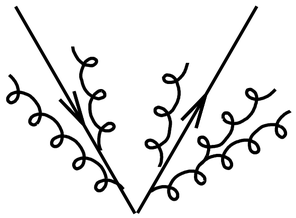

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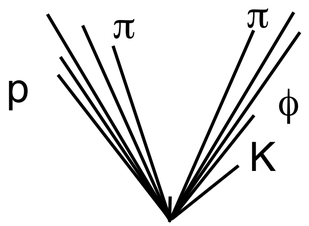

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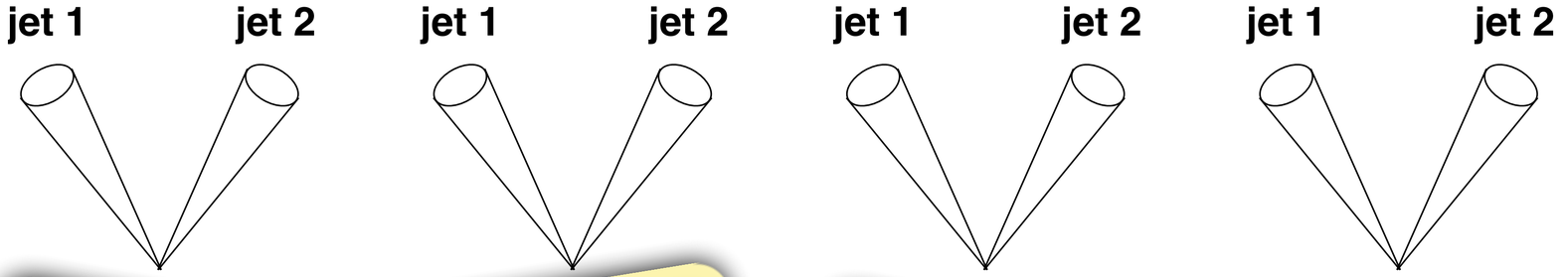
Jet | Def^n



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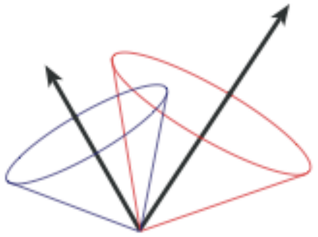

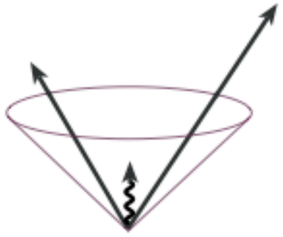

Infrared safety

- stable against adding soft parton emission

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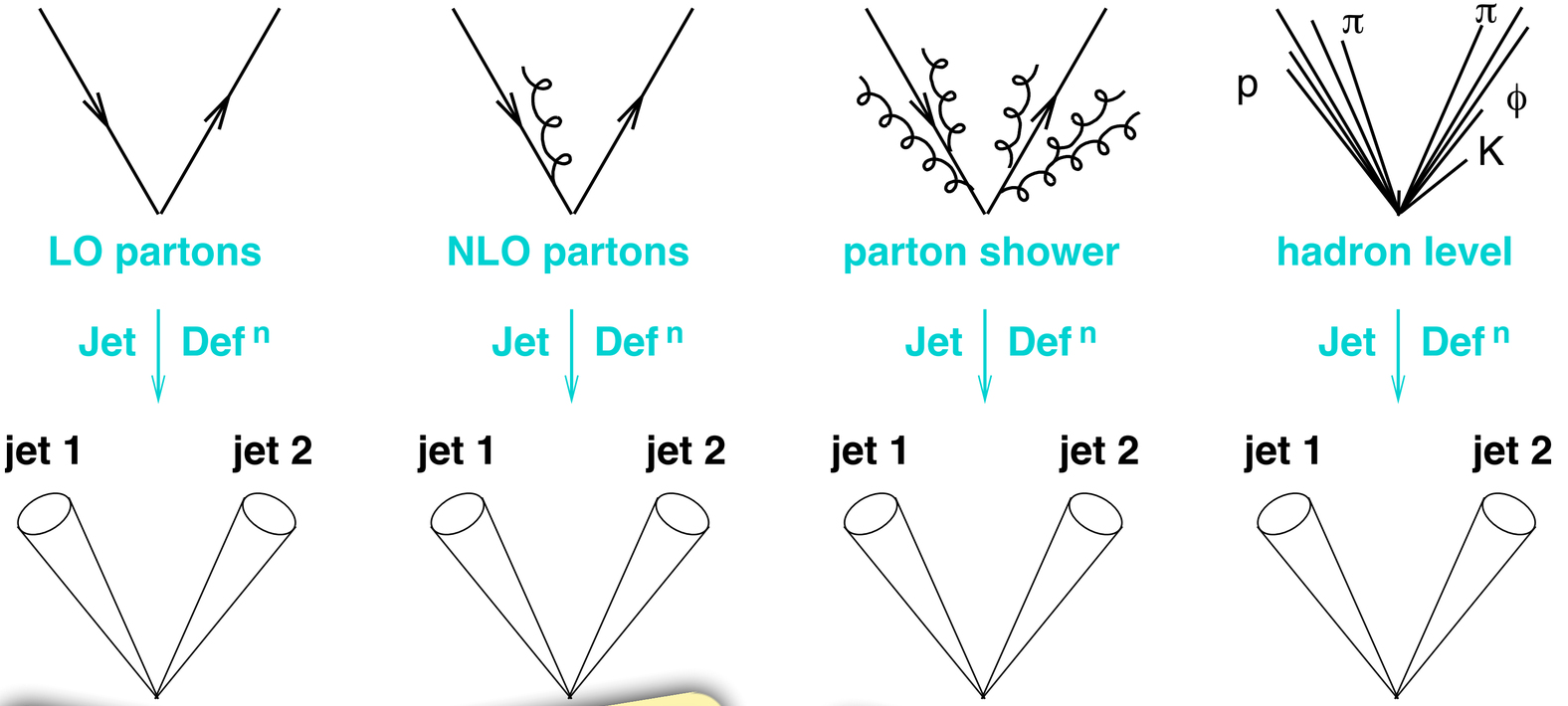

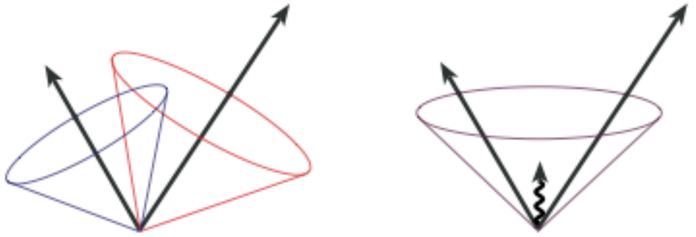

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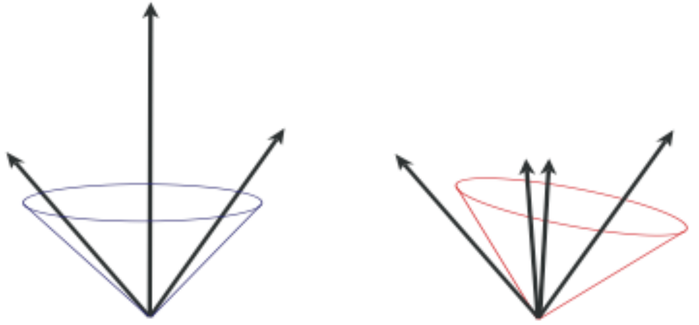

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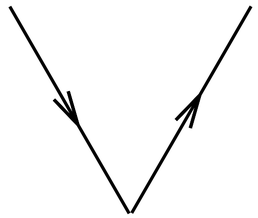
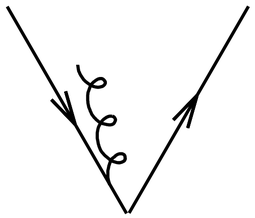
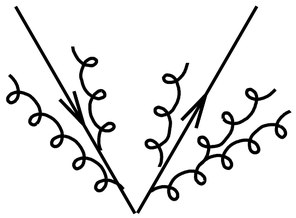


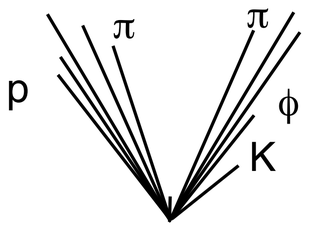
LO partons



NLO partons

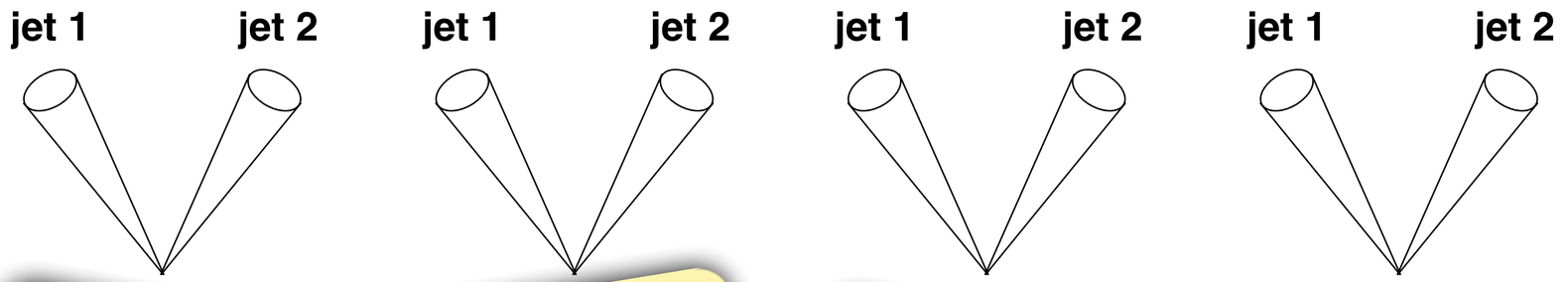


parton shower



hadron level

Jet | Def^n

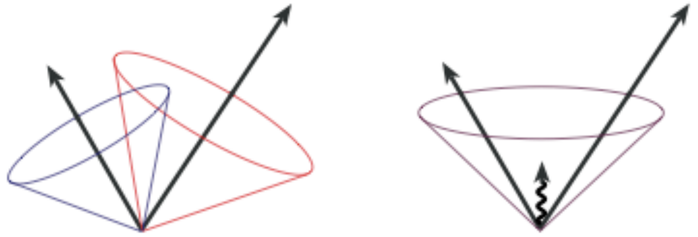


Jets

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

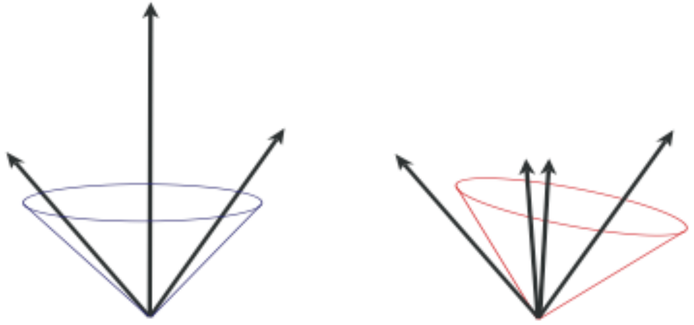
Jets

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



Infrared safety

- stable against adding soft parton emission



Collinear safety

- stable against replacing any parton with collinear pair

Jet Reconstruction

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

Jet Reconstruction

Iterative Cone Algorithms

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

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- Now standard at LHC

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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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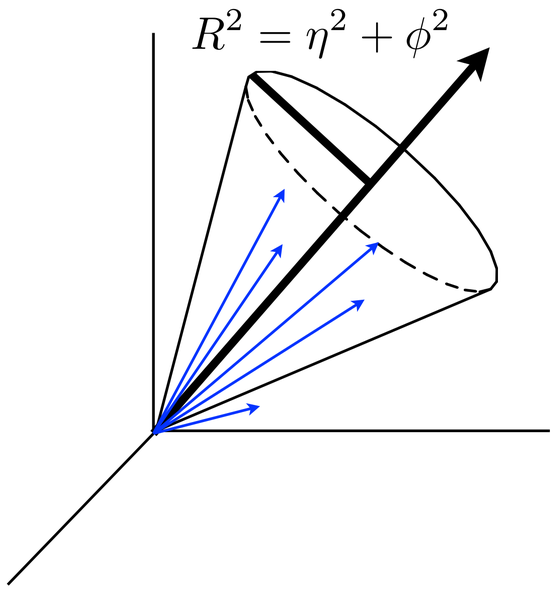

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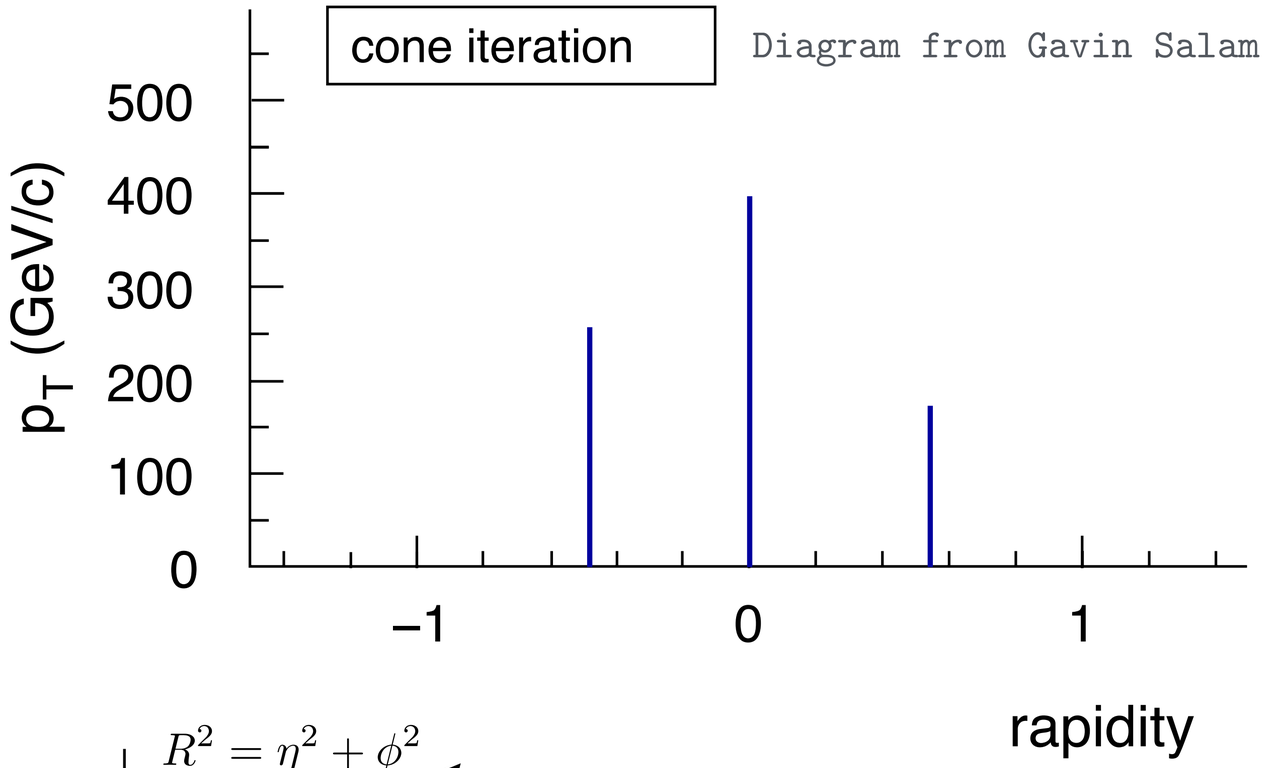

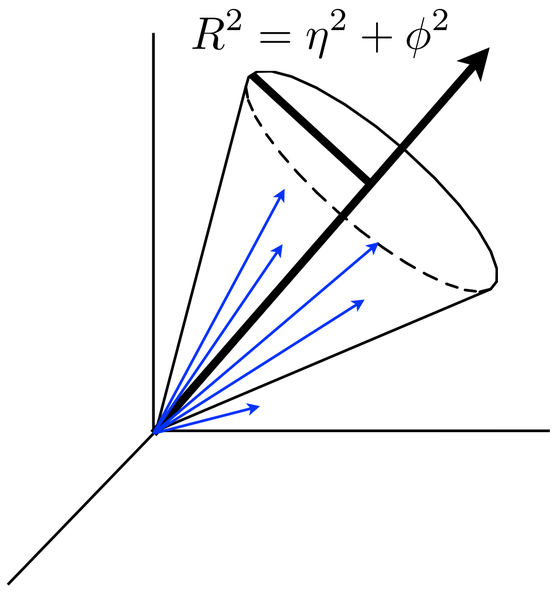

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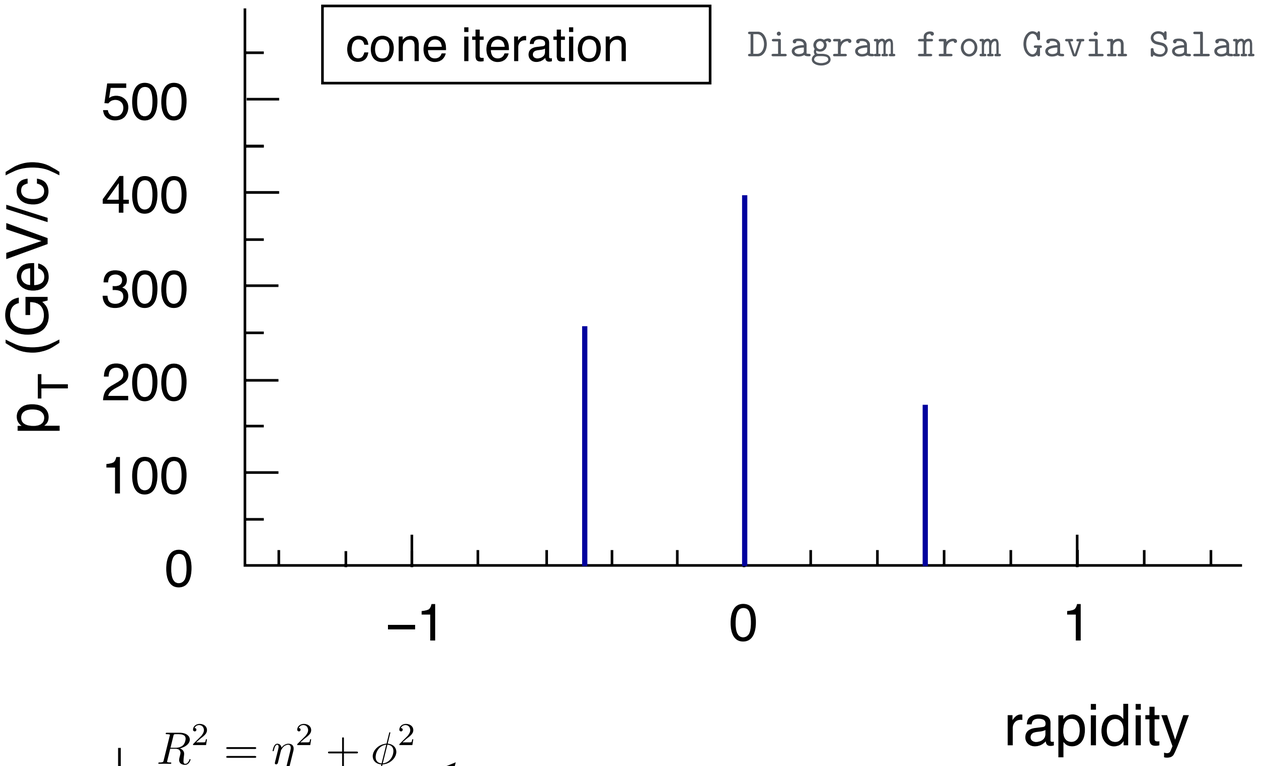

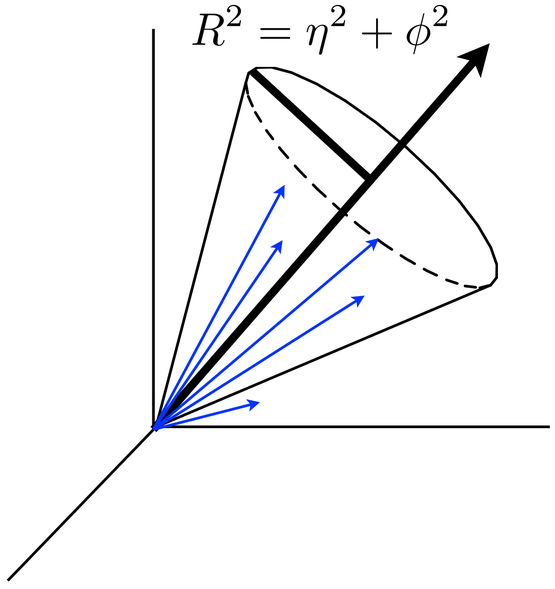

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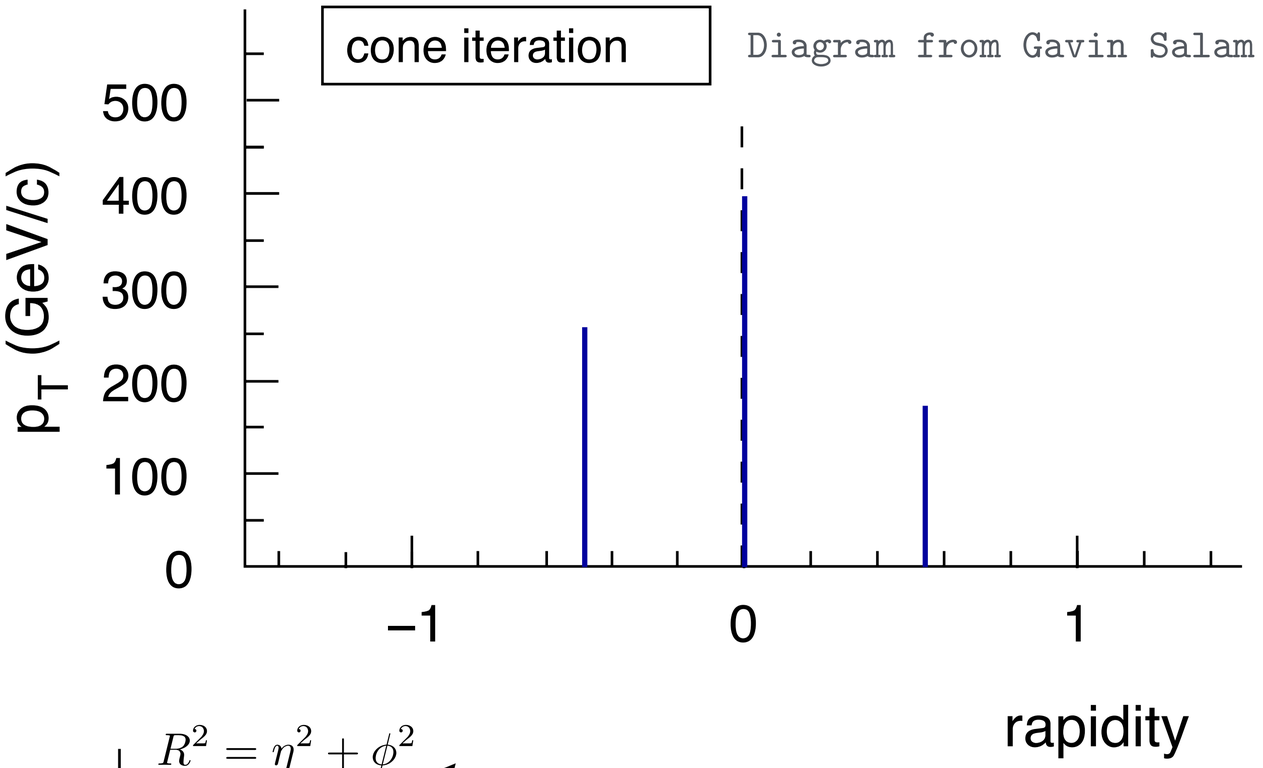

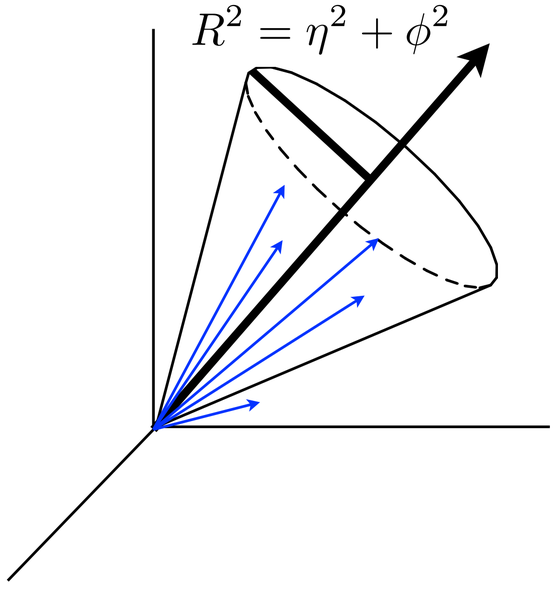

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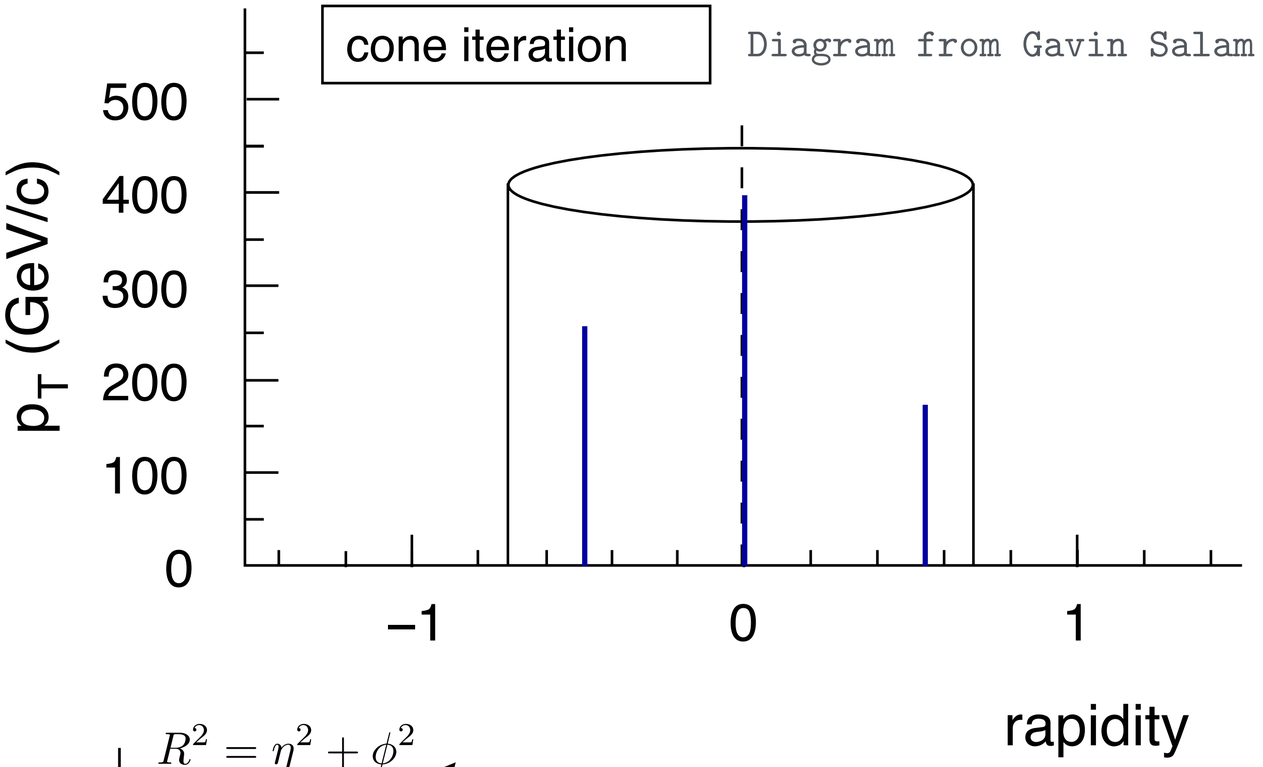

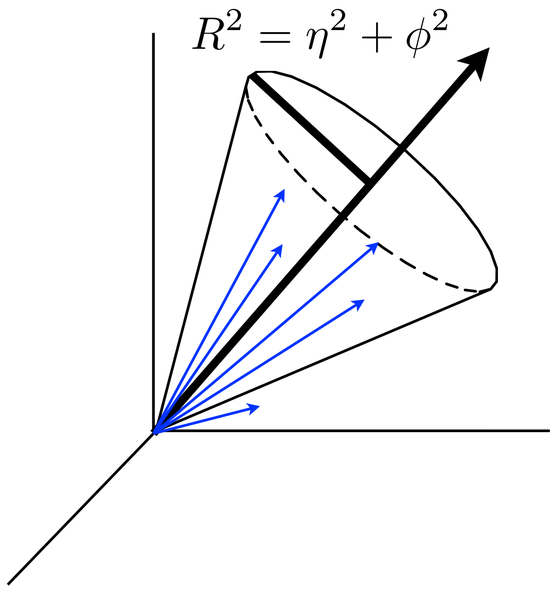

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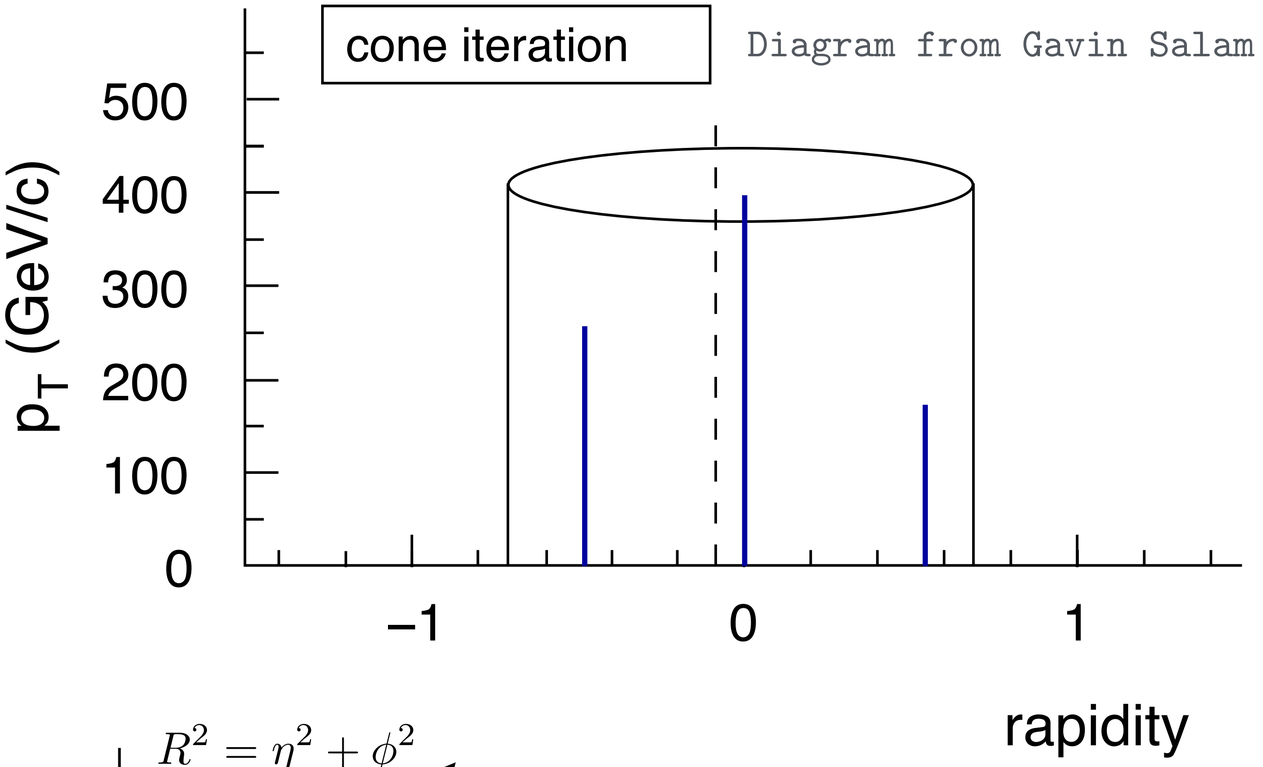

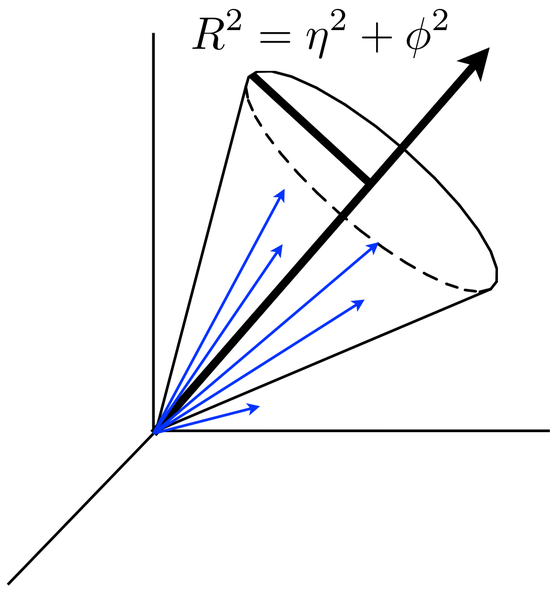

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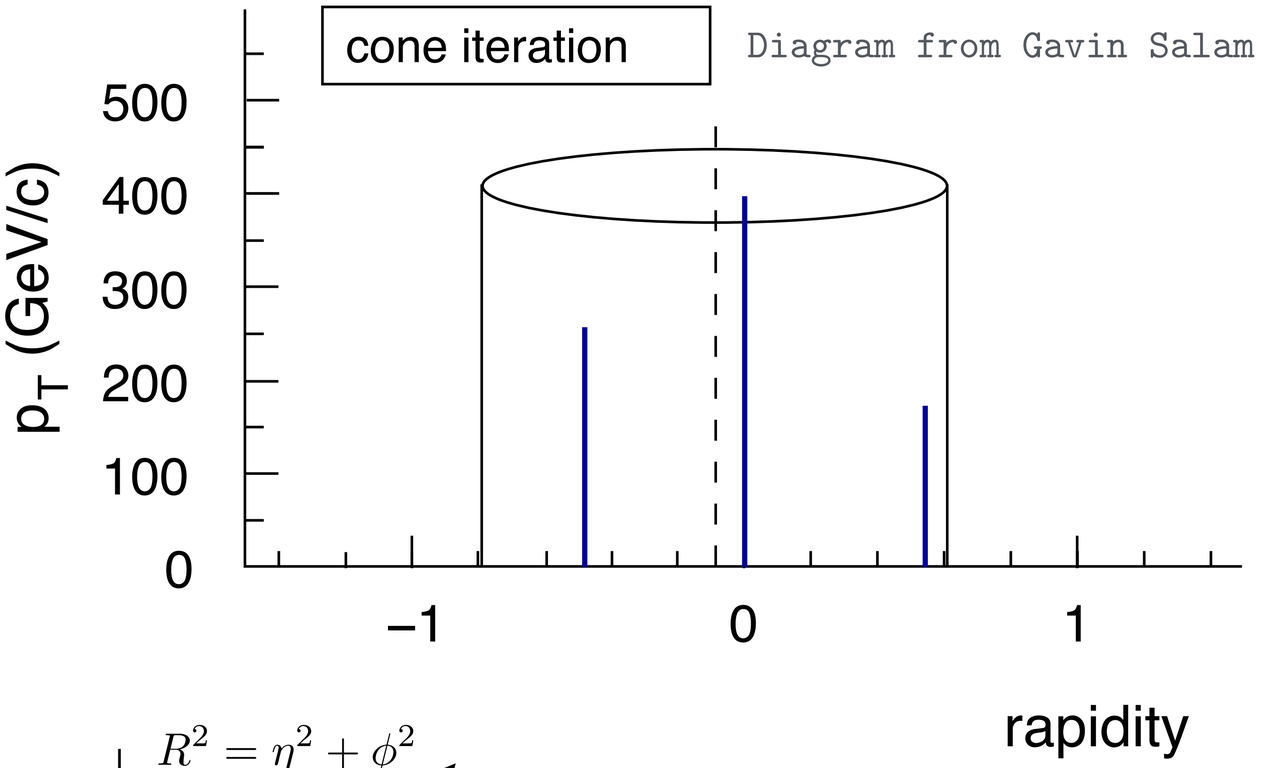

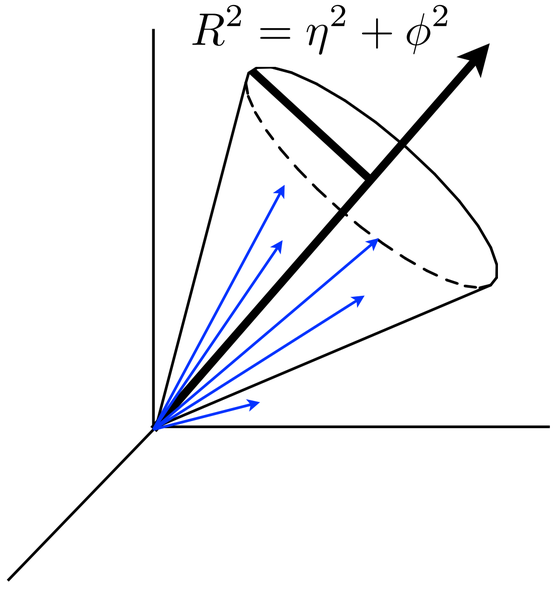

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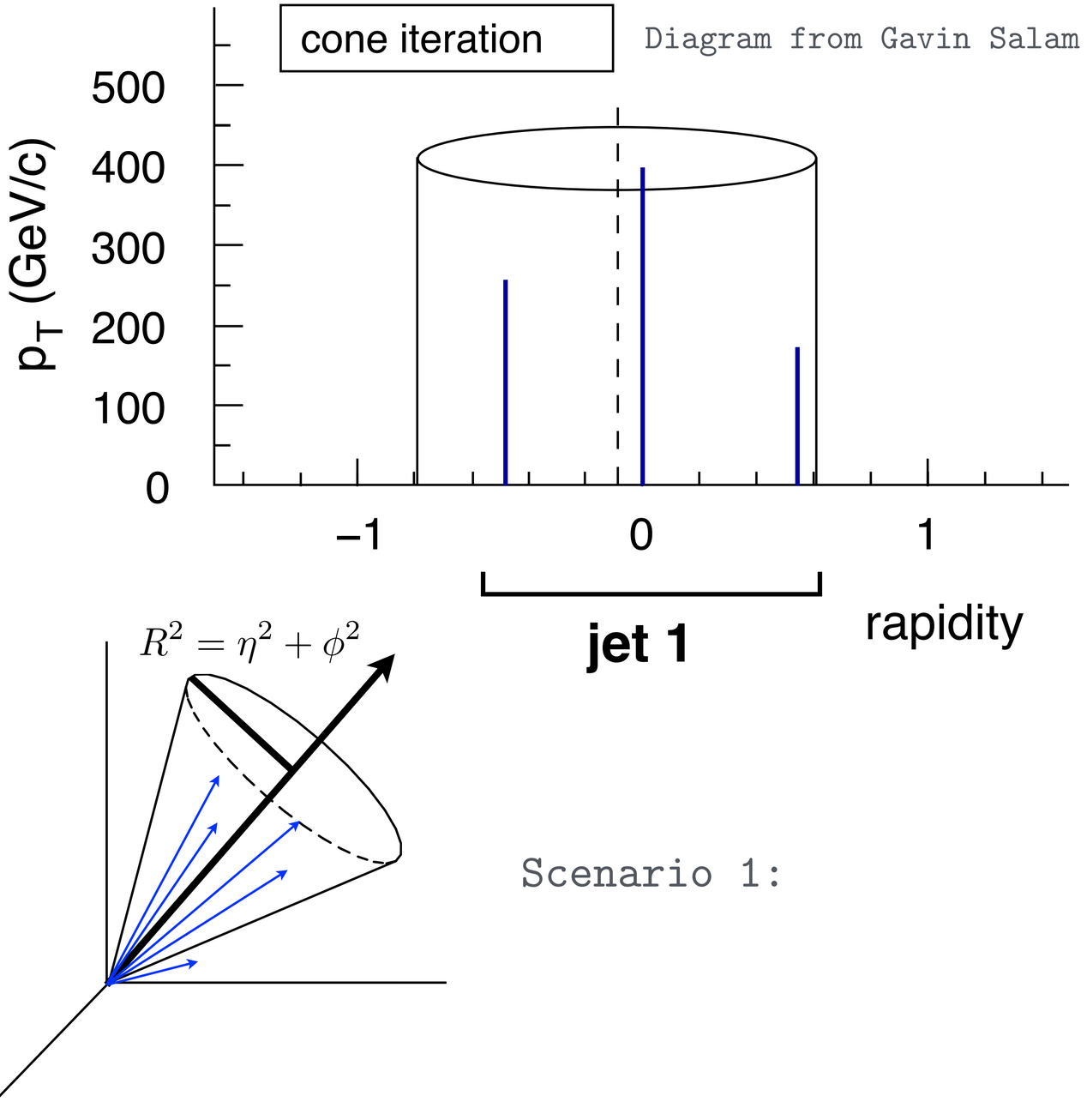

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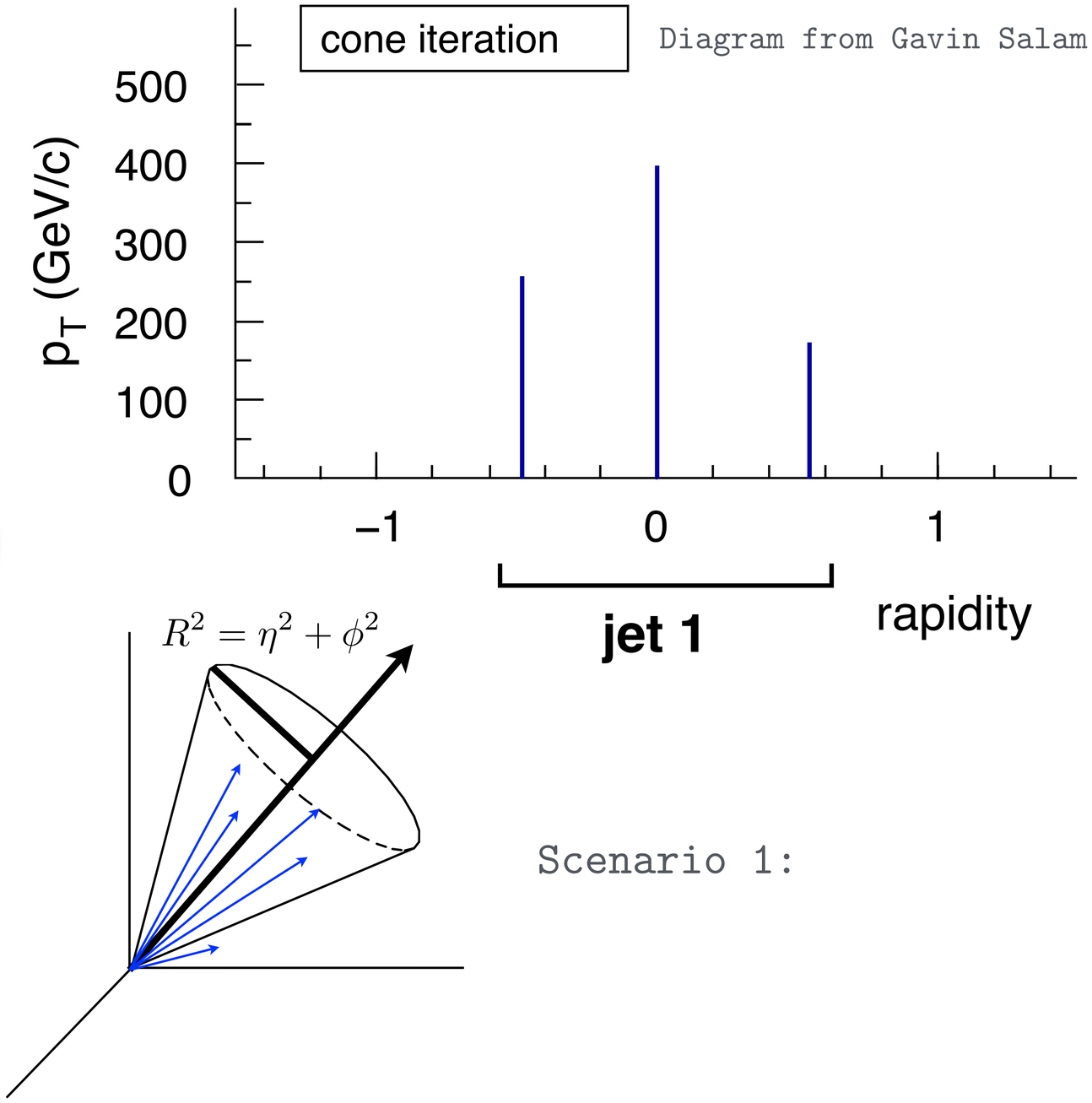

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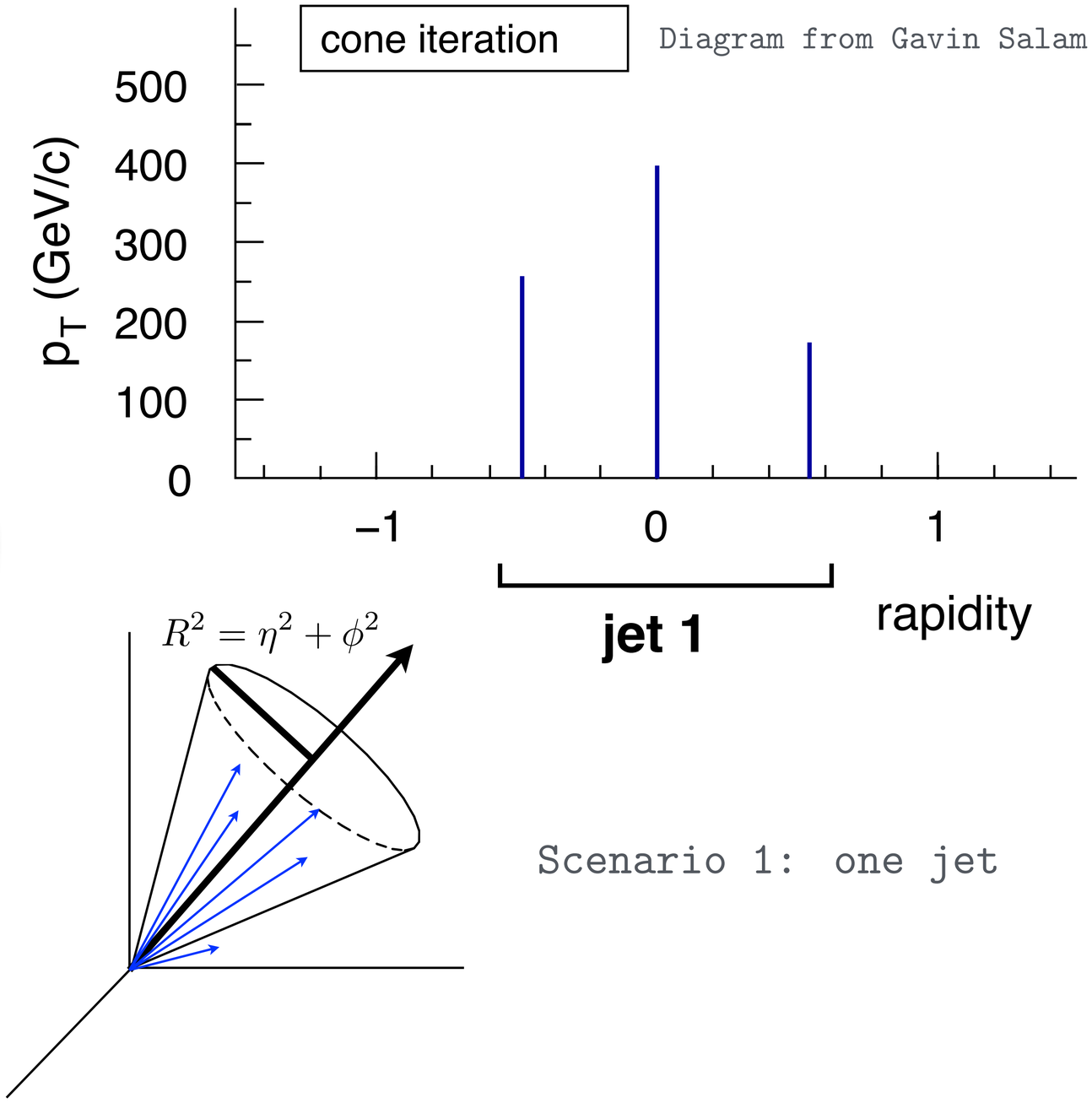

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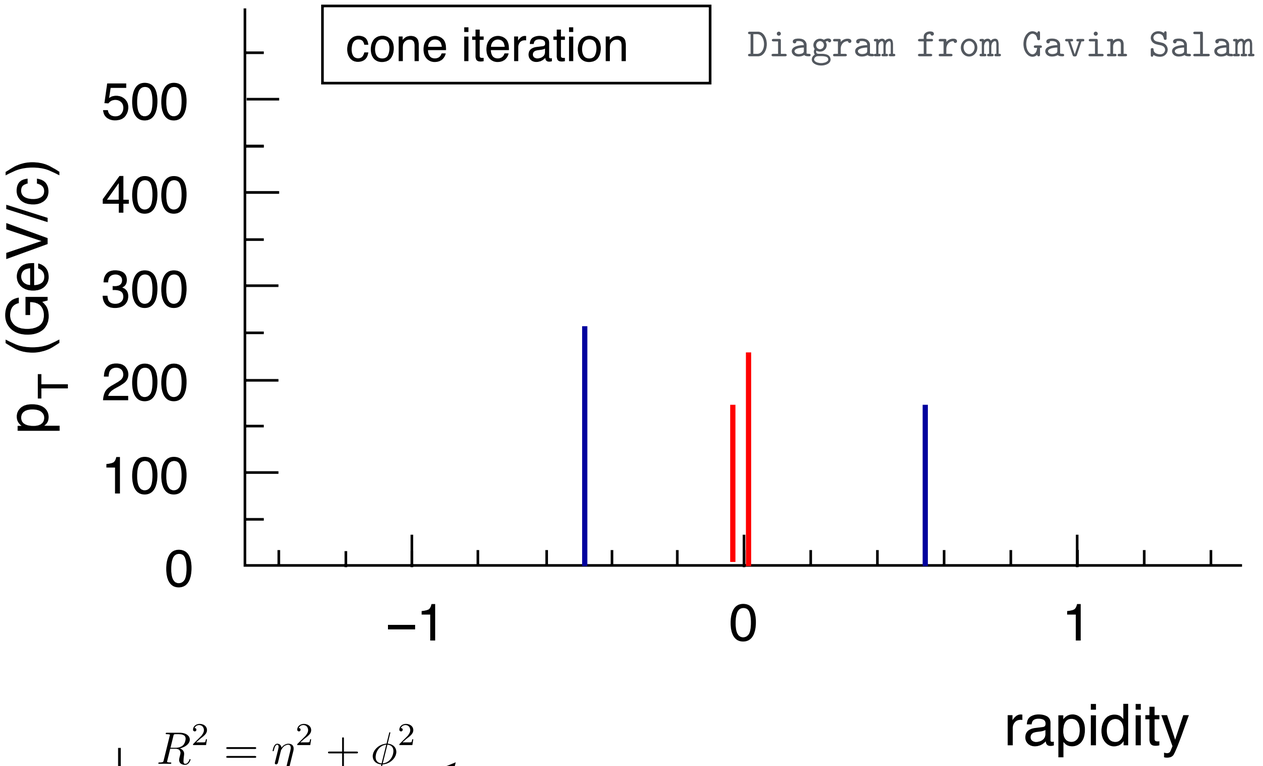

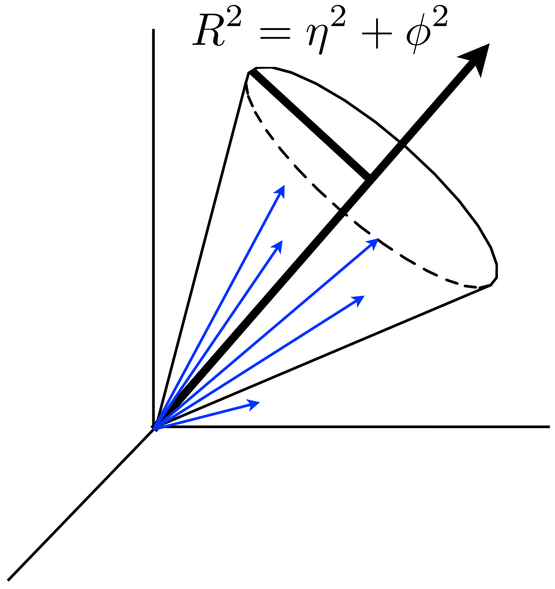

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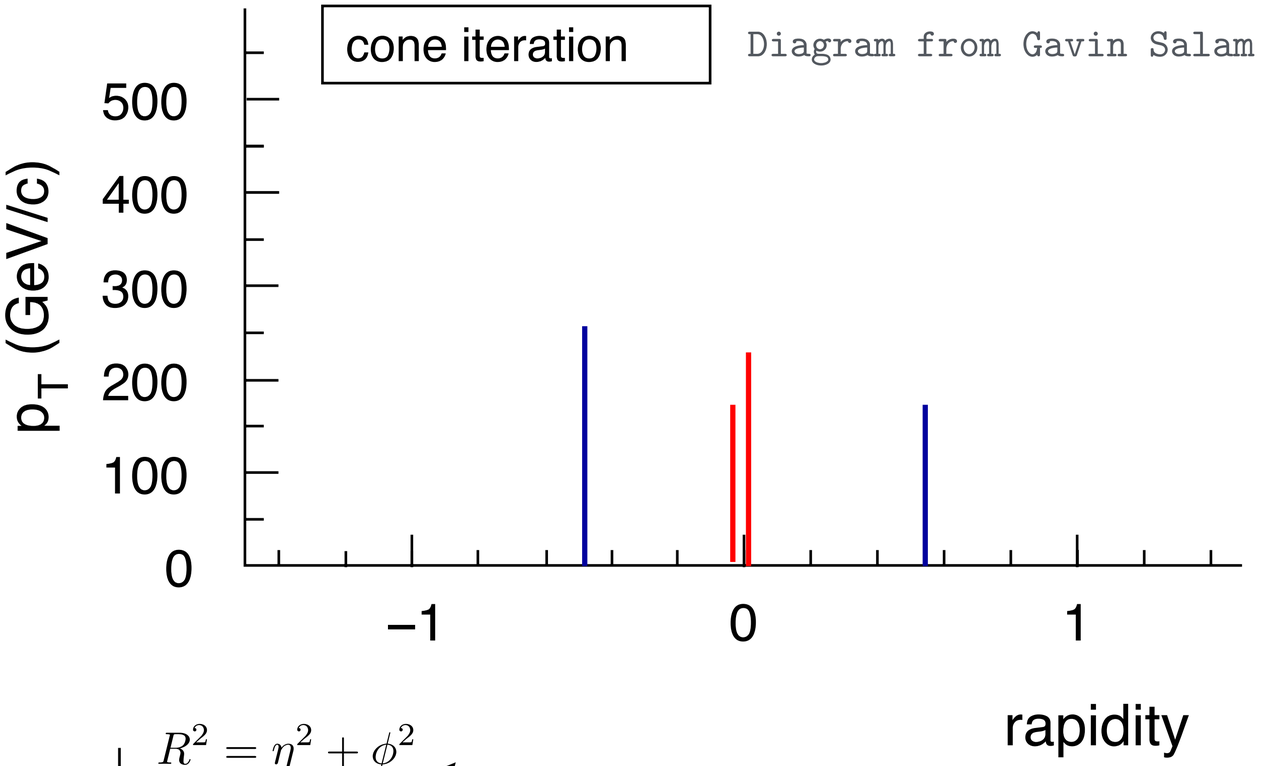

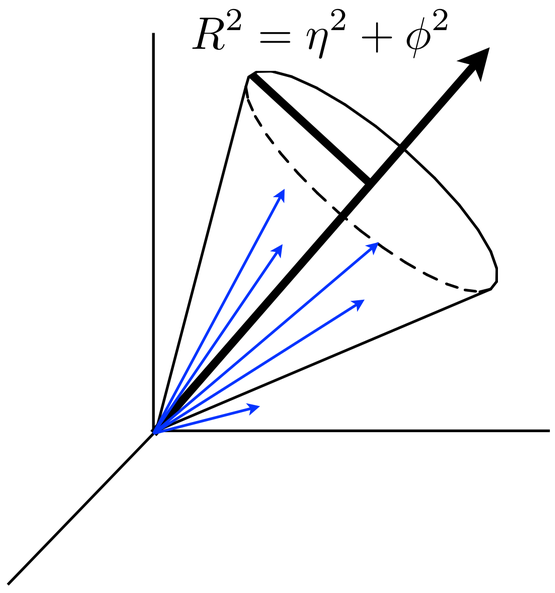

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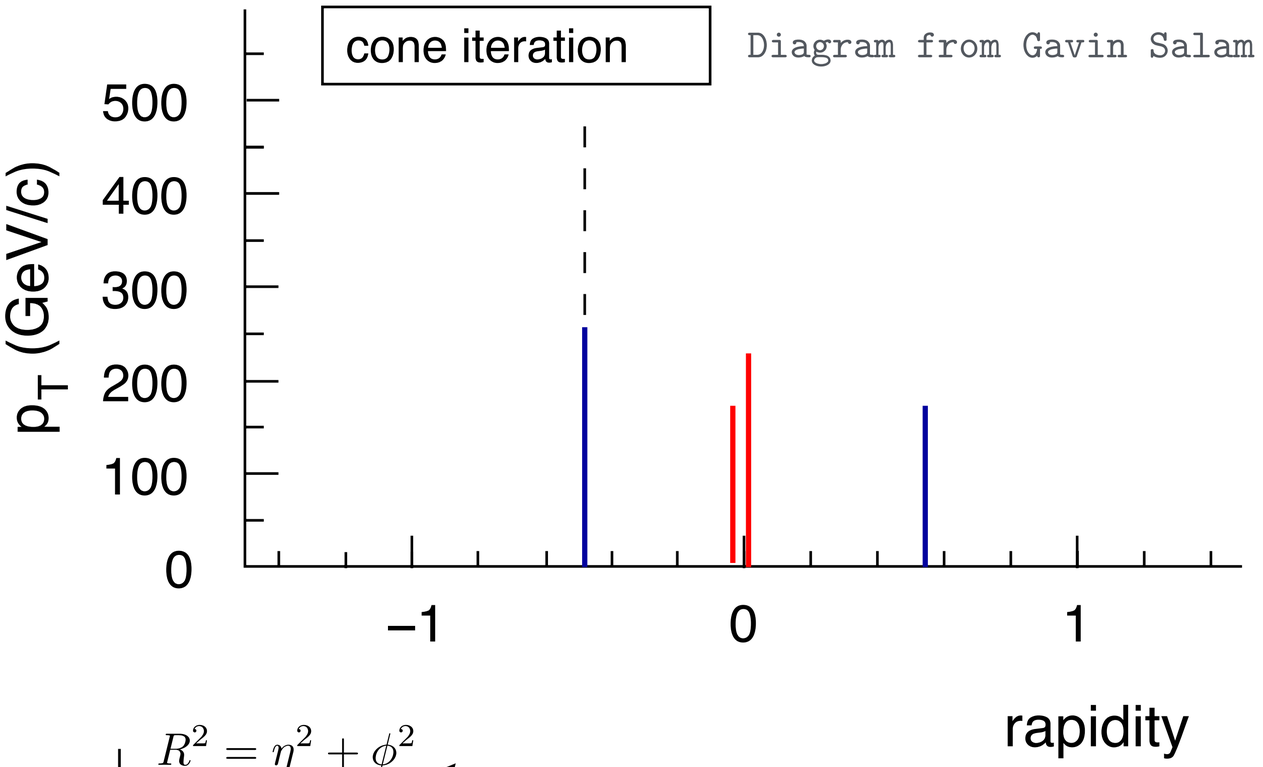

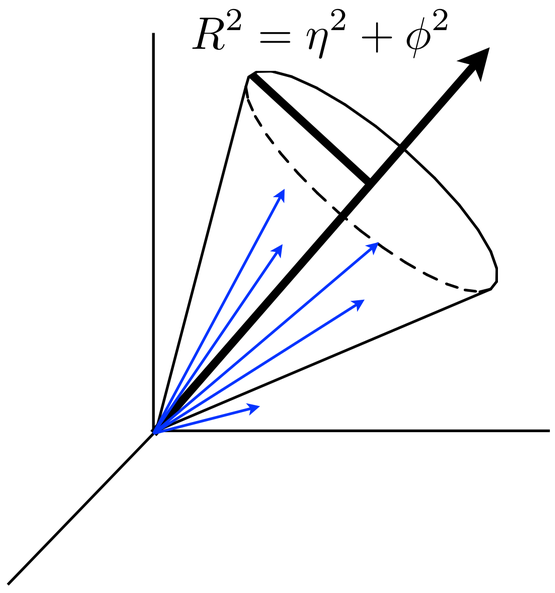

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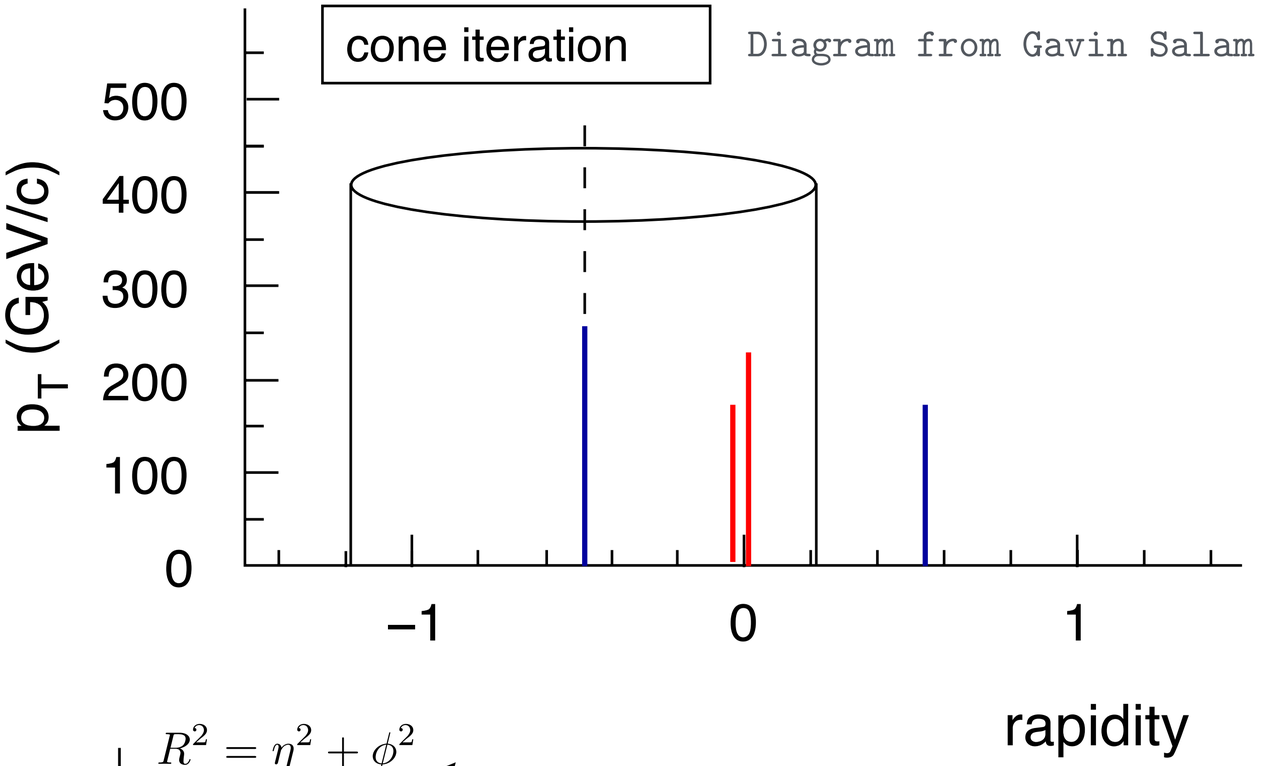

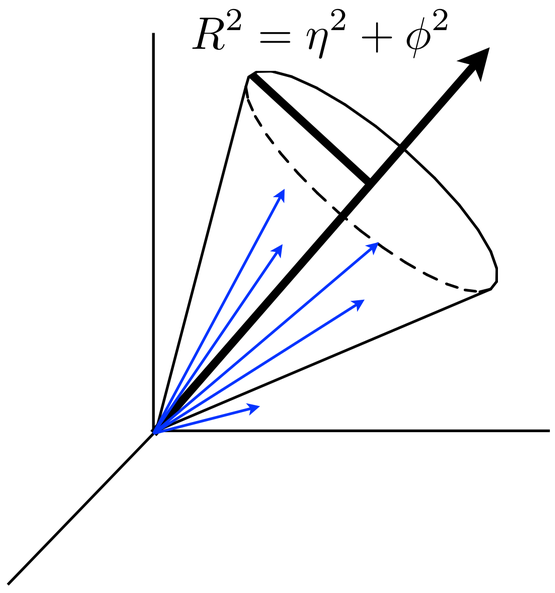

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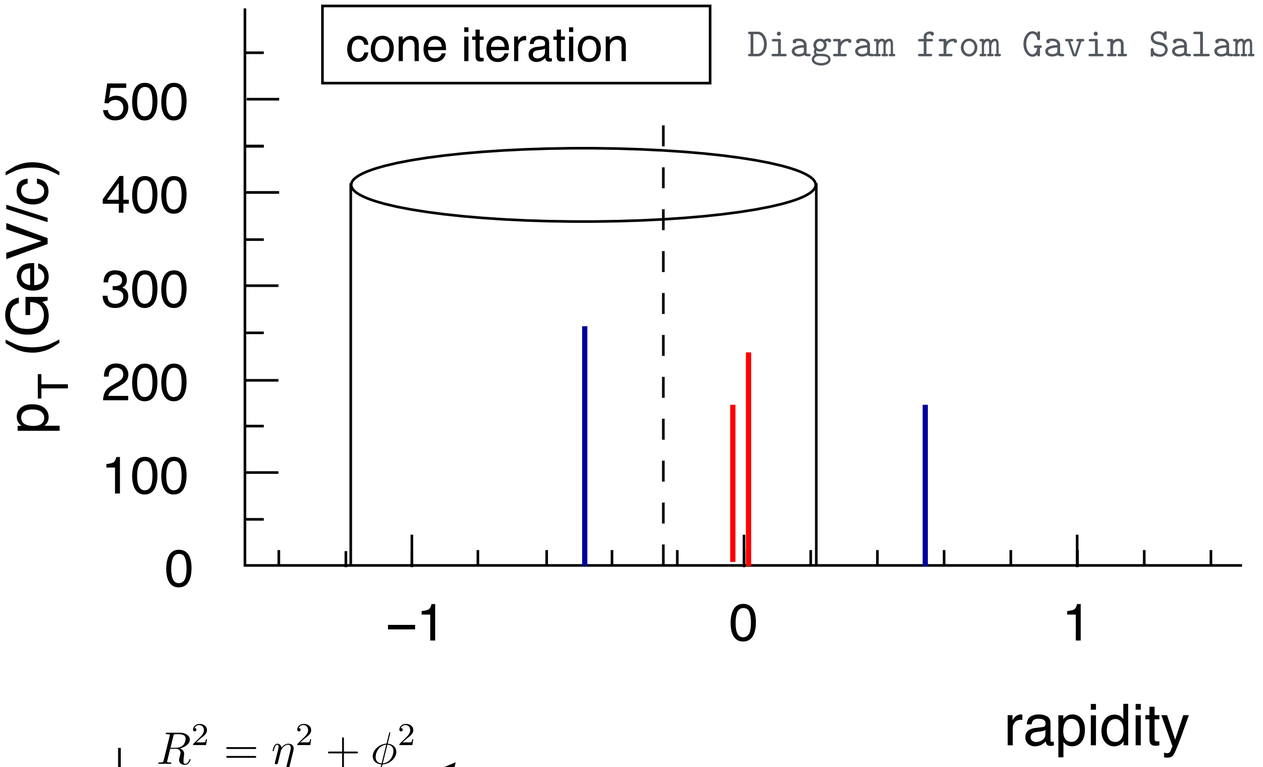

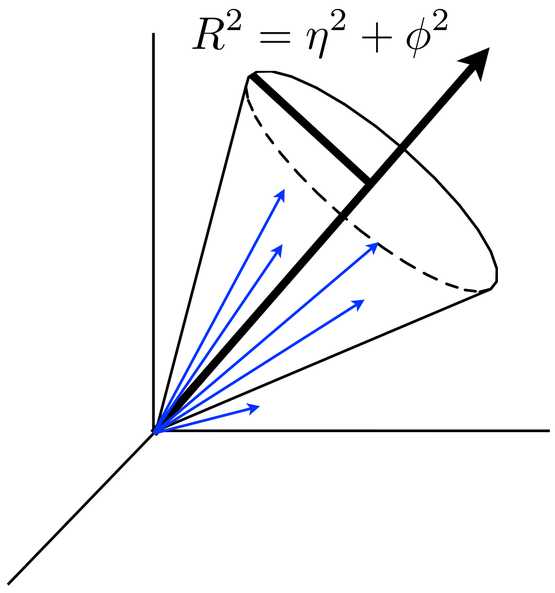

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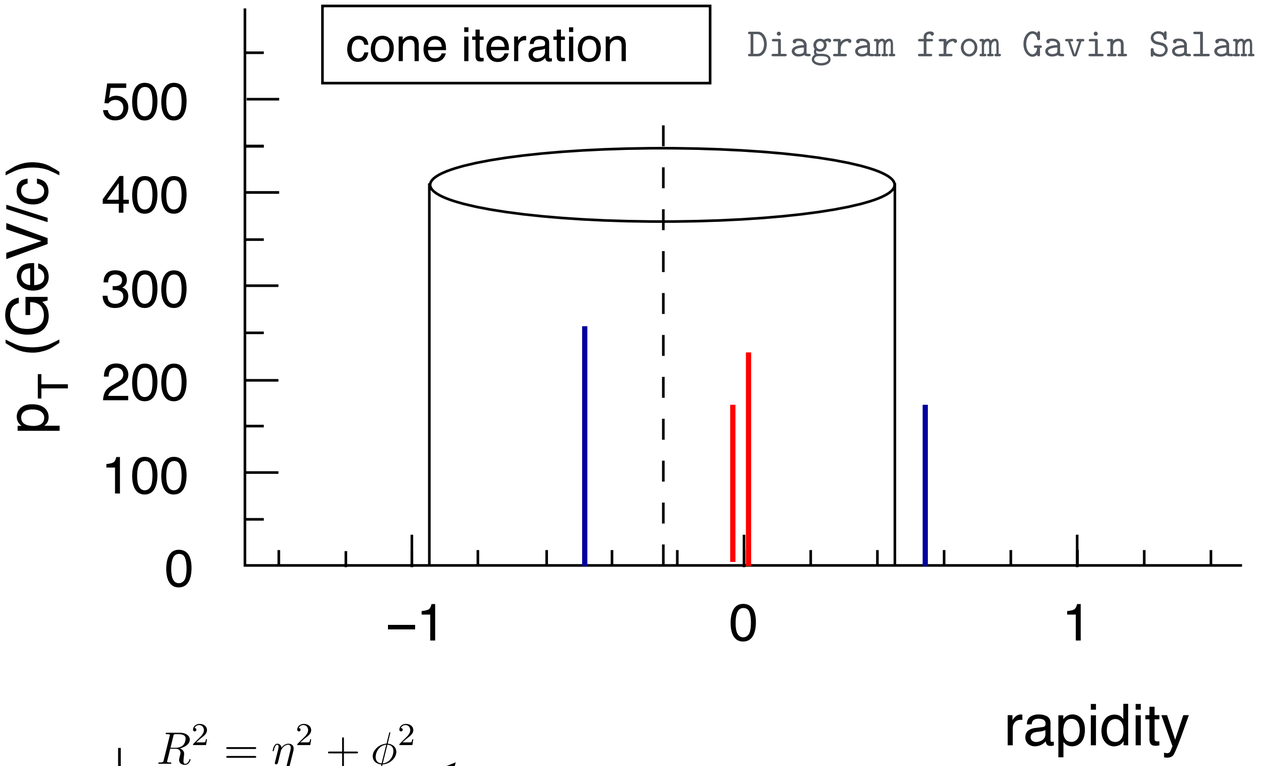

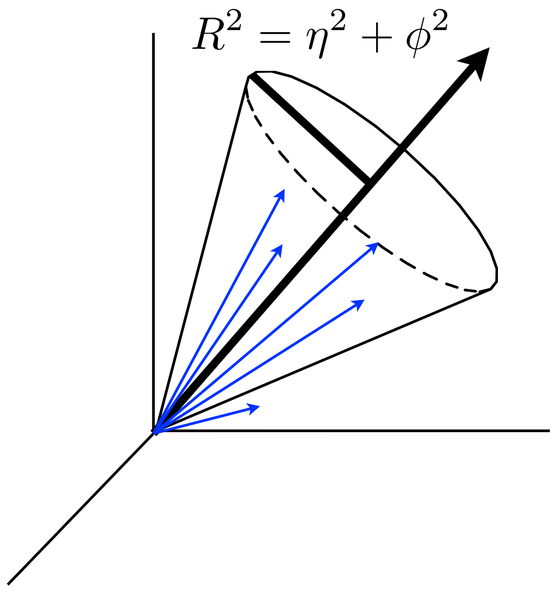

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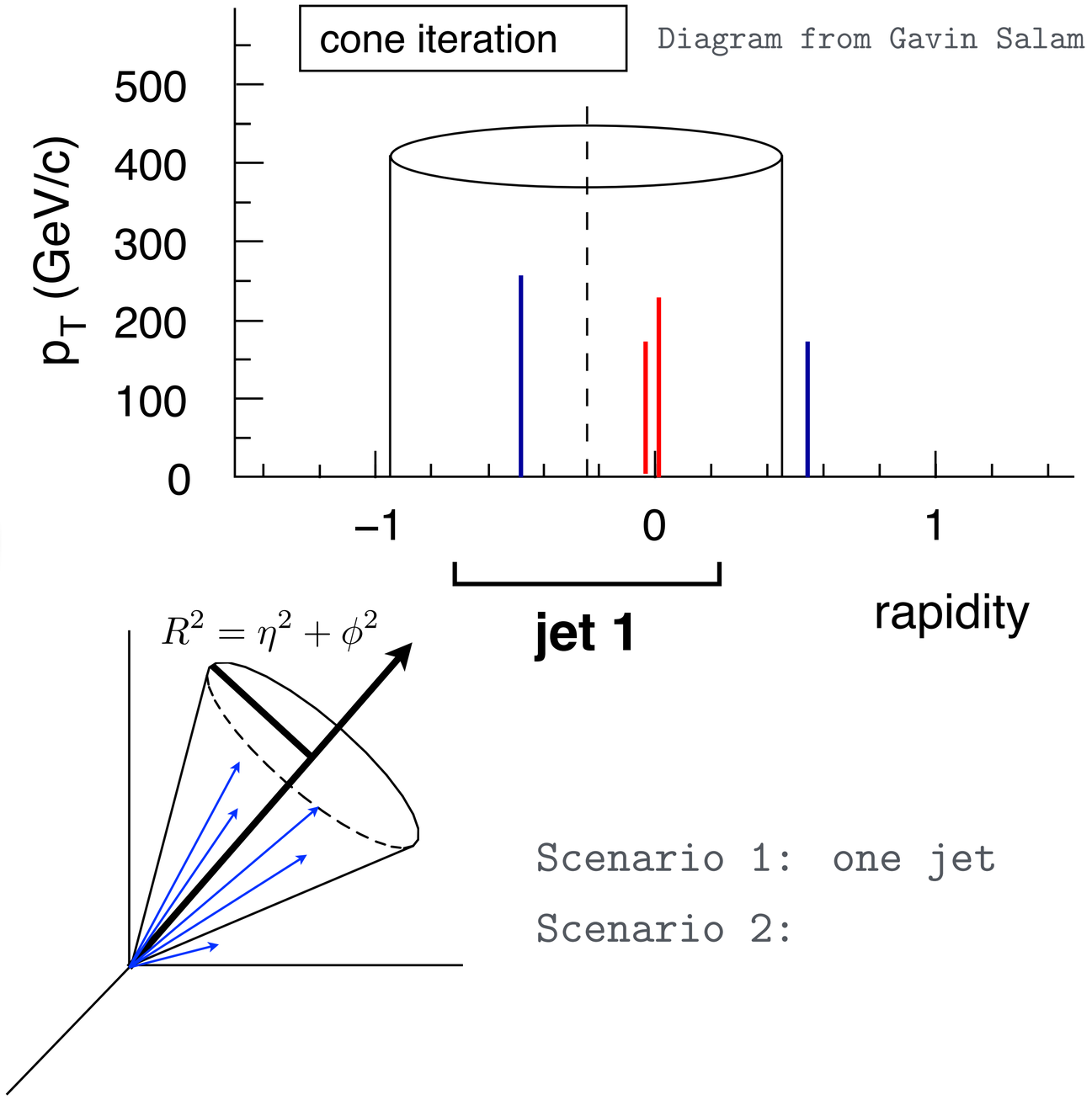

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Jet Reconstruction

Iterative Cone Algorithms

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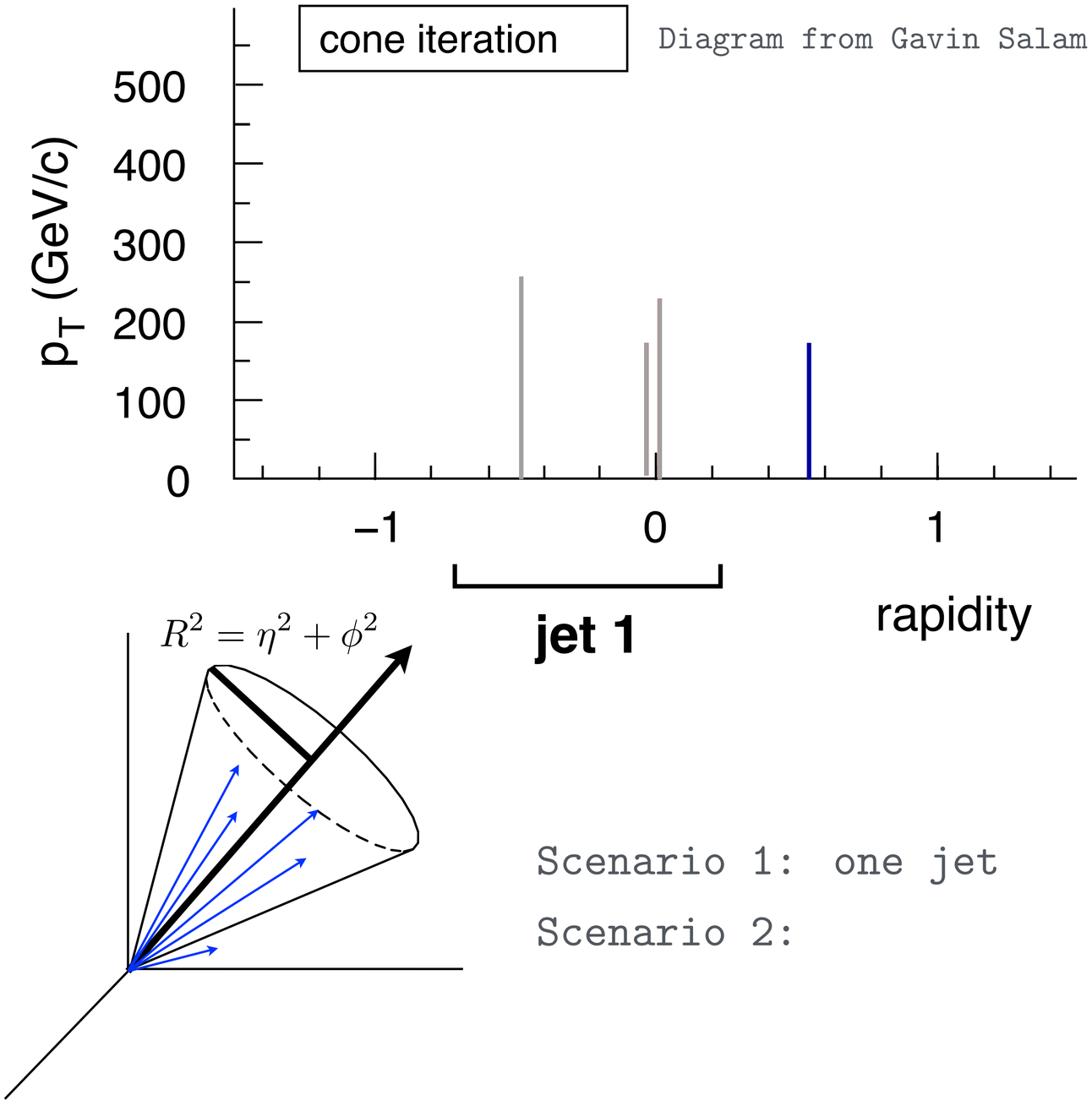

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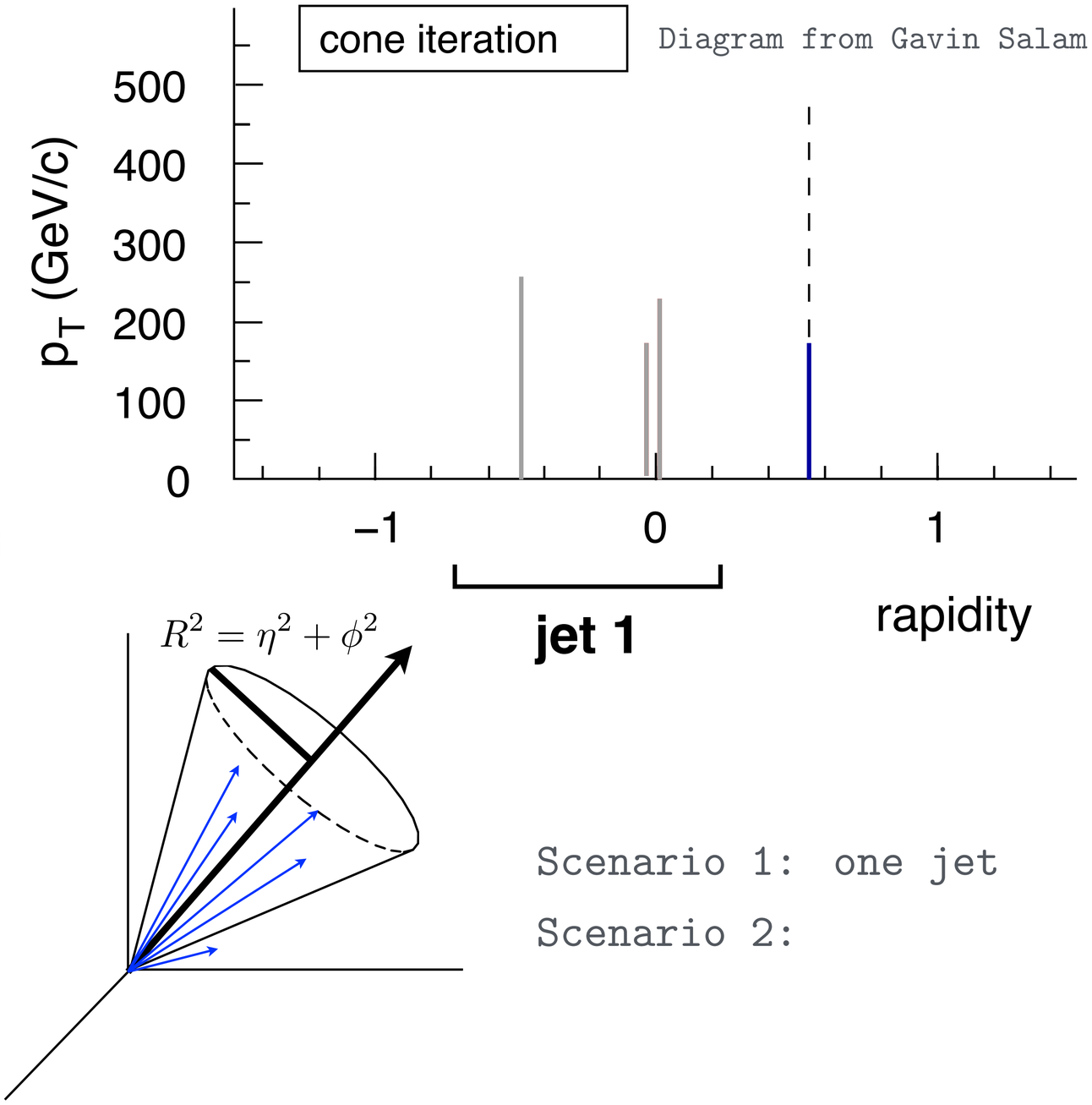

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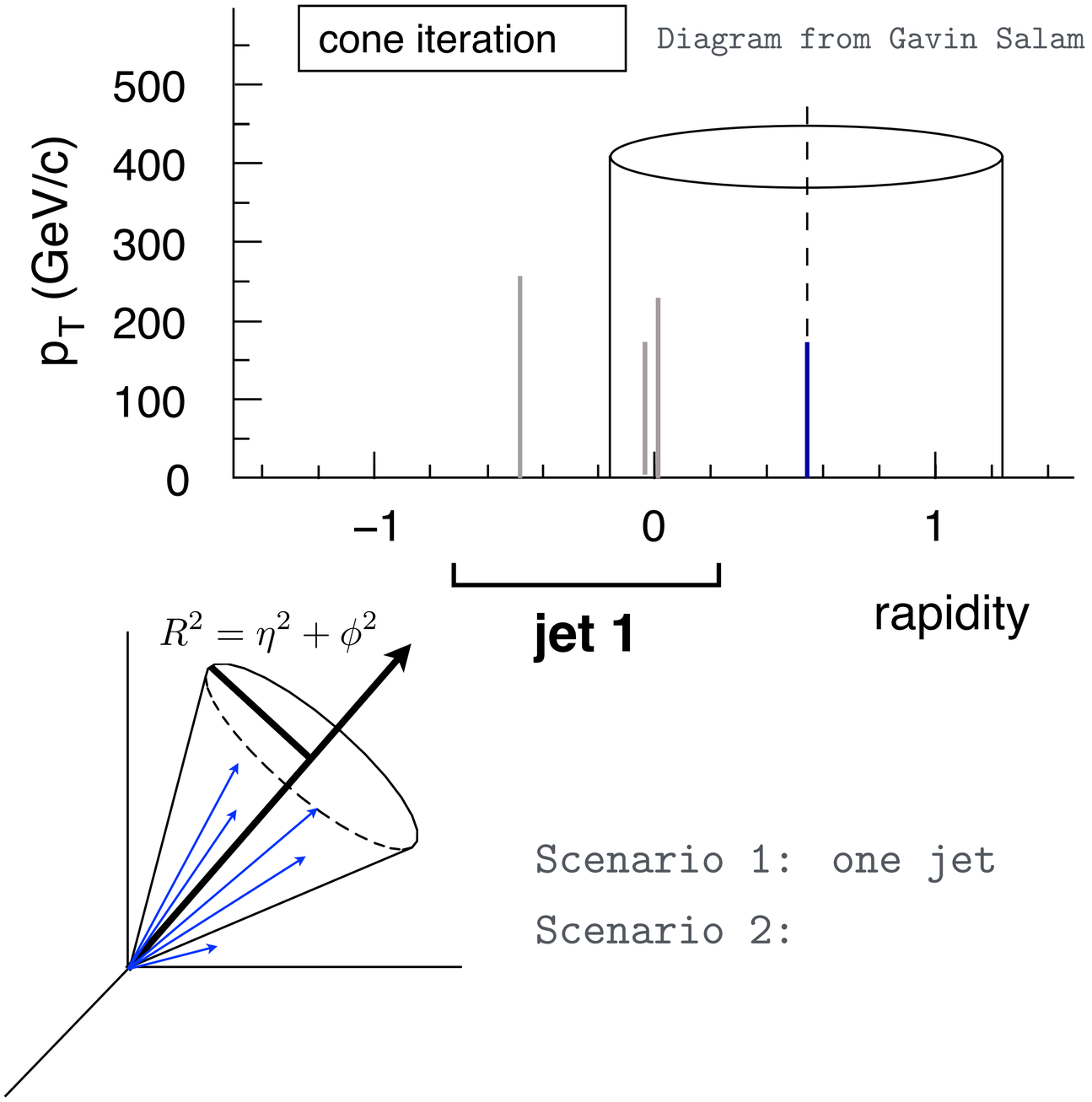

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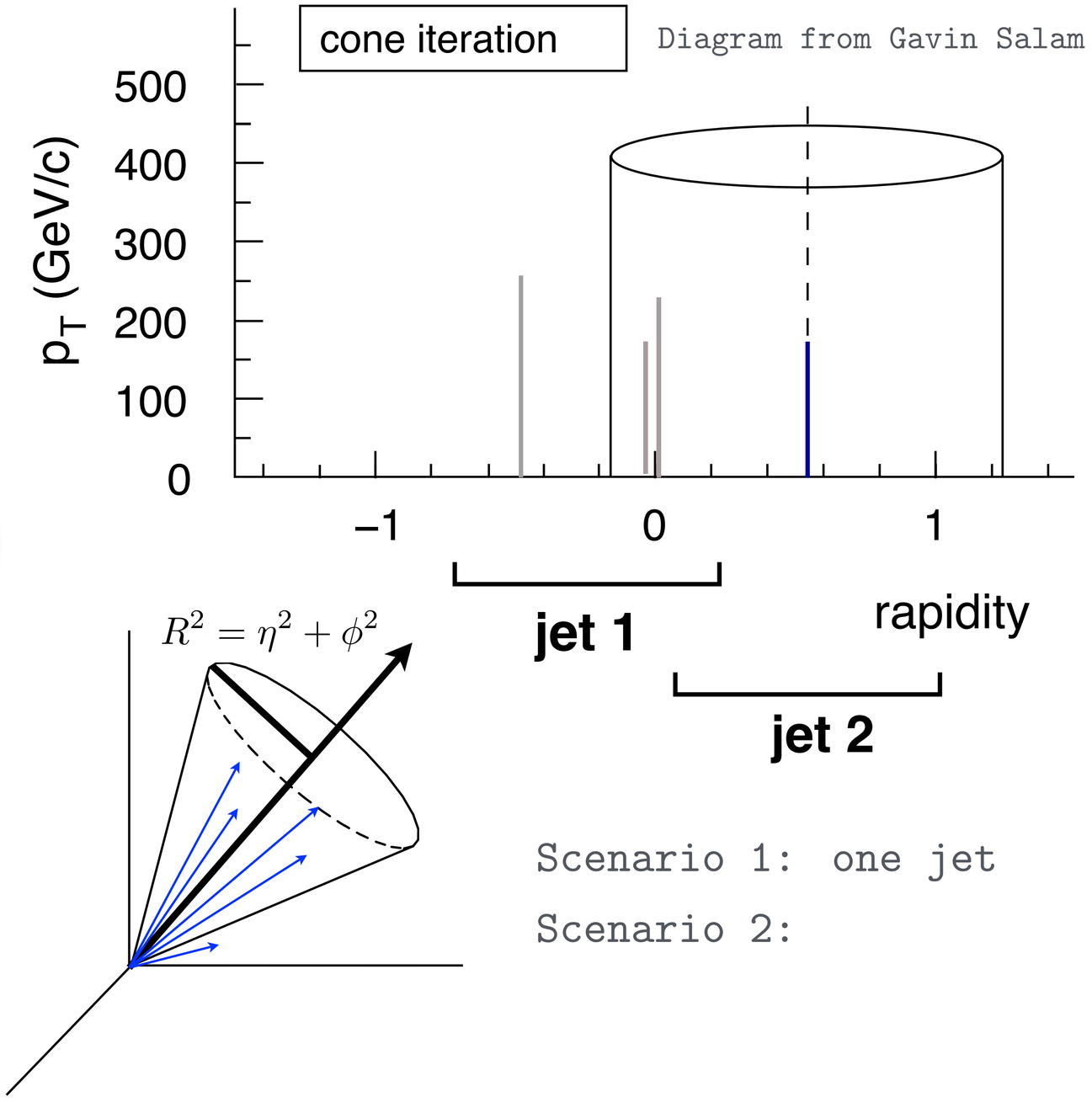

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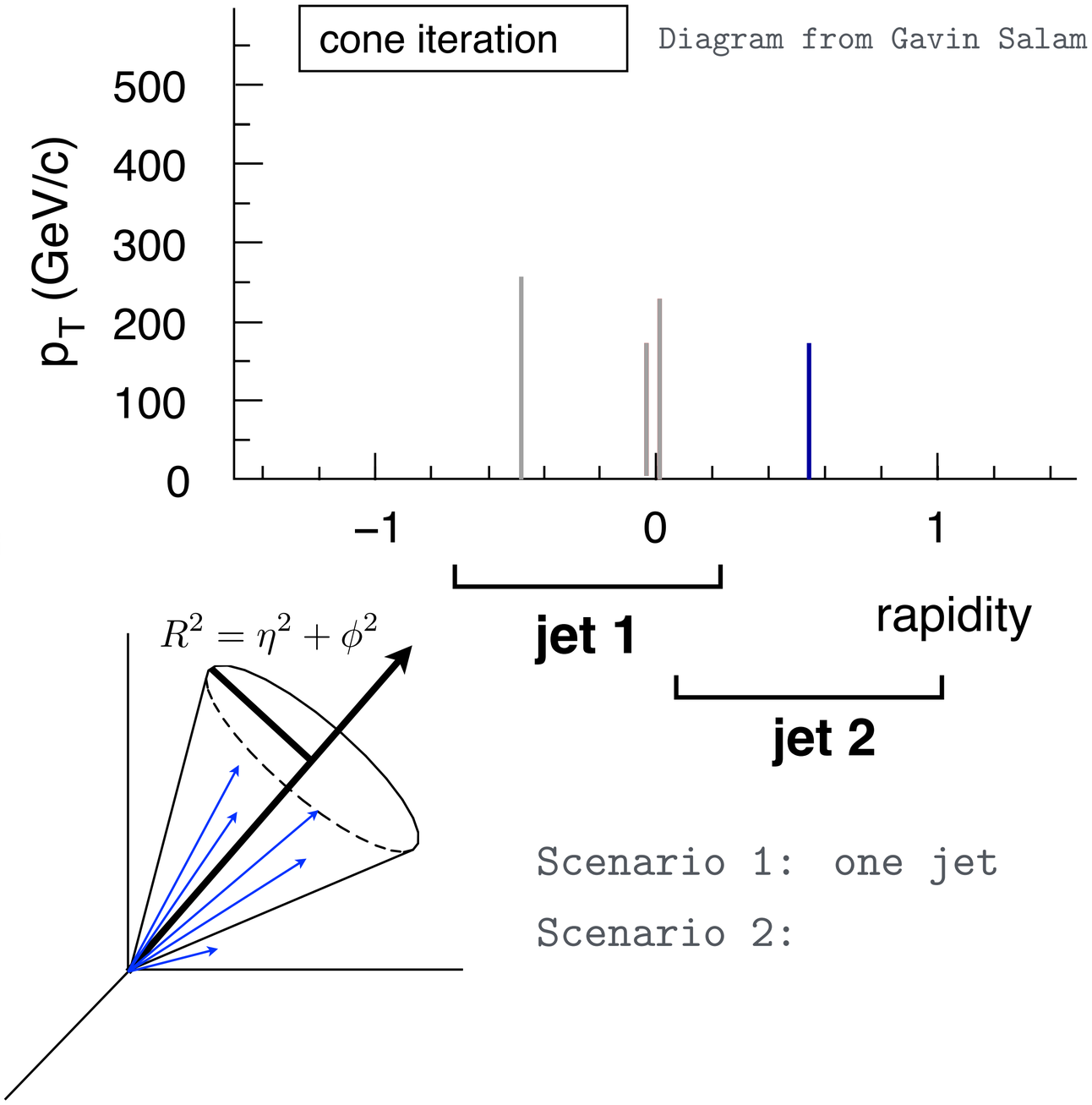

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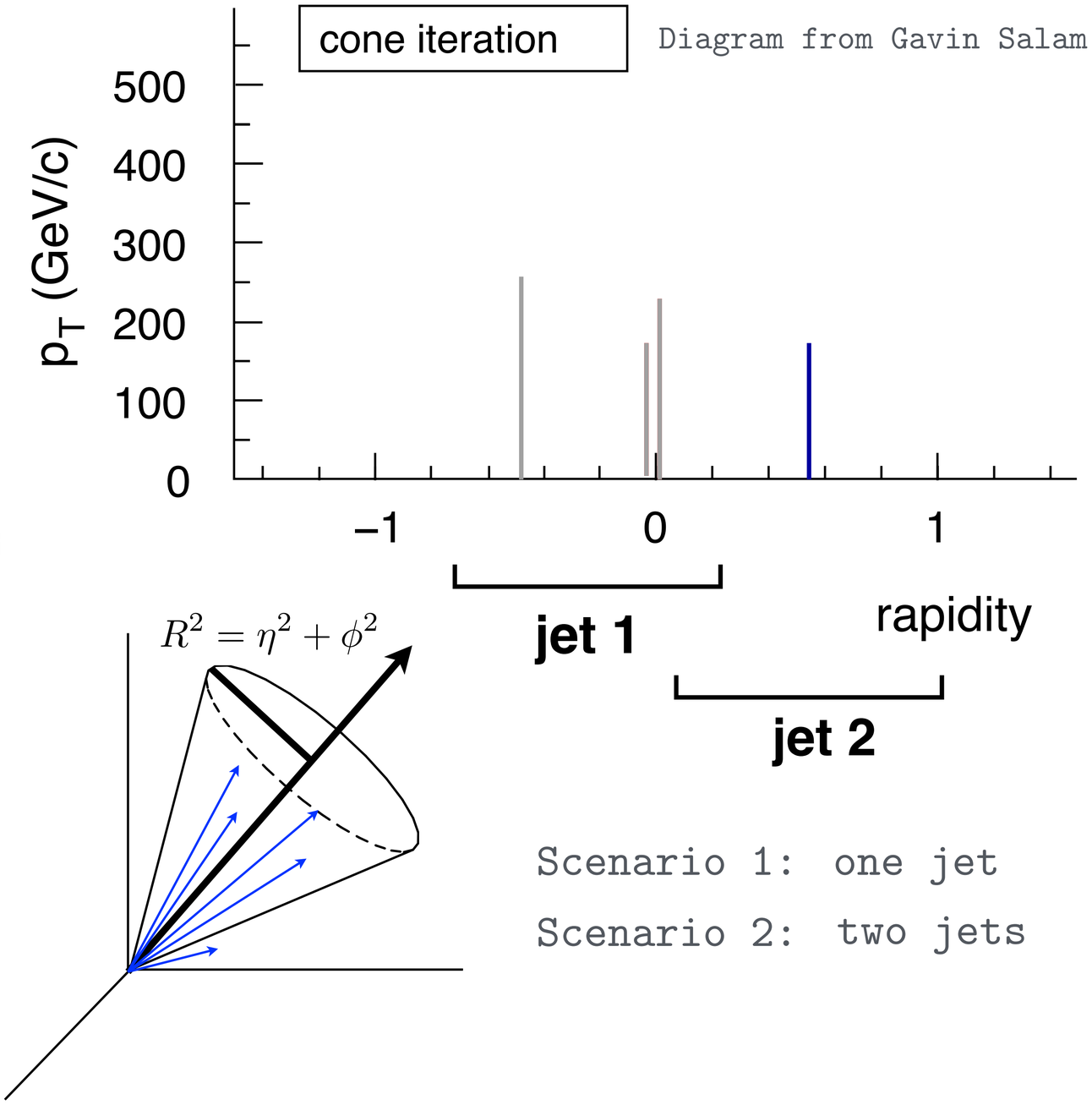

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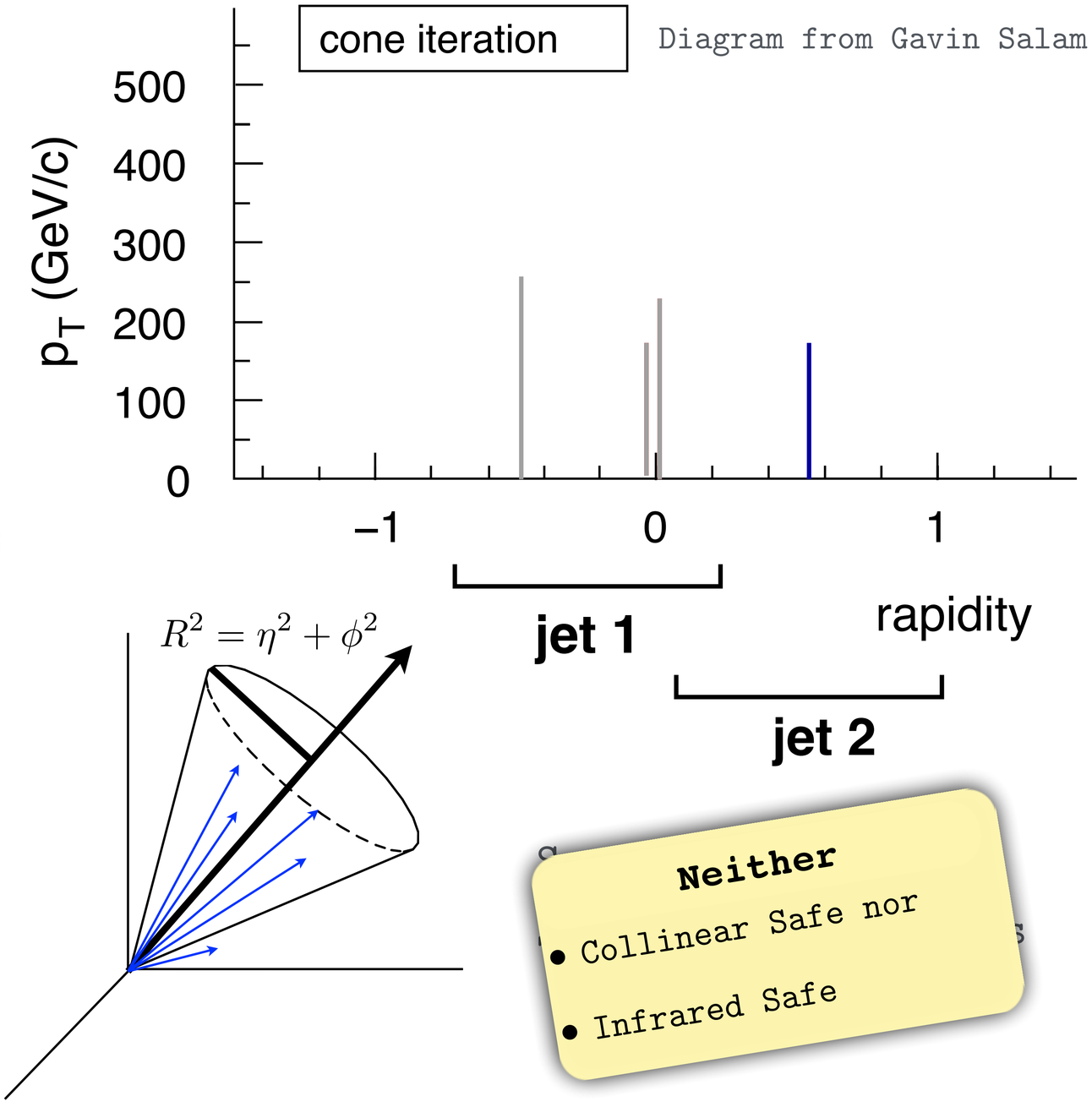

Neither

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Jet Reconstruction

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Sequential Clustering Algorithms

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Jet Reconstruction

JADE

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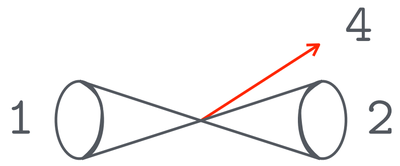

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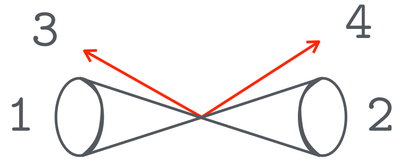

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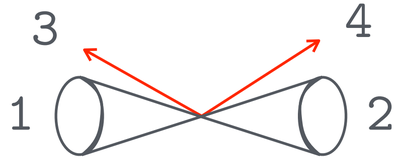

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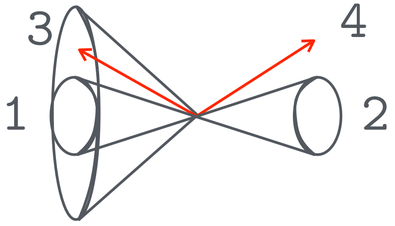

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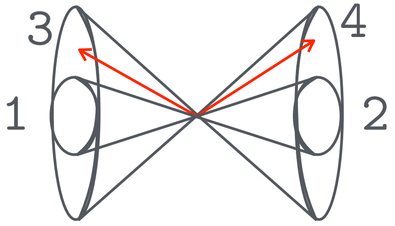

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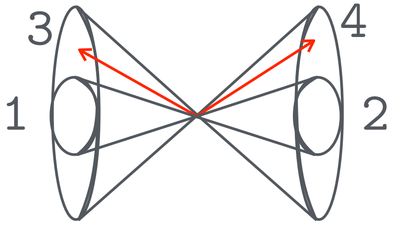

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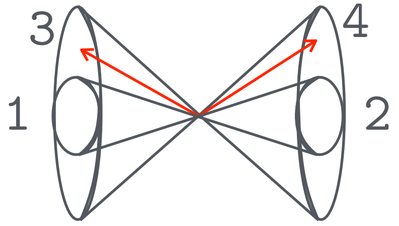

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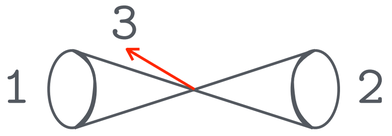

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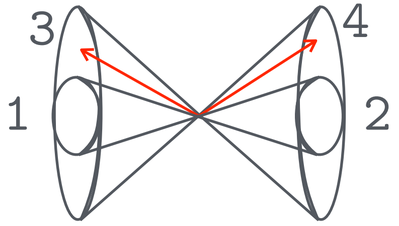

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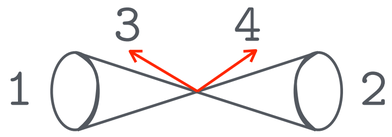
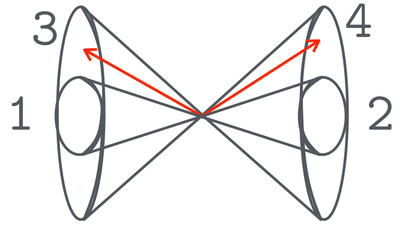
- Example: two soft gluons emitted close to q1 and q2; the gg invariant mass, y_{34}, can be smaller than that of any qg pairs and hence 3 jets can be reconstructed instead of 2



$y_{13} < y_{34}$; $y_{24} < y_{34}$



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Jet Reconstruction

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Advantages

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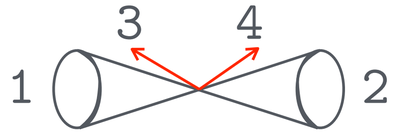

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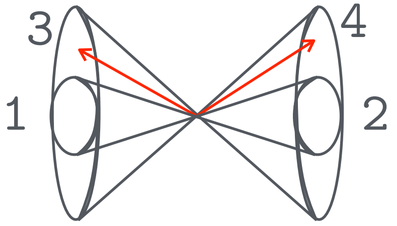

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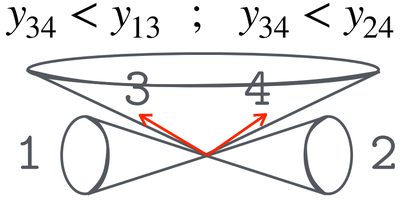

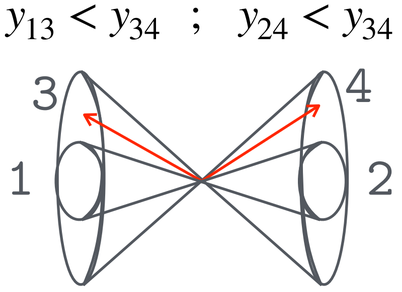

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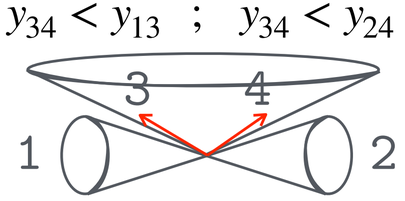
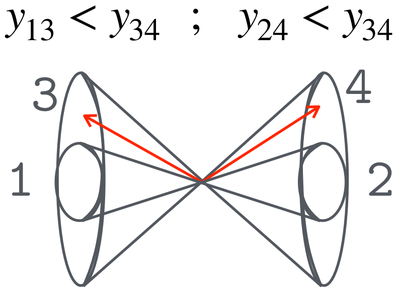


3rd "ghost" jet



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Jet Reconstruction

DURHAM

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Disadvantage

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

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Jet Reconstruction

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

Jet Reconstruction

kT Algorithm

Jet Reconstruction

kT Algorithm

- List of particles with

Jet Reconstruction

kT Algorithm

- List of particles with $k_{\mathrm{T}}^2 = p_x^2 + p_y^2$

Jet Reconstruction

kT Algorithm

- List of particles with $k_{\mathrm{T}}^2 = p_x^2 + p_y^2 \quad y = \frac{1}{2} \ln \frac{E + p}{E - p}$

Jet Reconstruction

kT Algorithm

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

Jet Reconstruction

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Jet Reconstruction

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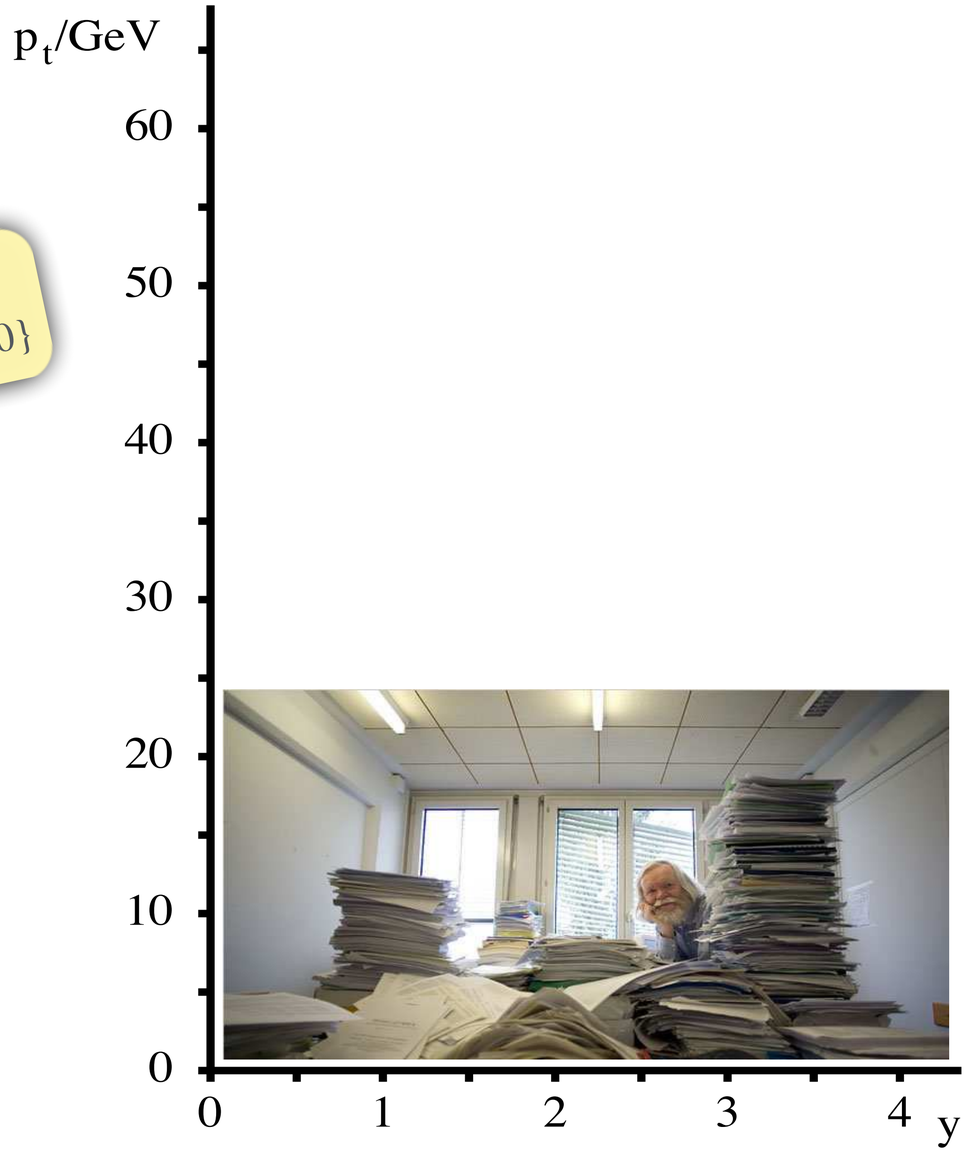

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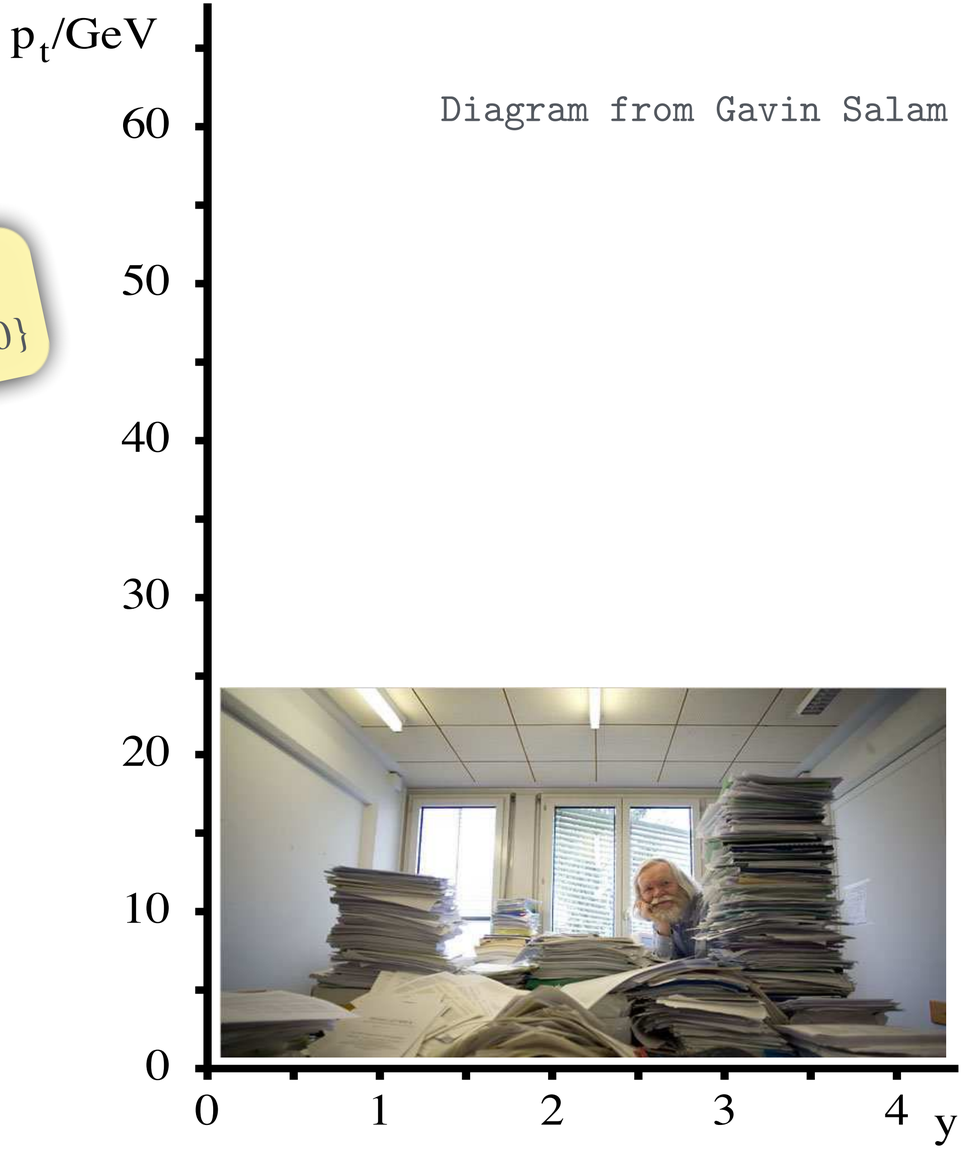

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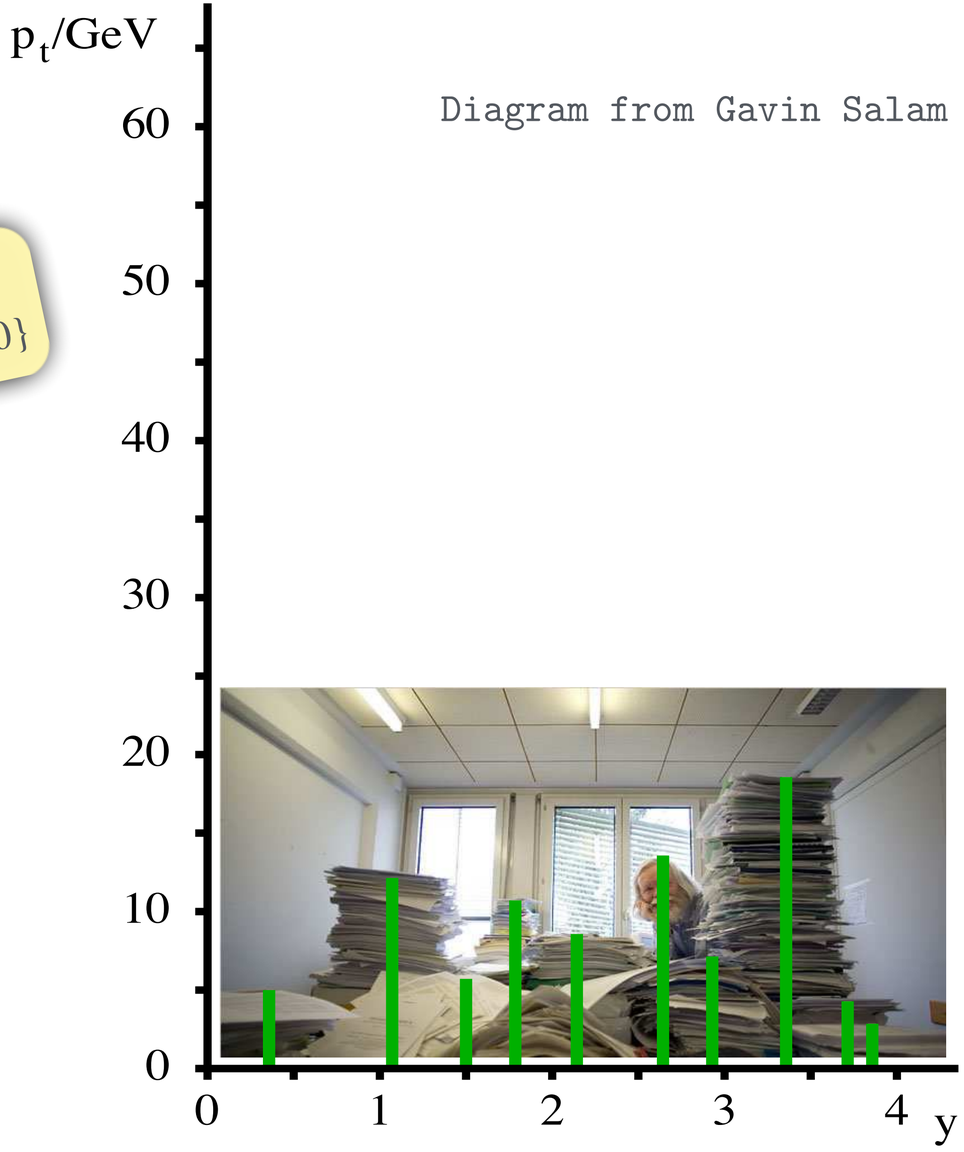

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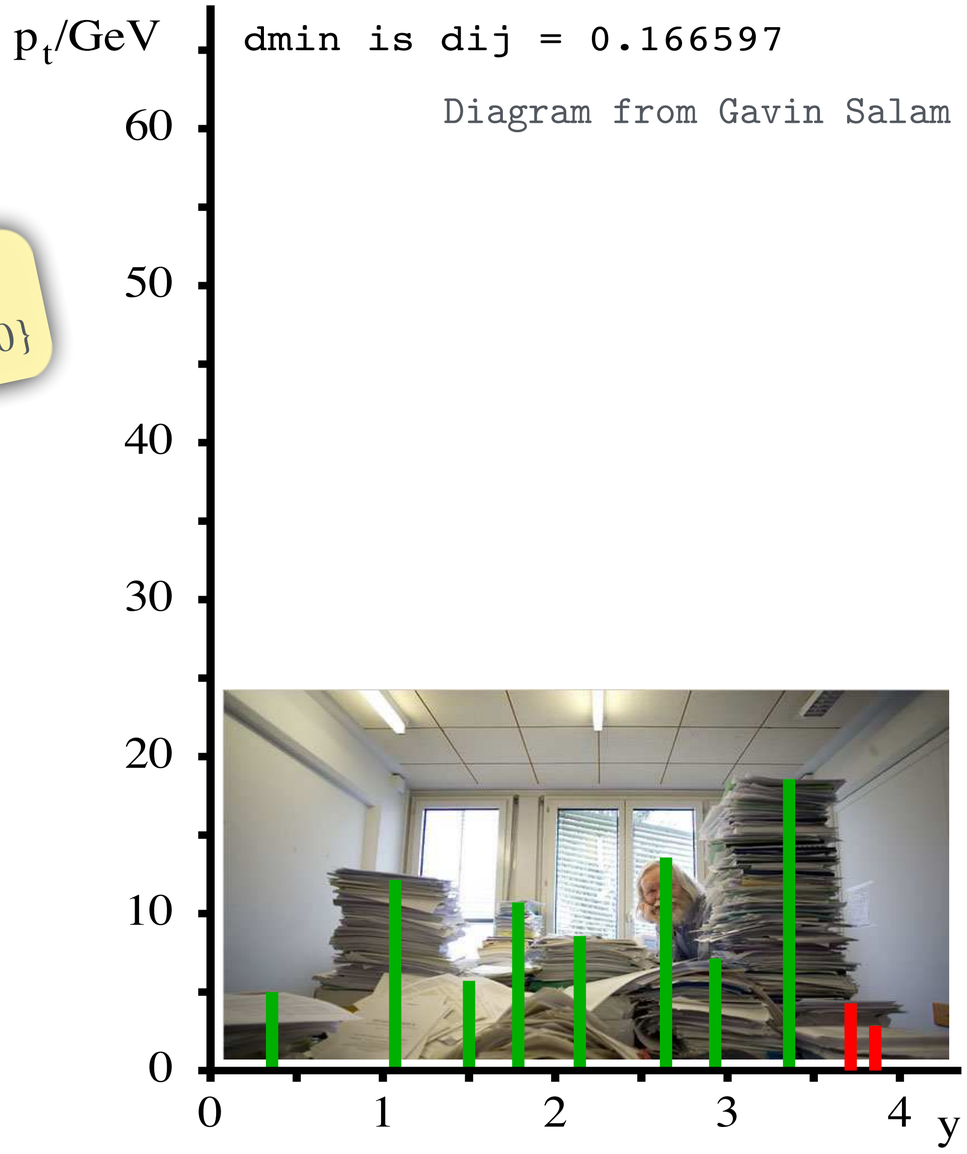

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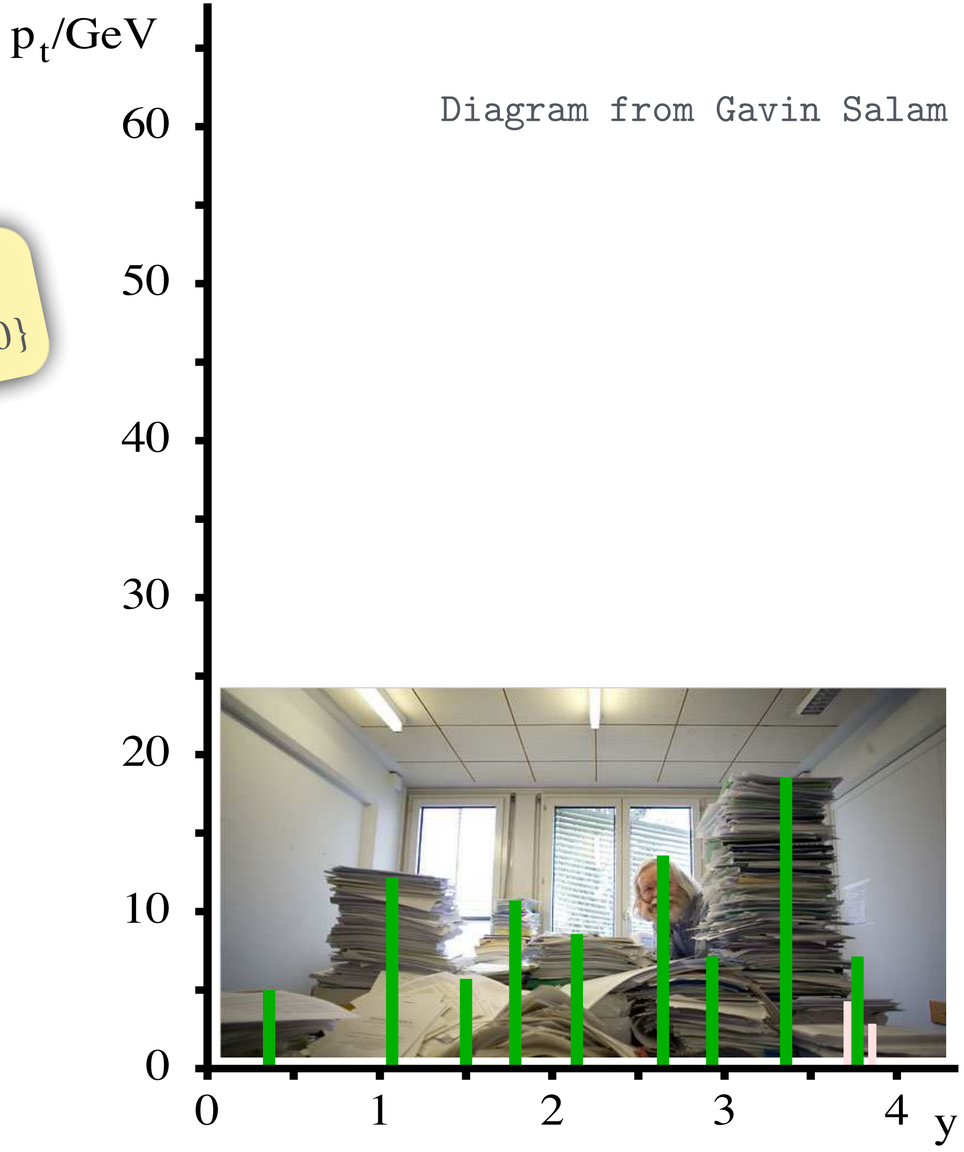

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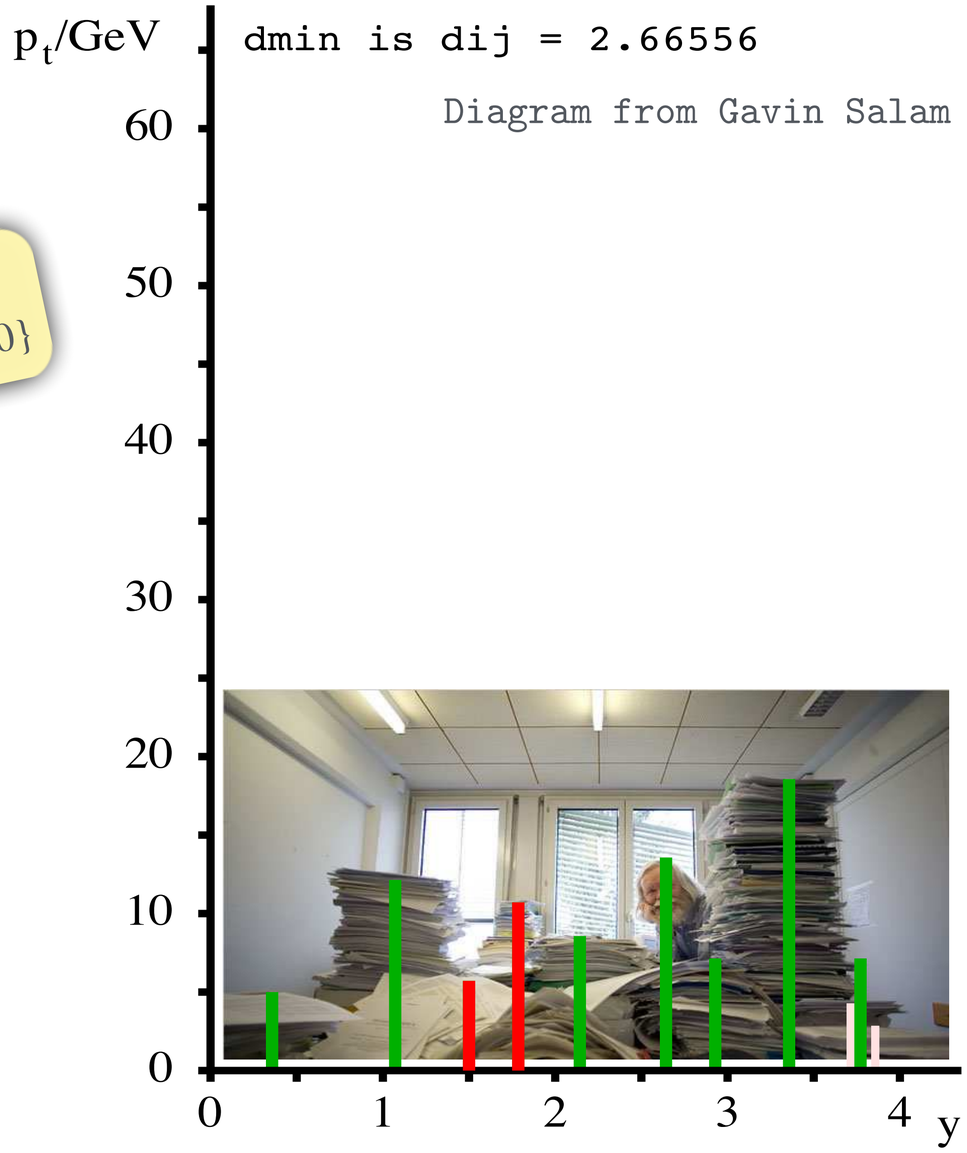

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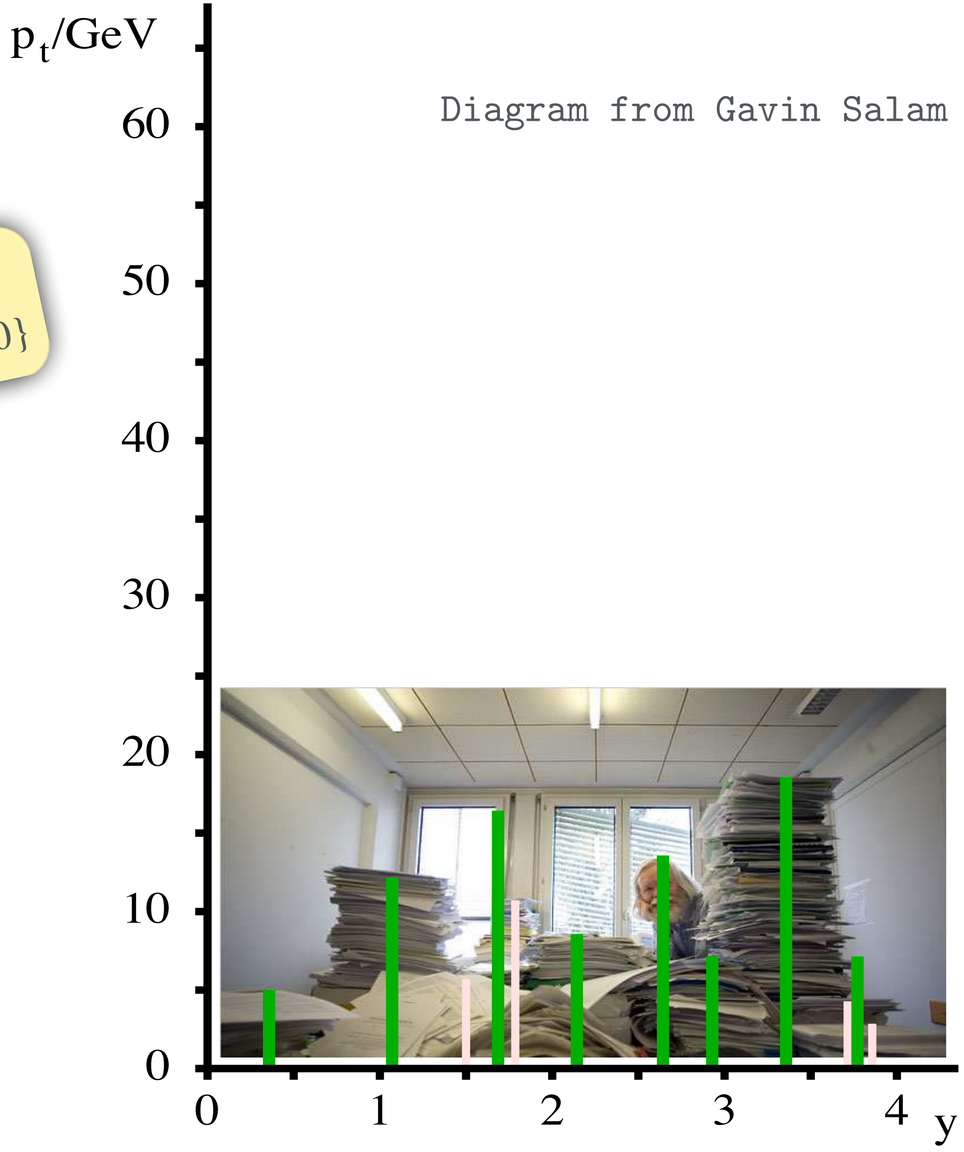

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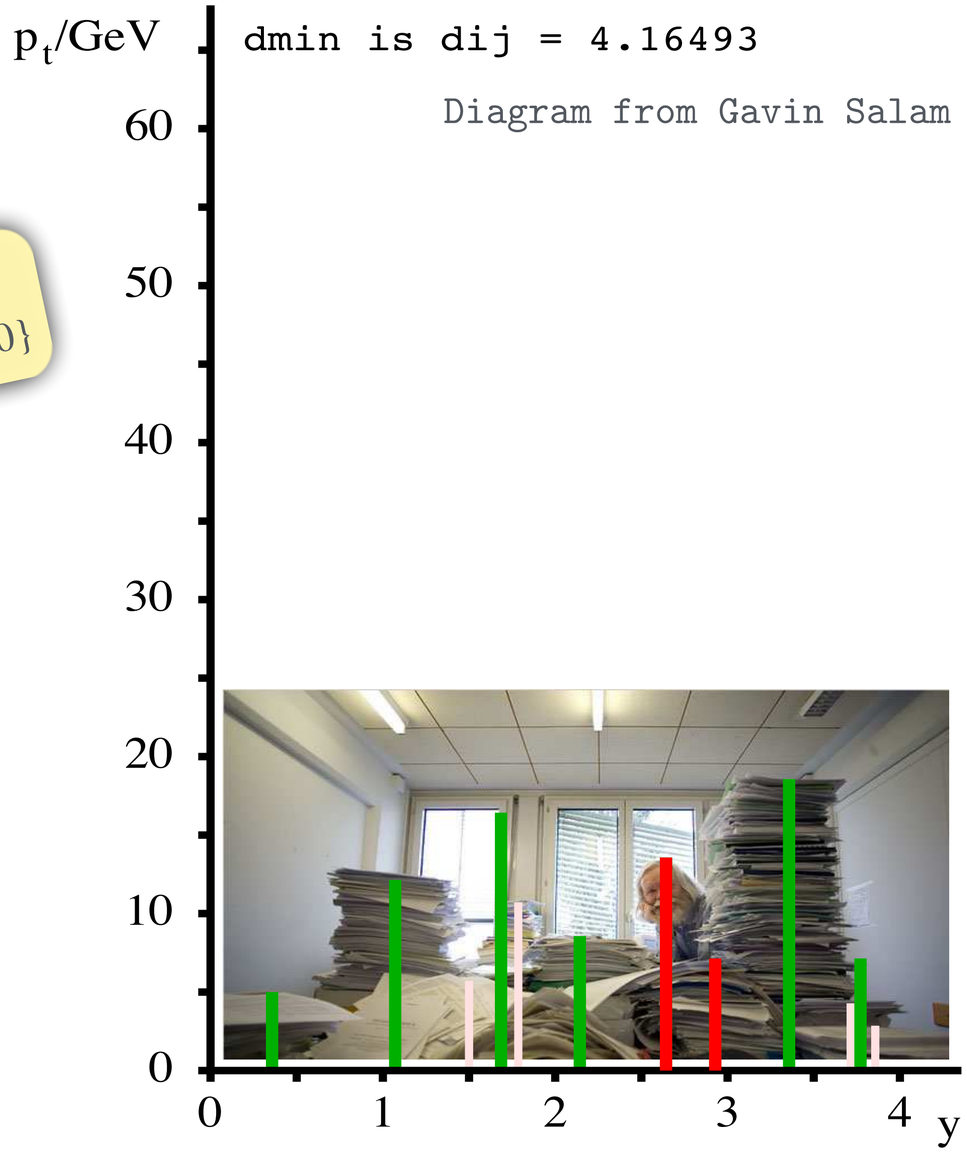

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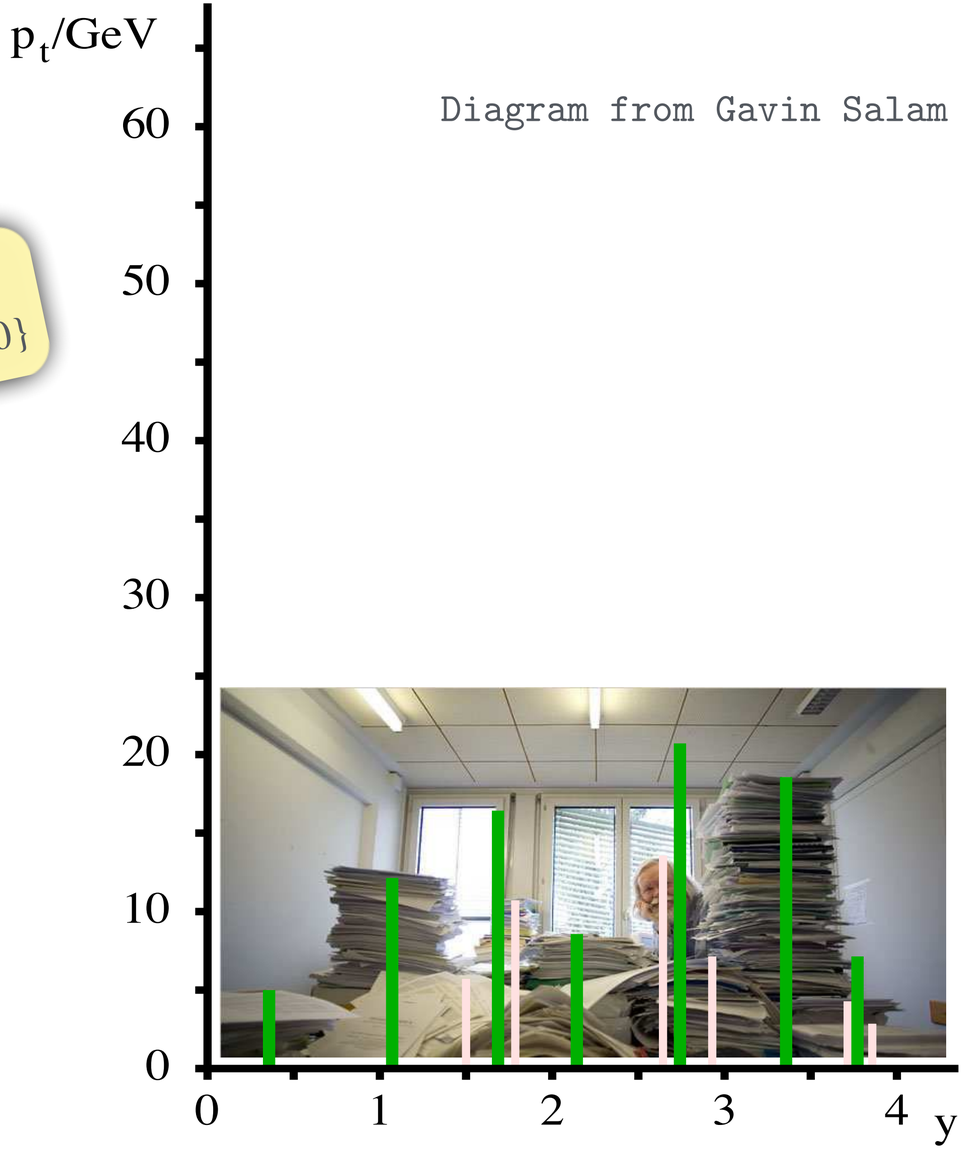

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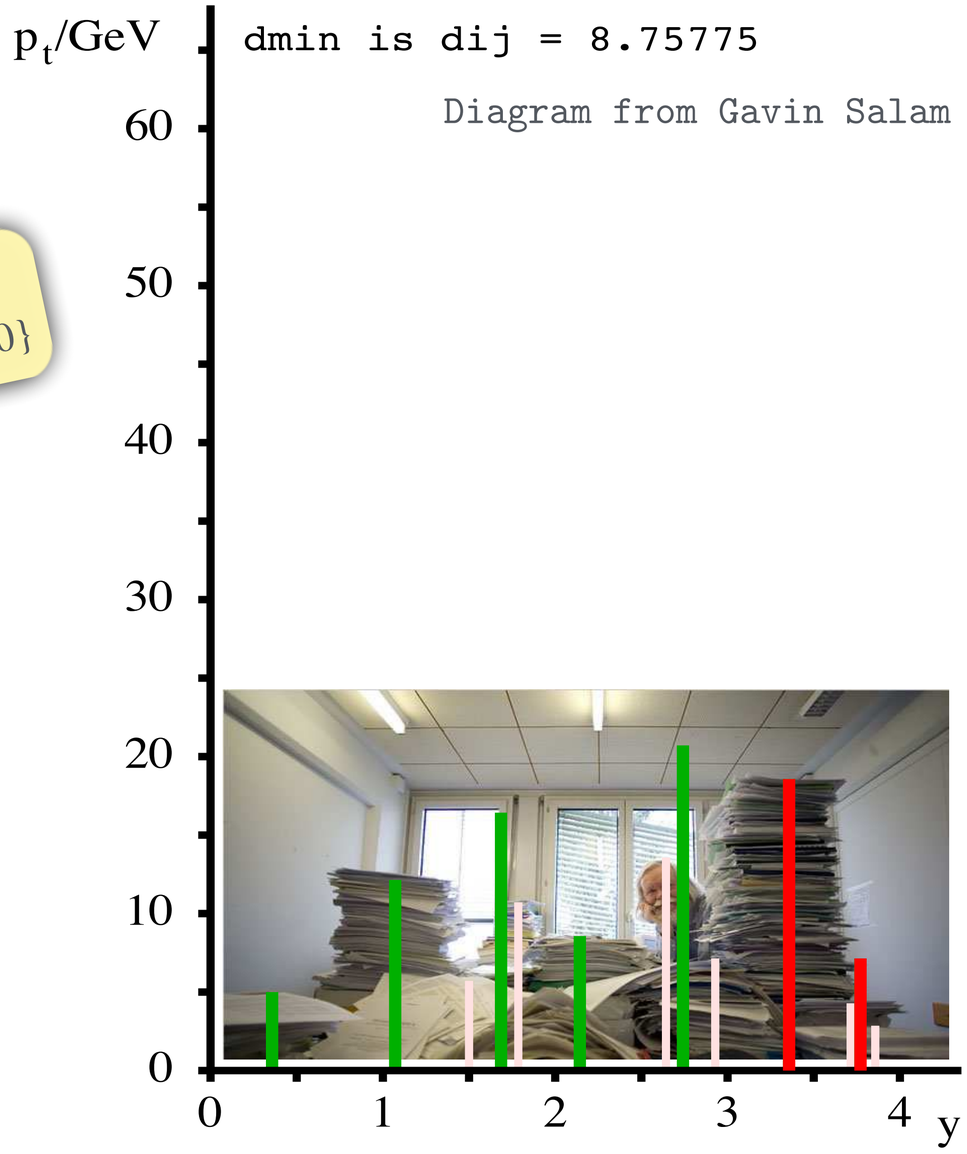

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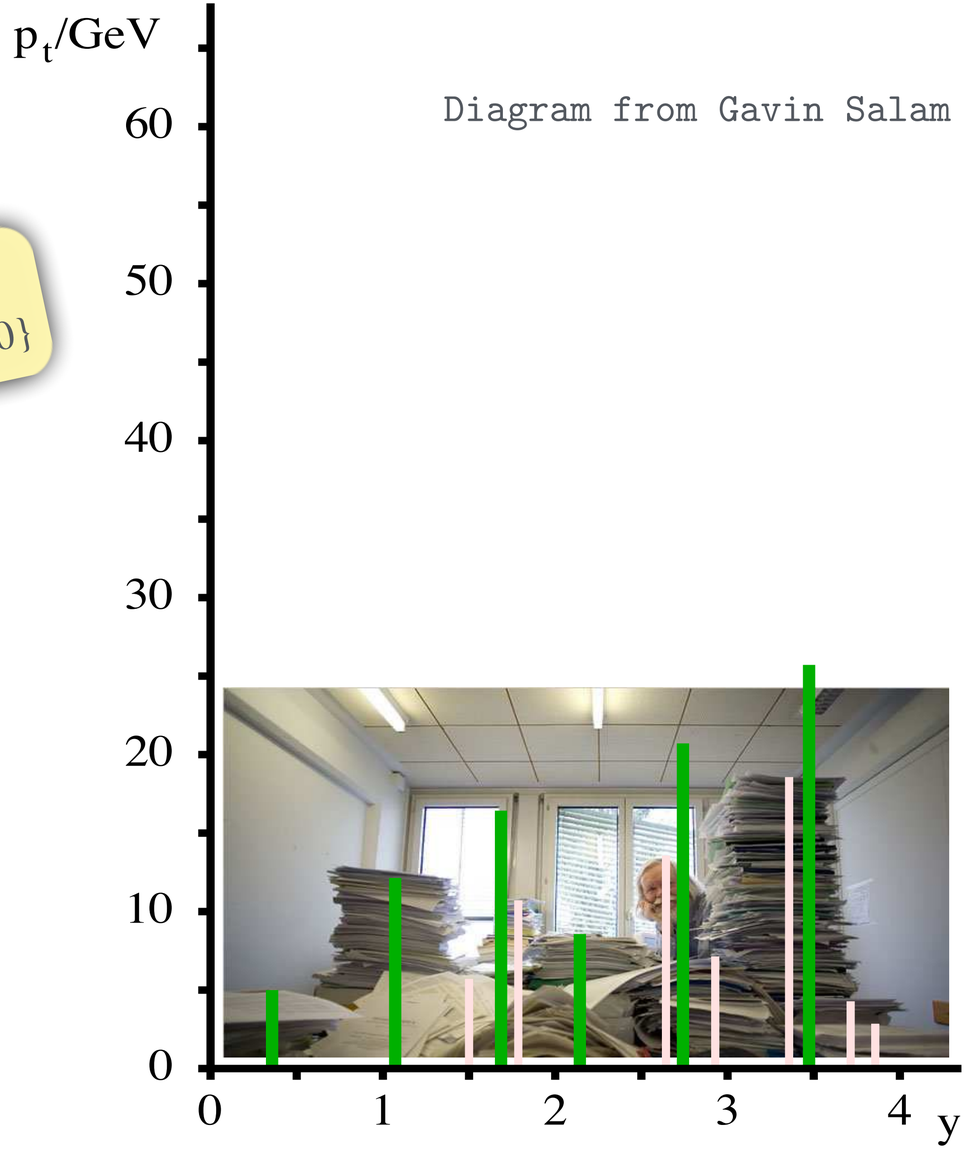

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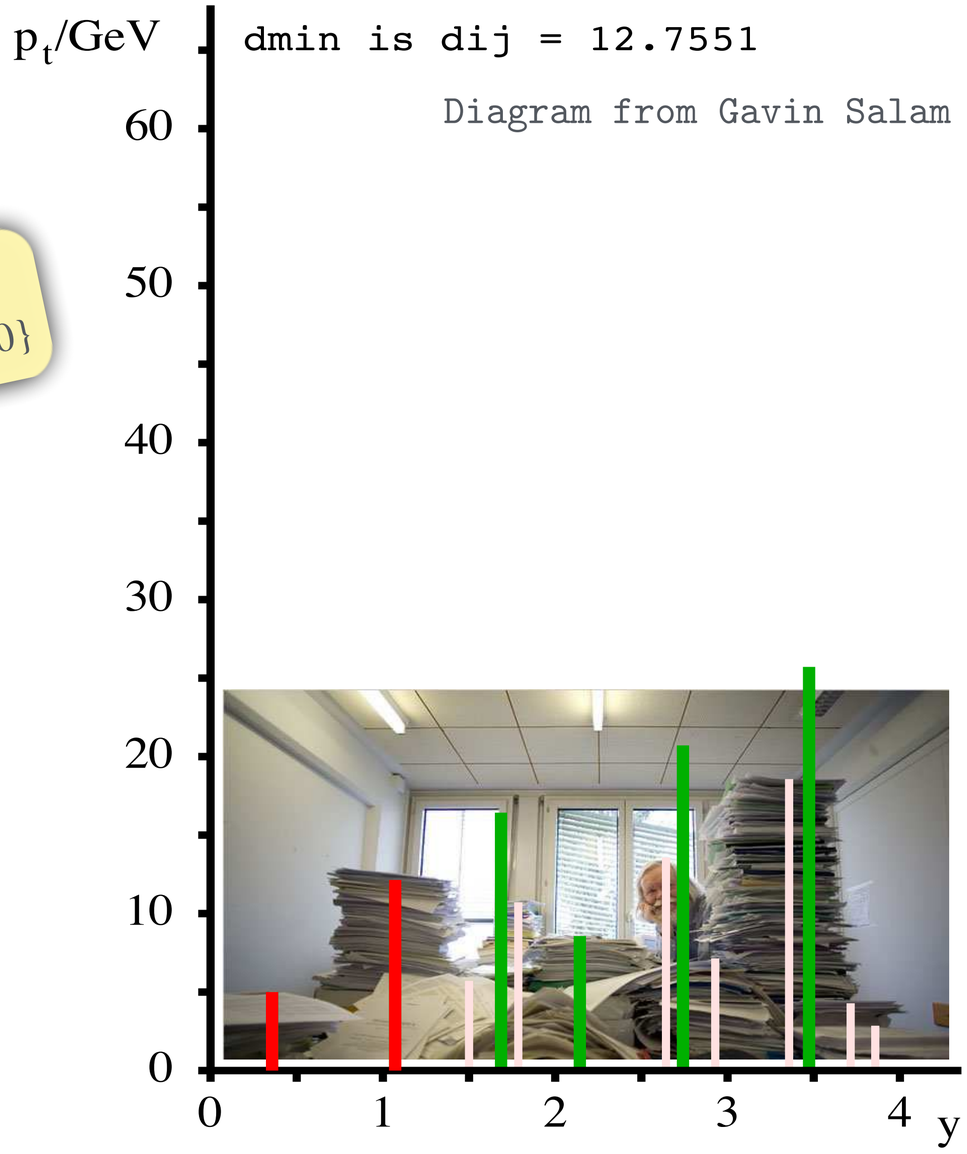

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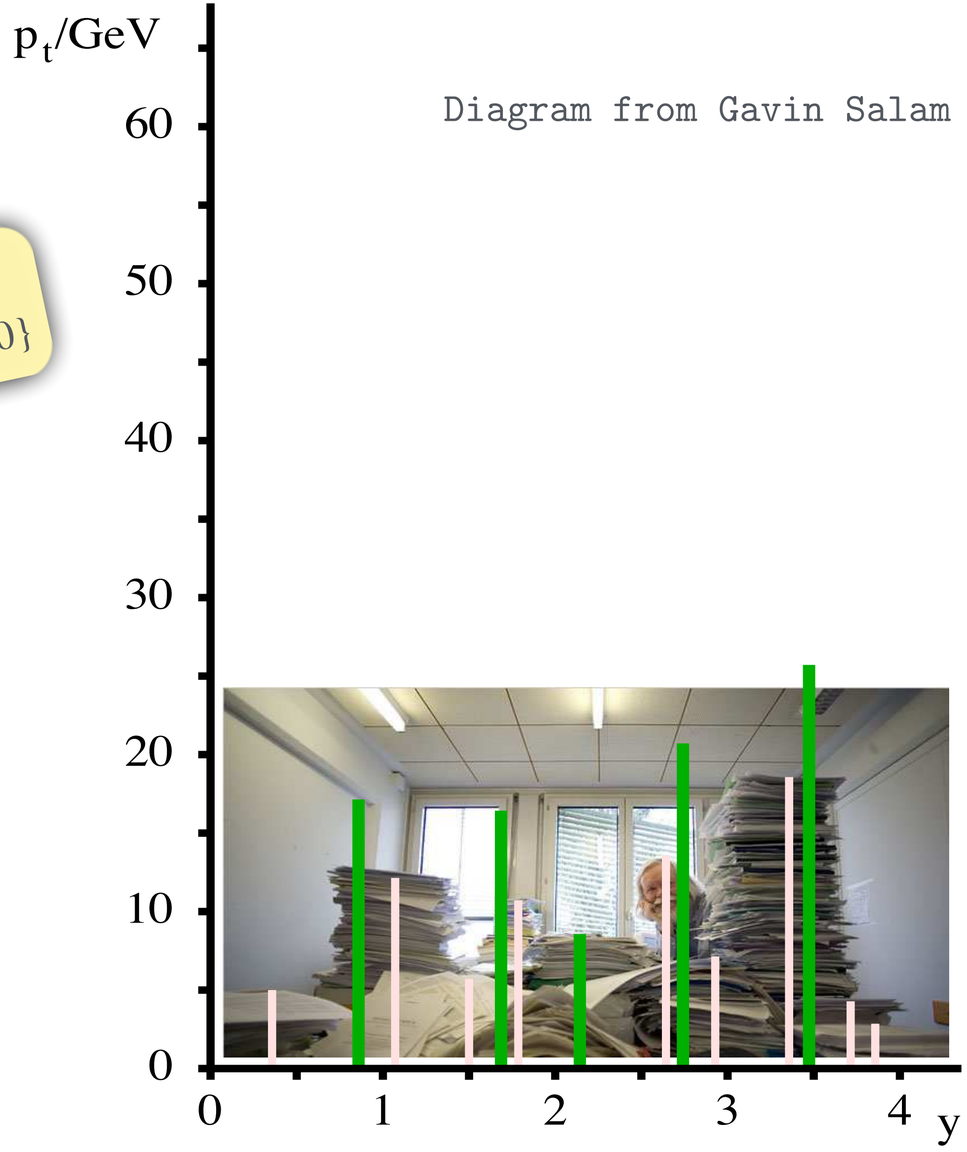

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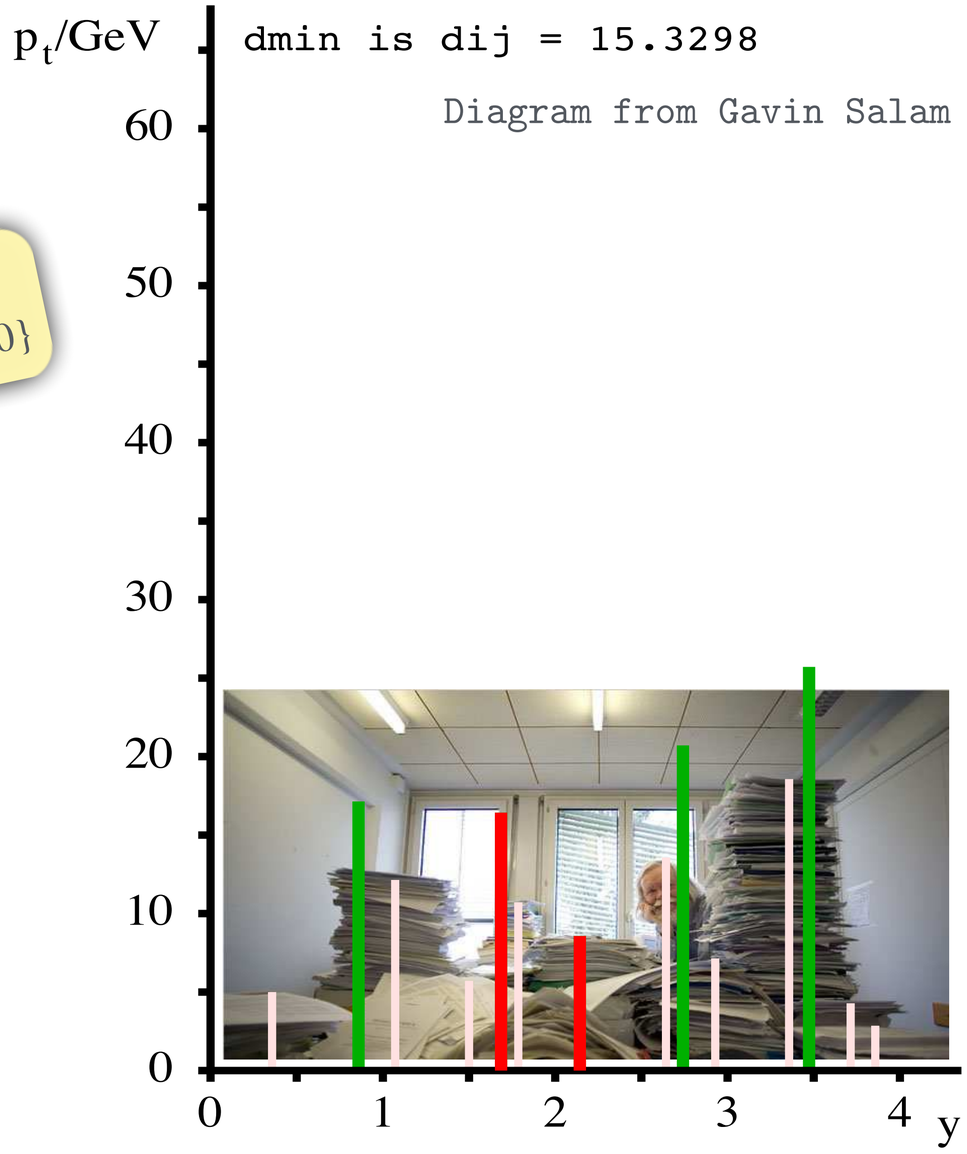

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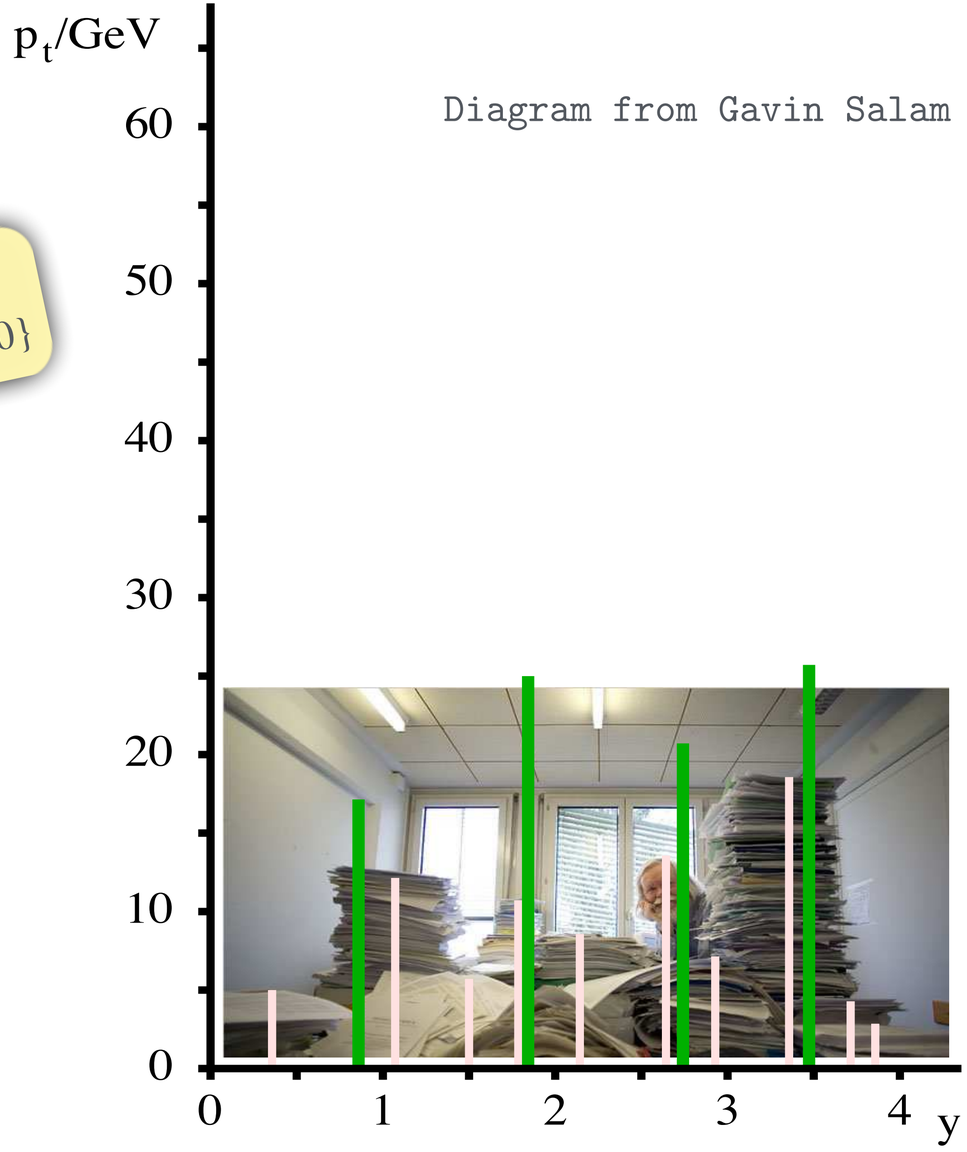

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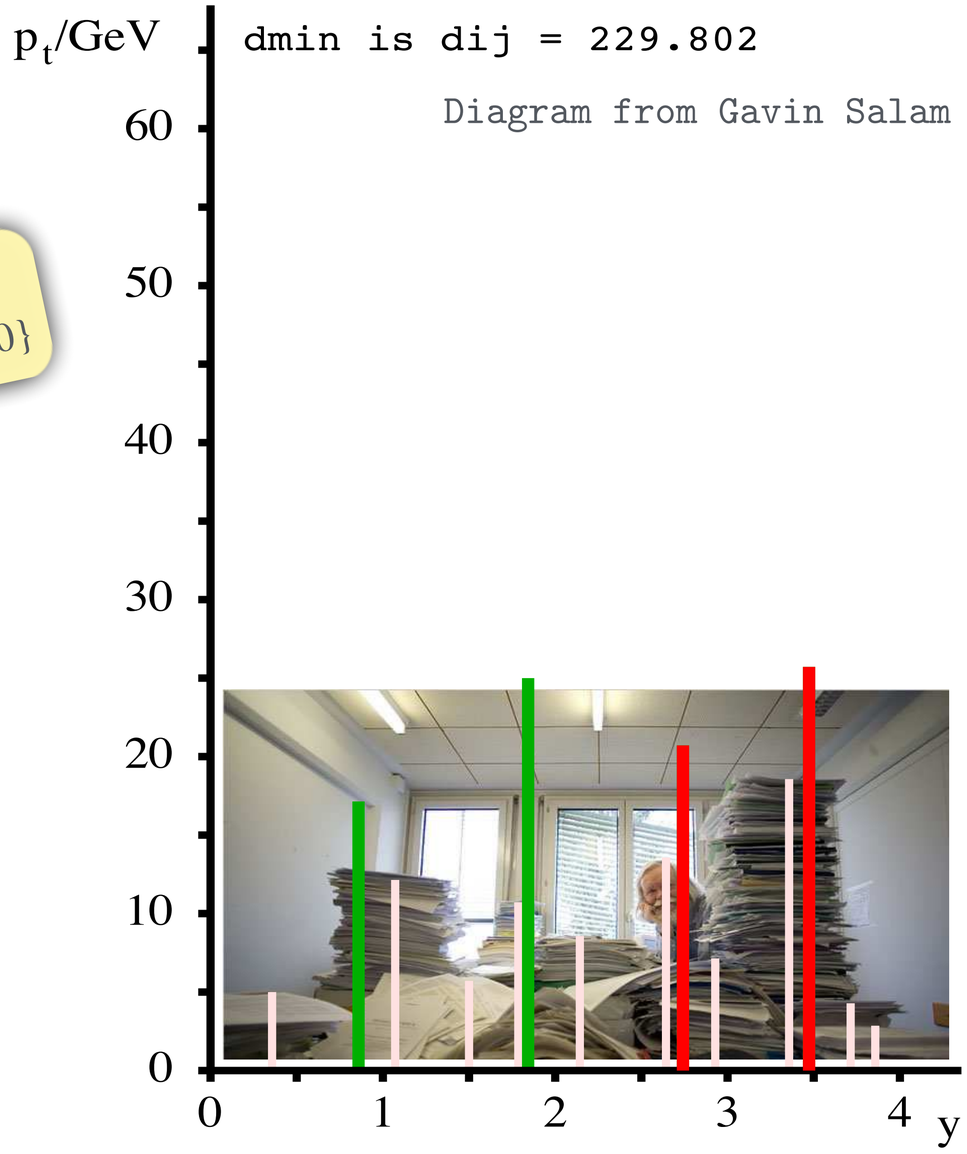

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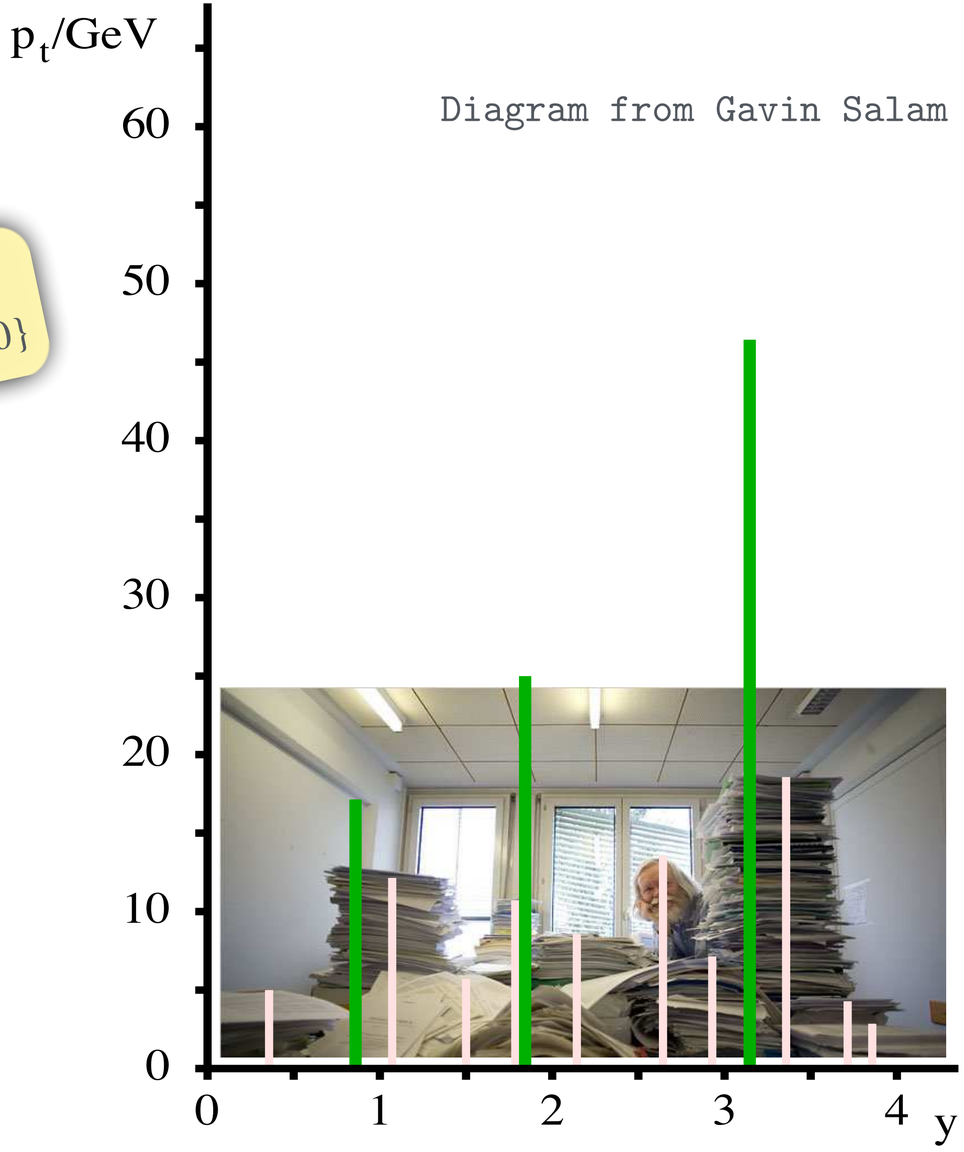

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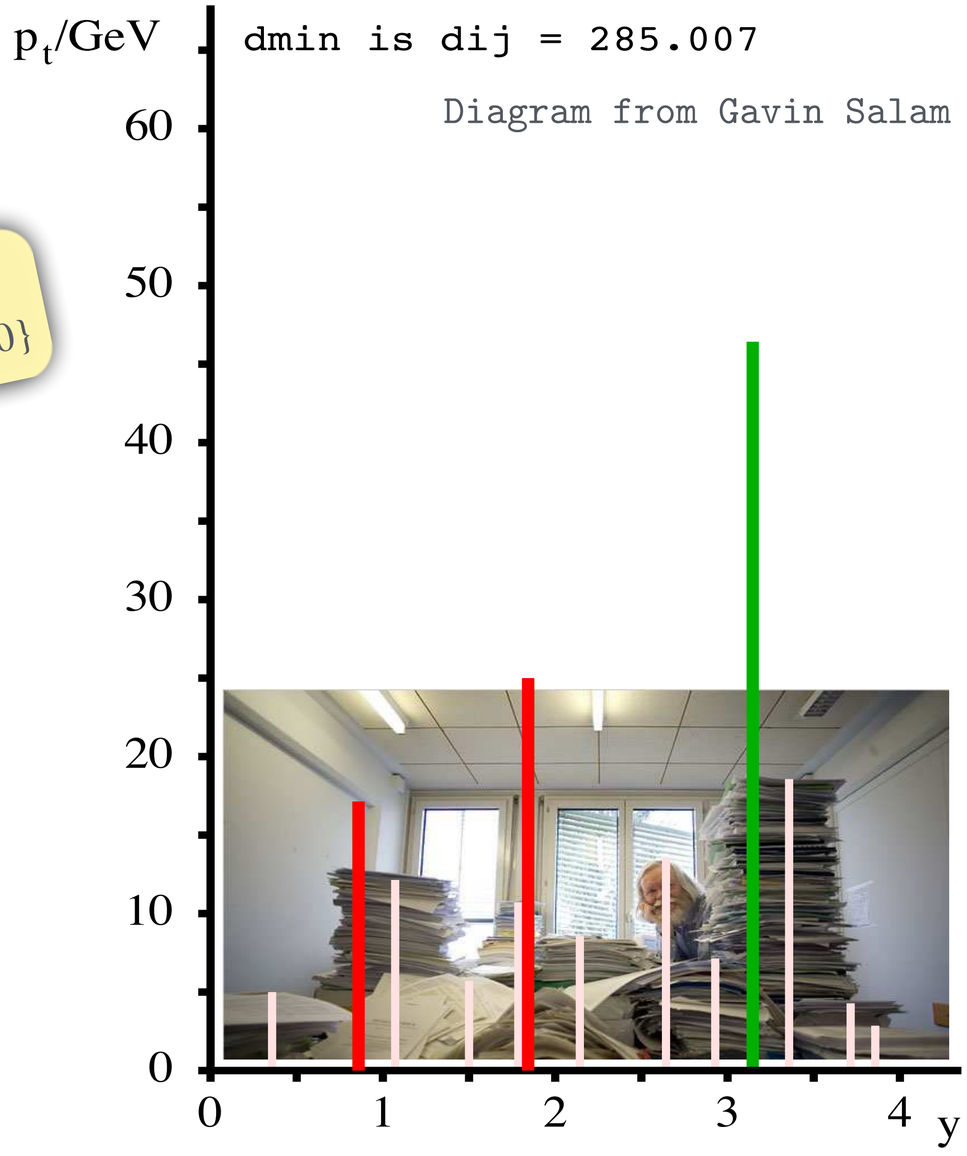

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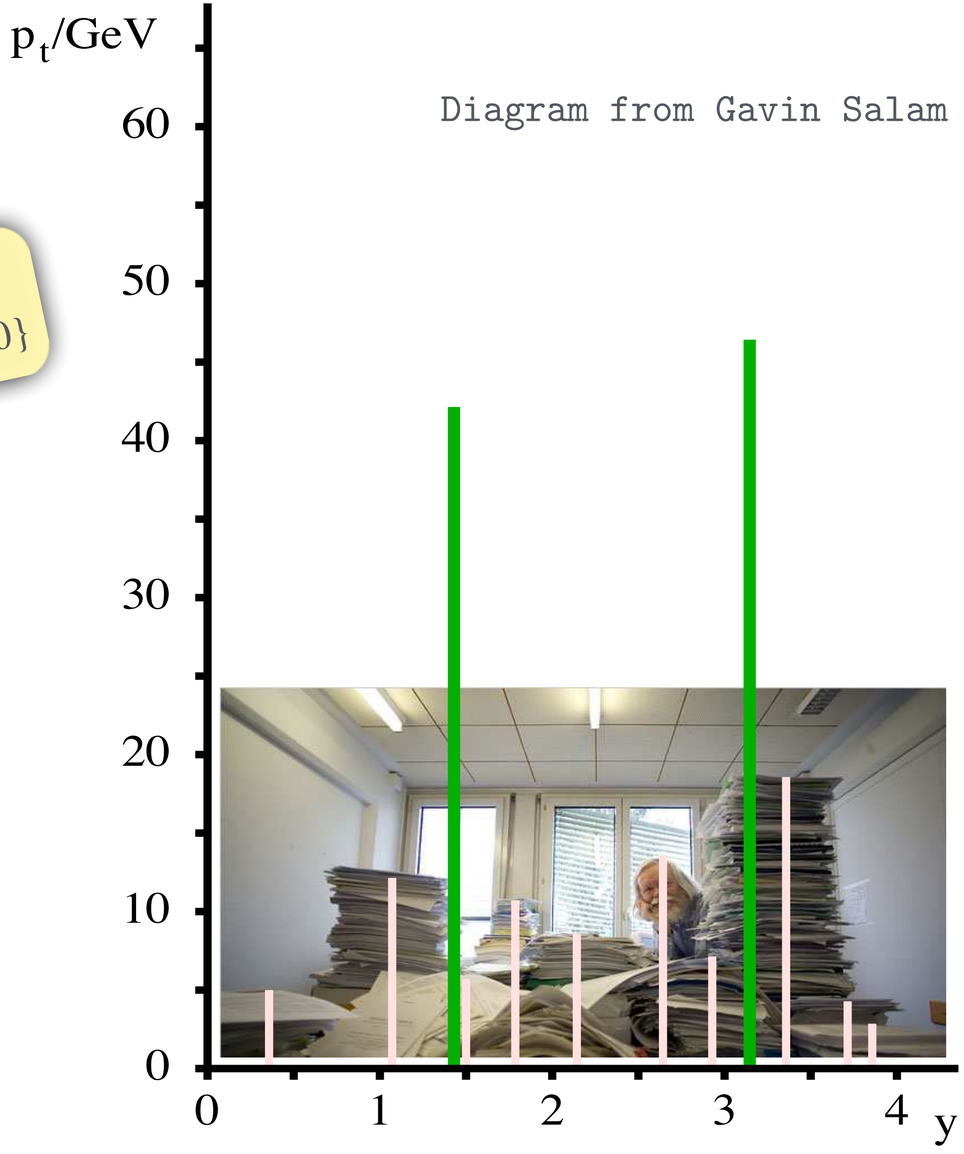

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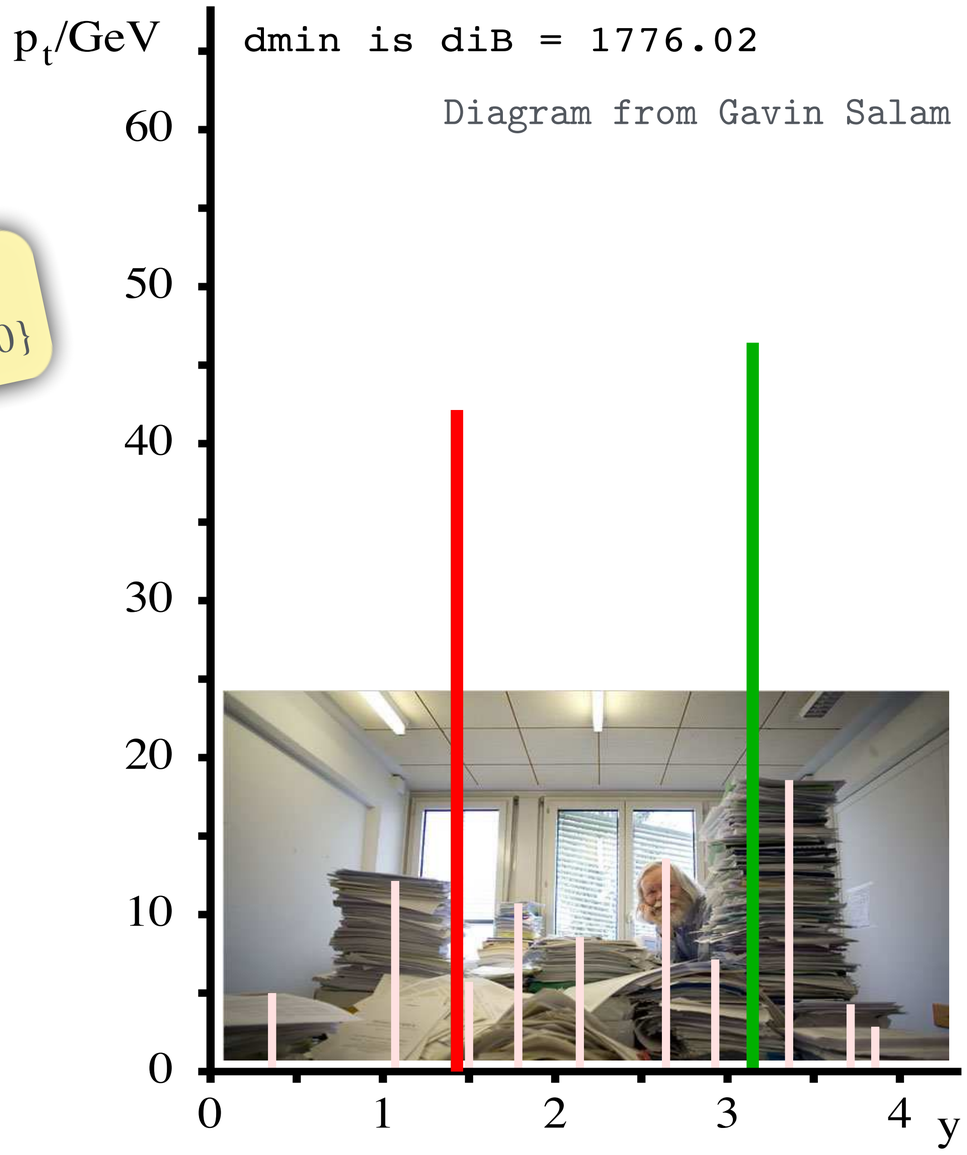

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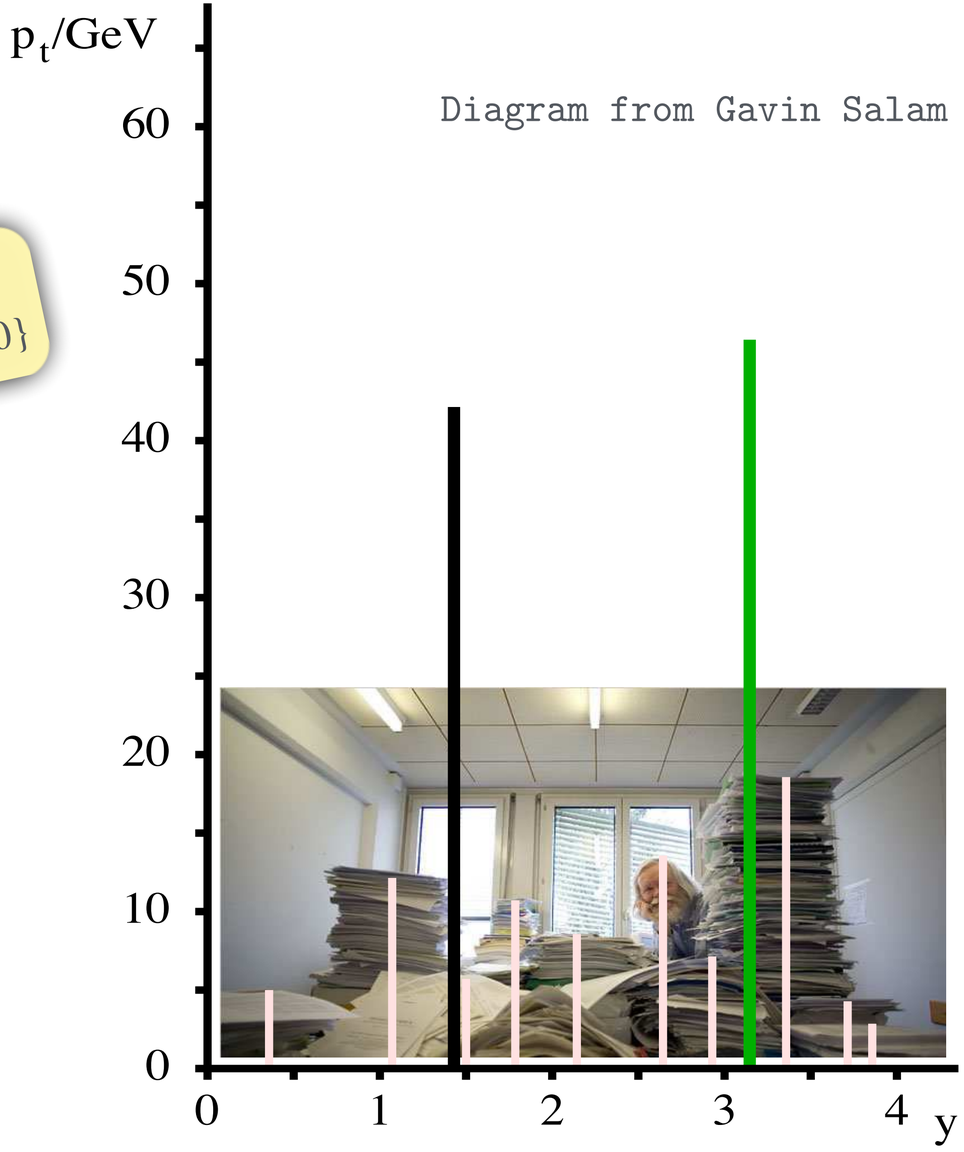

Jet Reconstruction

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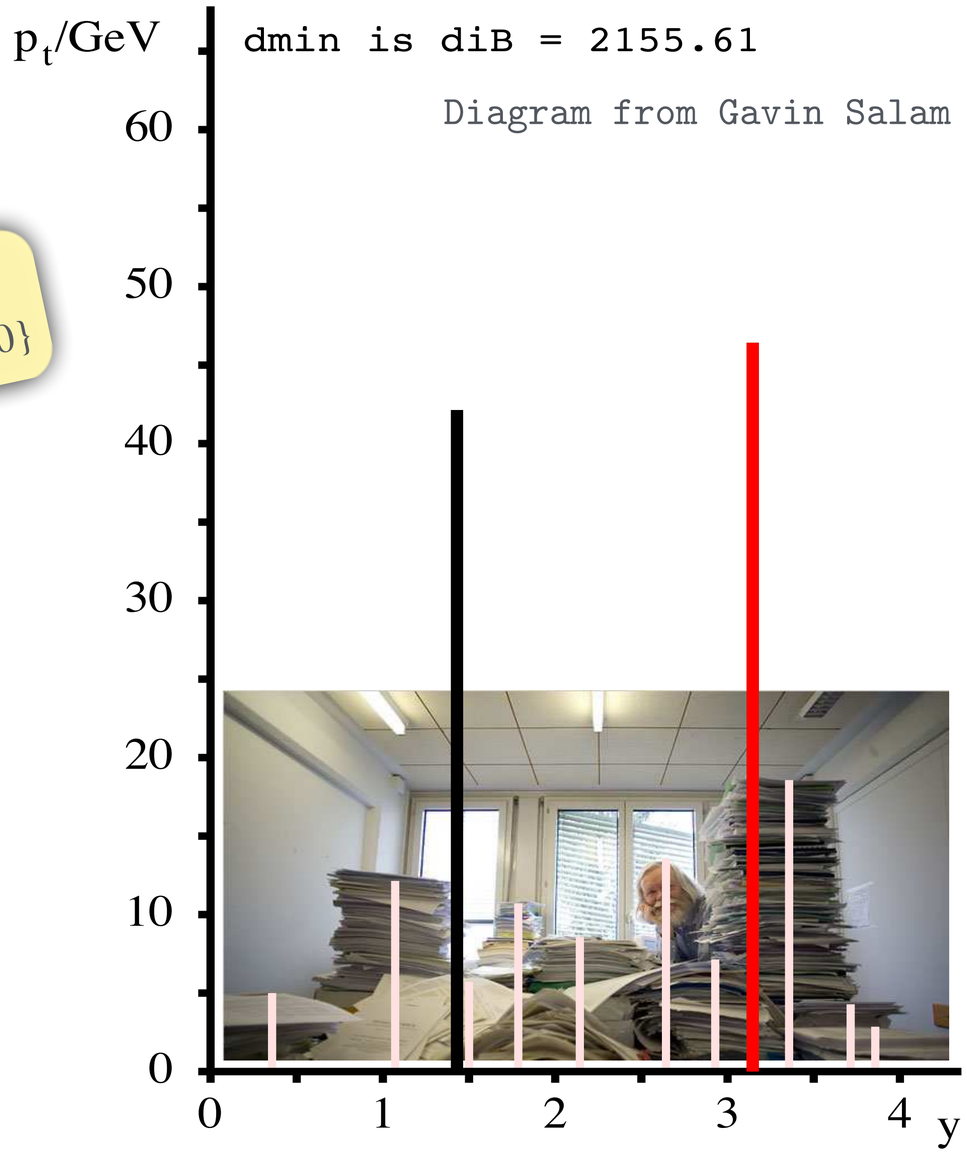

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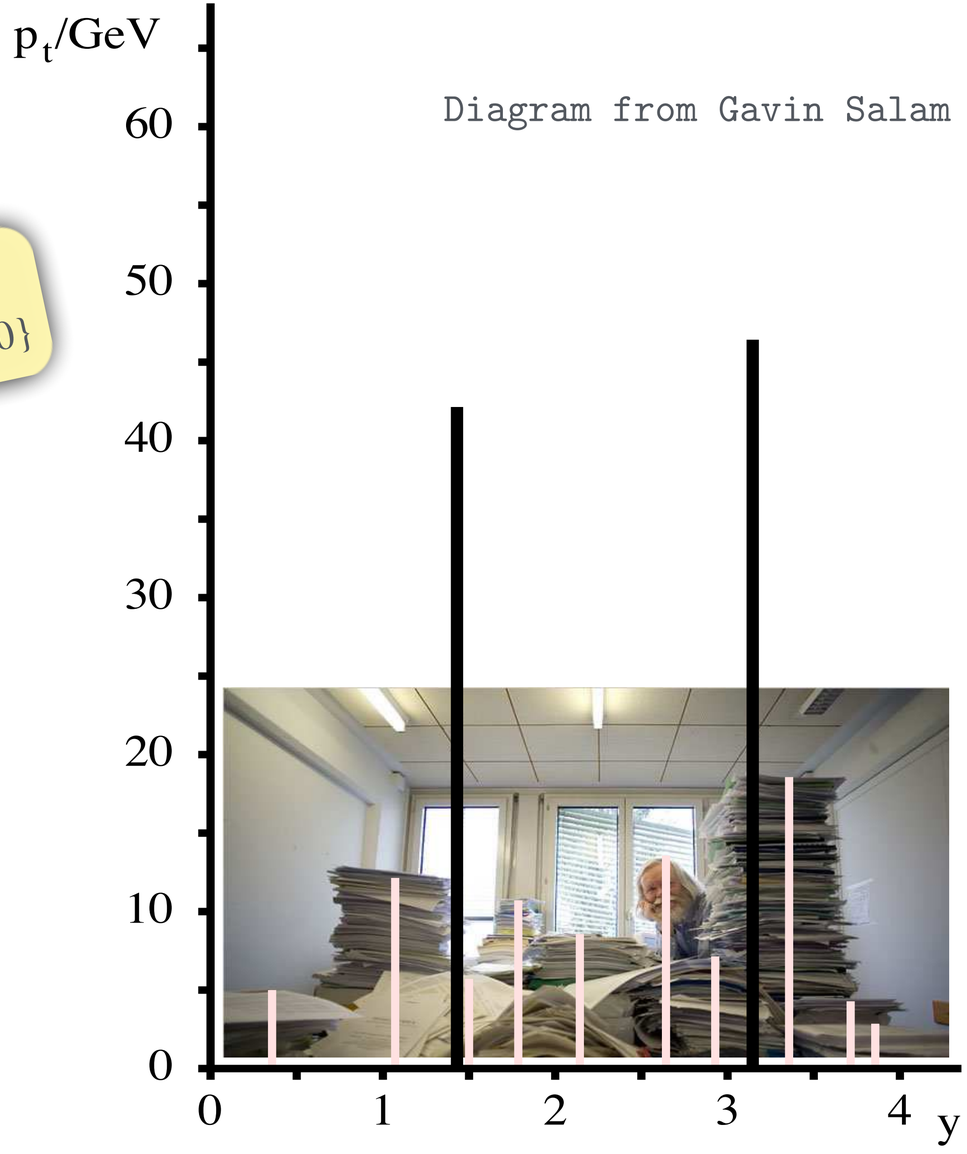

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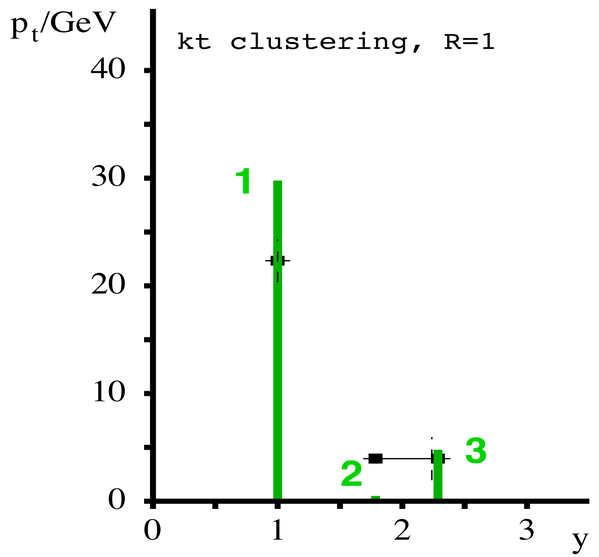

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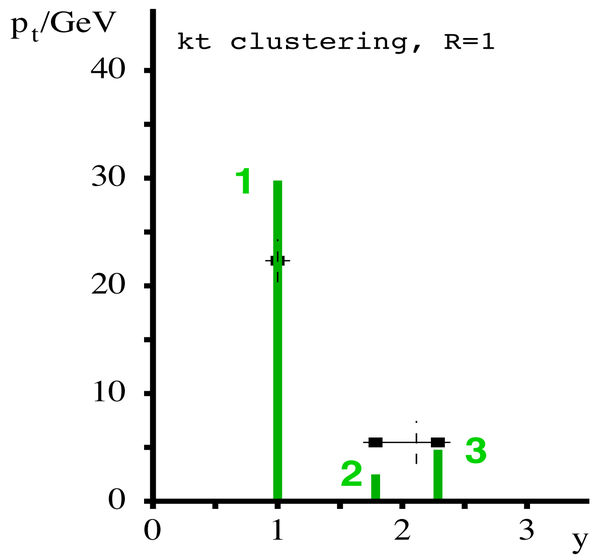

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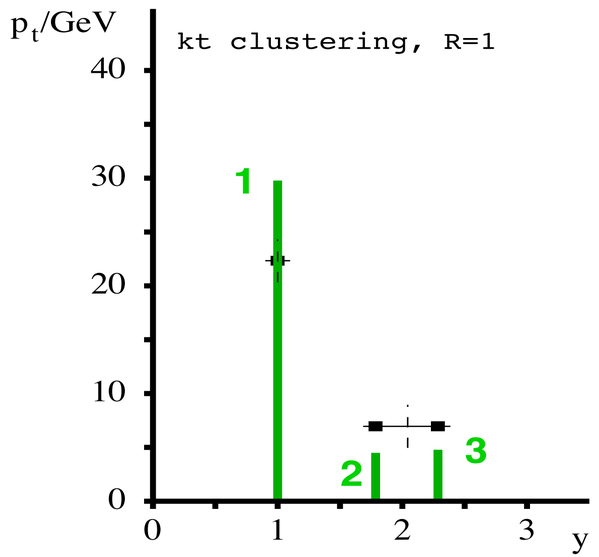

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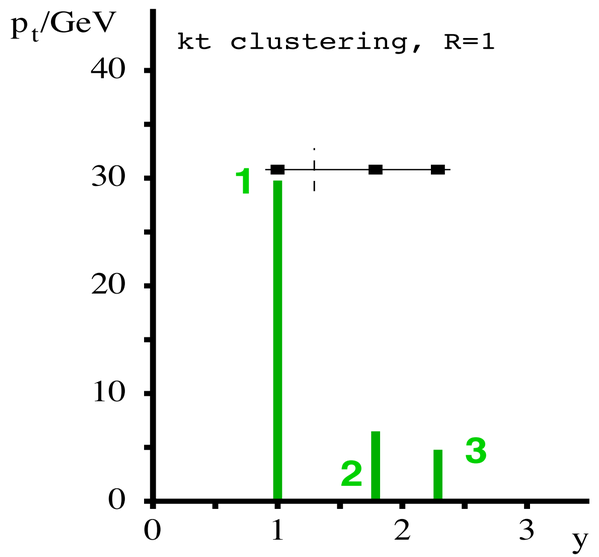

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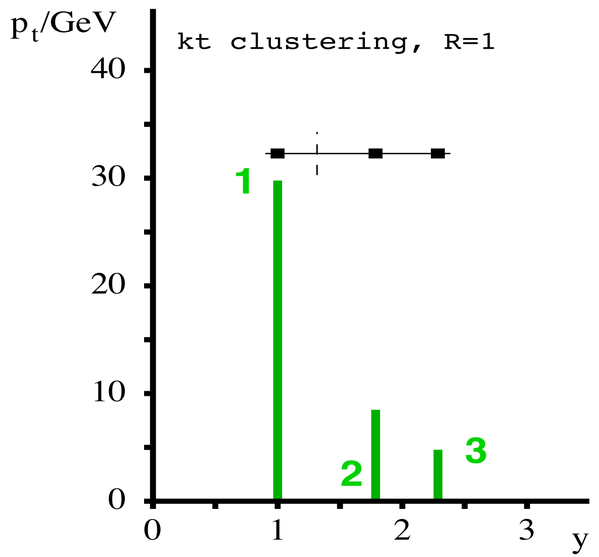

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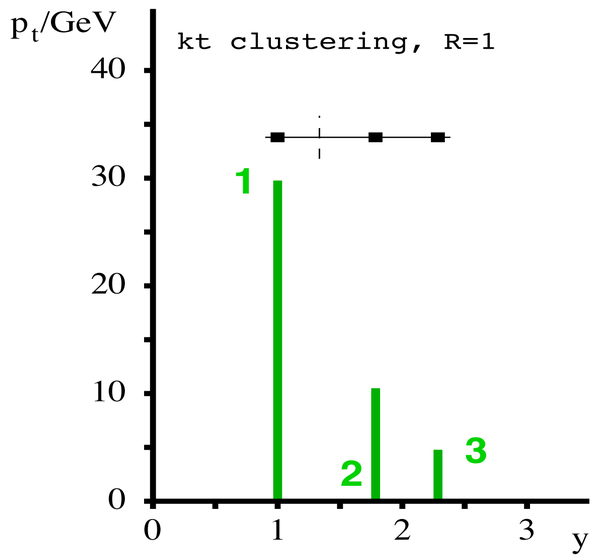

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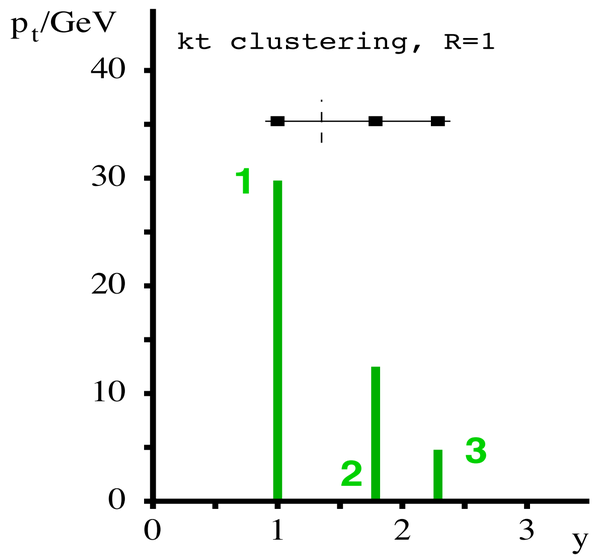

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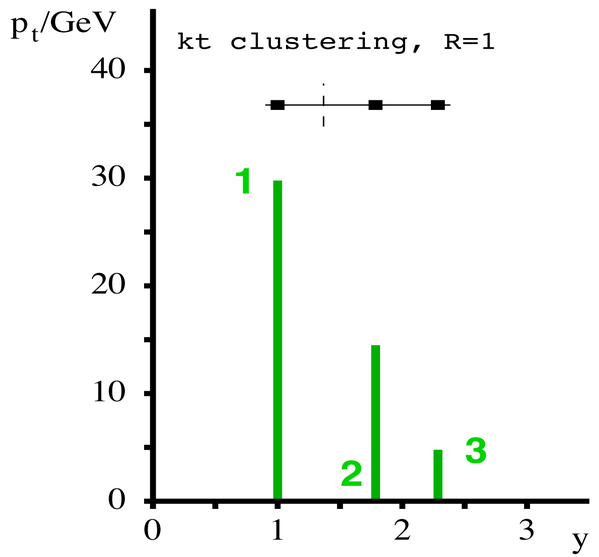

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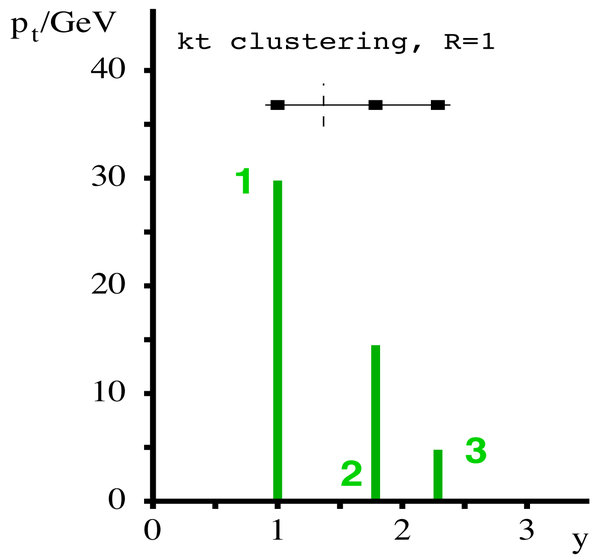

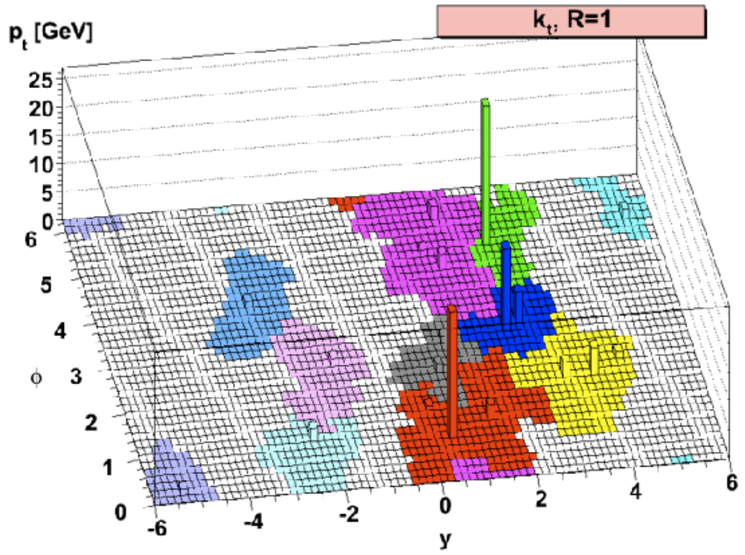

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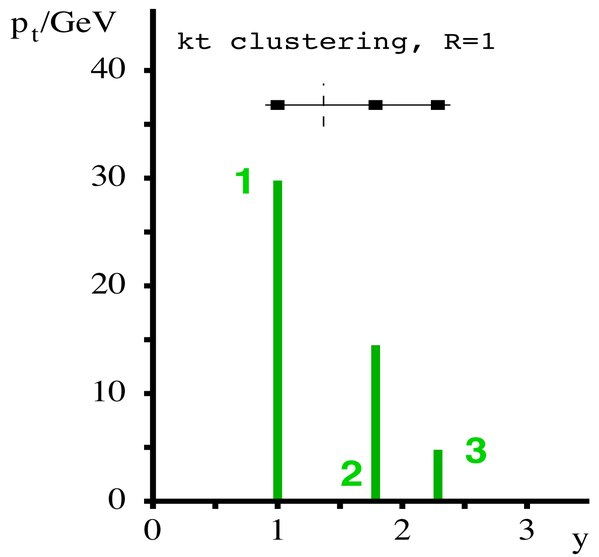

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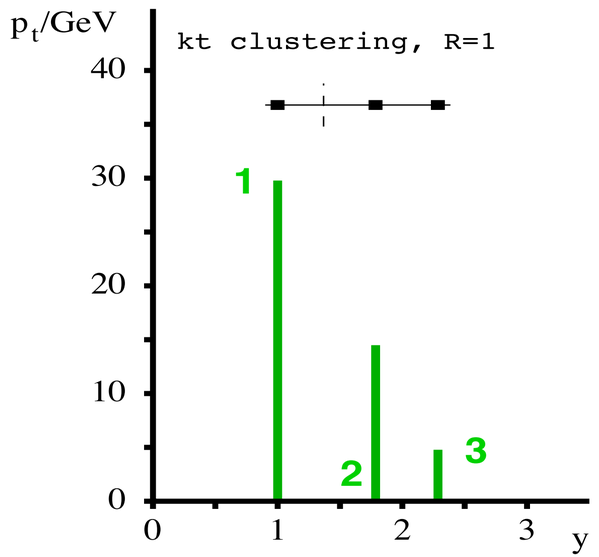

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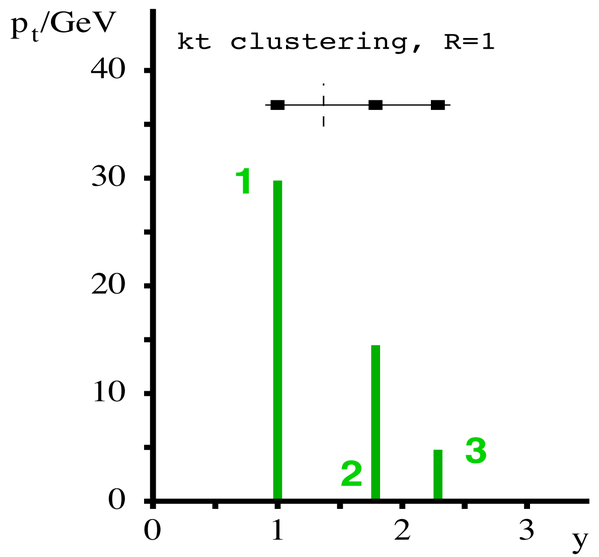

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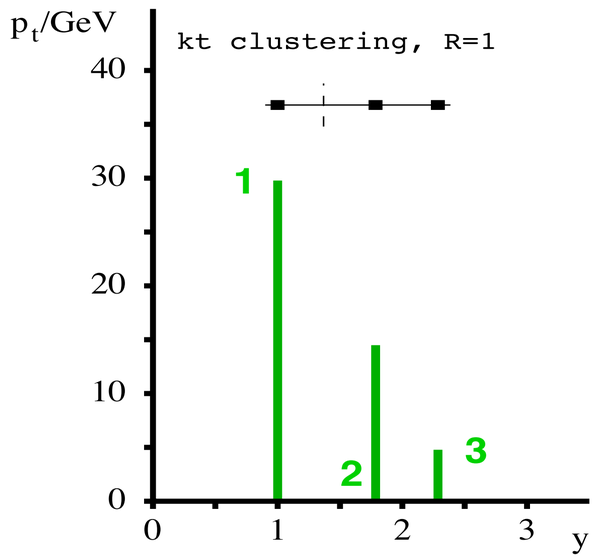

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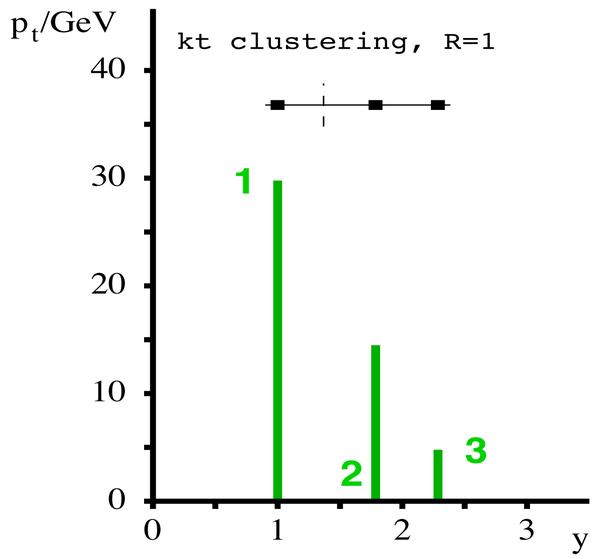

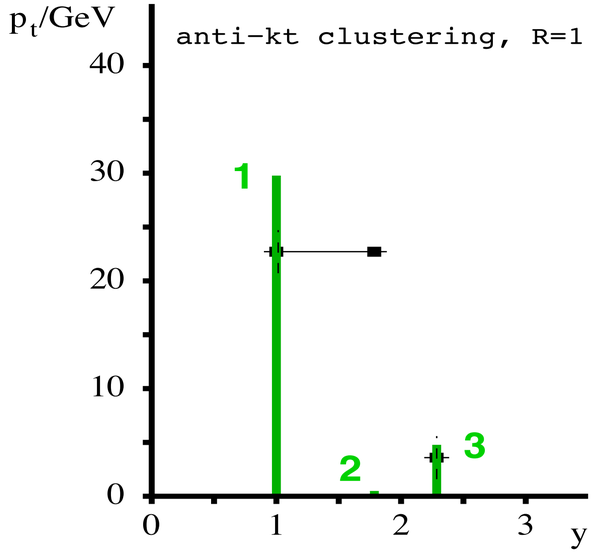

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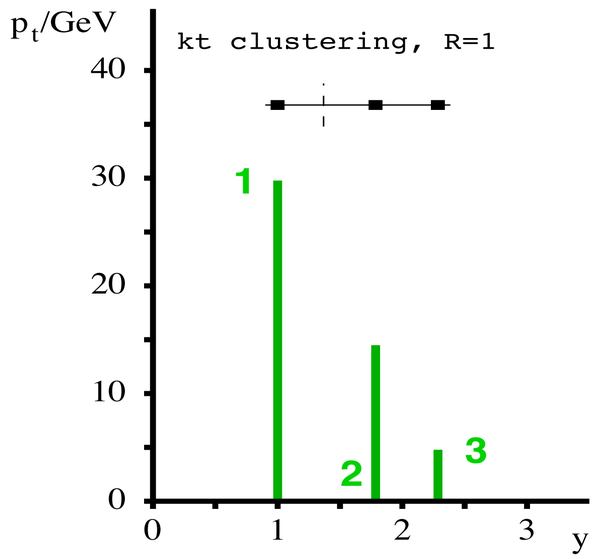

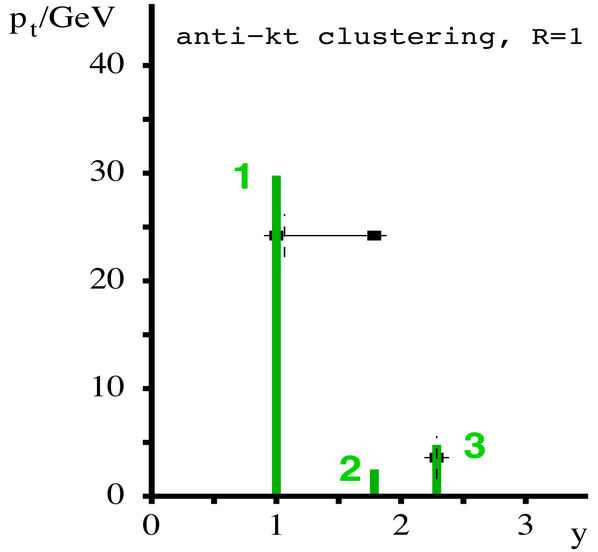

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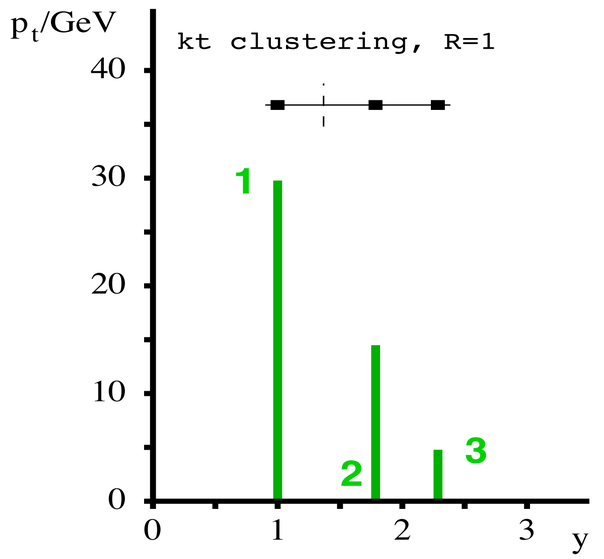

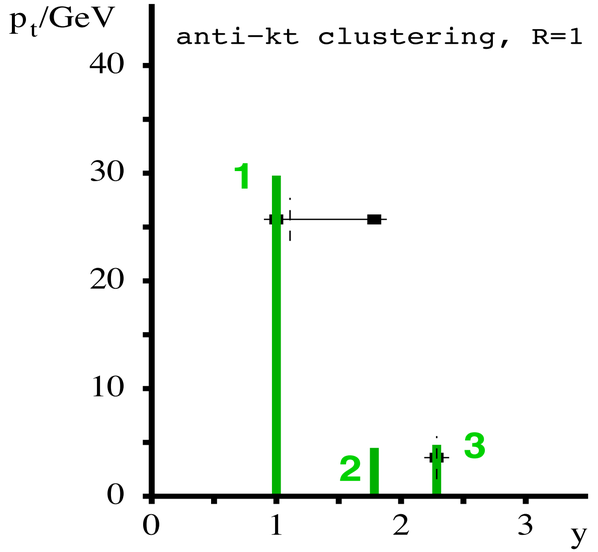

Diagrams from Gavin Salam

Jet Reconstruction

anti-kT Algorithm

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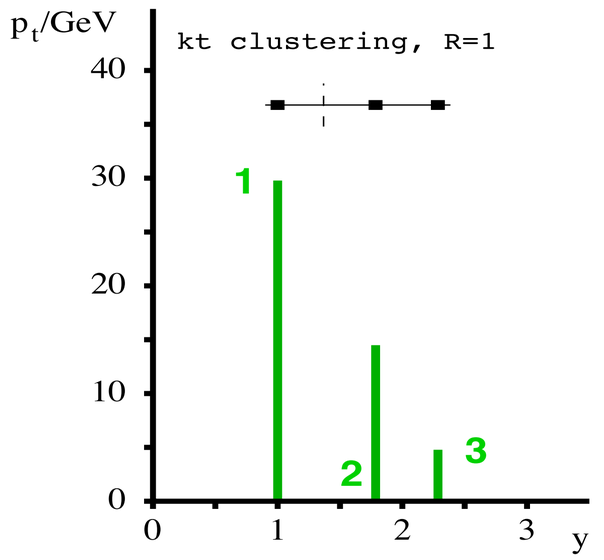

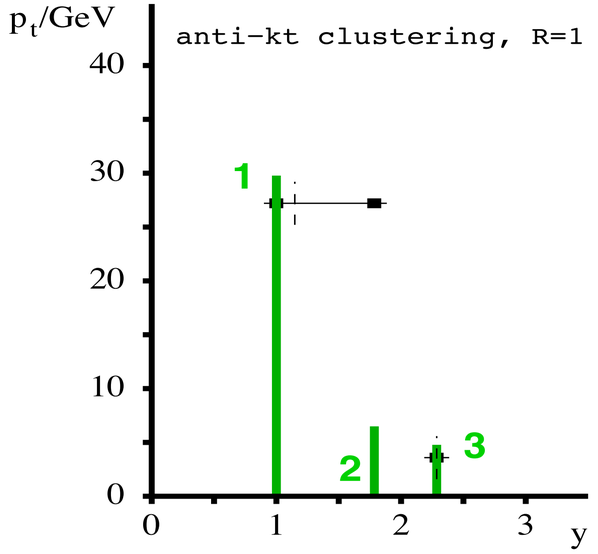

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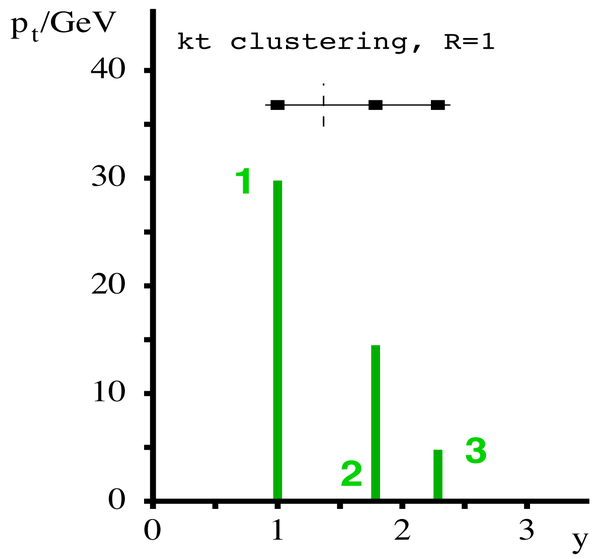

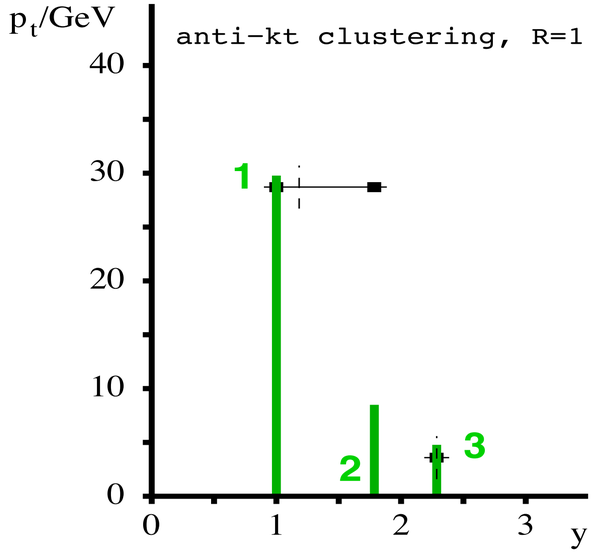

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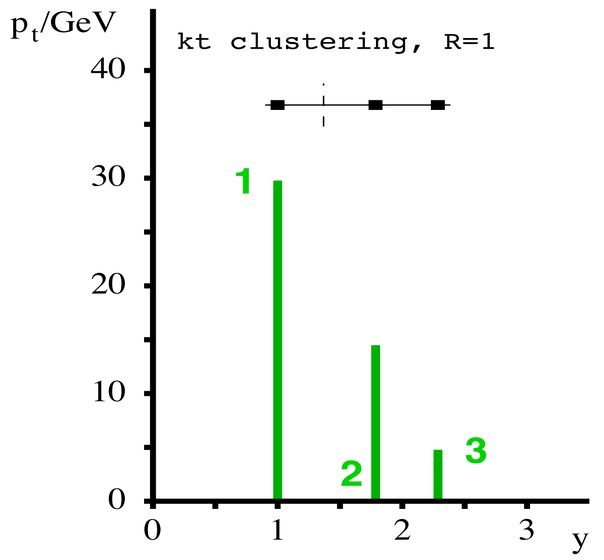

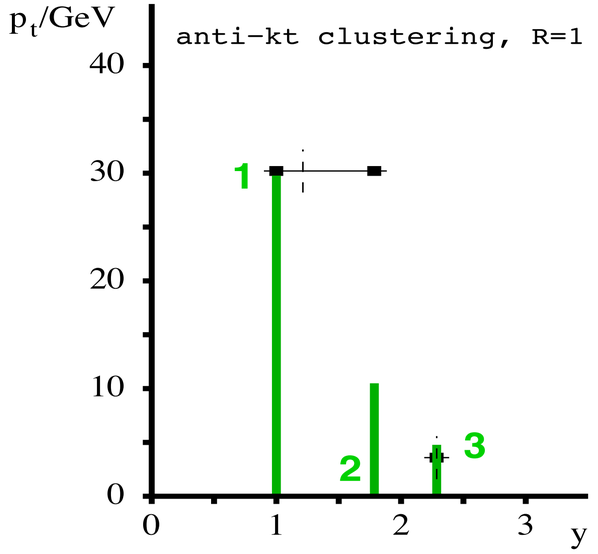

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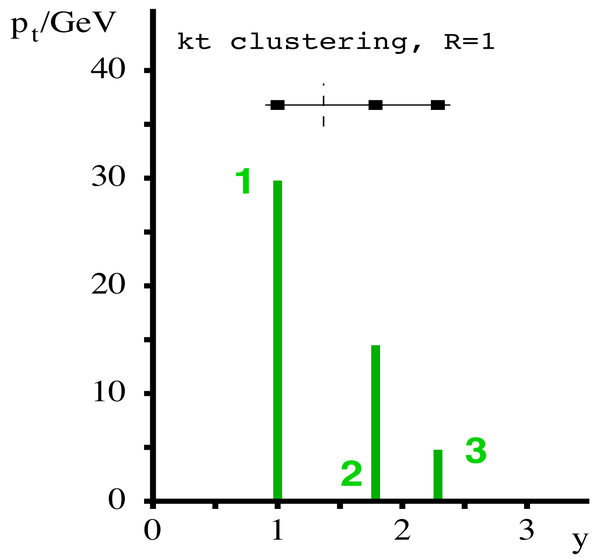

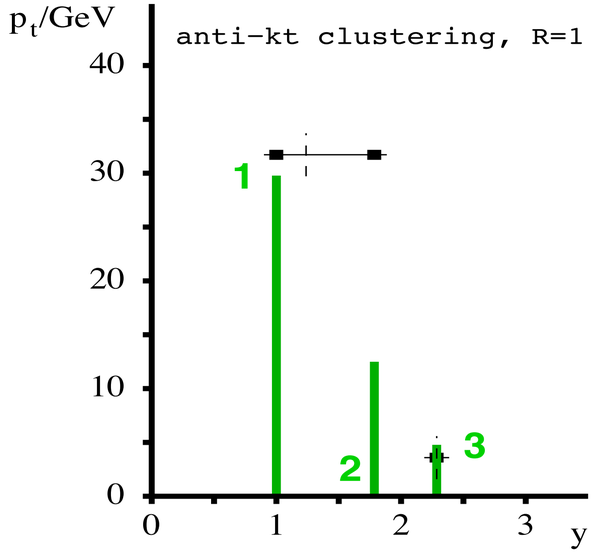

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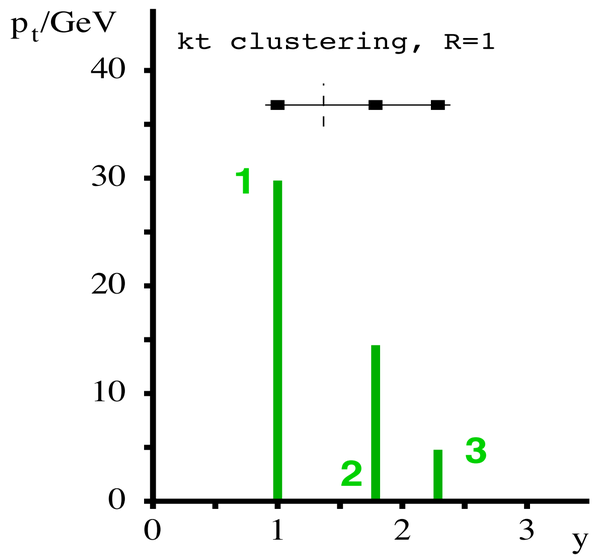

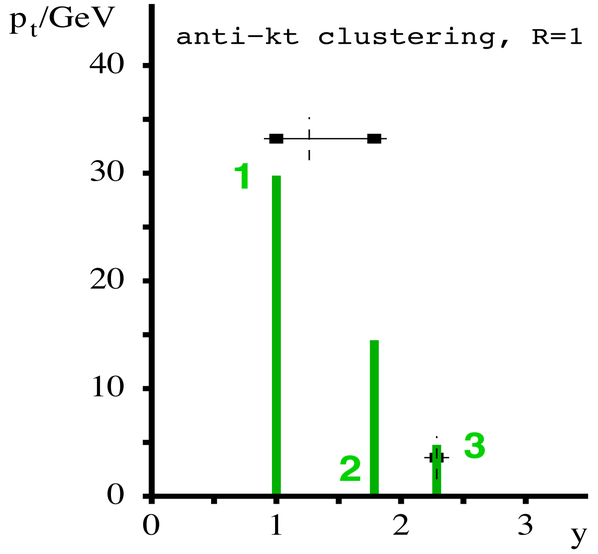

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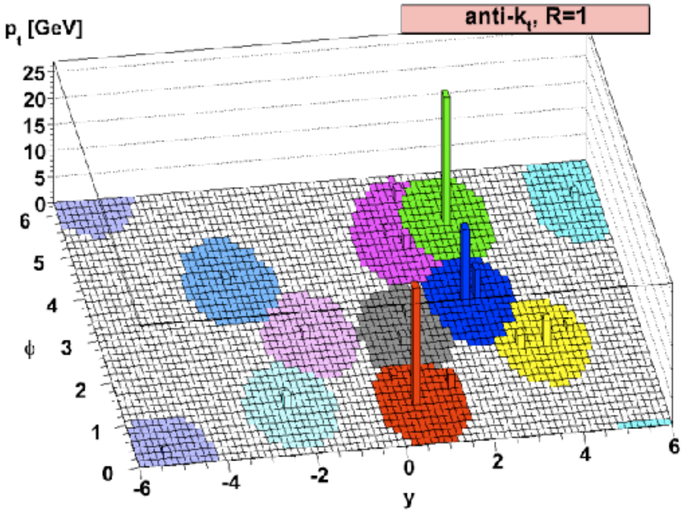

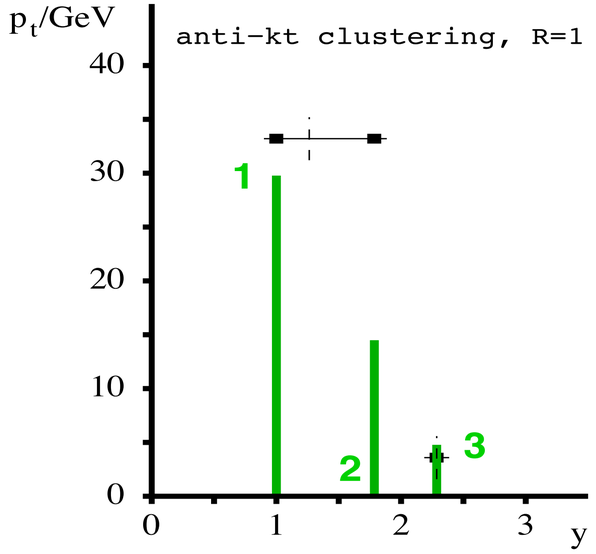

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CA Algorithm:
Often used in jet sub-structure

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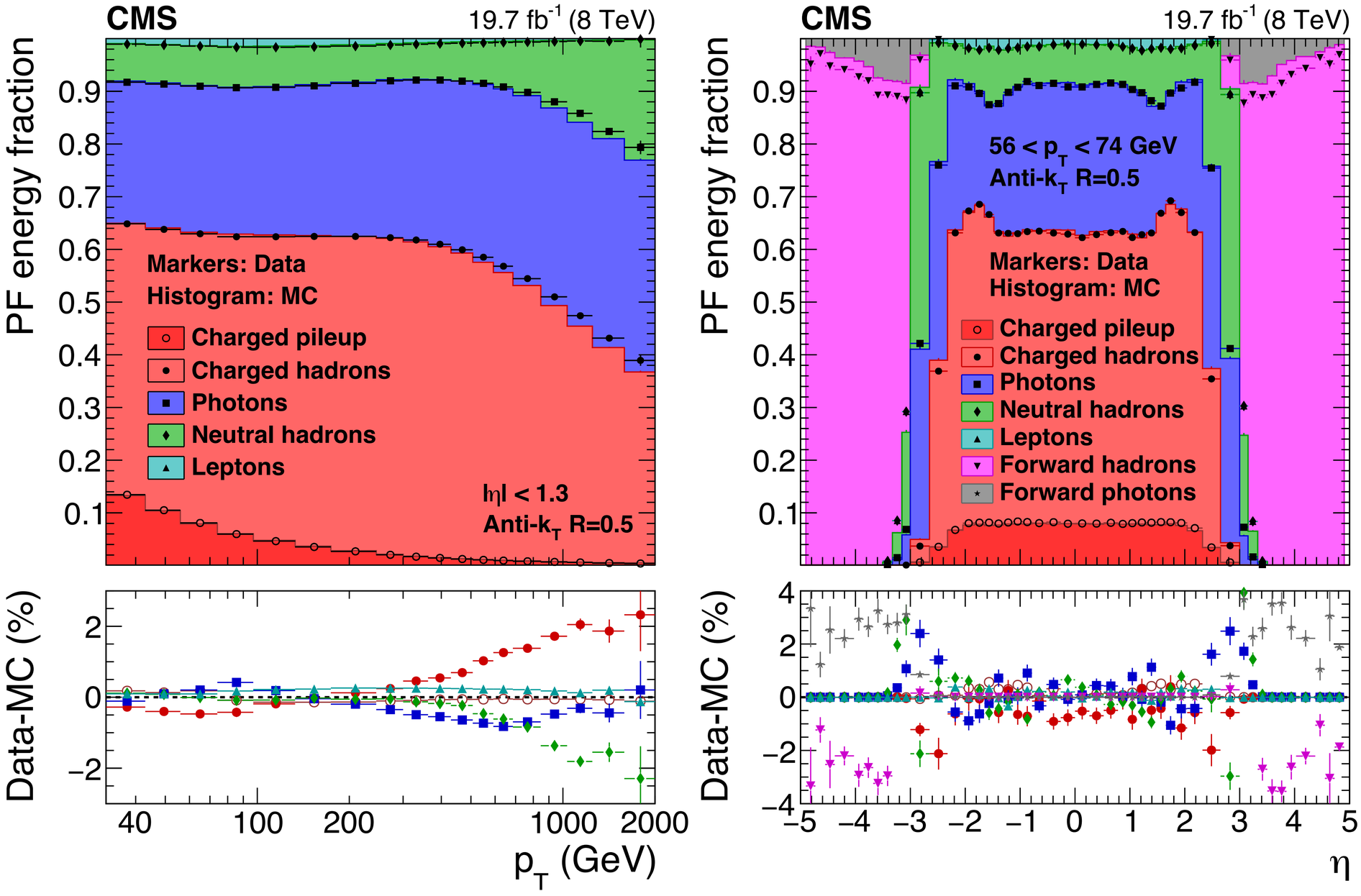
CA Algorithm:

Often used in jet sub-structure

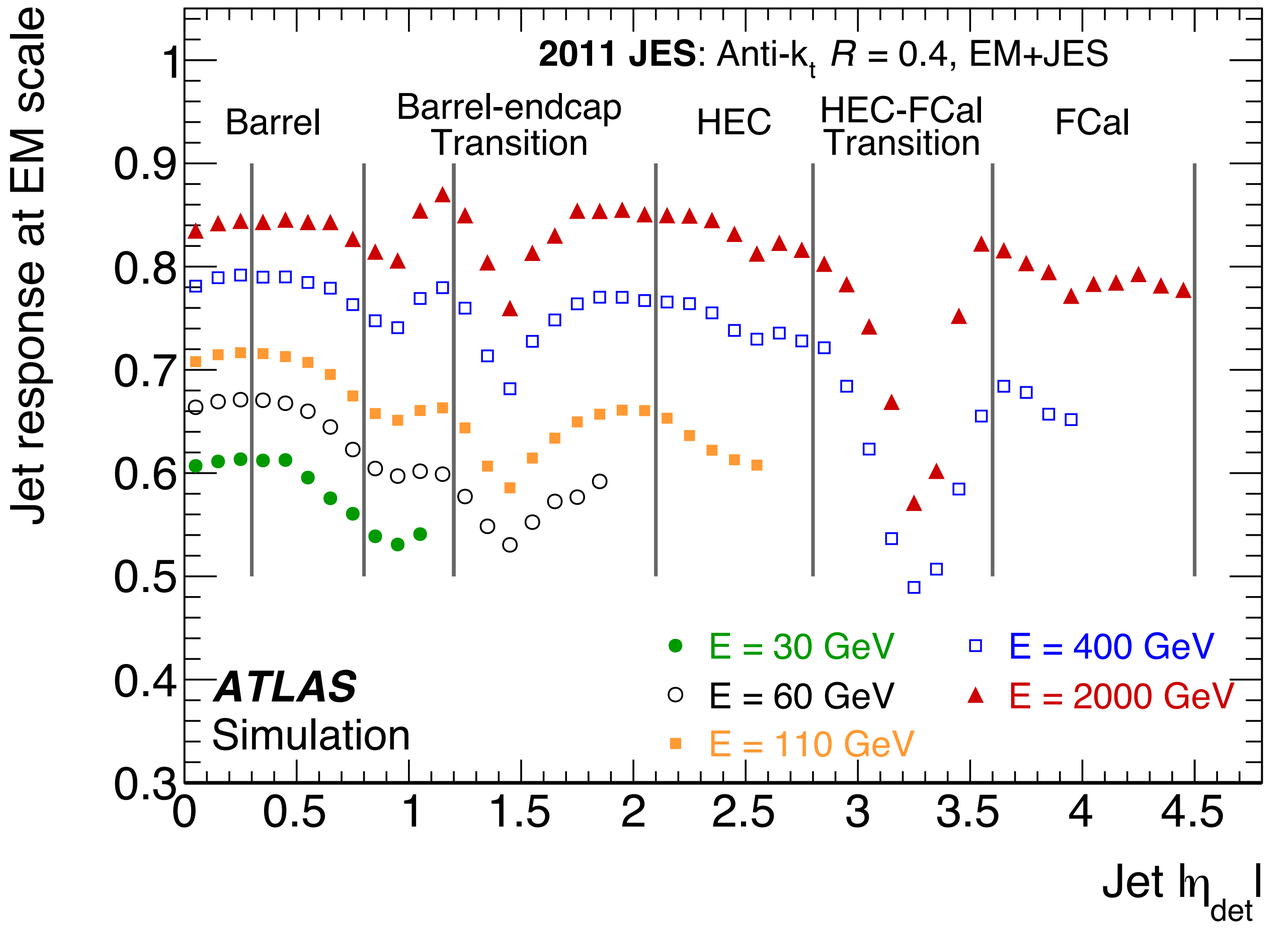
I am so very sorry!!

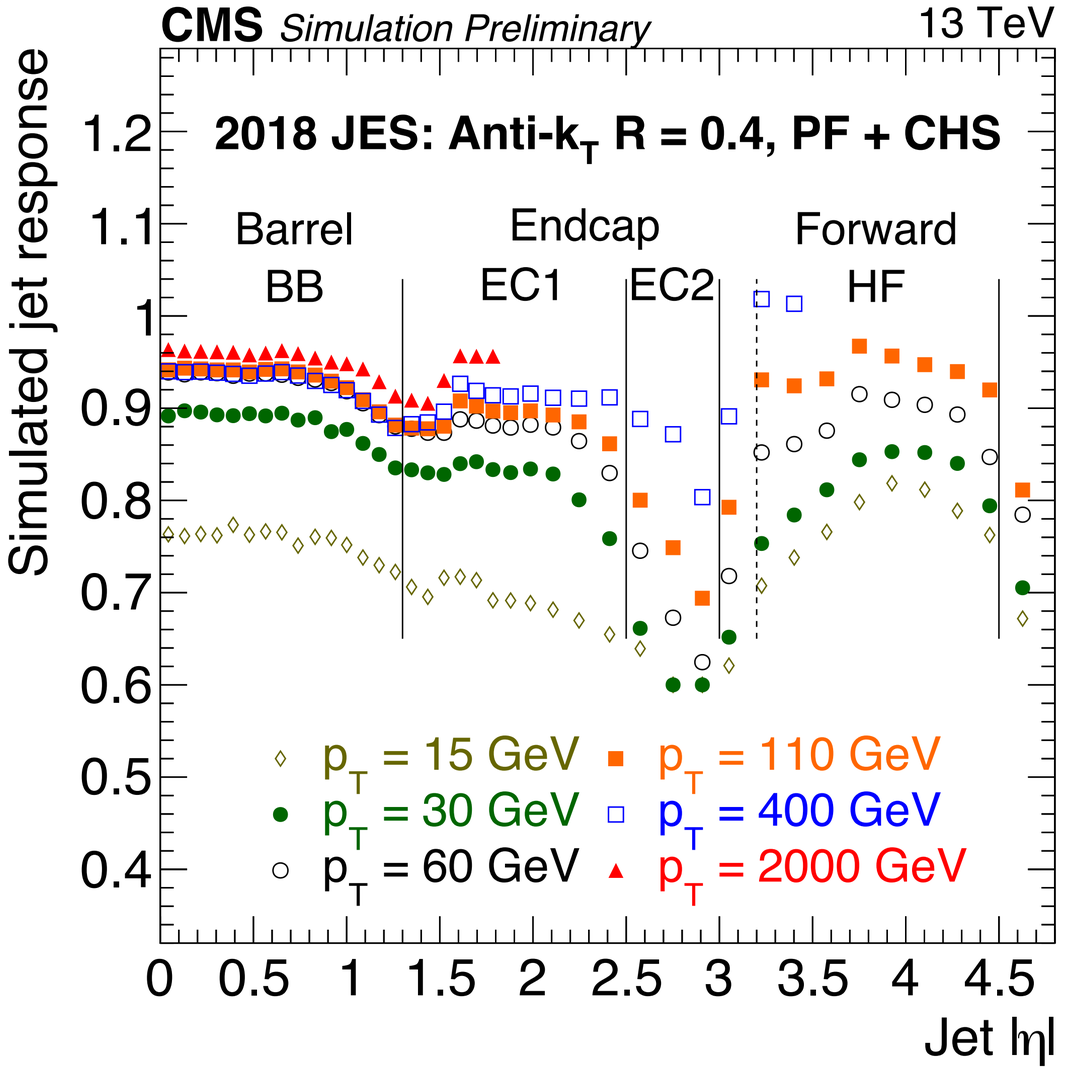
Just not enough time to discuss jet sub-structure -- but wow is it interesting!

Actual particle composition of jets



Done finding jets...



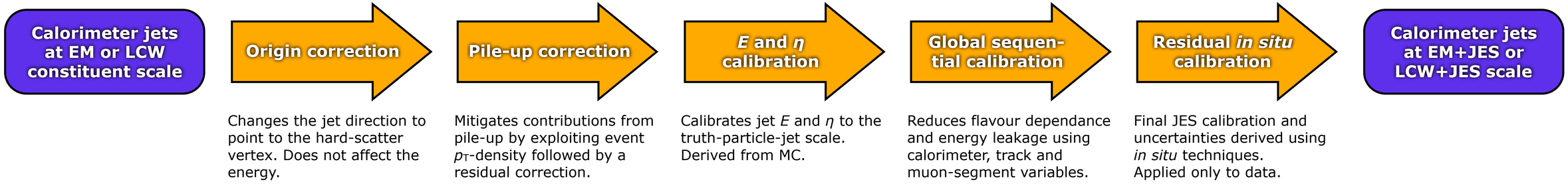


...must now calibrate !

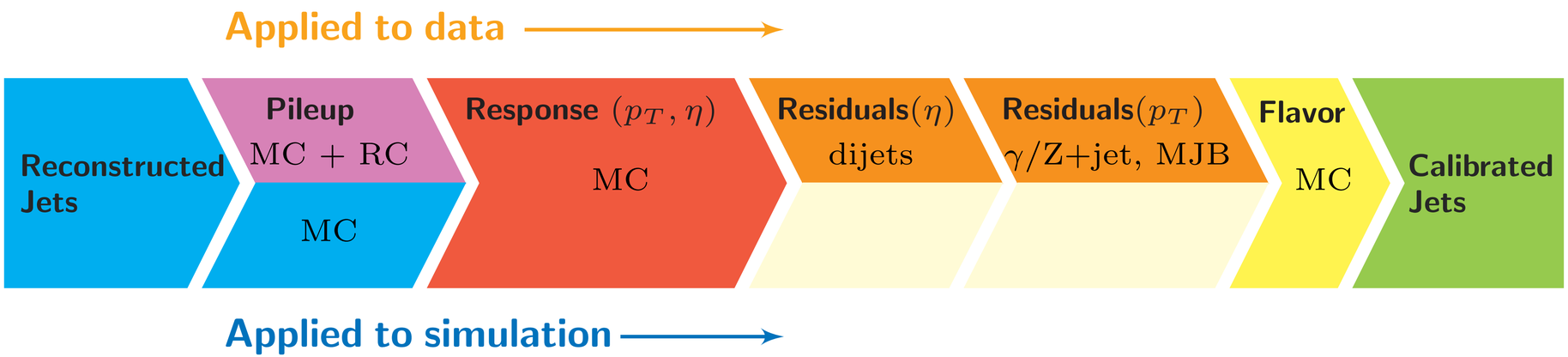
Jet Momentum Corrections

ATLAS

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



CMS



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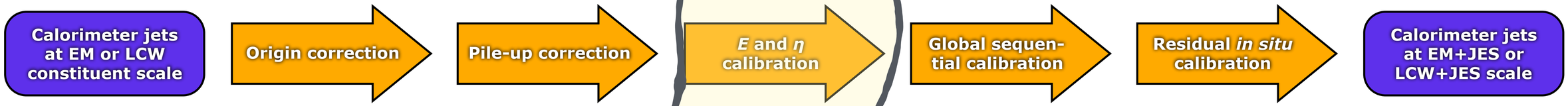


Changes the jet direction to point to the hard-scatter vertex. Does not affect the energy.

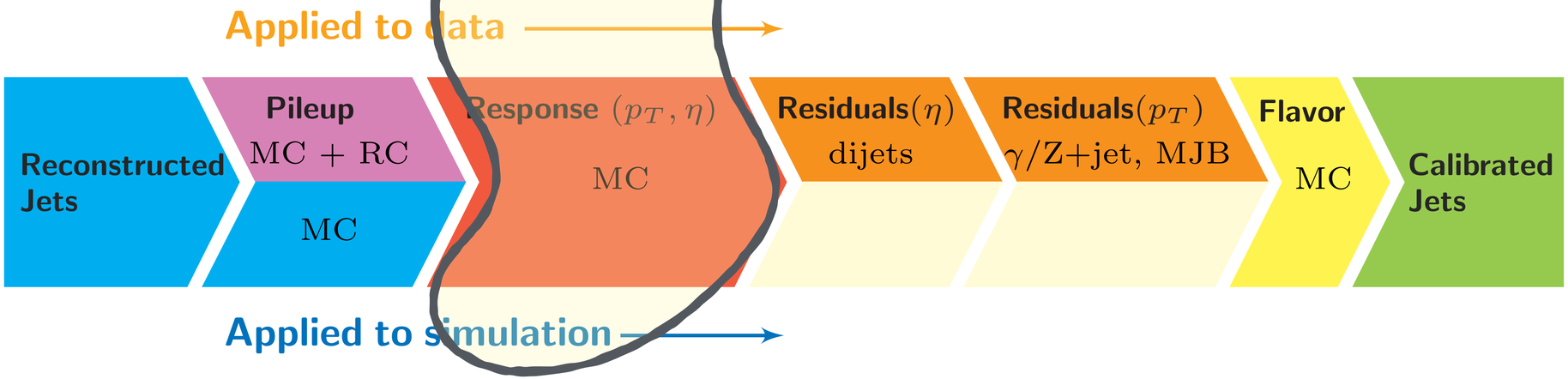
Mitigates contributions from pile-up by exploiting event p_T-density followed by a residual correction.

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

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

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

CMS



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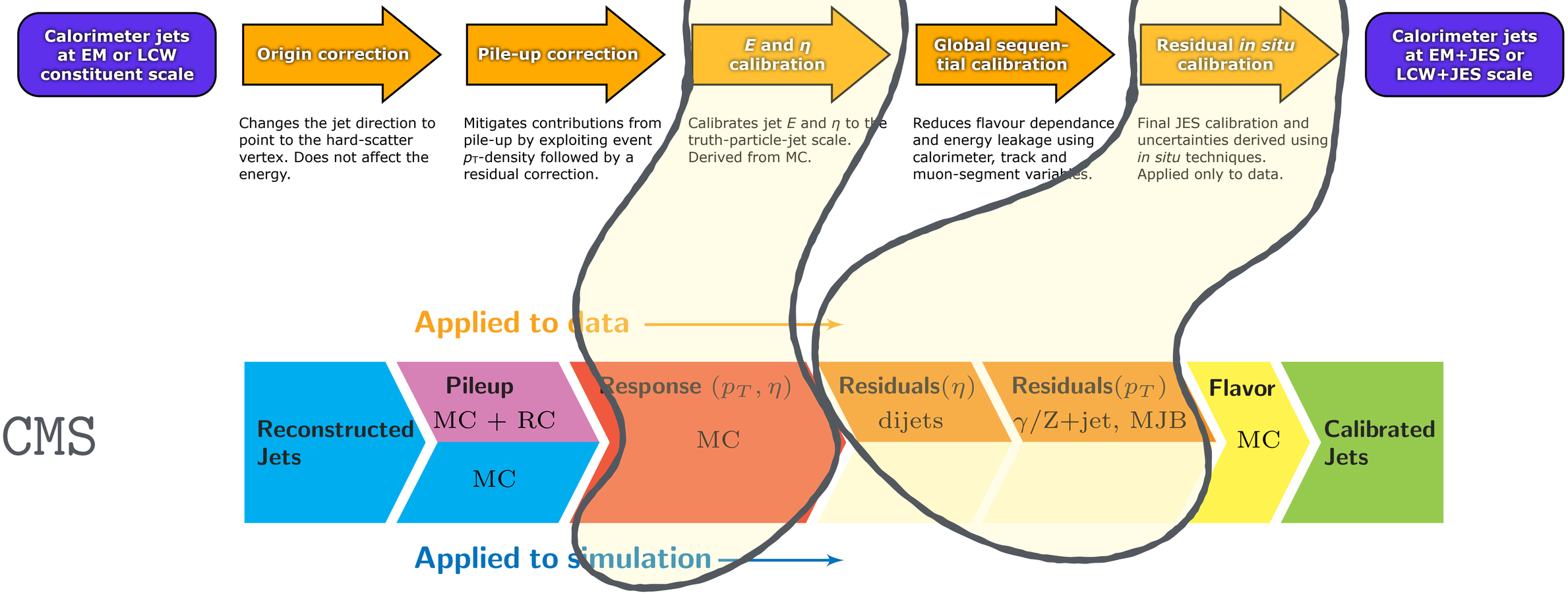

CMS

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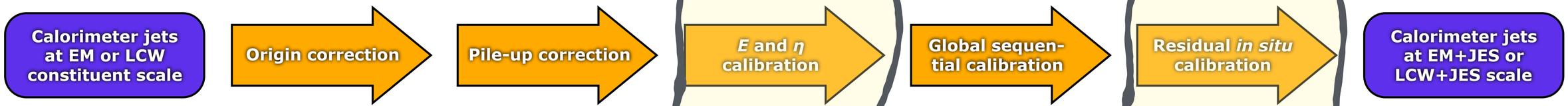

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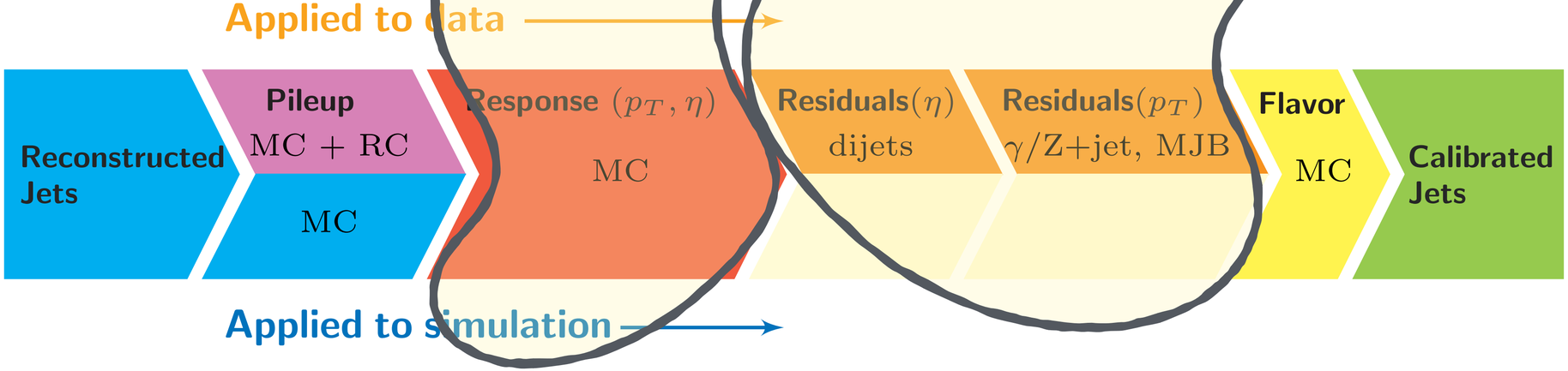
Reduces flavour dependance and energy leakage using calorimeter, track and muon-segment variables.

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

Discuss these (briefly) first

CMS



Jet Momentum Corrections

ATLAS

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

Discuss these (briefly) first

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.

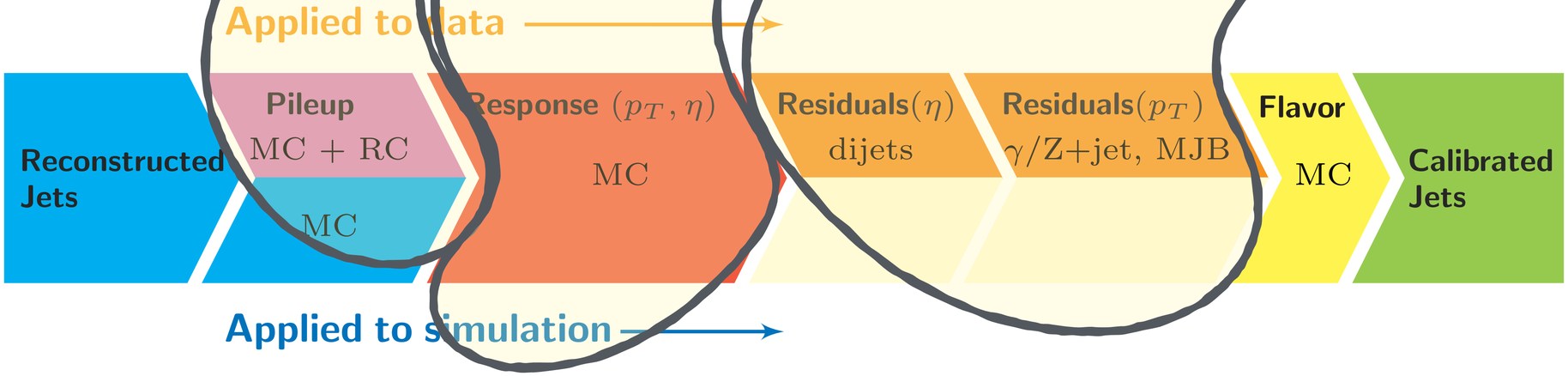
***E* and *η* calibration**
Calibrates jet *E* and *η* to the truth-particle-jet scale. Derived from MC.

Global sequential calibration
Reduces flavour dependance 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



Jet Momentum Corrections

ATLAS

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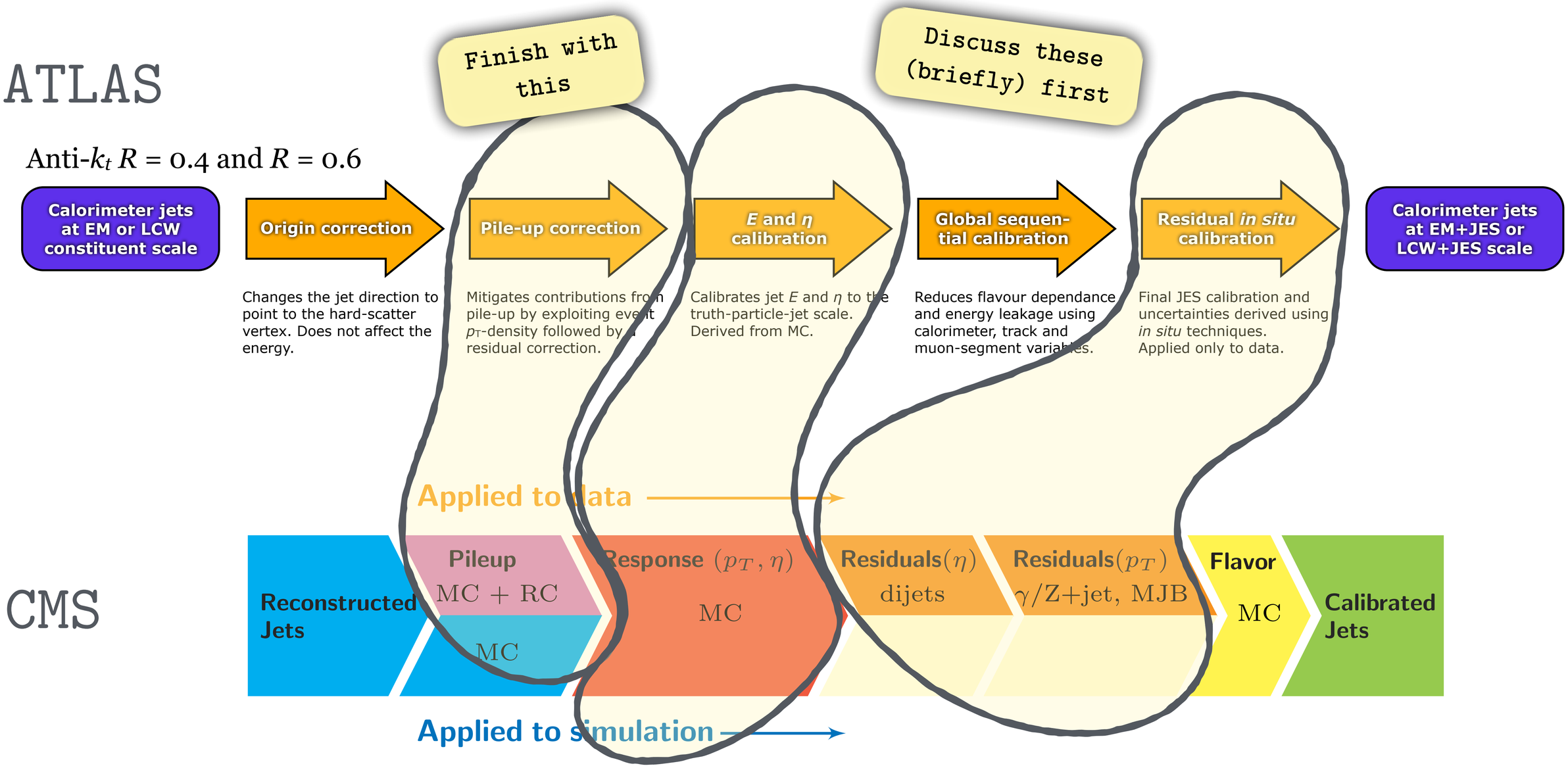
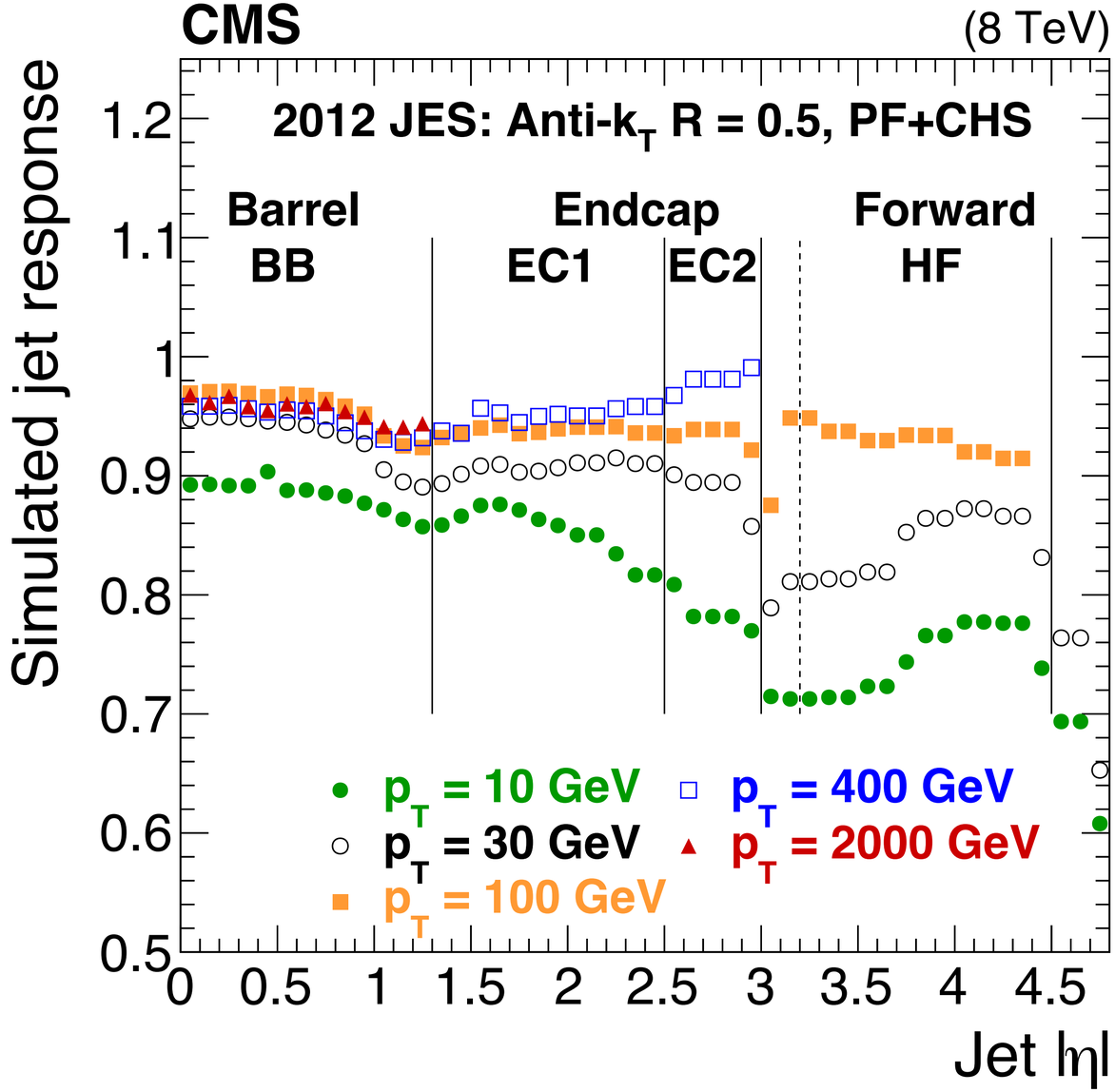
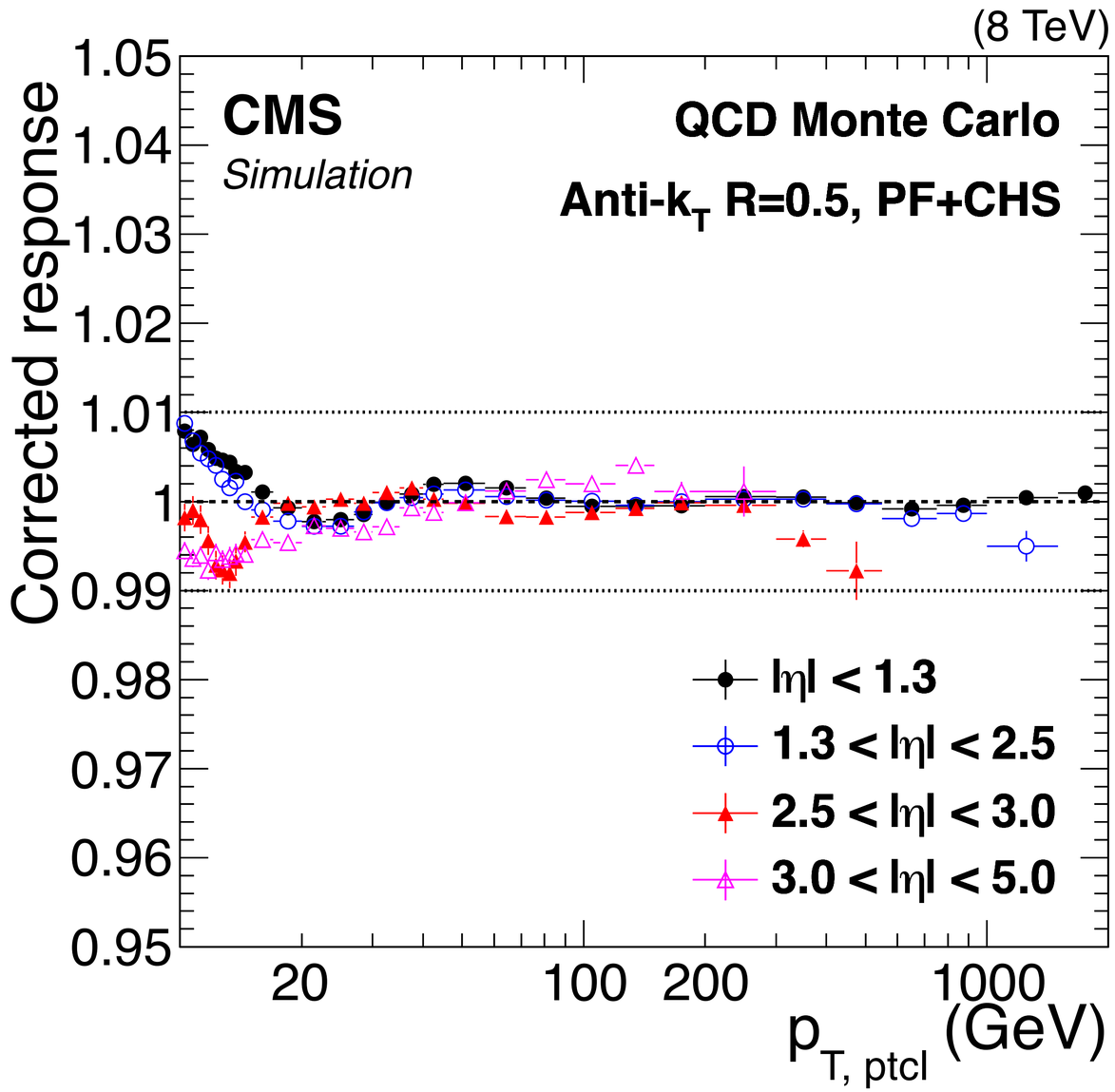


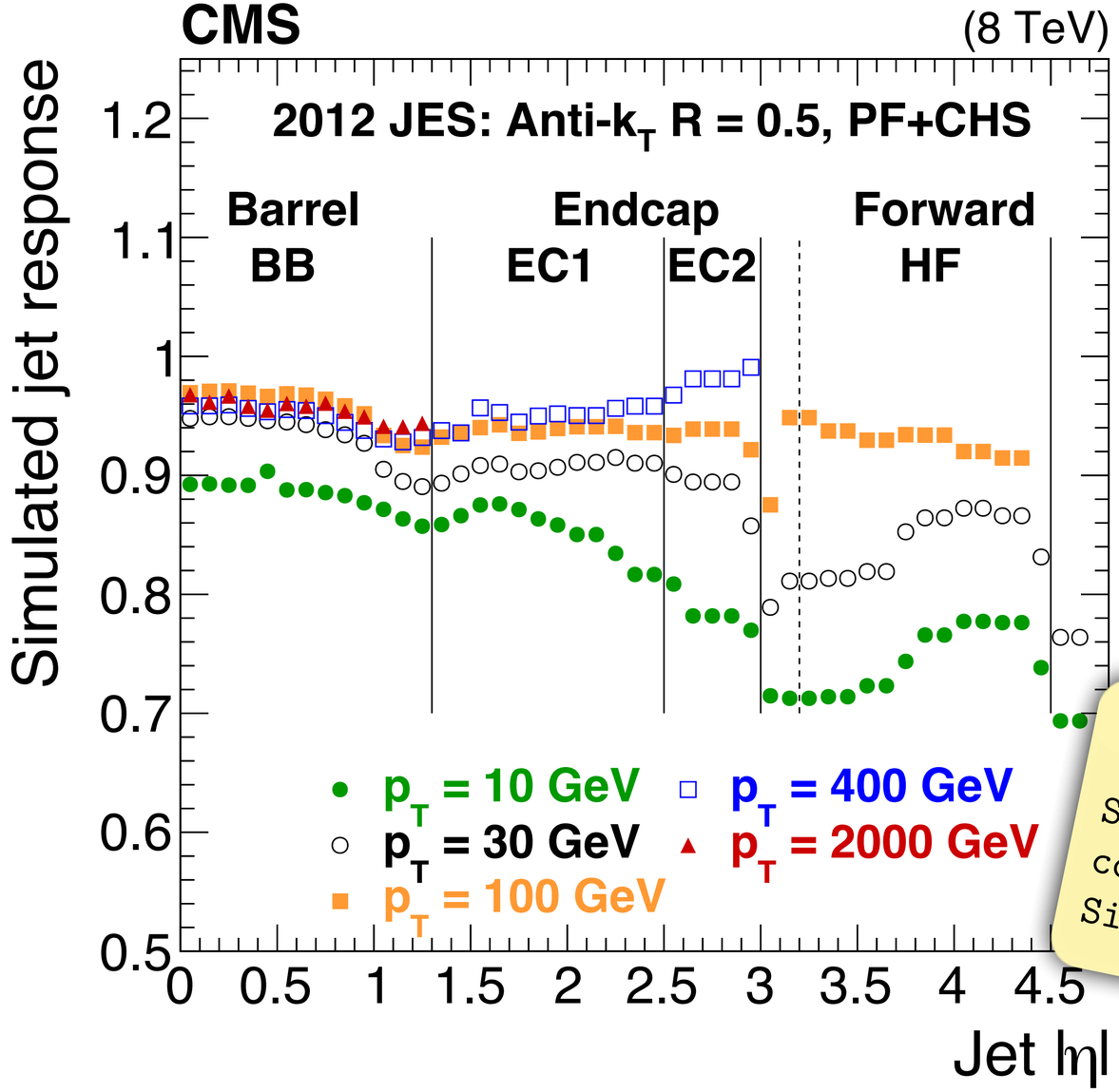
CMS

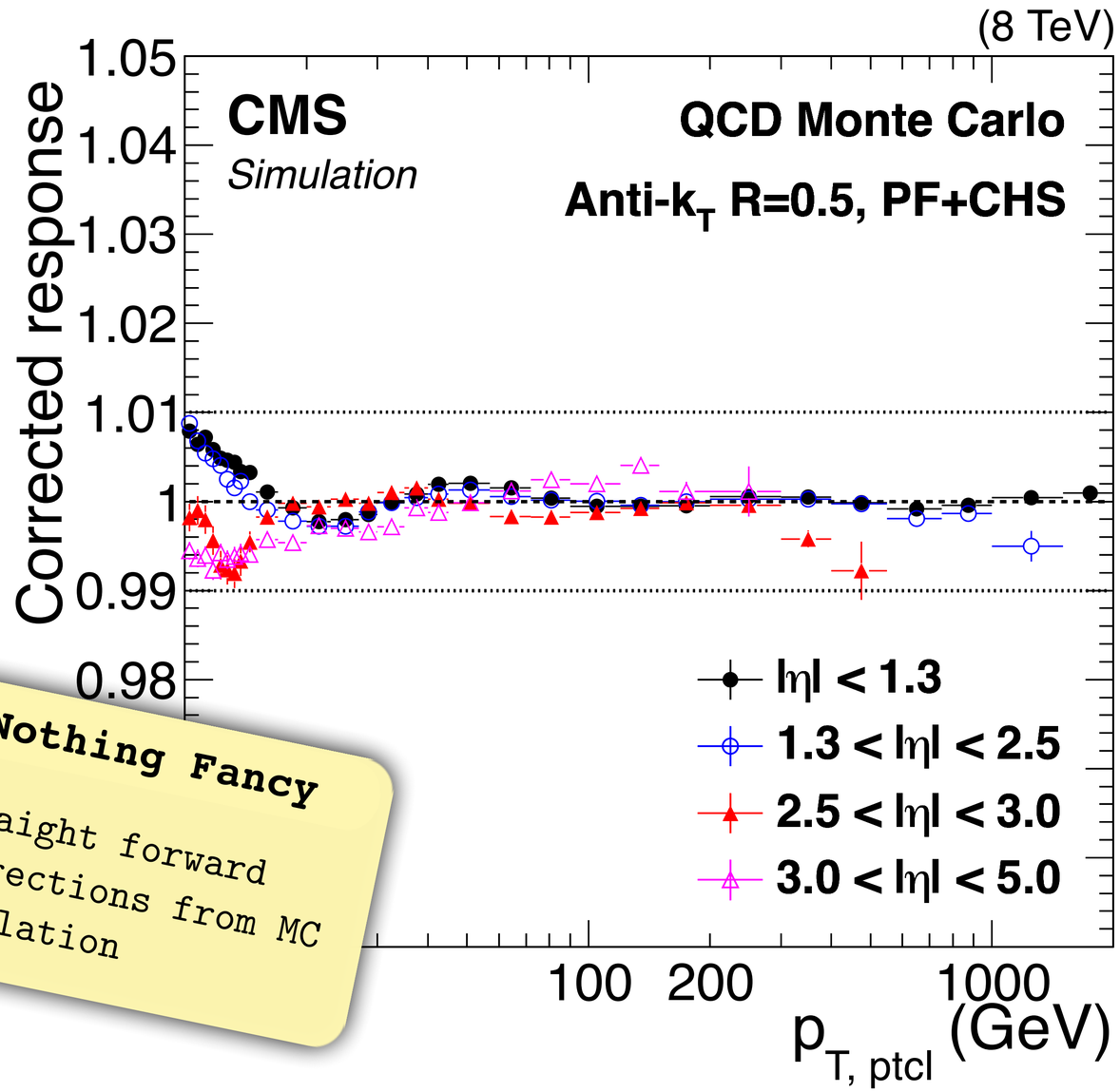
Step 1: Correct gross response using MC Simulation





Step 1: Correct gross response using MC Simulation





Nothing Fancy

Straight forward corrections from MC Simulation

Step 2: Relative η Residual-Correction using data

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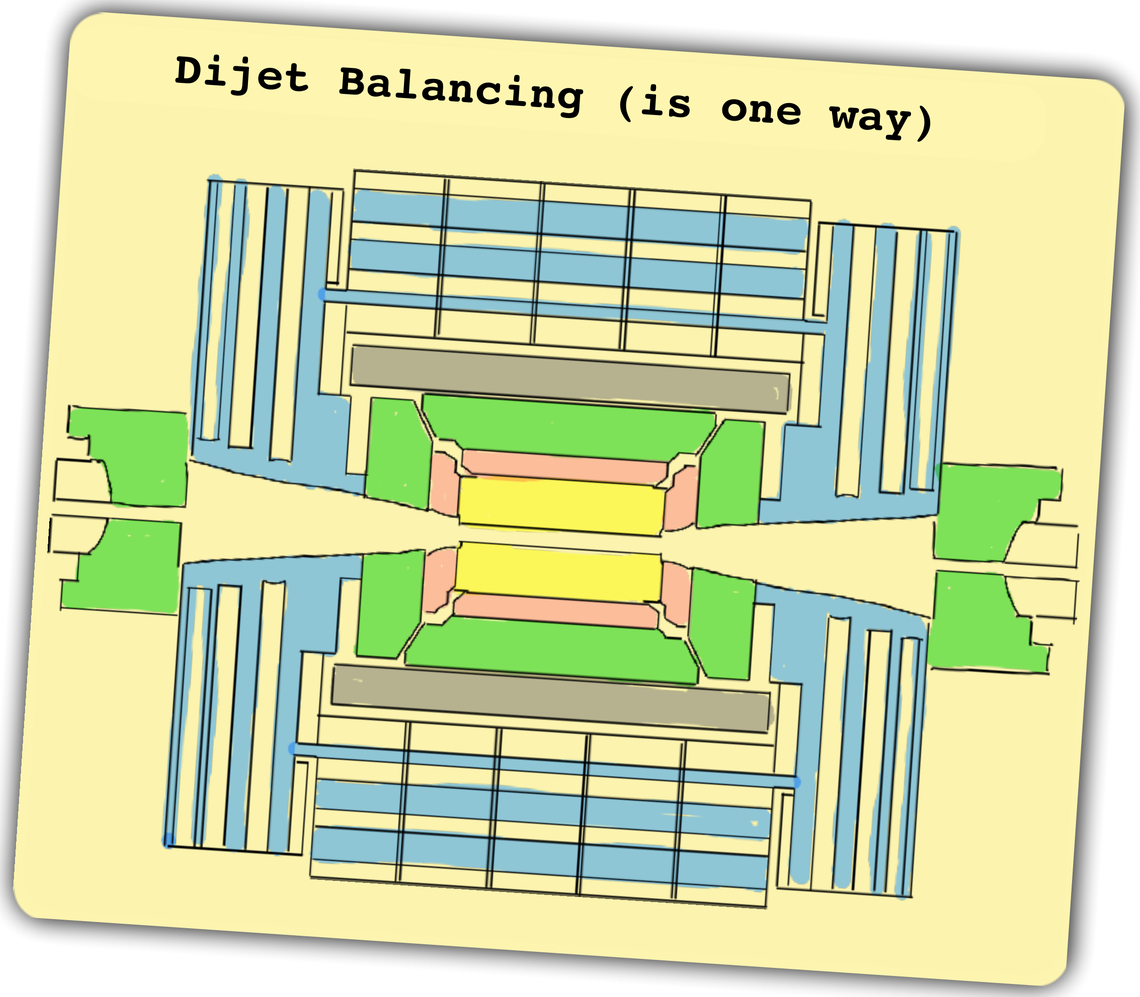

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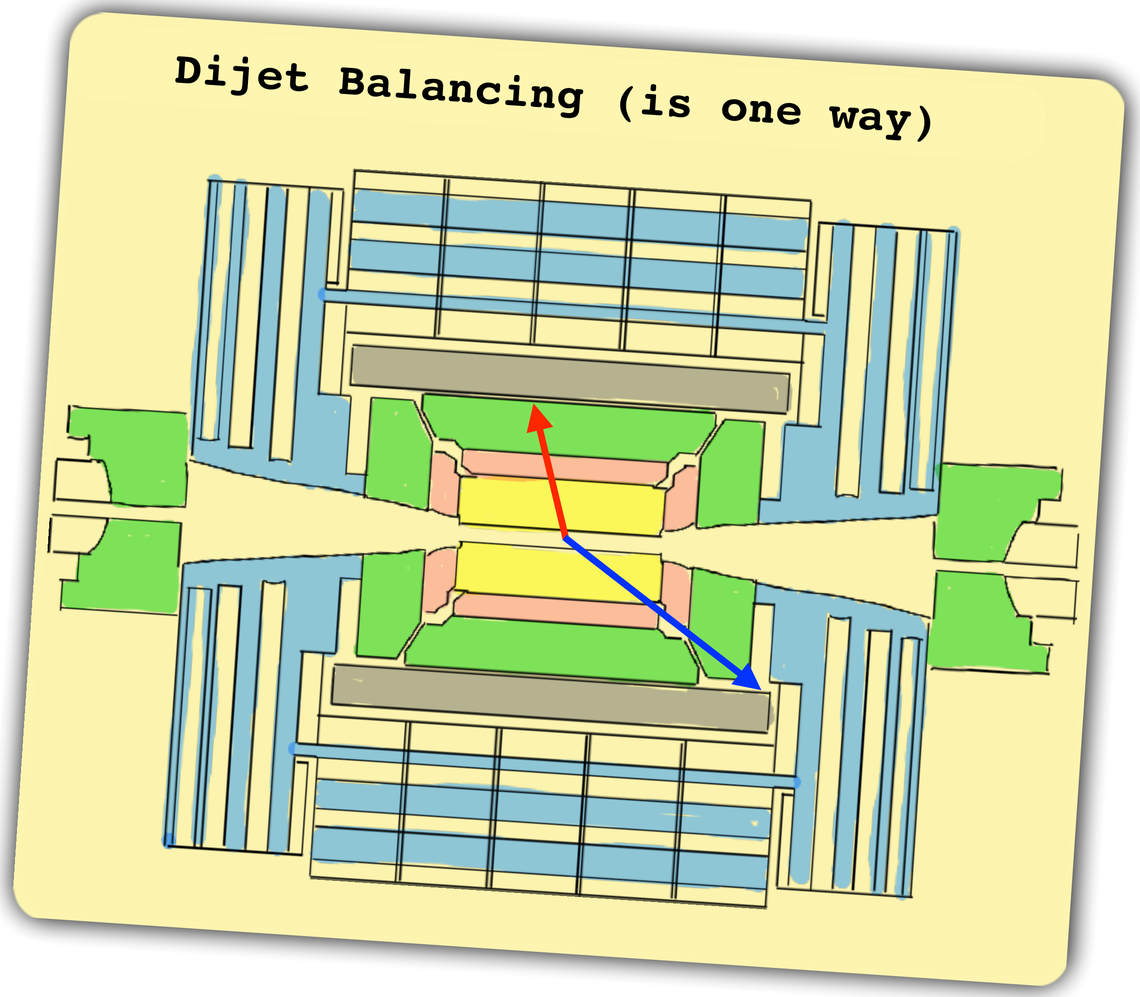

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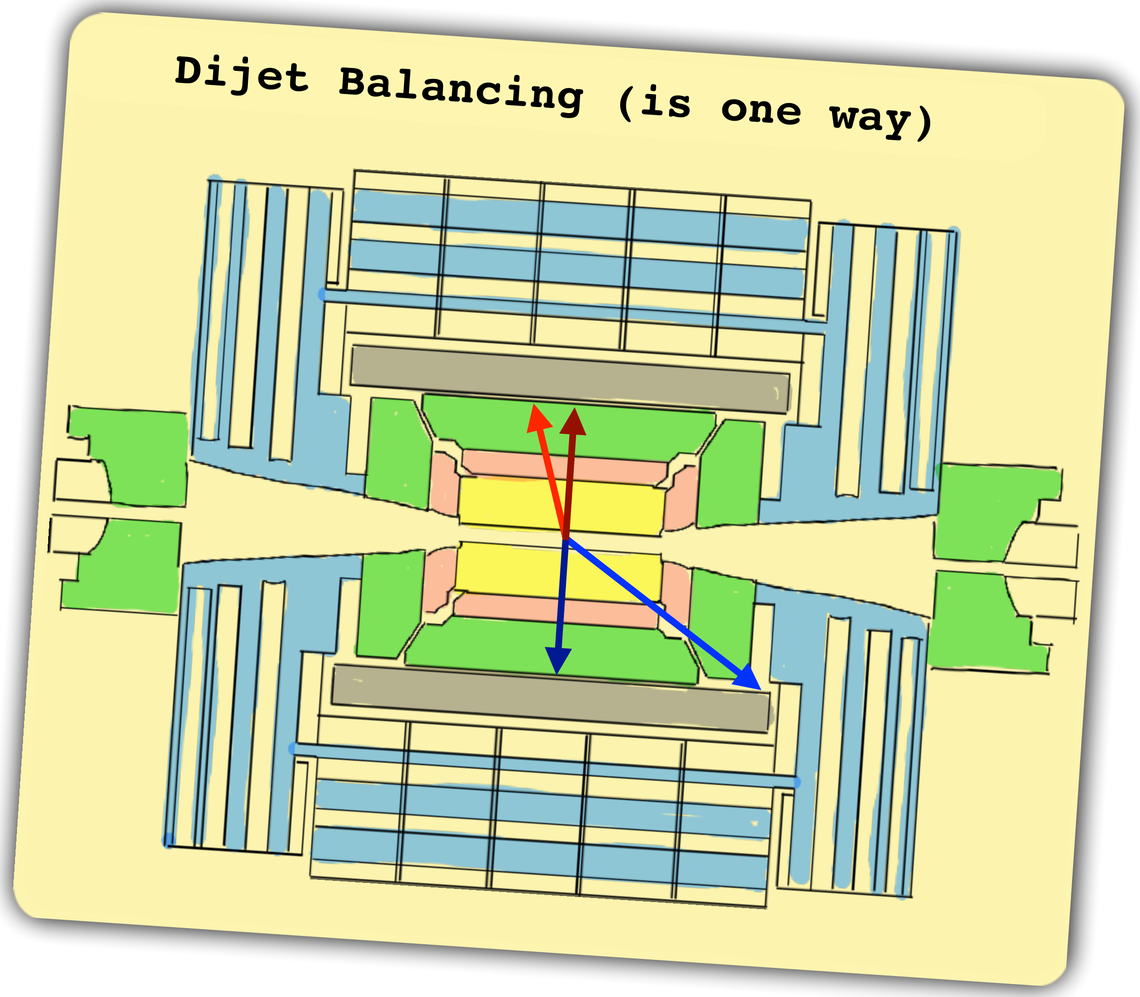

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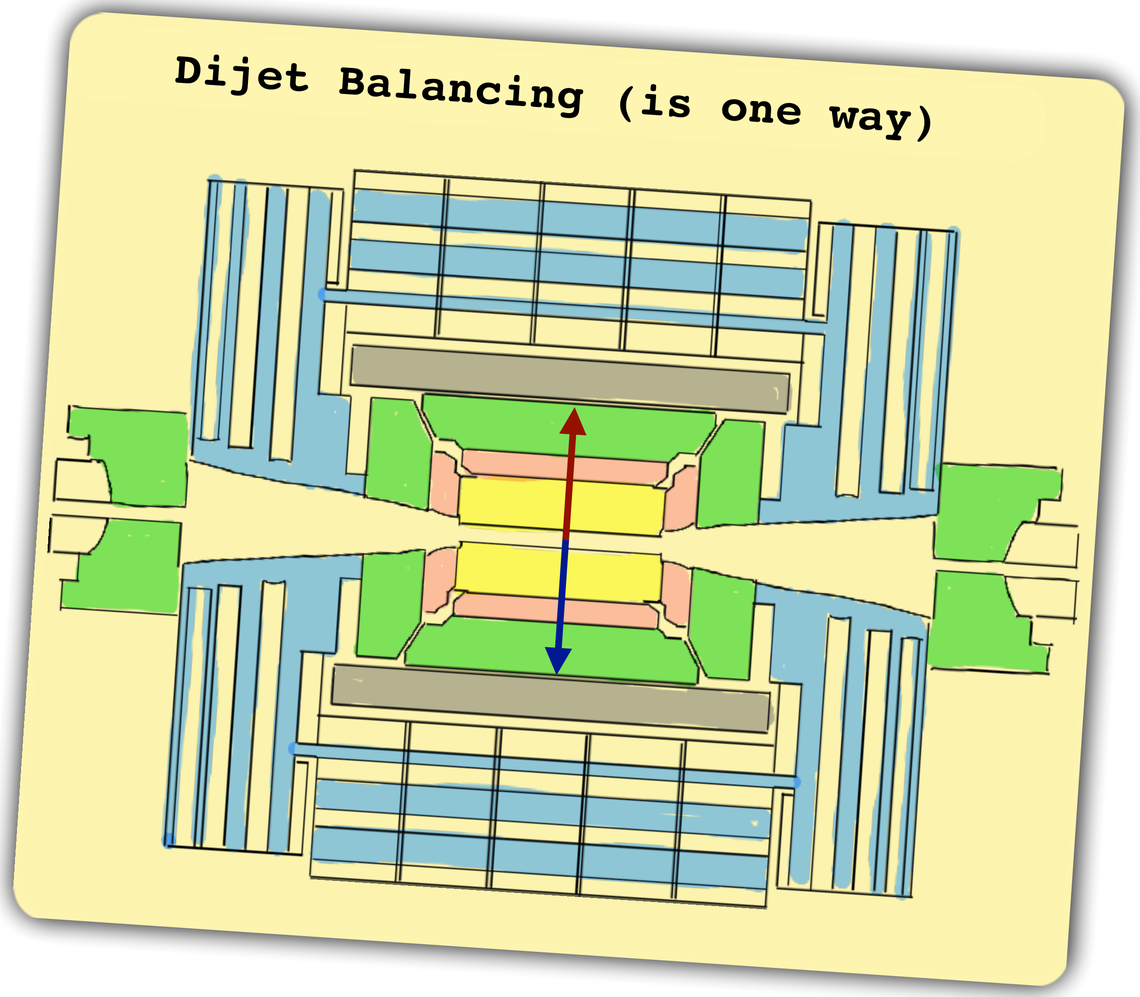

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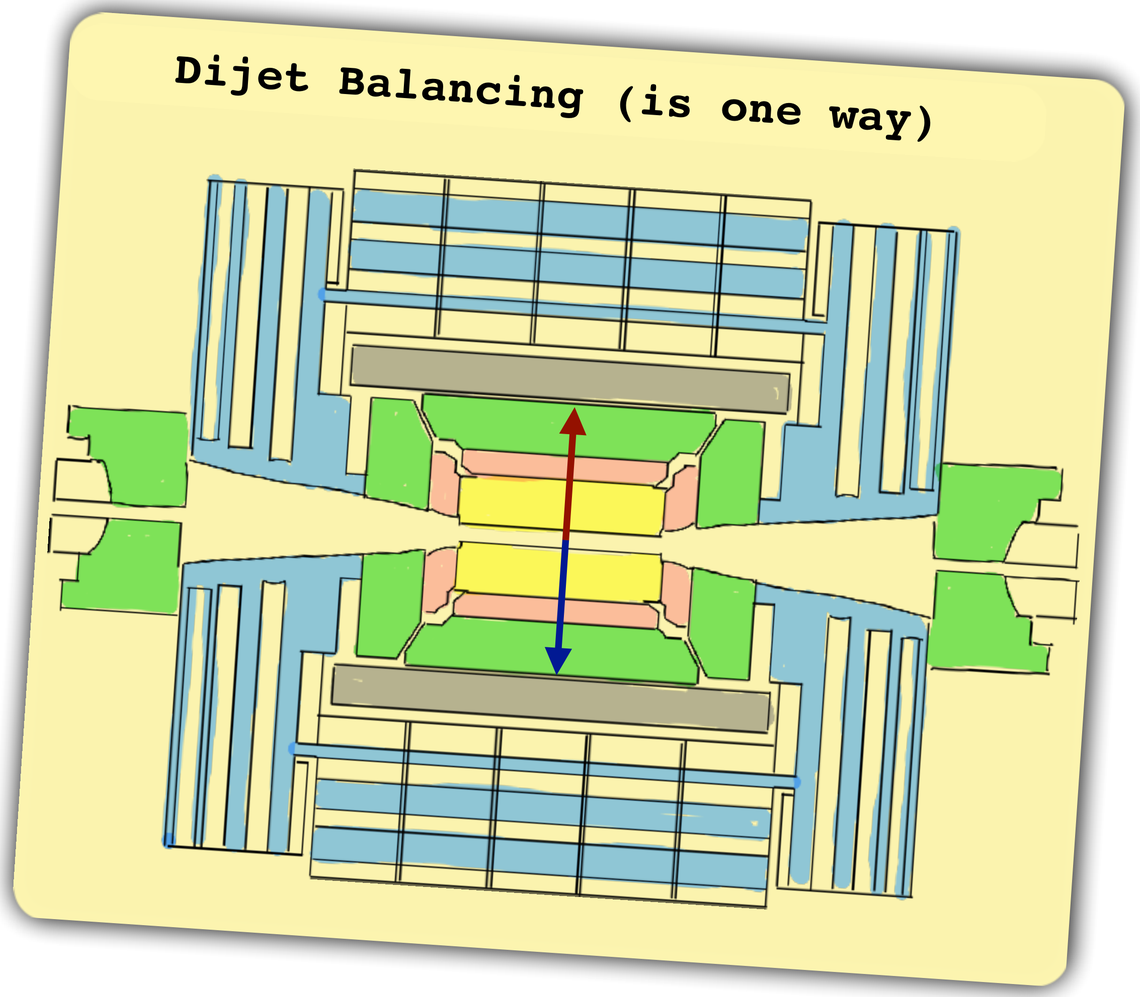

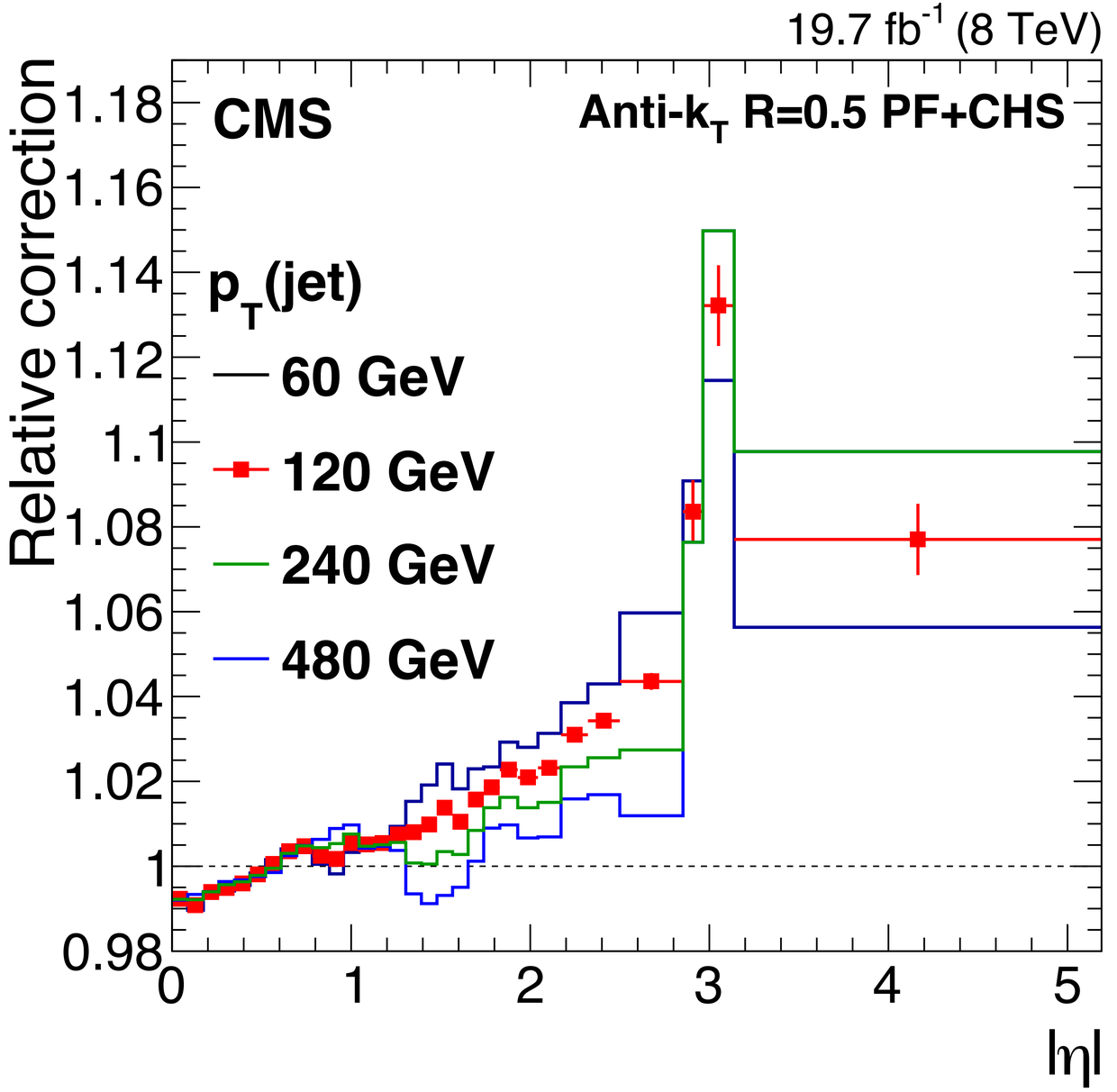

Step 3: Absolute p_{T} Residual-Correction using data

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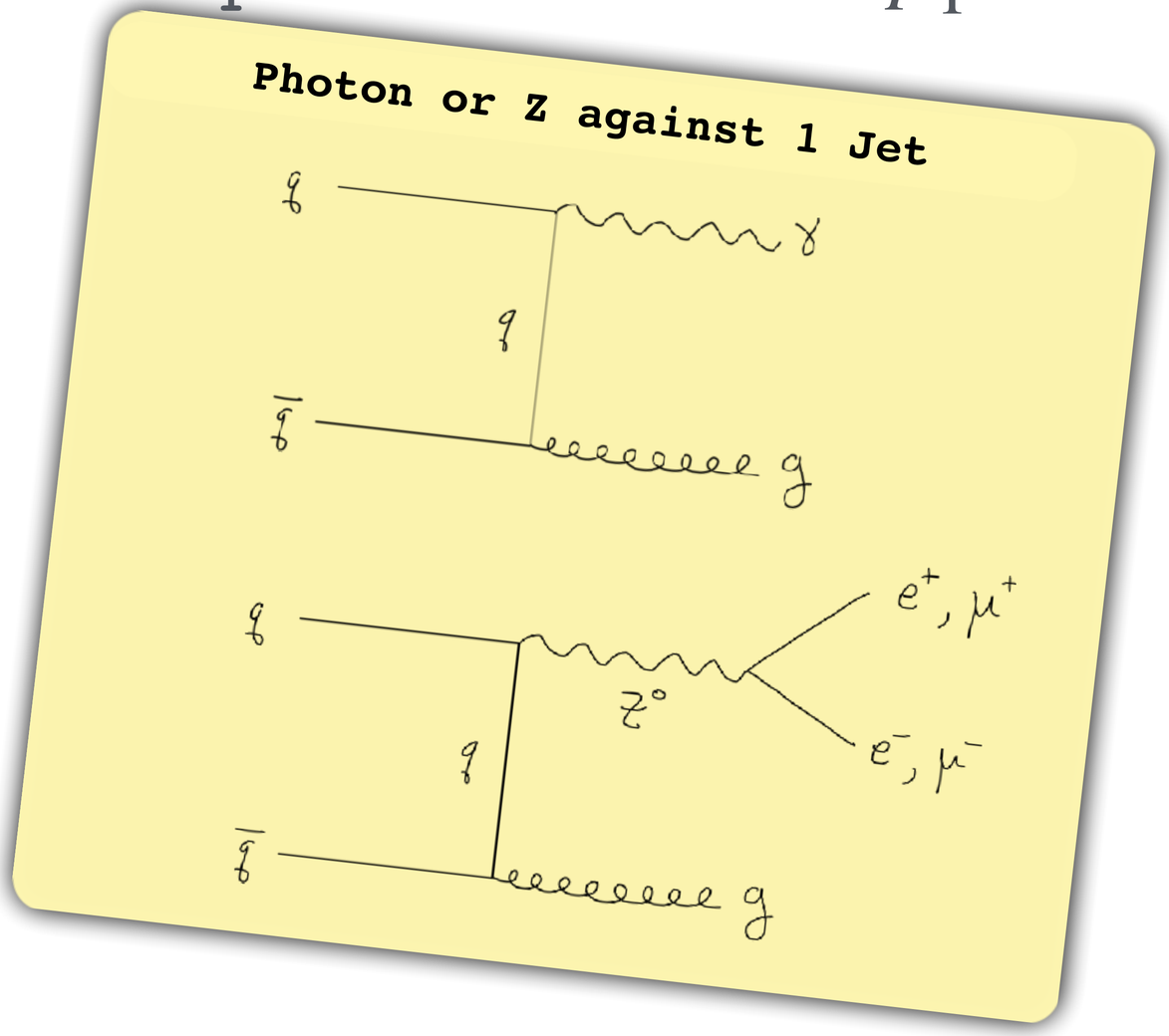

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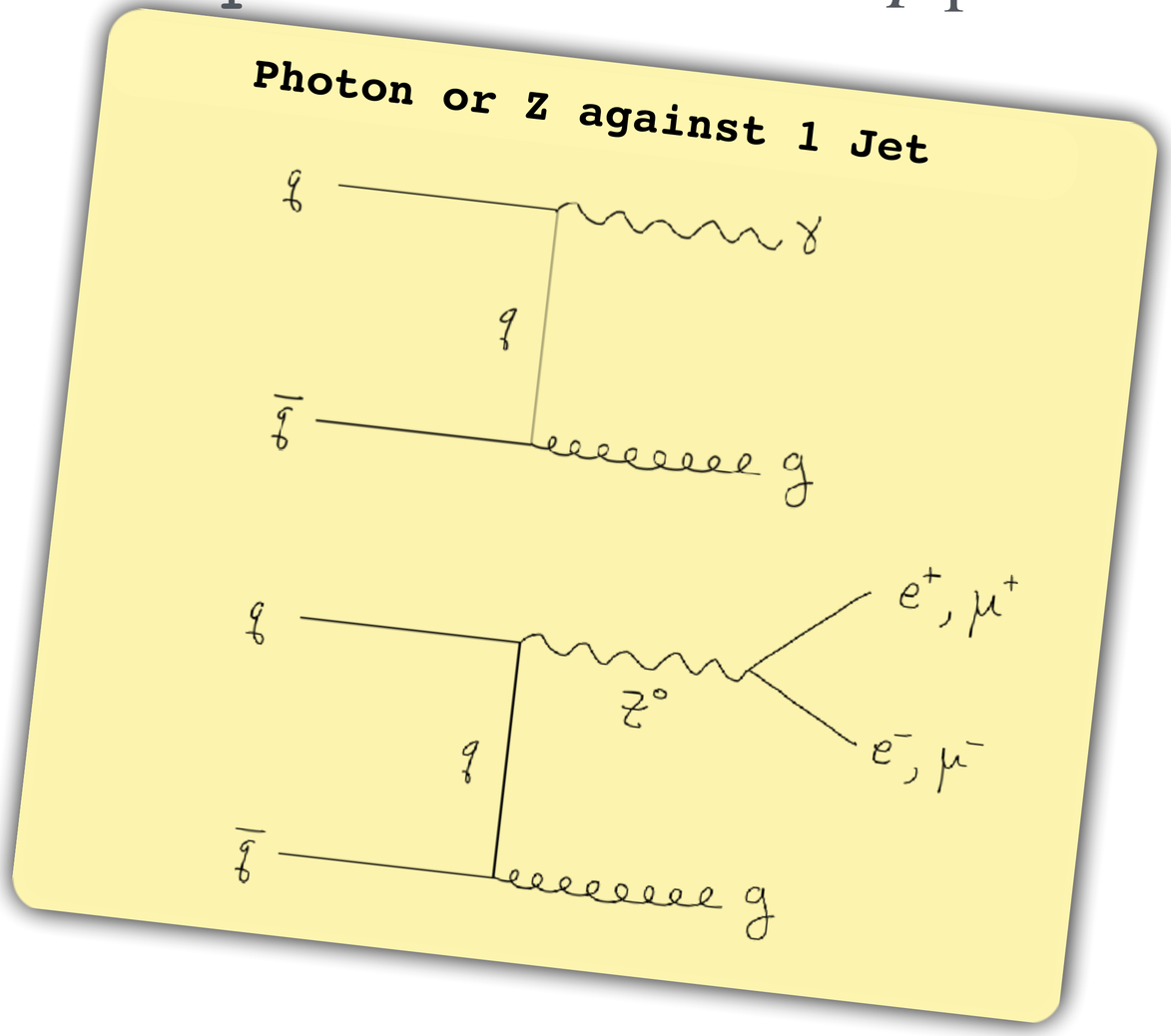

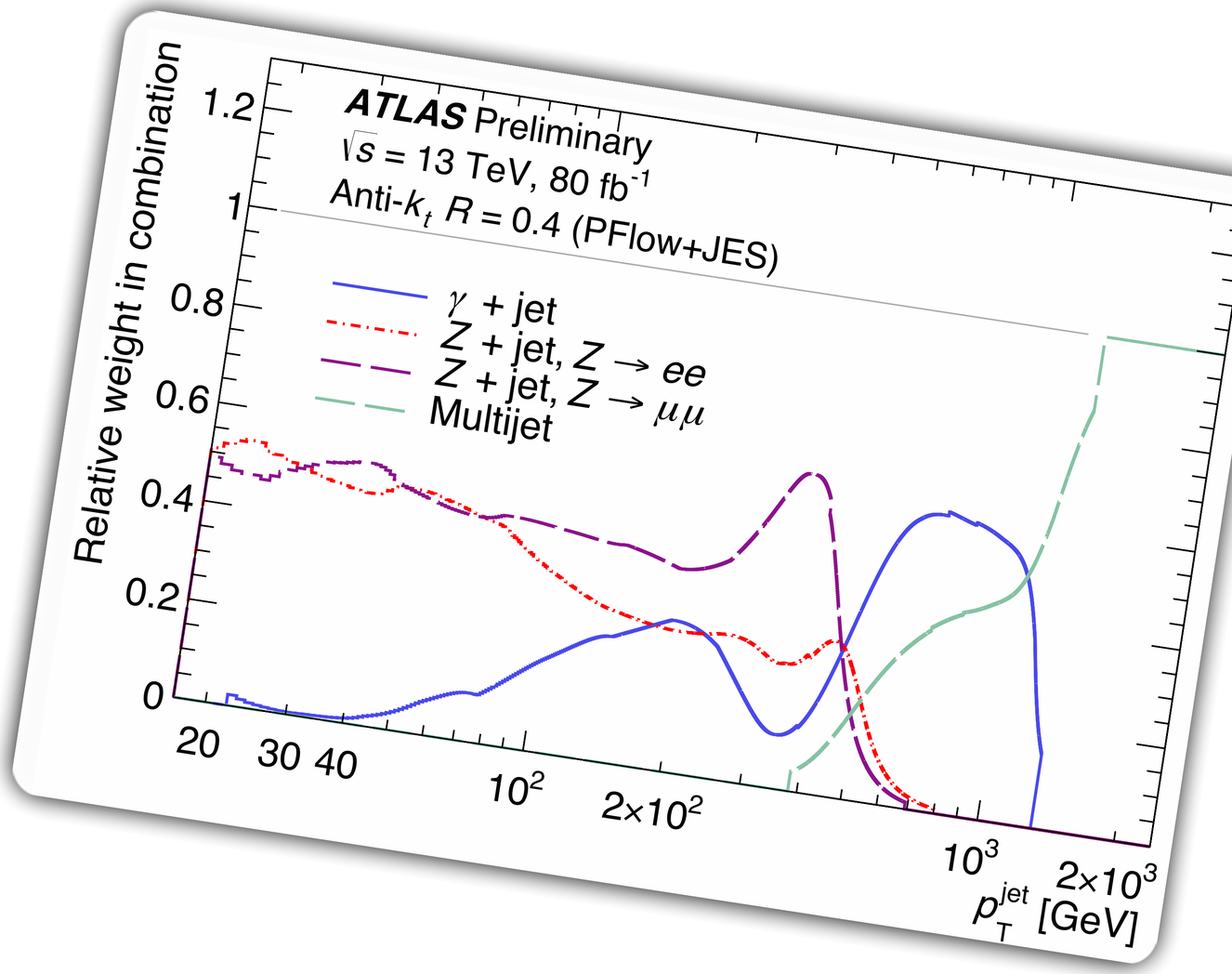

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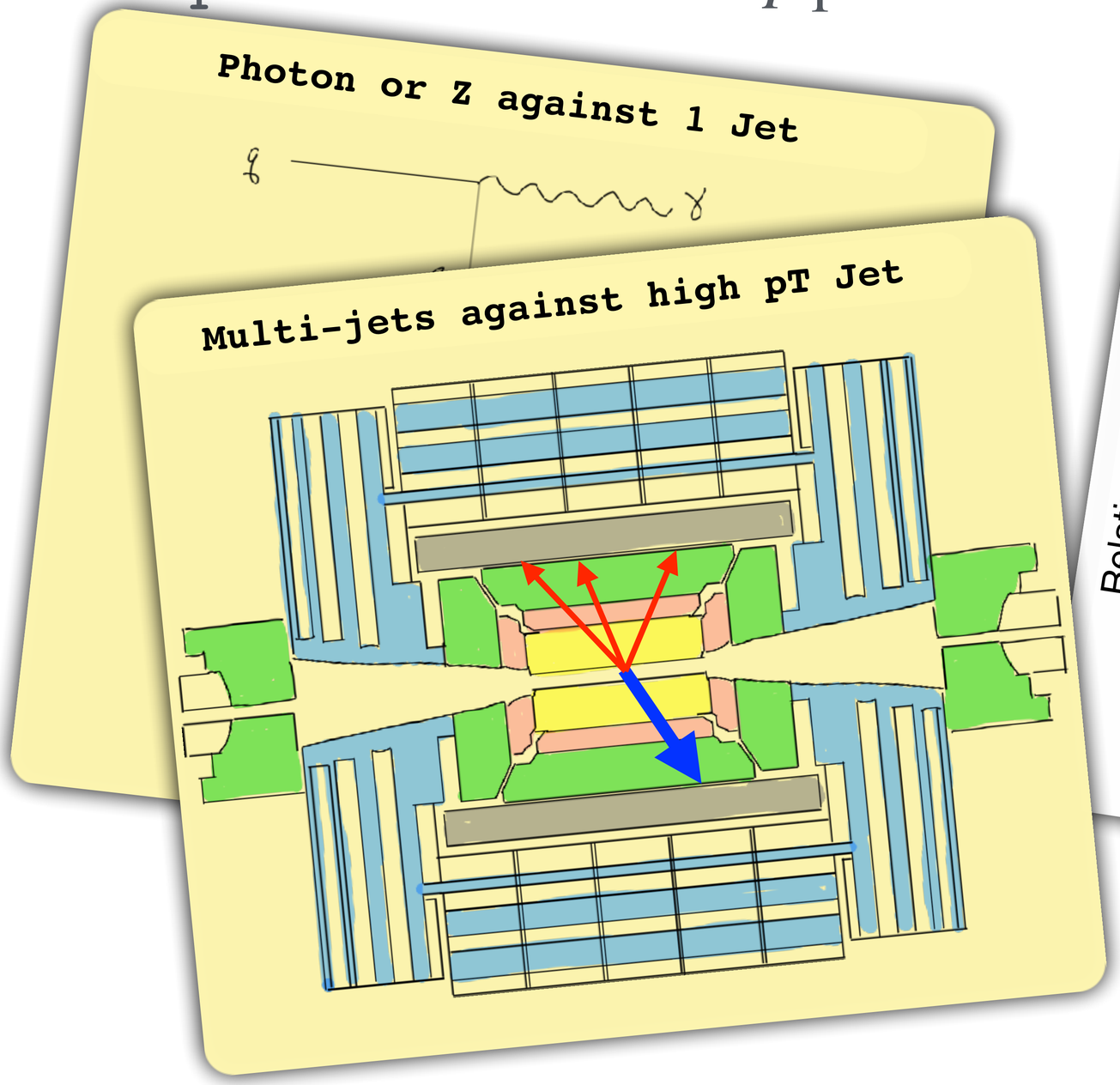

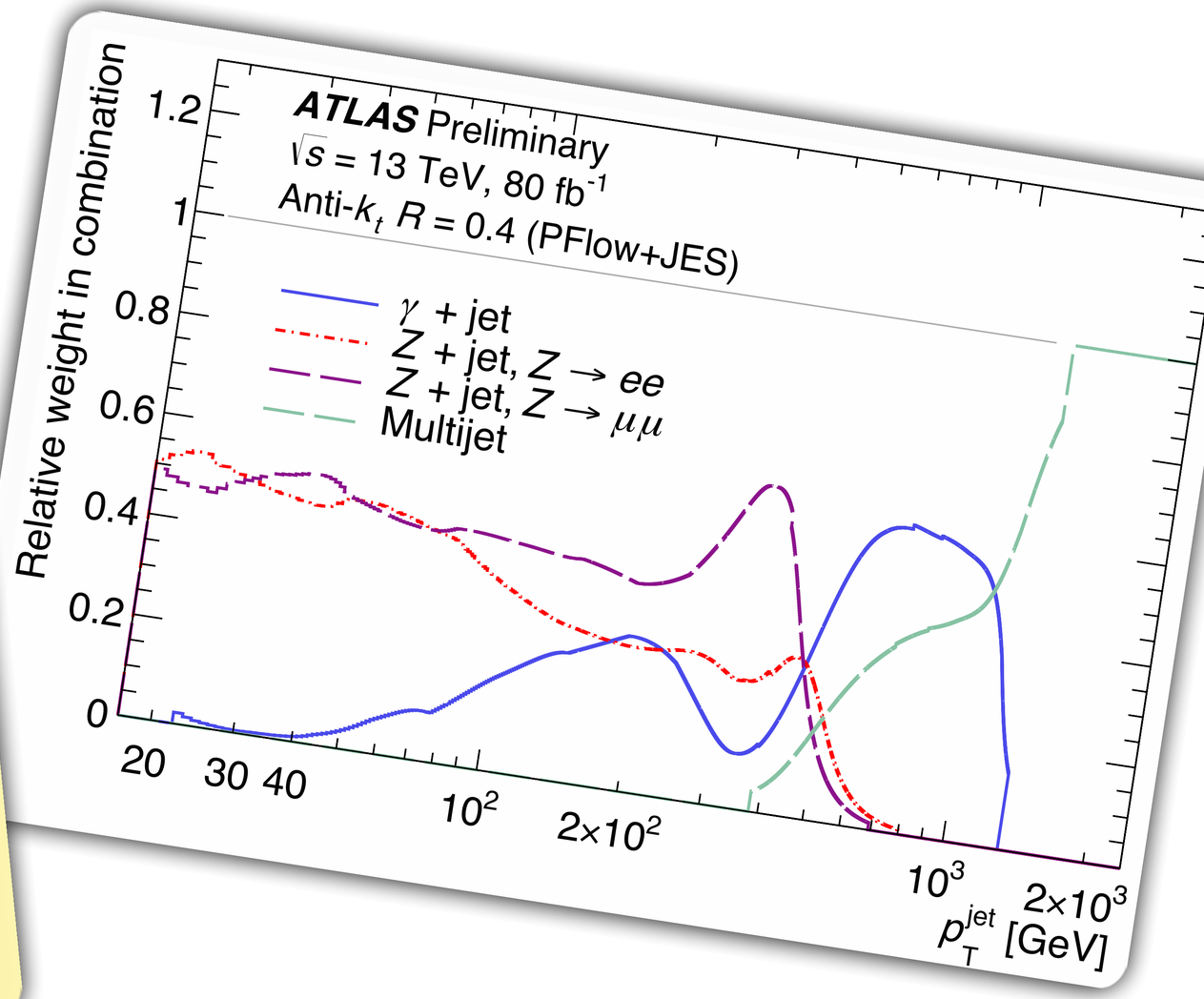

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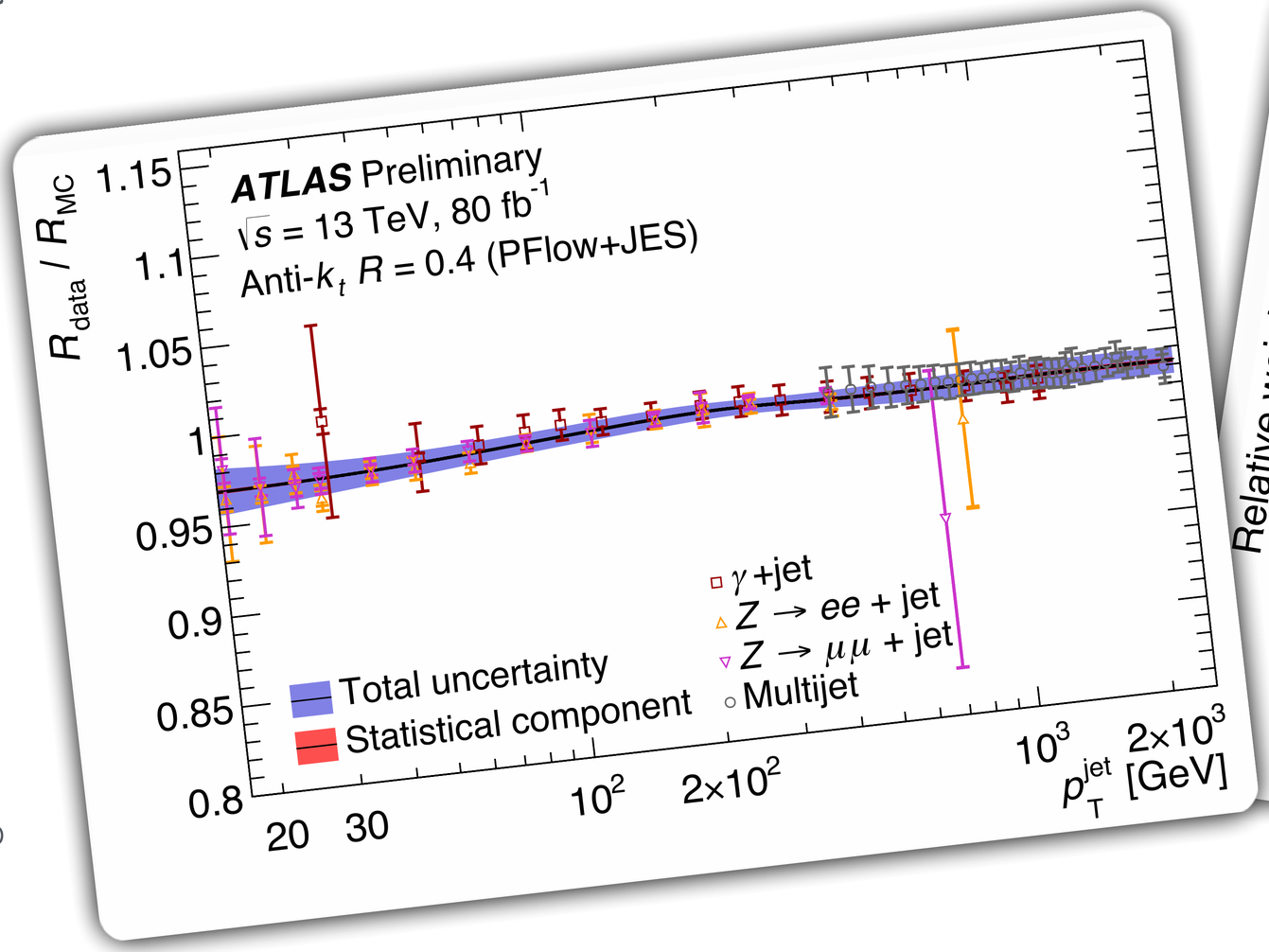
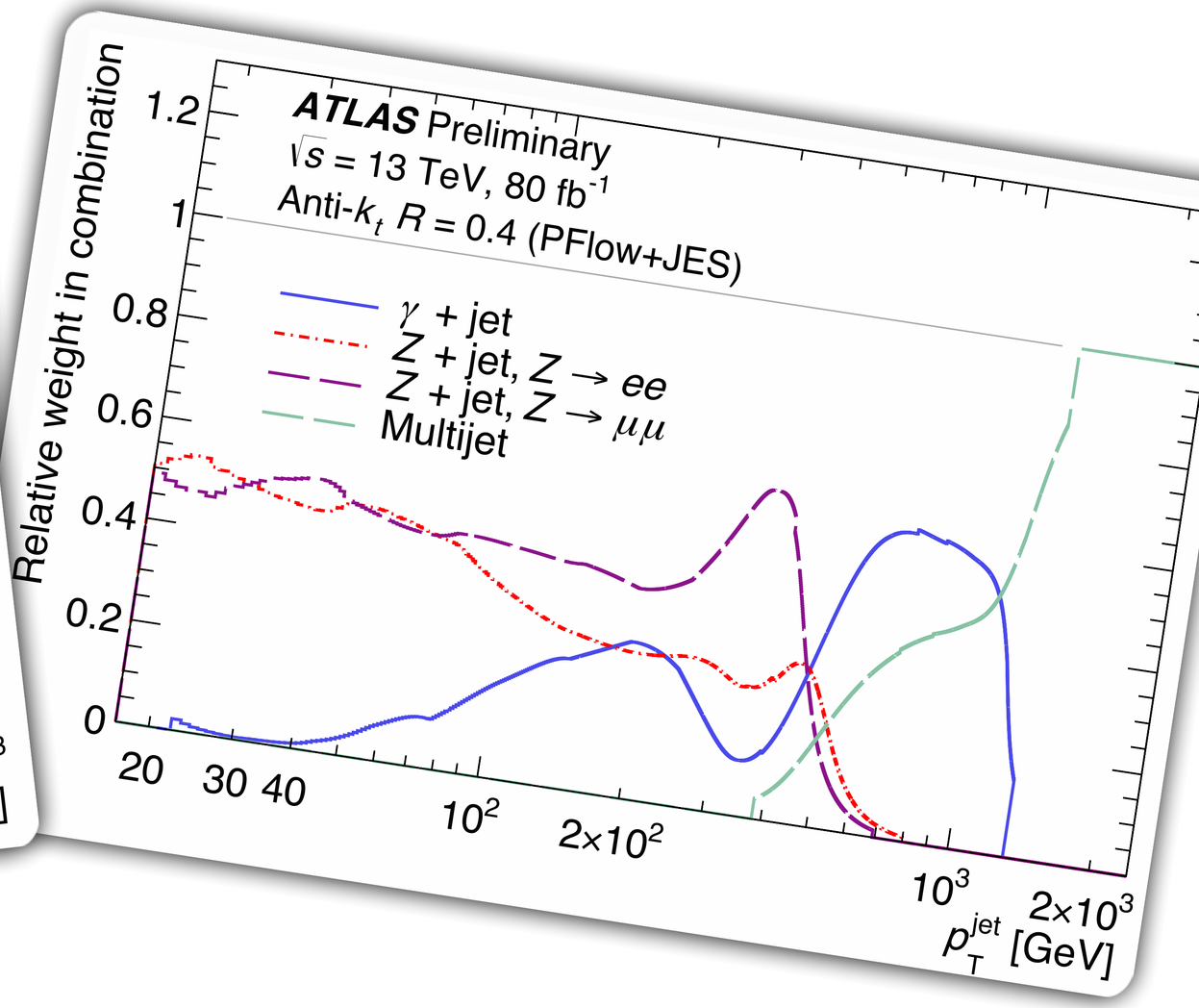
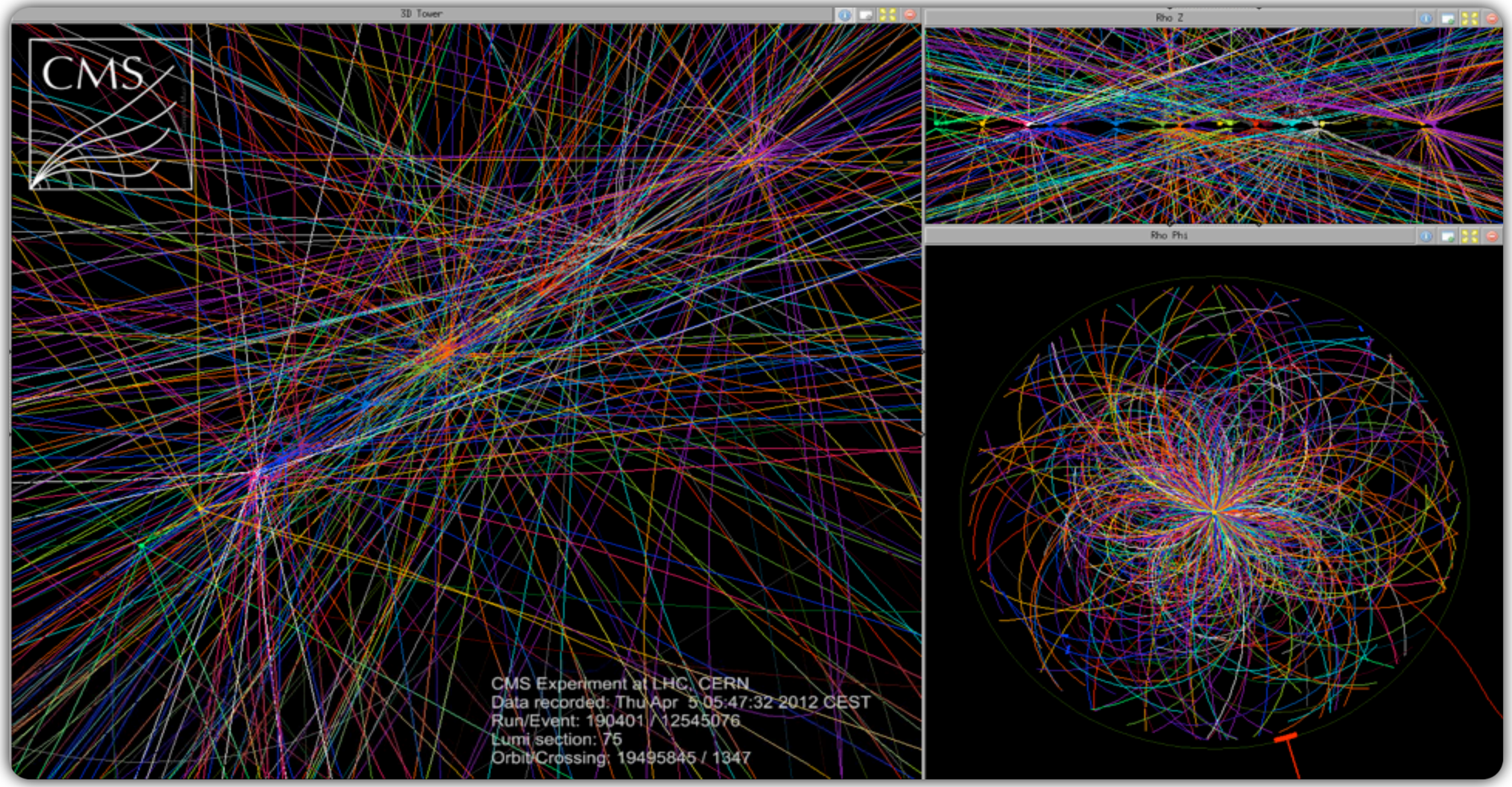




Step 0: Pileup Mitigation



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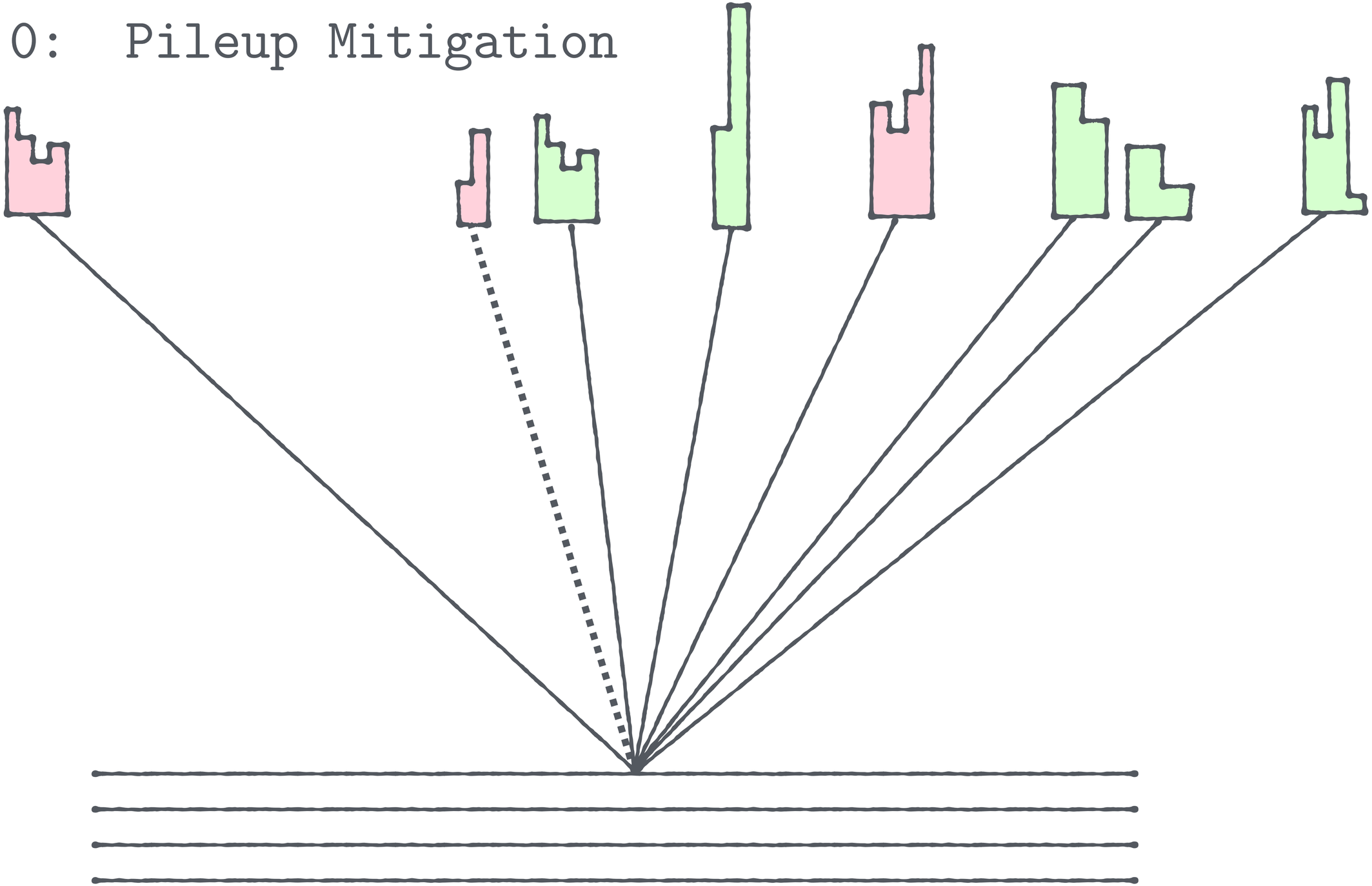

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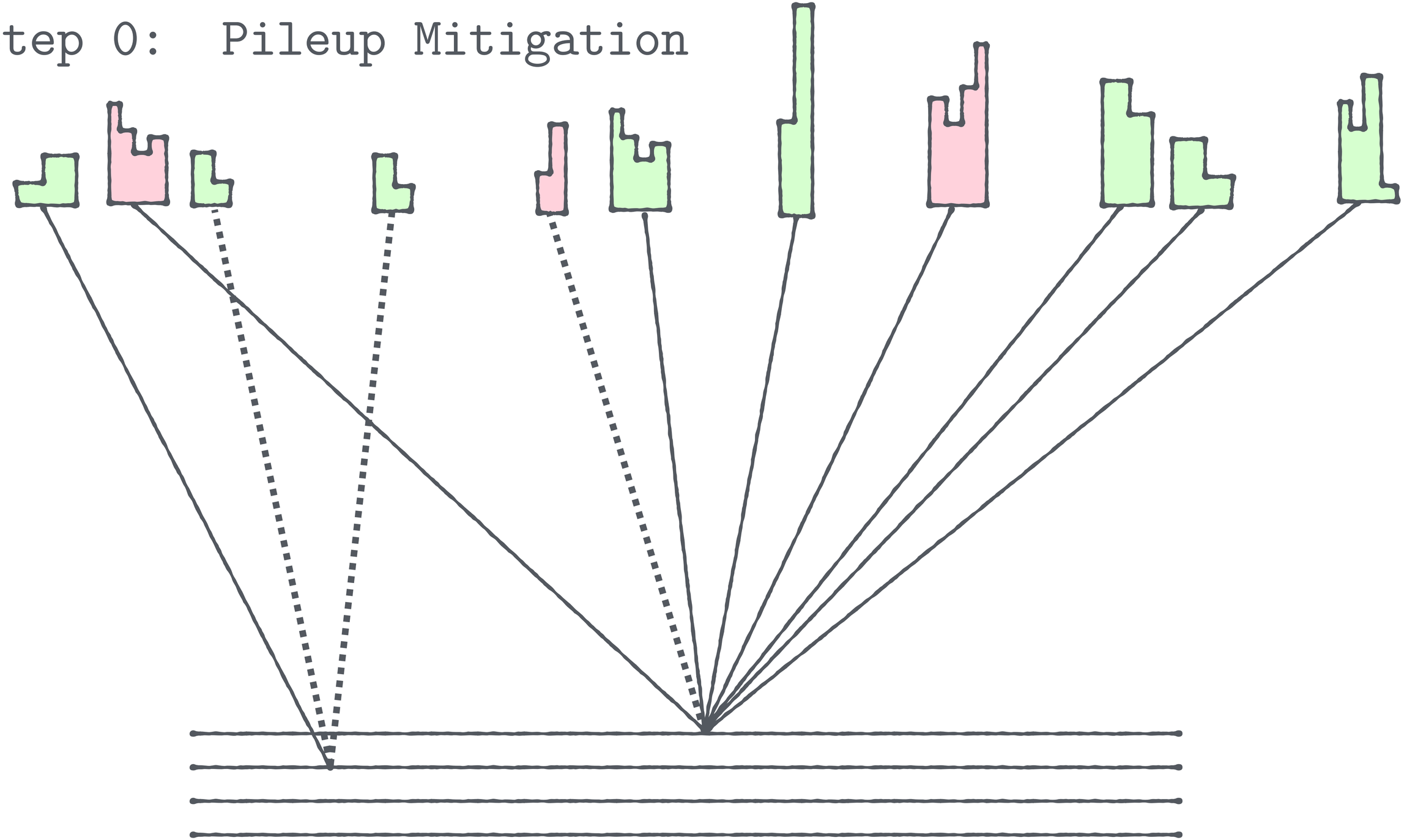

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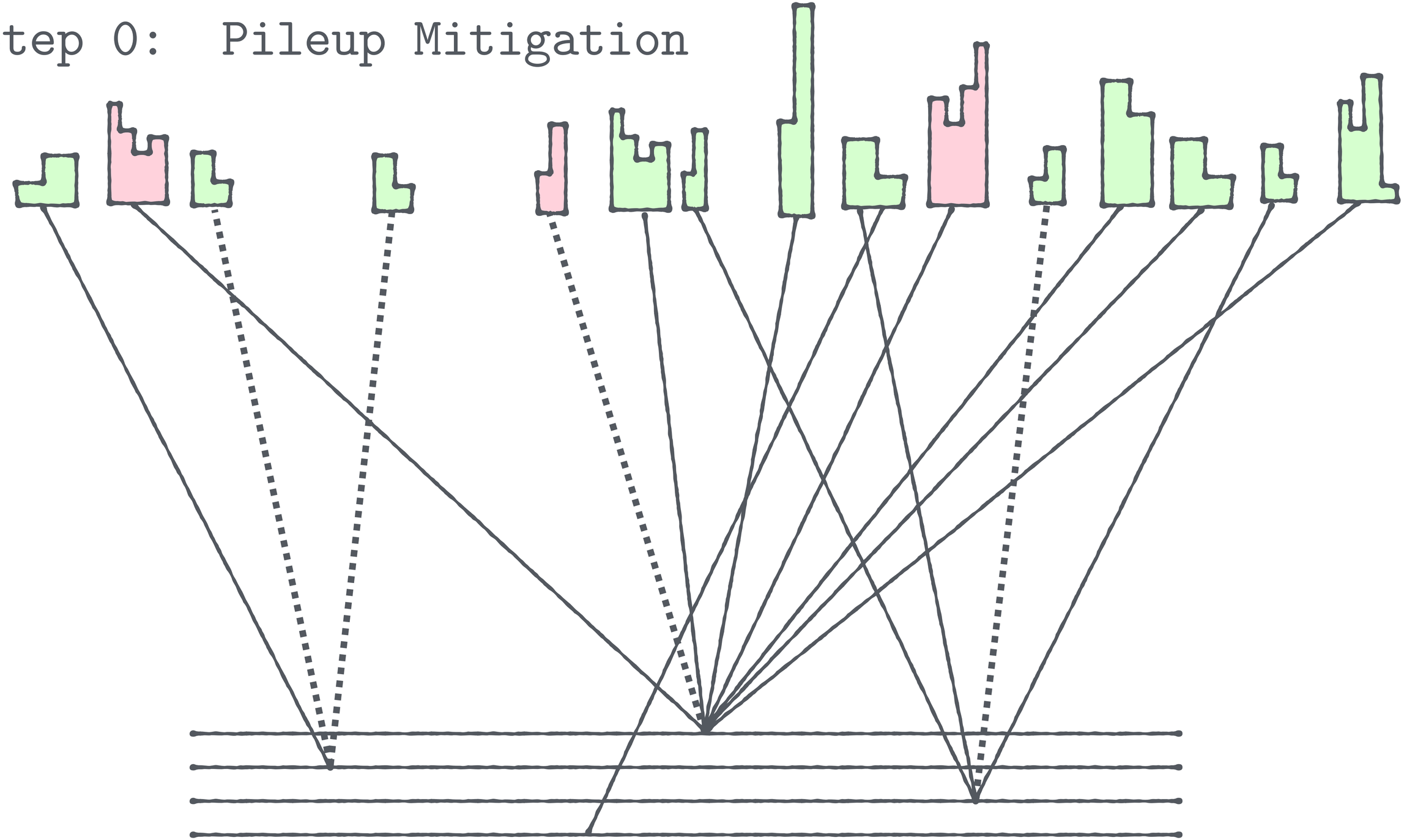

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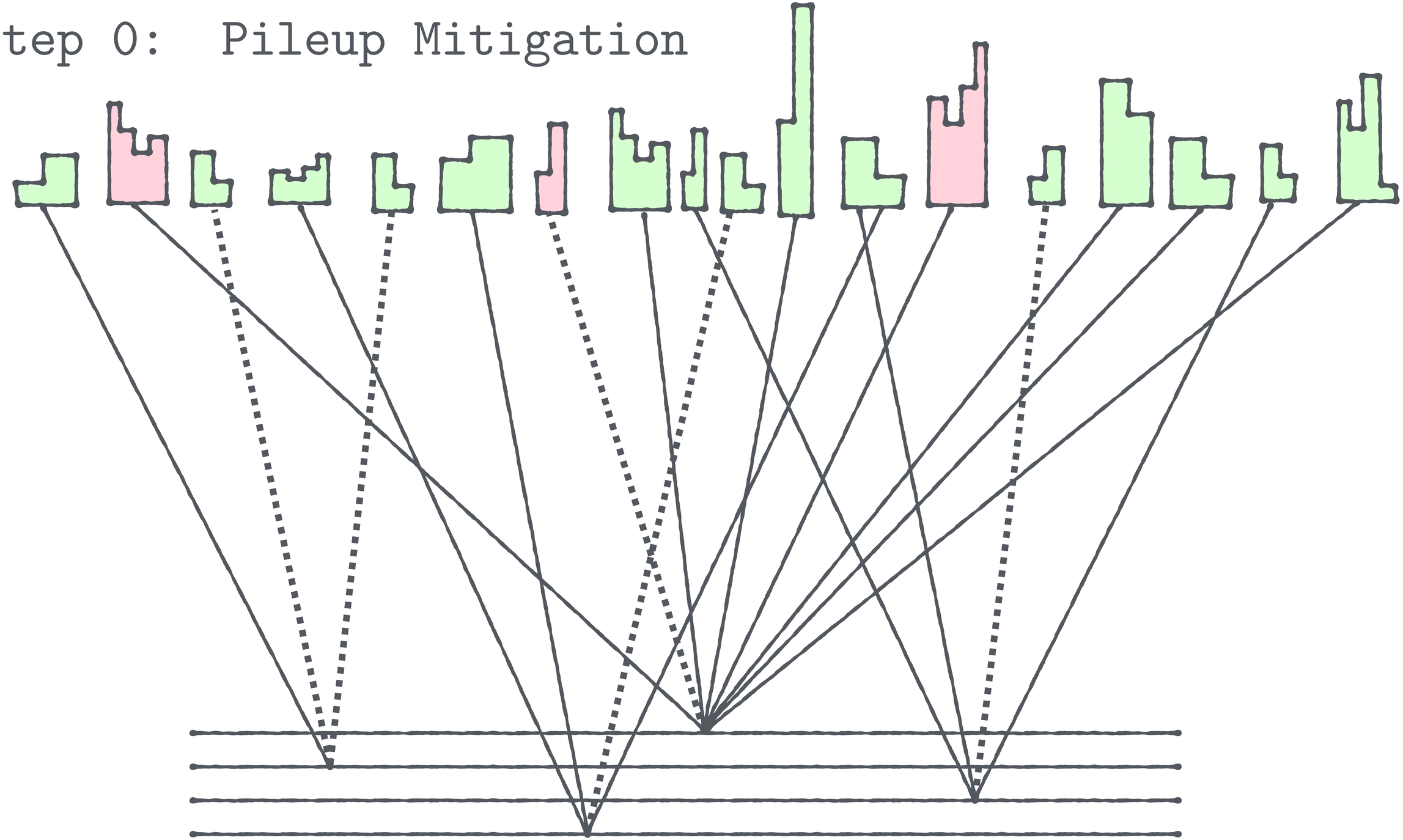

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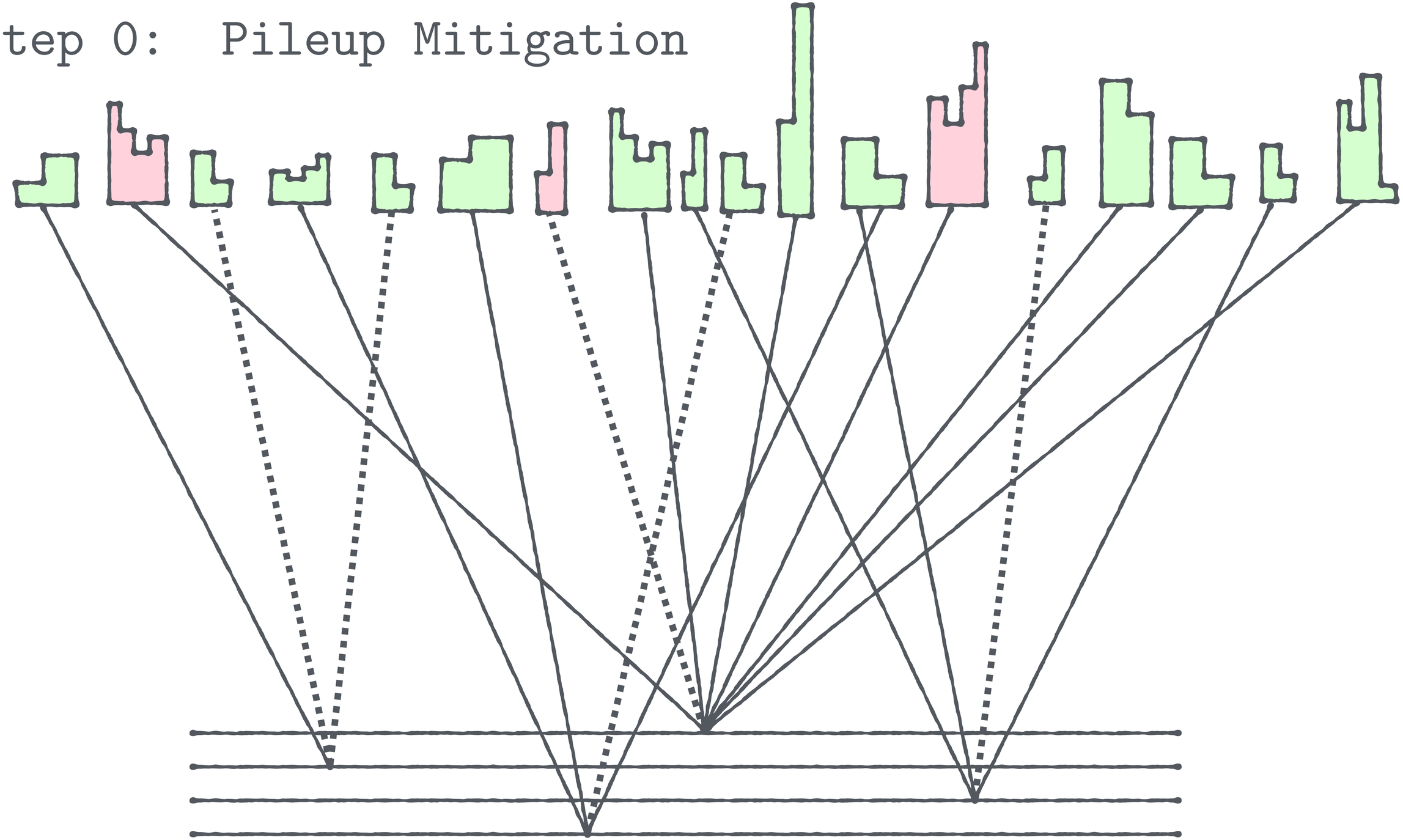

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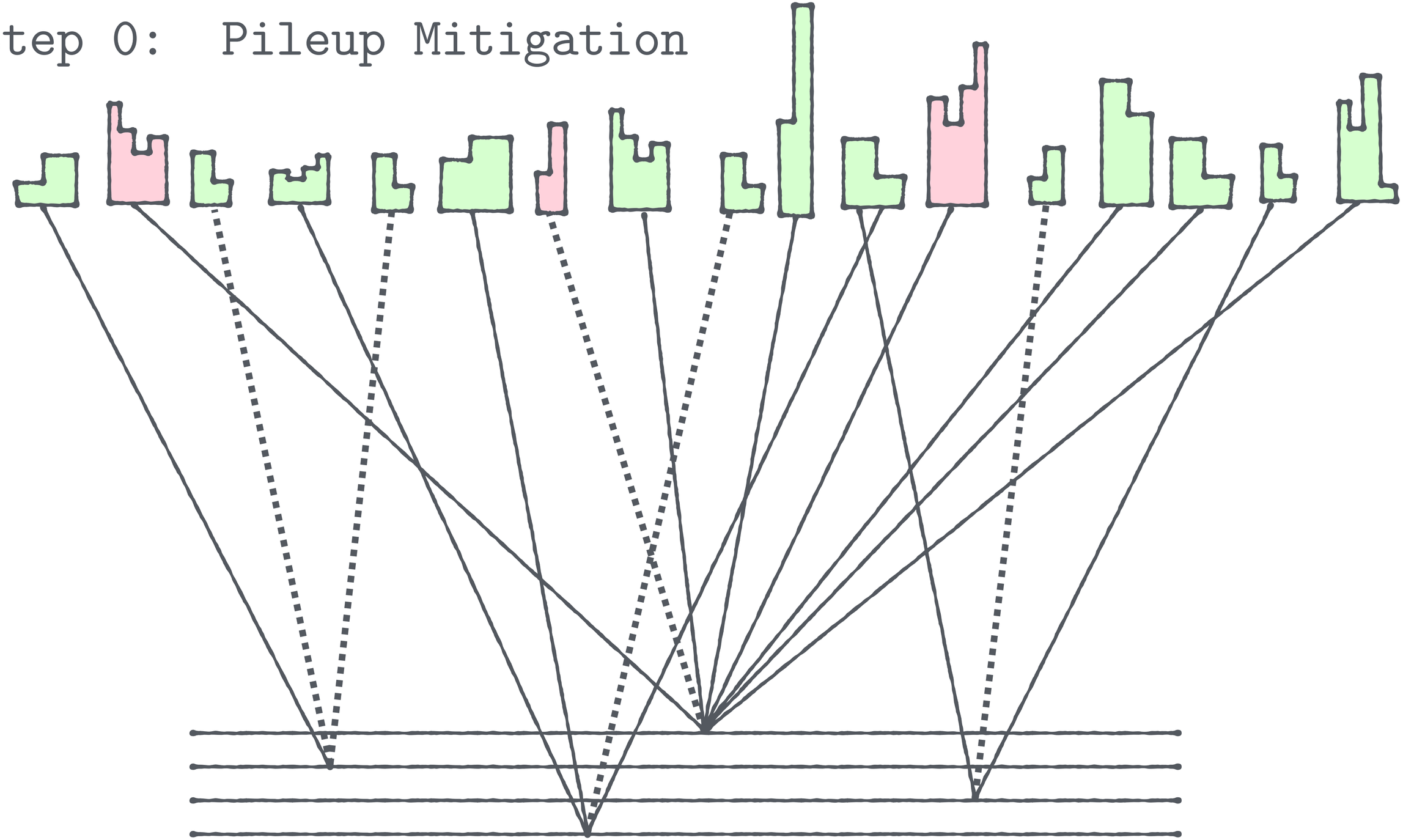

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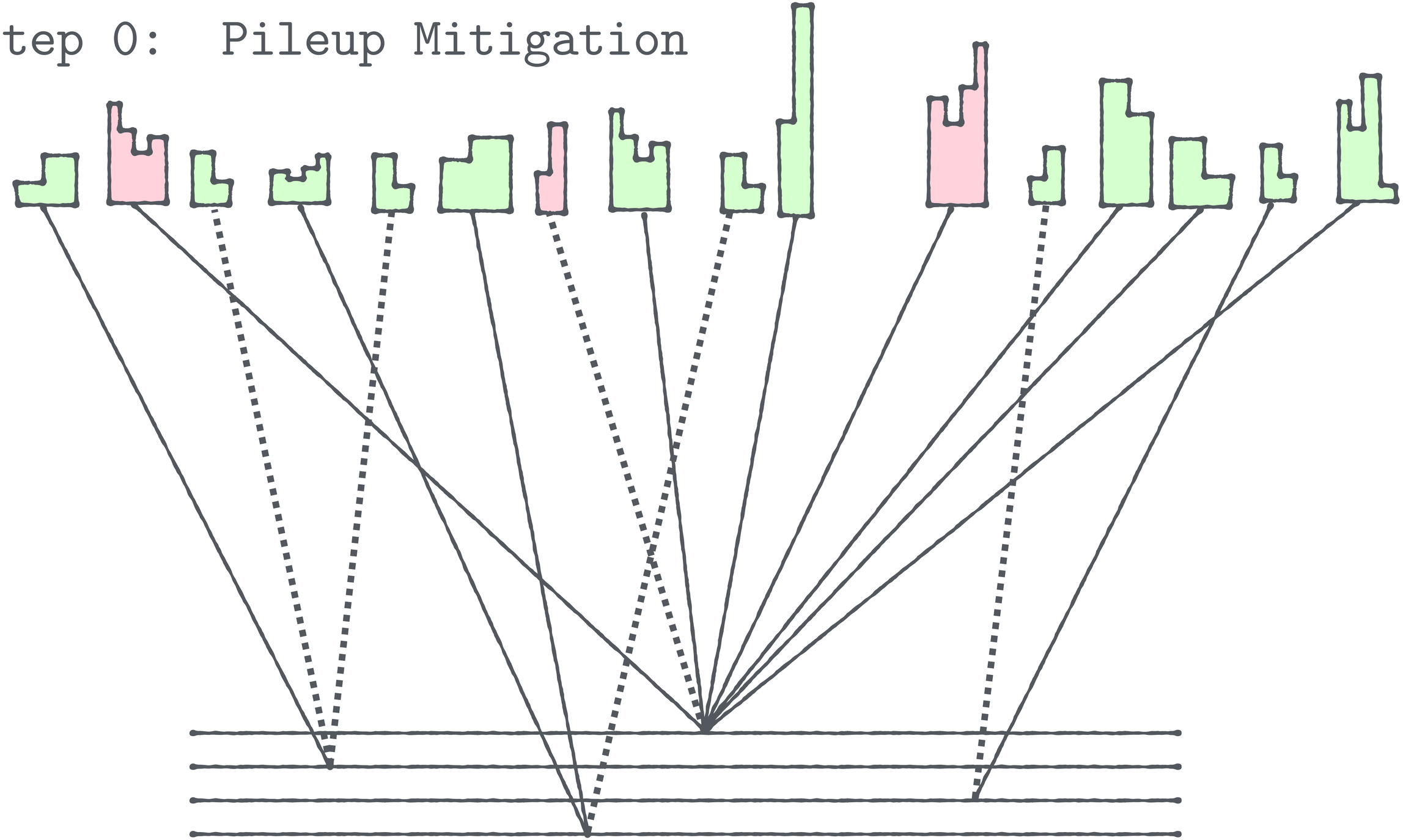

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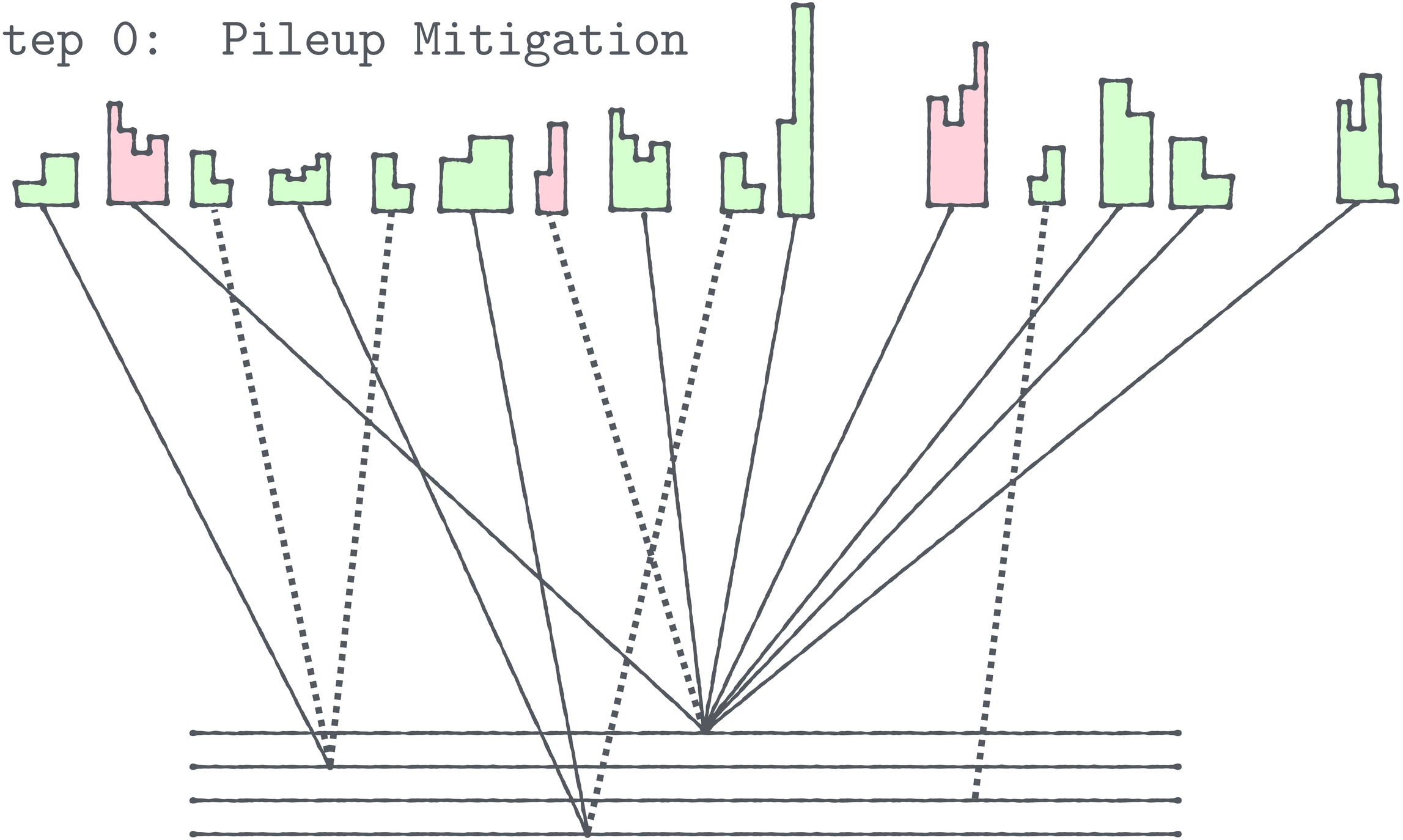

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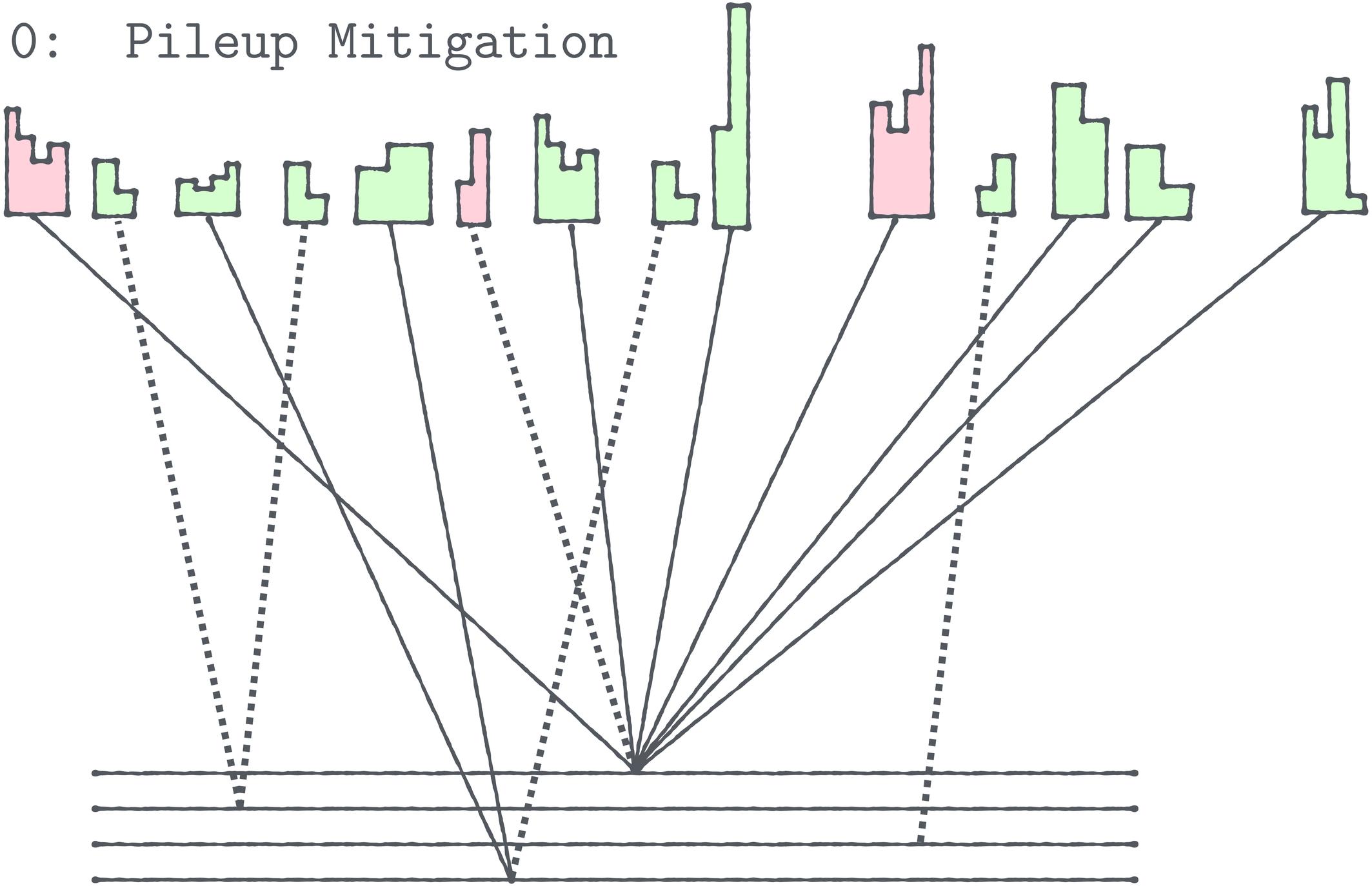

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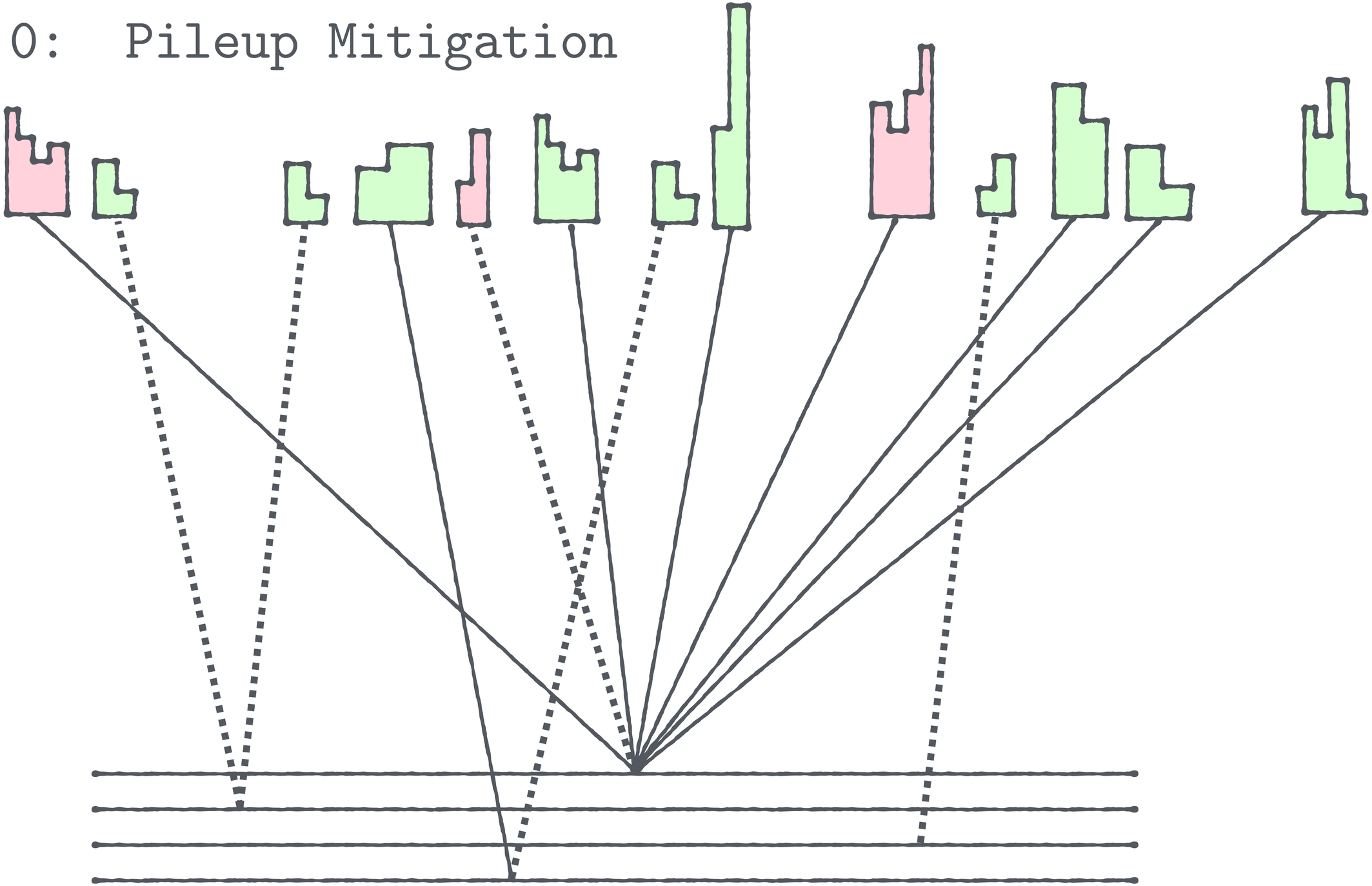

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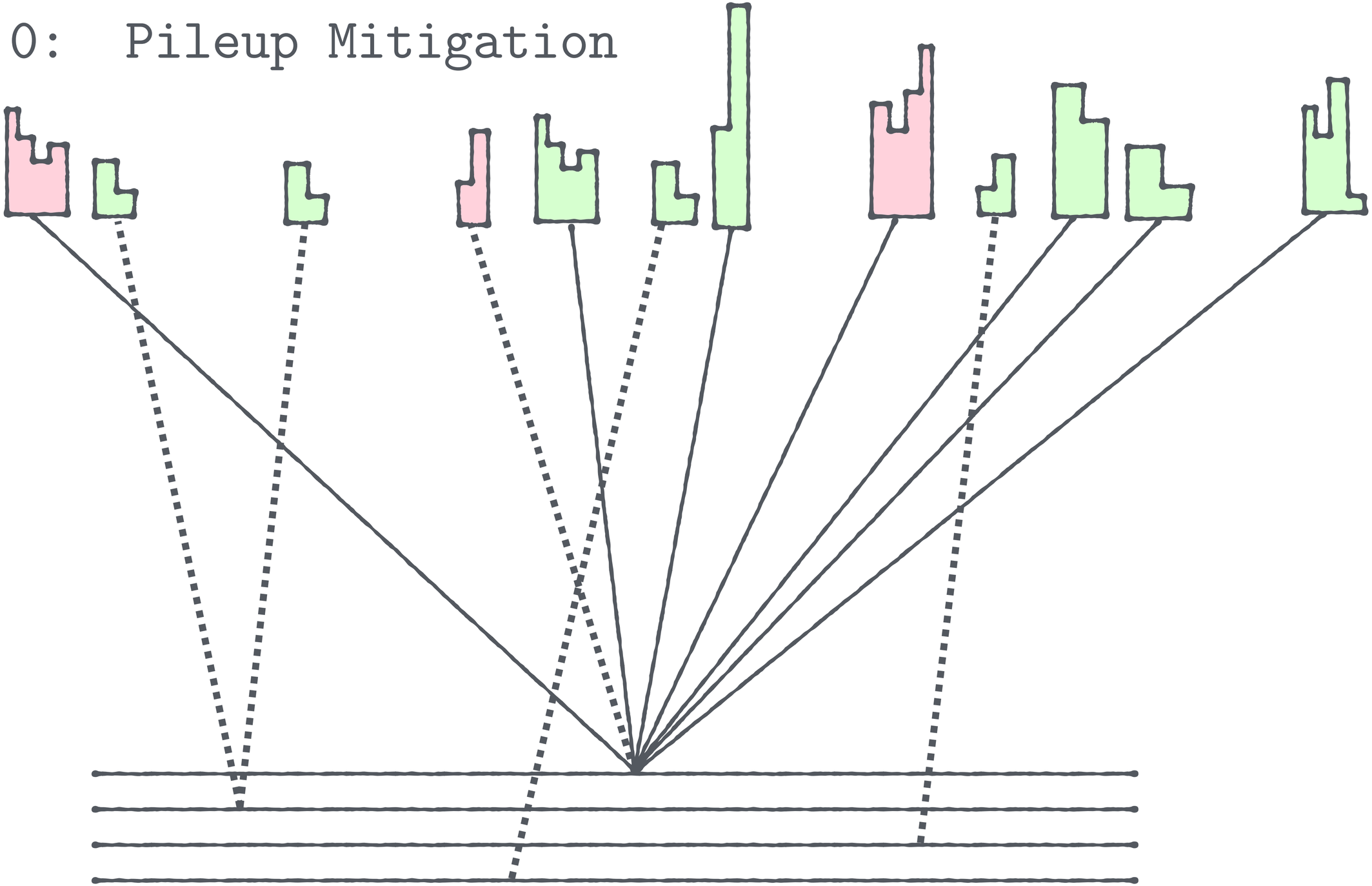

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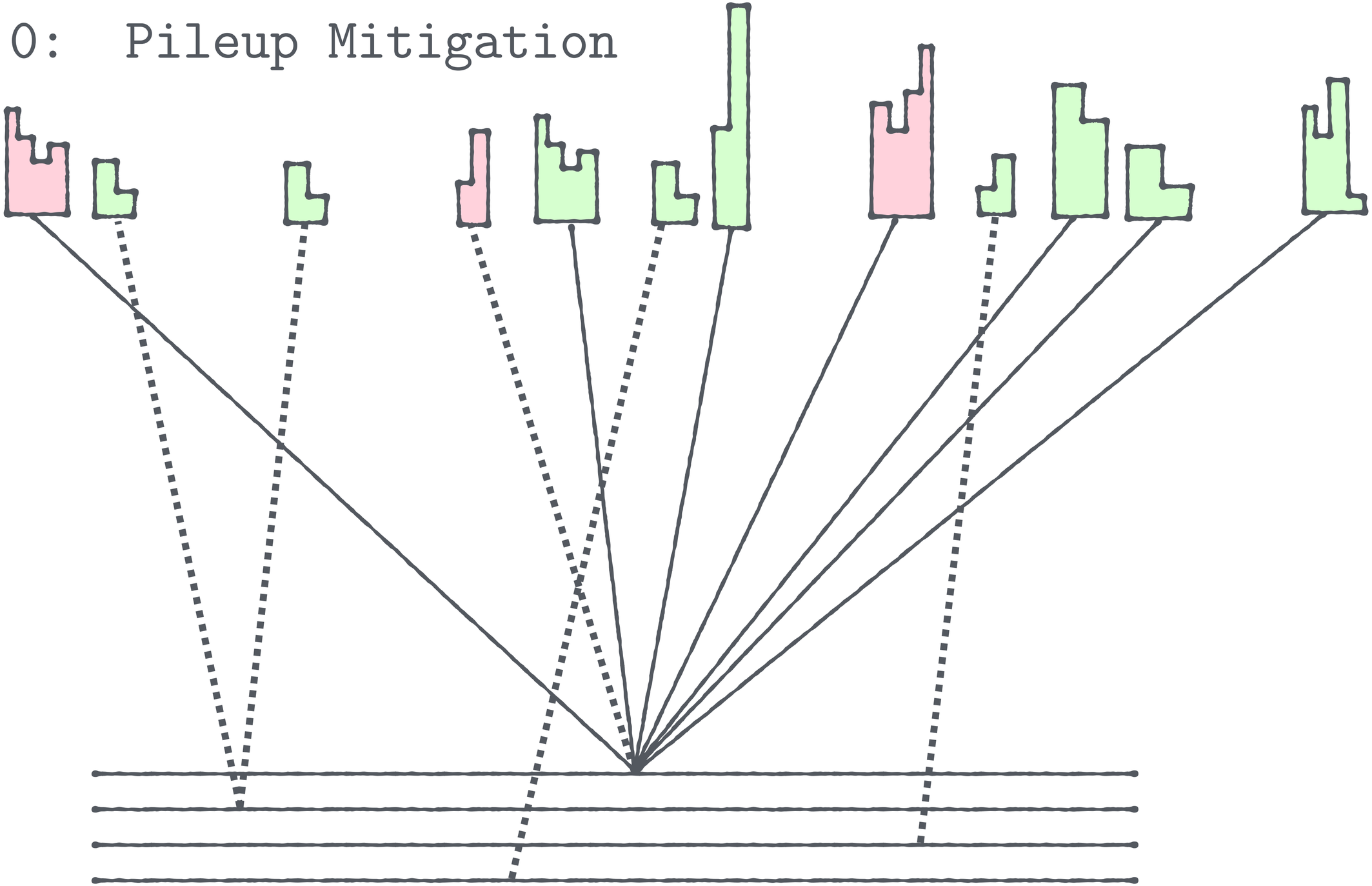

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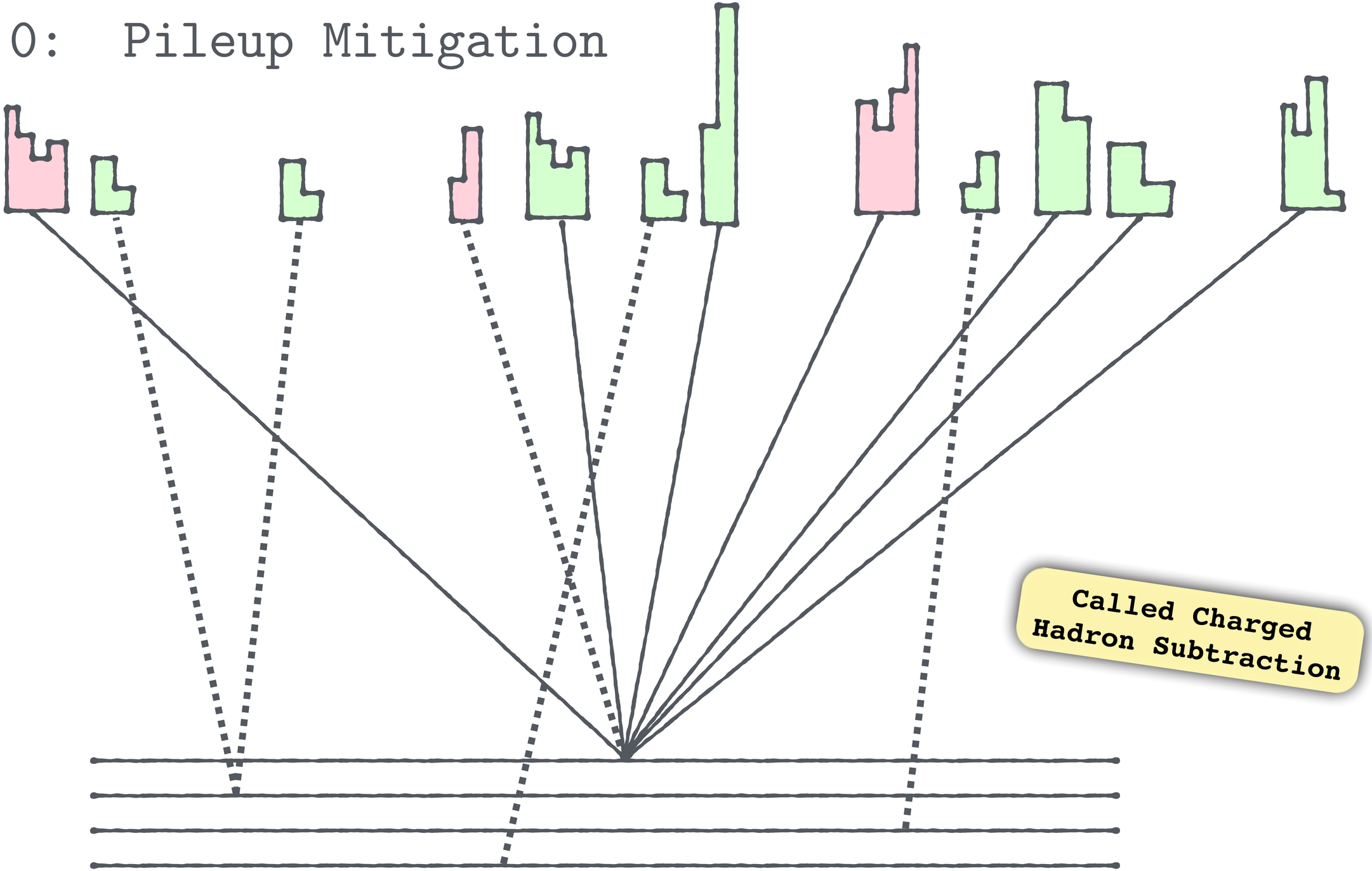

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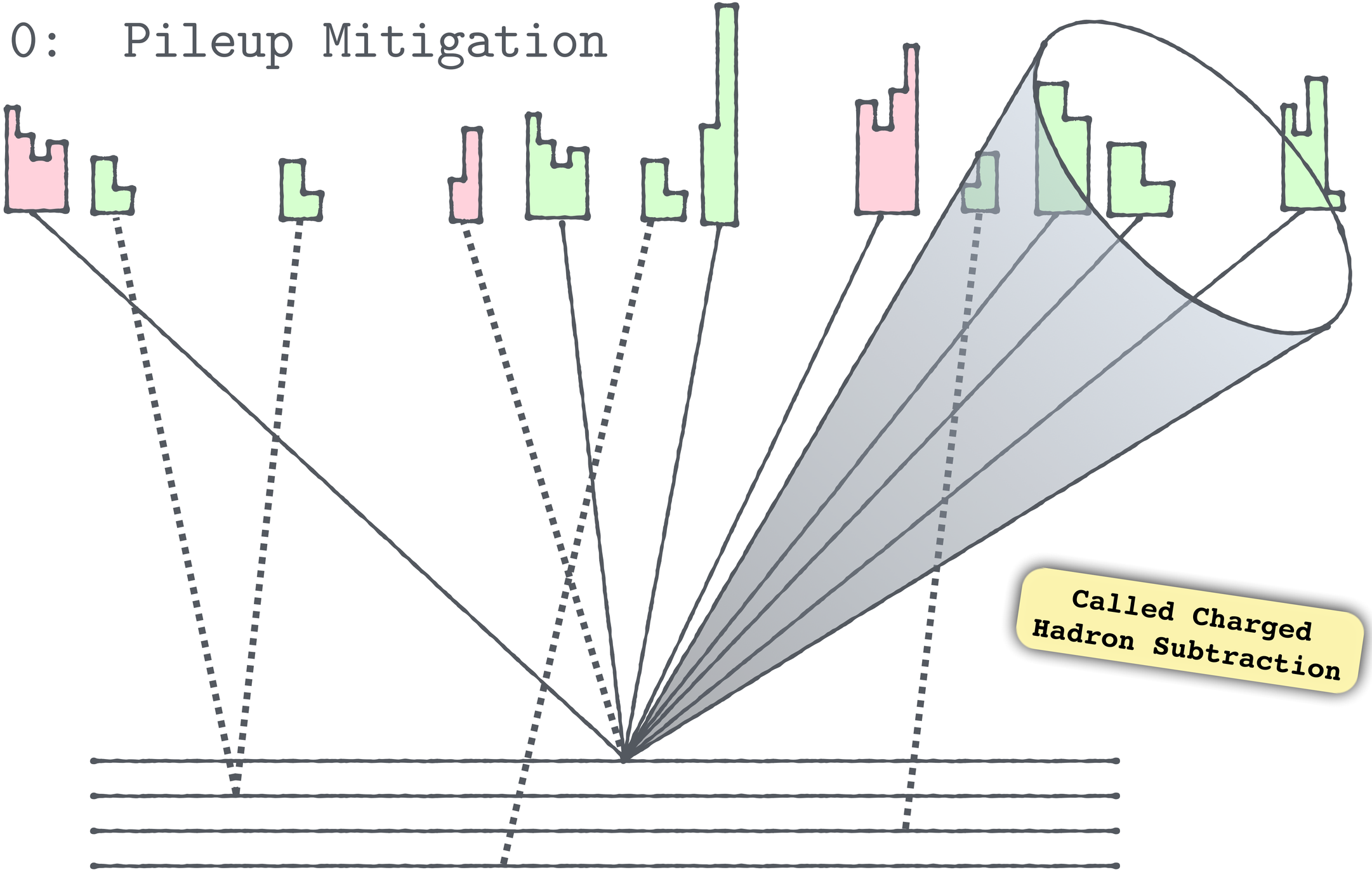

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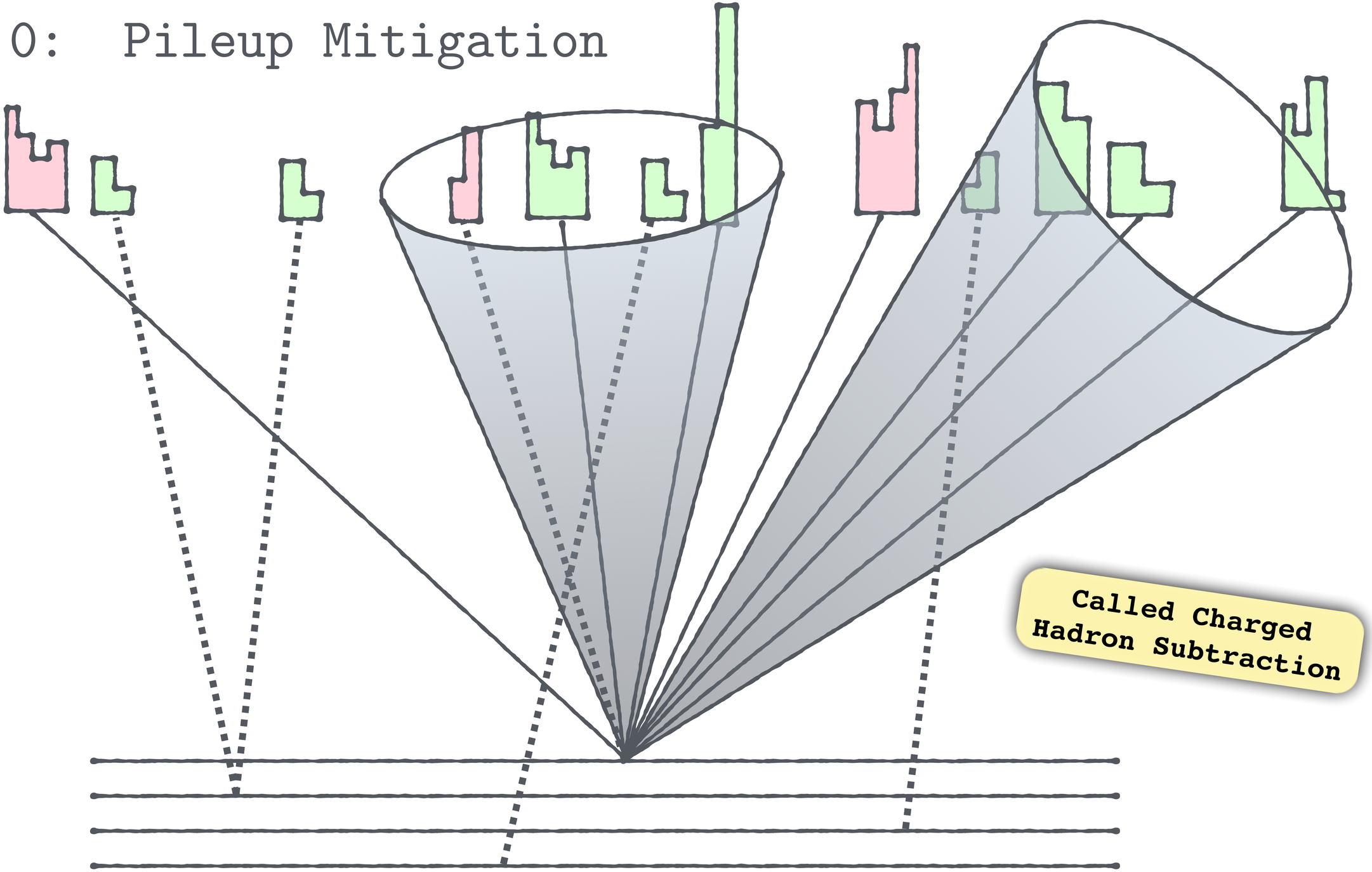

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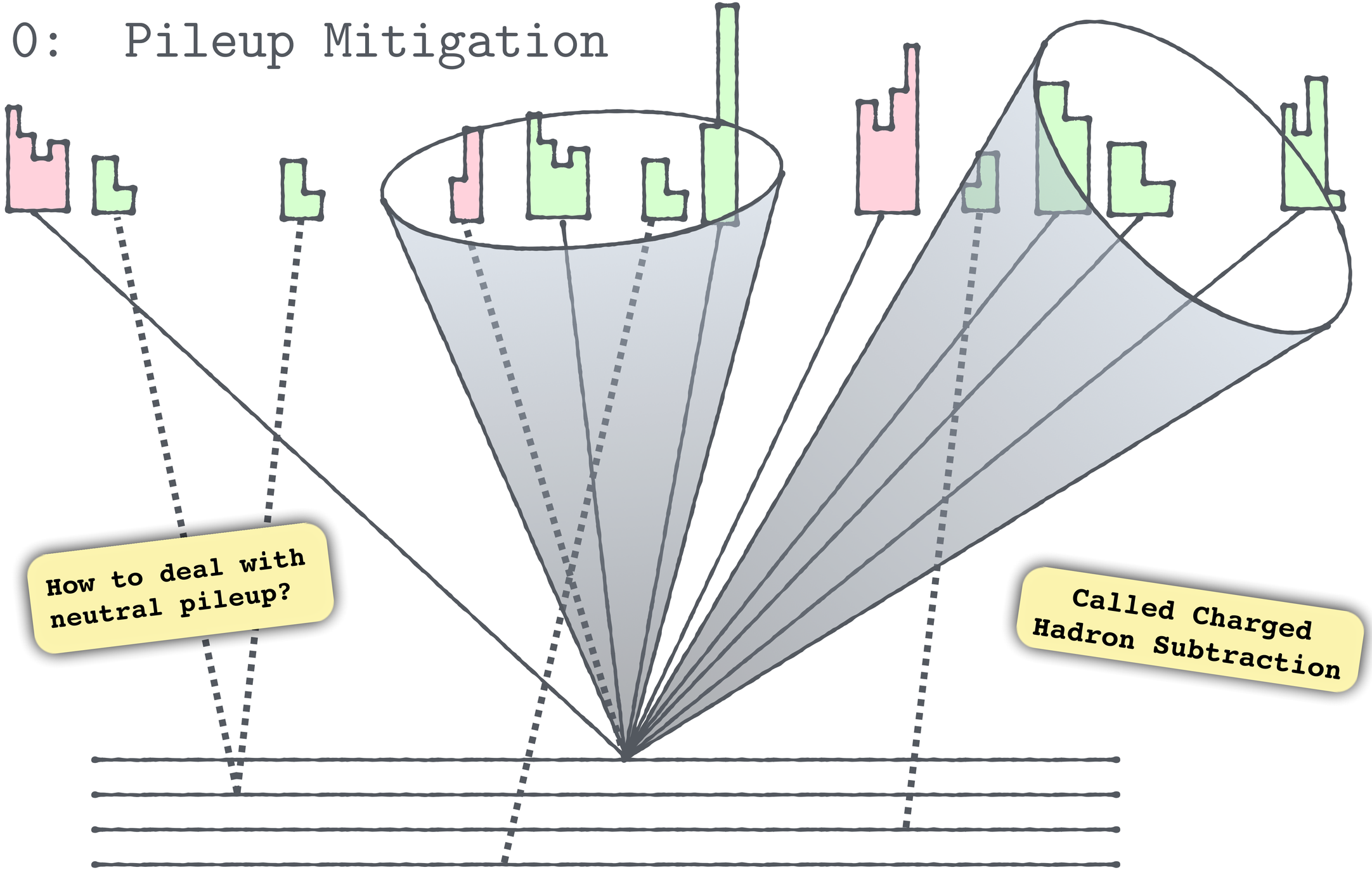

Pile Up Per Particle Identification

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

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

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

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

$$\alpha_i \equiv \sum_j \frac{p_{\mathrm{T},i}}{\Delta R_{ij}} \Theta(R_{\mathrm{min}} < \Delta R_{ij} < R_0)$$

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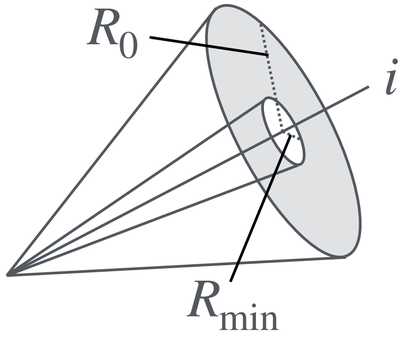

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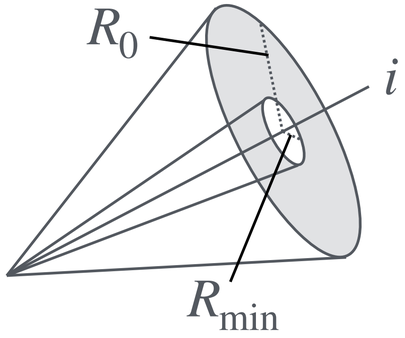

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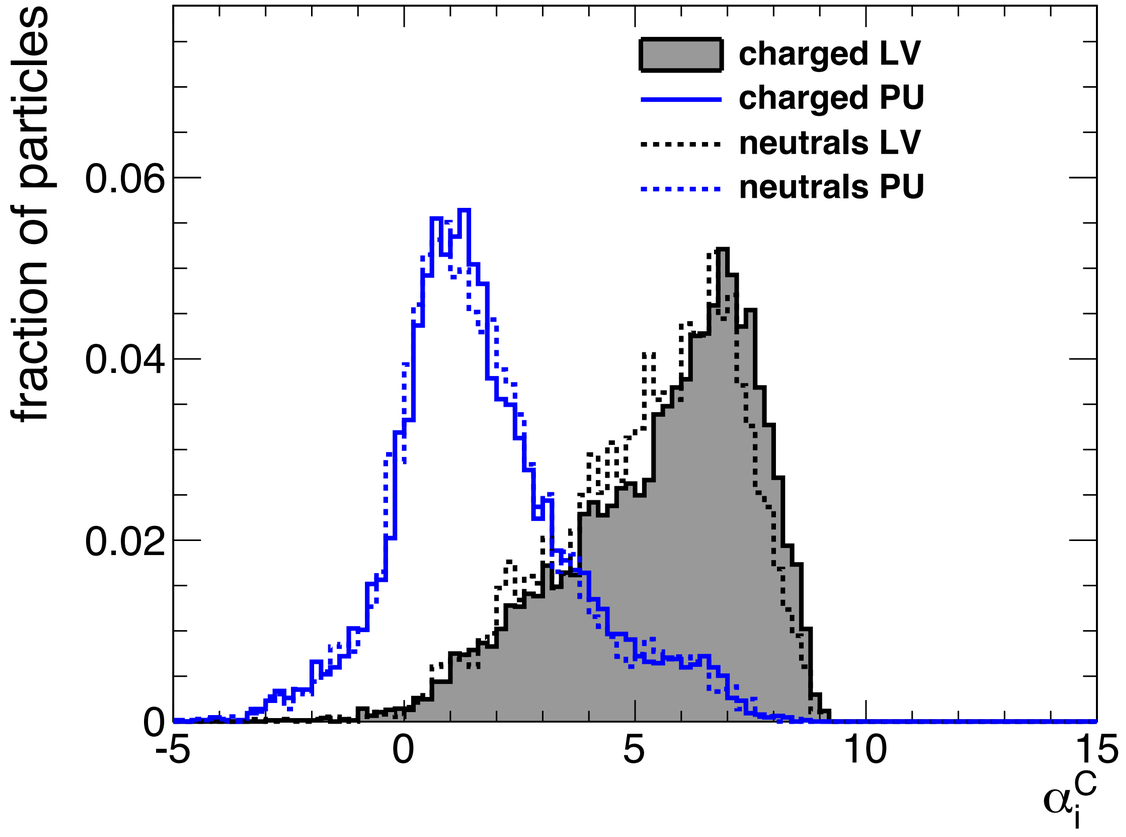

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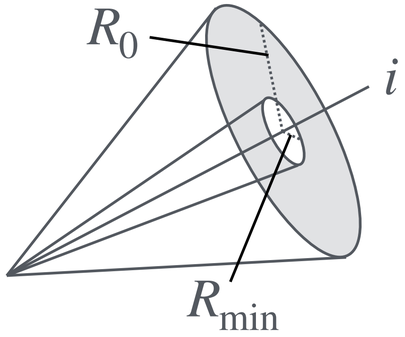

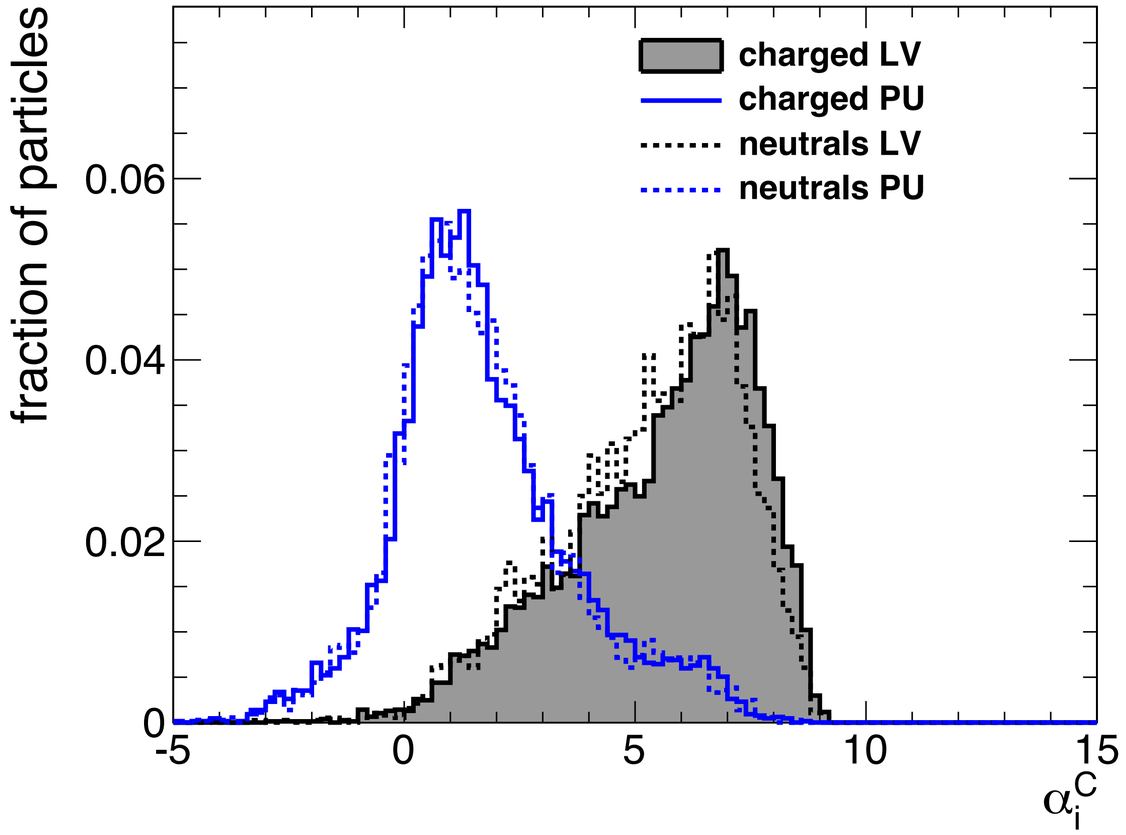

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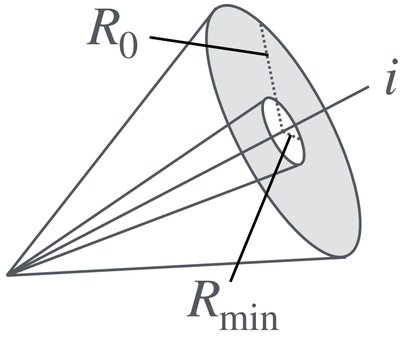

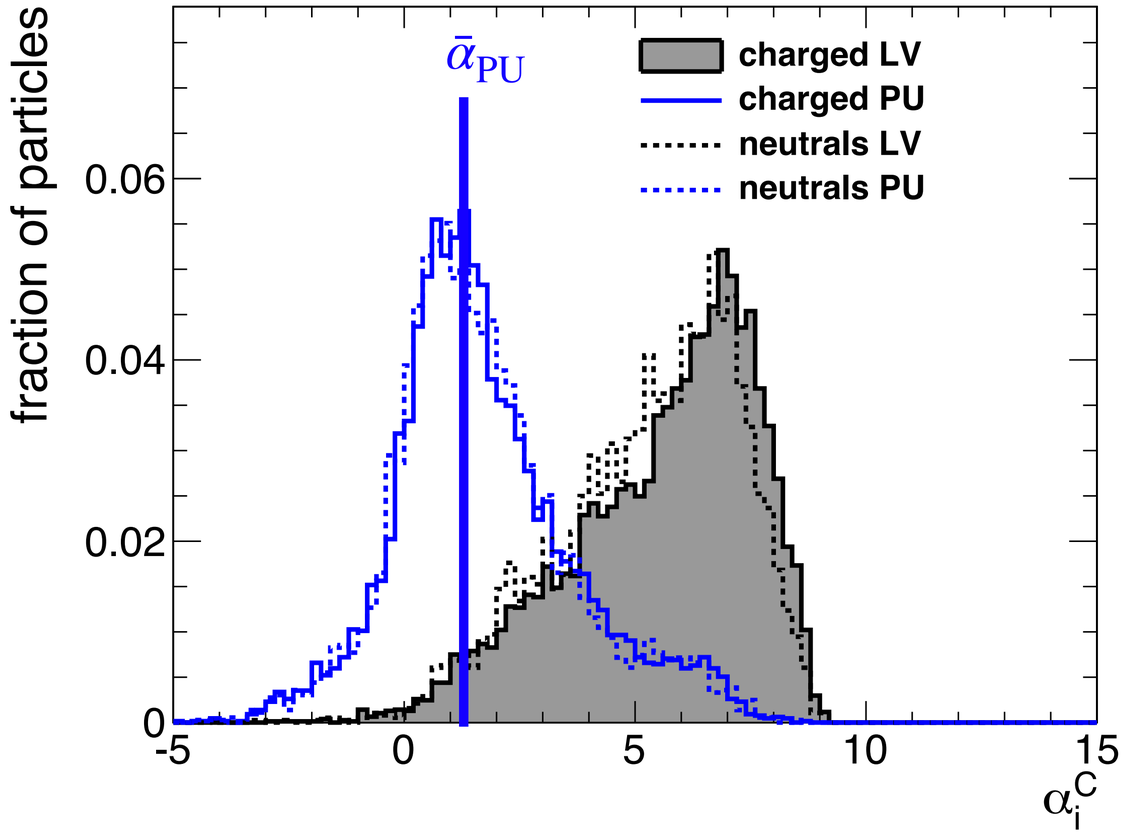

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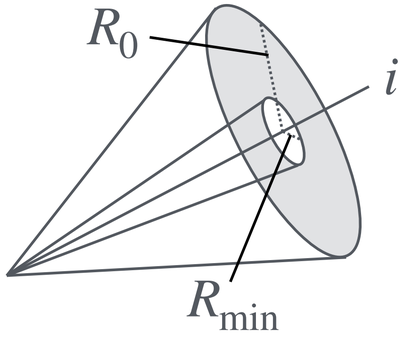

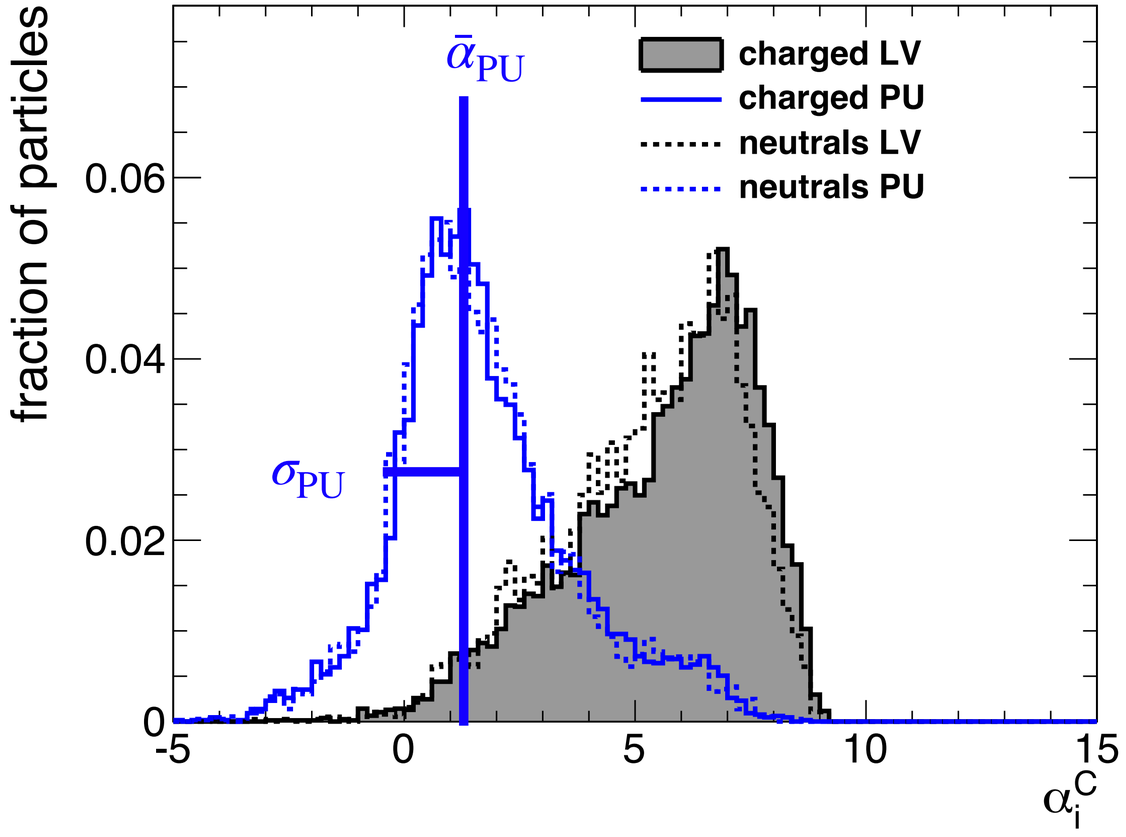

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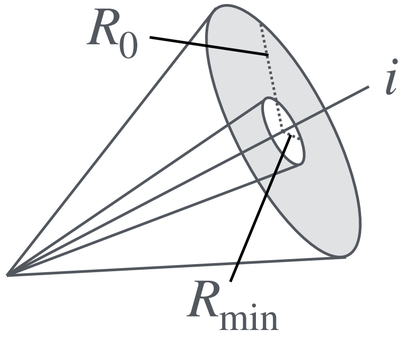
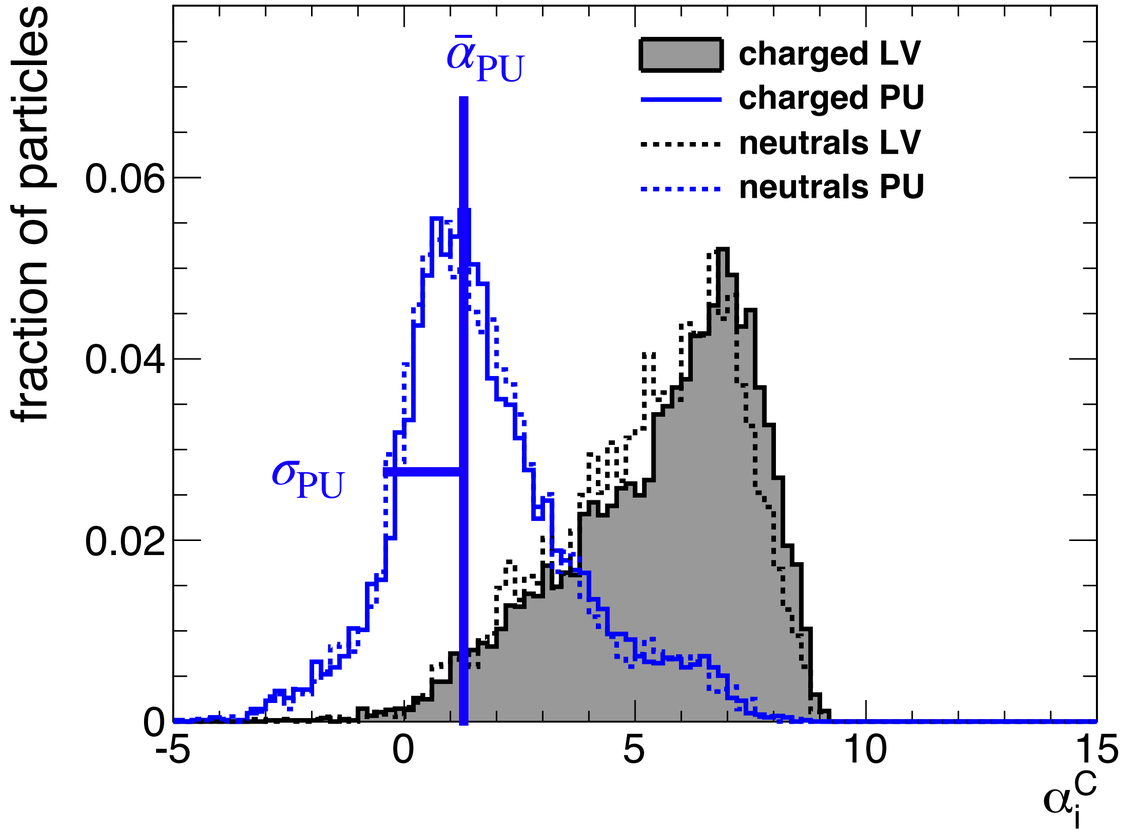


Now form a test statistic

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

and assign a weight as

$$w_i \equiv F_{\chi^2,\mathrm{NDF}=1}(\chi_i^2)$$



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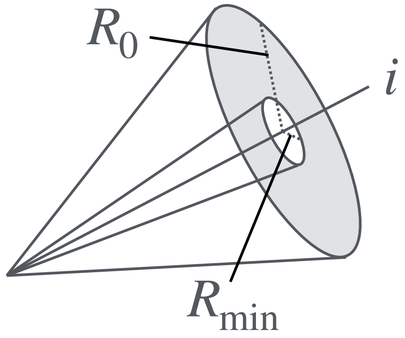

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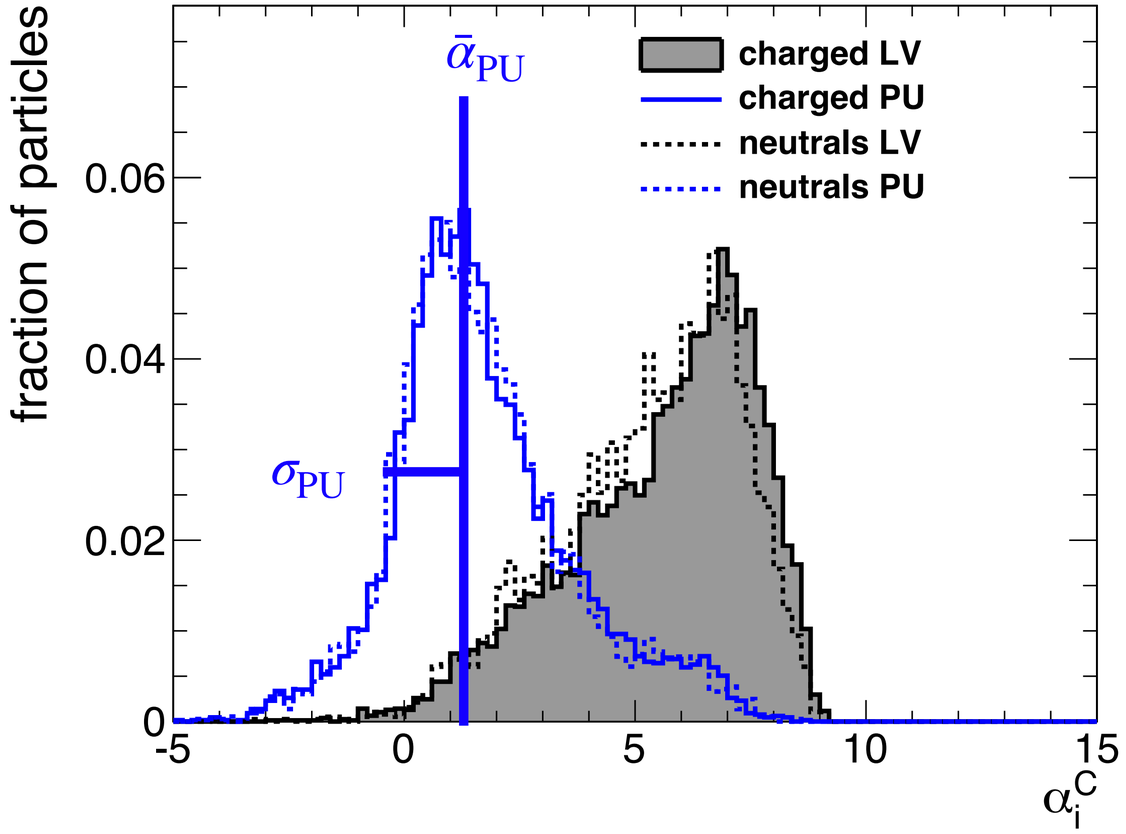

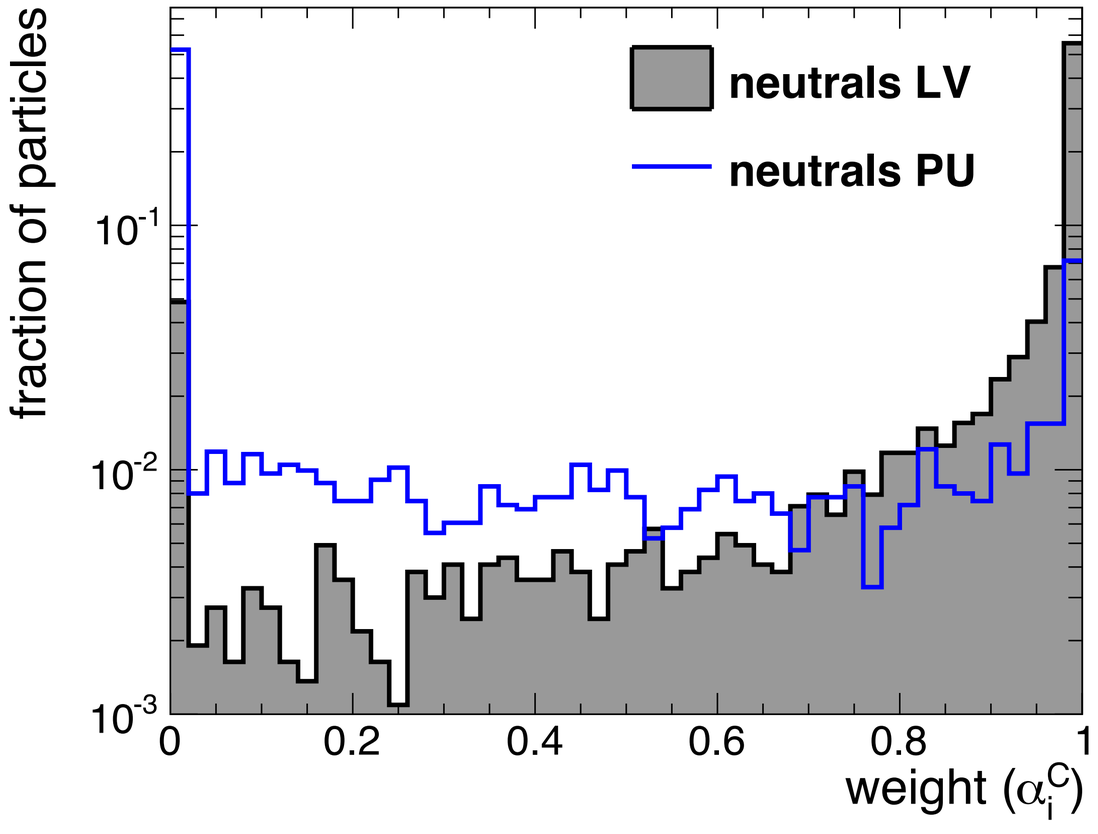

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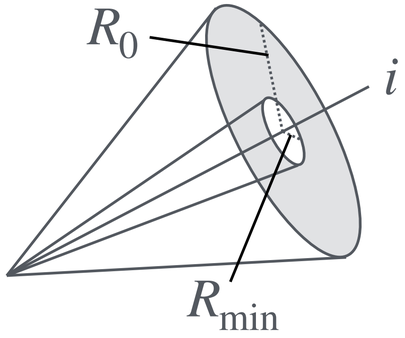

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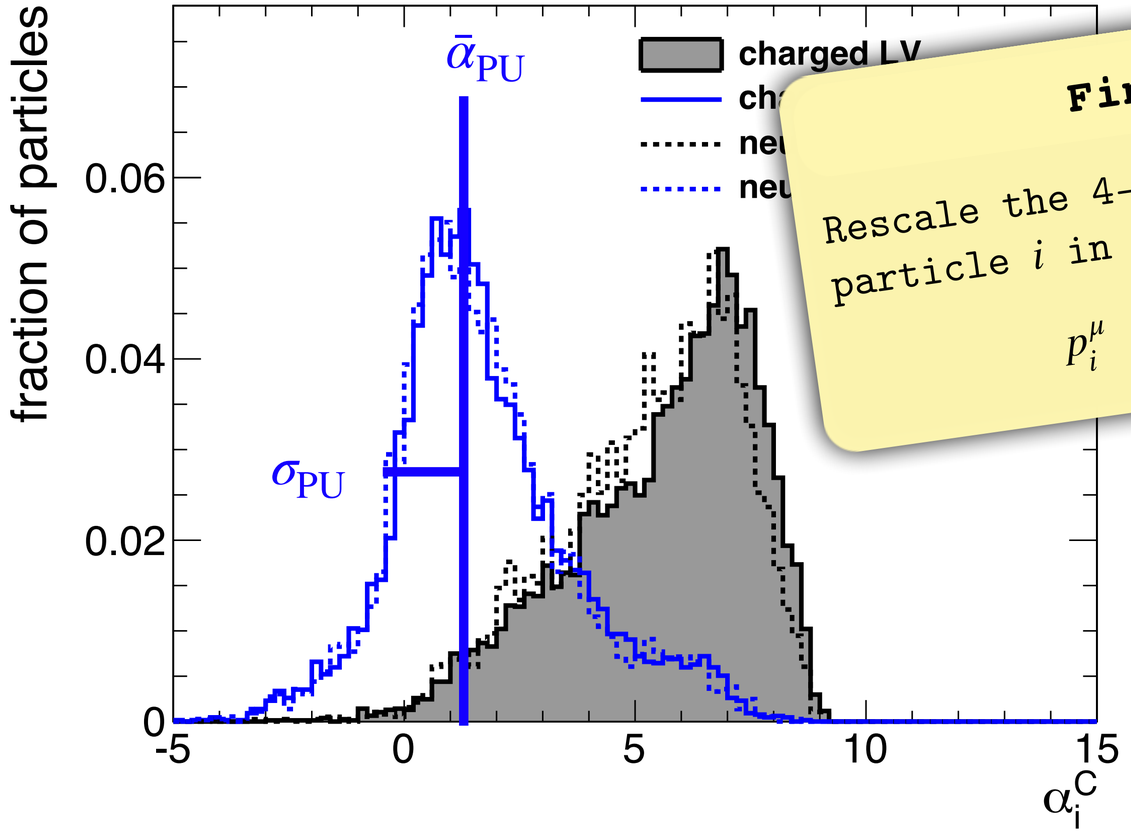
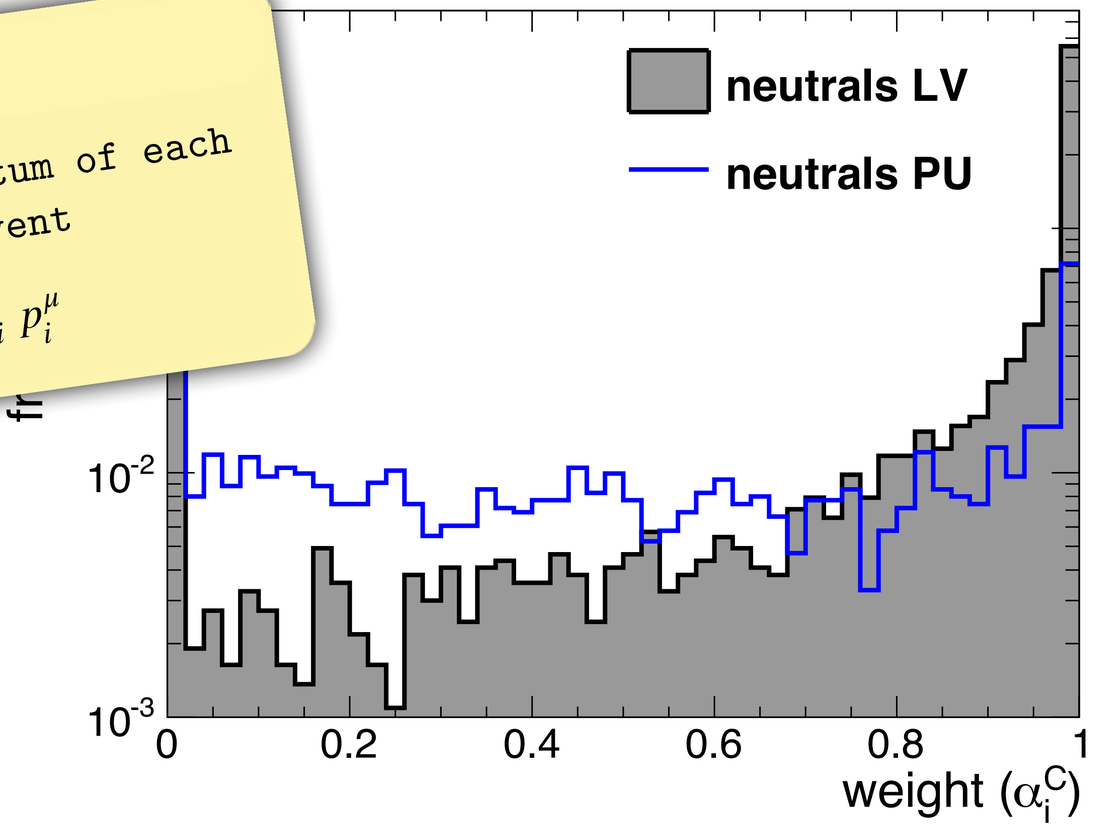
Finally

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

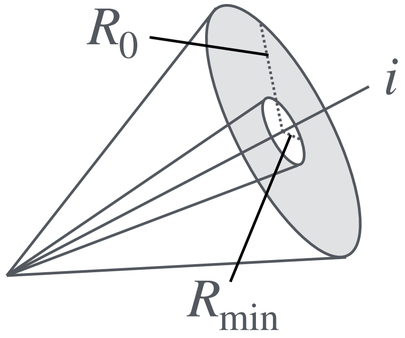
$$p^\mu_i \rightarrow w_i \, p^\mu_i$$





Form a shape variable

$$\alpha_i \equiv \sum_j \frac{p_{\mathrm{T},i}}{\Delta R_{ij}} \Theta(R_{\mathrm{min}} < \Delta R_{ij} < R_0)$$

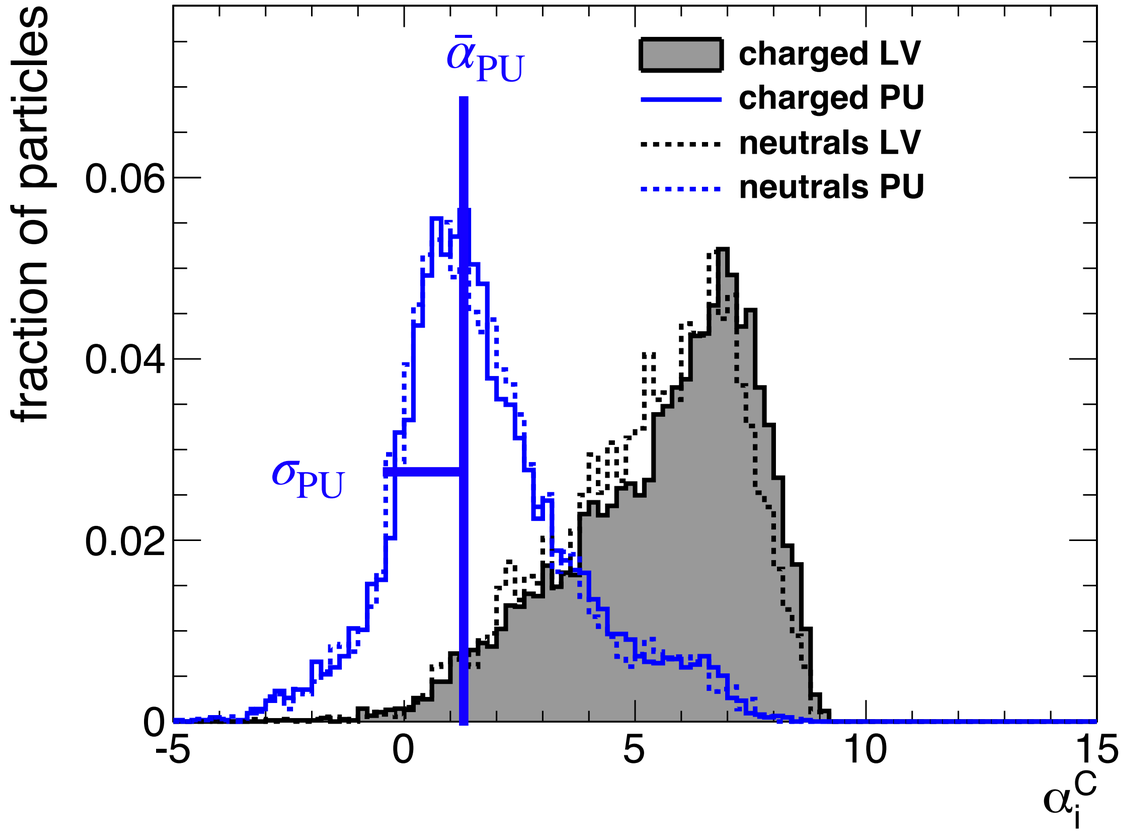


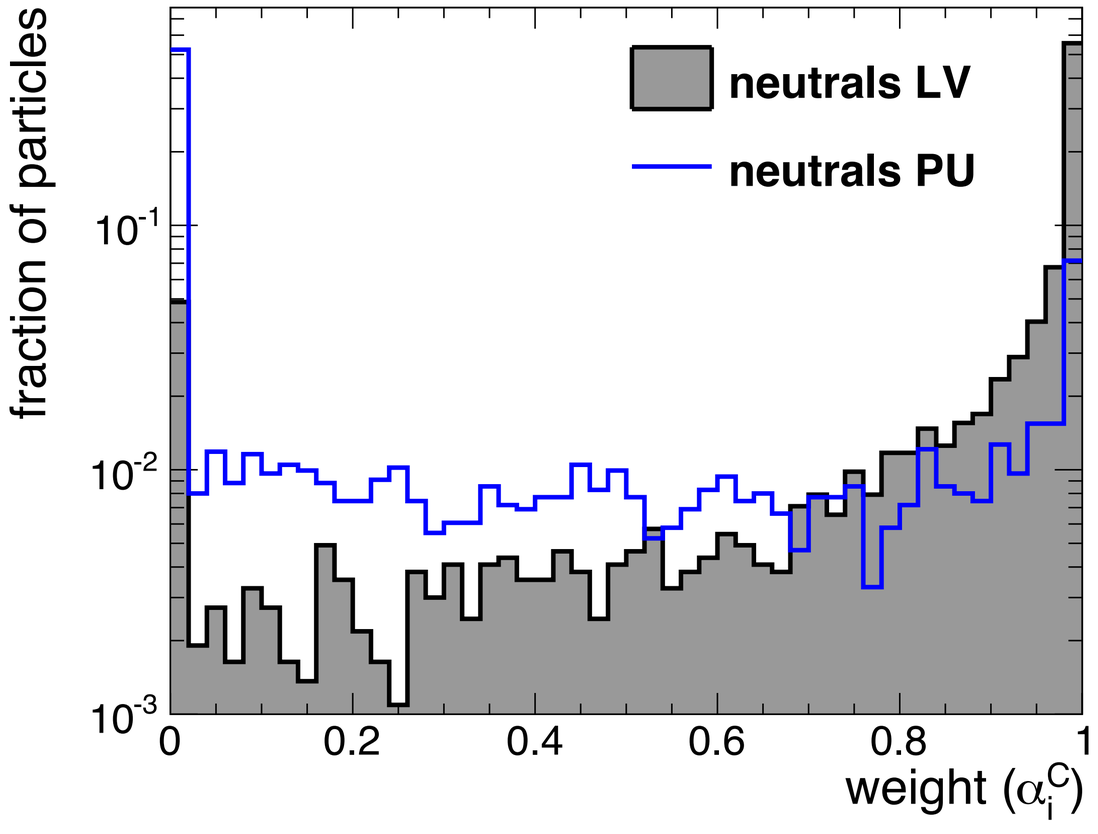
Now form a test statistic

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

and assign a weight as

$$w_i \equiv F_{\chi^2,\mathrm{NDF}=1}(\chi_i^2)$$





Pile Up Per Particle Identification

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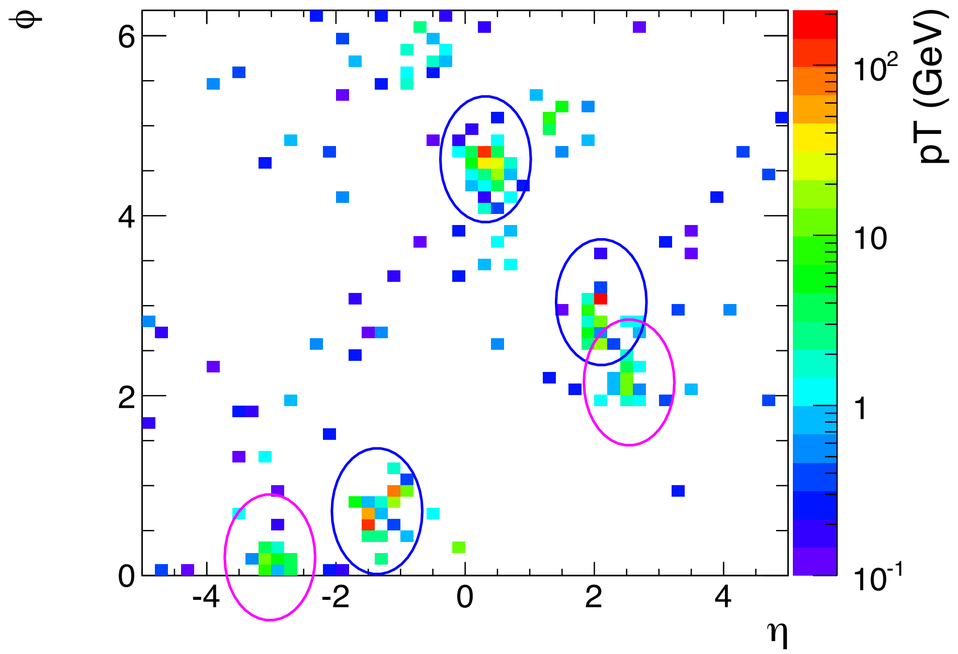

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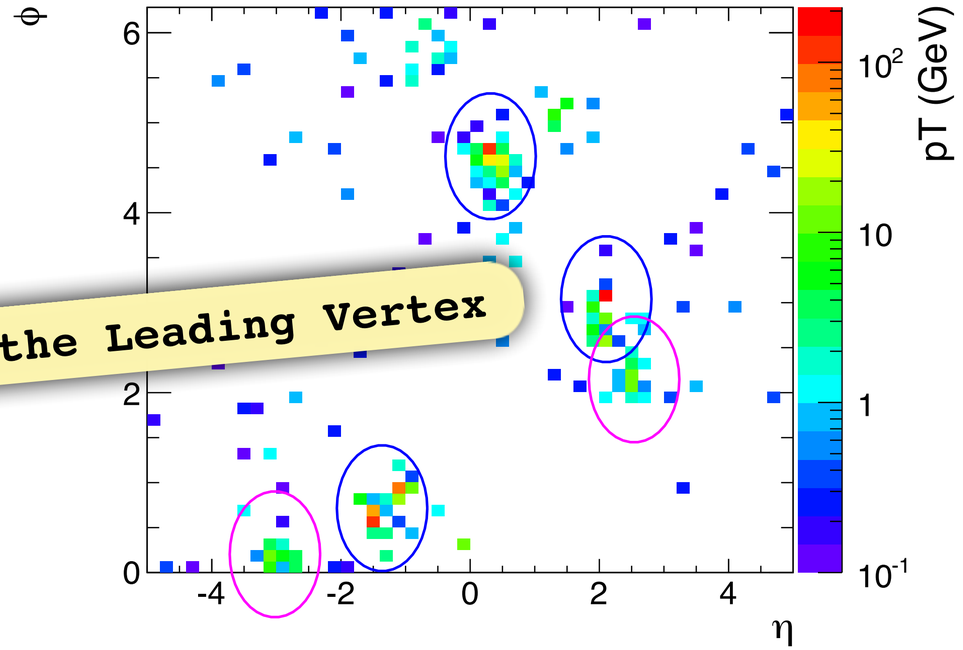
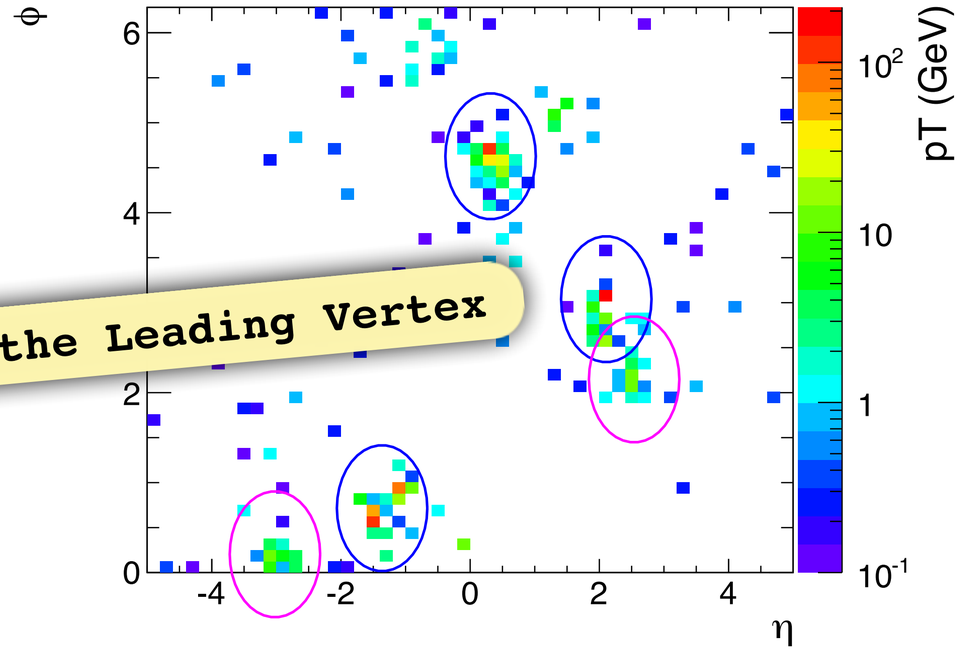
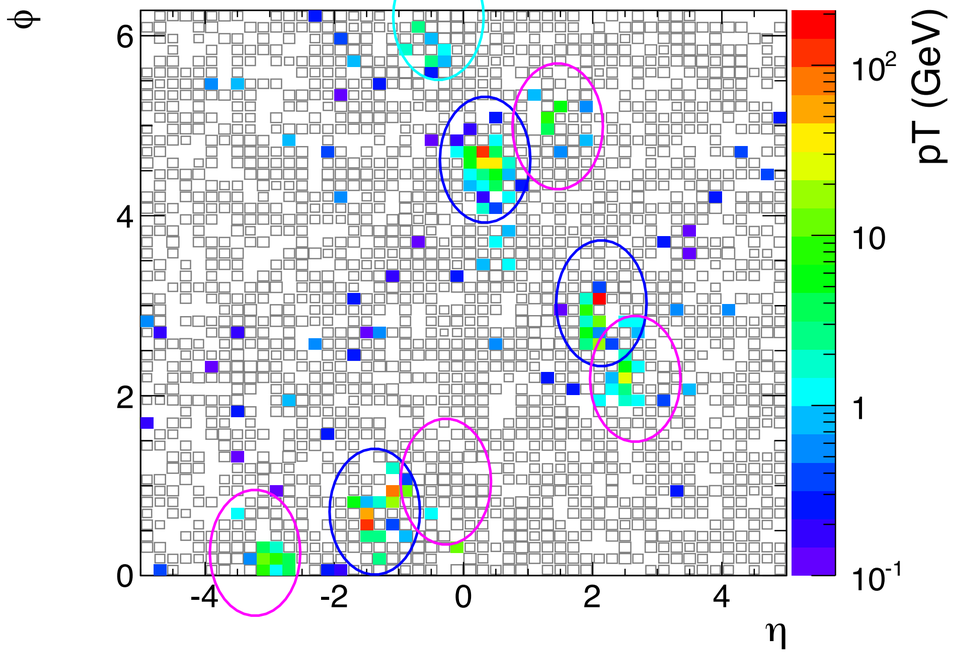


Just the Leading Vertex

Pile Up Per Particle Identification





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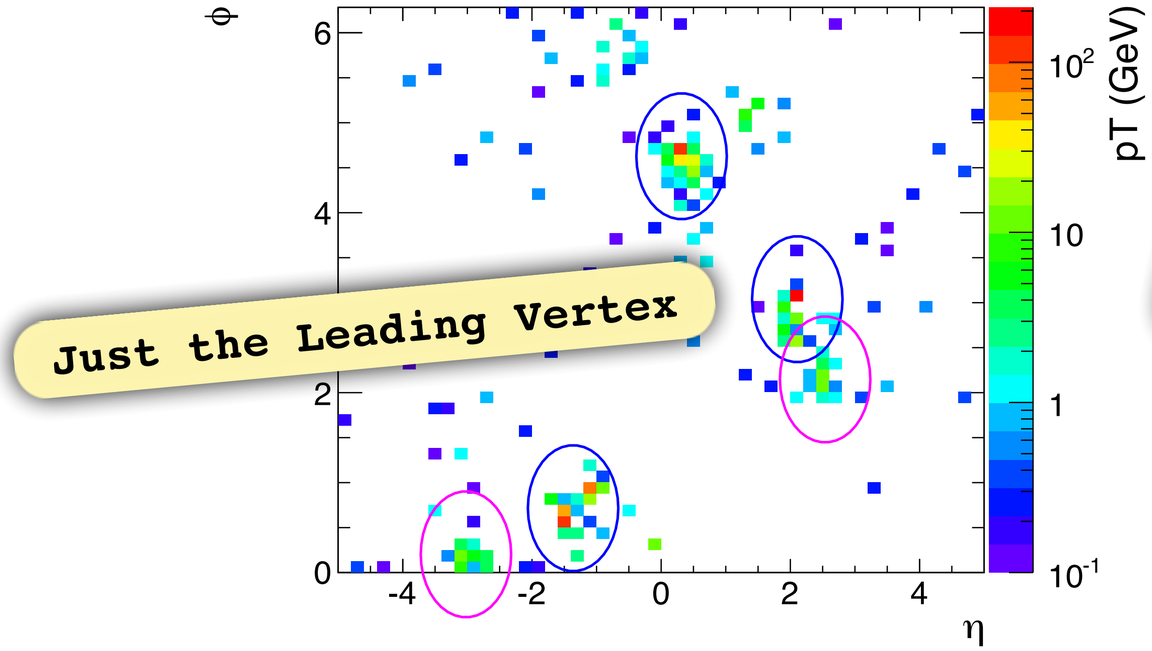

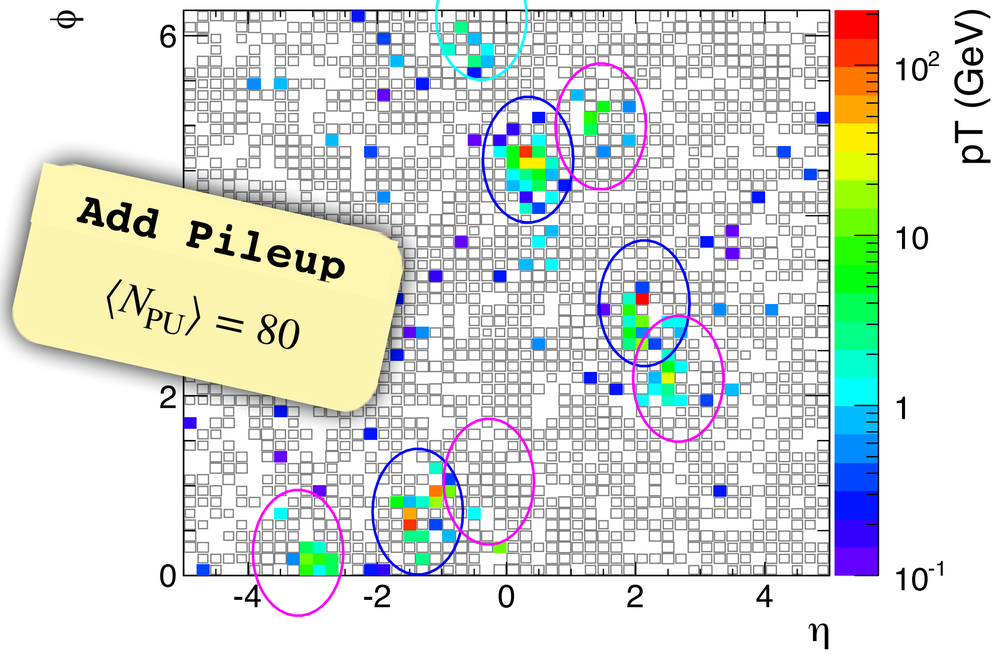

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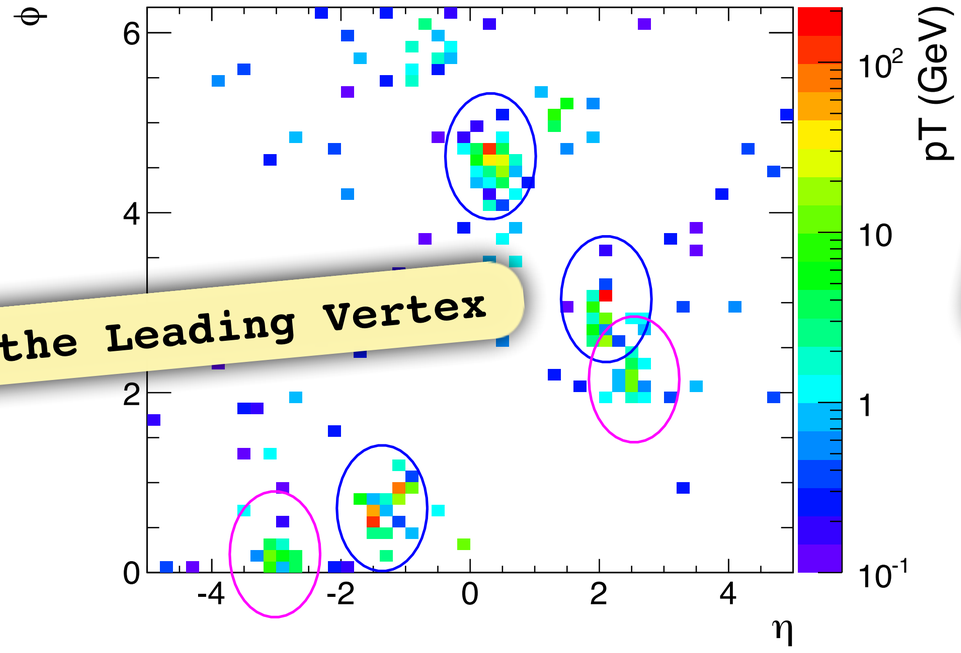

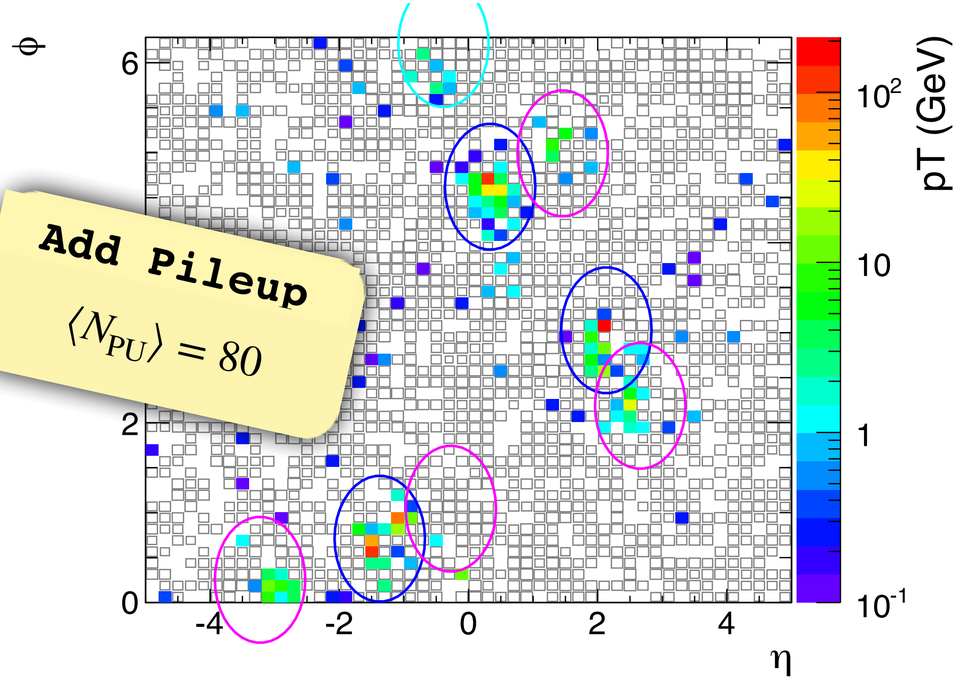

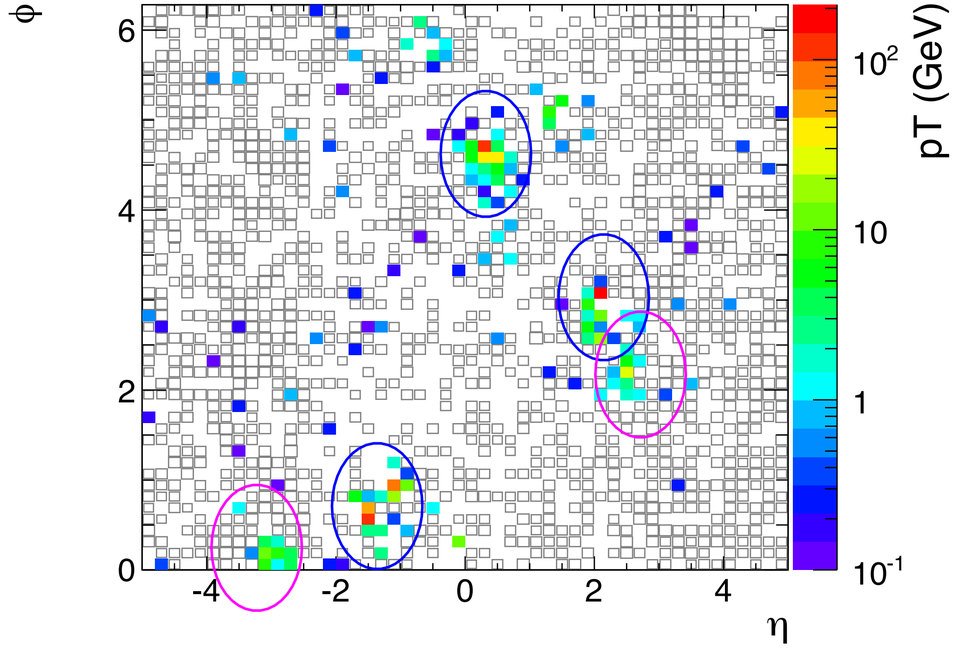

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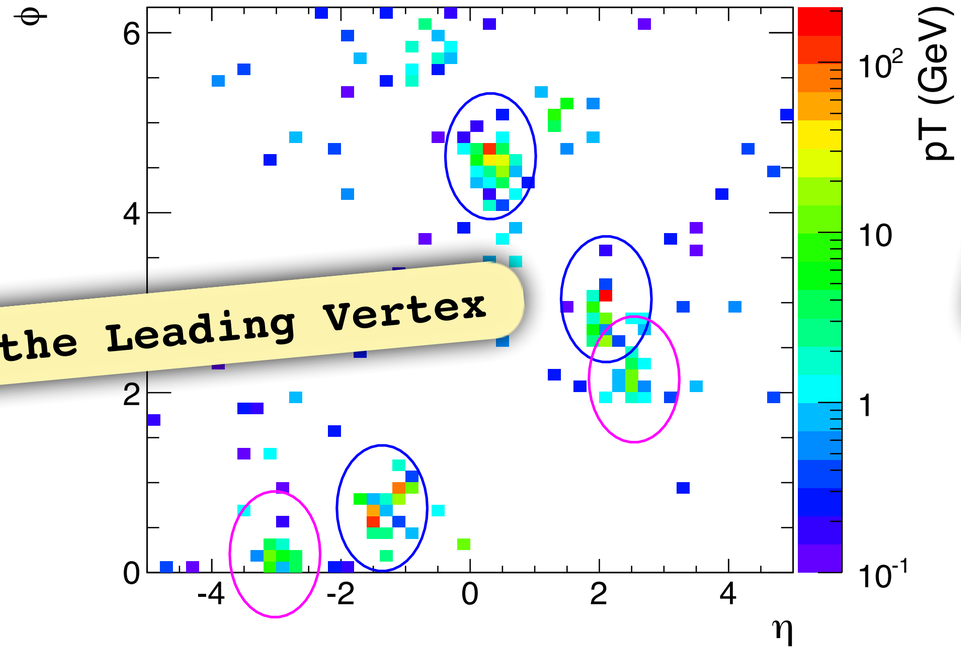

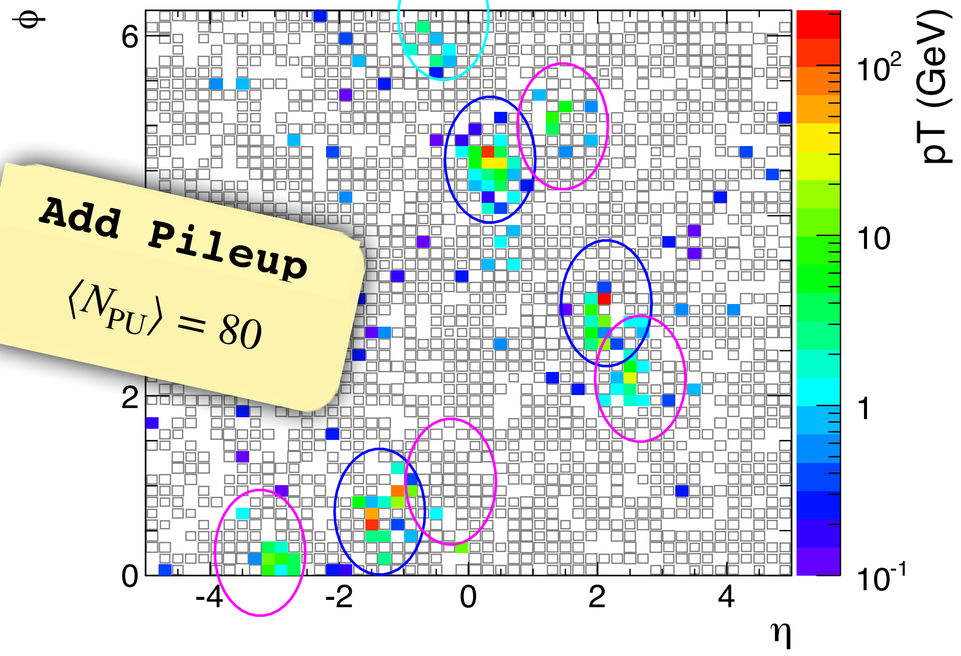

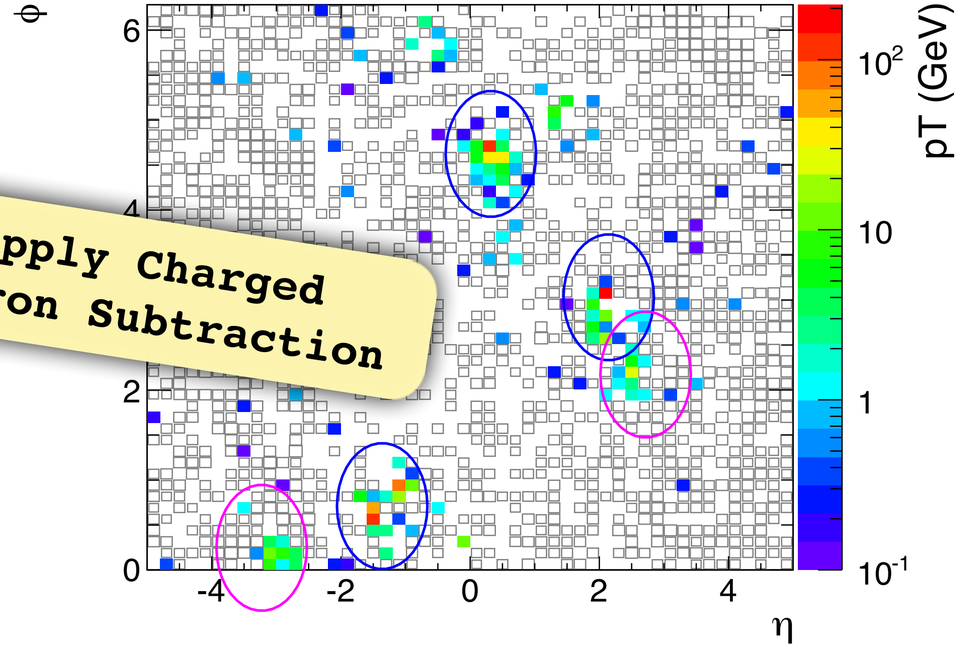

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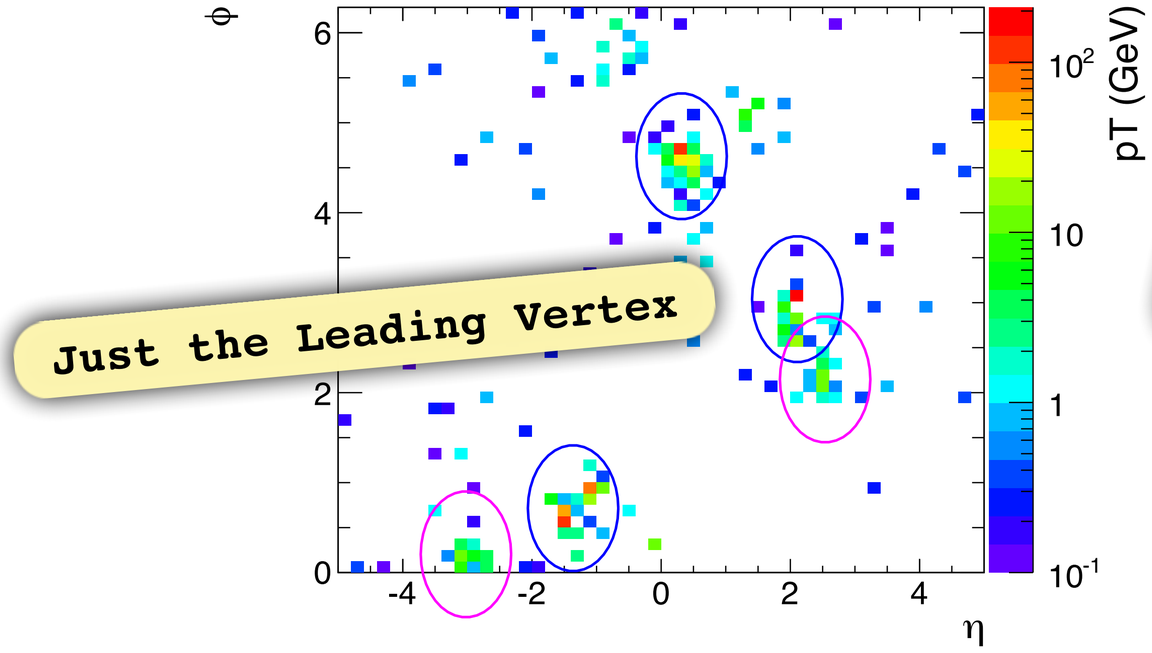

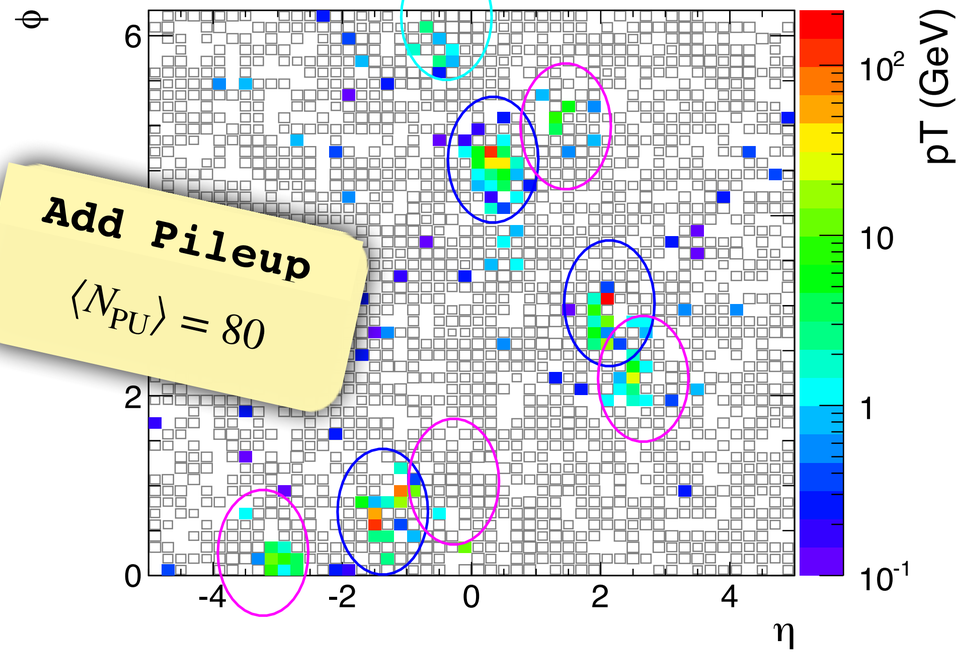

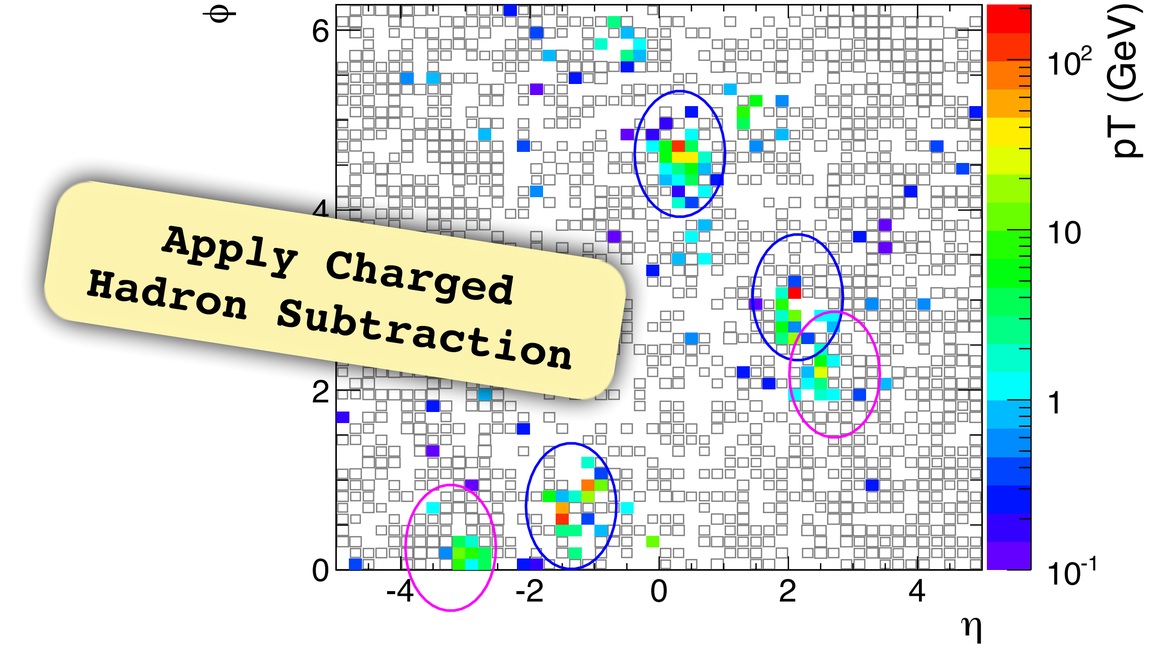

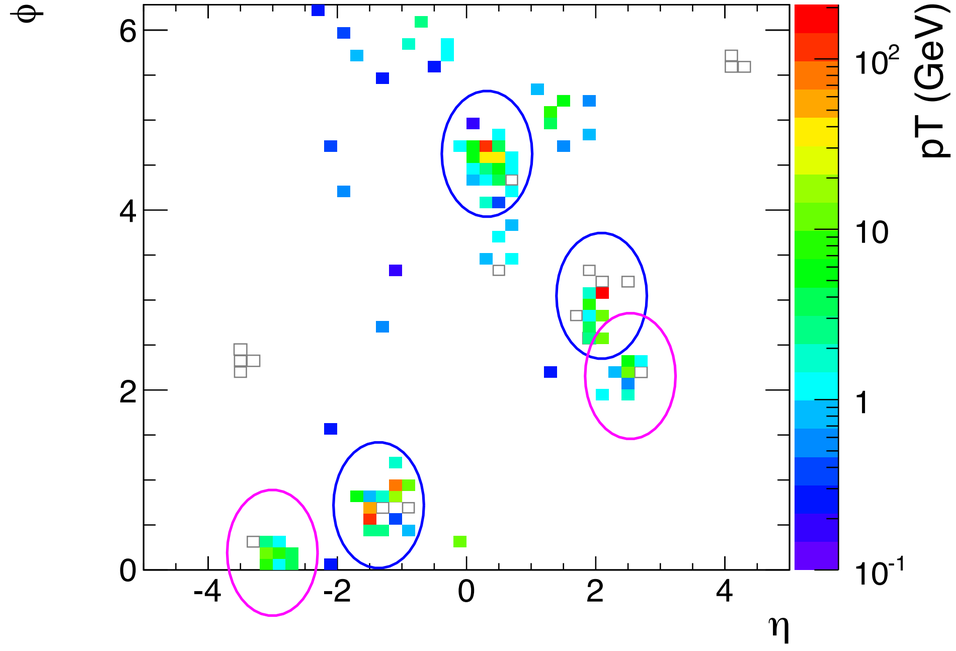

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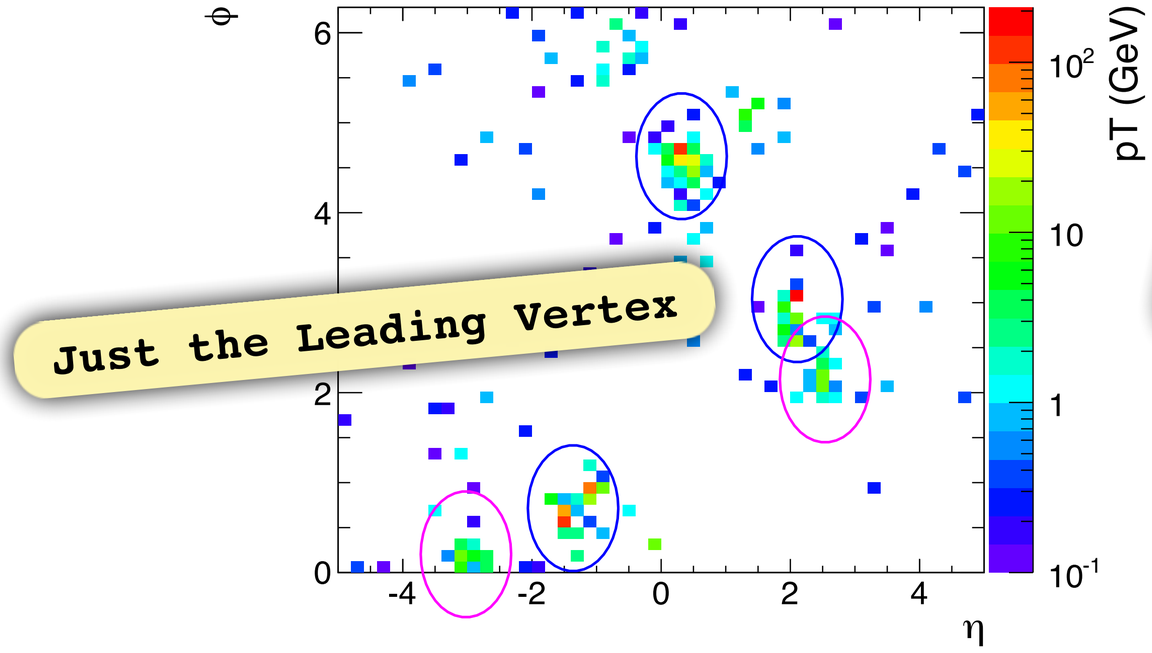

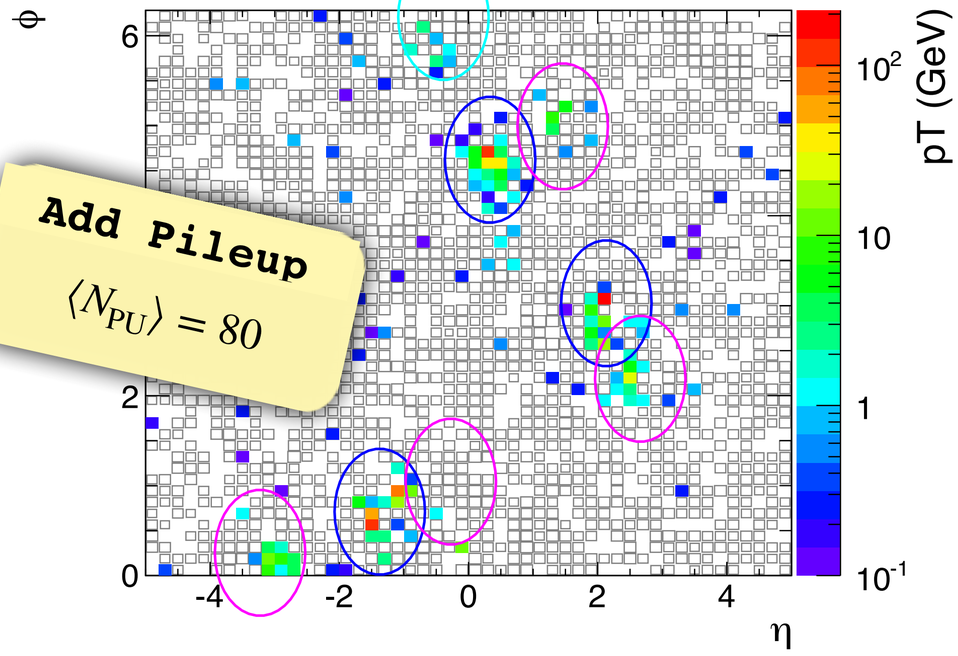

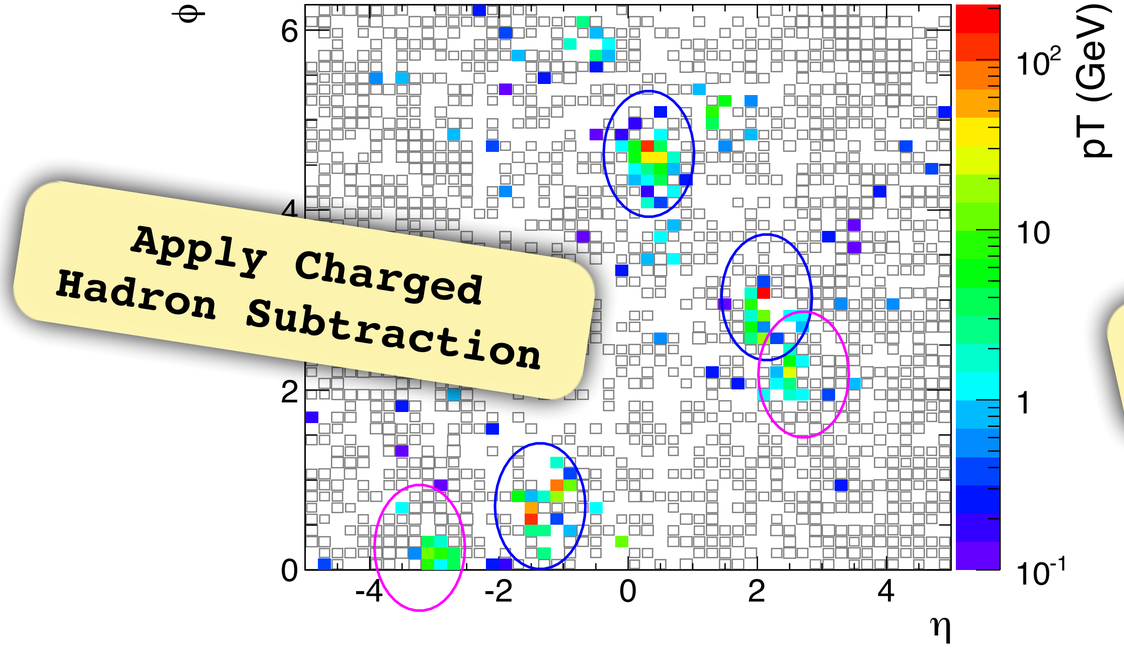

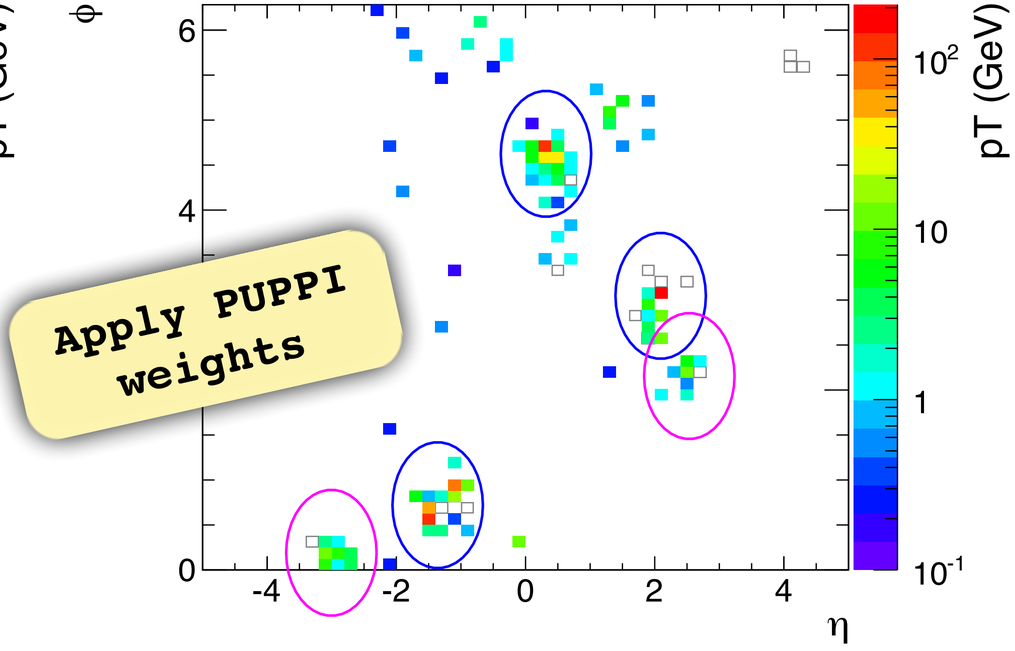

OK...I'll stop here