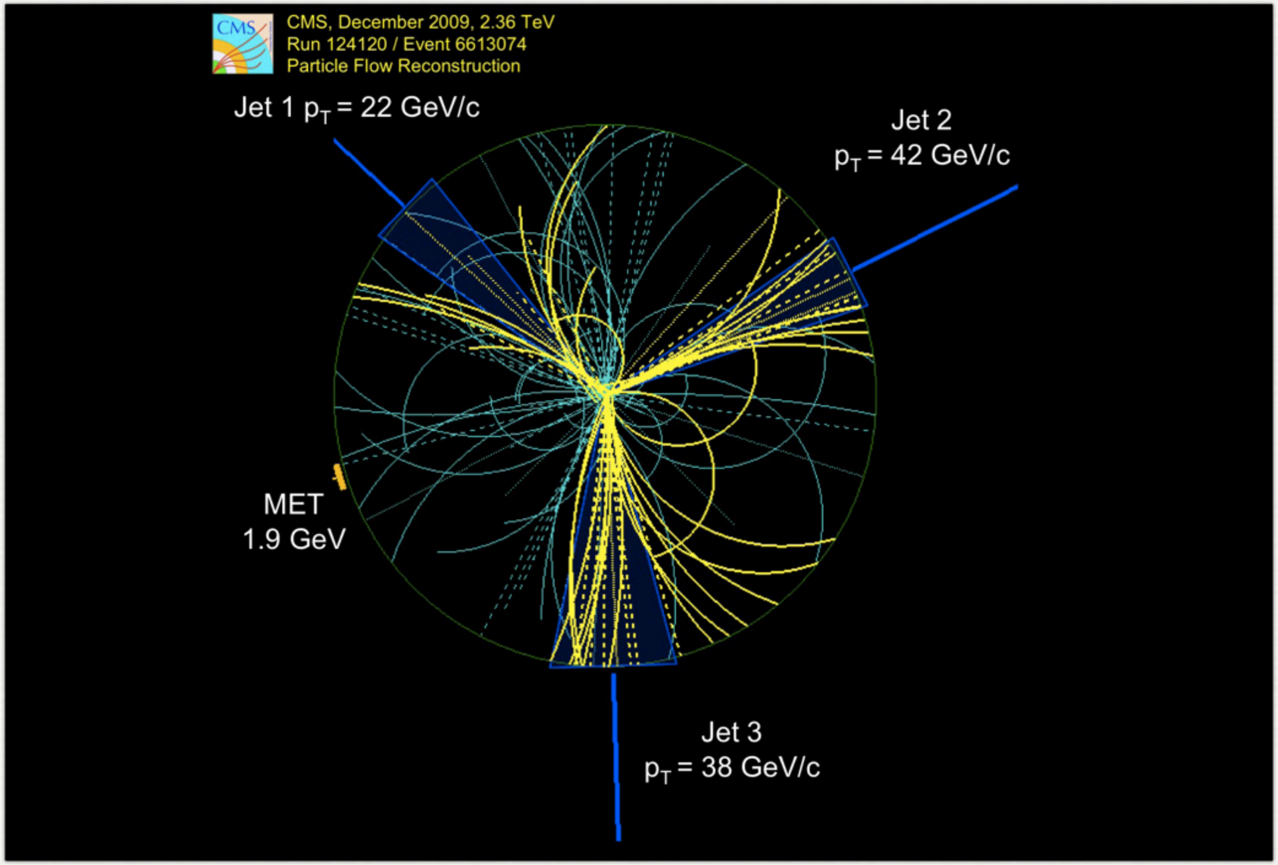
Particle ID: Lecture #1

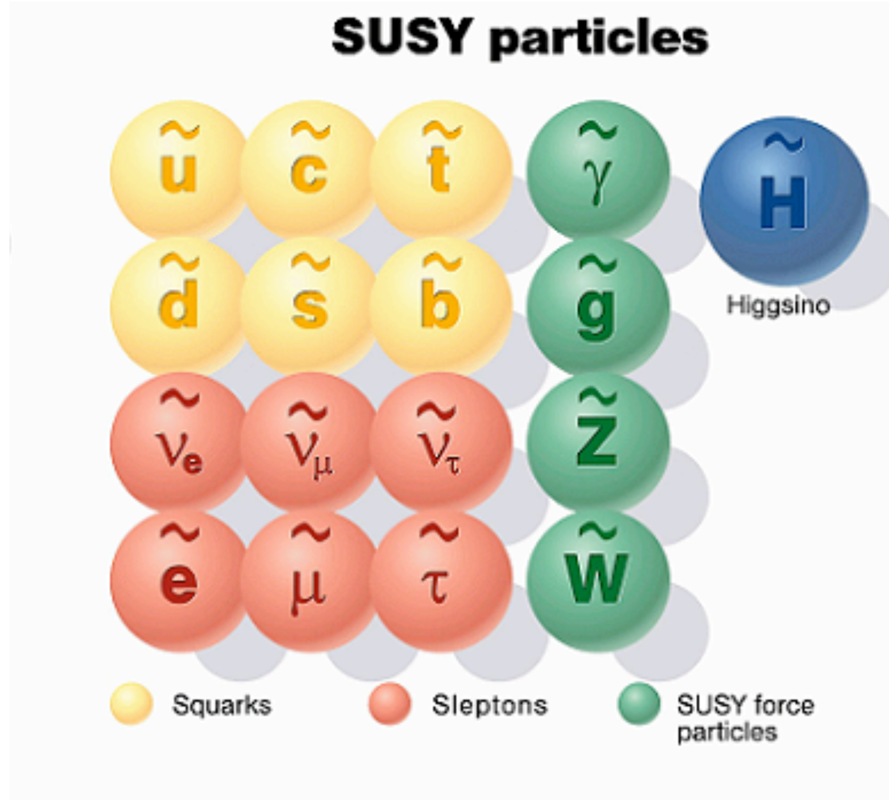
Fermilab
UIC University of Illinois at Chicago



Richard Cavanaugh, Fermilab & University of Illinois Chicago
LHC Physics Center co-Coordinator

Hadron Collider Physics Summer School
Fermilab, 14 August, 2012

LPC
LHC Physics Center


SUSY particles
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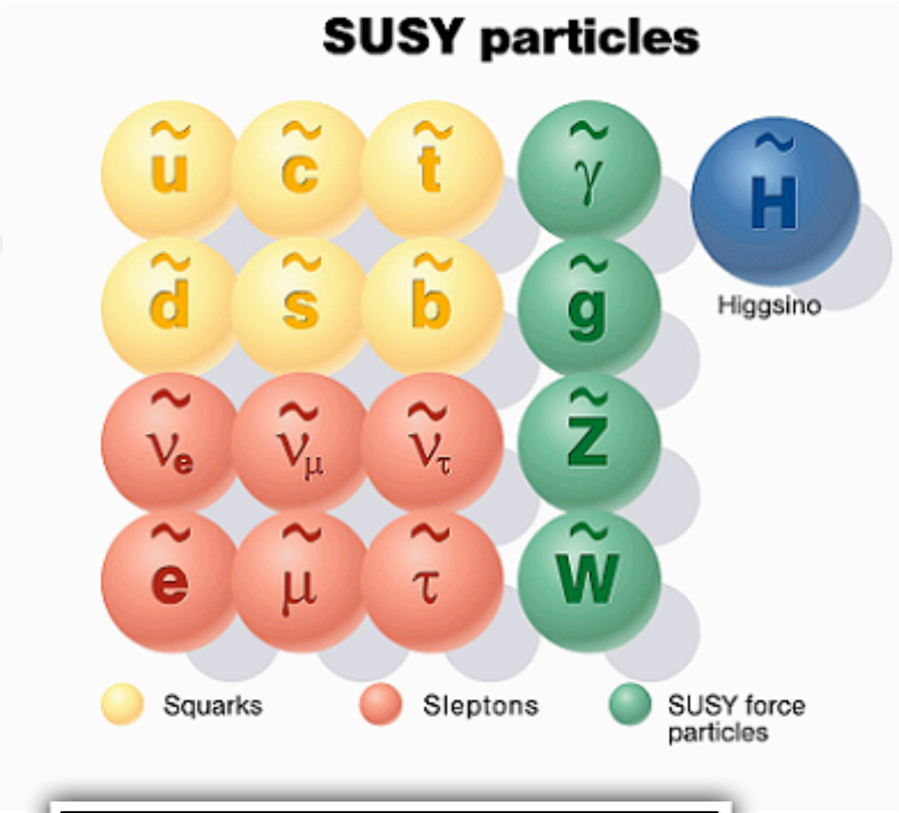
Squarks
Sleptons
SUSY force particles

Looking for New Physics



Heavy New Particles

- Decay into lighter particles
  - The "lighter particles" are the particles of the Standard Model

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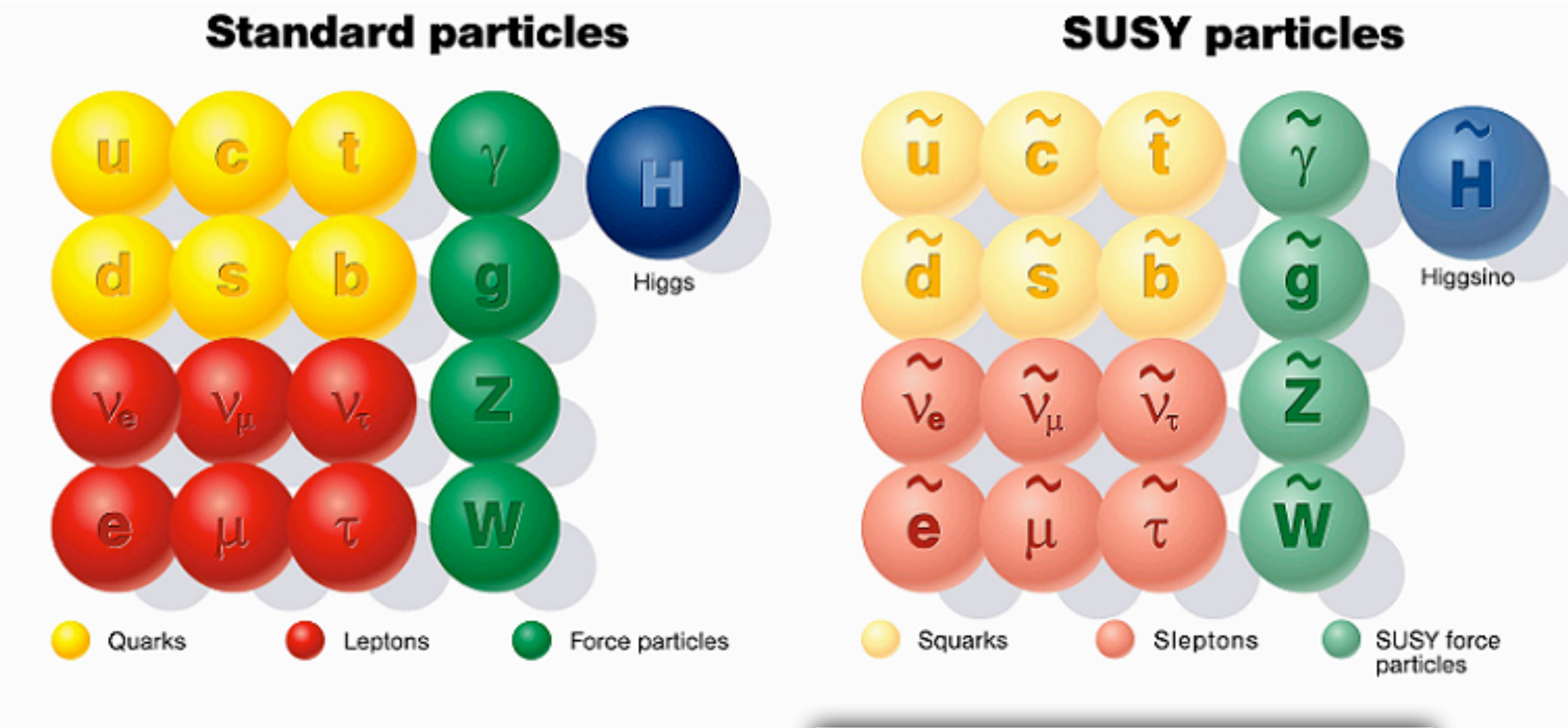

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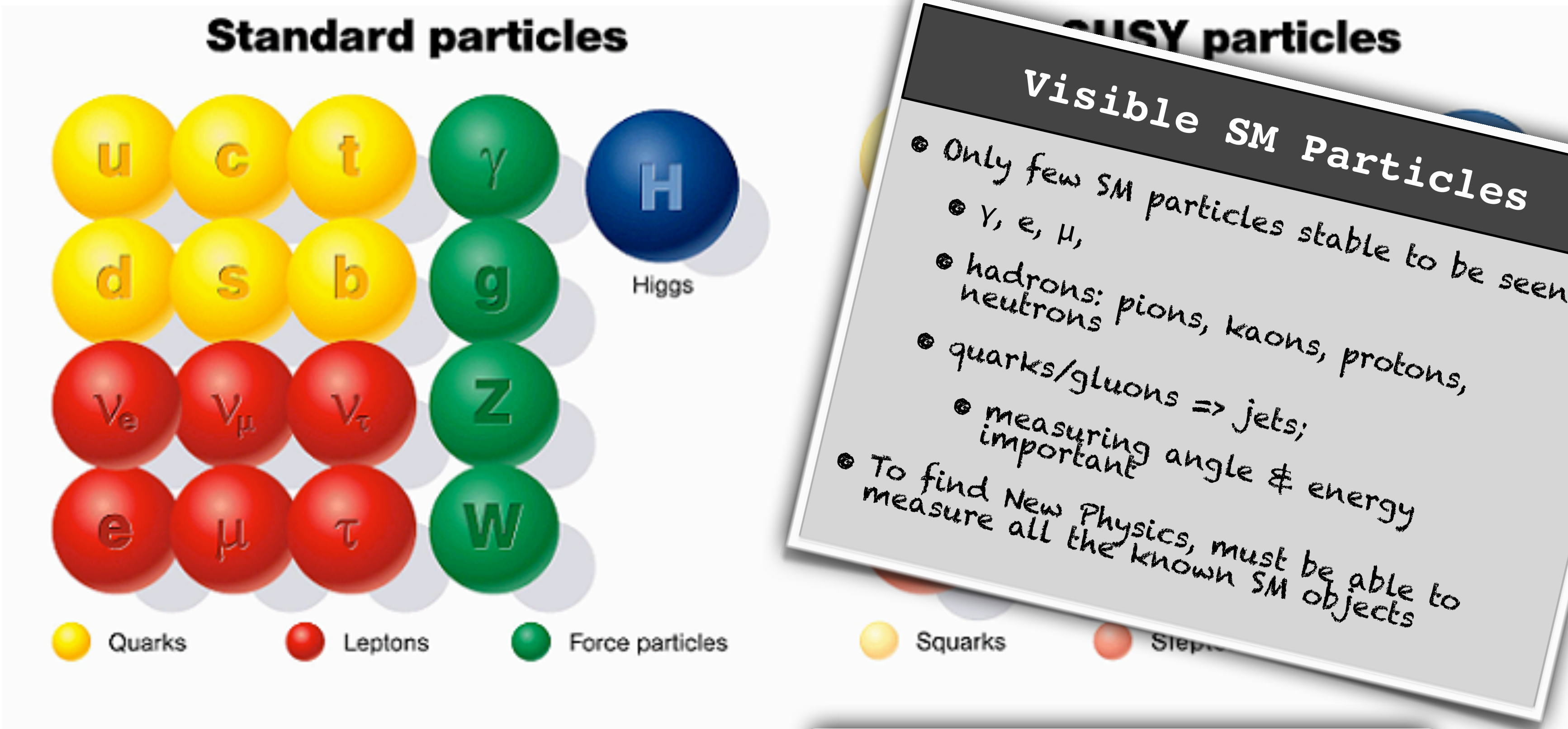

Visible SM Particles

- Only few SM particles stable to be seen:
  - γ, e, μ,
  - hadrons: pions, kaons, protons, neutrons
  - quarks/gluons => jets;
    - measuring angle & energy important
- To find New Physics, must be able to measure all the known SM objects

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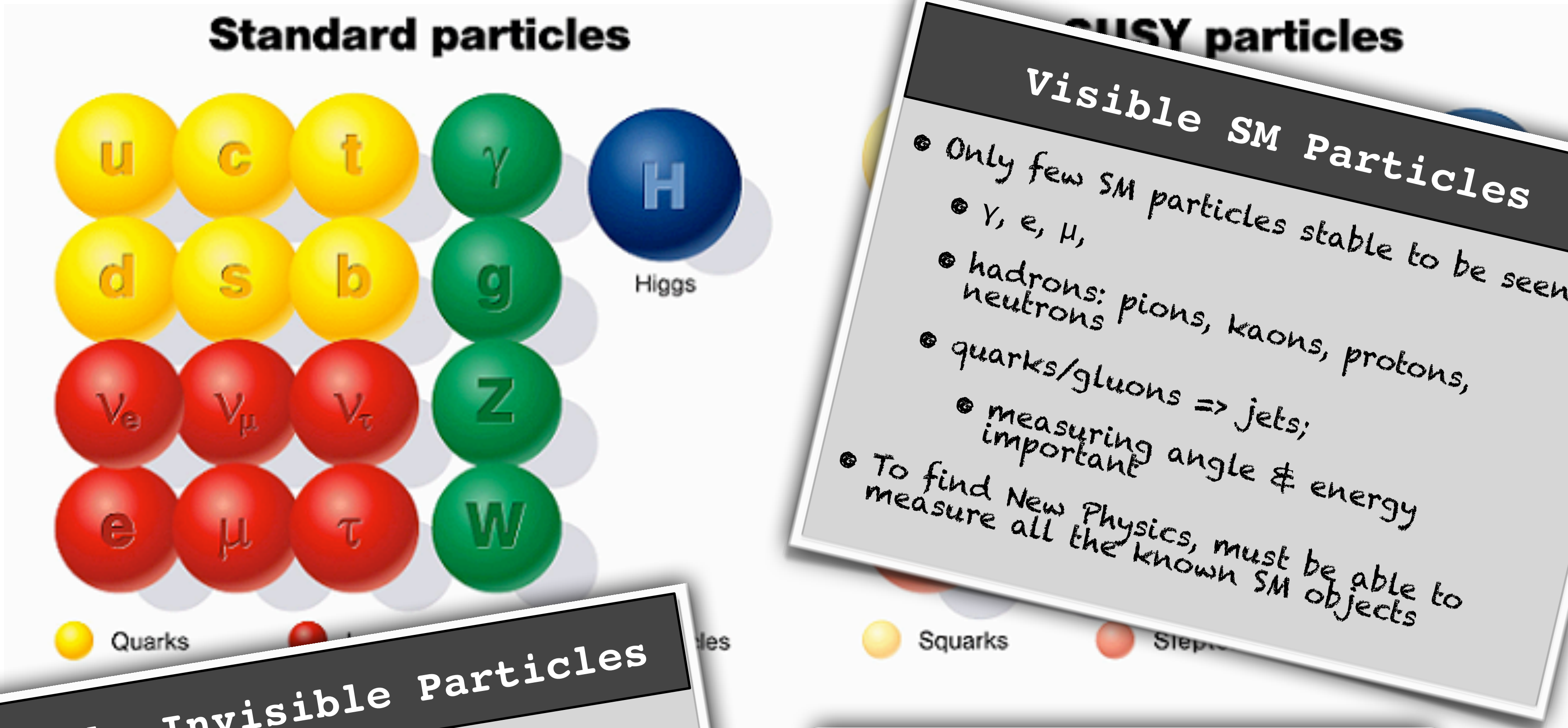

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Stable Invisible Particles

- Stable particles may leave detector unseen
  - SM Neutrinos do that all the time!
  - NEW Massive weakly interacting particles behave similarly
- Can be detected by observing missing momentum; must be able to measure it!

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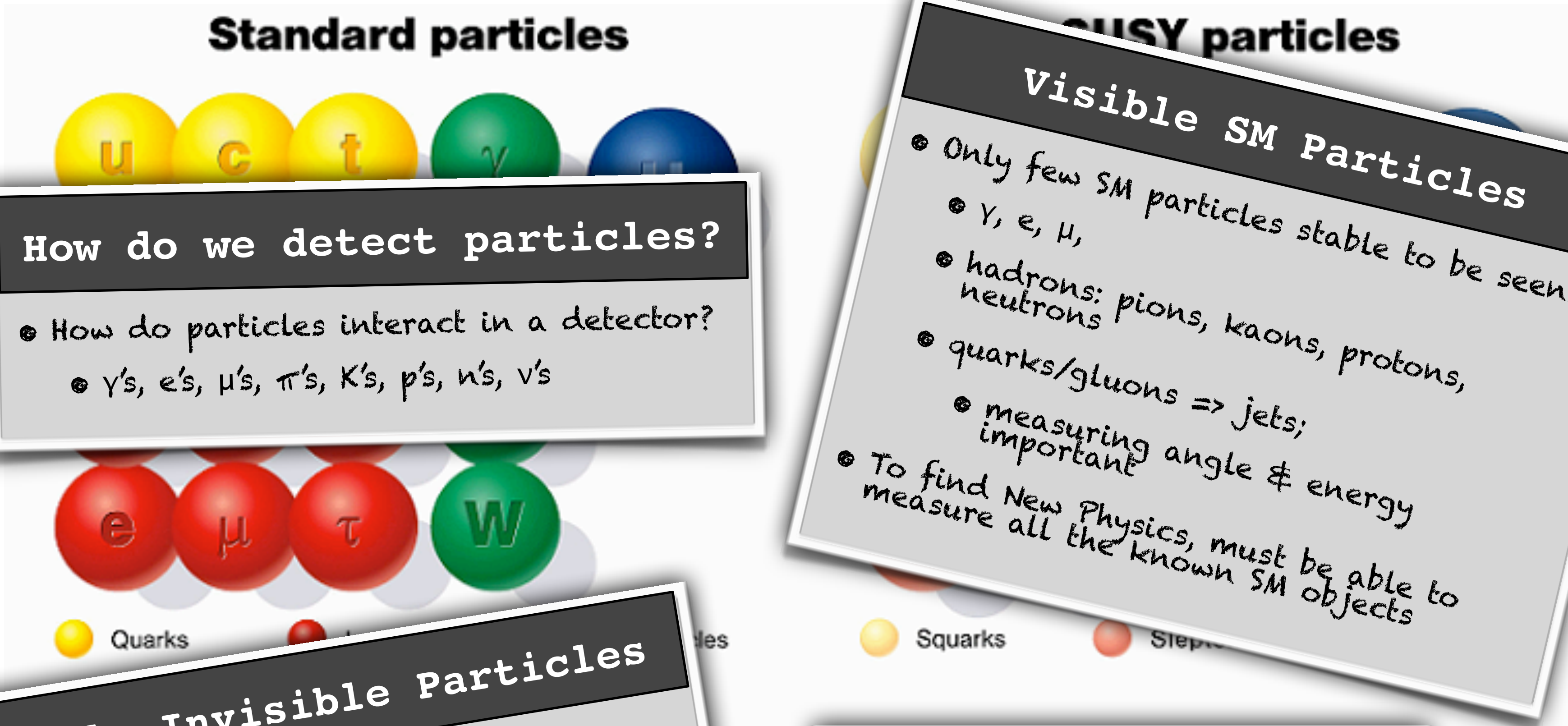

How do we detect particles?

- How do particles interact in a detector?
  - γ's, e's, μ's, π's, K's, p's, n's, ν's

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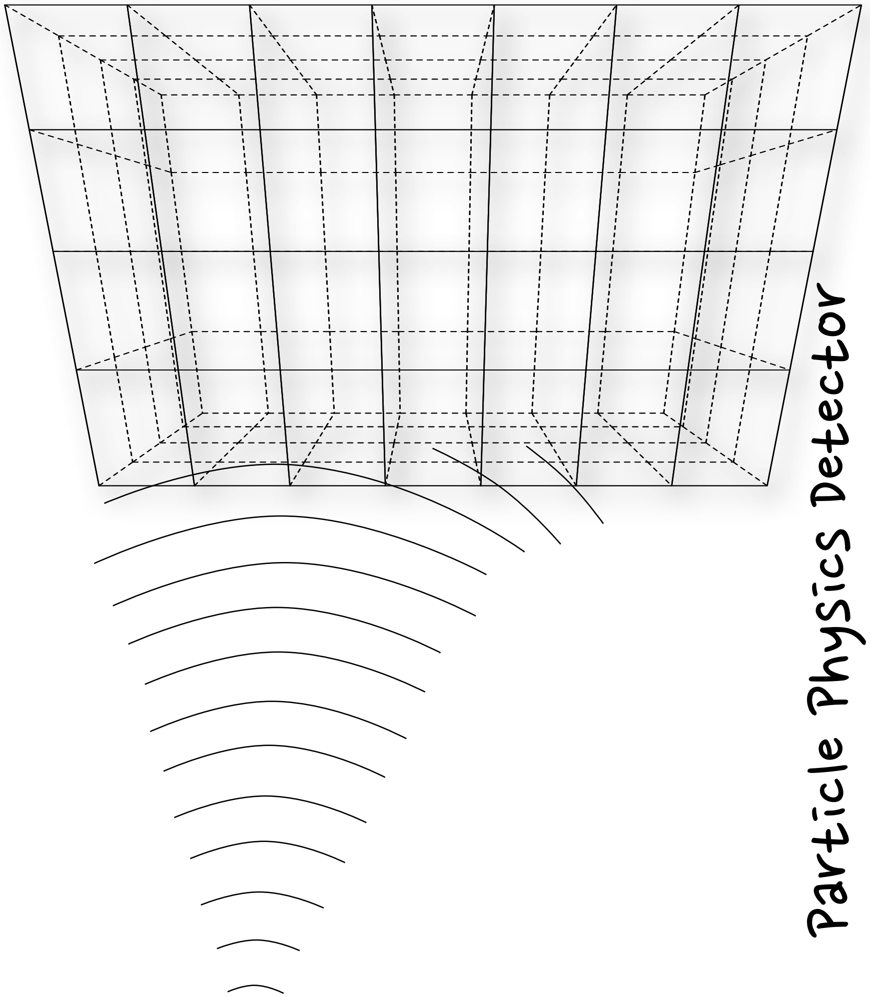
The Big Picture!



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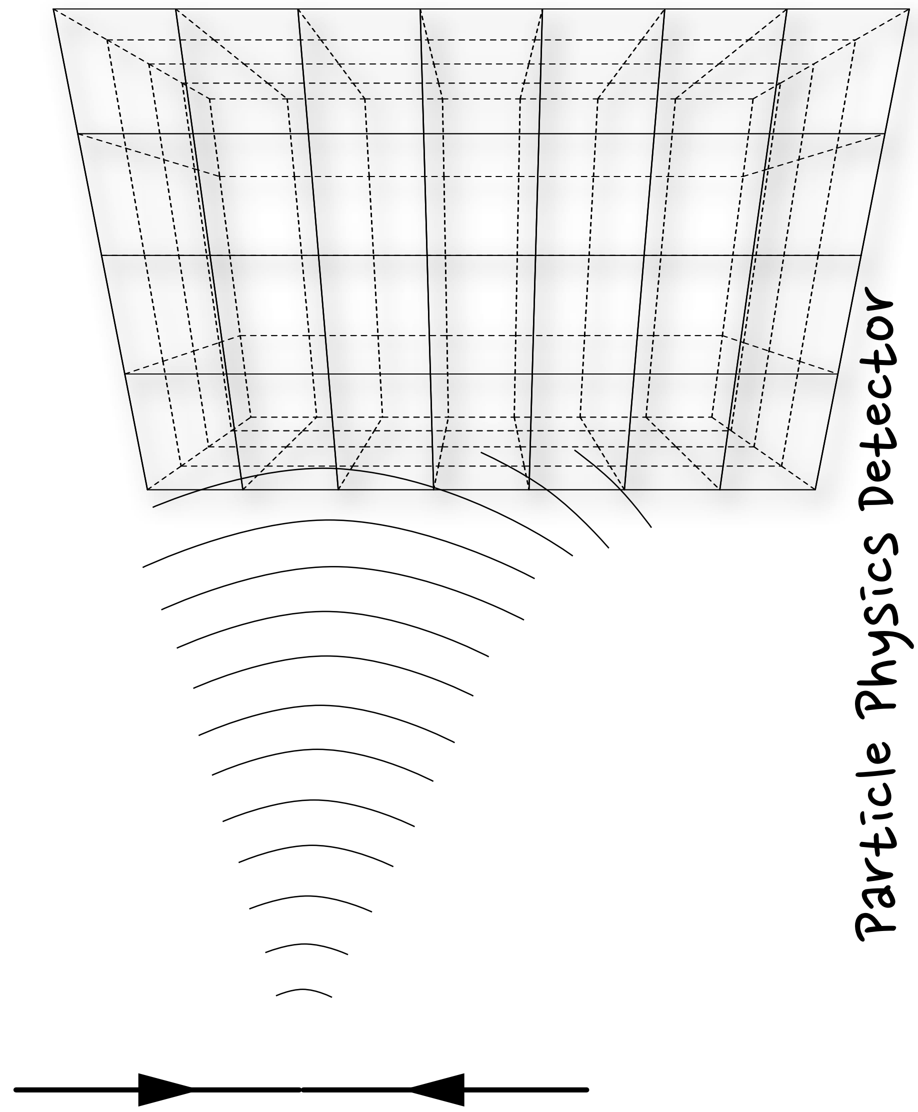

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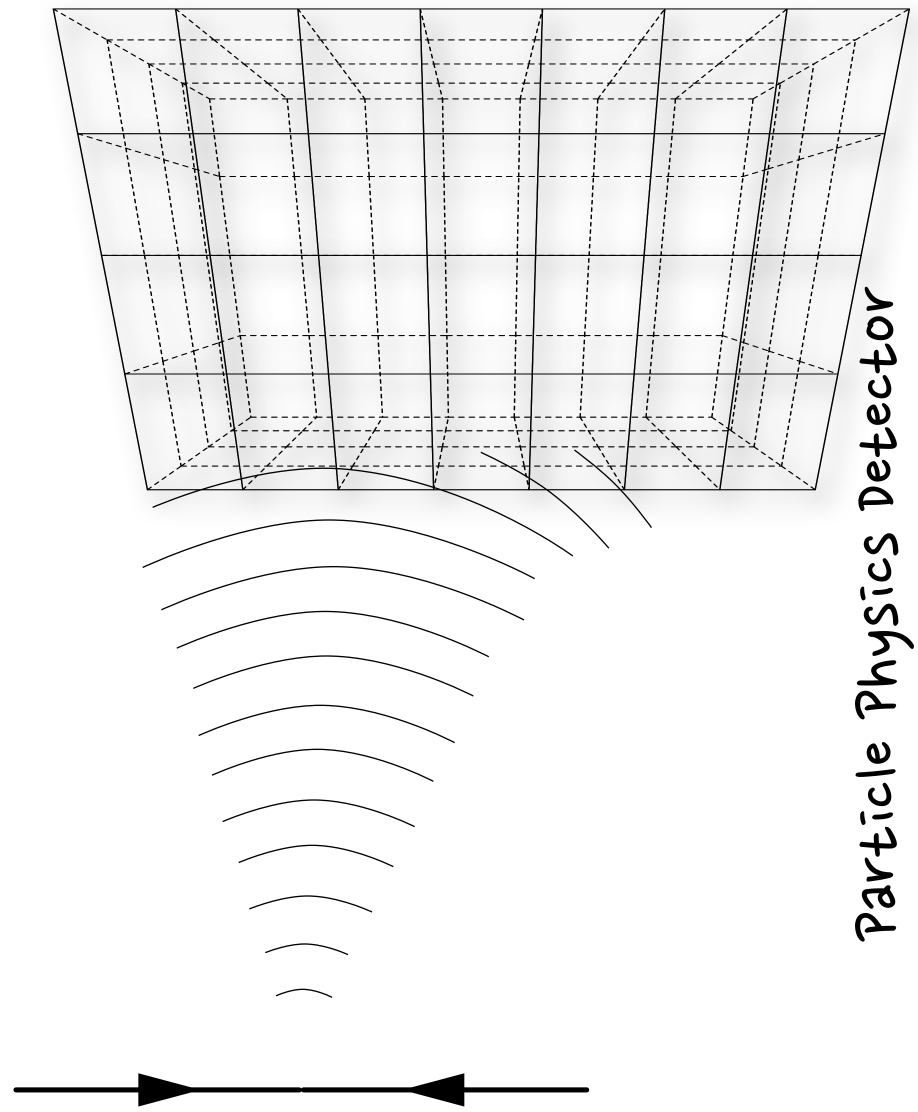

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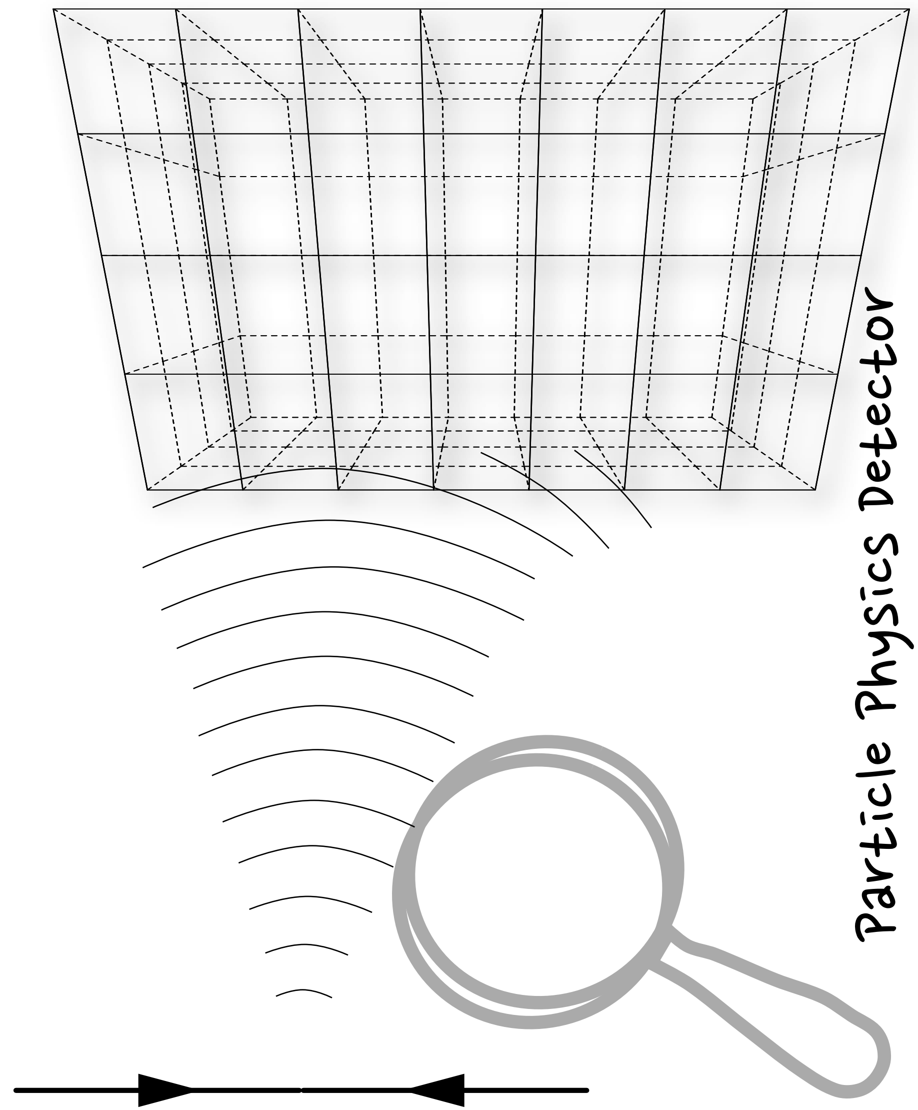

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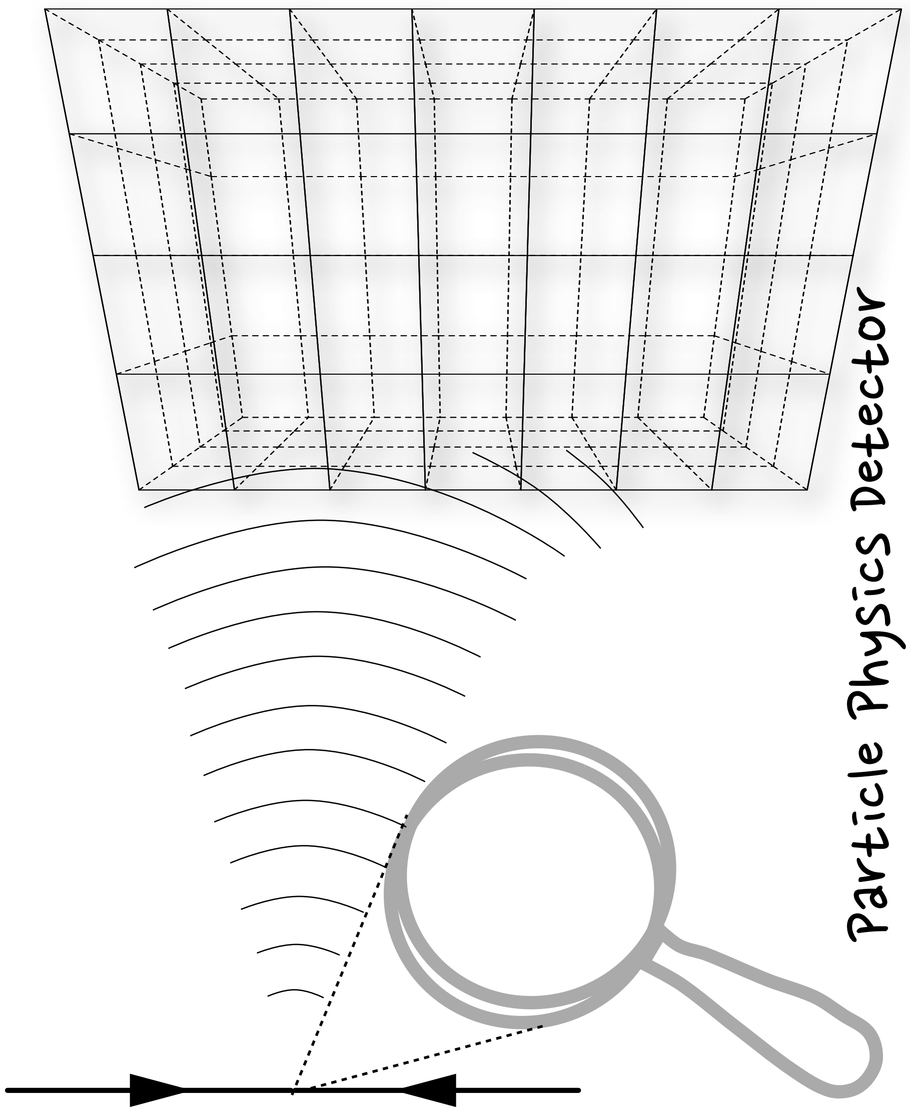

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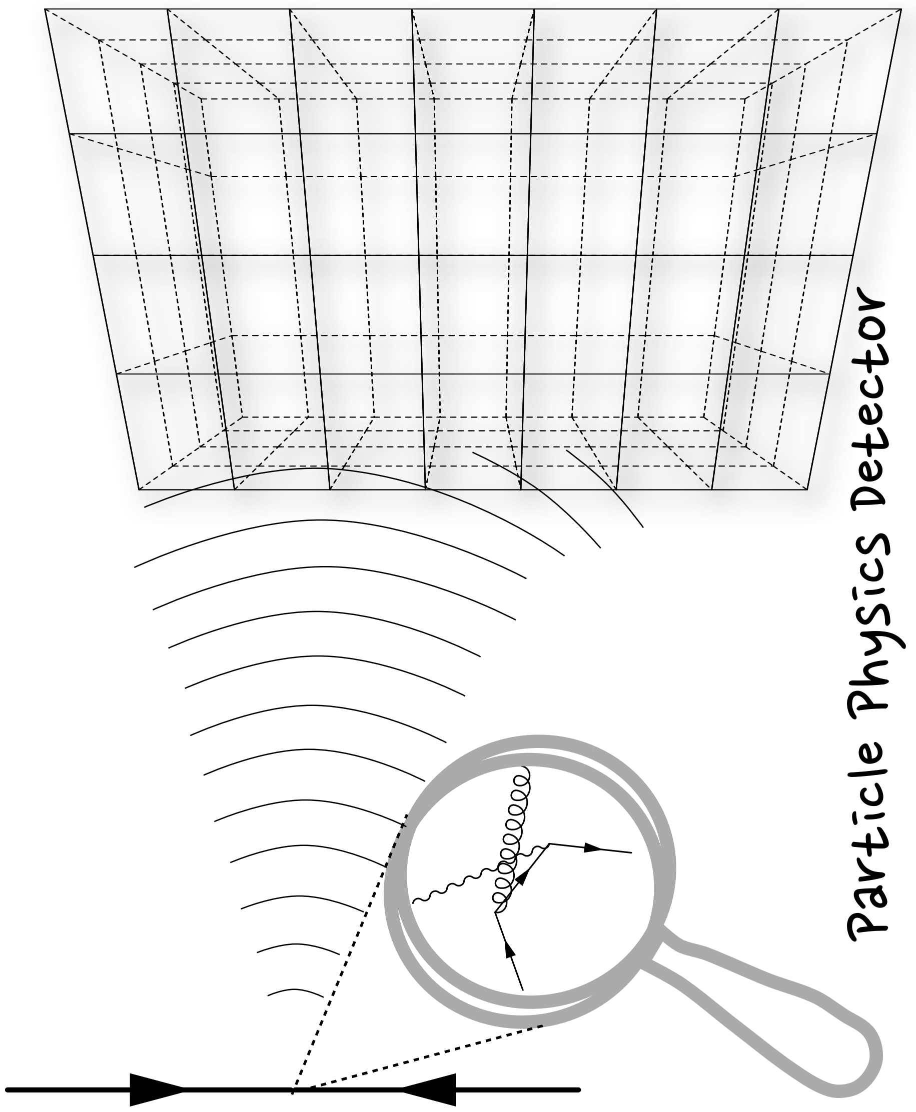

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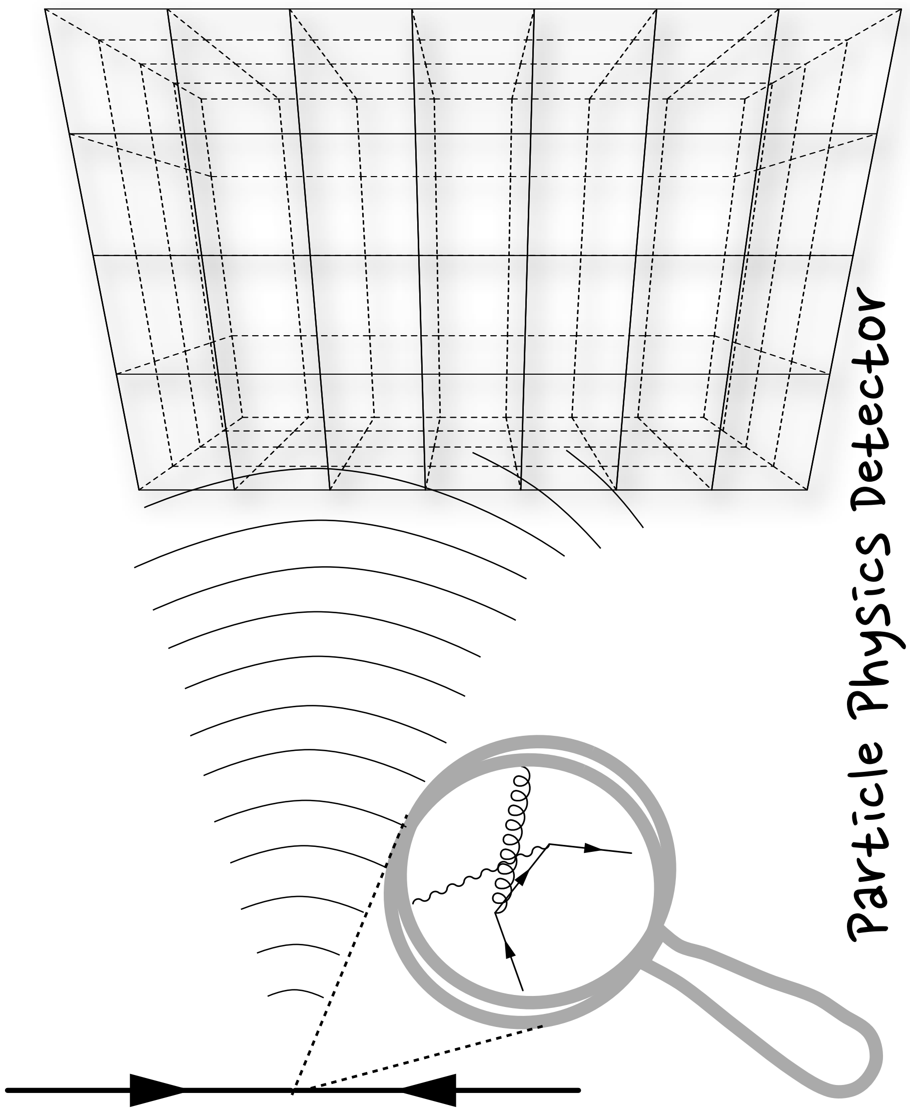
  - partons



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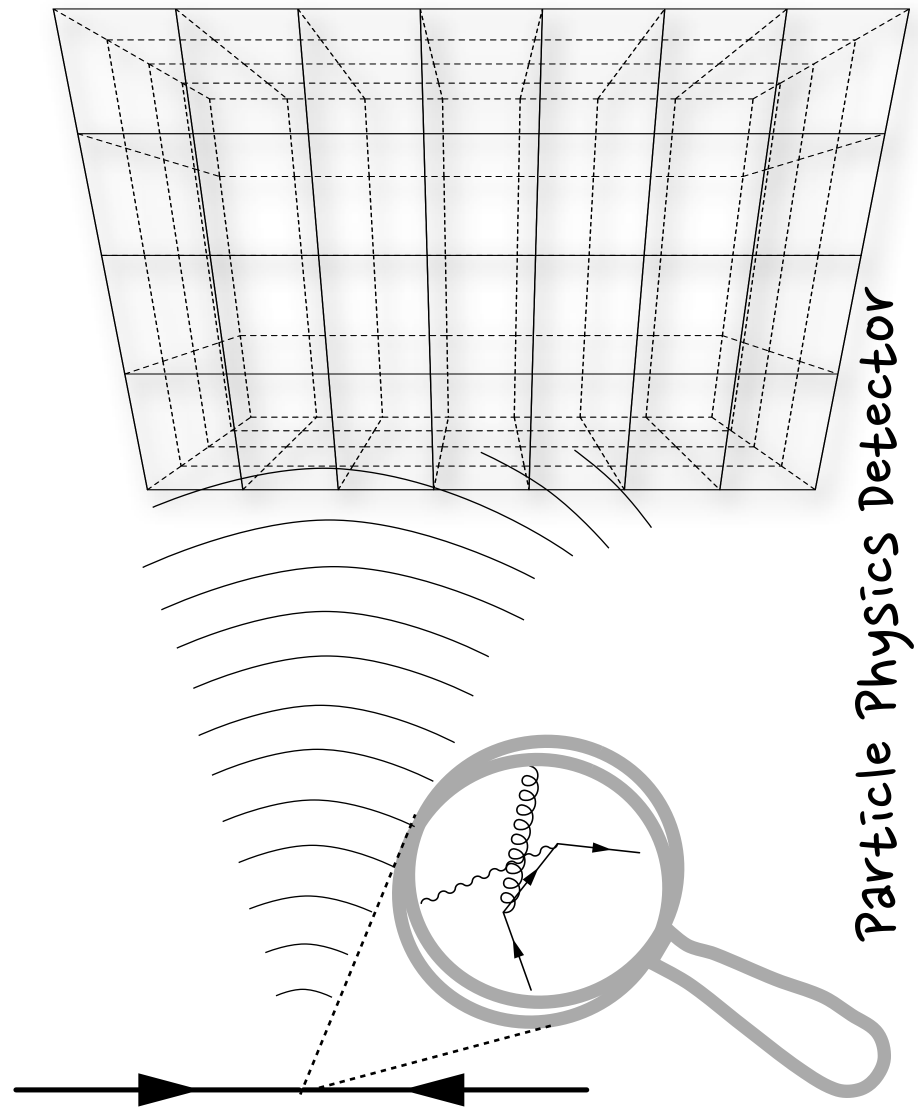
- **Partons =>**



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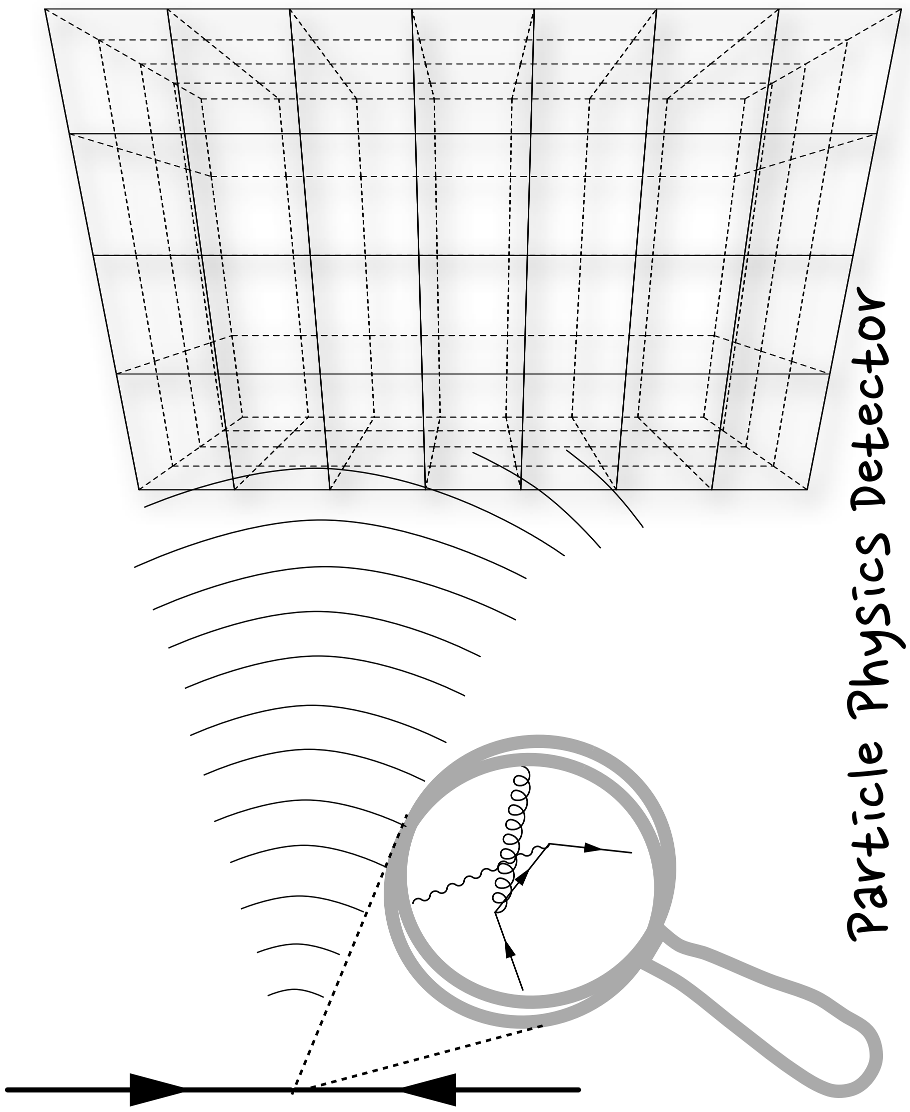
- **Physics process =>**
  - partons
- **Partons =>**
  - visible particles



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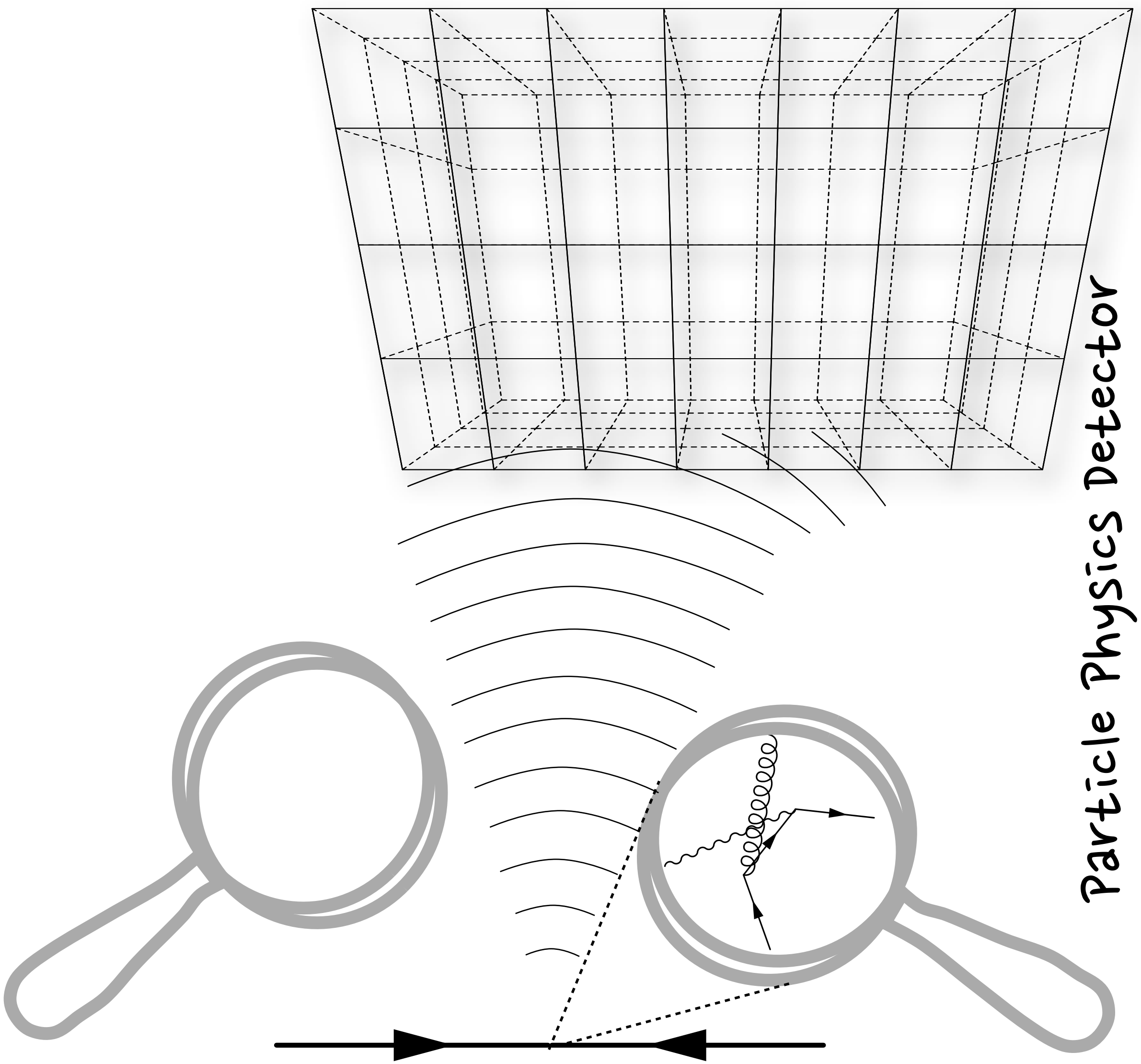

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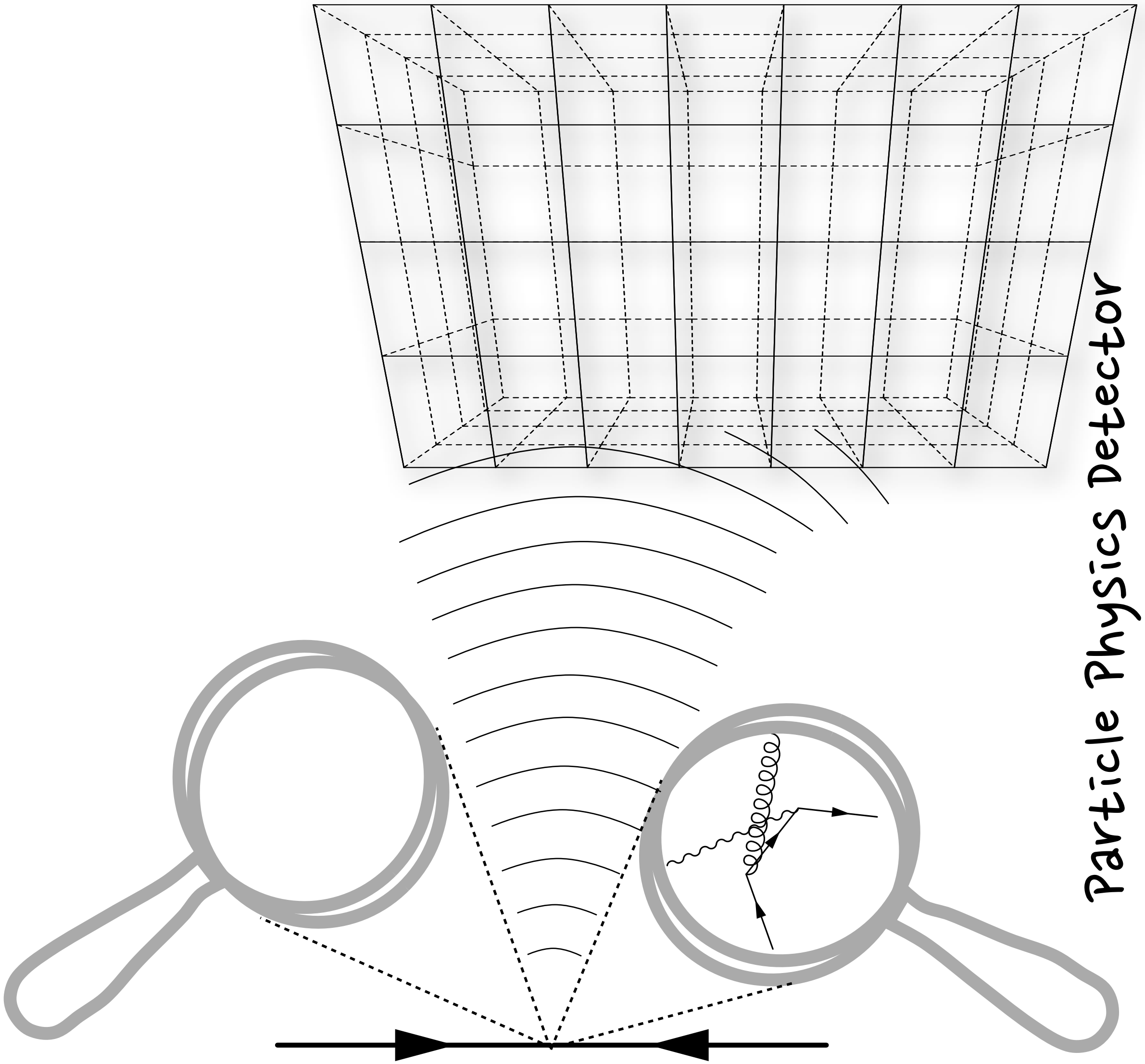

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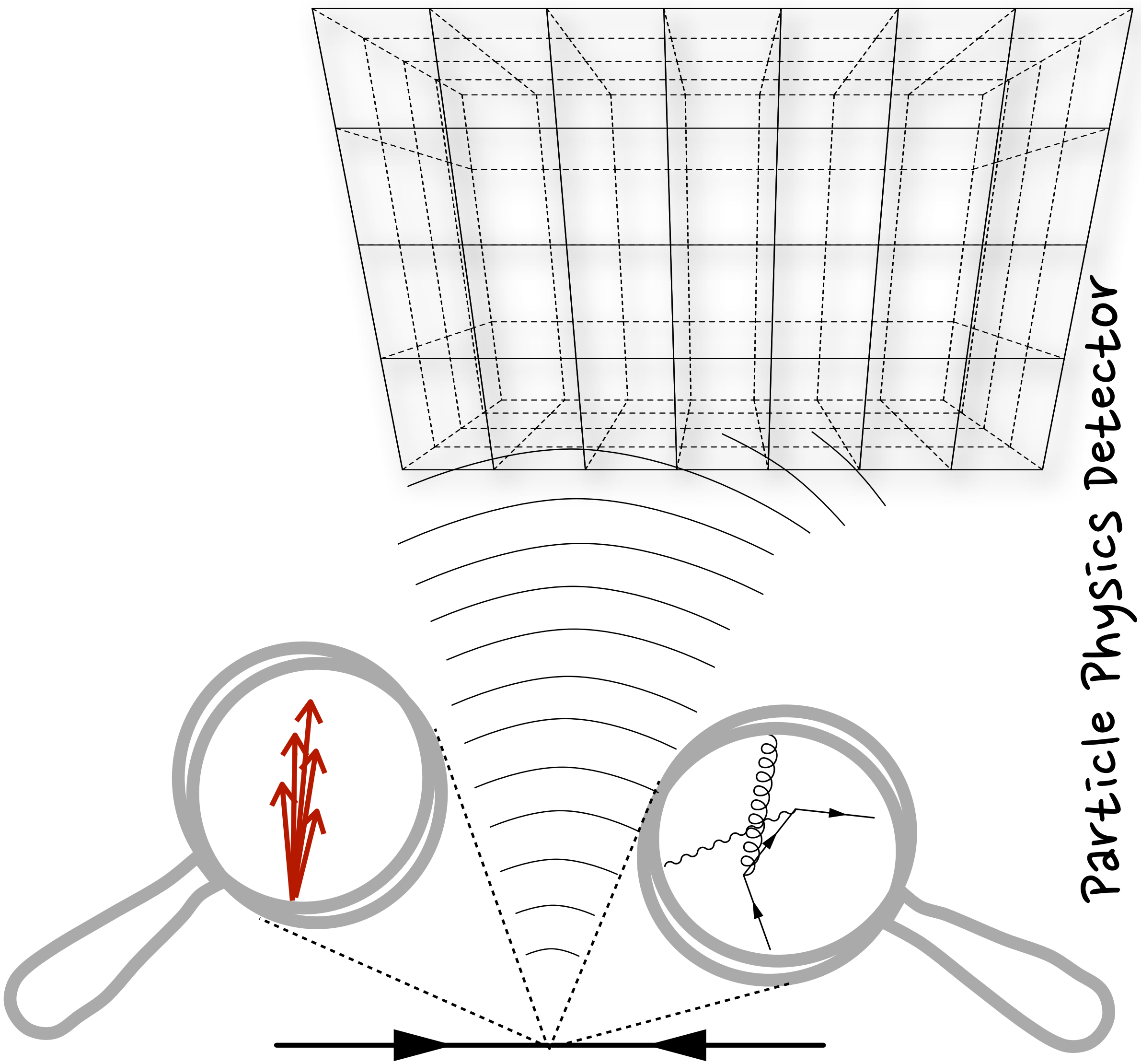

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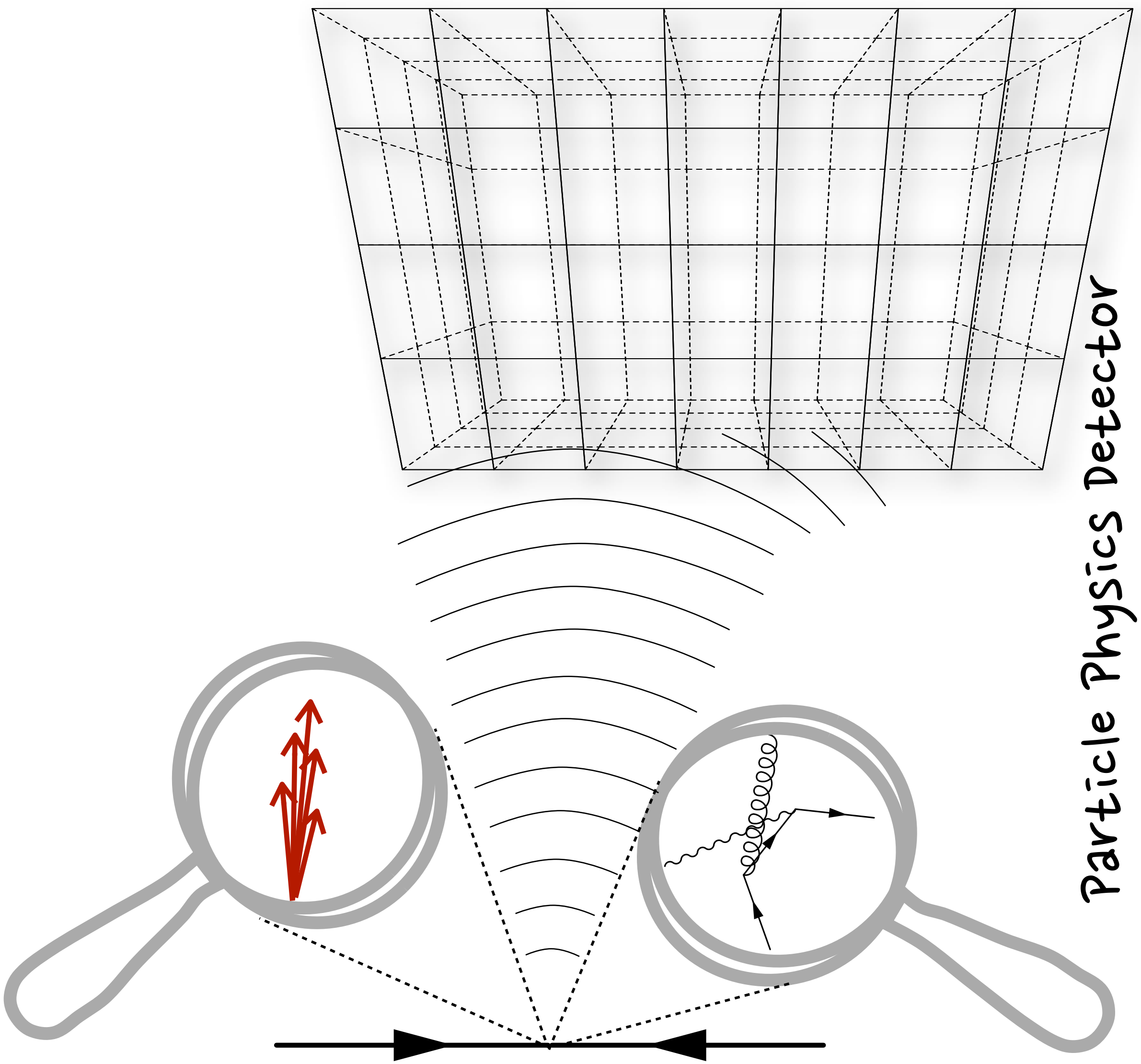

The Big Picture!

- **Physics process =>**
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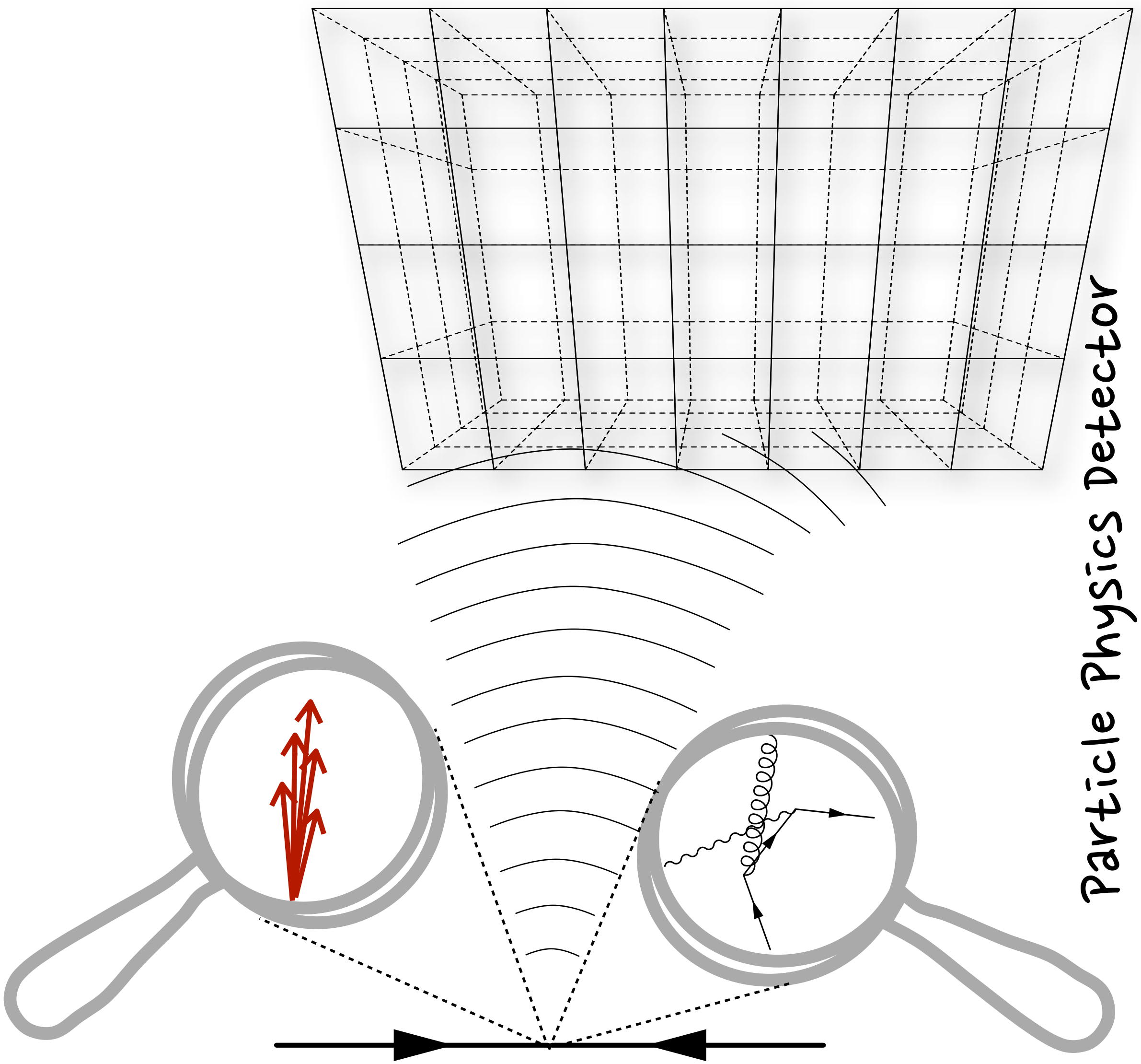
- **Visible particles =>**
  - detector hits



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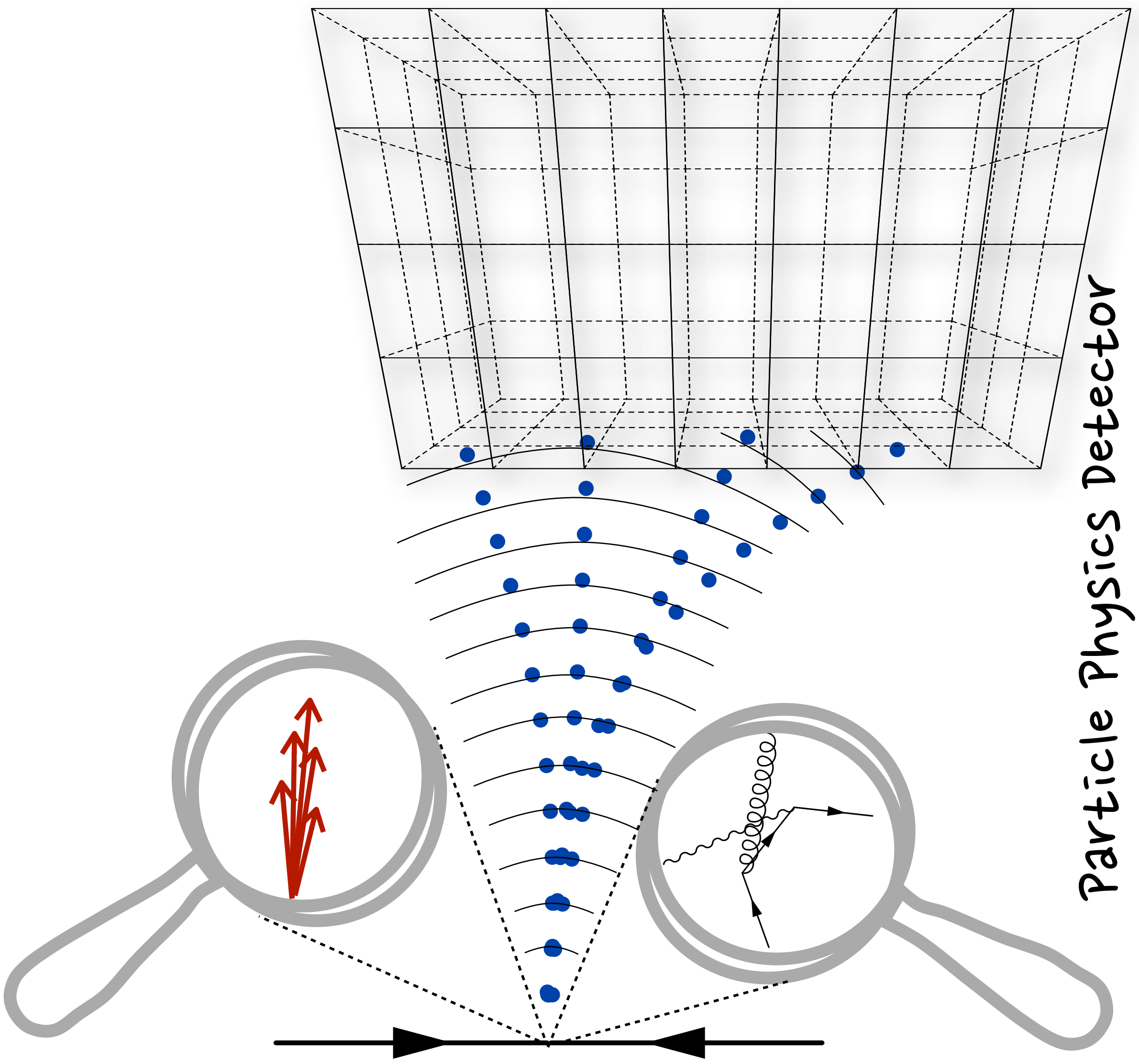

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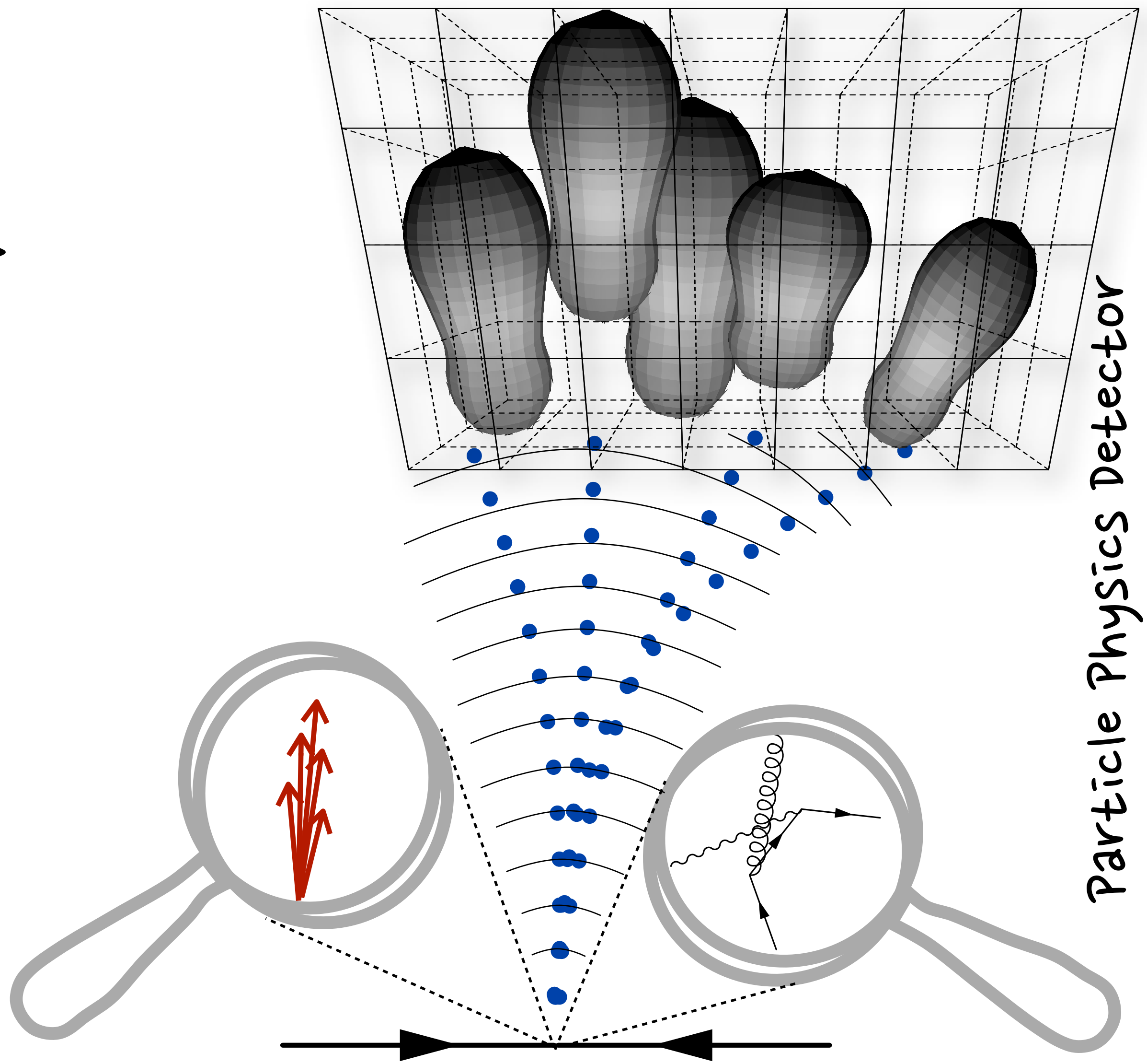

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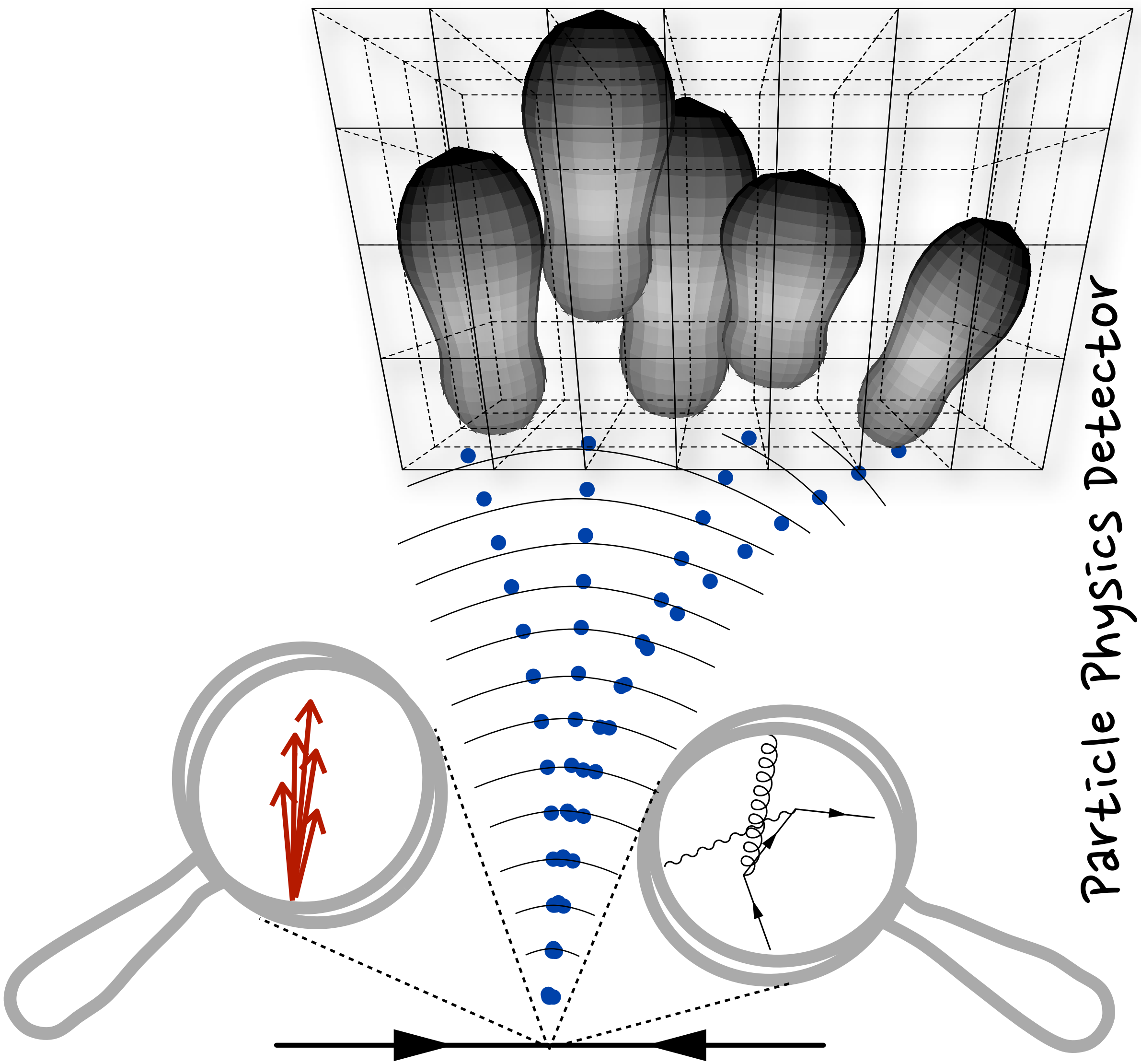

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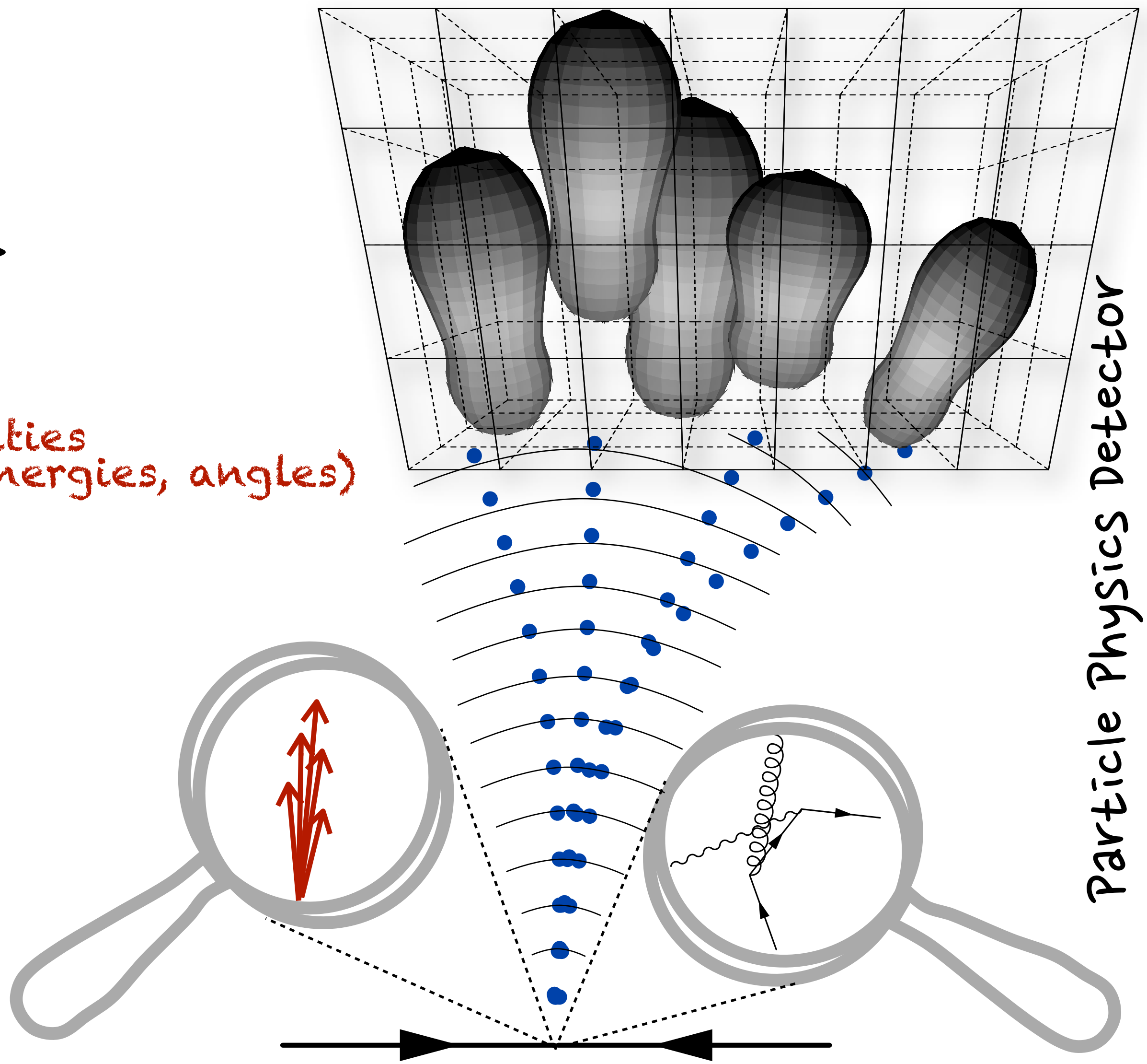

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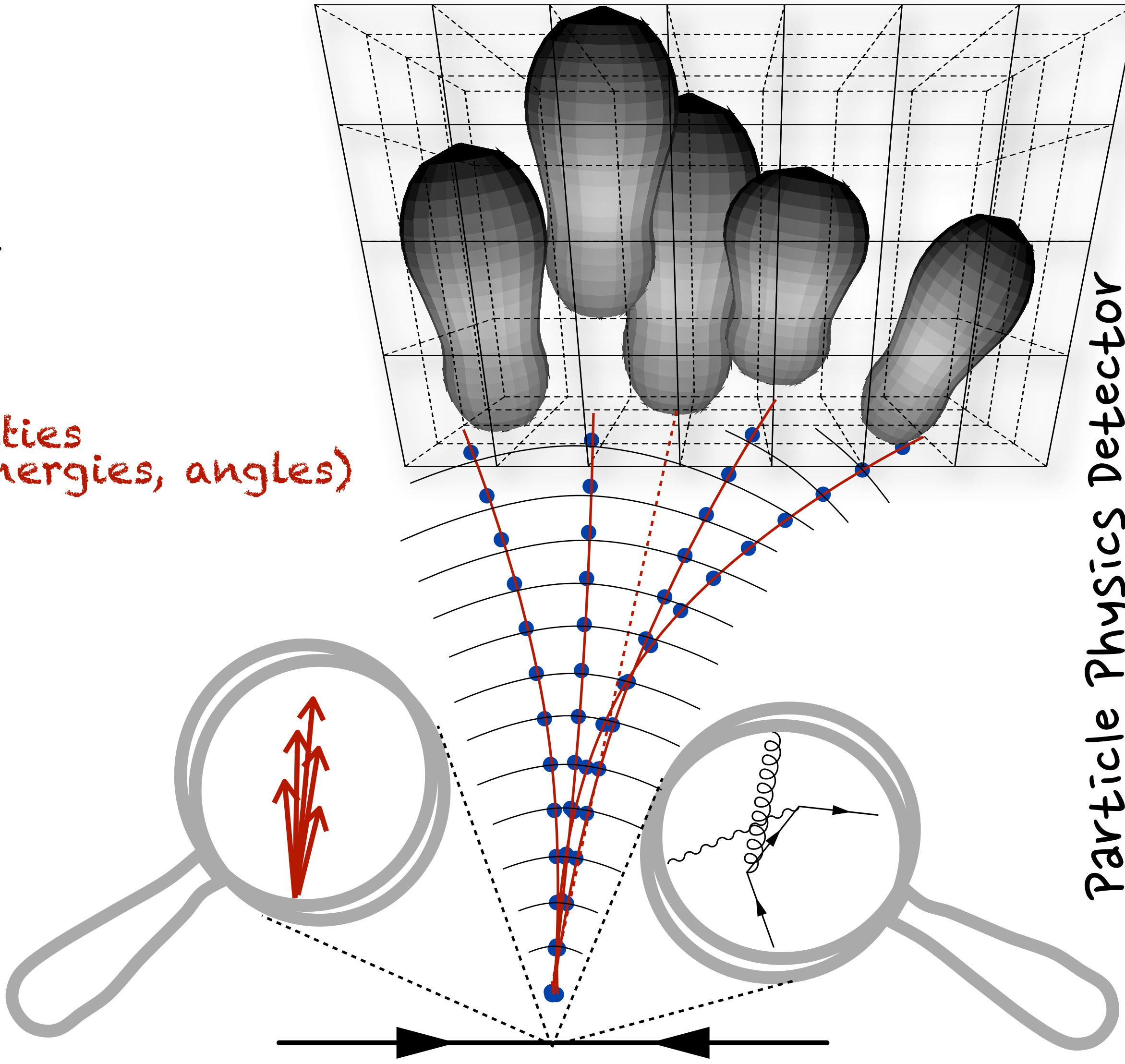

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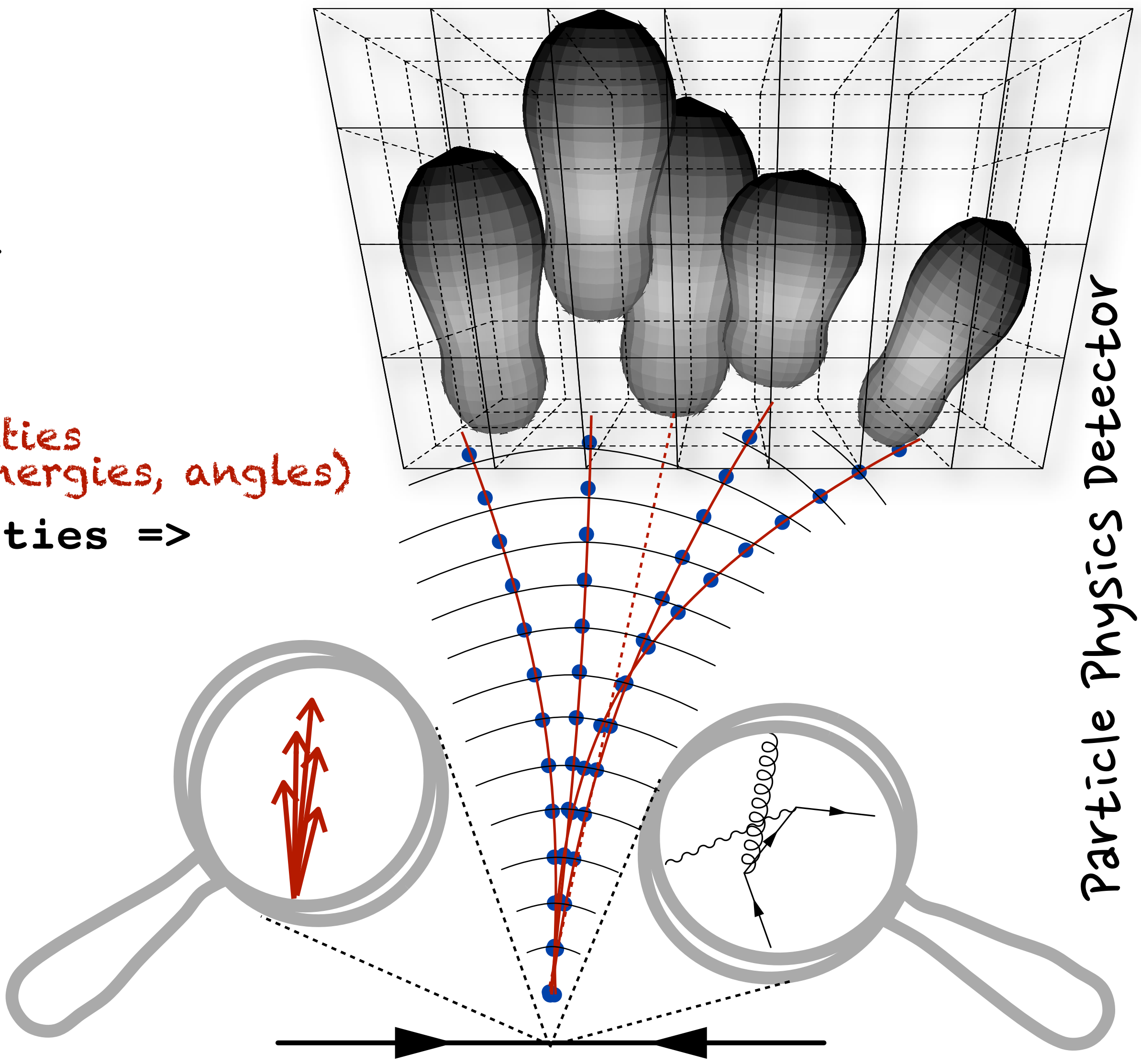

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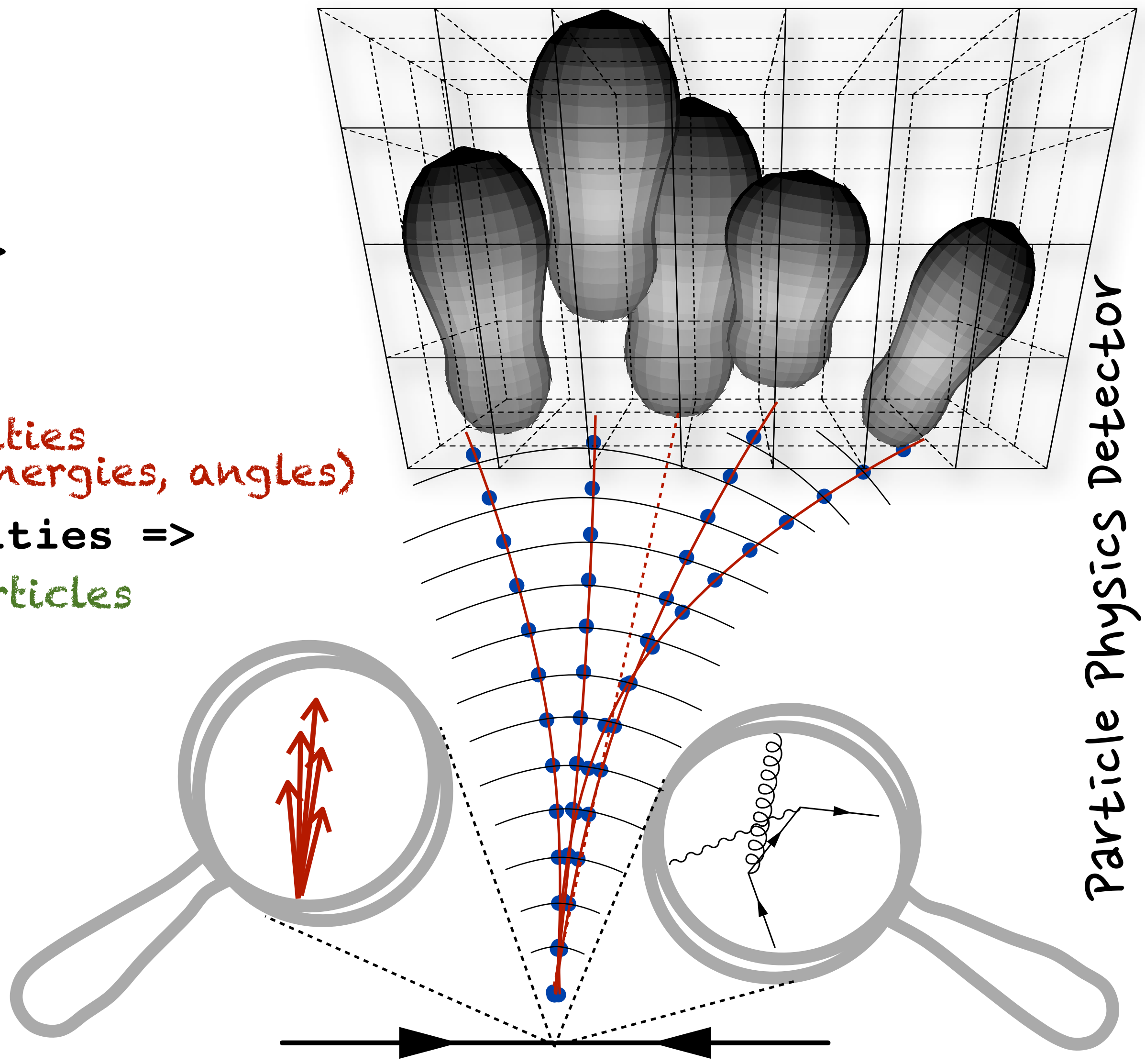

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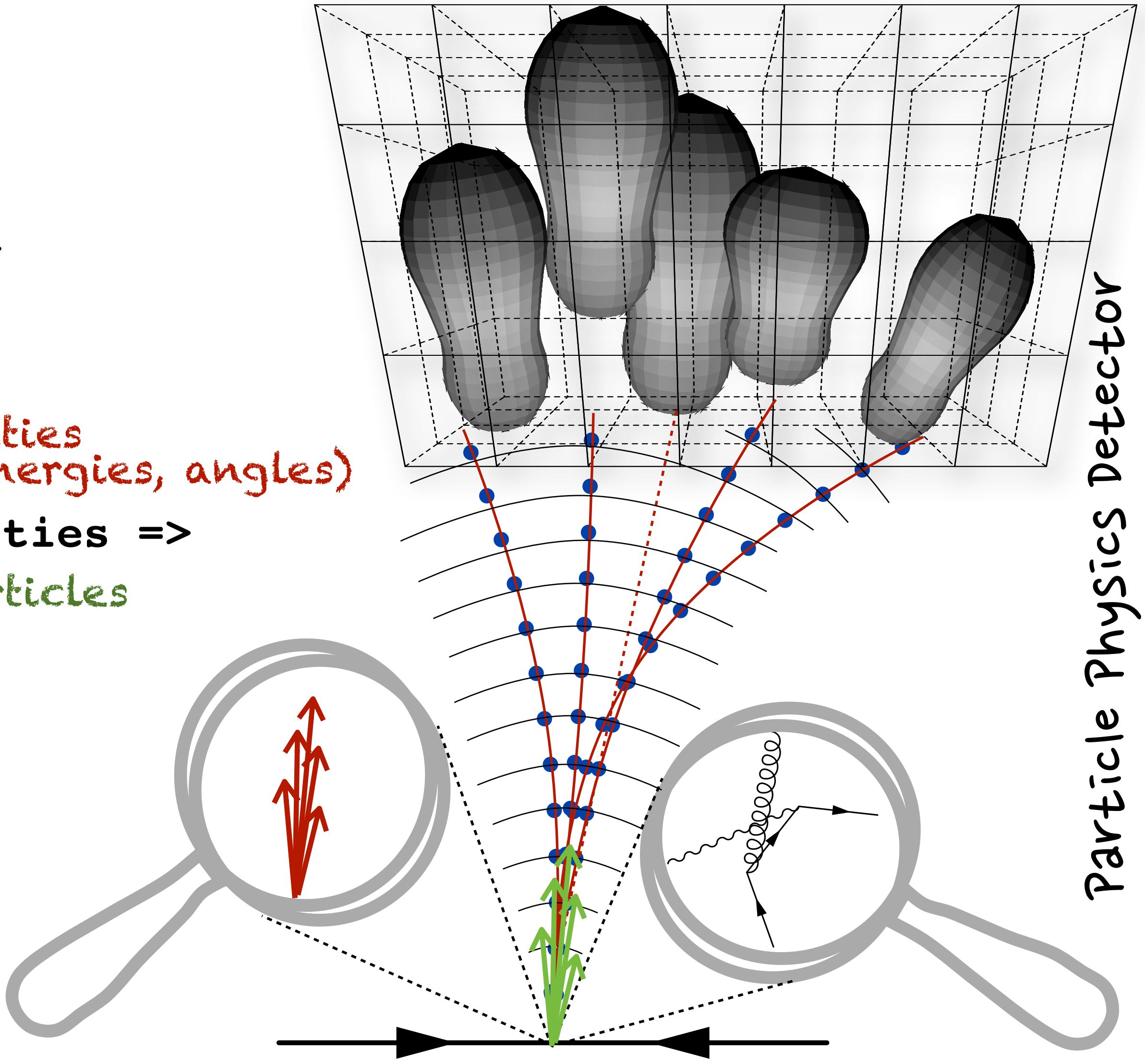

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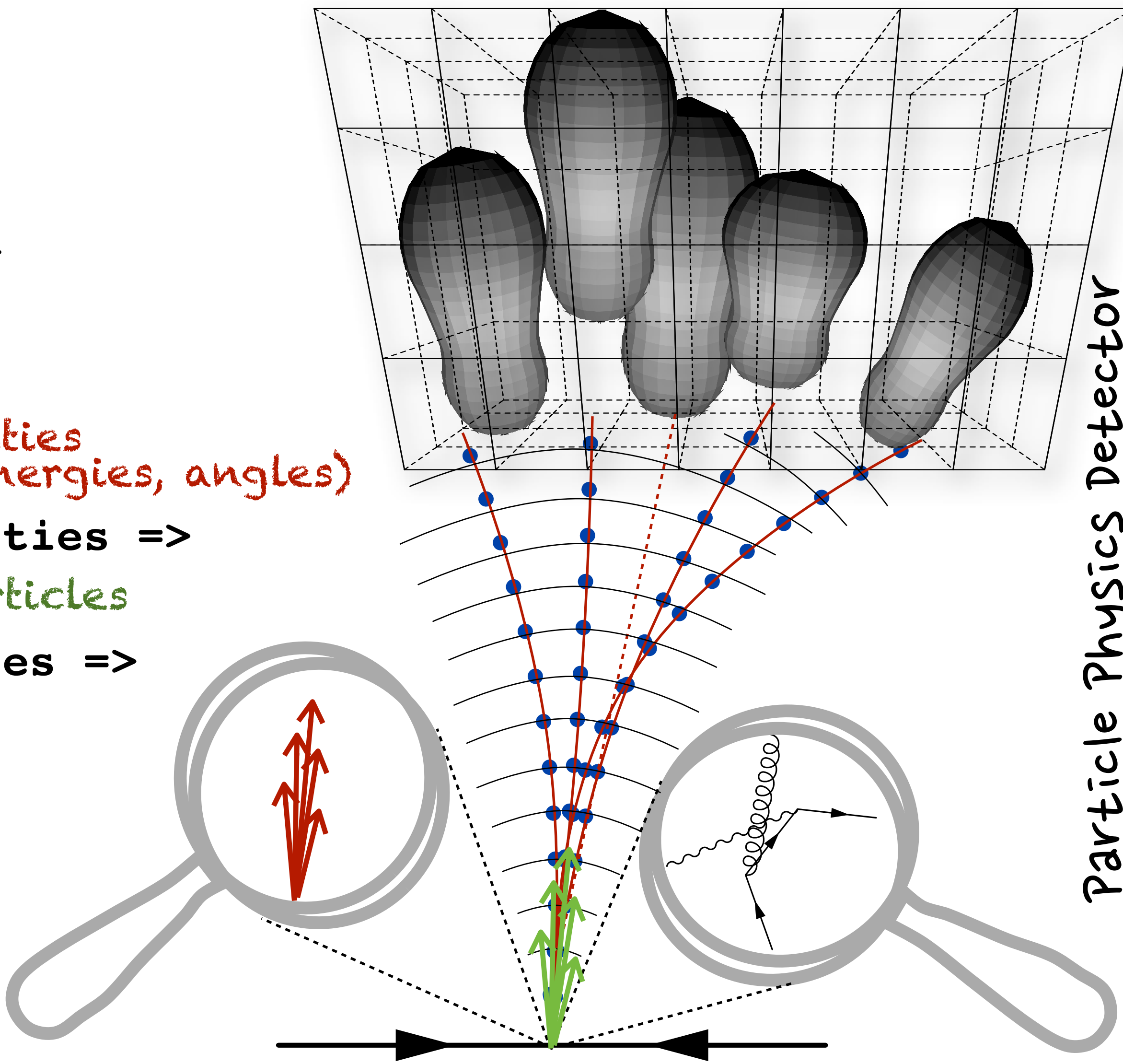

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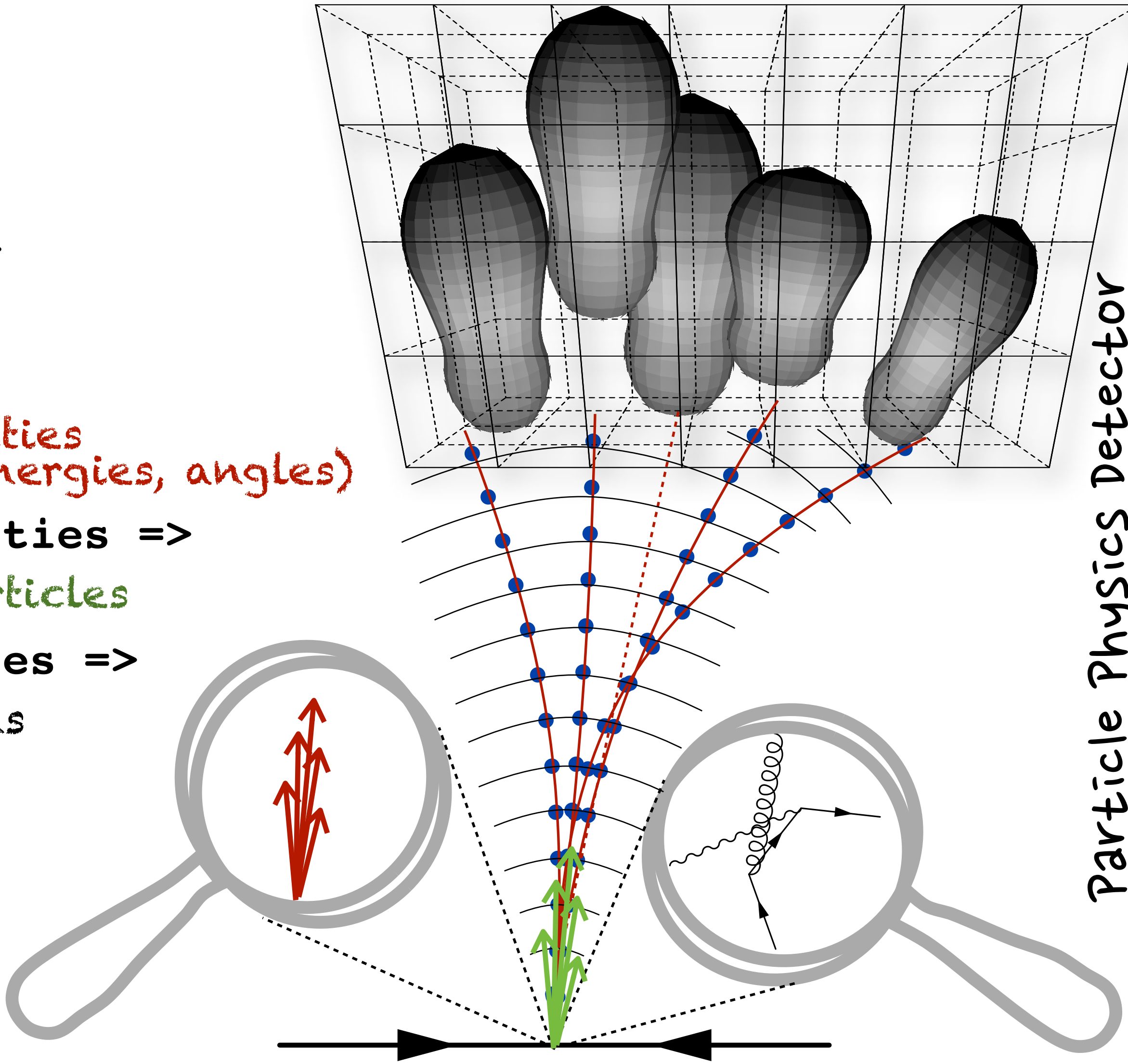

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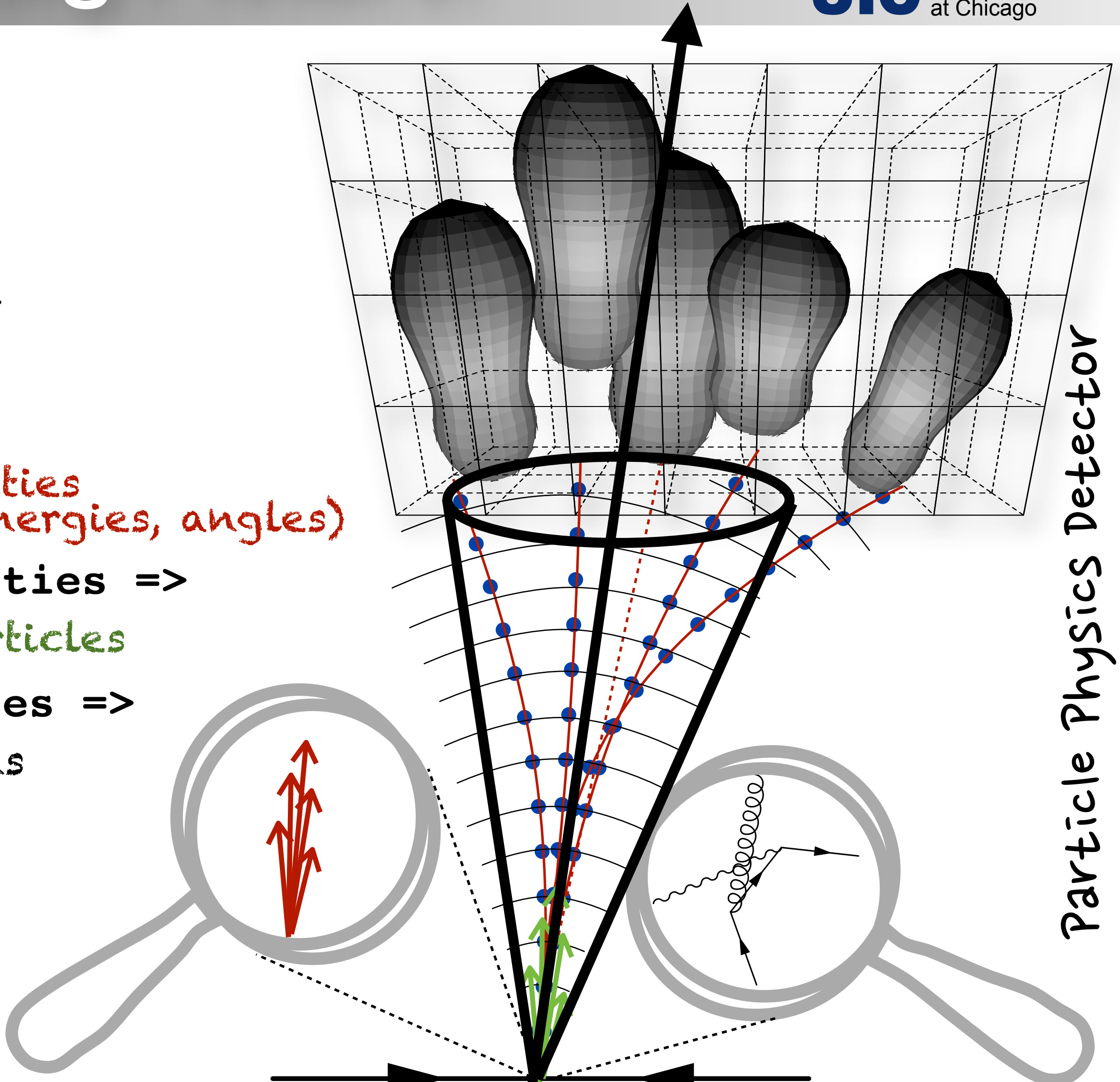

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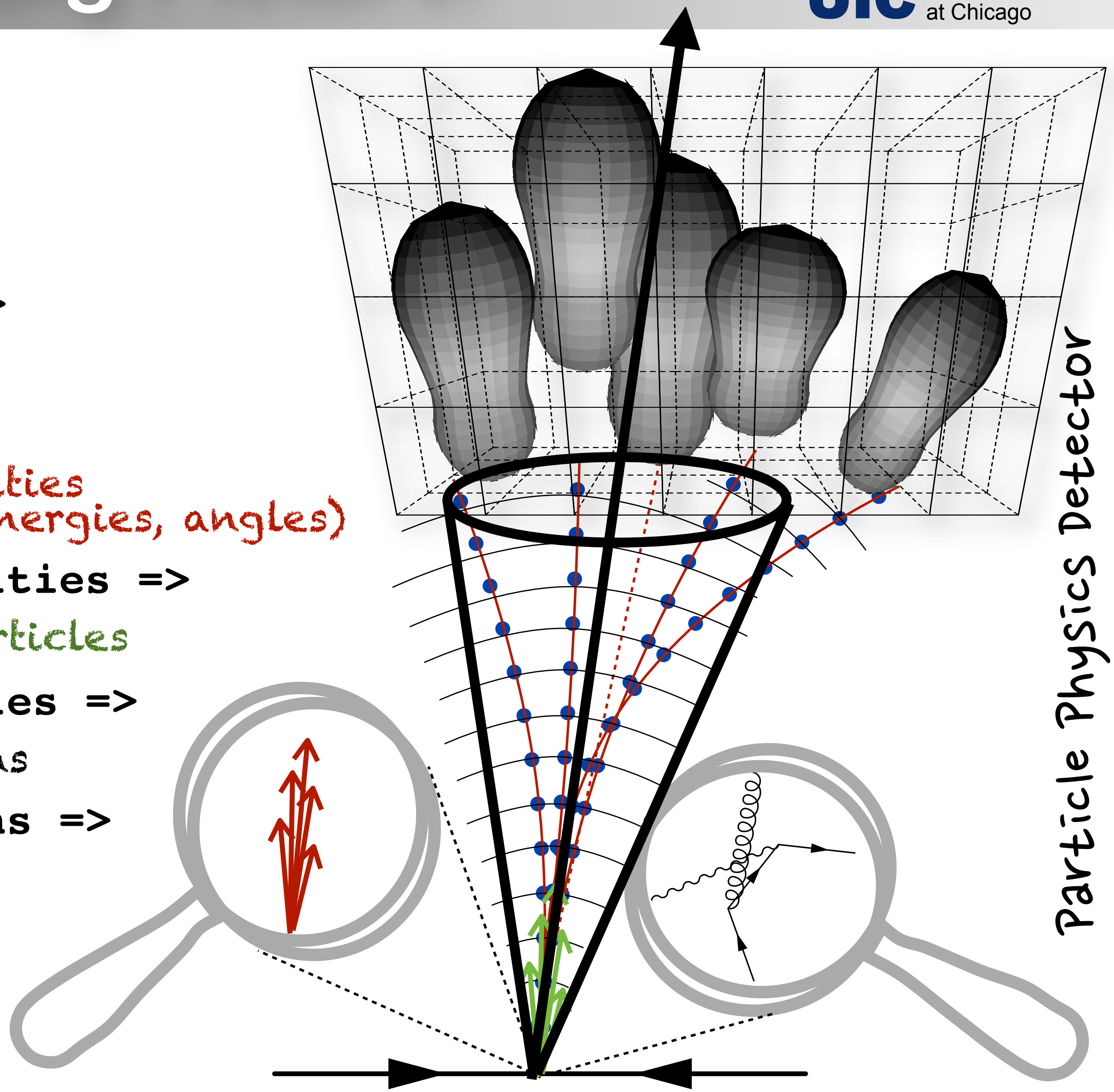

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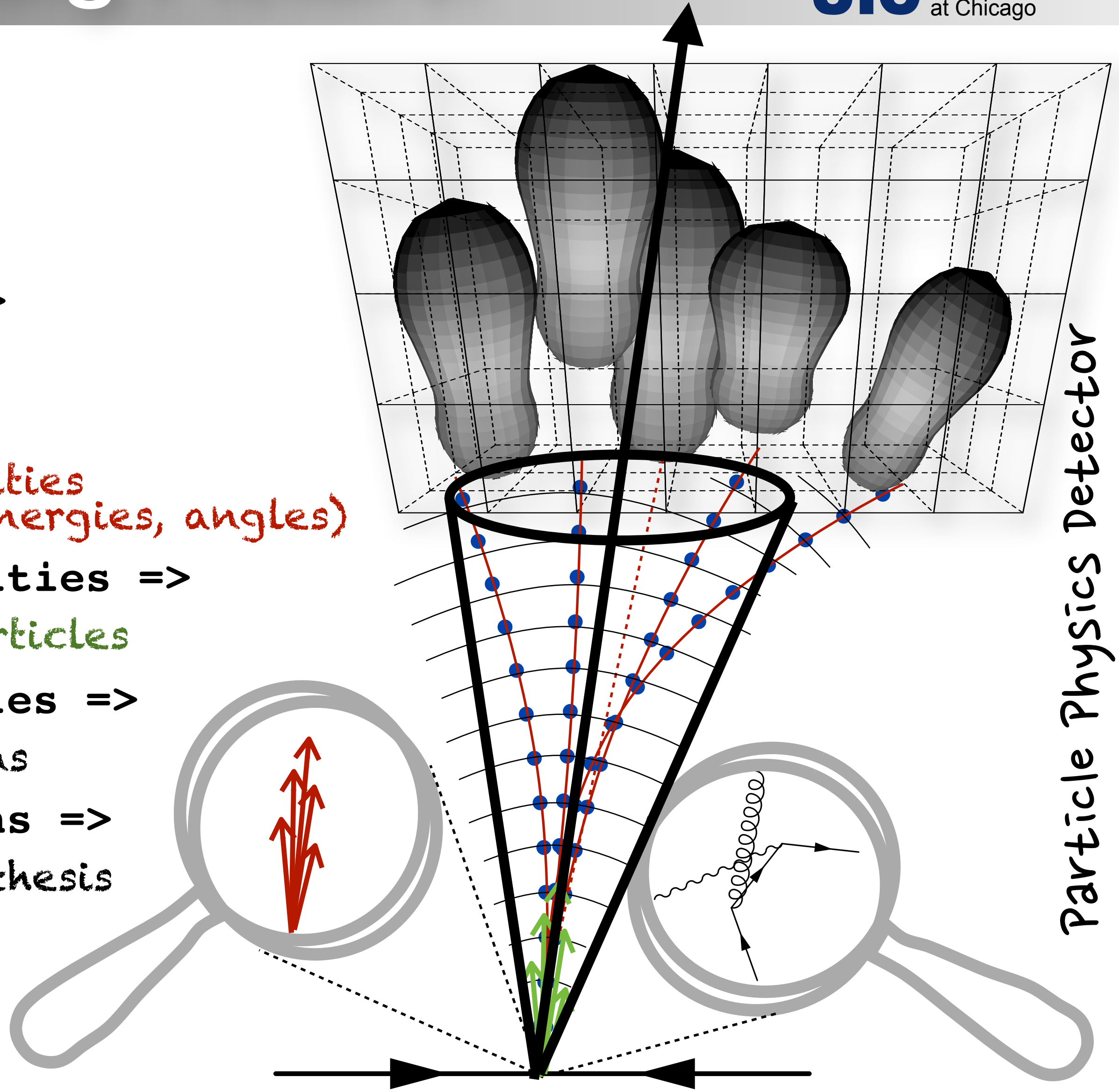
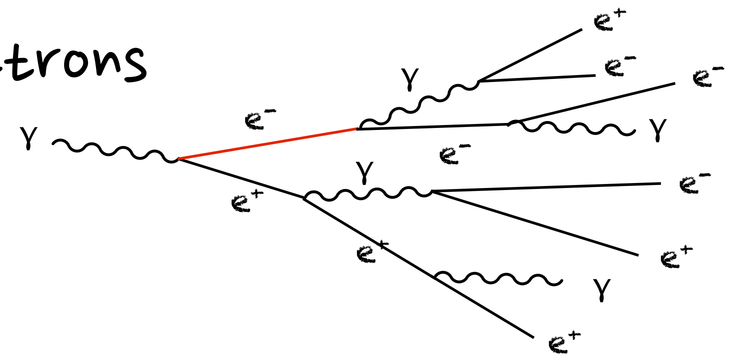


Particle interactions in material

Photons

Electrons



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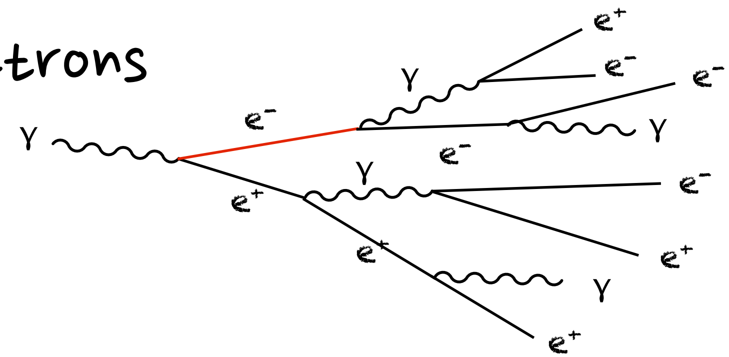
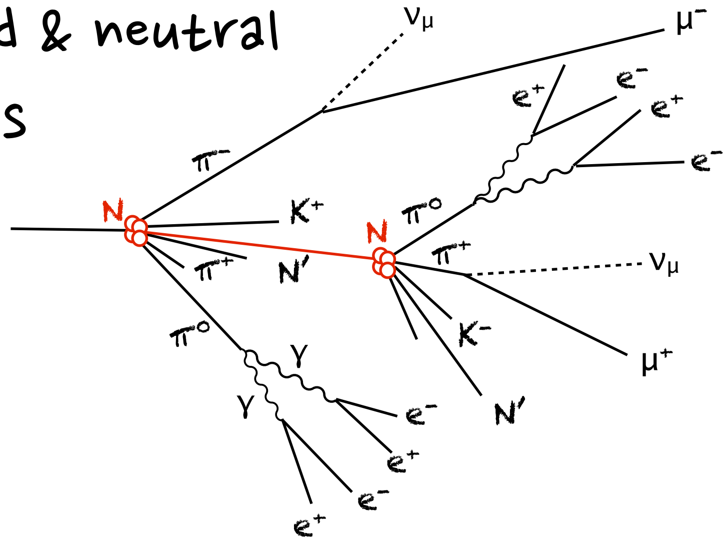


Particle interactions in material

charged & neutral hadrons



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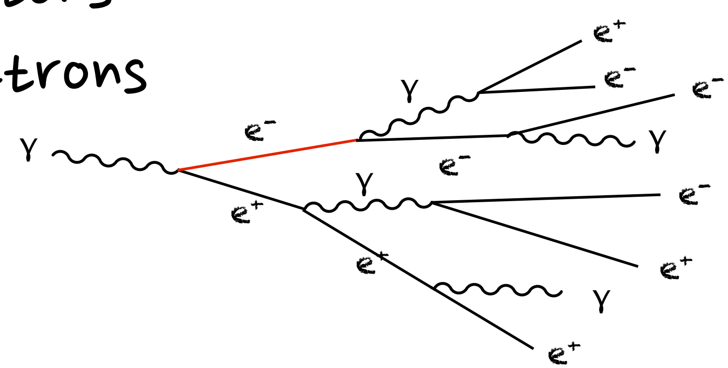

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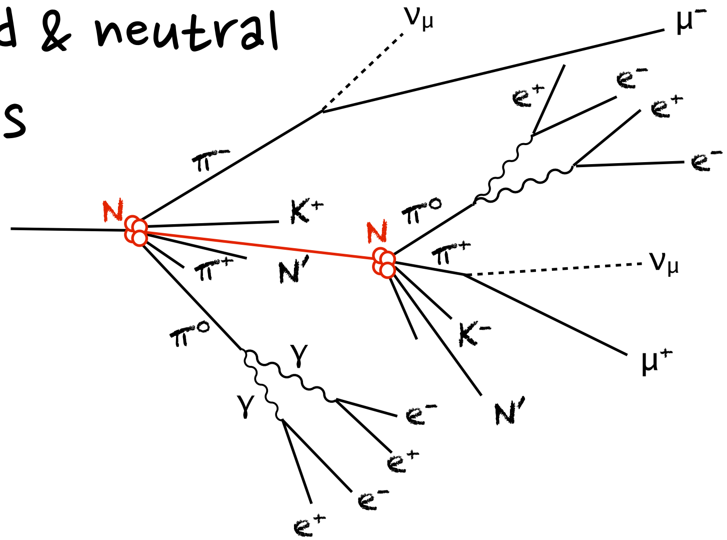

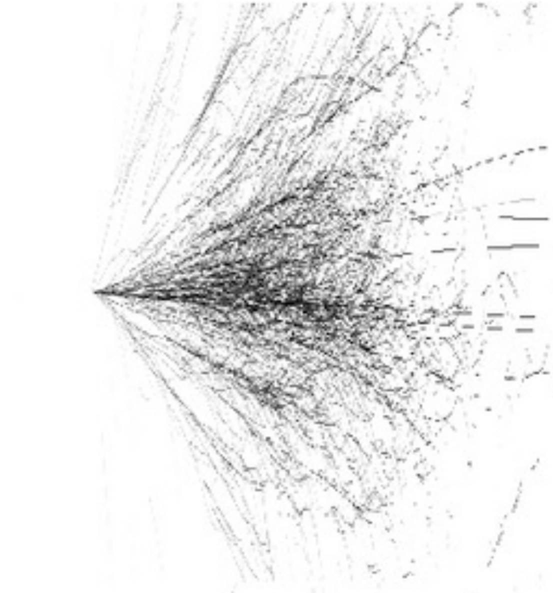

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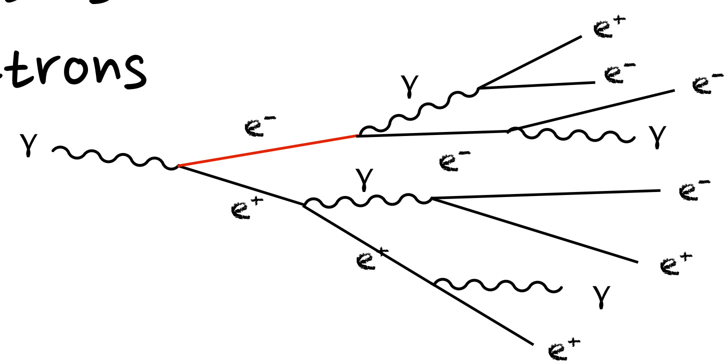

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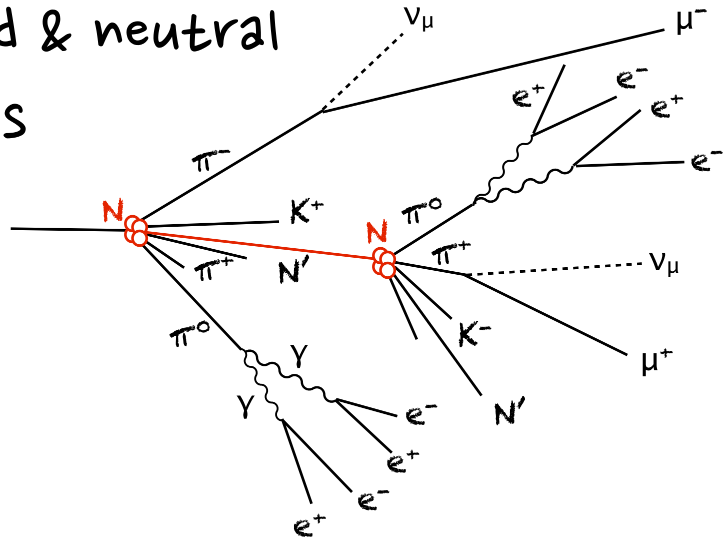

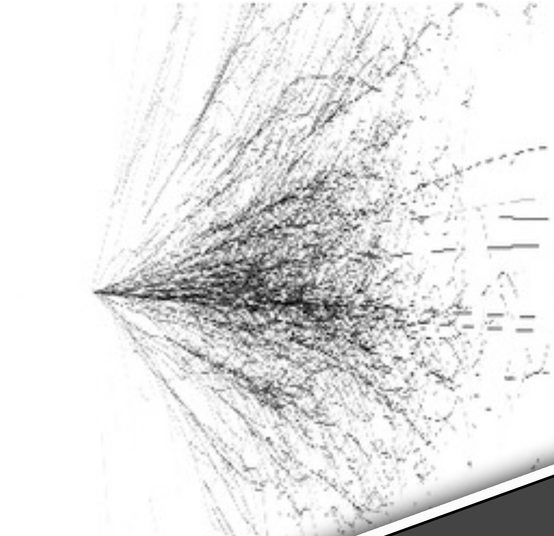

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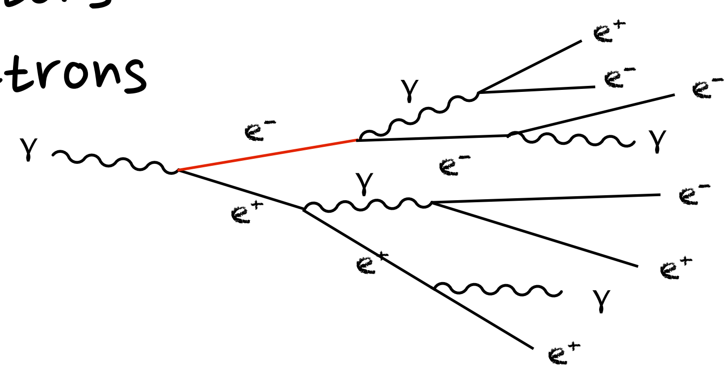

Radiation Length

- Characteristic distance over which the electron energy is reduced by a factor of 1/e due to radiation losses only

$$X_0 = \frac{716.4 \text{ g cm}^{-2} A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

- Higher Z materials have short length
  - want high-Z material for EM calorimeter
- Example: Lead $\rho = 11.4$ g/cm³ ; $X_0 = 5.5$ mm

Particle interactions in m

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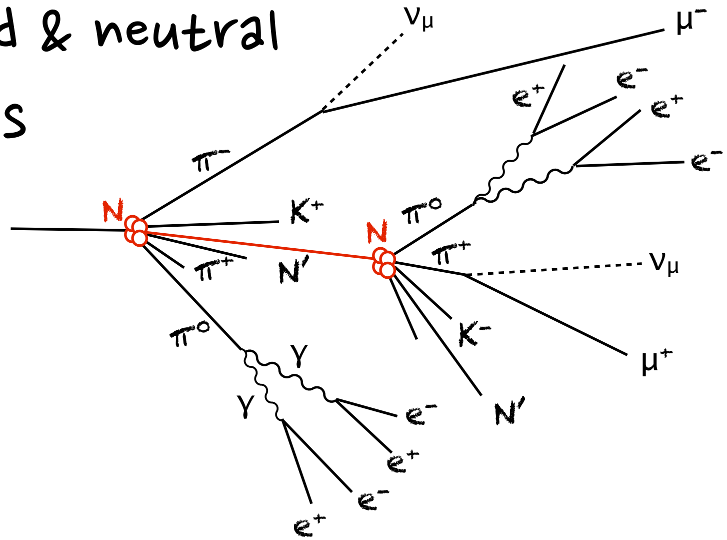

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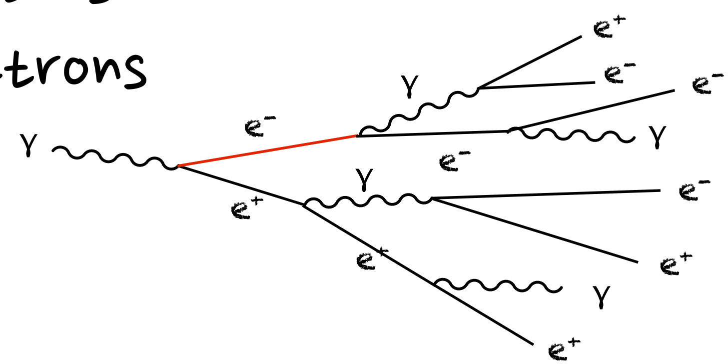

Nuclear Interaction Length

- Collisions of hadrons with nuclei produce hadronic showers

$$\lambda \approx 35\ \mathrm{g\ cm^{-2}}\, A^{1/3}$$

- Nuclear interaction length much longer in high-Z materials than EM radiation length $\lambda > X_0$
  - Hadronic showers develop later than EM showers; more diffuse
- Example: Lead $\lambda = 17$ cm

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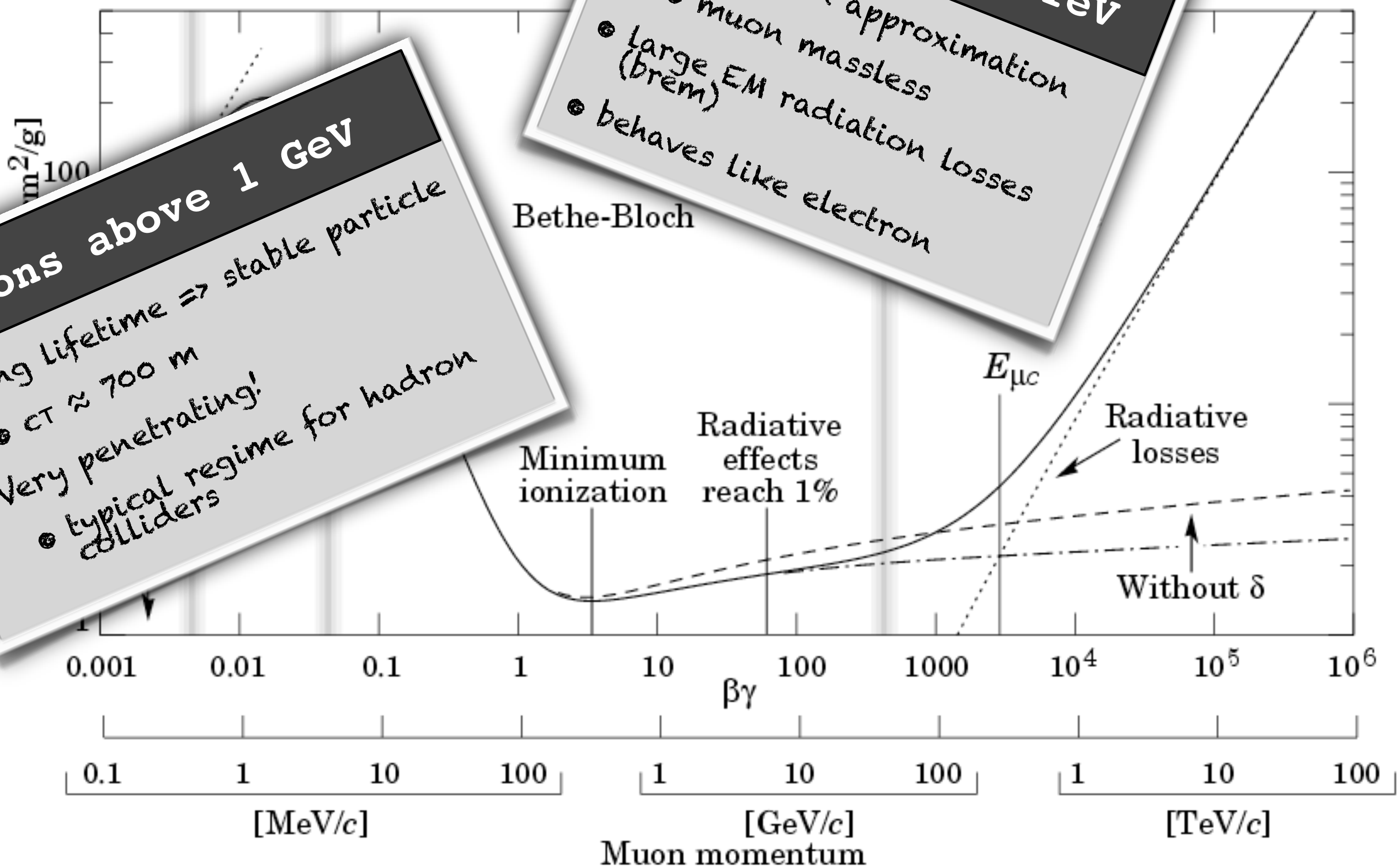


Muons above 1 GeV

- Long lifetime => stable particle
  - cτ ≈ 700 m
- Very penetrating!
  - typical regime for hadron colliders

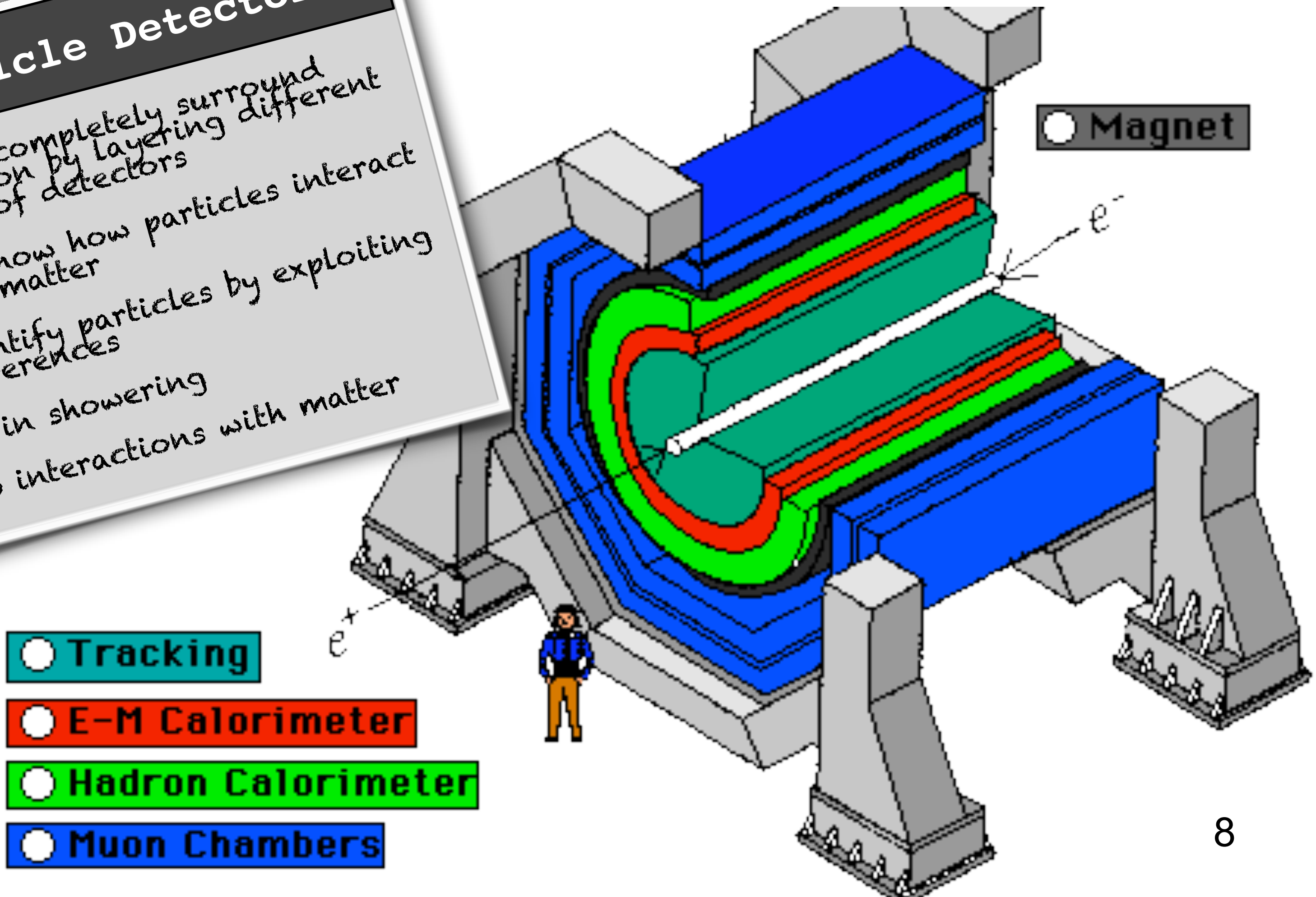
Muons above 1 TeV

- Very good approximation
  - muon massless
- large EM radiation losses (brem)
- behaves like electron

Detecting Particles

Particle Detector

- Goal: completely surround collision by layering different types of detectors
- We know how particles interact with matter
- Identify particles by exploiting differences
  - in showering
  - interactions with matter



8

Detecting Particles

Particle Detector

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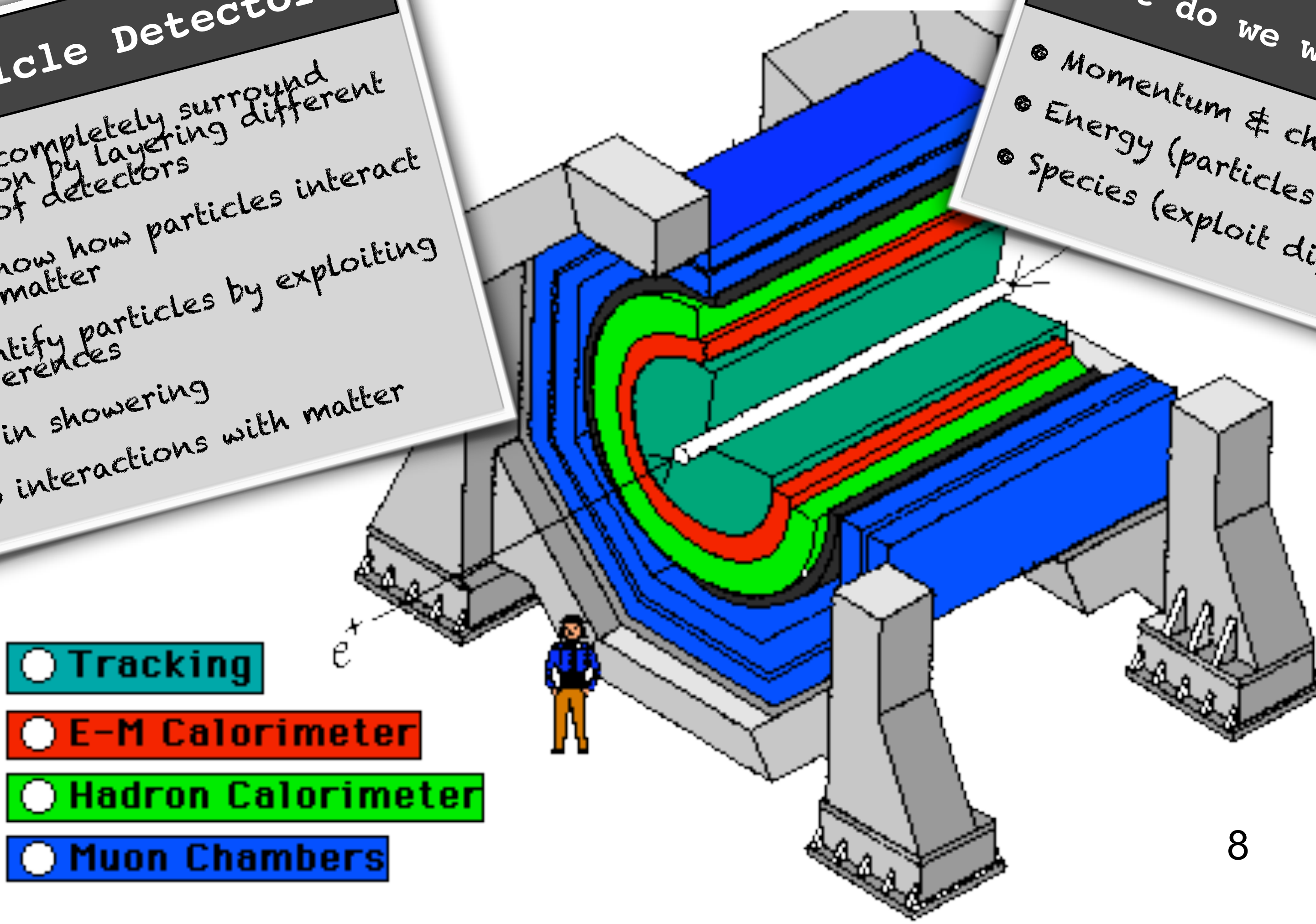
What do we want to know?

- Momentum & charge (B-field)
- Energy (particles are absorbed)
- Species (exploit differences)



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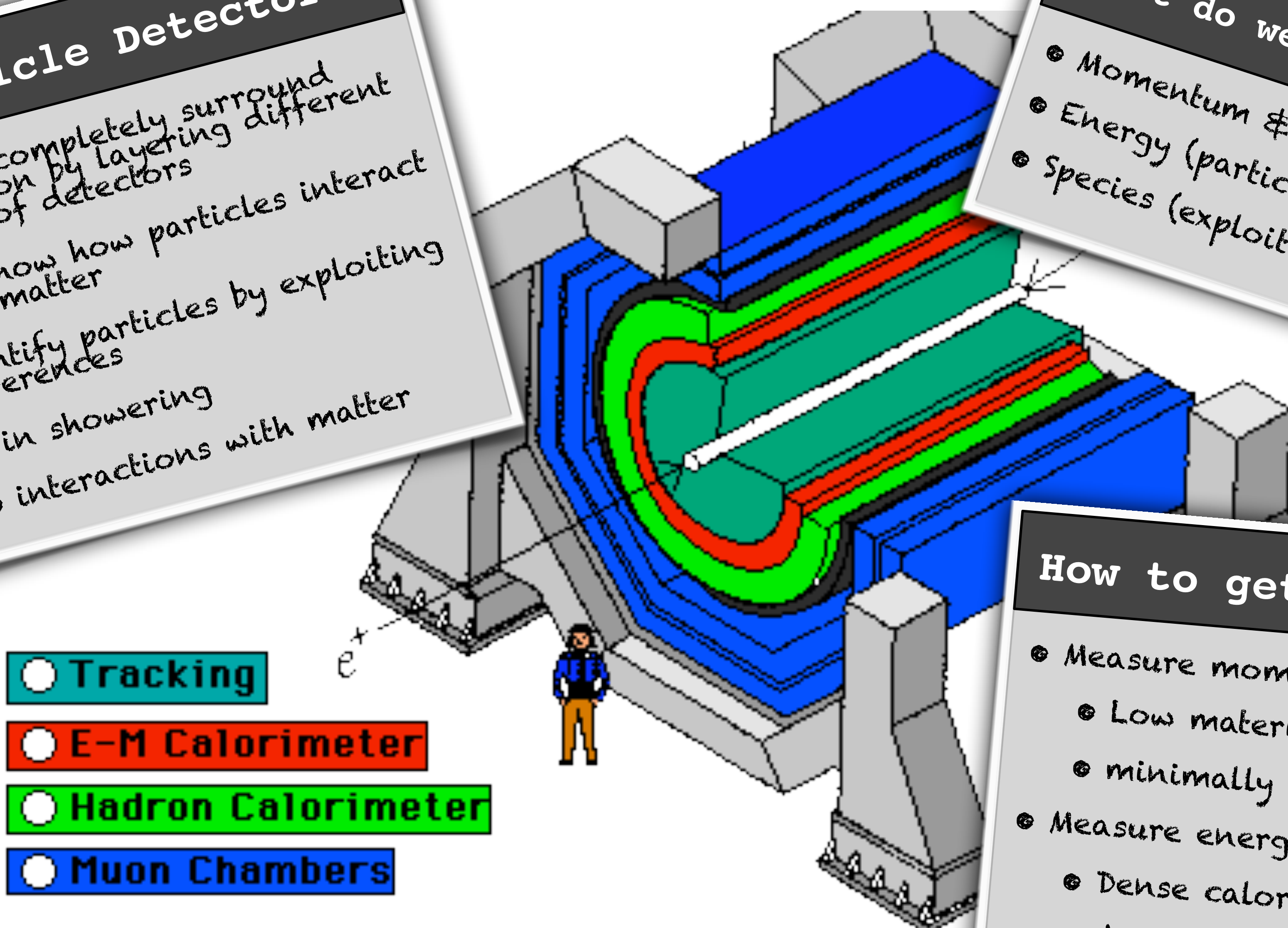
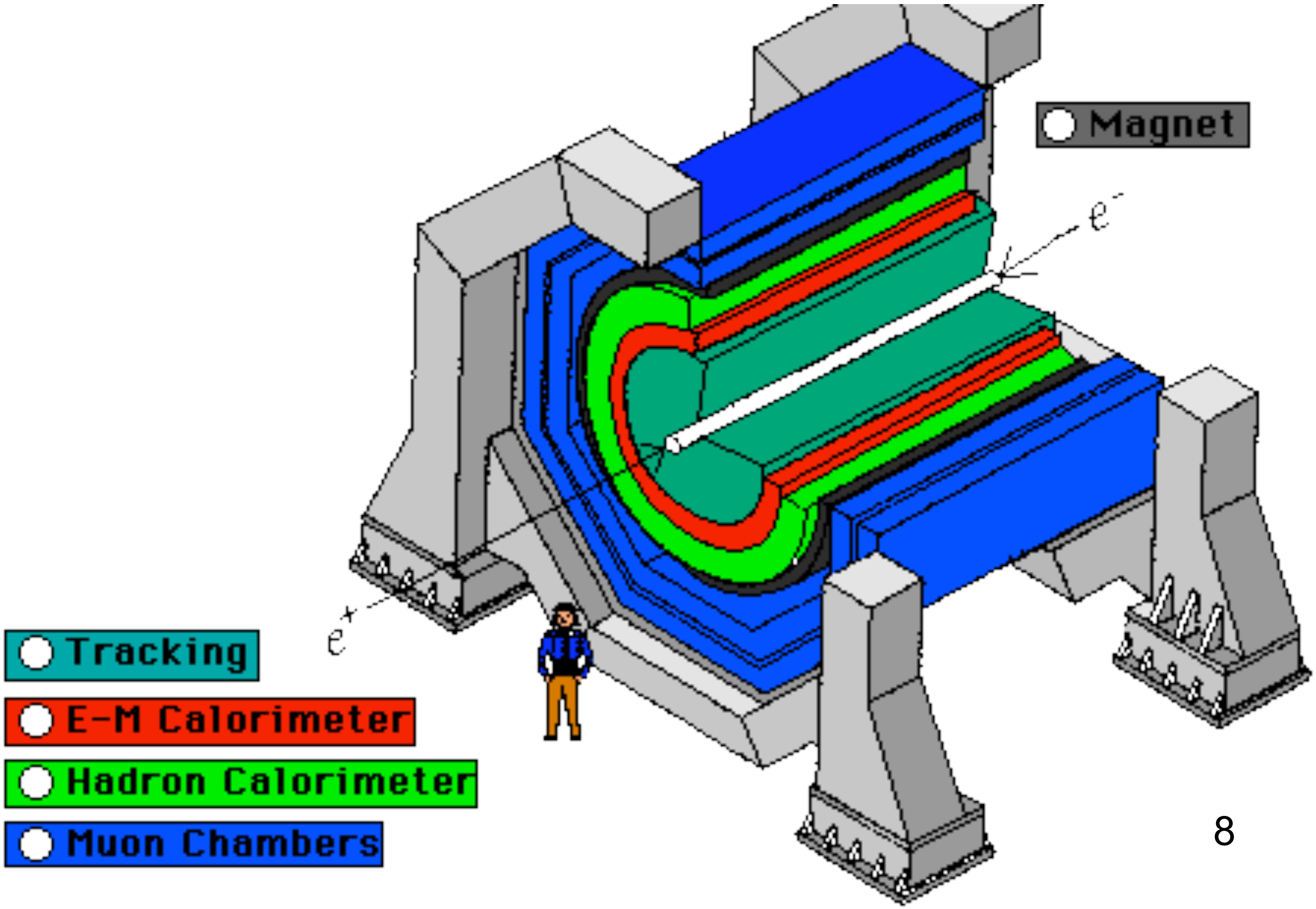


How to get that info?

- Measure momentum first
  - Low material tracking!
  - minimally disrupt particle
- Measure energy later
  - Dense calorimetry
  - destroy particle
- Note! There is redundant information in track momentum and calorimeter energy!

Detecting Particles

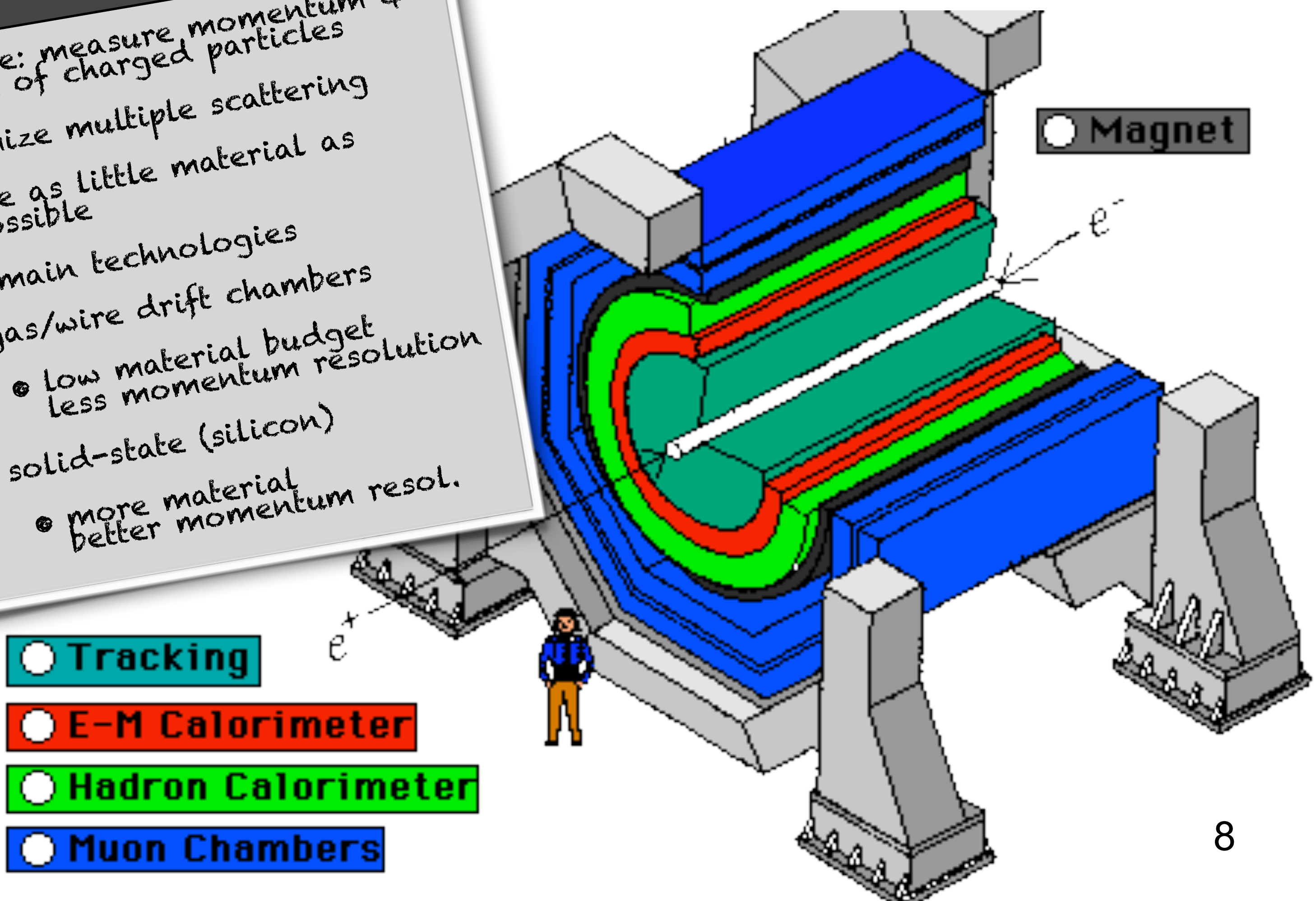


8

cting Particles

Inner Tracking Detectors

- Purpose: measure momentum & charge of charged particles
- minimize multiple scattering
  - use as little material as possible
- two main technologies
  - gas/wire drift chambers
    - low material budget less momentum resolution
  - solid-state (silicon)
    - more material better momentum resol.



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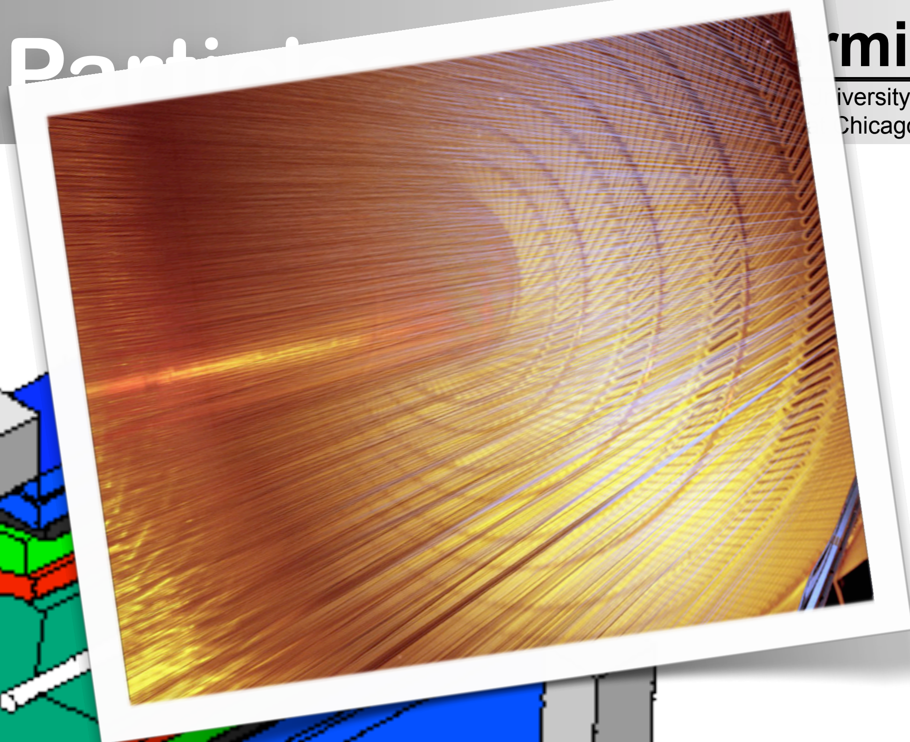

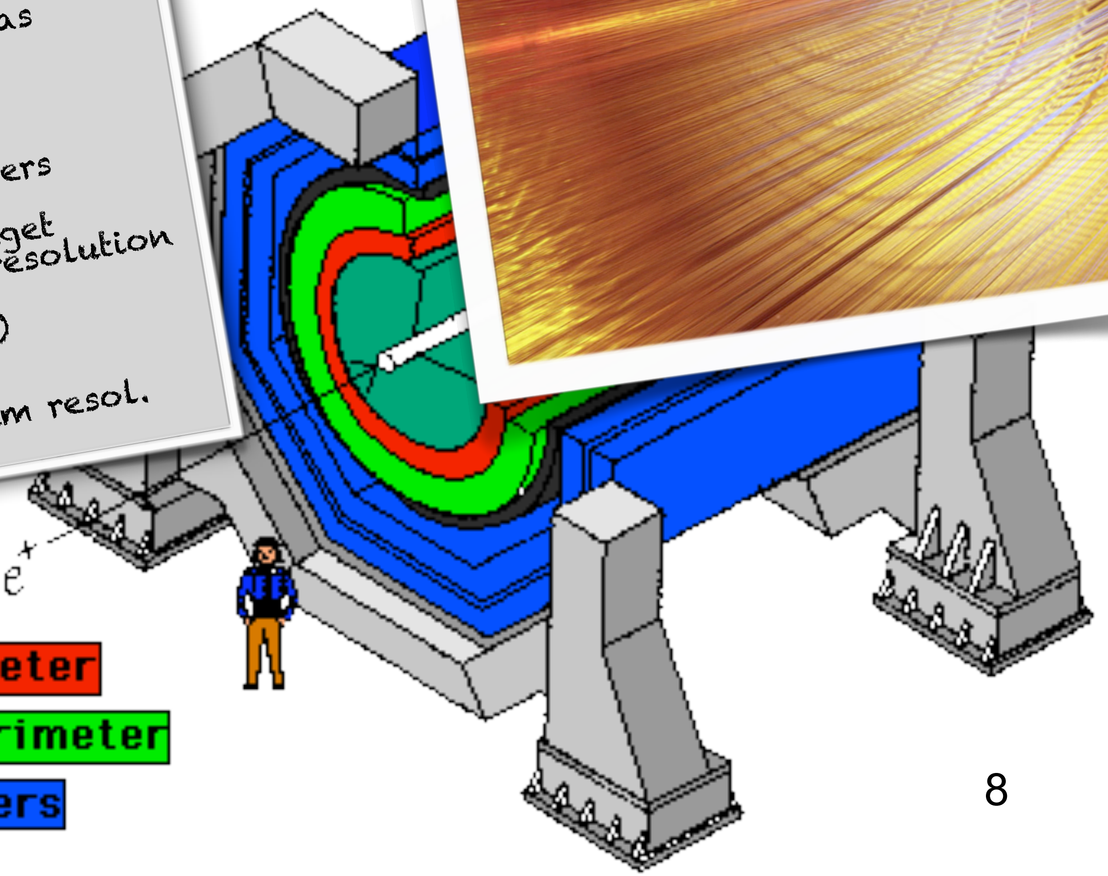

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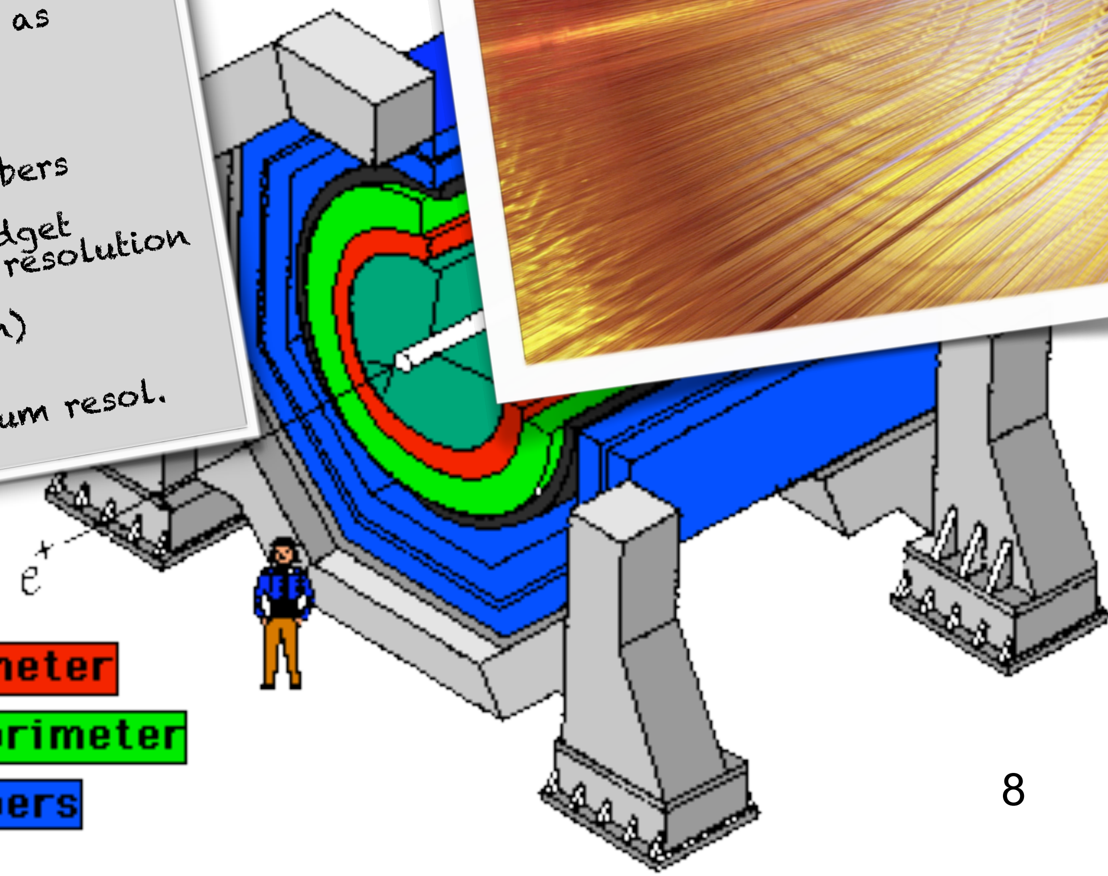

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Chicago

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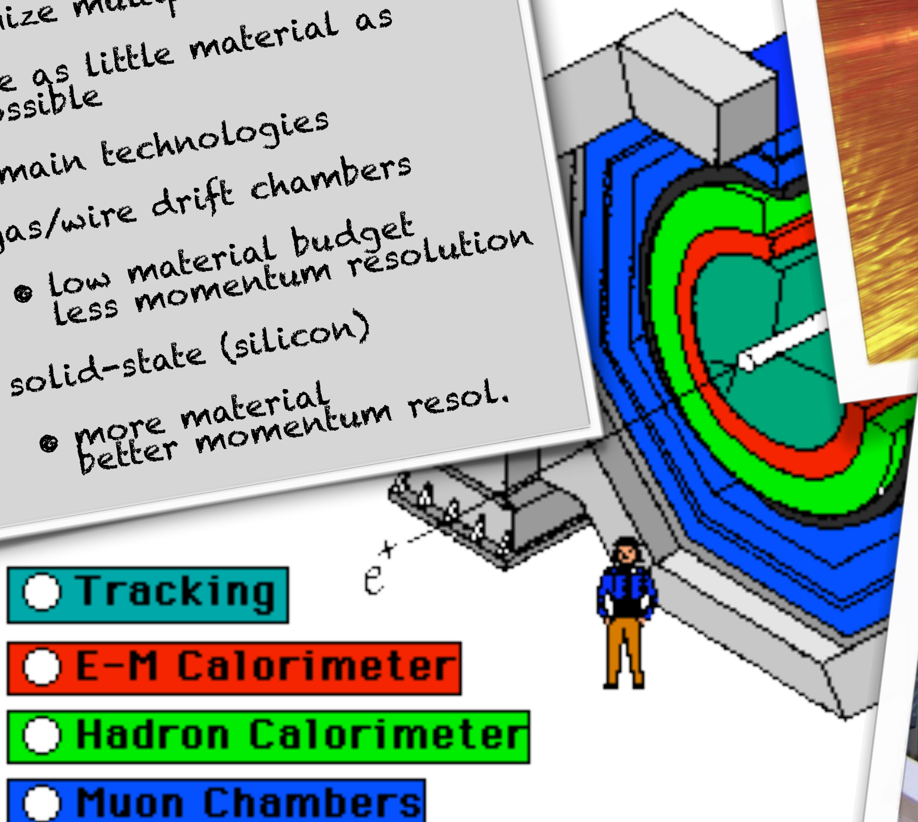

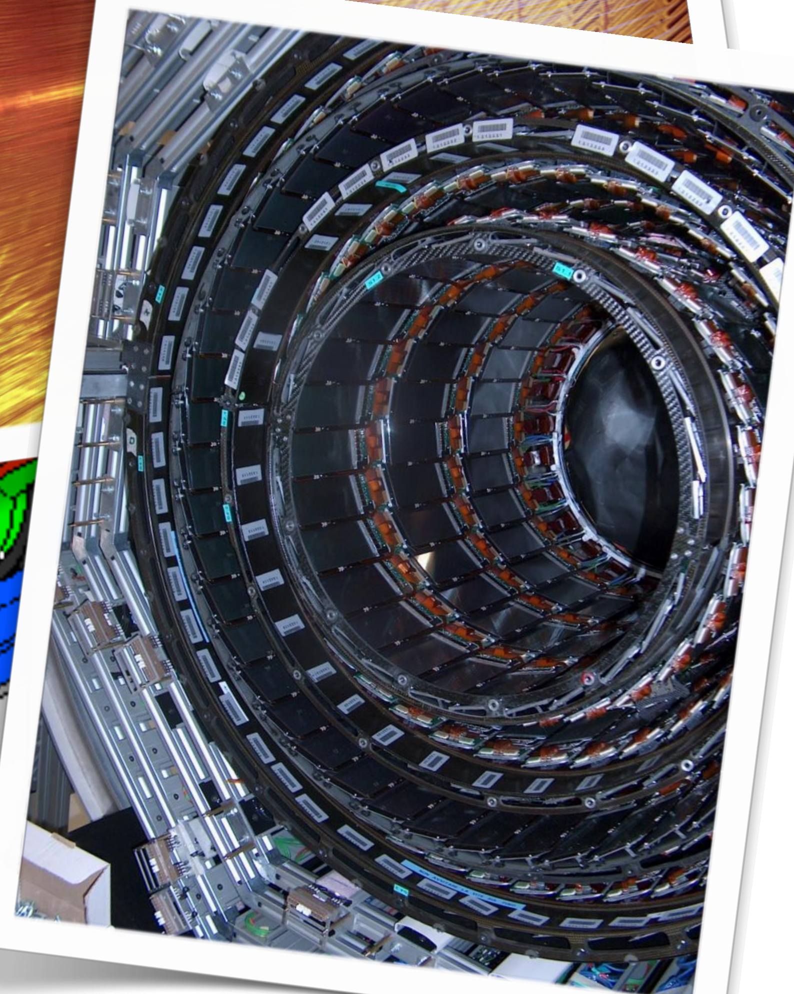

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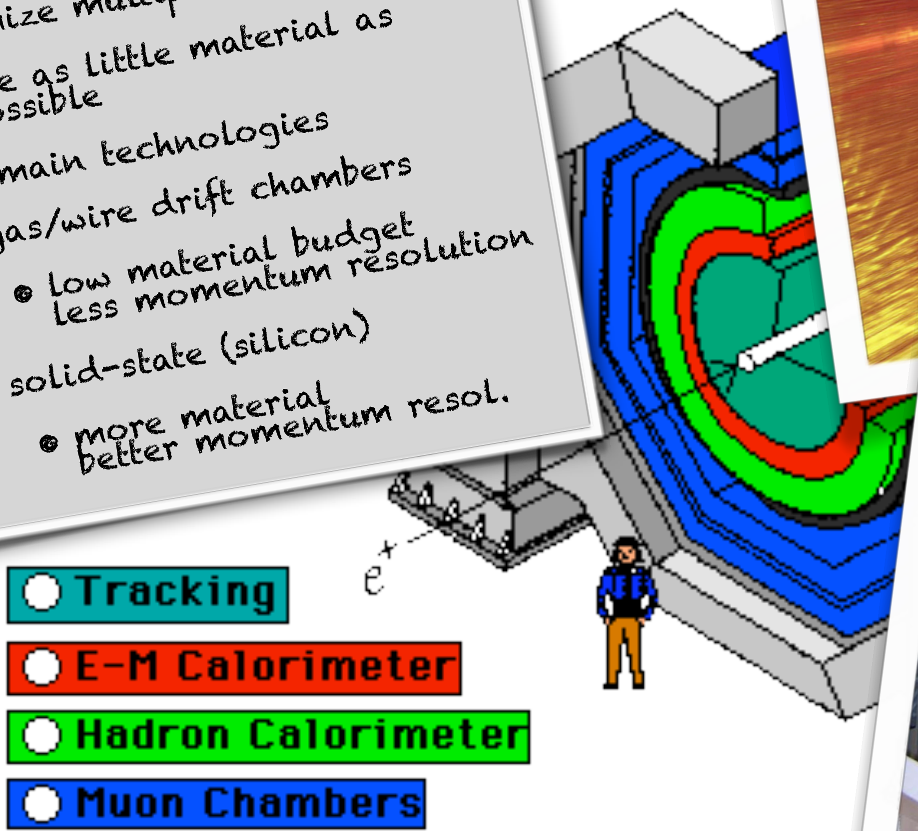

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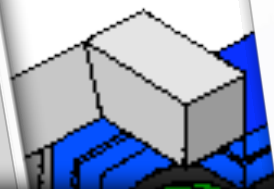
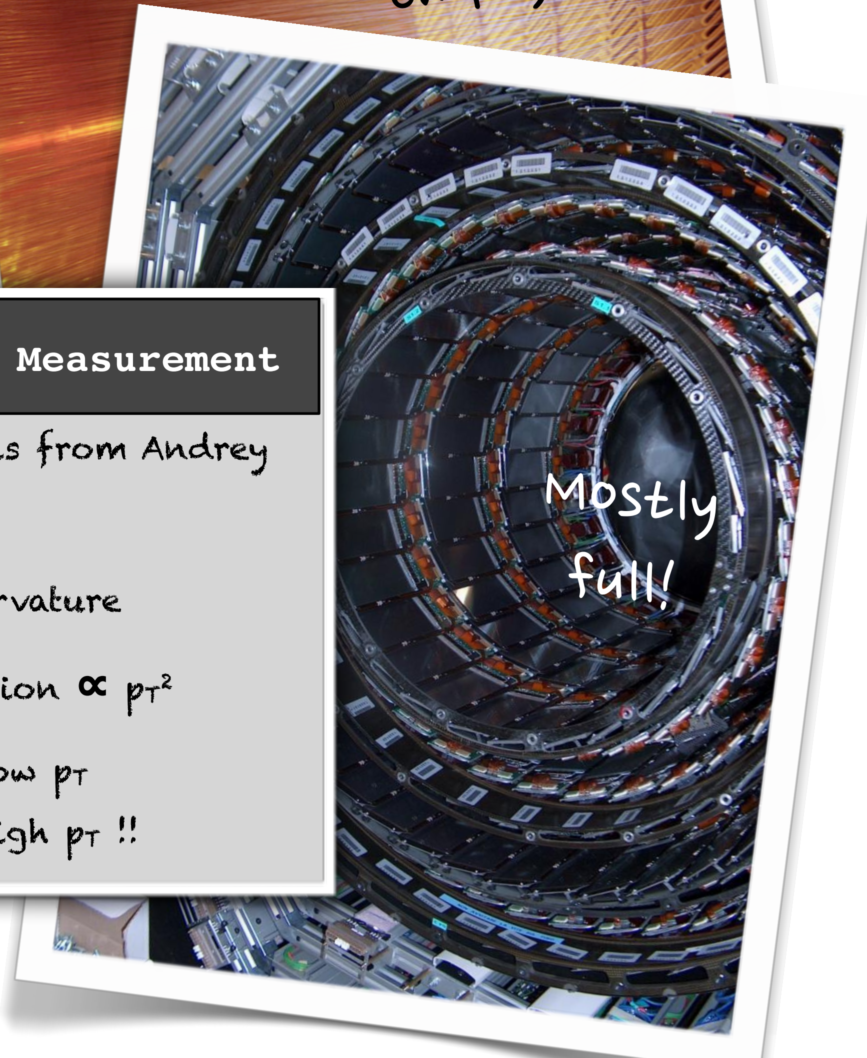


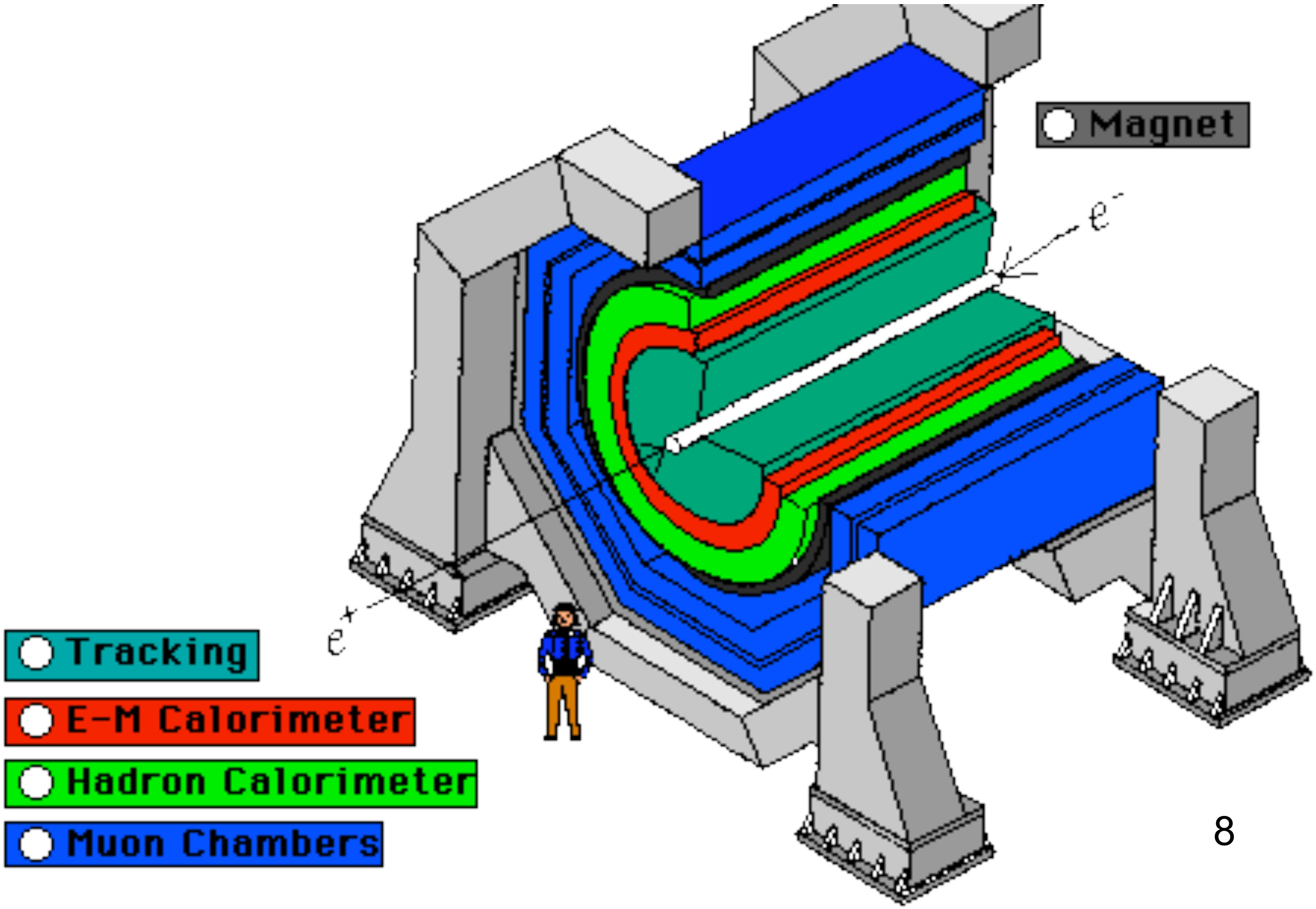
- Tracking
- E-M Calorime...
- Hadron Calor...
- Muon Chambers



Momentum & Charge Measurement

- You already know this from Andrey Korytov's lectures!
- Reminder:
  - $p_T \propto$ radius of curvature
  - Momentum resolution $\propto p_T^2$
    - gets better at low p_T
    - gets worse at high p_T !!

Detecting Particles

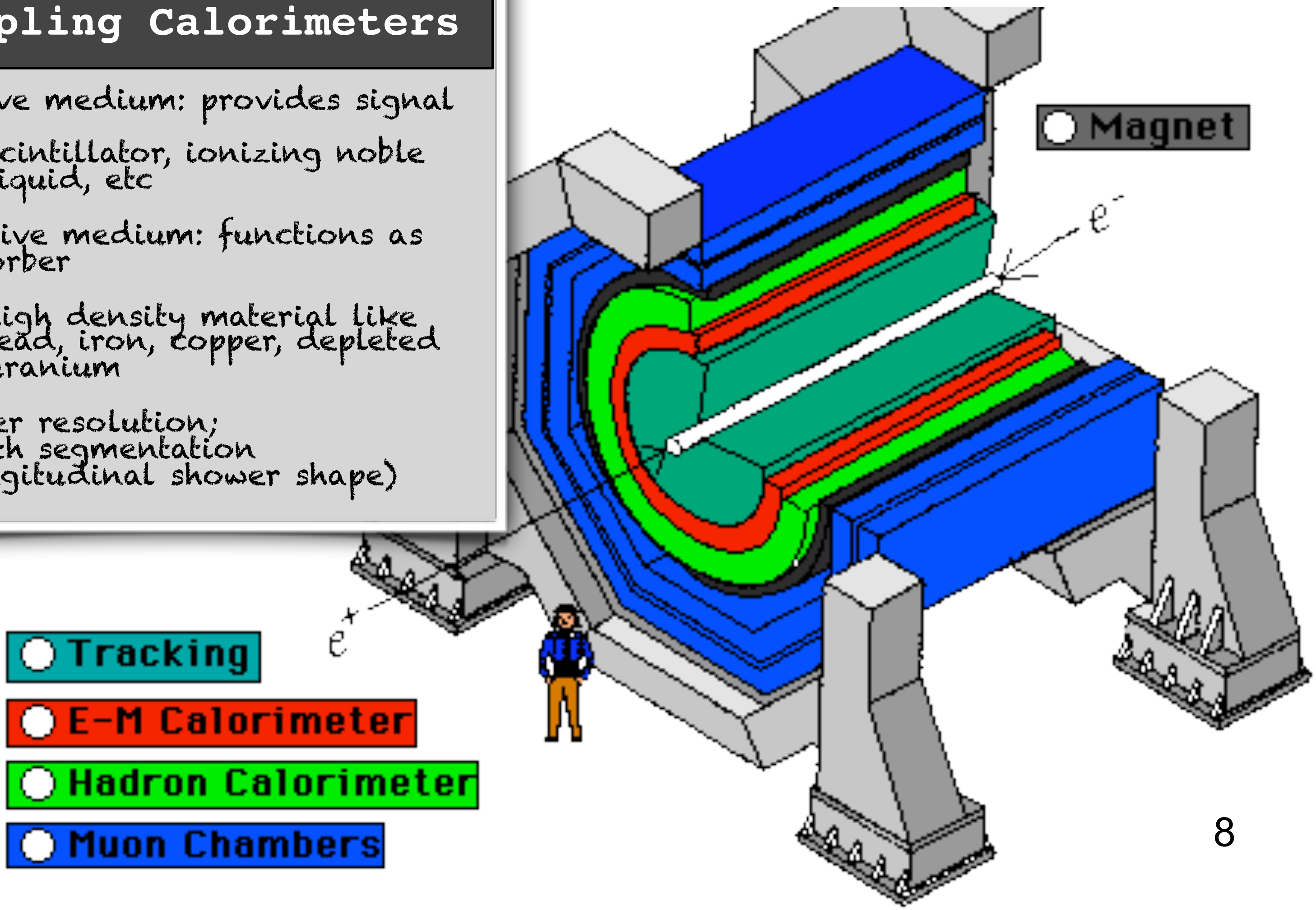


8

Detecting Particles

Sampling Calorimeters

- active medium: provides signal
  - scintillator, ionizing noble liquid, etc
- passive medium: functions as absorber
  - high density material like lead, iron, copper, depleted uranium
- lower resolution; depth segmentation (longitudinal shower shape)



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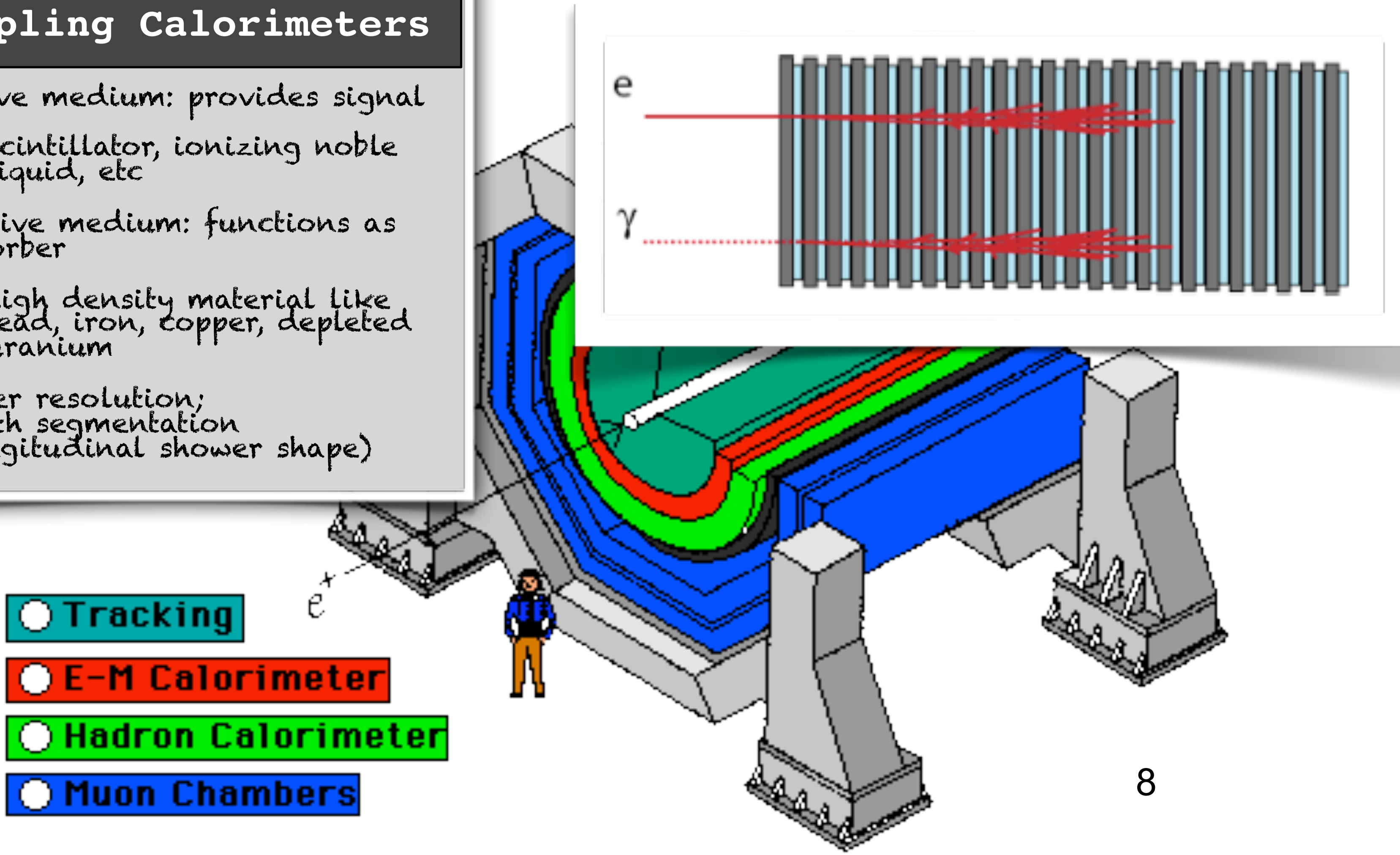

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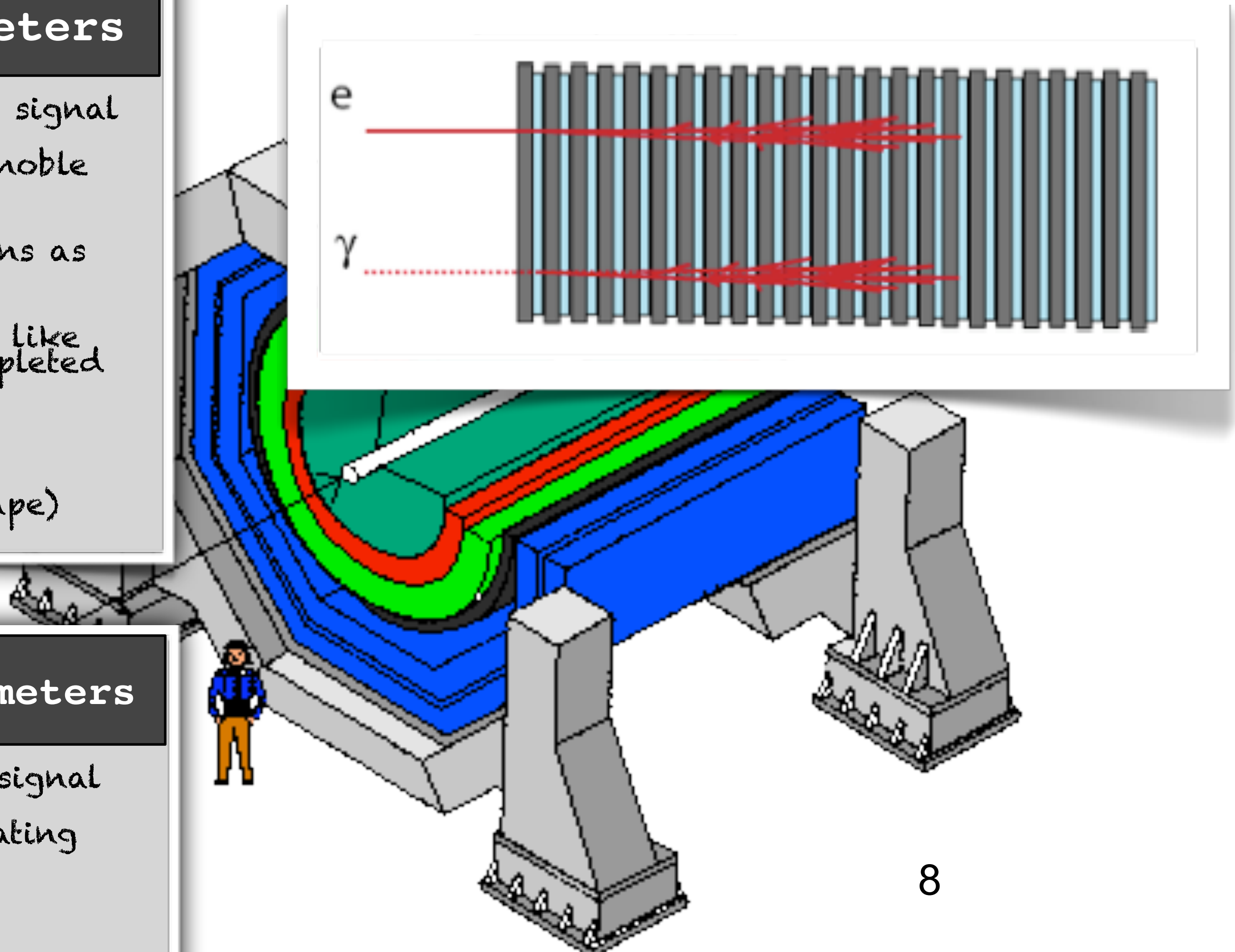

Homogeneous Calorimeters

- entire volume provides signal
- inorganic heavy scintillating crystals
  - CsI, NaI, & $PbWO_4$
  - ionizing noble liquids
- Better resolution
  no depth segmentation

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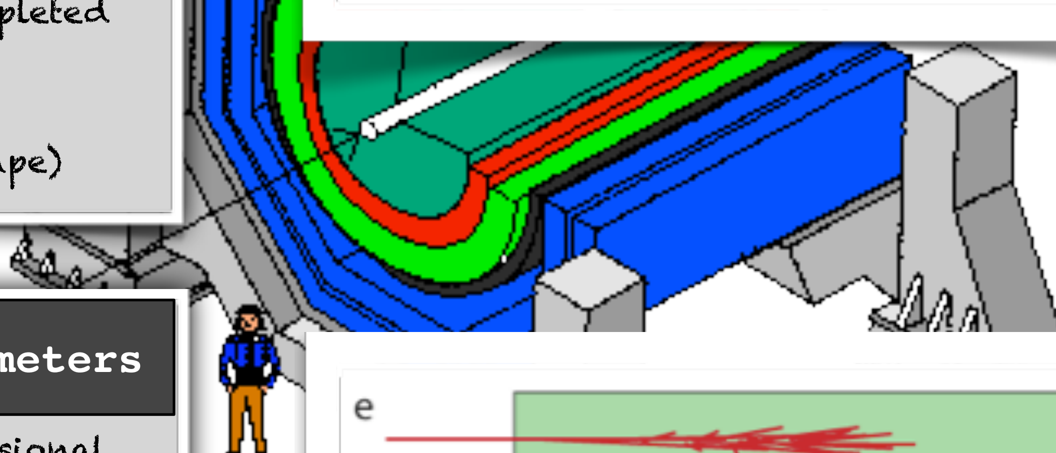

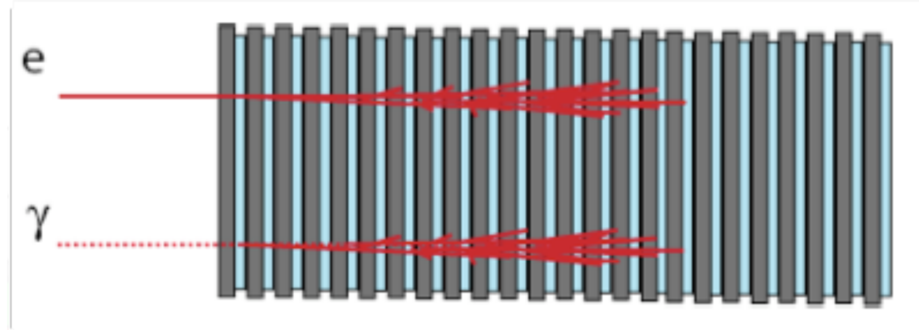

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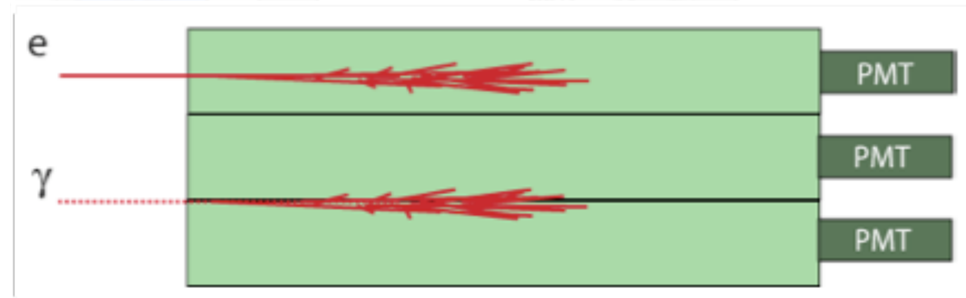

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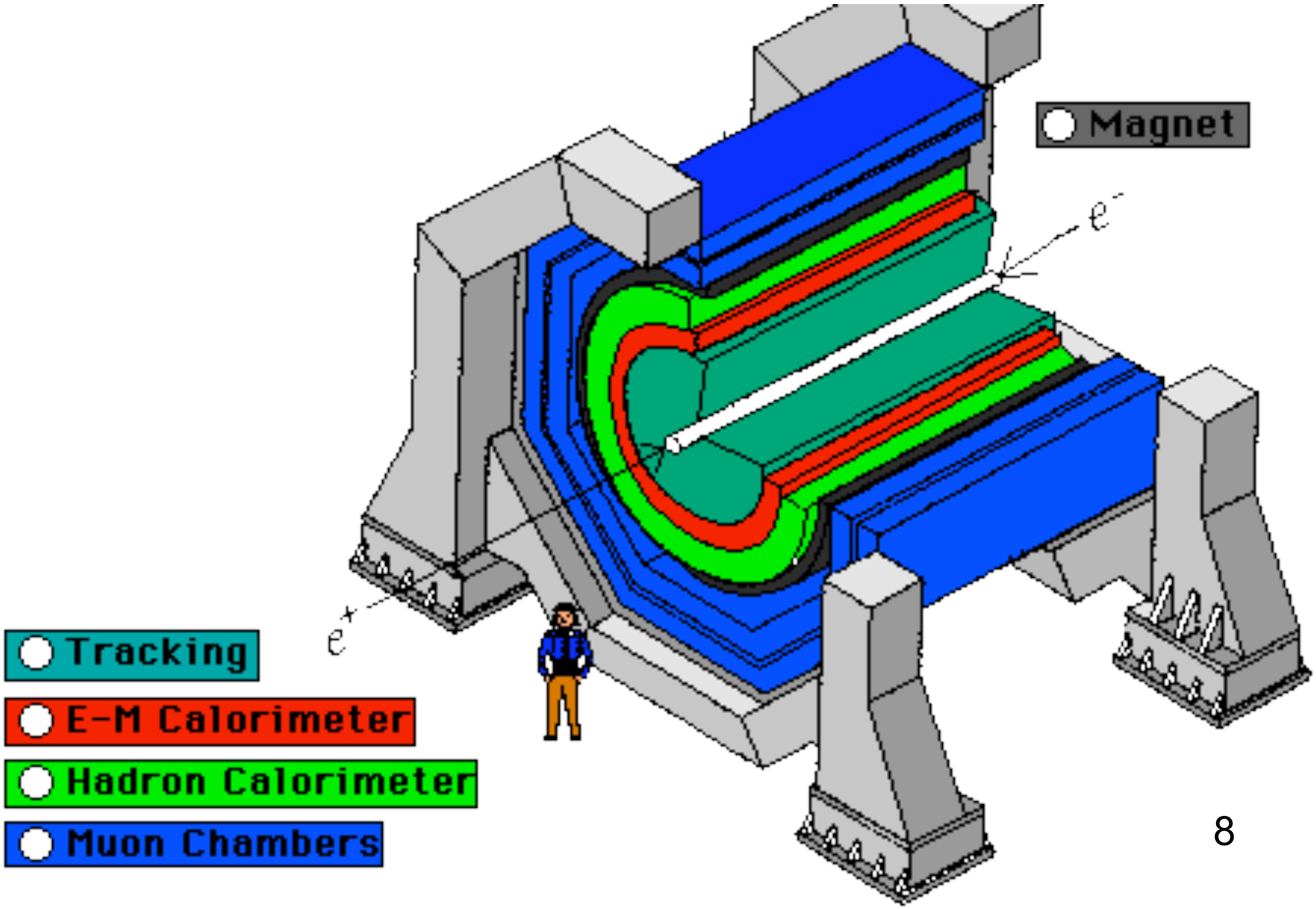
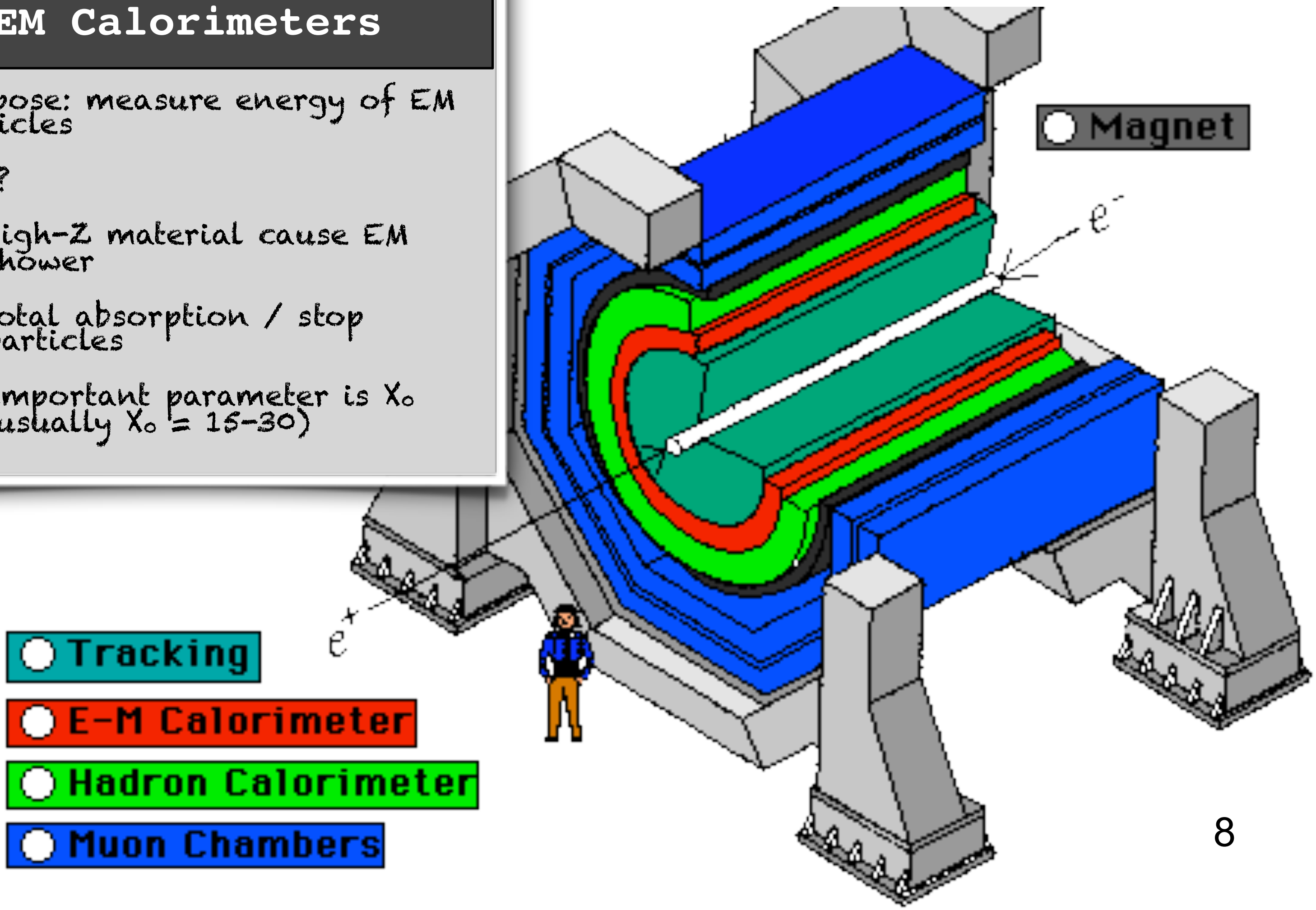


8

EM Calorimeters

- Purpose: measure energy of EM particles
- How?
    - High-Z material cause EM shower
    - total absorption / stop particles
    - Important parameter is X_0 (usually X_0 = 15-30)



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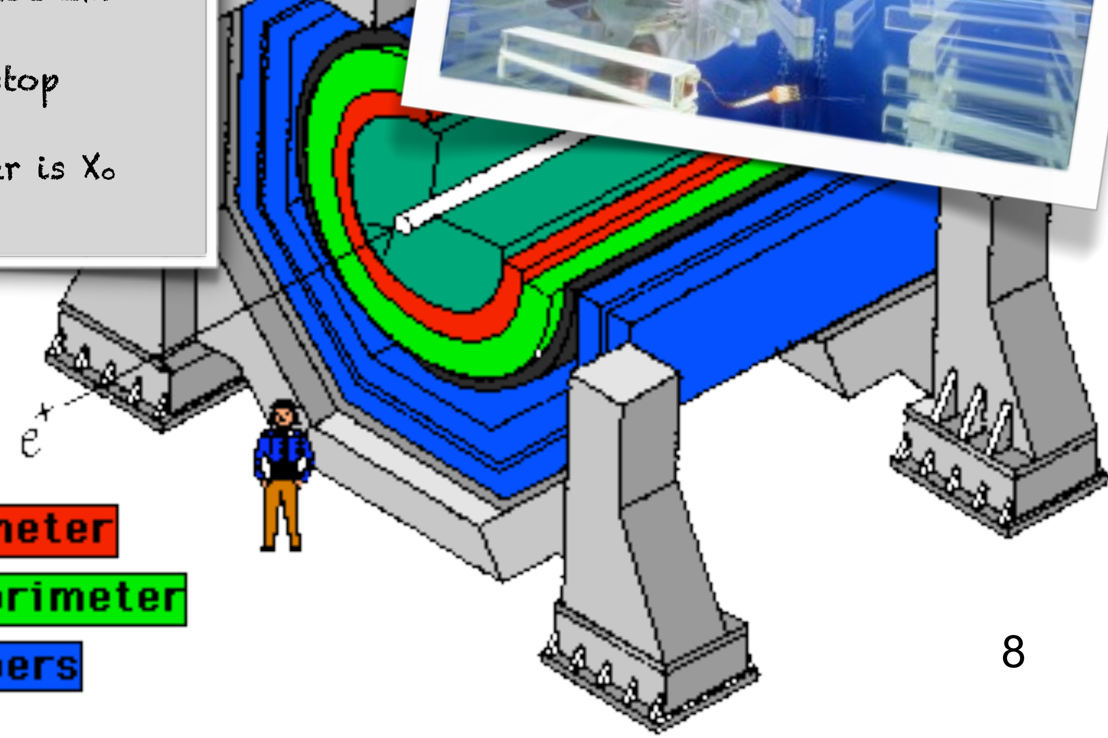

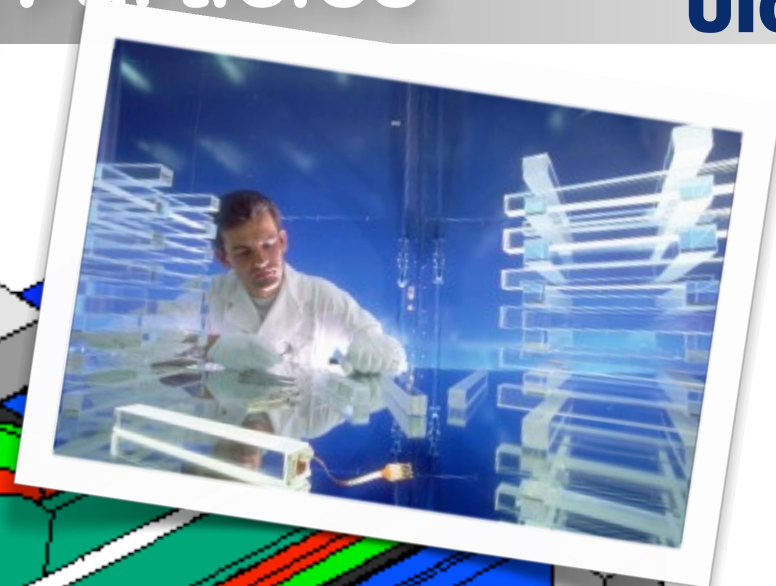

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Hadronic Calorimeter

- Purpose: measure energy of hadronic particles
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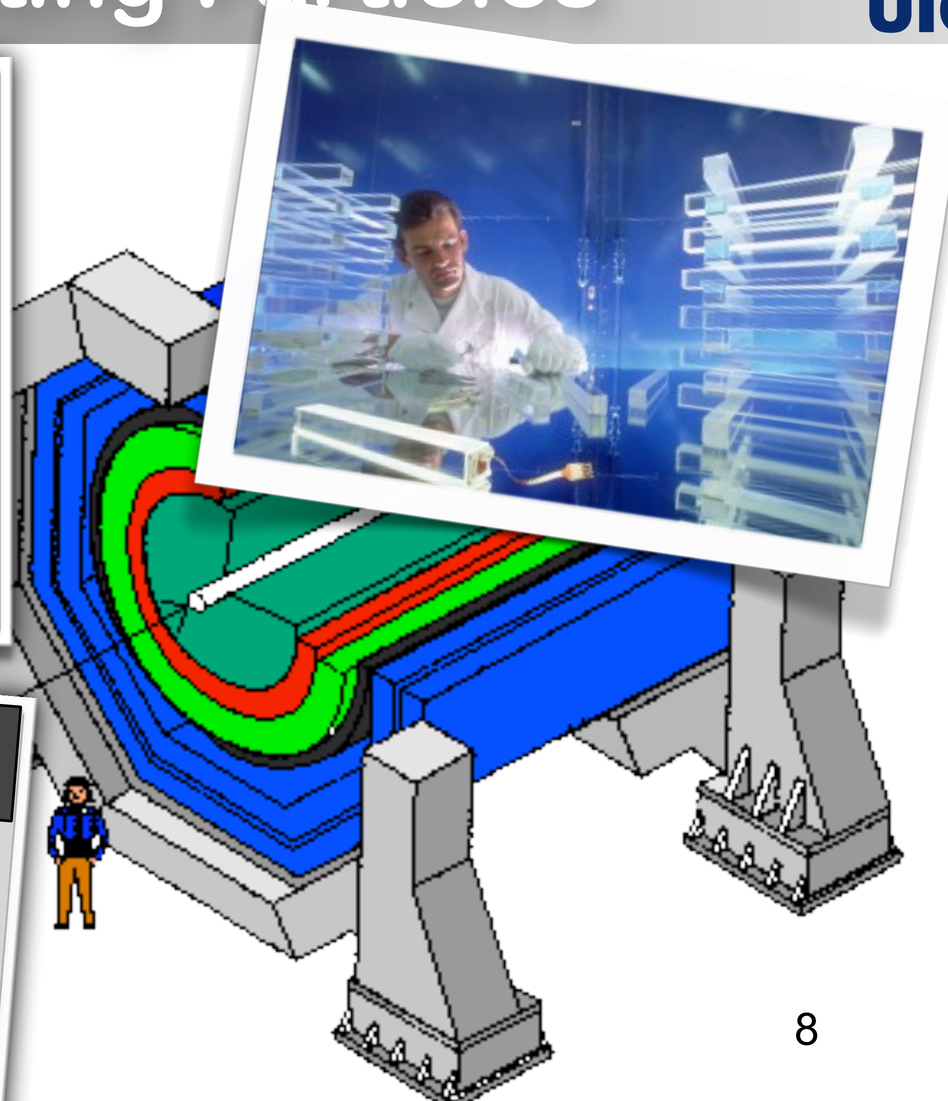
  - High density material cause hadronic shower
  - typically sampling calorimeters
  - Important parameter is λ (usually λ = 10-15)



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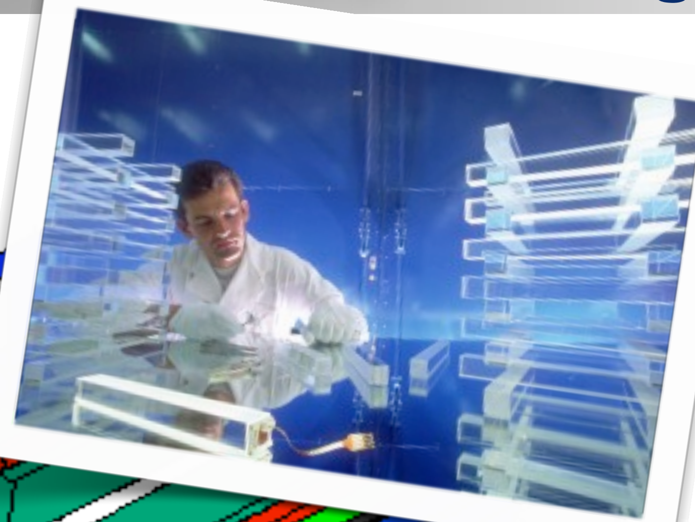

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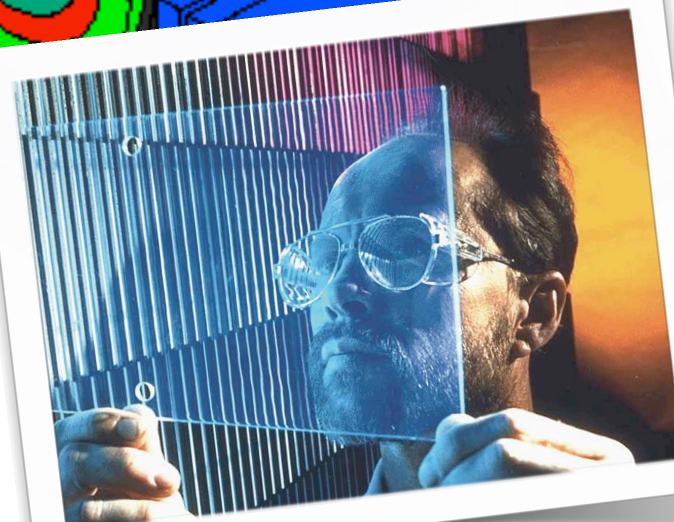

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Calor. Resolution

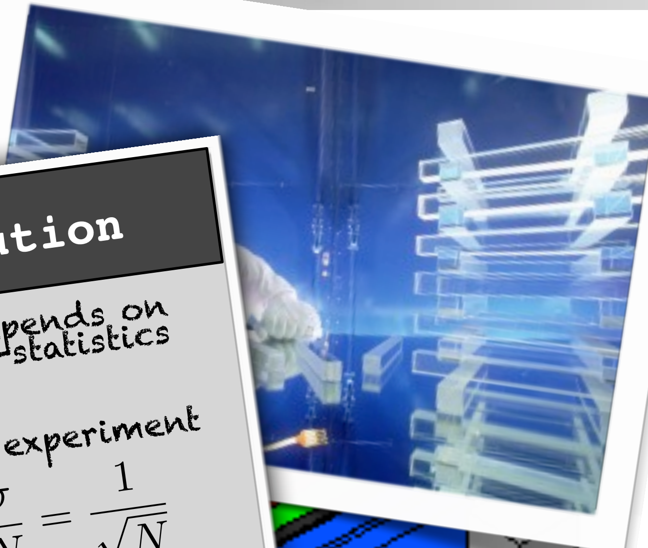
- Energy resolution depends on the amount of photo-statistics gathered
- Recall for counting experiment

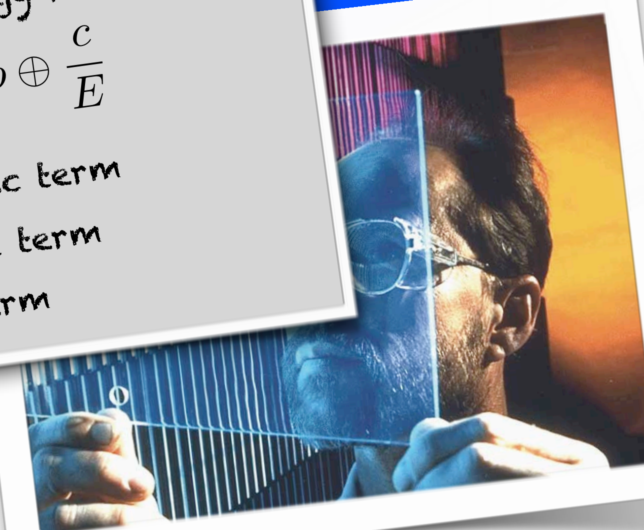
$$\sigma = \sqrt{N} \rightarrow \frac{\sigma}{N} = \frac{1}{\sqrt{N}}$$

- Calorimeter energy resolution:

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

  - a is stochastic term
  - b is constant term
  - c is noise term





R. Cavanaugh, HCPSS 2012

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ECAL vs HCAL Resolution

- EM Energy Resolution:
  - 1-10% / $\sqrt{E_T}$
- HAD Energy Resolution:
  - 50-100% / $\sqrt{E_T}$
- ECAL much better energy resolution than HCAL

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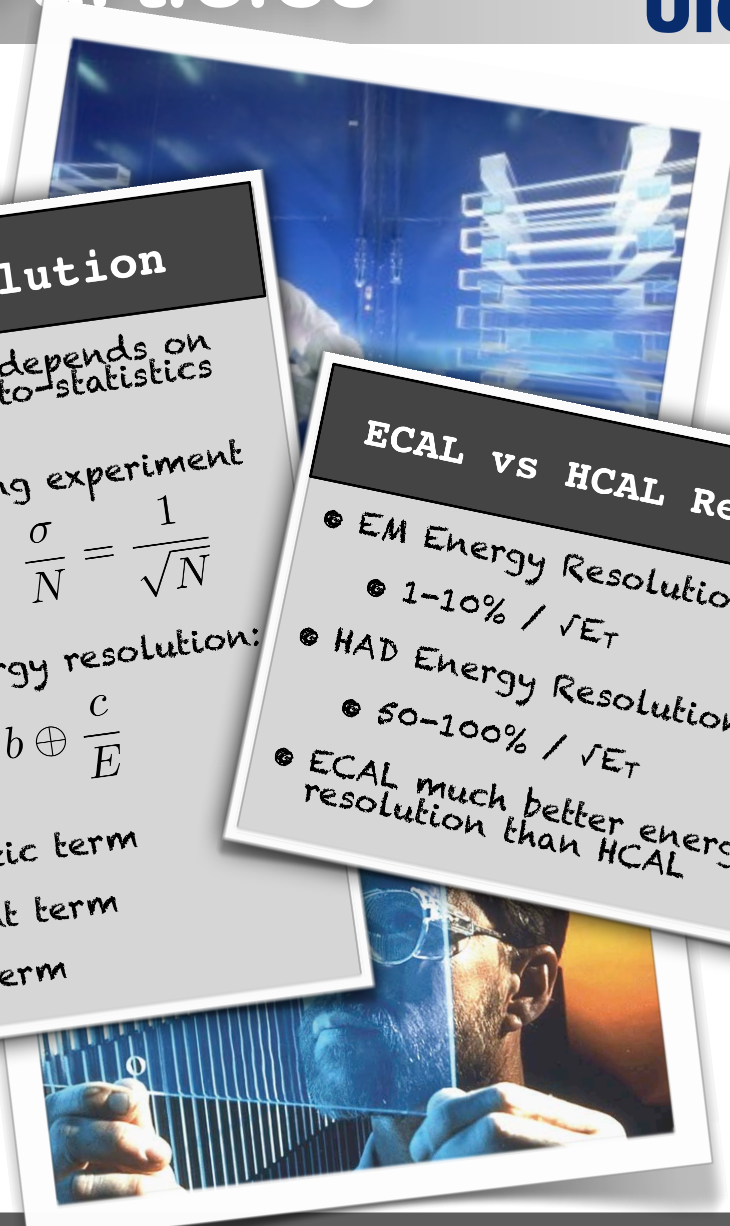

R. Cavanaugh, HCPSS 2012

LPC LHC Physics Center

Detecting Particles

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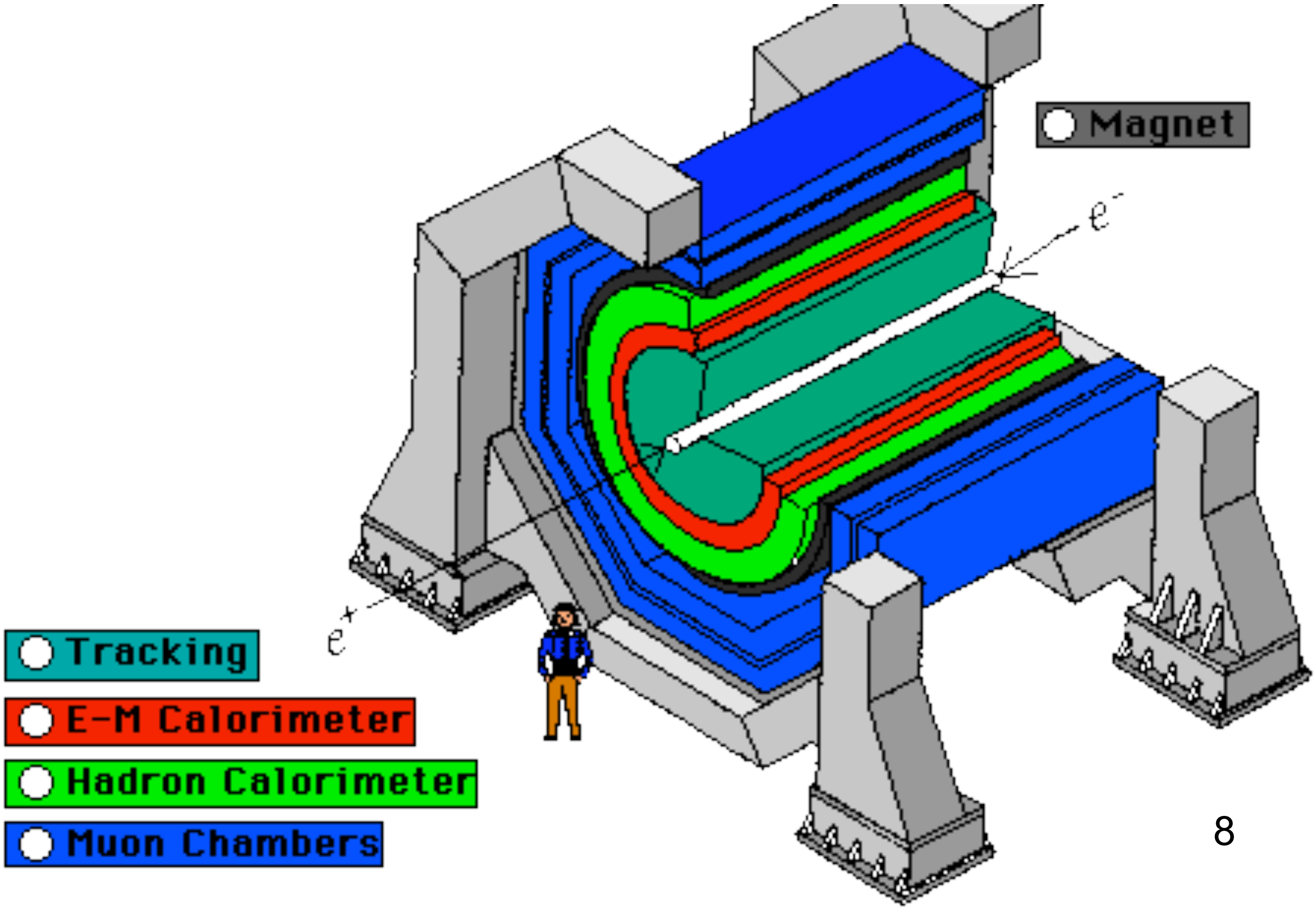

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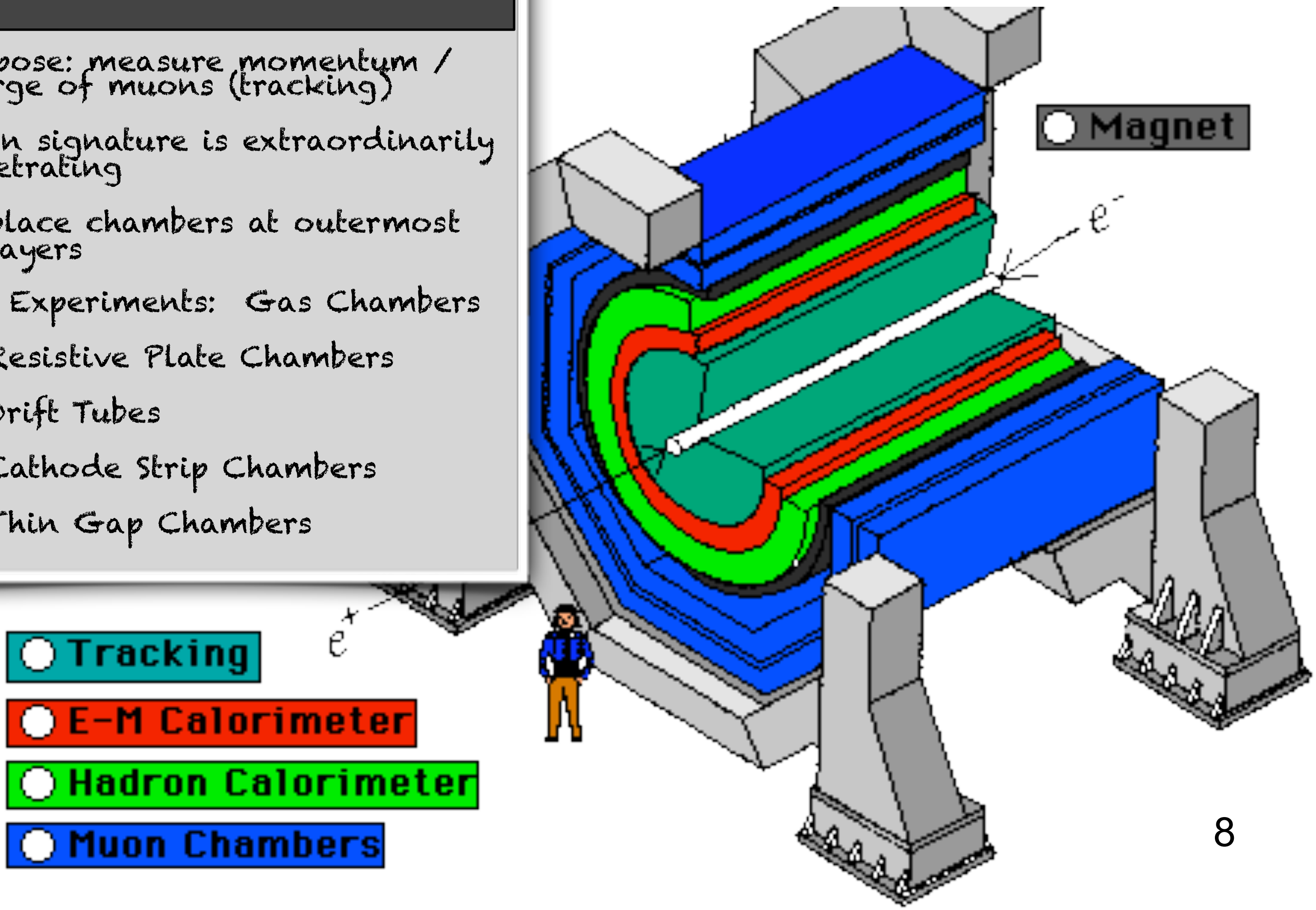
Detecting Particles

Muon Chambers

- Purpose: measure momentum / charge of muons (tracking)
- Muon signature is extraordinarily penetrating
  - place chambers at outermost layers
- LHC Experiments: Gas Chambers
  - Resistive Plate Chambers
  - Drift Tubes
  - Cathode Strip Chambers
  - Thin Gap Chambers



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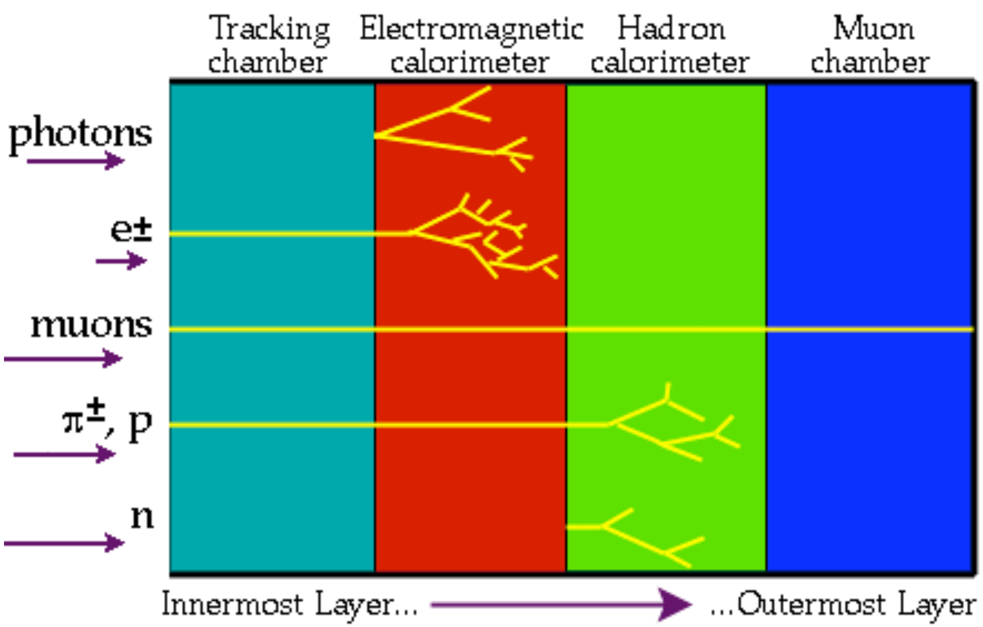
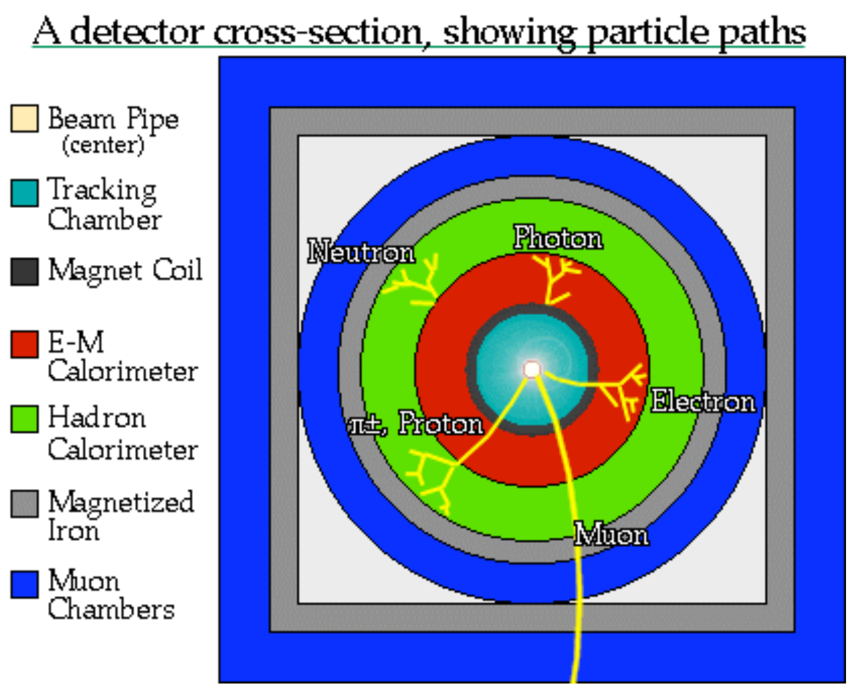
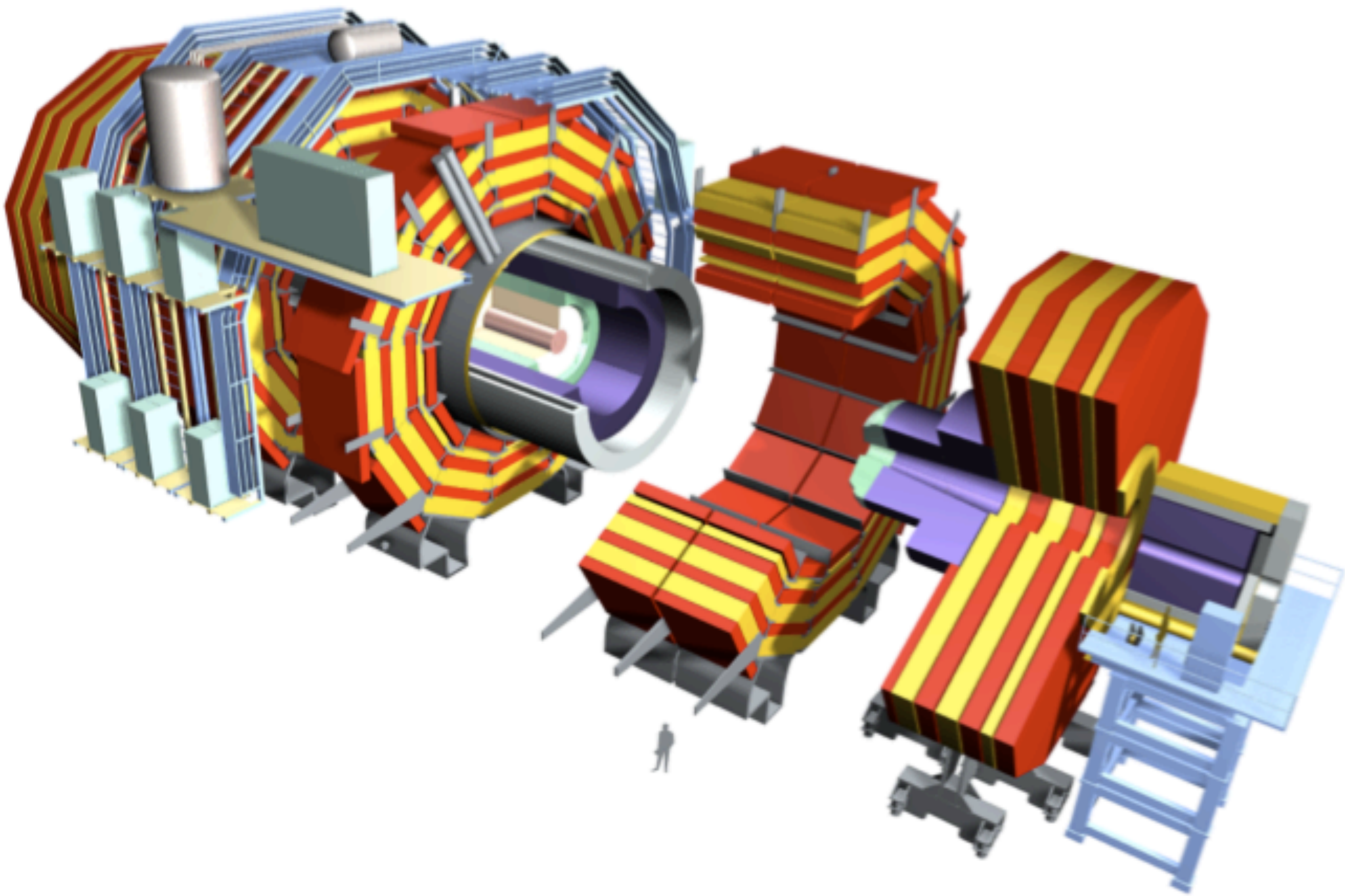
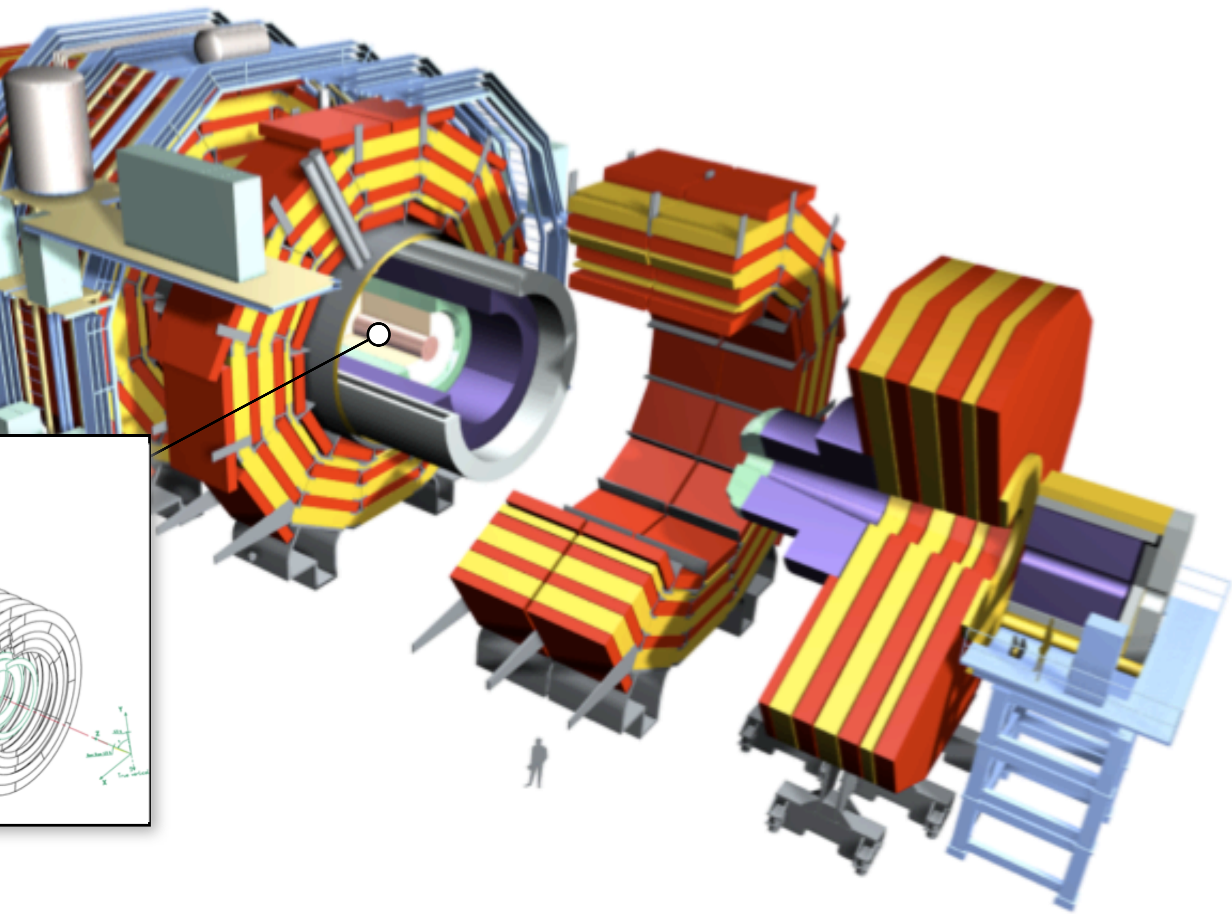
Particle Identification



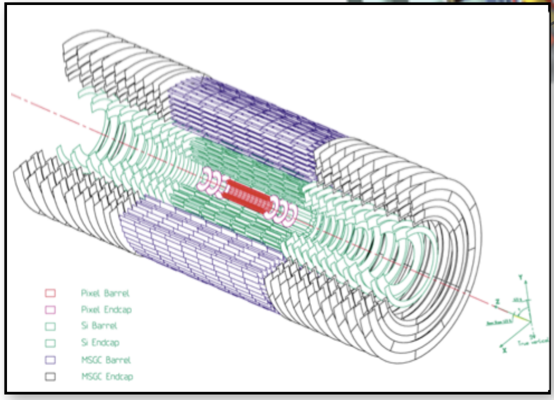


- **Electrons**
  - Deposit all energy in EM Calorimeter; matched to track
- **Photons**
  - Similar as electrons; but no track
- **Muons**
  - Match hits in muon chambers with hits in tracker
- **Charged Hadrons**
  - Deposit all energy in EM+HAD Calorimeters; matched to track
- **Neutral Hadrons**
  - Similar as Charged Hadrons; but no track
- **Neutrinos**
  - Pass through all material; measured indirectly by momentum imbalance





TRACKERs

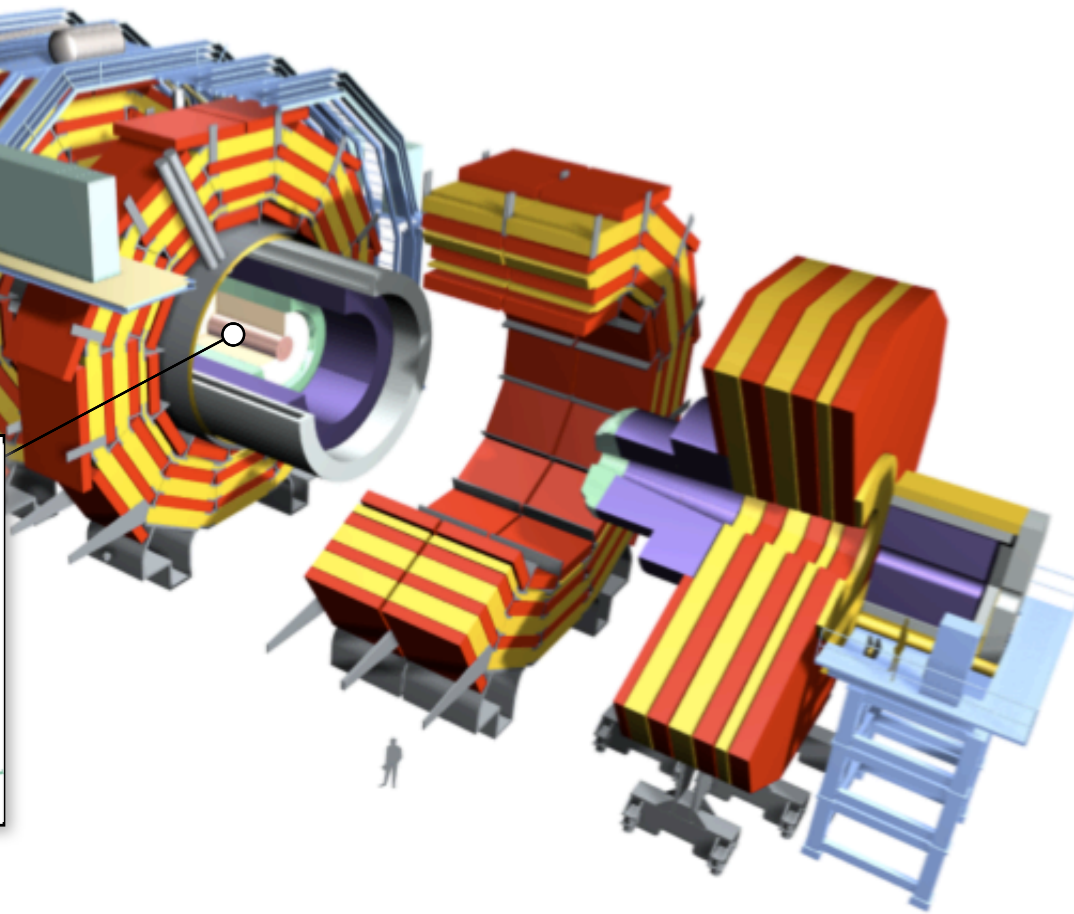


Silicon Microstrips
Pixels

CMS Detector

Fermilab
UIC University of Illinois at Chicago

CALORIMETERS



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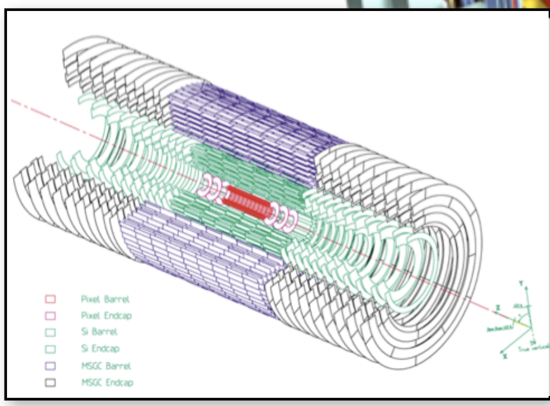

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CALORIMETERS

ECAL Scintillating $PbWO_4$ Crystals

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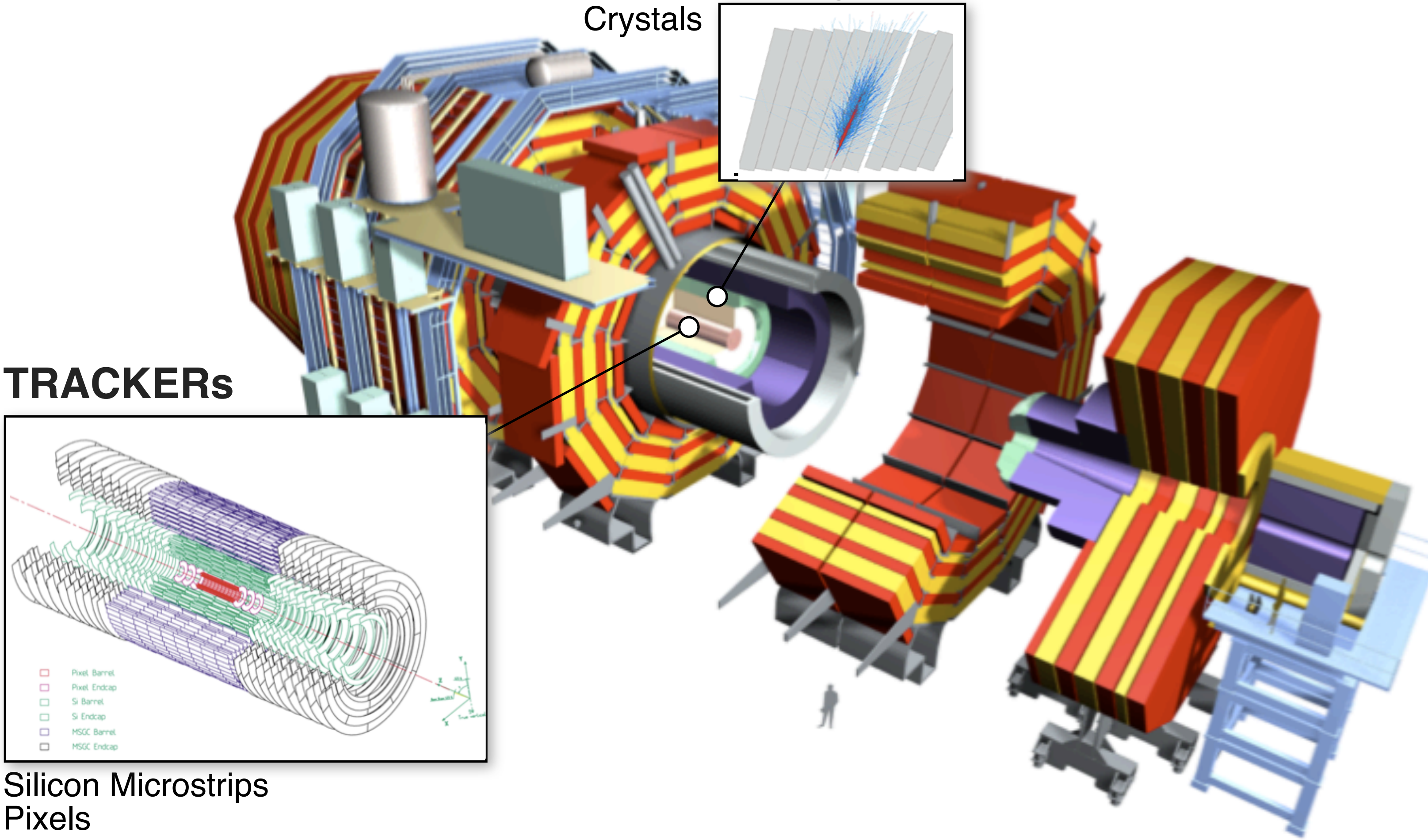

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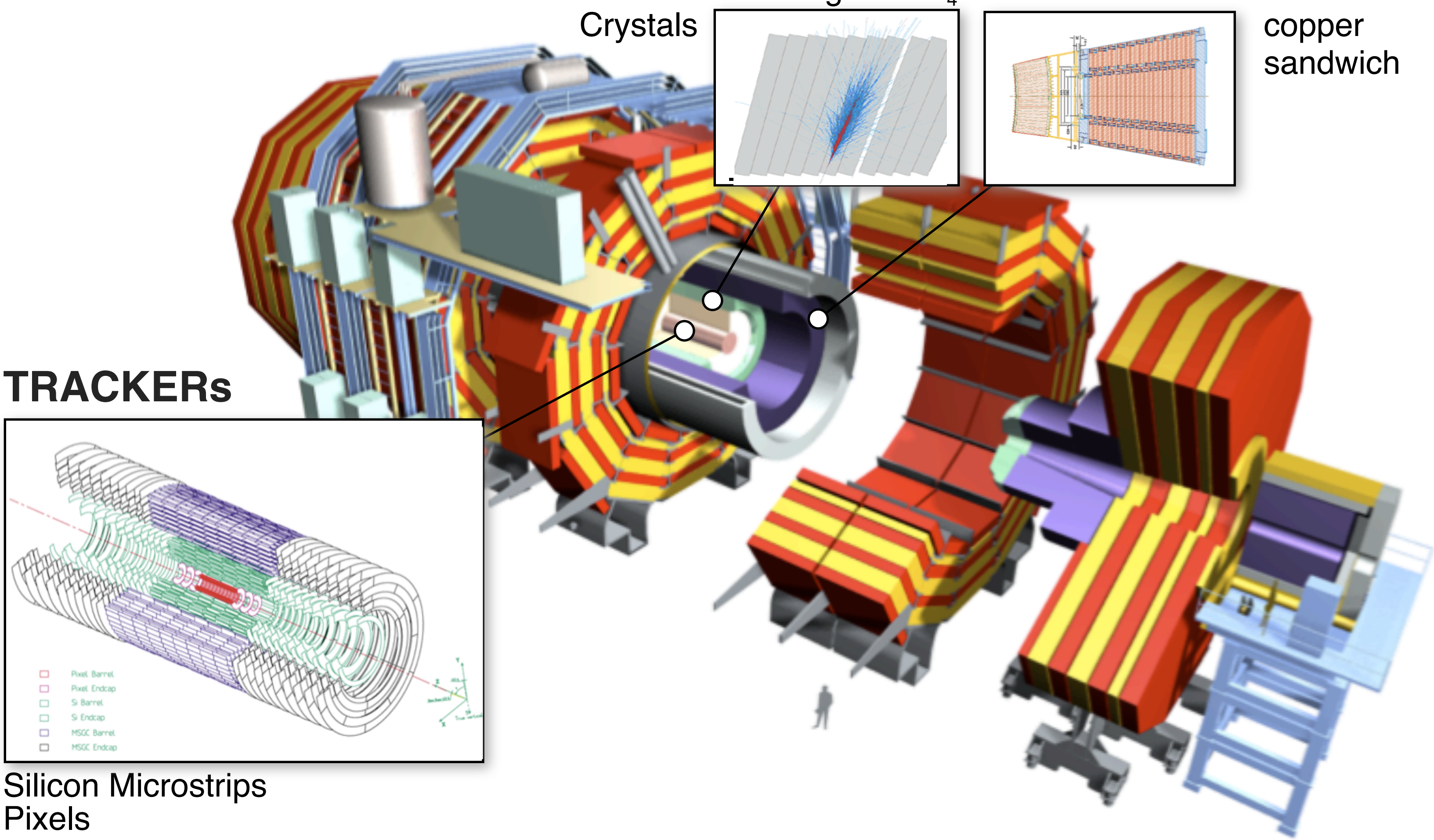

CMS Detector

SUPERCONDUCTING COIL

CALORIMETERS

ECAL Scintillating $PbWO_4$ Crystals

HCAL Plastic scintillator copper sandwich

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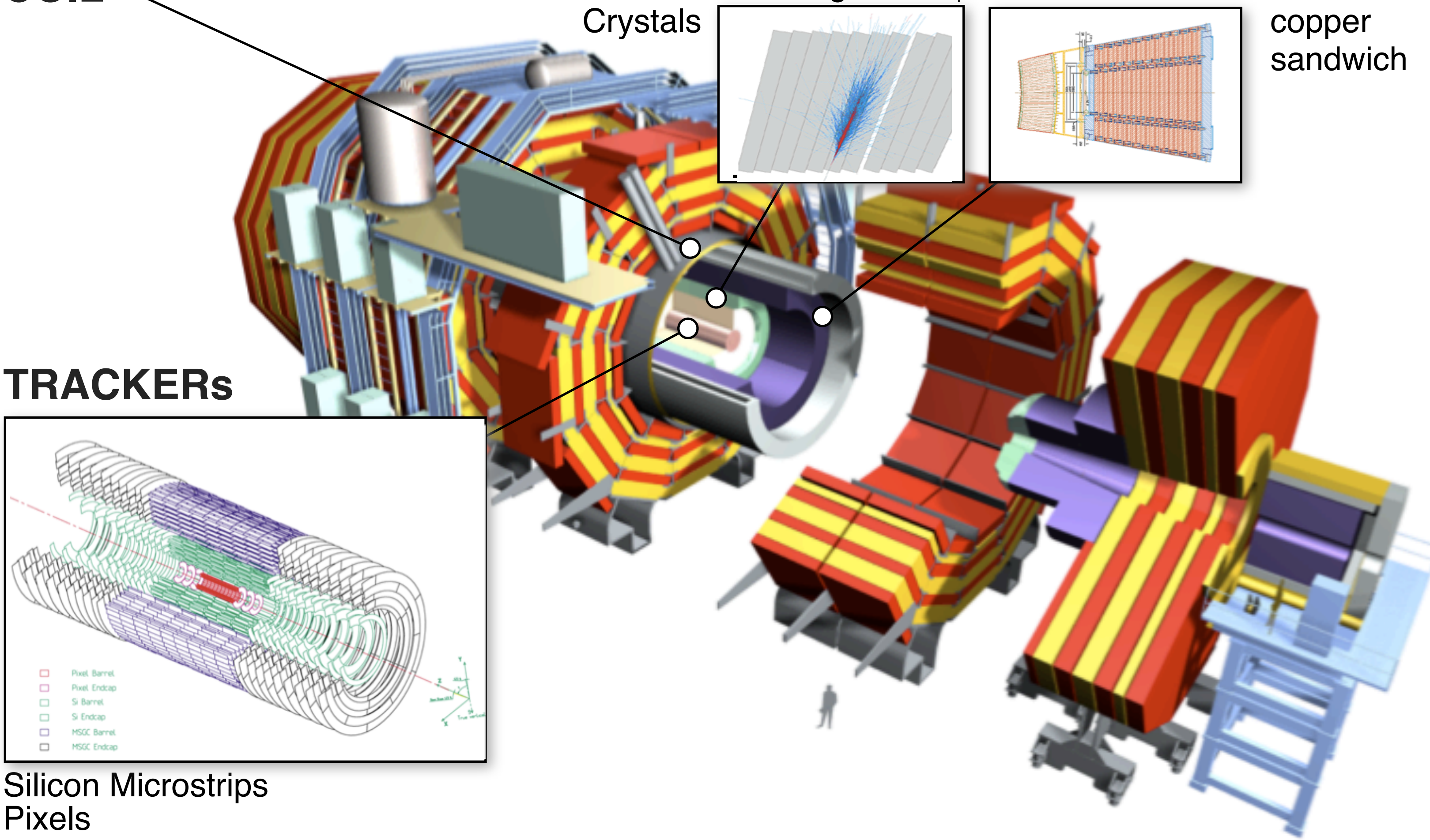

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Fermilab
UIC University of Illinois at Chicago

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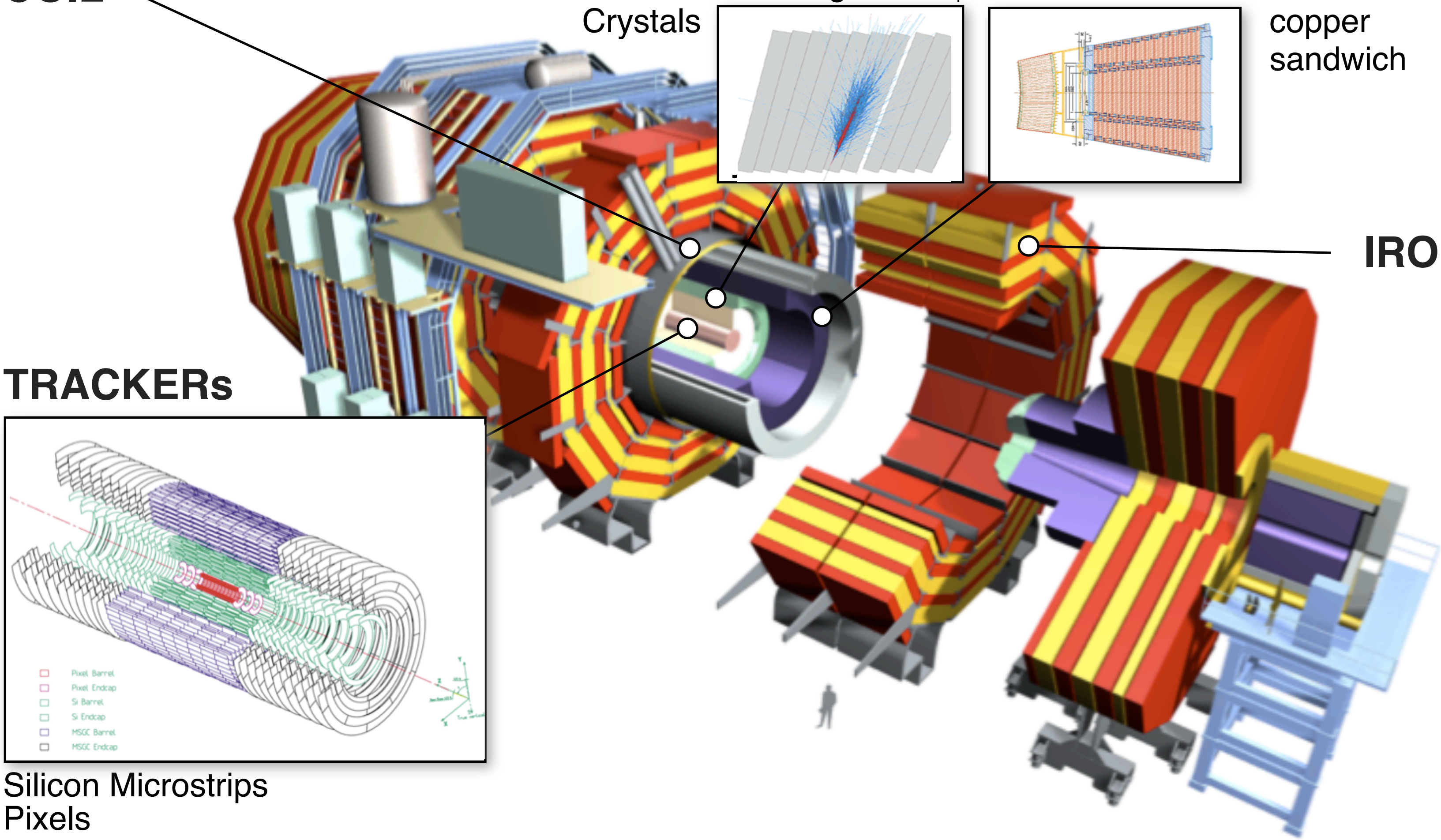
IRON YOKE

TRACKERs



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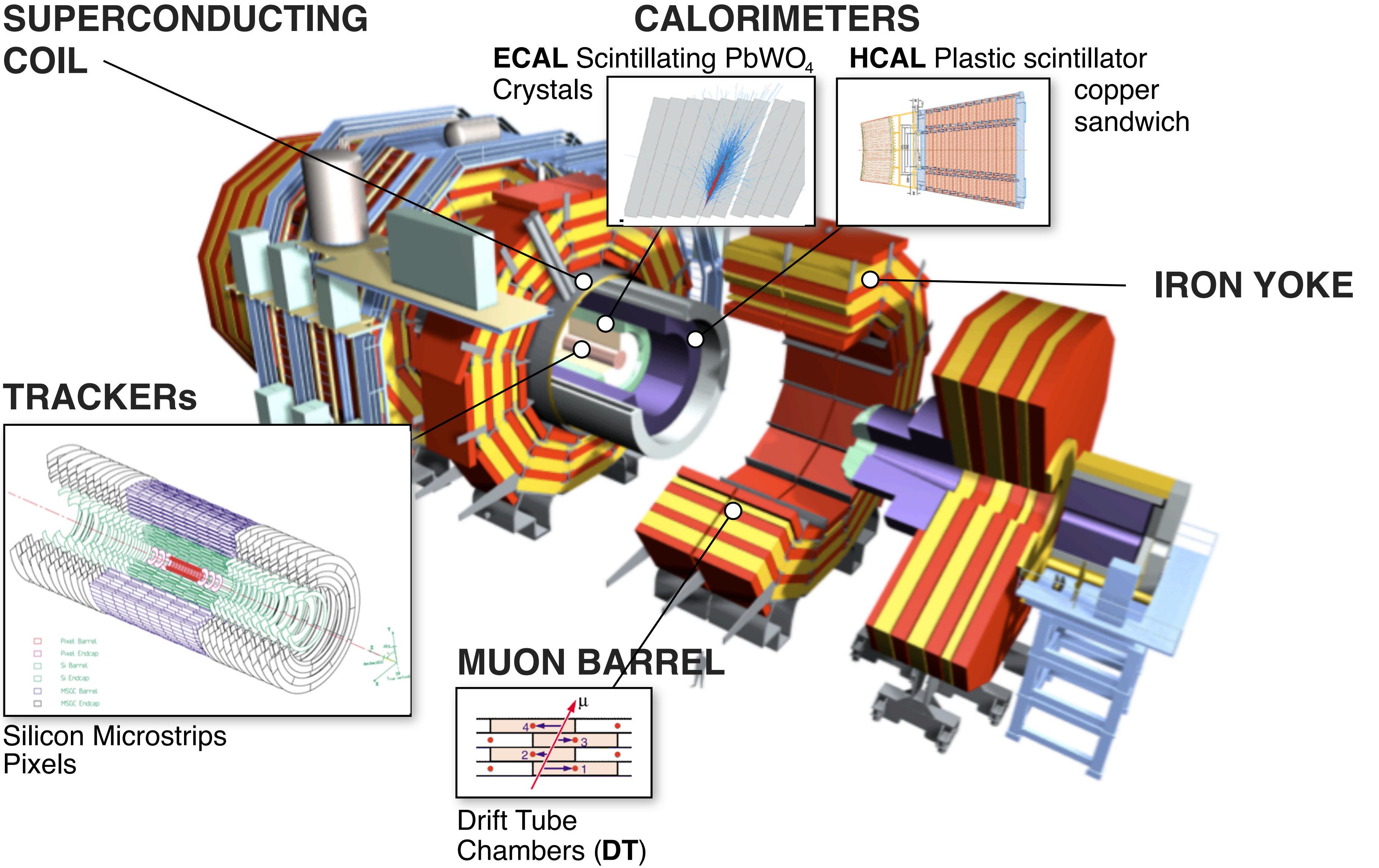

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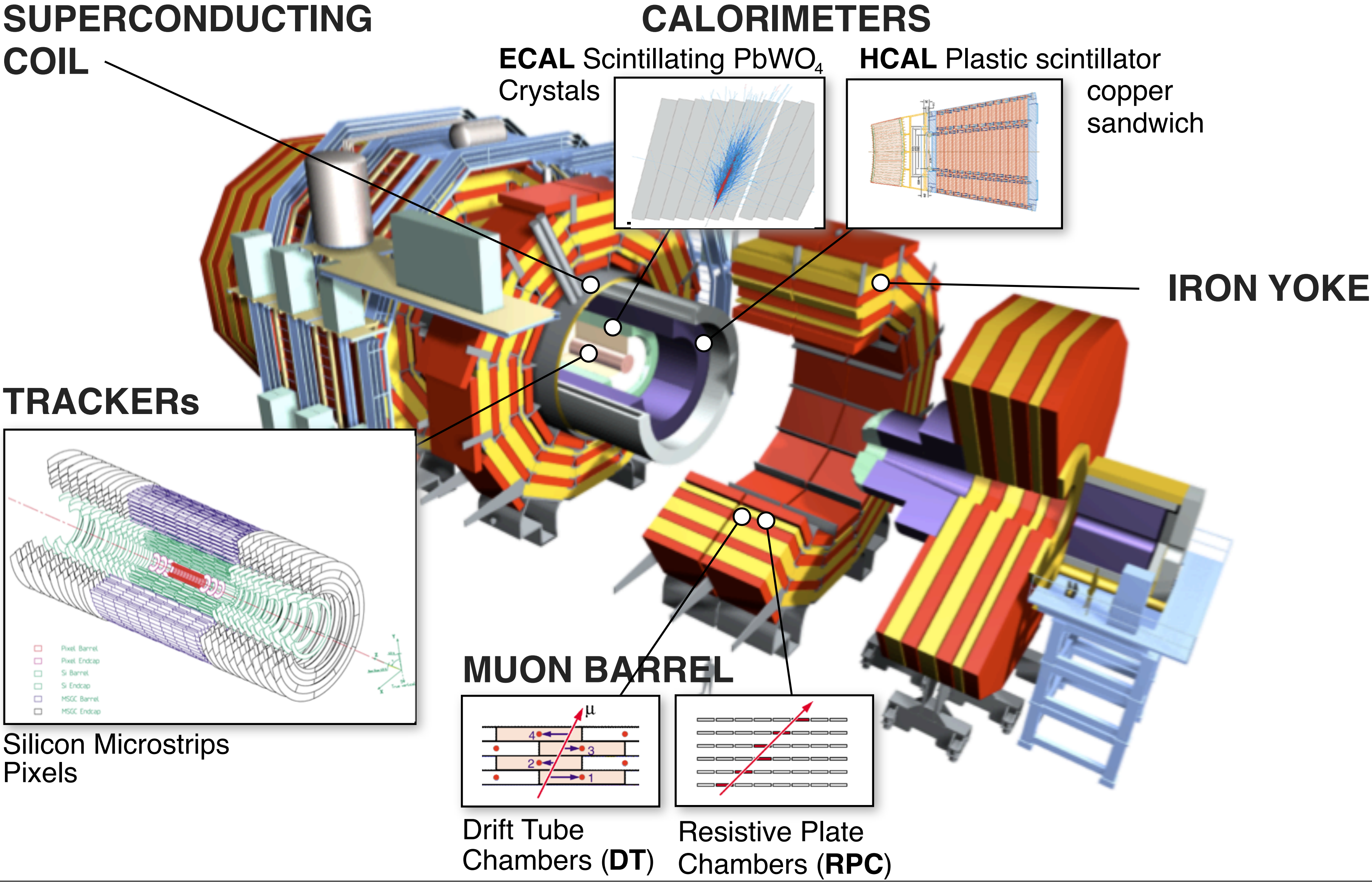

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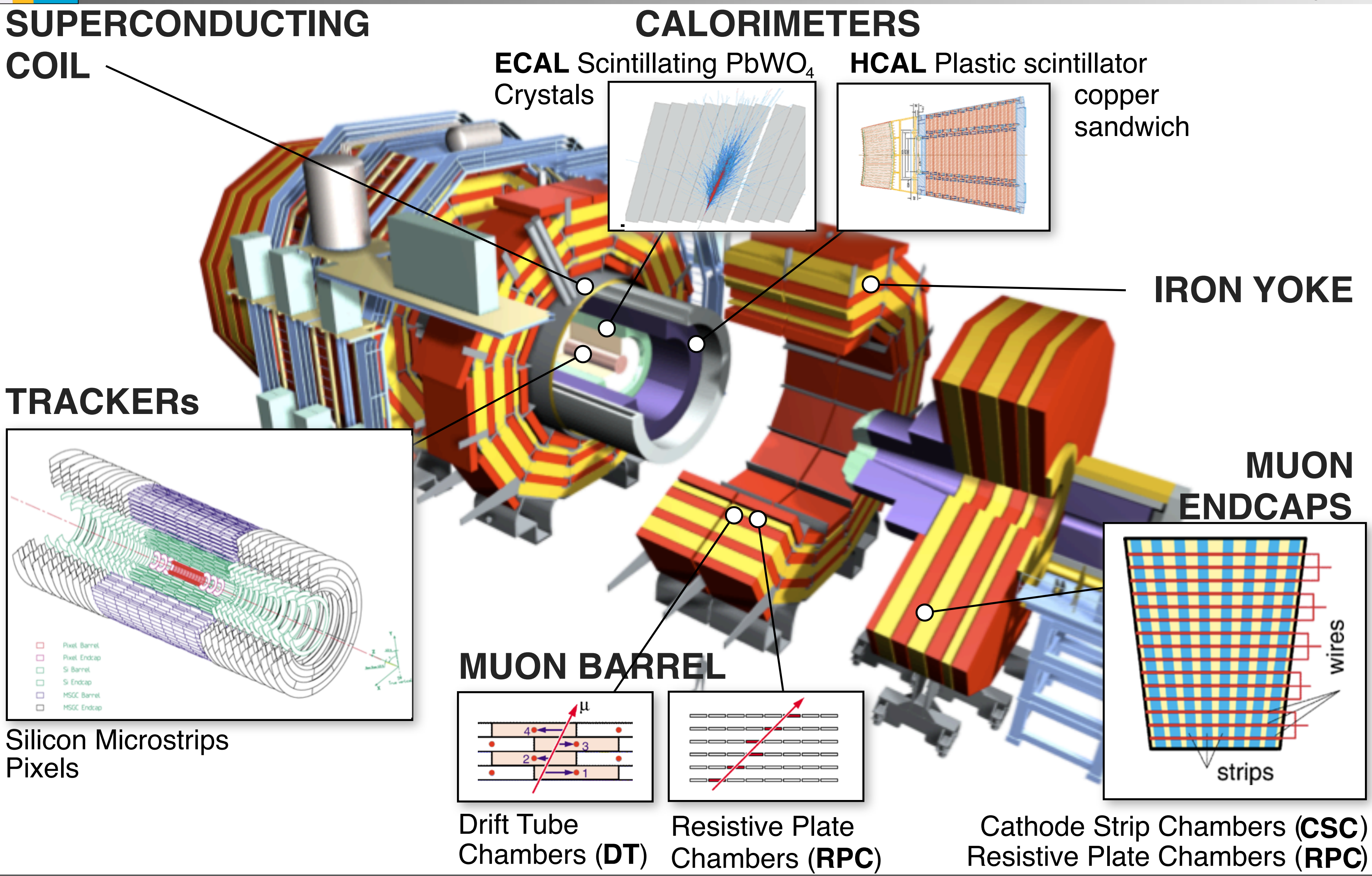

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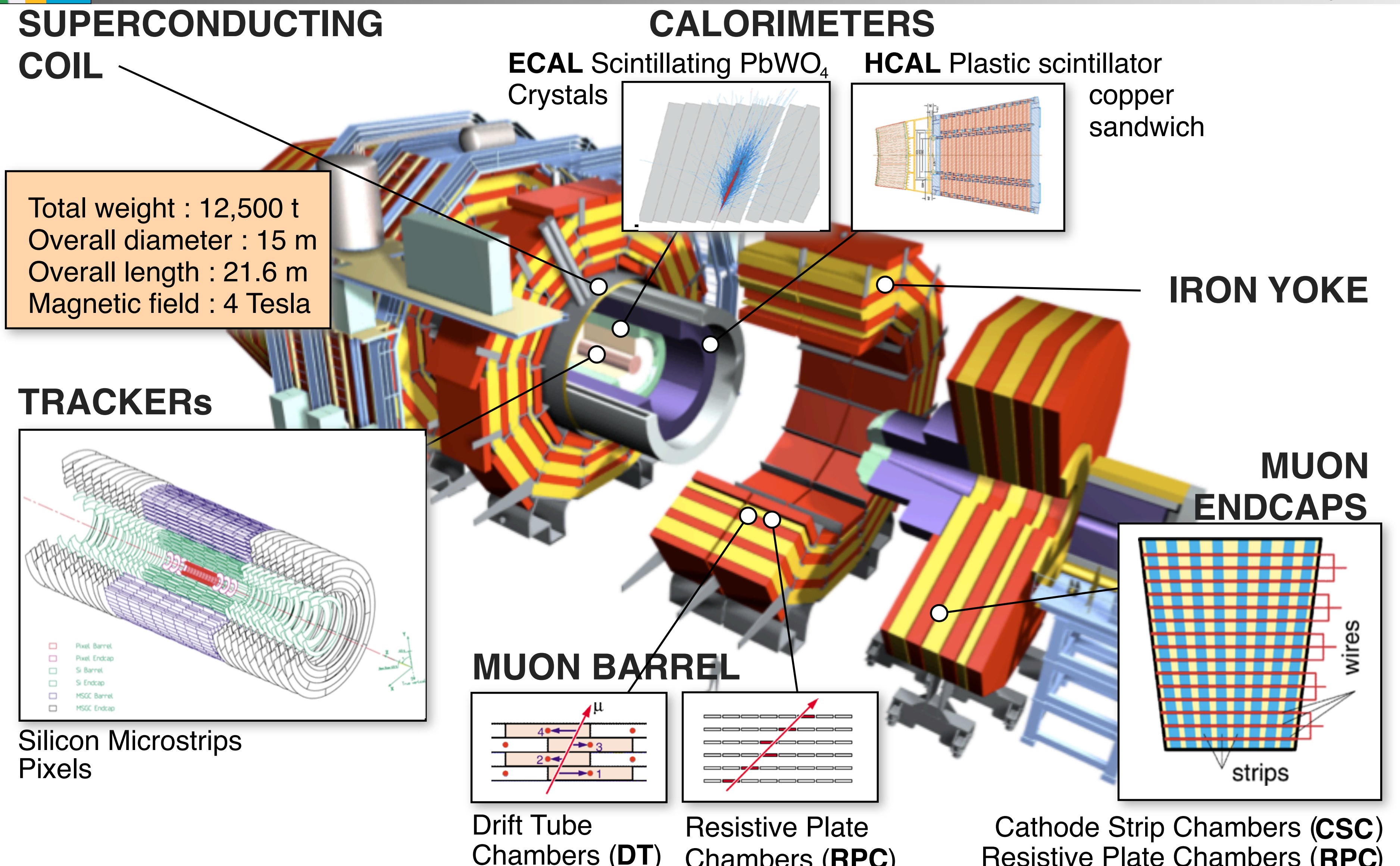
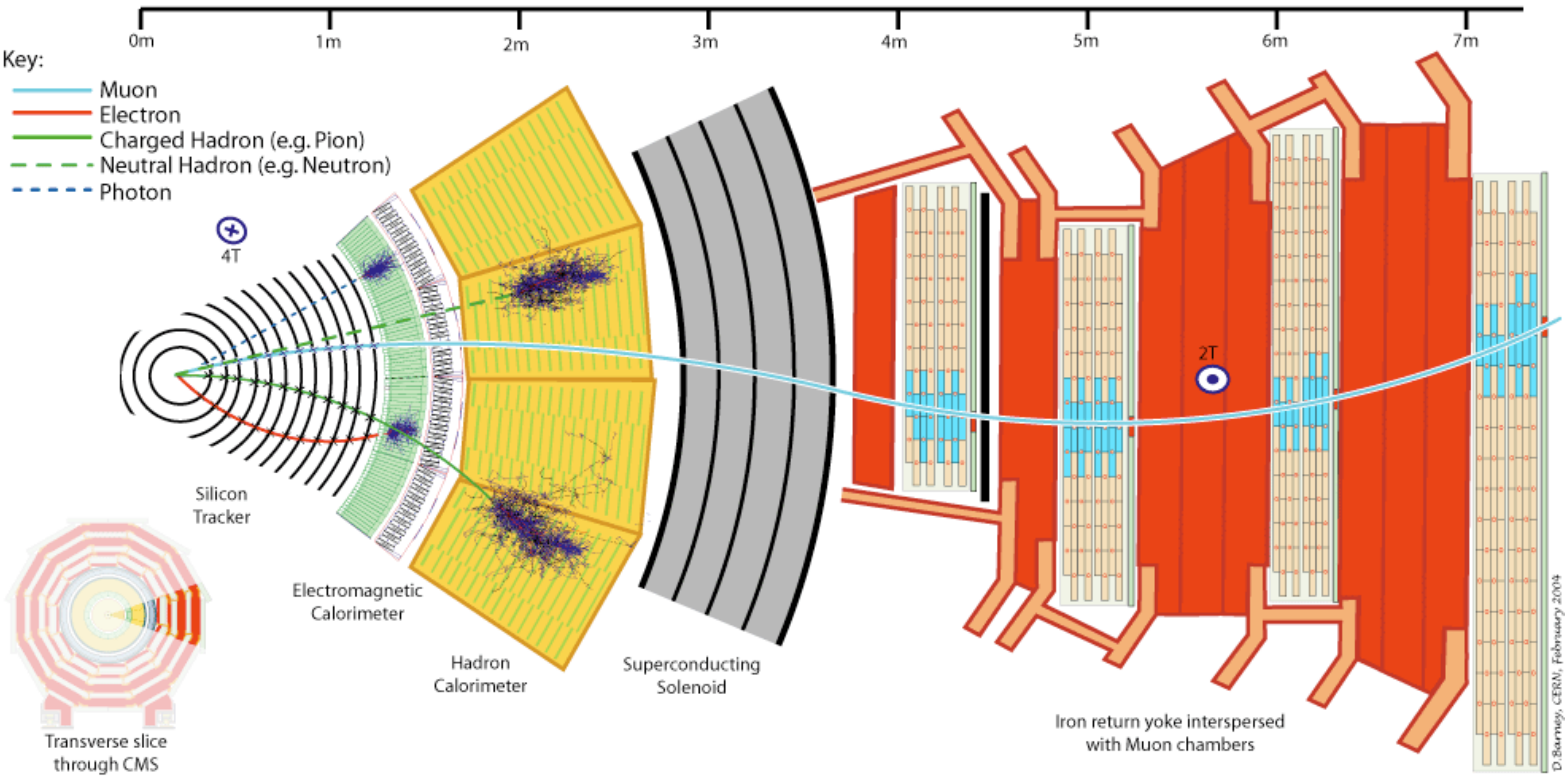
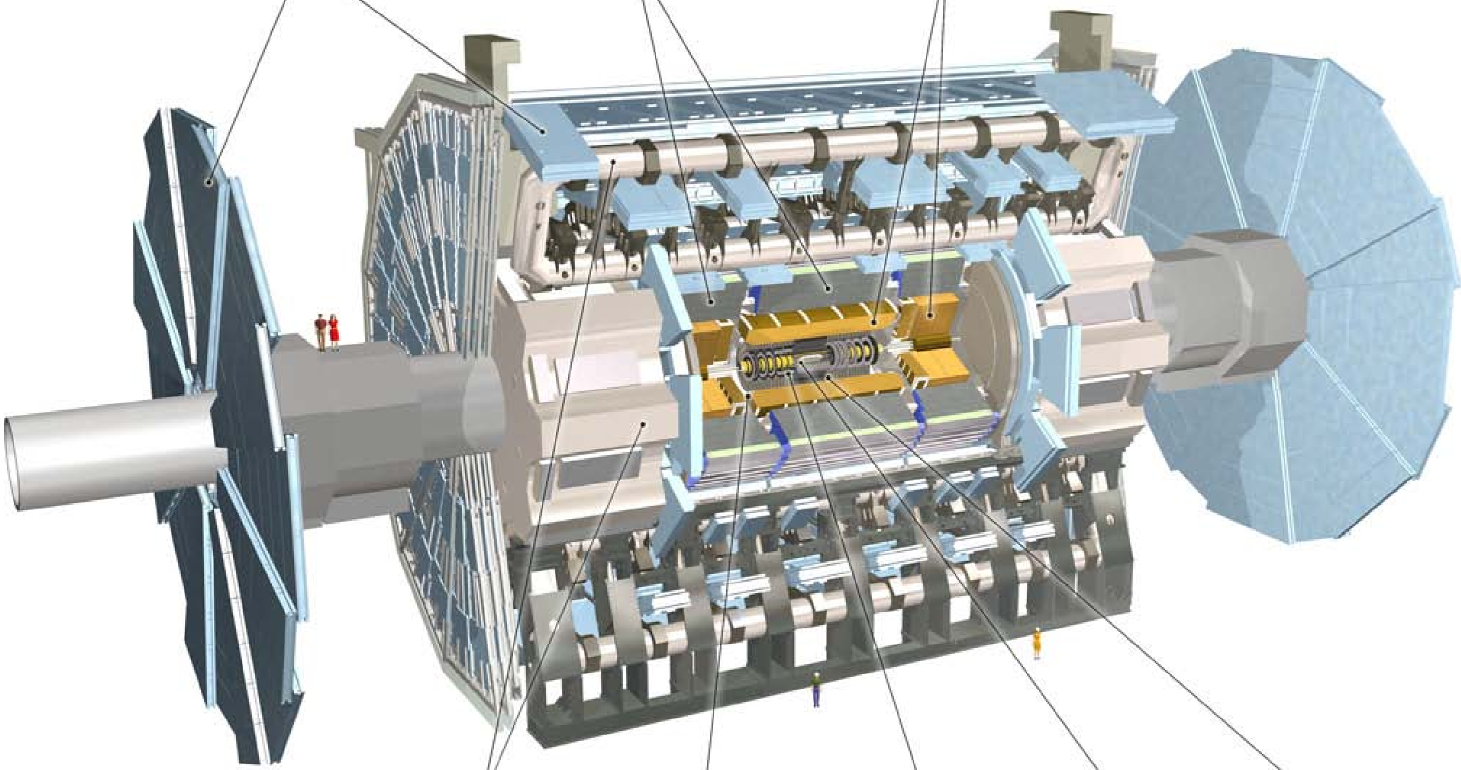


Particle Passage through CMS

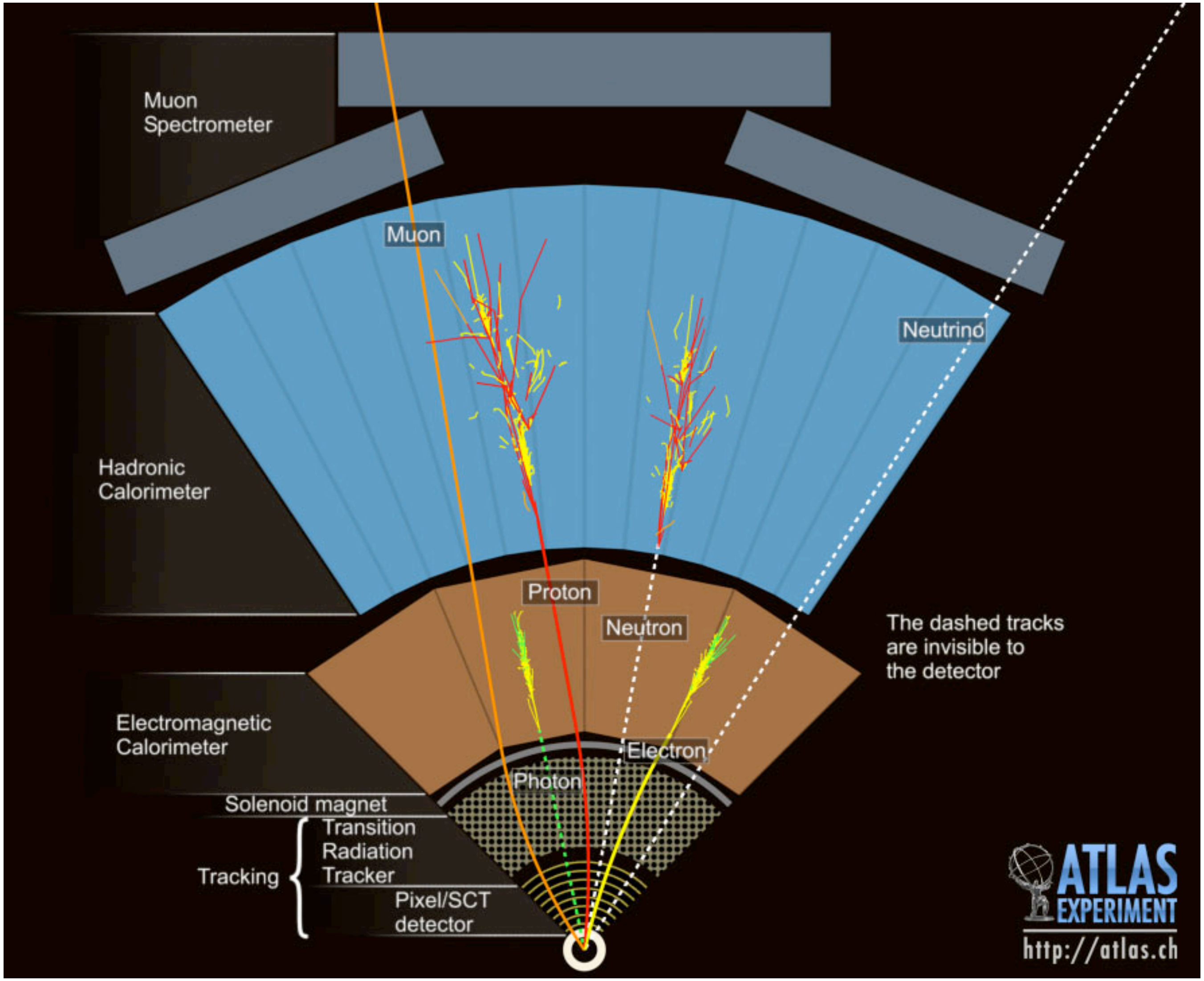


ATLAS Detector



Total weight : 7000 t
Overall length: 46 m
Overall diameter: 23 m
Magnetic field: 2T solenoid + toroid

Particle Passage through ATLAS



"Particle-Flow"

- "Follow particles" through the detector!
- Reconstruct and identify all particles
  - γ, e, μ, $\pi^{\pm}$, K_L^0, pile-up $\pi^{\pm}$, converted γ & nuclear interaction $\pi^{\pm}$,...
  - Use best combination of all sub-detectors for E, η, φ, and ID
- Provide consistent & complete list of ID'd & calibrated particles for
  - Tau reconstruction & Jet reconstruction
  - Missing & total Visible Energy determination
  - Other, analysis specific, objects (event or jet shape vars, etc)
- Use of Redundant Information: Calorimeter & Tracking

Desired Ingredients for PF

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  - high precision, high efficiency tracking is critical

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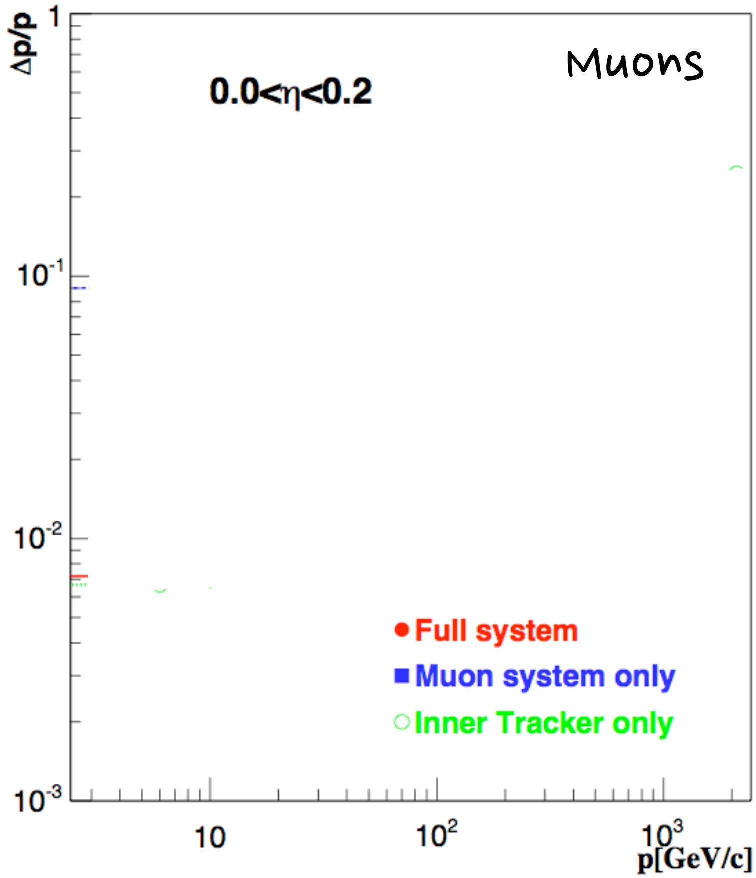
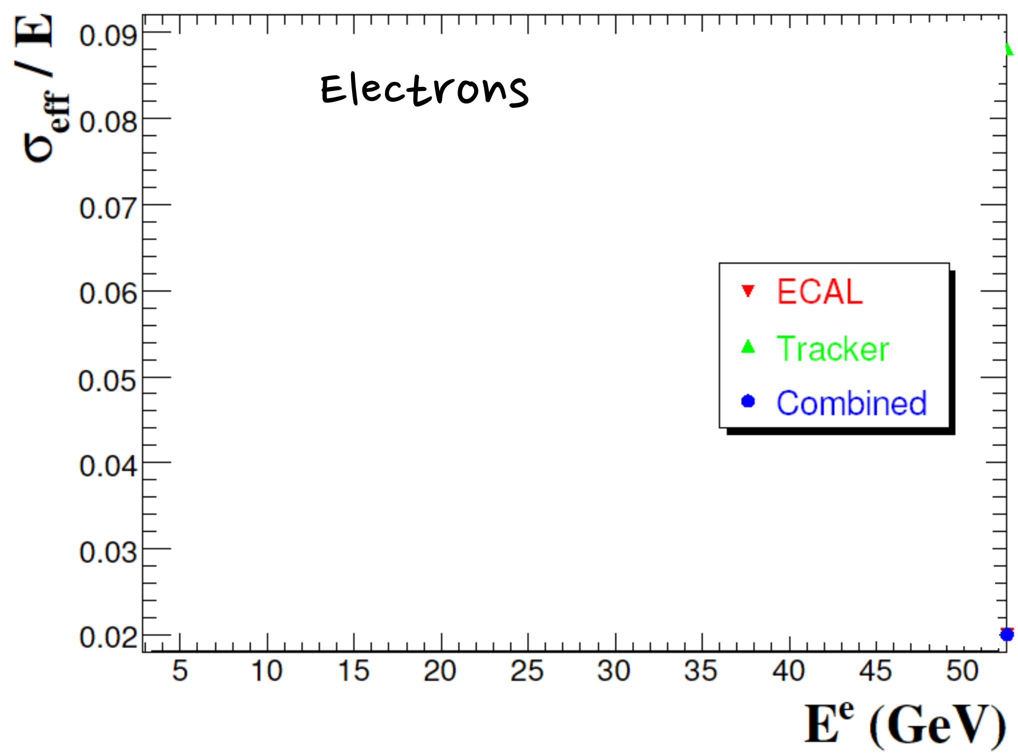
- **High Magnetic Field**
  - needed for good pT resolution
  - needed to separate charged from neutral particles
- **Highly Granular Calorimeter**
  - needed to separate charged from neutral particles
- **Good Calorimeter Energy Resolution is :**
  - needed for good photon, electron E resolution
  - not so critical for Hadrons

Using the Detailed Full Detector





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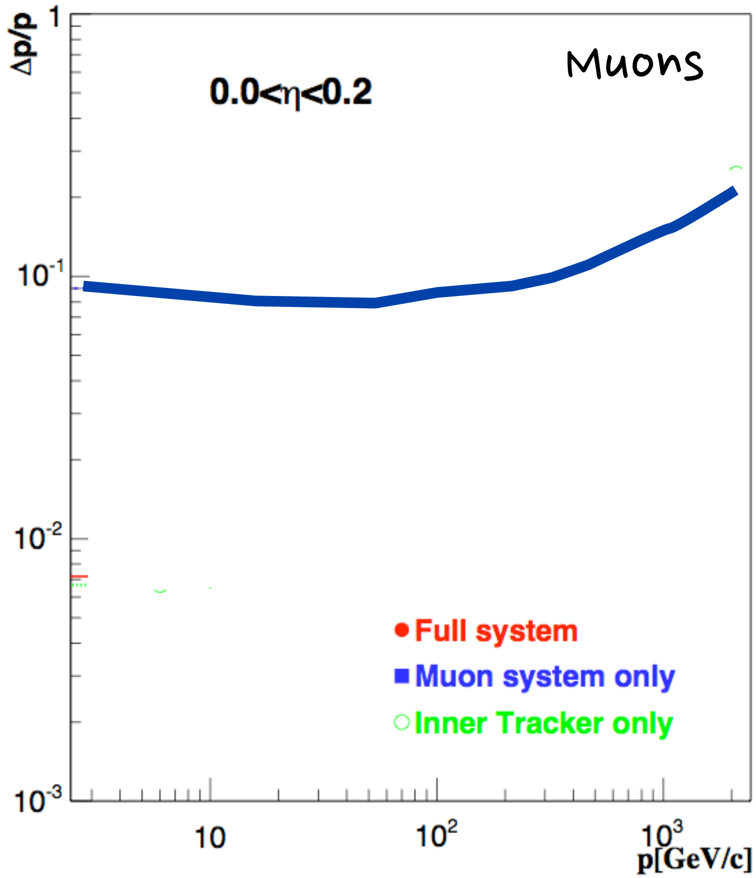

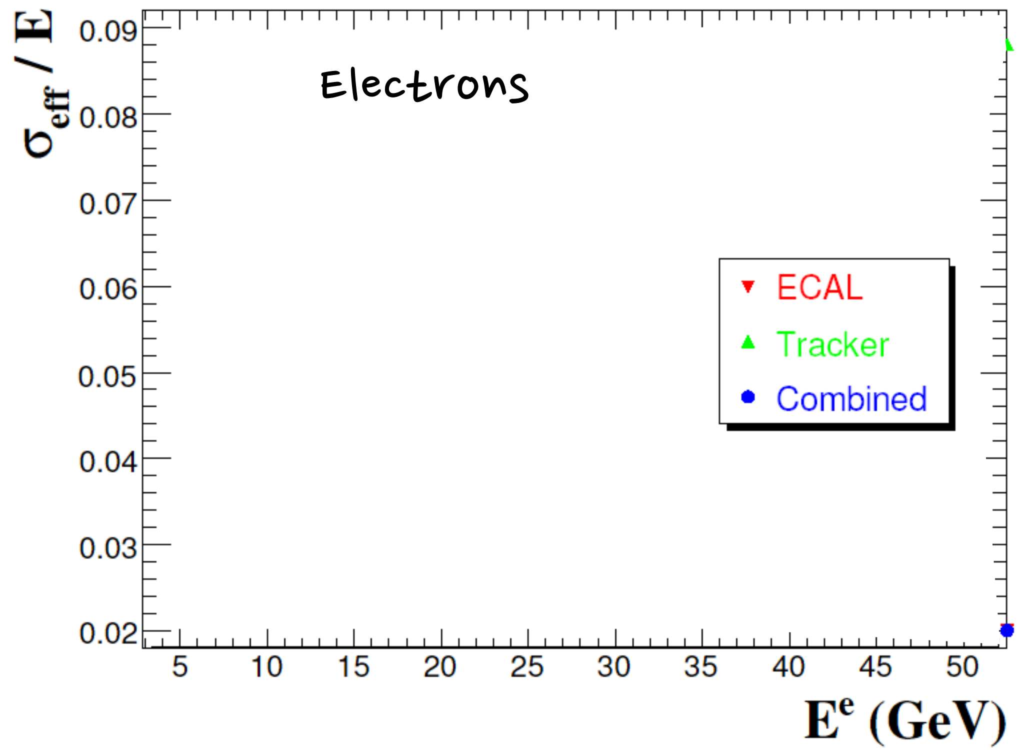

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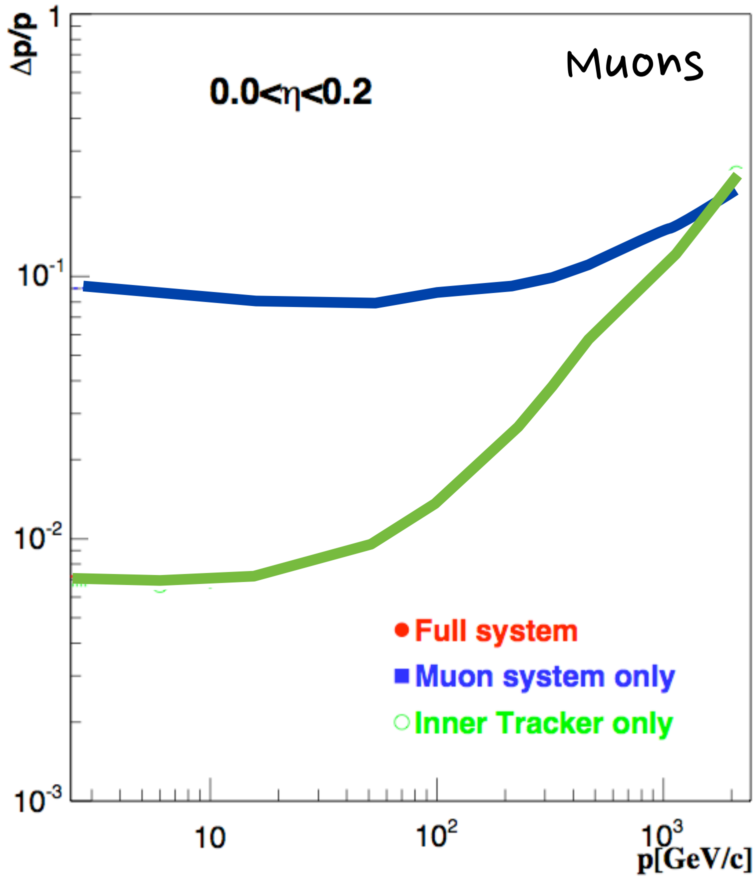

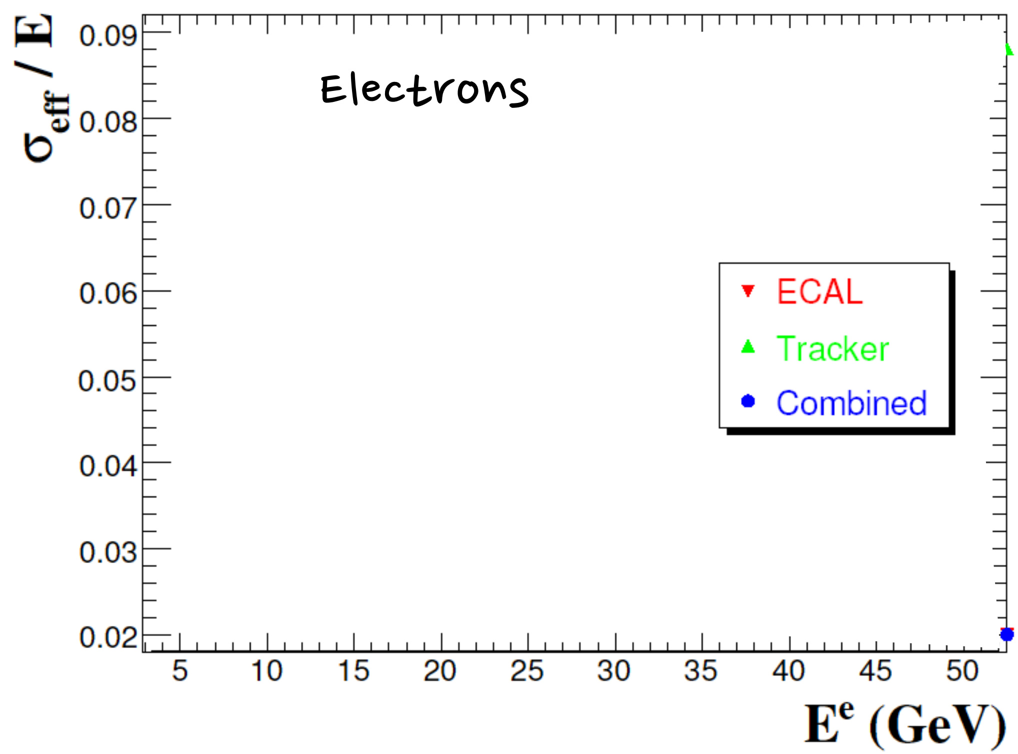

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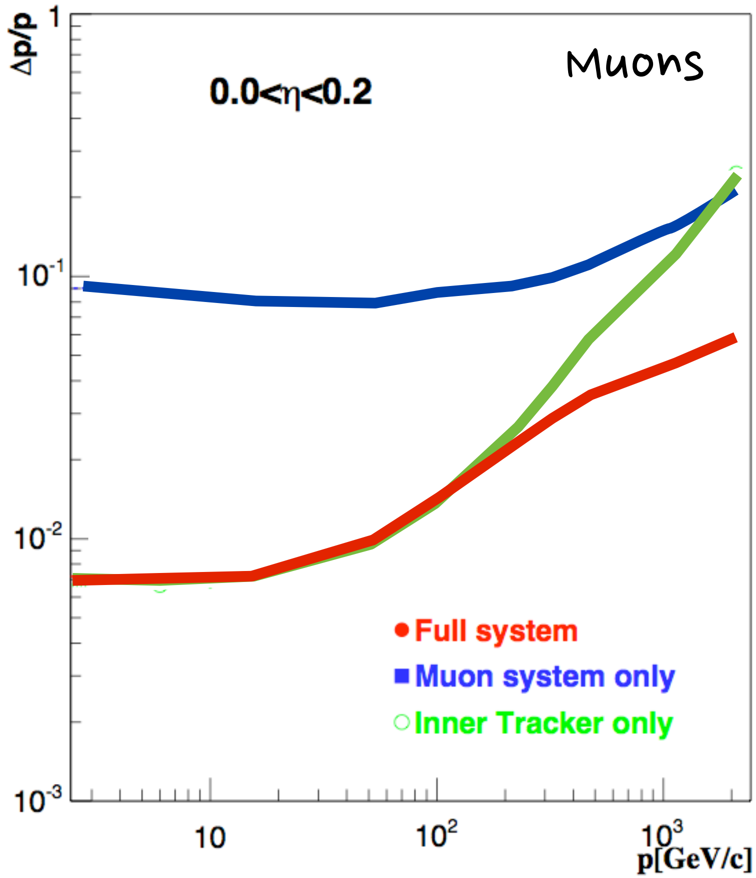

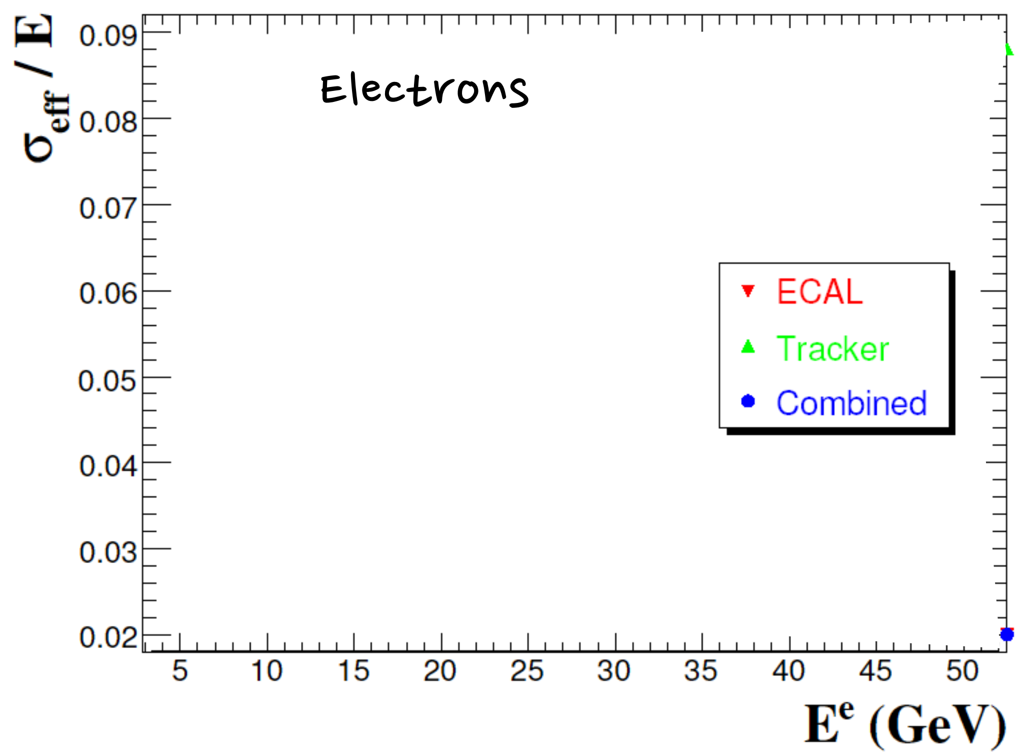

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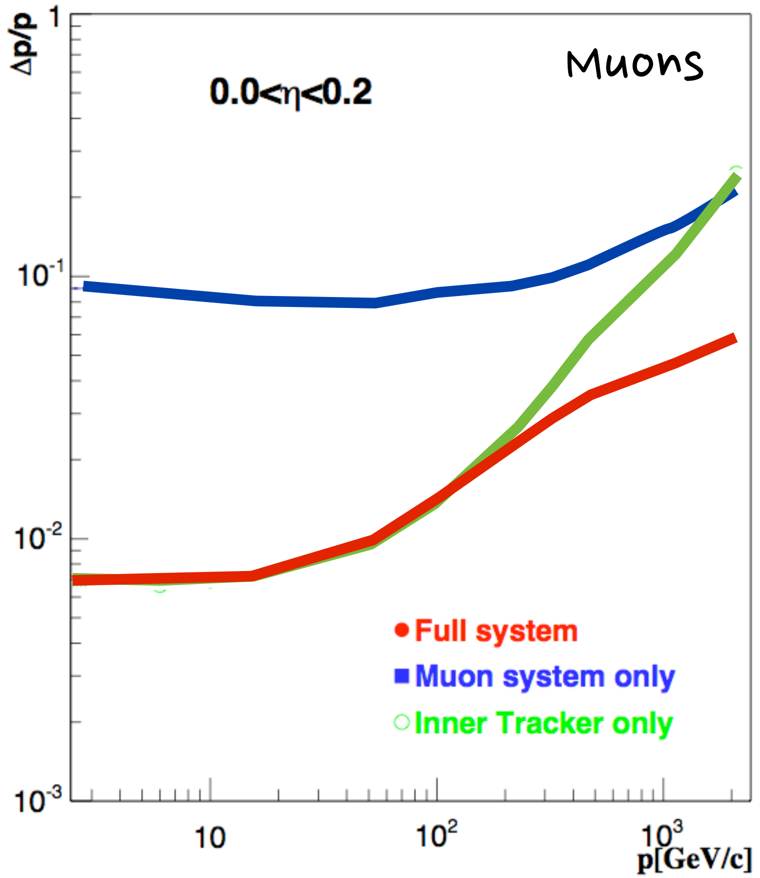

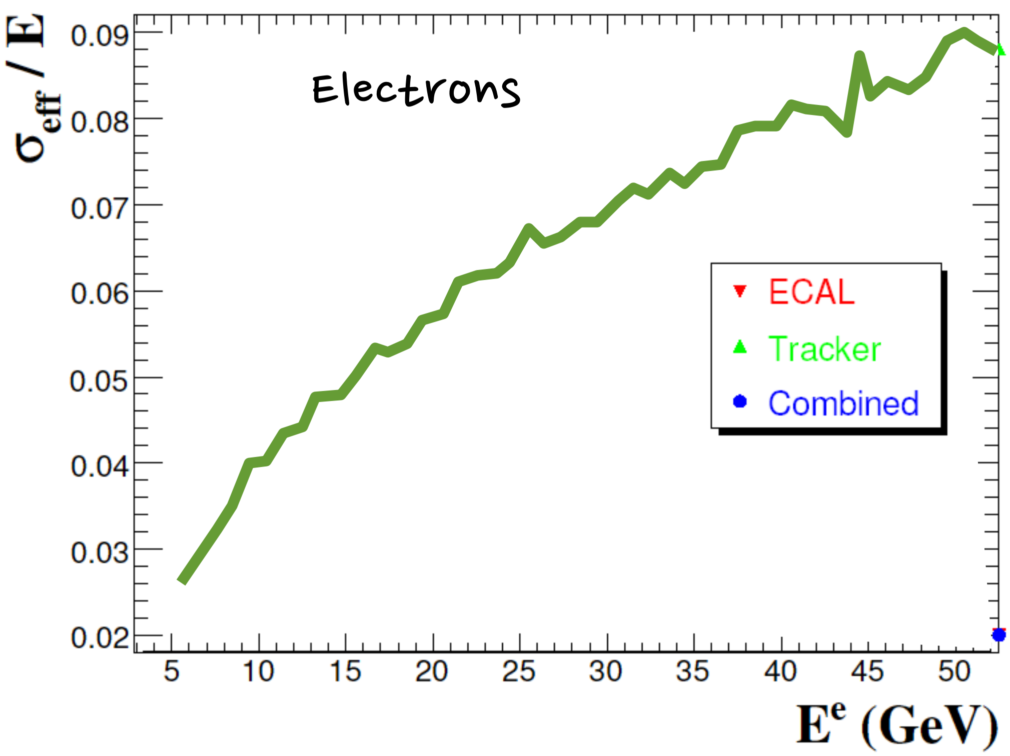

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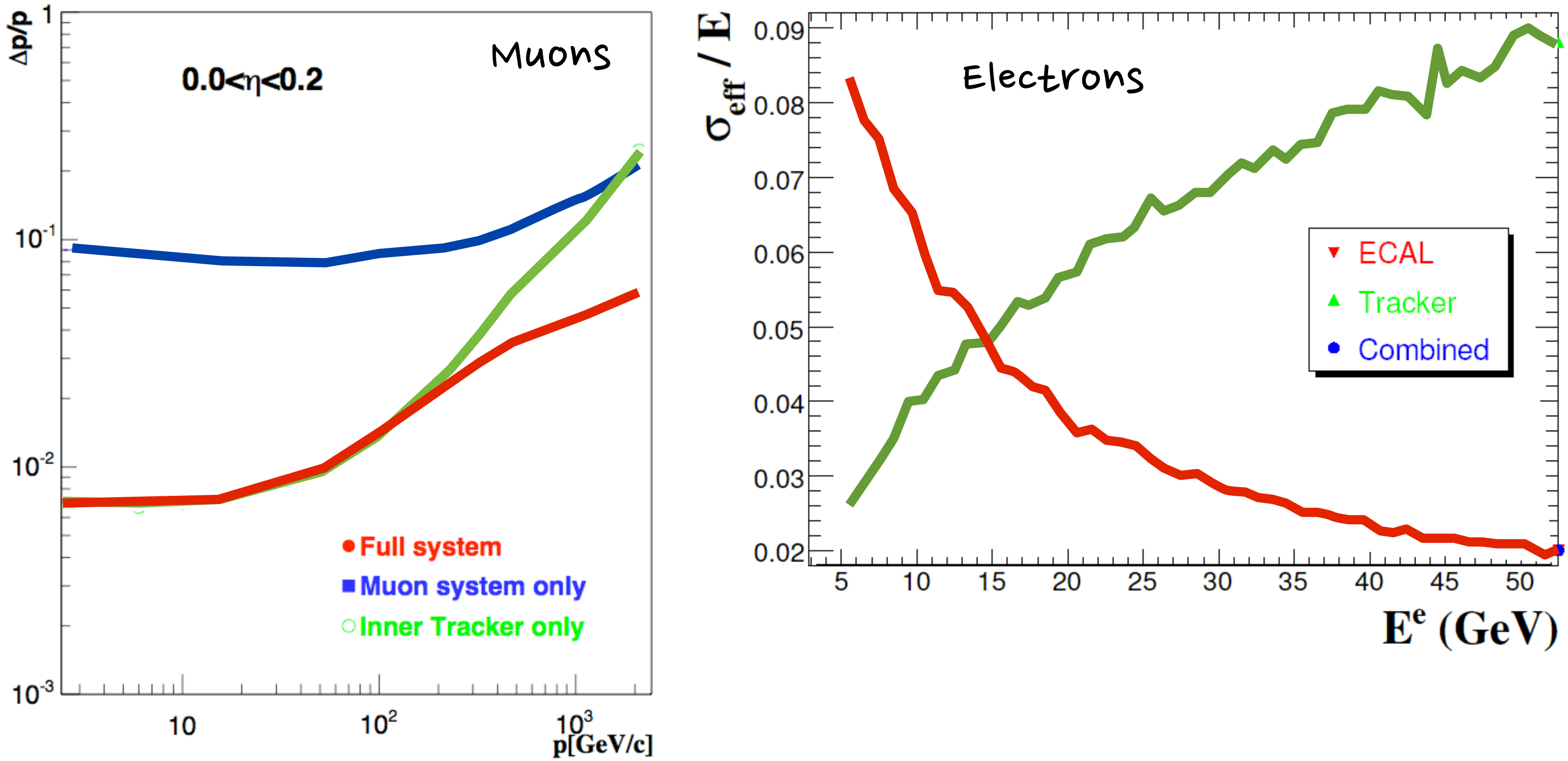

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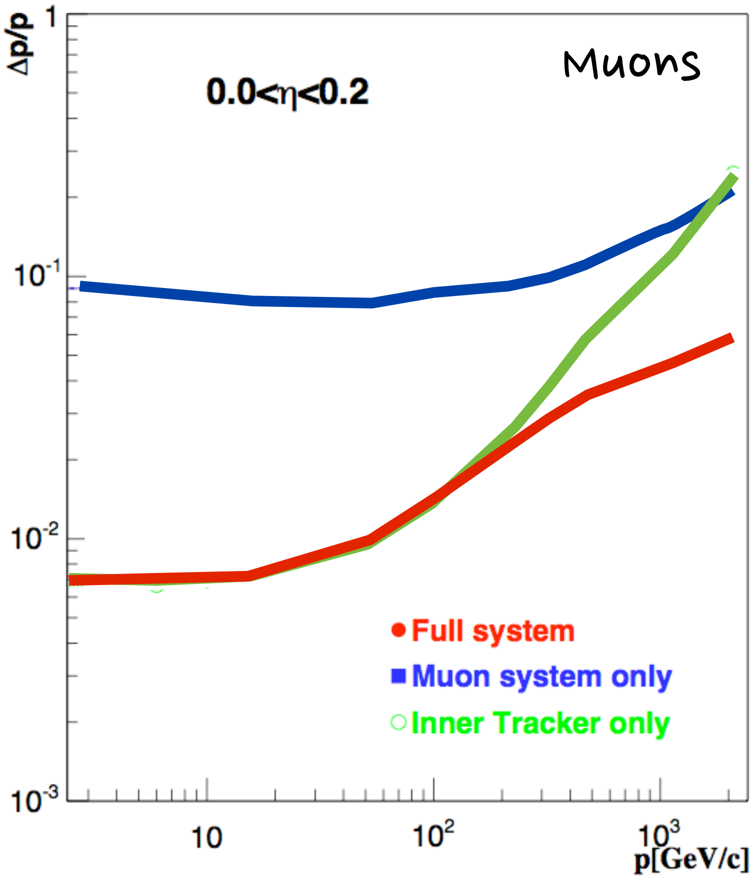

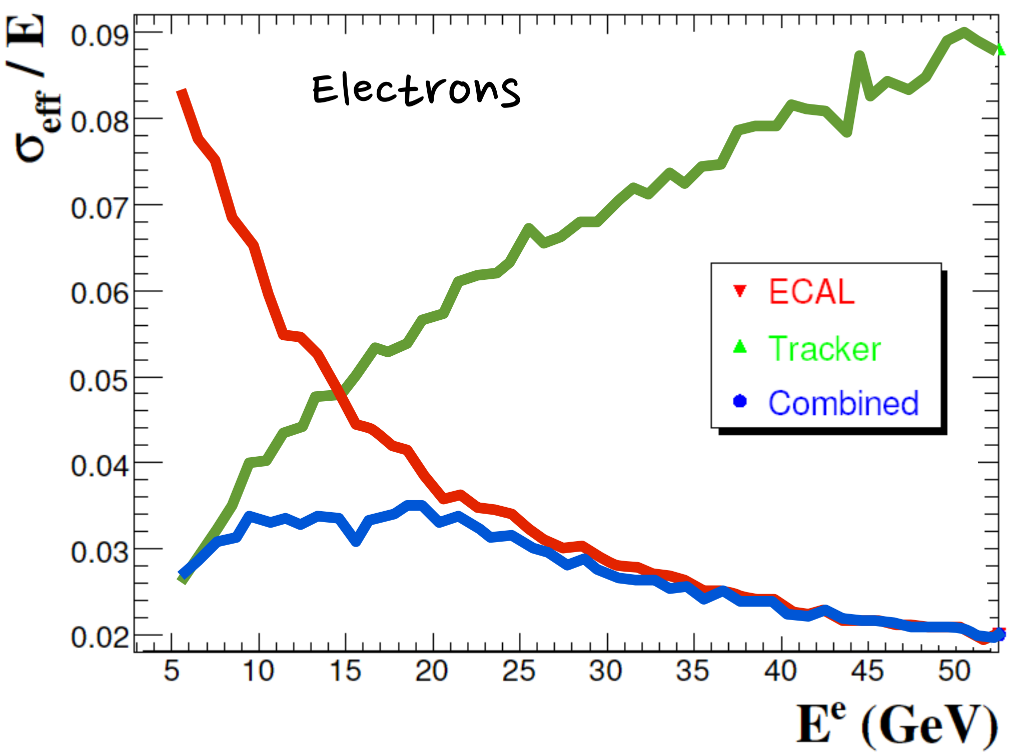

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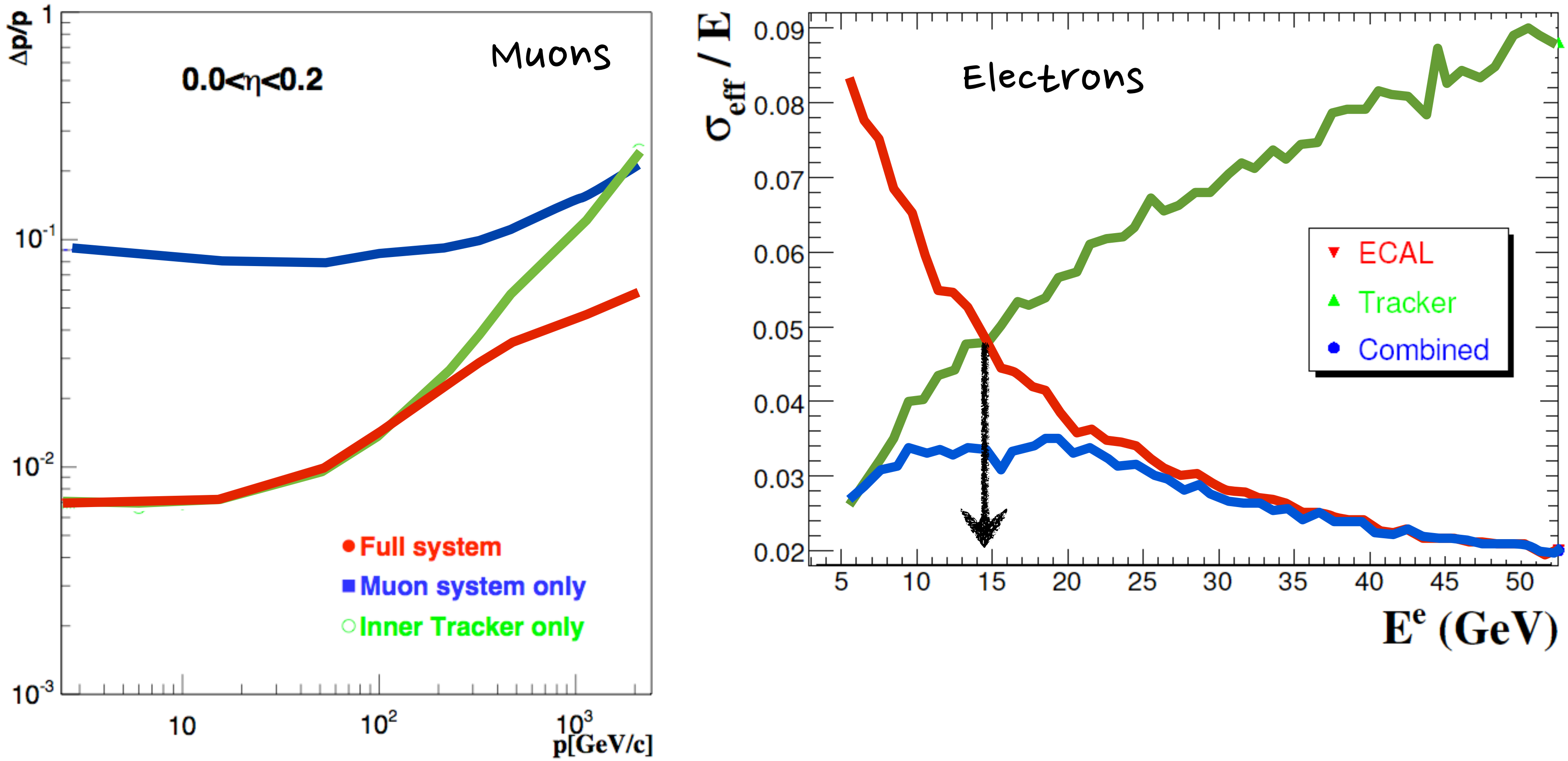

Back-of-envelope est. for $\pi^{\pm}$s

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calorimeter transverse energy uncertainty for charged hadrons:

$$\sigma(E_T) \approx 100\% \sqrt{E_T}$$

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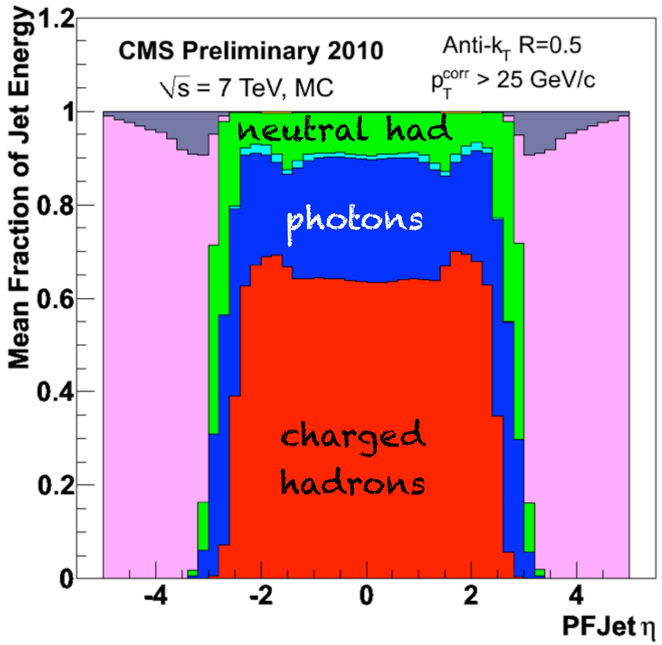
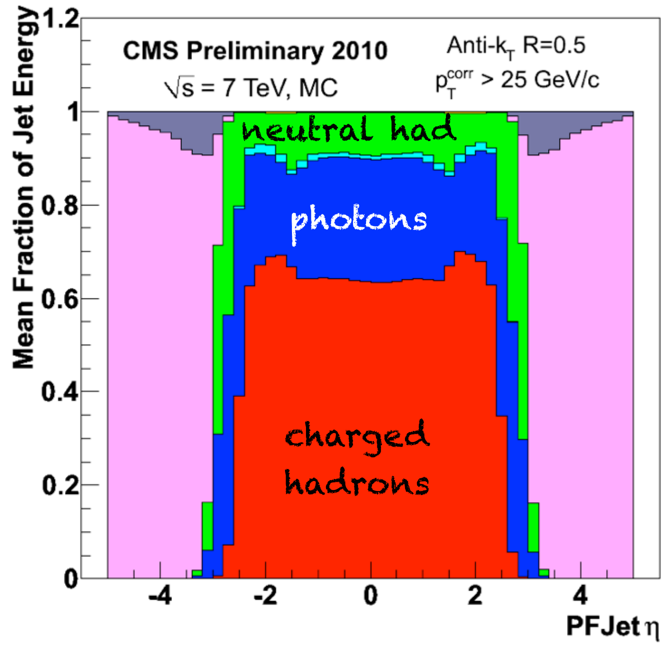
Set the Stage: Jet Composition



Set the Stage: Jet Composition

- **Charged particles : ~60%** Tracking
  - Mostly charged pions, kaons and protons, but also some electrons and muons



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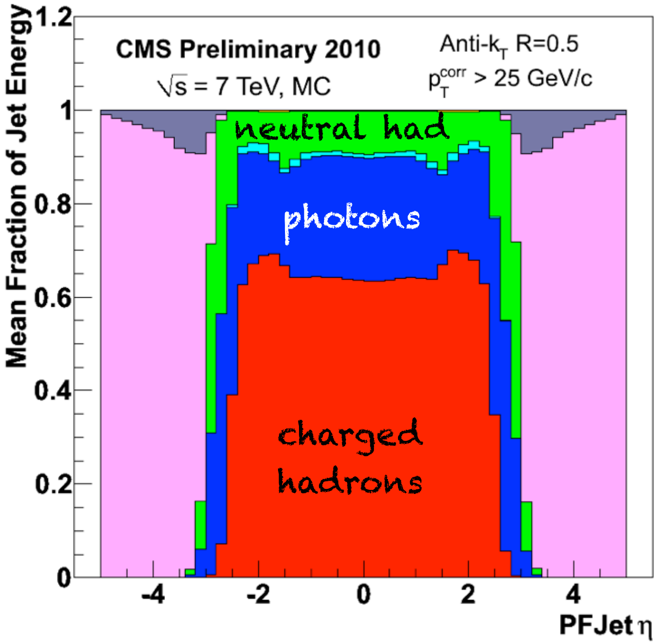

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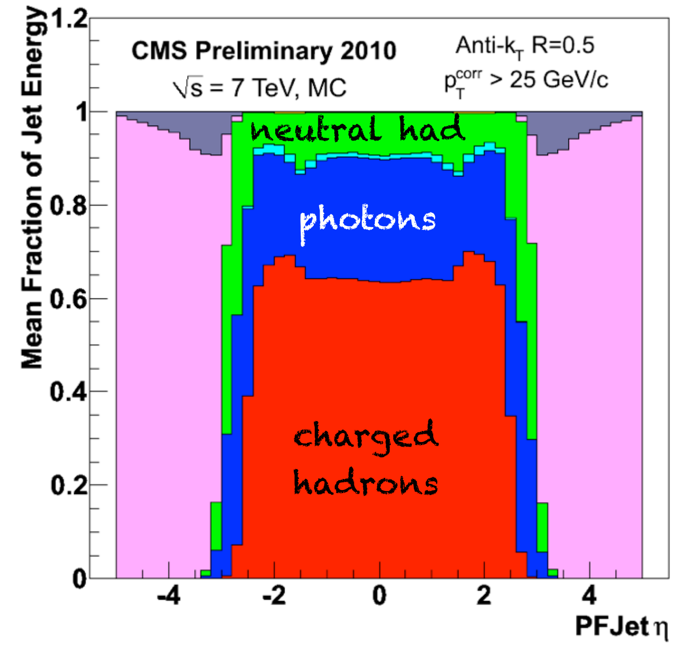
  - K^0_L, neutrons



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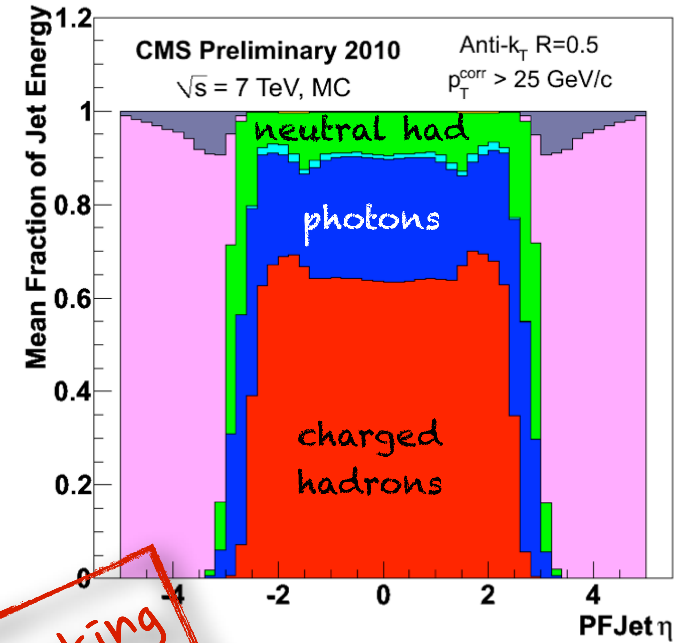
- **Short-lived neutral hadrons, "V^0's" : ~5%** Tracking
  - $K^0_S \to \pi^+\pi^-$, $\Lambda \to \pi^- p$, ..., but also γ conversions, and (more problematic) nuclear interactions in the detector material.



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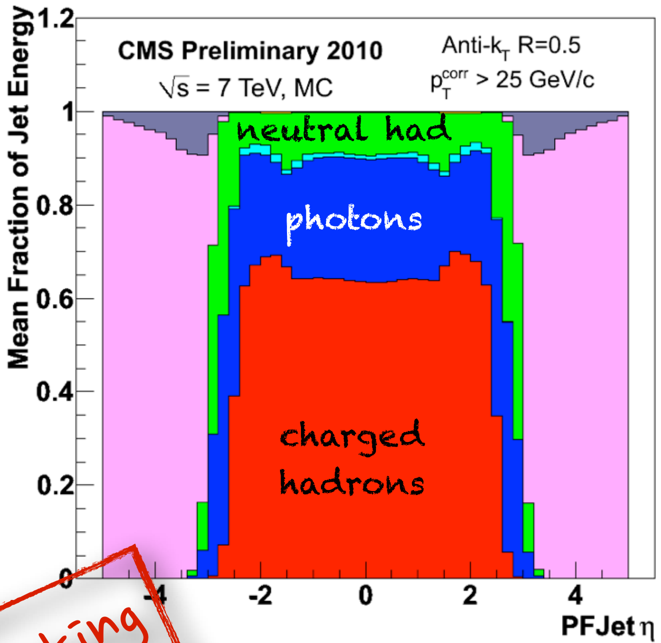
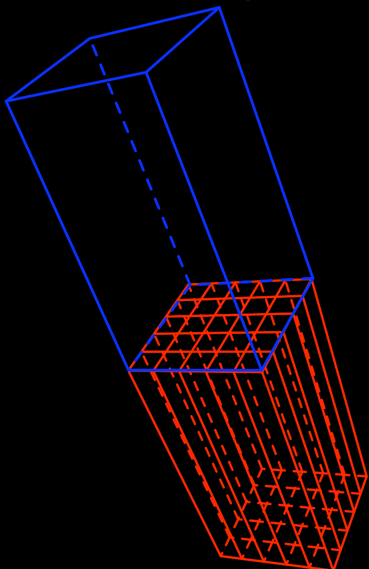
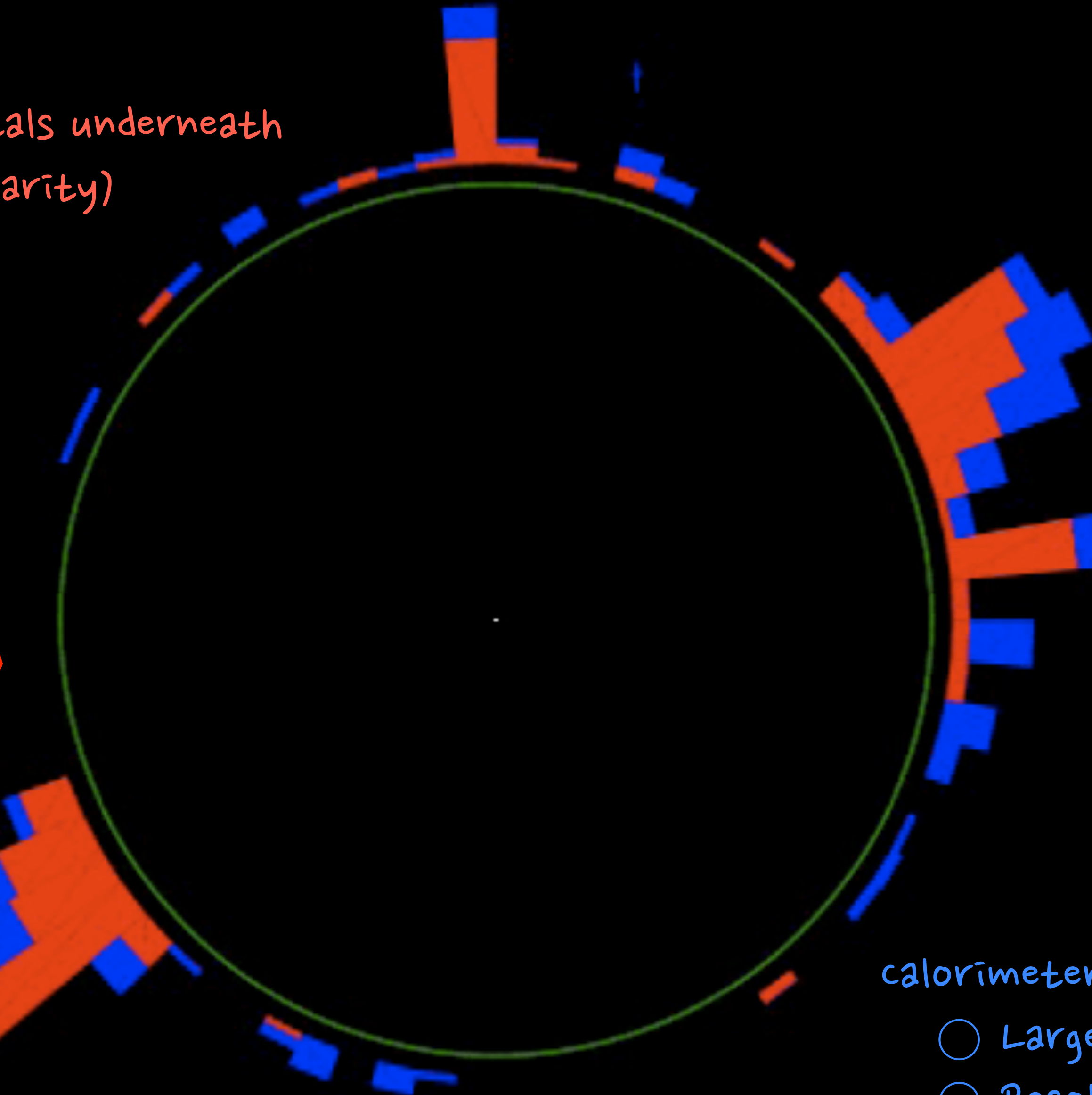


- **Full use of Detector Information significantly improves physics object performance** calorimeter Tower

- ◯ 1 HCAL cell
- ◯ 25 ECAL crystals underneath (loss of granularity)





calorimeter Jets

- ◯ Large Jet E corr.
- ◯ Resolution HCAL

$$\frac{\sigma}{E} \approx \frac{100\%}{\sqrt{E}}$$

calorimeter Tower

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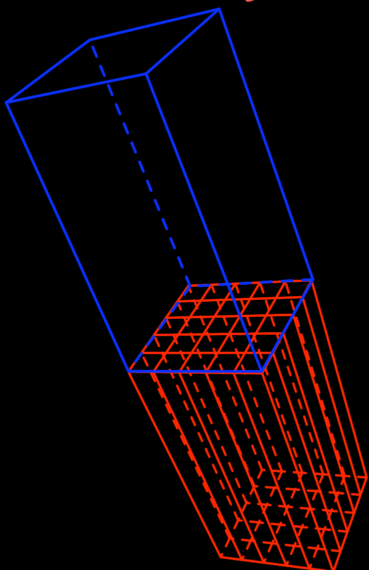
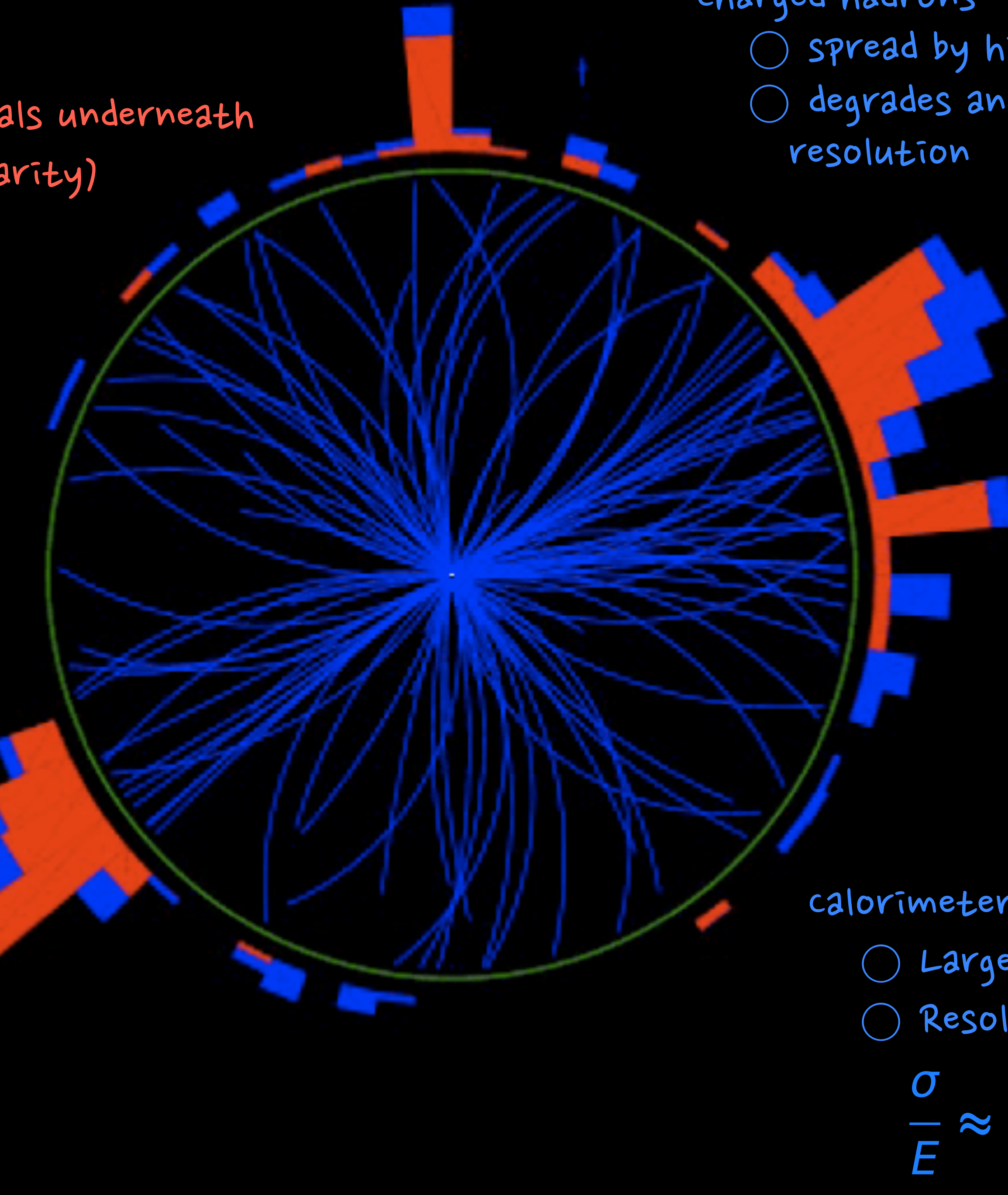


charged hadrons

- spread by high B-field
- degrades angular resolution



calorimeter Jets

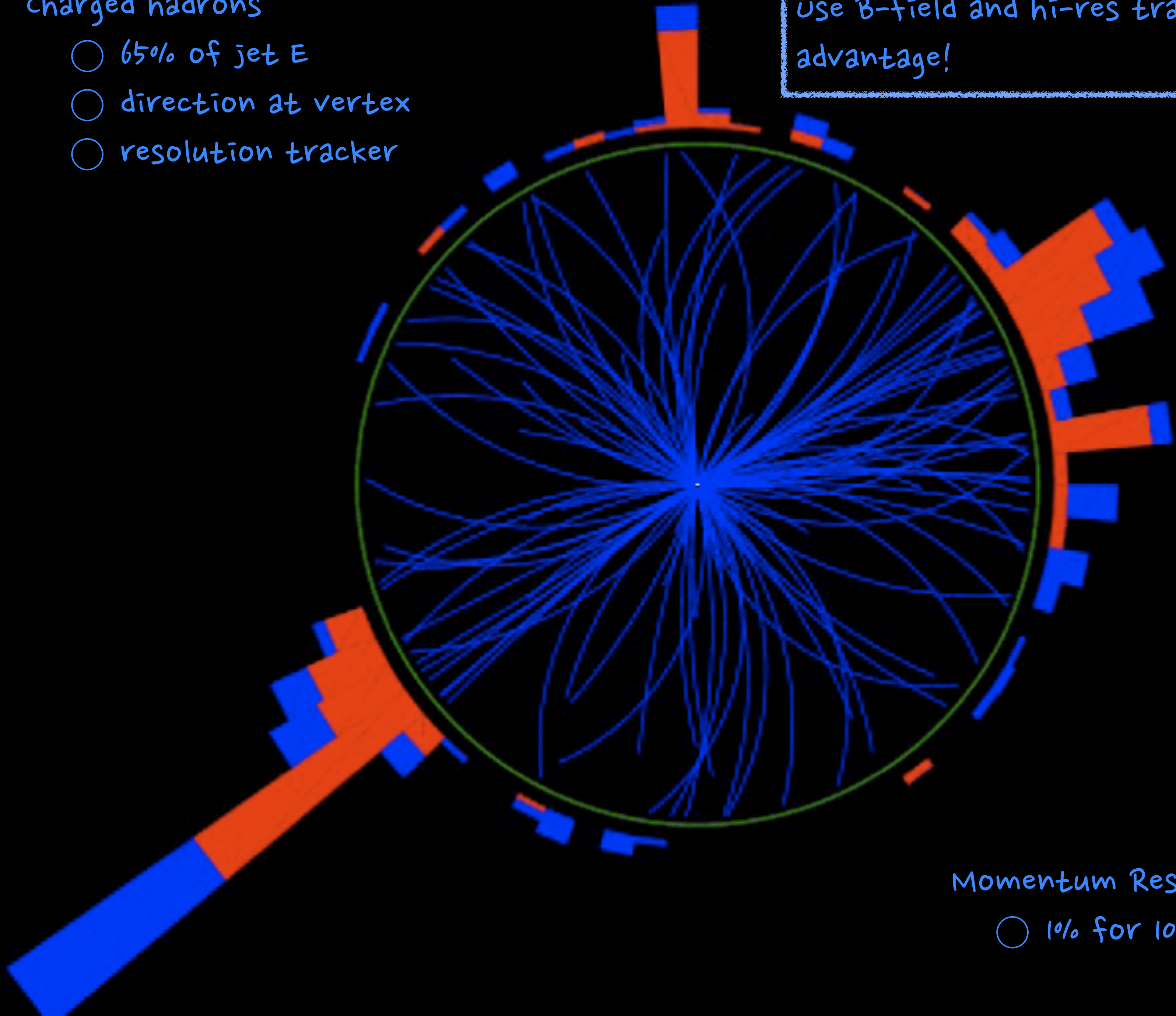
- Large Jet E corr.
- Resolution HCAL

$$\frac{\sigma}{E} \approx \frac{100\%}{\sqrt{E}}$$

charged hadrons

- 65% of jet E
- direction at vertex
- resolution tracker

Use B-field and hi-res tracker to our advantage!



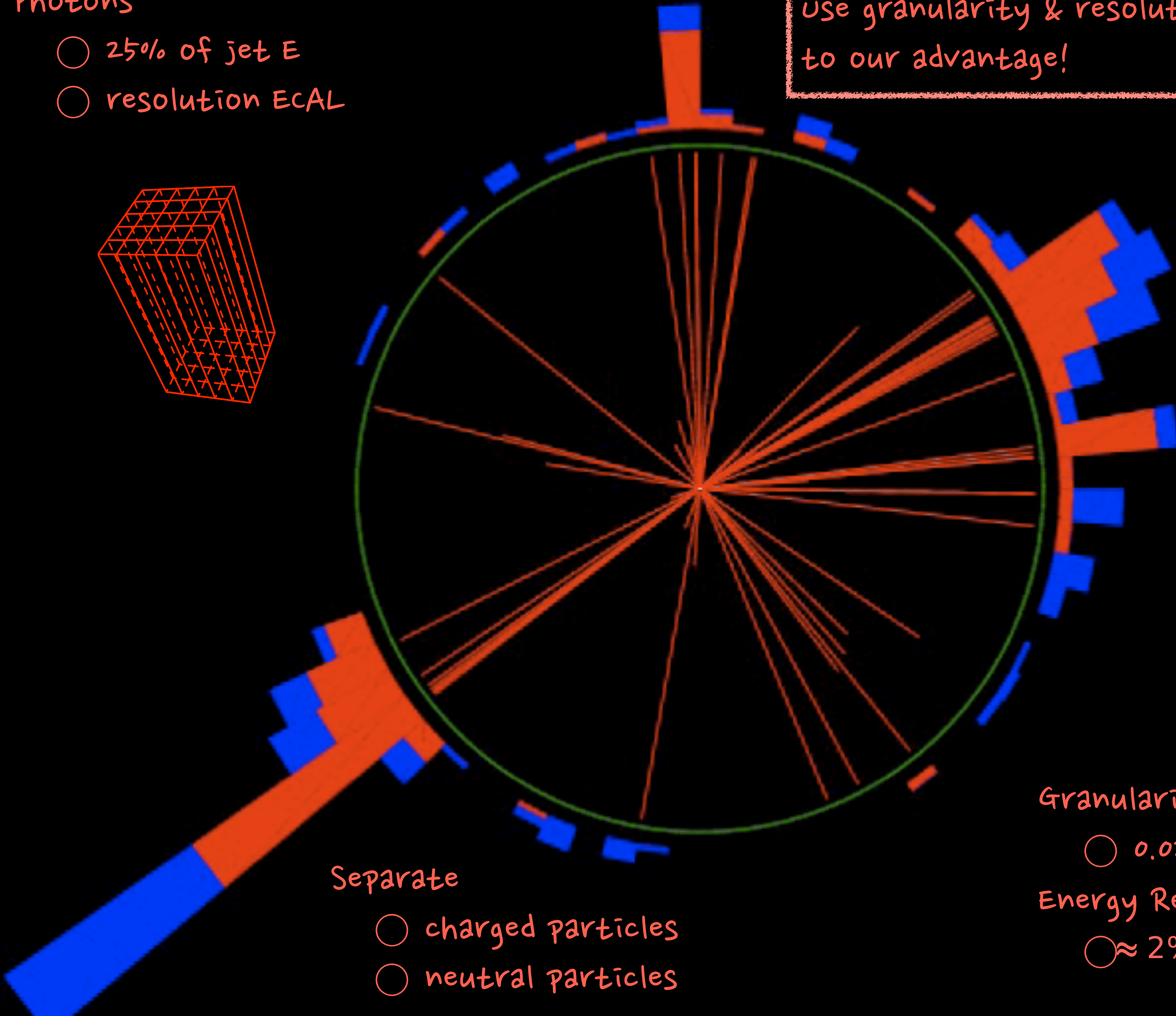
Momentum Resolution

- 1% for 100 GeV

Photons

- 25% of jet E
- resolution ECAL

Use granularity & resolution of ECAL to our advantage!



Separate

- charged particles
- neutral particles

Granularity

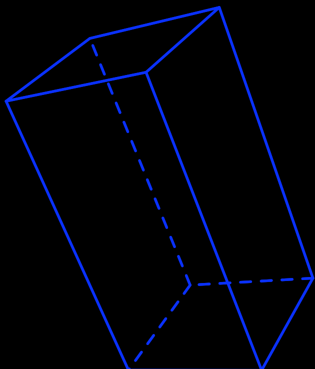
- 0.02 $(\Delta\eta \times \Delta\phi)$

Energy Resolution

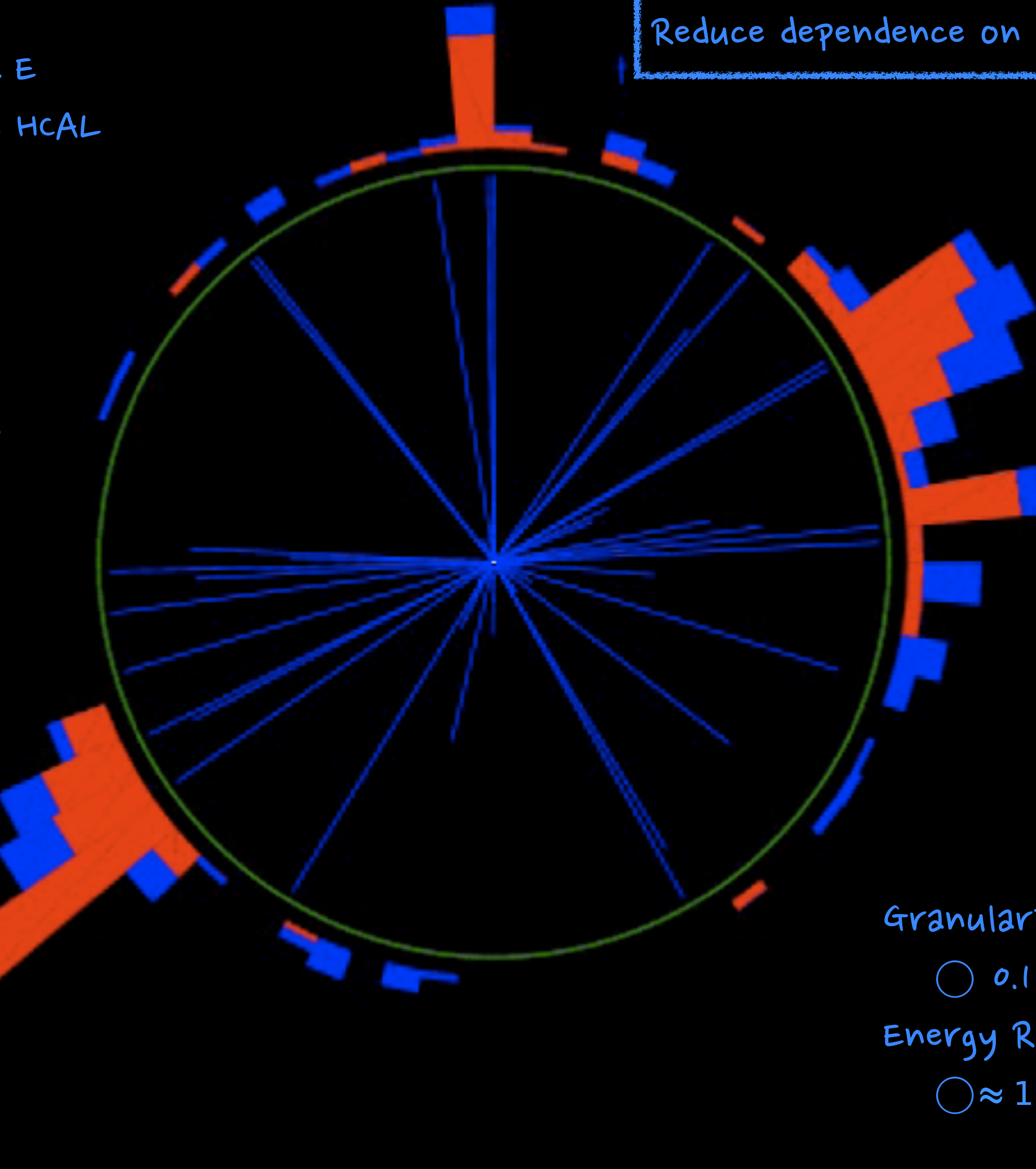
- $\approx 2\%/\sqrt{E}$

Neutral Hadrons

- 10% of jet E
- resolution HCAL



Reduce dependence on HCAL



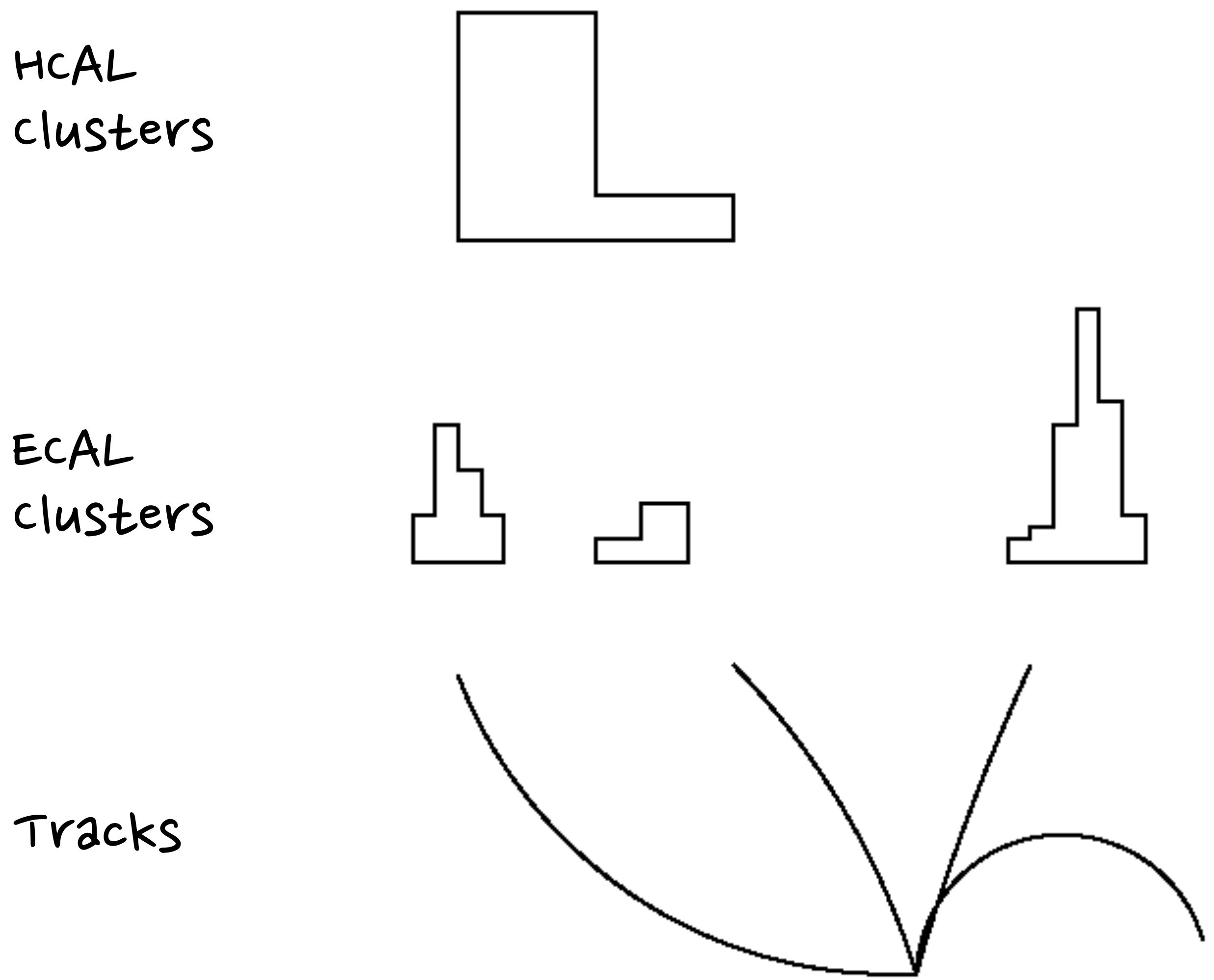
Granularity

- 0.1 $(\Delta\eta\times\Delta\phi)$

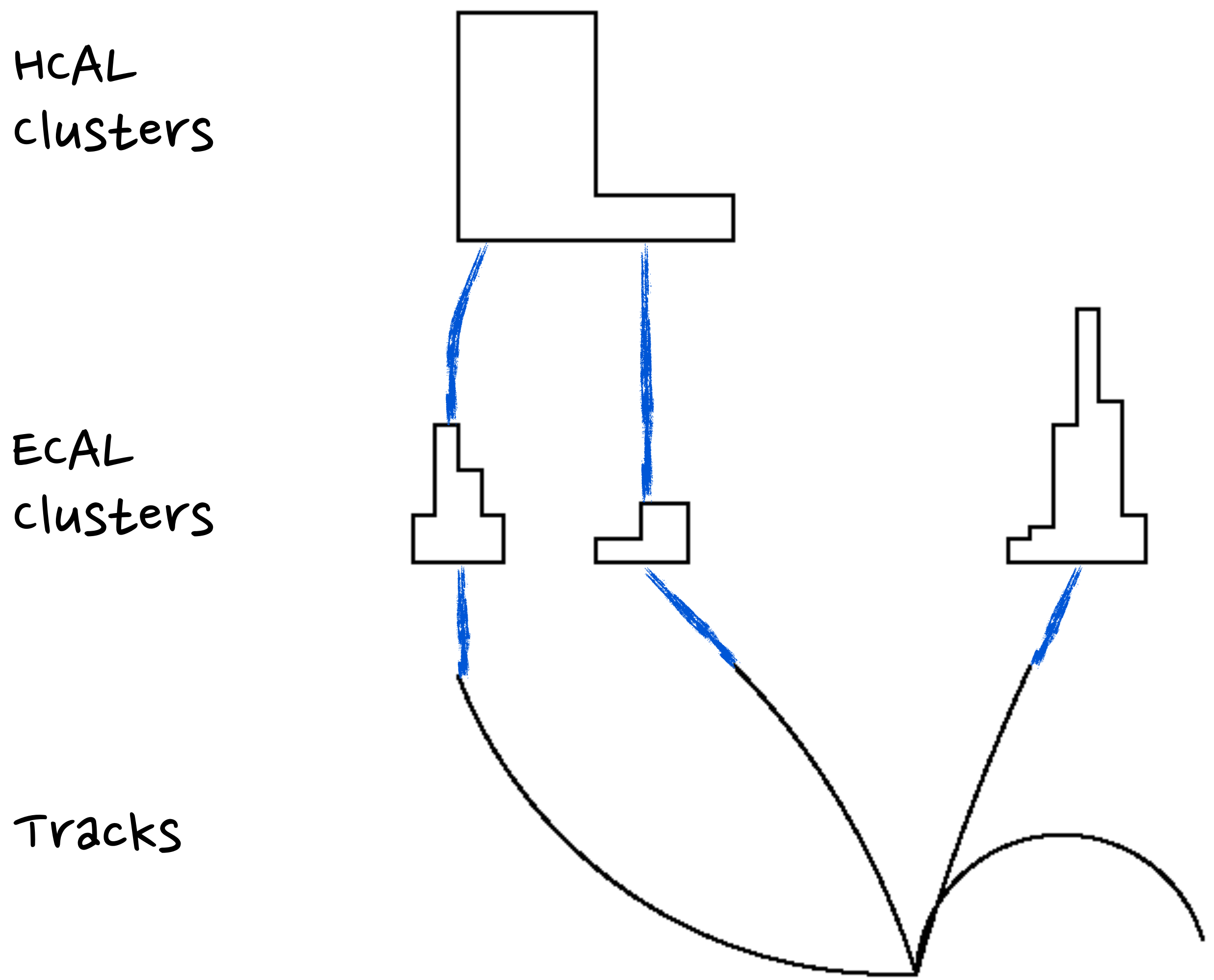
Energy Resolution

- $\approx 100\%/\sqrt{E}$

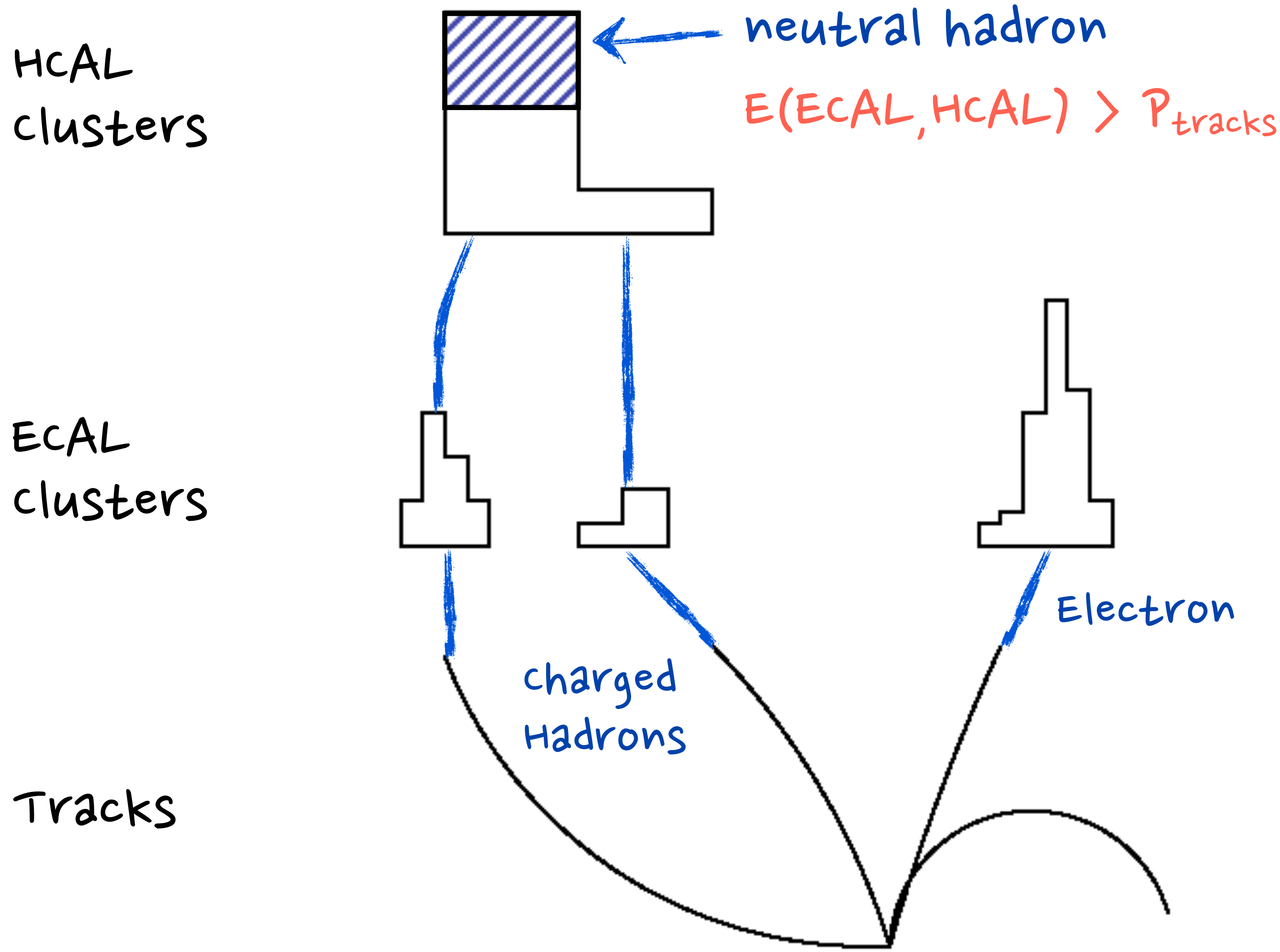
First Associate Hits within Each Detector



Then Link Across Detectors



Finally Apply Particle ID & Separation



Very Basic View of Particle Flow

"clean" the Event During Reconstruction!

Very Basic View of Particle Flow

Fermilab
UIC University of Illinois at Chicago

"clean" the Event During Reconstruction!

- **Find and "remove" muons (σ_{track})**

Very Basic View of Particle Flow

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Very Basic View of Particle Flow

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- Left with neutral hadrons (10%) (σ_{HCAL} + fake)

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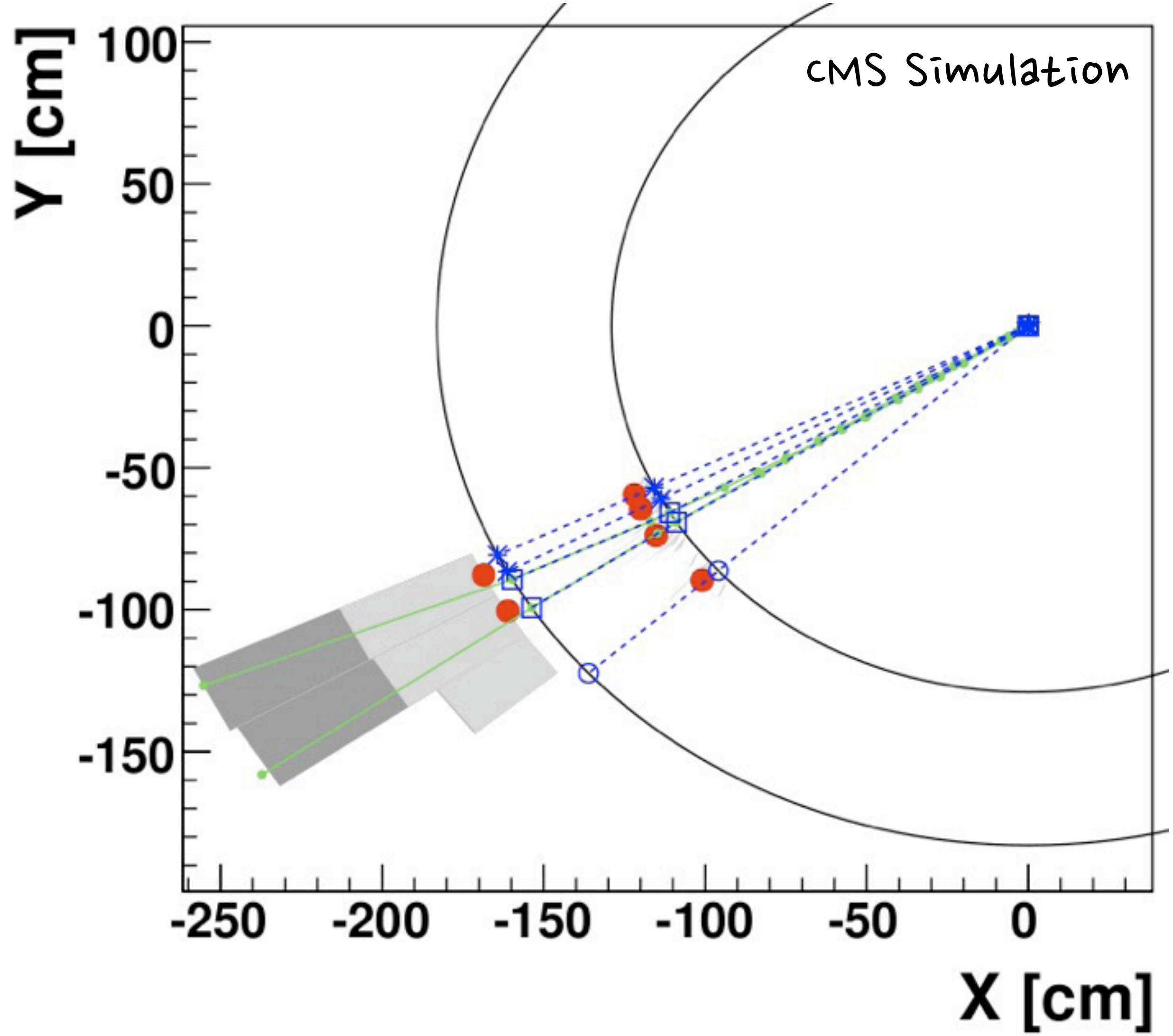
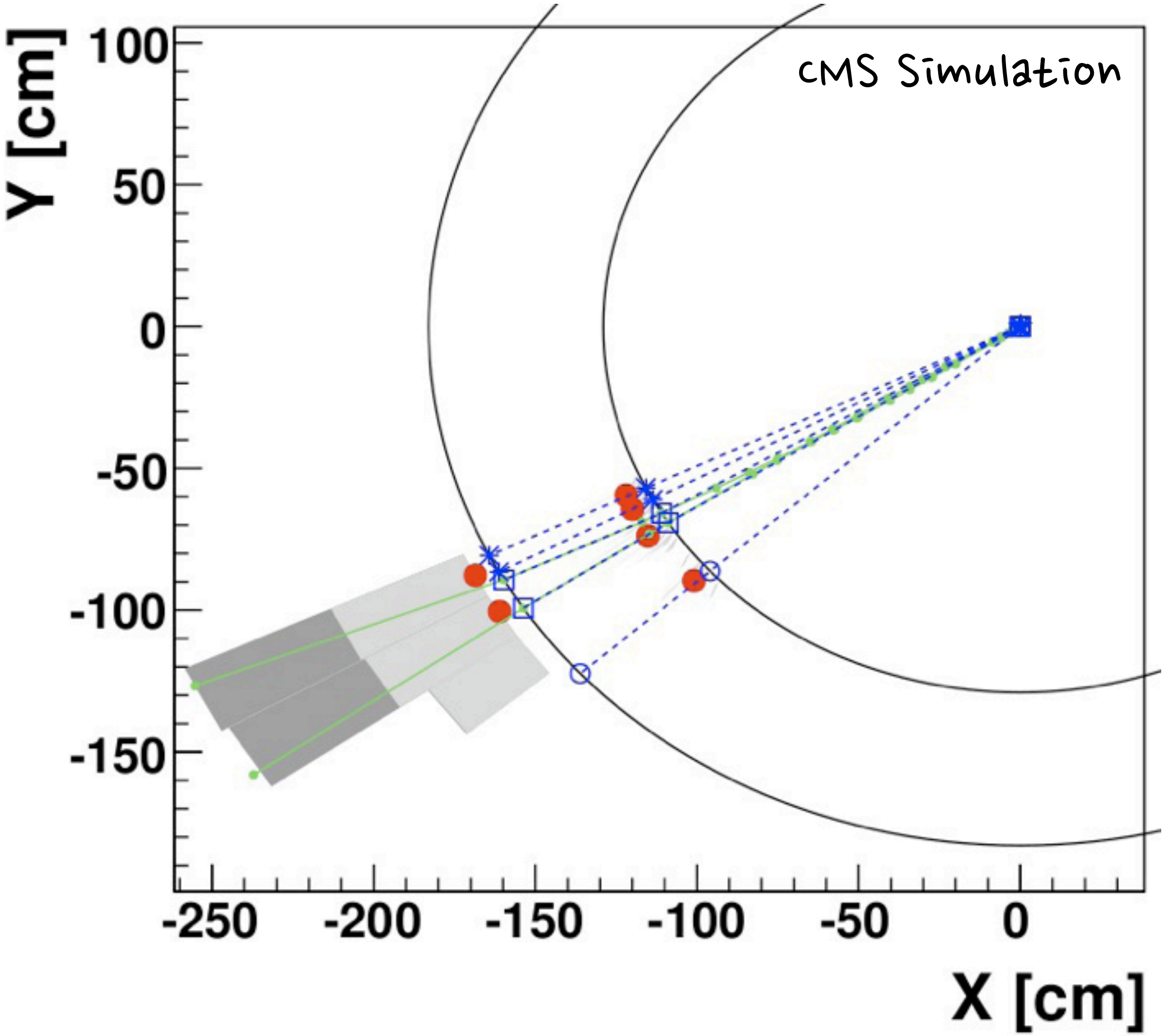
- Use above list of Reconstructed Particles to describe the entire event!

Let's take a simple example



Jet PT = 65 GeV/c

Let's take a simple example



Jet pT = 65 GeV/c

Four true particles:

π^+, π^-, π^0, K_L^0

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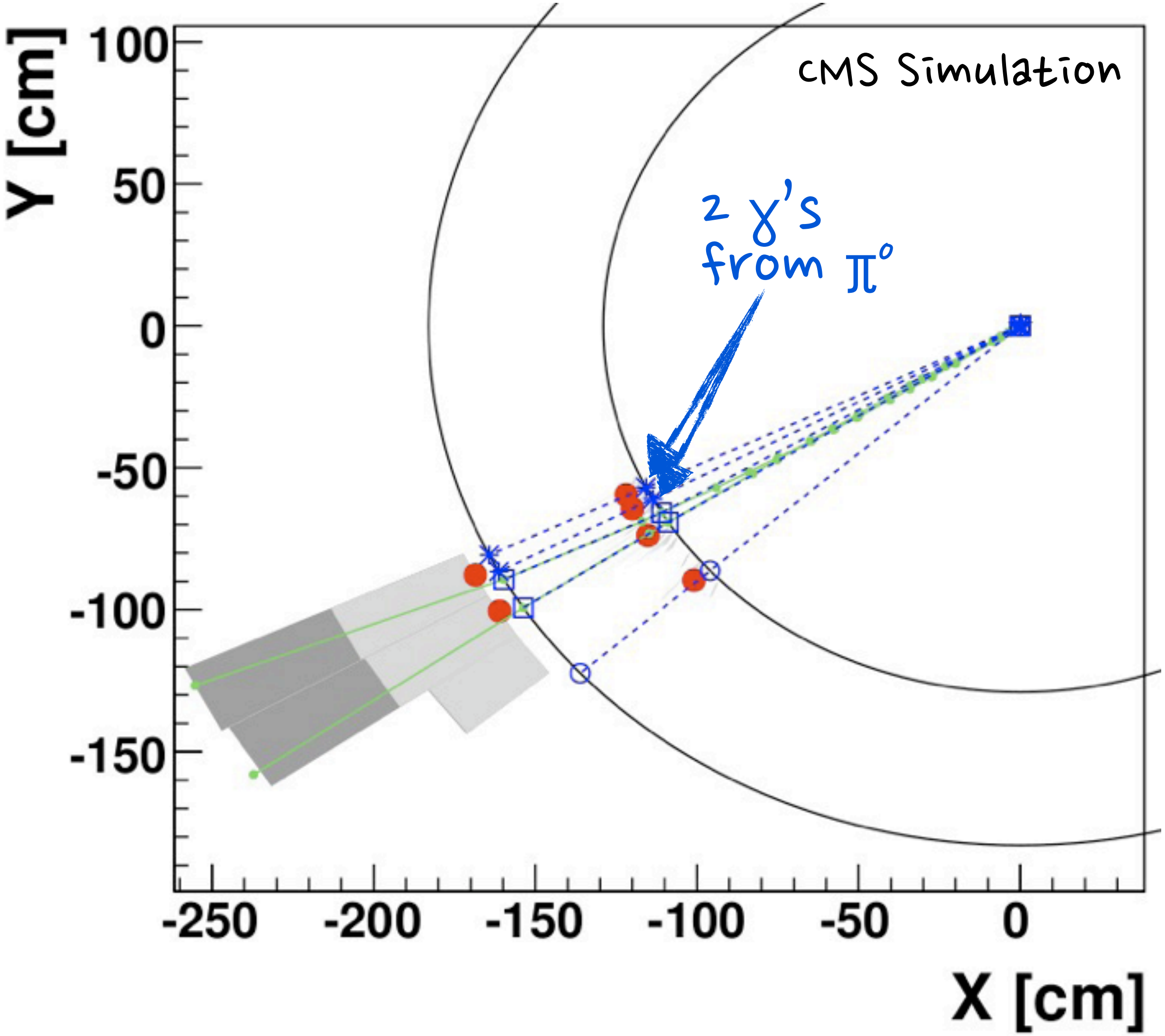

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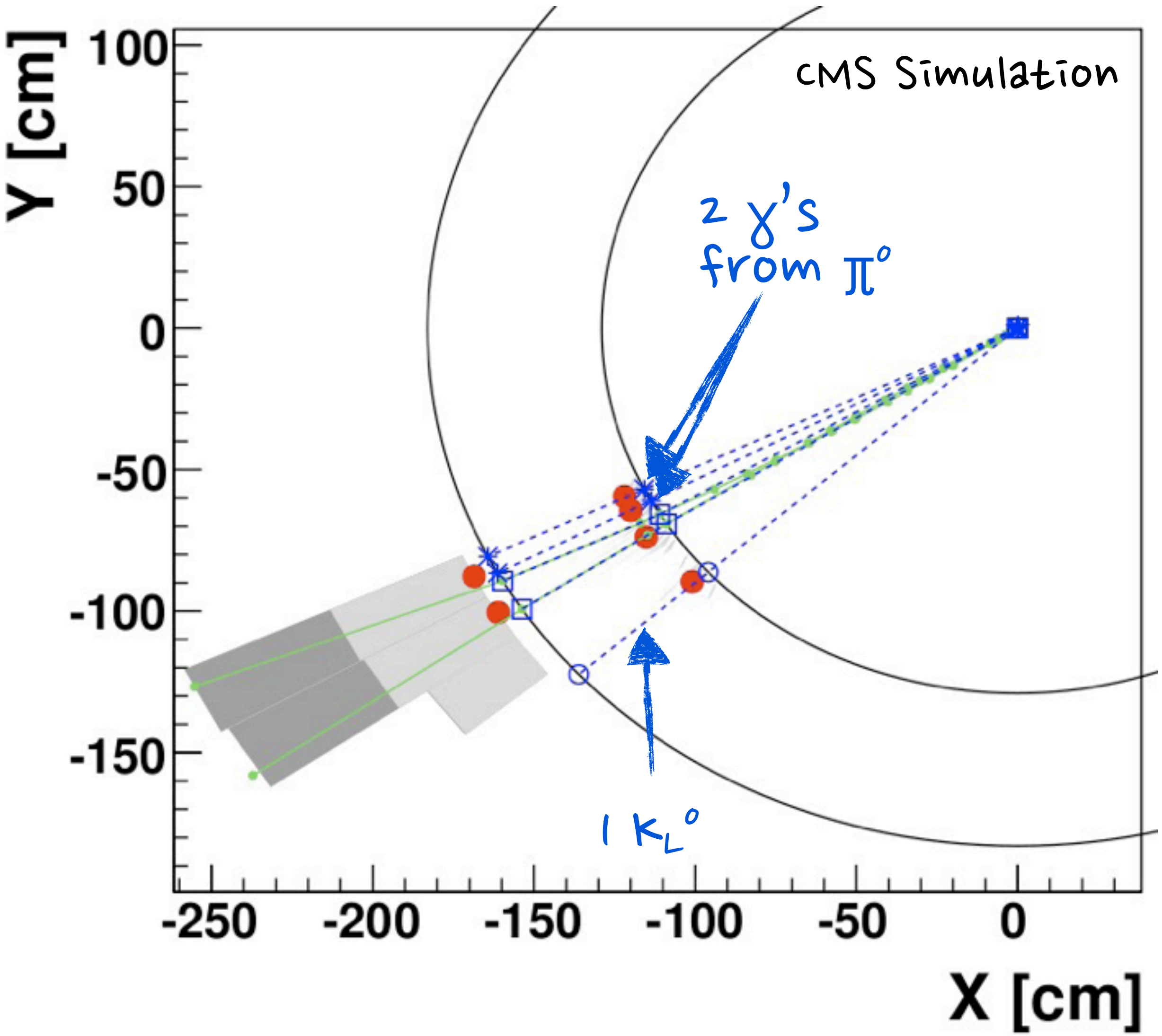

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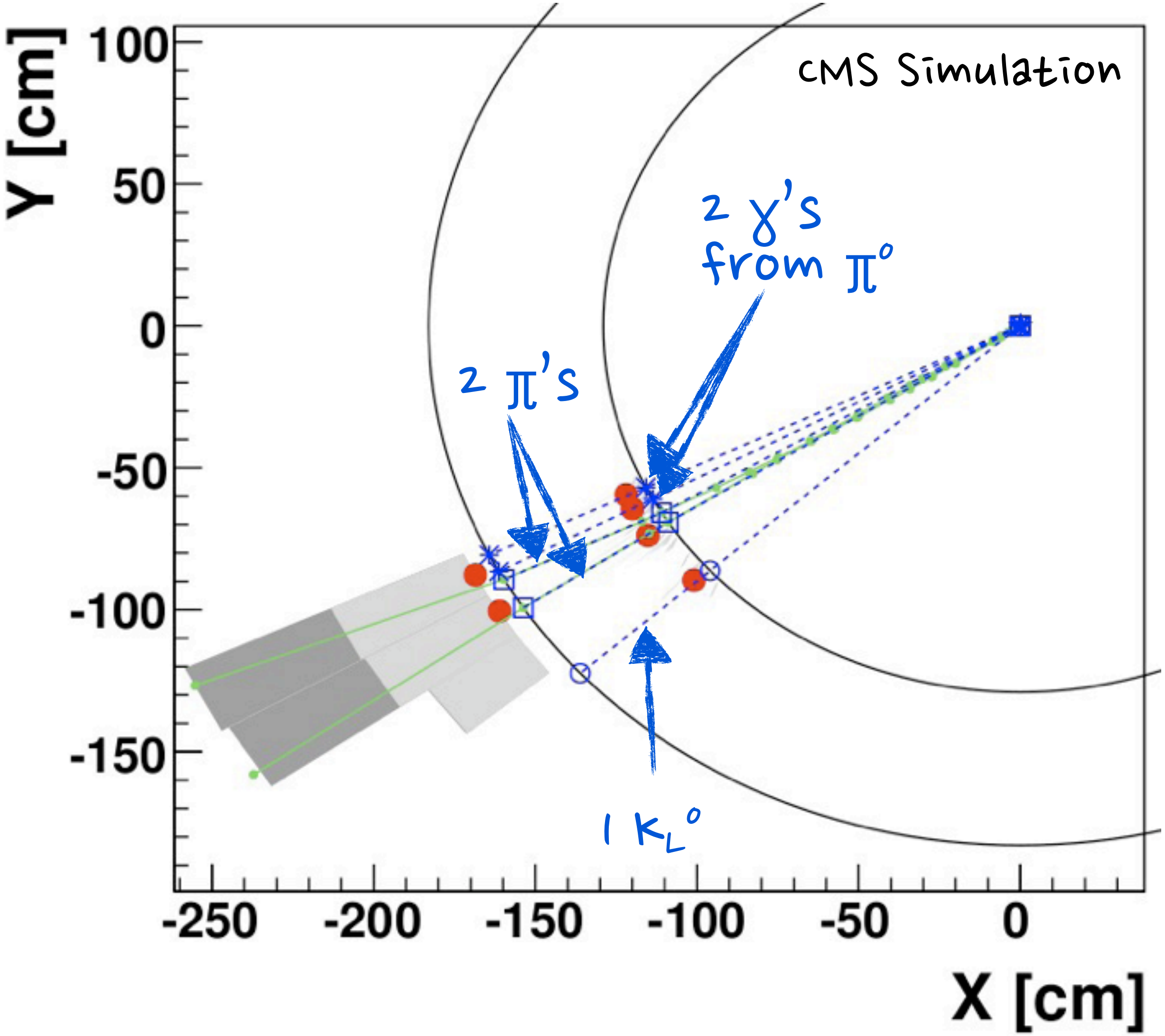

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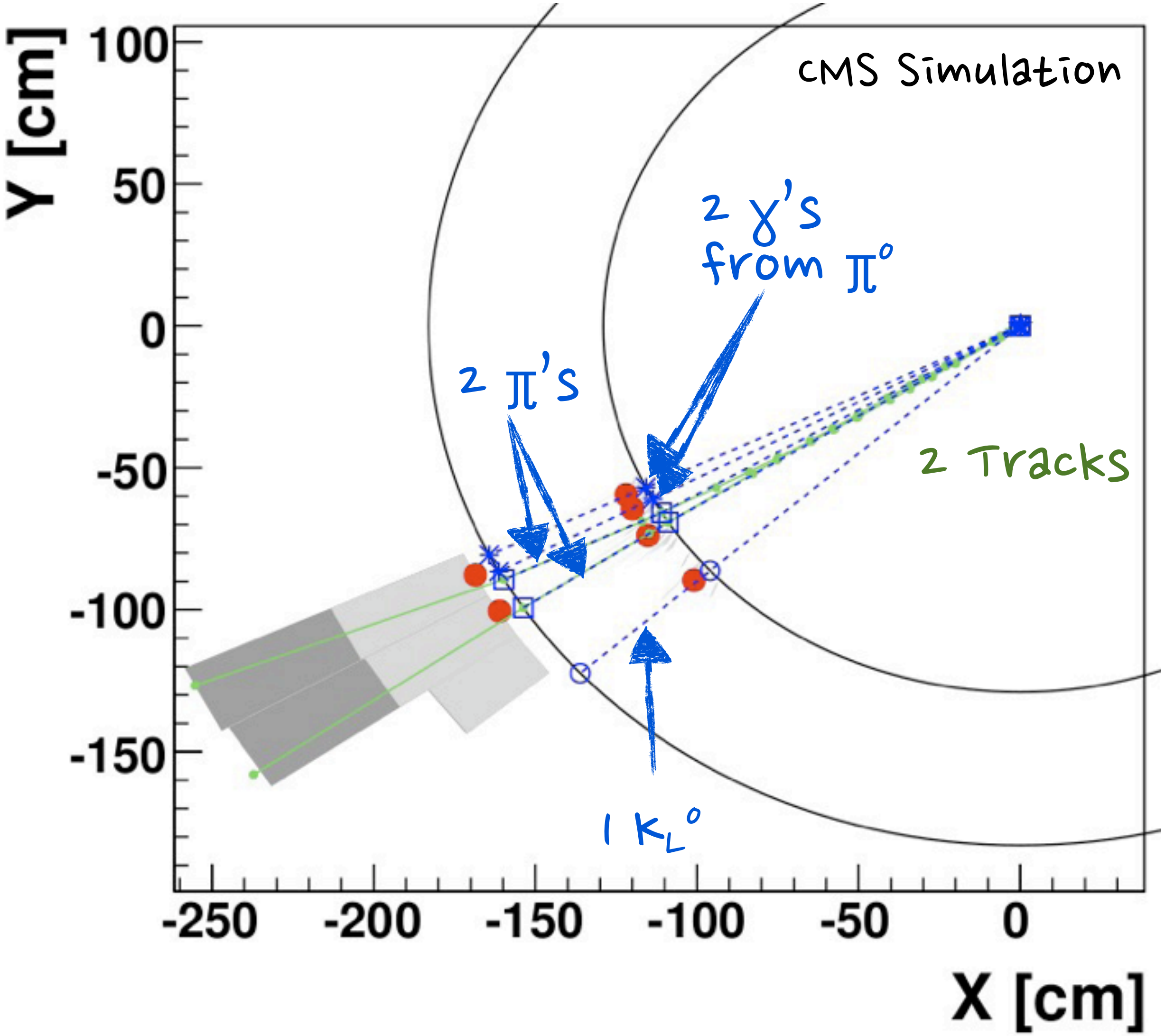

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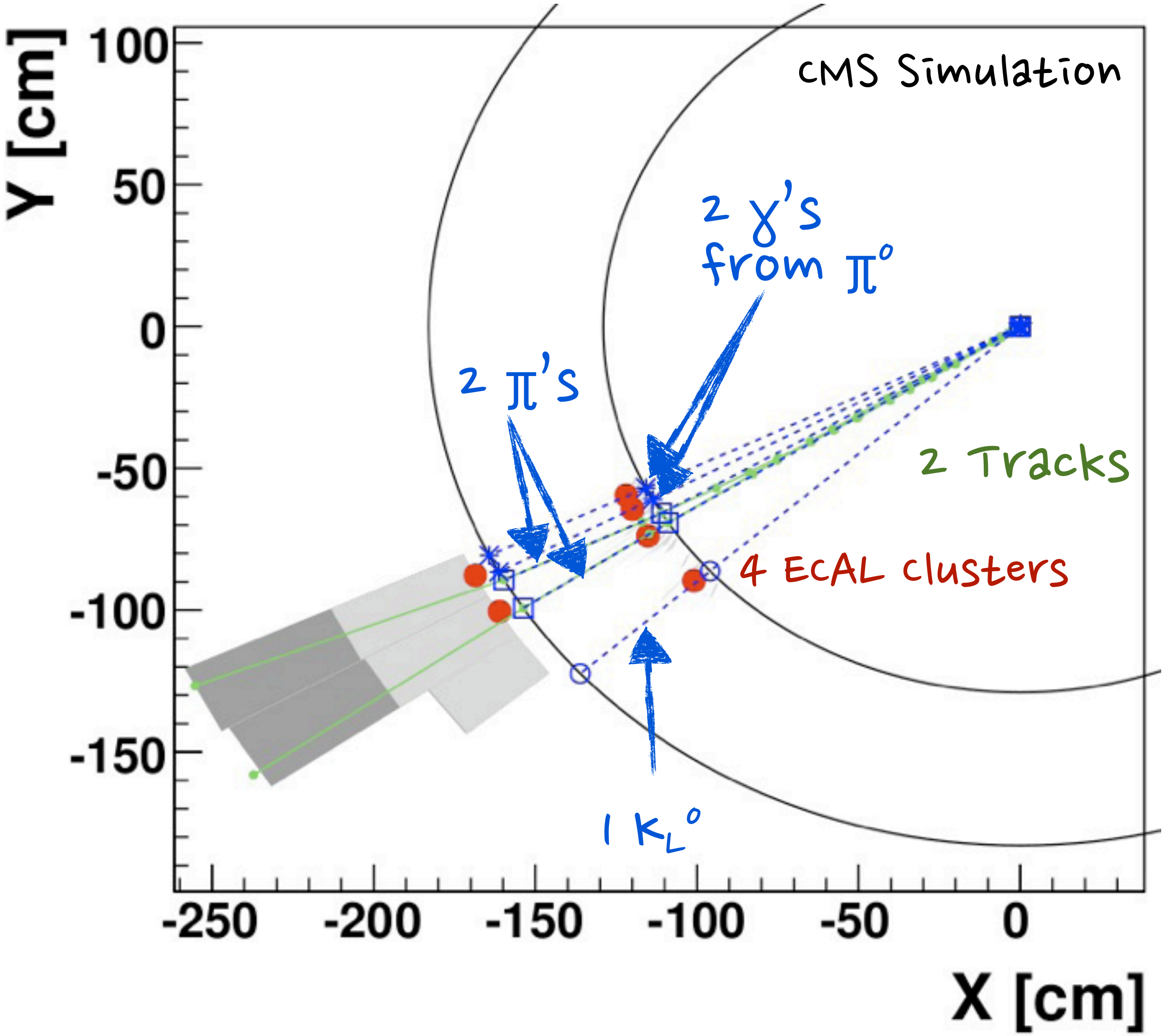

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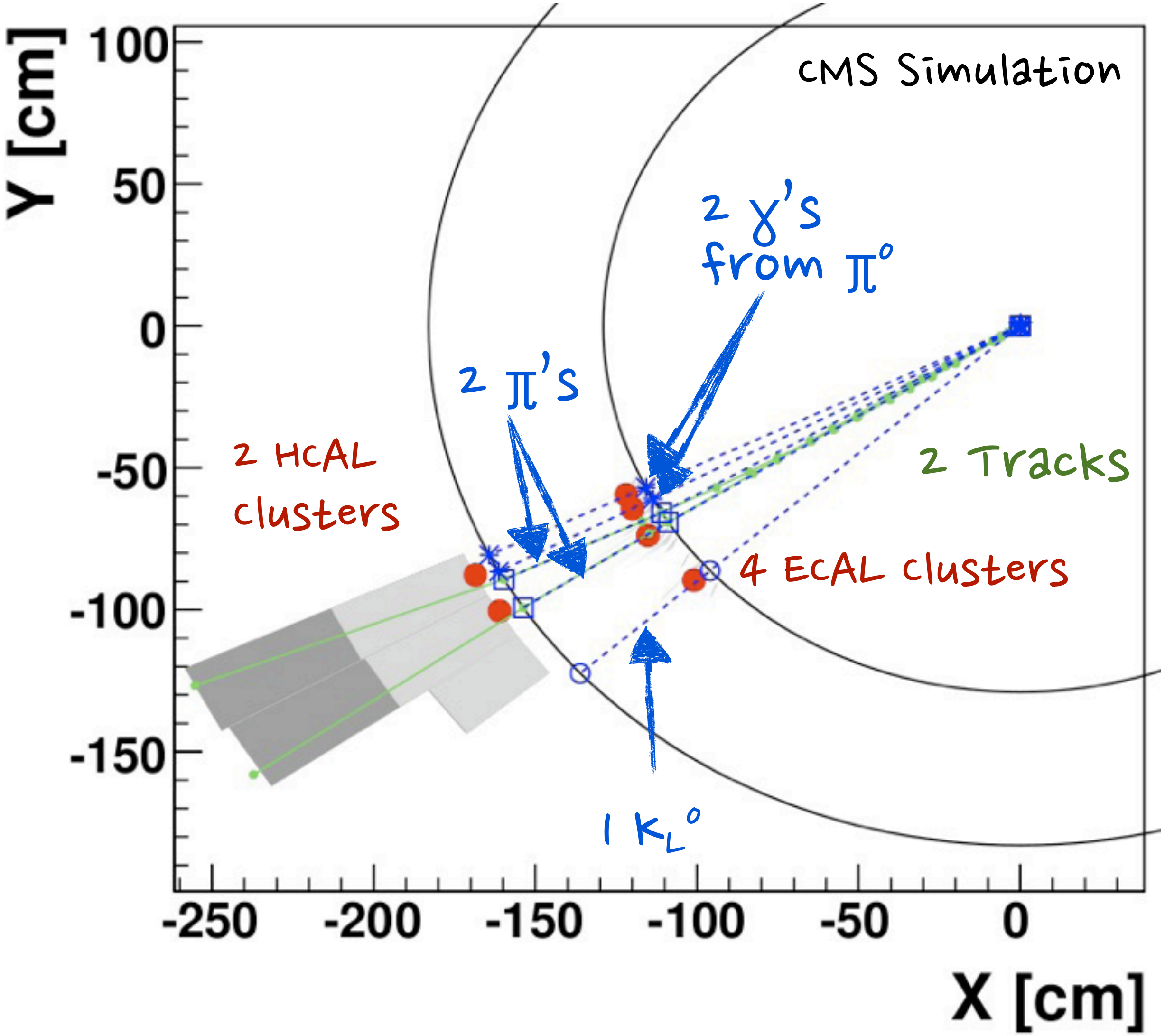

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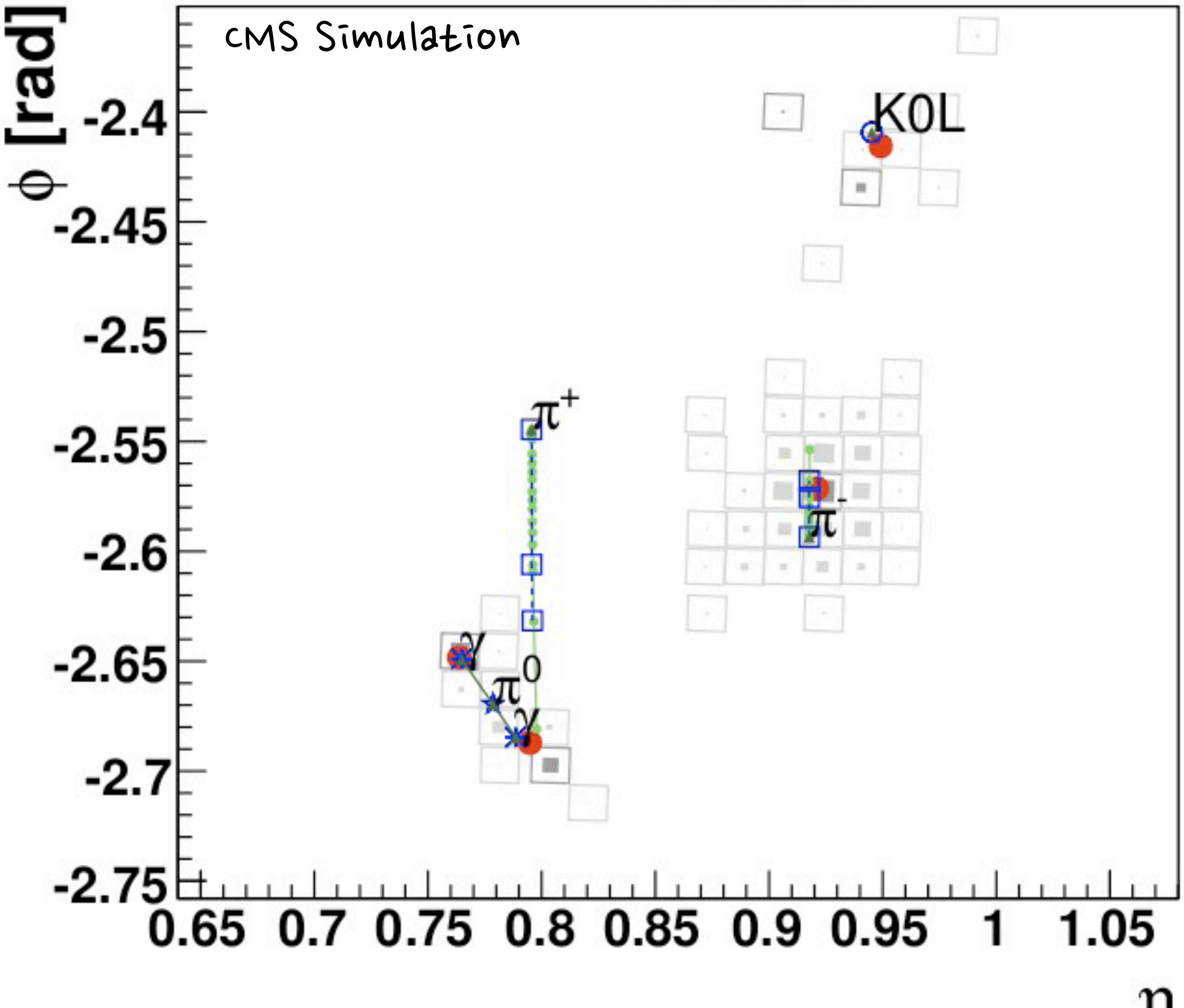
Switch to ECAL (η,φ) view



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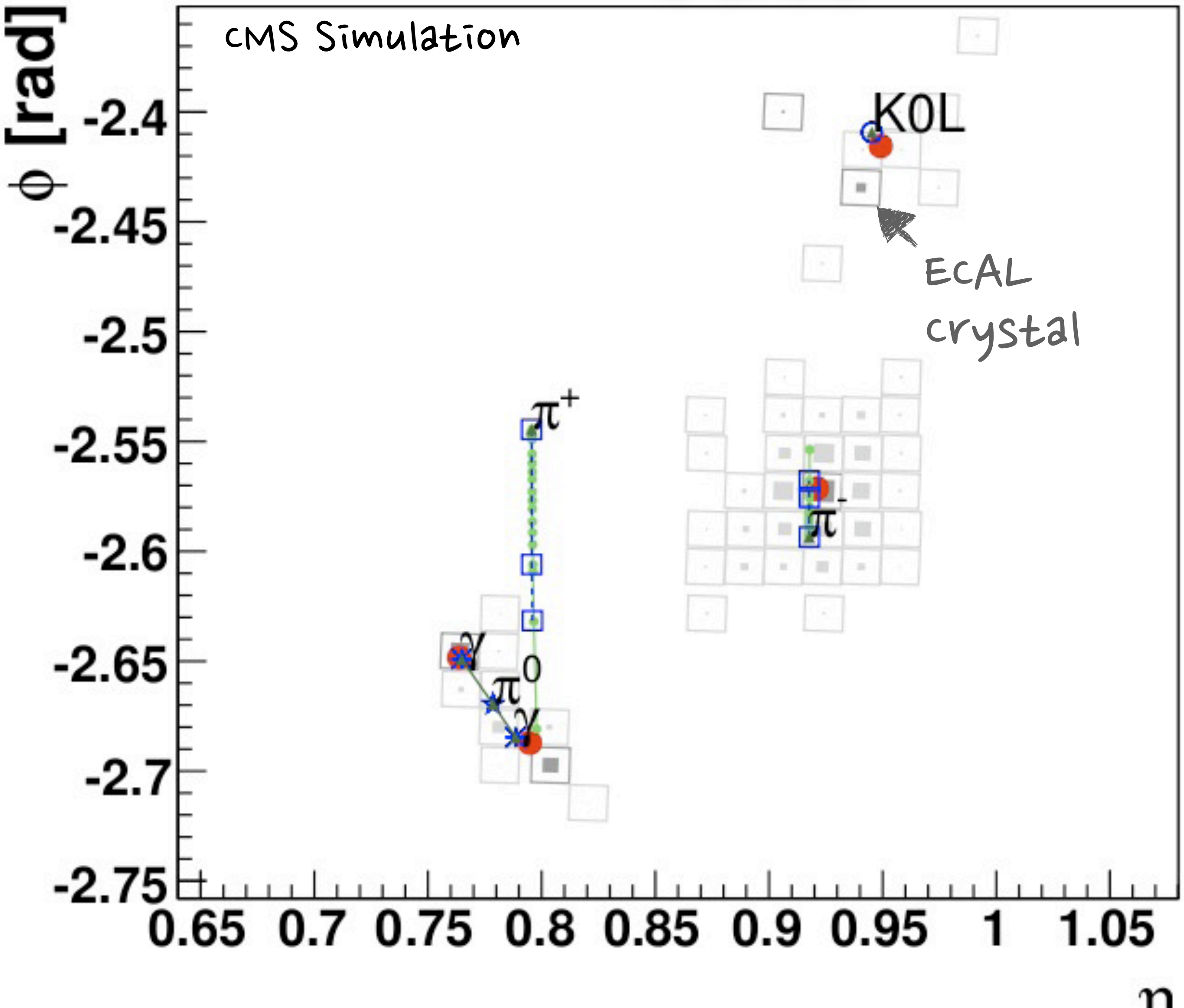

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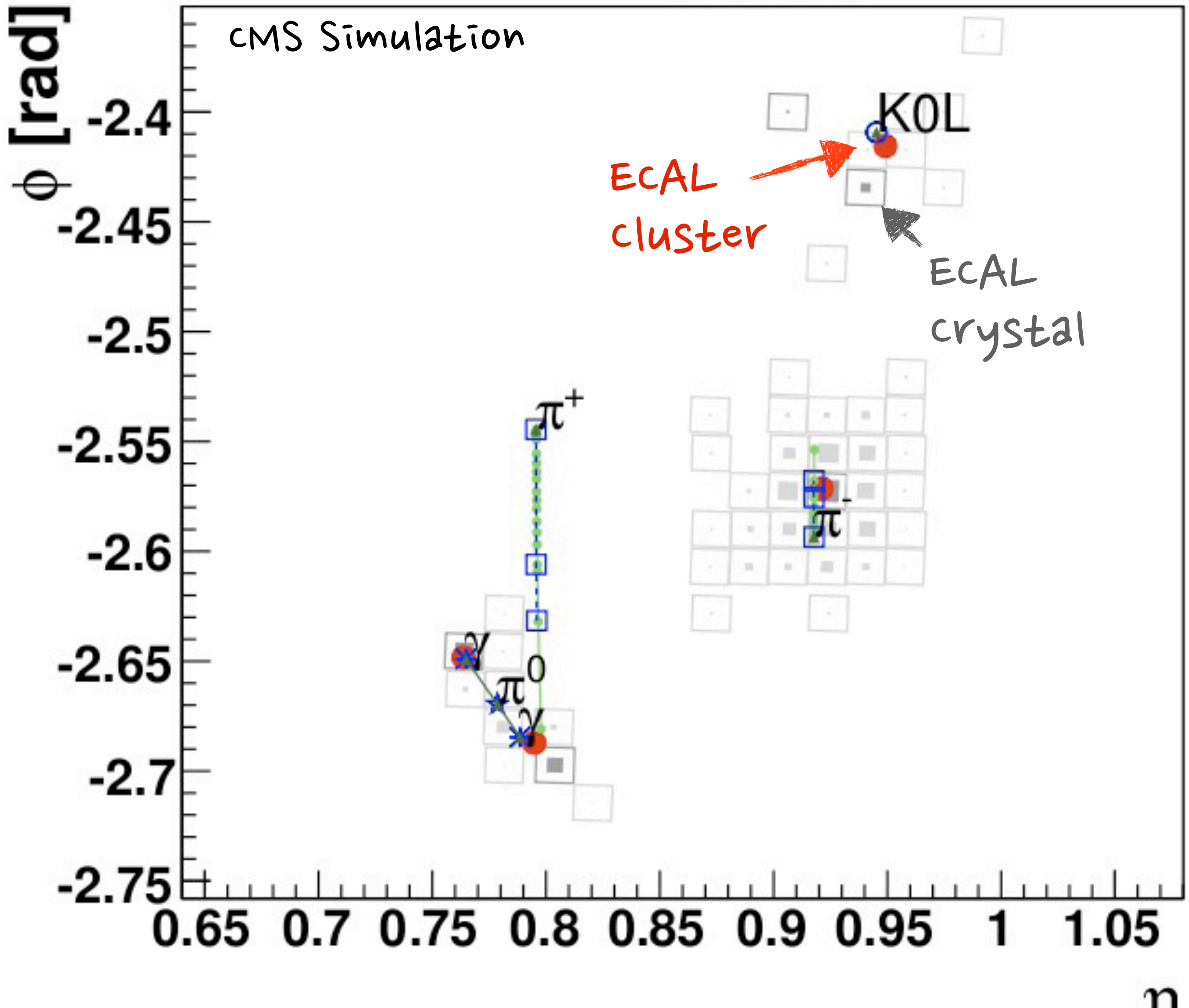

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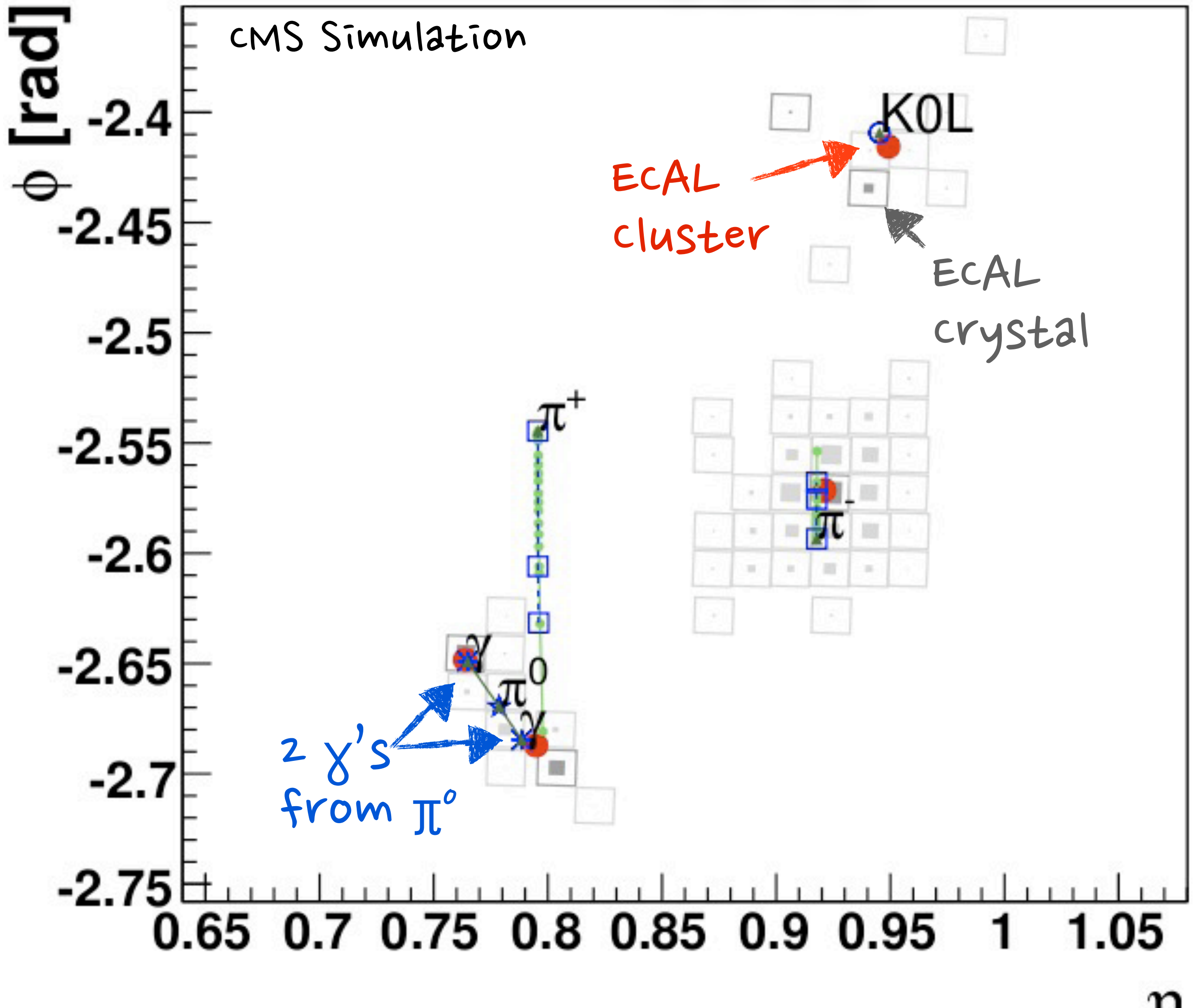

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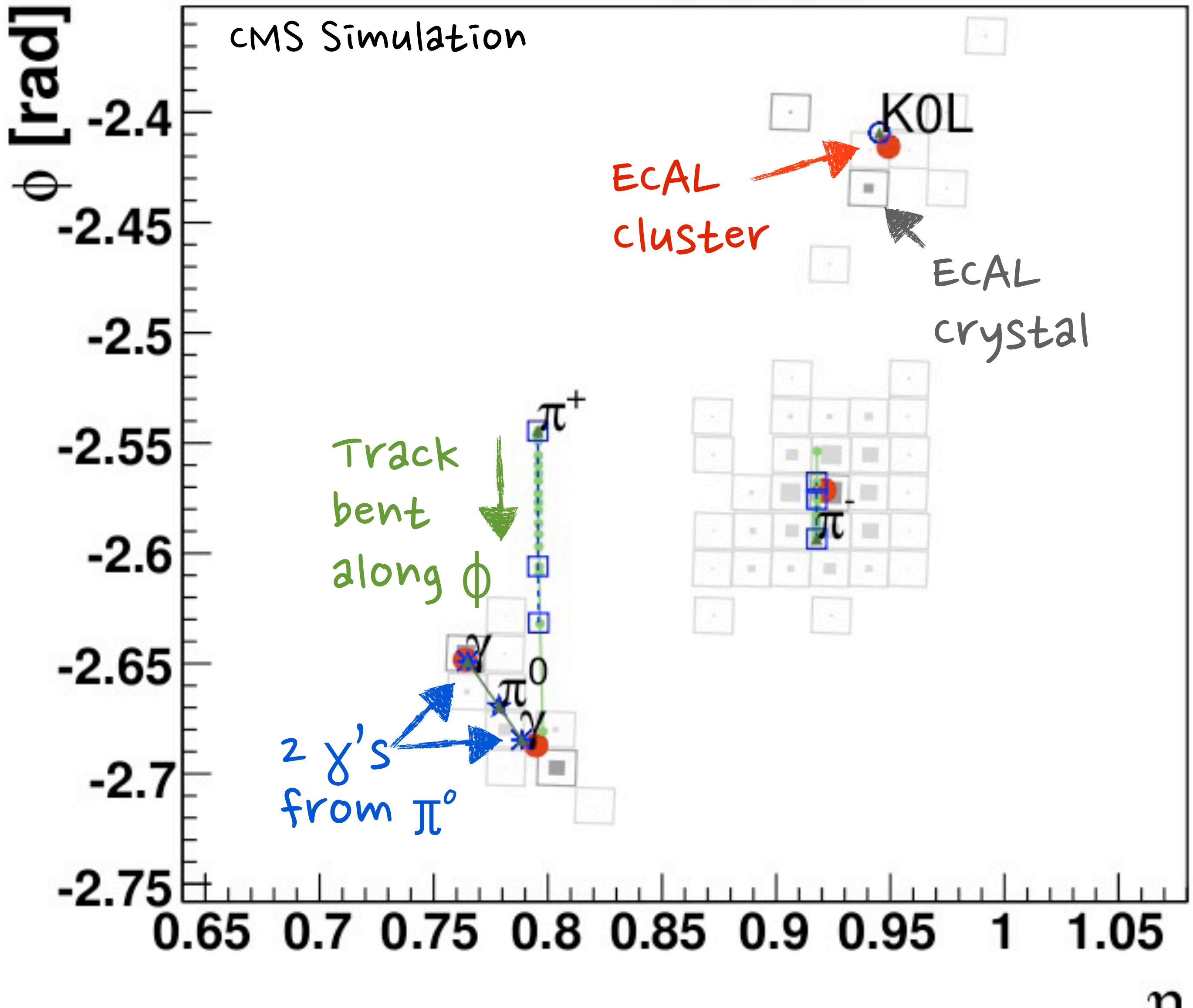

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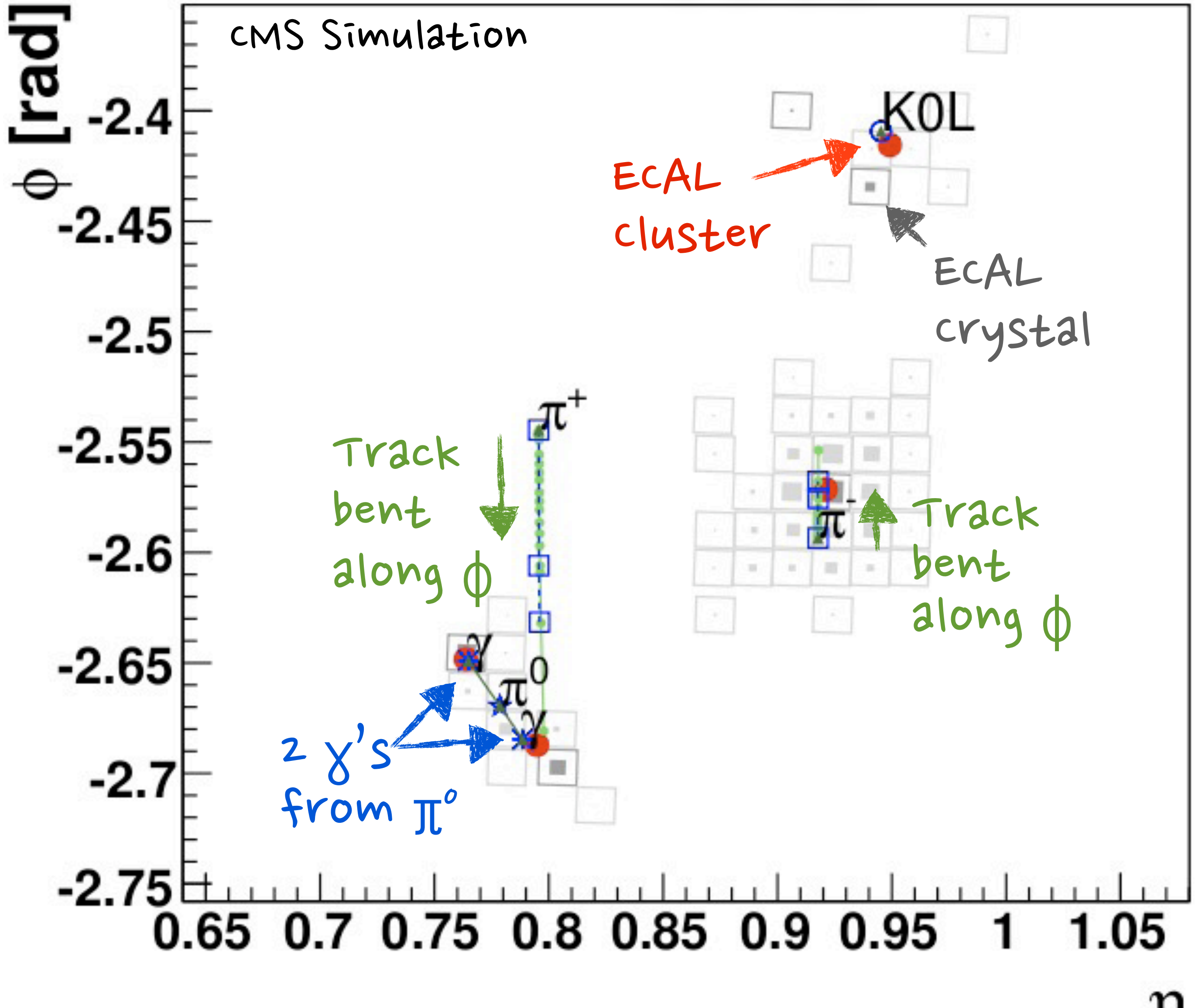
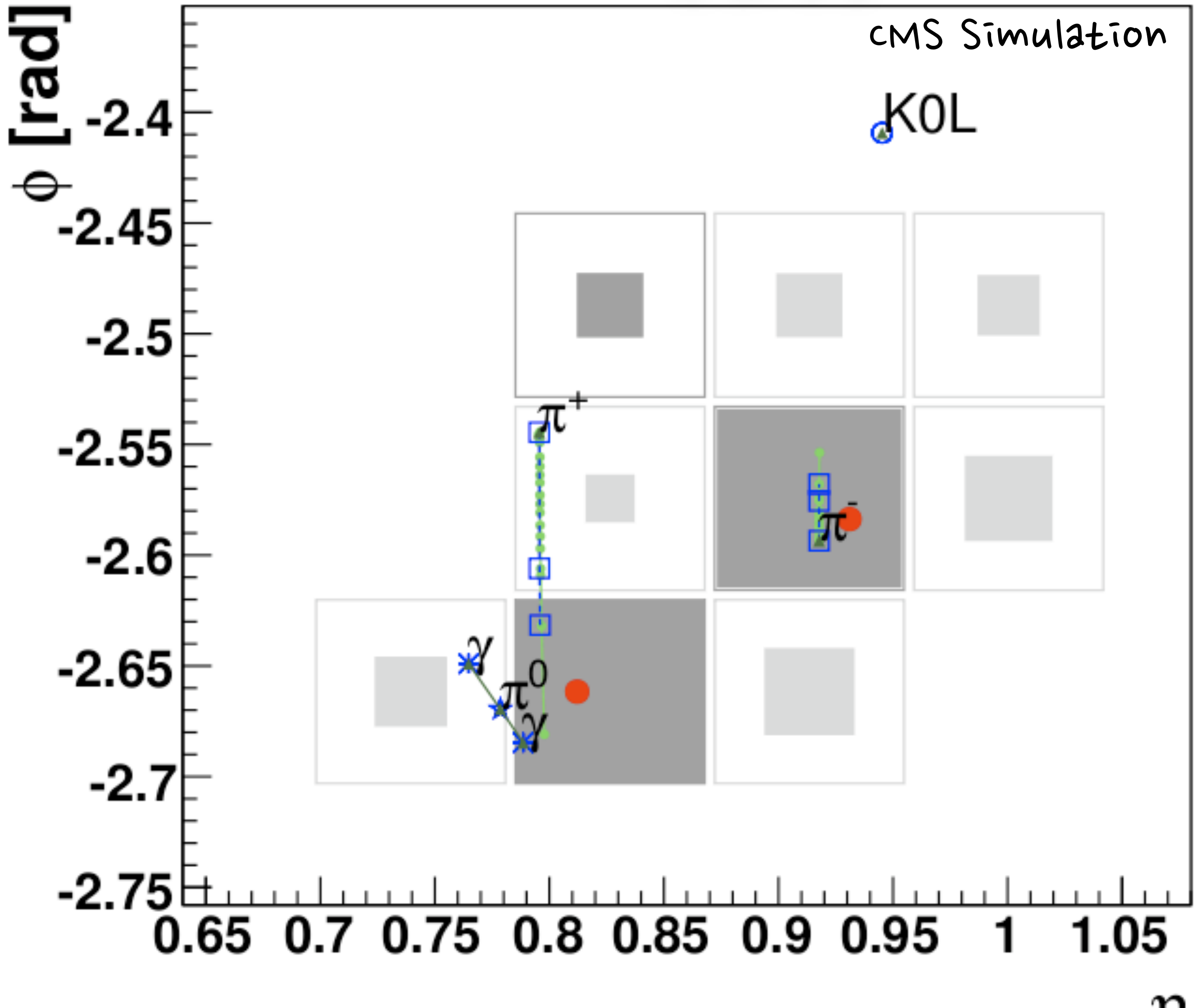


Switch to HCAL (η,φ) view



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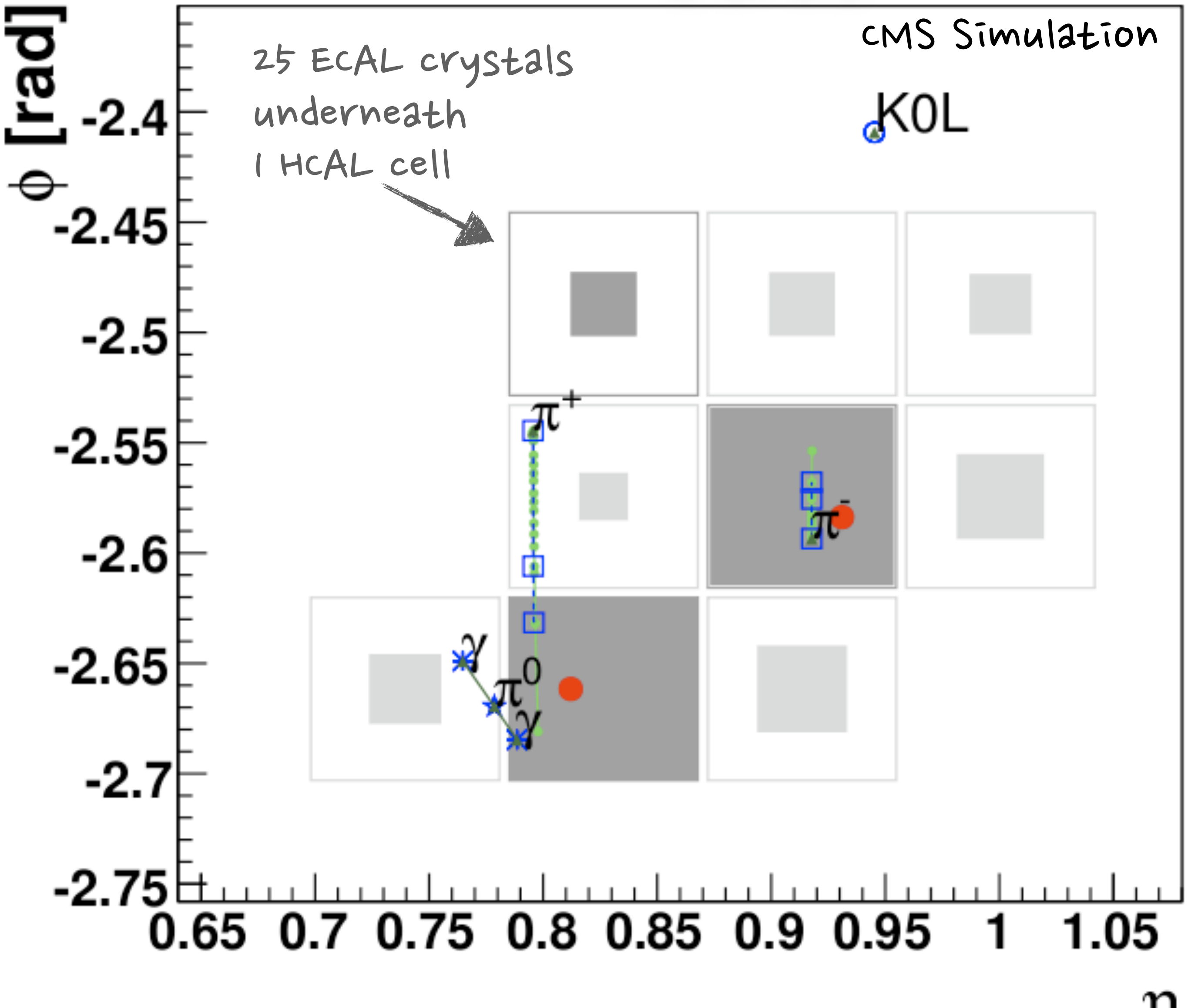

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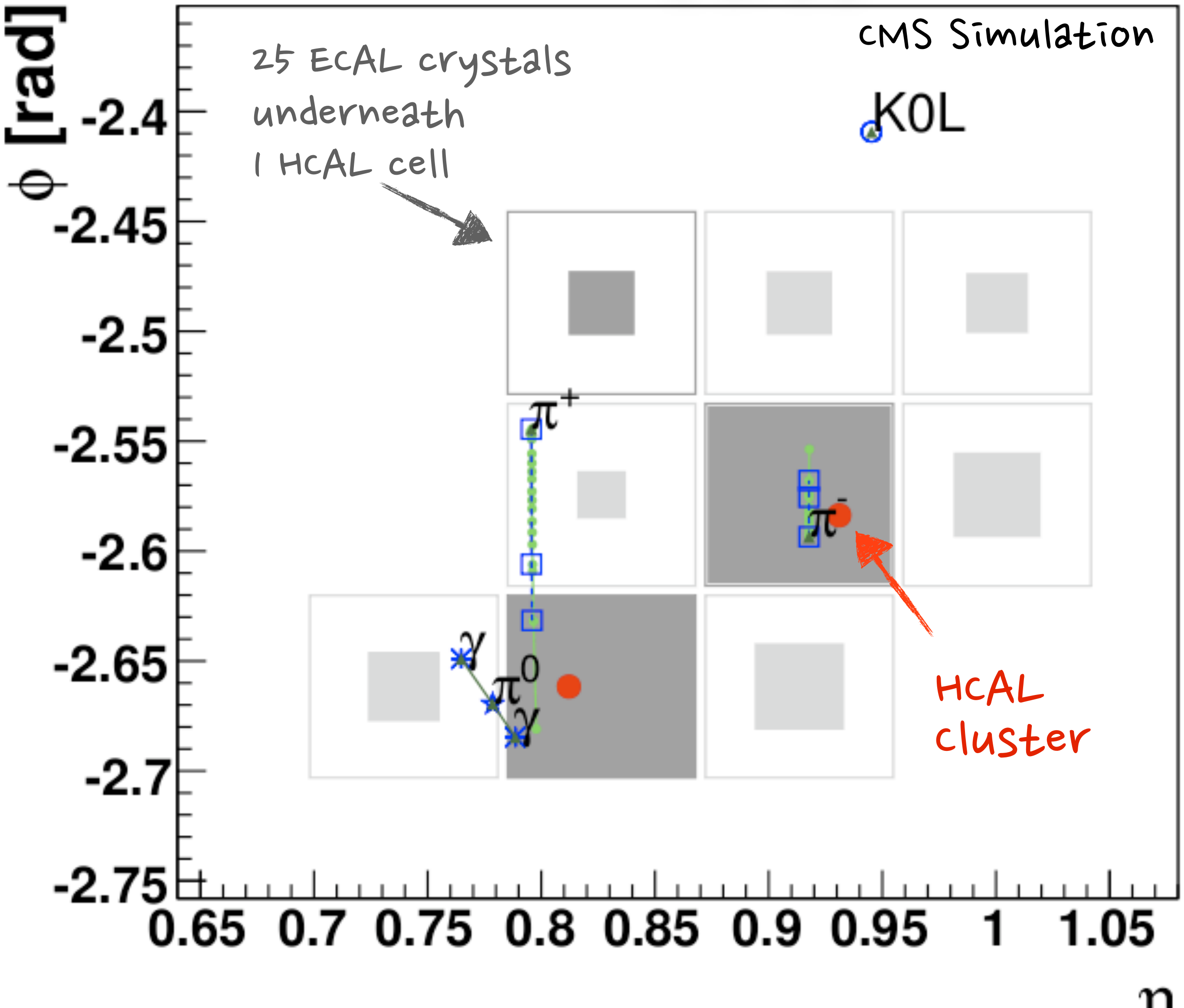
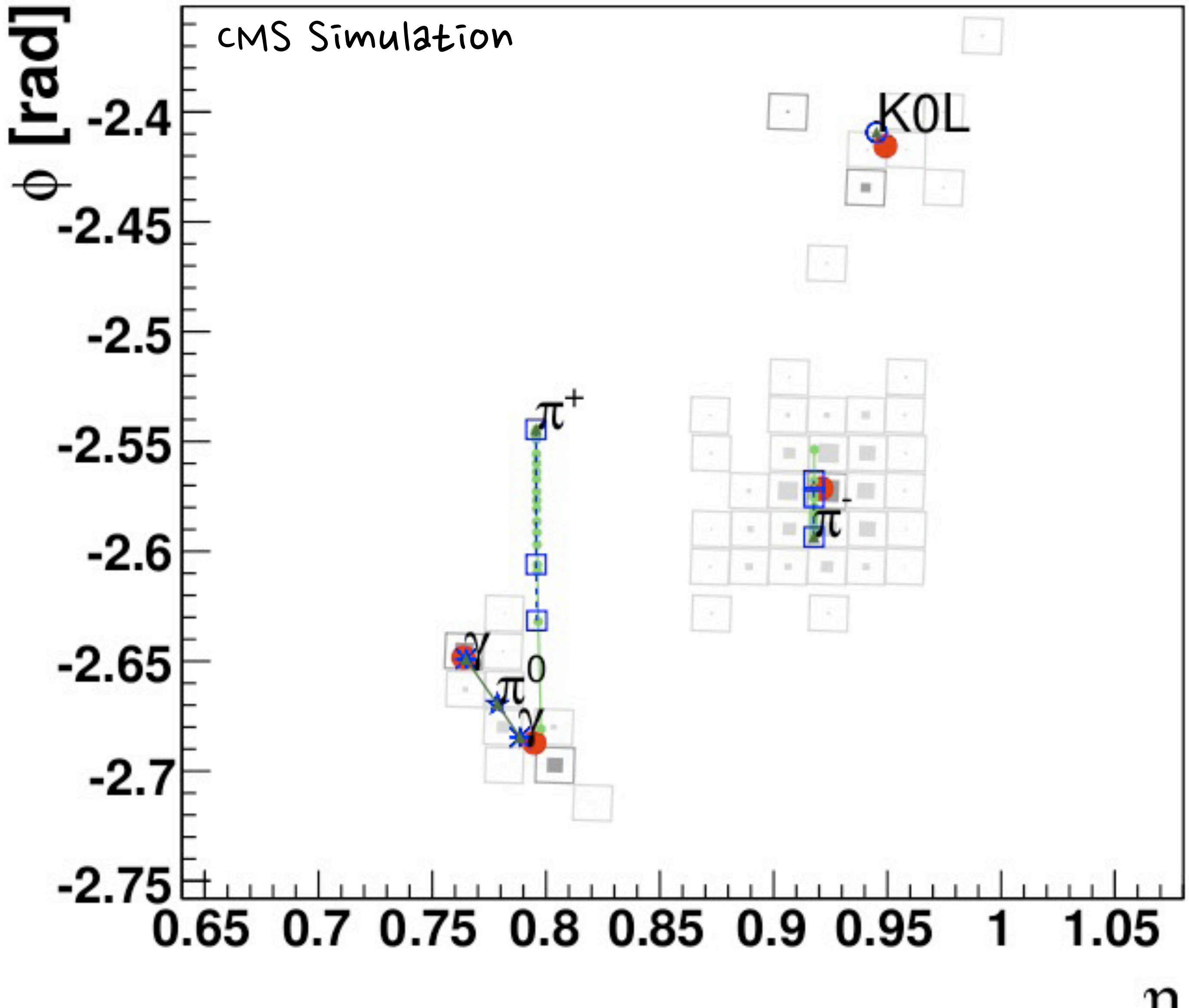


Track-Cluster Link ECAL



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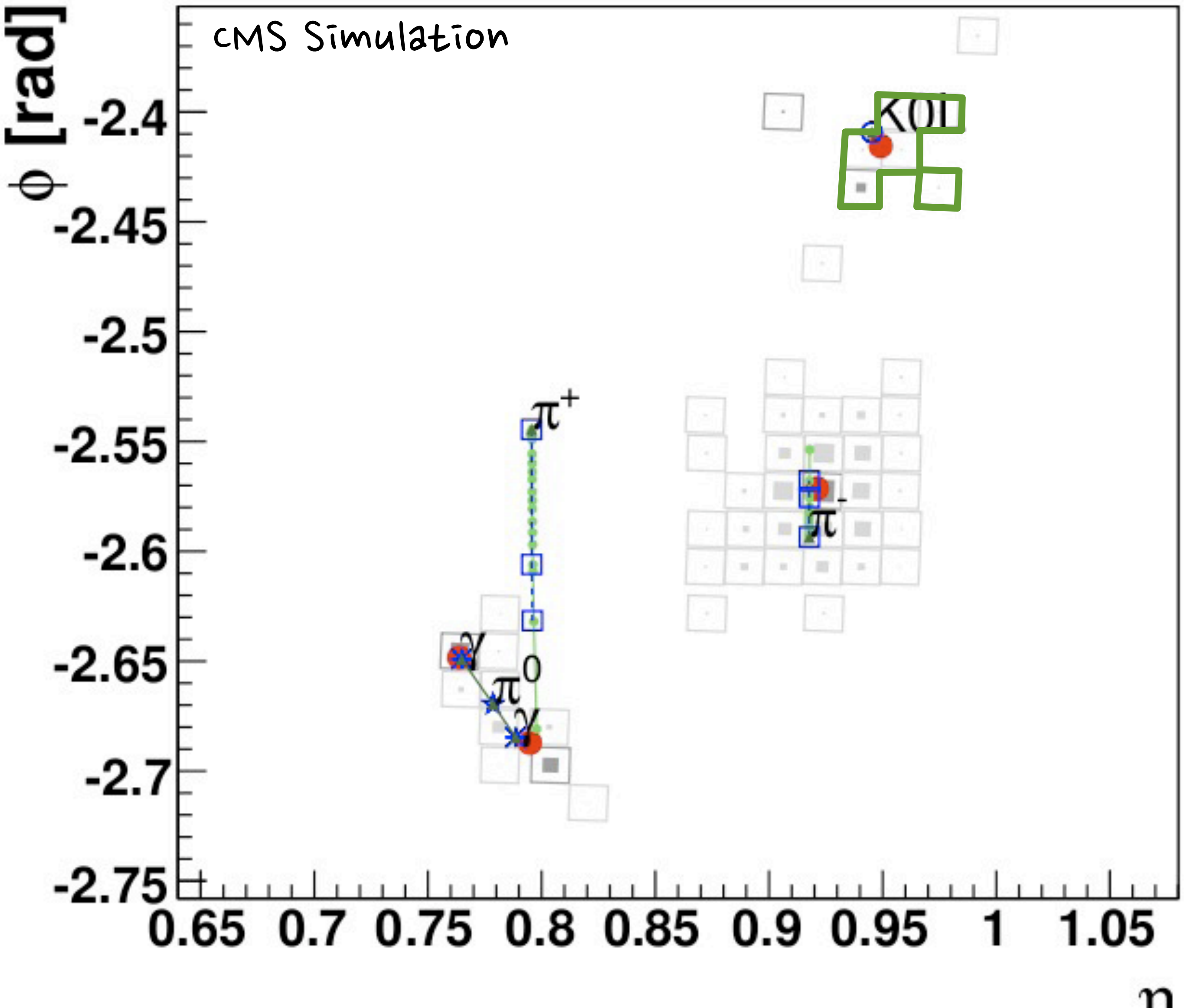
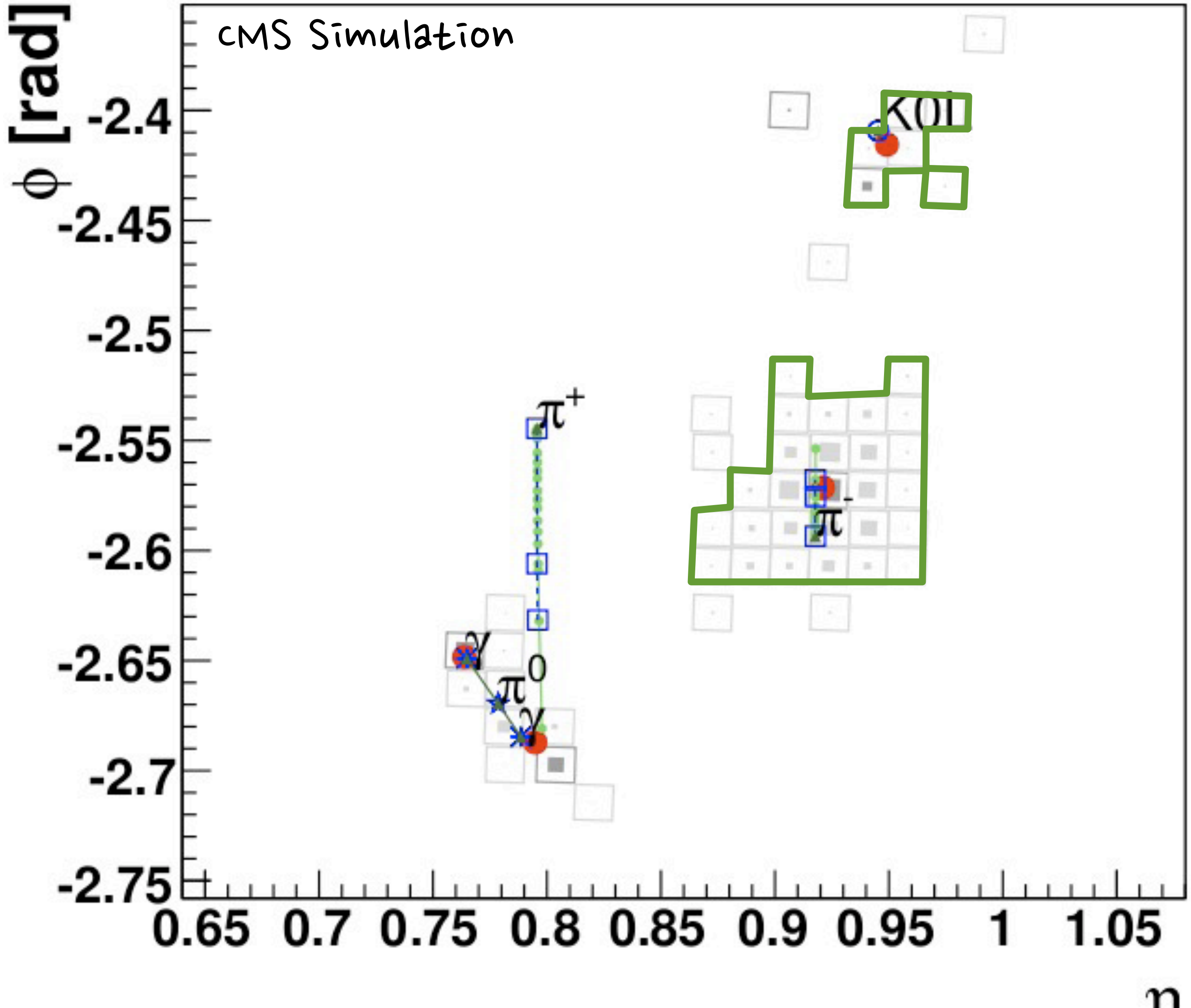
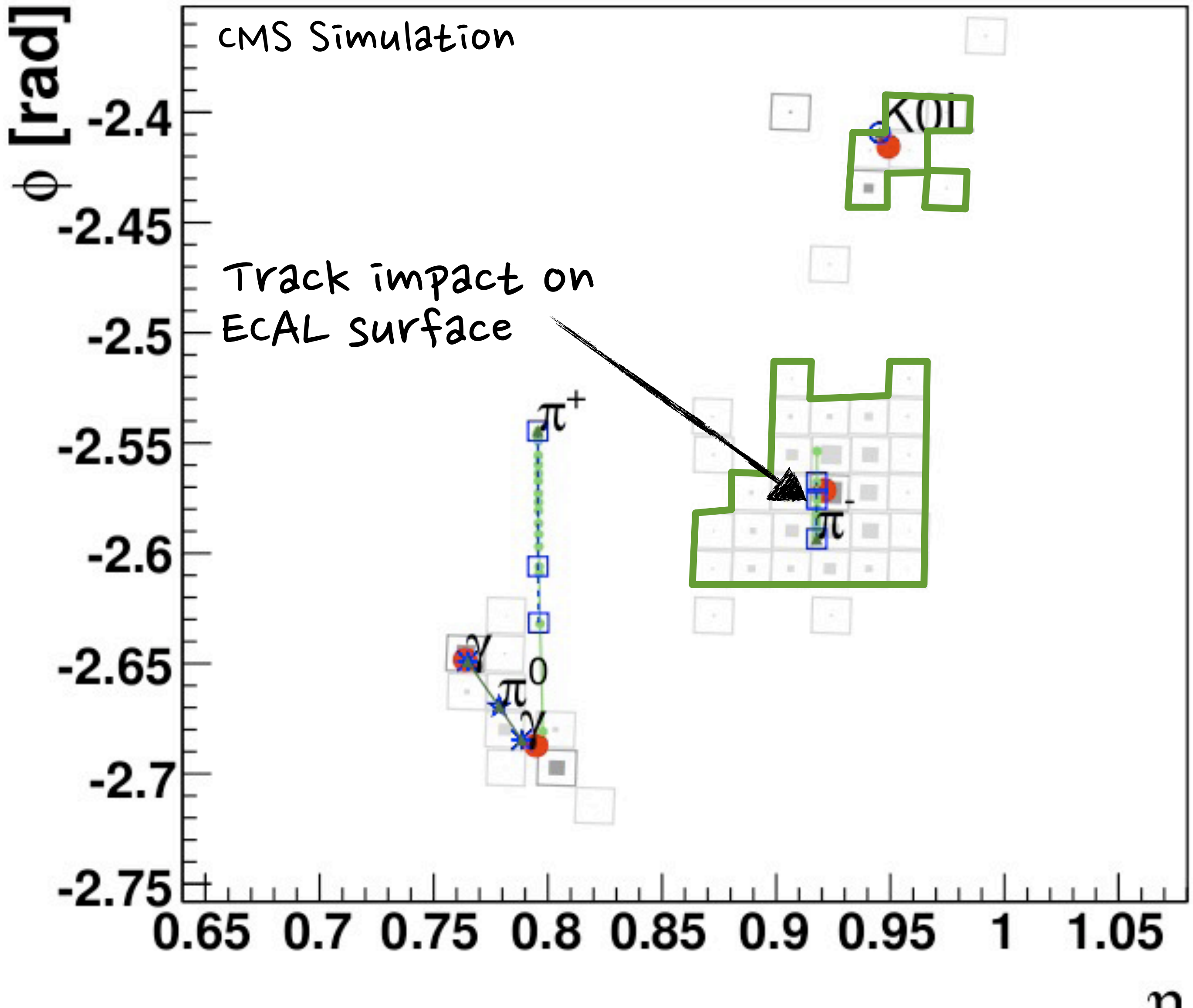


Track-Cluster Link ECAL

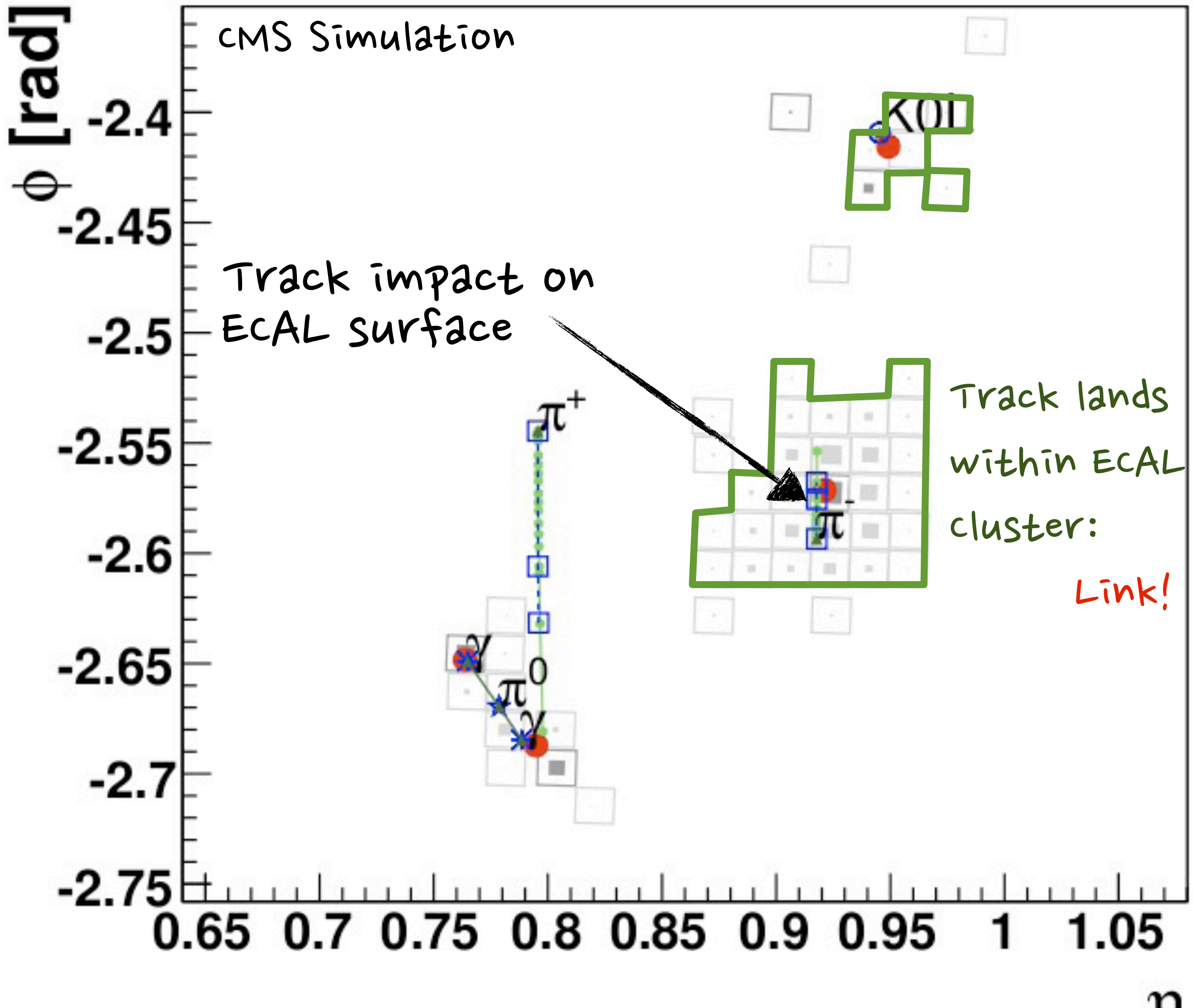


Track-Cluster Link ECAL

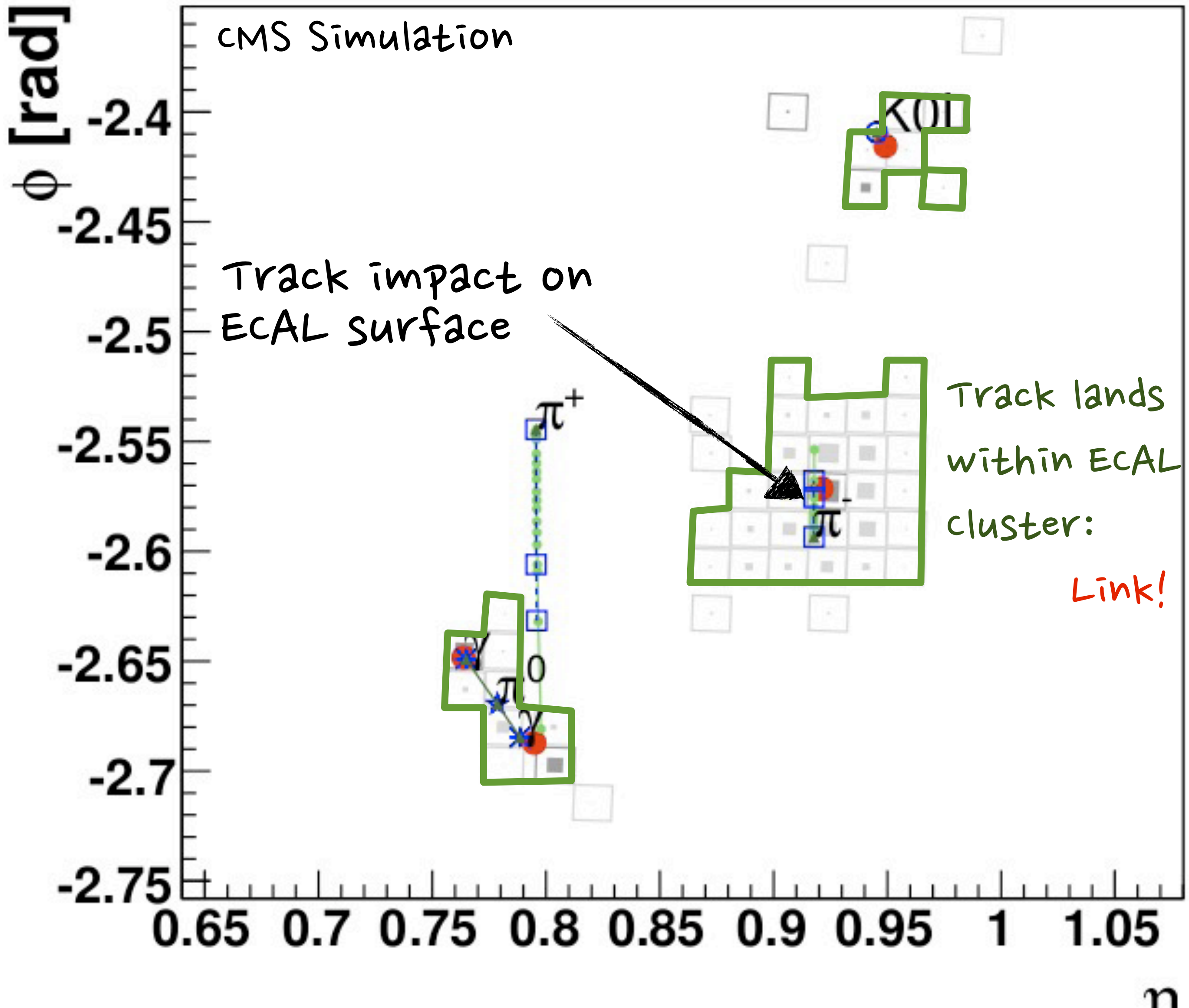


LPC
LHC Physics Center

Track-Cluster Link ECAL



Track-Cluster Link ECAL



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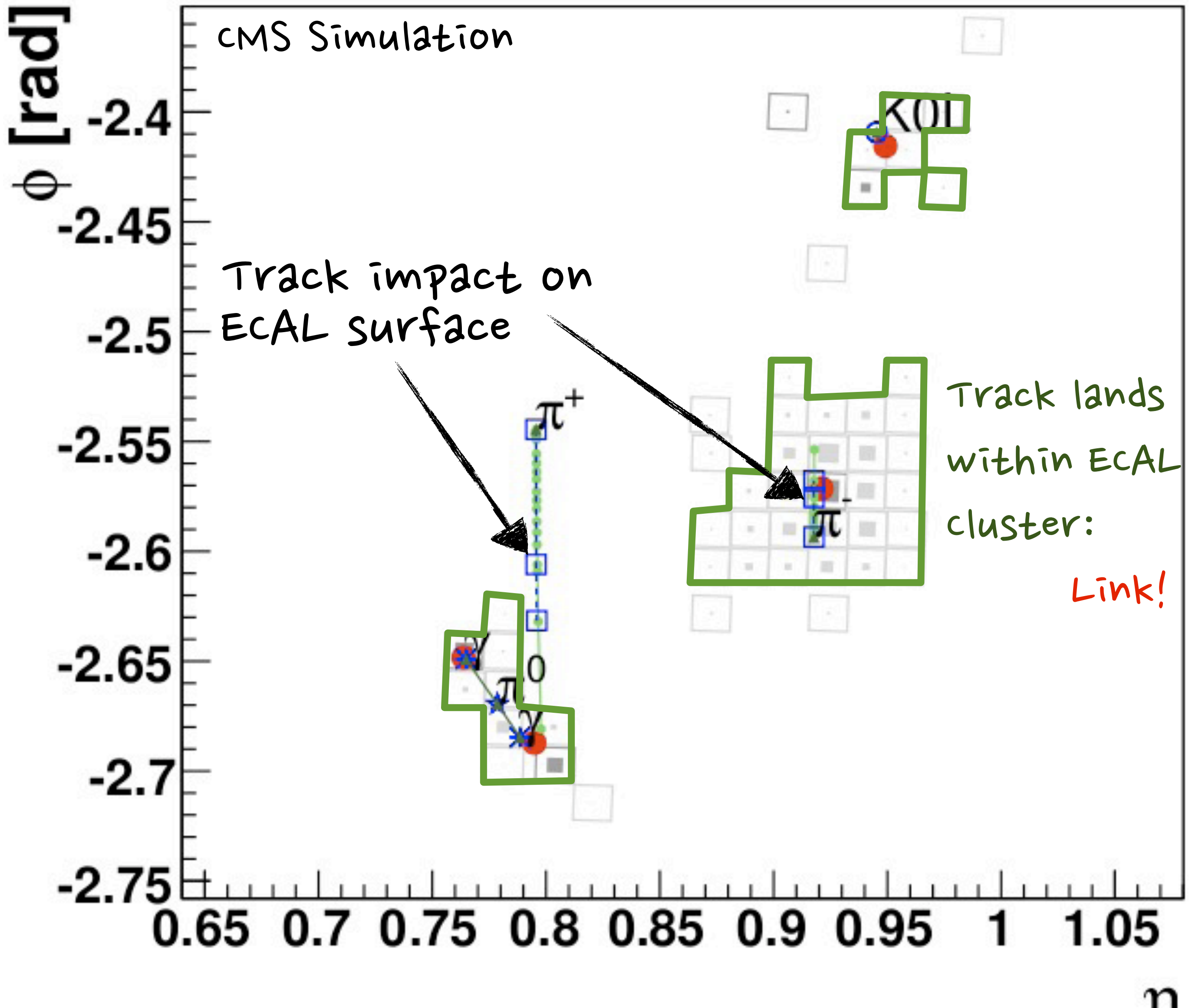
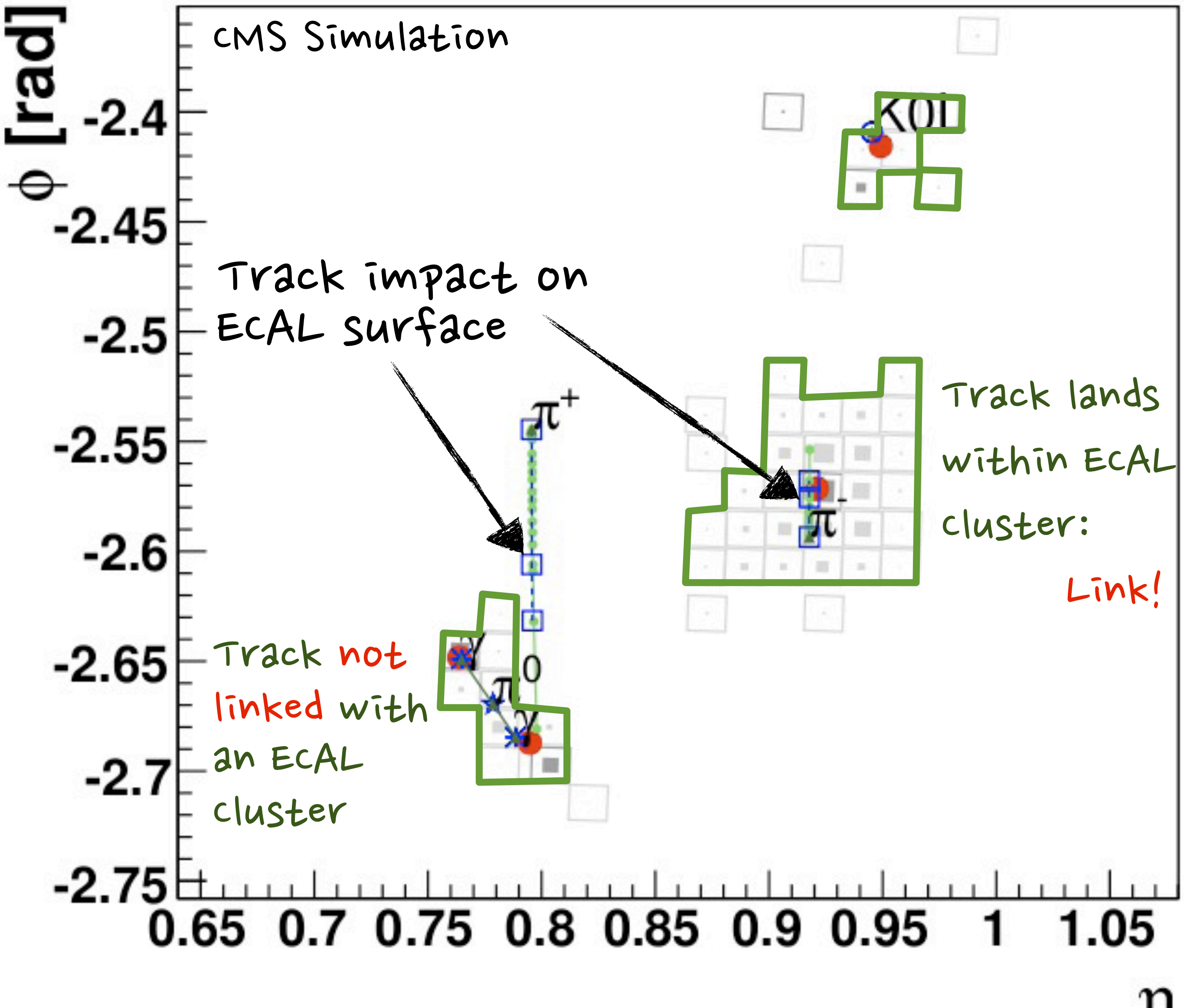
LPC LHC Physics Center

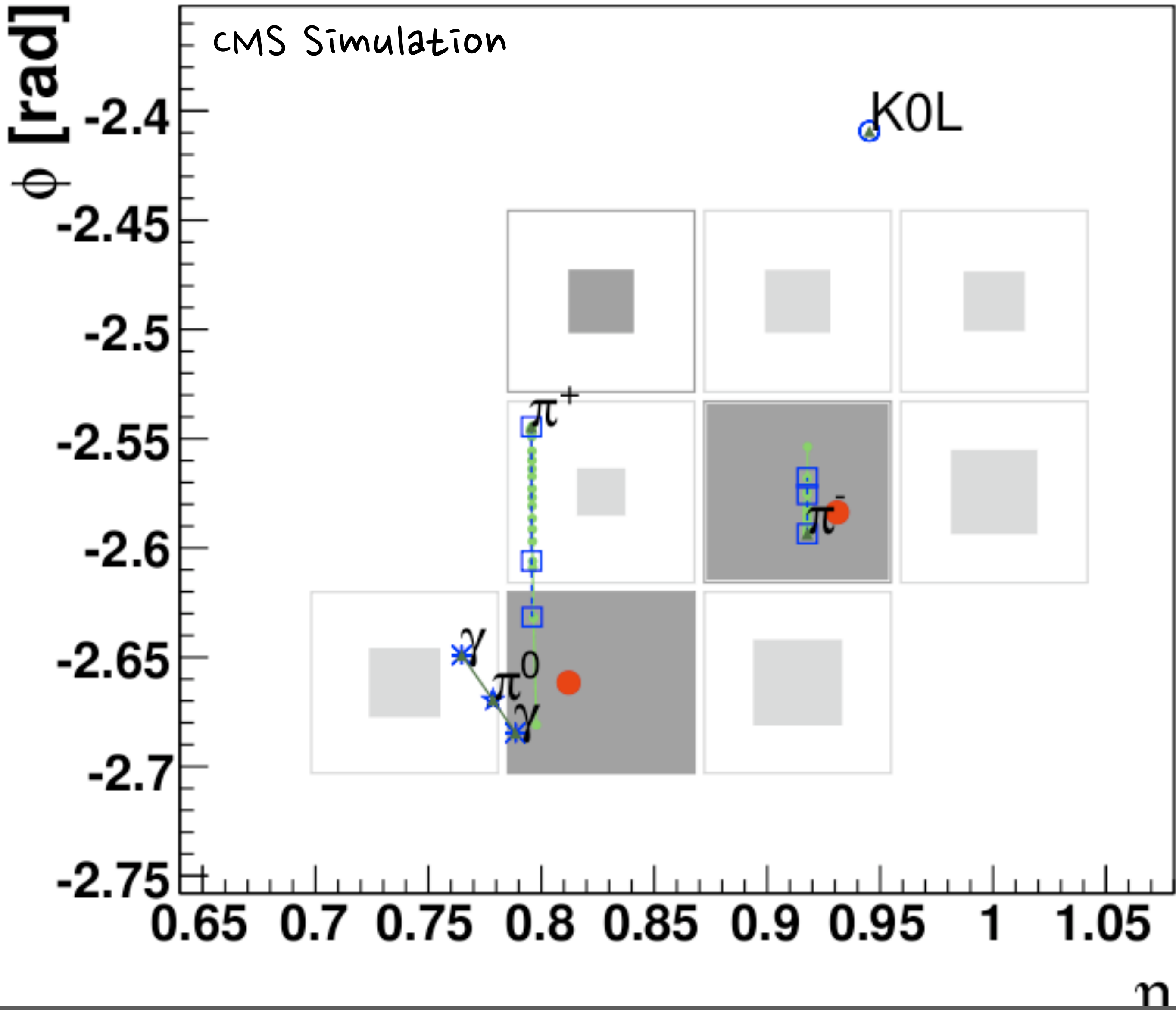
Track-Cluster Link ECAL



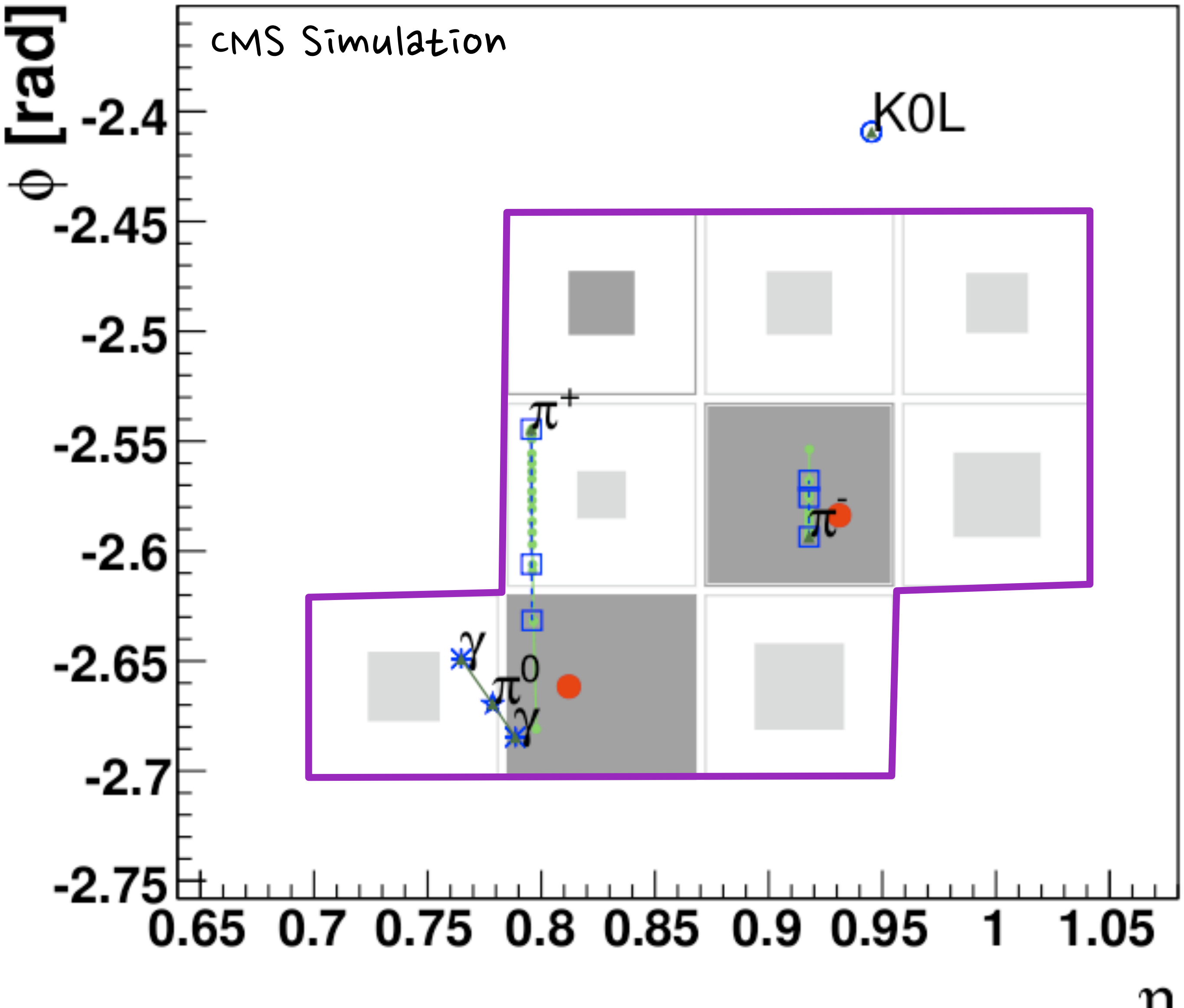
Track-Cluster Link ECAL



ECAL-HCAL Cluster Link



ECAL-HCAL Cluster Link



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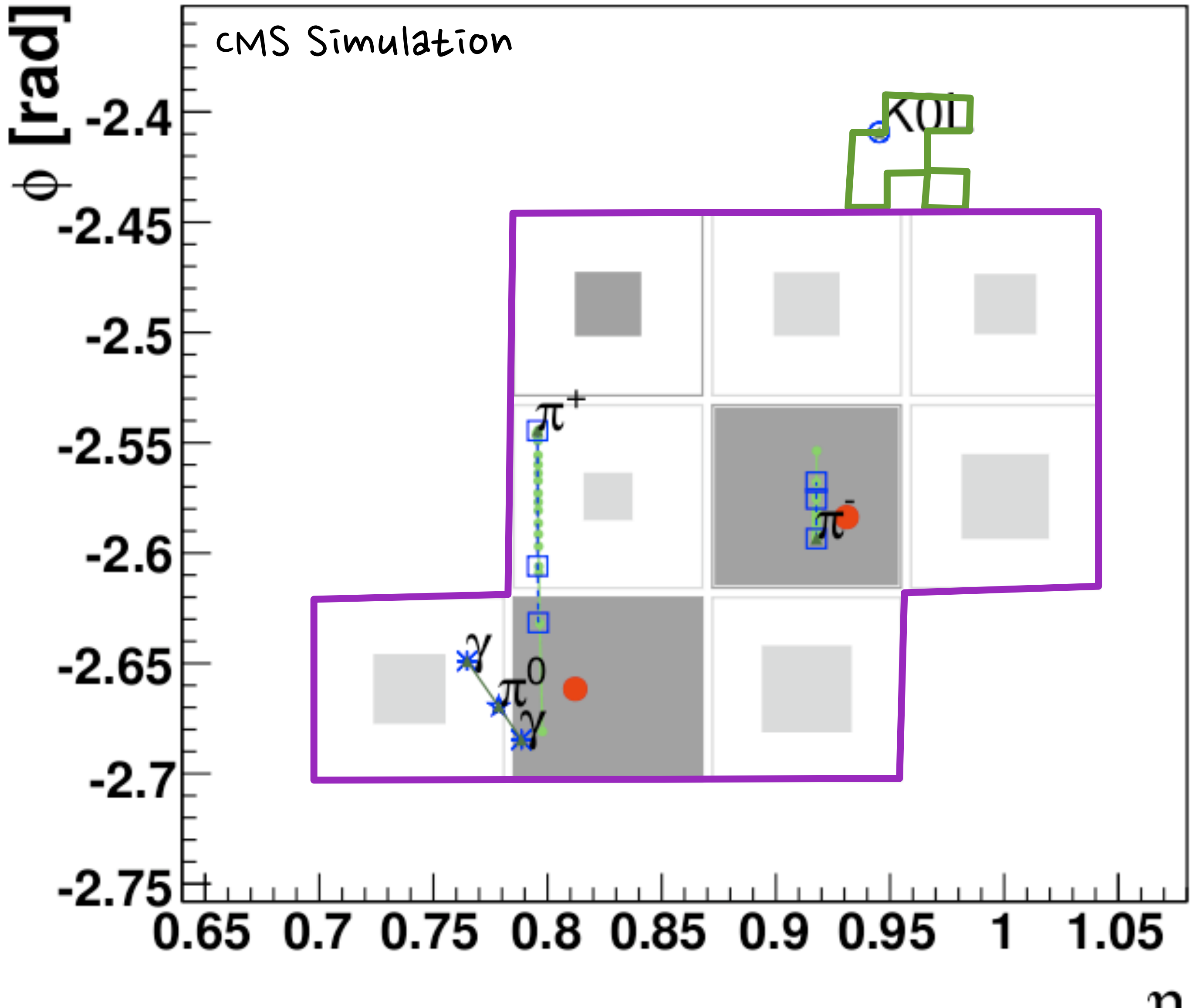
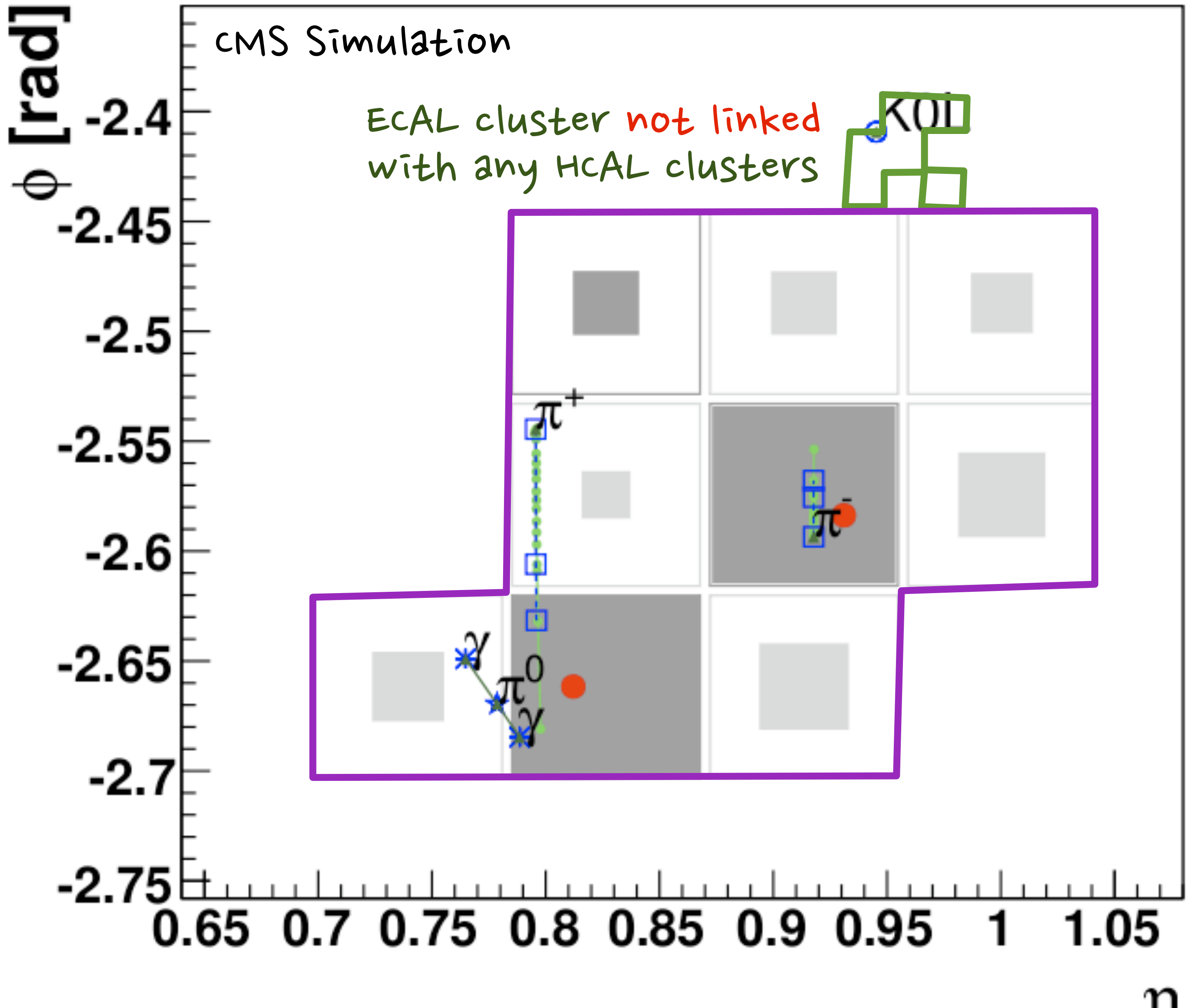
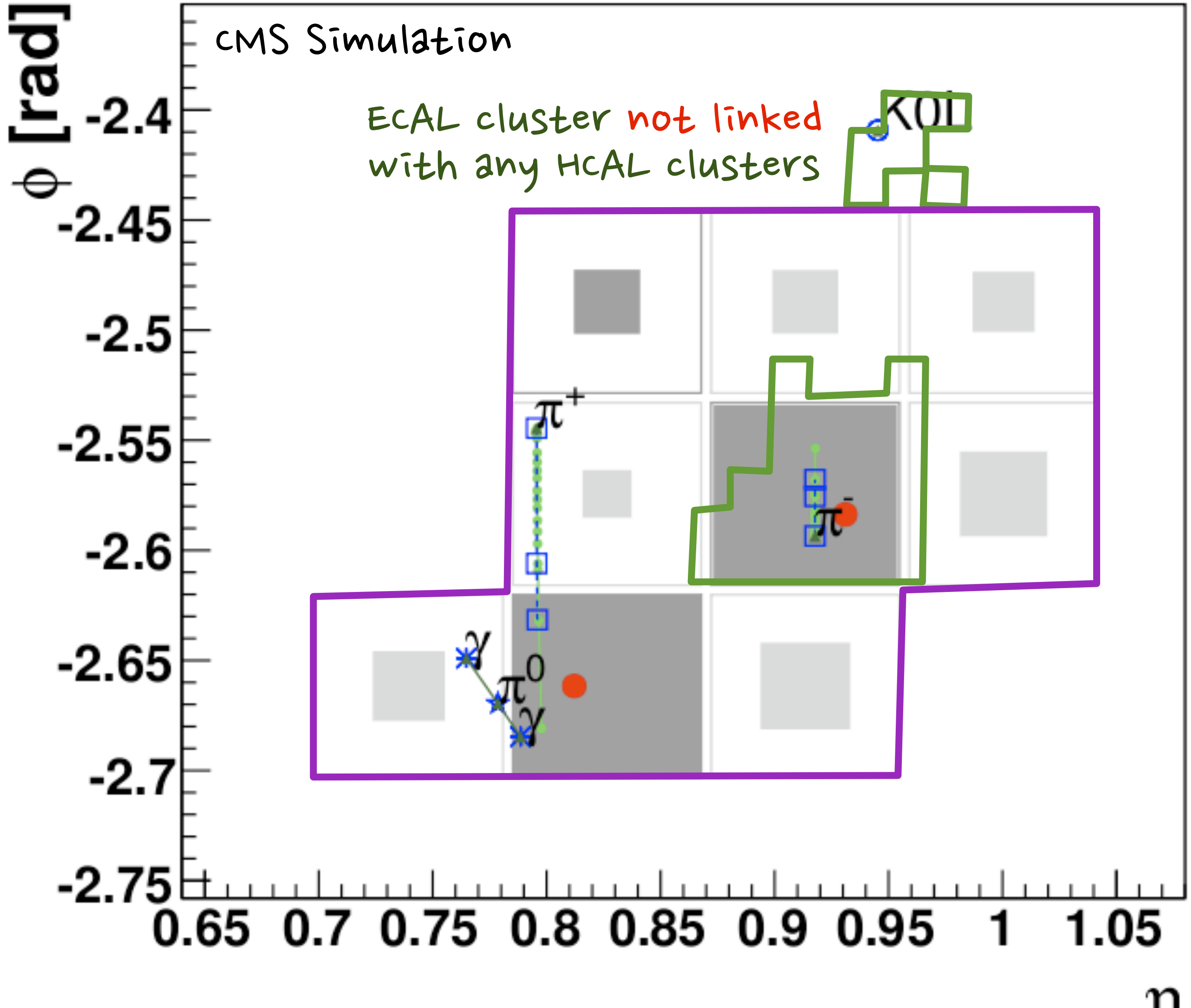


ECAL-HCAL Cluster Link



ECAL-HCAL Cluster Link



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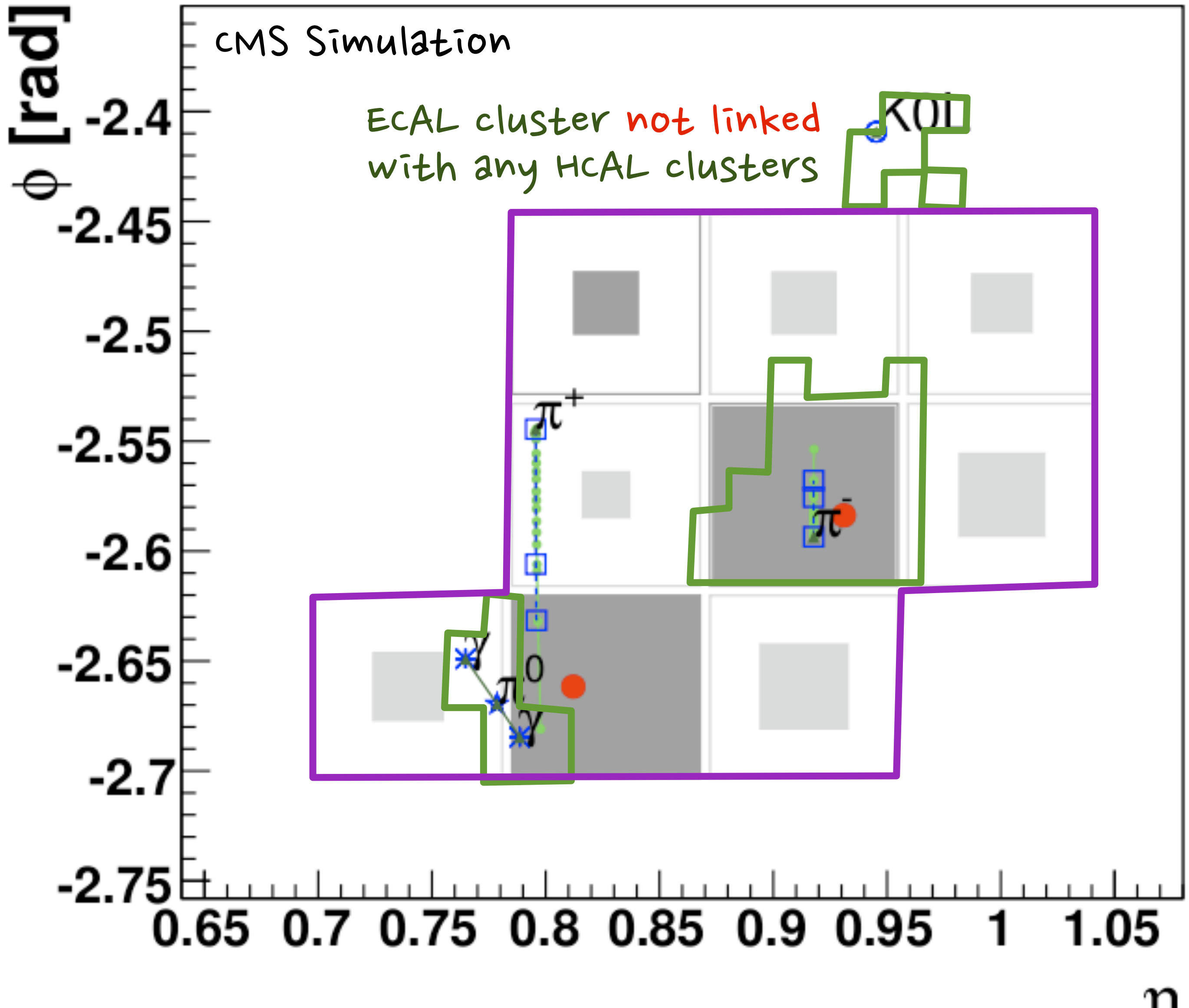

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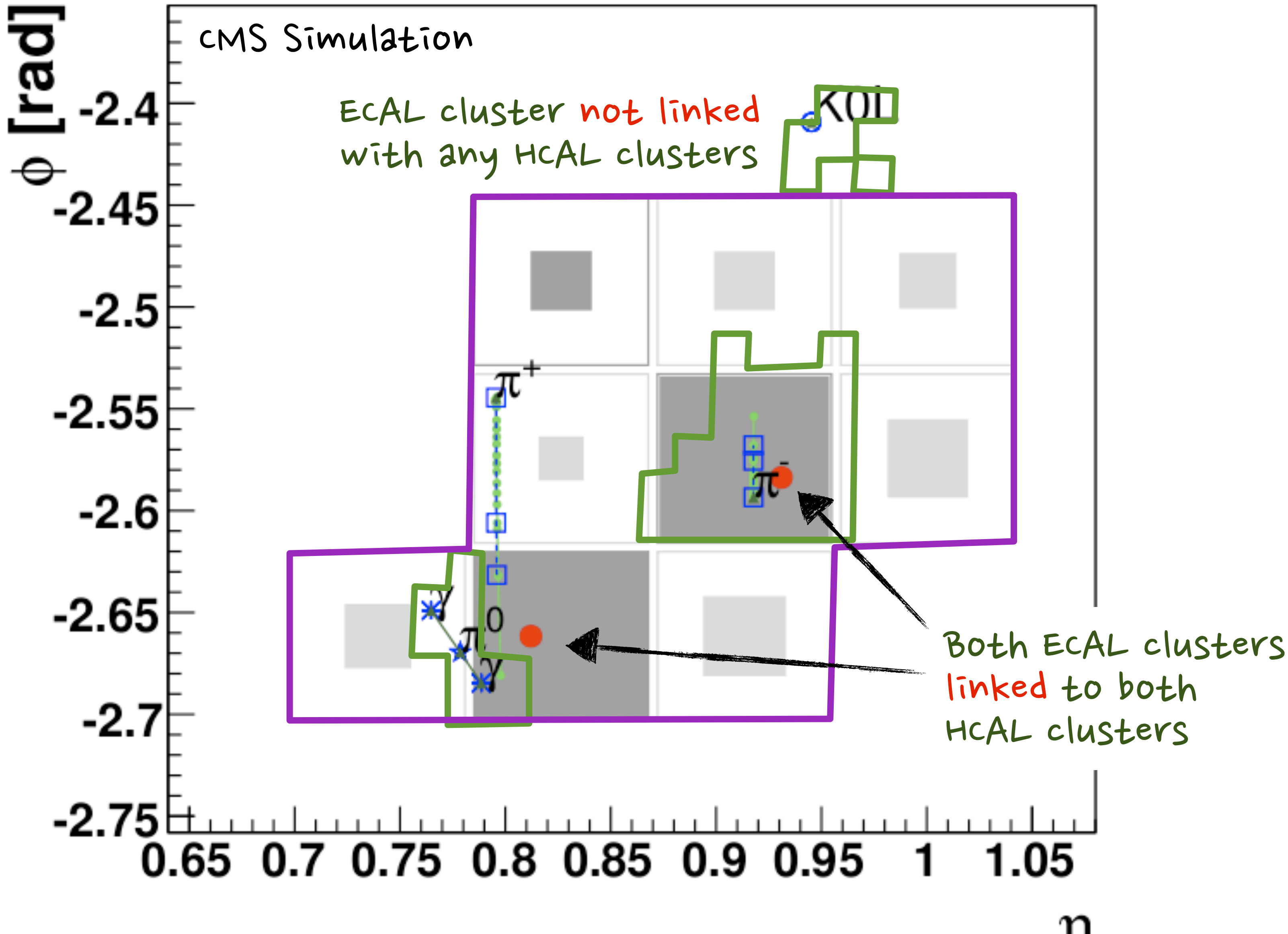
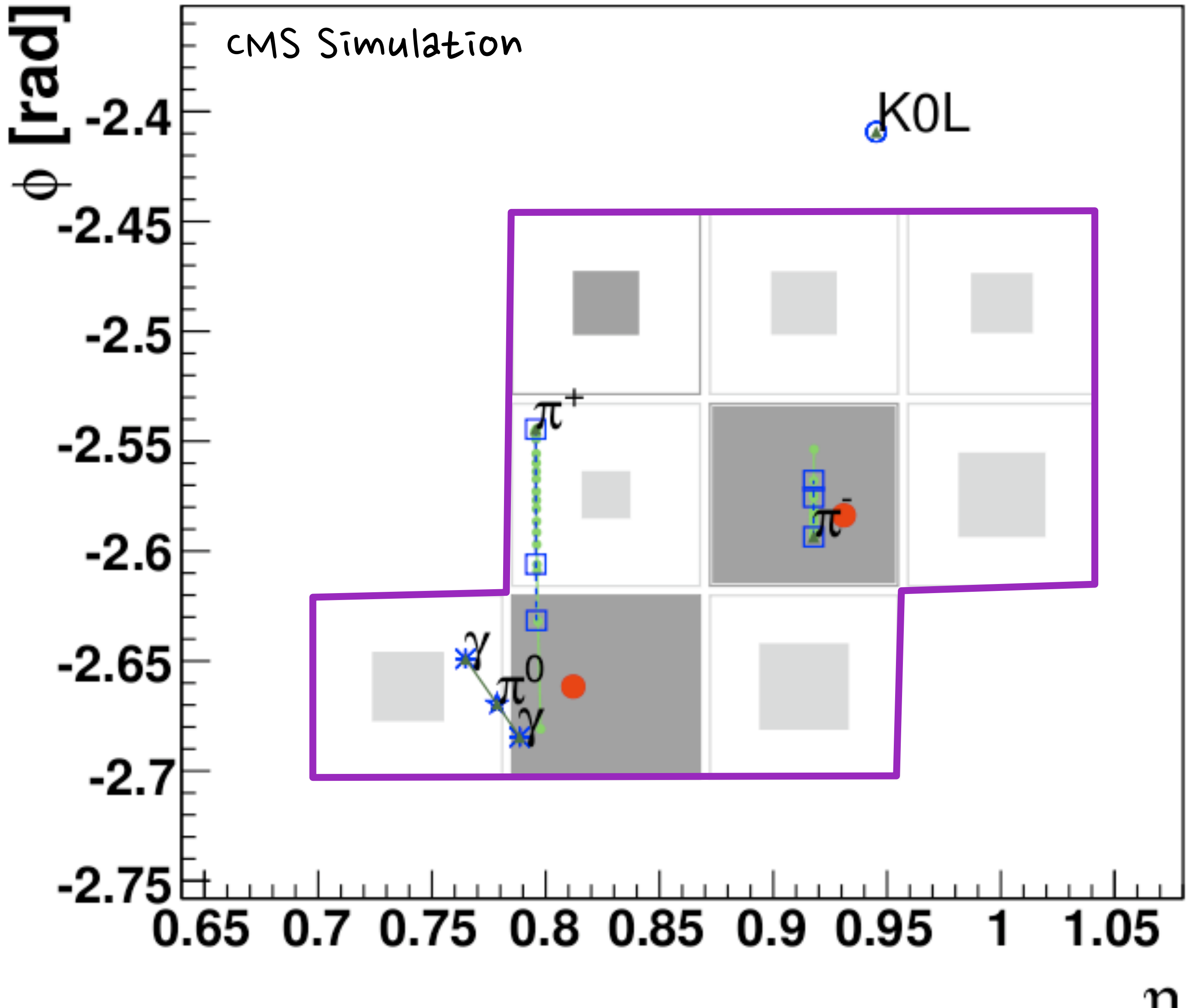
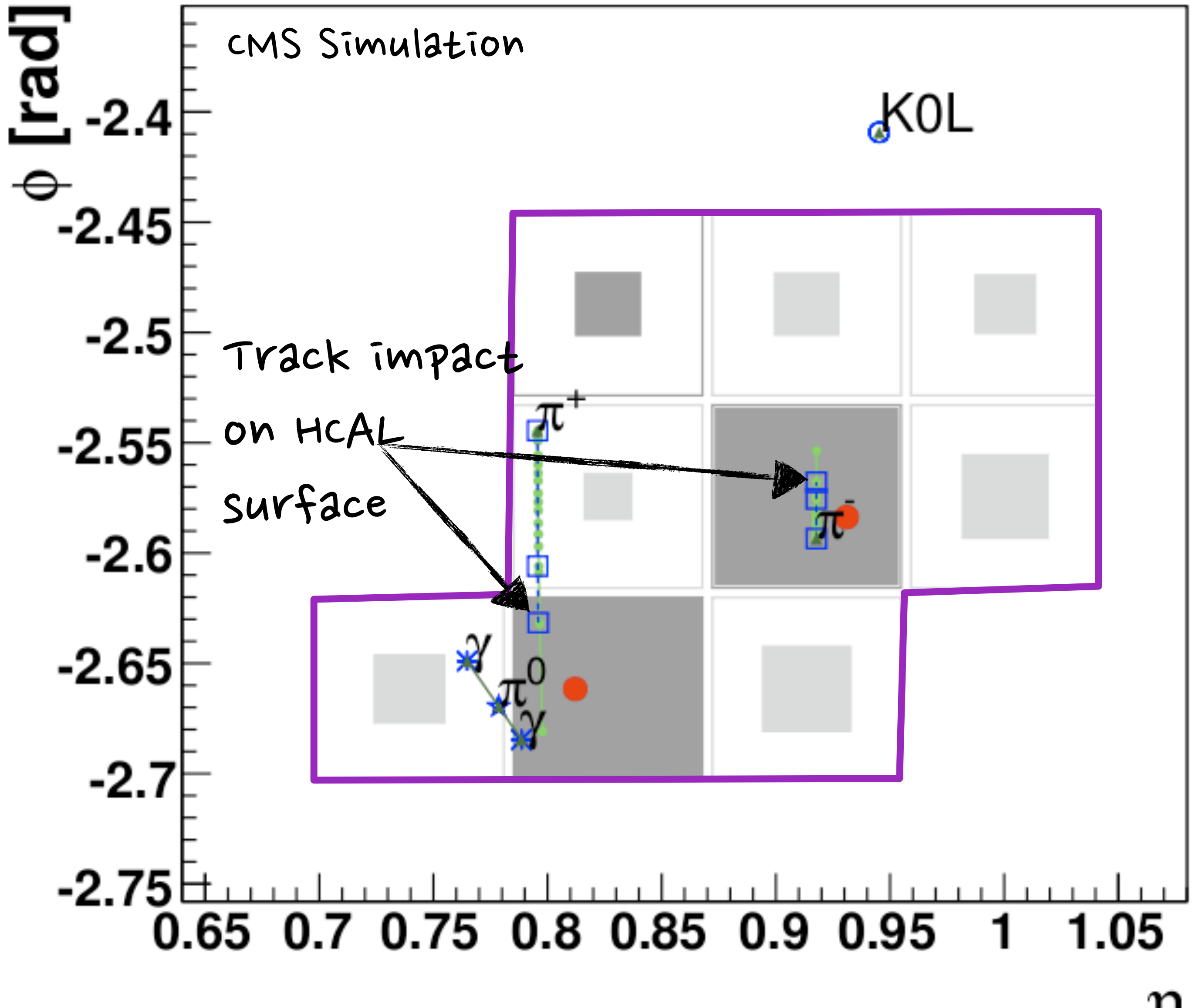


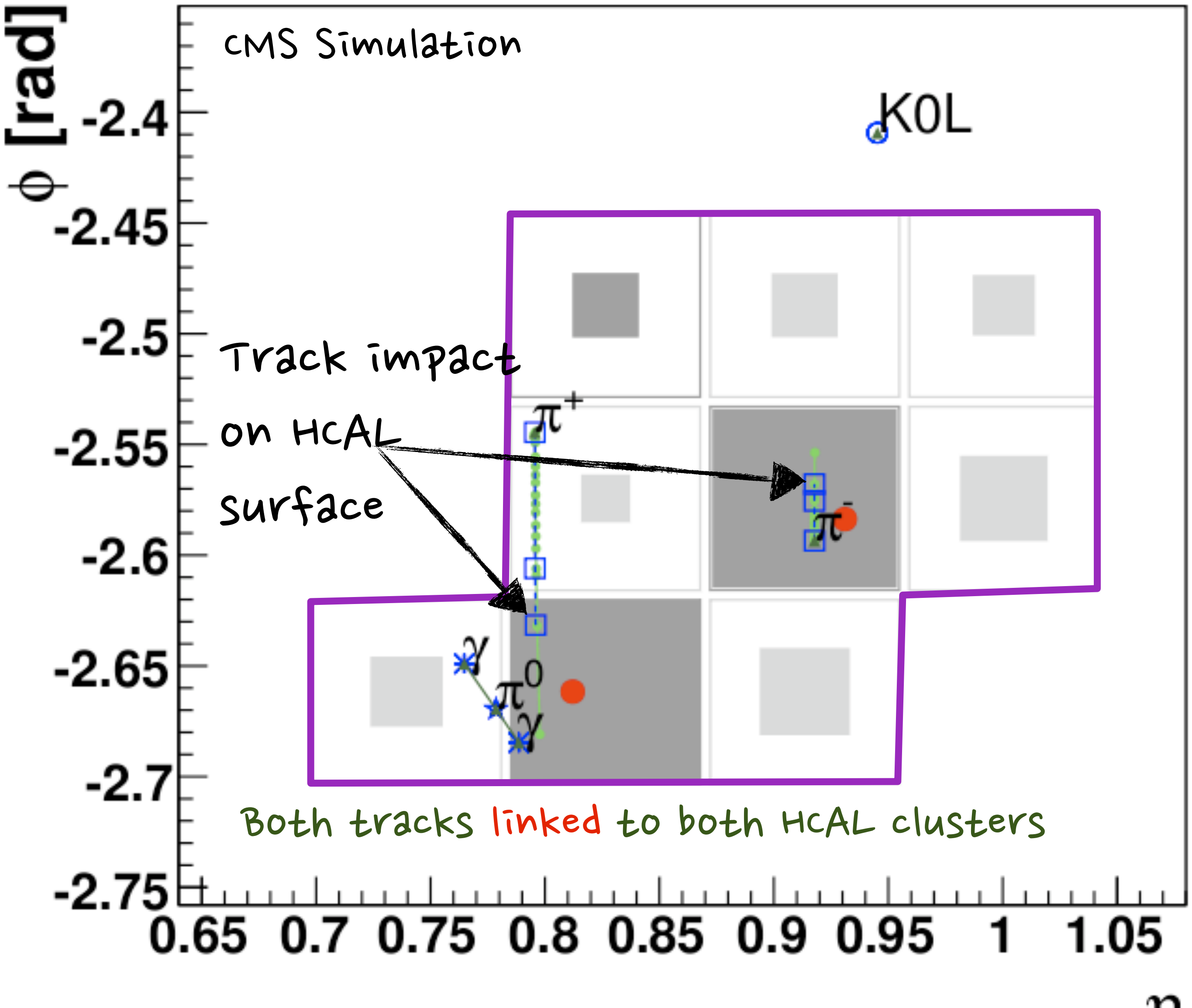
Track-Cluster Link HCAL



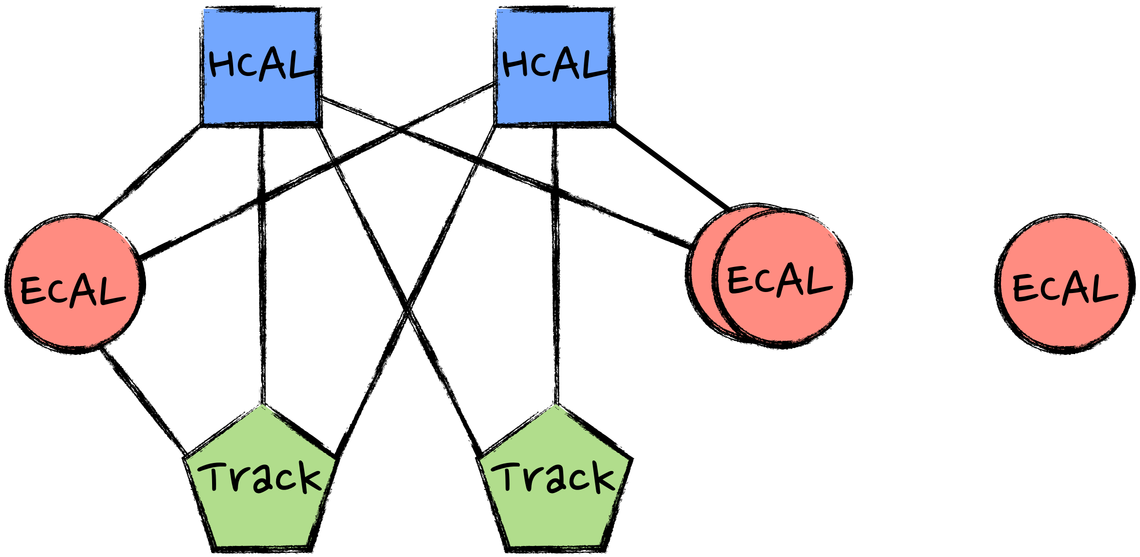
Track-Cluster Link HCAL



Track-Cluster Link HCAL

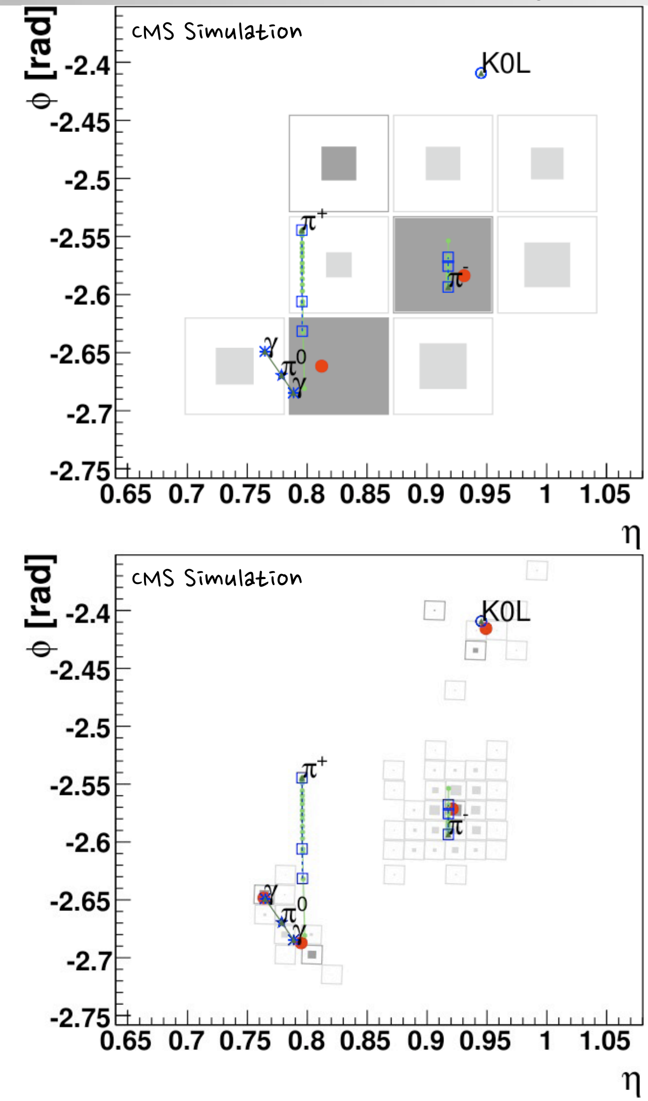


Particle Identification

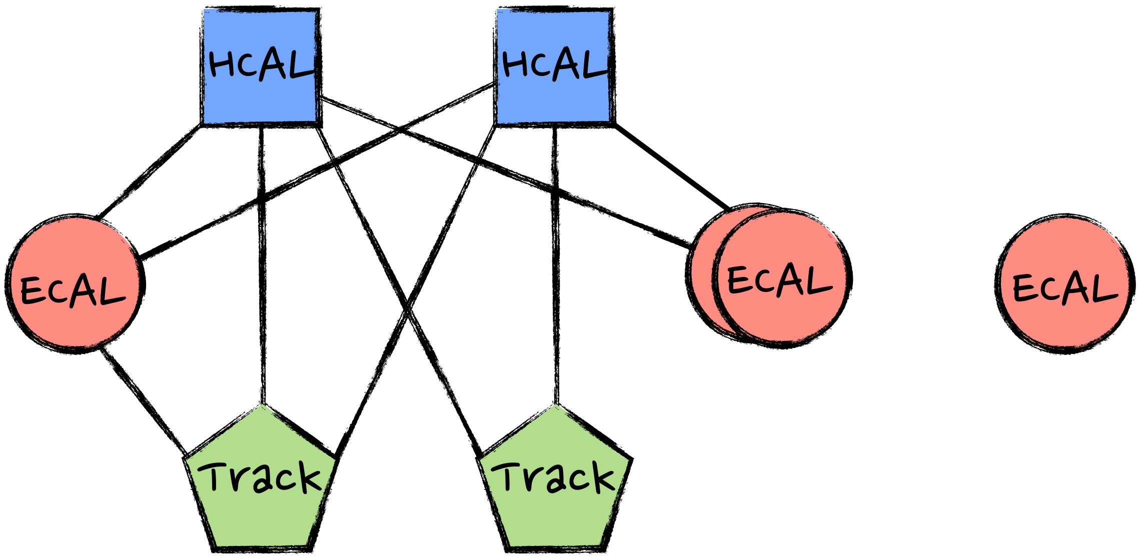


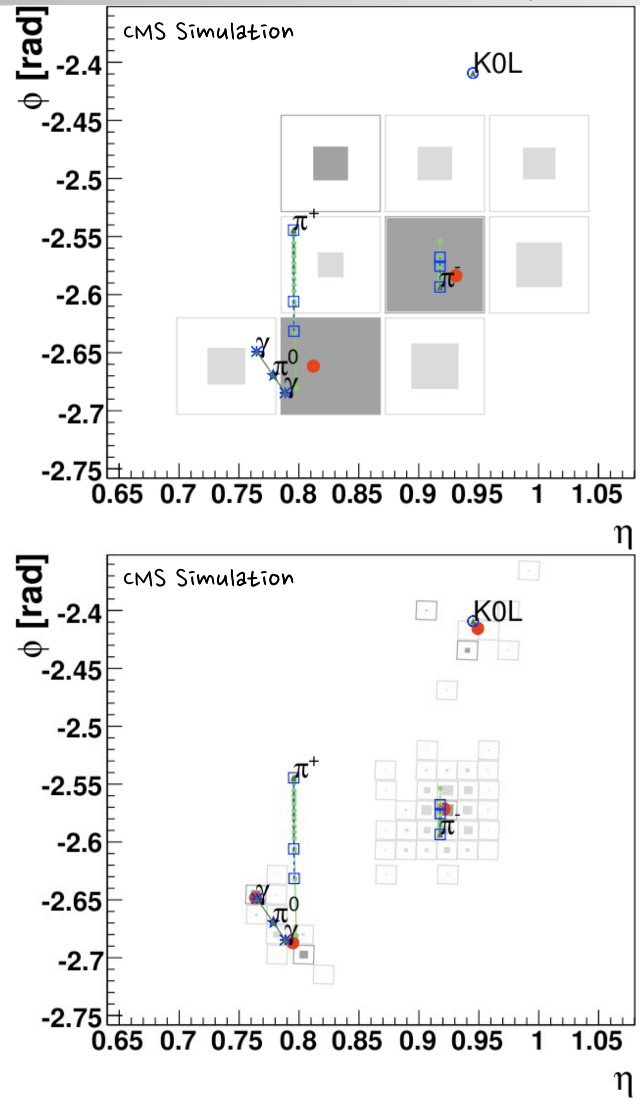
List of reconstructed particles:

{



Build "blocks" of linked elements



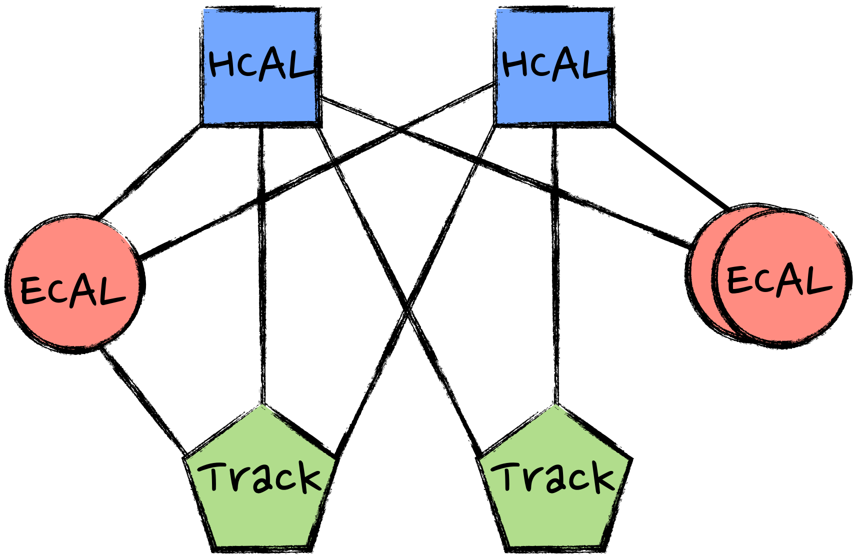


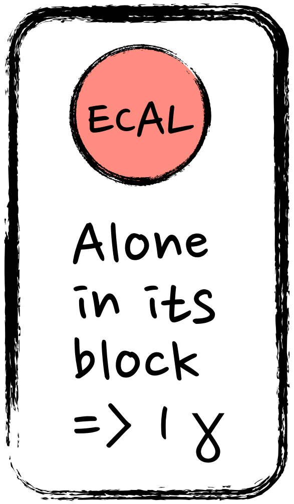
List of reconstructed particles:

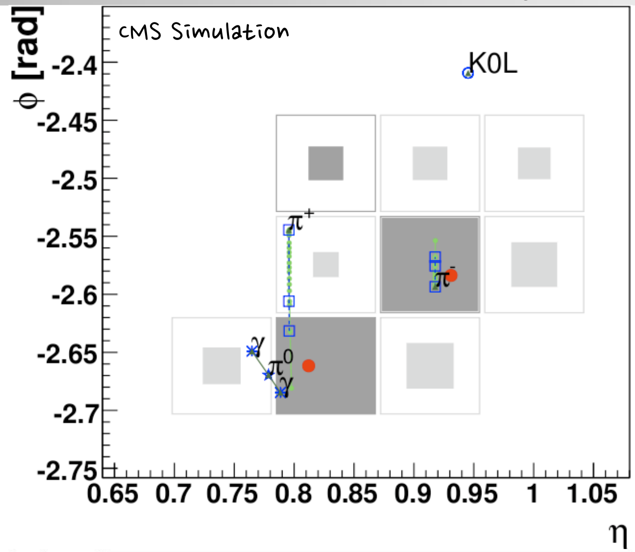
{

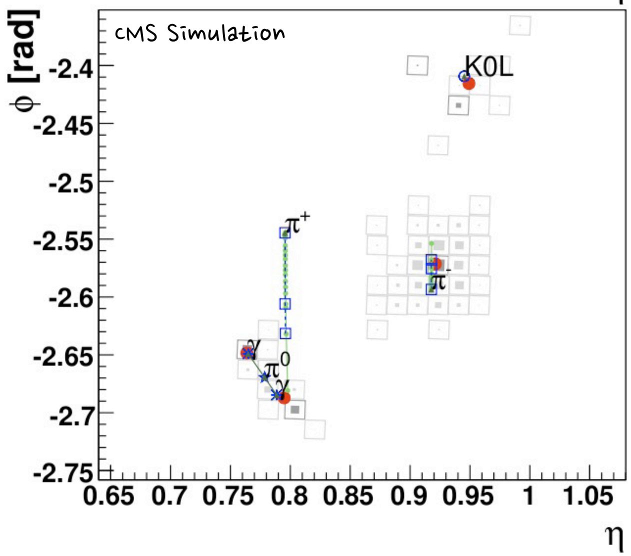
Particle Identification

Build "blocks" of linked elements







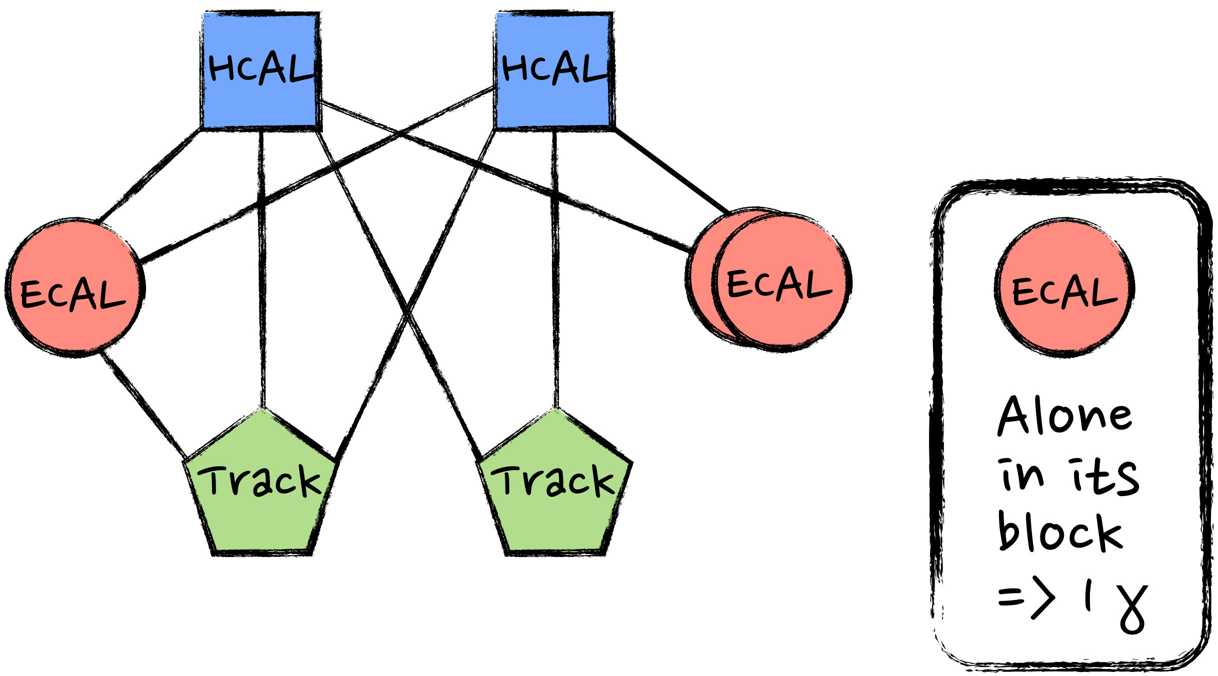


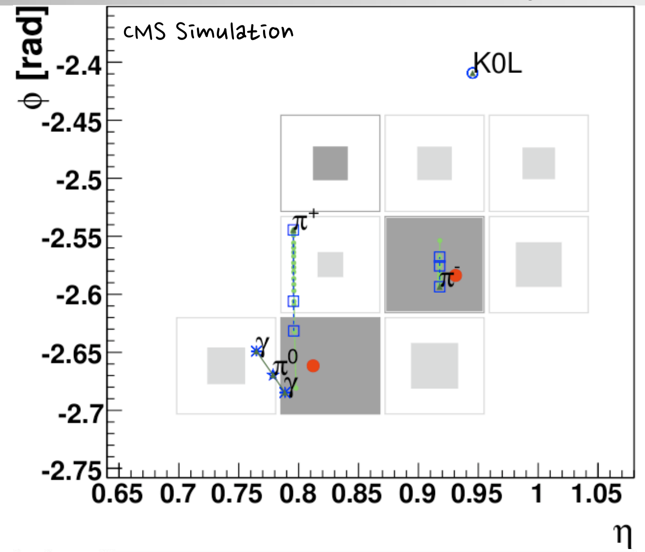
List of reconstructed particles:

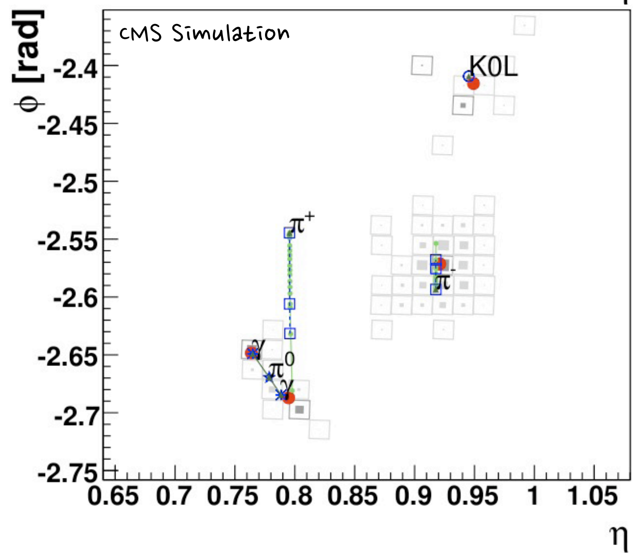
{

Particle Identification

Build "blocks" of linked elements



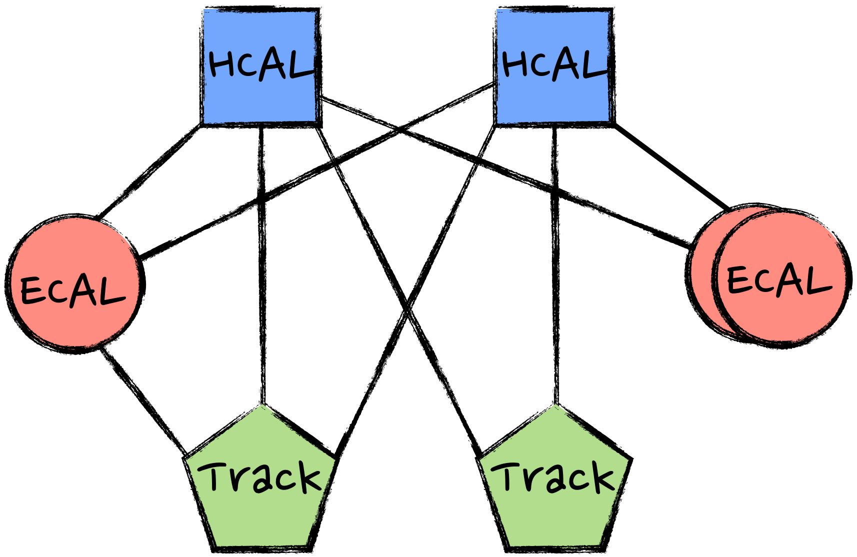


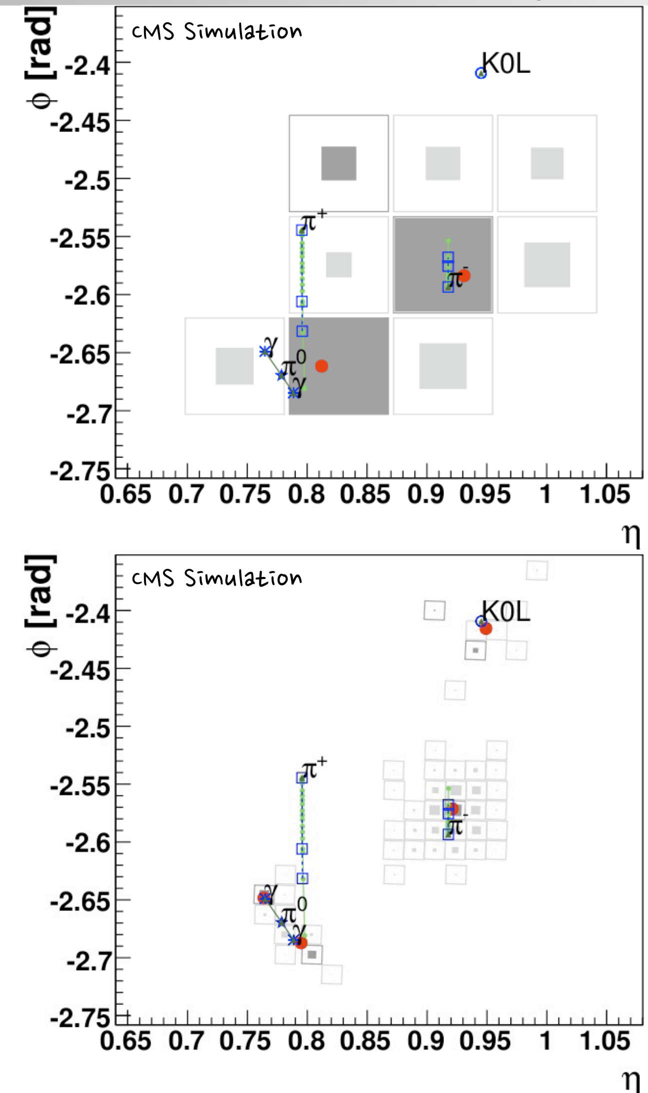


List of reconstructed particles:

{ γ

Particle Identification



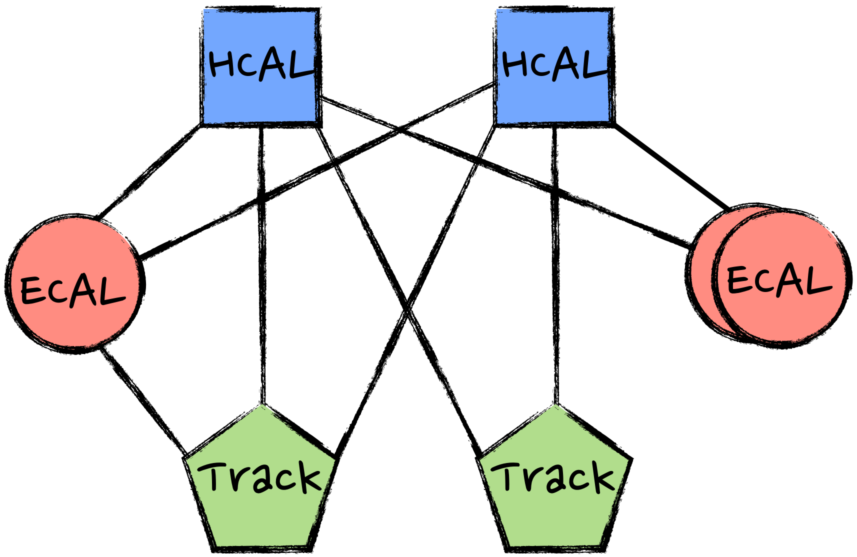


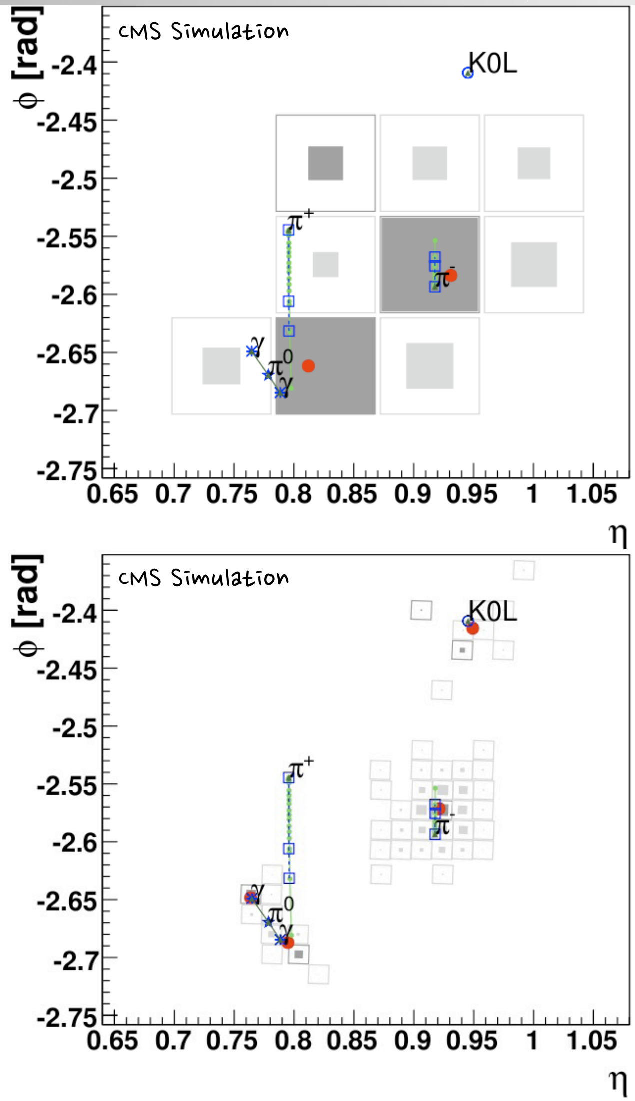
List of reconstructed particles:

{ γ

Particle Identification

Find isolated photons in the blocks



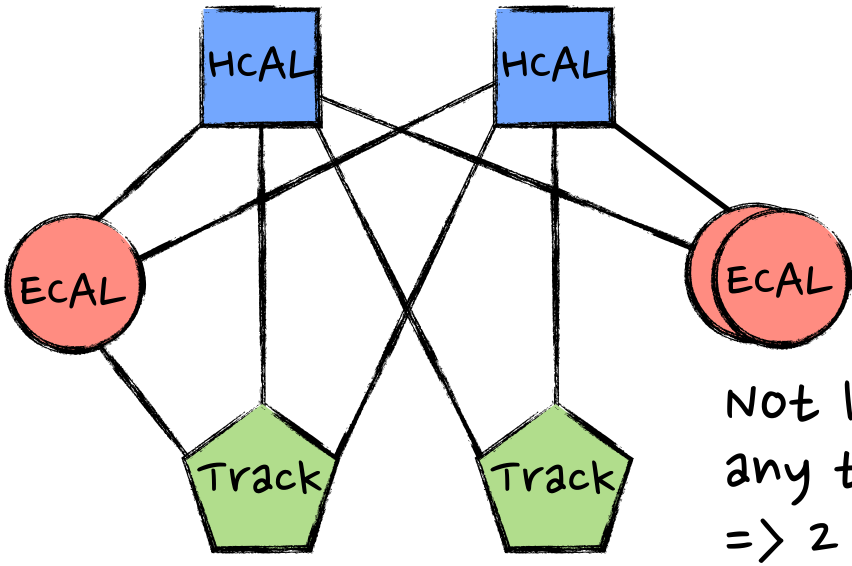


List of reconstructed particles:

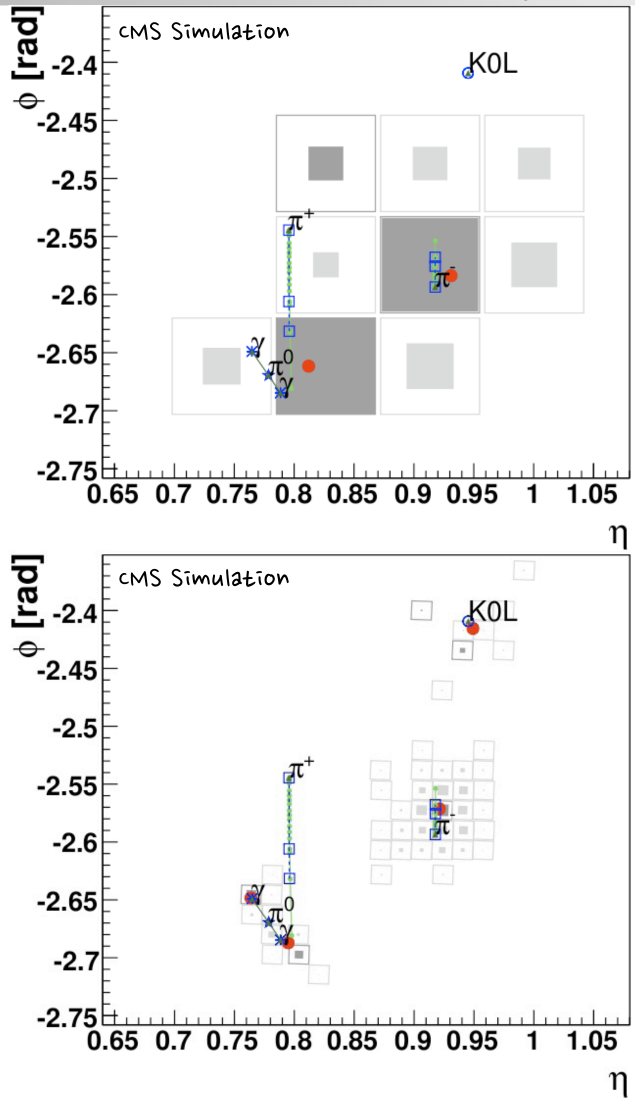
{ γ

Particle Identification

Find isolated photons in the blocks



Not linked to any track => 2 γ's

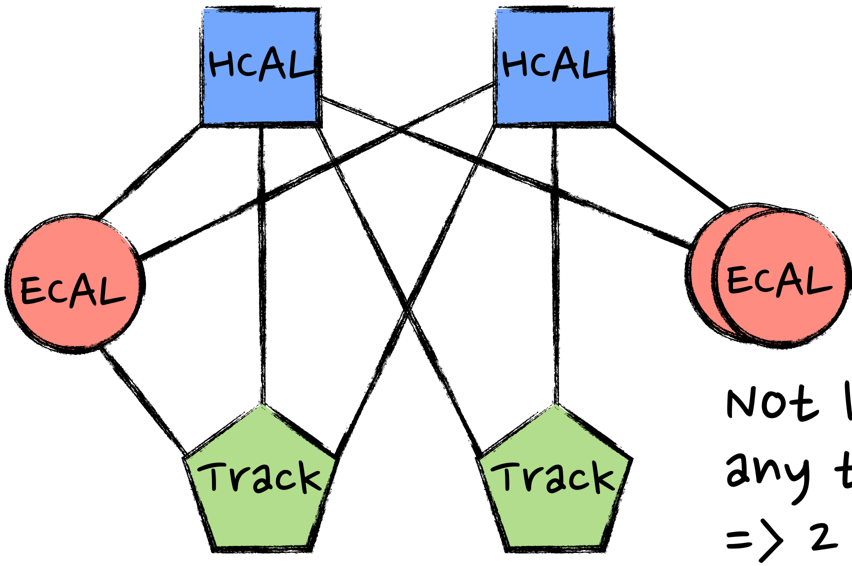


List of reconstructed particles:

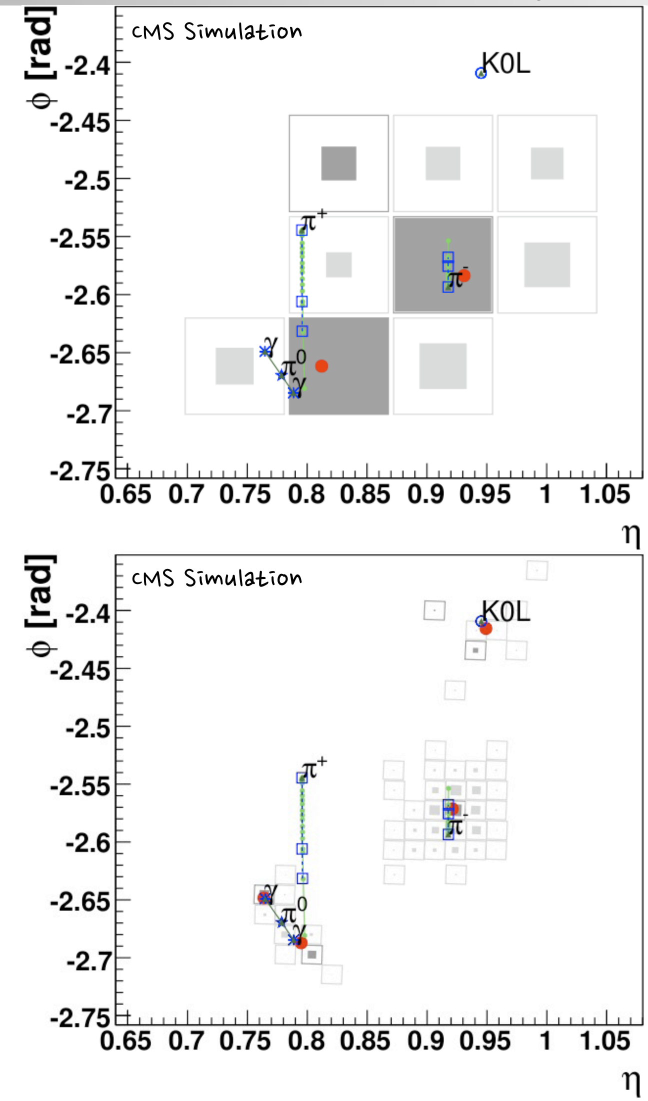
{ γ

Particle Identification

Find isolated photons in the blocks



Not linked to any track => 2 γ's

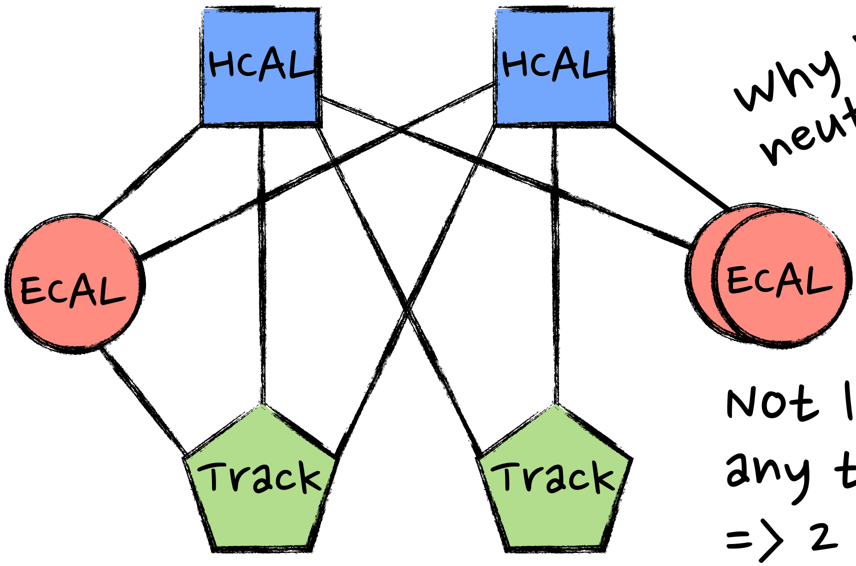


List of reconstructed particles:

{ γ, γ, γ

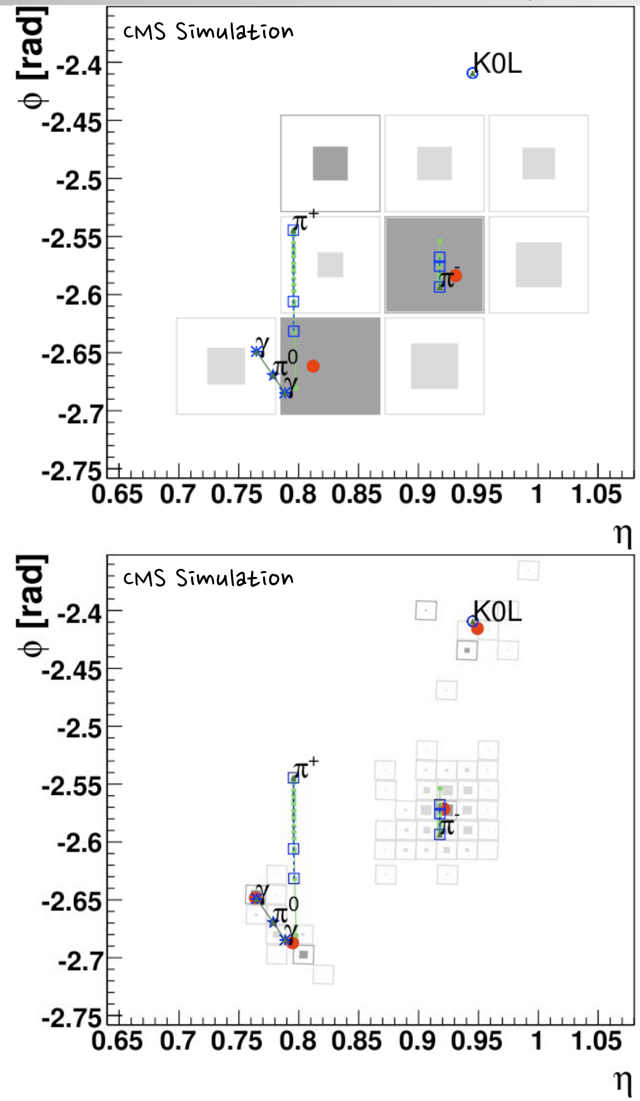
Particle Identification

Find isolated photons in the blocks



Why not neutral hadrons?

Not linked to any track => 2 γ's

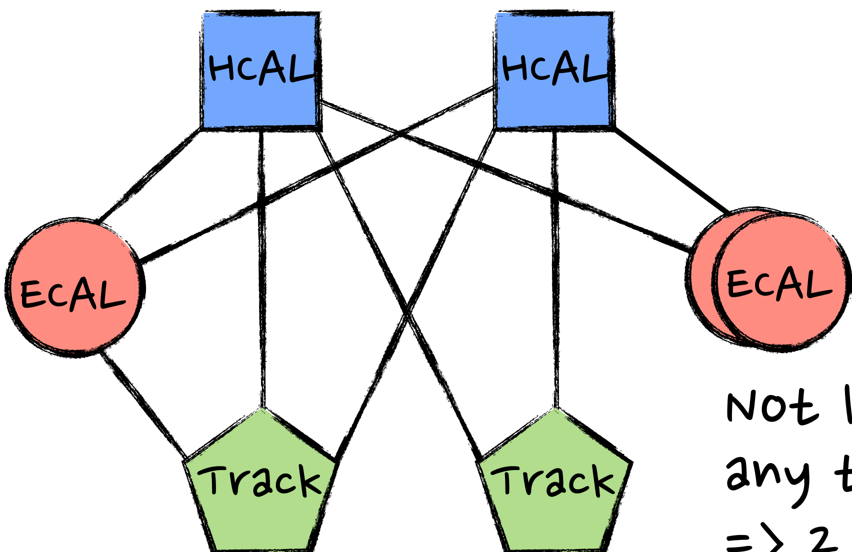


List of reconstructed particles:

{ γ, γ, γ

Particle Identification

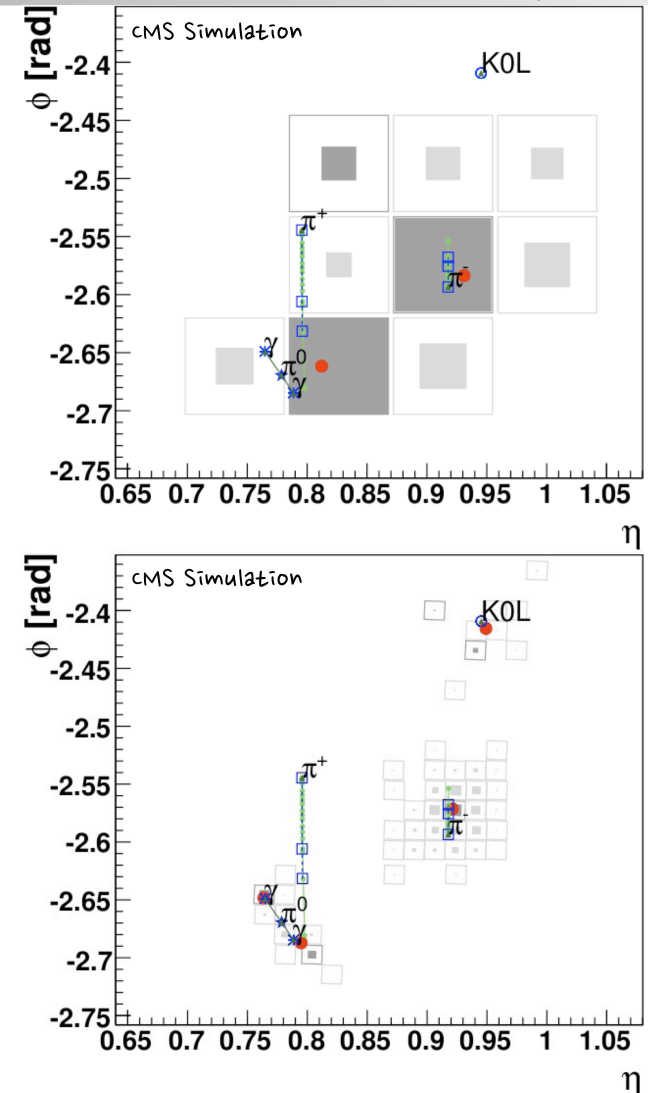
Find isolated photons in the blocks



Not linked to any track => 2 γ's

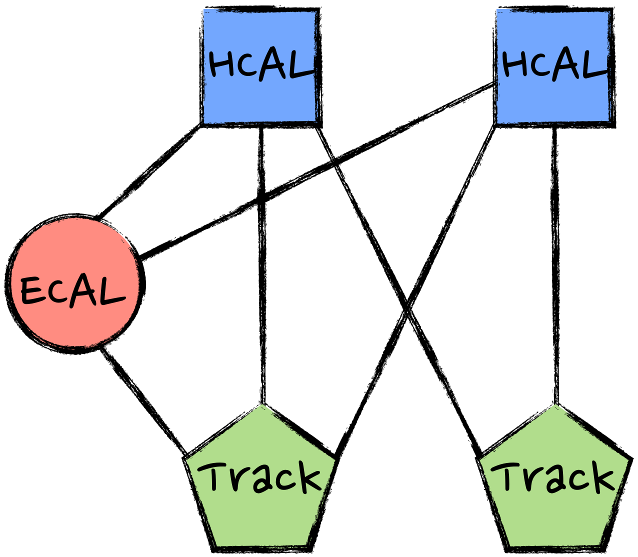
List of reconstructed particles:

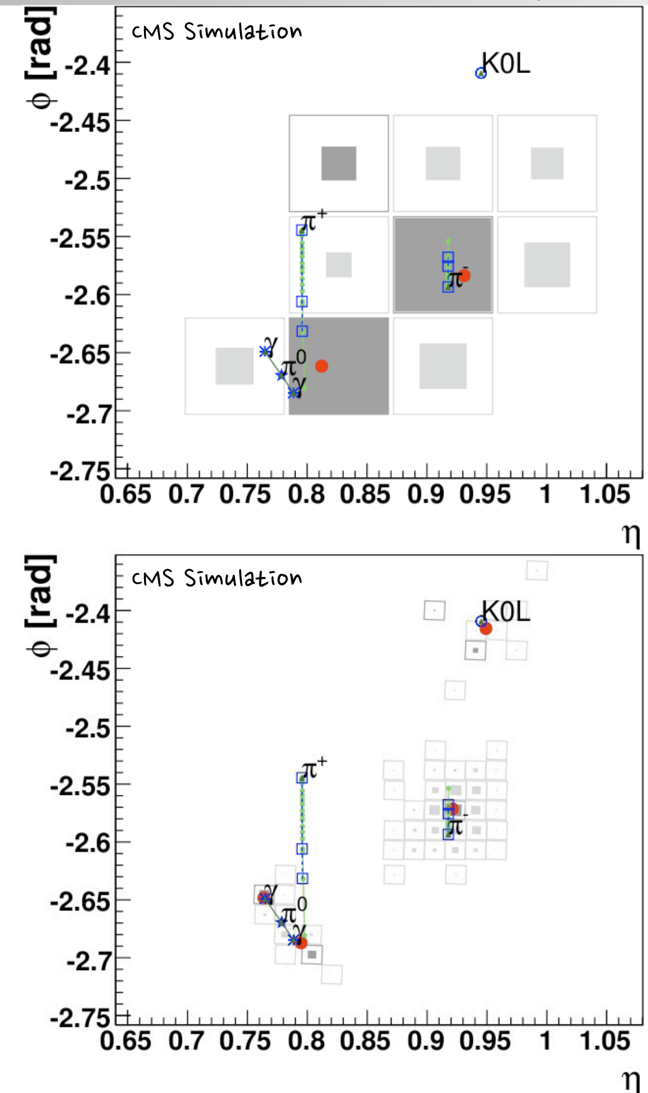
{ γ, γ, γ



R. Cavanaugh, HCPSS 2012
LHC Physics Center

Particle Identification

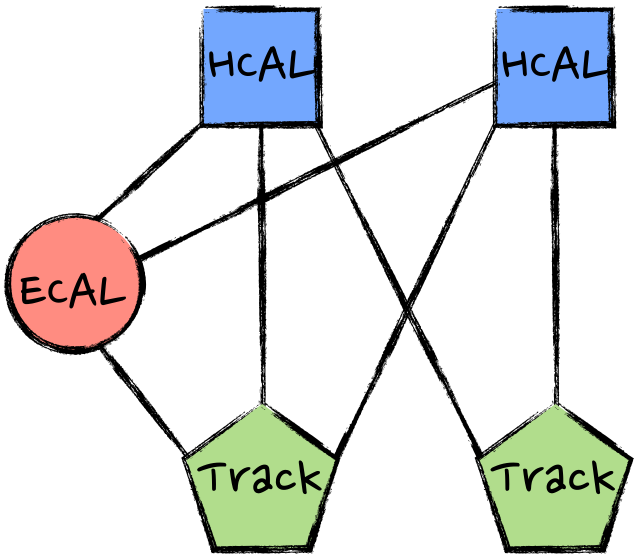




List of reconstructed particles:

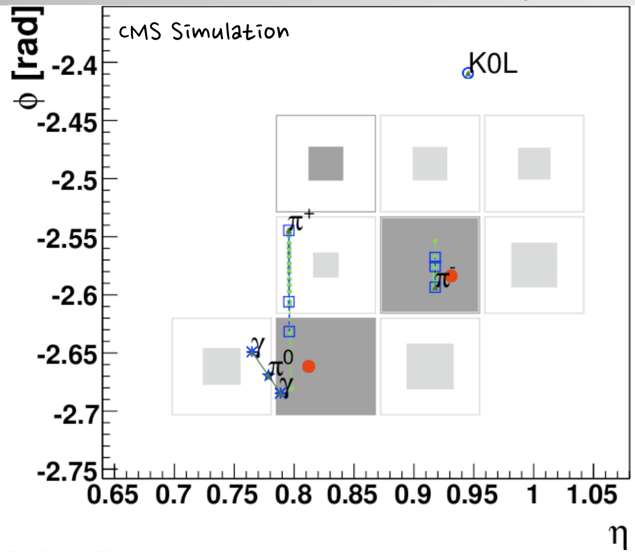
{ γ, γ, γ

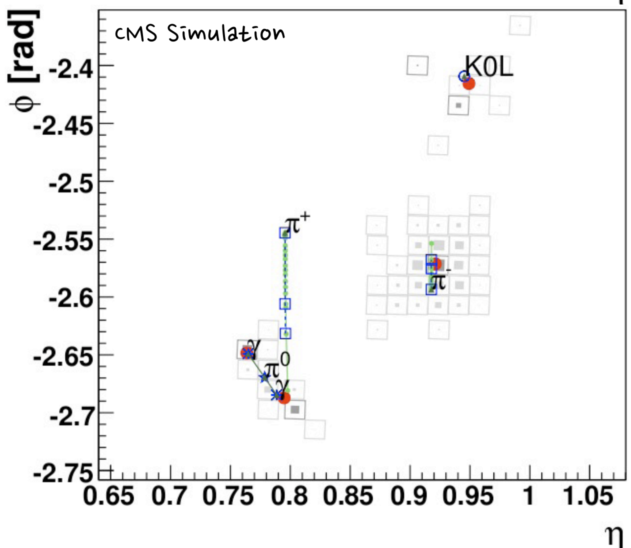
Simplified block (1st step)



List of reconstructed particles:

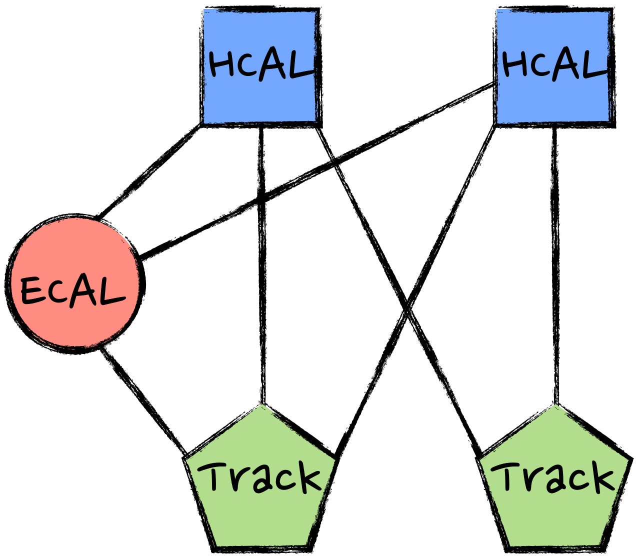
{ γ, γ, γ



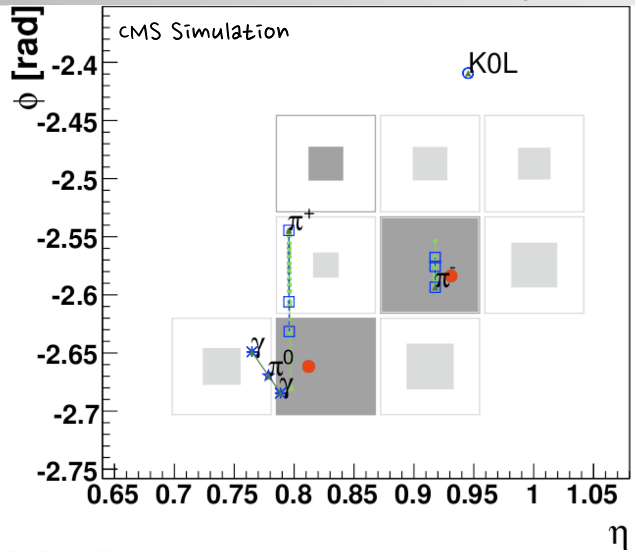


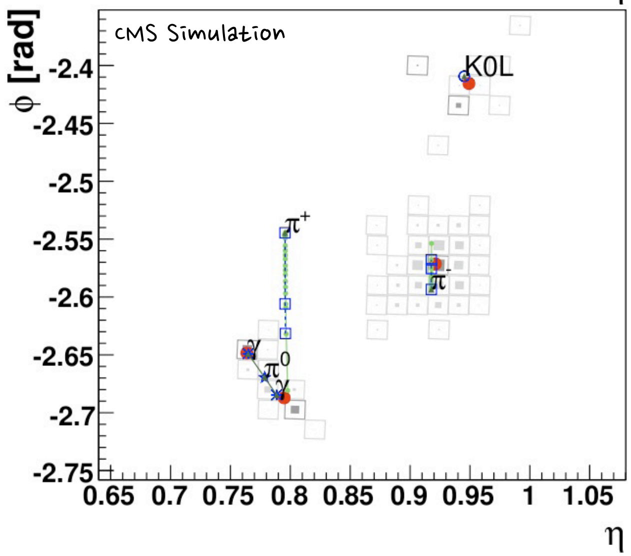
Particle Identification

Simplified block (1st step)



Optimise the use of HCAL granularity



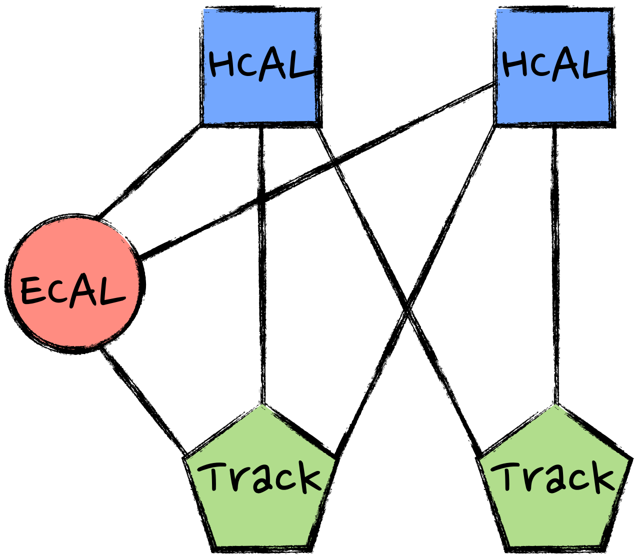


List of reconstructed particles:

{ γ, γ, γ

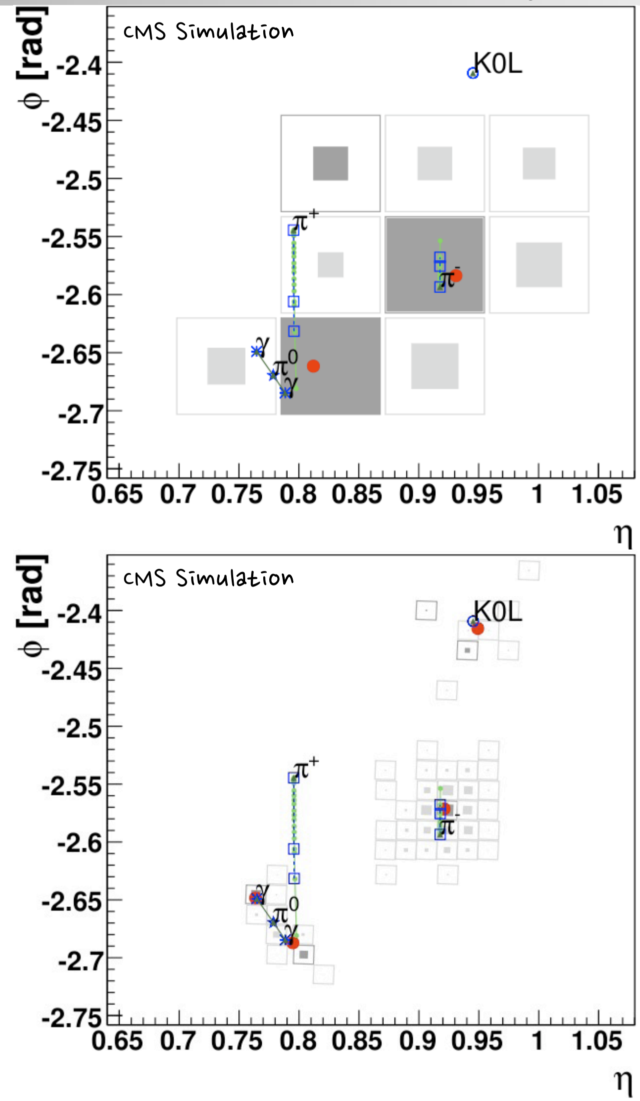
Particle Identification

Simplified block (1st step)



Optimise the use of HCAL granularity

keep only the link to the closest cluster

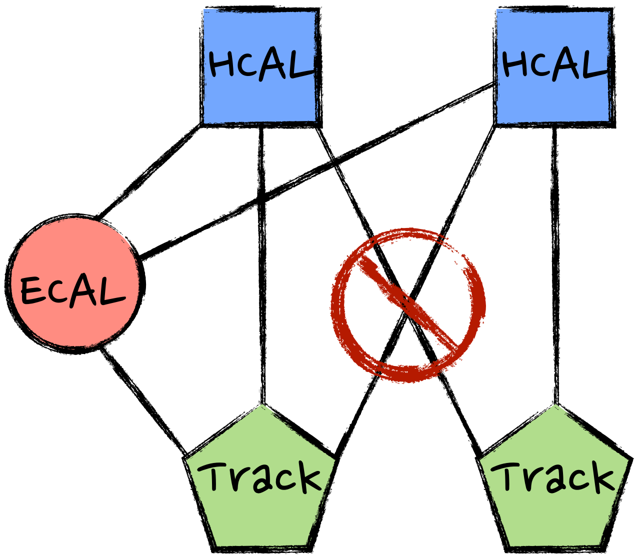


List of reconstructed particles:

{ γ, γ, γ

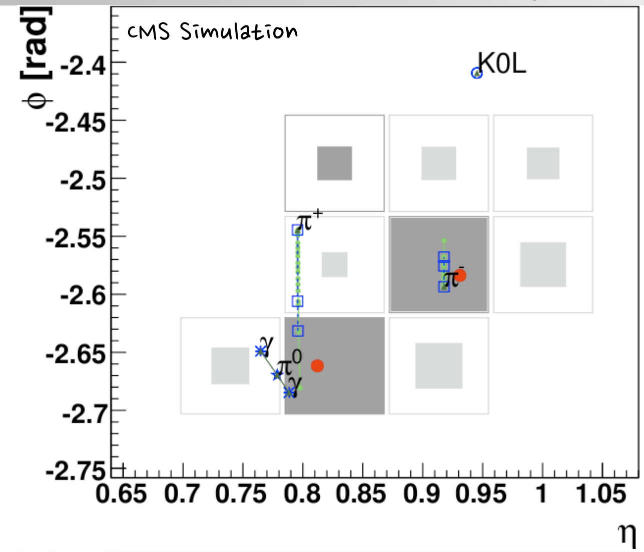
Particle Identification

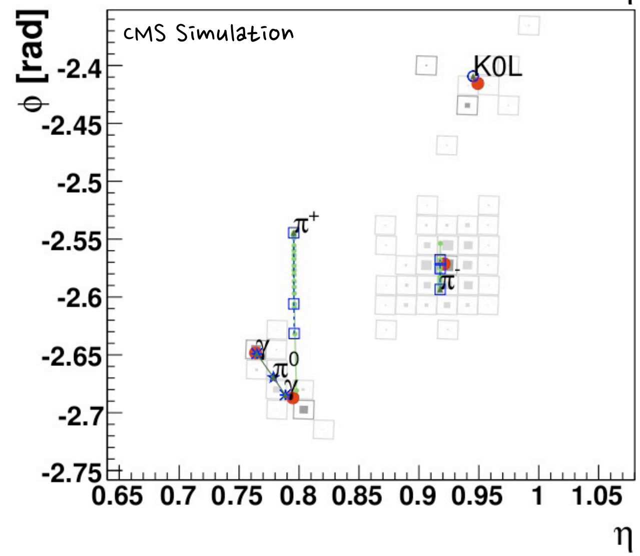
Simplified block (1st step)



Optimise the use of HCAL granularity

keep only the link to the closest cluster

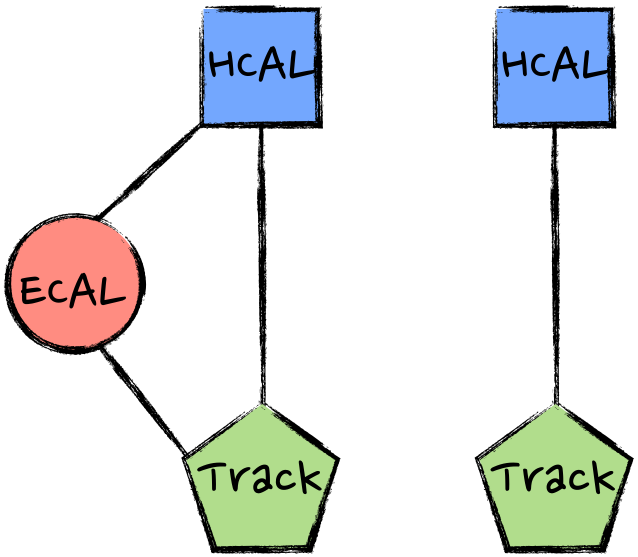


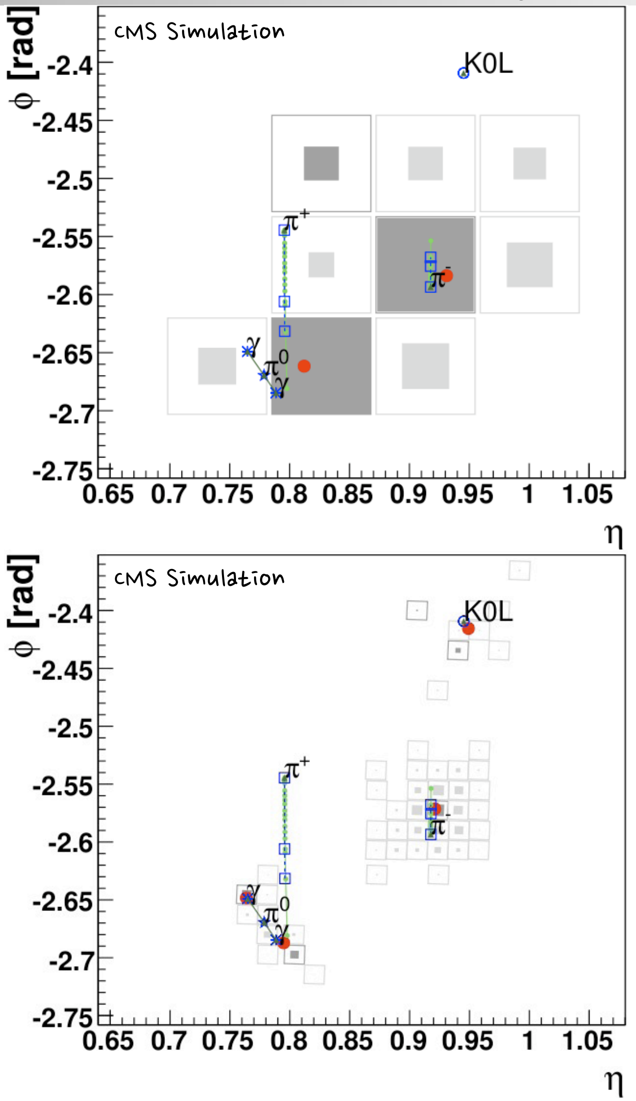


List of reconstructed particles:

{ γ, γ, γ

Particle Identification



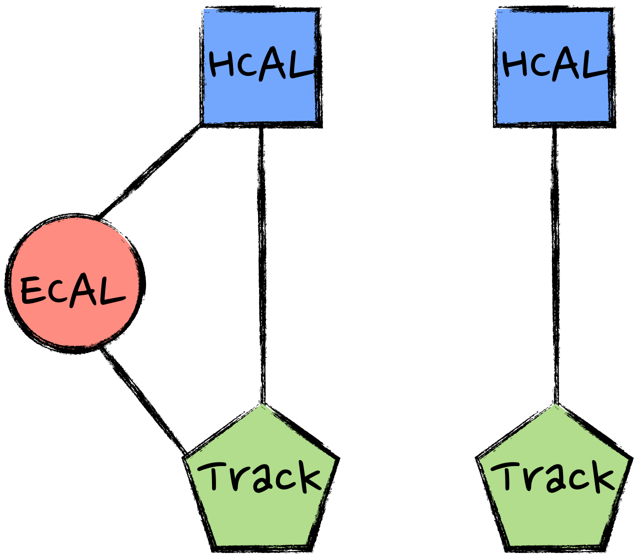


List of reconstructed particles:

{ γ, γ, γ

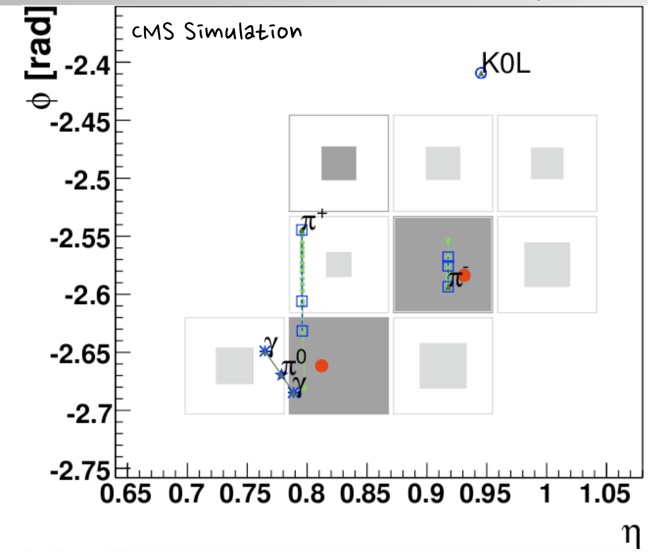
Particle Identification

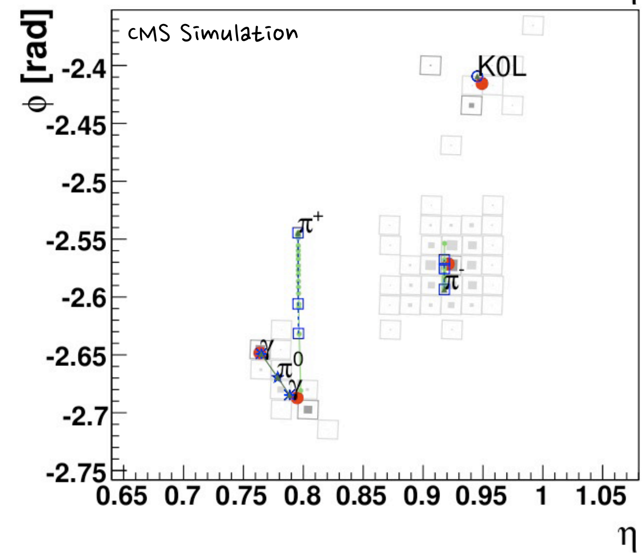
Further simplified (2nd step):
blocks are usually very small!



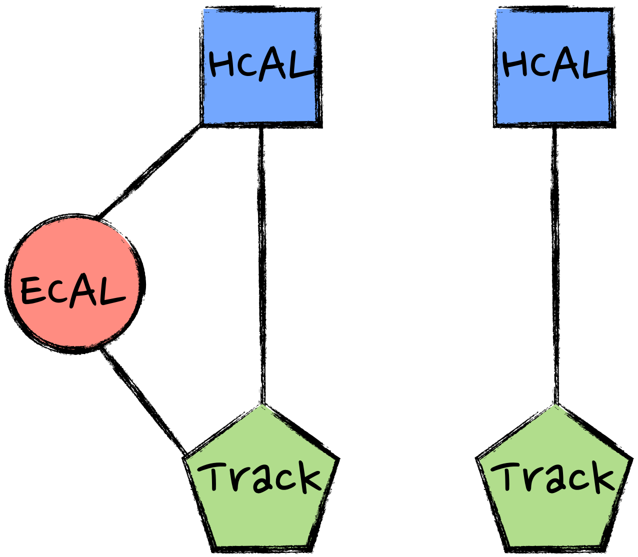
List of reconstructed particles:

{ γ, γ, γ





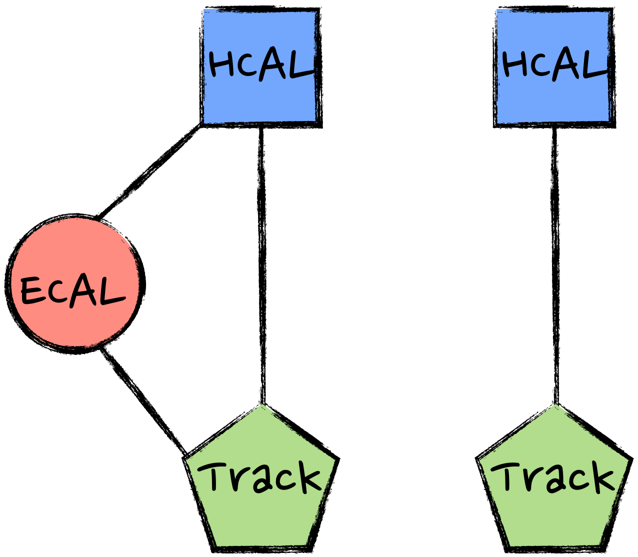
Particle Identification



List of reconstructed particles:

{ γ, γ, γ

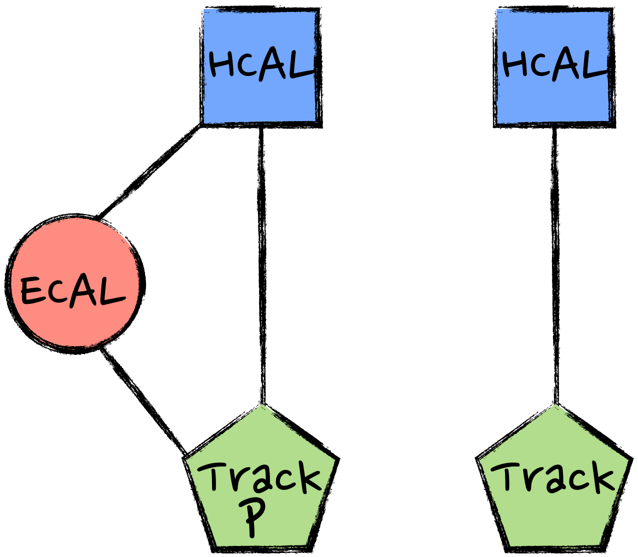
Find charged hadrons and merged photons / neutral hadrons



List of reconstructed particles:

{ γ, γ, γ

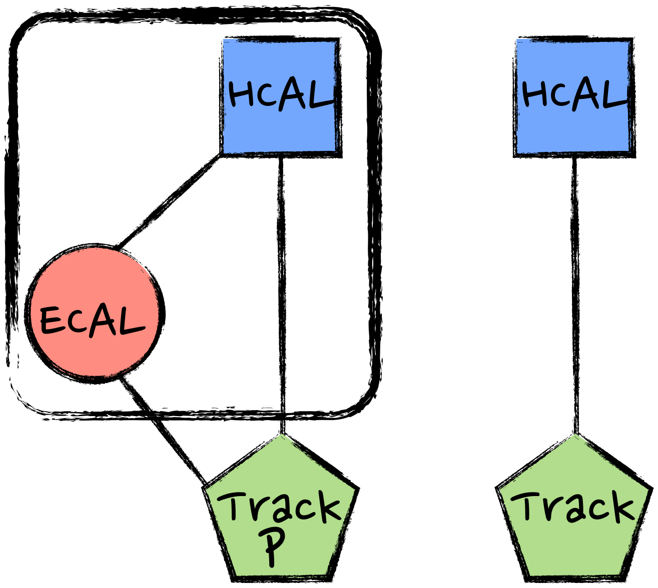
Find charged hadrons and merged photons / neutral hadrons



List of reconstructed particles:

{ γ, γ, γ

Find charged hadrons and merged photons / neutral hadrons

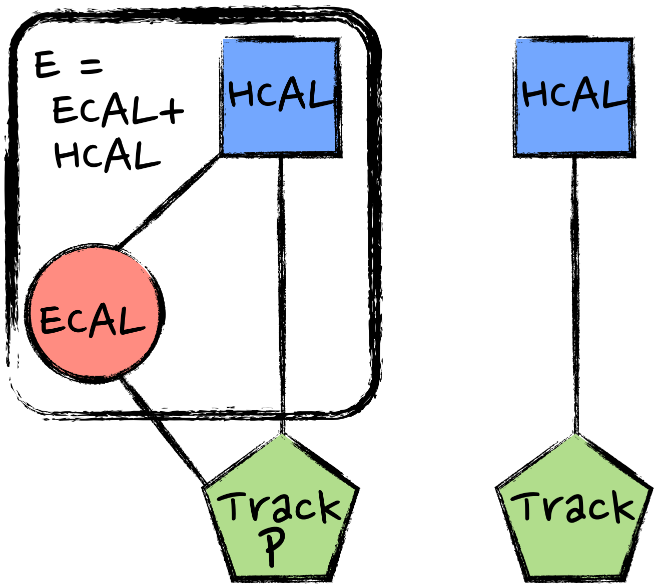


List of reconstructed particles:

{ γ, γ, γ

Particle Identification

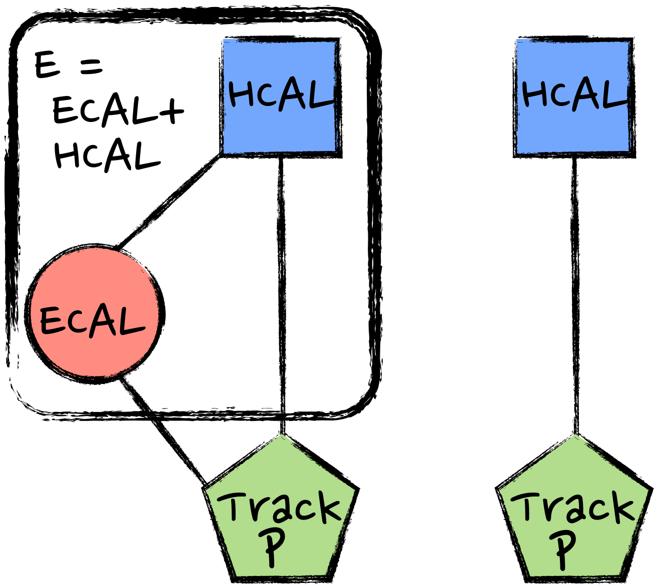
Find charged hadrons and merged photons / neutral hadrons



List of reconstructed particles:

{ γ, γ, γ

Find charged hadrons and merged photons / neutral hadrons

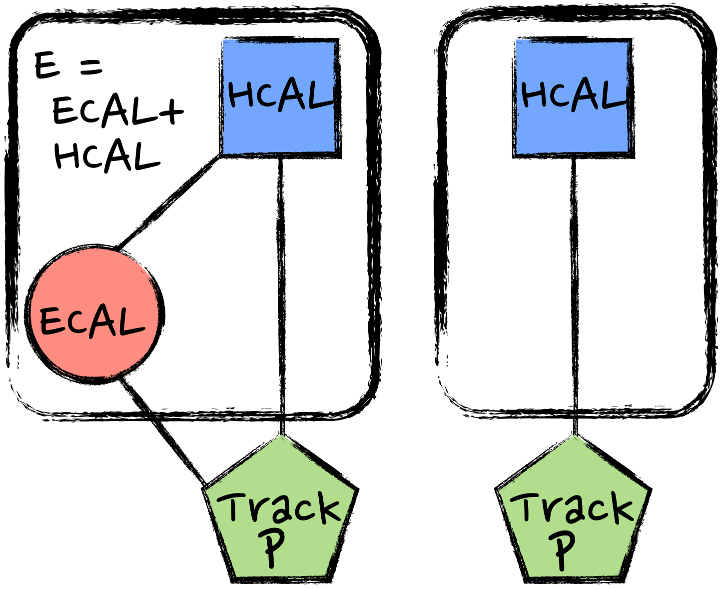


List of reconstructed particles:

{ γ, γ, γ

Particle Identification

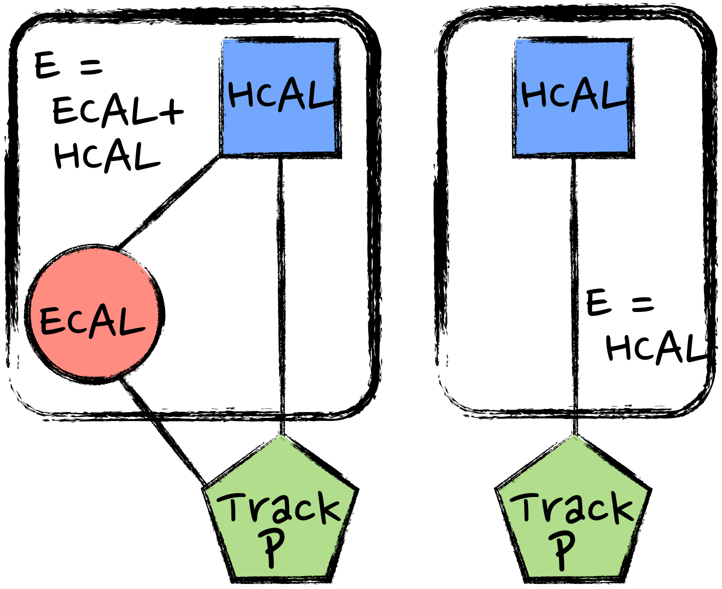
Find charged hadrons and merged photons / neutral hadrons



List of reconstructed particles:

{ γ, γ, γ

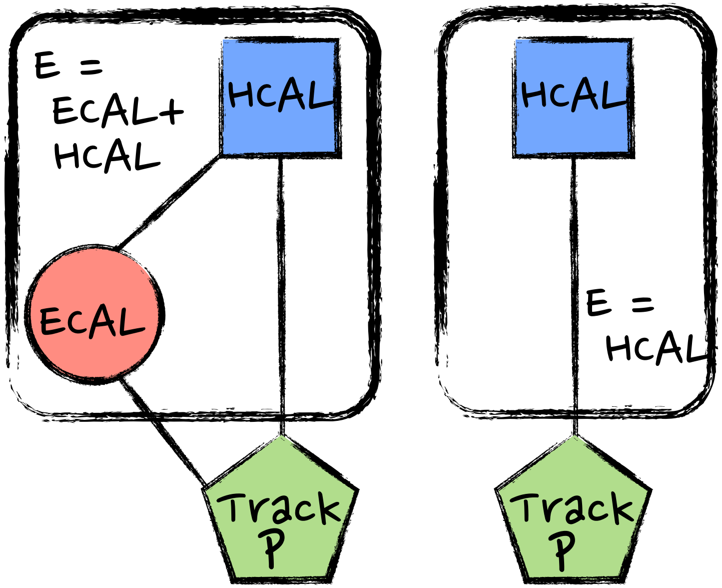
Find charged hadrons and merged photons / neutral hadrons



List of reconstructed particles:

{ γ, γ, γ

Find charged hadrons and merged photons / neutral hadrons



For each HCAL Cluster, compare:

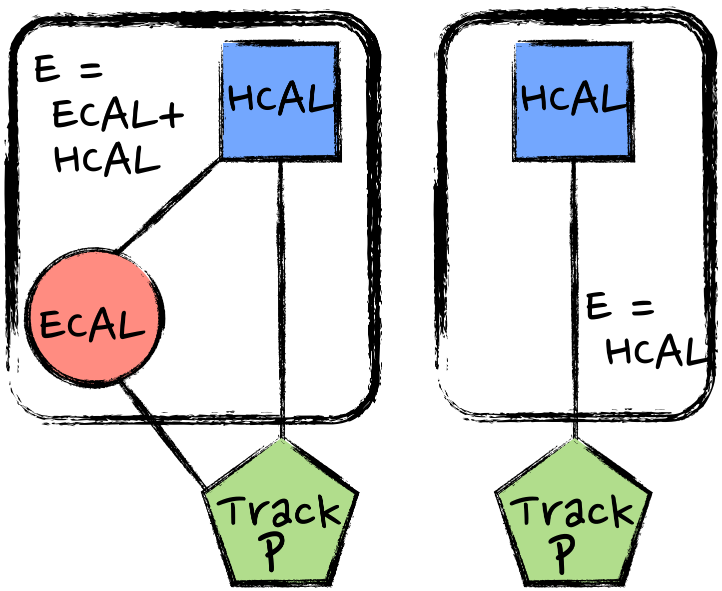
- Sum of track momenta p
- Sum of cluster energies E
  - linked to the tracks in ECAL and in HCAL "Hadron calibrated" (see later)

List of reconstructed particles:

{ γ, γ, γ

Particle Identification

Find charged hadrons and merged photons / neutral hadrons



For each HCAL Cluster, compare:

- Sum of track momenta p
- Sum of cluster energies E
  - linked to th…
  - in ECA…

…r)

If p and E are compatible:

- Identify charged hadrons only
  - one per track

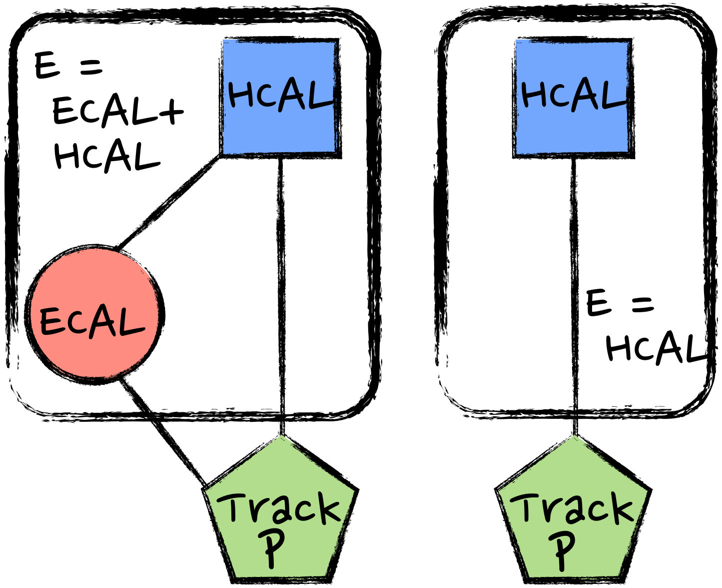
List of reconstructed particles:

{ γ, γ, γ

R. Cavanaugh, HCPSS 2012

Particle Identification

Find charged hadrons and merged photons / neutral hadrons



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  - linked to the ...
    in ECA...
  ...r)

If p and E are compatible:

- Identify charged hadrons only
  - one per track

If E > p + σ(E)

- Identify charged hadrons + photon / neutral hadrons

List of reconstructed particles:

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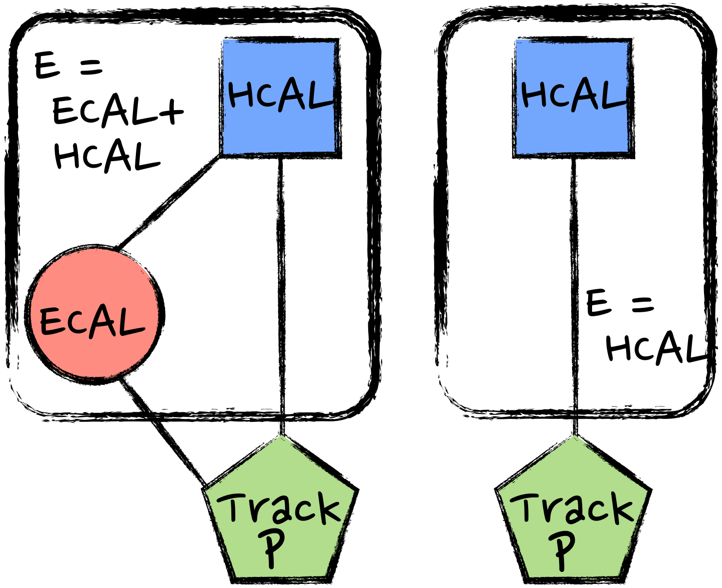

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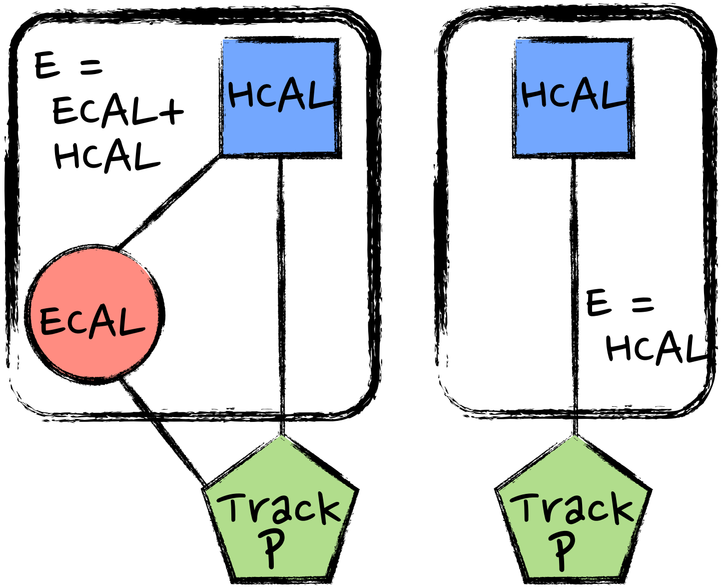

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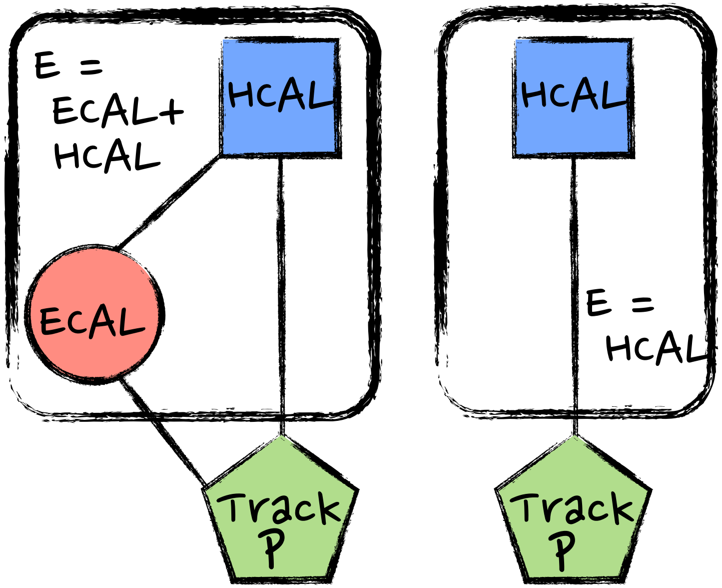

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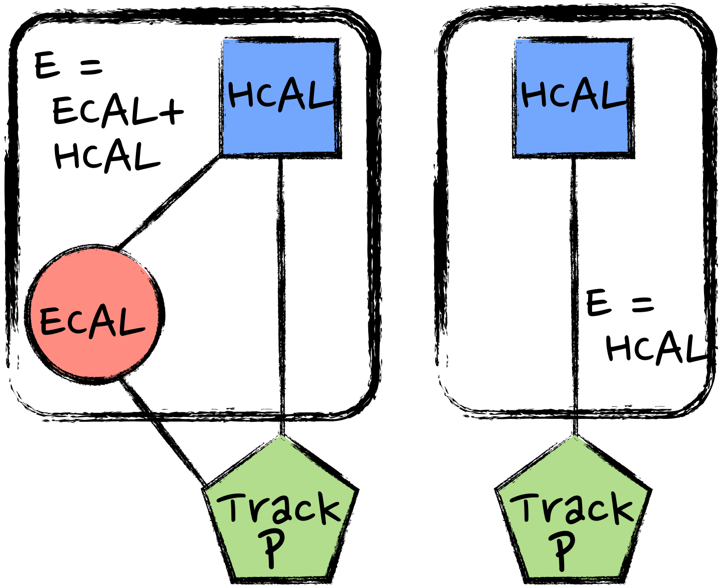

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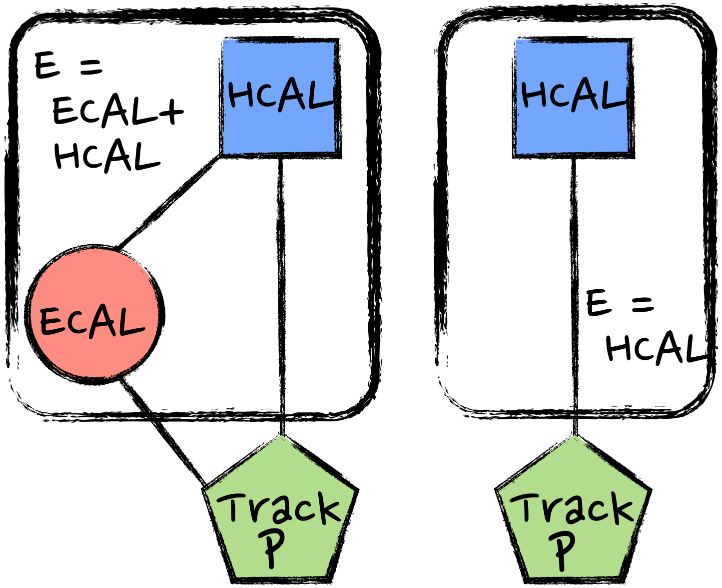

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R. Cavanaugh, HCPSS 2012

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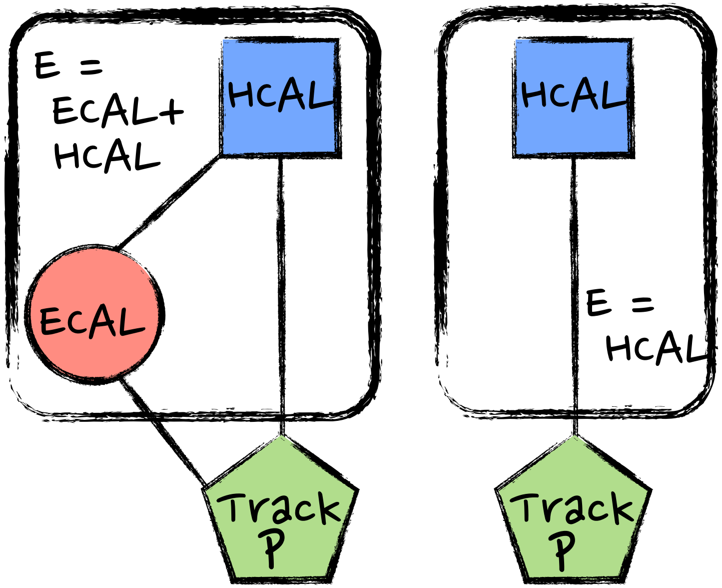

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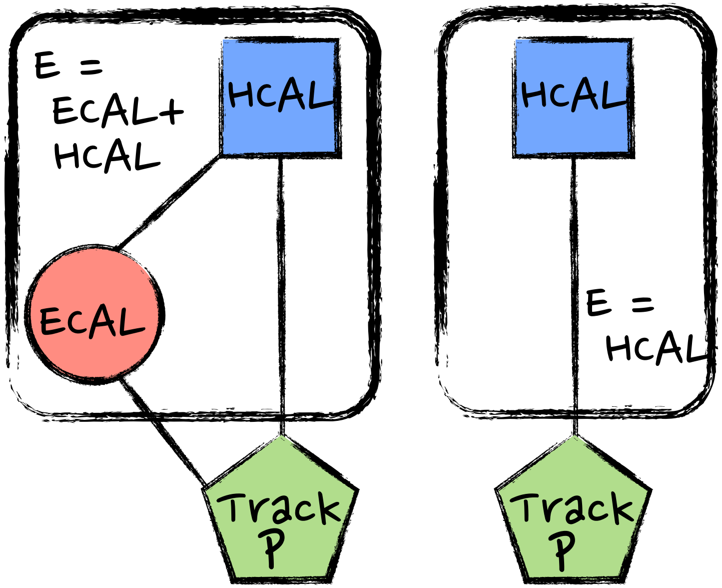

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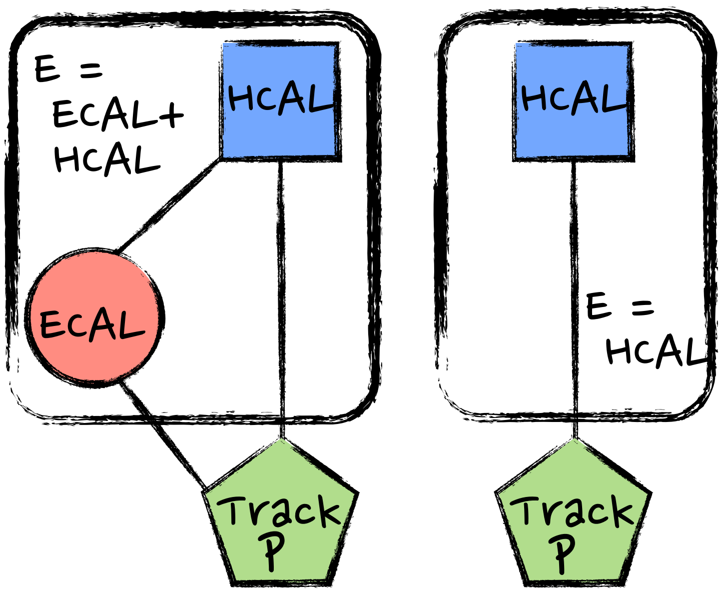

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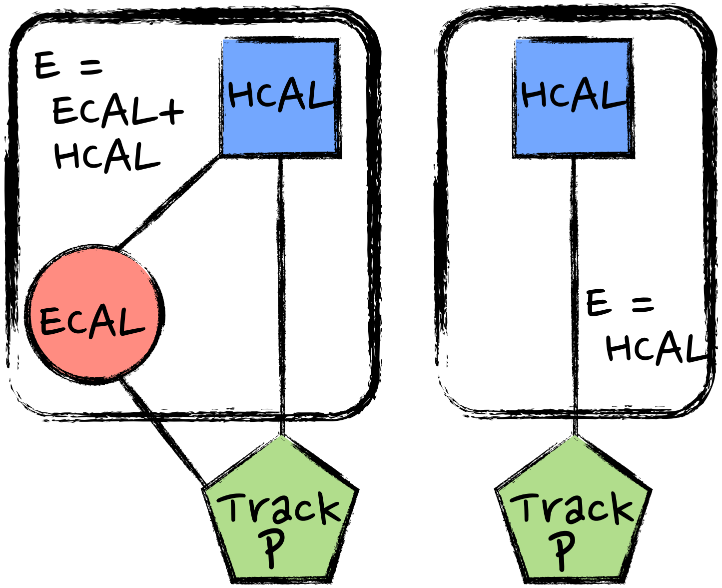

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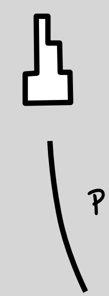

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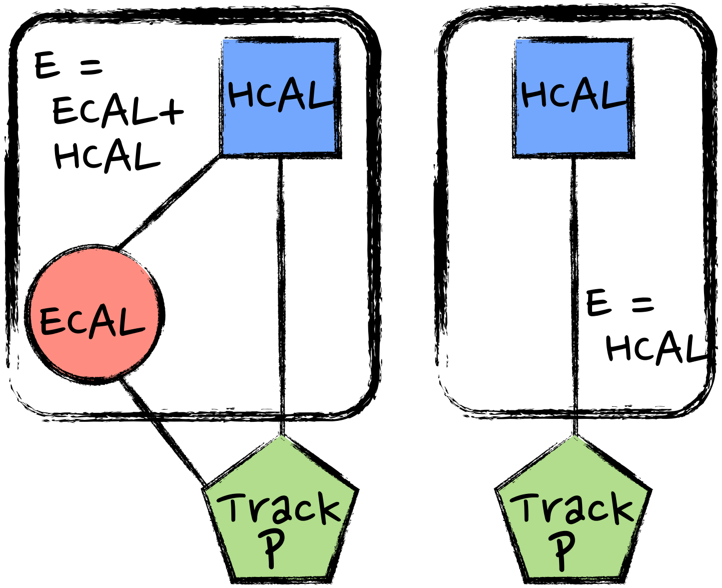

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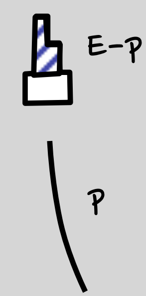

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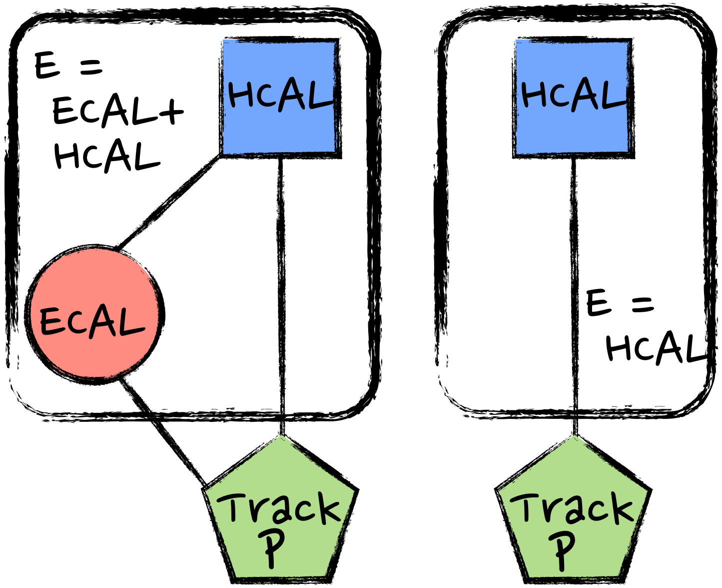

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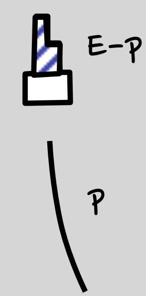

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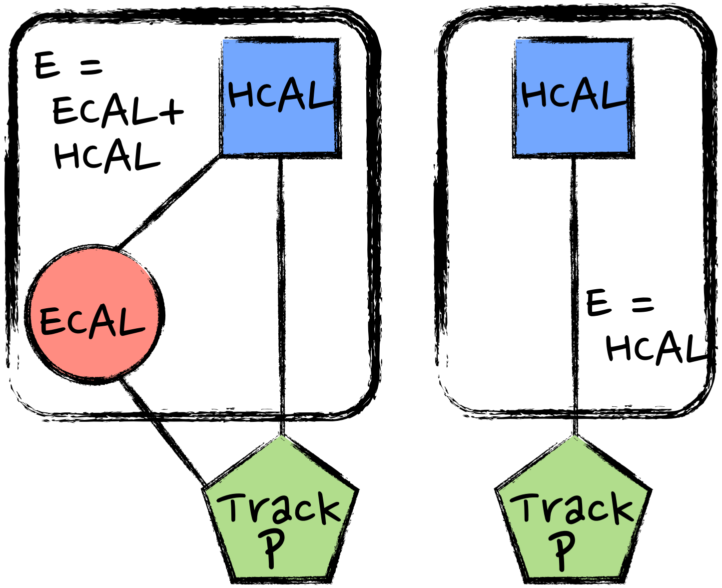

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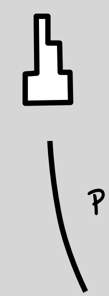

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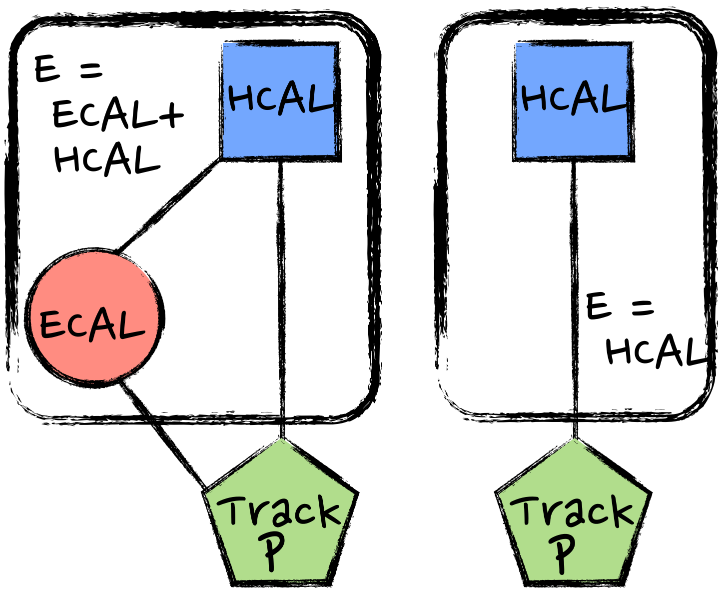

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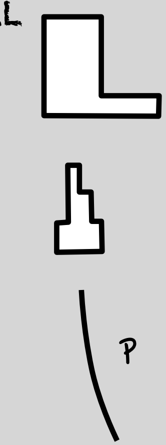

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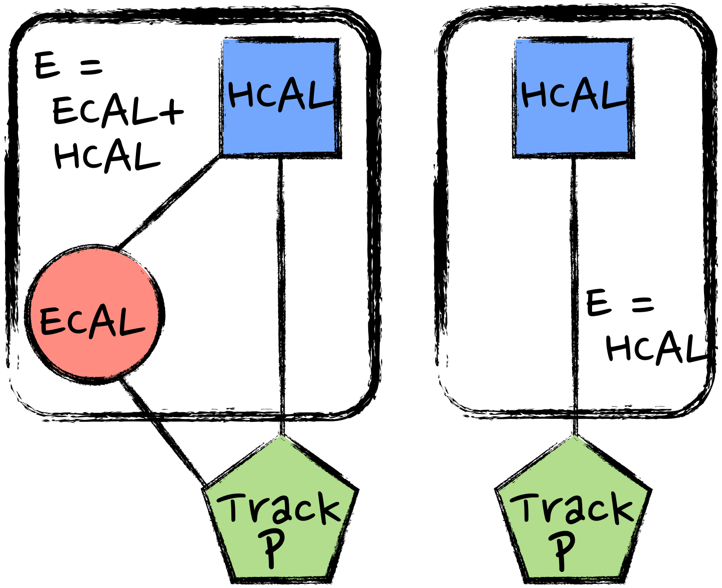

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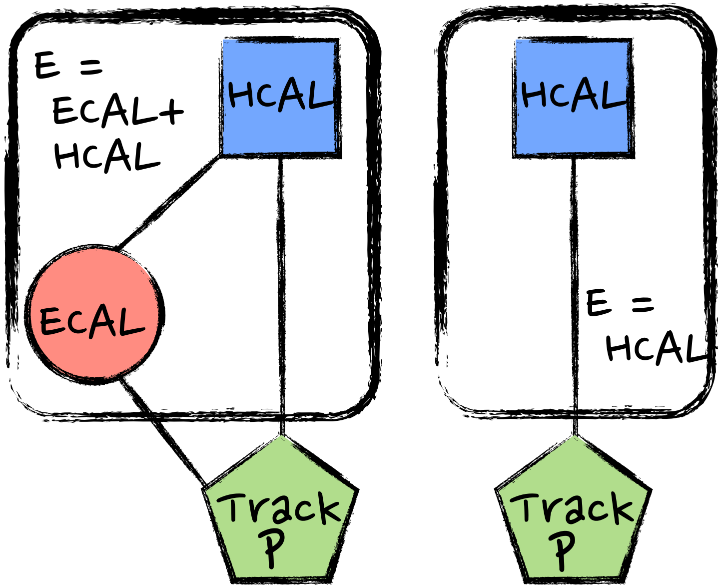

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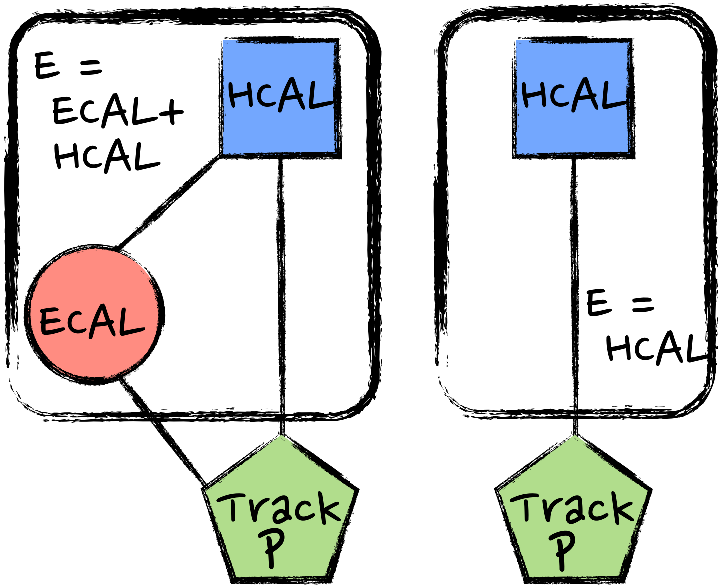

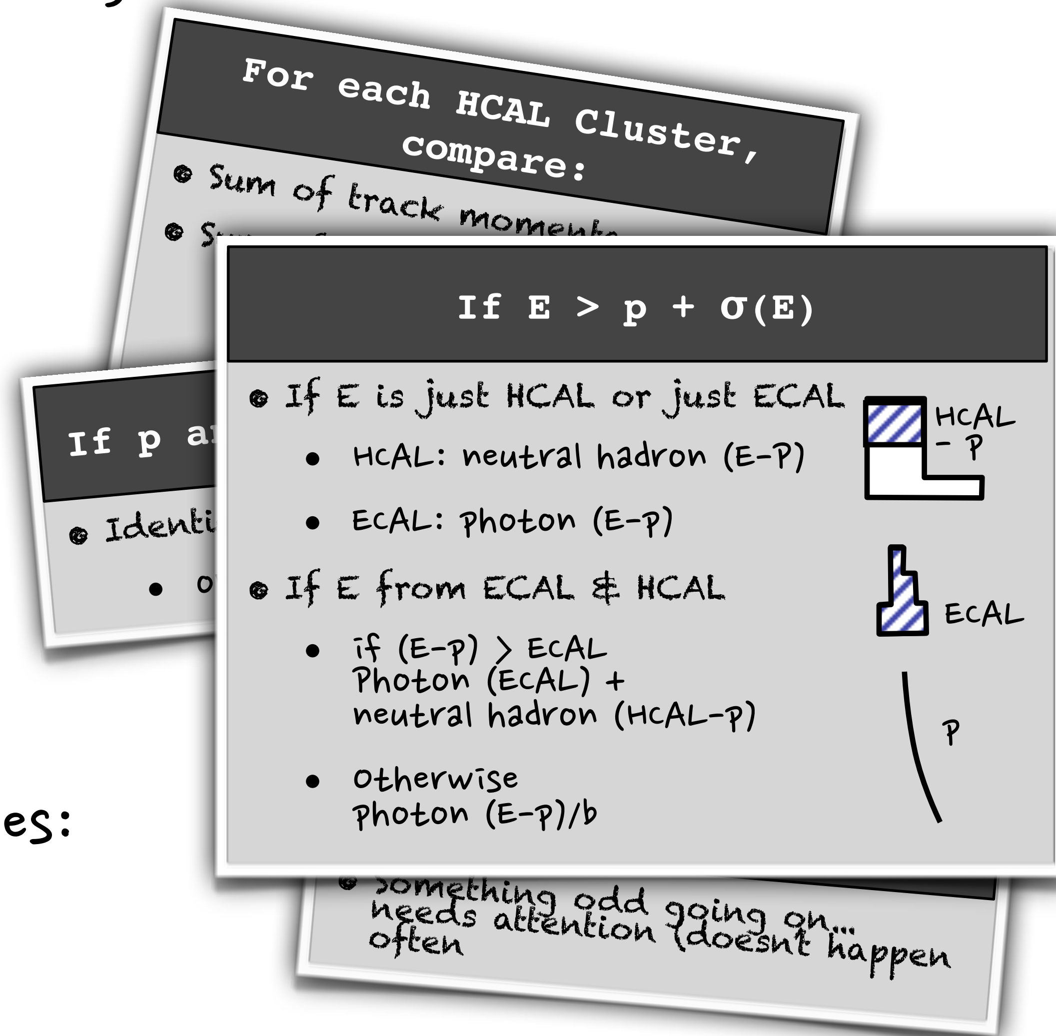

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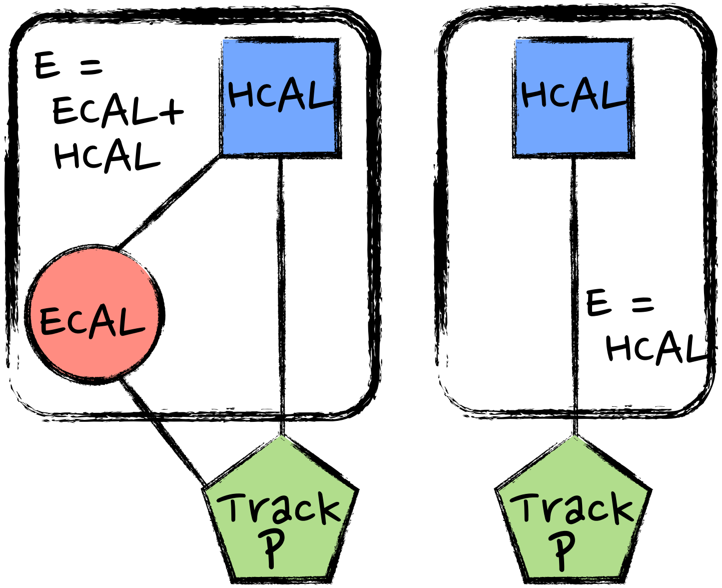

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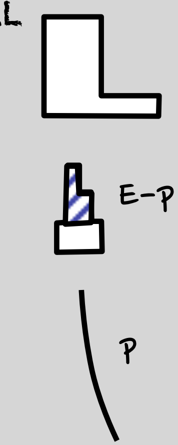

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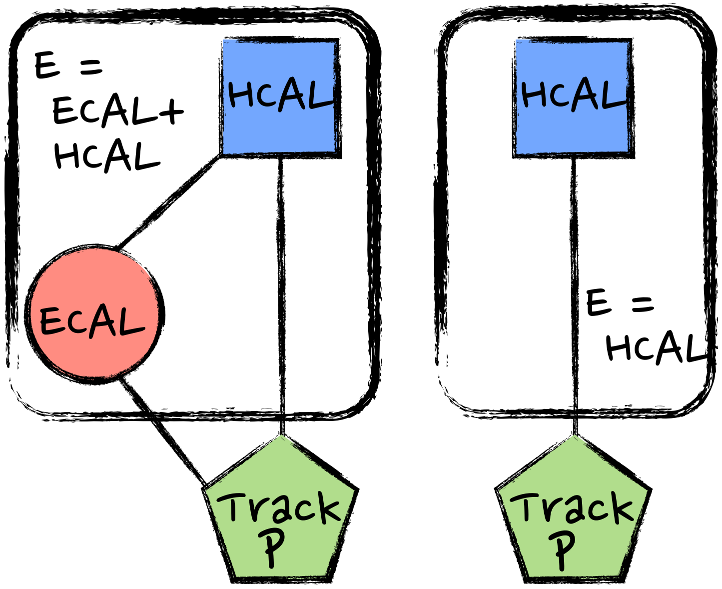

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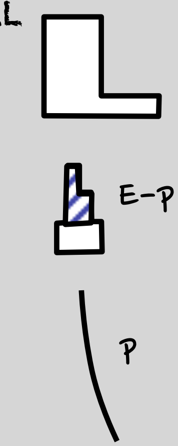

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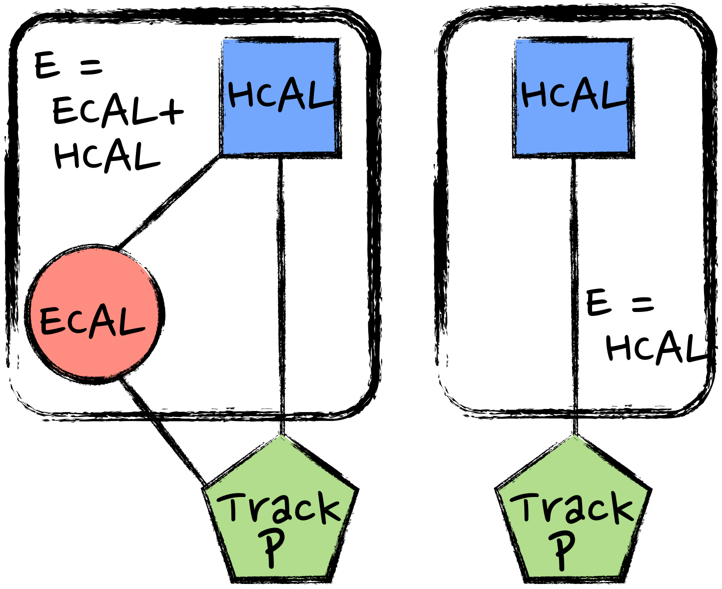

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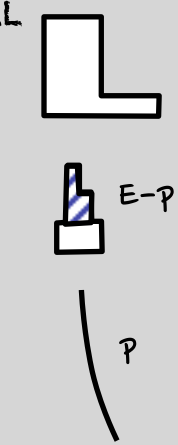

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Always give precedence to photons in ECAL

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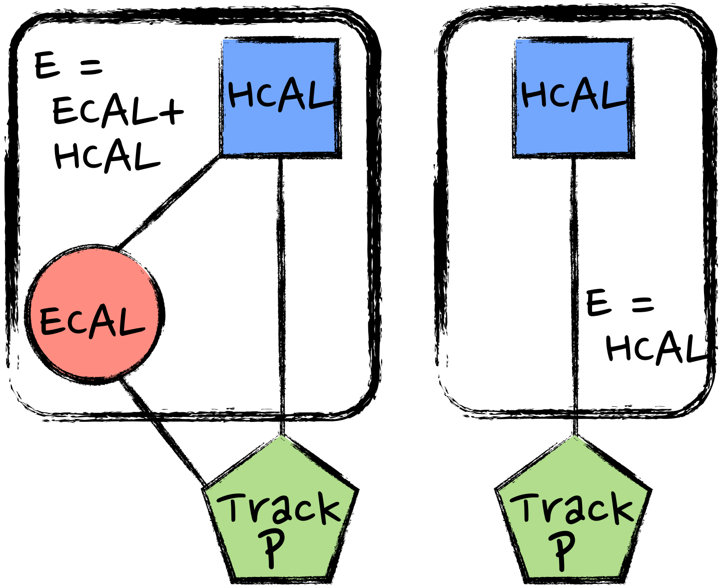

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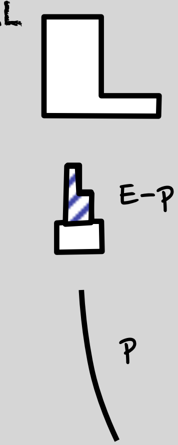

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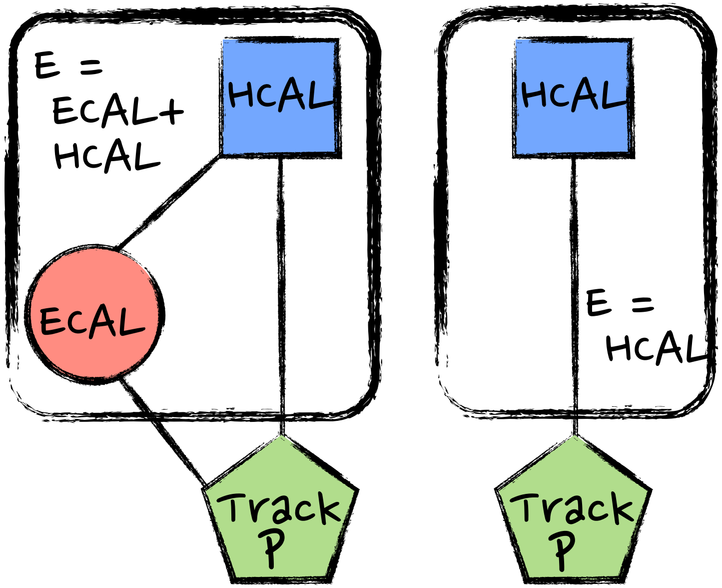

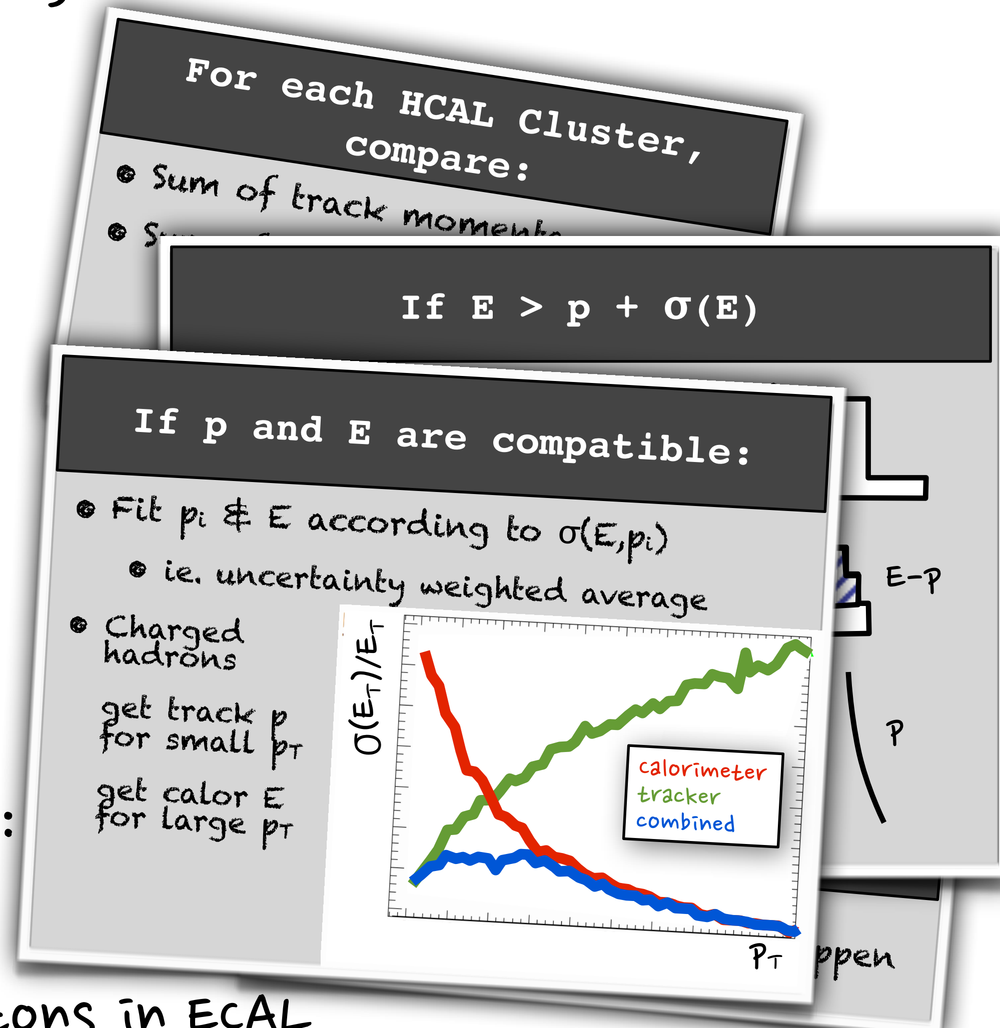

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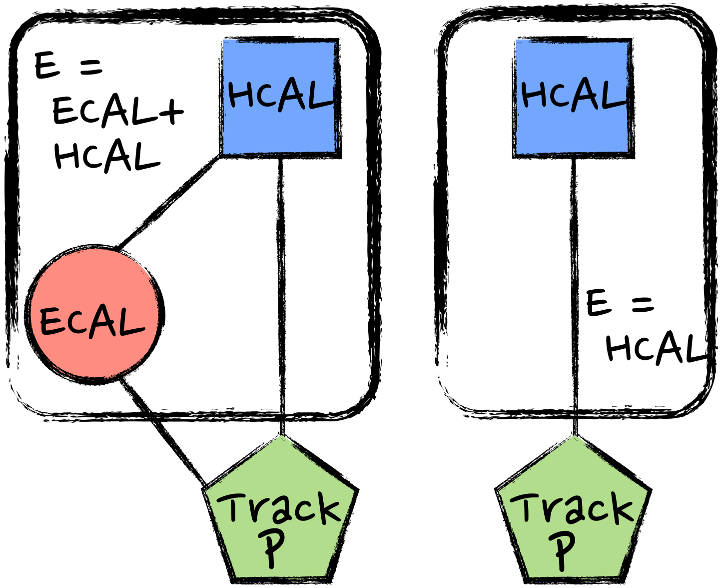

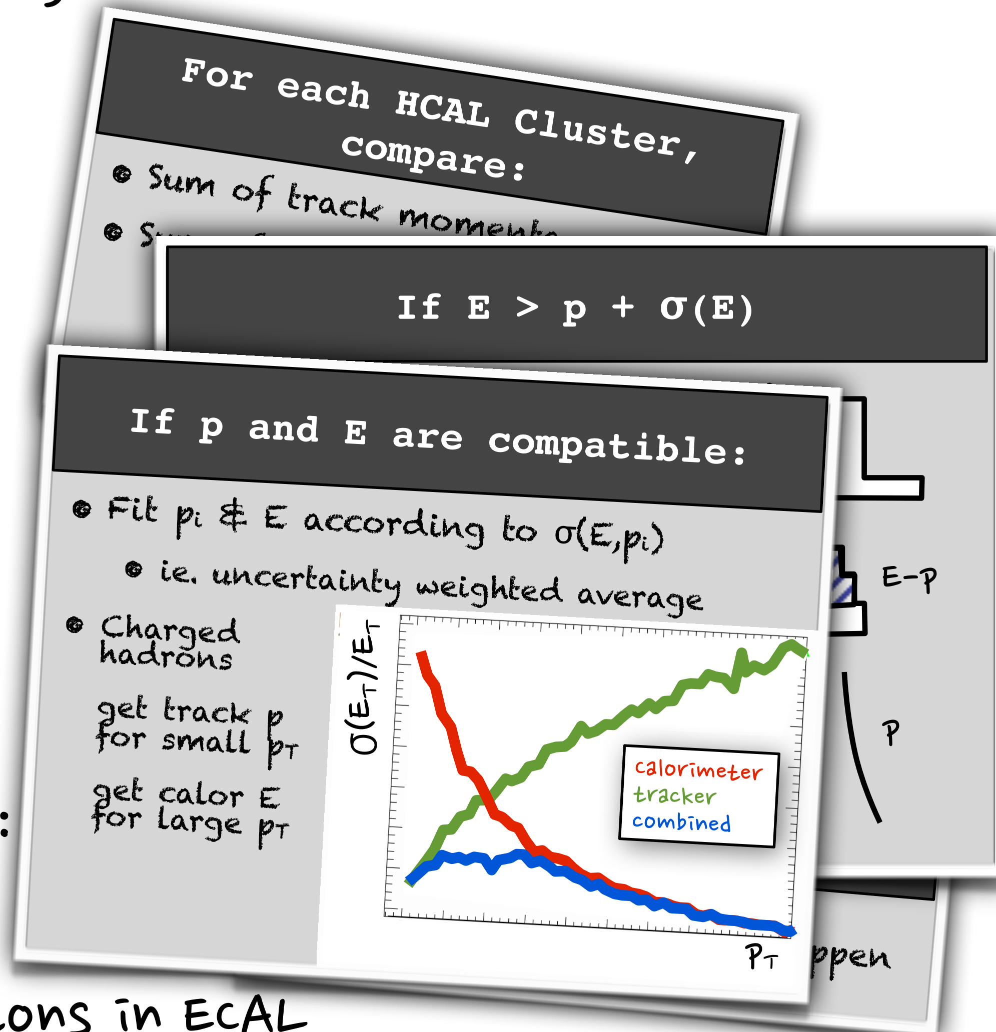

List of reconstructed particles:

{ γ, γ, γ, π−, π+ }

Always give precedence to photons in ECAL

In this Simple Example

In this Simple Example

- **Four particles generated : π+, π−, π0, and K_L^0**

In this Simple Example

- **Four particles generated : $\pi+$, $\pi-$, $\pi0$, and K_L^0**
- **Five particles reconstructed :**

R. Cavanaugh, HCPSS 2012

In this Simple Example

- **Four particles generated : π+, π–, π0, and K_L^0**
- **Five particles reconstructed :**
  - two oppositely-charged hadrons (π+ and π–)

In this Simple Example

- Four particles generated : $\pi+$, $\pi-$, $\pi0$, and K_L^0
- Five particles reconstructed :
  - two oppositely-charged hadrons ($\pi+$ and $\pi-$)
  - three photons

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- **Four particles generated : $\pi+$, $\pi-$, $\pi0$, and K_L^0**
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  - no neutral hadron

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- **Four particles generated : $\pi+$, $\pi-$, $\pi0$, and K_L^0**
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  - two oppositely-charged hadrons ($\pi+$ and $\pi-$)
  - three photons
    - two from π^0 decay and one from K_L^0 energy deposit
  - no neutral hadron
    - because for each of the two tracks, E compatible with p

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R. Cavanaugh, HCPSS 2012

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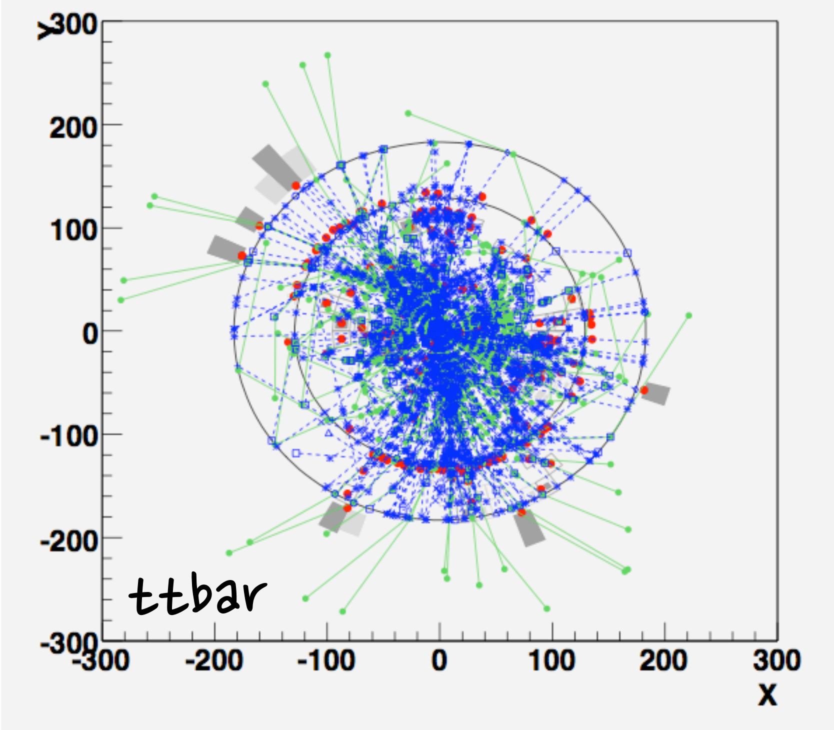

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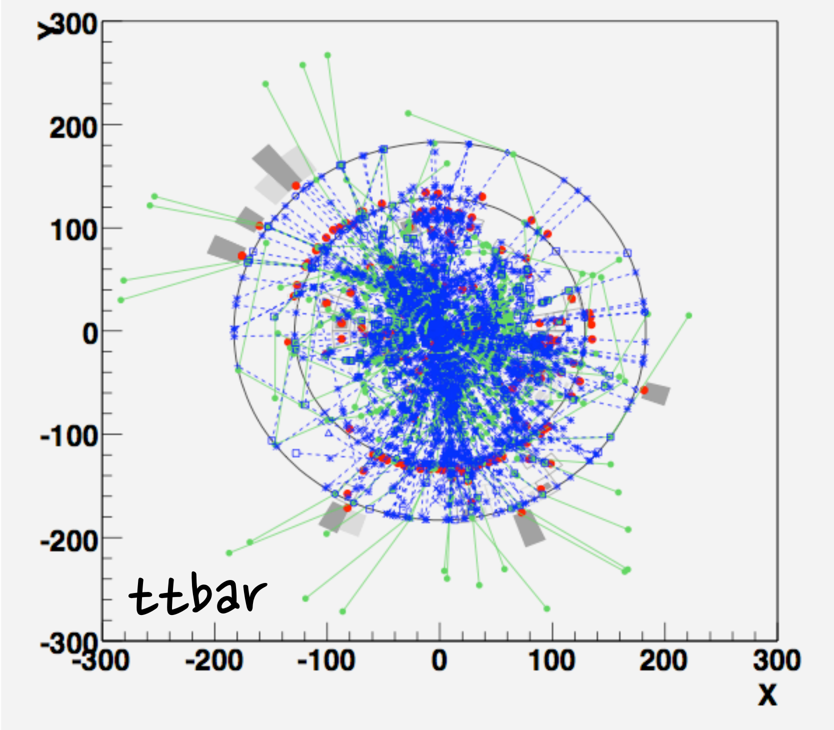

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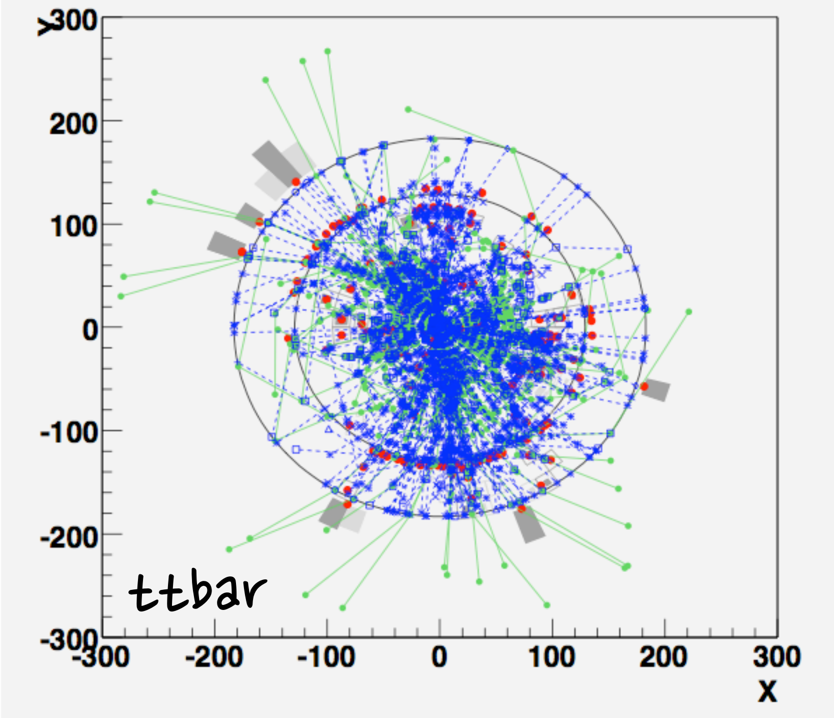

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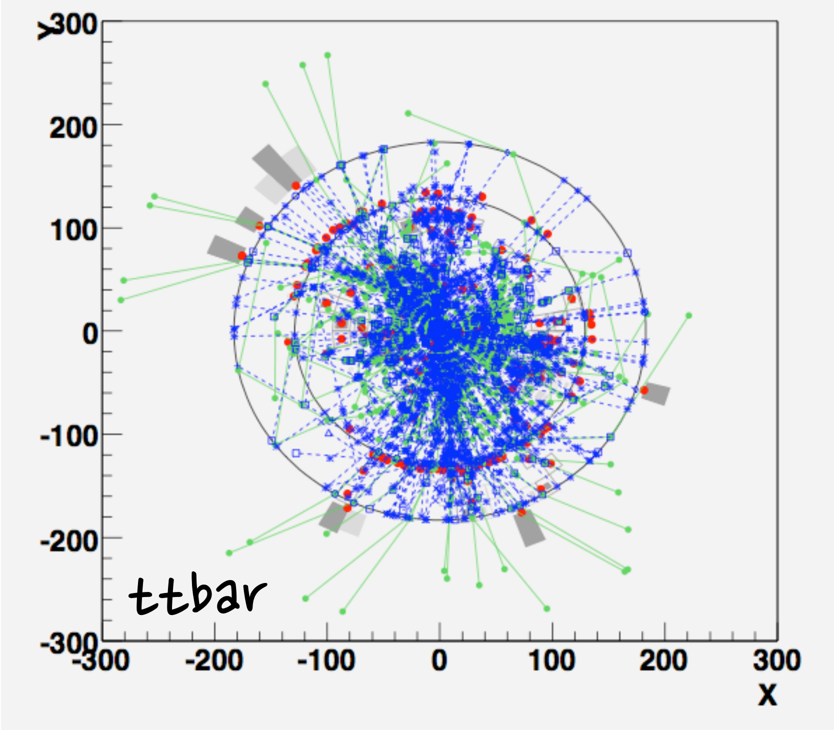

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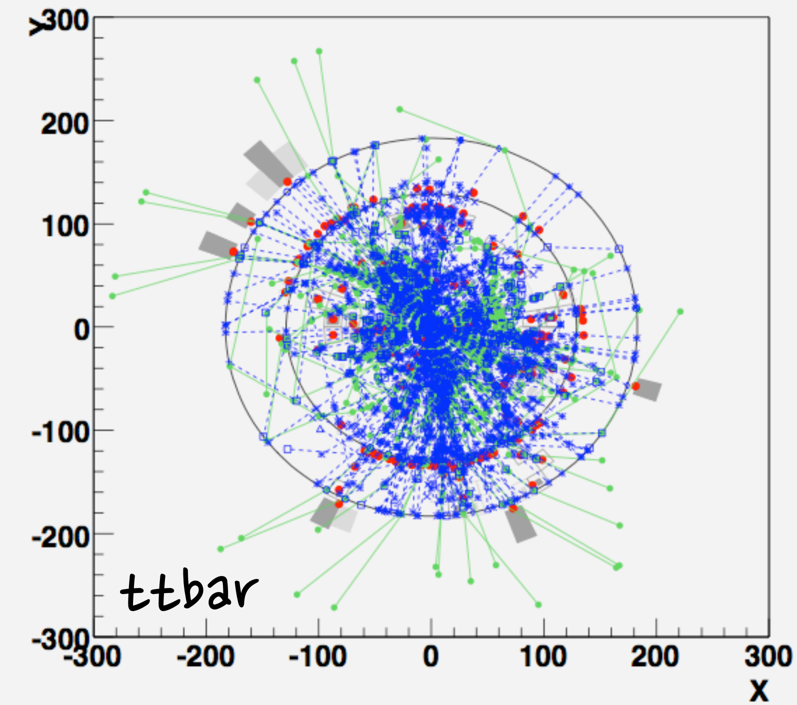

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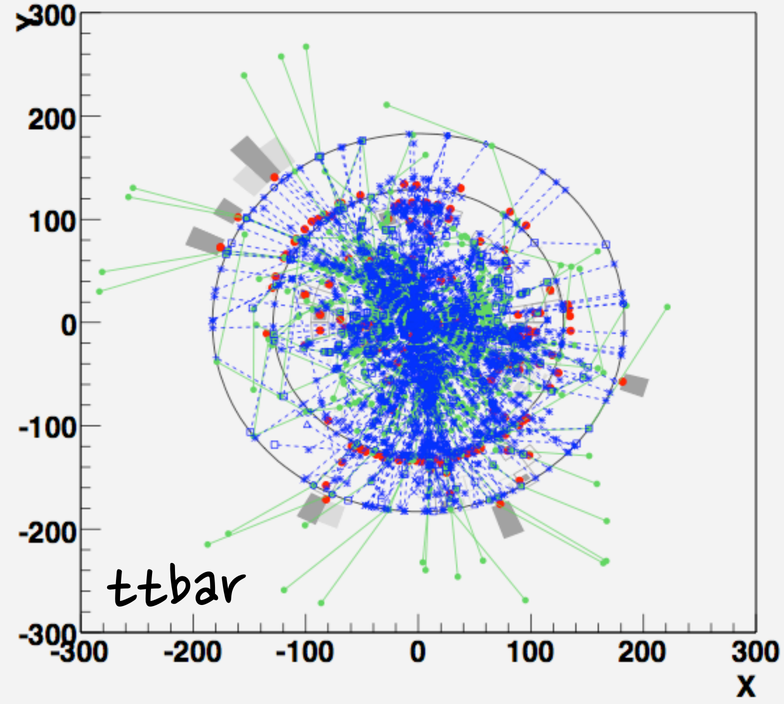

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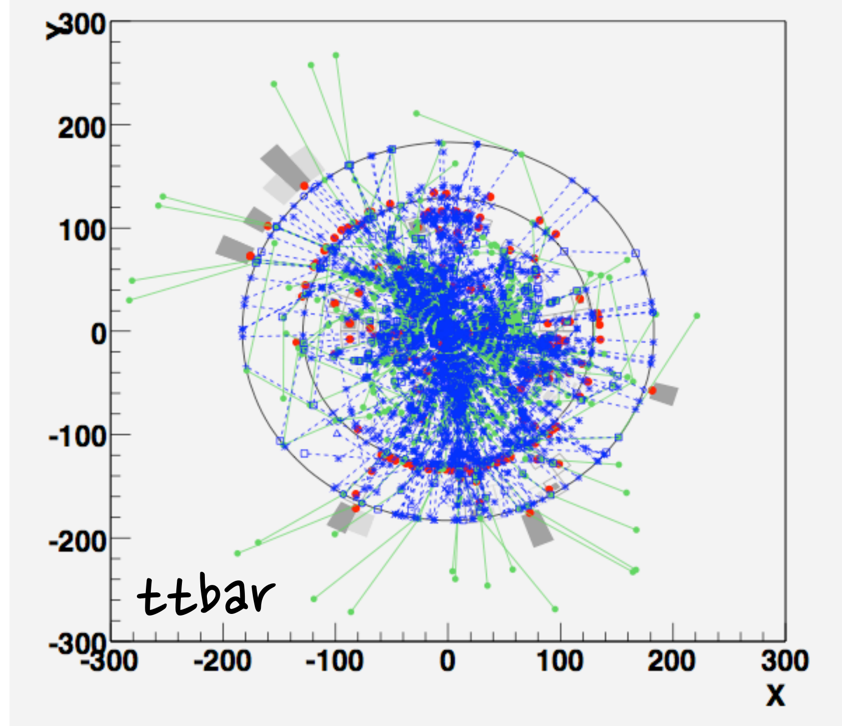

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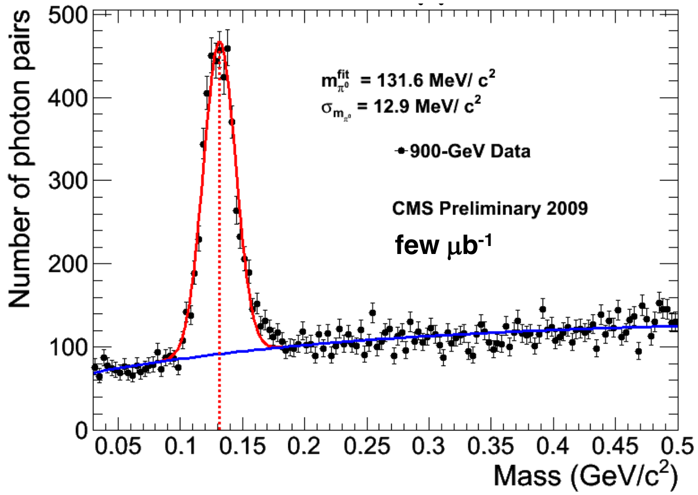

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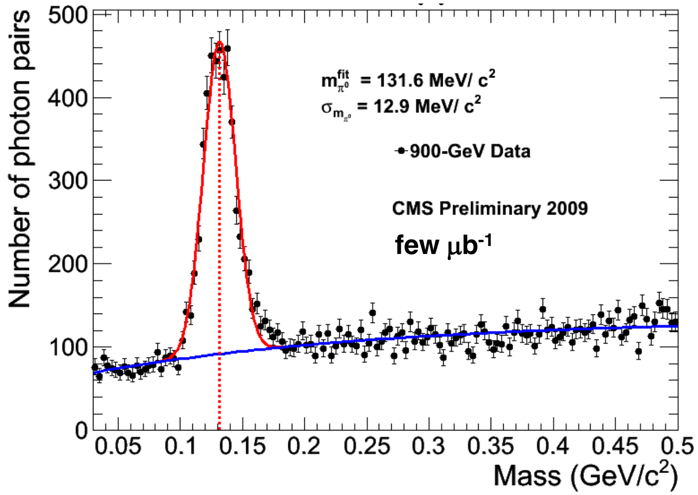

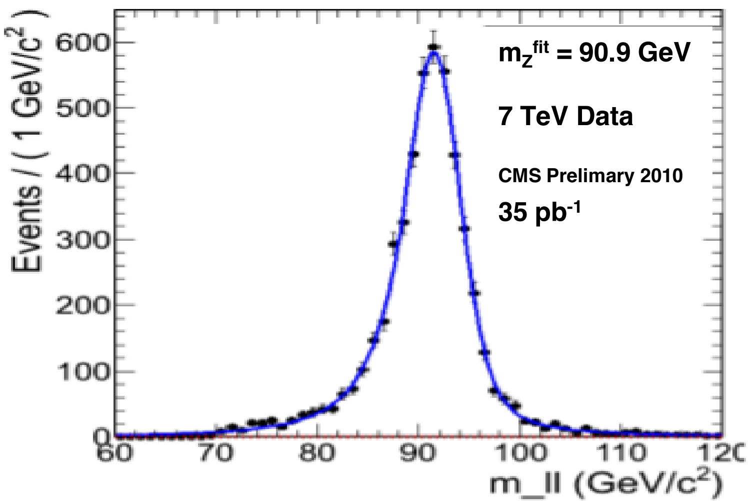

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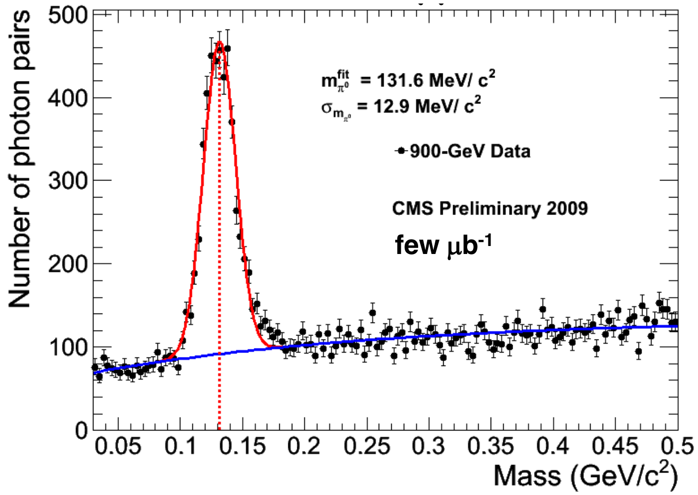

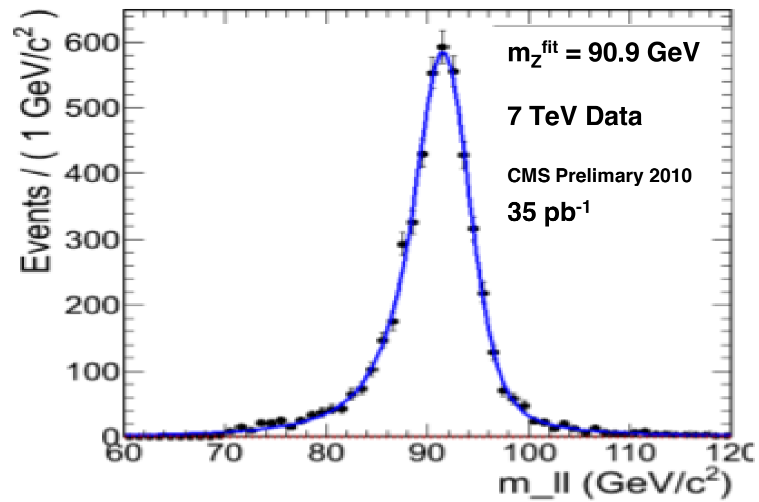

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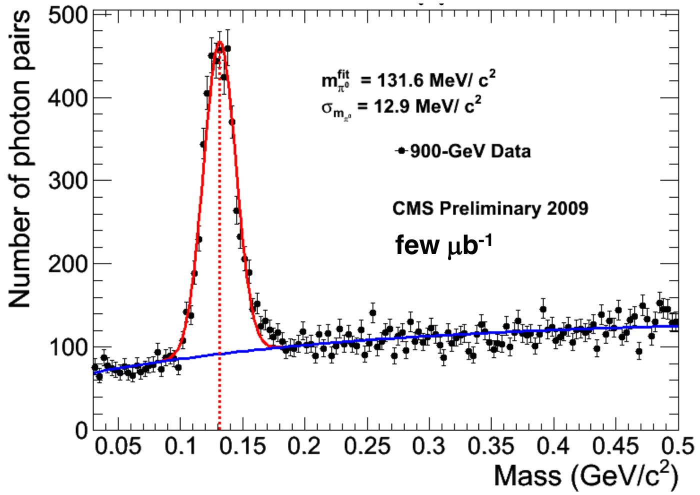

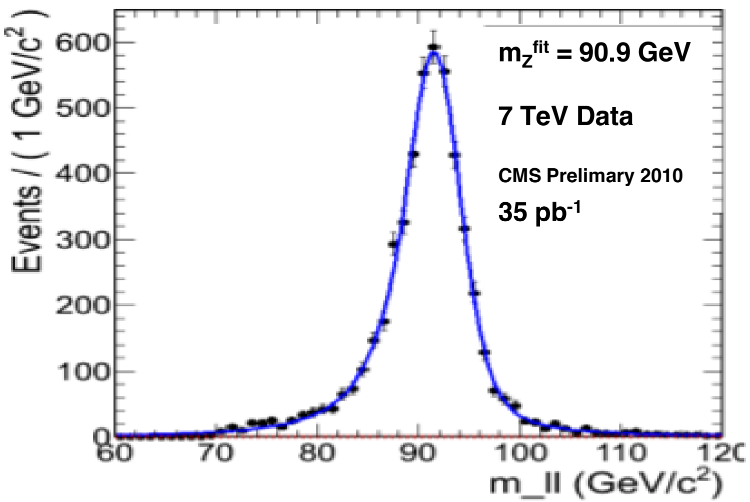

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Fermilab
UIC University of Illinois at Chicago

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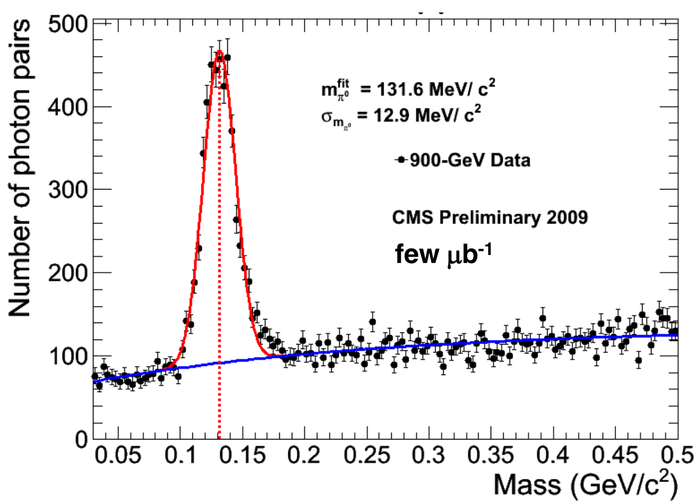

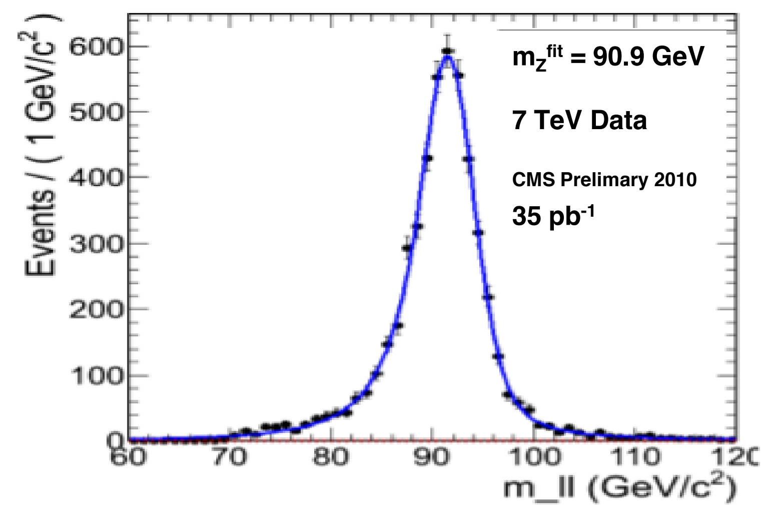

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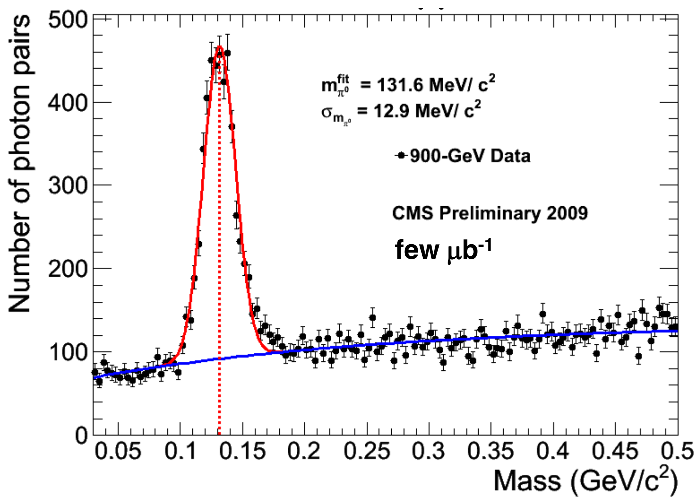

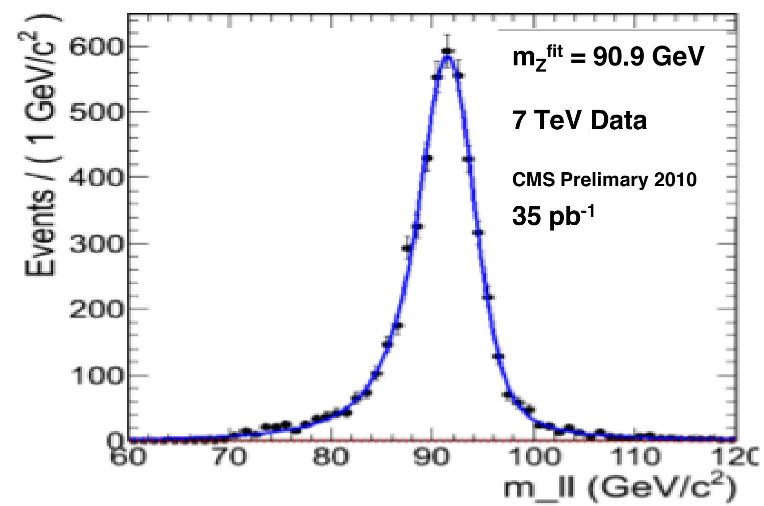

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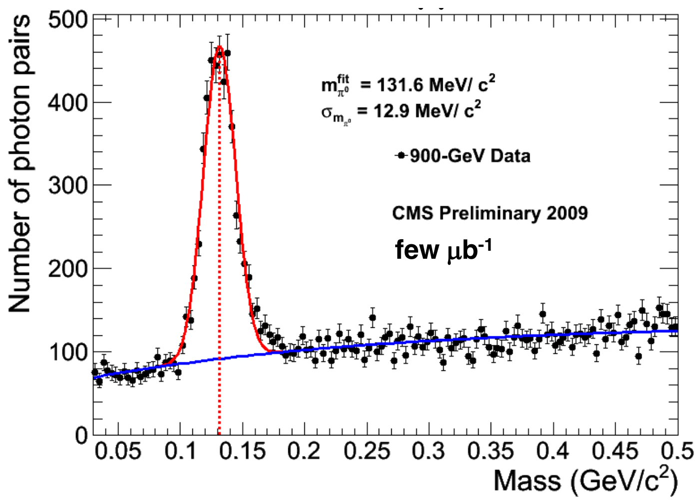

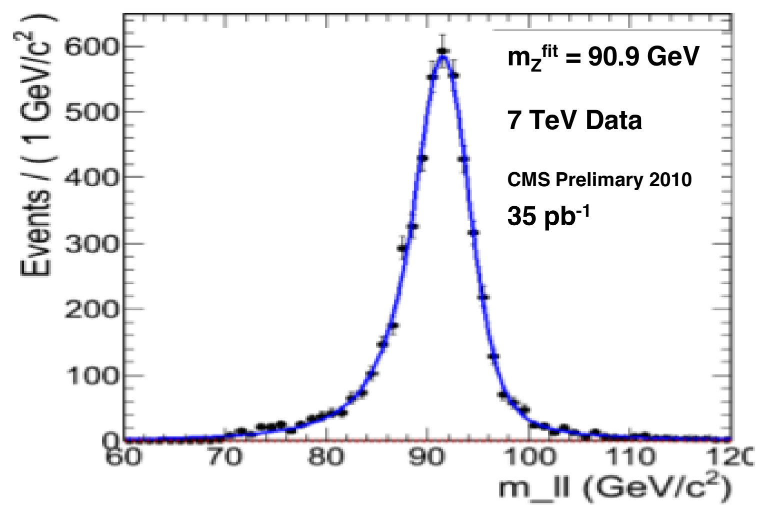

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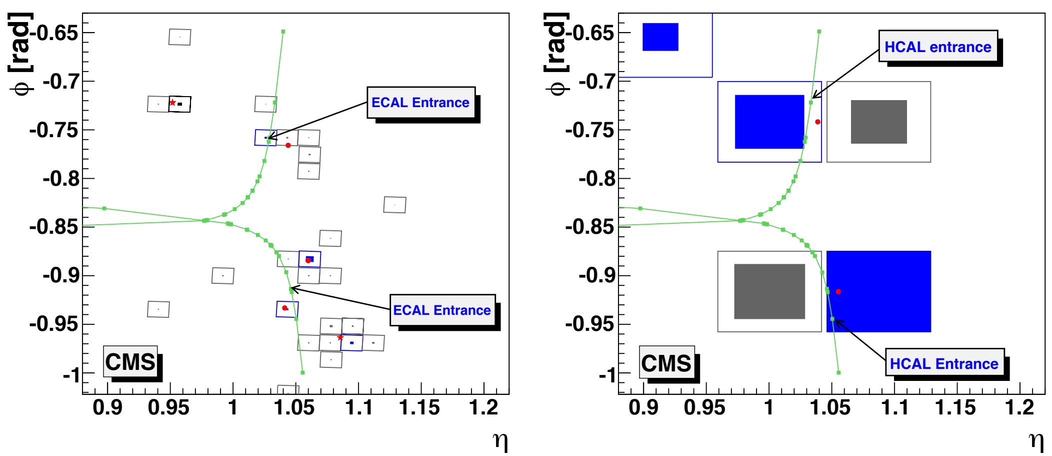

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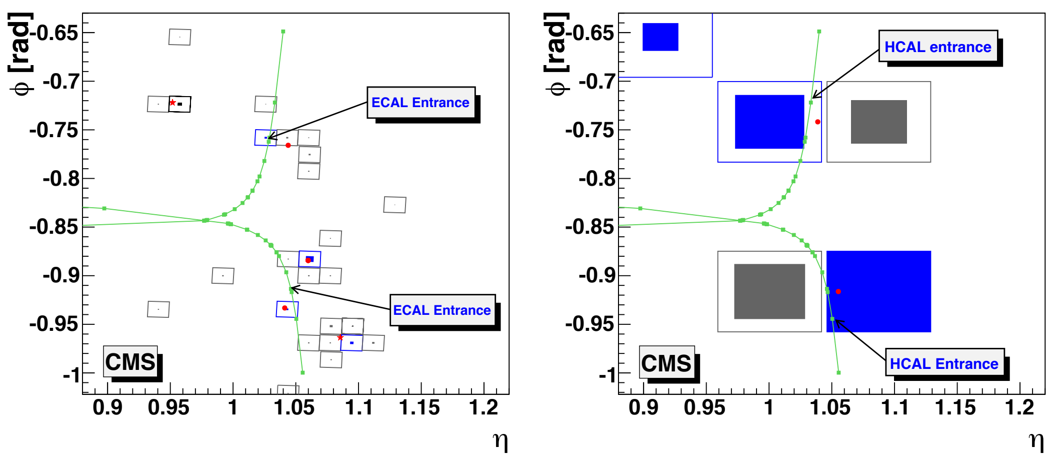

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Fermilab
UIC University of Illinois at Chicago

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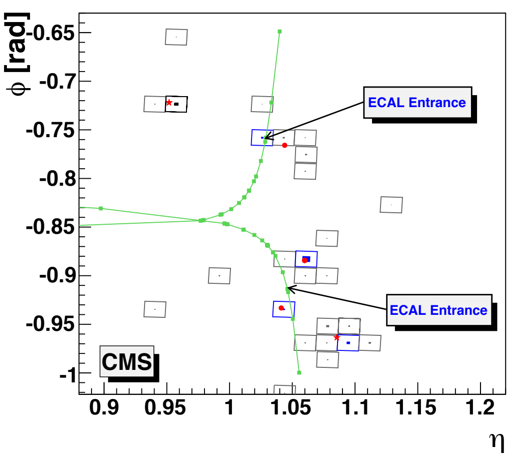

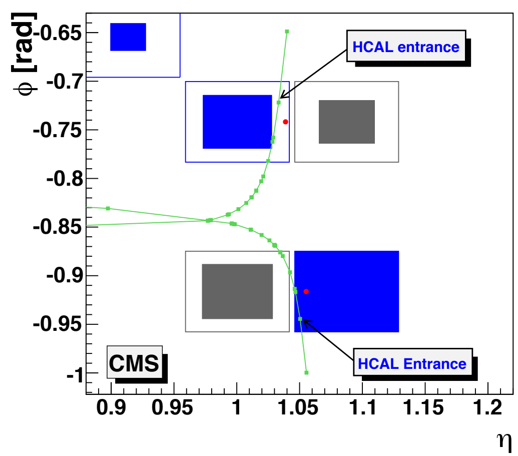

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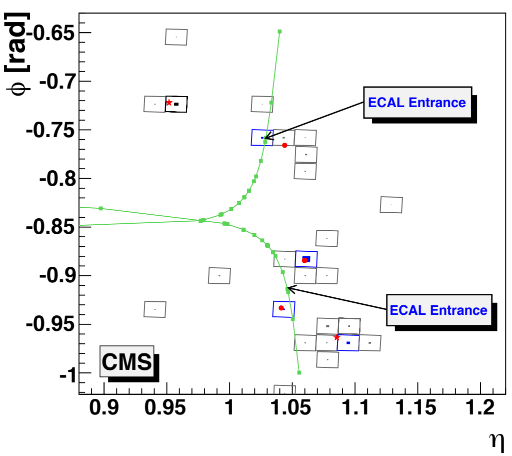
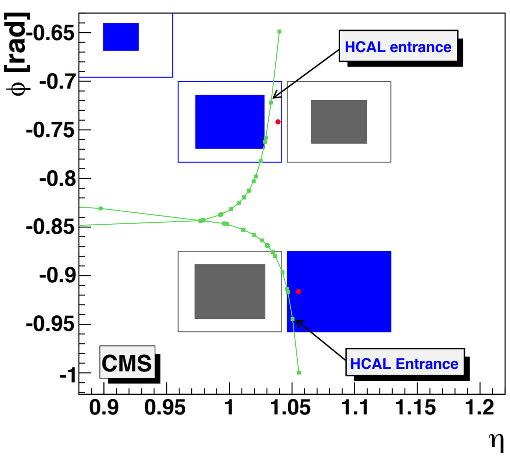
Granularity helps!





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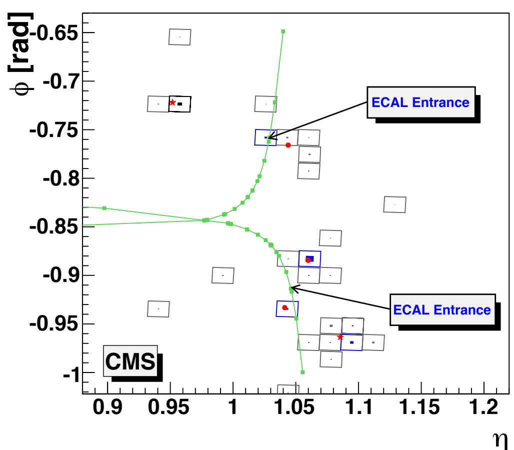

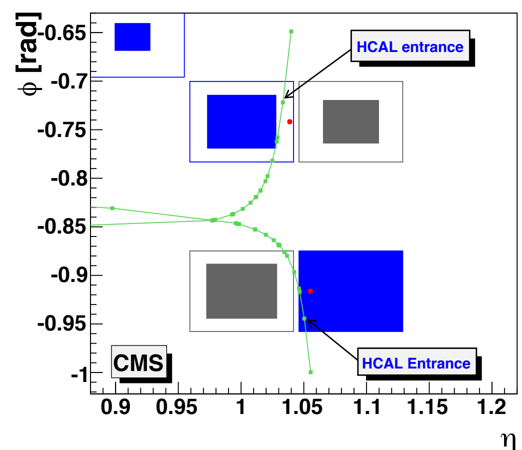

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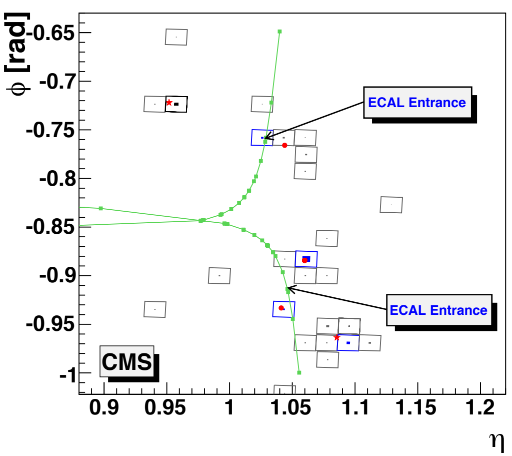

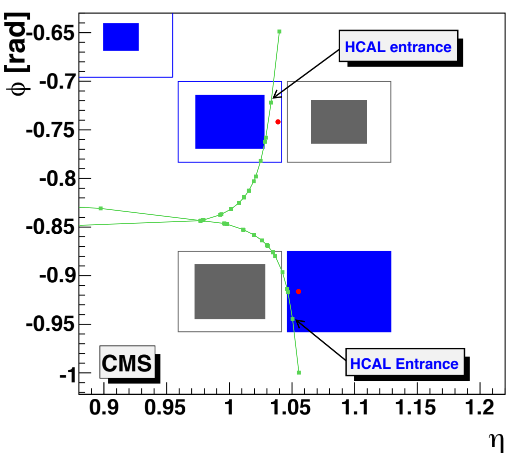

R. Cavanaugh, HCPSS 2012

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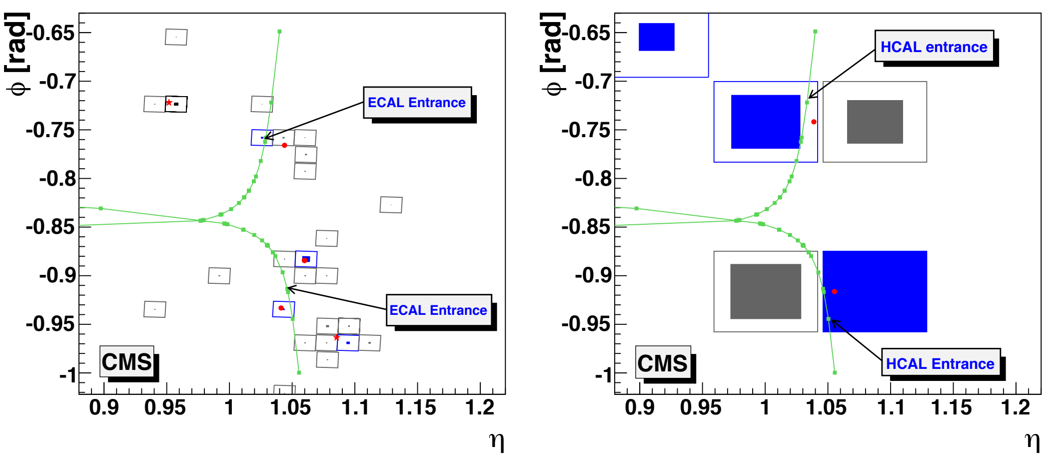
    - as function of p

Granularity helps!



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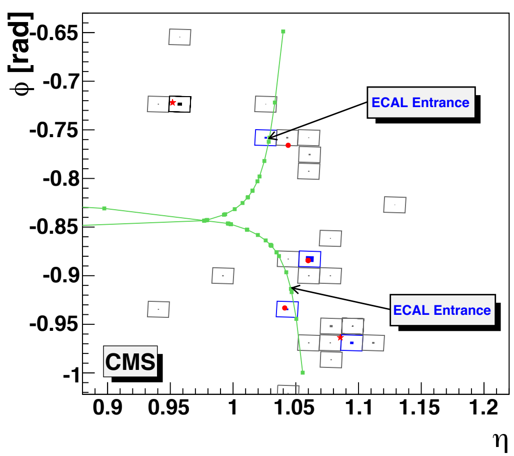

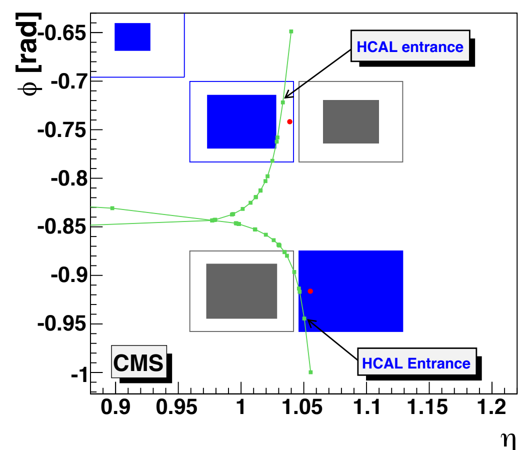

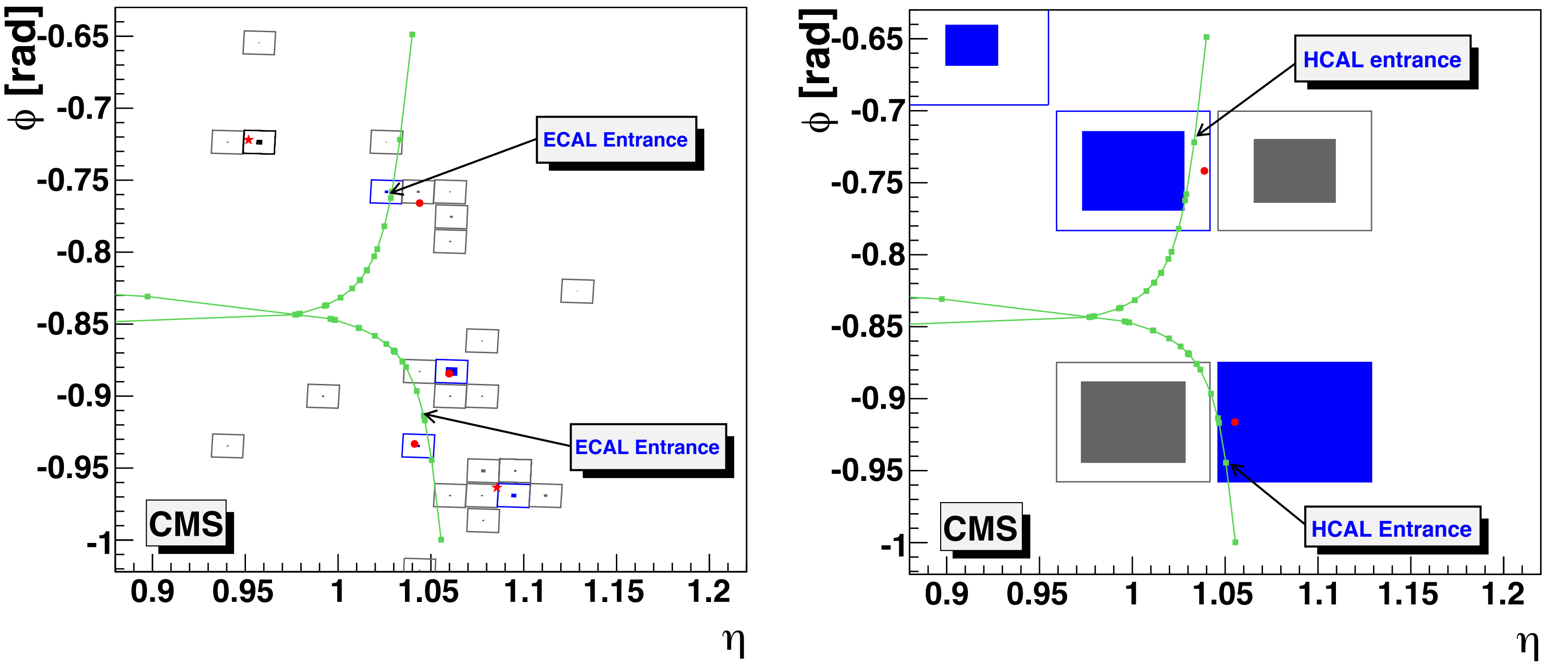

- **Track pointing "downwards"**
  - p = 14.64 GeV, ECAL = 1.87 GeV, HCAL = 7.35 GeV, E_{calib} = 14.33 GeV
- **Track pointing "upwards"**
  - p = 10.94 GeV, ECAL = 0.98 GeV, HCAL = 6.77 GeV, E_{calib} = 9.19 GeV
- **Gives 2 charged hadrons of 14.64 GeV & 10.94 GeV in the particle list**

Summary & Outlook

- OK...I'll stop here for today
- On Thursday, we will consider the case E << p
- We have a list of identified particles that provide a global event description of the entire collision
  - charged particles
  - photon candidates
  - neutral hadrons
- We need to identify which of those charged particles are:
  - electrons
  - muons
  - charged hadrons
- We also need to identify which of the photon candidates are
  - prompt photons
- More Thursday!