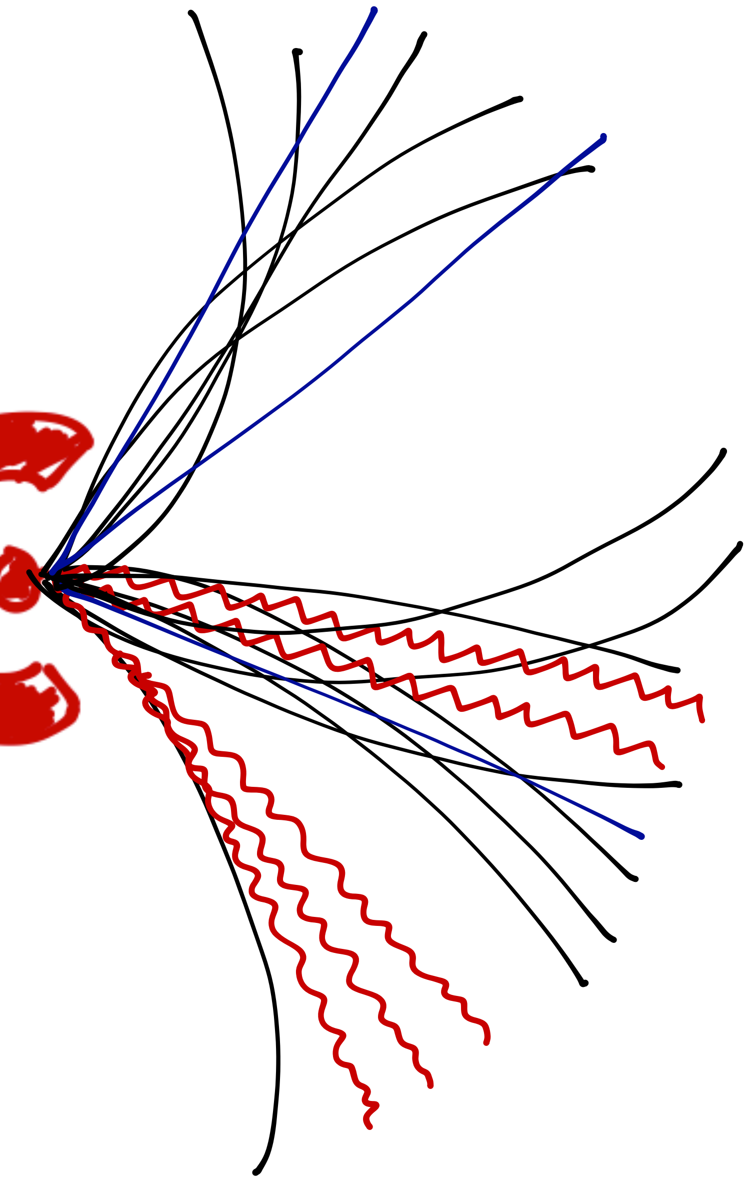
Thoughts on Event Reconstruction & Particle Flow

SLAC

100 TeV Workshop

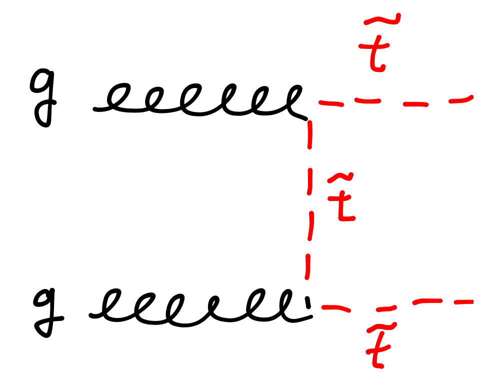


Richard Cavanaugh, UIC/FNAL

SLAC, 23-26 April, 2014

A 100 TeV Machine is a Discovery Machine

We want to discover new particles with it!



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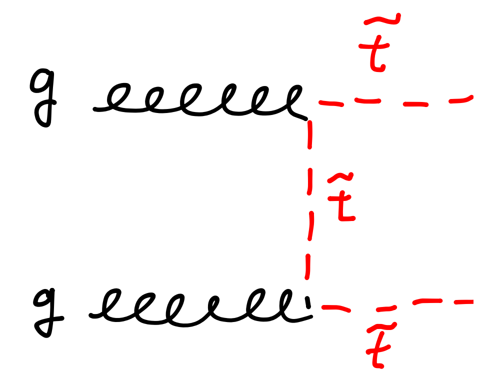

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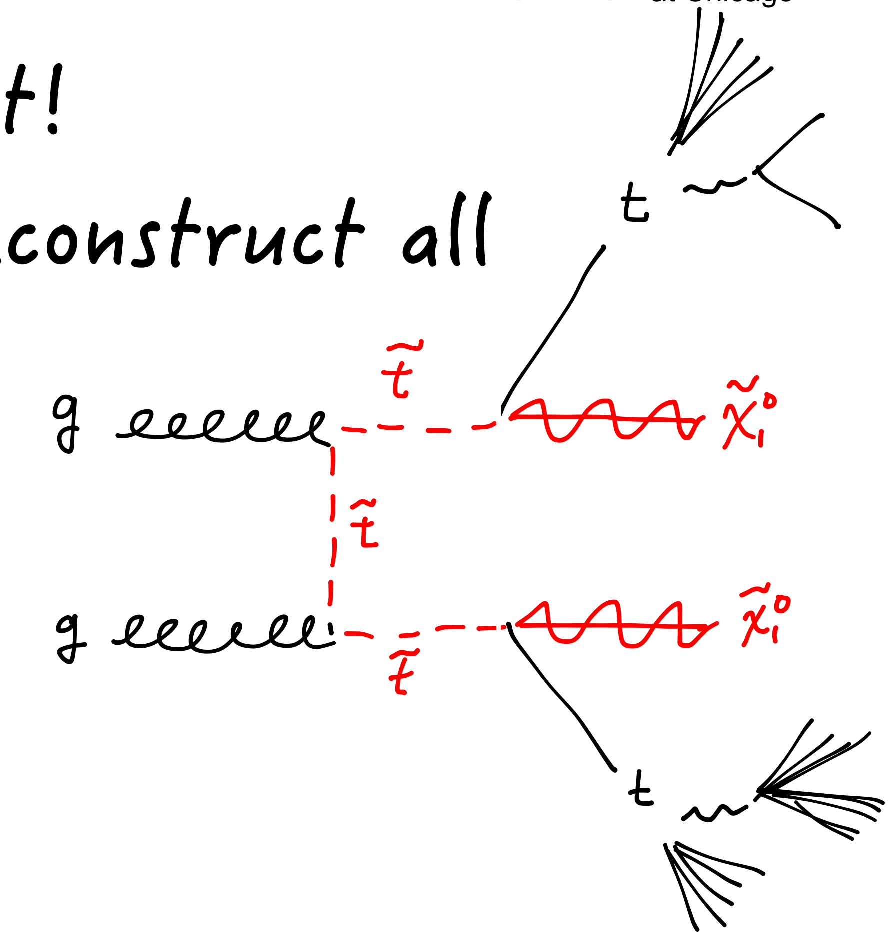

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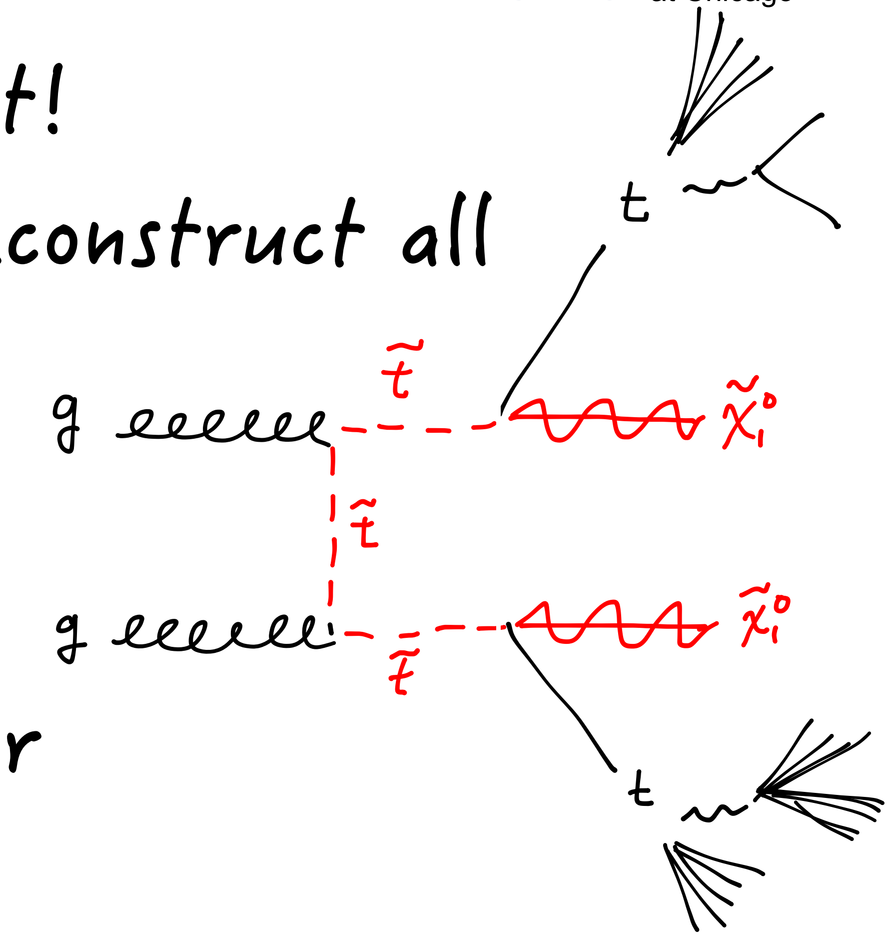

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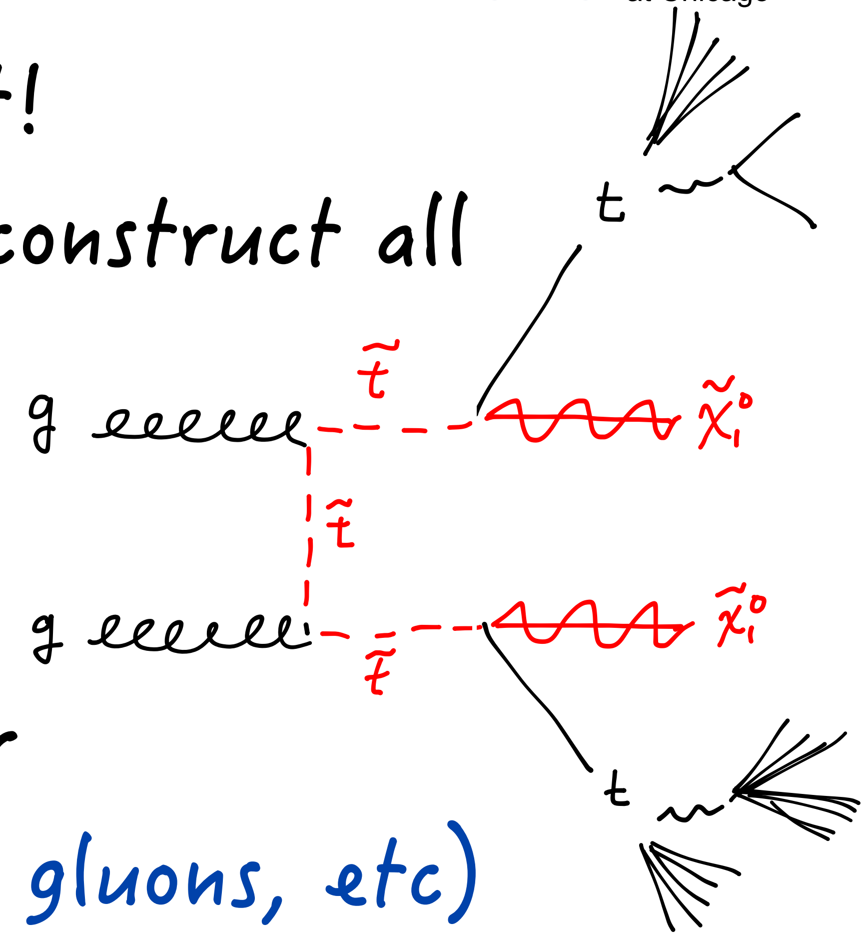

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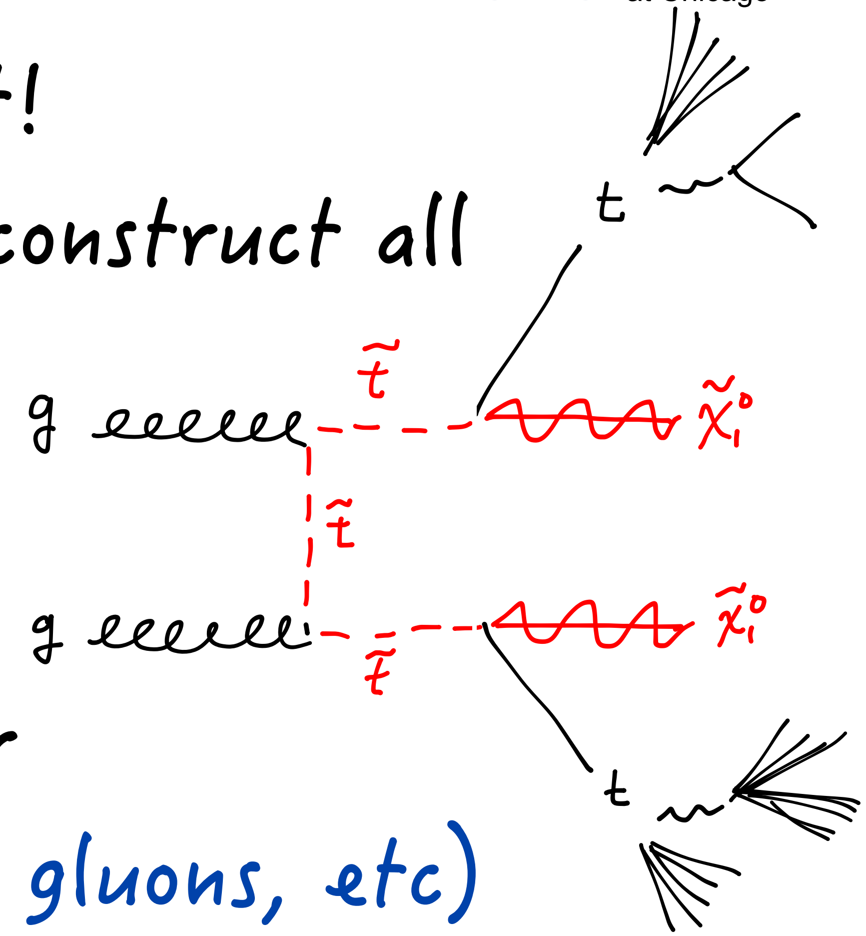

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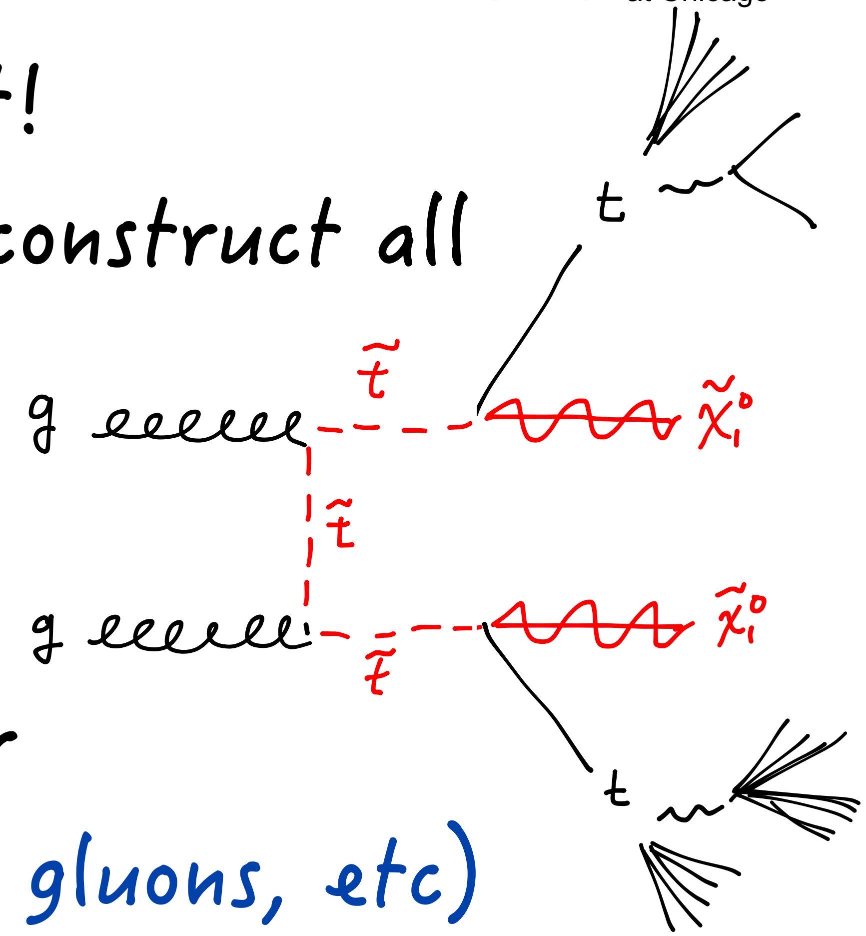

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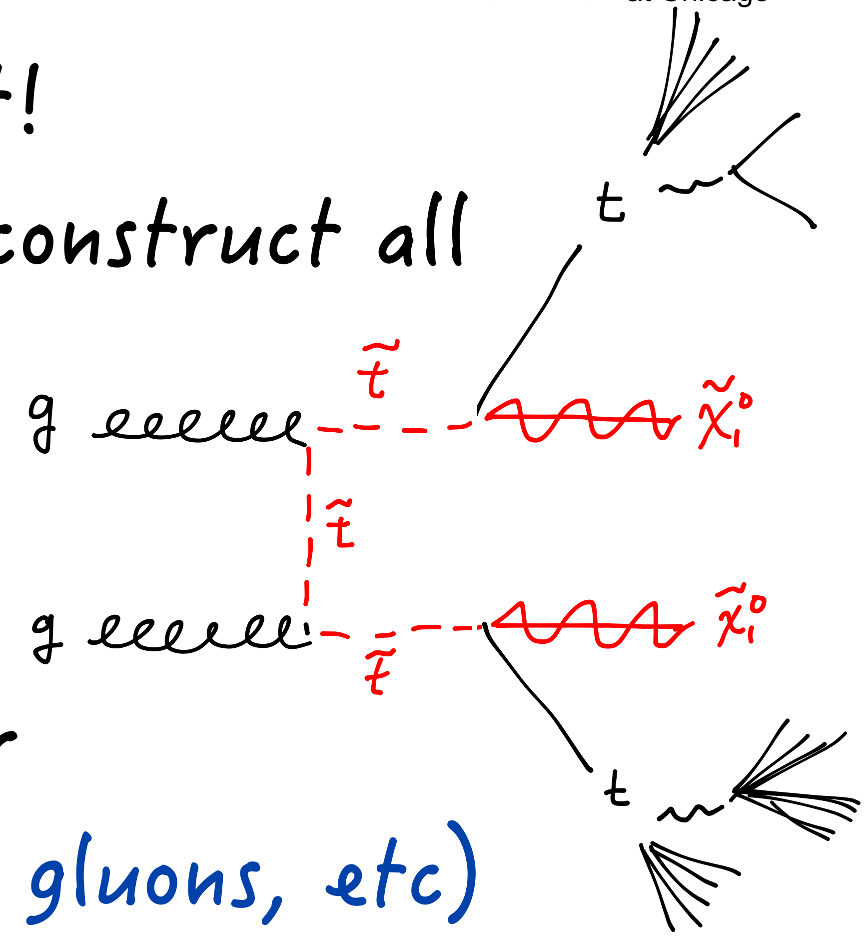

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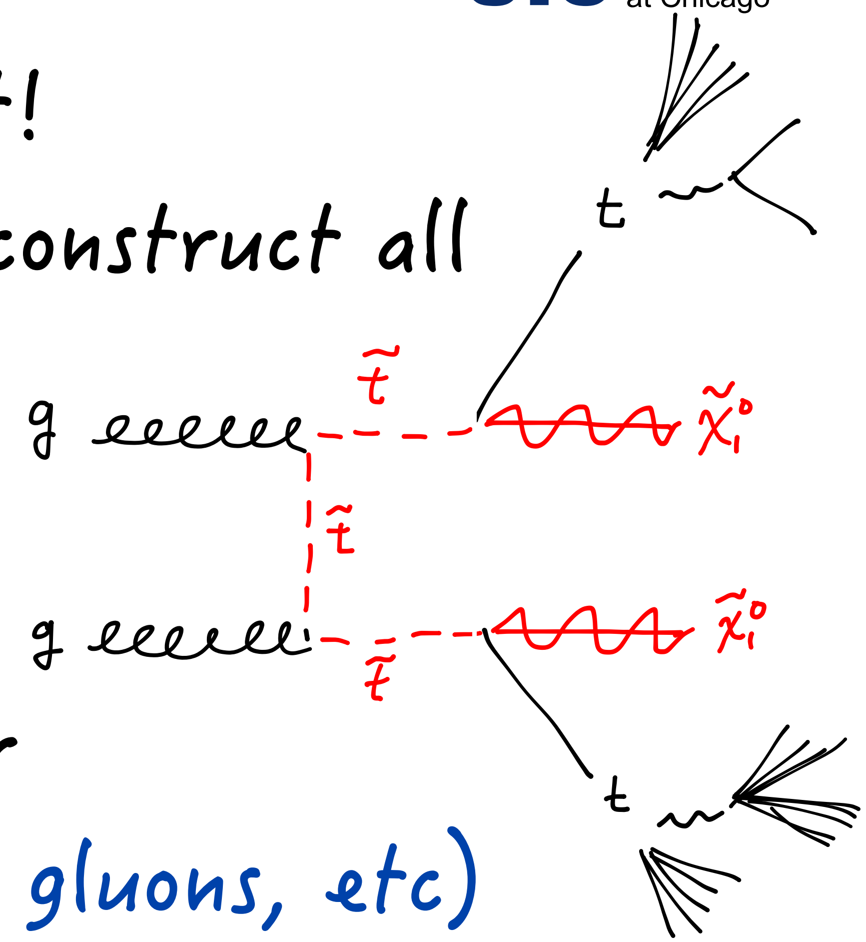

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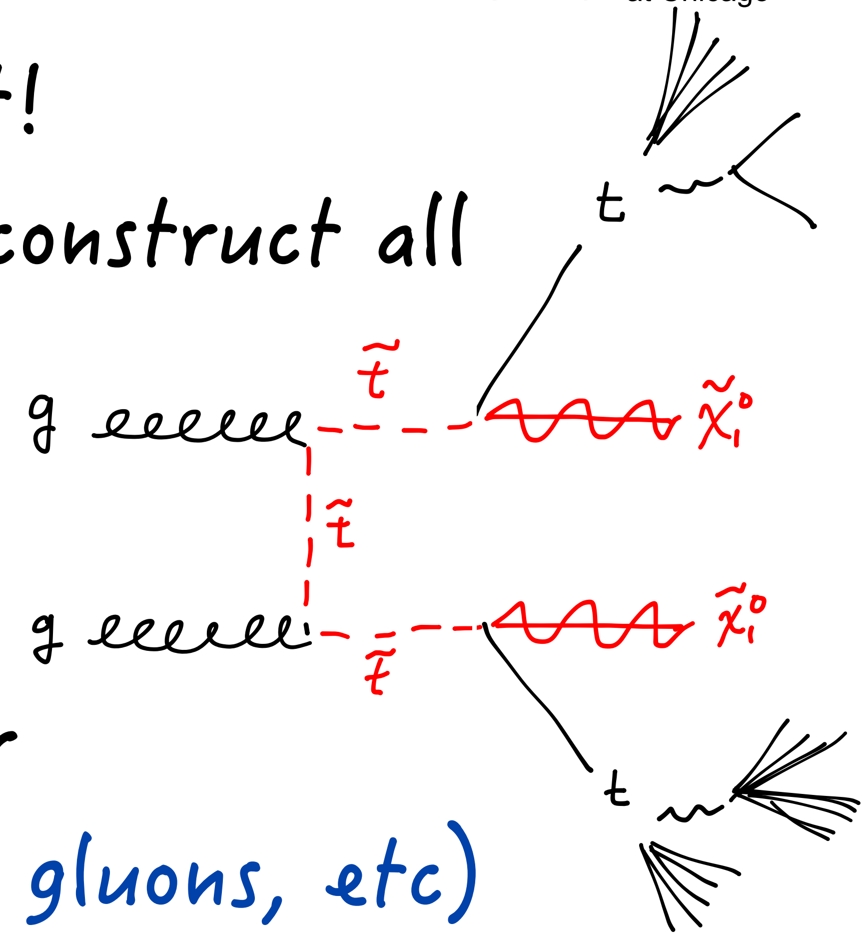

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Caveat: This talk is a simply a compilation of my own + other people's thoughts and ideas.

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Would like to especially thank:

Patrick Janot: Particle Flow originator and slides
Colin Bernet: Fruitful discussions on PF and slides
Sanjay Padhi: Fruitful discussions on 100 TeV
Meenakshi Narain: Fruitful discussions on 100 TeV

Why Particle Flow? A priori vs a posteriori

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      - Reduces (often eliminates) non-compensation effects; jet almost self-calibrated (only small, residual corrections)

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Physics Answers:

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- We know more today, than we did 30 years ago; (Intelligently) lower detector cost for more complex algorithms

Jet Composition at 0.1-10 TeV

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R. Cavanaugh 100 TeV Workshop, SLAC 23-26 August, 2014

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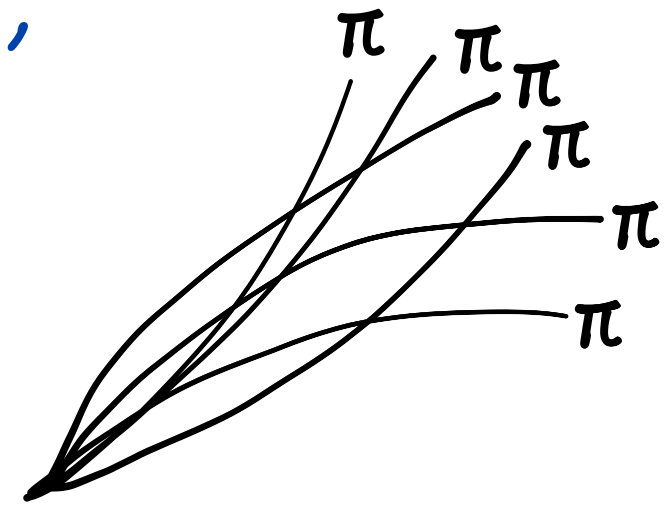
Mostly charged pions, kaons and protons, but also some electrons and muons (decays in flight, semi-lept. B decays)



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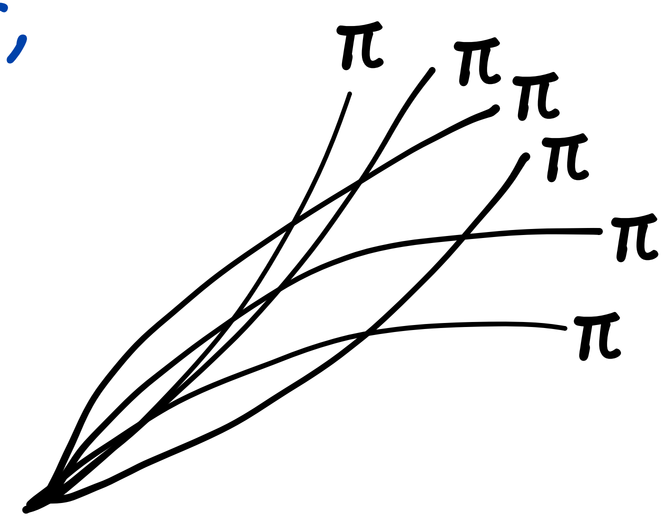

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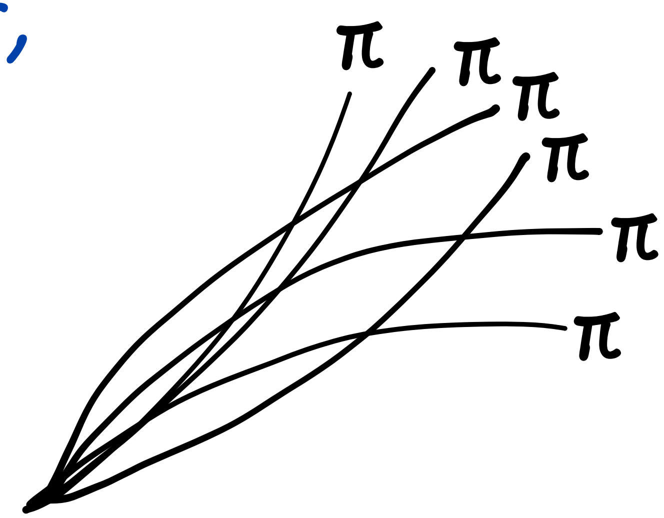

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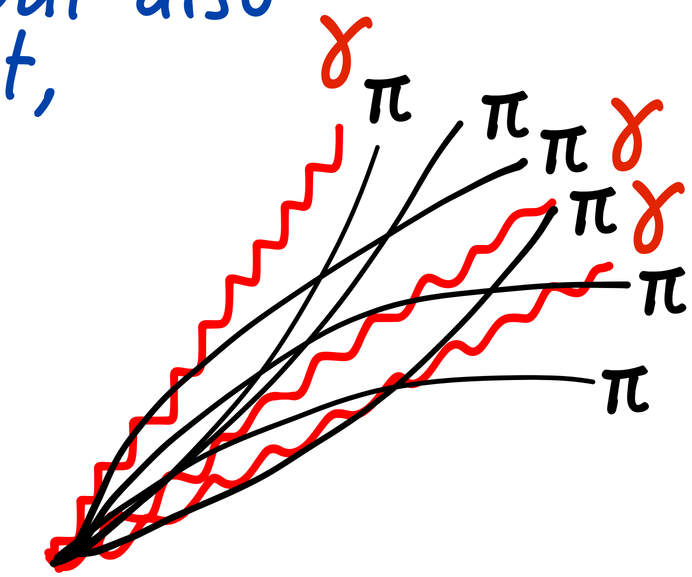

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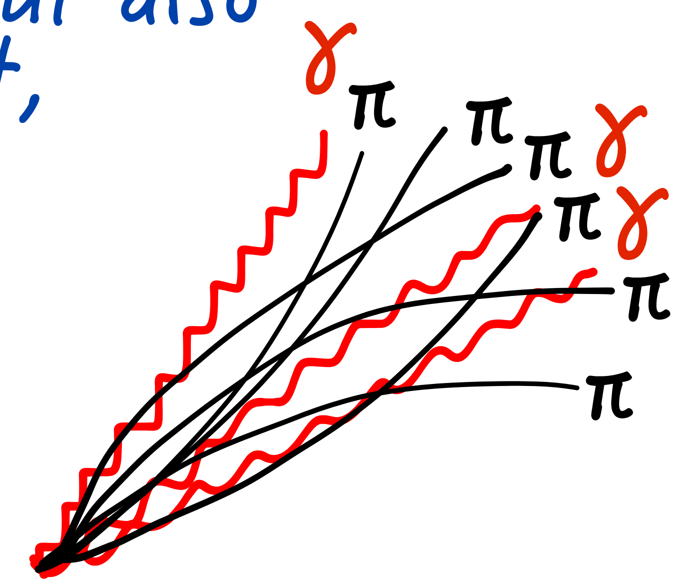

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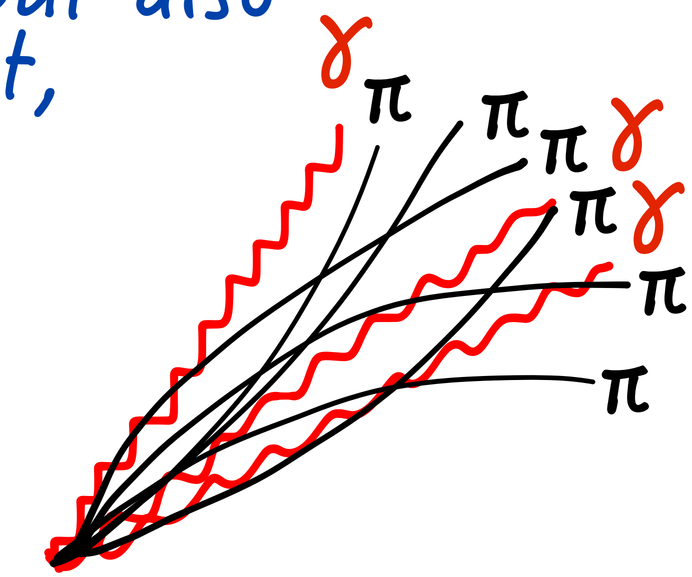

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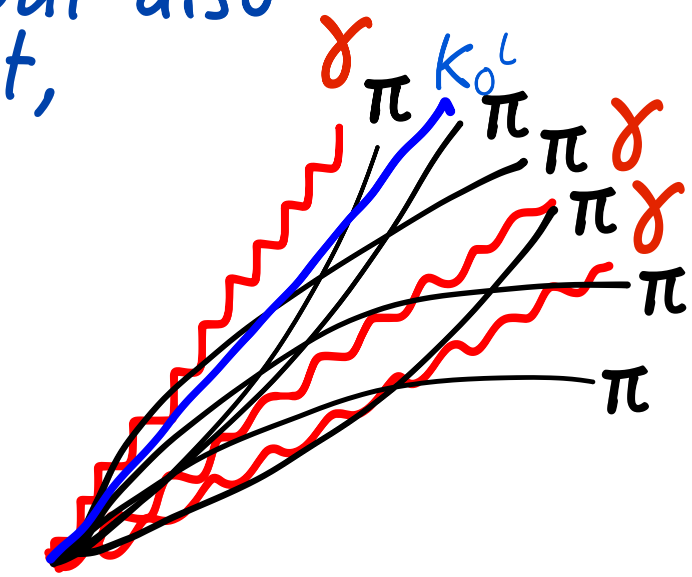

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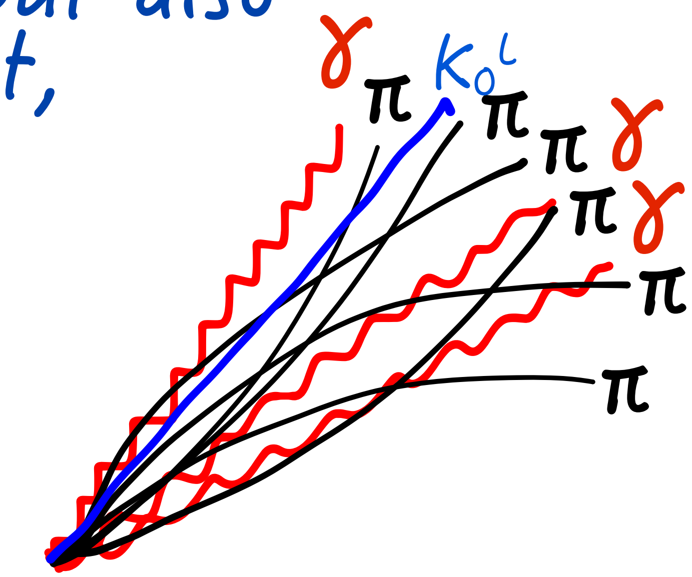

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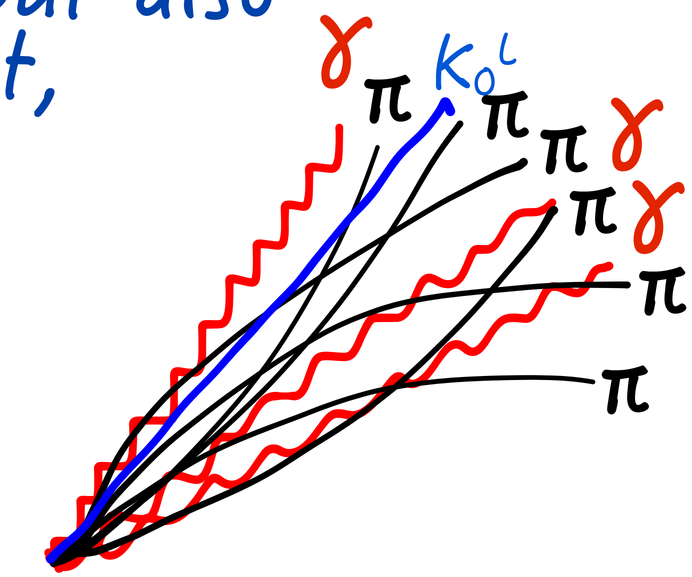

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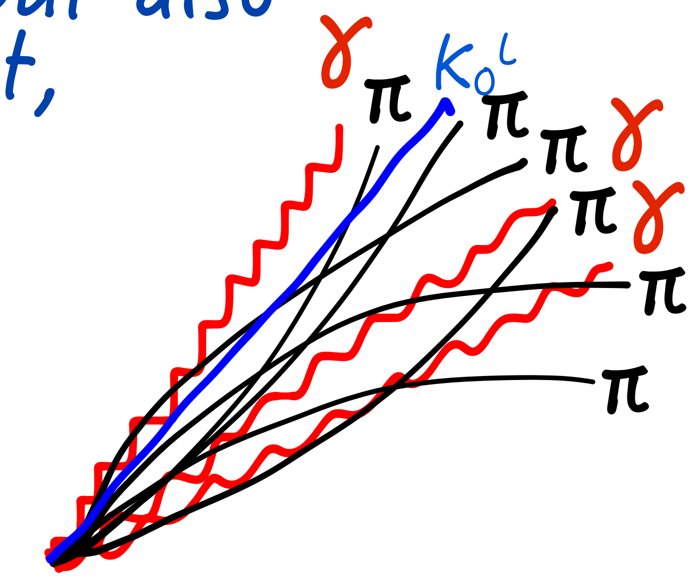

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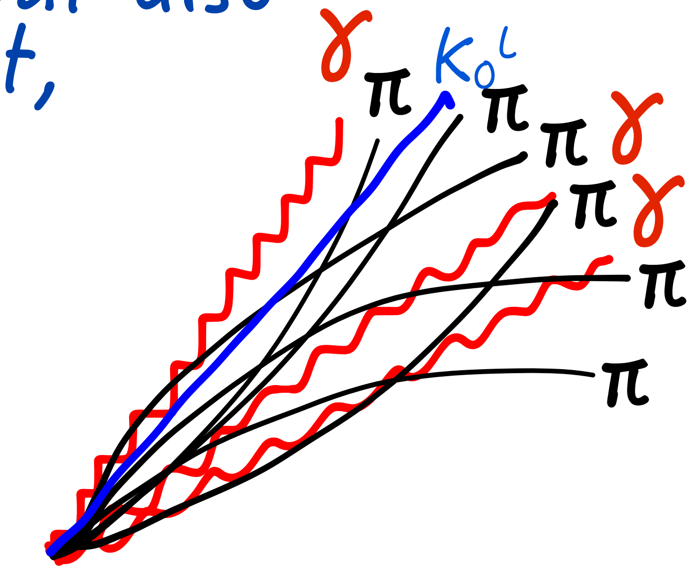

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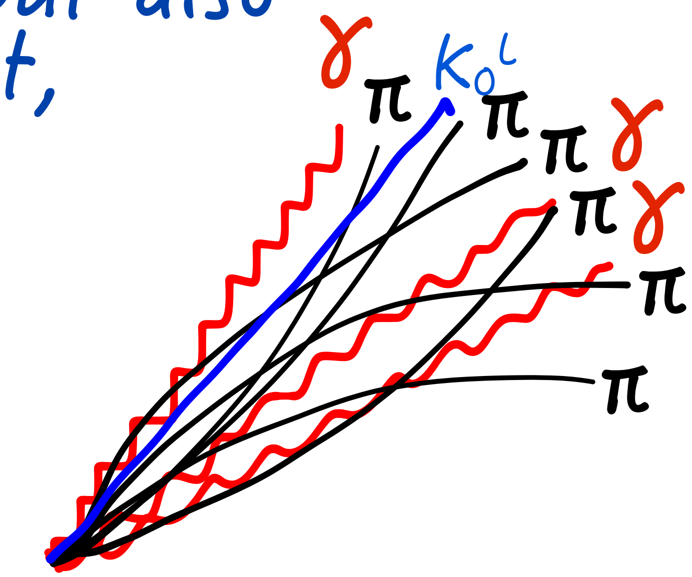

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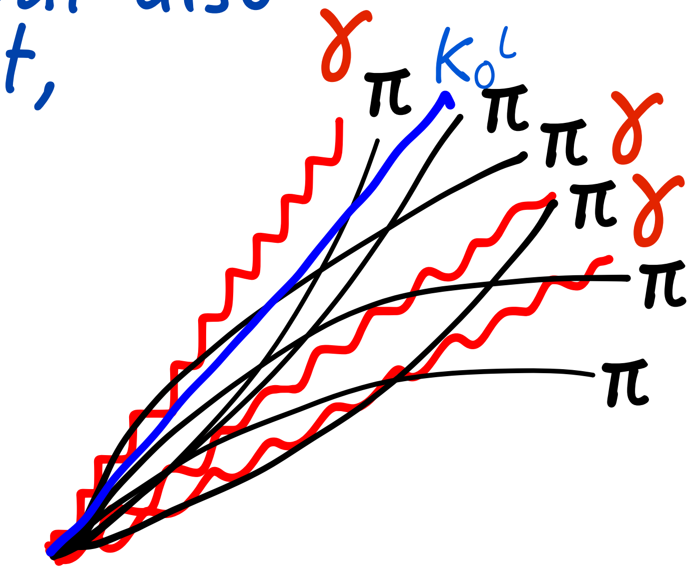

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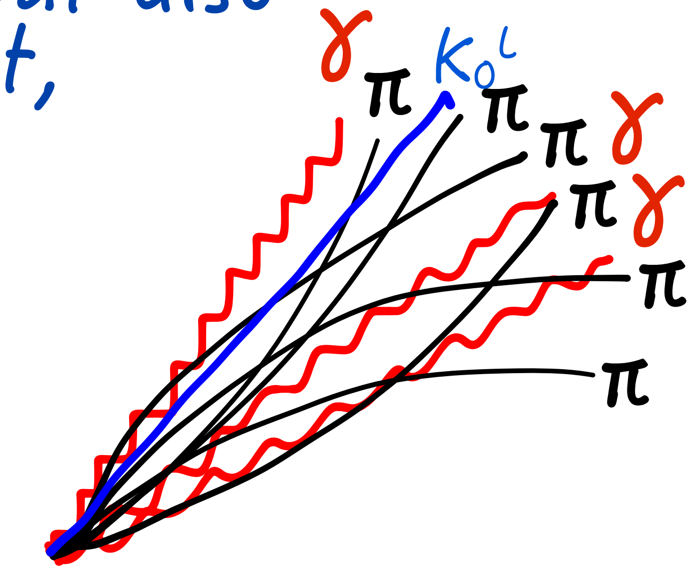

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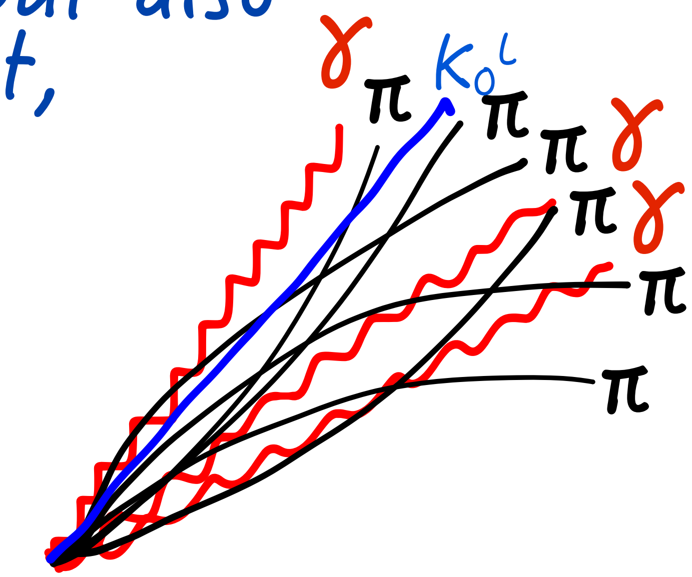

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Short-lived neutral hadrons, "V0's" : ~5%

$K_0^S \to \pi^+\pi^-$, $\Lambda \to \pi^- p$, ···, but also γ conversions, and (more problematic) nuclear interactions in the detector material

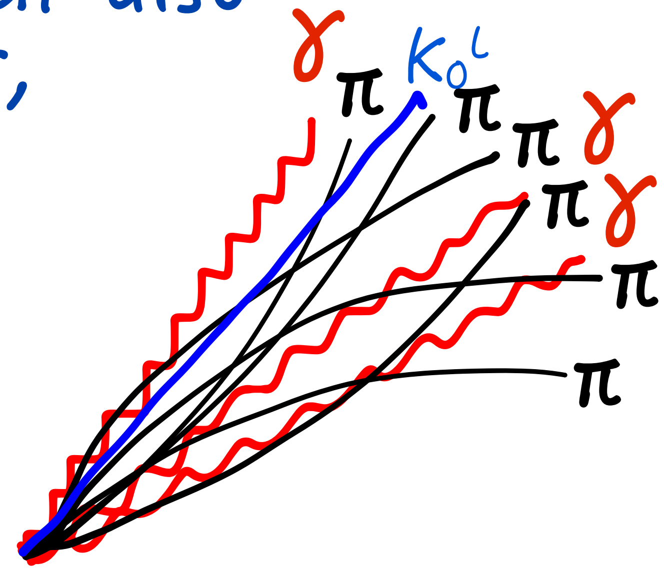
Neutrinos:

Mostly from weak radiation of W's, but also semi-leptonic b-quark decays

Jet Composition at ~~0.1-10~~ 100 TeV

Charged particles : ~60%

Mostly charged pions, kaons and protons, but also some electrons and muons (decays in flight, semi-lept. B decays)



Photons : ~25%

Mostly from π^0's, but also some genuine photons (brems,···)

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TeV Muon Considerations

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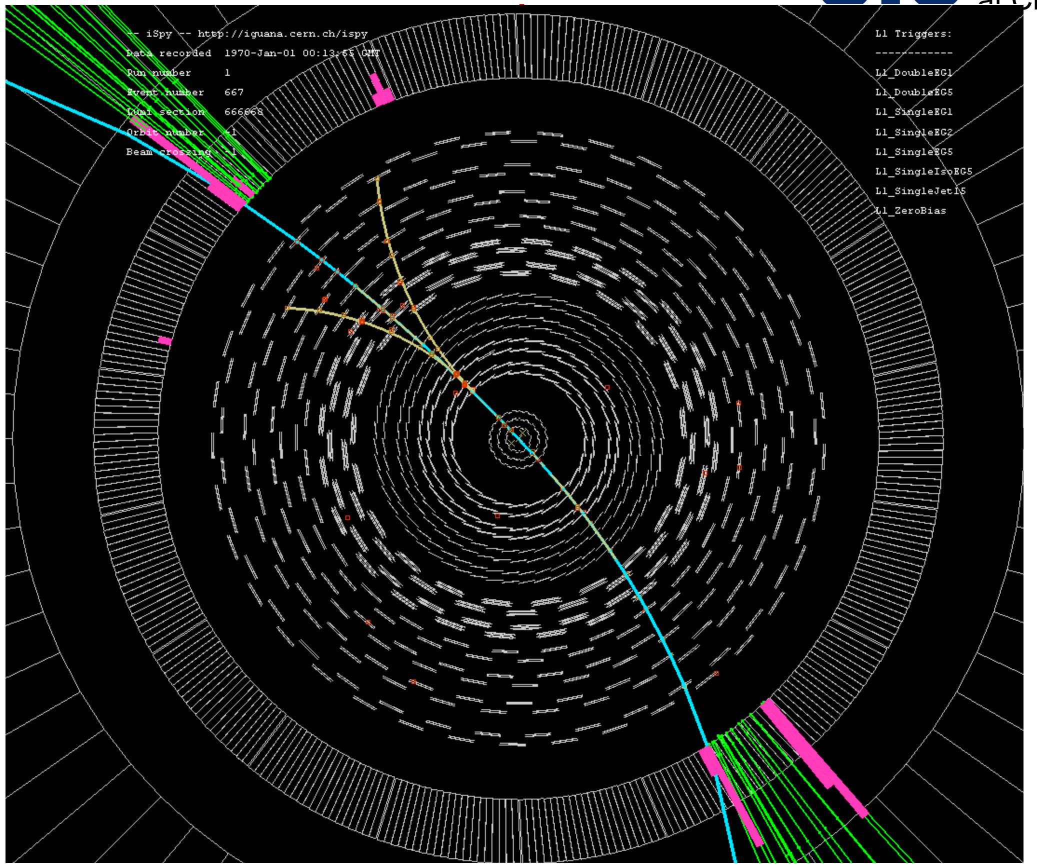
UIC University of Illinois at Chicago

TeV Muon Considerations

electrons brem in tracker



TeV Muon Considerations

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UIC University of Illinois at Chicago

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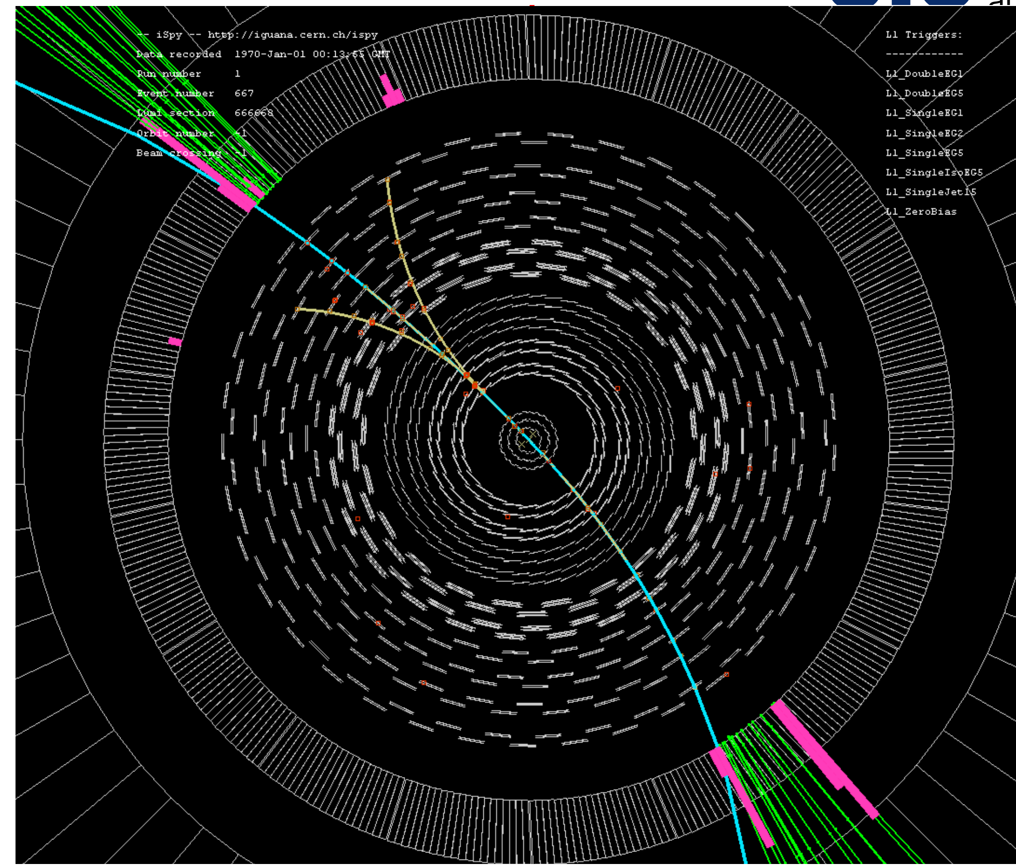
recovered in calorimeter



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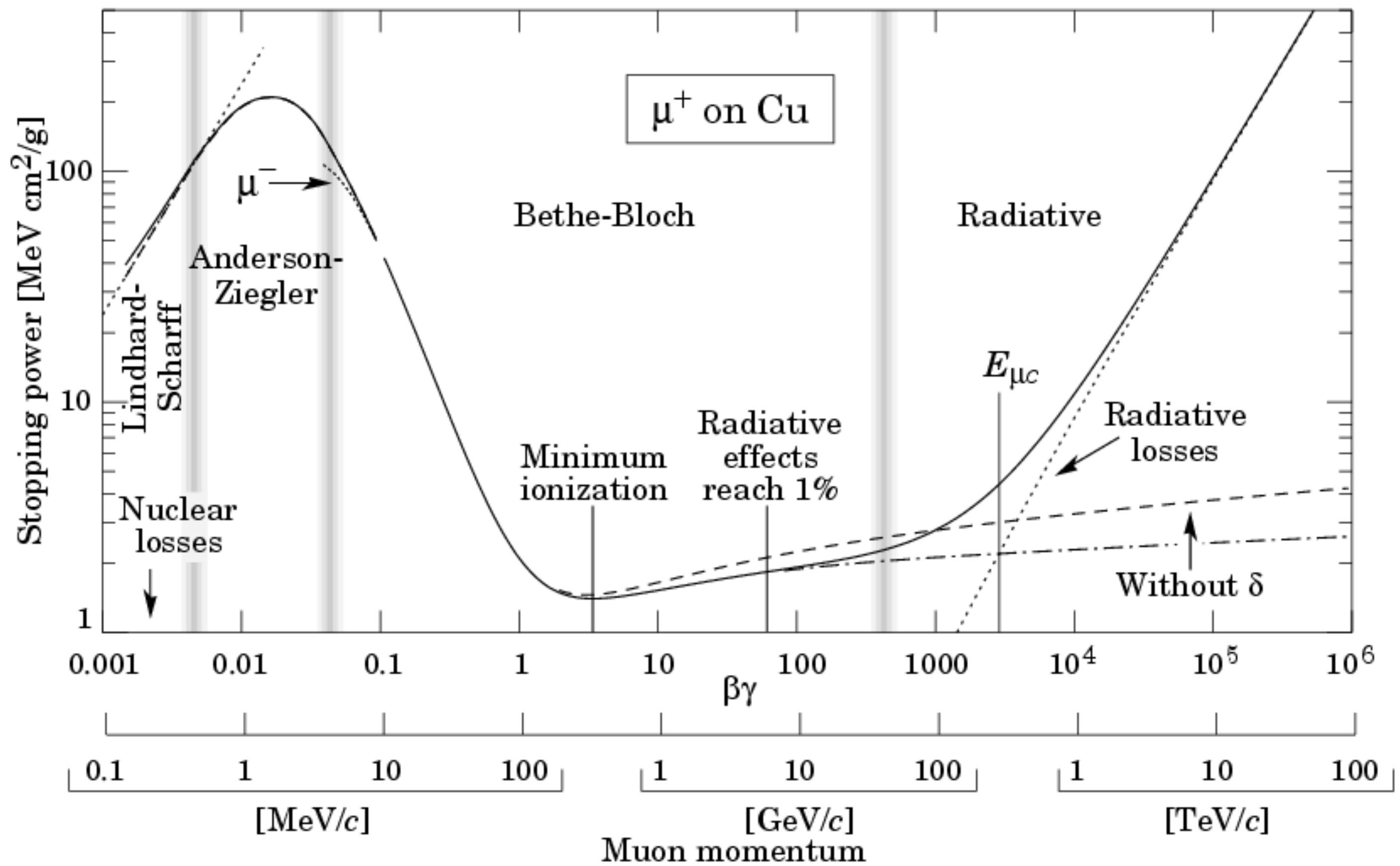

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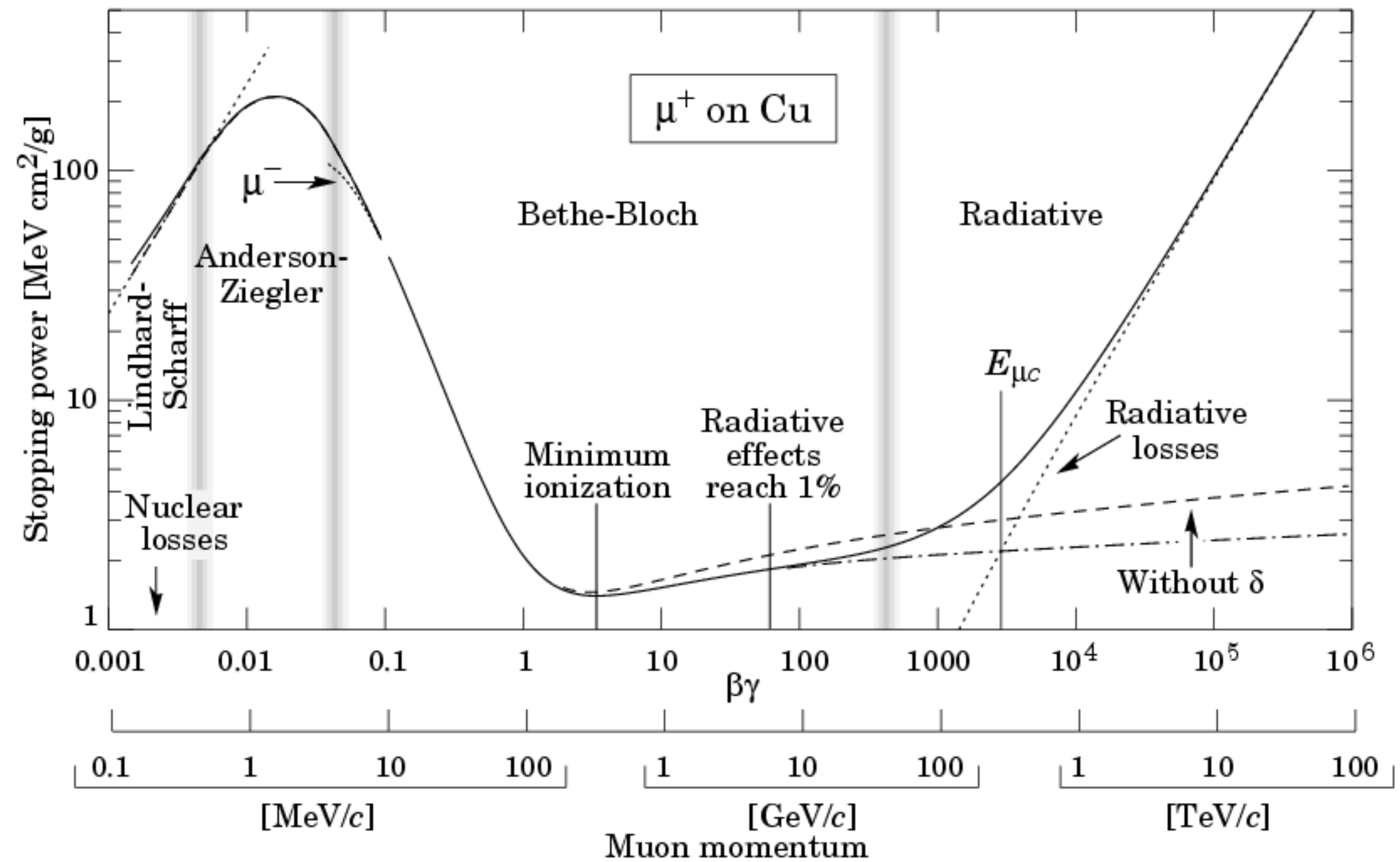

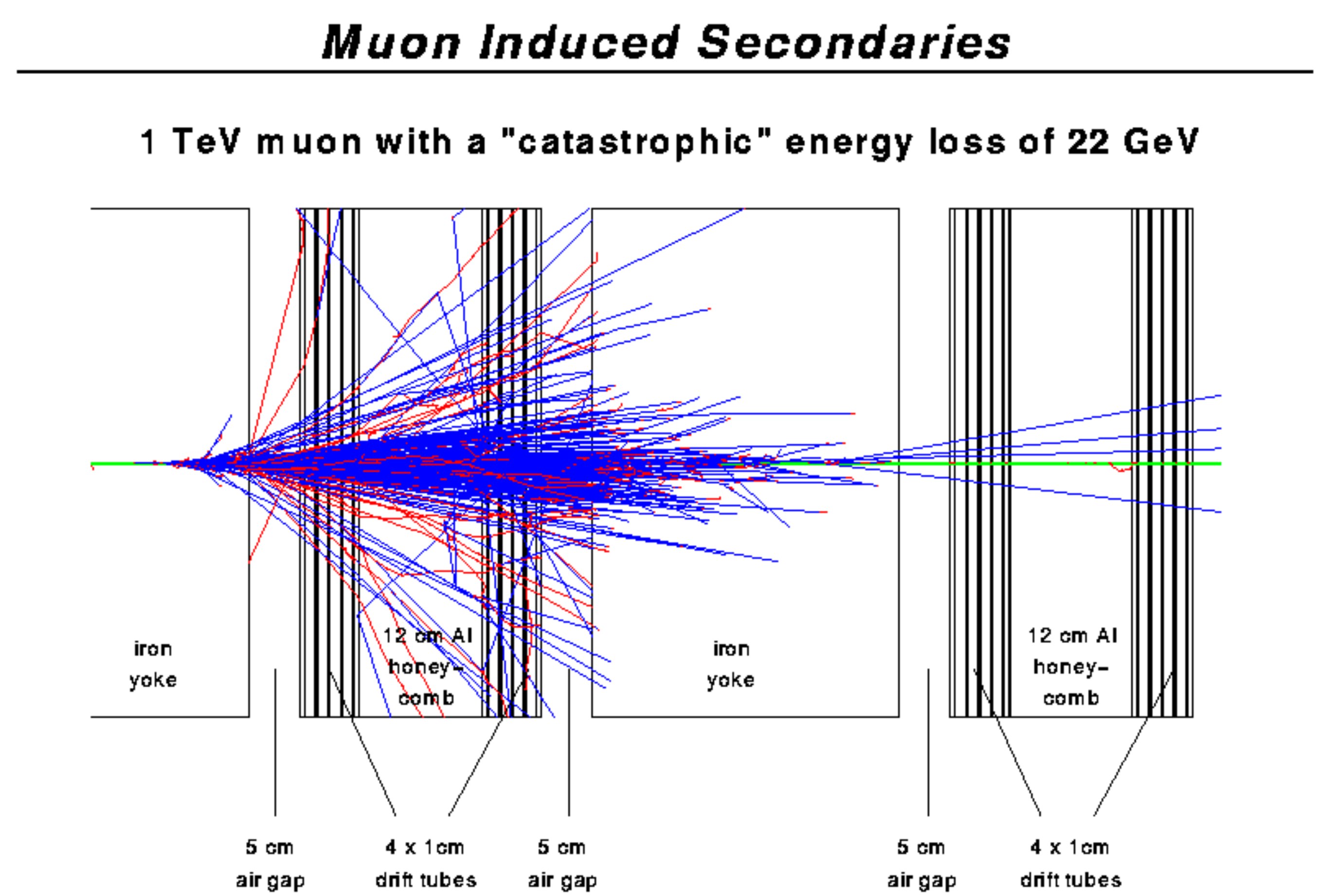

TeV Muon Considerations

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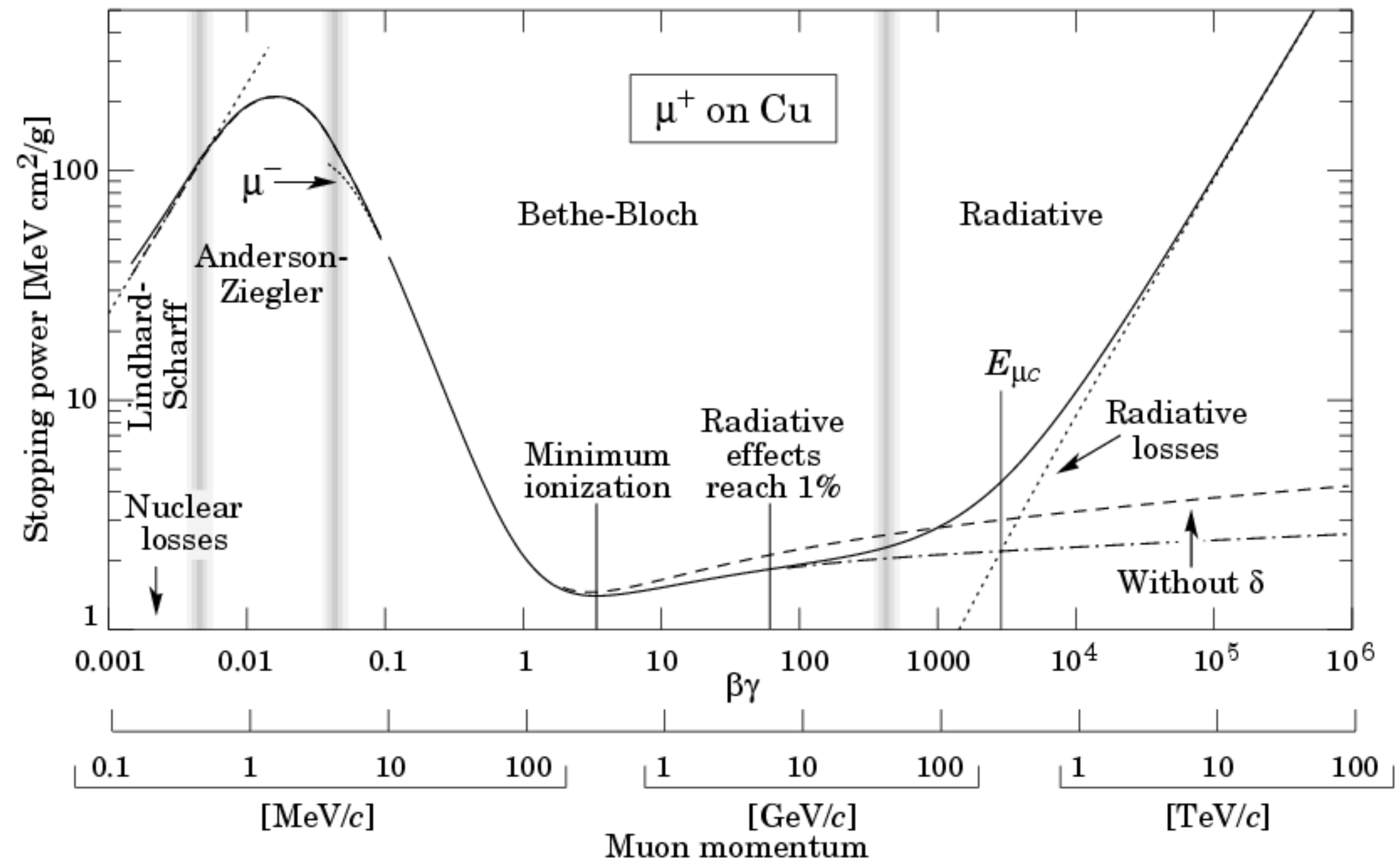
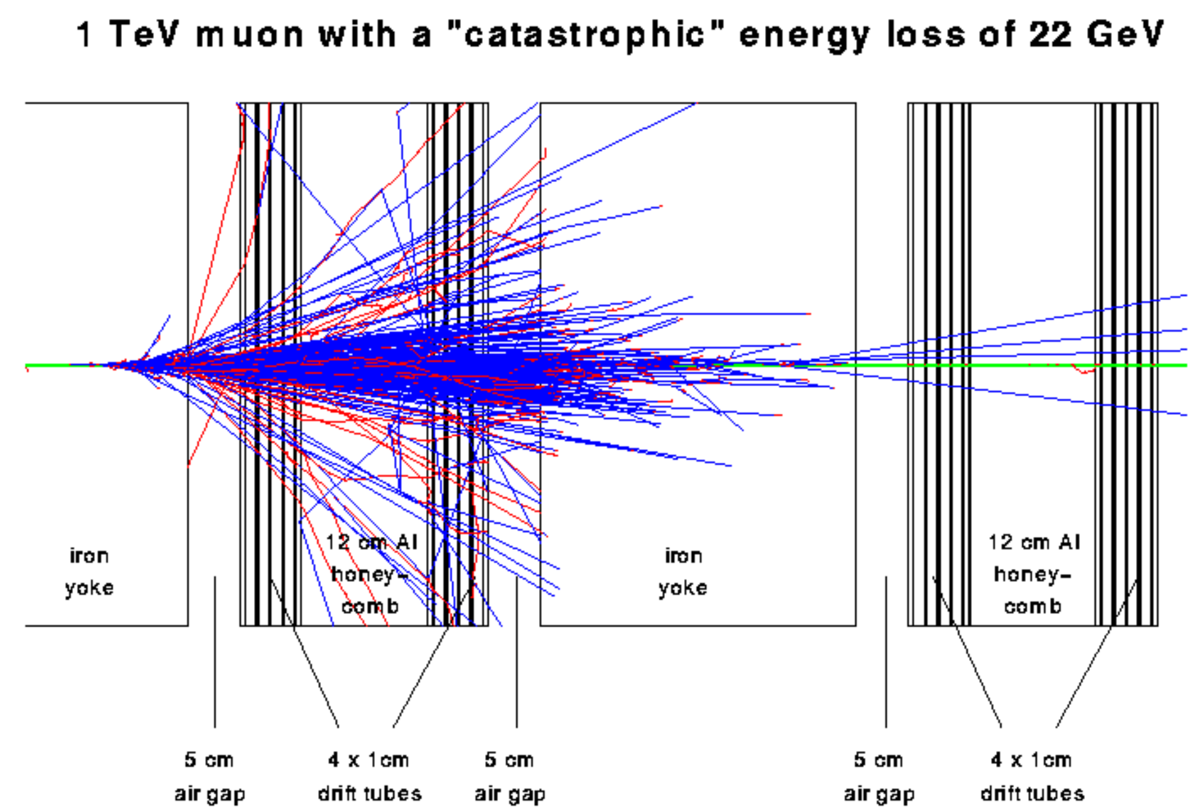


Muon Induced Secondaries



TeV Muon Considerations

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University of Illinois

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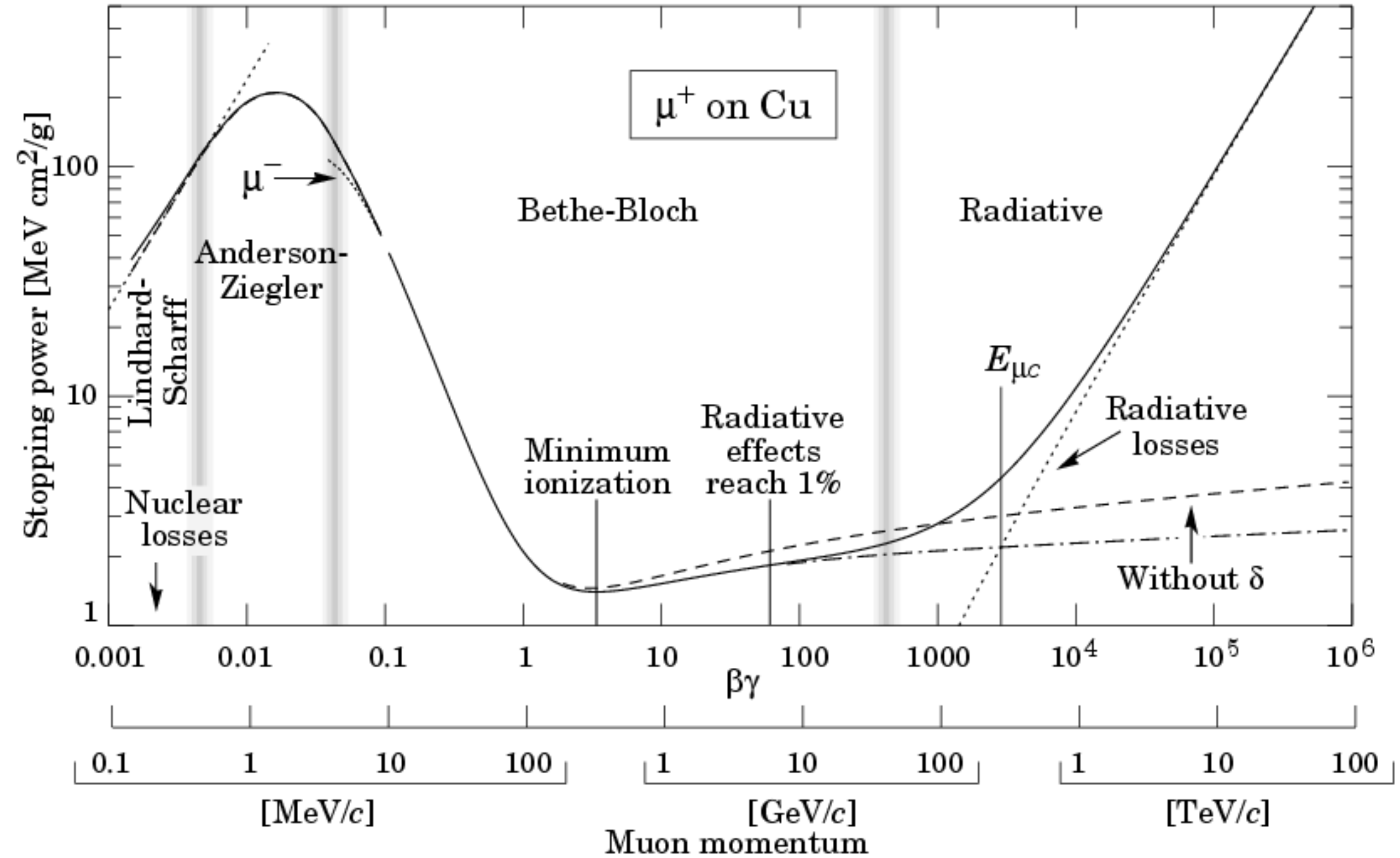

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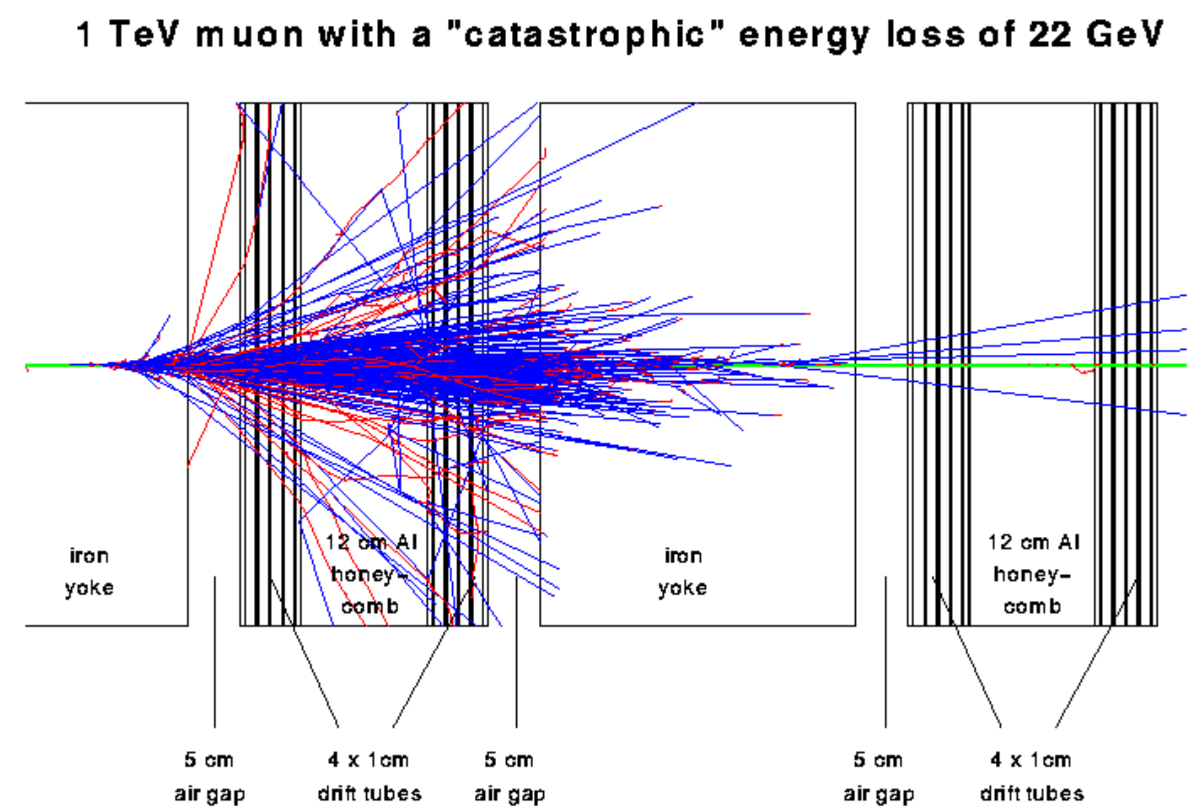

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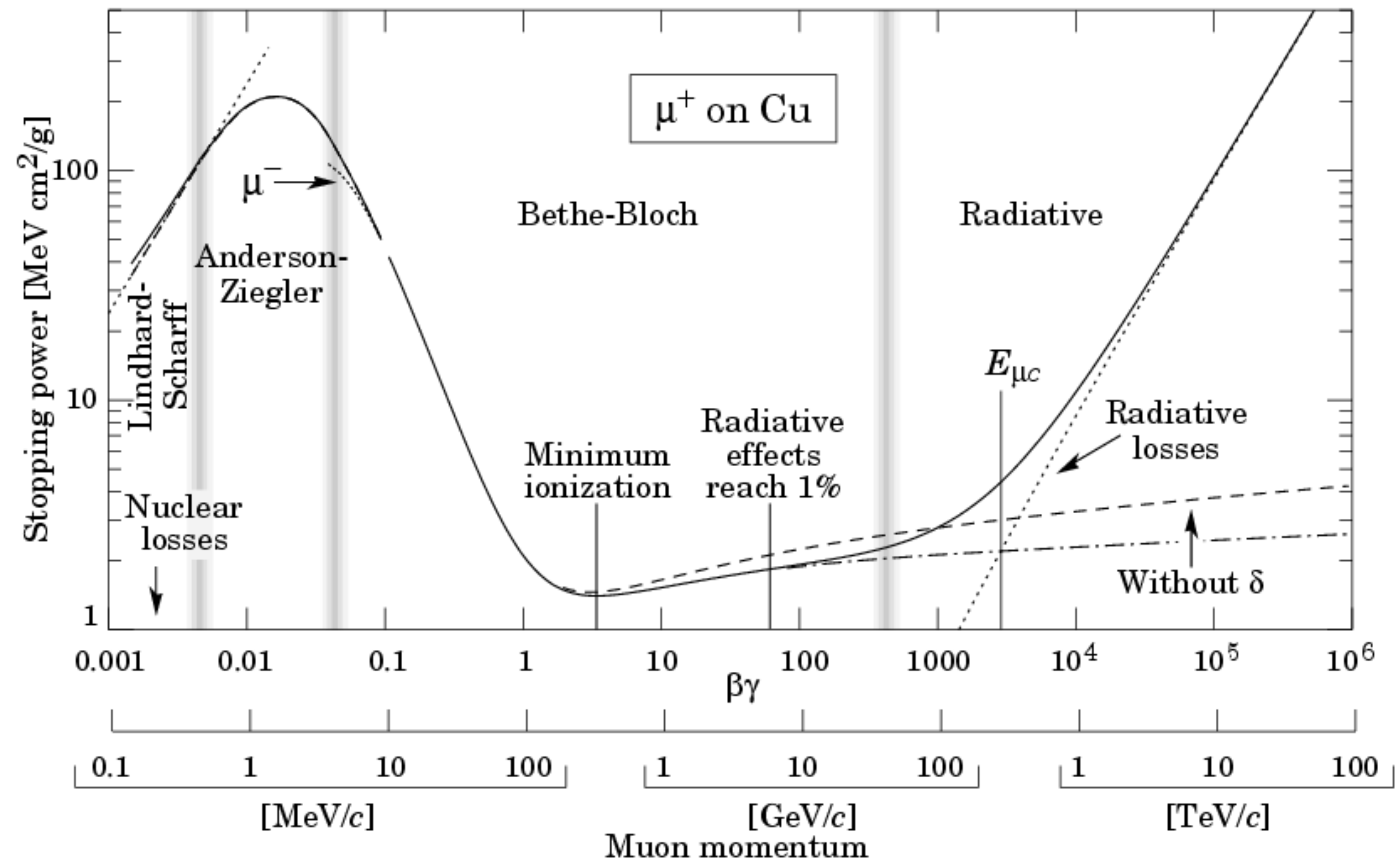

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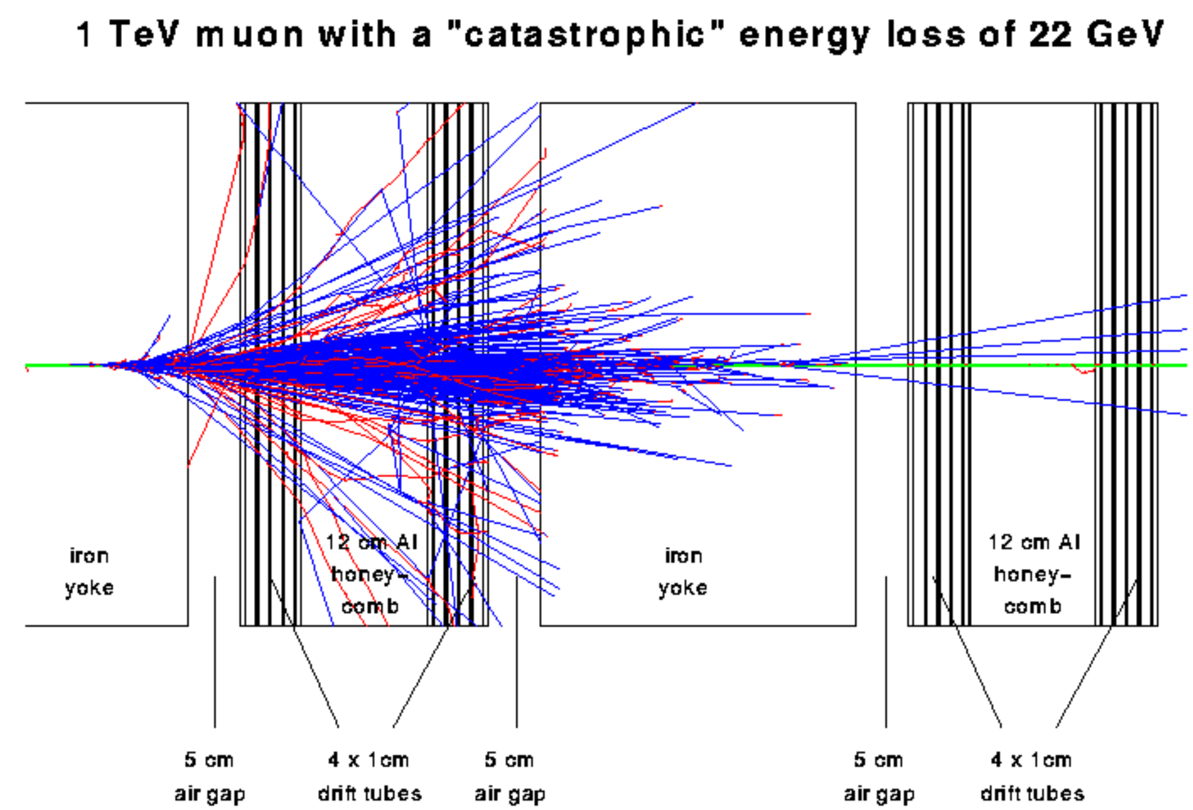

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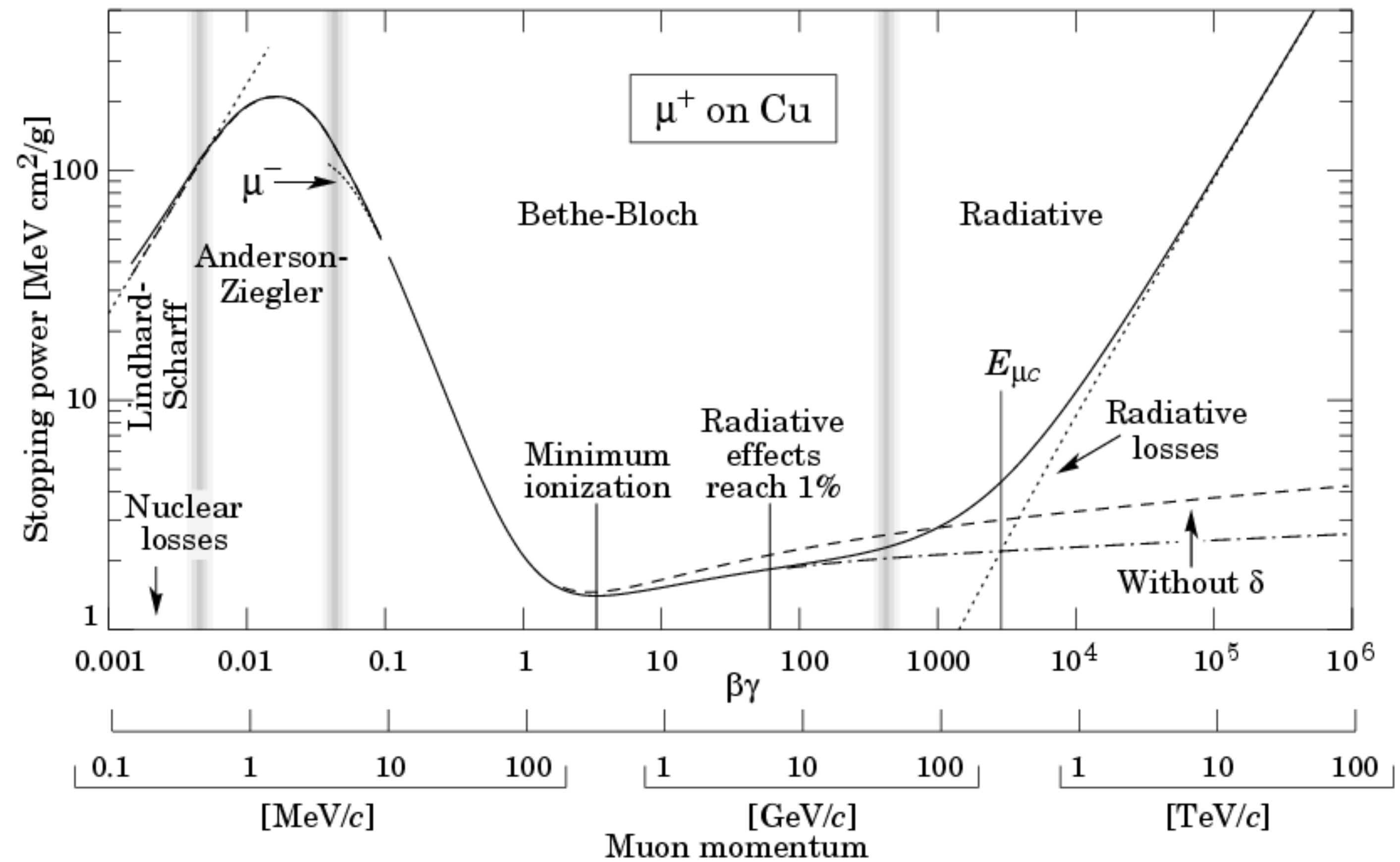

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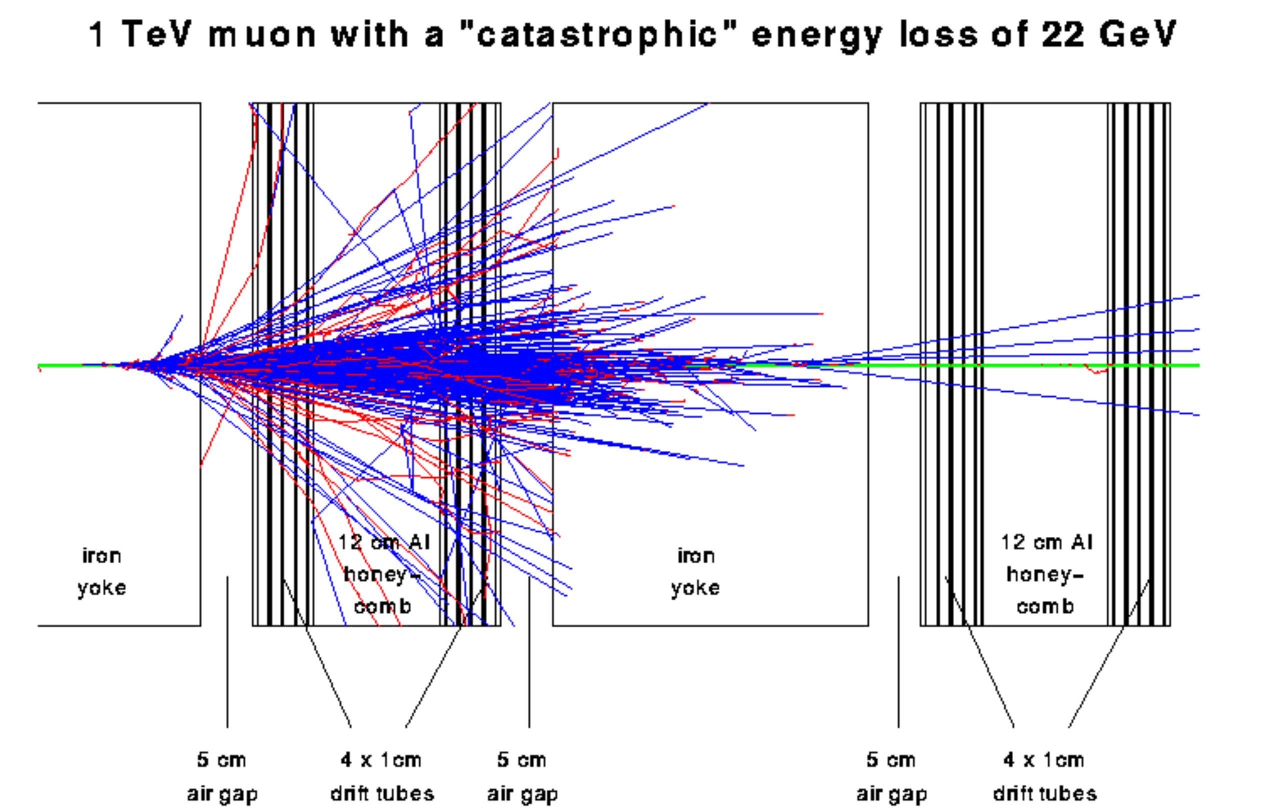

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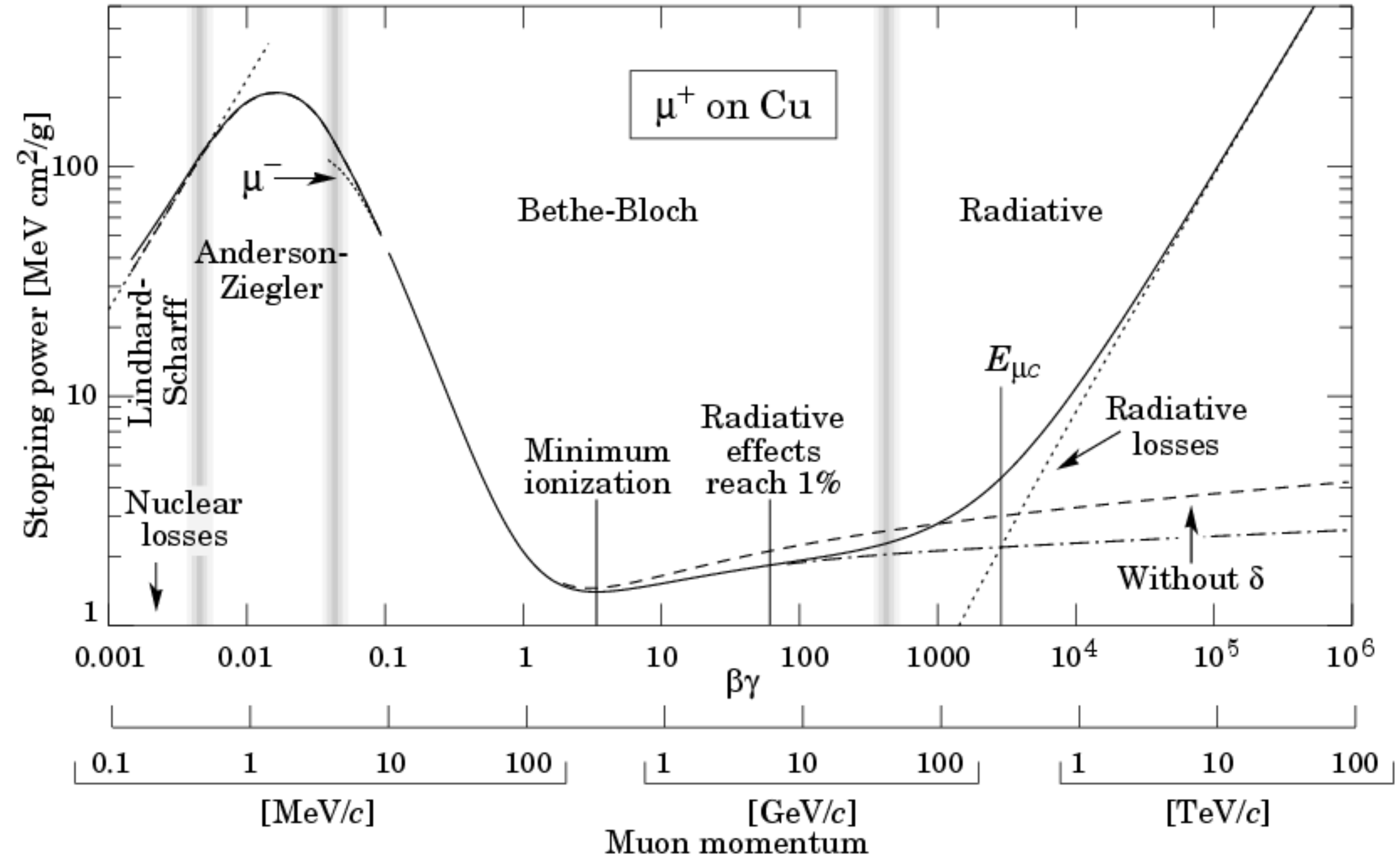

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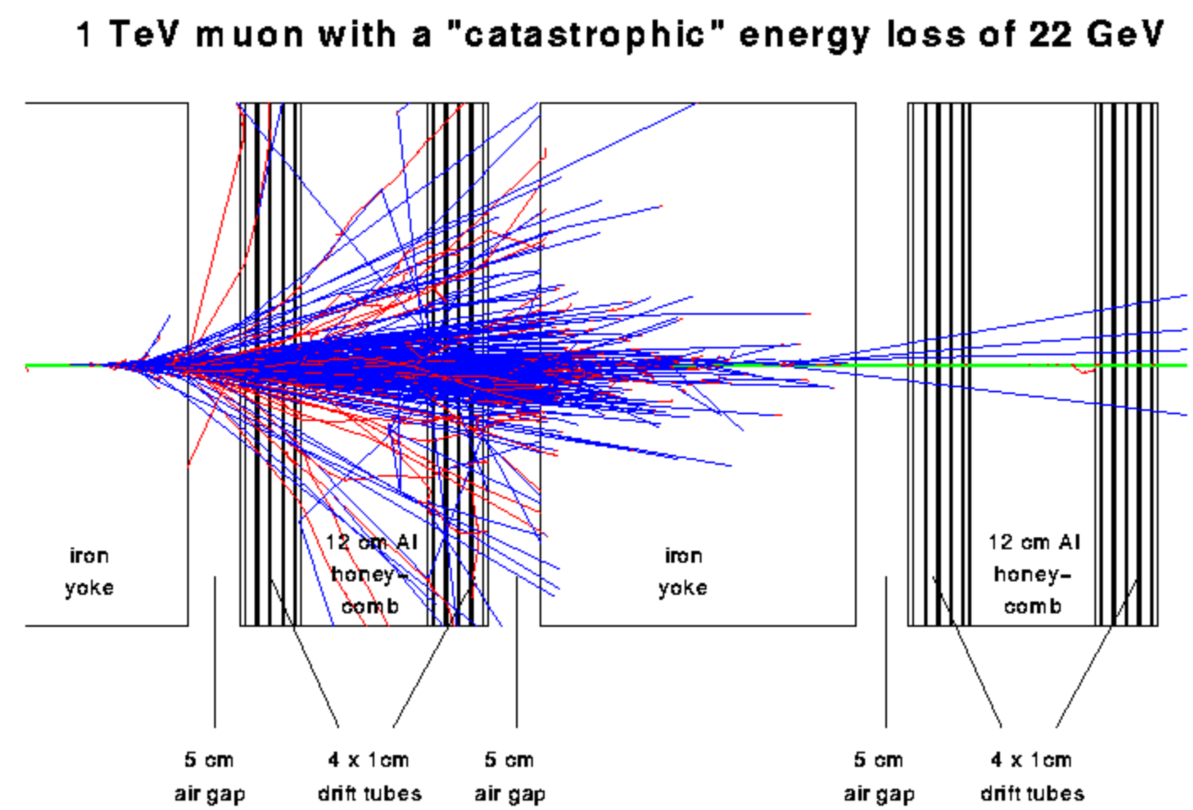

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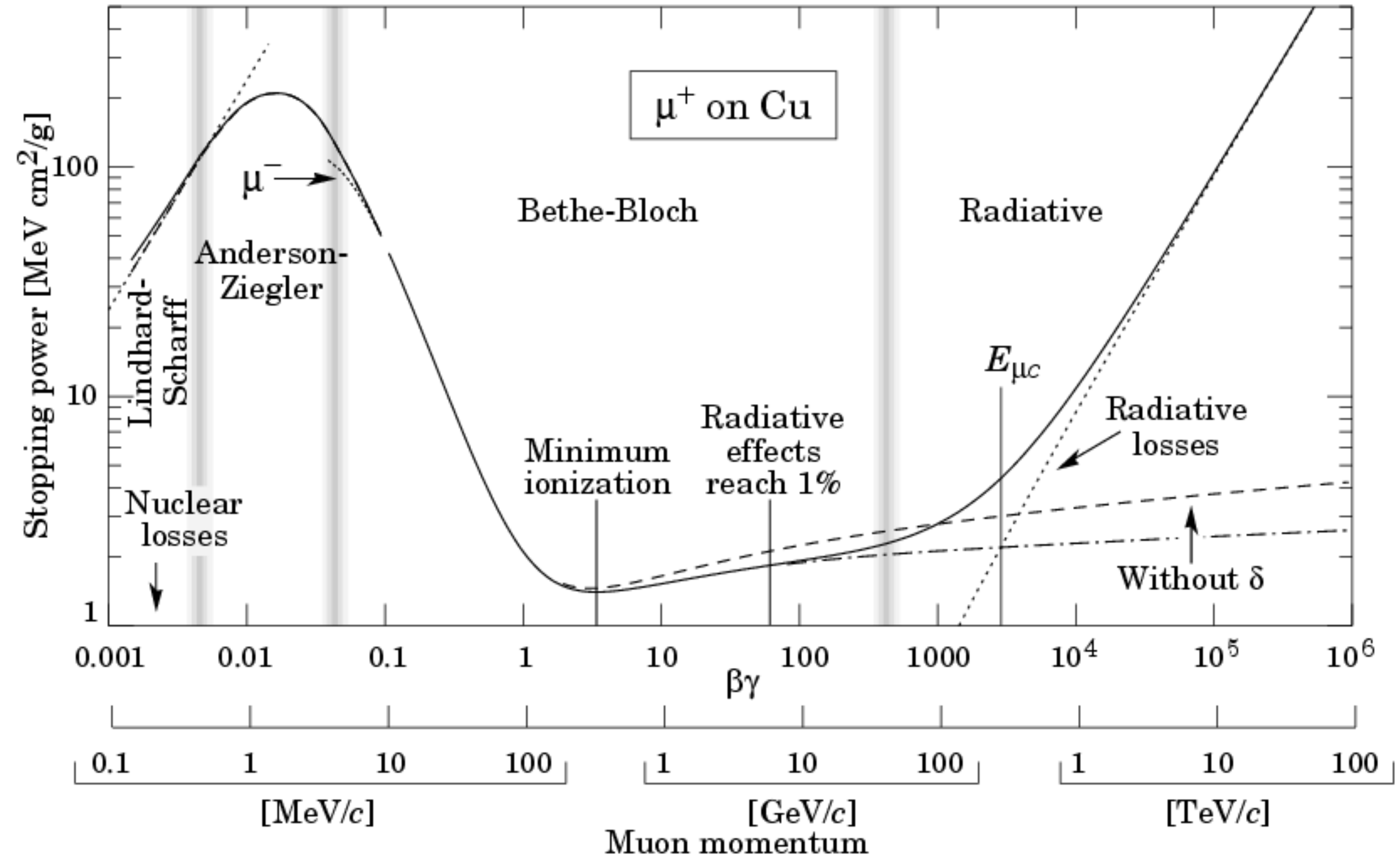

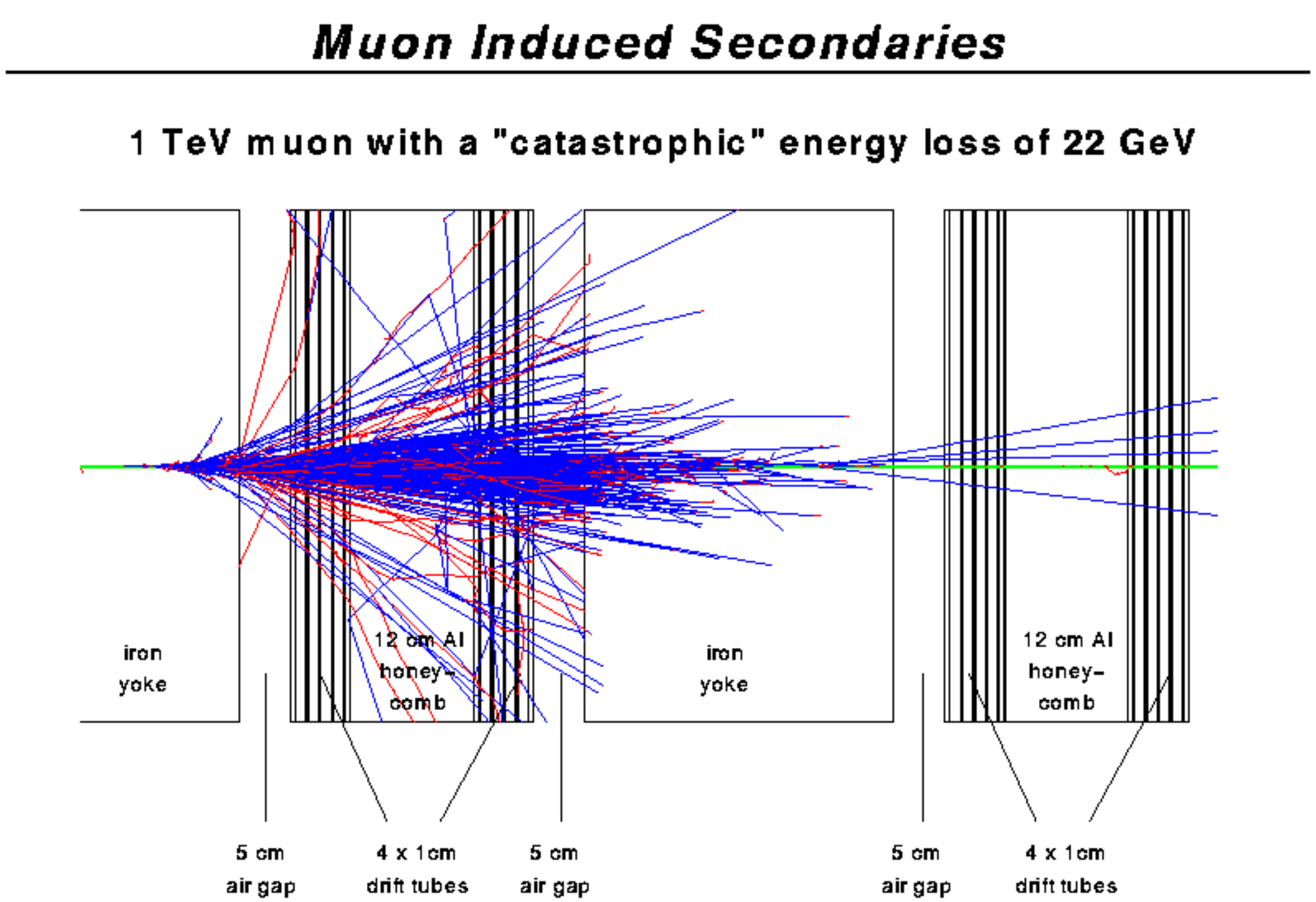

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University of Illinois

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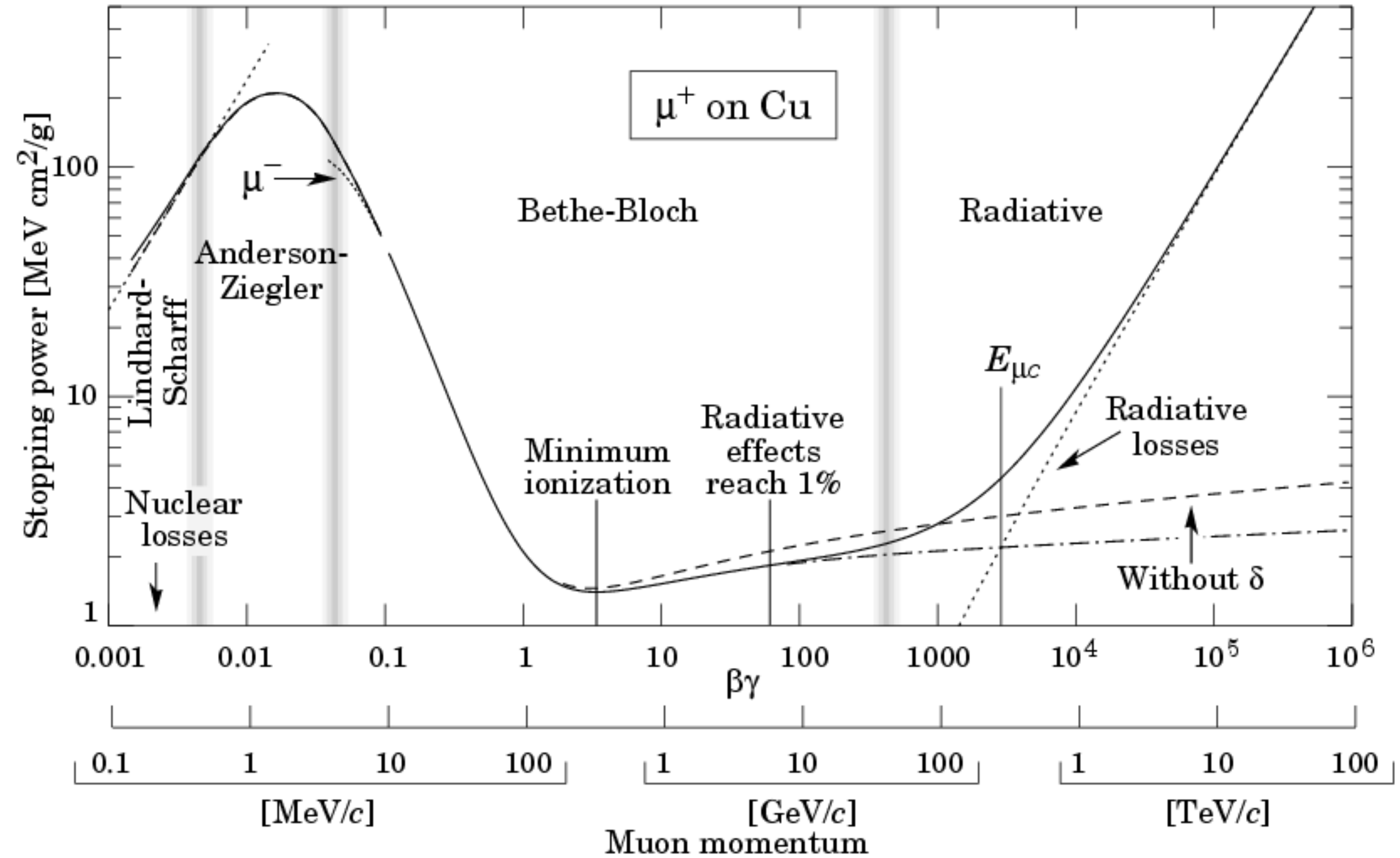
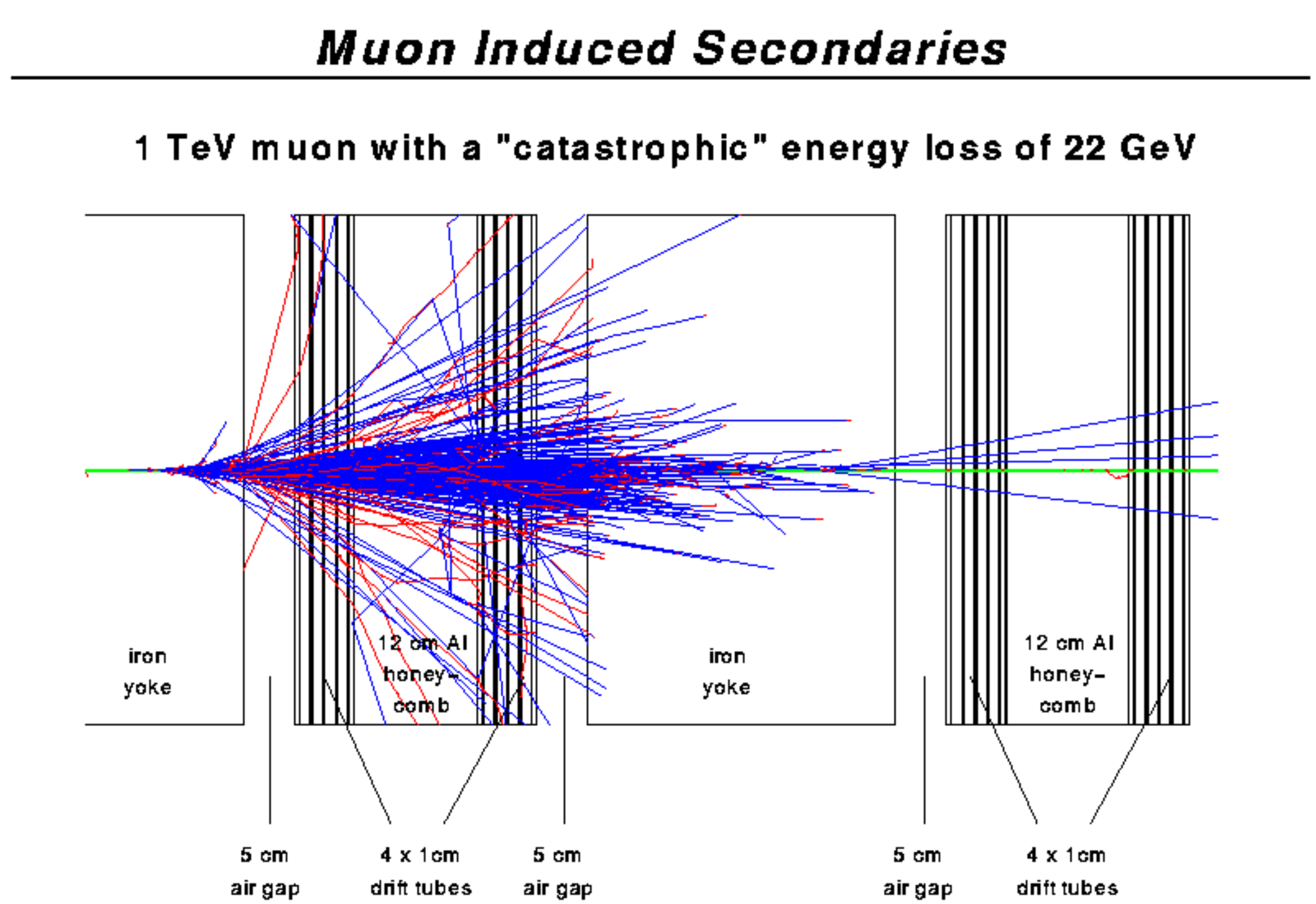
- LHC is a good testbed!





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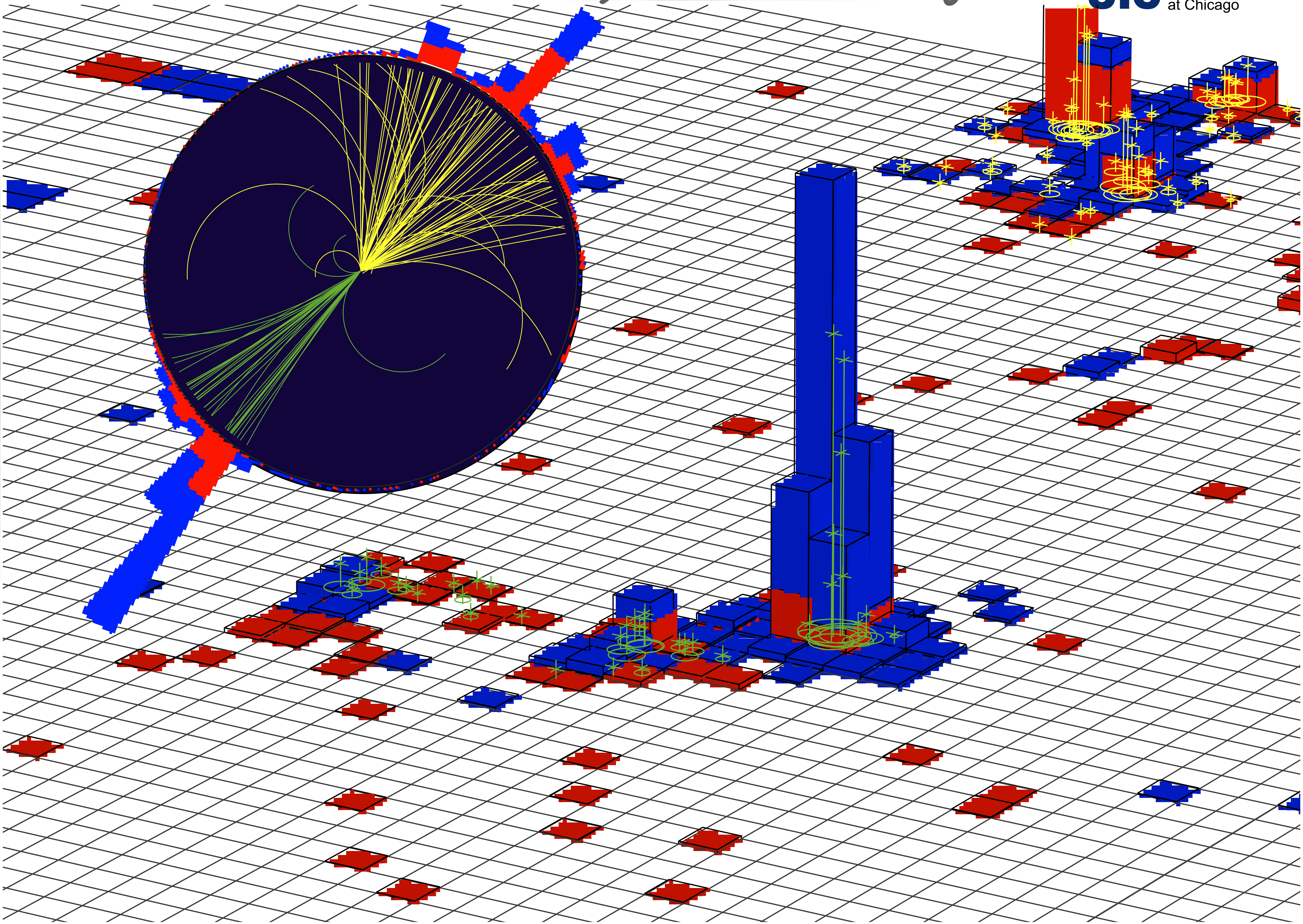
    - (care might need to be taken with Z->$\mu\mu$ and breming μ's)

Jet ID and Substructure; Boosted Objects



So what is Particle Flow?

means different things
to different people

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Reconstruct and identify all >> individual particles <<

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γ, e, μ, $\pi^{\pm}$, K_0^L, pile-up $\pi^{\pm}$, converted γ's & nuclear interaction $\pi^{\pm}$,...

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  - Better noise rejection

Particle Flow Algorithm

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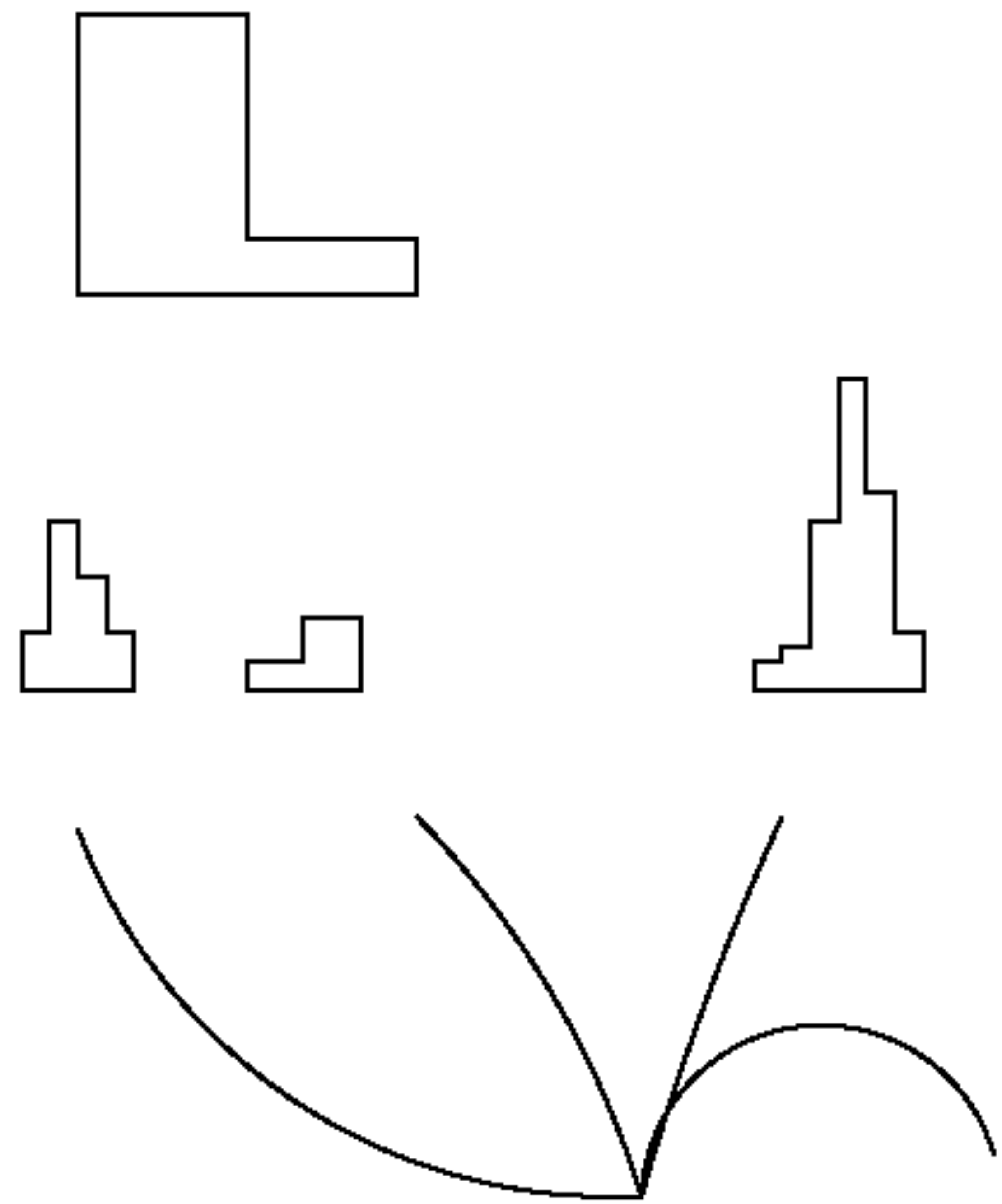
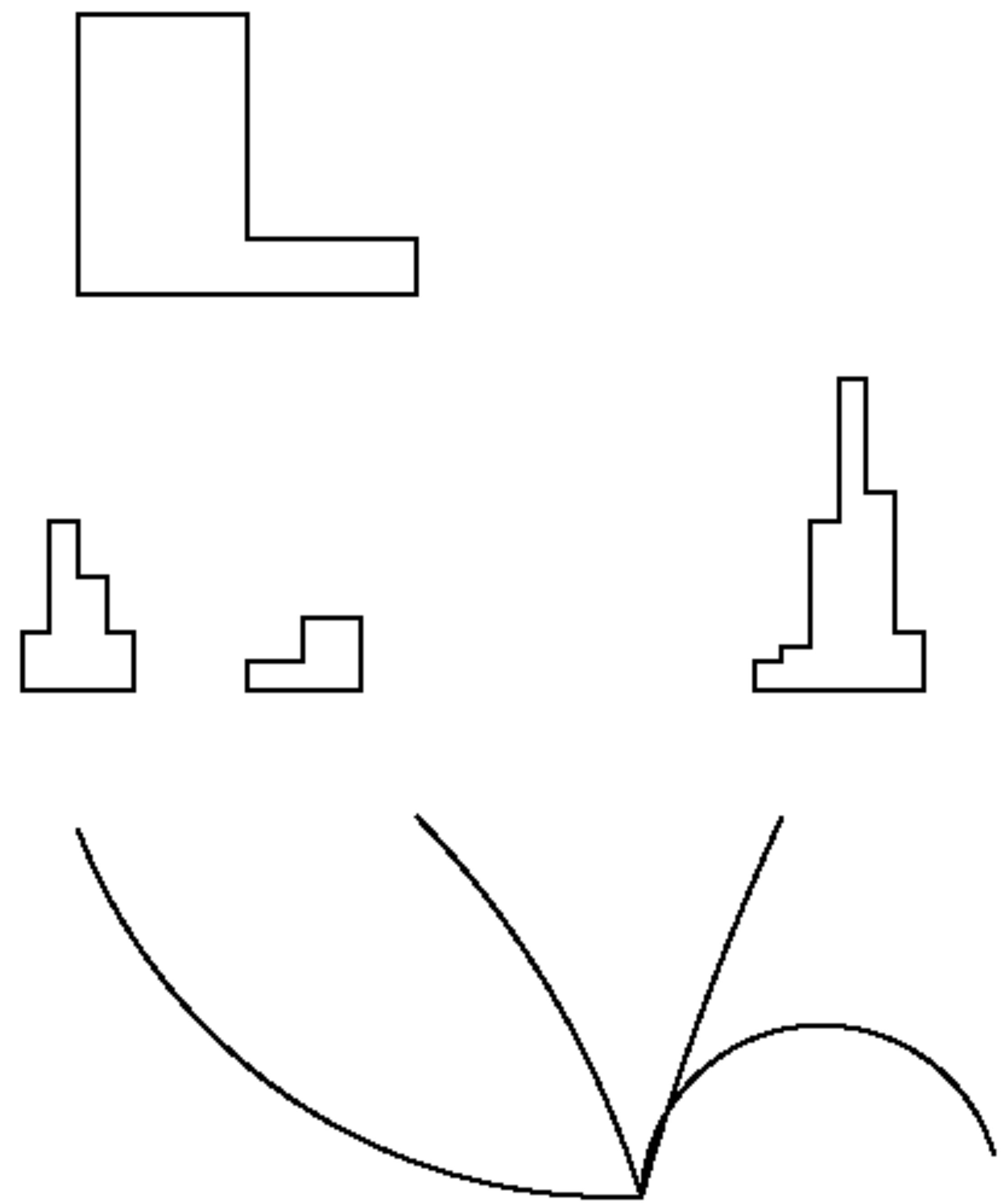


First Associate Hits within Each Detector



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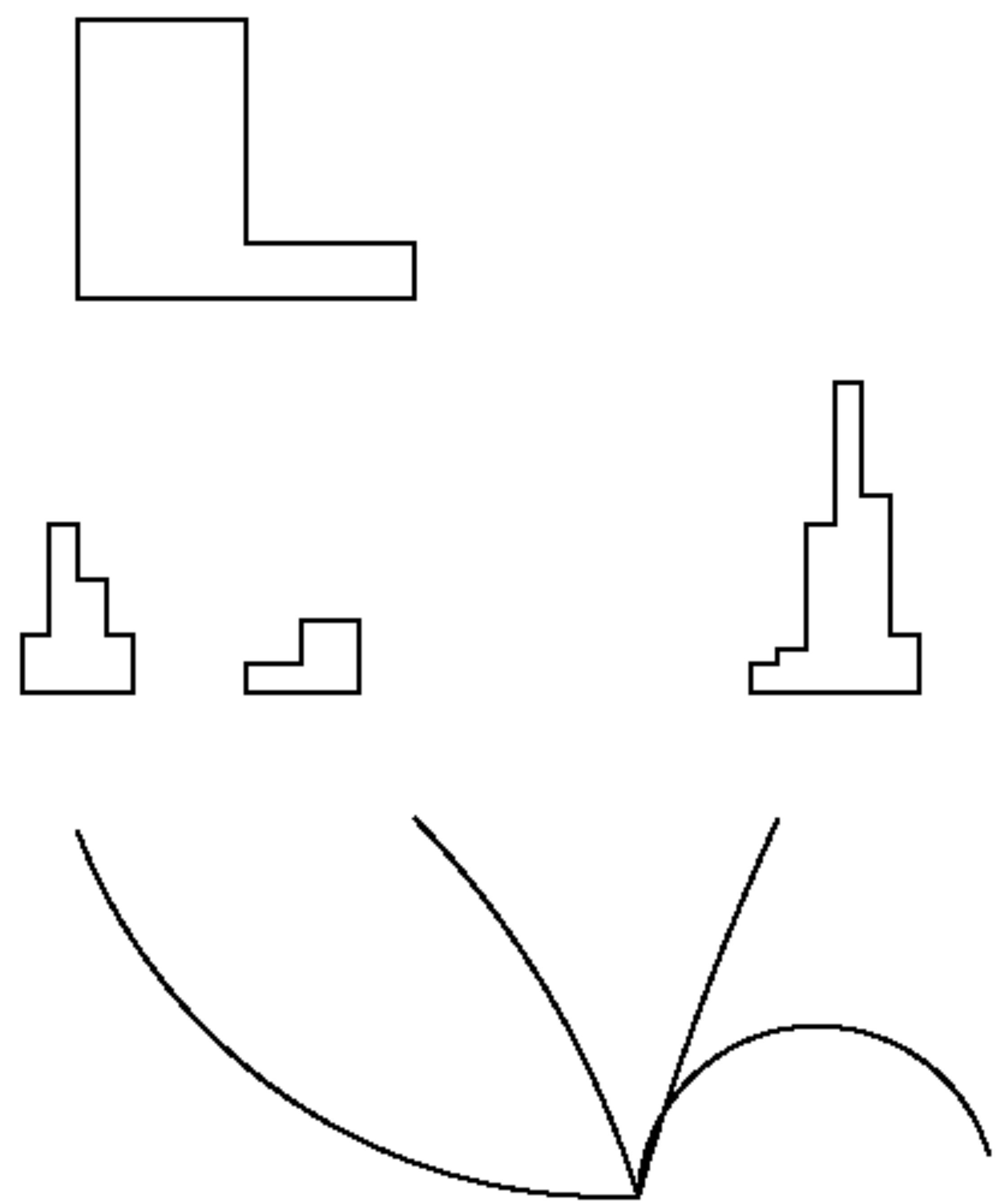

Tracks

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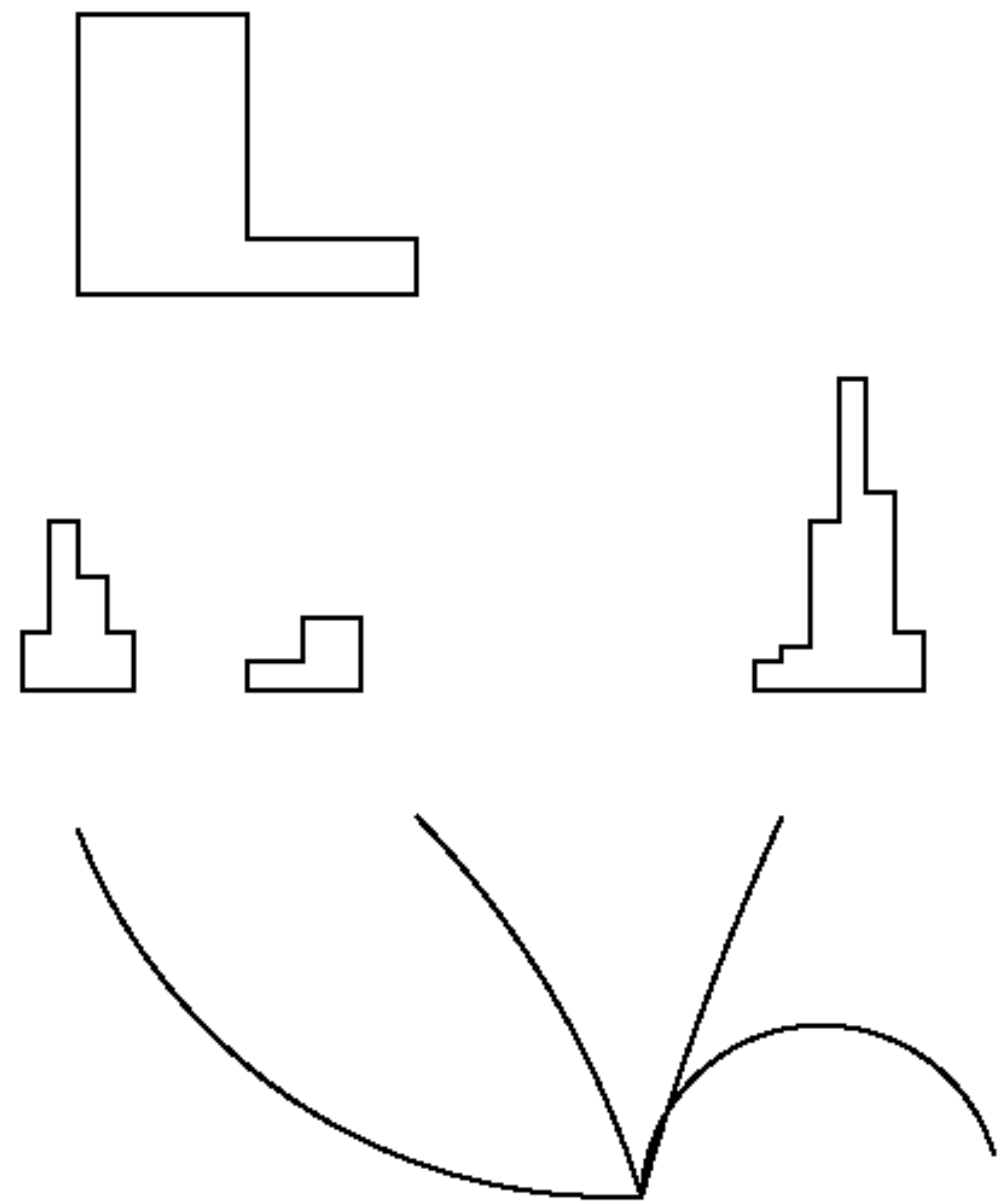
First Associate Hits within Each Detector

ECAL
Clusters

Tracks



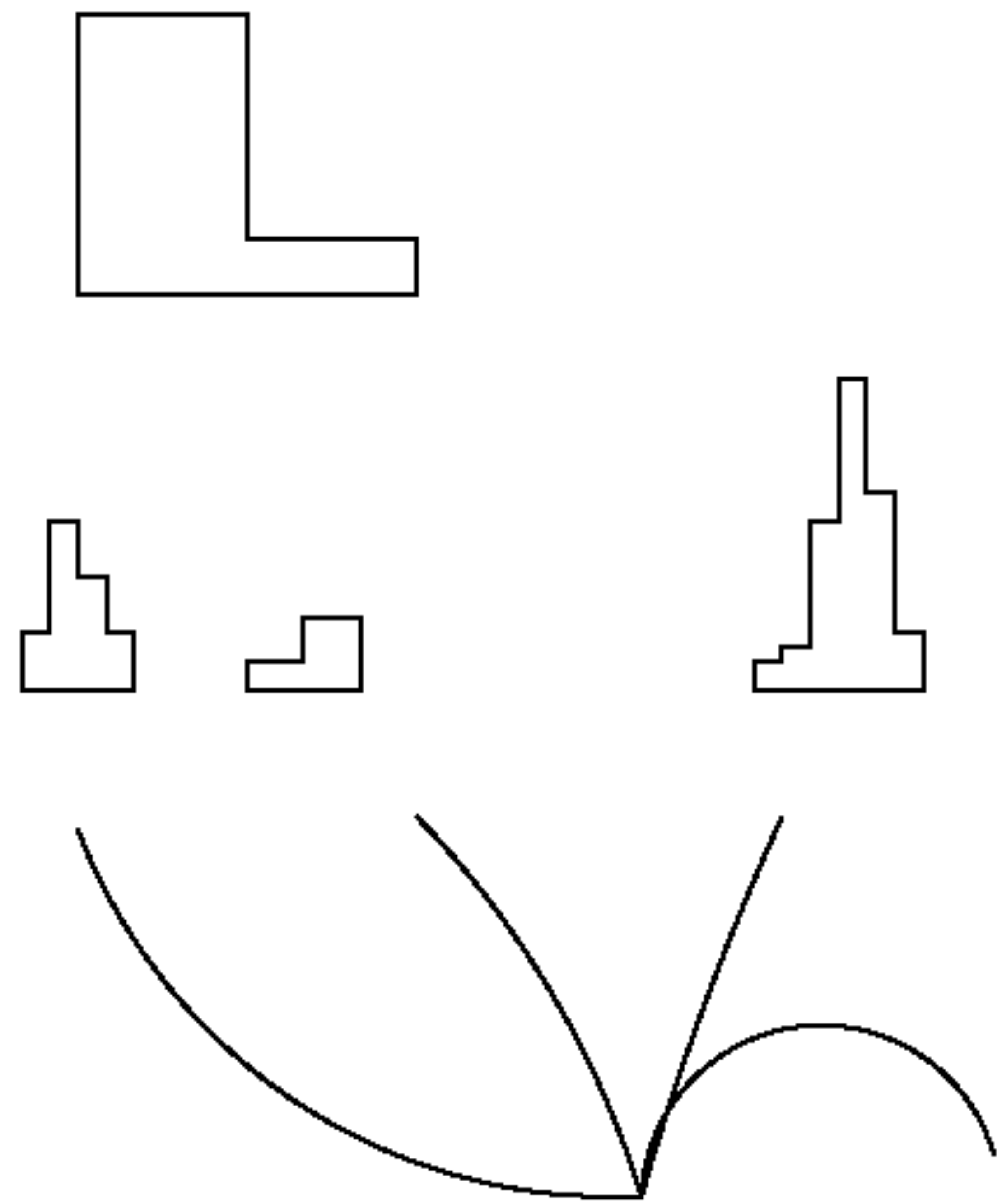
Particle Flow Algorithm

First Associate Hits within Each Detector

HCAL Clusters

ECAL Clusters

Tracks



Particle Flow Algorithm

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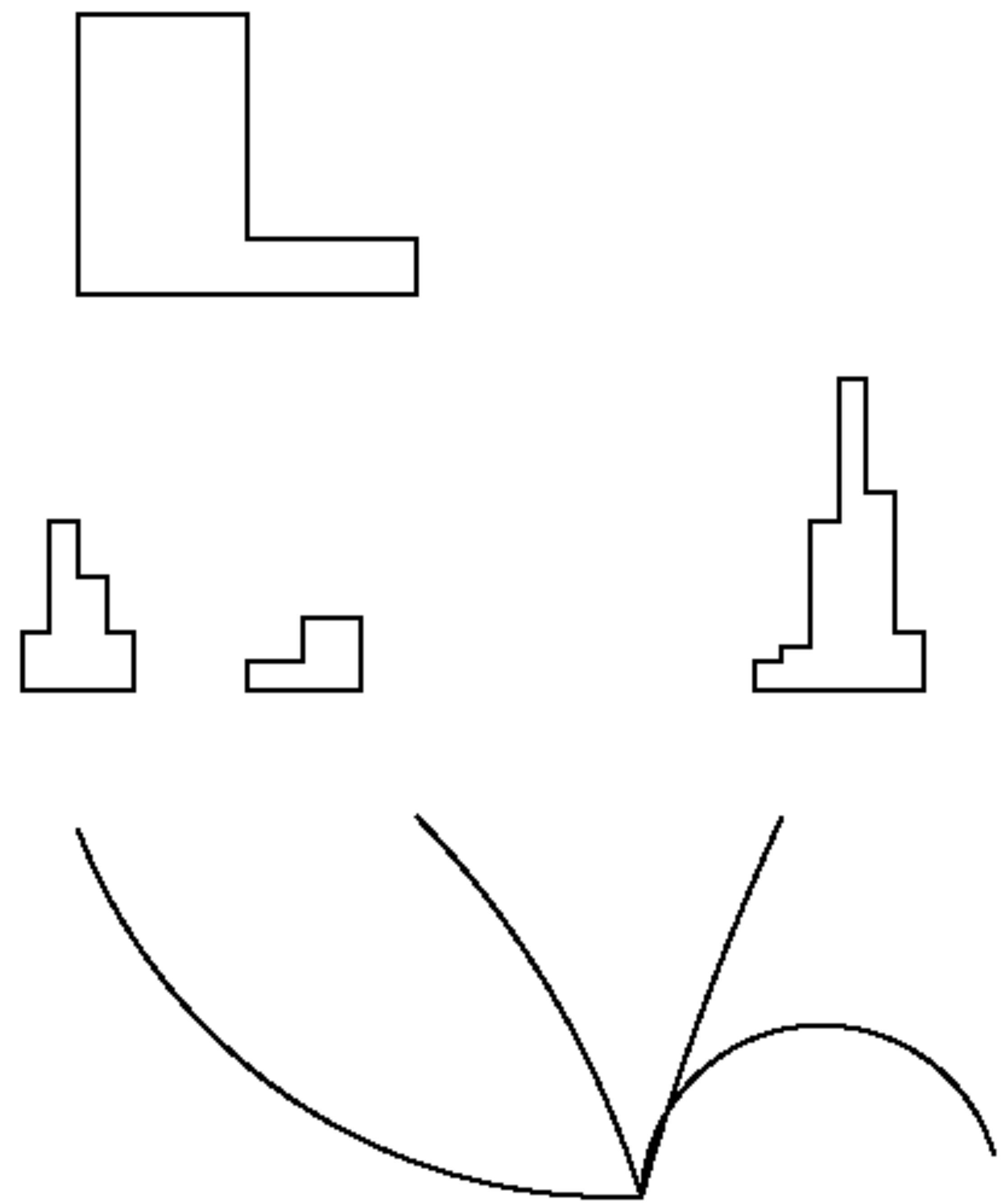

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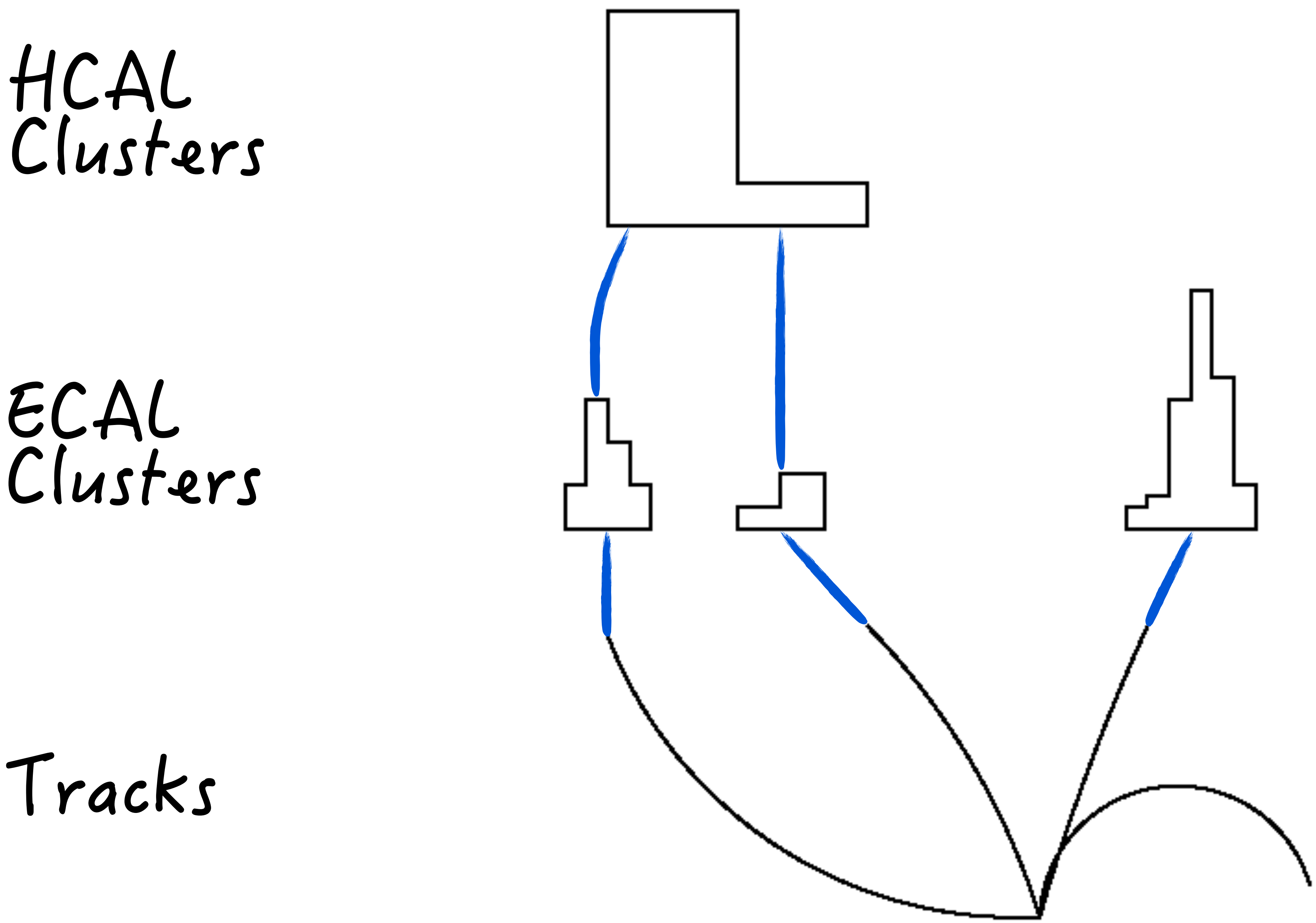
Then Link Across Detectors



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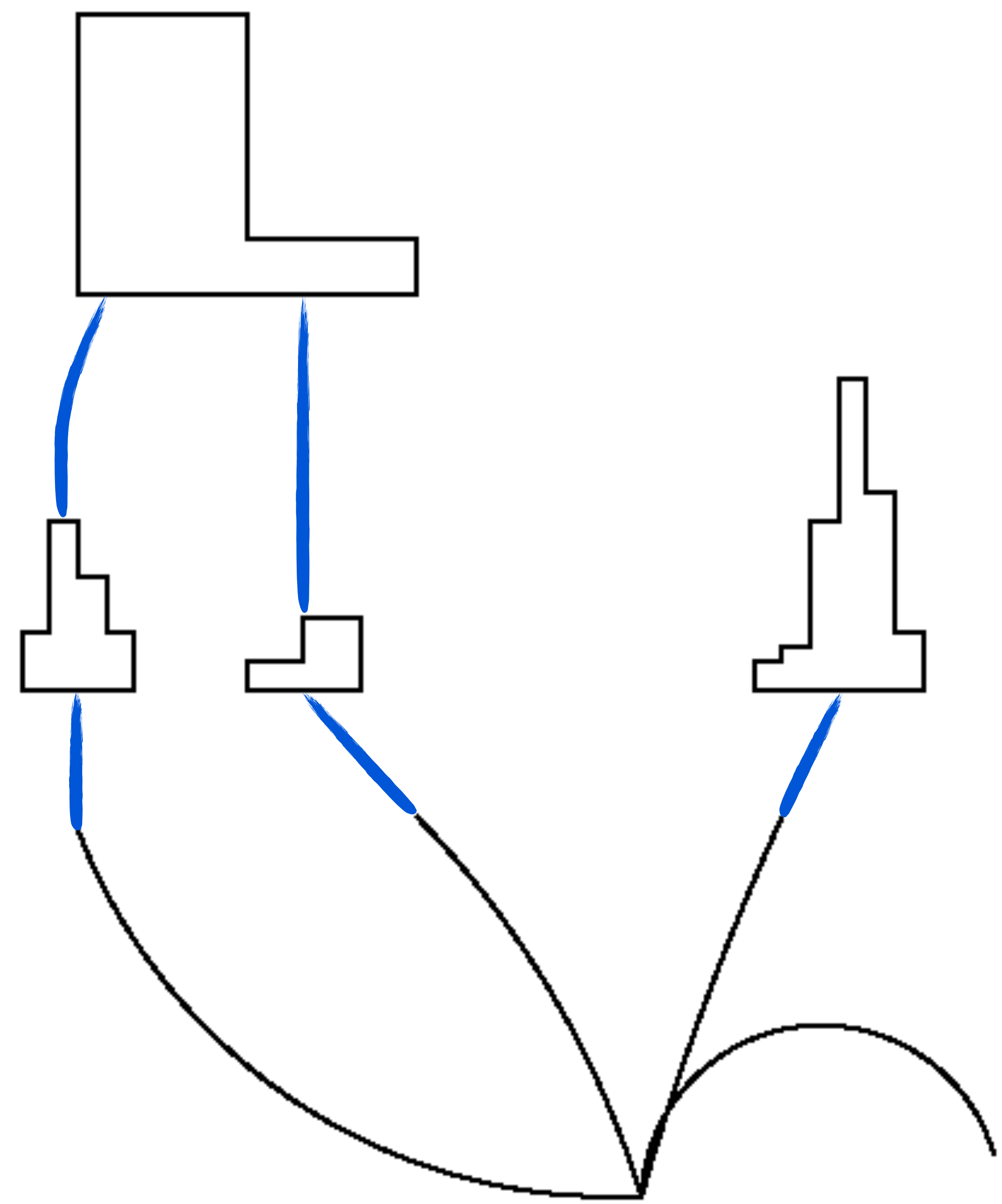

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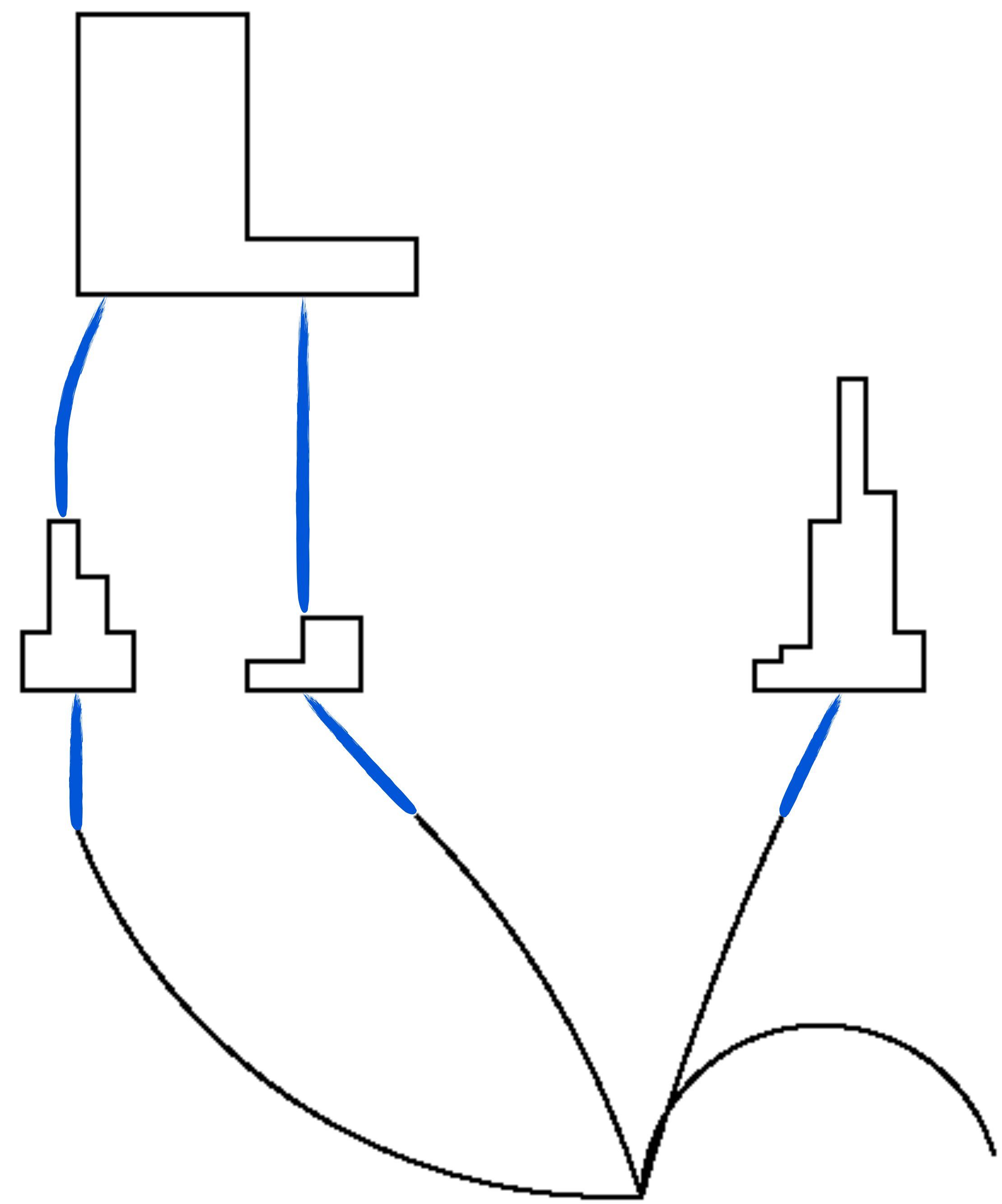
Finally, Apply Particle ID & Separation

HCAL Clusters

ECAL Clusters

Tracks



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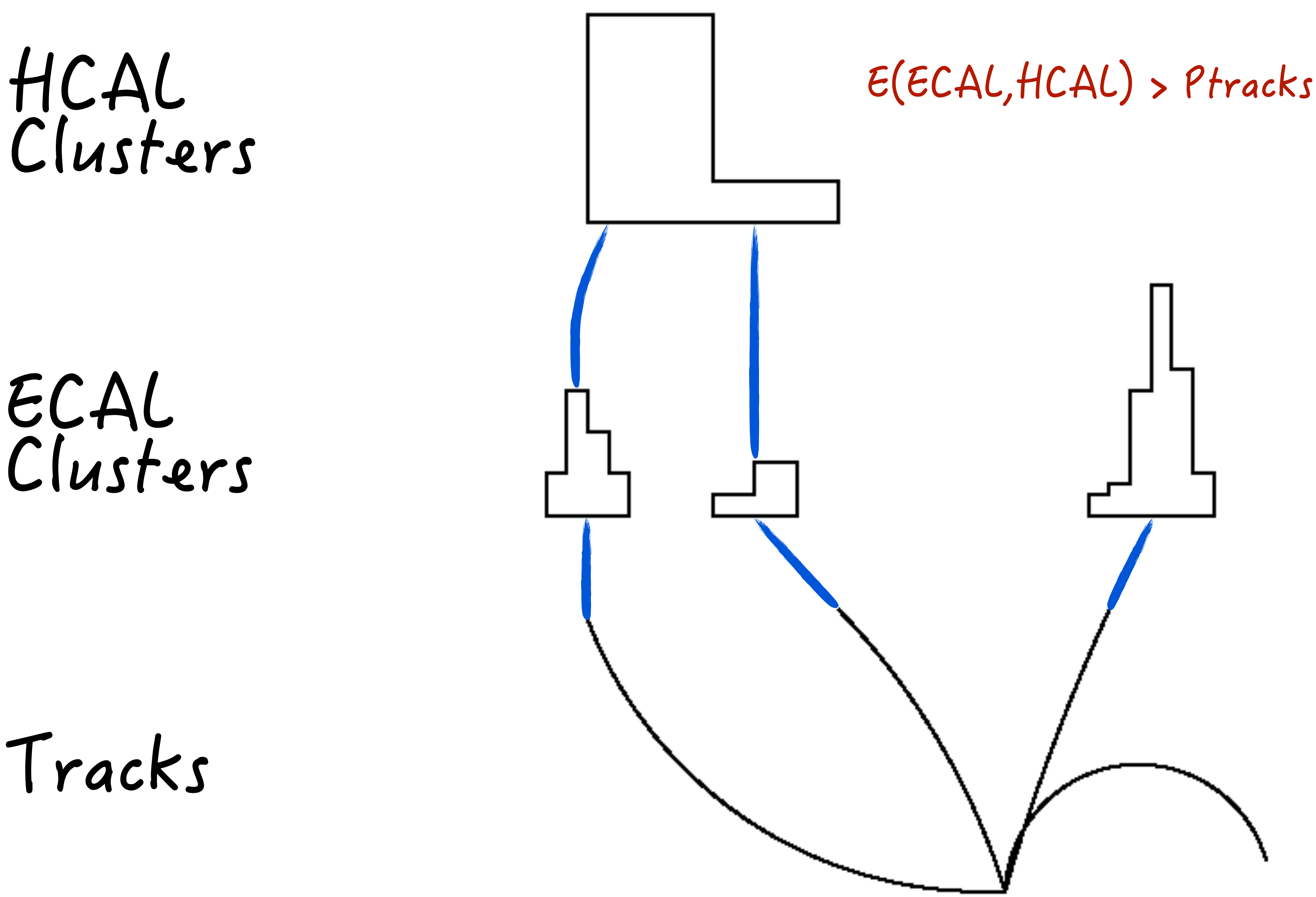

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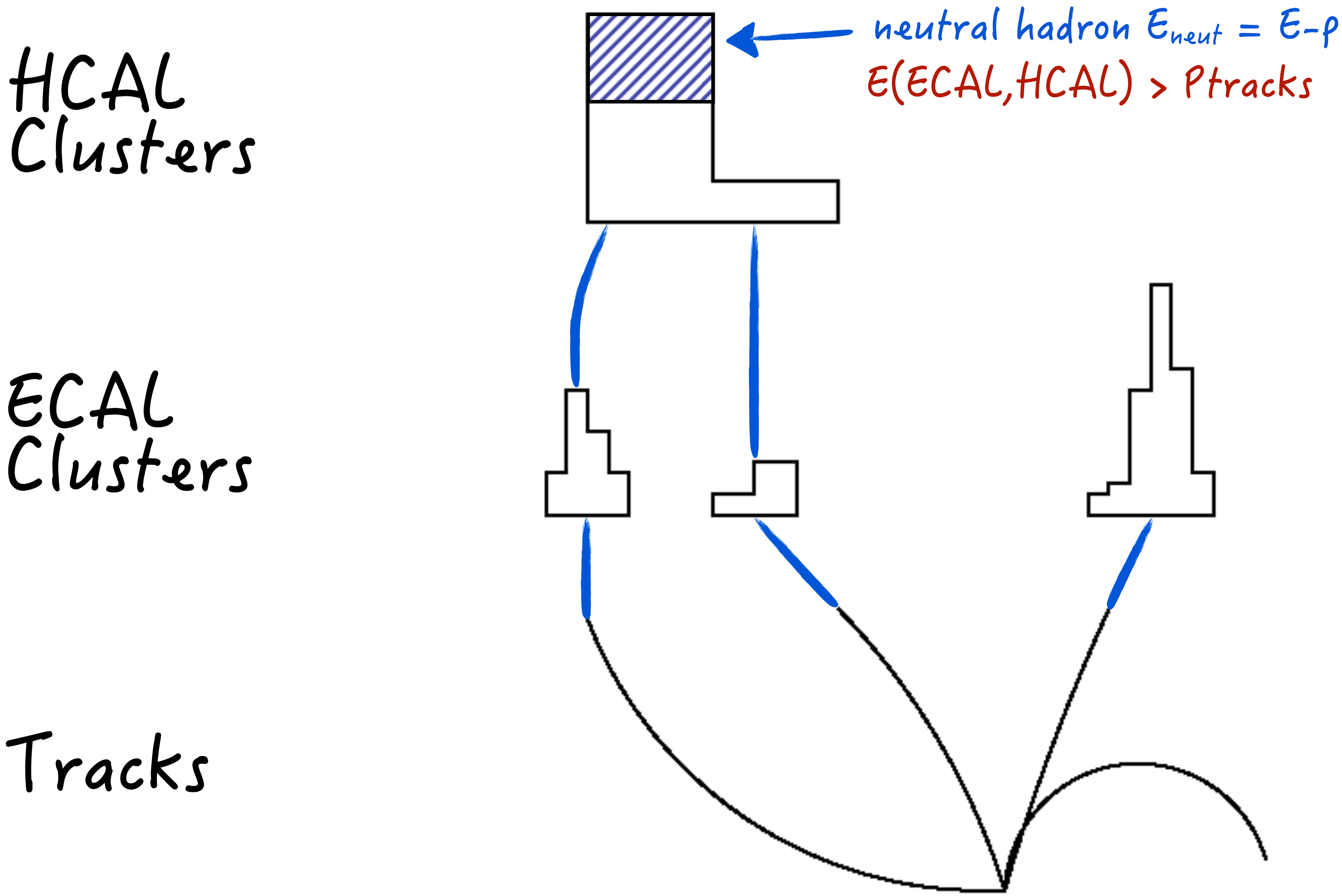

Very Basic View of Particle Flow

"Clean" the Event During Reconstruction!

Very Basic View of Particle Flow

"Clean" the Event During Reconstruction!

Find and "remove" muons

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"Clean" the Event During Reconstruction!

Find and "remove" muons (σ_{track})

"Clean" the Event During Reconstruction!

Find and "remove" muons (σ_{track})

Find and "remove" electrons

Very Basic View of Particle Flow

"Clean" the Event During Reconstruction!

Find and "remove" muons (σ_{track})

Find and "remove" electrons (min[σ_{track}, σ_{ECAL}])

Very Basic View of Particle Flow

"Clean" the Event During Reconstruction!

Find and "remove" muons (σ_{track})

Find and "remove" electrons (min[σ_{track}, σ_{ECAL}])

Find and "remove" converted photons

Very Basic View of Particle Flow

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"Clean" the Event During Reconstruction!

Find and "remove" muons (σ_{track})

Find and "remove" electrons (min[σ_{track}, σ_{ECAL}])

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Very Basic View of Particle Flow

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Very Basic View of Particle Flow

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UIC University of Illinois at Chicago

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Find and "remove" V0's

Very Basic View of Particle Flow

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Find and "remove" photons (σ_{ECAL})

Left with neutral hadrons (10%)

Very Basic View of Particle Flow

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UIC University of Illinois at Chicago

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

Very Basic View of Particle Flow

"Clean" the Event During Reconstruction!

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

Use above list of Particles to describe entire event!

Very Basic View of Particle Flow

"Clean" the Event During Reconstruction!

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Find and "remove" photons (σ_{ECAL})

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

Use above list of Particles to describe entire event!

Very Basic View of Particle Flow

Fermilab
UIC University of Illinois at Chicago

"Clean" the Event During Reconstruction!

10 TeV!

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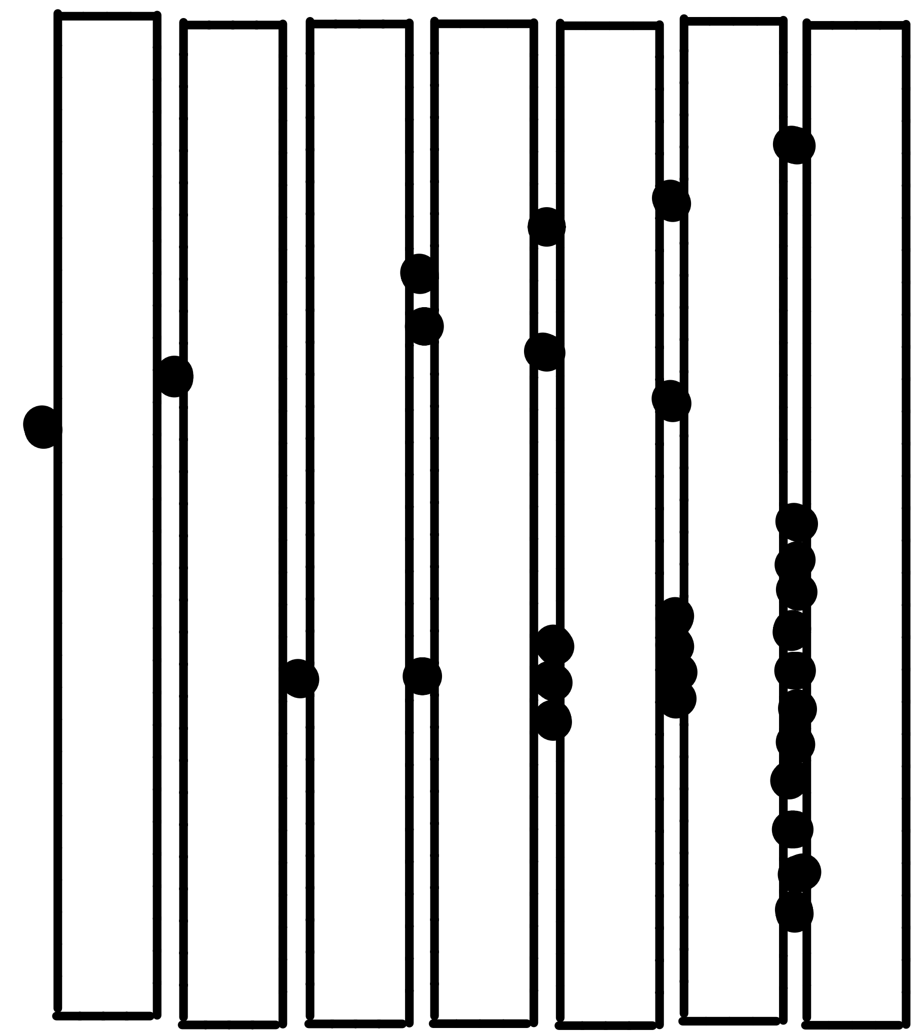
Find and "remove" converted photons (min[σ_{track}, σ_{ECAL}])
Find and "remove" charged hadrons (min[σ_{track}, σ_{HCAL}])
Find and "remove" V0's (σ_{track})
Find and "remove" photons (σ_{ECAL})
Left with neutral hadrons (10%) (σ_{HCAL} + fake)

Use above list of Particles to describe entire event!

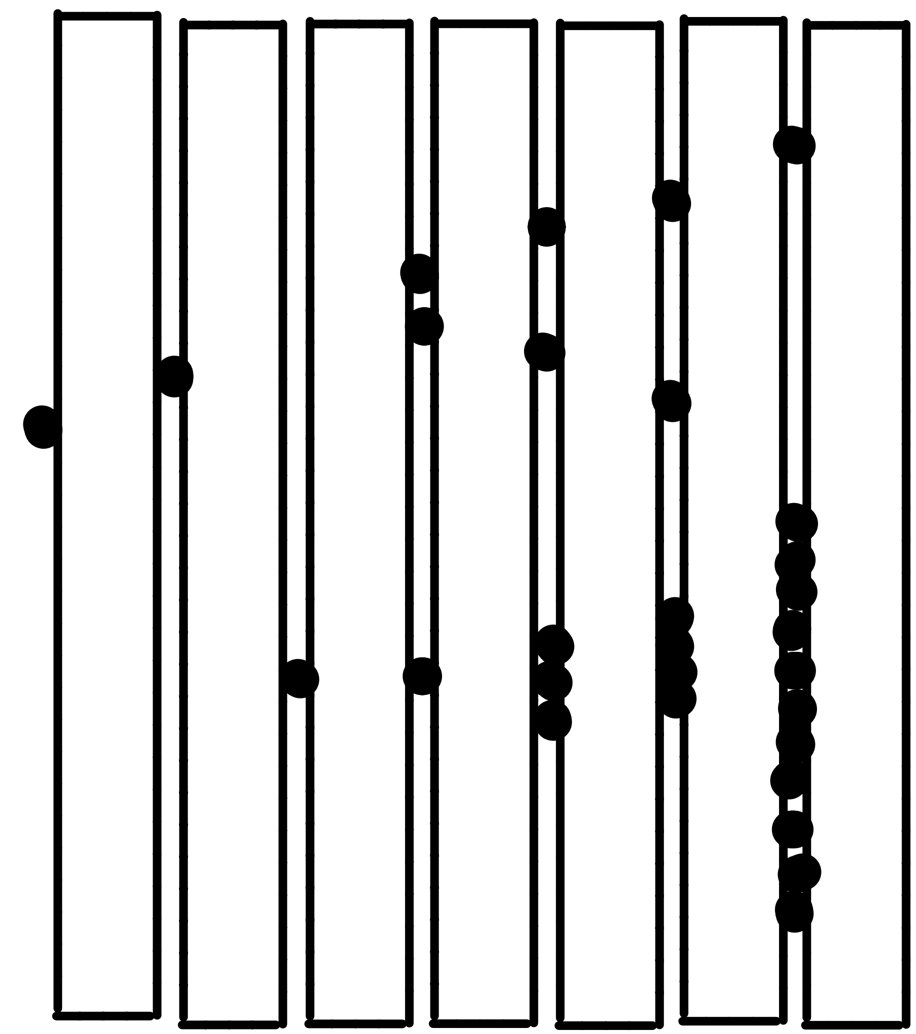
Calorimetric Particle Flow



Calorimetric Particle Flow

Fermilab
UIC University of Illinois at Chicago

Developed in context of ILC:
PandoraPFA

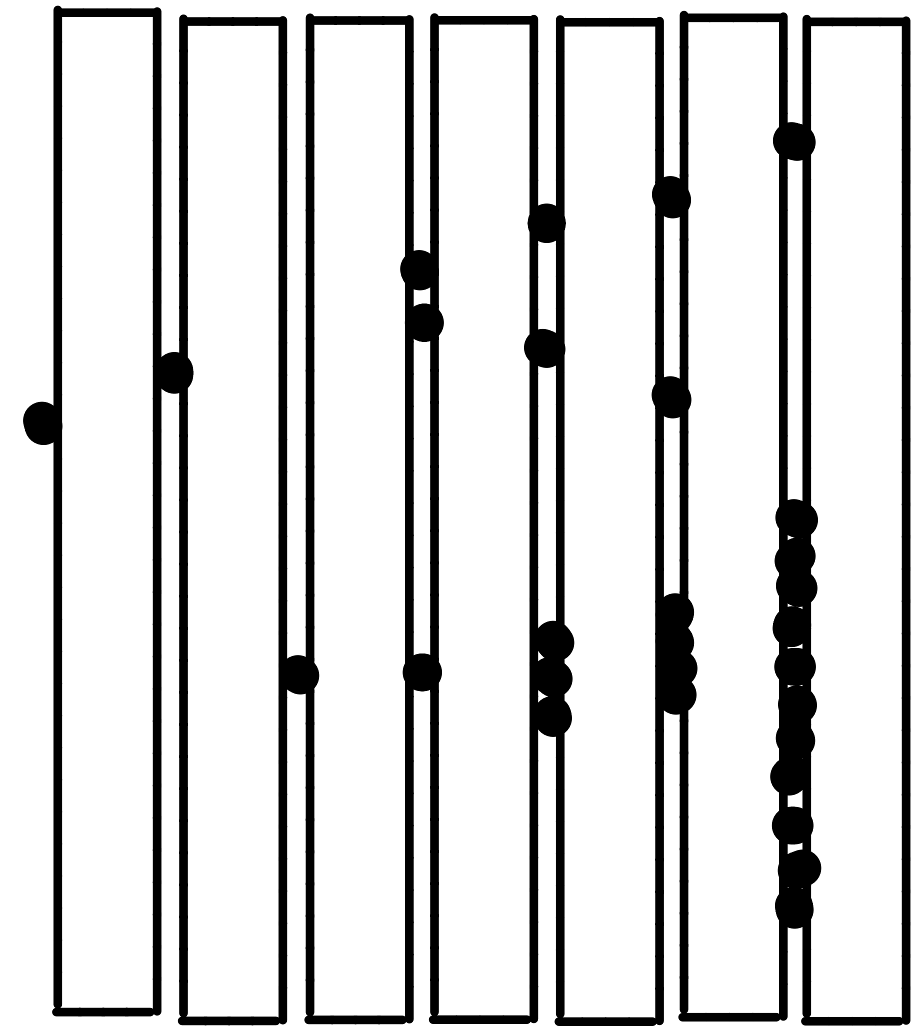


Calorimetric Particle Flow

Fermilab
UIC University of Illinois at Chicago

Developed in context of ILC: PandoraPFA

Several steps:

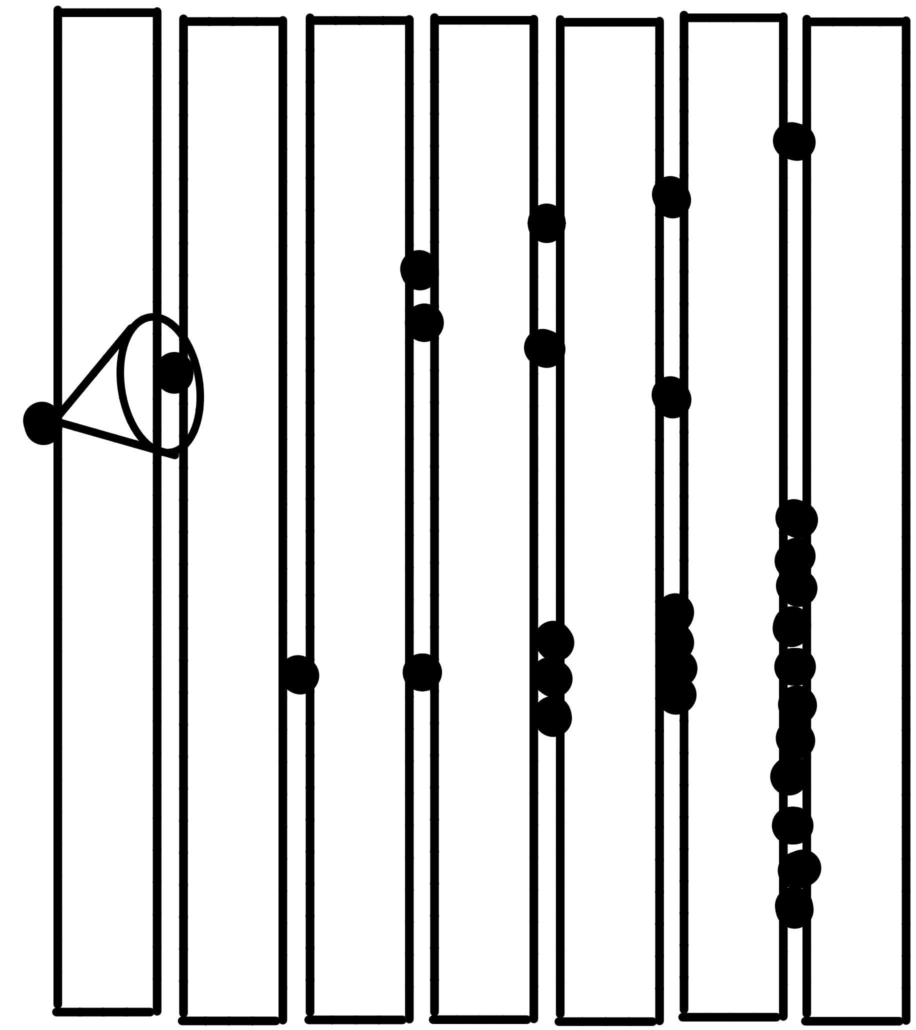


Calorimetric Particle Flow

Developed in context of ILC: PandoraPFA

Several steps:

- Loose clustering ECAL & HCAL



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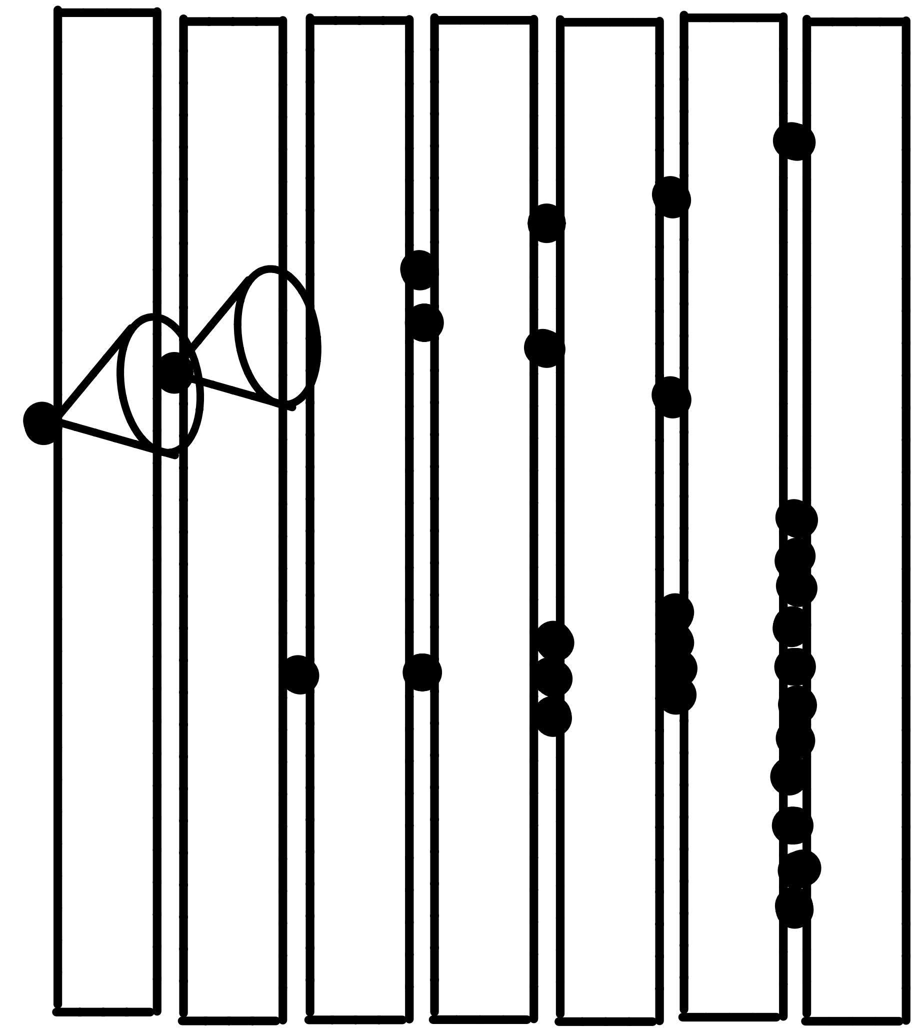

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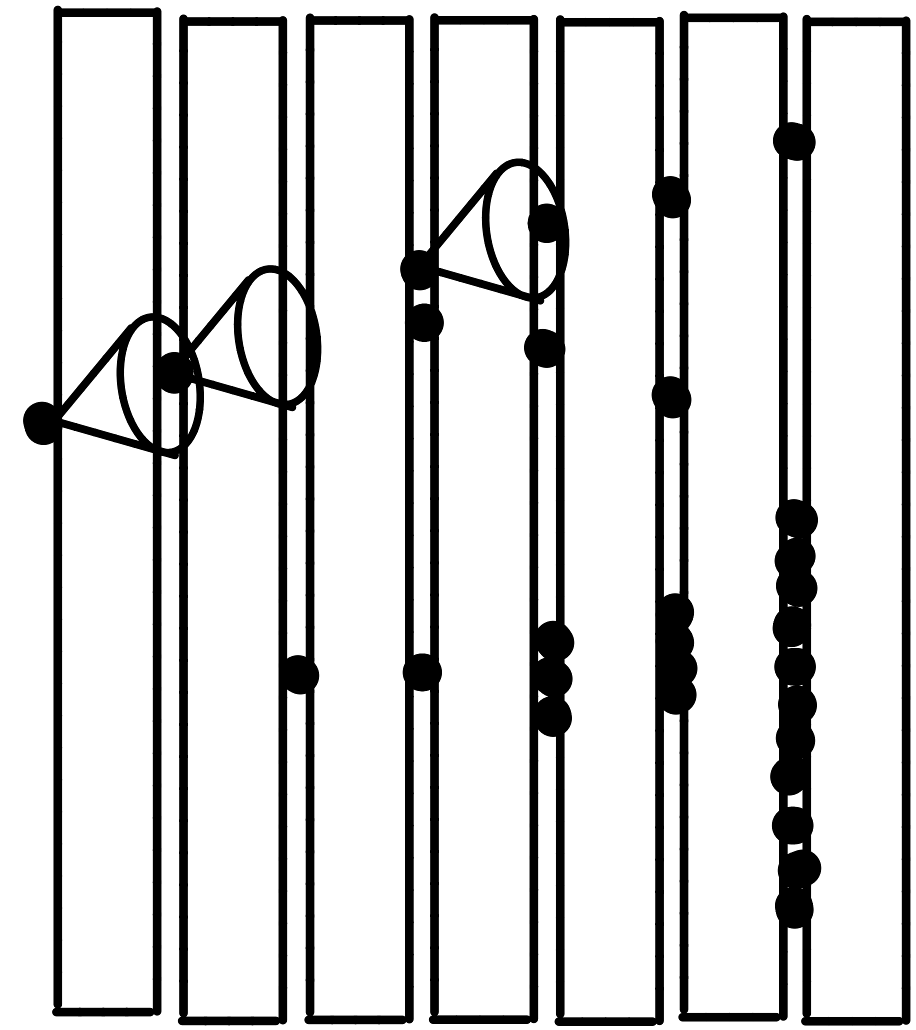

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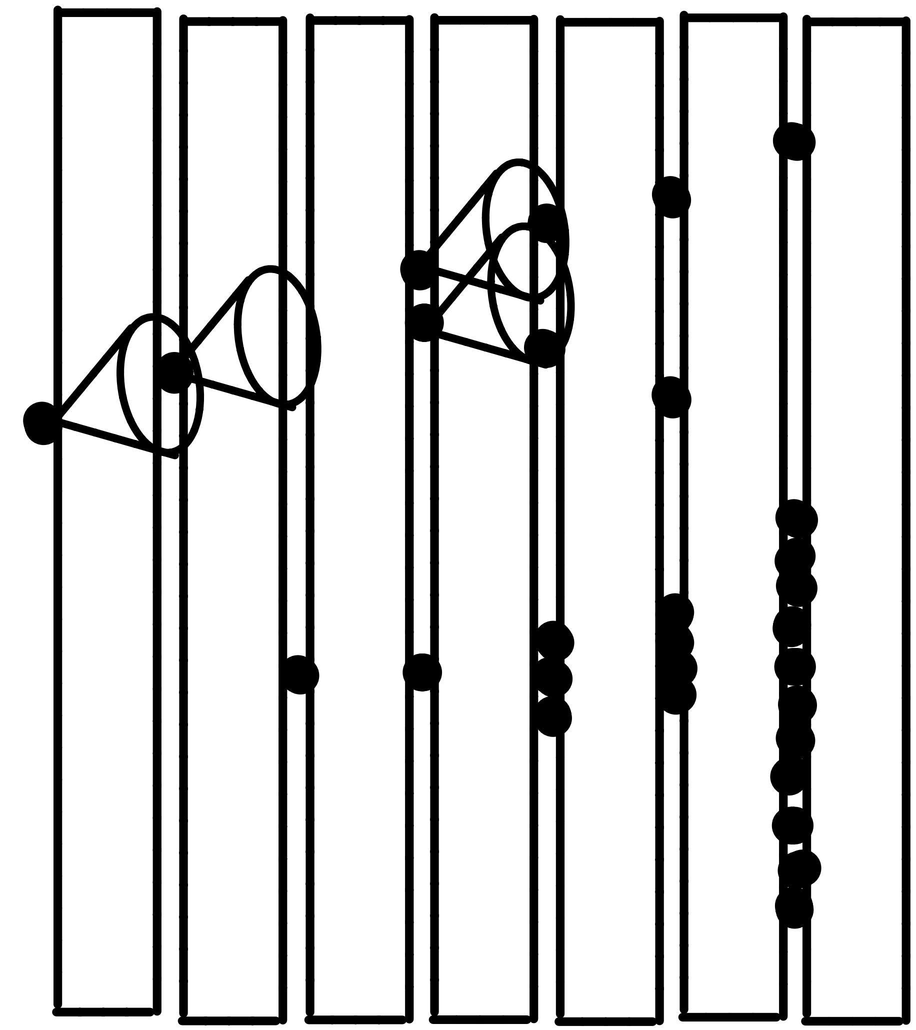

Fermilab
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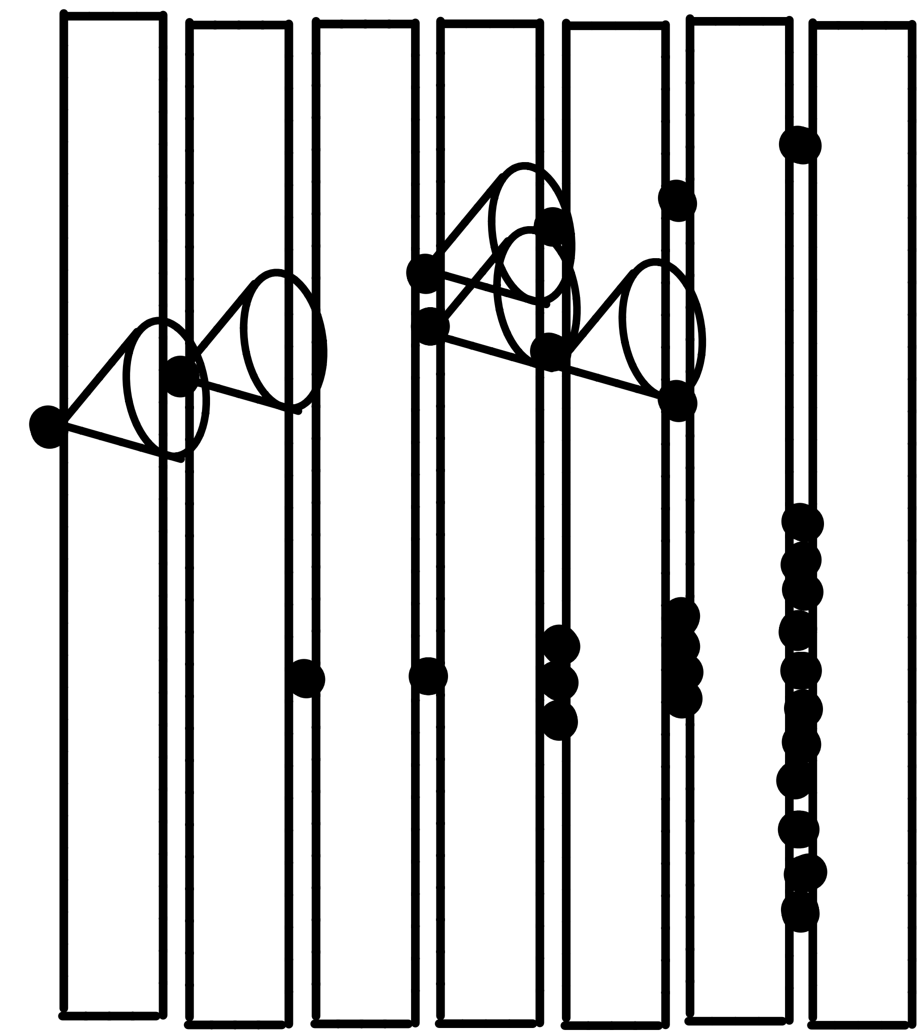

Calorimetric Particle Flow

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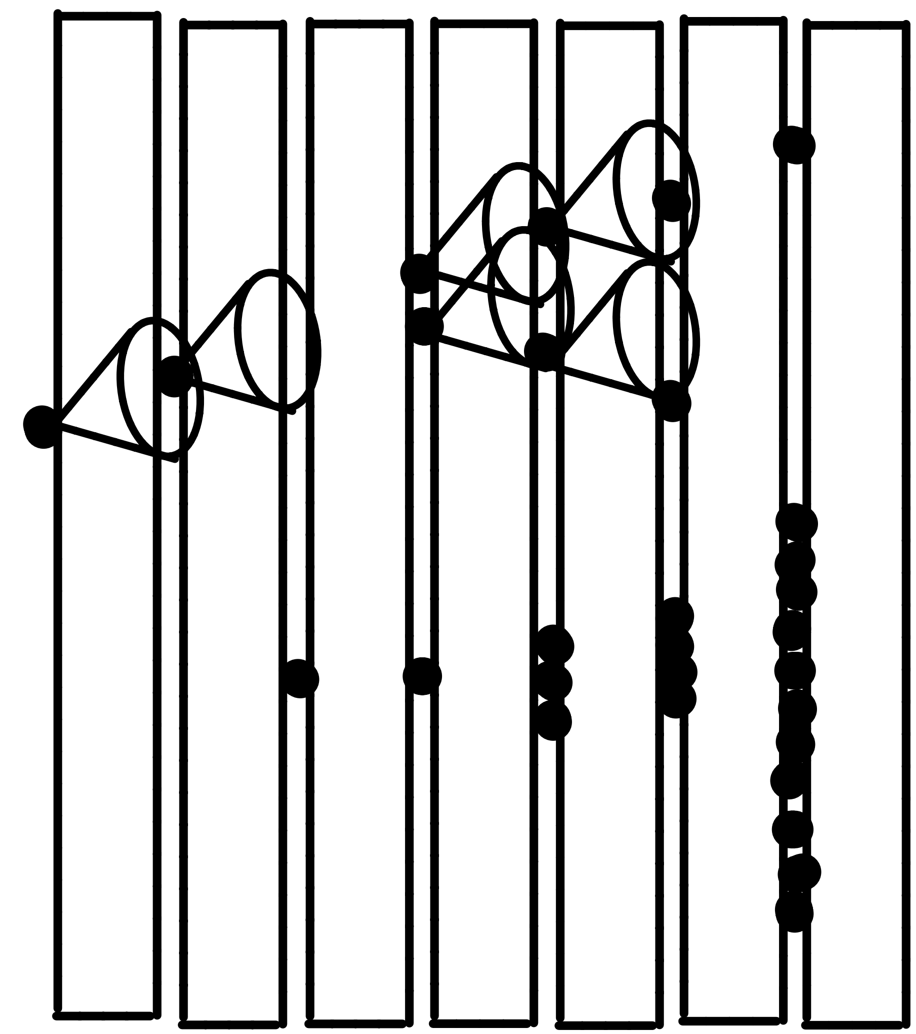

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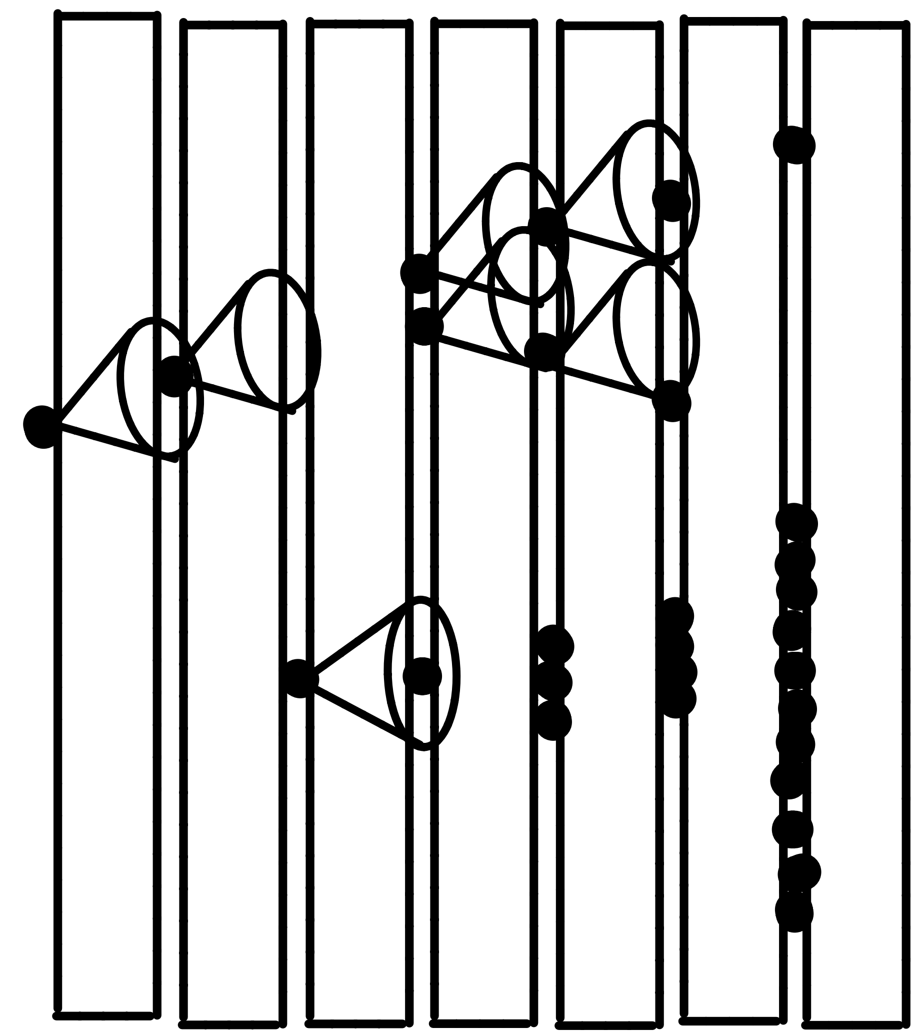

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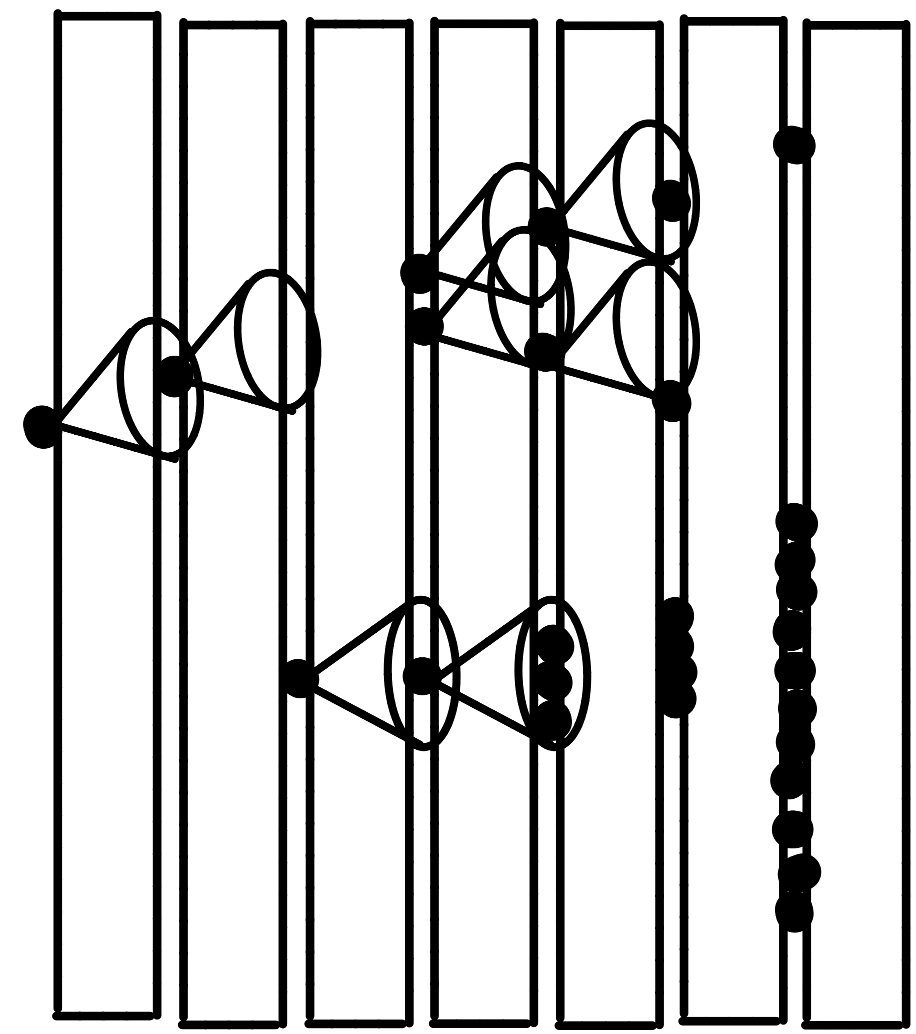

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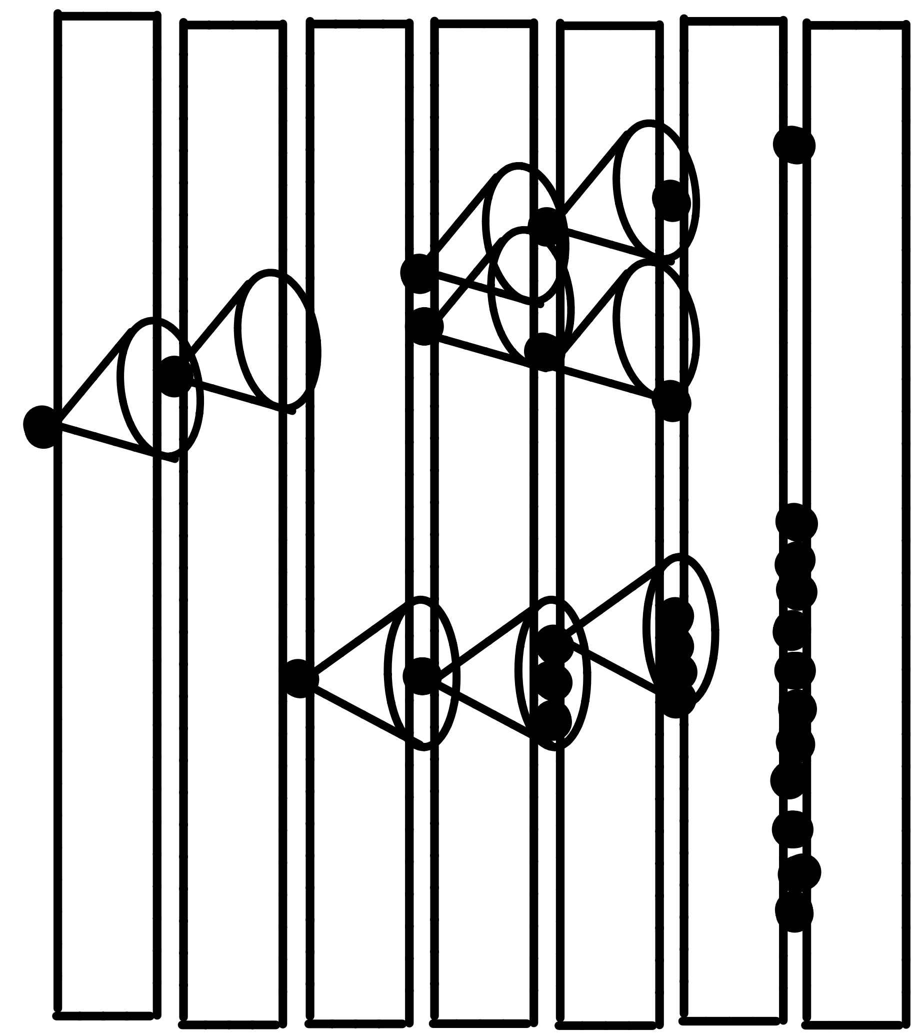

R. Cavanaugh 100 TeV Workshop, SLAC 23-26 August, 2014

Calorimetric Particle Flow

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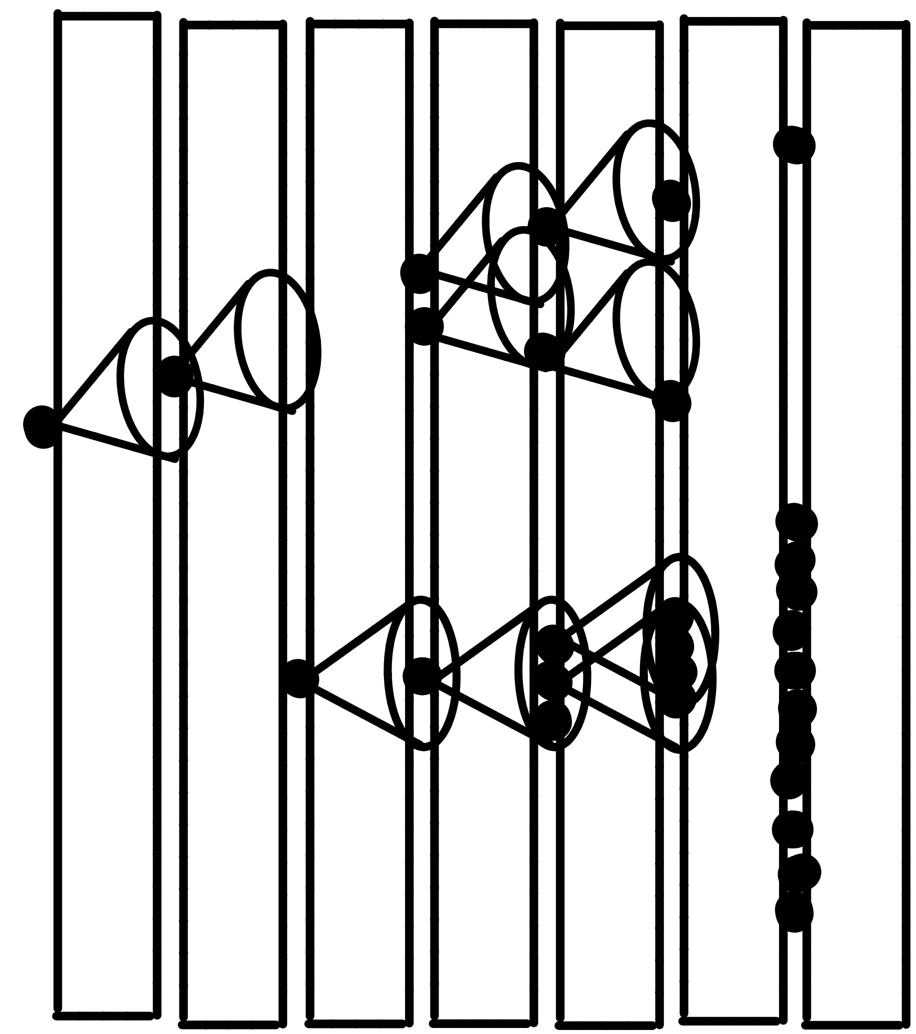

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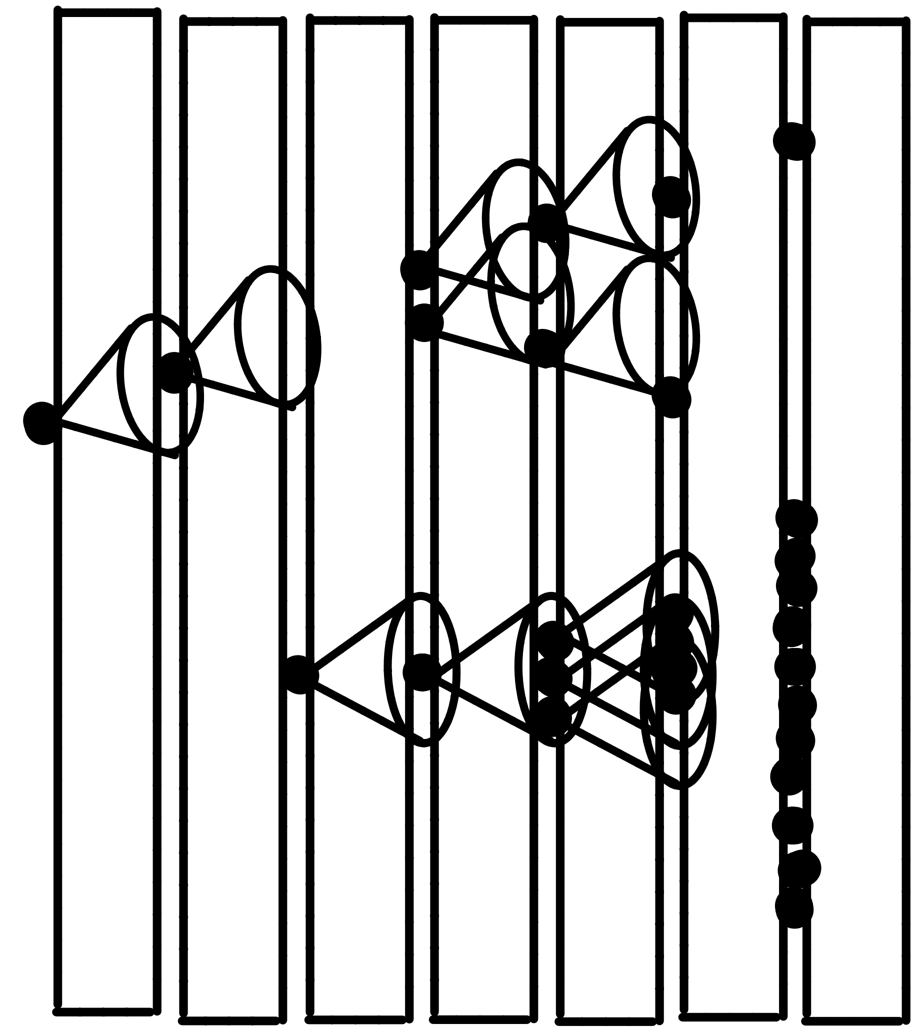
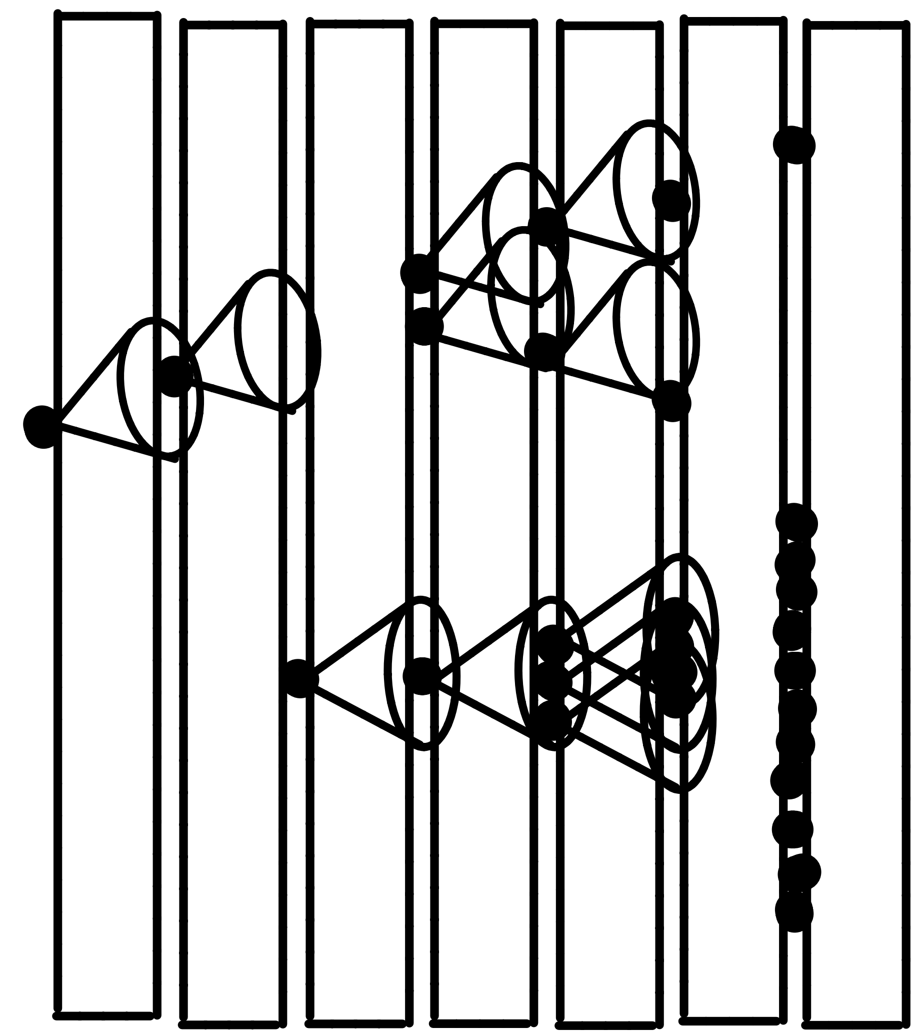


Calorimetric Particle Flow

Developed in context of ILC: PandoraPFA

Several steps:

- Loose clustering ECAL & HCAL
- Topological linking of clearly associated clusters



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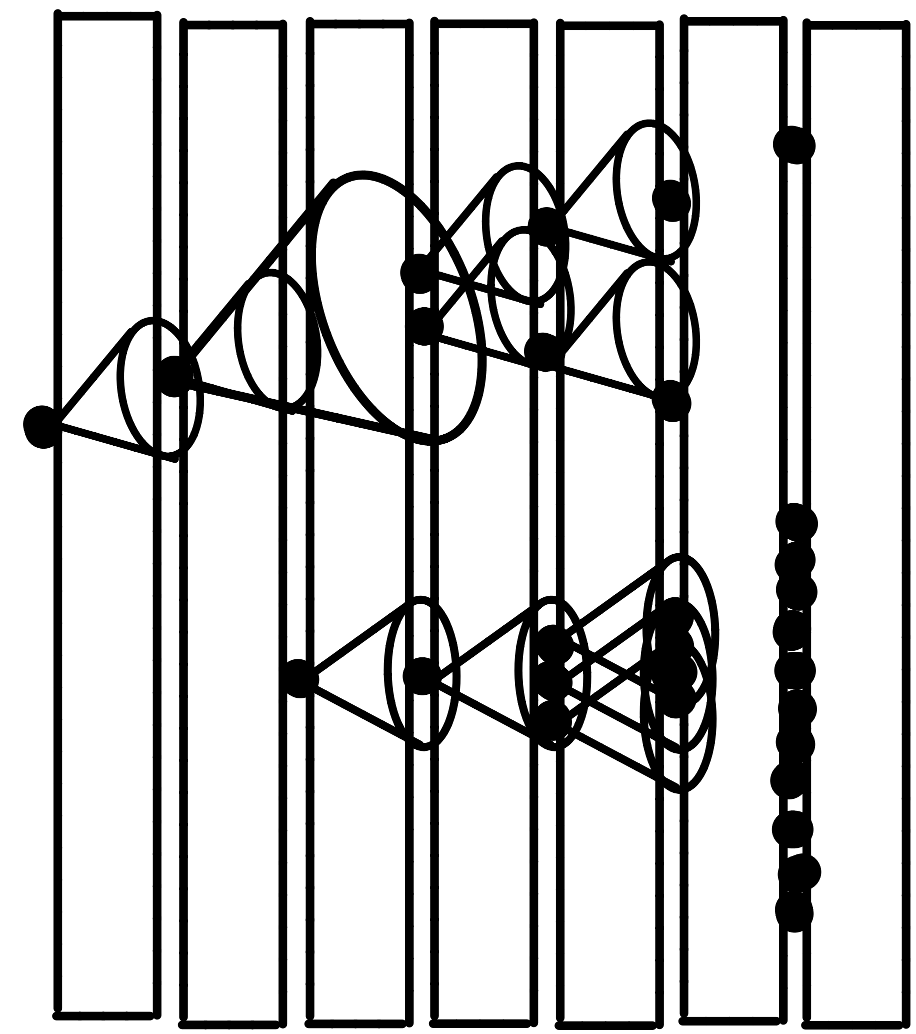

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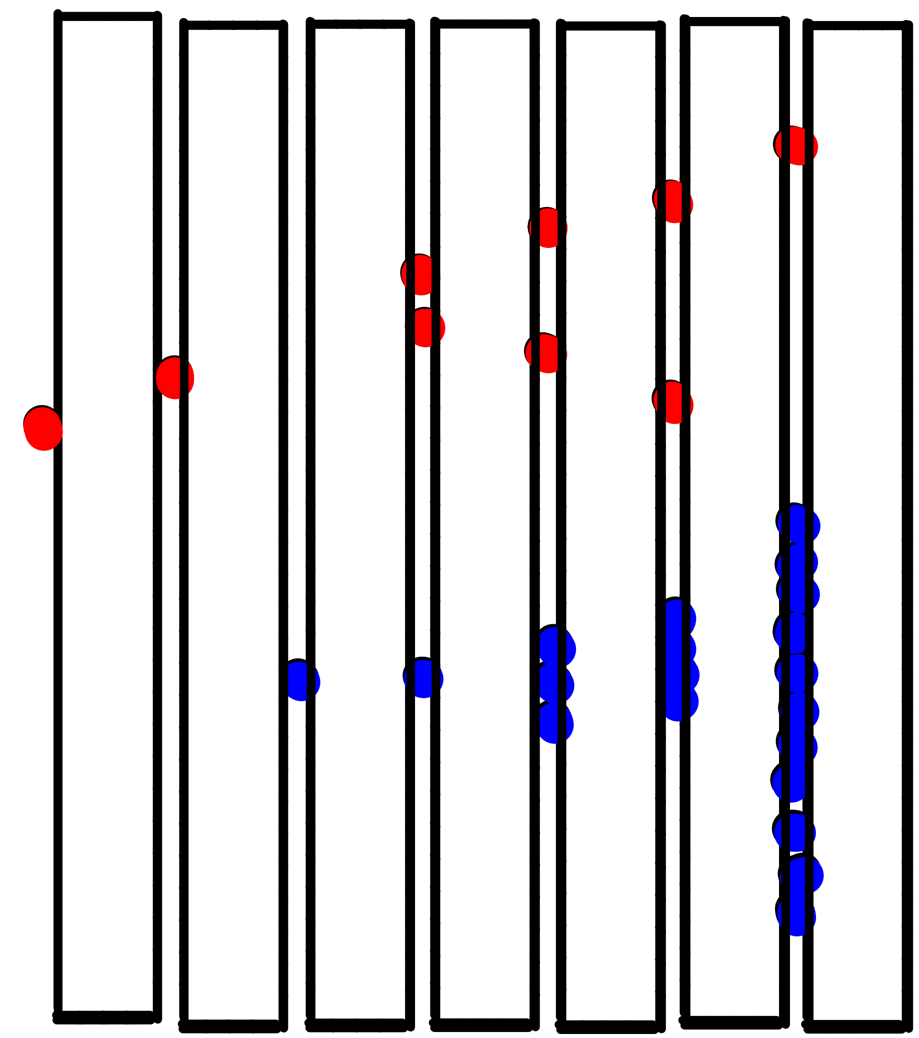
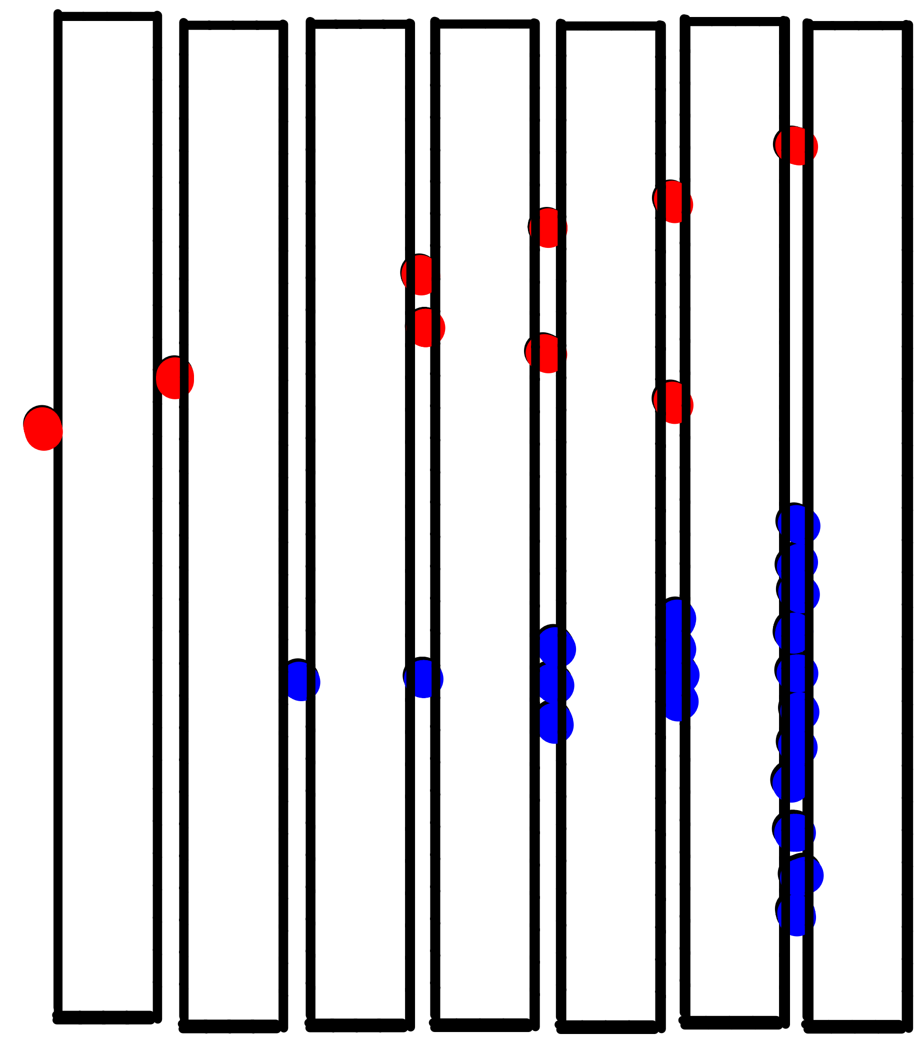


Calorimetric Particle Flow

Developed in context of ILC: PandoraPFA

Several steps:

- Loose clustering ECAL & HCAL
- Topological linking of clearly associated clusters
- Courser grouping of clusters
- Iterative reclustering
- Photon ID & recovery
- Fragment removal



Calorimetric Particle Flow

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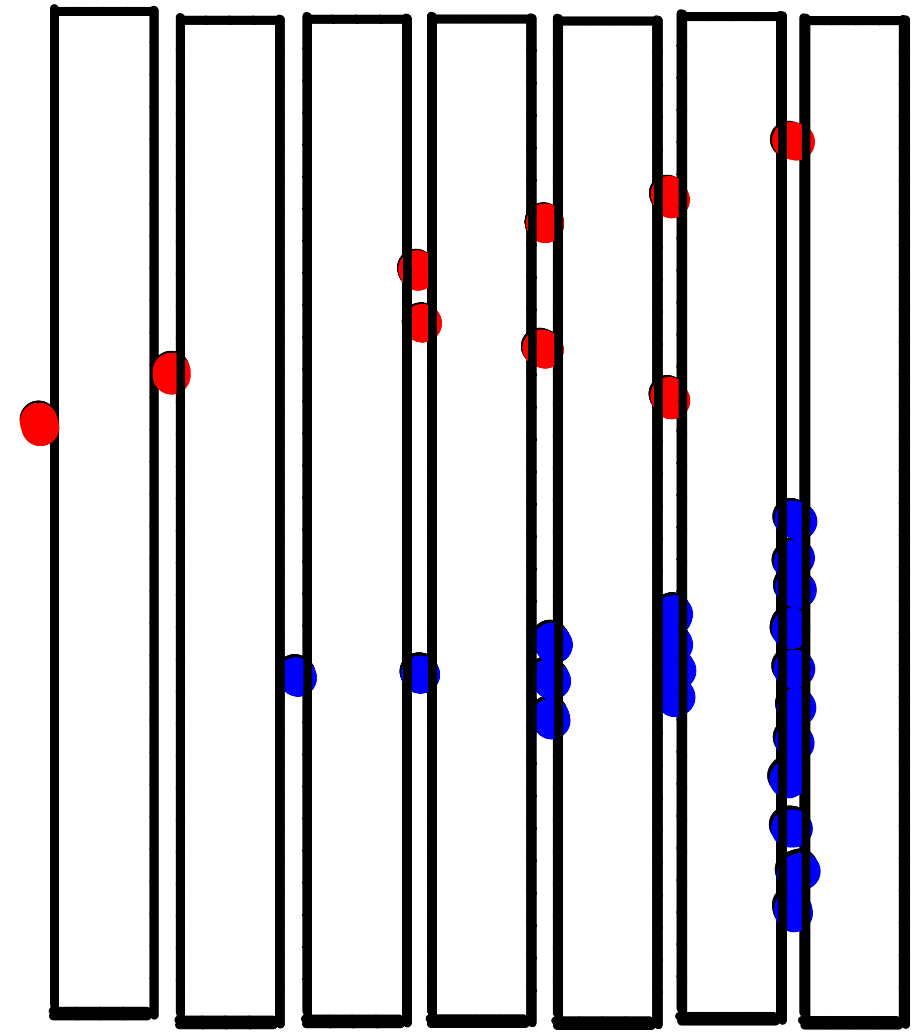
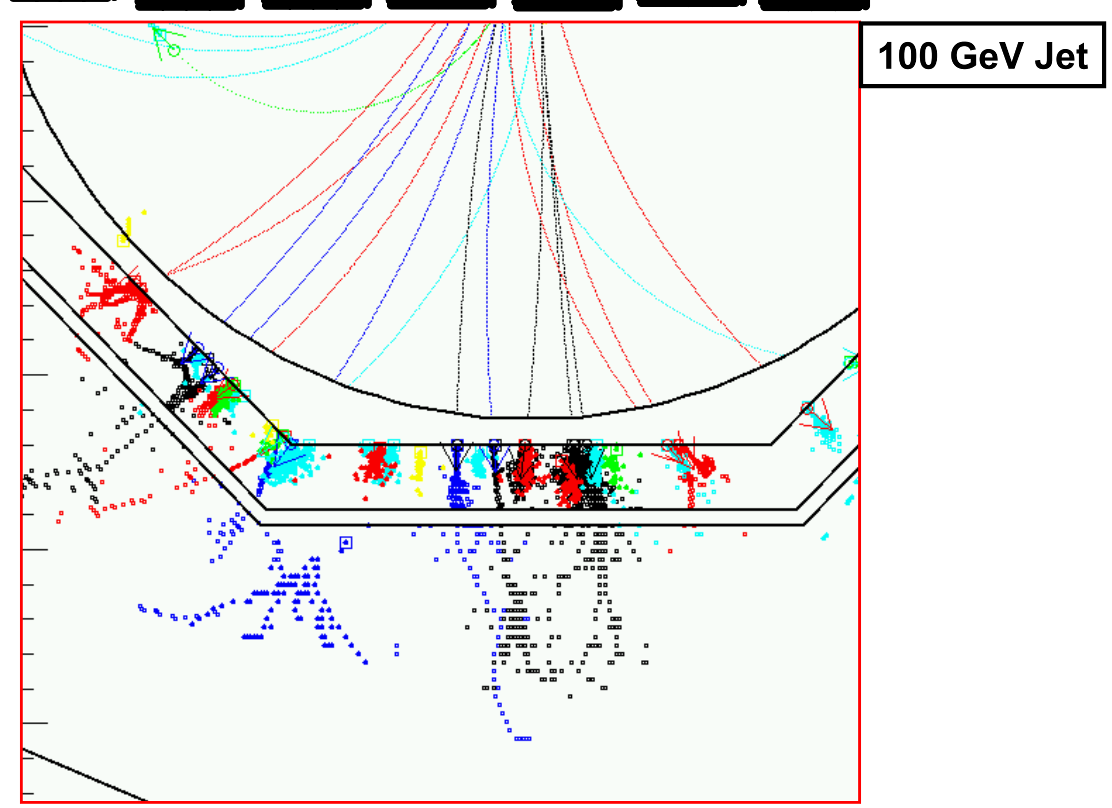
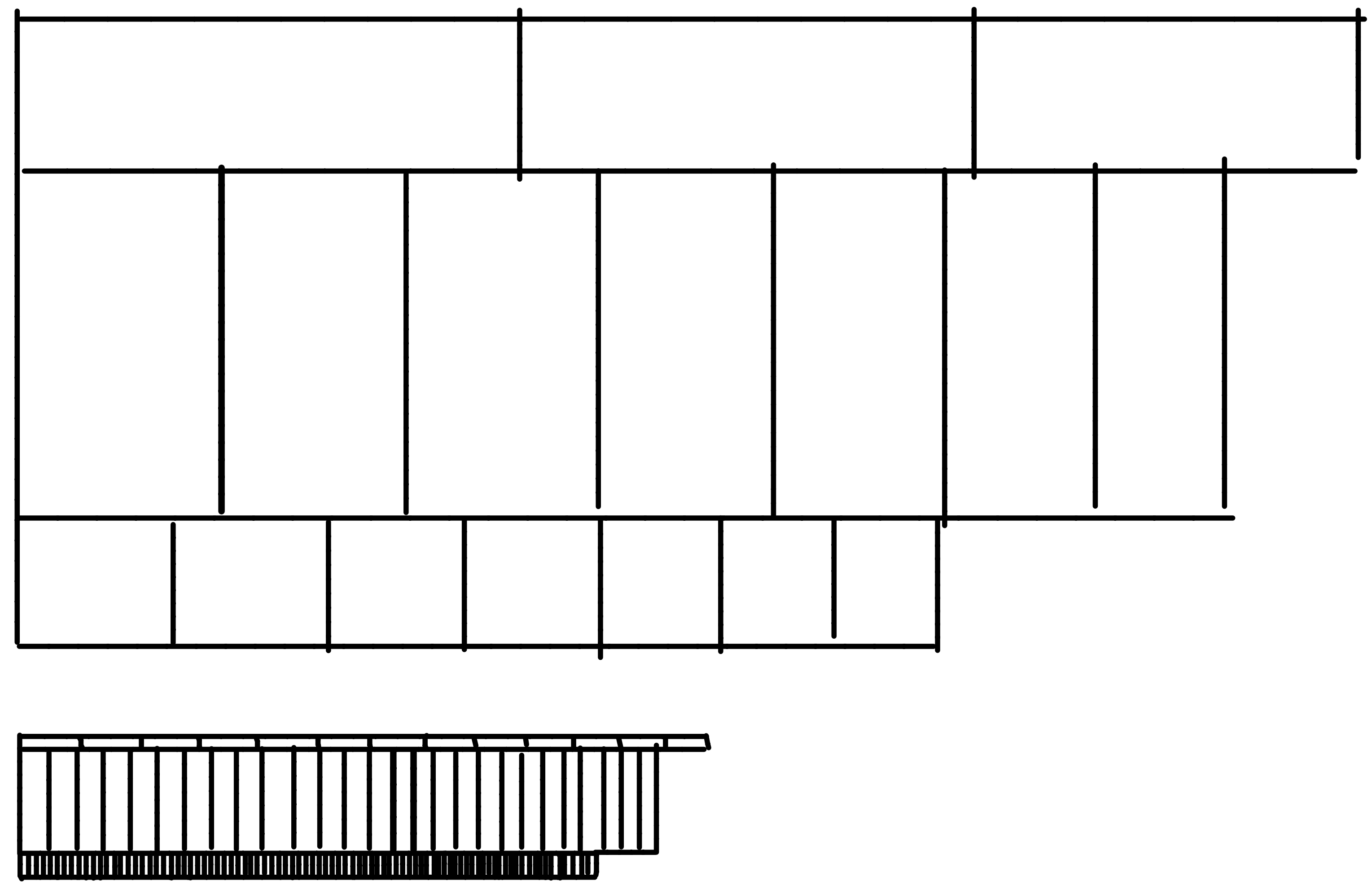
Several steps:

- Loose clustering ECAL & HCAL
- Topological linking of clearly associated clusters
- Courser grouping of clusters
- Iterative reclustering
- Photon ID & recovery
- Fragment removal
- Form final list of reconstructed particles



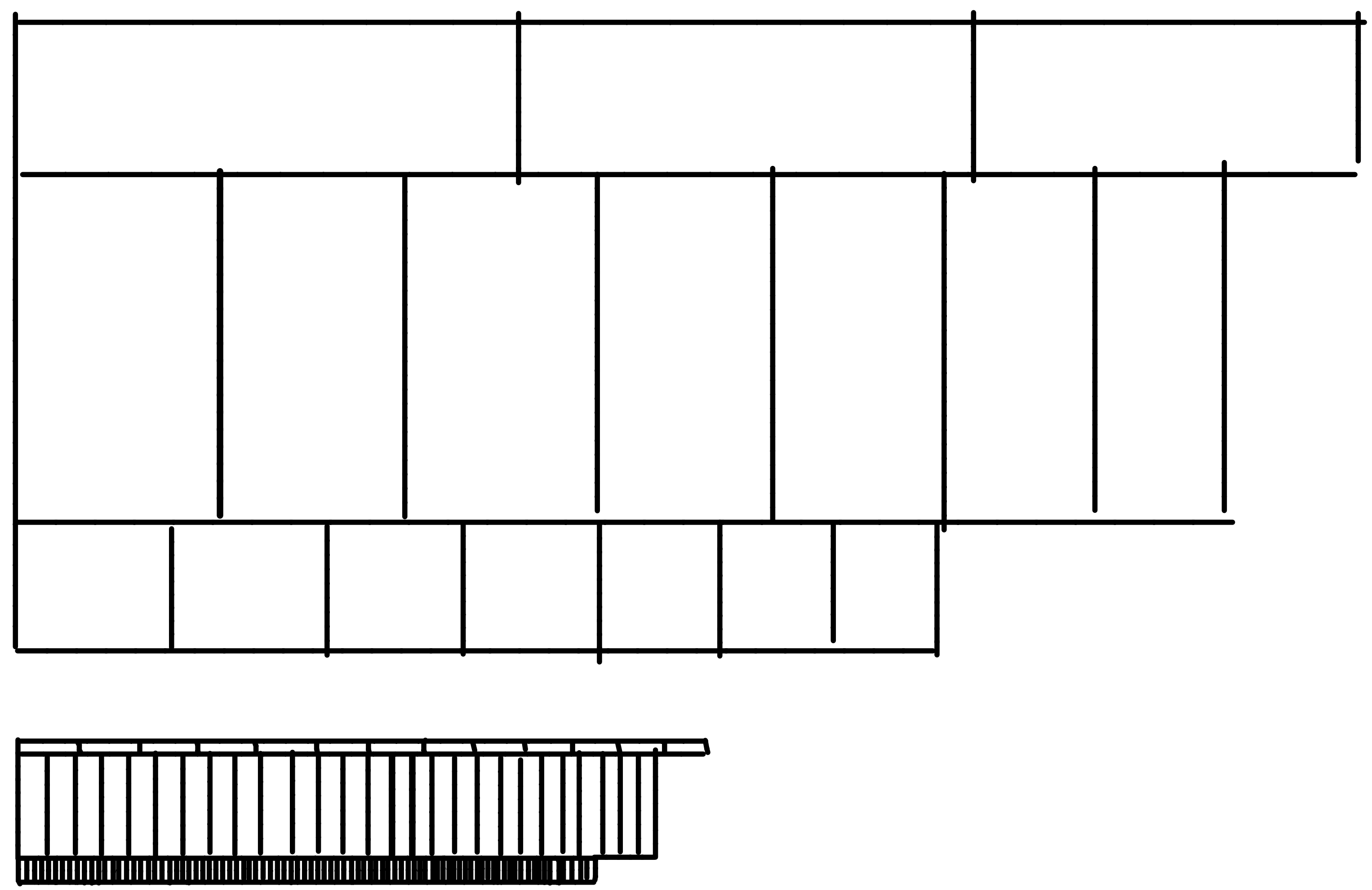


ATLAS Topo-Clusters



ATLAS Topo-Clusters

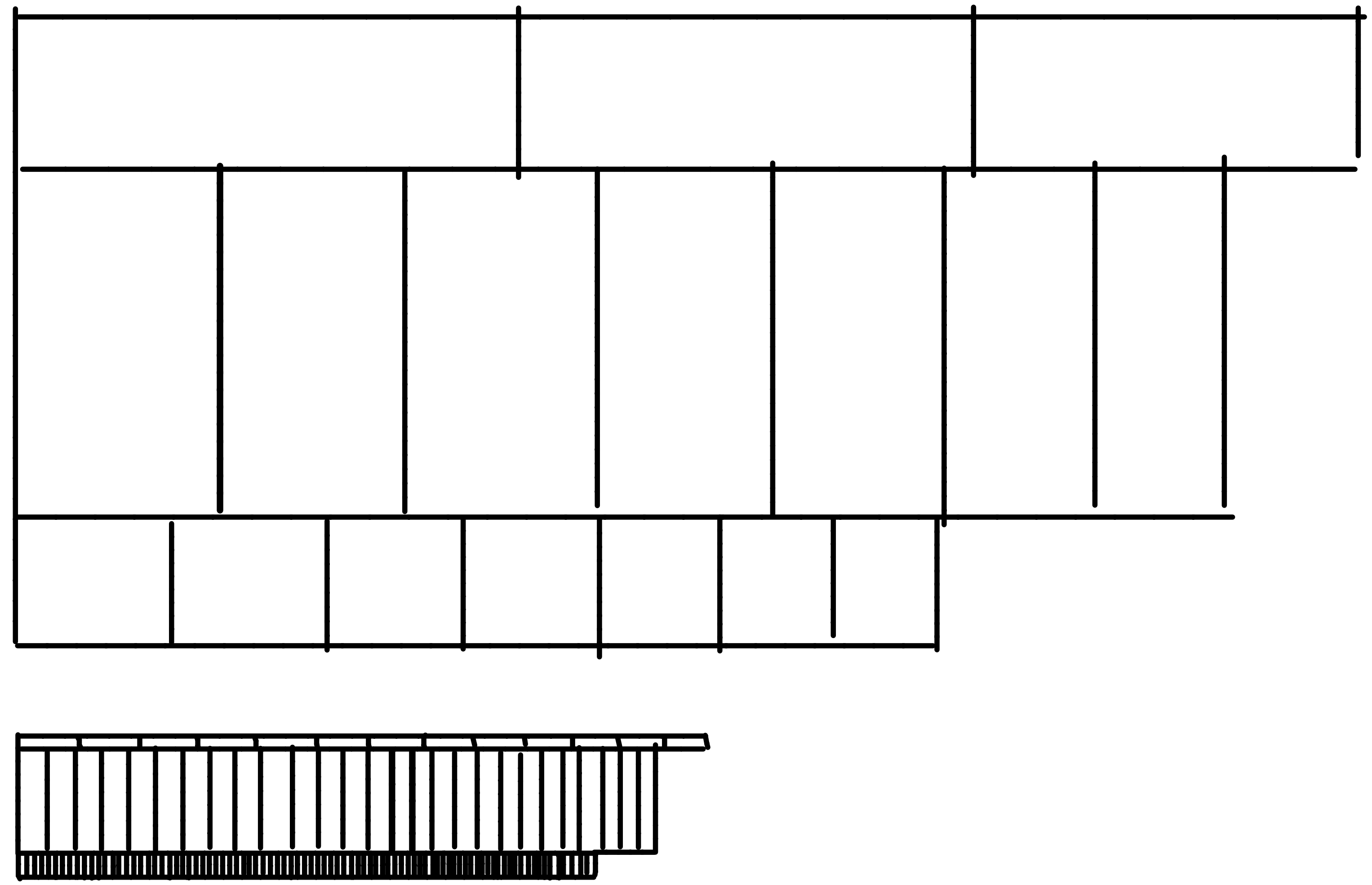
Individual particle showers



ATLAS Topo-Clusters

Individual particle showers

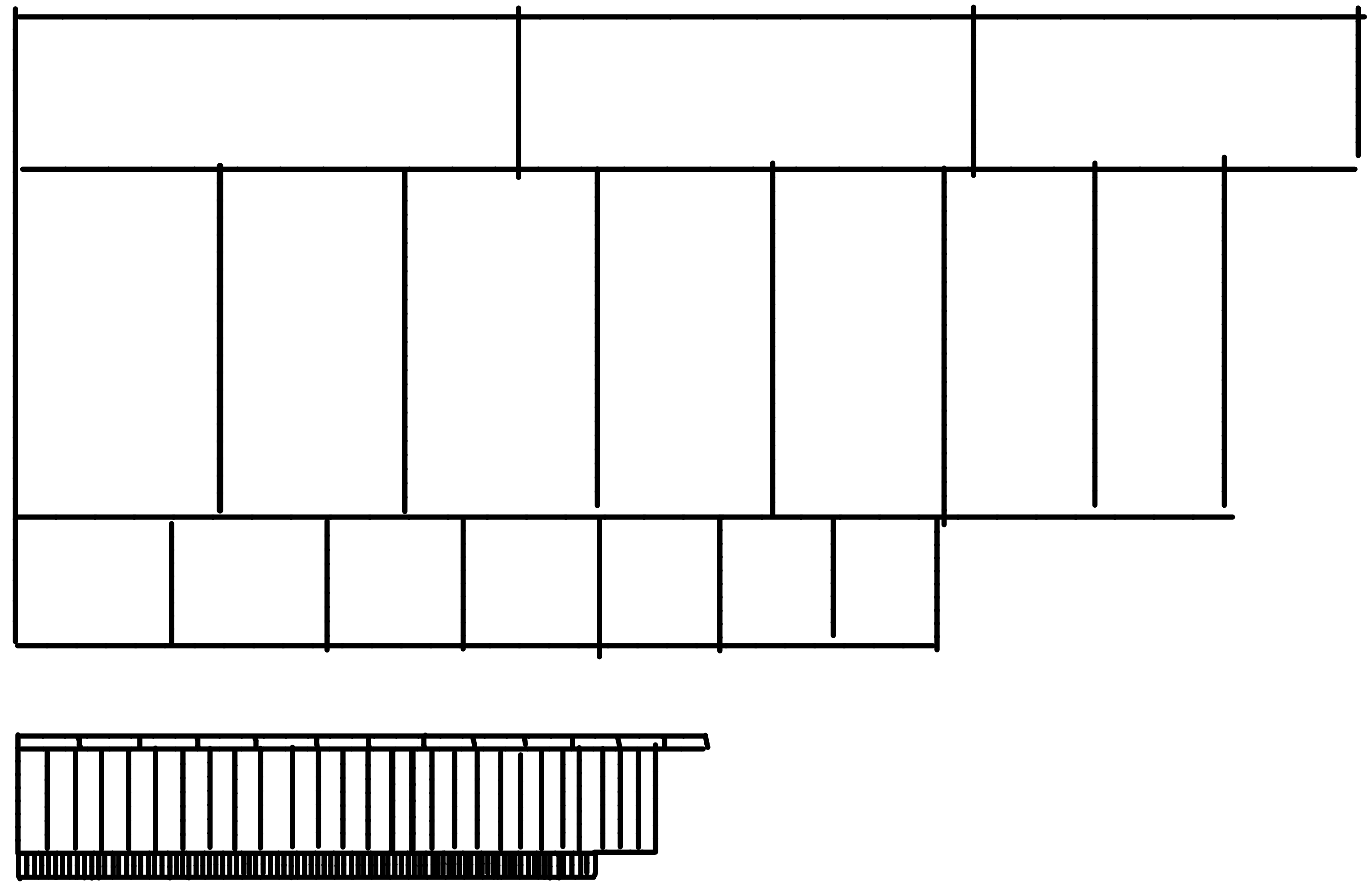
- Reco 3D clusters of cells



ATLAS Topo-Clusters

Individual particle showers

- Reco 3D clusters of cells
- seed is cell above a seed threshold



ATLAS Topo-Clusters

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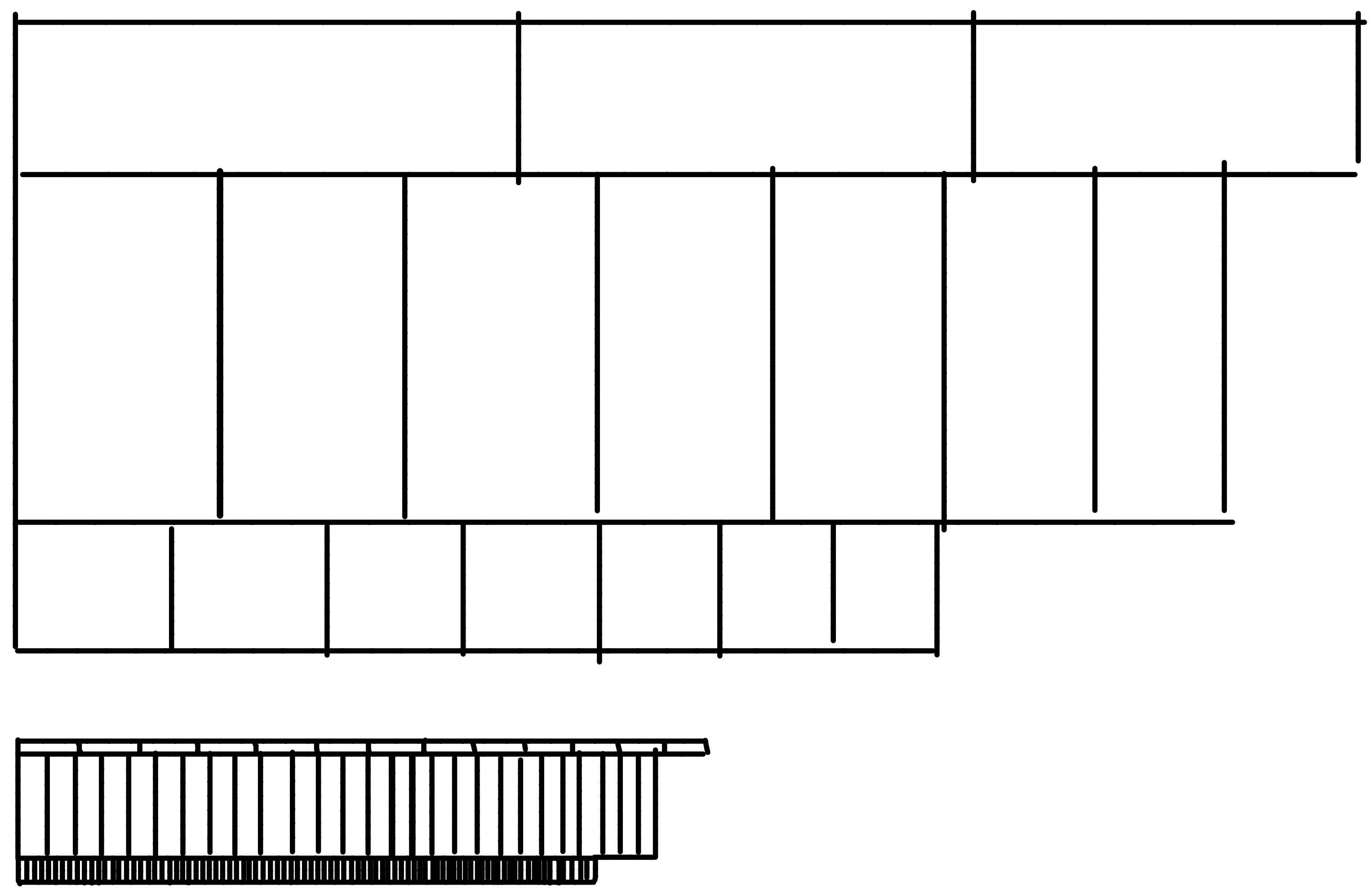

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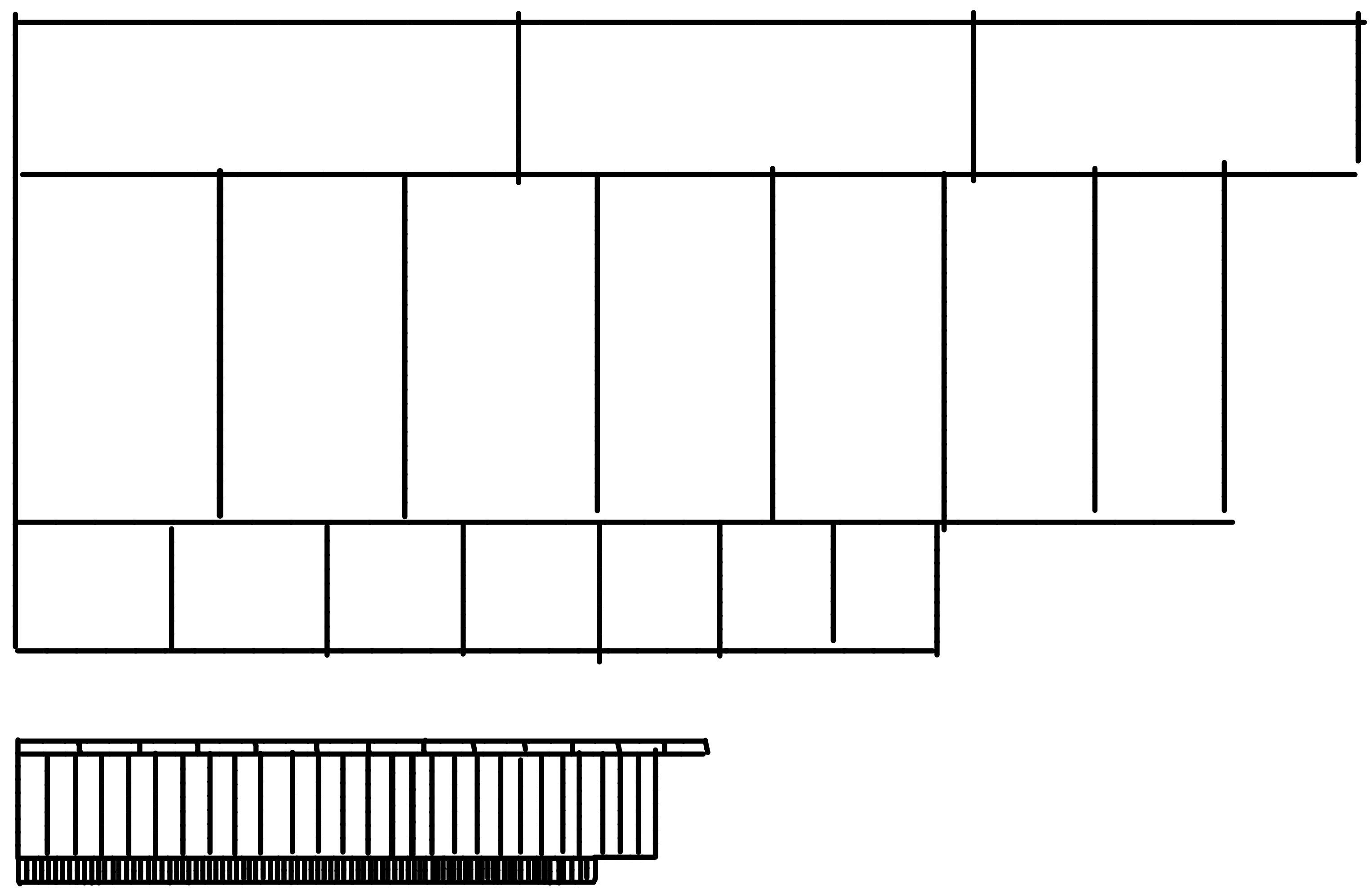
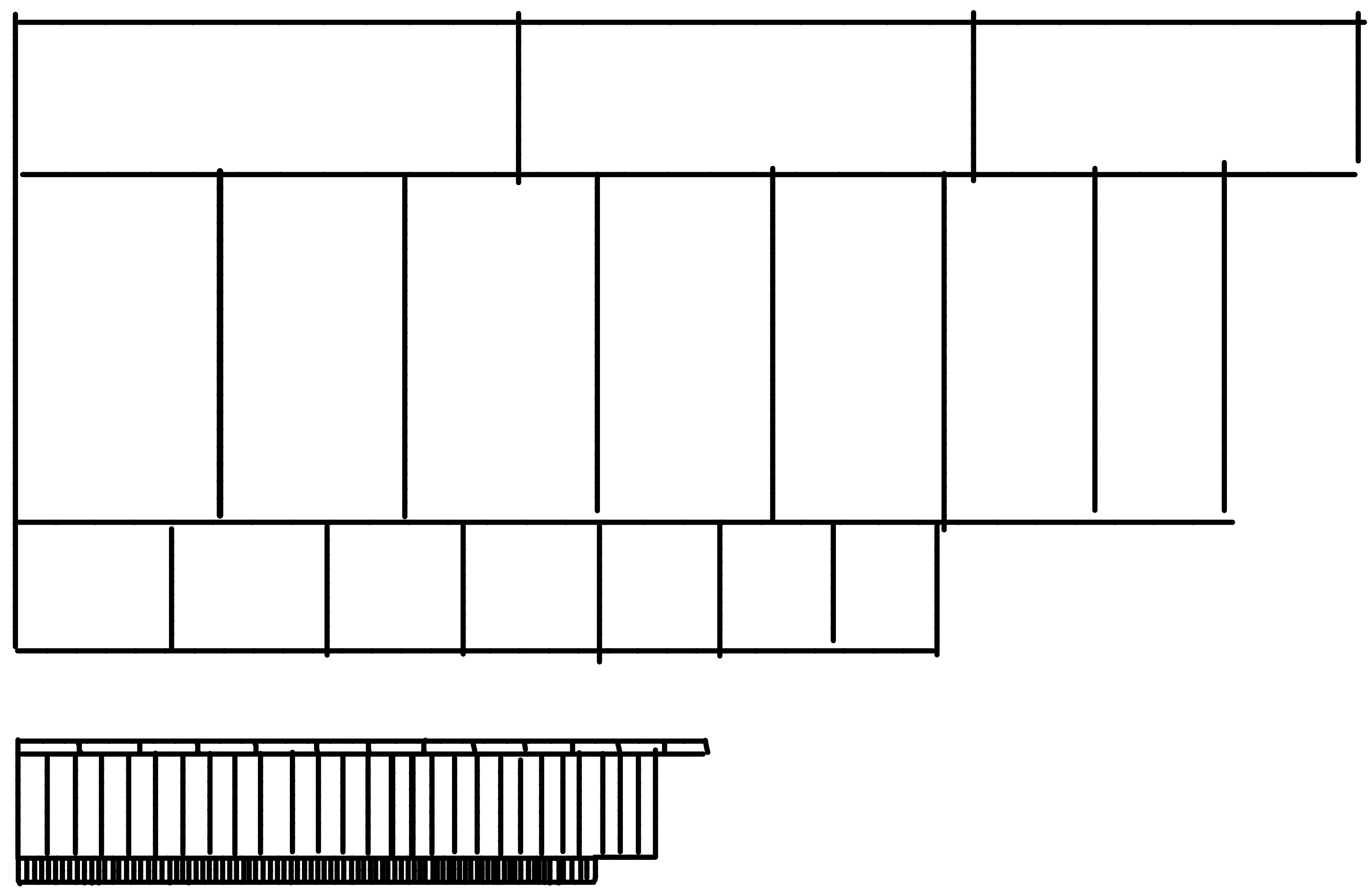


ATLAS Topo-Clusters

- Individual particle showers
  - Reco 3D clusters of cells
  - seed is cell above a seed threshold
  - link neighbouring cells above lower noise threshold
  - split cluster if more than one local maximum
- Use shape to locally calibrate



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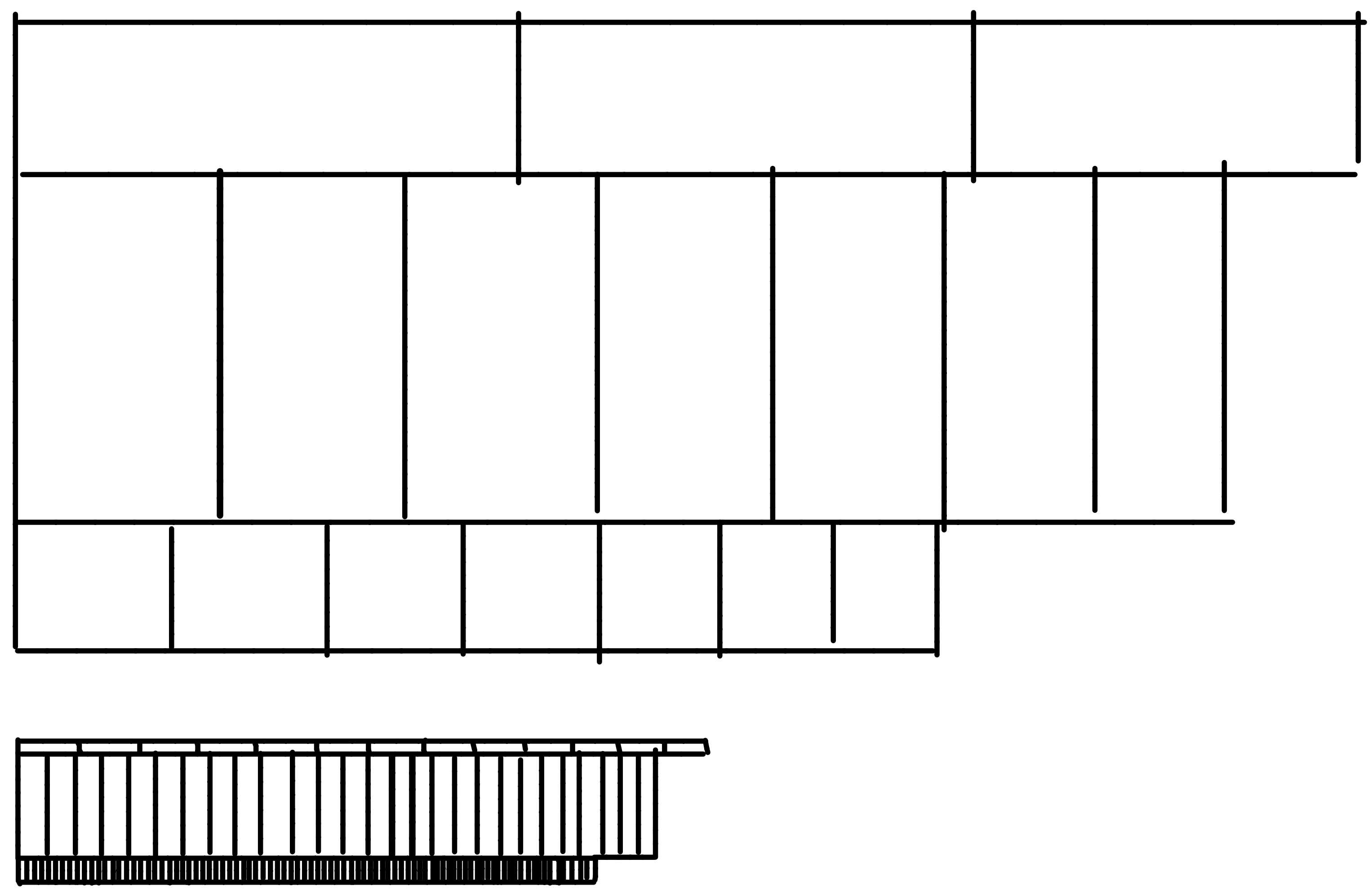
    - EM or HAD



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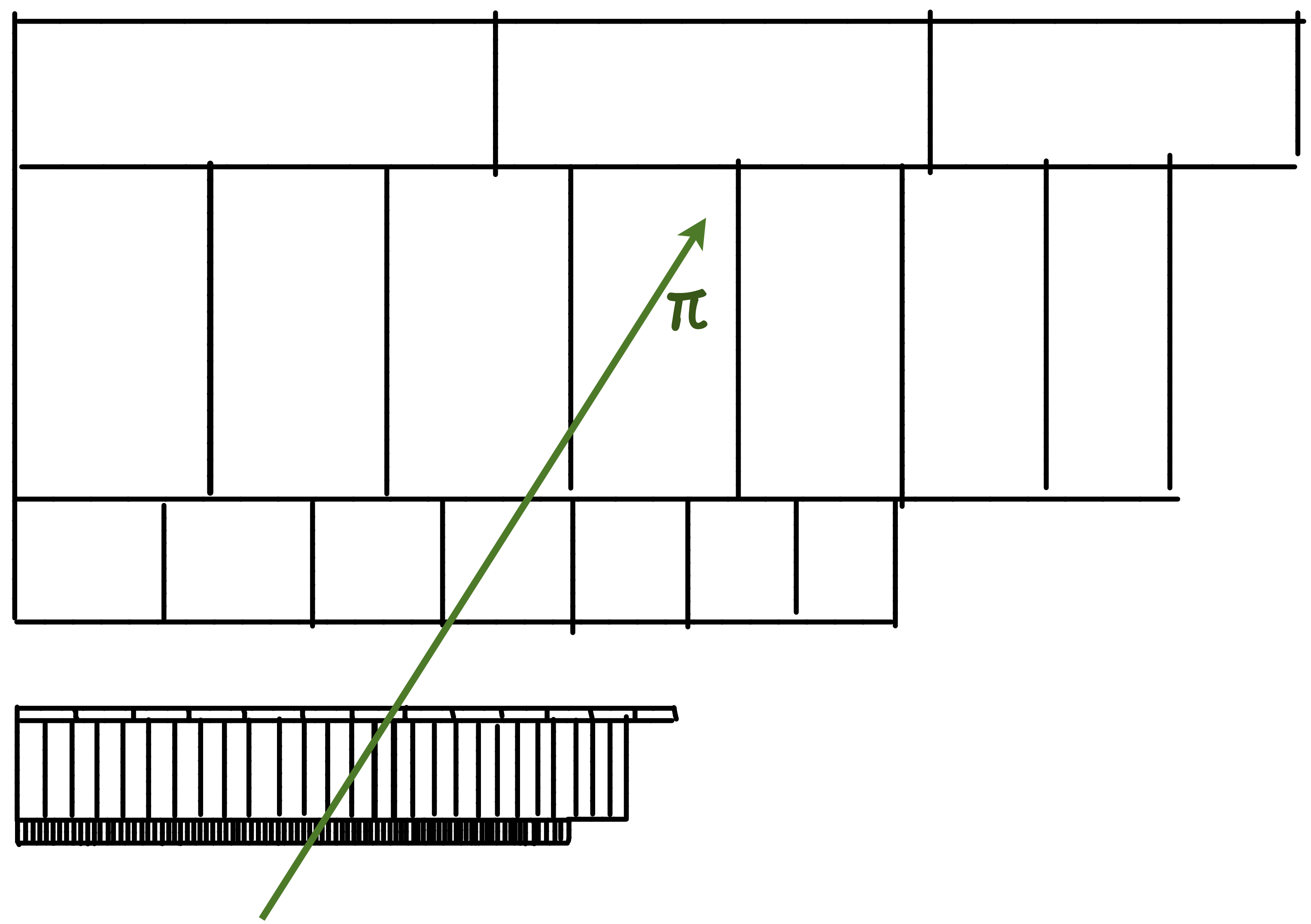

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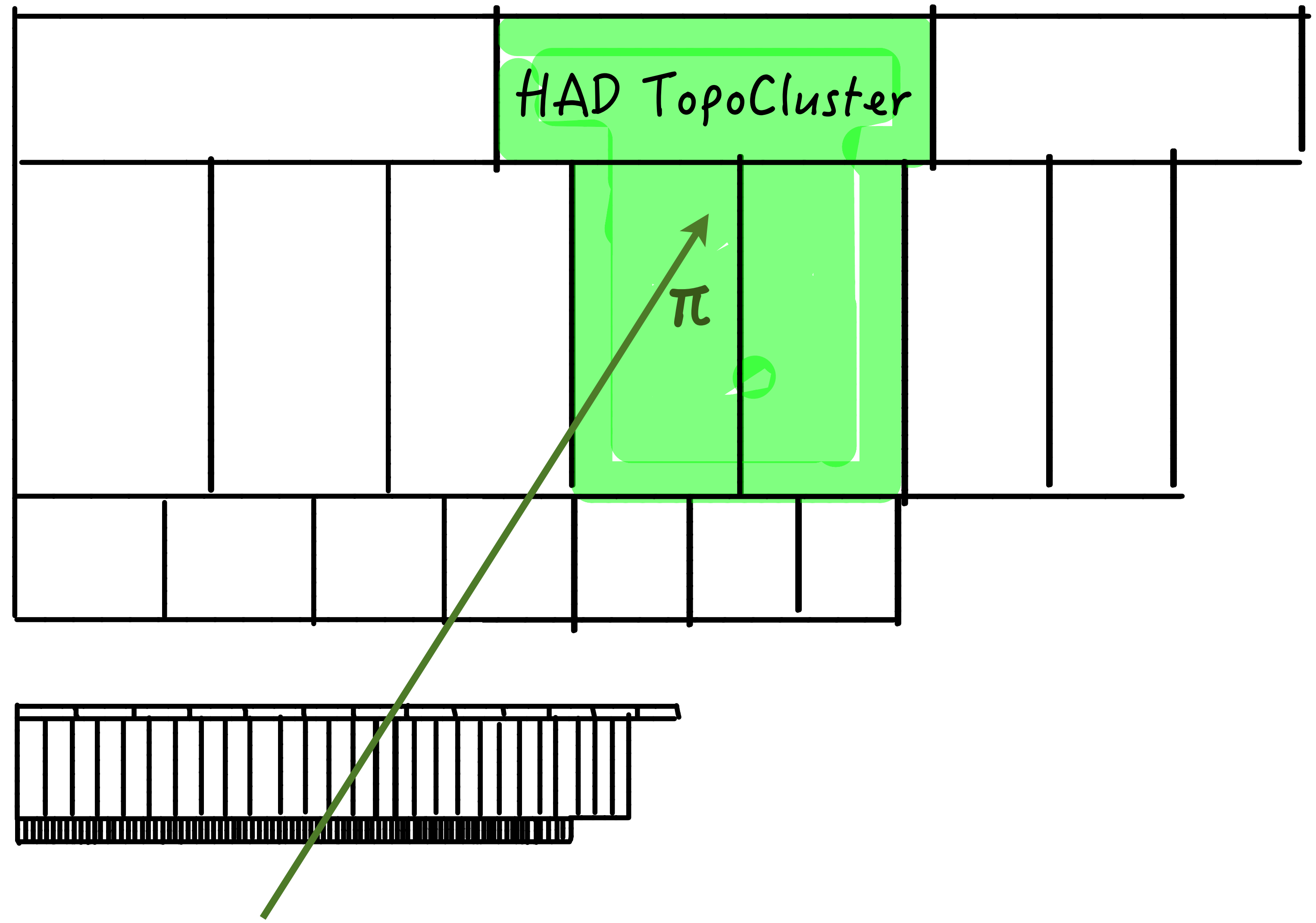

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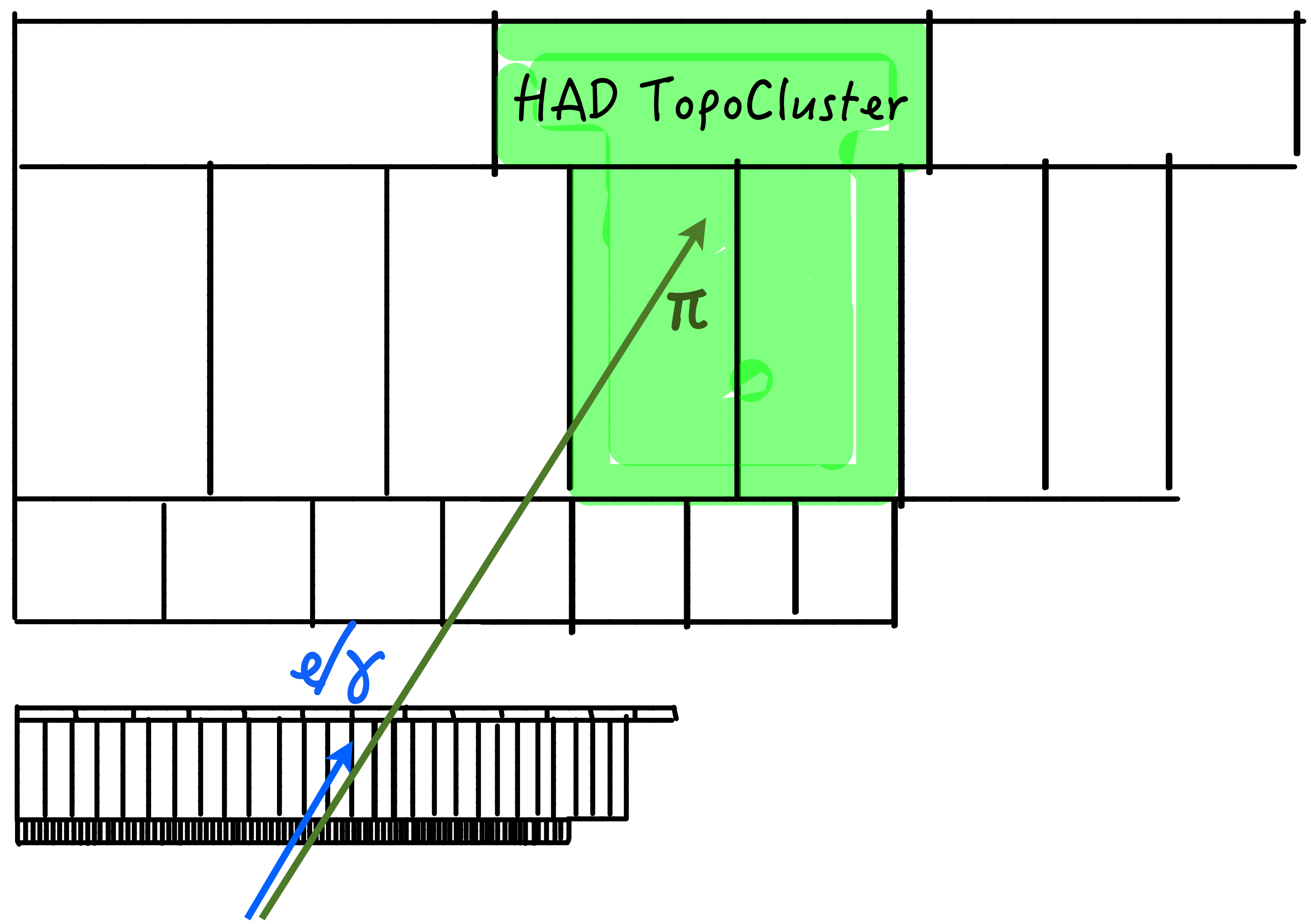

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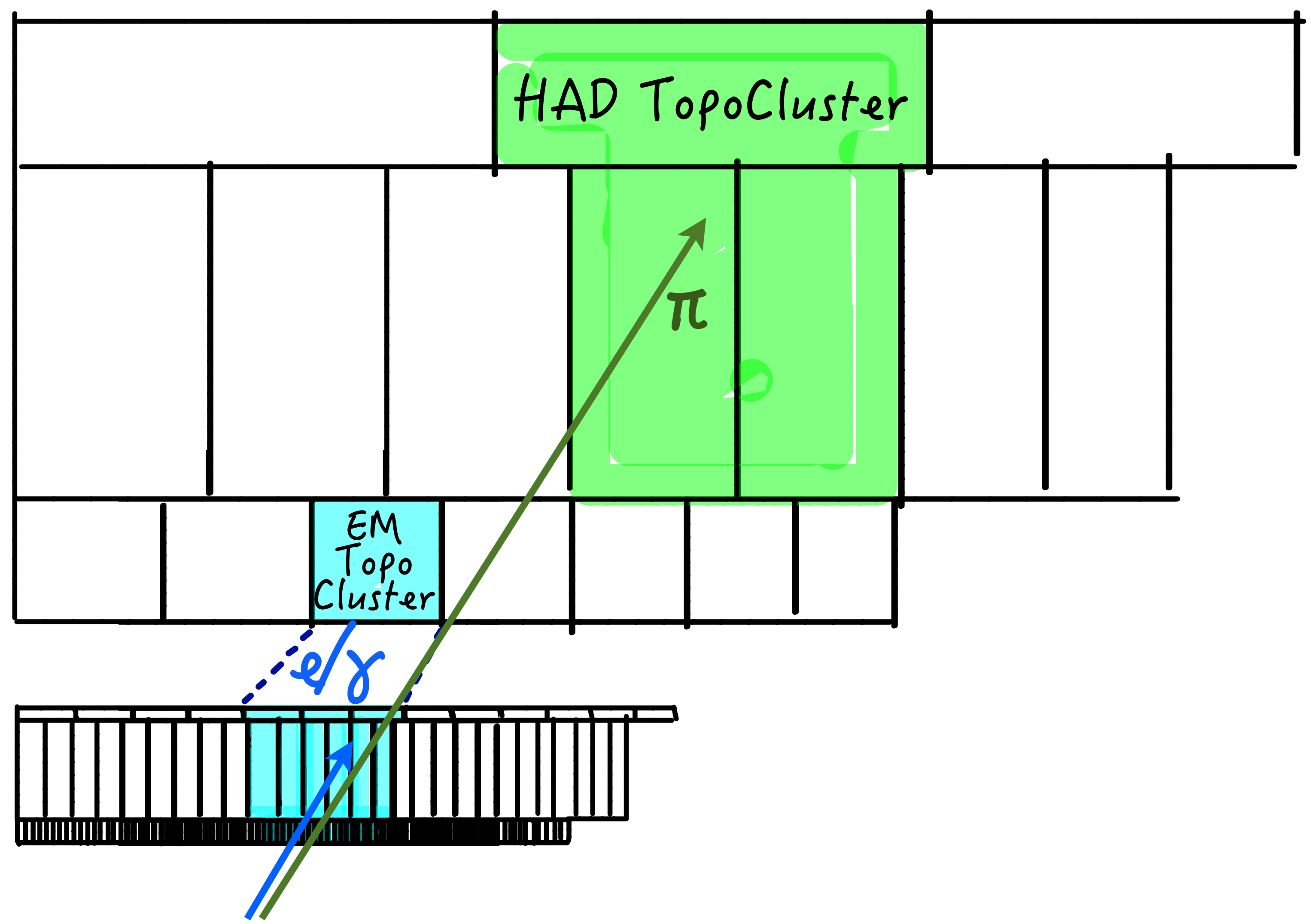

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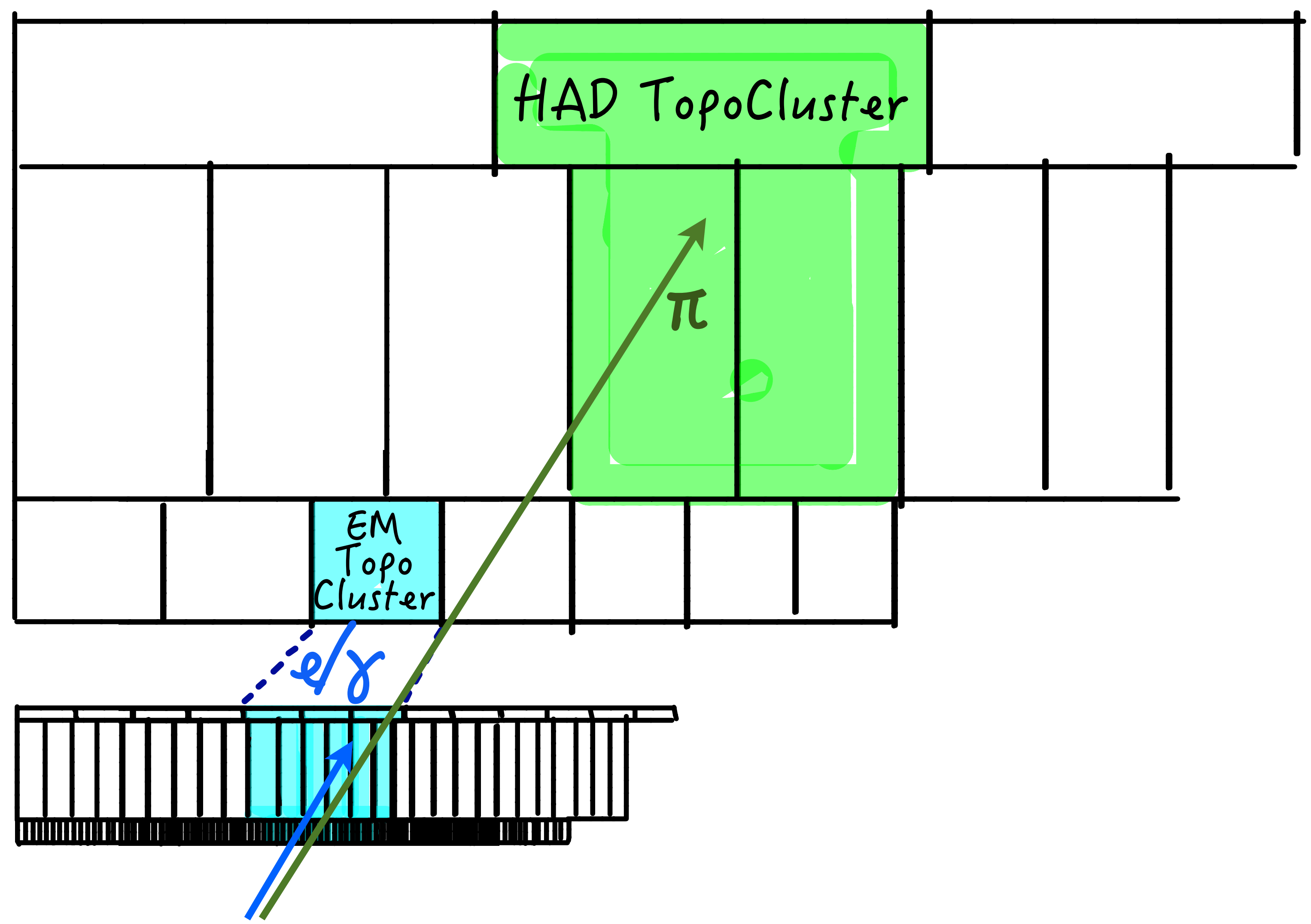

Shower overlap not always resolved

ATLAS Topo-Clusters

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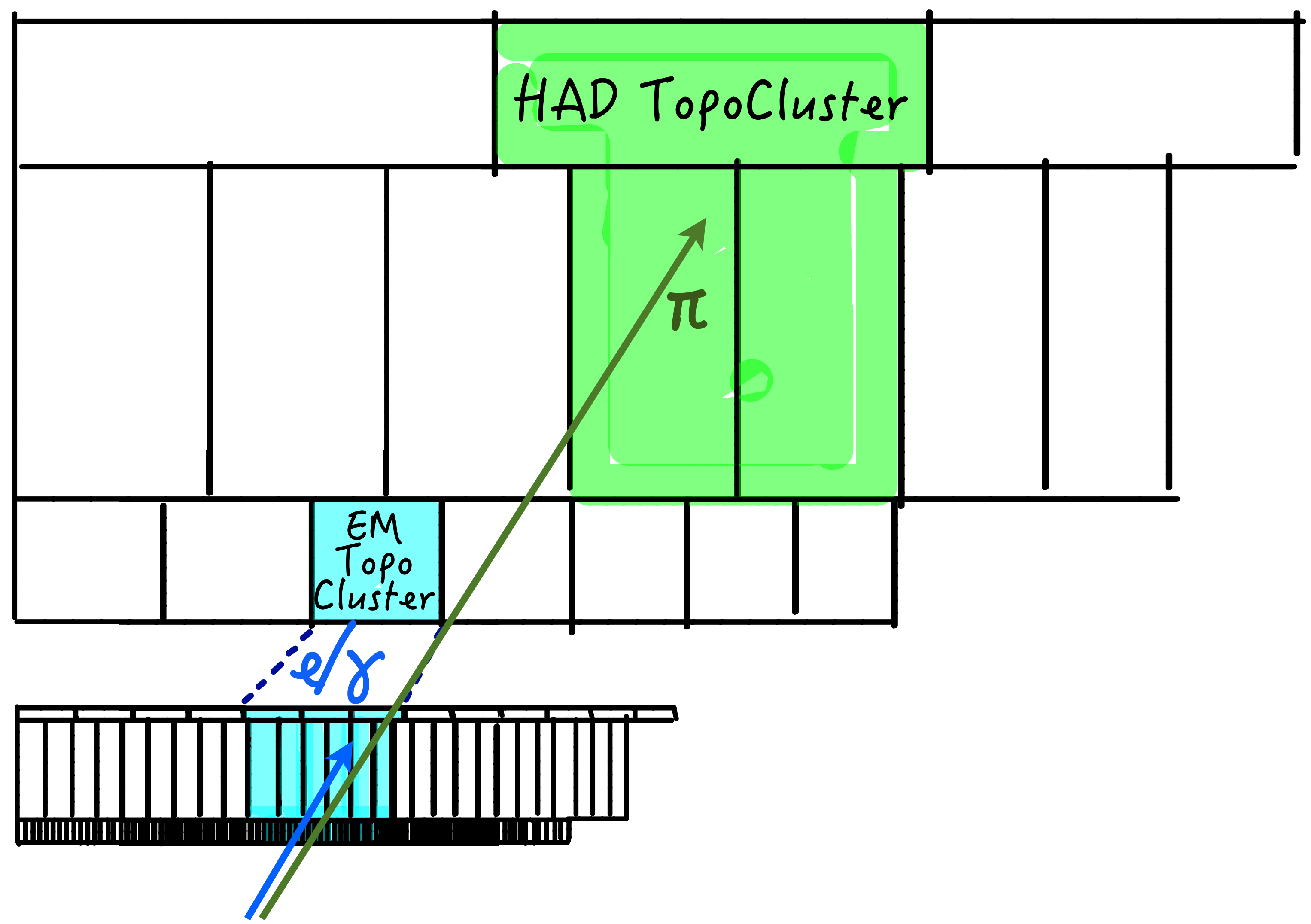

Shower overlap not always resolved

- represent merged particle showers

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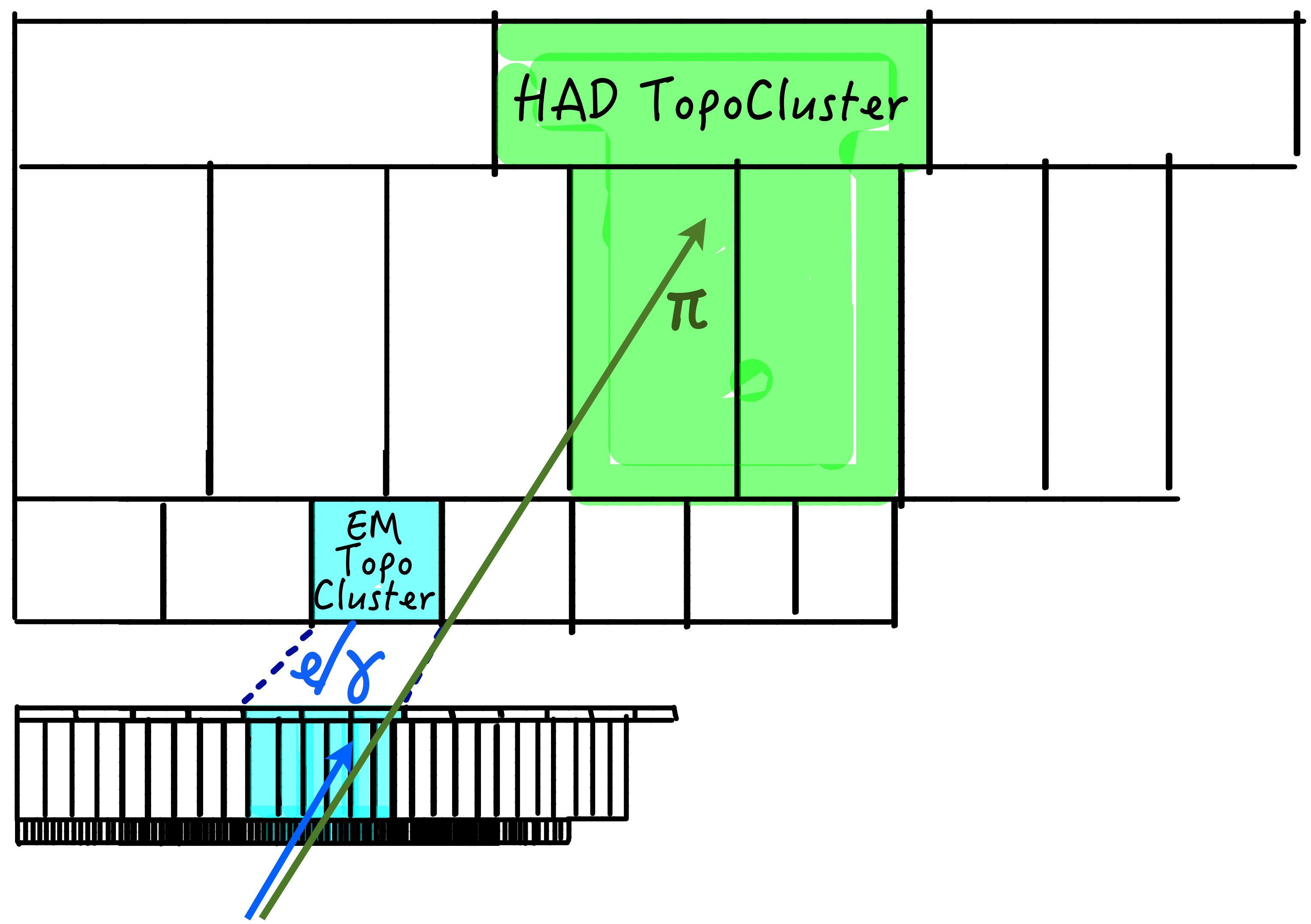
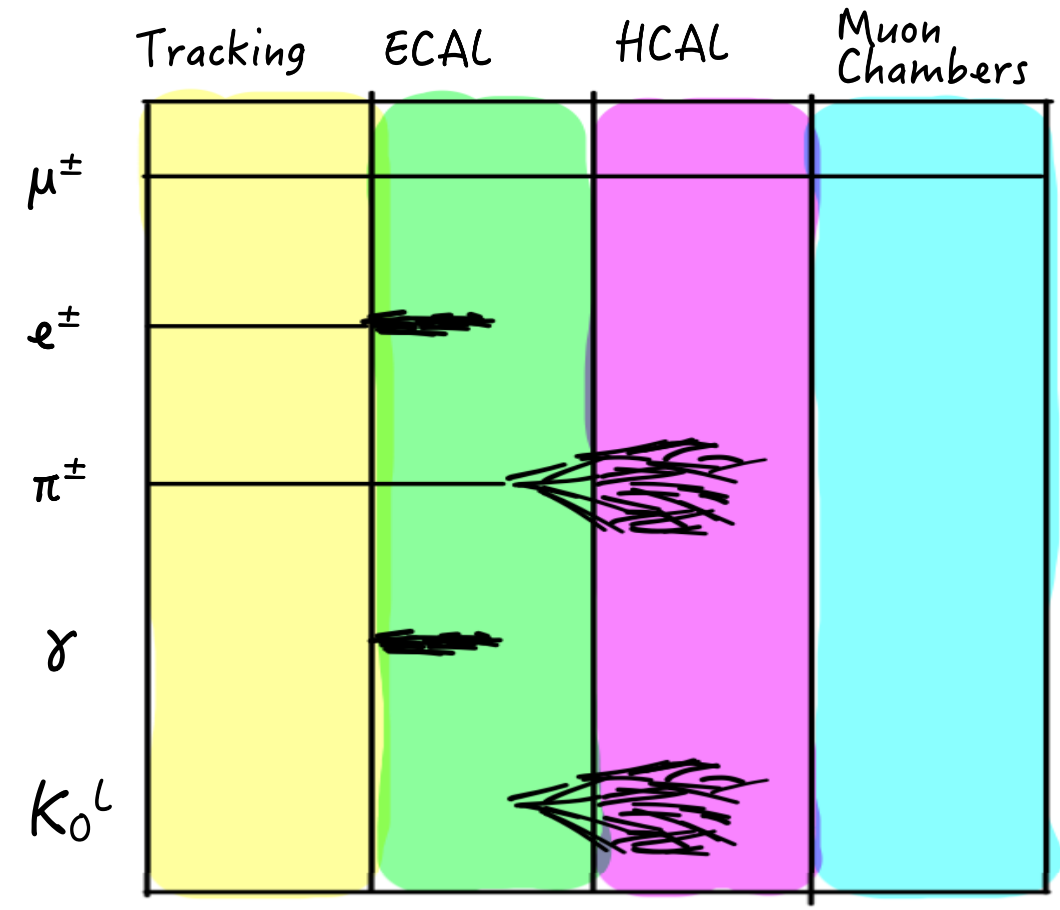


Shower overlap not always resolved

- represent merged particle showers

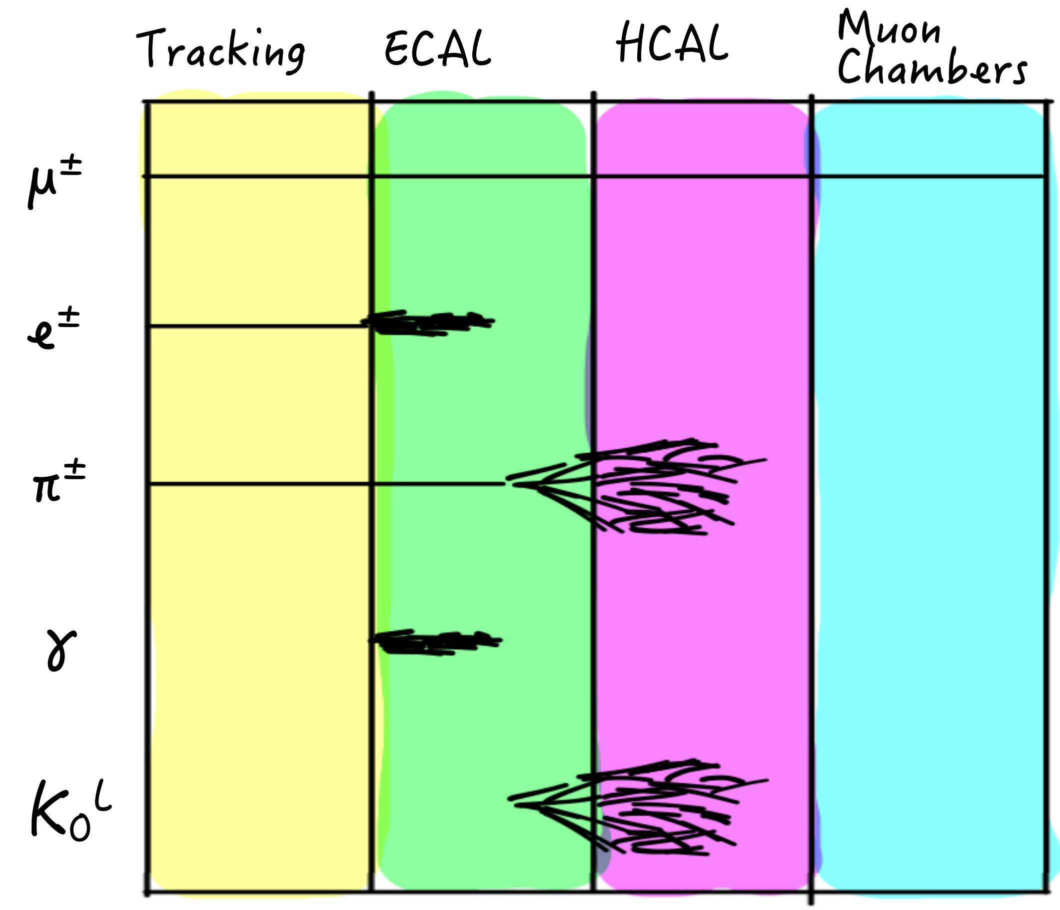
Can correlate individual TopoClusters with individual particles

Helpful Ingredients for PF



Helpful Ingredients for PF

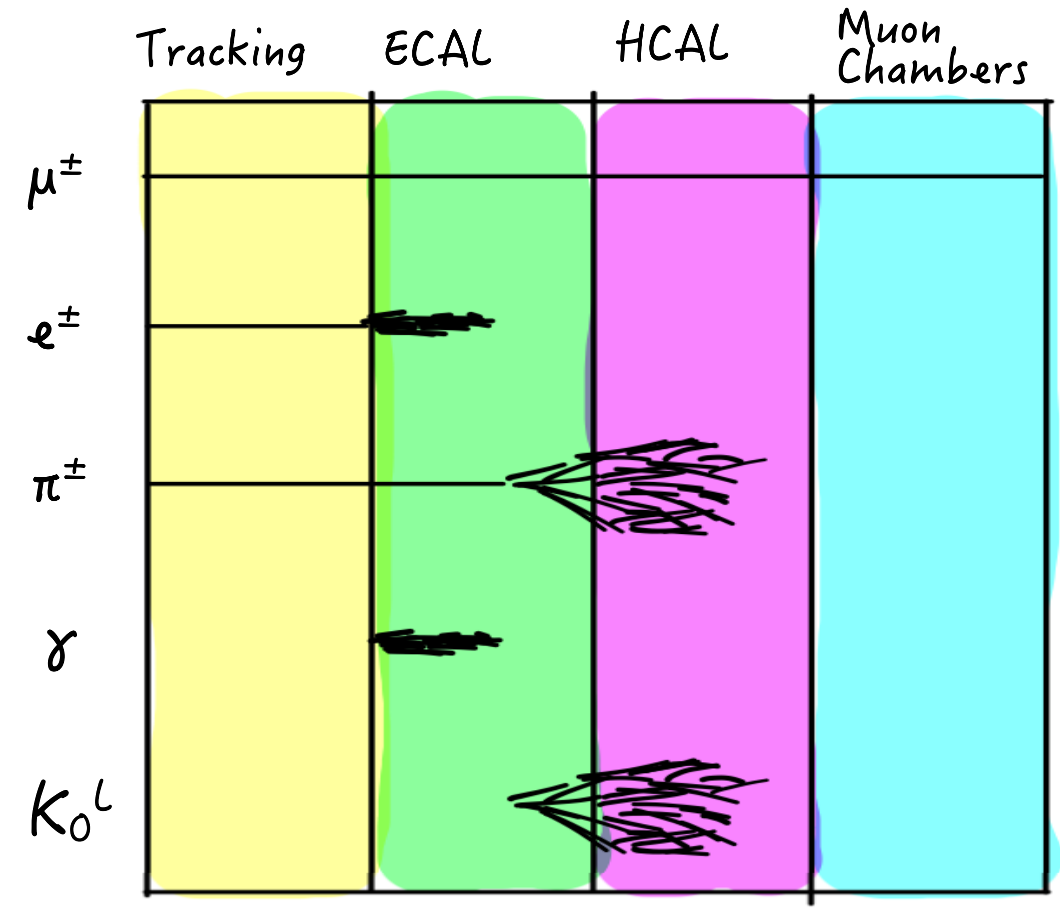
Large Radius, Low Material Tracker



Helpful Ingredients for PF

Large Radius, Low Material Tracker

high-precision, high-efficiency, low-fake rate is critical



Helpful Ingredients for PF

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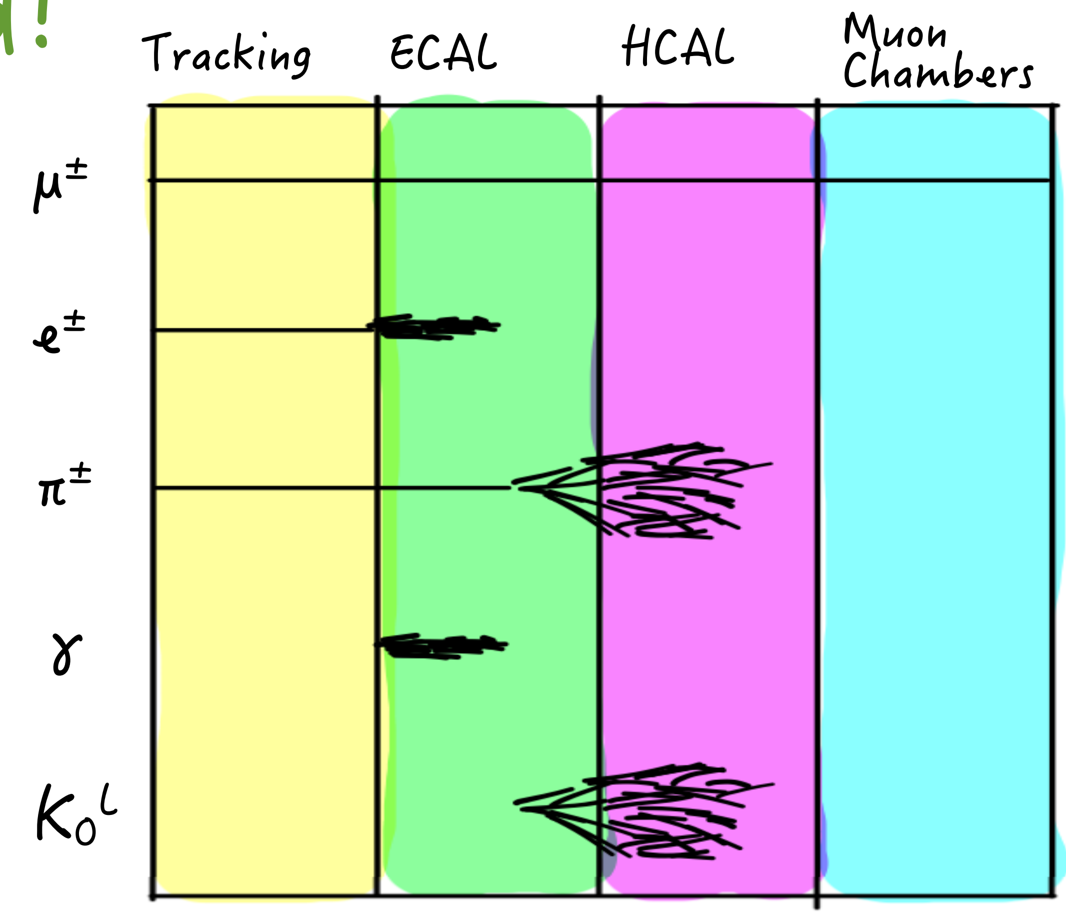

Helpful Ingredients for PF

Large Radius, Low Material Tracker **Good!**

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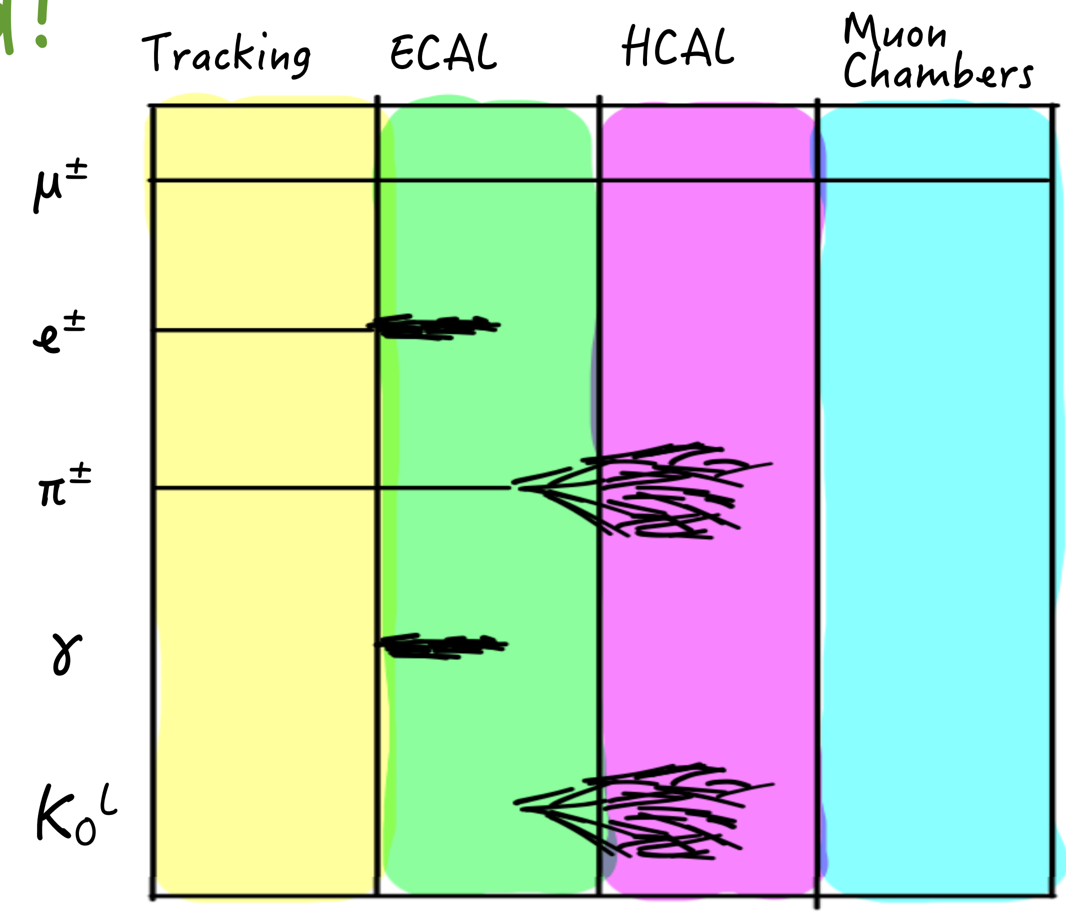
High Magnetic Field



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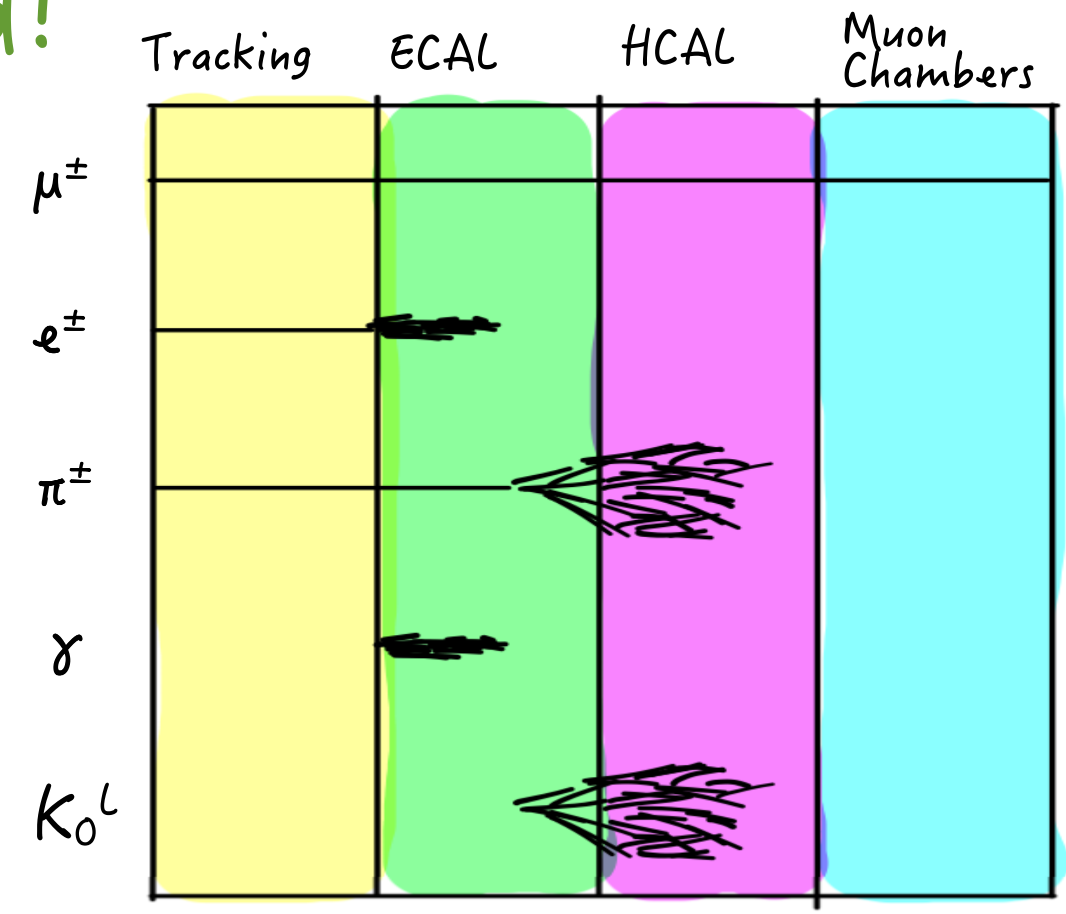
High Magnetic Field

excellent p resolution



Helpful Ingredients for PF

Large Radius, Low Material Tracker Good!

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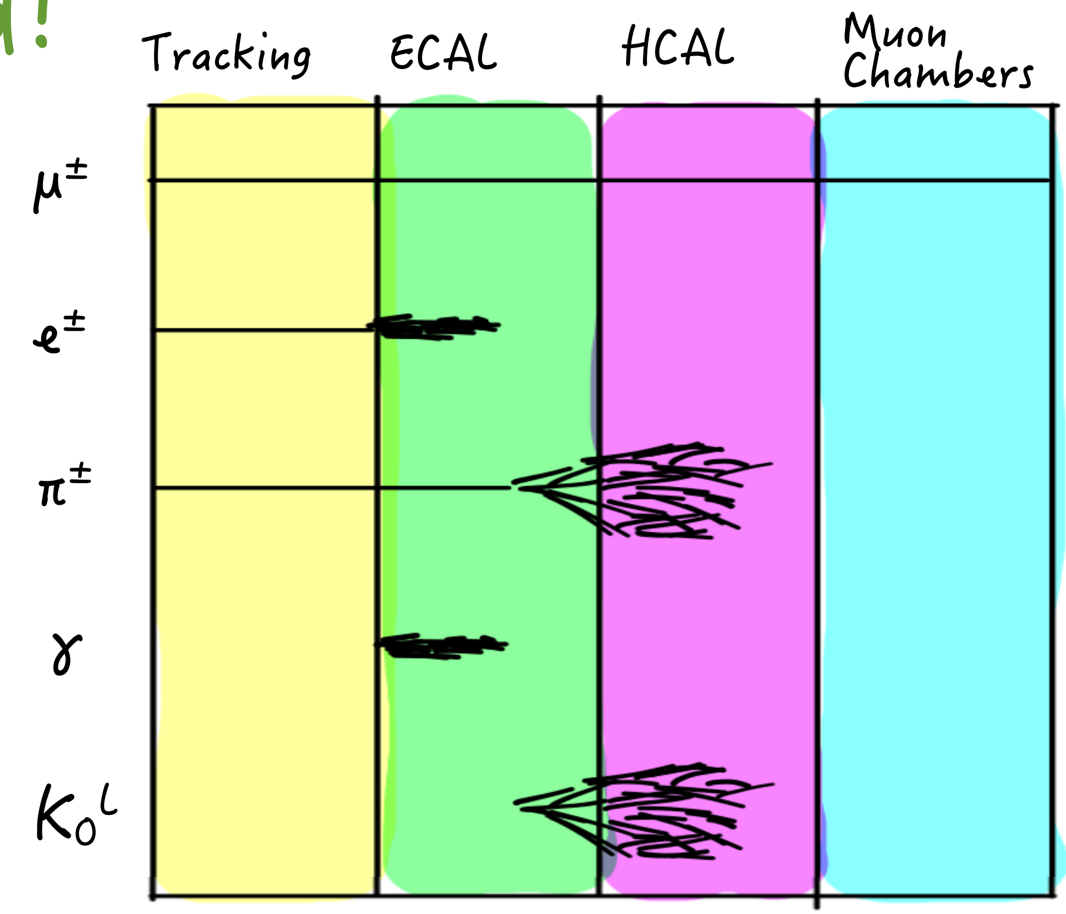
High Magnetic Field

- excellent p resolution
- separate charged from neutral particles



Helpful Ingredients for PF

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High Magnetic Field **Good!**

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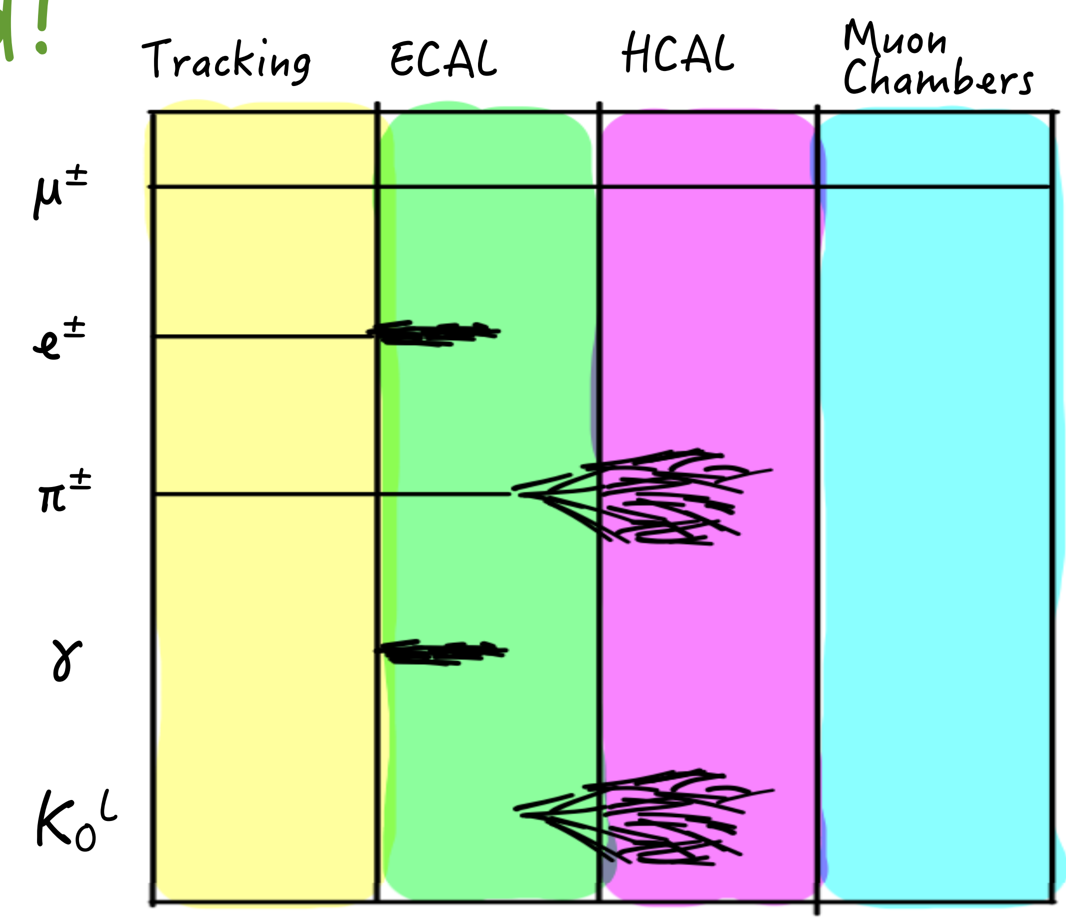

R. Cavanaugh 100 TeV Workshop, SLAC 23-26 August, 2014

Helpful Ingredients for PF

Large Radius, Low Material Tracker Good!

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High Magnetic Field Good!

- excellent p resolution
- separate charged from neutral particles

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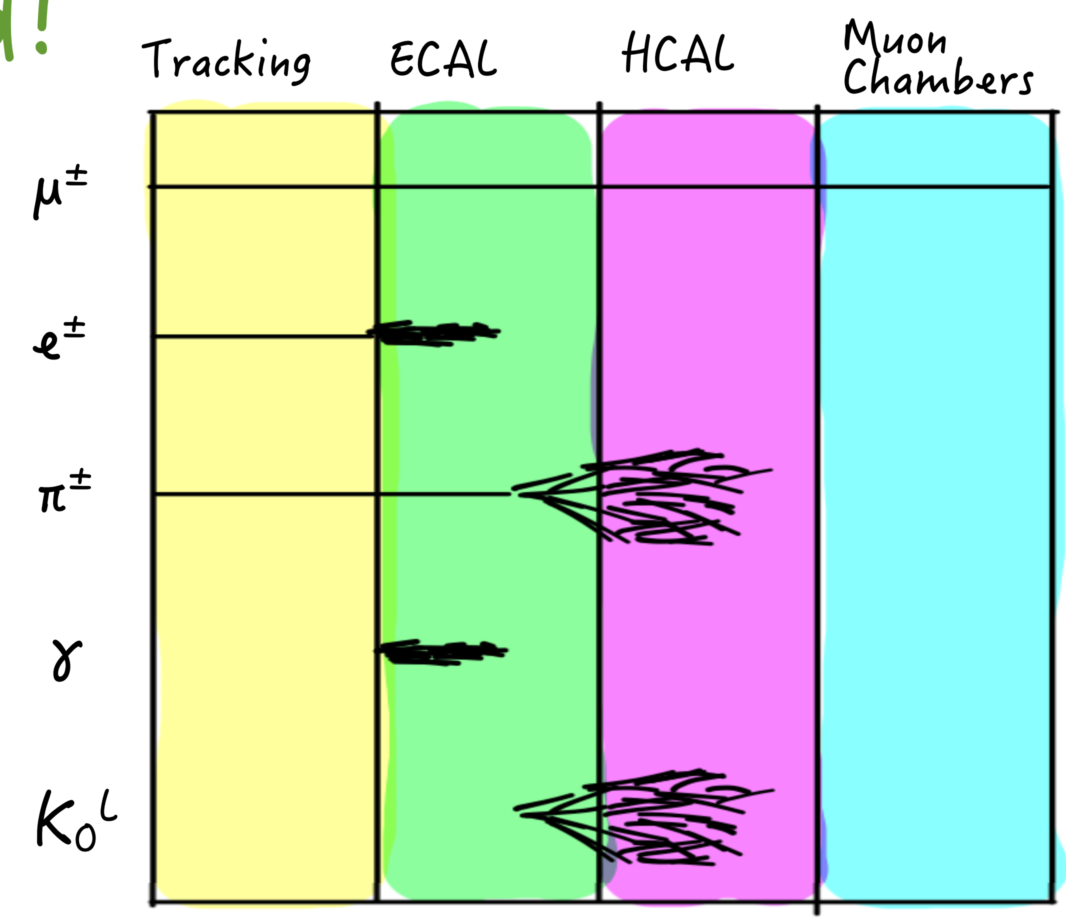

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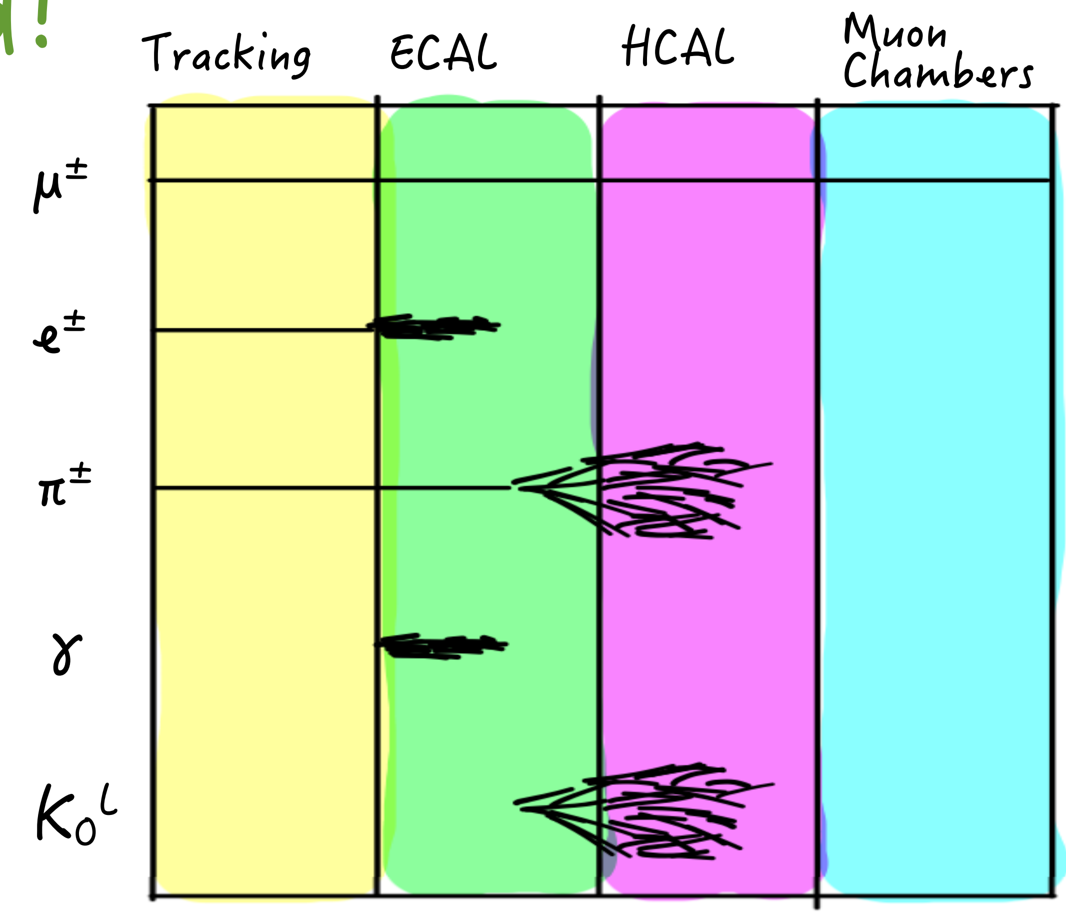

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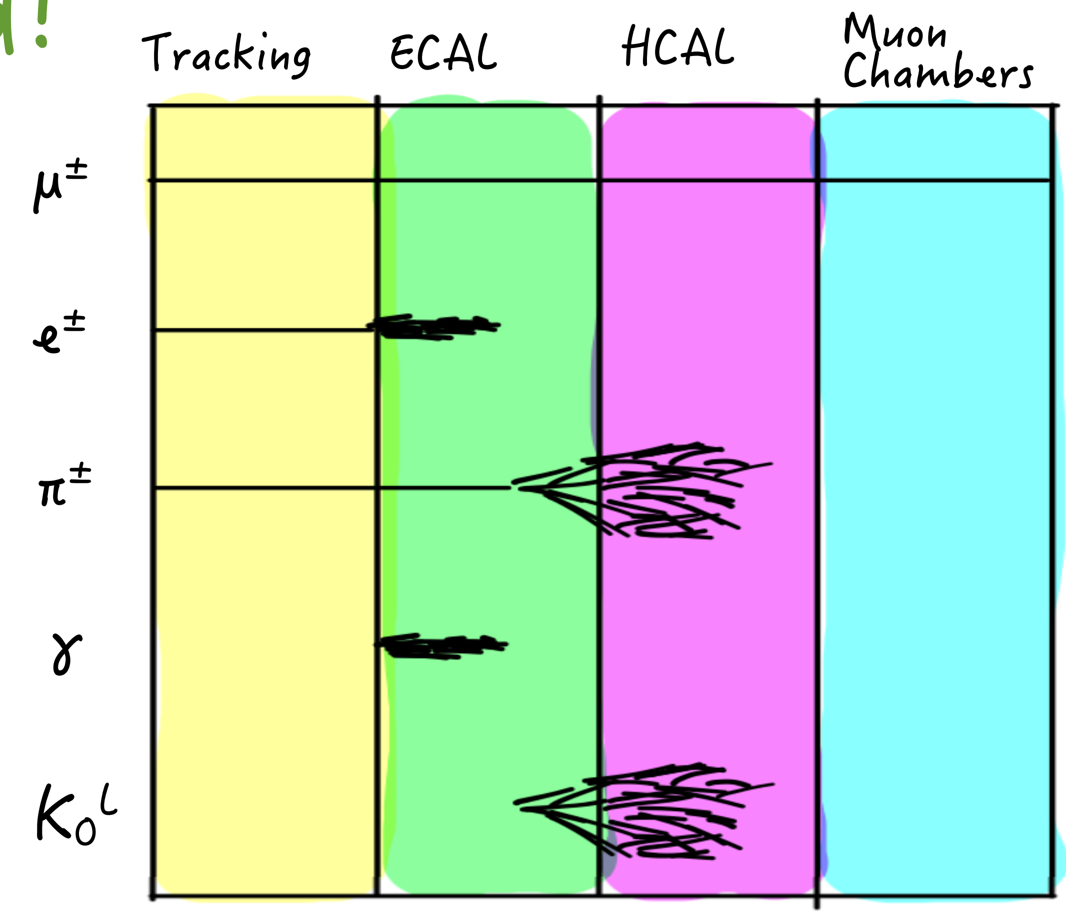

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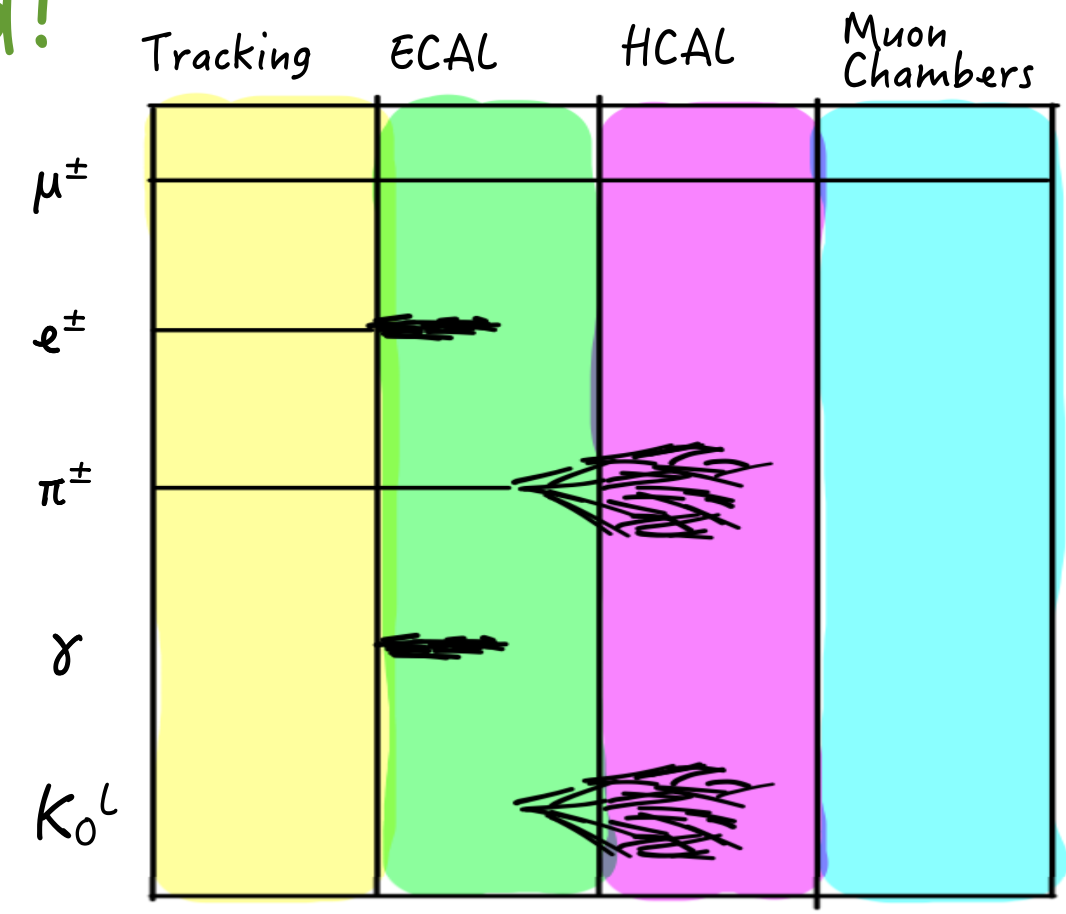

R. Cavanaugh 100 TeV Workshop, SLAC 23-26 August, 2014

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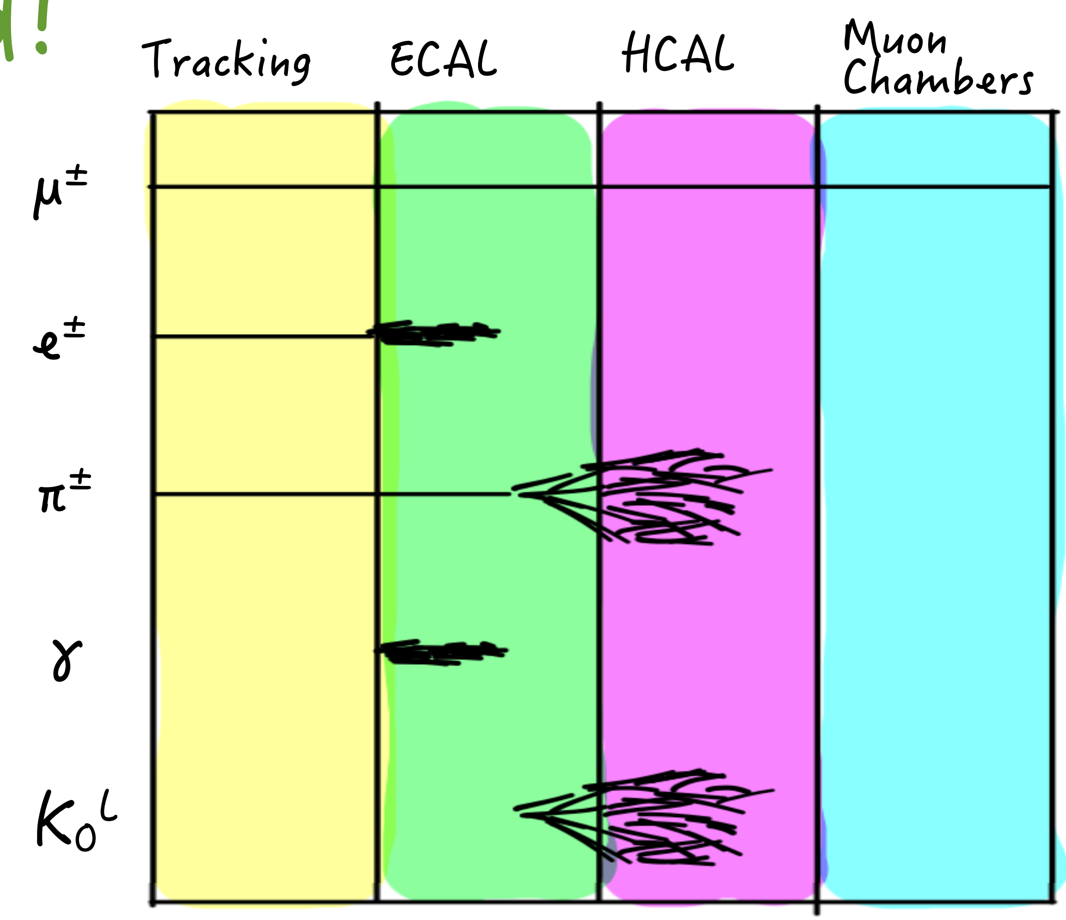

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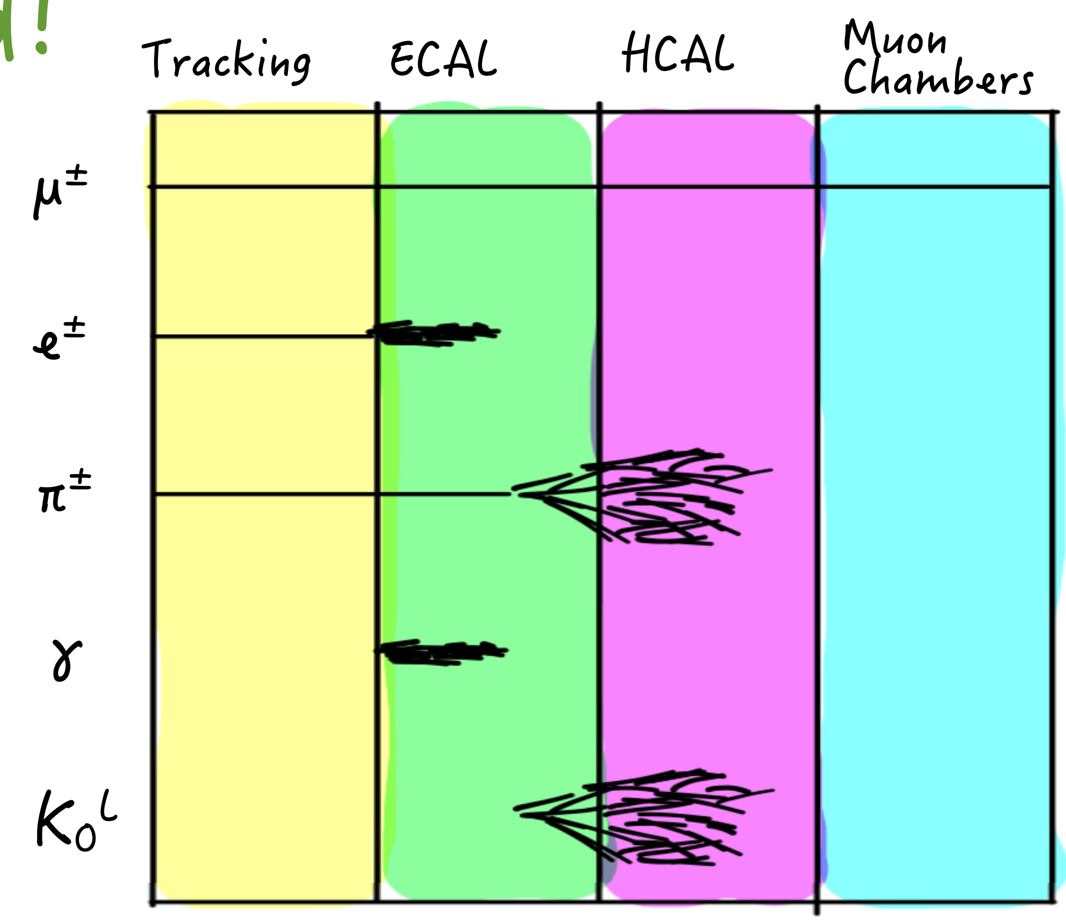

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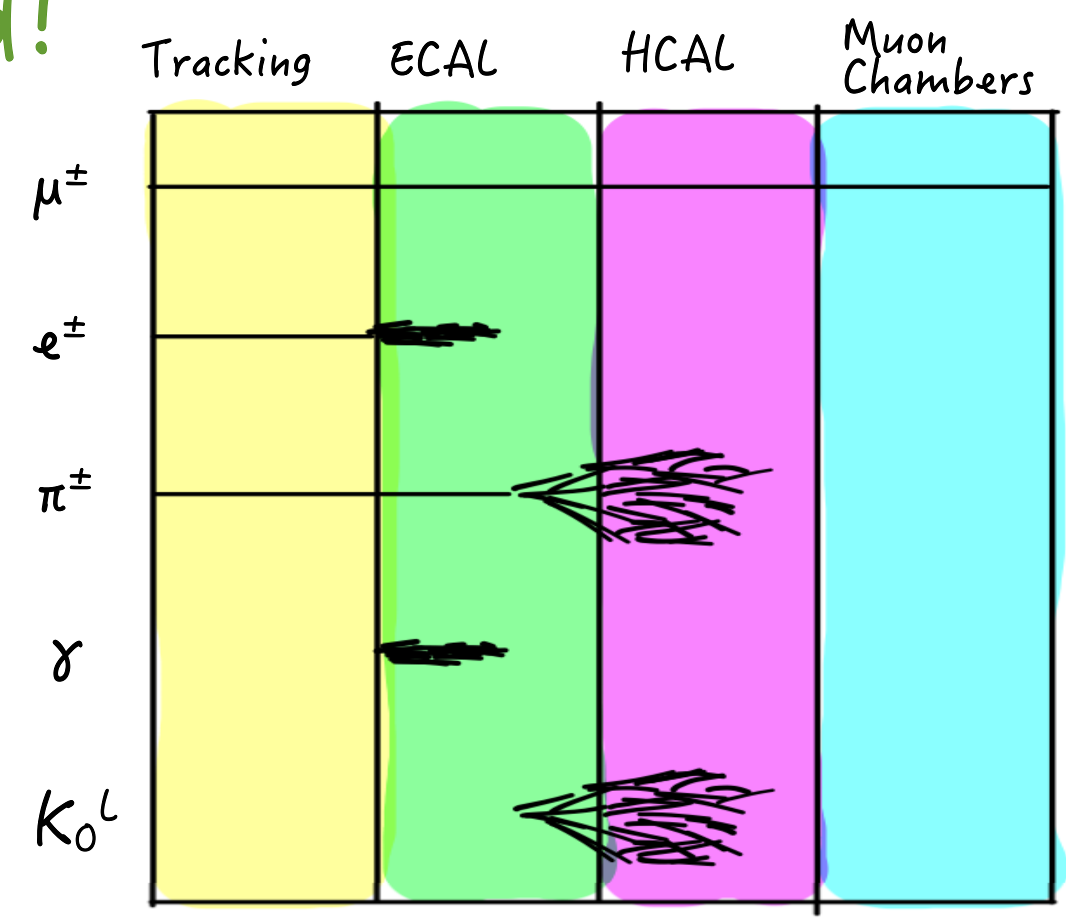

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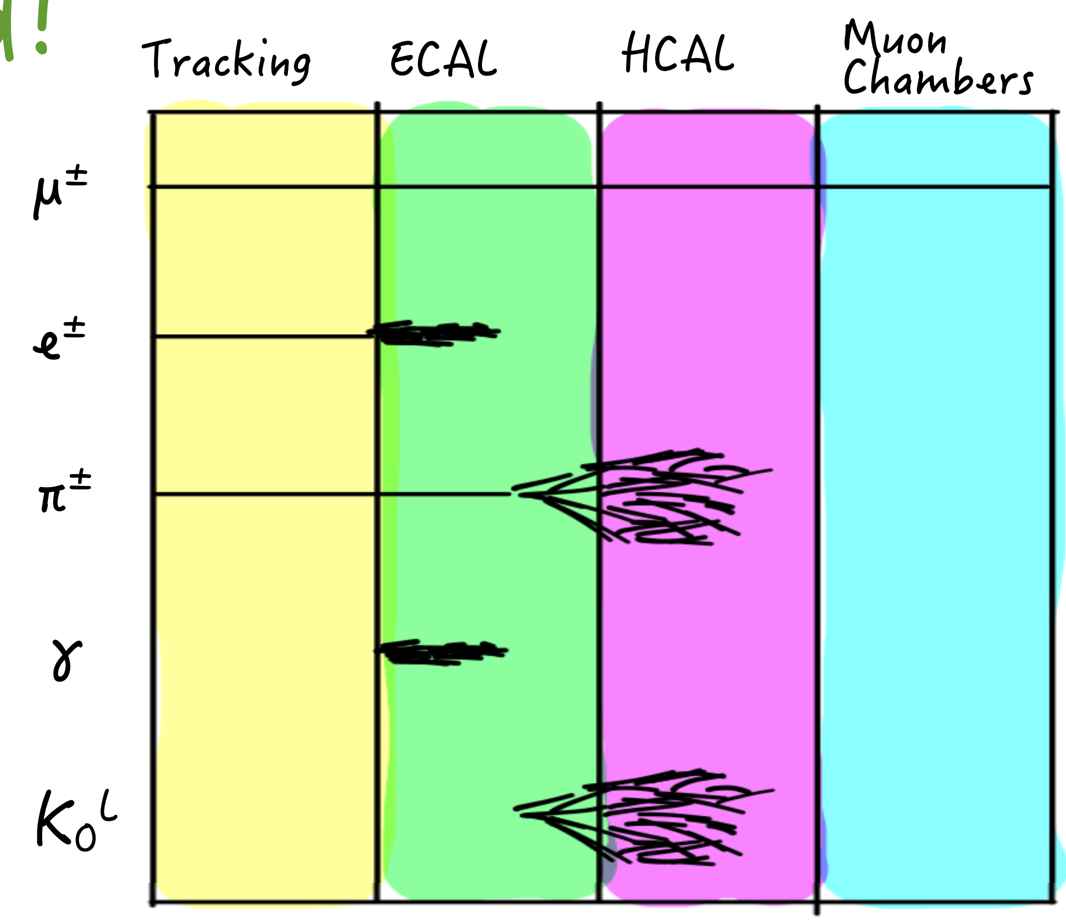

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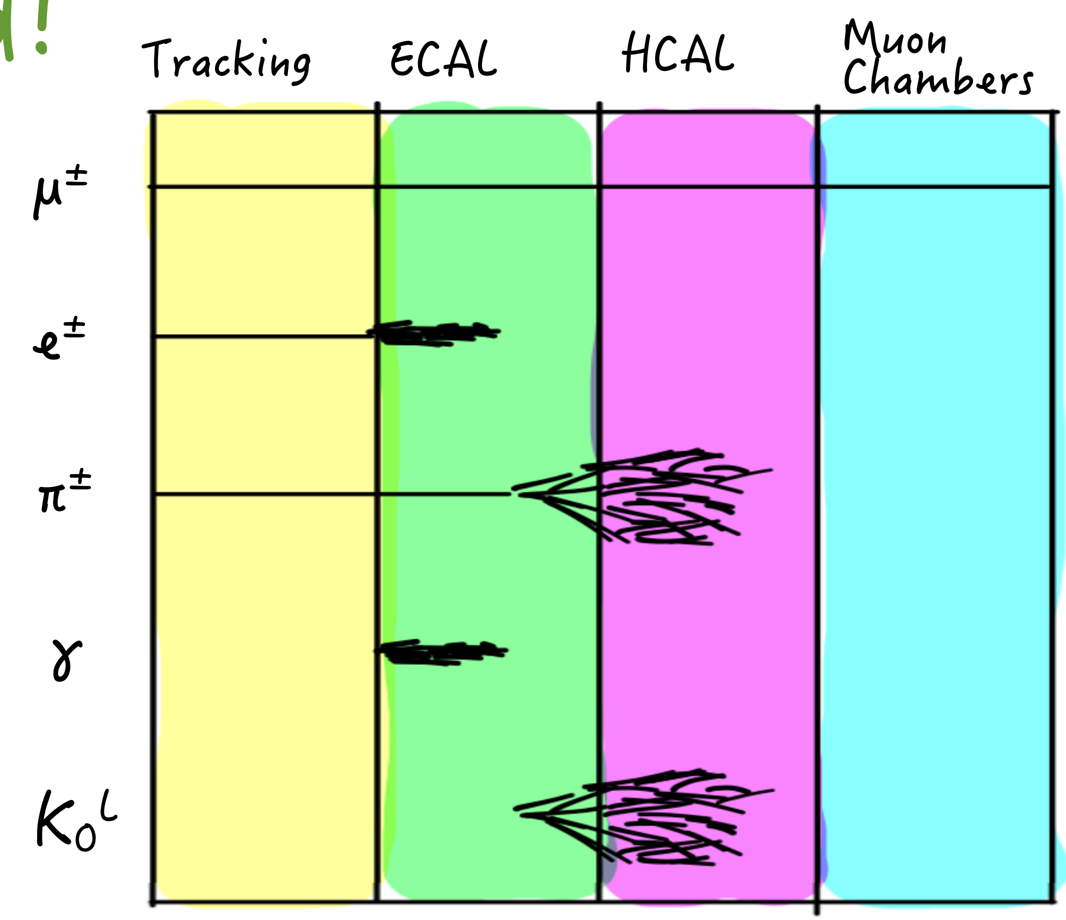

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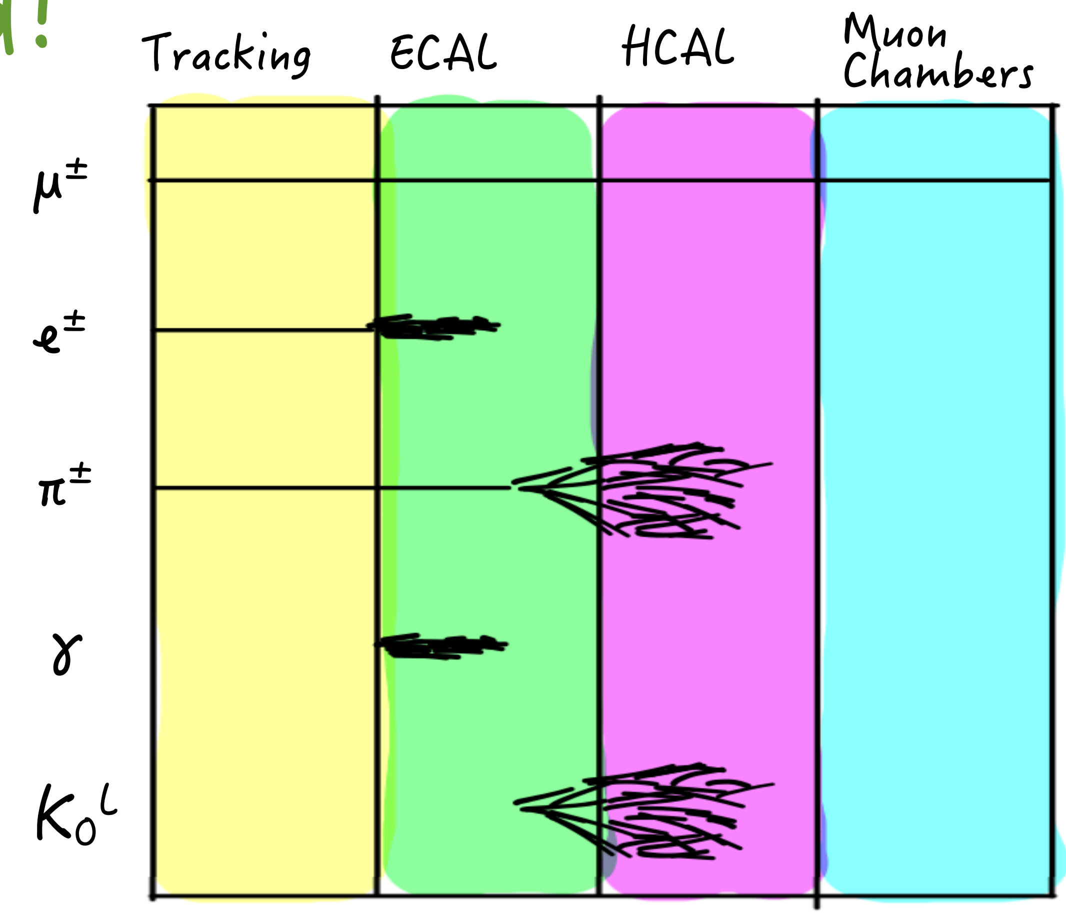

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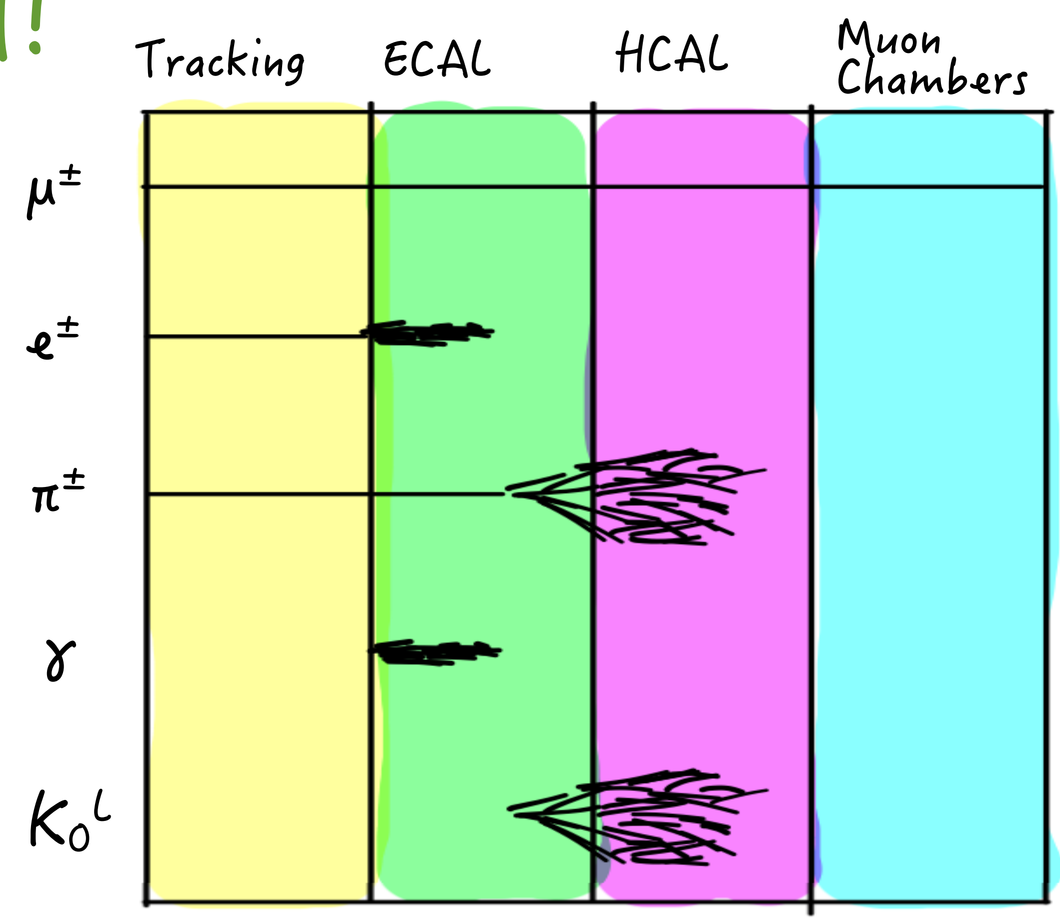

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If you have to choose: segmentation wins over resolution

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Fermilab
UIC University of Illinois at Chicago

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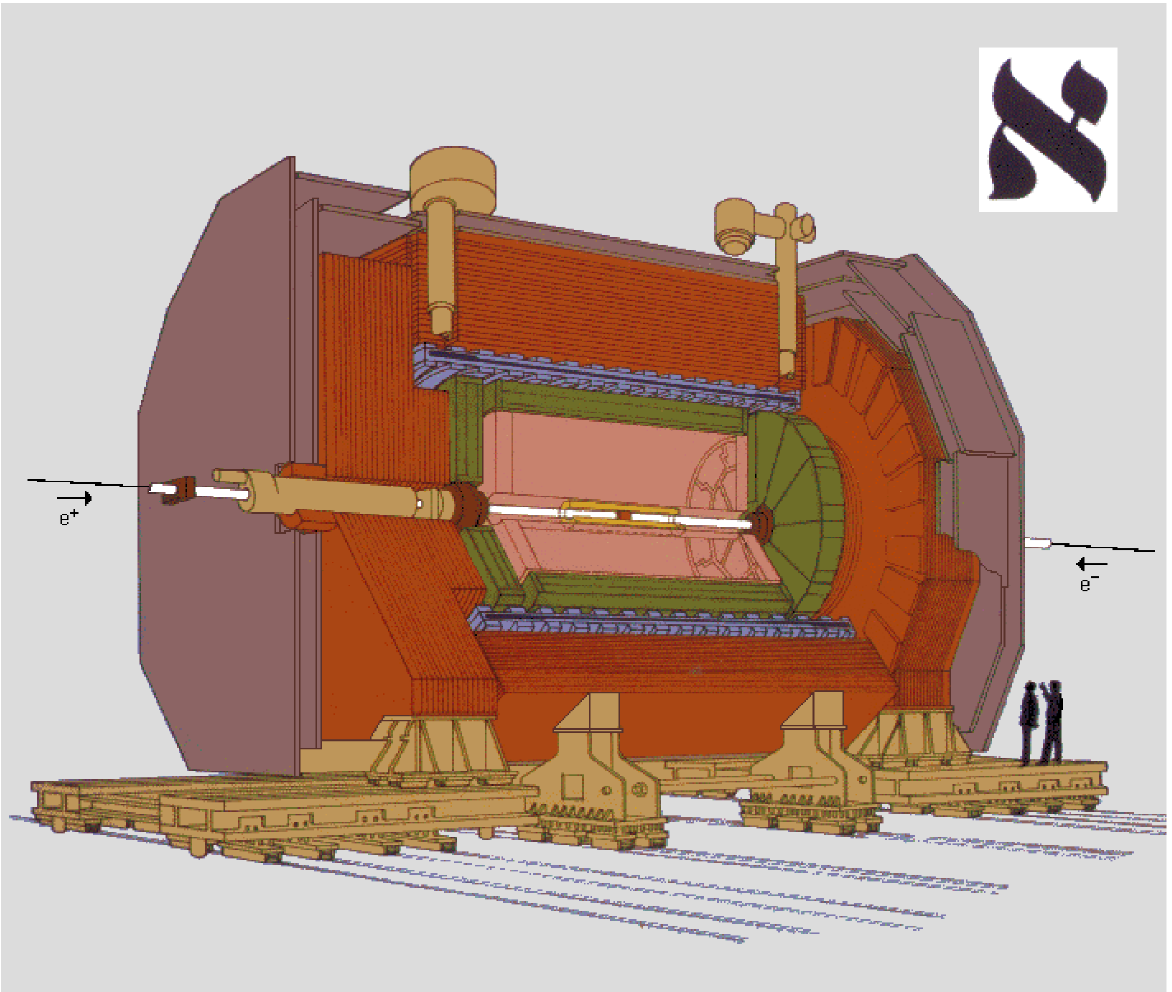

Vertex Detector

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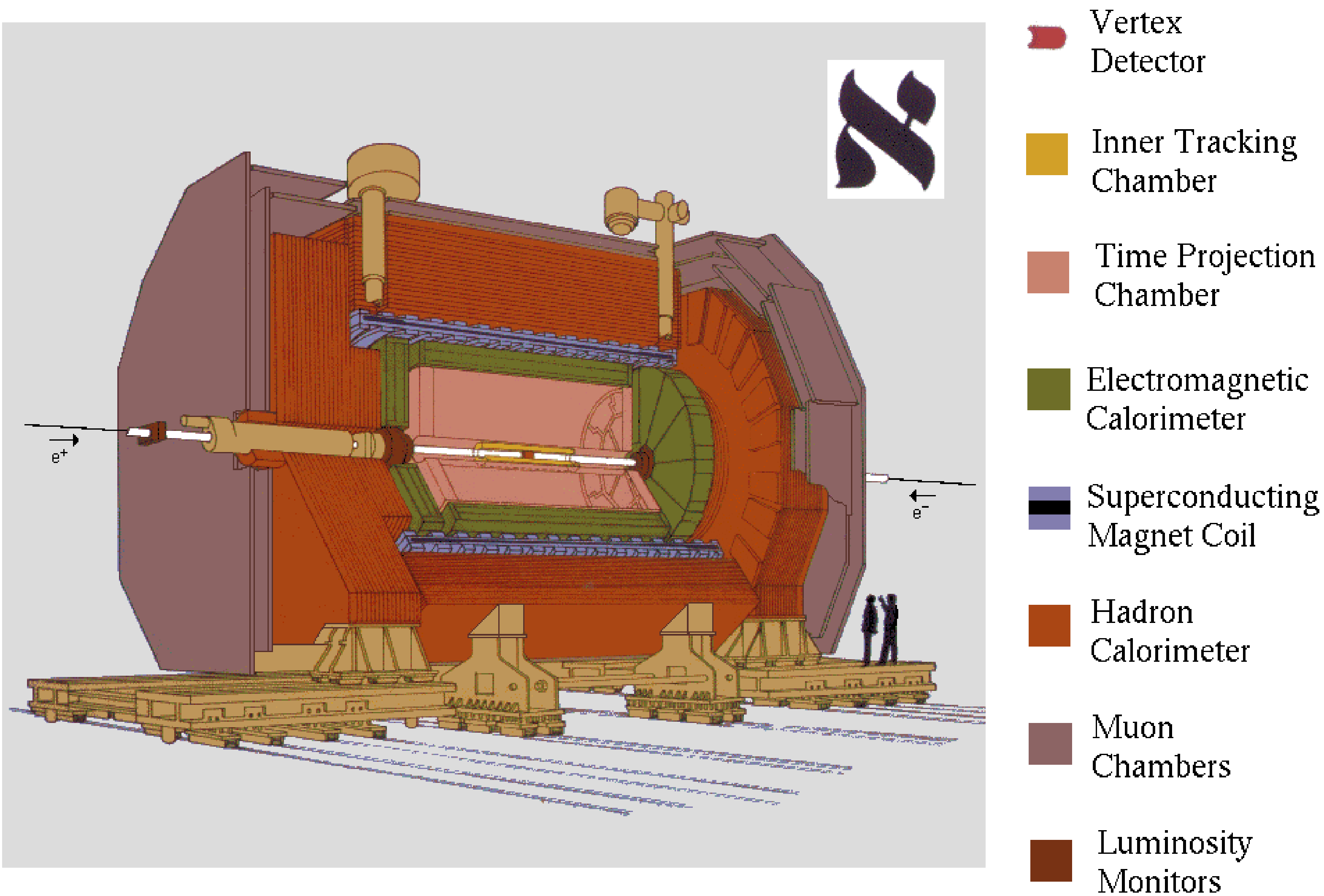

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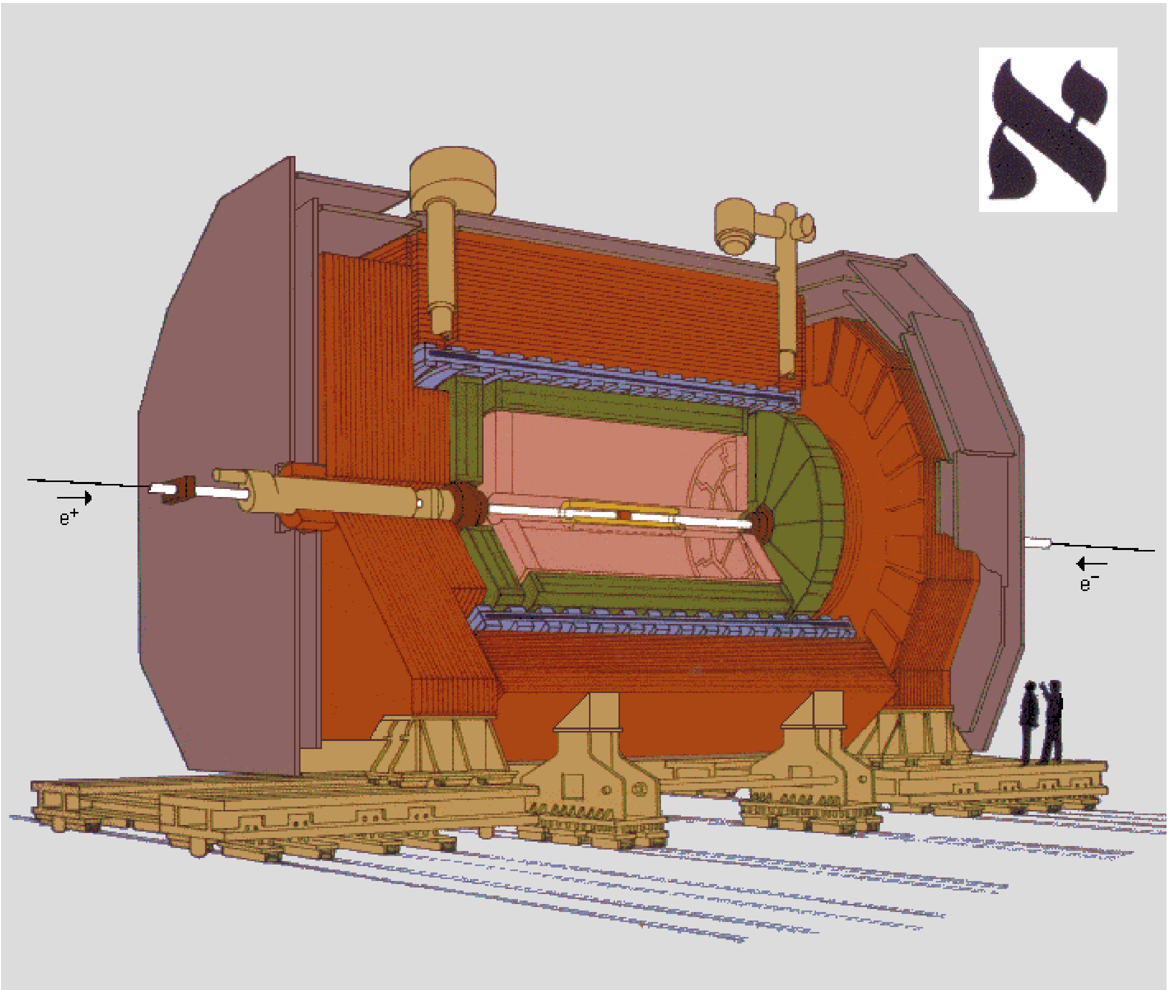

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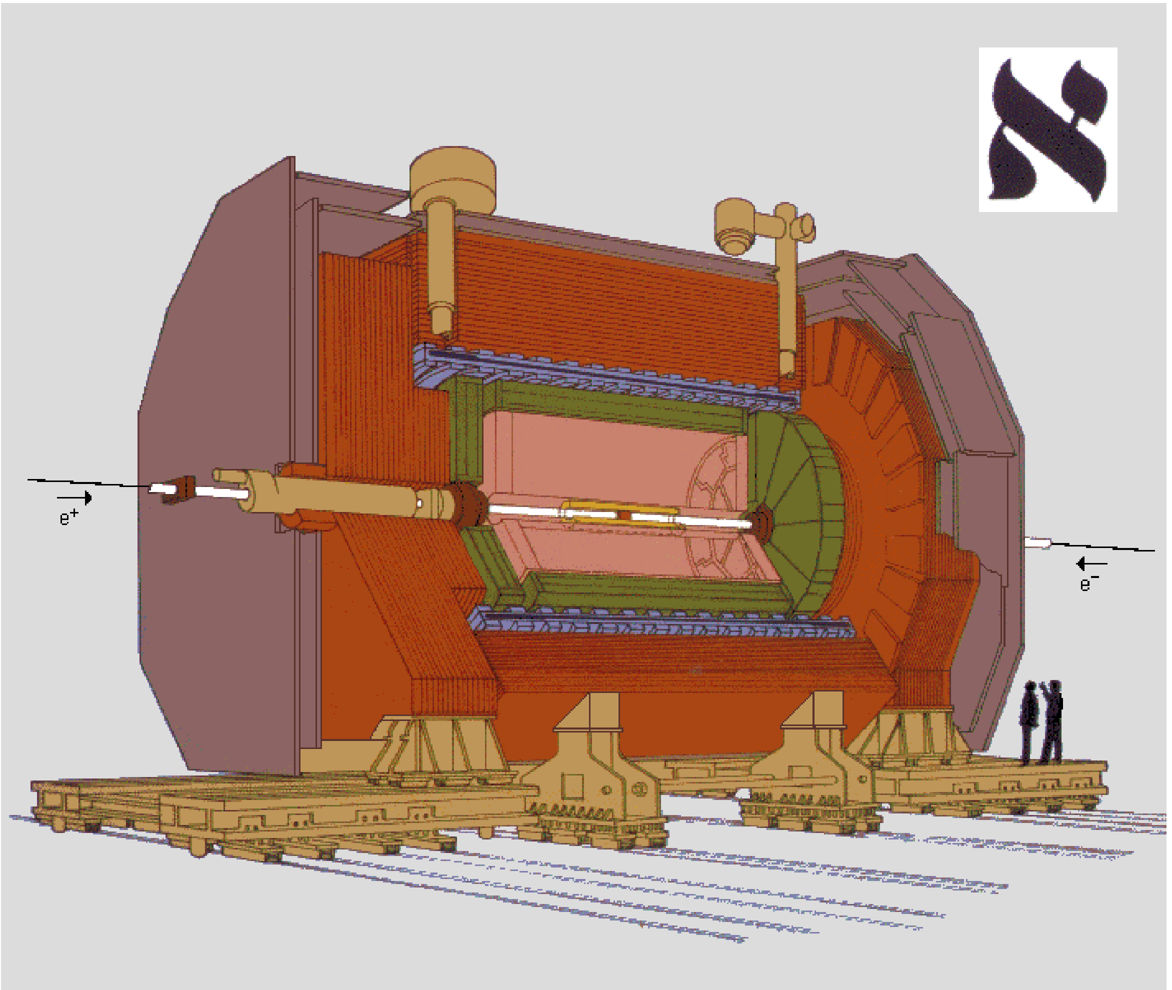

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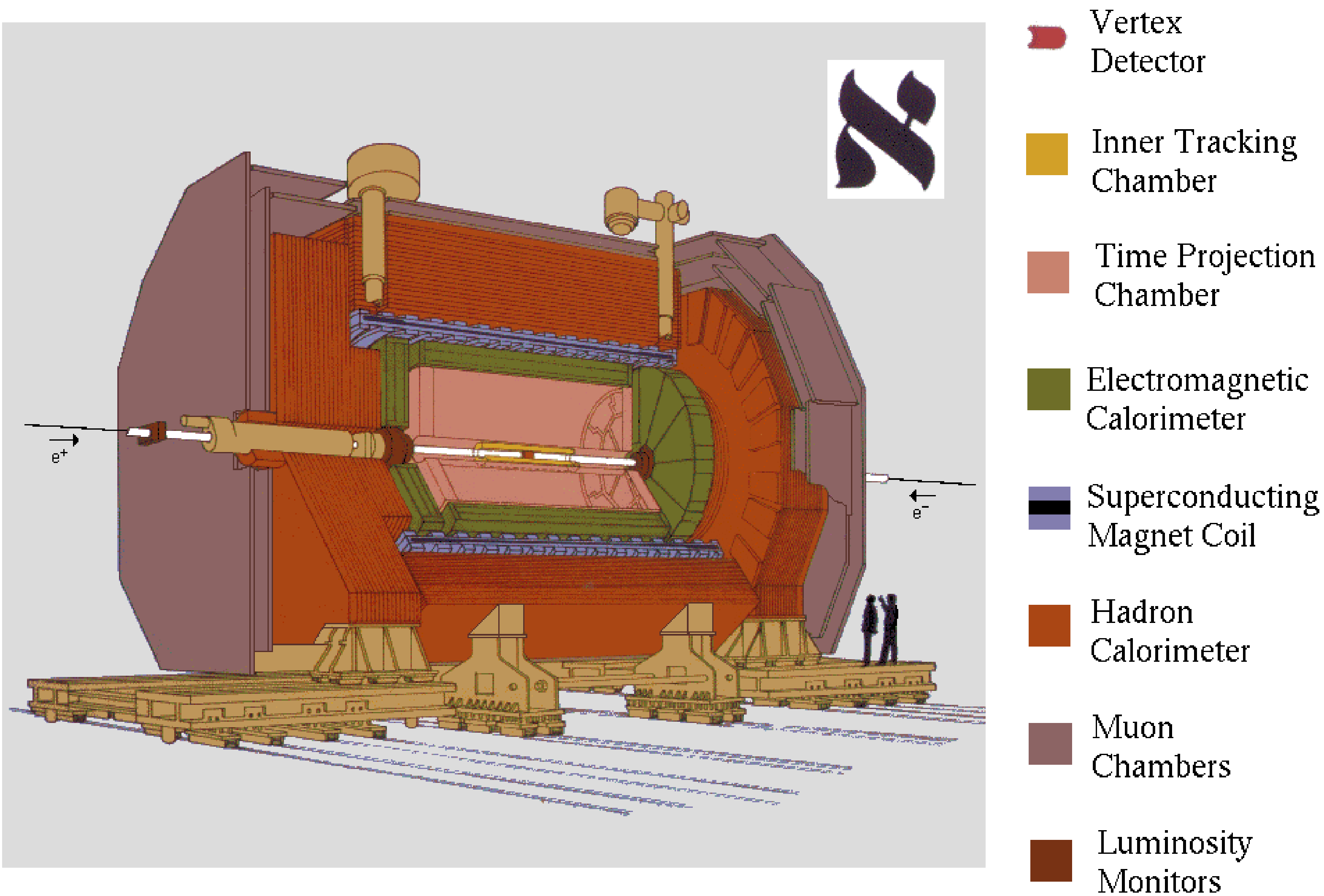

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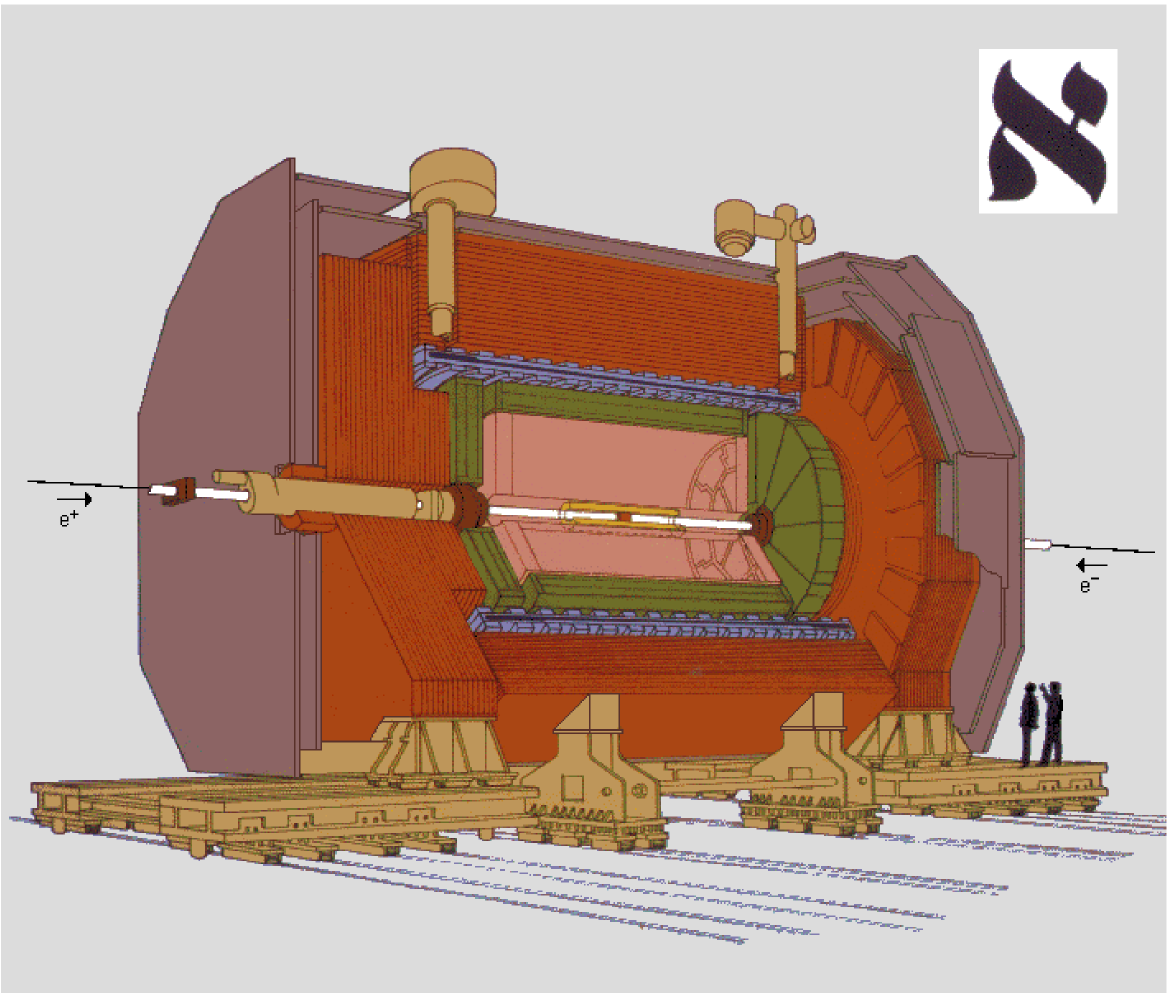

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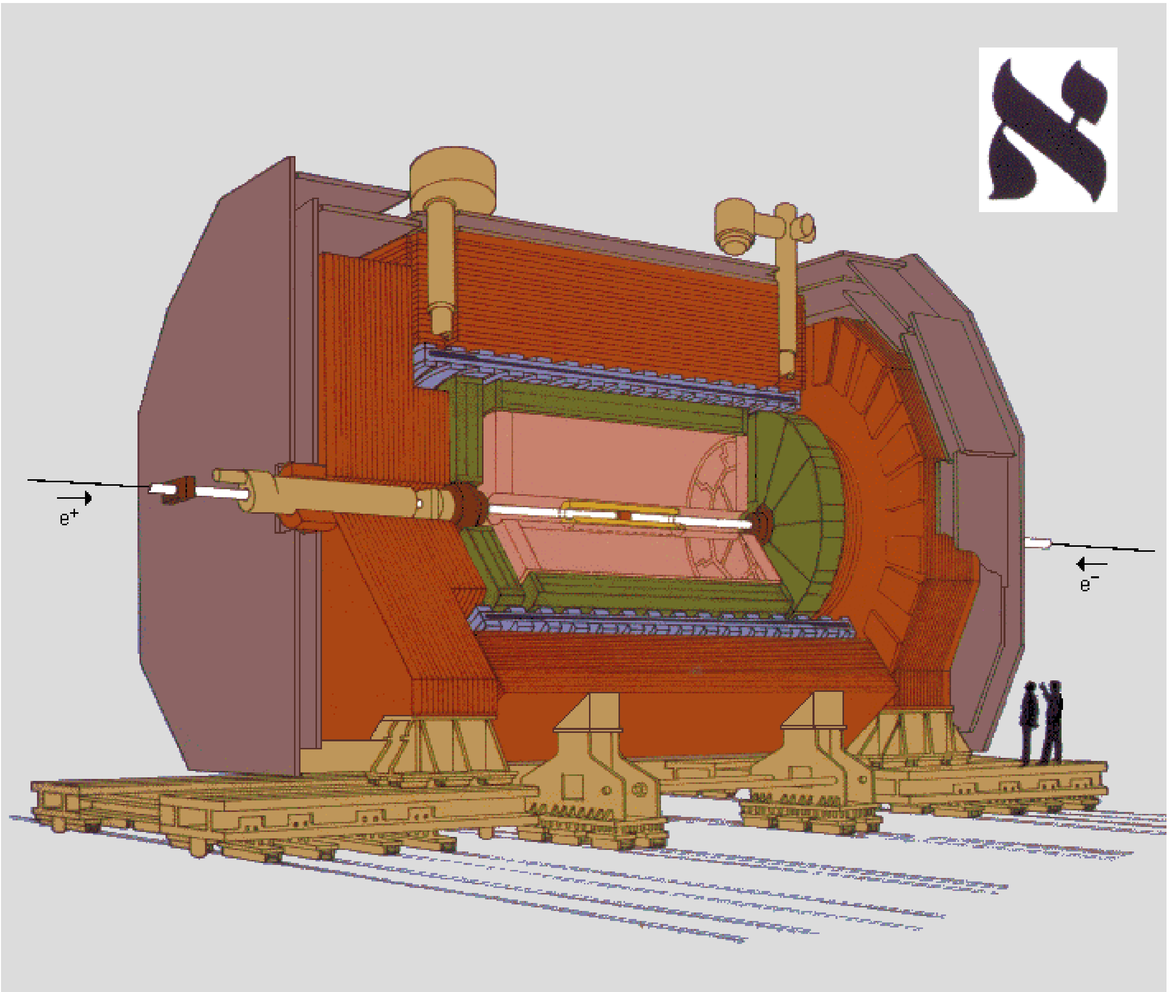
UIC University of Illinois at Chicago



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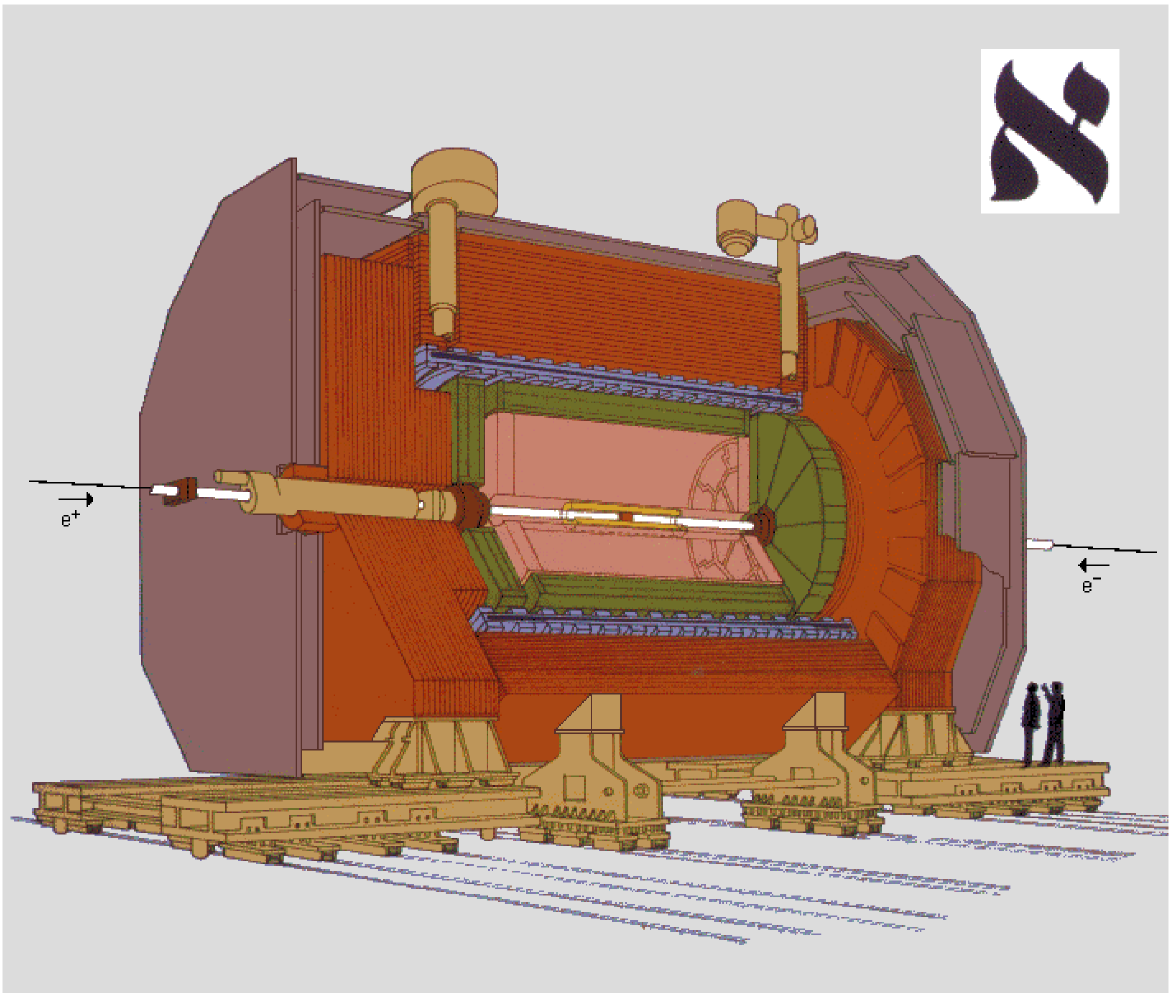

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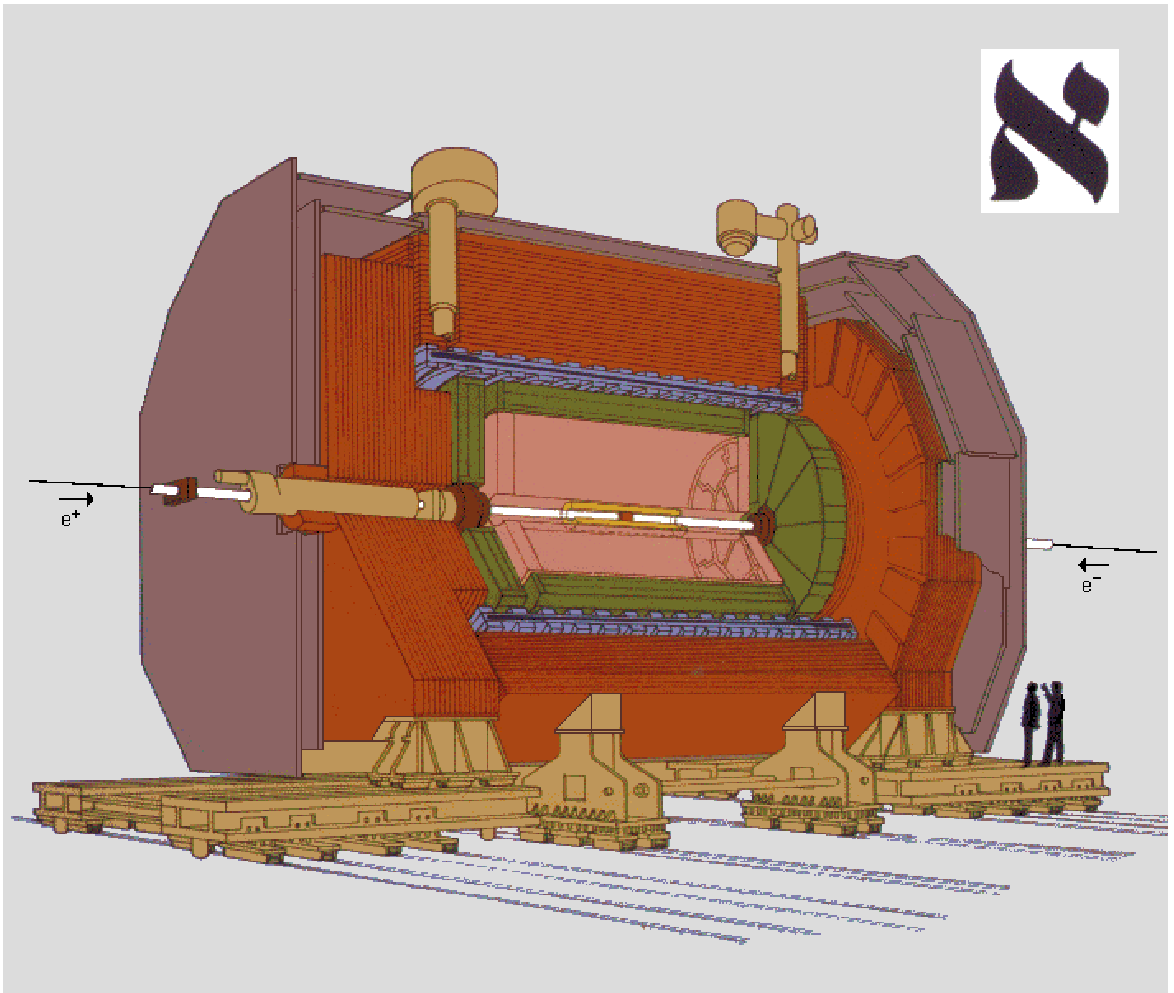

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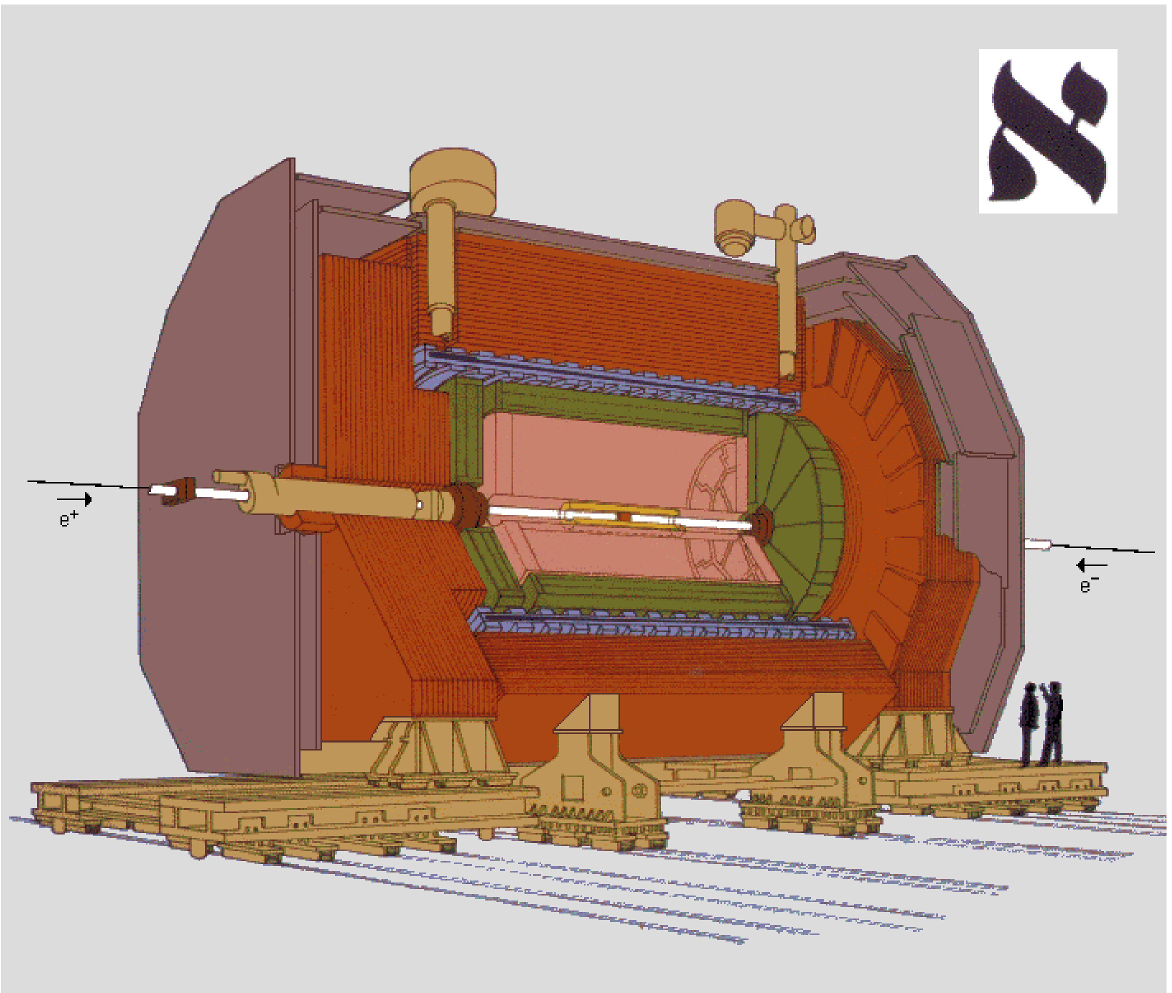

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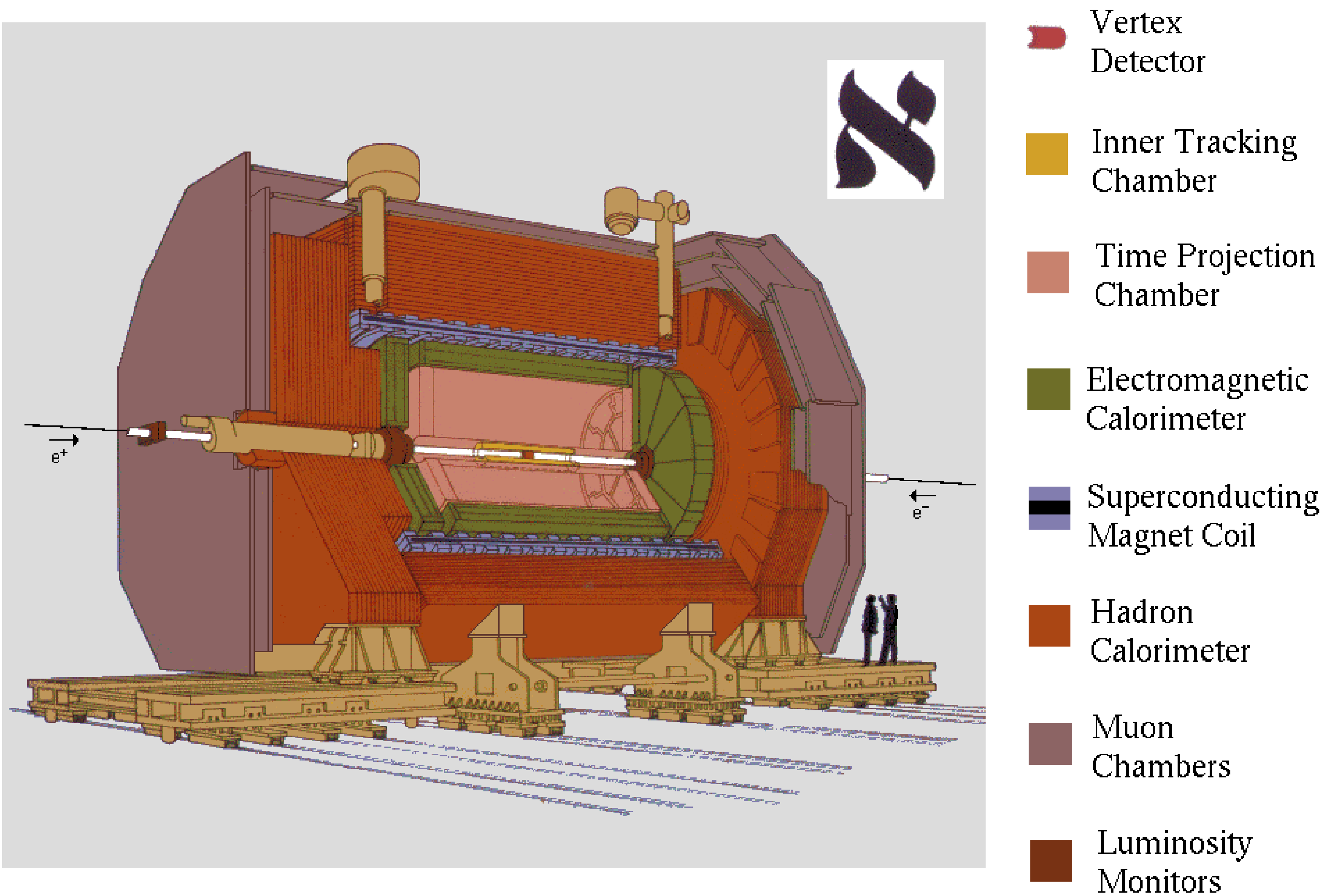

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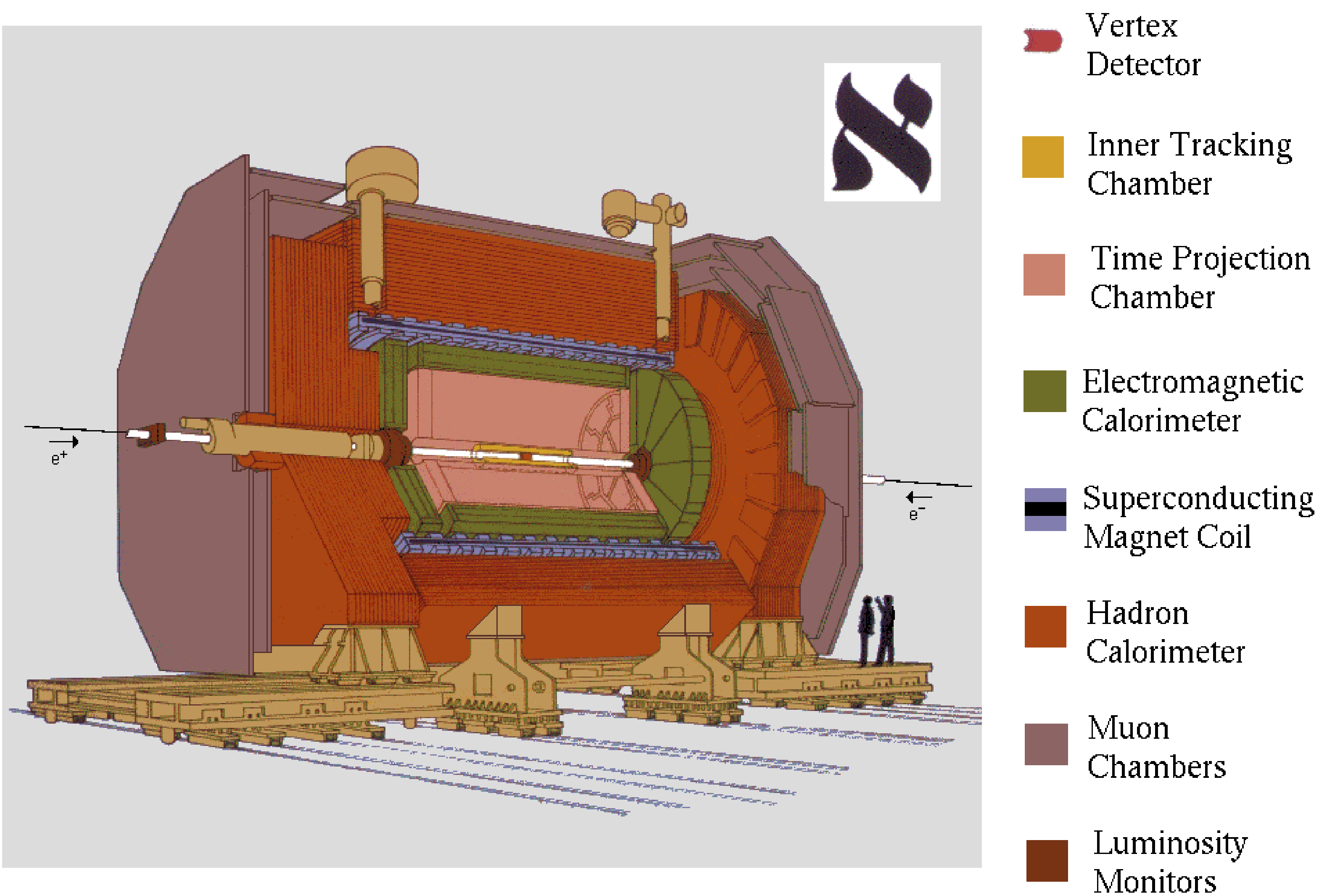

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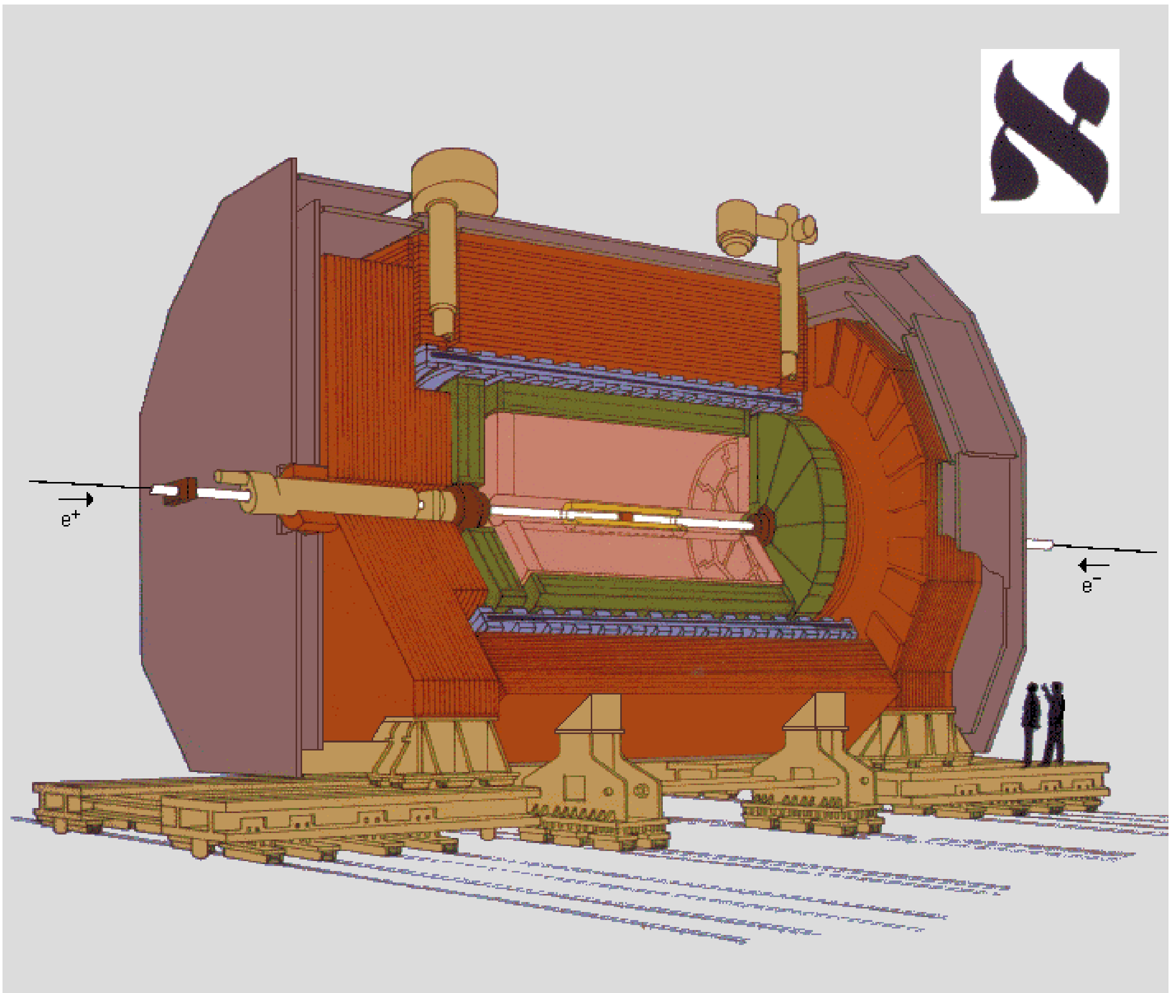

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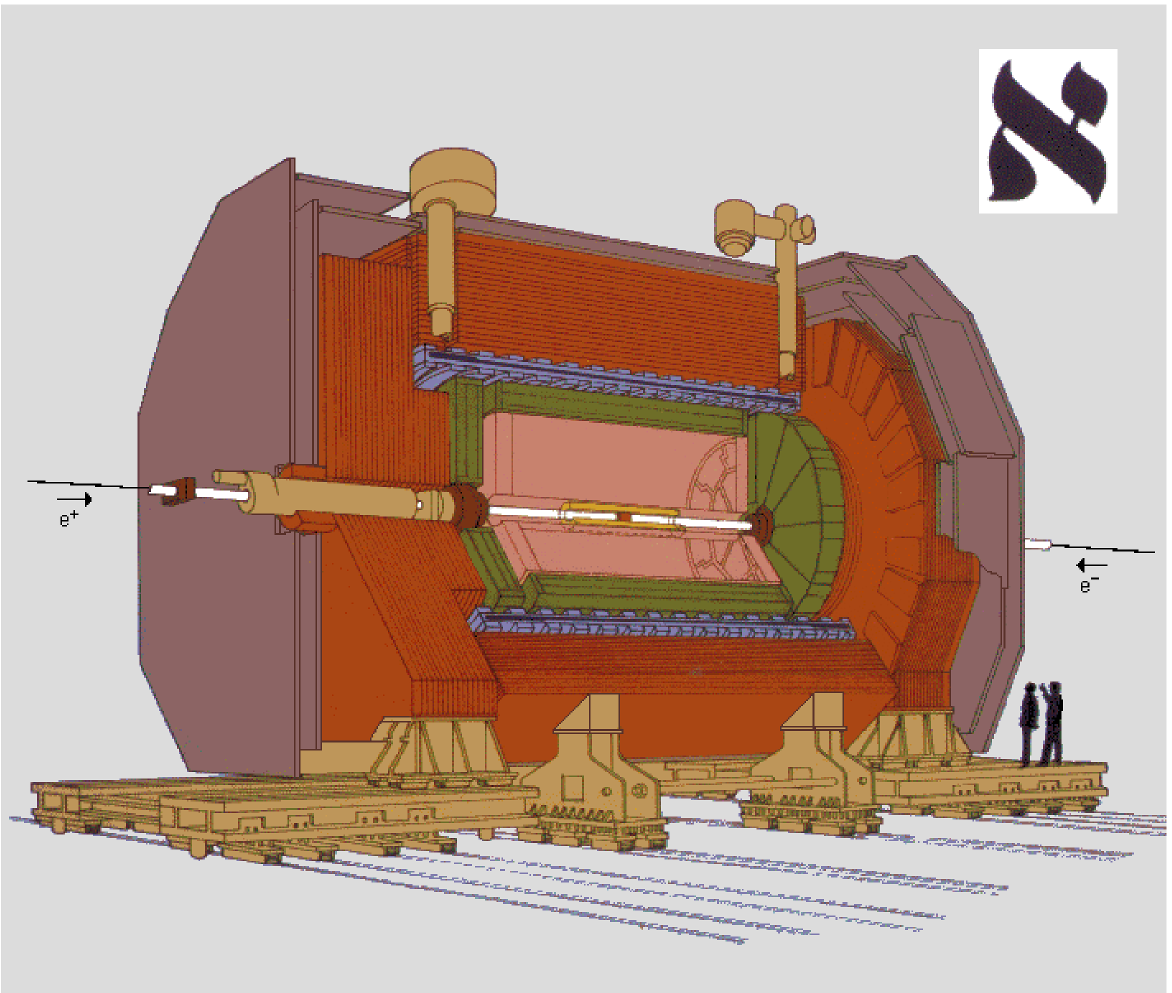

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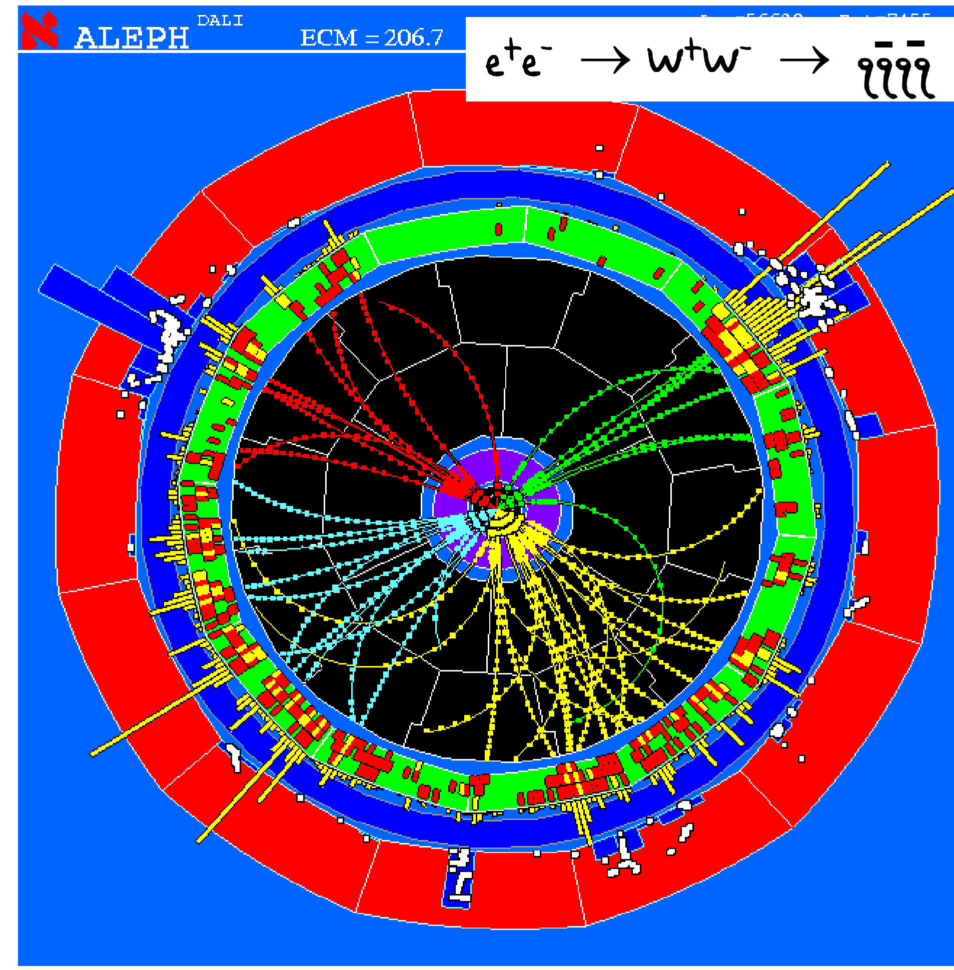

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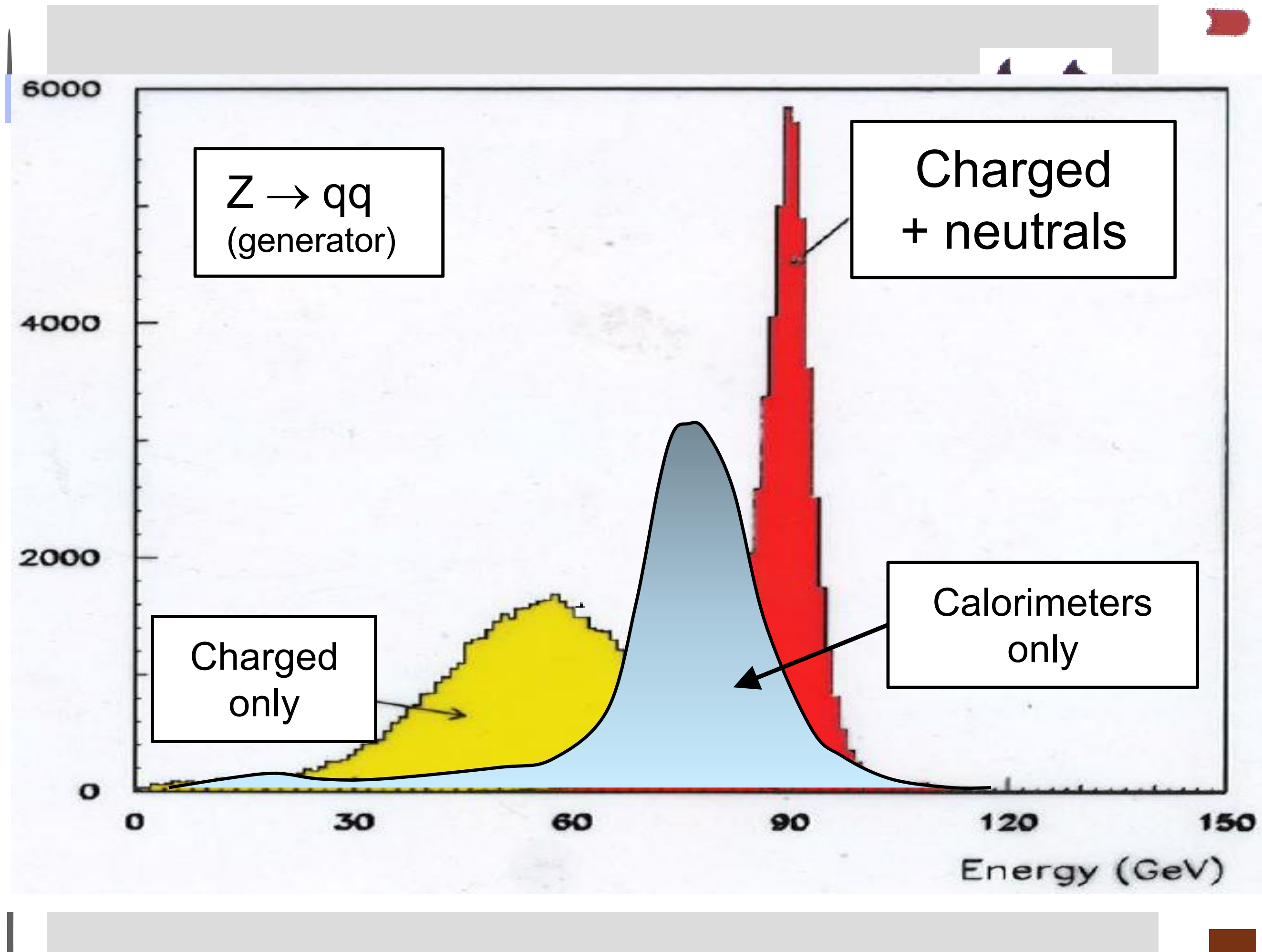

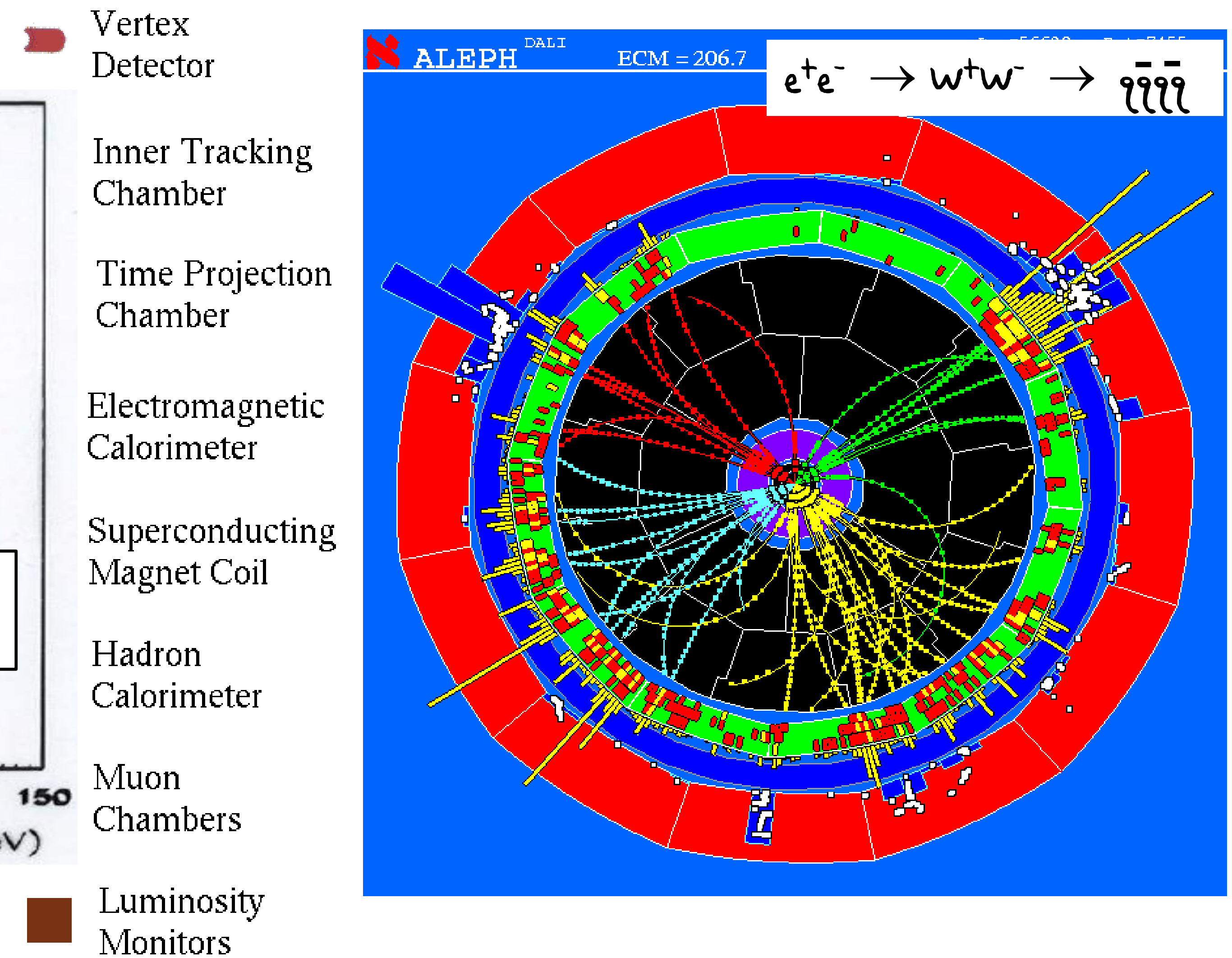

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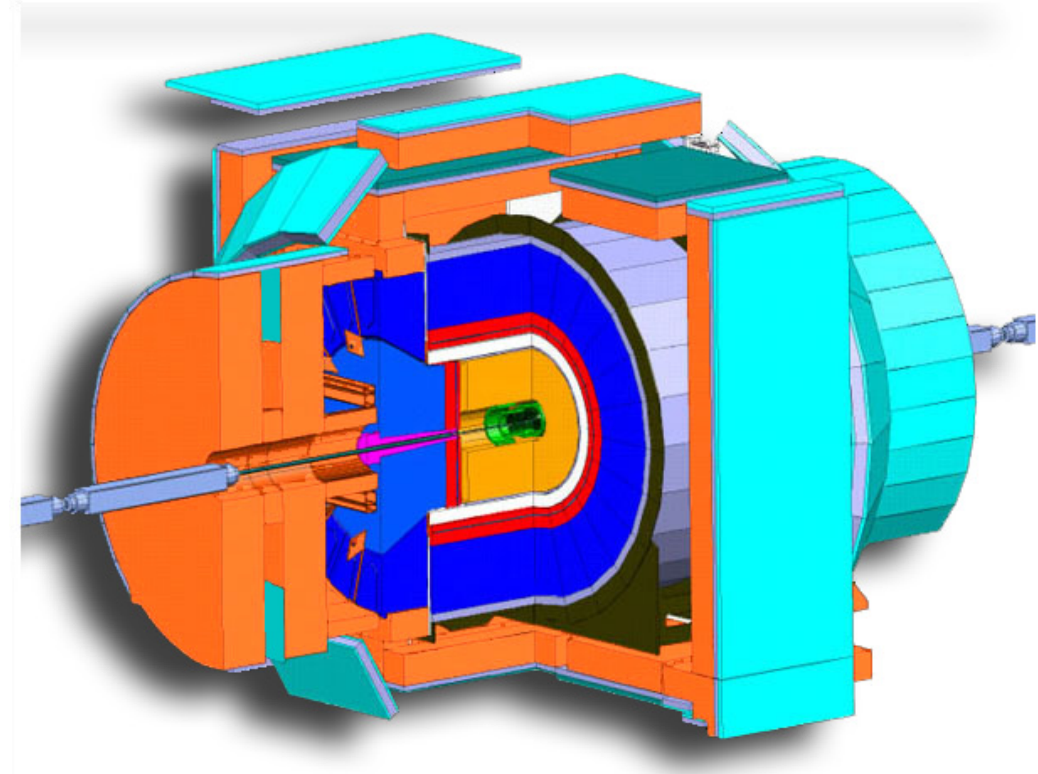
- Low Resolution: $\sigma \approx 100\%/\sqrt{E_T}$

Detectors not Suitable for Particle Flow

Detectors not Suitable for Particle Flow

CDF:

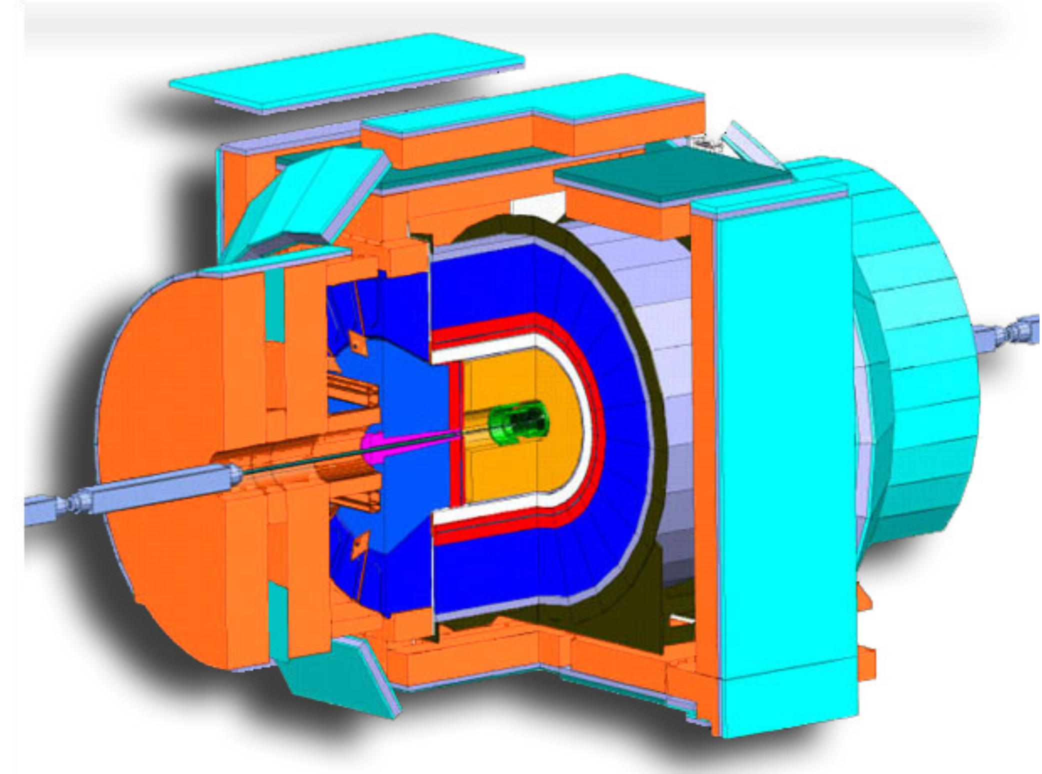


Detectors not Suitable for Particle Flow

Fermilab
UIC University of Illinois at Chicago

CDF:

Calorimeter



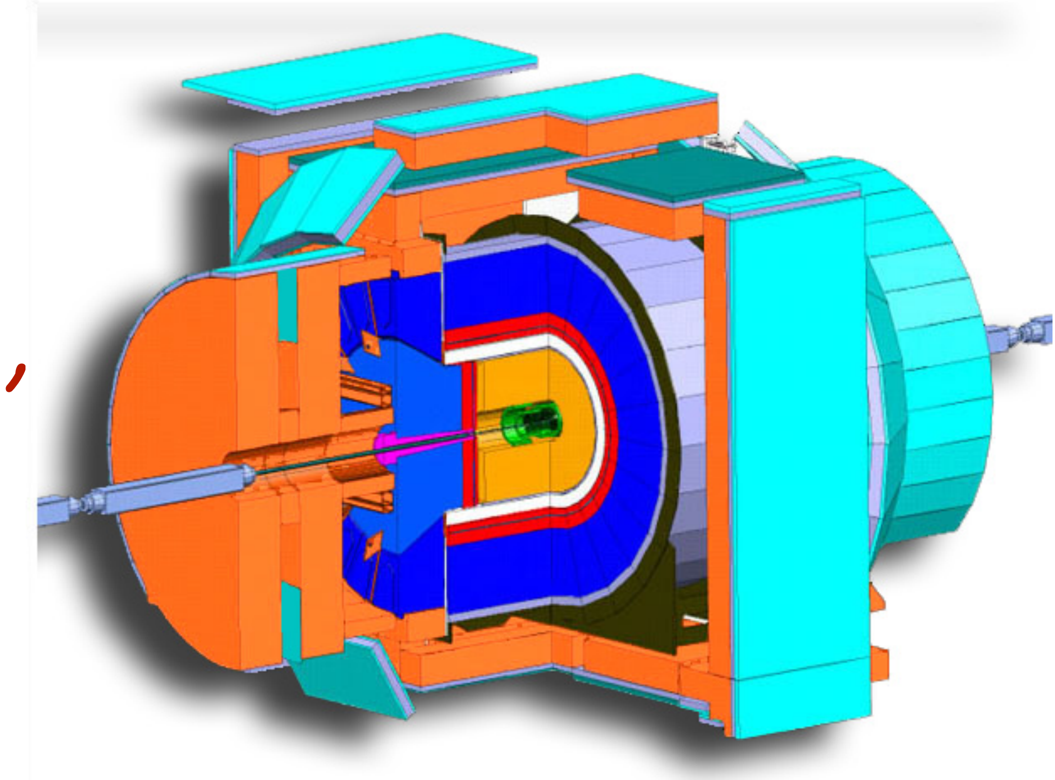
Detectors not Suitable for Particle Flow

Fermilab
UIC University of Illinois at Chicago

CDF:

Calorimeter

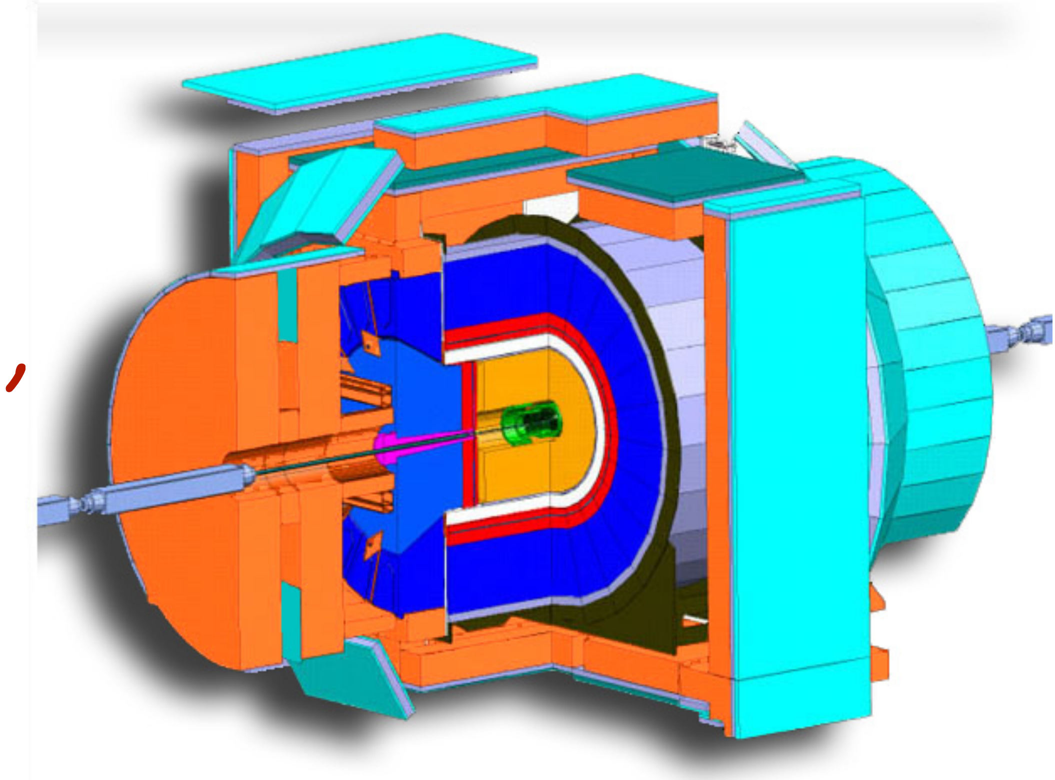
Granularity: $\Delta\phi \times \Delta\eta \approx 0.26 \times 0.11$,



Detectors not Suitable for Particle Flow

CDF:

- Calorimeter
  - Granularity: $\Delta\phi \times \Delta\eta \approx 0.26 \times 0.11$,
  - Resolution: HAD ~80%, EM ~15%



R. Cavanaugh 100 TeV Workshop, SLAC 23-26 August, 2014

Detectors not Suitable for Particle Flow

Fermilab
UIC University of Illinois at Chicago

CDF:

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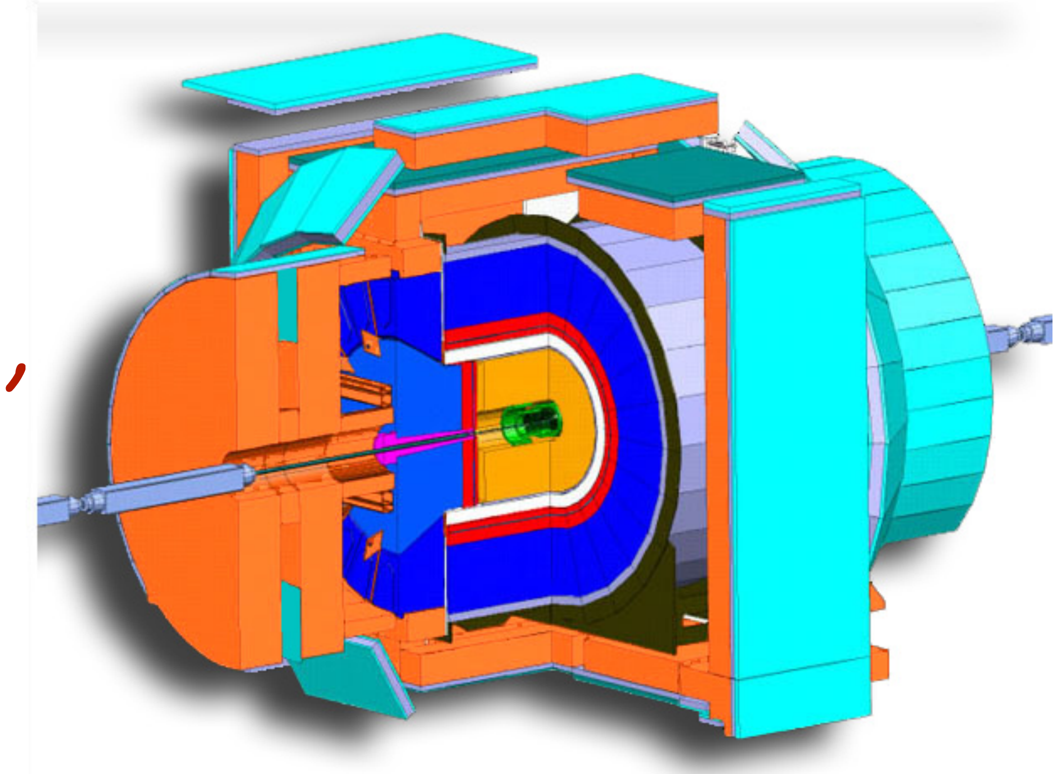
  - Granularity: $\Delta\phi \times \Delta\eta \approx 0.26 \times 0.11$,
  - Resolution: HAD ~80%, EM ~15%
- Tracker:



R. Cavanaugh 100 TeV Workshop, SLAC 23-26 August, 2014

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Calorimeter

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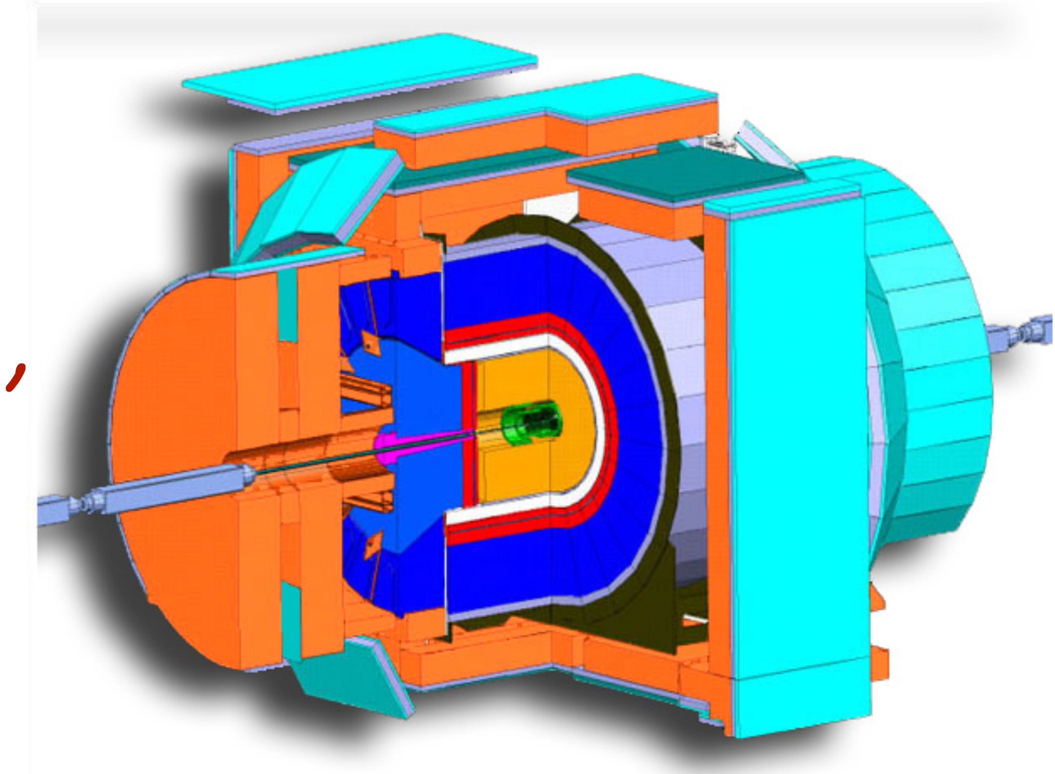
Tracker:

B-field ≈ 2T, Large volume
Solenoid before Calorimeter



Detectors not Suitable for Particle Flow

Fermilab
UIC University of Illinois at Chicago

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- Calorimeter
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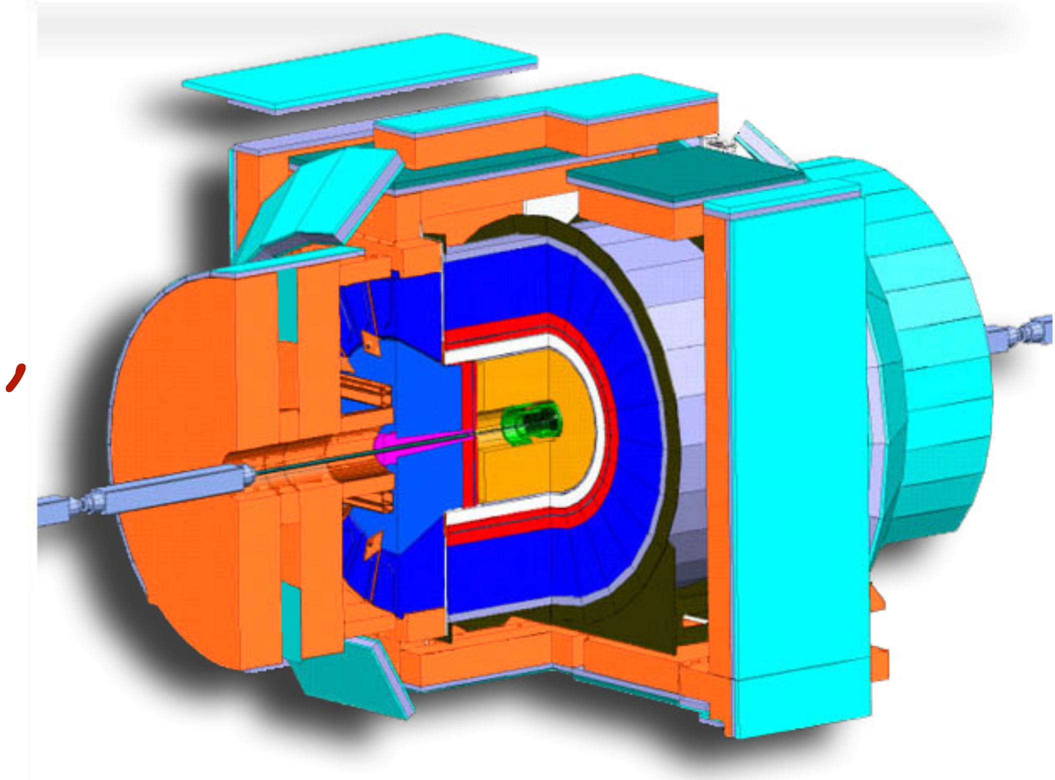
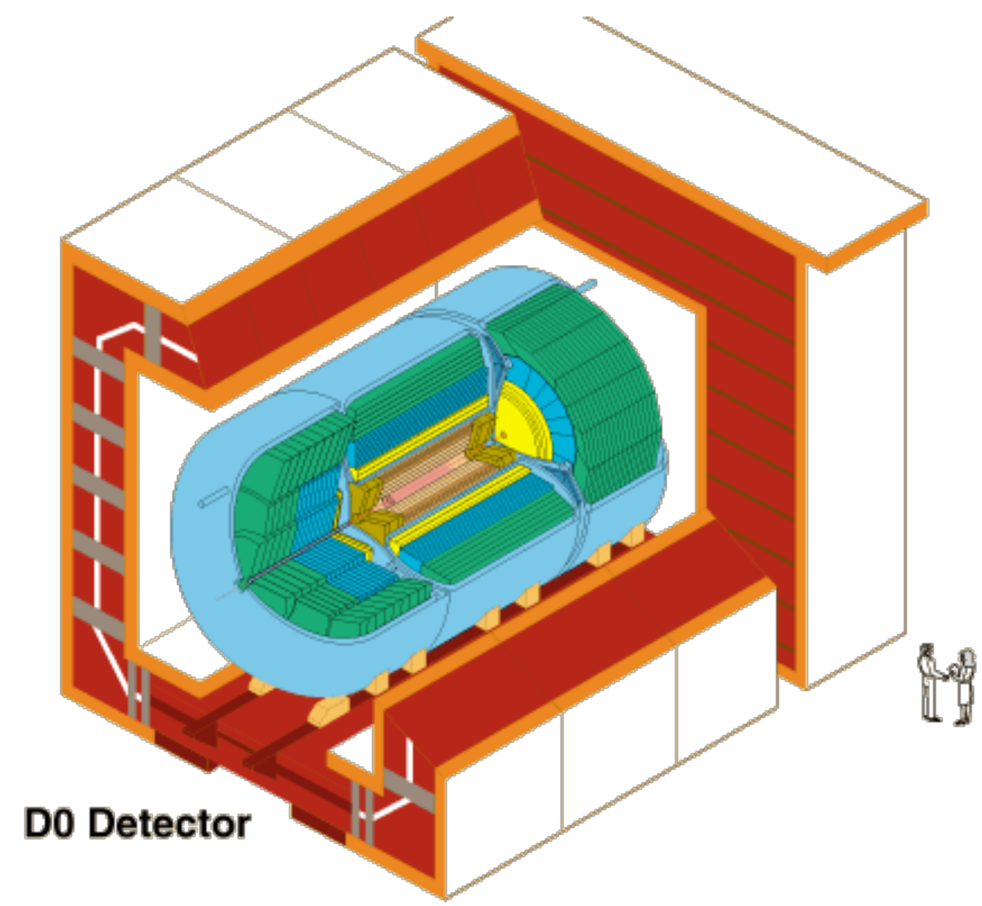


D0:



Detectors not Suitable for Particle Flow

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- Tracker:
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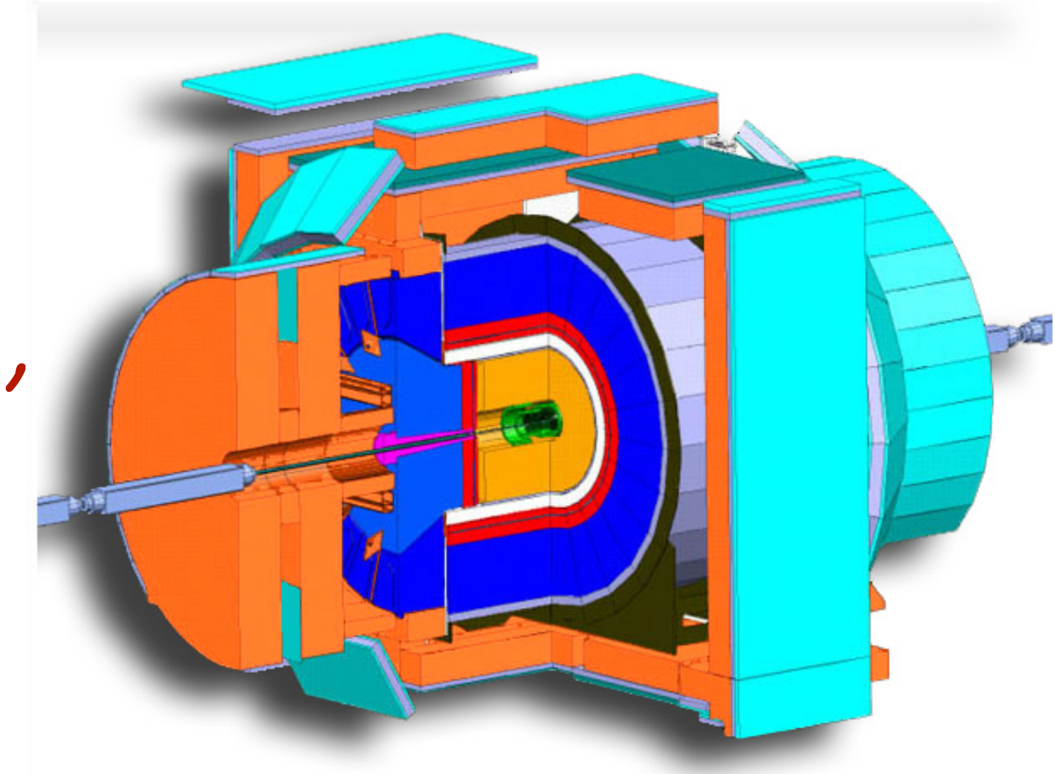
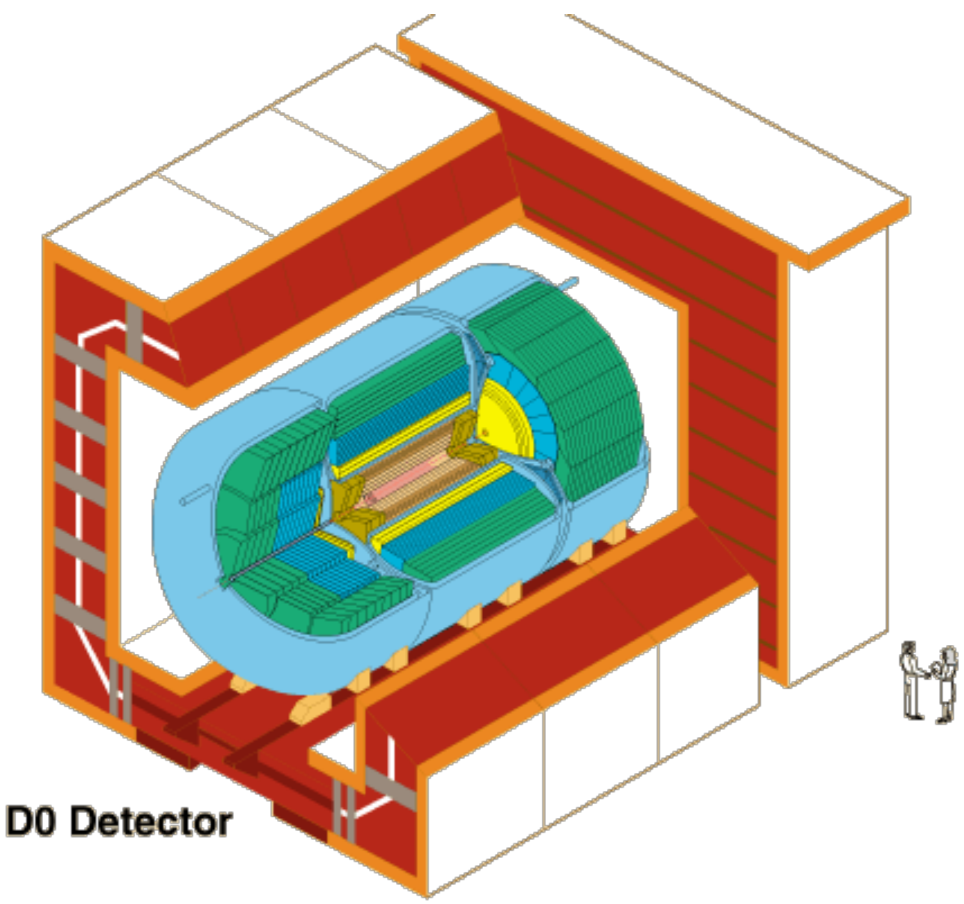


D0:

- Calorimeter

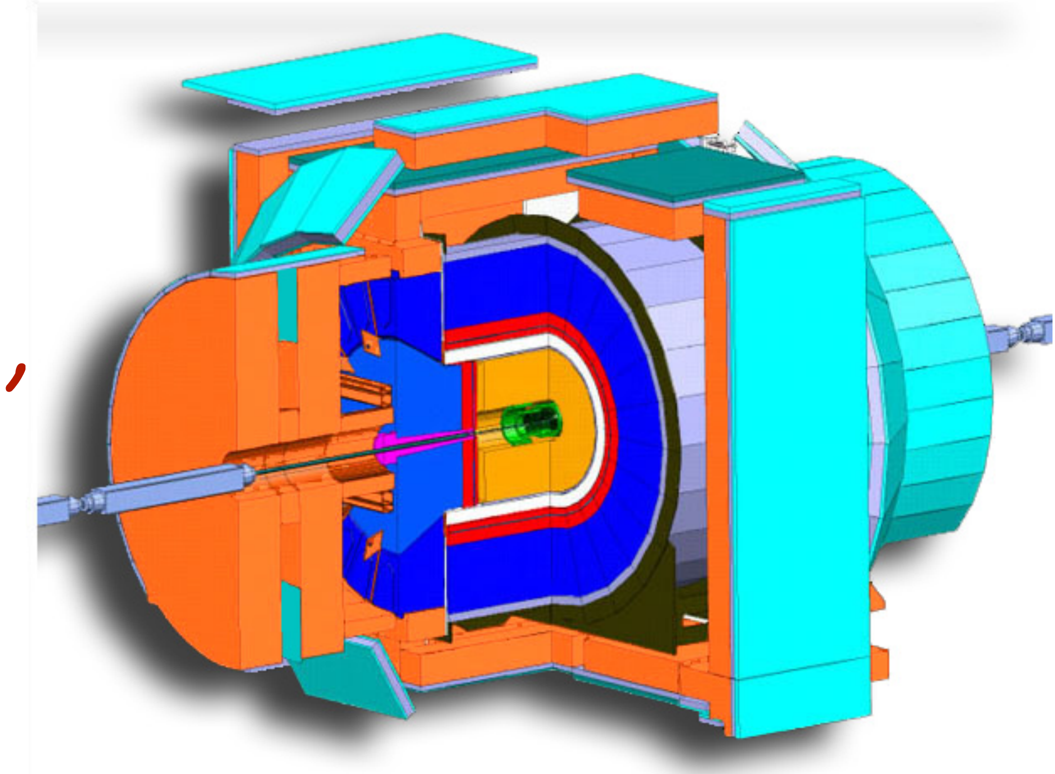


D0 Detector

Detectors not Suitable for Particle Flow

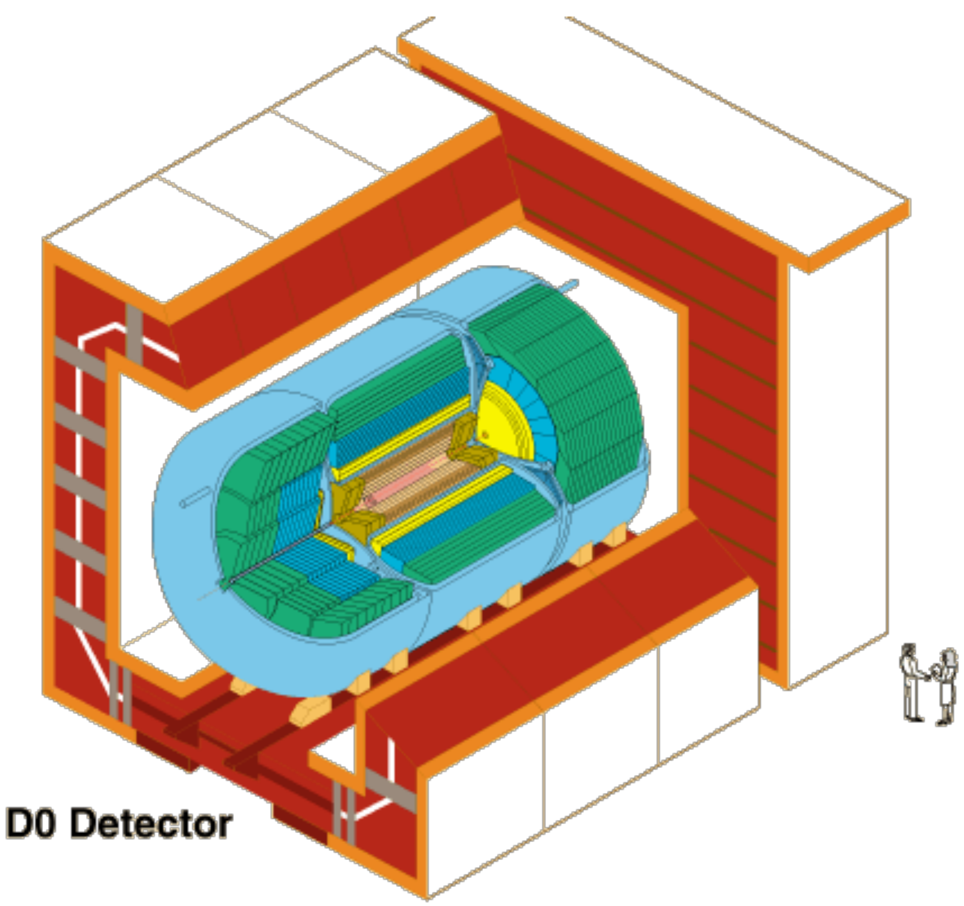
CDF:

- Calorimeter
  - Granularity: $\Delta\phi \times \Delta\eta \approx 0.26 \times 0.11$,
  - Resolution: HAD ~80%, EM ~15%
- Tracker:
  - B-field ≈ 2T, Large volume Solenoid before Calorimeter



D0:

- Calorimeter
  - Granularity: $\Delta\phi \times \Delta\eta \approx 0.1 \times 0.1$



D0 Detector

Detectors not Suitable for Particle Flow

R. Cavanaugh 100 TeV Workshop, SLAC 23-26 August, 2014

CDF:

- Calorimeter
  - Granularity: $\Delta\phi \times \Delta\eta \approx 0.26 \times 0.11$,
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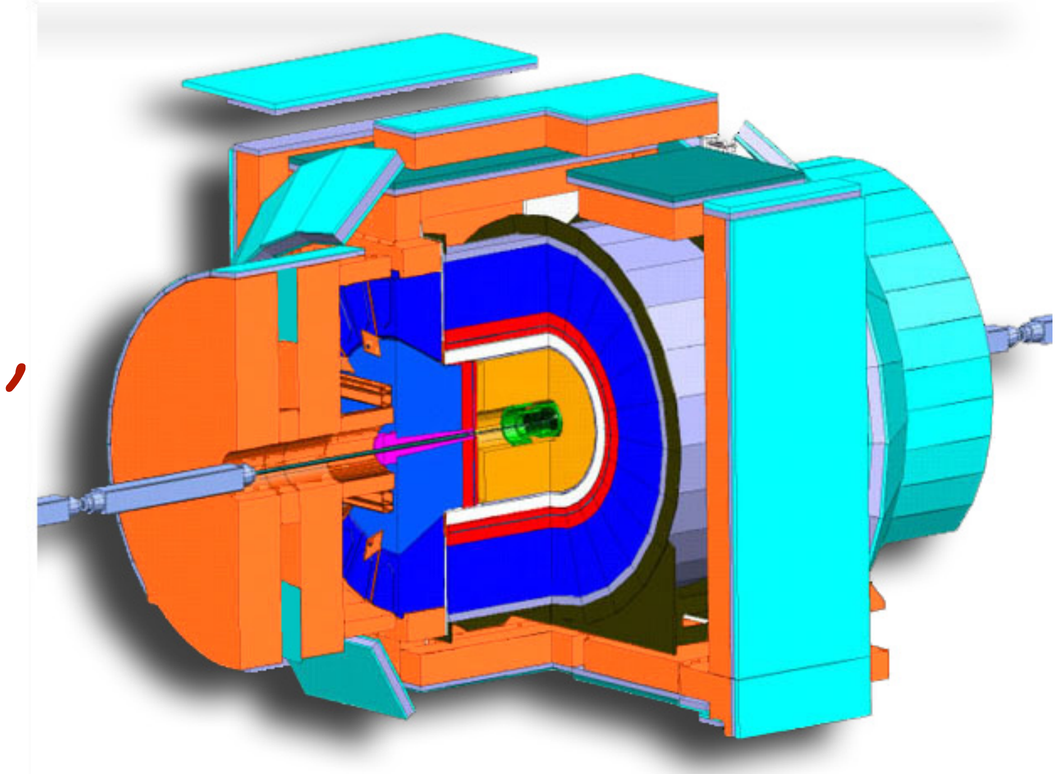
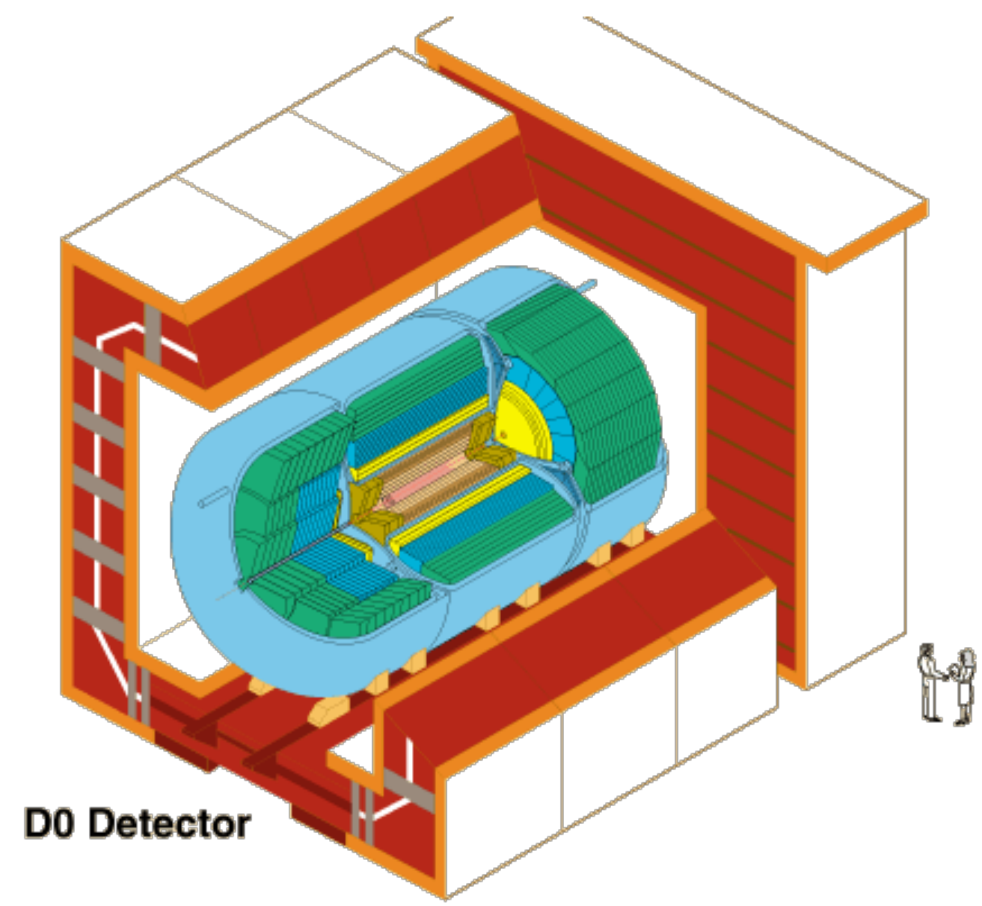


D0:

- Calorimeter
  - Granularity: $\Delta\phi \times \Delta\eta \approx 0.1 \times 0.1$
  - Resolution: HAD ~50%, EM ~15%



Detectors not Suitable for Particle Flow

Fermilab
UIC University of Illinois at Chicago

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Calorimeter

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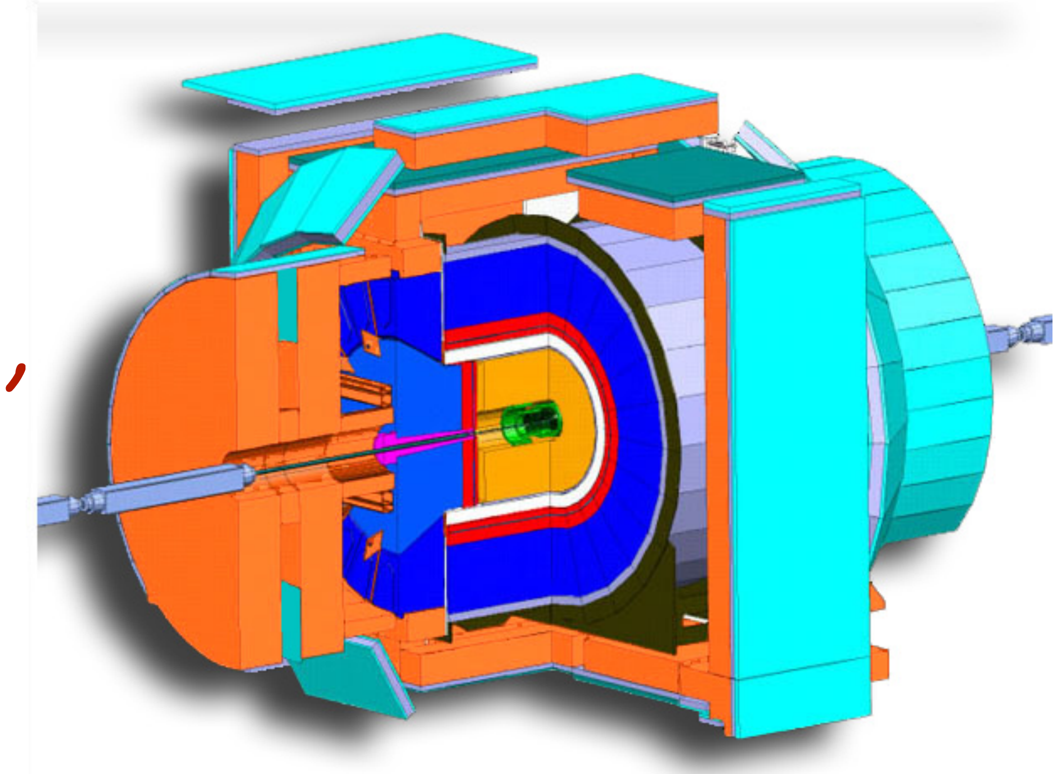
Solenoid before Calorimeter



D0:

Calorimeter

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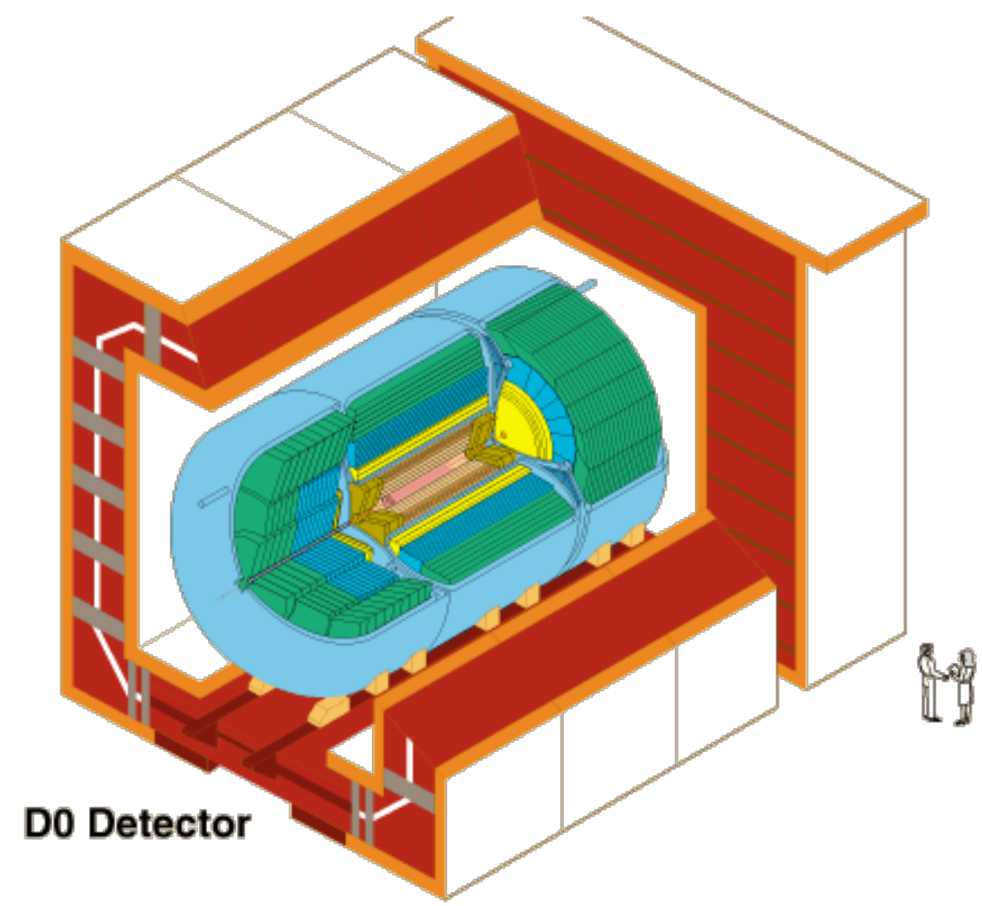
Tracker:



Detectors not Suitable for Particle Flow

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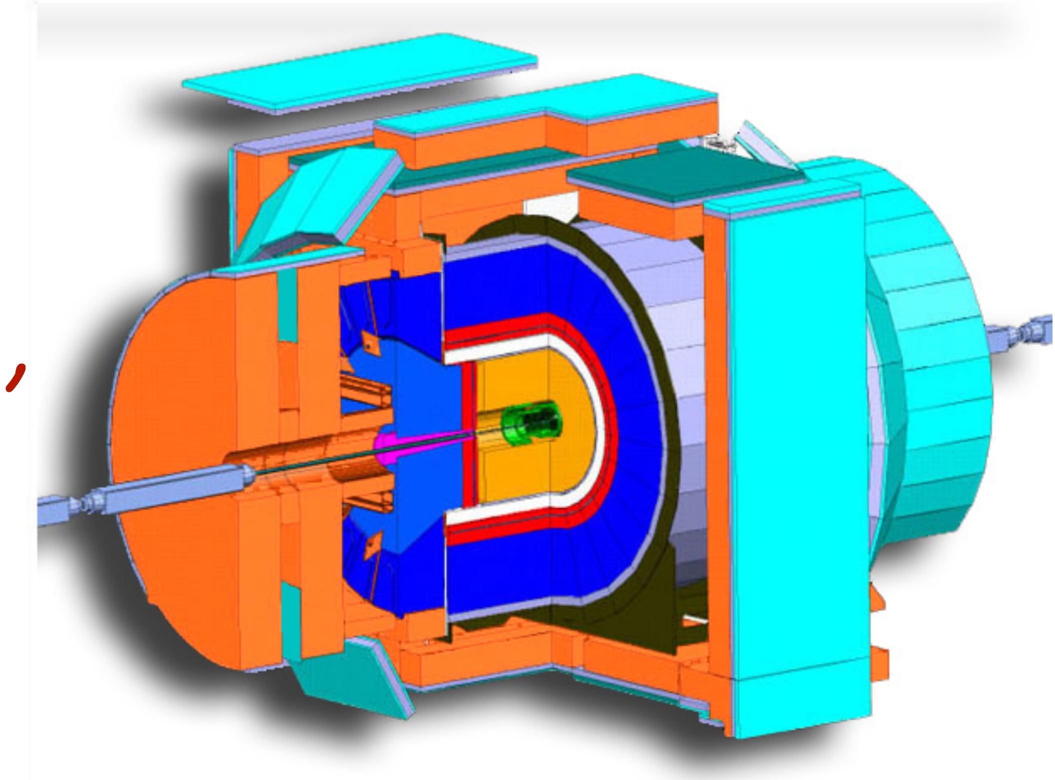
- Calorimeter
  - Granularity: $\Delta\phi \times \Delta\eta \approx 0.26 \times 0.11$,
  - Resolution: HAD ~80%, EM ~15%
- Tracker:
  - B-field ≈ 2T, Large volume Solenoid before Calorimeter



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- Calorimeter
  - Granularity: $\Delta\phi \times \Delta\eta \approx 0.1 \times 0.1$
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- Tracker:
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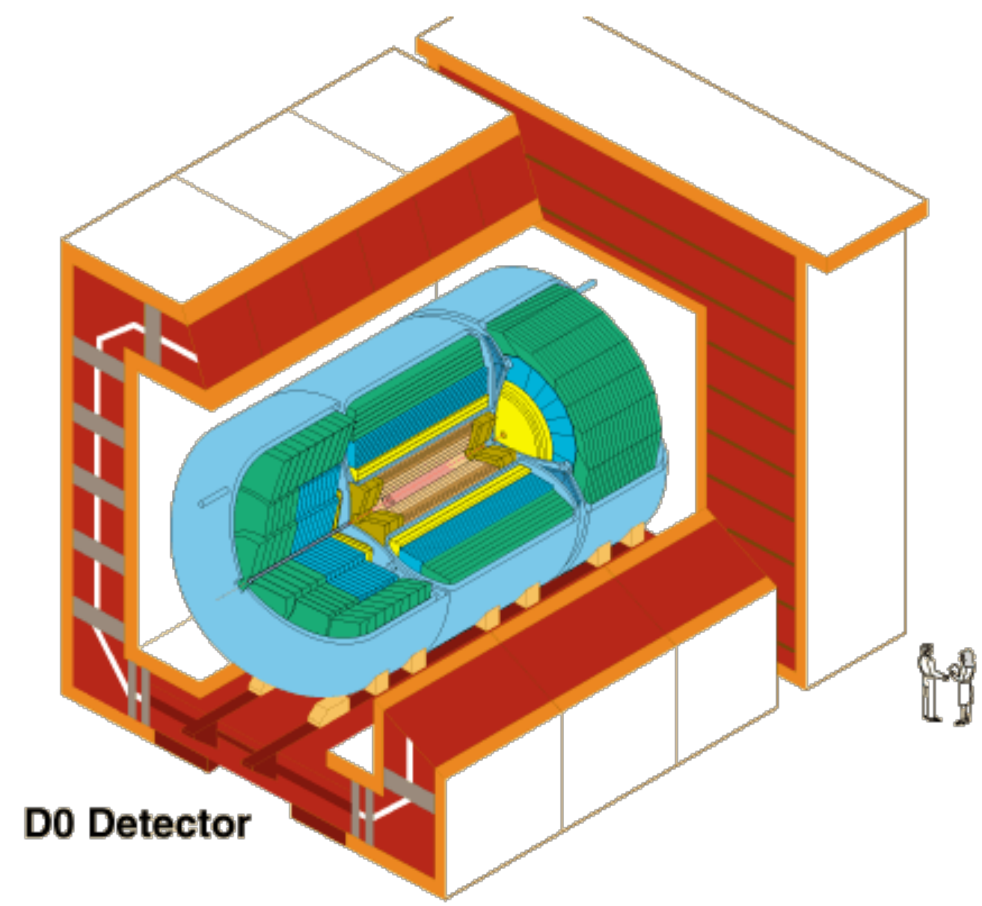
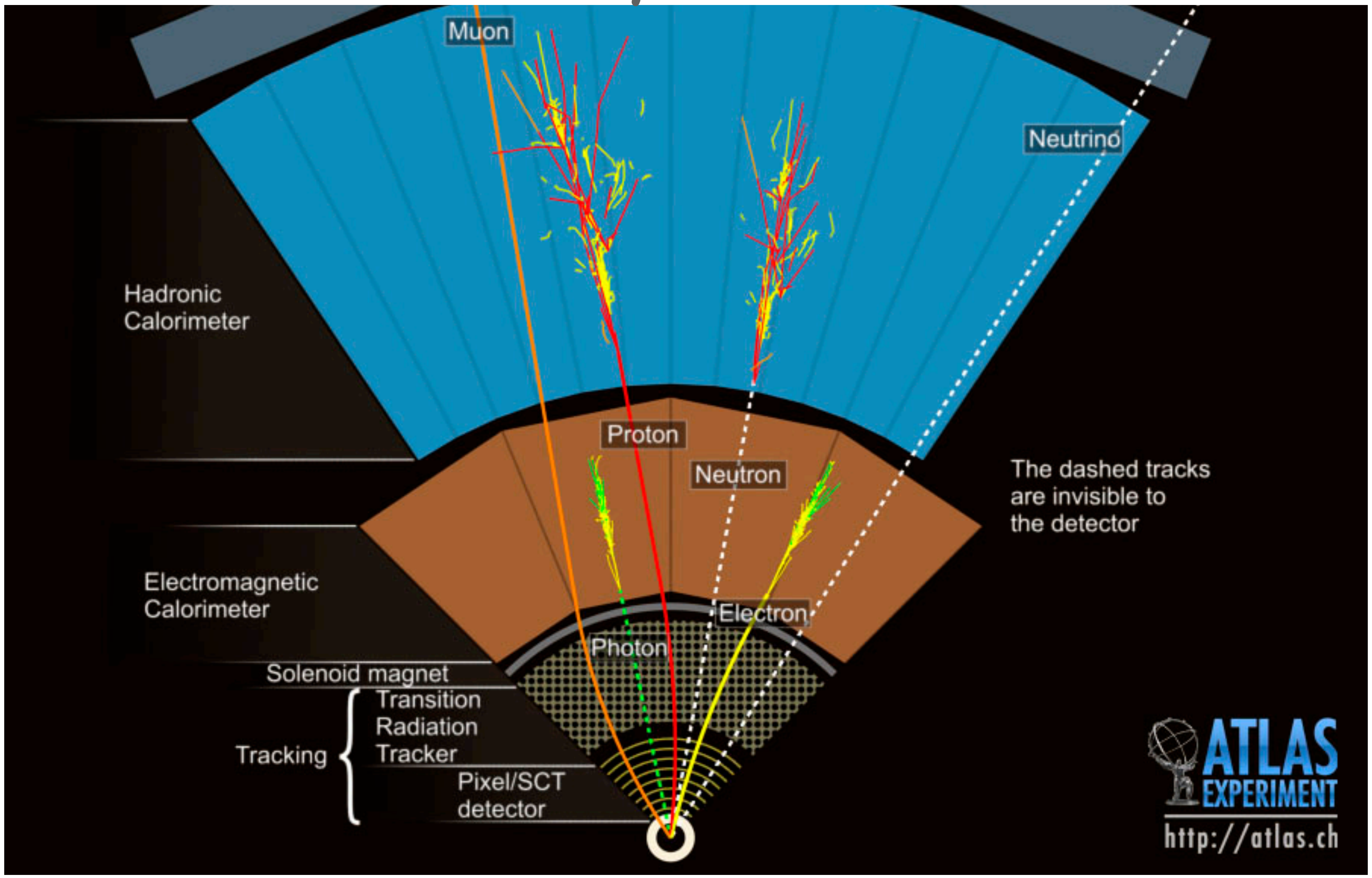
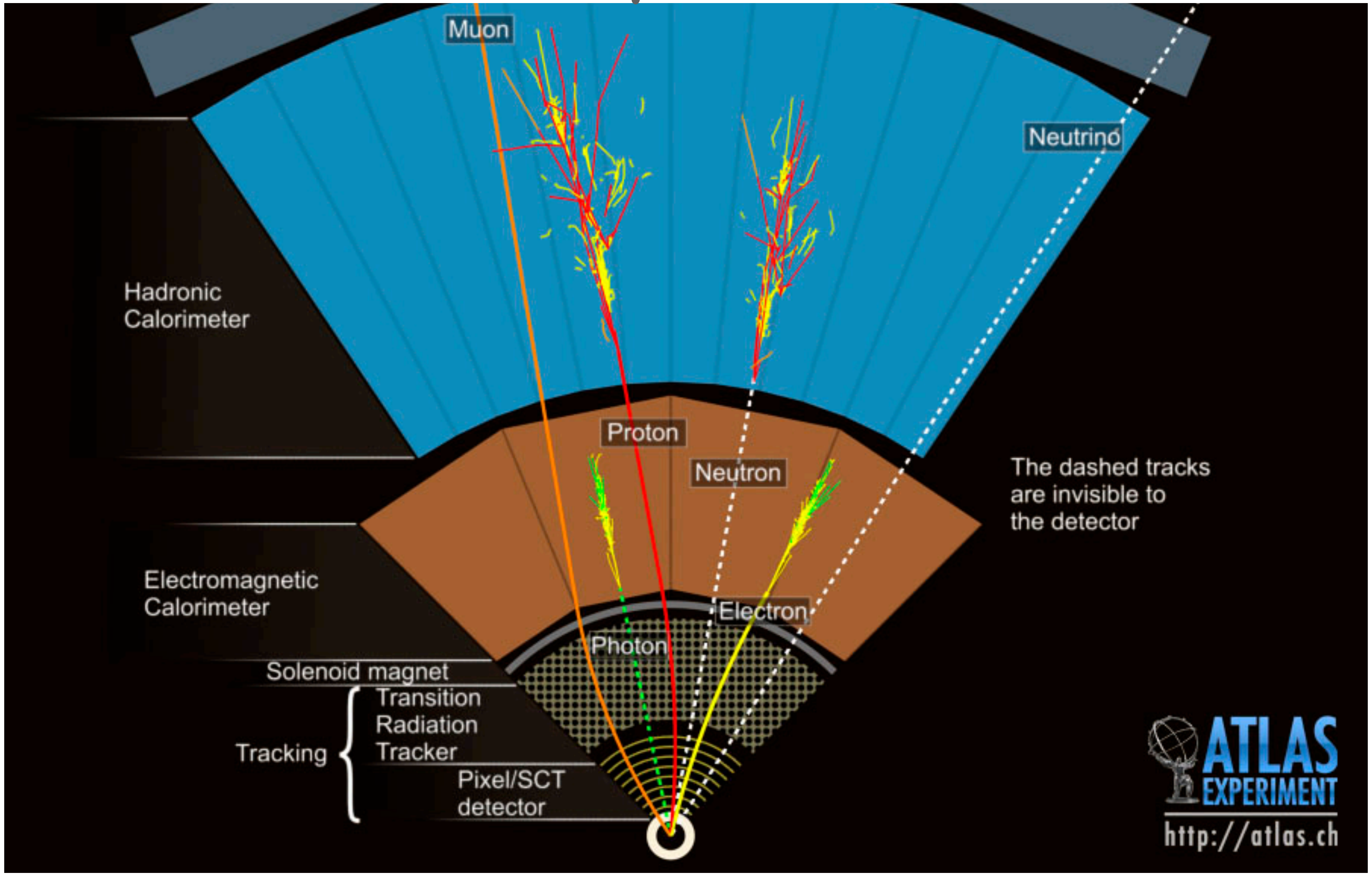


Hadron Collider Example: ATLAS

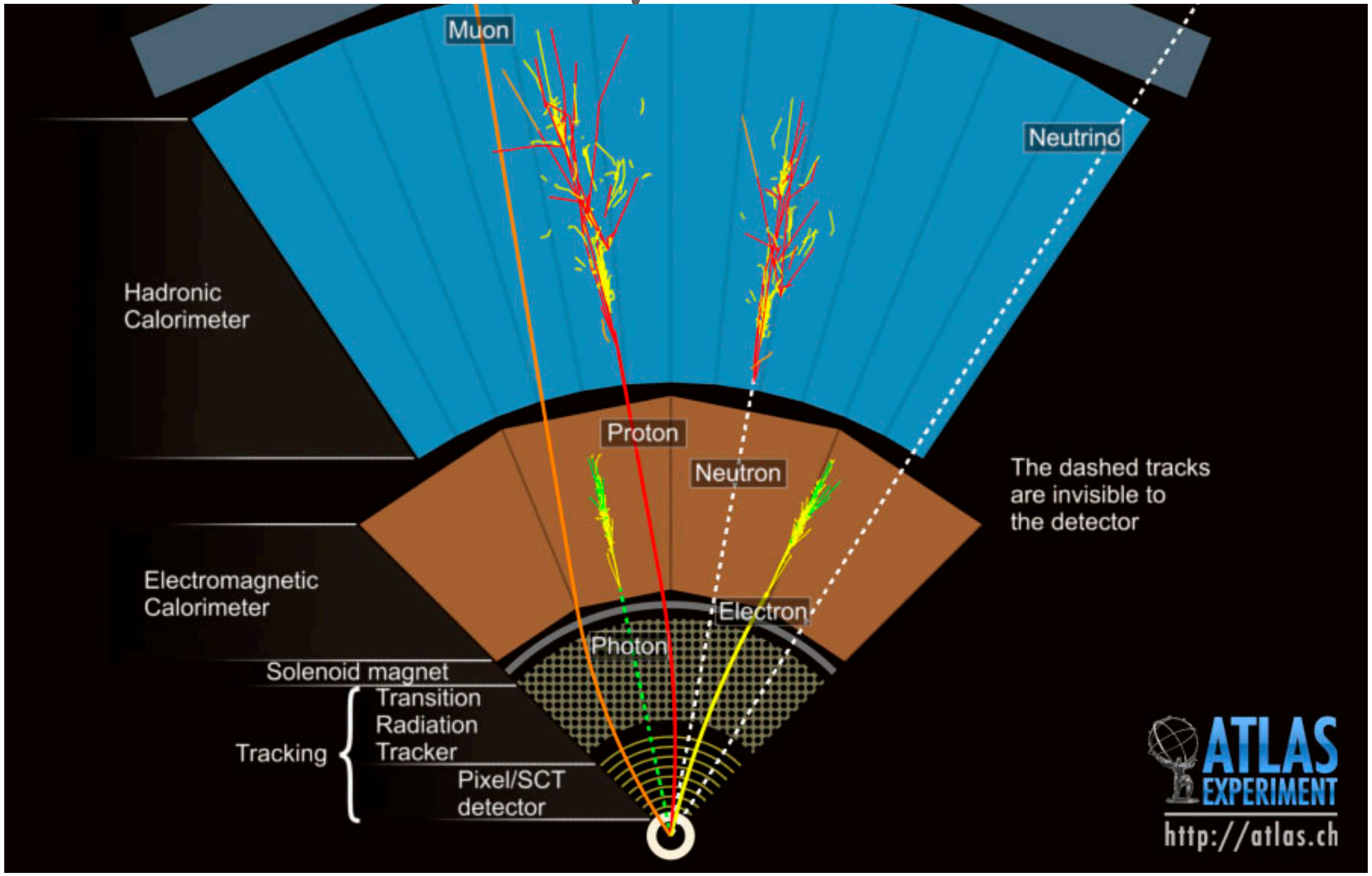


Hadron Collider Example: ATLAS



Tracking:

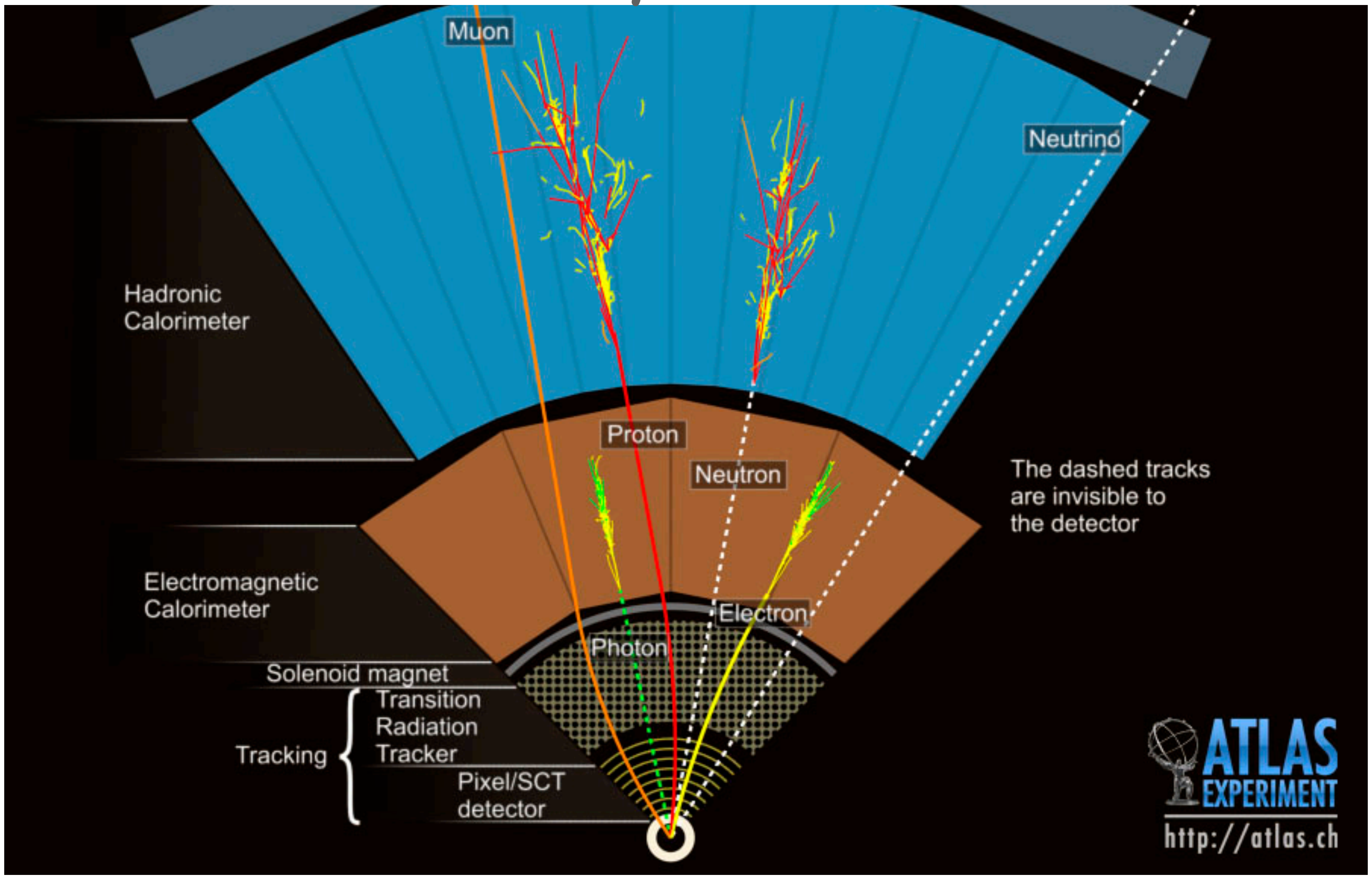
Hadron Collider Example: ATLAS



Tracking:

Large Vol: R > 1m, 3+4(+73) layers; Heavy

Hadron Collider Example: ATLAS



Tracking:

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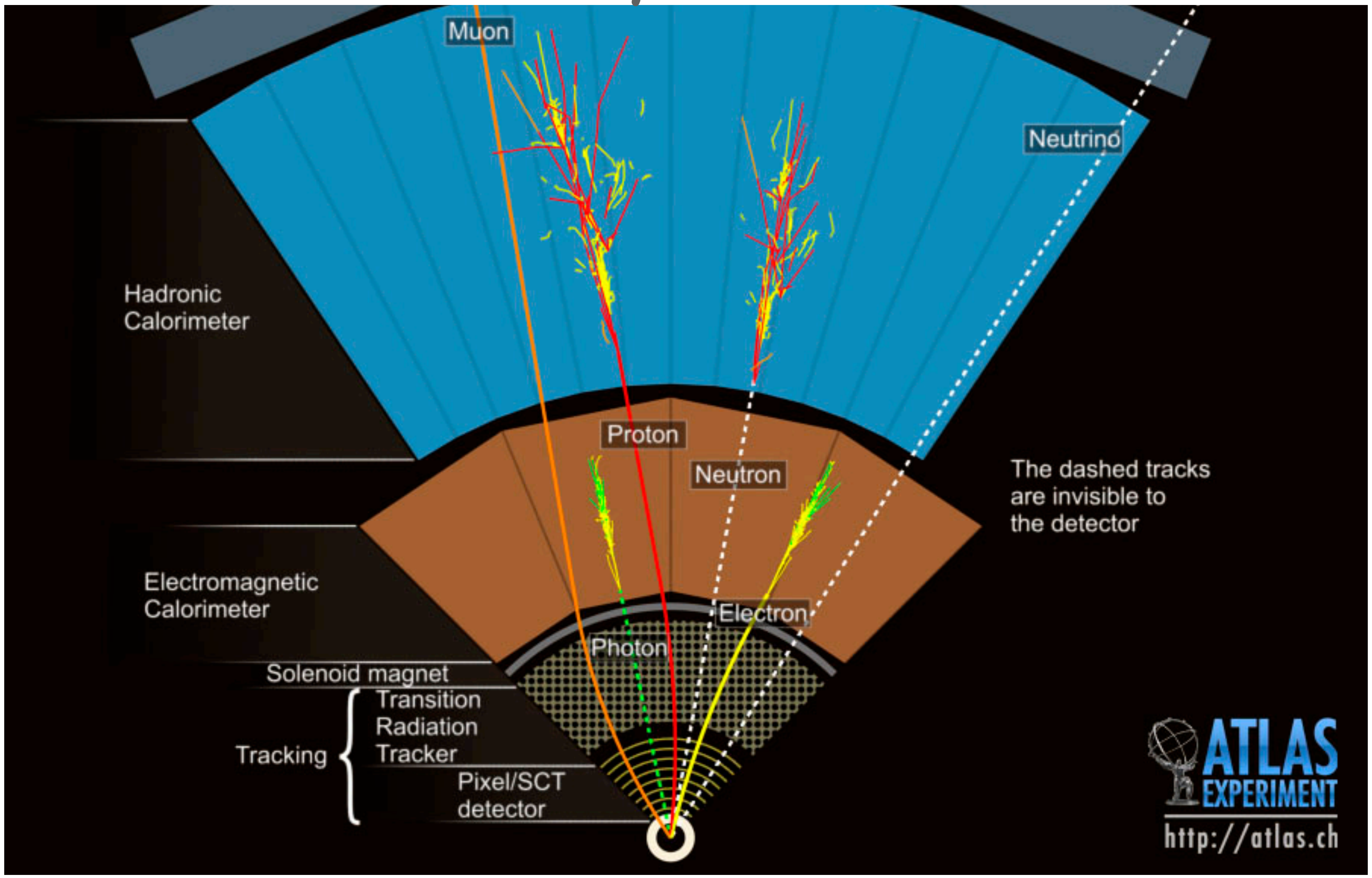
Eff ≈ 85% (~99%) π's (μ's); fake ≈ 1%

Hadron Collider Example: ATLAS



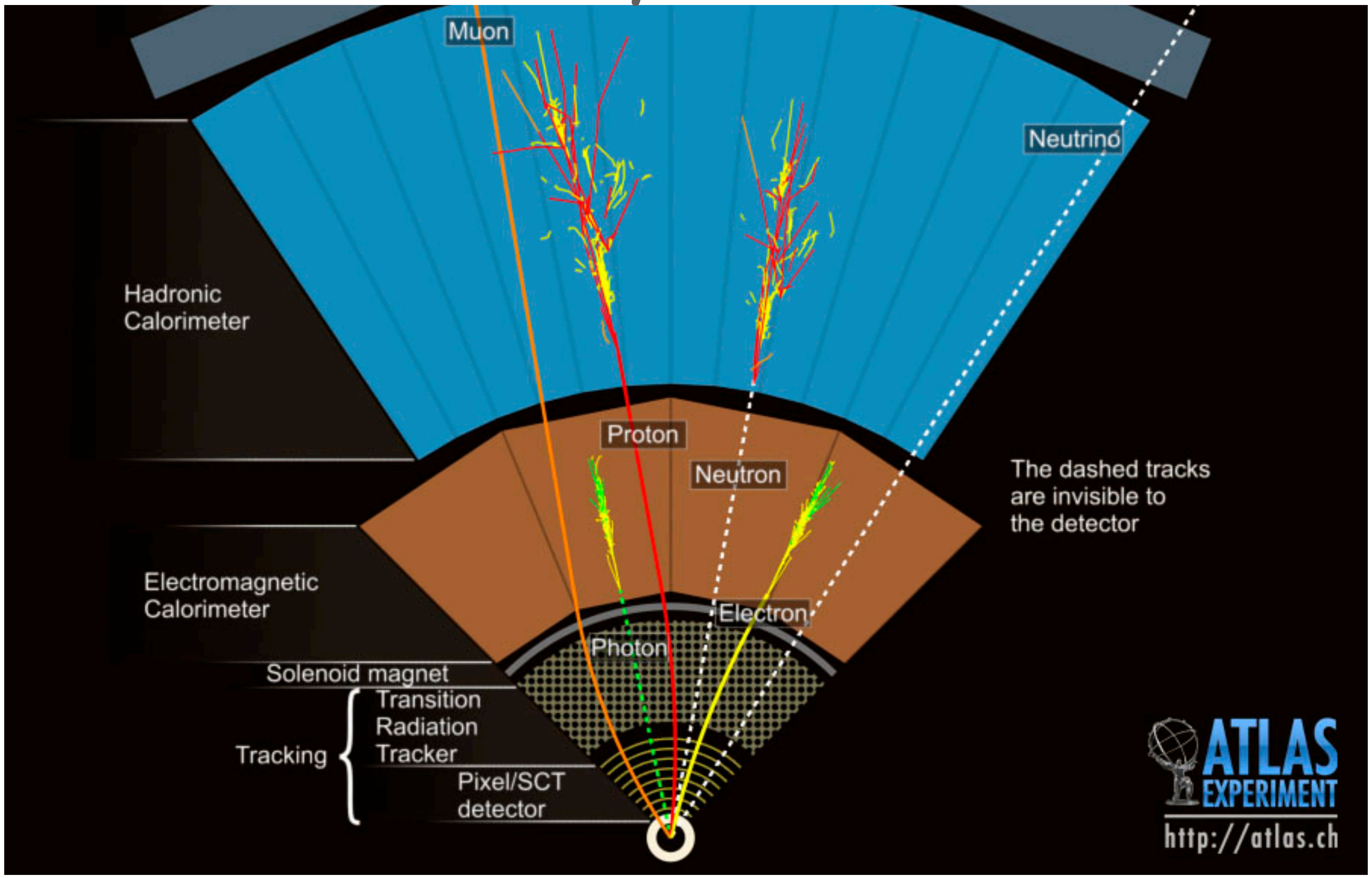
Tracking:

Large Vol: R > 1m, 3+4(+73) layers; Heavy

Eff ≈ 85% (~99%) π's (μ's); fake ≈ 1%

Fiducial accept: $|\eta| < 2.5$

Hadron Collider Example: ATLAS



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- Large Vol: R > 1m, 3+4(+73) layers; Heavy
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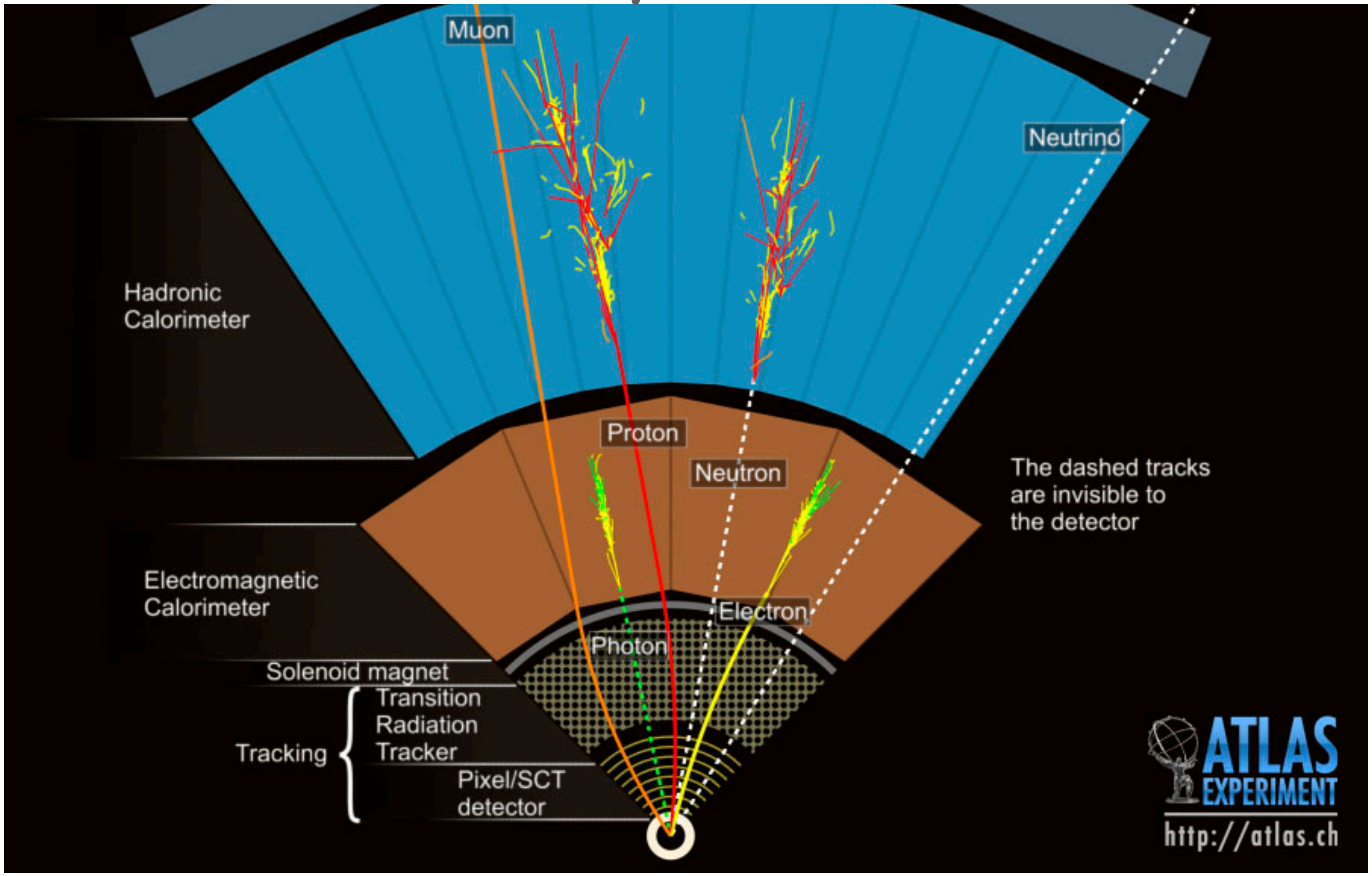
Hadron Collider Example: ATLAS



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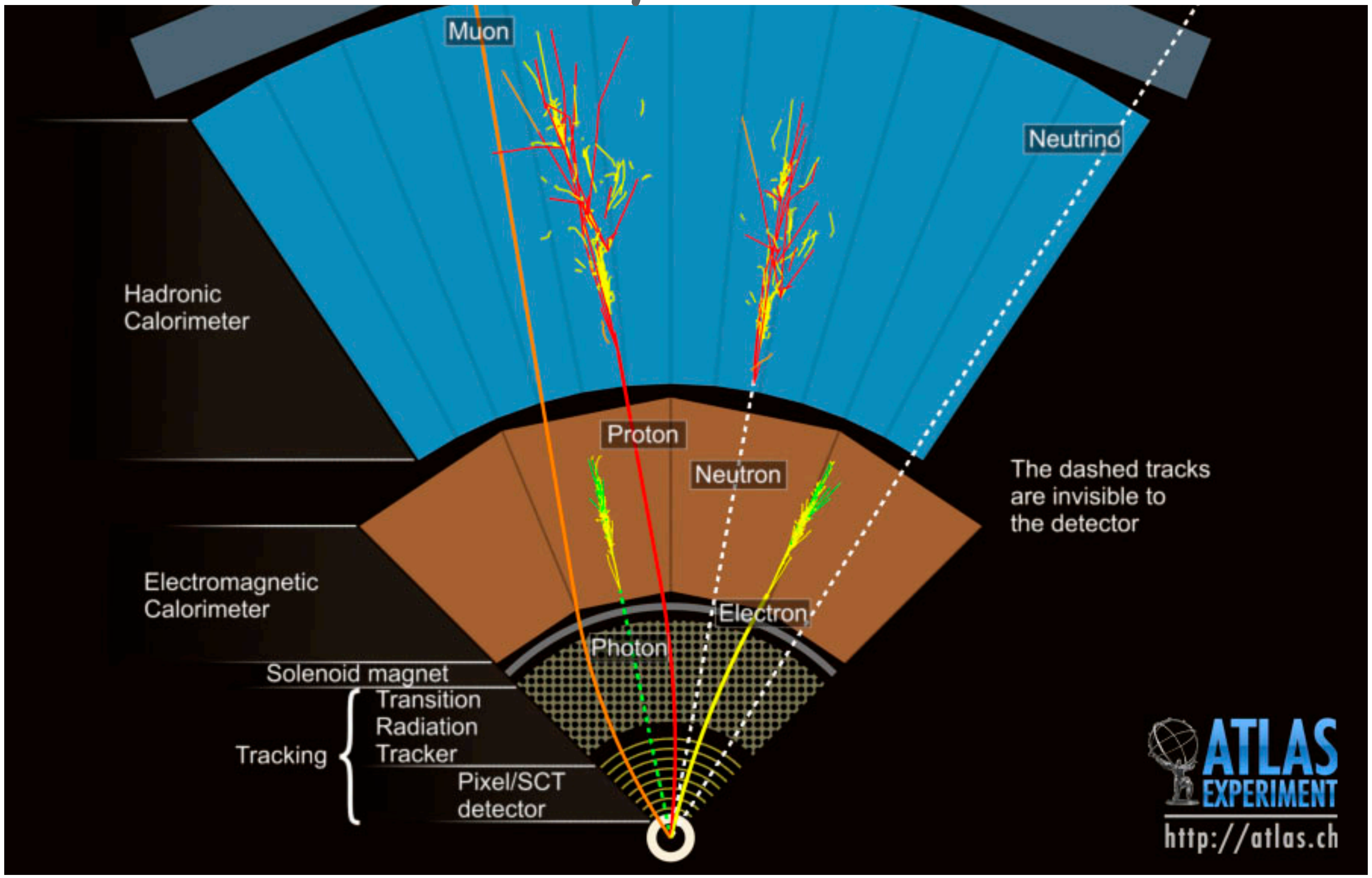
- Fiducial accept: $|\eta| < 2.5$
- tracks down to $p_T \approx 100$ MeV

Solenoid:

Hadron Collider Example: ATLAS



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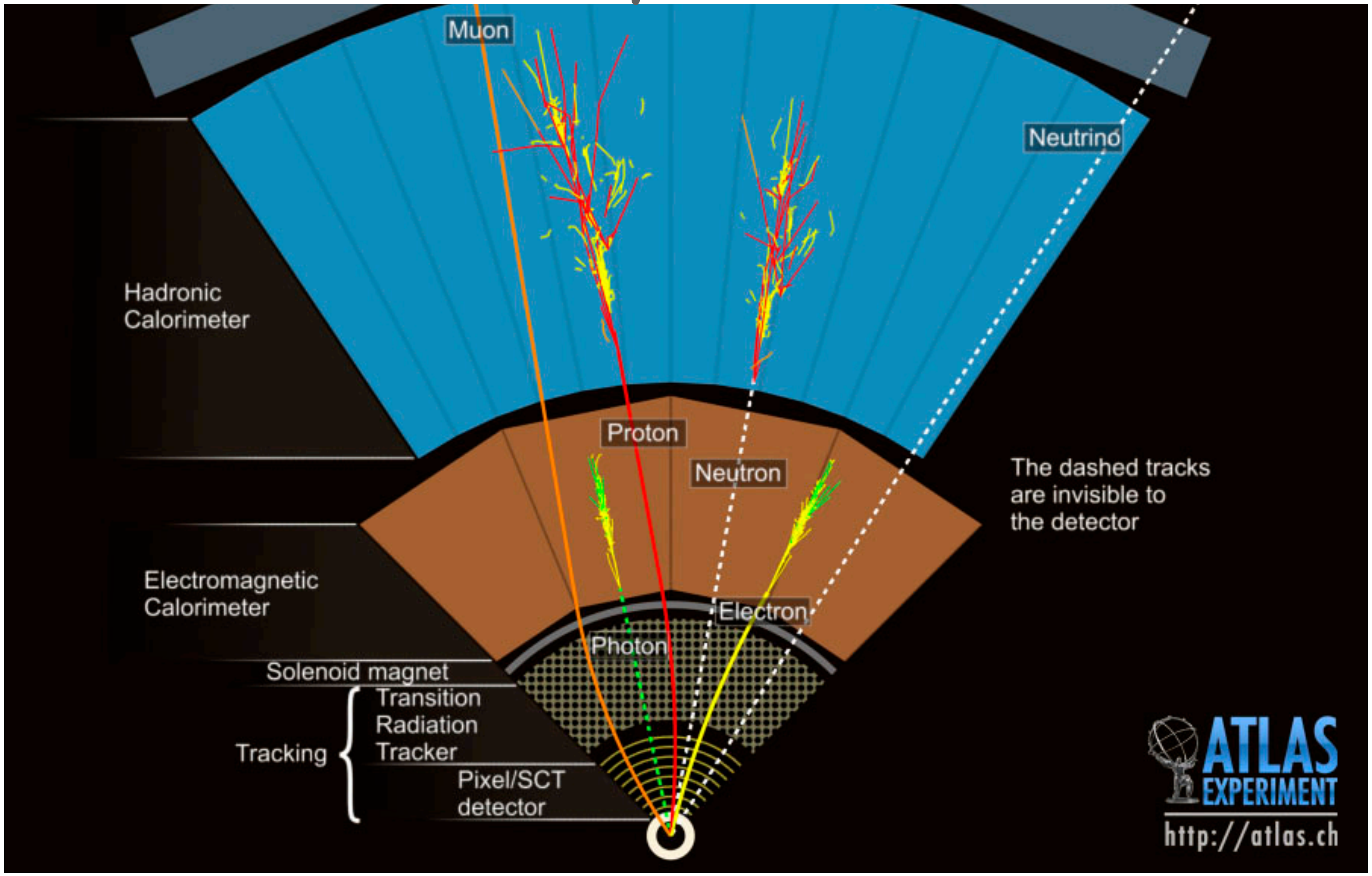
Solenoid:

- B-field = 2T; Solenoid before Calorimeter

Hadron Collider Example: ATLAS

Fermilab
UIC University of Illinois at Chicago



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Fiducial accept: $|\eta| < 2.5$

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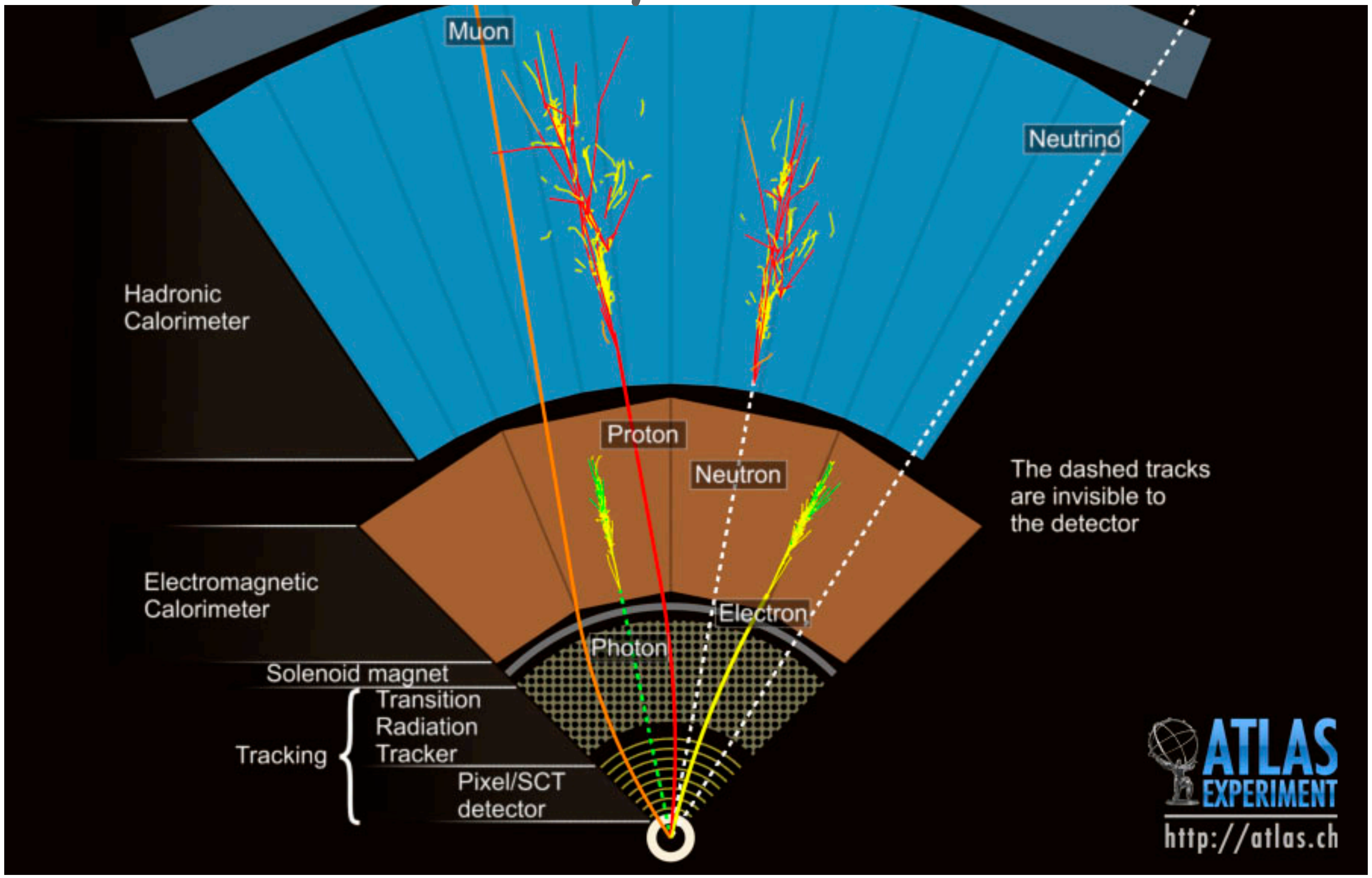
Solenoid:

B-field = 2T; Solenoid before Calorimeter

$\sigma(p_T)/p_T = 1.8\% + 60\%\ p_T$ [TeV]

Hadron Collider Example: ATLAS

Fermilab
UIC University of Illinois at Chicago



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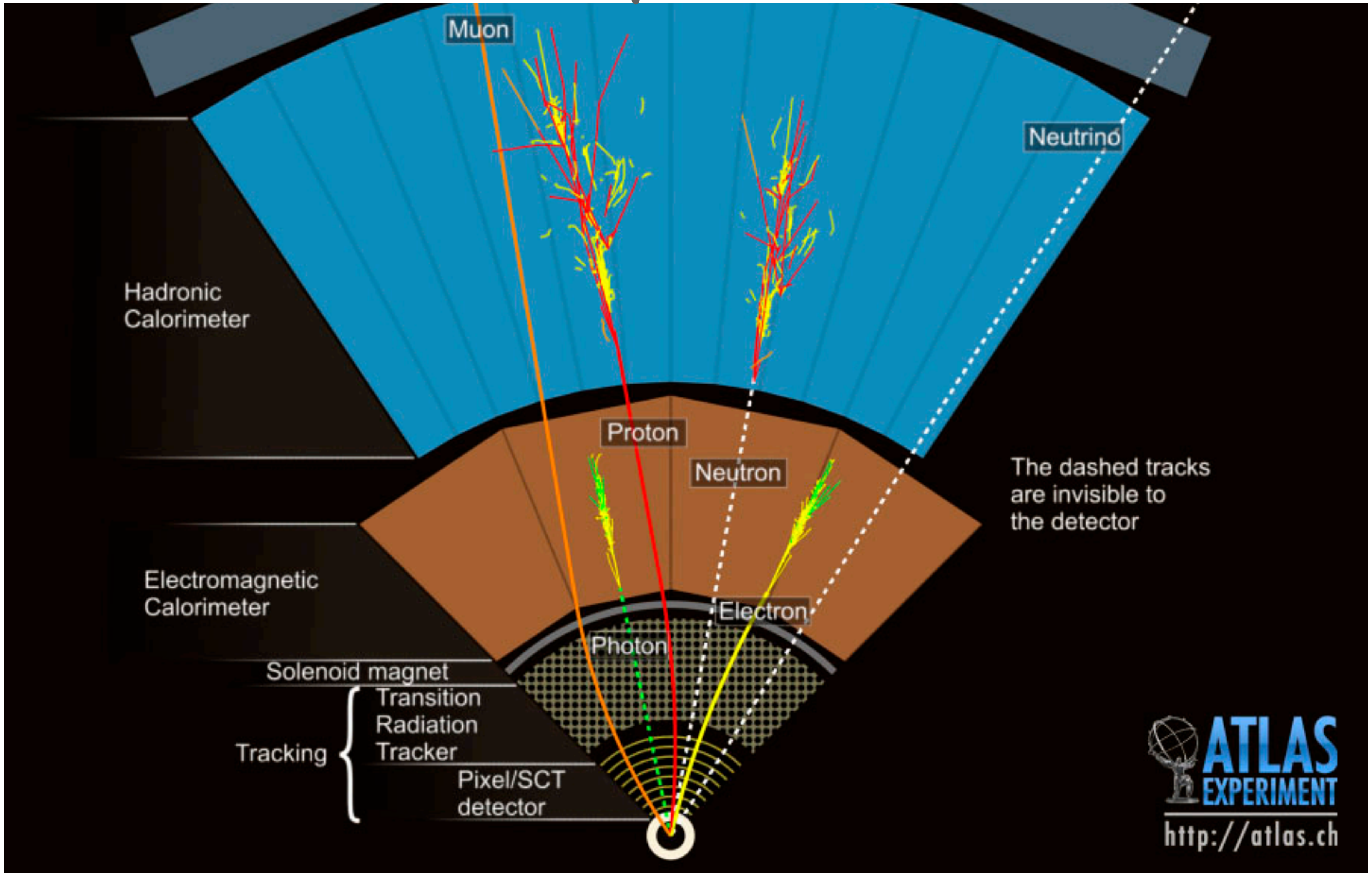
- B-field = 2T; Solenoid before Calorimeter
- $\sigma(p_T)/p_T = 1.8\% + 60\%\ p_T\ [\text{TeV}]$

ECAL:

Hadron Collider Example: ATLAS

Fermilab
UIC University of Illinois at Chicago



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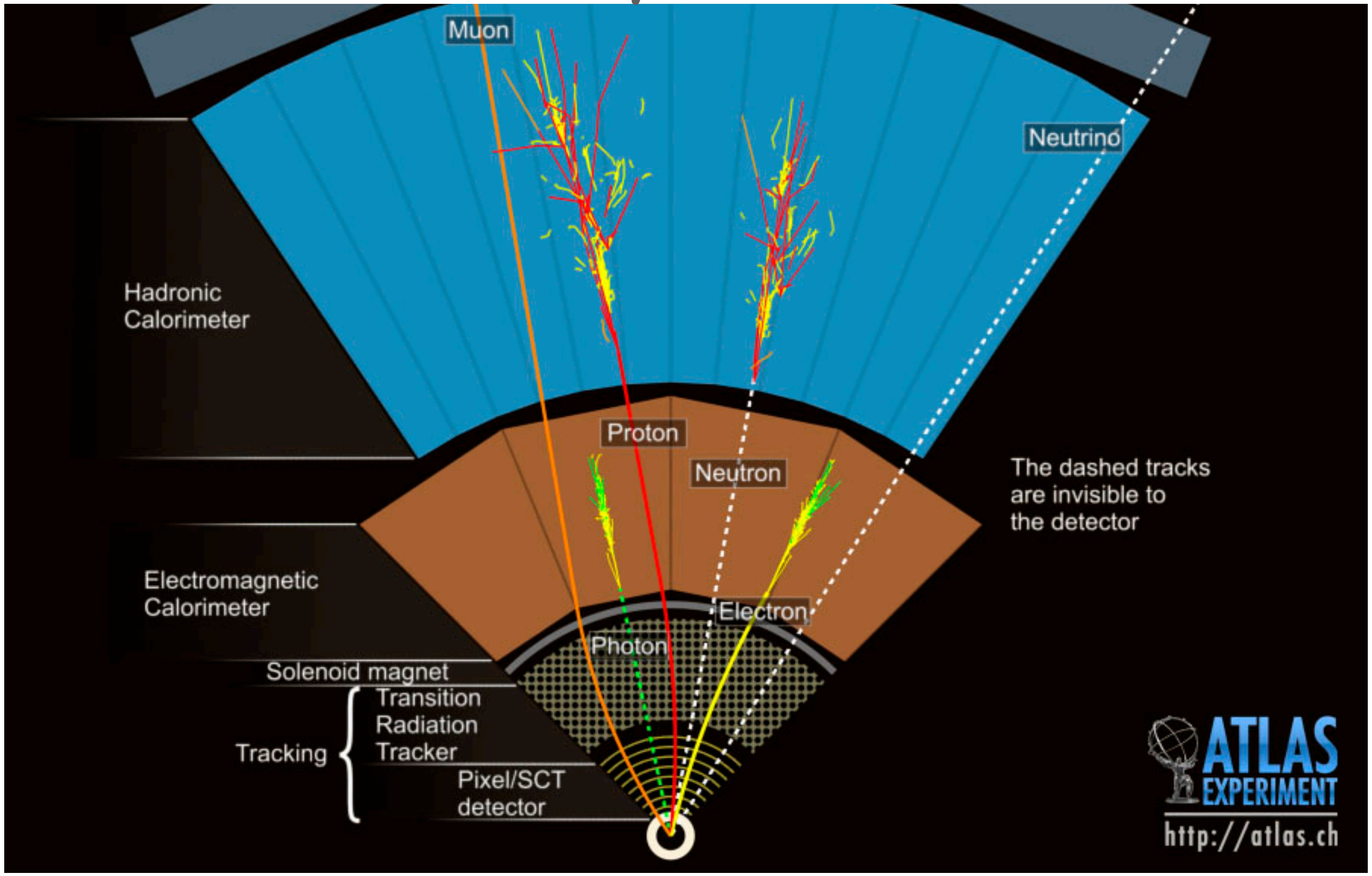
$\sigma(p_T)/p_T = 1.8\% + 60\%\ p_T\ [\text{TeV}]$

ECAL:

Segment: $\Delta\phi \times \Delta\eta \approx (0.025)^2$, 3 depths

Hadron Collider Example: ATLAS



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B-field = 2T; Solenoid before Calorimeter

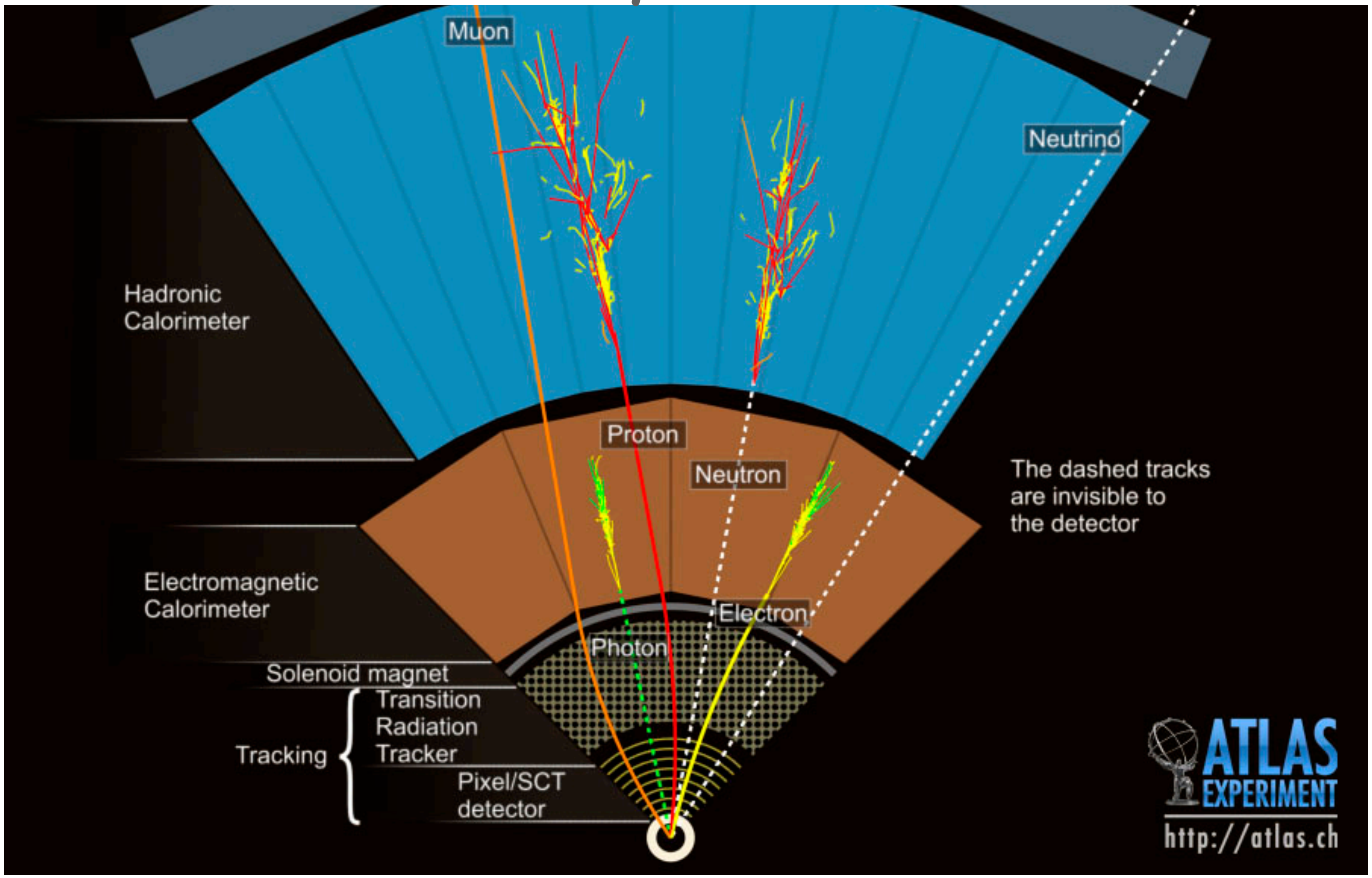
$\sigma(p_T)/p_T = 1.8\% + 60\%\ p_T$ [TeV]

ECAL:

Segment: $\Delta\phi \times \Delta\eta \approx (0.025)^2$, 3 depths

Fiducial accept: $|\eta| < 3.2$

Hadron Collider Example: ATLAS



Tracking:

- Large Vol: $R > 1m$, 3+4(+73) layers; Heavy
- Eff $\approx$ 85% (~99%) π's (μ's); fake $\approx$ 1%
- Fiducial accept: $|\eta| < 2.5$
- tracks down to $p_T \approx 100$ MeV

Solenoid:

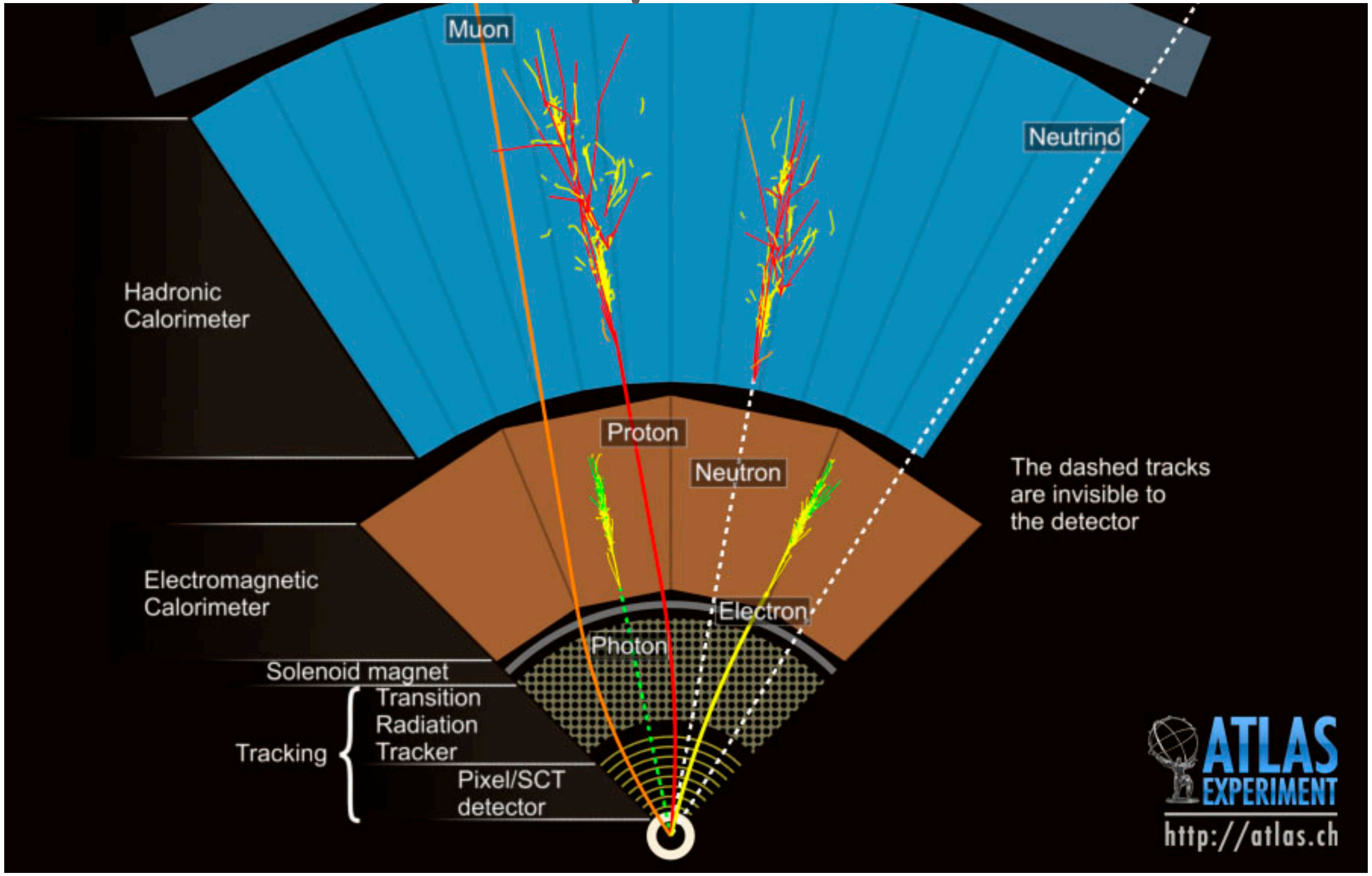
- B-field = 2T; Solenoid before Calorimeter
- $\sigma(p_T)/p_T = 1.8\% + 60\%\ p_T$ [TeV]

ECAL:

- Segment: $\Delta\phi \times \Delta\eta \approx (0.025)^2$, 3 depths
- Fiducial accept: $|\eta| < 3.2$
- Good Resolution: $\sigma \approx 10\%/\sqrt{E_T}$

Hadron Collider Example: ATLAS

Fermilab
UIC University of Illinois at Chicago



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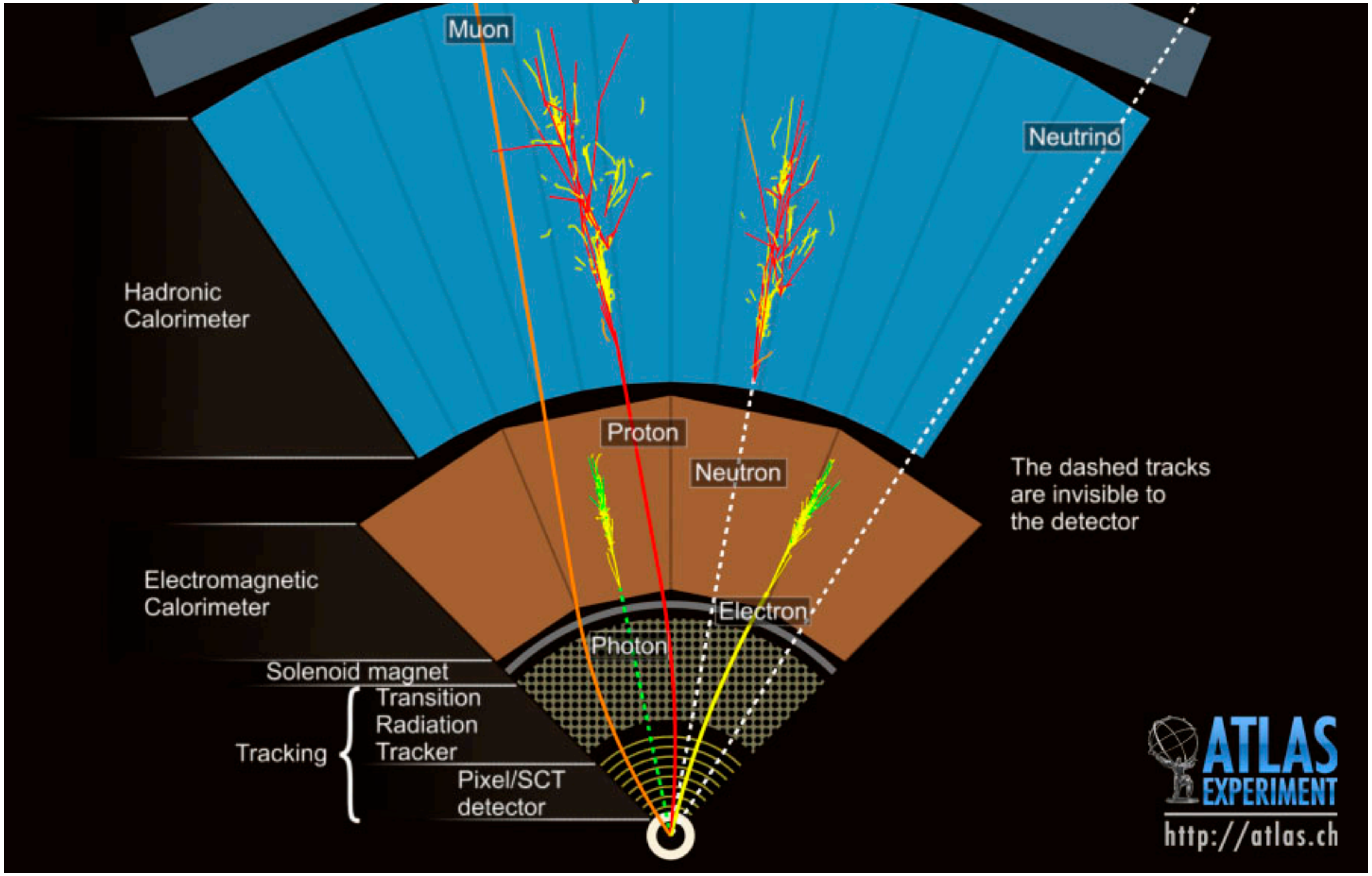
HCAL:

Hadron Collider Example: ATLAS



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Fiducial accept: $|\eta| < 2.5$

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Solenoid:

B-field = 2T; Solenoid before Calorimeter

$\sigma(p_T)/p_T = 1.8\% + 60\%\ p_T$ [TeV]

ECAL:

Segment: $\Delta\phi \times \Delta\eta \approx (0.025)^2$, 3 depths

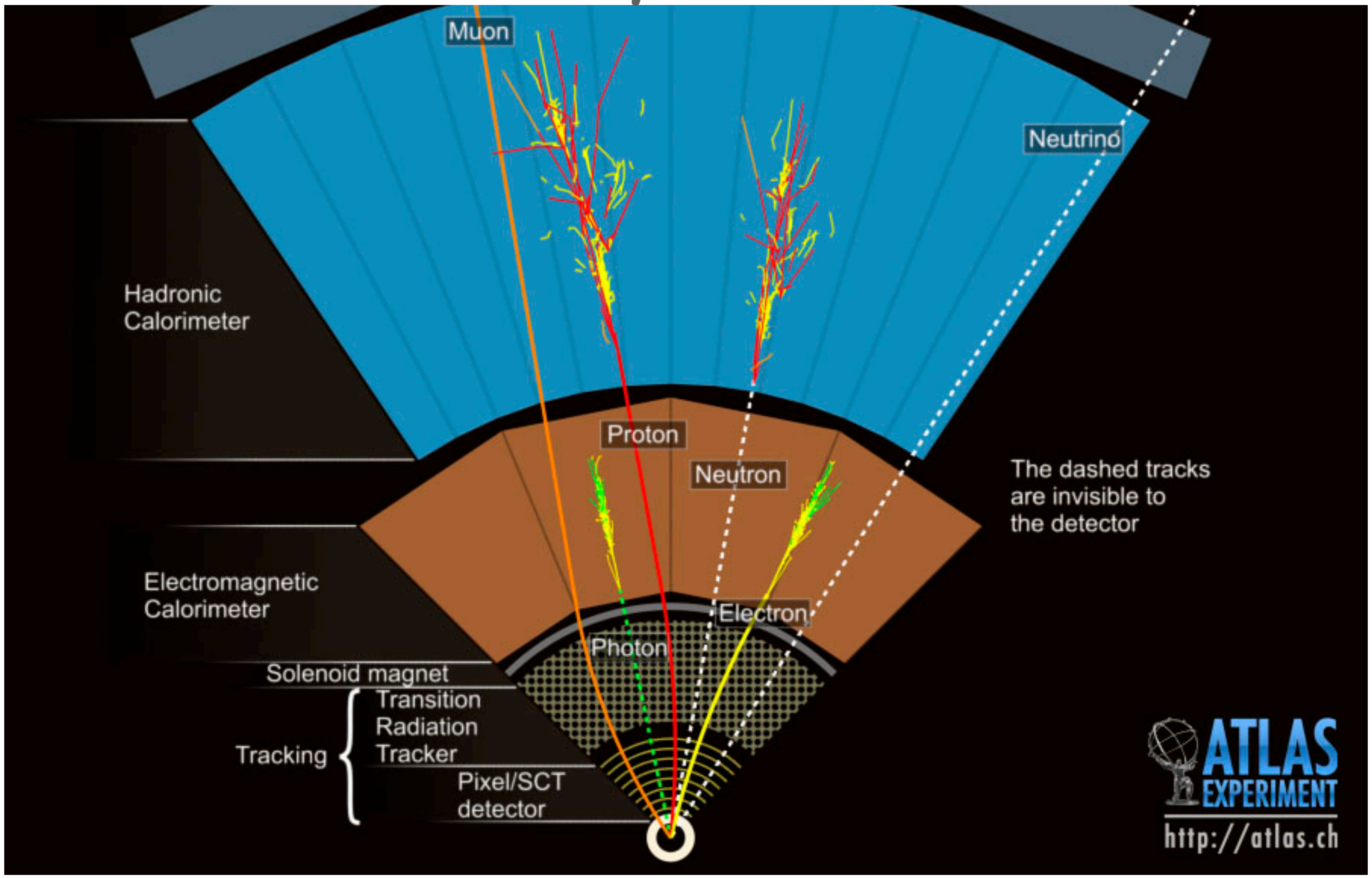
Fiducial accept: $|\eta| < 3.2$

Good Resolution: $\sigma \approx 10\%/\sqrt{E_T}$

HCAL:

Segment: $\Delta\phi \times \Delta\eta \approx (0.1)^2$, 3(4) depths

Hadron Collider Example: ATLAS



Tracking:

- Large Vol: R > 1m, 3+4(+73) layers; Heavy
- Eff ≈ 85% (~99%) π's (μ's); fake ≈ 1%
- Fiducial accept: $|\eta| < 2.5$
- tracks down to $p_T \approx 100$ MeV

Solenoid:

- B-field = 2T; Solenoid before Calorimeter
- $\sigma(p_T)/p_T = 1.8\% + 60\%\ p_T$ [TeV]

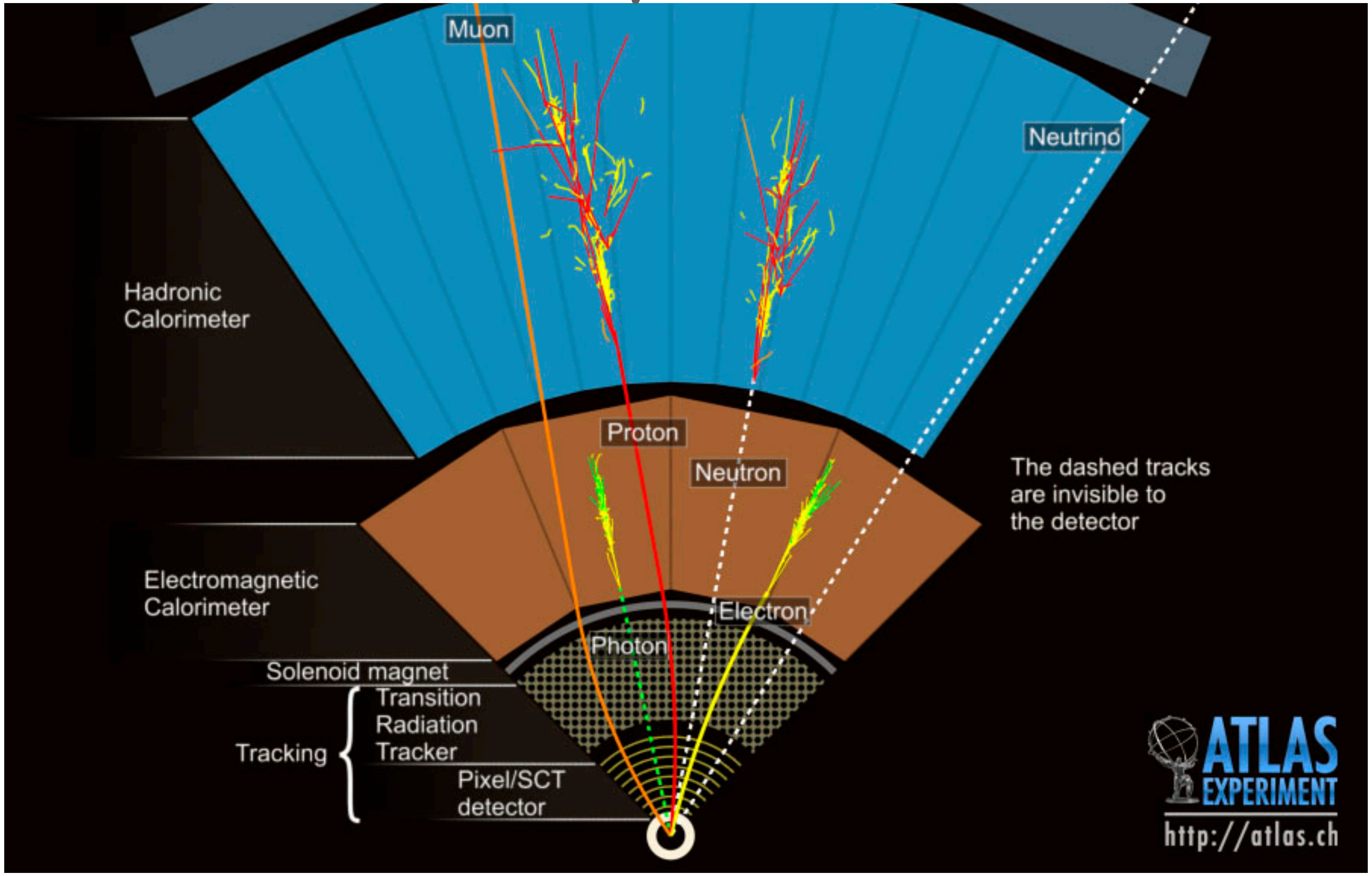
ECAL:

- Segment: $\Delta\phi \times \Delta\eta \approx (0.025)^2$, 3 depths
- Fiducial accept: $|\eta| < 3.2$
- Good Resolution: $\sigma \approx 10\%/\sqrt{E_T}$

HCAL:

- Segment: $\Delta\phi \times \Delta\eta \approx (0.1)^2$, 3(4) depths
- Fiducial accept: $|\eta| < 4.9$

Hadron Collider Example: ATLAS



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Solenoid:

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- $\sigma(p_T)/p_T = 1.8\% + 60\%\, p_T$ [TeV]

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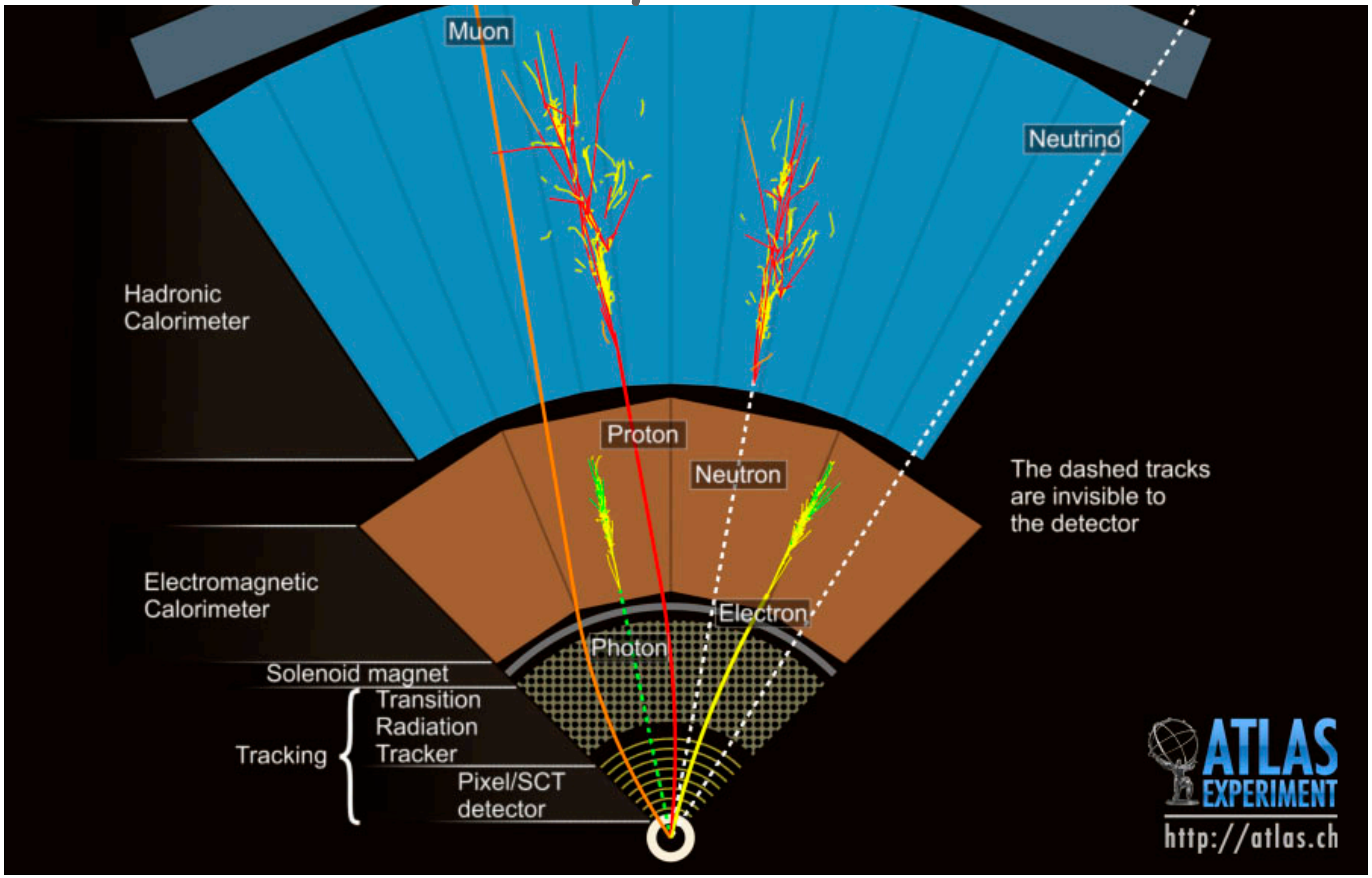
- Fiducial accept: $|\eta| < 3.2$
- Good Resolution: $\sigma \approx 10\%/\sqrt{E_T}$

HCAL:

- Segment: $\Delta\phi \times \Delta\eta \approx (0.1)^2$, 3(4) depths
- Fiducial accept: $|\eta| < 4.9$
- Excellent Resolution: $\sigma \approx 40\%/\sqrt{E_T}$

Hadron Collider Example: ATLAS

Fermilab
UIC University of Illinois at Chicago



Seems like a good candidate for PF …enough right conditions

Tracking:

Large Vol: R > 1m, 3+4(+73) layers; Heavy

Eff ≈ 85% (~99%) π's (μ's); fake ≈ 1%

Fiducial accept: $|\eta| < 2.5$

tracks down to $p_T \approx 100$ MeV

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B-field = 2T; Solenoid before Calorimeter

$\sigma(p_T)/p_T = 1.8\% + 60\%\ p_T$ [TeV]

ECAL:

Segment: $\Delta\phi \times \Delta\eta \approx (0.025)^2$, 3 depths

Fiducial accept: $|\eta| < 3.2$

Good Resolution: $\sigma \approx 10\%/\sqrt{E_T}$

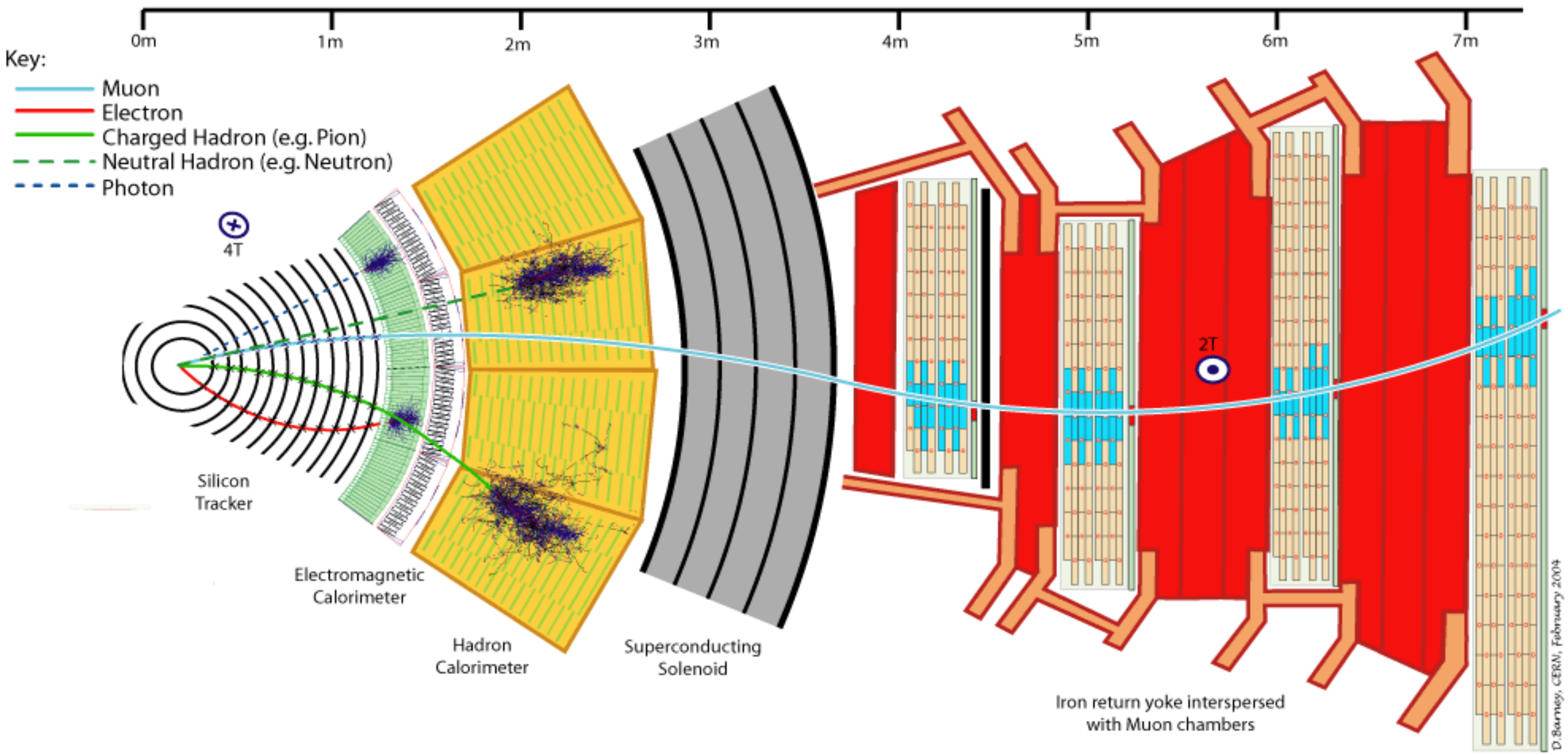
HCAL:

Segment: $\Delta\phi \times \Delta\eta \approx (0.1)^2$, 3(4) depths

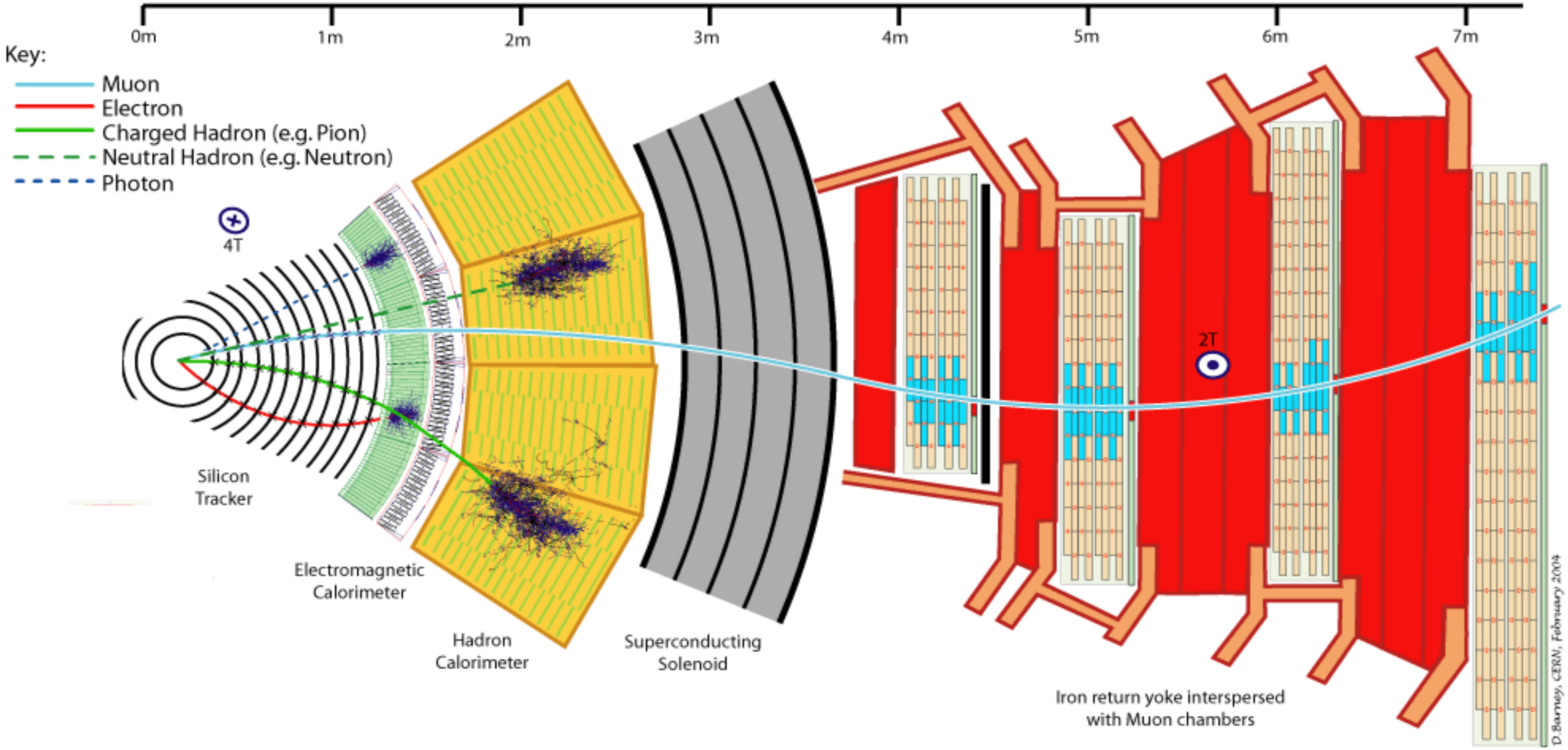
Fiducial accept: $|\eta| < 4.9$

Excellent Resolution: $\sigma \approx 40\%/\sqrt{E_T}$

Hadron Collider Example: CMS



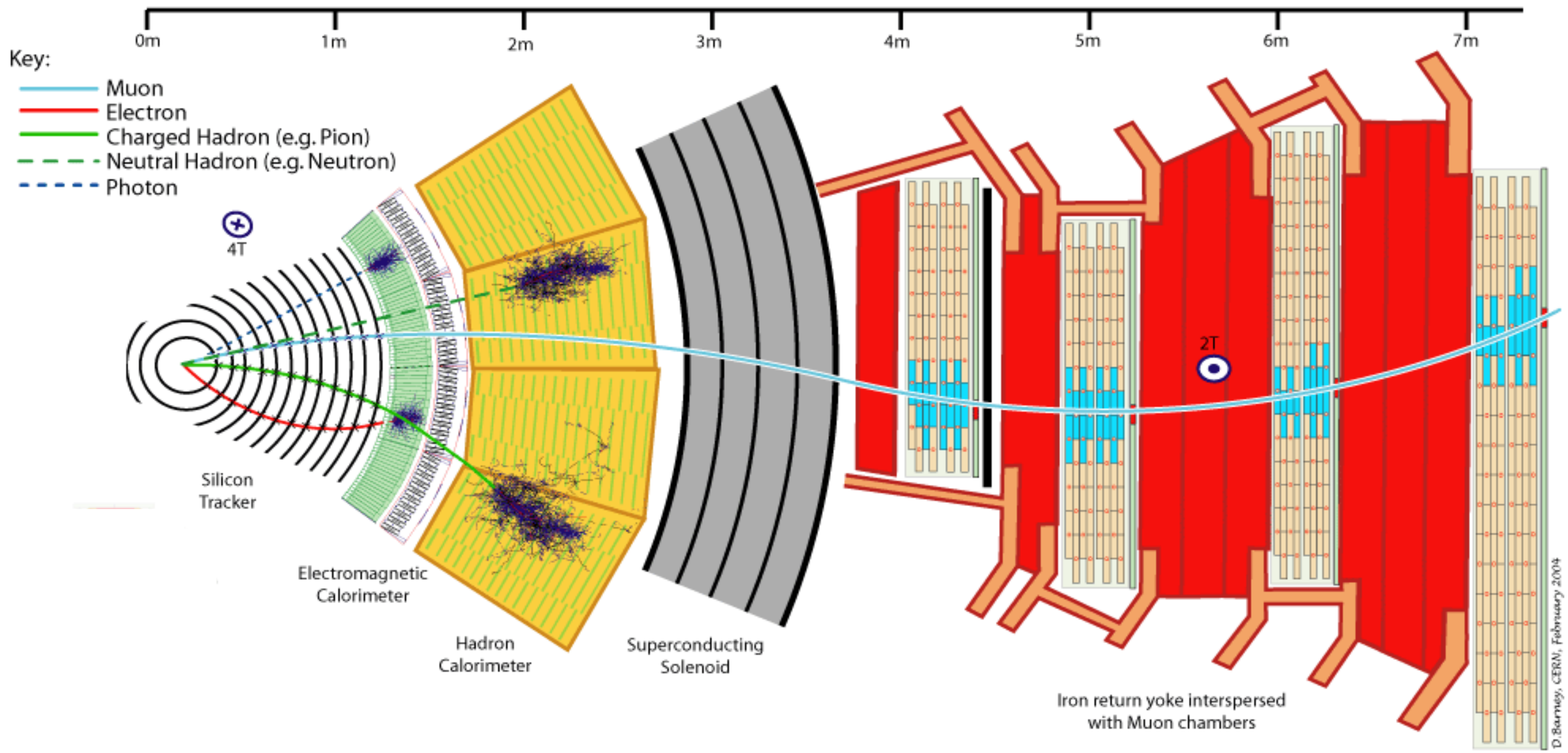
Hadron Collider Example: CMS



Tracker:

Hadron Collider Example: CMS

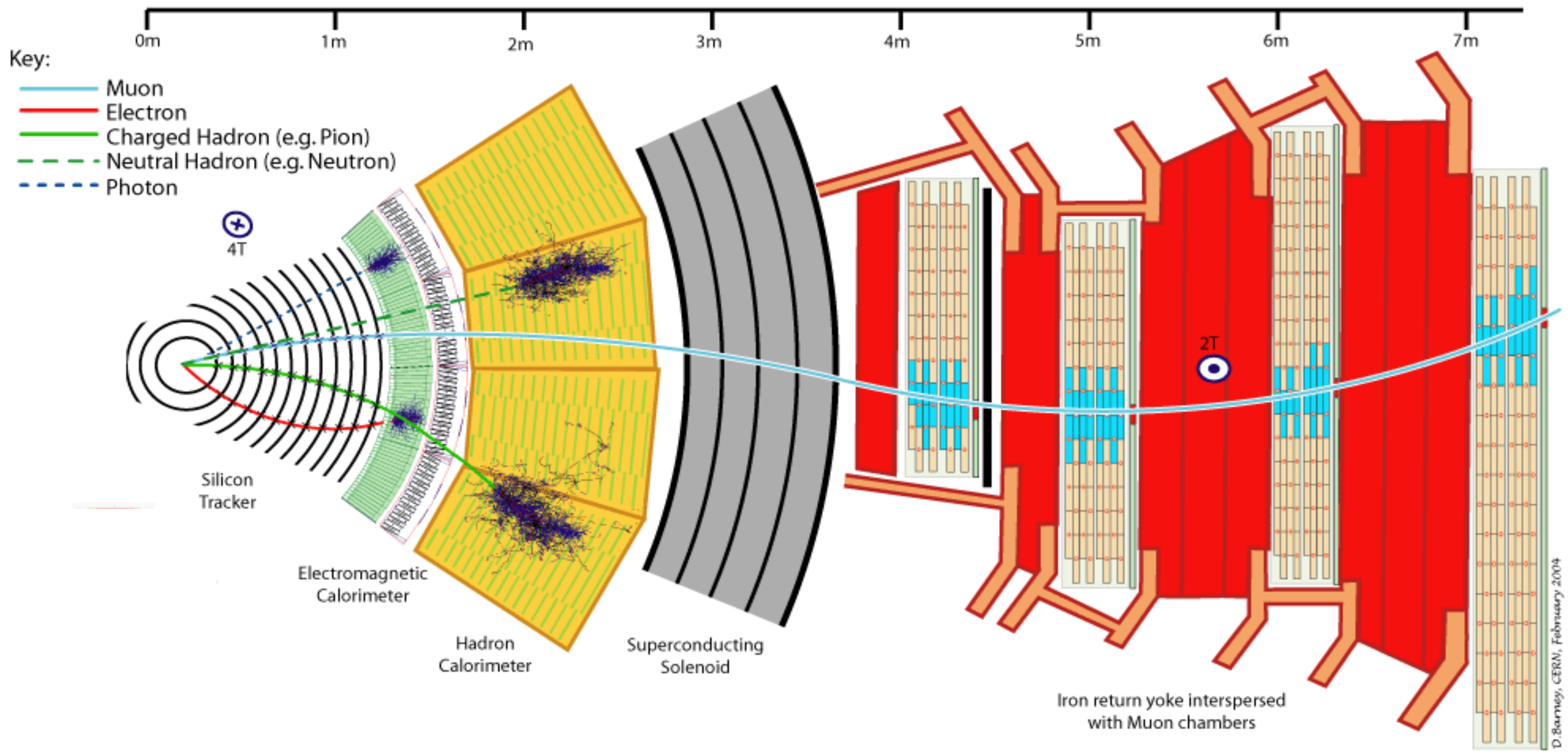
R. Cavanaugh
100 TeV Workshop, SLAC 23-26 August, 2014



Tracker:

Large Vol (R > 1m, 3+10 layers), Heavy;

Hadron Collider Example: CMS

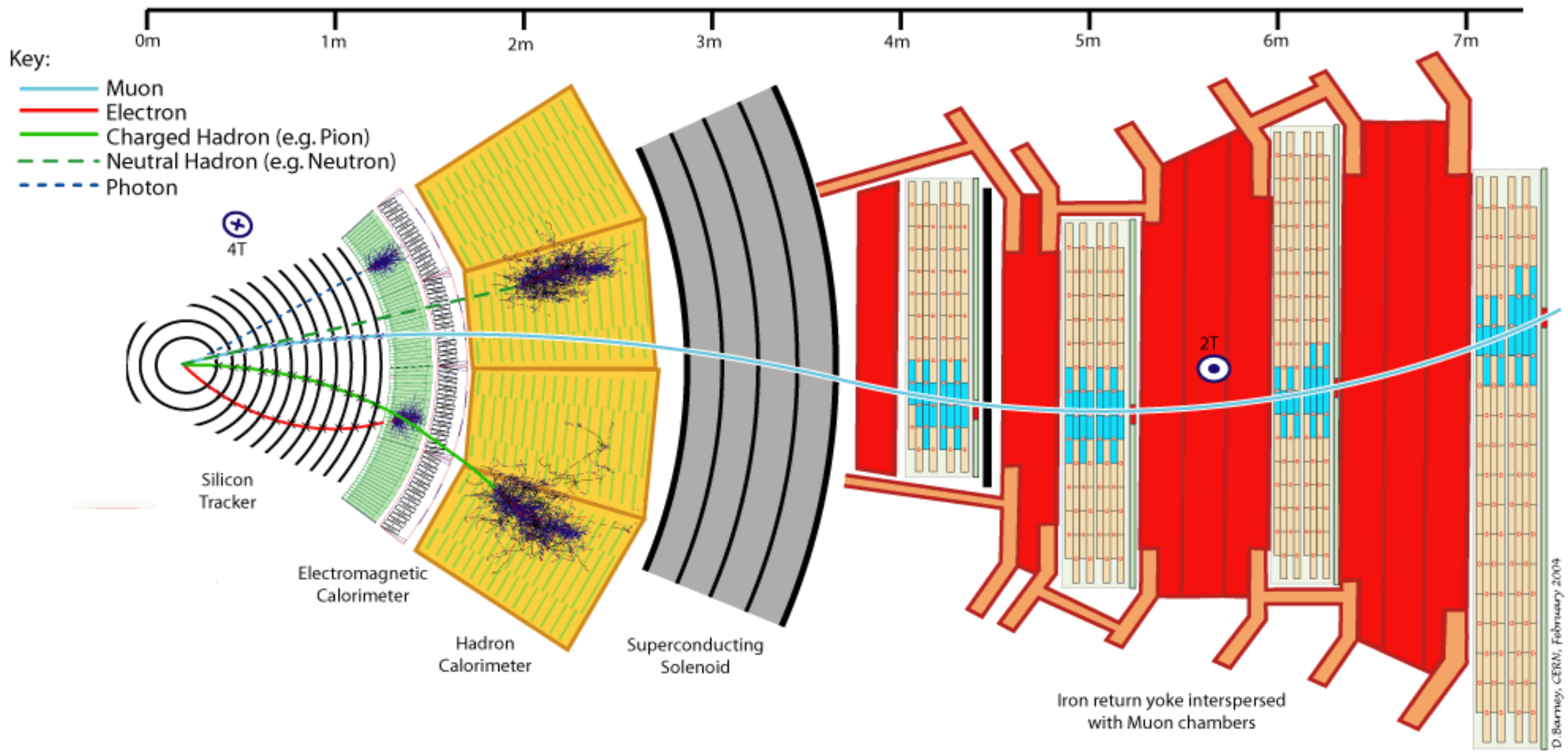


Tracker:

Large Vol (R > 1m, 3+10 layers), Heavy;

Eff ≈ 95% (99%) π's (μ's); fake ≈ 1%

Hadron Collider Example: CMS



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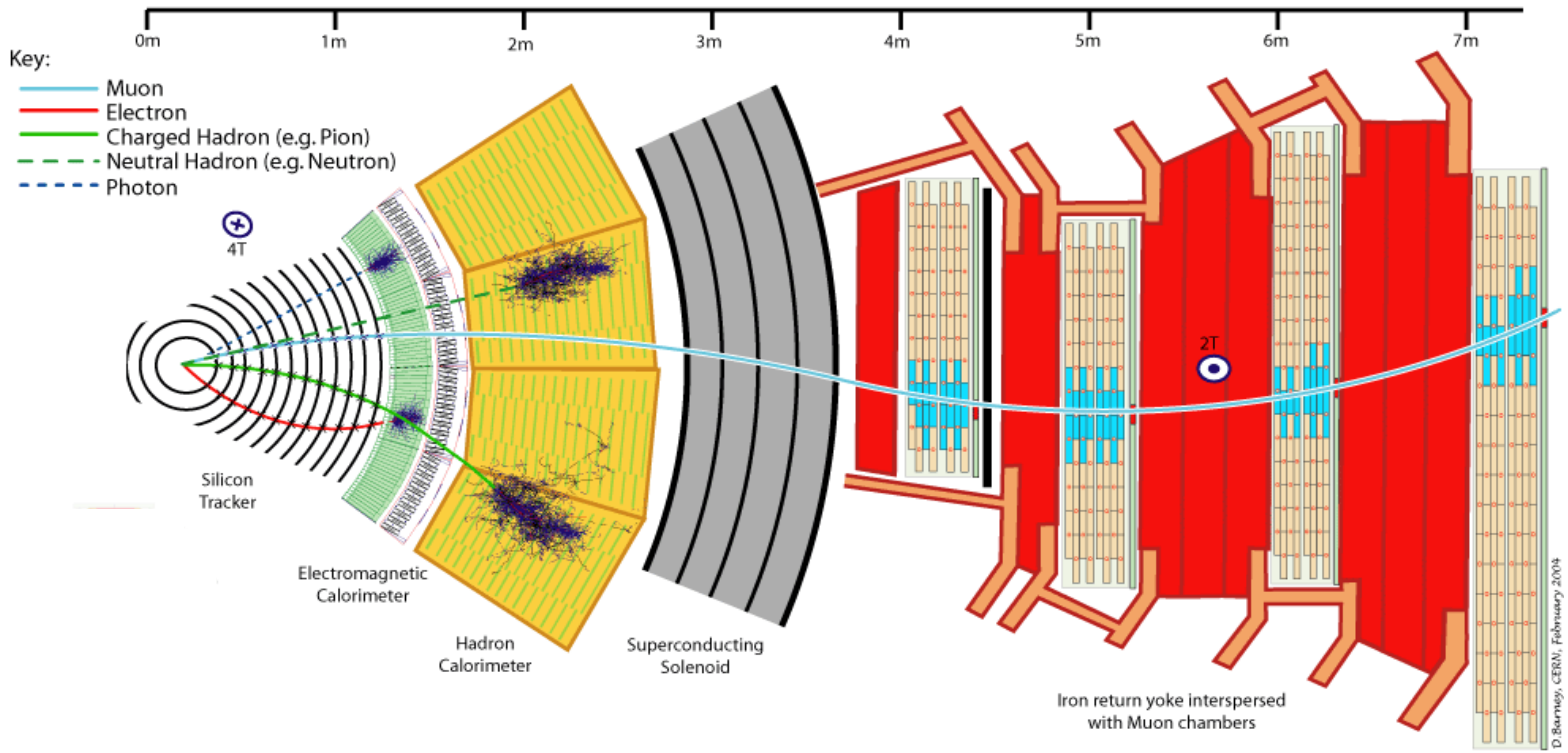
Fermilab
UIC University of Illinois at Chicago



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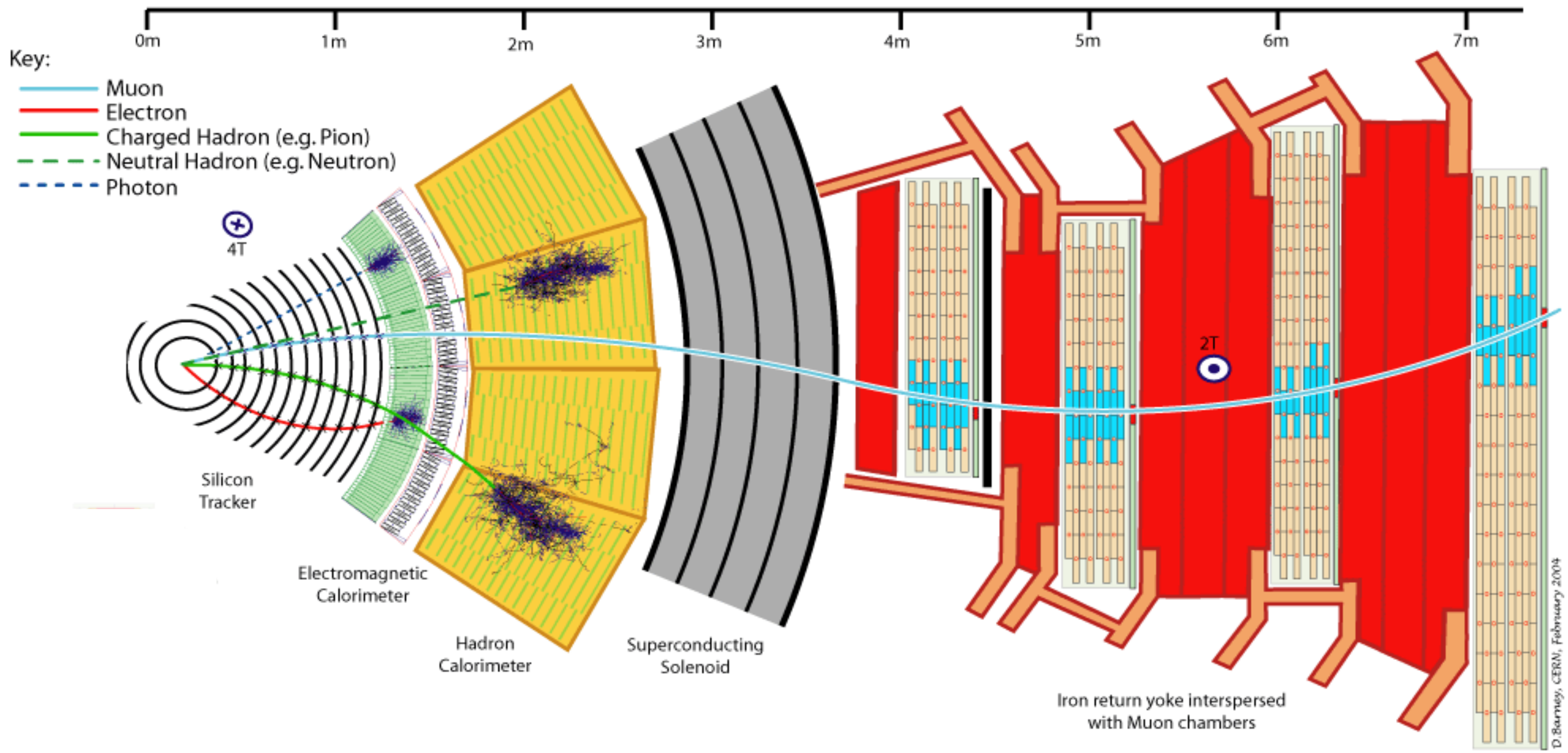

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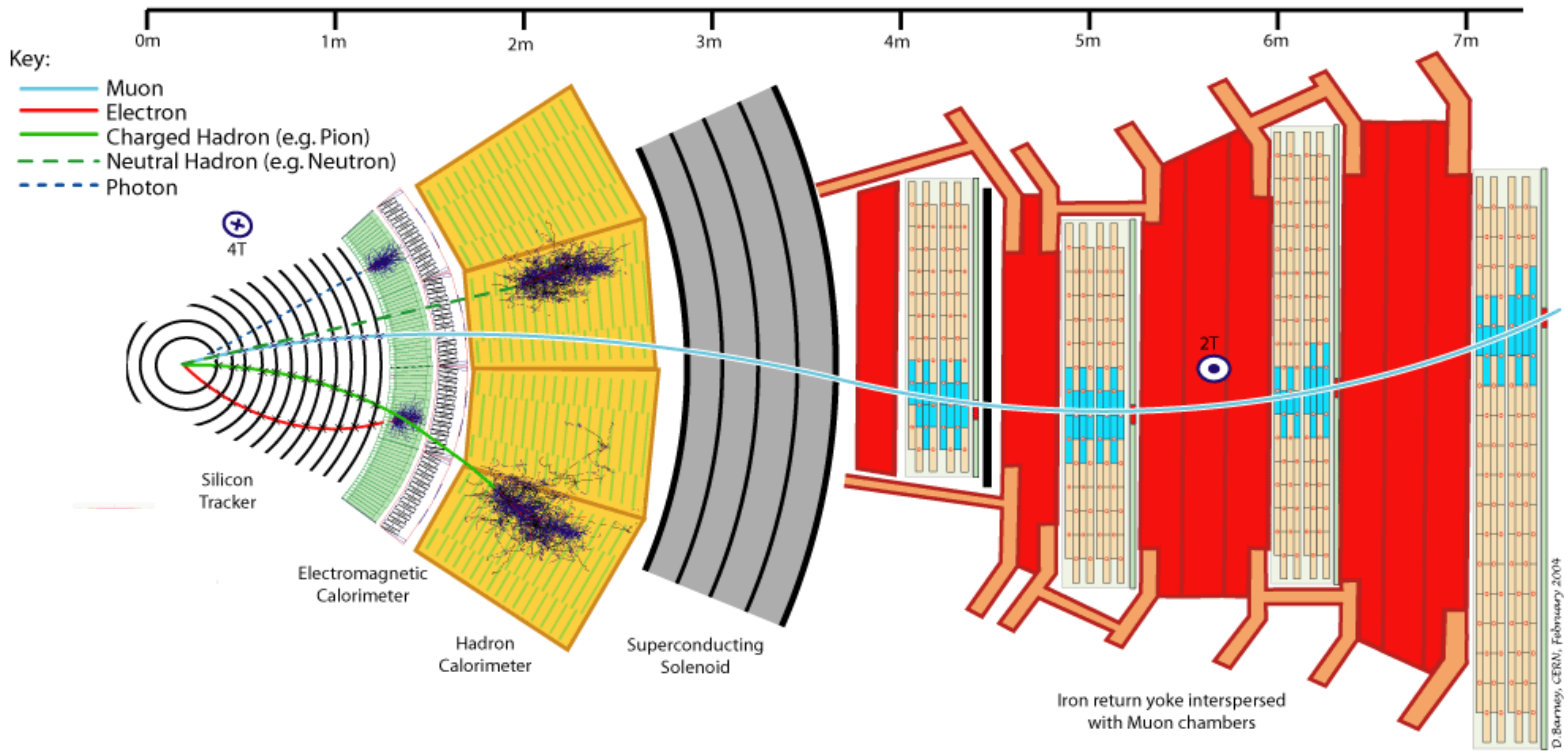
Hadron Collider Example: CMS

R. Cavanaugh 100 TeV Workshop, SLAC 23-26 August, 2014



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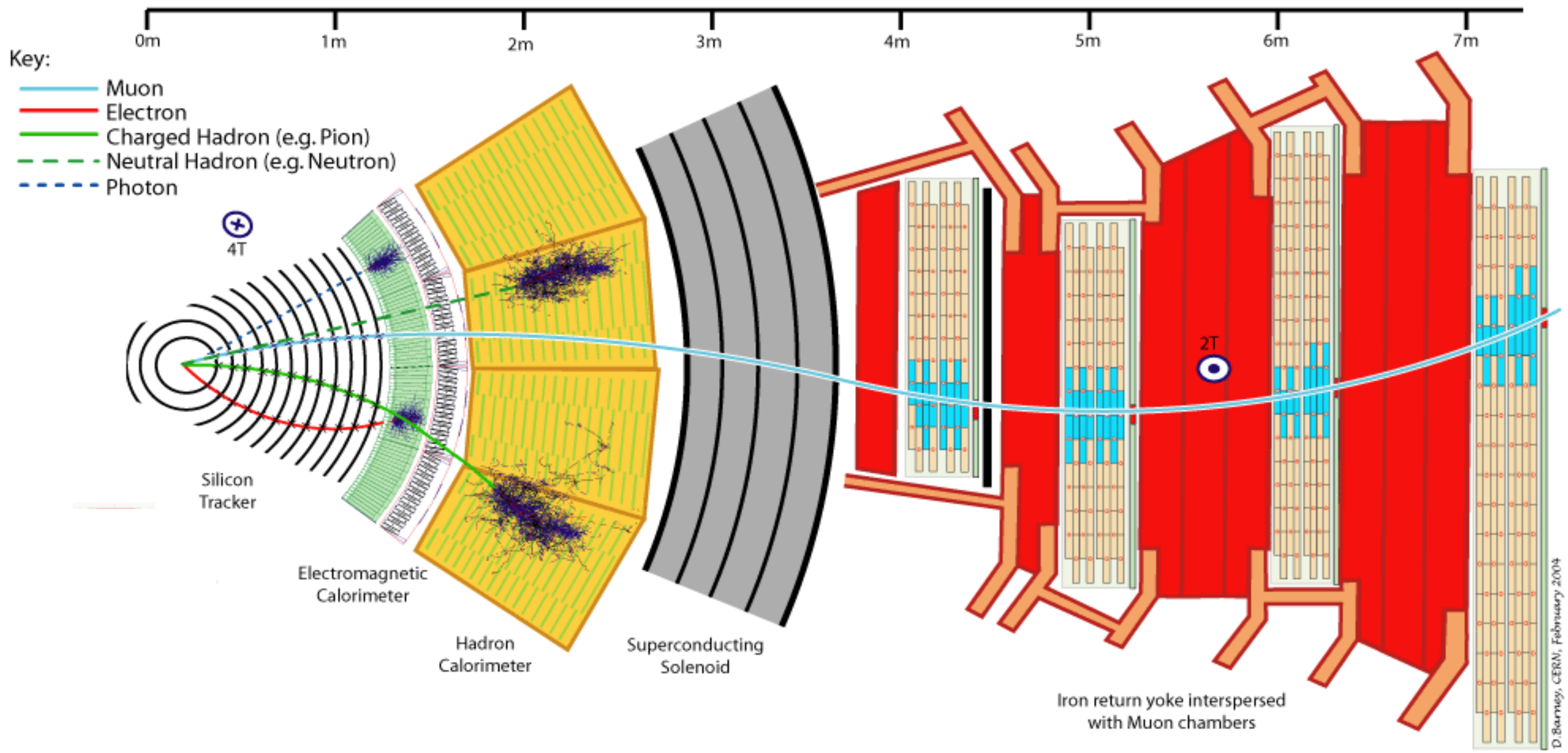

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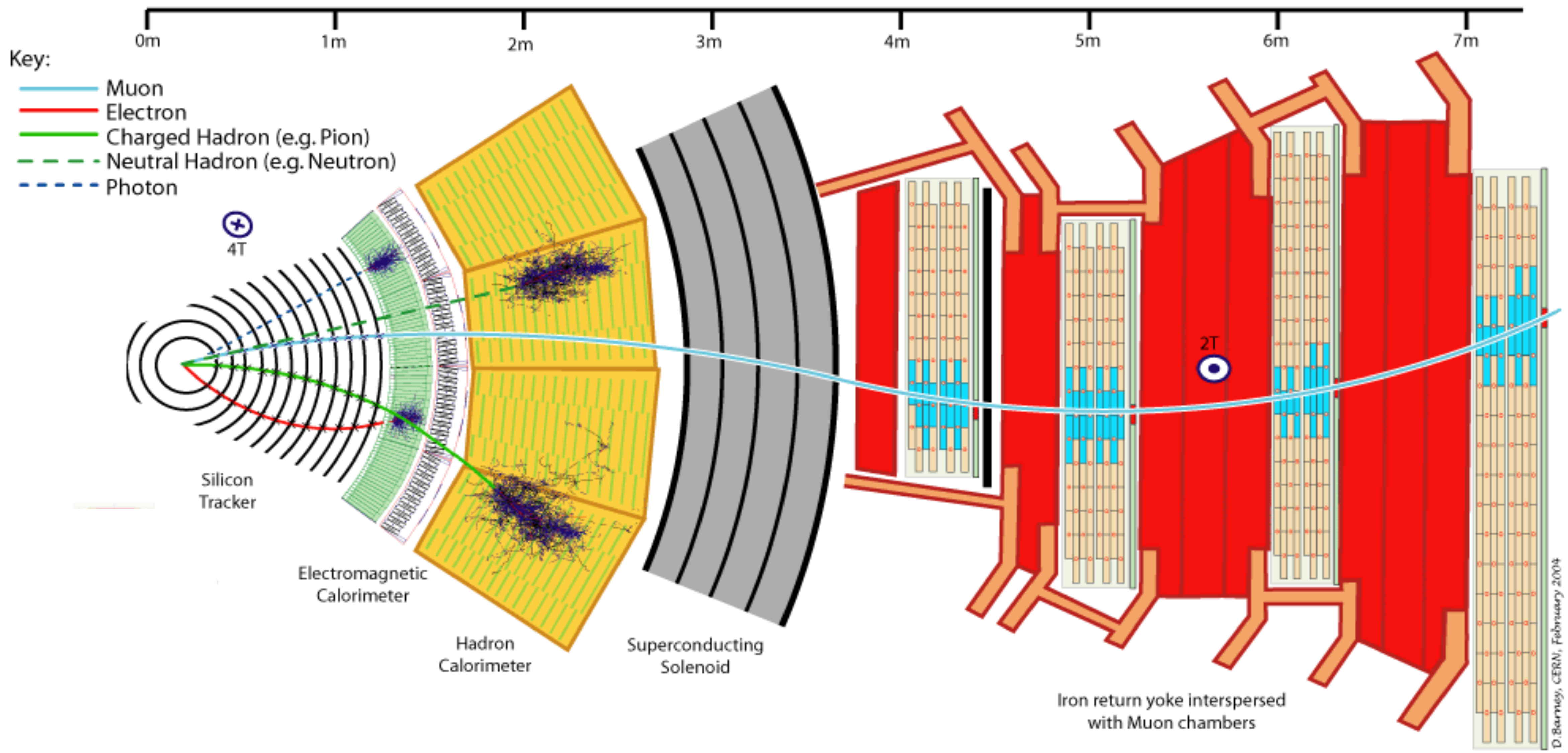

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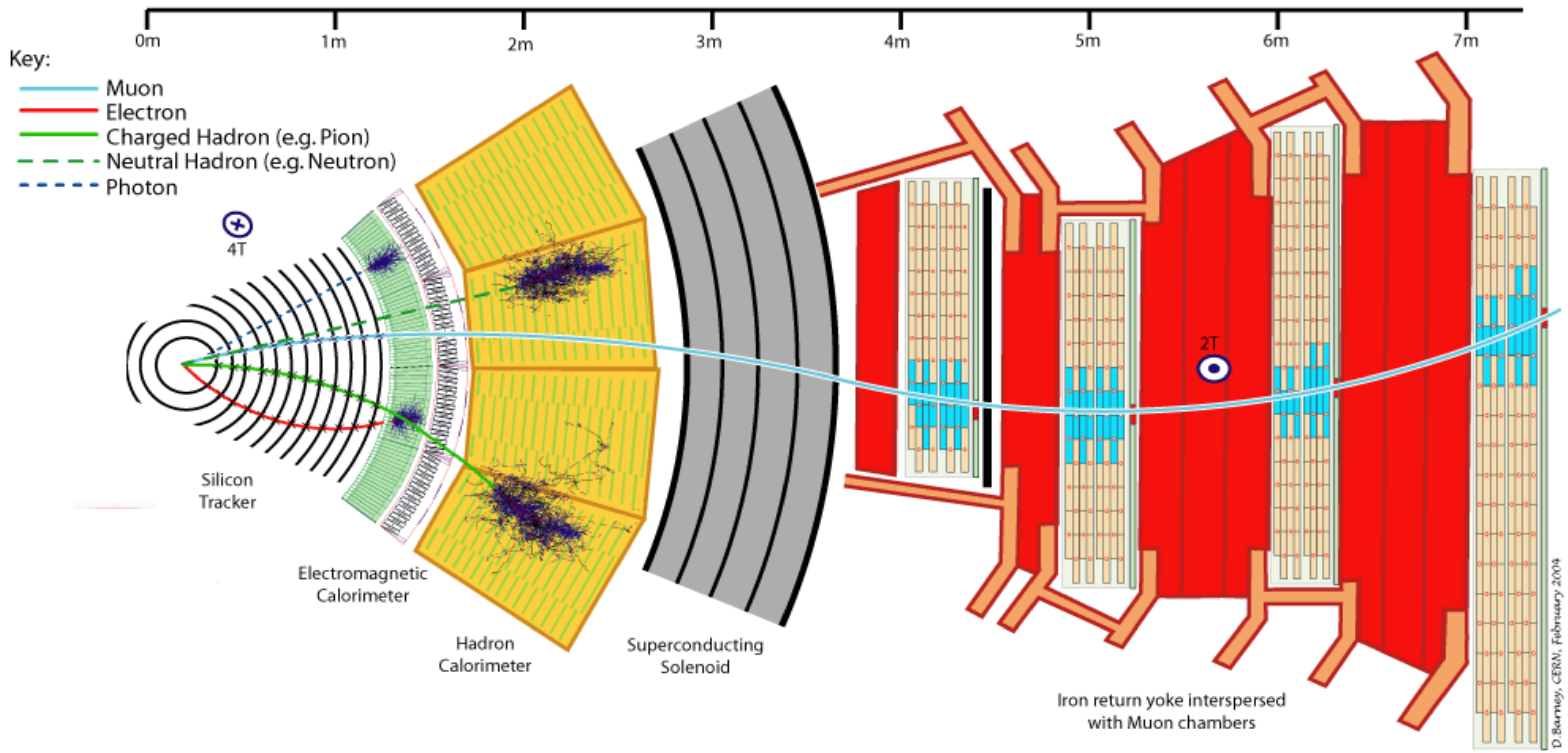
Hadron Collider Example: CMS

R. Cavanaugh   100 TeV Workshop, SLAC   23-26 August, 2014



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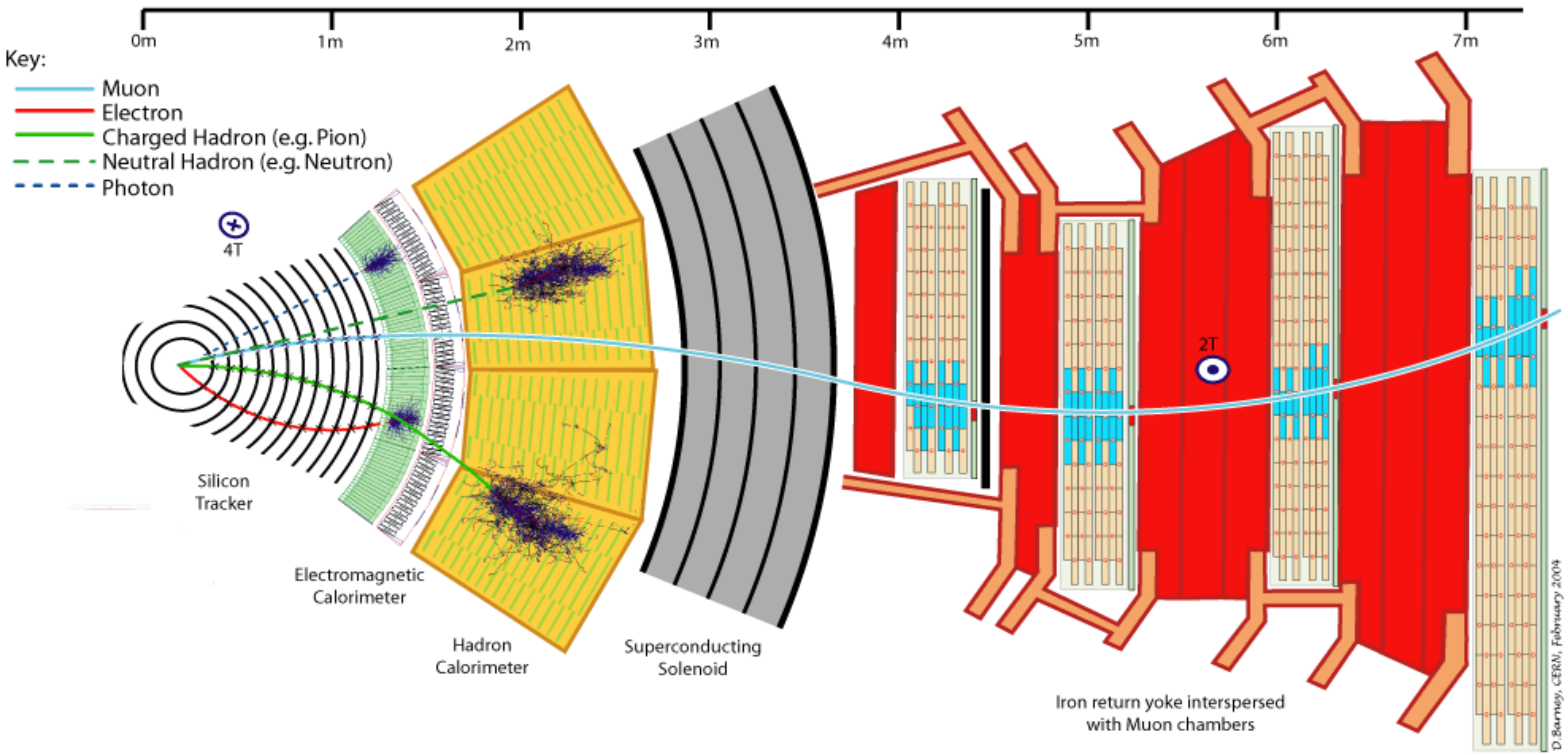

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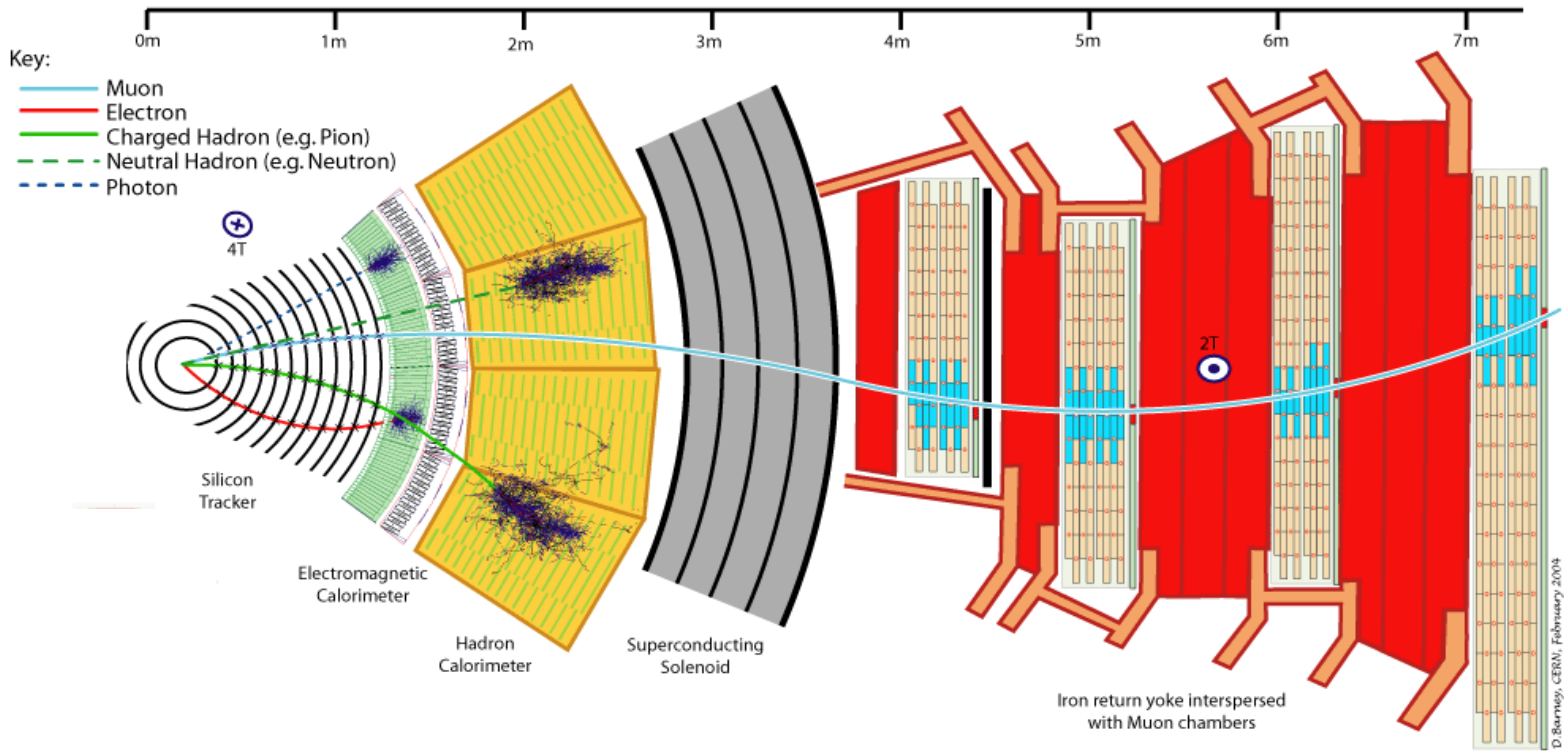
Fermilab
UIC University of Illinois at Chicago



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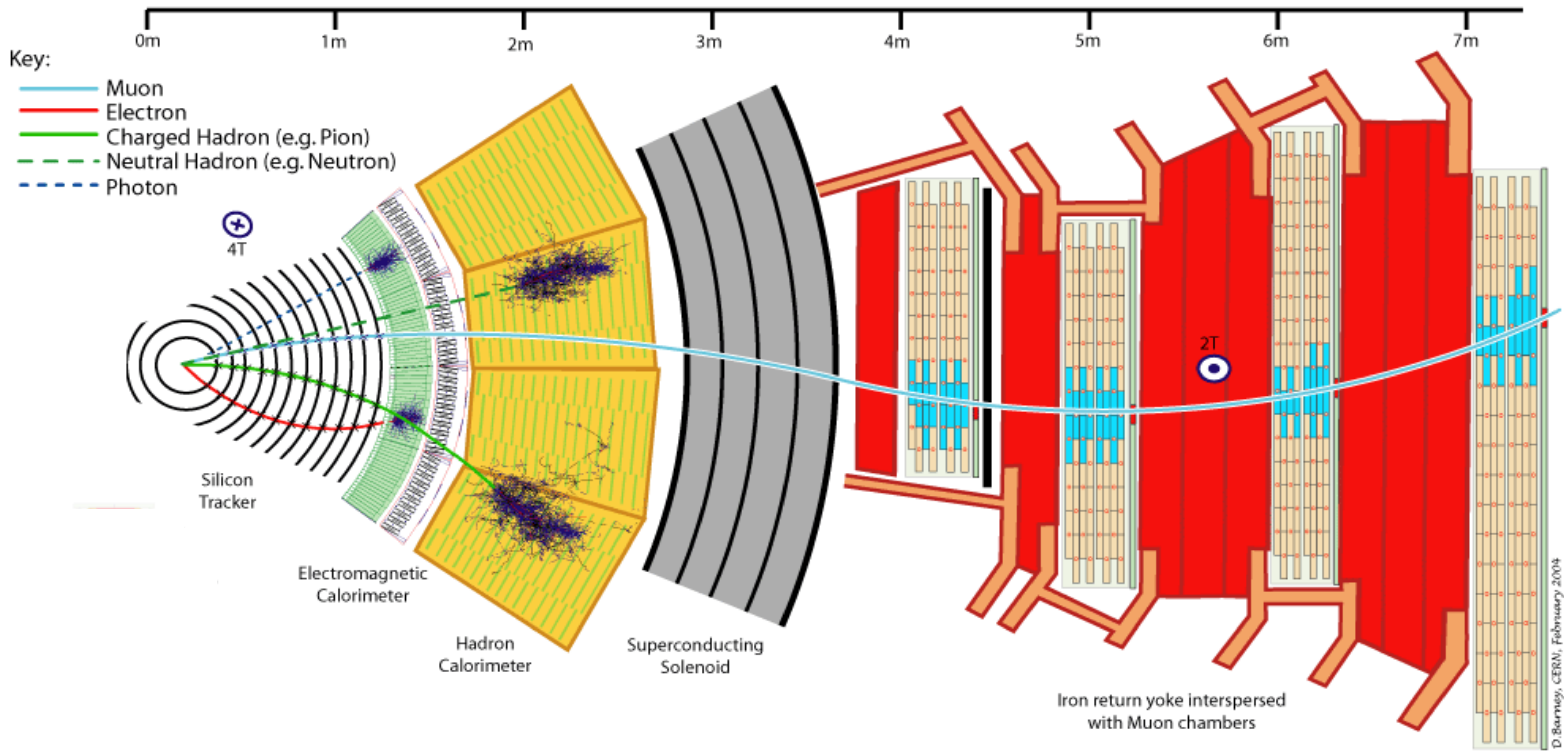

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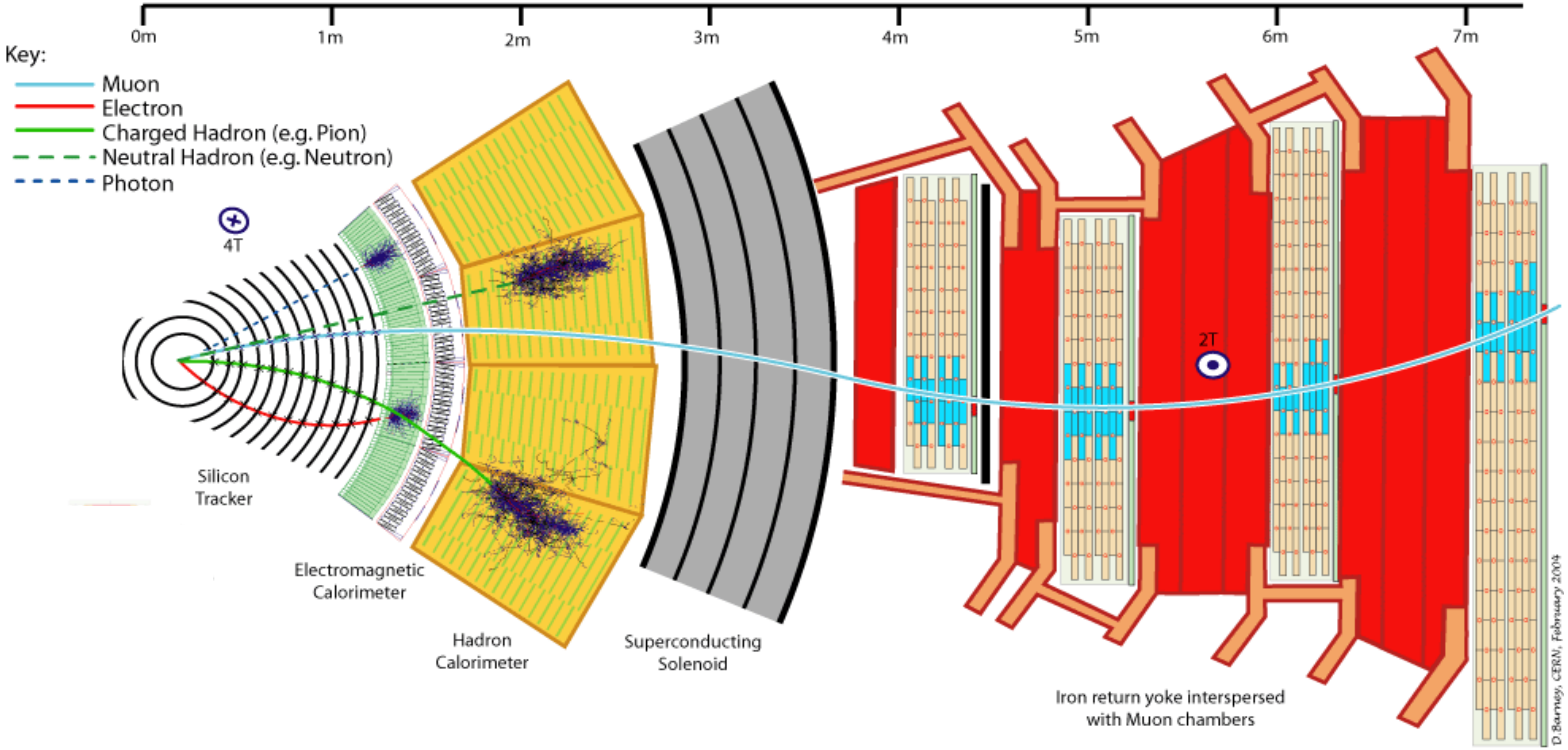

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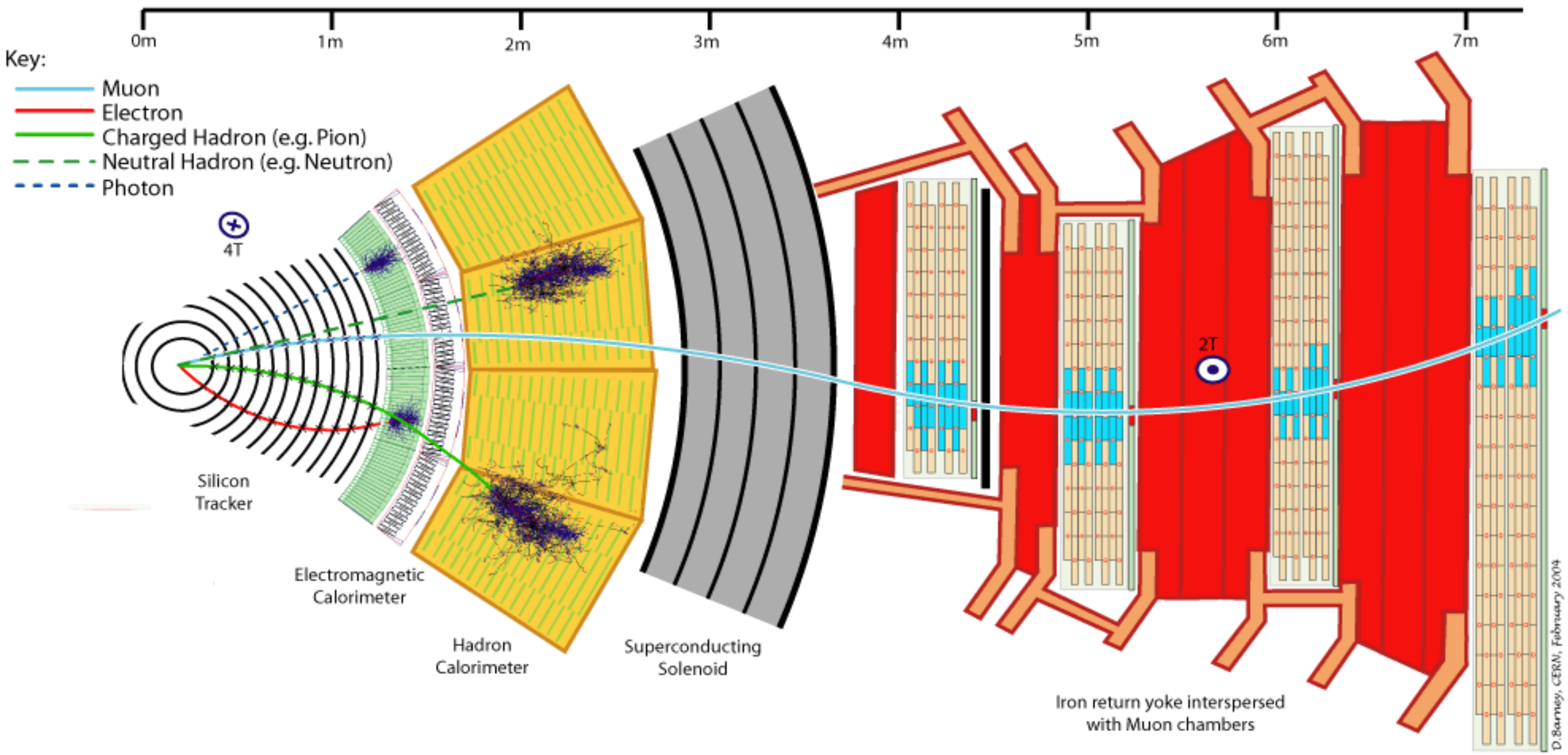

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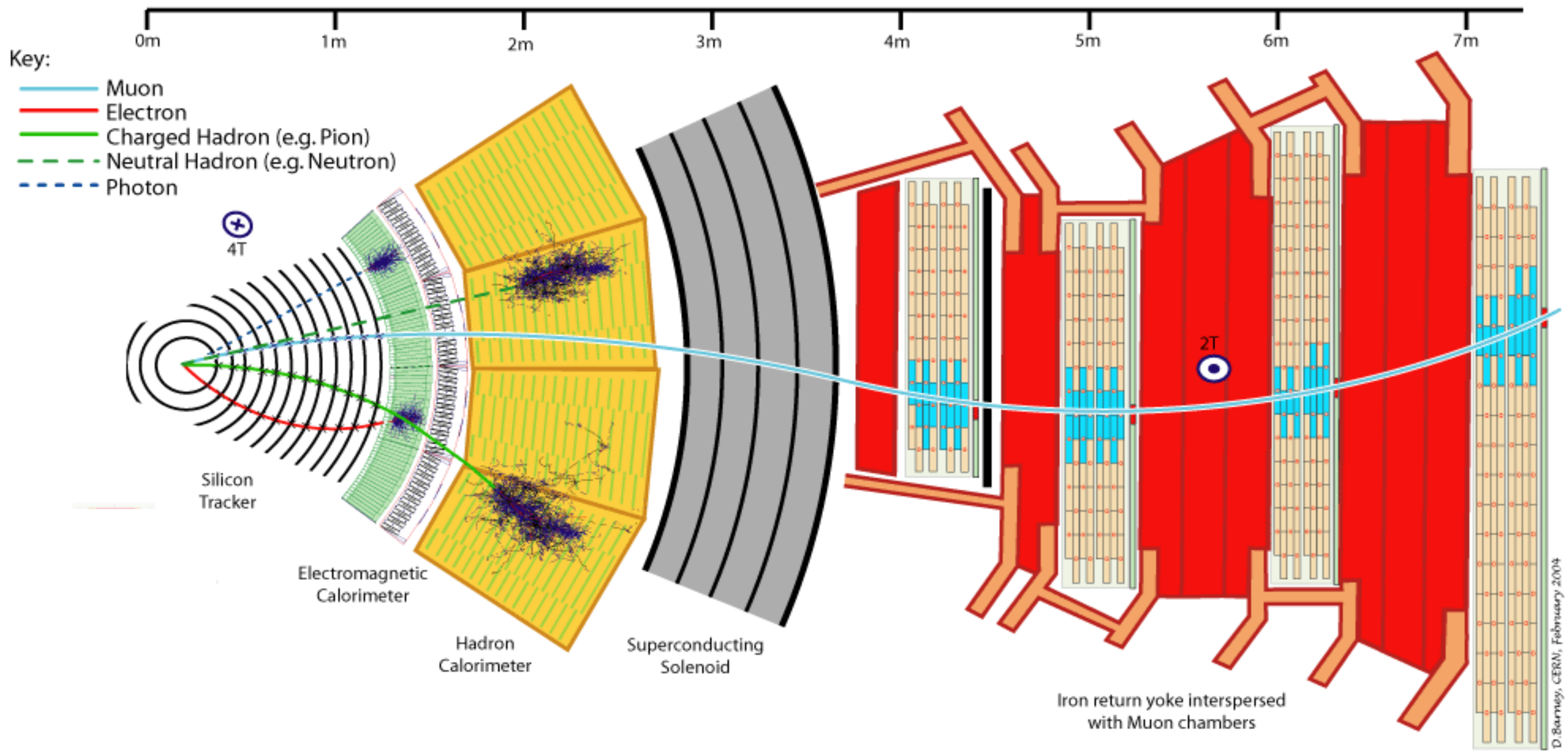

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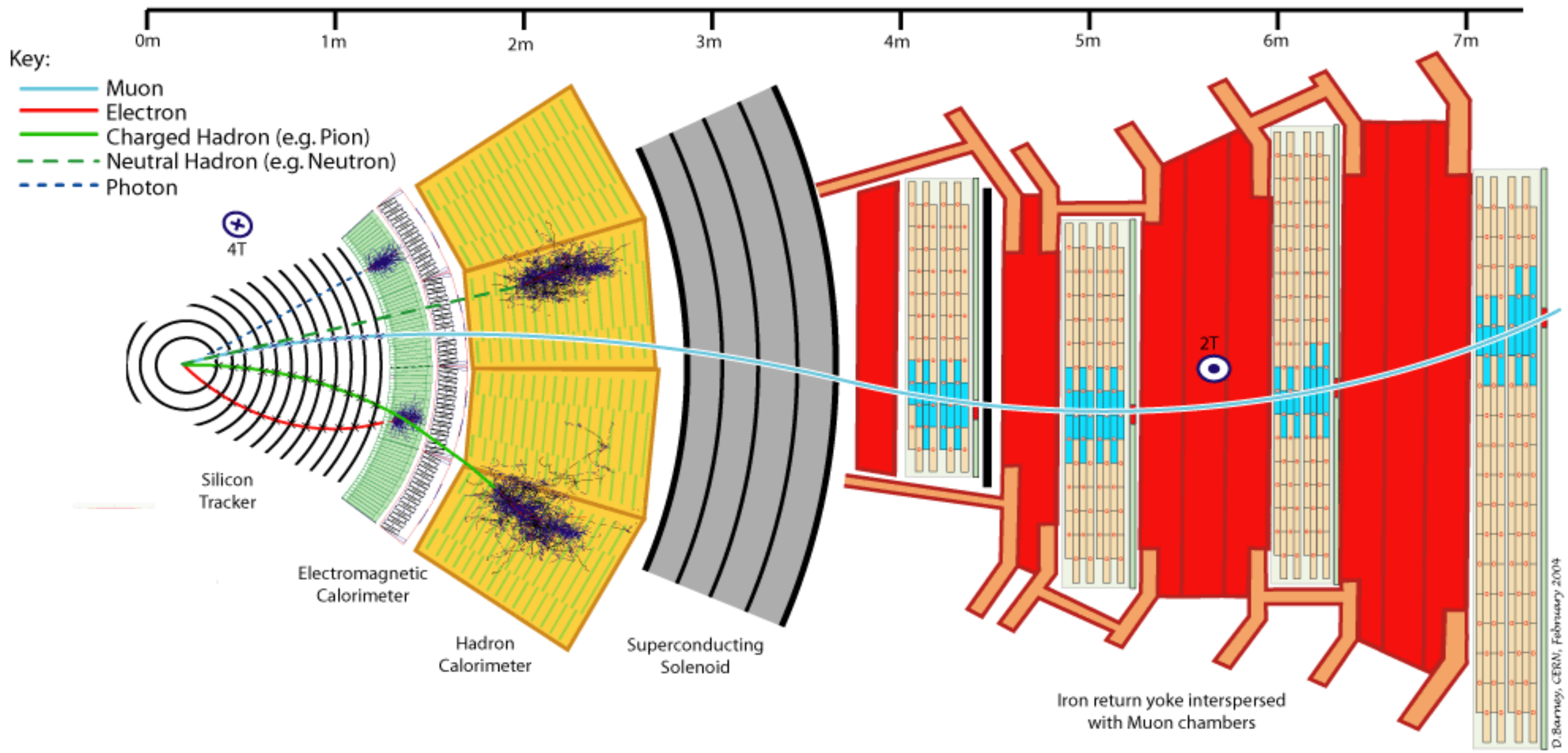

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Seems like a good candidate for PF ...enough right conditions

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Example: Devil is in the Details!

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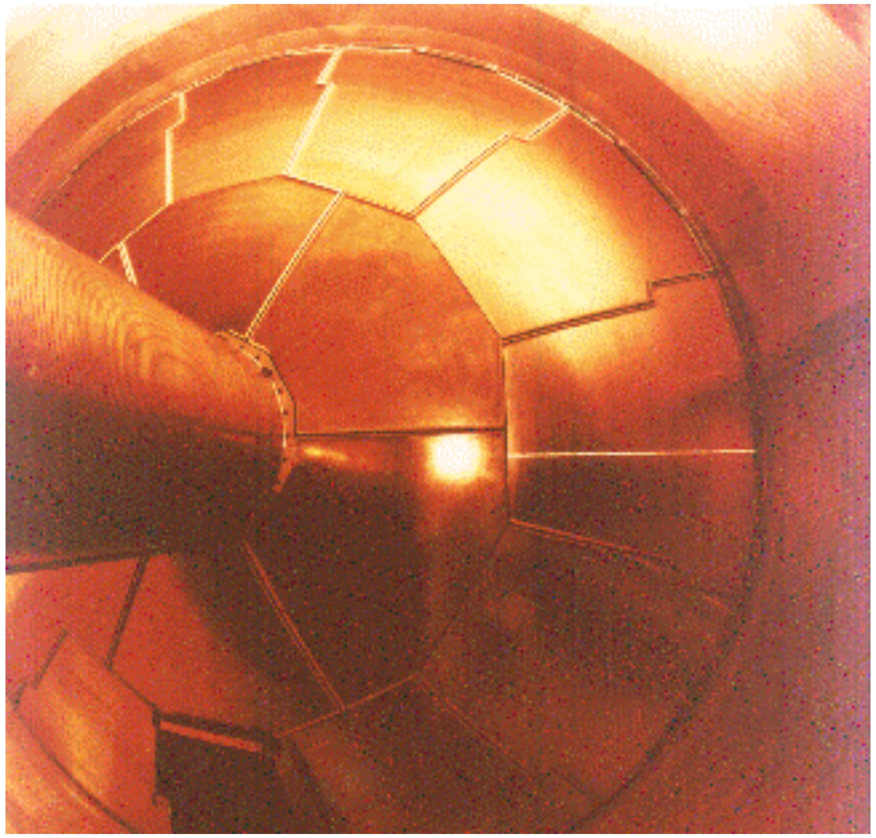

Tracking played a central role in both ALEPH and CMS Particle Flow Algorithms. But...

ALEPH Tracker mostly empty

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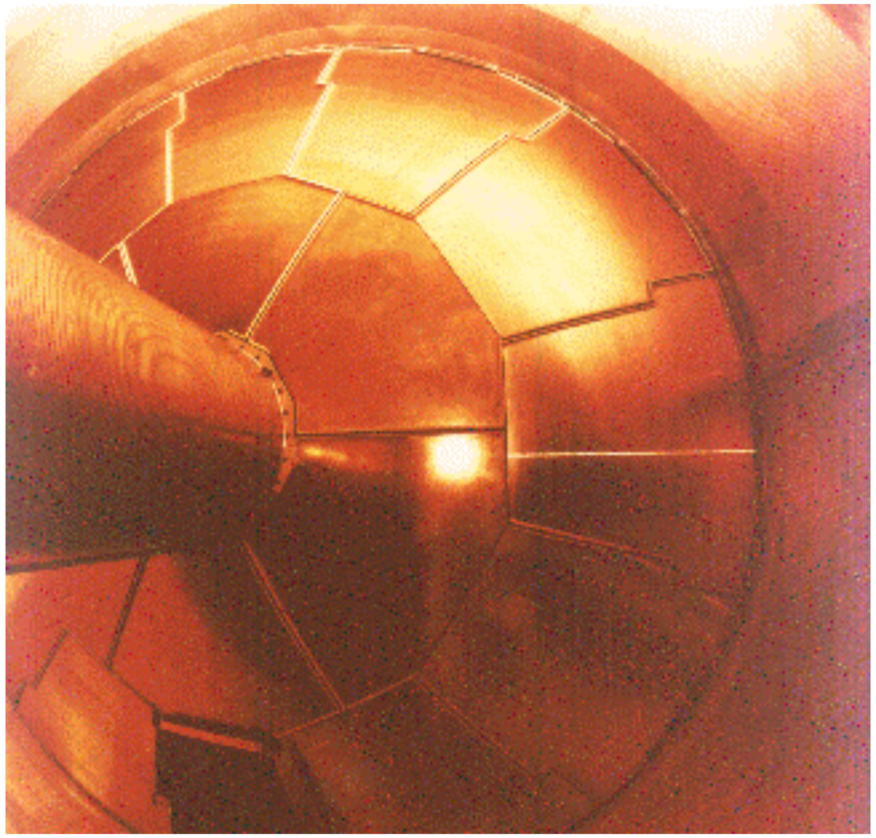

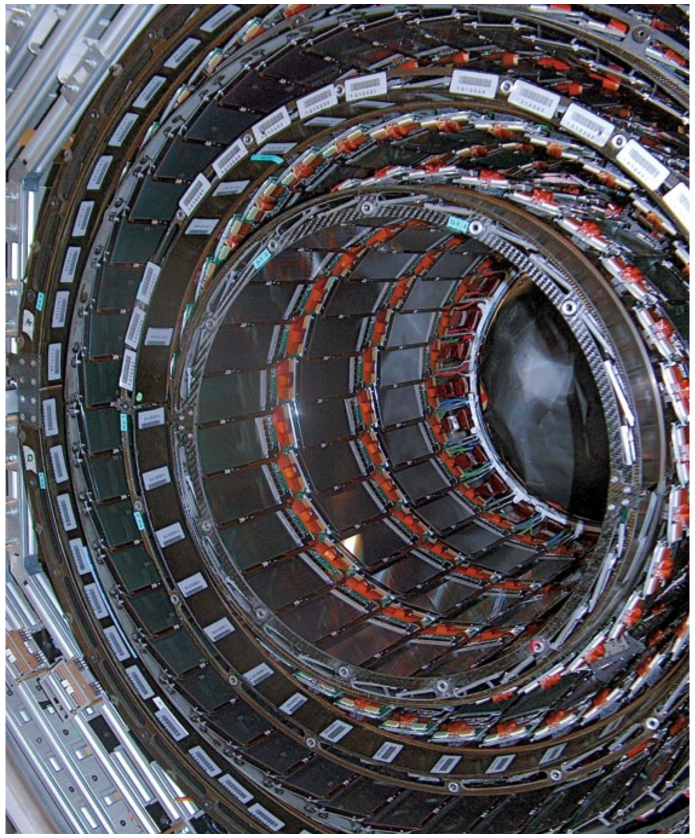

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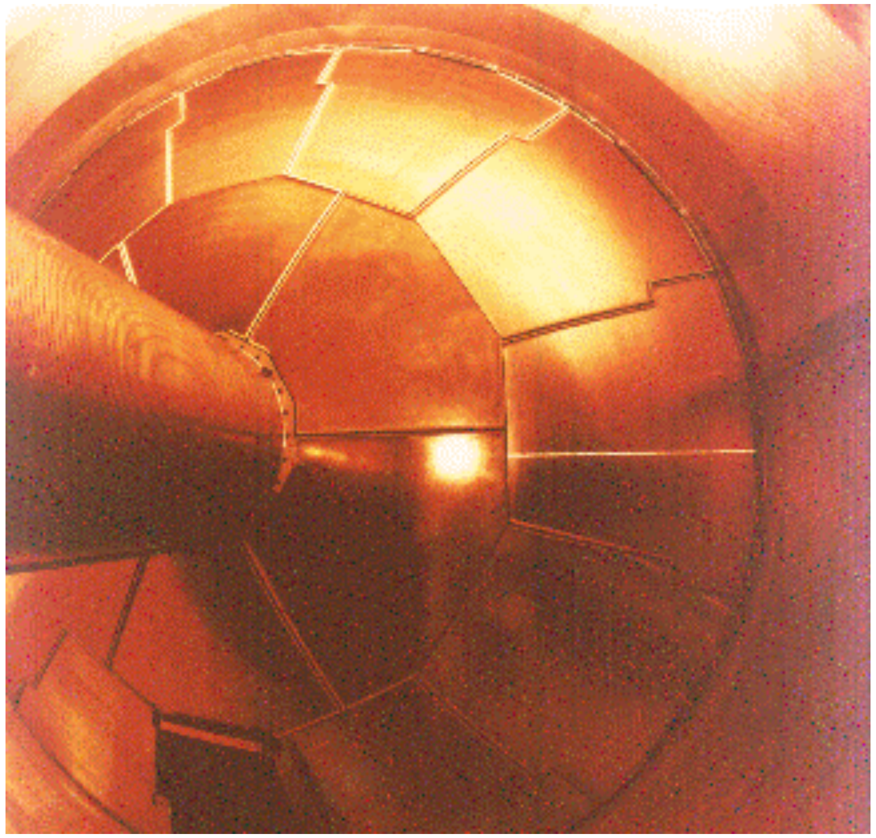

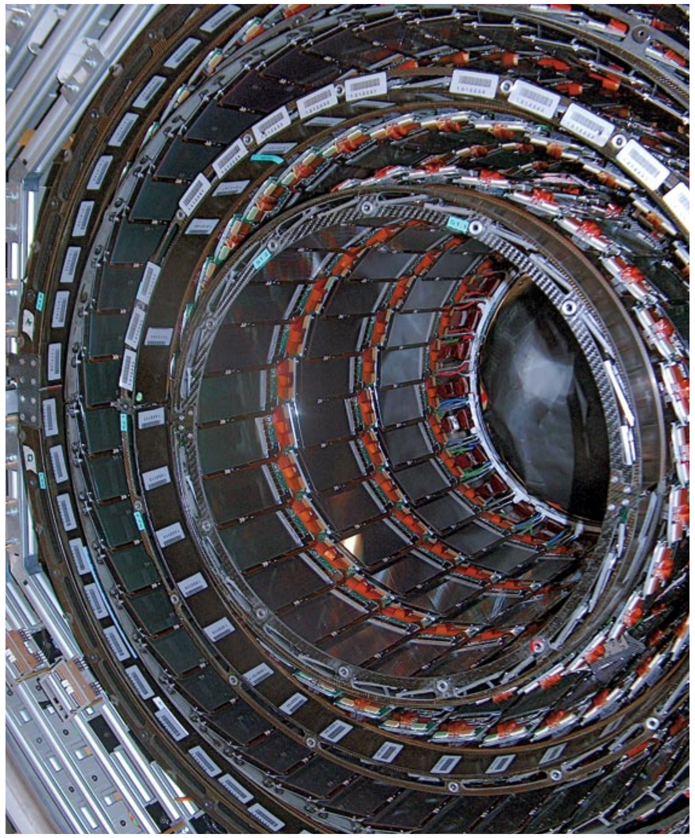

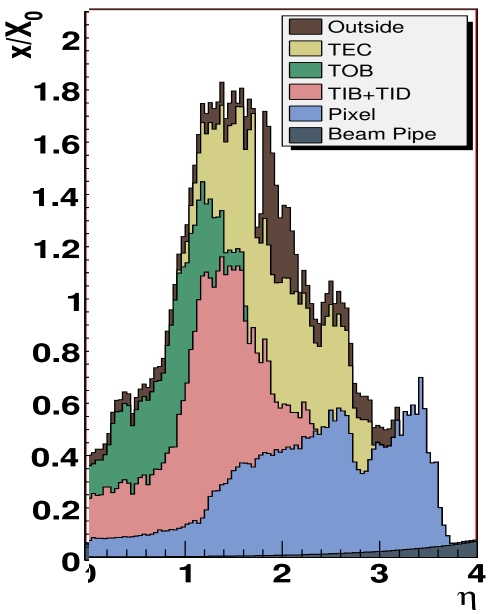

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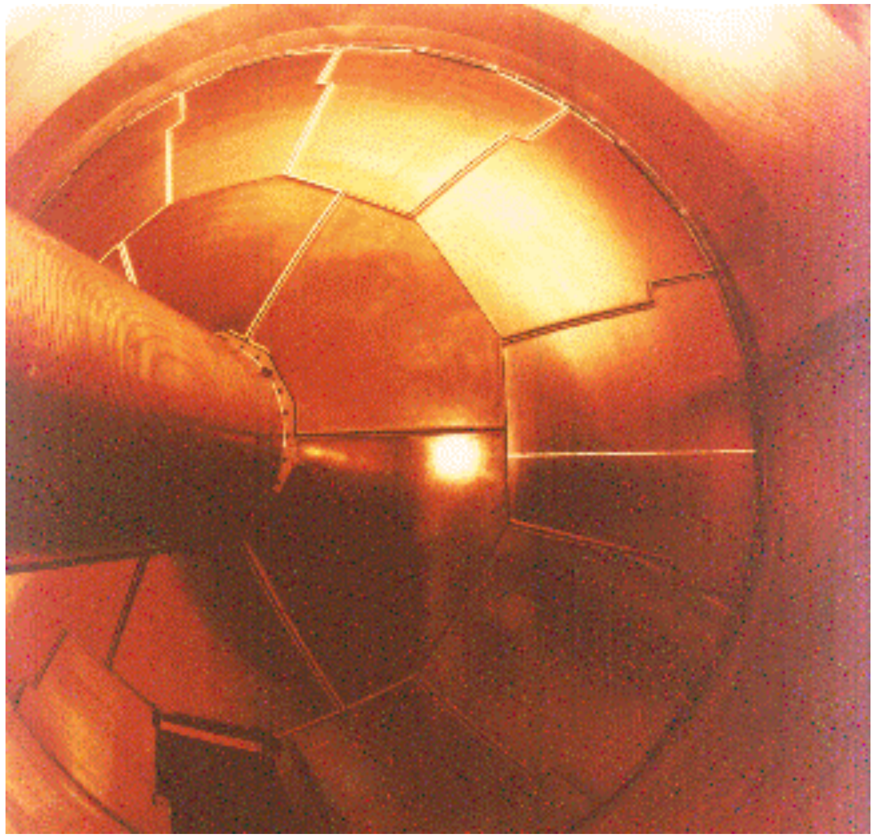

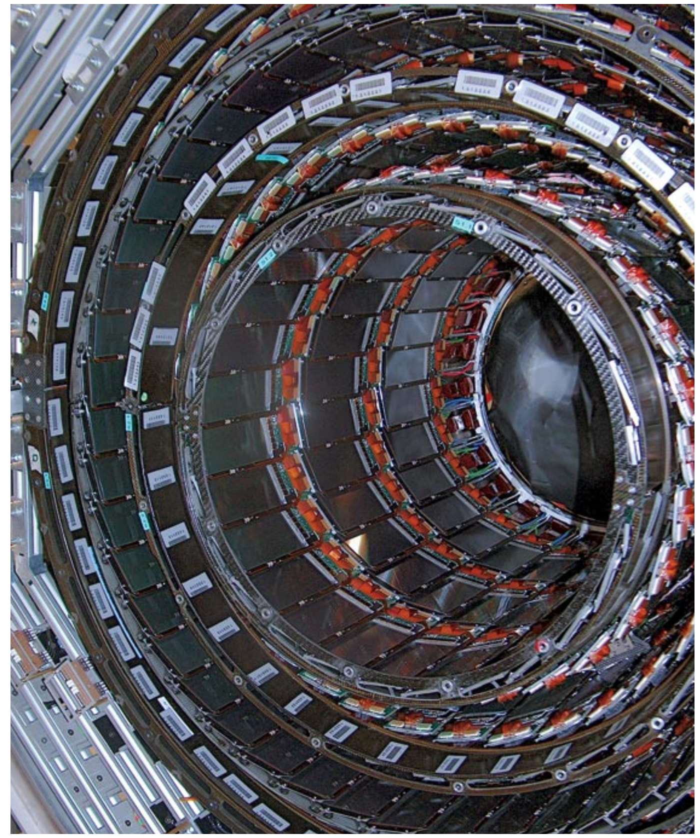

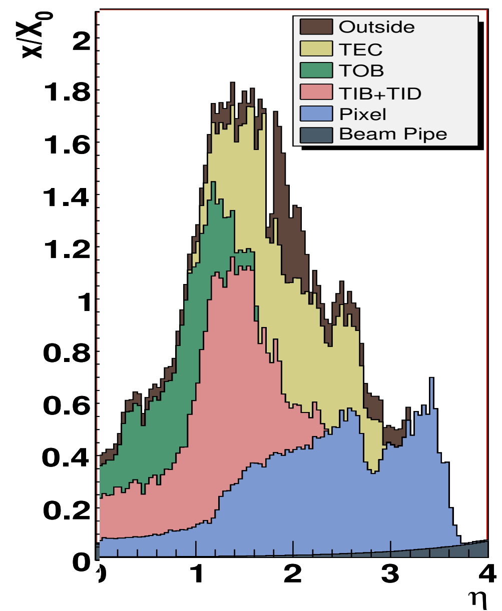

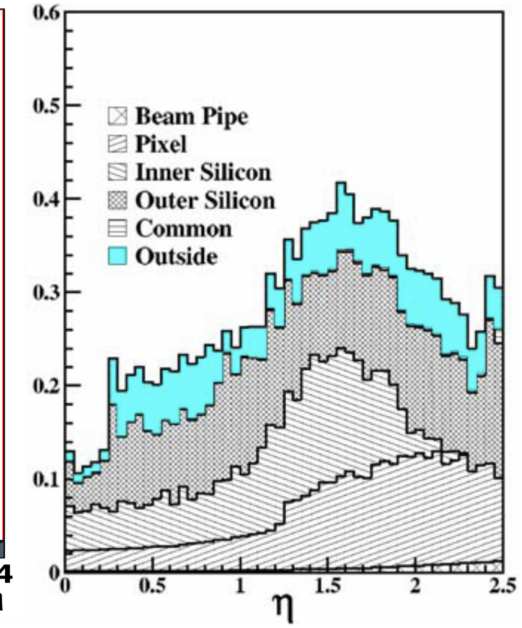

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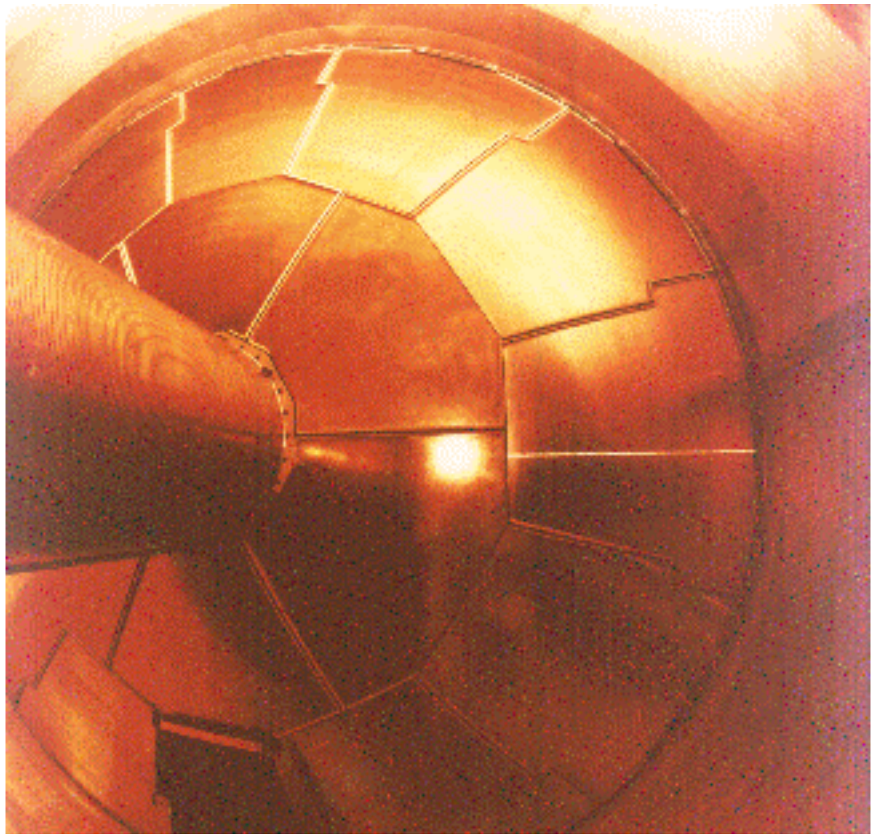

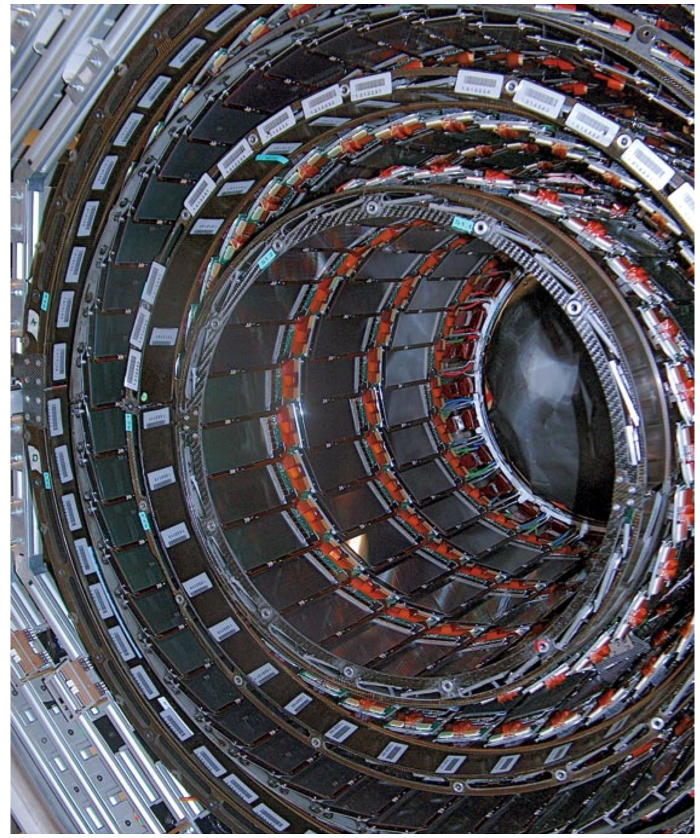

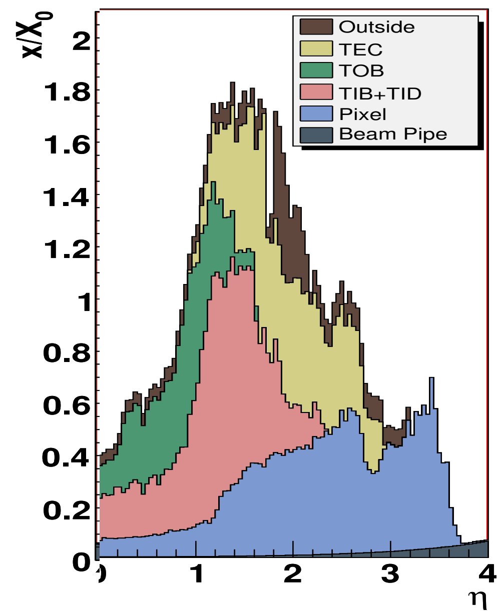

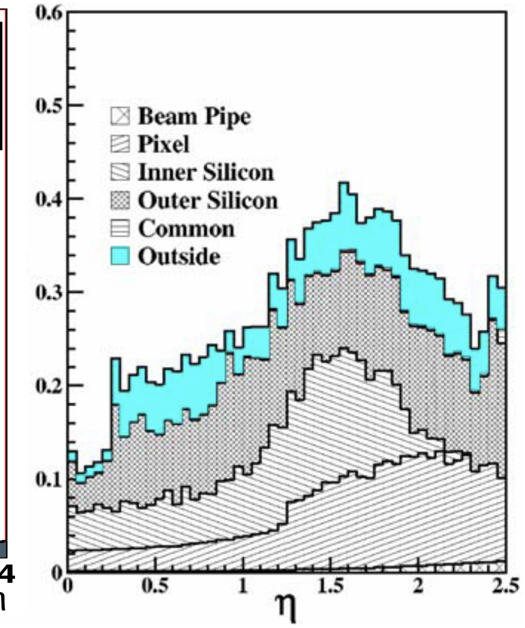

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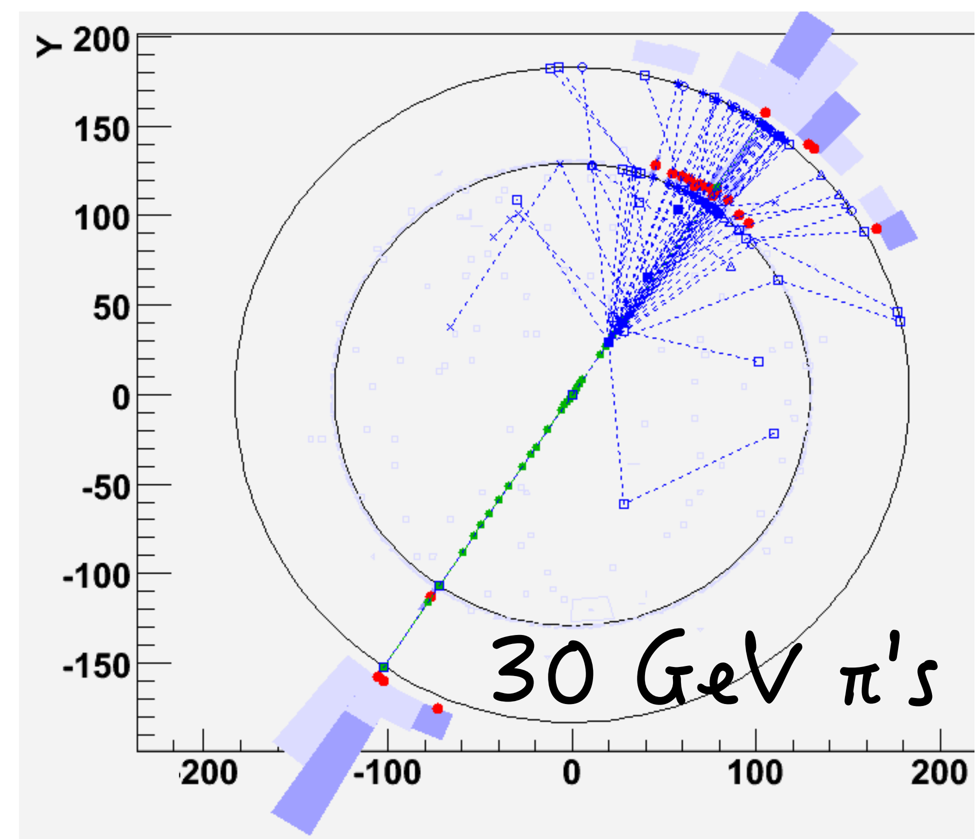

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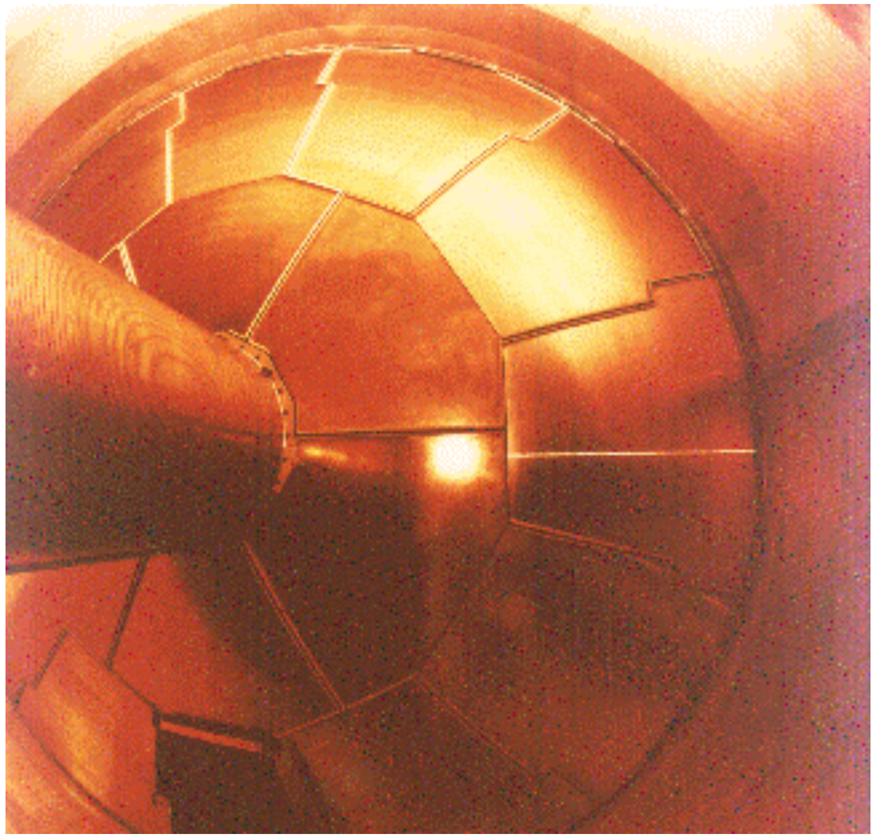

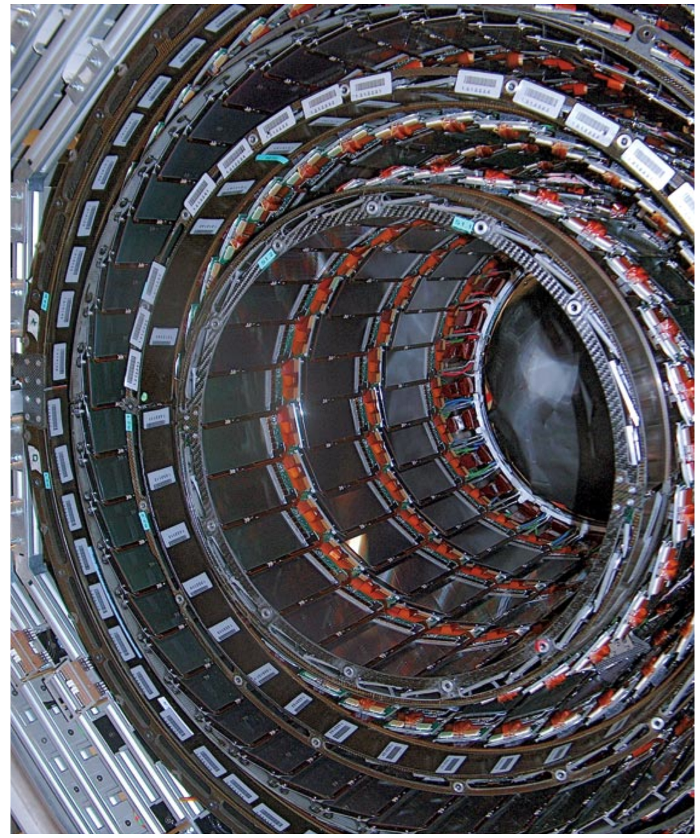

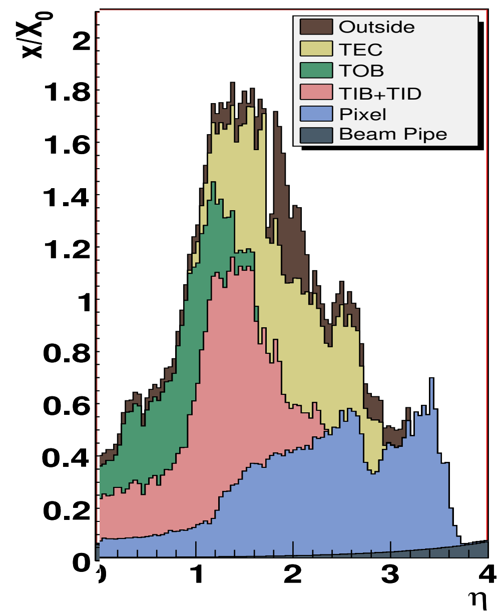

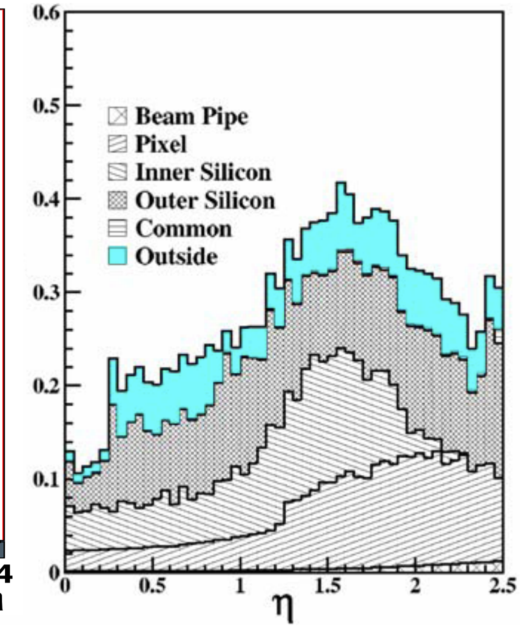

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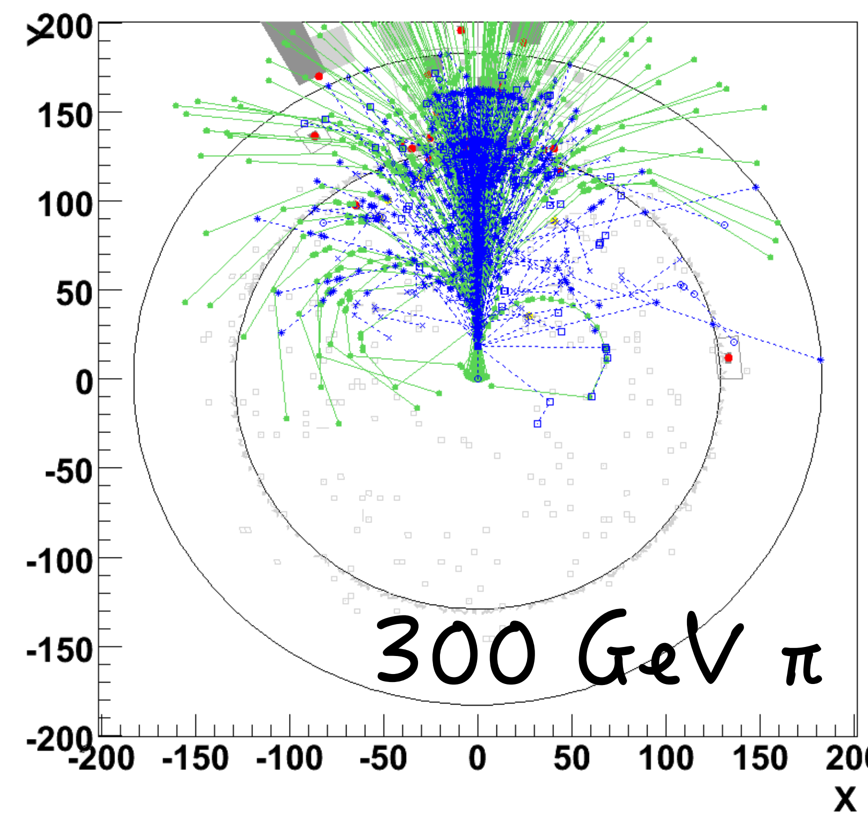

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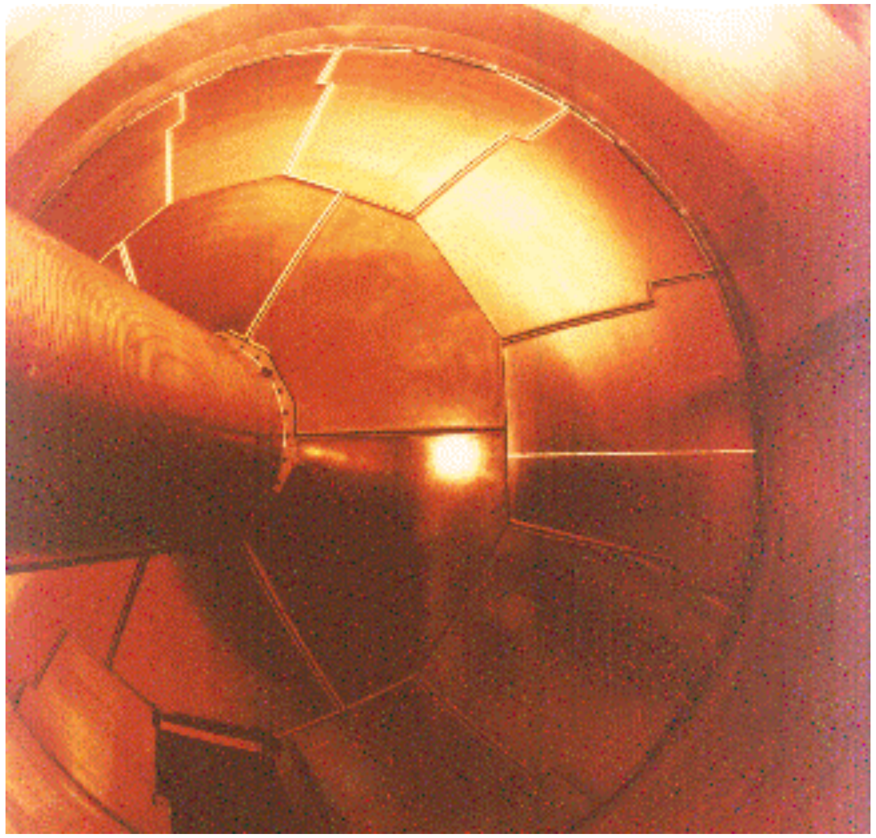

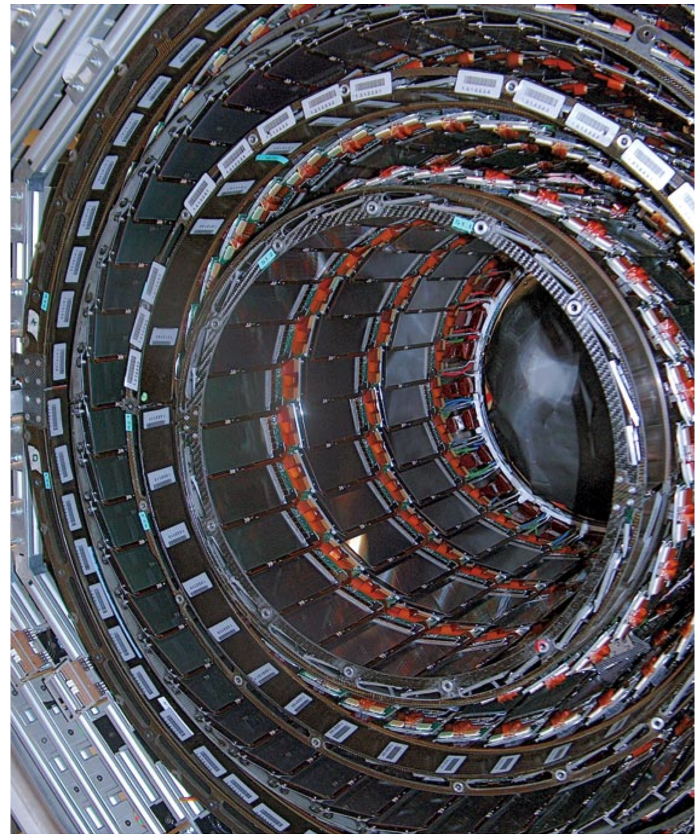

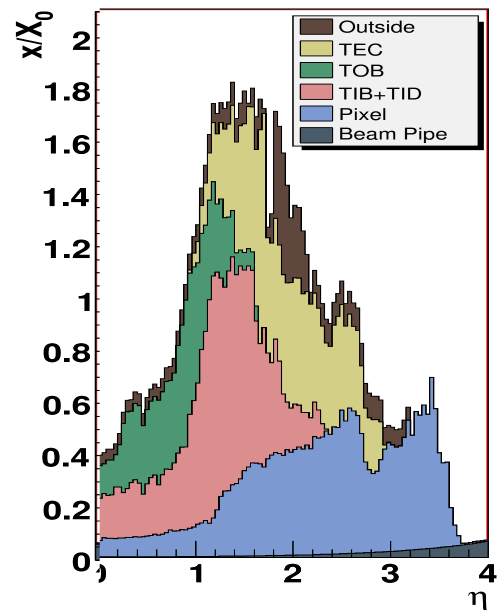

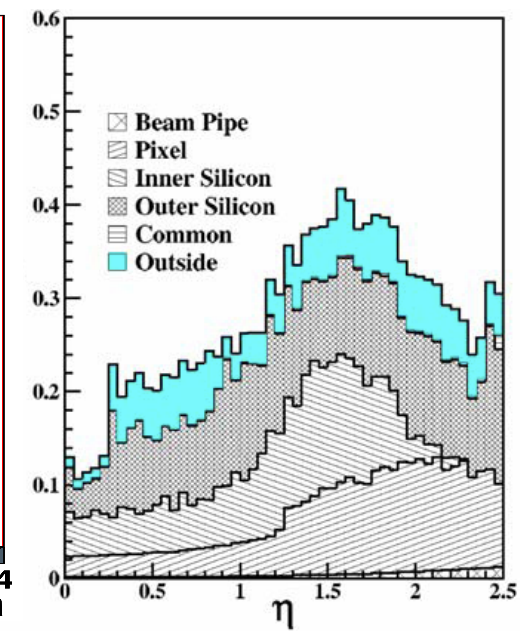

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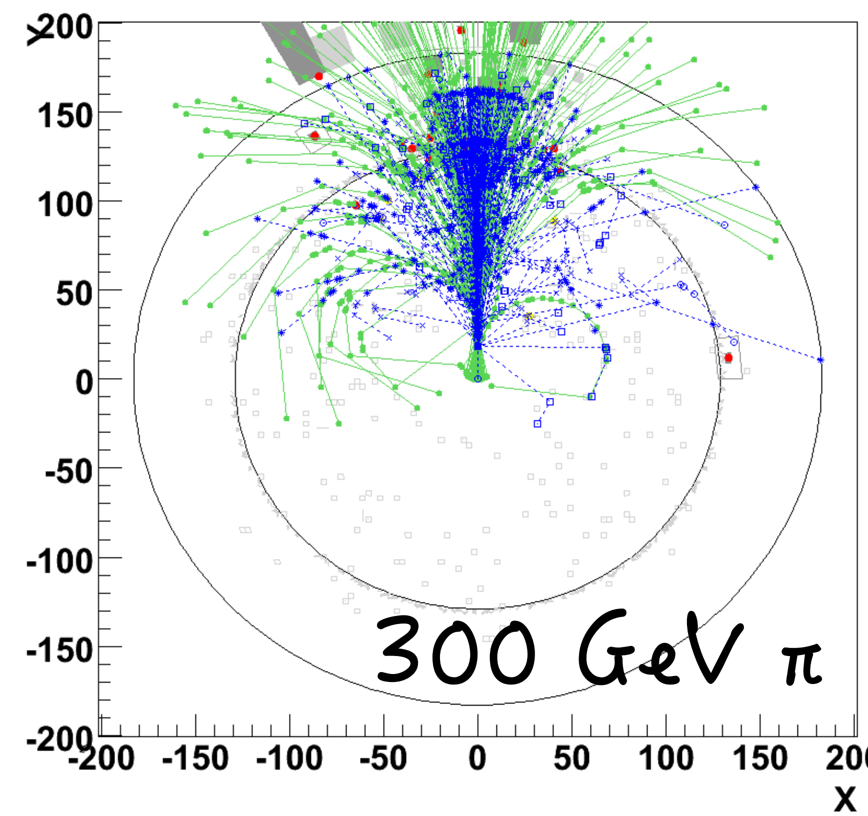
Initial tracking step: $\varepsilon \approx 85\%$; $f \approx 20\%$



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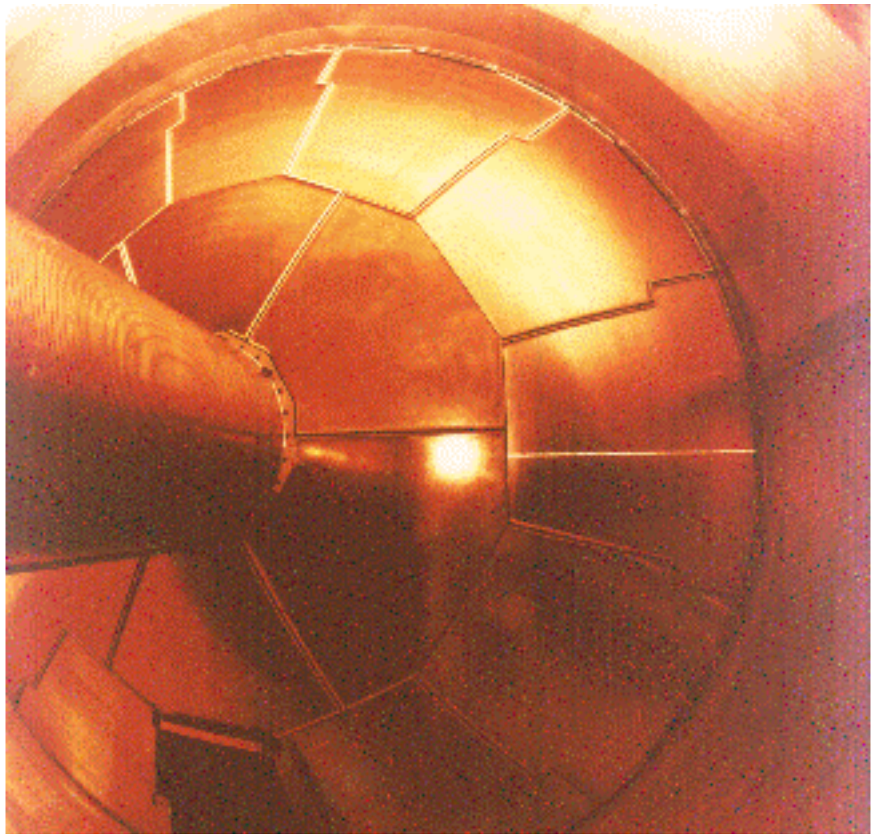

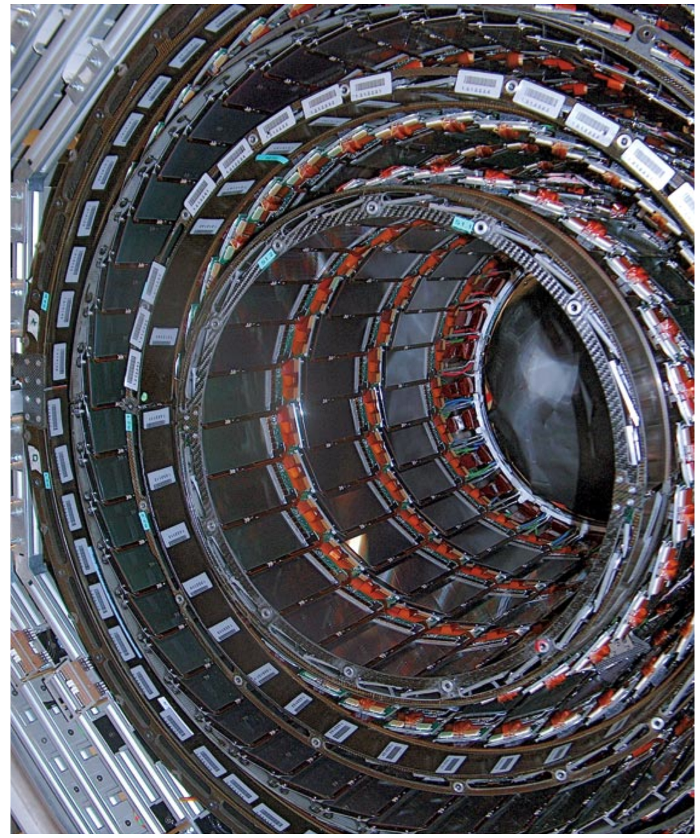

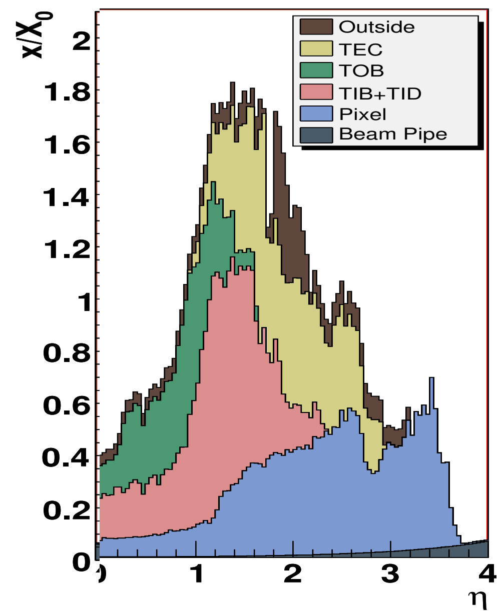

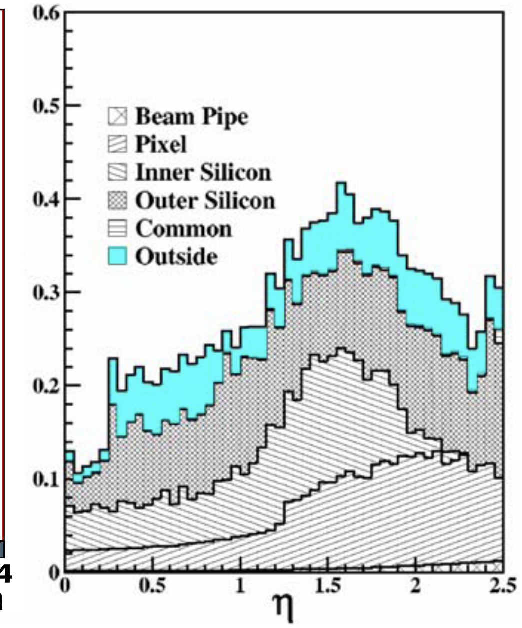

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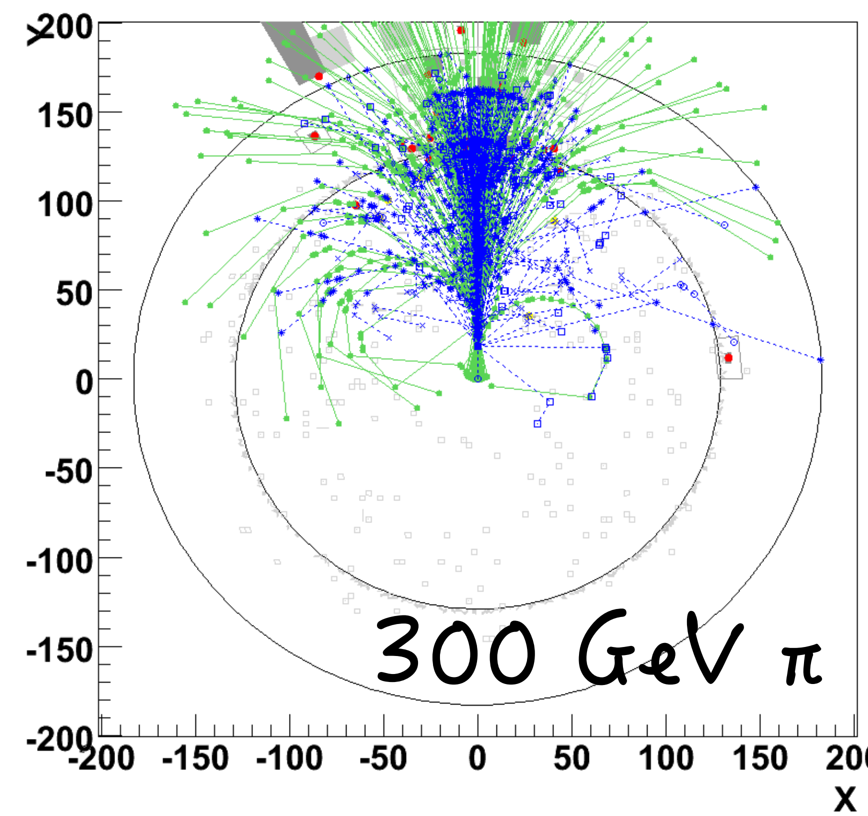
- Initial tracking step: $\varepsilon \approx 85\%$; $f \approx 20\%$
- after working hard: $\varepsilon \approx 95\%$; $f \approx 1\%$



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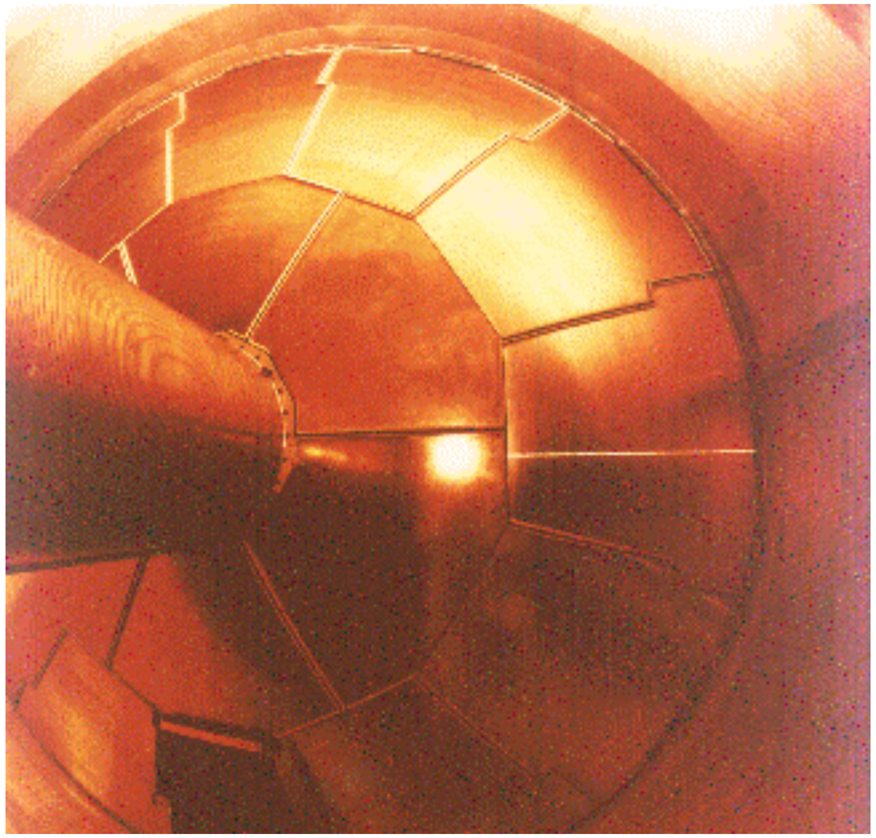
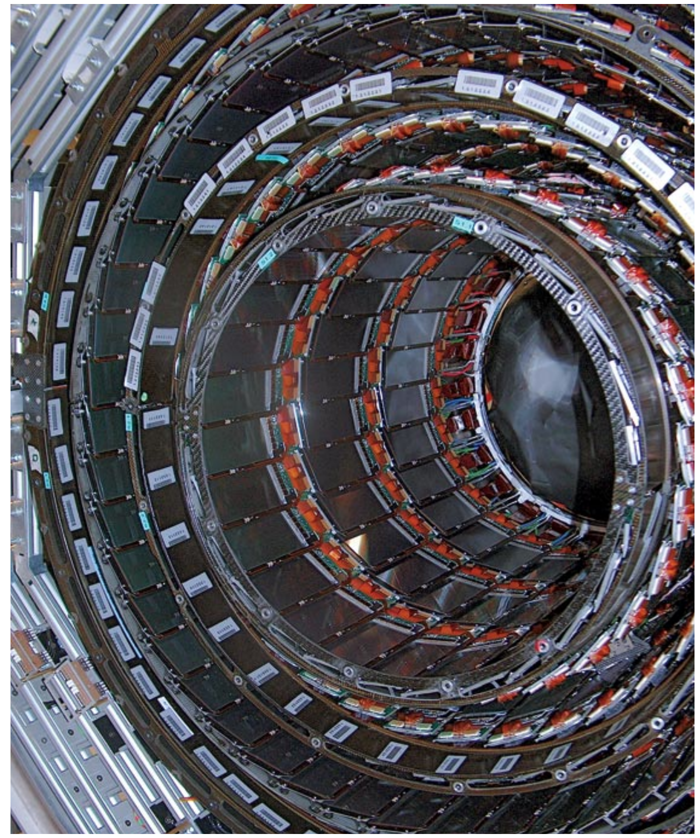
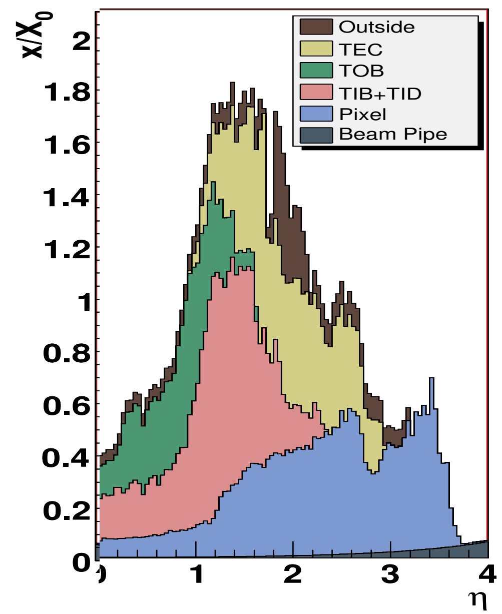
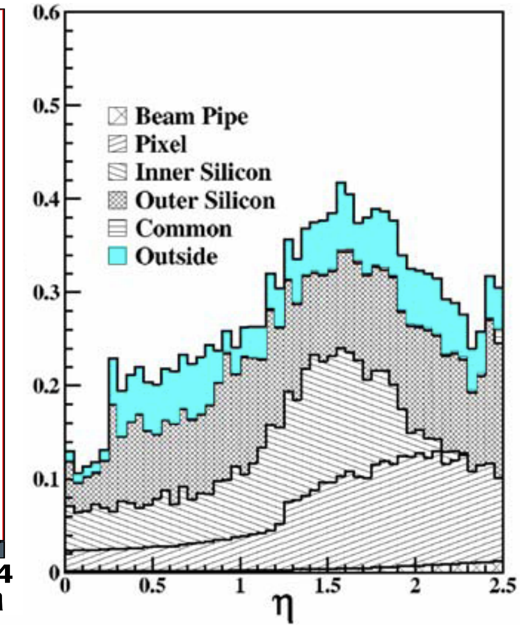








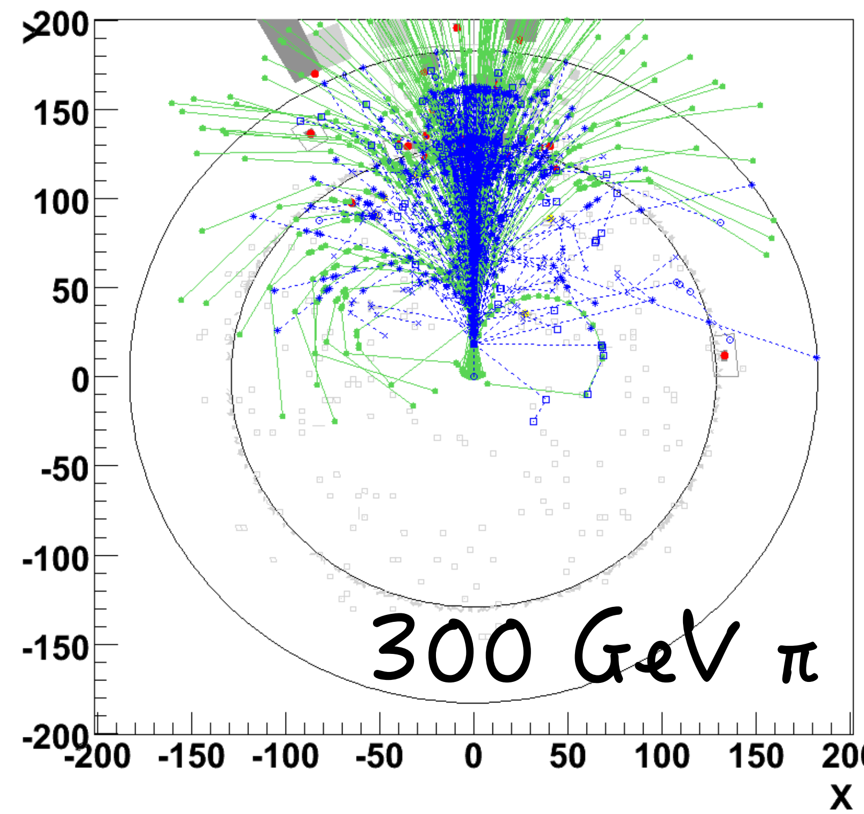
Tracking played a central role in both ALEPH and CMS Particle Flow Algorithms. But...

- ALEPH Tracker mostly empty
- CMS Tracker mostly full

CMS: 20% of all hadrons undergo a nuclear interaction inside tracker volume

- Initial tracking step: $\varepsilon \approx 85\%$; $f \approx 20\%$
- after working hard: $\varepsilon \approx 95\%$; $f \approx 1\%$

(must then link secondaries to calo clusters, to avoid double counting)



Particle Flow...

Particle Flow...

...as a methodology...

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is very Generic! lepton, hadron, 0.1, 10, 100 TeV all follow same ideas

Particle Flow...

Fermilab
UIC University of Illinois at Chicago

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  - ALEPH, CMS used PF (absolutely critical for jets, MET, pile-up, etc)
  - ATLAS does "not" use PF (not as critical...but could still benefit)

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- there are minor differences, of course...

Designing the LHC Experiments

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R. Cavanaugh   100 TeV Workshop, SLAC   23-26 August, 2014

CMS is radically different from detectors of the previous generations

High Interaction Rate

pp interaction rate **1 billion interactions/s**
Data can be recorded for only ~10^2 out of 40 million crossings/sec
Level-1 trigger decision takes ~2-3 μs
⇨ **electronics need to store data locally (pipelining)**

Large Particle Multiplicity

~ <20> superposed events in each crossing
~ 1000 tracks stream into the detector every 25 ns
need highly granular detectors with good time resolution for low occupancy
⇨ **large number of channels (~ 100 M ch)**

High Radiation Levels

⇨ **radiation hard (tolerant) detectors and electronics**

Slide taken from J. Virdee

Transparency from the early 90's

We are now asking the same questions for 100 TeV...

Designing the LHC Experiments

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Very good muon identification and momentum measurement
Trigger efficiently and measure sign of TeV muons dp/p < 10%

High energy resolution electromagnetic calorimetry
~ 0.5% @ E_T ~ 50 GeV

Powerful inner tracking systems
Momentum resolution a factor 10 better than at LEP

Slide taken from J. Virdee

Hermetic calorimetry
Good missing E_T resolution

(Affordable detector)

Transparency from the early 90's

We are now asking the same questions for 100 TeV...

Some thoughts on tracking at 0.1, 10, 100 TeV?

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In addition to many layers of precise position measurements, one needs a large, powerful magnet

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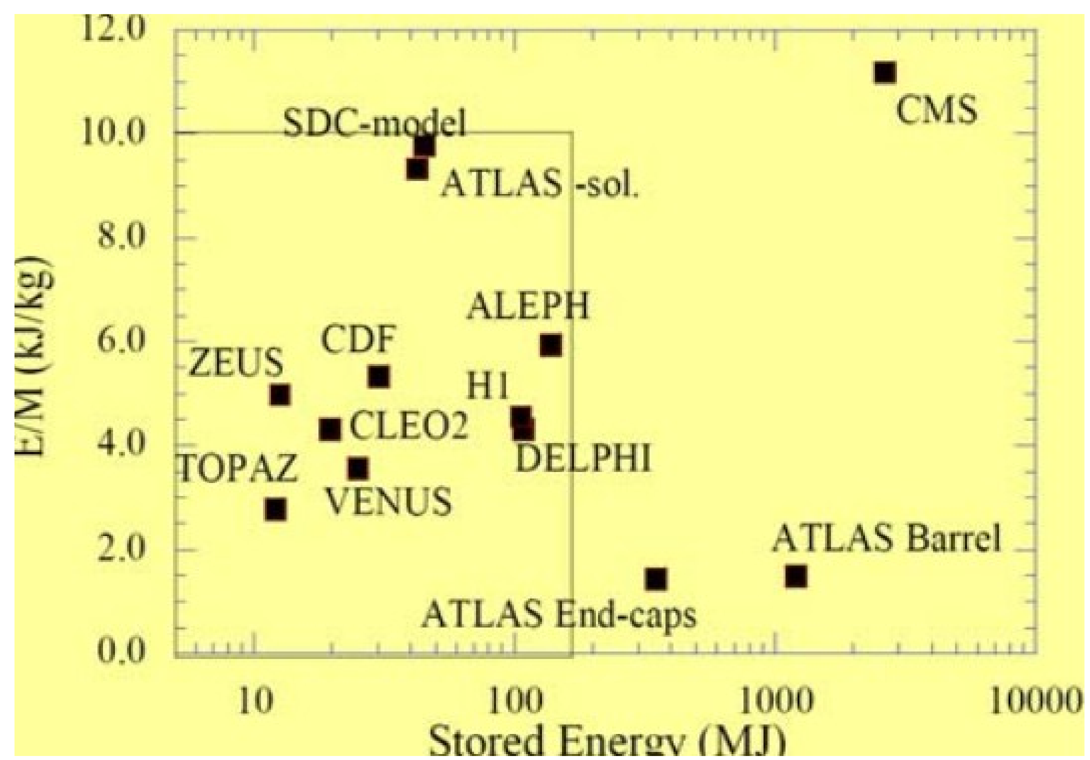

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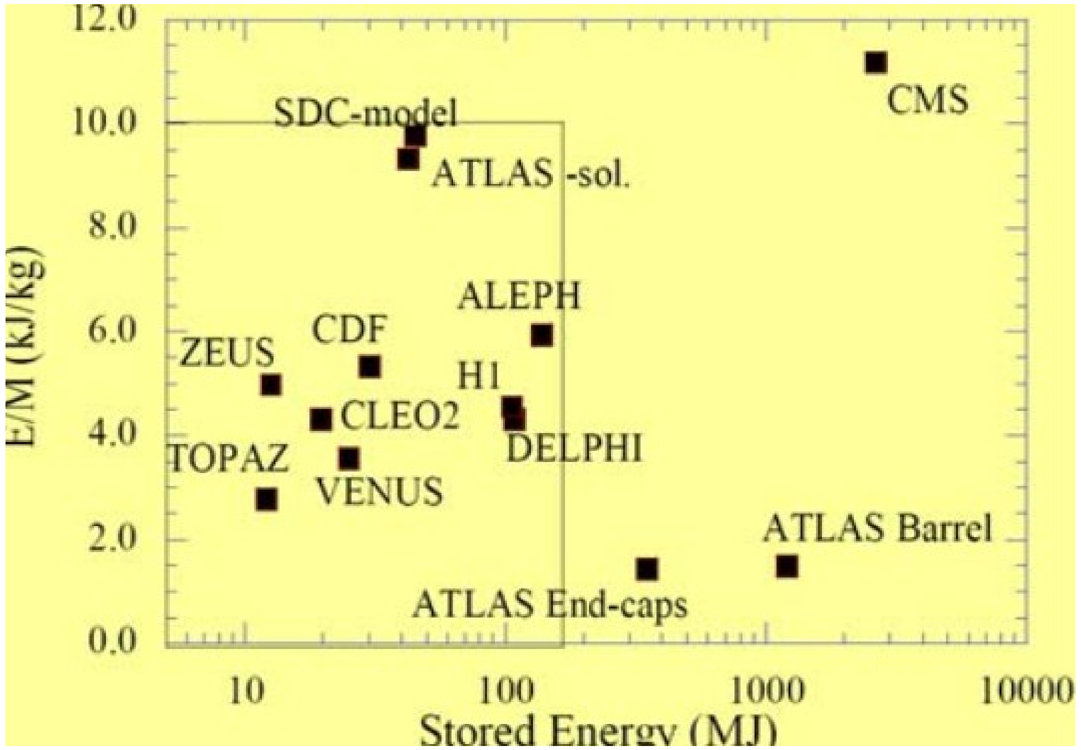

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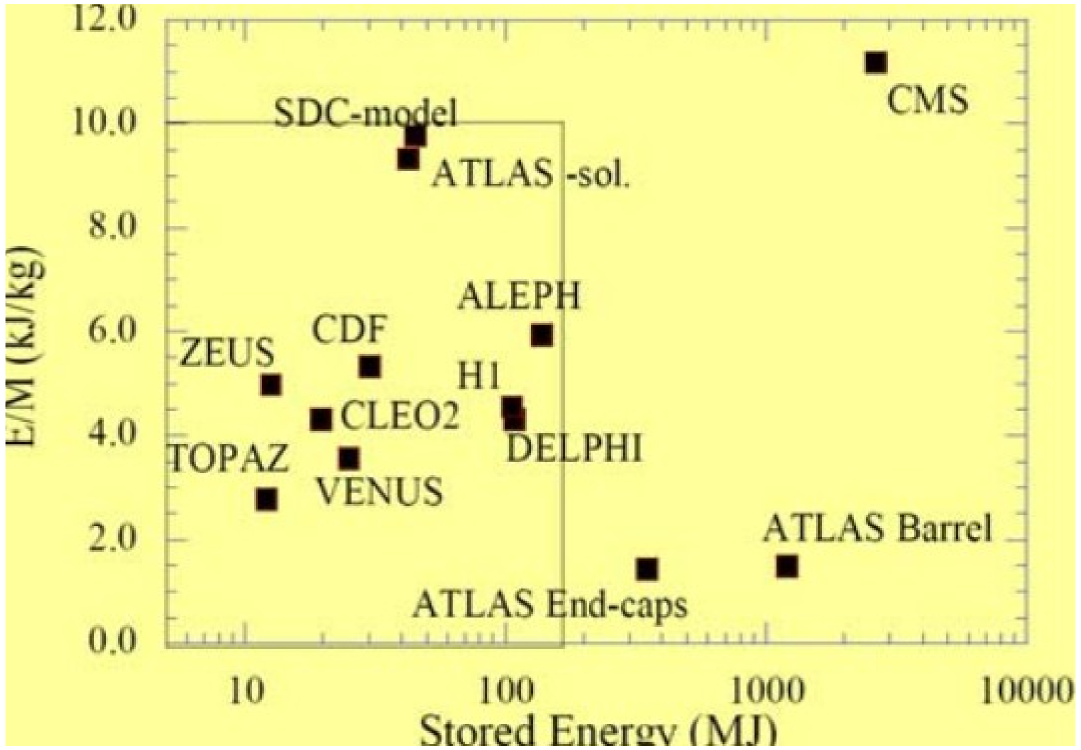
(For same B, R scales with $\sqrt{E}$)
(See Todesco)



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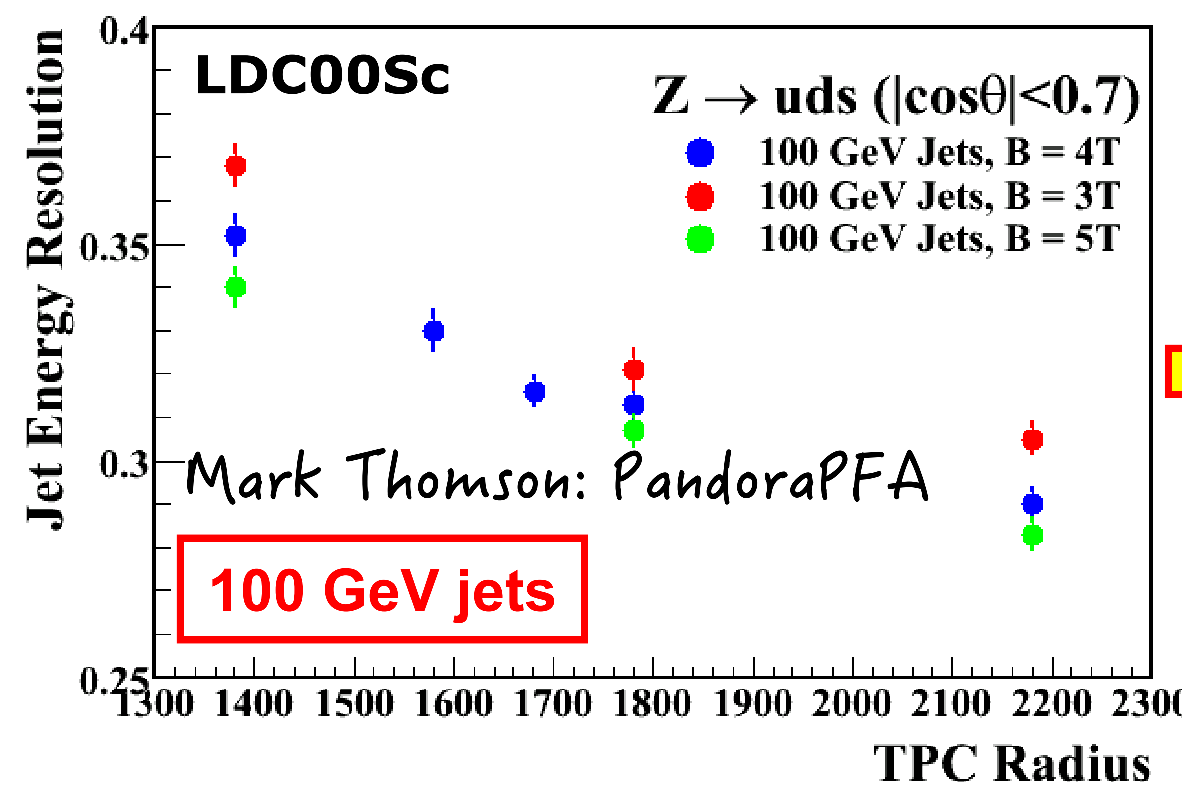

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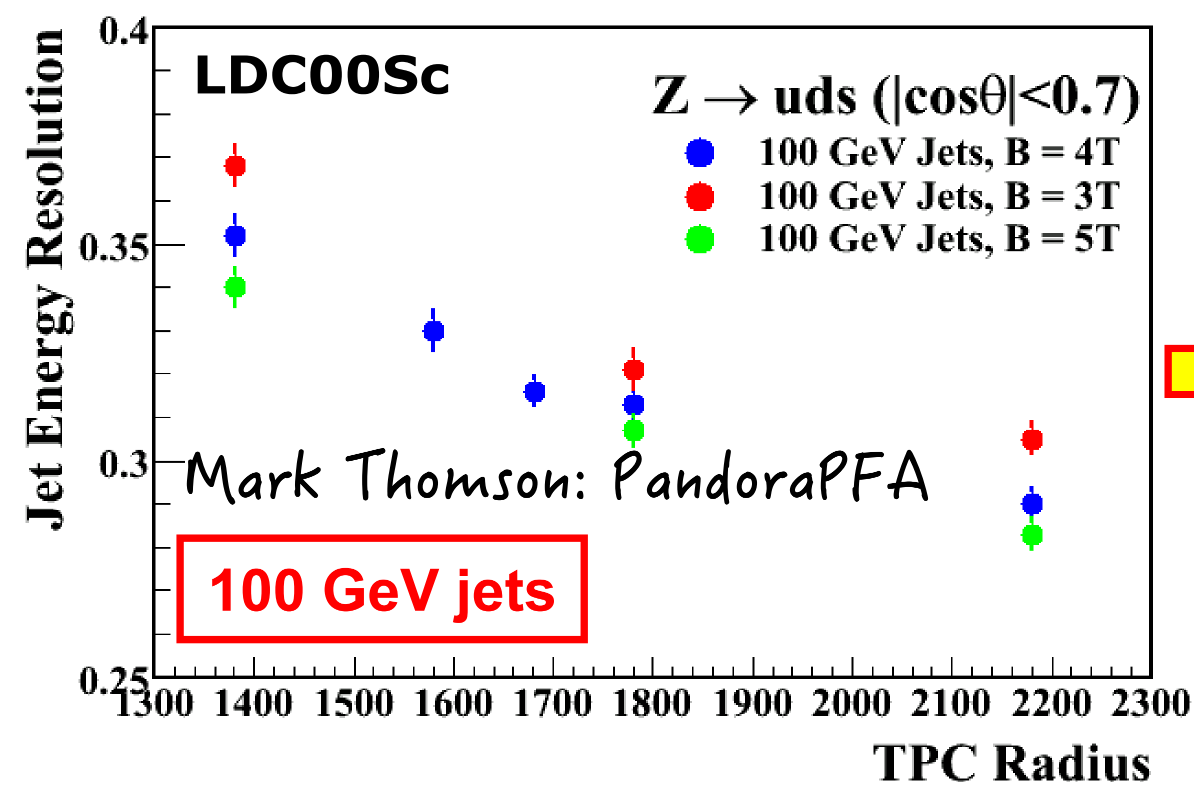

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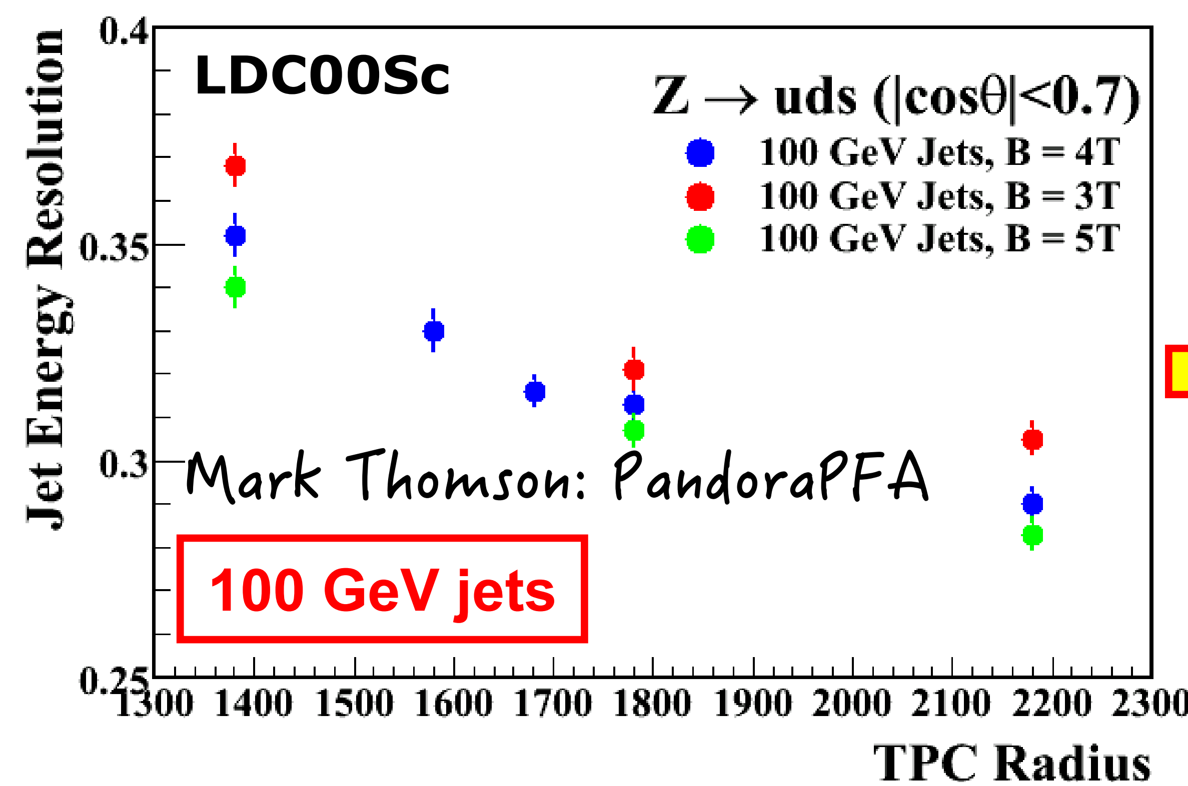
- more calorimeter surface area => more calorimeter cells for same (LHC) cell size
- suggests VLHC will need better segmentation (more readout channels) than LHC



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⟹

See Sanjay Padhi's Talk at Beijing

Parametrized detector for 100 TeV proton collider (baseline)

1. Large Solenoid + return yoke: Magnetic Field: 5T, 24m long and 5m radius
2. Central Tracker (including pixel detector)
   - Acceptance within $|\eta| < 4$
   - Momentum resolution $\sigma/p_T \approx 1.5 \times 10^{-4} \oplus 0.005$
   - Efficiencies similar (not same) to CMS Phase-II ECFA studies
3. EM Calorimeter (PbWO4) $\sigma/E = 2.0\%/\sqrt{E} \oplus 0.5\%$
4. Hadronic Calorimeter $\sigma/E = 50\%/\sqrt{E} \oplus 3\%$
5. Forward Calorimeter (needed for VBF and other studies) up to $|\eta| \sim 6$
   $\sigma/E = 100\%/\sqrt{E} \oplus 5\%$
6. Muon detector
   - Acceptance within $|\eta| < 4$
   - Momentum resolution $\sigma/p_T \approx 1\%@100\ GeV - 10\%@10s\ TeV$
   - Efficiencies similar (not same) as CMS Phase-II ECFA studies