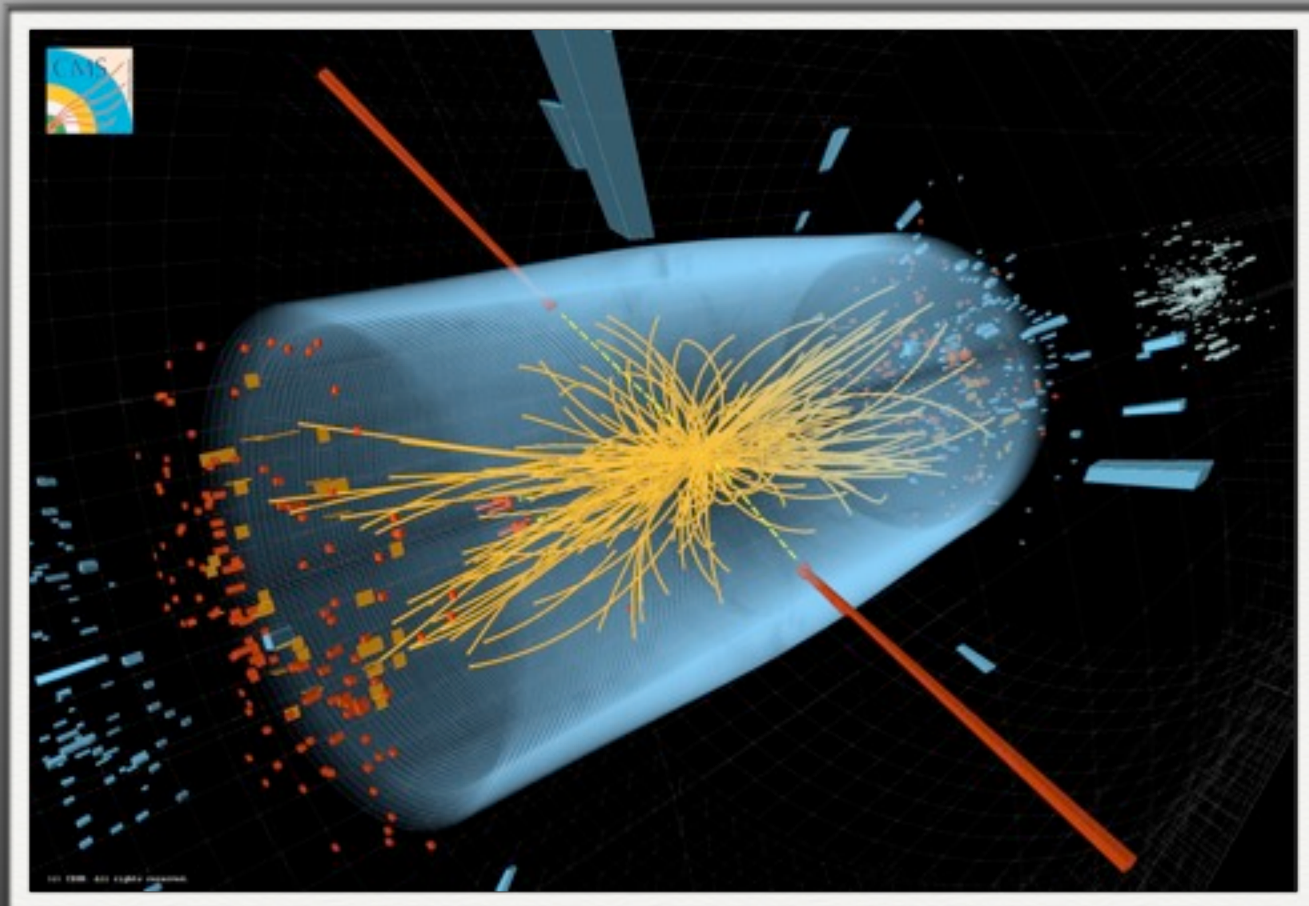
Particle ID: Lecture #2



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

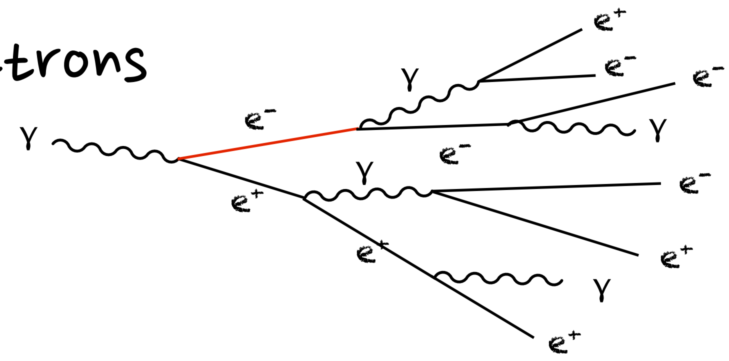
Hadron Collider Physics Summer School
Fermilab, 14 August, 2012

LPC LHC Physics Center

Particle interactions in material

Photons

Electrons



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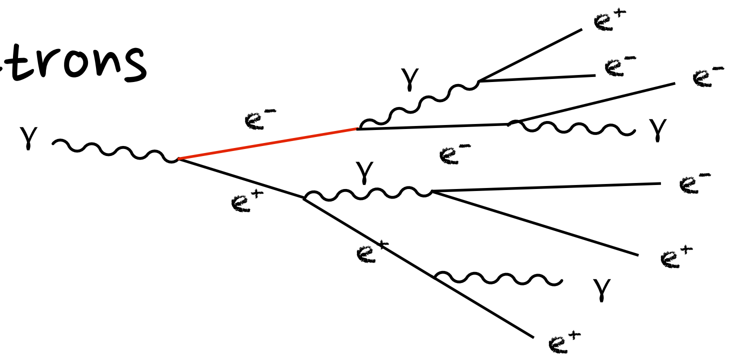
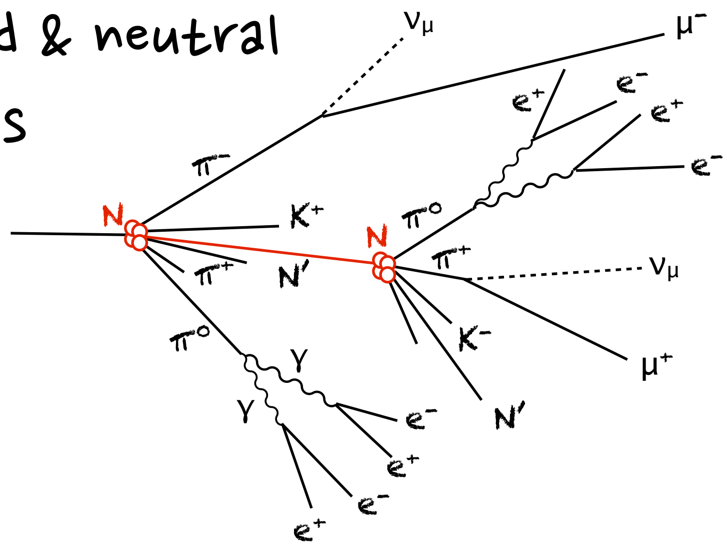


Particle interactions in material

charged & neutral hadrons



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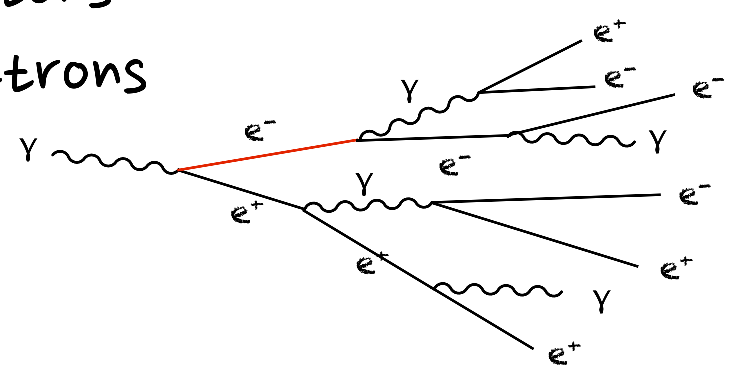

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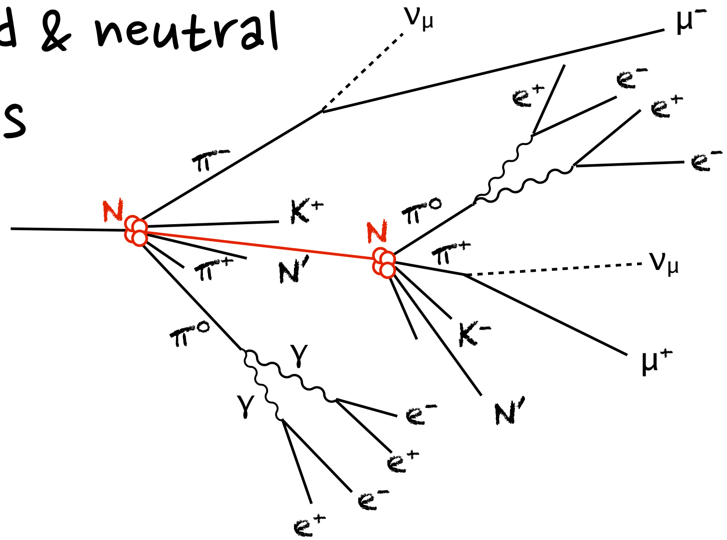

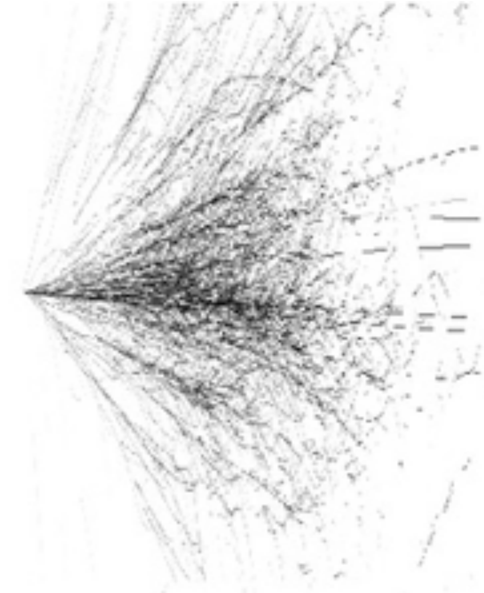

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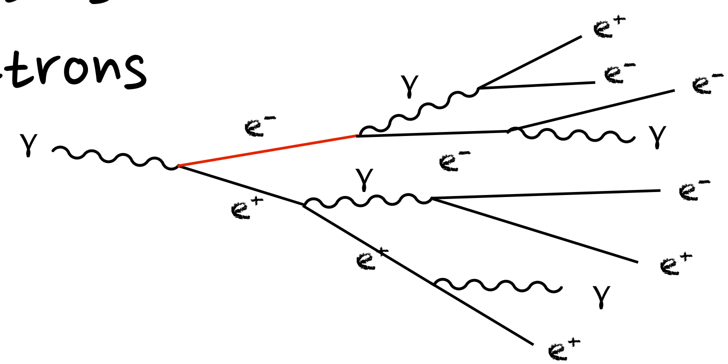

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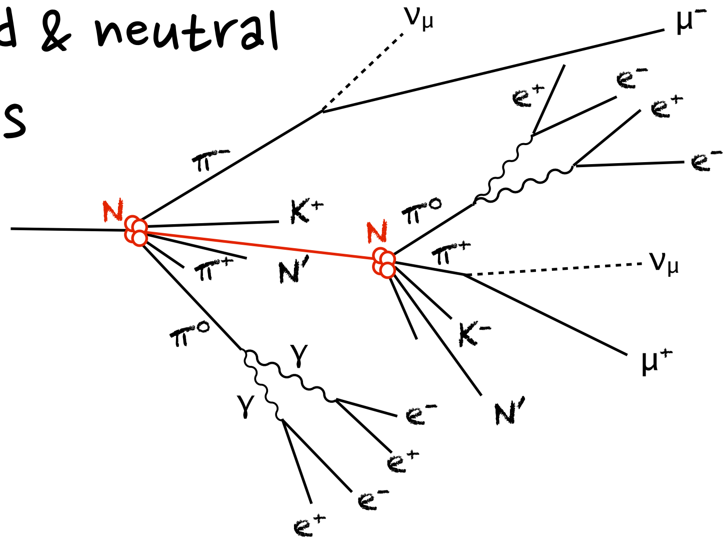

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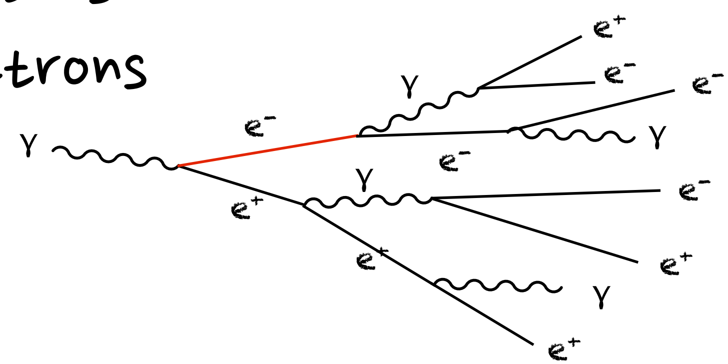

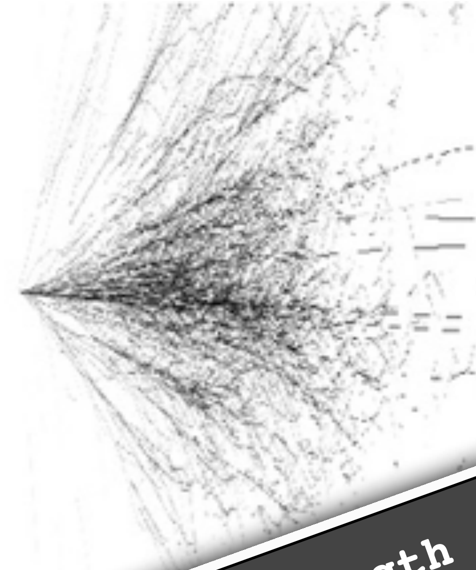

Radiation Length

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

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

- Higher Z materials have short length
  - want high-Z material for EM calorimeter

Example: Lead
$\rho = 11.4\ \mathrm{g/cm^3}$; $X_0 = 5.6$ mm

Particle interactions in m

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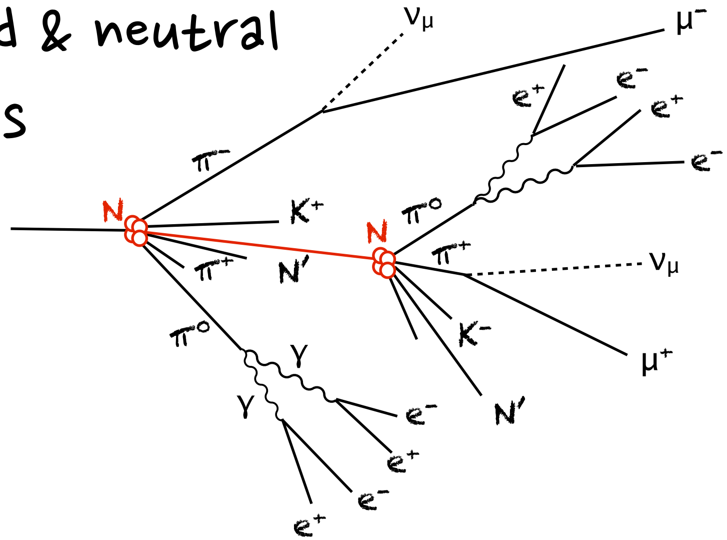

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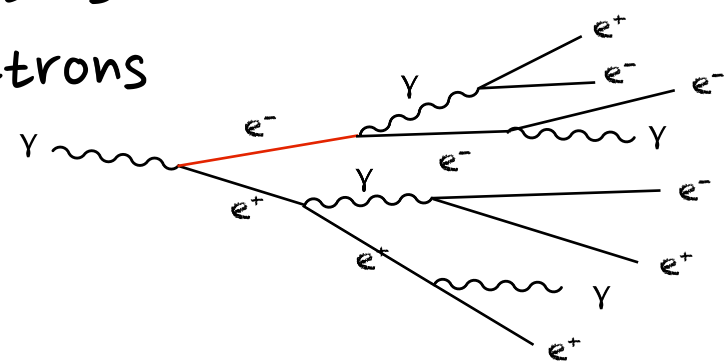

Nuclear Interaction Length

- Collisions of hadrons with nuclei produce hadronic showers

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

- 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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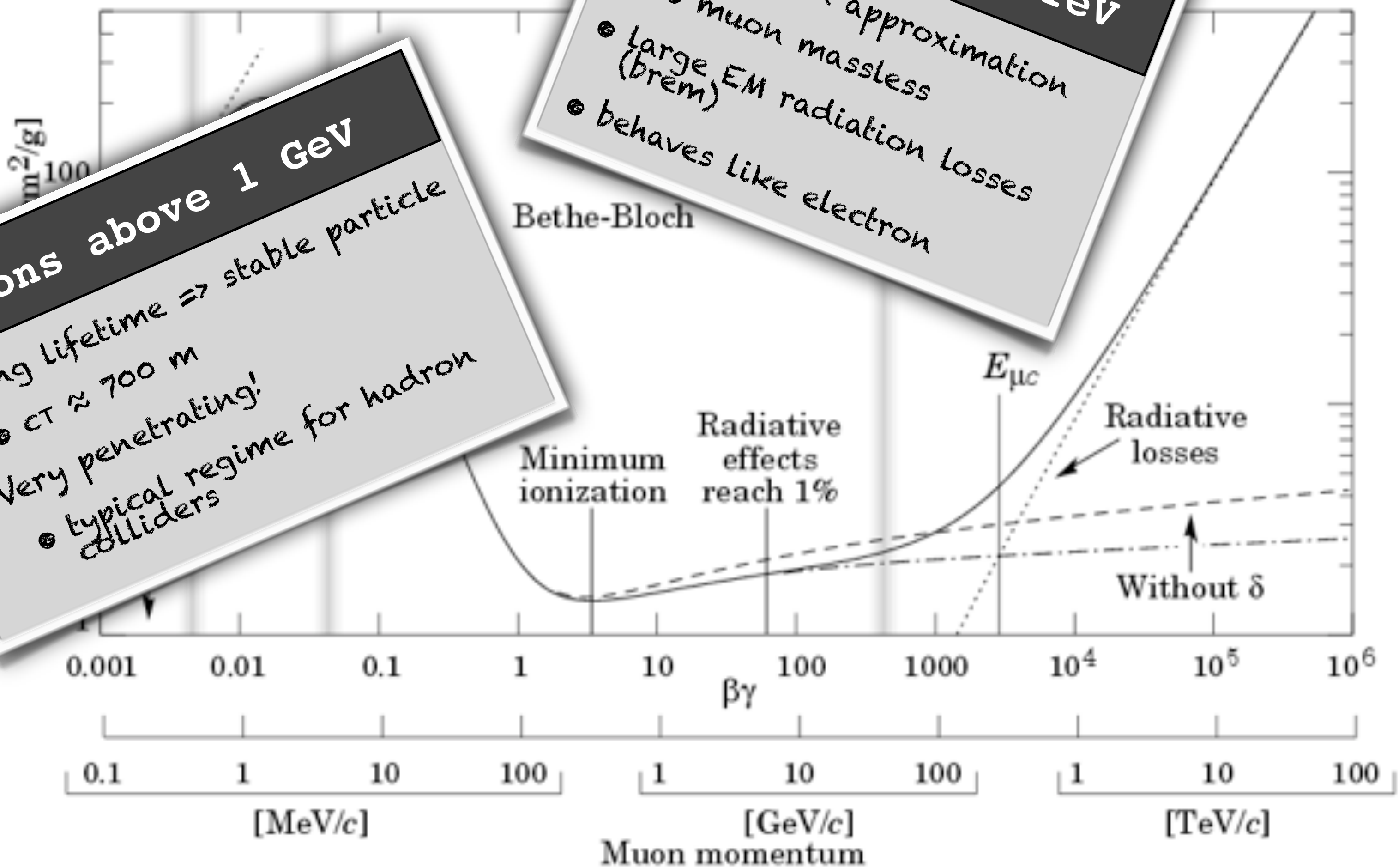
Particle interactions in material



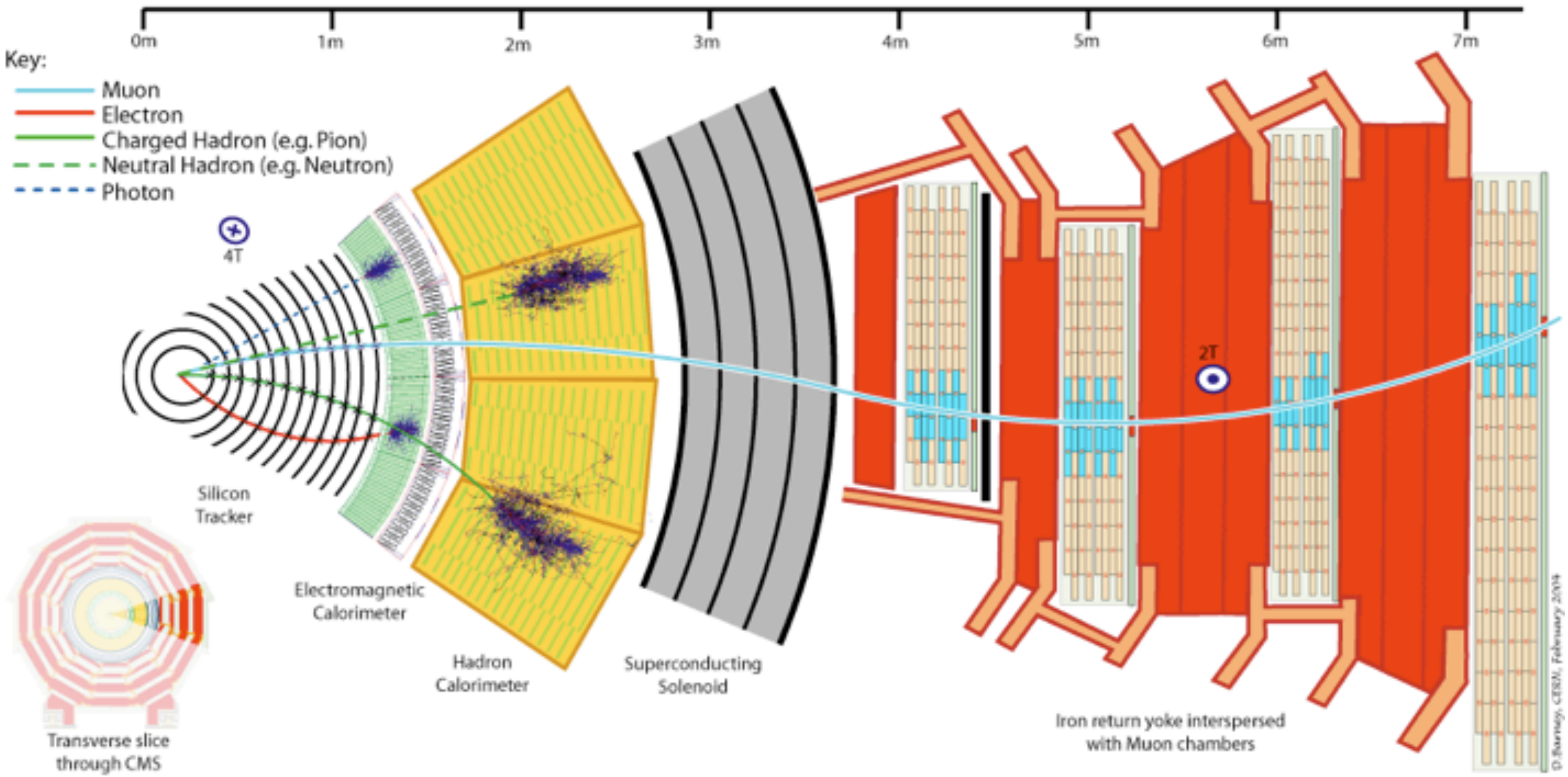
Muons above 1 GeV

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

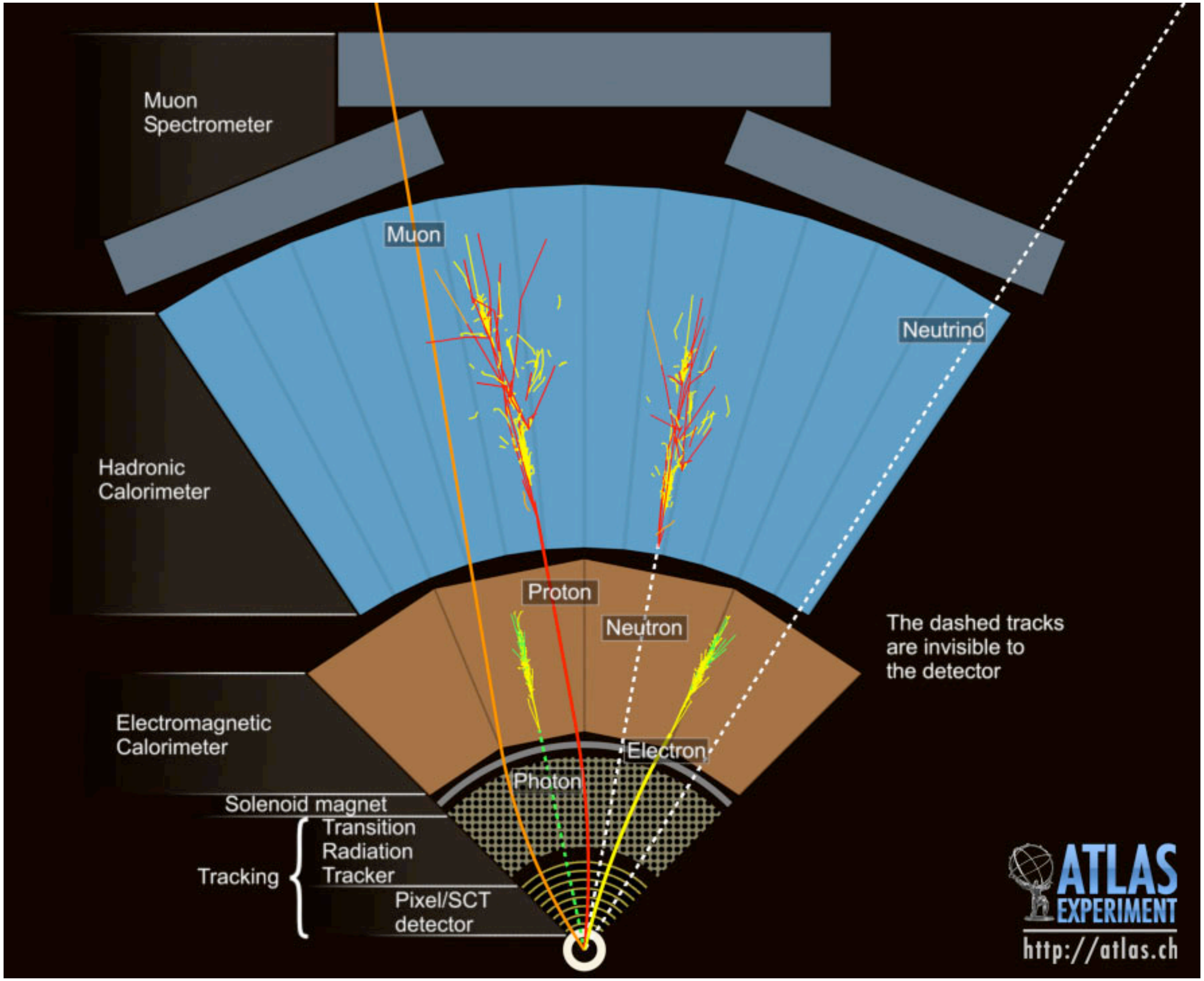
Muons above 1 TeV

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

Particle Passage through CMS

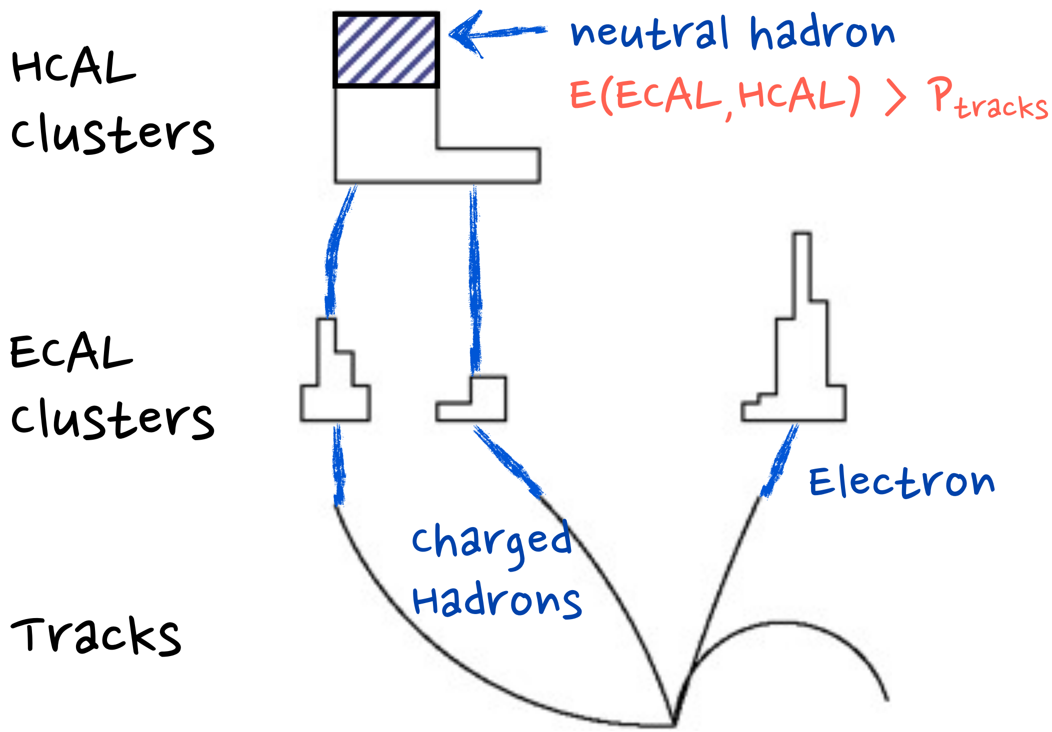


Particle Passage through ATLAS



Particle Flow Algorithm

In a nutshell



- **Aim: 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

Last Time

- **We arrived at a list of visible...**
  - charged particles: could be p^+, $\pi^\pm$, $e^\pm$, $\mu^\pm$, ...
  - neutral photons: could be prompt γ's
  - neutral hadrons: could be n^0, K_L^0, ...
  - Then there was the case of $E \ll p$, when separating merged charged & neutral particles
- **Today:**
  - consider the case when $E \ll p$
  - identify which of the charged particles above are:
    - charged hadrons (1st)
    - electrons (2nd)
    - muons (last)
  - We also need to identify which of the photons are
    - prompt photons (3rd)
  - No need to further identify the neutral hadrons...

R. Cavanaugh, HCPSS 2012

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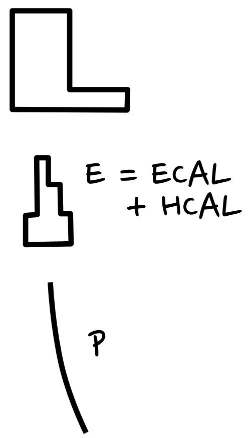

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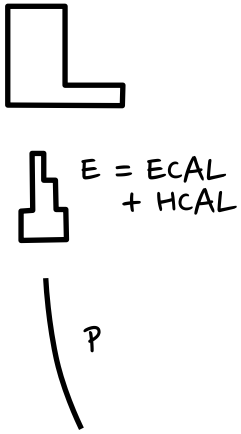

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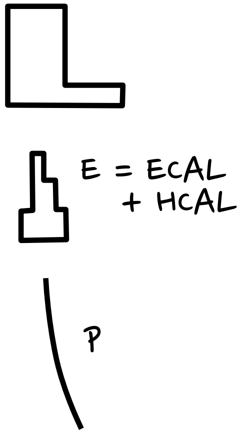

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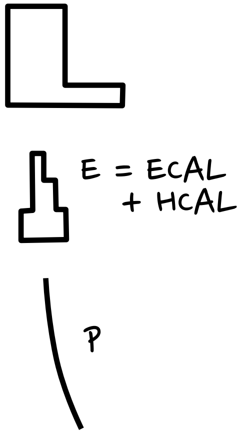

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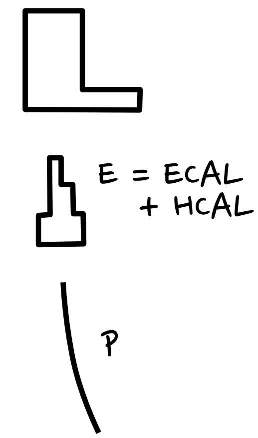

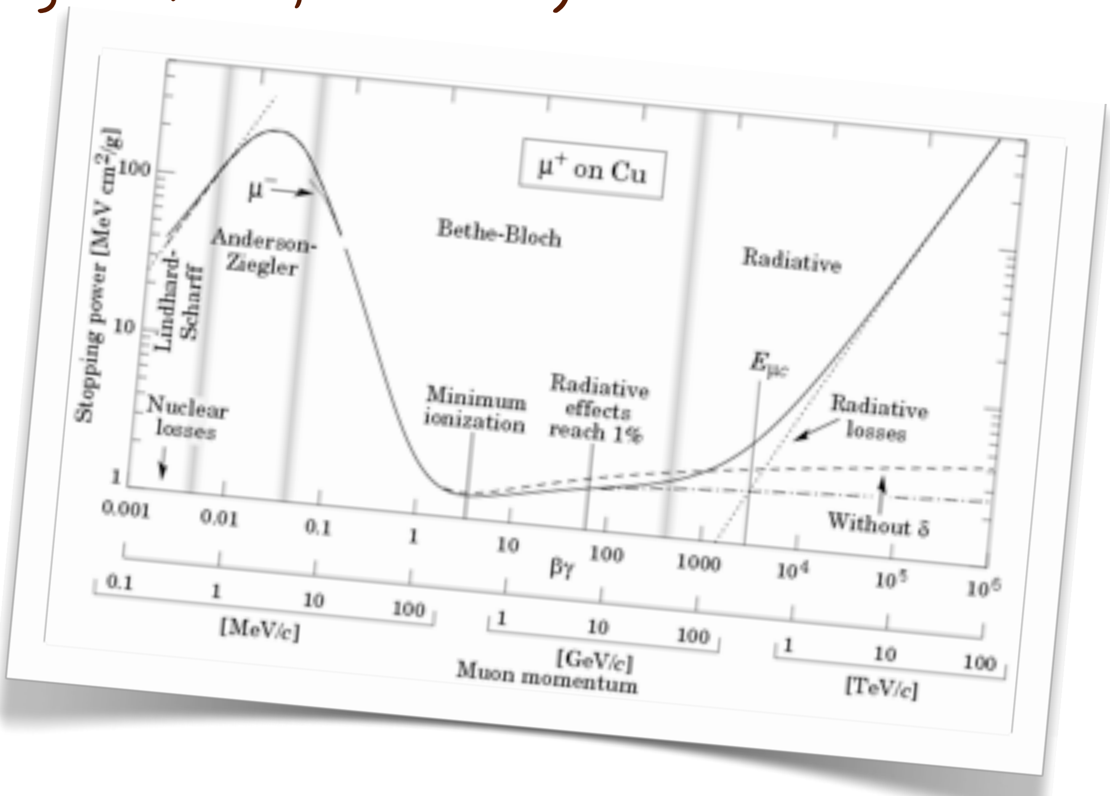

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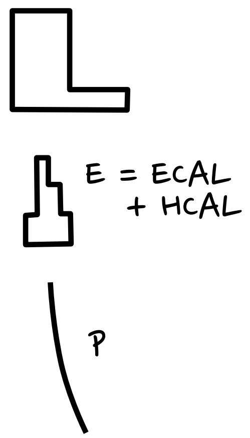

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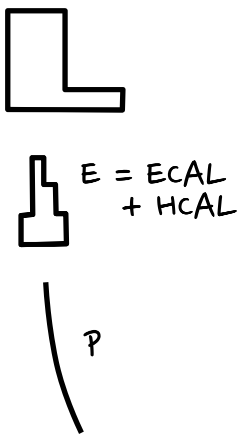

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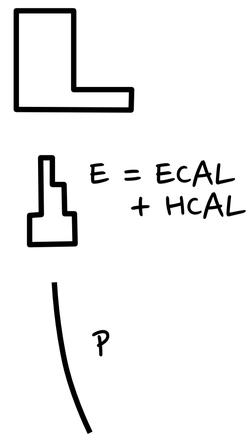

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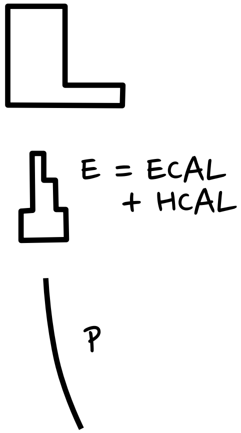

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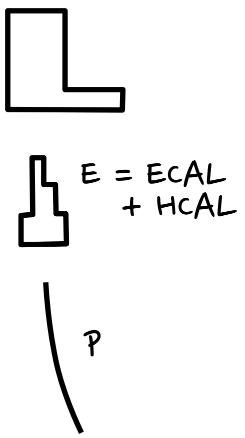

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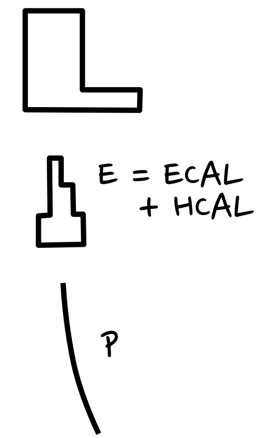

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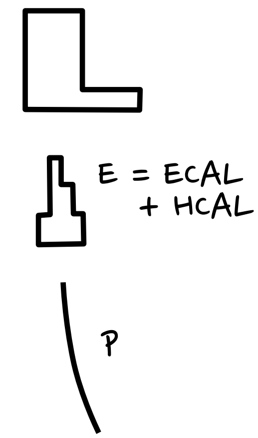

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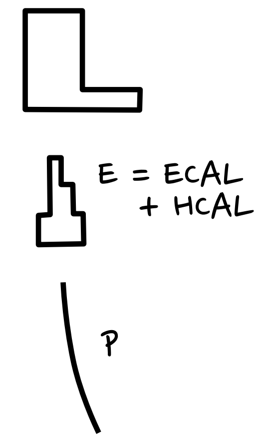

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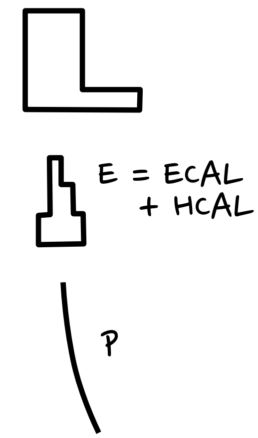

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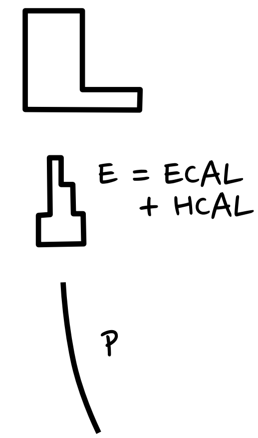

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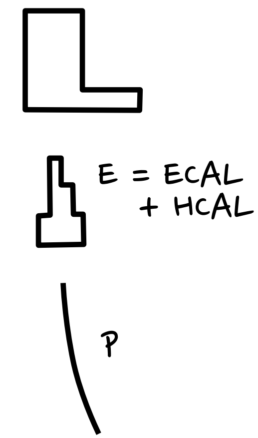

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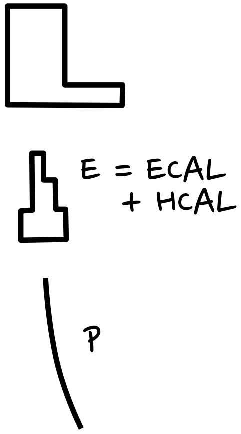

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- **Philosophy:**
  - use all detectors to improve particle ID/Reco

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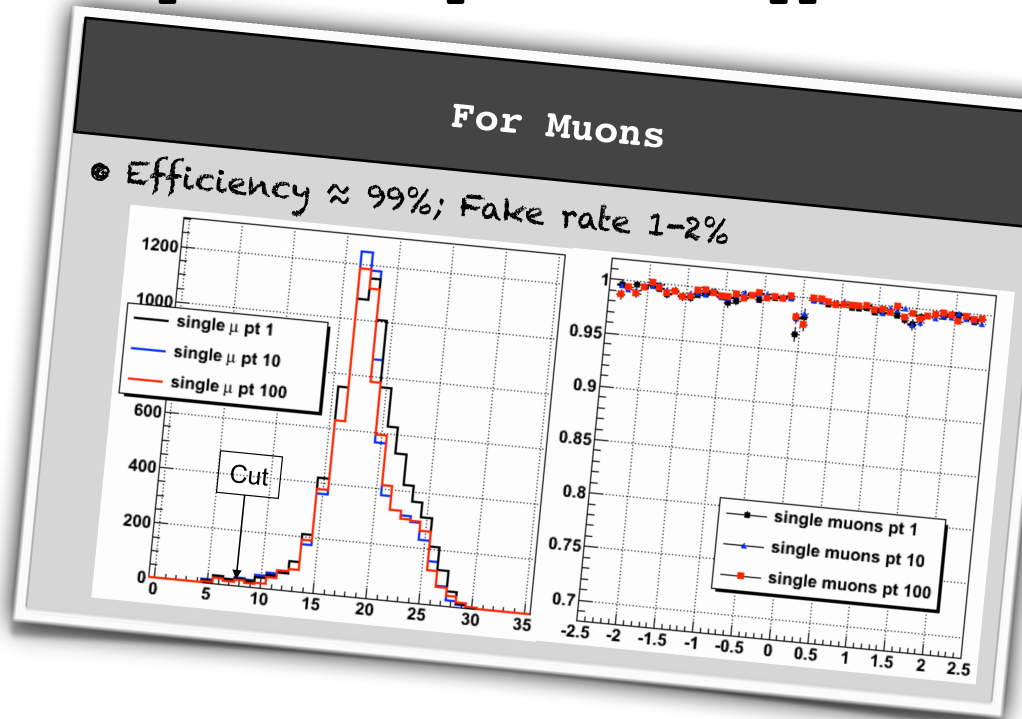

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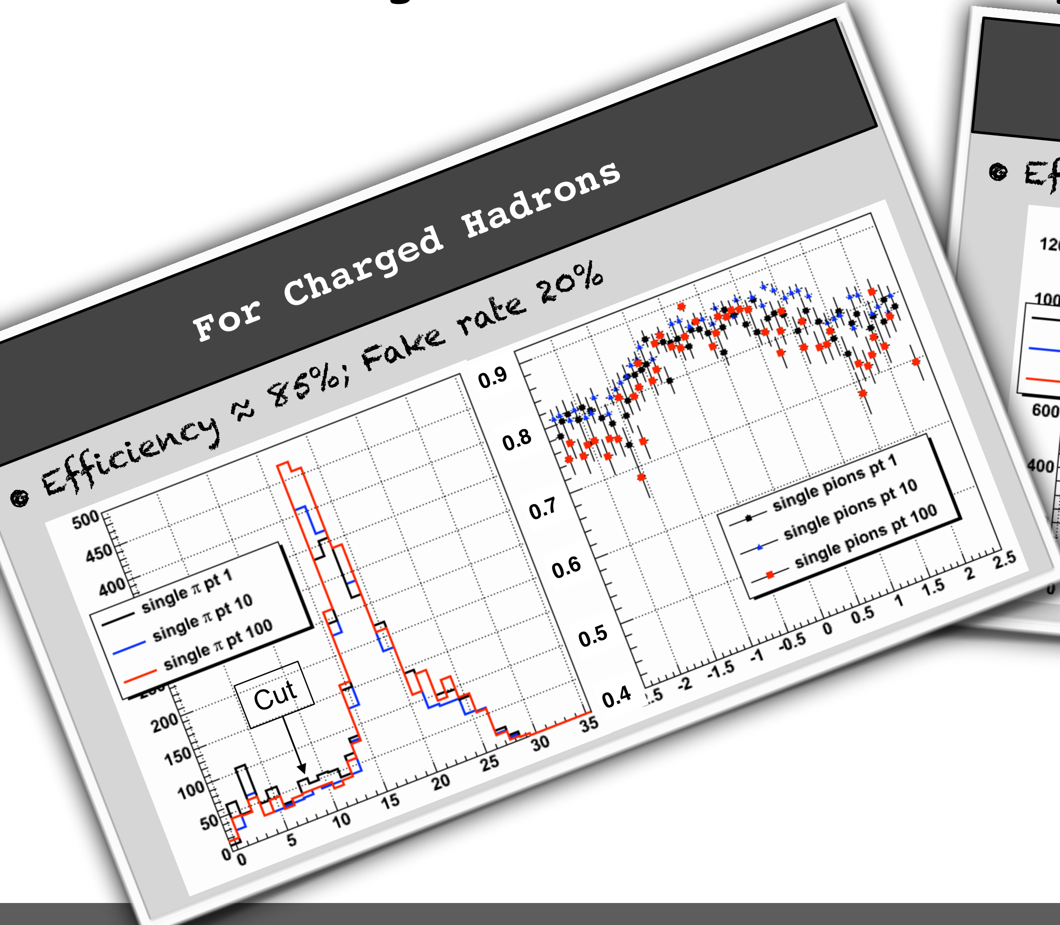

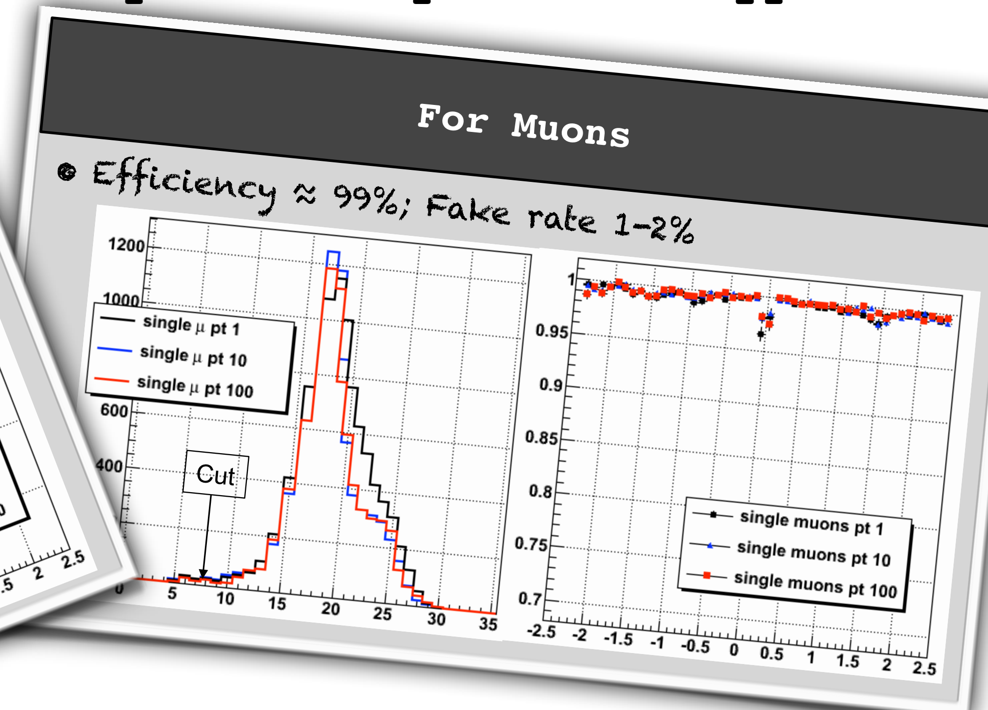

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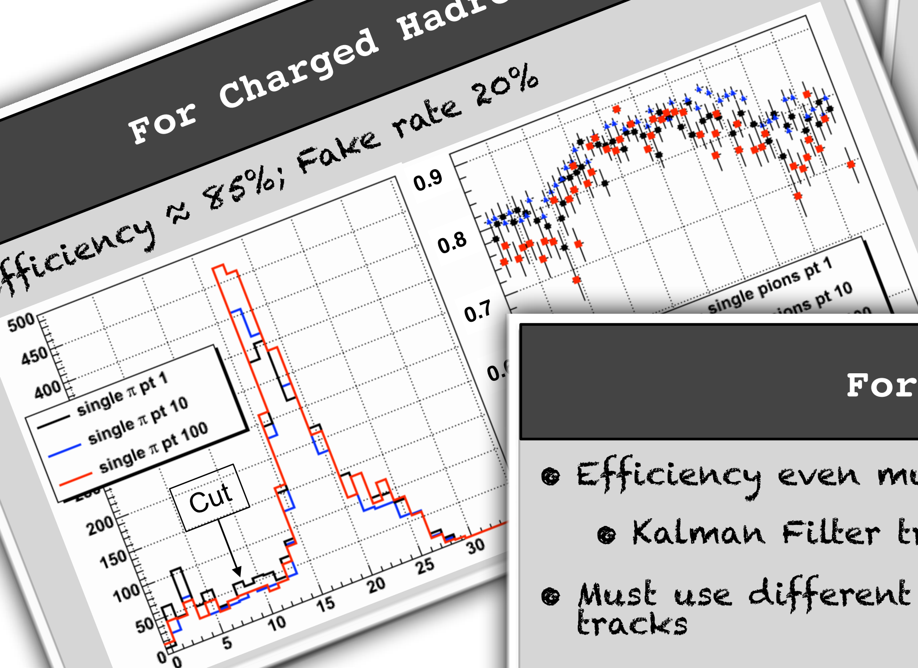
For Charged Hadrons

- Efficiency ≈ 85%; Fake rate 20%



For Muons

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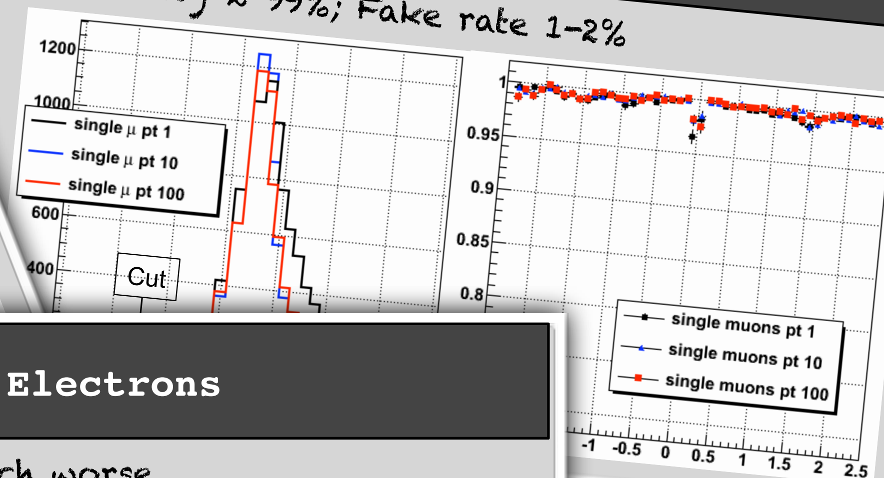

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- Must use different method to find electron tracks
  - Gaussian Sum Filter (more later)

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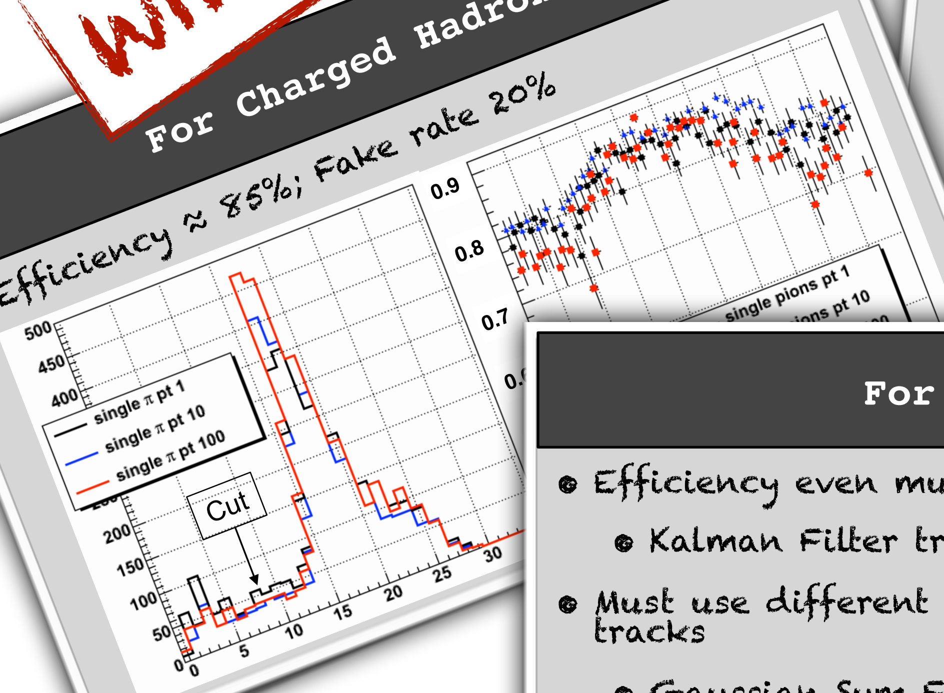

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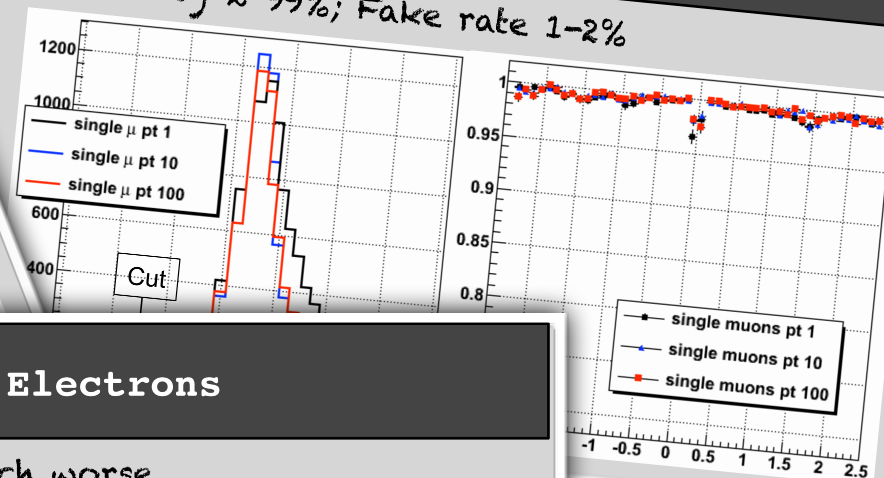

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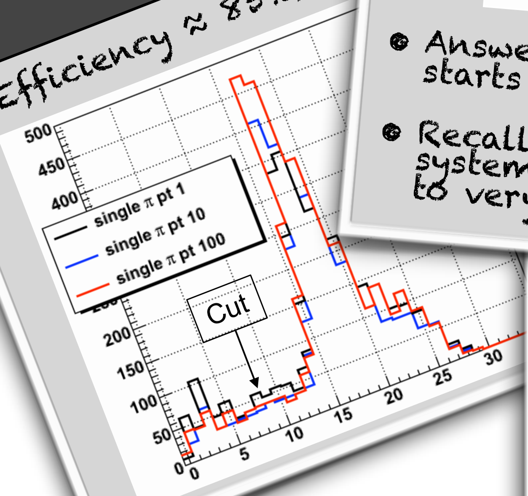
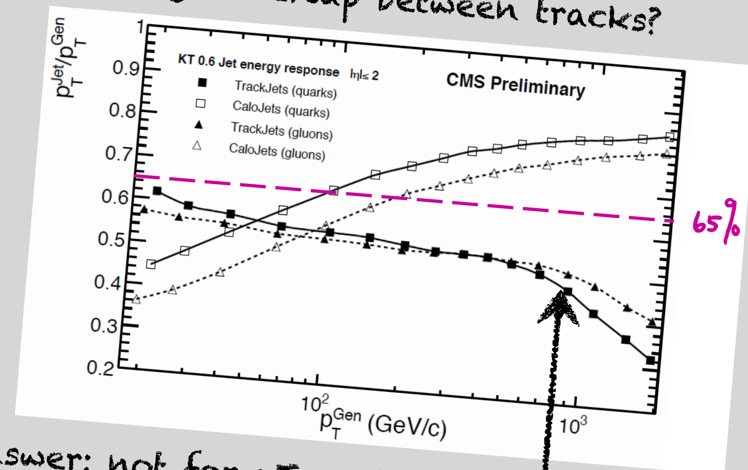
For Charge[...]

- Efficiency ≈ 85%; Fa[...]



Could it be due to high occupancy inside jets?

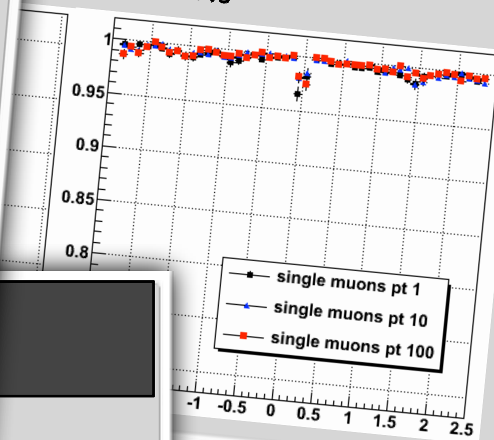
- Hence large overlap between tracks?



- Answer: not for pT up to 800 GeV, where it starts to appear
- Recall: 10+60 million channels in tracker system! The tracker has very low occupancy up to very large numbers of particles

Muons

- [...]e rate 1-2%



- Efficiency even much [...]
  - Kalman Filter tracking finding doesn't work!
- Must use different method to find electron tracks
  - Gaussian Sum Filter (more later)

Answer: Tracker Material!

- **LHC Trackers are primarily silicon based => heavy!**

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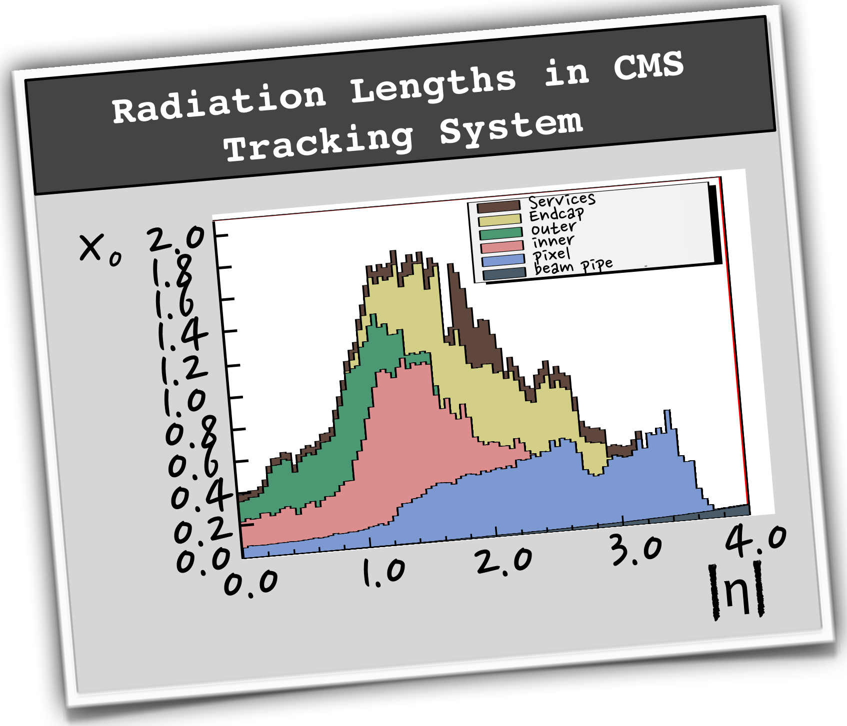

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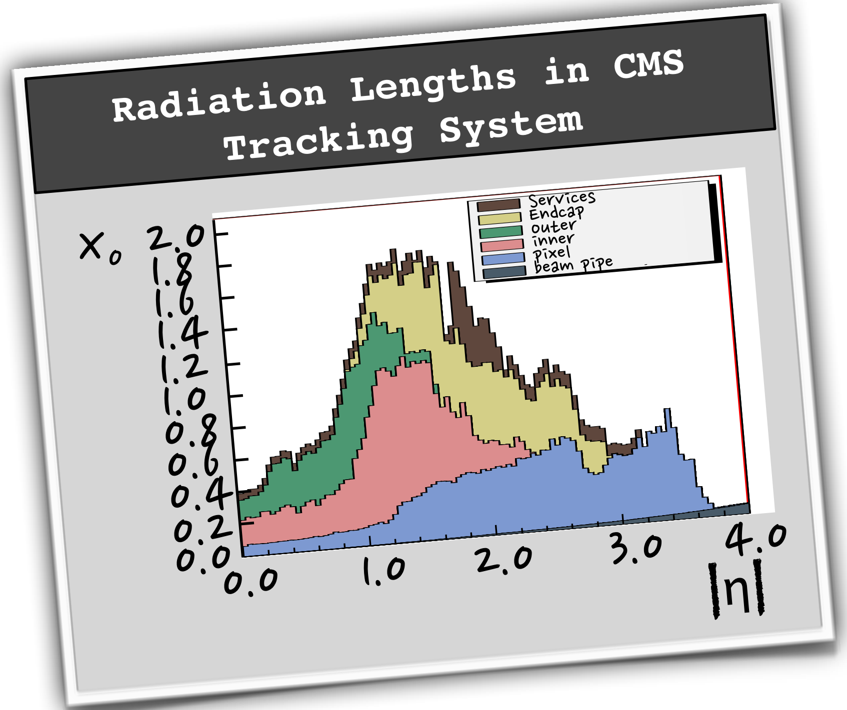

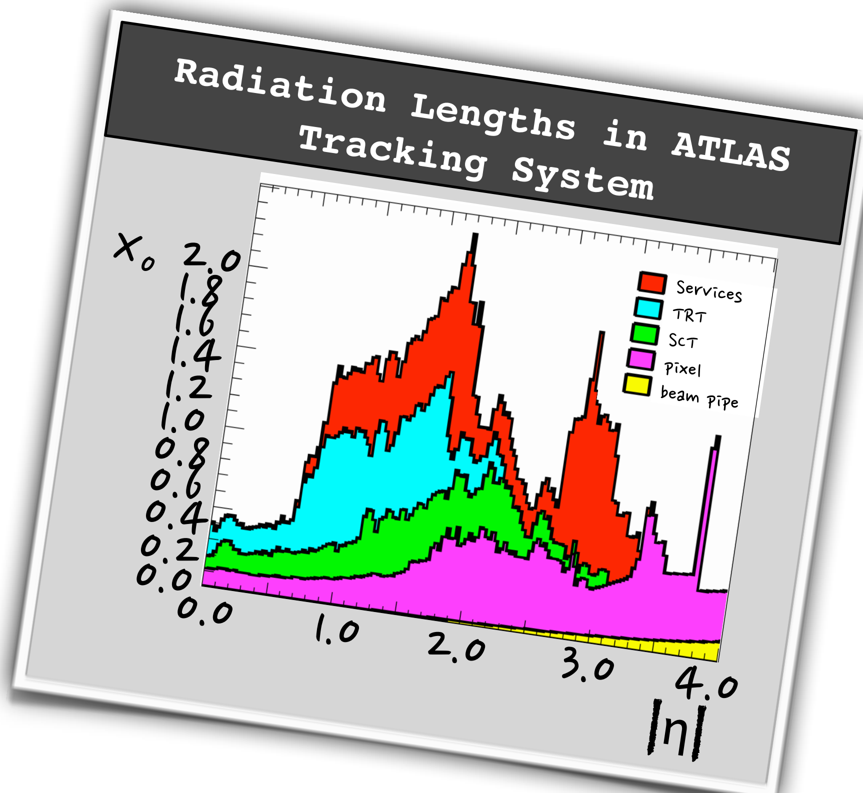

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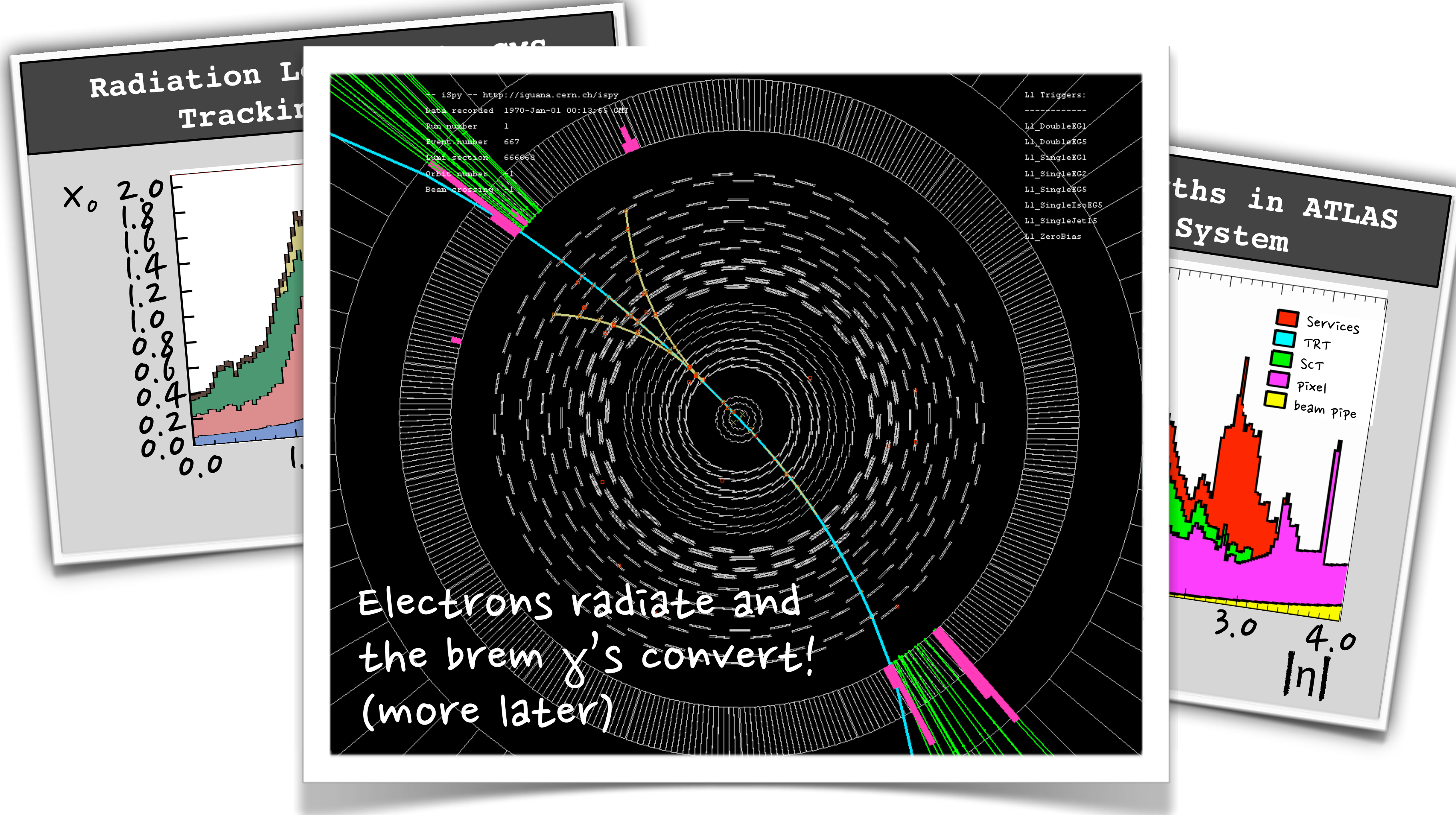

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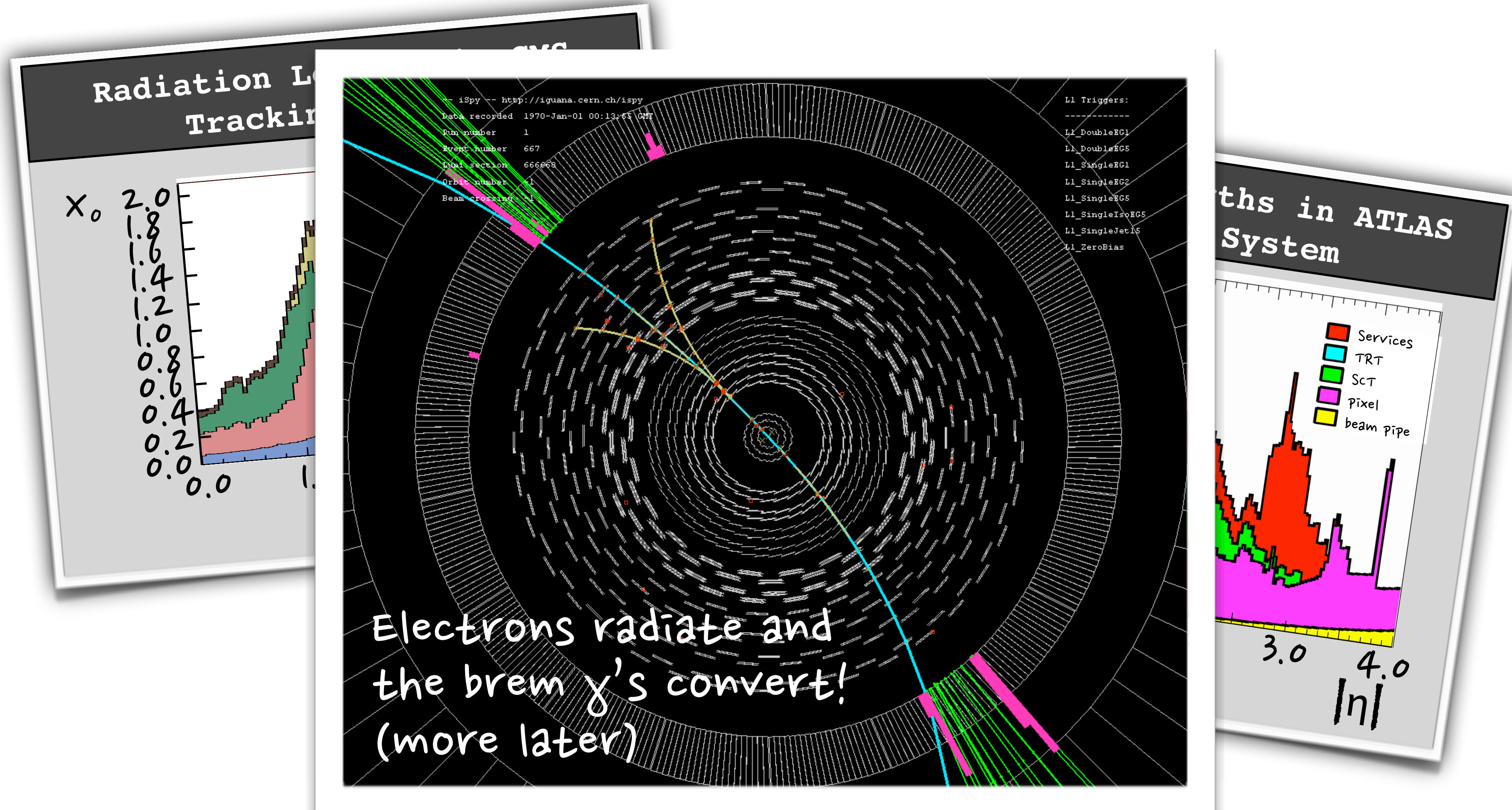

The LHC Trackers act like Electromagnetic pre-showers!

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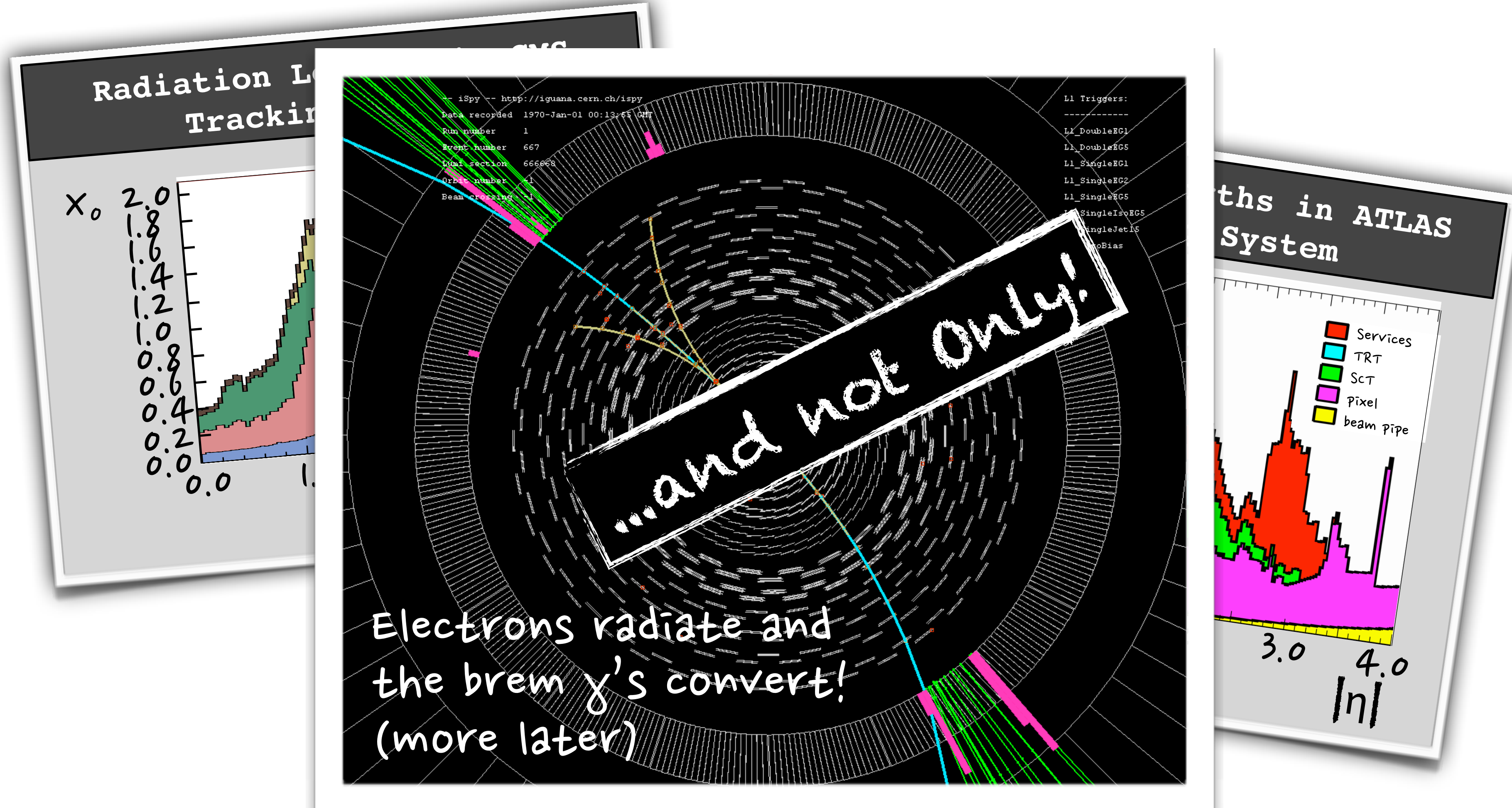

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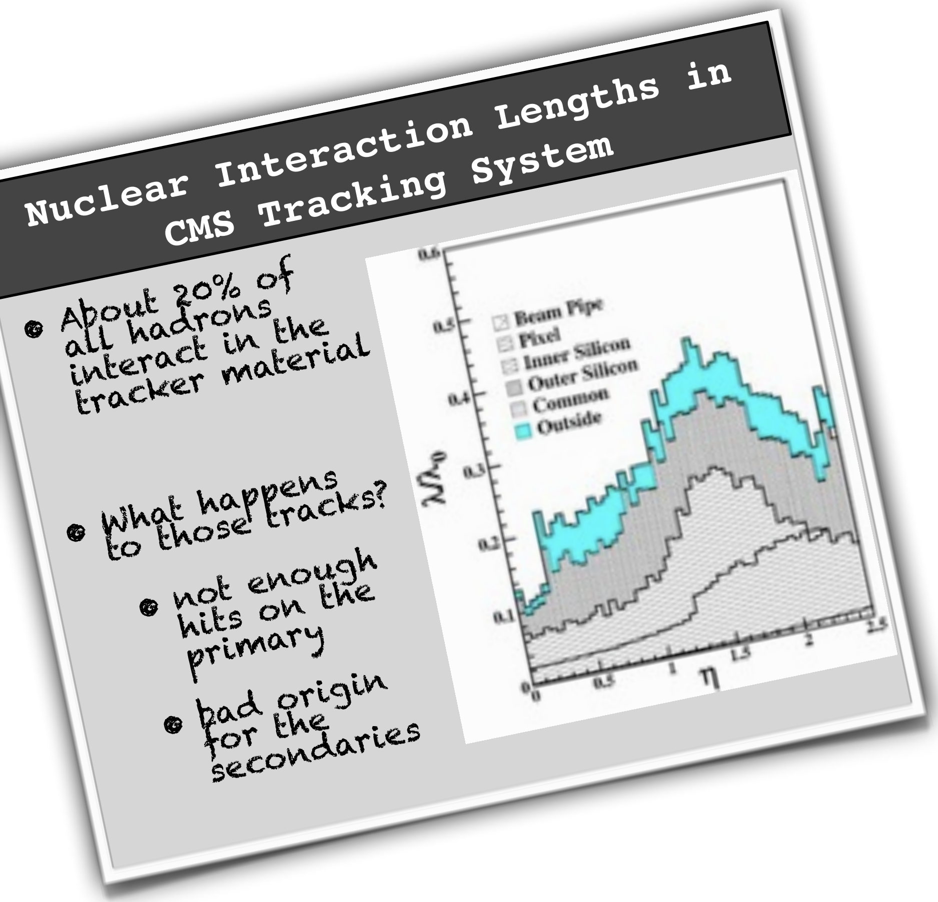

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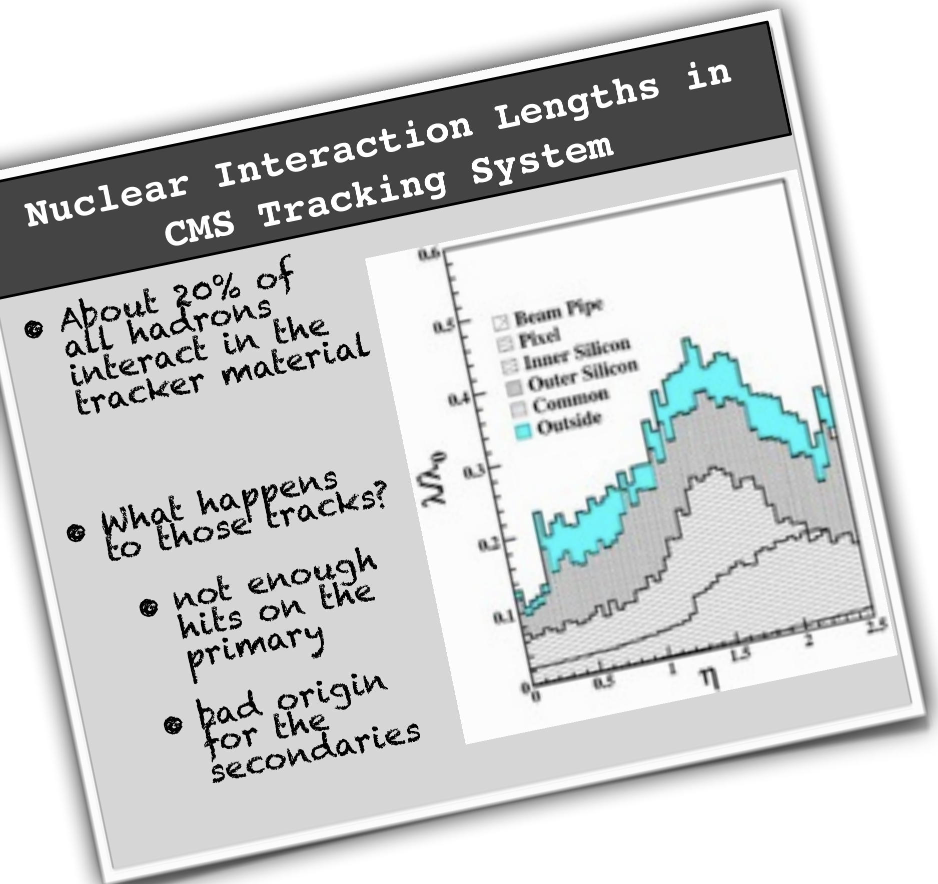

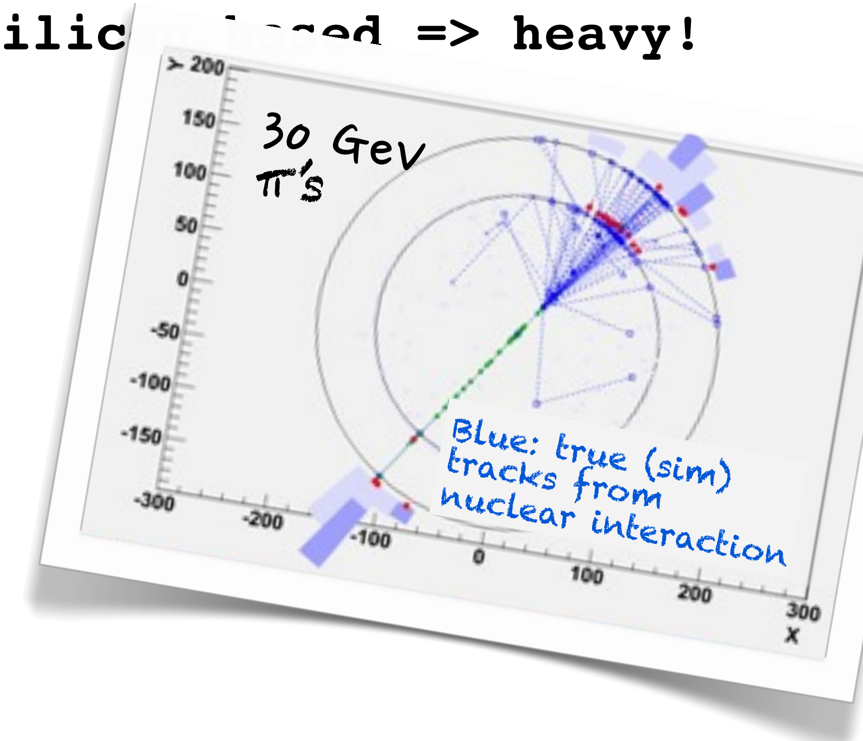

R. Cavanaugh, HCPSS 2012

Answer: Tracker Material!

Fermilab
UIC University of Illinois at Chicago

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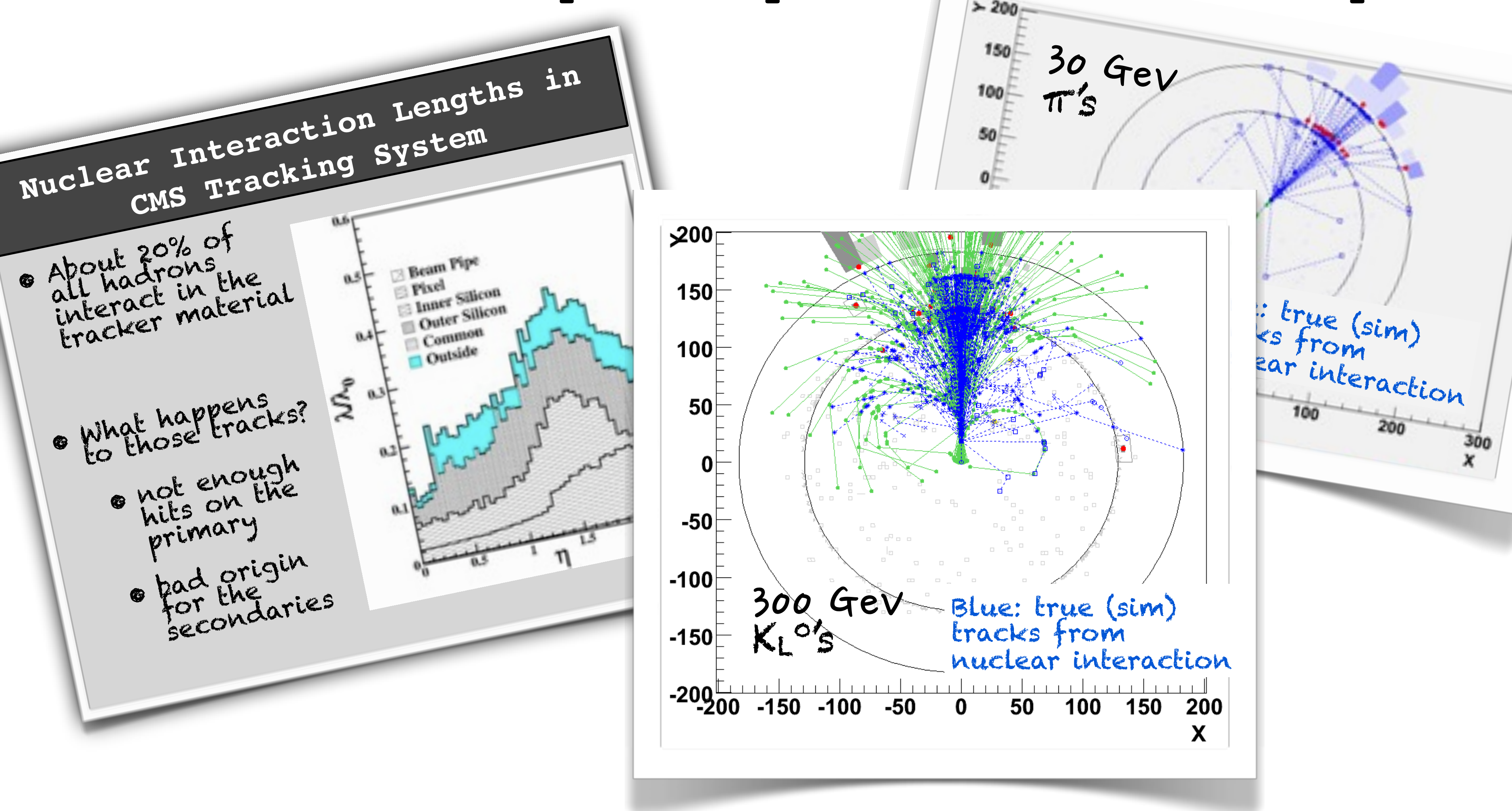

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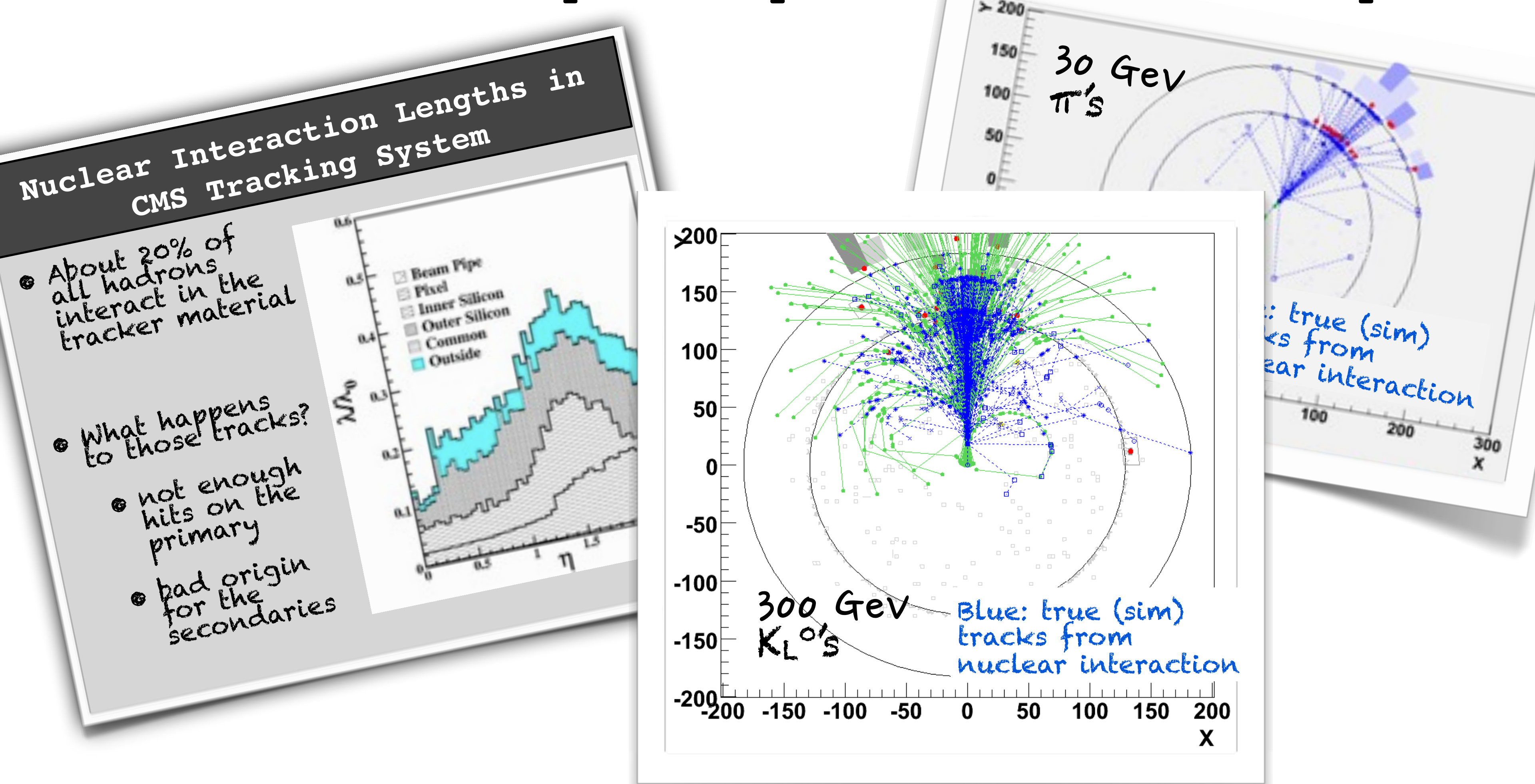

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Nuclear Interactions in Tracker

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  - So, reduce the number of hits fed to the track finder

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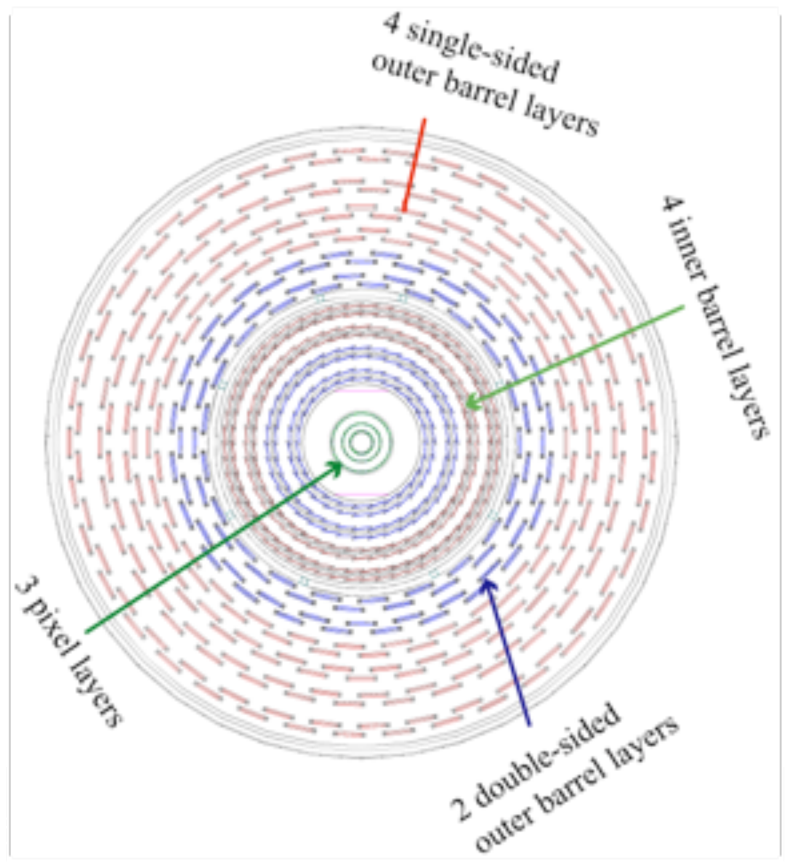
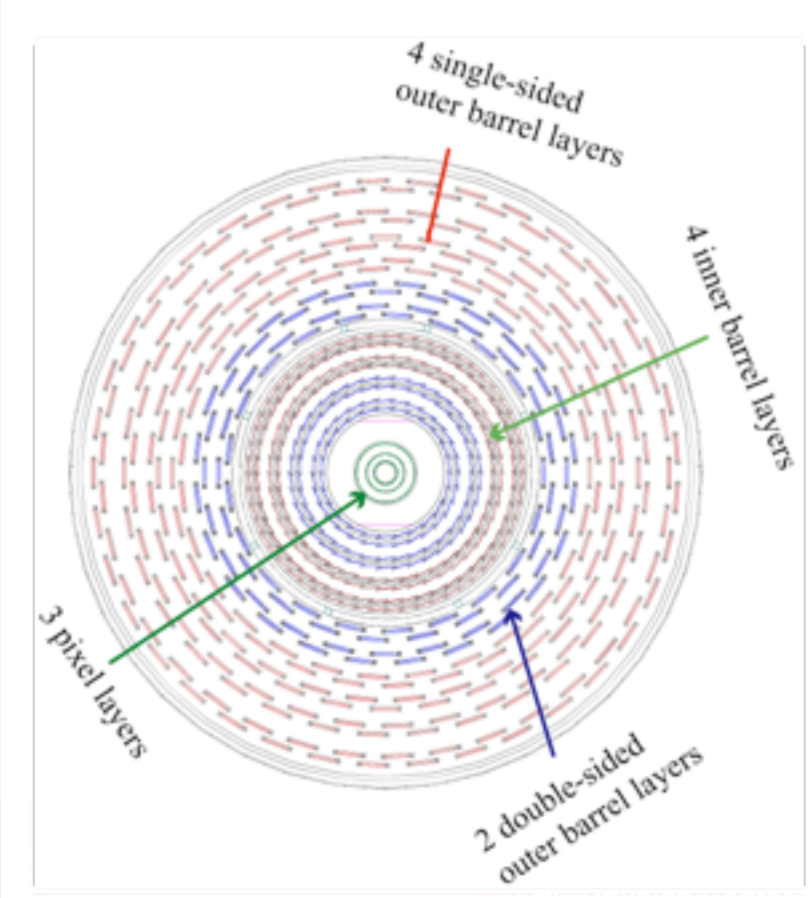


Nuclear Interactions in Tracker

- **Fake tracks come from wrong combinations of hit associations**
  - So, reduce … of hits fed to the track finder

Start from a very pure track seeding

- Example: 3 pixel hits, very tight origin constraint, pT > 0.9 GeV
  - 75% efficiency, less than 1% fakes
- Reconstruct corresponding tracks (≳ 3 hits) & "remove" the used hits
  - 40% of the hits are removed



Nuclear Interactions in Tracker

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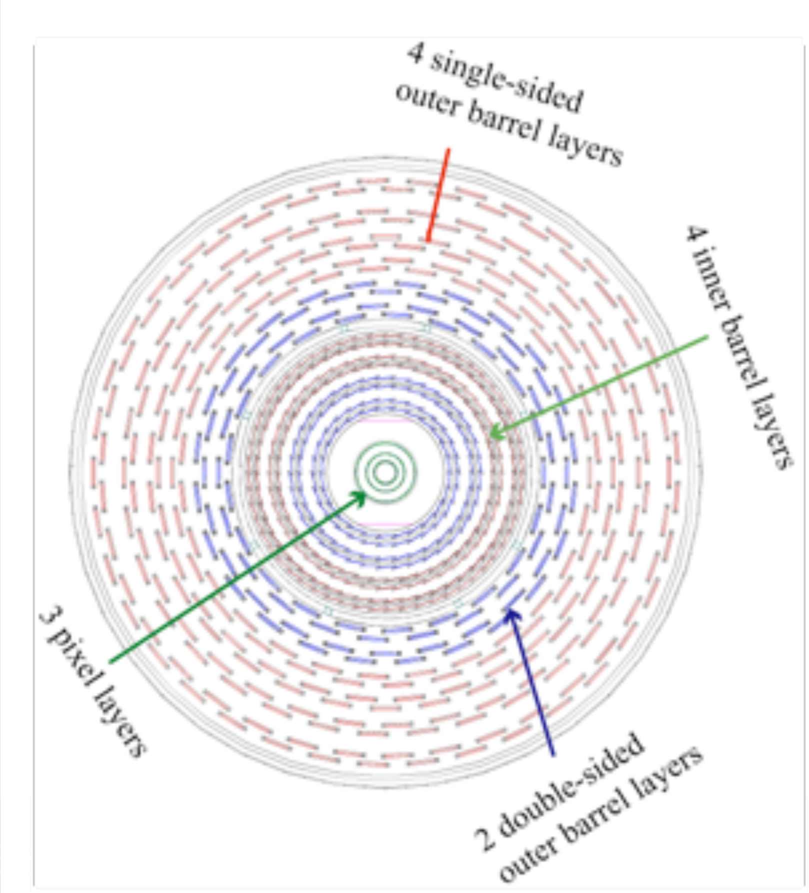
Start from a very pure track seeding

- … pixel hits, very tight origin … GeV

Next, try a looser seeding on 60% remaining hits

- Example: 2 pixel hits, very tight origin constraint, pT > 0.9 GeV
  - adds 15% efficiency, still less than 1% fakes
  - Combinatorial possibilities much less
- Reconstruct the corresponding tracks (≥ 3 hits) & remove the used hits
  - 10% of the hits are removed in this 2nd iteration



Nuclear Interactions in Tracker

Fermilab
UIC University of Illinois at Chicago

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Start from a very pure track seeding

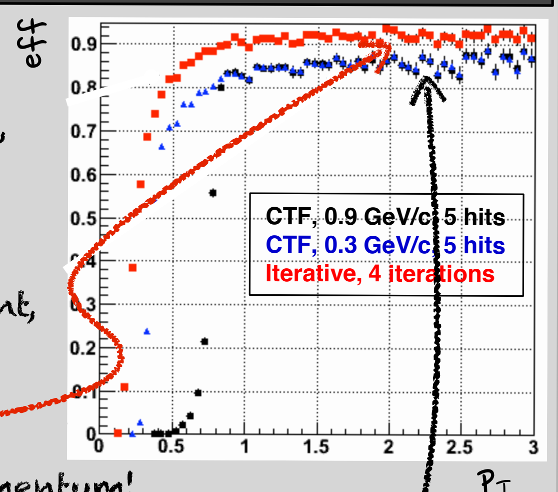
...pixel hits, very tight origin
...GeV

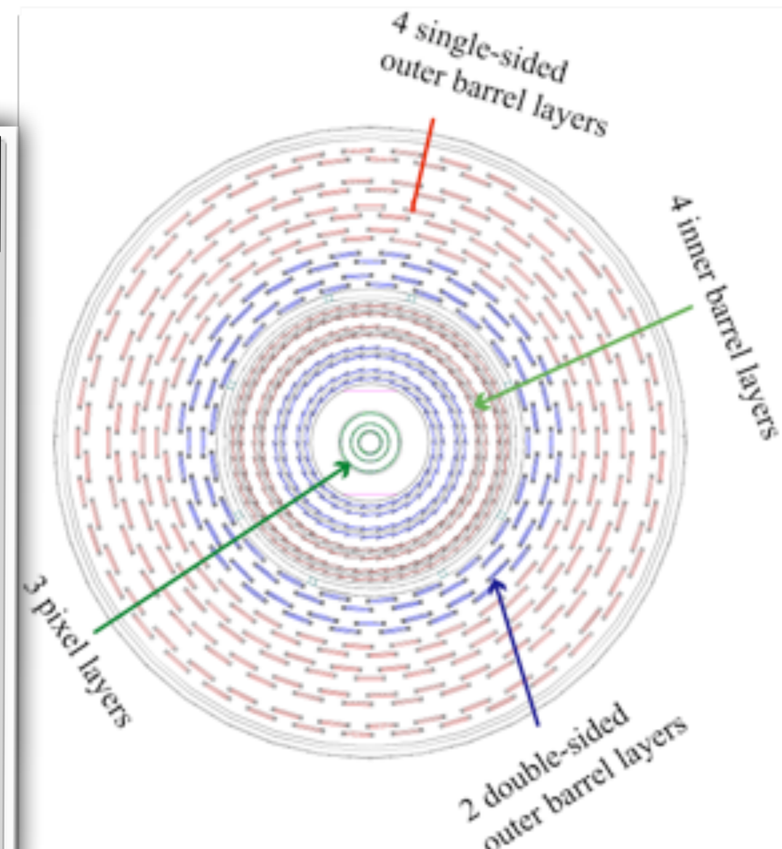
Next, try a looser seeding on 60% remaining hits

...very tight origin

And so on...with more iterations

- 3rd iteration:
  - 3 pixel hits, tight origin constraint, pT > 0.2 GeV
- 4th iteration:
  - 2 pixel hits, looser origin constraint, pT > 0.3 GeV
  - 93% efficiency, 1-2% fake rate
  - down to very low momentum!
- Recall original situation
  - 85% efficiency, 20% fake rate





Nuclear Interactions i

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pixel hits, very tight origin
GeV

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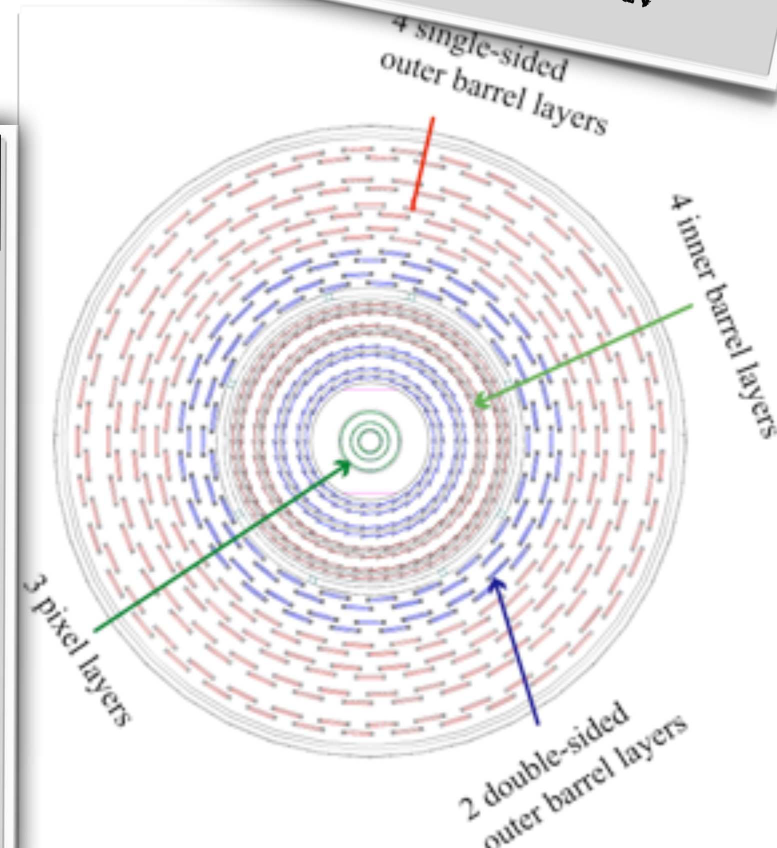
hits, very tight origin

And even try to catch secondary tracks

- Interactions, conversions, decays,...
- 5th iteration:
  - Inner tracker seeding, loose origin constraint, pT > 0.5 GeV
- 6th iteration:
  - Outer tracking seeding, very loose origin constraint, pT > 0.8 GeV



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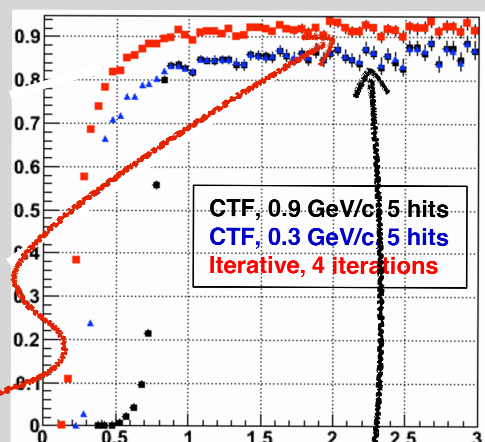

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That's a lot of work!

What's the reward?

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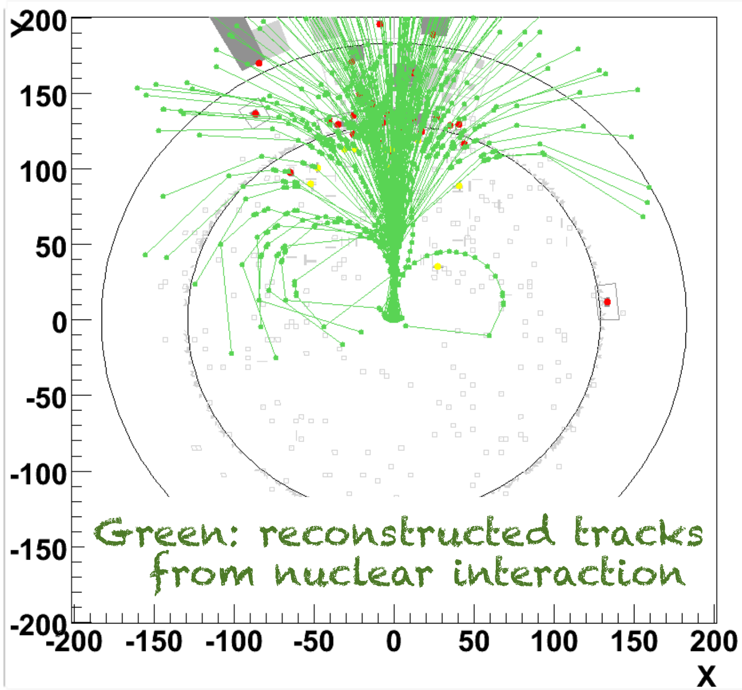

Green: reconstructed tracks from nuclear interaction

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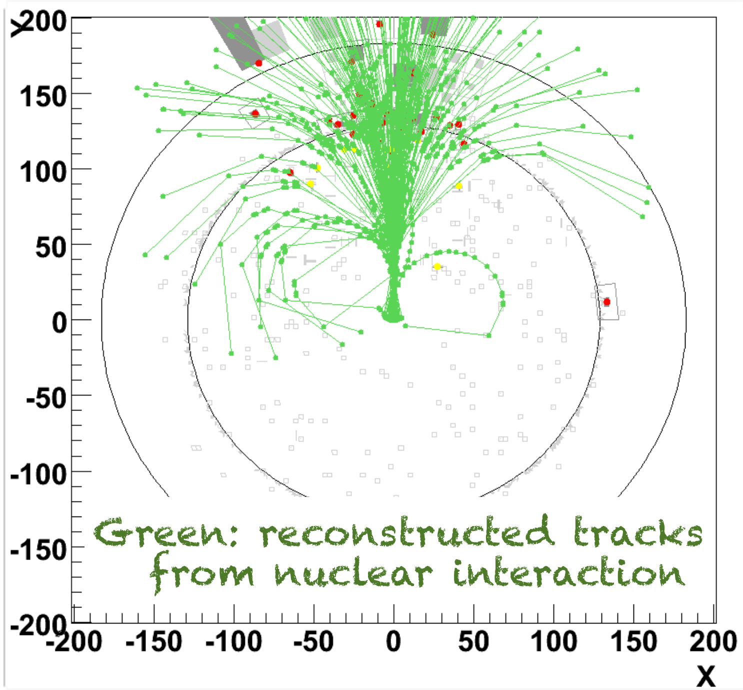

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Many real tracks reconstructed with inner vs outer seeding

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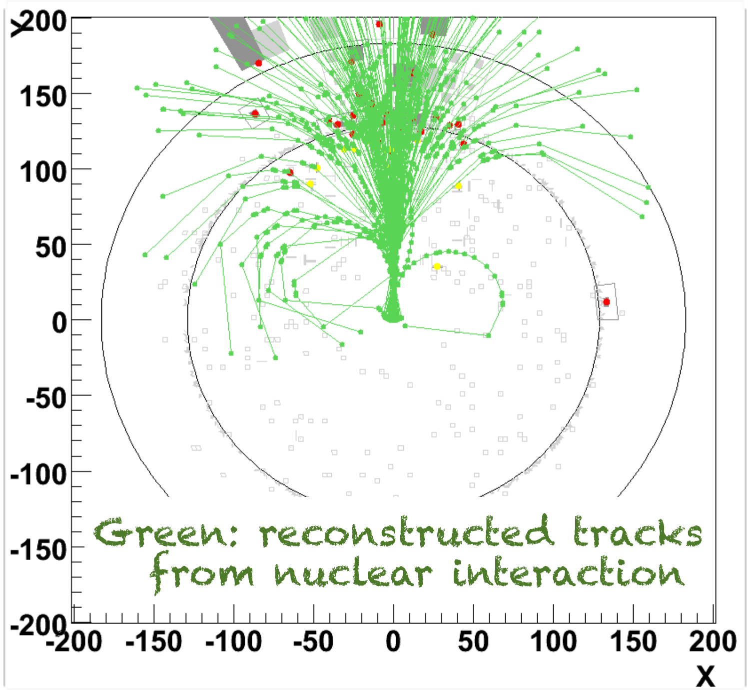

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Next problem: avoid double counting primary vs secondaries

- Create a "link by vertex" between primaries and secondaries
  - choose the best energy determination
  - primary track usually has more hits (5-6)
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Ma...

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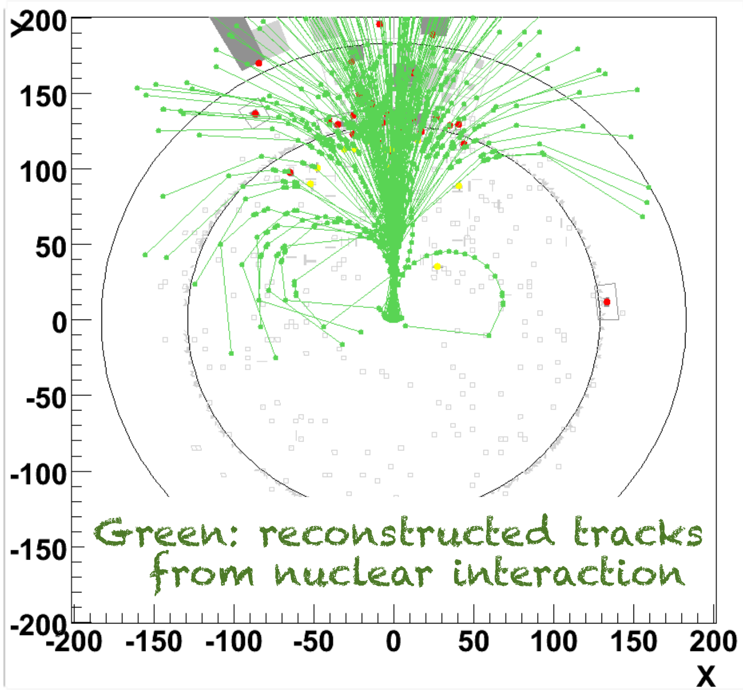

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Philosophy: reconstruct & identify as many particles as possible!

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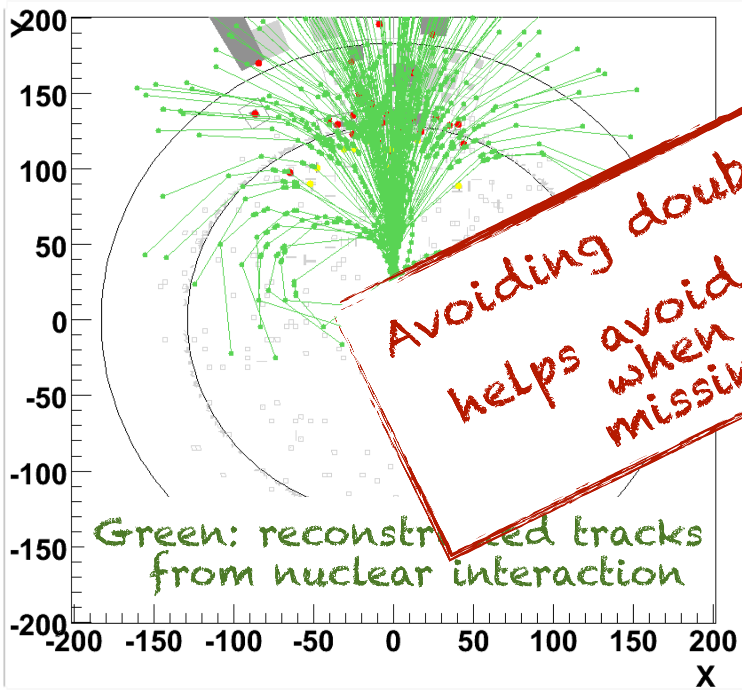

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Avoiding double counting energy
=>
helps avoid non-gaussian tails
when reconstructing
missing energy (later)

M...

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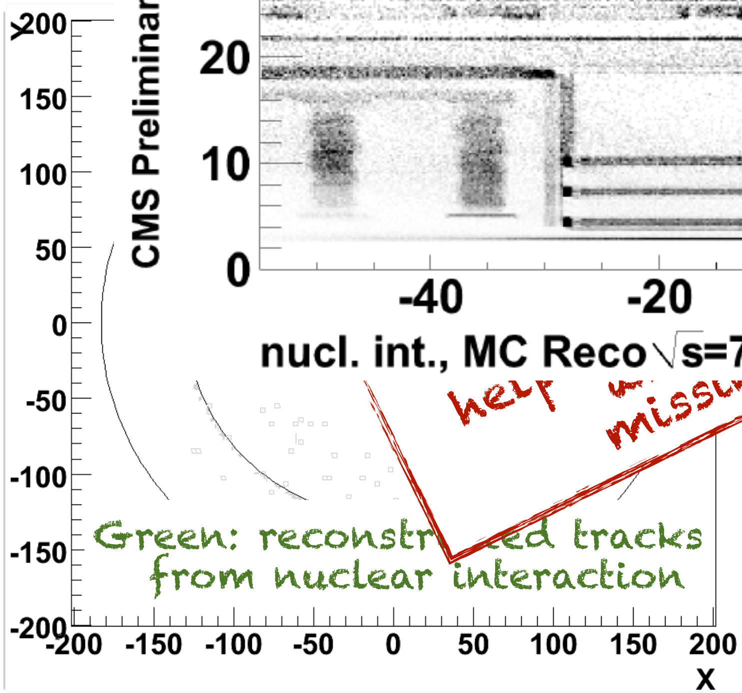
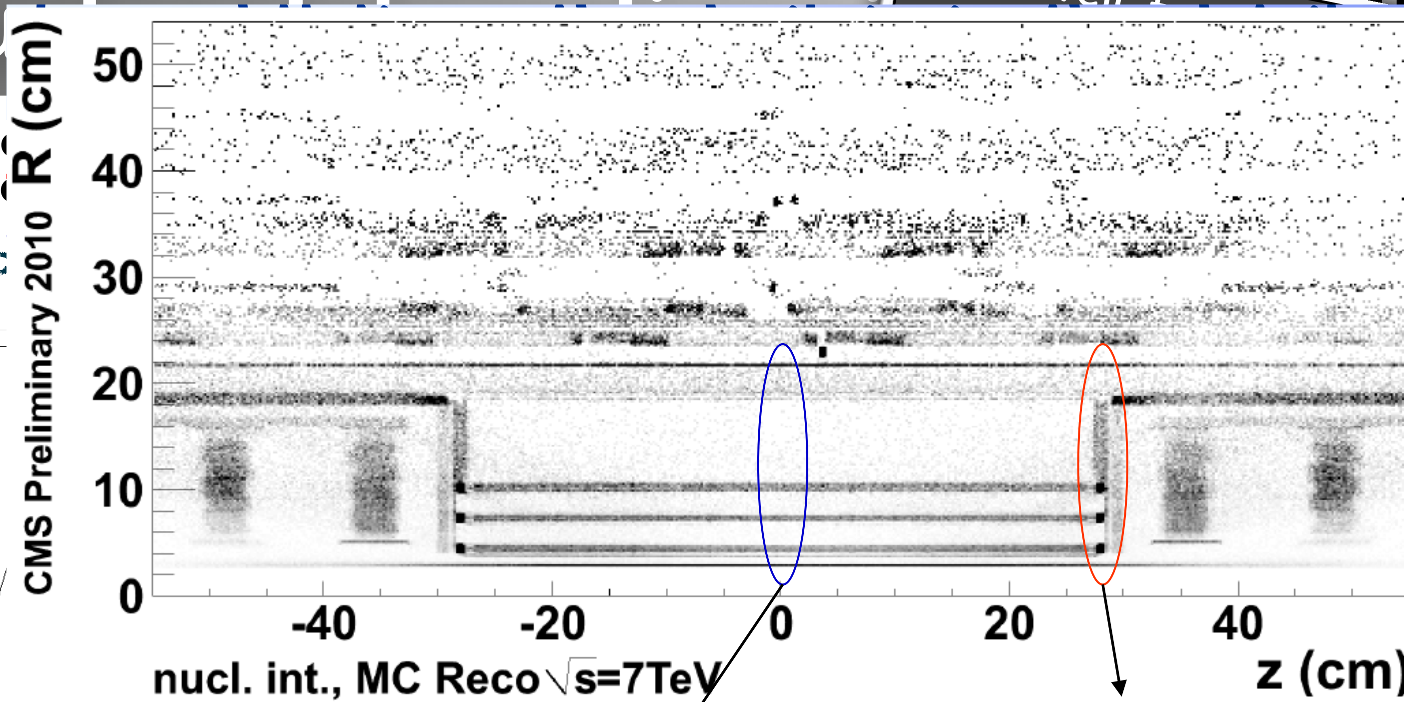
Nu

- **Fak ass**
  - Sc





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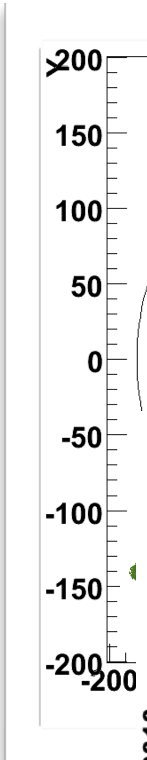

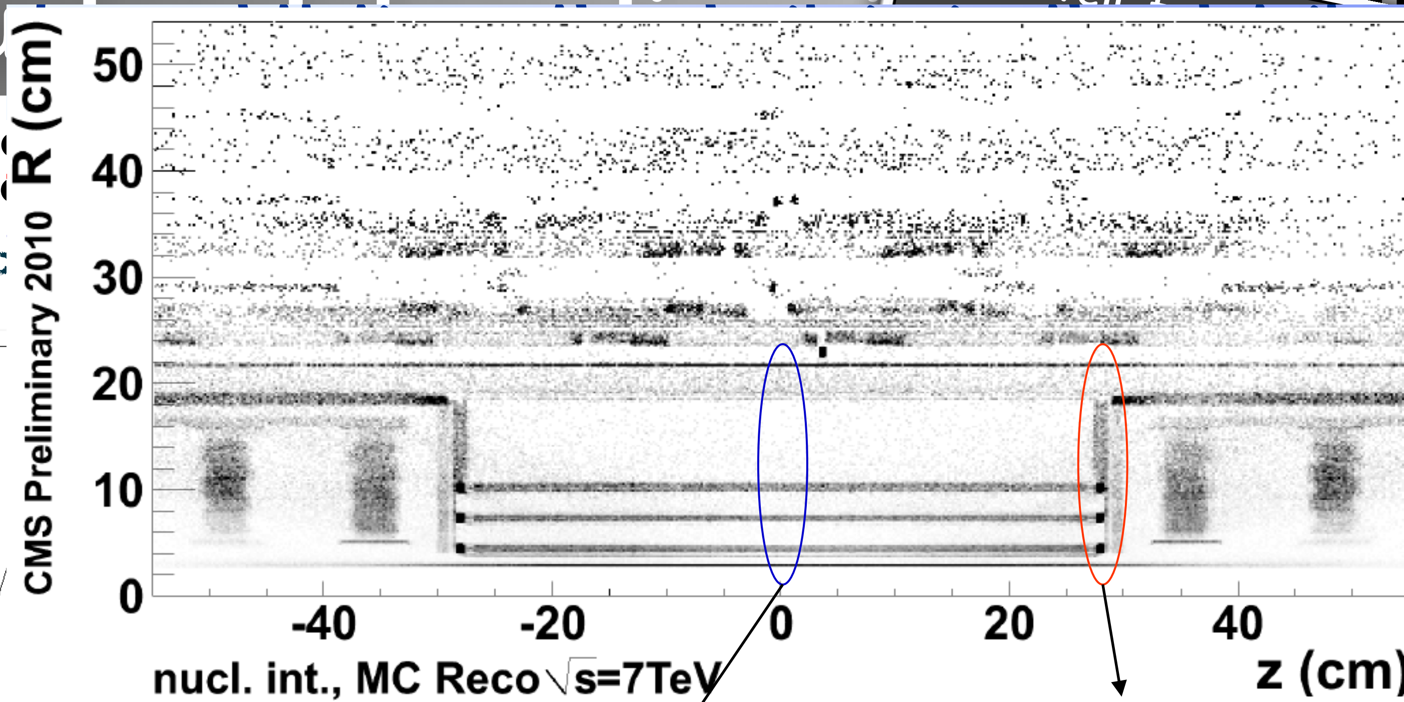

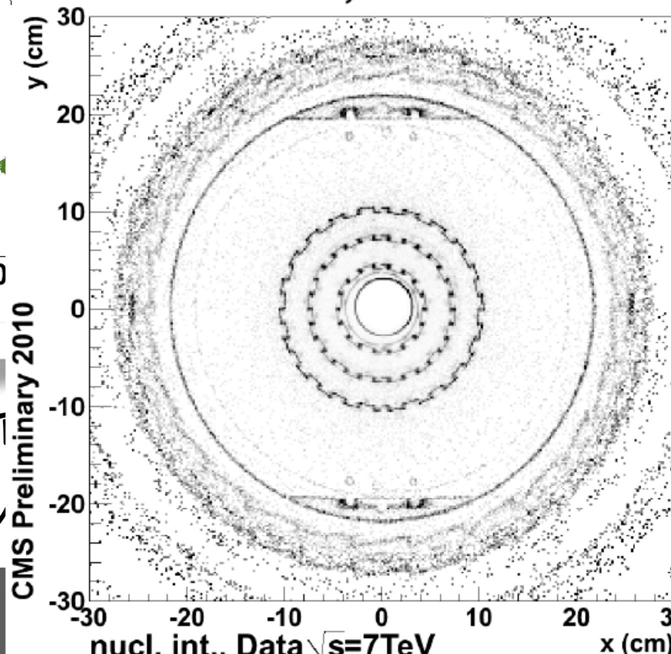

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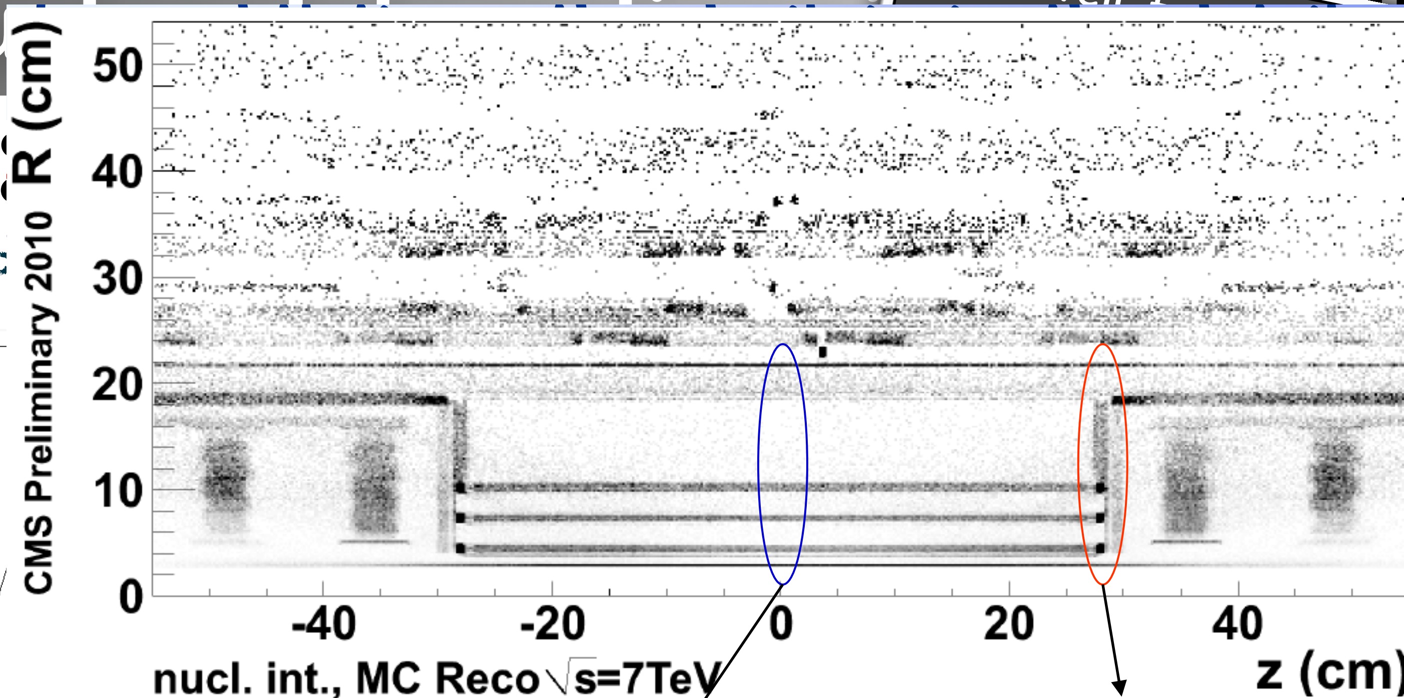

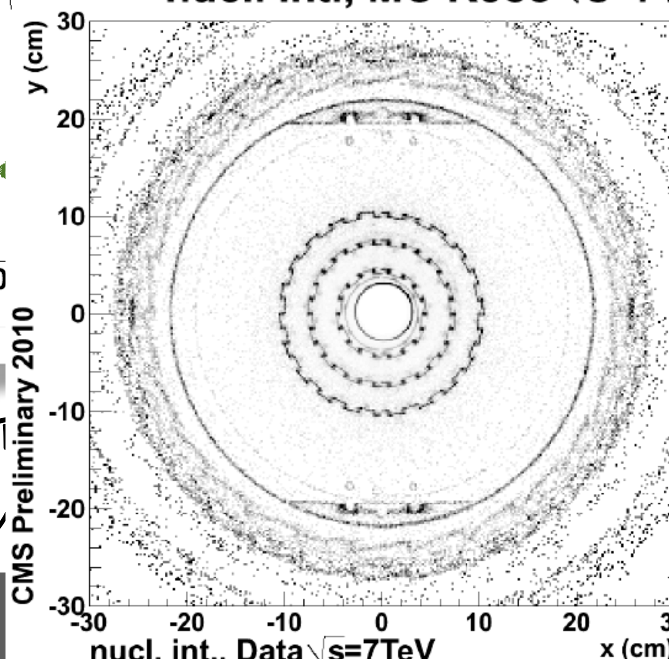

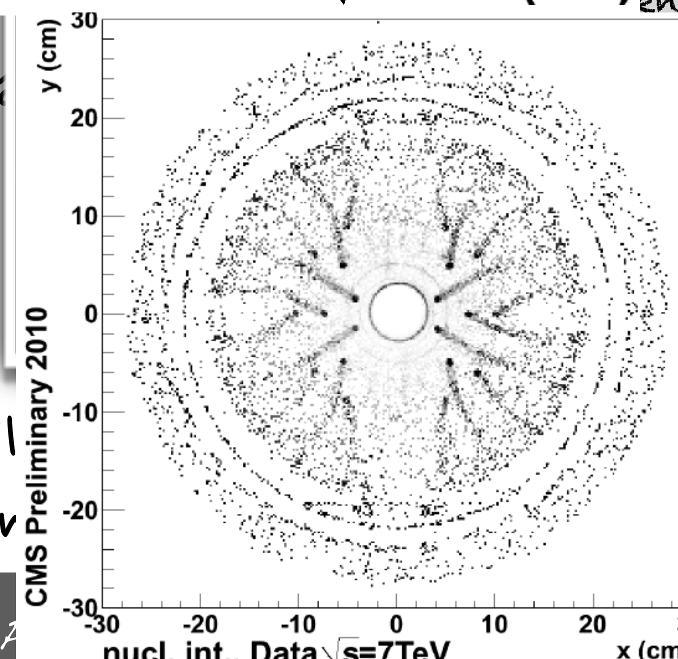

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ID Individual Hadrons

ID Individual Hadrons

Particle	m [MeV]	Quarks	Main decay	Lifetime	$c\tau$ [cm]
$\pi^\pm$	140	$u\bar{d}$	$\mu\nu_\mu$	2.6×10^{-8} s	780
$K^\pm$	494	$u\bar{s}$	$\mu\nu_\mu$, $\pi^\pm\pi^0$	1.2×10^{-8} s	370
K_S^0	498	$d\bar{s}$	$\pi\pi$	0.9×10^{-10} s	2.7
K_L^0	498	$d\bar{s}$	$\pi\pi\pi$, $\pi l\nu$	5×10^{-8} s	1550
p	938	uud	stable	$> 10^{25}$ years	∞
n	940	udd	$pe\nu_e$	890 s	2.7×10^{13}
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Why?

- Instead of making do with jet reconstruction
  - some physics requires the ID of individual hadrons
- Most are unstable, and decay into a few long-lived particles

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- Since the interactions of charged hadrons are similar, the most direct way to distinguish them is to determine their (rest) mass
- Their momentum is measured by the tracking system, so this is equivalent to determining their velocity, since $p = \gamma m v$, so $m = p/\gamma v = p/\gamma\beta c$

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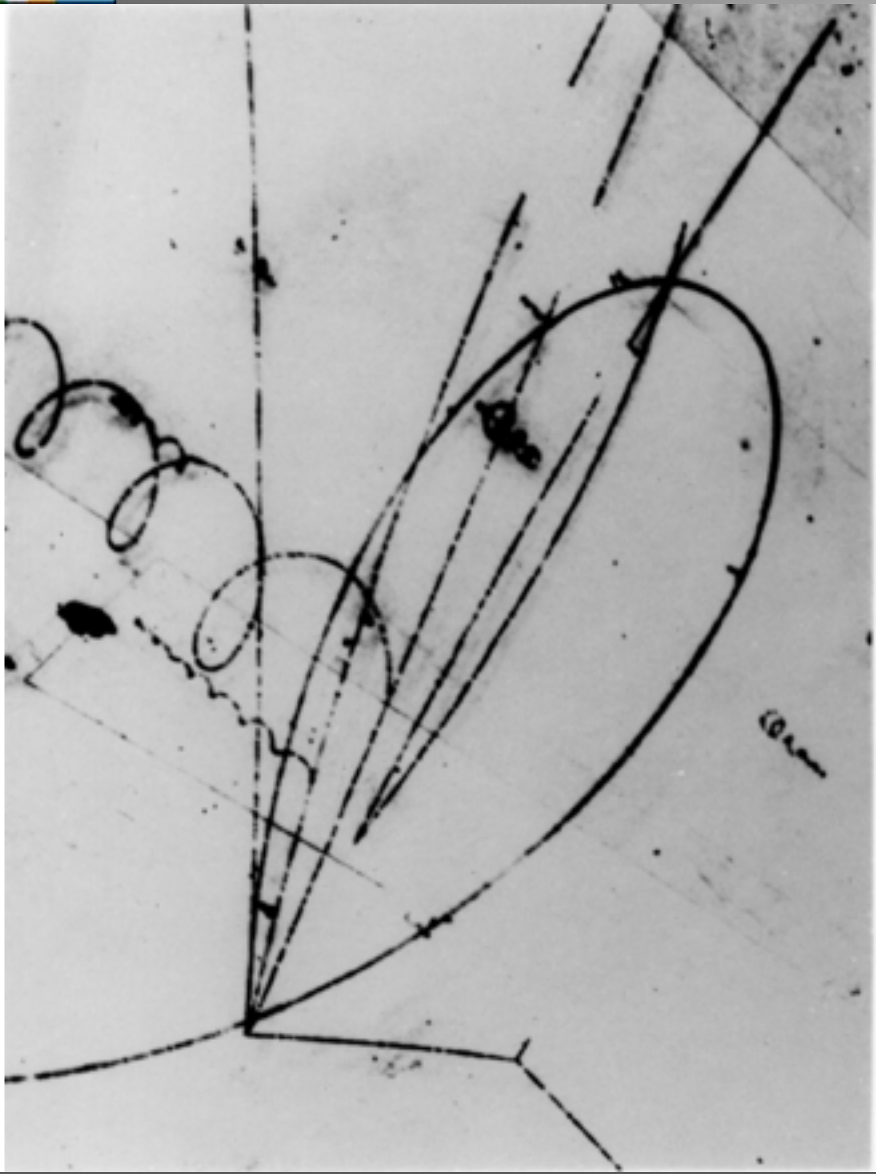
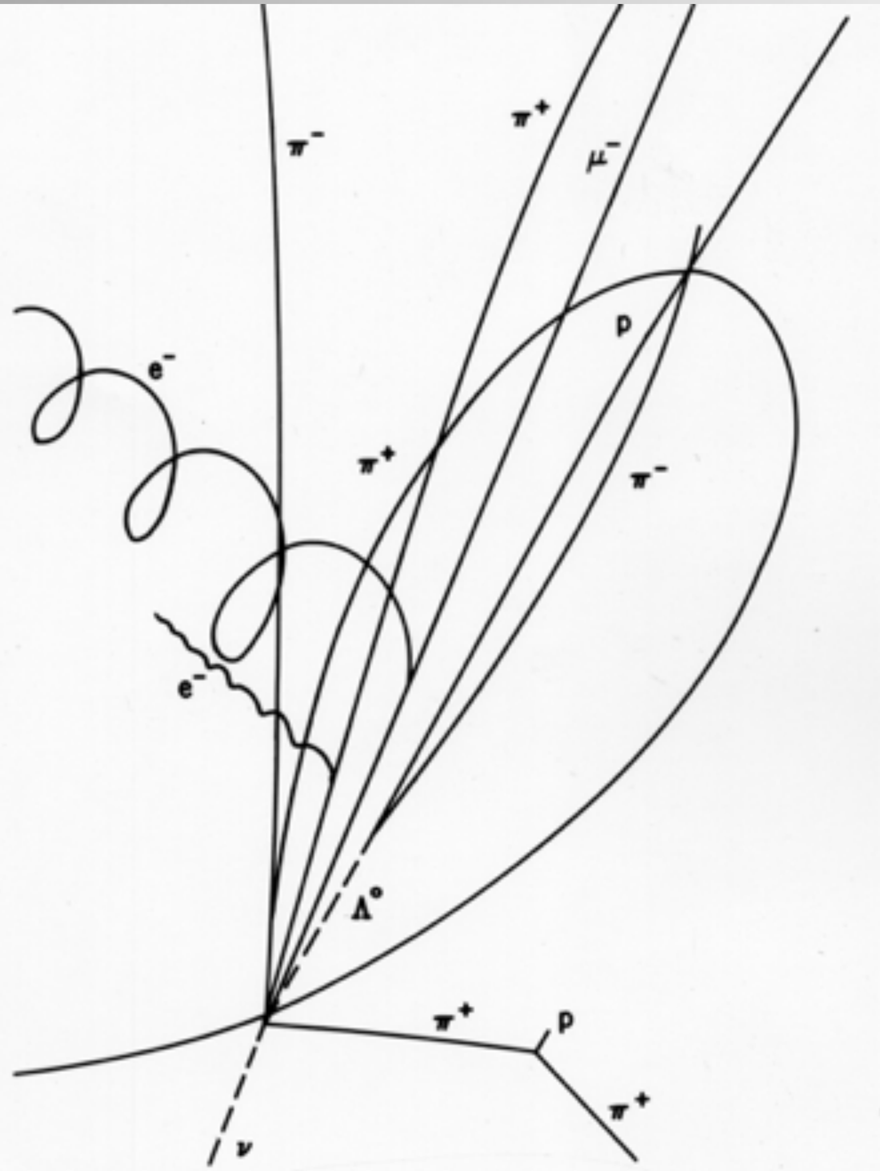
Four main processes

- Most direct is to measure the *Time Of Flight (TOF)* of the particles over a fixed distance
- Alternatively one can look at the detail of their interaction with matter The main source of energy loss is via *Ionization (dE/dx)*
- If the velocity of the particle changes compared to the local speed of light it will radiate photons, detected as *Transition radiation*
- If a particle travels at greater than the local speed of light, it will radiate *Cherenkov radiation*

Neutral Hadron ID





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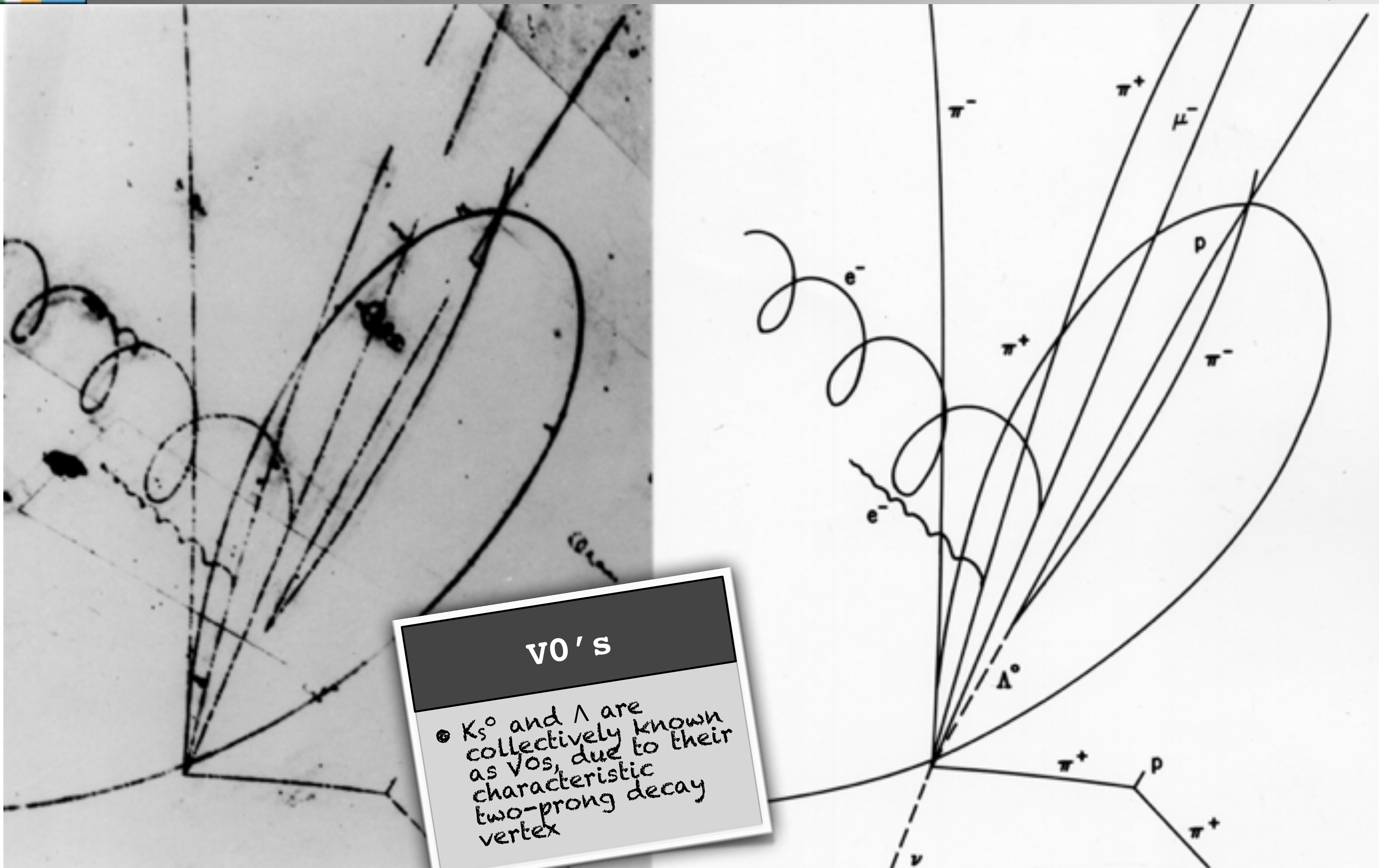
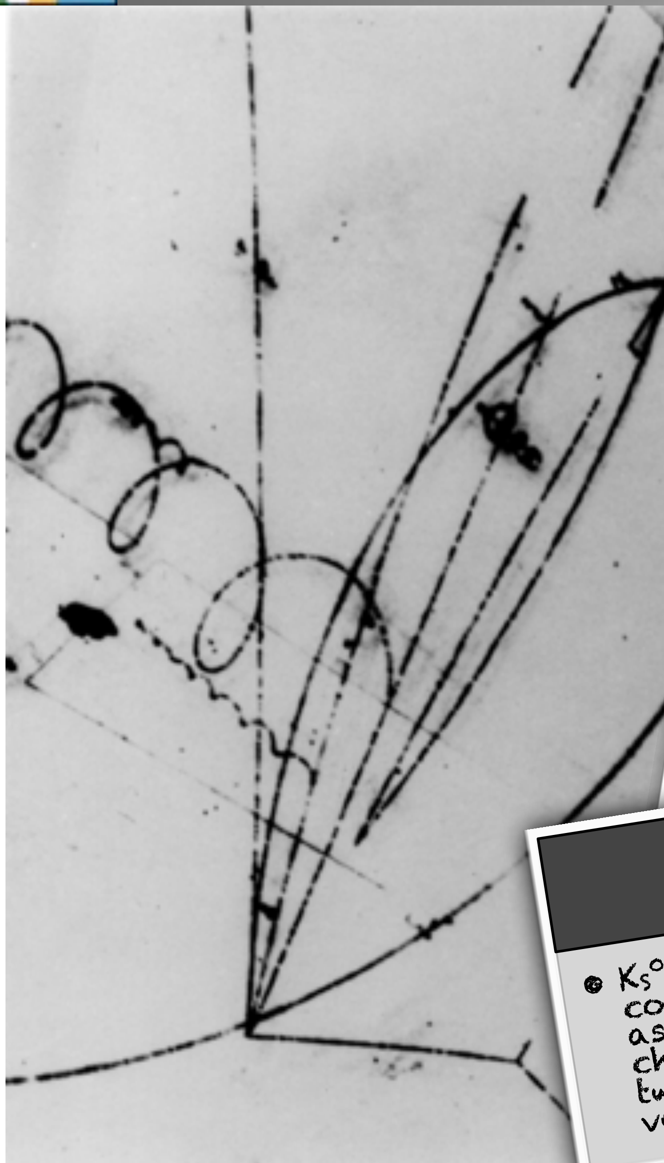
Neutral Hadron ID

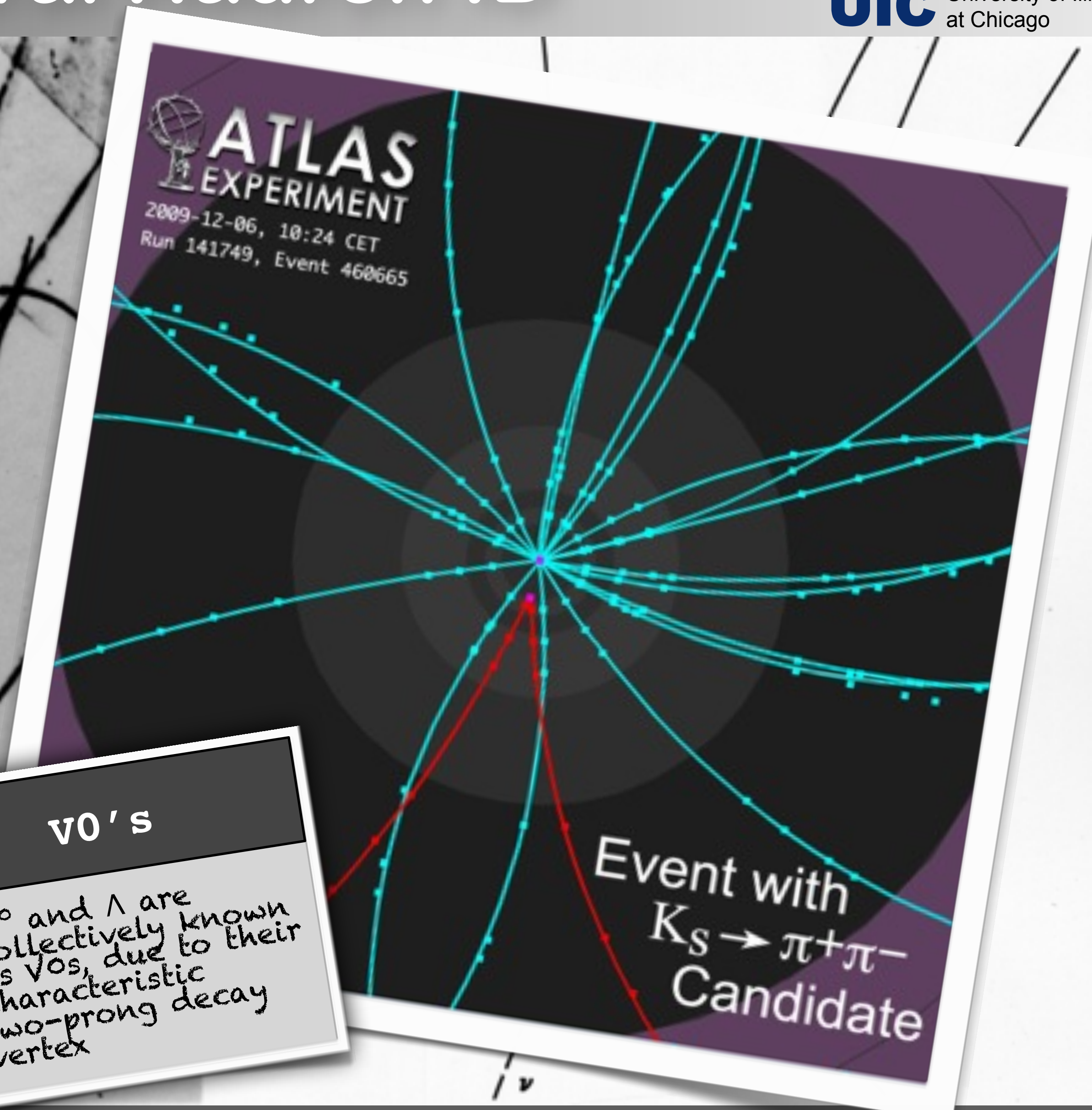


V0's

- K_S^0 and Λ are collectively known as V0s, due to their characteristic two-prong decay vertex

Neutral Hadron ID





V0's

- K_S^0 and Λ are collectively known as V0s, due to their characteristic two-prong decay vertex

Extreme Hadron ID!

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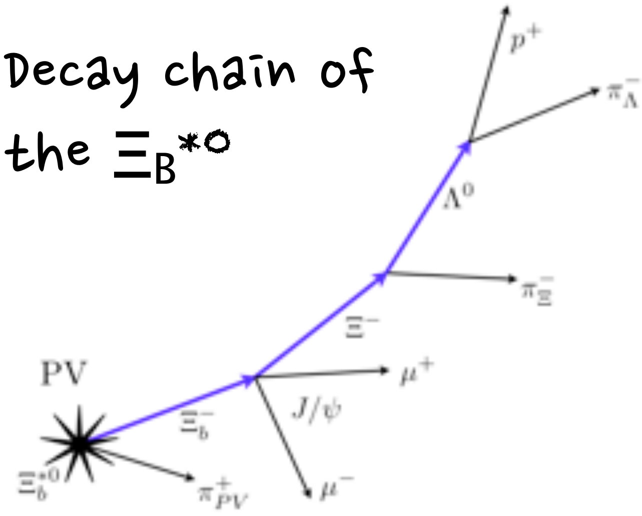
Decay chain of the Ξ_B^{*0}



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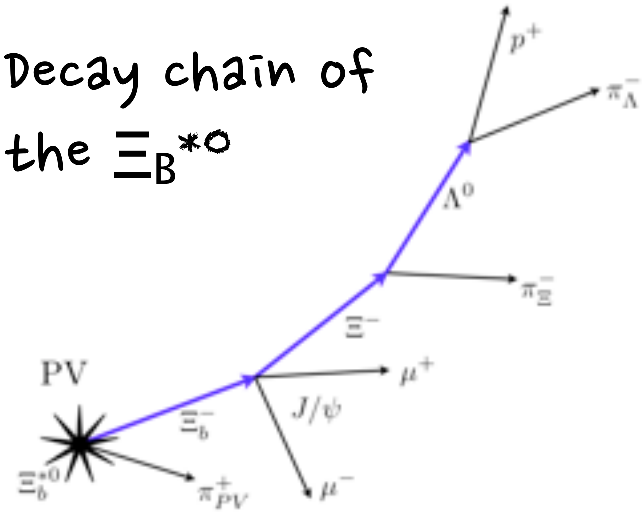

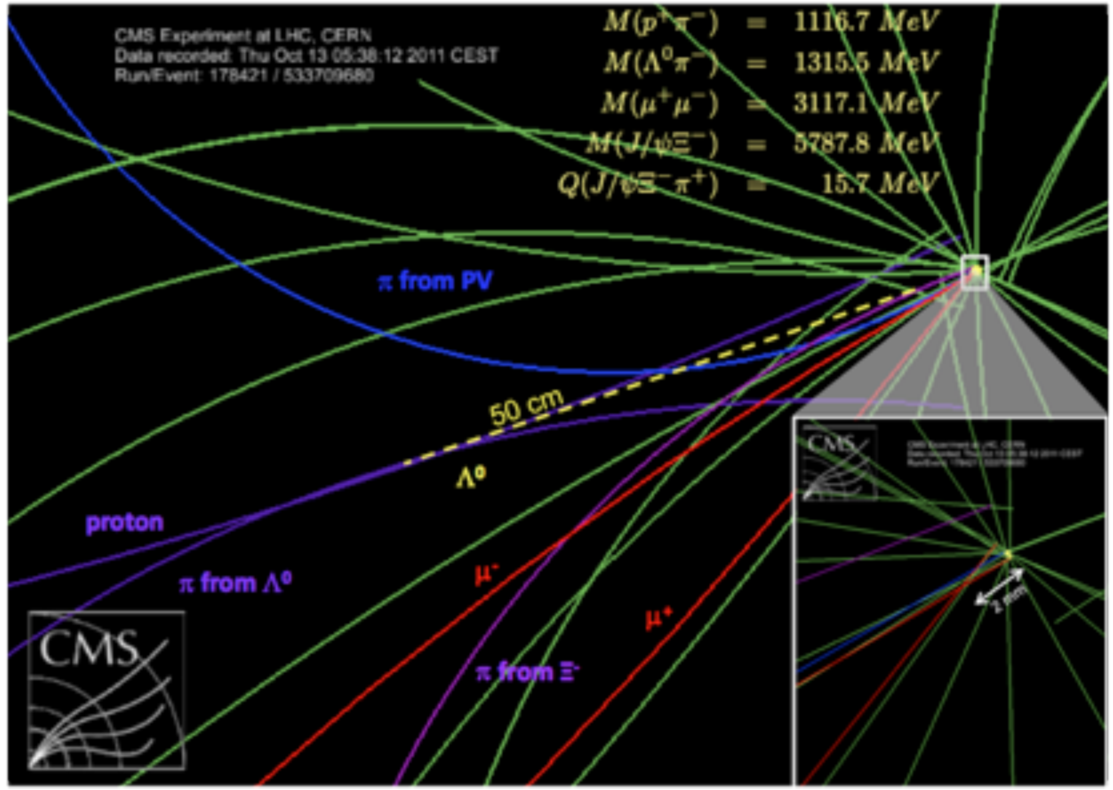

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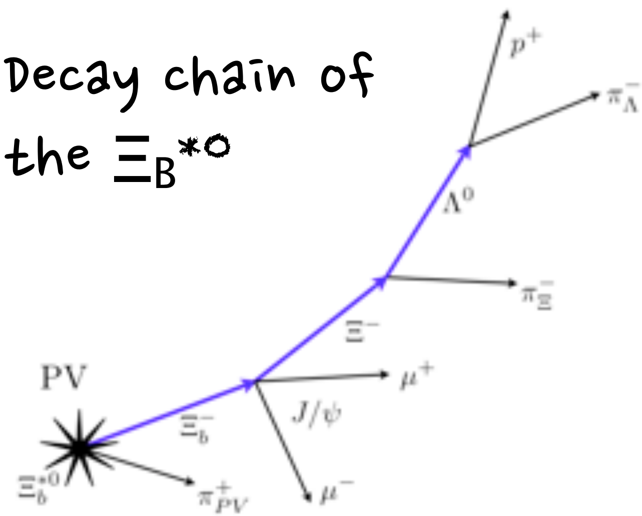

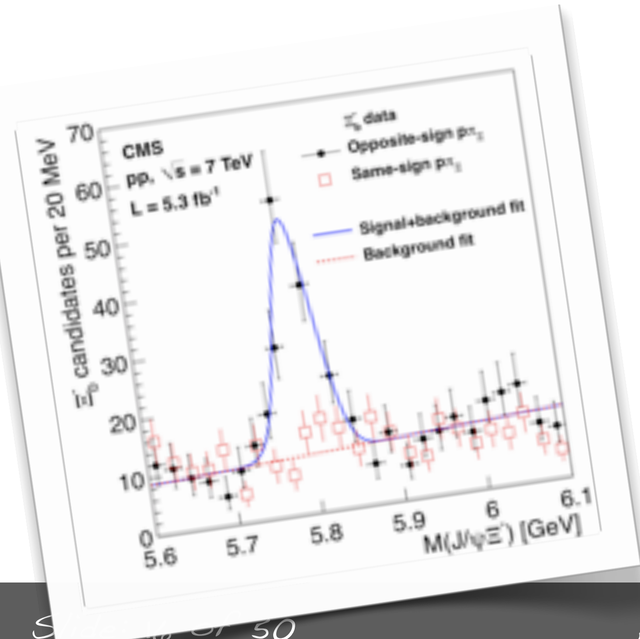

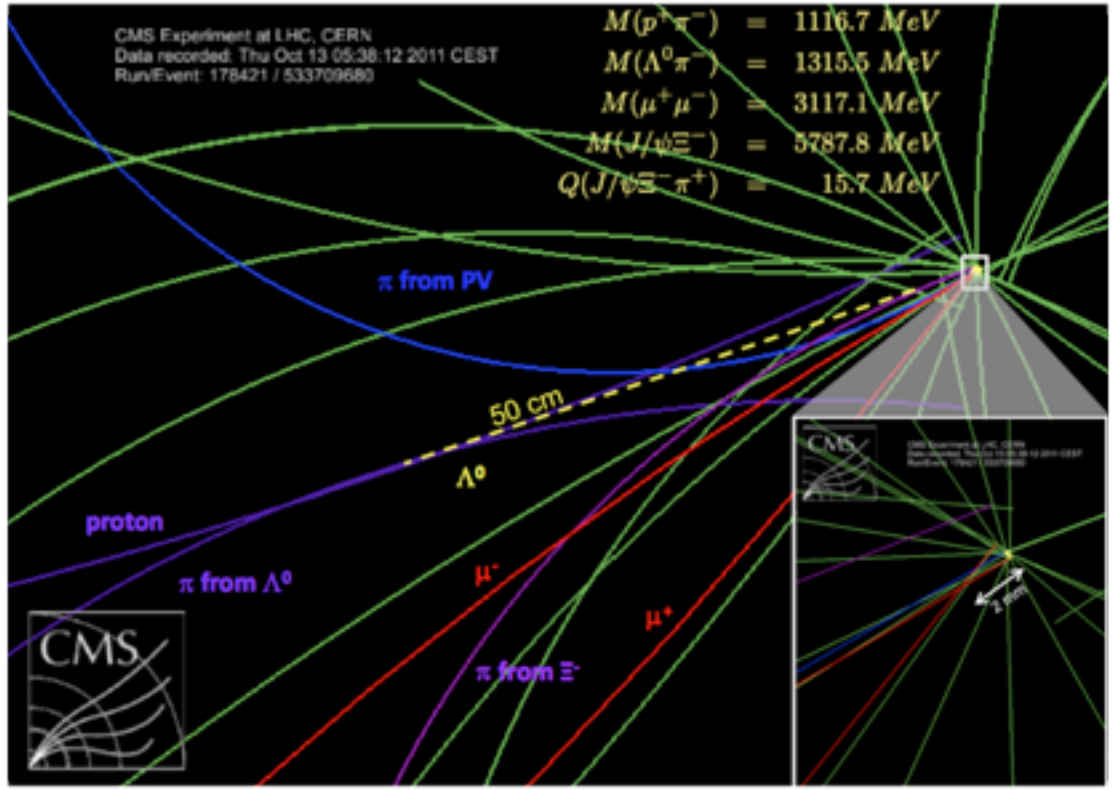

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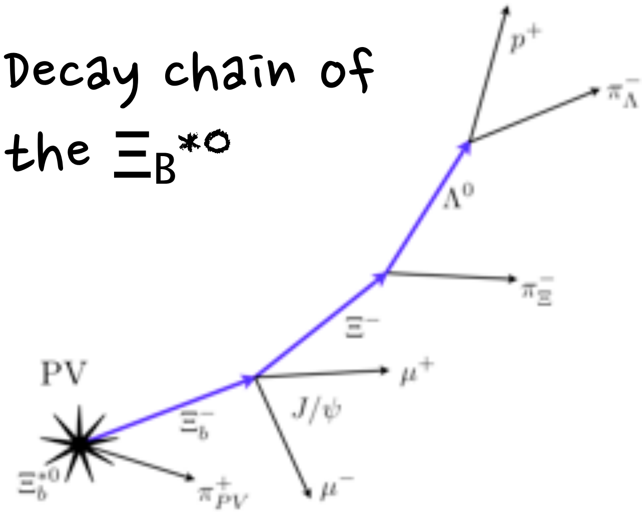

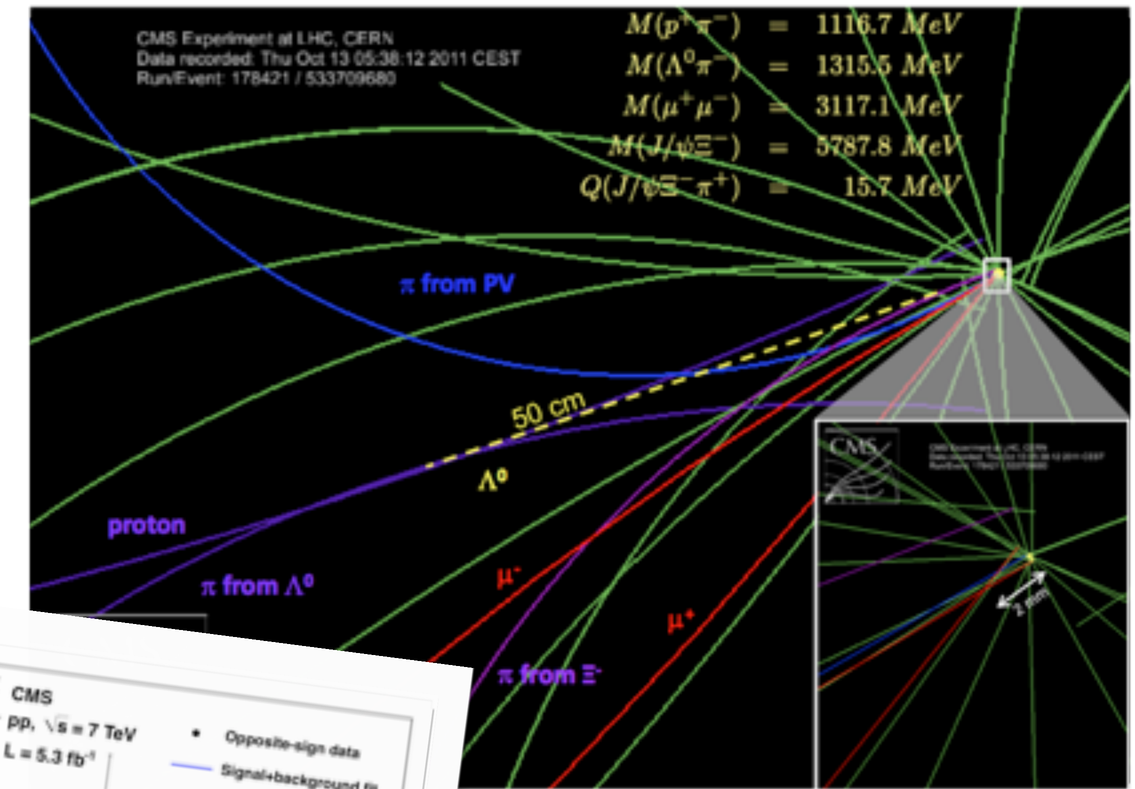

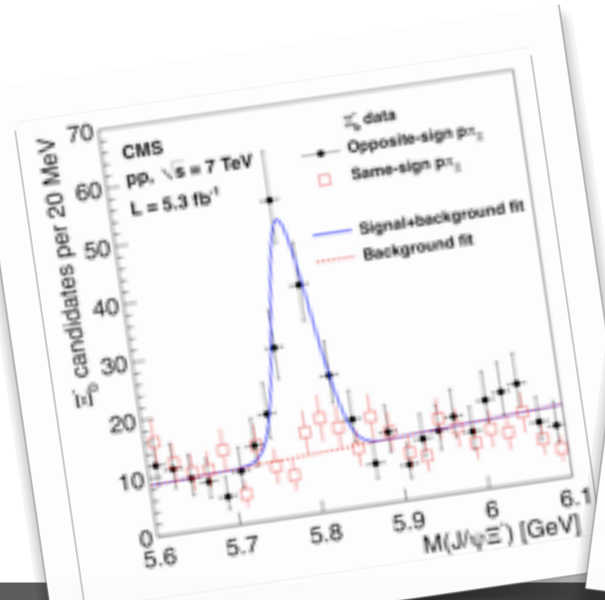

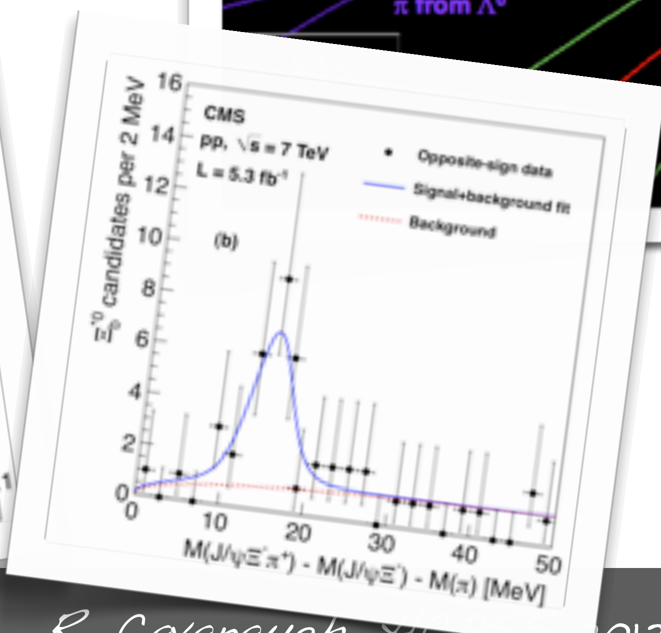

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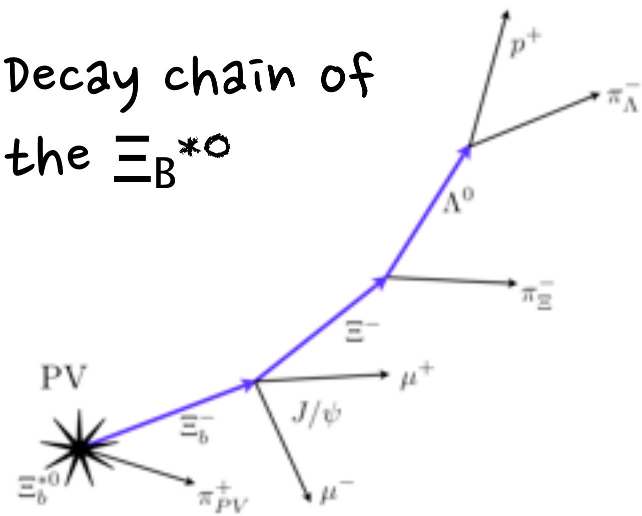

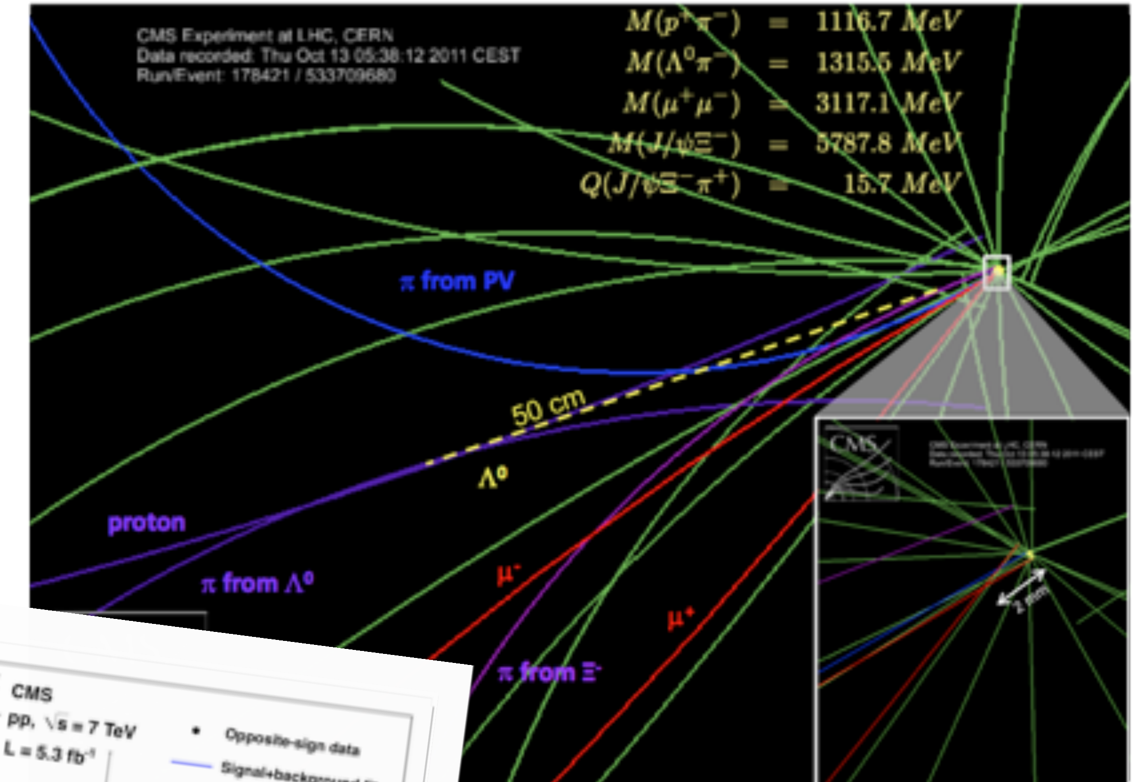

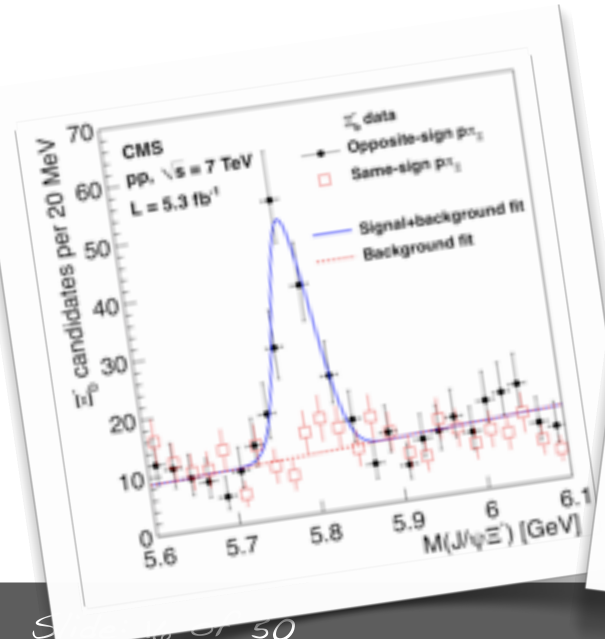

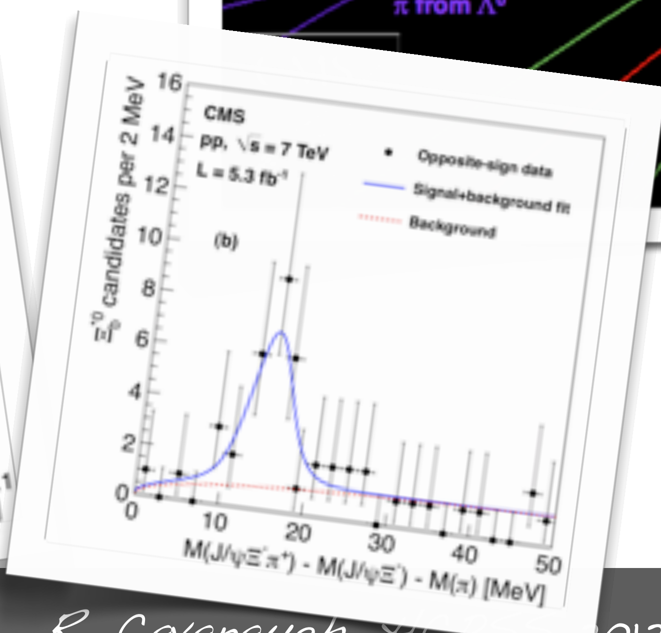

New baryon discovered!

Charged Hadron ID

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Motivation

- Charged hadrons (π, K, p) are all effectively stable, and have similar interactions
  - track + hadronic shower
- However, identifying them can be crucial, in particular for the study of hadronic decays

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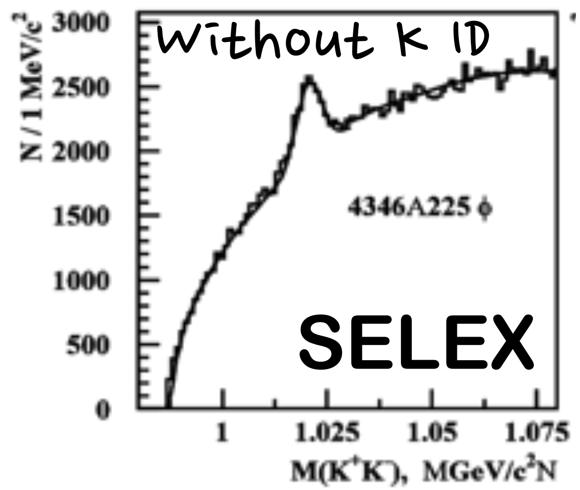

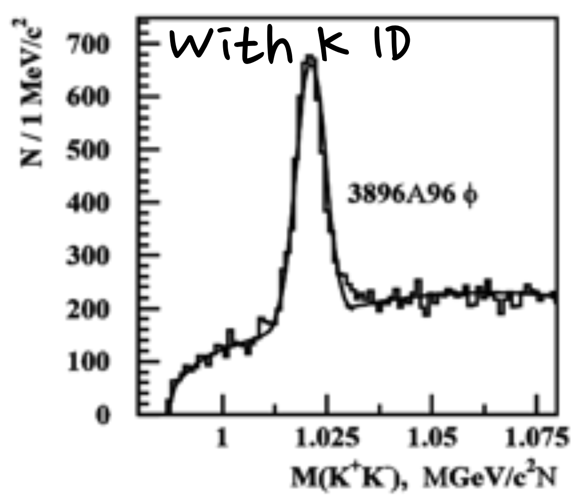

R. Cavanaugh, HCPSS 2012

Time Of Flight

Time Of Flight

Simple Concept

- measure the time difference between two detector planes
  $\beta = d / c\,\Delta t$
- At high energy, particle speeds are relativistic, closely approaching to c
- Example:
  - For a 10 GeV K,
    - time to travel 12 m is 40.05 ns,
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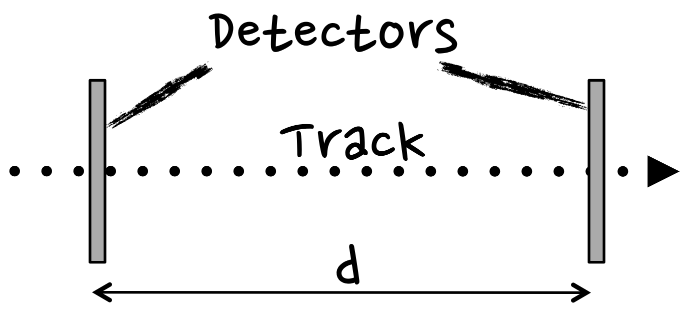

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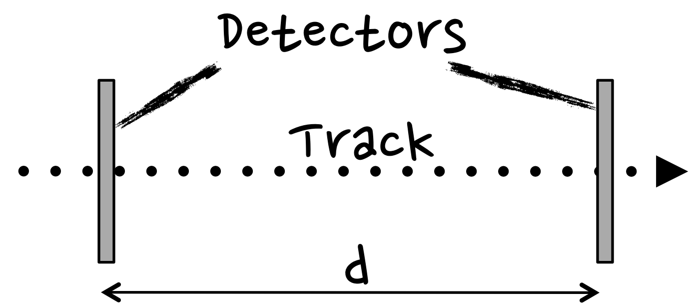
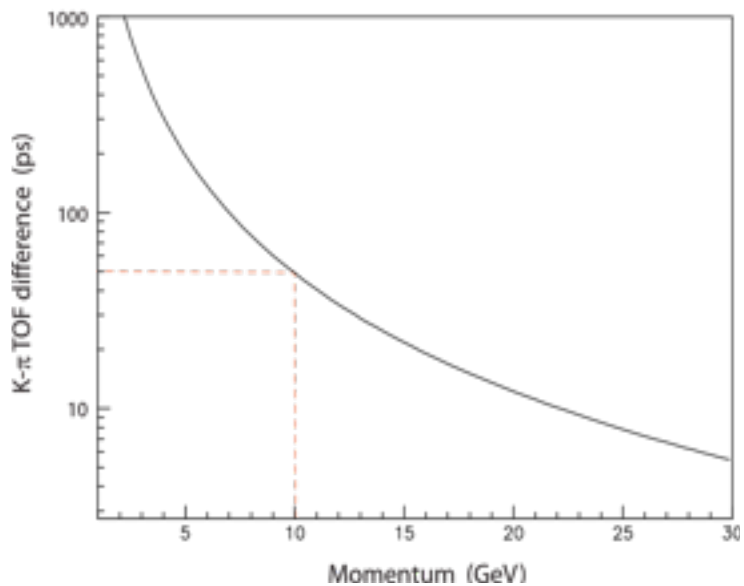


TOF difference for d = 12 m



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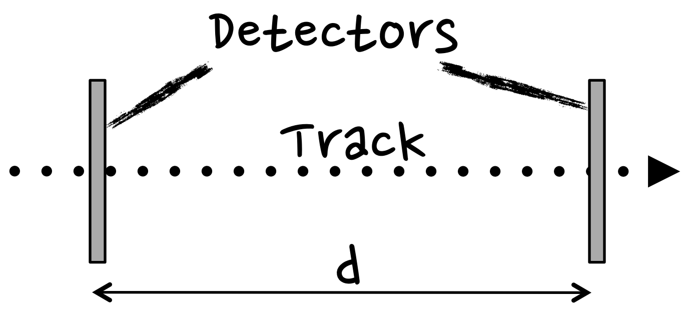

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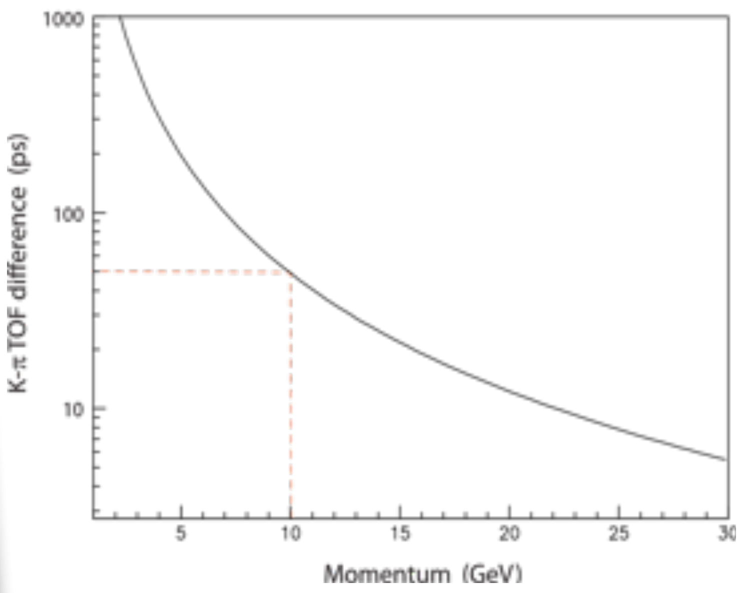

Modern Detectors

- (+ readout electronics) have resolution $\sigma(t) \sim 10$ ns, fast enough for the LHC (bunch crossings 25 ns apart) but need $\sigma(t) < 1$ ns to do useful TOF
- TOF gives good ID at low momentum. Very precise timing required for p > 5 GeV

Ionization

Ionization

Concept

- Charged particles passing through matter can knock out electrons from atoms of the medium: ionization
- Energy loss described by the Bethe-Bloch formula, which gives the universal velocity dependence:

$$dE/dx \propto \log(\beta^2 \gamma^2) / \beta^2$$

- This can be used to identify particles, particularly at low momentum where dE/dx varies rapidly

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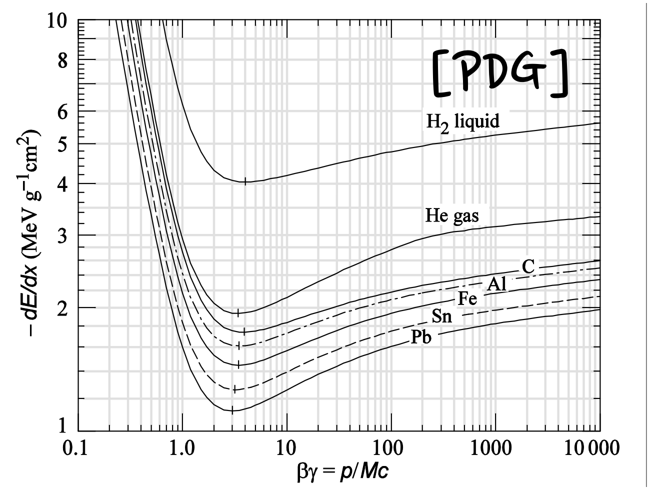

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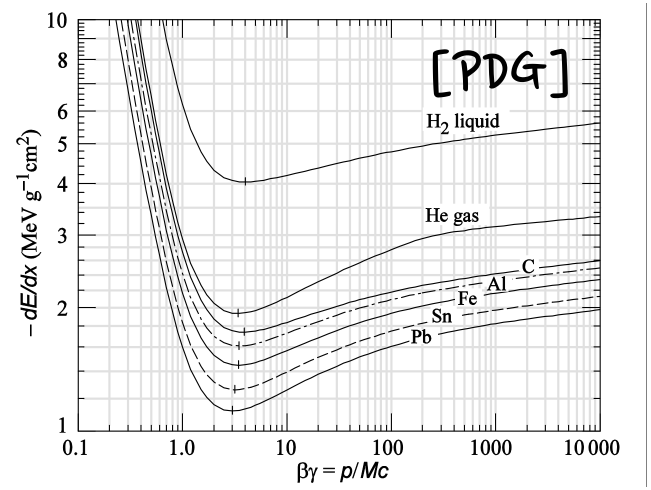

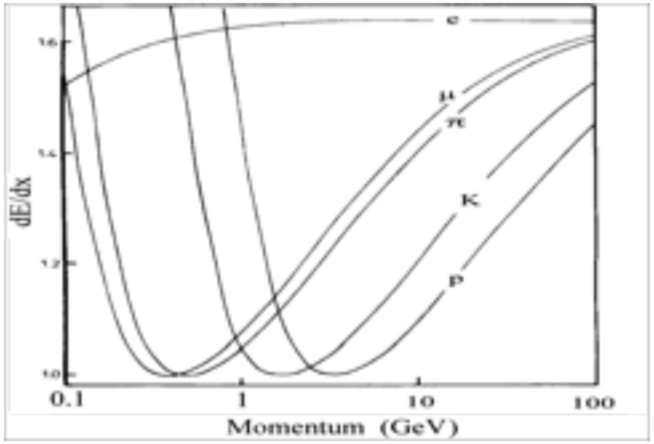

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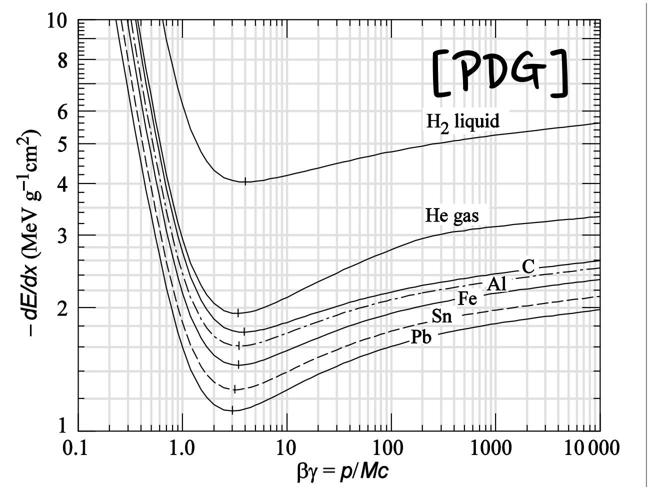

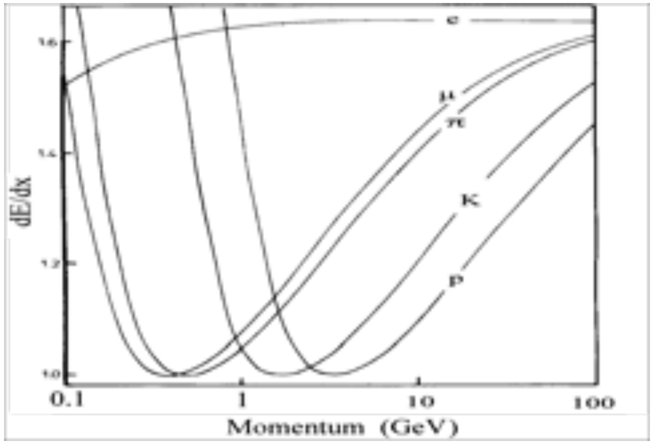

Considerations

- *Advantage:* uses existing detectors needed for tracking (but requires the accurate measurement of the charge)
- *Note:* these techniques all provide signals for charged leptons e, μ as well as π, K, p. But m(μ) ≈ m(π), so they are not well separated (dedicated detectors do a better job)

Transition Radiation

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- Local speed of light in medium with refractive index n is $c' = c/n$
- If particle's relative velocity v/c' changes, particle will radiate photons
  - change of direction -> Synchrotron rad
  - change of speed -> Bremsstrahlung rad
  - change of index n -> Transition rad
- Transition rad emitted whenever relativistic charged particle traverses border between two media having different dielectric constants $n = \sqrt{\varepsilon}$
- Emitted energy proportional to boost γ of particle
  - can discriminate electrons from pions!
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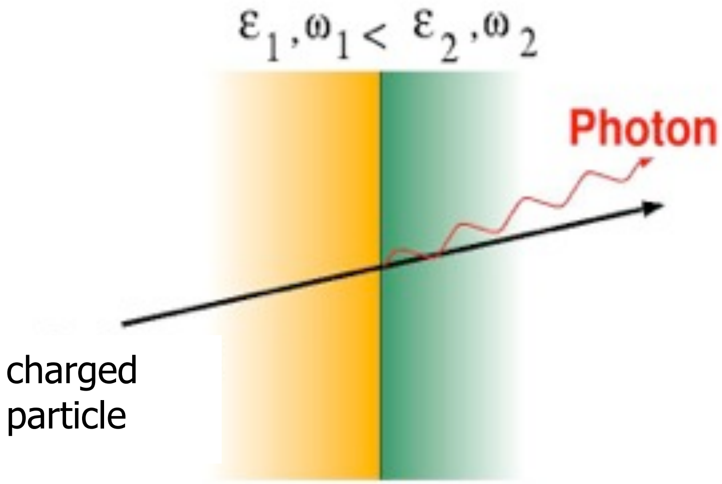

Черенков Radiation

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Considerations

- Named after the Russian scientist P. Cherenkov who was the first to study the effect in depth (he won the Nobel Prize for it in 1958)
- From Relativity, nothing can go faster than the speed of light c (in vacuum)
- However, due to the refractive index n of a material, a particle can go faster than the local speed of light in the medium $c' = c/n$
- This is analogous to the bow wave of a boat travelling over water or the sonic boom of an aeroplane travelling faster than the speed of sound

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- Cherenkov light is produced when charged particle goes faster than the speed of light
  - $\cos\theta_c = 1 / \beta n$
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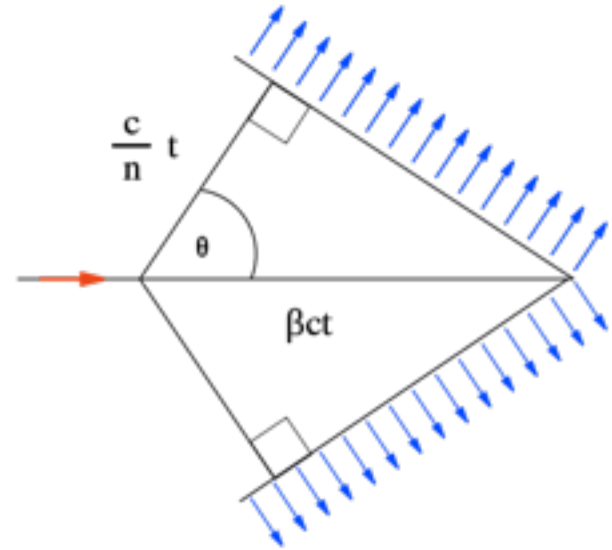

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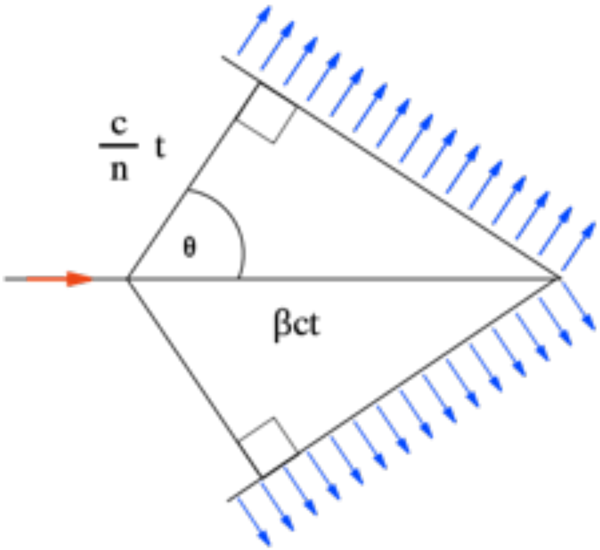

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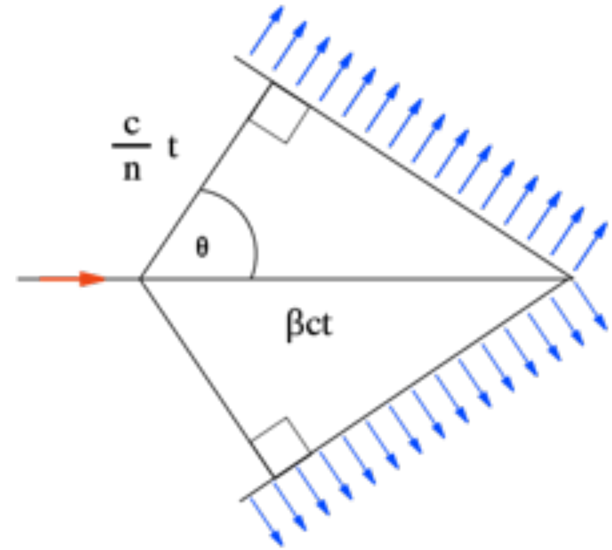
Example:

- Using this construction, we can determine (roughly) the boat speed:
  - $\theta \approx 70^{\circ}$, v_{wave} = 2 knots on water
  - $v_{boat} = v_{wave}/\cos\theta \approx 6$ knots



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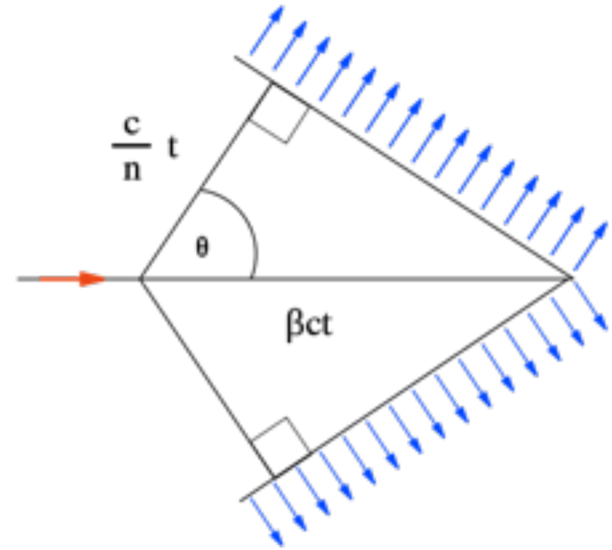

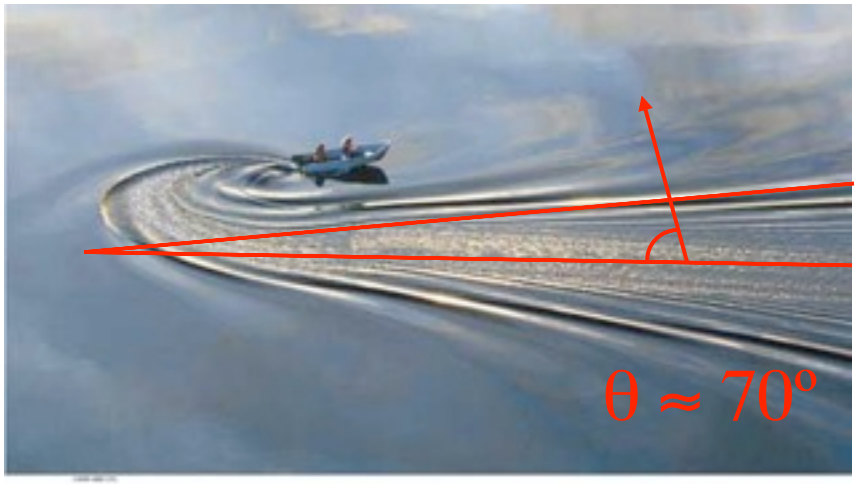

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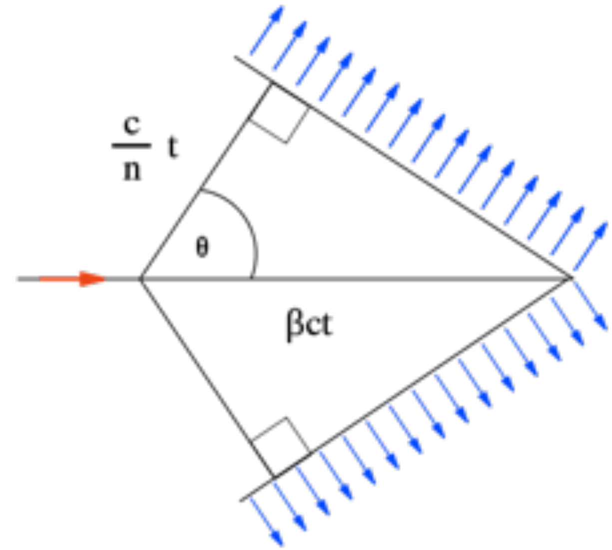
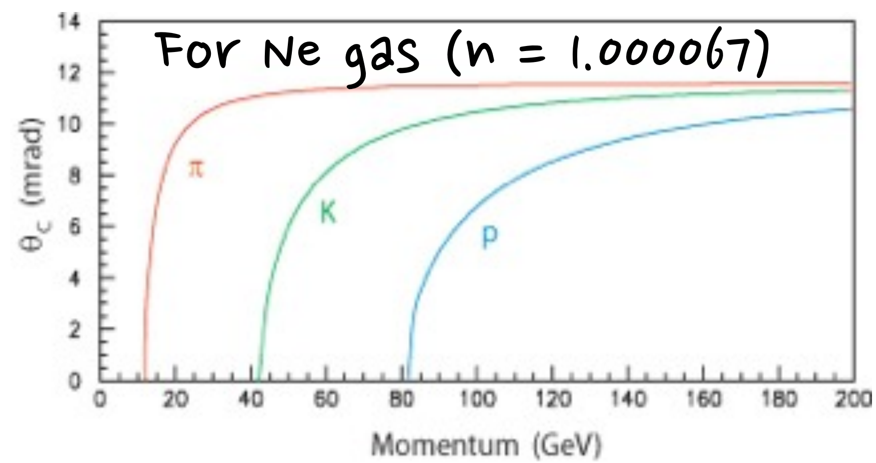
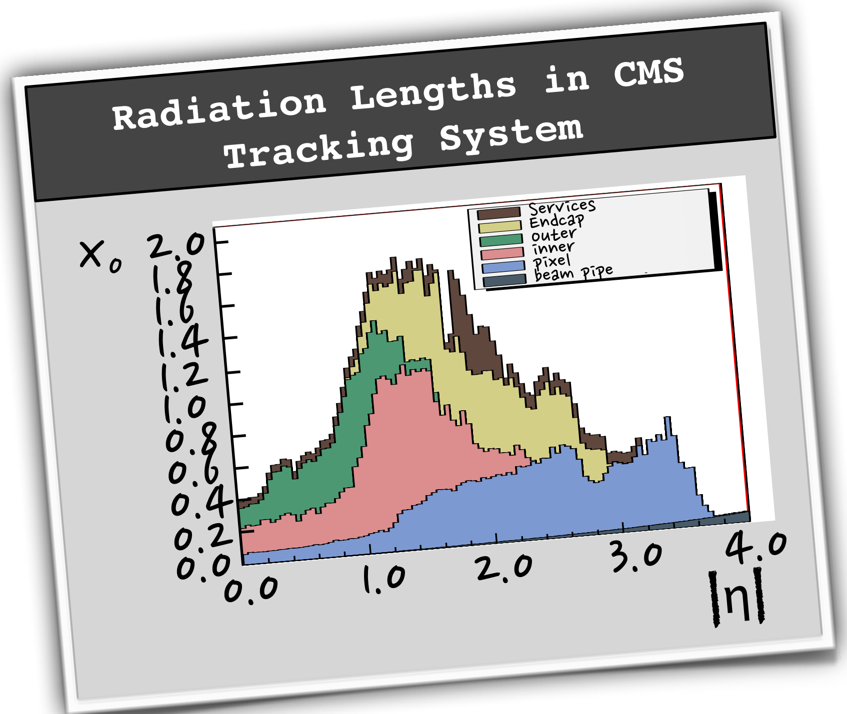
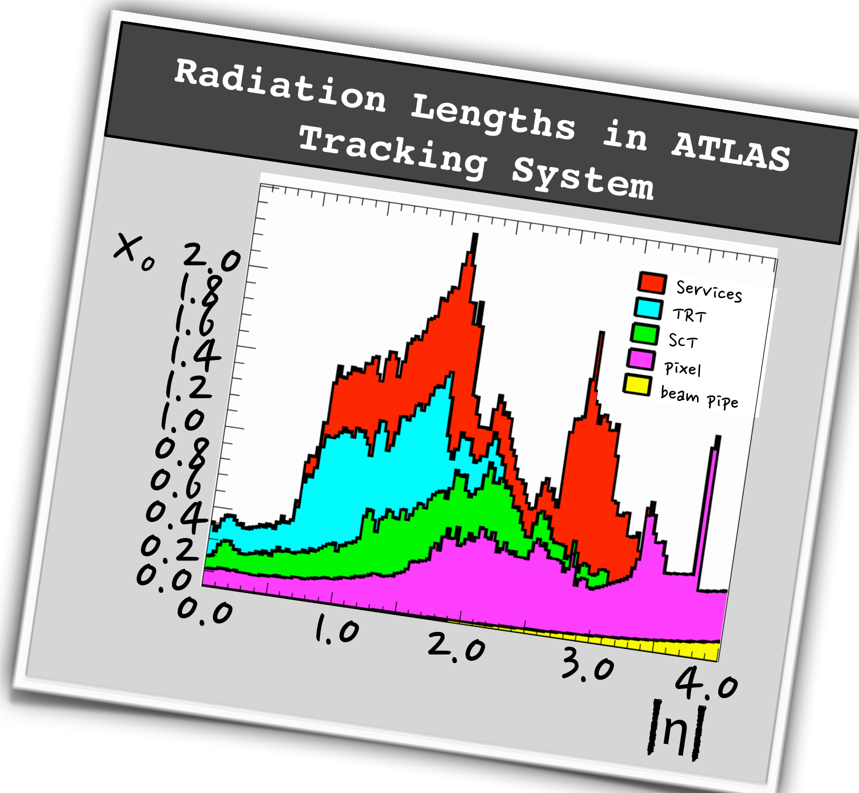




Come back to Electrons & Photons

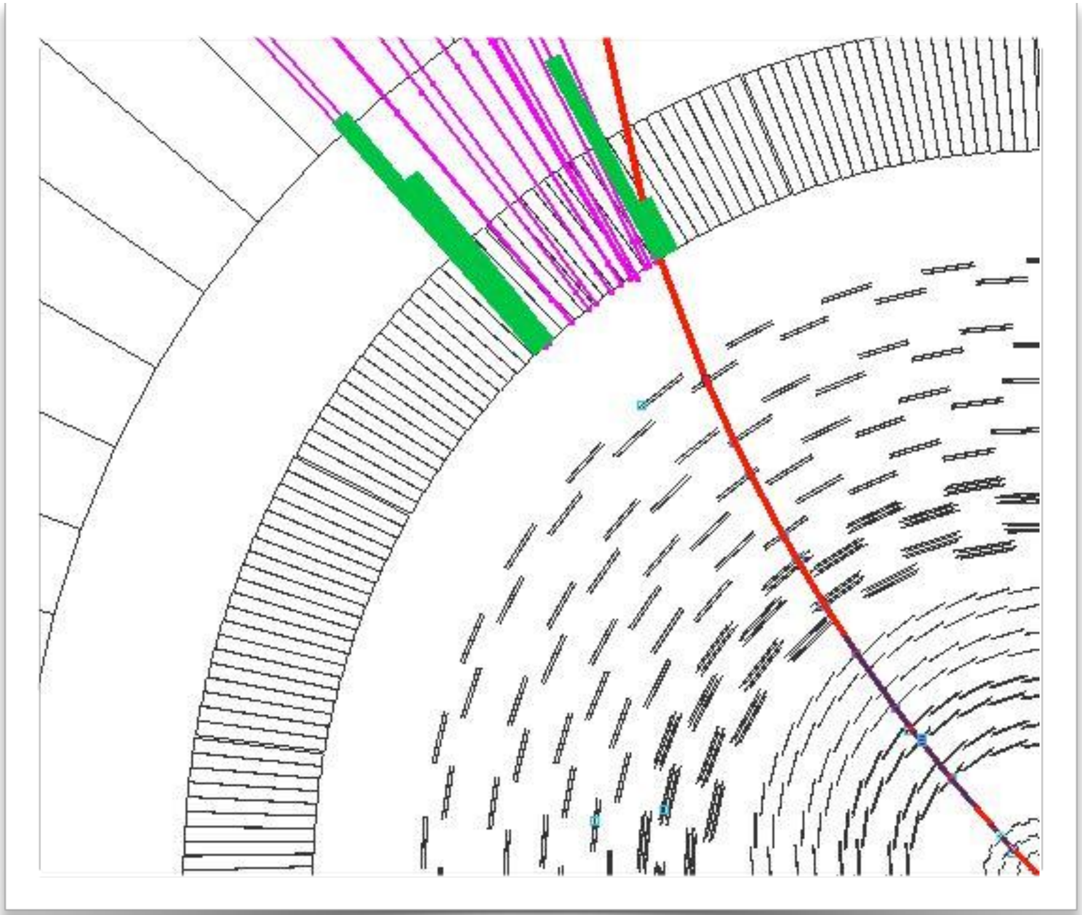
- **Indeed, the LHC Trackers are heavy!**





The LHC Trackers act like Electromagnetic pre-showers!

Electron Identification



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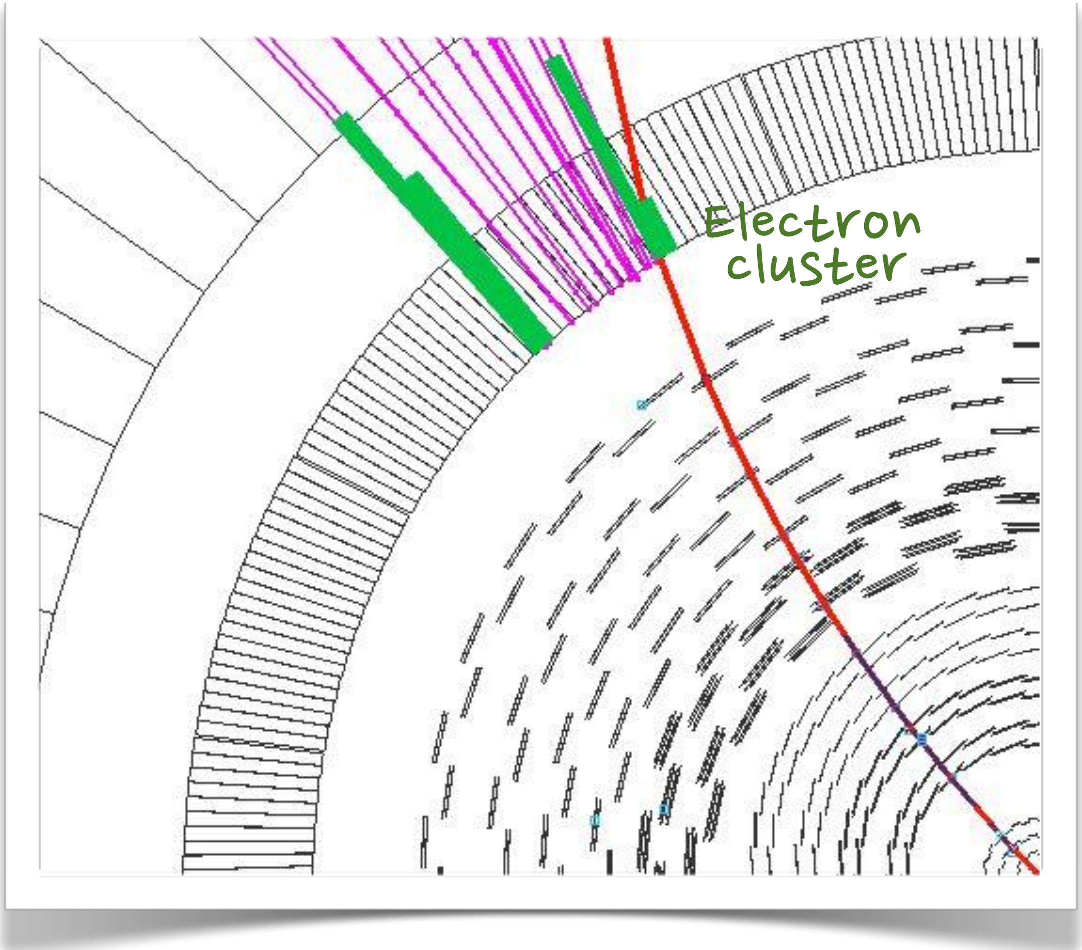

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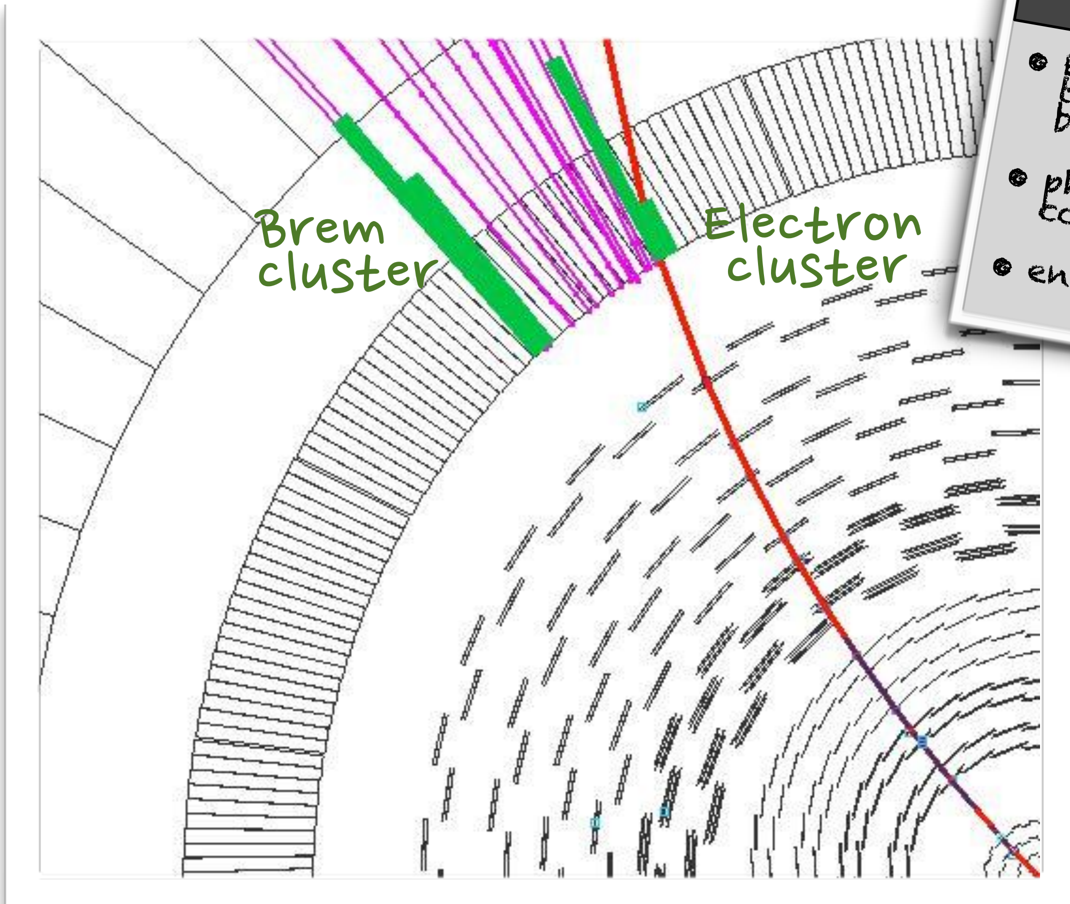

Huge Effect!

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

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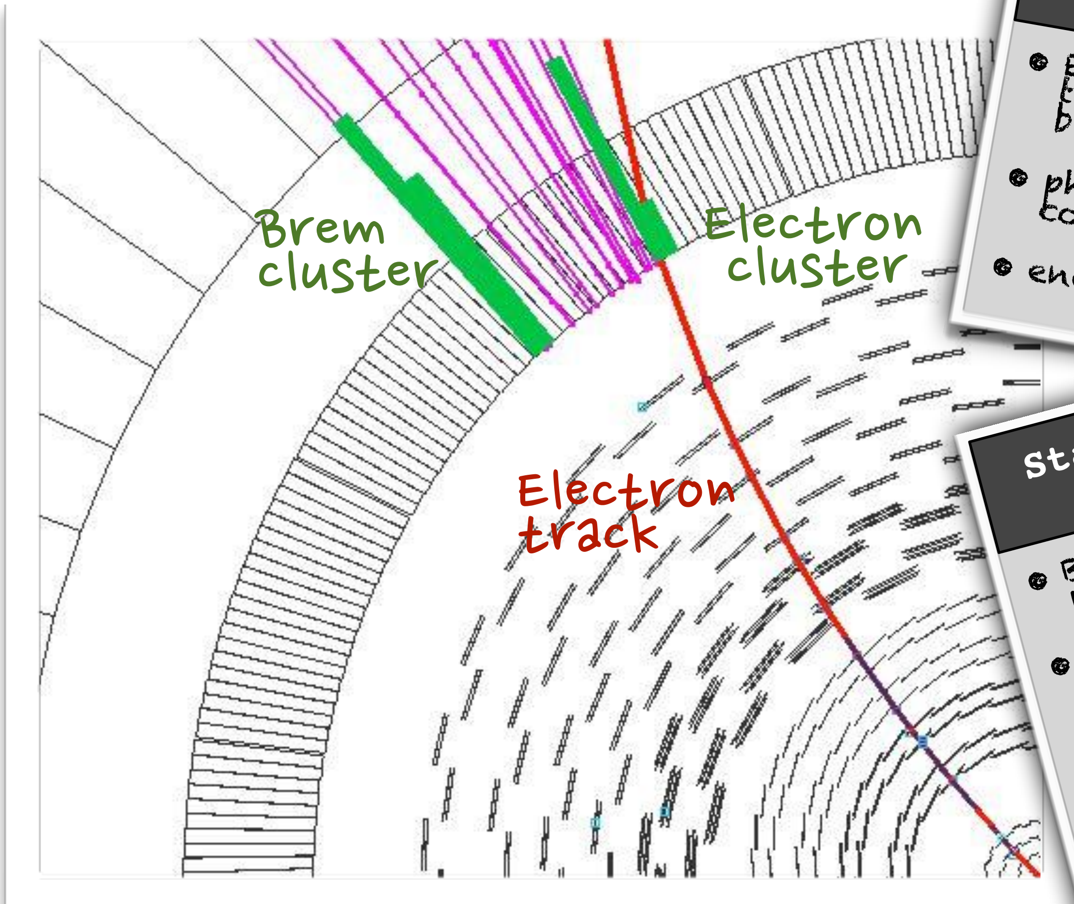

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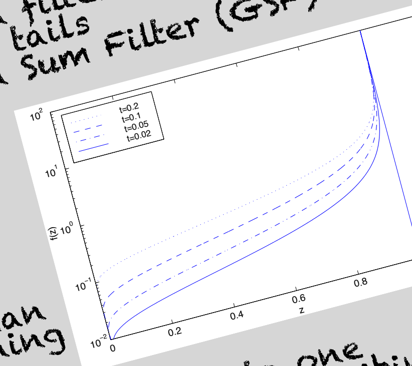
Standard KF tracking fails for electrons!

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



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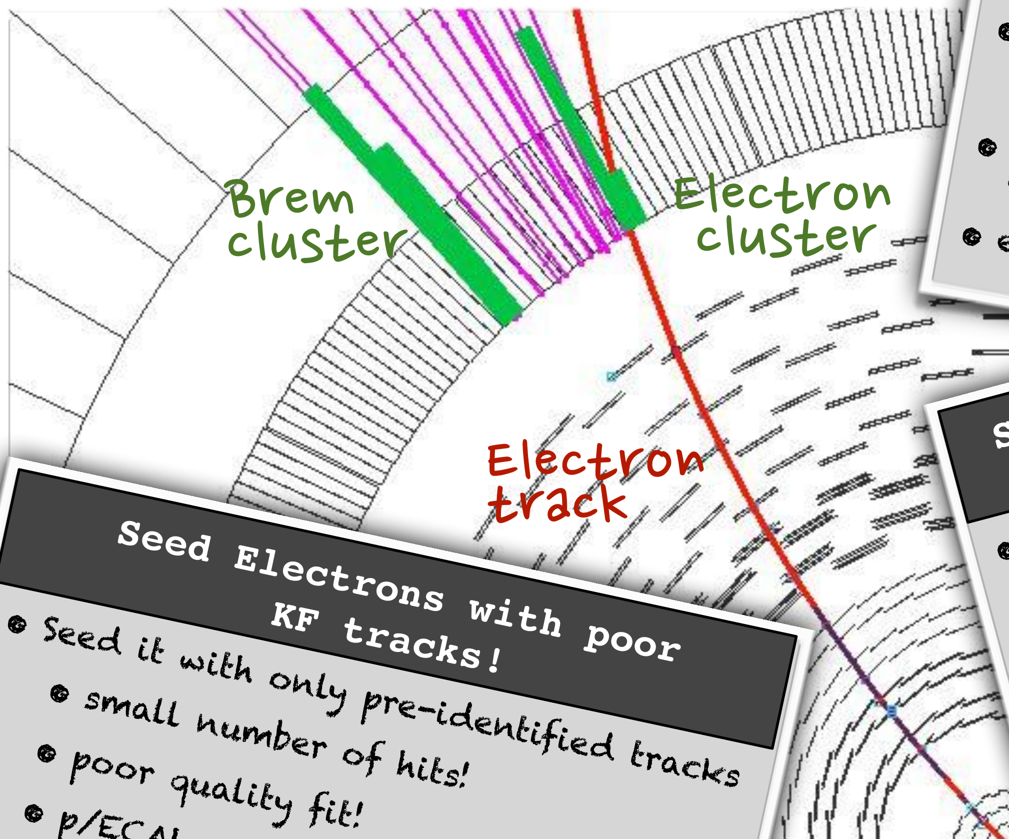

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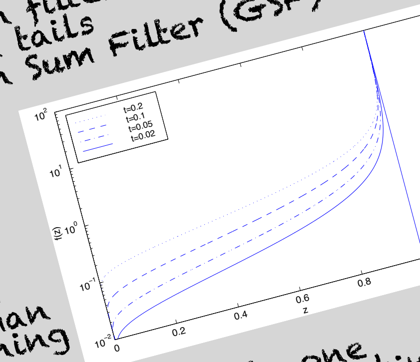
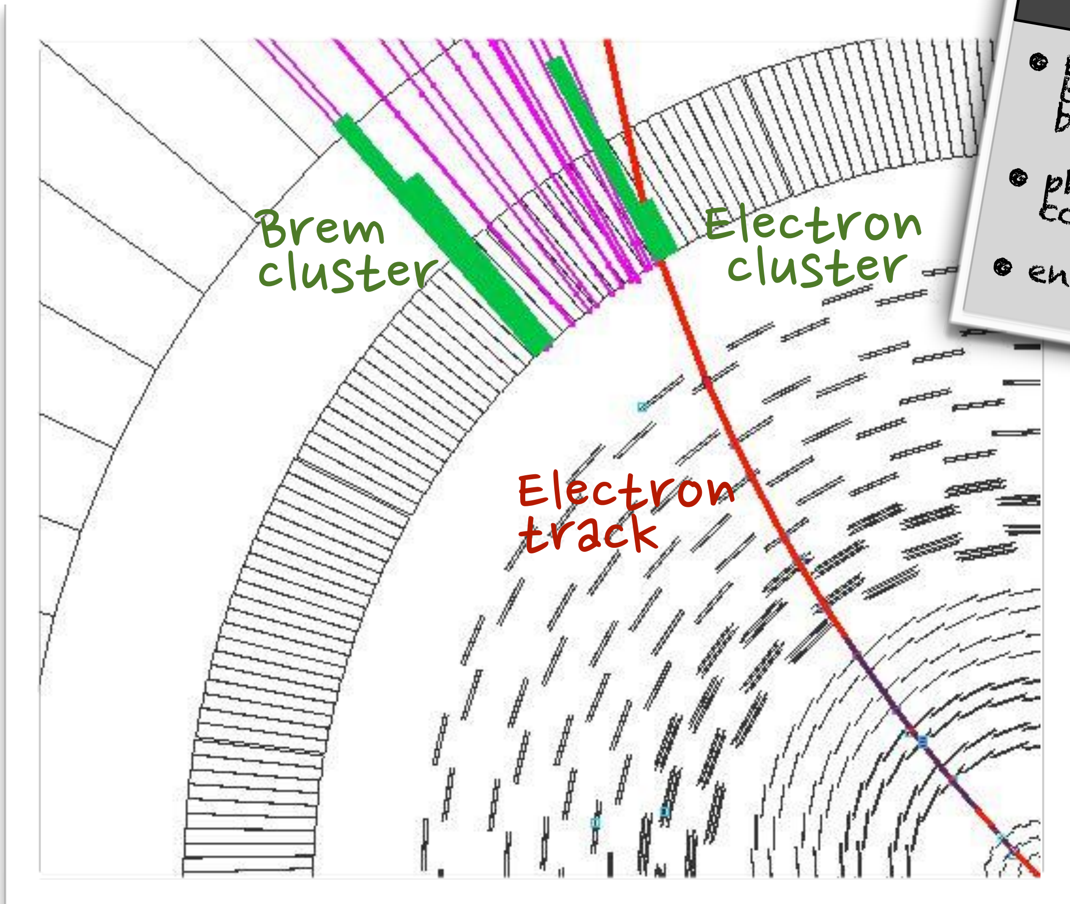


Seed Electrons with poor KF tracks!

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

Electron Identification



Huge Effect!

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

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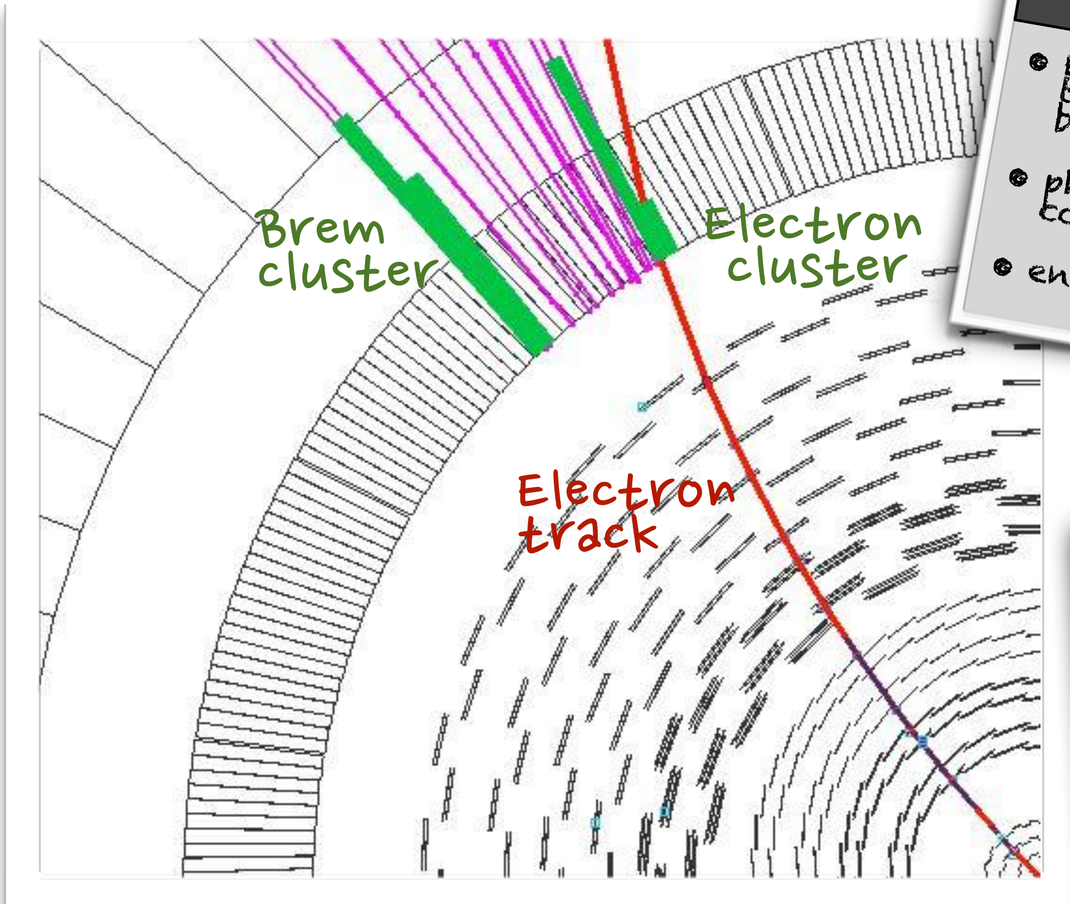

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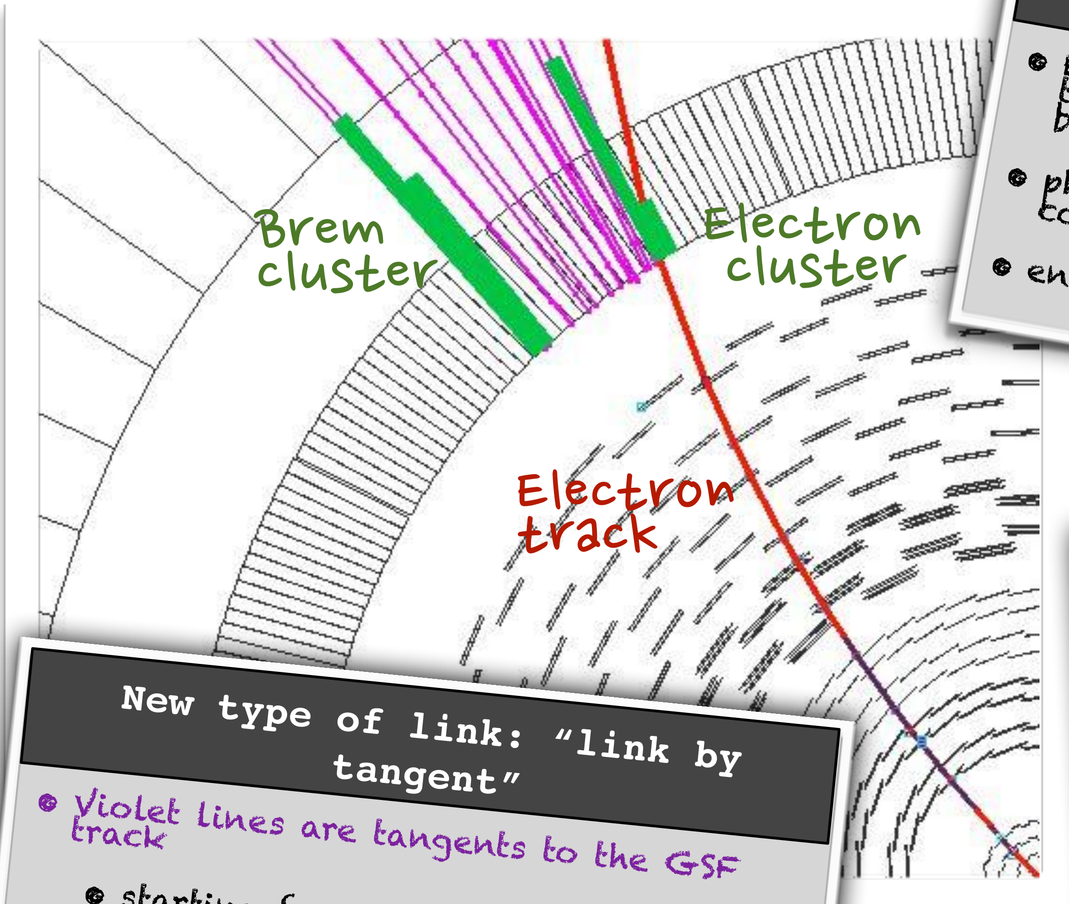

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New type of link: "link by tangent"

- Violet lines are tangents to the GSF track
  - starting from each tracker layer

If tangent points to a ECAL cluster
  - link cluster to track

Another possible handle
  - test compatibility between ECAL cluster and Δp along GSF track

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Fermilab
UIC University of Illinois at Chicago

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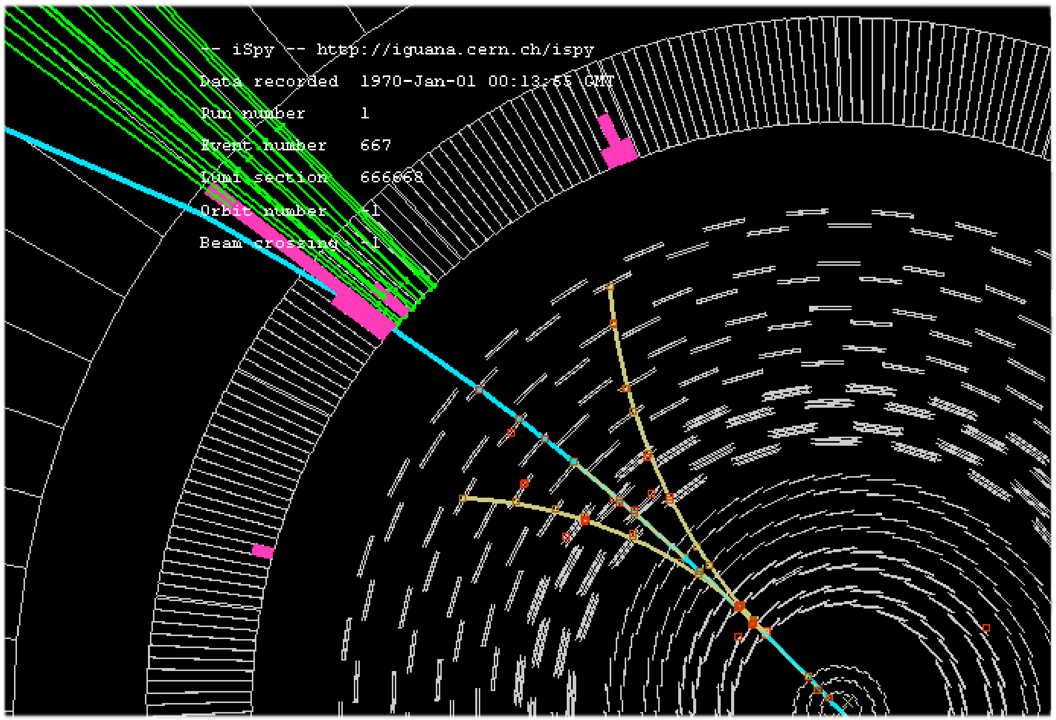

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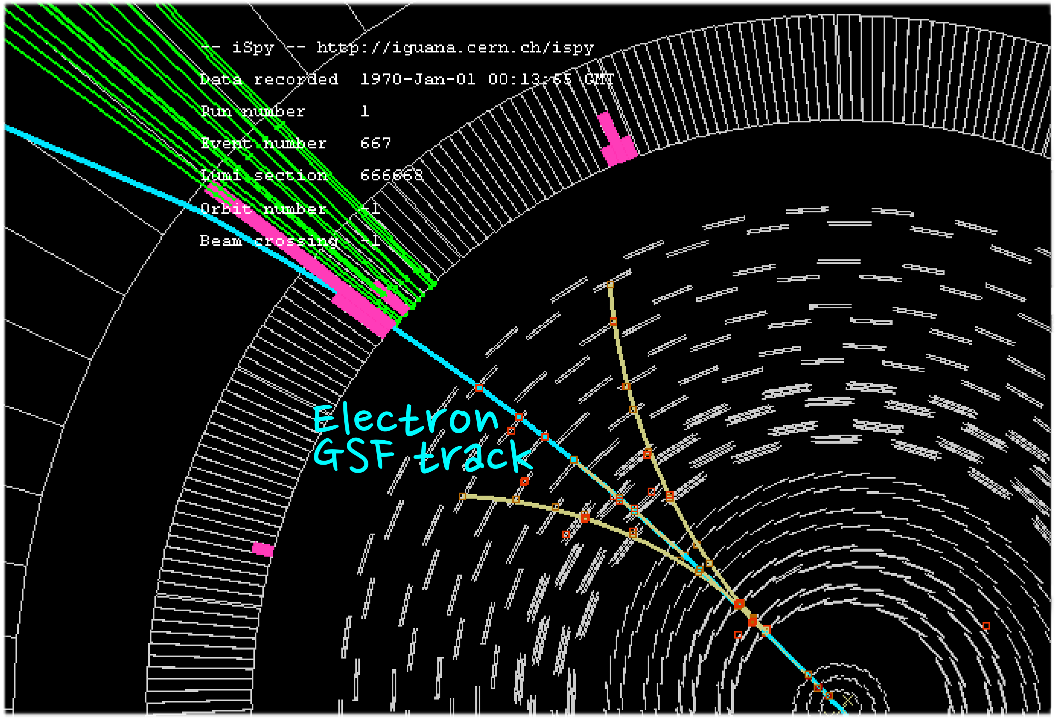

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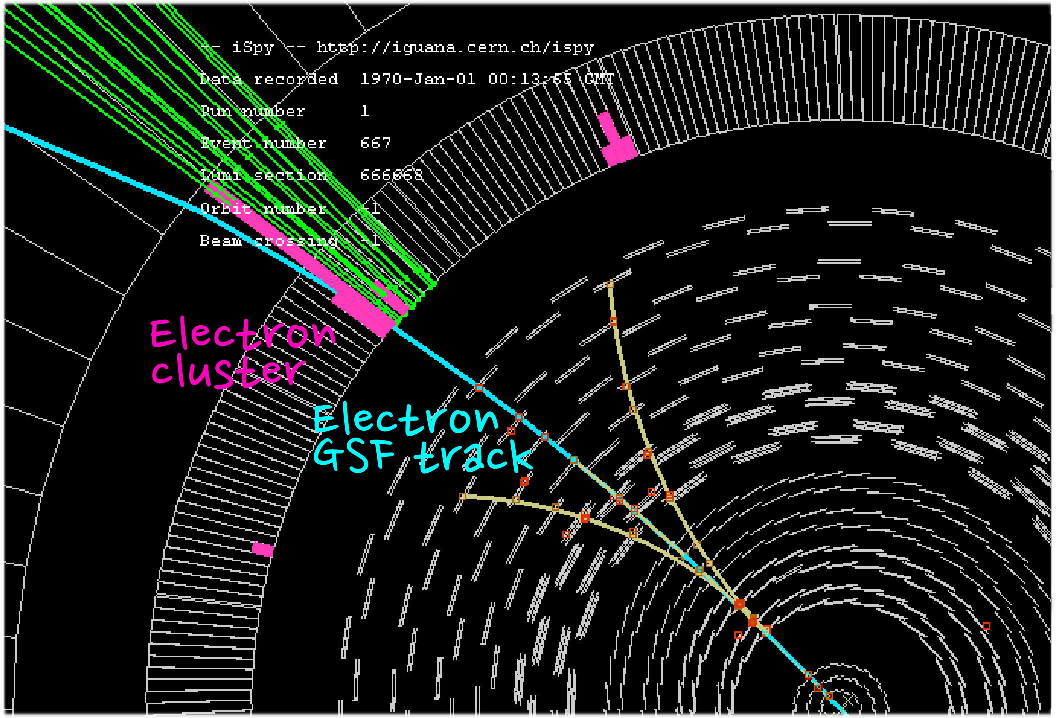

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R. Cavanaugh, HCPSS 2012

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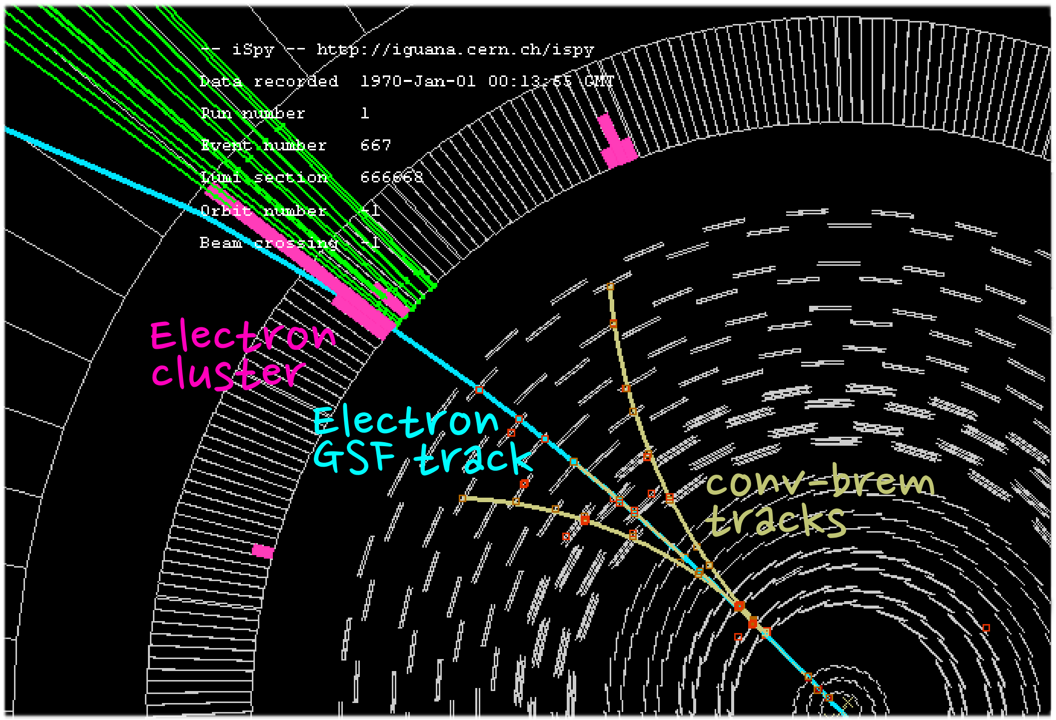

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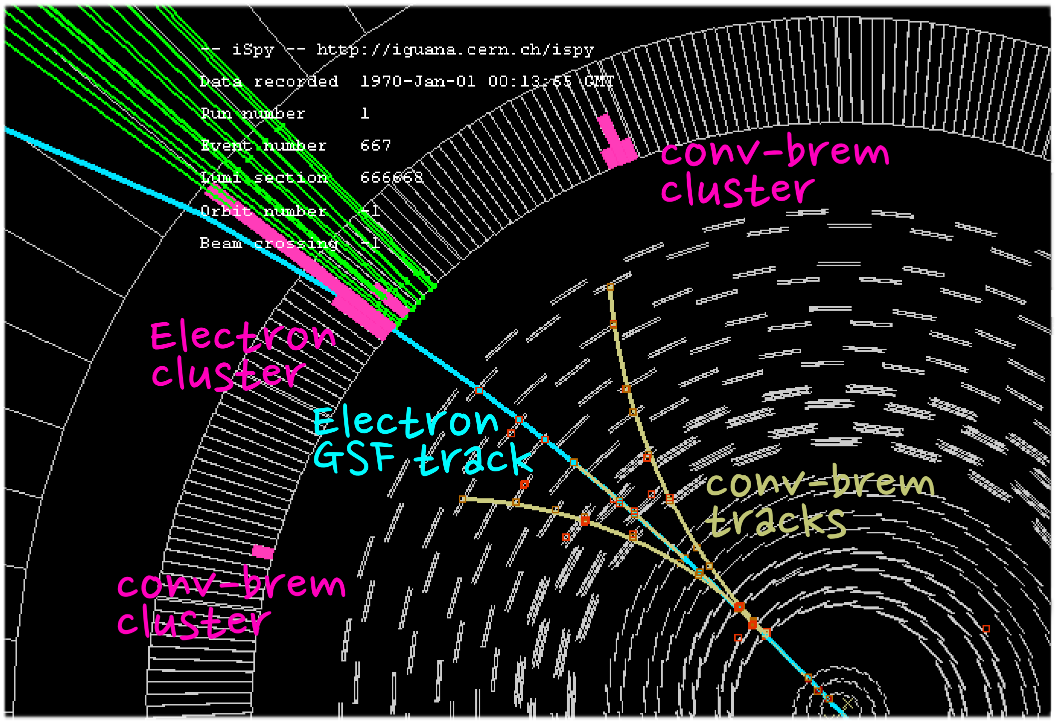

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Electron Identification

Recovering the converted Bremsstrahlung photons

- Tracks recovered by the 5th and 6th step of iterative tracking
    - linked by vertex to the original electron track (similar to π nuclear interactions)
    - Linked to ECAL clusters in standard way

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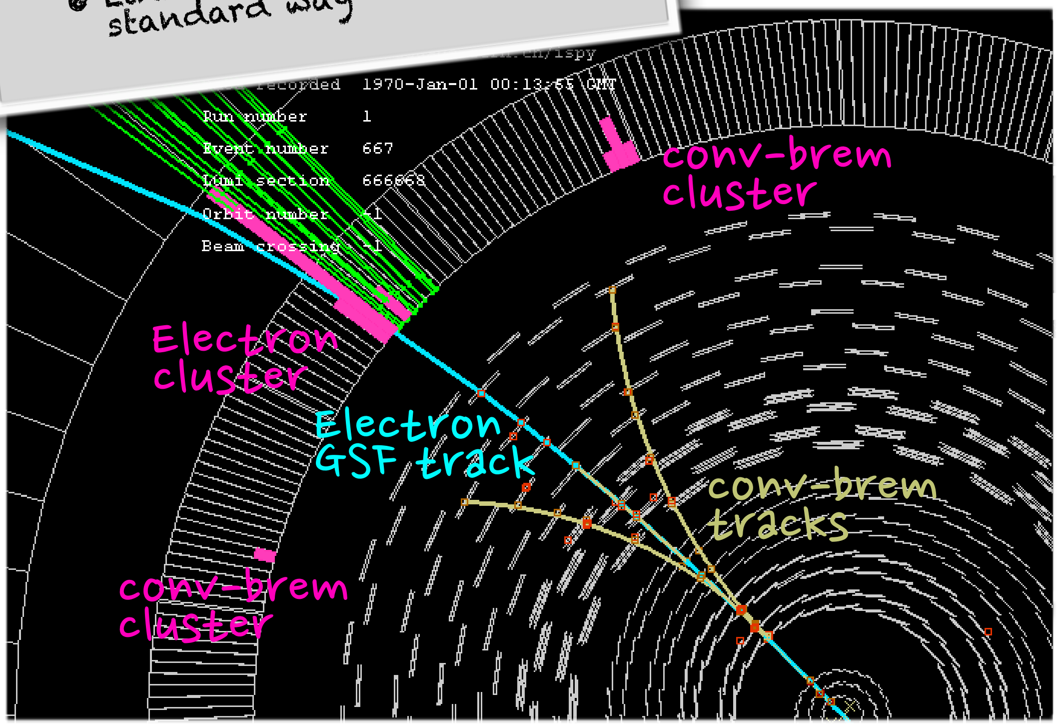

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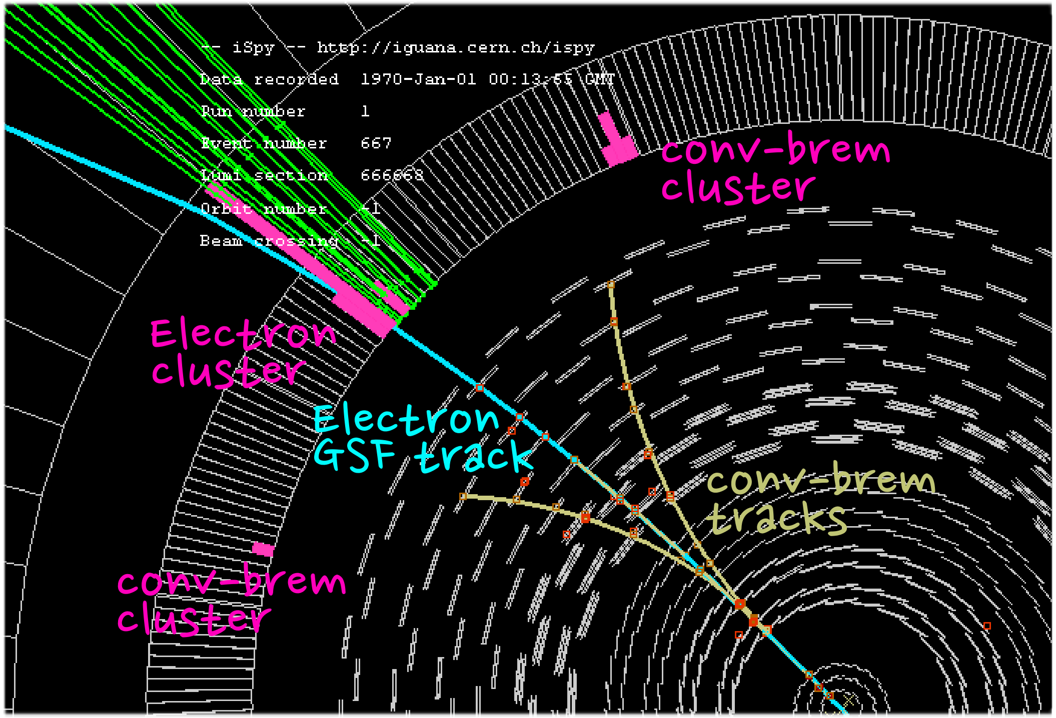
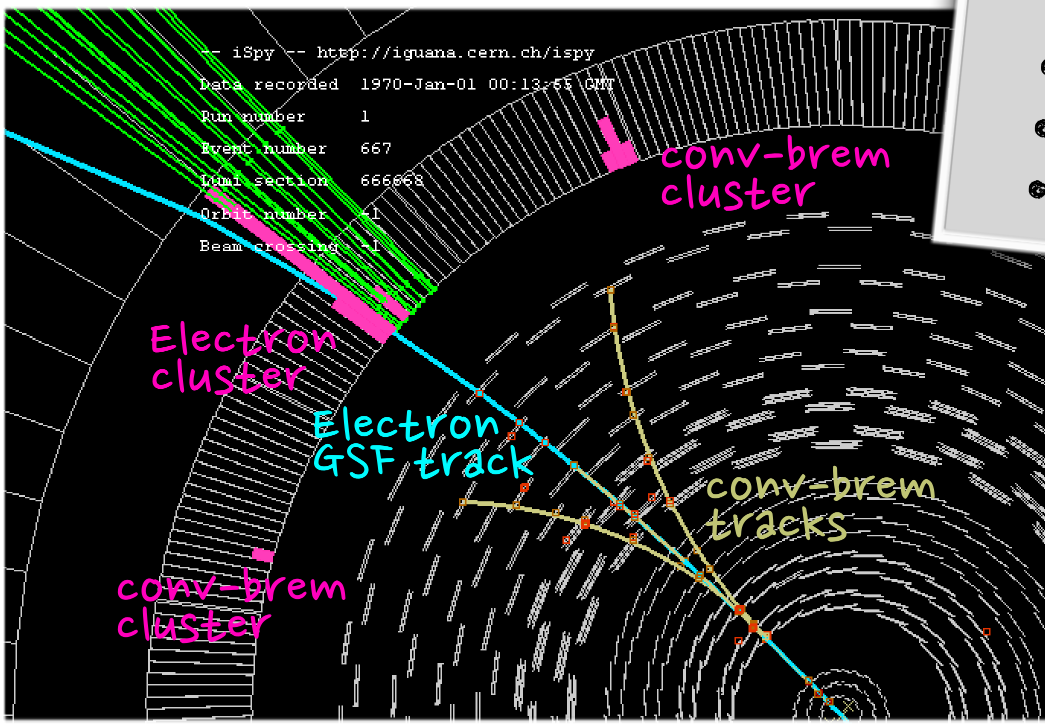


Electron Identification

Use Tracker as Preshower!

- electrons radiate; pions dont!
- Use the following to discriminate
  - Number of hits of the KF tracks
  - Energy loss along GSF track: $\Delta p = p_{in} - p_{out}$
  - Number of Brem γ's associated with track
  - Compare E_{brem} and $\Delta p = p_{in} - p_{out}$
  - Compare $E_{electron} + E_{brem}$ and p_{in}
  - etc



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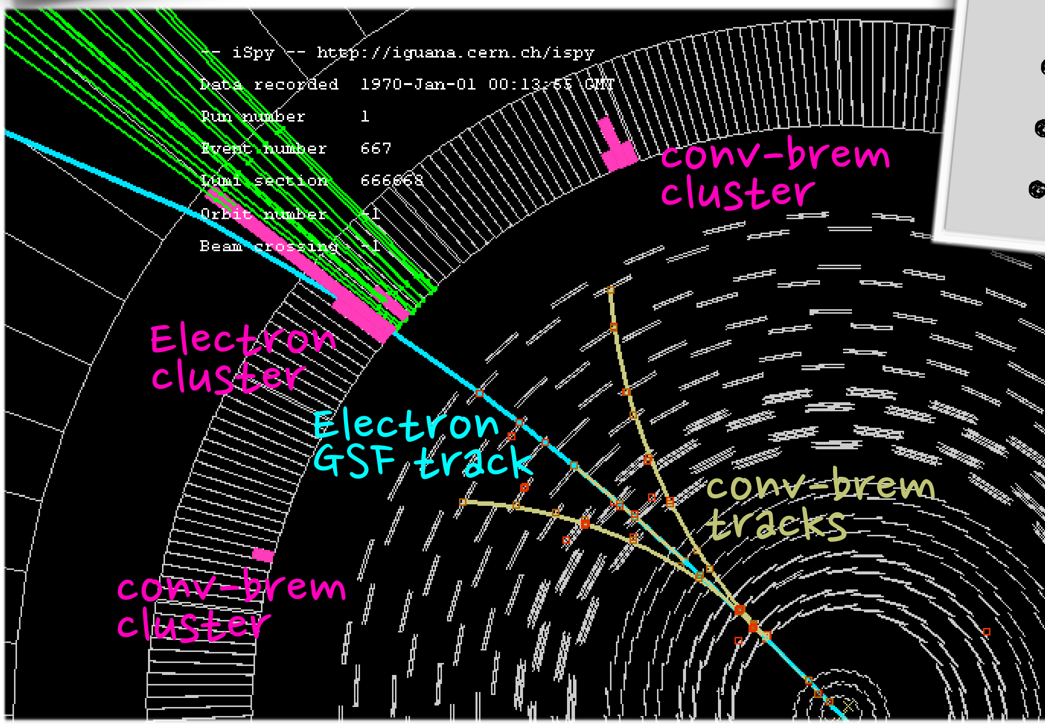
LPC LHC Physics Center

Electron Identification

Use cluster information!

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



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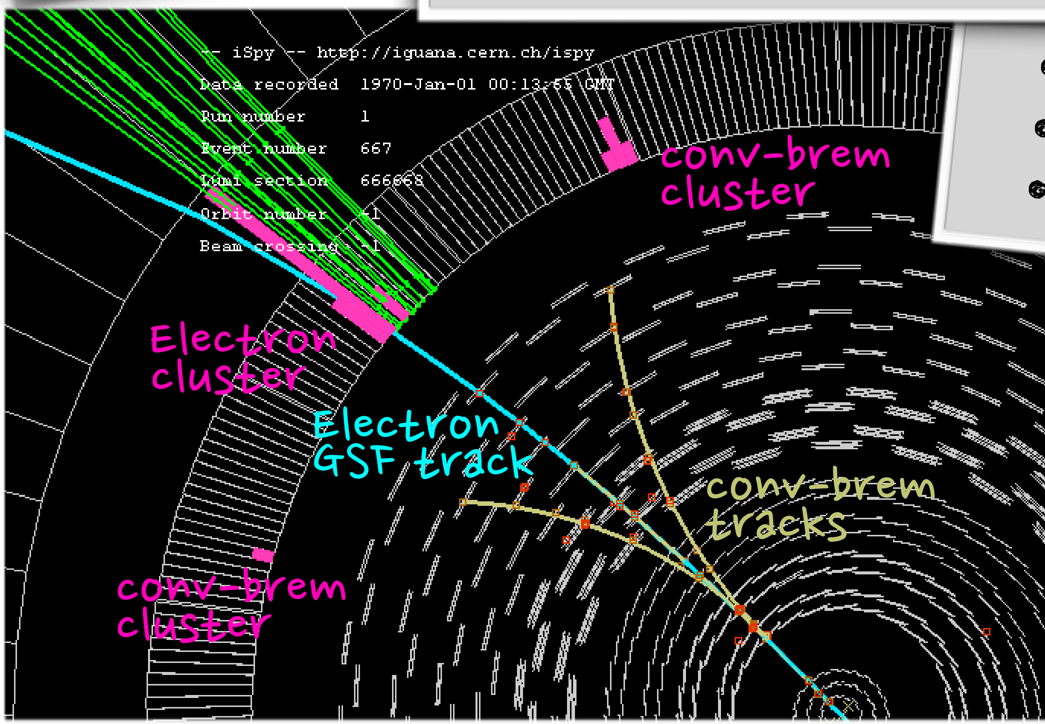
Combine into Multivariate Discriminator

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



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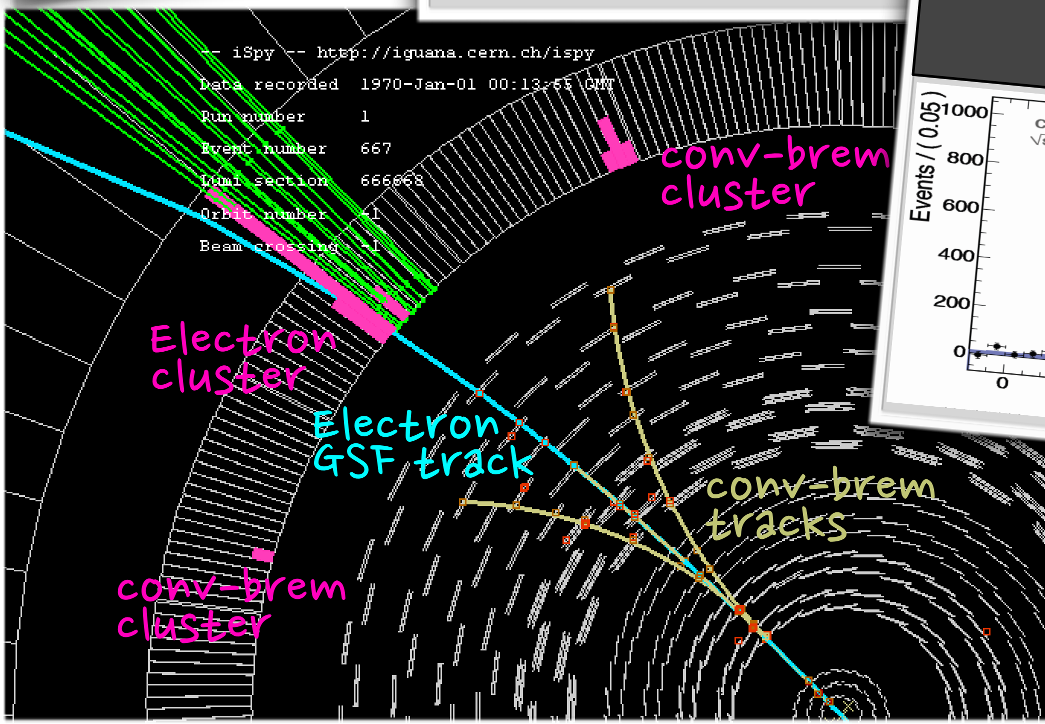
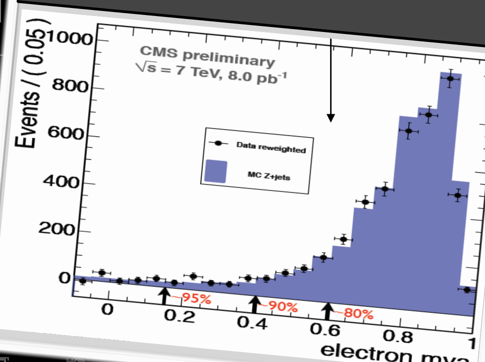


Z⁰ => e+e-



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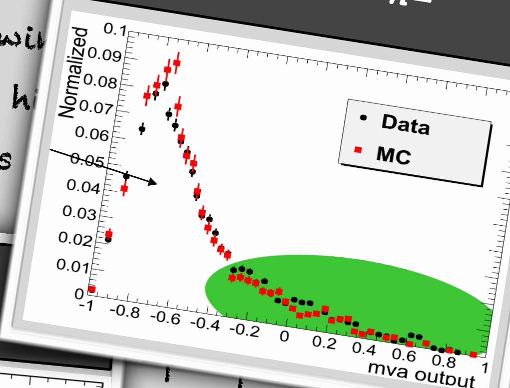
Use Tracker

- electrons radiat
- llowi
- of hi
- loss

Ebrem and pin

K_S^0 => π+π-



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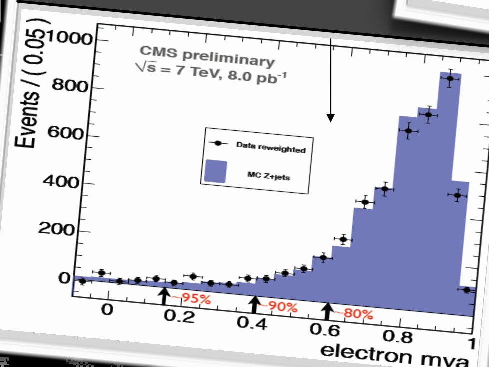

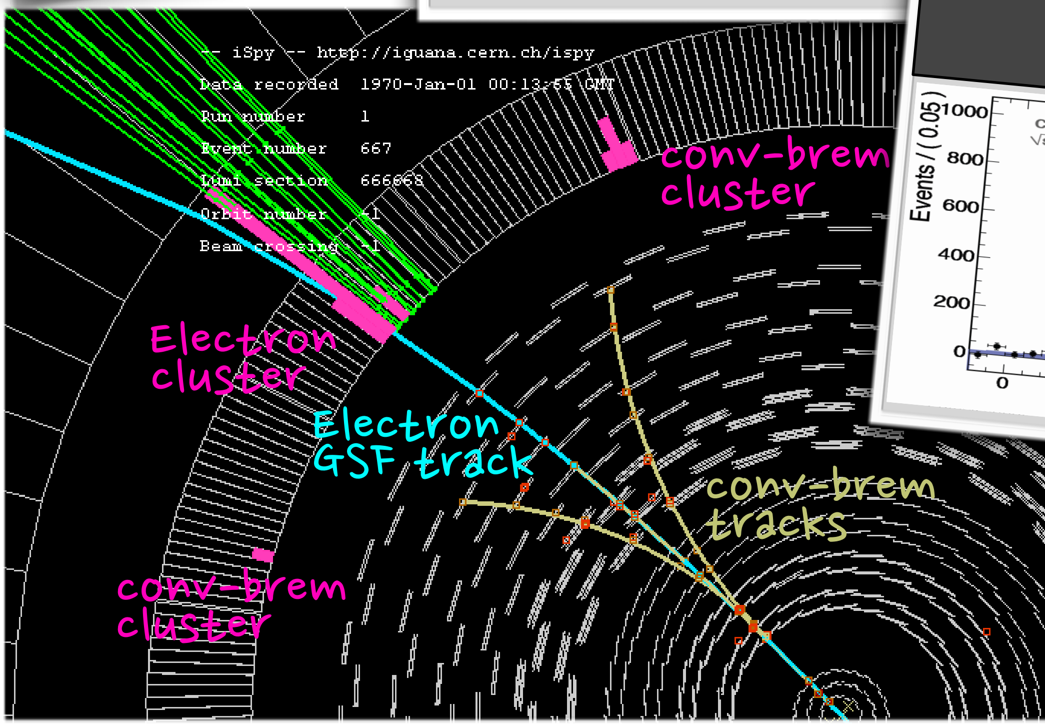

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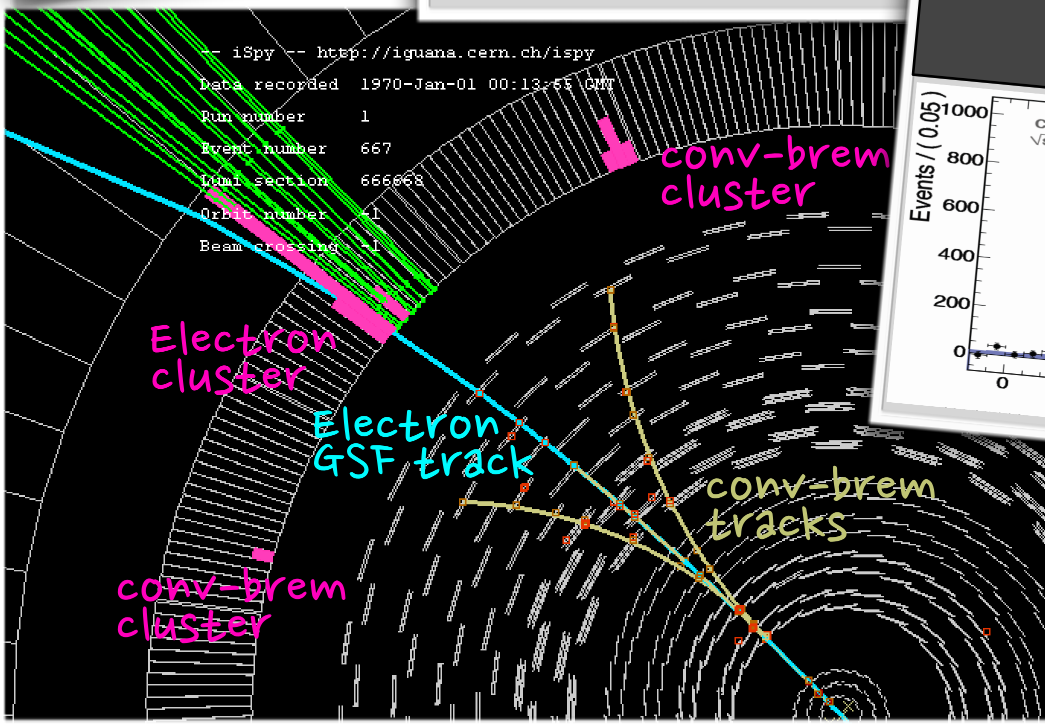
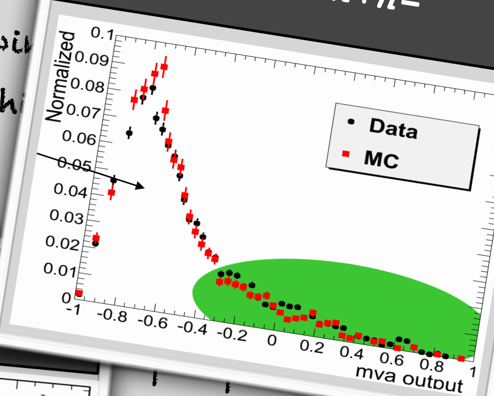


$K_S^0 \Rightarrow \pi^+\pi^-$



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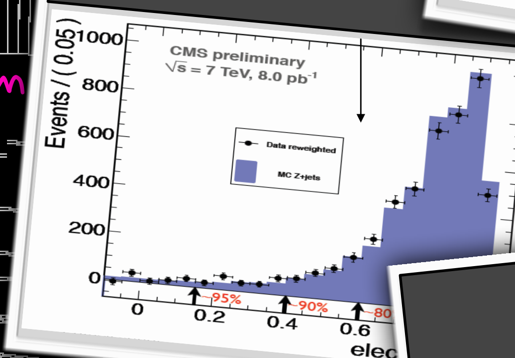
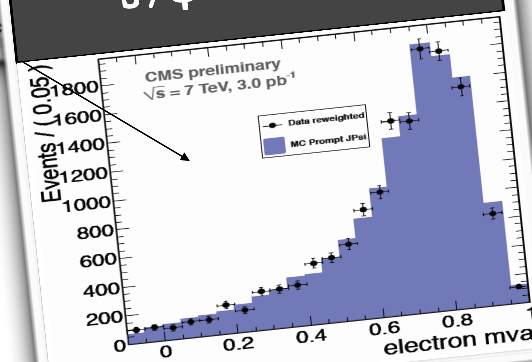


$J/\psi \Rightarrow e^+e^-$



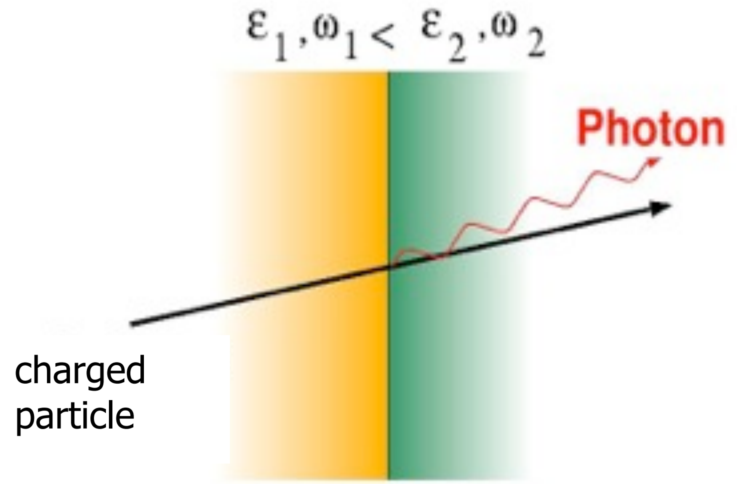
Electron Identification

Transition Radiation

- Local speed of light in medium with refractive index n is $c' = c/n$
- If particle's relative velocity v/c' changes, particle will radiate photons
  - change of direction -> Synchrotron rad
  - change of speed -> Bremsstrahlung rad
  - change of index n -> Transition rad
- Transition rad emitted whenever relativistic charged particle traverses border between two media having different dielectric constants $n = \sqrt{\varepsilon}$
- Emitted energy proportional to boost γ of particle
  - can discriminate electrons from pions!
  - (also discriminate hadrons at high energy)

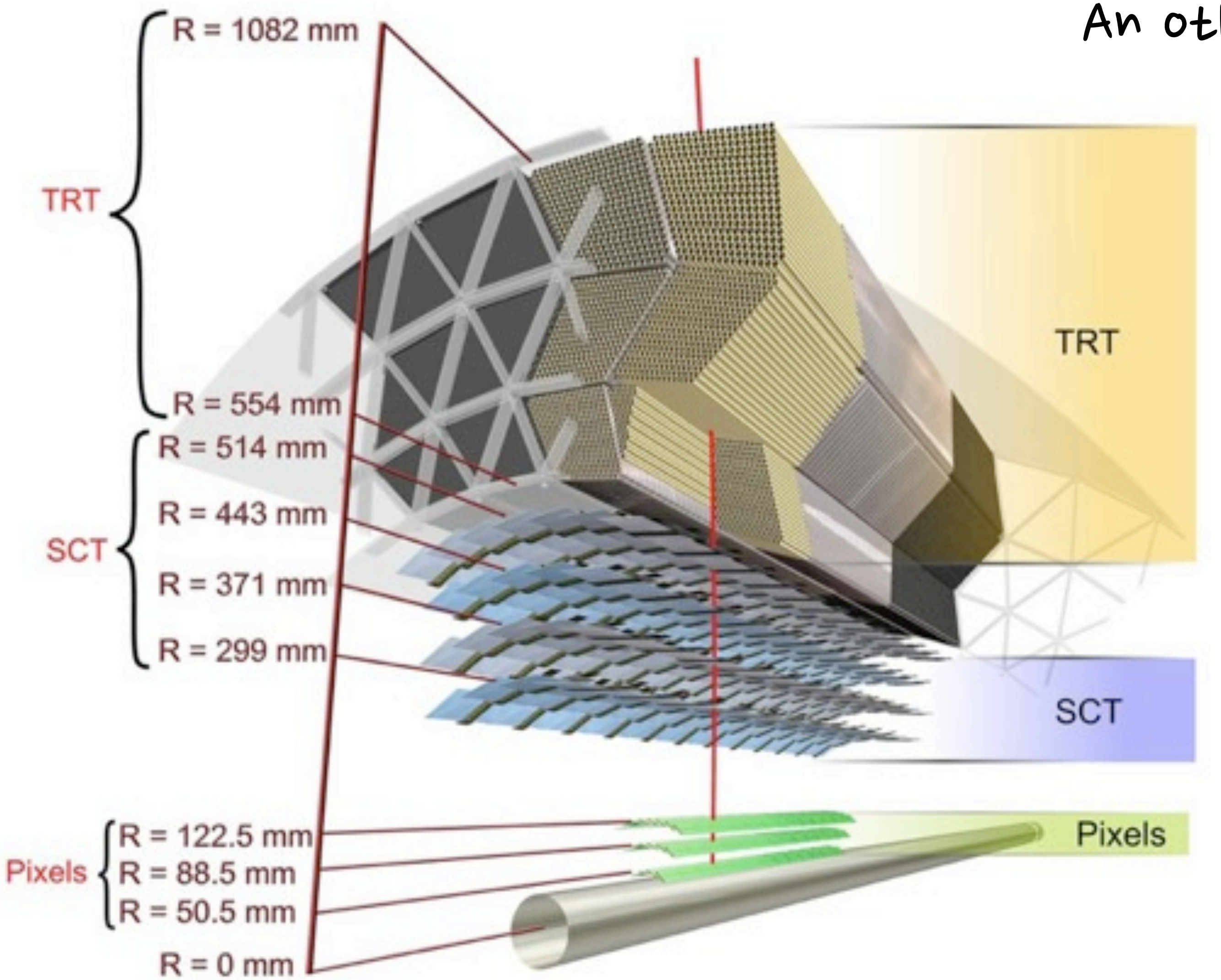
An other way...

Recall:



Dedicated Electron ID

An other way...



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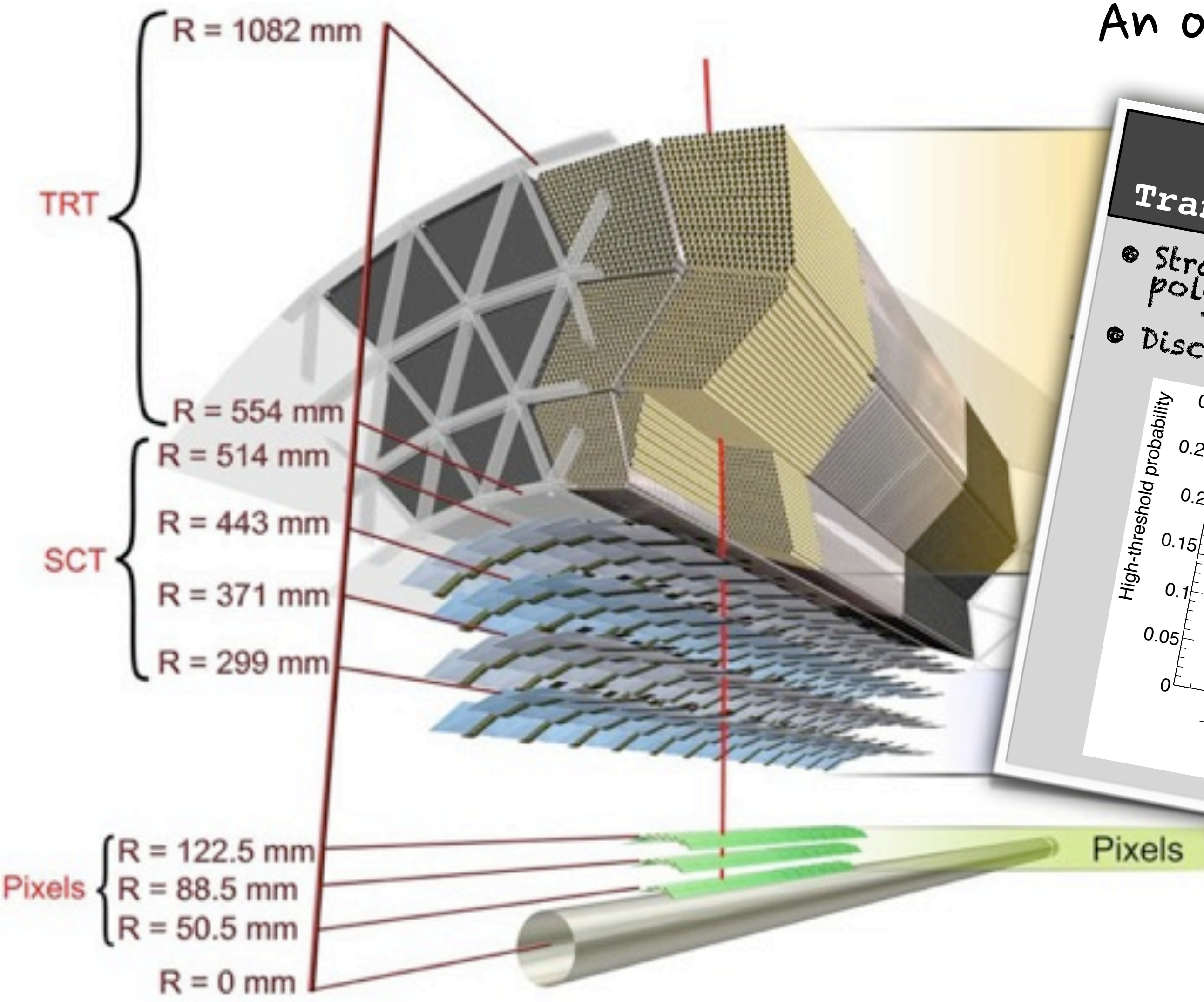
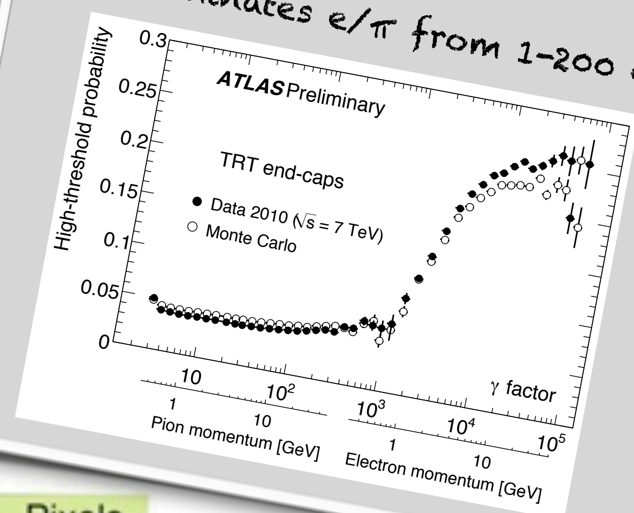


An other way...

ATLAS Transition Radiation Tracker

- Straw tubes interleaved with polypropylene radiator
- Discriminates e/π from 1-200 GeV



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Electron Identification

An other way...

EM calorimeter clusters

Form "Super" Clusters

- Different strategy to recover energy of brem photons and conversion pairs
- Seed clusters can be
  - nearest neighbor algorithm
  - rectangular window (brem recovery)
- SuperCluster
  - collect clusters in long φ-road
- Classify cluster as electron, photon, or converted photon
  - match cluster to track(s)
  - Use MVA (cluster shape, etc)
- Calculate energy & direction
  - Energy weighted sum
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this way works well for isolated electrons; tends to miss non-isolated ones

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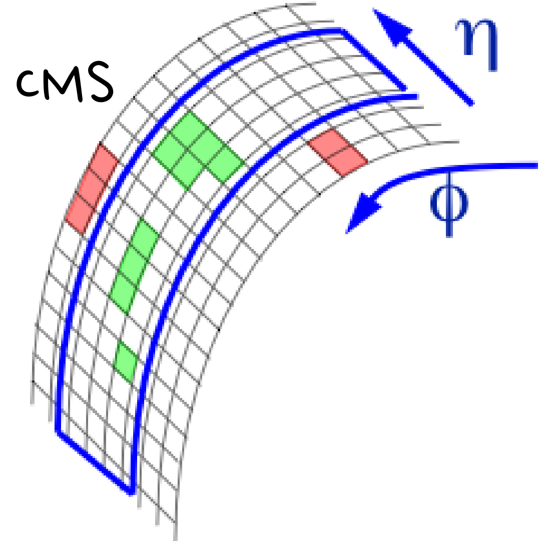

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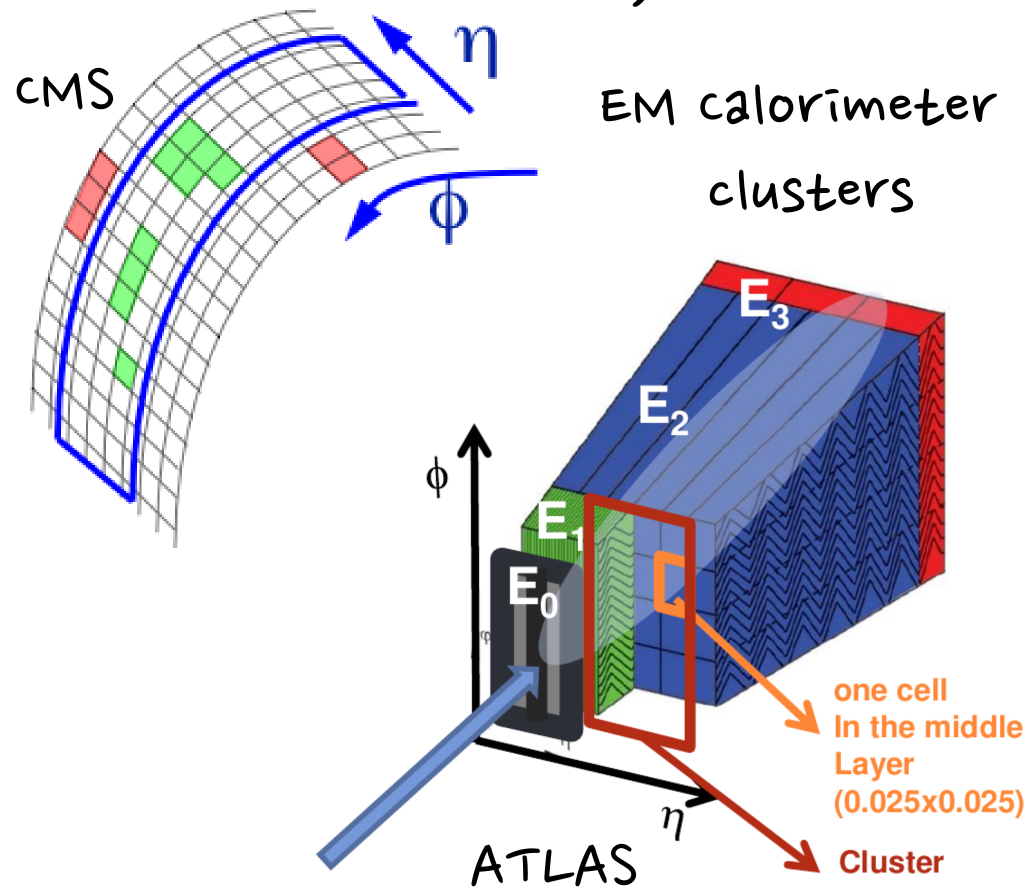

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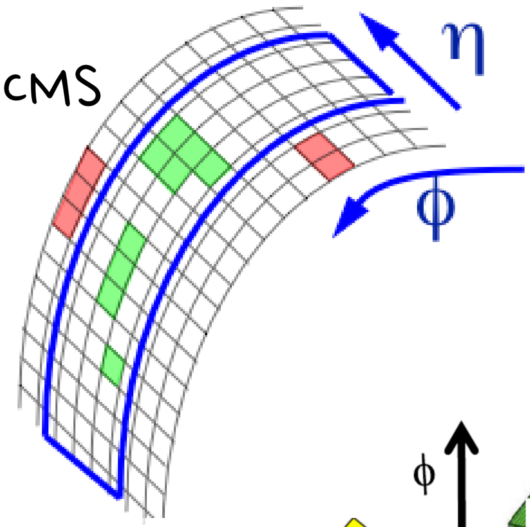

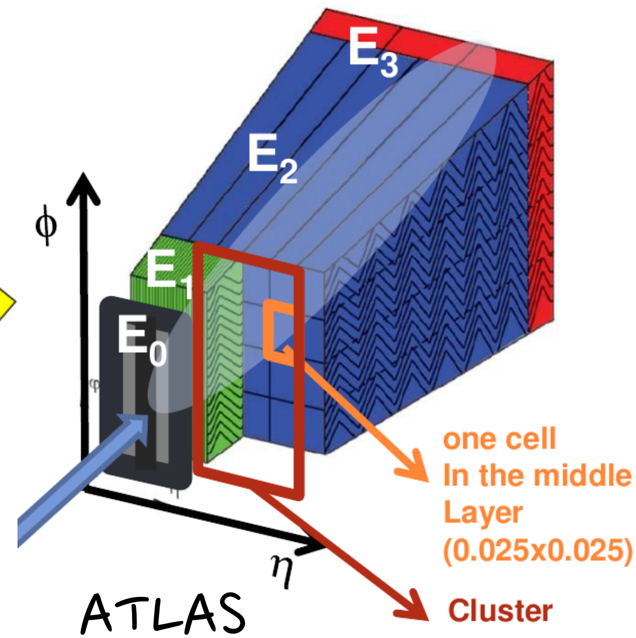

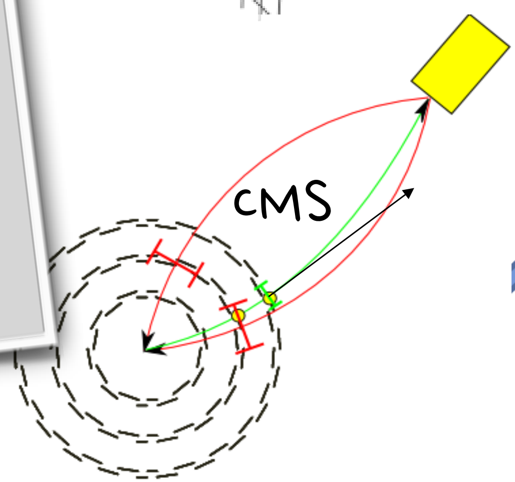

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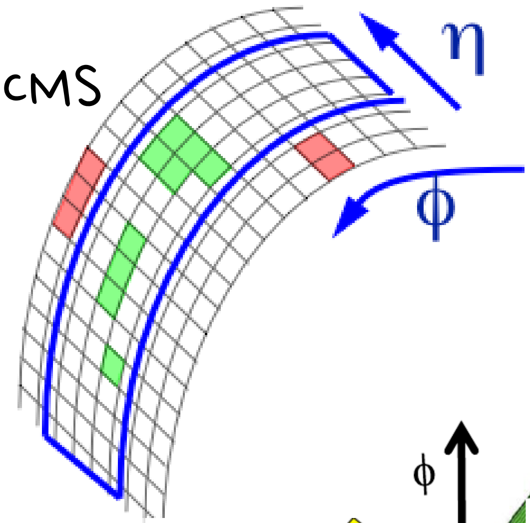
Discriminating electrons

- electrons vs hadrons
  - e.g. fraction of TRT hits, fraction of energy in layer 1, etc
- electrons vs conversions
  - e.g. number of hits in innermost pixel layer

An other way...



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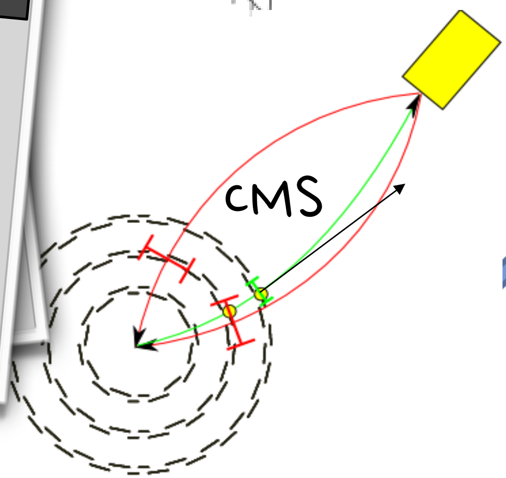

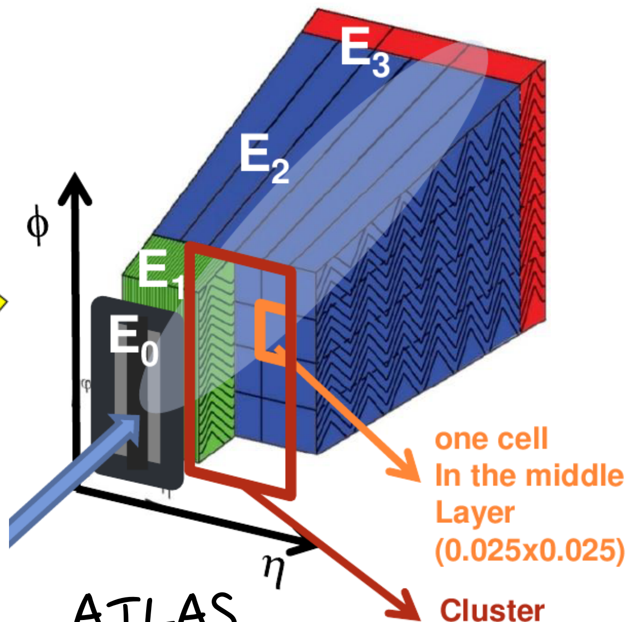

ATLAS

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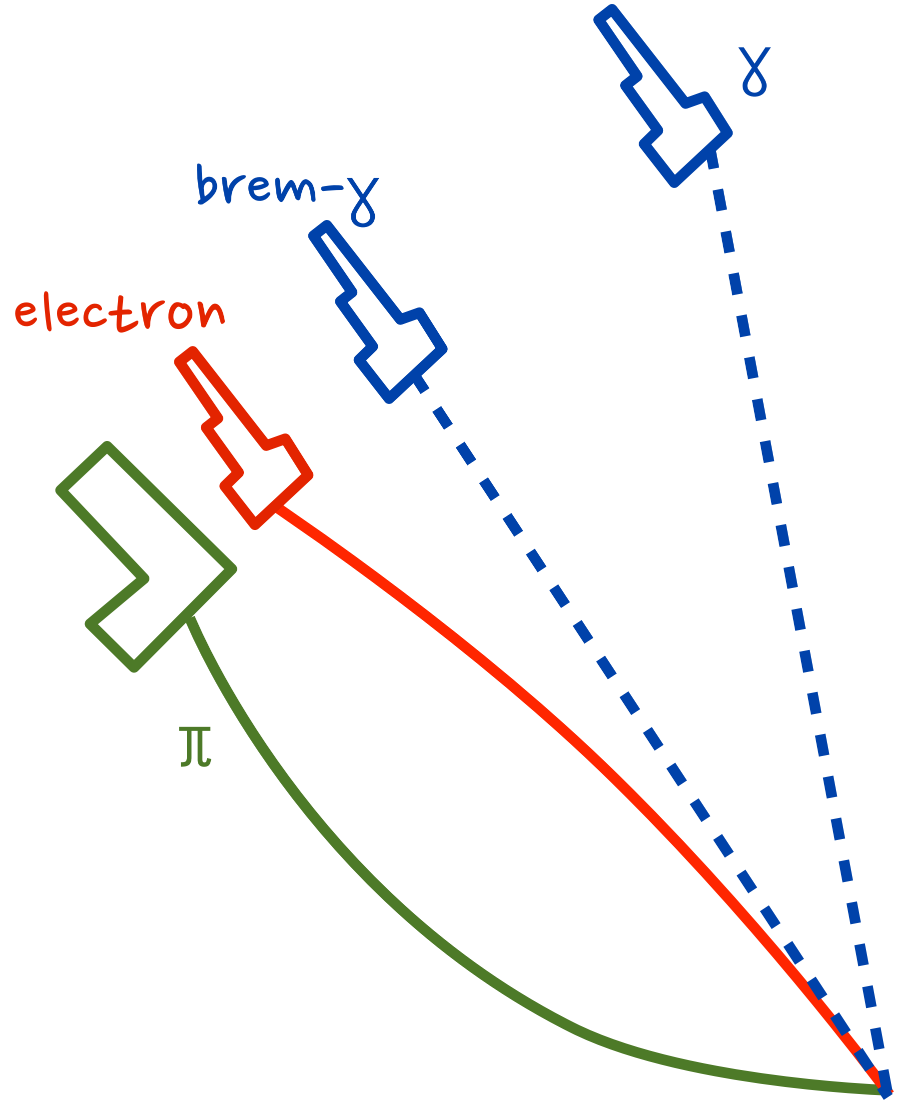
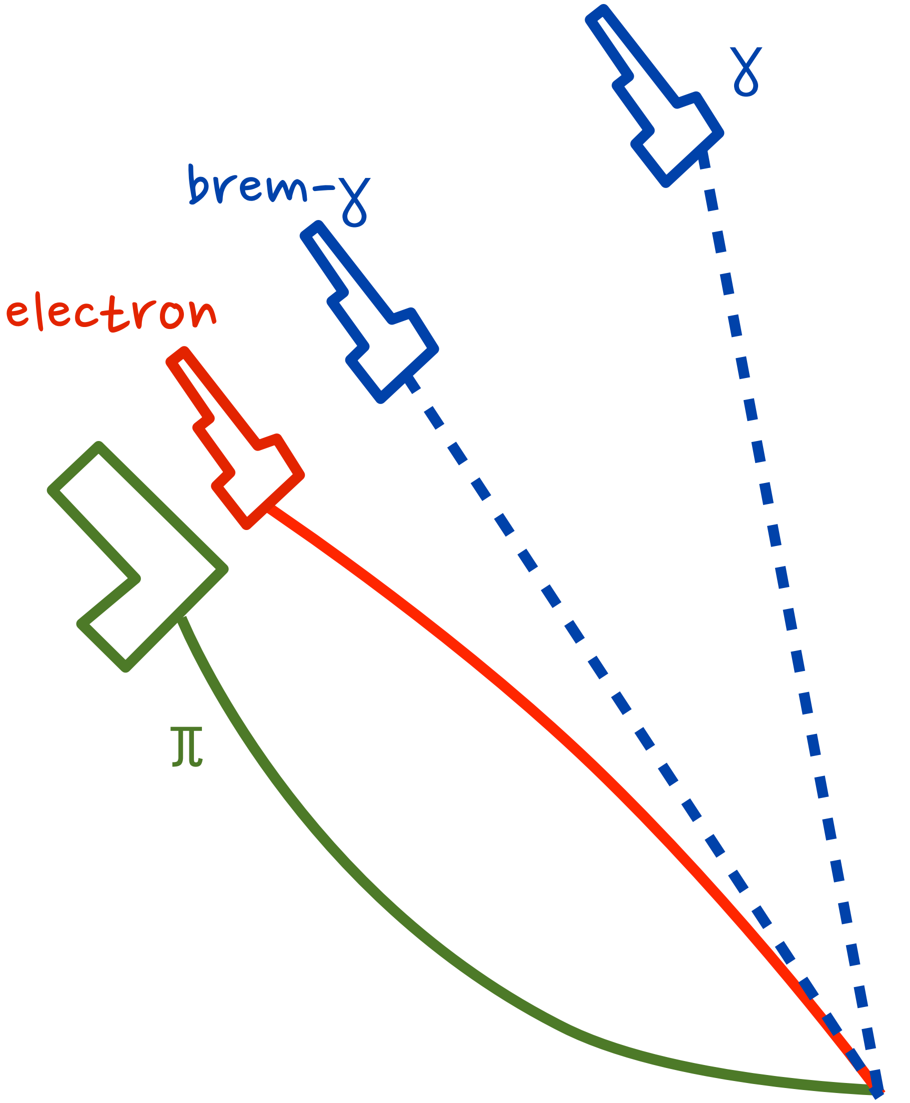


Isolation from other particles

- Use simple angular distance $\Delta R = \sqrt{(\Delta\varphi^2 + \Delta\eta^2)} \approx 0.3$
  - between electron and surrounding particles



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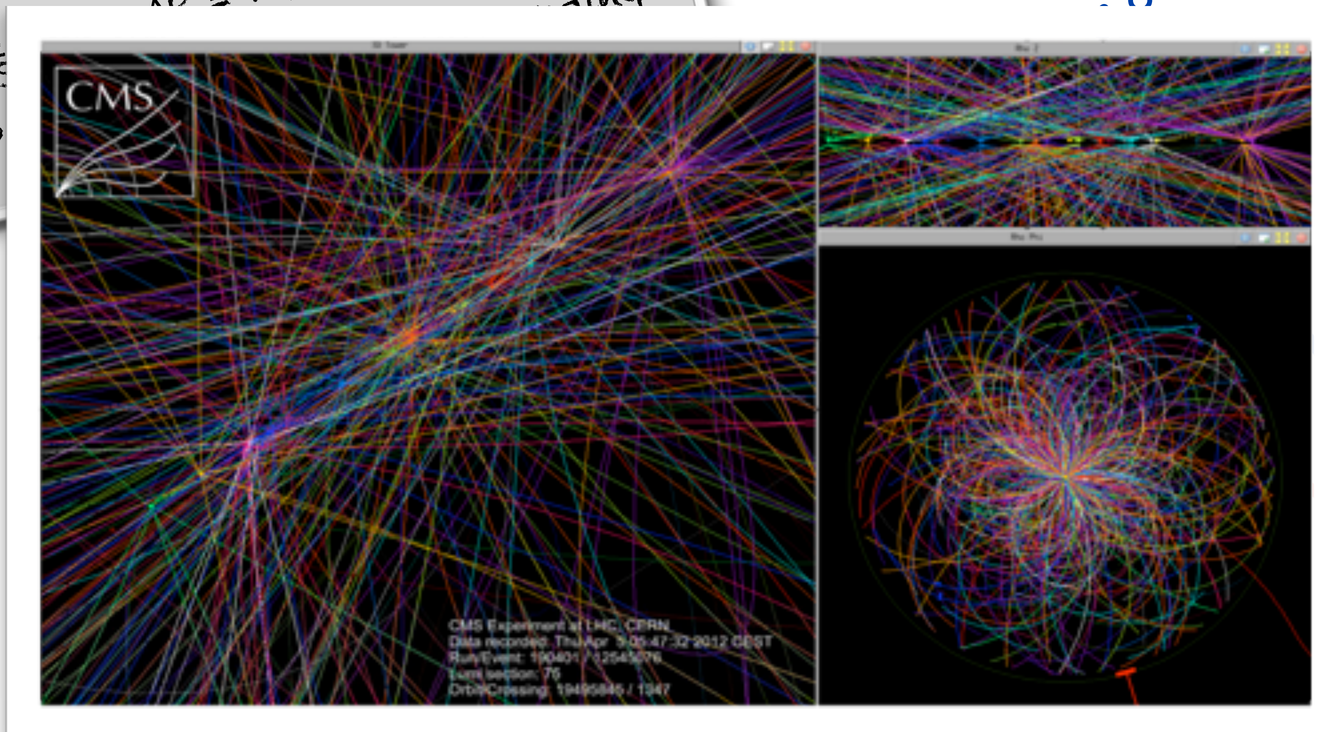

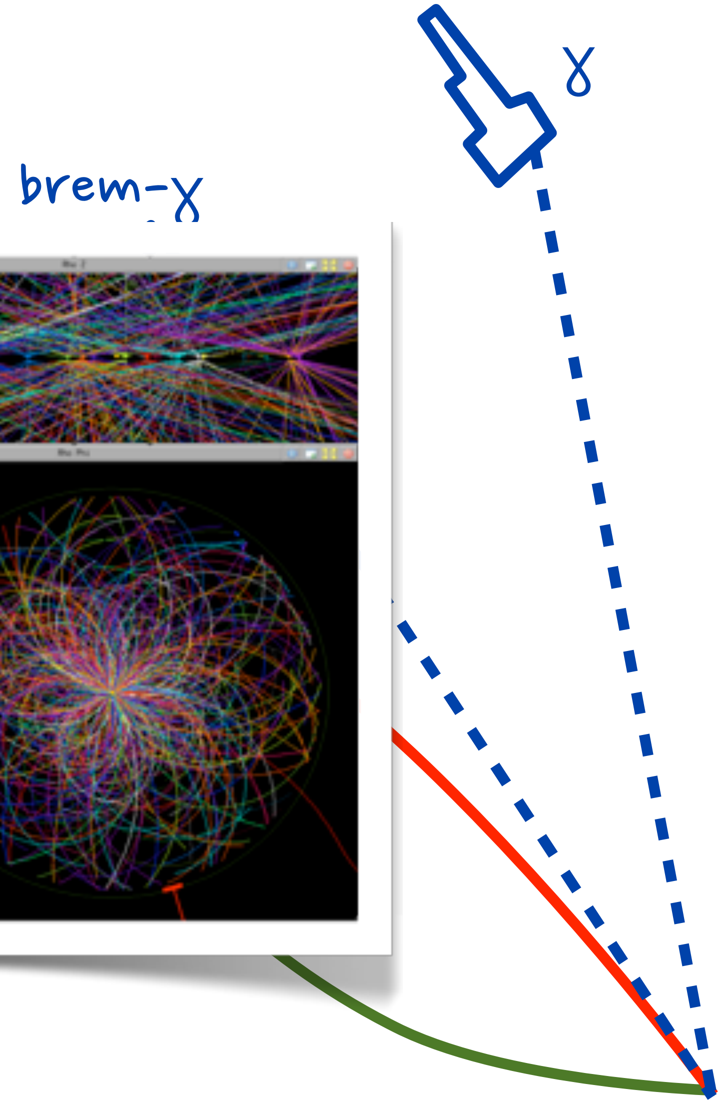

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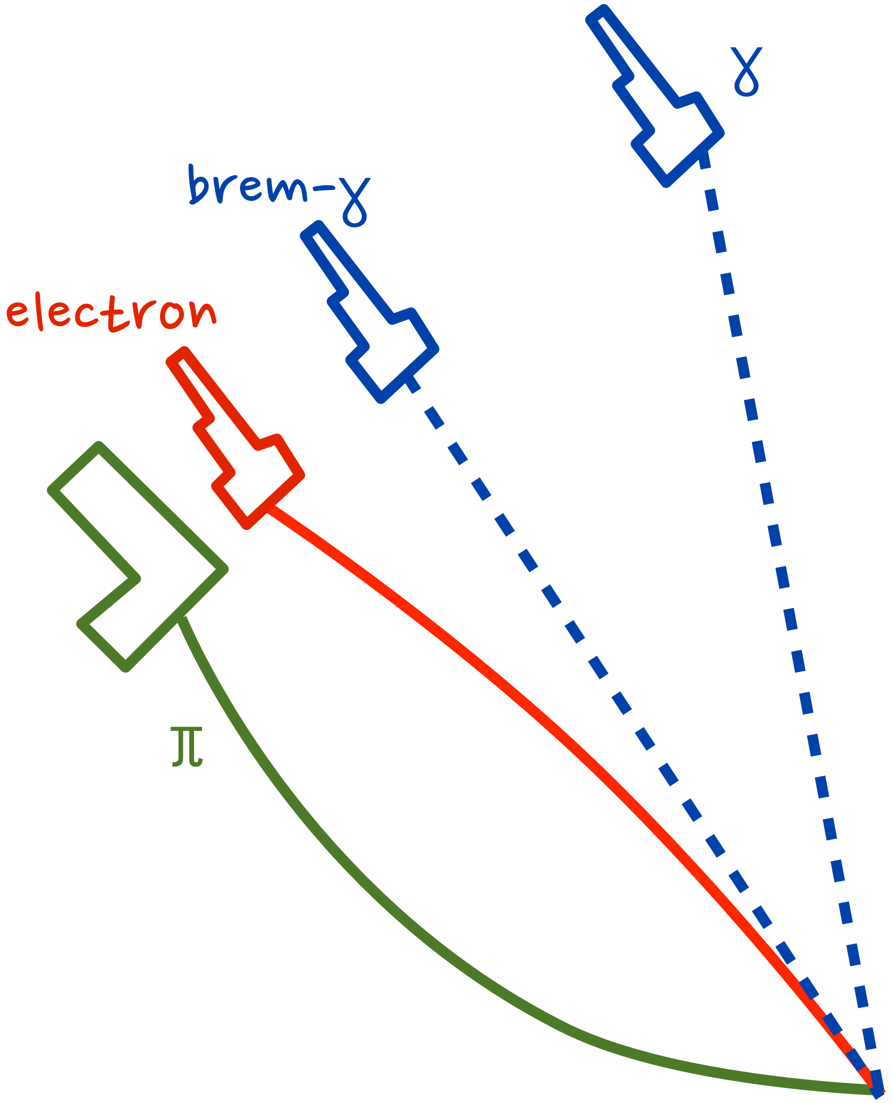

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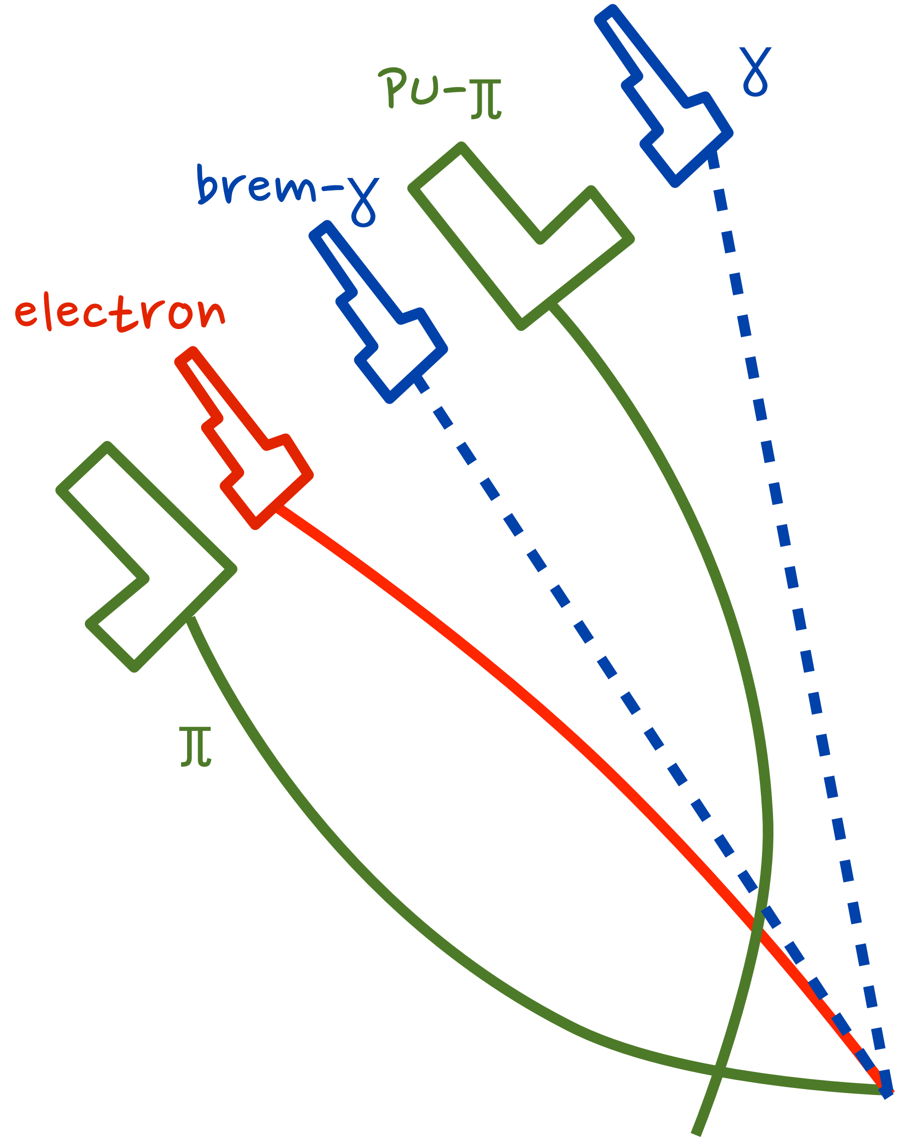

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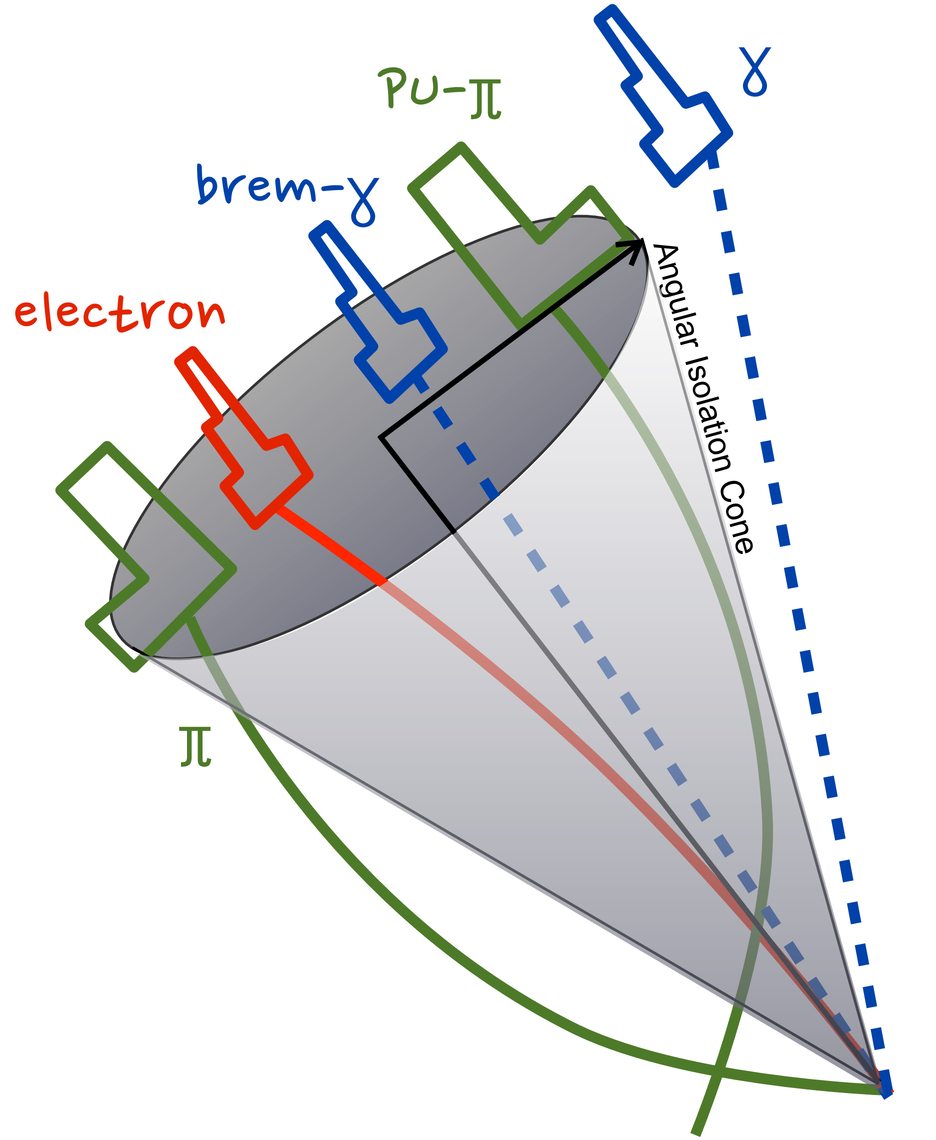

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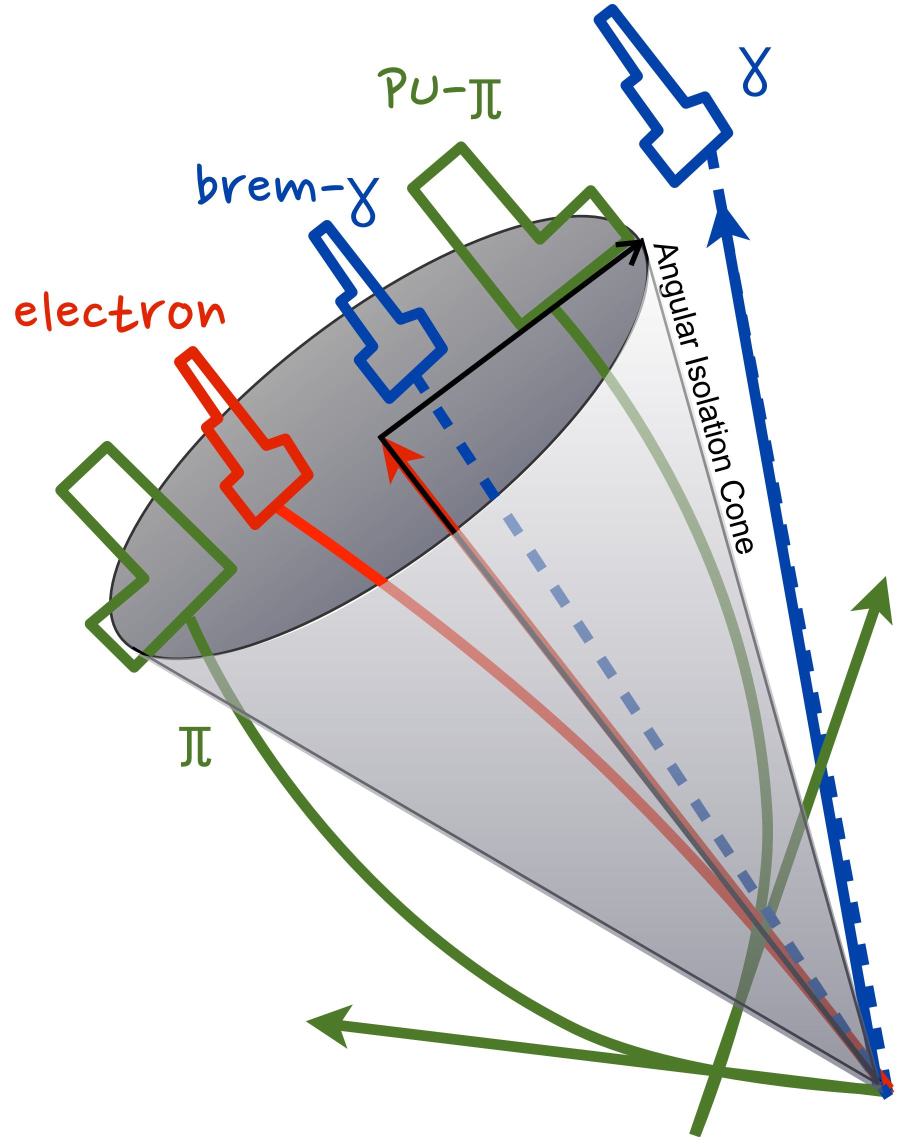

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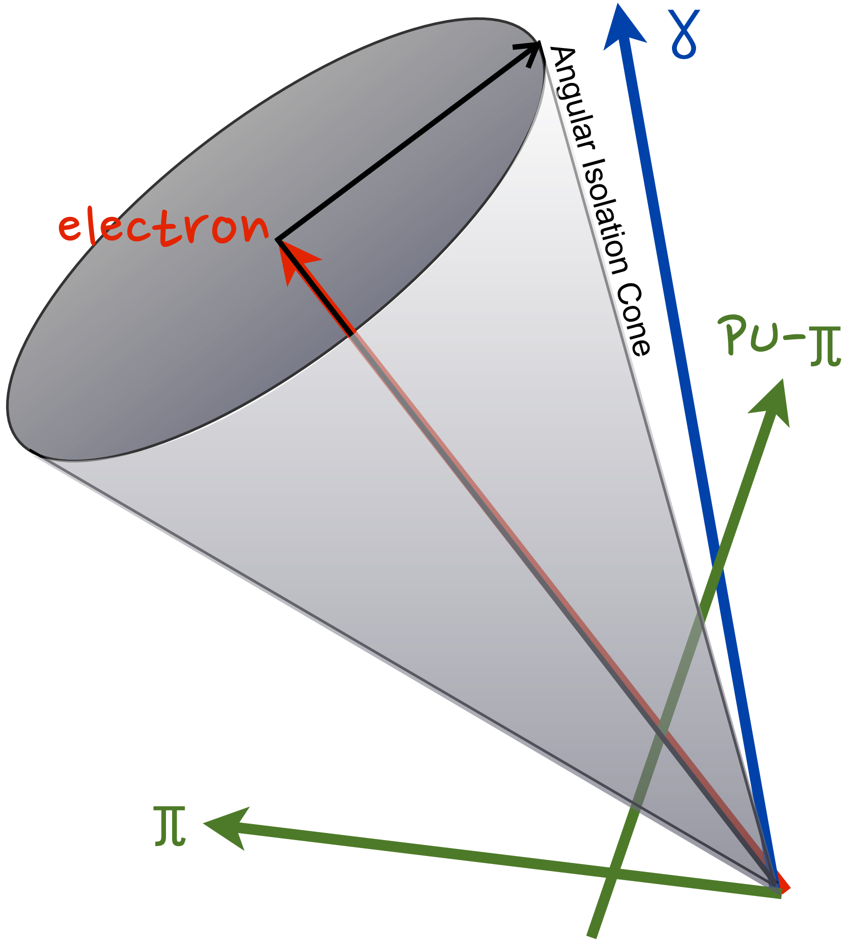

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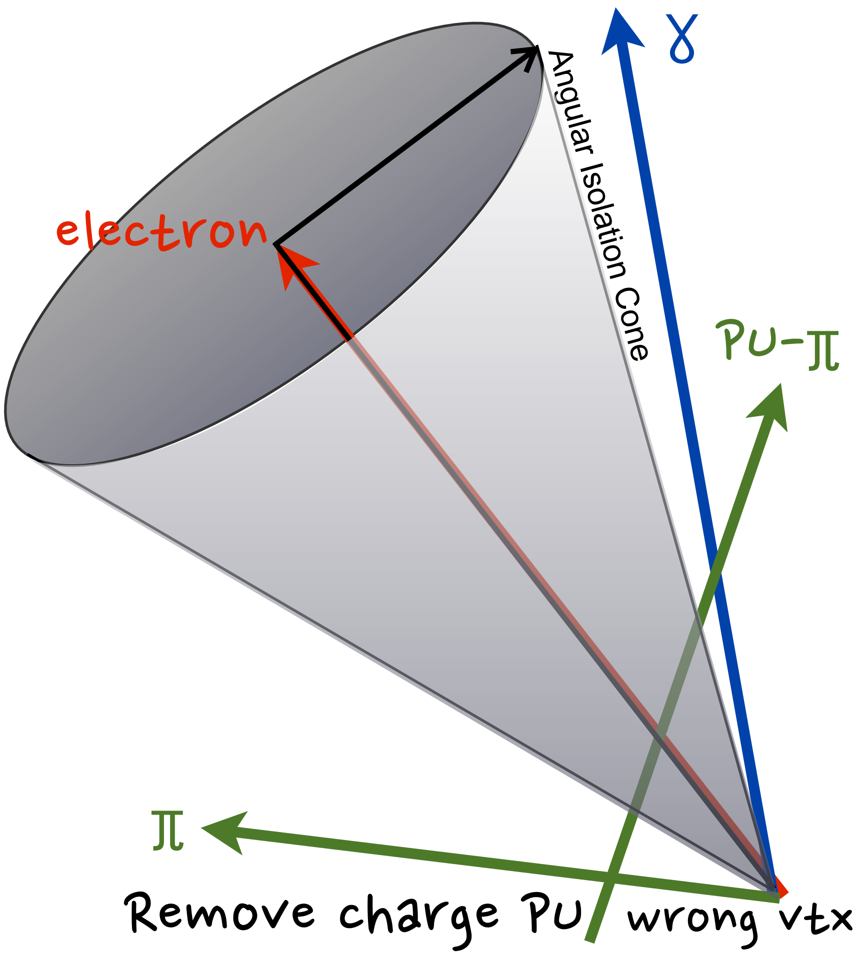

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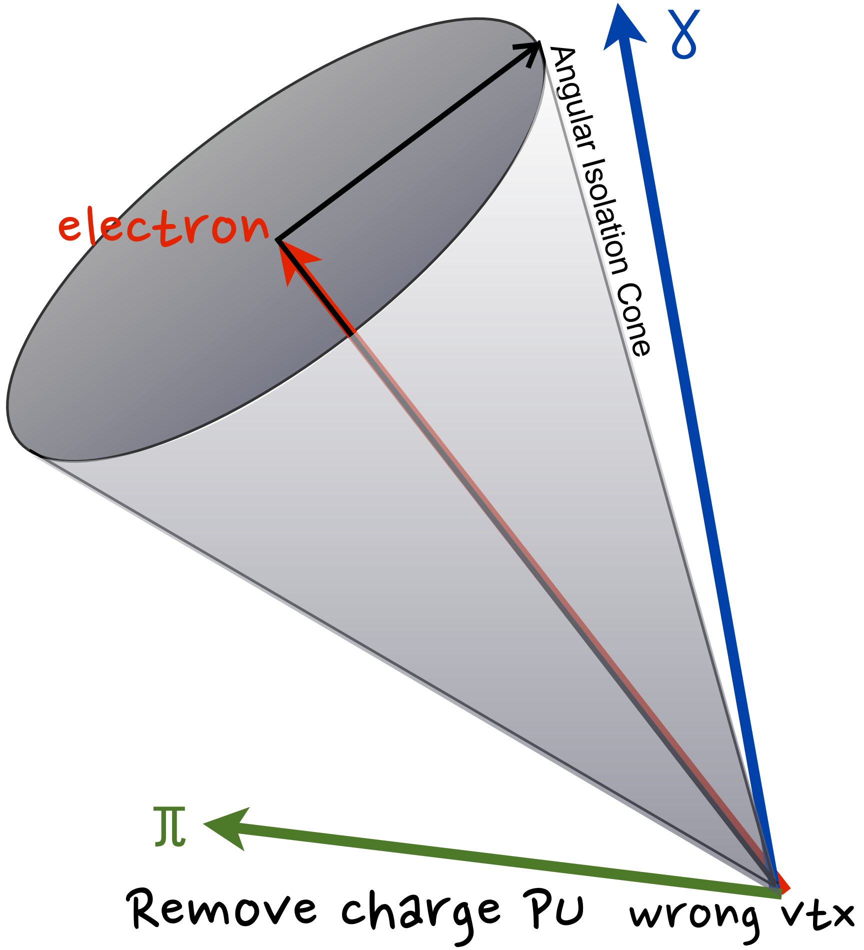

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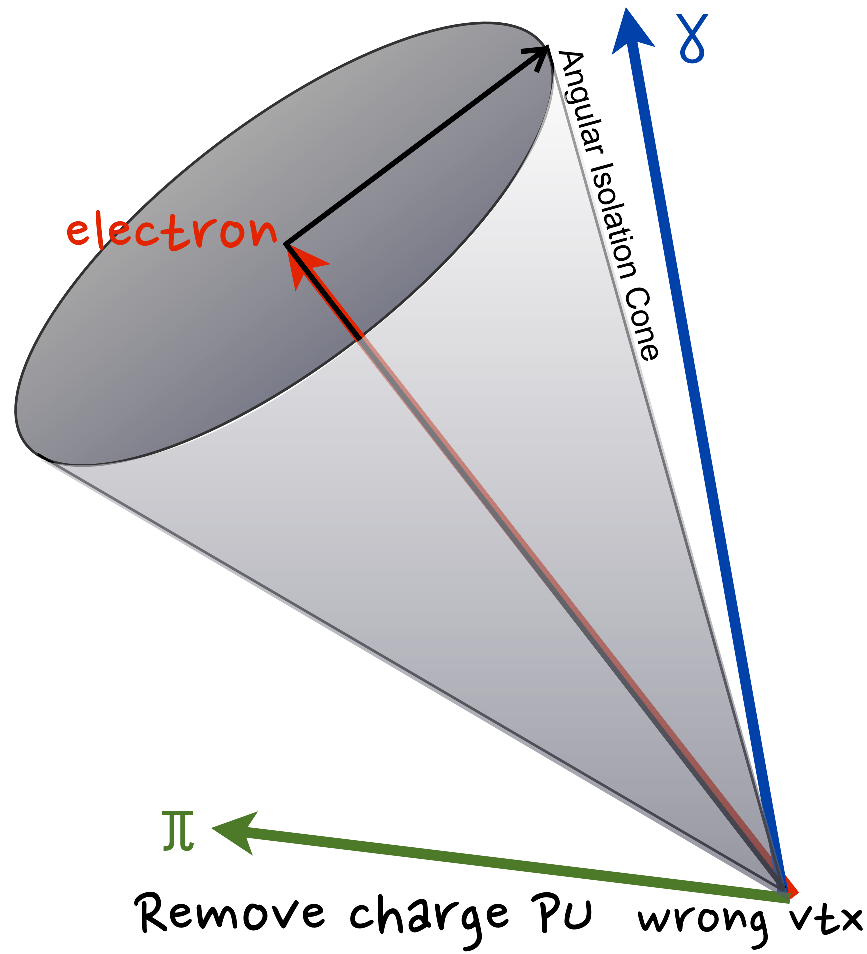

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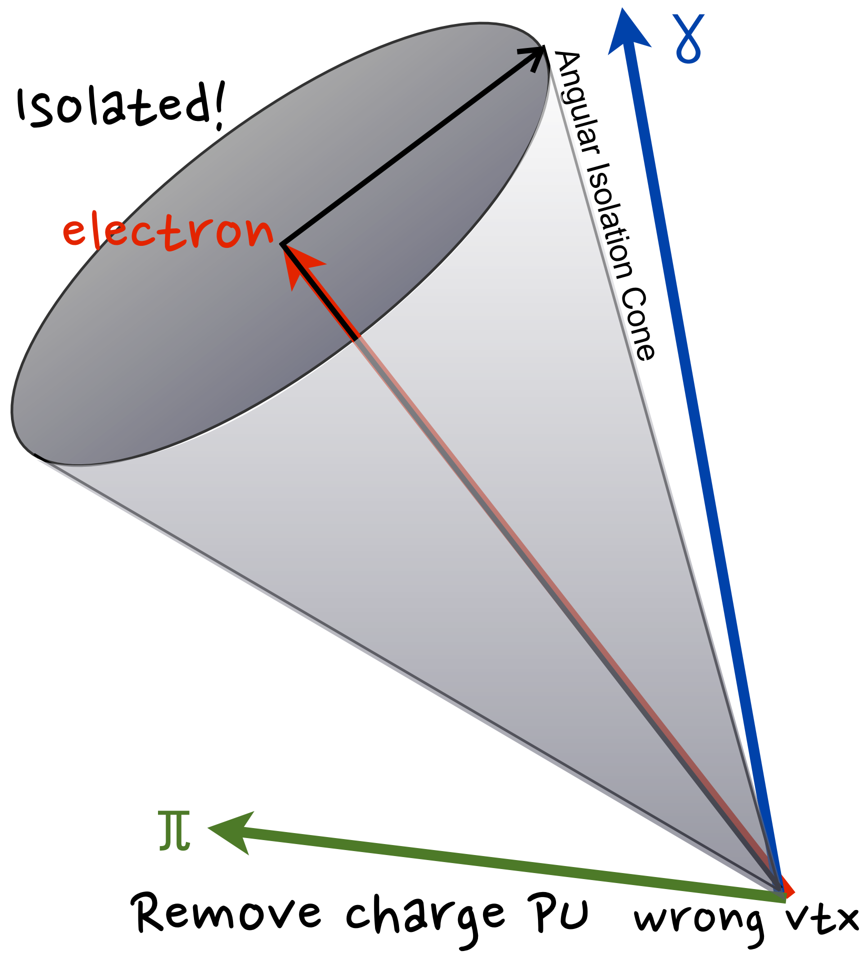

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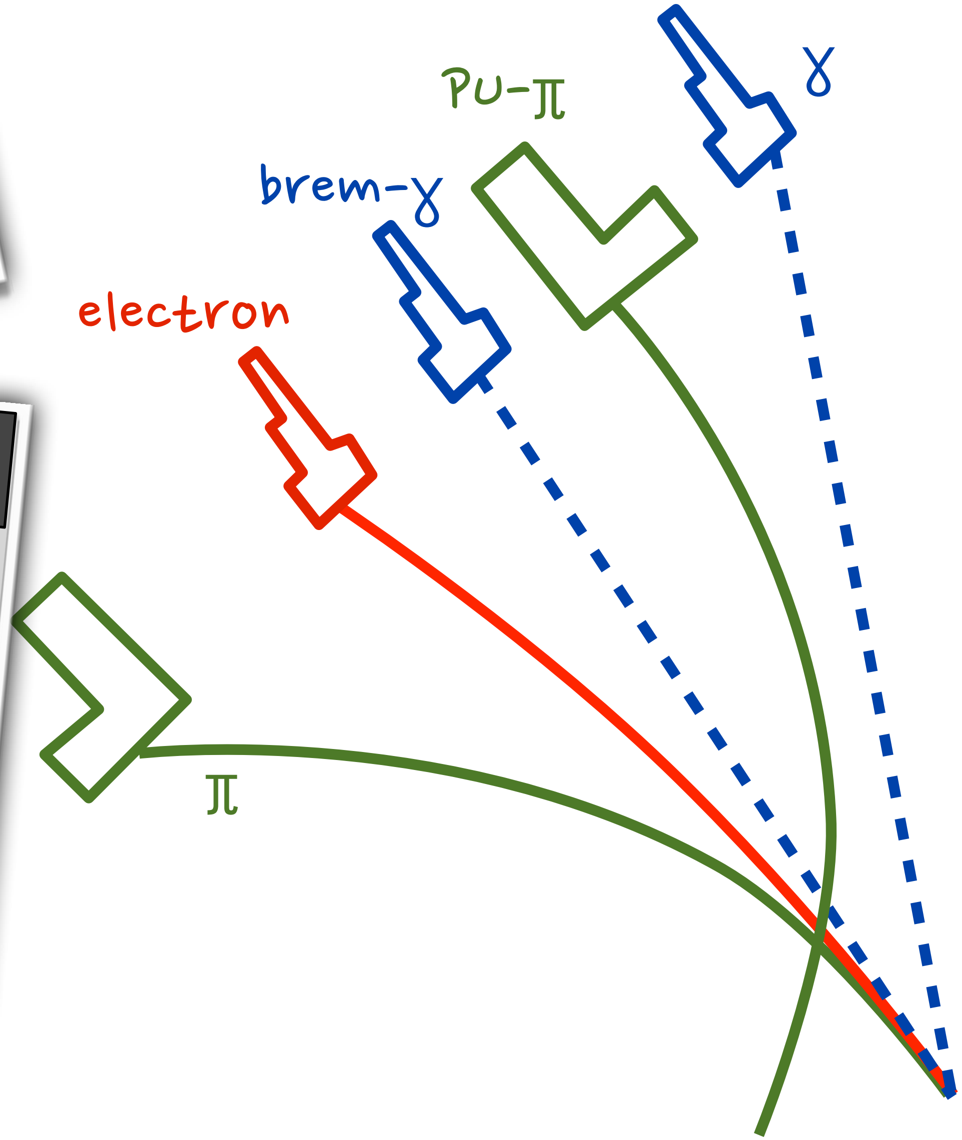

R. Cavanaugh, HCPSS 2012

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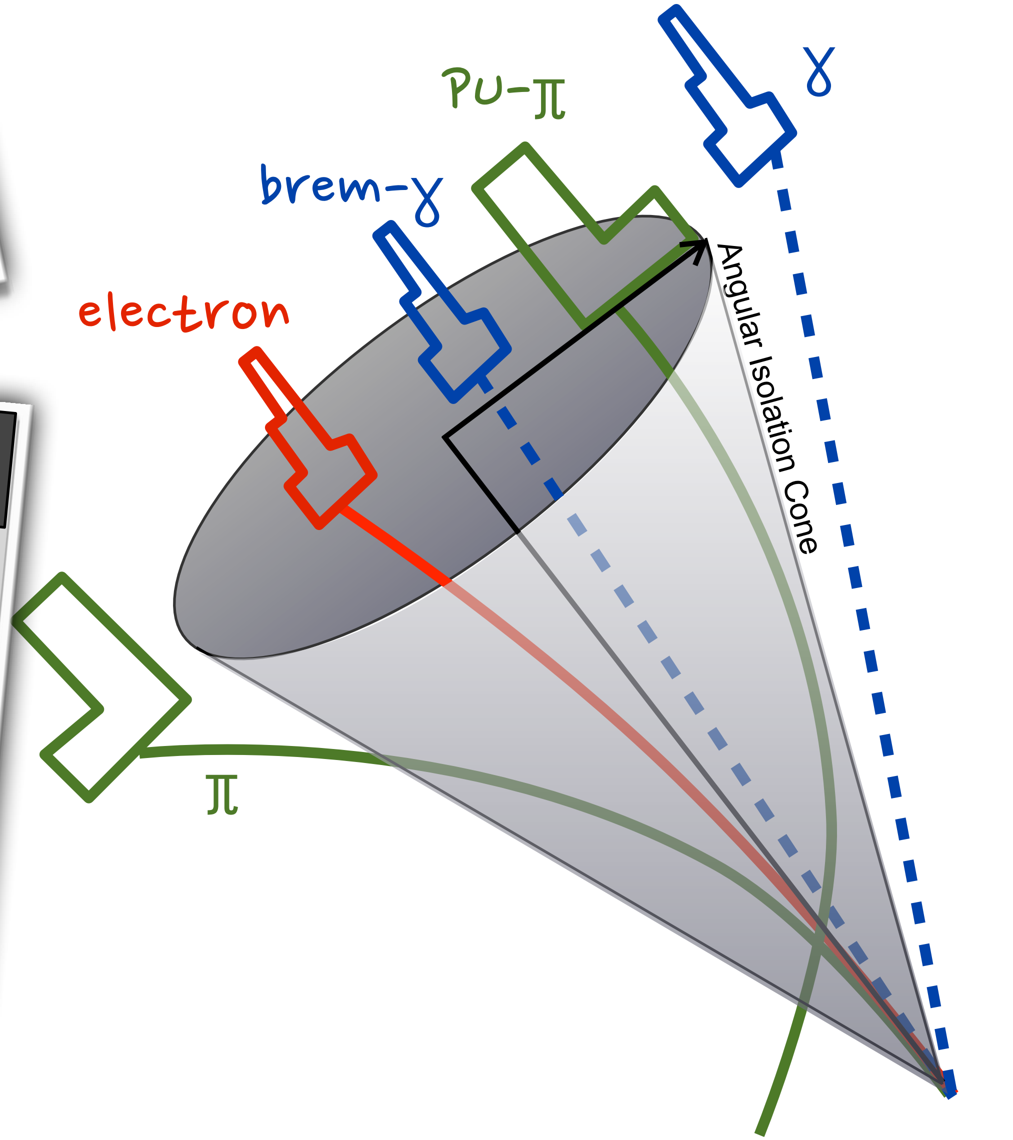

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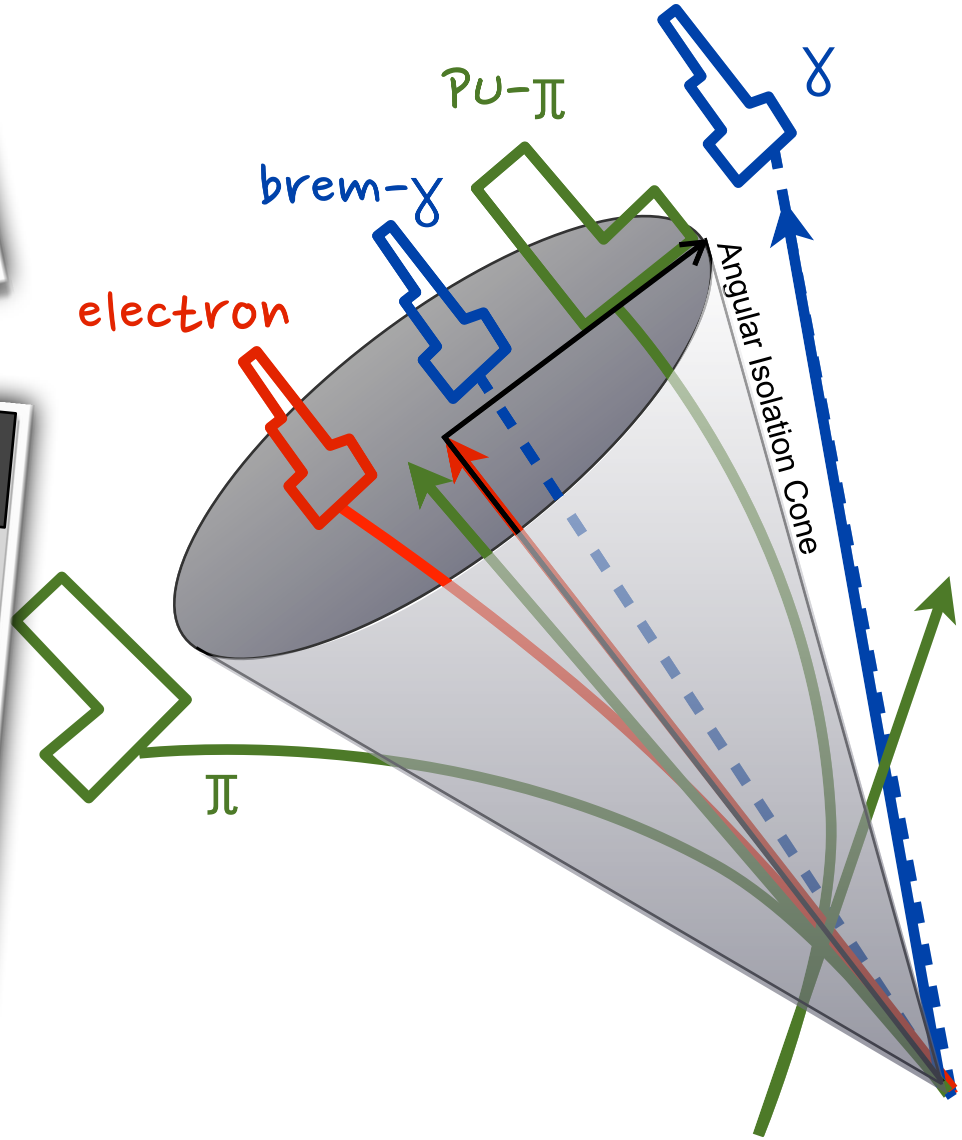

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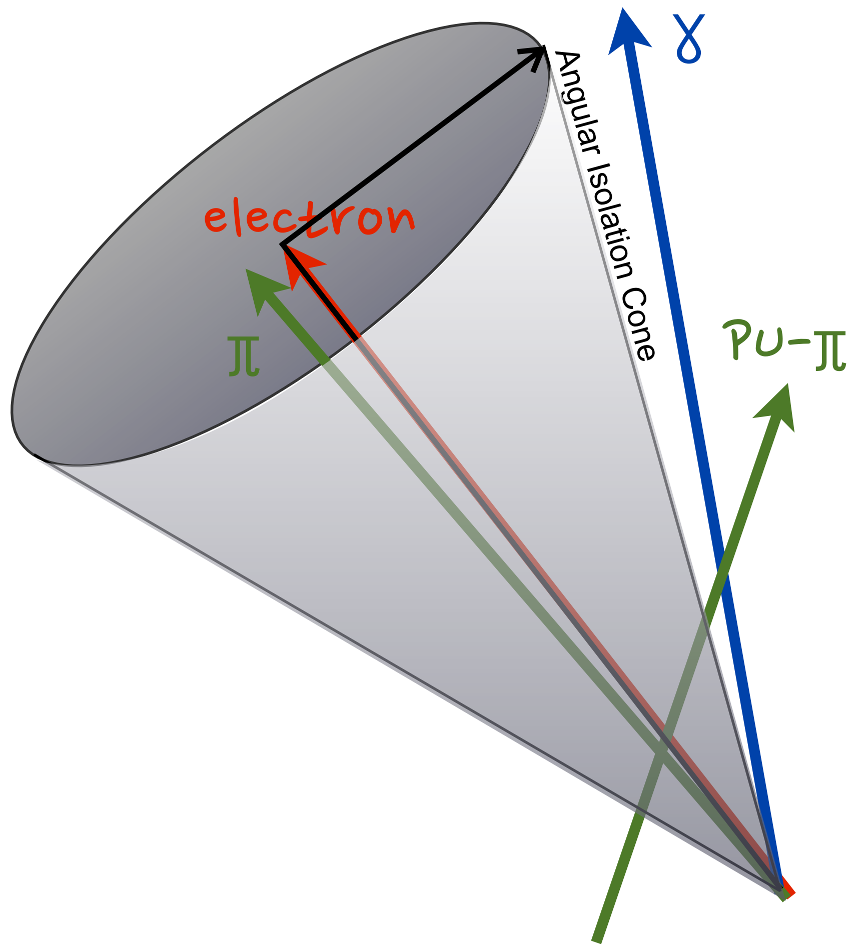

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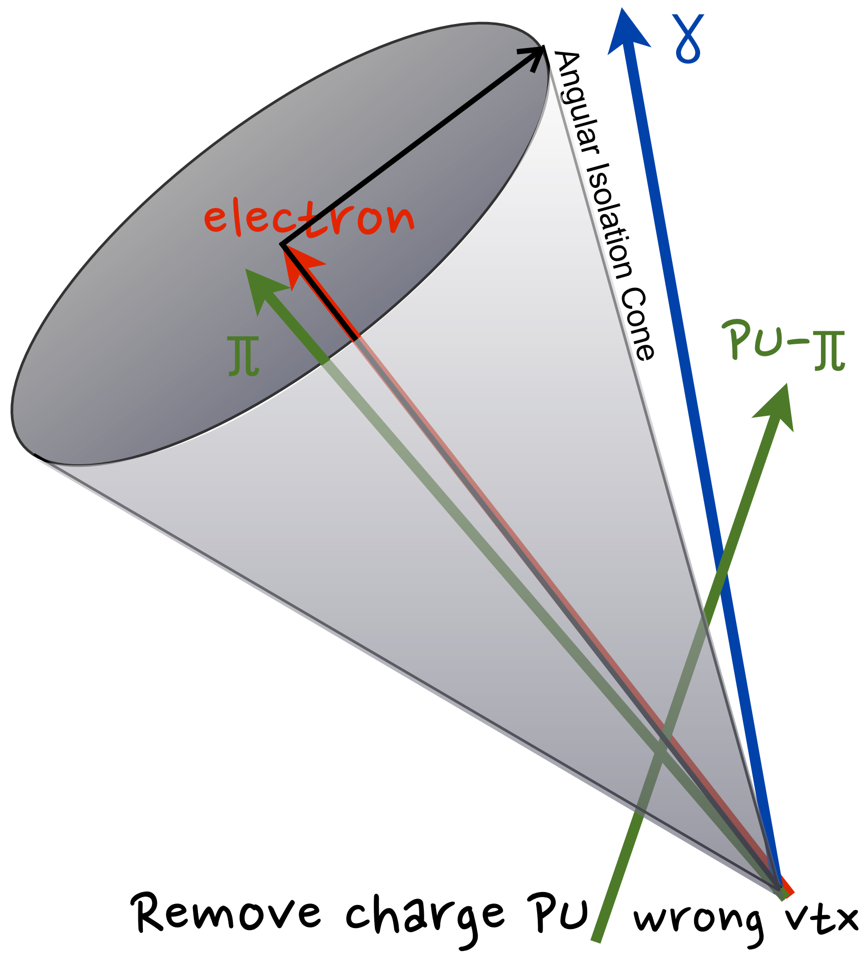

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LPC LHC Physics Center

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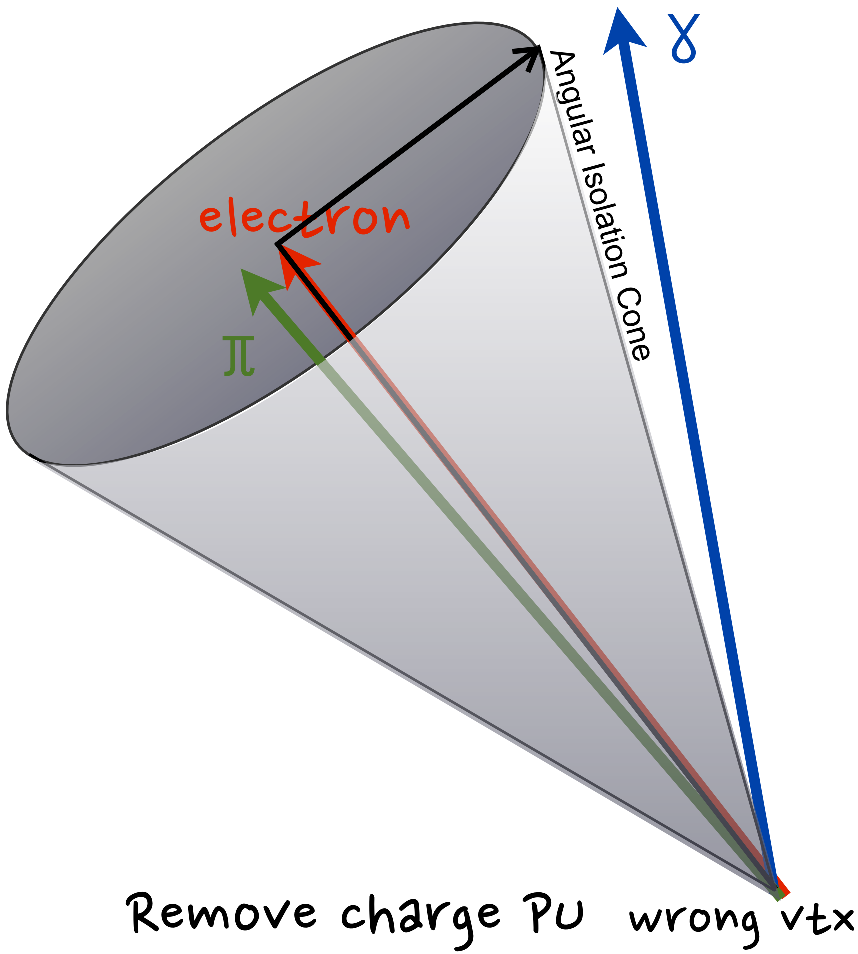

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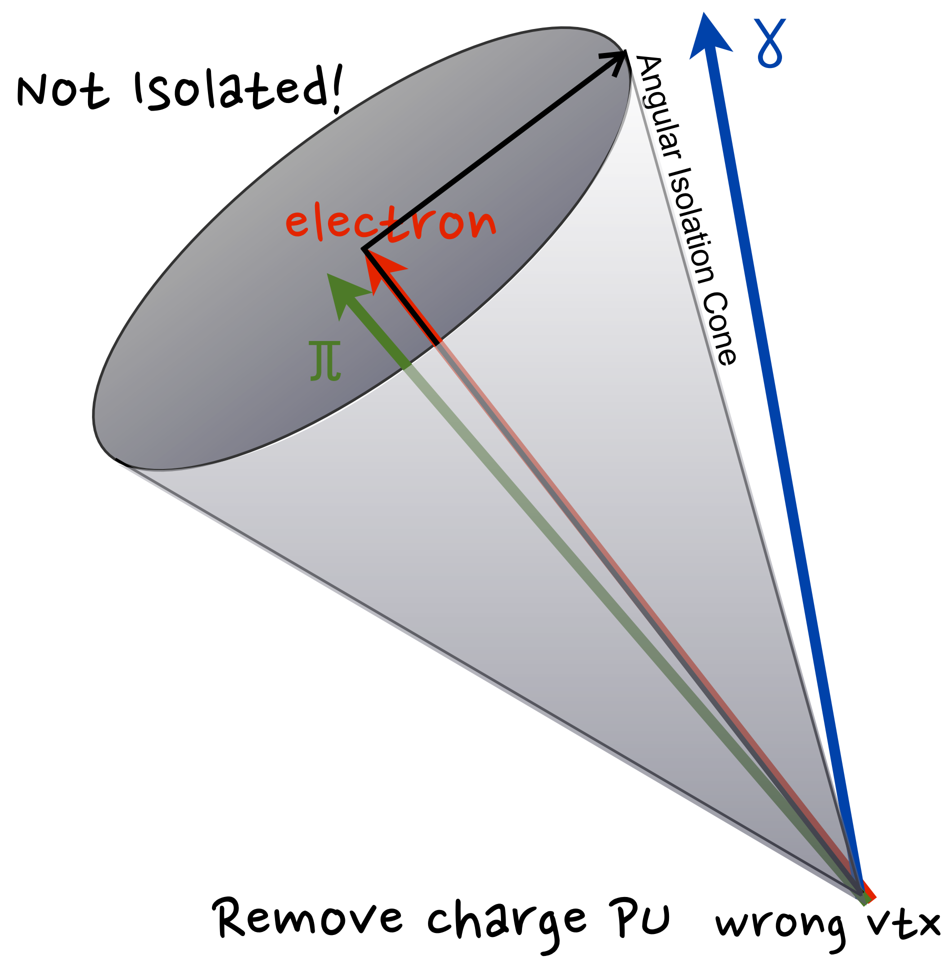

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- Tag: Select a well reconstructed, tight selected electron from a sample of single electron triggered events
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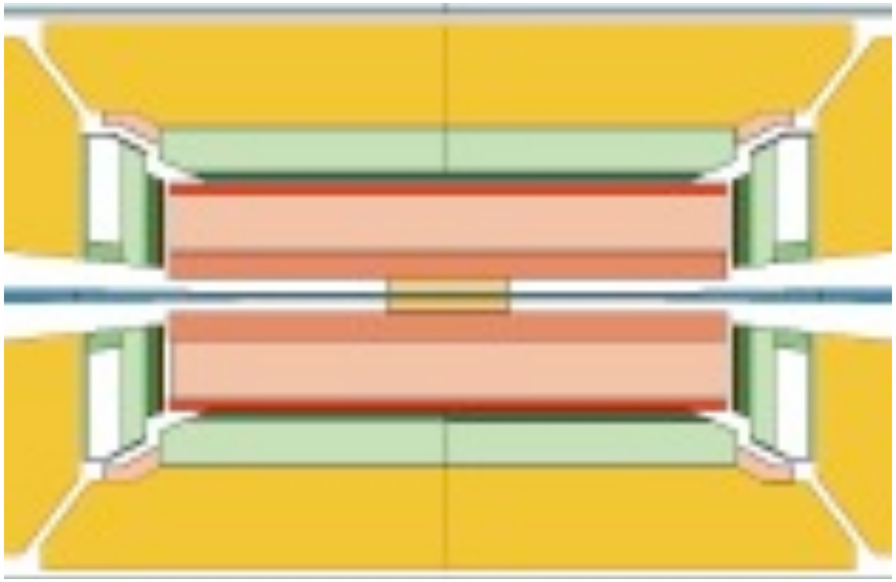

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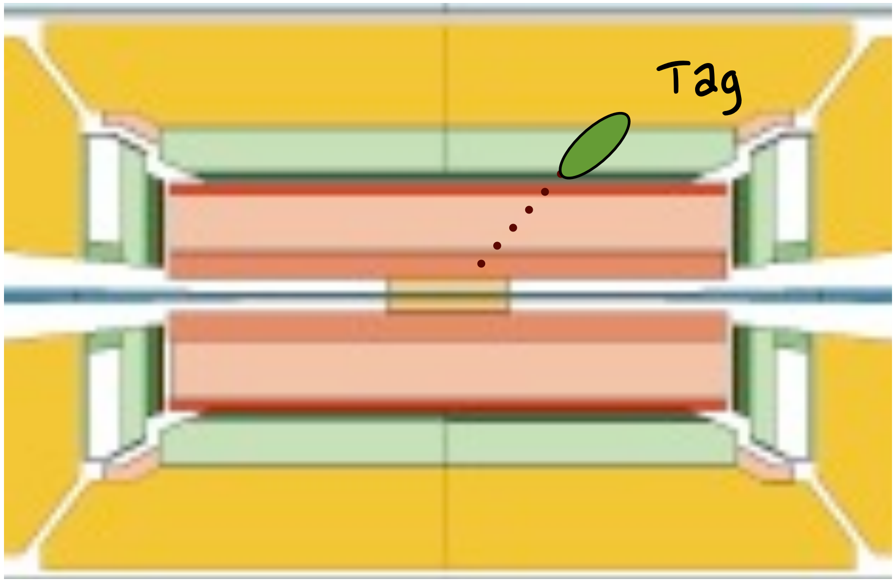

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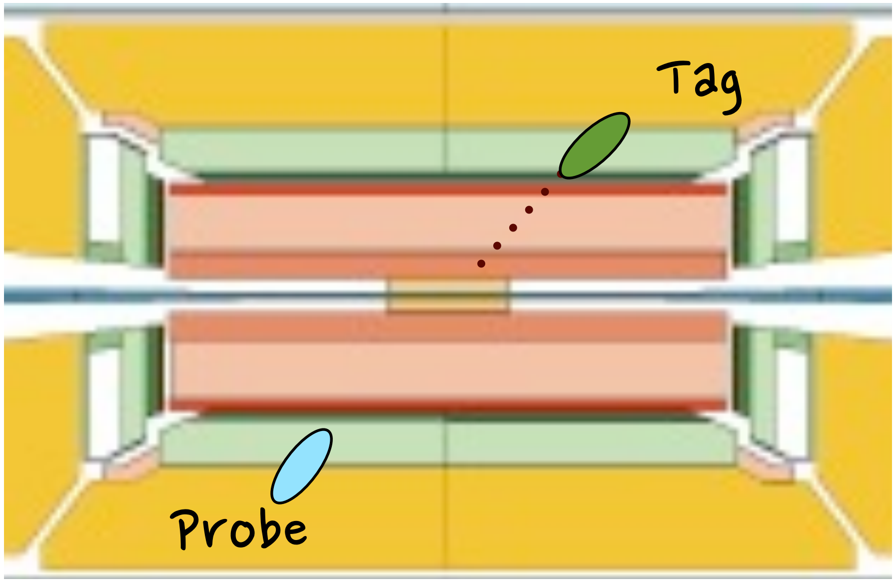

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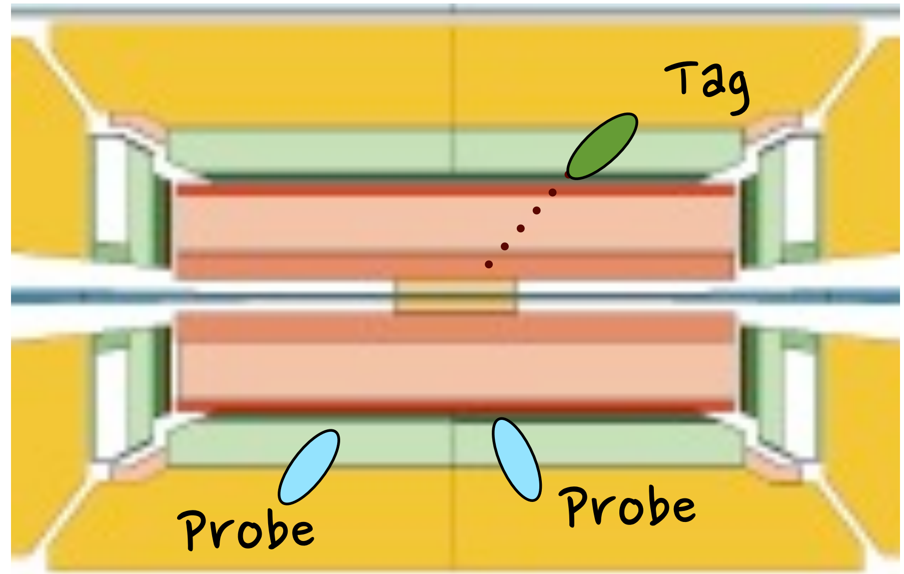

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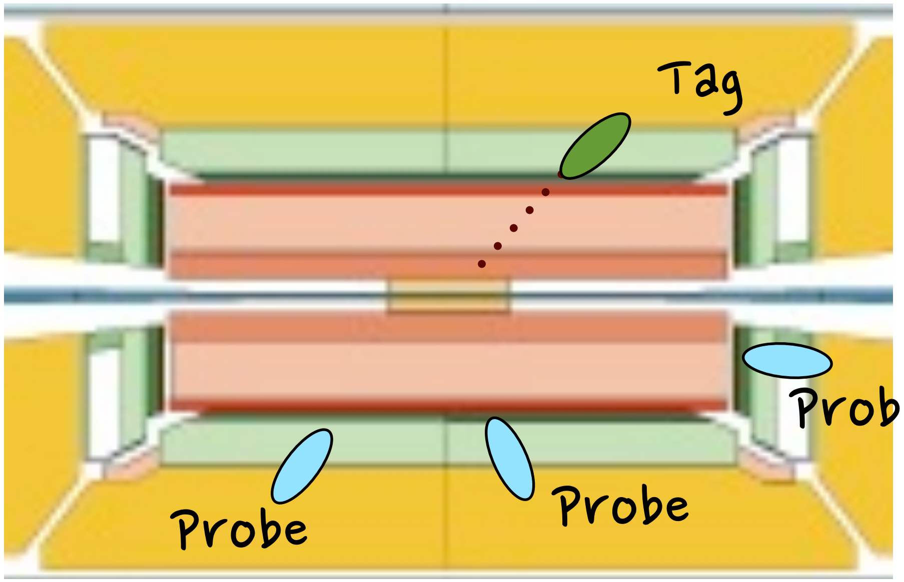

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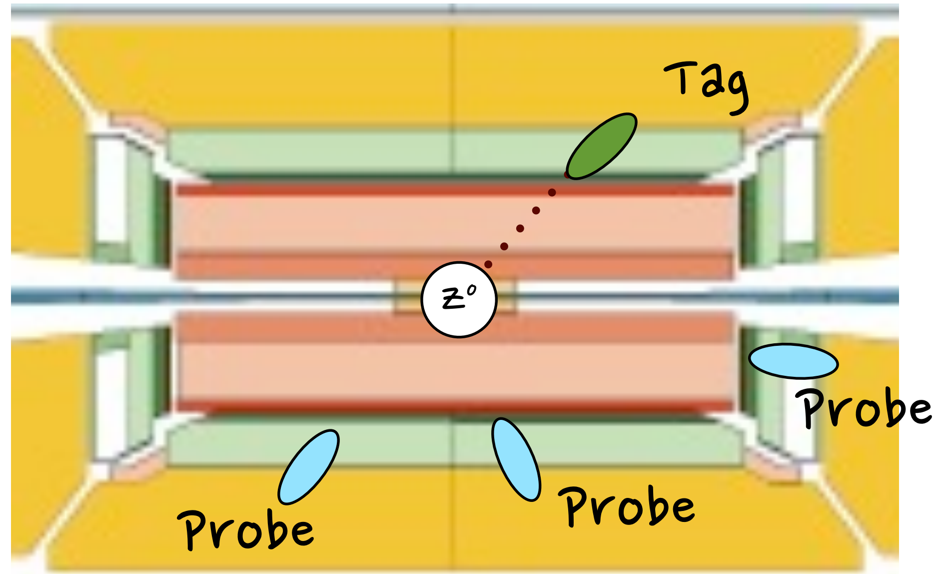

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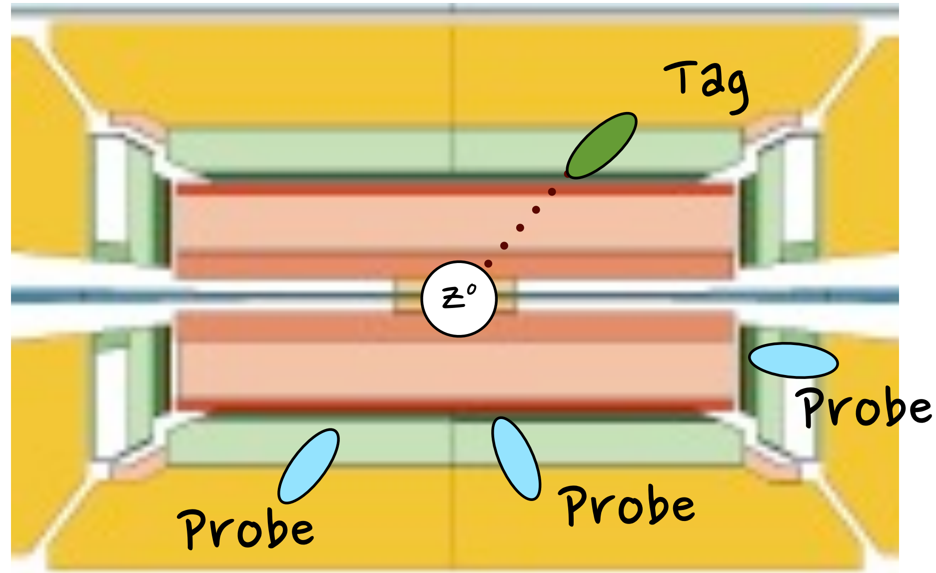

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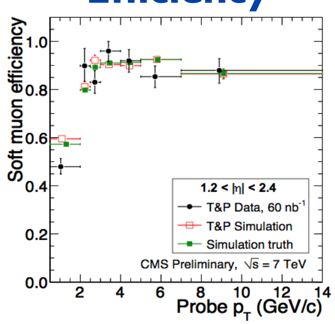

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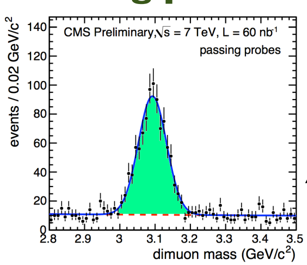
Passing probes



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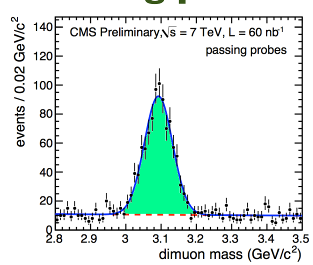

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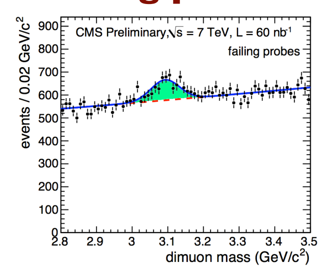
Failing probes



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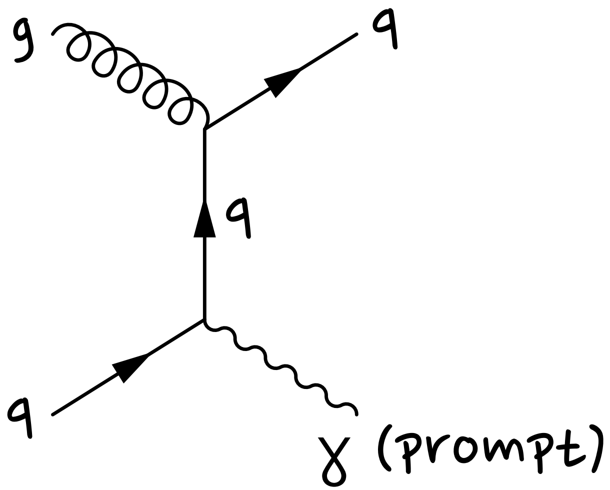

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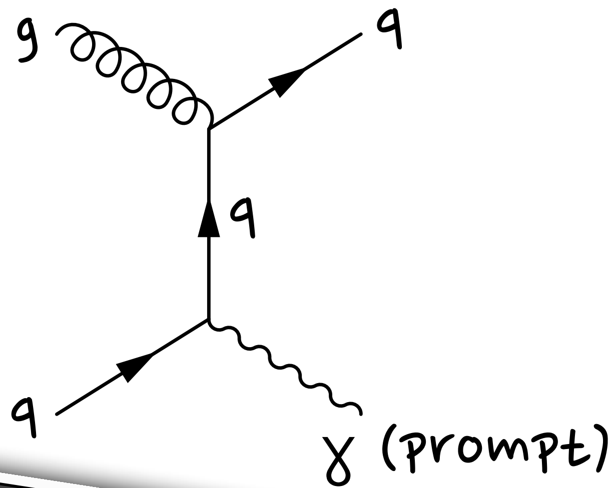

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- Unconverted photons have no redundancy: calorimeter only!
- Not many handles
    - Shower shape consistent with EM object
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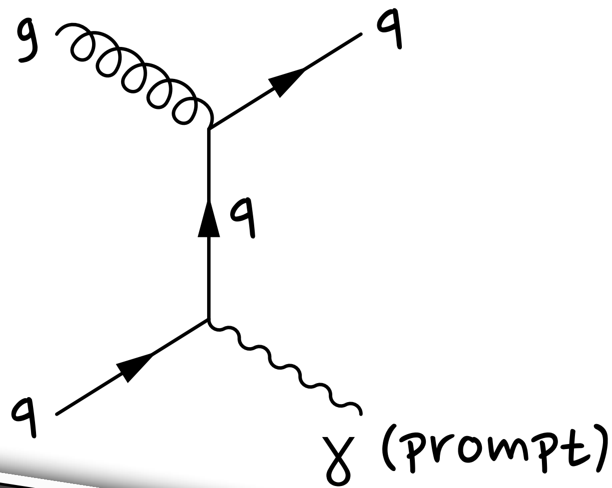

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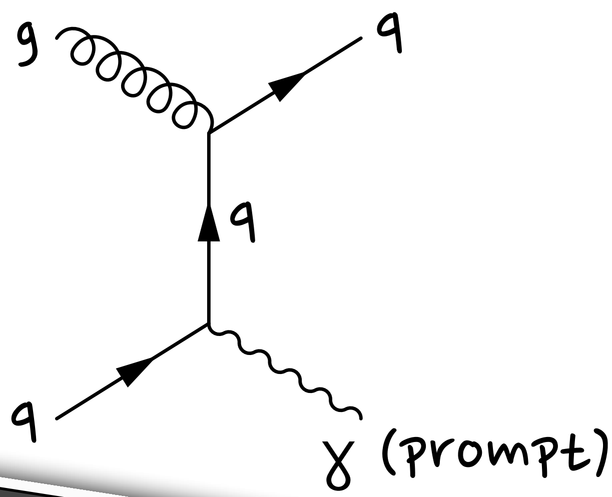

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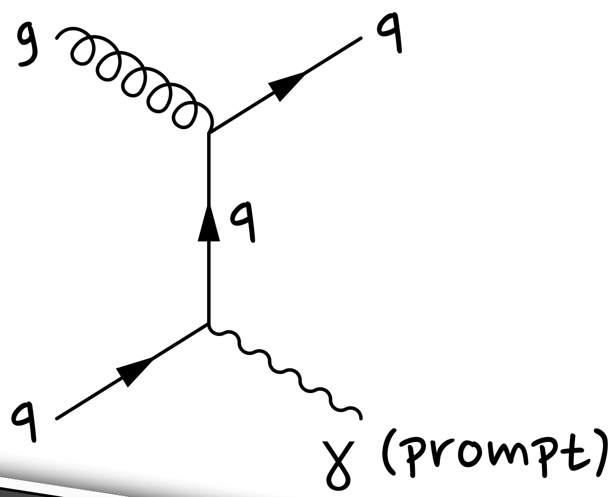

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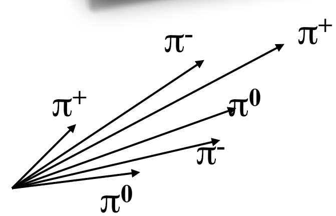

normal jet

Different jet backgrounds

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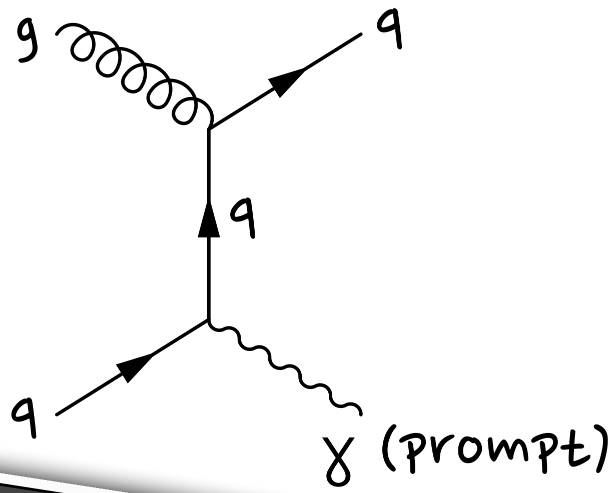

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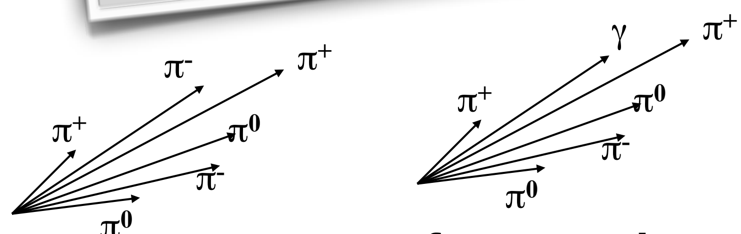

normal jet **fragmentation γ**

Different jet backgrounds

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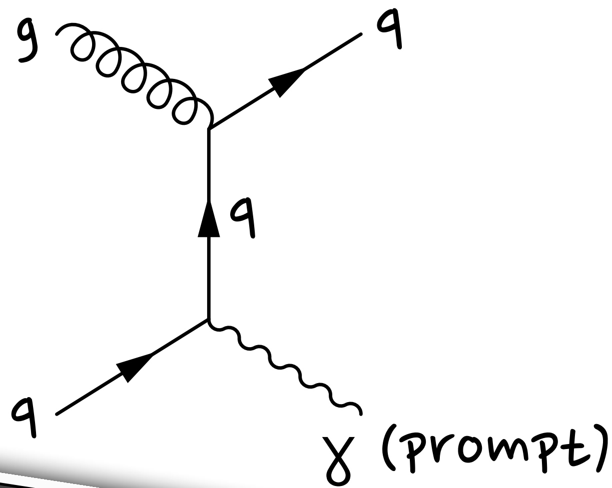

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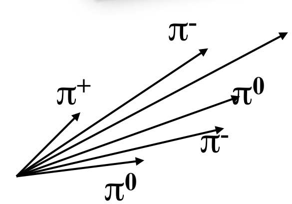

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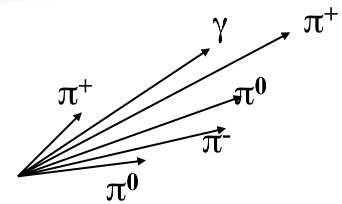
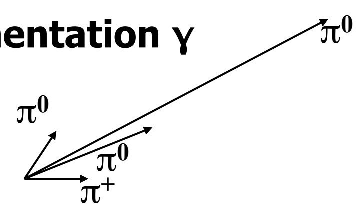


fragmentation γ

Different jet backgrounds



fluctuated jet: most energy is carried by π^0

Prompt Photon ID

What do γ's look like?

- Depends on the experiment details!
- CMS ECAL lives inside the B-field
- Electrons in ECAL shower
  - spread radially out from impact point
  - also bend in φ
- Photons often pair convert
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- Effect: "Jurasic symbol"

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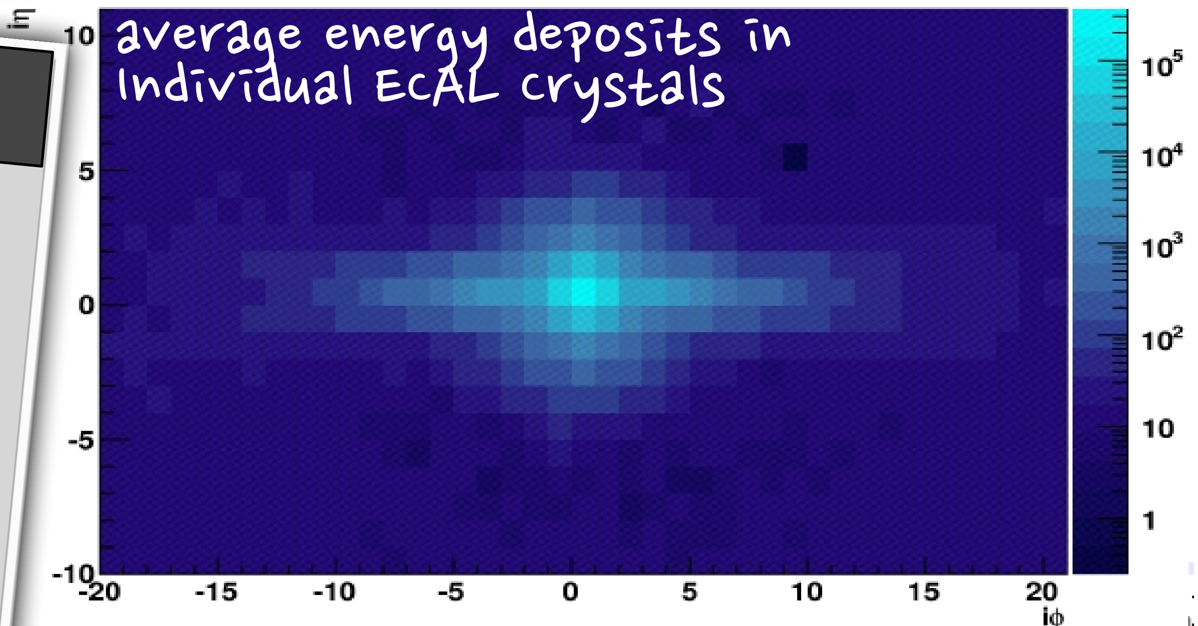

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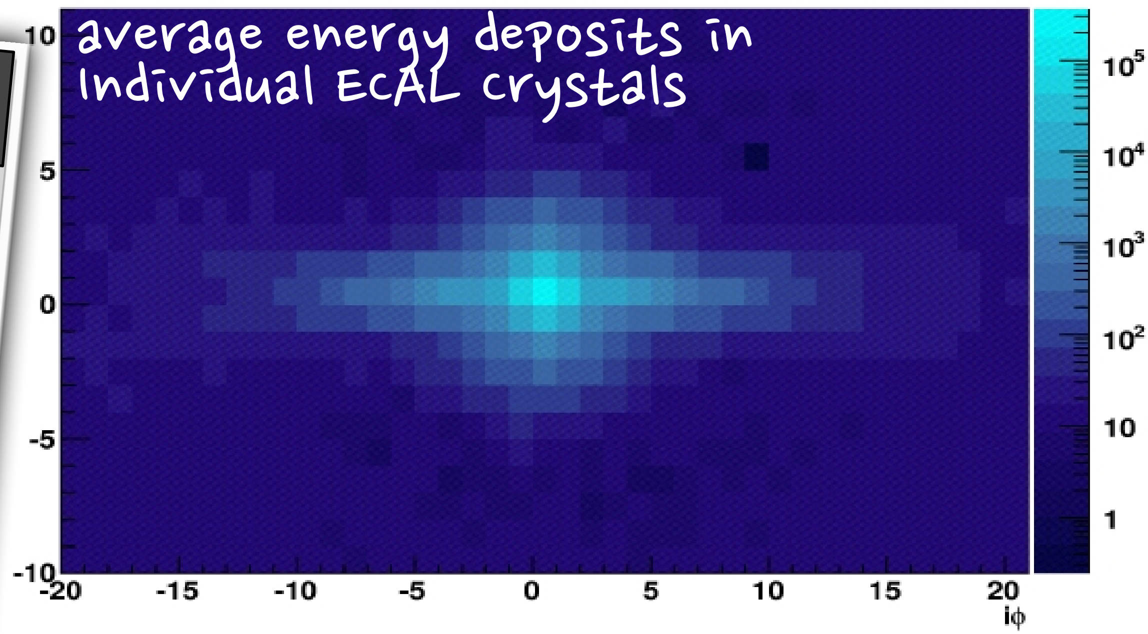
Clusters & Superclusters

- Cluster nearby cells together
- Ensure all energy is gathered
  - due to converting photons (or electron brem)
  - make clusters of clusters "superclusters" along φ
- Not particle-flow based algorithm!



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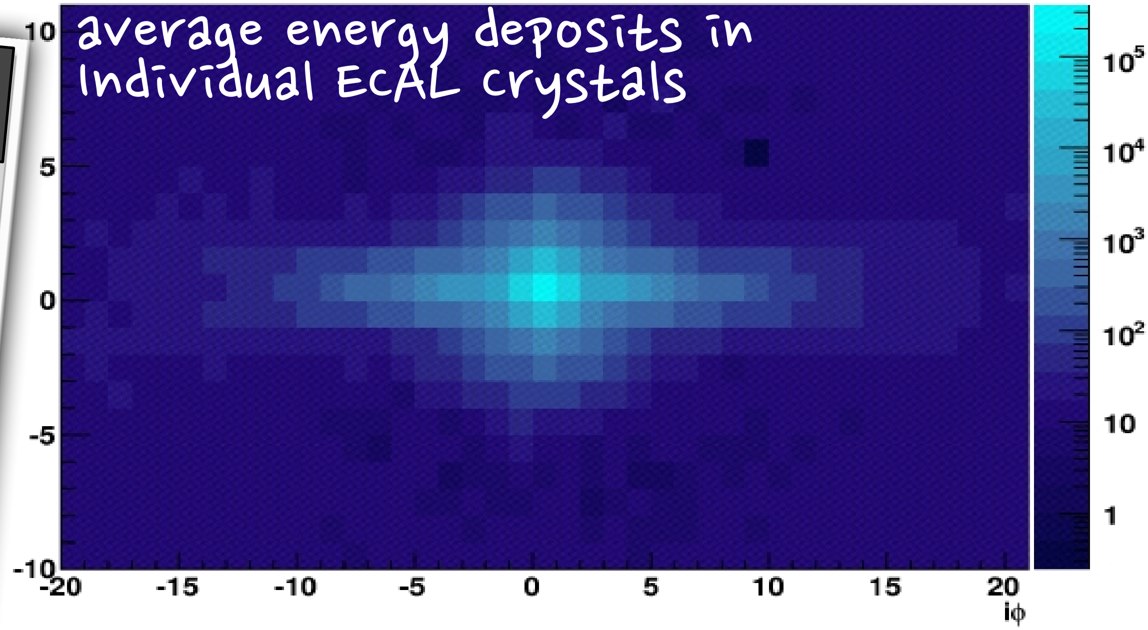

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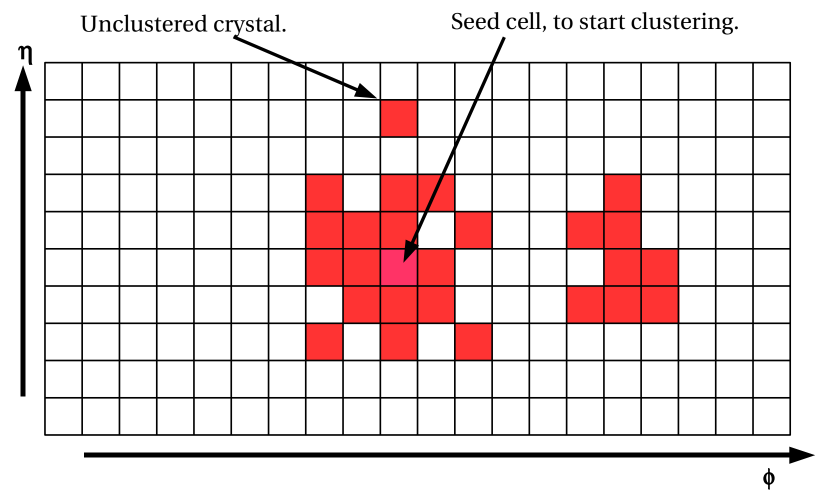

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Fermilab
UIC University of Illinois at Chicago

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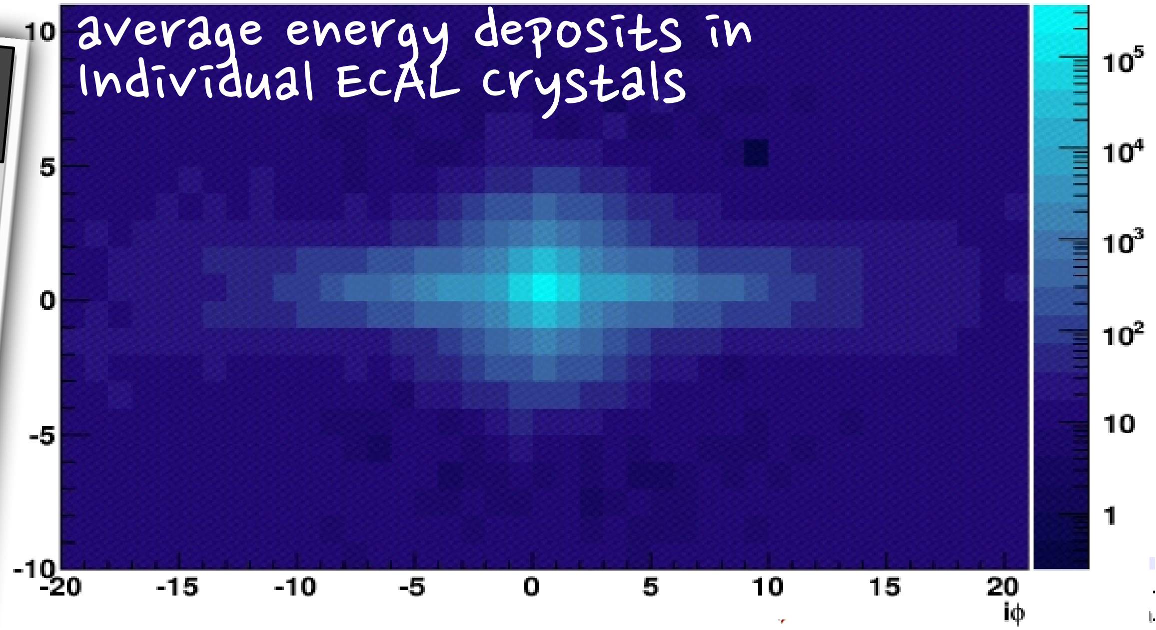

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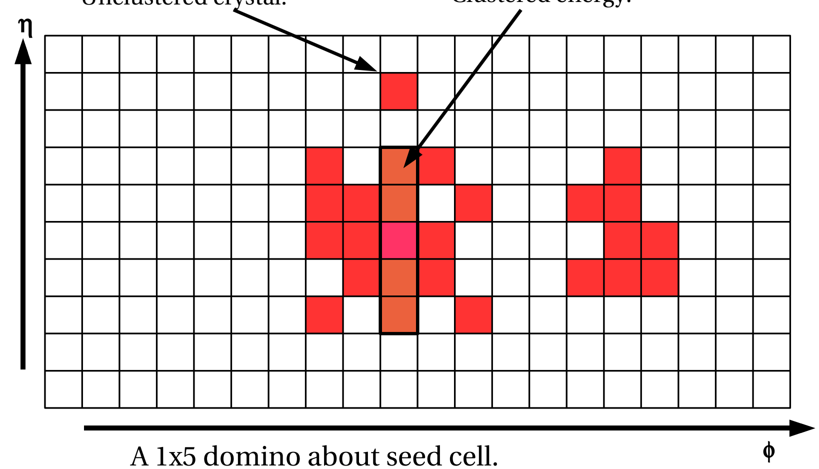

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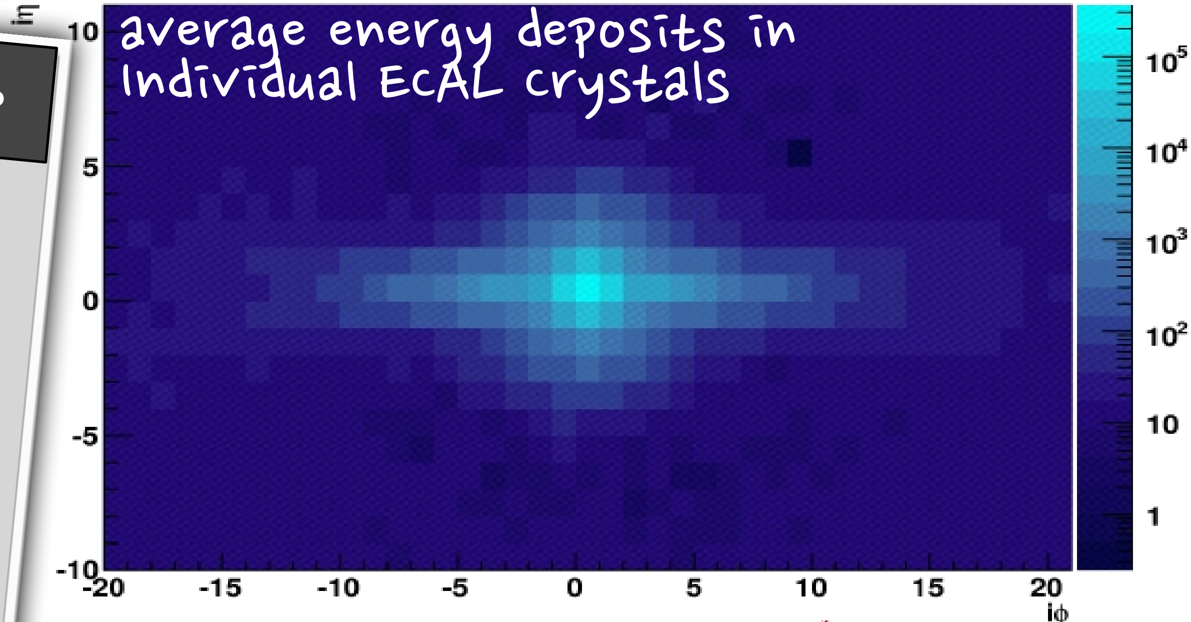

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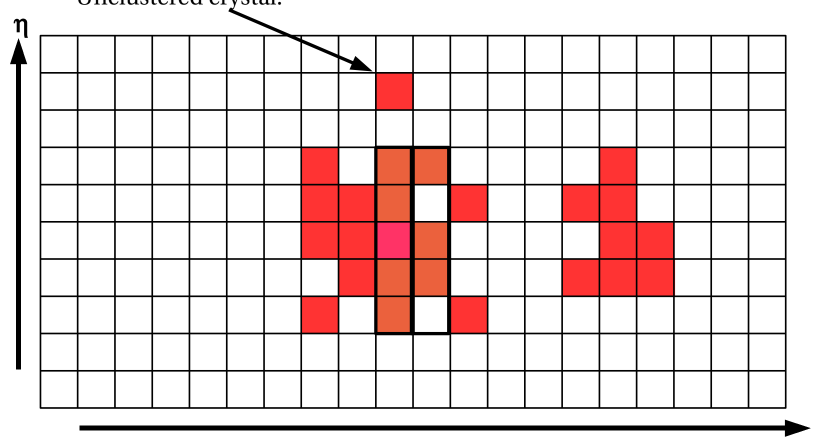

Take a step in ϕ and make a second domino.

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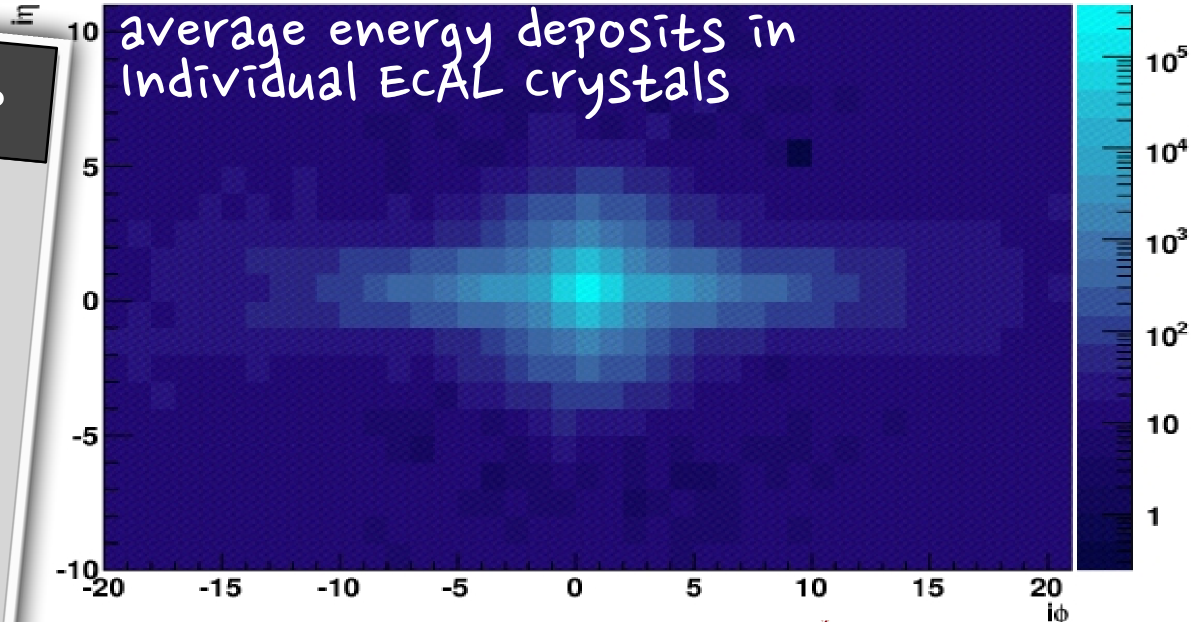

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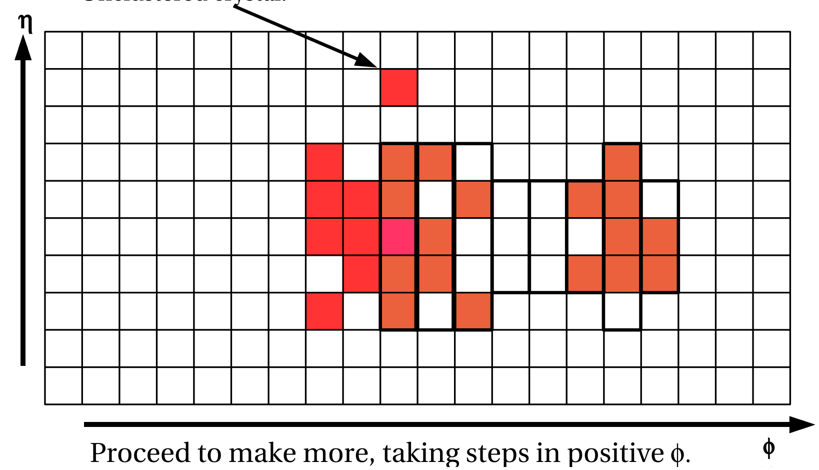

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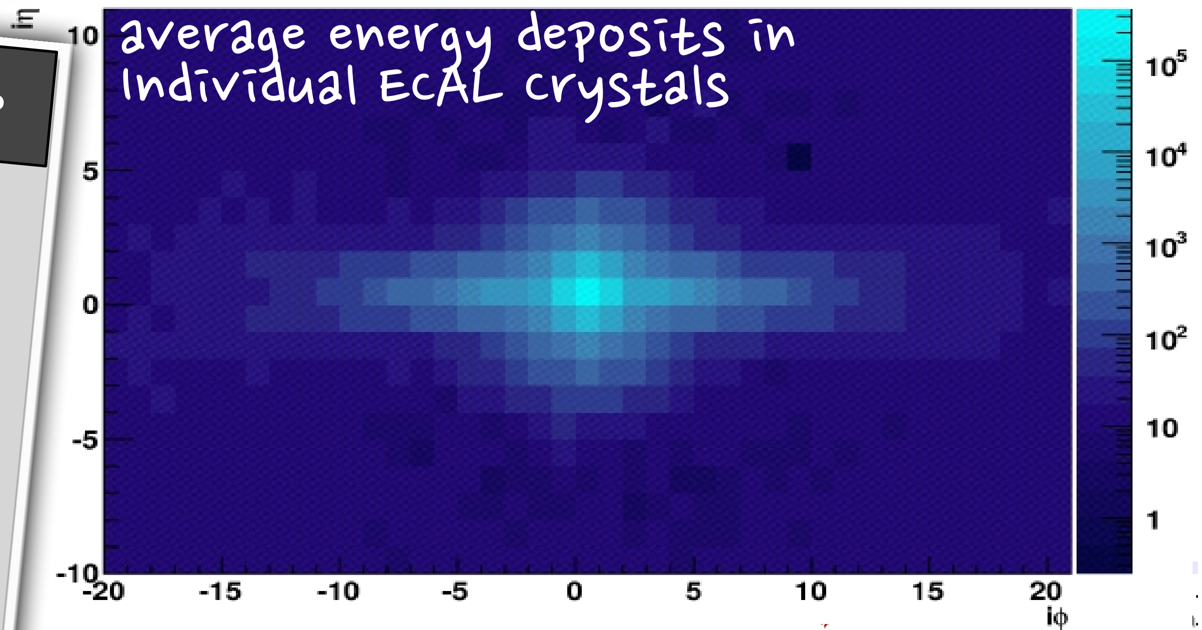

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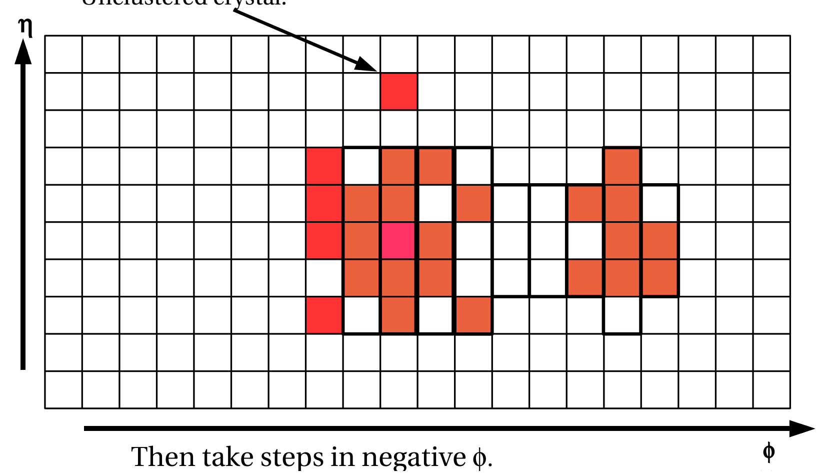

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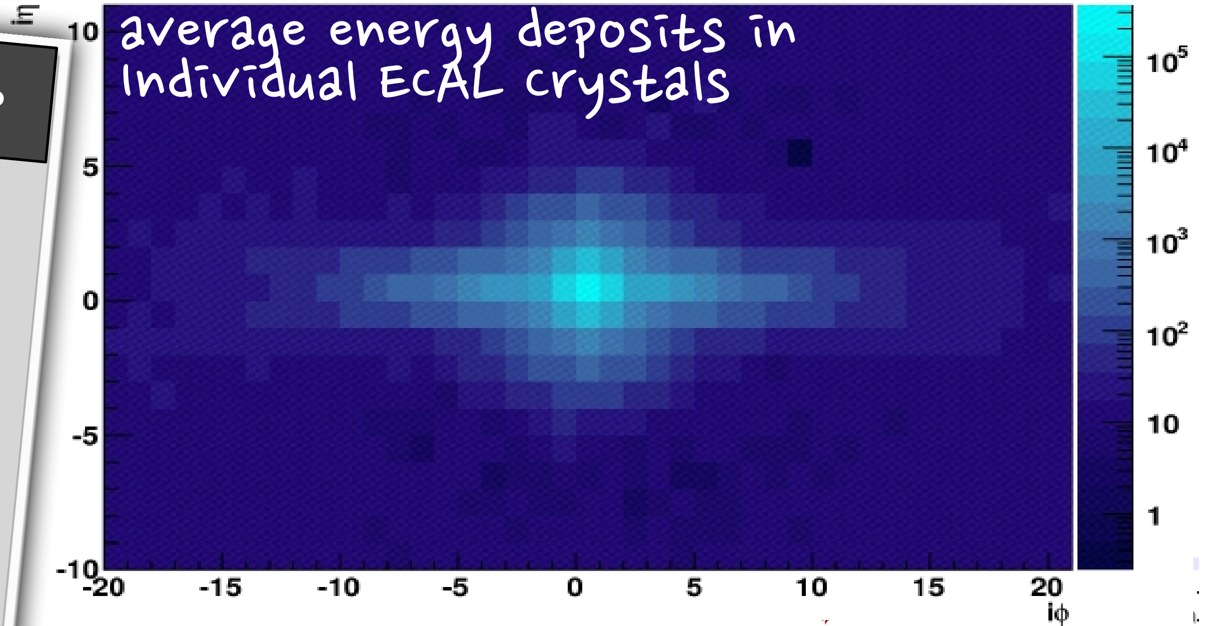

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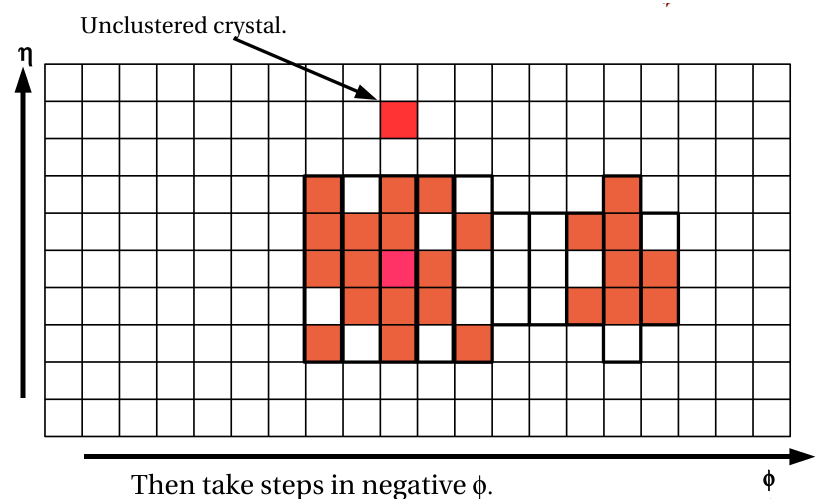

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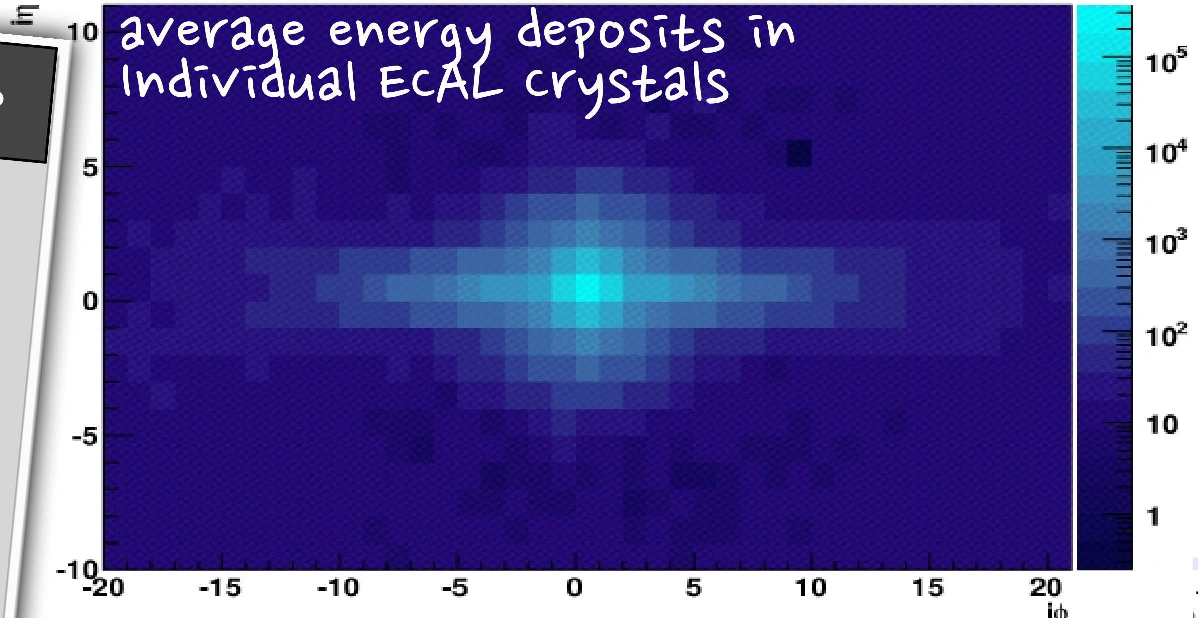

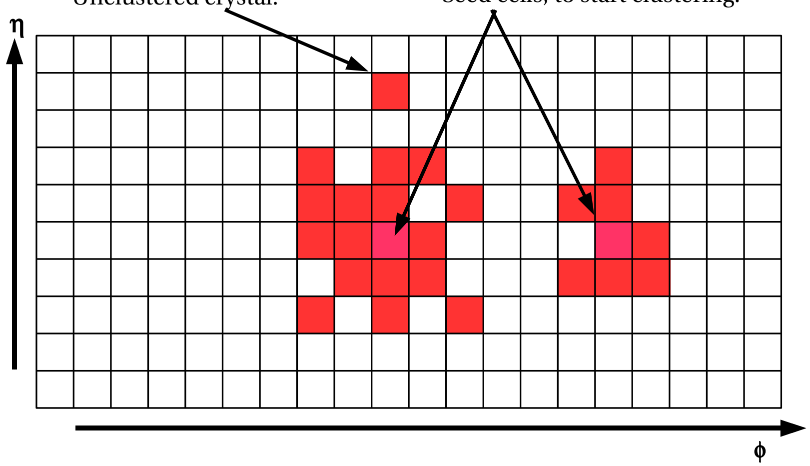

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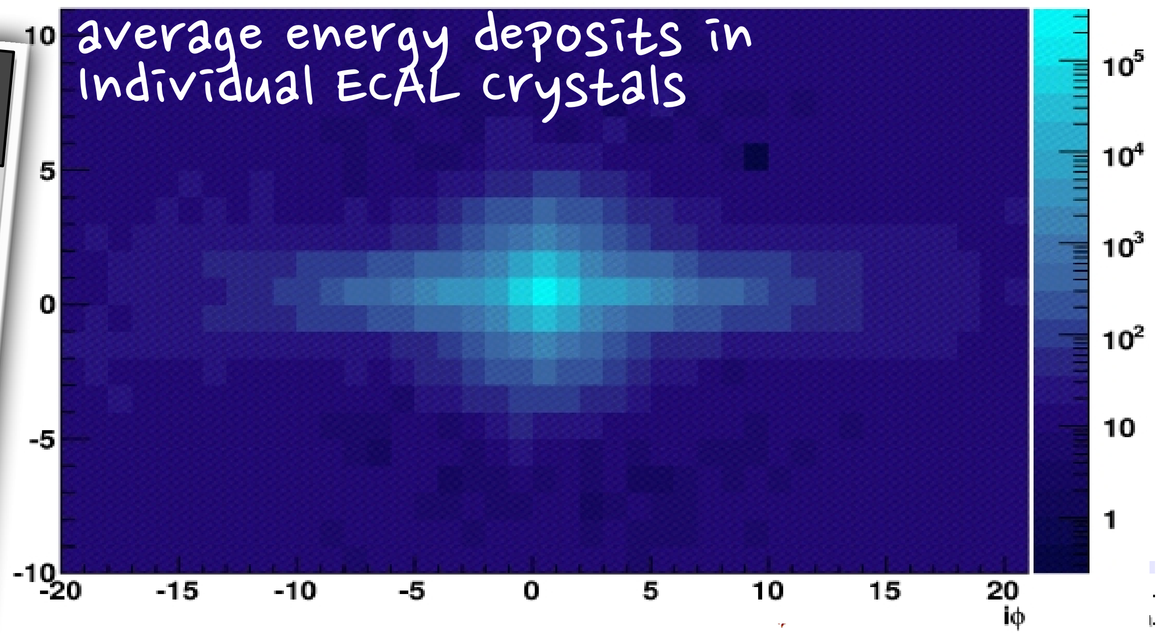

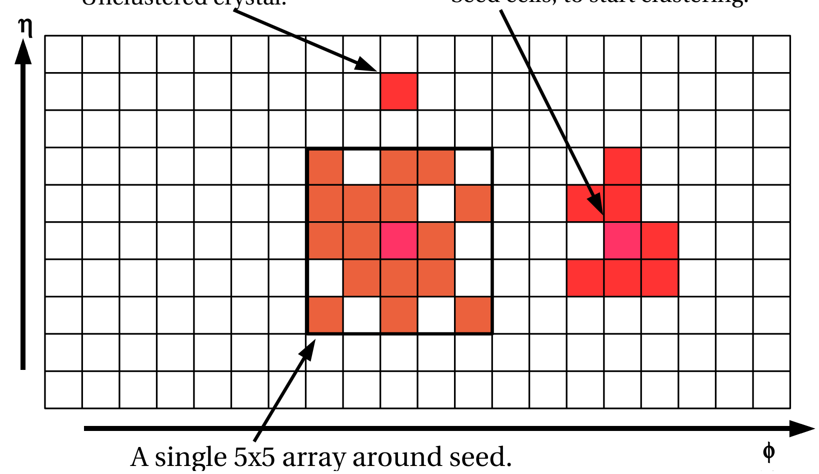

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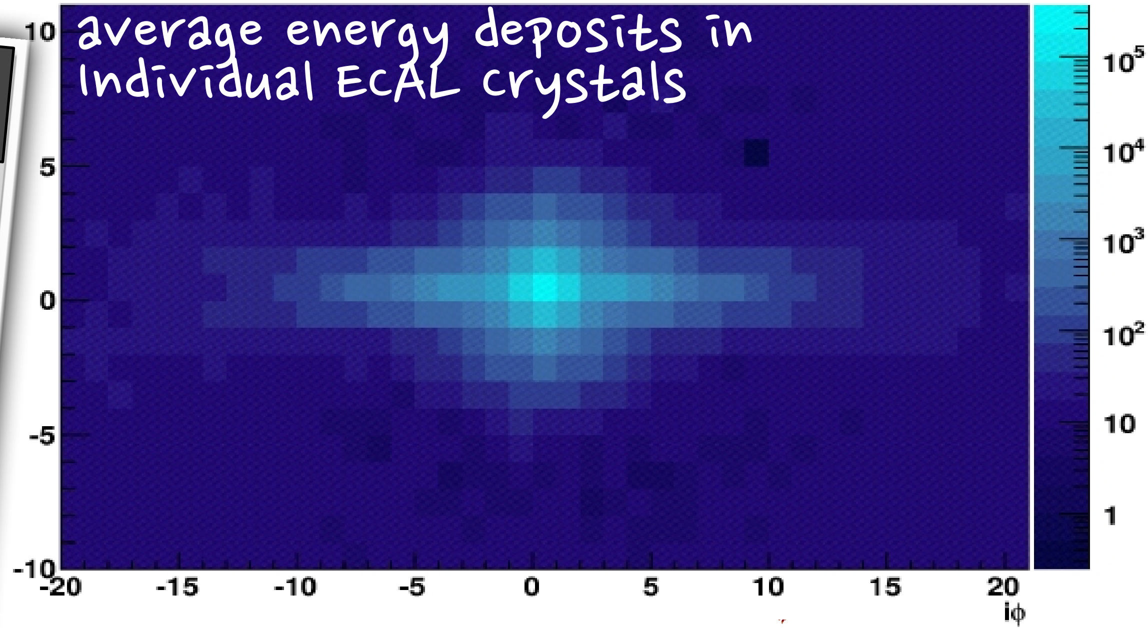

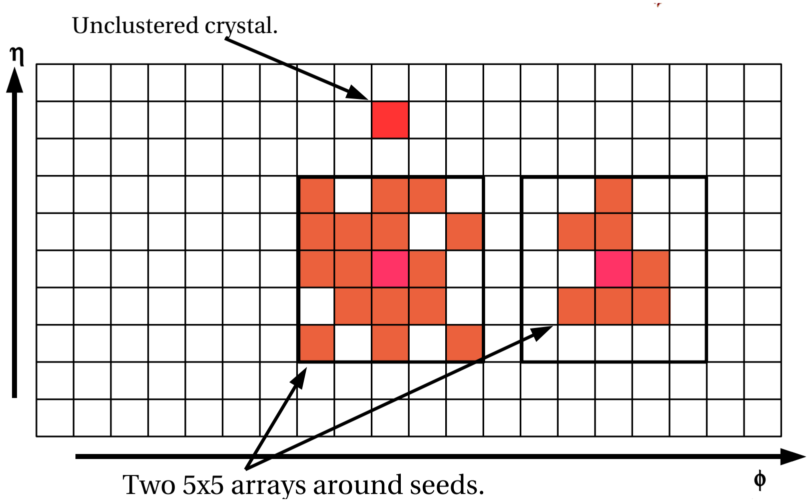

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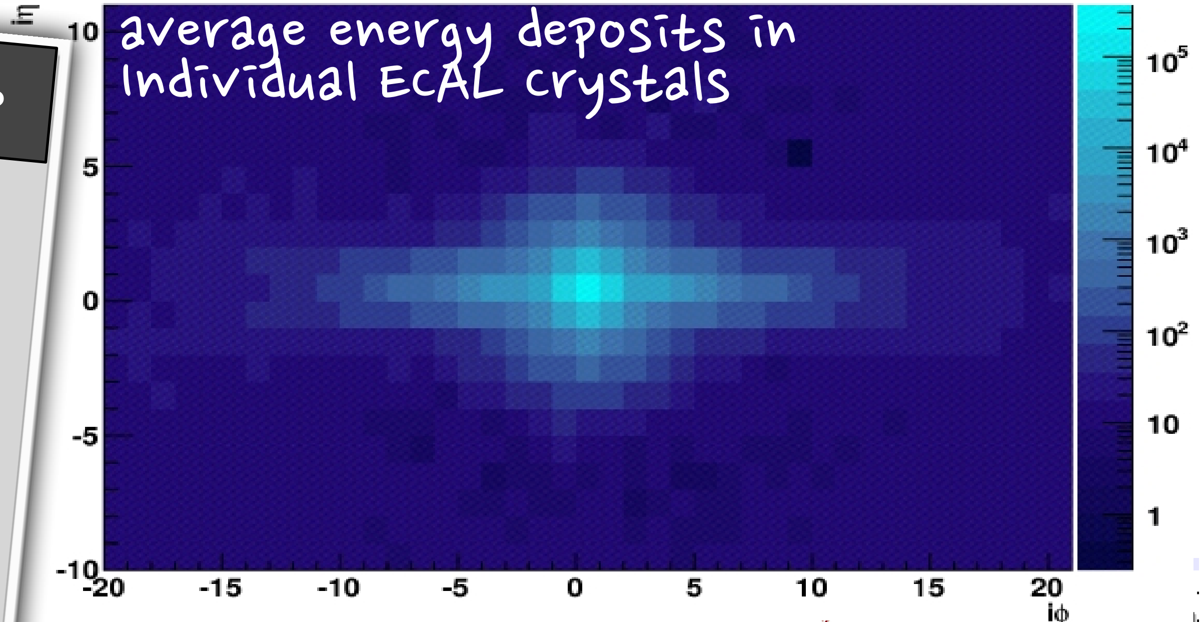

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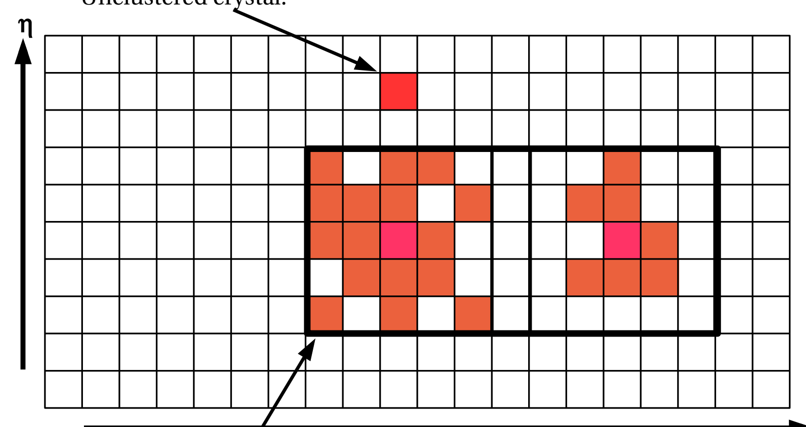

A multi5x5 supercluster, containing two 5x5 clusters.

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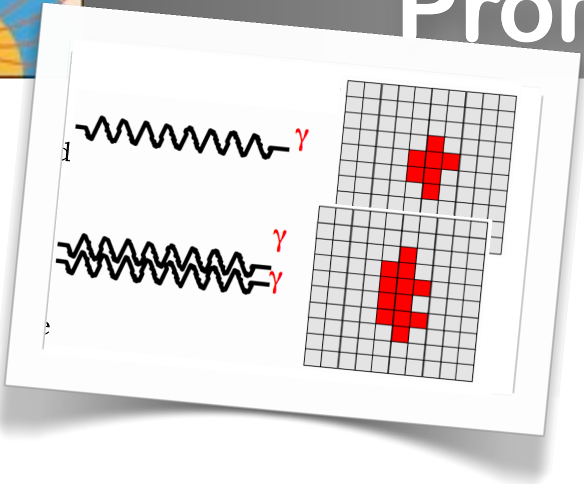
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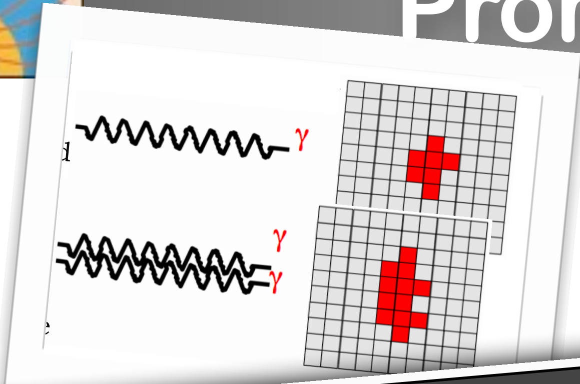

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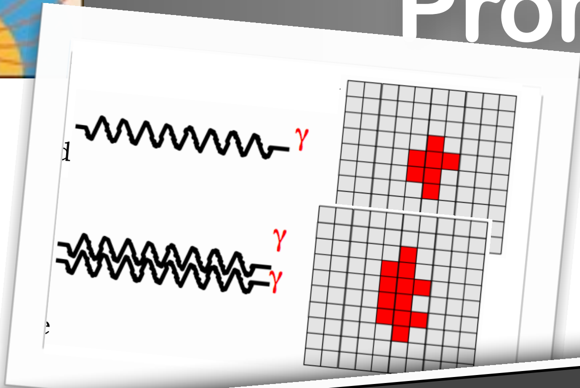

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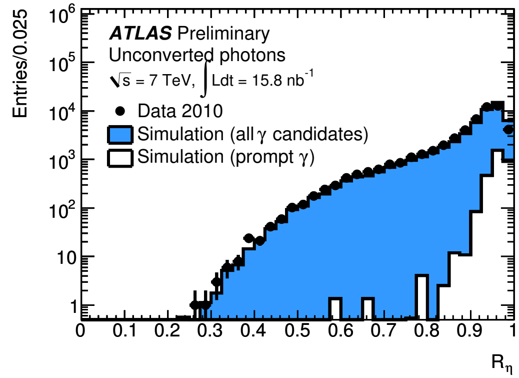

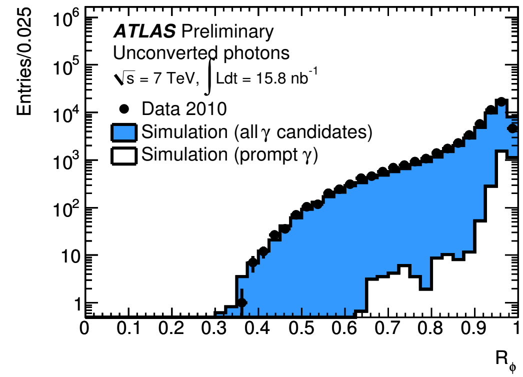

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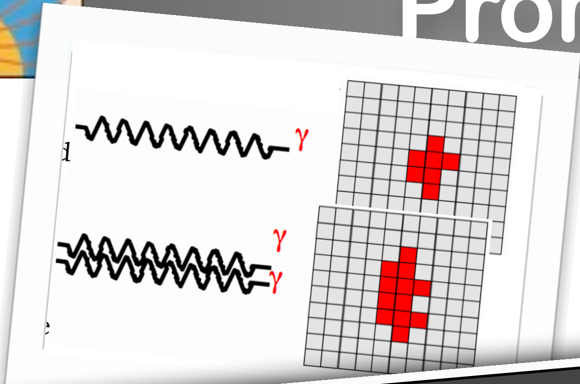

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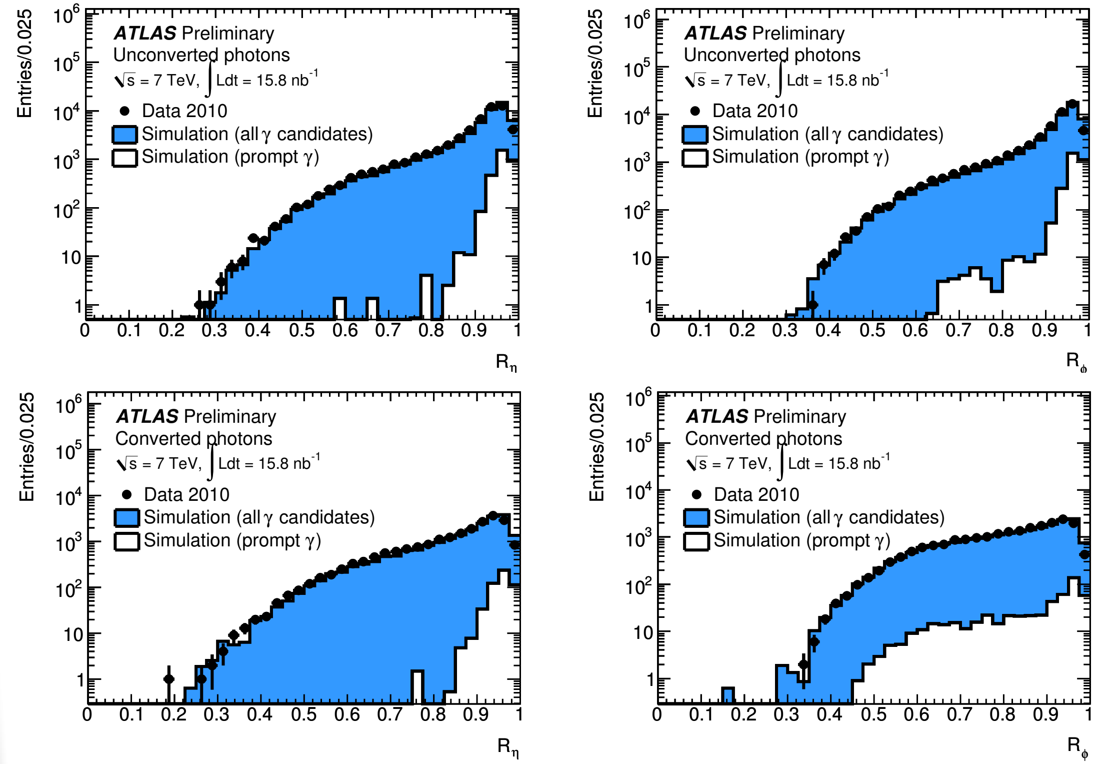

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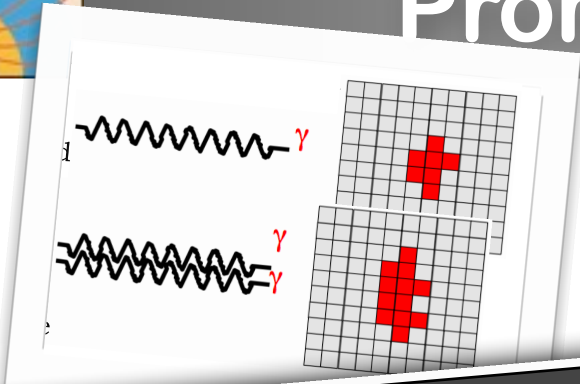

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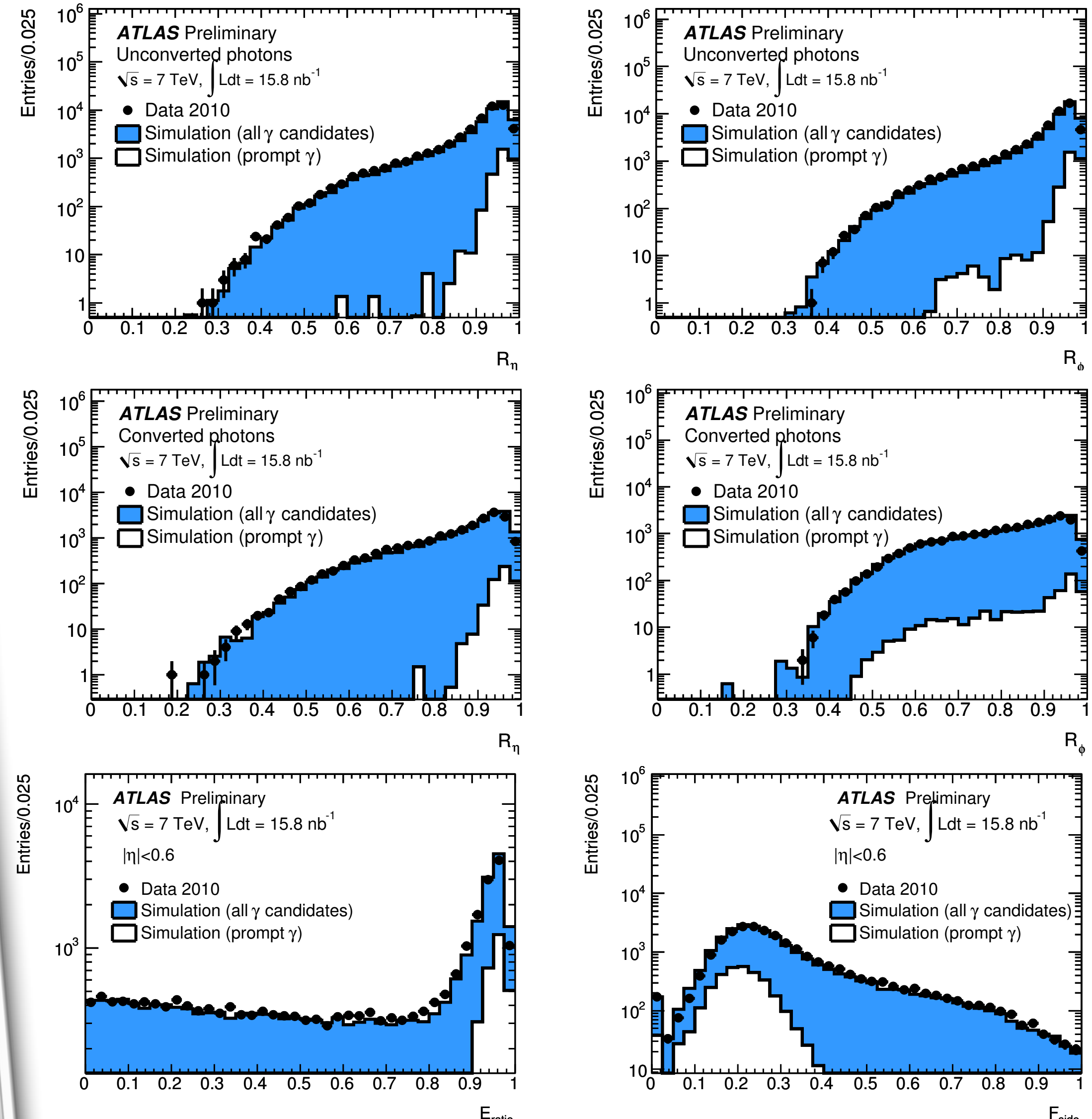

LPC LHC Physics Center

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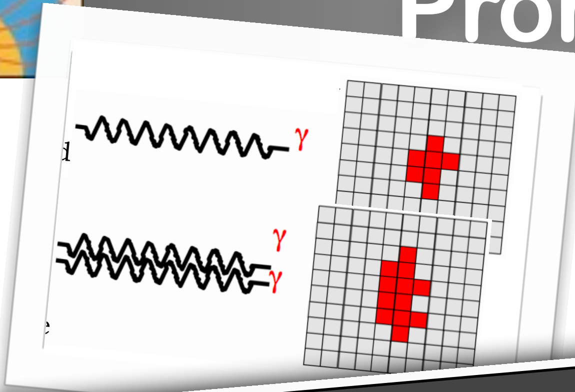

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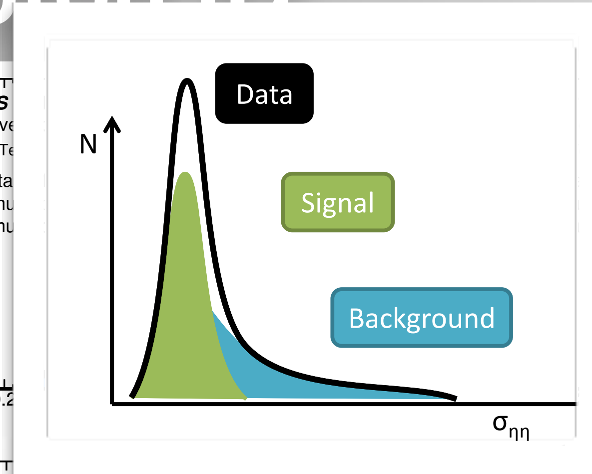

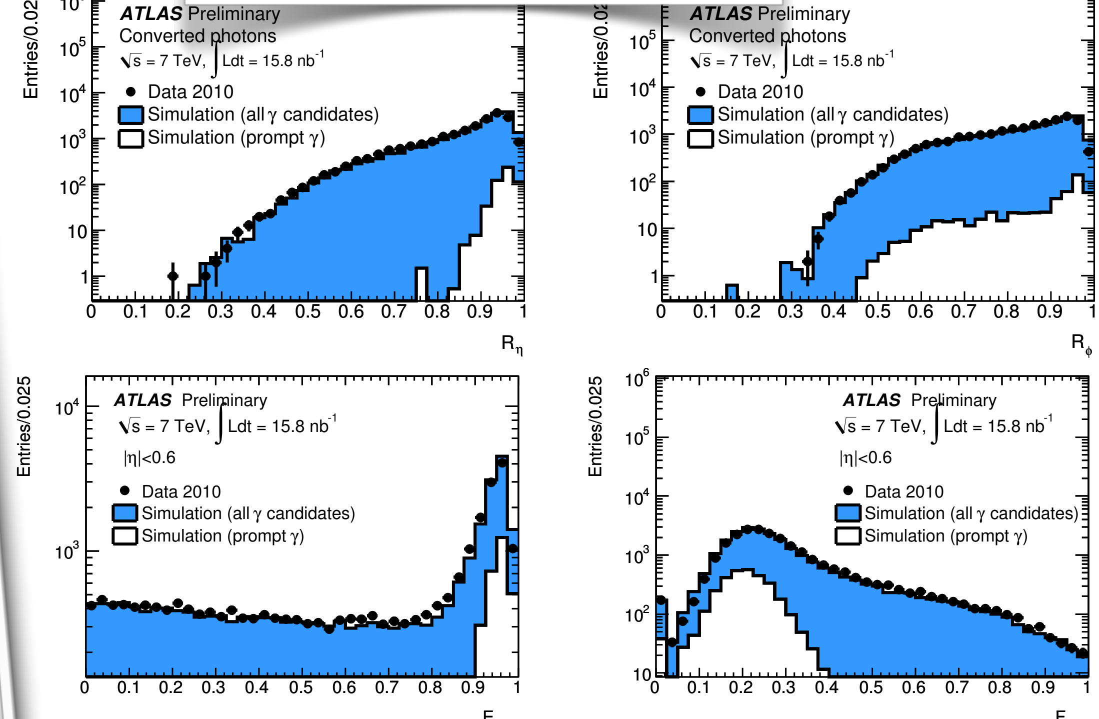

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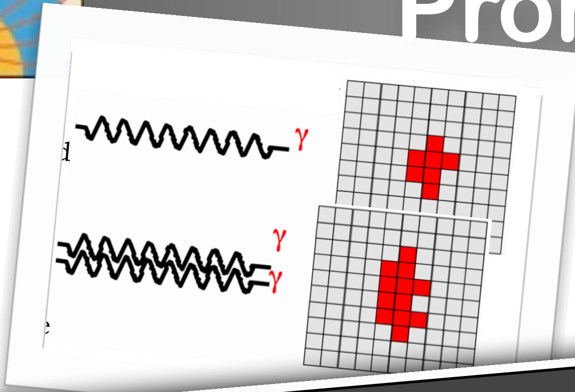

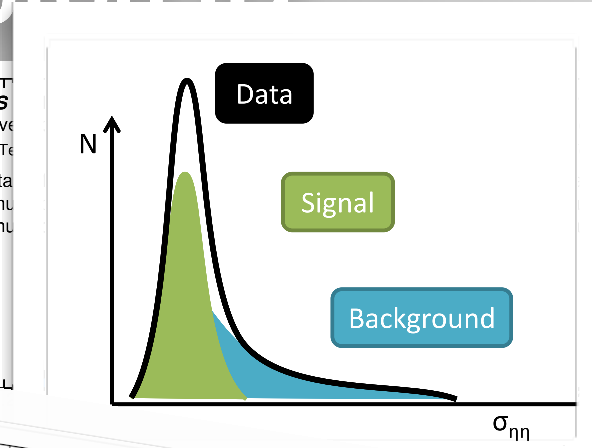

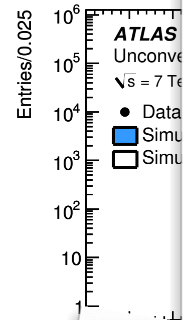

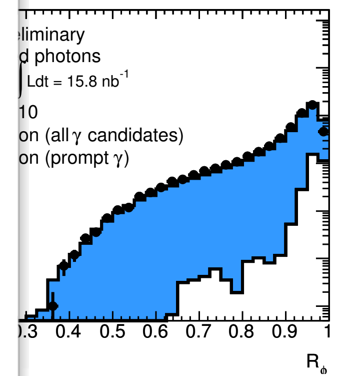

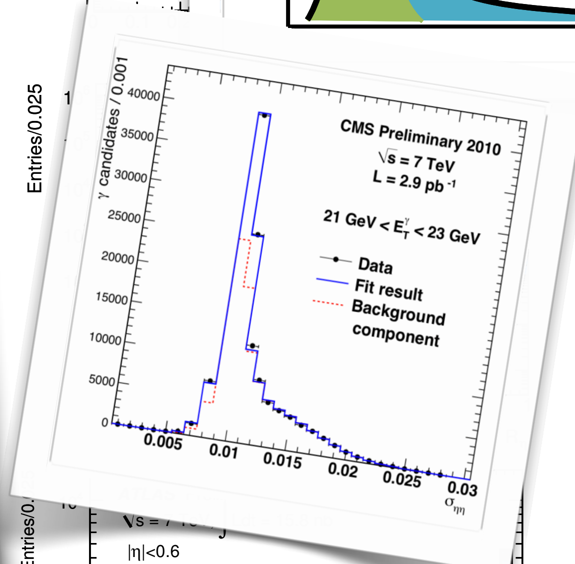

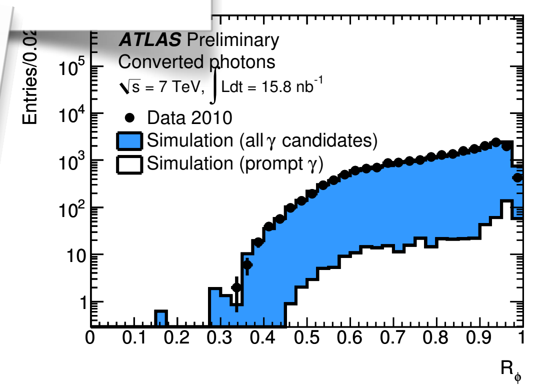

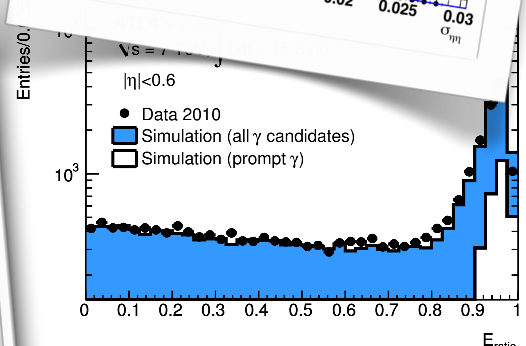

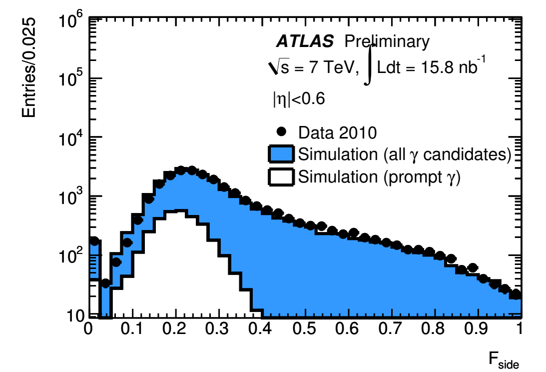

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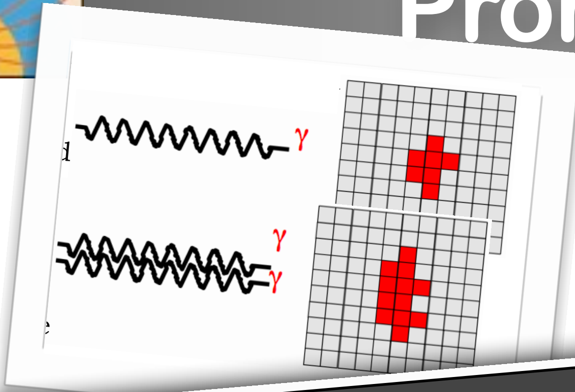

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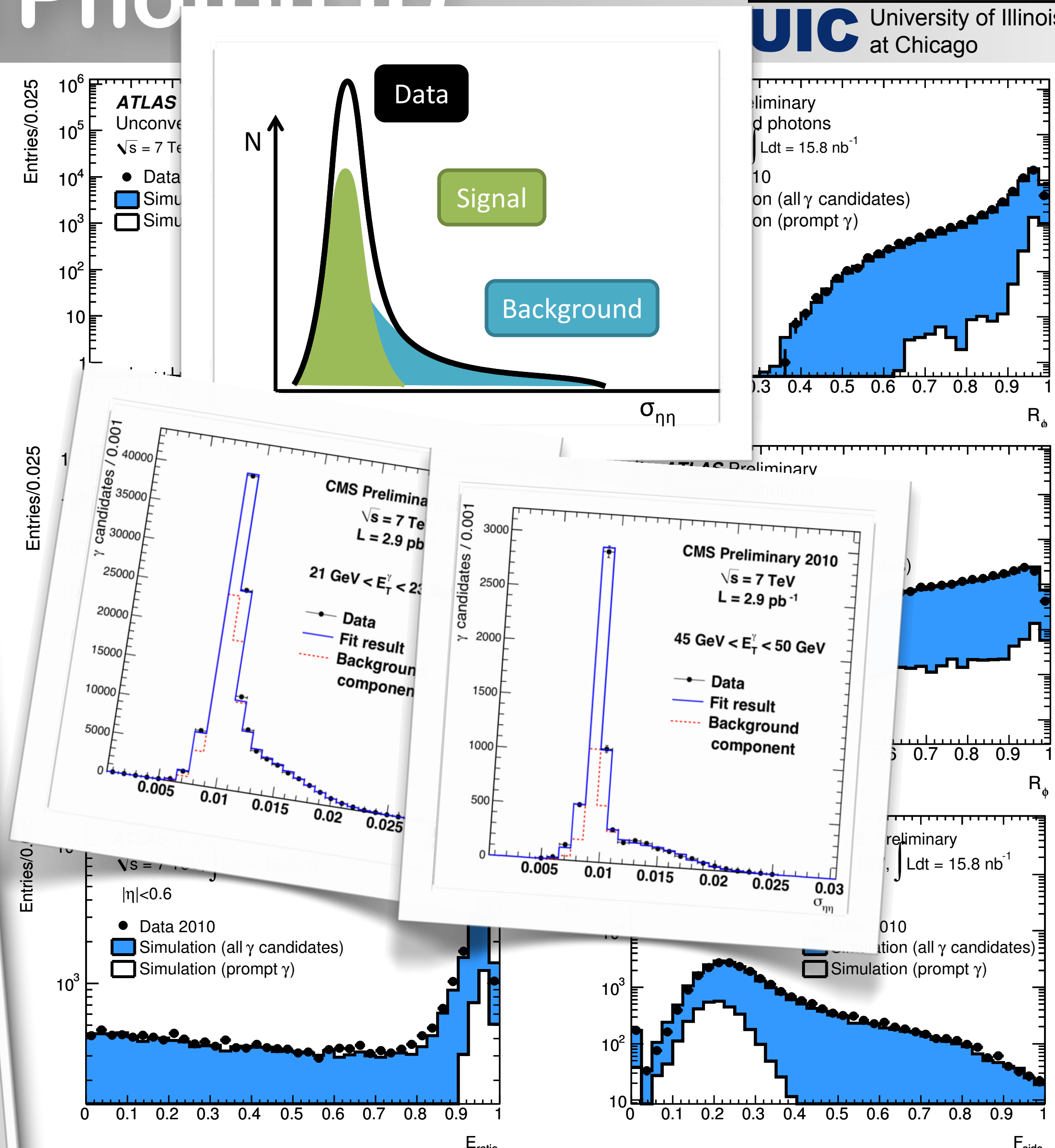

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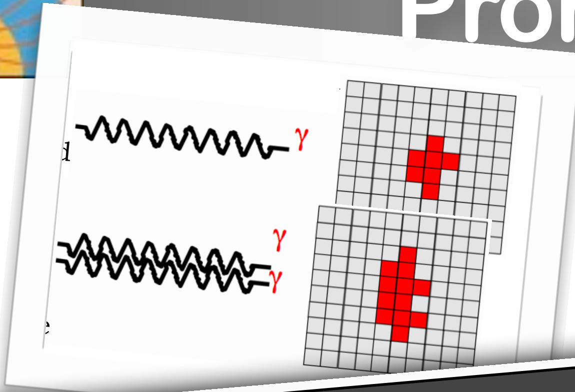

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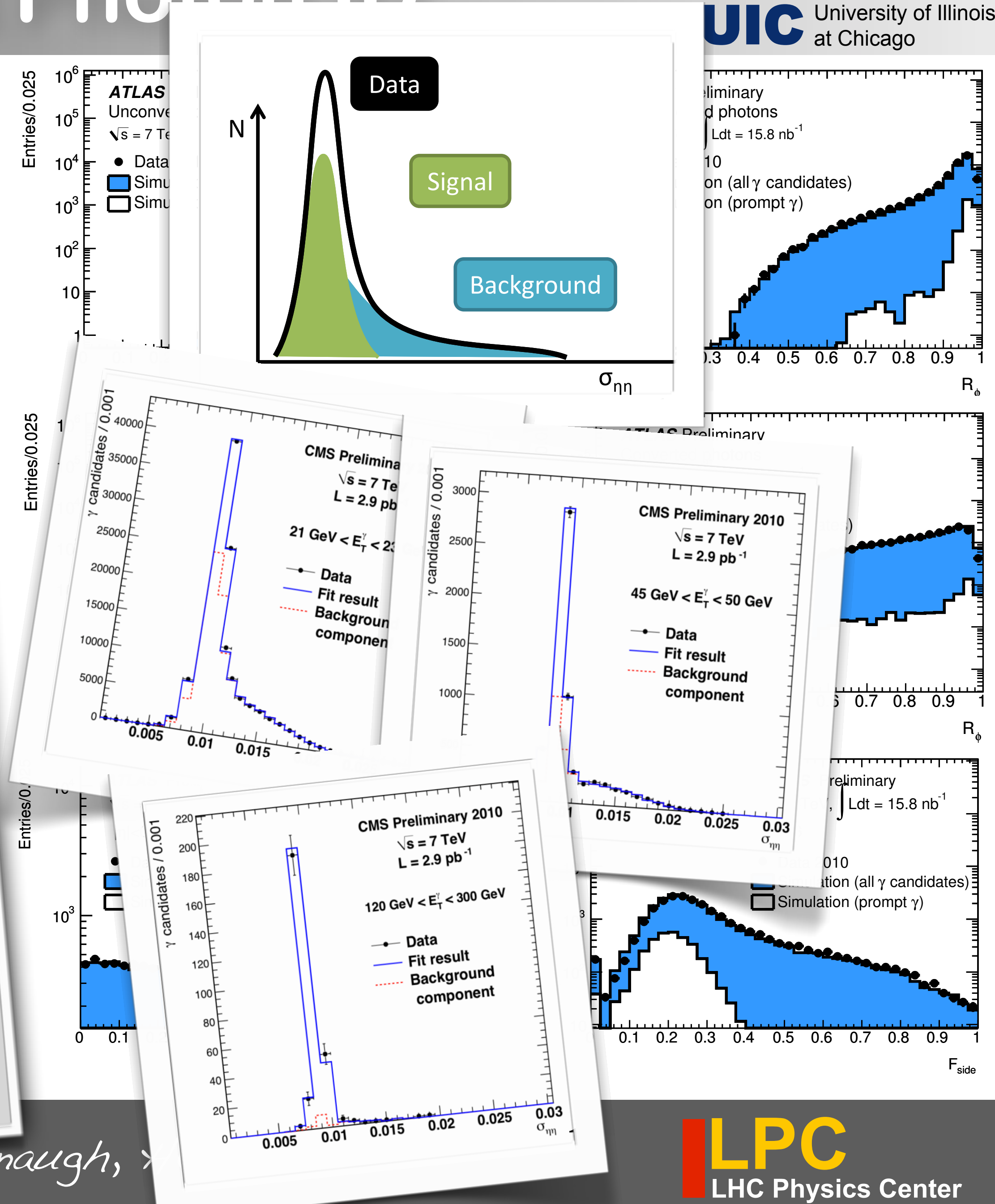

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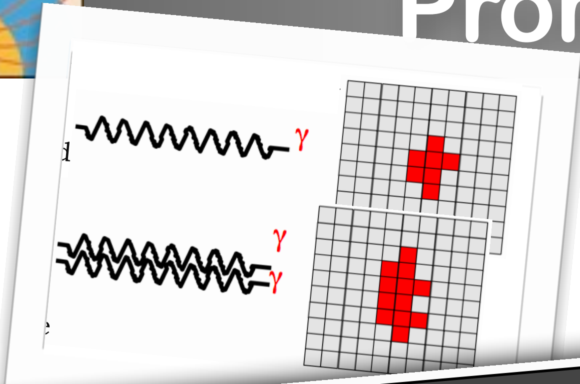
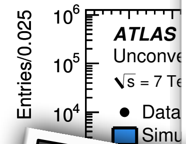
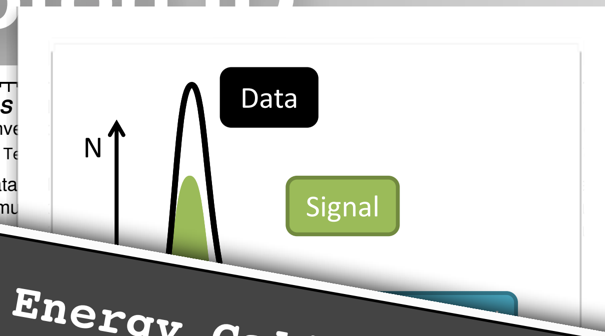
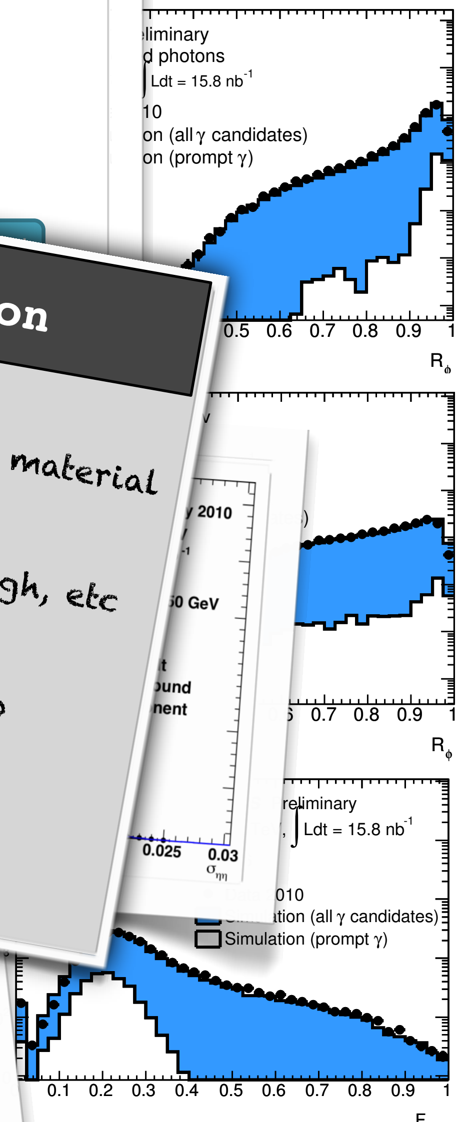
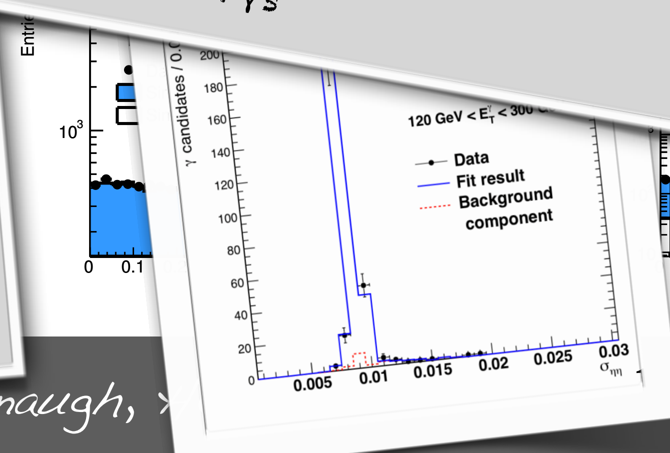










Shower shape variables

Pre-select γ's

- R_η = 3x7/7x7 ratio of energies in η
- R_φ = 3x7/7x7 ratio of energies in φ
- w_η = RMS width along η of cluster
- $E_T(had)/E_T$ = hadronic E fraction

ID π^0 giving two sep. showers

- E_{ratio} = Ratio of 1st & 2nd maxima along η
- ΔE = diff between 2nd max and min

ID π^0 giving two merged showers

- F_{side} = energy in 7 cells centered around 1st max (excluding the core cells)
- w_{s3} = RMS width of core cells

Energy Calibration

- Correct clustered energy for
  - losses due to interactions in material
  - rear leakage
    - due to cracks, punch through, etc
  - lateral leakage
    - due to fixed cluster window

Do this separately for

- unconverted γ's
- converted γ's

Photon Identification

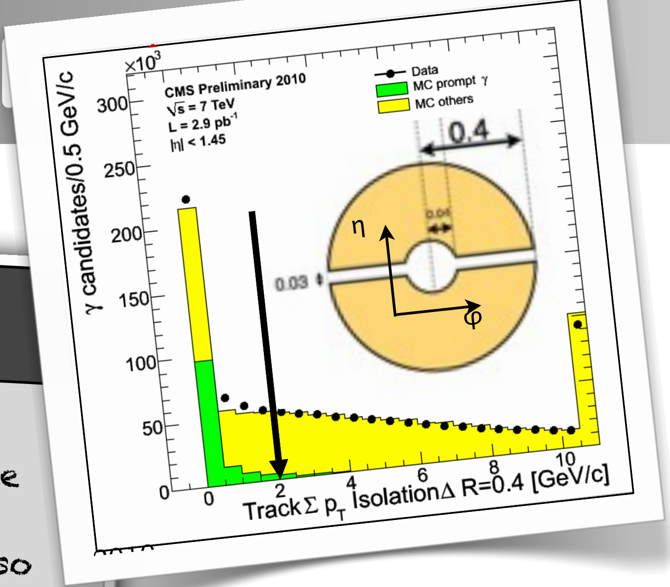
Photon Identification

Non-PF Isolation

- cone 0.4
  - centered on γ candidate (include ECAL & HCAL, tracker) e.g.

    I = Trk Iso + HCAL Iso + ECAL Iso
  - ATLAS: exclude 5x7 EM cells around barycenter
  - CMS: exclude "Jurasic" symbol around barycenter
- small lateral leakage subtracted on average
- ambient energy density subtracted on average (UE + PU)
- γ candidates having $<$ 3 GeV isolation considered "isolated"

Photon



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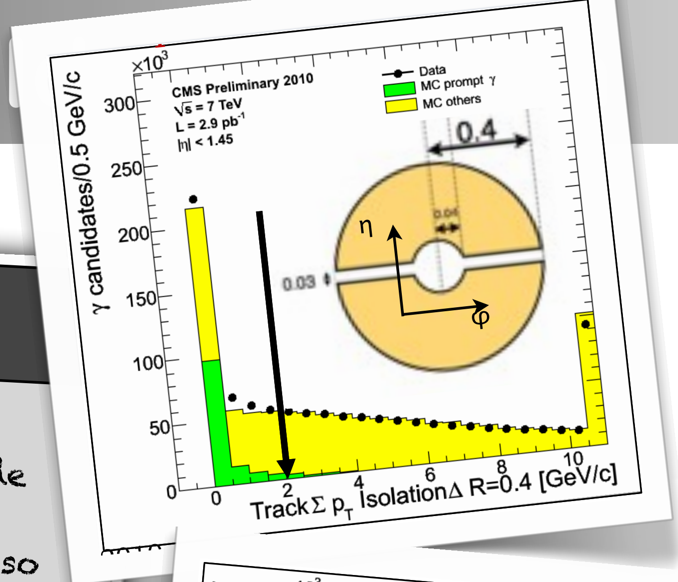

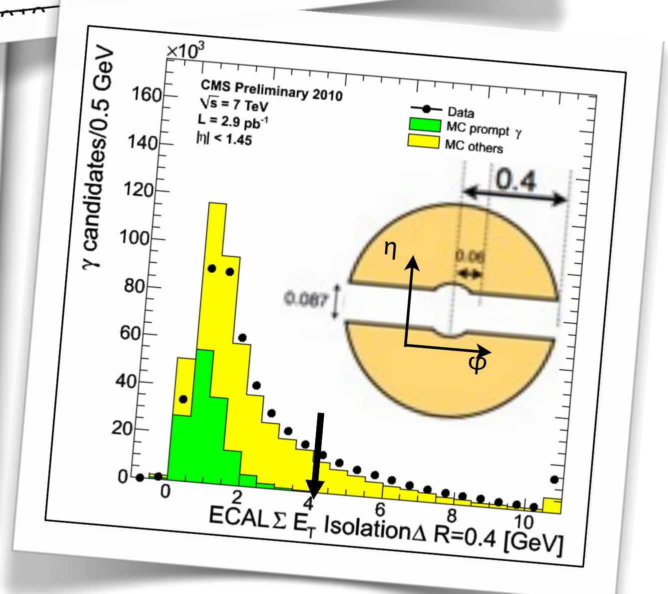

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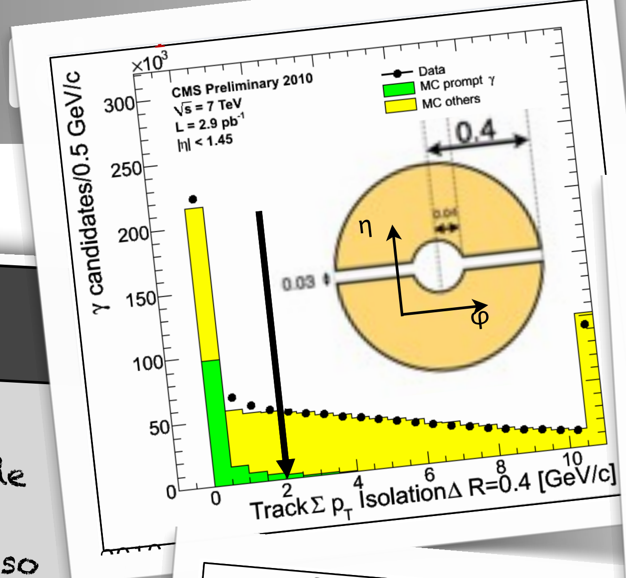

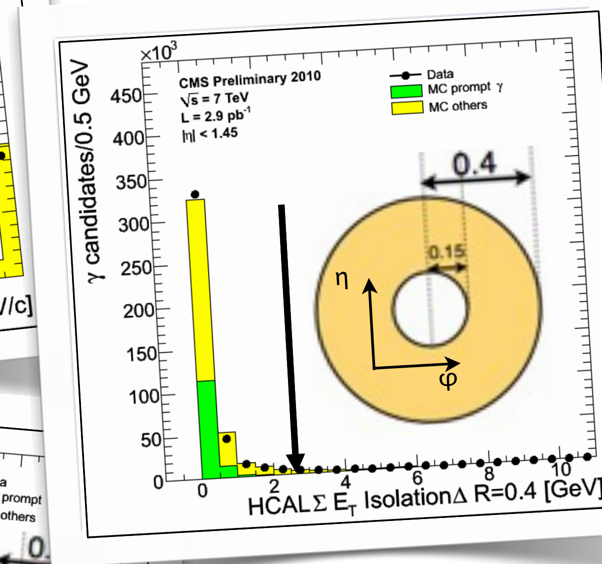

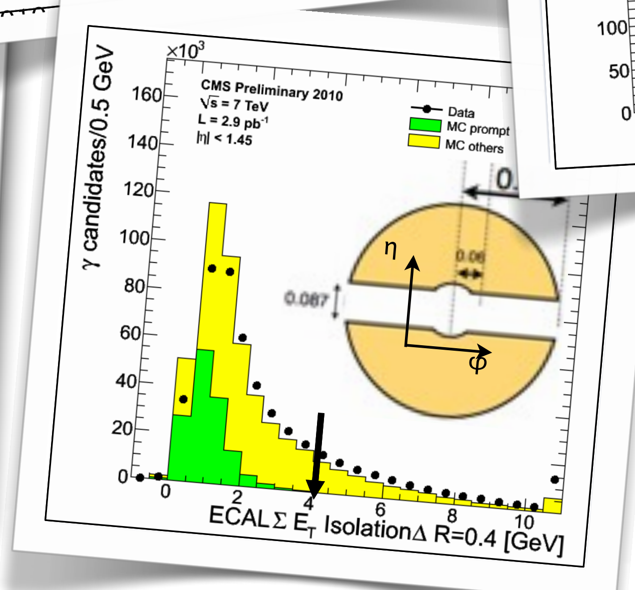

LPC LHC Physics Center

Photon

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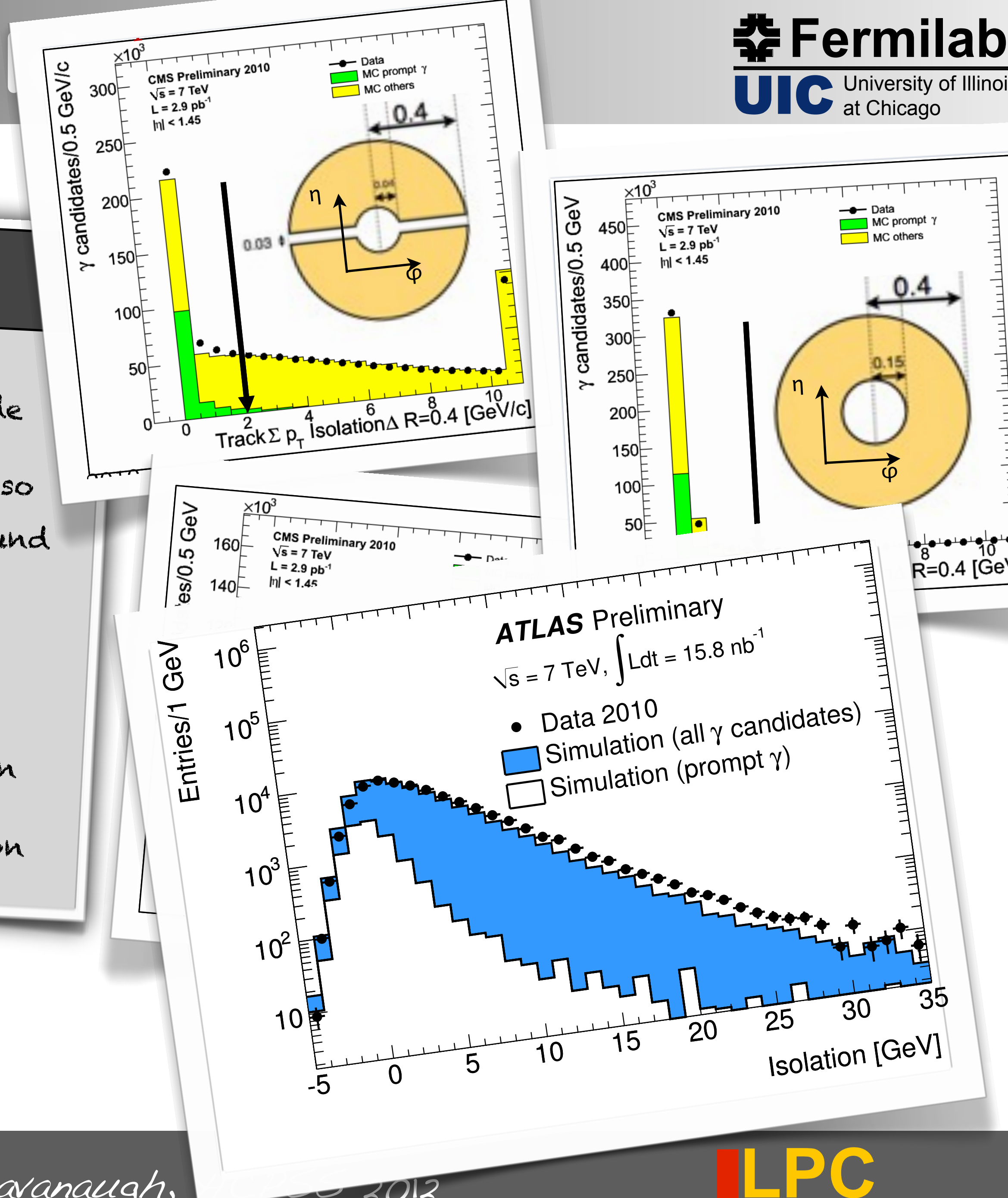
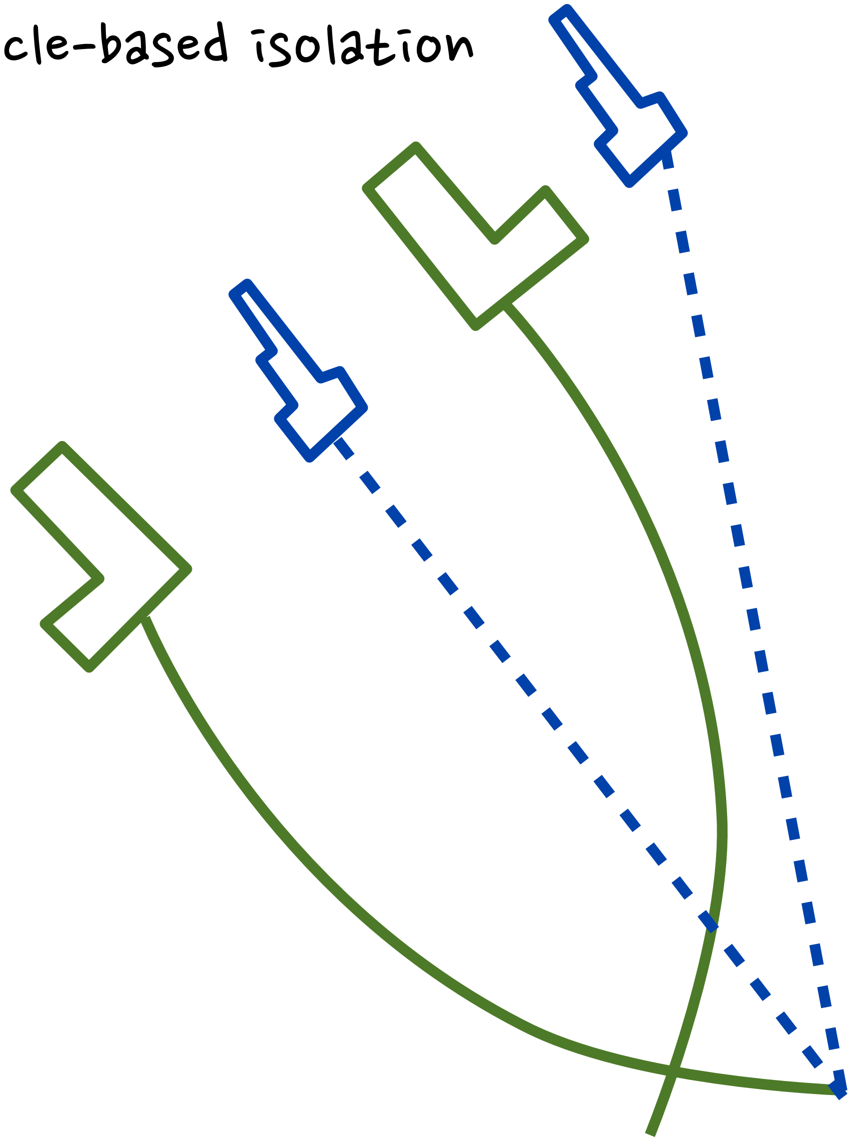


Photon Identification

Particle-based isolation



Isolation from other particles

- Absolute energy in cone:

$$I = \sum p_T(\mathrm{h}^\pm) + \sum E_T(\gamma) + \sum E_T(\mathrm{h}^0)$$

- Relative energy in cone:

$$I = \frac{\sum p_T(\mathrm{h}^\pm) + \sum E_T(\gamma) + \sum E_T(\mathrm{h}^0)}{p_T(\mathrm{e}^\pm)}$$

- Apply average correction for neutral PU
  - determine from event energy density
- Typically require I < 15%
  - efficiency ≈ independent of PU!

Photon Identification

Isolation from other particles

- Use simple $\Delta R = \sqrt{(\Delta\varphi^2 + \Delta\eta^2)} \approx 0.3$ angular distance
  - between electron and surrounding particles

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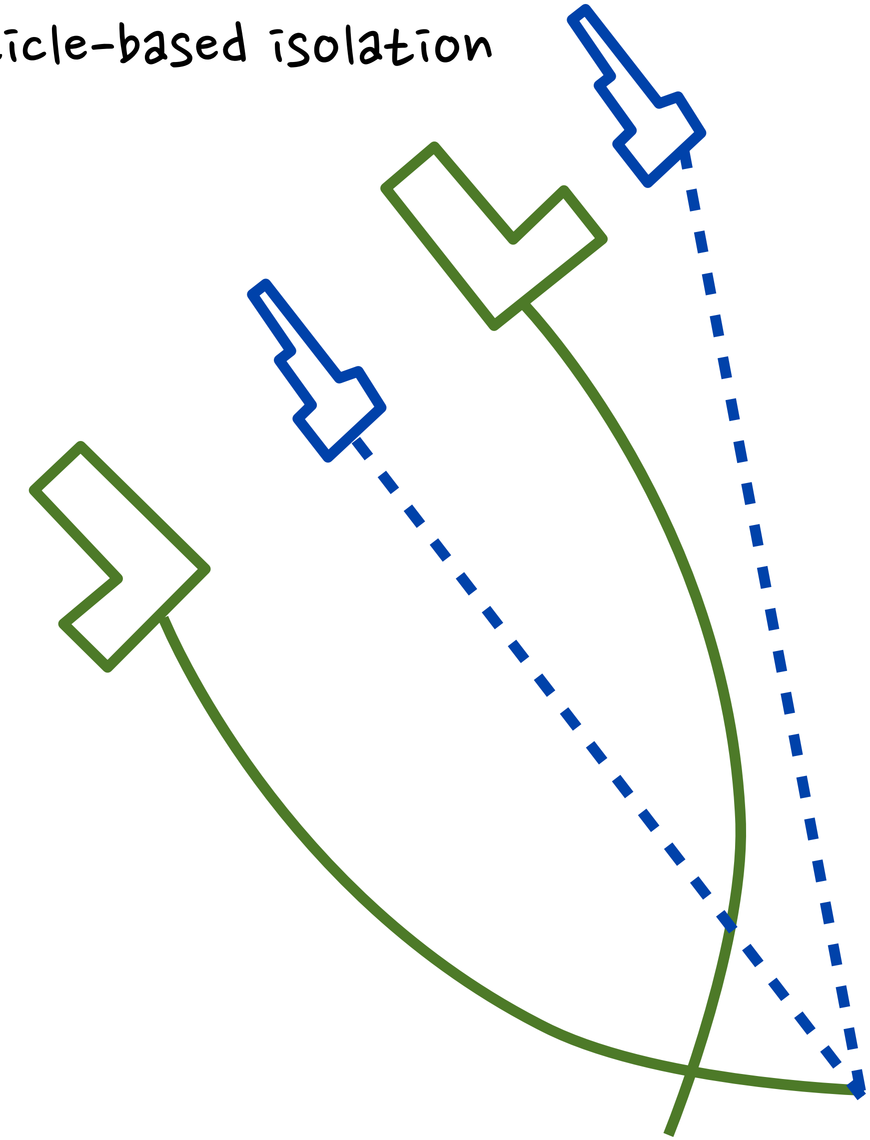

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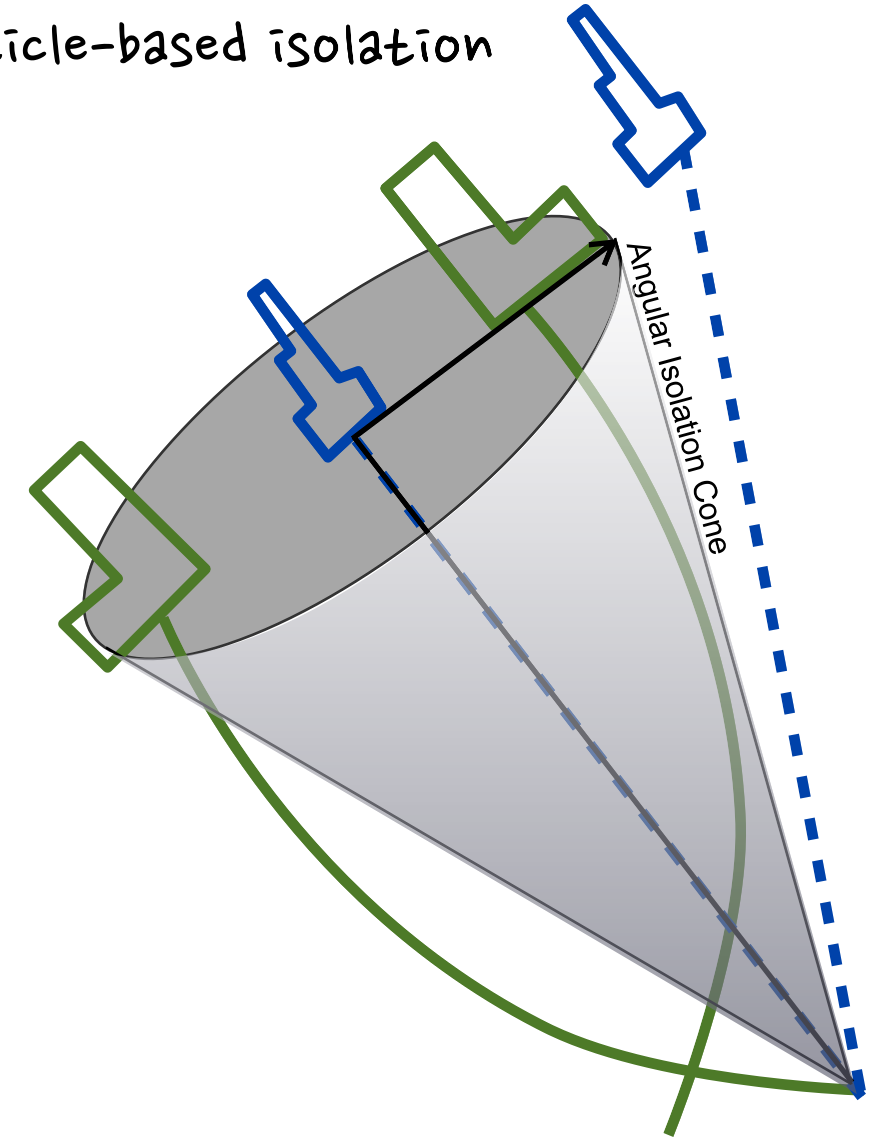

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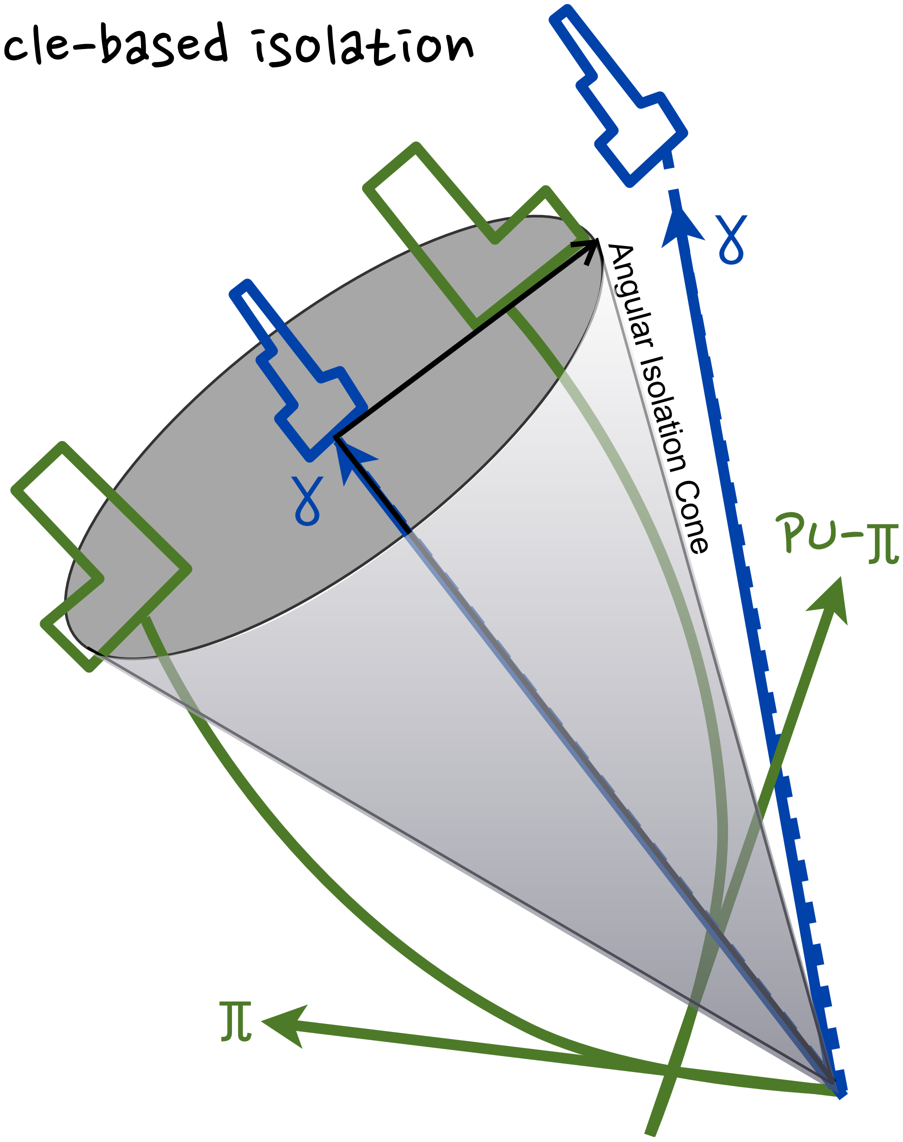

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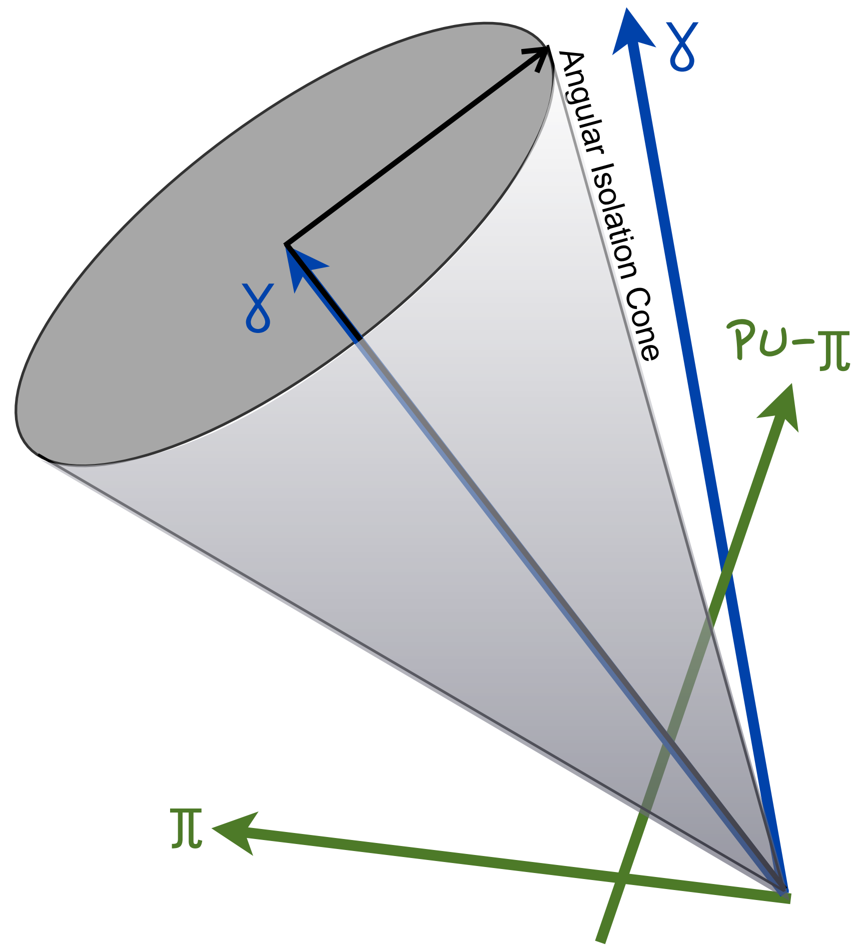

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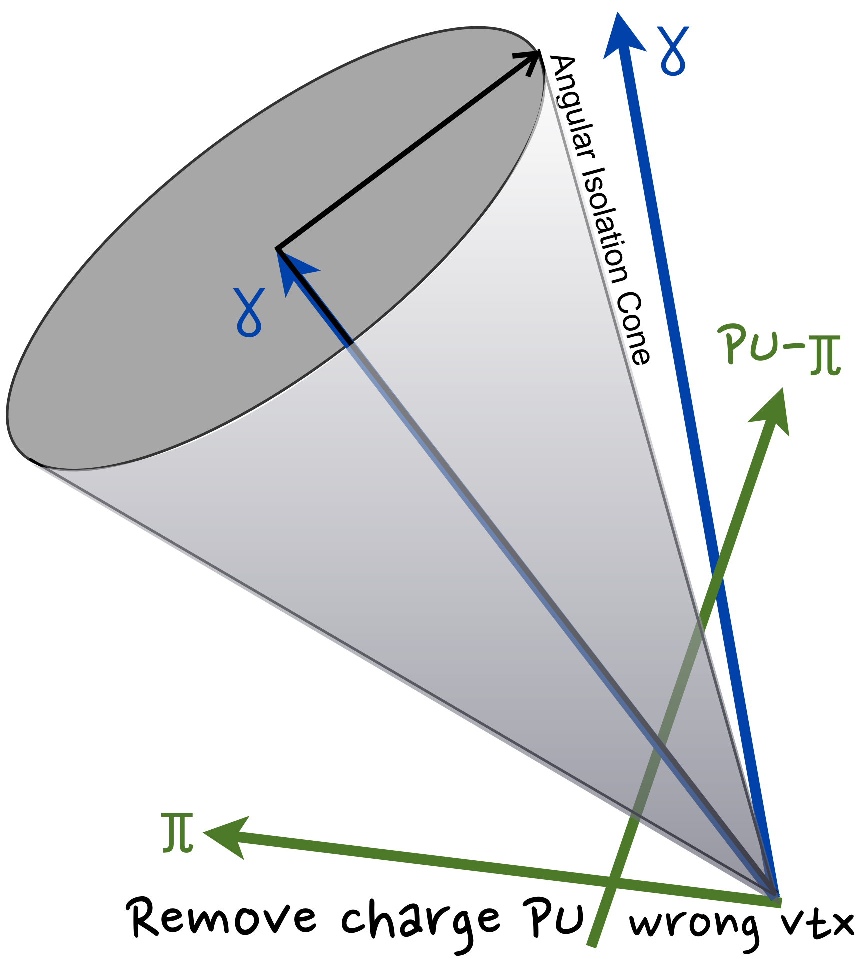

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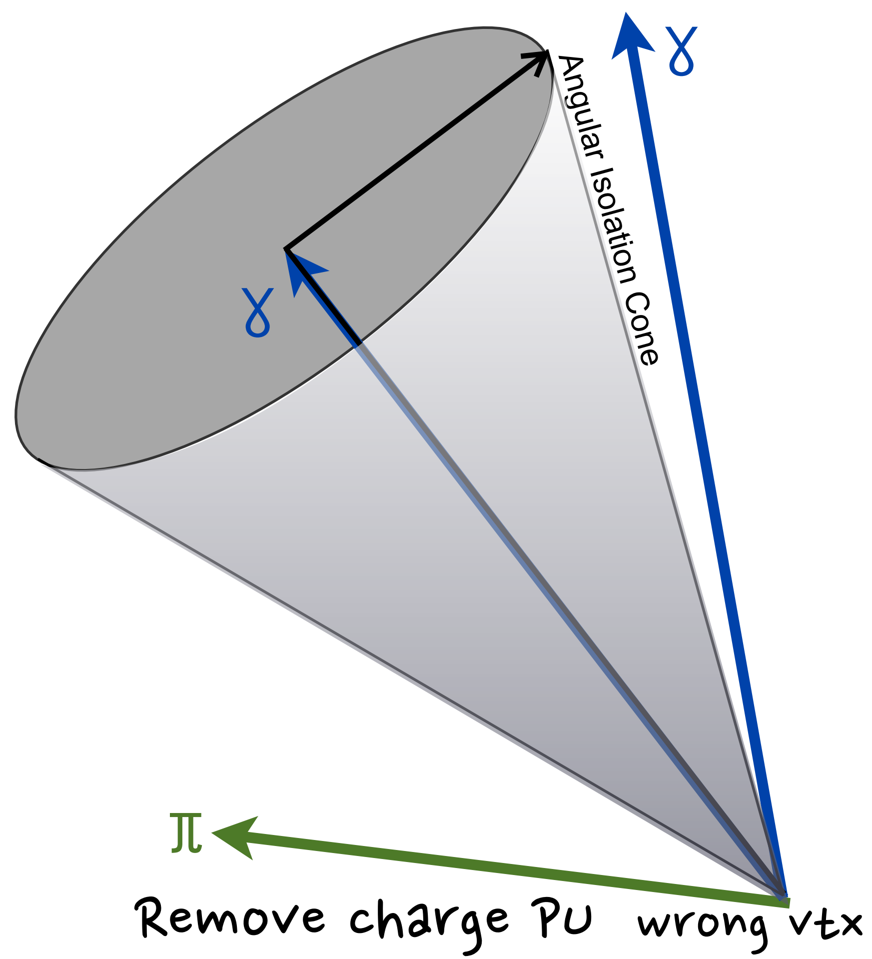

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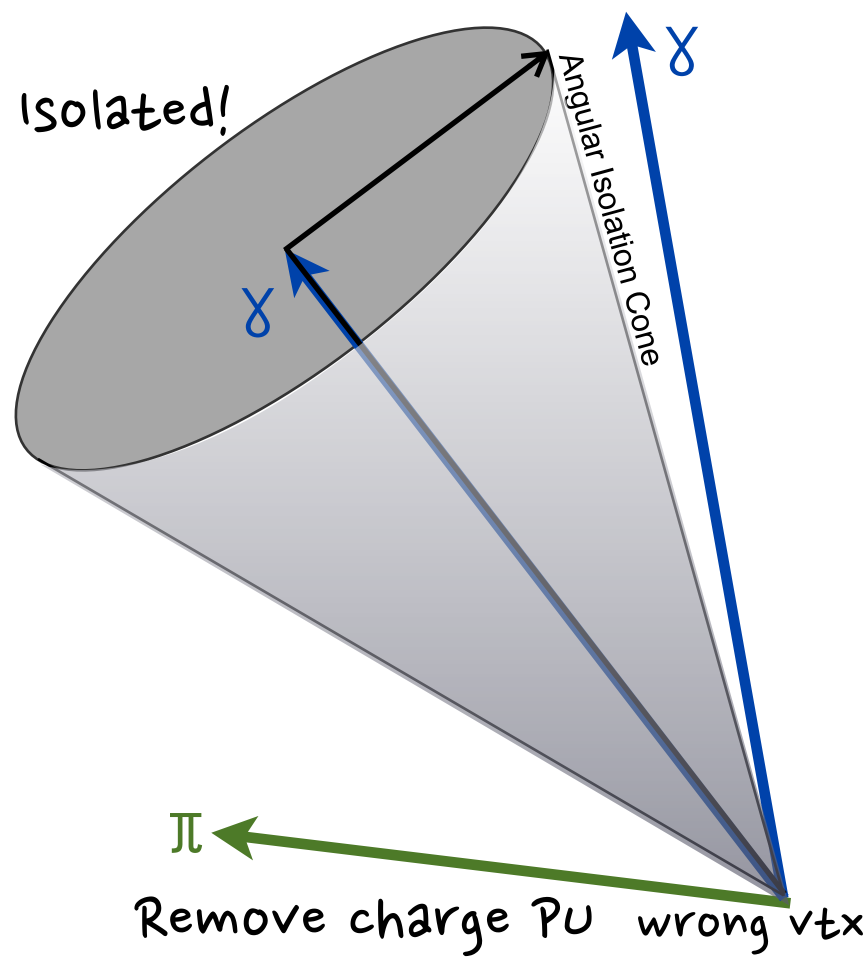

Measuring Efficiency/Purity

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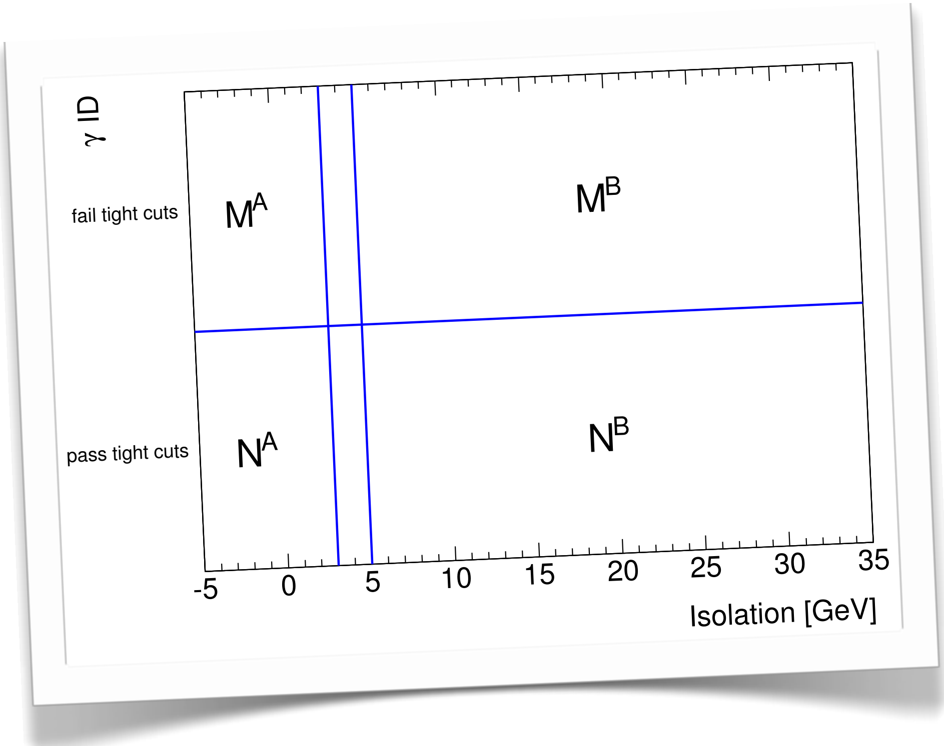

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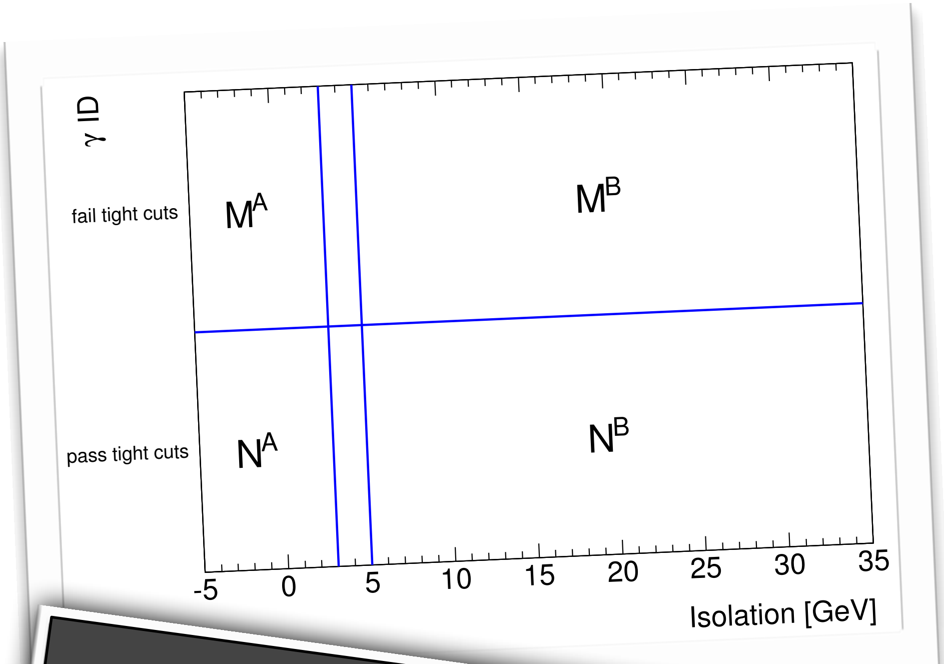

Photon yield and purity

- Assuming that γ ID is uncorrelated with the Isolation, then the number of γ's is:
  - $N(\gamma) = N^A - \text{background}$
  - $\text{background} = N^B\, M^A/M^B$
- And the γ purity is just:
  - $P = 1 - N^B/N^A\, M^A/M^B$

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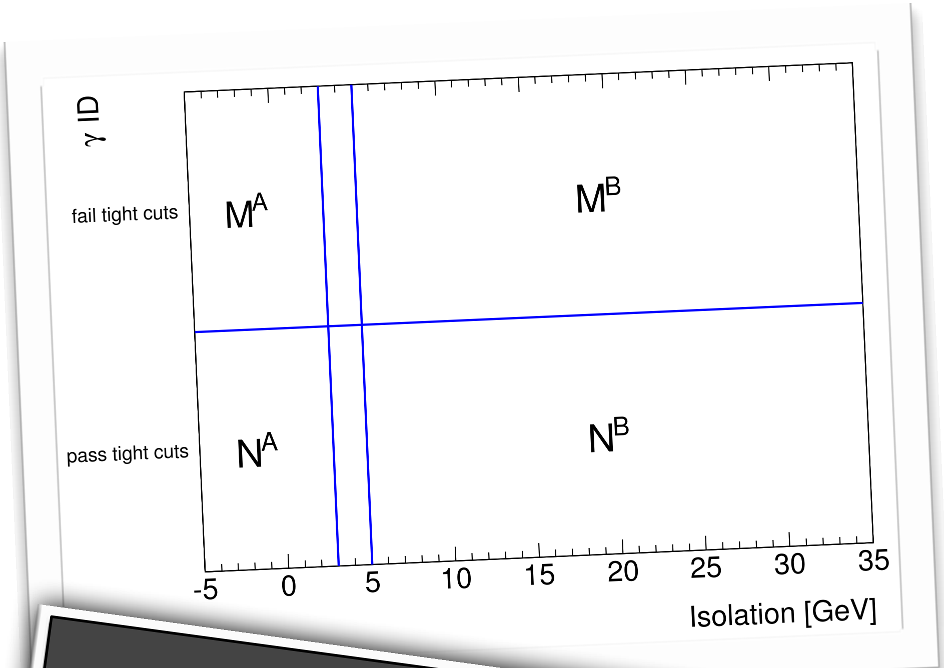

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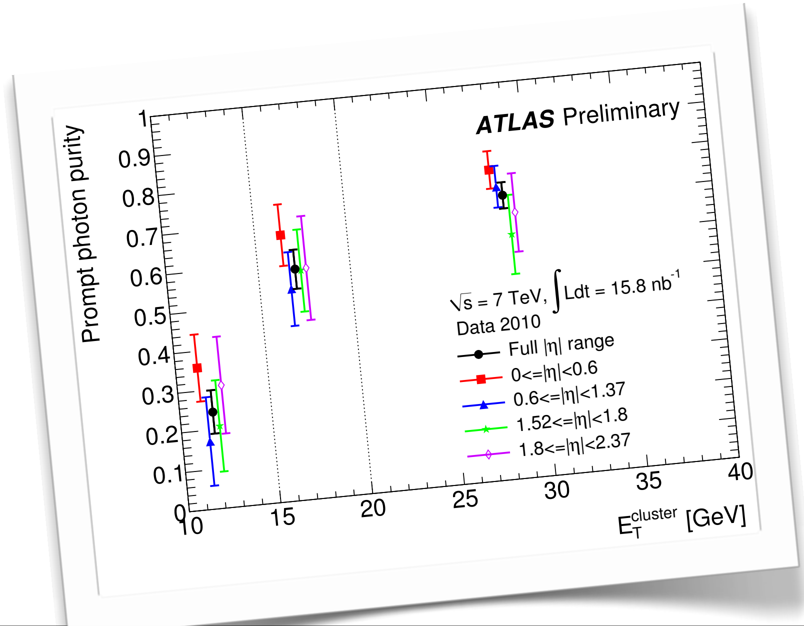

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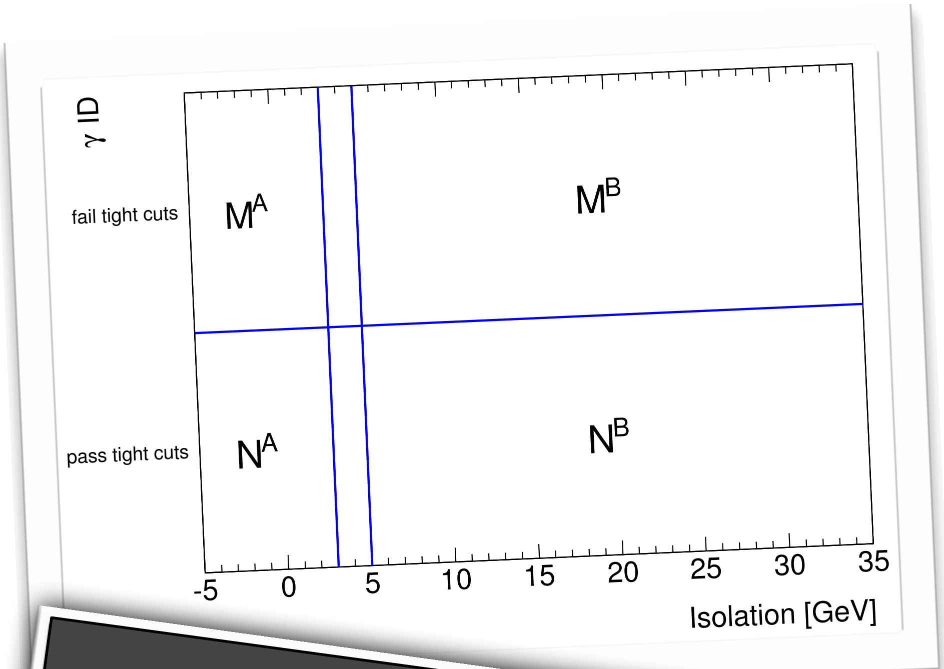

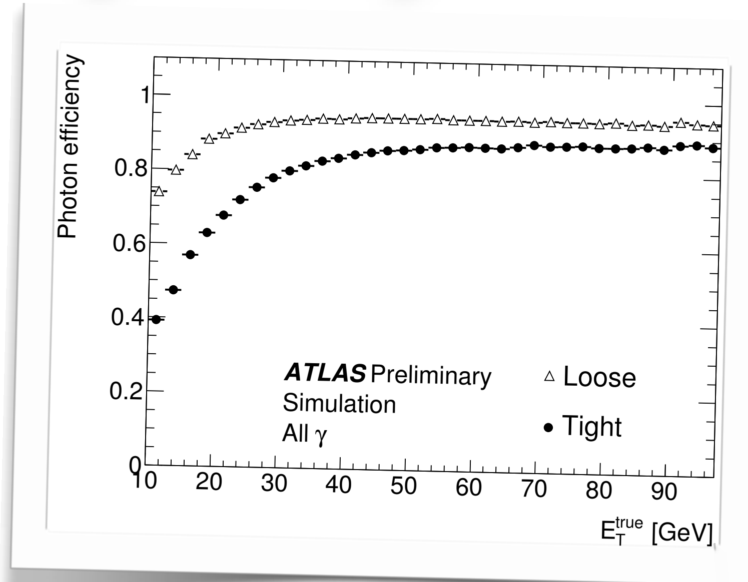

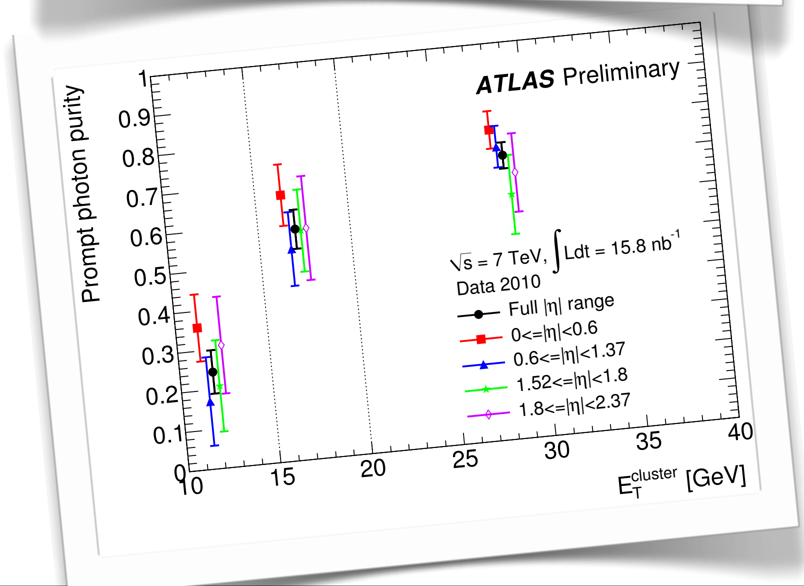

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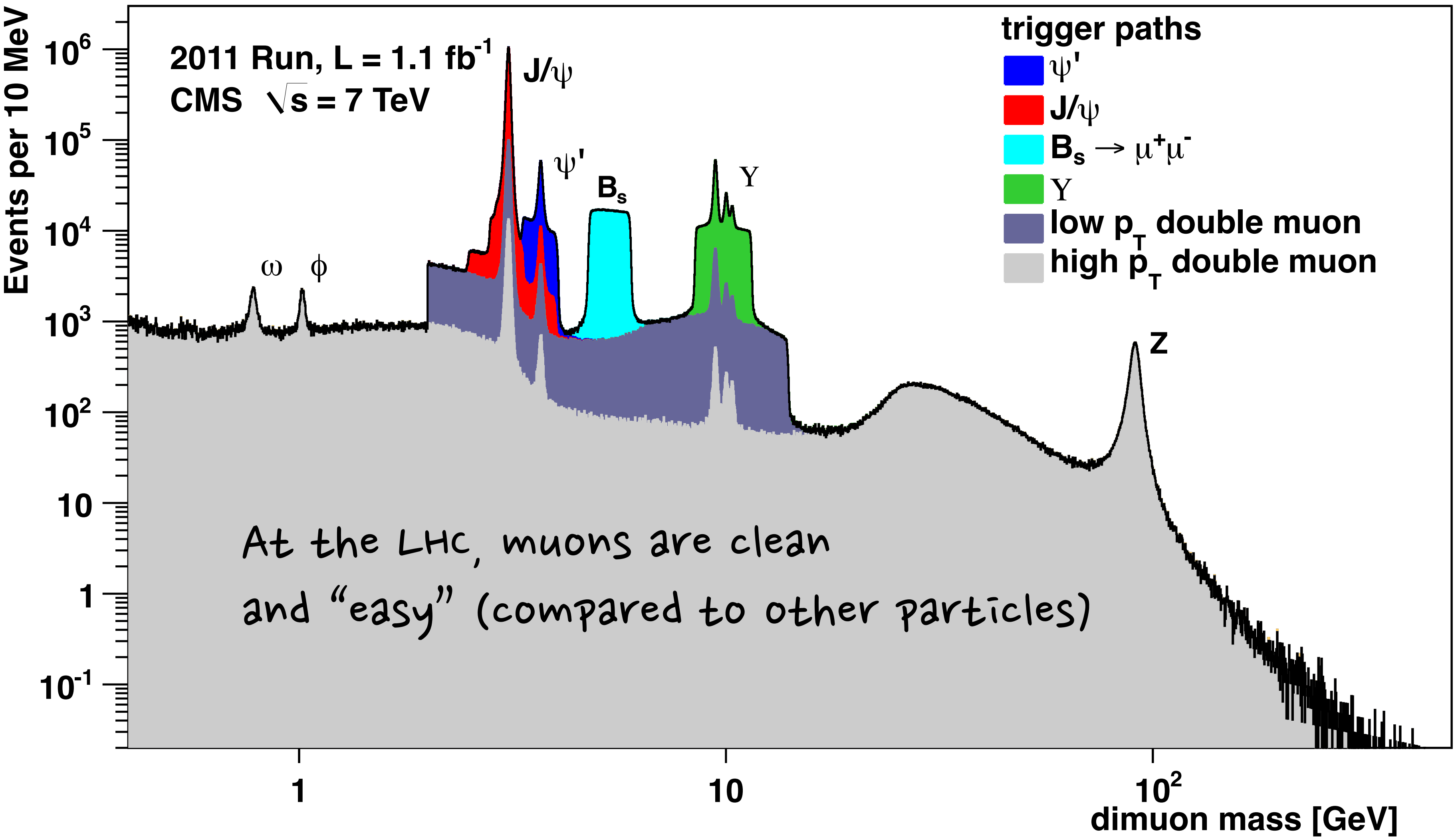
A spectroscopist's delight!

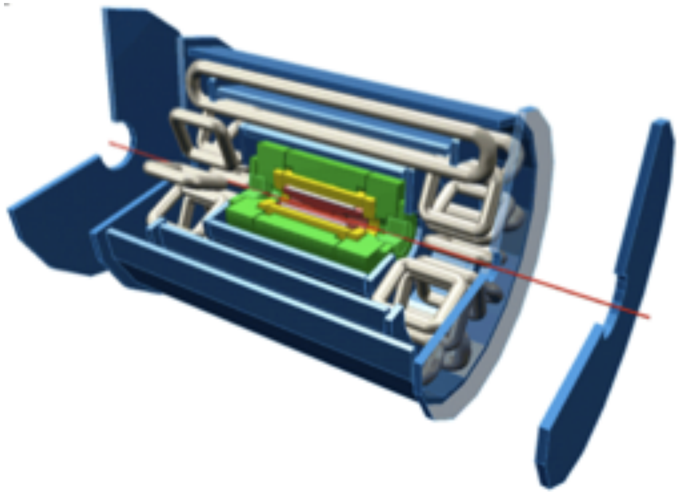
The power of muon identification!



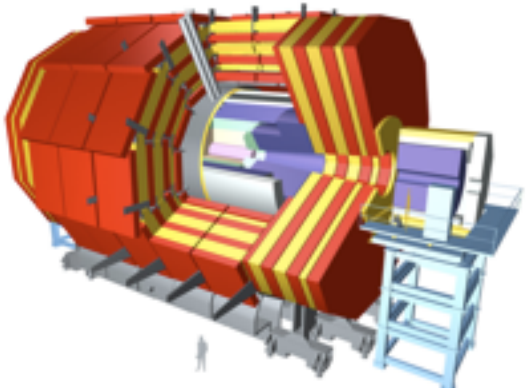
At the LHC, muons are clean and "easy" (compared to other particles)

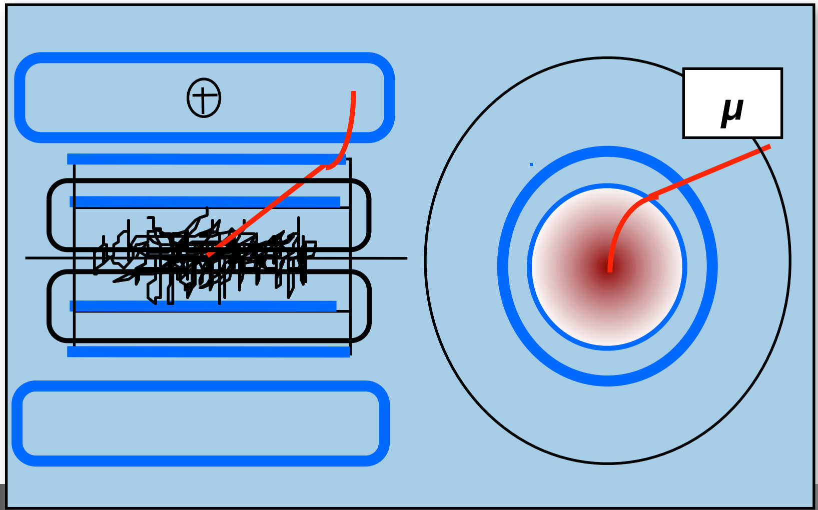
LHC pp experiments

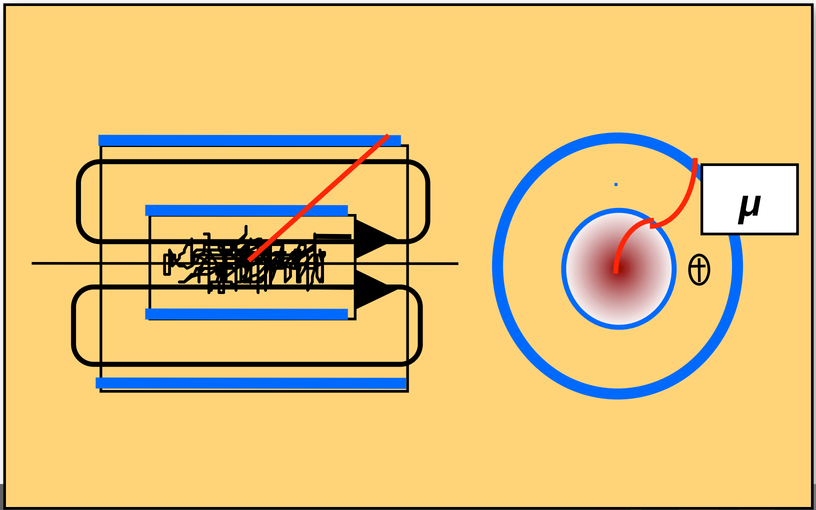
ATLAS



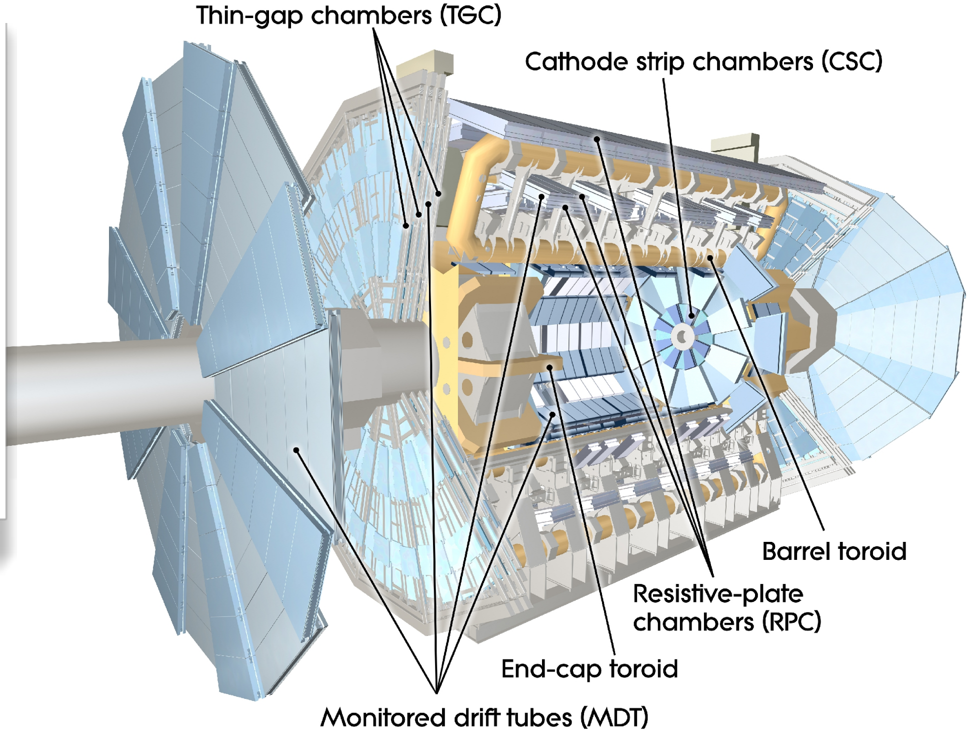
CMS

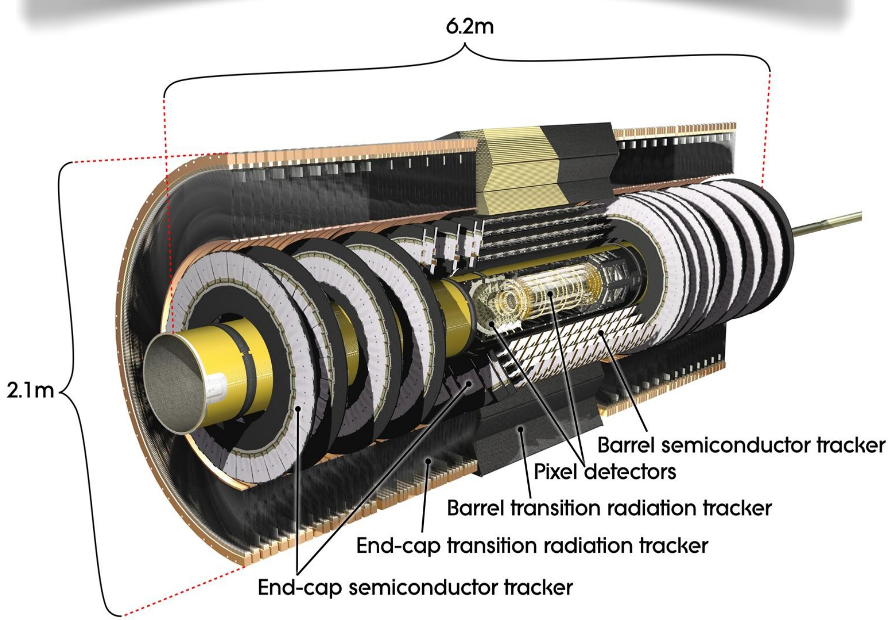




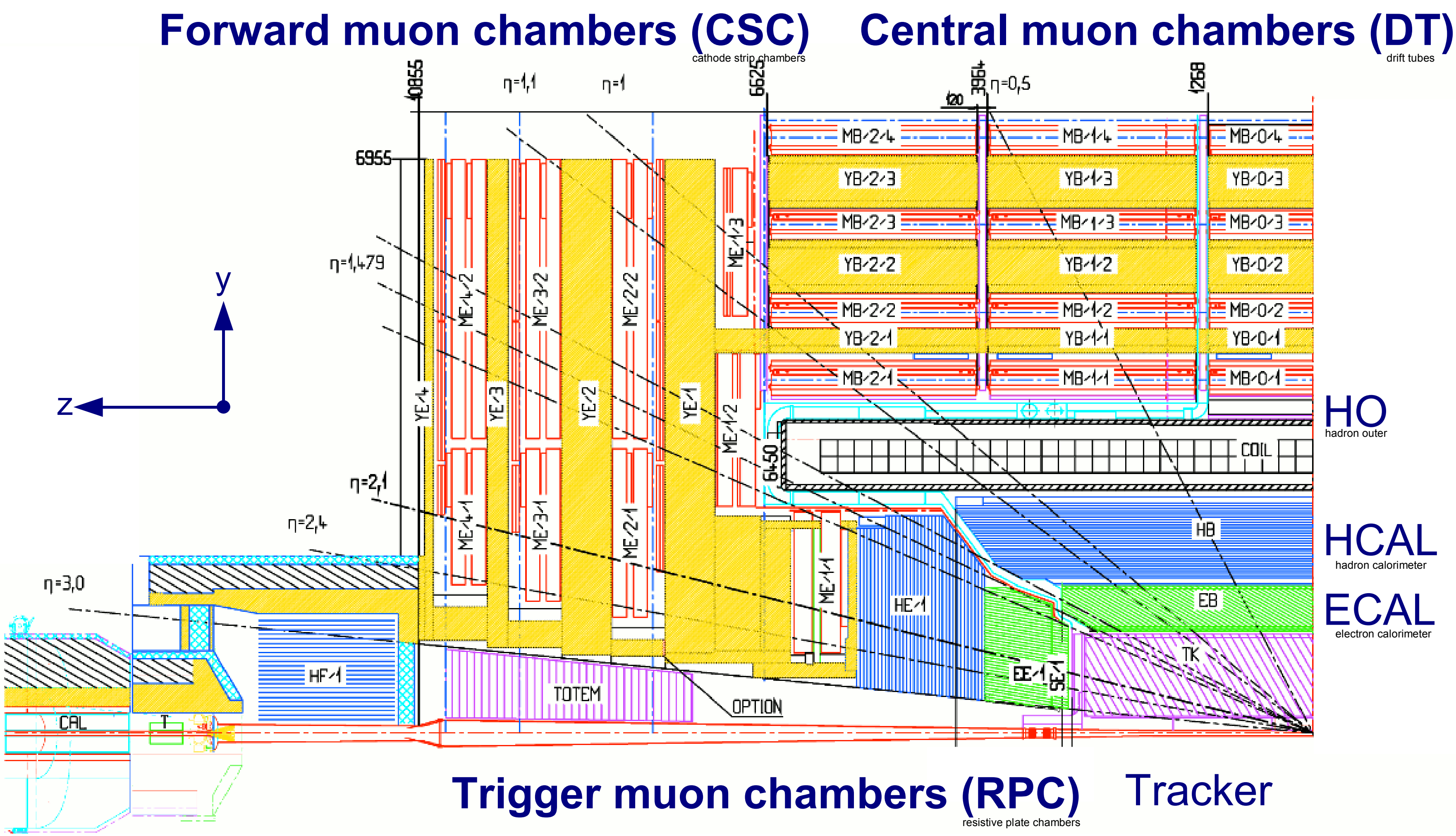


- Use a toroidal field (about 0.5T)
- **Precision chambers**
  - Monitored Drift Tubes in barrel and endcaps
    3 layers for |η|<2.0, 2 layers for 2.0 < |η| < 2.7,
    resolution of 35 μm per chamber
  - Cathode Strip Chambers :
    1 layer (inner) for 2.0 < |η| < 2.7,
    resolution in precise coordinate of 40 μm per station
- **Trigger chambers**
  - Resistive Plate Chambers in barrel (|η| < 1.05),
    1.5 ns of time resolution
  - Thin Gap Chambers in endcaps (1.05 < |η| < 2.7)





- Inside solenoid (2T)
- Pixels, SemiConductor Tracker, Transition Tradiation Tracker
- Cover |η| ≤ 2.5 region, except TRT (|η| ≤ 2)


Forward muon chambers (CSC)
cathode strip chambers
Central muon chambers (DT)
drift tubes
HO
hadron outer
HCAL
hadron calorimeter
ECAL
electron calorimeter
Trigger muon chambers (RPC)
resistive plate chambers
Tracker
MB/2/4
MB/1/4
MB/0/4
YB/2/3
YB/1/3
YB/0/3
MB/2/3
MB/1/3
MB/0/3
YB/2/2
YB/1/2
YB/0/2
MB/2/2
MB/1/2
MB/0/2
YB/2/1
YB/1/1
YB/0/1
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MB/1/1
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ME/3/2
ME/2/2
ME/1/3
ME/1/2
ME/4/1
ME/3/1
ME/2/1
ME/1/1
YE/4
YE/3
YE/2
YE/1
COIL
HB
HE/1
EB
EE/1
SE/1
TK
HF/1
TOTEM
OPTION
CAL
T
η=1,1
η=1
η=0,5
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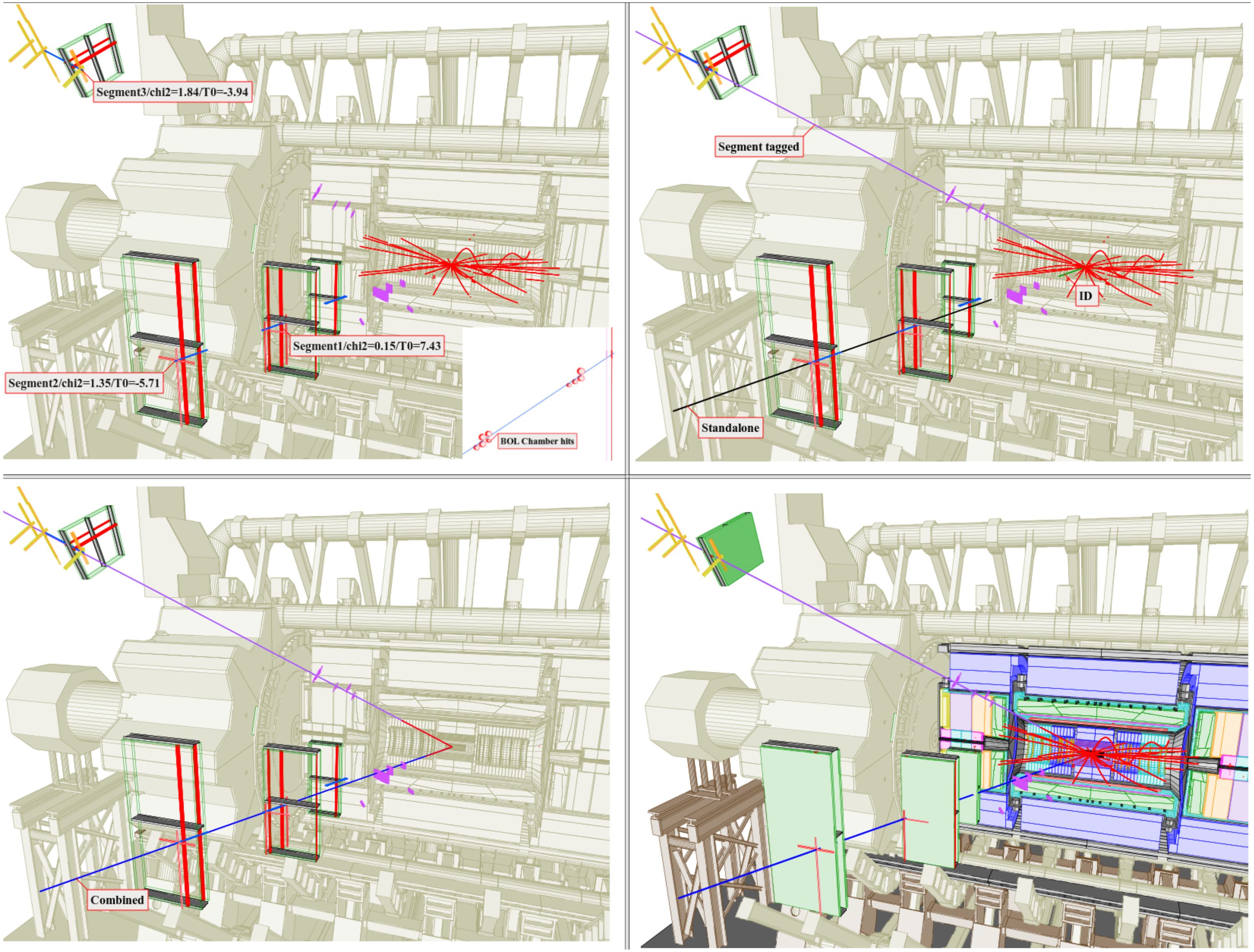
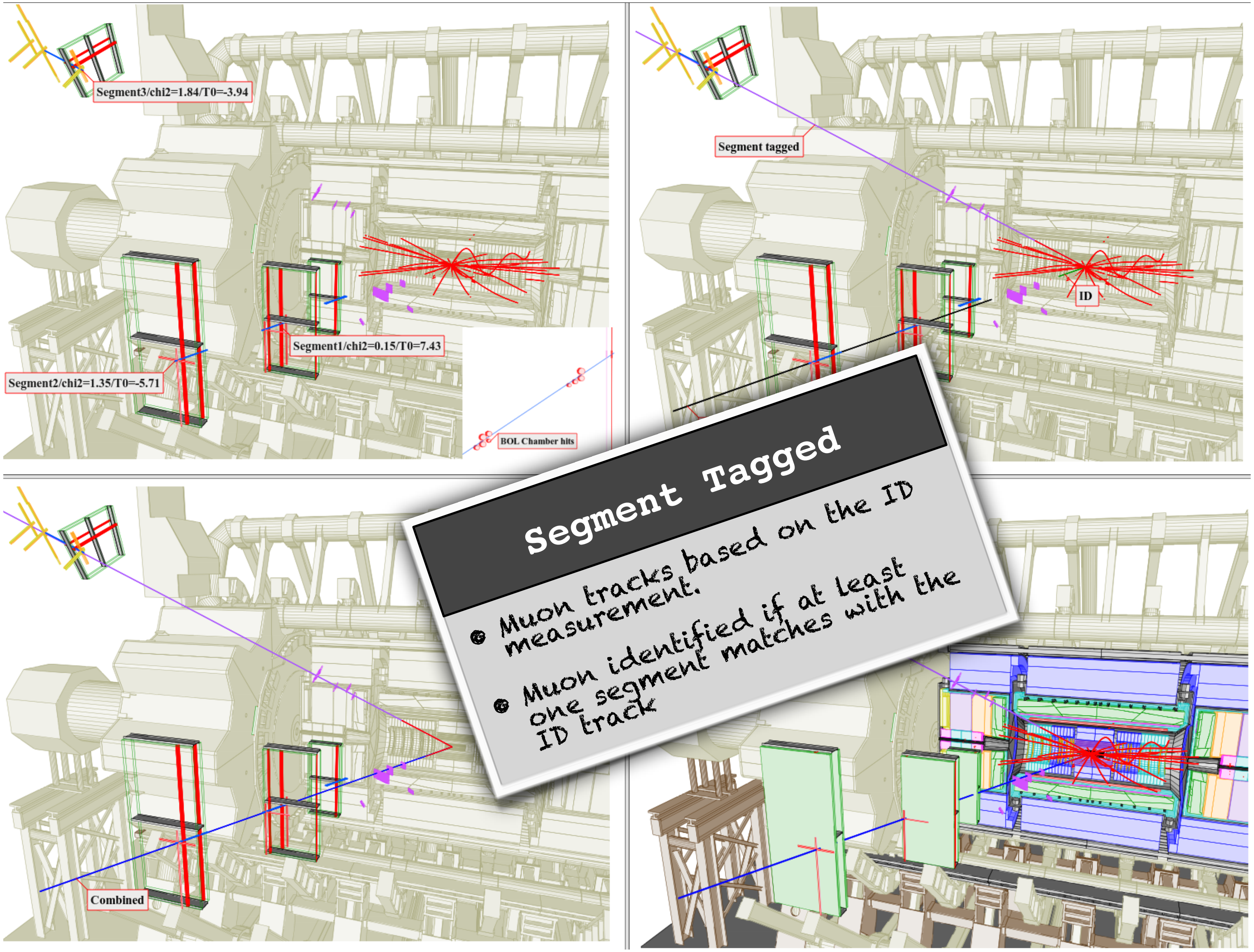
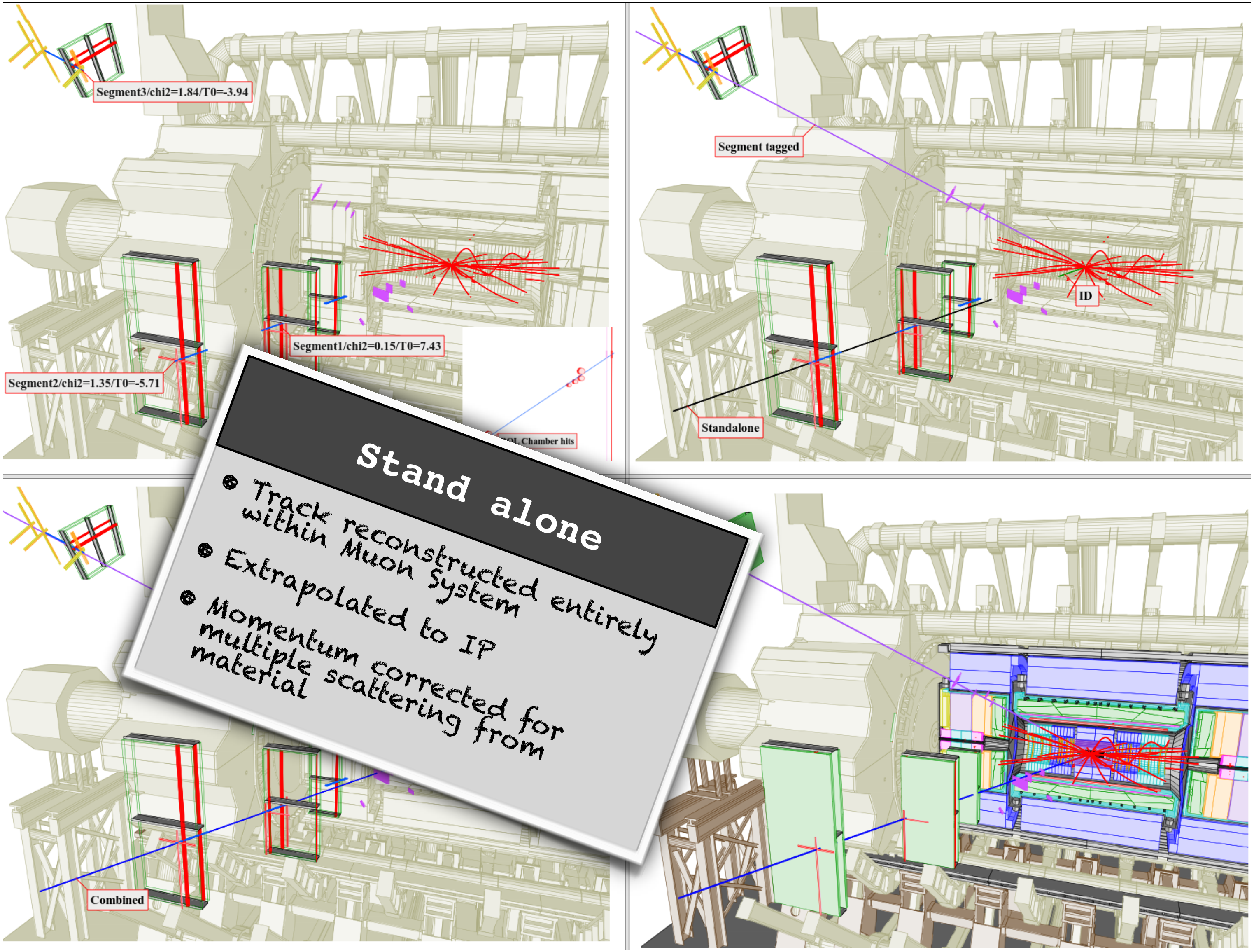
10855
6625
3964
1268
6955
6450
120
y
z


Segment3/chi2=1.84/T0=-3.94
Segment1/chi2=0.15/T0=7.43
Segment2/chi2=1.35/T0=-5.71
BOL Chamber hits
Segment tagged
ID
Standalone
Combined



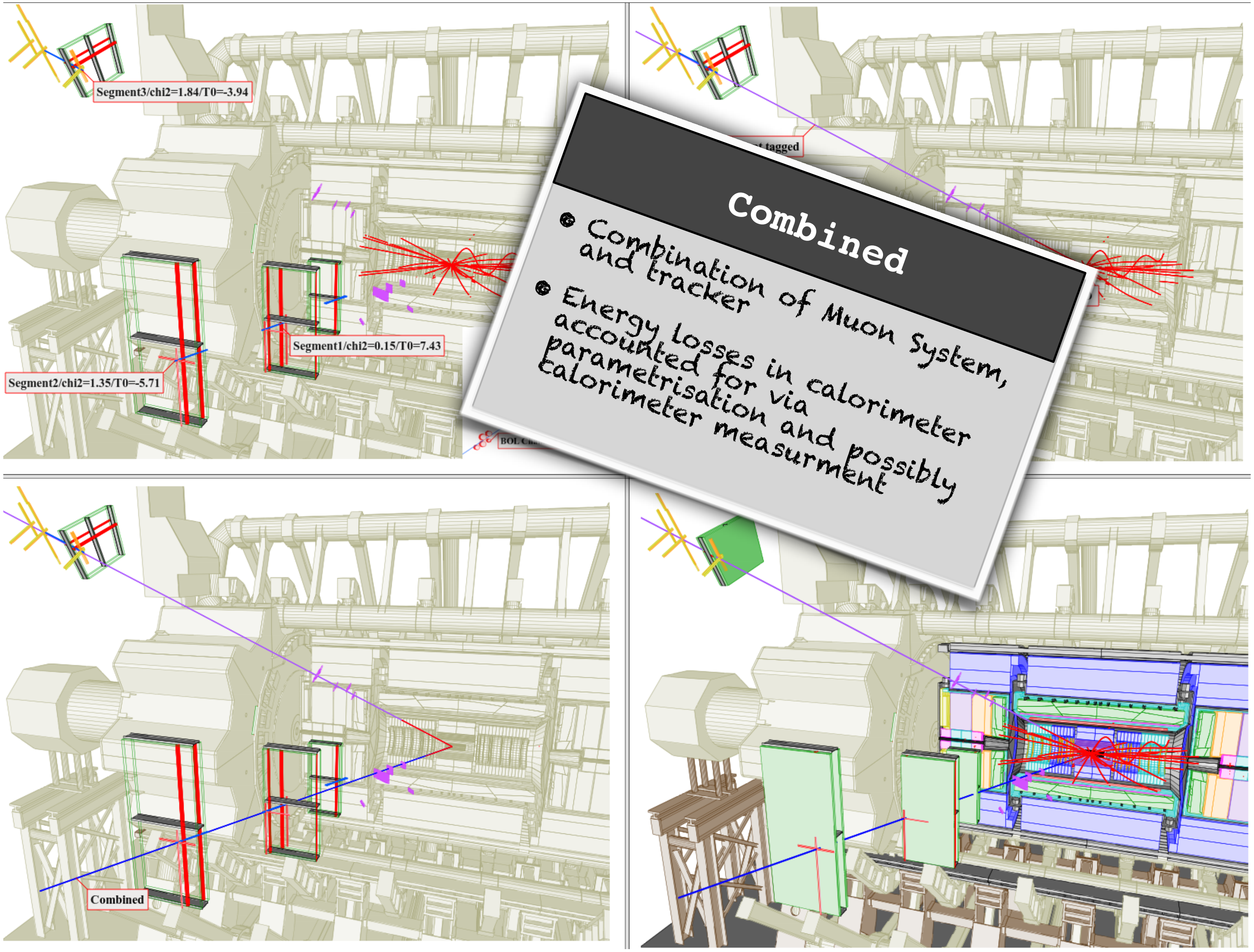
Segment Tagged

- Muon tracks based on the ID measurement.
- Muon identified if at least one segment matches with the ID track



Stand alone

- Track reconstructed entirely within Muon System
- Extrapolated to IP
- Momentum corrected for multiple scattering from material

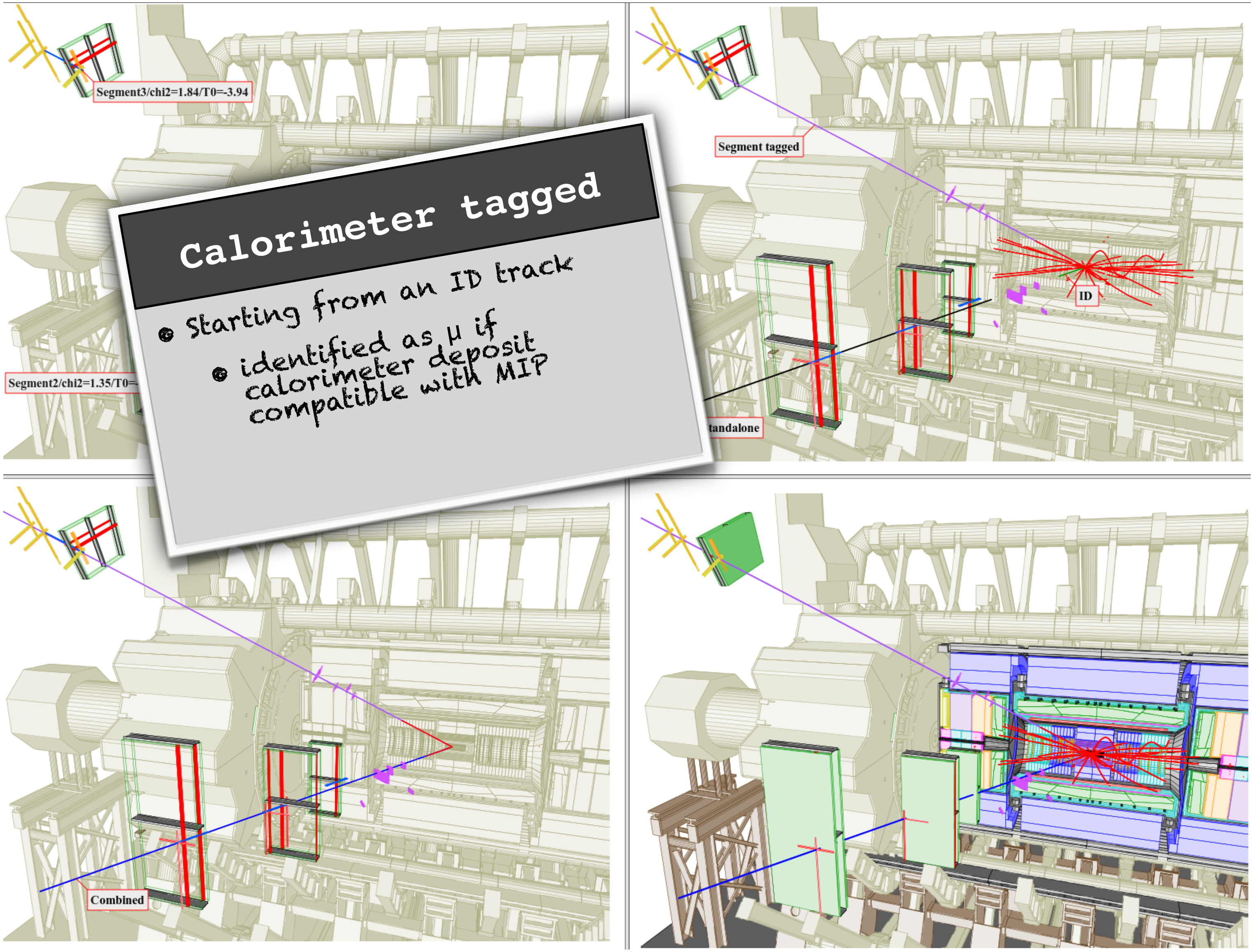


Combined

- Combination of Muon System, and tracker
- Energy losses in calorimeter accounted for via parametrisation and possibly calorimeter measurment

Calorimeter tagged

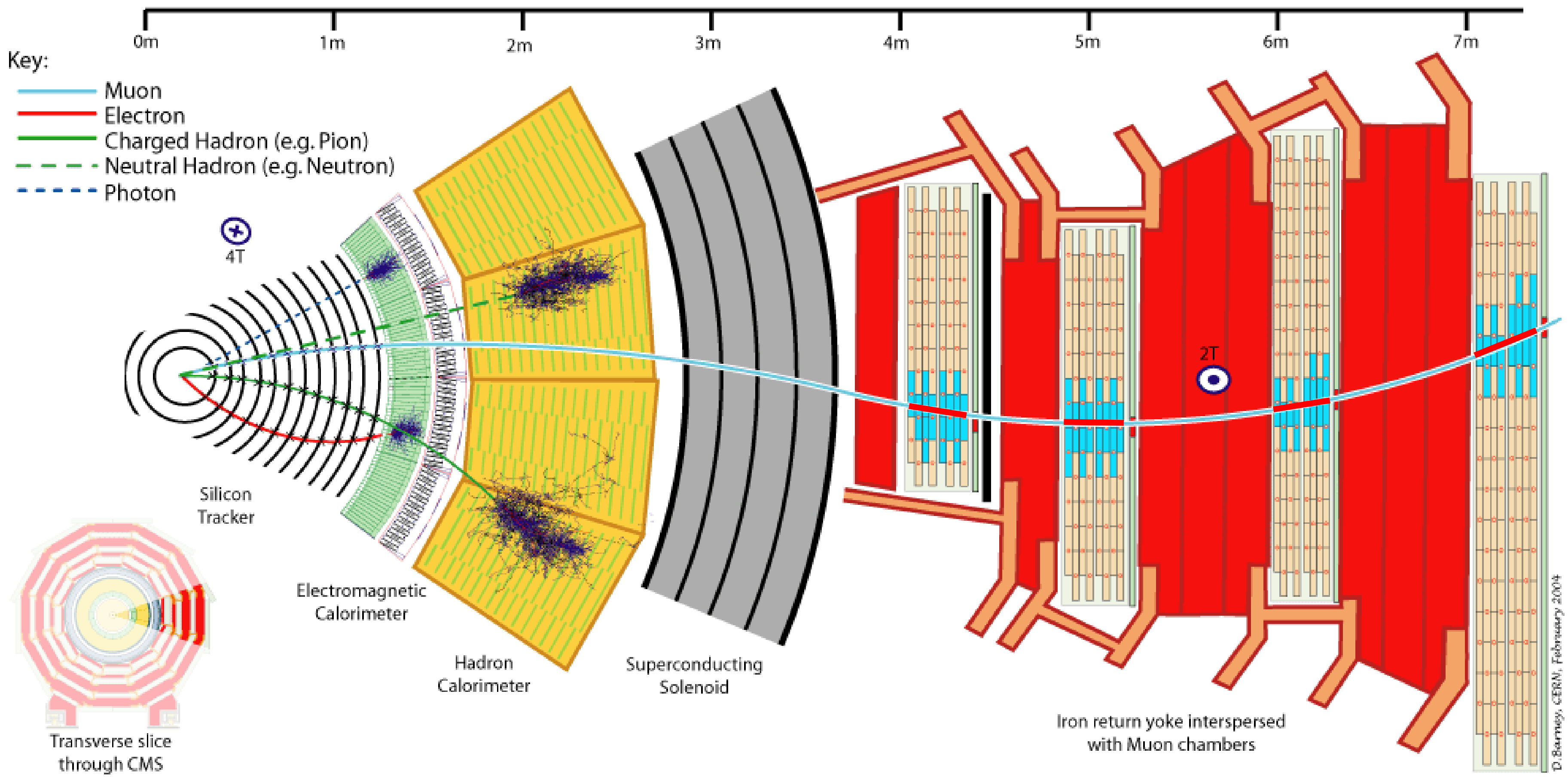
- Starting from an ID track
  - identified as μ if calorimeter deposit compatible with MIP



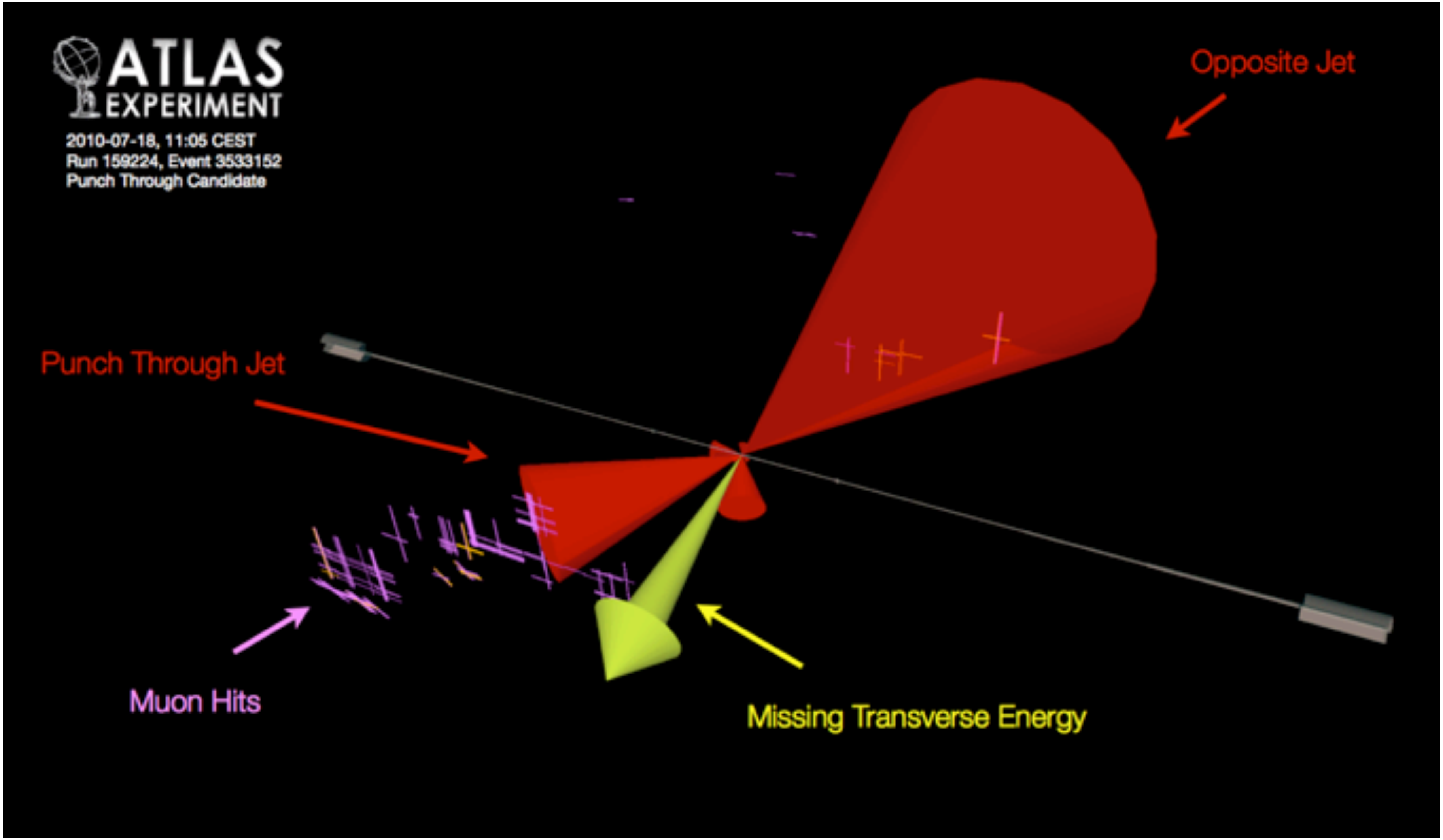
Muon Identification

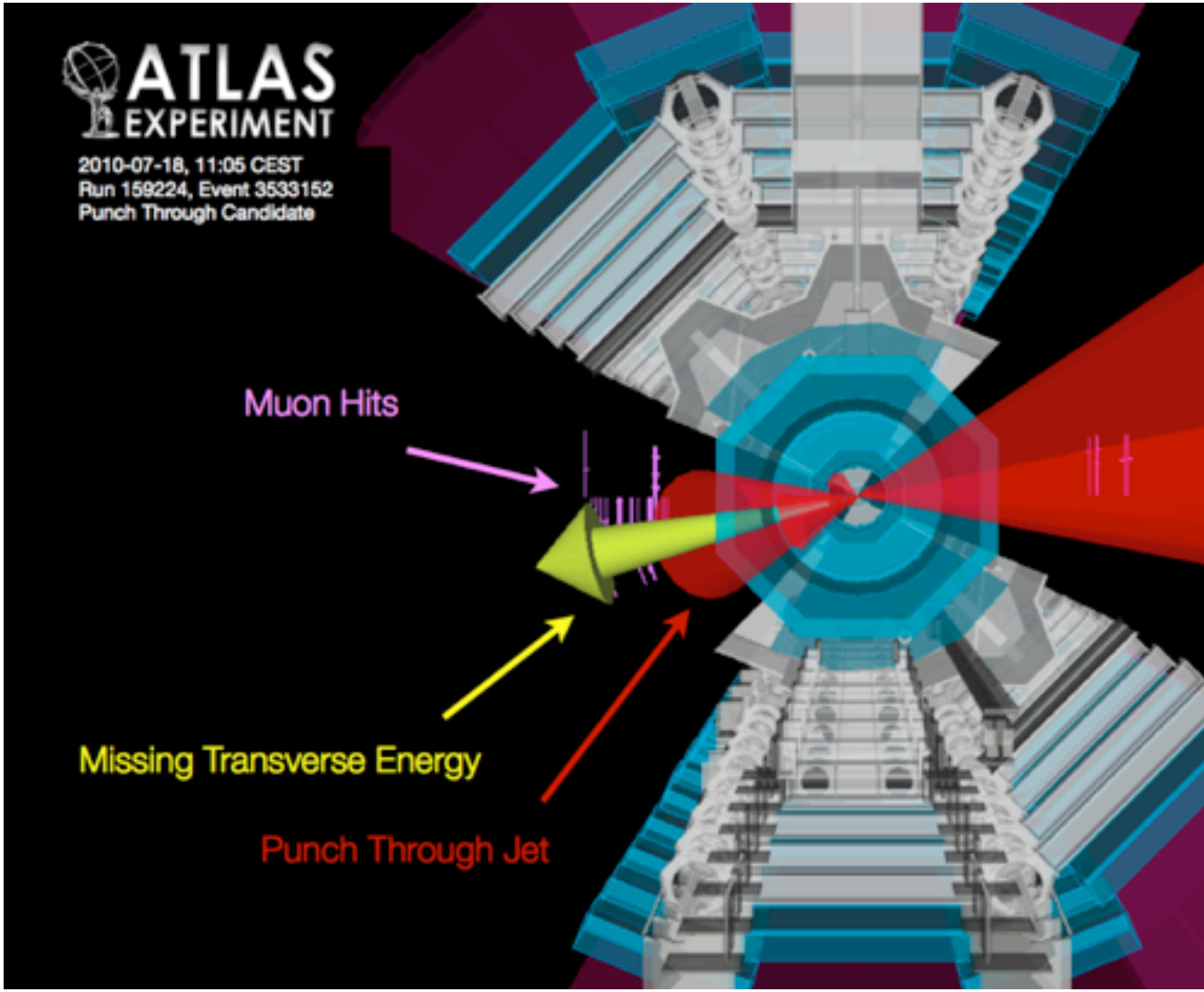
Tracker μ, Standalone μ and Global μ

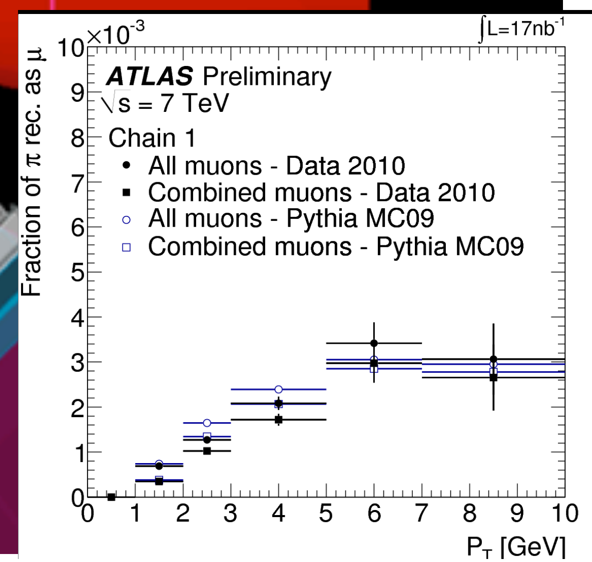
inside-out → ← outside-in



Muons


ATLAS EXPERIMENT
2010-07-18, 11:05 CEST
Run 159224, Event 3533152
Punch Through Candidate
Opposite Jet
Punch Through Jet
Muon Hits
Missing Transverse Energy


ATLAS EXPERIMENT
2010-07-18, 11:05 CEST
Run 159224, Event 3533152
Punch Through Candidate
Opposite Jet
Muon Hits
Missing Transverse Energy
Punch Through Jet


$\int L = 17 nb^{-1}$
$\times 10^{-3}$
ATLAS Preliminary
$\sqrt{s}$ = 7 TeV
Chain 1
All muons - Data 2010
Combined muons - Data 2010
All muons - Pythia MC09
Combined muons - Pythia MC09
Fraction of π rec. as μ
P_T [GeV]

Summary & Outlook

- **We now have a complete list of identified individual particles**
  - e, γ, μ, π, K_L^0, PU-π
  - This list of particles describes the entire event
    - all detector hits are used; redundancy exploited;
    - unused energy avoided; double counting of energy avoided
  - Some of these particles can be identified as prompt
    - we discussed electrons, photons, muons
  - pile-up can be removed from isolation consideration
- **Next, we will use the above list of particles to identify composite or unstable particles**
  - hadronic decays of τ-lepton, quark/gluon jets, b-jets, t-jets, and V's
- **More tomorrow!**