Experimental Methods in Hadron Colliders

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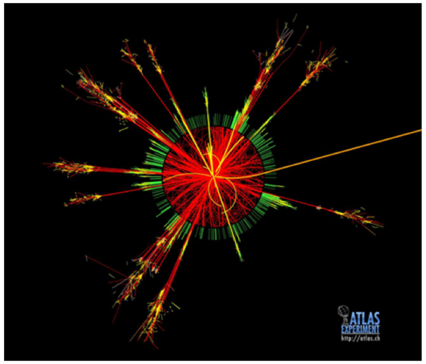
2019 CERN LATIN-AMERICAN SCHOOL OF HEP
Cordoba, Argentina, March 13-26, 2019

Outline

- Hadronic Collisions: The Basics
  - The Large Hadron Collider
  - The Anatomy of Hadronic Collisions
  - Particle Detectors & Detector Technologies
- Experimental Methods
  - Object Identification
  - The Particle Flow Event Reconstruction
  - Jet Substructure Techniques
  - Physics of Hadron Collisions: Measuring Production Rates & Masses
- Down the Standard Model Ladder
  - QCD, W/Z, Top, Higgs
- Beyond the Standard Model Searches
  - Motivation and some examples
- Outlook: HL-LHC and beyond

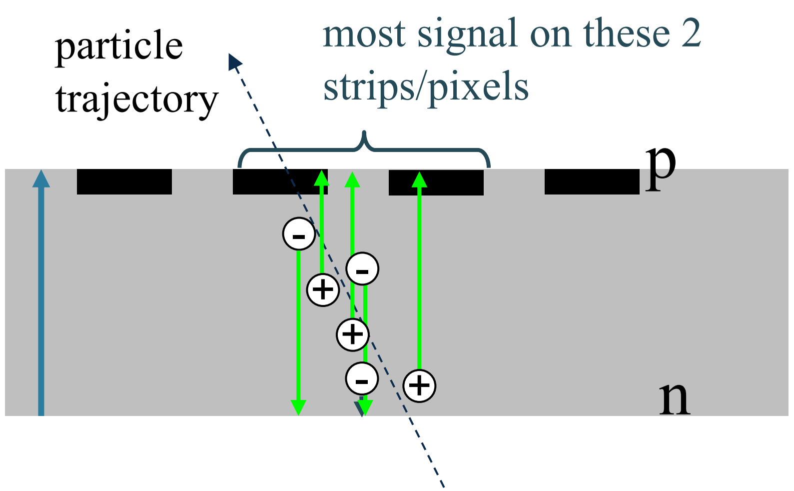


OBJECT IDENTIFICATION

From detector pulses to a particle trajectory

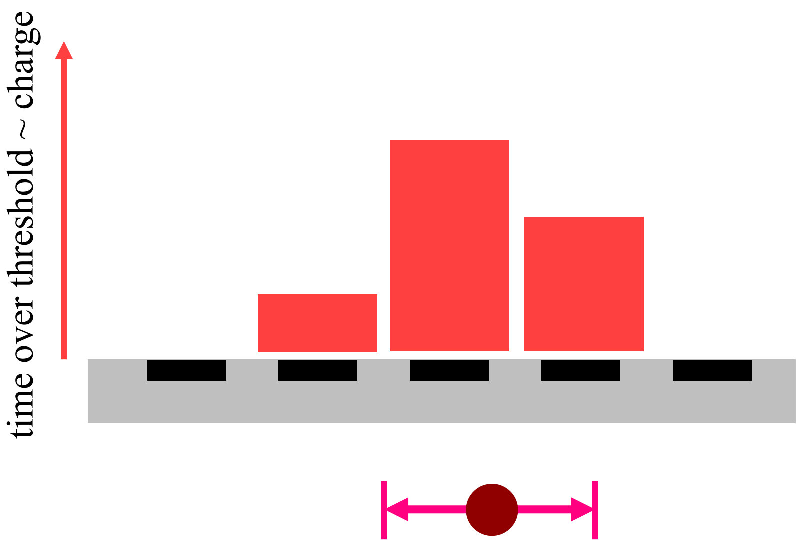
Building Clusters

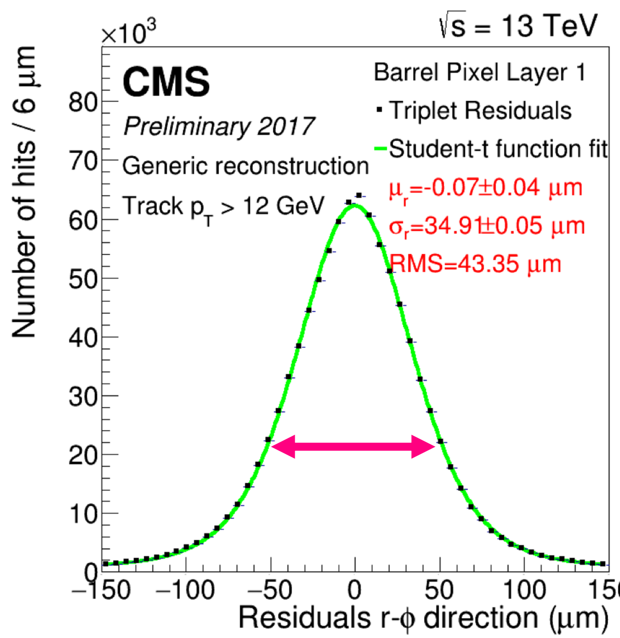
- Silicon trackers: Reverse-biased p-n junction
  - Electric field sweeps out any thermally produced electron-hole pairs (fully depleted sensor)
  - Charged particle produces **electron-hole pairs** which **induce signal** on implanted electrodes
  - On-detector electronics amplify signal, apply threshold and/or pedestal subtraction
  - Adjacent pixel/strips with charge combined into clusters



Building hits

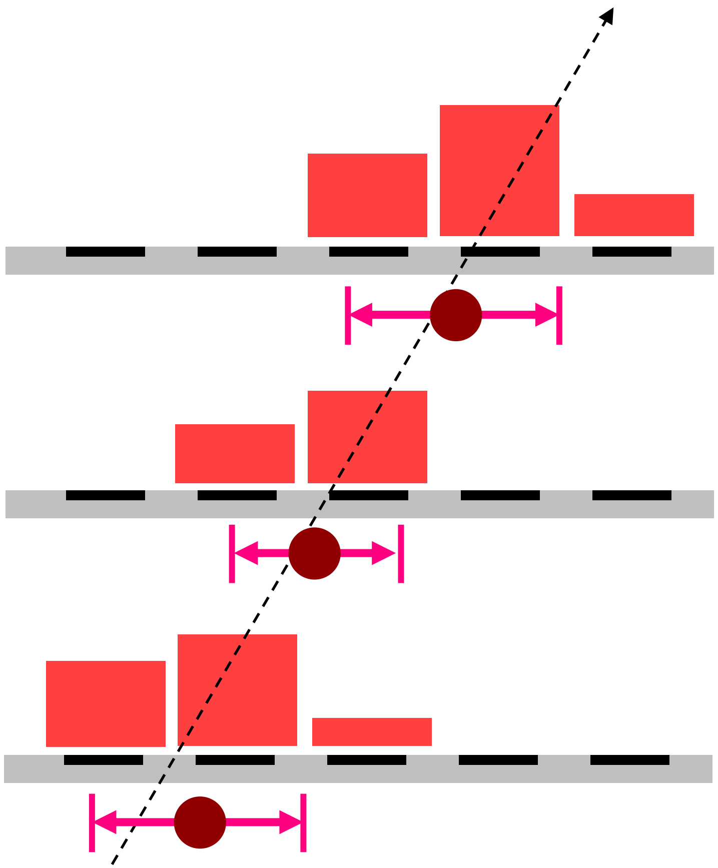
- Start from charge information: cluster centroid
  - Interpolate from edges or make a template fit - latter has significant advantage after irradiation
- But need *resolution* of hit location for track fit
  - **Resolution** = width of (Gaussian) distribution of residuals (difference between track position and estimated cluster centroid)





Building tracks

- Particle trajectory are reconstructed from hits in the detectors
- Seed tracks built with 3-4 hits in pixel detector
- Kalman filter for track extrapolation and subsequent fit to helical trajectory



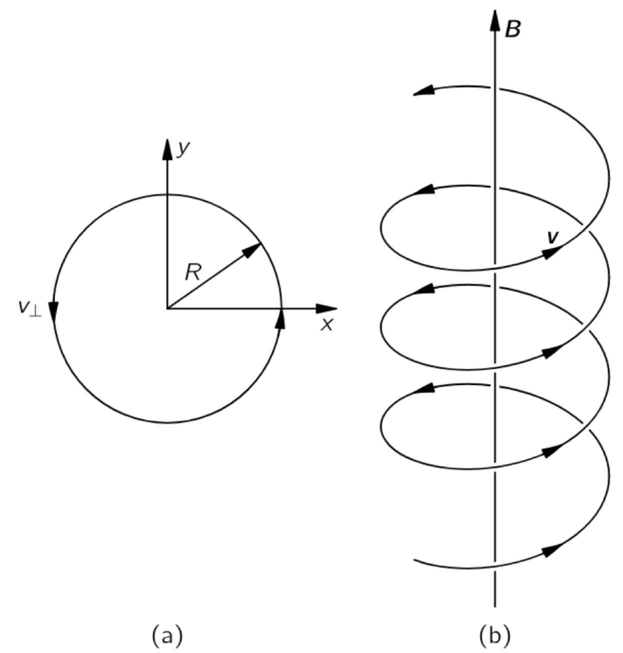
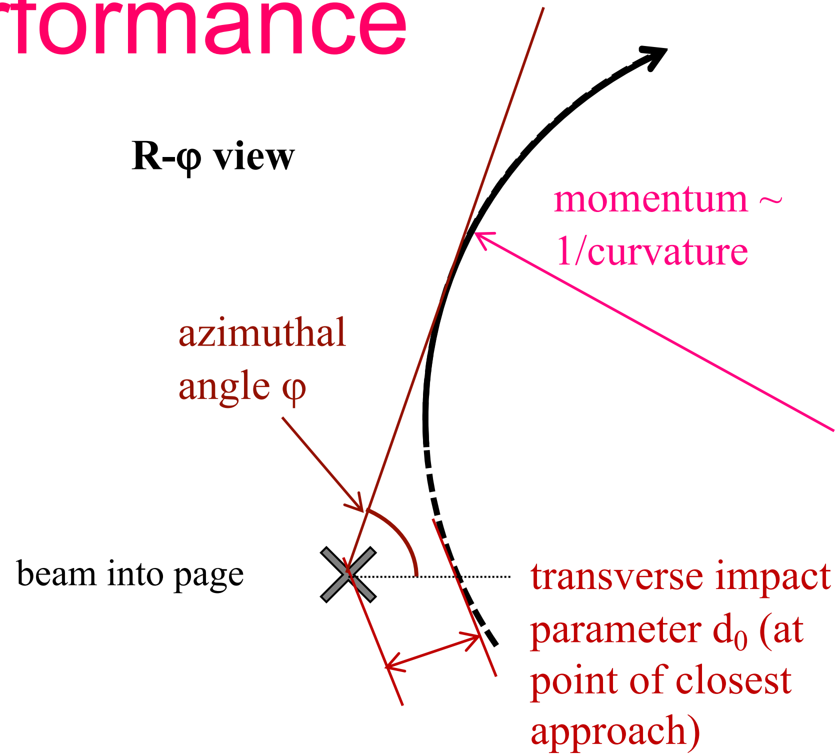
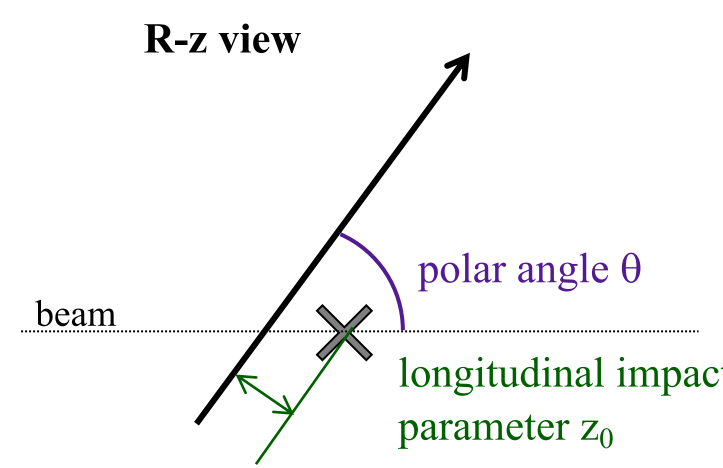


Fig. 29–1. Motion of a particle in a uniform magnetic field.

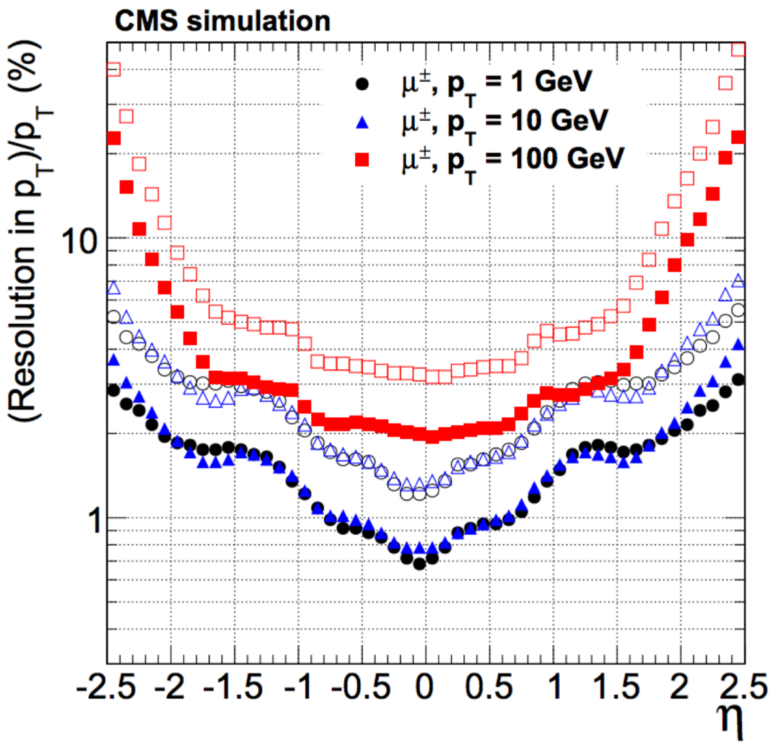
Tracking performance

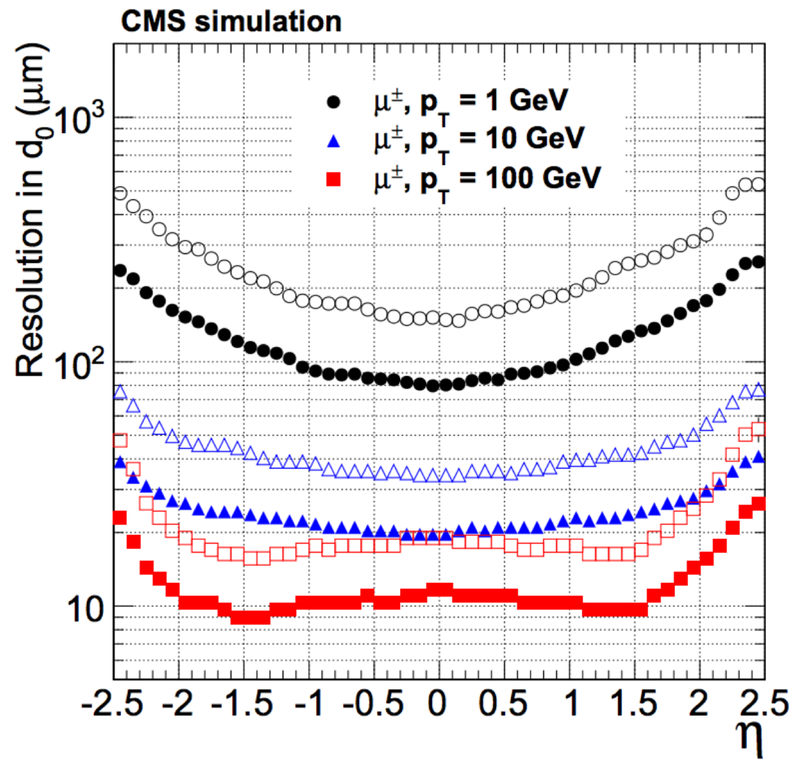
- Tracking is fundamental to charged particle reconstruction + ID
- Helical trajectory defined by 5 track parameters
  - 2 impact parameters
  - 2 angles
  - curvature/momentum
- For each track, interested in
  - Transverse momentum
  - Impact parameter
    - Displaced tracks from decay of particles such as b-quark hadrons
- Vertex reconstruction





Tracking performance at CMS



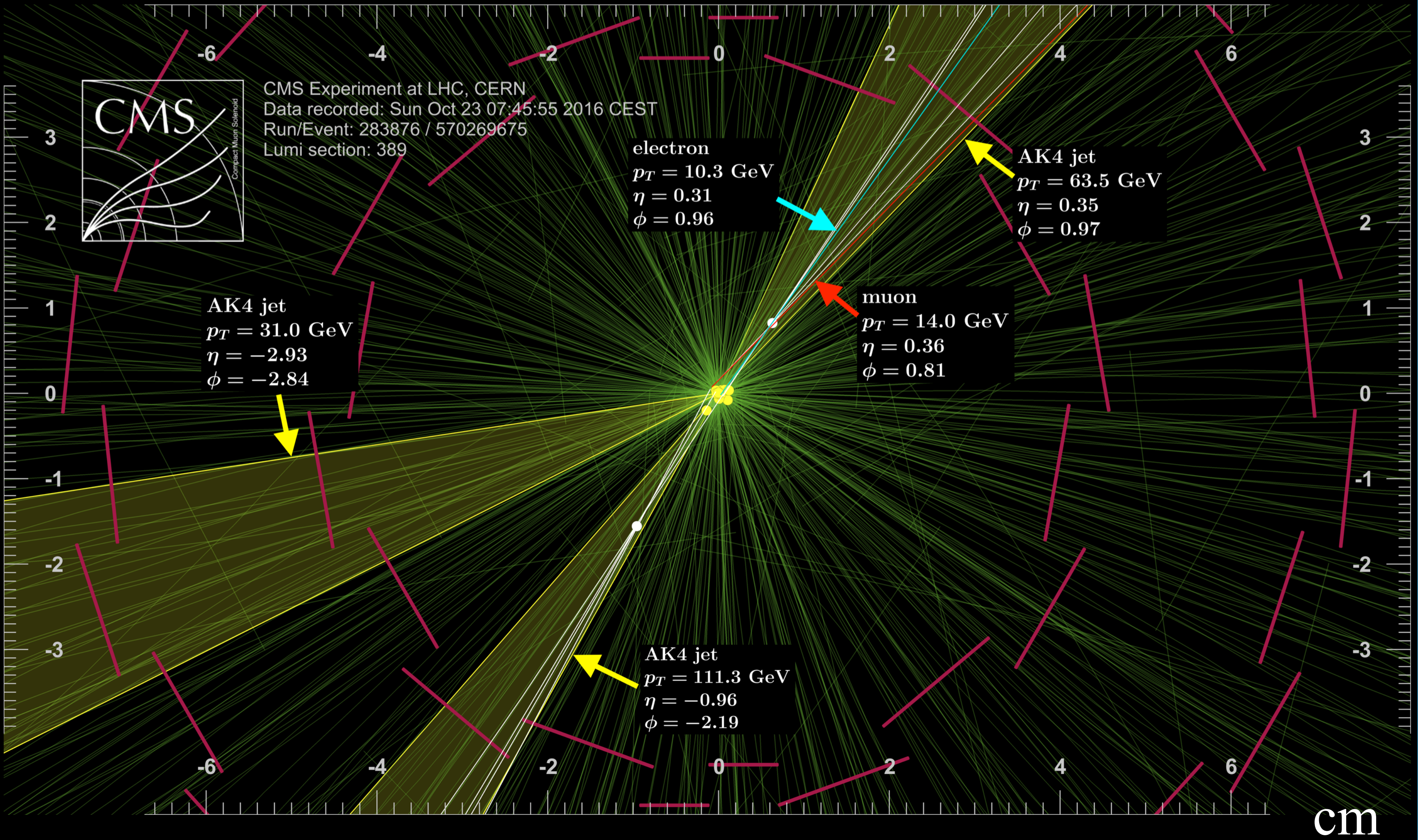


Harder to measure curvature of straighter (higher-momentum) tracks

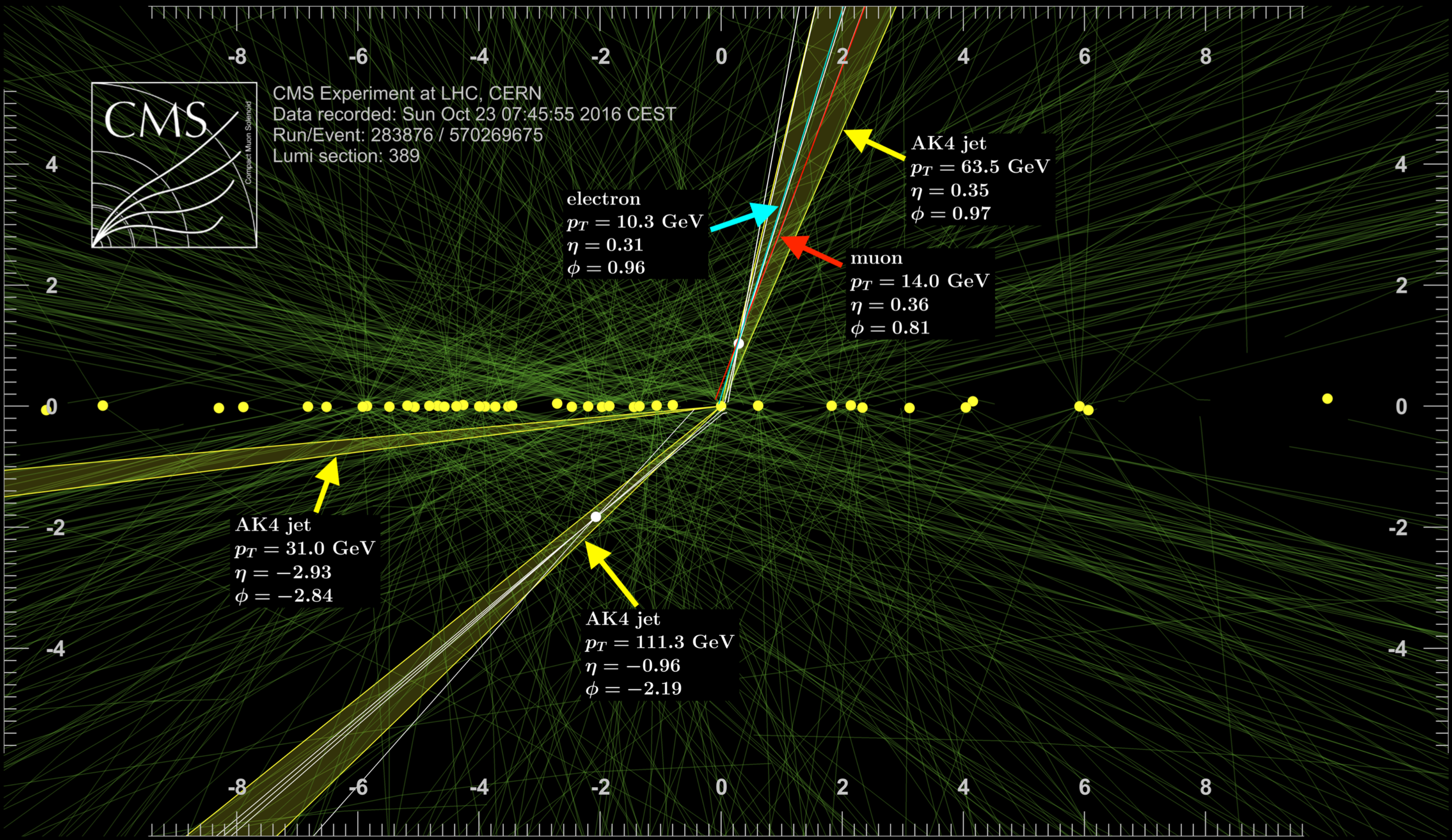
Harder to extrapolate lower-momentum tracks: scattering in material matters

$$\left(\frac{\sigma_{p_T}}{p_T}\right)^2 \propto \underbrace{\boxed{c_1 \cdot \left(\frac{p_T}{BL^2}\sqrt{\frac{720}{N+4}}\right)^2}}_{\text{curvature}} + \underbrace{\boxed{c_2 \cdot \left(\frac{1}{B\sqrt{LX_0}}\right)^2}}_{\text{multiple scattering}}$$

For CMS:
magnetic field B = 3.8 T
tracker radius L = 1.2 m
number of measurements N >10



CMS
Compact Muon Solenoid
CMS Experiment at LHC, CERN
Data recorded: Sun Oct 23 07:45:55 2016 CEST
Run/Event: 283876 / 570269675
Lumi section: 389
electron
$p_T = 10.3$ GeV
$\eta = 0.31$
$\phi = 0.96$
AK4 jet
$p_T = 63.5$ GeV
$\eta = 0.35$
$\phi = 0.97$
muon
$p_T = 14.0$ GeV
$\eta = 0.36$
$\phi = 0.81$
AK4 jet
$p_T = 31.0$ GeV
$\eta = -2.93$
$\phi = -2.84$
AK4 jet
$p_T = 111.3$ GeV
$\eta = -0.96$
$\phi = -2.19$
-6
-4
-2
0
2
4
6
3
2
1
0
-1
-2
-3
cm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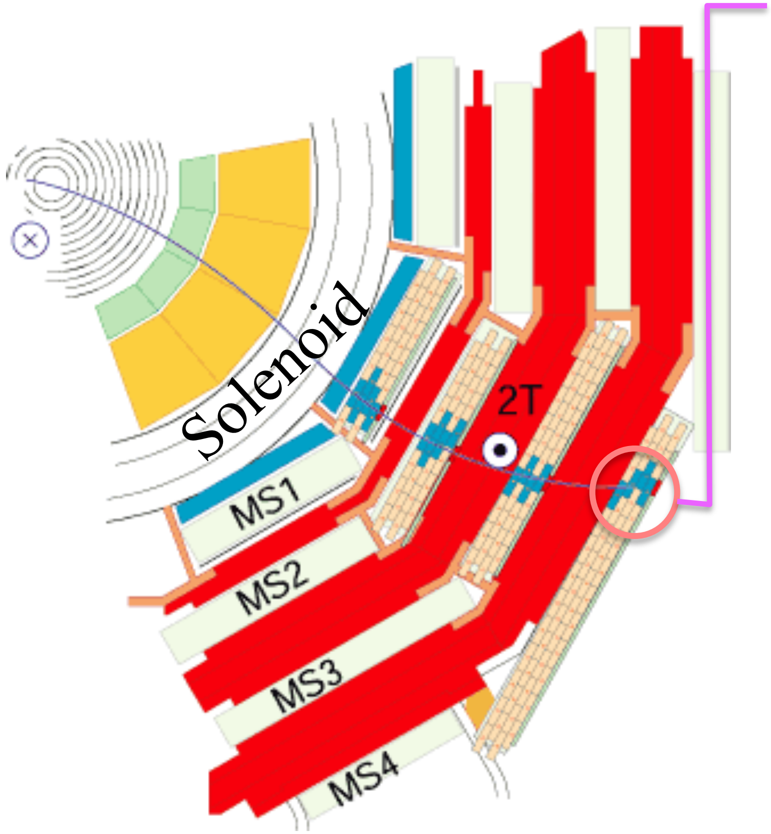
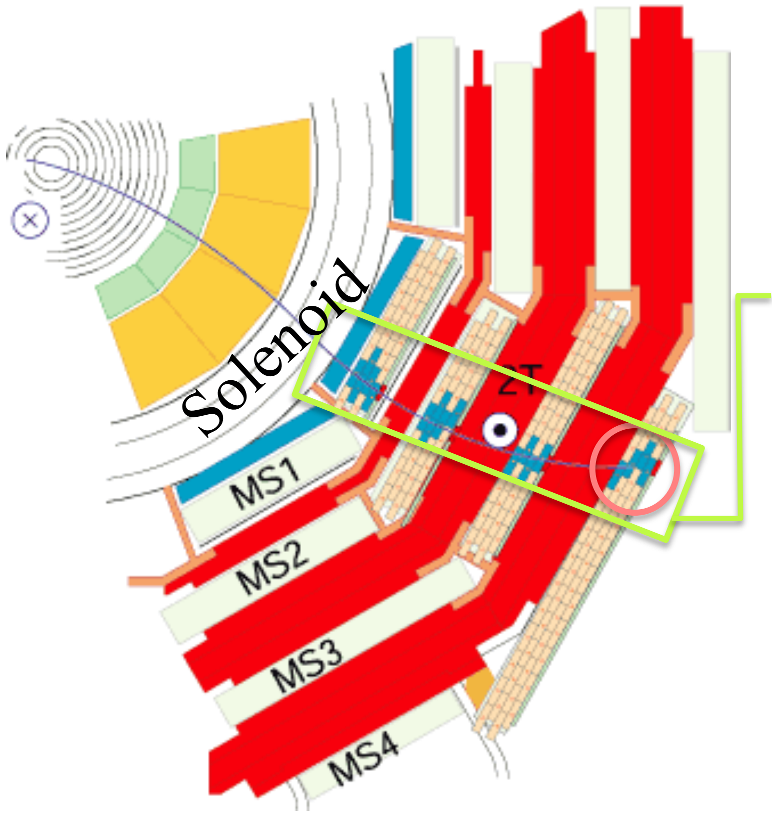
Muon Identification



- Local Muon
  - Hits from subdetectors
  - Track Segments from hits
- Standalone Muon
  - Combine track segments into a muon trajectory in muon system
- Global Muon
  - Reconstruct Muon Tracker Track
  - Combine Standalone muon and Muon Tracker Track into a Global Muon (global fit)

Muon Identification



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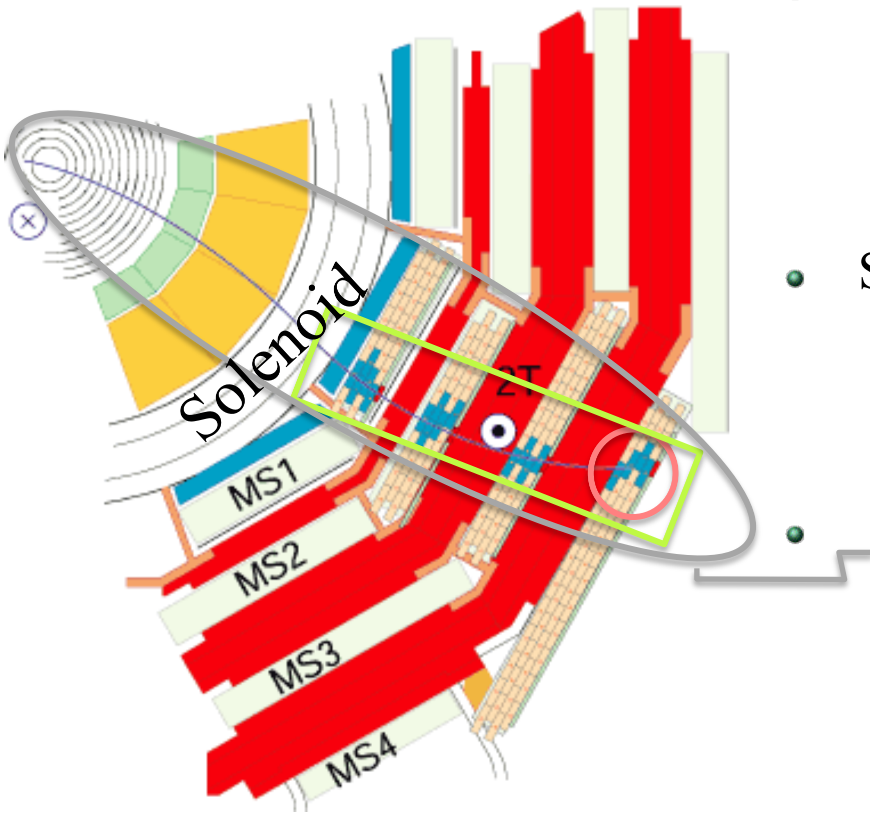

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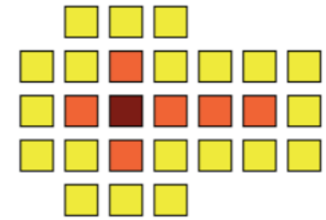
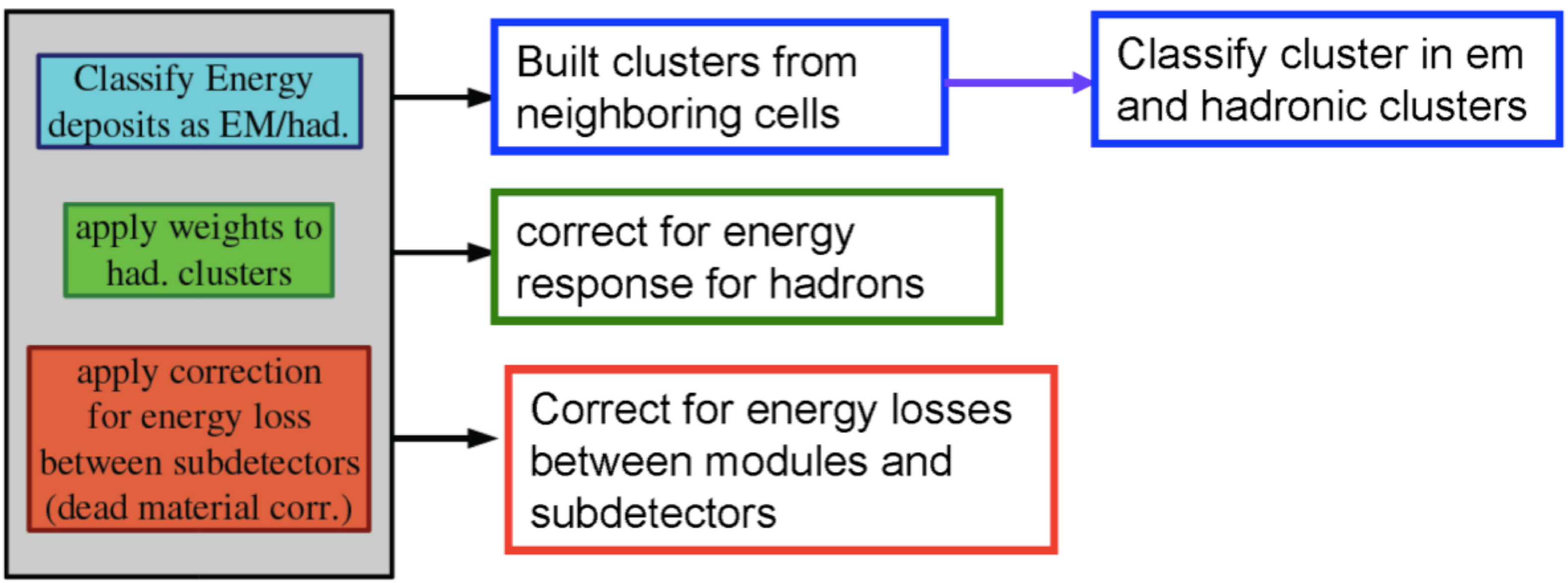
Calorimeter Cluster Reconstruction

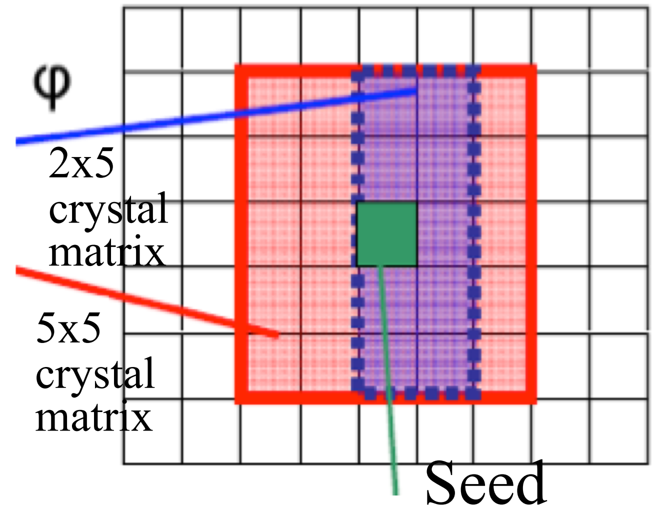
- Clusters are reconstructed from seeds, which start from cells with the highest energy deposits (> 4σ), clustered with neighbors of > 2σ
- Apply energy corrections and classify clusters in EM and hadronic depending on the fraction of energy in each Cal
- Combine with tracking information

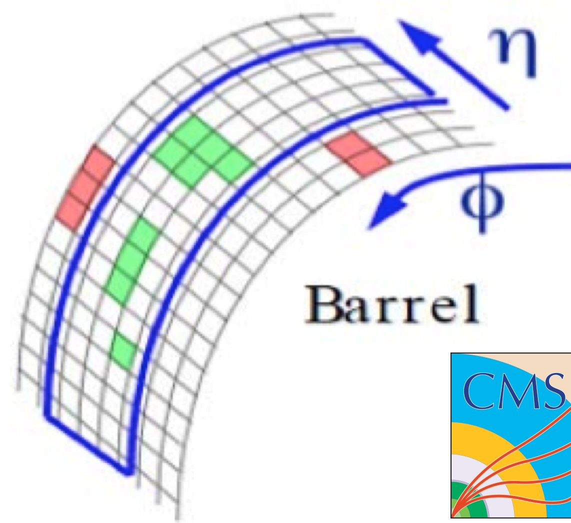




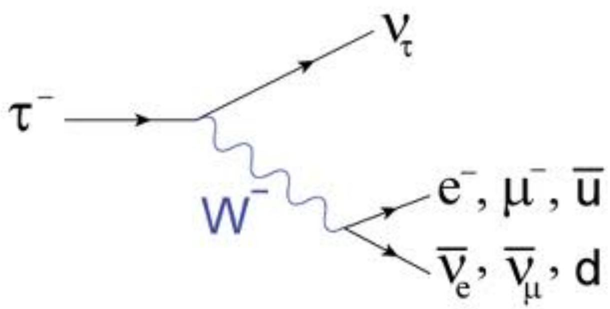
γ/e Reconstruction

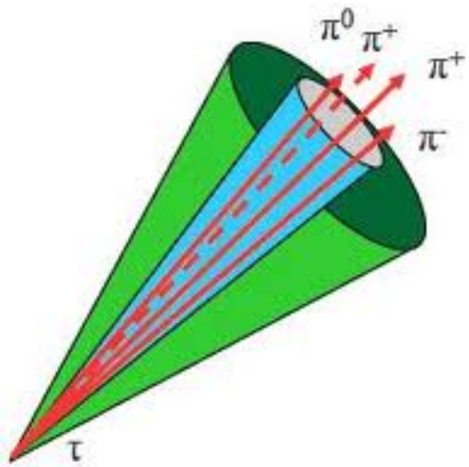
- 97% of unconverted photon is contained in a 5x5 crystal matrix.
- The electron energy is spread in ϕ due to the solenoidal magnetic field
  - Electrons radiate by bremsstrahlung
  - Photons have 50% probability to convert to e^+e^- in the tracker
- Define Superclusters to recover energy
  - Narrow rows in η, long in bending direction ϕ
- Photons: no pixel hits consistent with track from interaction region
- Electrons: pixel hits match required
  - E & p_T is a combination of Ecal and tracking information.





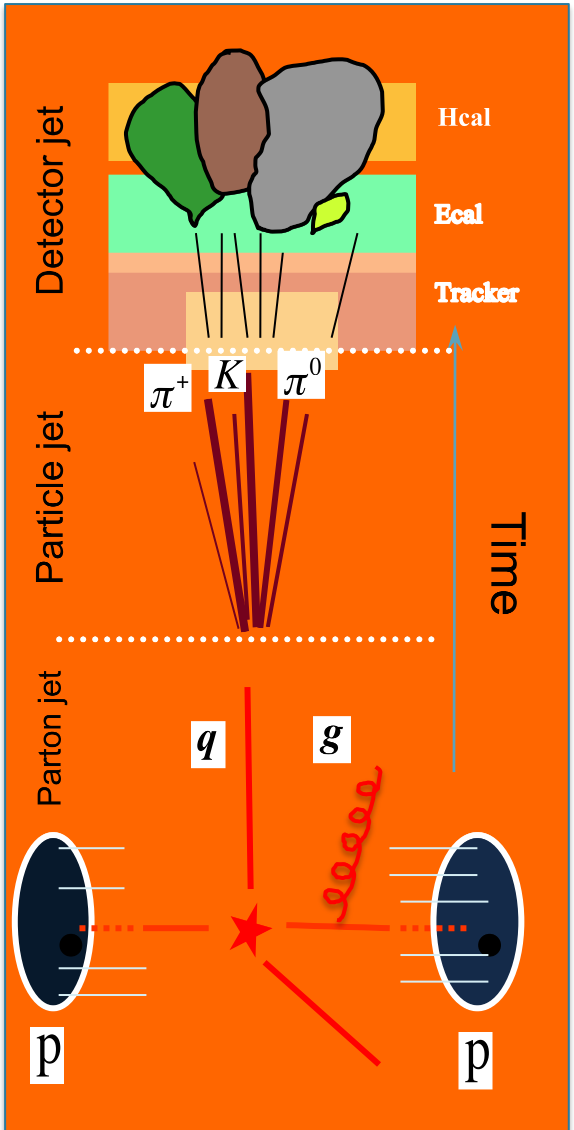
Tau Identification





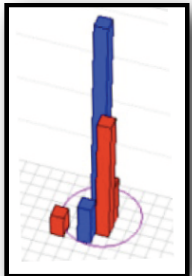
- Large mass (1.77 GeV) as compared to μ (106 MeV) and electron (0.5 MeV)
- Hadronic decay 2/3 of the time
- Typically one or three charged mesons (π^+,π^-), up to 2 neutral mesons (π^0), and a ν_τ, with π^0 decaying to two γ
- Appears in detector as a narrow jet
- Additional ID obtained from tracking information (1 and 3 prong decay)
- Leptonic decay typically included in electron/muon final state with lower efficiency due to the lower p_T of the secondary lepton

Jets



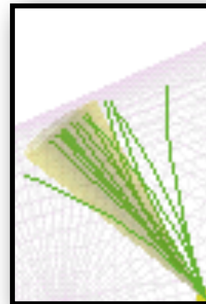
- Experimental signature of quarks and gluons
  - spray of collimated colorless particles
- Parton jet
  - made of quarks and gluons (after hard scattering and before hadronization)
- Particle jet
  - composed of final state colorless particles (after hadronization)
- Detector jet
  - reconstructed from measured energy depositions and tracks

Jet Identification



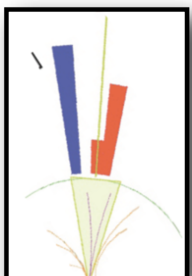
Calorimeter Jets

- **using ECAL and HCAL information**



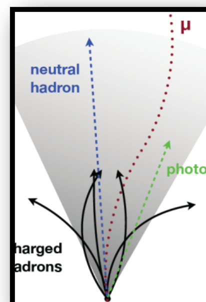
Track Jets

- **using TRACKER information**



Jet plus Track

- **using ECAL, HCAL, and TRACKER information**



Particle Flow Jets

- **from identified charged and neutral hadrons, γ, e, μ using all detector components**

- Clustering algorithm defines the jet
  - may be applied at any level (parton, particle, detector)
  - takes as input different elements (Calo, Tracks, PF)
- Two main types:
  - Fixed Cone & Sequential Clustering

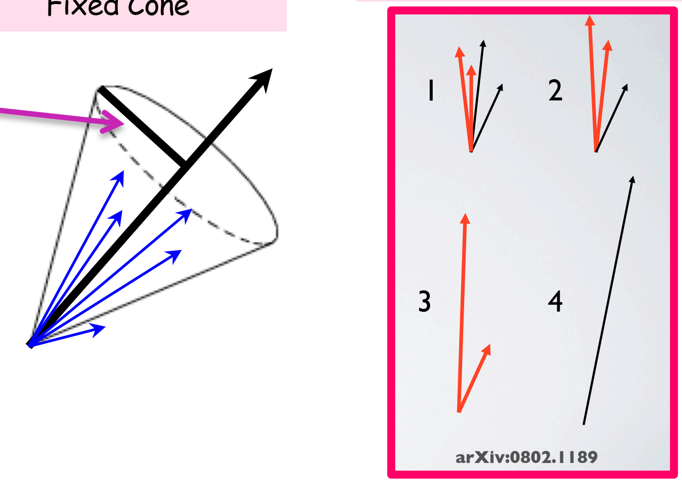
Jet Clustering Algorithms

- Fixed Cone
  - Variations in how to choose seed and cone size (R= 0.3…1.0)
- Sequential Clustering
  - Pairwise examination of input 4-vectors
  - Merging determined by proximity in space and transverse momentum
  - If $d_{ij} < d_{ii}$, combine particles
  - If $d_{ii} < d_{ii}$, i is a jet

$$\boxed{R^2 = \eta^2 + \phi^2}$$

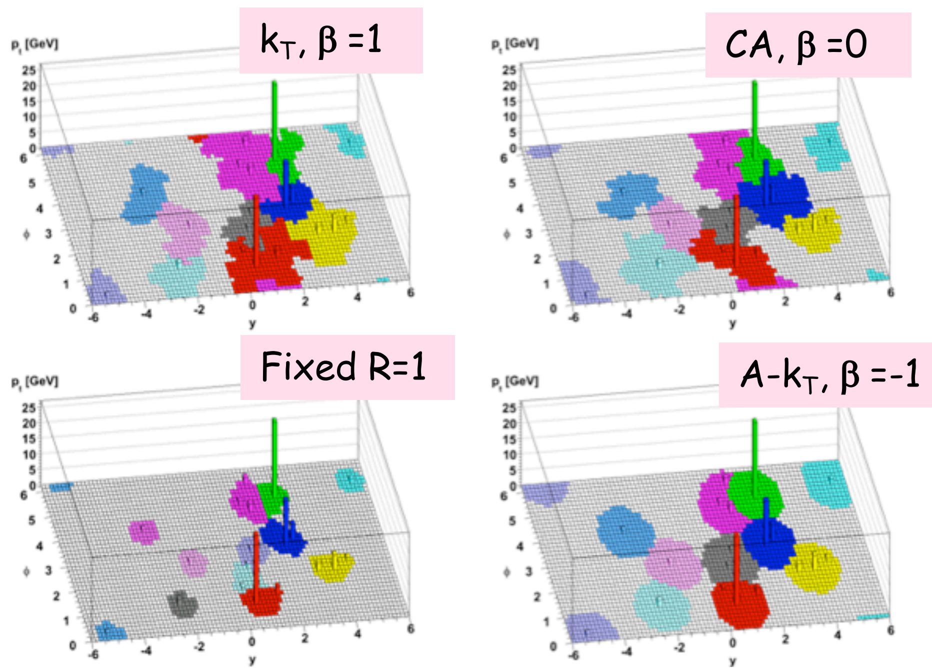
Fixed Cone

Sequential Clustering



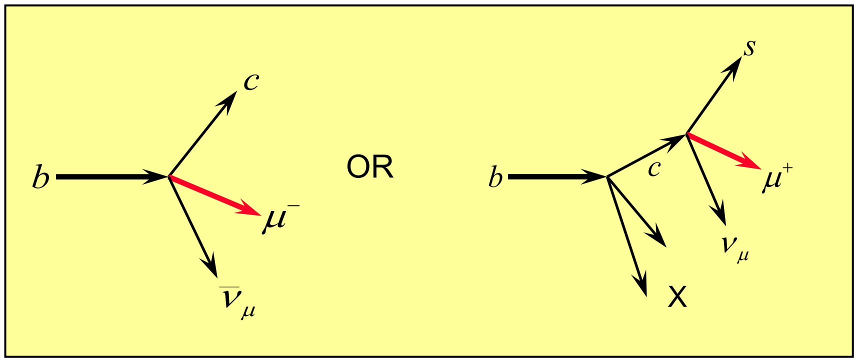
$$d_{ij} = \min(p_{T,i}^{2\beta}, p_{T,J}^{2\beta})\frac{\Delta R_{ij}^2}{R^2} \qquad d_{ii} = p_{T,i}^{2\beta}$$

$$\beta = \begin{cases} -1, & \text{Anti-}k_T \\ 0, & \text{Cambridge-Aachen} \\ 1, & k_T \end{cases}$$

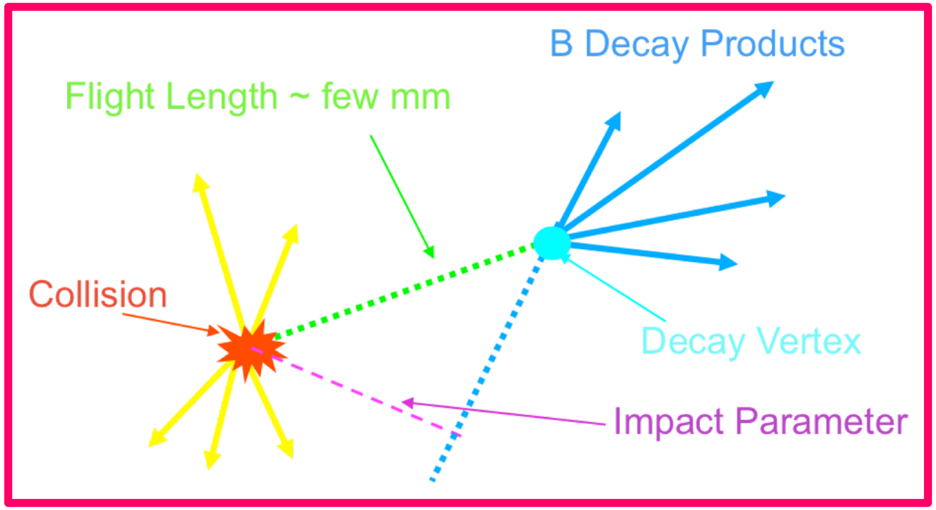


b-jet Identification

- Semileptonic decays of the b-quark
  – $B(b \rightarrow \mu + X) \approx 20\% \Rightarrow$ detect μ in jets

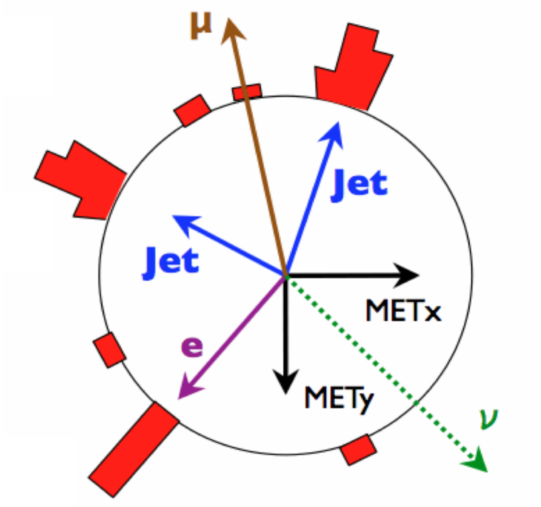


- life time ≈ 1.5 ps ⇒ cτ ≈ 0.5 mm
  – Look for secondary vertices or tracks with large impact parameter w.r.t. interaction point



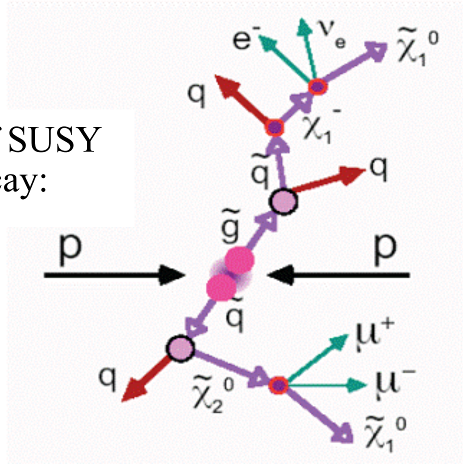
- b-tagging algorithms combine with a multivariate approach the information from:
  – impact parameter significance of charged-particle tracks
  – the presence of a lepton in the jet and its properties
  – the presence and properties of reconstructed secondary vertices

Missing Transverse Energy (MET)



- SM processes producing MET
  - Leptonic decays of top and W boson
- New Physics processes producing MET
  - Weakly interacting exotic particles in models with extra dimensions: monojets + MET
  - Production of Lightest SUSY Particles (LSP) in cascade decays, which would go undetected.
- Fake MET originates from non-reconstructed particles or from non-uniform detector response

Example of SUSY cascade decay:

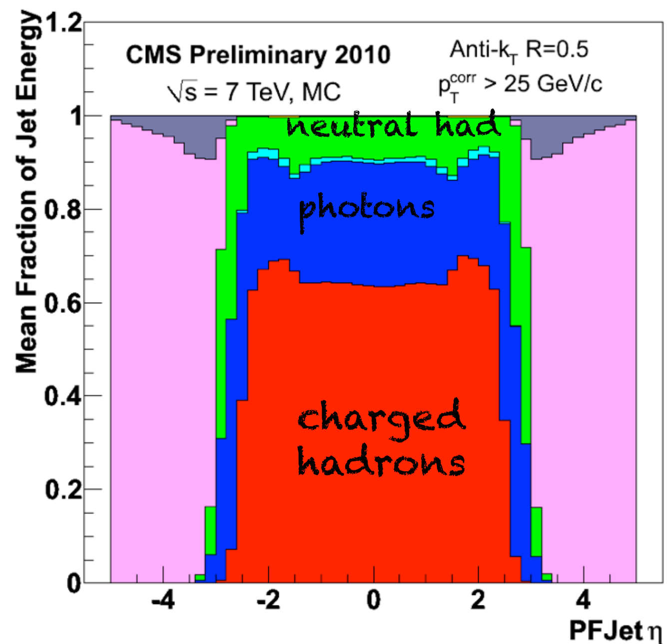


We infer the presence of a neutrino or any other particle that does not interact with our detector from the imbalance in the transverse momentum

PARTICLE FLOW EVENT RECONSTRUCTION

Set the Stage: Jet Composition

- Charged particles : ~60%
  - Mostly charged pions, kaons and protons, but also some electrons and muons
- Photons : ~25%
  - Mostly from π^0's, but also some genuine photons (bremstrahlung)
- Long-lived neutral hadrons : ~10%
  - K^0_L, neutrons
- Short-lived neutral hadrons, "V0's" : ~5%
  - $K^0_S \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow \pi^- p$, …, but also γ conversions, and (more problematic) nuclear interactions in the detector material



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- Photons : ~25%
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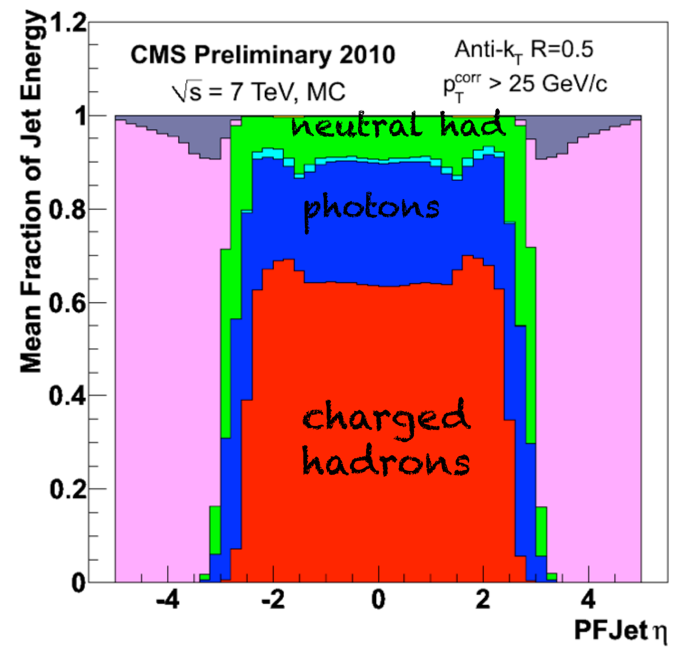
Trackin

ECA

HCA

Trackin

Full use of Detector Information should significantly improve Jet performance



Back-of-the-envelope estimate for $\pi^{\pm}$

- Calorimeter transverse energy uncertainty for charged hadrons:

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

- Tracker transverse momentum uncertainty for charged hadrons:

$$\sigma(p_T) \approx 0.01\% \ (p_T)^2$$

- The point at which the calorimeter resolution overcomes the tracker resolution is (very roughly):

$$\frac{\sigma(p_T)}{p_T} \approx \frac{\sigma(E_T)}{E_T} \qquad \rightarrow \quad p_T \approx 10^{\frac{8}{3}} \approx 464 \text{ GeV}$$

Goals of Particle Flow

- Reconstruct and identify all particles
  - γ, e, μ, $\pi\pm$, $K_L{}^0$, pile-up $\pi\pm$, converted g & nuclear interaction $\pi\pm$,...
  - Use best combination of all sub-detectors for E, η, φ, p_{ID}

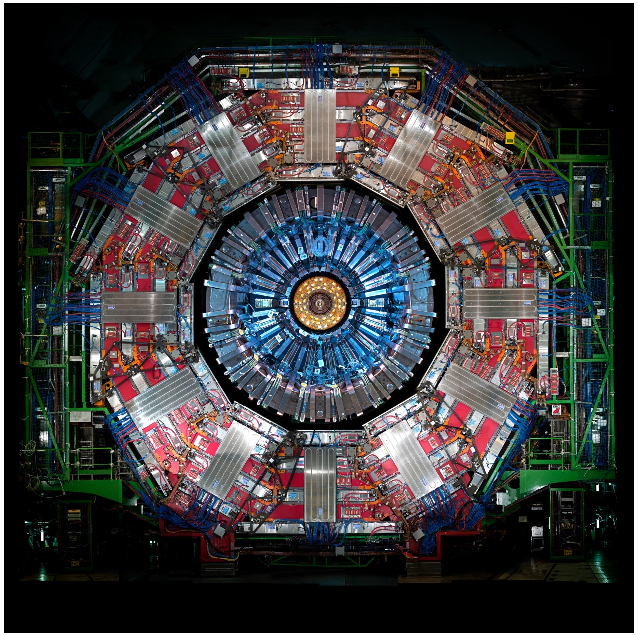
- Provide consistent & complete list of ID's & calibrated particles for
  - Tau reconstruction & Jet reconstruction
  - Missing & total Visible Energy determination
  - Other, analysis specific, objects (event or jet shape variables, etc.)

- Use of Redundant Information: Calorimeter & Tracking
  - Good: Better Calibration (data driven) and Resolution possible
  - Challenge: Must have accurate accounting

- Very different from "Traditional" Tau, Jet, MET Reconstruction…

Required Elements for PF

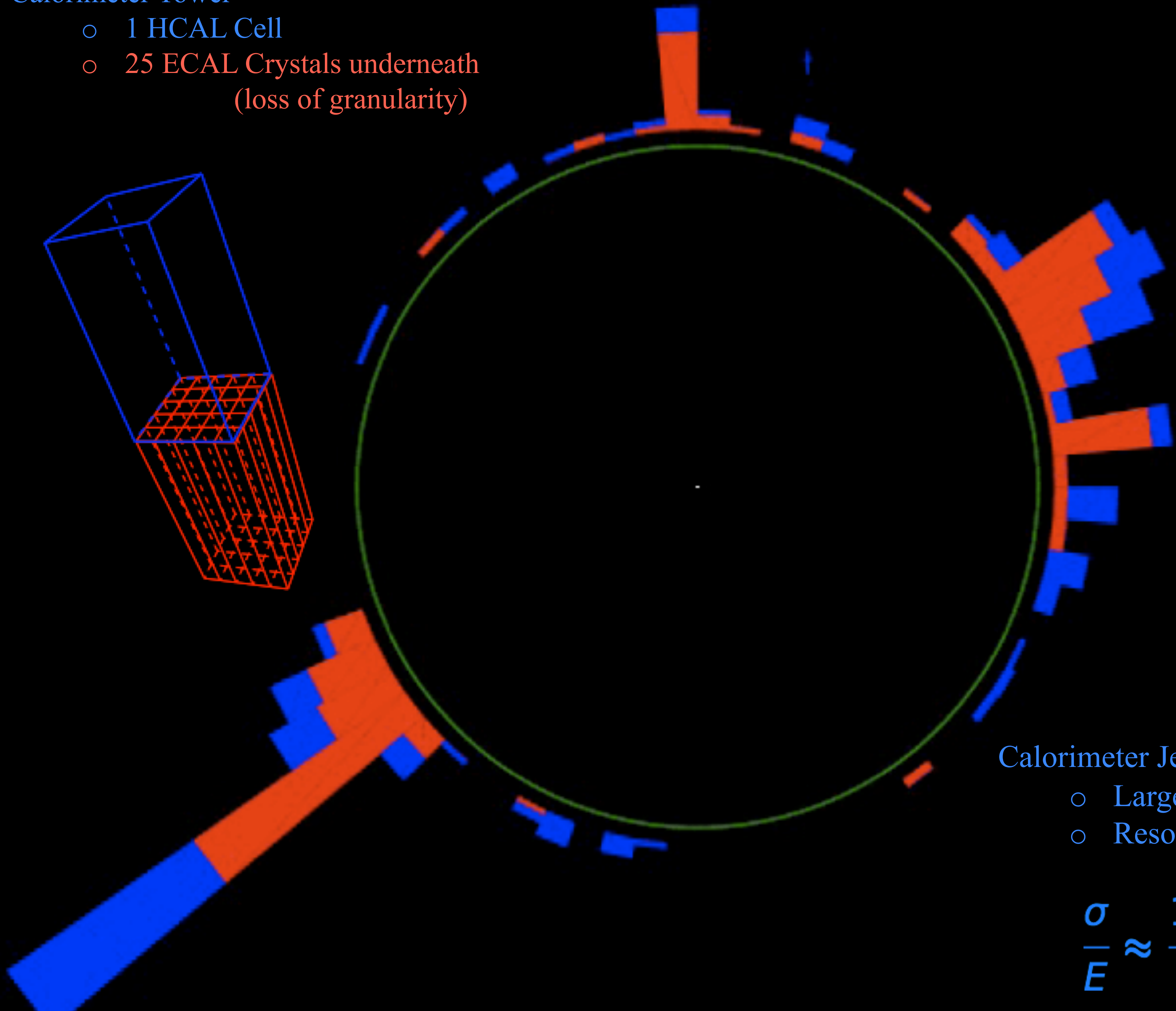
- Large Volume Tracker
  - high precision, high efficiency tracking is critical
- High Magnetic Field
  - needed for good p_T resolution
  - needed to separate charged from neutral particles
- Highly Granular Calorimeter
  - needed to separate charged from neutral particles
- Good Calorimeter Energy Resolution is :
  - needed for good photon, electron E resolution
  - not so critical for Hadrons
- Originally developed in lepton colliders
  - Adopted by CMS, now also by ATLAS



CMS is ideally suited to exploit the Particle Flow Event Reconstruction

Calorimeter Tower

- 1 HCAL Cell
- 25 ECAL Crystals underneath (loss of granularity)



Calorimeter Jets

- Large Jet E Corr.
- Resolution HCAL

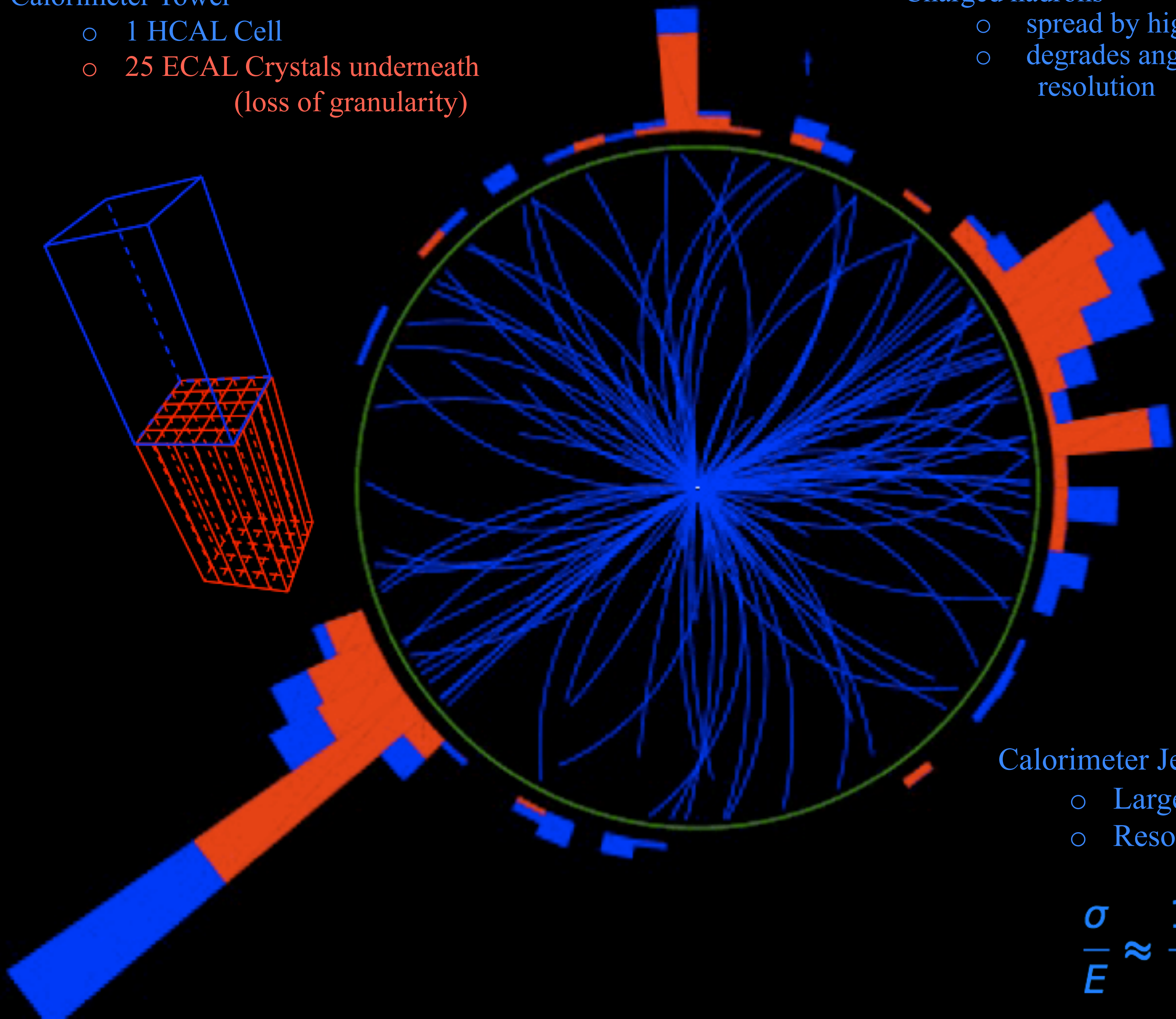
$$\frac{\sigma}{E} \approx \frac{100\%}{\sqrt{E}}$$

Calorimeter Tower

- 1 HCAL Cell
- 25 ECAL Crystals underneath (loss of granularity)

Charged hadrons

- spread by high B-field
- degrades angular resolution



Calorimeter Jets

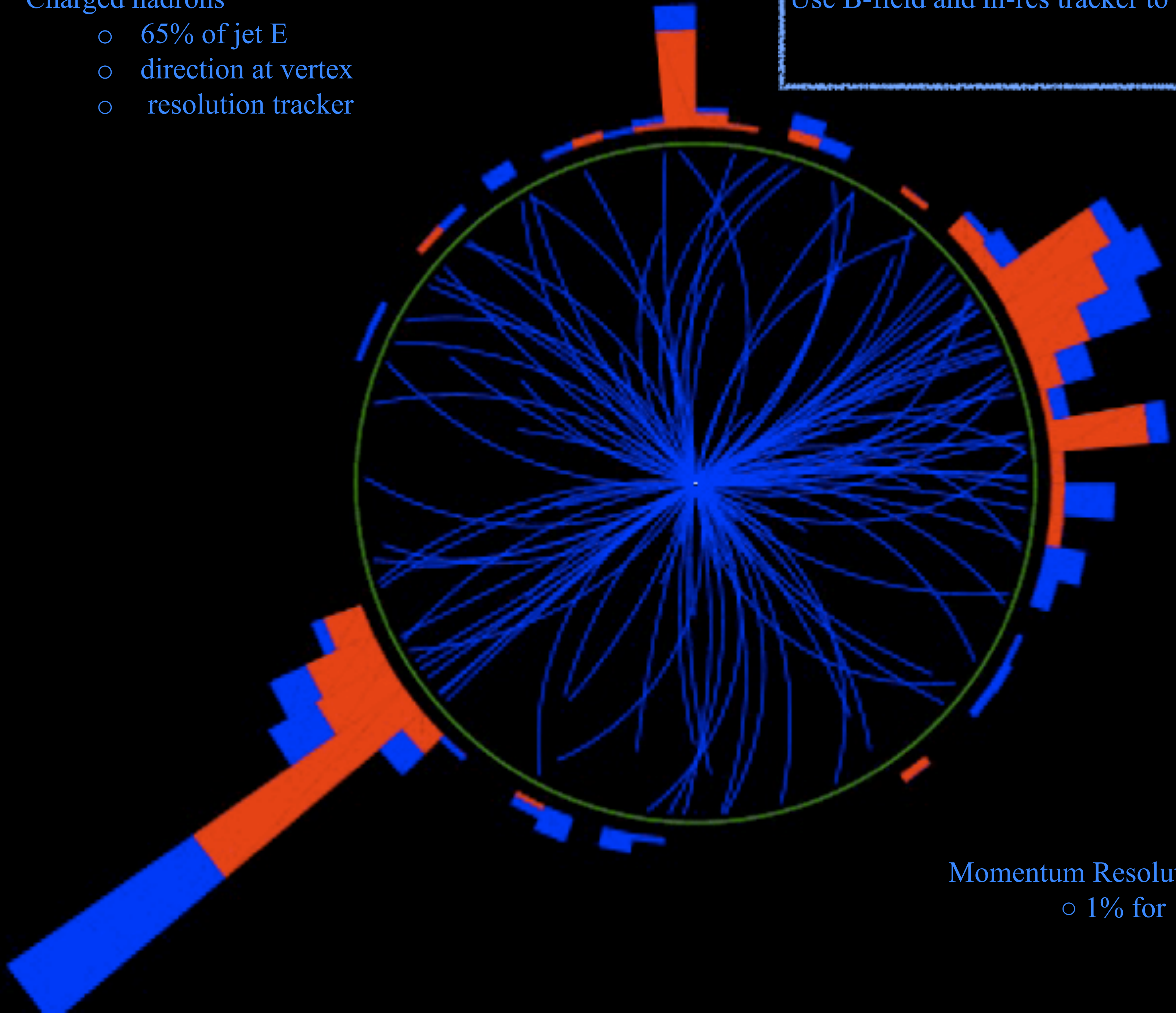
- Large Jet E Corr
- Resolution HCAL

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

Charged hadrons

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

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

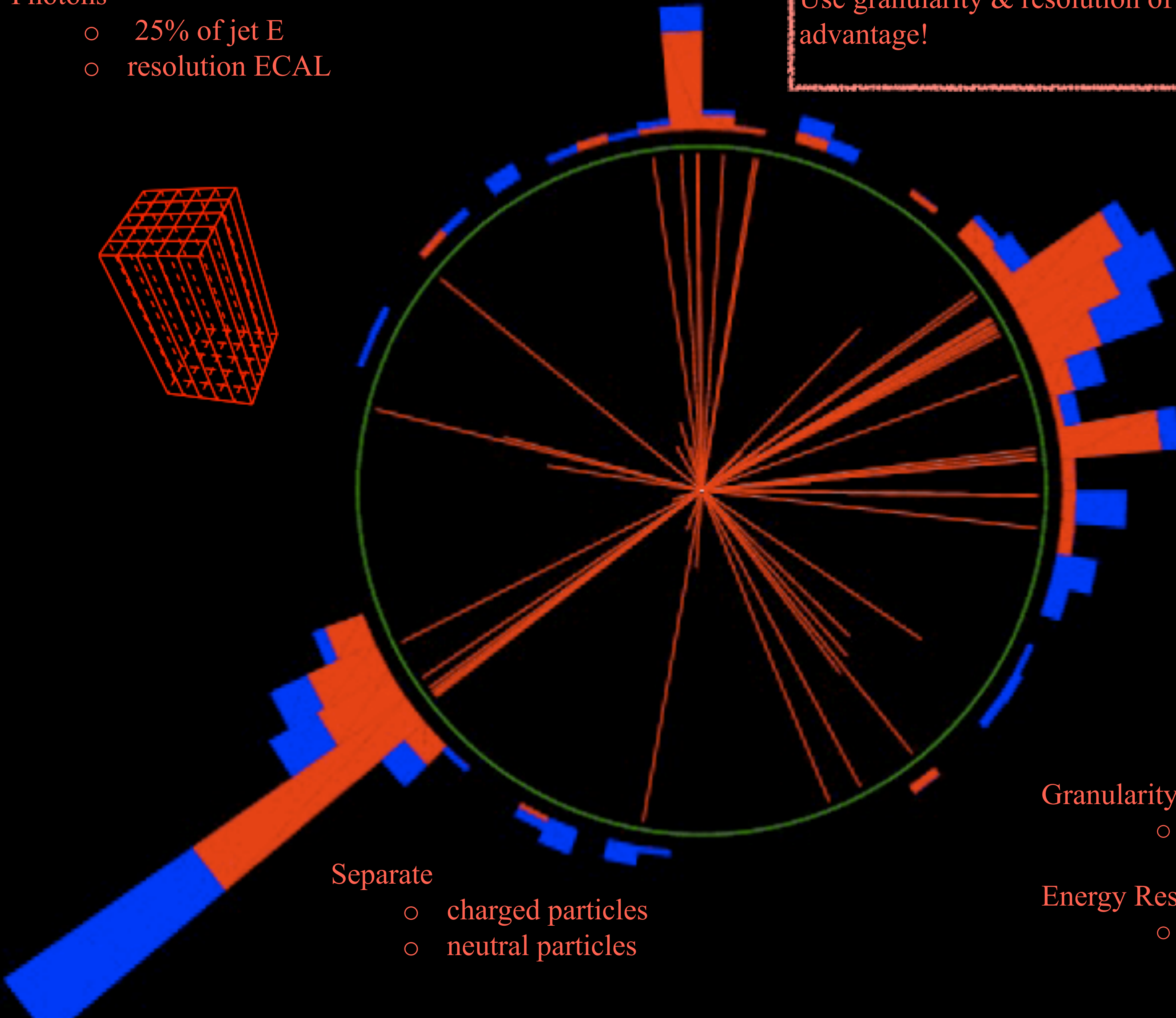


Momentum Resolution

- 1% for 100 GeV

Photons
- 25% of jet E
- resolution ECAL

Use granularity & resolution of ECAL to our advantage!



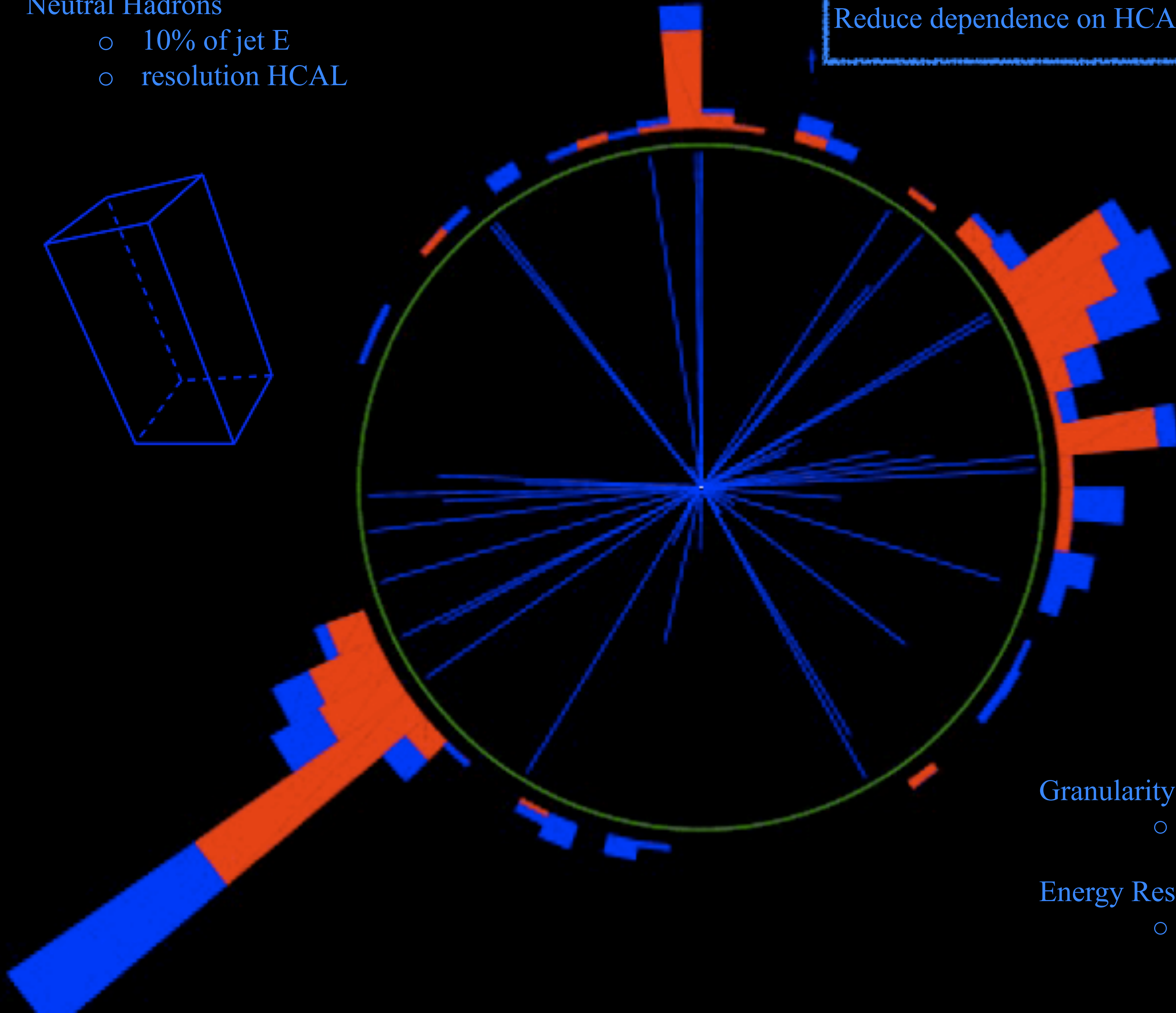
Separate
- charged particles
- neutral particles

Granularity
- 0.02 ($\Delta\eta \times \Delta\varphi$)

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

Neutral Hadrons

- 10% of jet E
- resolution HCAL



Reduce dependence on HCAL

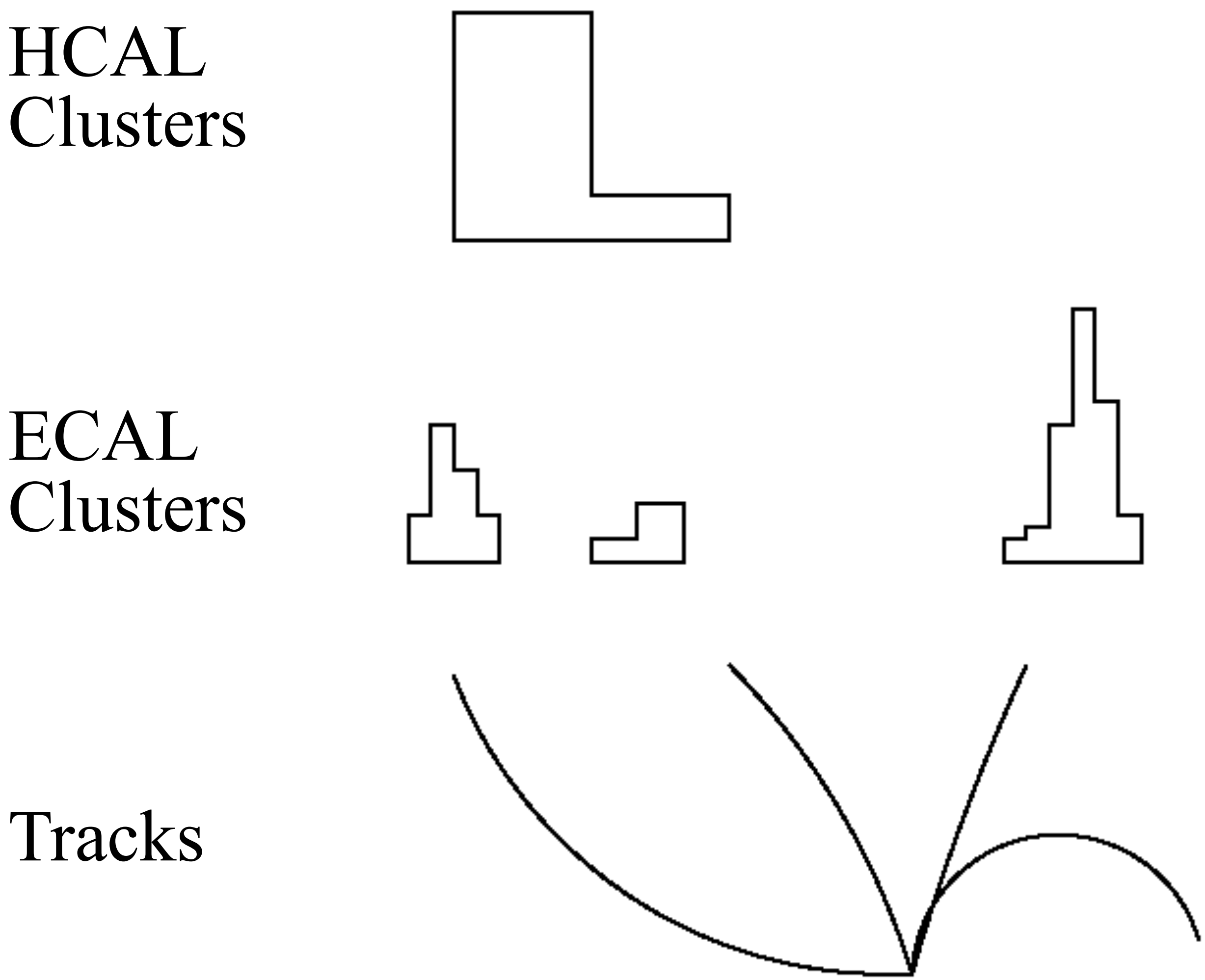
Granularity

- 0.1 ($\Delta\eta x \Delta\varphi$)

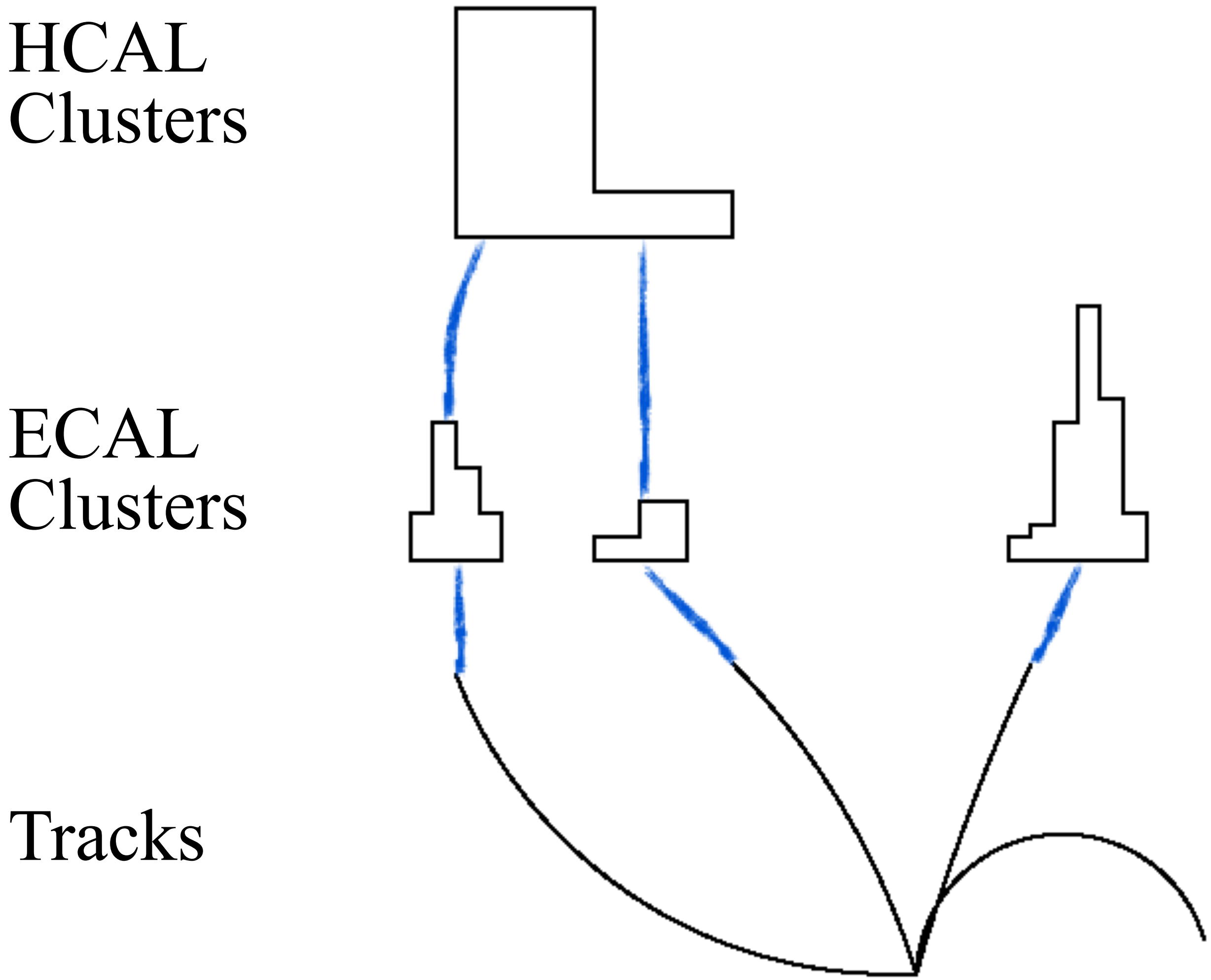
Energy Resolution

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

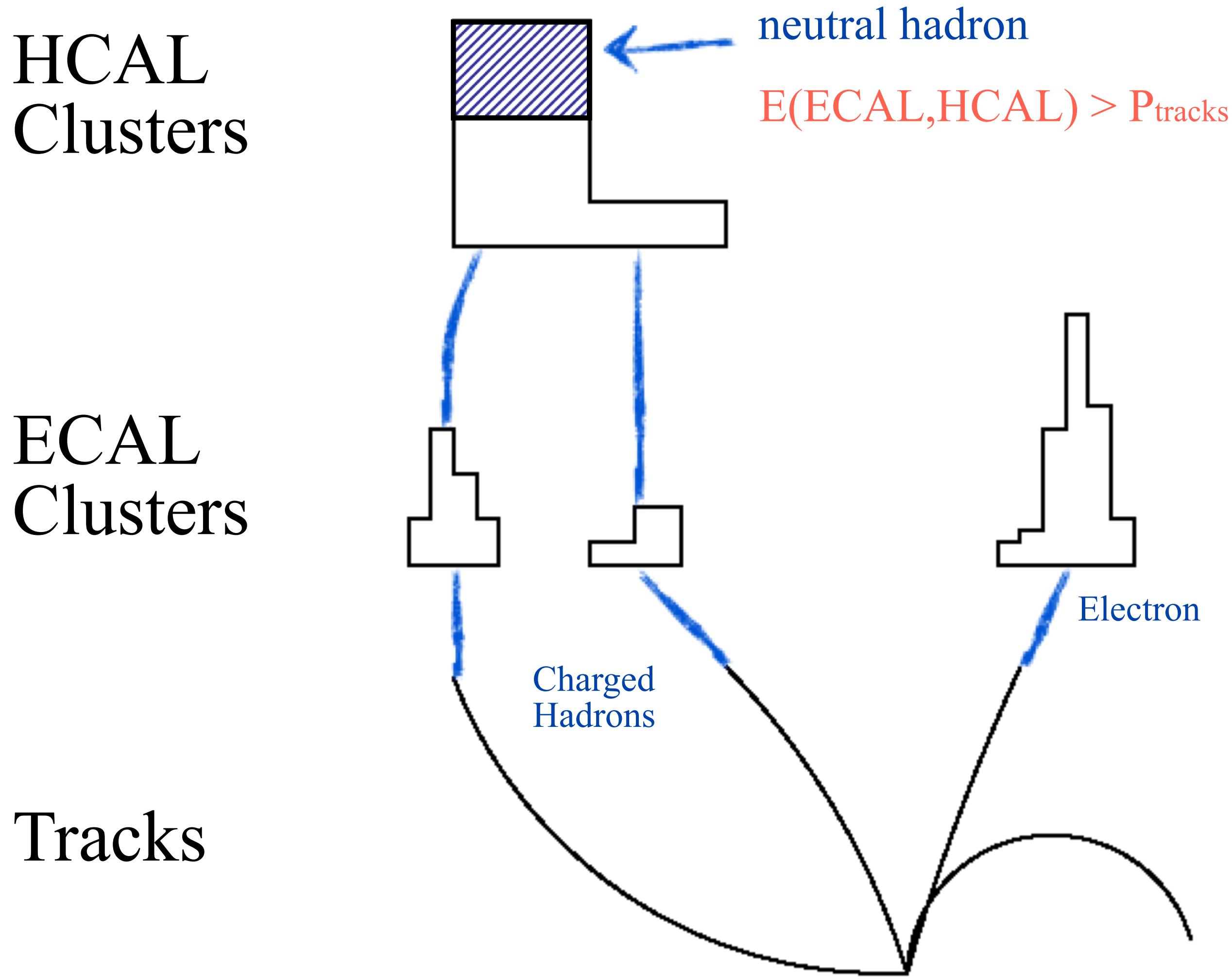
First Associate Hits within Each Detector



Then Link Across Detectors

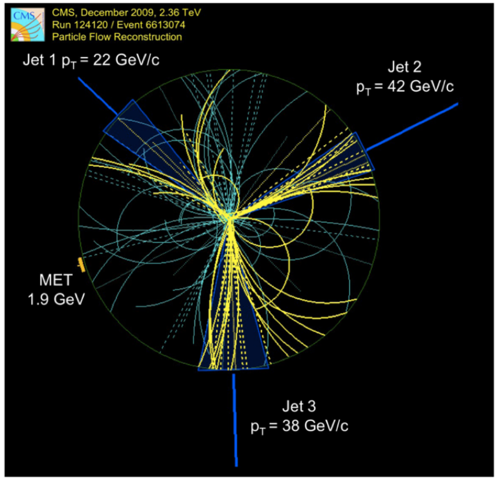


Finally Apply Particle ID & Separation

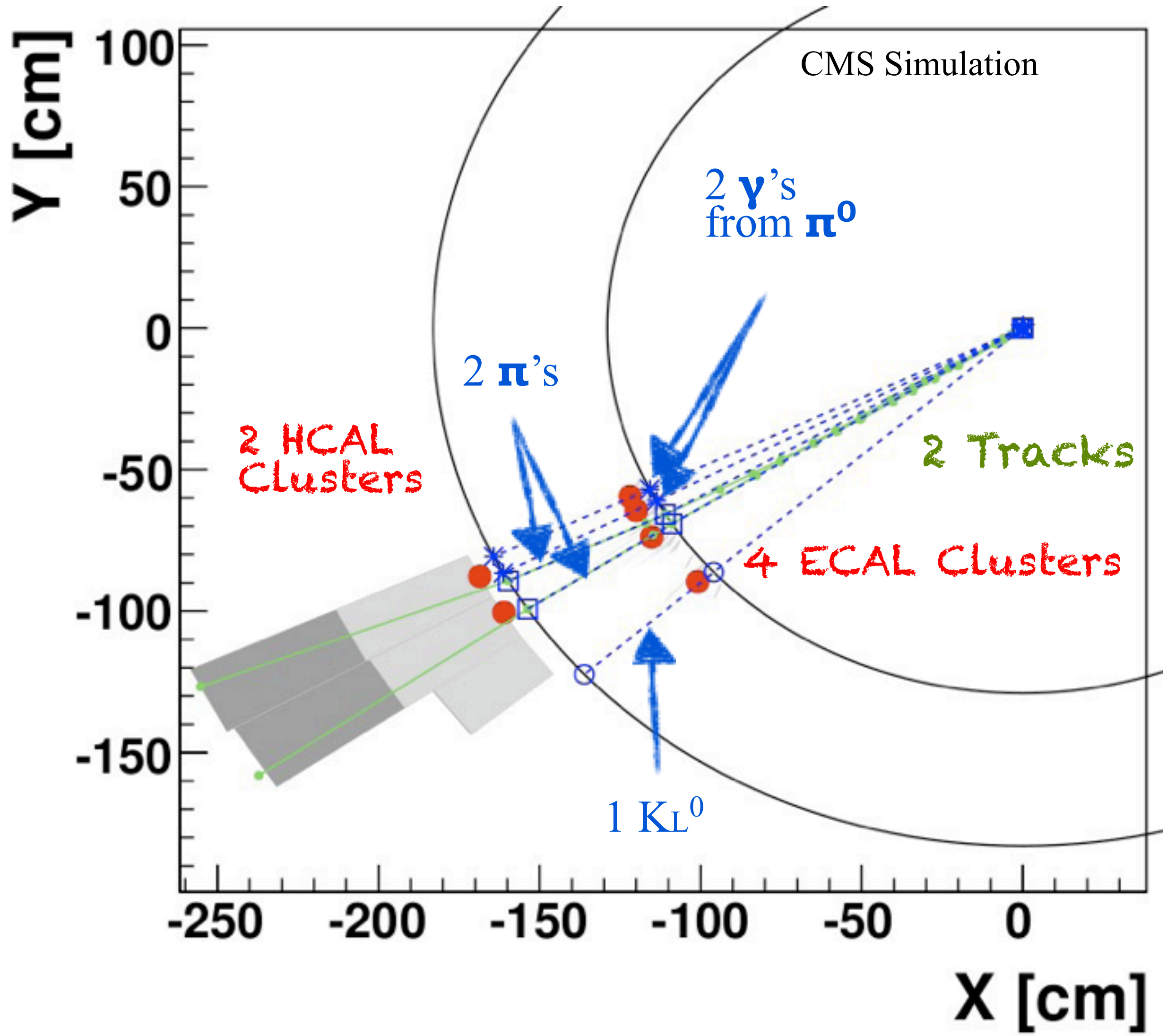


"Clean" the Event During Reconstruction

- Find and "remove" muons (σ_{track})
- Find and "remove" electrons (min[σ_{track}, σ_{ECAL}])
- Find and "remove" converted photons (min[σ_{track}, σ_{ECAL}])
- Find and "remove" charged hadrons (σ_{track})
- Find and "remove" V^0's (σ_{track})
- Find and "remove" photons (σ_{ECAL})
- Left with neutral hadrons (10%) (σ_{HCAL} + fake)
- Use above list of Reconstructed Particles to describe the entire event



Let's take a simple example

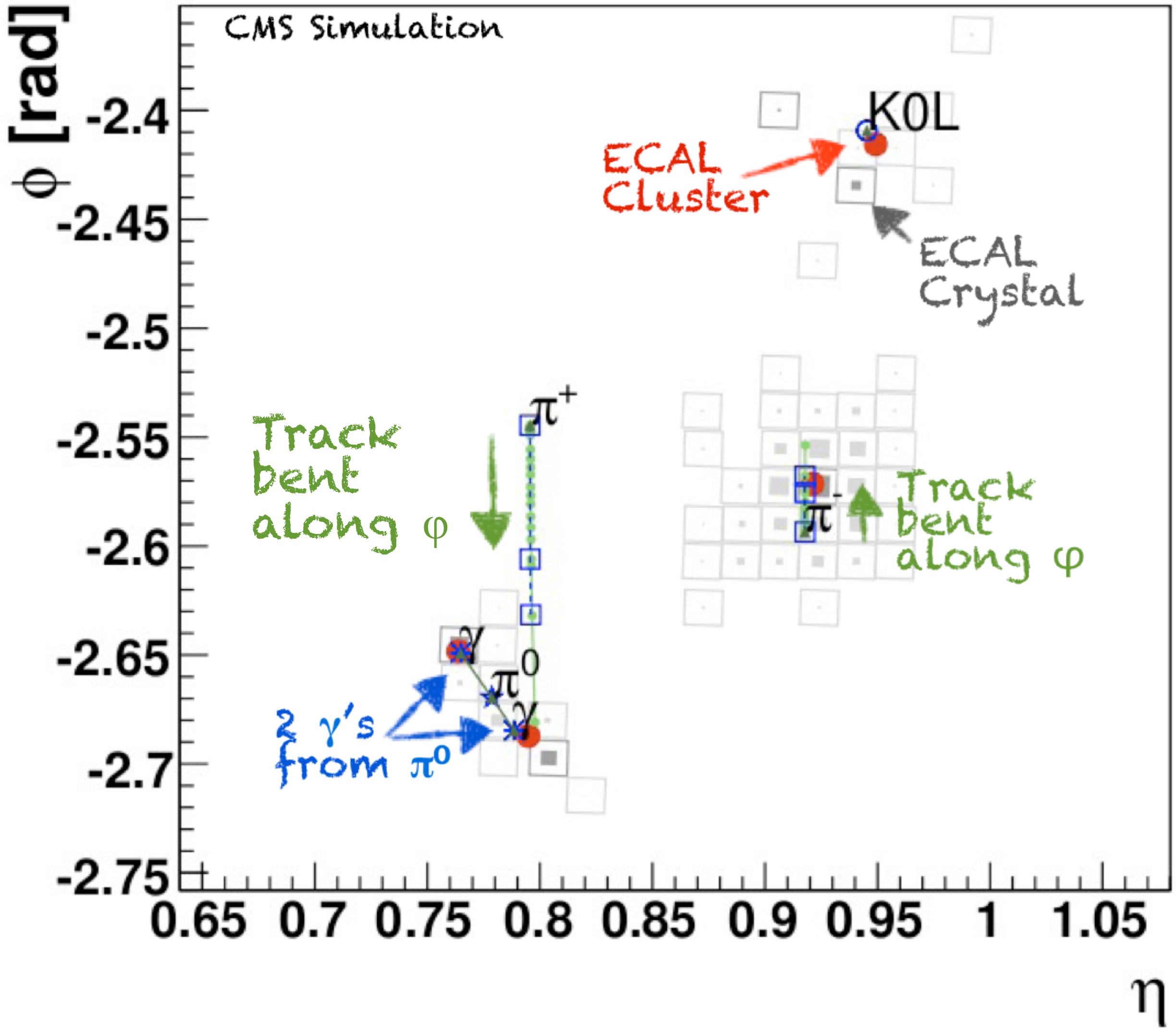


Jet pT = 65 GeV/c

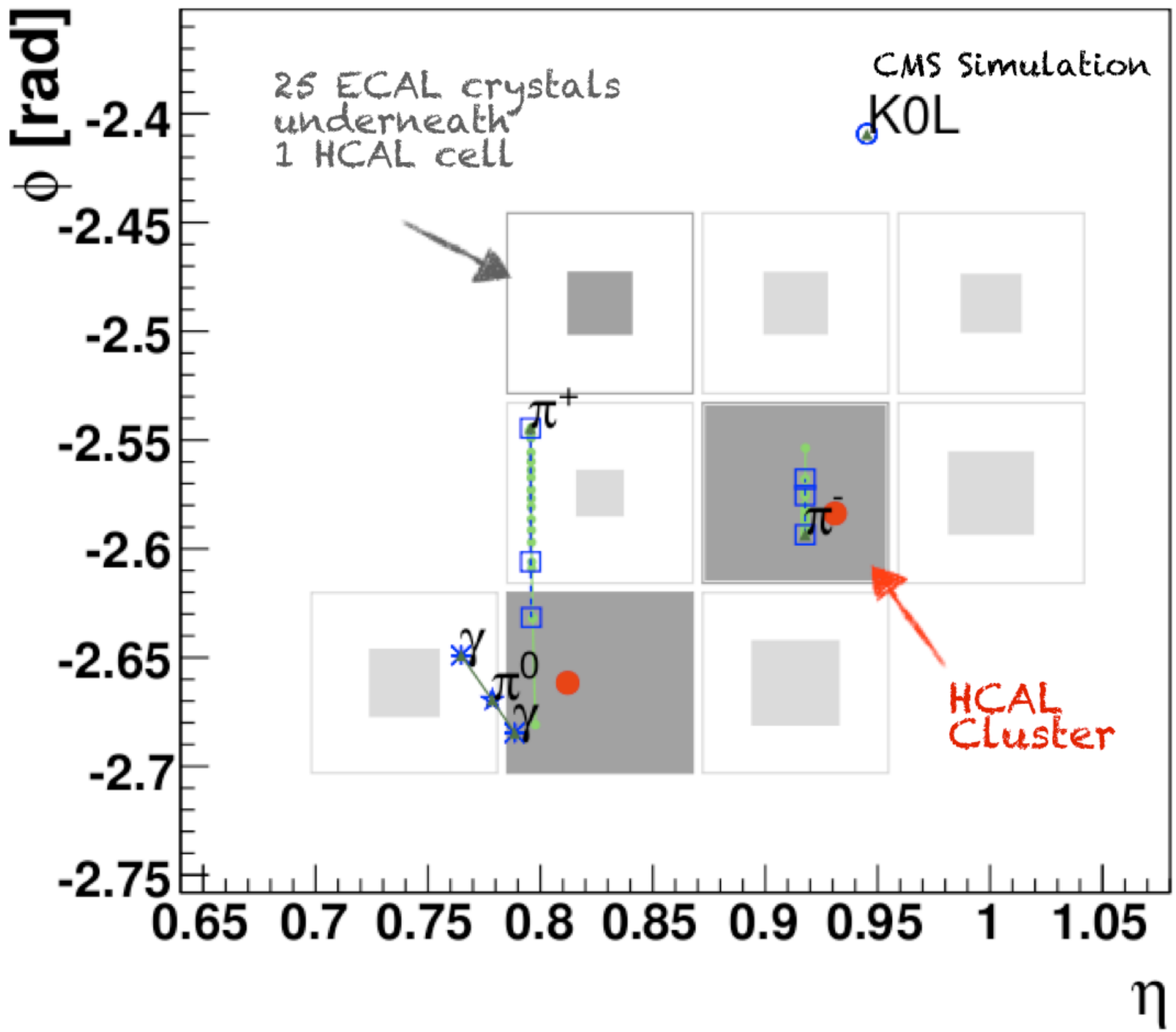
Four true particles:

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

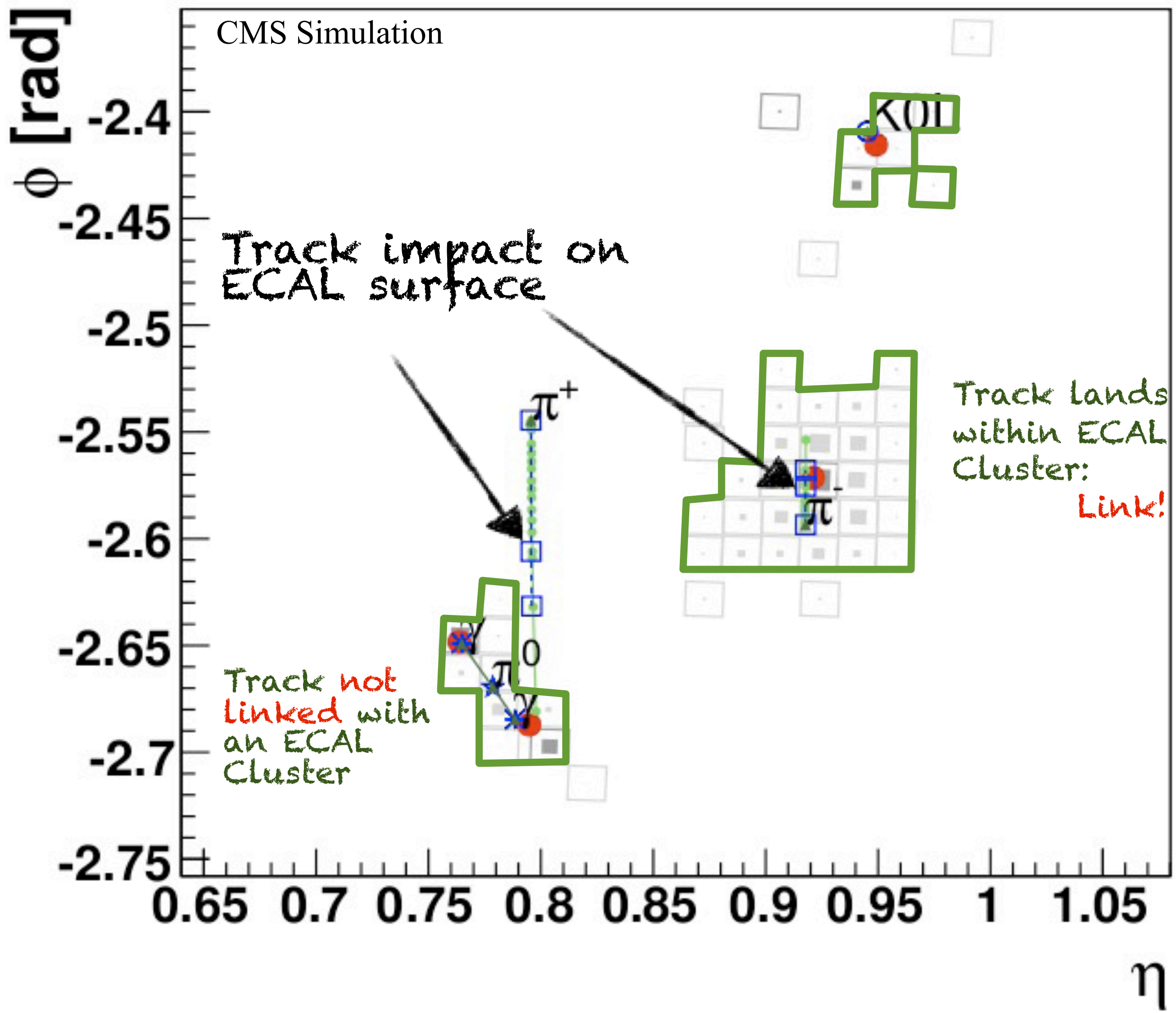
Switch to ECAL (η,φ) View



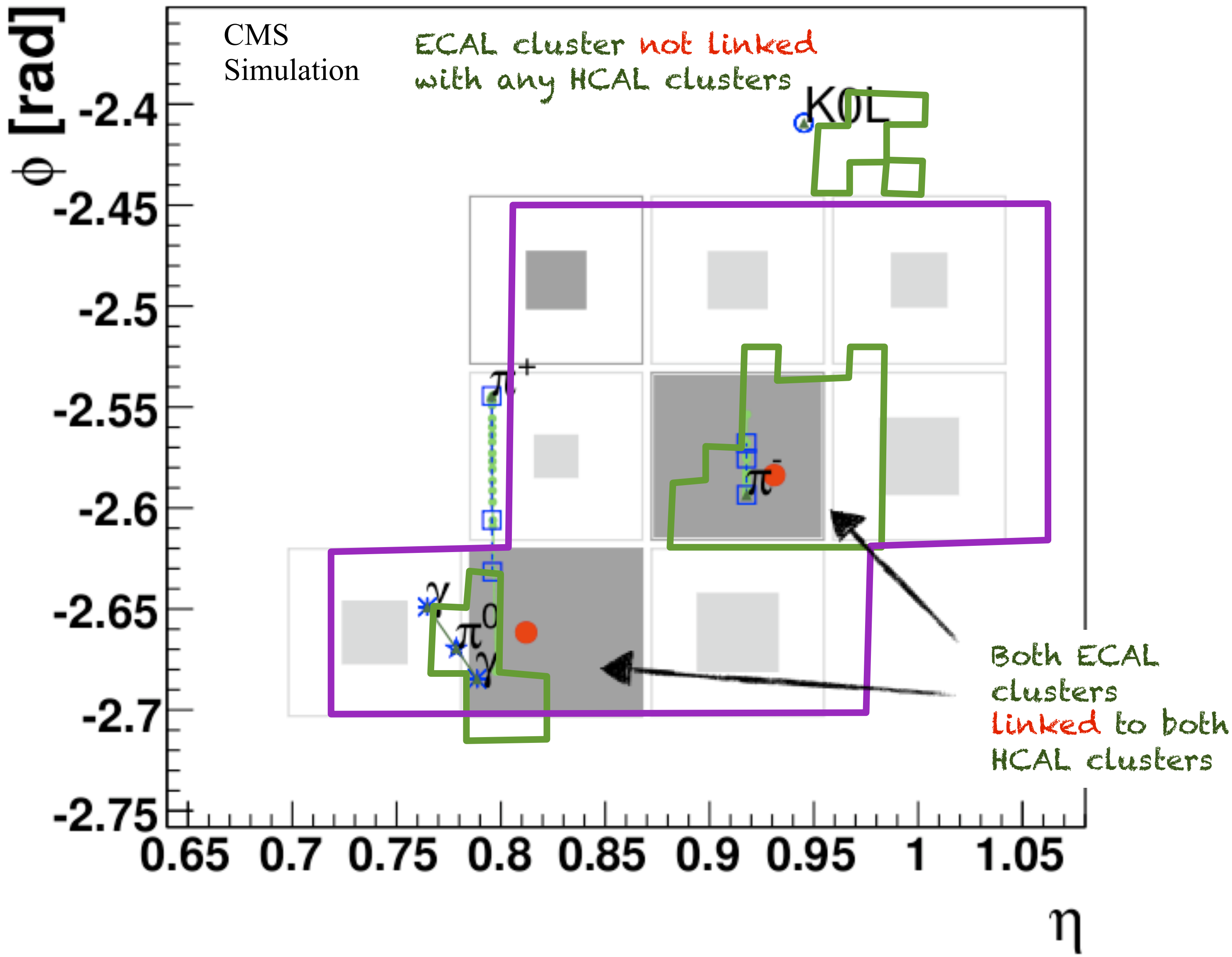
Switch to HCAL (η,ϕ) View



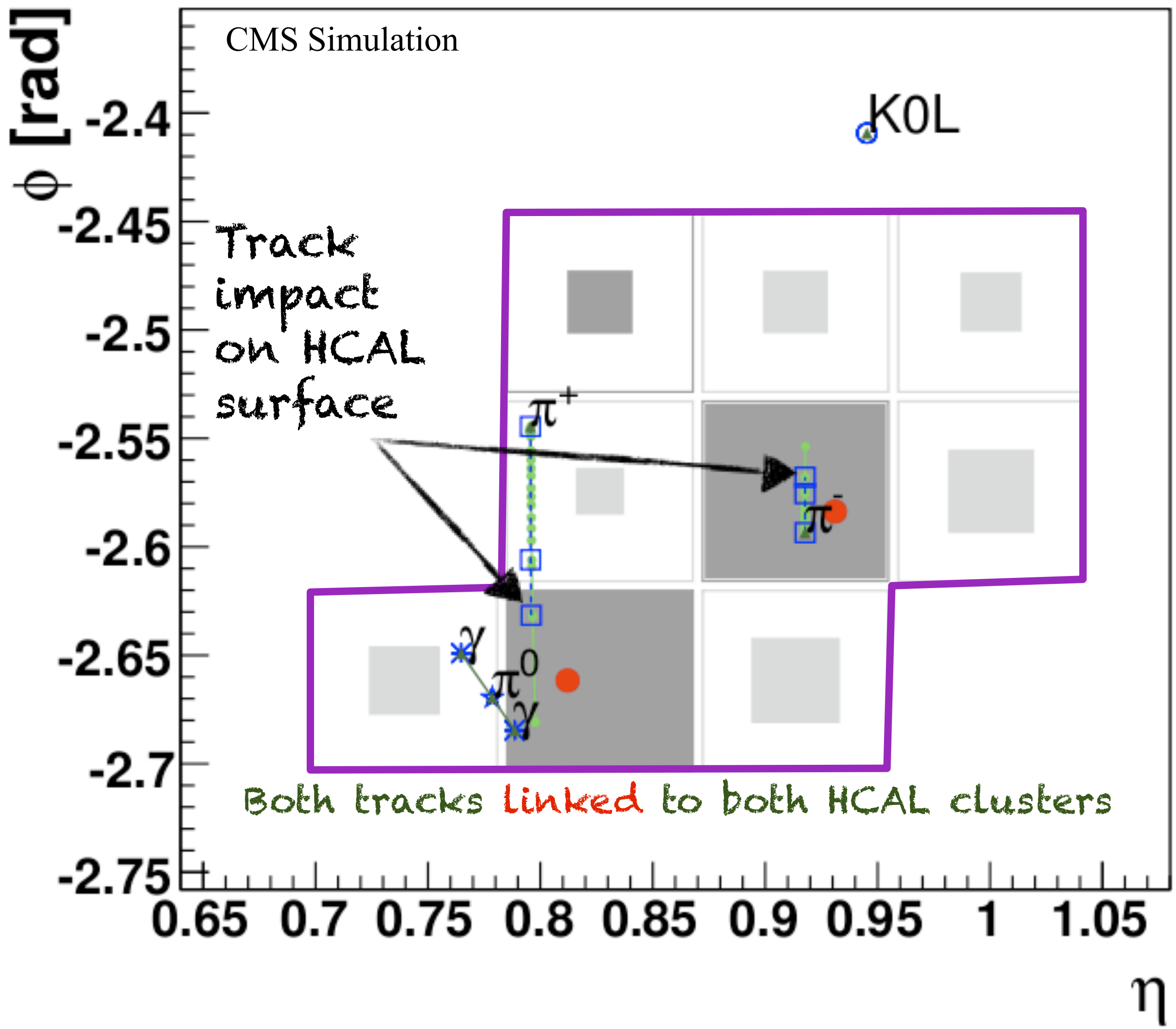
Track-Cluster Link ECal



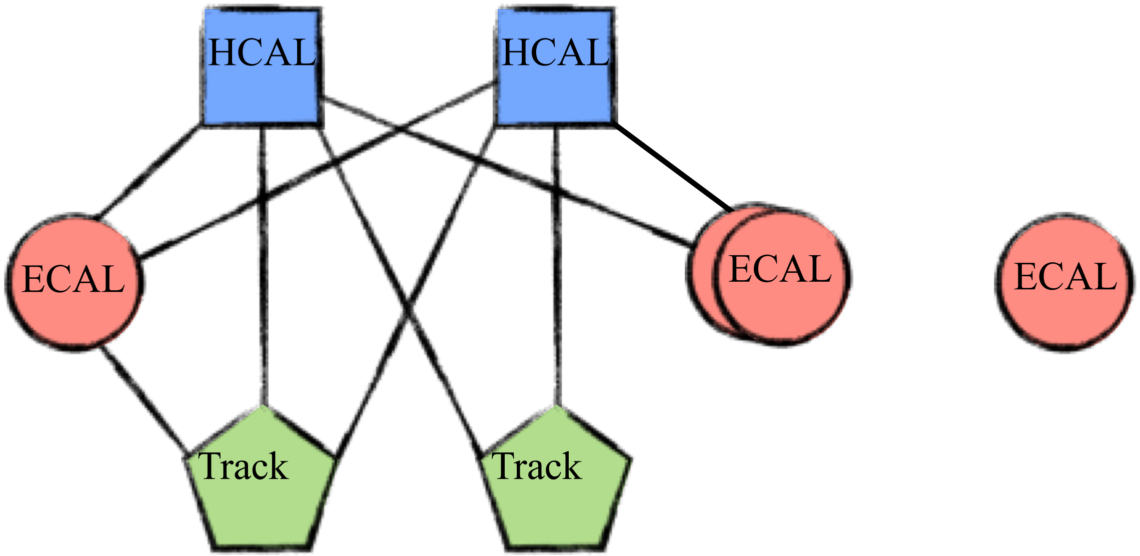
ECal-HCal Cluster Link



Tracker-Cluster Link HCal

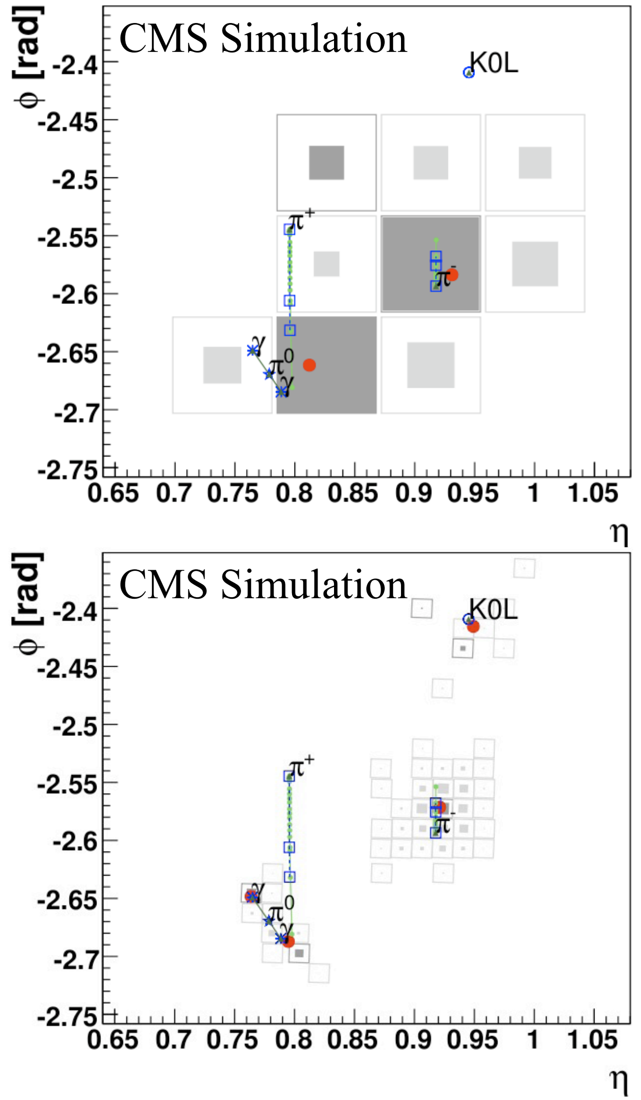


Particle Identification

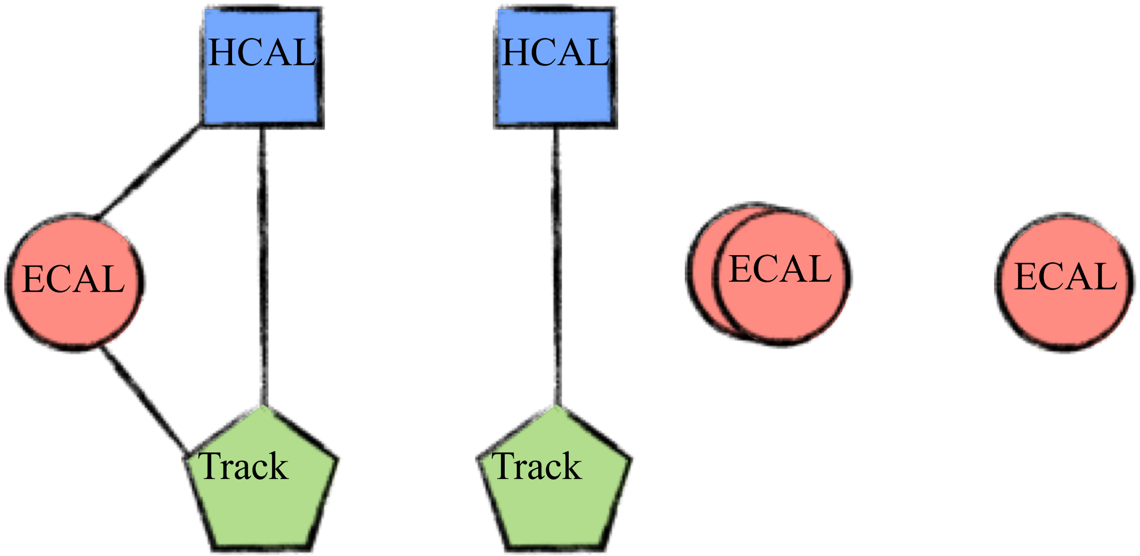


List of reconstructed particles:

{ }

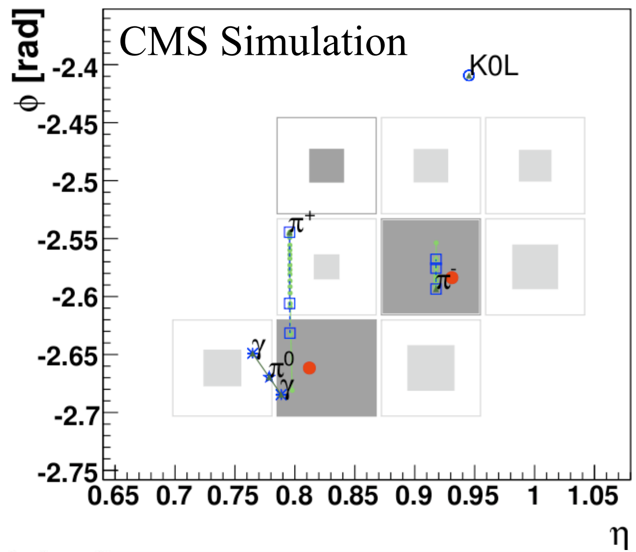


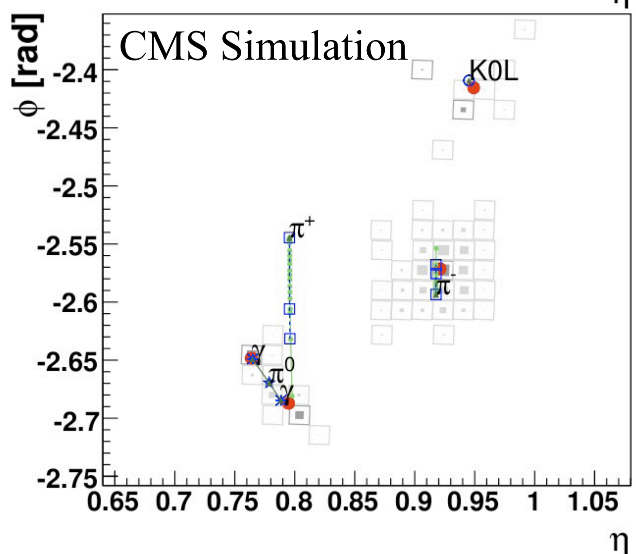
Particle Identification



List of reconstructed particles:

{ $\boldsymbol{\gamma}$, $\boldsymbol{\gamma}$, $\boldsymbol{\gamma}$, π^+, π^- }

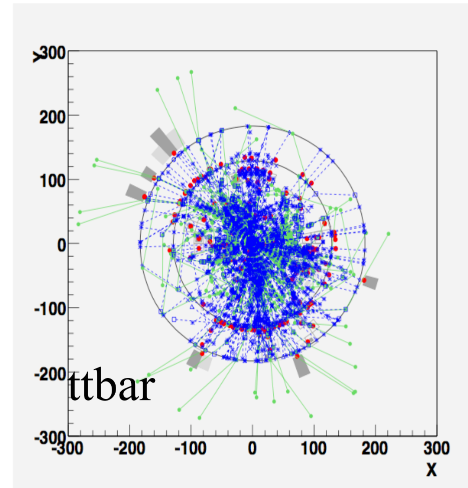




Simple example, nevertheless...

- The Particle Flow Algorithm scales to large particle multiplicities

- Analysis of leading jet from an all-hadronic ttbar simulated event:



MC Particles

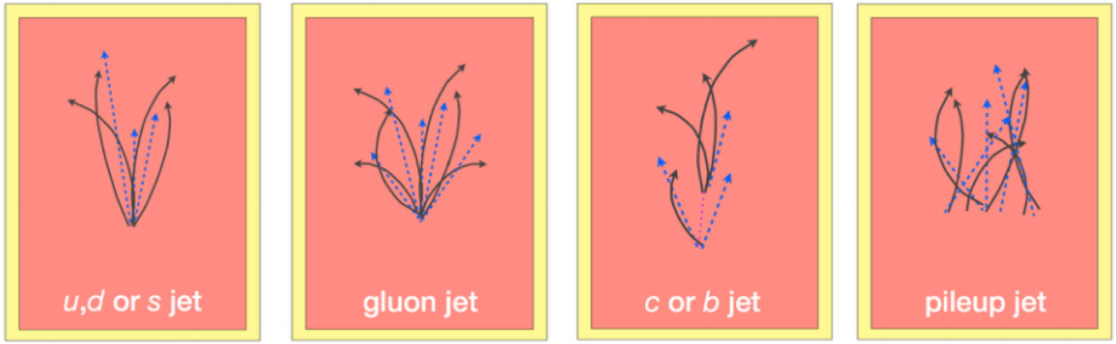
```
#0  PDG code:130,     p/pt/eta/phi: 20.3845  16.7688  -0.645422  1.49343
#1  PDG code:211,     p/pt/eta/phi: 17.2954  15.0452  -0.540329  1.45624
#2  PDG code:211,     p/pt/eta/phi: 11.453    9.82512 -0.567975  1.4245
#3  PDG code:22,      p/pt/eta/phi: 7.75683   6.52999 -0.603777  1.46632
#4  PDG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

Reco Particles

```
#0  PFCandidate type: 5 E/pT/eta/phi 31.929   26.176   -0.651     1.493,
#1  PFCandidate type: 1 E/pT/eta/phi 17.237   14.994   -0.540     1.456,
#2  PFCandidate type: 1 E/pT/eta/phi 11.540    9.900   -0.568     1.425,
#3  PFCandidate type: 4 E/pT/eta/phi  9.684    8.195   -0.594     1.420,
#4  PFCandidate type: 4 E/pT/eta/phi  6.663    5.602   -0.606     1.388,
#5  PFCandidate type: 1 E/pT/eta/phi  5.720    5.170   -0.457     1.124,
...
```

JET SUBSTRUCTURE TECHNIQUES

New Field: Jet Substructure Techniques

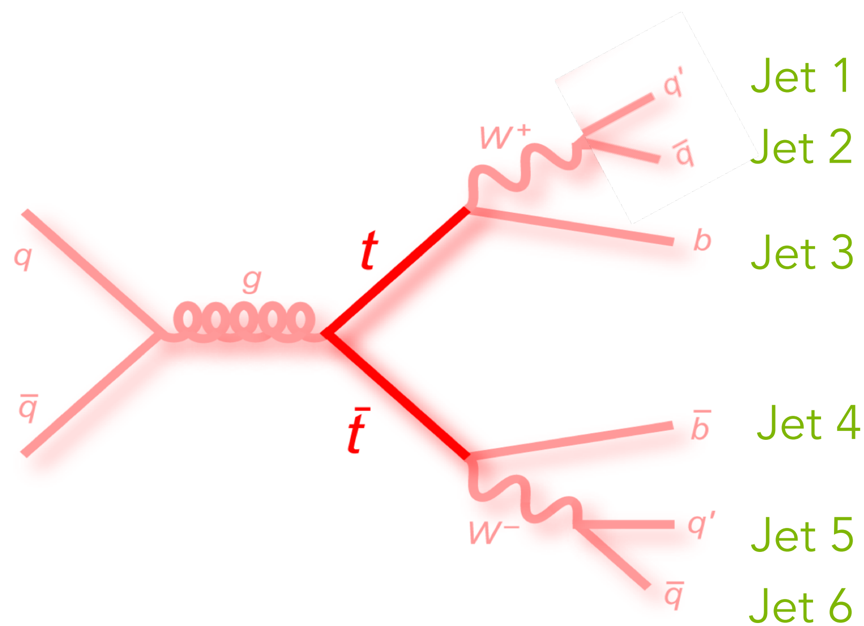


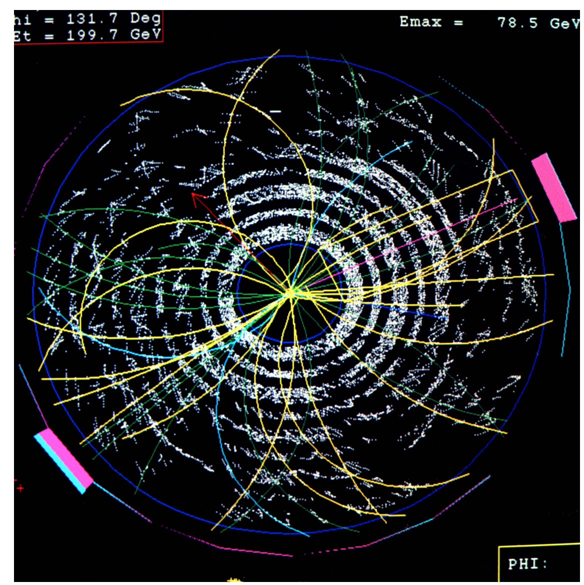
- Qualitatively different quarks/gluons produce different jet topologies
  - Different radiation patterns & lifetimes
  - Can use topologies to discriminate

- Jets can also form from hadronic decays of high-p_T heavy particles
  - $W/Z \rightarrow qq$, $H \rightarrow bb$, $t \rightarrow Wb \rightarrow qqb$
  - By looking at these patterns we can gain useful information about the process in the event
  - Can be used to identify new physics signatures

Historical Perspective

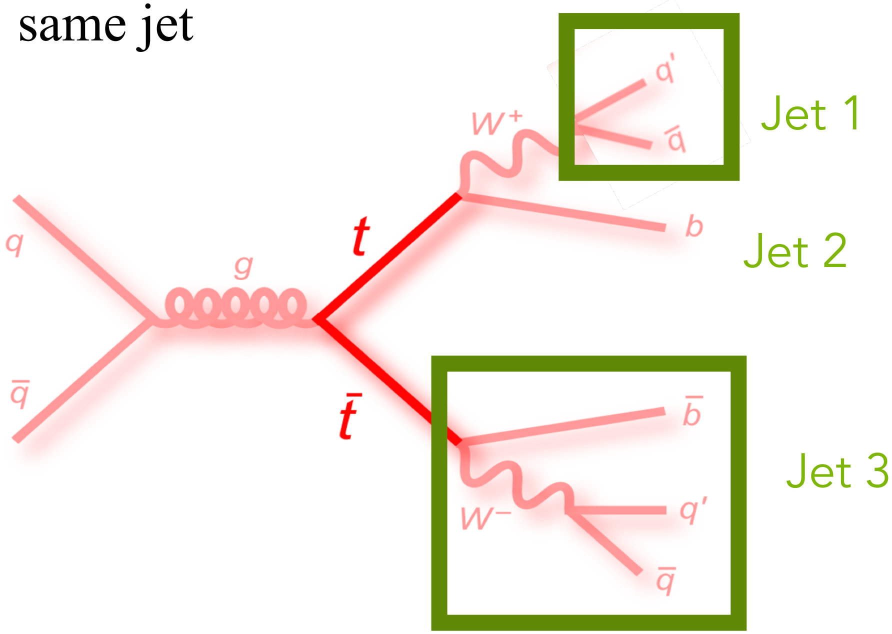
- Identifying SM ttbar events historically done by associating one object to each final state decay product
  - Combine objects to reconstruct each top quark
  - Combinatorics can become unwieldy
    - 6+ jets in all-hadronic decay mode!

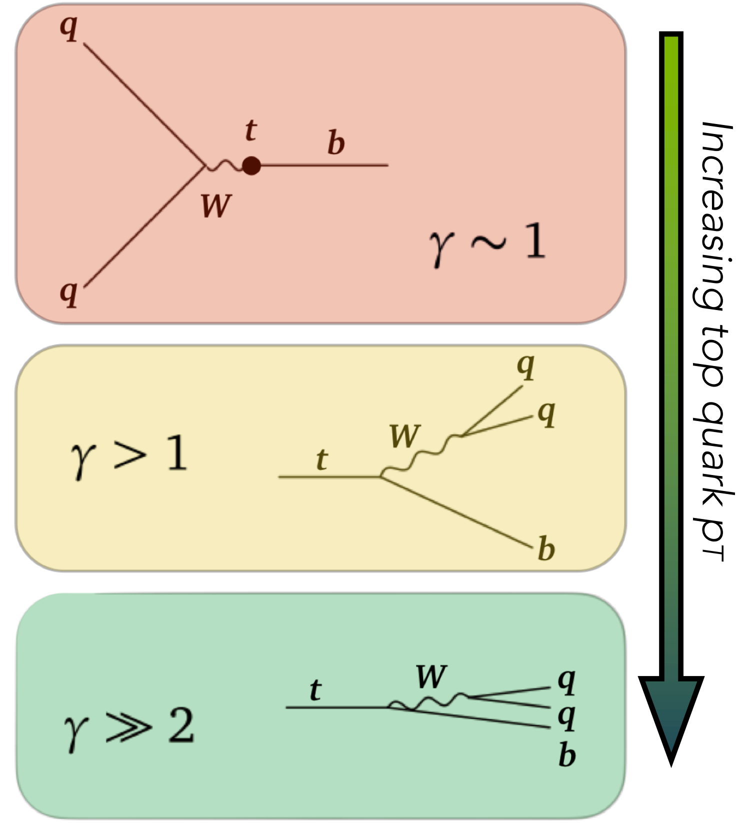


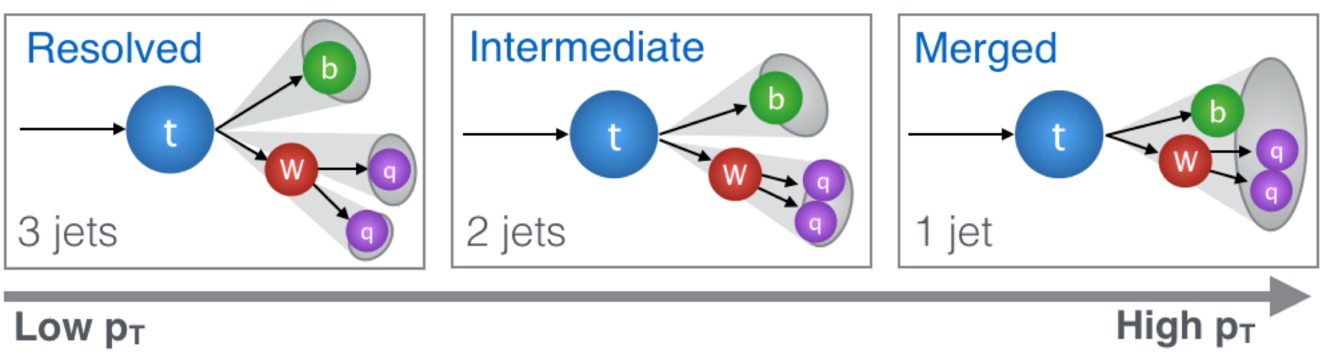


Historical Perspective

- If the top quarks are boosted, the decay products are collimated → reconstructed in the same jet



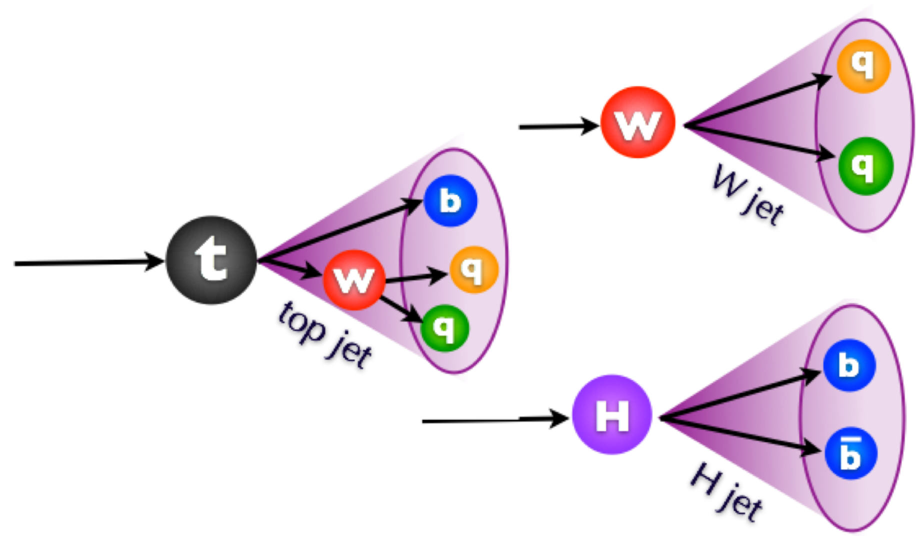


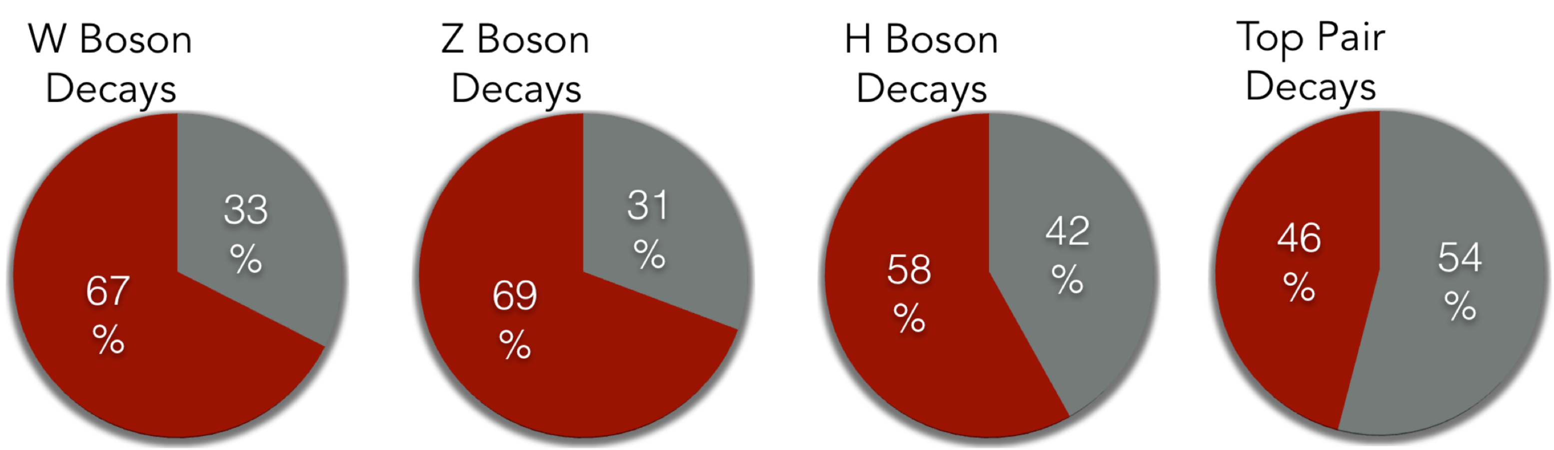


Hadronic final states become accessible using Jet Substructure

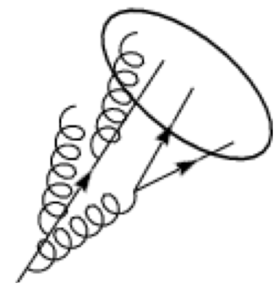
Hadronic Final States

- Large amount of acceptance can be gained from hadronic channels
- These merged decays can be used in other cases as well
  - W, Z, Higgs bosons



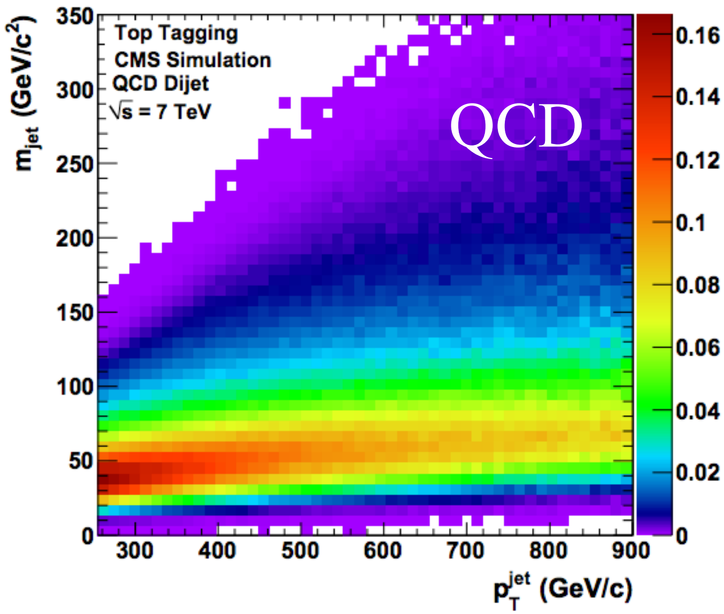


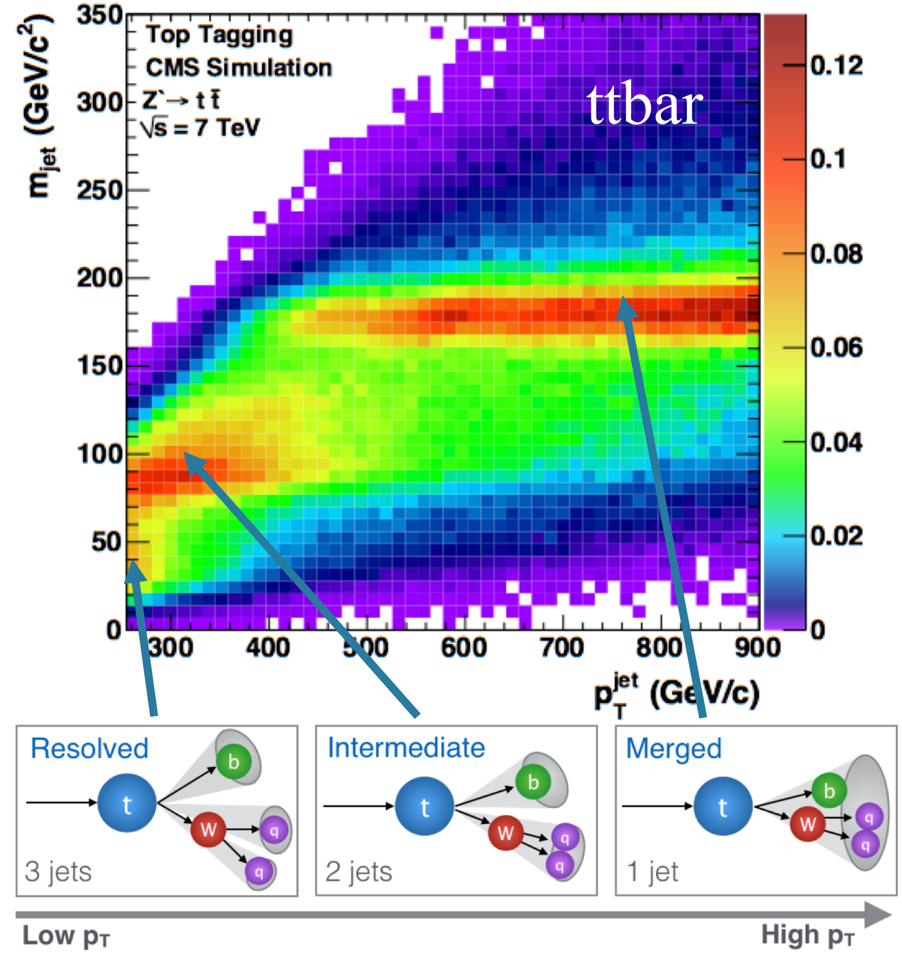
Jet Mass



$$\langle m^2 \rangle \sim \frac{C\alpha_S}{\pi} p_T^2 R^2$$

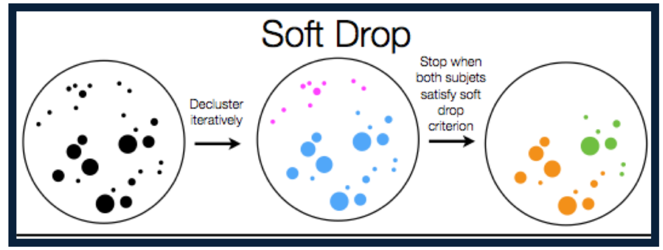
- Computed by adding up constituent particle 4-vectors and computing the mass
- Choose R = 0.8 for heavy object reconstruction
  - Merged W/Z at p_T ~200 GeV
  - Merged top at p_T ~400 GeV

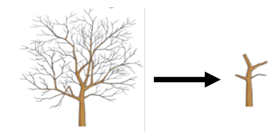


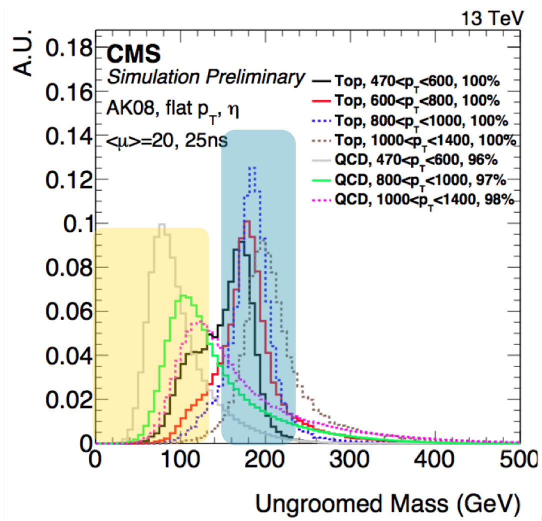


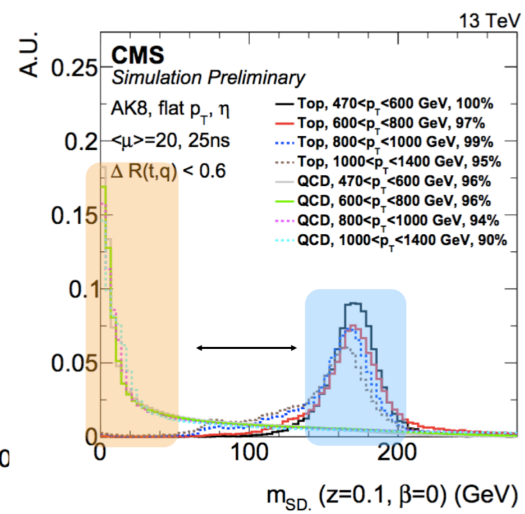
Jet Grooming

- Some discrimination obtained when using this ‘raw’ jet mass
- We can do better by looking inside the jet at the individual constituents
- Using jet grooming algorithms can improve the discrimination between QCD and top quark jets
- Basic idea: remove soft and wide-angle radiation from within the jet
  - Decluster Iteratively using smaller R
  - Merged top quarks can be identified with a window around the top quark mass







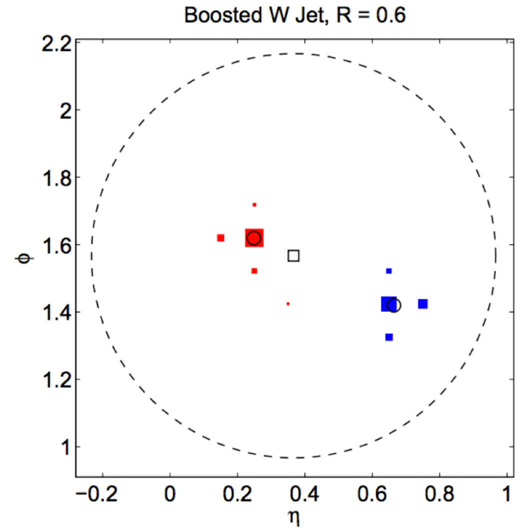


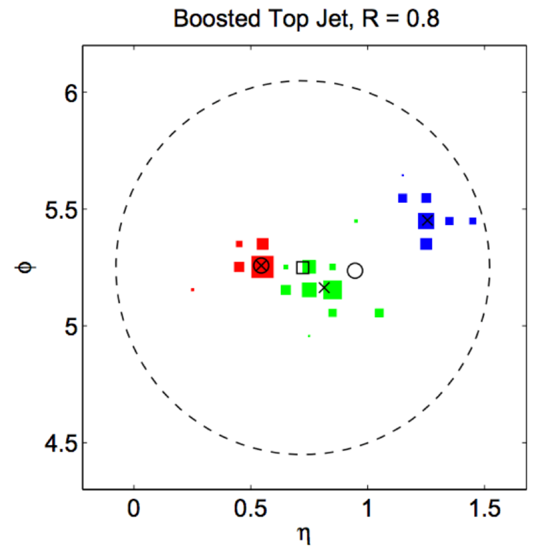
Dramatically improves the separation of QCD and top quark jets

Topological Algorithms

- We know how many final state objects to expect from the decay of different heavy objects
- Can look inside the jet for the expected substructure
  - Top decays → 3 subjets
  - W/Z/H decays → 2 subjets
- A quantity called N-subjettiness is a measure of how consistent a jet is with a hypothesized number of subjets
  - Low τ_N → consistent with N (or fewer) subjets
  - Ratios used for additional discrimination

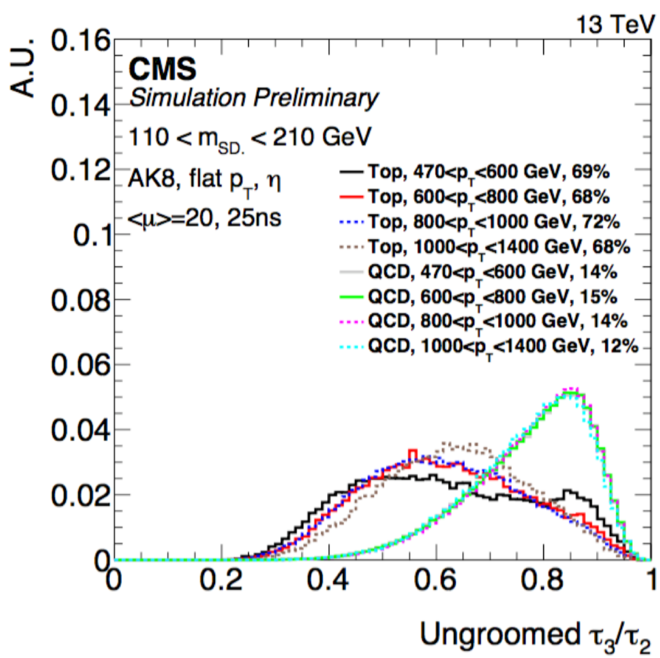
$$\tau_N = \frac{1}{\sum_i p_{T,i} \cdot R} \sum_i p_{T,i} \cdot \min(\Delta R_{1,i}, \Delta R_{2,i}, \ldots, \Delta R_{N,i})$$

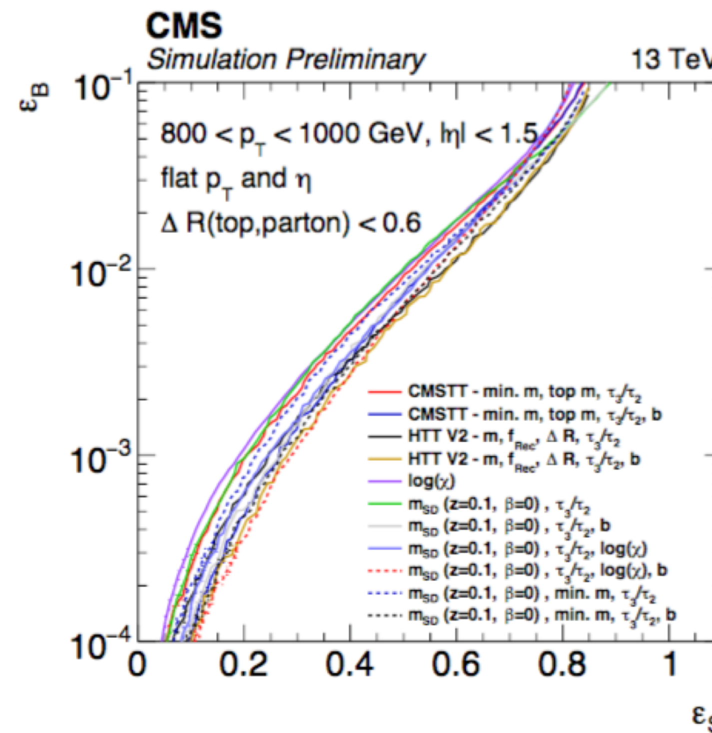




Combining all Information

- Ratios used for discrimination
  - $\tau3 / \tau2$ for top quark jets
  - $\tau2 / \tau1$ for W/Z/H jets
- Provides additional power when used in conjunction with the groomed jet mass



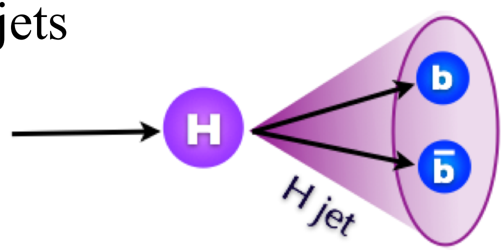


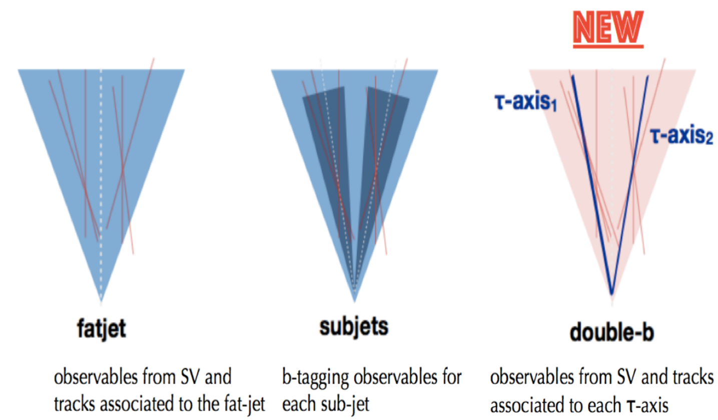
Combined Algorithms

- The algorithms provide mutual information that increases performance
  - Choice of combination used for top quark identification in 13 TeV analyses: Soft-drop mass + N-subjettiness (+ b-tagging)

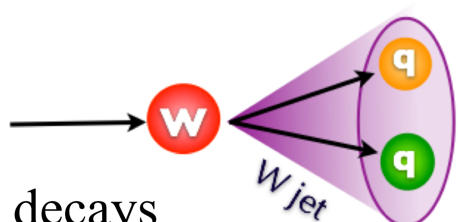
Beyond Hadronic Top Decays

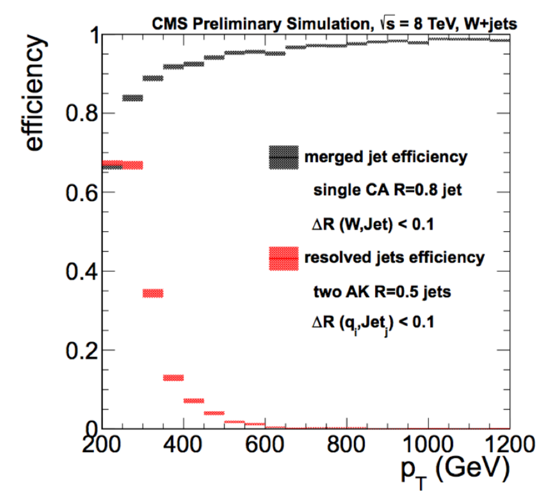
- Similar developments for other boosted heavy object identification
- Higgs tagging
  - Look for massive jets with 2 b-tagged subjets



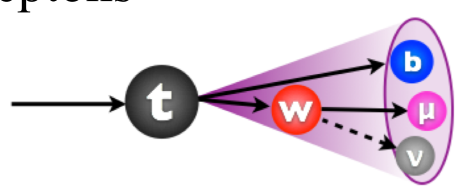


- W/Z tagging
  - Use τ2 / τ1 for 2-prong decay mode
  - Single-jet reconstruction more efficient at high pT



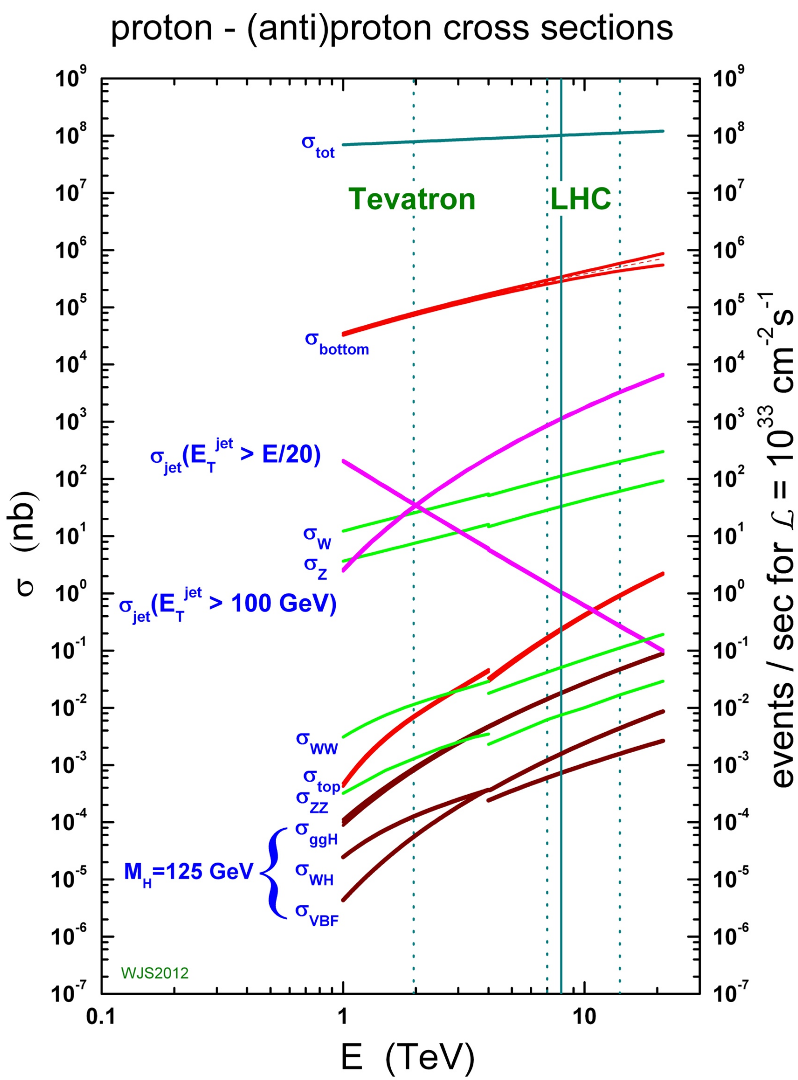


- Leptonic top quark decays
  - Non-isolated leptons



THE PHYSICS OF HADRON COLLISIONS

Hadronic Cross Sections



PROS

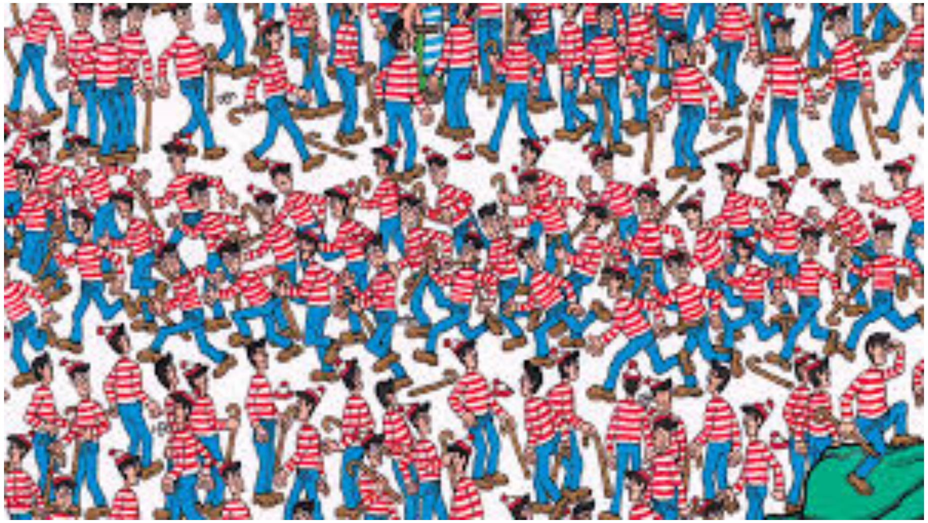
- Wide variety of processes produced
  - Enables rich physics program
  - Model-independent searches possible
    - Do not need theory to tell us what to look for

CONS

- Production Cross Sections span 12-13 orders of magnitude
  - Collision rate overwhelmed by mundane processes
  - Background discrimination and modeling crucial

Background

- Two types
  - Instrumental (fake)
    - Detector Malfunction
    - Object Misidentification
  - Physics (irreducible)
    - Higher rate process with identical final states than our signal
- Two options
  - Reduce to negligible level
  - Define "control regions" that are dominated by each of the main backgrounds & extract the signal performing simultaneous fits on both the signal and background dominated regions



What do we want to measure?

- Hadron Colliders are Discovery Machines
  - W/Z @ SpS in 1983
  - ttbar @ Tevatron in 1995
  - Higgs @ LHC in 2012
- Rate of a given process
  - Total Cross Sections
  - Differential Cross Sections
- Particle Properties
  - Mass, Width, Spin, Couplings…
- Search for New Physics
  - Model-specific
  - Model-independent
  - Infer from deviations from precision measurements of SM predictions

From Hitoshi Murayama

Recipe to measure a cross section

Number of observed candidates
(fitted or counted)

Number of background candidates
(measured from data
or calculated from theory)
(minimize)

Cross section in cm^2
(or μb, nb, pb)

$$\sigma = \frac{N_{\rm obs} - N_{\rm backg}}{\epsilon \cdot \int \mathcal{L} dt}$$

Efficiency/acceptance
(maximize)

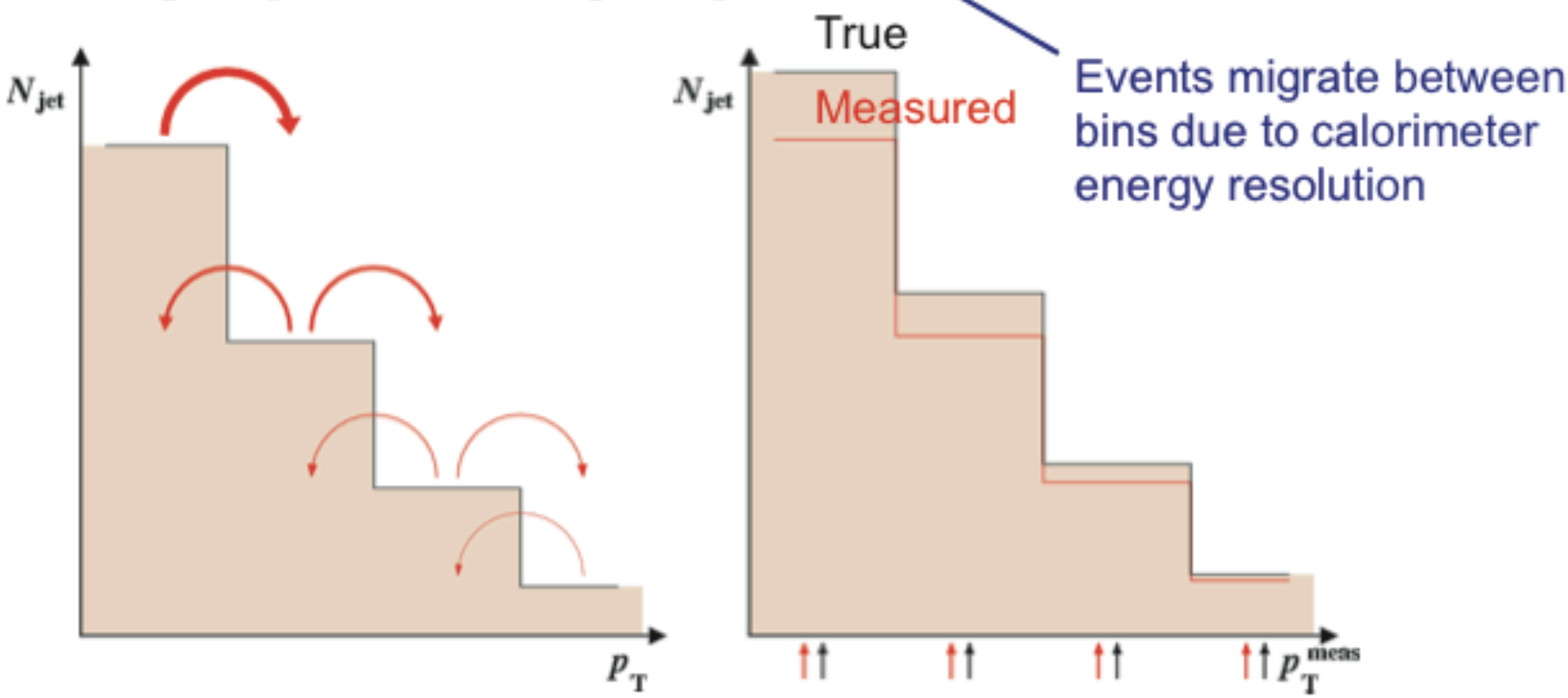
Integrated Luminosity in cm^{-1}
(or μb^{-1}, nb^{-1}, pb^{-1})
(maximize,
unless systematically limited)

$$\frac{\delta\sigma}{\sigma} = \sqrt{\frac{\delta N_{\rm obs}^2 + \delta N_{\rm backg}^2}{(N_{\rm obs} - N_{\rm backg})^2} + \left(\frac{\delta\mathcal{L}}{\mathcal{L}}\right)^2 + \left(\frac{\delta\epsilon}{\epsilon}\right)^2}$$

Differential cross section

Worry about the shape (particularly steeply falling distribution) and finite resolution:

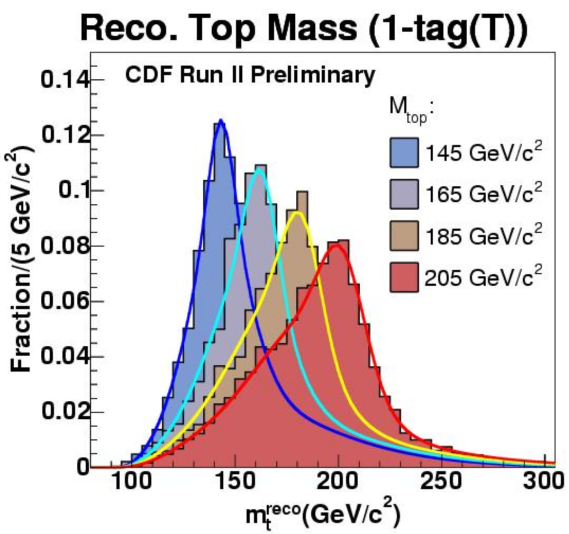
$$\frac{d^2\sigma}{dp_T dy} = \frac{N}{\epsilon \cdot L \cdot \Delta p_T \Delta y} \cdot C_{\text{smear}} \text{ vs. } p_T$$



Differential cross sections typically "un-smeared" to compare with predictions

Mass and other Particle Properties

Precision measurement ⇒ maximize statistical significance + minimize systematic uncertainties (jet energy scale, signal/background modeling)



Main mass extraction techniques:

- Template methods: typically, one mass per event from kinematic fit, compare data to MC templates
- Dynamical methods: event by event weights according to quality of agreement with signal and background differential cross-sections

Also used for other properties

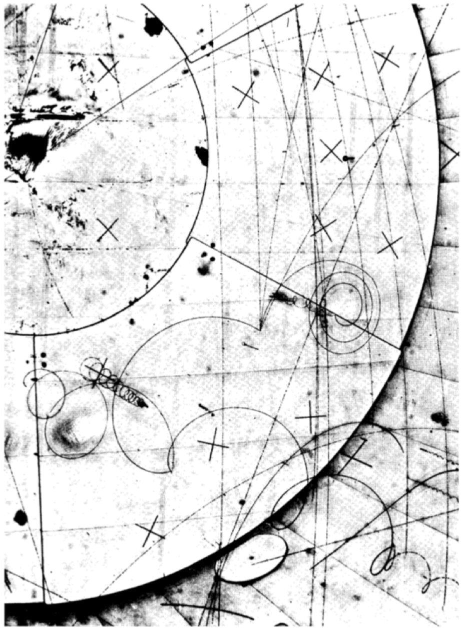
$$P(x;m_{top}) = \frac{1}{\sigma}\int d^n\sigma(y;m_{top})\,dq_1 dq_2\, f(q_1) f(q_2)\, W(x\,|\,y)$$

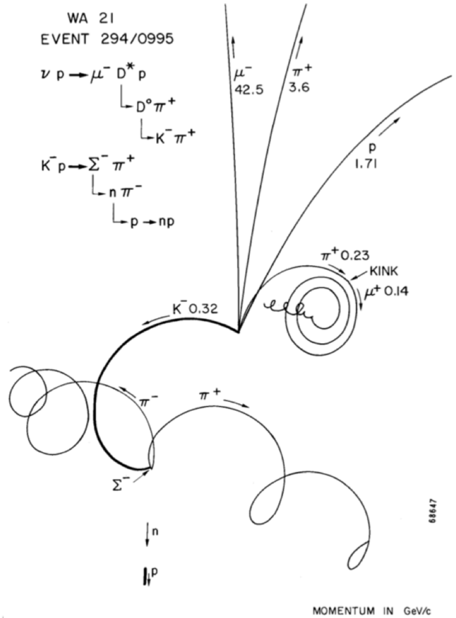
differential cross-section (LO matrix element)

PDF's

Transfer function: mapping from parton level variables (y) to reconstructed level variables (x)

Simplest Search: Resonance Particles



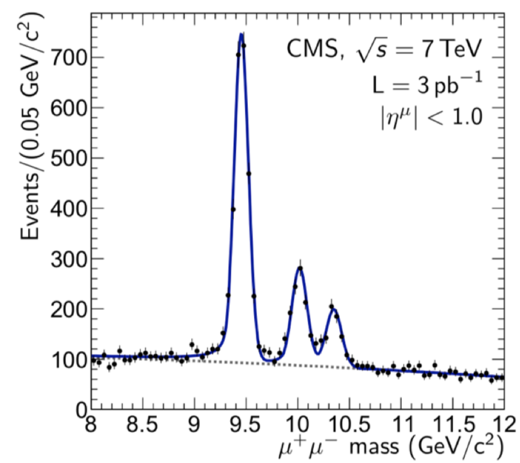


- Particles with lifetime ~10^{-23} s travel less than the nuclear diameter
  - By measuring the energy and momenta of the decay products, we can calculate

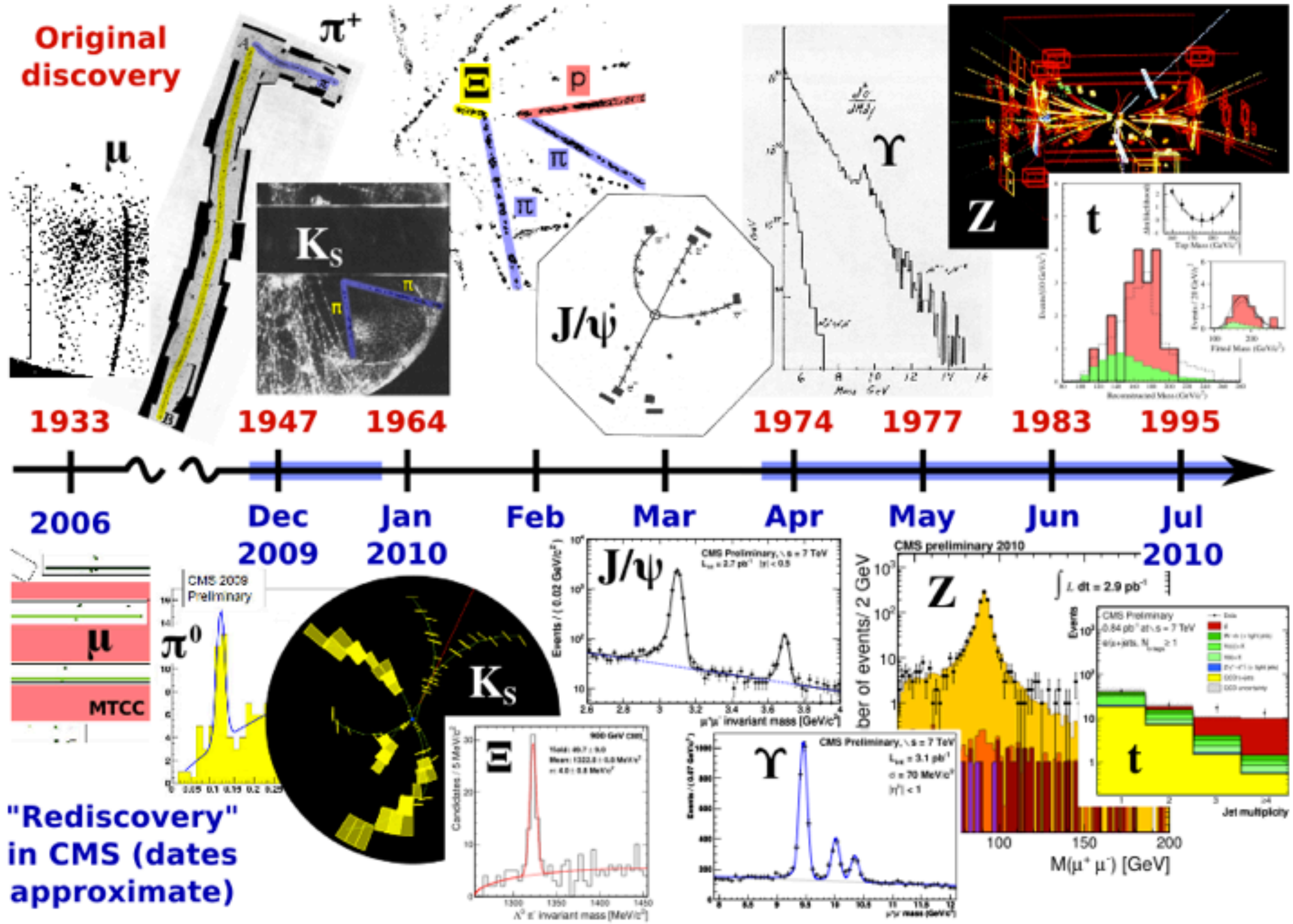
$$x = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2 c^2}$$

- x will give the mass of the parent particle or a continuous range of values in case of prompt production

- Hadrons with mean lives of ~10^{-8}-10^{-10}s can travel a few mm at the speed of light before decaying
- Can easily identify each particle’s decay product and determine the particle mass and how long it lived



Invariant Masses



TOMORROW: DOWN THE SM LADDER

QCD

W and Z Bosons

Top Quarks

Higgs Bosons

MANY THANKS TO EVERYONE WHO CONTRIBUTED MATERIAL! (KNOWINGLY OR NOT ☺)

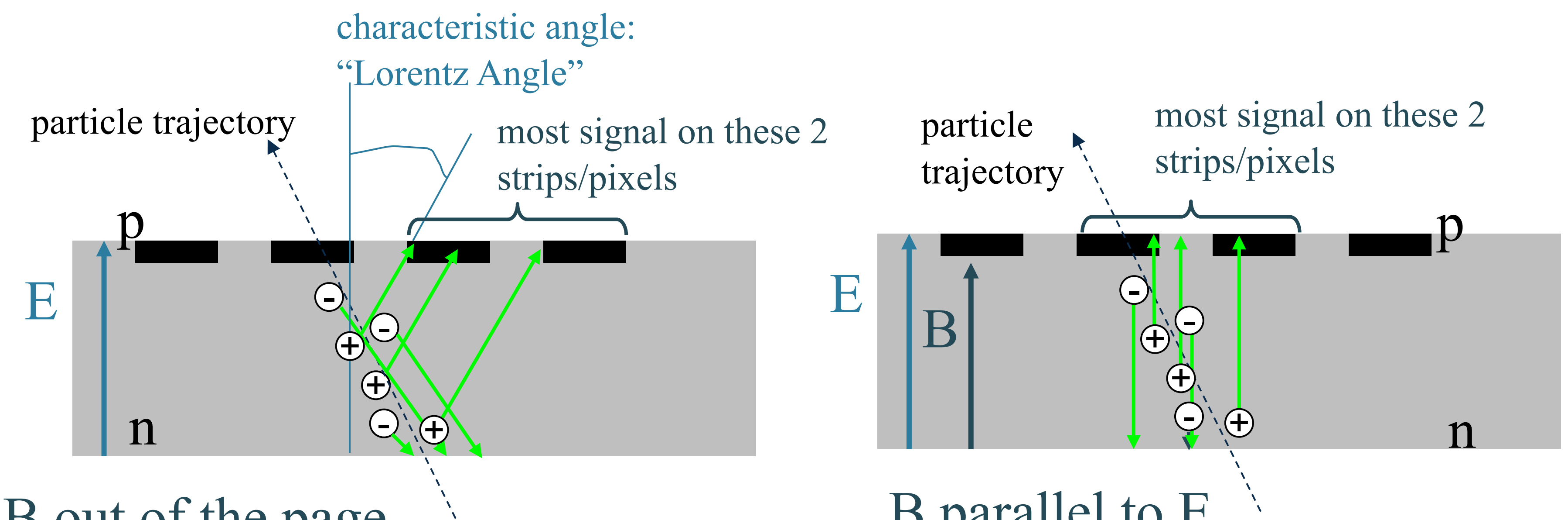
Special Thanks to Richard Cavanaugh & Justin Pilot

BACKUP

Electron-hole pairs drift

- Charges drift under the influence of the E and B fields
  - **Lorentz angle** = angle of charge drift relative to the E field
  - Drift direction offset the same for positive and negative

$$\vec{F} = q\vec{E} + q\vec{v}\times\vec{B}$$



B out of the page
typical of barrel

B parallel to E
typical of forward