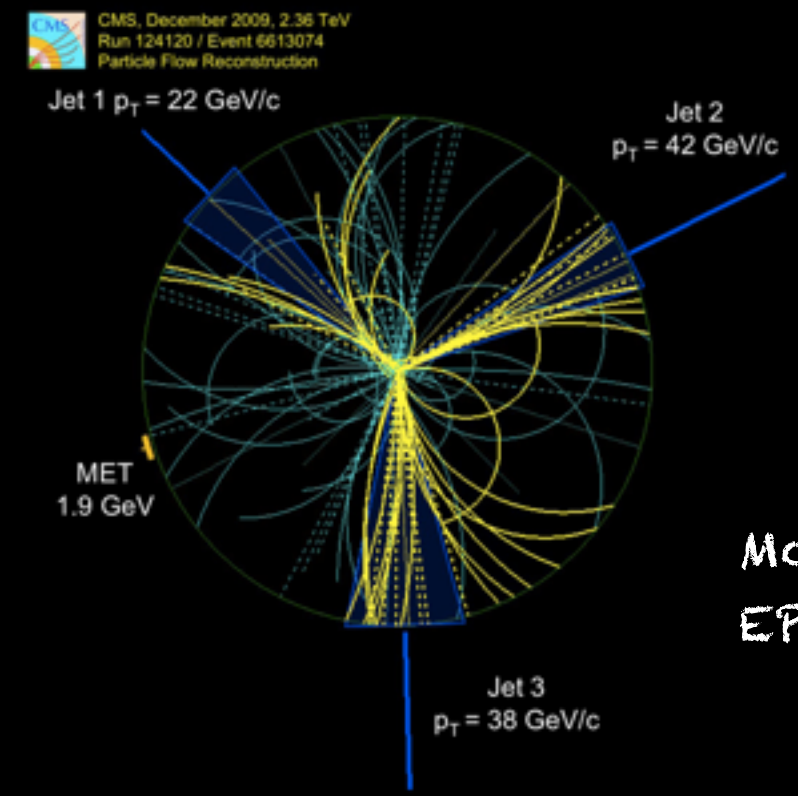
"Experimental Results from CMS"

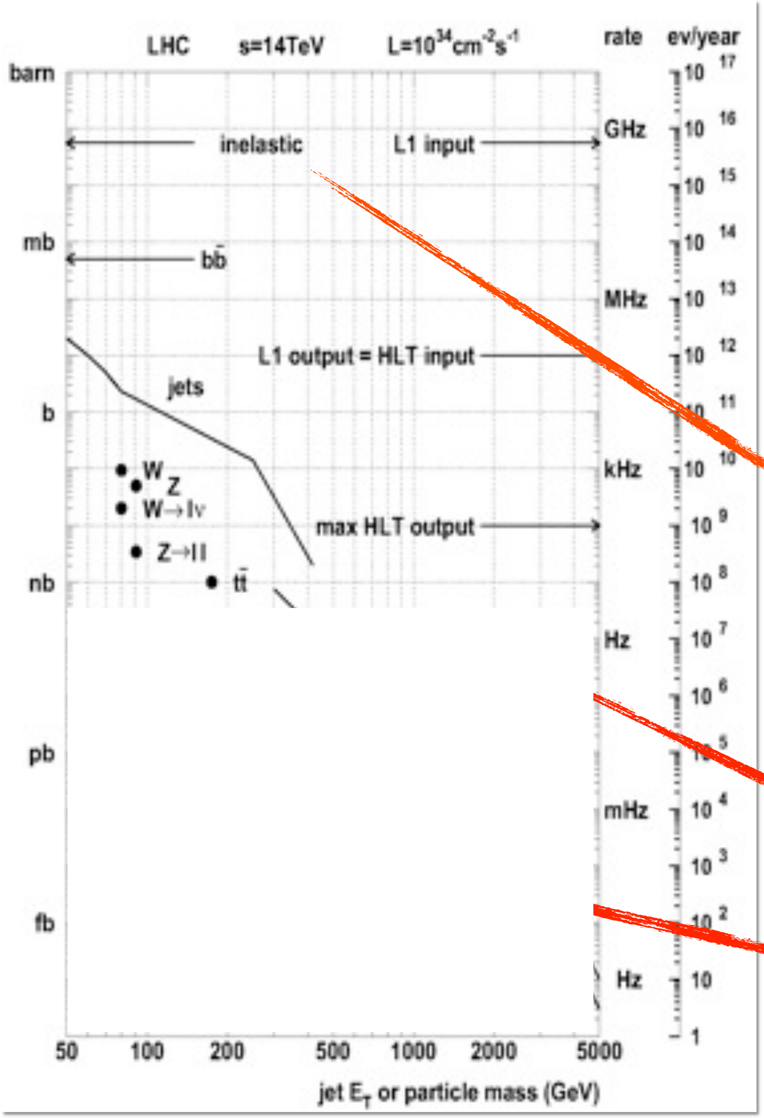


Moratorium on EPS results

Richard Cavanaugh
Fermilab & University of Illinois - Chicago

CTEQ Summer School, Madison Wisconsin
16 July, 2011

Production Cross Sections at the LHC



- Cross sections and background estimates (measured, calculated) tell us what minimum energy and luminosity we need from the colliding beams and therefore what the detector must be able to handle
- Production dynamics determine the range of energies and angles we need to measure

Inelastic background events produced at a rate of 1 GHz.

Supersymmetry ~ 1Hz

Detectable Higgs production ~ 1 milliHz

A Detector to Look for New Physics

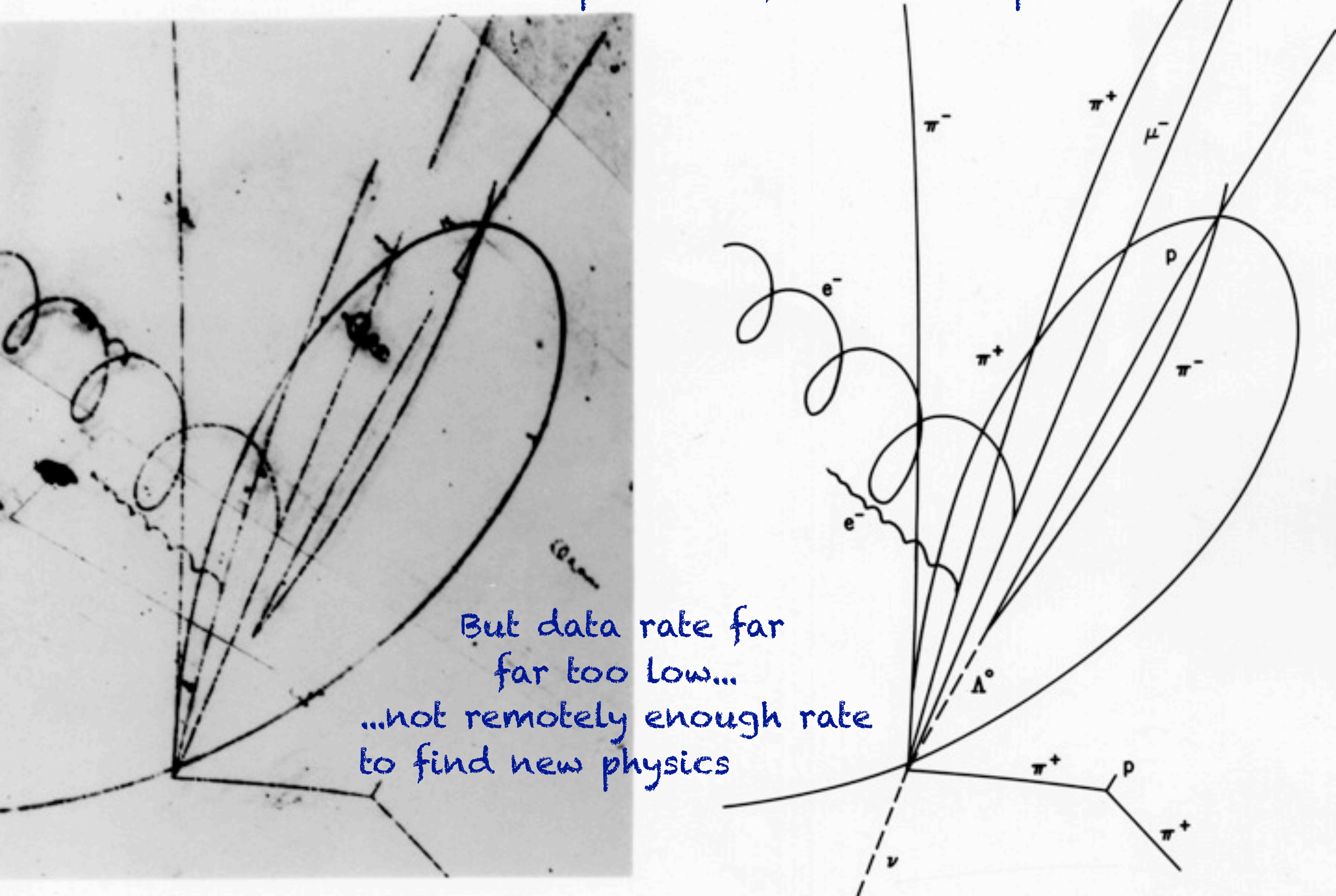
- There are a variety of possible decay modes for the Standard Model Higgs, depending on its mass
- There are many candidates for new physics
  - Supersymmetry
  - New interactions, e.g. Technicolor
  - Extra dimensions
  - Right-handed gauge bosons
  - Many, many more ….
- A " discovery detector", also called a "general purpose detector" at LHC must be able to study all these states and separate the interesting events from a much larger background of uninteresting stuff that has the nasty habit of mimicking new physics and misleading us

How can we do this?

- Heavy objects decay into lighter objects
  - The "lighter objects" are the particles of the Standard Model
    - Photons, electrons, muons, τ leptons, jets (light quarks u,d, s and gluons)- especially "b-jets", "charm jets", "top", Ws, and Zs
      - Only a few particles are stable enough to be measured directly: e,μ,γ, plus some hadrons: pions, kaons, protons, neutrons
    - Partons, quarks and gluons, manifest themselves as jets of particles so identifying "jets" and measuring their angle and energy becomes important
  - It is a requirement for finding new physics to be able to measure all the known SM objects
- Particles may leave the detector without interacting
  - Neutrinos are known SM particles that do that all the time
  - There may be NEW massive weakly interacting particles that behave similarly
- These can be "detected" by observing missing transverse energy , "MET", so it is a requirement to be able to detect it

One possibility is using the old technology of Bubble Chambers...

...where one has a "picture" of individual particles



But data rate far far too low...

...not remotely enough rate to find new physics

Experimental Challenge

CMS is radically different from detectors of the previous generations

High Interaction Rate

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

Large Particle Multiplicity

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

High Radiation Levels

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

Slide taken from J. Virdee

(CMS) Design Criteria

Very good muon identification and momentum measurement

Trigger efficiently and measure sign of TeV muons dp/p < 10%

High energy resolution electromagnetic calorimetry

~ 0.5% @ E_T ~ 50 GeV

Powerful inner tracking systems

Momentum resolution a factor 10 better than at LEP

Hermetic calorimetry

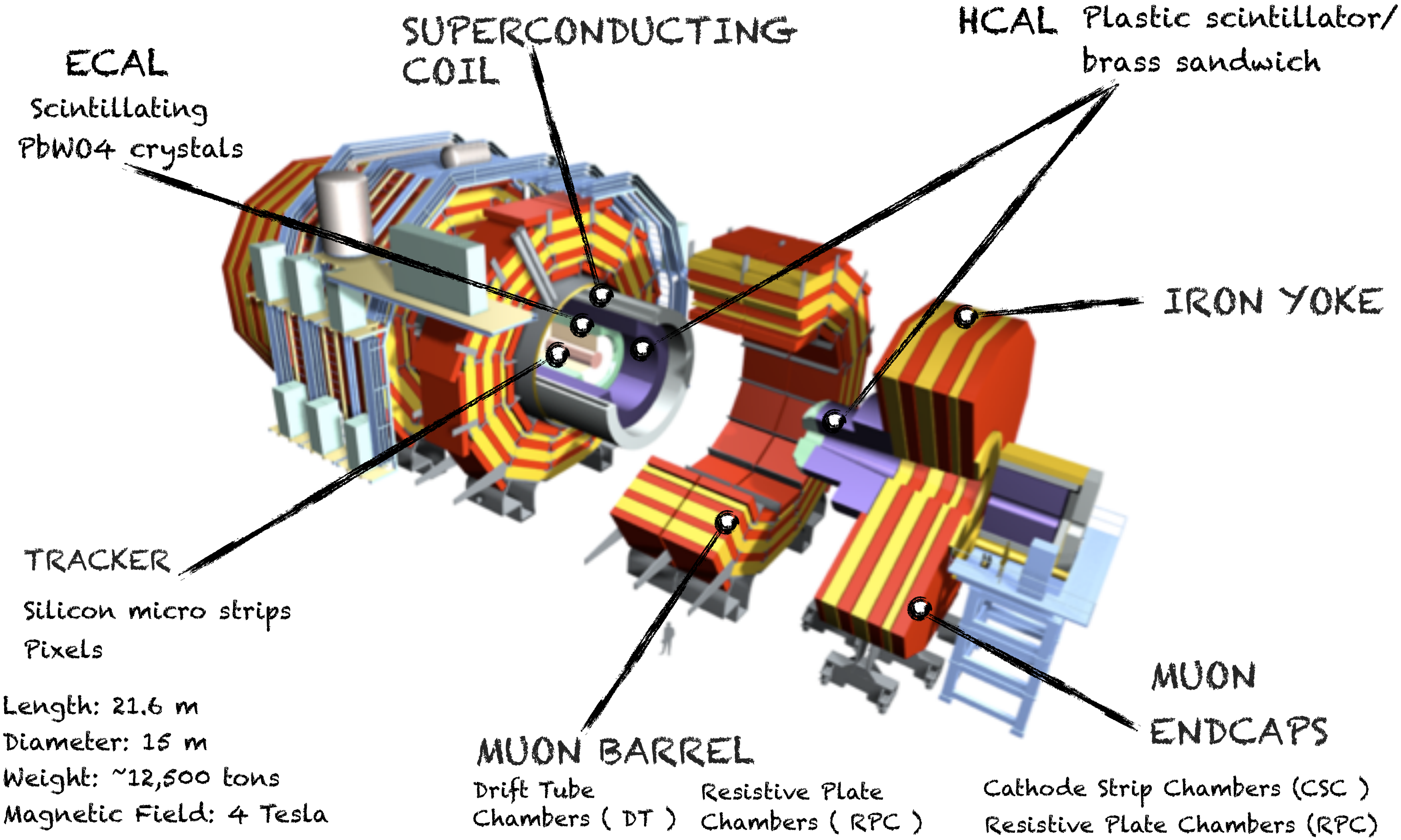
Good missing E_T resolution

(Affordable detector)

Slide taken from J. Virdee

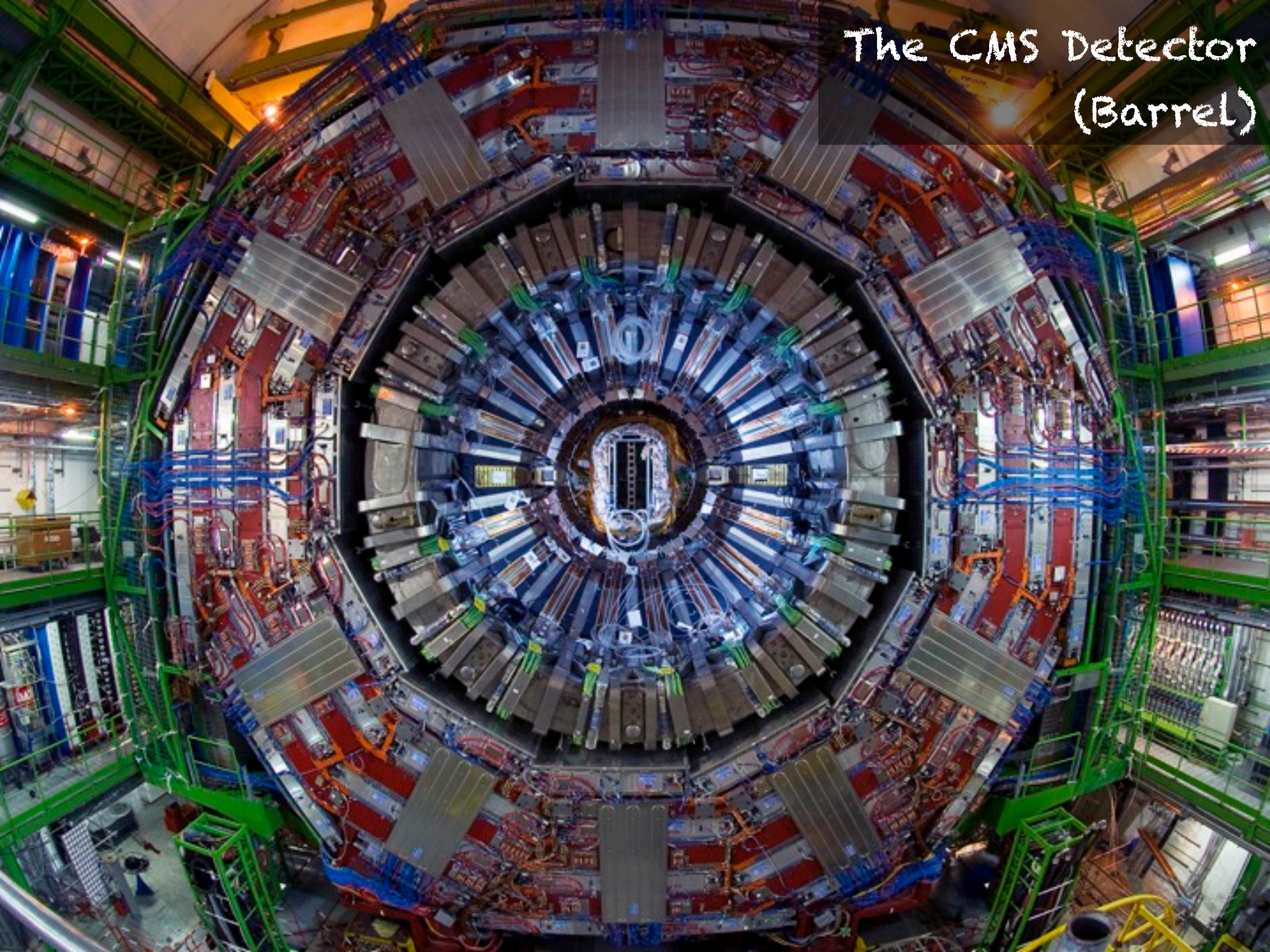
Transparency from the early 90's

CMS Detector



Length: 21.6 m
Diameter: 15 m
Weight: ~12,500 tons
Magnetic Field: 4 Tesla

The CMS Detector (Barrel)



Particle Flow Event Reconstruction

- This is the way I was taught to do physics
  - Similar (in spirit) to Bubble Chamber pictures
- Method of choice at e+e- colliders
  - very clean environment
  - low particle multiplicity compared to number of readout channels
- Historically not used at hadron colliders
  - very messy environment
  - high particle multiplicity compared to number of readout channels
- CMS uses Particle Flow Event Reconstruction

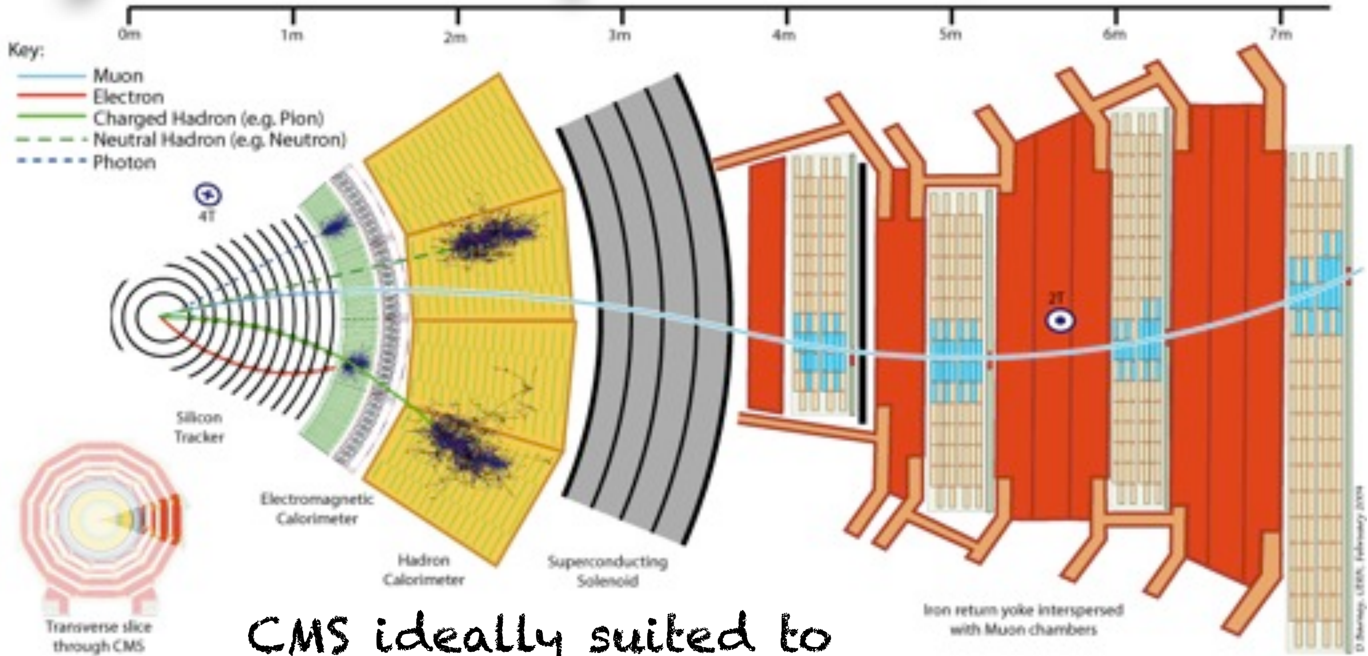
Goal of Particle-Flow

- 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 CMS sub-detectors for E, η, φ, pID
- Provide consistent & complete list of ID'd & calibrated particles for
  - Tau reconstruction & Jet reconstruction
  - Missing & total Visible Energy determination
  - Other, analysis specific, objects (event or jet shape vars, etc)
- Use of Redundant Information: Calorimeter & Tracking
  - Good: Better Calibration (data driven) and Resolution possible
  - Challenge: Must have accurate accounting
- Very different from "Traditional" Tau, Jet, MET Reconstruction...

Required Ingredients for PF

- Large Volume Tracker
  - high precision, high efficiency tracking is critical
- High Magnetic Field
  - needed for good pT resolution
  - needed to separate charged from neutral particles
- Highly Granular Calorimeter
  - needed to separate charged from neutral particles
- Good Calorimeter Energy Resolution is :
  - needed for good photon, electron E resolution
  - not so critical for Hadrons

Key CMS Components for PF



CMS ideally suited to reconstruct & identify particles

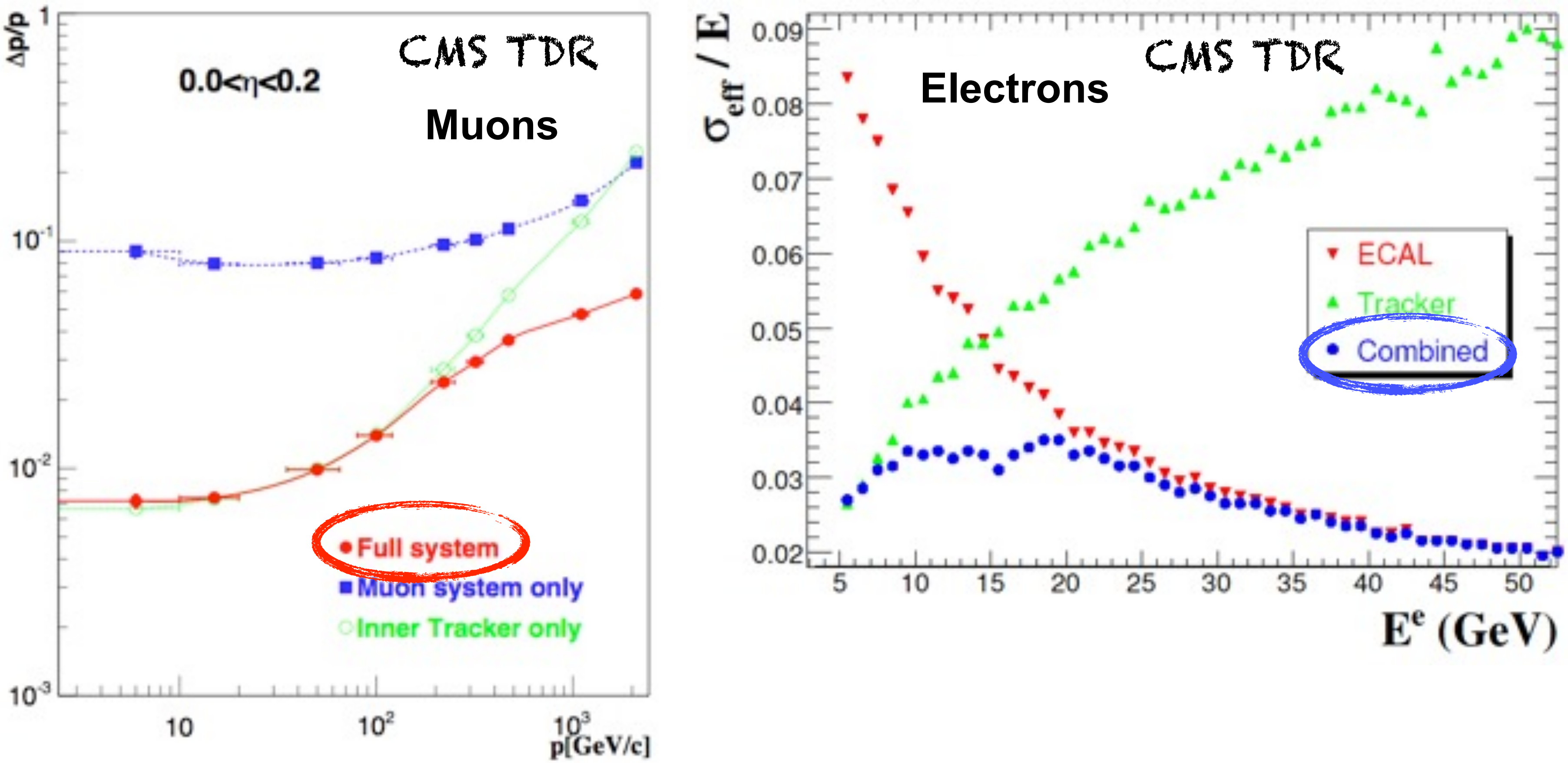
- Tracker:
  - Large Volume, High Accept: R > 1m, 3+10 layers, $|\eta| < 2.6$
  - Eff. ≈ 95%(99%) π's(μ's); fake rate ≈ 1%; $p_T < 150$ MeV
- Solenoid:
  - High B-Field = 3.8 T
- ECAL:
  - Fine Granularity, High Accept: $\Delta\eta \times \Delta\varphi = (0.0187)^2$; $|\eta| < 3.0$
  - High Resolution: $\sigma \approx 3\%/\sqrt{E_T}$

ATLAS vs. CMS

	ATLAS	CMS
Ecal+Hcal pion resolution	$\frac{\sigma}{E_T} \approx \frac{40\%}{\sqrt{E_T}}$	$\frac{\sigma}{E_T} \approx \frac{100\%}{\sqrt{E_T}} \oplus 7\%$
MET resolution (TDR)	$\frac{\sigma(\not{E}_T)}{\Sigma E_T} \approx \frac{50\%}{\sqrt{\Sigma E_T}}$	$\frac{\sigma(\not{E}_T)}{\Sigma E_T} \approx \frac{120\%}{\sqrt{\Sigma E_T}} \oplus 2\%$
Inner tracker resolution (TDR)	$\frac{\sigma(p_T)}{p_T} \approx 1.8\% \oplus 60\%\ p_T$ (p_t in TeV)	$\frac{\sigma(p_T)}{p_T} \approx 0.5\% \oplus 15\%\ p_T$ (p_t in TeV)
B field inner region	2 Tesla : p_T swept < 350 MeV	4 Tesla : p_T swept < 700 MeV

ATLAS has better calorimetry ; CMS has better tracking

Improve CMS MET resolution using full detector



Significant improvement achieved for leptons
by using the Detailed Full Detector...

...why not for taus,
...and also Jets & MET ?

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

Calorimeter transverse energy uncertainty for charged hadrons:

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

Tracker transverse momentum uncertainty for charged hadrons:

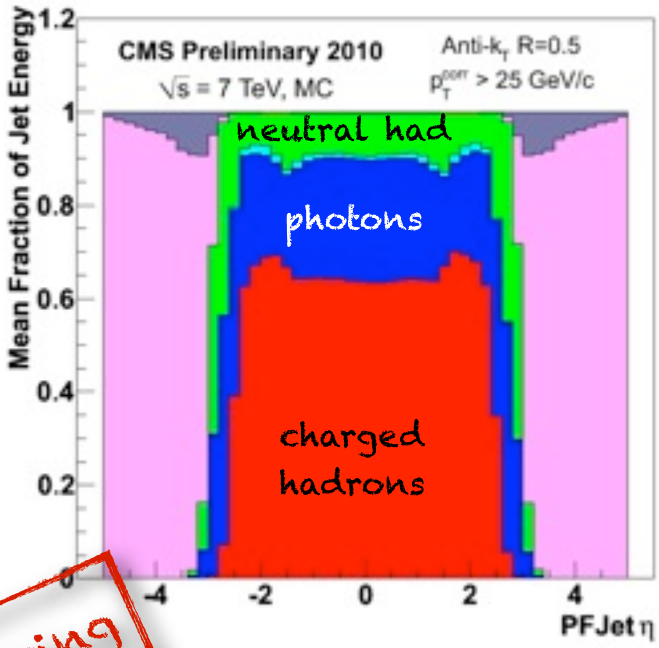
$$\sigma(p_T) \approx 0.01\% \ (p_T)^2$$

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

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

Set the Stage: Jet Composition

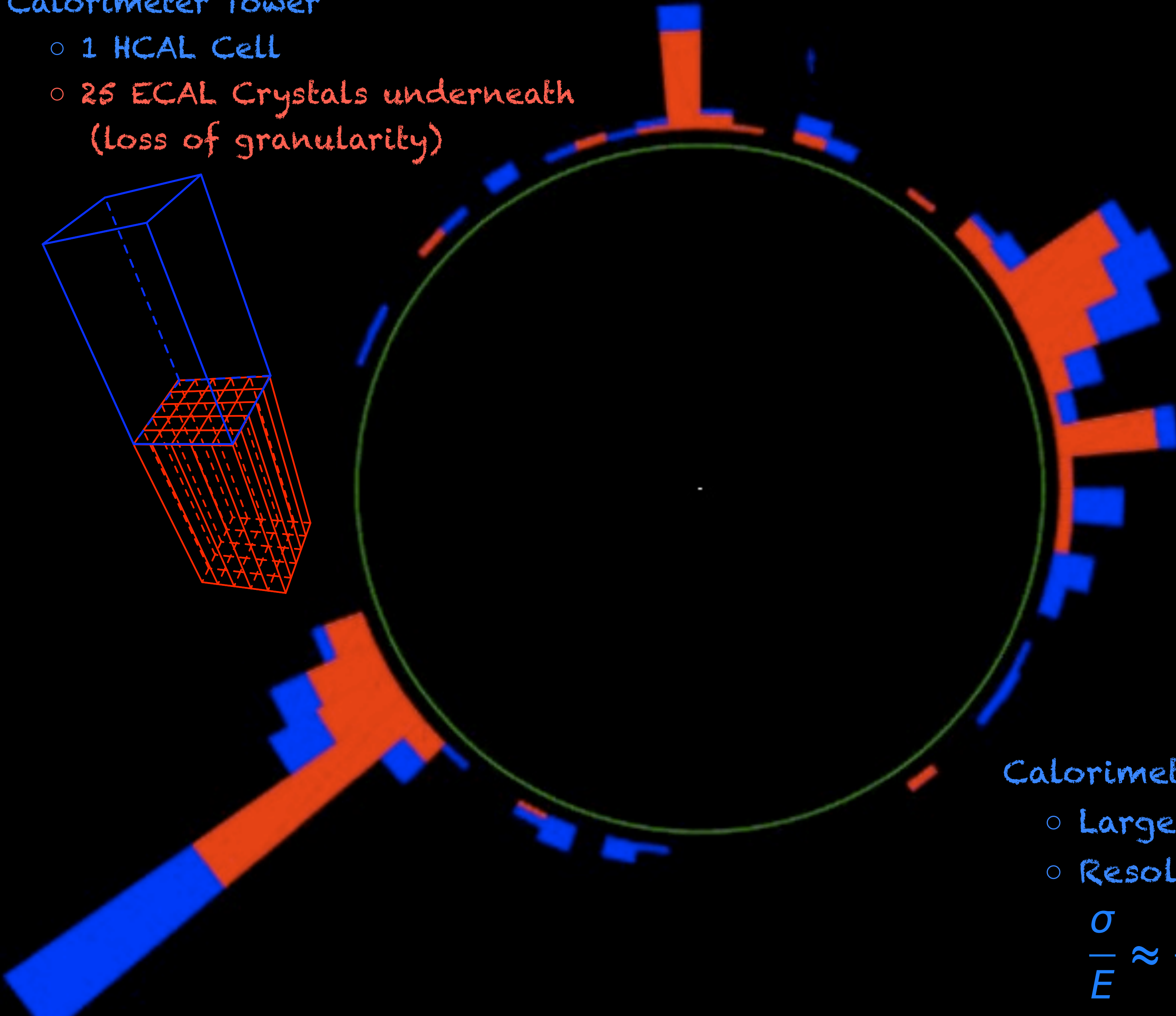
- Charged particles : ~60% Tracking
  - Mostly charged pions, kaons and protons, but also some electrons and muons
- Photons : ~25% ECAL
  - Mostly from π^0's, but also some genuine photons (brems,...)
- Long-lived neutral hadrons : ~10% HCAL
  - K^0_L, neutrons
- Short-lived neutral hadrons, "V^0's"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



- Again, full use of Detector Information should significantly improve Jet performance

Calorimeter Tower

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



Calorimeter Jets

- Large Jet E Corr.
- Resolution HCAL

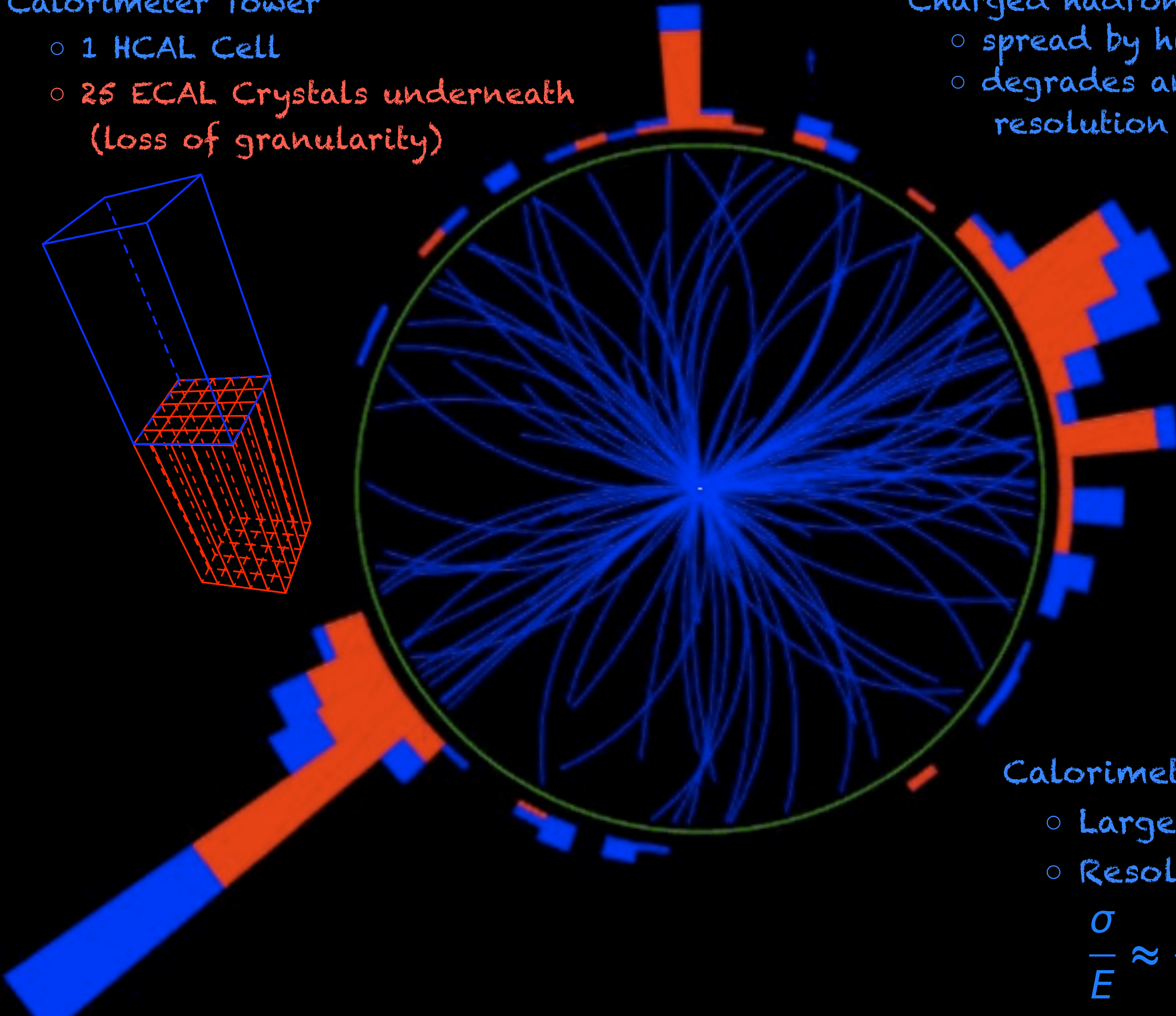
$$\frac{\sigma}{E} \approx \frac{100\%}{\sqrt{E}}$$

Calorimeter Tower

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

Charged hadrons

- spread by high B-field
- degrades angular resolution



Calorimeter Jets

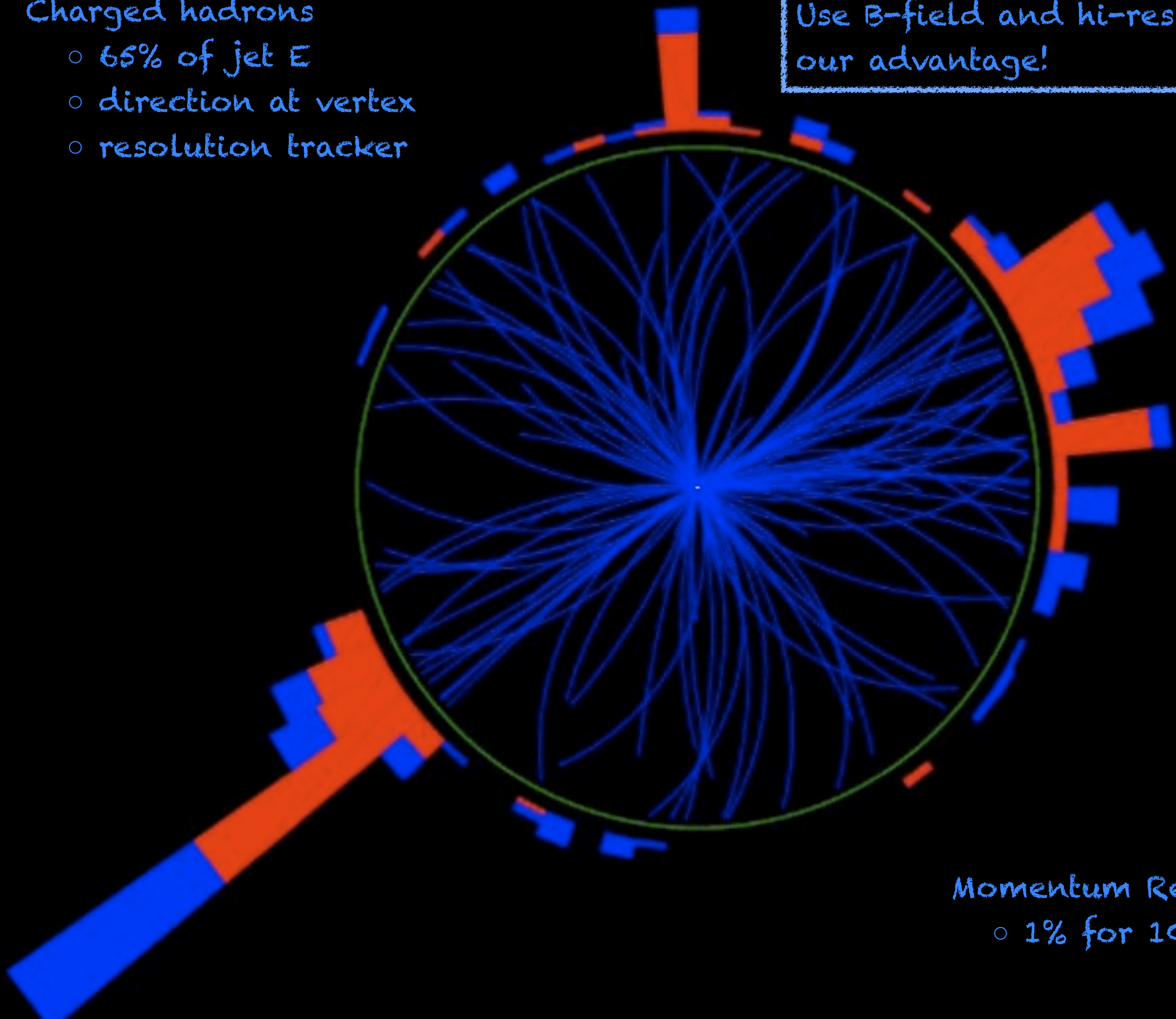
- Large Jet E Corr.
- Resolution HCAL

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

Charged hadrons

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

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

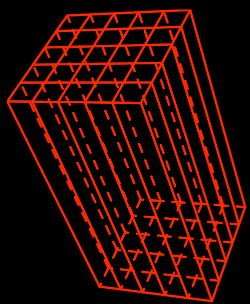


Momentum Resolution

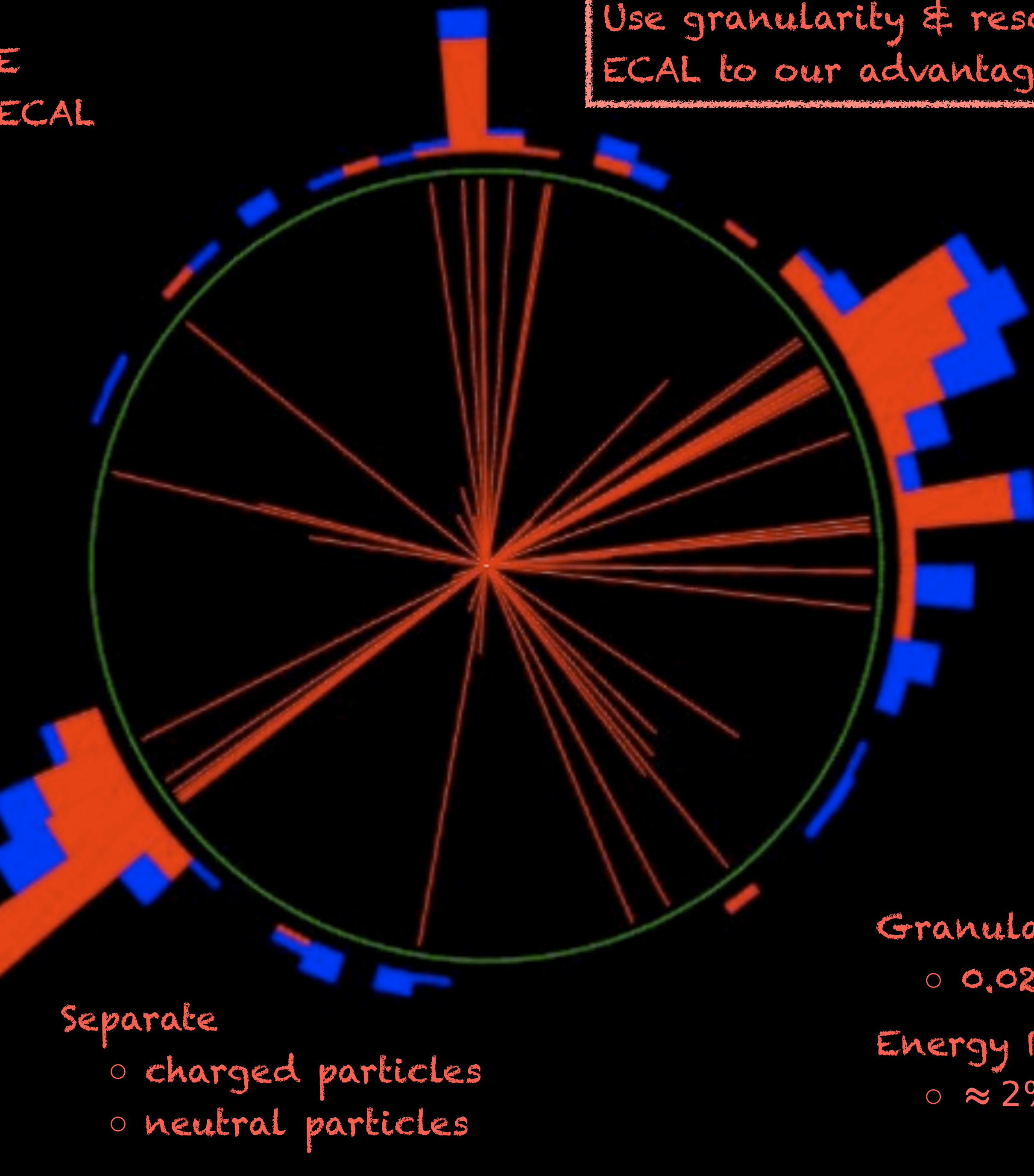
- 1% for 100 GeV

Photons

- 25% of jet E
- resolution ECAL



Use granularity & resolution of ECAL to our advantage!



Separate

- charged particles
- neutral particles

Granularity

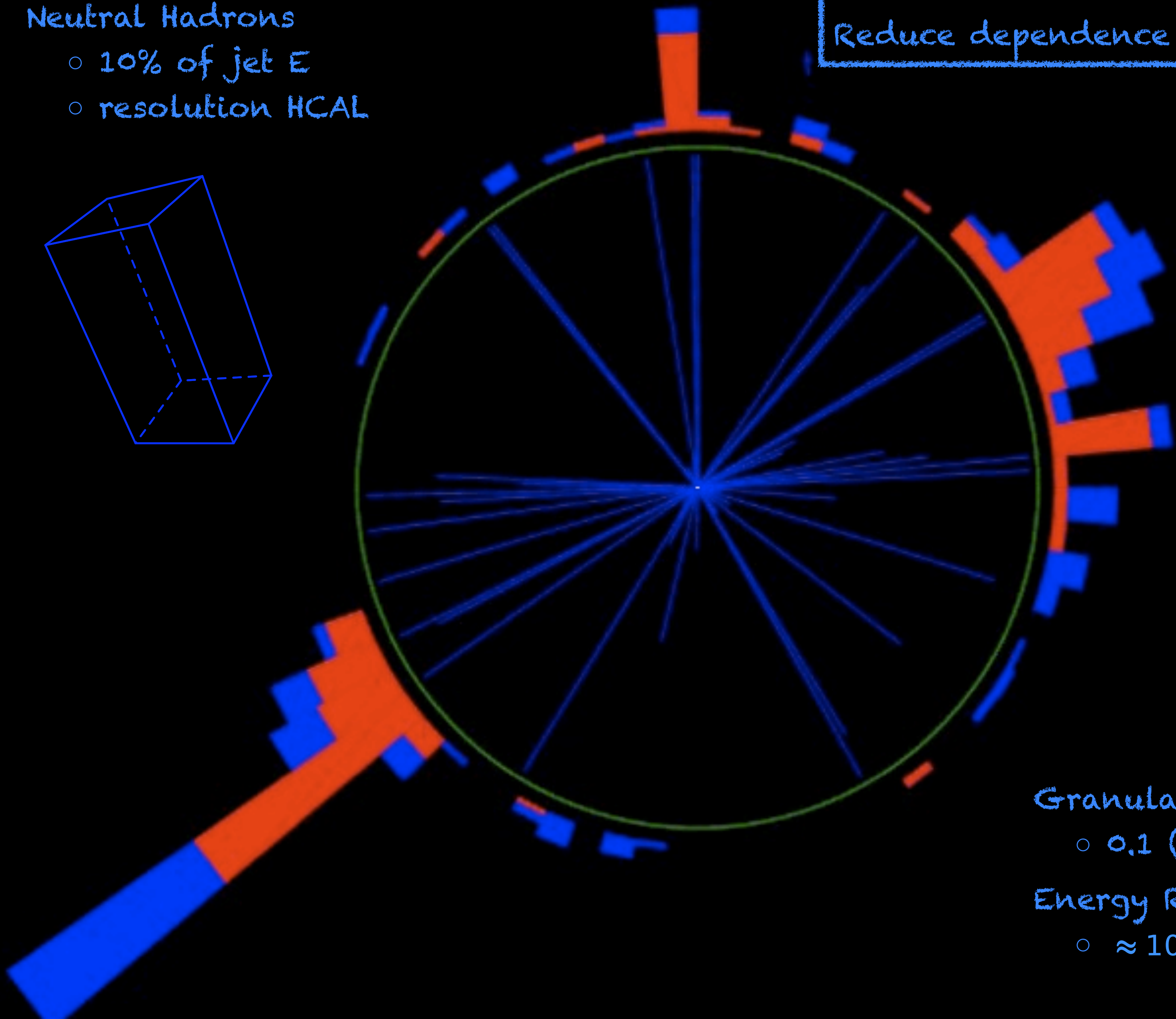
- 0.02 ($\Delta\eta \times \Delta\varphi$)

Energy Resolution

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

Neutral Hadrons

- 10% of jet E
- resolution HCAL



Reduce dependence on HCAL

Granularity

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

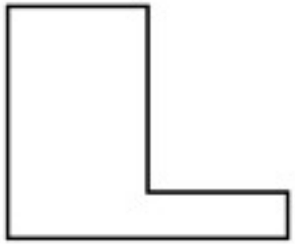
Energy Resolution

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

Particle Flow Algorthm

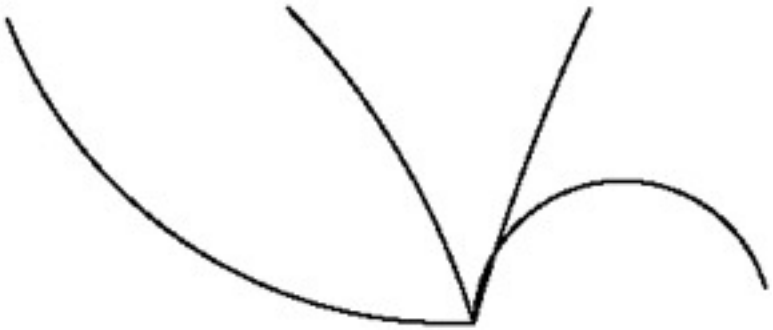
First Associate Hits within Each Detector

HCAL Clusters



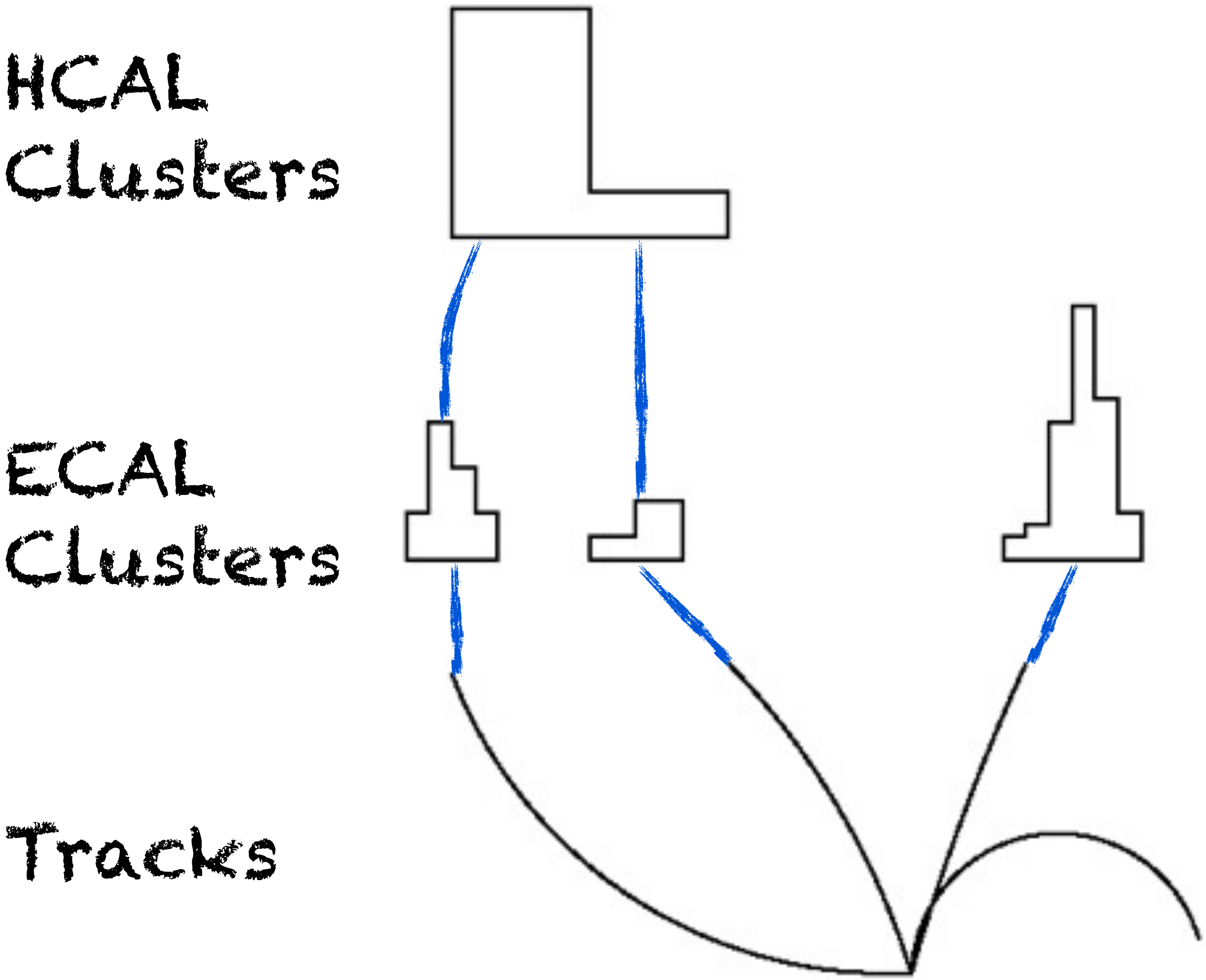
ECAL Clusters

Tracks



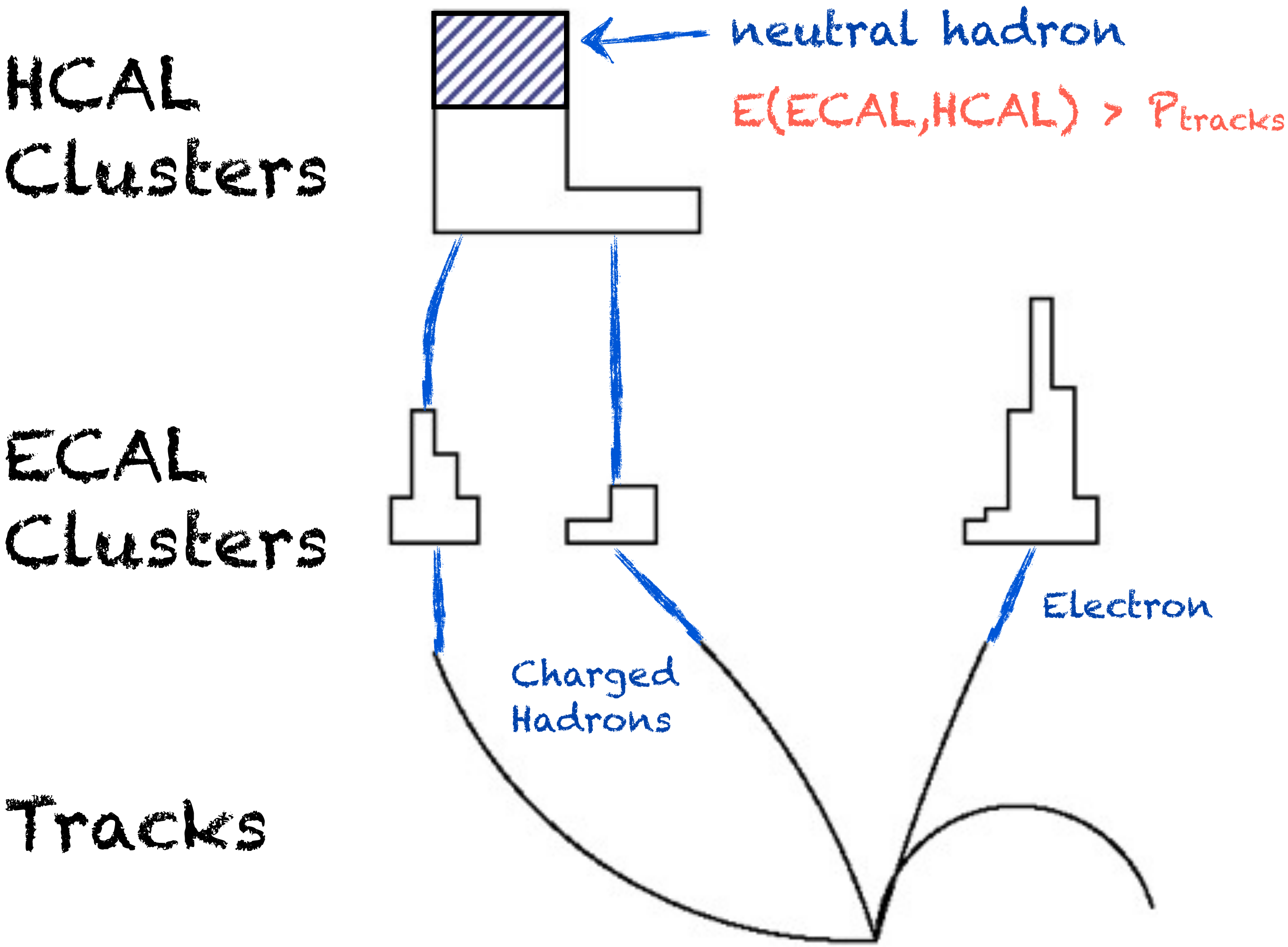
Particle Flow Algorthm

Then Link Across Detectors



Particle Flow Algorithm

Finally Apply Particle ID & Separation



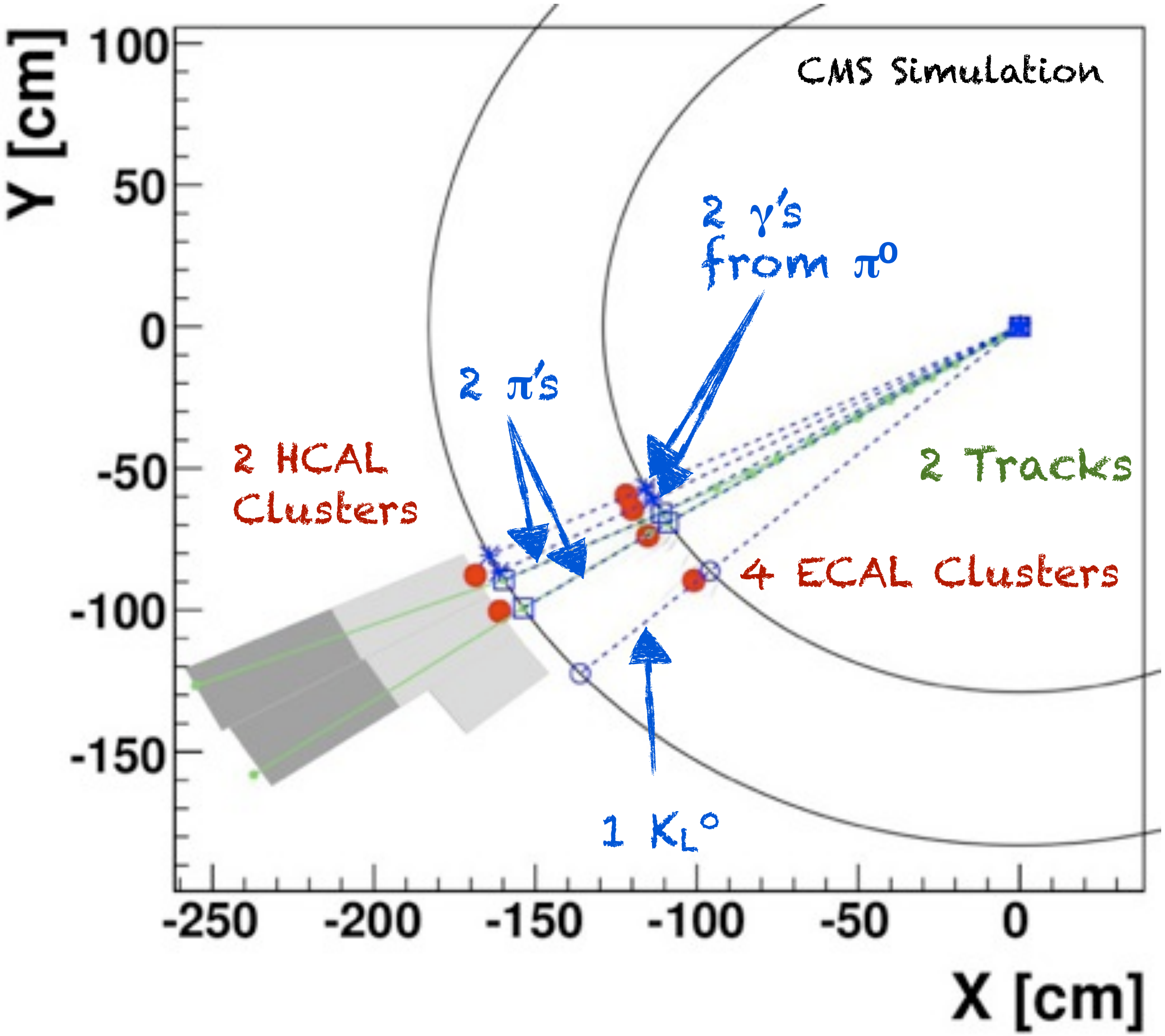
Very Basic View of Particle Flow

"Clean" the Event During Reconstruction!

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

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

Let's take a simple example

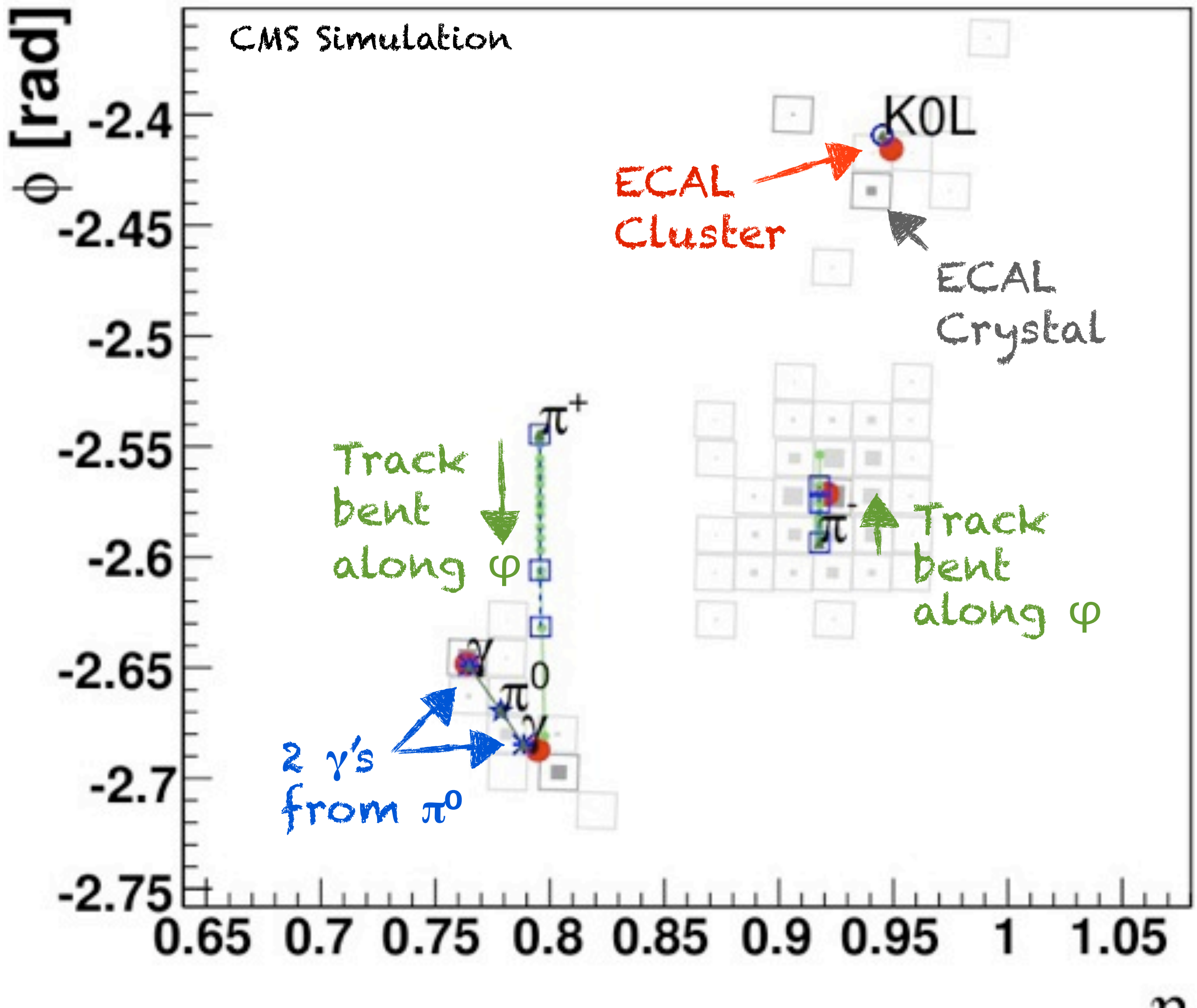


Jet pT = 65 GeV/c

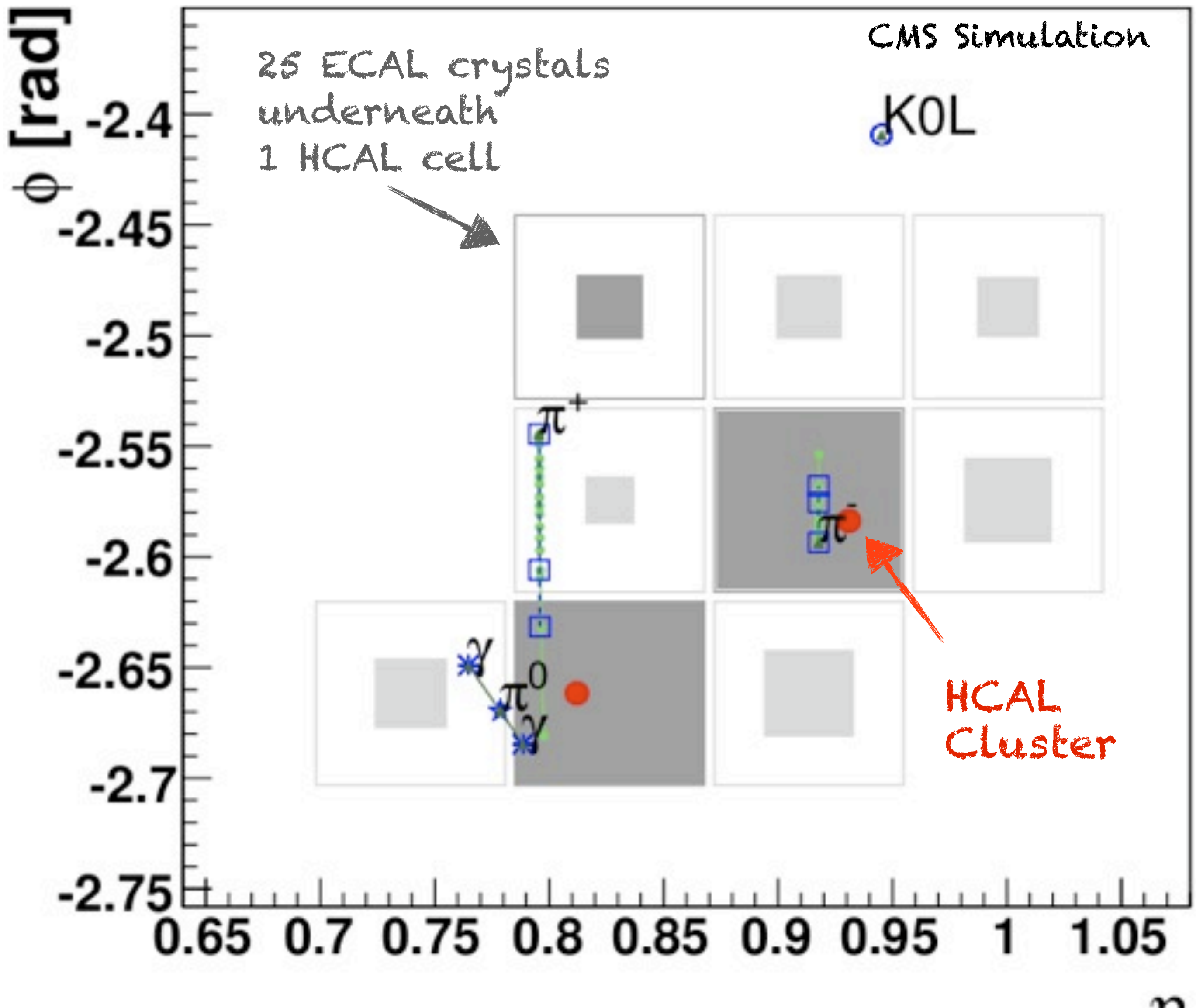
Four true particles:

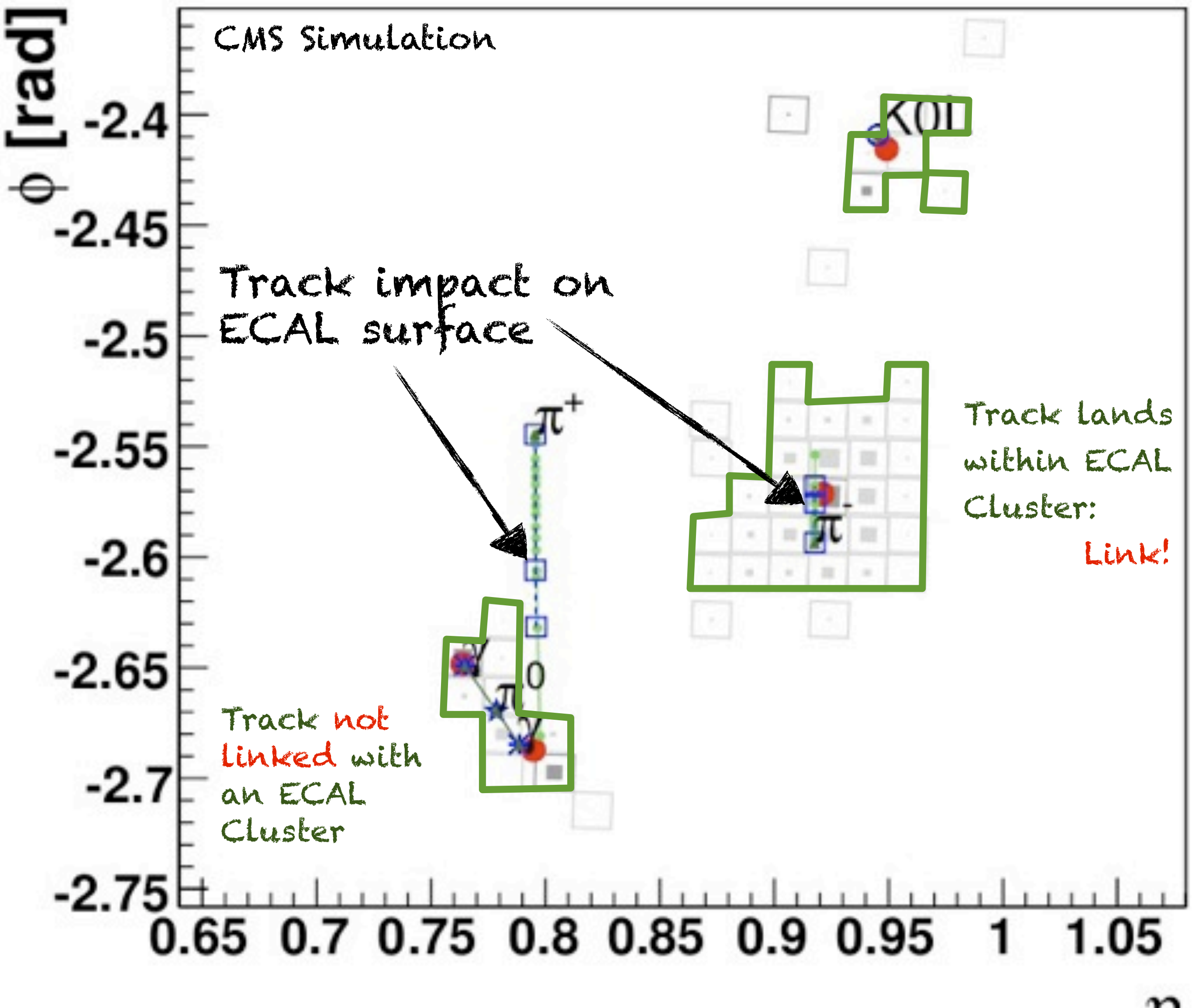
$$\pi^+, \pi^-, \pi^0, K_L^0$$

Switch to ECAL (η,φ) view



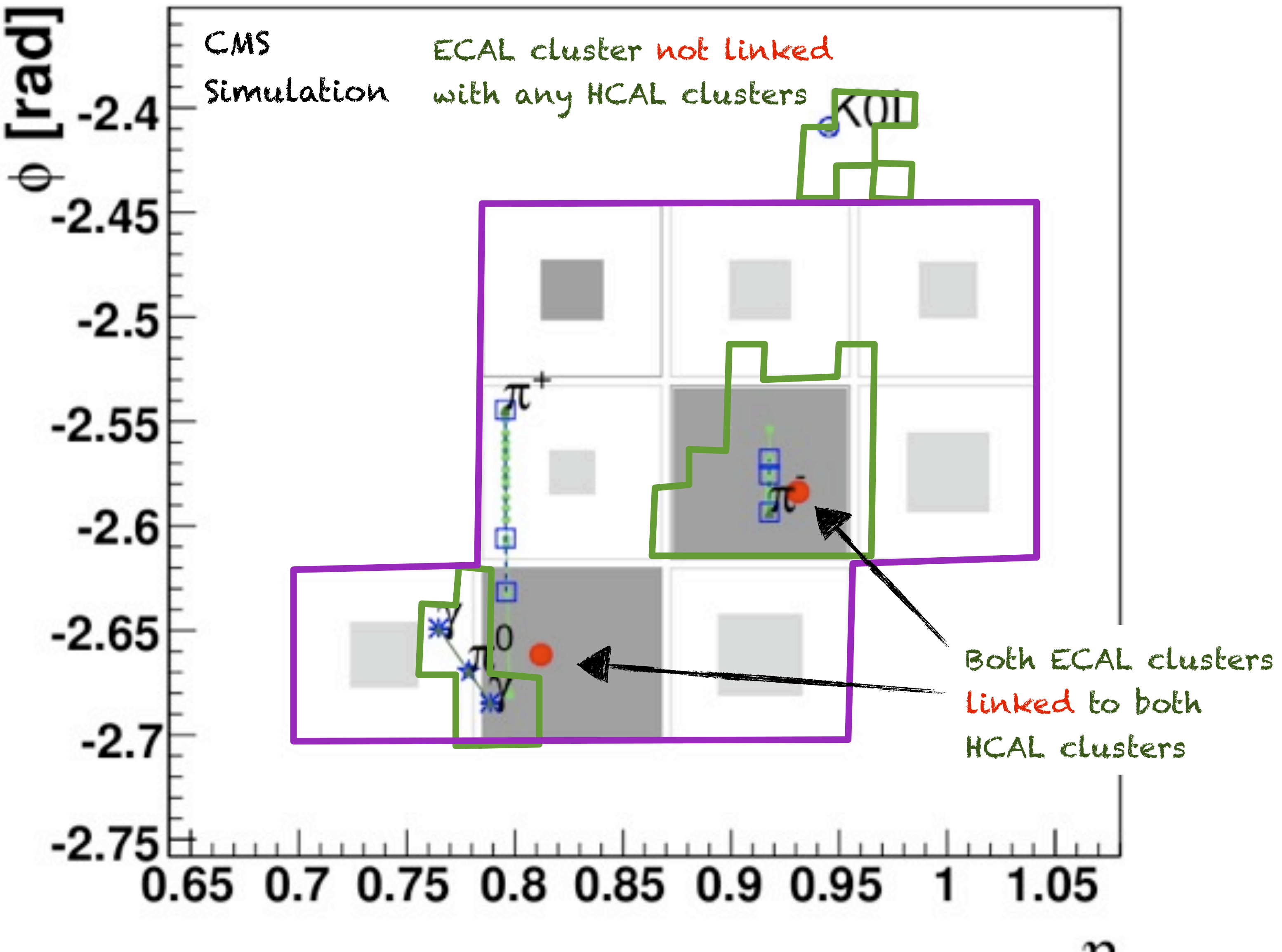
Switch to HCAL (η,φ) view

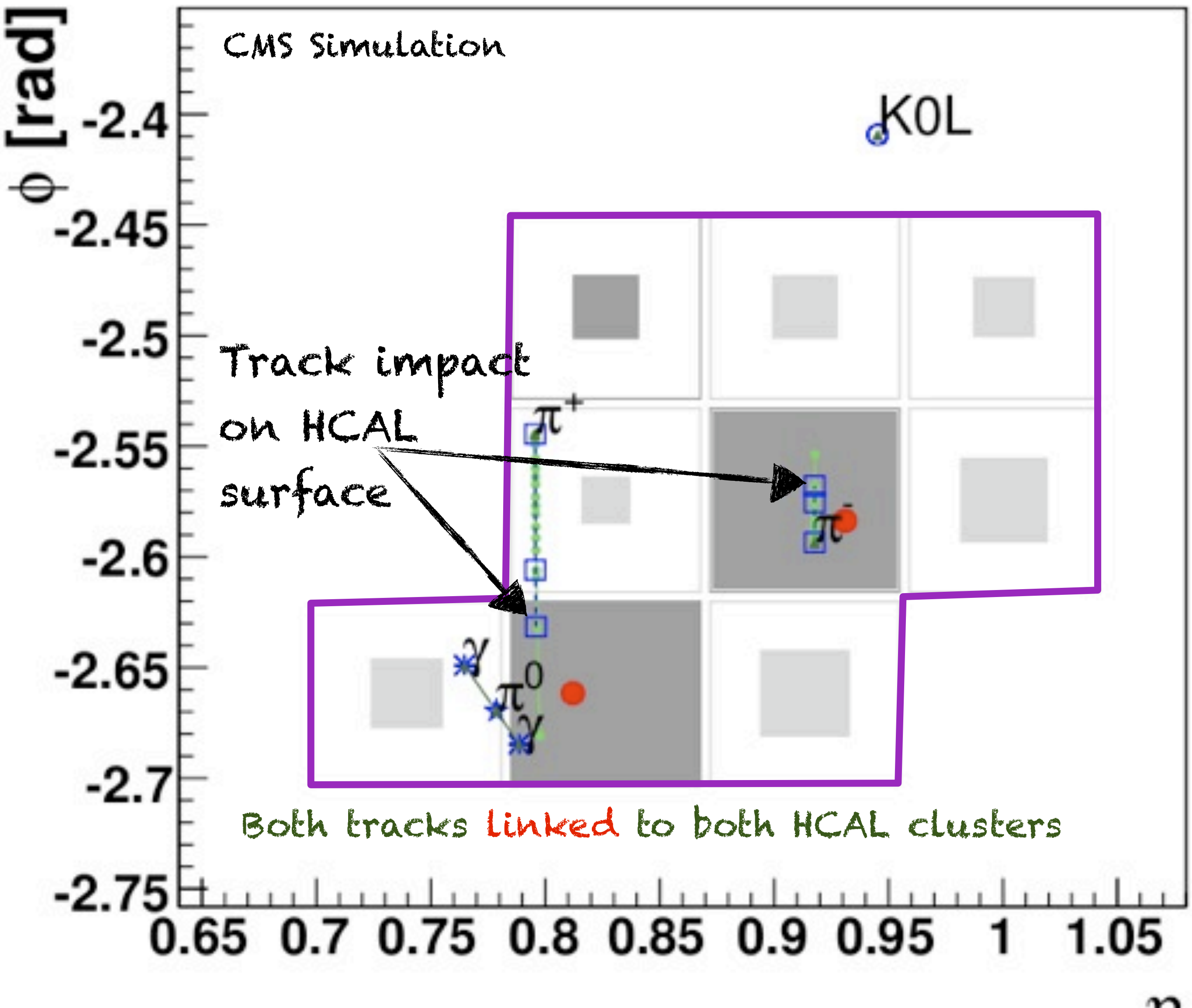




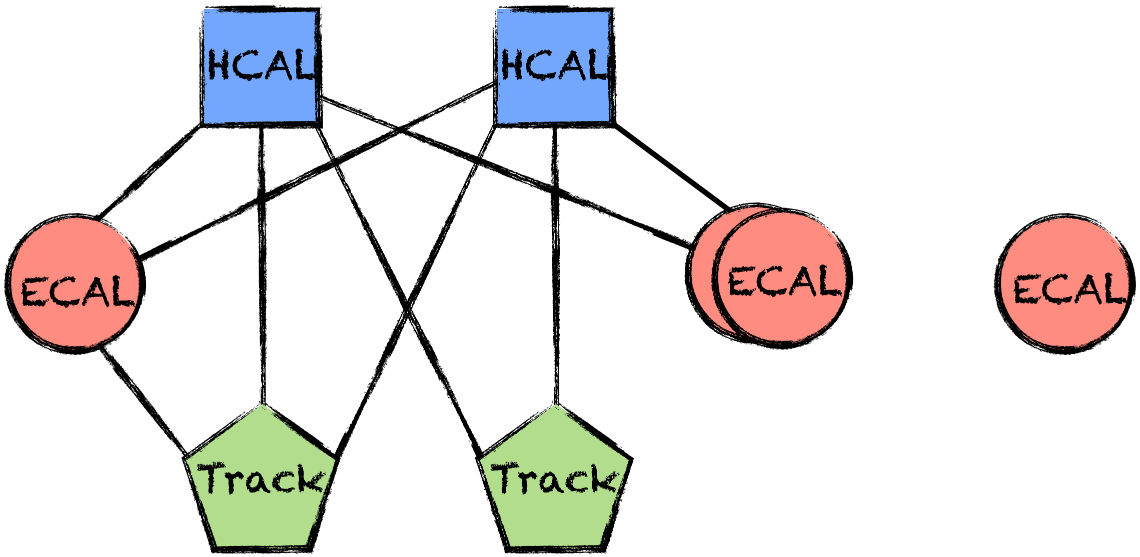
CMS Simulation
Track impact on ECAL surface
Track lands within ECAL Cluster:
Link!
Track not linked with an ECAL Cluster
K0L
π^+
π^-
π^0
γ
γ
ϕ [rad]
-2.4
-2.45
-2.5
-2.55
-2.6
-2.65
-2.7
-2.75
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
1.05
η

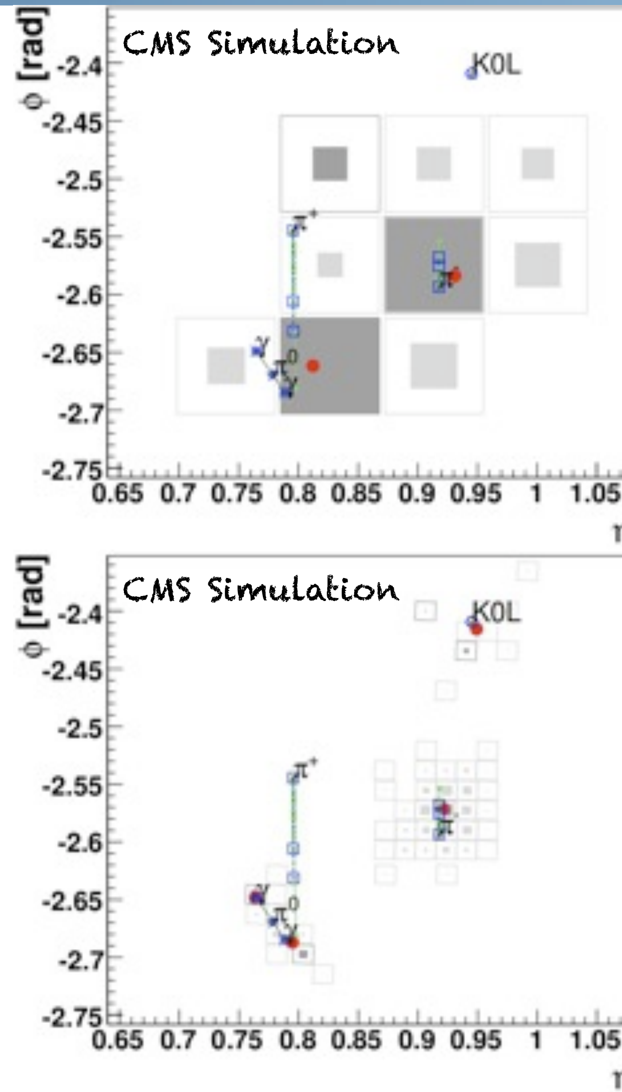
ECAL-HCAL Cluster Link




CMS Simulation
φ [rad]
-2.4
-2.45
-2.5
-2.55
-2.6
-2.65
-2.7
-2.75
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
1.05
η
K0L
Track impact on HCAL surface
Both tracks linked to both HCAL clusters

Particle Identification

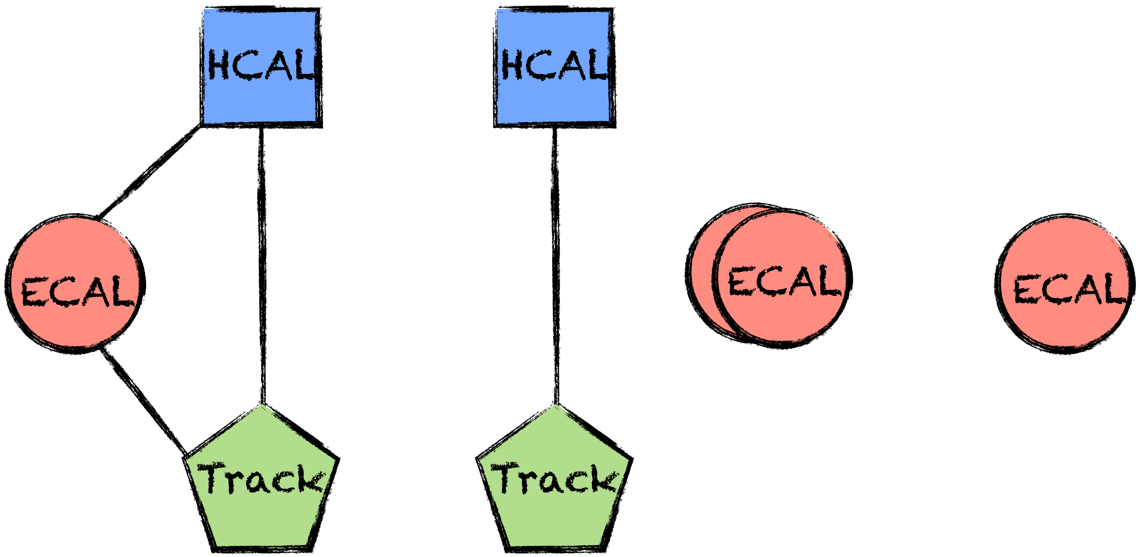


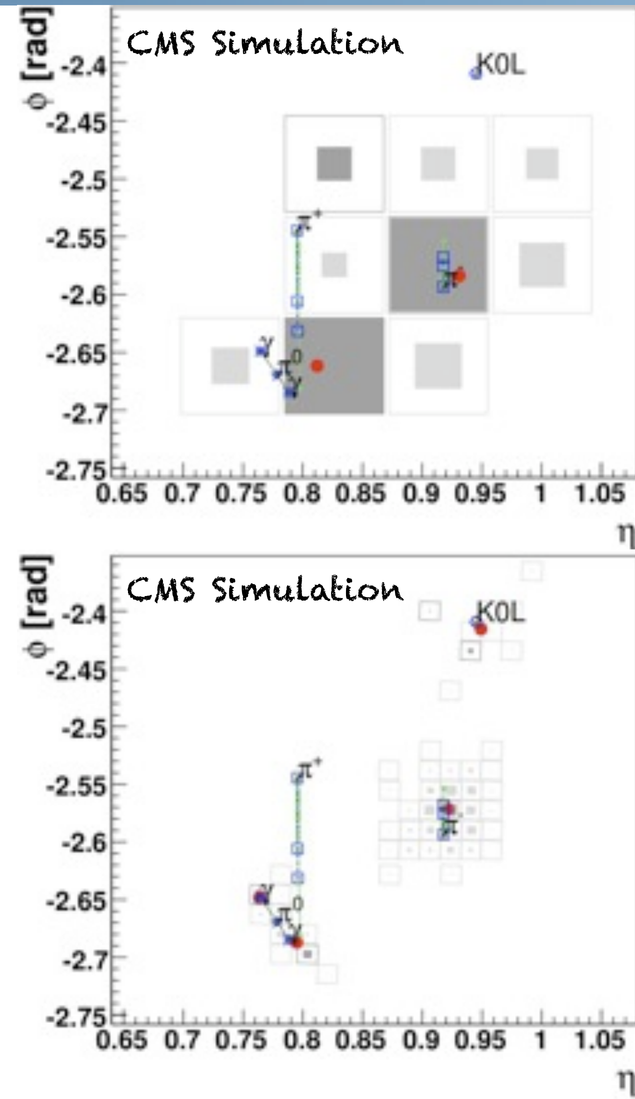


List of reconstructed particles:

{ }

Particle Identification

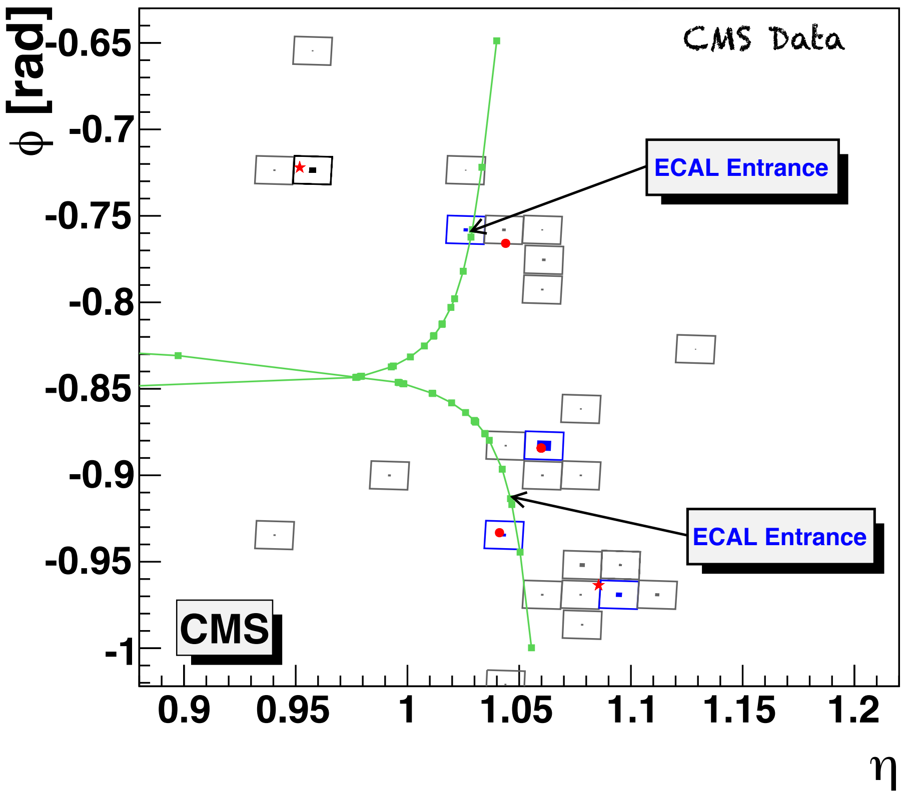


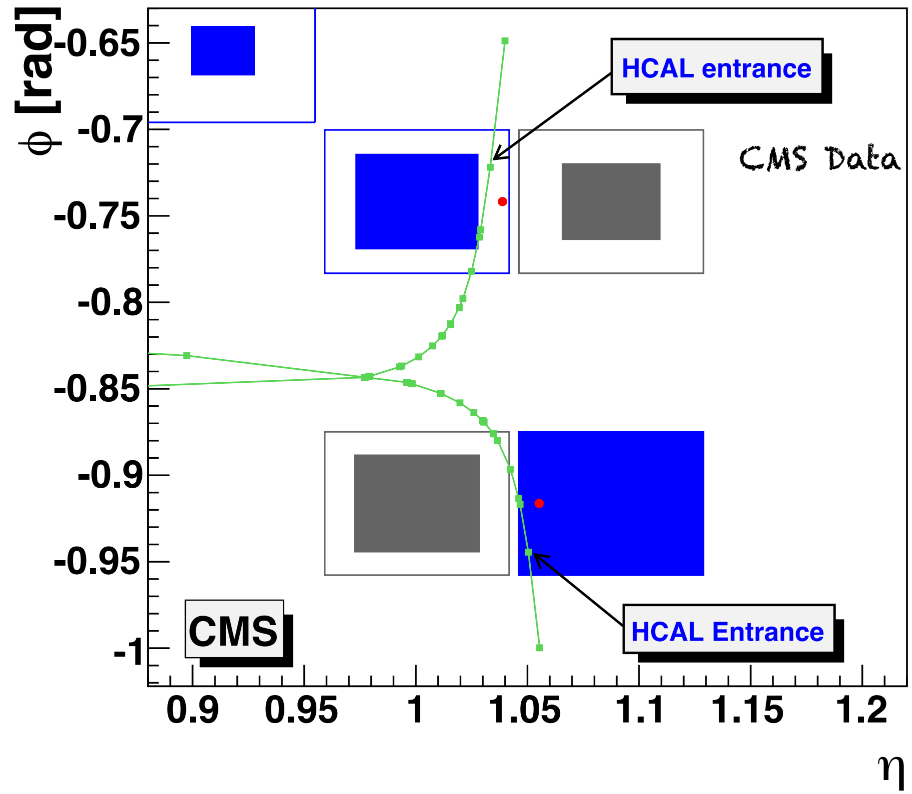


List of reconstructed particles:

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

Single π's in Data



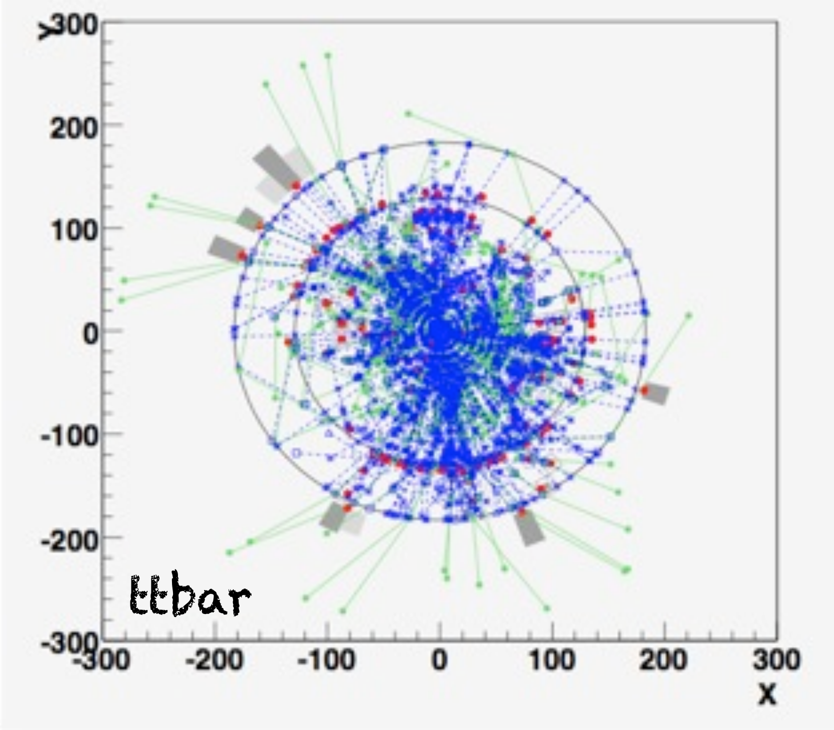


Event scanning: Link algo performing as expected in data

That was a simple example, nevertheless...

...The Particle Flow algorithm scales to large particle multiplicities!

Analysis of the leading jet from all hadronic ttbar simulated event at the right:



MC Particles

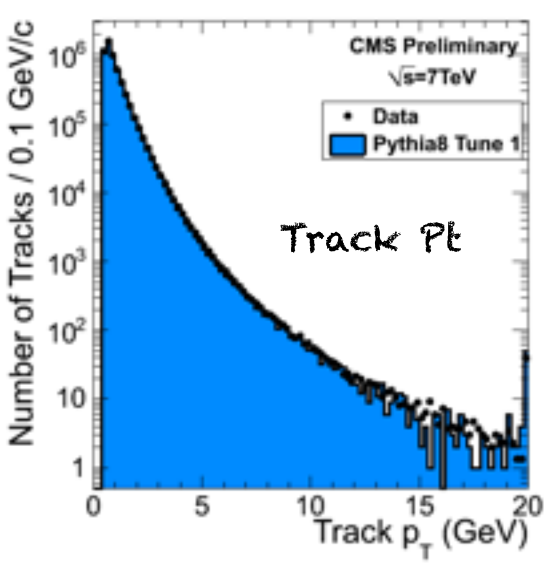
#0	PDG code:130,	p/pt/eta/phi: 20.3845	16.7688	-0.645422	1.49343
#1	PDG code:211,	p/pt/eta/phi: 17.2954	15.0452	-0.540329	1.45624
#2	PDG code:211,	p/pt/eta/phi: 11.453	9.82512	-0.567975	1.4245
#3	PDG code:22,	p/pt/eta/phi: 7.75683	6.52999	-0.603777	1.46632
#4	PDG code:22,	p/pt/eta/phi: 7.26097	6.17551	-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
...					

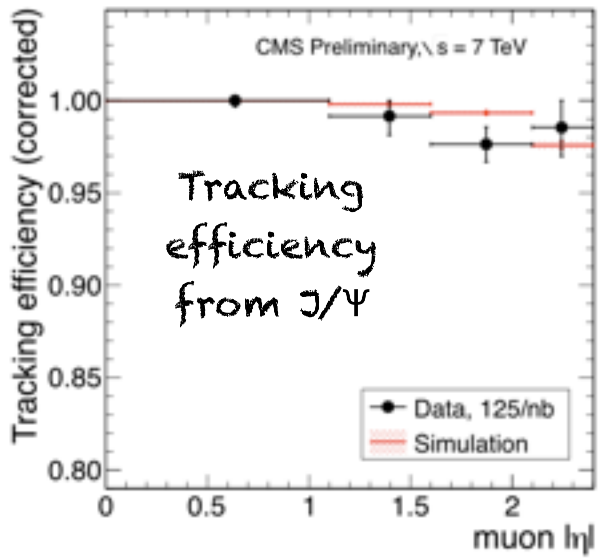
Reco Particles

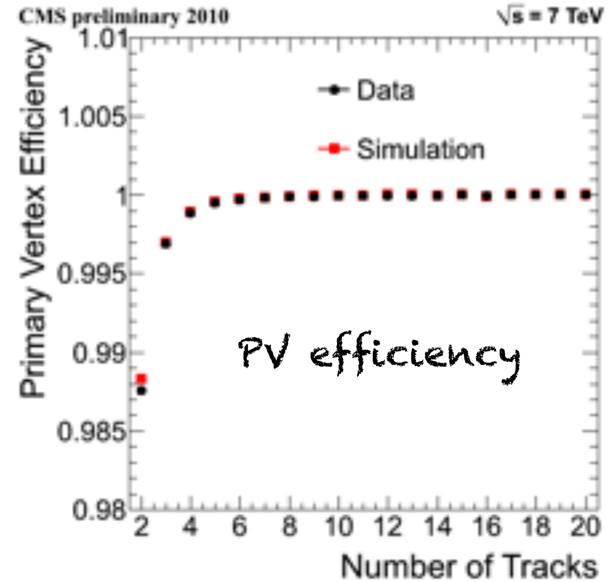
#0	PFCandidate type: 5	E/pT/eta/phi 31.929	26.176	-0.651	1.493,
#1	PFCandidate type: 1	E/pT/eta/phi 17.237	14.994	-0.540	1.456,
#2	PFCandidate type: 1	E/pT/eta/phi 11.540	9.900	-0.568	1.425,
#3	PFCandidate type: 4	E/pT/eta/phi 9.684	8.195	-0.594	1.420,
#4	PFCandidate type: 4	E/pT/eta/phi 6.663	5.602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

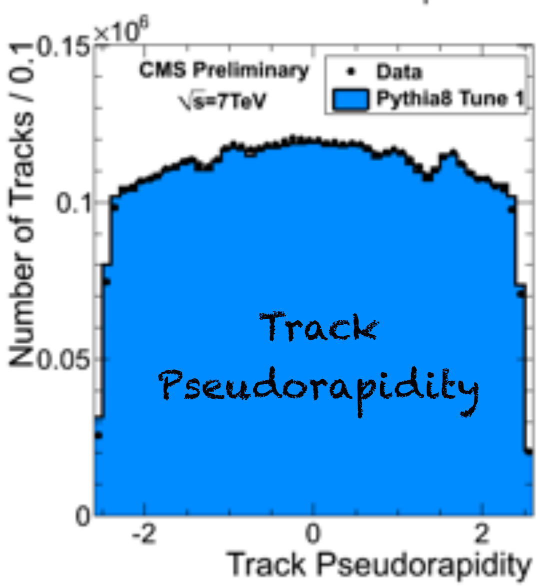
Tracker Performance

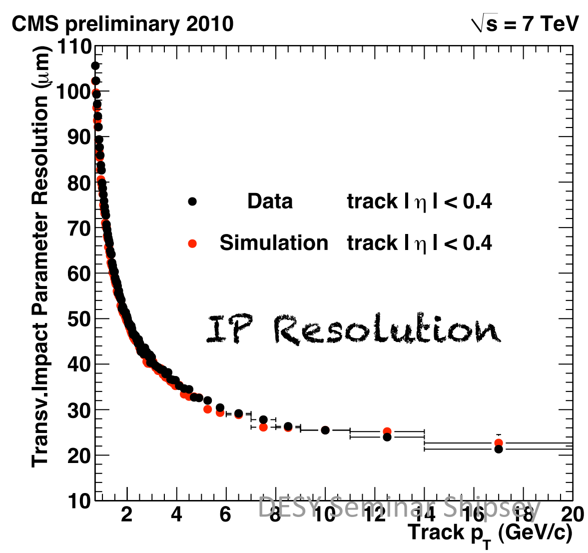
- 75 million channels, 200 m² of silicon > 98% operational
- Remarkable agreement between data and simulation

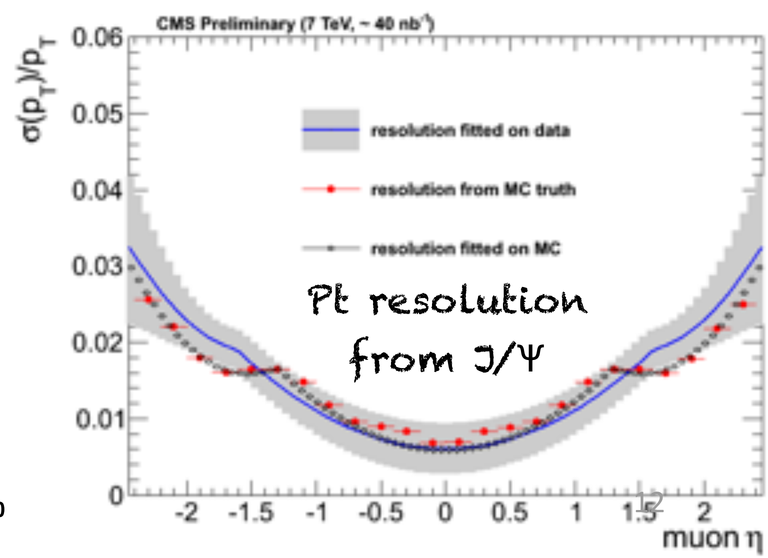








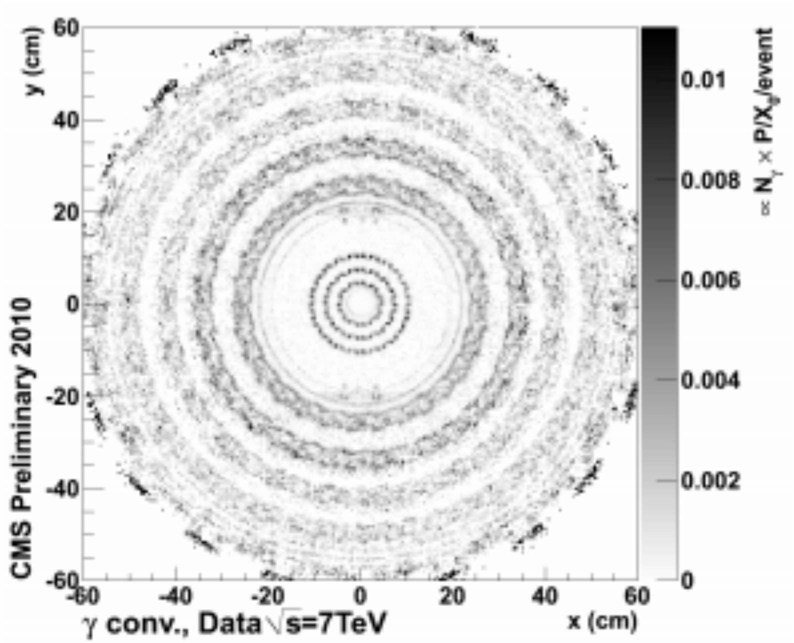




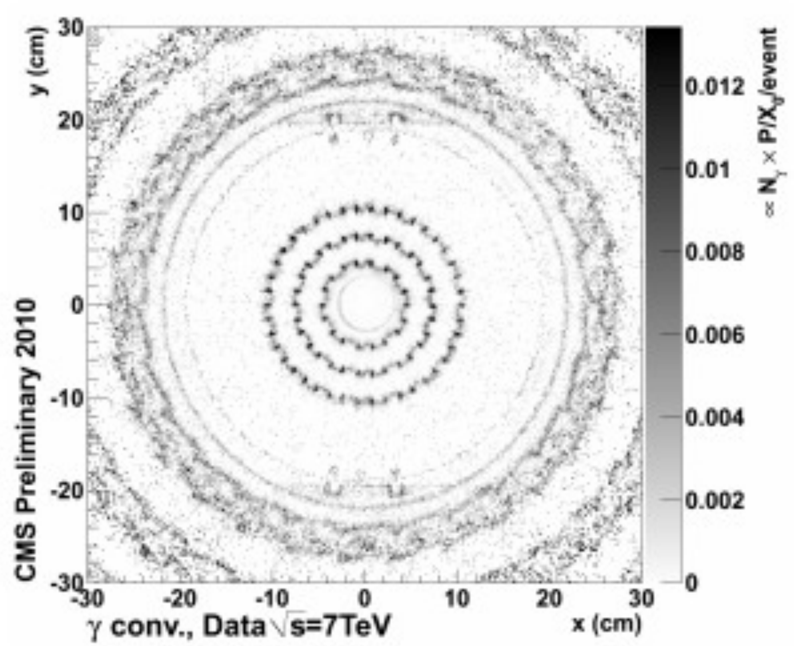
The Silicon Strip Tracker

- Excellent tracking performance allows one to see the Tracker from photon conversions

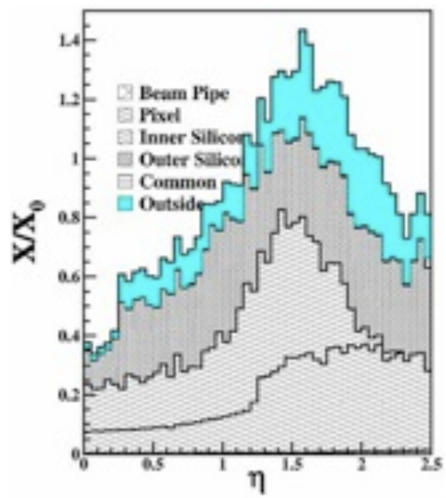
Silicon Strip Tracker inner barrel

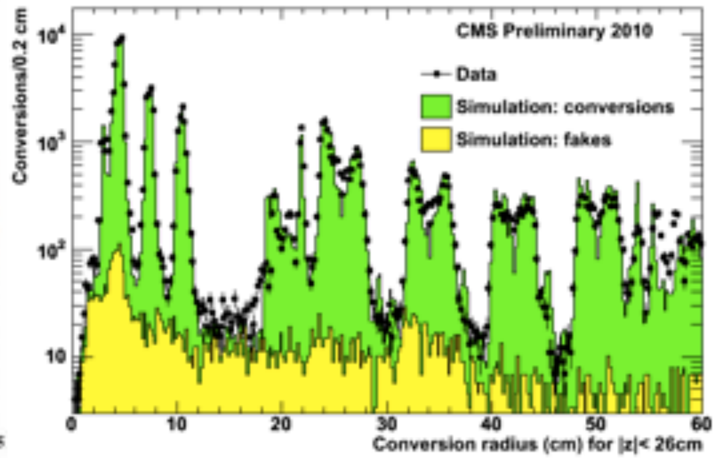


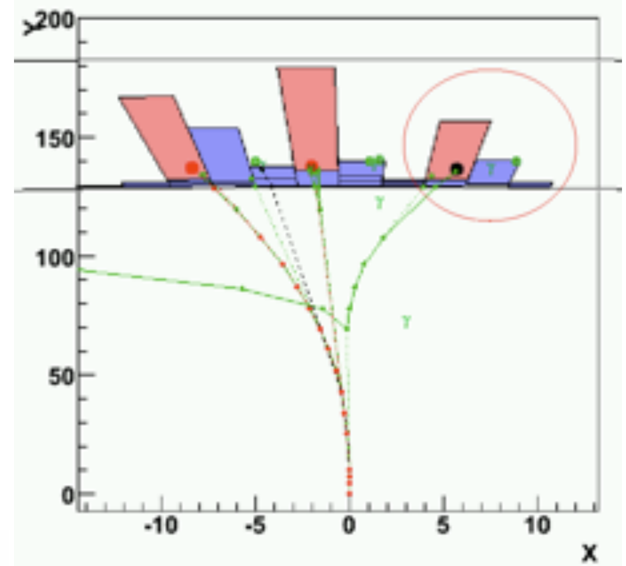
Zoom to the pixel barrel

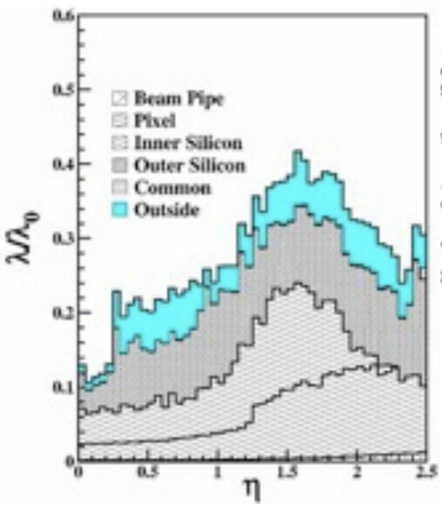


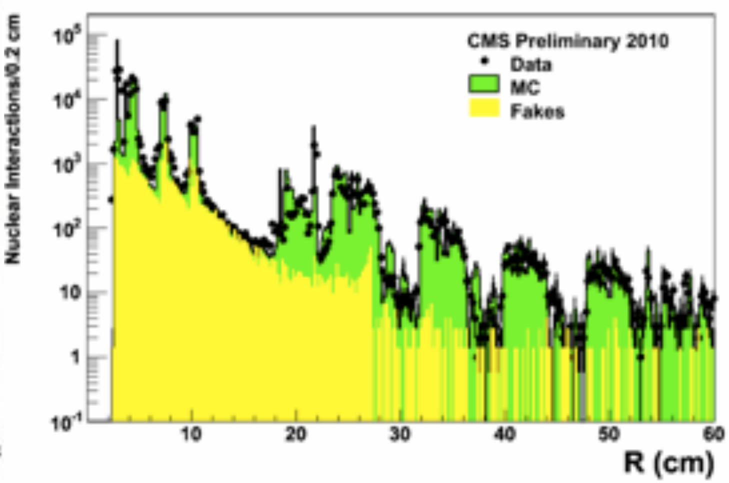
Tracker Material: Important!

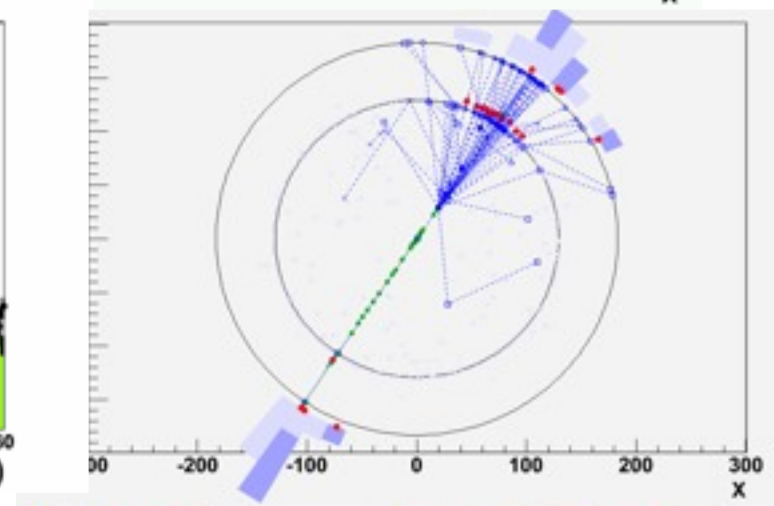




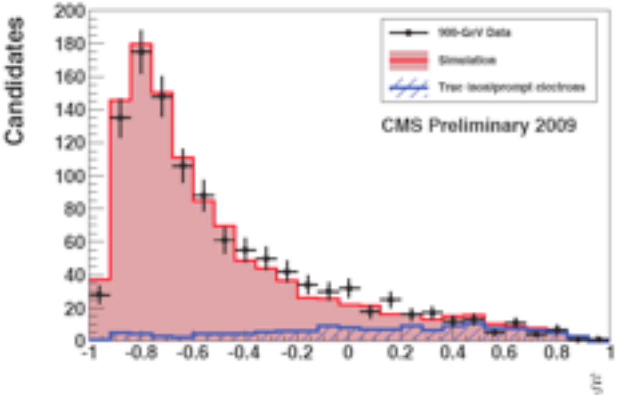


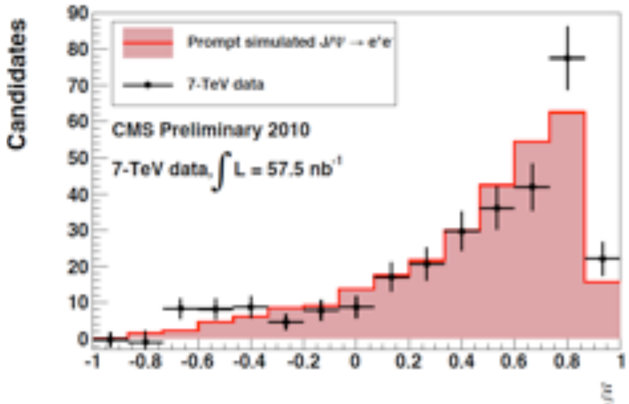


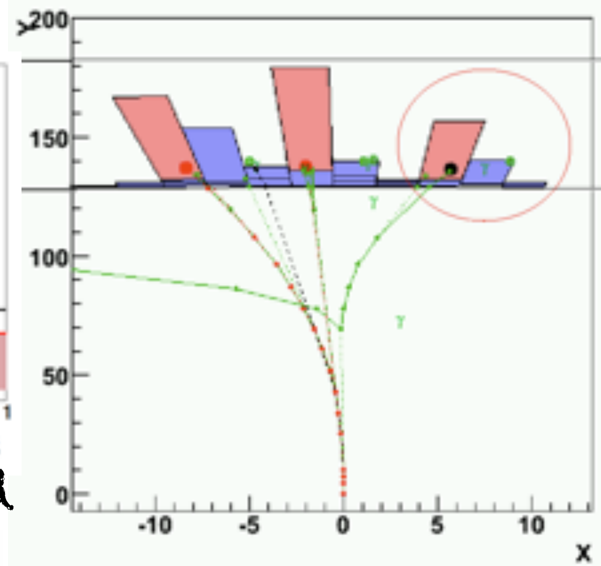




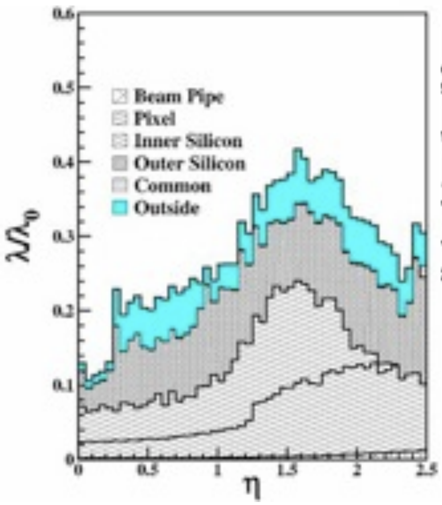
Tracker Material: Important!

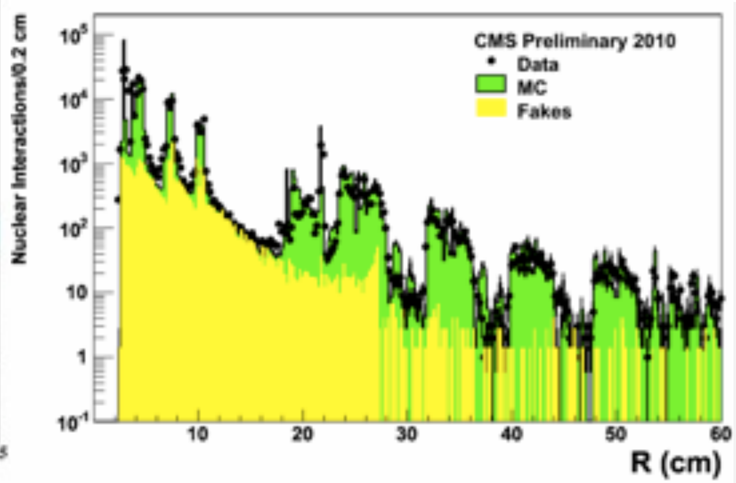


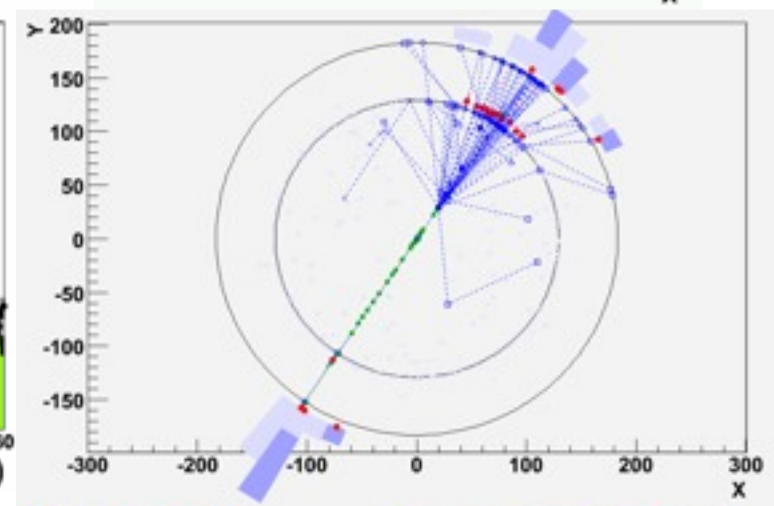




PF Electron Reconstruction well advanced

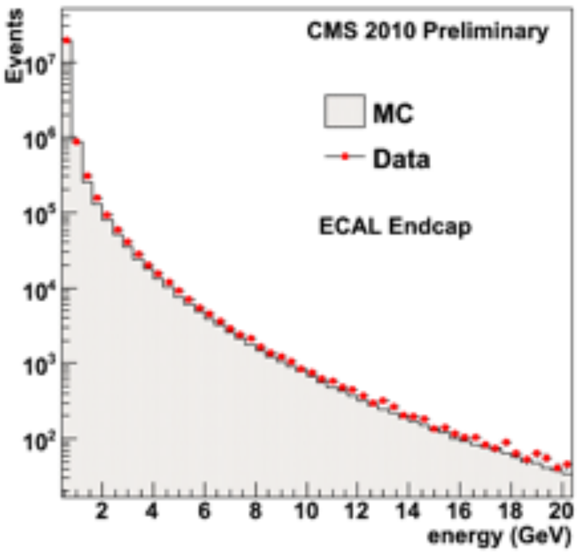


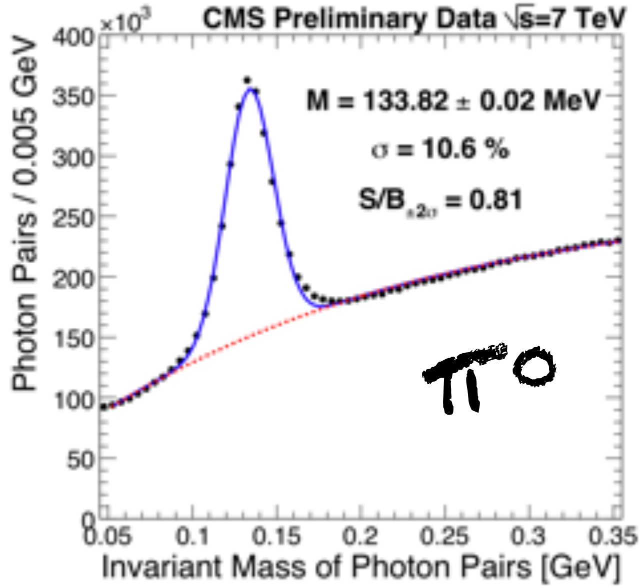




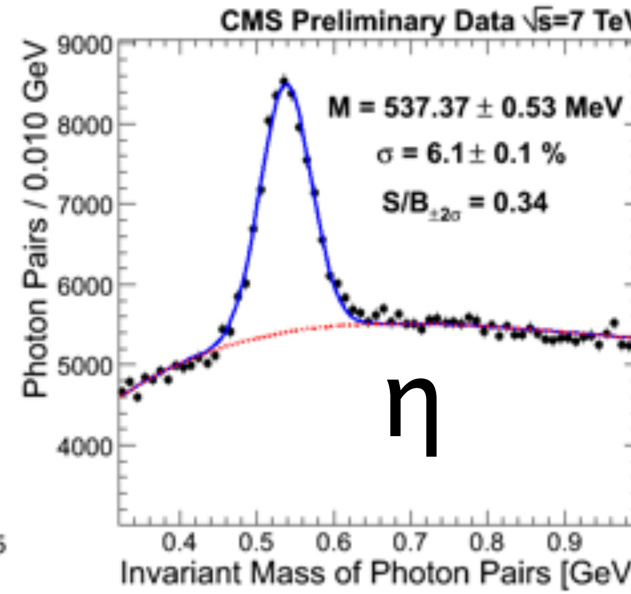
Reconstruct π-Nuclear Interaction; but 100% efficiency not critical

ECAL Performance

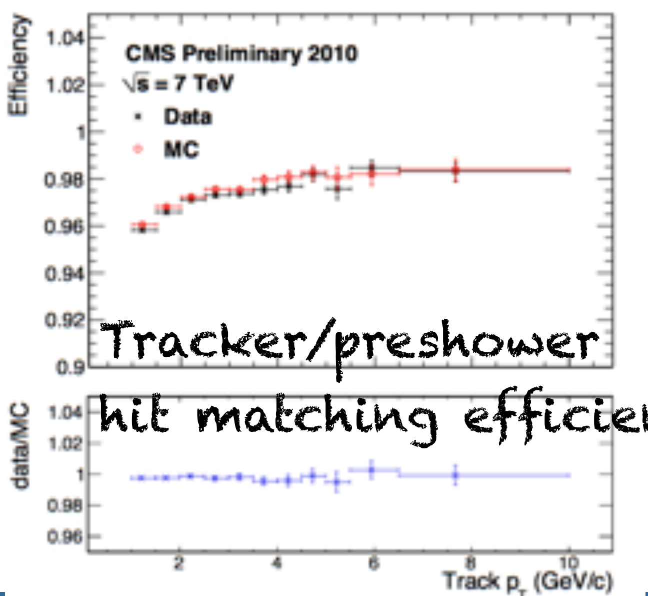




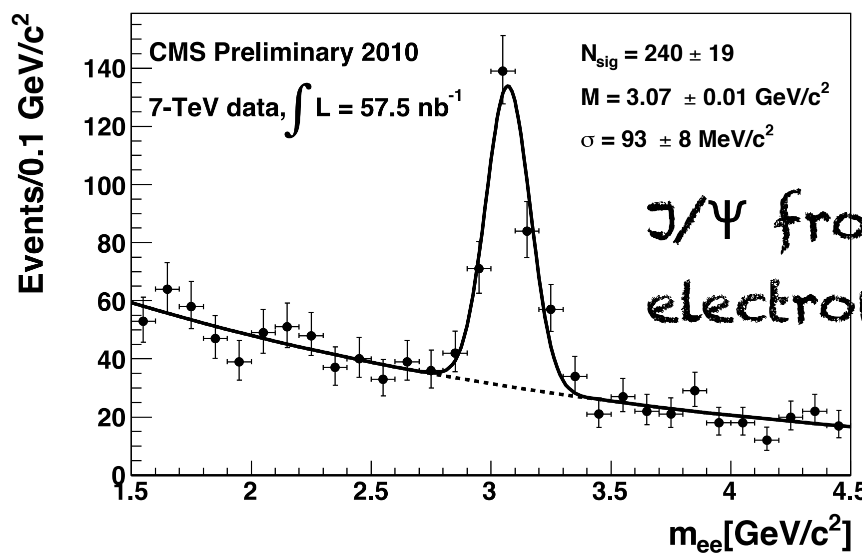
π^0



η



Tracker/preshower hit matching efficiency

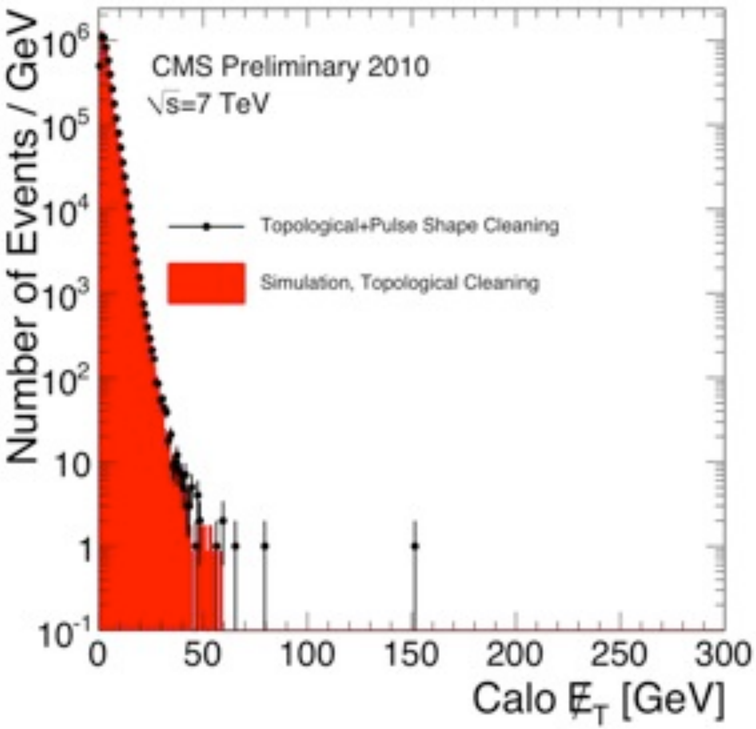


J/Ψ from PF electrons

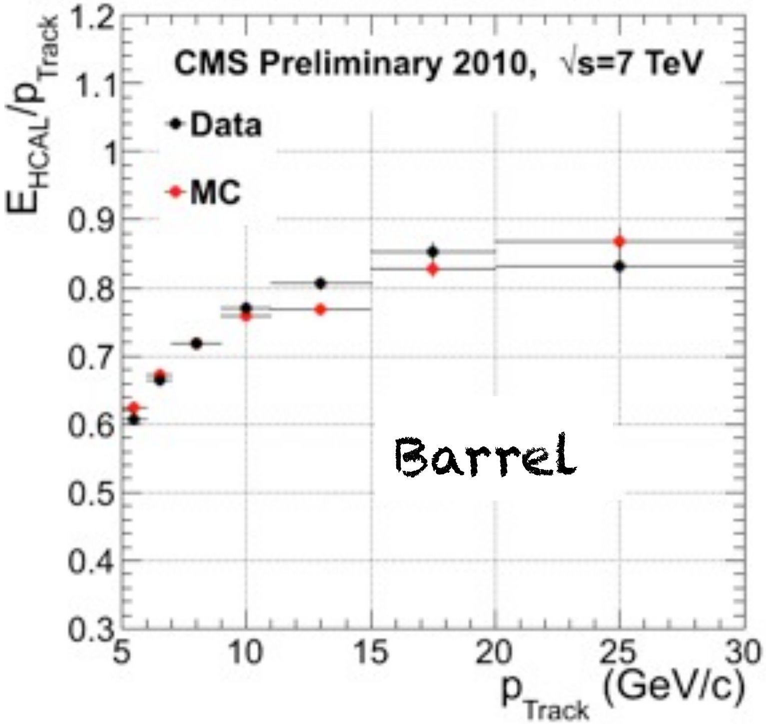
HCAL Performance

- Very good performance of noise cleaning
- Excellent agreement with simulation

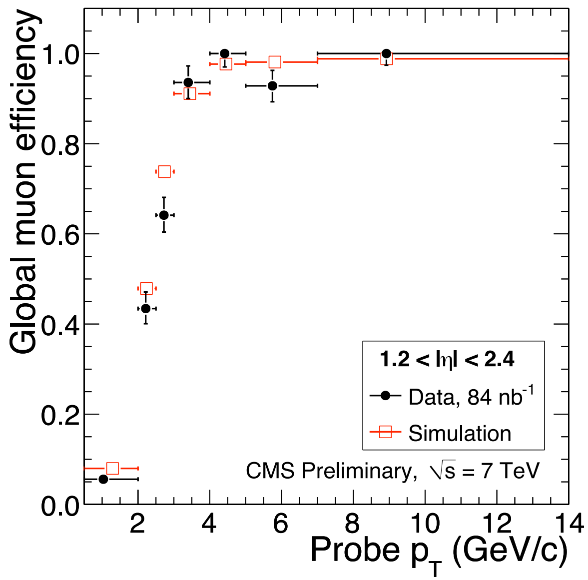
Calorimetric MEt

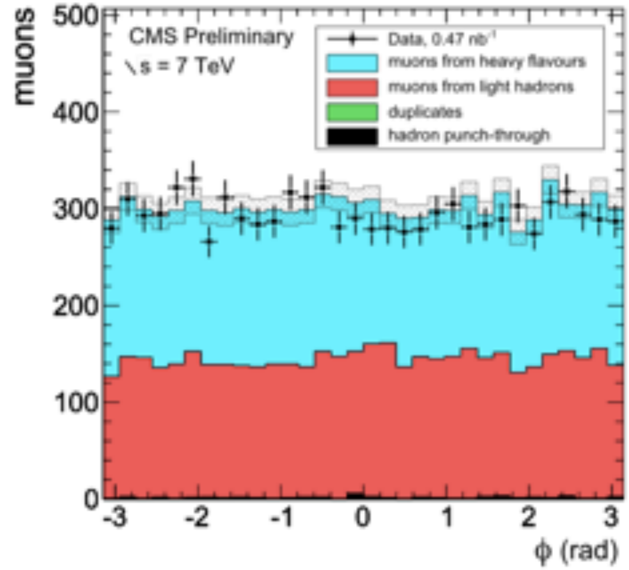


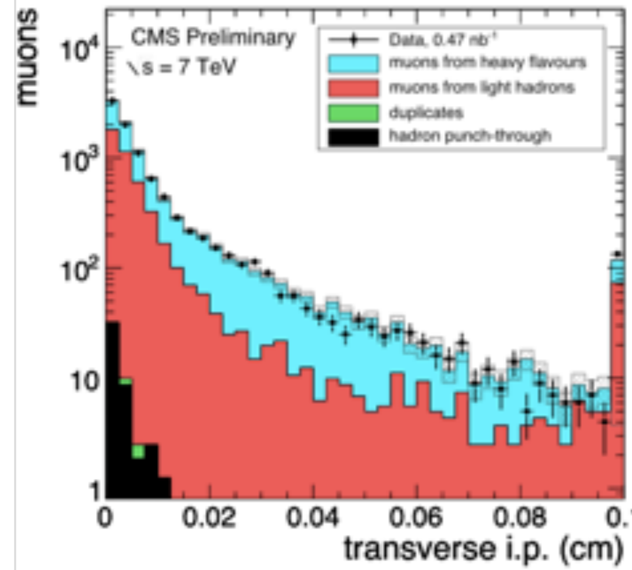
Mean response vs track momentum

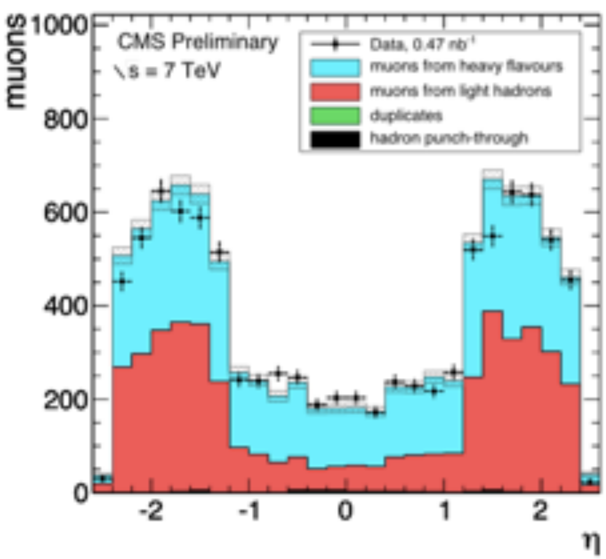


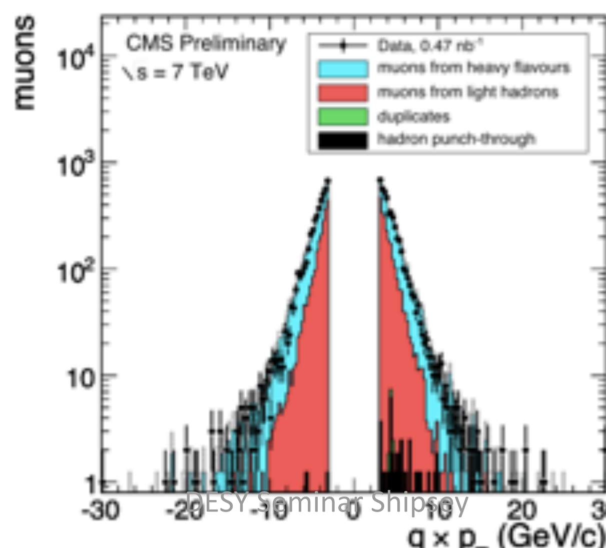
Muon Performance

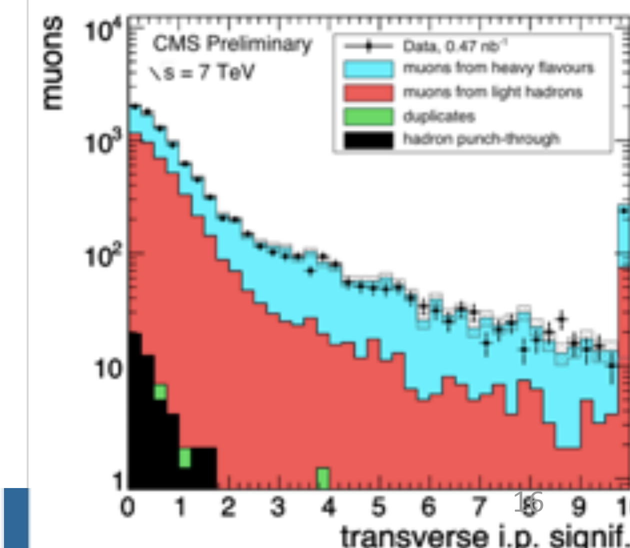






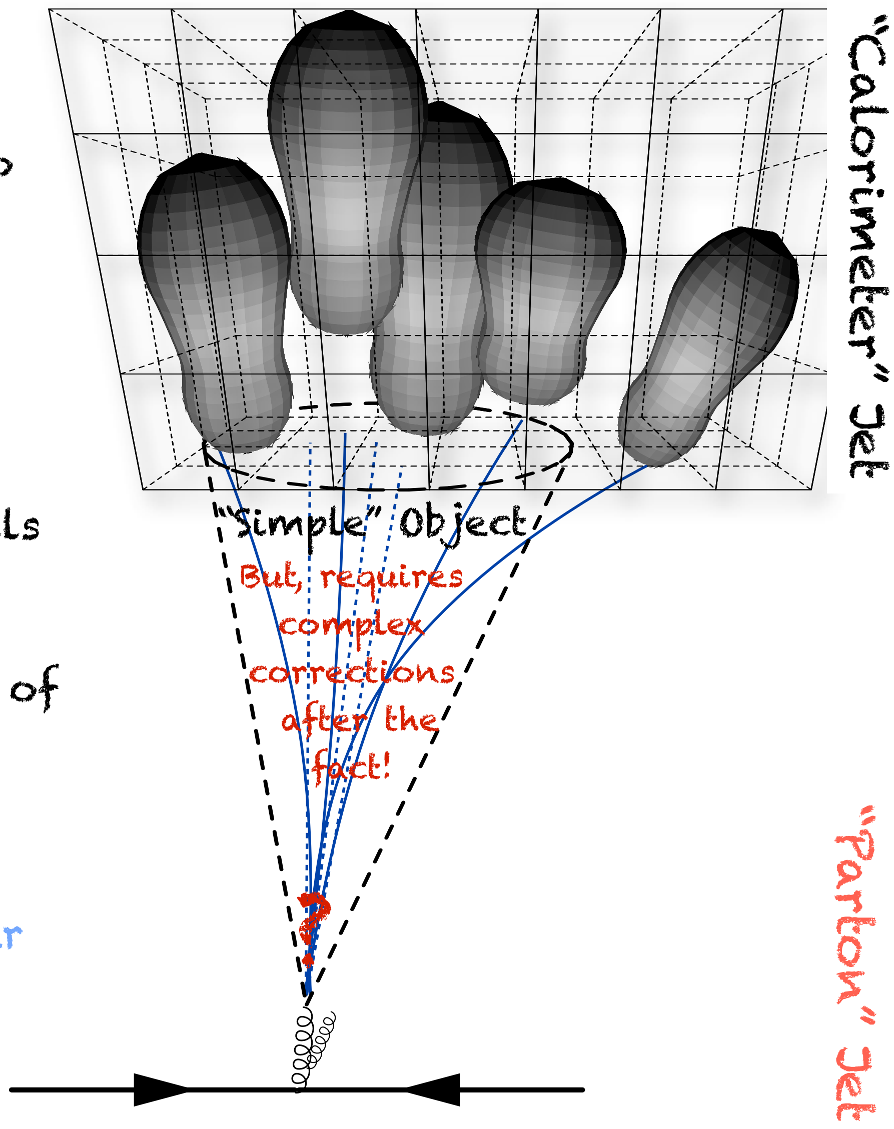






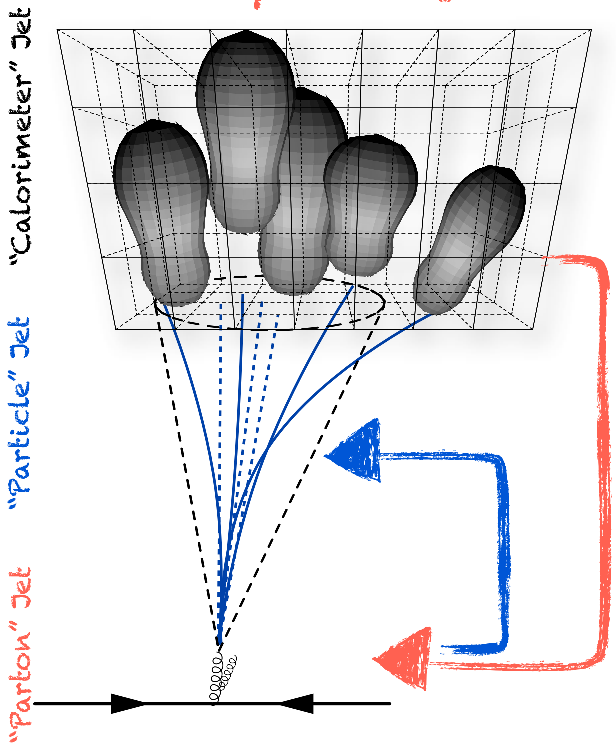
Traditional Calorimeter Jets

- Hard Scatter of coloured partons
  - not observable
- Fragmentation of coloured partons into colourless particles
  - not observable
- Propagation of particles to calorimeter
  - observable
- Deposition of energy in calorimeter cells
  - observable
- Calorimeter provides a consistent view of the entire event:
  - traditional reconstruction method
    - no worry of overlapping tracks on coarsely granular calorimeter
  - So called "simple" Objects

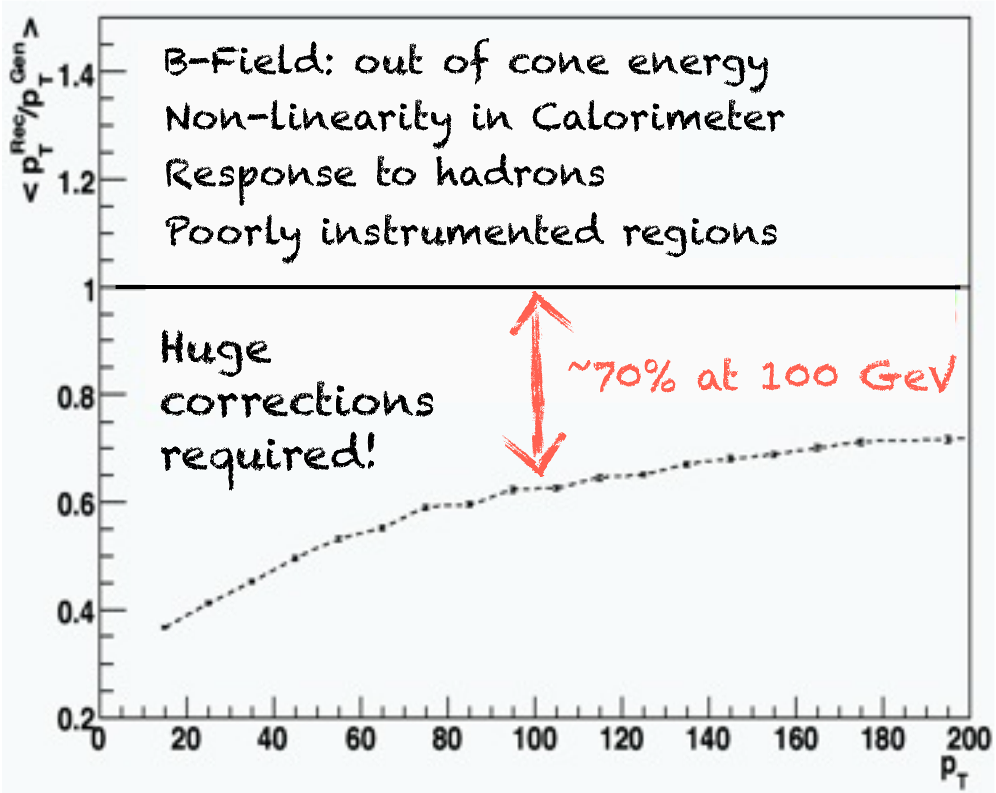


Correcting Traditional Jets

Simpler objects not necessarily easier to understand



- Detector effects corrected by comparing reconstructed jet to parton probe (e.g. photon)
  - true-jets contain particles swept away from B field: pT < 0.7 GeV



- $k = E_{T_{rec}}/E_{T_\gamma}$: Correction $1/k$ a function of E_T & η
  - depends on flavour, jet algos (+params), noise, PU, etc.
  - does not generalise!

Jet Reconstruction

- Approaching Self-calibration
  - much smaller residual corrections
    5% compared with 65% at 100 GeV
  - Nearly independent of Jet Flavour
- Better Energy Resolution
  - Factor 3 at 15 GeV (tracker dominates)
  - Converges to Calorimeter at high pT
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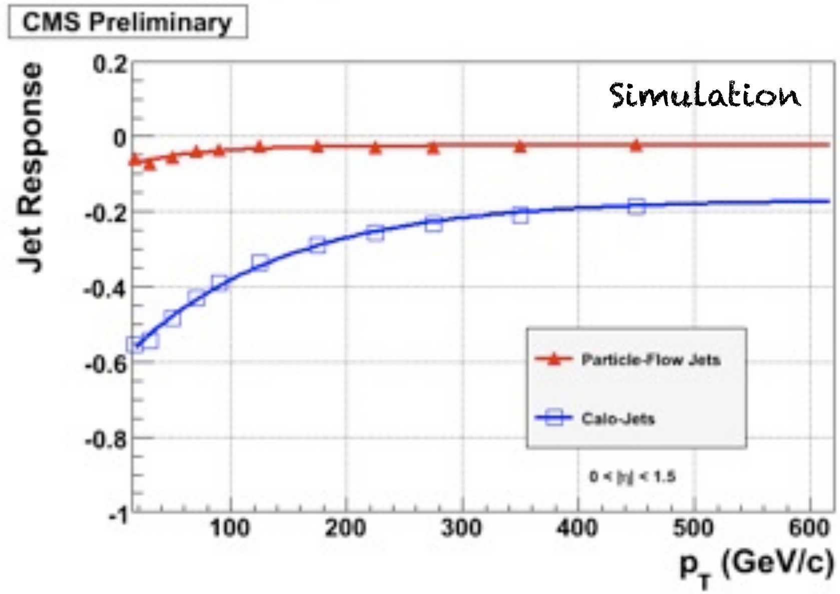

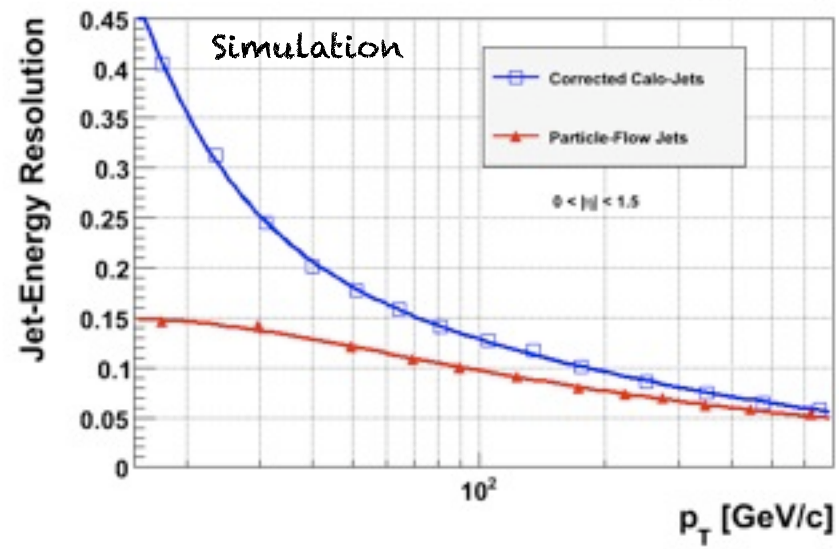

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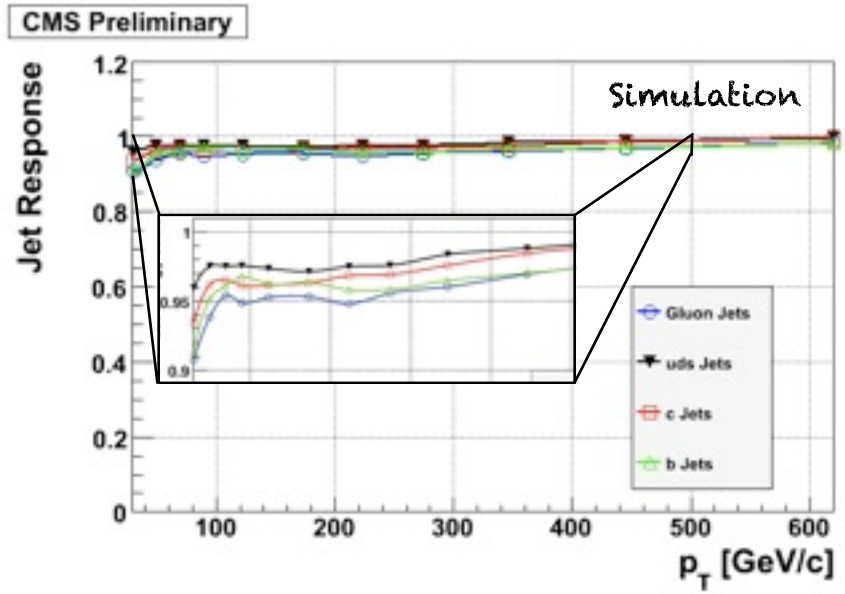

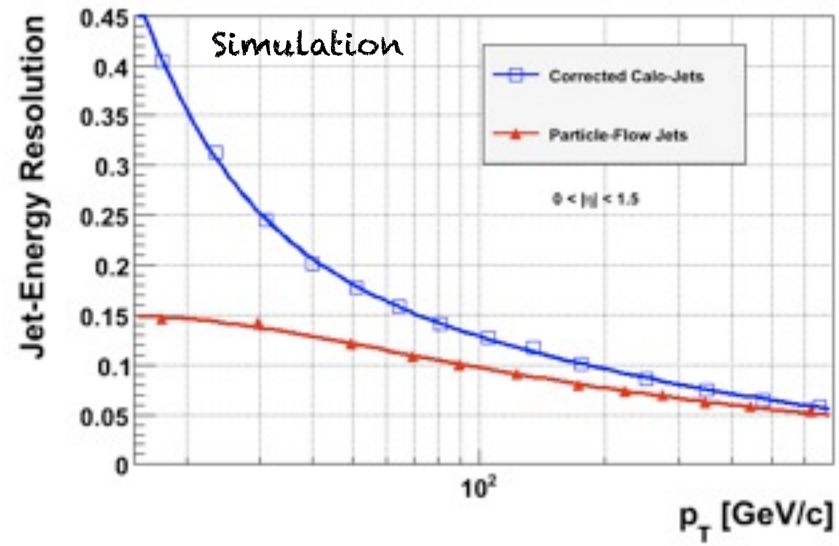

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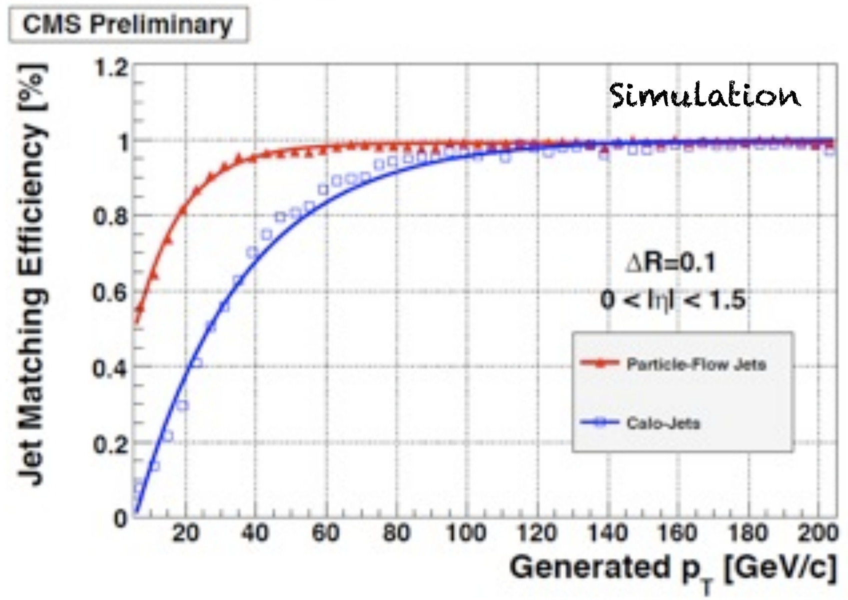

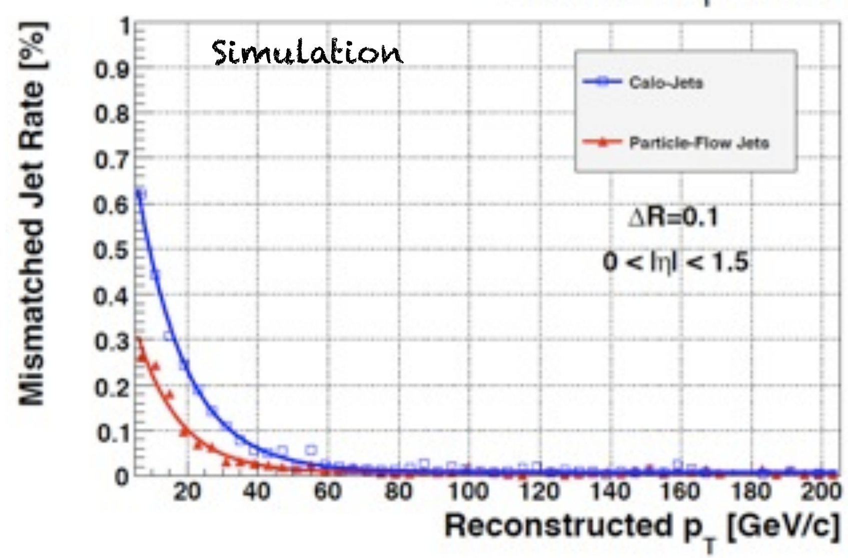

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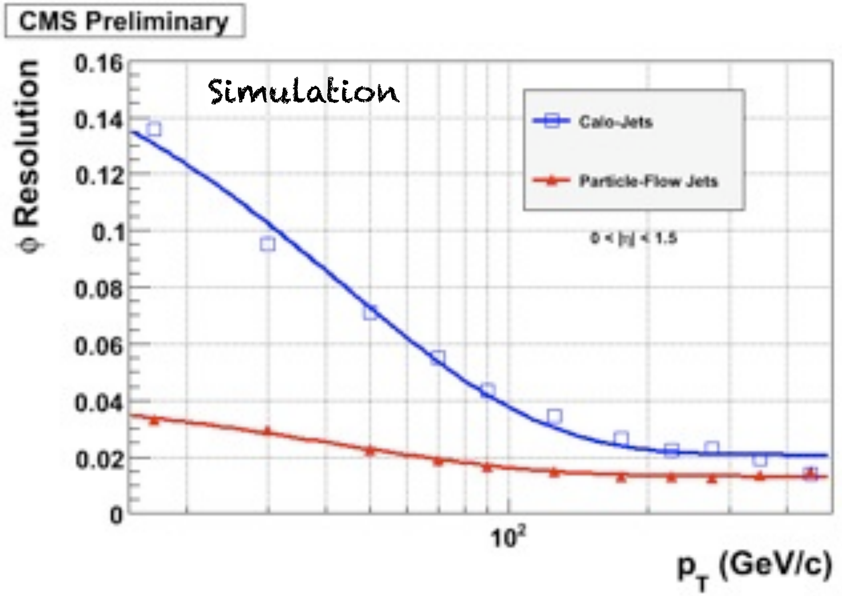

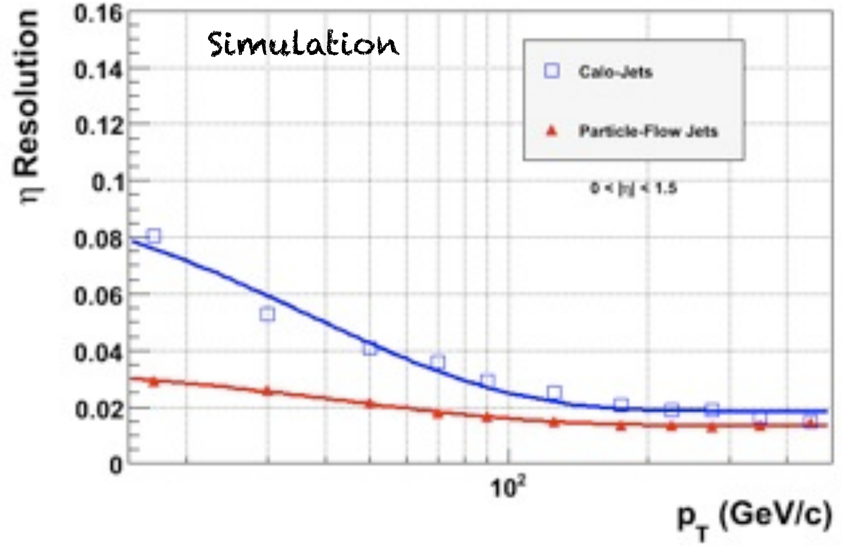

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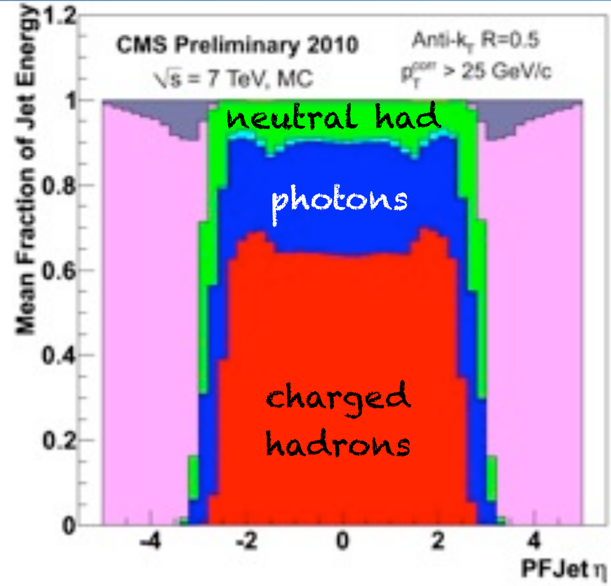
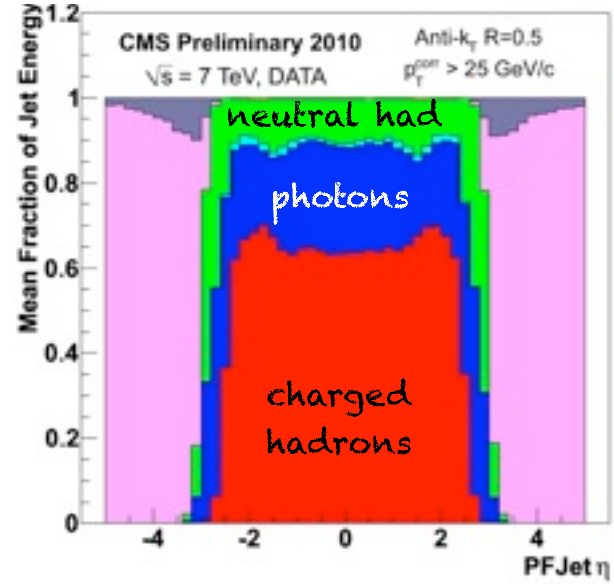
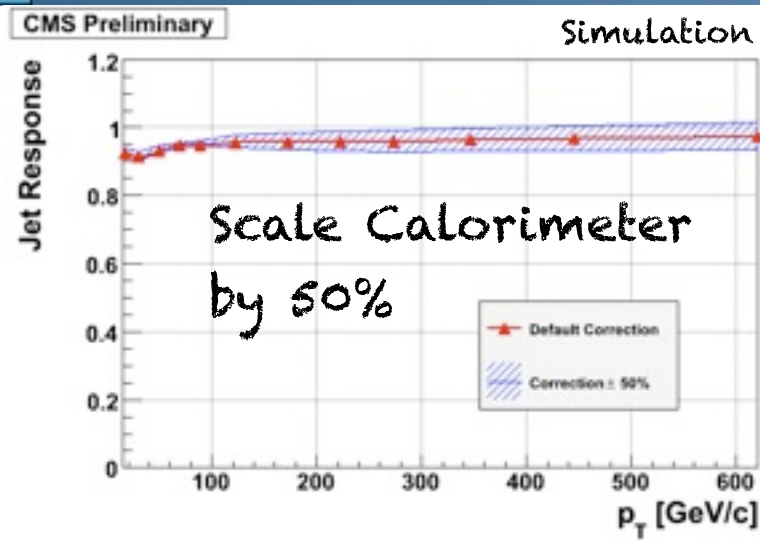
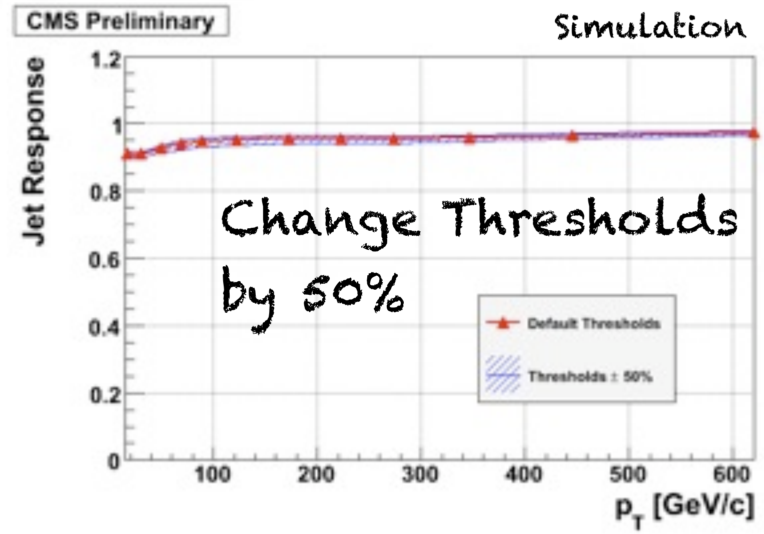
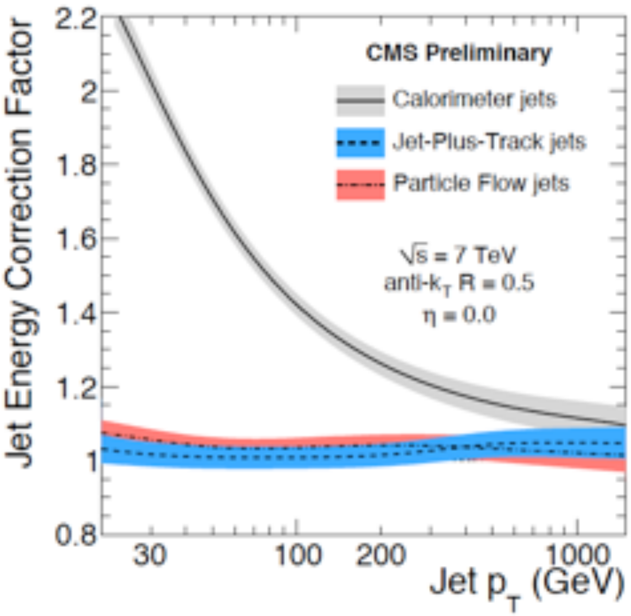


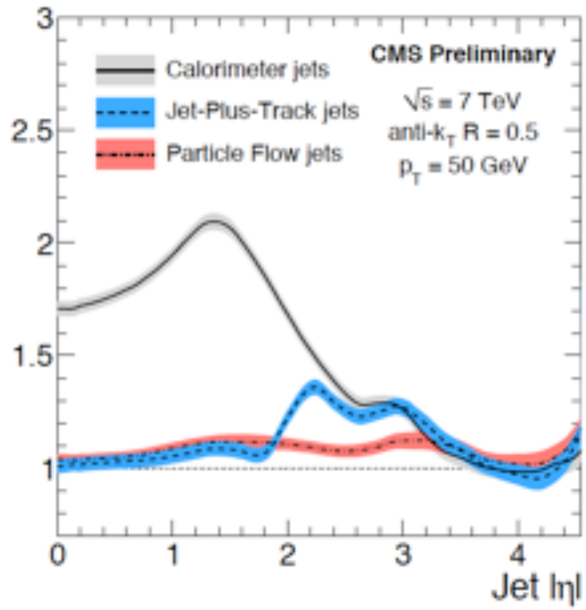


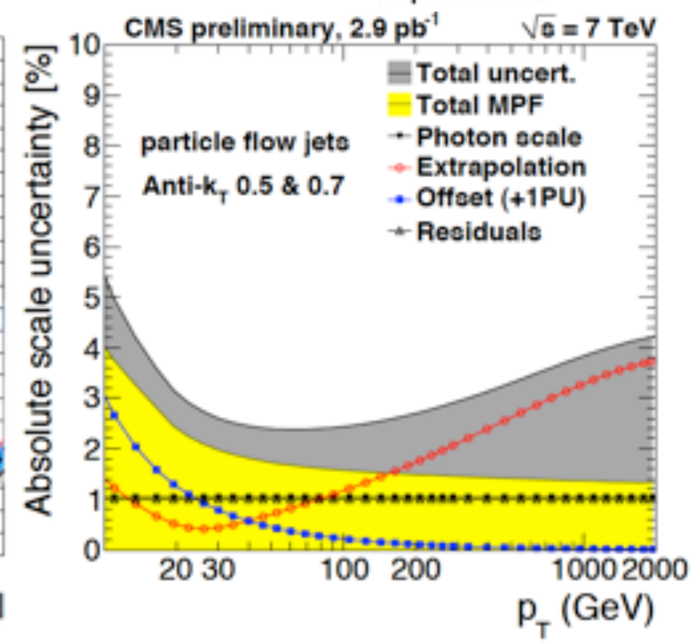
Jet Energy Scale











Missing ET using Particle Flow

- MET is the transverse momentum vector sum over all reconstructed particles:

$$\vec{\not{E}}_T = -\sum_{\text{particles}} (p_x\hat{\mathbf{i}} + p_y\hat{\mathbf{j}})$$

- The list of reconstructed particles form a global event description, provided by the PF Algorithm:
  - { $\mu^{\pm}$, $e^{\pm}$, γ, $\pi^{\pm}$, K_L^0, pile-up particles, etc }
- The PF Algorithm exploits full ensemble & redundancy of all CMS detectors
  - { tracker, ECAL, HCAL, muon system }
  - Does not depend on the Monte Carlo Simulation
  - Depends only minimally on any response/calibration maps
    - Robust against large calorimeter calib changes in tracker acceptance

What does MET depend on?

- Depends on particle multiplicity in the event
  - inefficient particles create fake MET
  - fake particles create fake MET
- Depends on particle momenta in the event
  - poorly measured particles create fake MET
- A good (combined) measure of this is:
  - summed transverse momenta of event "ΣE_T":
    - more particles → more ΣE_T
    - more momenta → more ΣE_T

- Study performance of MET vs ΣE_T

MET Performance

- MET is the very last step
  - Benefits from all progress in the jets!
  - Will continue to benefit from further progress!
- Better able to measure zero-MET (e.g as in QCD)
  - Improved estimate of event visible energy
    - better measure of "zero" imbalance
  - 60% better at 500 GeV of Sum ET
- Better able to measure real-MET (e.g. as in ttbar)
  - Improved Energy Response
    - Calibrated within 5% above 20 GeV
  - Improved Energy Resolution
    - Nearly factor 2 near 100 GeV
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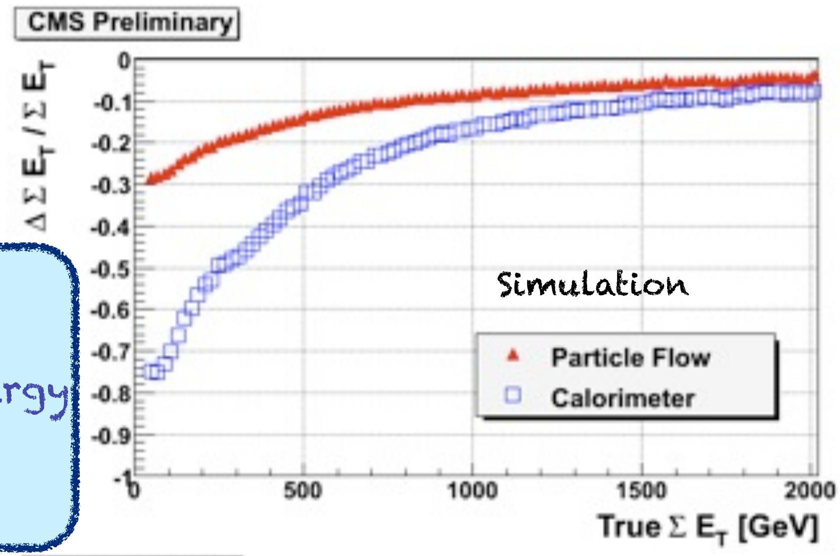
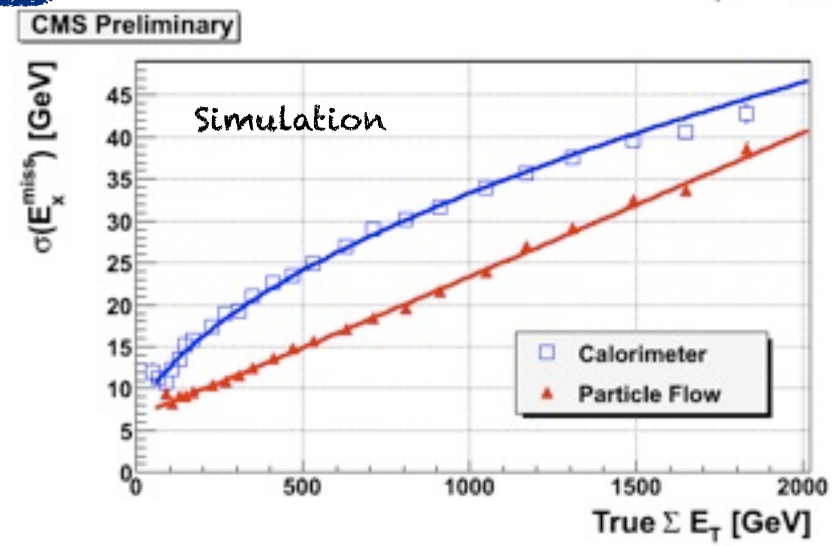
  - Improved Angular Resolution
    - Factor 2 up to (even >) 200 GeV





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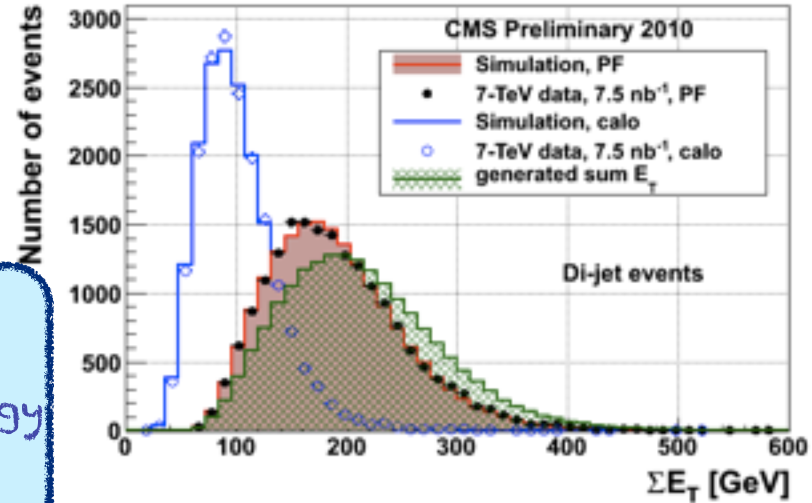
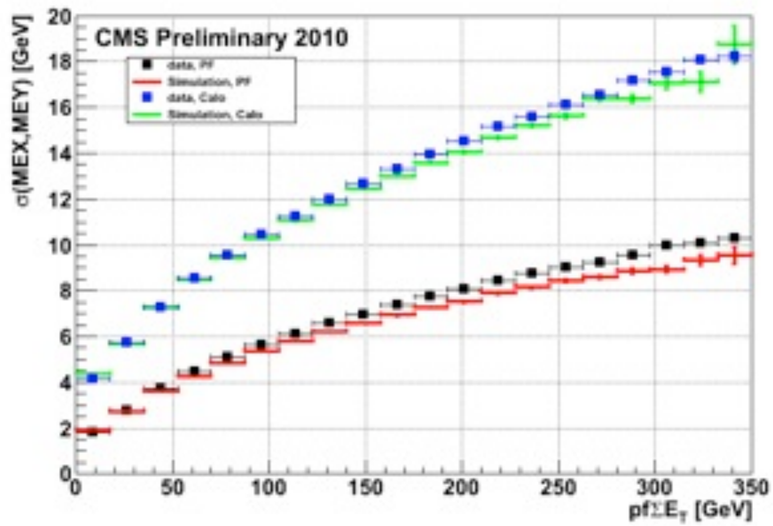


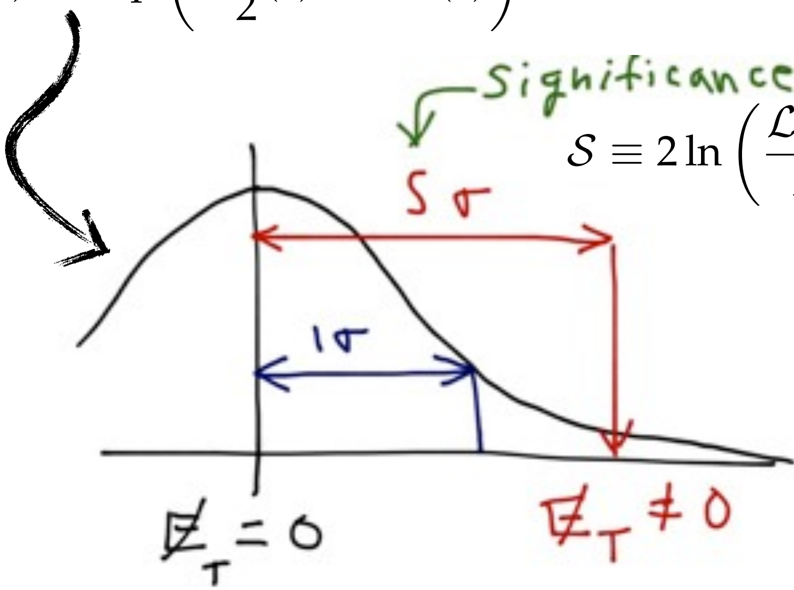


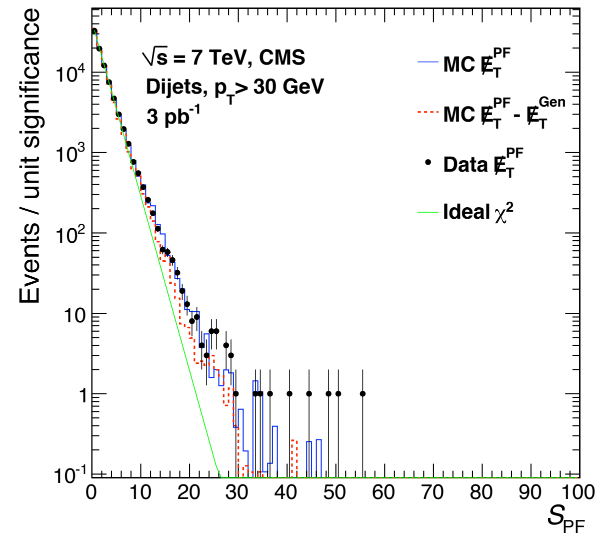
Missing E_T Significance

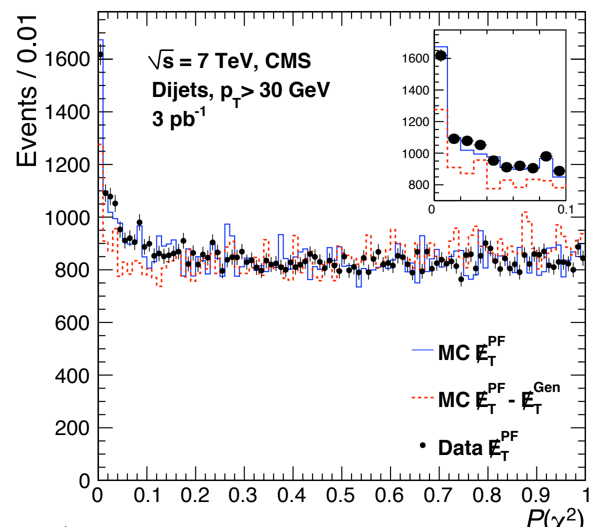
- p_T uncertainty measured for each & every particle
  - Charged particles: track covariance matrix
  - Neutral particles: test beam data
- Use error propagation over all particles to find total significance that observed MET is compatible with zero MET

$$\mathcal{L}(\vec{\varepsilon}) \sim \exp\left(-\frac{1}{2}(\vec{\varepsilon})^T \mathbf{V}^{-1}(\vec{\varepsilon})\right)$$

$$\mathcal{S} \equiv 2\ln\left(\frac{\mathcal{L}(\vec{\varepsilon}=\sum\vec{\varepsilon}_i)}{\mathcal{L}(\vec{\varepsilon}=0)}\right)$$







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- Real true MET events (& badly reconstructed events) peak at zero $P(\chi^2)$

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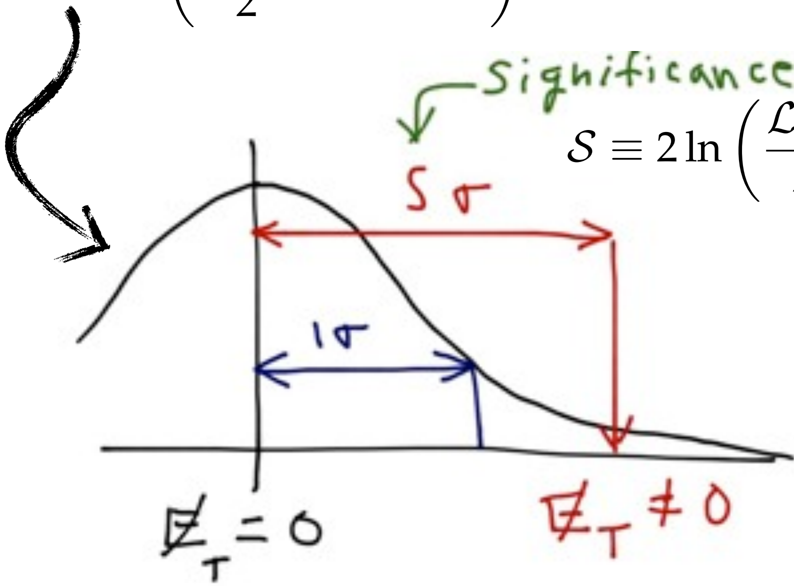

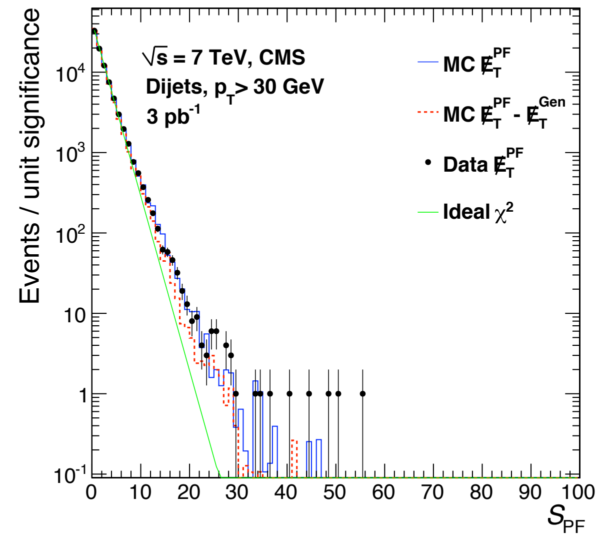

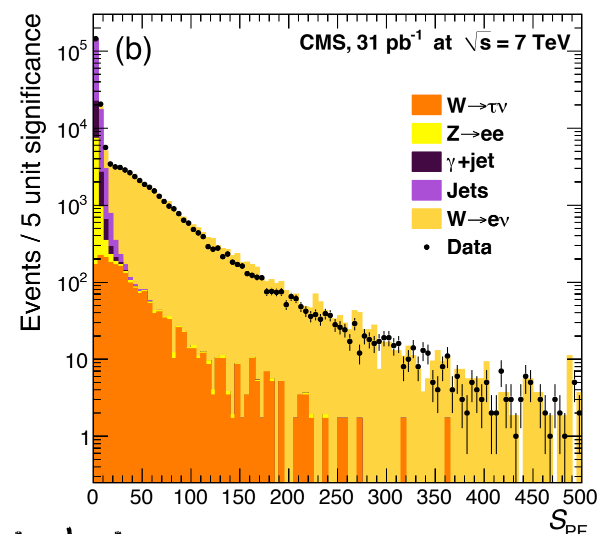

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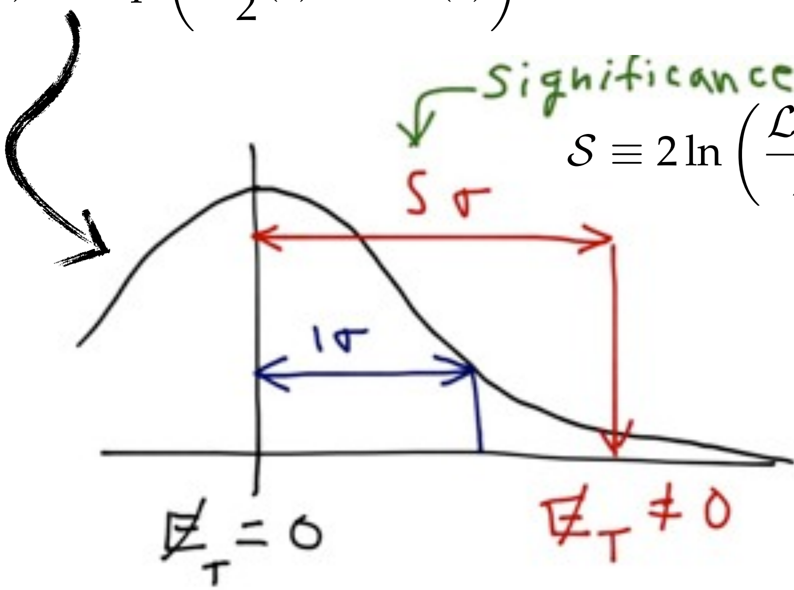
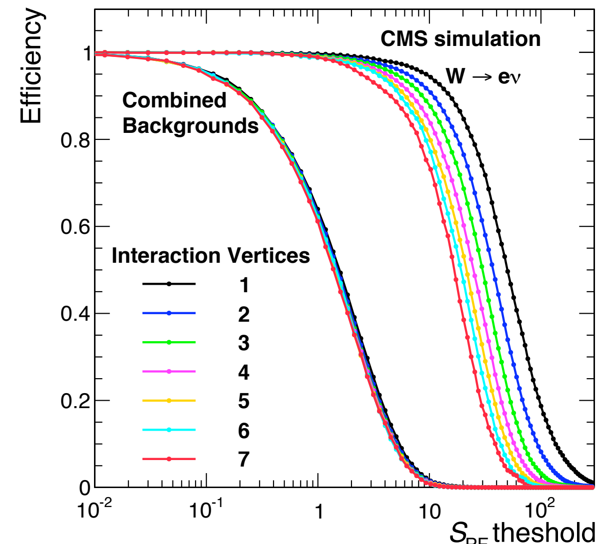
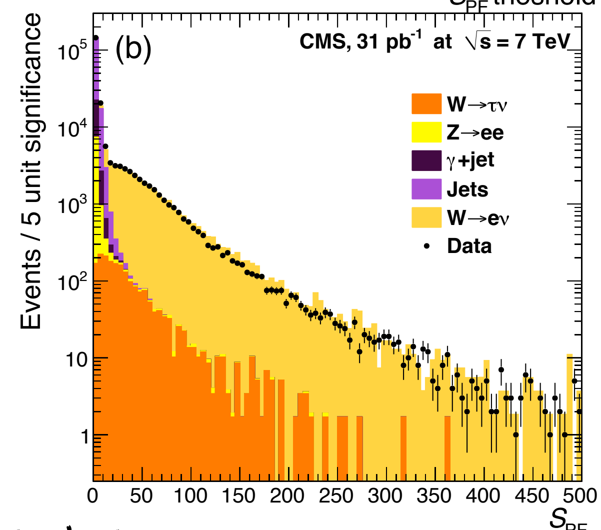
$$\mathcal{L}(\vec{\varepsilon}) \sim \exp\left(-\frac{1}{2}(\vec{\varepsilon})^{T}\,\mathbf{V}^{-1}\,(\vec{\varepsilon})\right)$$



$$\mathcal{S} \equiv 2\ln\left(\frac{\mathcal{L}(\vec{\varepsilon} = \sum \vec{\varepsilon}_i)}{\mathcal{L}(\vec{\varepsilon} = 0)}\right)$$





- Zero true MET events should follow a flat $P(\chi^2)$ distribution
- Real true MET events (& badly reconstructed events) peak at zero $P(\chi^2)$

Conclusion

- OK...I'll stop here for today...
  - tomorrow, physics from CMS
- The CMS Detector is in excellent condition
- Particle Flow in CMS works extraordinarily well!
  - individual particles: leptons, hadrons, photons
  - Jets (light quark, heavy quark, hadronic tau)
  - Missing (transverse) energy (momentum)
- CMS is pursuing a rich menu of LHC Physics
  - Standard Model Benchmarks
    - QCD, W, Z, top
  - Searches for new Physics
    - Higgs
    - Supersymmetry
    - Extra Dimensions, etc

Tomorrow

Stay tuned for EPS results this coming week.