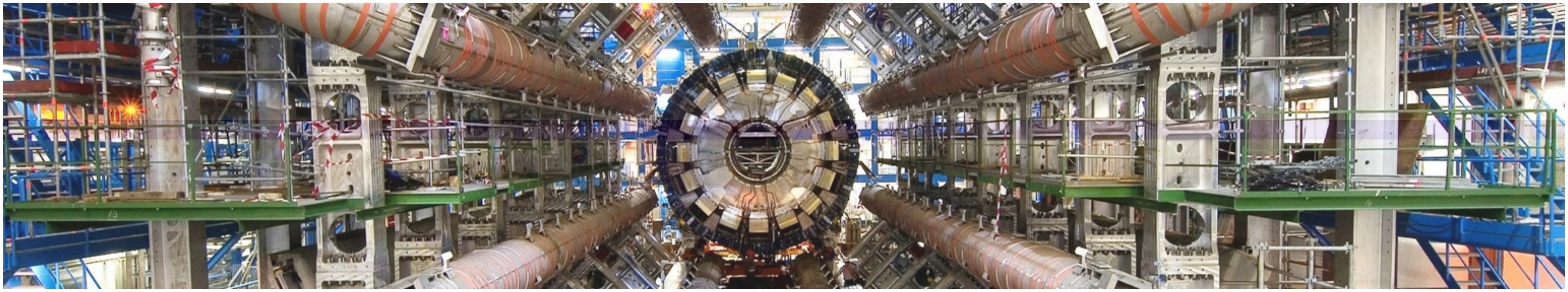

Event Reconstruction and Particle Identification

Part Two

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Hadron Collider Physics Summer School

August 21, 2014

Outline for Today

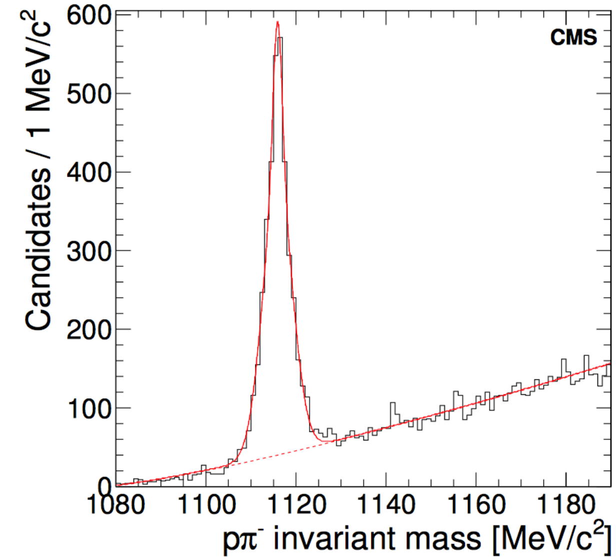
- Neutral particle ID techniques (γ ,π^0, K, Λ,…)
  - V0 identification with tracking detectors
  - Photon vs. Electron shower shapes
- Electron reconstruction
  - Converted photon reconstruction
  - Isolation requirements and calculations
- Muon reconstruction
  - Combined reconstruction and measurements
  - Punch-through and charge mis-identification
- Measurements of particle ID efficiencies and fake rates
  - Tag-and-probe methods
  - "Matrix methods"
- Introduction to Particle Flow algorithms
  - Practical examples and results from particle flow

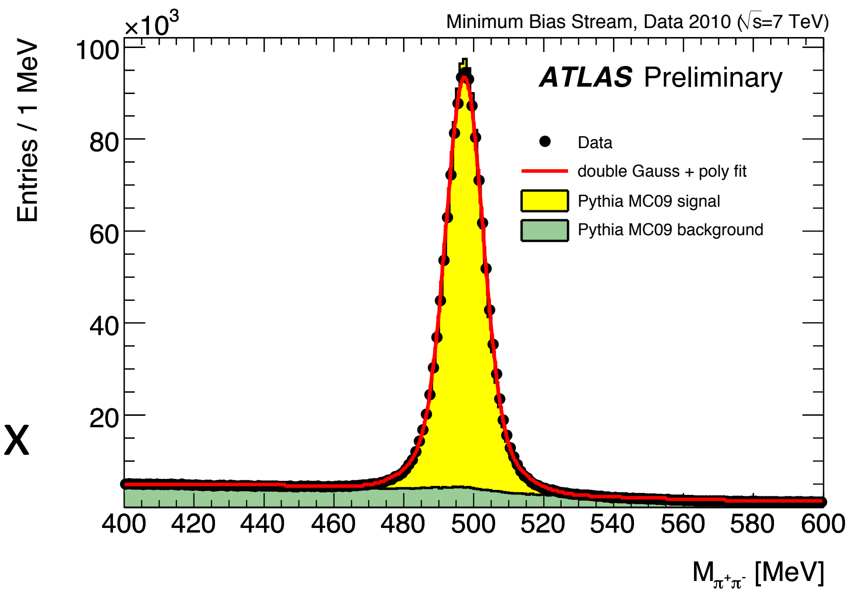
Neutral Particle ID: γ, π^0, K^0, Λ^0, n

- Short interlude on neutral particles, before electrons and muons
- Neutral particles with no tracks must be distinguished by their calorimeter signatures
- Fortunately, many of these neutral particles decay before the calorimeter, so they can be reconstructed appropriately
- Key points:
  - $\gamma/\pi^0(\gamma\gamma)$ discrimination depends on shower shape and isolation
  - K^0/Λ^0 hadrons decay non-promptly to charged particles
- Won't say much about neutrons today
  - No use case for specific neutron PID (unlike π^0 in τ lepton decay)
  - Included naturally in the neutral hadronic shower component (but be careful about EM energy scale vs. hadronic energy scale)

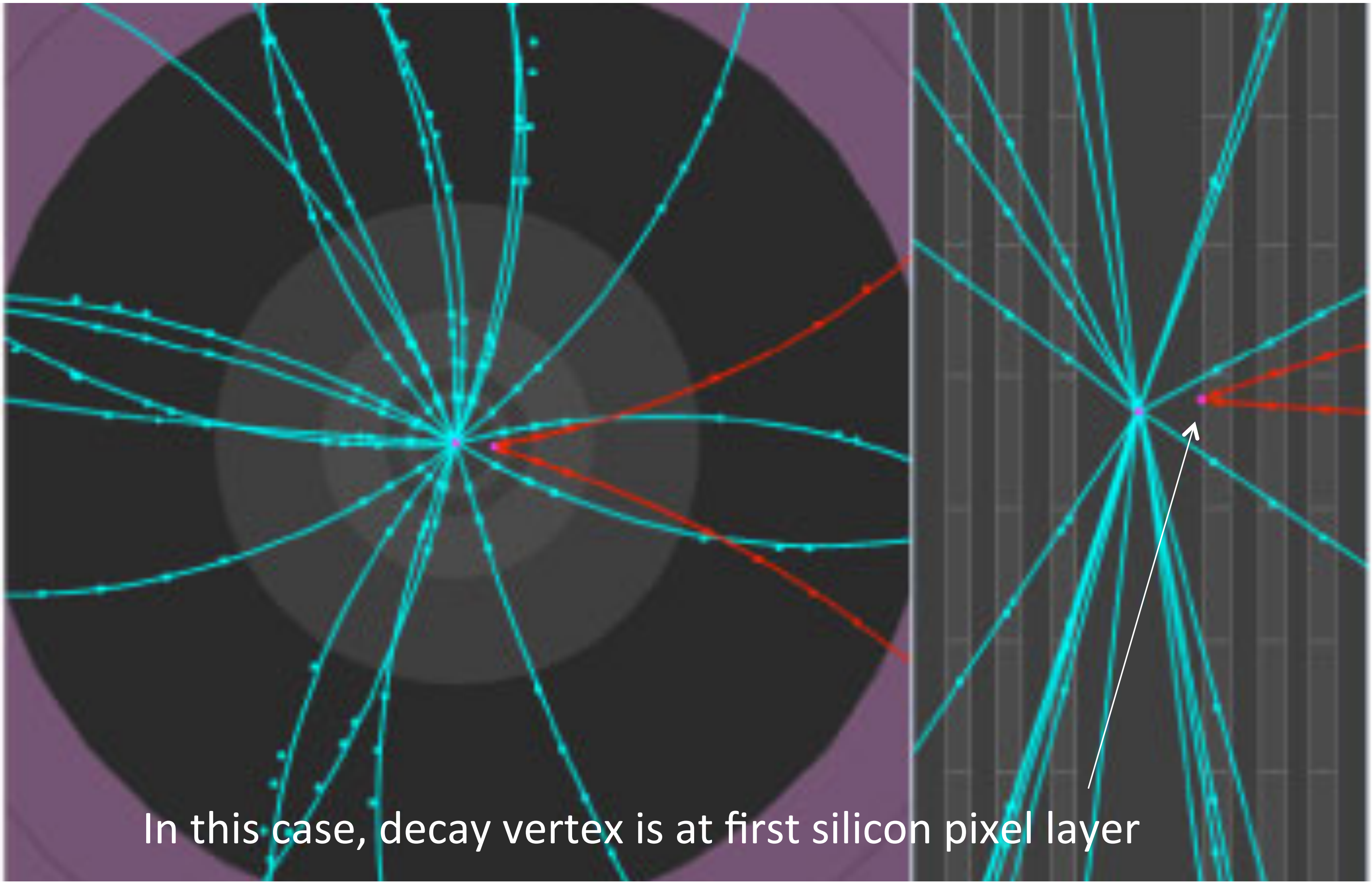
K^0 mesons and Λ^0 baryons

- Weakly decaying neutral particles with unusually long lifetimes:
  - K^0_S $c\tau$ = 2.7 cm; dominant decay to $\pi^+\pi^-$
  - Λ^0 $c\tau$ = 7.9 cm; dominant decay to $p^+\pi^-$
- Two oppositely-charged tracks *vertexed*
  - No particle ID required; mass peak suffices
- Require vertex to be displaced from IP
  - CMS requires 15σ (vertex + beamspot uncerts.)
- Mass comparison with simulation
  - Magnetic field
  - Track fitting
  - Material description
- Will need to identify and remove V^0 vertices when tagging b-decay vertex





Reconstructed K^0 decay

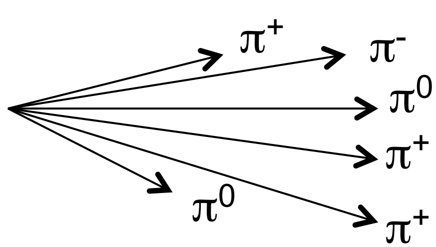


Photon ID

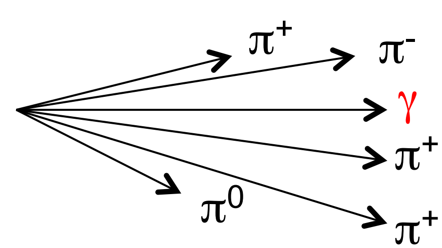
- Often combined as "e\\γ ID" because of nearly identical showers
- Backgrounds to be rejected:
  - Non-prompt γ/π^0 from hadronic jets
  - Hadronic particles with early-initiated showers
- Shower development was covered in J. Mans's lectures
  - We will focus on shower shape variables that discriminate against backgd
- Converted vs. unconverted photons
  - Inner tracker material can result in photon conversions to e^+e^- pair
  - Electrons are bent in the magnetic field
  - CMS ECAL is inside magnetic field, so electrons in shower also bend
  - Reconstructing conversions requires special tracking (not inside-out)
- Define two (and sometimes three) different levels of photon ID
  - Loose identification: used for trigger selection, rough sample construction
  - Tight identification: used for final offline selections, comparison with loose

Prompt γ vs. π^0 Decays

- "Prompt" γ are produced in the hard scatter instead of in shower
  - Probe of electroweak couplings; important background to searches
  - To be distinguished from γ in jets, decays of other particles
- π^0 mesons nearly always decay to 2γ with $c\tau$ = 25 nm
  - Photons would have same calo shape as prompt photons
  - Fortunately m_π is small enough that the 2 photons end up together in calo
  - No tracks to vertex, but we can treat this calo cluster as a single object
- What are the differences between γ and π^0 in the detectors?
  - Distribution of energy in electromagnetic calorimeter
  - Prompt γ are isolated from other particles, while π^0 are not isolated

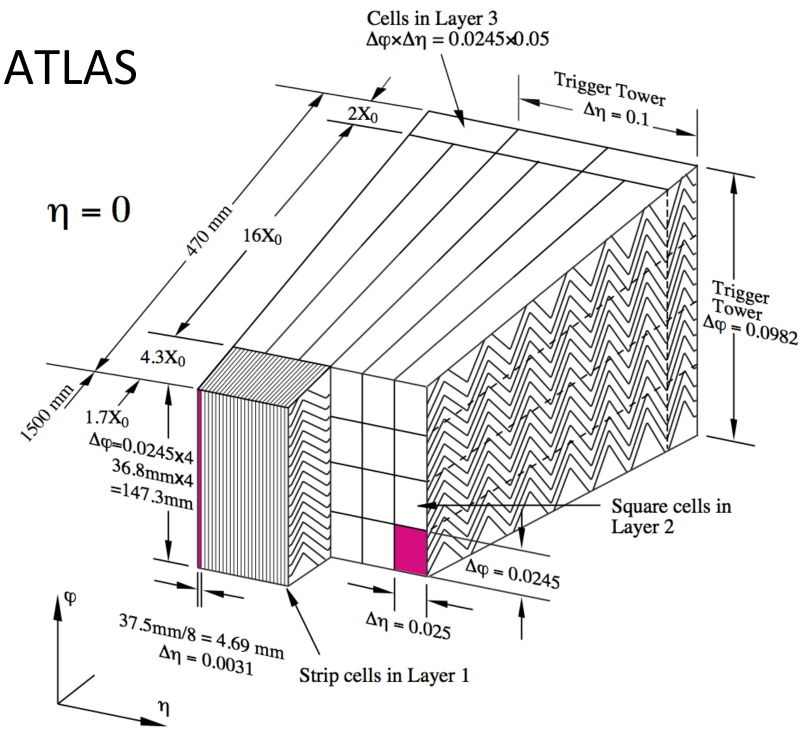


or even



Calorimeter Geometry and γ/π^0 Separation

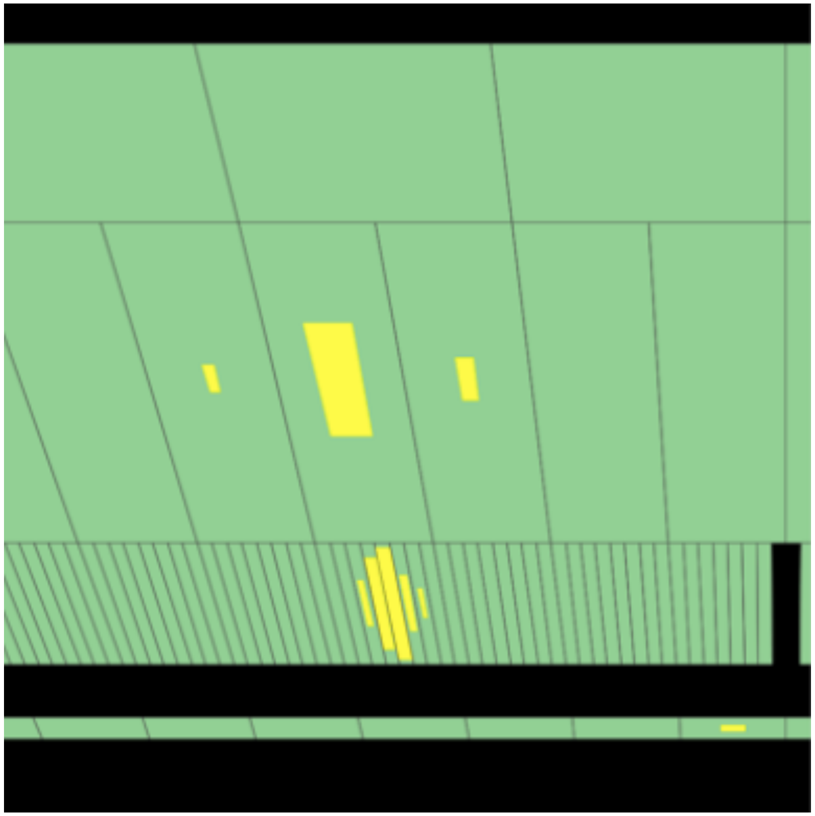
ATLAS

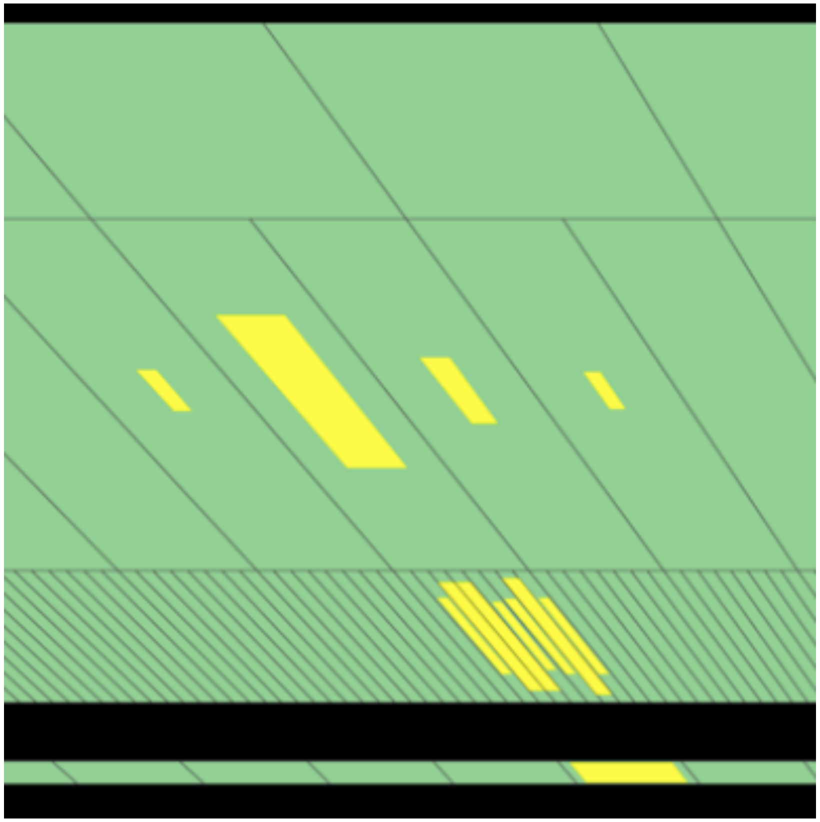


- Layer 1 segmentation:
  - 0.0031 x 0.1 in η-ϕ
- Collects all brem photons in a given η strip
- Not segmented in r
  - 0.0174 × 0.0174 in η-ϕ
- Total is 25.8 X_0 deep
  - Pb-Si preshower 2+1 X_0

ATLAS γ/π^0 Events

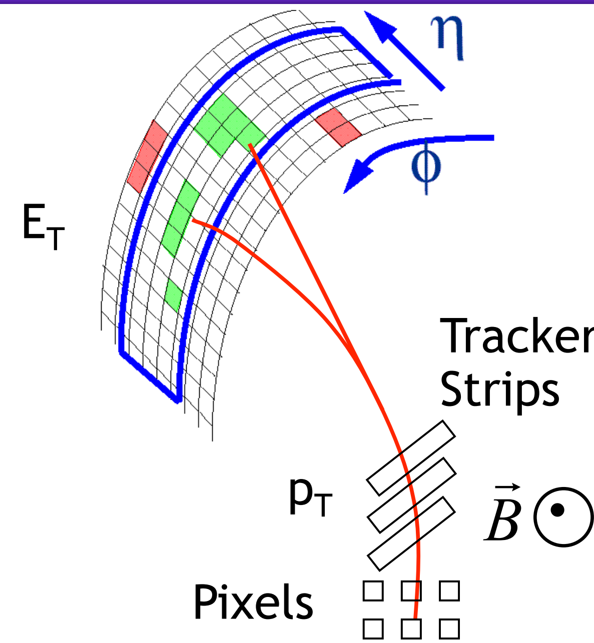
- Use finely segmented first layer to observe clear separation of EM clusters from π^0 decay (only showing cal cells with E>200 MeV)
- Combined energy deposit in second layer used to determine total energy of original π^0. No energy leaked into 3rd layer or HCAL

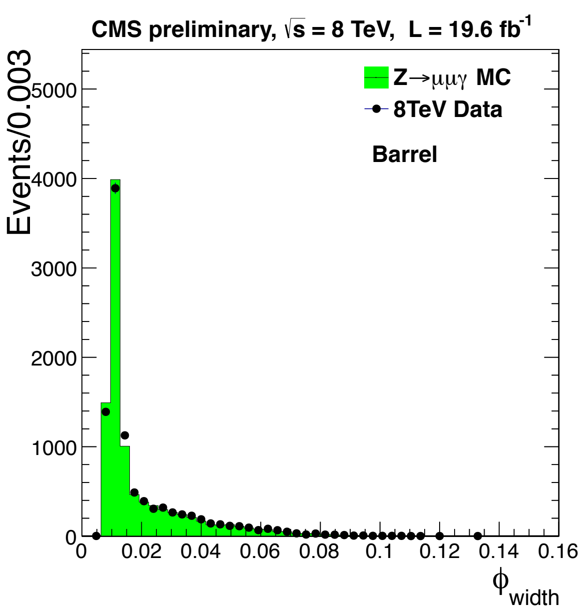


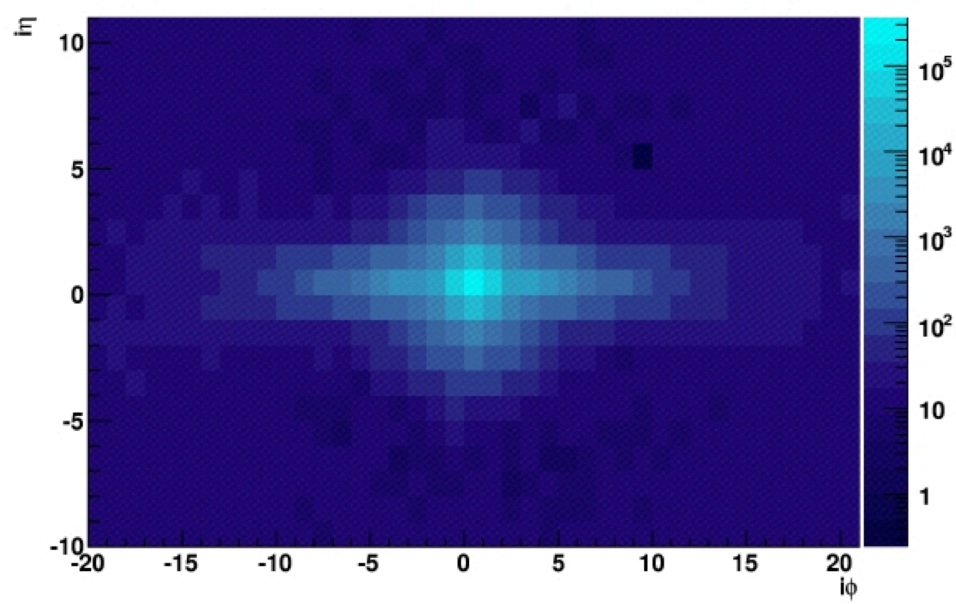


Electron/Photon ID: Shower Shape

- CMS has unique feature: ECAL shower is inside strong B field
  - Electrons/positrons in shower are spread into a long cluster in ϕ
- Simple clusters around local maxima are merged into *superclusters* of variable size
  - Use size information as discriminant







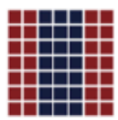
Photon ID: Shower Shape Variables

Variables and Position

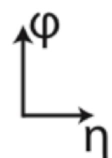
	Strips	2nd	Had.
Ratios	f_1, f_{side}	R_η*, R_ϕ	$R_{\text{Had.}}$*
Widths	$w_{s,3}$, $w_{s,tot}$	$w_{\eta,2}$*	-
Shapes	ΔE, E_{ratio}	* Used in PhotonLoose.	

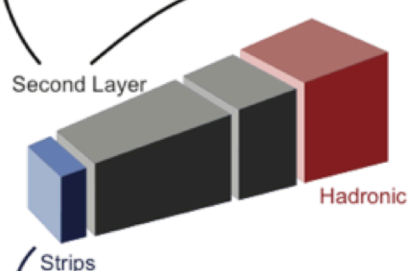
Energy Ratios

$$R_\eta = \frac{E^{S2}_{3\times7}}{E^{S2}_{7\times7}}$$



$$R_\phi = \frac{E^{S2}_{3\times3}}{E^{S2}_{3\times7}}$$





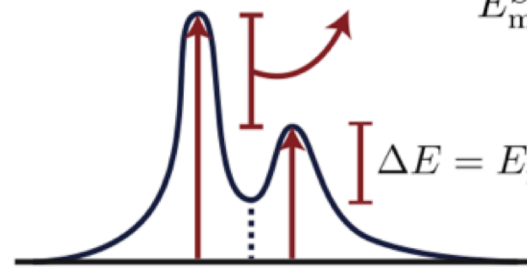
$$R_{\text{Had}} = \frac{E_T^{\text{Had}}}{E_T}$$

$$f_1 = \frac{E_{S1}}{E_{\text{Tot.}}}$$

$$f_{\text{side}} = \frac{E_7^{S1} - E_3^{S1}}{E_3^{S1}}$$

Shower Shapes

$$E_{\text{ratio}} = \frac{E^{S1}_{\max,1} - E^{S1}_{\max,2}}{E^{S1}_{\max,1} + E^{S1}_{\max,2}}$$

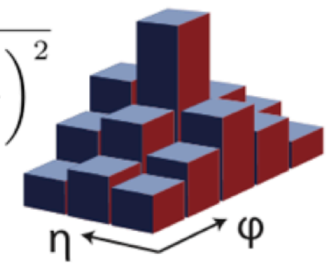


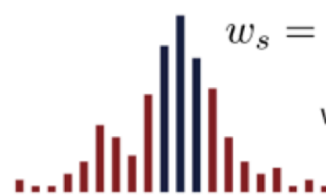
$$\Delta E = E^{S1}_{\max,2} - E^{S1}_{\min}$$

Widths

$$w_{\eta,2} = \sqrt{\frac{\sum E_i \eta_i^2}{\sum E_i} - \left(\frac{\sum E_i \eta_i}{\sum E_i}\right)^2}$$

Width in a 3×5 (Δη×Δφ) region of cells in the second layer.





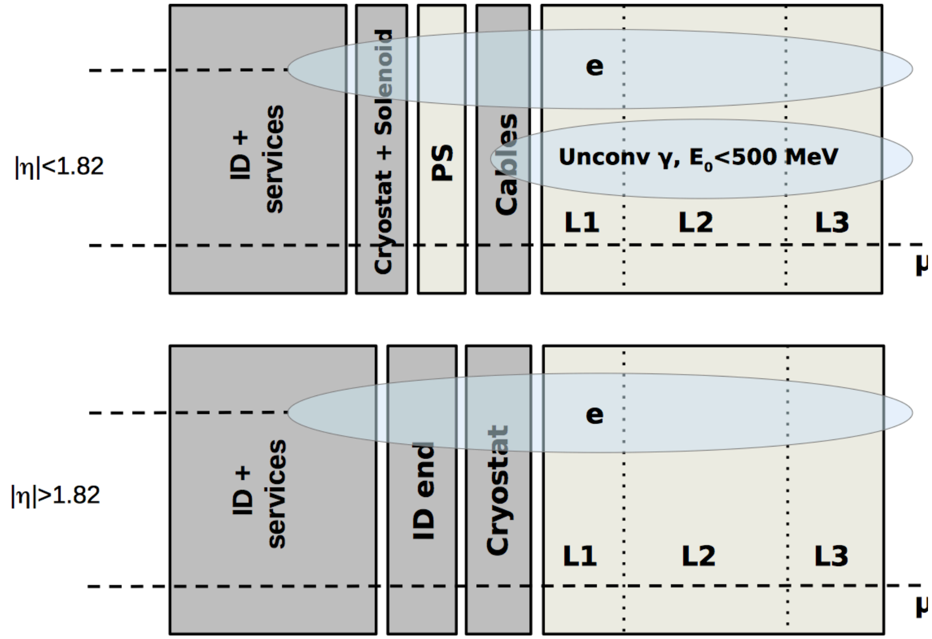
$$w_s = \sqrt{\frac{\sum E_i (i - i_{\max})^2}{\sum E_i}}$$

ws3 = w_1 uses 3 strips in η; wstot is defined similarly, but uses 20 strips.

*ATL-COM-PHYS-2013-60, Phys. Rev. D **83**, 052005*

Electron ID

arXiv:1407.5063

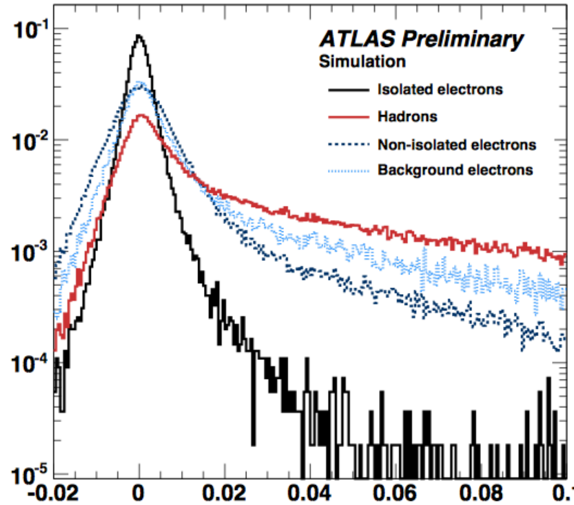


- Varying levels of Electron ID
- Loose selection [also trigger]:
  - Simple common e/γ requirements on hadronic leakage, shower width
- Medium selection:
  - Width measurement with strips
  - Track-shower matching
- Tight selection:
  - Tight track-shower matching
  - Inner pixel hits, transition radiation
  - Isolation requirements
- Final electron momentum and position are weighted combination of measurements from the tracking system and calorimeters
  - Must model uncertainties as a function of energy and detector region

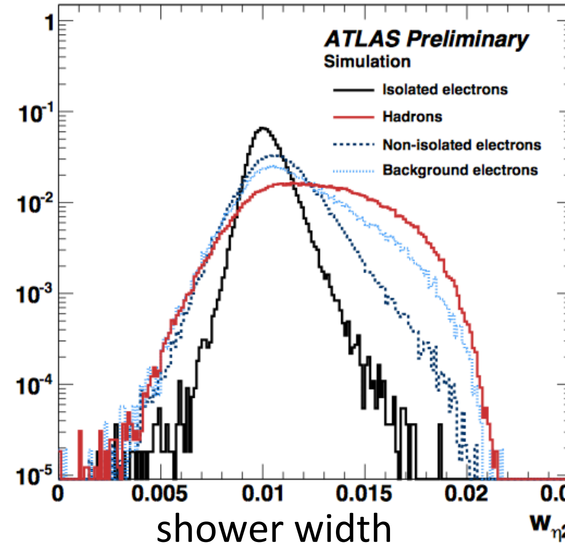
Electron ID Shower Shapes

From J. Alison

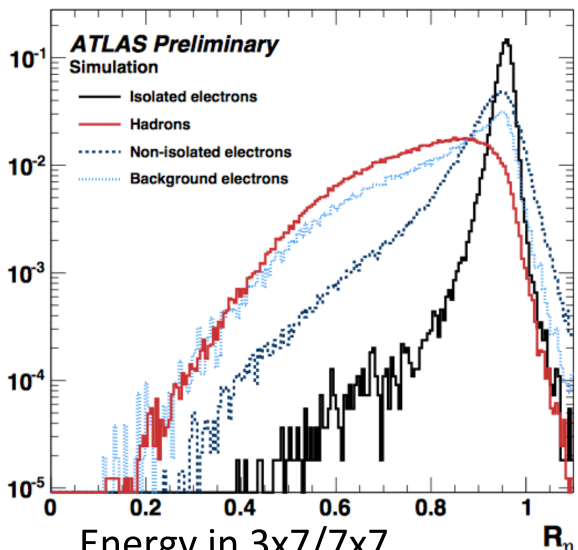
- Electrons are contained in ECAL
- Narrow shower
- Ideally, a single high-energy strip
- ATLAS uses strips for finer resolution



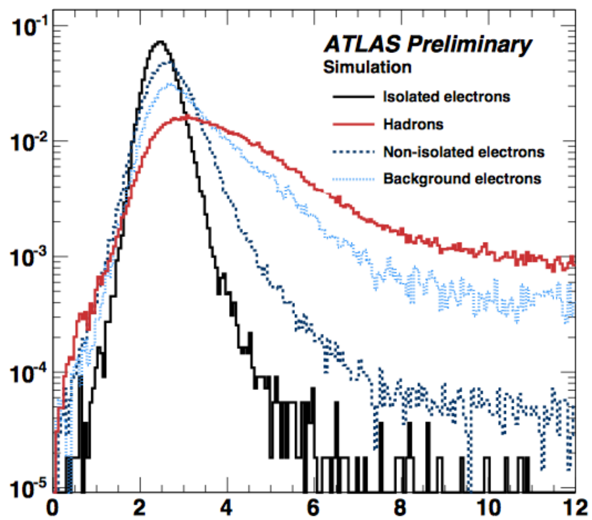
leakage fraction into HCAL



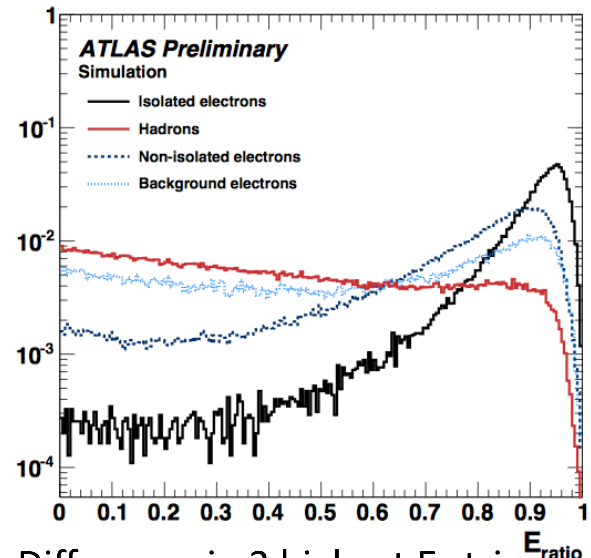
shower width



Energy in 3x7/7x7



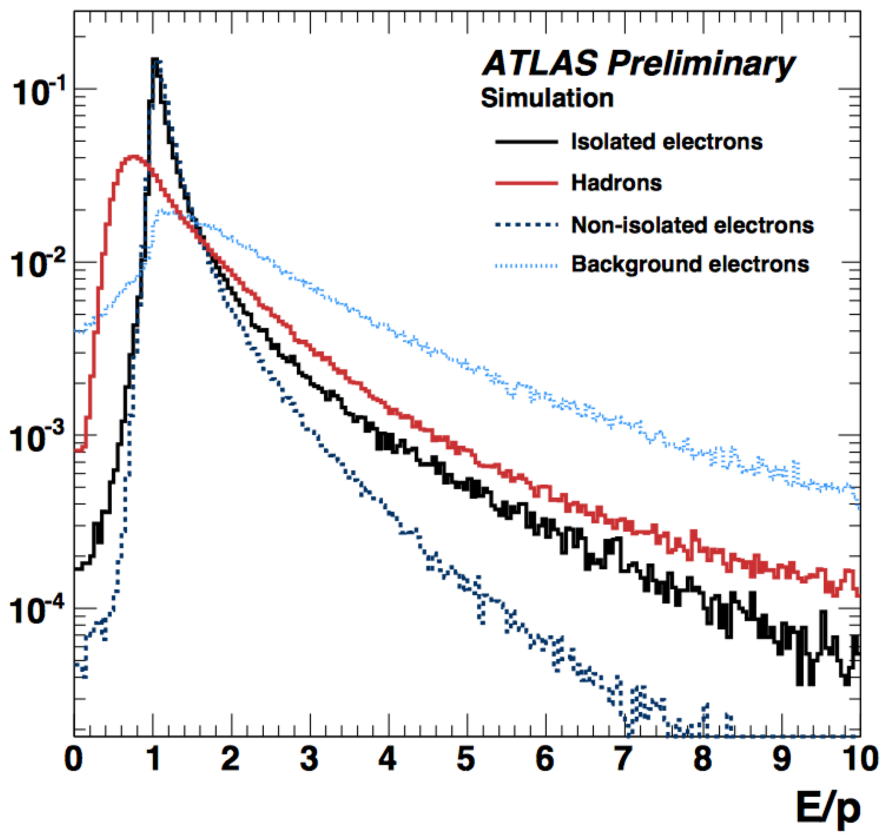
Width (2nd moment) in strips

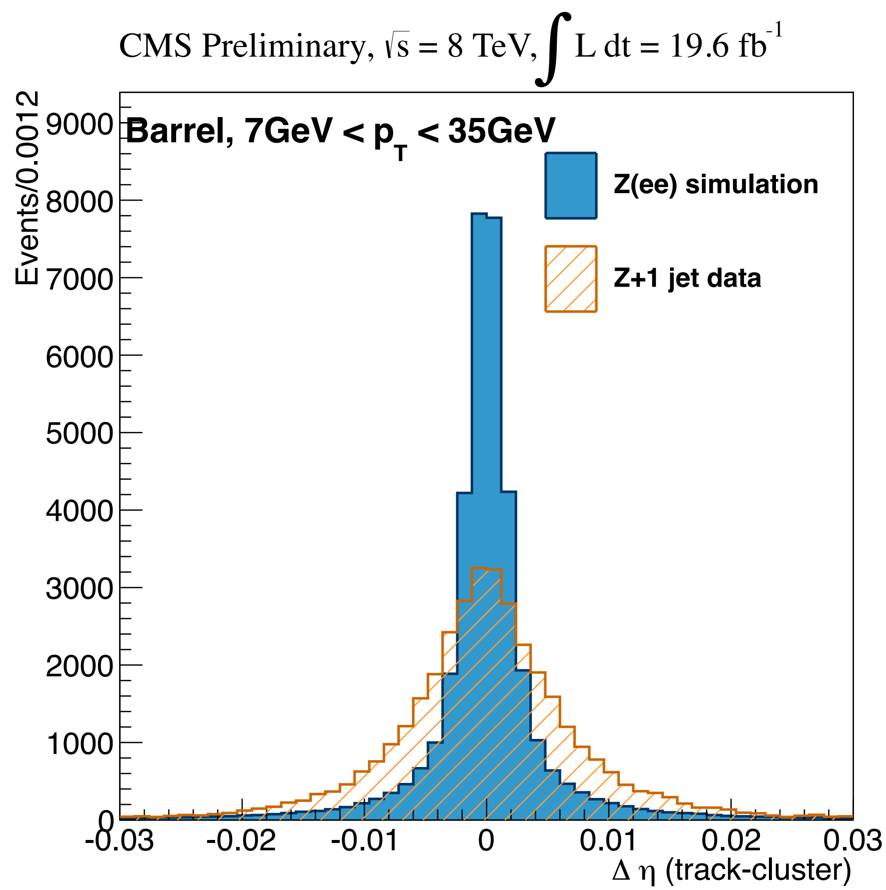


Difference in 2 highest E strips

Electron ID: Tracks and E/p

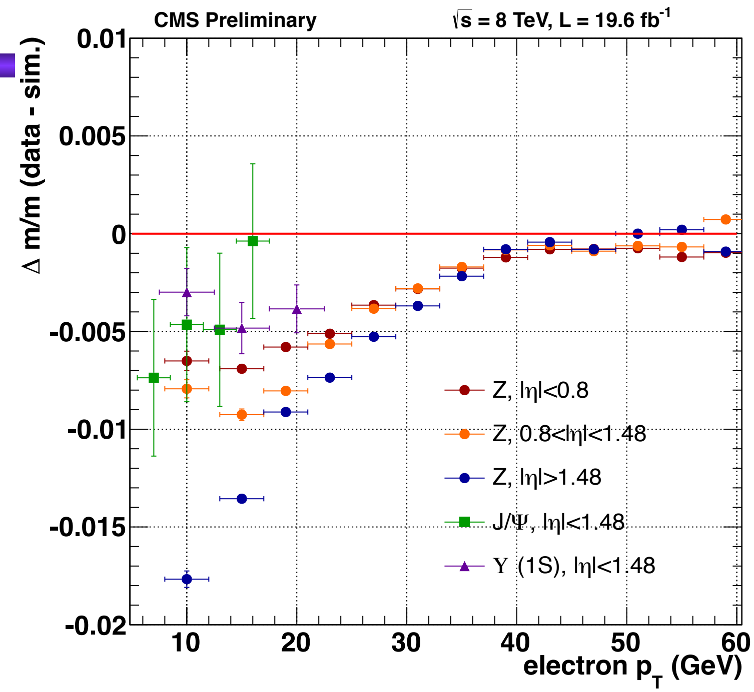
- Track energy and extrapolation must match ECAL cluster
- Andi Salzburger talked about recovering the bremsstrahlung radiated by the electron: Gaussian Sum Filter extension to Kalman





Momentum Calibration

- Use known mass resonances to calibrate electron momentum
  - J/ψ and Z di-electron spectrum
- Proof of correct calibration
  - Data/MC agreement
  - Reasonable bias and pulls
- These plots all use GSF fitting



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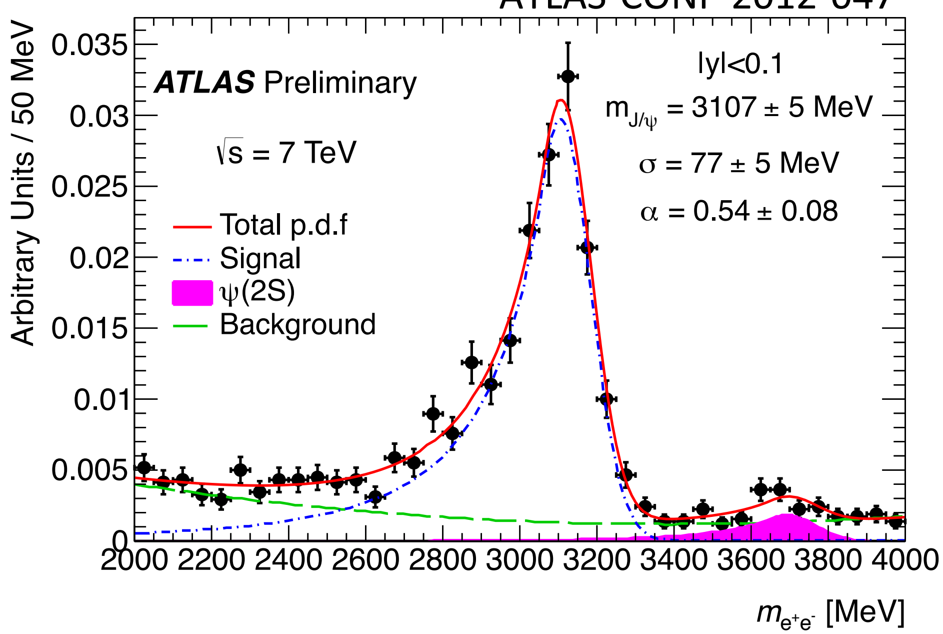
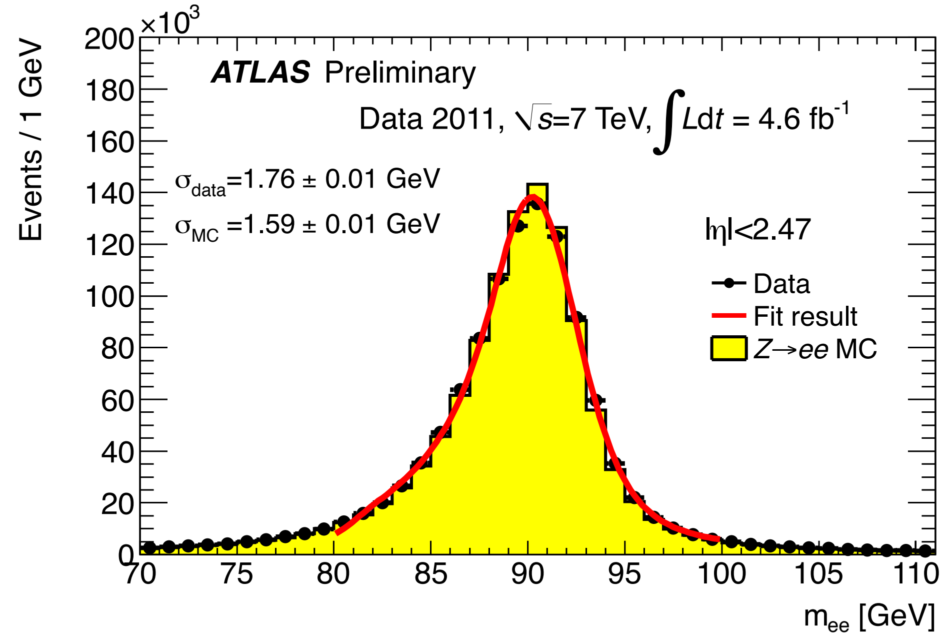
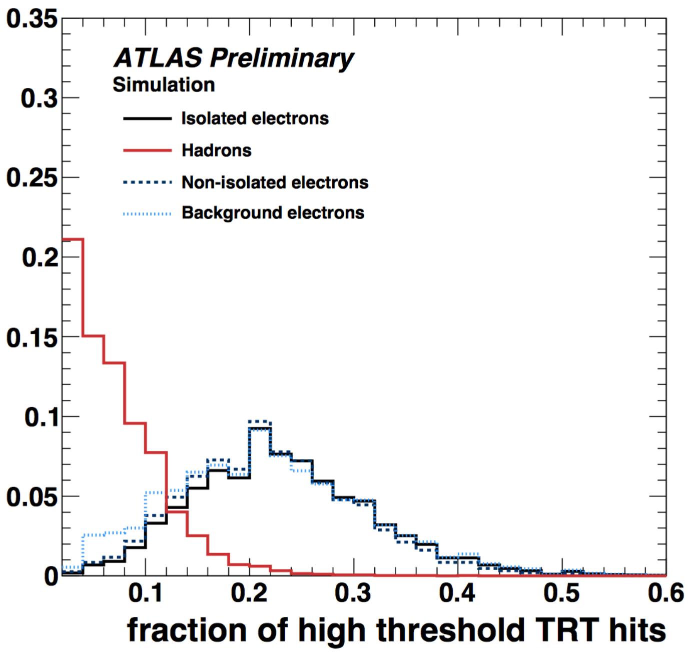
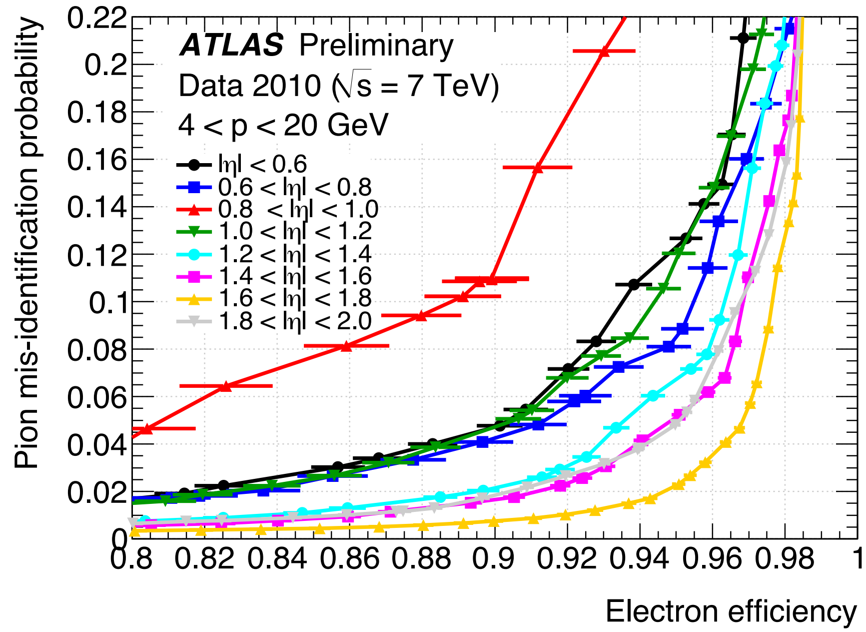


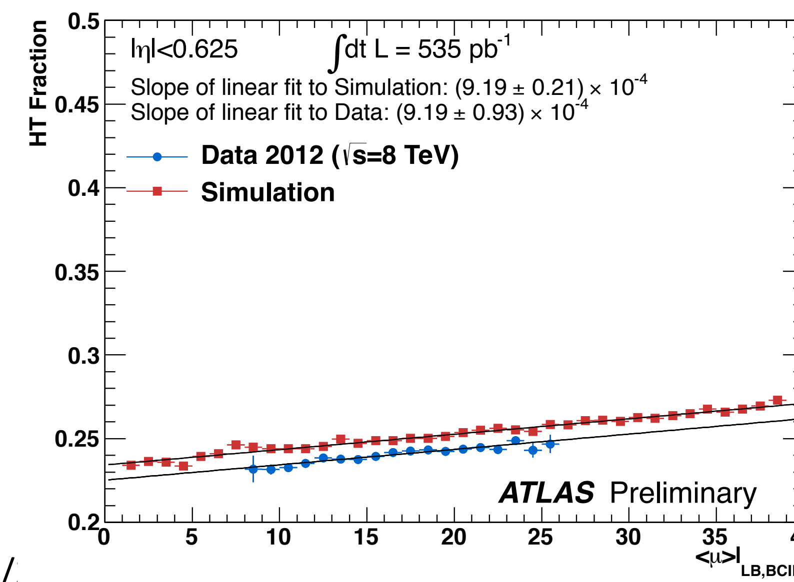


Transition Radiation for Electron ID

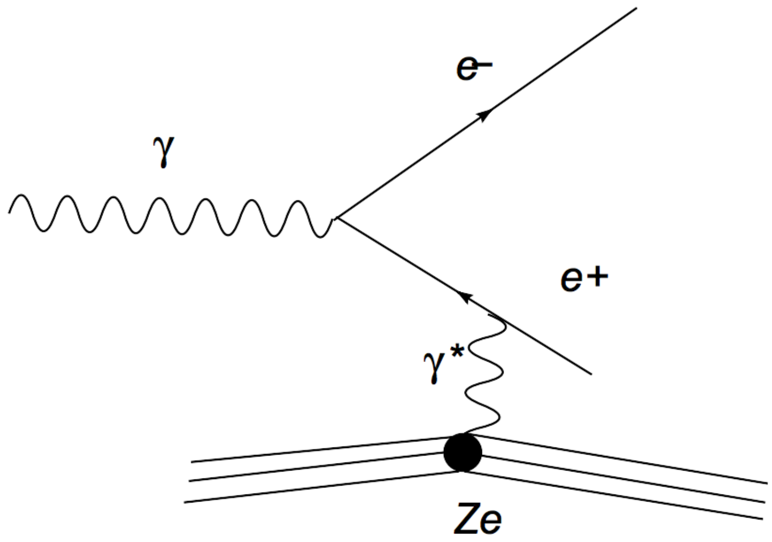




- Input: total TRT hits, ratio of hits above High Threshold (6 keV)
  - Part of multivariate ID, no cut values
- HT ratio (for electrons from Z decay) varies slowly with pileup



Photon Conversion to e^+e^- Pair

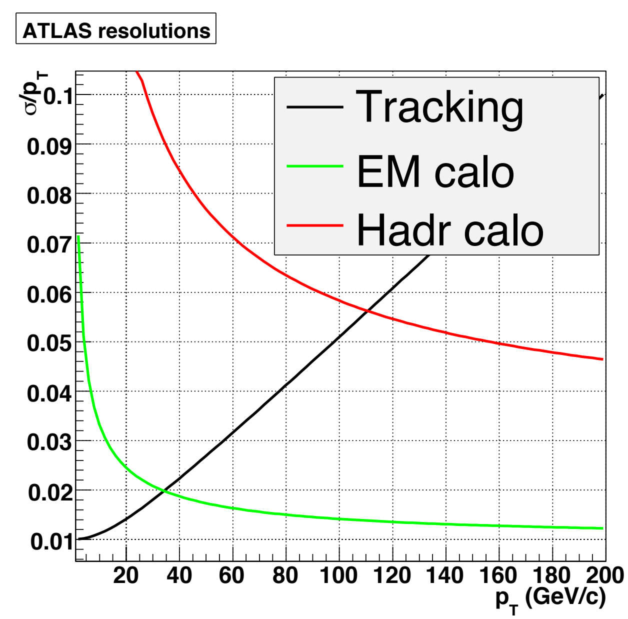


- Momentum must be shared by recoiling nucleus

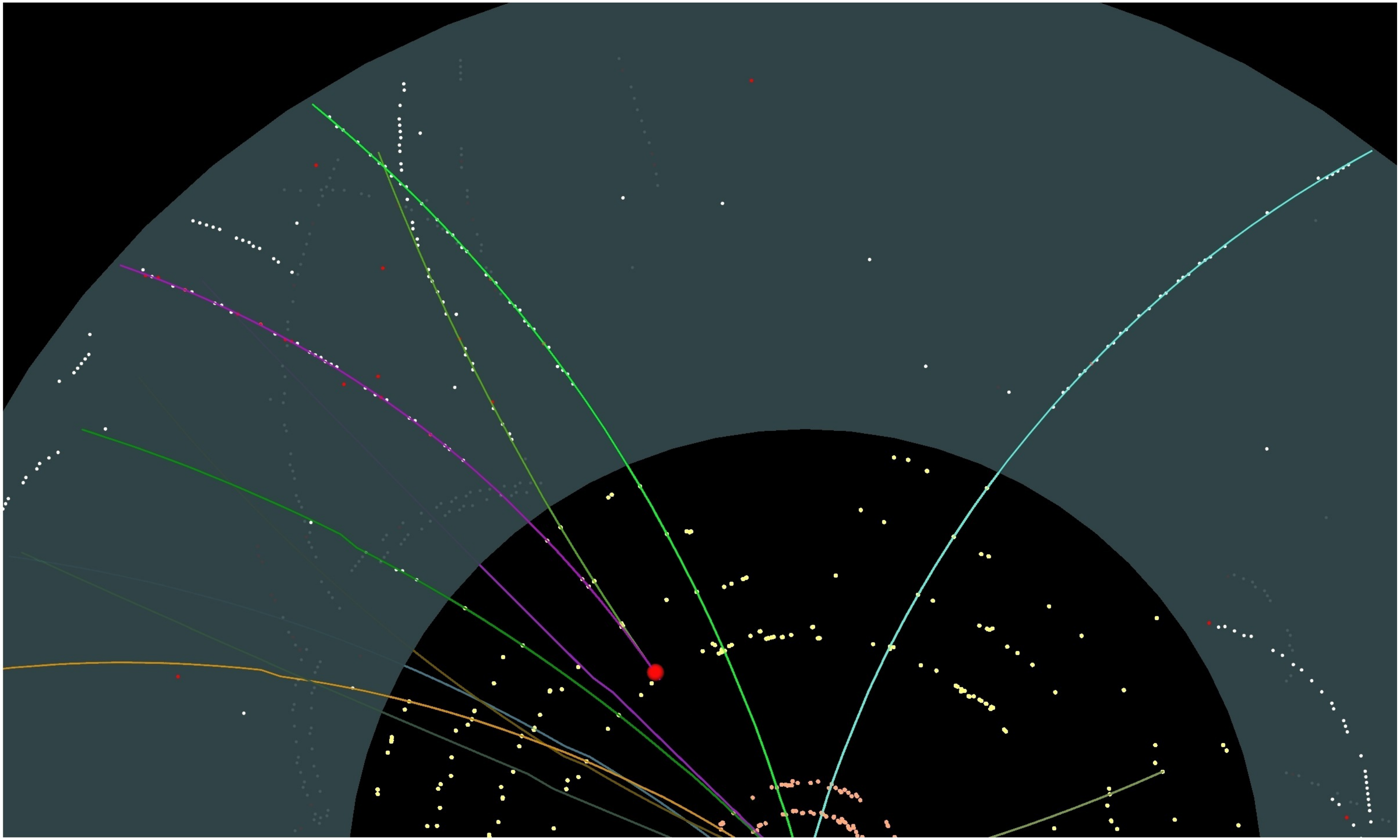
$$\sigma = \frac{7A}{9X_0N_A}$$

  - X_0 depends on material, density
- Same as first part of EM shower
  - Silicon detector as “pre-shower”

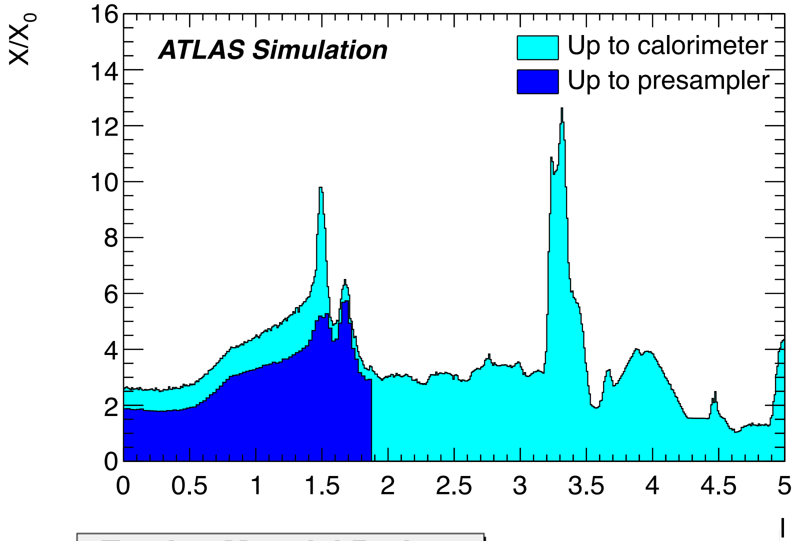
- Vertex strategy is similar to V^0 reconstruction (use as cross-check)
- In many cases, the converted photons are easier to measure as a positron-electron pair

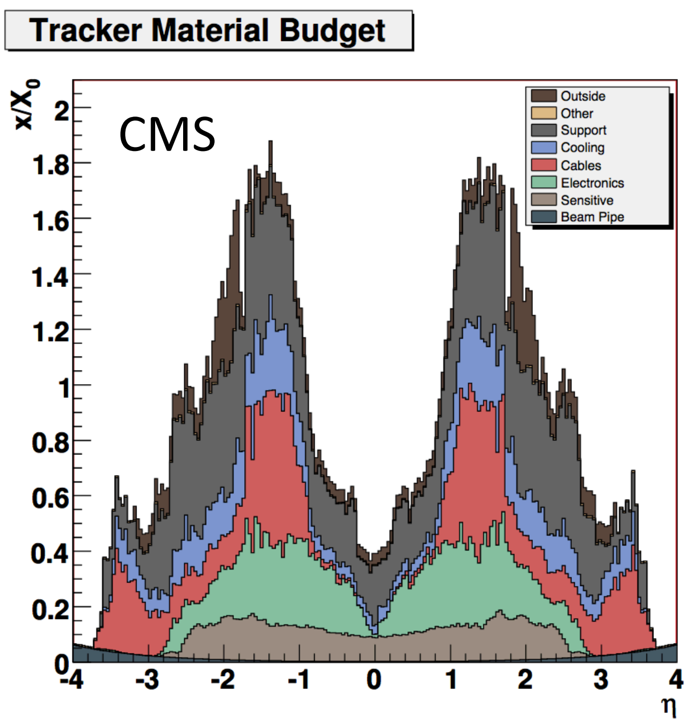


Conversion in ATLAS Silicon Detector

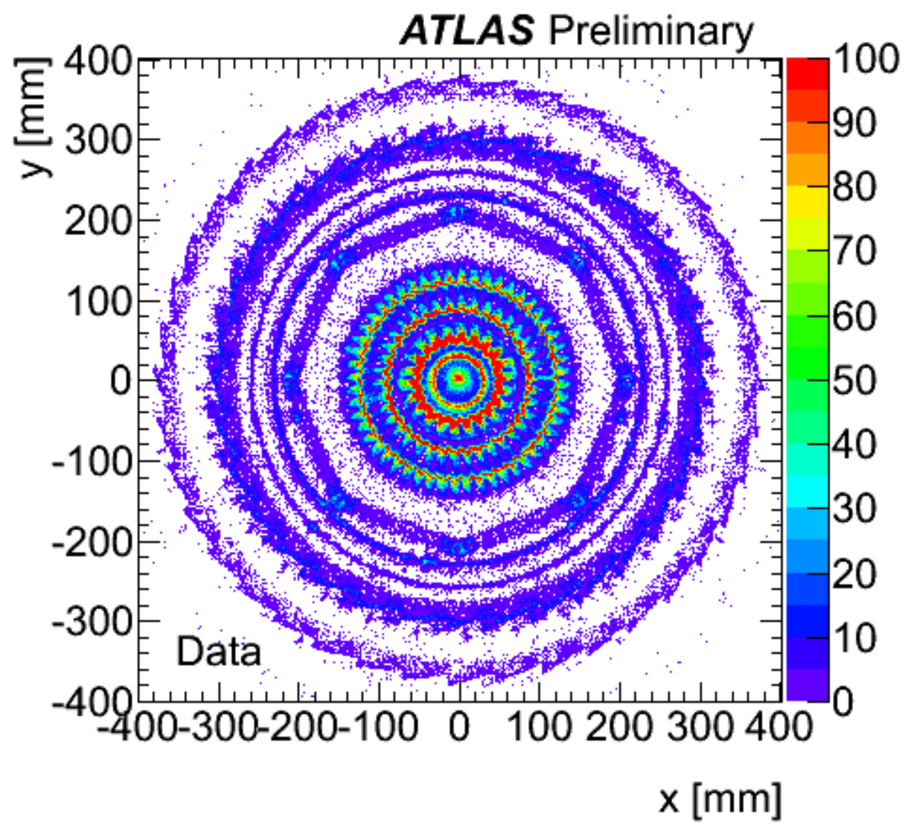


Dependence on Material



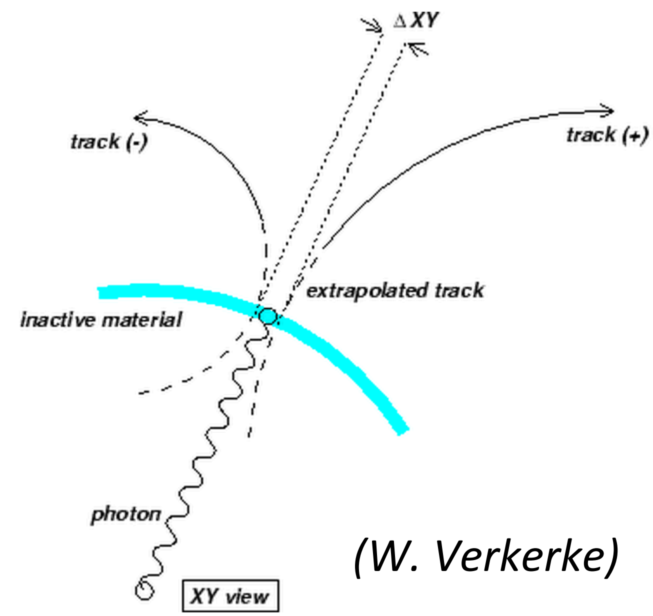


- Direct measurement of differential material *in-situ*
- Radial resolution: O(3mm)
- Feed back into Kalman filter



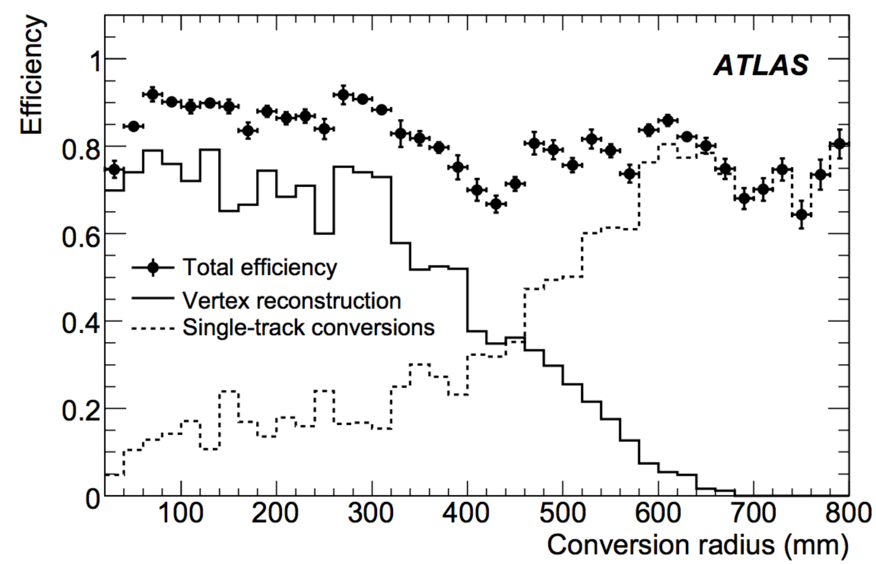
Reconstructing Converted Photons

- Characteristic ΔXY=0 and Δθ=0
- Select electron tracks (incl. TR HT cut)
- Vertex fit is another fast Kalman filter
  - Apply constraints (common vertex pos. and opening angle) using Lagrange multipliers
  - DCA is used as first estimate of vertex pos.



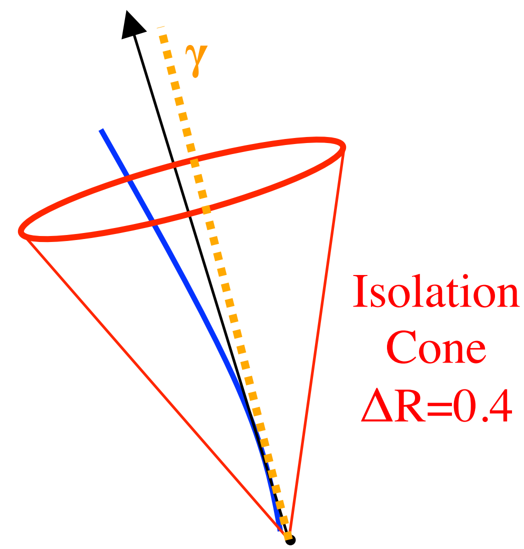
(W. Verkerke)

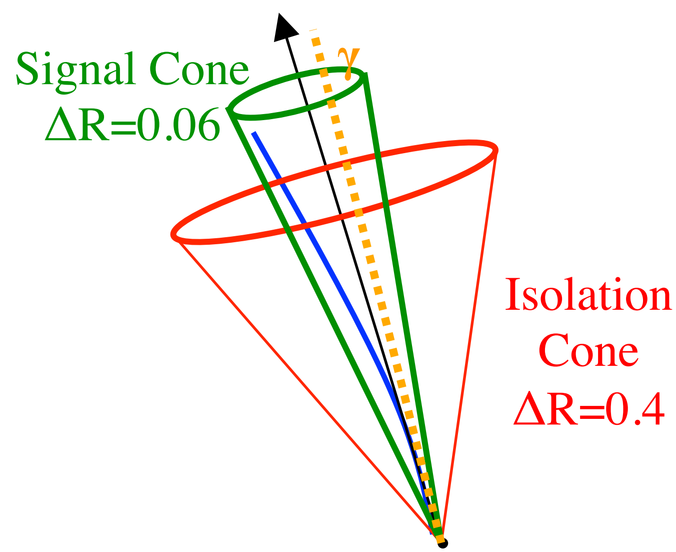
- Conversions at large radius may have tracks merged into 1 trk
- Asymmetric conversions may have only 1 trk passing p_T cuts
- Single-track conversions: electrons with no hit in 1st layer



Isolation Requirements for Photons

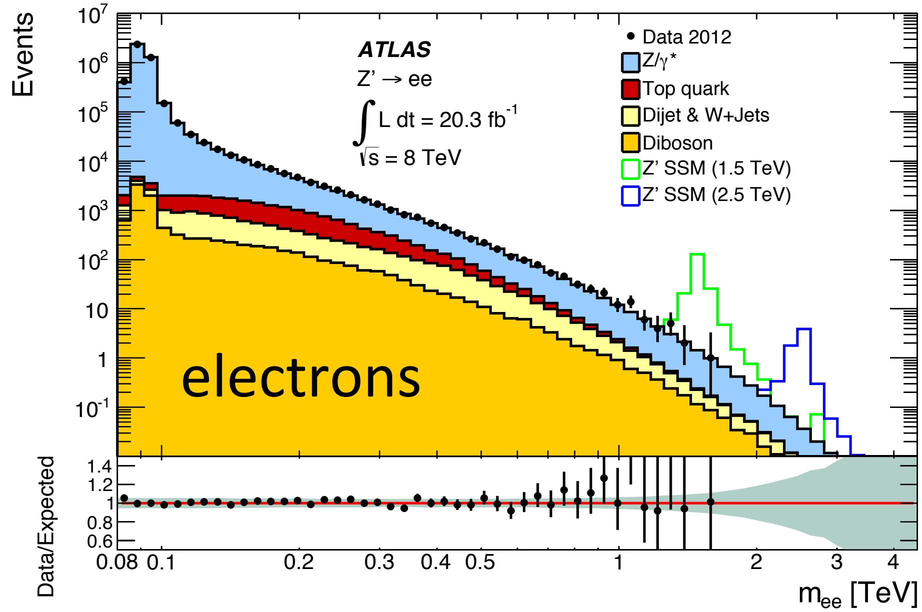
- "Prompt" or "direct" photons are isolated from jet activity
- Need isolation metric insensitive to soft activity
- Cone isolation based on:
  - Tracks: sum p_T around γ
  - Calo cells/clusters: sum E or E_T, not including the photon
- Isolation needs to account for
  - Soft underlying event
  - Pileup correction in calo
  - Jets and other particles
- Tune cone sizes to minimize effects of pileup and jet activity in the event

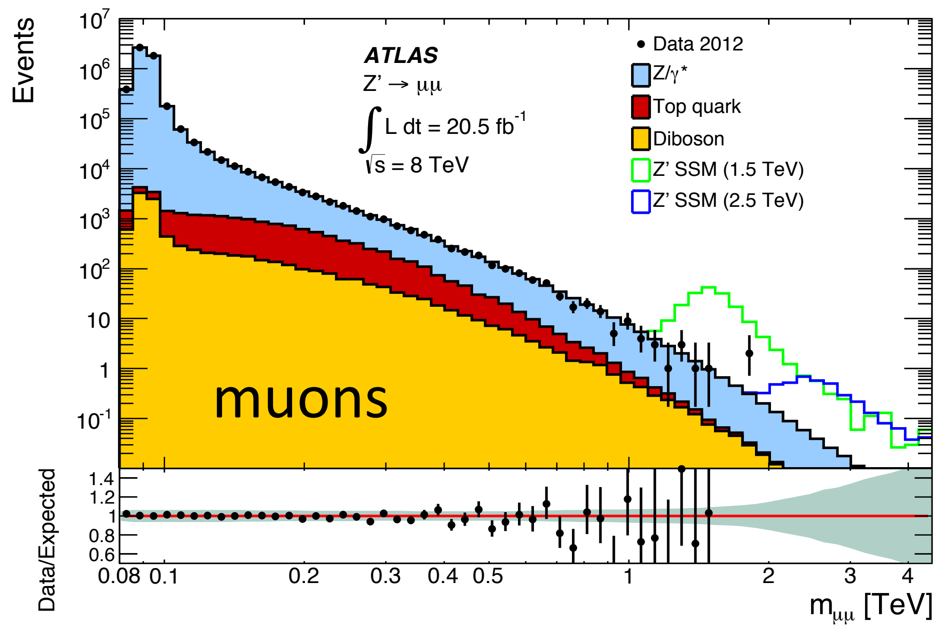




Muon Reconstruction: Motivation

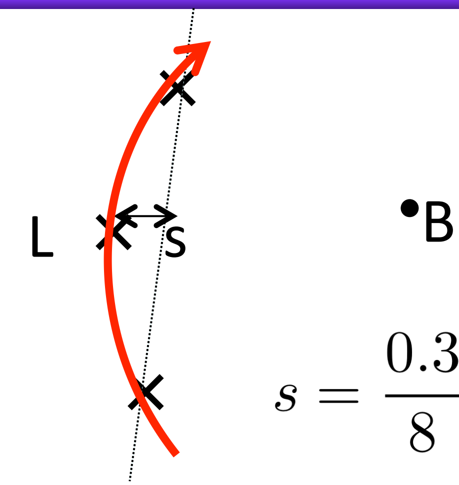
- Maintain good resolution for 1 TeV muons from Higgs decays and exotic resonance decays
  - Electron resolution from calorimeter improves as $E^{-0.5}$
  - Muons are limited to tracking resolution (geometric effects)
- Maintain good efficiency for soft muons (<5 GeV) that will curl up inside calorimeters
  - Low-p_T muons from b-jets
  - Low-p_T muons from H(ZZ) decay



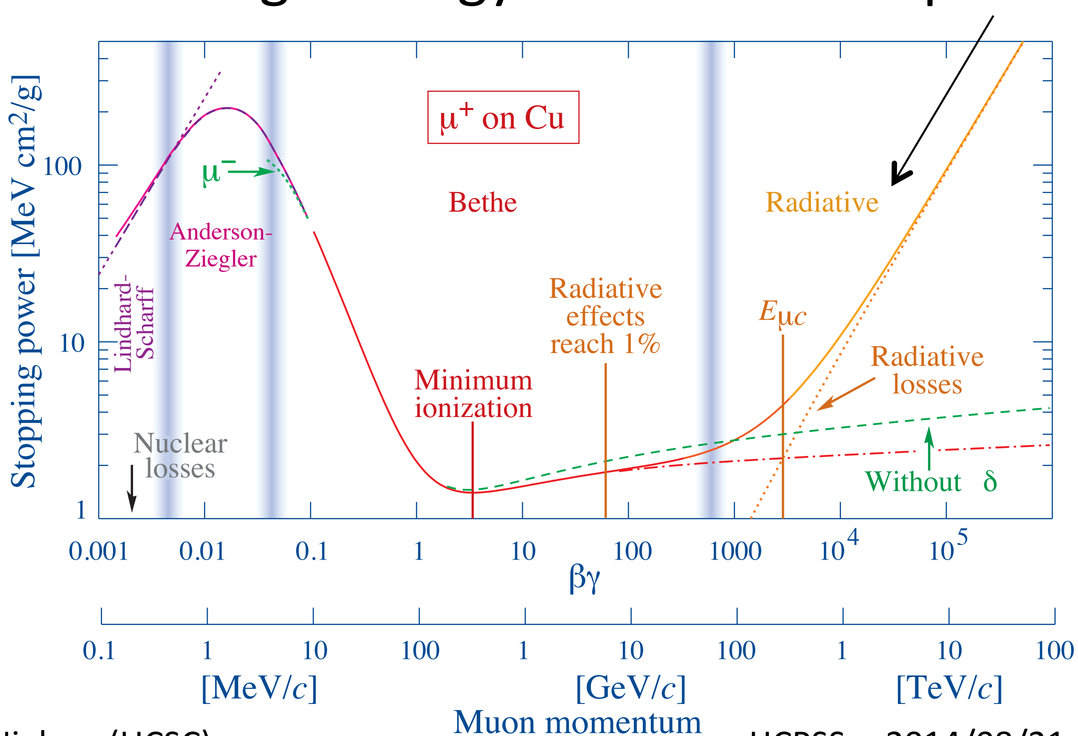


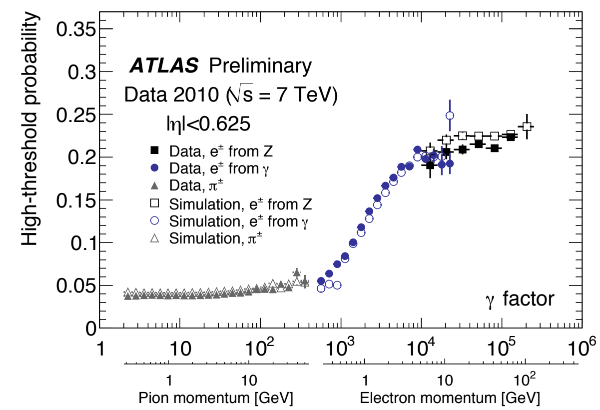
Challenge of High-Momentum Muons

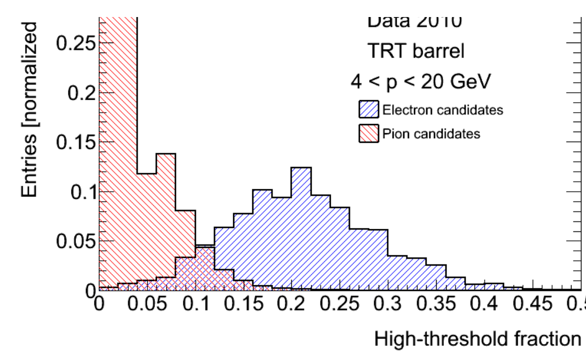
- Detector gives the sagitta measurement, which is translated to curvature
- Measuring sagitta of 1 TeV muon requires large L <u>and</u> large B
  - Different approaches for ATLAS and CMS
- Ultra-high energy muons radiate photons!



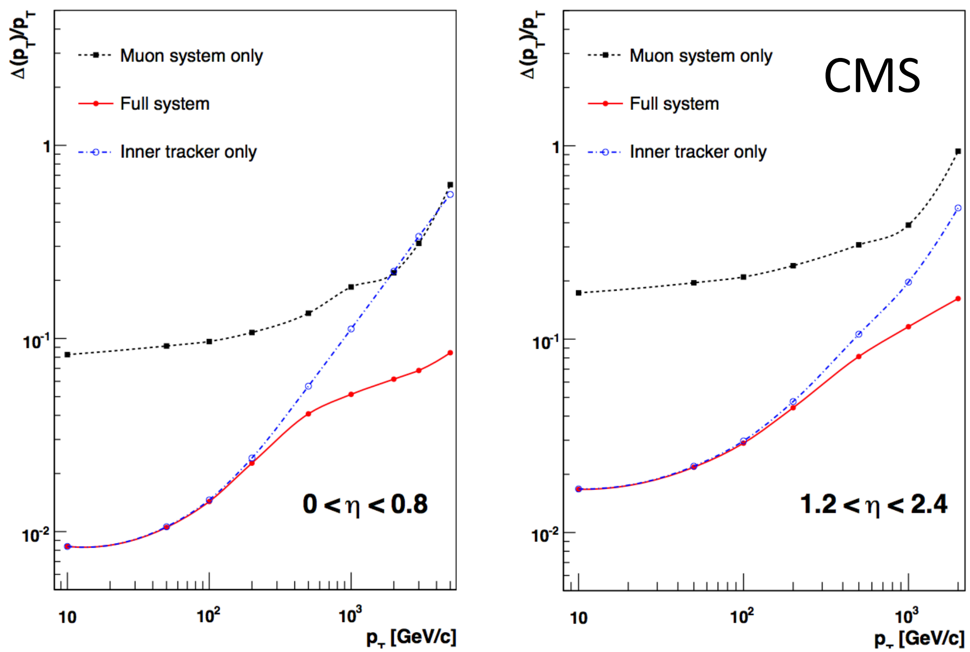
$$s = \frac{0.3}{8}\frac{L^2 B}{p_T}$$

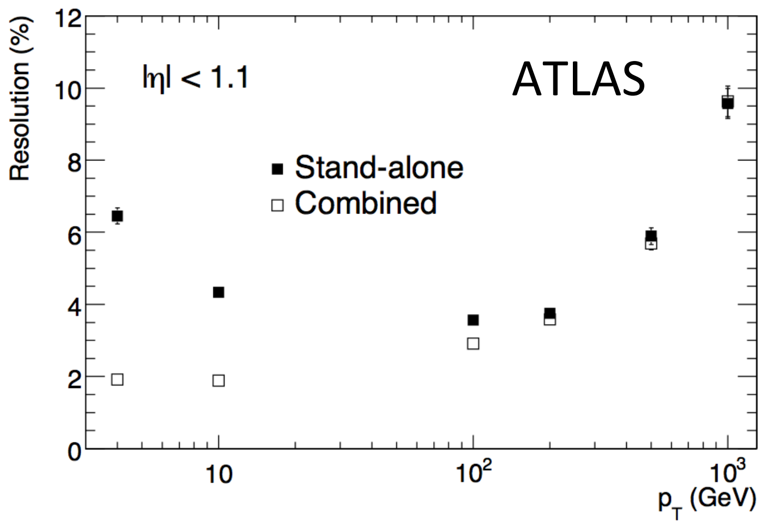






Standalone vs. Combined Reconstruction

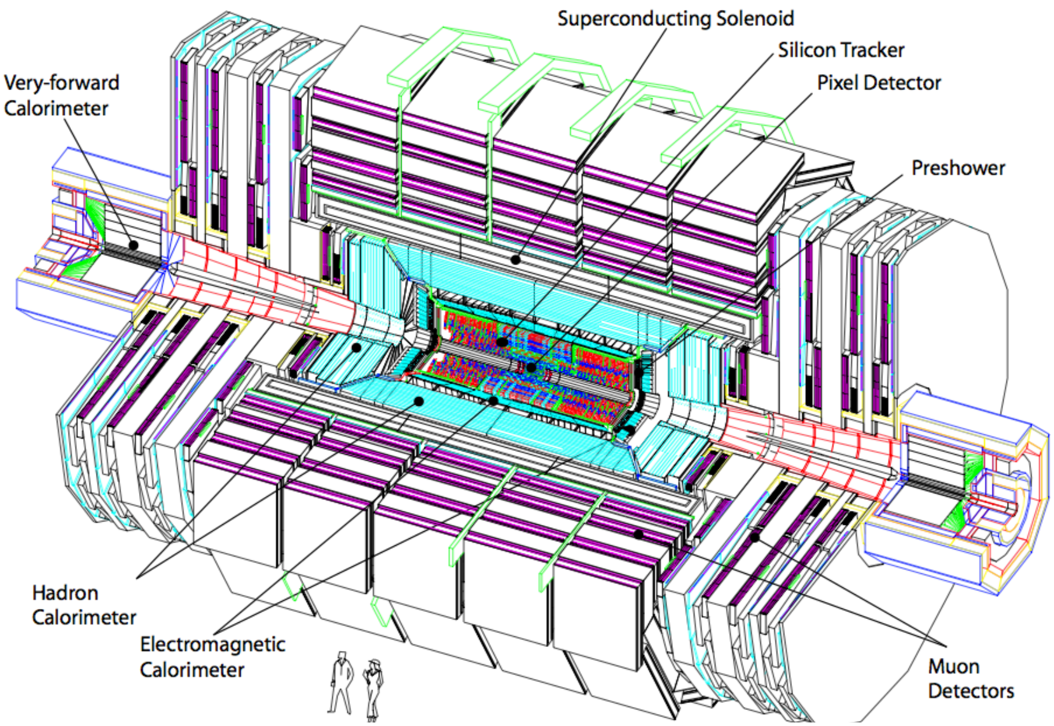




- Extrapolate inner track to muon chambers to match segments and form combined/global tracks
- Good low-p_T resolution depends on inner track
  - Excellent hit resolution
  - No gaps in coverage
  - Large CMS tracker
- Good resolution at p_T=1 TeV
  - Still CMS silicon tracks!
  - For ATLAS, stand-alone muon spectrometer

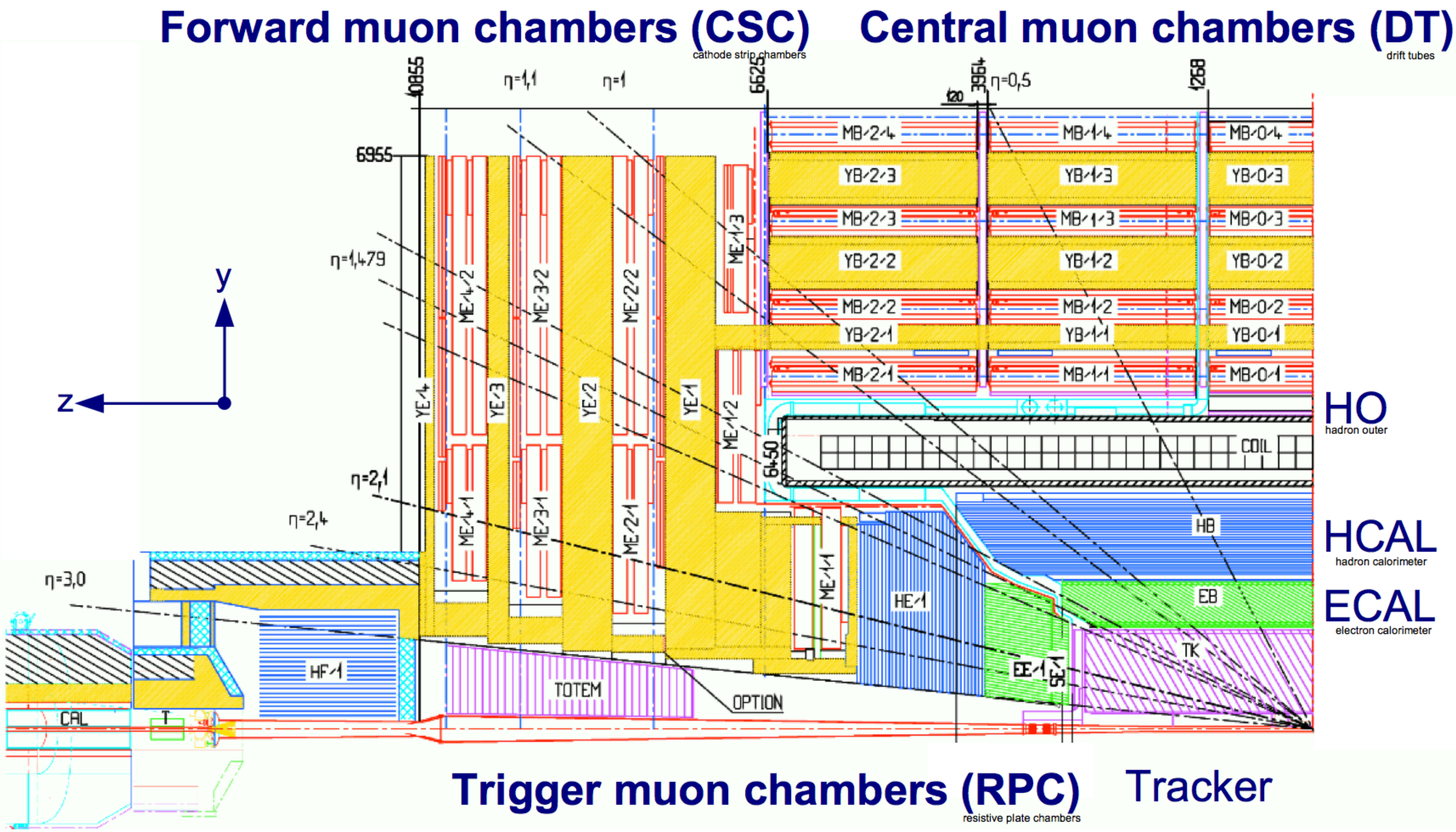
Extended Muon Coverage

- Muon chambers are always at large radius for particle ID purposes
  - Requires large surface area for complete solid angle coverage
  - Therefore requires inexpensive detector technologies
  - Inevitable holes for cables and cooling going to inner detectors
  - Different magnetic field configurations and radiation environments require different technologies

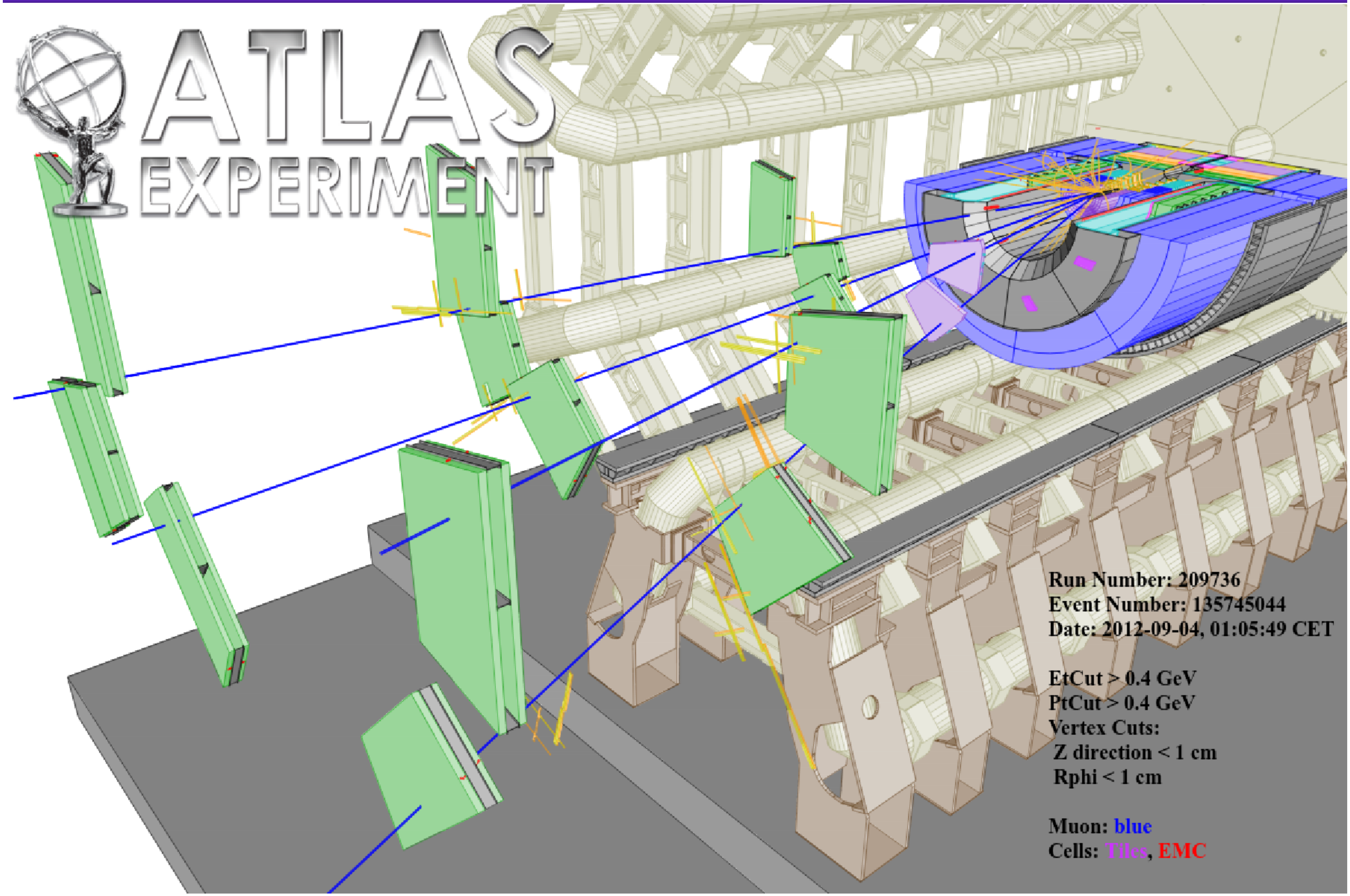


CMS Muon Coverage

Challenge to maintain consistent coverage over all η

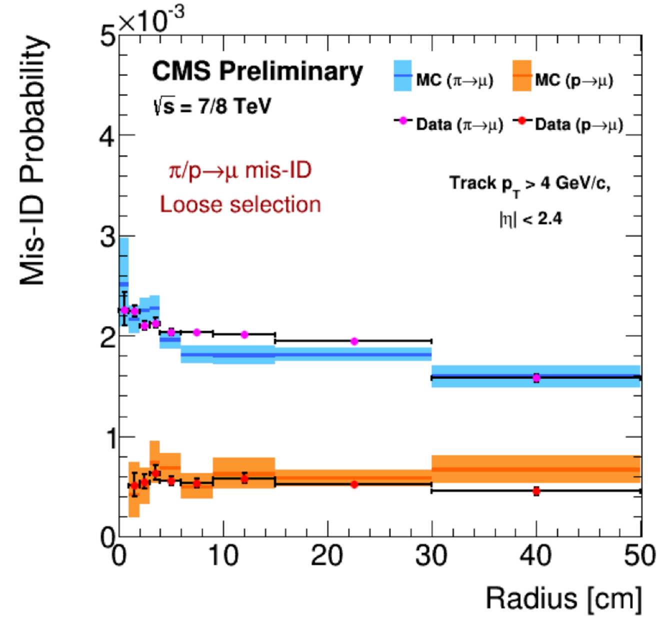


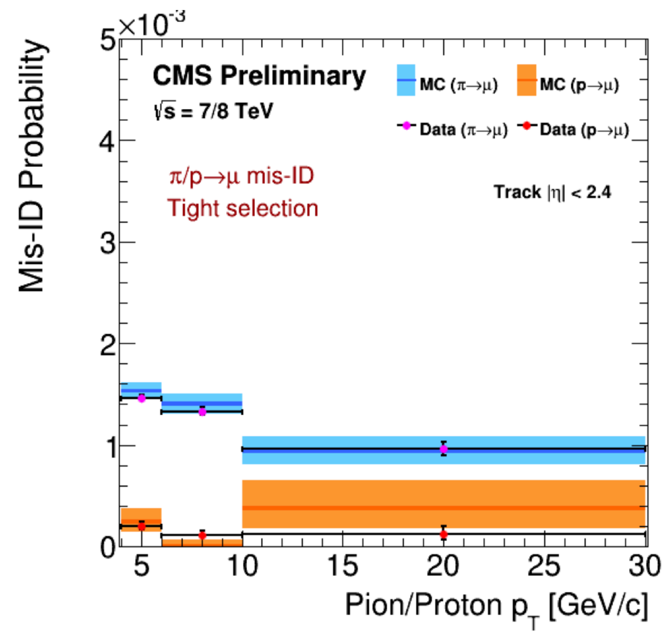
Higgs Decay in Forward Region



"Punch-Through" Effects: Muon Mis-ID

- Are the muons from the hard scatter really the only particles making it all the way out to the muon system?
- At least three other possibilities (total <1% for CMS):
  - "Decay-in-flight": true muons produced in decays of heavy flavor or even from decays of π produced in hadronic shower ($c\tau_{\pi}$ = 8 m) [biggest effect]
  - "Punch-through": hadronic shower penetrates entire HCAL. Survival probability goes as $\exp(-L/\lambda)$, with interaction length λ
  - "Sail-through": particle does not initiate hadronic shower [very unlikely for these large cross section interactions]
- But be careful: the Run 1 CDF detector was limited to 80 cm of iron
  - Fe: 132 g/cm^2 / 7.87 g/cm^3 = 17 cm interaction length
  - So there were perhaps 6-7 interaction lengths in front of the muon system (compare to 16 for CMS); this was fixed for Run 2

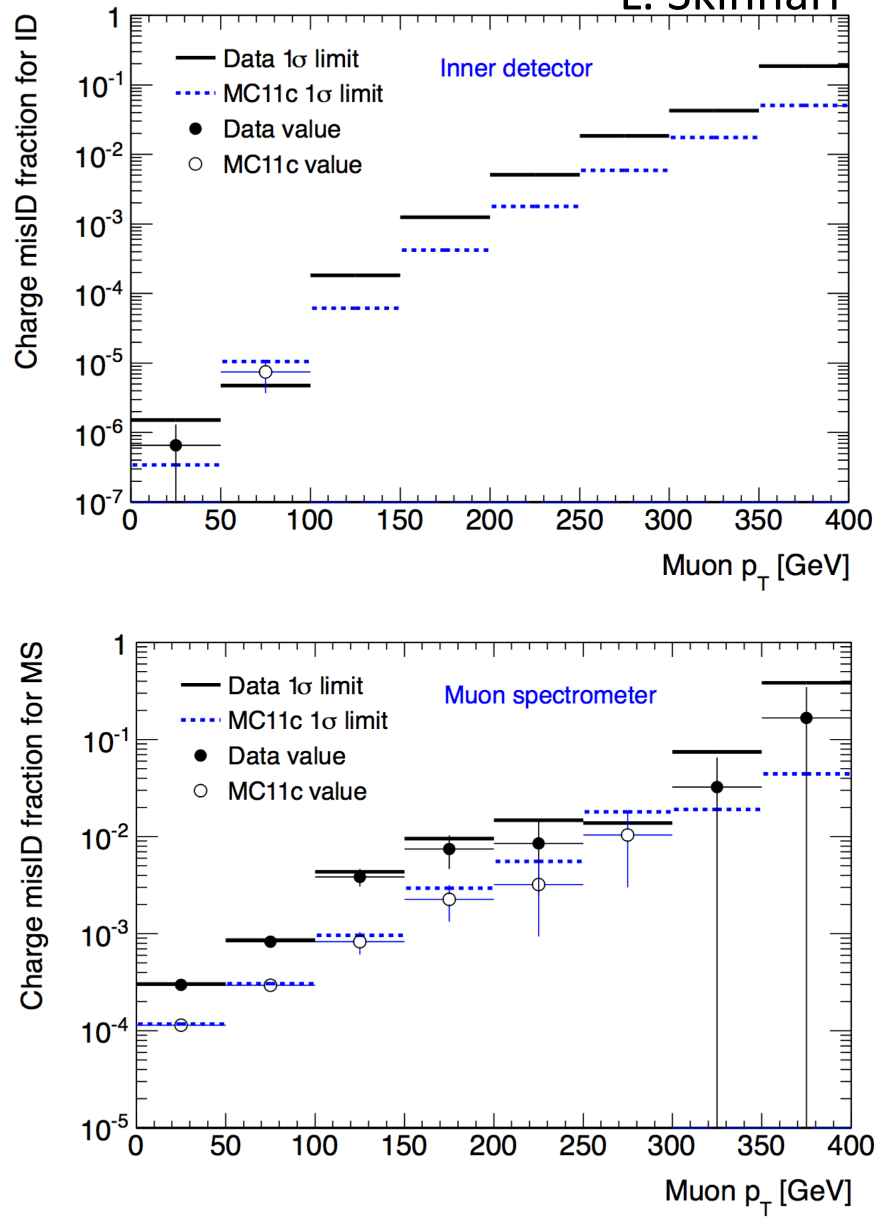




Charge Mis-Identification

L. Skinnari

- Detector measurement of sagitta is actually curvature
- For very high-p_T tracks, curvature resolution can lead to charge flipping
  - Electrons have additional bremsstrahlung mechanism
- Estimate from muon pairs under the Z mass peak
  - Assumed to be oppo-sign pairs
- These rates are most important for searches for same-sign lepton pairs
  - Compare inner silicon tracker and muon spectrometer



Efficiency and Fake Rate Estimates

- Monte Carlo simulations are effective for estimating simple rates
  - Geometric acceptance
  - Reconstruction efficiency (modulo data/MC scale factors, usually close to 1)
  - Number of hits in tracker
- Not so effective for estimating fake rates because of
  - Fragmentation functions and soft particle isolation
  - Tails of shower shape distributions
  - Rare reconstruction effects or physical processes
  - Distributions for complicated quantities (missing E_T, MVA outputs)
- Preferred method is to measure efficiency scale factors and fake rates from *in-situ* data samples
  - Somehow this is more true at hadron colliders than e^+e^- colliders
  - Sometimes not even possible because of limited sample at edges of kinematic phase space; show extrapolation is reasonable

Tag-and-Probe Methods

- If a muon and another particle happen to combine to m_Z, what is the other particle?
  - "Tag" a lepton with tight ID
  - Fixes flavor of partner "probe"
- Measure efficiency of tight ID on the "probe" particles,
  - This depends on loose efficiency being as near as possible to 100%
- For practical purposes, derive scale factors for use on MC
  - Allows extrapolation into more complicated phase spaces
  - Points out improvements needed in generator and simulation

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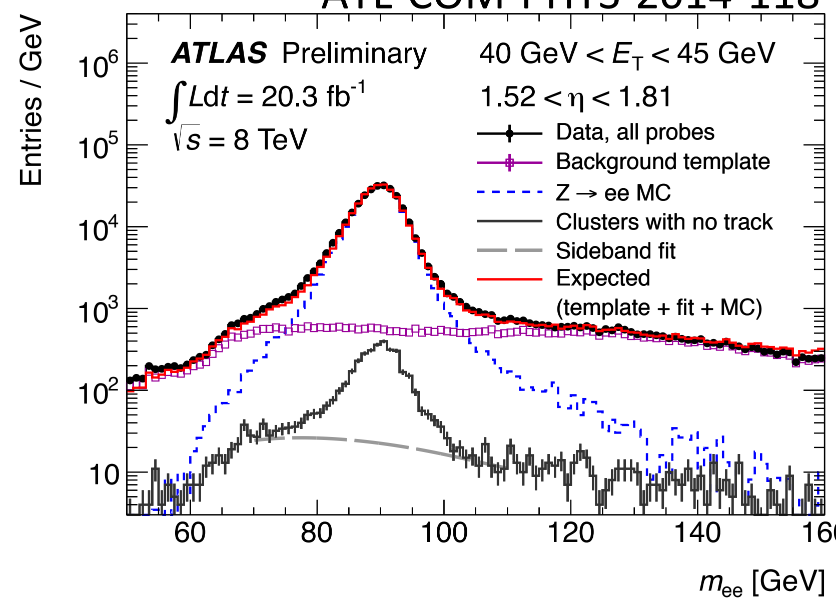
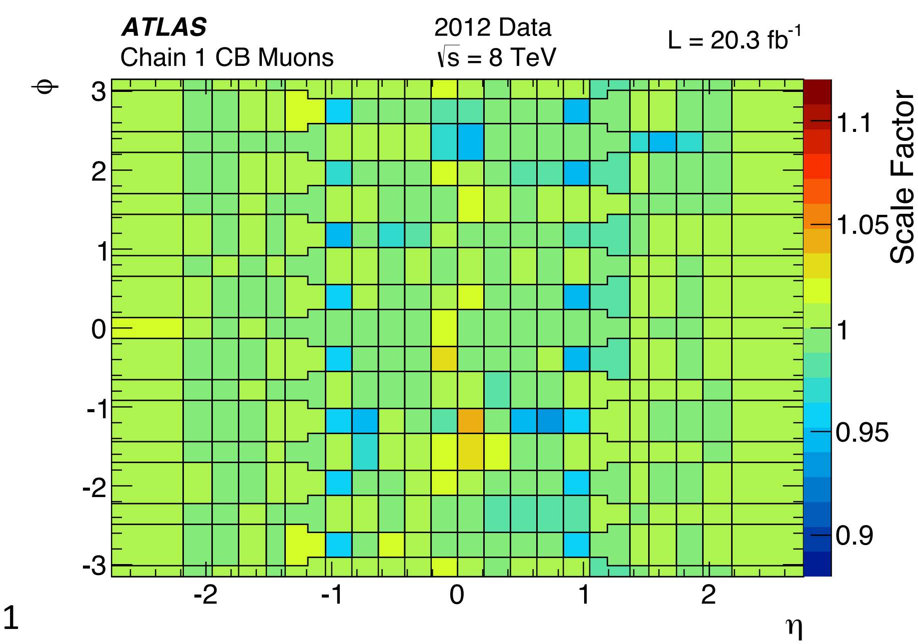
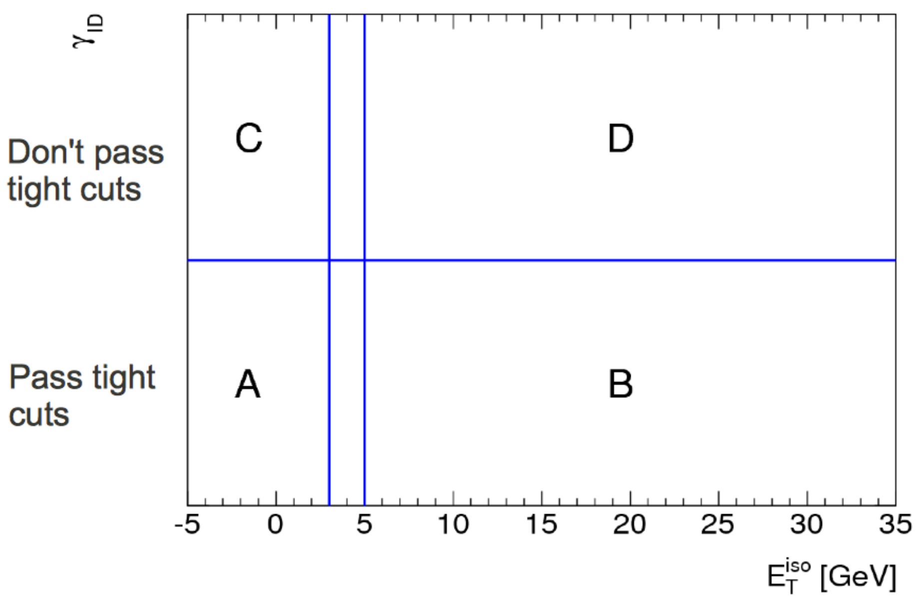




"ABCD" or "Matrix" Methods



$$N_A^{yield} = N_A - N_A^{bkg} = N_A - R^{bkg}\frac{(N_B^{obs} - N_B^{sig})(N_C^{obs} - N_C^{sig})}{N_D^{obs} - N_D^{sig}}$$

$$R^{bkg} = \frac{N_A^{bkg}\,N_D^{bkg}}{N_C^{bkg}\,N_B^{bkg}} \qquad c_x = \frac{N_x^{sig}}{N_A^{sig}} \qquad \text{from MC}$$

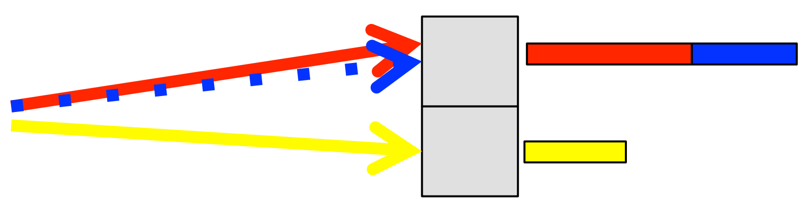
- Assume ID requirements (shower shape, etc.) are not correlated with isolation E_T
- Measure extrapolation factor between background-dominated regions C,D
- Apply factor to data in B to find background in A

$$N_A = N_B \times \frac{N_C}{N_D}$$

- More complicated versions subtract known signal contamination in B,C,D

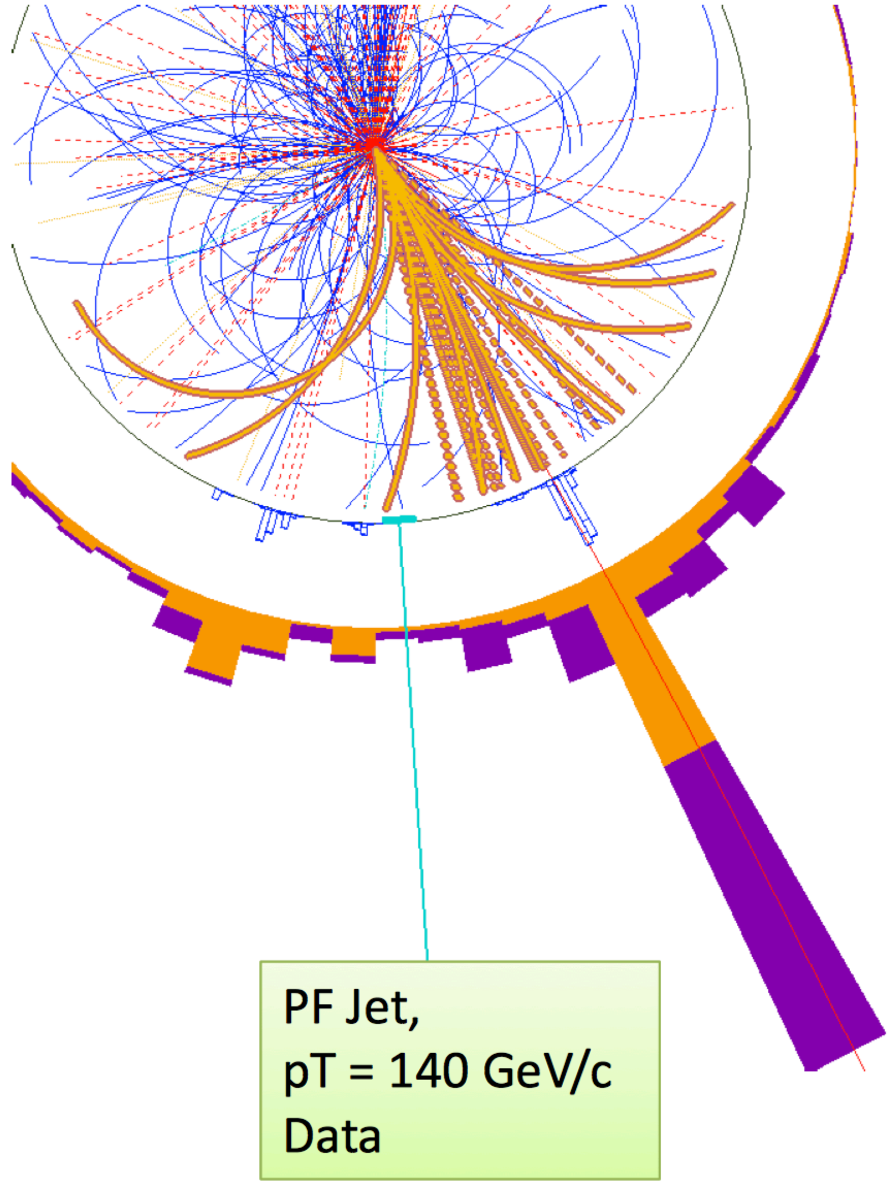
Particle Flow

- Calorimeter fluctuations contribute to large uncertainties for measurements of low-energy particles: 1/N = 1/√E effect
  - Results in large uncertainties for jet energy and missing E_T measurements
- Can we use the tracking measurements instead to find the energies of the low-energy charged particles? Still need calo for neutrals…
- This method has been used successfully at e^+e^- collider experiments
  - Can it possibly work at a hadron collider? YES – CMS has made it work
- Expect improvements where there is a mix of low-p_T charged and neutral particles in close proximity
  - Hadronic jets, tau lepton signatures, missing E_T measurements
  - Typical jet composition is 60% charged, 25% photons, 15% neutral hadrons

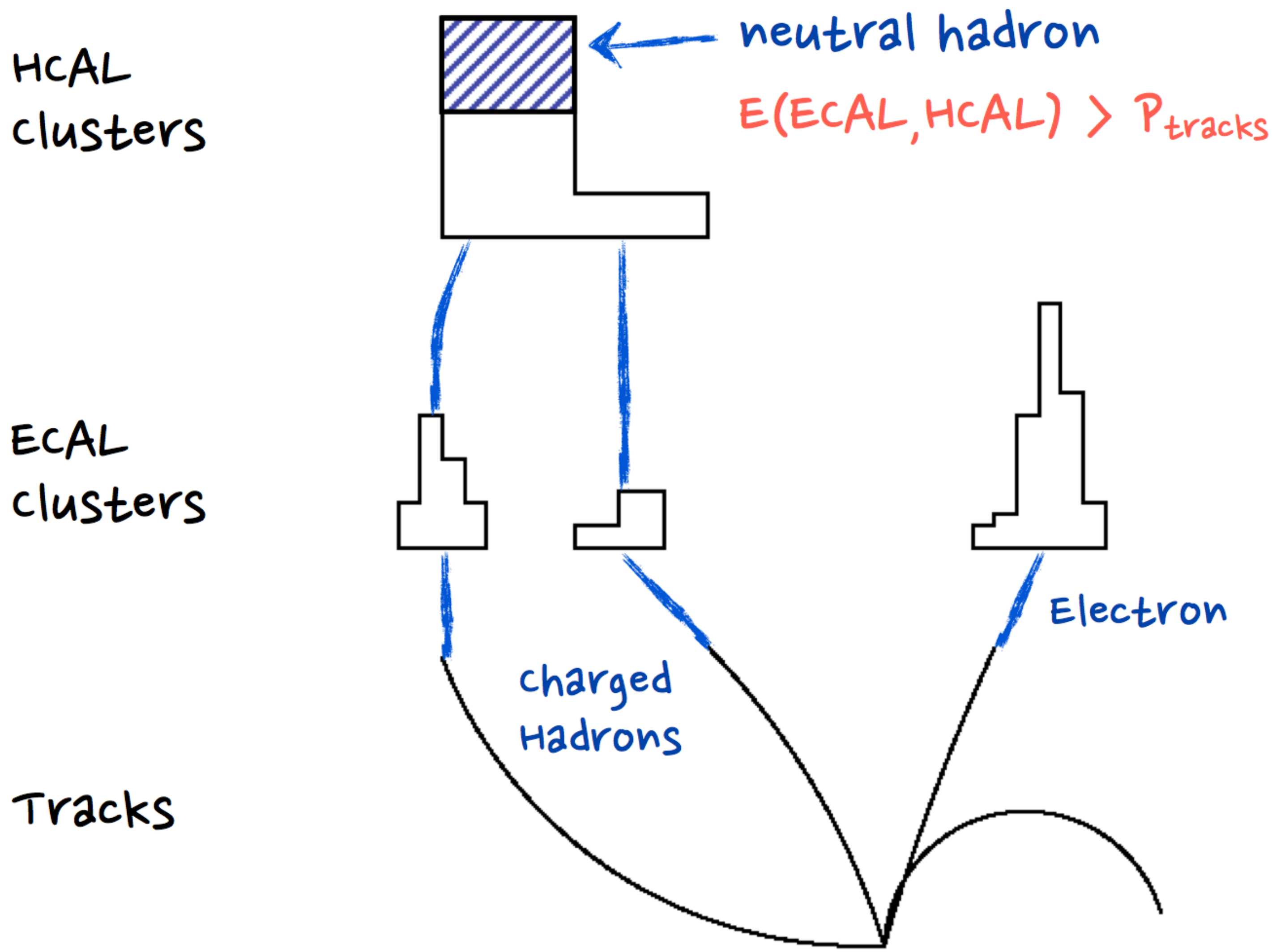


Detector Requirements

- Need to spread out charged particles to avoid merging
- Highly granular calorimeter
- High-resolution tracker
- Particle ID w/o extra material
- High B field at large radius
  - CMS: 3.8 T x 1.3 m
  - ATLAS: 2.0 T x 1.2 m
  - D0: 2.0 T x 0.8 m
- Very efficient tracking algos
- Physicist requirements: several years to tune the algorithms and minimize mis-associations!



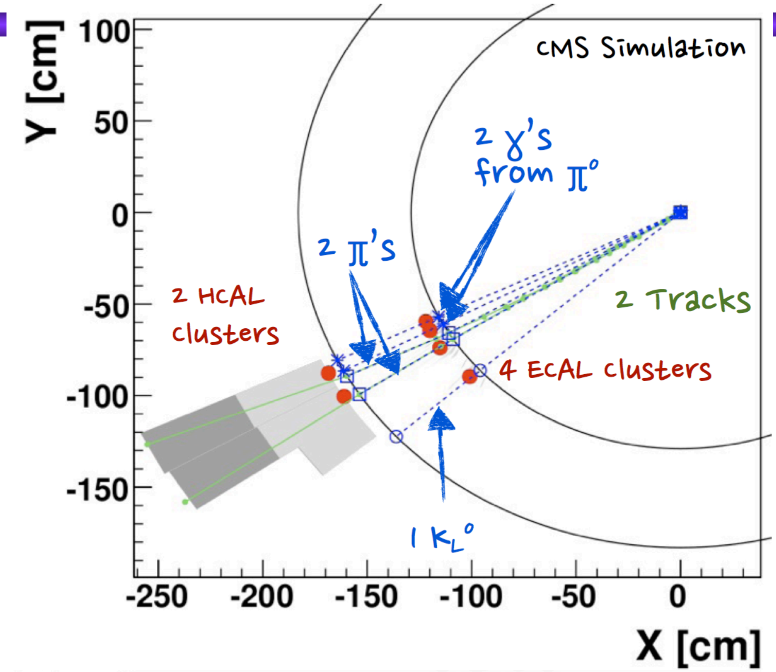
Basic Concepts for Particle Flow

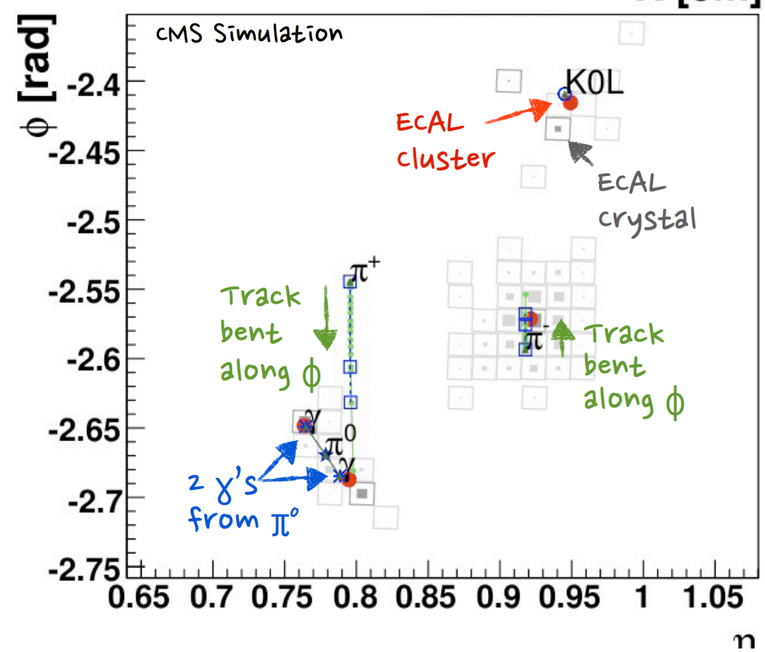


Diagrams from R. Cavanaugh and P. Janot

Matching Tracks to Calorimeter Cells

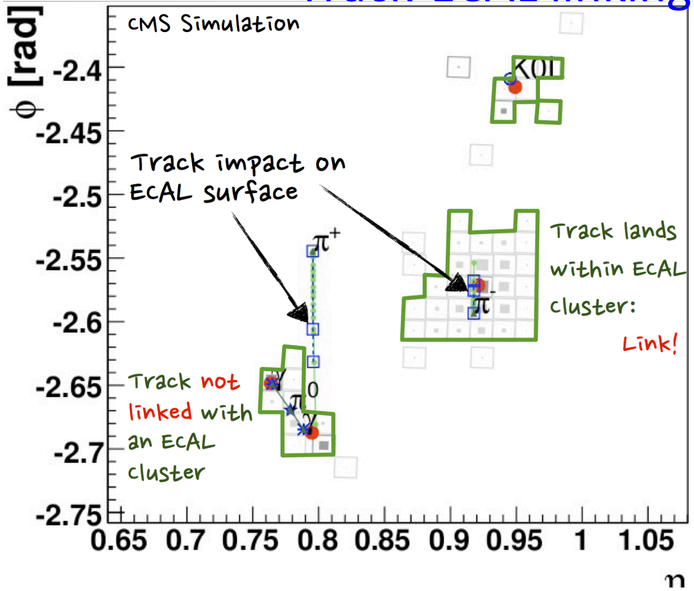
- Link algorithm produces "blocks" of inputs (track/ECAL/HCAL)
  - Extrapolate track to ECAL shower max and HCAL 1λ
  - Link to the cluster at that position
  - Also extrapolate track tangents to recover bremsstrahlung from electrons
  - Link ECAL and HCAL clusters when their boundaries overlap
  - Link to muon standalone tracks using a matching χ^2
- Excess energy in the clusters gives rise to a "particle-flow neutral hadron" or "particle-flow photon", depending on ECAL or HCAL



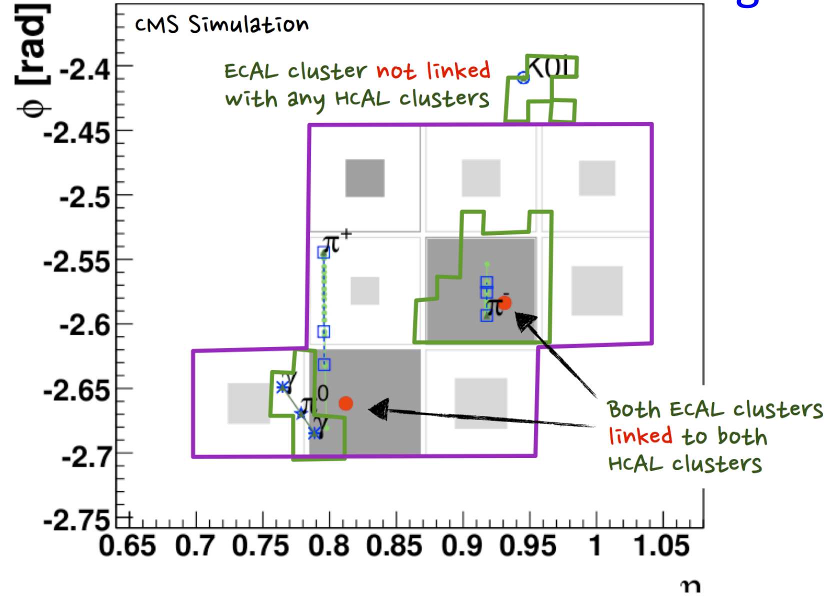


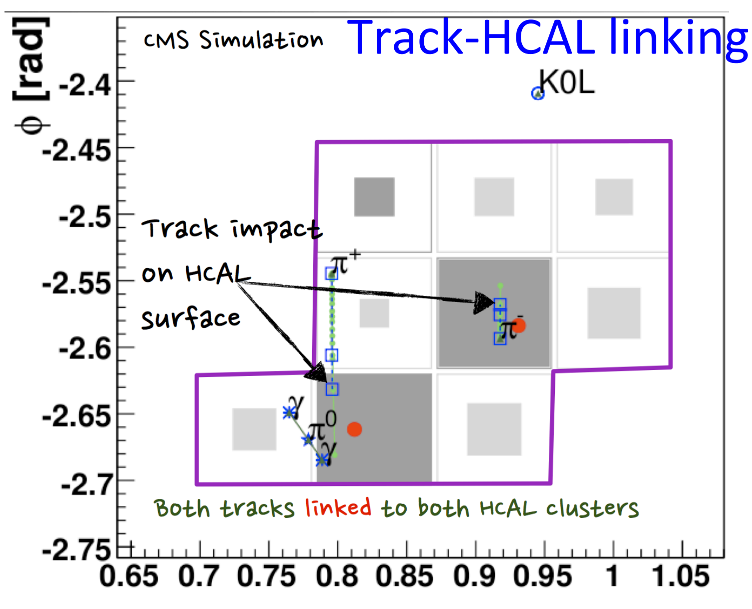
Particle Flow Algorithm

Track-ECAL linking



ECAL-HCAL linking





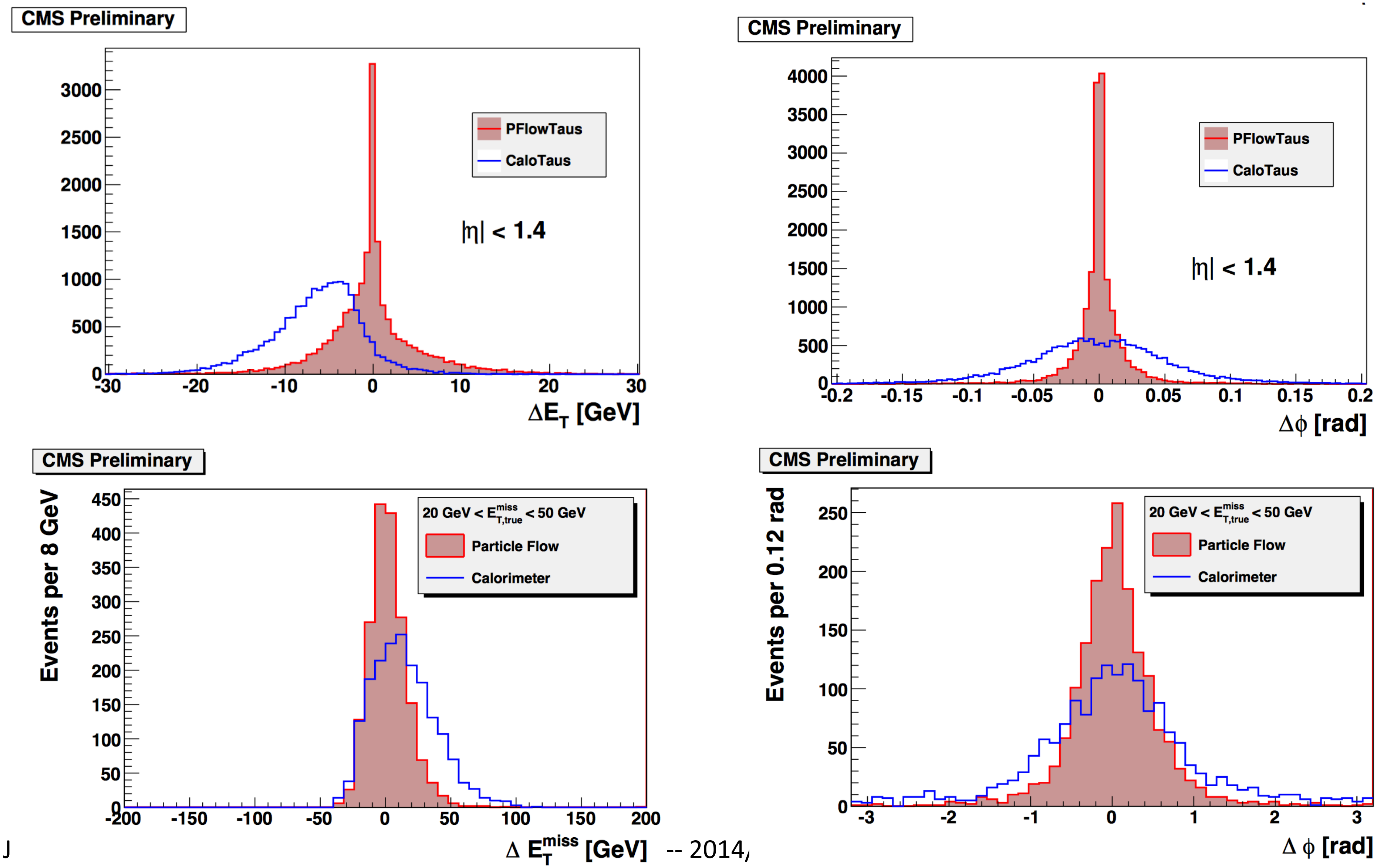
Particle Flow Sequence

- Find and “remove” muons (σ_{track})
- Find and “remove” electrons (min[σ_{track}, σ_{ECAL}])
- Find and “remove” charged hadrons (σ_{track})
- Find and “remove” converted photons (min[σ_{track}, σ_{ECAL}])
- Find and “remove” V0’s (σ_{track})
- Find and “remove” photons (σ_{ECAL})
- Left with neutral hadrons (10%) (σ_{HCAL} + fake)
  - Same relative uncertainty on these remaining hadrons, but the total contribution to the jet/event energy has been significantly reduced

- Final steps are to combine particles that have been found into a total jet/tau/event energy

Performance of Particle Flow Algorithm

- Striking improvements in tau and missing E_T energy and direction



Summary of Today's Topics

- Neutral particle ID includes calorimeter *and* tracking
  - Unconverted and converted γ, π^0, V^0 decays
- Requirements on e/γ shower shapes depend on detector geometry
  - Common requirements to reject π^0 decays and other jet deposits
  - Isolation requirements required for prompt photon selection
- Photon conversions are a winning ID strategy!
  - Clean reconstruction using powerful new silicon tracking systems
  - Combination of tracker+calorimeter is still best at high energy
- Muon reconstruction combines inner and outer tracking results
- Leverage tight vs. loose selections to measure ID efficiency
  - Variations on "matrix method" solve systems of equations for contributions
- Particle flow algorithms are the cutting edge for detectors with good tracking efficiency; potential to improve jet/MET resolution

Plan for Tomorrow

- Jet reconstruction
  - Jet clustering algorithms and calculations
  - Jet cleaning (calorimeter effects)
  - Pileup subtraction and assignment techniques
- Tau lepton reconstruction
  - Tau lepton decay signatures
  - Tau lepton identification algorithms
- Heavy-flavor tagging
  - Geometry of heavy-flavor hadron decays
  - Multivariate techniques and calibration
- W boson and top quark tagging
  - Jet grooming techniques, boosted jet shape calculations
  - Top-tagging algorithms
- Missing E_T

Guide to Further Reading

- Lectures by Rick Cavanaugh at HCPSS 2012: https://indico.fnal.gov/sessionDisplay.py?sessionId=11&confId=5615
- Public results of reconstruction performance in experiments:
  - ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome#Combined_Performance_Groups_Simu
  - CMS: http://cms.web.cern.ch/org/cms-papers-and-results
  - ALICE: https://twiki.cern.ch/twiki/bin/view/ALICEpublic/ALICEPublicResults#Physics_Working_Group_PP
  - LHCb: http://lhcbproject.web.cern.ch/lhcbproject/CDS/cgi-bin/index.php