LHC Physics
GRS PY 898 B8

Lecture #6

Tulika Bose

Feb. 23rd, 2009

Lepton Identification

Seminar Schedule

SPRING BREAK	
3/16/2009 (Mon)	Seminar (Higgs: Phil Lawson)
3/23/2009 (Mon)	Seminar (SUSY: Adam Avakian); Veronica Sanz
3/30/2009 (Mon)	Seminar (Exotica: Cory Fantasia)
4/6/2009 (Mon)	Seminar (Exotica: David Schaich)
4/13/2009 (Mon)	Seminar (Electroweak: Keith Otis)
4/20/2009 (Mon)	University Holiday
4/23/2009 (Thurs) (unusual day)	Seminar (QCD: John Roush)
4/27/2009 (Mon)	"Conference"

Seminars this week

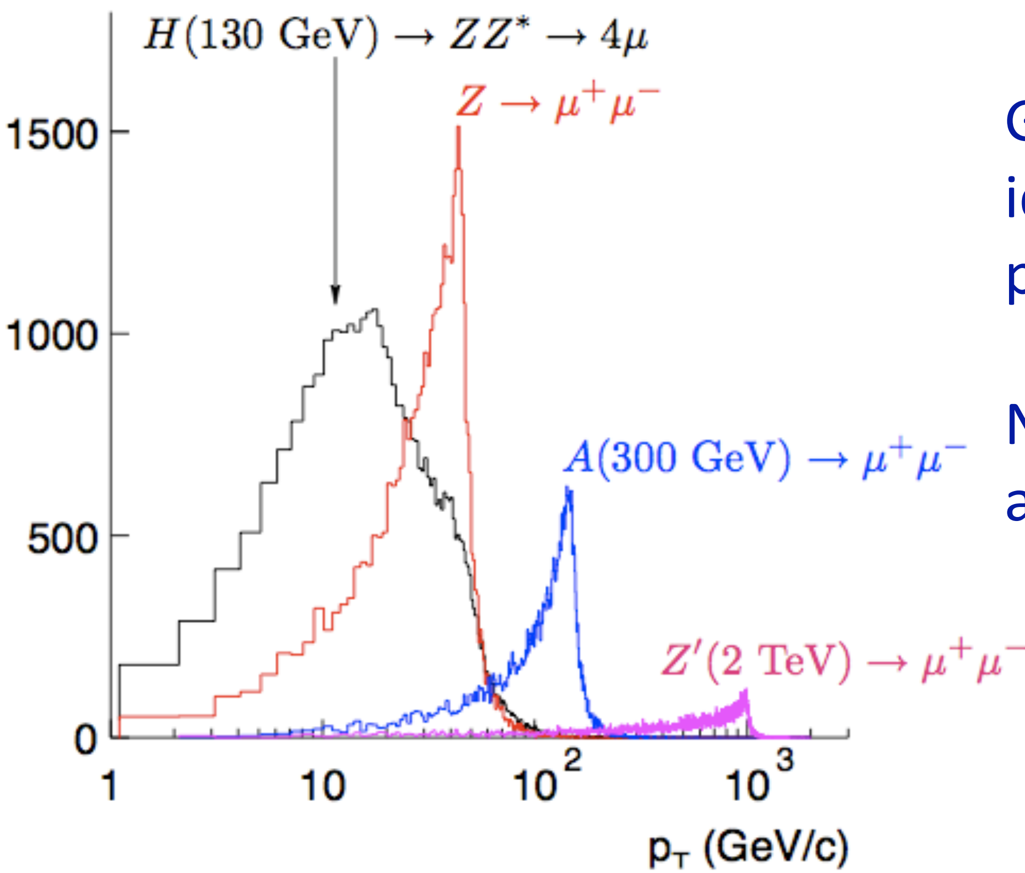
Feb26	Ketevi Assamagan Brookhaven National Laboratory	What can we learn about the Higgs with 10/fb at the LHC?
Feb25	Dan Duggan Florida State University	Recent results of the photon plus heavy flavor jet cross sections at D0

Special day and room: PRB 261, Wednesday 4:00-5:00 PM

References

- Hadron Collider Summer School: http://hcpss.web.cern.ch/hcpss/
- Commissioning of Particle ID with early LHC data
  - (arXiv:0808.3820)
- Electron/Photon Identification in ATLAS and CMS
  - (arXiv: 0709.2479)

Muons @ LHC

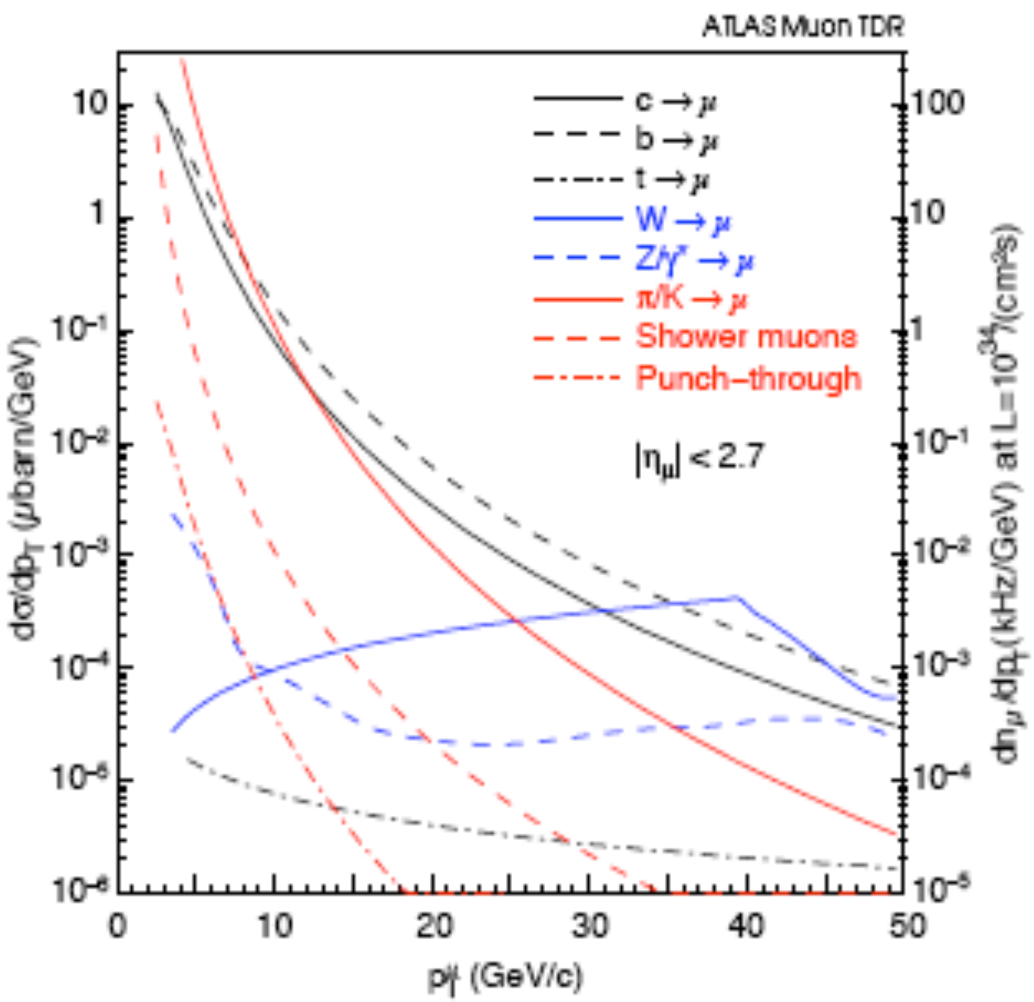


Good muon reconstruction and identification is crucial for physics at the LHC

Need high efficiency detection and over wide momentum range

Muon Identification

Inclusive muon cross sections



Muon Identification Tasks:

1. Trigger on high-p_T single muons and muon pairs
2. Measure muon momenta (independently of tracker)
3. Reject muons from pion/kaon decays, showers and punch-throughs

Expected composition of muon L1 trigger at ~ 10 GeV

- About 50% heavy flavors
- About 50% π/K decays

Most muons are real but also non-isolated and embedded in jets with wide range of transverse energies

Limiting Factors

Energy loss in the calorimeters:

- Energy loss $\sim$3 GeV with $\lesssim$20% fluctuation.
- Larger fluctuations can be measured by the calorimeters

$\rightarrow$ Neglible influence on $\frac{\Delta p_t}{p_t}$ for $p_t \gtrsim 10$ GeV/c.

Multiple scattering (MS) in the calorimeters:

- Negligible for ATLAS: $\frac{\Delta p_t}{p_t}|_{MS} \sim 10^{-3}$.

Multiple scattering and bending power in the muon system:

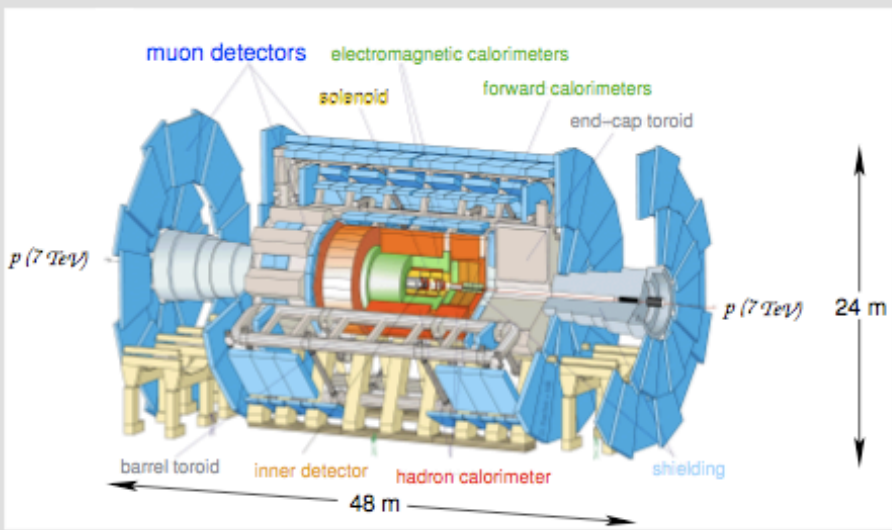
- $\frac{\Delta p_t}{p_t} \propto \frac{\sqrt{\text{material in the muon system } [X_0]}}{\int B\, dl}$.

Resolution of the muon chambers:

- Spatial resolution σ of the muon chambers is the limiting factor for $\frac{\Delta p_t}{p_t}$ for high $p_t \sim 1$ TeV/c.
- $\frac{\Delta p_t}{p_t} \propto \sigma$ for $p_t \sim 1$ TeV/c.

Muon Systems

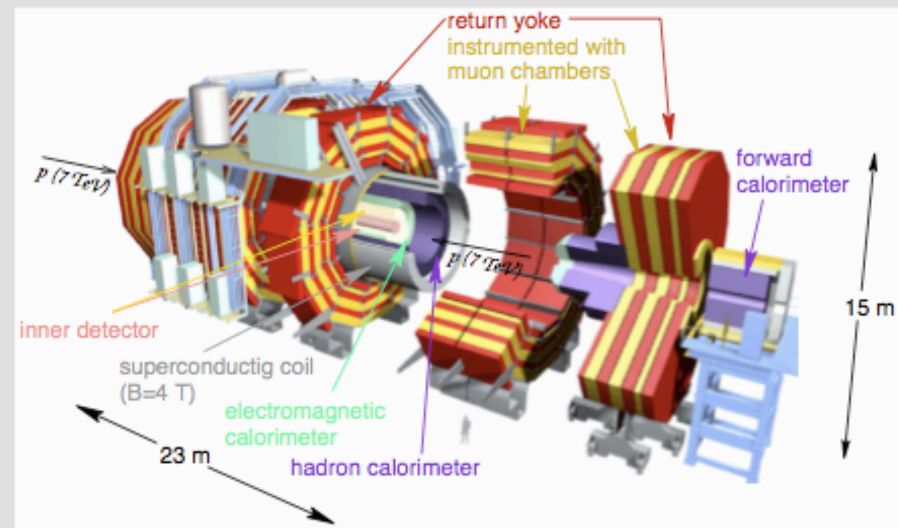
ATLAS



- Focus on stand-alone muon reconstruction.

→ Air-core toroid → minimization of multiple scattering.

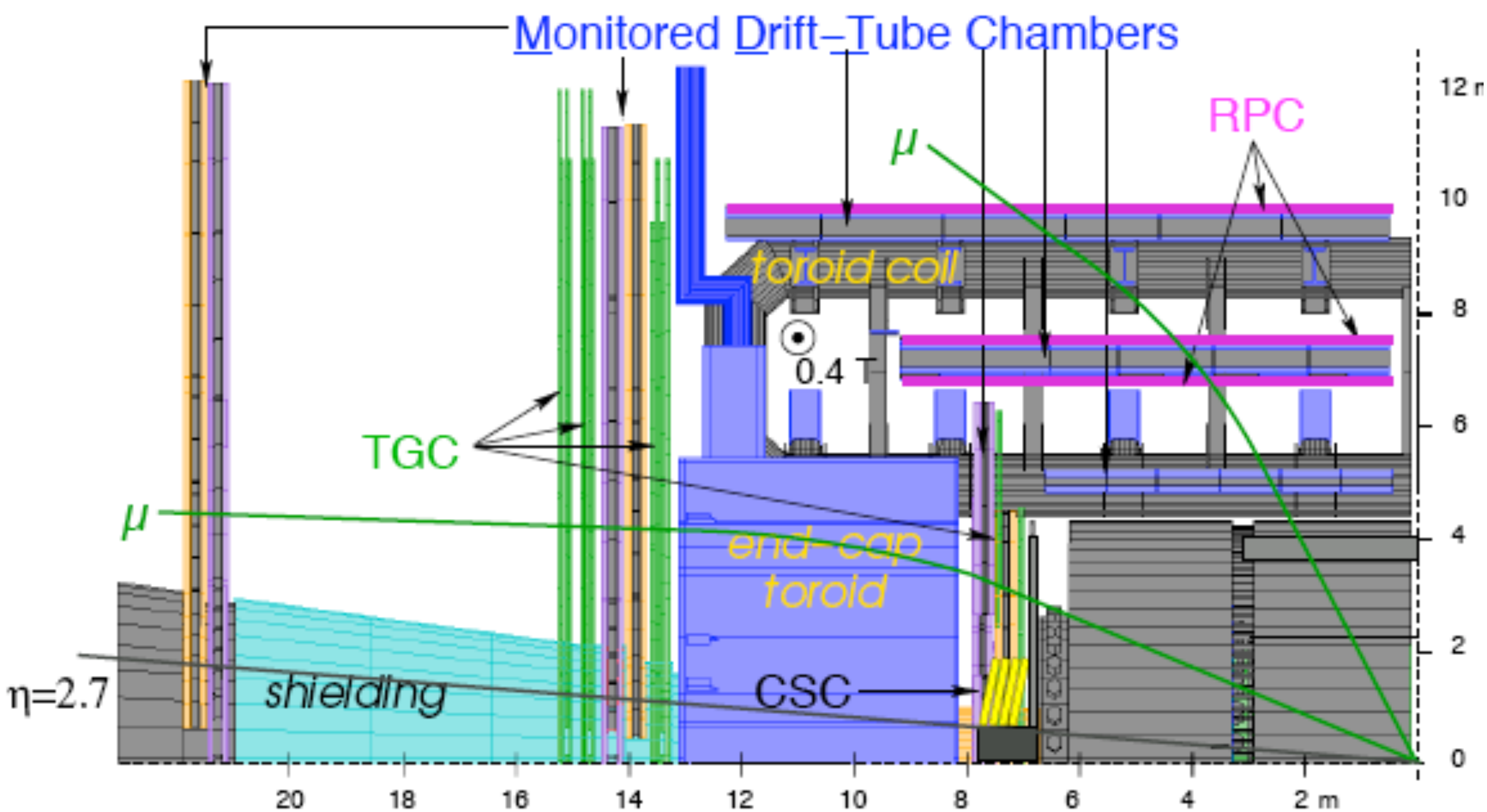
CMS



- Focus on high $\int B\,dl$ in the inner detector and compactness.
- Instrumented return yoke of the solenoid to achieve high bending power.

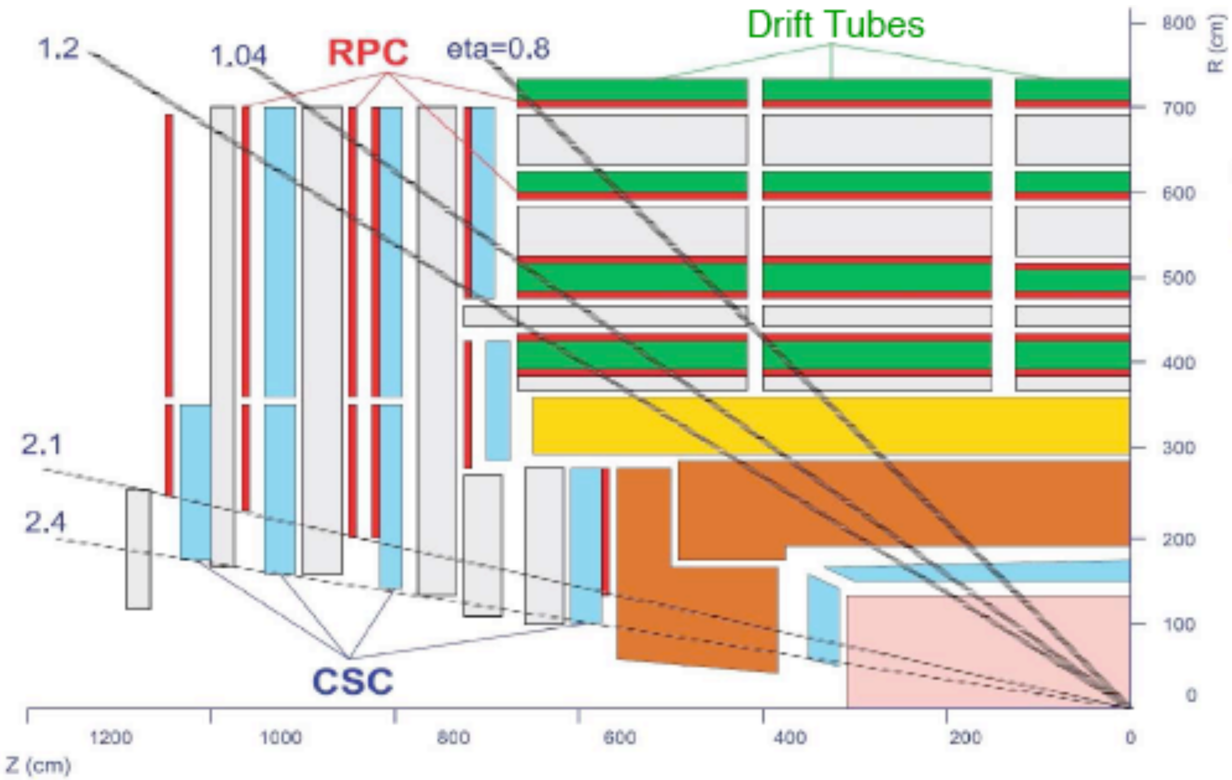
TABLE 11 Main parameters of the ATLAS and CMS muon chambers

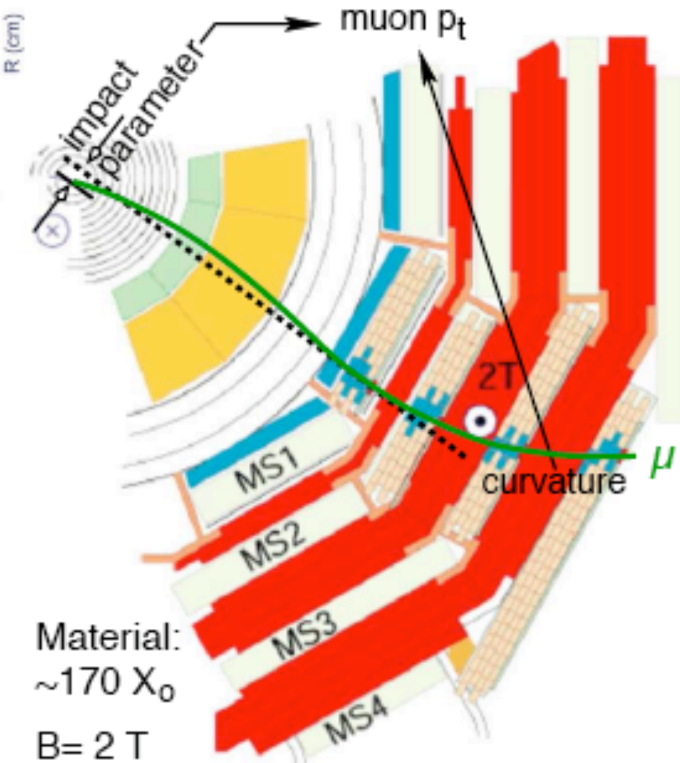
	ATLAS	CMS
Drift Tubes	MDTs	DTs
-Coverage	$\|\eta\| < 2.0$	$\eta\| < 1.2$
-Number of chambers	1170	250
-Number of channels	354,000	172,000
-Function	Precision measurement	Precision measurement, triggering
Cathode Strip Chambers		
-Coverage	$2.0 < \|\eta\| < 2.7$	$1.2 < \|\eta\| < 2.4$
-Number of chambers	32	468
-Number of channels	31,000	500,000
-Function	Precision measurement	Precision measurement, triggering
Resistive Plate Chambers		
-Coverage	$\|\eta\| < 1.05$	$\|\eta\| < 2.1$
-Number of chambers	1112	912
-Number of channels	374,000	160,000
-Function	Triggering, second coordinate	Triggering
Thin Gap Chambers		
-Coverage	$1.05 < \|\eta\| < 2.4$	—
-Number of chambers	1578	—
-Number of channels	322,000	—
-Function	Triggering, second coordinate	—



ATLAS muon spectrometer

- Excellent stand-alone capabilities and coverage in open geometry
- Complicated geometry and field configuration (large fluctuations in acceptance and performance over full potential η x ϕ coverage (|η| < 2.7)

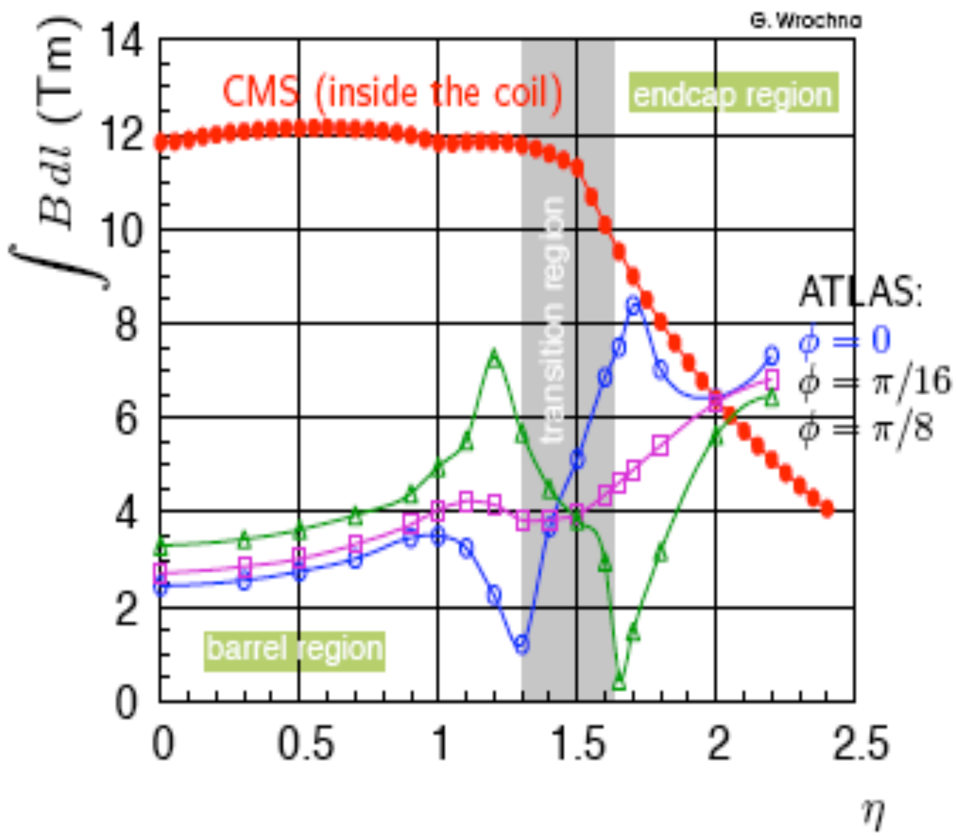




CMS muon spectrometer

- Superior combined momentum resolution in central region
- Limited stand-alone resolution and trigger (at very high luminosities) due to multiple scattering in iron
- Degraded overall resolution in the forward regions ($|\eta| > 2.0$) where solenoid bending power becomes insufficient

Comparison



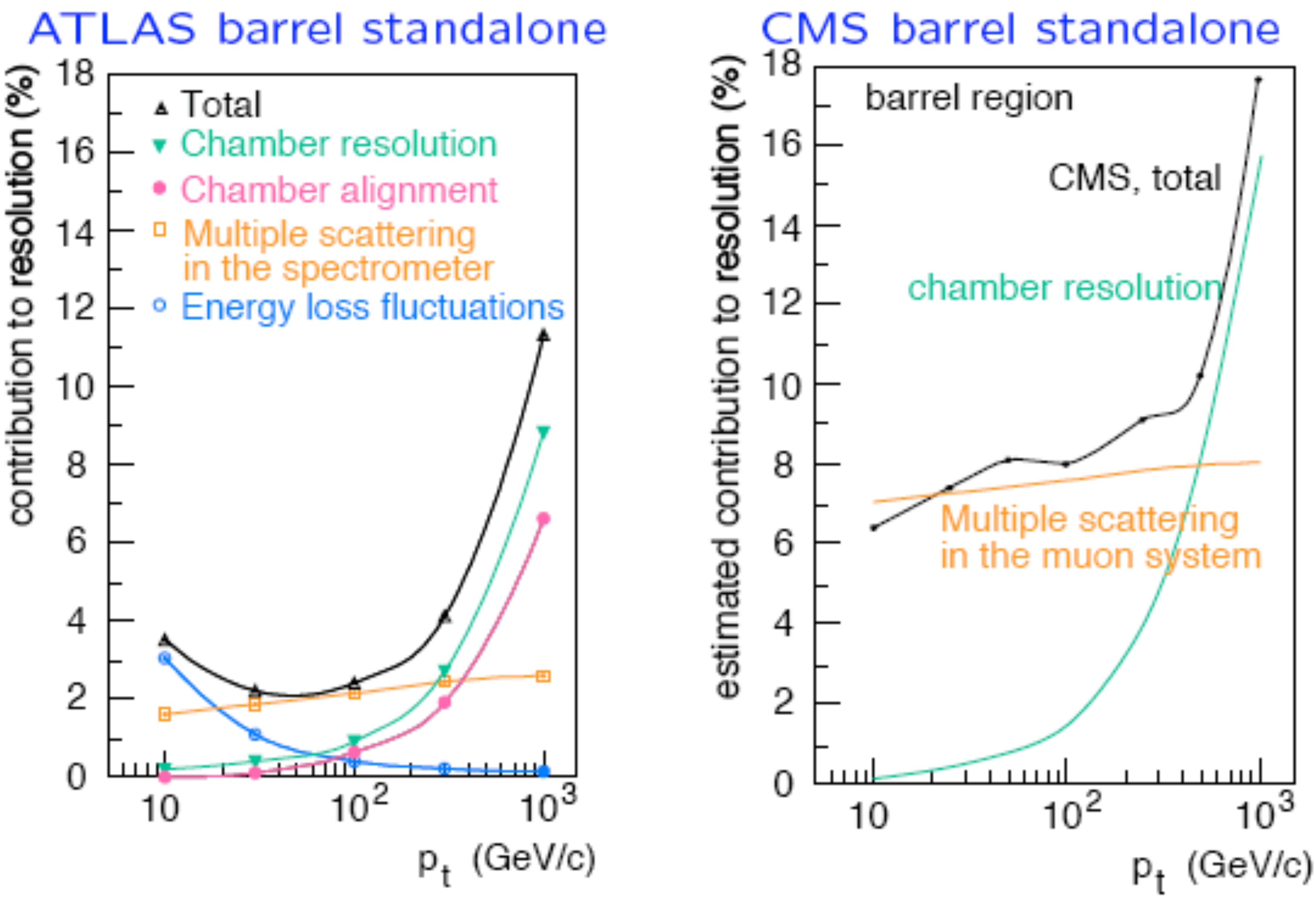
Barrel: $\approx 5\times$ higher bending power in CMS, but $\approx 14\times$ larger multiple scattering.

$\rightarrow$ $\approx 3\times$ worse p_t resolution in CMS.

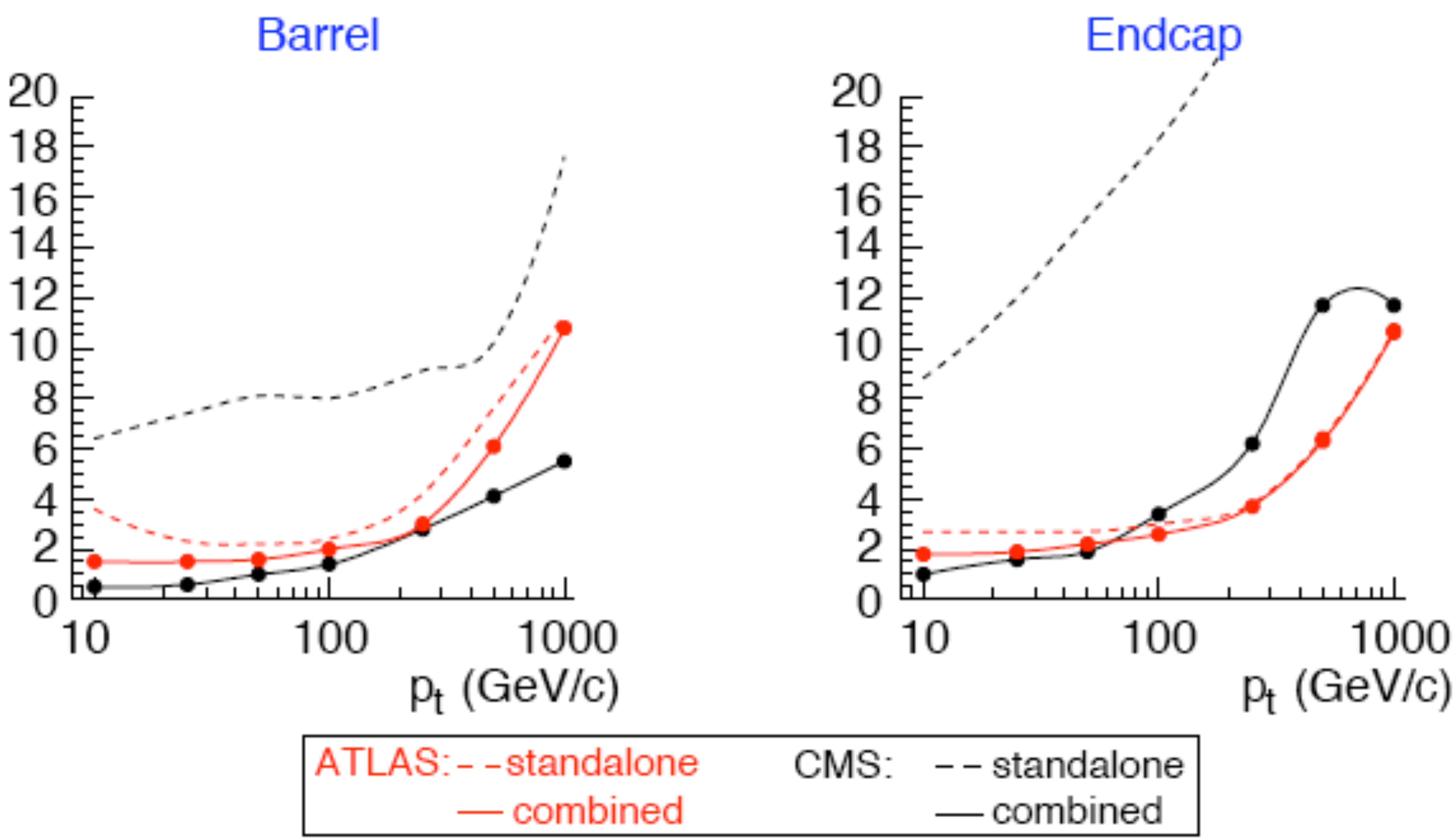
Endcap: similar bending powers, $\approx 10\times$ large multiple scattering.

$\rightarrow$ $\approx 5\times$ worse p_t resolution in CMS.

Comparison


ATLAS barrel standalone
contribution to resolution (%)
Total
Chamber resolution
Chamber alignment
Multiple scattering
in the spectrometer
Energy loss fluctuations
p_t (GeV/c)
CMS barrel standalone
estimated contribution to resolution (%)
barrel region
CMS, total
chamber resolution
Multiple scattering
in the muon system
p_t (GeV/c)

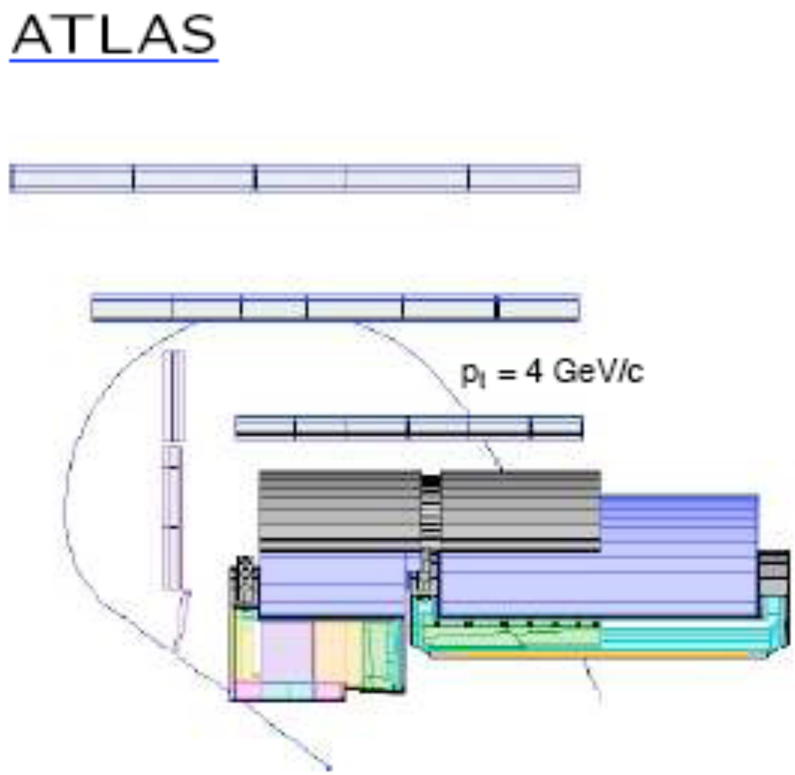
Comparison

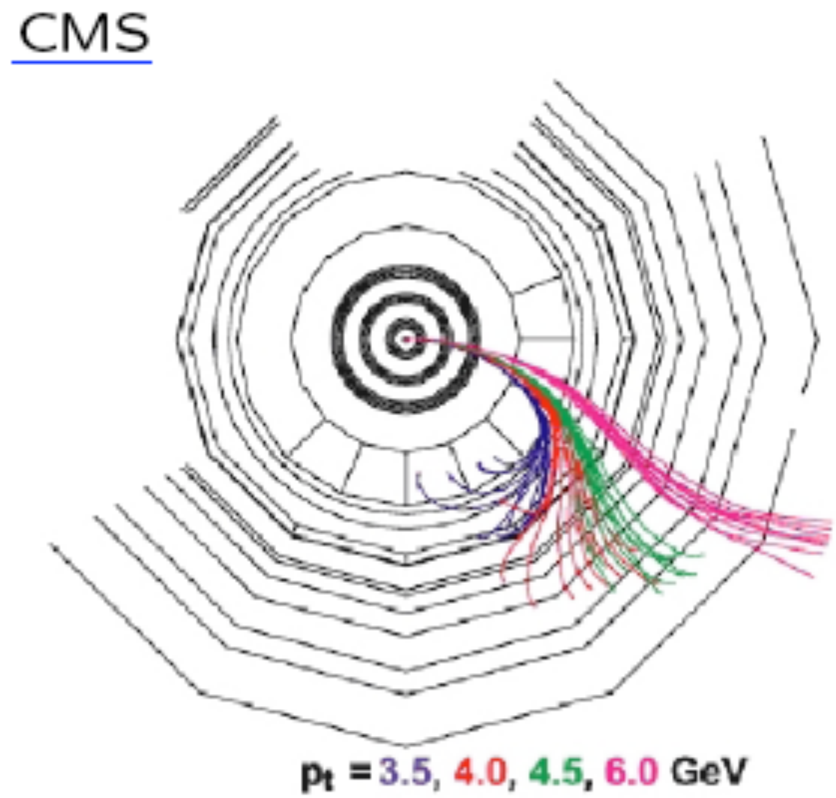


Barrel
Endcap
20
18
16
14
12
10
8
6
4
2
0
10
100
1000
p_t (GeV/c)
ATLAS: - - standalone
— combined
CMS: - - standalone
— combined

Comparison

Parameter	ATLAS	CMS
Pseudorapidity coverage:		
- Muon measurement	$\|\eta\| < 2.7$	$\|\eta\| < 2.4$
- Triggering	$\|\eta\| < 2.4$	$\|\eta\| < 2.1$
Dimensions (m):		
- Innermost (outermost) radius	5.0 (10.0)	3.9 (7.0)
- Innermost (outermost) disk (z-point)	7.0 (21-23)	6.0-7.0 (9-10)
Segments/super-points per track for barrel (end-caps)	3 (4)	4 (3-4)
Magnetic field B (T)	0.5	2
- Bending power (BL, in T·m) at $\|\eta\| \approx 0$	3	16
- Bending power (BL, in T·m) at $\|\eta\| \approx 2.5$	8	6
Combined (stand-alone)		
momentum resolution at:		
- p = 10 GeV and $\eta \approx 0$	1.4% (3.9%)	0.8% (8%)
- p = 10 GeV and $\eta \approx 2$	2.4% (6.4%)	2.0% (11%)
- p = 100 GeV and $\eta \approx 0$	2.6% (3.1%)	1.2% (9%)
- p = 100 GeV and $\eta \approx 2$	2.1% (3.1%)	1.7% (18%)
- p = 1000 GeV and $\eta \approx 0$	10.4% (10.5%)	4.5% (13%)
- p = 1000 GeV and $\eta \approx 2$	4.4% (4.6%)	7.0% (35%)



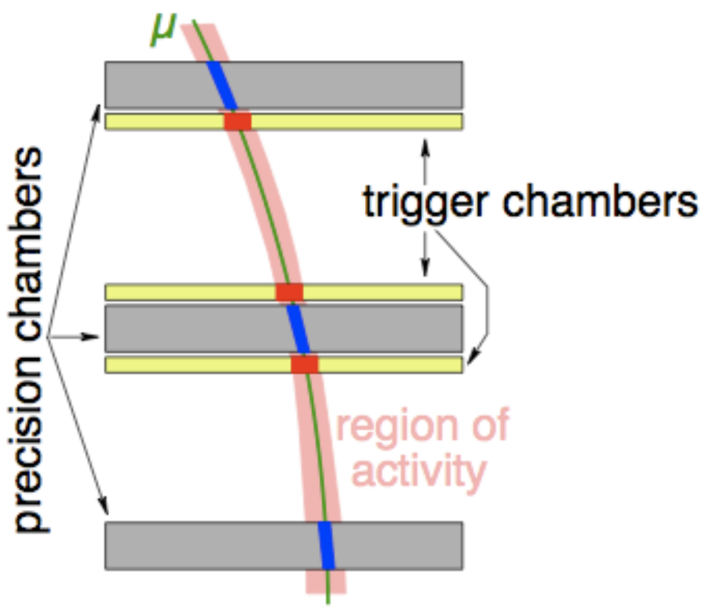


Requirements for muon identification and reconstruction at low p_T

- Identify track stub in first layer of muon system
- Check for minimum ionising signals in last layers of hadron calorimeter
- Match as precisely as feasible (within limitations due to large MS and energy loss in calorimetry) measured track in inner detector with track stub in muon system

Track Reconstruction in the Muon System

Both experiments reconstruct muon tracks in the following steps:



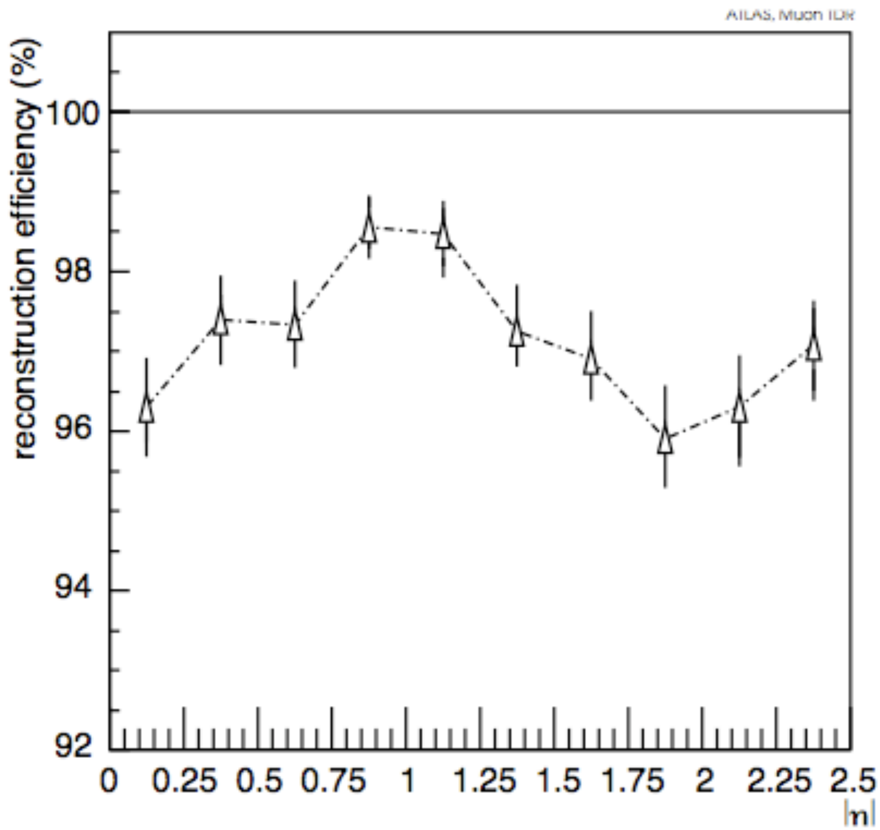
1. Definition of regions of acticity (RoA).
2. Reconstruction of local straight segments in the RoA.
3. Combination of local segments.
4. Global fit in the muon system.

Finally combination with the inner detector

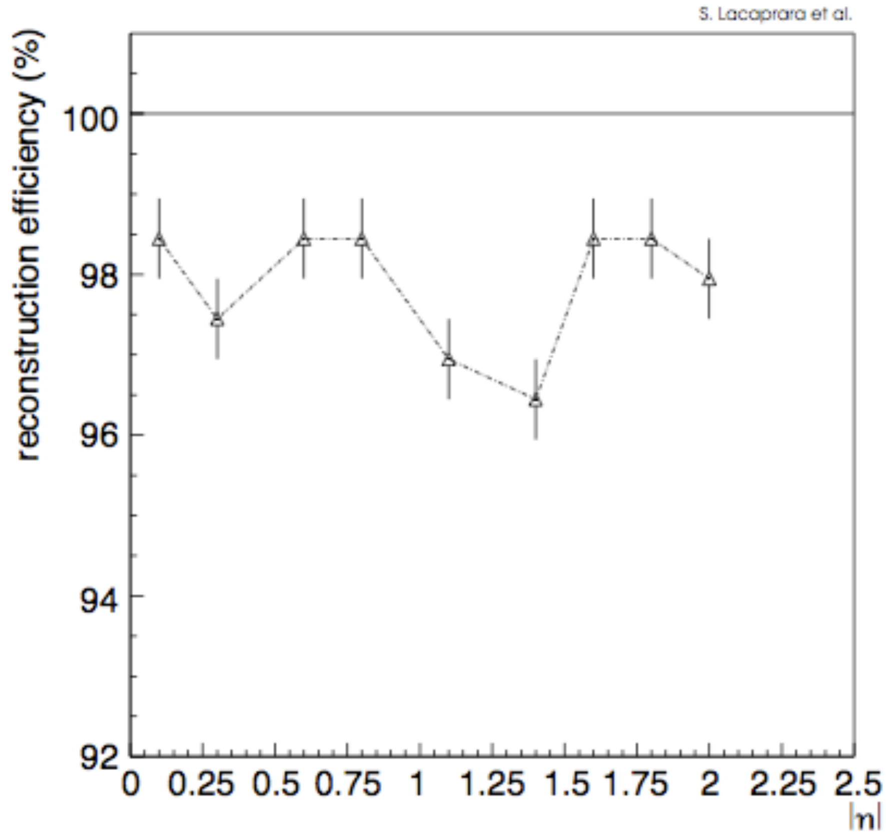
- to refine the momentum measurement,
- to identify low-p_t muons,
- to identify isolated muons.

Tracking Efficiency

ATLAS

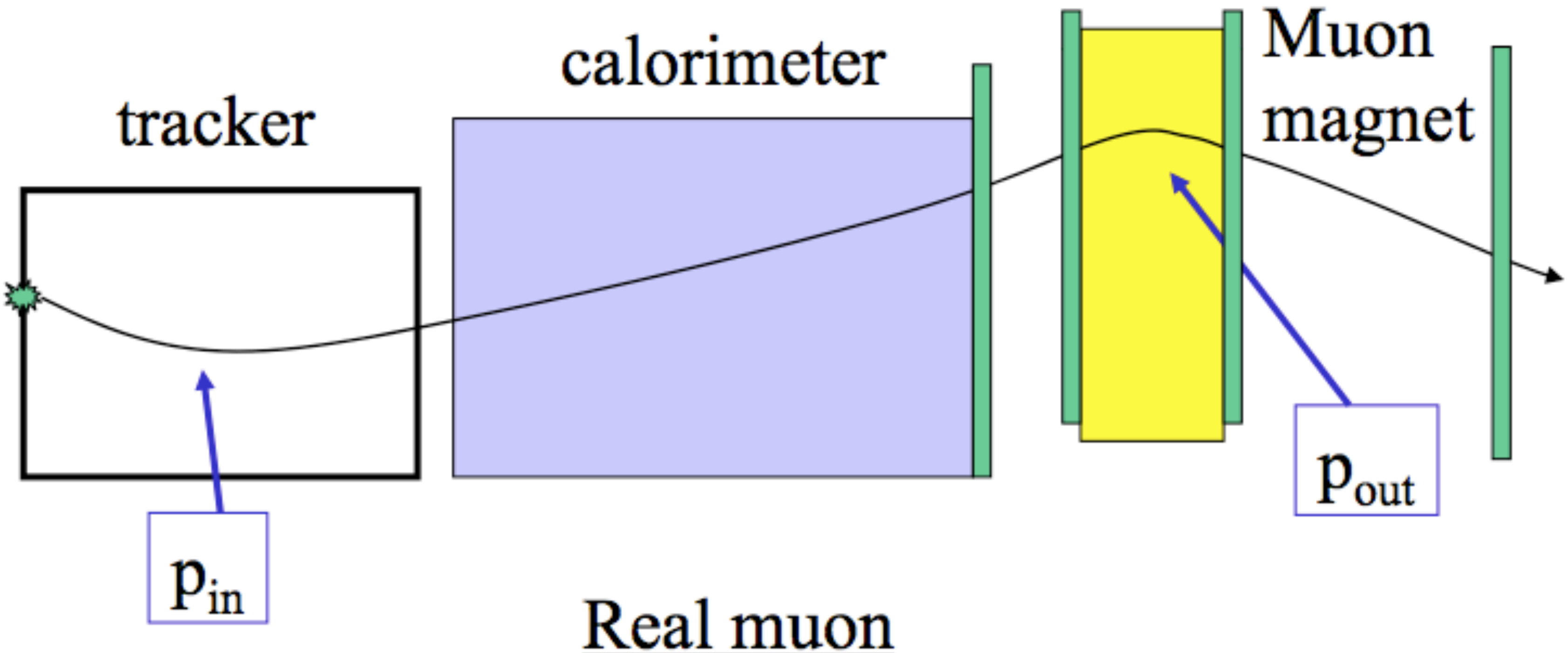


CMS



High tracking efficiency $> 96\%$ in both detectors.

Muon Signal

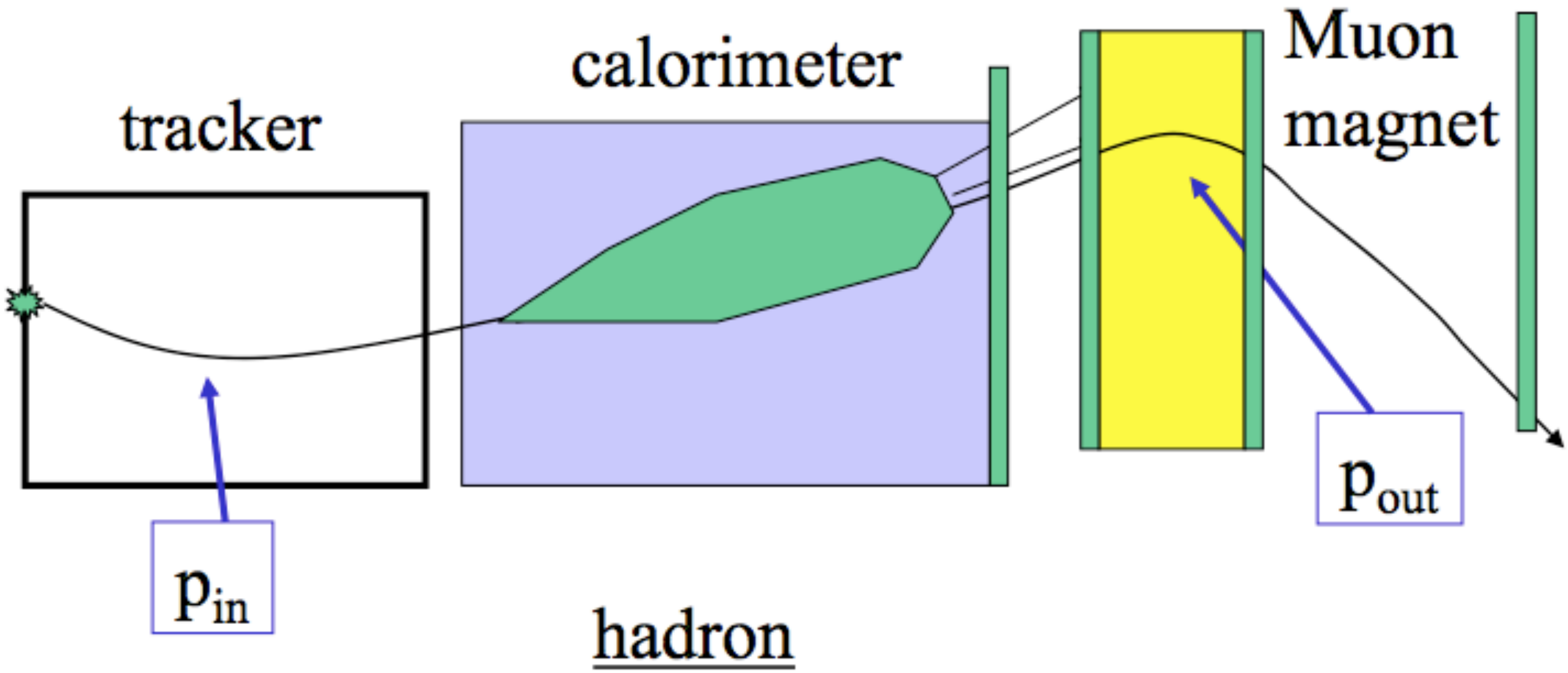


$p_{in} \approx p_{out} + {}_{Eloss}$

Better resolution comes from the tracker

p_{out} dominated by multiple scattering (or showering)

Background 1: punch-through/decay-in-flight



$P_{in} >> p_{out} + {}_{Eloss}$

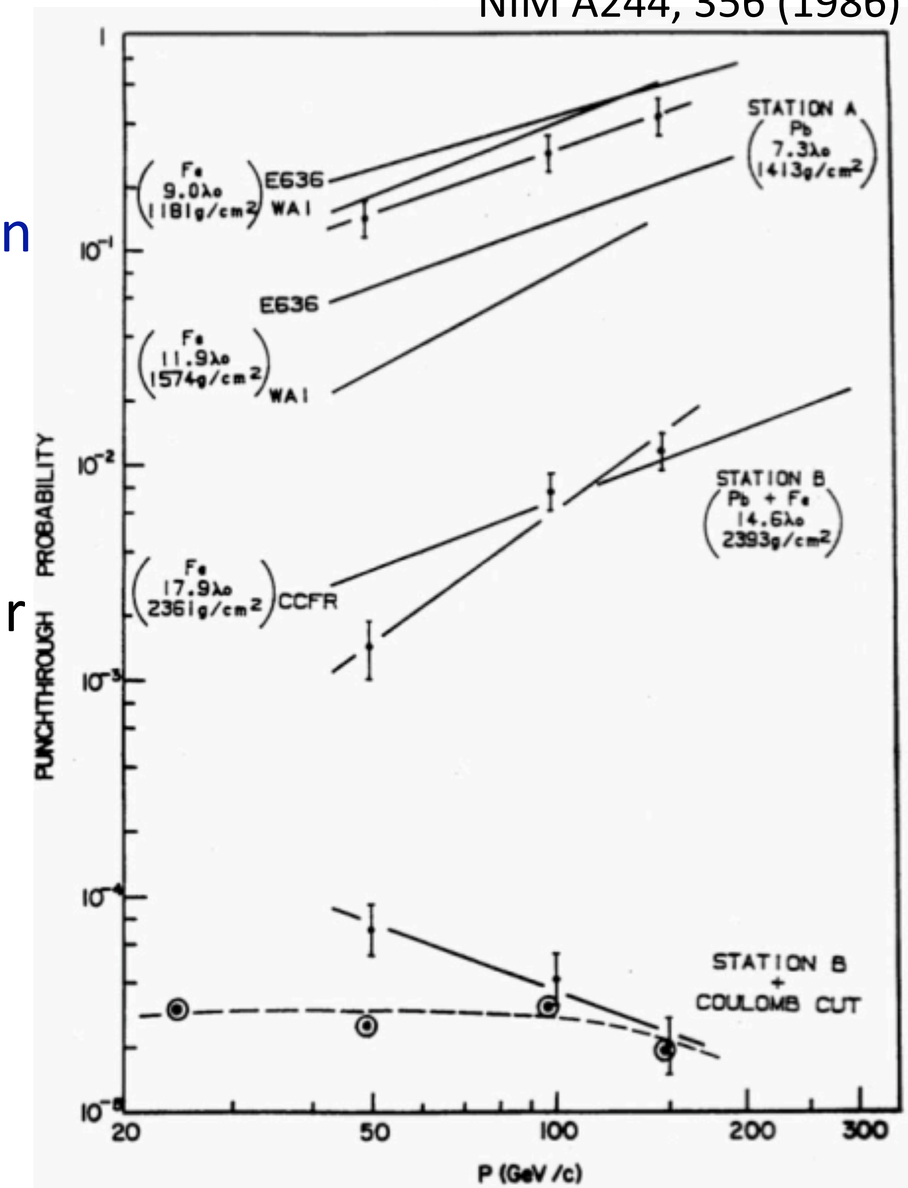
Outer punch-through or decay track points back to parent hadron
But momenta do not match

Punch-through

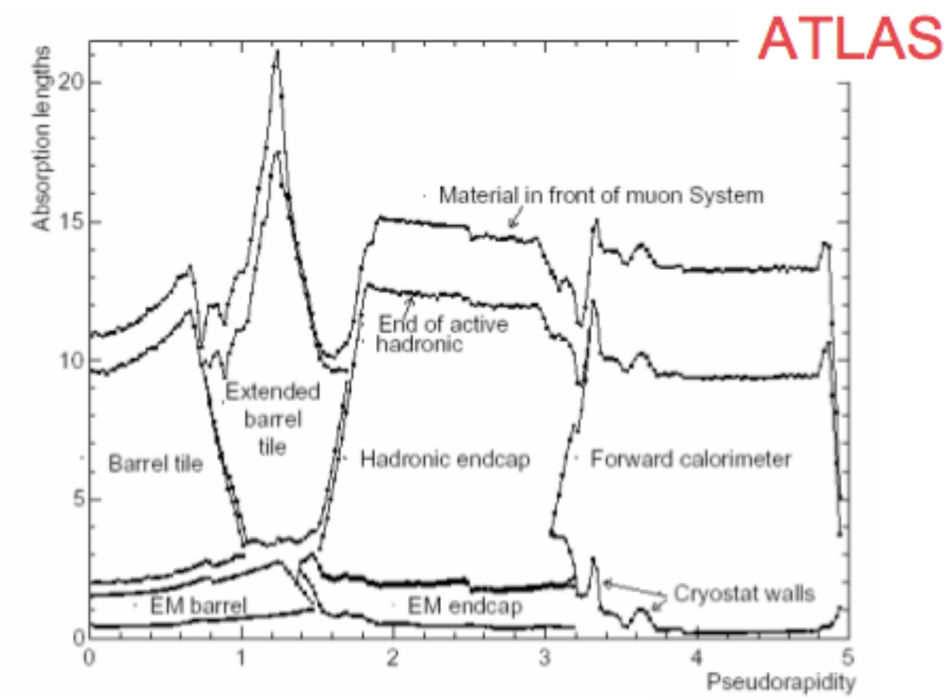
NIM A244, 356 (1986)

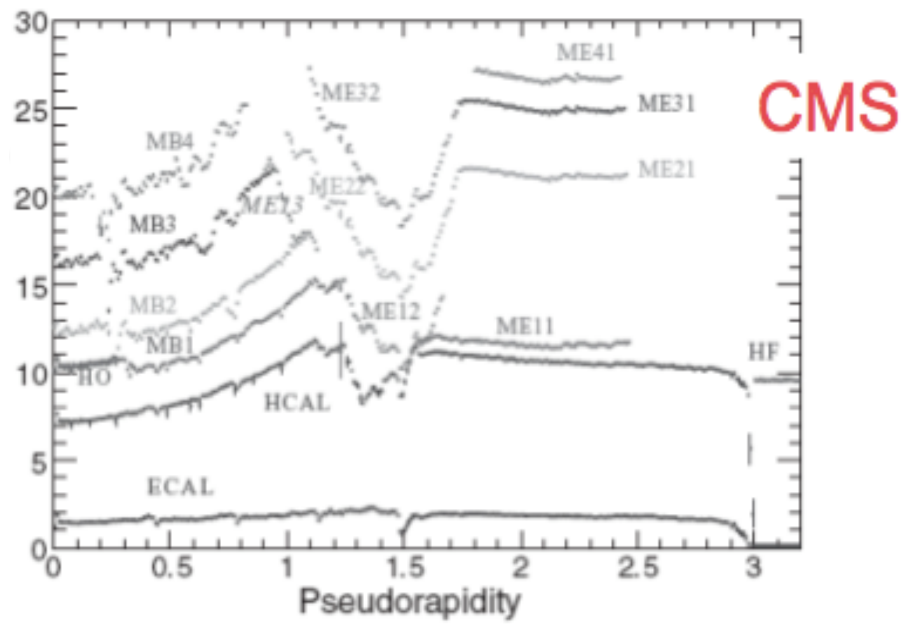
- Punch-through is defined as particles from late developing hardon showers that get into the muon system

- Minimize punch-through by:
  - Material as measured in nuclear interaction strengths λ_I
  - (Muon system surrounds the calorimeter)
  - Good track matching

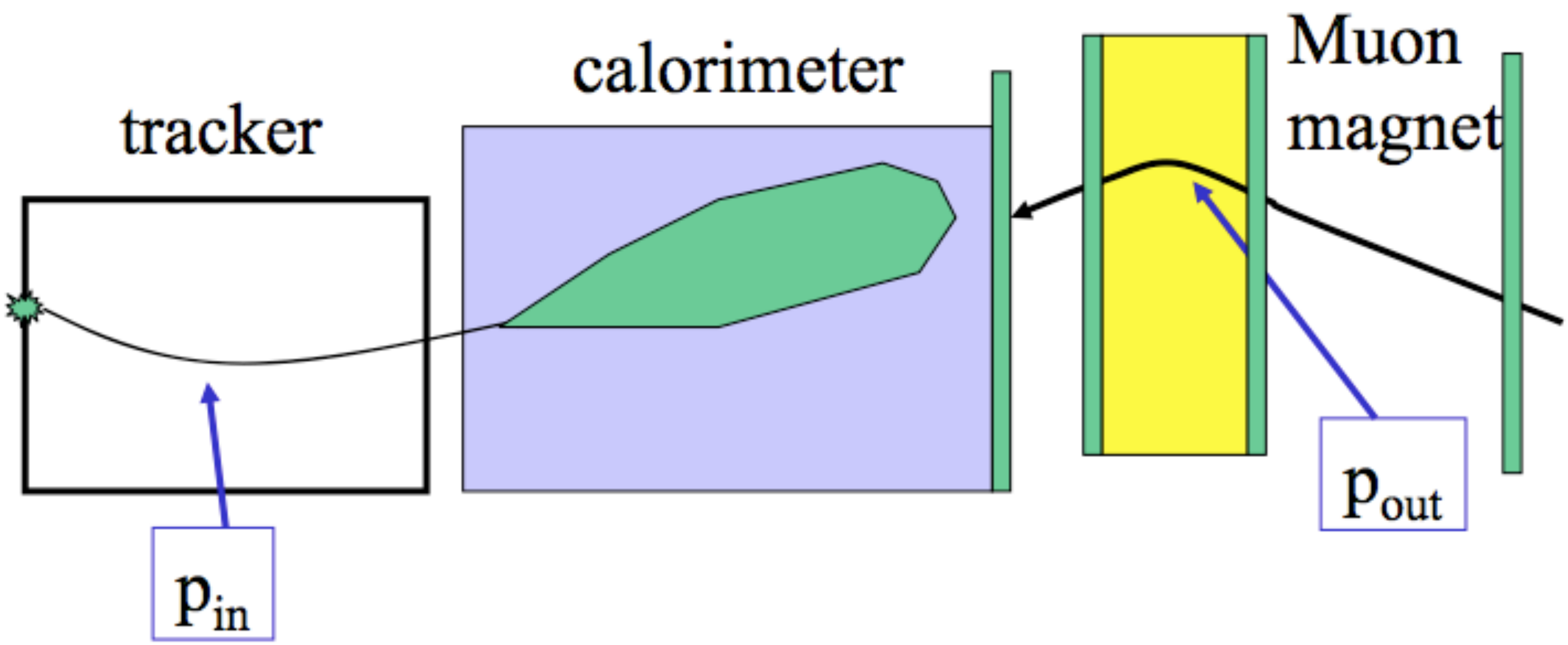


Punch-through





Background 2: halo/backscatter



P_{in} ? p_{out} + $_{Eloss}$

Good timing (scintillators) can get rid of most of these

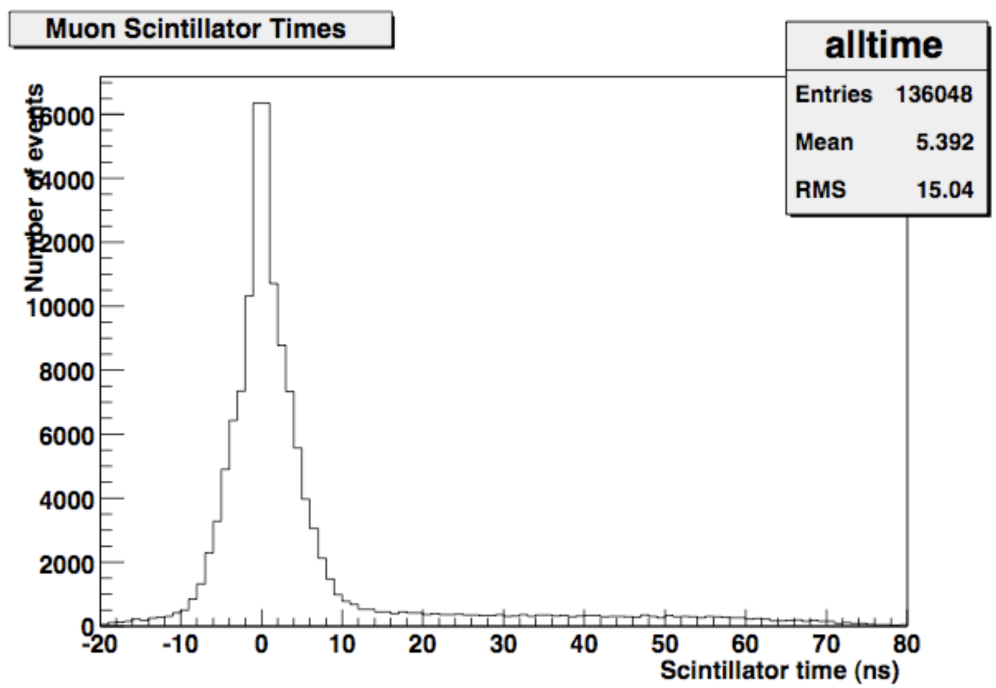
Strategies for muon identification

- # of muon hits and fit quality (chi2/d.o.f)
  - Rejects combinatorics and poorly measured muons
- Impact parameter to vertex
  - Rejects most cosmic rays, beam halo
  - (but can also reject muons from long-lived decays)
- Spatial matching with central track
  - Improves momentum resolution
  - Rejects combinatorics
- Time of flight information
  - Rejects most cosmics rays, beam halo
  - (but can also reject new heavy massive stable particles)

Cosmic Ray background

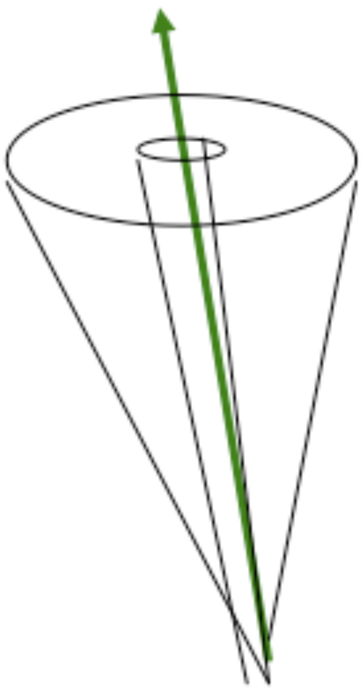
- Arrival times for cosmic ray muons are uncorrelated with beam crossing
  - => flat background in time
    - Cut on tight window timing window around t=0 using fast counter

- Require track to point back to the primary vertex



Isolation

- Typical method for selecting muons from W/Z decays instead of muons from b/c decays
  - Isolation in calorimeter and/or tracker
- Isolation criteria:
  - Upper limit on calorimeter energy in hollow cone around muon
  - Upper limit on sum of track pT in a hollow cone around muon
  - Minimum separation between muon and nearest jet



Isolation

- Optimal isolation thresholds can change with muon energy
  - Both i.e. fixed isolation thresholds and those proportional to muon energy are used
- When using jet-based isolation, what if the jet is not reconstructed or falls below a threshold
  - Creates dependence on jet reconstruction algorithms
  - Difficult to use for low momentum muons
- Isolation efficiency will tend to decrease with increase in inst. Luminosity
  - Luminosity dependent thresholds ?
  - Book-keeping can be very difficult
- Efficiency will strongly depend on event type
  - Efficiency may be different for $W\to\mu\nu$ and ttbar$\to\mu\nu$ jjjj
- Isolation requirements in the trigger need to be as loose as possible…

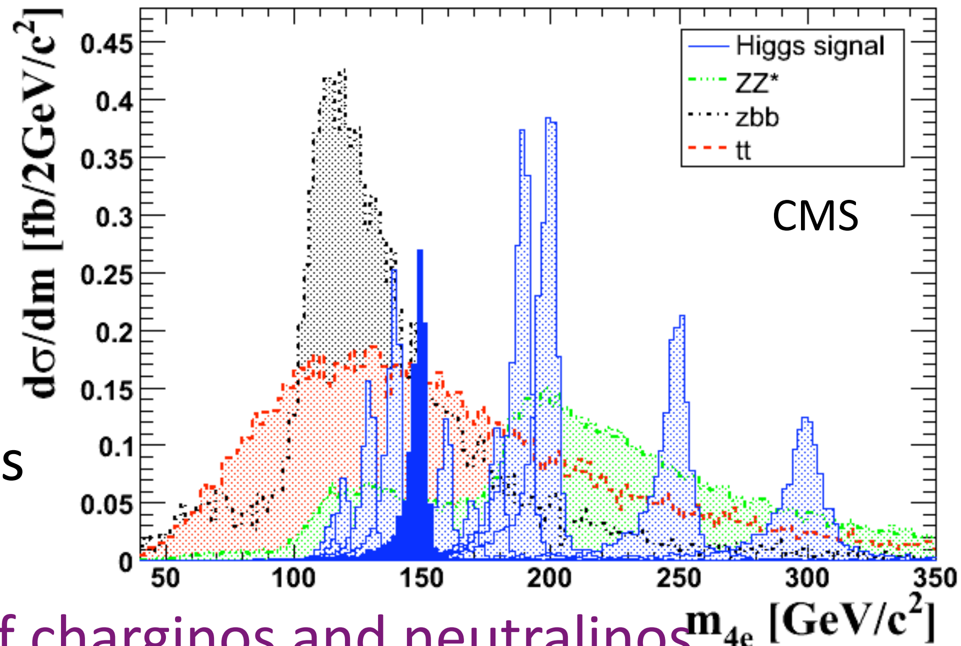
Very High Energy Muons

- Above energies of 0.35 TeV muons start to create photons and e+e- pairs which create EM showers in the material
  - Can fake the signature of electrons and photons
  - Can destroy the usual signature of isolated muons
- Options:
  - Use calorimeter information to reject such muons
  - Restrict momentum information to inner tracker (i.e. before shower)

Electron/Photon Identification @ LHC

Electrons/Photons @ LHC

- Higgs search
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow ZZ(*) \rightarrow 4e$
- BSM
  - High mass resonances
  - SUSY
    - Leptonic decays of charginos and neutralinos

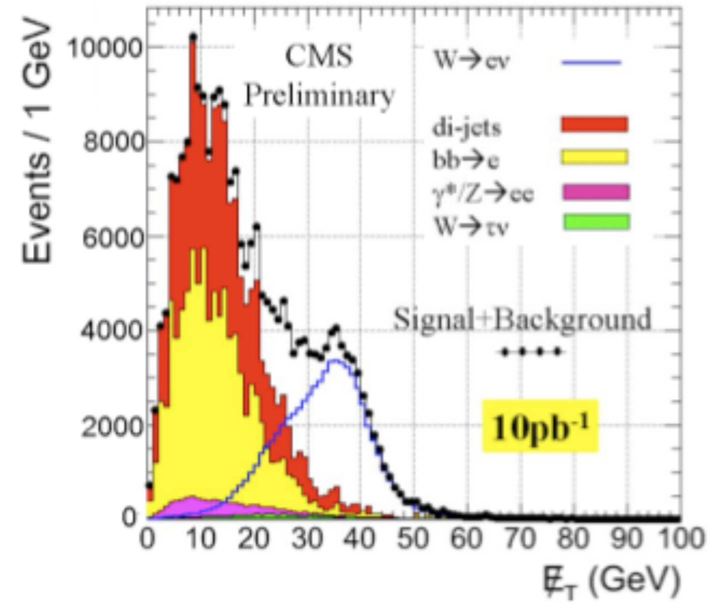


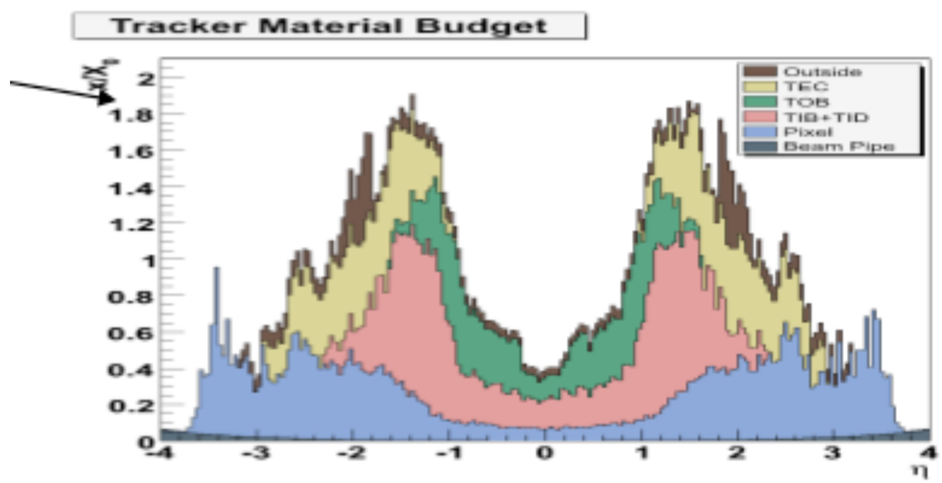
- Many SM processes, top, $Z \rightarrow ee$, $W \rightarrow e\nu$
  - Backgrounds to new signals
  - Calibration processes

Issues

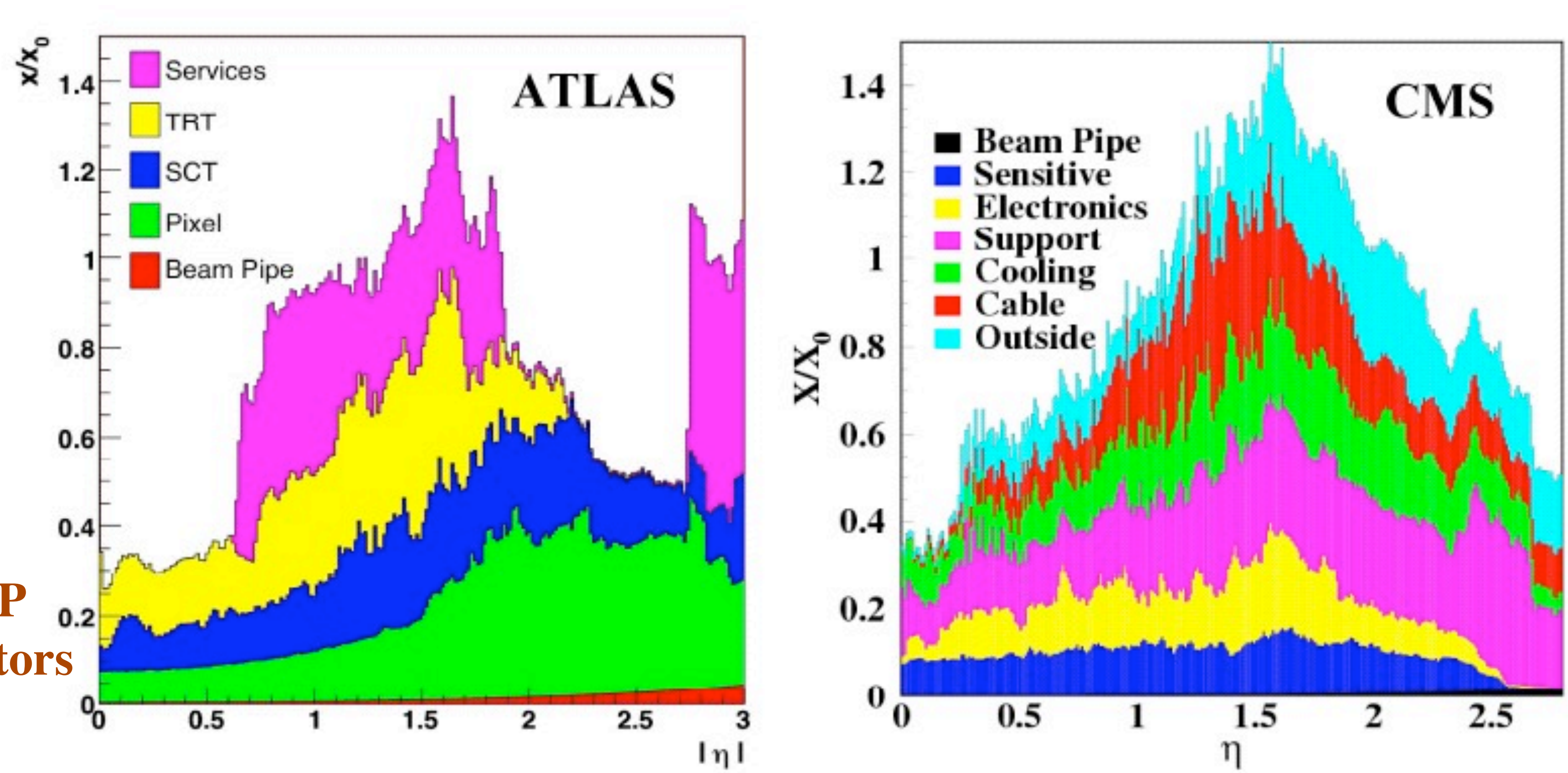
- Challenging kinematics and/ or background conditions

- Main problem:
  - Tracker material budget in front of calorimeters
    - Causes electron bremsstrahlung
    - Causes photons to pair produce
  - 3.8 T magnetic field (CMS)





Tracker Material



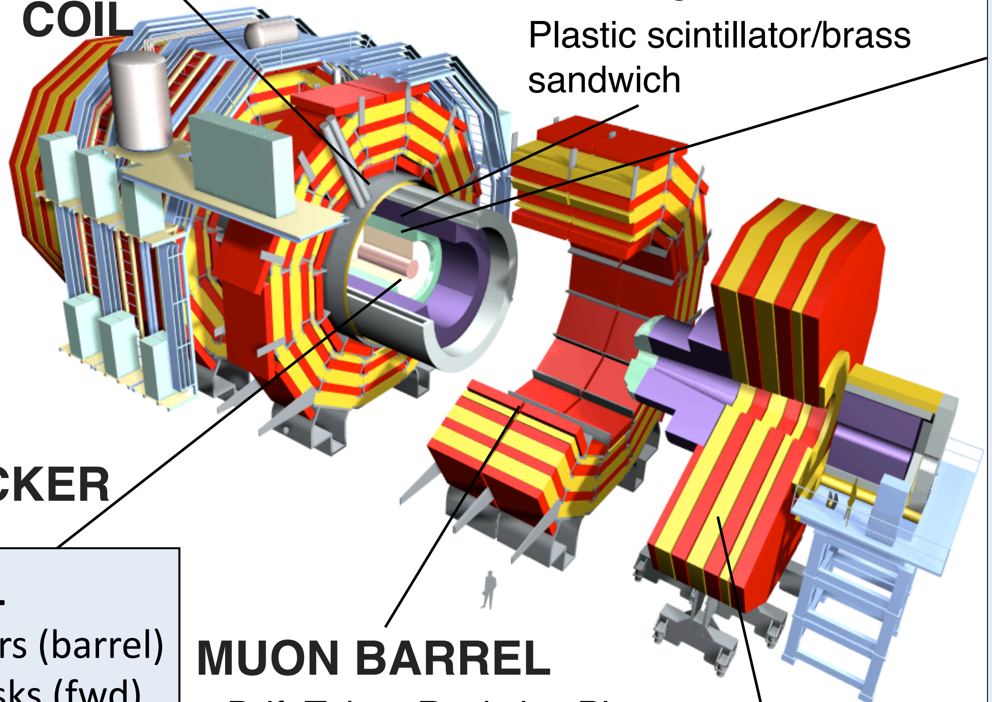
LEP detectors

The CMS Detector

CALORIMETERS

SUPERCONDUCTING COIL

HCAL
Plastic scintillator/brass sandwich



TRACKER

PIXEL
3 layers (barrel)
2x2disks (fwd)

SST
>8 hits,
depending on η

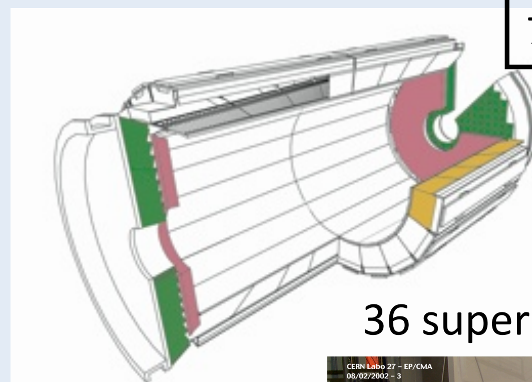
$|\eta|<2.5$

MUON BARREL
Drift Tube   Resistive Plate
Cathode Strip Chambers

Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

ECAL Scintillating $PbWO_4$ crystals

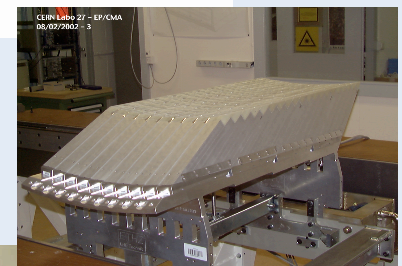
75848 Xtals



36 supermodules

4 dees

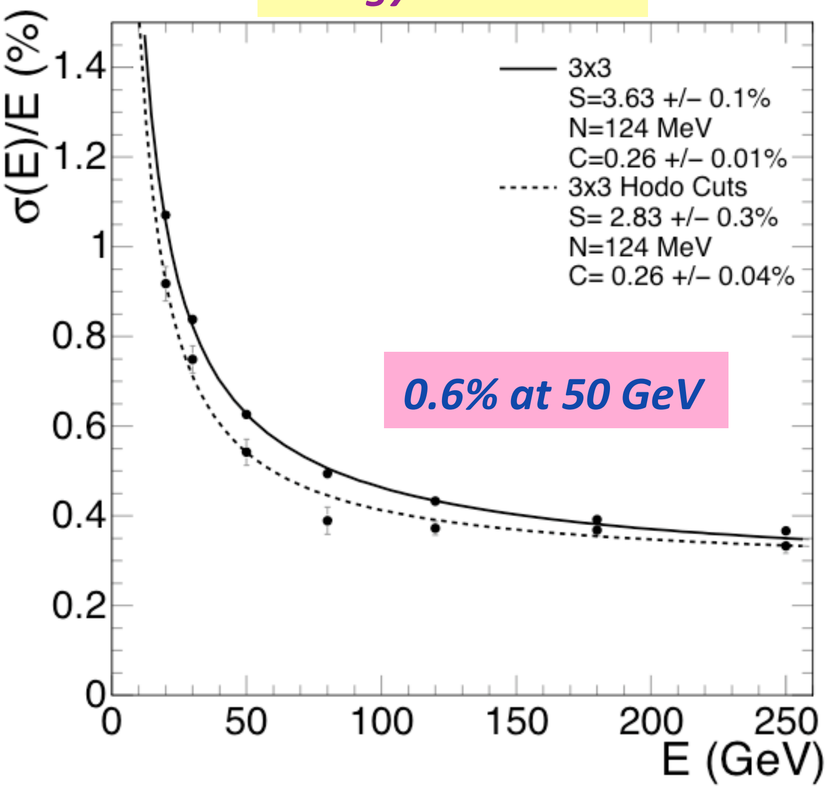
$|\eta|<2.6$

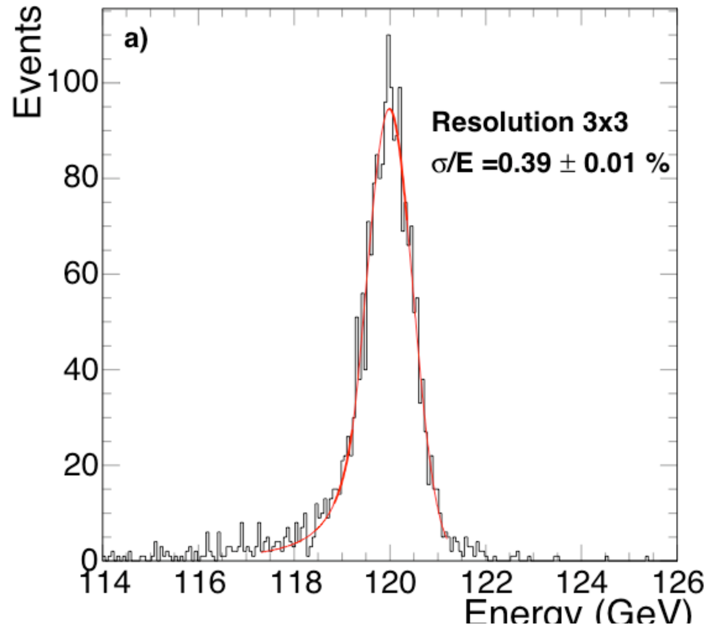


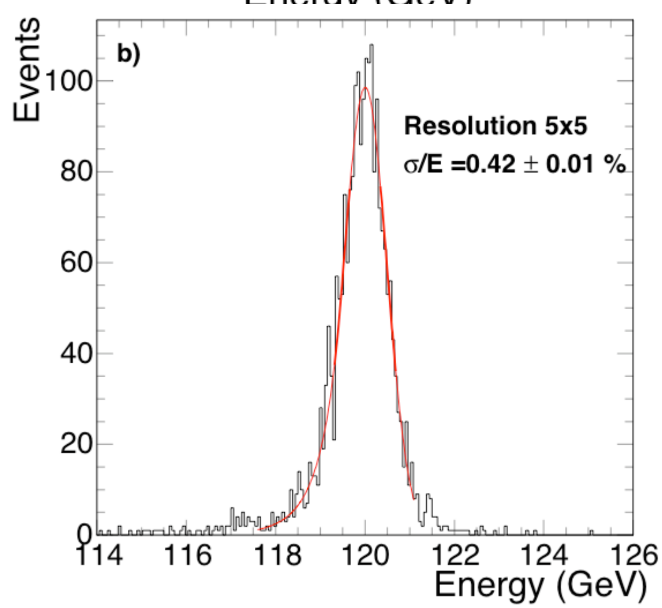
2x5 Xtal modules

CMS PbWO4 Calorimetry

Energy resolution

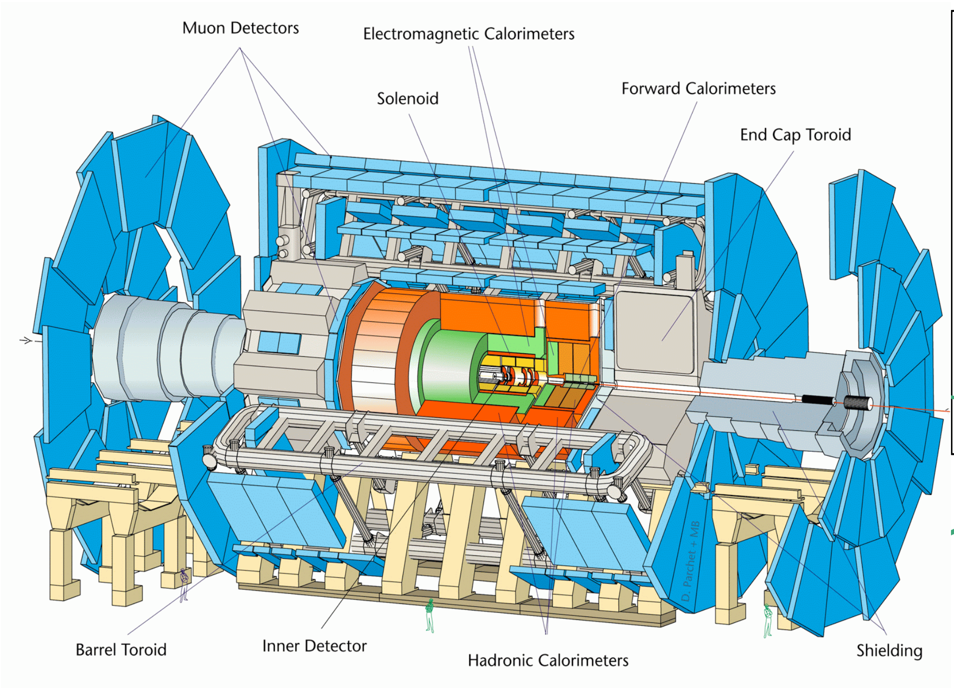






$$\frac{\sigma(E)}{E} = \frac{2.8\ \%}{\sqrt{E}} \oplus \frac{124\ \mathrm{MeV}}{E} \oplus 0.26\ \ \%$$

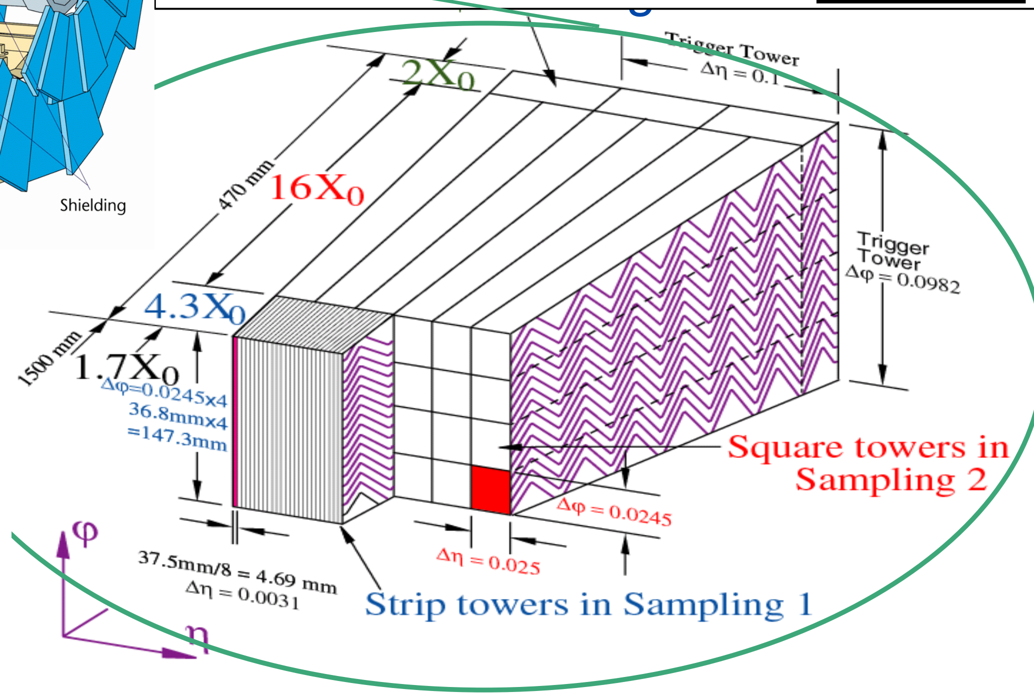
The ATLAS Detector



Liquid Argon EM calorimeter:

- ✓ $\sigma_E/E = 10\%/\sqrt{E} \oplus 24.5\%/E \oplus 0.7\%$
- ✓ linearity better than 0.5% up to 300 GeV
- ✓ shower direction with s_q ~50 mrad / √ E
- ✓ fine granularity of 1st compartment
- ✓ shower shape measurement

|η|<2.5



- 3 layers Pixel Detector
- 4 layers Semi-Conductor Tracker (SCT)
- 73-layer Transition Radiation Detector (TRT) [only within |η|<2.0, provides PID!]
    - electrons cause large energy depositions due to the transition radiation
- 2T solenoidal magnetic field

ATLAS/CMS E/γ performance

<u>Photons at 100 GeV</u>

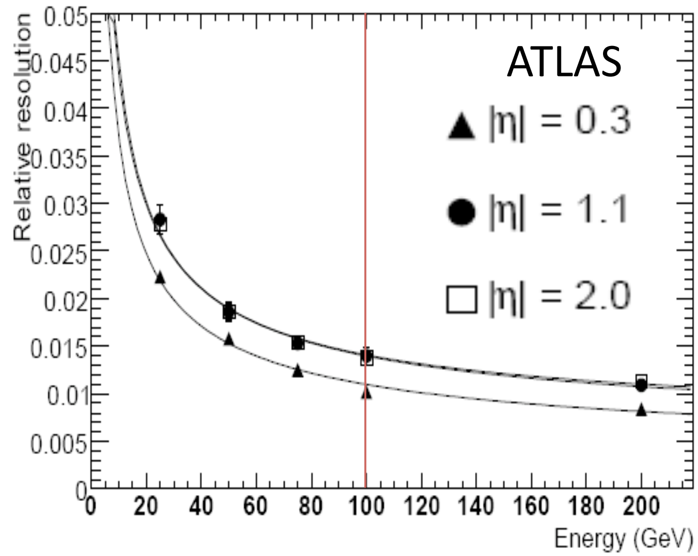
ATLAS: 1-1.5%

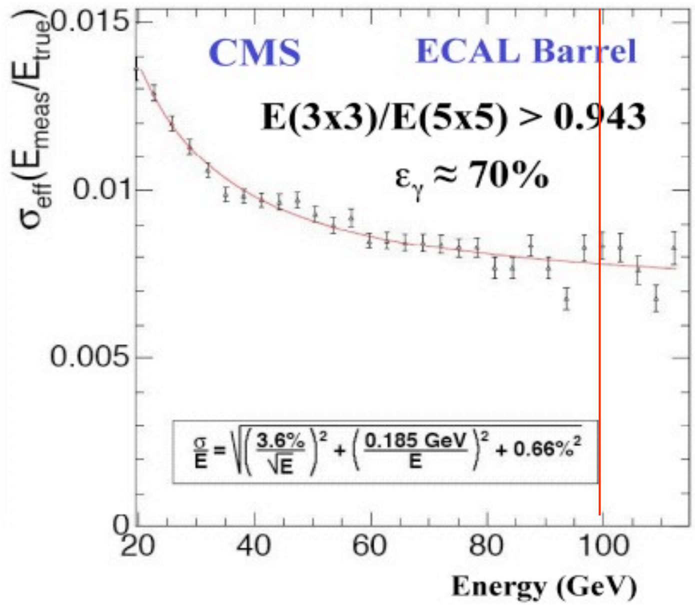
energy resol. (all γ)

CMS: 0.8%

energy resol.

(e_γ ~ 70%)





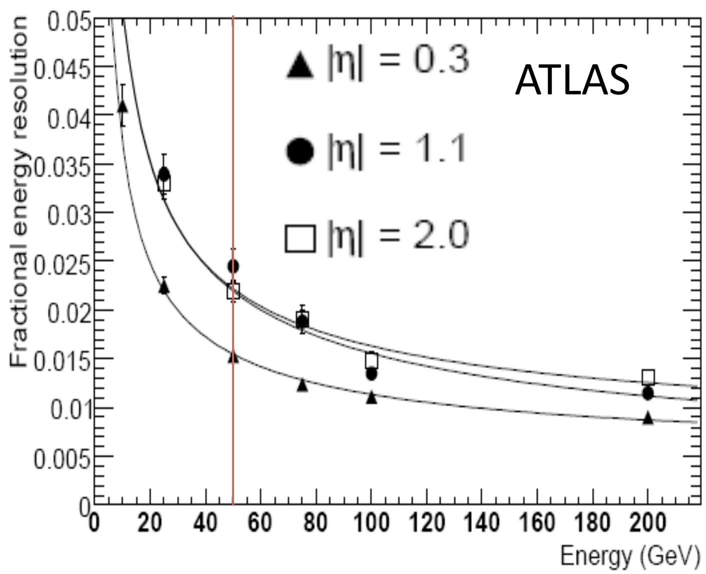
<u>Electrons at 50 GeV</u>

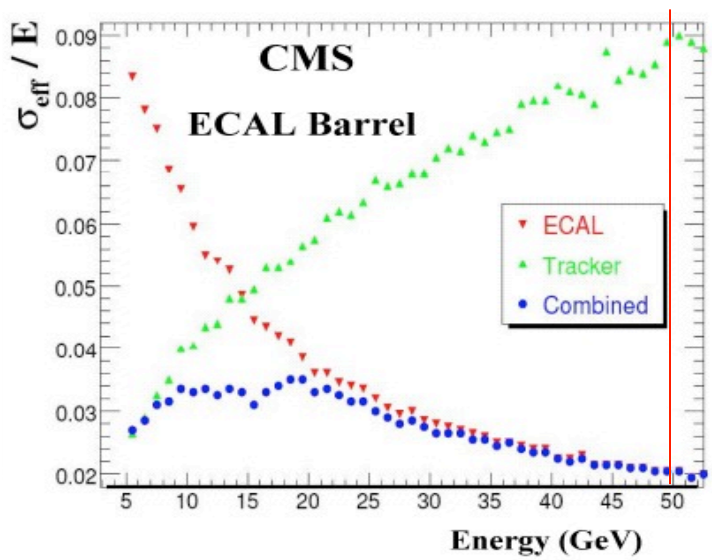
ATLAS: 1.5-2.5%

energy resol.

(use EM calo only)

CMS: ~ 2.0% energy resol. (combine EM calo and tracker)





Similar electron and photon performances in CMS and ATLAS!

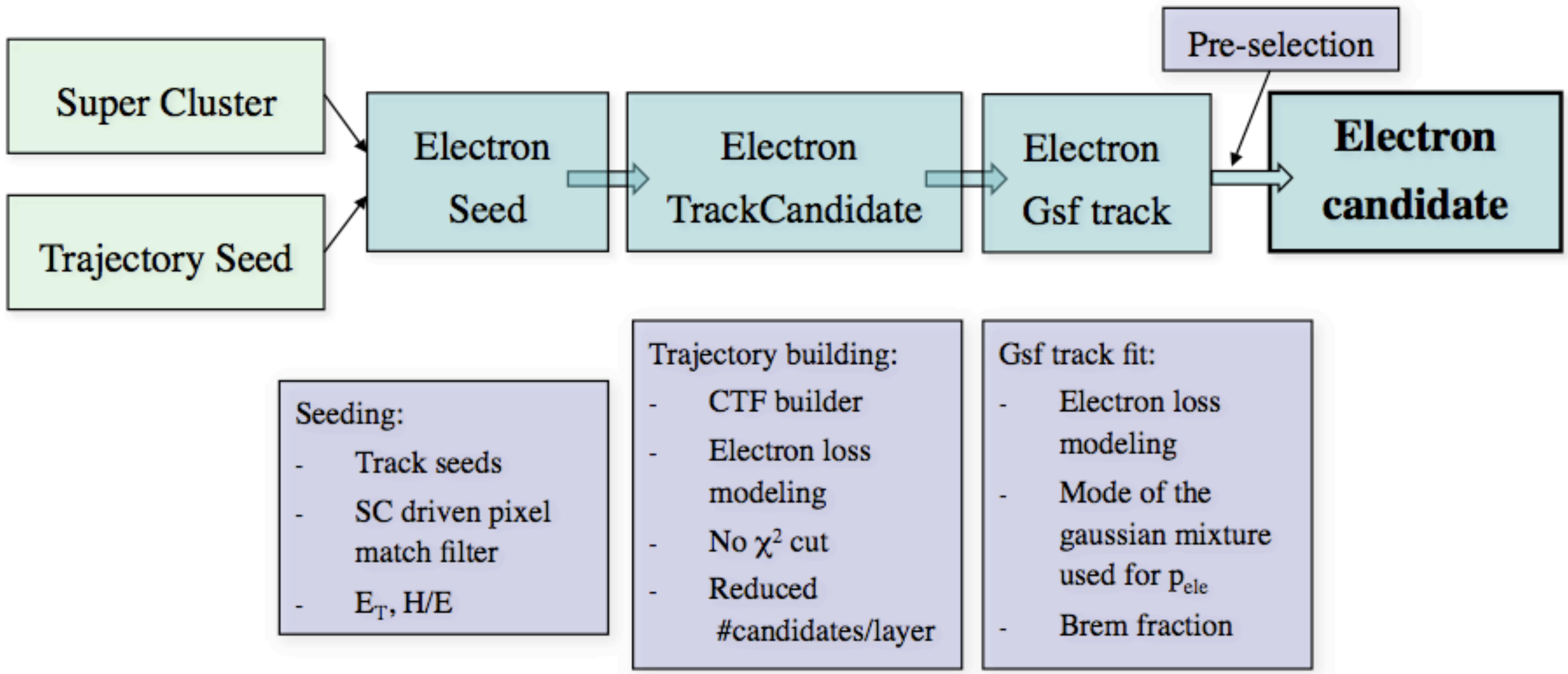
Electron/Photon Reconstruction

- Calorimeter-based reconstruction
  - Used for photons and electrons
  - Photons do not match any track or match a conversion
- Electrons need to have a loose track match in (η,ϕ) and in energy vs momentum
  - Bremsstrahlung recovery is part of default electron reco in CMS; various algorithms exist in ATLAS
- Soft-electrons (low-p_T and electrons in jets): extrapolate Inner Detector tracks to the calorimeter

Particle ID is challenging: e/jet ~ 10^{-5} at 40 GeV

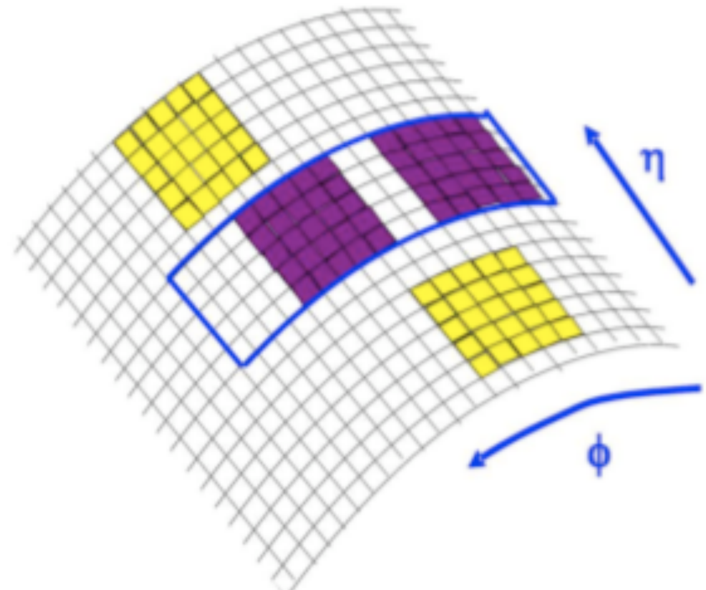
Electron Reconstruction Strategy

Combination of ECAL and Tracker Information



Energy Clustering in ECAL

- Bremsstrahlung recovery
  - Search for the highest ET crystal
  - Narrow η – larger ϕ window around the seed
  - Superclusters are built by collecting clusters of crystals in the road
- Energy estimation
  - Sum of the energies of the crystals in the supercluster
- Position estimation
  - Energy weighted mean position of the crystals in the supercluster

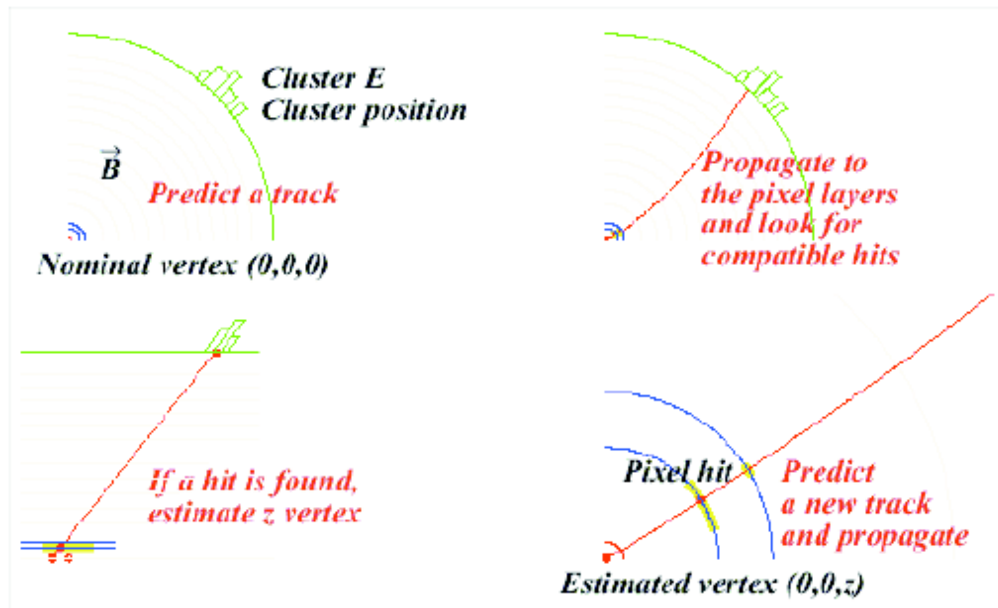


$$x = \frac{\sum x_i \cdot W_i}{\sum W_i}$$

$$W_i = W_0 + \log\left(\frac{E_i}{\sum E_j}\right)$$

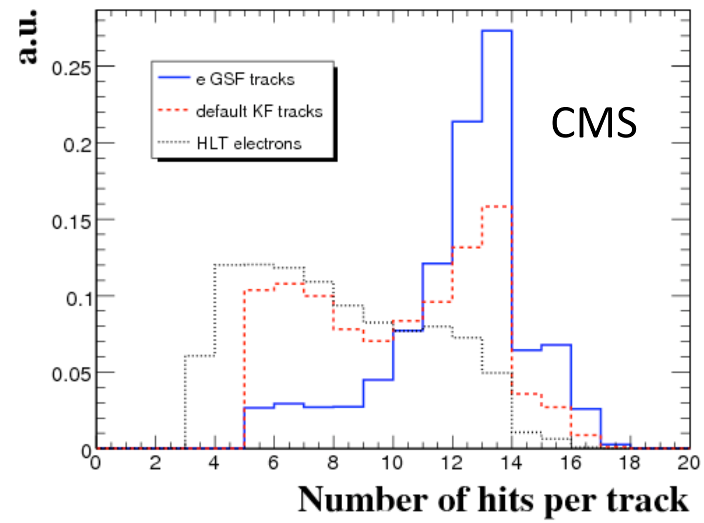
Electron Seeding

- Search for the tracking seeds in the pixel detector is driven by energy weighted mean position of super-cluster
- Use primary vertex to construct trajectory between supercluster and vertex
- Look for pixel hits in window about trajectory
- Using pixel seeds build trajectory in to out and look for associated silicon tracker hits
- Fit trajectory
- Correct cluster energy for energy loss in material

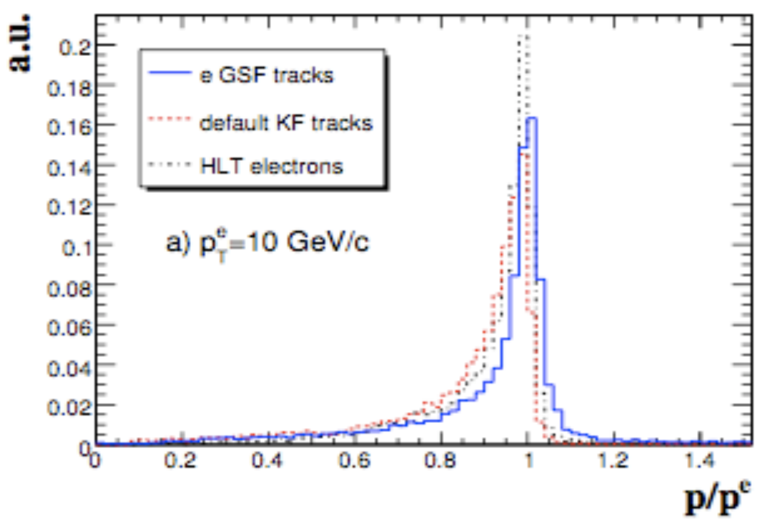


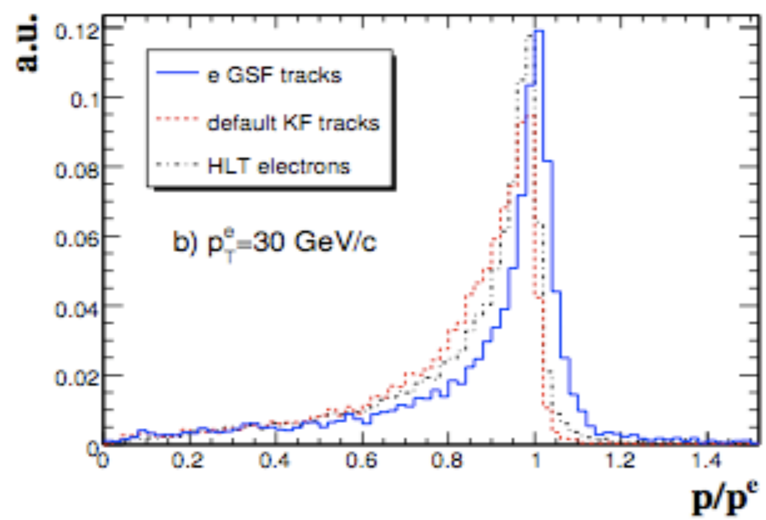
Electron track reconstruction

- Start electron tracking with seeds from supercluster driven match filter
  - Energy loss for electrons is highly non gauss
  - (Bethe-Heitler) energy loss modeled by seve gaussians
  - The Gaussian Sum Filter is used
    - Loose χ2 (two best candidates are kept)
    - a minimum of 5 hits required



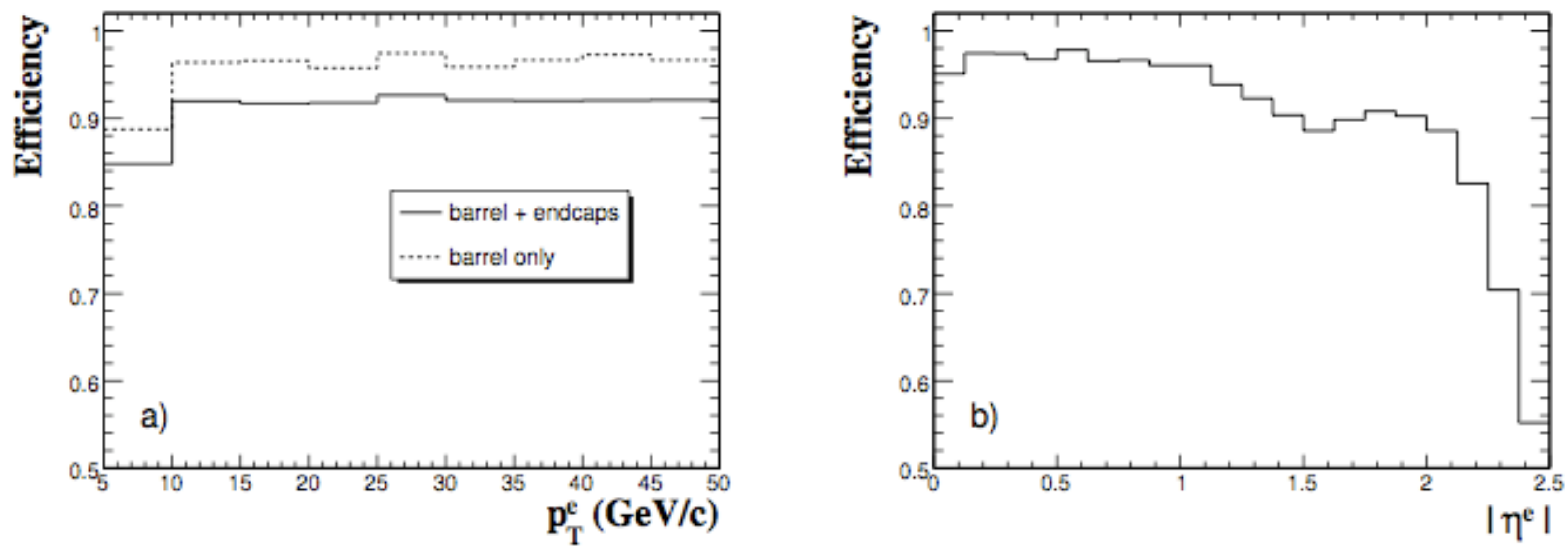
Differences owing to choices of trajectory building parameters and energy loss modeling





Efficiencies

CMS

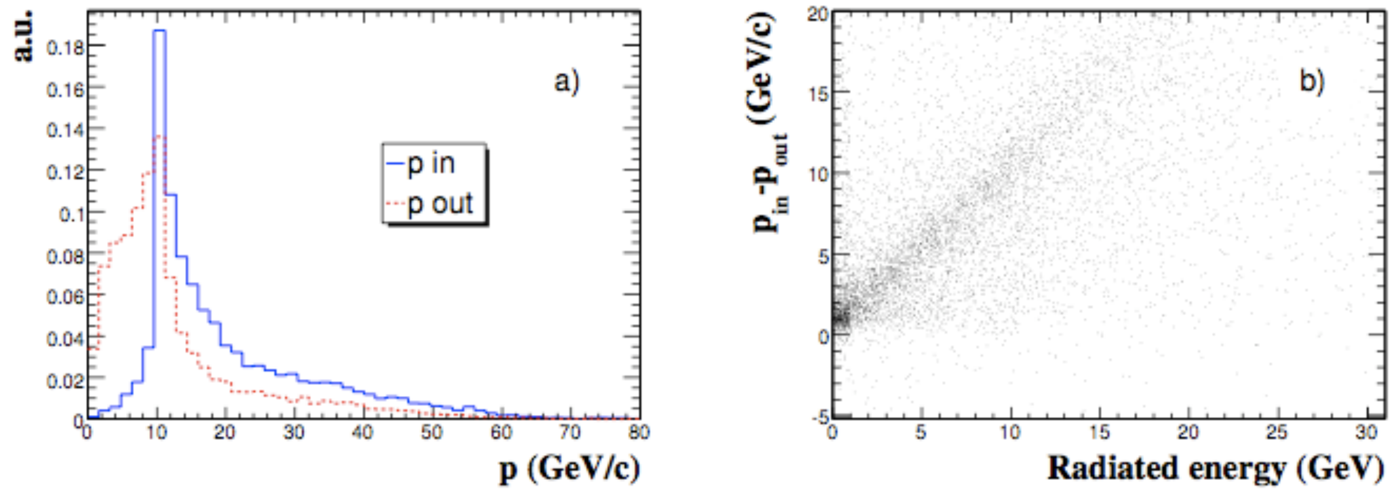


Performance

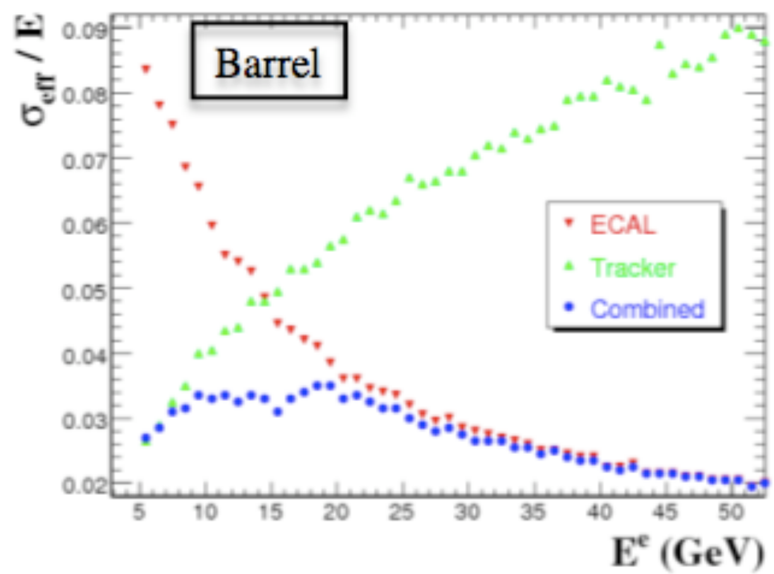
- Bremsstrahlung fraction

CMS

brem fraction: $(p_{in}-p_{out})/p_{in}$



P_{in}: momentum at the vertex
P_{out}: momentum at the outermost hit
$p_{in}-p_{out}$ ~ integral amount of bremsstrahlung



- ECAL and Tracker estimates are combined to obtain the final electron momentum magnitude

Electron pre-selection

- After the GSF track fit, track-supercluster associations from the pixel match are preselected to build candidate electrons
- Aim is to be as efficient as possible with low fake rate
- Pre-selection should be suited to any physics analysis involving primary electrons
  - Minimum transverse energy: $E_T > 4$ GeV
  - An η, ϕ geometrical matching: $\Delta\eta < 0.02$, $\Delta\phi < 0.1$
  - A cut on hadronic energy behind cluster: $H/E < 0.2$

Electron Candidate Efficiency

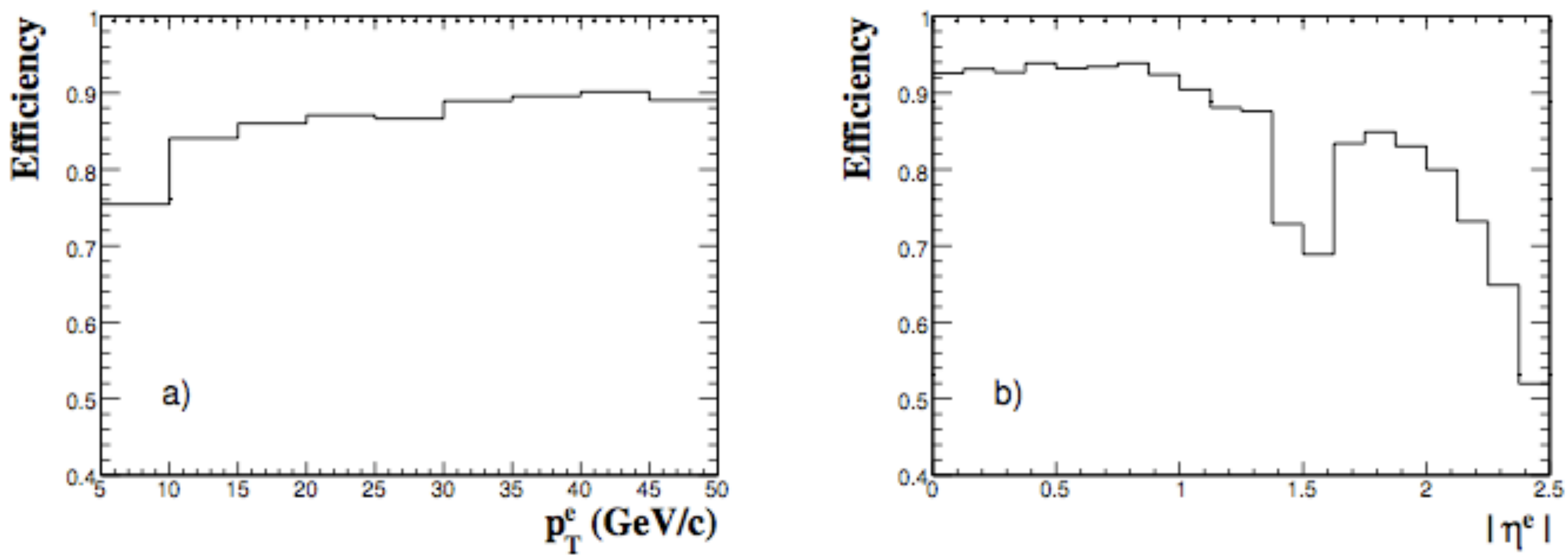


Figure 19: Electron candidate efficiency for electrons from Higgs boson decays $H \to ZZ^* \to e^+e^-e^+e^-$ after preselection and for $m_H = 150$ GeV$/c^2$: a) as a function of p_T^e; b) as a function of η^e.

Electron Identification

- At startup use cut-based identification based on simple and well understood variables
- Variables should be as insensitive as possible to tracker mis-alignment
- Variables:
  - H/E: Ratio of energy in HCAL behind SuperCluster to SuperCluster energy
  - $\Delta\eta$: Delta η between SuperCluster position and track direction at vertex
  - $\Delta\phi$: Delta ϕ between Supercluster position and track direction at vertex
  - $\sigma_{\eta\eta}$: cluster shape covariance

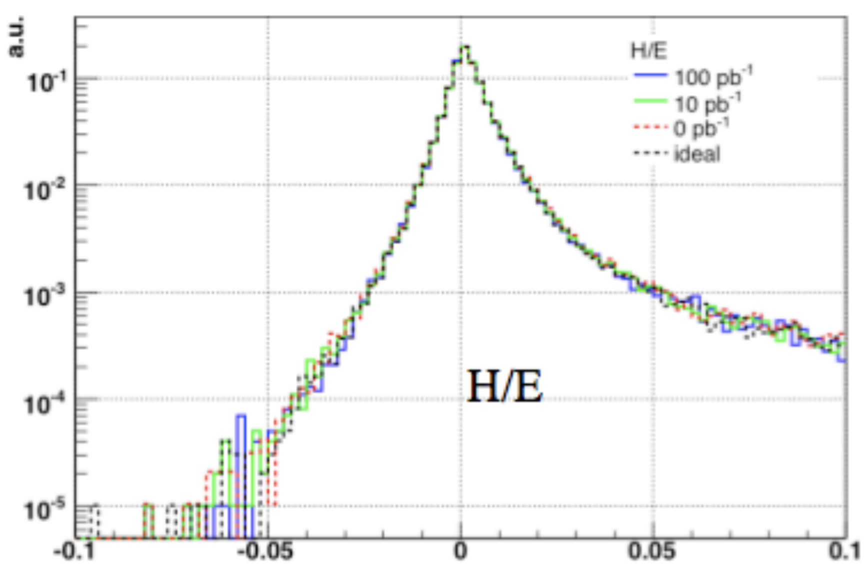
Electron Identification

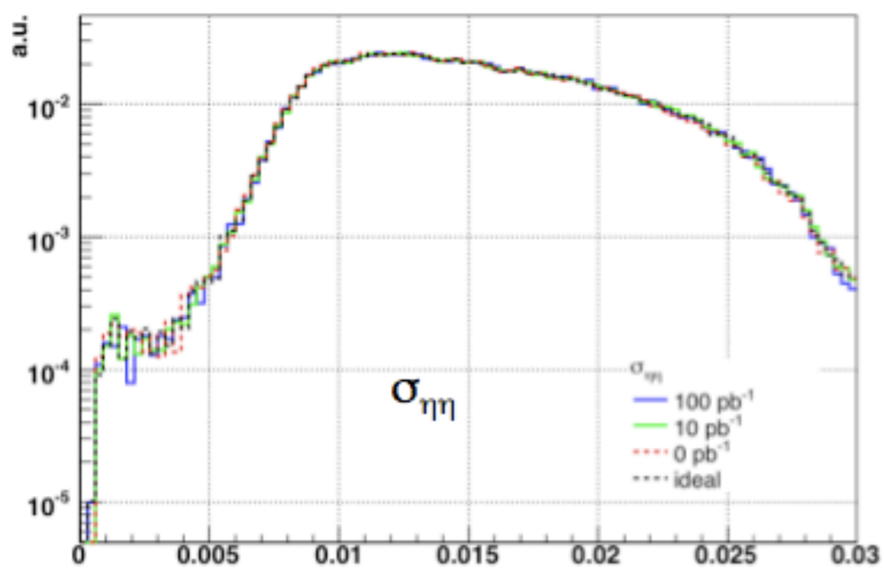
"loose" set of thresholds

Variable	barrel	endcap
H/E	0.115	0.150
DeltaEta	0.0090	0.0105
DeltaPhi	0.090	0.092
SigmaEtaEta	0.0140	0.0275

"tight" set of thresholds

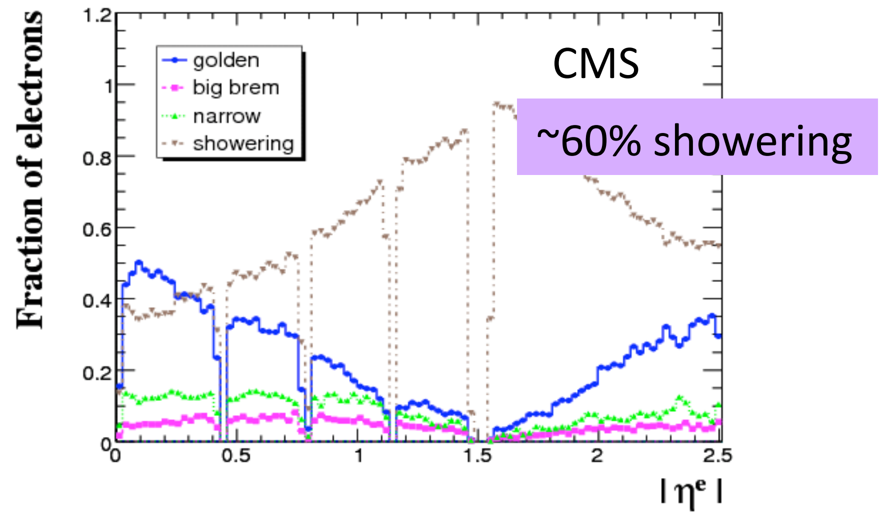
Variable	barrel	endcap
H/E	0.015	0.018
DeltaEta	0.0025	0.0040
DeltaPhi	0.020	0.020
SigmaEtaEta	0.0092	0.0250

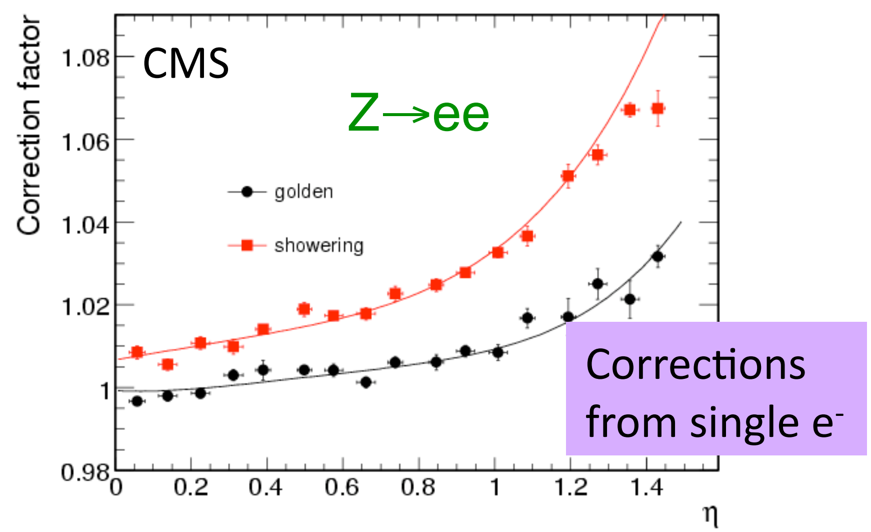




E-scale corrections, e classes

- Different track-cluster patterns due to brem in tracker material
- E-scales corrections depend on classes
  - « golden electrons »
    - Good E/p and phi match
    - Low brem fraction
  - « big brem electrons »
    - Good E/p match
    - High brem fraction
  - « narrow electrons »
    - Good E/P match
    - Intermediate brem fraction
  - « showering electrons
    - Bad E/Pmatch, brem clusters
- Tuned using Z→ee data
  - MC needed for low p_T region





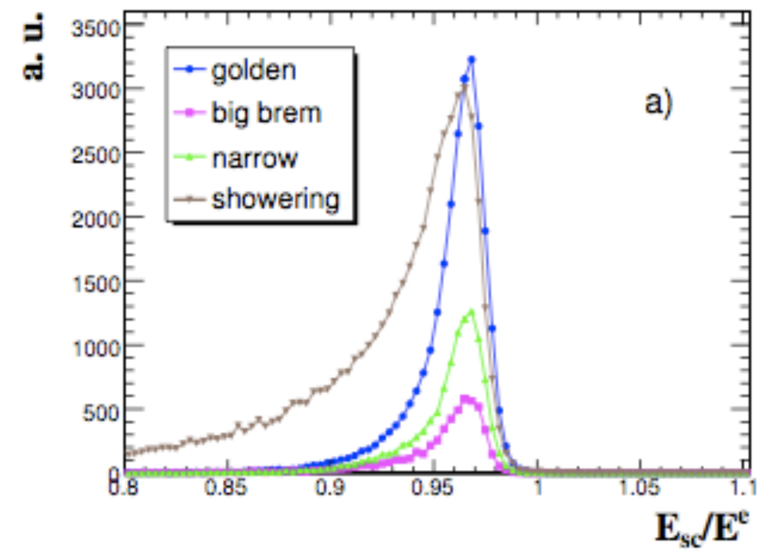
Electron Classes

1. Golden Electrons: less than 20% brem which is fully recovered

2. Big Brem: >50% brem which is fully recovered

3. Narrow: 20-50% brem which is fully recovered

4. Showering (Bad). Brem which is not recovered due to photon conversion



Before correction…

Electron Classes

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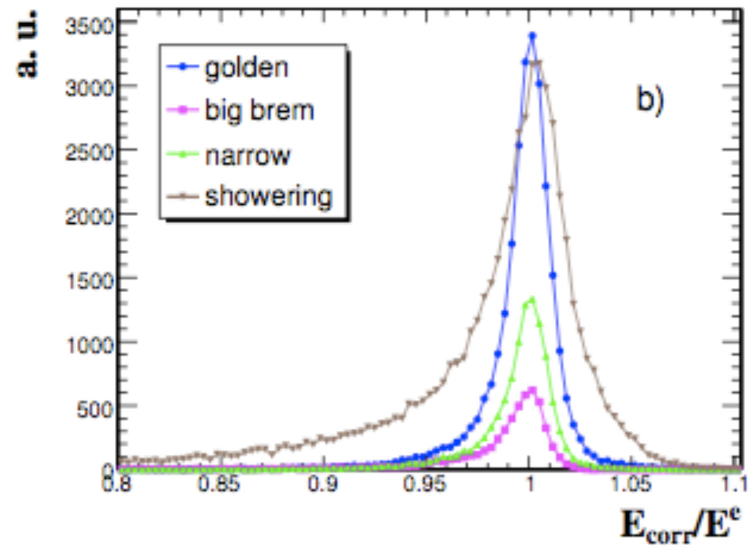
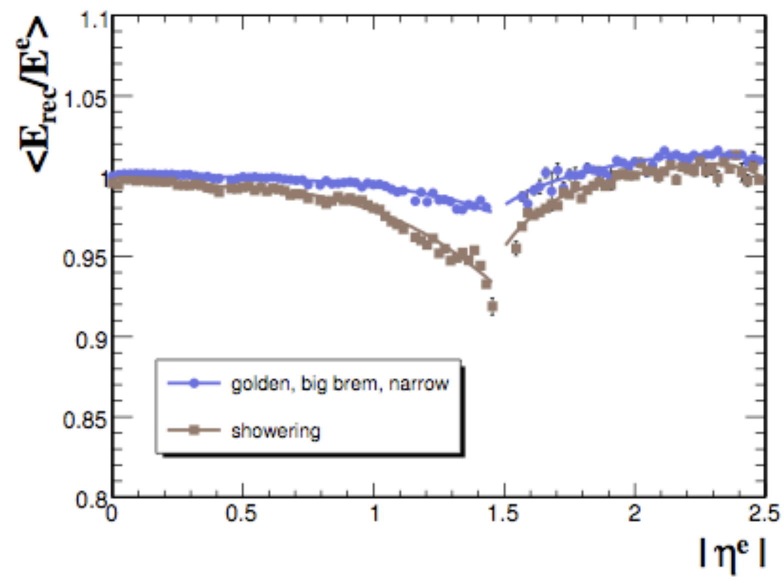
After correction…

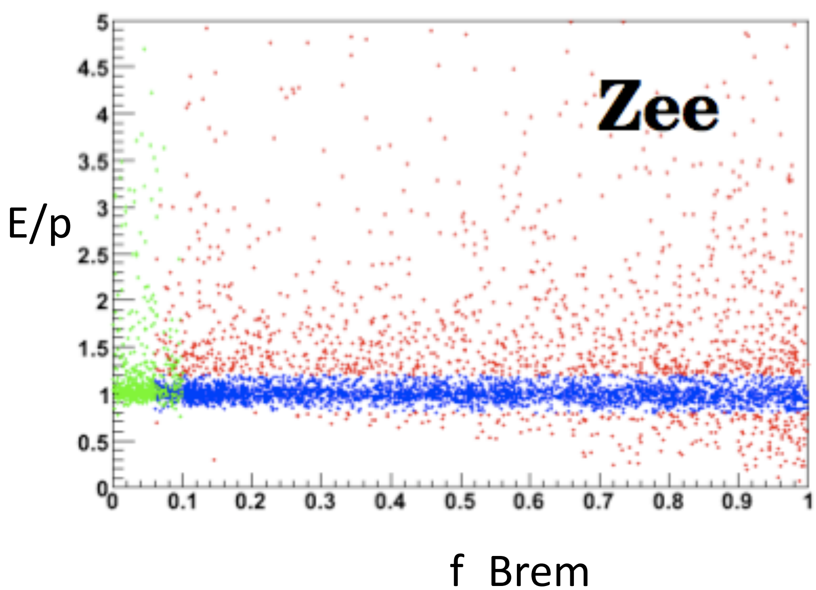
CMS

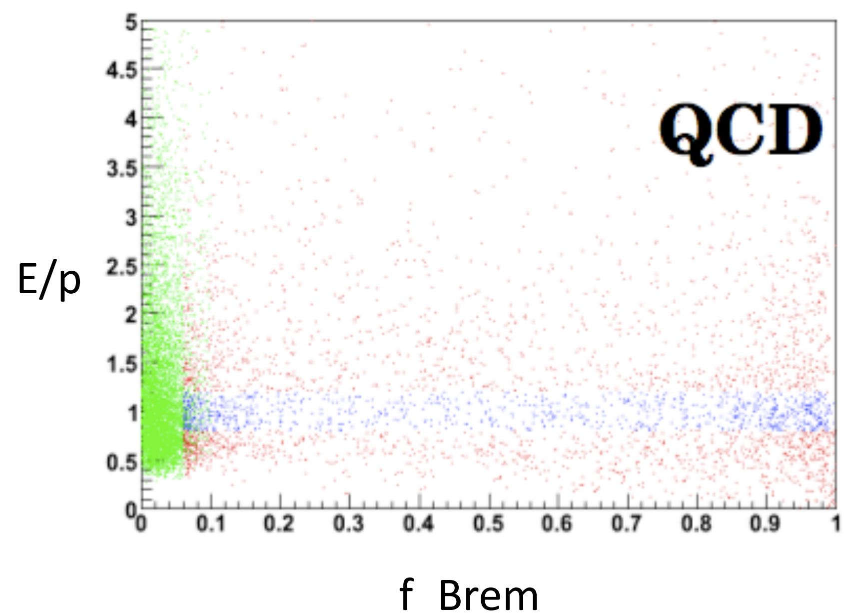




"Class-based" ID

- Can also introduce class based identification with three classes based on E/p and fBrem
  - Bremming electrons with E/p ~ 1 (little contamination from fakes)
  - Low brem electrons (high population from both real and fake electrons)
  - Bad track, E/p ≠ 1

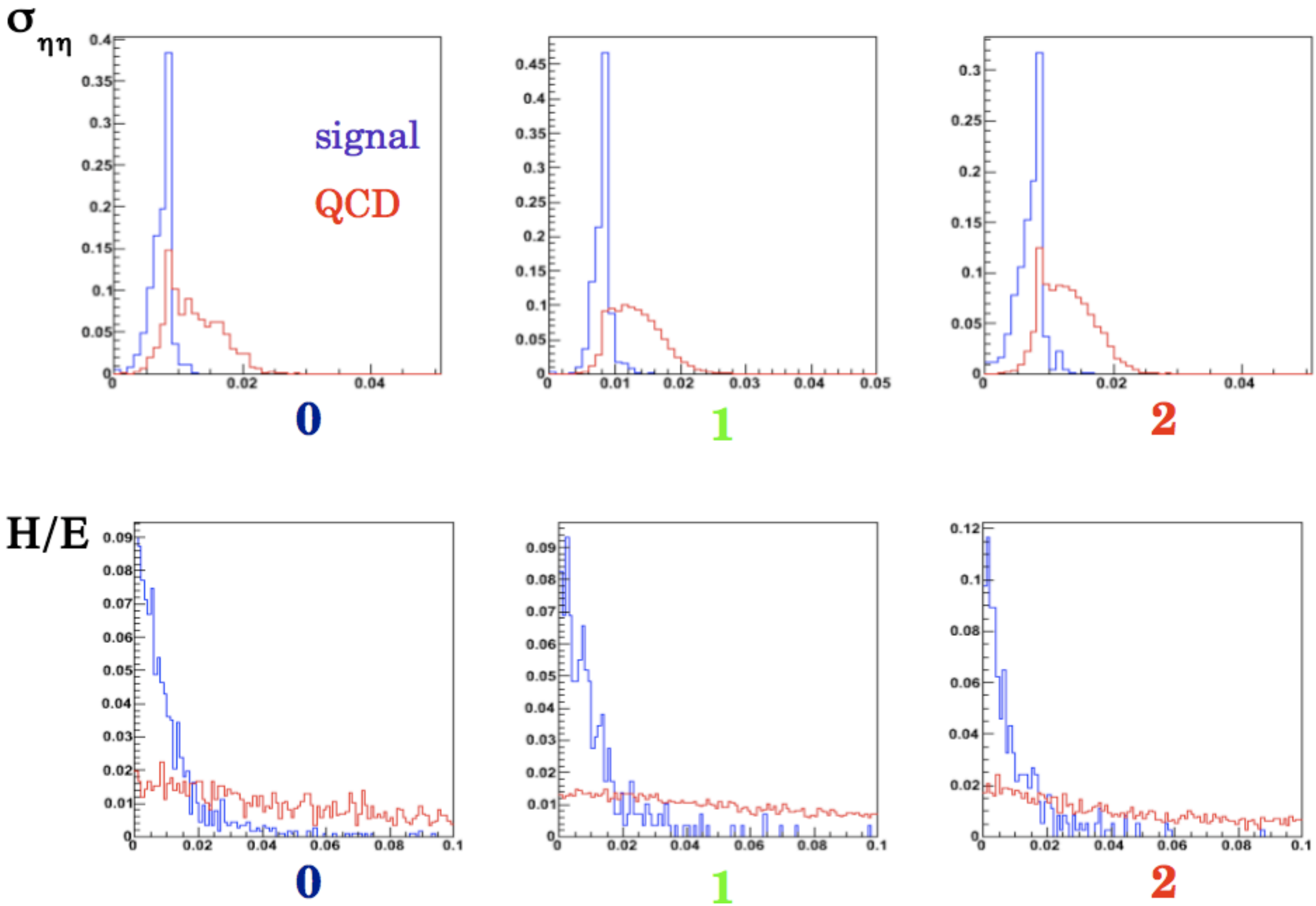




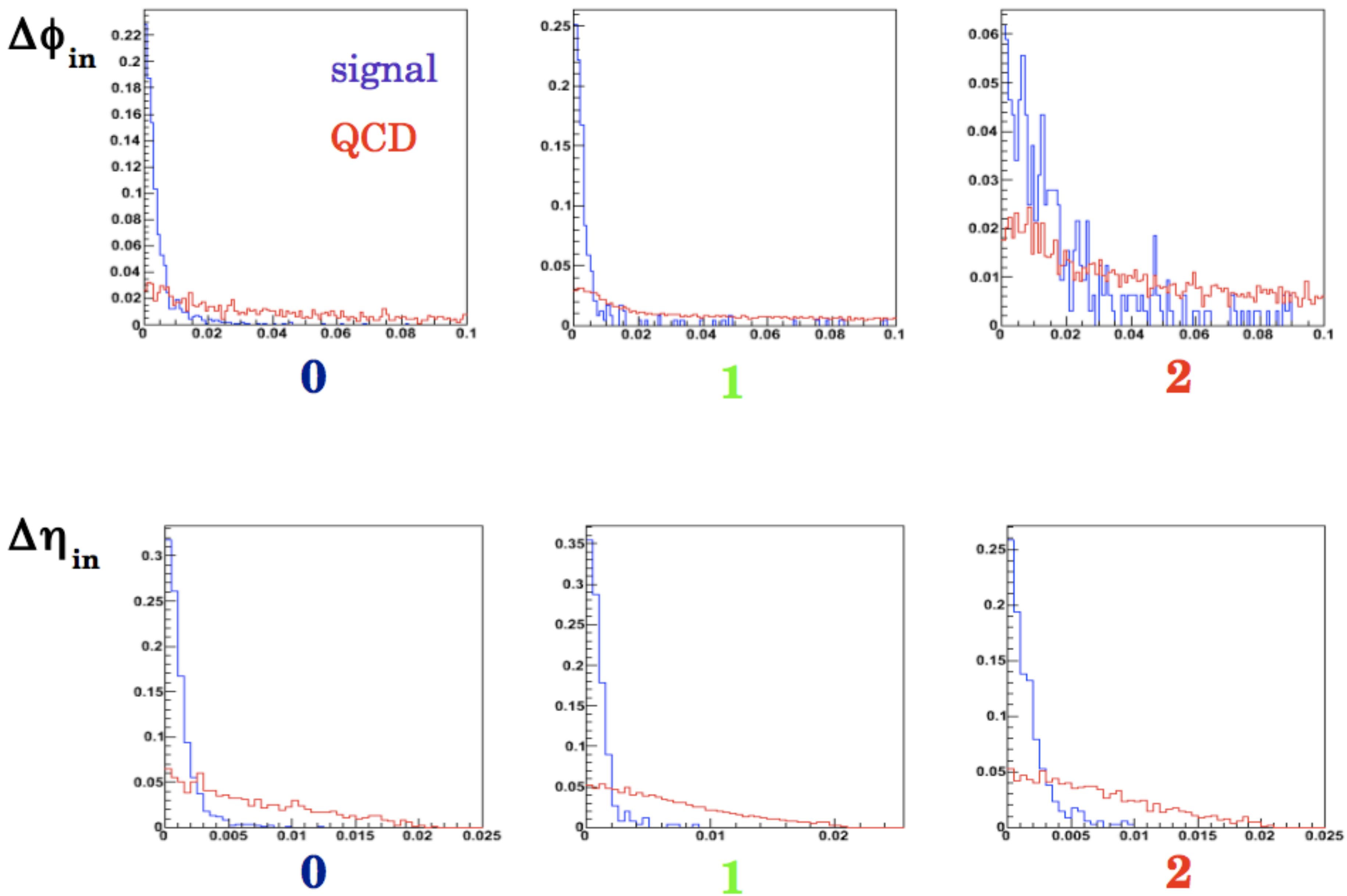
Class-based ID

1. E/p is often well measured for electrons
2. Electrons usually radiate a good deal of energy in the tracker
3. E/p is not often measured to be less than 1 for electrons

1. Fakes from jets usually have fBrem around 0 (just charged pion tracks…)
2. Many fakes from jets have $E/p<1$ partly because of the low response of ECAL to charged pions…



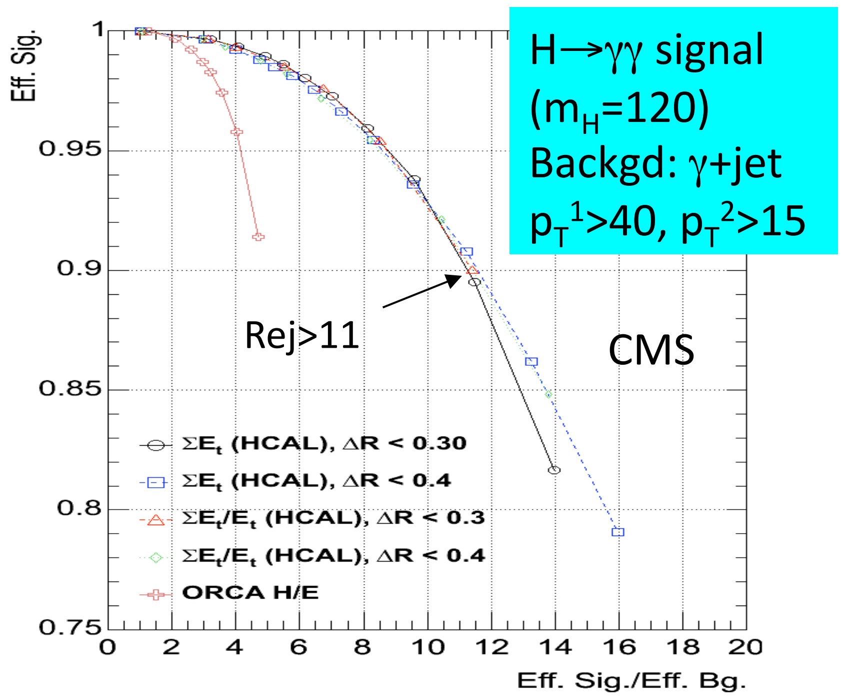
σηη
signal
QCD
0
1
2
H/E
0
1
2

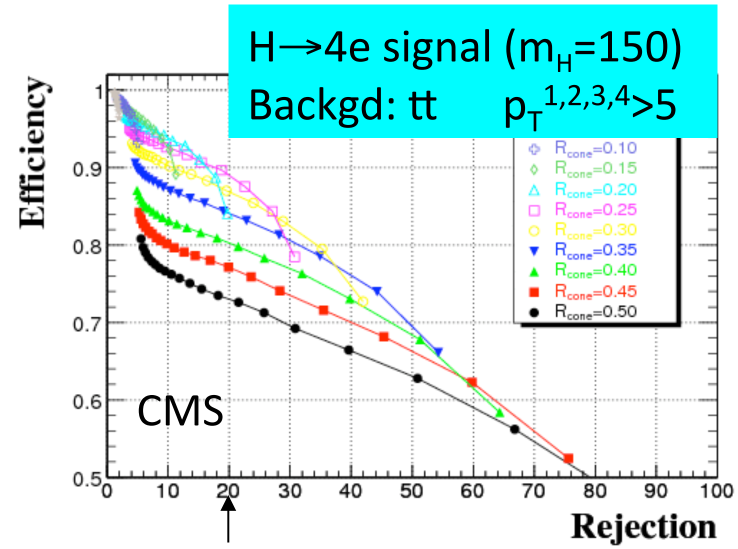


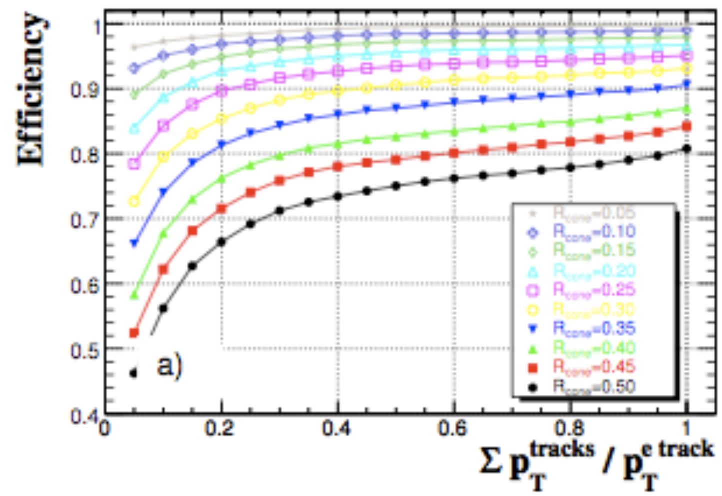
$\Delta\phi_{in}$
signal
QCD
0
1
2
$\Delta\eta_{in}$
0
1
2

e/jet,γ/jet separation: isolation

- Isolation is a very powerful tool to reject jet backgrounds
  - Track based isolation
  - Calorimeter isolation
  - Combined isolation





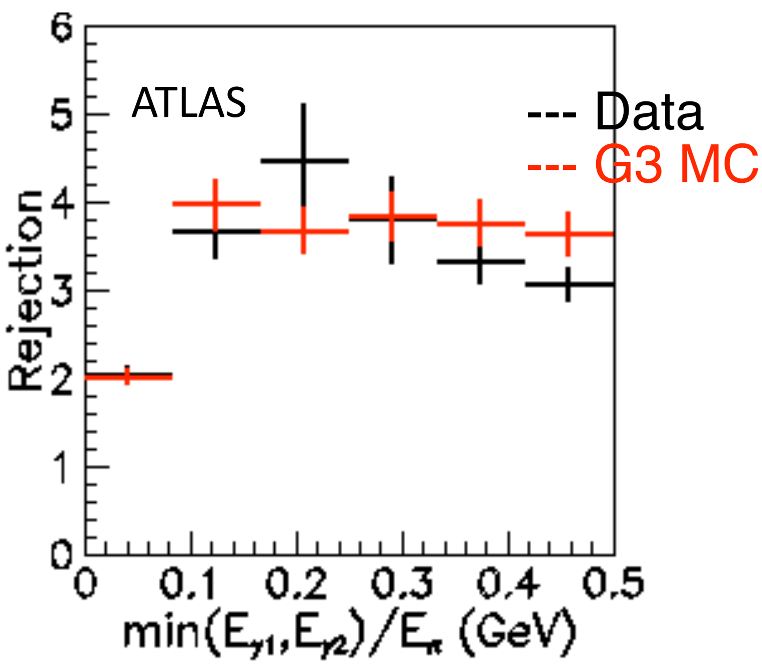


Different working points can be chosen based on the necessary background rejection

π^0/γ separation

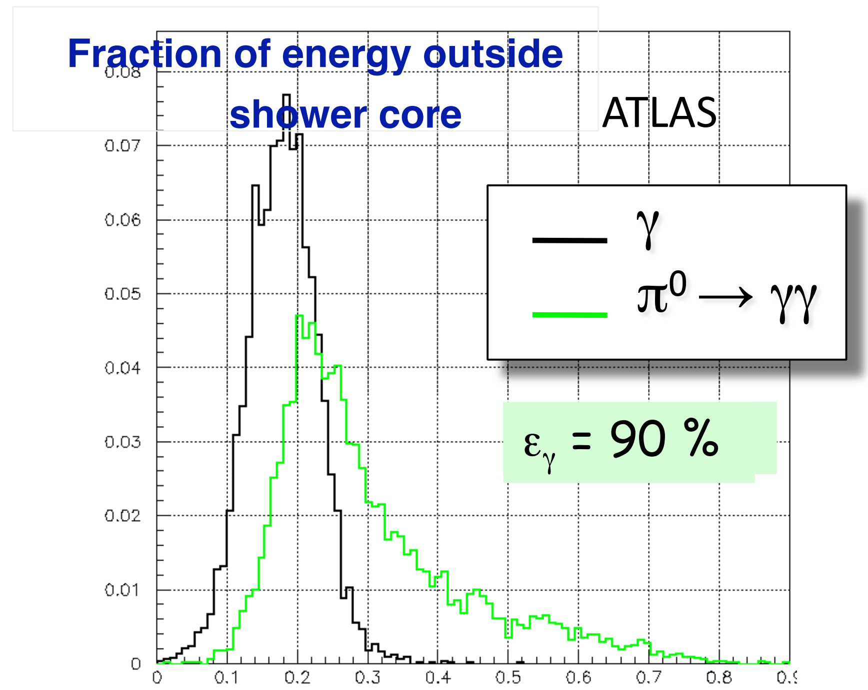
- Once isolation has been applied, only jet with little hadronic activity remains

Results from TB 2002 @50 GeV



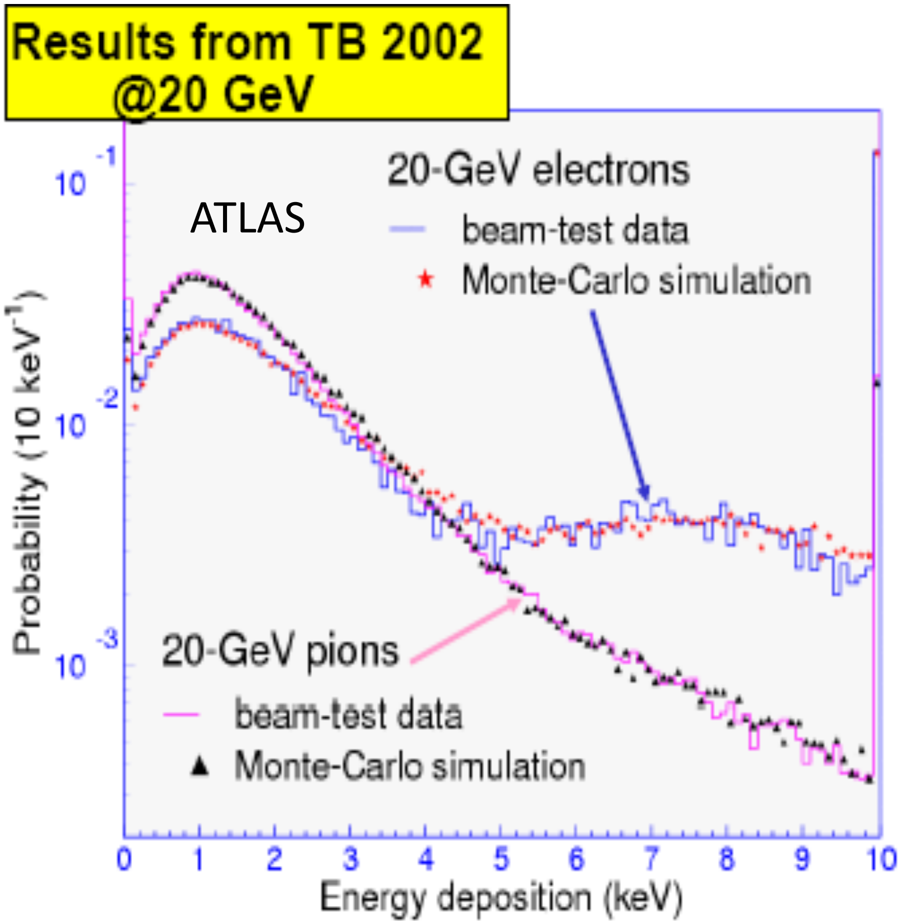
$R_{\pi 0}$ (data) = 3.18 ± 0.12 (stat)
$R_{\pi 0}$ (MC) = 3.29 ± 0.10 (stat)

Results from G4 full simulation

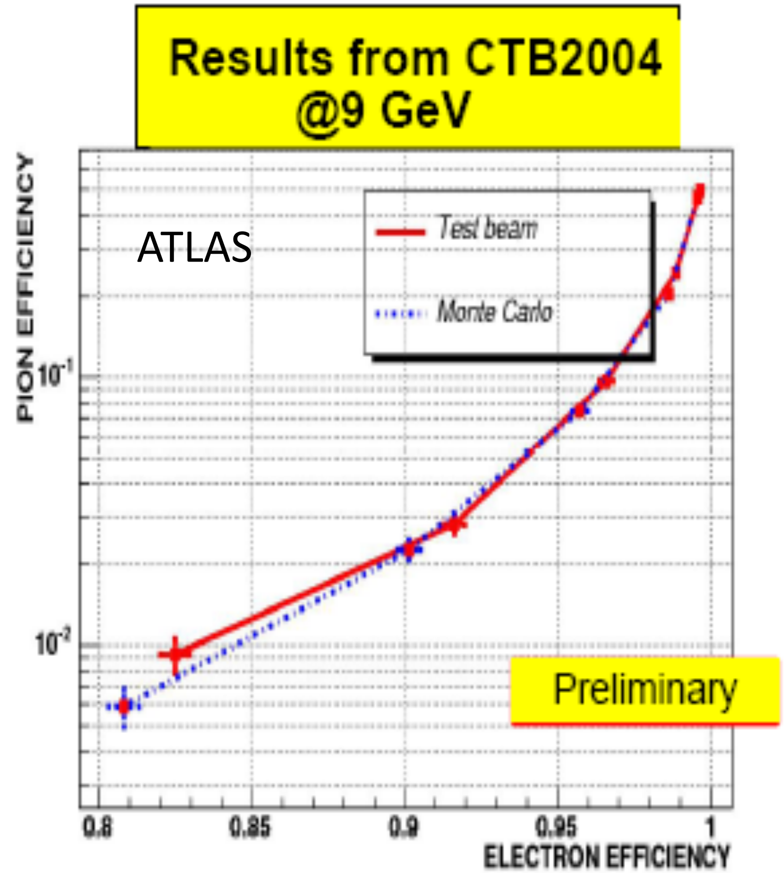


$R_{\pi 0}$ (G4) = 3.2 ± 0.2

Separation using TRT



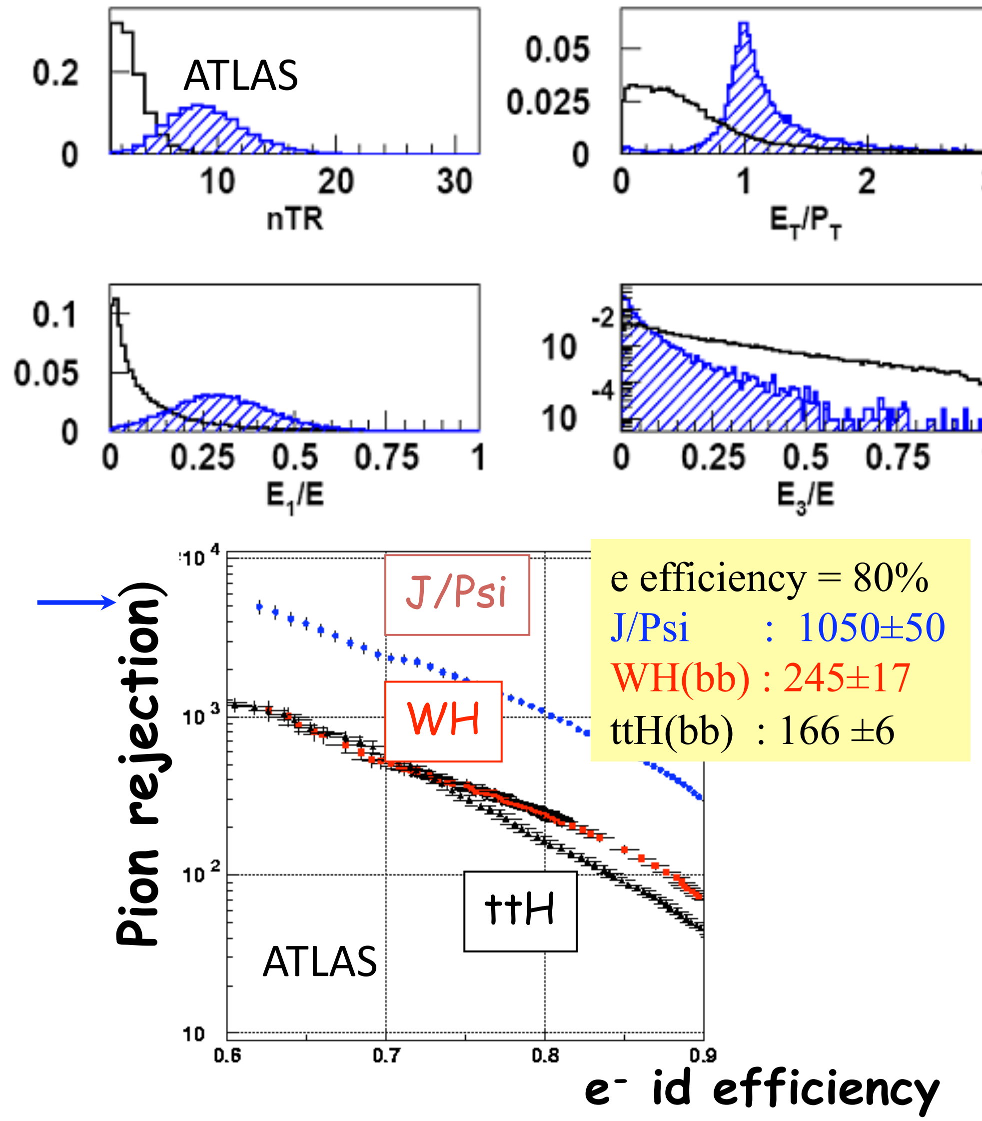
Typical TR photon energy depositions in the TRT are 8-10 keV
Pions deposit about 2 keV



90% electron efficiency
2×10^{-2} pion efficiency

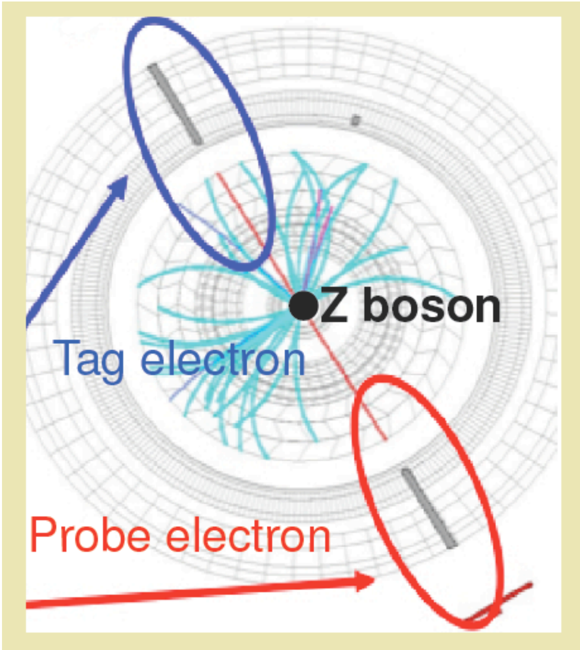
Electrons from b's

- Reconstruction of electrons close to jet is difficult
  - Dedicated algorithm required
- ATLAS low p_T algorithm:
  - Start with track reconstruction
  - Build cluster around extrapolated track
  - Calculate cluster properties
  - pdf and neural net for ID
- Performances on single tracks
- Soft e^- b-tagging efficiency
  - ATLAS: 60% for R=150 (WH)
  - CMS: 60-70% above 10 GeV miss rate ~1.5% (tt and QCD)



ID efficiency

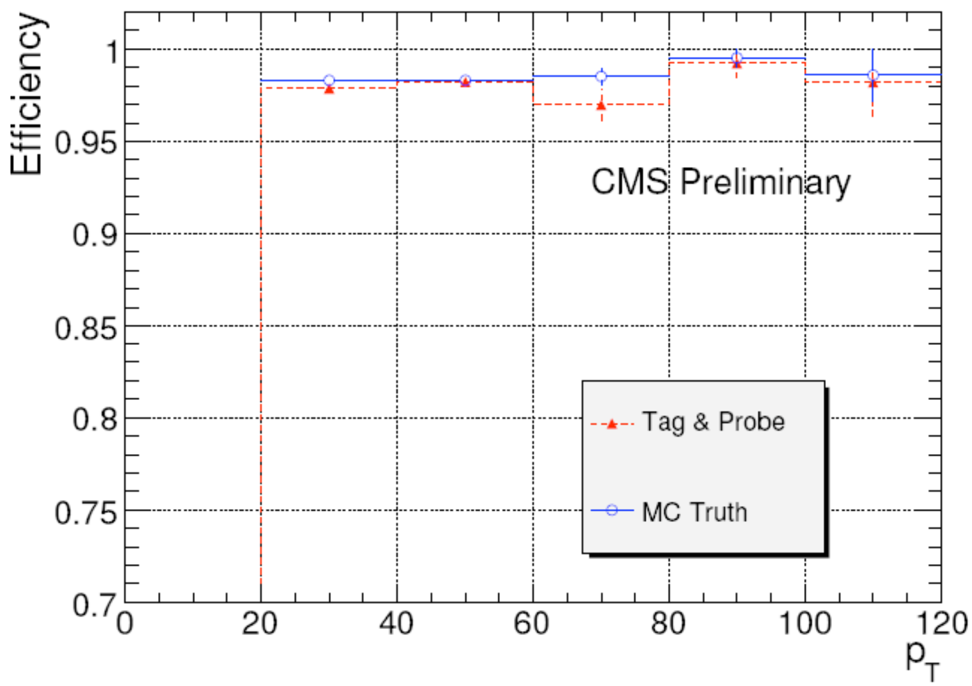
- Common method is “tag and probe”
- Uses event from known resonances (Z->μμ, J/Psi->μμ and electron modes)
- Tag lepton:
  - Passes strict ID requirements
  - Typically require a single muon/electron trigger to be satisfied
- Probe lepton:
  - Reconstructed (but does not need to pass strict ID cuts)
- Require invariant mass of tag and probe leptons to match resonance (Z or J/Psi) mass

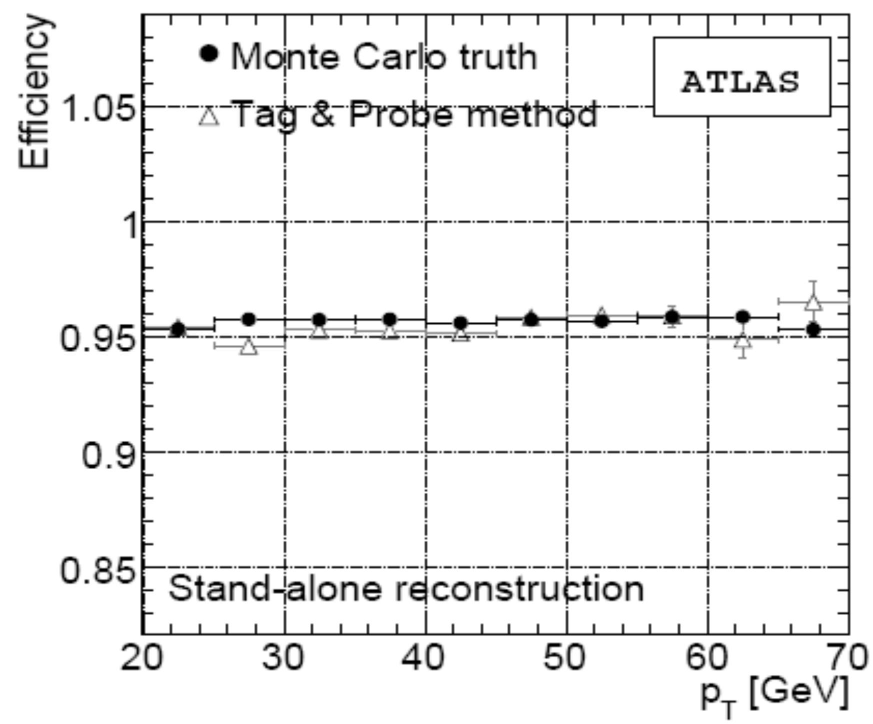


$$\varepsilon = \frac{\#\ \text{of probes passing ID cuts}}{\text{Total}\ \#\ \text{of probes}}$$

ID efficiency

Agrees well with truth-matching (<~1%)
MC to go from e→γ in early data
Later on use Z→μμγ for photon efficiency





Z→μμ

Taus and Jets next time