Calorimetry at Colliders

I will give 2 lectures:

Part 1 (yesterday): Calorimeter basic principals and general features

Part 2 (today) : Precision measurement with calorimeters – turning them into scientific instruments

=> Focus today will be on photons and jets in collider detectors at the LHC (ATLAS and CMS)

Outline

The path is

Careful design and quality control during construction

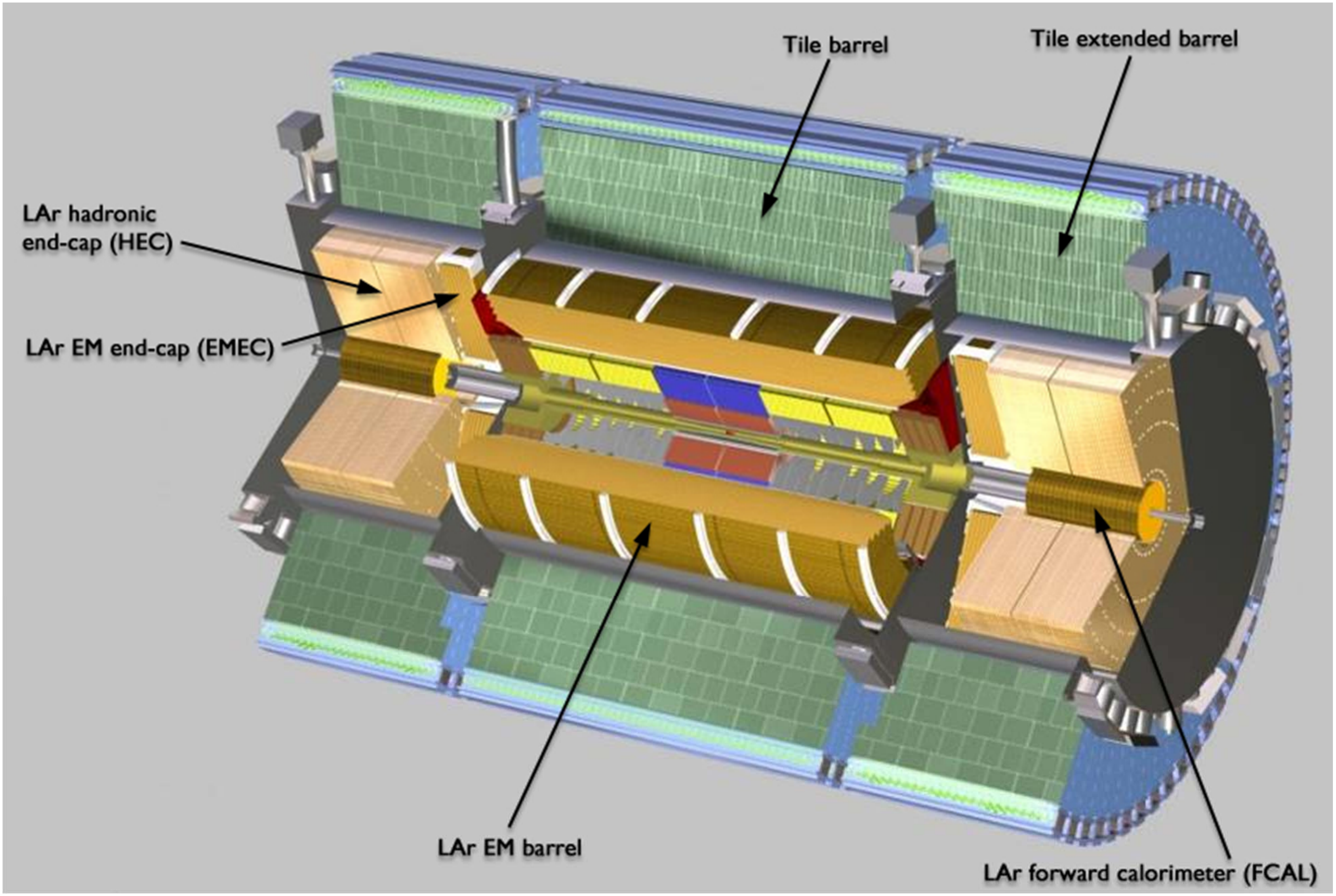
Calibration and monitoring during data-taking (including *in situ* measurements)

=> Photon reconstruction and measurement

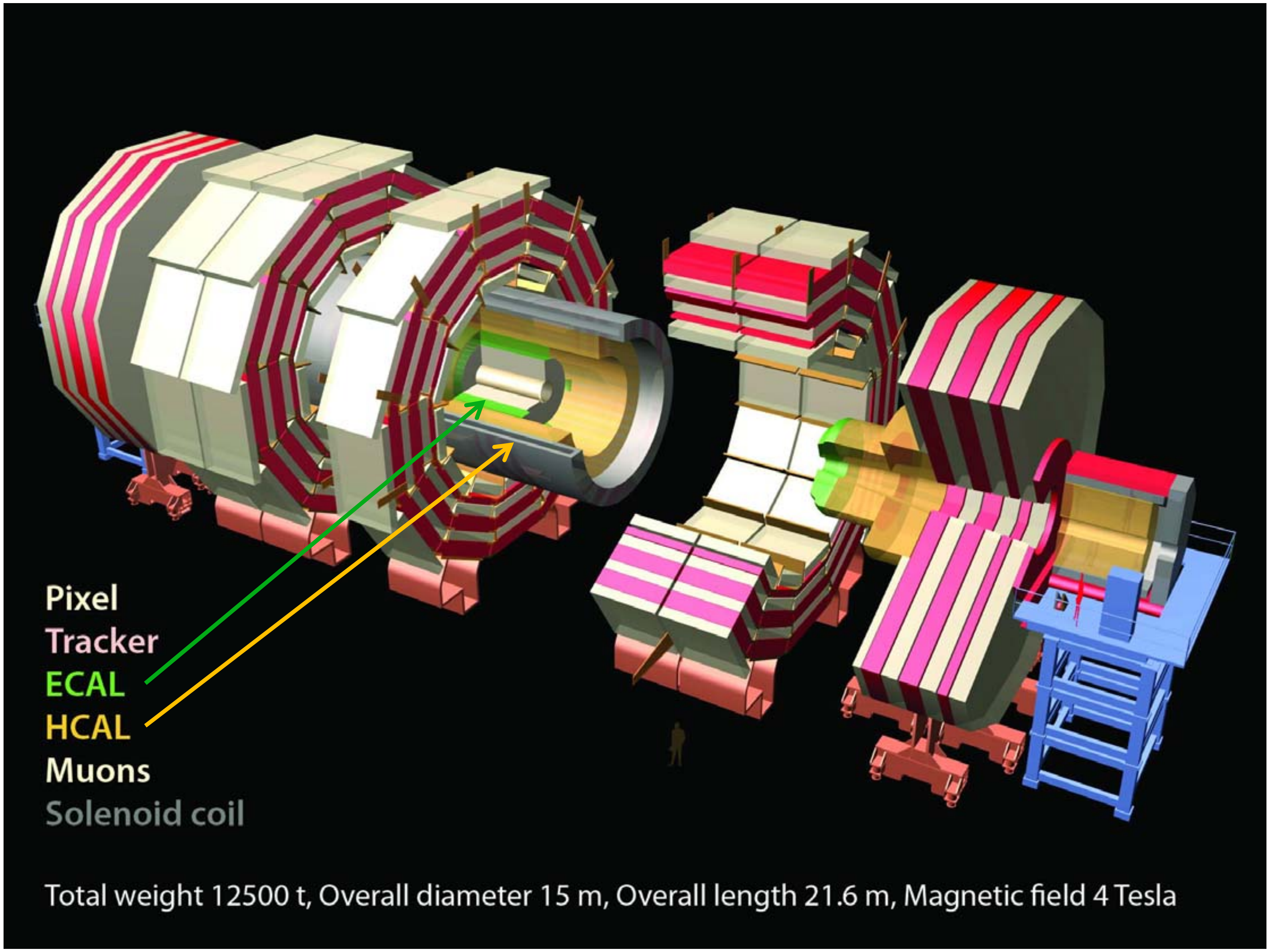
=> Jet reconstruction and measurement

Apologies – these are "nuts and bolts" issues and so I will draw largely from the detector on which I have worked: ATLAS

Design Choices: ATLAS Calorimeter System



Design Choices: CMS

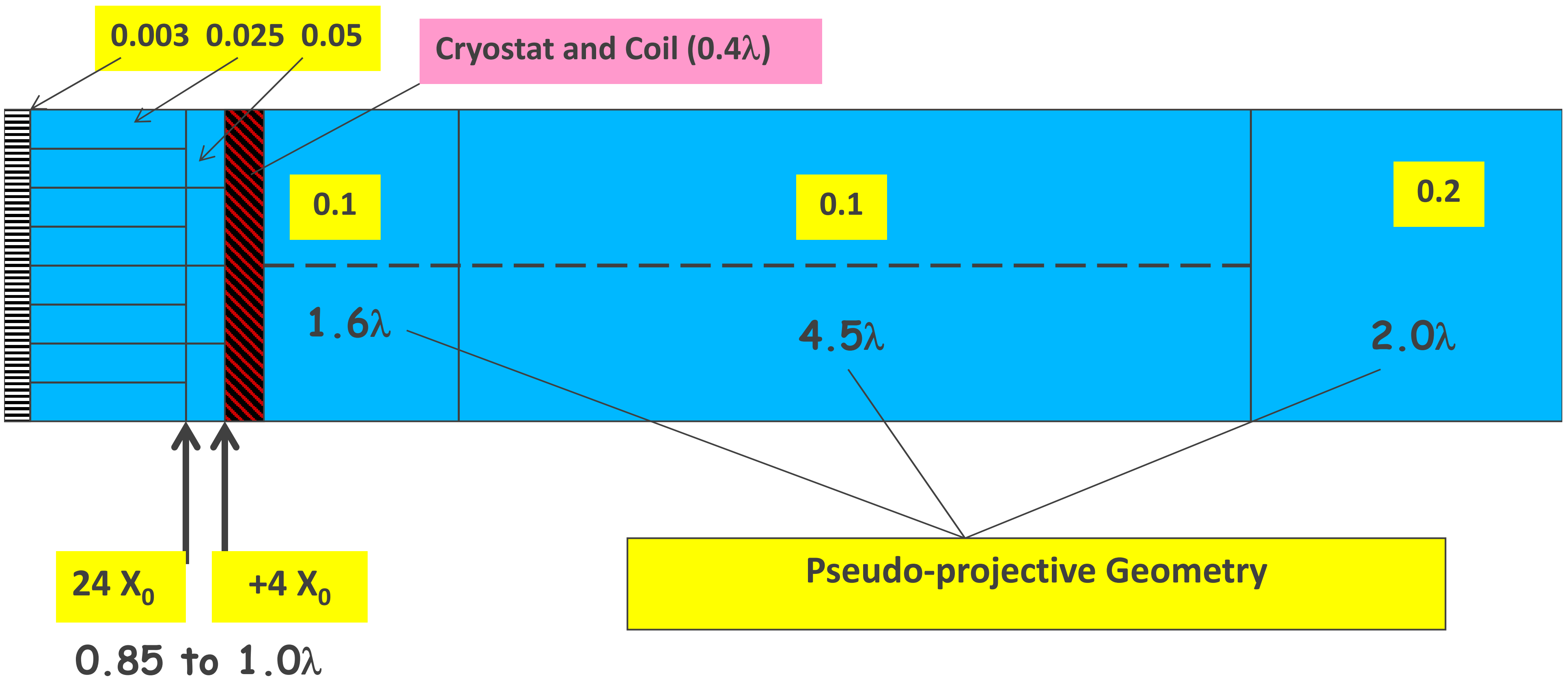


Absorber properties

	X_0 (cm)	λ_{int}(cm)
Pb	0.56	17.0
$PbWO_4$	0.89	18.0
Fe	1.76	16.8
Cu	1.43	15.1

	t_{em}	t_{had}
ATLAS, Tilecal (Fe)	1.0	0.11
CMS HCAL (Cu)	3.5	0.33

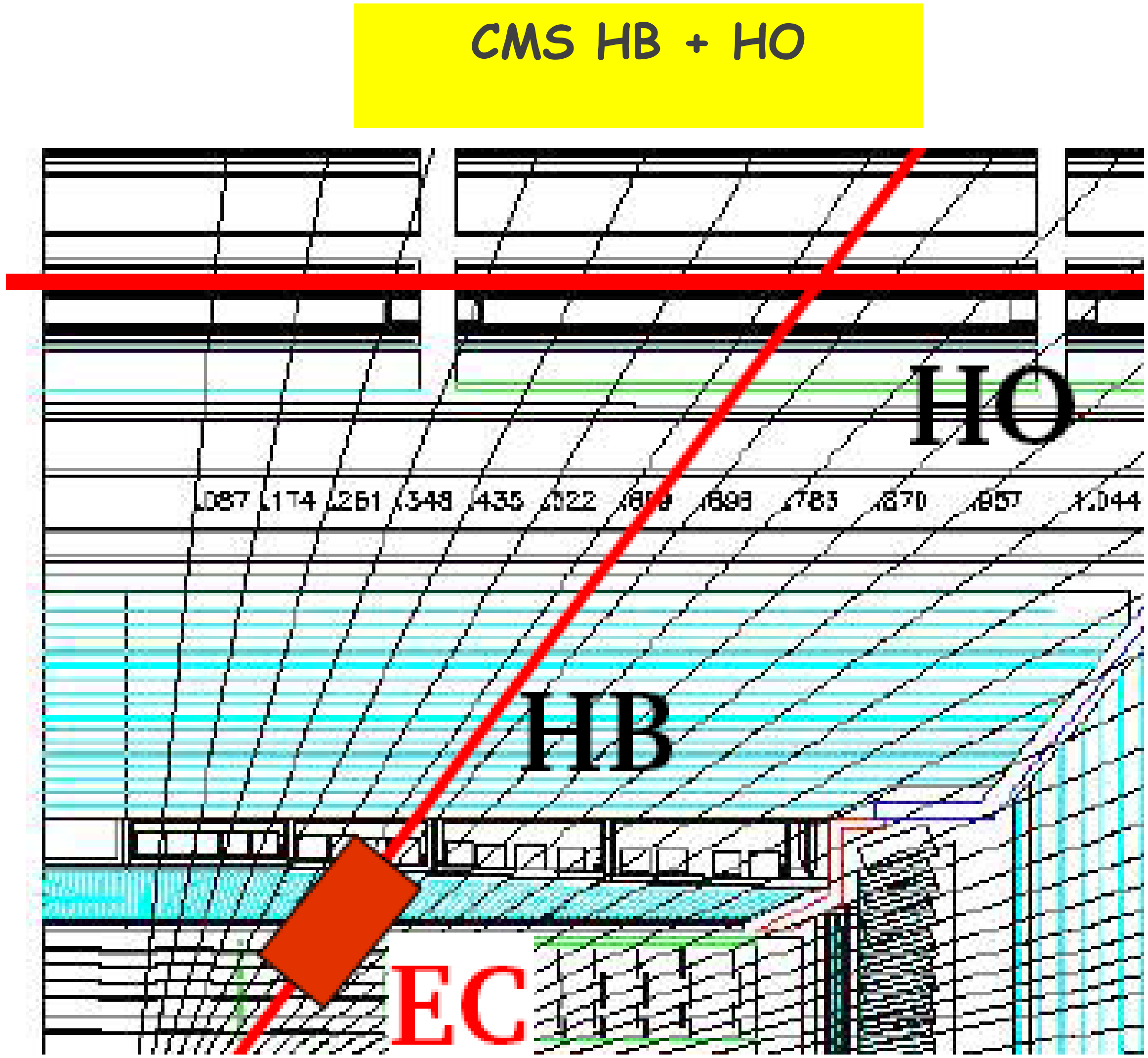
ATLAS Barrel Calorimeter Segmentation



η Segmentation as function of Depth at η~0.4

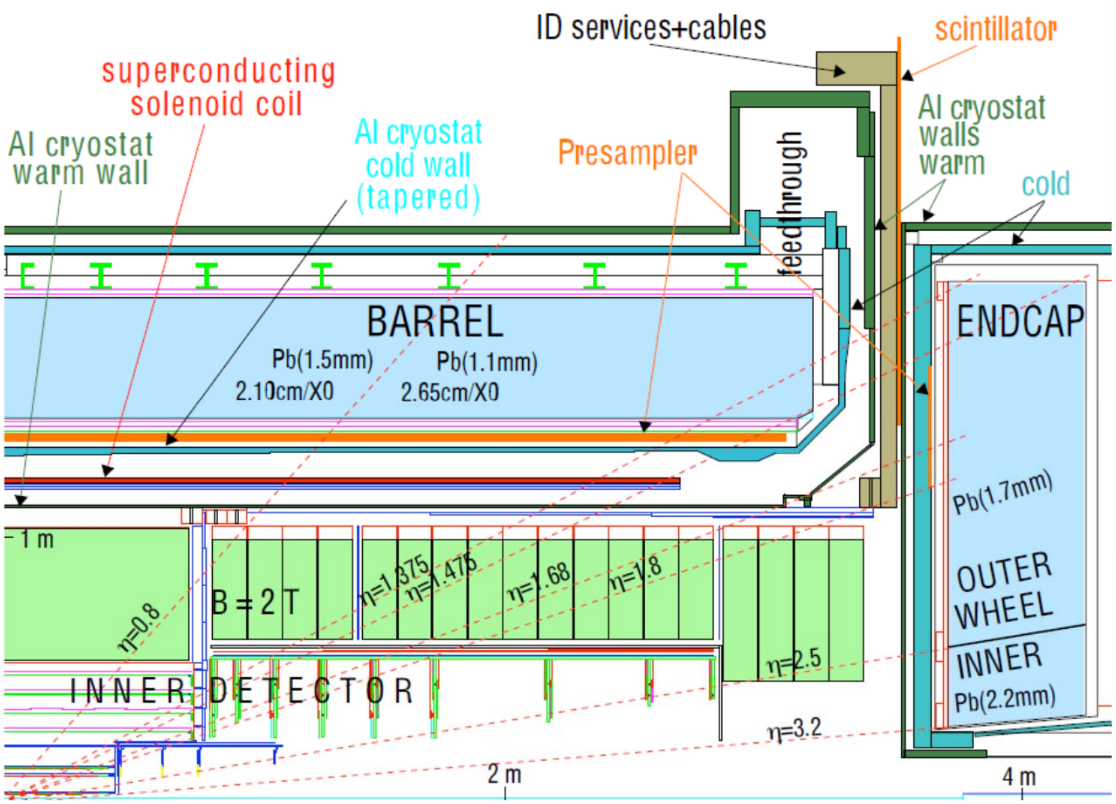
CMS Calorimeter Depth Segmentation

1.1 λ Tail Catcher (h<0.4)
1.4 λ Coil
5.9 λ [Fe/Cu] Scintillator(1+16)
Space for ECAL Readout
1.1λ Lead Tungstate ECAL

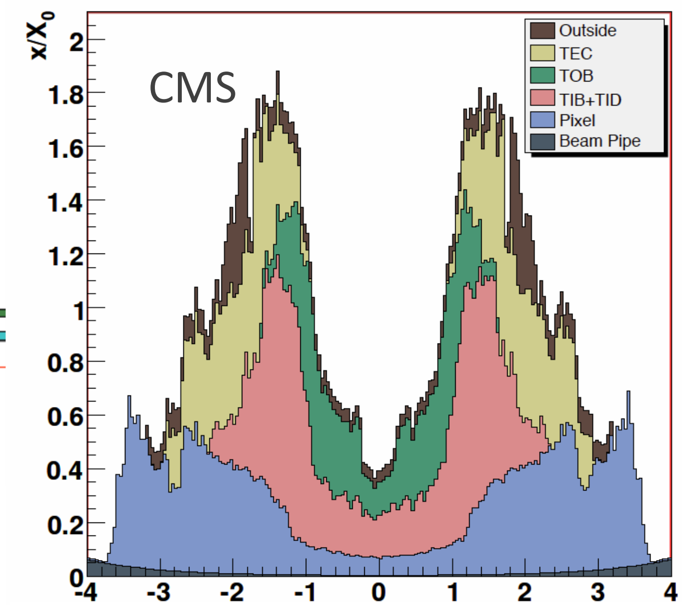


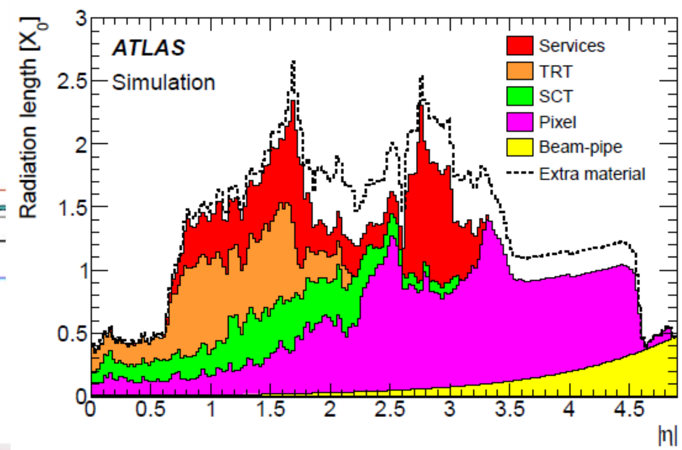
Material in front of the calorimeter (examples)

ATLAS Barrel/Endcap Interface



Material in front of the calorimeter





Design Features/ Expected Performance

- **ATLAS**

  Cryostat+ Coil (0.4 λ) is between the barrel electromagetic and hadronic calorimeters

  Absorber plates run normal to the beamline

  2 tesla magnetic field

  $\sigma_E/E \sim 50\%/\sqrt{E} + 3.0\ \%$ (for $|\eta| < 3$)

- **CMS**

  5cm Cu sampling; 17 sampling layers

  Tail Catcher

  e/h > 2 in crystal EM calorimeter

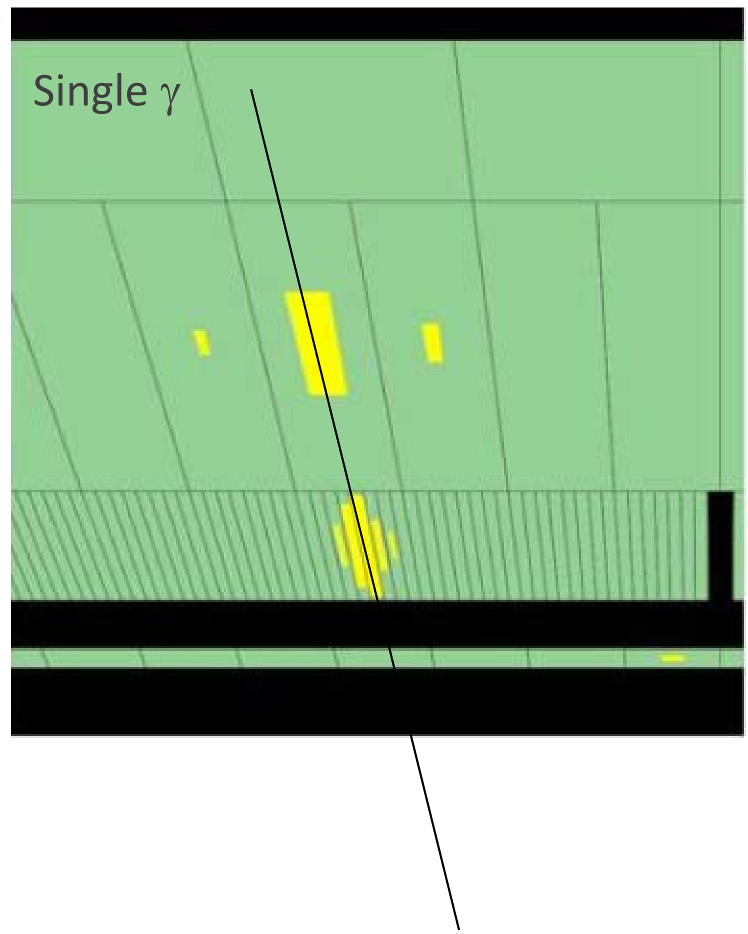
  4 tesla magnetic field

  $\sigma_E/E \sim 100\%/\sqrt{E} + 4.5\ \%$

Key feature of ATLAS EM Calorimeter: Fine Granularity and Pointing

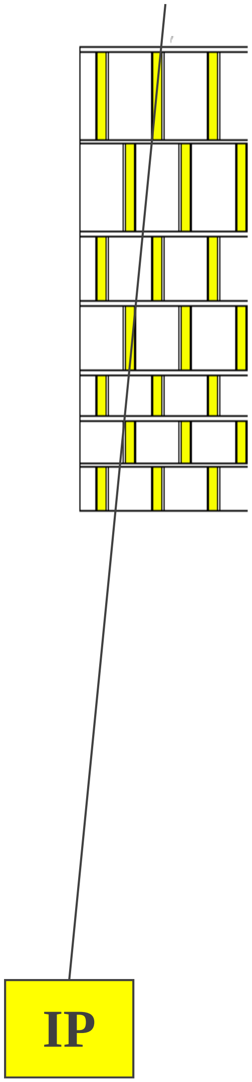
Measure energy-weighted centroid as a function of depth and use to reconstruct the trajectory of the photon

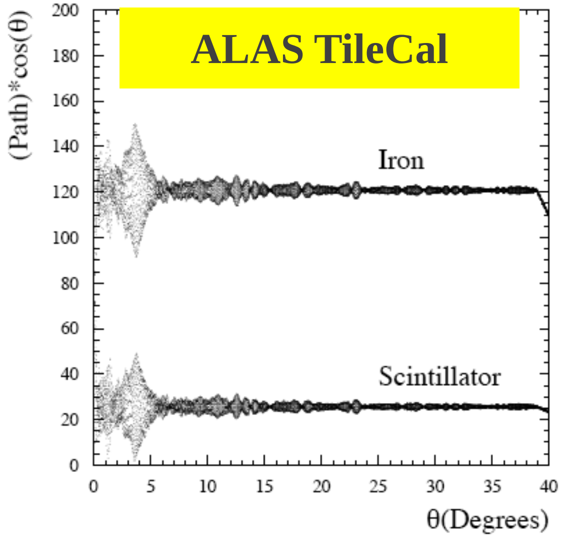
Pointing resolution is sufficient to match to the primary vertex to within a few mm.

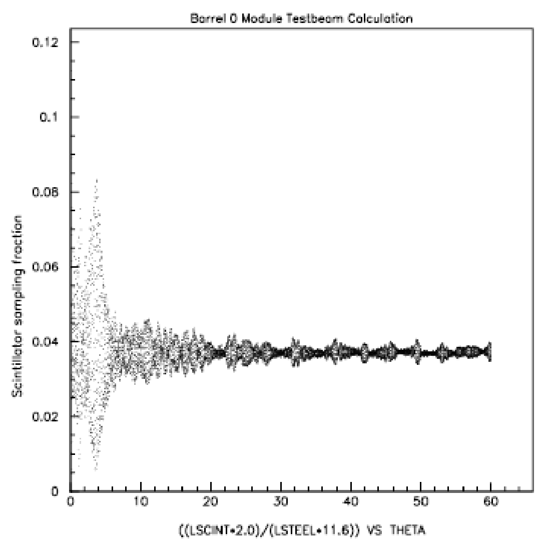


Construction and Calibration

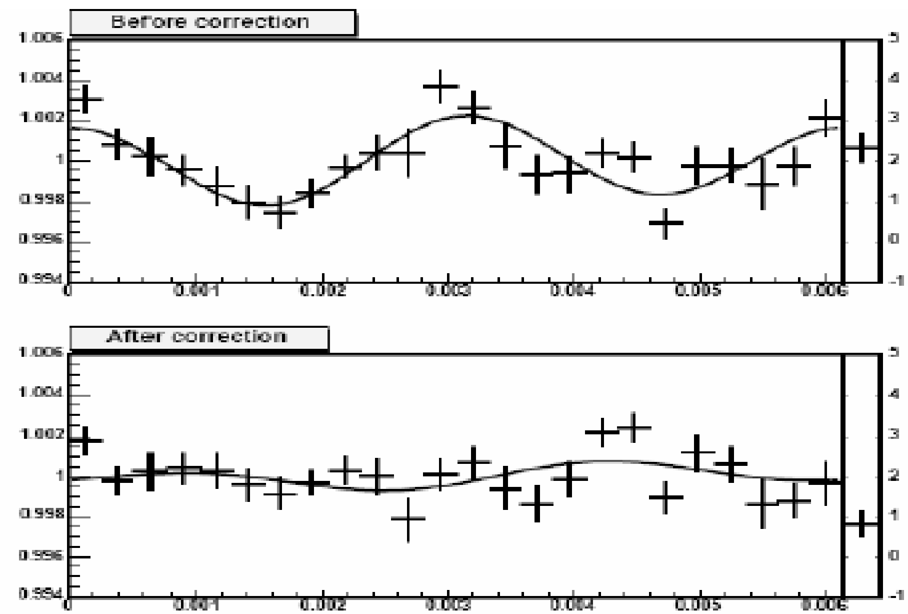
Layer Response/Sampling Uniformity: ATLAS





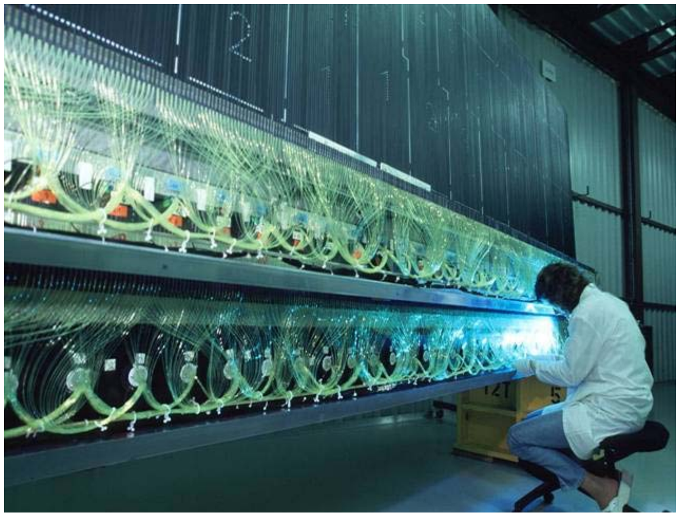


ALAS Liquid Argon Accordian



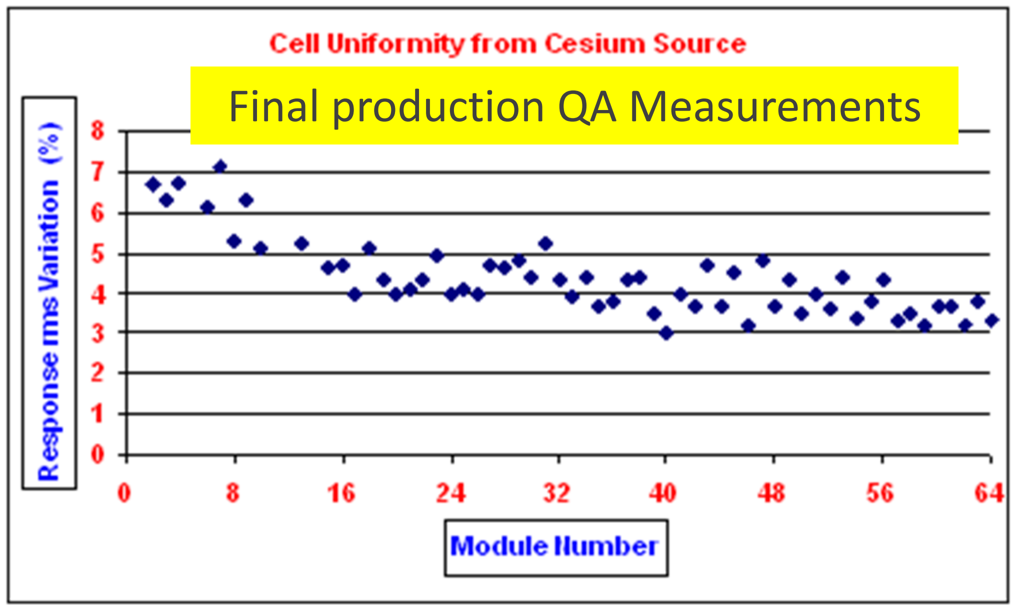
Phi Modulation from Accordian Structure: can correct for e/γ but not in jets.

Construction: e.g. ATLAS Barrel Hadronic Calorimeter



Goal here is maximum affordable uniform light yield throughout the detector

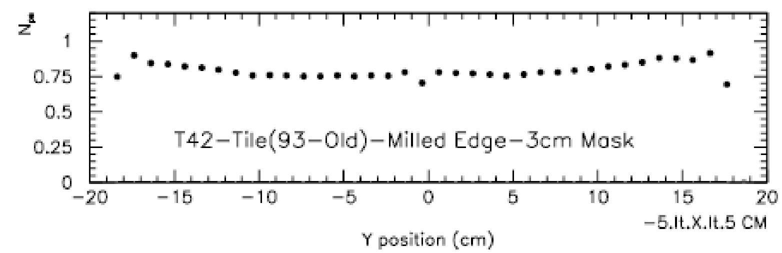
Depth segmentation is essential to realize this -> to limit the effect of light attenuation in the readout fibers

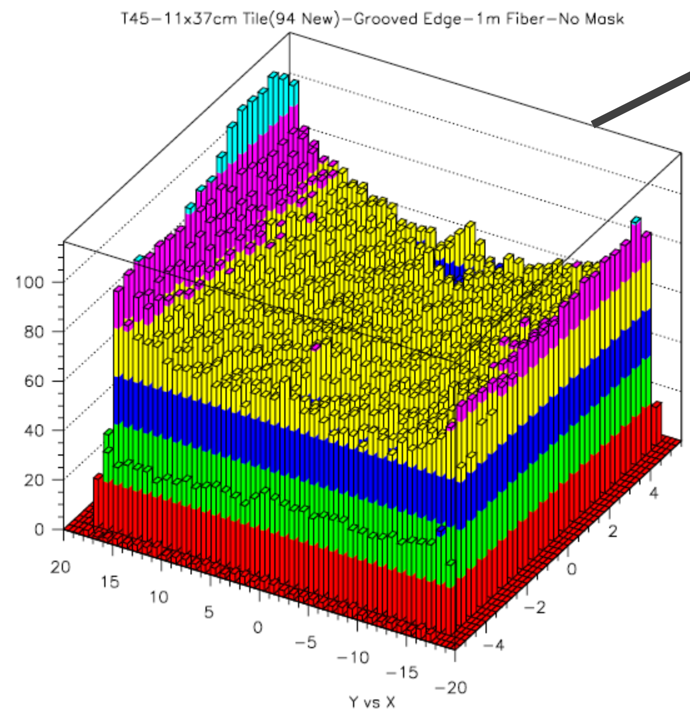


Layer Response: Signal Measurement

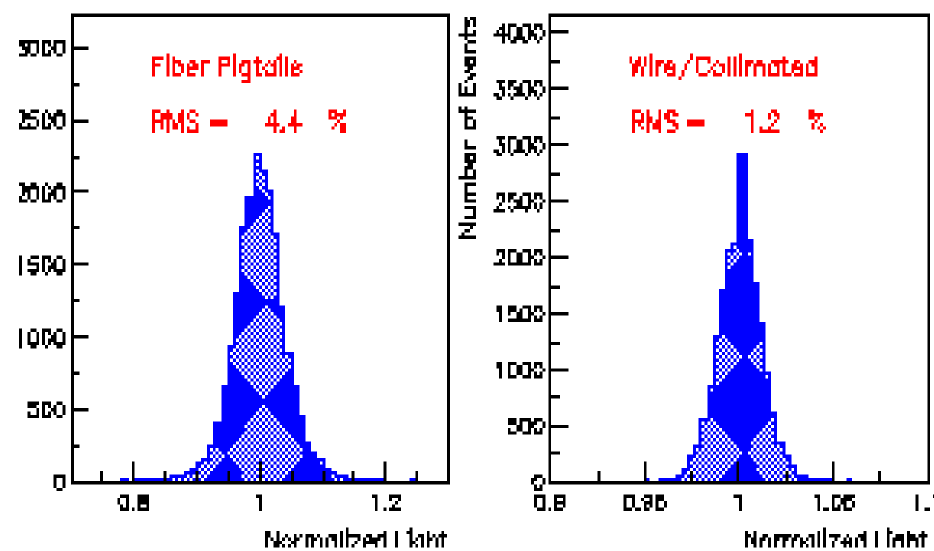
ATLAS Scintillator Tile Response Across Surface

Mask



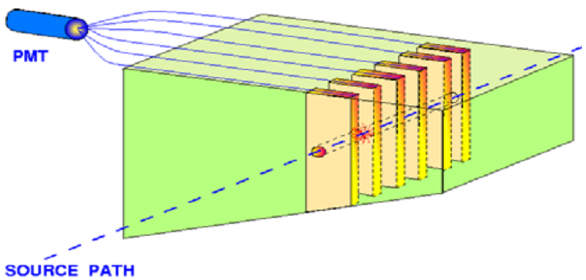


CMS Fiber Uniformity



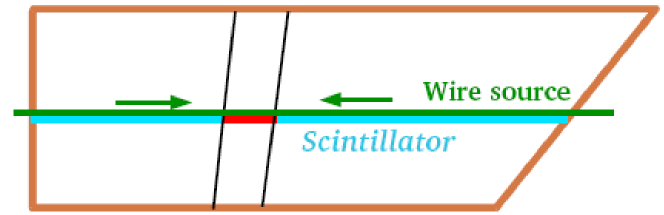
rms <Layer Light Yield> = 4.6%

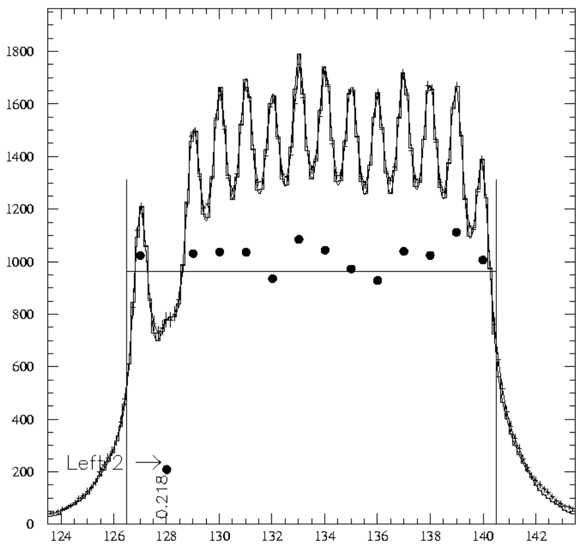
Global Calibration and Uniformity using Cs^{137}

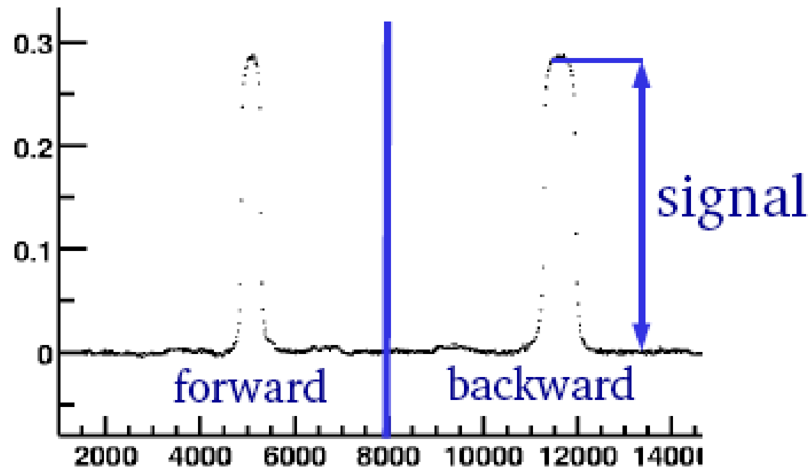


ATLAS Source Path

CMS source path

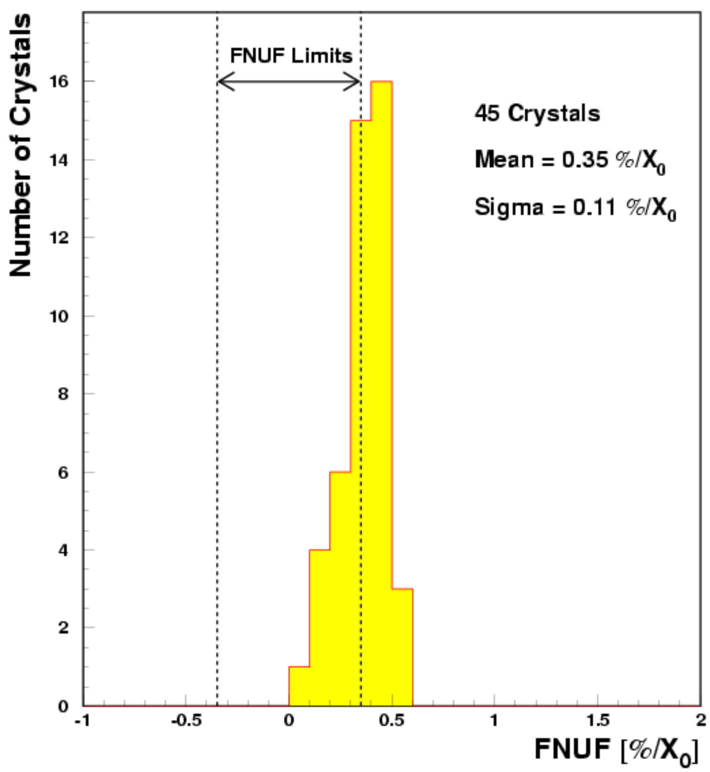






Ultimate calibration pC/GeV from test beam

Crystal Calorimeters need similar QA



To measure light yield uniformity a Co-60 source is scanned along the length of the crystal and data is acquired by the HPMT at every 1cm interval. The light yield data are fitted with a straight line from which the uniformity is derived.

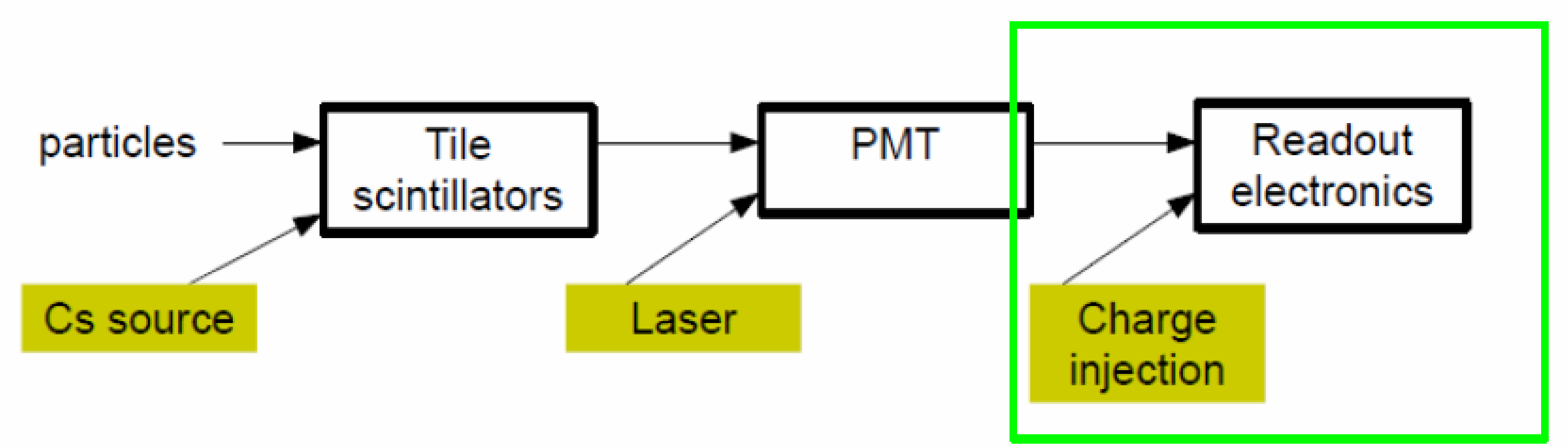
In the barrel detector, it was found that the uniformity was not adequate to meet the requirements. Roughening one of the polished crystal faces decreased the non-uniformity to within acceptable limits. It was hoped that endcap crystals would display satisfactory uniformity and so the additional cost and complication of roughening could be avoided.

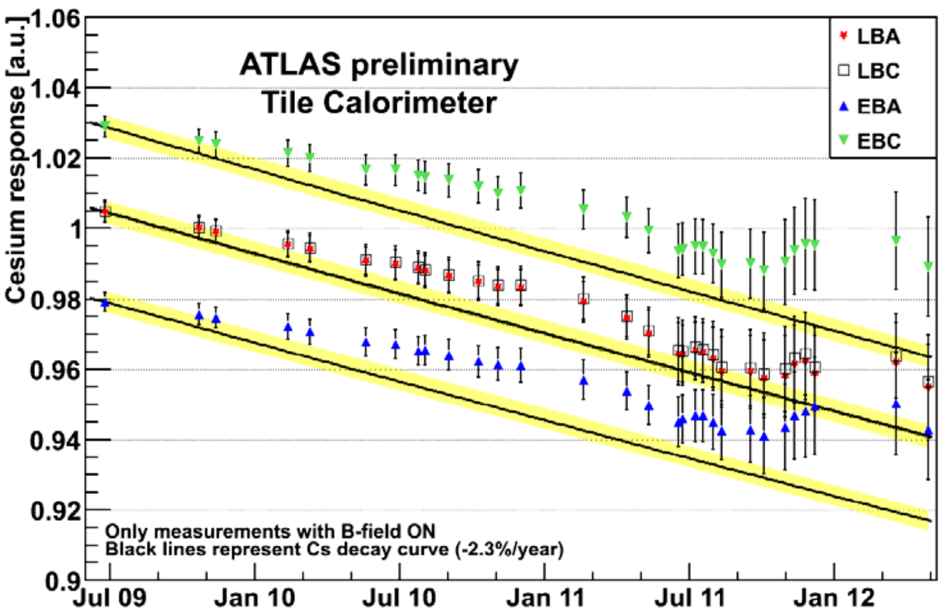
Simulations have shown that the change in light yield per cm can be no more than 0.4% if the target energy resolution is to be met.

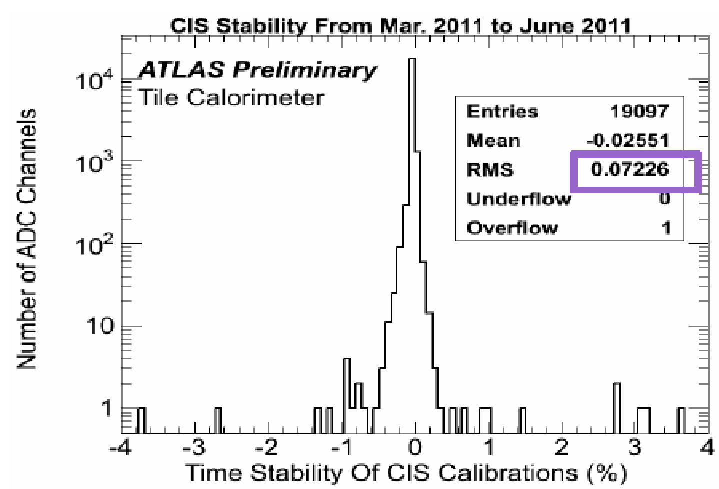
From Imperial College Web Page
http://www.hep.ph.ic.ac.uk/cms/ecal/fnuf.html

Monitoring and calibration during operations

Optical chain calibration – for scintillator





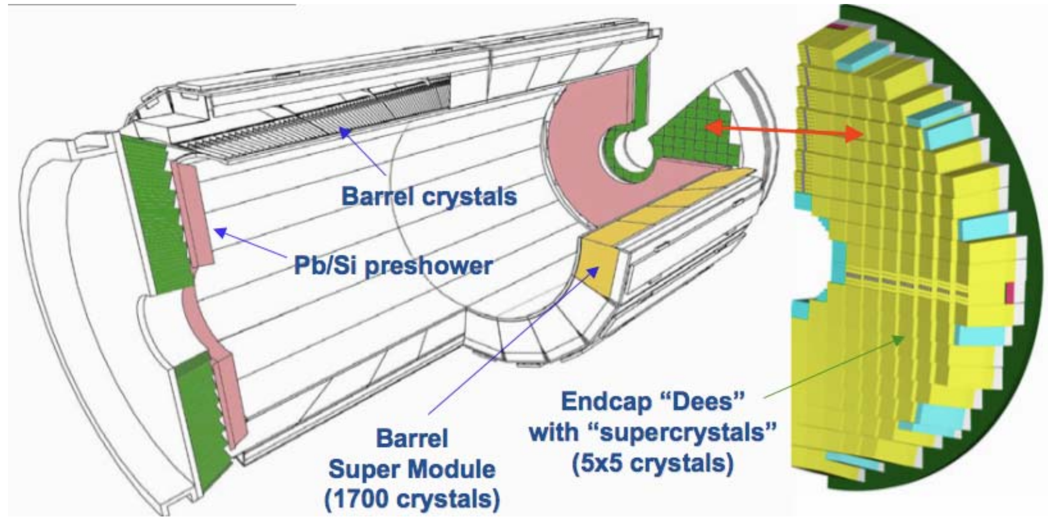


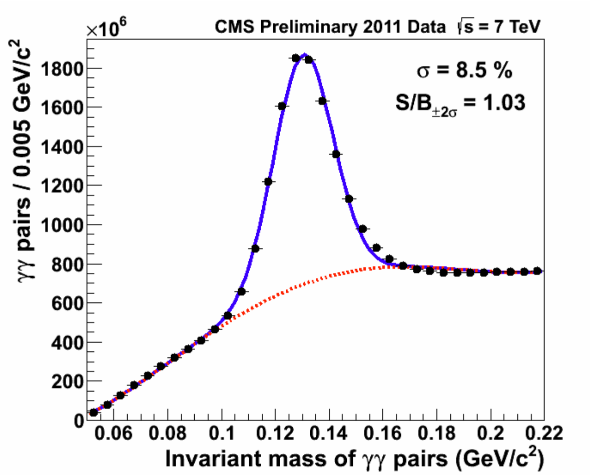
CMS EM Crystal Calorimeter Calibration *in situ*

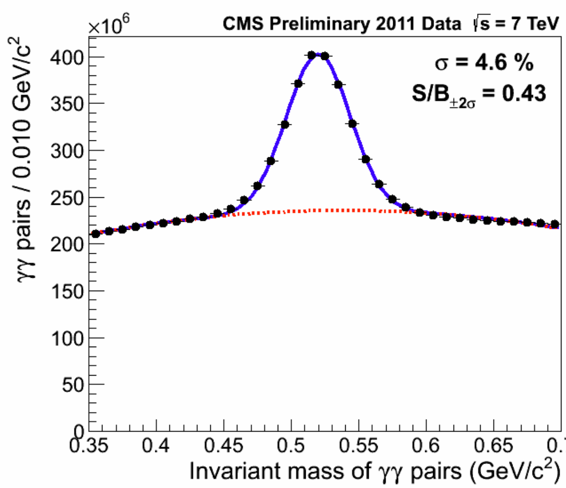
Laser used to calibrate out time dependent effects

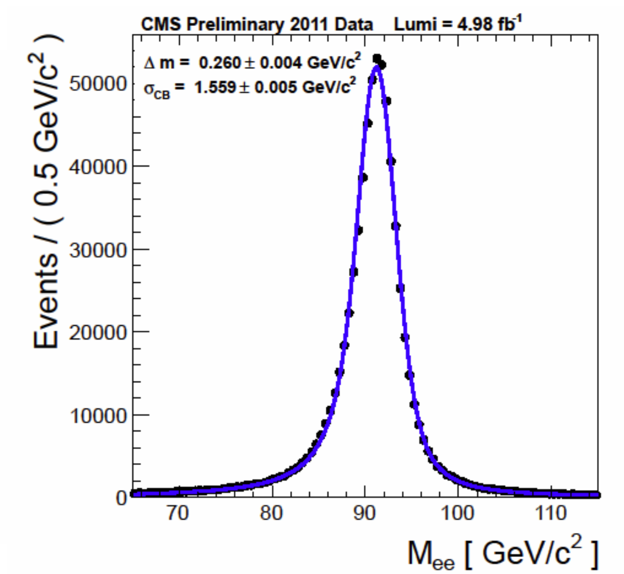
Stability monitored with W electrons:0.1 (0.4)%

Global scale from π^0, η and Z decays



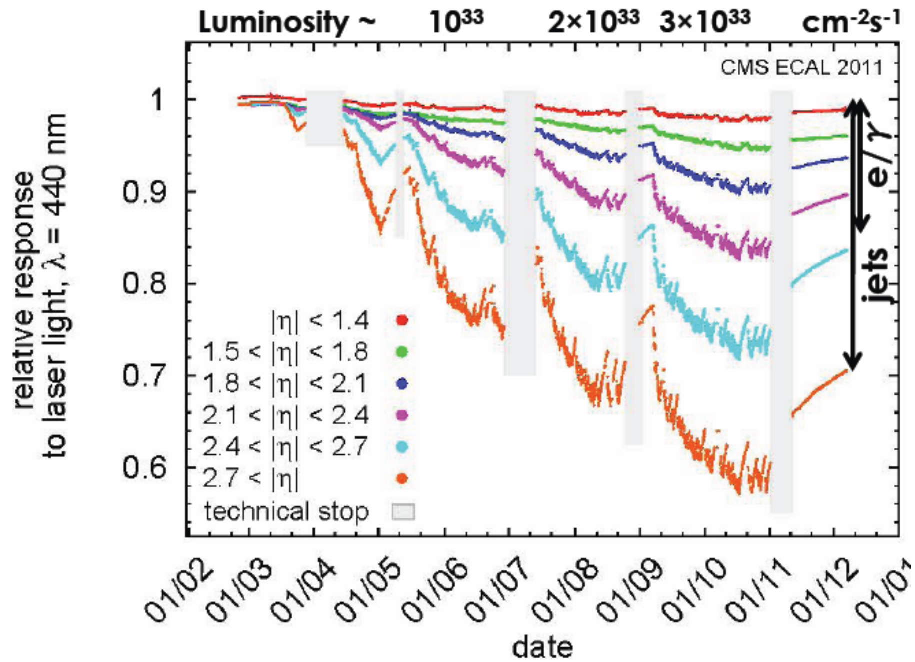




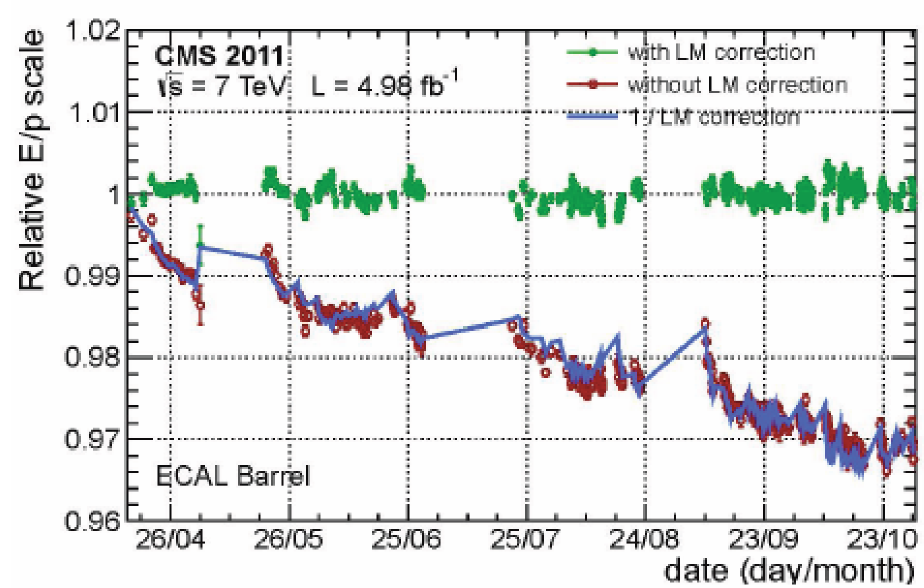


Change in response due to radiation dose - e.g. CMS crystals

Monitor using laser calibration system

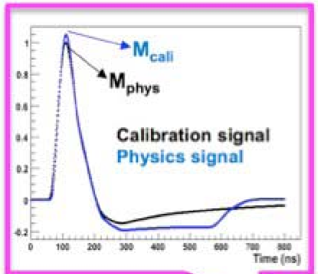


Validate correction using in situ response using E/p in W →eν



Calorimeters absorb almost all of the outgoing energy from collisions. Radiation damage is an important concern for scintillator and crystal calorimeters as both are subject to a reduction in signal yield due to the formation of color centers in the scintillator or glass. Degradation is reversible at some level.

Liquid Argon – robust but not without work too!



ADC to DAC (Ramps)

Pulse samples

$$E_{\text{cell}} = F_{\mu A \to MeV} \cdot F_{DAC \to \mu A} \cdot \frac{1}{\frac{M_{phys}}{M_{cali}}} \cdot R \cdot \sum_{j=1}^{N_{samples}} a_j \left(s_j - p \right)$$

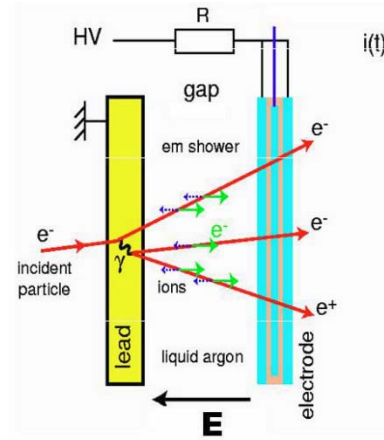
Cell energy

Sampling fraction

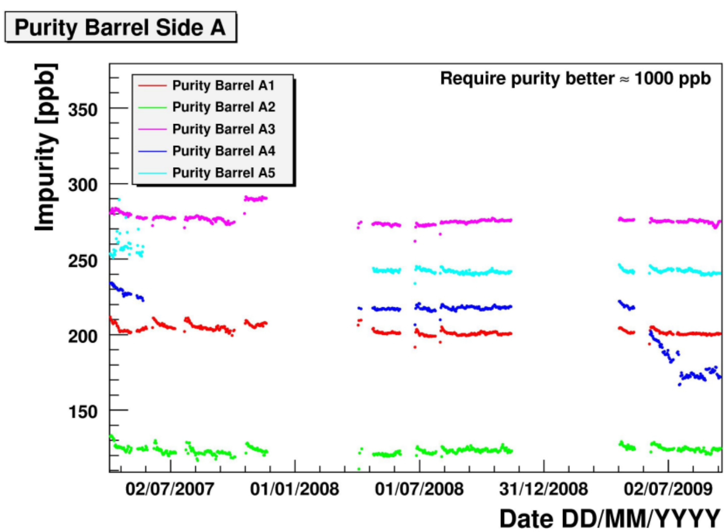
Calibration board

Optimal filtering coefficients

ADC Pedestals



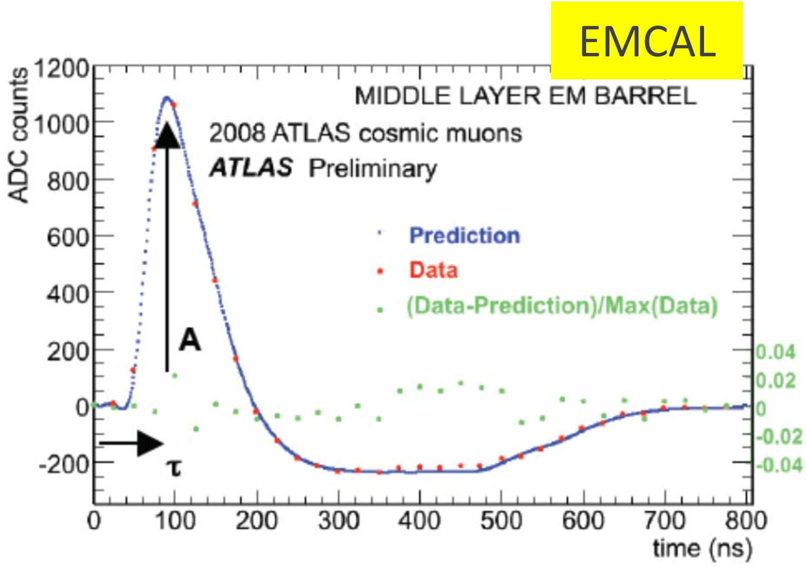
Control drift gap and HV

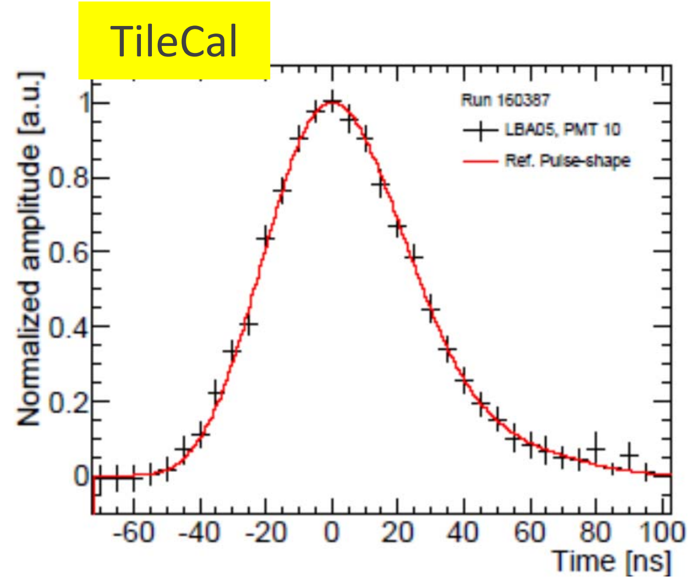


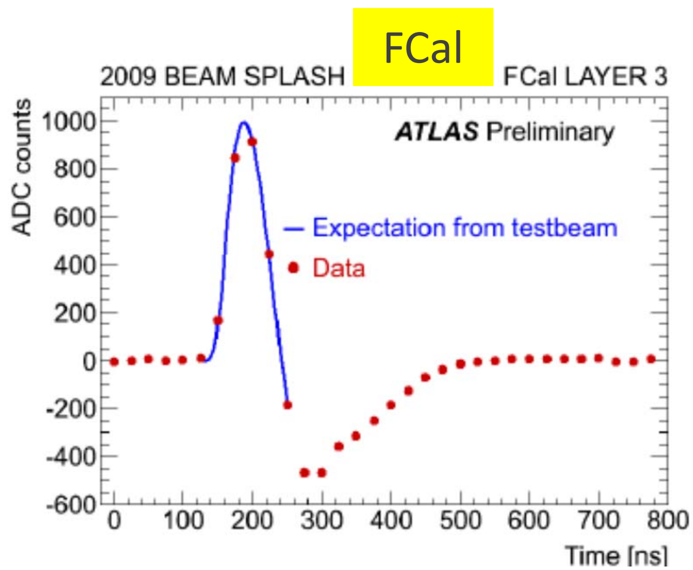
Sampling fraction: From test beam
ADC to DAC: Amplitude vs voltage Calib. runs
ADC Pedestals: Pedestal calibration runs

Optimal filter coefficients are a fancy way to sum samples to minimize impact of electronic noise and pileup.

Pile-up







Depends on:

- Signal shaping
- Digital filter used to reconstruct E,t
- Occupancy (cell size, inst. luminosity)
- Bunch structure

In-time => calibrate out
Out-of-time => contributes to noise

e/γ identification and measurement

This is almost entirely the job of the electromagnetic calorimeter:

use the transverse and longitudinal shower development to identify
(remembering that pre-shower can play a role here)

Use the well calibrated signal to measure the energy

Use the reconstructed position in the calorimeter along with the interaction vertex to measure the momentum vector

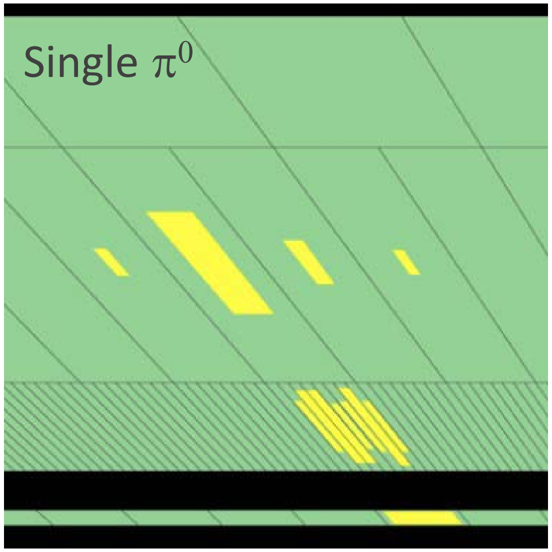
Add in the track to identify an electron, veto on a track (of sufficient momentum) to identify a photon

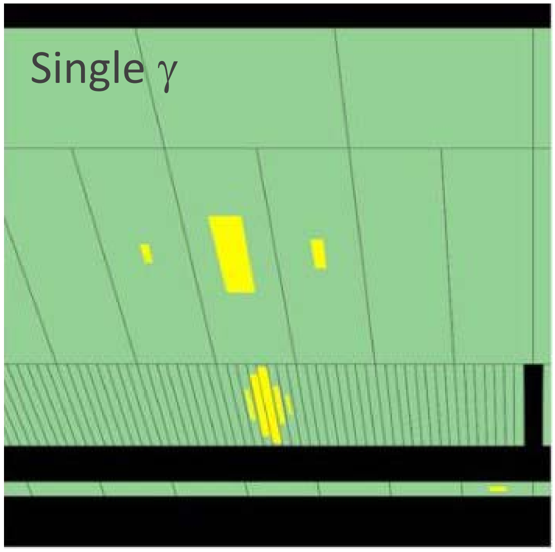
Photon identification and reconstruction in ATLAS

Goal is to separate prompt photons from photon-like objects from jet fragmentation to ~single π^0

Use the fine lateral and longitudinal segmentation of the calorimeter to accomplish this

Barrel Layer 1 dη size 0.003 (~5mm) ~5 X0 thick

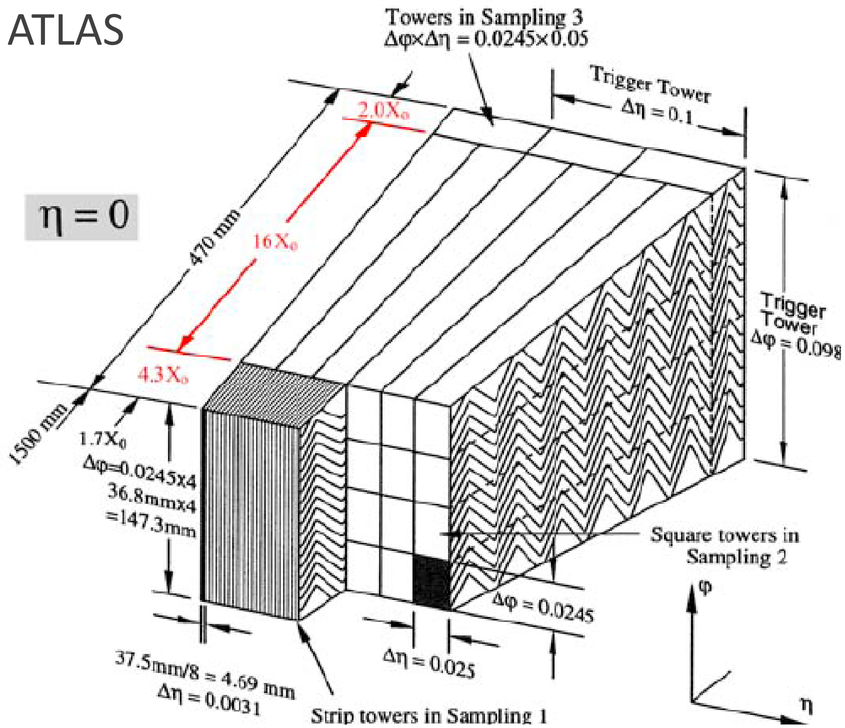


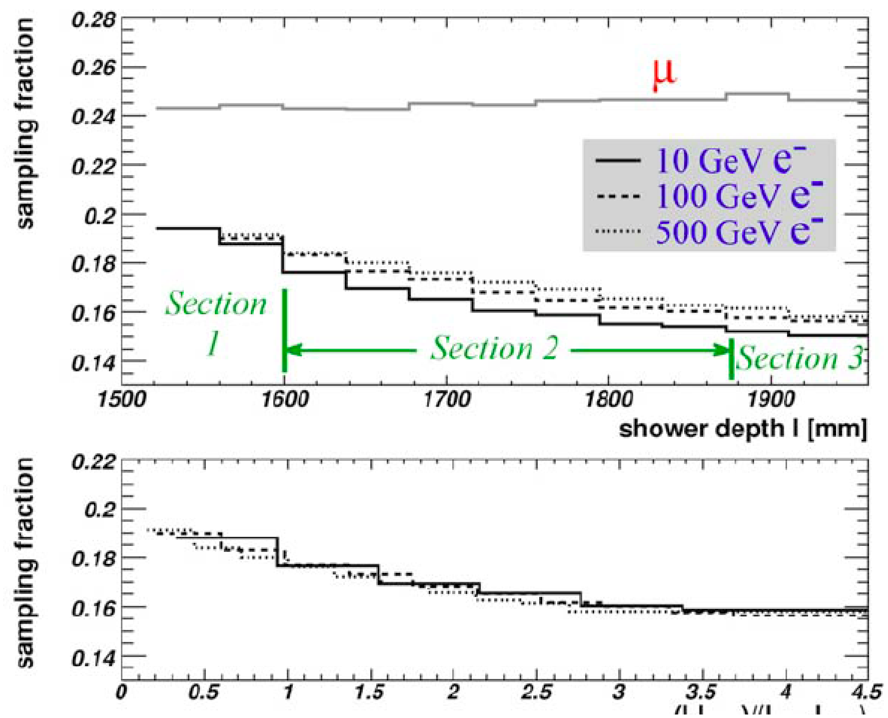


Also apply energy and track momentum isolation – not part of discussion in this talk

Compute segment weights using EGS Monte Carlo simulation of electromagnetic showers.

ATLAS





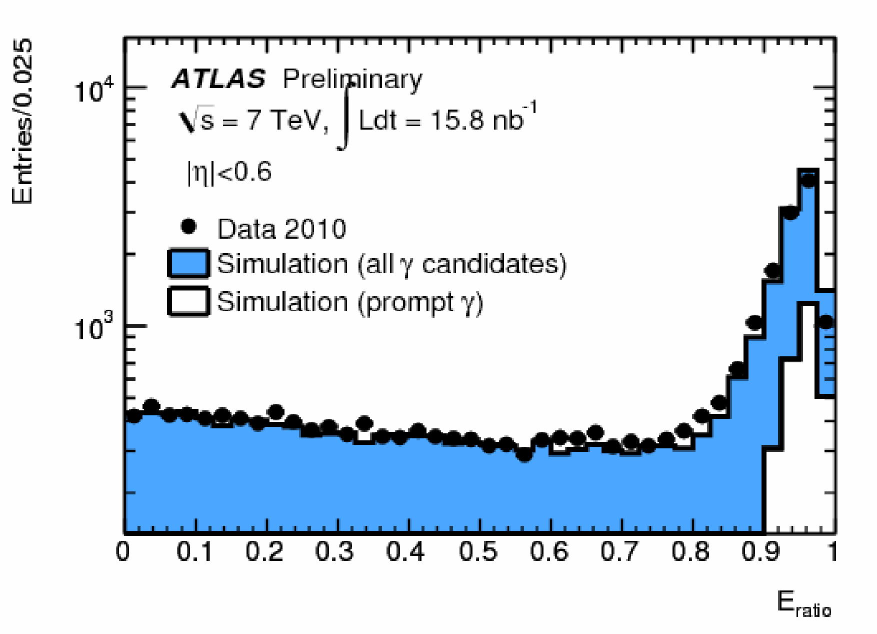
$$E^{rec} = \left(a(E) + b(E)\ E_0^{vis} + c(E)\ (E_0^{vis} \cdot E_1^{vis})^{0.5} + \frac{1}{d(E)\ f_{samp}} \sum_{i=1,3} E_i^{vis} \right) \cdot f_{\text{cell impact}}(\Delta\Phi) \cdot (1 + f_{\text{leakage}})$$

Depth dependent weights are correct for only one type of incident particle (g's need different weights from $e^{\pm}$)

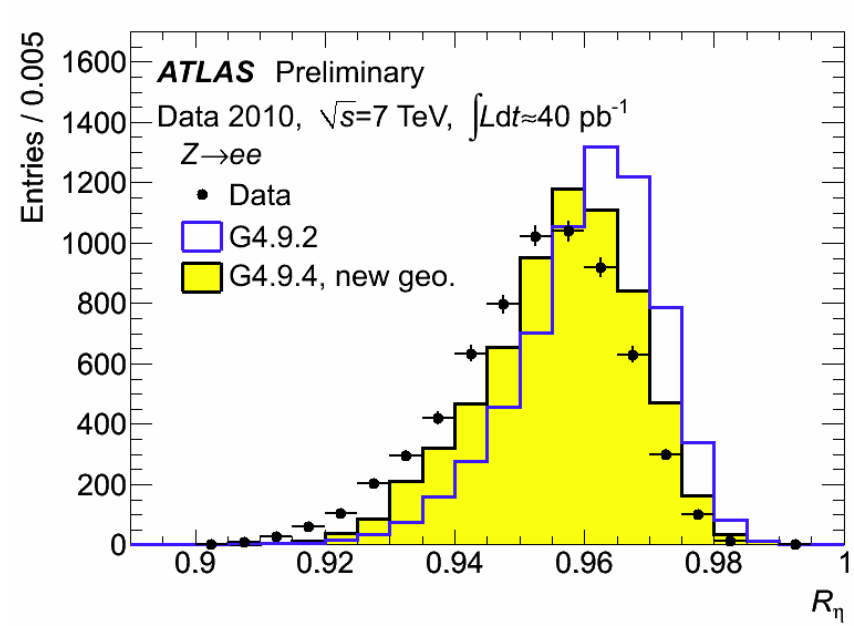
Also determine corrections for energy no included in the reconstructed cluster

Compare shower development in data with that in MC

Asymmetry of 1st and 2nd maximum in Layer 1
(E(max1)-E(max2))/(E(max1)+E(max2))



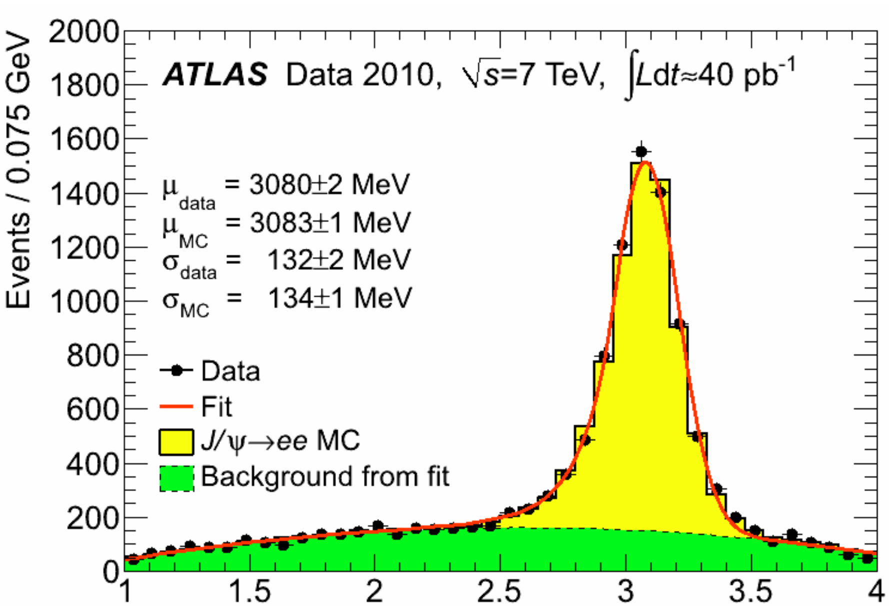
E(3x7) / E(7x7) cells in the second Layer



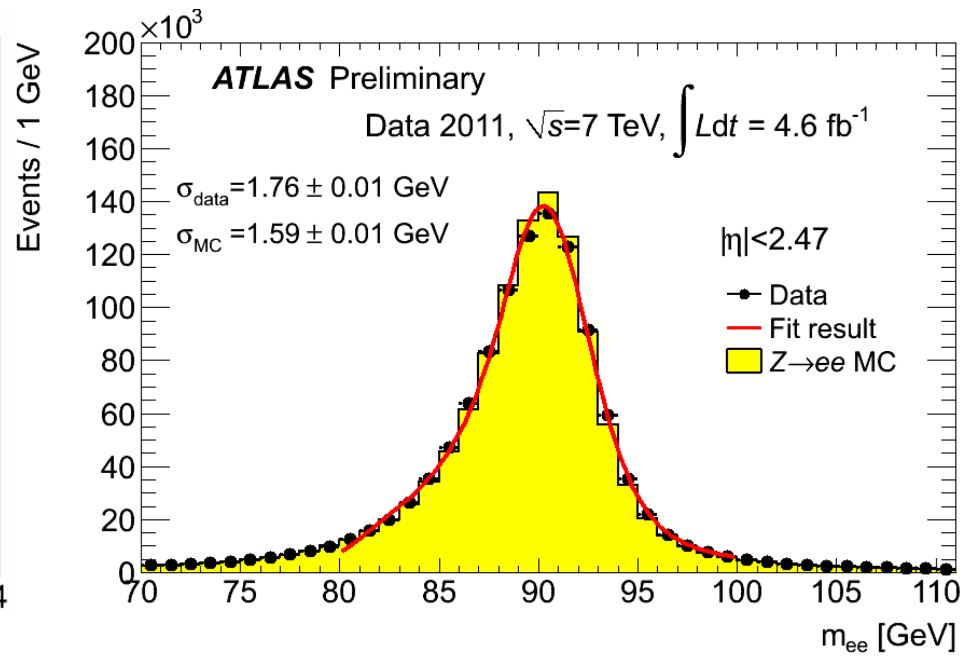
Do this for ALL shower development variables used in e/γ identification. Tune geometry if needed. Any mismatch between MC and data -> systematics

Validate reconstruction and calibration using well understood particles

J/ψ

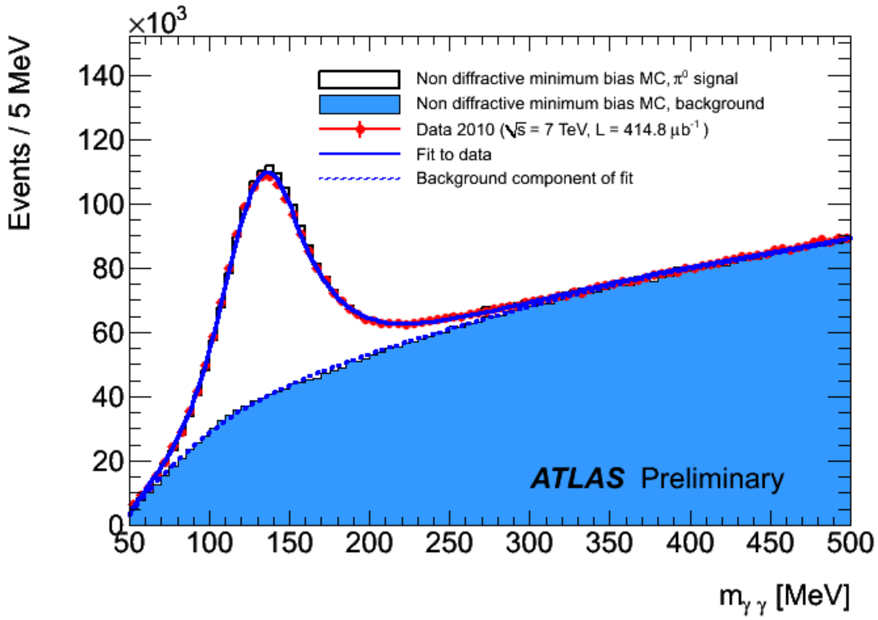


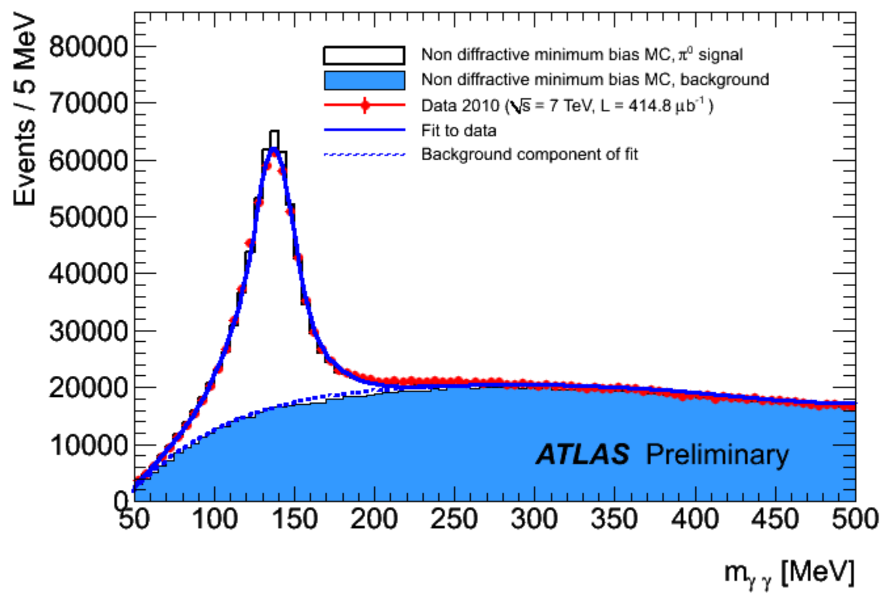
Z→e⁺e⁻



NB. Here again it essential that Monte Carlo be in good agreement with the experimental data.

Neutral pions



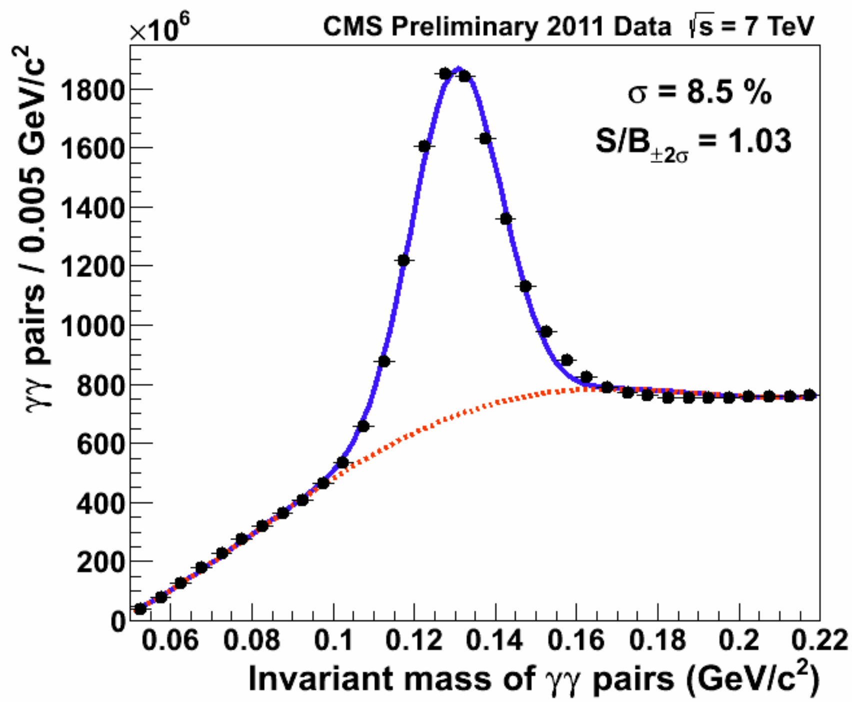


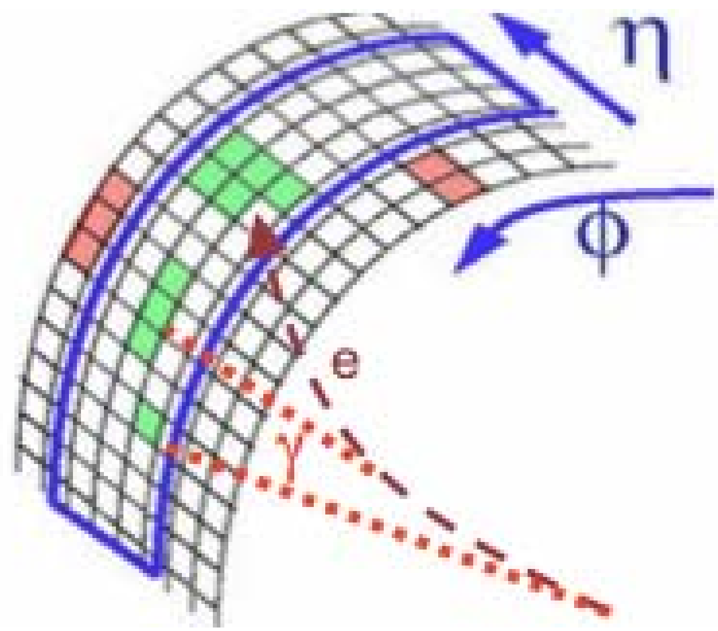
CMS Photon Reconstruction and Measurement

No depth segmentation, but awesome resolution

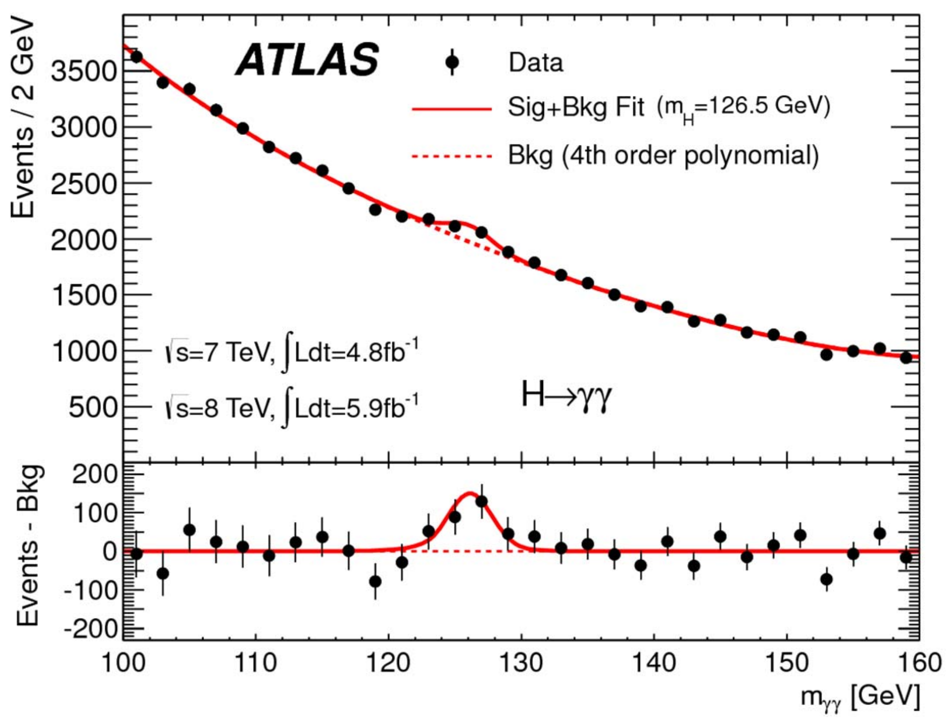
$$\frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt{E\ (GeV)}} \oplus \frac{0.128}{E\ (GeV)} \oplus 0.3\%$$

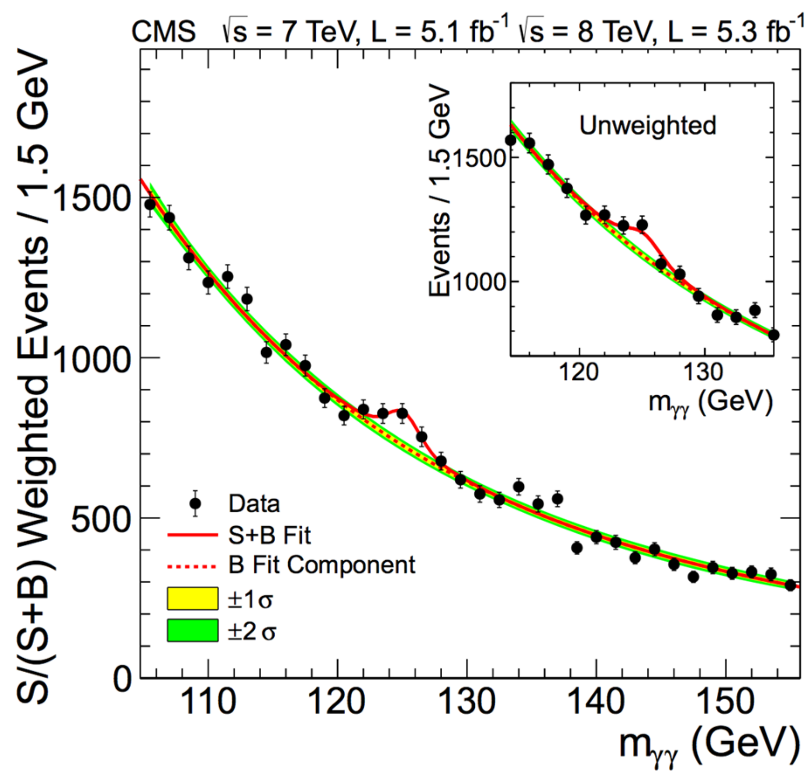
MC plays similar role in determination of corrections for upstream material and un-clustered energy





Net result: A Higgs-Like Boson decaying to two photons





But there is more…

Hadronic Calorimetry – the measurements of jets

Calorimeters are ESSENTIAL to Measure Jets AND Jets are ESSENTIAL for Much of the LHC Physics Program

- Top Mass
- Compositeness/SUSY
- WBF Higgs Production
- Inclusive Jet x-section
- Di-Jet Mass Spectrum
- Z + 1,2,3.. Jets
- W + 1,2,3.. Jets
- $\gamma\gamma$ + Jet
- Luminosity

Count Jets

Measure Jet Energies

Measure jet angular distributions

Use Jet Vetos

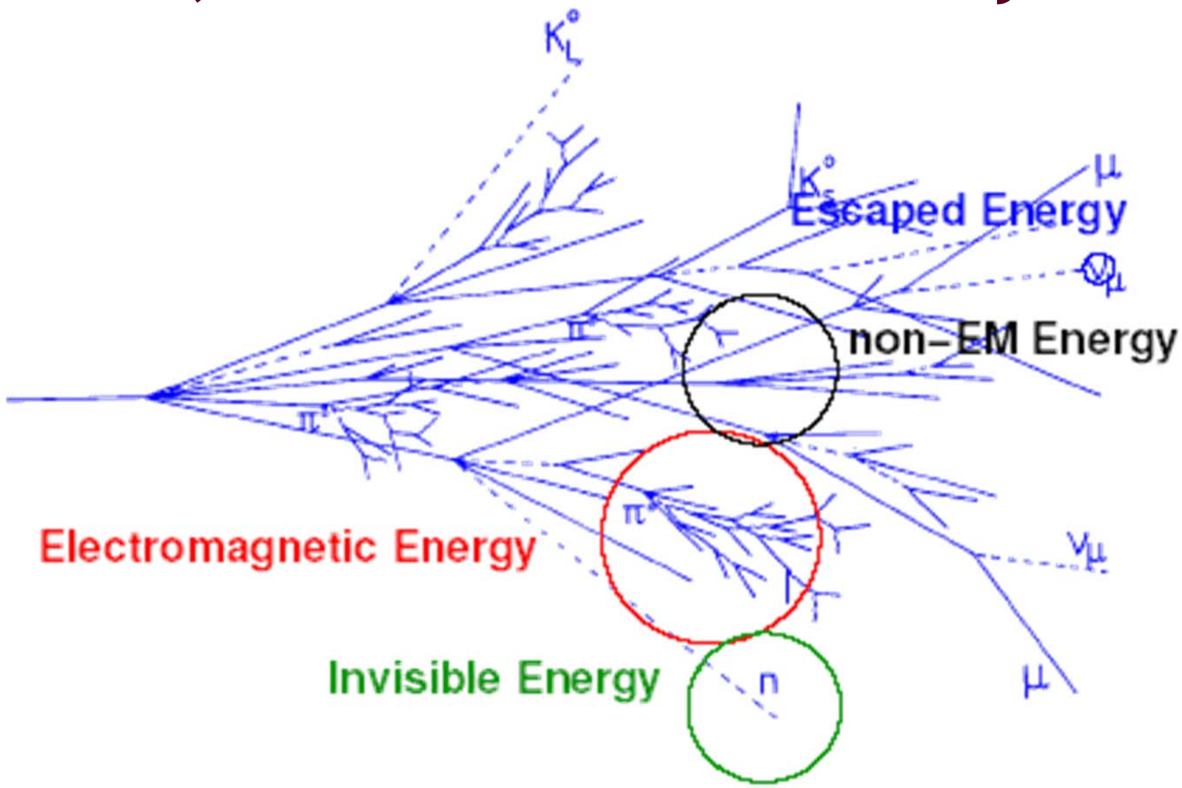
Tag jets in the forward region

Estimate Standard Model Backgrounds

Connect observed energy in the detector to the parton energy.

When one includes the measurement of energy isolation around photons and muons, then hadron calorimeters play a role in ALL LHC physics

From lecture 1, we know this is not easy

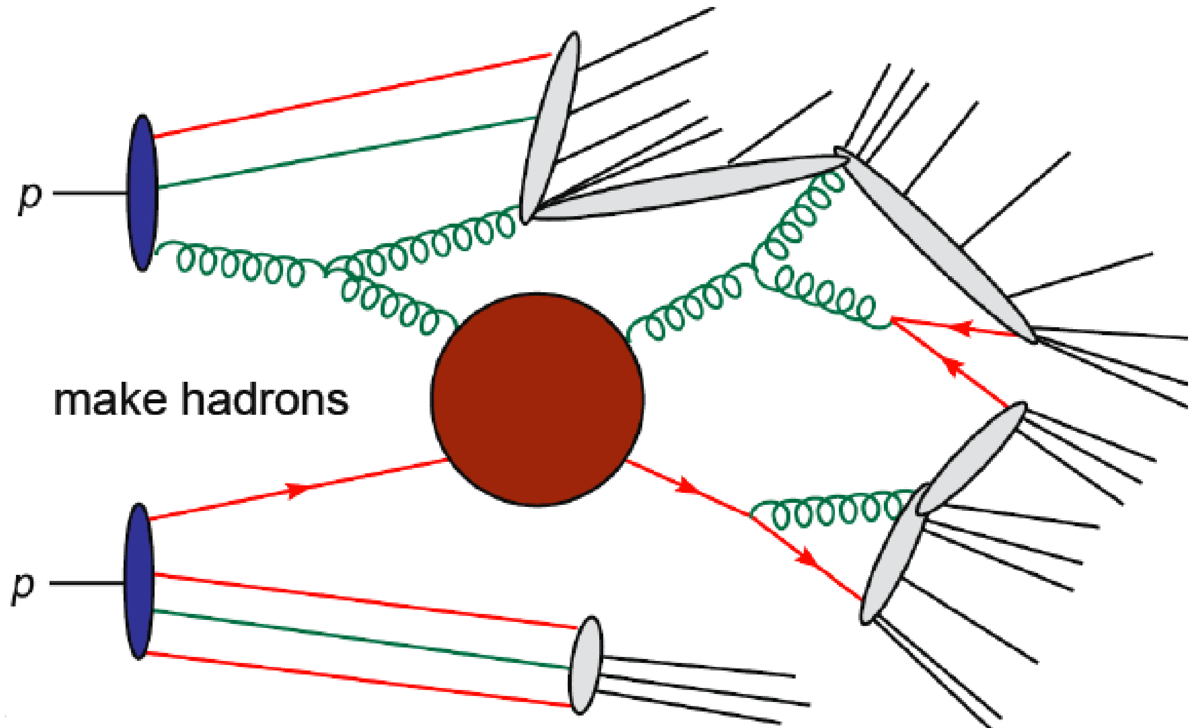


So we are going to use a Monte Carlo simulation to model the detector response and determine weighting as a function of location of the shower and its energy density in the calorimeter to correct the measured signal for e/h ≠1

But. We Aren't Dealing with Single Particles !!

Monte Carlos in pictures

Splitting probability: $P_g(q^2) = \int_0^1 dz \frac{\alpha_s(q^2)}{2\pi} \hat{P}_{gg}(z)\Theta(q^2 - q_0^2)$



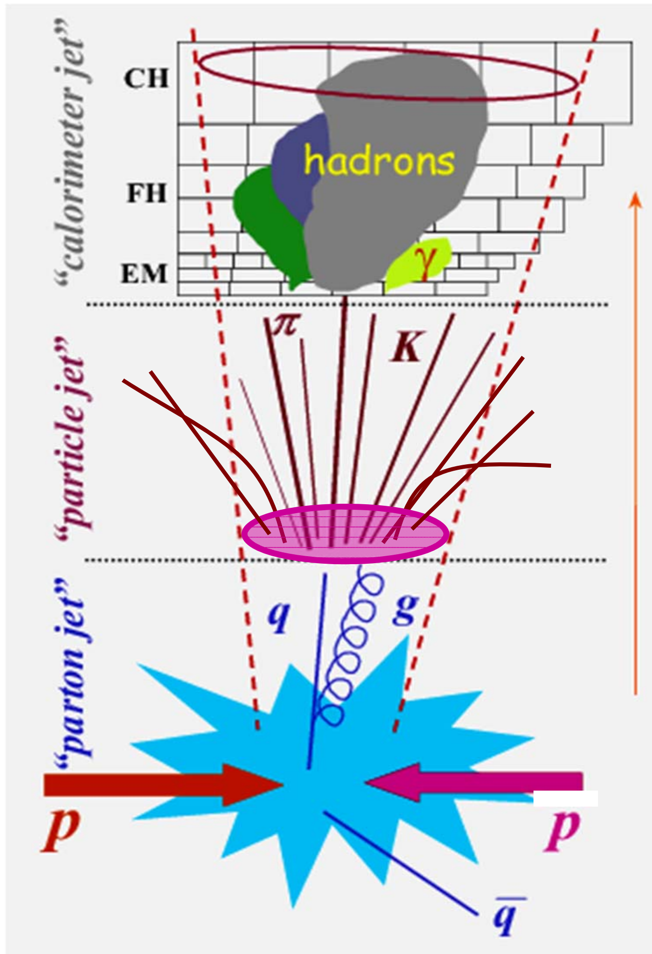
Sudakov

$\Delta_g(Q^2, q^2) = \exp[-\int_{q^2}^{Q^2} \frac{d\tilde{q}^2}{\tilde{q}^2} P_g(\tilde{q}^2)]$

L. Dixon, 7/20/06 Higher Order QCD: Lect. 1 5

The Physics: $\Sigma F(E_{particle})$ -> $G(E_{jet})$

Physics/Simulation/Detector Modeling

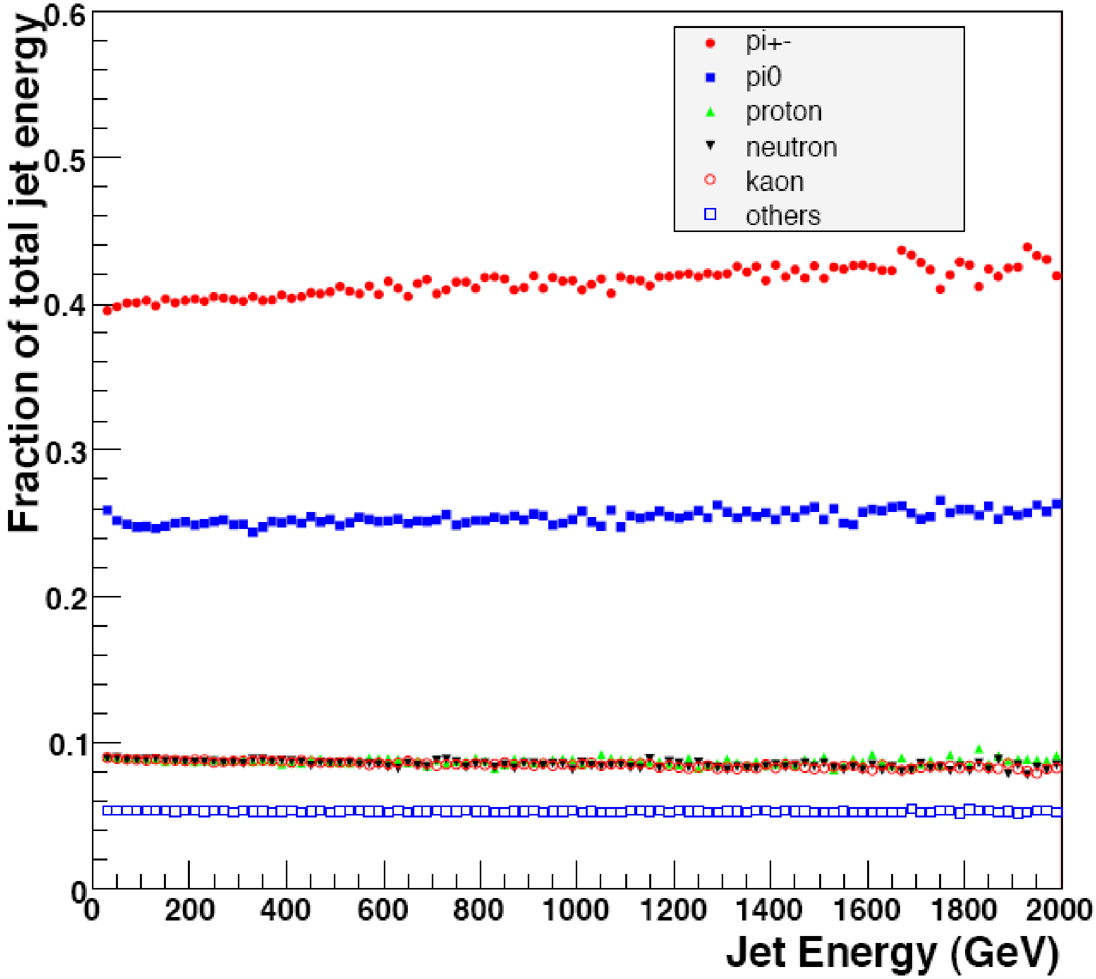


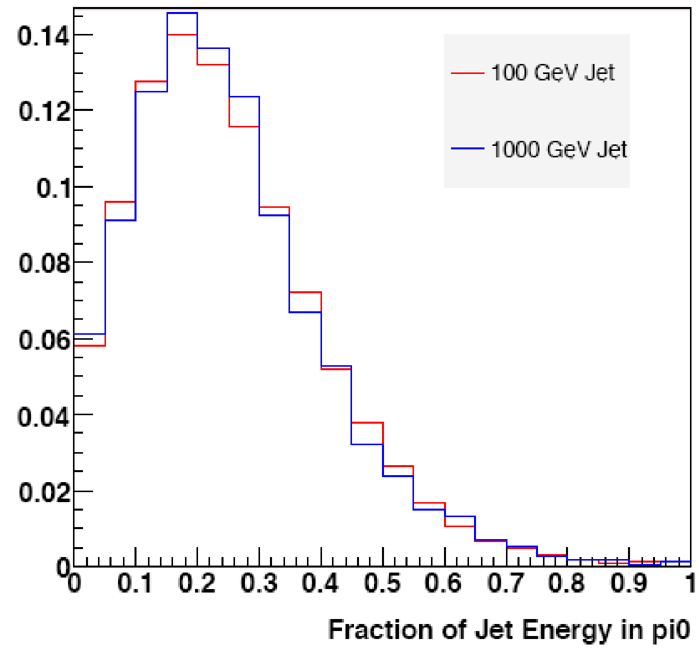
Detection/Event Measurement/Reconstruction and Physics Analysis

Interface Hadronic Shower Model to your favorite event generator

Fraction of jet energy carried by different particles

From Monte Carlo





ATLAS Pythia/GEANT Simulation Studies

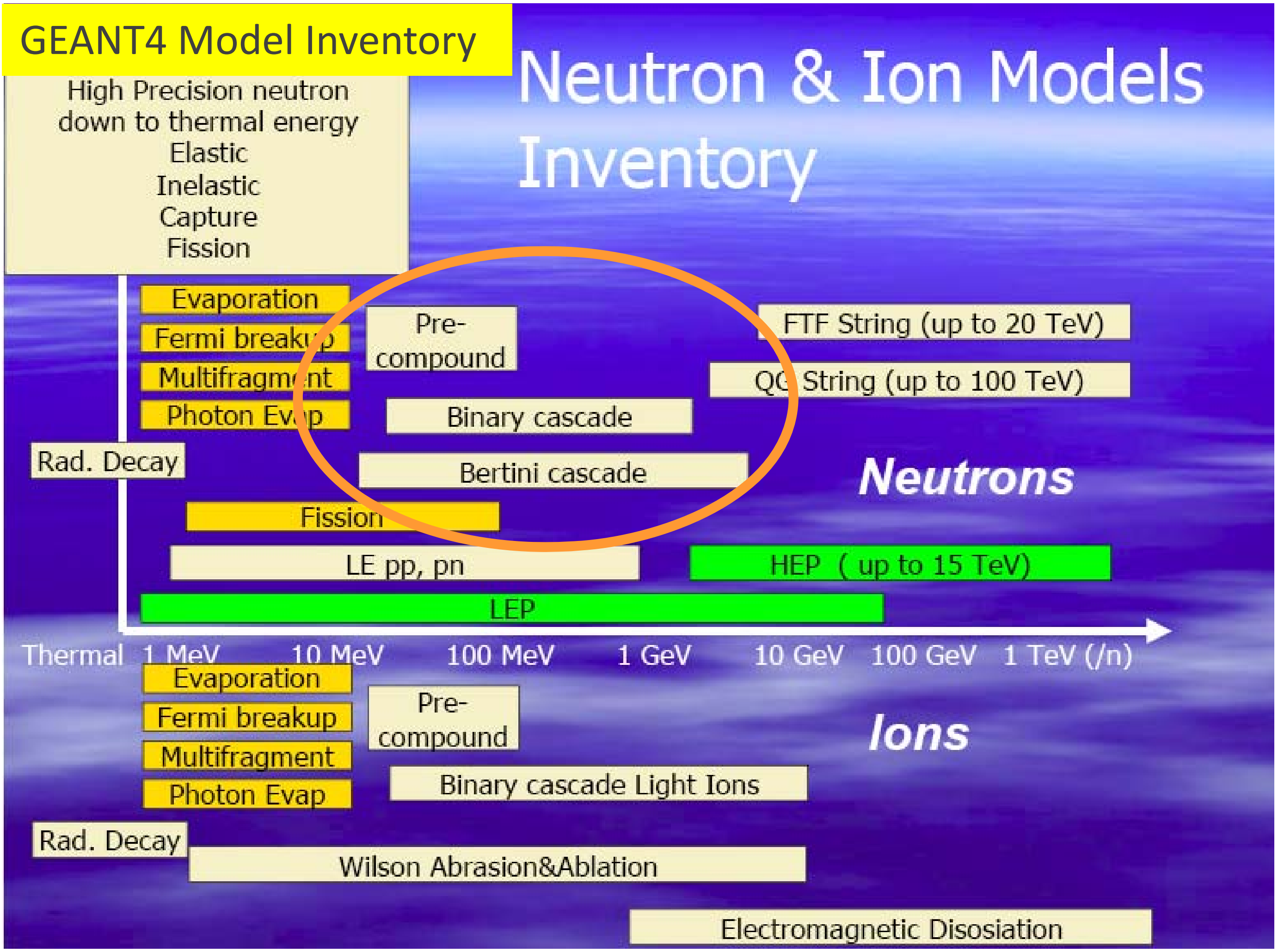
An essential detail at the LHC

High Energy Models

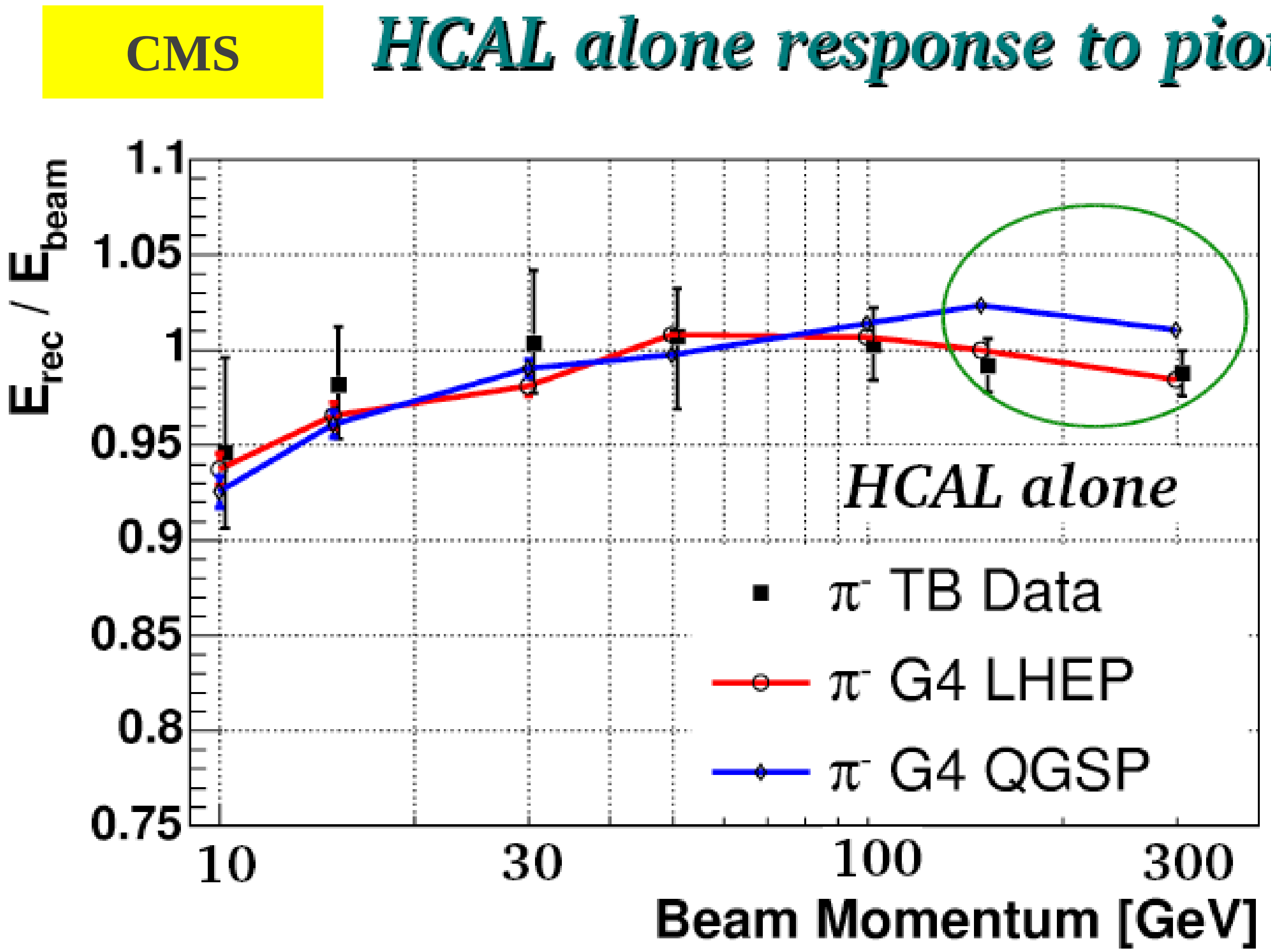
- Geant4 has three models for high energies (15 GeV < E < ~10 TeV):
  - high energy parameterized (HEP) : derived from GHEISHA, depends mostly on fits to data with some theoretical guidance
  - quark-gluon string (QGS) : theoretical model with diffractive string excitation and decay to hadrons
  - Fritiof fragmentation (FTF) : alternate theoretical model with different fragmentation function
- Of the two theoretical models (QGS and FTF) QGS seems to work better in most situations
- Most used and tested models are HEP and QGS

[WRIGHT]

Modeling calorimeter response



But must validate GEANT4 model

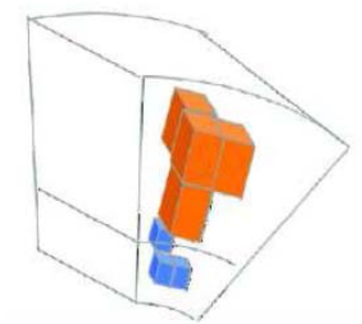


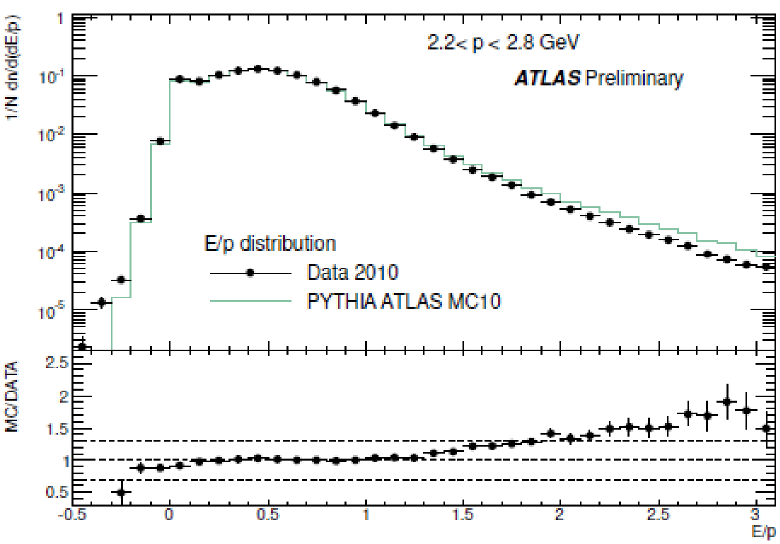
LHEP models better the high energy calorimeter response. QGSP has less leakage on the back due to shorter shower.

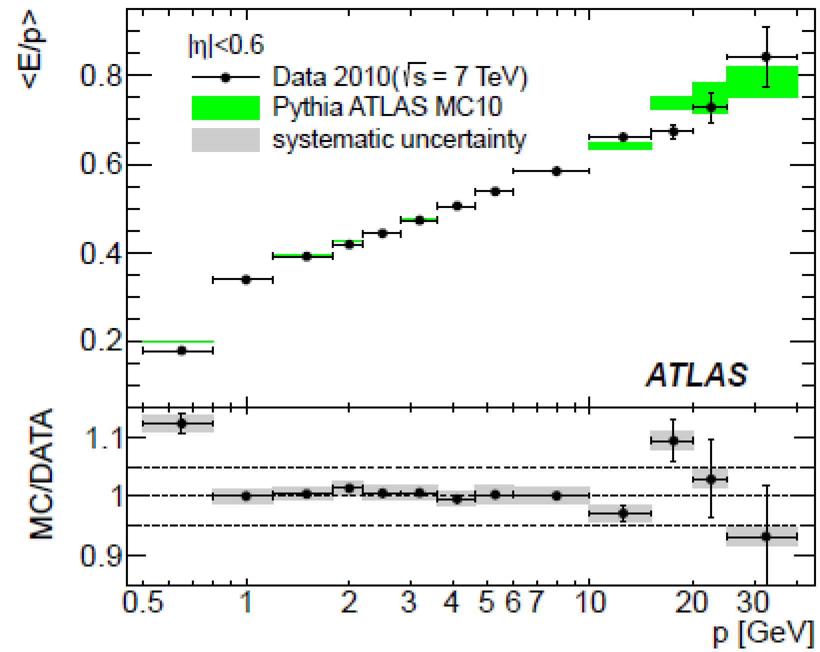
[DAMGOV]

Validate/tune MC using Single Hadron Response

Extrapolate charged tracks to the calorimeter and sum energy in cells within 0.2 in ΔR of the track impact point



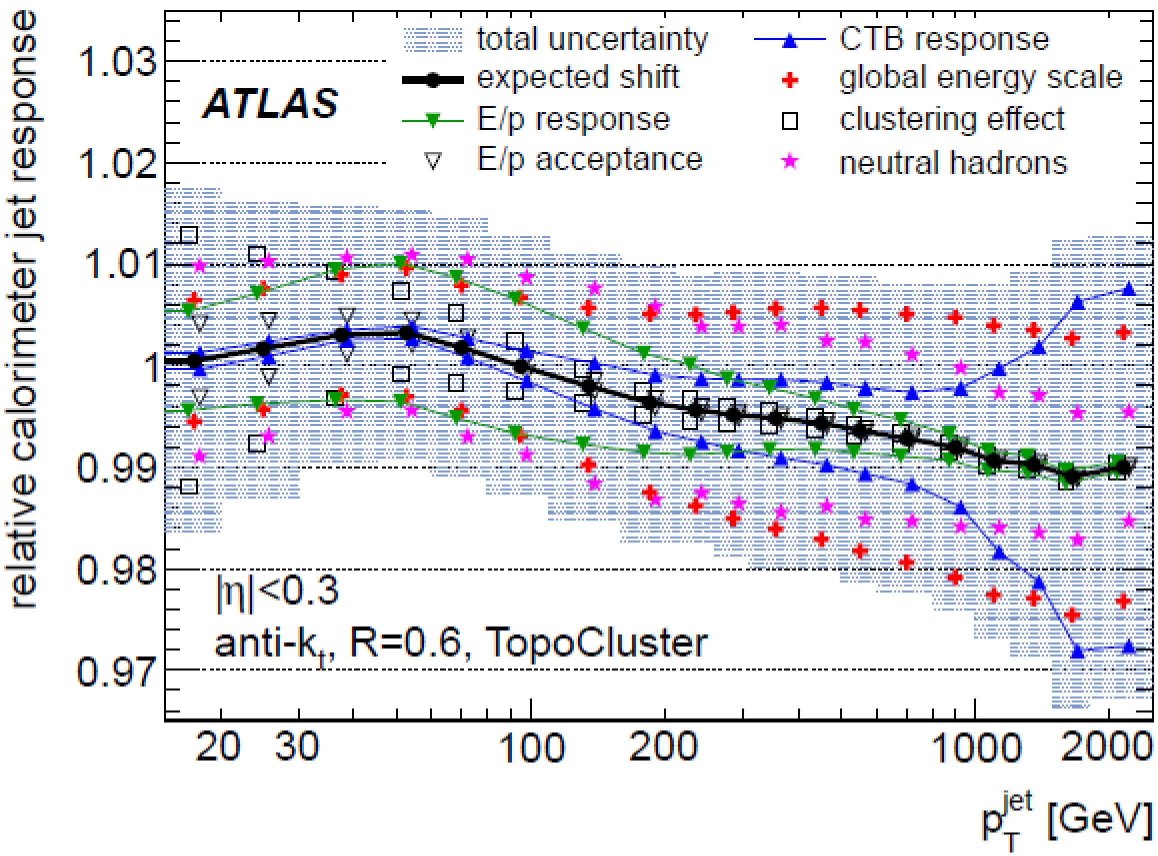




- Data are well described by MC within 2% for $2 < p < 10$ GeV
- Perform similar *in situ* measurements for K's and Λ's identified in resonance decays
- Use MC to calculate inversion factors to go from measured jet energy to true jet energy

Final Systematic uncertainty on Jet Energy Scale

Propagate energy response of all particles in a jet to estimate overall systematic uncertainty



E/p response
Testbeam response
Clustering thresholds
Noise
$Z \rightarrow e^+e^-$ global energy scale
Response to neutral hadrons

Calorimeter Energy Weighting Schemes

Determine Weights which account for jet fragmentation as well as shower development characteristics of single particles to optimize energy resolution

$\Rightarrow$ **Depends on the absorber and calorimeter geometry**

Calorimeter Segment Weighting

Weight Cells according to Energy Density (as in H1) - but weights are independent of Jet Energy

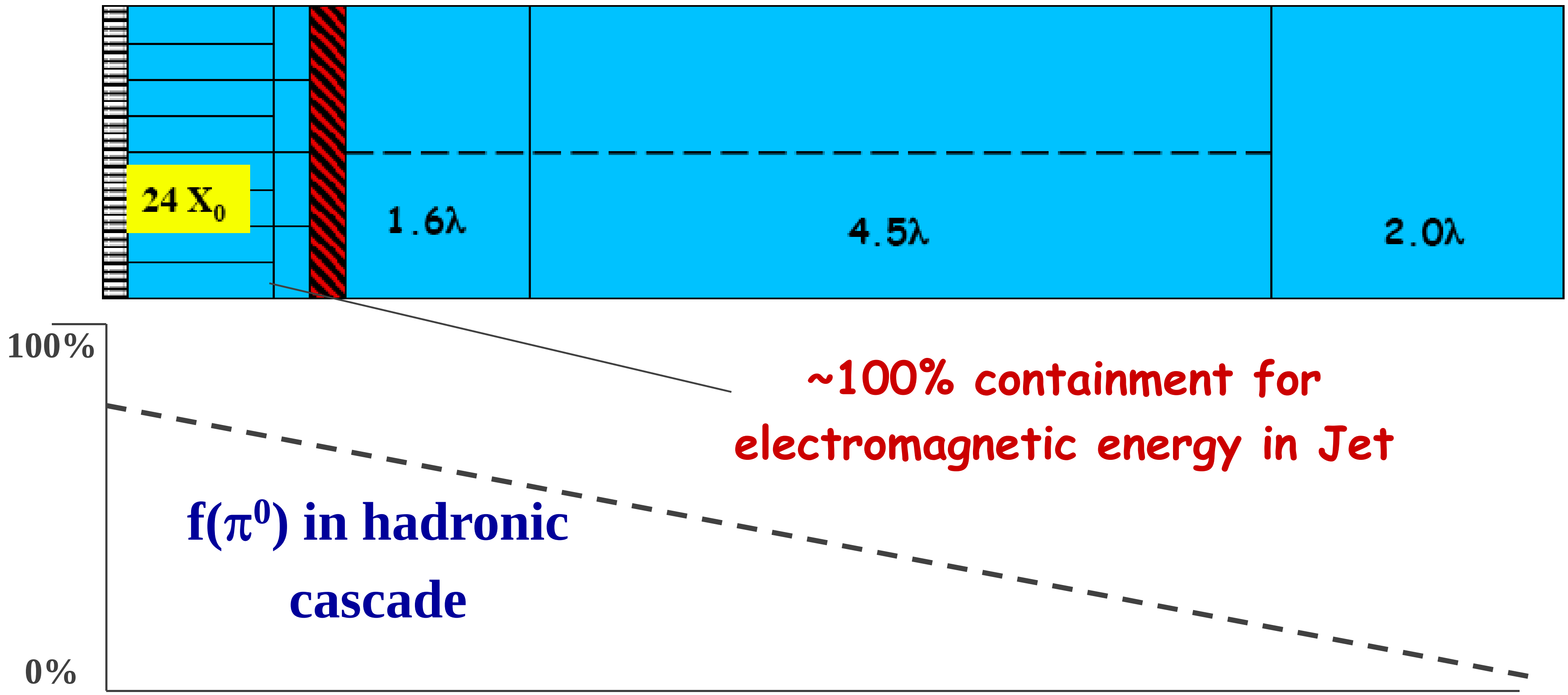
Weight Cells according to Energy Density - but weights are dependent on Jet Energy

Local Cell Calibration – sophisticated Monte Carlo correction procedure which is possible with fine segmentation

Weight depth segments (sampling layer) - weights are dependent on Jet Energy (A. Gupta, JP)

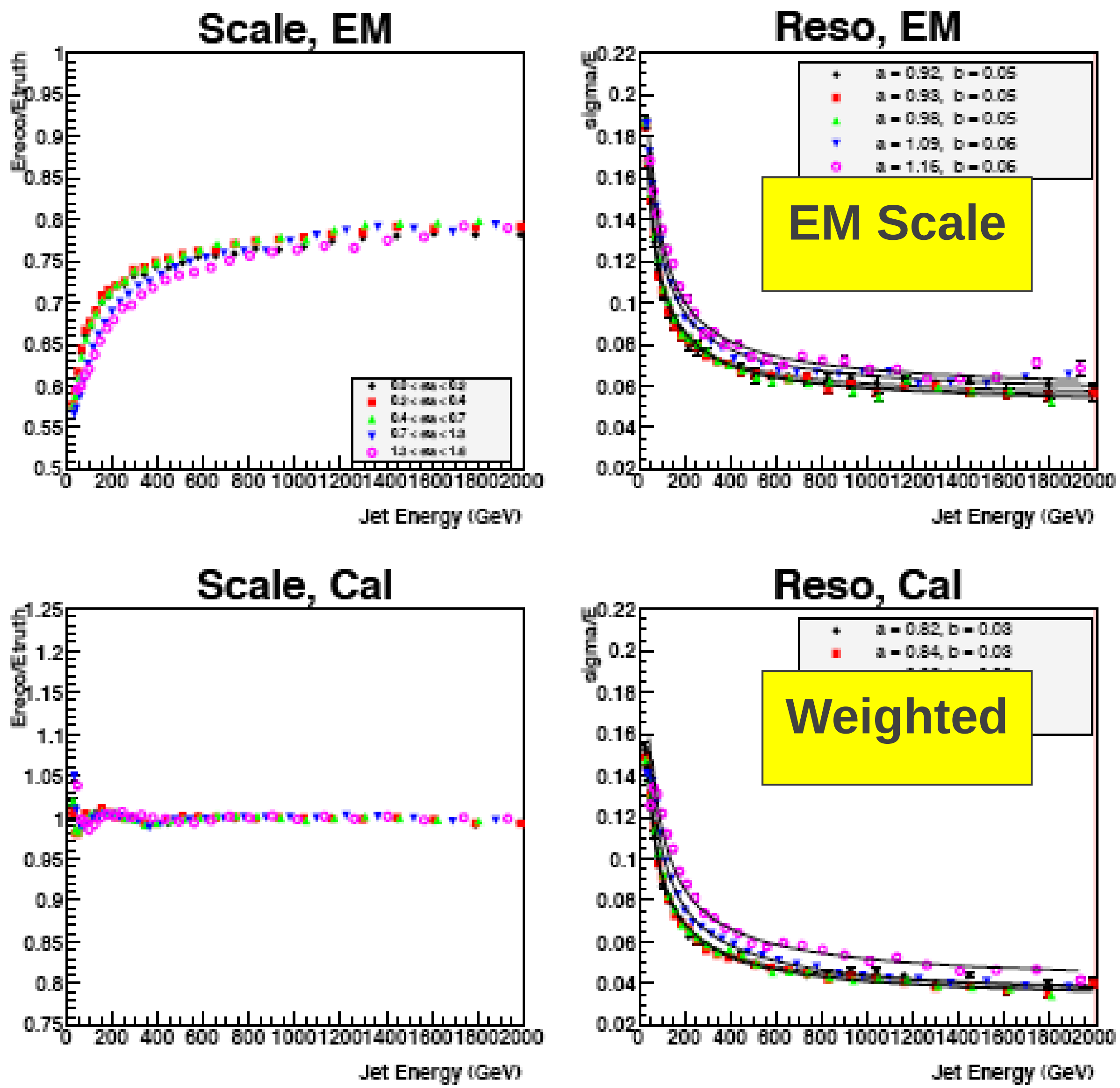
All schemes require a noise treatment, and optimization algorithm - typically Monte Carlo "Truth" versus "reconstructed energy" in the calorimeter to minimize resolution

Why Might SIMPLE Layer Weighting Work for Jets ?

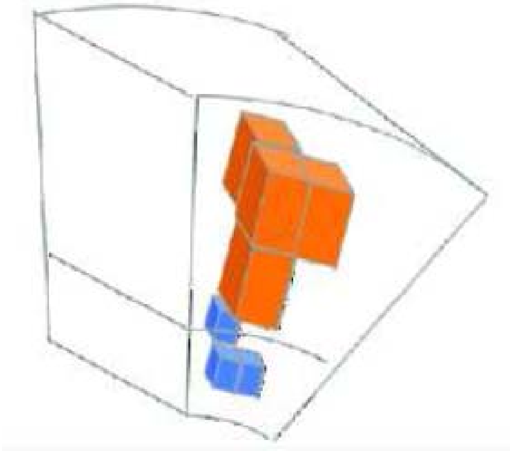


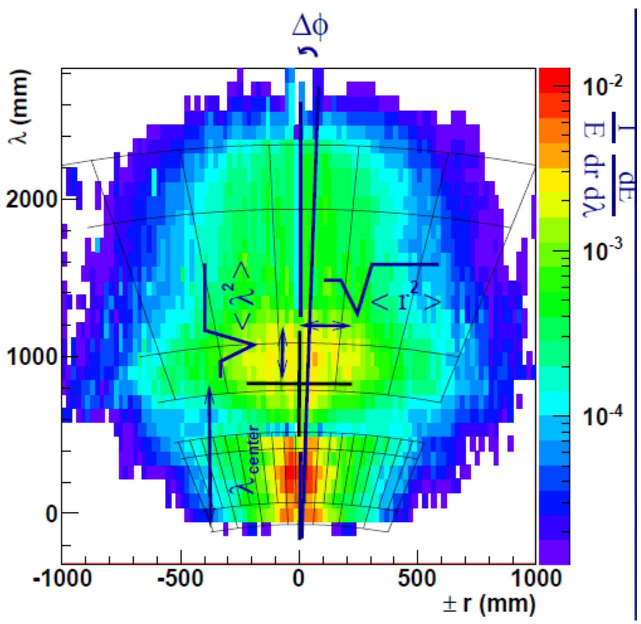
Result

Even this simple weighting greatly improves linearity and resolution



Local Calibration of Clusters (I) : ATLAS





Classify as clusters as electromagnetic, hadronic or unknown based on shower properties: Width; depth; energy density

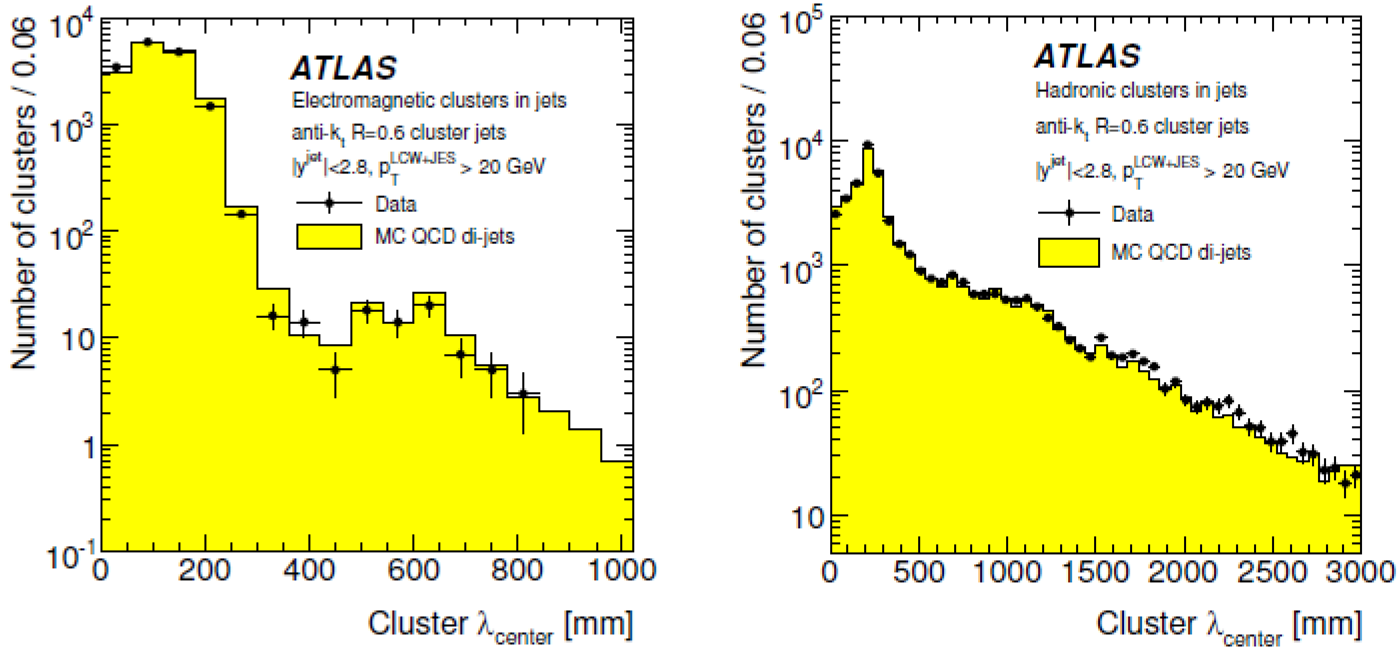
Determine weights in single pion Monte Carlo to calibrate the reconstructed cluster energy back to the true deposited energy based on its classification

EM and HAD weights are applied to all clusters according to the em probability from the classification

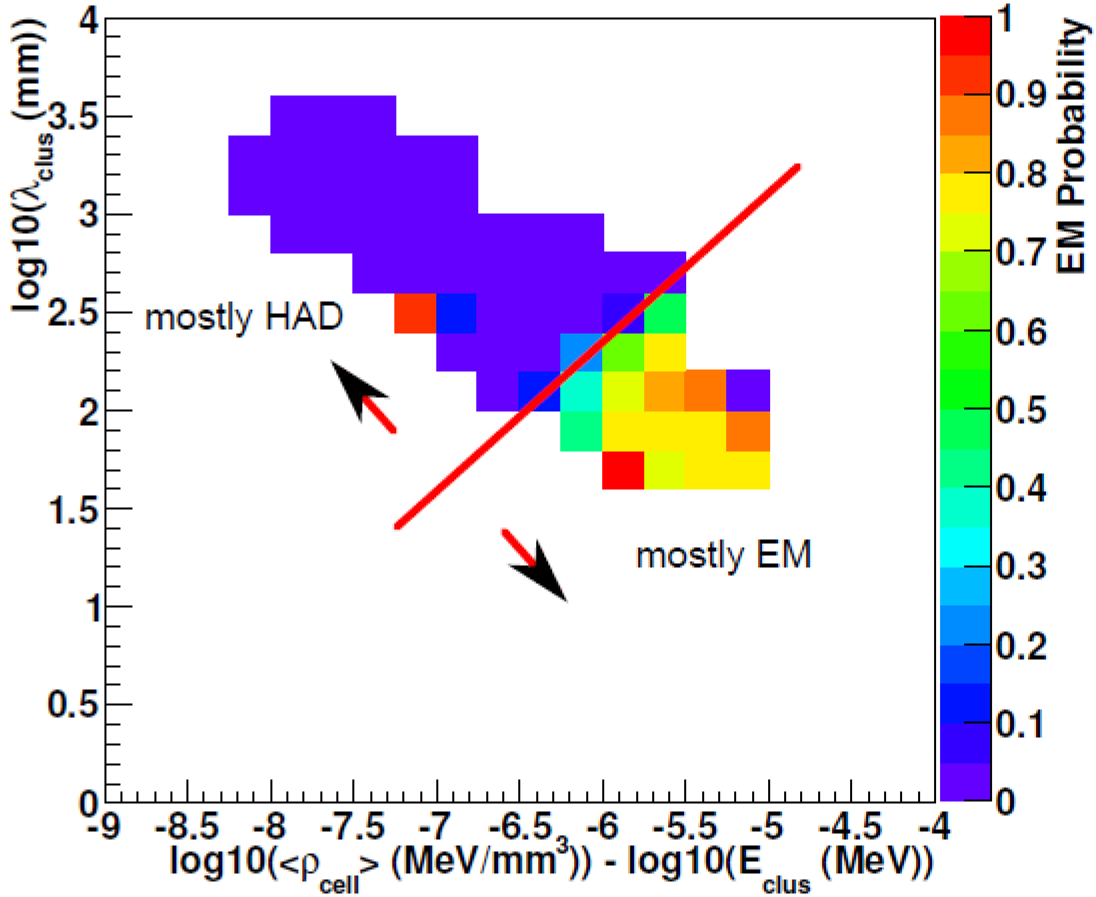
$w = p^{EM} \times w_{EM} + (1 - p^{EM}) \times w_{HAD}$

Use Monte Carlo to determine weights to correct for dead material (such as in front of the calorimeter or between the EM and hadronic sections)

Ensure that cluster properties in data are well described by the Monte Carlo



General features reproduce the simple model

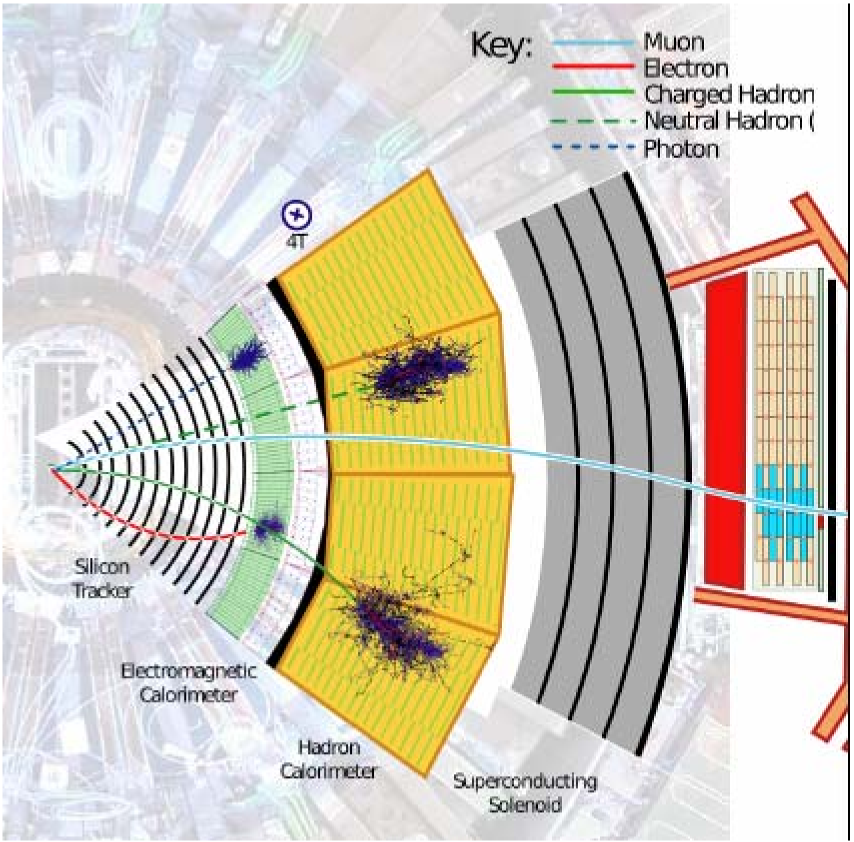


Energy Flow: CMS

Tries to reconstruct individual PF-candidates to form jets
•Charged hadrons
•Photons
•Neutral Hadrons
•Electrons, Muons

Takes advantage the momentum resolution of the CMS tracker in a 4 Tesla magnetic field and the high resolution crystal calorimeter

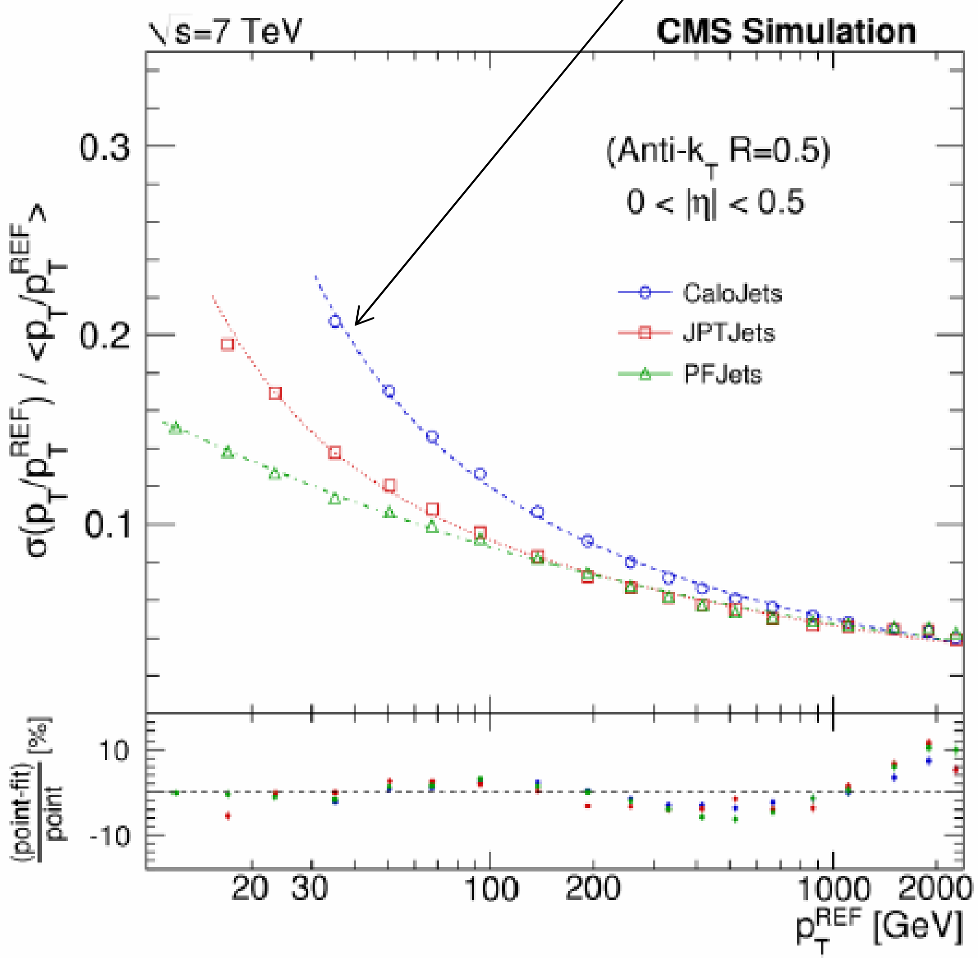
Also has the advantage that e/pi is > 2 in the crystal calorimeter !



Classify clusters depending on location and whether a charged track is pointed at them

Result from simulation

~120%/√E



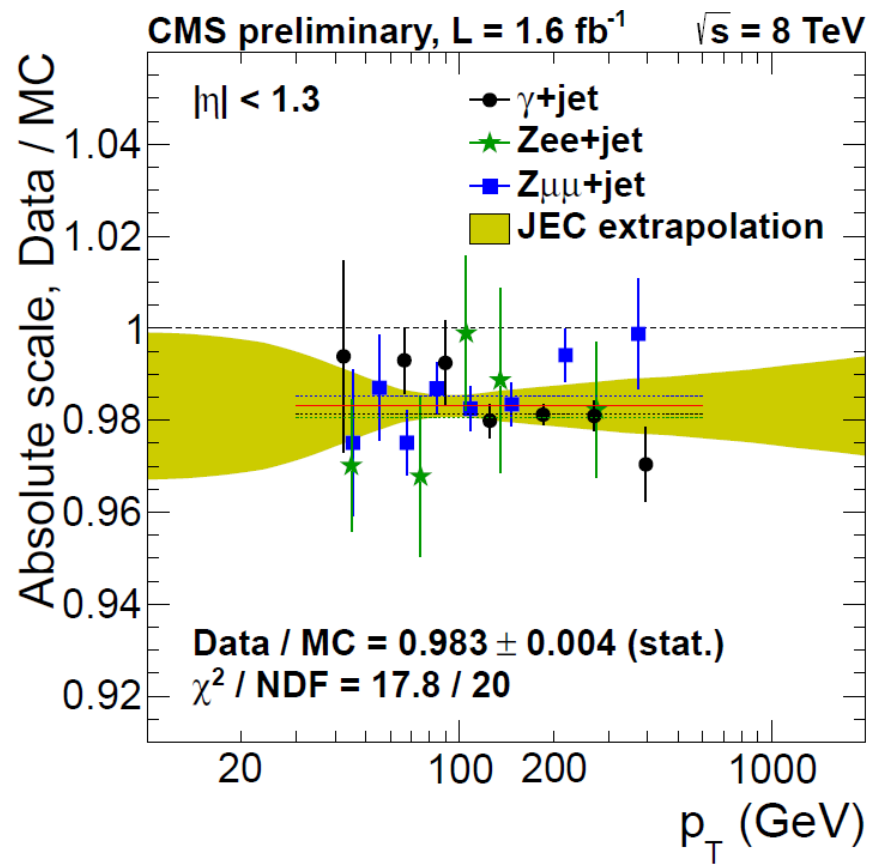
Global Energy Scale Validation – for completeness

The validation of the energy scale is done using momentum balance in physics events:

γ + Jet
Z + Jet

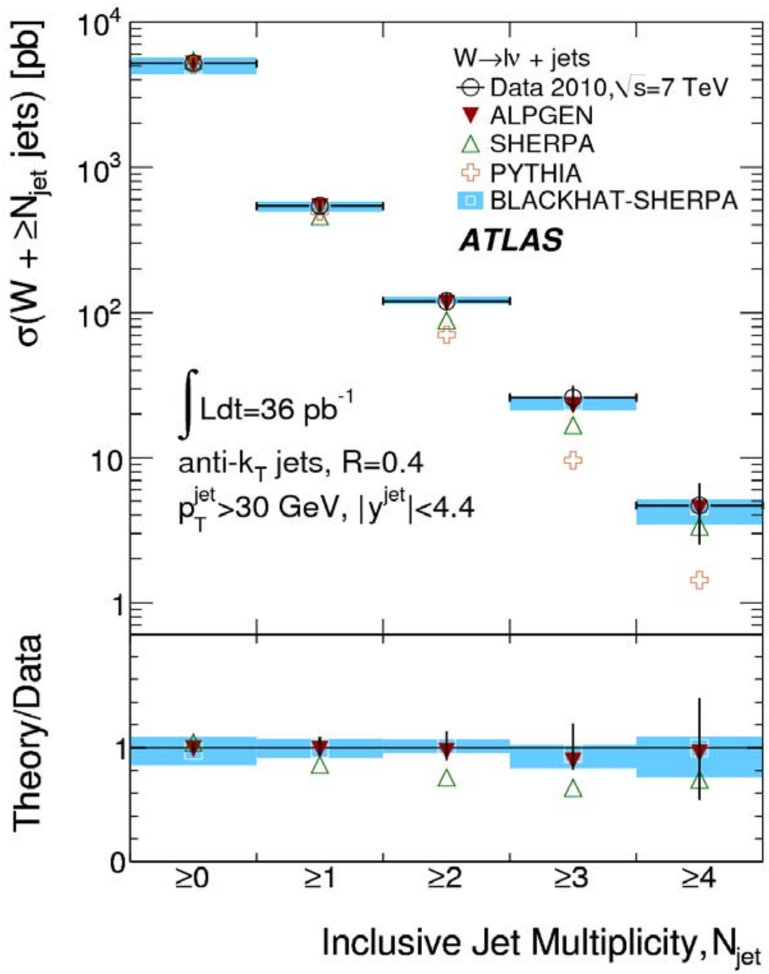
And

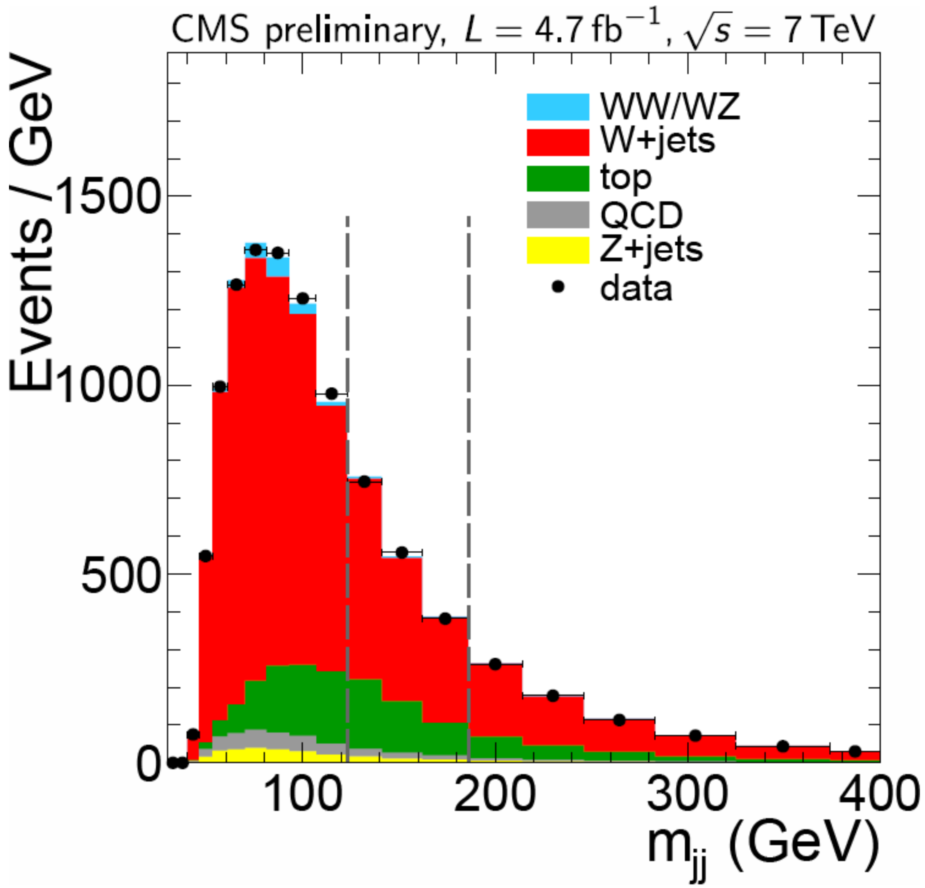
By the W mass measurement in Top events



The systematic uncertainties then include significant contributions from physics and in particular gluon radiation and the parton showering model

The net result (a couple of examples)





M_{jj} in W + 2 Jet events

Thank You for Your Attention

Some Reference Material

- **[AMALDI], Physica Scripta Vol23 (1981) 409-424**
- **[KOEN] http://kaon.kek.jp/~scintikek/pdf/koen-17-nov.pdf**
- **[ABRAMOWICZ] NIM 180 (1981) 429**
- **[FRIEND] NIM 136 (1976) 505-510**
- **[AMARAL] NIM A443 (2000) 51-70**
- **[GREEN]** http://www-ppd.fnal.gov/eppofficew/Academic_Lectures/Past_Lectures.htm
- **[HUGHES] SLAC-PUB 404 (1990)**
- **[WIGMANS] CALOR0**
  http://ilcagenda.cern.ch/getFile.py/access?contribId=87&sessionId=5&resId=0&materialId=slides&confId=522
- **[GABRIEL] NIM A927 (1993) 1-99**
- **[JOB] NIM A340 (1994) 283-292**
- **[CDFJNIM] hep-ex/0510047**
- **[DAMGOV] CALOR06**
  http://ilcagenda.cern.ch/getFile.py/access?contribId=106&sessionId=35&resId=0&materialId=slides&confId=522
- **[WRIGHT] CALOR06**
  http://ilcagenda.cern.ch/materialDisplay.py?contribId=107&sessionId=35&materialId=slides&confId=522
- **[GFLASH], NIM A290 (1990) 469**
- **CALOR 2012, http://indico.ads.ttu.edu/conferenceDisplay.py?confId=3**