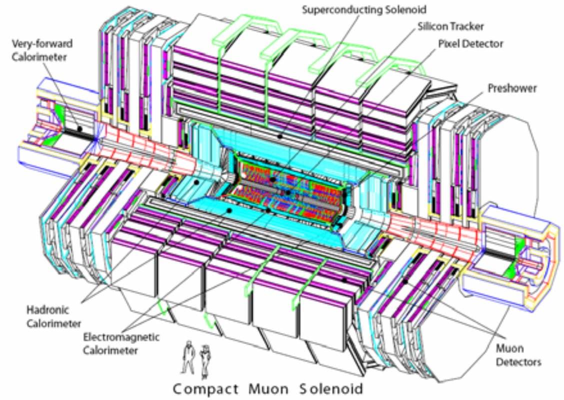
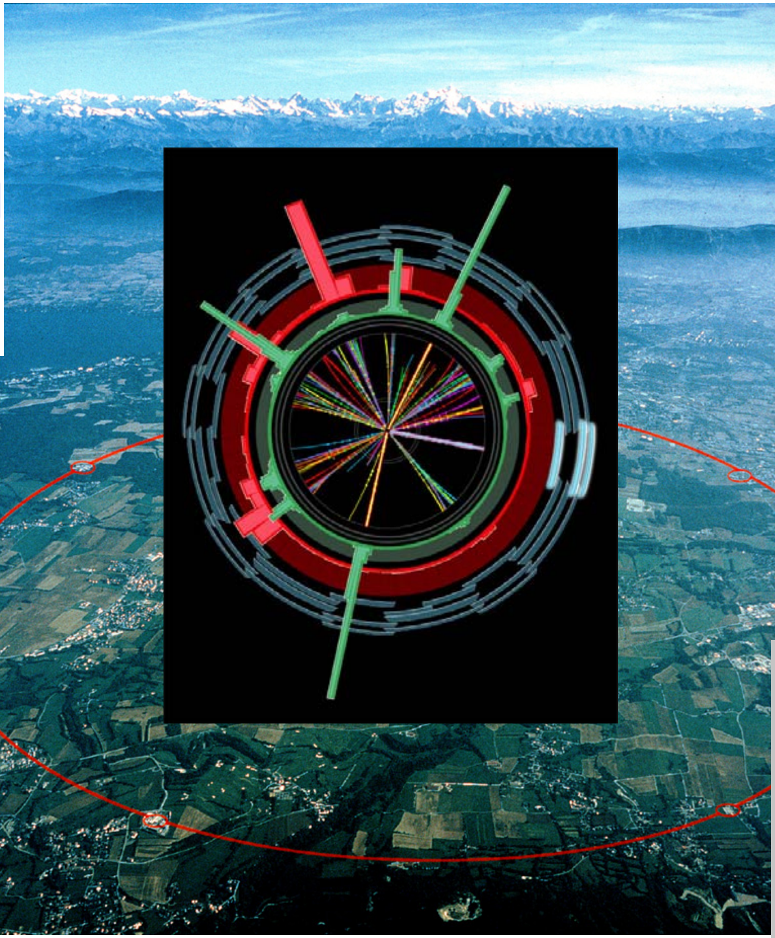
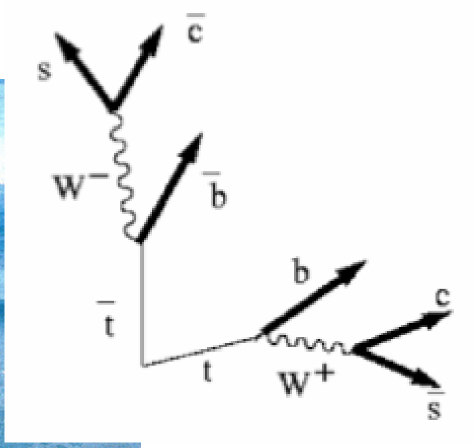
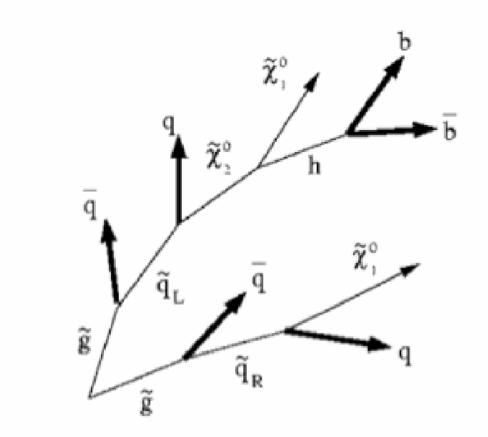
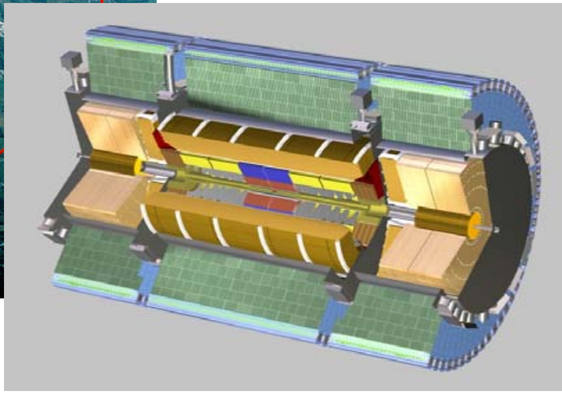
Hadron Calorimetry at the LHC











J. Proudfoot, SSI 2006

One of My Hats

"These Guys are Good"

Hadron 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.

Scope of this talk

ATLAS and CMS Hadron Calorimeters are SAMPLING Calorimeters using Lead/Cu/Fe/W Absorber, with scintillator, and liquid argon readout

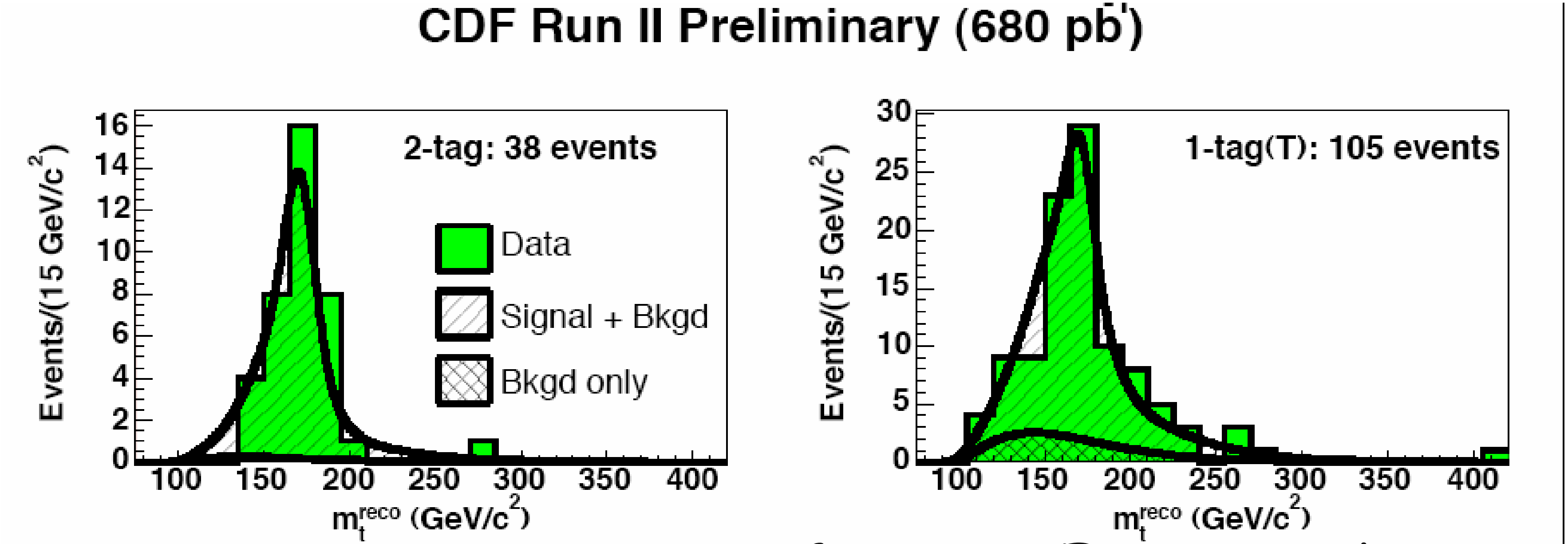
⇒won't discuss compensation by nuclear fission (e.g. ZEUS)

⇒Won't discuss physics of total absorption (crystal/glass) calorimeters

⇒Will illustrate using the readout technology I know best - scintillator - This fits in well with the CMS HCAL which uses megatiles (as developed for the SDC)

To Set The Scale

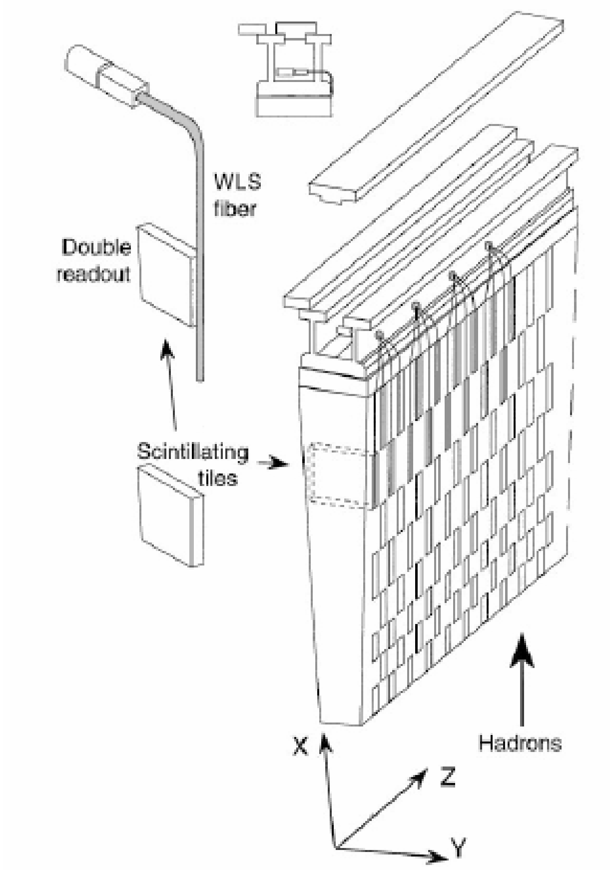
The required PRECISION is what differentiates LHC Calorimeters from those of earlier generations



Systematic uncertainty from Jet Energy Scale is

1.8 GeV/c^2

ATLAS Barrel Hadron Calorimeter



Fe/Scint with WLS fiber Readout via PMT

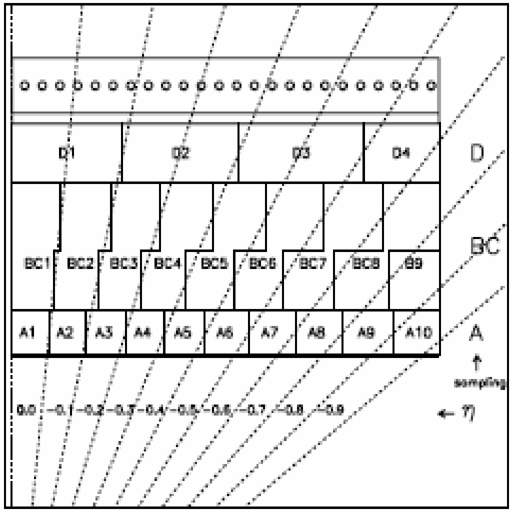


Figure 5-15 Cell geometry of half of a barrel module. The fibres of each cell are routed to one PMT. The PMTs are located in the open circles shown in the girder region.

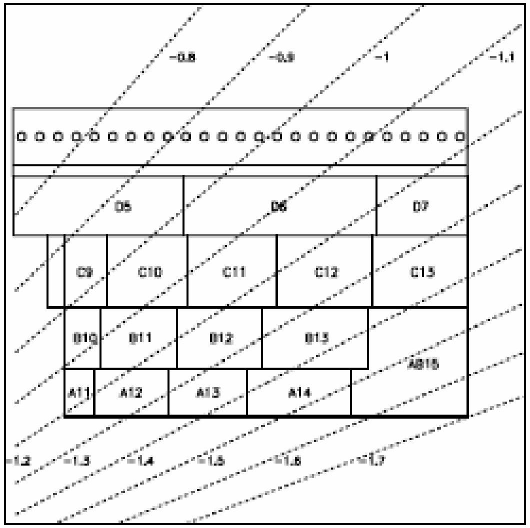
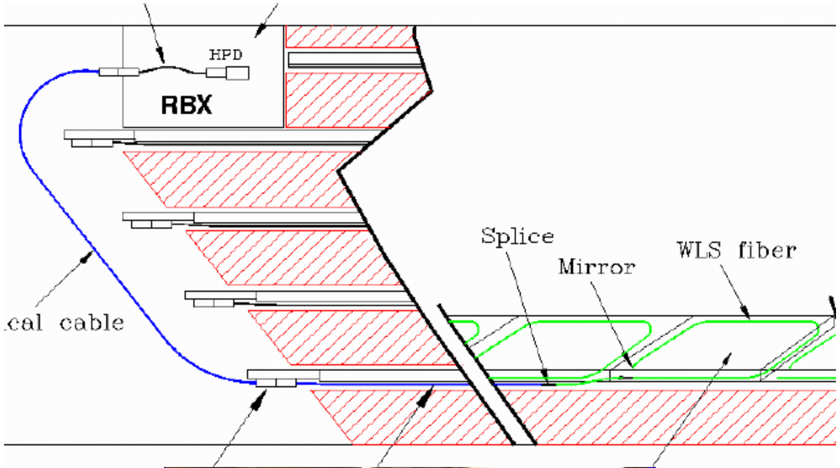


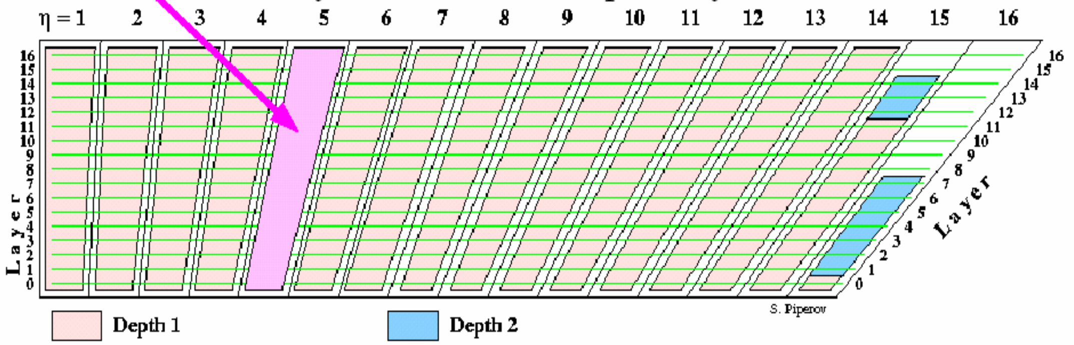
Figure 5-16 Proposed cell geometry for the extended barrel modules (version "a la barrel").

CMS Hadron Calorimeter



Brass/Scint with WLS fiber readout via APD

HB1: tower like – layers a summed optically

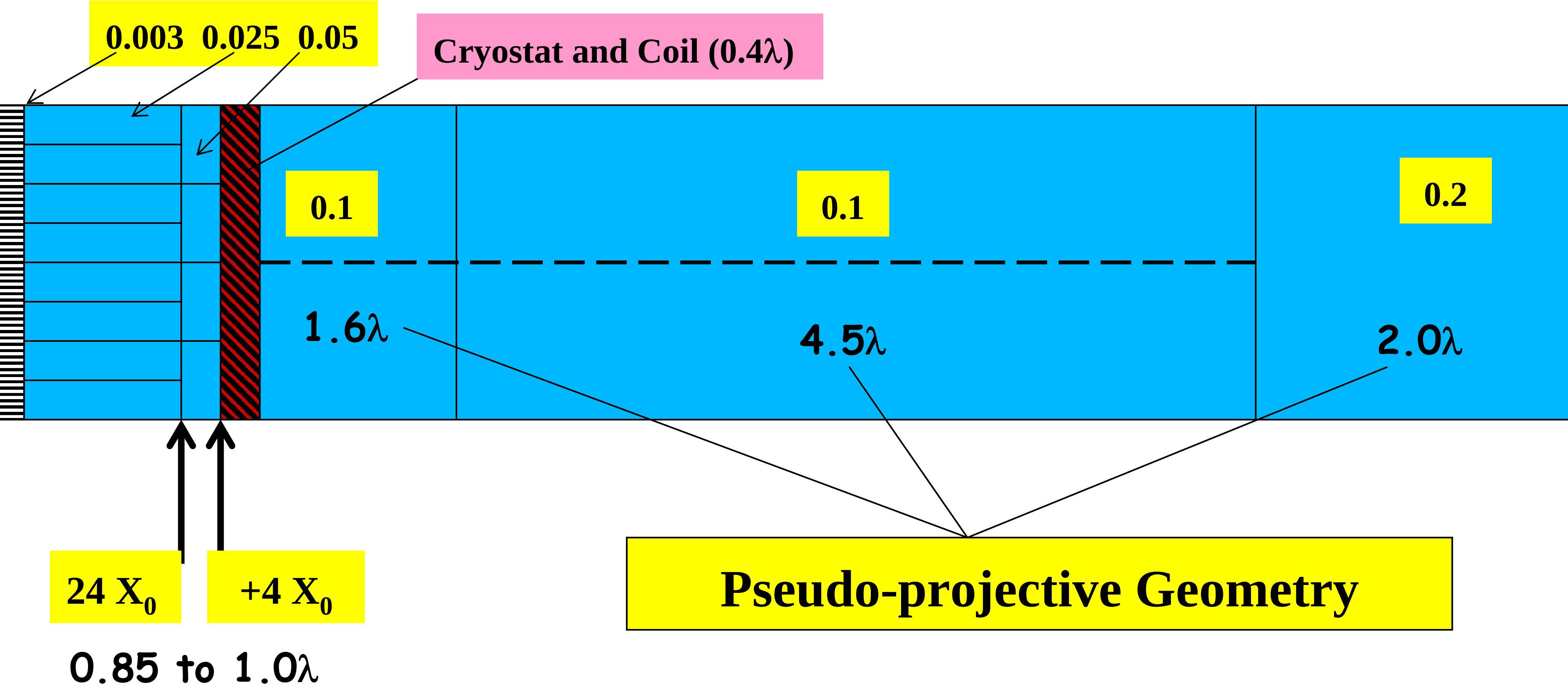


Absorber Properties

	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

CMS HB + HO

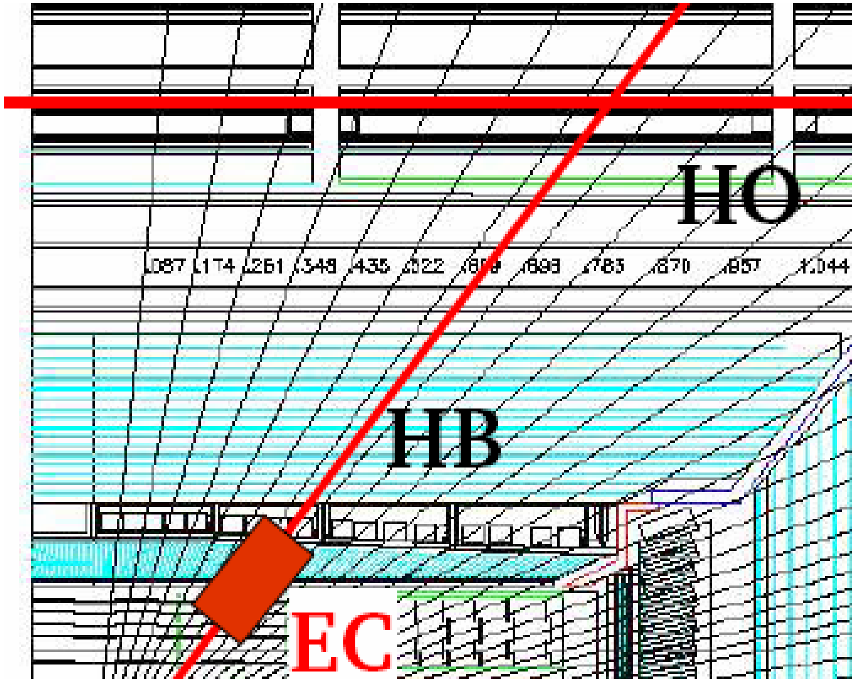
1.1 λ Tail Catcher (η<0.4)

1.4 λ Coil

5.9 λ [Fe/Cu] Scintillator(1+16)

Space for ECAL Readout

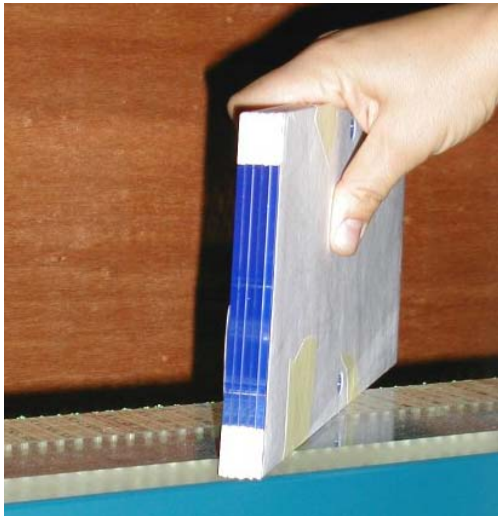
1.1λ Lead Tungstate ECAL



Interesting Features/ Design Choices

- **ATLAS**
  - Cryostat+ Coil (0.4 λ) is between the barrel electromageтic and hadronic calorimeters
  - $\sigma_E/E \sim 50\%/\sqrt{E} + 3.0\ \%$ (for $|\eta| < 3$)
  - Absorber plates run normal to the beamline
- **CMS**
  - 5cm Cu sampling; 17 sampling layers
  - Tail Catcher
  - e/h > 2 in crystal EM calorimeter
  - $\sigma_E/E \sim 100\%/\sqrt{E} + 4.5\ \%$

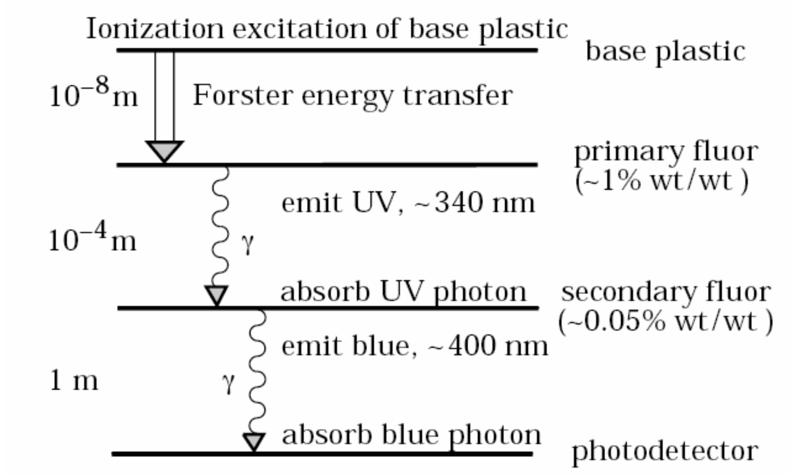
Scintillator Tiles ? What are They?



Birk's Law

Ionization Quenching

$$\frac{d\mathscr{L}}{dx} = \mathscr{L}_0 \frac{dE/dx}{1 + k_B\, dE/dx}$$



Ionization excitation of base plastic

base plastic

10^{-8}m

Forster energy transfer

primary fluor
(~1% wt/wt)

emit UV, ~340 nm

10^{-4}m

γ

absorb UV photon

secondary fluor
(~0.05% wt/wt)

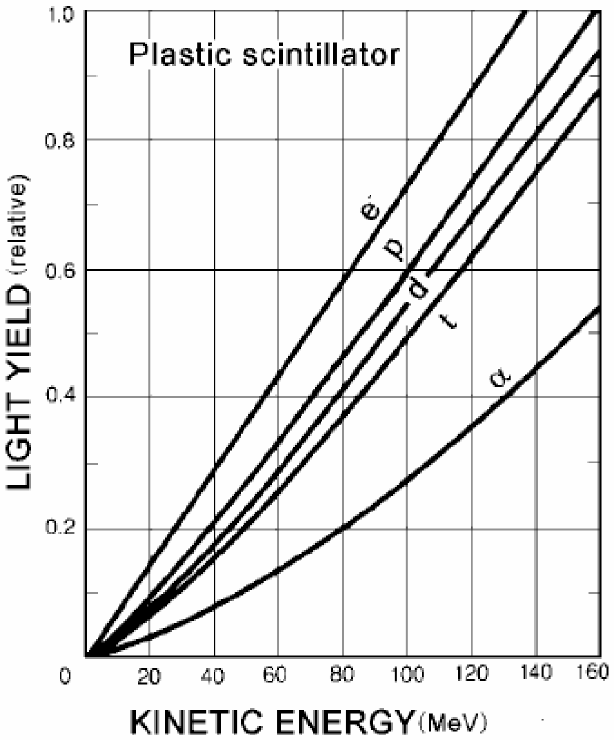
emit blue, ~400 nm

1 m

γ

absorb blue photon

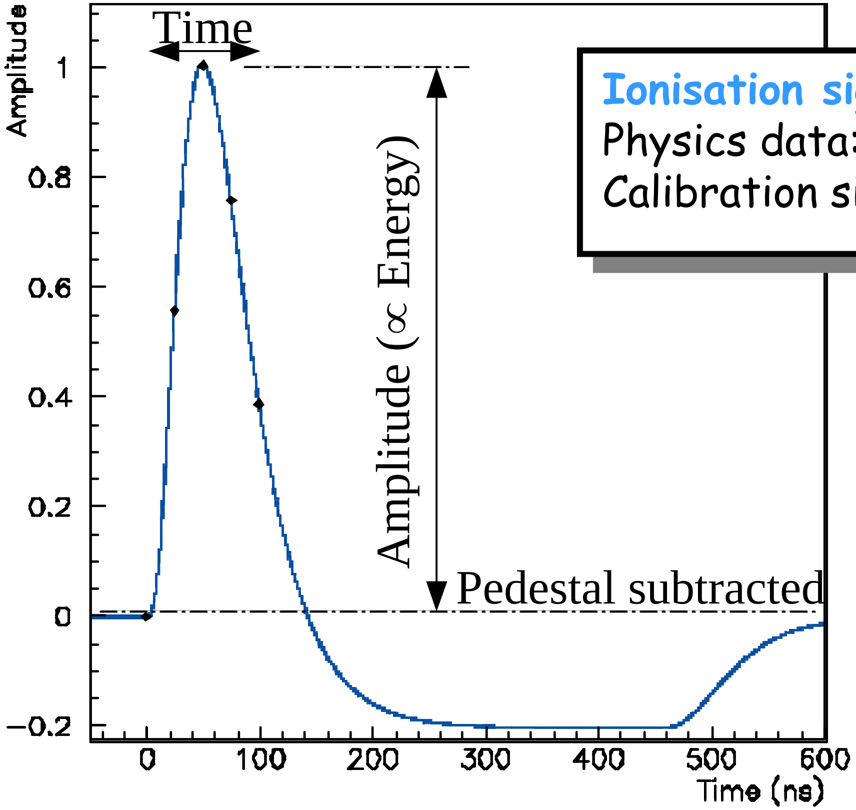
photodetector



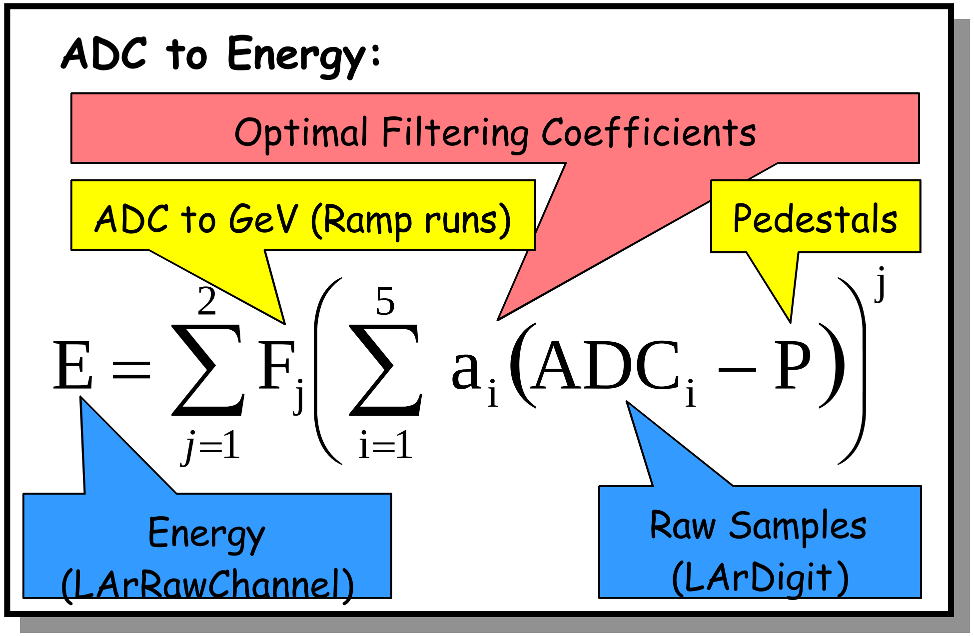
Signal Pulse Length 20-60 nsec

[KOEN]

In ATLAS, the Electromagnetic Calorimeter and the Endcap Hadron Calorimeters use Liquid Argon for Ionization Measurement



Ionisation signal is sampled: 25ns, 12 bit ADC, 3 gains
Physics data: Usually 5 samples (6 samples in TB)
Calibration signal: Up to 32 samples (to determine waveform)



ADC to Energy:

Optimal Filtering Coefficients

ADC to GeV (Ramp runs)

Pedestals

$$E = \sum_{j=1}^{2} F_j \left(\sum_{i=1}^{5} a_i \left(ADC_i - P \right) \right)^j$$

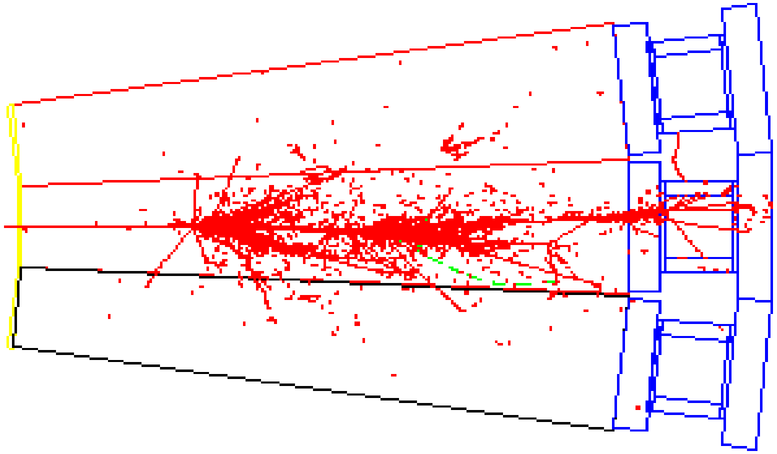
Energy (LArRawChannel)

Raw Samples (LArDigit)

This technology has 2 specific technical issues: pileup and noise

And Must Calibrate Electronics

Sampling Calorimetry



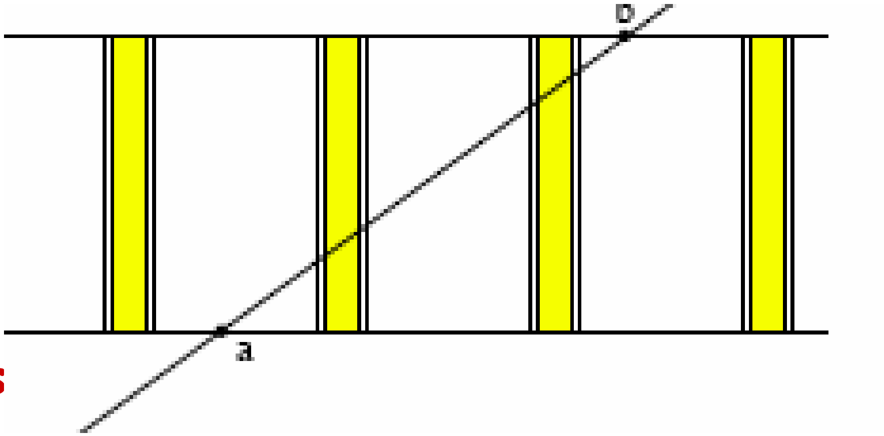
- As the name suggests, a calorimeter measures particle energy
- A SAMPLING calorimeter is a calorimeter in which the medium in which the particle energy is deposited is interleaved with additional layers to periodically sample the energy
- We infer the total energy deposited from the ionization deposited in the sampling layers - by converting it to an electrical signal and digitising it.

Calorimeters in Particle Physics

- **Advantages**
  - Measure neutrals as well as charged hadrons and photons
  - Resolution improves with particle energy (unlike the case for the measurement of a particle momentum in a magnetic field)
  - If hermetic (i.e. covers a large fraction of the kinematic acceptance for the process in question) can be used to infer the presence of ***neutrinos*** in the final state
  - Can provide a fast trigger
- **Disadvantages**
  - Generally, calorimeters have a non-linear response to charged hadrons
  - Hadron calorimeters need to be BIG to provide adequate containment for high energy particles. Cost vs performance compromises must be made

Calorimeter Performance

- The precision of the measurement depends on many well known factors:
  - Sampling fraction
  - Sampling frequency
  - Detection uniformity
  - Detection efficiency
  - Readout geometry
  - Noise
  - Properties of the showers medium
  - Properties in the medium in which the shower develops
- The calorimeter must be deep enough to contain the showers of interest. This is of order 10 interaction lengths



Sampling Calorimetry - Characteristics

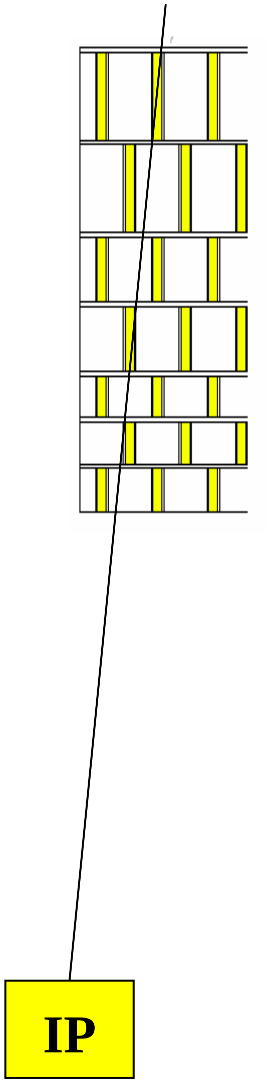
- All energy in the shower is ultimately lost to ionization, dE/dx
- Sampling fraction is $\sum(dE/dx)_{\text{active medium}} / \sum(dE/dx)_{\text{absorber}}$
- The energy measurement is in principal linear, i.e.
  - $E_{\text{particle}} = k * \{(dE/dx)_{\text{absorber}}/(dE/dx)_{\text{active medium}}\} * \sum(dE/dx)_{\text{active medium}}$
- Energy deposition is statistical and depends on the number pf particles in the shower which contribute to ionization
  - $N_{\text{shower}} \sim E_{\text{particle}}/E_{\text{critical}}$
  - For an electromagnetic cascade the critical energy, E_{critical} ,is characterized by the energy at which ionization dominates over pair production
  - For a hadronic cascade the critical energy is characterized by the energy for Pion multiplication (e.g. $\pi p \to \pi\pi p$)
- Resolution $\sigma_E \sim 1/\sqrt{N_{\text{shower}}}$ => $\sigma_E \sim 1/\sqrt{E_{\text{particle}}}$

Sampling Fluctuations

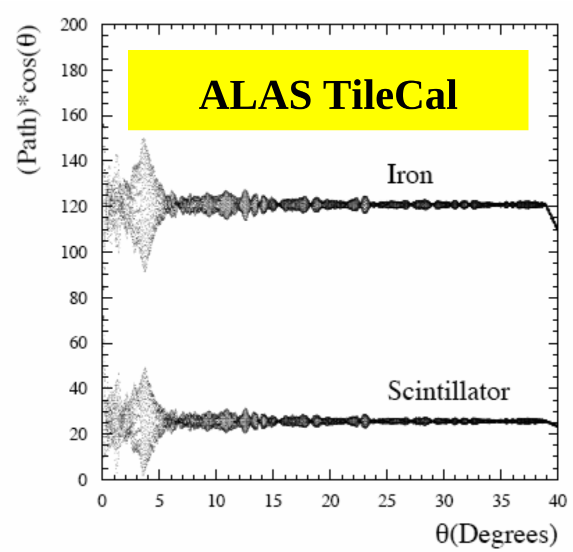
- **Path length fluctuations also affect the measurement resolution of a sampling calorimeter**
  - just consider a sampling period of 2λ vs a sampling period of 0.1λ
- **Numerically, this term in the resolution function is dependent on the type of showering particle**
  - For electromagnetic showers $\sigma(E)/E = k\,\sqrt{(t_{em}/E)}$, where t_{em} is the absorber thickness expressed in radiation lengths
  - For hadronic showers $\sigma(E)/E = k\,\sqrt{(t_{had}/E)}$, where t_{had} is the absorber thickness expressed in interaction lengths

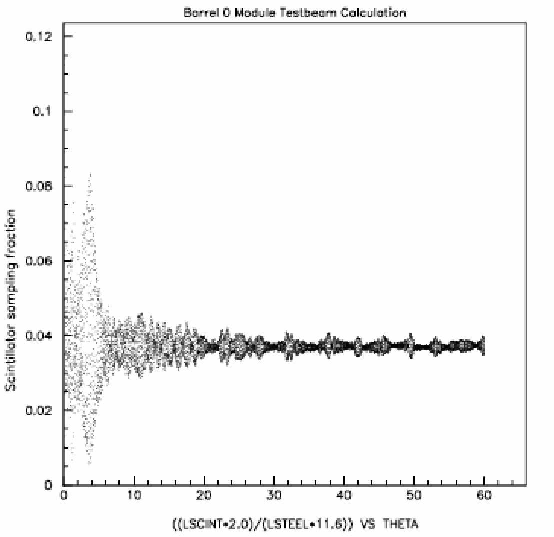
For a much more detailed discussion, see the beautiful paper by [AMALDI]

Layer Response/Sampling Uniformity

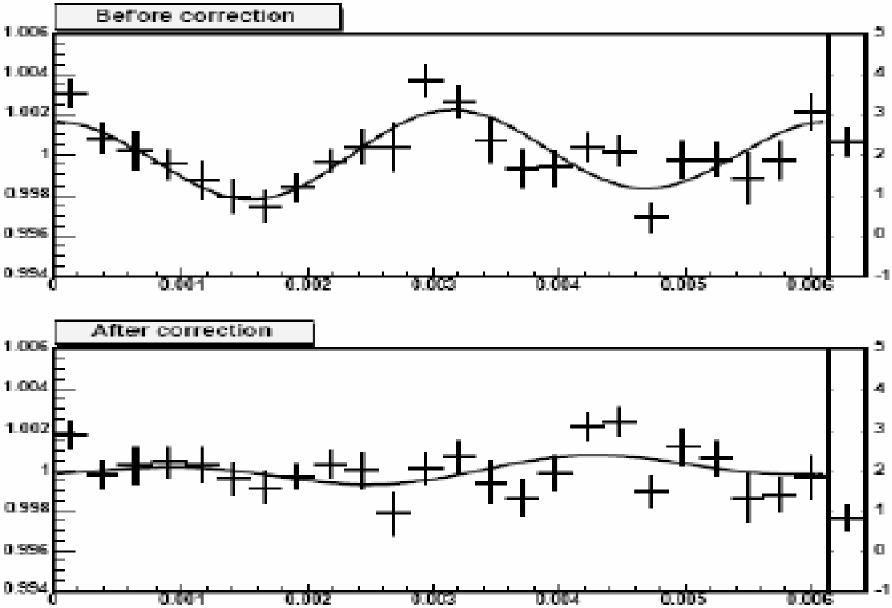


ALAS TileCal





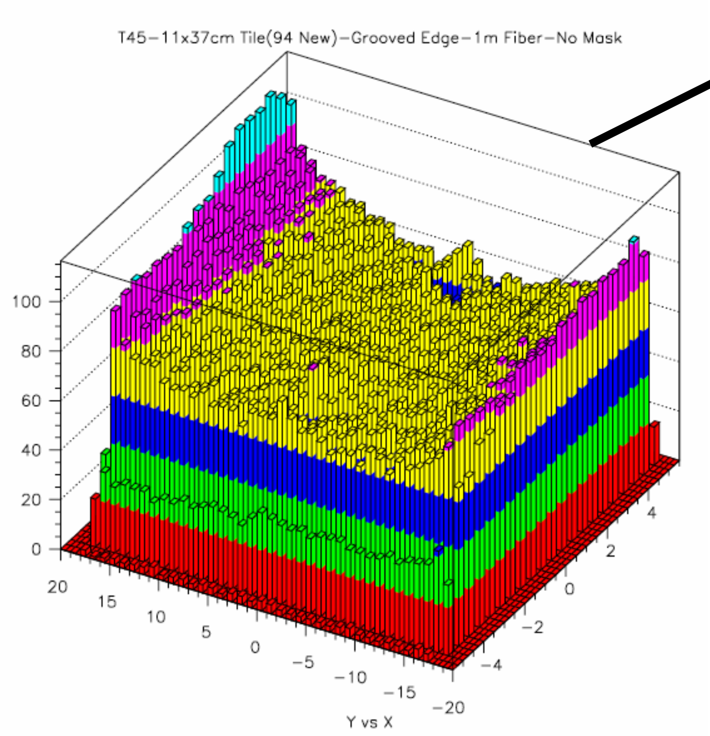
ALAS Liquid Argon Accordian



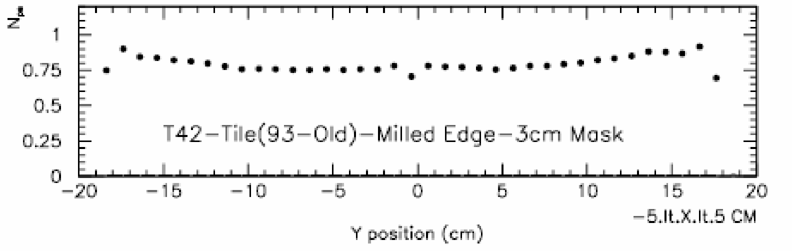
Phi Modulation from Accordian Structure: can correct for e/γ but not in jets.

Layer Response: Signal Measurement

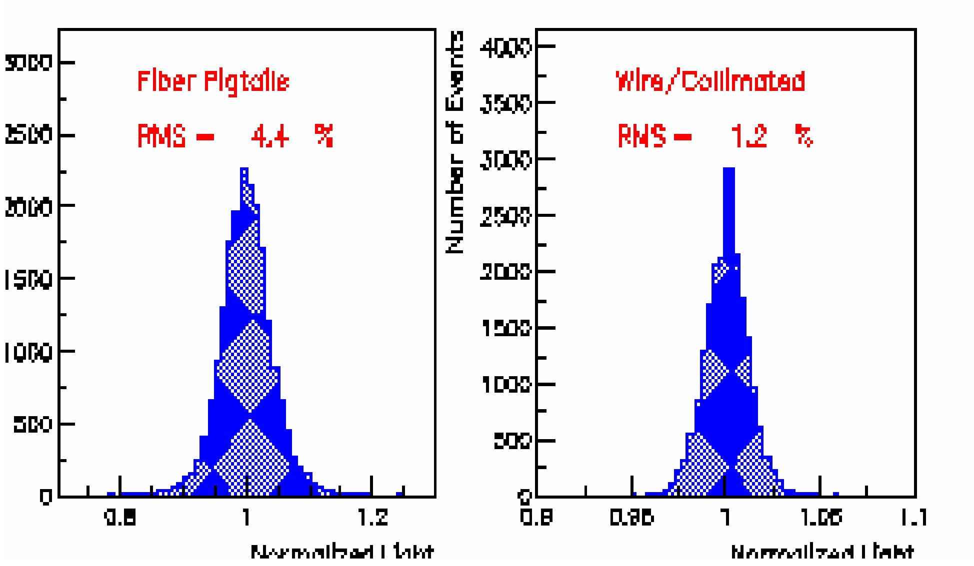
ATLAS Scintillator
Tile Response
Across Surface



Mask

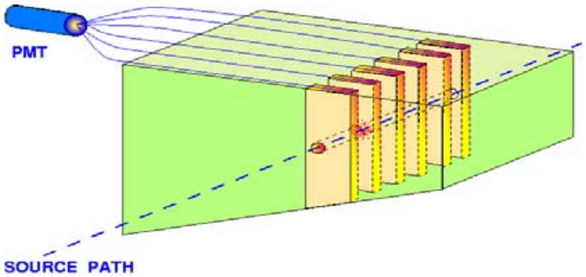


CMS Fiber Uniformity



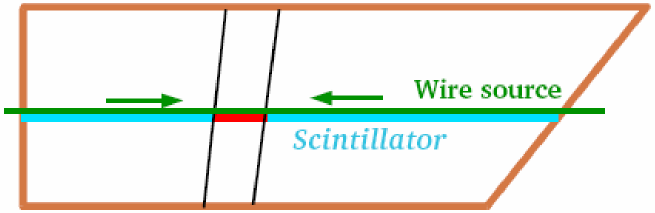
rms <Layer Light Yield> = 4.6%

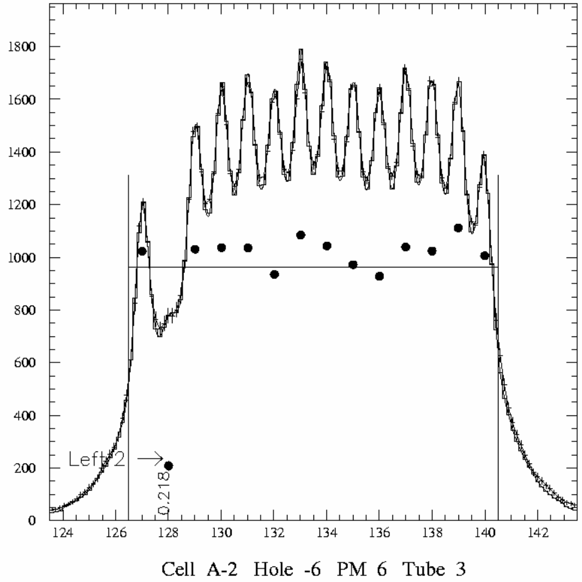
Global Calibration and Uniformity using Cs^{137}

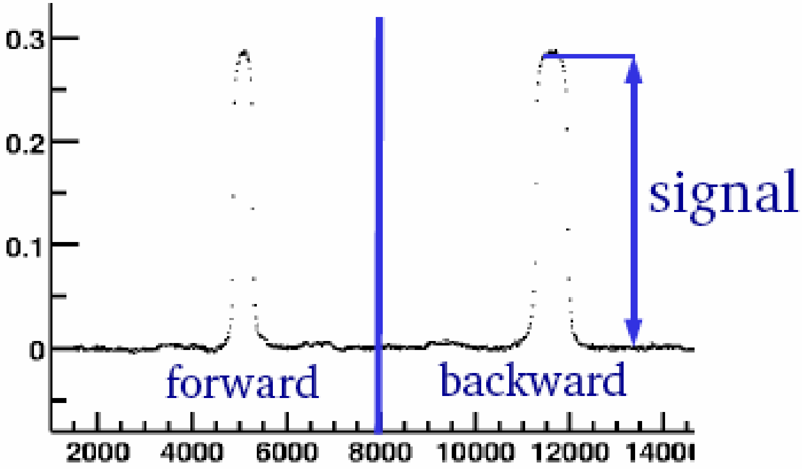


ATLAS Source Path

CMS source path







Global Energy Scale

Measure response to high energy particle beams. Establish:

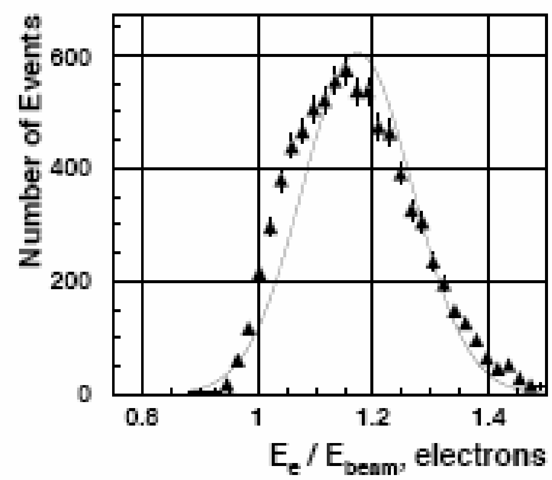
- e/source response ratio
- e/π response ratio
- pC/Gev (Calibration Constant)
- pe/GeV (60-80 for TileCal, my estimate is ~20 for CMS HCAL)

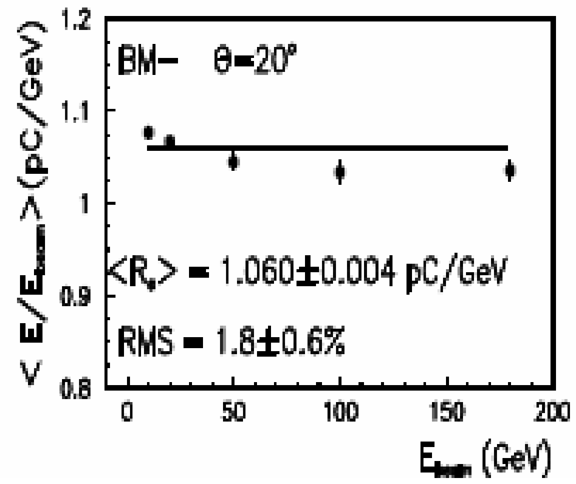
Energy Scale

CMS HCAL: 50 GeV π^- with MIP in ECAL

ATLAS TileCal: Set to electromagnetic scale using electrons

ATLAS TileCal





Sounds Pretty Easy ?

⇒Measured Ionization = F ($E_{particle}$)

⇒In an ideal world this would be linear

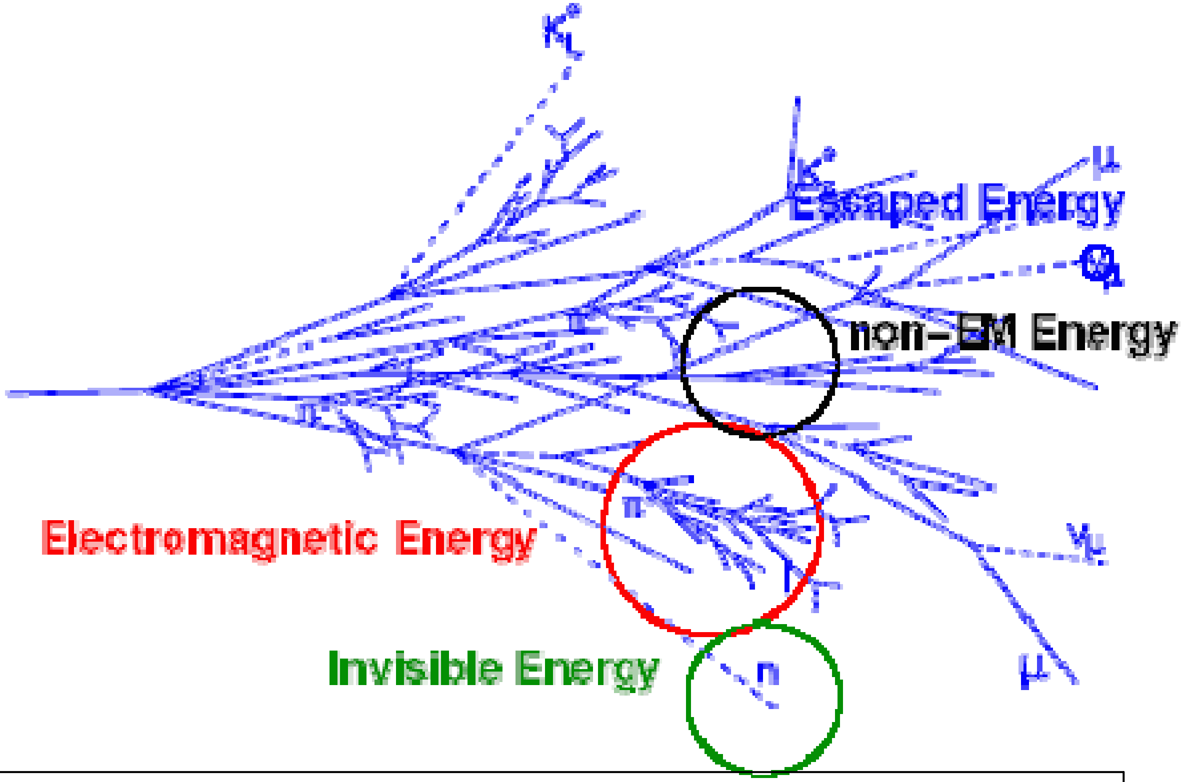
⇒In an ideal world the signal response for any given detector layer would be uniform

⇒In the real world F is non-linear and inverting this to obtain the most accurate estimate of the incident particle is THE major issue for both the resolution and linearity of any calorimeter

BECAUSE

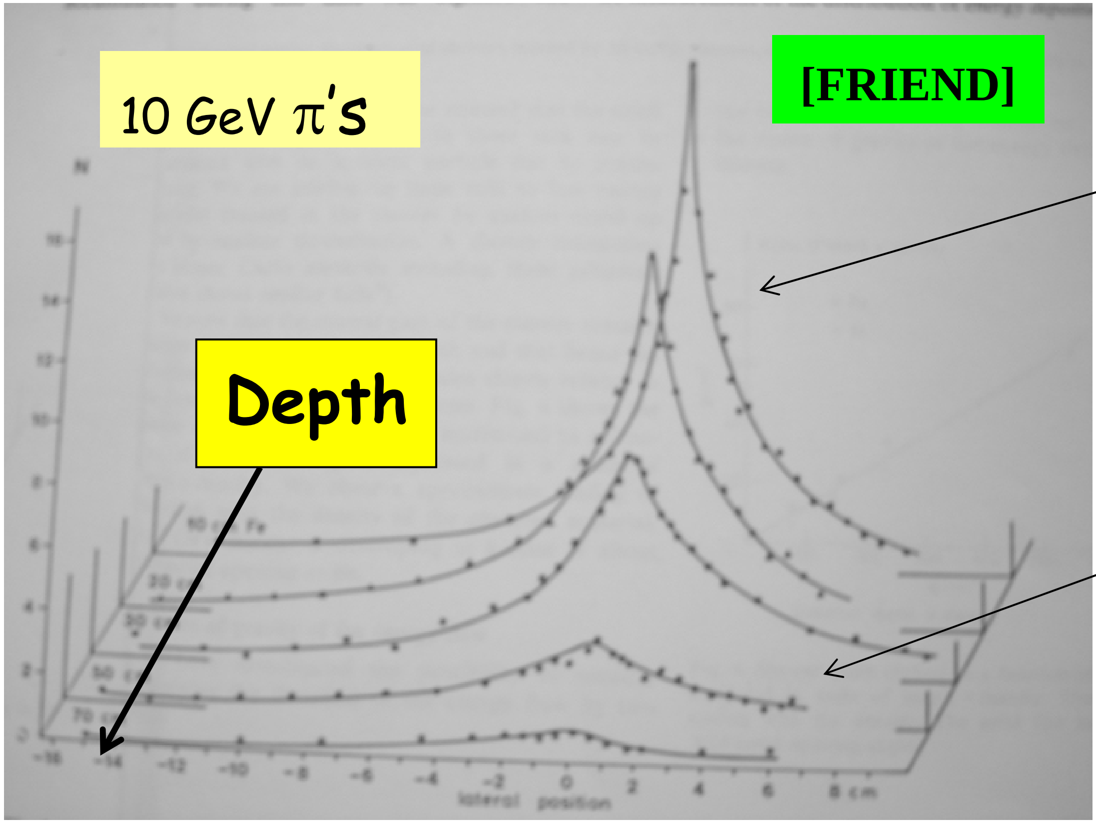
Response for Single Hadrons: F($E_{particle}$)

Can Only Be Computed using a Monte Carlo Model



- EM energy (eg $\pi^0\rightarrow\gamma\gamma$) : O(50%)
- Visible non-EM energy (eg dE/dX) : O(25%)
- Invisible non-EM energy (eg nuclear breakup) :O(25%)
- Escaped energy (eg ν) :O(1%)

Hadron Shower Development (I)



Dense core associated with deposition of electromagnetic energy

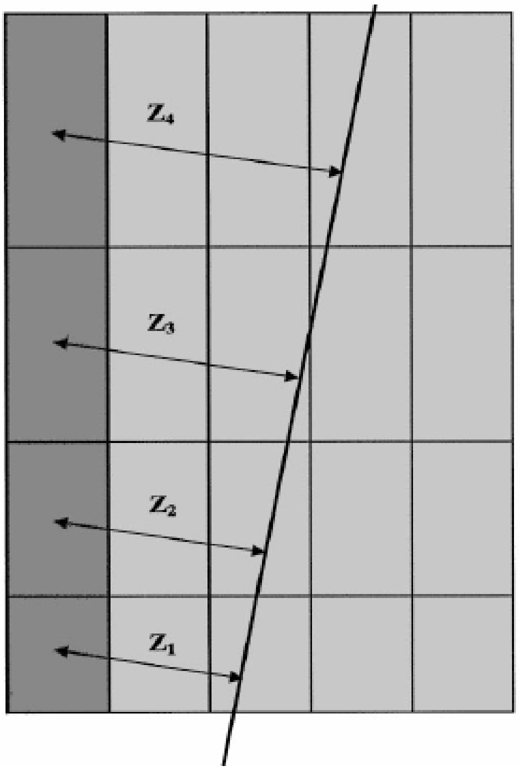
Tail associated with deposition of hadronic energy

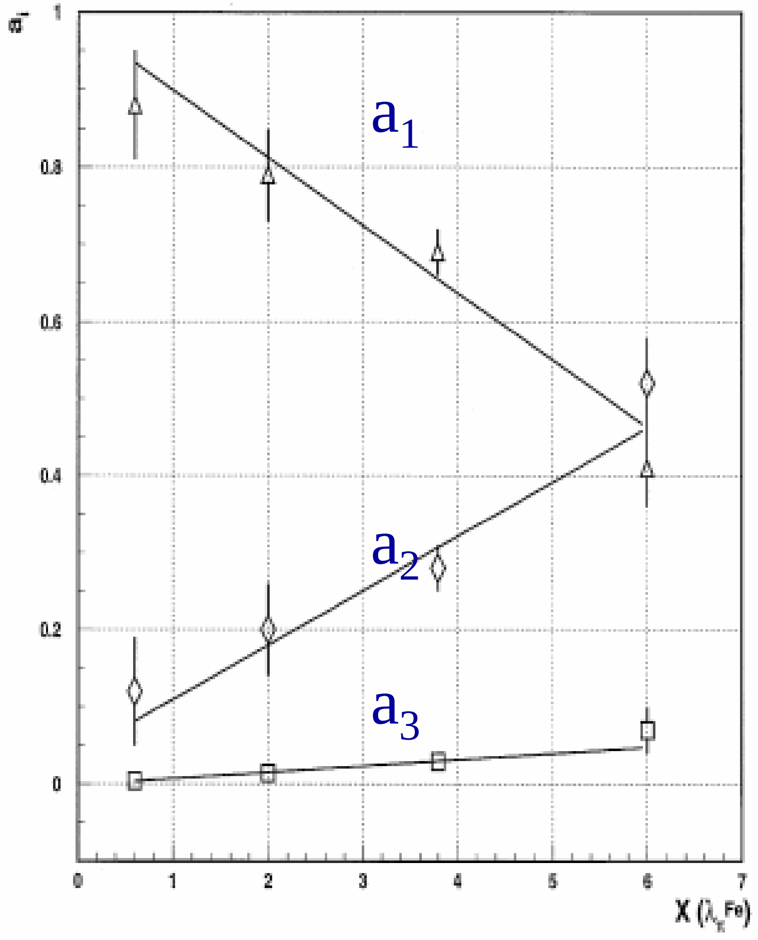
Shower width increases linearly with depth x density

Contribution from electromagnetic energy diminishes with shower depth

Tiled Calorimeter Prototype

$$f(z) = \frac{E_0}{2B}\sum_{i=1}^{3} a_i e^{-|z|/\lambda_i}$$





[AMARAL]

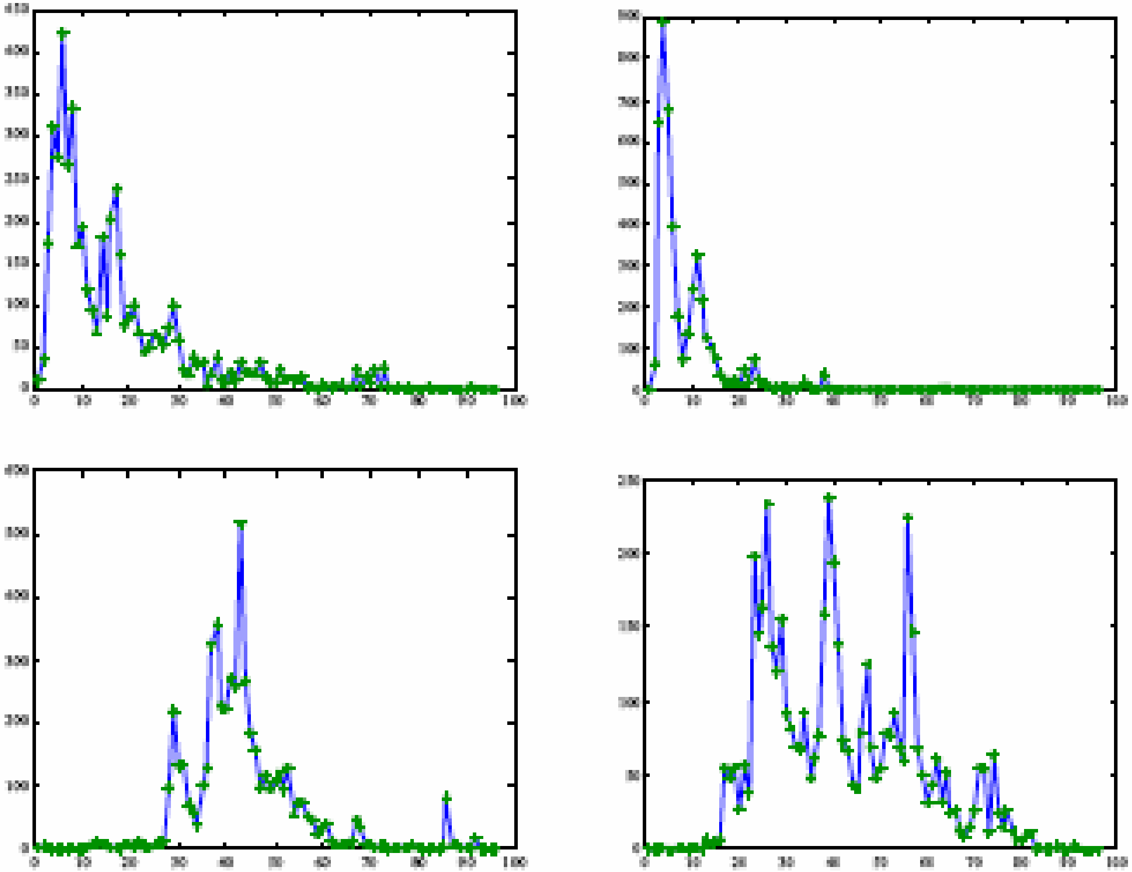
$\langle\lambda_1\rangle$=23mm , $\langle\lambda_2\rangle$=58mm, $\langle\lambda_3\rangle$~250mm

Hadron Shower Development (II)

96 Layers of Pb/Scintillator Sampling Depth is 0-6 λ [GREEN]

Fluctuations in depth are indicative of the fluctuations associated with the deposition of electromagnetic energy

Substantial event-to-event variation. Therefore any useful correction must be event-by-event



Fraction of Energy Carried by π^0's

[AMARAL]

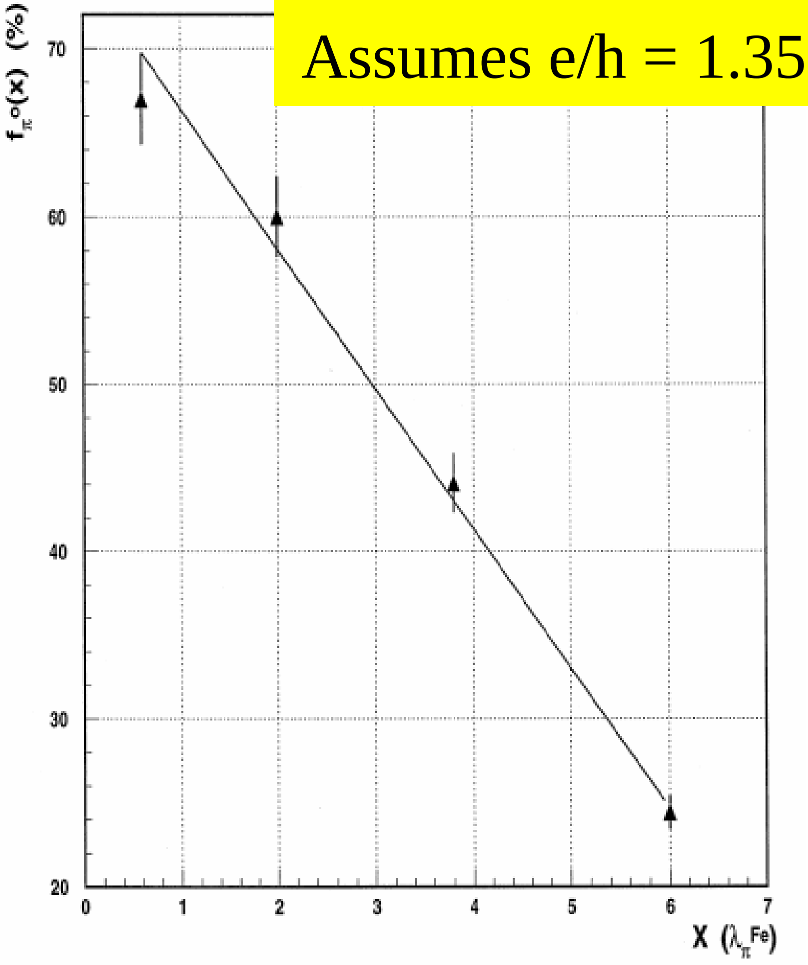
Integrate the contribution for the first component to obtain the fraction of energy carried by π^0's

$$f_{\pi^0} = \frac{a_1 \lambda_1}{\sum_{i=1}^{3} a_i \lambda_i}. \tag{29}$$

For the entire Tile Calorimeter this value is (53 ± 3)% at 100 GeV.

The observed π^0 fraction, f_{π^0}, is related to the intrinsic actual fraction, f'_{π^0} by the equation

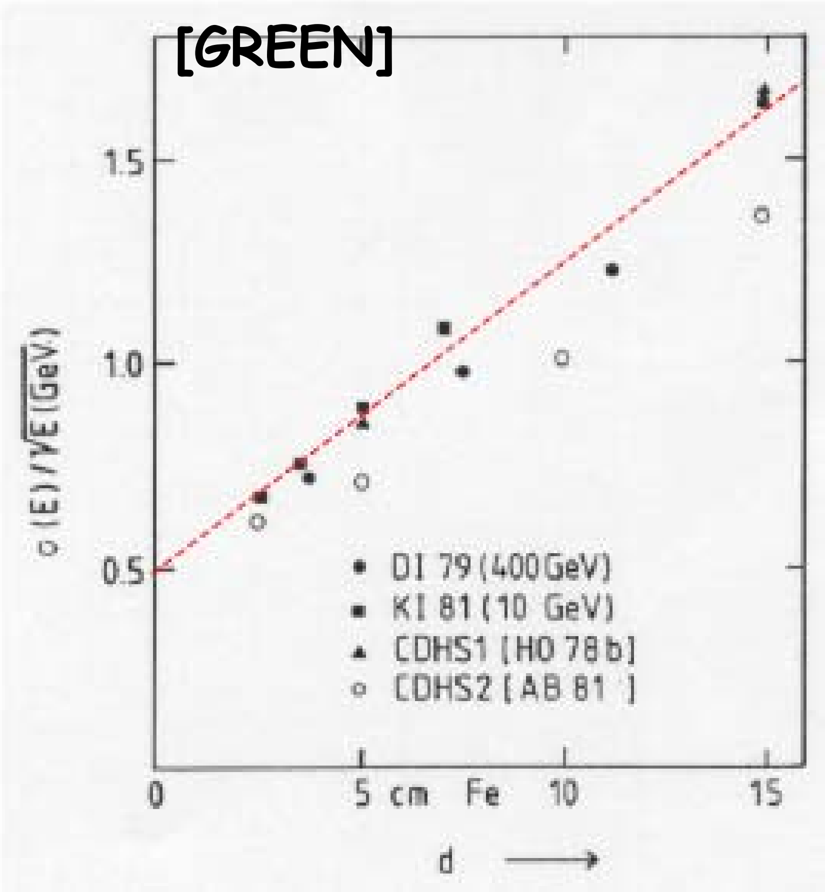
$$f_{\pi^0}(E) = \frac{eE'_{\mathrm{em}}}{eE'_{\mathrm{em}} + hE'_{\mathrm{h}}} = \frac{e/h\, f'_{\pi^0}(E)}{(e/h - 1) f'_{\pi^0}(E) + 1} \tag{30}$$



Assumes e/h = 1.35

Fig. 20. The $f_{\pi^0}(x)$ fractions of hadronic showers as a function of x.

Binding Energy Fluctuations



The Stochastic coefficient scales as t_{had} as expected.

The non-zero intercept indicates that this is not the full story =>

(nuclear) binding energy fluctuations

Sample-to Sample Correlations

Relevant for the correction of the measured energy for dead material (coils, cryostats and the like)

Flat => No Correlation

Proportional => Strong Correlation

[HUGHES]

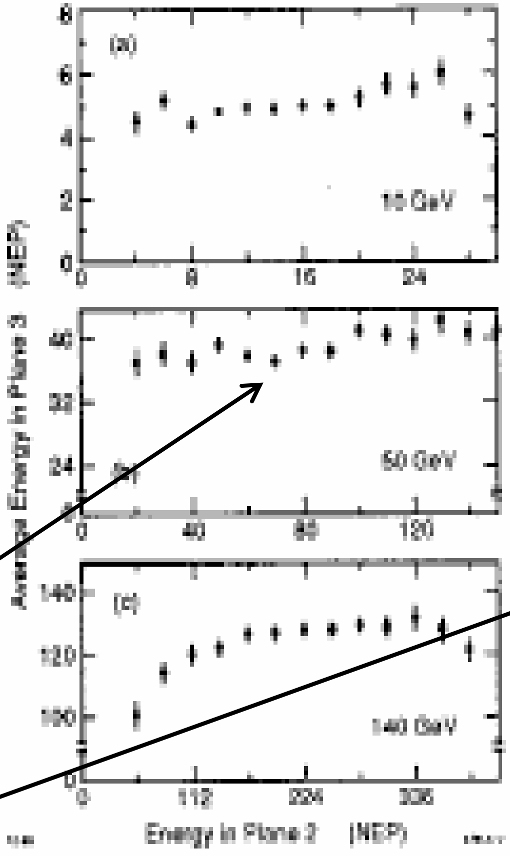


Fig. 13. Average shower energy deposited in the third plane from the vertex as a function of the shower energy

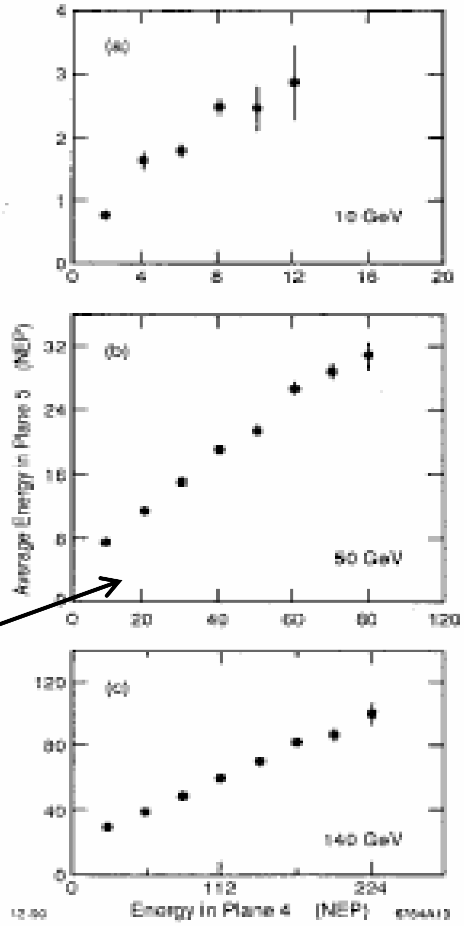


Fig. 14. Average shower energy deposited in the fifth plane from the vertex as a function of the shower energy deposited in the fourth

Plane 3 vs 2

Plane 5 vs 4

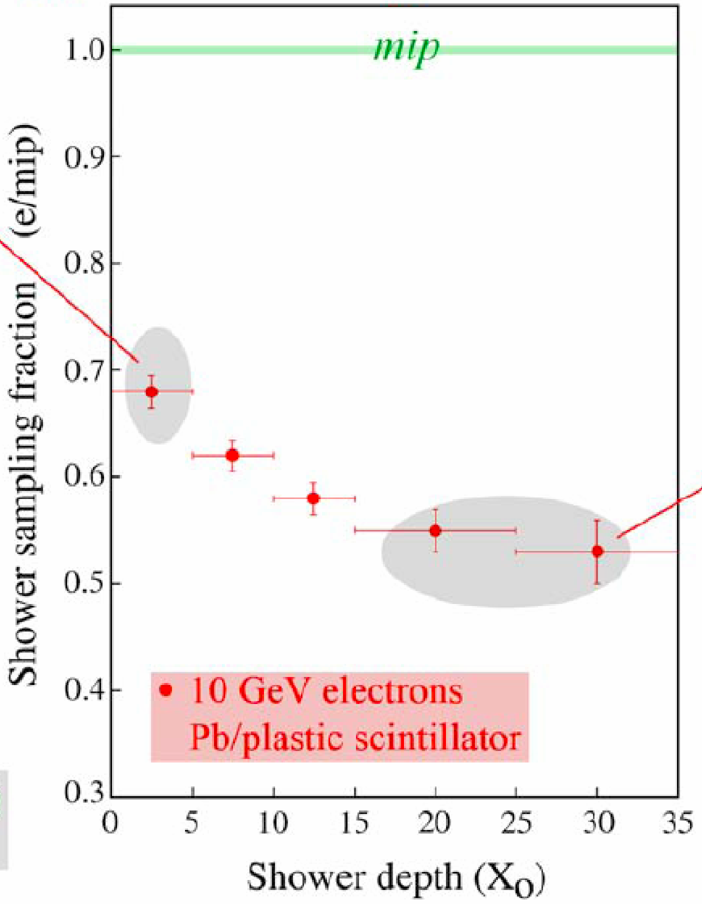
Features of Hadronic Showers: Recap

We have now established several of the important "well-known" features of hadronic showers:

- In general e/π relative response is not equal to 1
- A large fraction of the energy is deposited through em showers (π^0's)
- The starting point for the em component various wildly (little sample to sample correlation early in cascade)
- Fluctuations in binding energy appear to be the principal mechanism which limit the precision of the measurement of the energy of the incident particle
- The transverse shower shape is a function of the depth of the shower

But- Even Electromagnetic Showers Are not Simple

*The sampling fraction changes as shower develops**



shower dominated by mip's

shower dominated by soft γ's

* *By as much as 30%!*

At Least in Pb/Scintillator Sampling Calorimeter

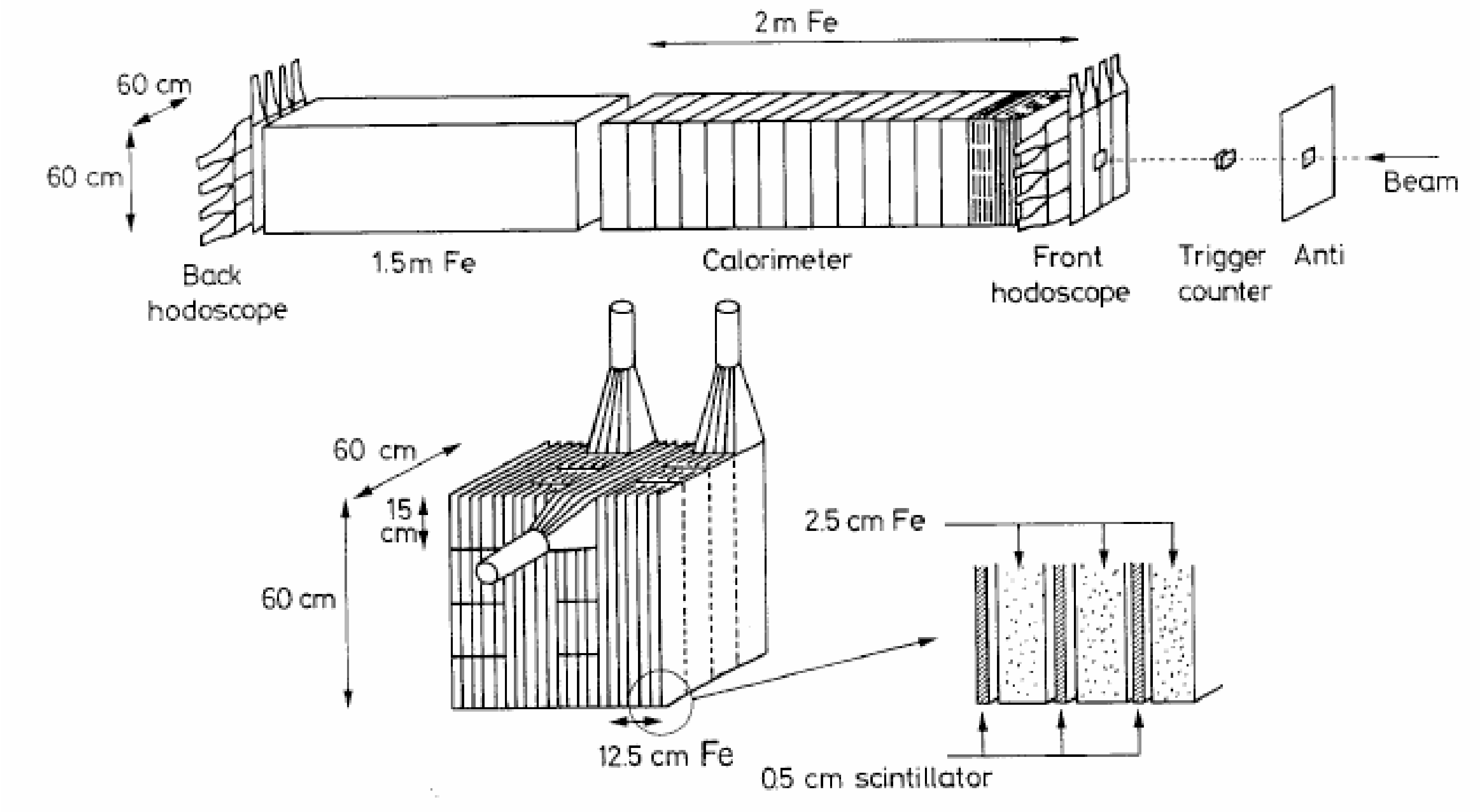
[Wigmans]

CALOR2006

Simple picture is only a useful approximation

The Way to Address These Issues (I)

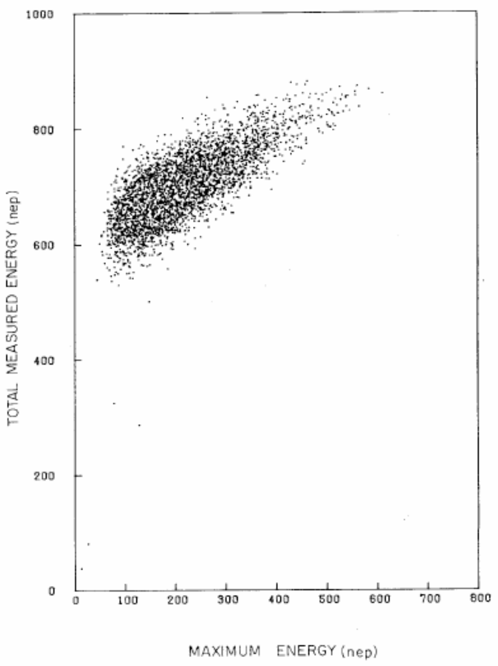
Use Longitudinal Segmentation

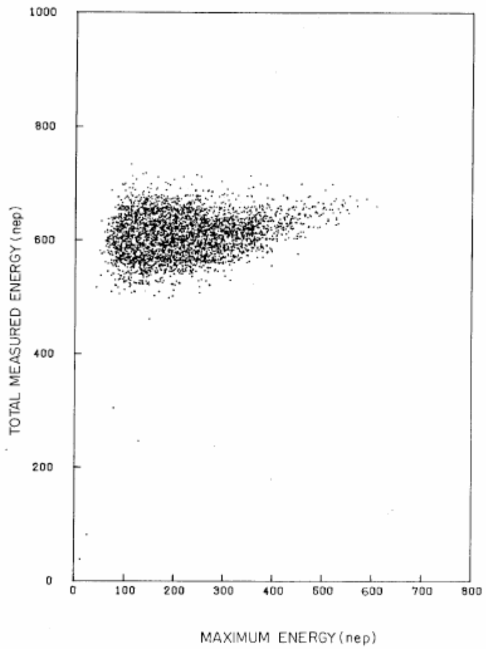


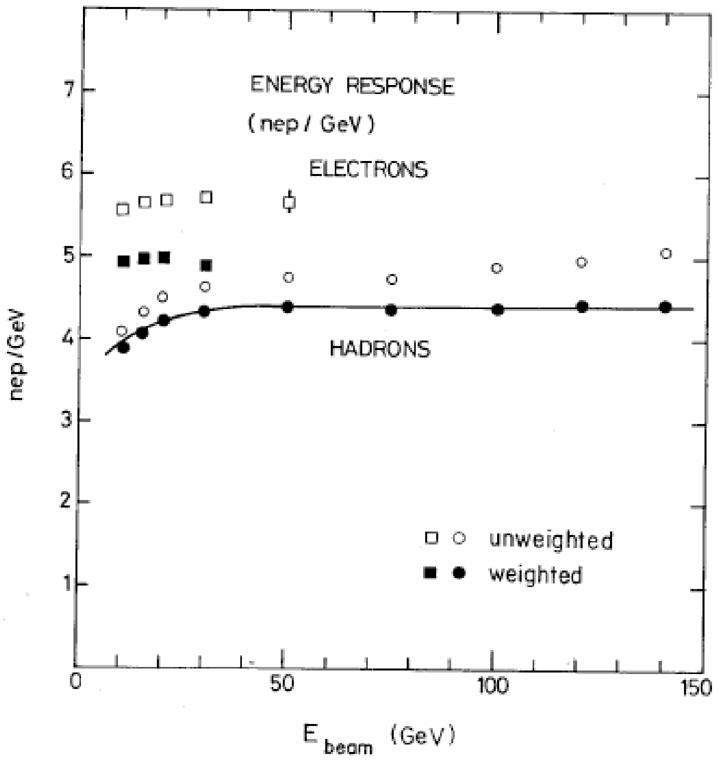
[ABRAMOWICZ]

The Way to Address These Issues (II)

Weight Signals as a Function of Depth to Minimize resolution



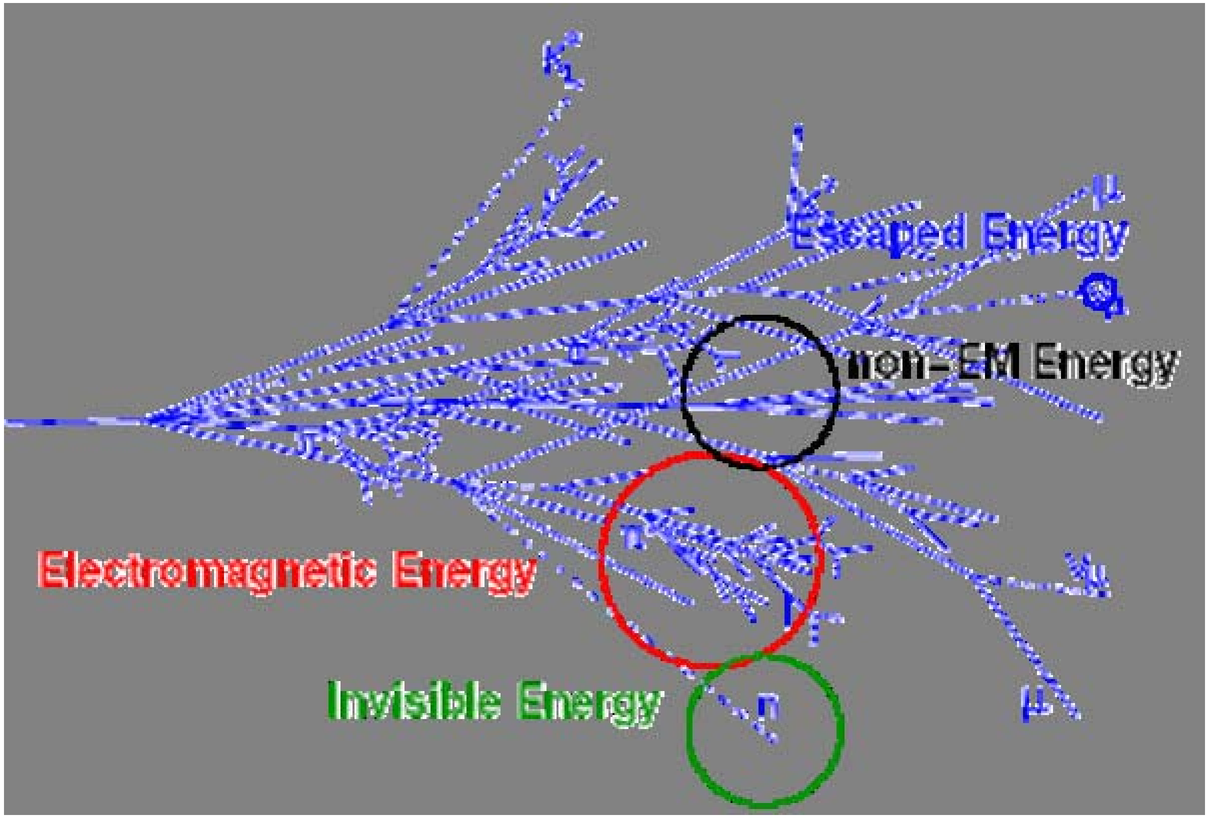




Response to electrons is not equal to the response to hadrons

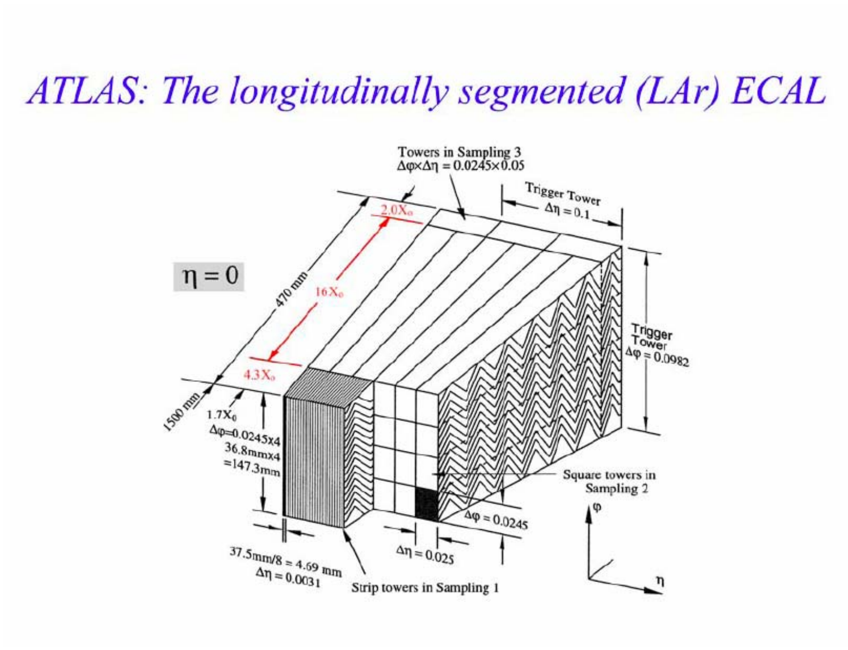
Shower Weights by Segment

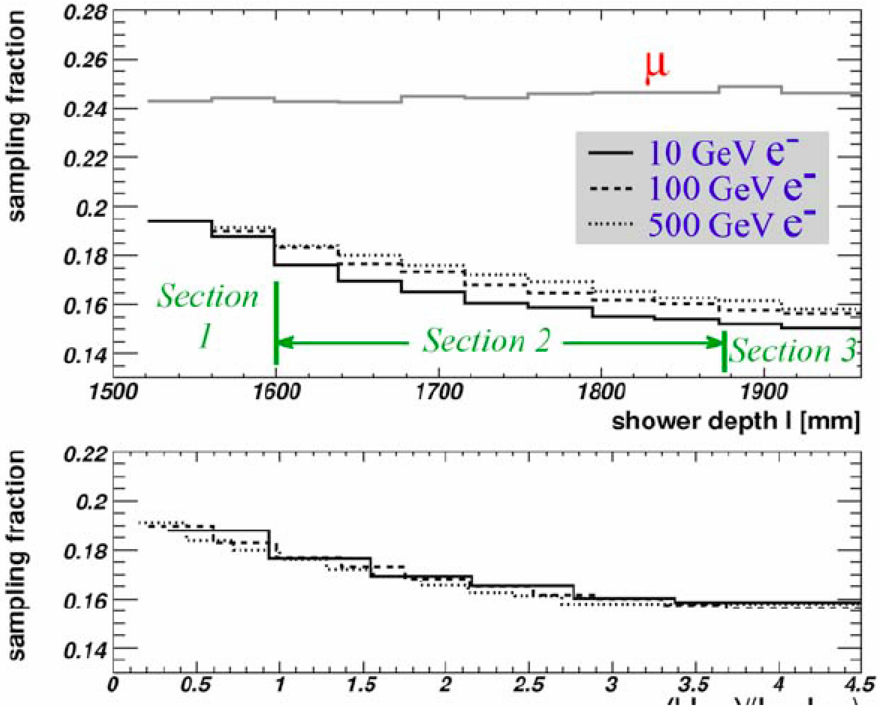
How do we determine the weights?



By Monte Carlo

Example: EGS4 is used to compute segment weights in the ATLAS Liquid Argon Calorimeter


ATLAS: The longitudinally segmented (LAr) ECAL



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

Depth dependent weights are correct for only one type of incident particle (γ's need different weights from e$^{\pm}$) In particular they have the wrong dependence for the electromagnetic component of a hadron cascade.

Use a Monte Carlo Model to obtain Ioniz^{n}(part.) = F(E_{part})

CALOR Code circa 1990-based on codes used for shielding calculations

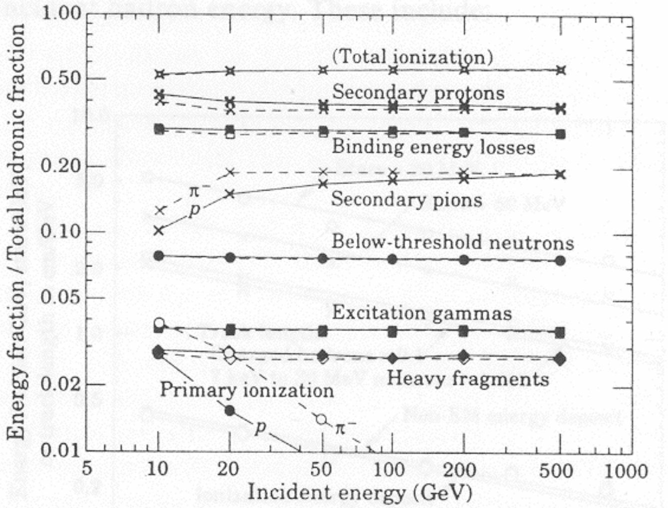


Fig. 5. Hadronic energy loss by various mechanisms in cascades initiated by protons (solid lines) and negative pions (dashed lines) in iron, as simulated with CALOR. Energy deposits are given as fractions of the energy not carried by π^0's. "Total ionization" is the sum of primary and secondary ionization by pions and protons, and is shown to demonstrate the constancy of the sum of all ionization contributions. Exclusive of this subtotal, the sum of the contributions at each energy is unity.

[GABRIEL]

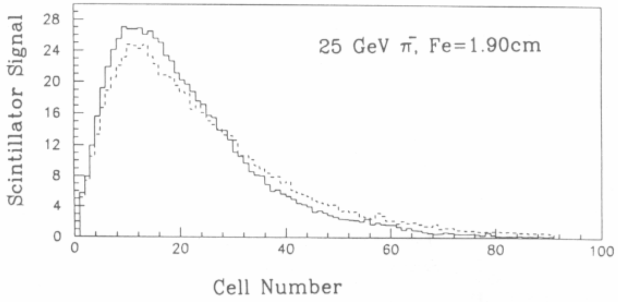


Fig. 9. Longitudinal hadronic shower profile for the homogeneous iron–scintillator configuration (conf. 2) for the 25 GeV pions. The solid histograms are the CALOR89 results and the dotted the test measurements. The histograms are normalized conserving the area under the curves.

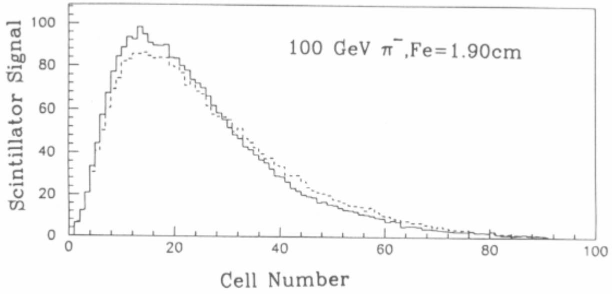
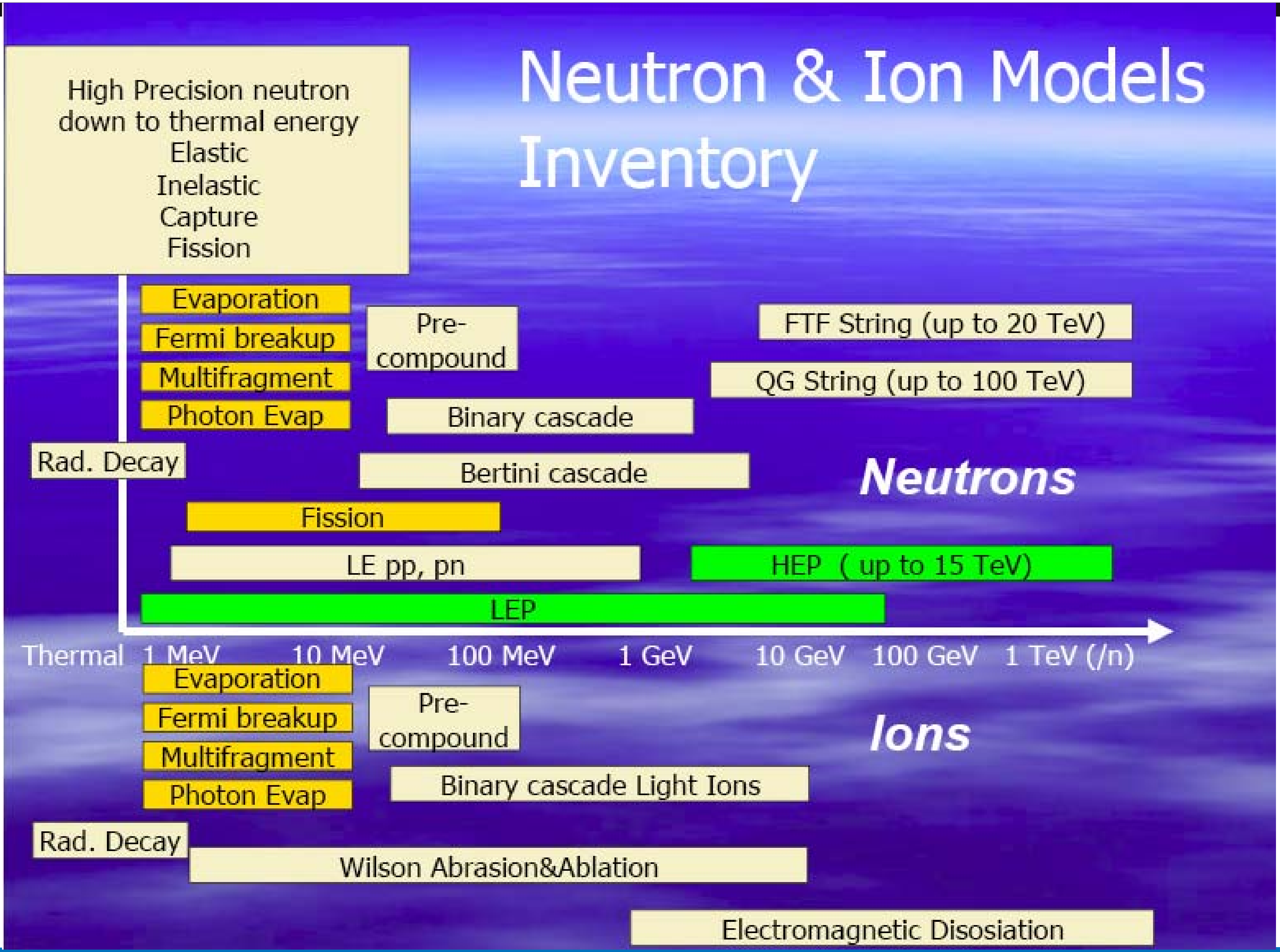


Fig. 10. Longitudinal hadronic shower profile for the homogeneous iron–scintillator configuration (conf. 2) for the 100 GeV pions. The solid histograms are CALOR89 results and the dotted the test measurements. The histograms are normalized conserving the are under the curves.

[JOB]

The Modern Era - GEANT4



Neutron & Ion Models Inventory

High Precision neutron
down to thermal energy
Elastic
Inelastic
Capture
Fission

Neutrons

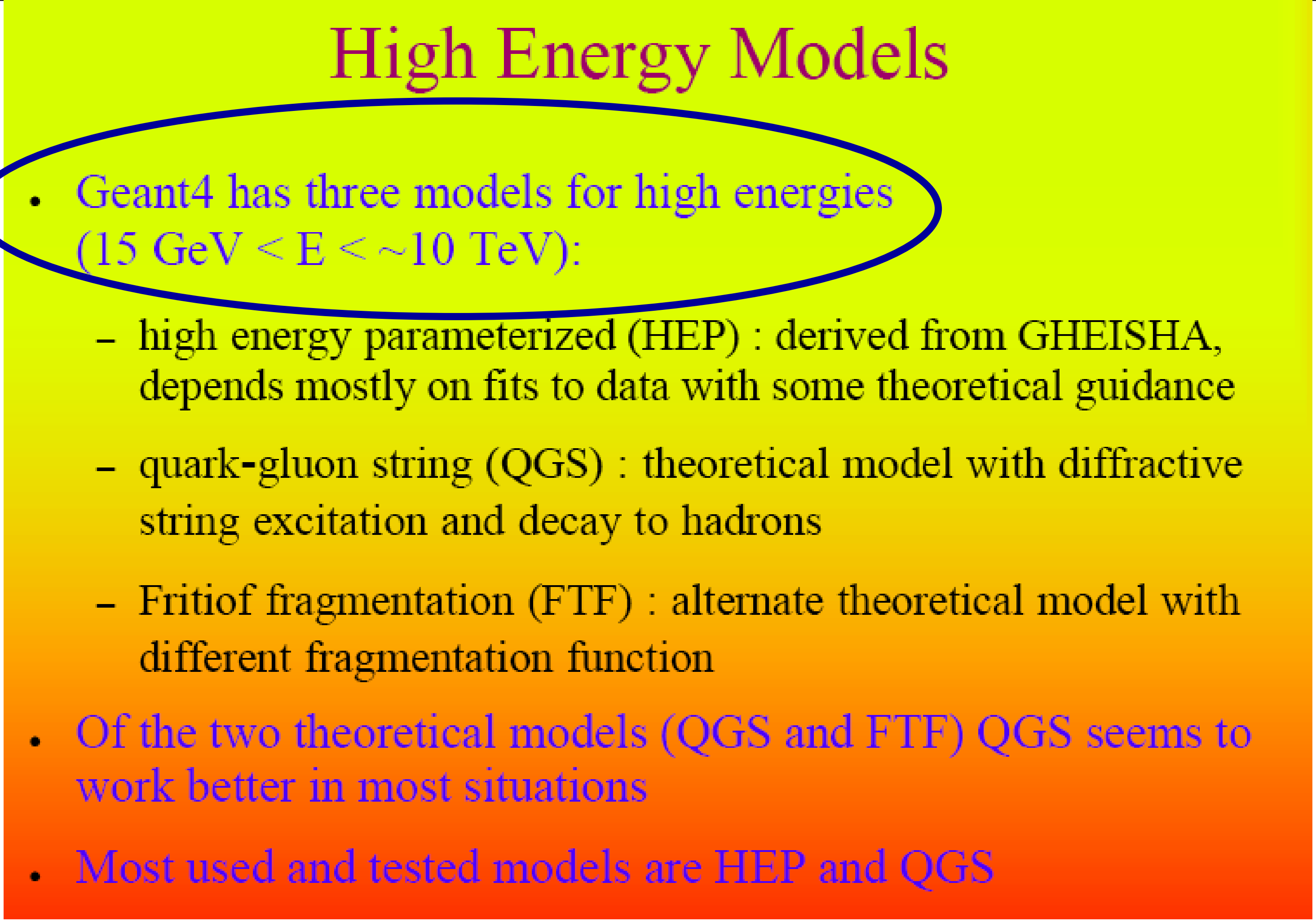
Evaporation
Fermi breakup
Multifragment
Photon Evap
Pre-compound
FTF String (up to 20 TeV)
QG String (up to 100 TeV)
Binary cascade
Rad. Decay
Bertini cascade
Fission
LE pp, pn
HEP (up to 15 TeV)
LEP

Thermal 1 MeV 10 MeV 100 MeV 1 GeV 10 GeV 100 GeV 1 TeV (/n)

Ions

Evaporation
Fermi breakup
Multifragment
Photon Evap
Pre-compound
Binary cascade Light Ions
Rad. Decay
Wilson Abrasion&Ablation
Electromagnetic Disosiation

An essential detail at the LHC



High Energy Models

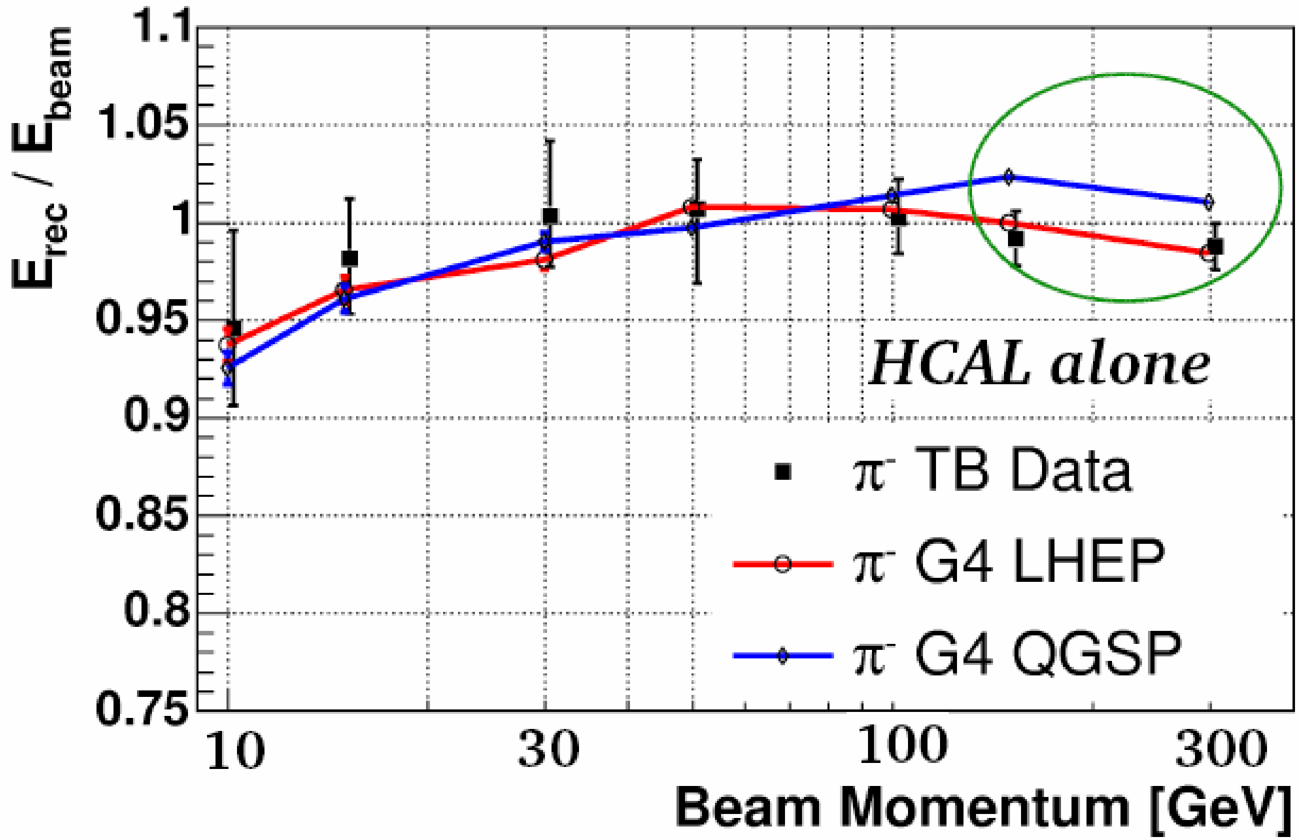
- Geant4 has three models for high energies (15 GeV $< E <$ ~10 TeV):
  - high energy parameterized (HEP) : derived from GHEISHA, depends mostly on fits to data with some theoretical guidance
  - quark-gluon string (QGS) : theoretical model with diffractive string excitation and decay to hadrons
  - 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]

But must validate GEANT4 model

CMS

HCAL alone response to pions



LHEP models better the high energy calorimeter response.

QGSP has less leakage on the back due to shorter shower.

[DAMGOV]

Shower Modeling: GFLASH (An Aside)

But full simulation takes huge amounts of cpu time per event

Therefore must also develop a fast shower simulation

Use parameterizations for the longitudinal and lateral shower development

(See CDFJNIM for details and further references)

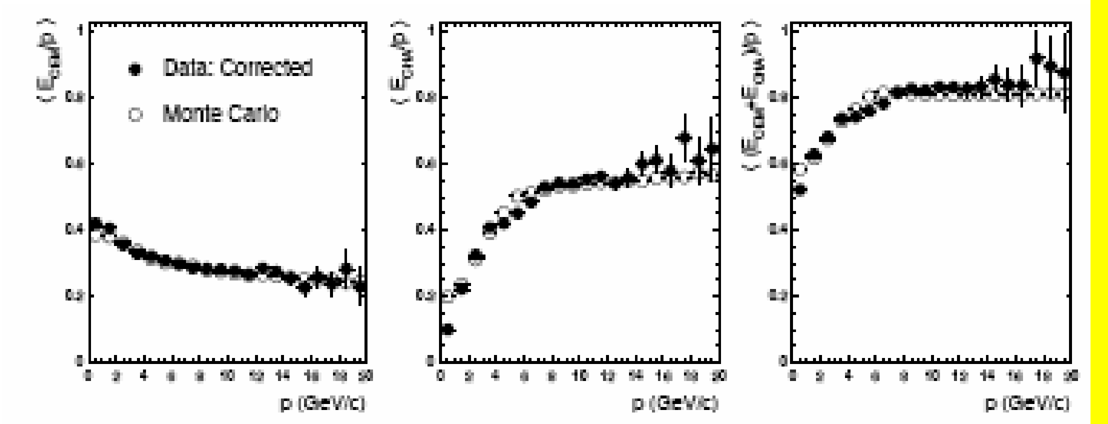
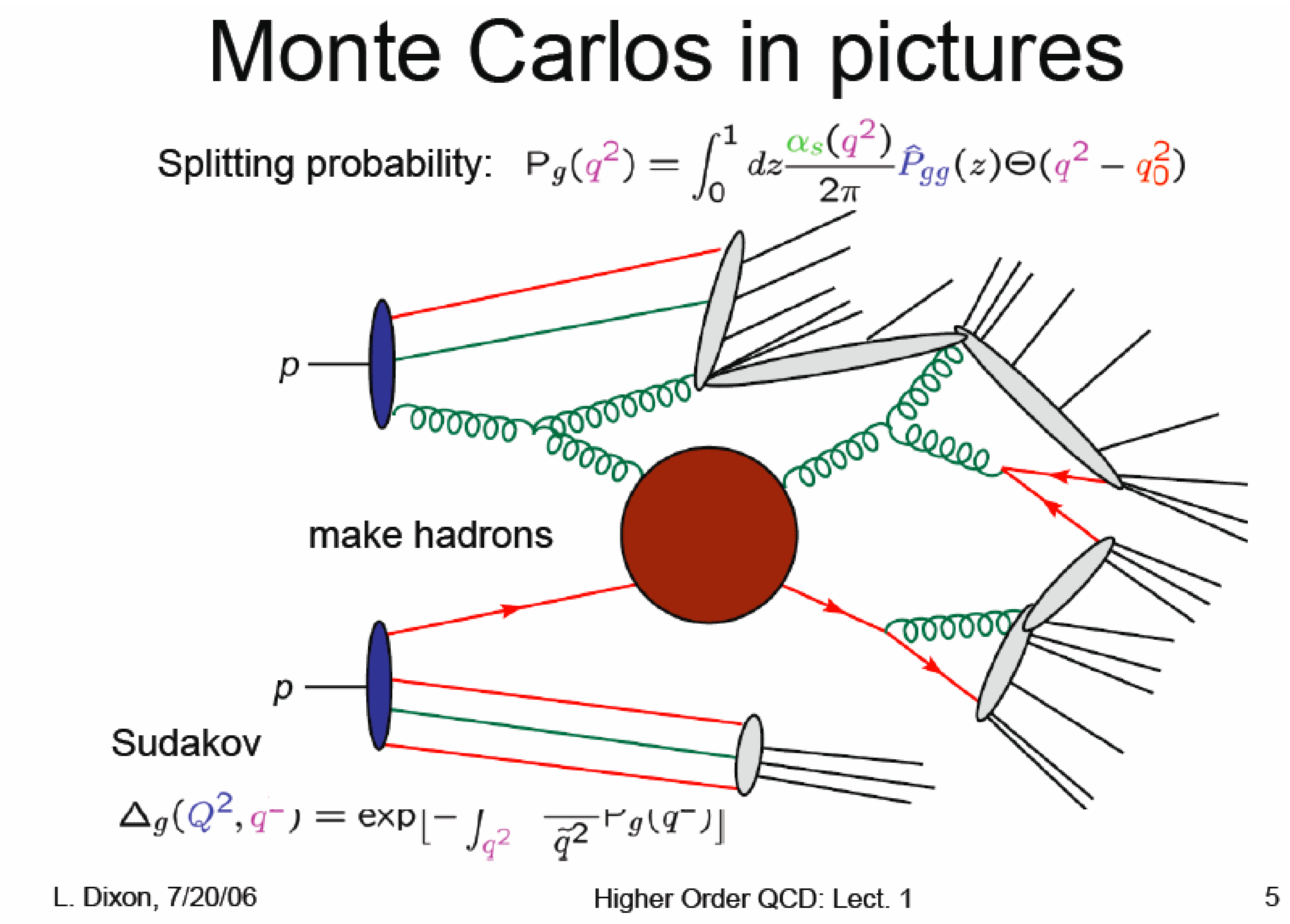


Figure 5: Fractional energy observed in the central calorimeter as a function of incident particle momenta. The top row shows $\langle E_{CEM}/p \rangle$, $\langle E_{CHA}/p \rangle$ and $\langle (E_{CEM}+E_{CHA})/p \rangle$ for data signal (triangles) and background (histogram) and for single track MC simulation (open circles). The bottom row shows the same distributions for data after background subtraction (full circles) and MC simulation (open circles).

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



Monte Carlos in pictures

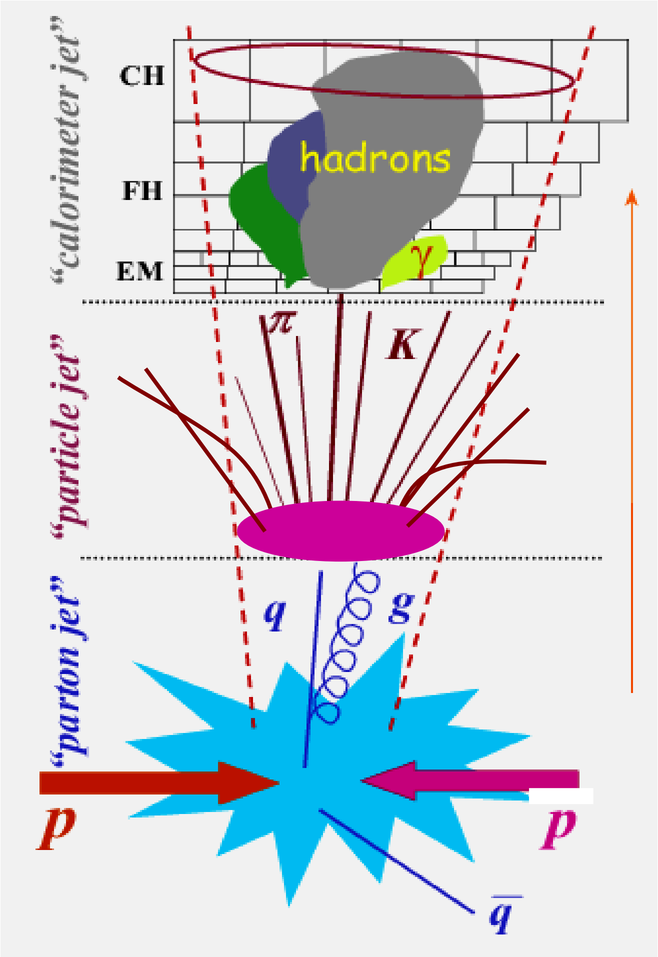
Splitting probability: $\mathrm{P}_g(q^2) = \int_0^1 dz \frac{\alpha_s(q^2)}{2\pi} \hat{P}_{gg}(z) \Theta(q^2 - q_0^2)$

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

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

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

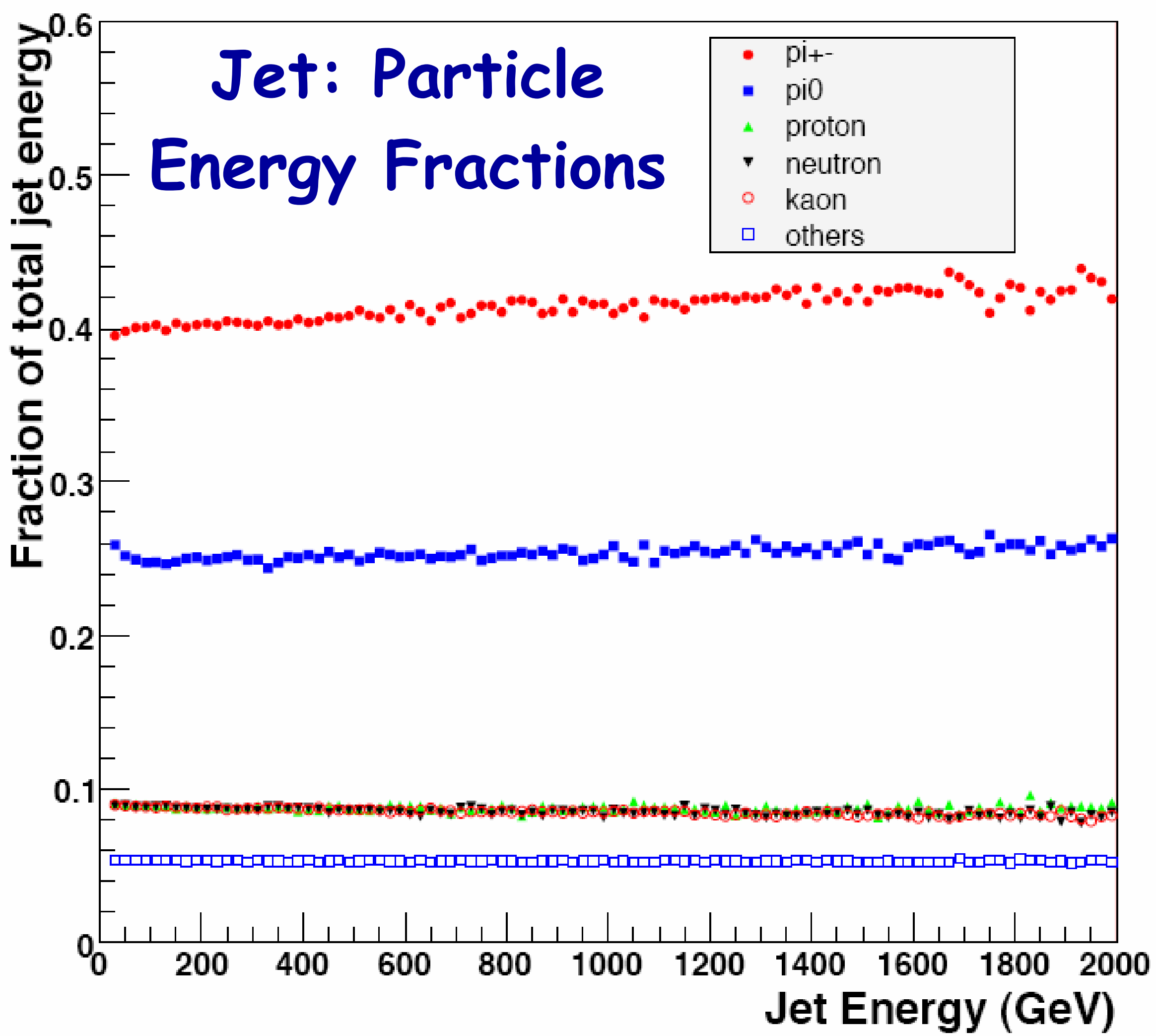
Physics/Simulation/Detector Modeling

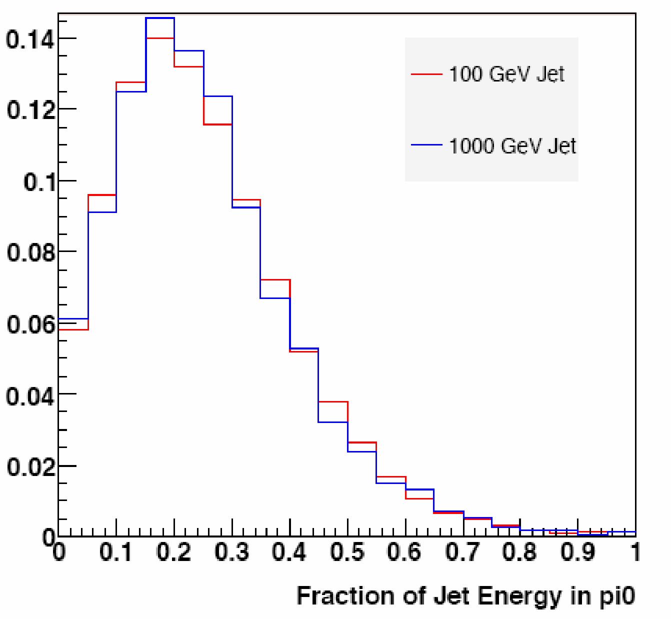


Detection/Event Measurment/Reconstruction and Physics Analysis

Interface Hadronic Shower Model to your favorite event generator

What Does the Monte Carlo Generate?





ATLAS Pythia/GEANT Simulation Studies, in collaboration with A. Gupta

Weighting Schemes

Determine Weights which Account for Jet Fragmentation as well as shower development characteristics of single particles

For this subject, which depends in detail on the absorber and geometrical geometry for the calorimeter I will only discuss ATLAS

{CMS is performing similar studies, many of which are described on the CMS web site}

Calorimeter Segment Weighting:ATLAS Style

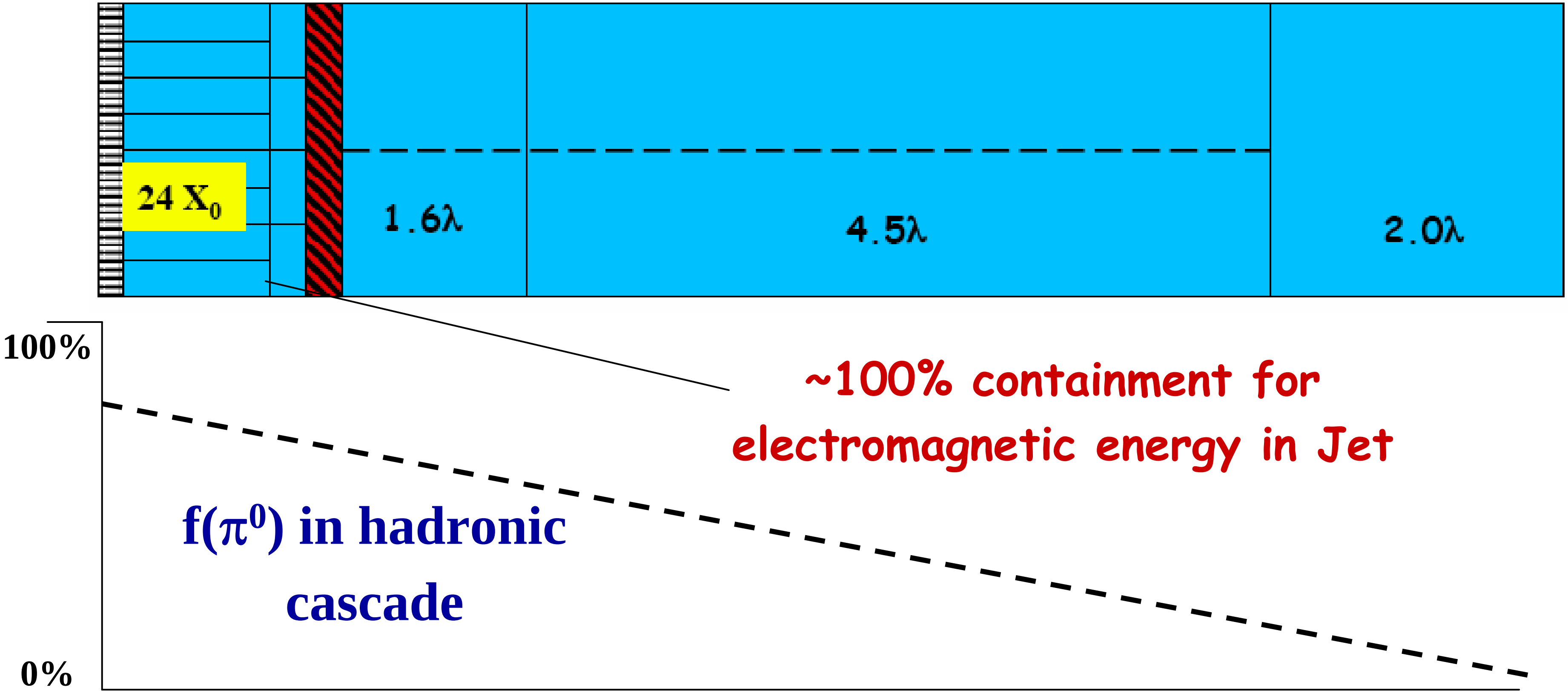
Weight Cells according to Energy Density (as in H1) - but weights are independent of Jet Energy

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

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 ?



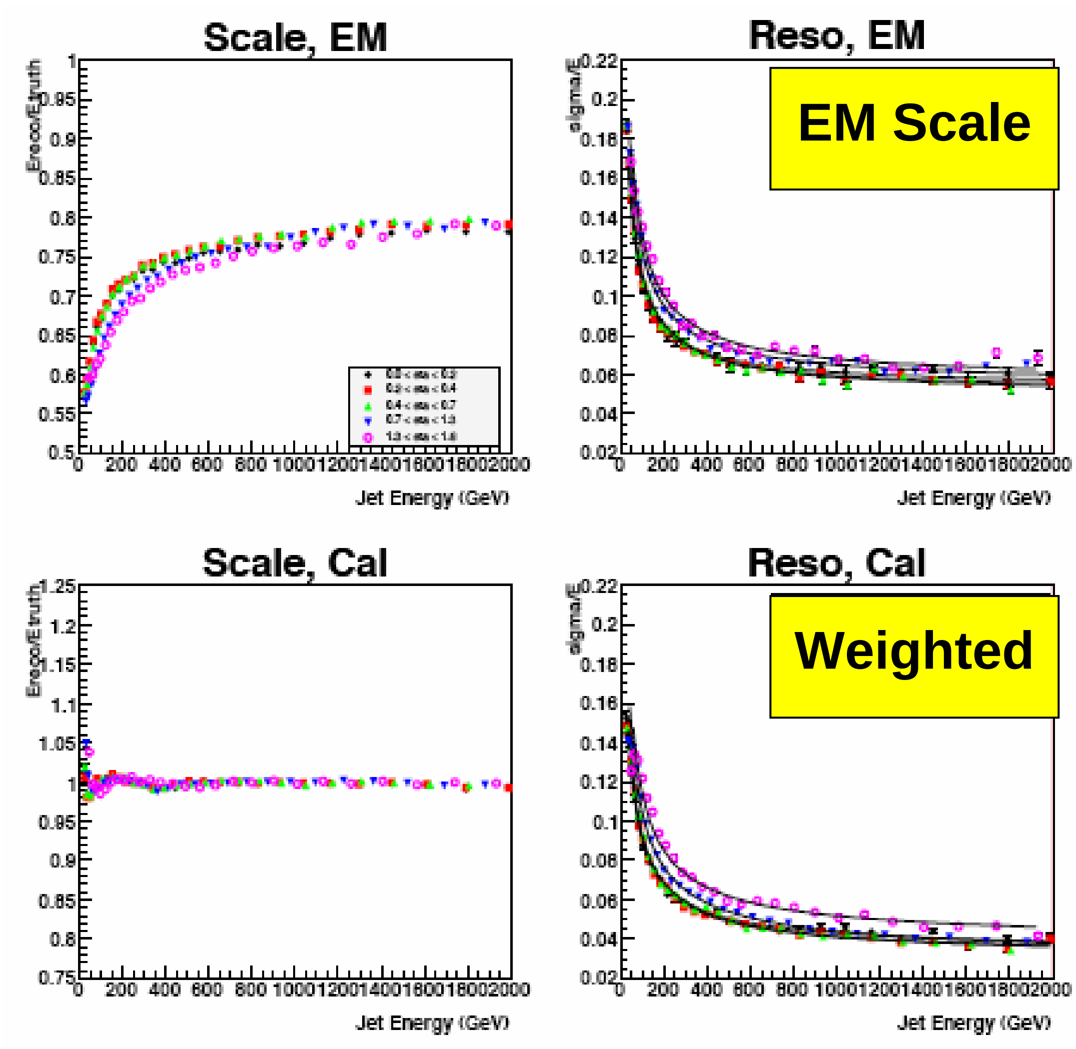
~100% containment for electromagnetic energy in Jet

$f(\pi^0)$ in hadronic cascade

A Preliminary Result

Even this simple weighting greatly improves linearity and resolution

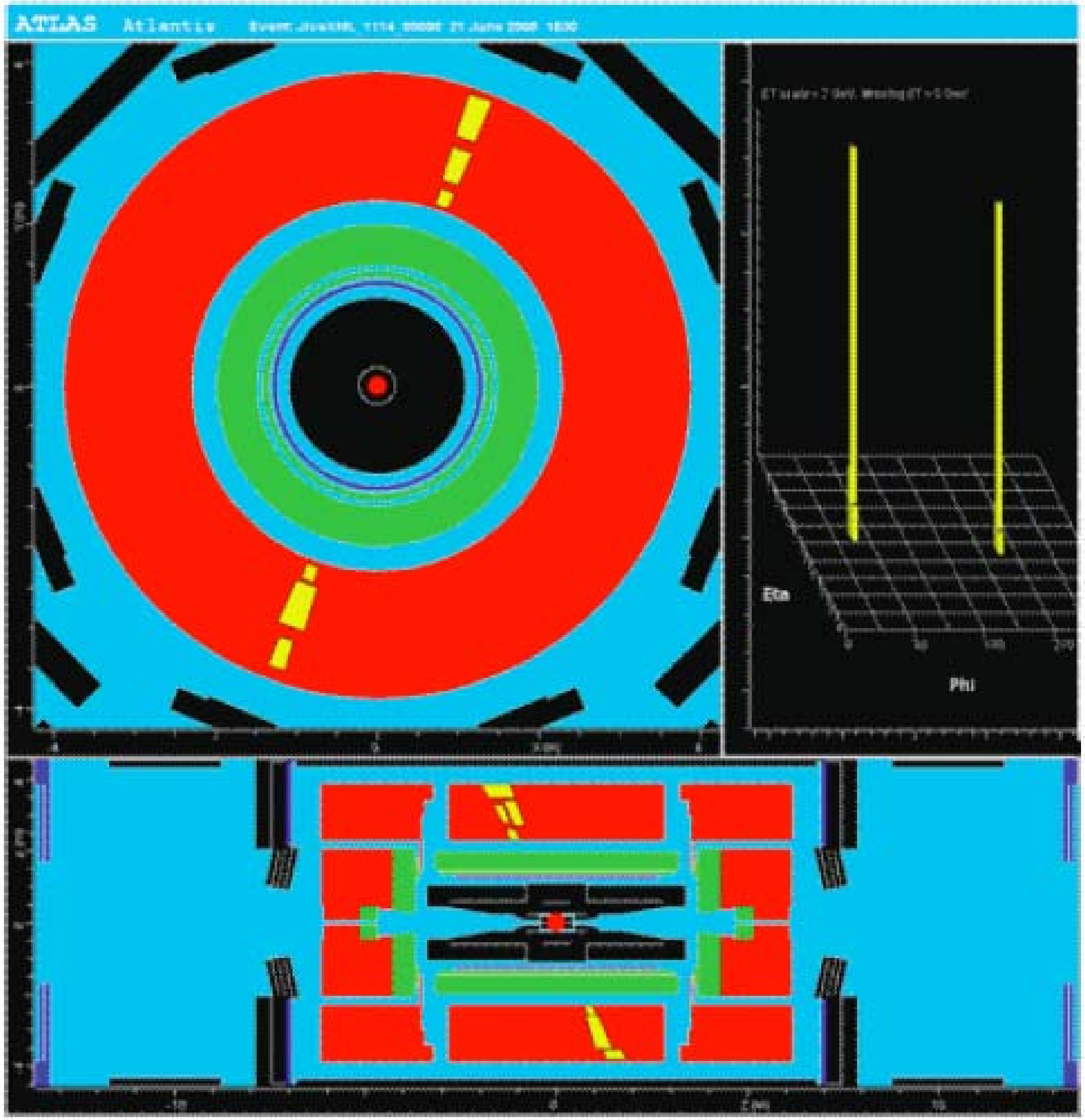
The other approaches also work well and the merits of the different schemes are being discussed



Summary

- Hadron calorimeters may be "blunt objects" but without them many of the physics processes of the LHC will be lost to us
- The reconstruction of jet energies in calorimeters is one of the more complex analysis procedures of any at the LHC - complicated by their intrinsic non-uniformity ($e/h \neq 1$)
- Precision reconstruction of jet energies and the reconstruction of the associated partons is not possible without segmented calorimeters and complex and tuned Monte Carlo codes
- On the other hand, SUSY will first be signaled by high P_t Jets and Missing Transverse Energy in these detectors

A Cosmic Ray in The ATLAS Calorimeter



Some Reference Material

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- **[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**