#### **CALORIMETRY**

A short course on the most important instruments used in particle physics

Richard Wigmans (Texas Tech University)

Lecture 3

Calibration of calorimeters
Calorimetry at the LHC

#### Calibration

The pitfalls of longitudinal segmentation

#### Calibration of longitudinally segmented devices

- Imagine a Cherenkov calorimeter, e.g. lead glass

- High-energy electrons develop showers in this

- On average, 10 p.e. per GeV deposited energy 100 GeV e gives a signal of 1000 p.e., 20 GeV e gives a signal of 200 p.e., etc.

- Shower particles < 0.3 MeV give NO Č light

- The relative contribution of such particles increases with depth

- If this detector is cut into 3 parts, the relationship between deposited energy and resulting signal is then, e.g.

 $I:15 \ p.e./GeV$   $II:10 \ p.e./GeV$   $III:5 \ p.e./GeV$ 

These constants have been derived for 100 GeV e, which deposit, on average, 30/40/30% in these 3 parts, and thus give, on average, a signal of 1000 p.e., as before

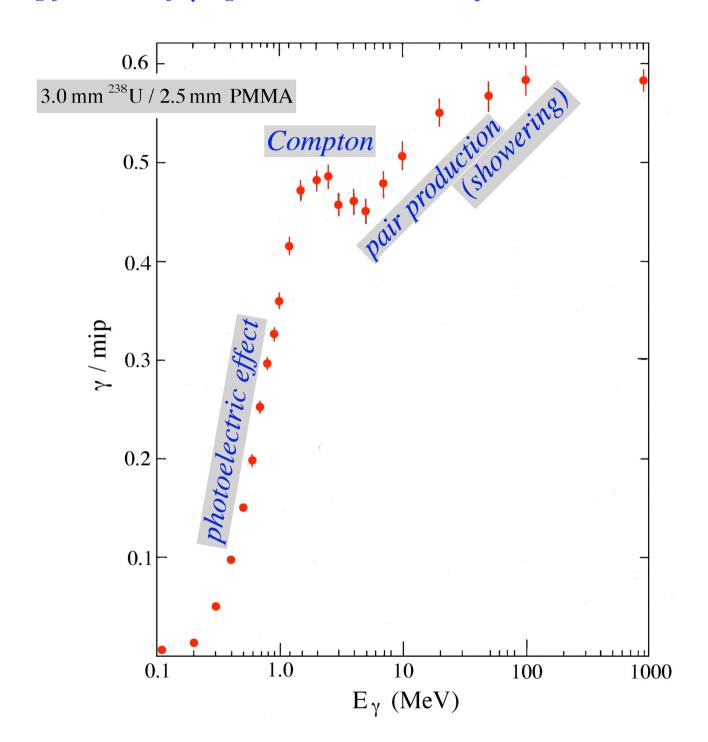
- However, a low-energy shower deposits most of its energy in part I. Based on these calibration constants, its energy is OVERESTIMATED
- And for an em shower starting in section III (e.g.  $\gamma$  from  $\pi^{\circ}$  decay), the energy is systematically UNDERESTIMATED
  - Non-linearity + energy dependence on starting point shower

## Calibration of calorimeter systems

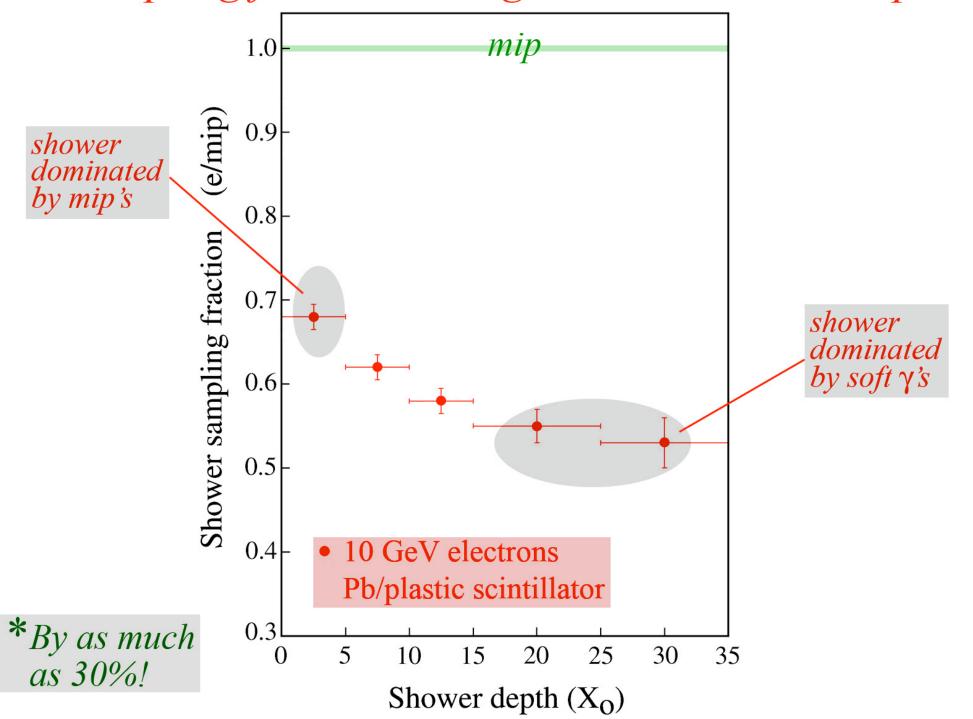
- Determine relationship between *signal* (pC, p.e.) and *energy* (GeV)
- Fundamental problem in sampling calorimeters:
  Different shower components are sampled differently
  Shower composition changes as shower develops
  - → Sampling fraction changes with the shower age (also E dependent)

How to intercalibrate the sections of a longitudinally segmented calorimeter?

#### Sampling fraction of \u03c4s, generated at random points inside a calorimeter

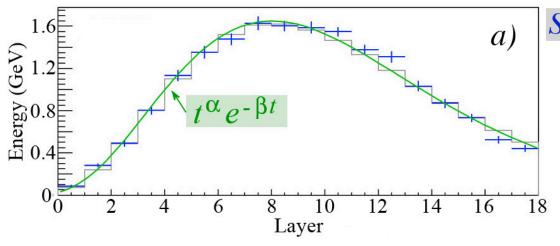


## The sampling fraction changes as shower develops\*



#### Calibration misery of longitudinally segmented devices

Example: AMS (em showers!)



Source: NIM A490 (2002) 132

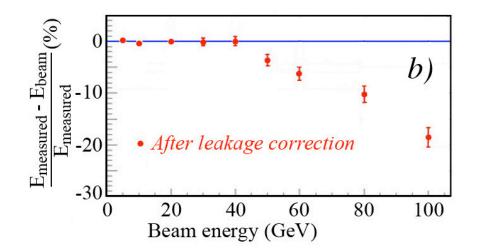
Pb/scintillating fiber (18 layers)
Calibrated with mip's:
11.7 MeV/layer

Leakage estimated from fit to measured shower profile

#### However:

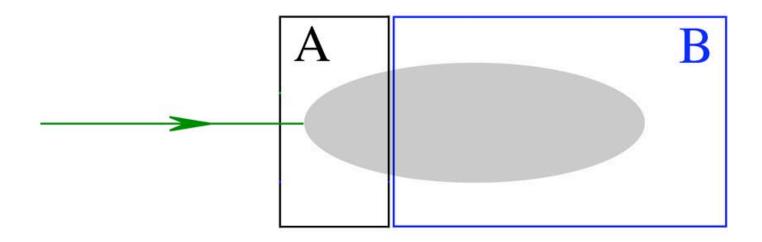
In em shower, signal per GeV decreases as shower develops

(leakage) energy based on measured signals underestimates reality



Required very elaborate MC simulations to solve, since effects depend on energy and direction incoming particle

#### A widely used technique for calibrating segmented devices



Minimize 
$$Q = \sum_{j=1}^{N} \left[ E - A \sum_{i=1}^{n} S_{ij}^{A} - B \sum_{i=1}^{n} S_{ij}^{B} \right]^{2}$$

 $\longrightarrow$  Determine A,B

## Calibrating longitudinally segmented calorimeters

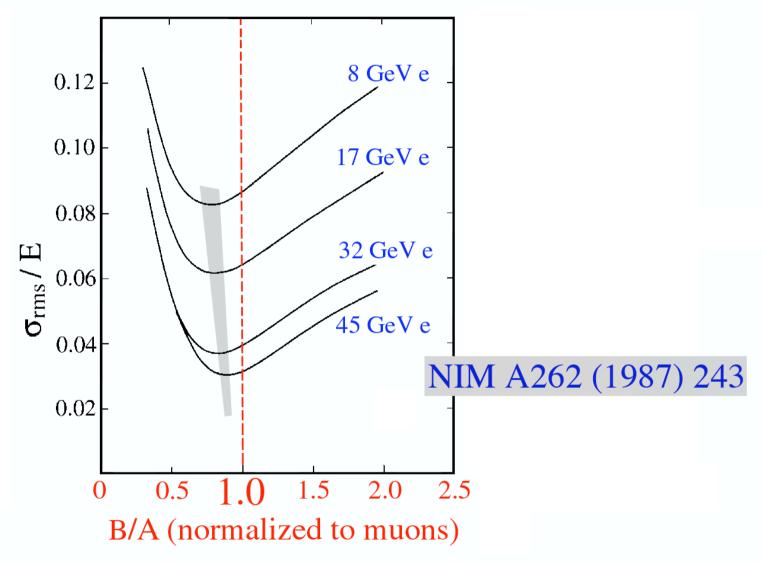


FIG. 6.2. The fractional width  $\sigma/E$  of the signal distributions for electrons of different energies, as a function of the value of the intercalibration constant B/A of the HELIOS calorimeter system. The dashed line corresponds to the intercalibration constant derived from muon measurements [Ake 87].

#### Results of miscalibration: Non-linearity

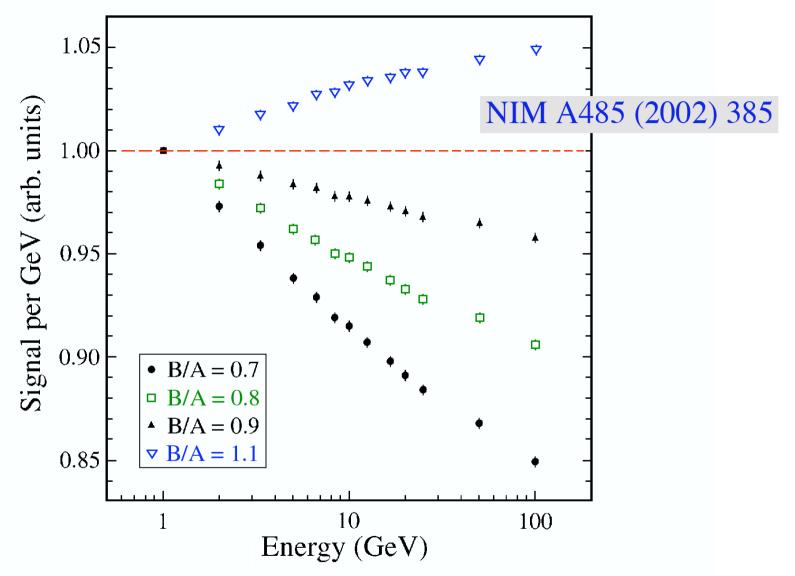


Figure 12: Signal nonlinearity for electrons resulting from miscalibration of a longitudinally segmented calorimeter. The total calorimeter response (average signal per unit of energy) is given for 3 different values of the ratio of the calibration constants for the 2 longitudinal segments, B/A. See text for details.

## Results of miscalibration: Mass dependence

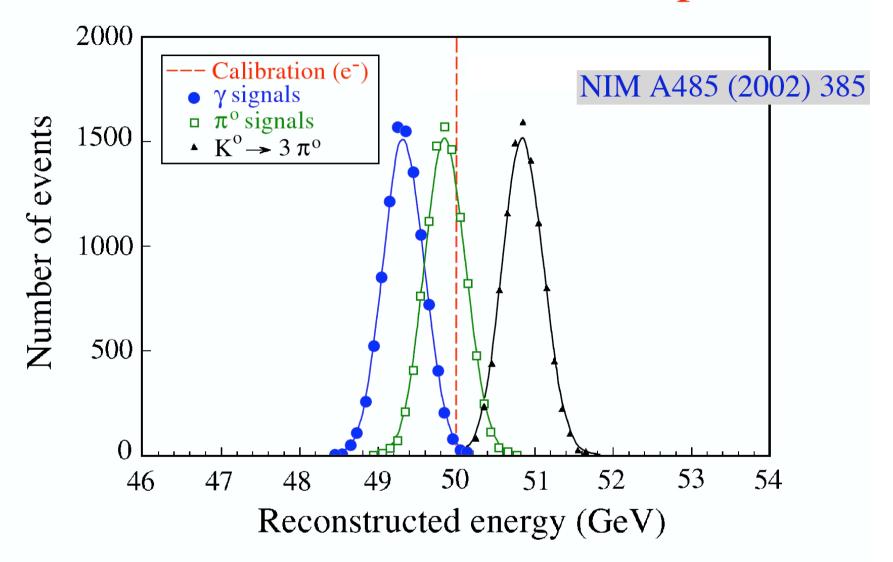


Figure 14: Signal distributions for  $\gamma$ s and various hadrons decaying into all- $\gamma$  final states. All particles have the same nominal energy and the detector, which has an intrinsic resolution of 0.5% for em showers of this energy, was calibrated with electrons using B/A=0.8. See text for details.

#### A comment for those who want to "optimize" energy resolution

Energy resolution = precision with which the energy of a particle or jet showering in the calorimeter can be determined

A narrow signal distribution may ONLY be interpreted as a good energy resolution if it is centered around the correct energy value

Therefore, signal linearity is an integral aspect of good energy resolution

#### Intercalibrating sections by minimizing total signal width

#### **GIVES WRONG RESULTS!**

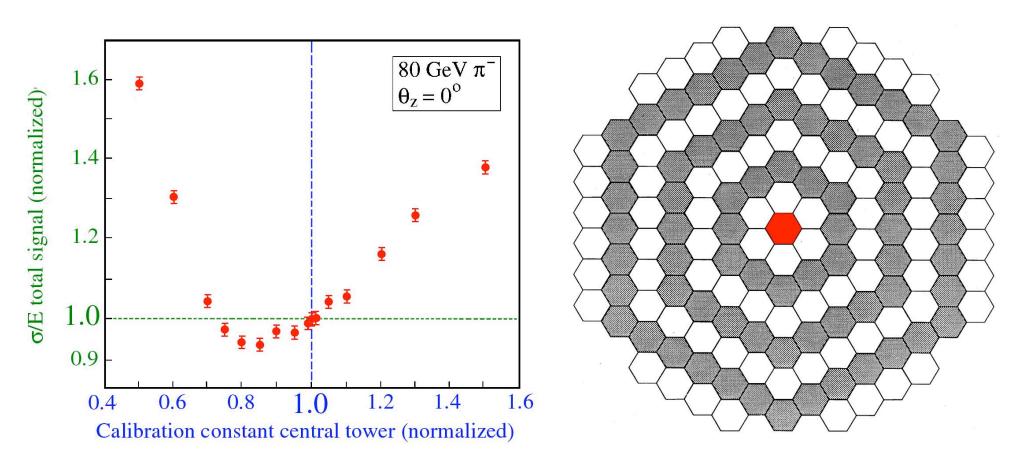


Figure 11: The fractional width,  $\sigma/E$ , of the signal distribution for 80 GeV  $\pi^-$  in the SPACAL detector as a function of the weighting factor applied to signals from the central calorimeter tower into which the pion beam was steered. The calorimeter towers were calibrated with high-energy electrons [7].

From: NIM A485 (2002) 385.

#### Hadronic showers

- Large fraction of energy is deposited through em showers  $(\pi^{o})$
- Starting point of the em component(s) fluctuates wildly
- Non-em shower energy primarily deposited by
  - spallation protons
  - evaporation neutrons

These particles are also sampled very differently than mip's

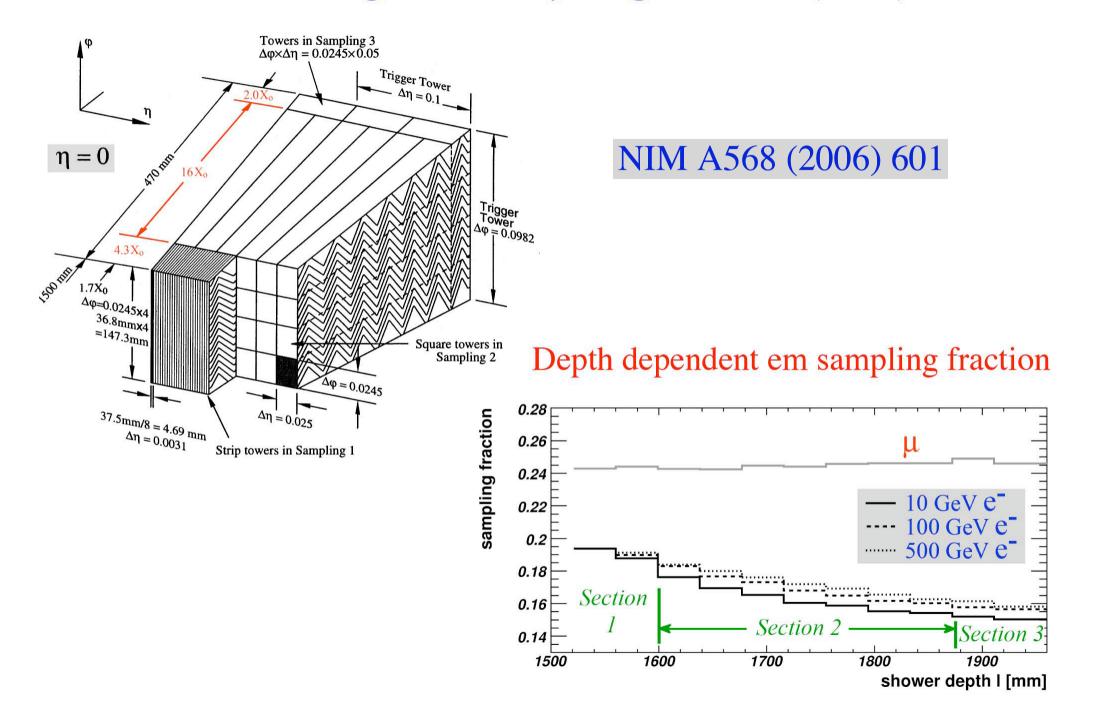
• In addition, the calorimeter response to the em/non-em components is not the same (e/h  $\neq$  1, non-compensation)

#### So what to do?

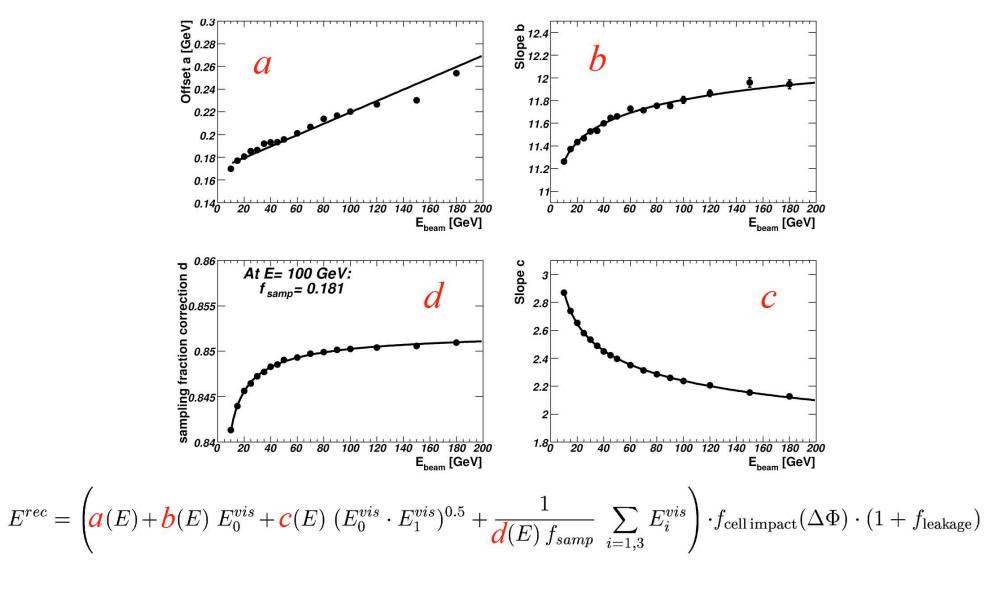
• Determine the calibration constants of the longitudinal segments on the basis of

Monte Carlo simulations!!!

## ATLAS: The longitudinally segmented (LAr) ECAL



## ATLAS: Energy reconstruction ECAL



#### Monte Carlo simulations of hadronic shower development

- Reliable simulations are of crucial importance for detector development, optimization and understanding
- Simulations based on incorrect/incomplete input of the important physics processes cannot be expected to produce meaningful results (regardless of your computing power!)
- In shower development, most of the energy is deposited in the very last stages. In multi-GeV electromagnetic showers, a large fraction of the energy is deposited by electrons with energies in the keV range.

  As we saw earlier, this has important consequences for em calorimetry

In multi-GeV hadronic showers, most of the energy is deposit in the nuclear stage: MeV-type nuclear reactions, nuclear deexcitation, transport of p.n.

Therefore, it is crucial to simulate that part correctly.

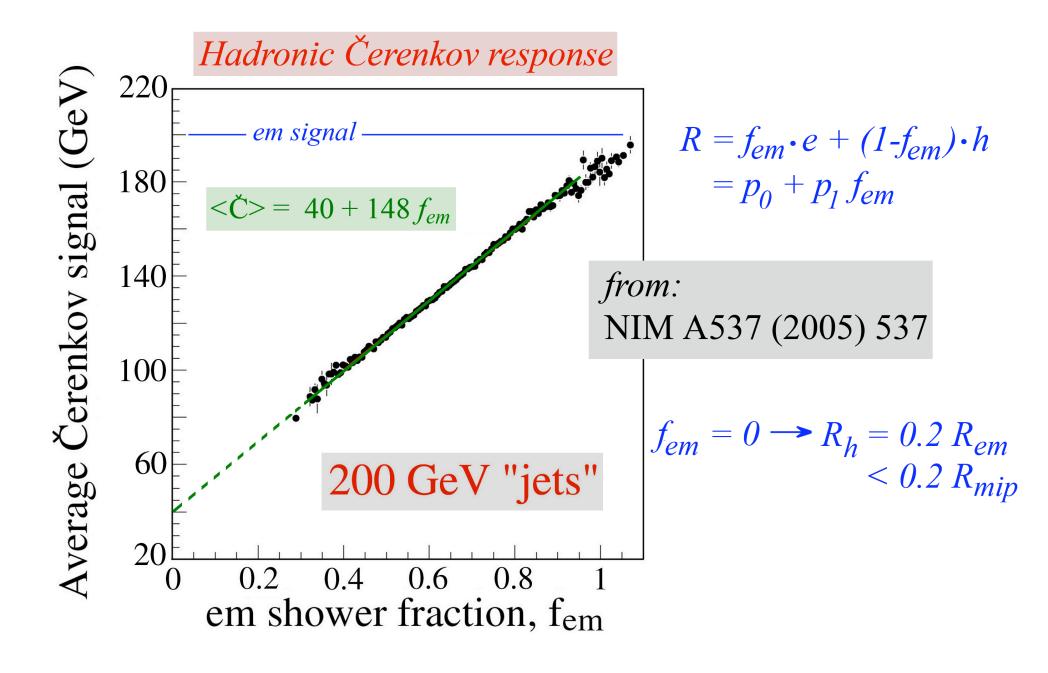
#### The non-electromagnetic shower component (1)

How do we know that protons dominate (~80%!) of the non-em signals?

1) Because of the small hadronic signals (i.e. large e/h values) of calorimeters that are blind to these protons.

In quartz-fiber calorimeters (n = 1.46), only particles with  $\beta > 0.69$  emit Čerenkov light, i.e.  $E_{kin} > 0.2$  MeV for electrons and > 350 MeV for protons

## DREAM: Measure $f_{em}$ event-by-event



#### The non-electromagnetic shower component (2)

How do we know that protons dominate (~80%!) of the non-em signals?

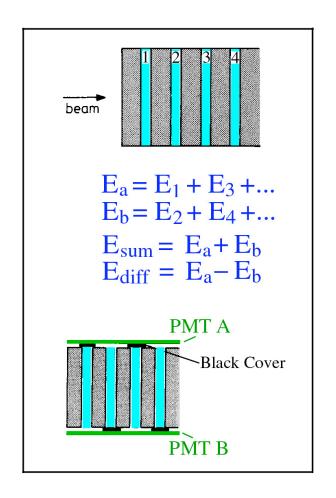
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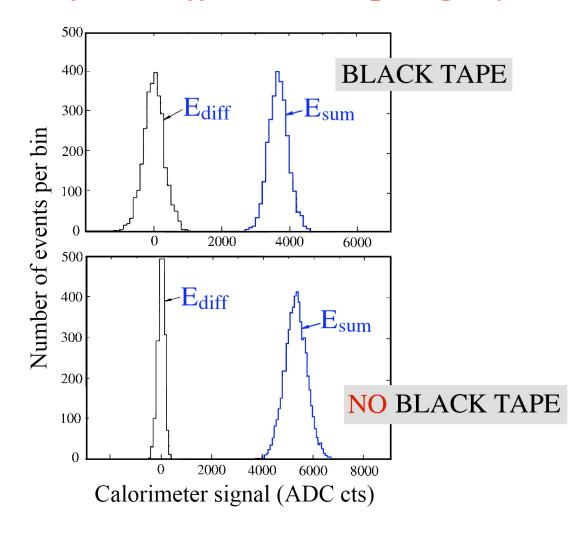
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2) Because of the absence of correlations between the signals from adjacent active layers in fine-sampling hadron calorimeters

The calorimeter from the example had 0.06  $\lambda_{int}$  thick sampling layers. A mip would lose on average 12.7 MeV traversing these layers.

#### Correlations between signals from different sampling layers





Fluctuations	10 mm lead	/ 2.5 mm plastic
(%)	Electrons	Pions
$\sigma_{ m A},\sigma_{ m B}$	$36.0\pm1.0$	$60.5 \pm 1.0$
$\sigma_{ m sum}$	$24.5 \pm 1.0$	$43.5 \pm 1.0$
$\sigma_{ m diff}$	$25.8 \pm 1.0$	$42.3 \pm 1.0$

*from:* NIM A290 (1990) 335

#### The crucial elements of hadronic shower simulations (2)

#### Where do these protons come from?

#### 1) Nuclear spallation.

Spallation protons typically carry  $\sim 100$  MeV kinetic energy. Their range is typically of the order of the thickness of sampling layers in hadron calorimeters.

#### 2) Nuclear reactions induced by neutrons, e.g. (n,p) reactions

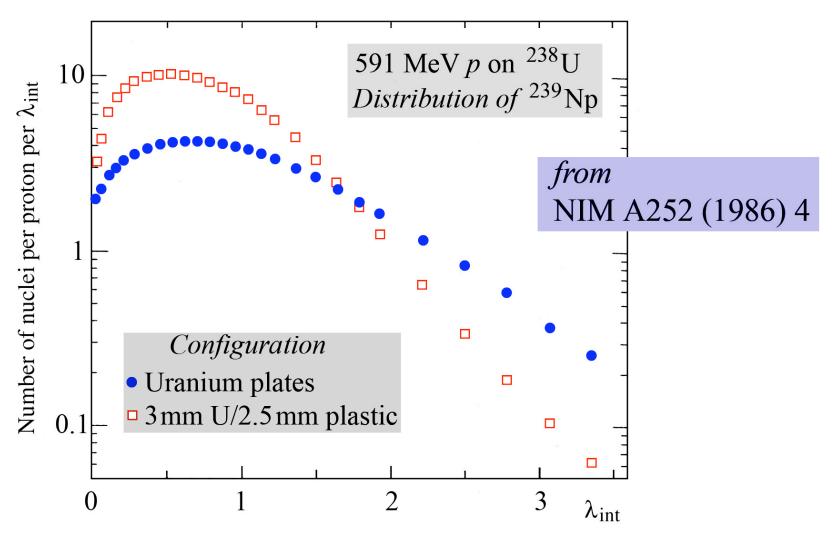
These protons have kinetic energies comparable to those of the (evaporation) neutrons that generated them (< 10 MeV)

These neutrons outnumber spallation protons by an order of magnitude

Measurements of neutron production in hadronic showers:

> 40 per GeV in some materials (NIM A252 (1986) 4)

#### The importance of hydrogen in the absorbing structure



(Nuclear evaporation) neutrons are typically produced with  $E_{kin} \sim$  few MeV. Elastic n-p scattering slows these neutrons down.

<sup>239</sup>Np is produced by thermal neutron capture in uranium

## The special role of neutrons in calorimetry

In calorimeters with hydrogenous active material, neutrons lose a major fraction of their kinetic energy through elastic *n-p* scattering in that material.

The recoil protons may contribute to the signals.

Therefore, the *neutron component may be very efficiently sampled* in such calorimeters. The sampling fraction may be much larger than for the other shower particles.

This is the key element of *compensation*.

## GEANT4 based simulations of hadron showers

• MC simulations are still not in a state in which they can be considered a useful tool for design and optimization of detectors

Crucial experimental data sets (ZEUS-Pb, ZEUS-noncorrelation, U-plastic) have never been (even approximately) reproduced by GEANT and (therefore) tend to be ignored by GEANT developers

## A few recent quotes from the published literature: On pion detection in ATLAS: NIM A607 (2010) 372

The measurements were compared to simulated results obtained using Geant 4. The simulation predicts a larger response and a lower energy resolution than what was measured.

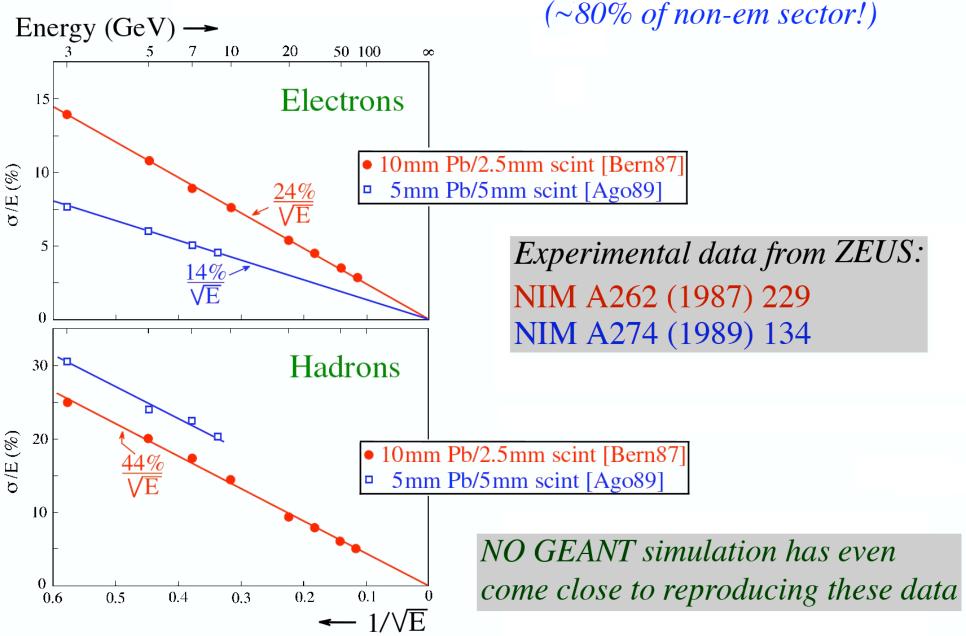
#### On hadronic shower profiles (ATLAS): NIM A615 (2010) 158

The experimental data have been compared with the results of GEANT4 simulation, using two basic physics lists, LHEP and QGSP, as well as extensions where the Bertini intra-nuclear cascade is used. Neither of these physics lists is able to reproduce the data in the whole energy range satisfactorily,

#### Benchmark data for hadronic shower MC simulations

Sensitive test for correct implementation of nuclear effects

(~80% of non-em sector!)



# Aspects of the calibration of Calorimeter systems at colliders

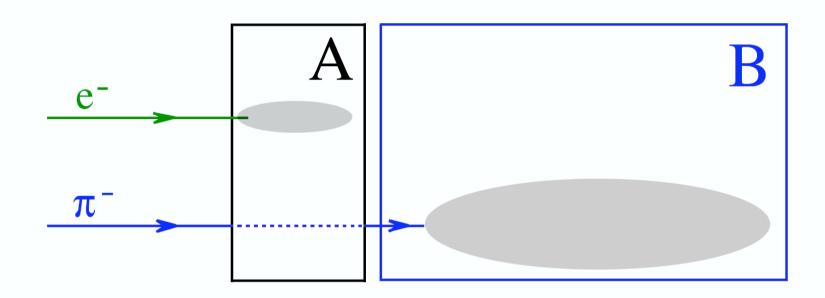
(developed without meaningful guidance from MC)

- Minimizing total width of signal distributions B/A < 1
  - non-linearity, systematic mismeasurement of energy, ...
- Each section its own particles (calibrate hadronic section with pions that penetrate the em section without starting a shower) B/A > 1
- Use the em scale for all sections B/A = 1

#### General comment:

Energy resolution is determined by event-to-event fluctuations Therefore, application of overall weighting factors to signals from different detector sections has NO effect on energy resolution

# Another method used in practice Calibrate each section with its own particles



- Problem: How about hadrons that start shower in section A?
  - Energy systematically mismeasured depending on *e/h* values of sections A,B
  - Reconstructed energy depends on starting point of shower

## Wrong B/A: Response depends on starting point

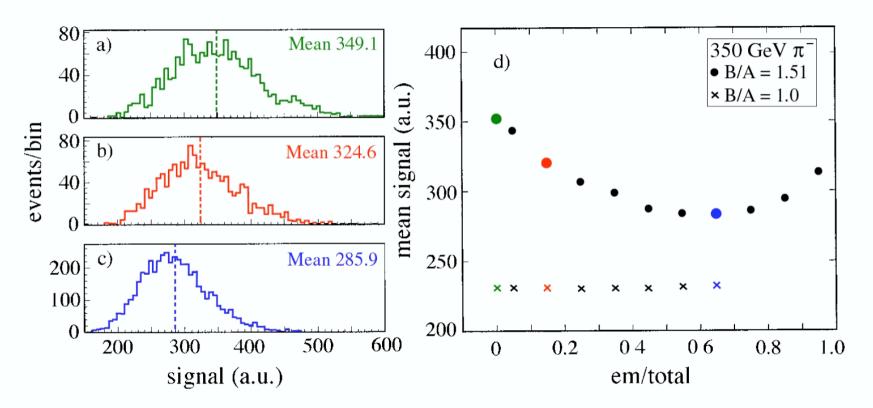


FIG. 6.10. Signal distributions for 350 GeV pion showers in a longitudinally segmented quartz-fiber calorimeter, for events in which different fractions of the (unweighted) shower energy were recorded in the em calorimeter section. Shown are distributions for which this fraction was compatible to zero (a), 10-20% (b), or 60-80% (c). The average calorimeter signal for 350 GeV pions, as a function of this fraction, is shown in diagram (d). The calorimeter was calibrated on the basis of B/A=1.51 in all these cases, as required for reconstructing the energy of 350 GeV pions that penetrated the em compartment without undergoing a strong interaction. Diagram (d) also contains results (the crosses) obtained for a calorimeter calibration on the basis of B/A=1.

From: NIM A409 (1998) 621

Different depth segments calibrated in the same way (B/A = 1)

In this way, one may avoid some of the problems encountered for  $B/A \neq 1$  (non-linearity, reconstructed energy depends on starting point shower,...)

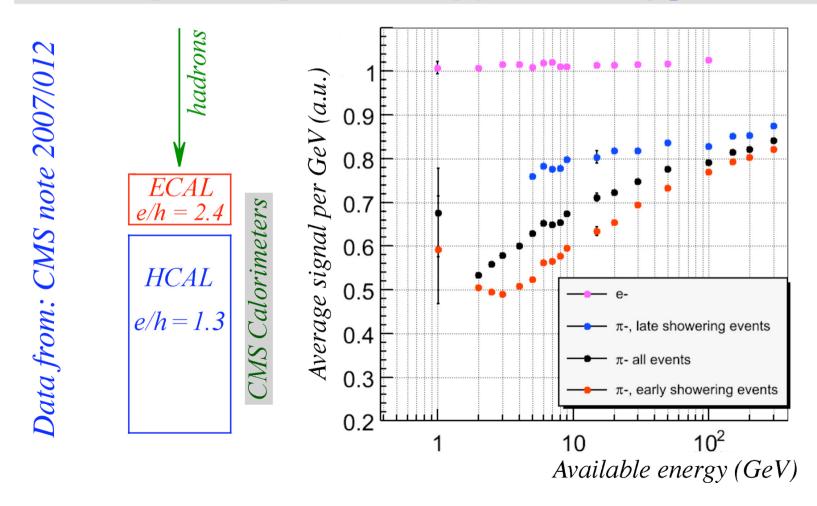
#### However:

- Be careful interpreting the results (e.g. leakage estimates AMS)
- Starting point dependence remains if different sections have different e/h

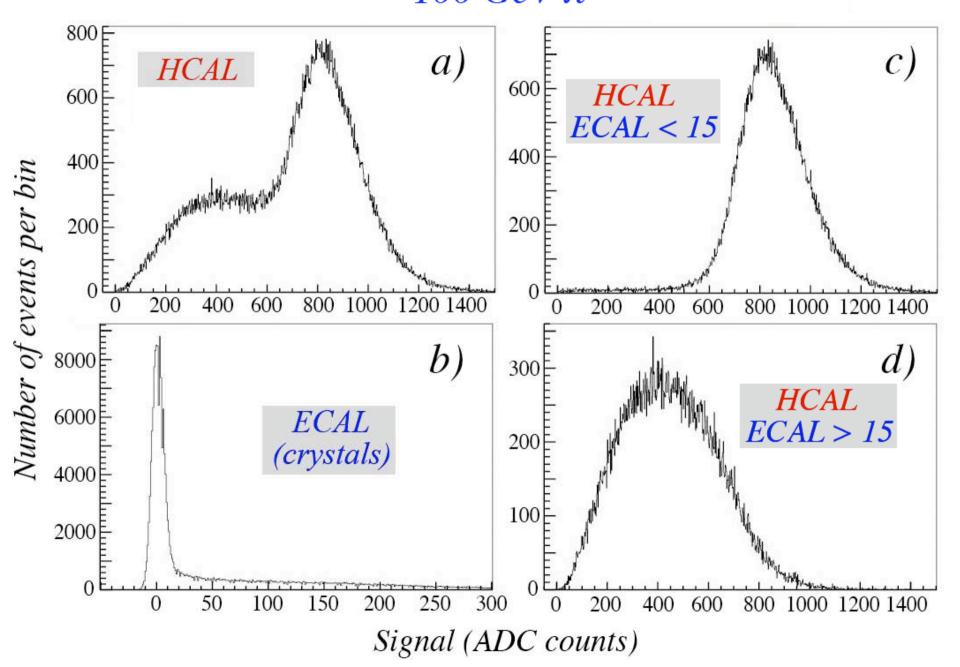
## Use the em scale for all sections (B/A = 1)Hadronic response and signal linearity in CMS

CMS pays a price for its focus on em energy resolution ECAL has e/h = 2.4, while HCAL has e/h = 1.3

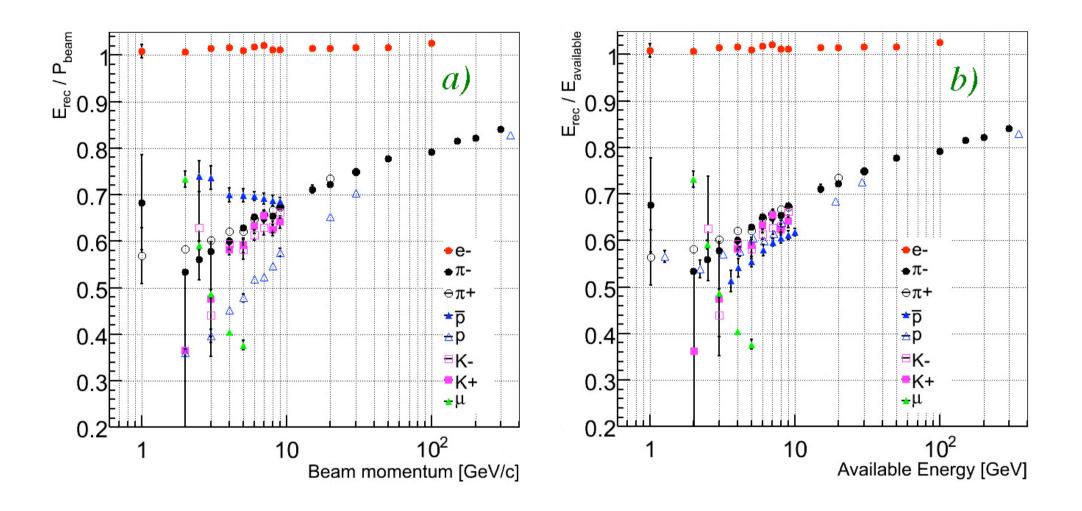
-> Response depends strongly on starting point shower



## Pion signals in crystal ECAL + scintillator HCAL 100 GeV π<sup>-</sup>



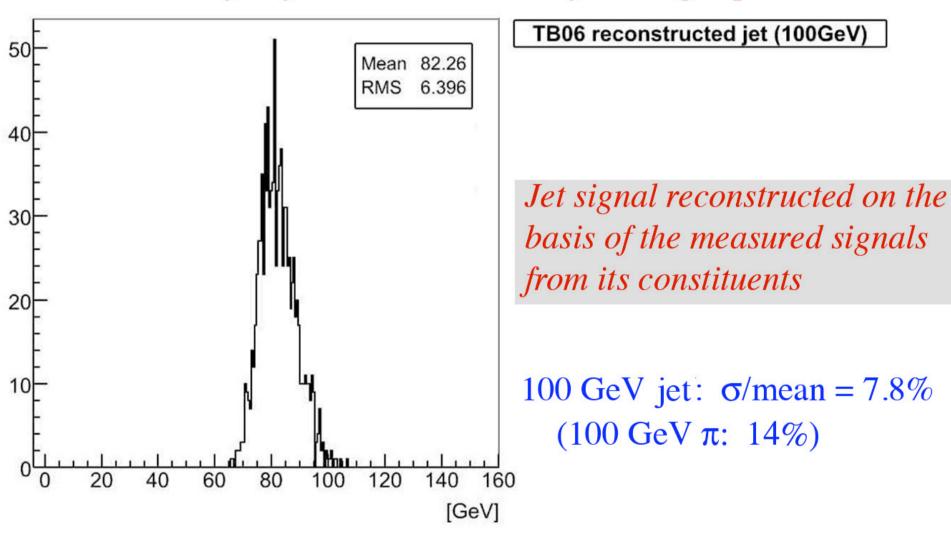
#### Single particles and jets in the CMS calorimeters



Calorimeter response does not only depend on starting point of the shower, but also on the particle type

## Some good news:

#### Situation for jets is better than for single particles



Fluctuations in energy sharing between ECAL/HCAL smaller for jets!

#### Using test beam data to determine the jet energy scale (CMS)

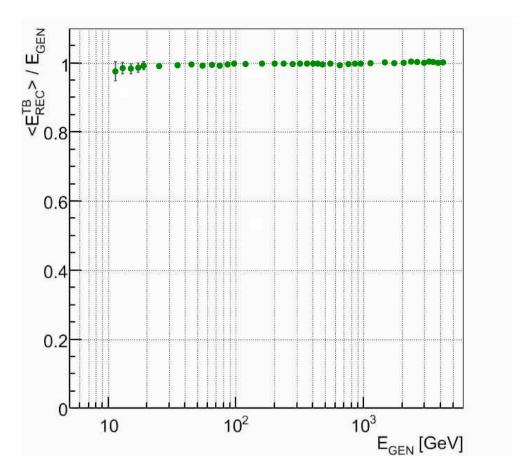


Figure 5.18: Average calorimeter response to jets after the test beam particles were corrected. Almost linear response at 1 confirms the validity of our jet reconstruction based on test beam data.

Average calorimeter response to jets after correcting the response of individual jet fragments for e/h effects

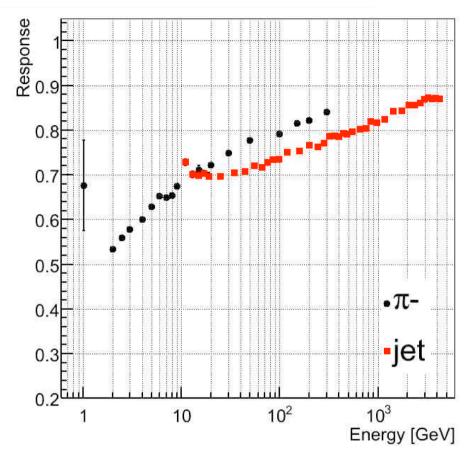


Figure 5.20: The jet response is lower than charged pion response, because a jet consists of mostly low energy (< 10 GeV) particles and the low calorimeter response to these particles reduces the jet response with respect to charged pions.

Correction factor (1/response) as a function of E for single pions and jets

From: PhD thesis K.Z. Gumus (TTU, 2008)

#### How do we know calibration is correct?

• Check with a "known" energy deposit

em calorimeter: Use electrons whose momenta are measured with tracker

hadronic section: Use hadrons whose momenta are measured with tracker and which penetrate em section before starting shower

Problem: Using these calibration constants, energy of hadrons that start shower in the em section will be systematically mismeasured

• The ultimate check is the correct reconstruction of physics objects

$$Z \rightarrow e^+e^ J/\psi \rightarrow e^+e^ Y \rightarrow e^+e^-$$
 (91.2 GeV/c<sup>2</sup>) (3.10 GeV/c<sup>2</sup>) (9.46 GeV/c<sup>2</sup>)

(cf. the "self-calibrating" D0 calorimeter)

#### How do we know calibration is correct? (2)

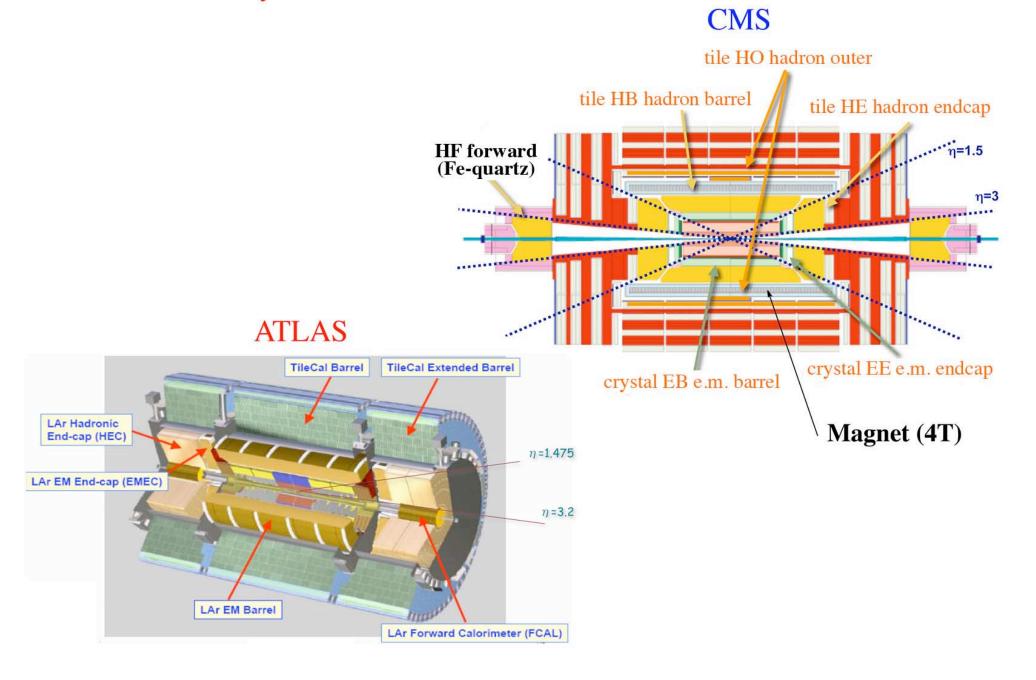
- For hadron calorimeter, there is no such "easy" calibration object Since UA2 (1983), no experiment has observed W,Z in jet/jet invariant mass distributions.
  - Argument: QCD background is too high.
- However, how about Z → b b̄?
   CDF, D0, ATLAS, CMS should have samples comparable in size to Z → e<sup>+</sup>e<sup>-</sup>
   Why isn't the Z seen in invariant mass distributions of b jets?
   QCD background should be very small.
- Other options: W from t-decay, W/Z from W+jet-jet events Need several fb<sup>-1</sup> to get meaningful event sample
- General problem with calibration of "jet energy scale" in calorimeters with e/h ≠ 1:
   Any method is only valid for a specific class of events, and gives wrong results for other types of events
   (e.g. jets with leading π<sup>o</sup>vs. jets with leading π<sup>±</sup>)

#### A final word about longitudinal segmentation

If your calorimeter is not longitudinally segmented, you are NOT tempted to intercalibrate the segments wrongly

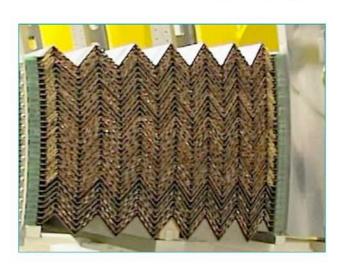
My pet pief: There is nothing that one can achieve with longitudinal segmentation that one cannot achieve (better) with other means

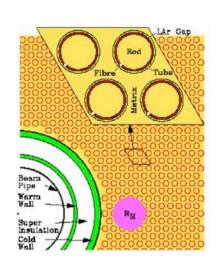
#### Calorimetry in ATLAS and CMS

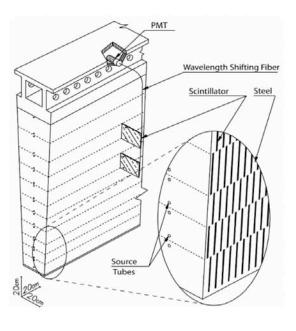


## Novel features of LHC calorimeters (1) ATLAS

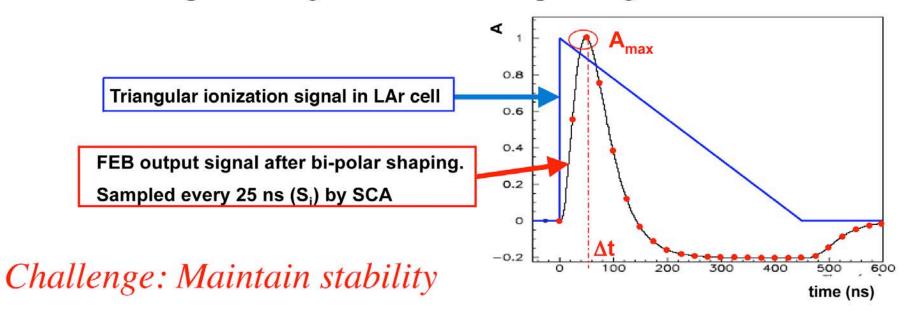
Unusual sampling geometries







Incomplete charge collection in Liquid Argon



# Novel features of LHC calorimeters (2) CMS

- New type of crystal (PbWO<sub>4</sub>)
- Quartz fiber calorimetry (HF)
- Readout: *Avalanche Photo Diodes* (EB) *Hybrid Photo Diodes* (HB)
- Entire barrel calorimeter *inside 4T magnetic field*
- Extremely non-compensating components (HF: e/h = 4.7, ECAL: e/h = 2.4)

#### Both ATLAS and CMS

- *Number of electronic channels* one order of magnitude larger than in previous experiments of this type
- Event rates two orders of magnitude larger

## Challenges to LHC calorimeters (1) Operating conditions

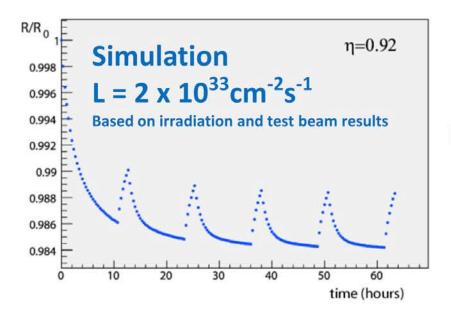
- Maintain stability
  - Temperature: LAr  $\pm 10$  mK, PbWO<sub>4</sub> / APD  $\pm 0.1$  °C

At very high luminosities, beam-induced heating may become an issue. The calorie becomes a relevant unit for the forward calorimeters. CMS HF:  $@10^{34}$  cm<sup>-2</sup> s<sup>-1</sup> 12 J/s + effects of induced radioactivity

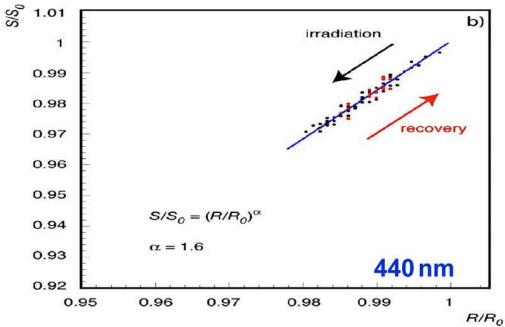
- Electronic noise (LAr, HPD)
- Induced radioactivity
   Will limit possibilities for access and maintenance
- Radiation damage effects
   PbWO<sub>4</sub> crystals, plastic scintillator, APD. Requires careful monitoring.
   Distinguish between recoverable/permanent damage

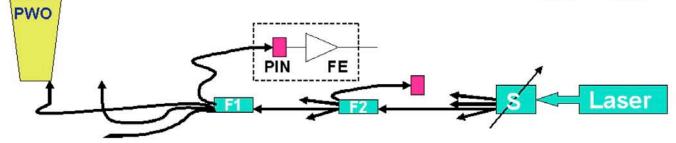
### Radiation damage of $PbWO_4(1)$

- Signals are sensitive to low levels of radiation (rads)
- Only *light transmission* is affected not the scintillation mechanism
- Recovery on a time scale of hours



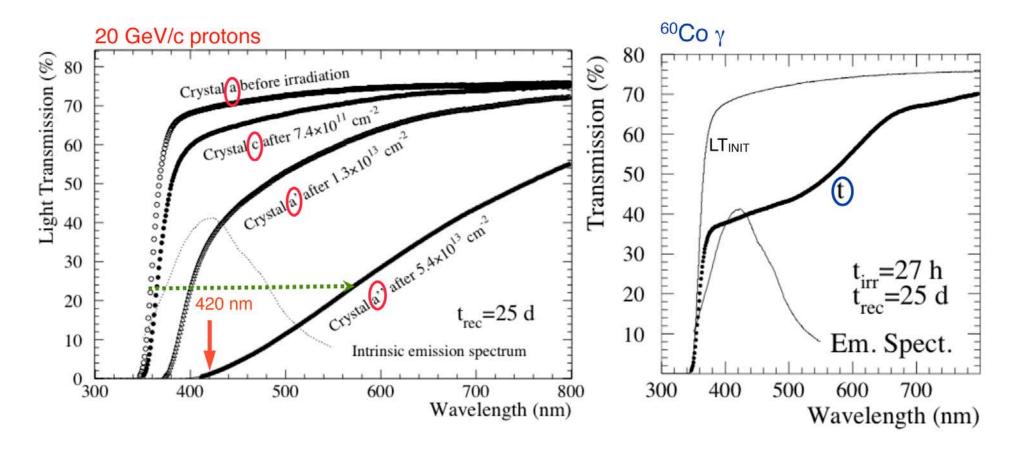
Effects monitored through response to laser light (440, 796 nm)





### Radiation damage of $PbWO_4$ (2)

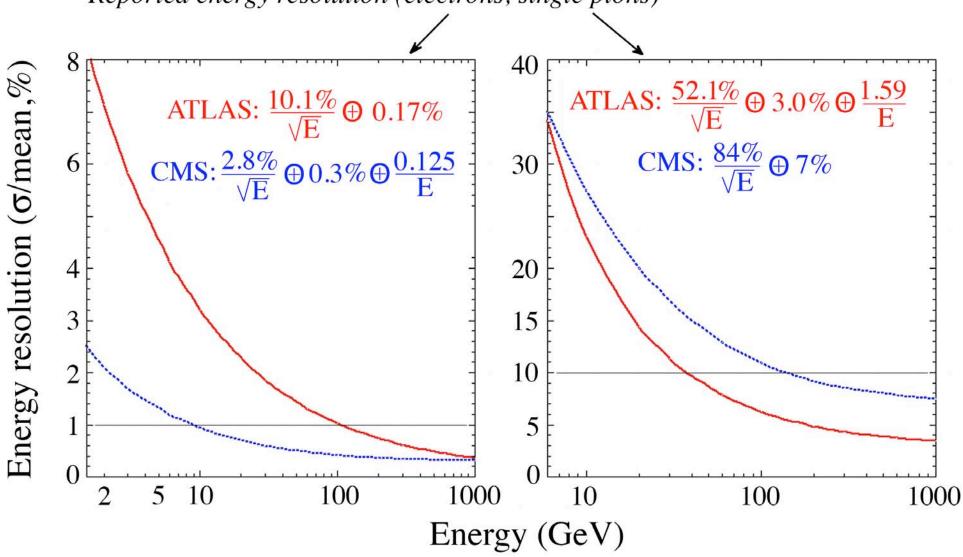
- Effect on light transmission different for  $\gamma$ 's and charged hadrons
- Observed band edge shift is permanent
- Induced attenuation characteristics consistent with Rayleigh scattering



- Scintillation mechanism does not seem to be affected
- → effects can be monitored with lasers

## Challenges to LHC calorimeters (2) Performance

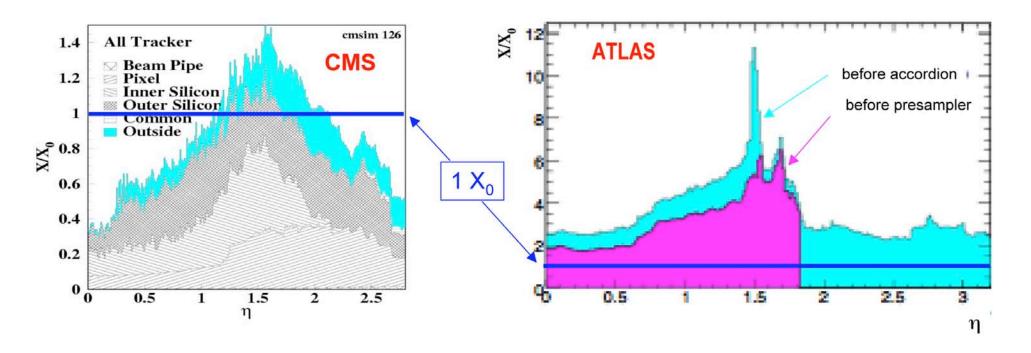
Reported energy resolution (electrons, single pions)



These resolutions are not always realistic!

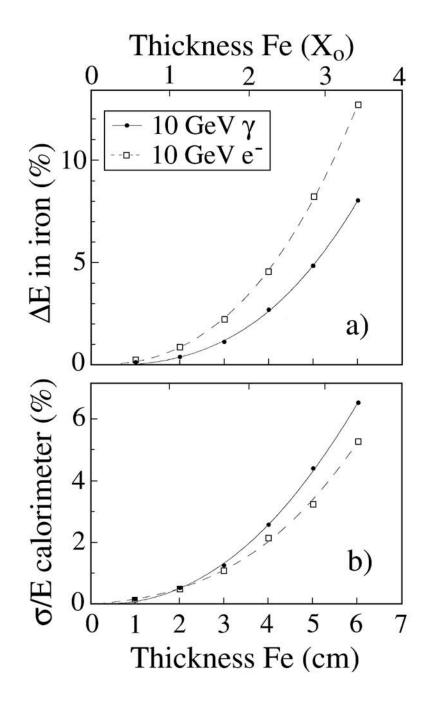
# Challenges to LHC calorimeters (3) Electromagnetic performance

- Calorimeters designed to be sensitive to  $H^{o} \longrightarrow \gamma \gamma$
- Upstream material will reduce that sensitivity



- Effects of upstream material different for electrons and  $\gamma$ 's (electrons: bremsstrahlung,  $\gamma$ 's convert into  $e^+e^-$ )
- The effect on the energy resolution is larger for  $\gamma$ 's

### Effects of upstream material



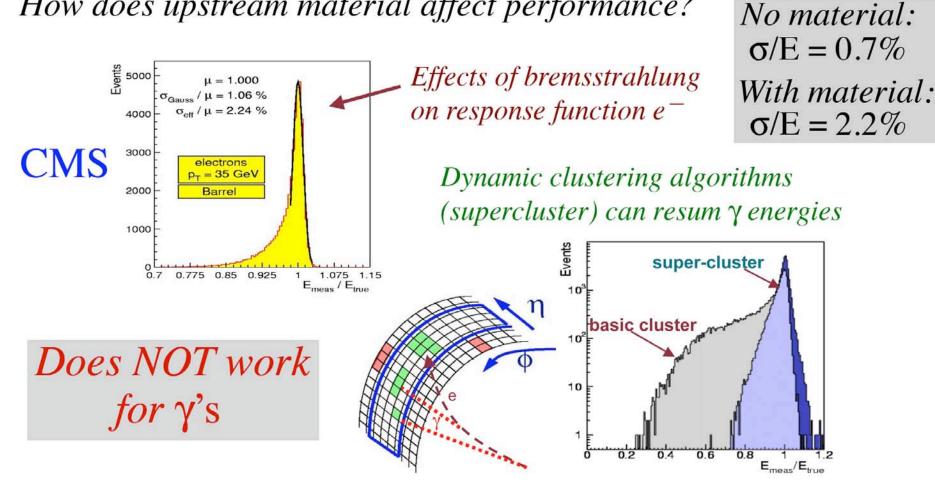
Electrons lose more energy

Energy resolution worst for γ

From: NIM A485 (2002) 385

### Challenges to LHC calorimeters (4) Electromagnetic performance

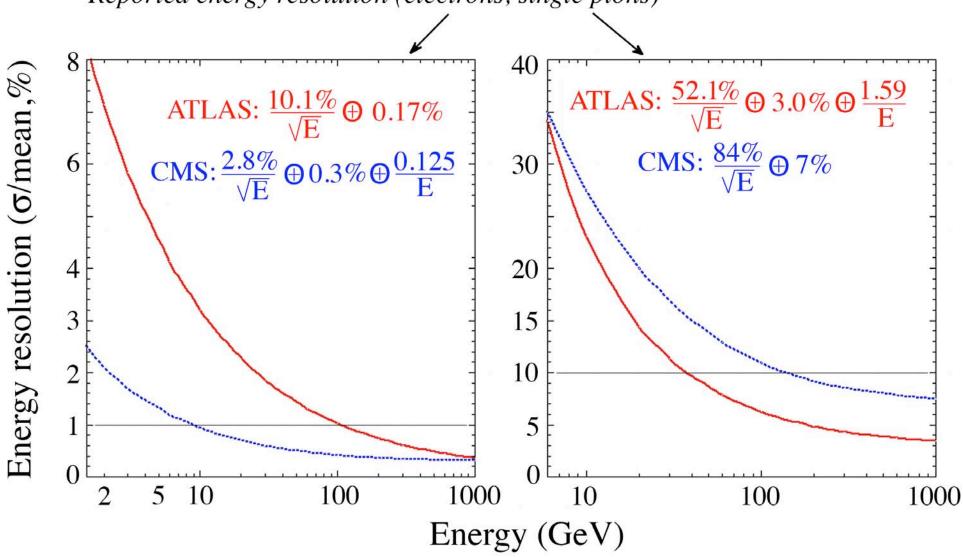
How does upstream material affect performance?



• ATLAS: Much more upstream material, but they count on Preshower Detector,  $E_1/E_2$  to recover lost energy

## Challenges to LHC calorimeters (2) Performance

Reported energy resolution (electrons, single pions)

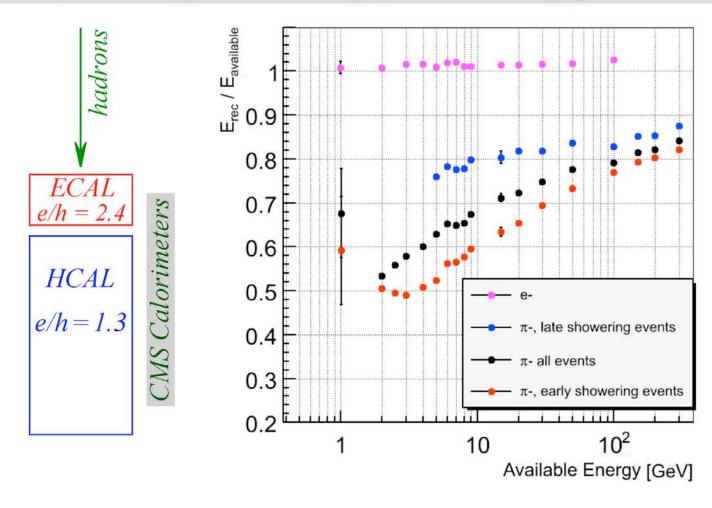


These resolutions are not always realistic!

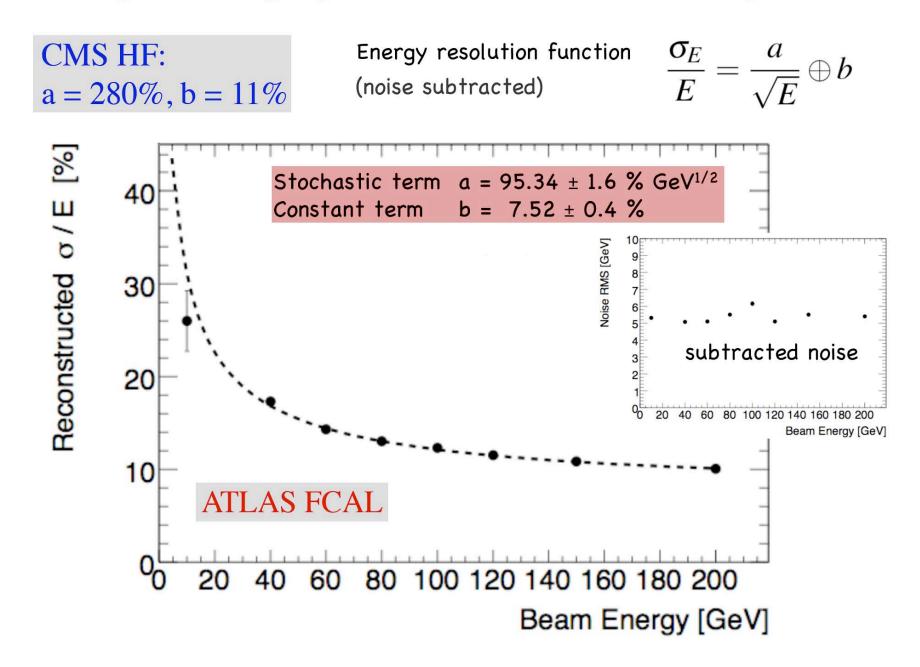
## Challenges to LHC calorimeters (5) Hadronic performance

CMS pays a price for its focus on em energy resolution ECAL has e/h = 2.4, while HCAl has e/h = 1.3

-> Response depends strongly on starting point shower

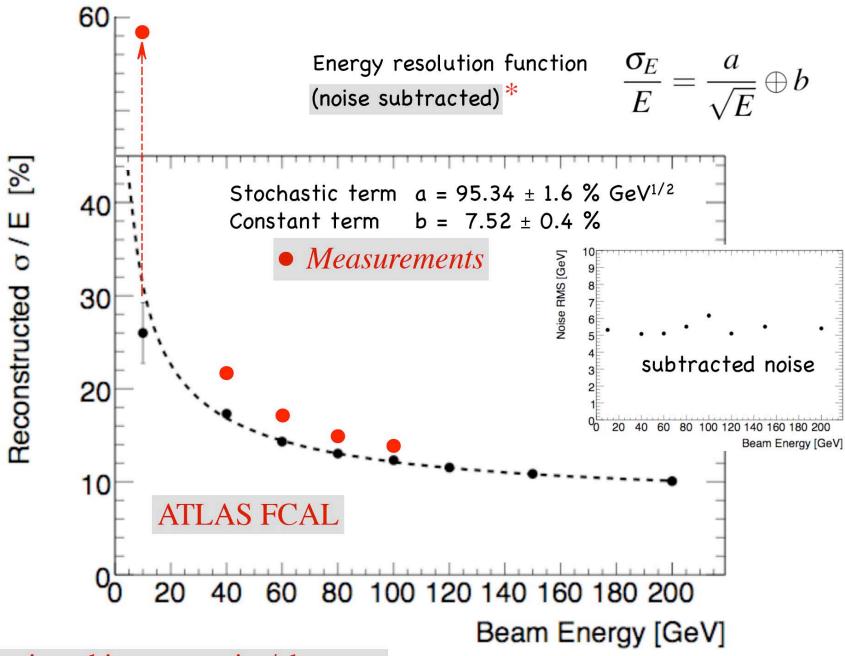


#### In terms of hadron performance, ATLAS is clearly better



From: L. Heelan, CALOR08, Pavia May 2008.

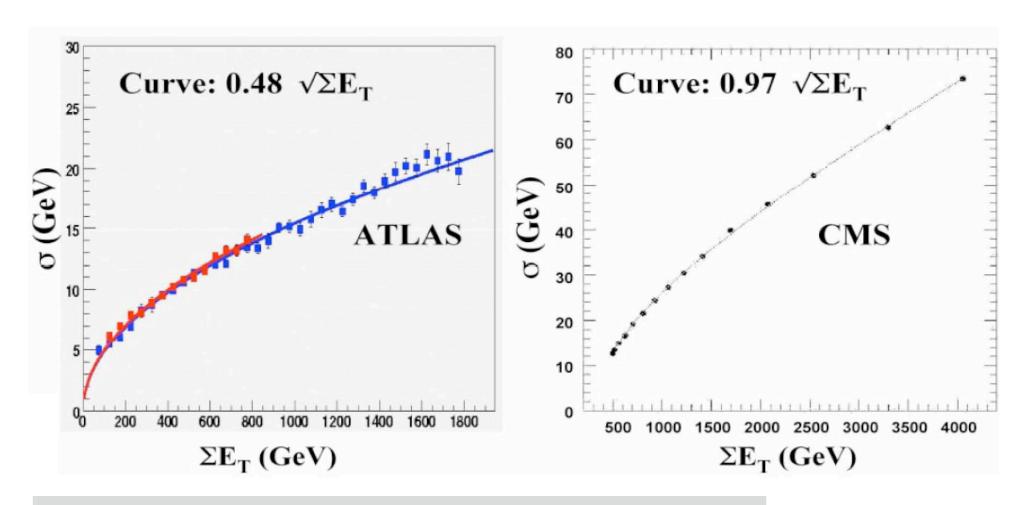
#### But let's not pretend that performance is better than it is



\* Not mentioned in summaries/abstracts

### Hadronic performance and physics

What matters for physics is the precision with which missing transverse energy can be measured



E. Longo: CALOR 08, Pavia, May 2008

# Challenges to LHC calorimeters (6) Miscellaneous challenges

#### • "Nuclear counter" effect in APD's of CMS crystals

Charged shower particles give much larger signals in Si than  $\gamma$ 's (100 eh pairs/ $\mu$ m). This may affect hadronic signals if the APD is located near the shower maximum of an energetic  $\pi$ ° produced in the PbWO<sub>4</sub> crystals.

#### Very small sampling fraction of CMS HF

Light yield is 0.2 photoelectrons/GeV → charged particle traversing PMT and generating 10 Cherenkov photoelectrons mimics 50 GeV energy deposit!

#### • High-luminosity effects on liquid argon

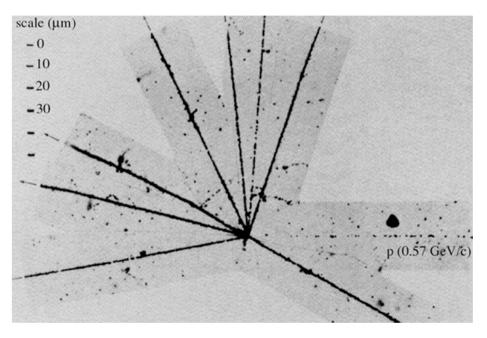
Charge build-up, electric field changes/breakdown, changing drift velocity Radiolysis of impurities, pressure build-up (FCAL) .....

#### The "Texas tower effect"

Caused by placing readout elements that produce HUGE signals for one particular type of shower particle in the path of the developing shower

#### Examples:

- 1) Calorimeters with gas (wire chamber) readout,  $f_{\rm samp} \sim 10^{-5}$ . If gas contains H, neutron scattering in gas may transfer 1 MeV to p. This will look like an energy deposit of 100 GeV (CDF).
- 2) CMS ECAL (lead tungstate crystals read out by Avalanche Photo Detectors



Charged nuclear fragments may be 100 - 1000 times minimum ionizing. When traversing an APD, they may create a signal 100,000 times larger than that from a scintillation photon.

Example: In CMS ECAL, such events may fake energy deposits of tens of GeV.

# Challenges to LHC calorimeters (7) Calibration and the jet energy scale

- This is possibly the greatest challenge
- Good energy resolution is only meaningful if the central value of the signal distribution has the correct energy
- Calibrating a longitudinally segmented calorimeter system is highly non-trivial
- It requires very *reliable simulations*, which are lacking for hadron showers
- It requires *verifiability*, which is in short supply for hadron showers
- Prediction: We will hear a lot about this in the next 20 years

#### Monte Carlo simulations and hadron calorimetry

#### • Hadron calorimetry

GEANT/GEISHA/FLUKA .... have not contributed anything to our fundamental understanding of hadron calorimetry

Progress in understanding has been made *despite* these programs

Simulations are *flawed at fundamental levels*, e.g.  $\pi^0$  production and neutron contributions to the signals, which are crucial for understanding hadron calorimetry

Benchmark data for tests of MC simulations:

- E. Bernardi *et al.*, NIM **A262** (1987) 229
- G. d'Agostini *et al.*, NIM **A274** (1989) 134
- N. Akchurin *et al.*, NIM **A408** (1998) 380.

#### Benchmark data for hadronic Monte Carlo

Test of  $\pi^0$  production modelling

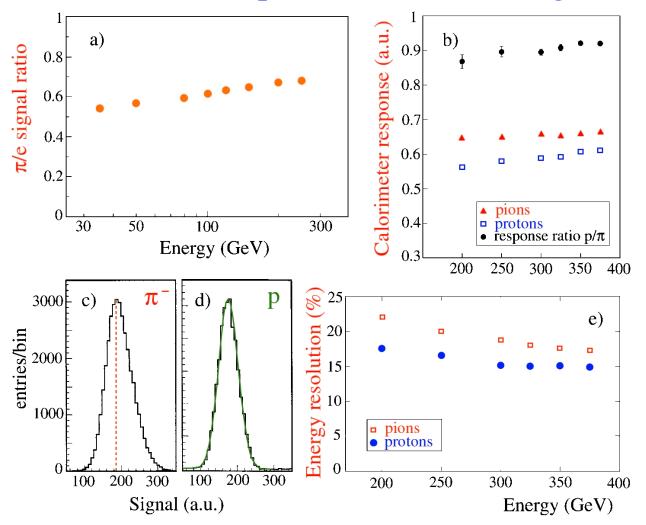
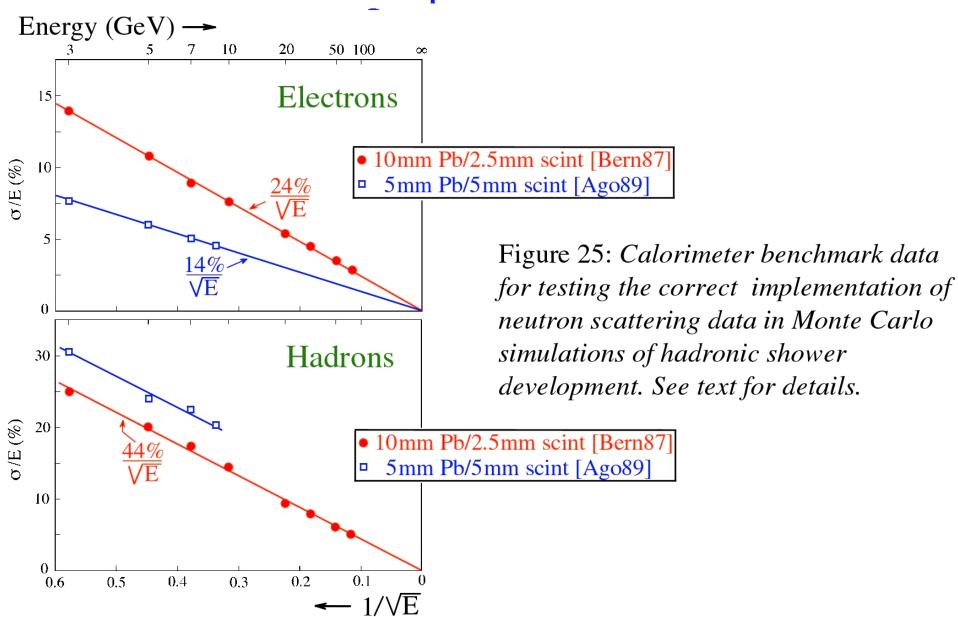


FIG. 8.27. Calorimeter benchmark data for testing the correct implementation of  $\pi^0$  production in Monte Carlo simulations of hadronic shower development. Experimental data from a copper/quartz-fiber calorimeter, showing the  $\pi/e$  signal ratio as a function of energy (a), the response to protons and pions, as well as the ratio of these responses, as a function of energy (b), the response functions to 300 GeV pions (c) and protons (d), and the energy resolutions for pions and protons as a function of energy (e) [Akc 97].

# Benchmark data for hadronic Monte Carlo Test of description neutron effects



#### Conclusions (LHC)

- The LHC calorimeters are truly remarkable instruments, designed with very ambitious goals in mind. Many novel features.
- They will face many challenges to meet these goals
- Especially the necessary em calorimeter performance may in practice turn out to be (too) difficult to reach and maintain
- Quality of the hadron calorimetry suffers from the emphasis placed in the design on the electromagnetic performance, especially in CMS.

(pet pief) Longitudinal segmentation = calibration trouble GEANT is (unfortunately) still rather useless for hadron calorimetry