On the Calibration of Segmented Calorimeters

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Outline :

- What is the problem?
- How to deal with it?
- Examples from practice
- Conclusions

LESSONS FROM 25 YEARS OF R&D

- *LESSON 1:* Energy resolution is determined by *fluctuations*, ***not*** by average values

- *LESSON 2:* Digital calorimetry has been tried *and abandoned,* for good reasons

- *LESSON 3:* A narrow signal distribution is useless if the mean value is incorrect
  Correct energy scale is at least as as important as good resolution

- *LESSON 4:* *Longitudinal segmentation means asking for (calibration) trouble*

- *LESSON 5:* GEANT based MC simulations of hadronic shower development are *fundamentally flawed* $\longrightarrow$ useless as design tool

- *LESSON 6:* If you want to improve hadronic calorimeter performance
  $\longrightarrow$ *reduce/eliminate the (effects of) fluctuations that dominate the performance* :

  i) Fluctuations in the em shower fraction, f_{em}
  ii) Fluctuations in visible energy (nuclear binding energy losses)

# *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?*

The sampling fraction changes as shower develops*

shower dominated by mip's

shower dominated by soft γ's

*By as much as 30%!

- 10 GeV electrons
  Pb/plastic scintillator
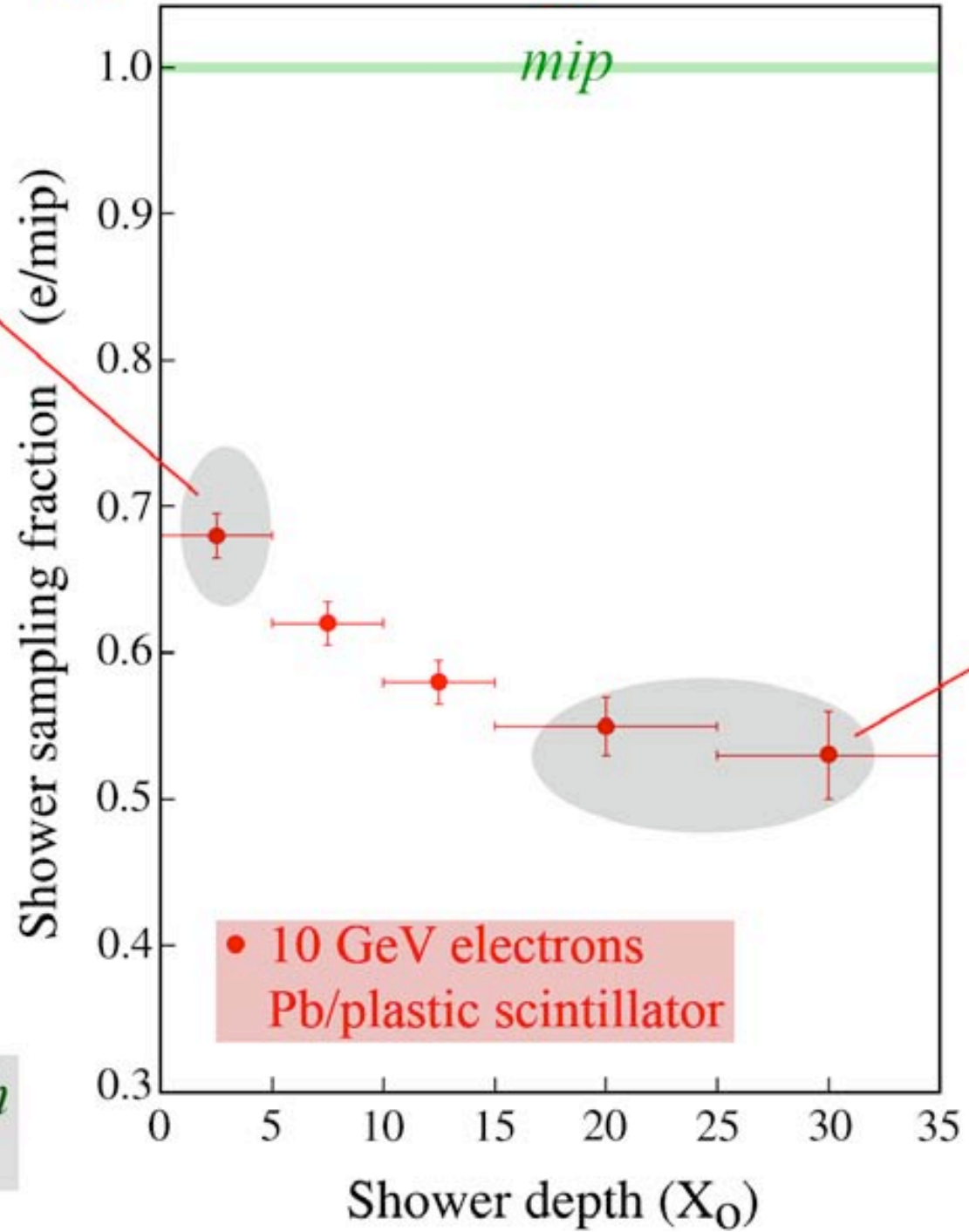
Electromagnetic showers:
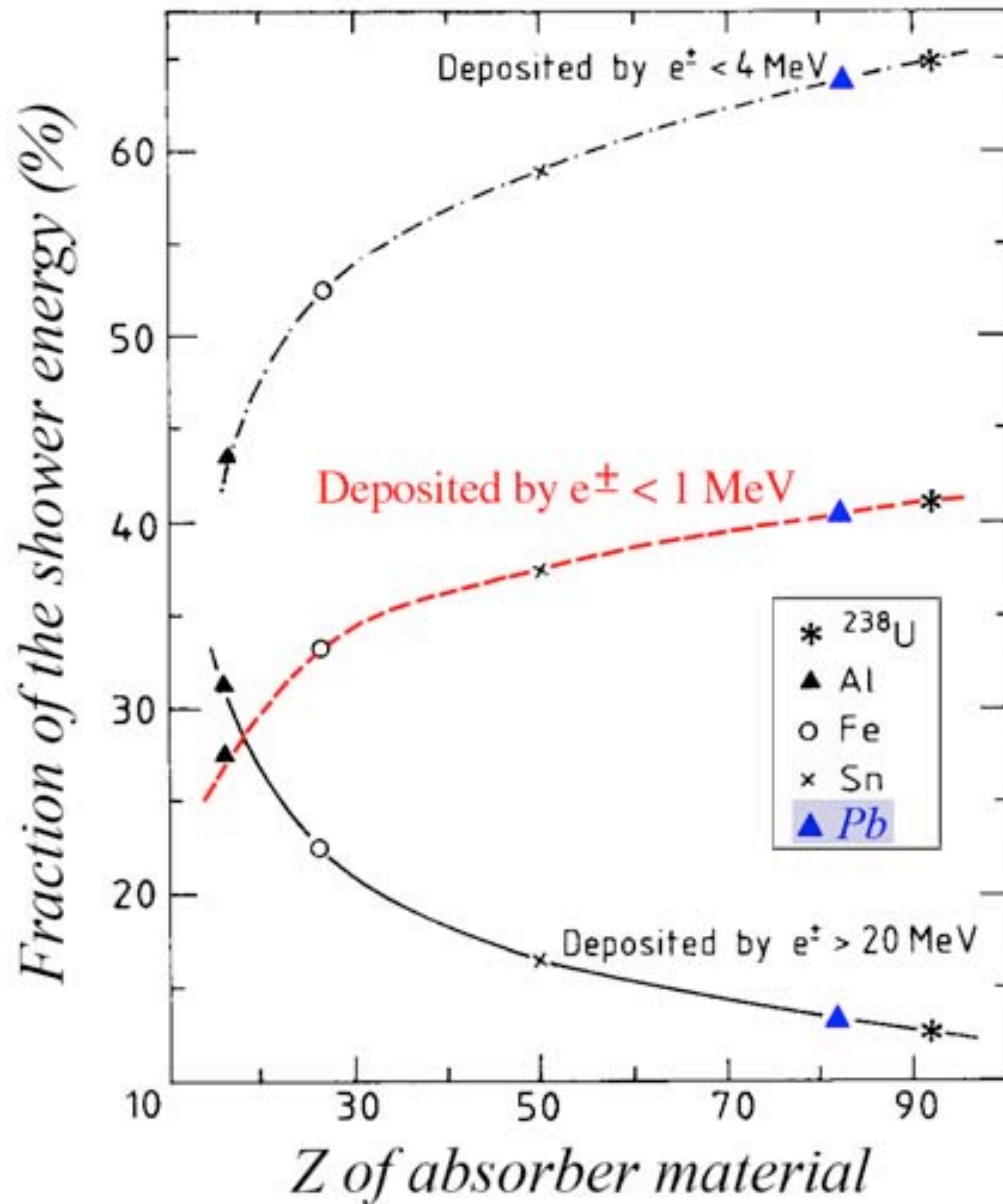## The importance of SOFT shower particles

FIG. 2.10.

The composition of em showers.

Shown are the percentages of the energy of 10 GeV electromagnetic showers deposited through shower particles with energies below 1 MeV (dashed curve), below 4 MeV (the dash-dotted curve) or above 20 MeV (the solid curve), as a function of the Z of the absorber material.
Results of EGS4 simulations.

Range of Compton/photoelectrons in calorimeter materials
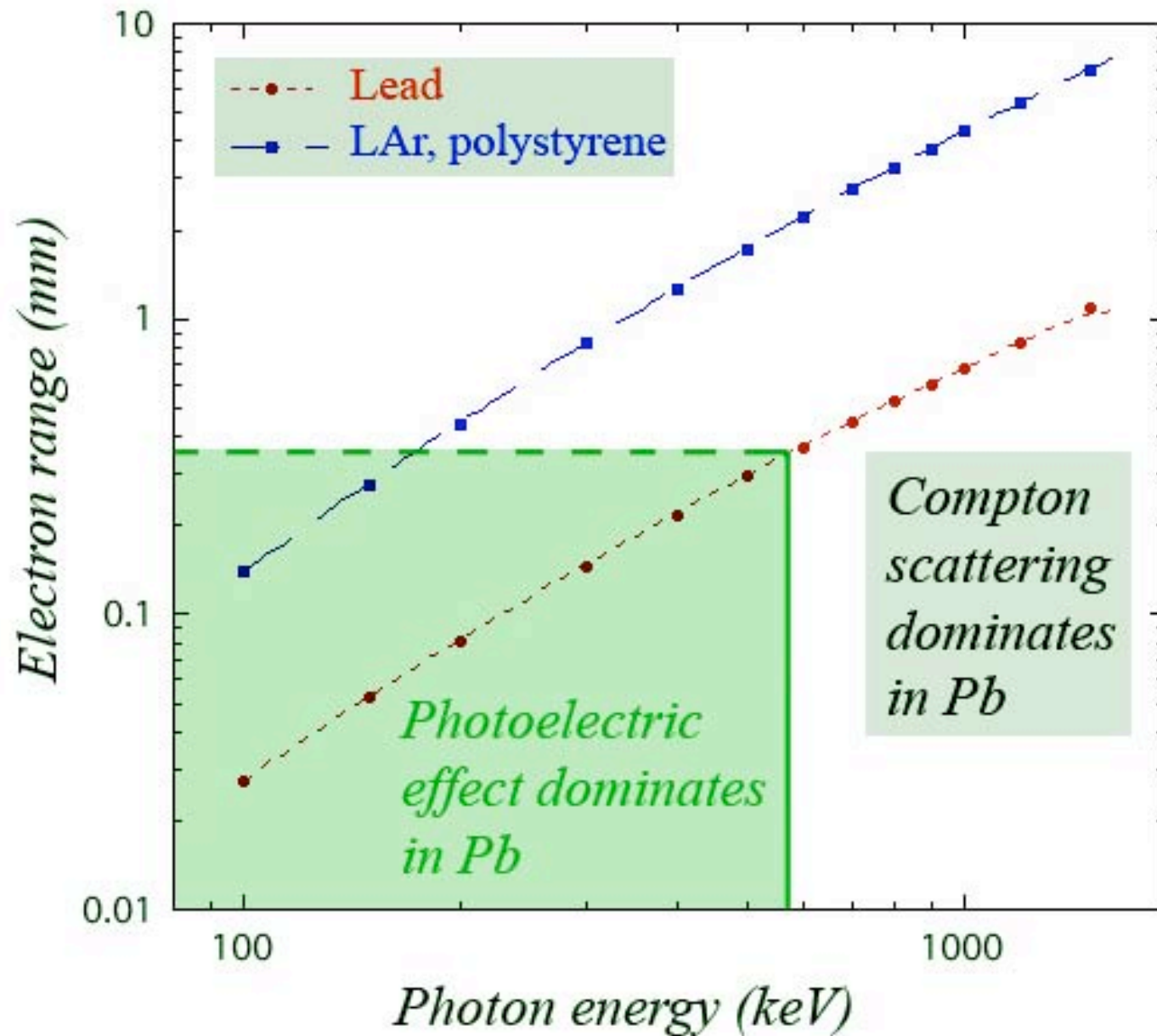
N.B.
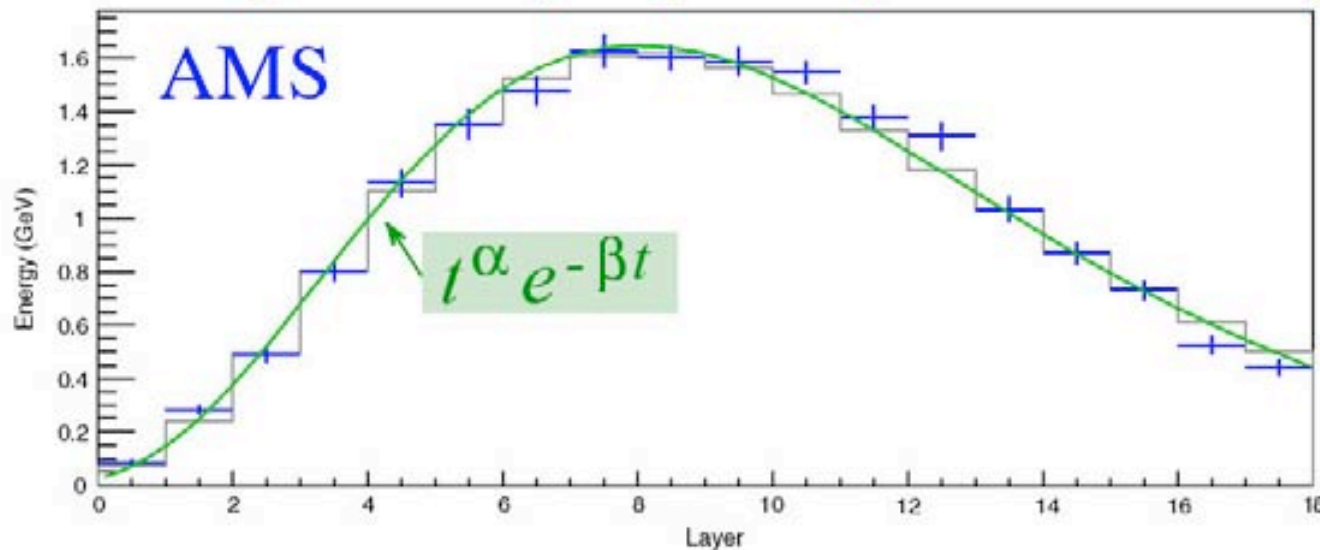About half of the total em shower energy is deposited by photons in this energy range!

$\sigma_{p.e.} \sim Z^{4.5}$

What is the problem? (summary)

- Shower particles contributing to the signals of sampling calorimeters typically have a *range* that is much *smaller than the distance between sampling layers*

  ➡ *Only small fraction of shower particles contribute to signal!*

- Signal of a sampling calorimeter is sum of signals from individual *contributing* shower particles (*N "mips"*)

- *The energy equivalent* of one signal unit (*"mip"*) varies with the *depth* of the shower, in an *energy dependent* way

- If shower energy is distributed over several calorimeter segments, *how to determine then the energy equivalence of the signals in these individual segments???*

CALIBRATION MISERY

Consequences of depth dependence sampling fraction
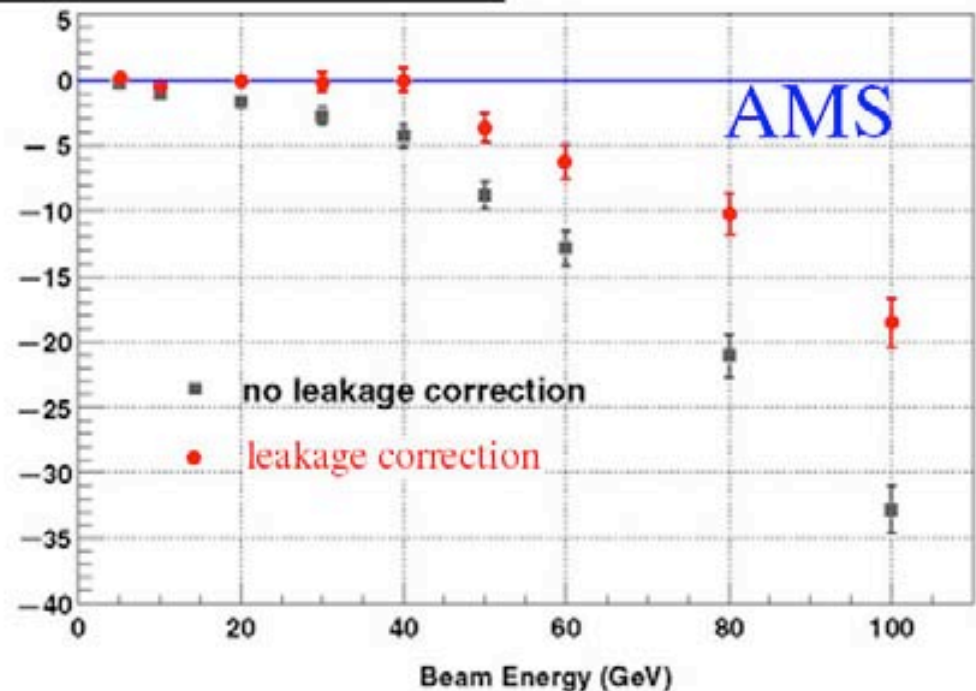

AMS

$t^\alpha e^{-\beta t}$

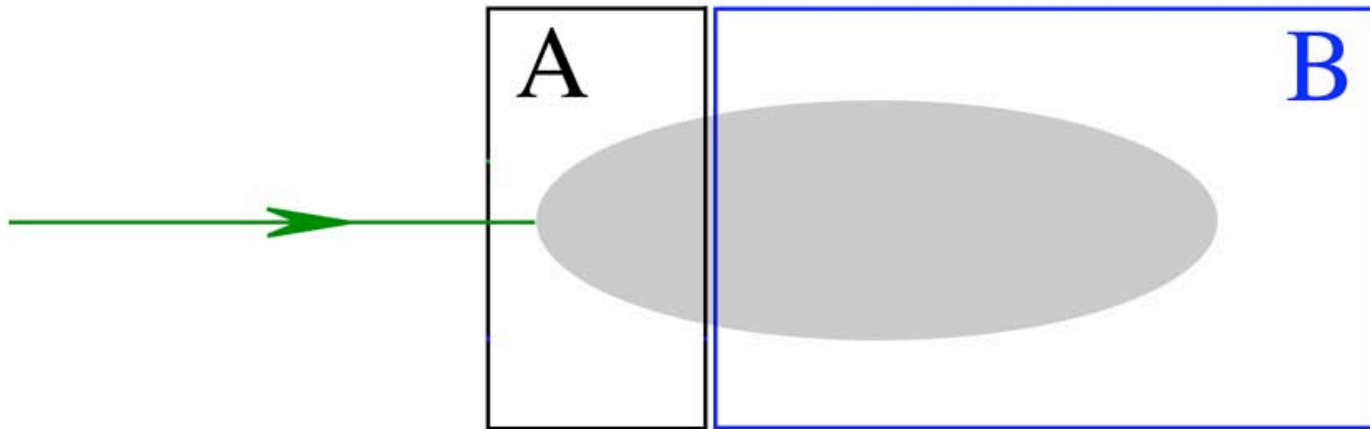NIM A490, 132 (2002)

Pb/scintillating fiber
18 layers (17 X_0)

Calibrated with mip's:
11.7 MeV/layer

Shower leakage:
(under)estimated on basis
of fit to longitudinal profile

Measured energy-Beam Energy (%)

AMS

■ no leakage correction

● leakage correction

Beam Energy (GeV)

A widely used technique for calibrating segmented devices

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

$\longrightarrow$ *Determine A,B*

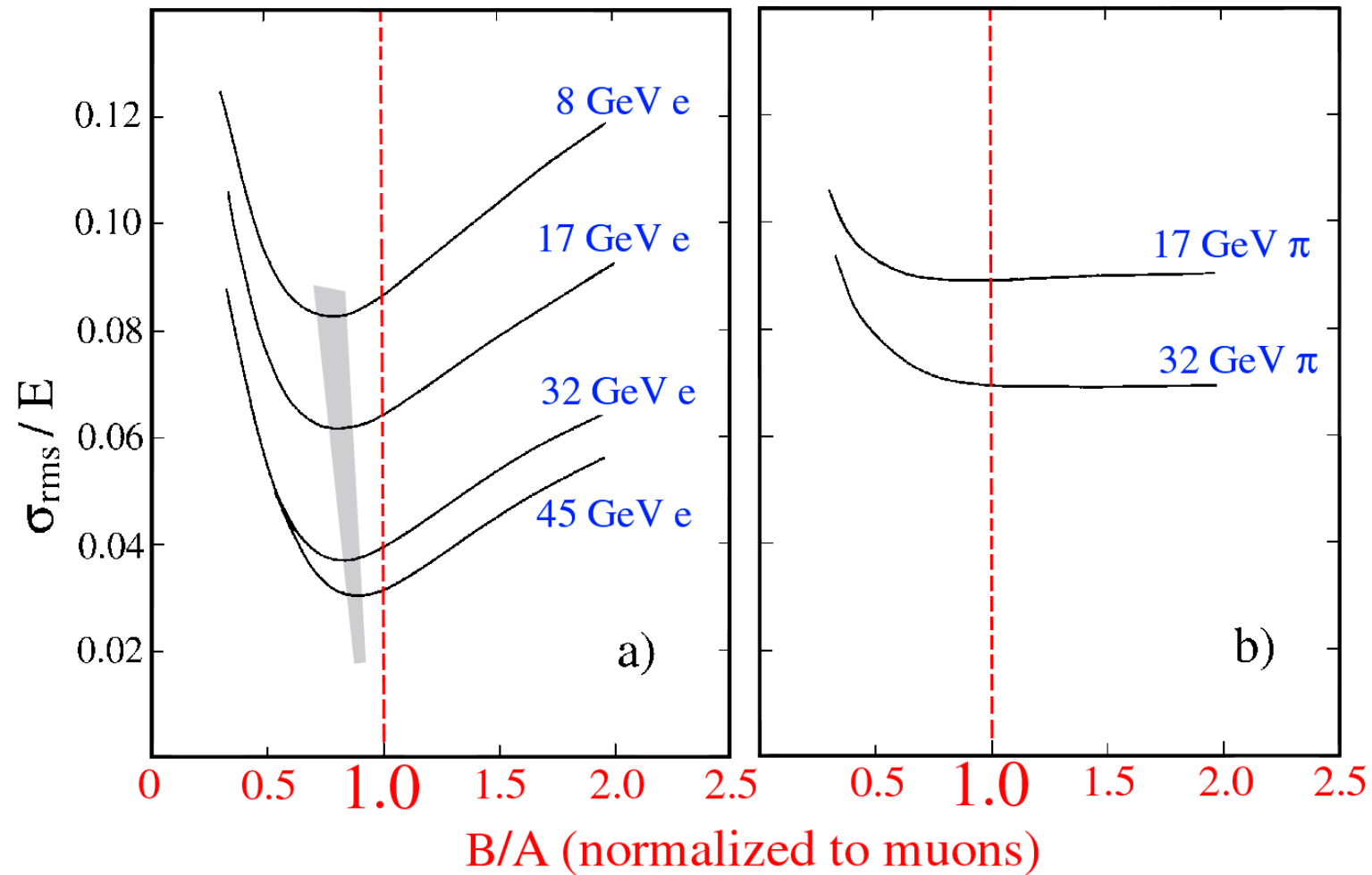# Calibrating longitudinally segmented calorimeters

FIG. 6.2. The fractional width σ/E of the signal distributions for electrons (a) and pions (b) 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].
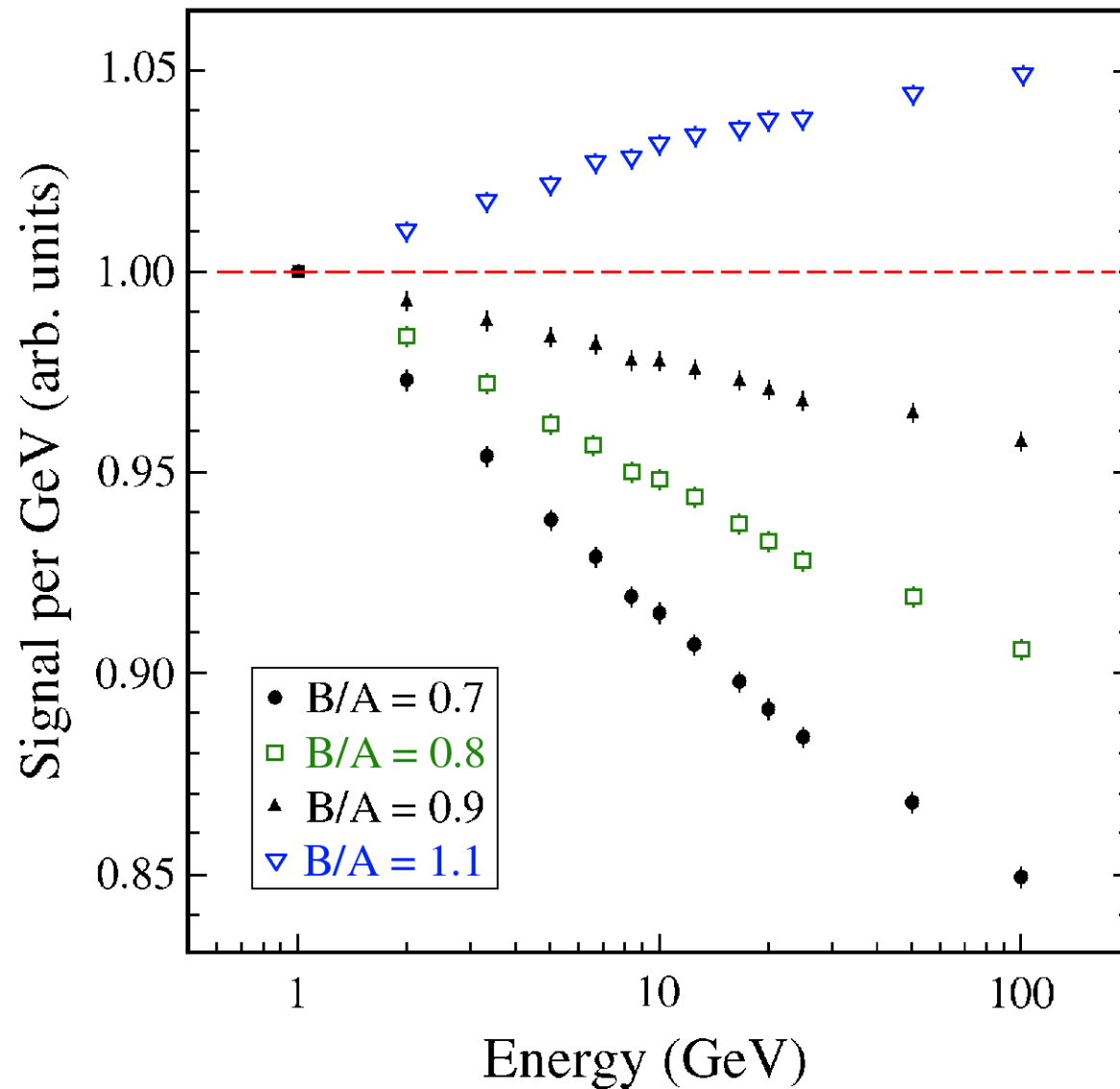
Results of miscalibration: Non-linearity

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.
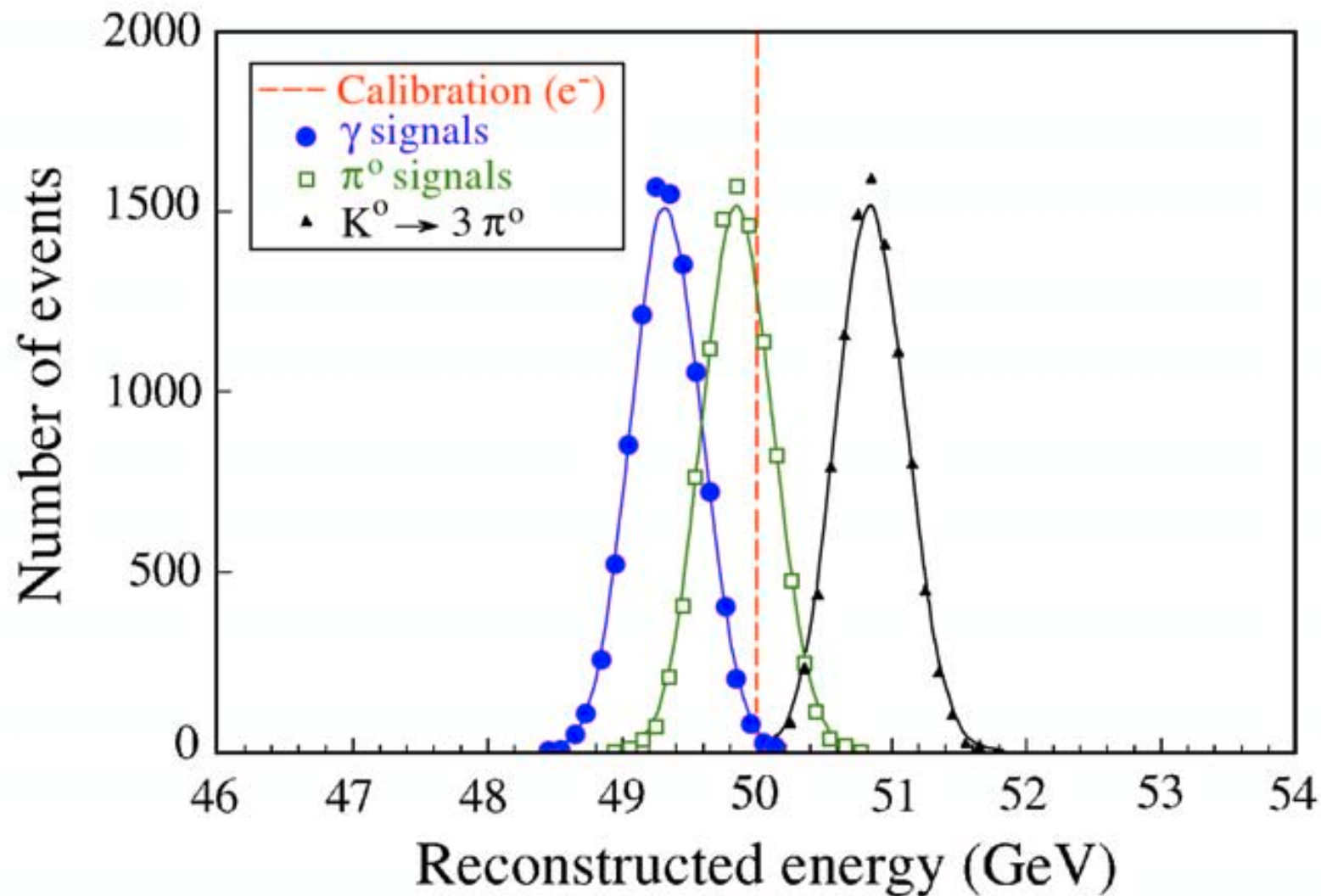
Results of miscalibration: Mass dependence

Figure 14: Signal distributions for γs and various hadrons decaying into all-γ 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.

Calibration by Minimizing Total Width

- ## *Effects of such calibration methods:*

  - Calibration constants are energy dependent

  - Response non-linearity is introduced

  - Systematic mismeasurement of energy
    ($e.g.$, π^0, e and γ of same energy give different measurement results)

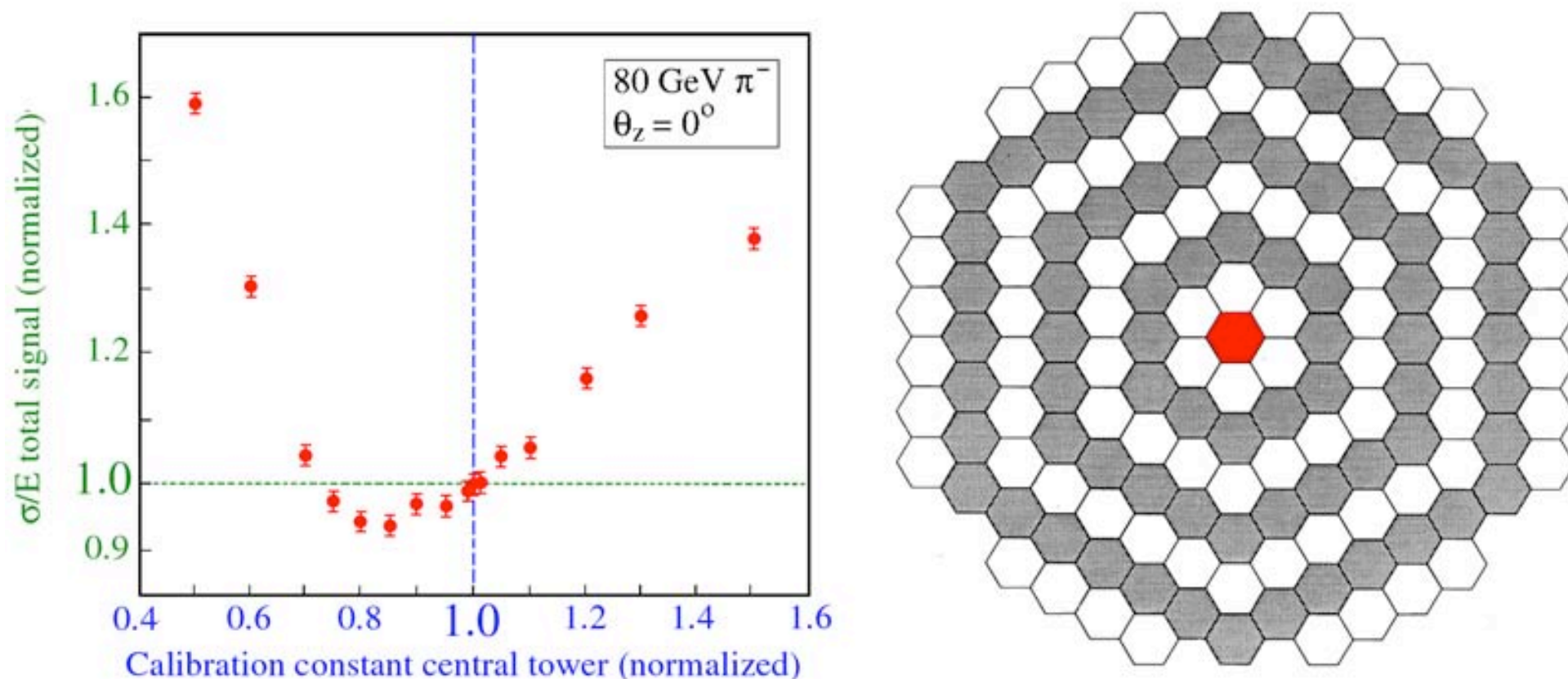# Problems with this method are NOT limited to longitudinal segmentation and electromagnetic showers

Figure 11: The fractional width, σ/E, of the signal distribution for 80 GeV π^- 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].
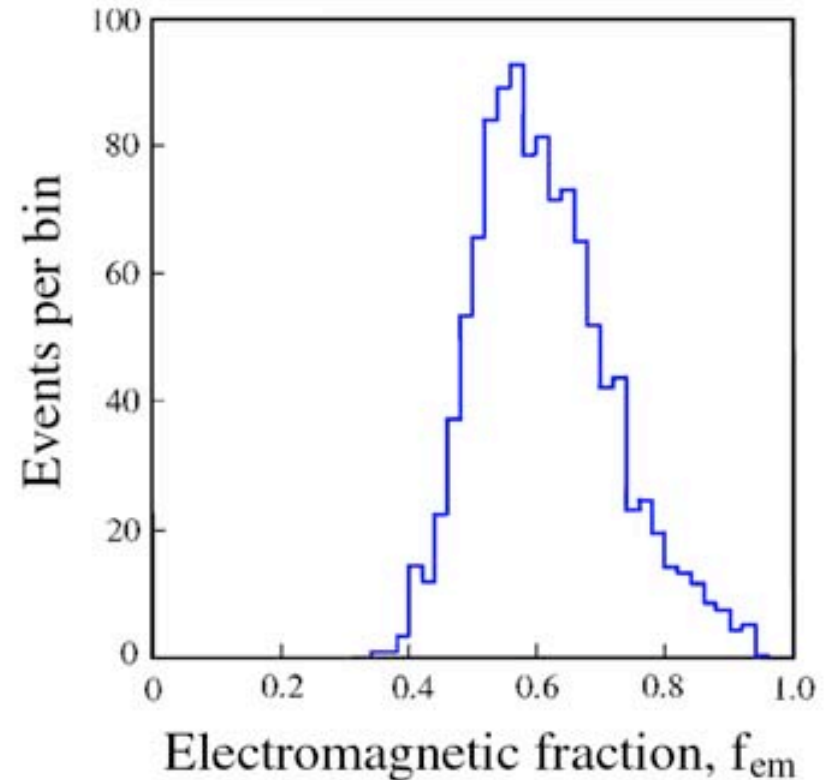
Hadronic showers

- *Large fraction of energy is deposited through em showers (π^0)*

- *Starting point of the em component(s) fluctuates wildly*
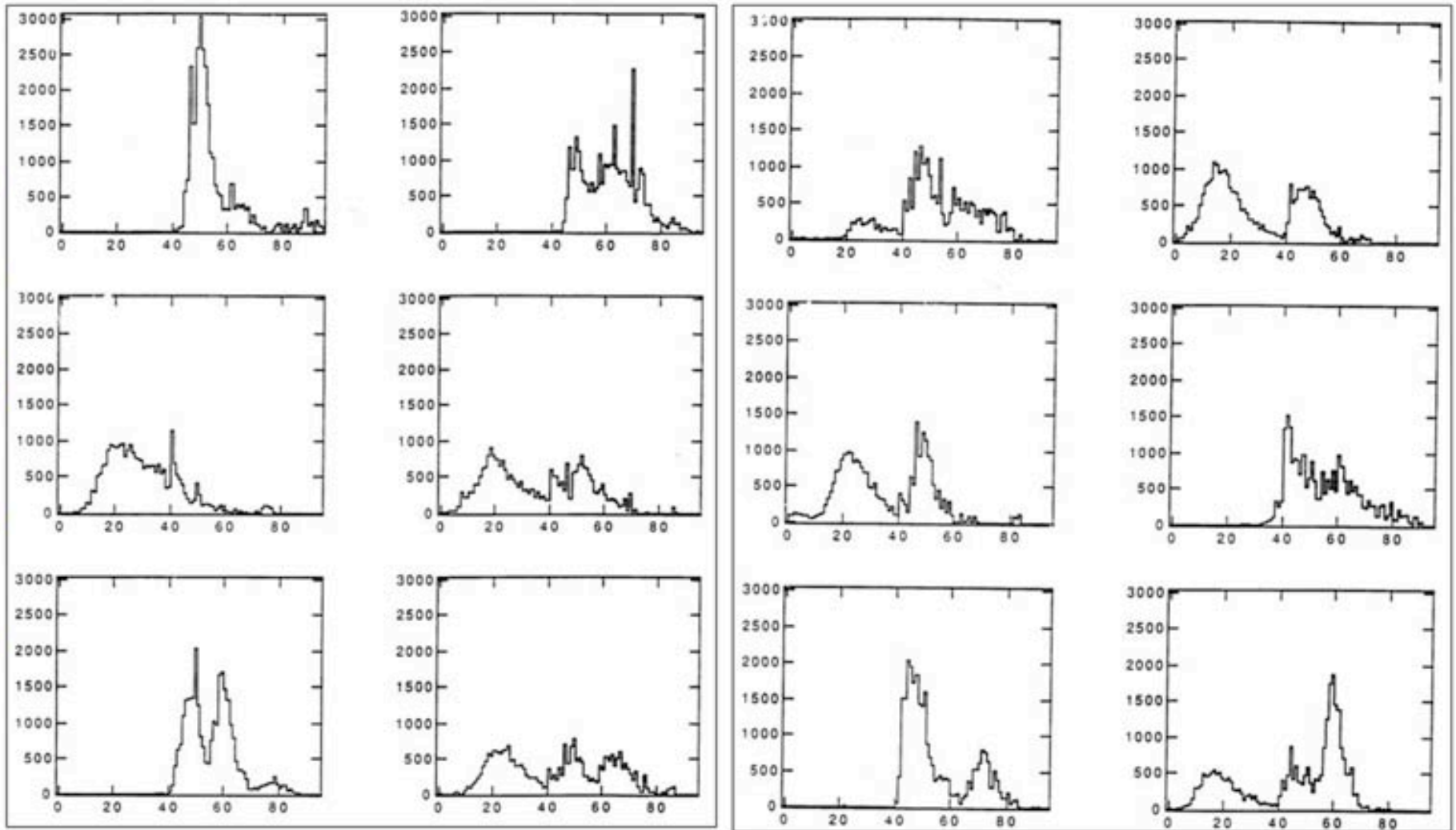
The electromagnetic fraction of hadron showers
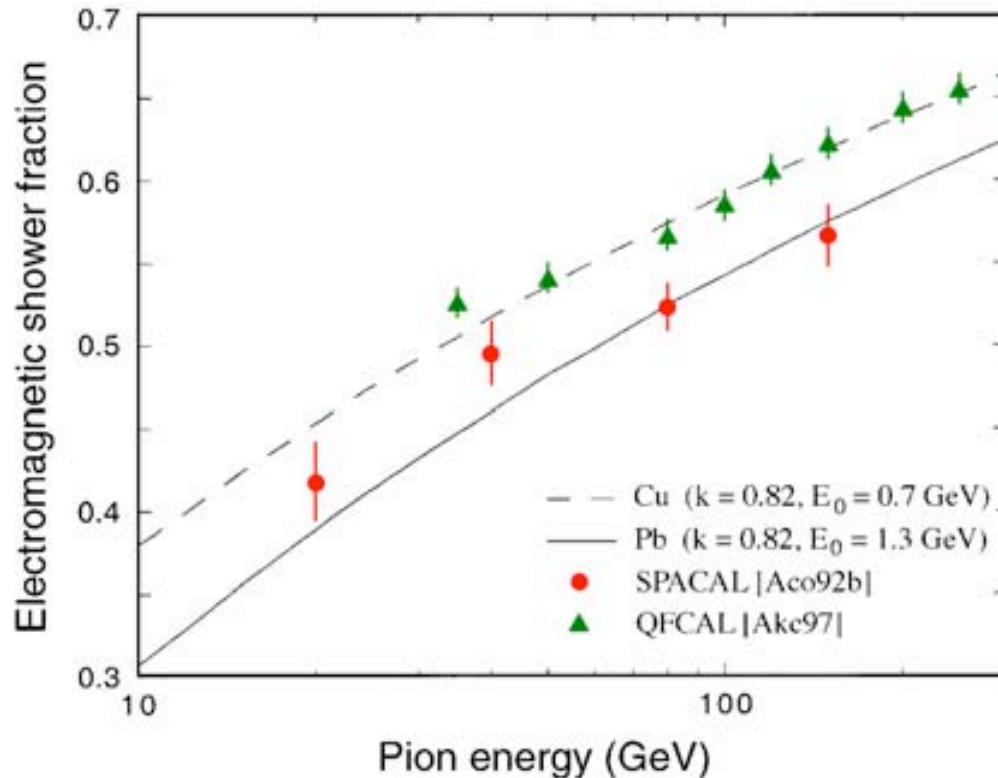
The em fraction is, on average,
large and energy dependent

Fluctuations in f_{em} are
large and non-Poissonian

π° *production is NOT limited to the em section!*

Signal per layer (a.u.)

—— *depth (0 - 6 λ)* ——→

270 GeV π in Pb/scintillator
(hanging-file experiment)

Hadronic showers

- *Large fraction of energy is deposited through em showers (π^0)*

- *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)*

$\Rightarrow$ *Calibration problems even worse than for em calorimeters*

Alternative method: Each section its own particles
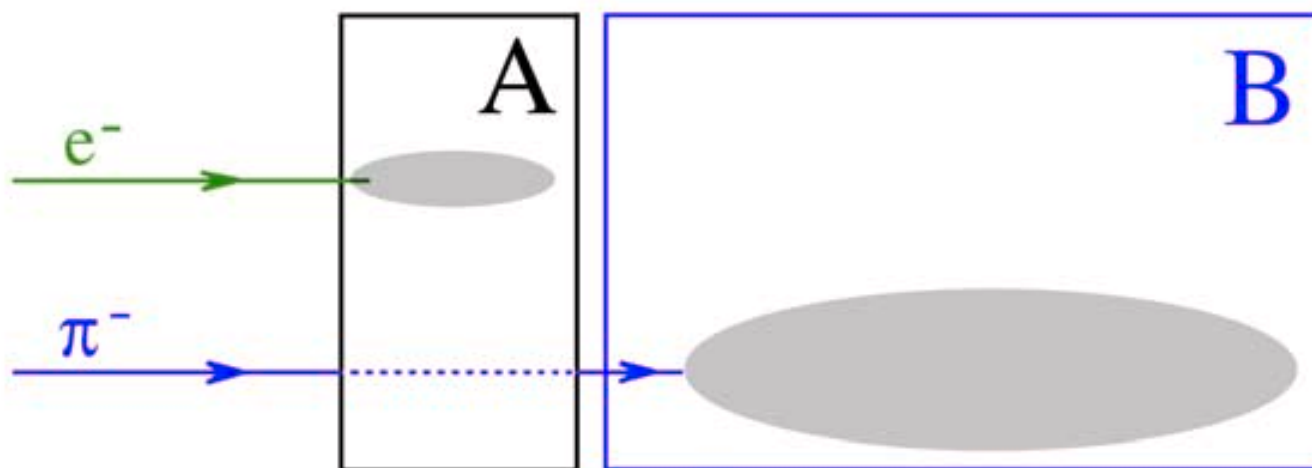
- **Problem:** How about hadrons that start shower in section A?

  - Energy systematically mismeasured
    depending on *e/h* values of sections A,B

  - Reconstructed energy depends on starting point of shower
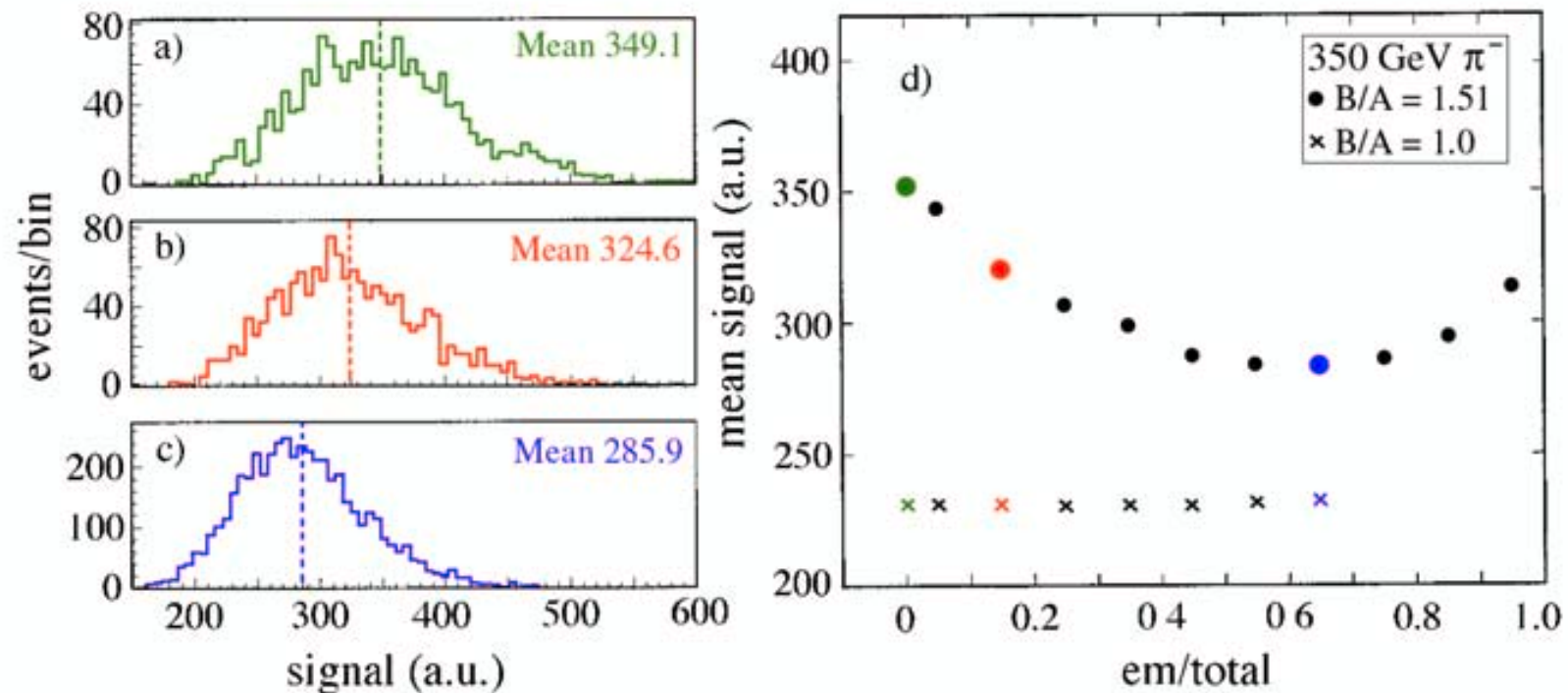
Wrong B/A: Response depends on starting point

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 [Gan 98].
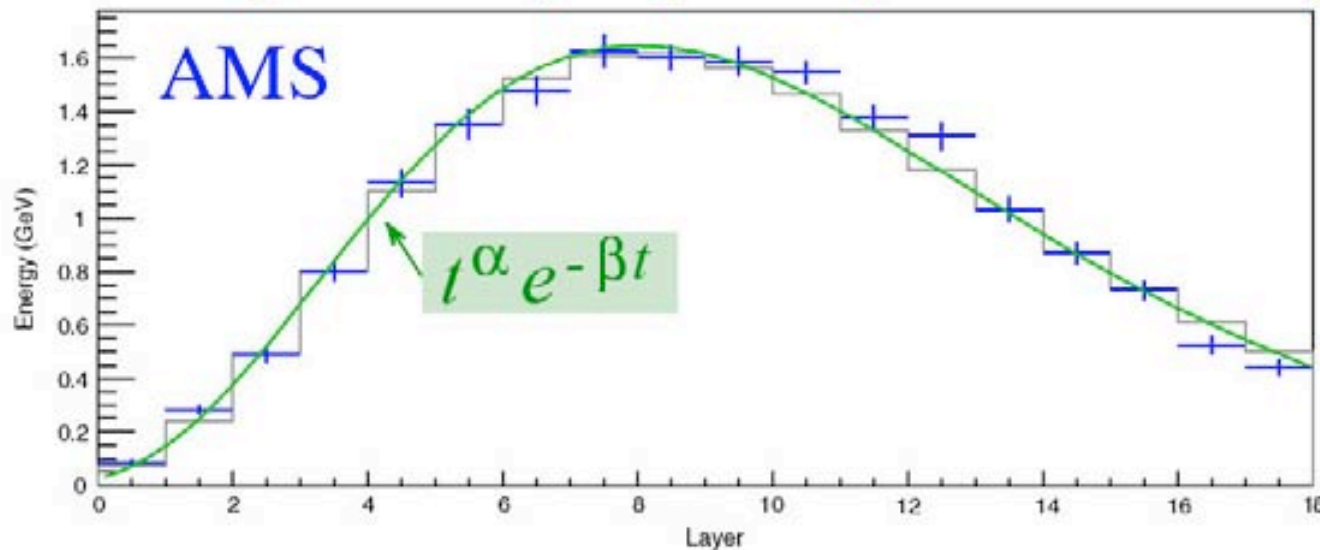
Preliminary conclusions

- Calibration is a very delicate issue

- Discussed strategies (and several others used in practice)
  only work for a subset of events
  (electrons of certain energy, pions penetrating em section, ...)

- Negative consequences for the rest of the events
  - Systematic mismeasurement of energy
  - Reconstructed energy depends on starting point shower
  - Signal non-linearity, ...

- A more correct method: $B/A = 1$
  i.e. calibrate all calorimeter sections in the same way

H o w e v e r ....

CALIBRATION MISERY

Consequences of depth dependence sampling fraction
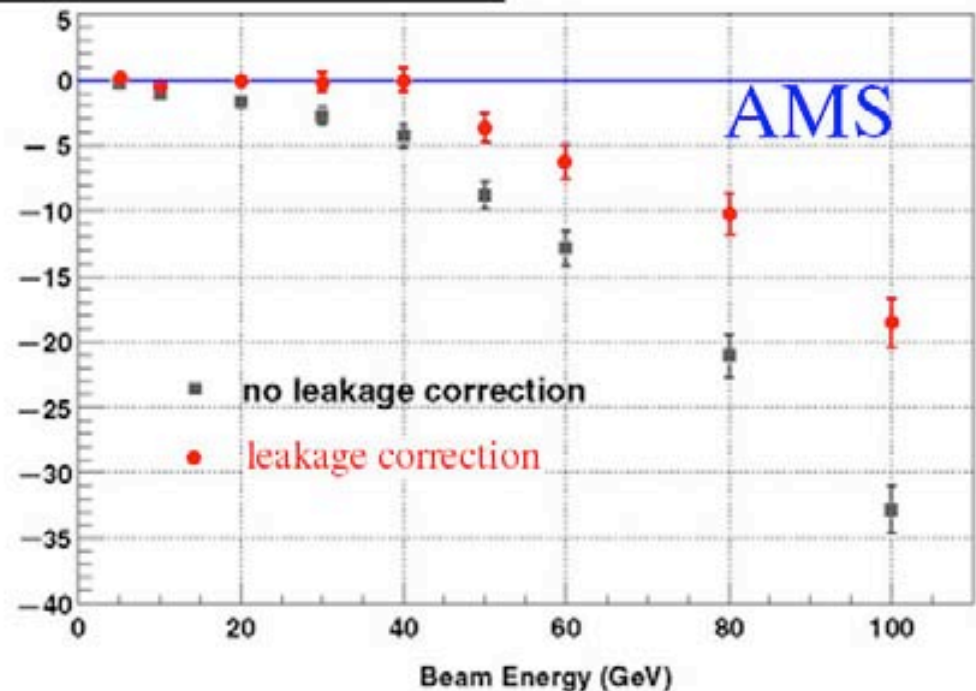
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NIM A490, 132
(2002)

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Shower leakage:
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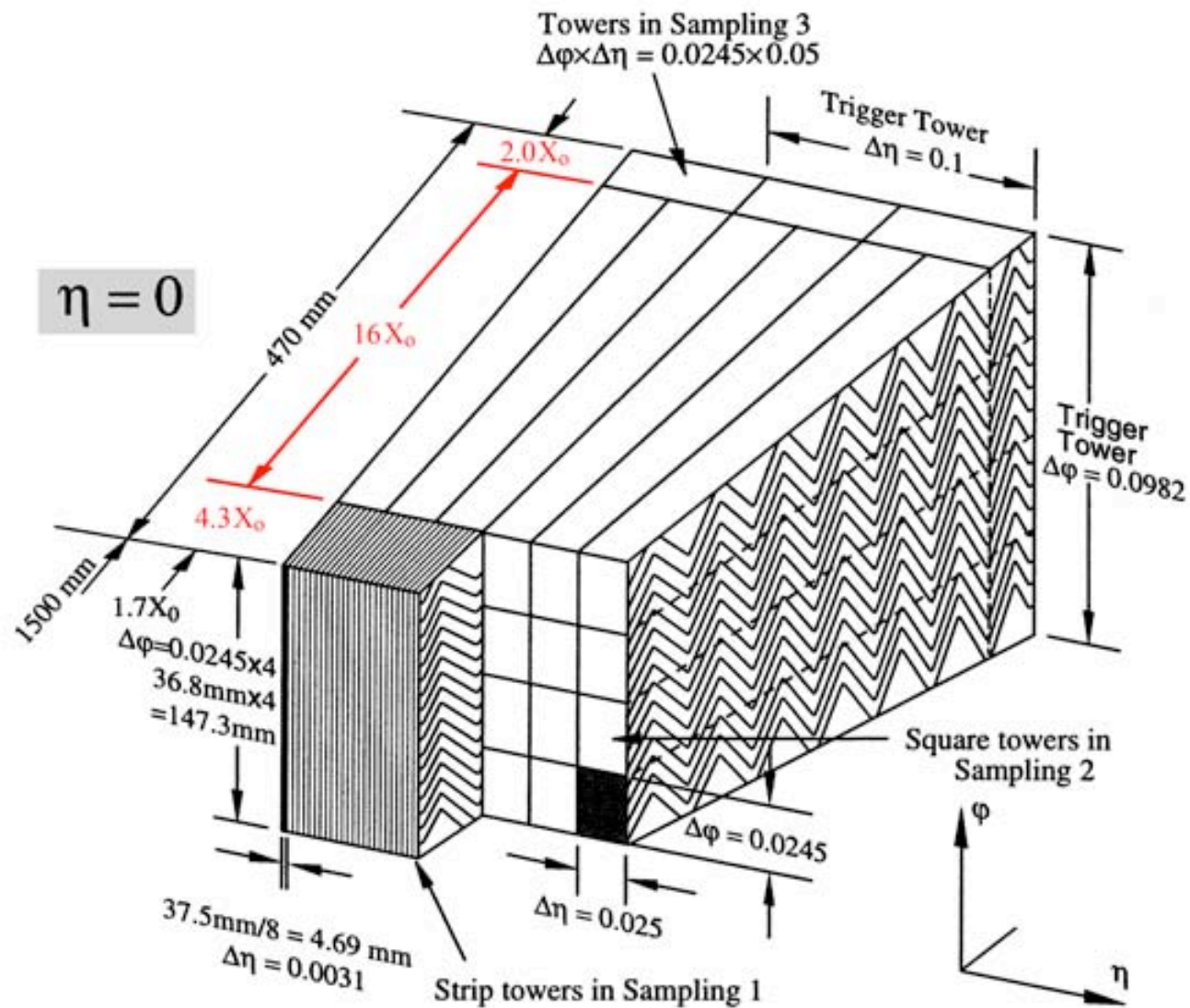of fit to longitudinal profile

Measured energy-Beam Energy (%)

AMS

■ no leakage correction

● leakage correction

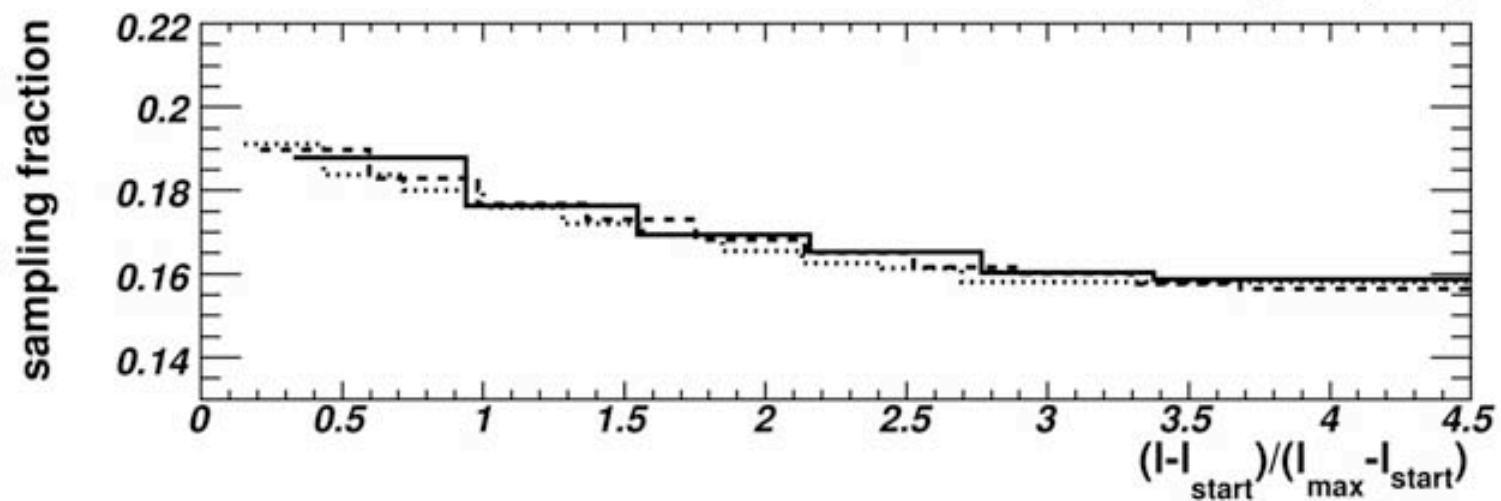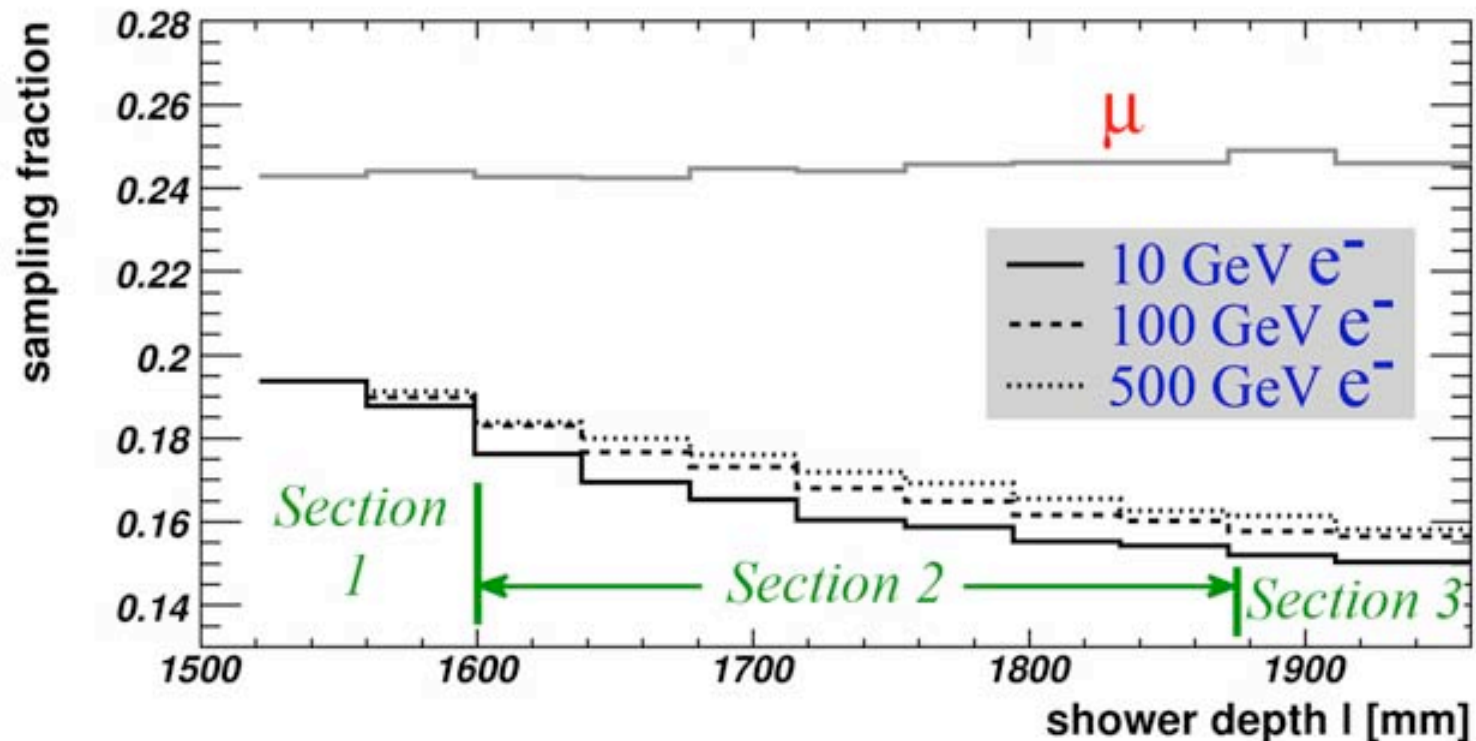Beam Energy (GeV)

So what to do?

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

Monte Carlo simulations!!!

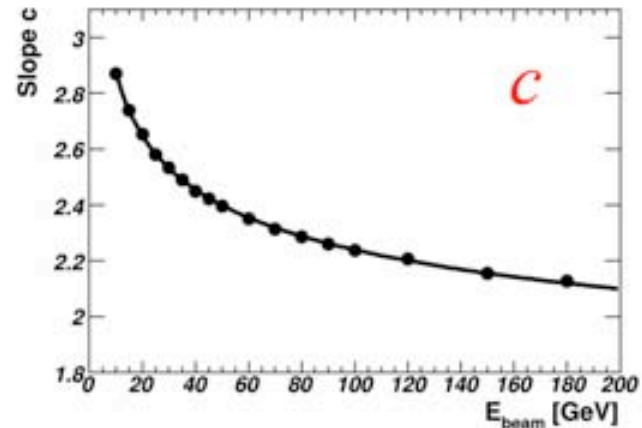# ATLAS: The longitudinally segmented (LAr) ECAL
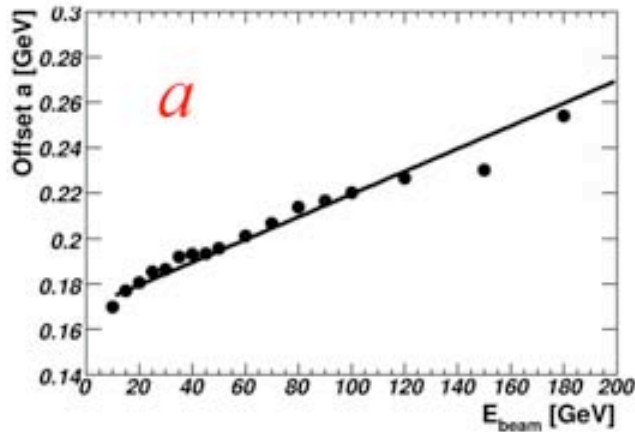

Towers in Sampling 3
$\Delta\varphi \times \Delta\eta = 0.0245 \times 0.05$

Trigger Tower
$\Delta\eta = 0.1$

$\eta = 0$

470 mm

$2.0X_0$

$16X_0$

$4.3X_0$

Trigger Tower
$\Delta\varphi = 0.0982$

1500 mm

$1.7X_0$
$\Delta\varphi = 0.0245 \times 4$
36.8mm$\times$4
=147.3mm

Square towers in Sampling 2

$\Delta\varphi = 0.0245$

φ

37.5mm/8 = 4.69 mm
$\Delta\eta = 0.0031$

$\Delta\eta = 0.025$

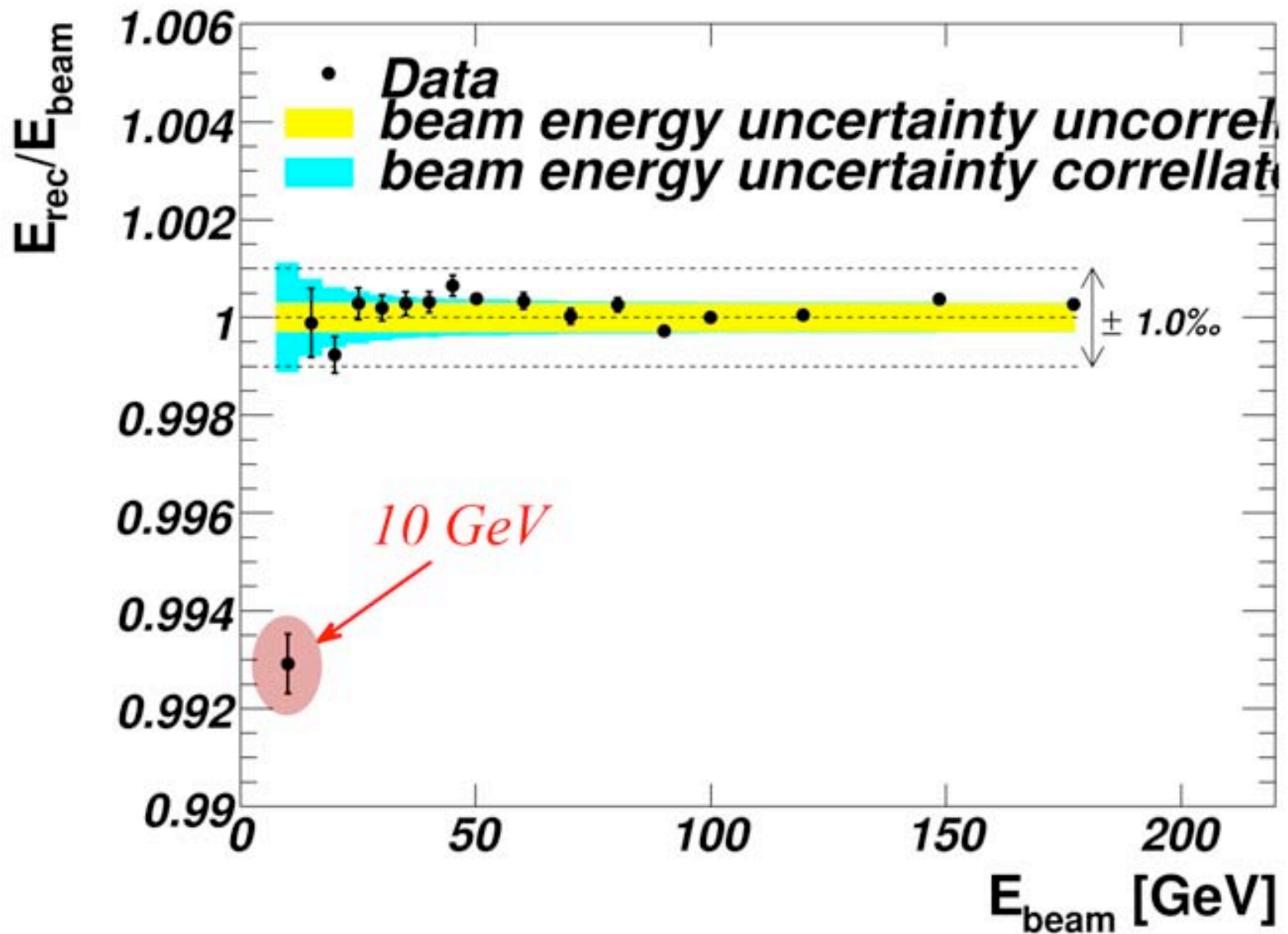Strip towers in Sampling 1

η

ATLAS: Depth dependent em sampling fraction

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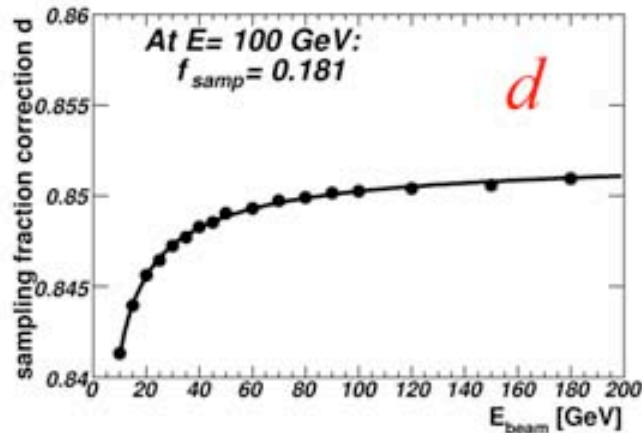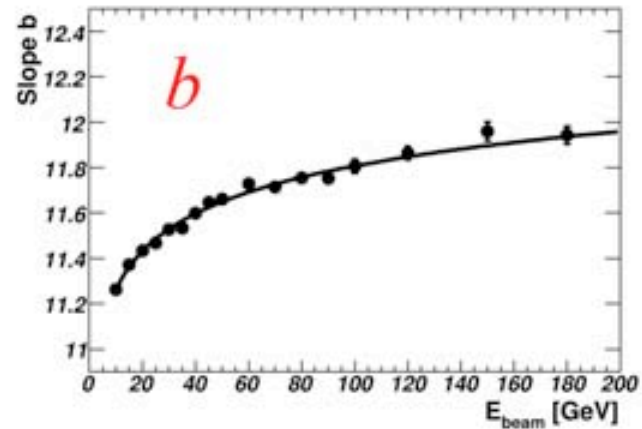
$$E^{rec} = \left(a(E) + b(E)\, E_0^{vis} + c(E)\, (E_0^{vis} \cdot E_1^{vis})^{0.5} + \frac{1}{d(E)\, f_{samp}} \sum_{i=1,3} E_i^{vis} \right) \cdot f_{\text{cell impact}}(\Delta\Phi) \cdot (1 + f_{\text{leakage}})$$

ATLAS: Electromagnetic signal linearity

However, this scheme is only valid for electrons!
(elctron showers ≠ photon showers ≠ π^0 showers)
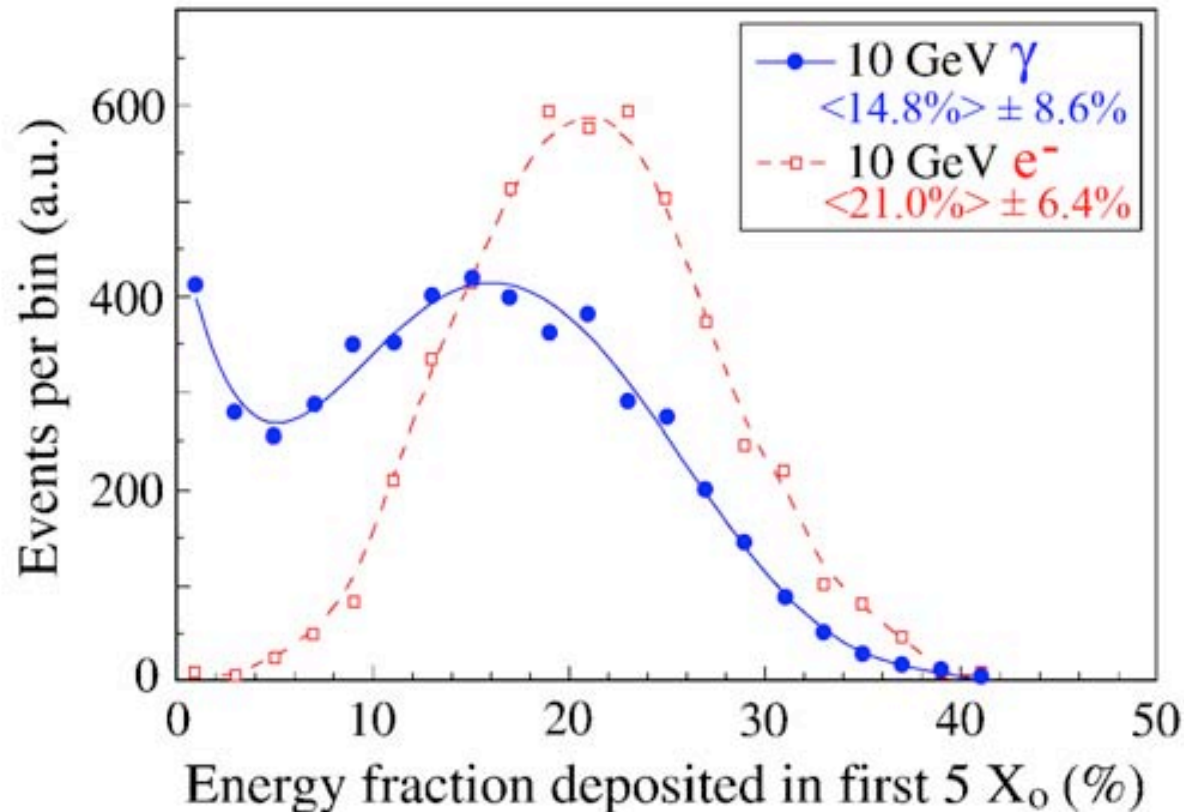
Distribution of the energy fraction deposited in the first 5 radiation lengths by 10 GeV electrons and γs showering in lead. Results of EGS4 simulations.

Some final thoughts

- *Calibration of a longitudinally segmented sampling calorimeter is a nightmare*

- *I don't know how to do it*

- *More sections* $\longrightarrow$ *more problems*

How to avoid these problems??

- *No longitudinal segmentation (what's the purpose anyway?)*

- *Use homogeneous calorimeters*

- *Use sampling calorimeters with $Z_{abs} \approx Z_{act}$*