Effects of calorimeter peculiarities on the jet energy scale

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Jet energy scale = How to interpret calorimeter signals?

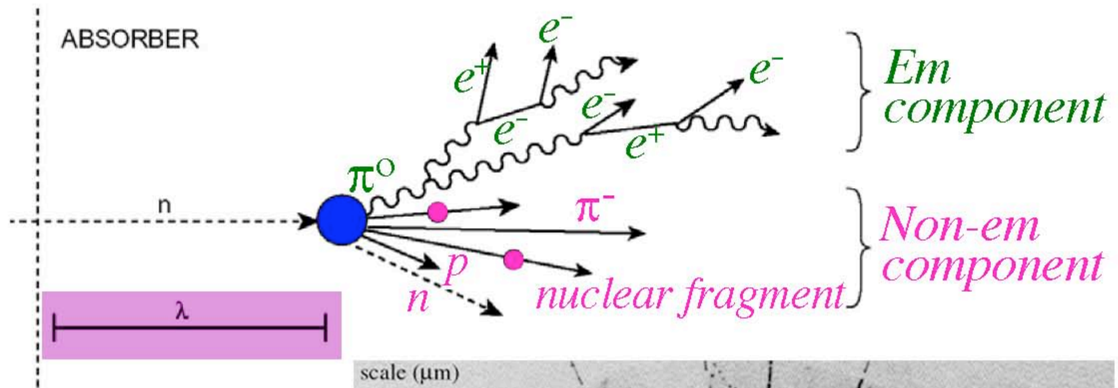
(far from trivial!)

Outline:

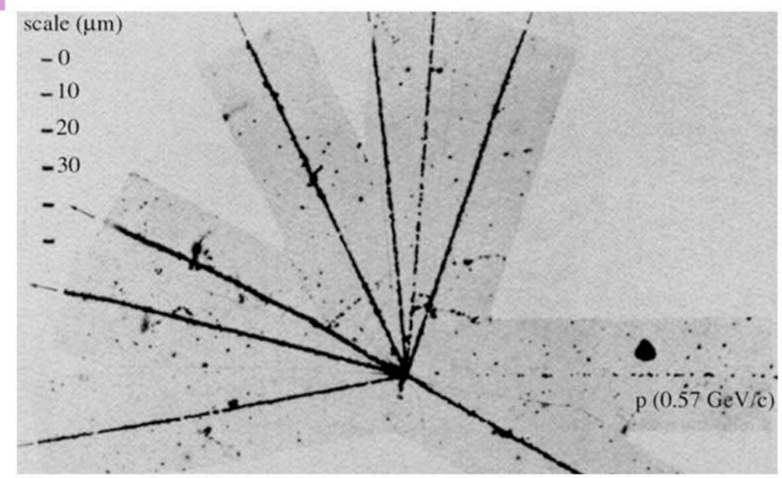
- *General aspects of the calorimeter response to jets*
- *Calibration misery*
- *Failing Monte Carlos*
- *The future of hadron calorimetry*
- *Conclusions*

The physics of hadronic shower development

- *A hadronic shower consists of two components*



- **Electromagnetic component**
  - electrons, photons
  - neutral pions → 2 γ
- **Hadronic (non-em) component**
  - charged hadrons $\pi^{\pm}$,$K^{\pm}$ (20%)
  - nuclear fragments, p (25%)
  - neutrons, soft γ's (15%)
  - break-up of nuclei *("invisible")* (40%)

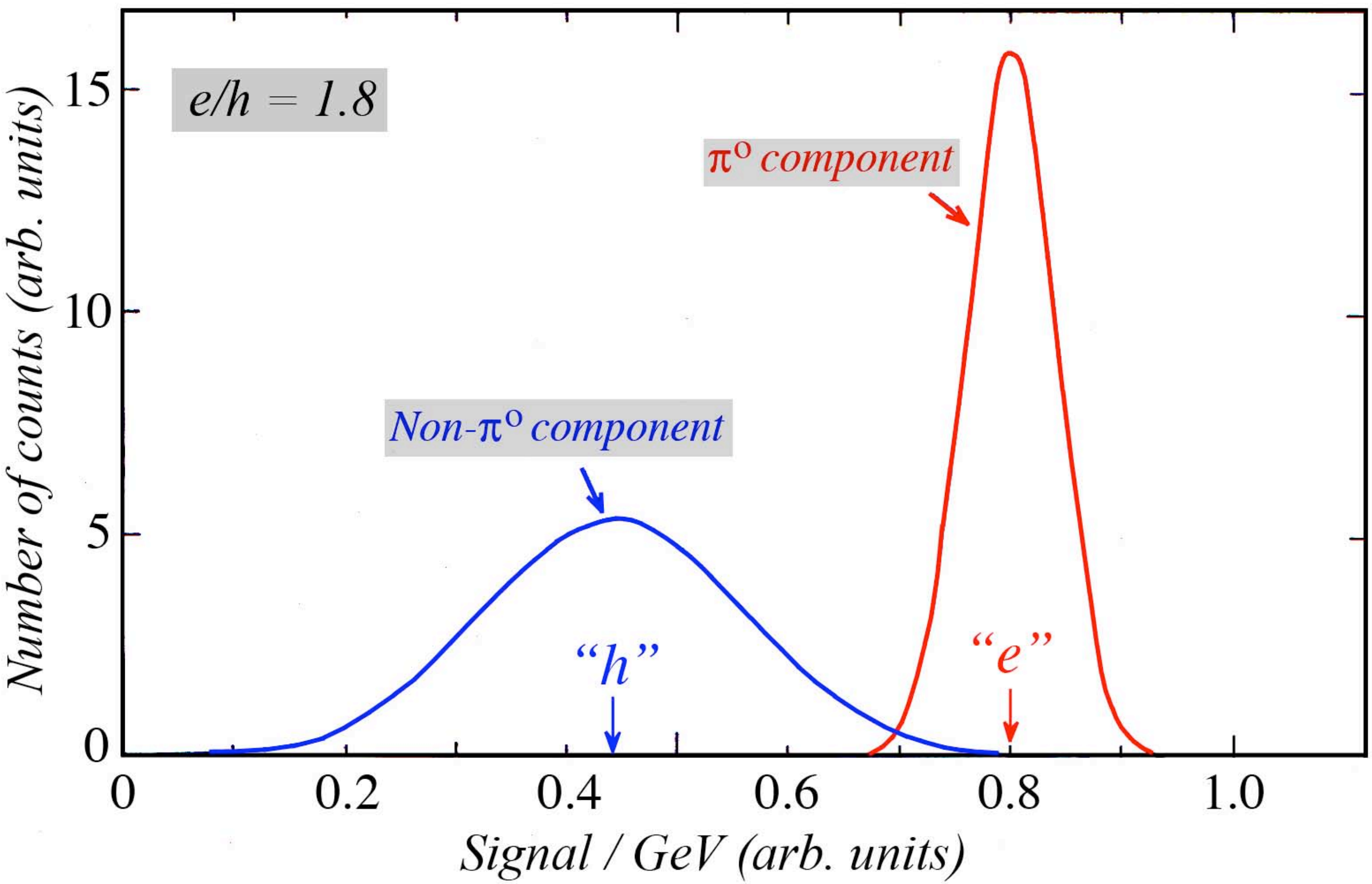


- *Important characteristics for hadron calorimetry:*
  - *Large, non-Gaussian fluctuations in energy sharing em/non-em*
  - *Large, non-Gaussian fluctuations in "invisible" energy losses*

(e.g. 100 GeV π: energy resolution ZEUS 3.5%, D0 7%)

The calorimeter response to the two shower components is NOT the same

(mainly because of nuclear breakup energy losses in non-π^o component)



This effect is quantified by the e/h ratio. For example, in crystal calorimeters, e/h ~ 2, i.e. 50% of the non-em energy deposit is invisible

e/h

its effects on calorimeter preformance

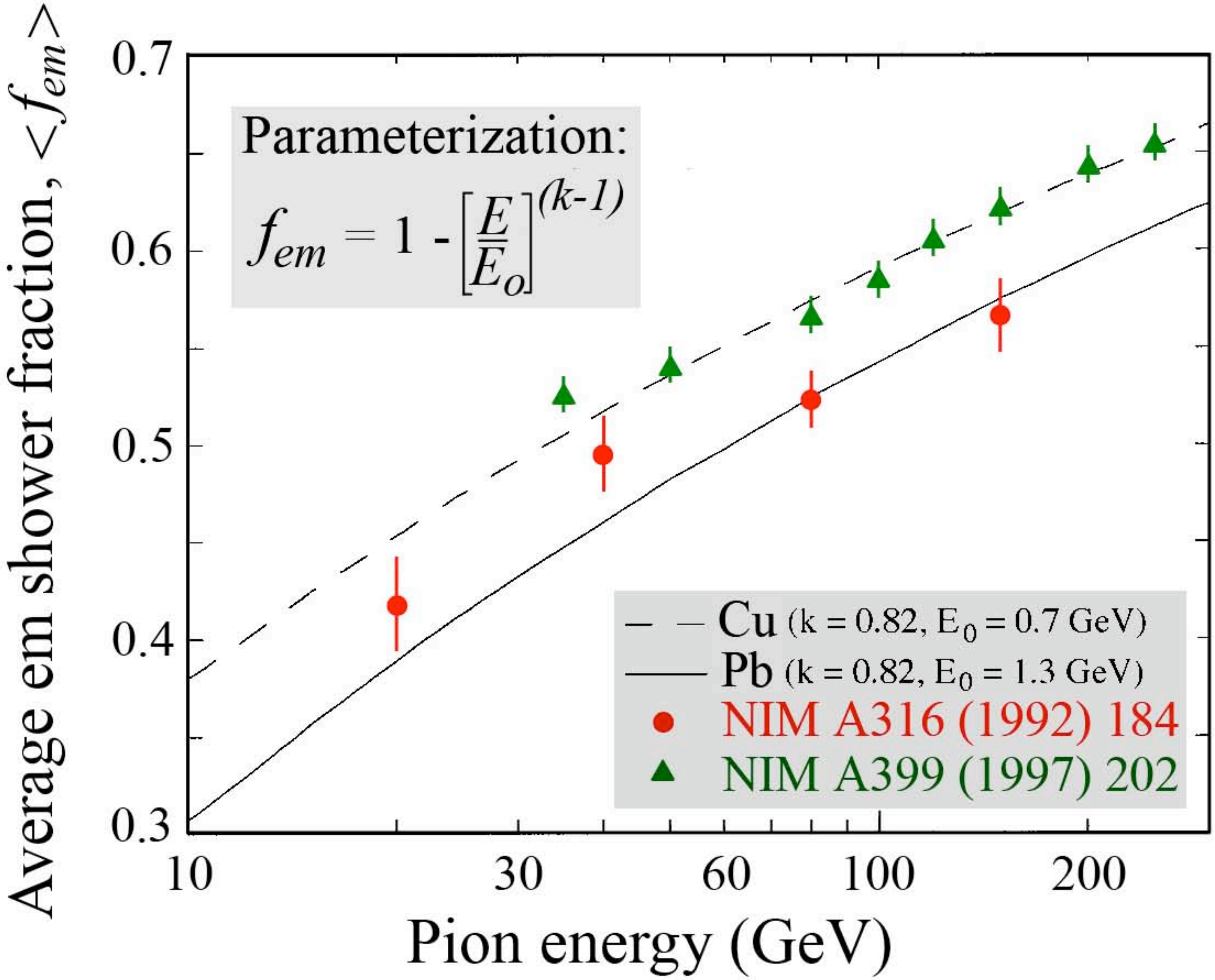
The electromagnetic component of hadron showers

Characteristics affecting calorimeter performance in crucial ways

Let f_{em} (= E_{em}/E_{tot}) be the *em shower fraction*

Characteristic	*Consequence for calorimetry*
• $\langle f_{em} \rangle$ increases with energy	Hadronic signal non-linearity

The em shower fraction, f_{em} (1)



$\langle f_{em} \rangle$ is *large, energy dependent* and *material dependent*

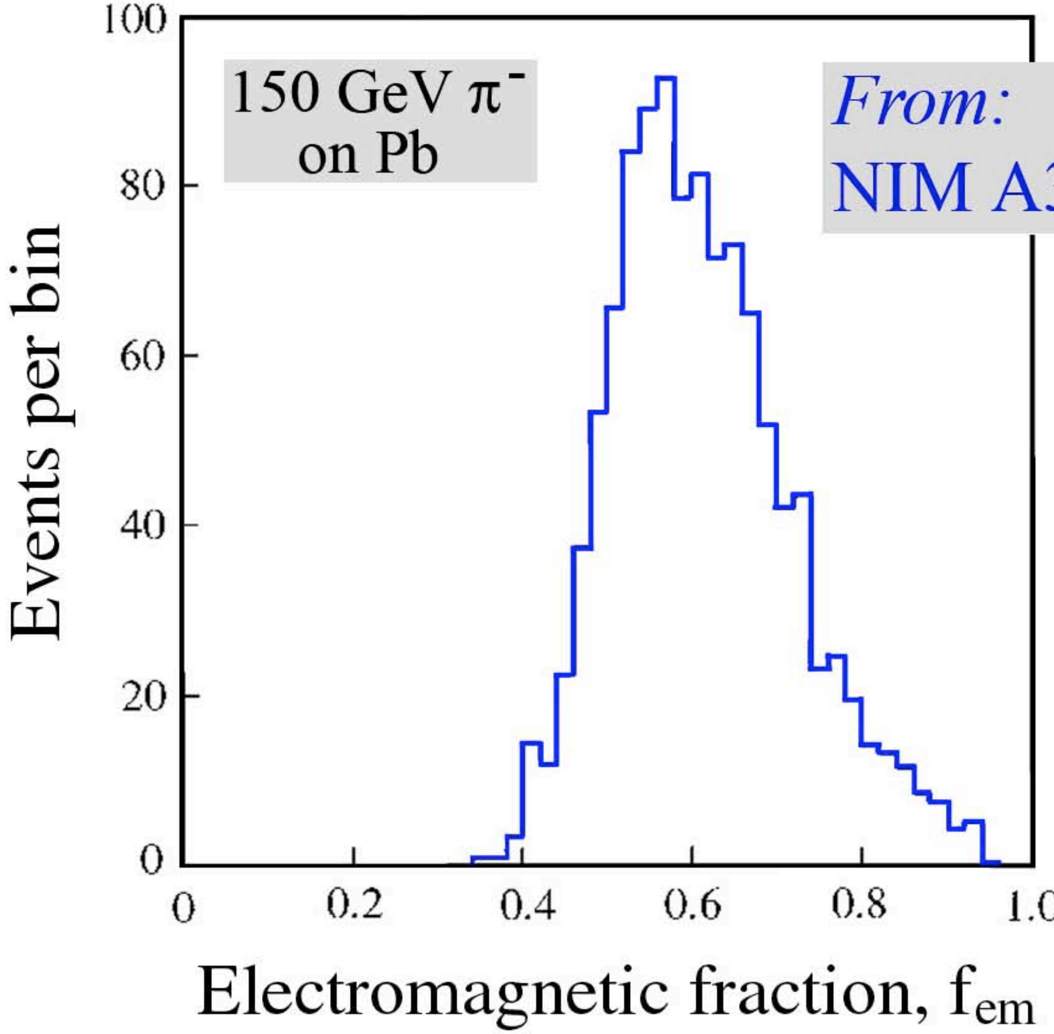
The electromagnetic component of hadron showers

Characteristics affecting calorimeter performance in crucial ways

Let f_{em} (= E_{em}/E_{tot}) be the *em shower fraction*

Characteristic	*Consequence for calorimetry*
• $<f_{em}>$ increases with energy	Hadronic signal non-linearity
• Fluctuations in f_{em} non-Poissonian	Non-Gaussian response function Deviations from $E^{-1/2}$ scaling

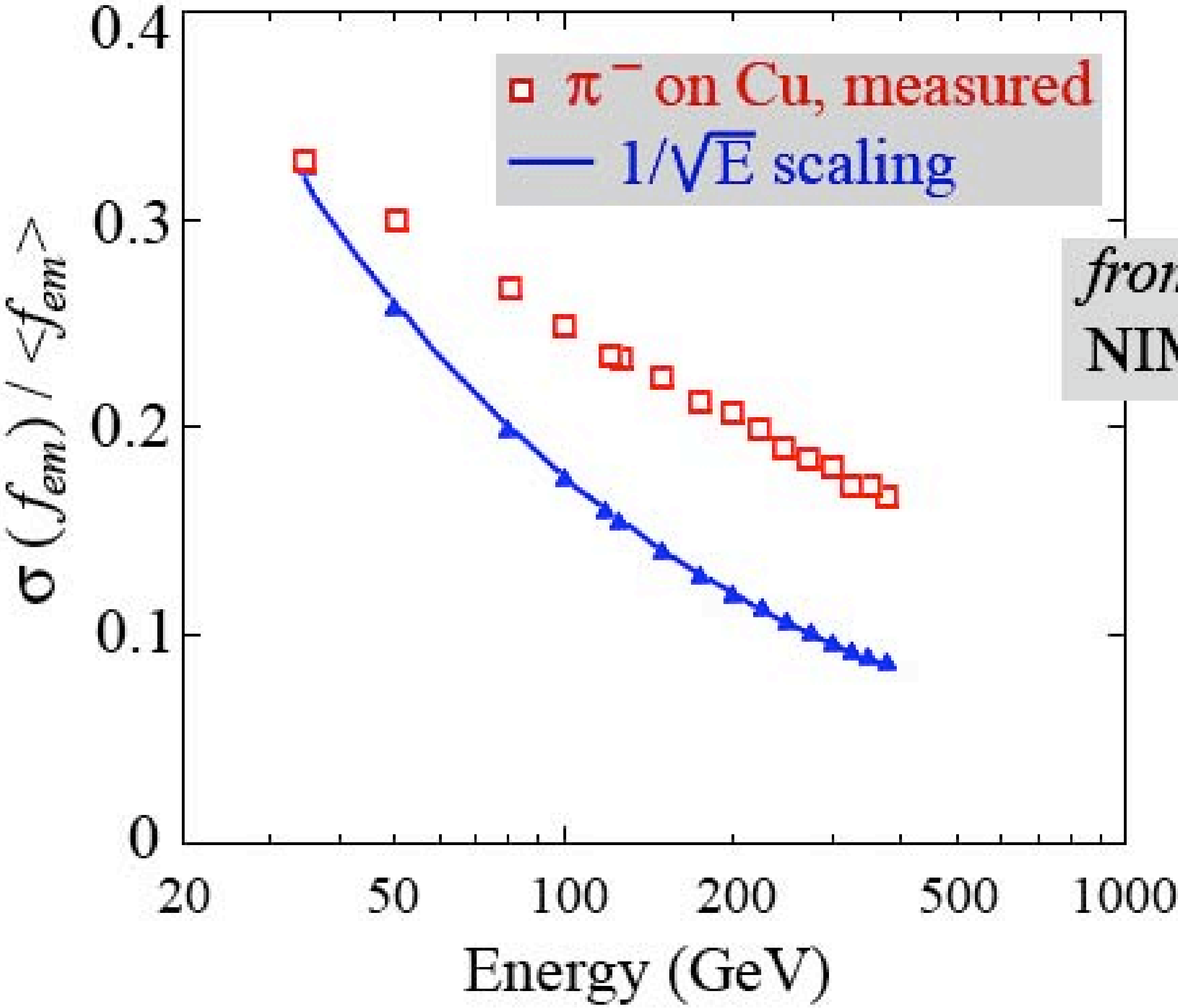
The em shower fraction, f_{em} (2)



From:
NIM A316 (2002) 184

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

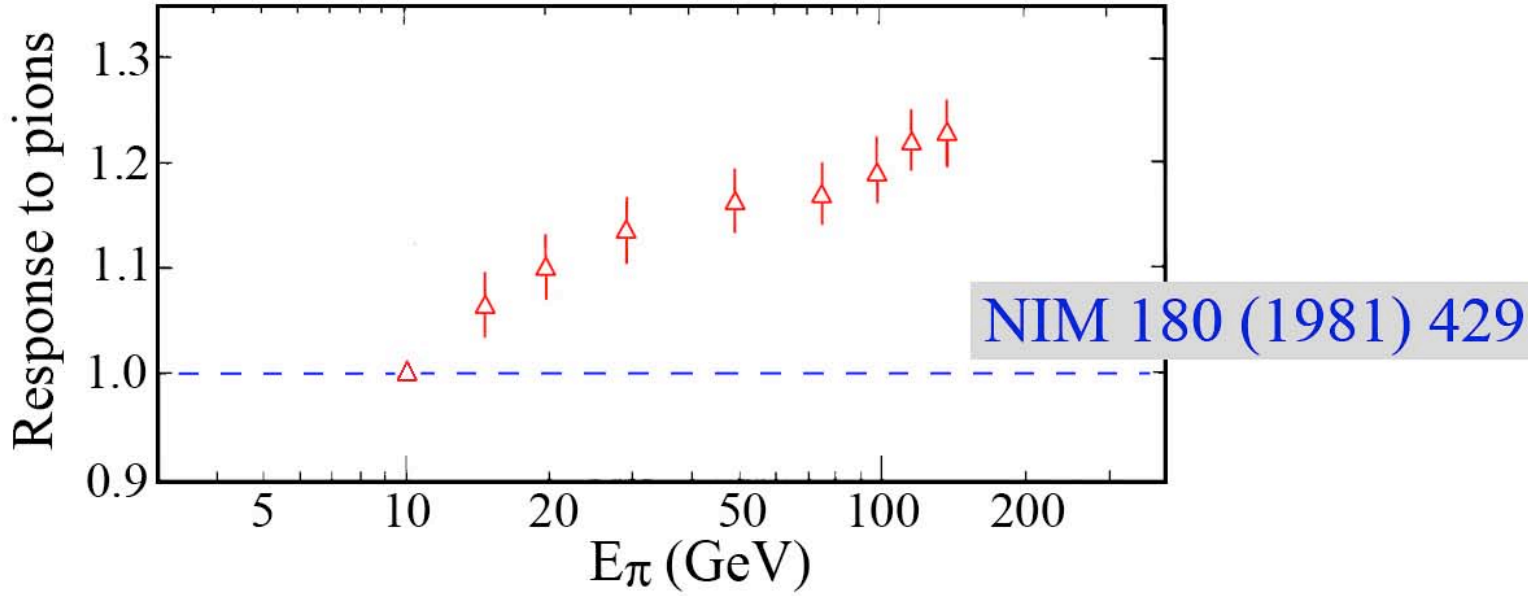
The em shower fraction, f_{em} (3)

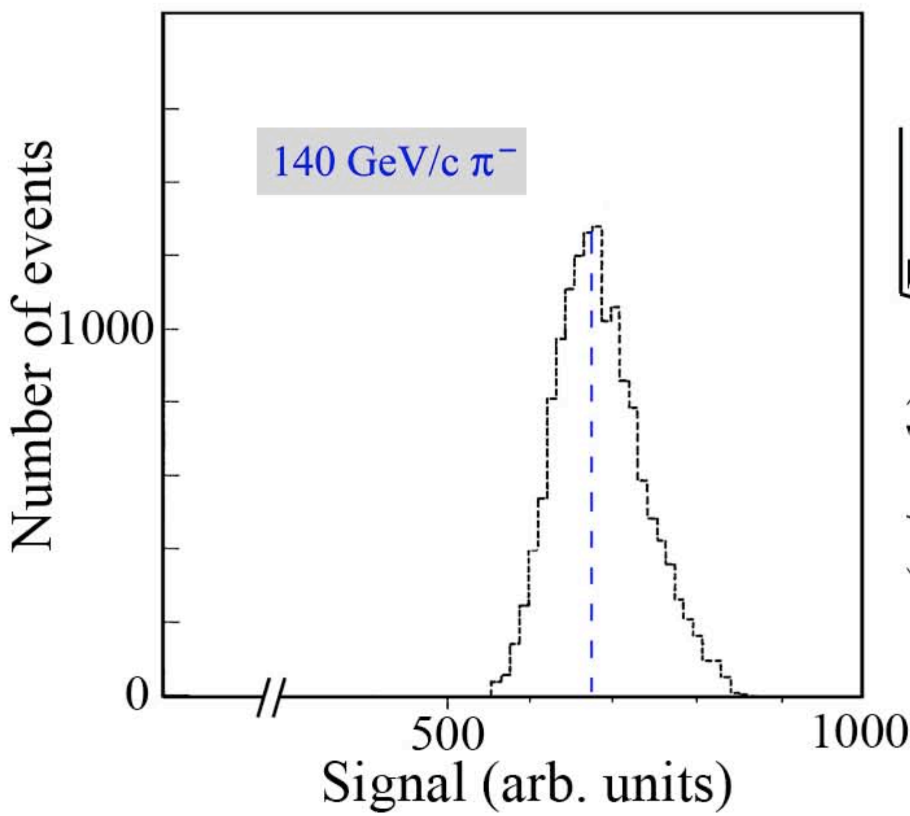


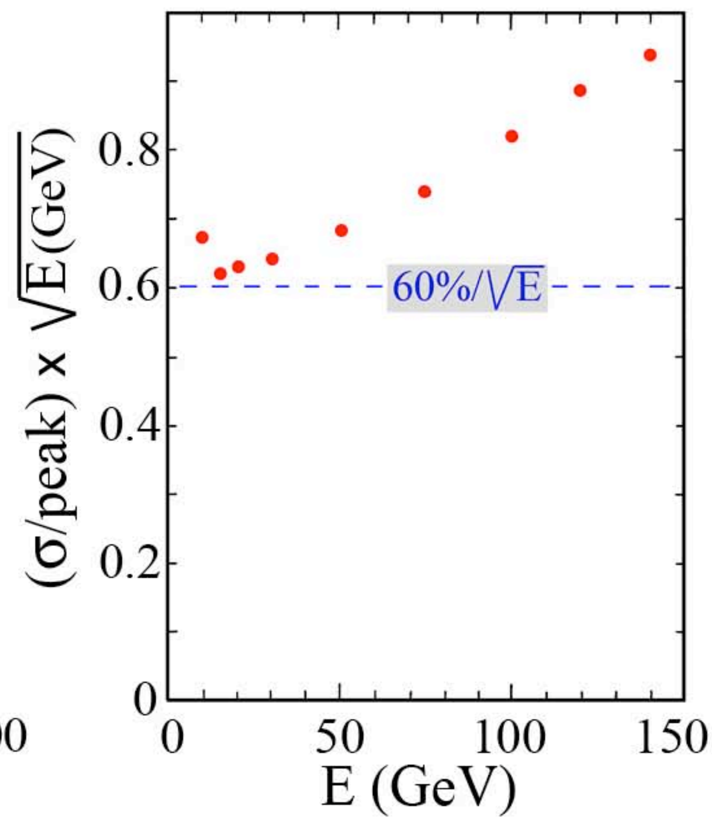
from
NIM A399 (1997) 202

Fluctuations in f_{em} are non-Poissonian

π^o *effects in a calorimeter with e/h = 1.5*







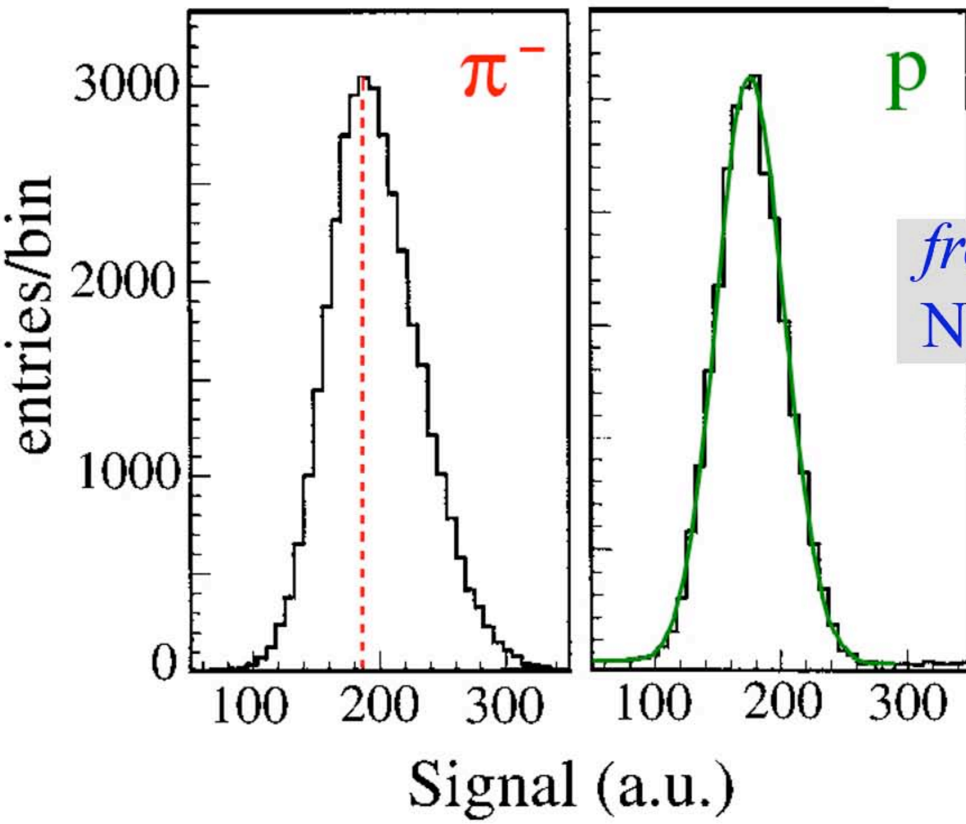
The electromagnetic component of hadron showers

Characteristics affecting calorimeter performance in crucial ways

Let f_{em} (= E_{em}/E_{tot}) be the *em shower fraction*

Characteristic	*Consequence for calorimetry*
• $<f_{em}>$ increases with energy	Hadronic signal non-linearity
• Fluctuations in f_{em} non-Poissonian	Non-Gaussian response function Deviations from $E^{-1/2}$ scaling
• Differences between *p* and π	Differences in response Differences in response function

The em shower fraction, f_{em} (4)



300 GeV showers
in Cu

from:
NIM A408 (1998) 380

f_{em} fluctuations are different in π- and *p*-induced showers

The electromagnetic component of hadron showers

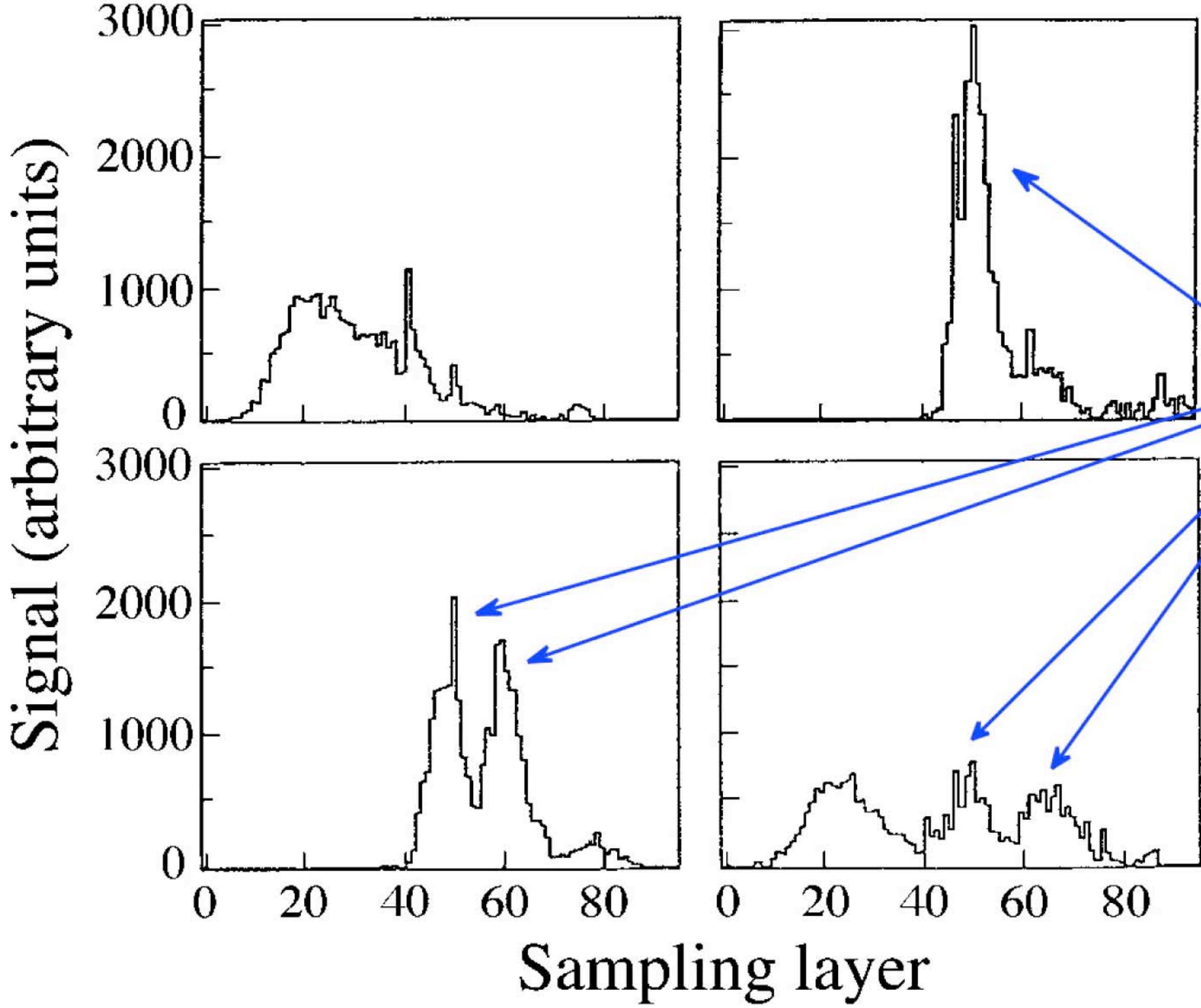
Characteristics affecting calorimeter performance in crucial ways

Let f_{em} (= E_{em}/E_{tot}) be the *em shower fraction*

Characteristic	*Consequence for calorimetry*
• $\langle f_{em} \rangle$ increases with energy	Hadronic signal non-linearity
• Fluctuations in f_{em} non-Poissonian	Non-Gaussian response function Deviations from $E^{-1/2}$ scaling
• Differences between *p* and π	Differences in response Differences in response function
• Em component distributed over entire shower development	No “characteristic” profiles

Calibration problems for hadronic shower detection

π^o production may take place anywhere in the absorber



- depth (0 - 6 λ) →

270 GeV π in Pb/Fe/scint.
(hanging-file calorimeter)

π^o production in HAD section

The em shower component is sampled more efficiently than the non-em one

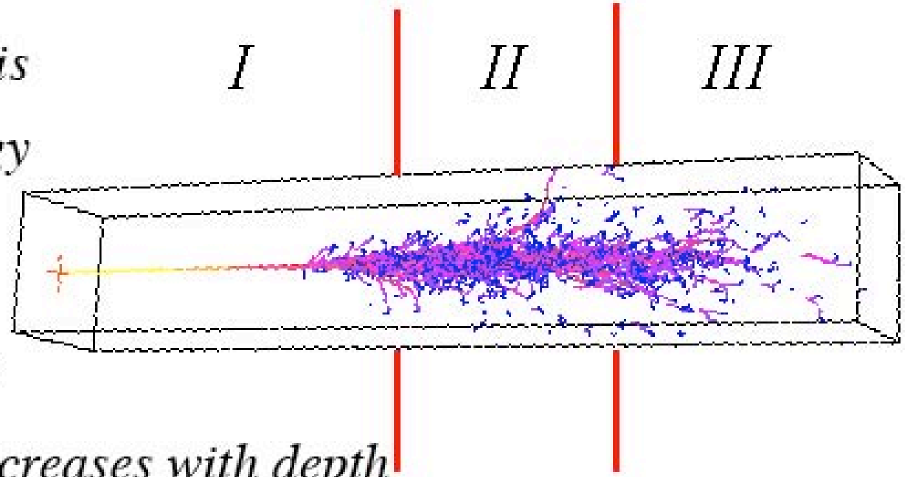
The calibration constant of each individual sampling layer thus depends on the type of event.

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. γ from π° decay), the energy is systematically UNDERESTIMATED

→ Non-linearity + energy dependence on starting point shower

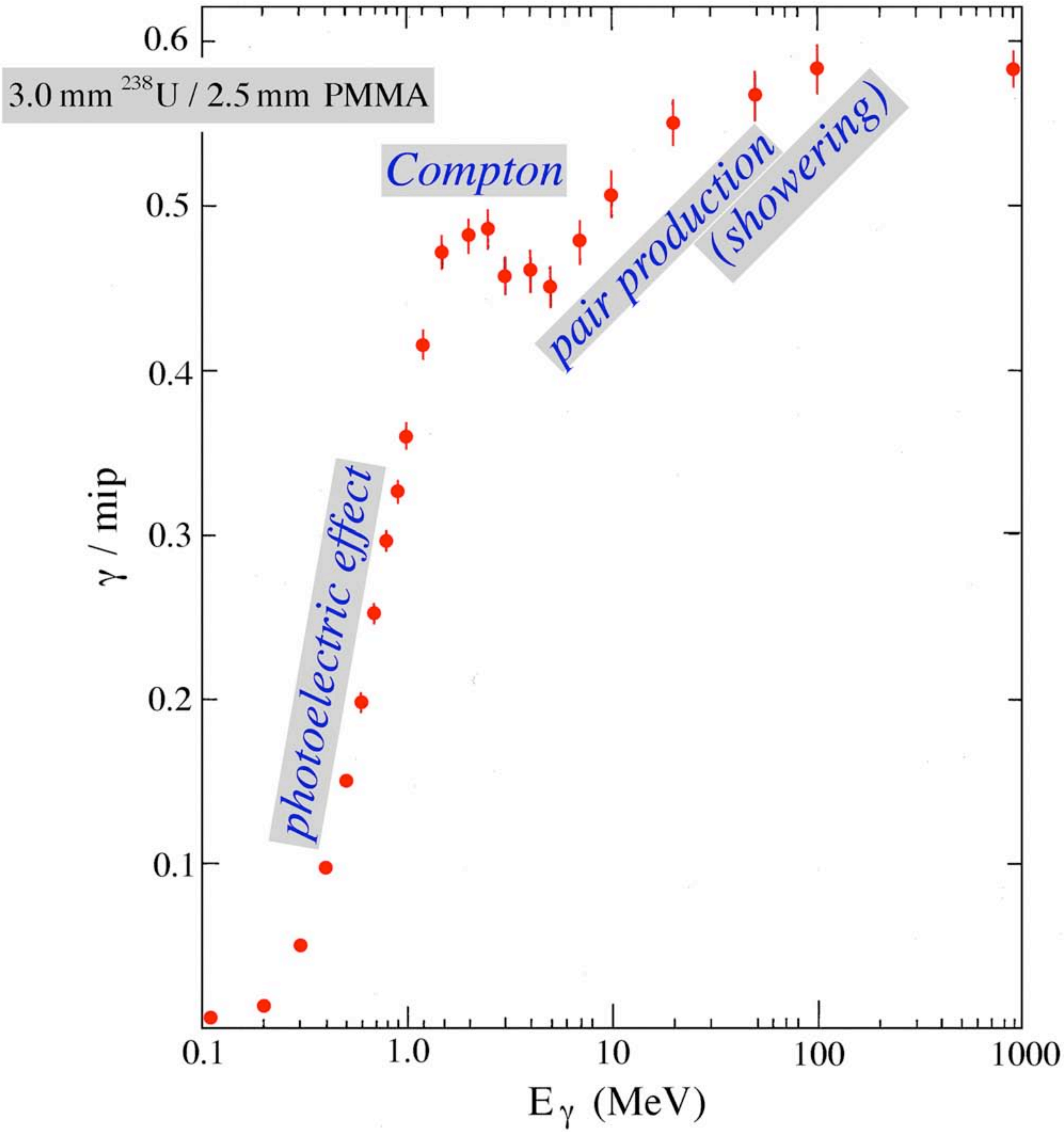
Calibration of calorimeter systems

- Determine relationship between *signal* (pC, p.e.) and *energy* (GeV)

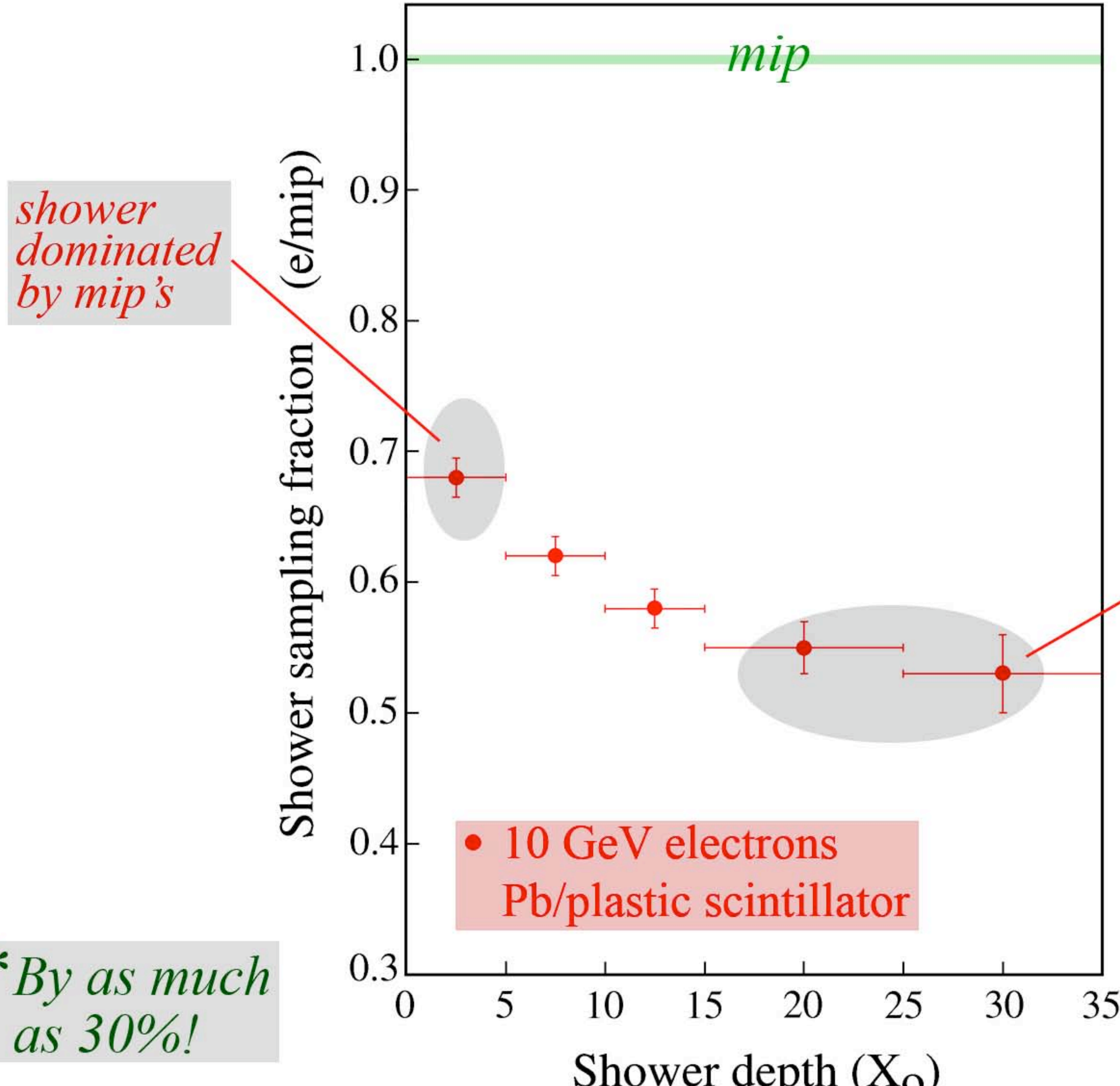
- *Fundamental problem in sampling calorimeters:*
  Different shower components are sampled differently
  Shower composition changes as shower develops
  → *Sampling fraction changes with the shower age* (also E dependent)

How to intercalibrate the sections
of a longitudinally segmented calorimeter?

Sampling fraction of γs, generated at random points inside a calorimeter



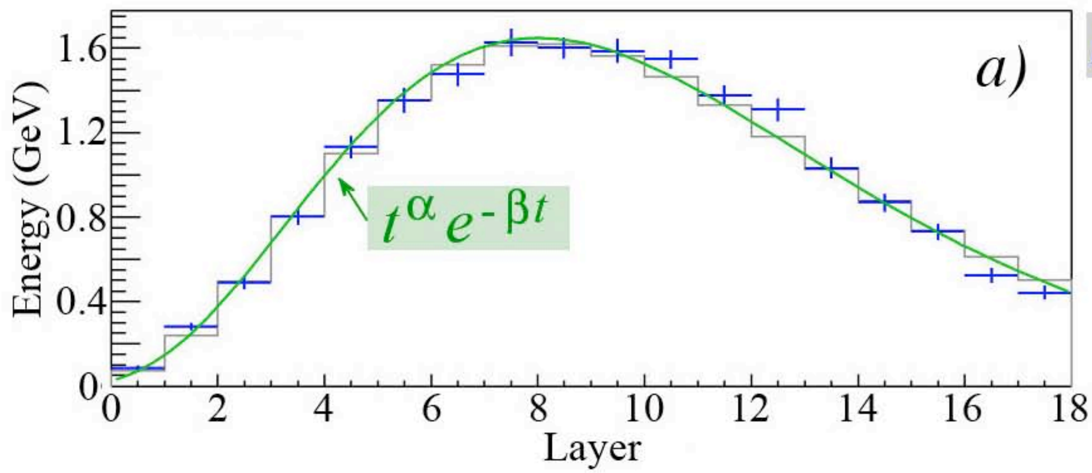
*The sampling fraction changes as shower develops**



**By as much as 30%!*

Calibration misery of longitudinally segmented devices

Example: AMS (em showers!)



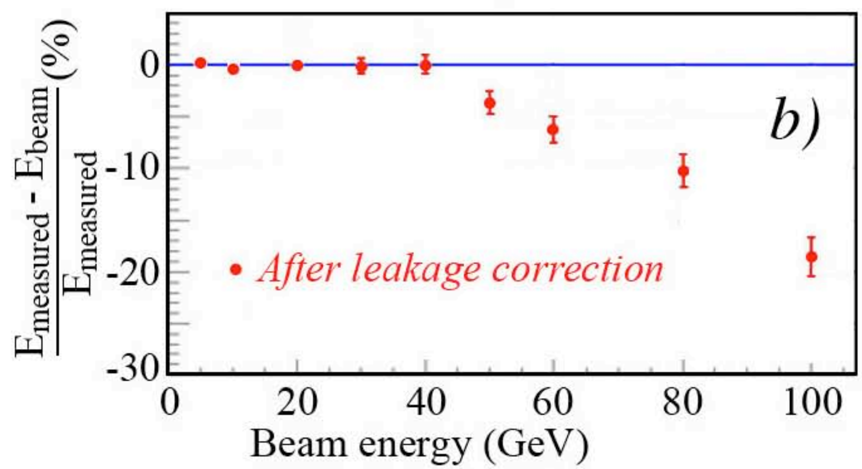
Source: NIM A490 (2002) 132

Pb/scintillating fiber (18 layers)

Calibrated with mip's: 11.7 MeV/layer

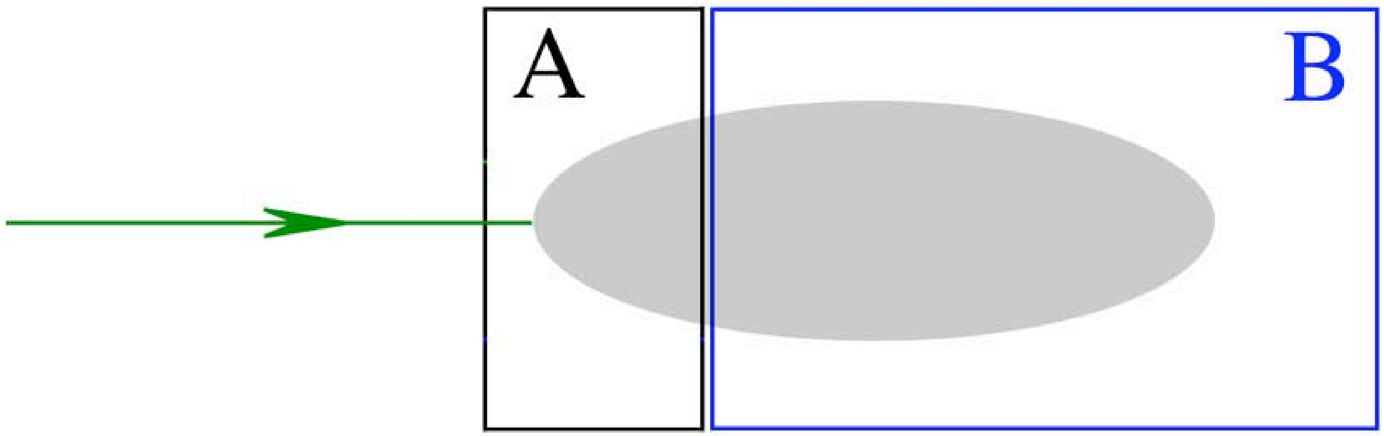
Leakage estimated from fit to measured shower profile

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

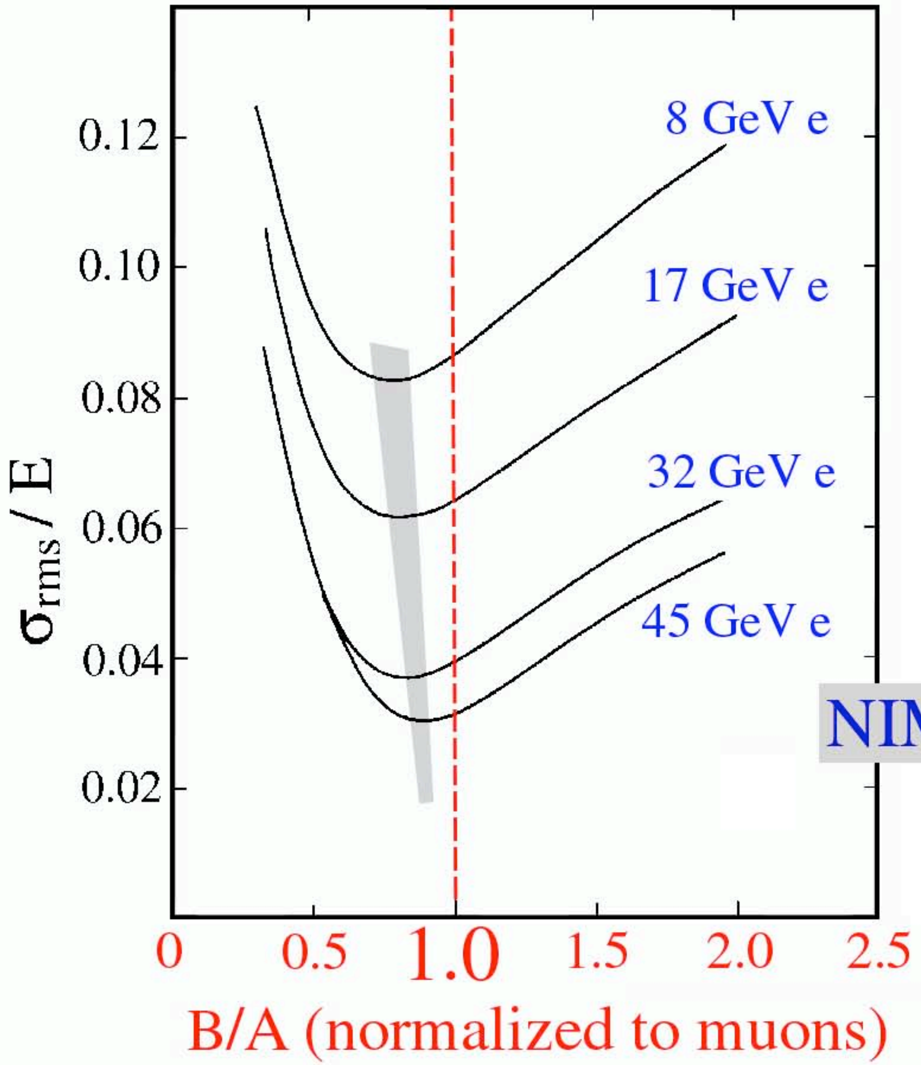
A widely used technique for calibrating segmented devices



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

→ *Determine A,B*

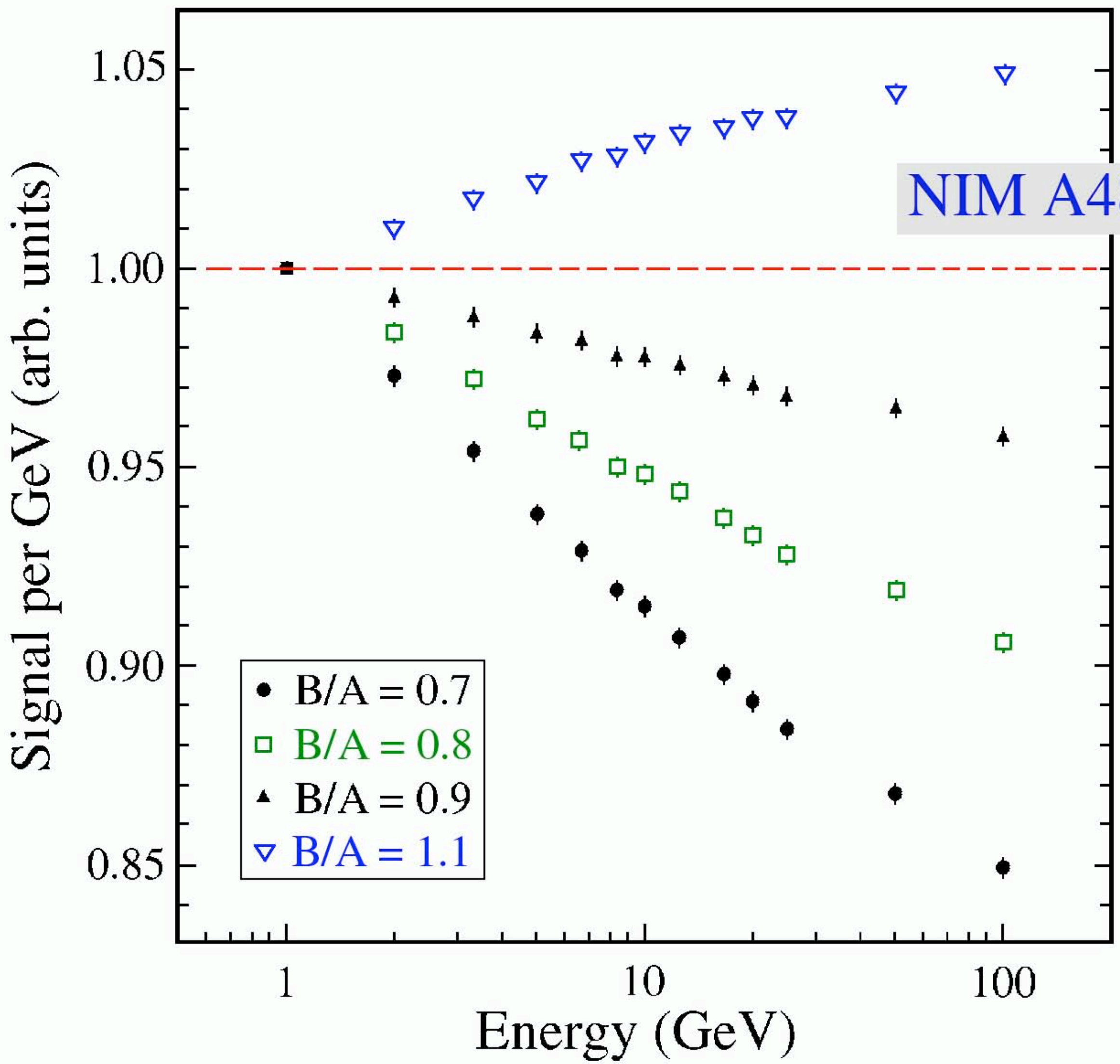
Calibrating longitudinally segmented calorimeters



NIM A262 (1987) 243

FIG. 6.2. The fractional width σ/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



NIM A485 (2002) 385

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

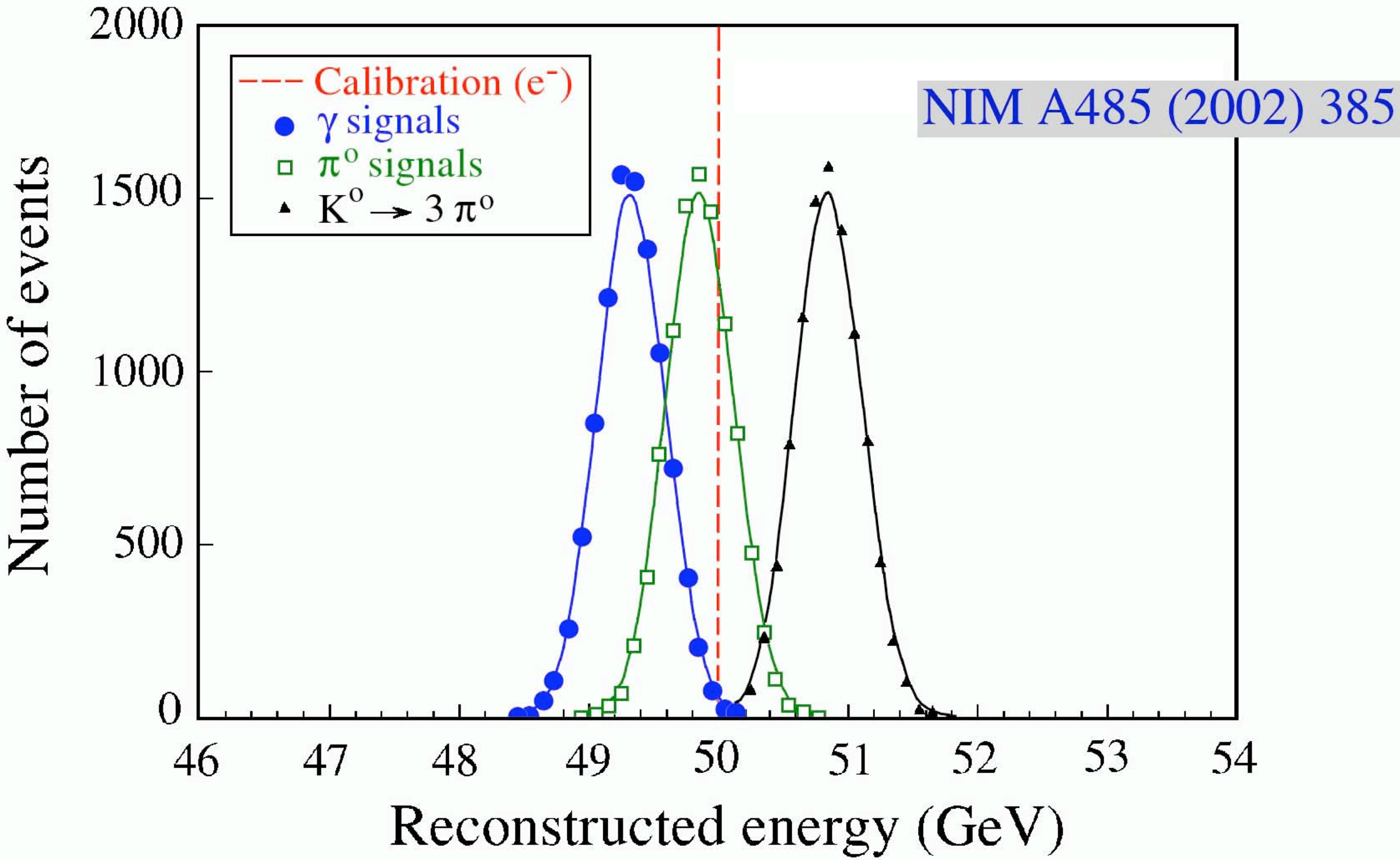


Figure 14: Signal distributions for γs and various hadrons decaying into all-γ final states. All particles have the same nominal energy and the detector, which has an intrinsic resolution of 0.5% for em showers of this energy, was calibrated with electrons using $B/A = 0.8$. See text for details.

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

Hadronic showers

Additional complications for intercalibrating longitudinal sections

- *em showers (from π^{o} decay) can start anywhere*
- *sampling fraction of non-em component also changes with depth*
- *response to em and non-em components not the same (if e/h $\neq$ 1)*
- *large event-to-event fluctuations in energy sharing em/non-em*

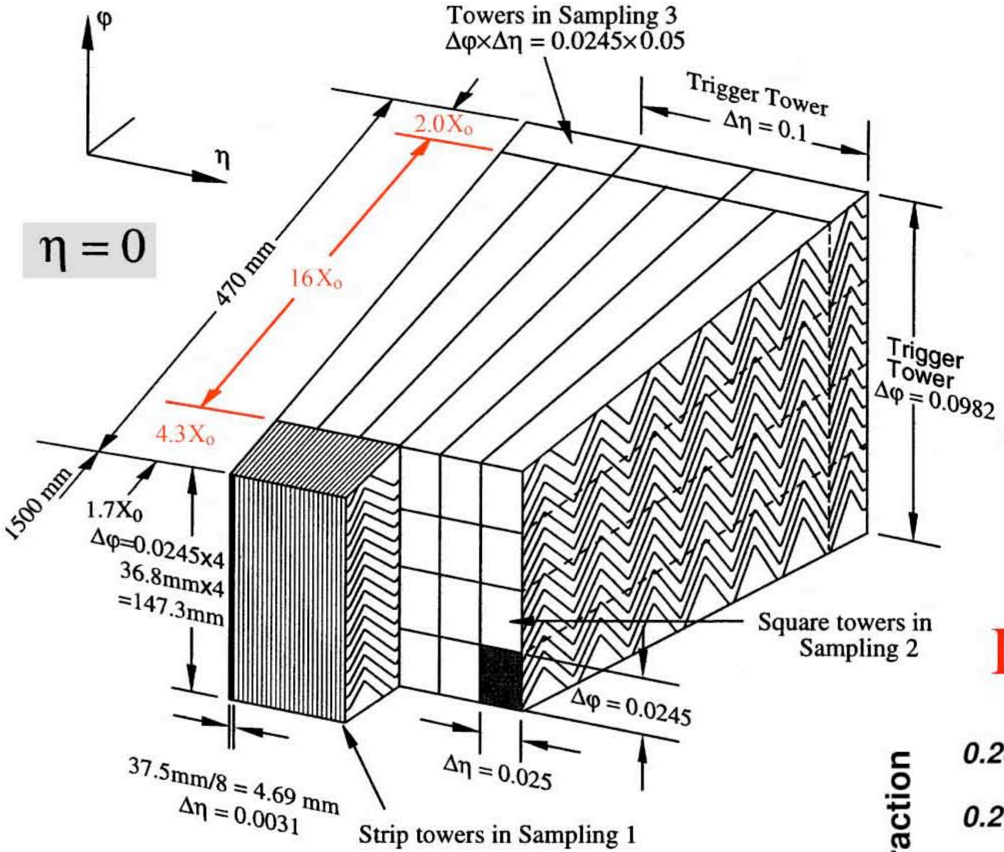
$\Rrightarrow$ *Calibration problems even worse than for em calorimeters*

So what to do?

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

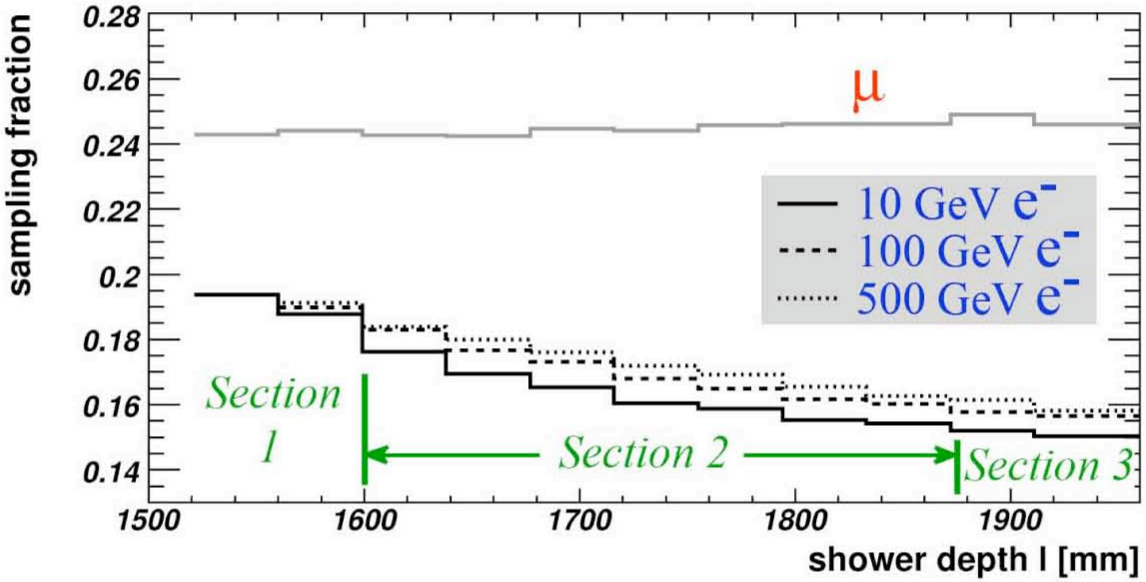
Monte Carlo simulations!!!

ATLAS: The longitudinally segmented (LAr) ECAL

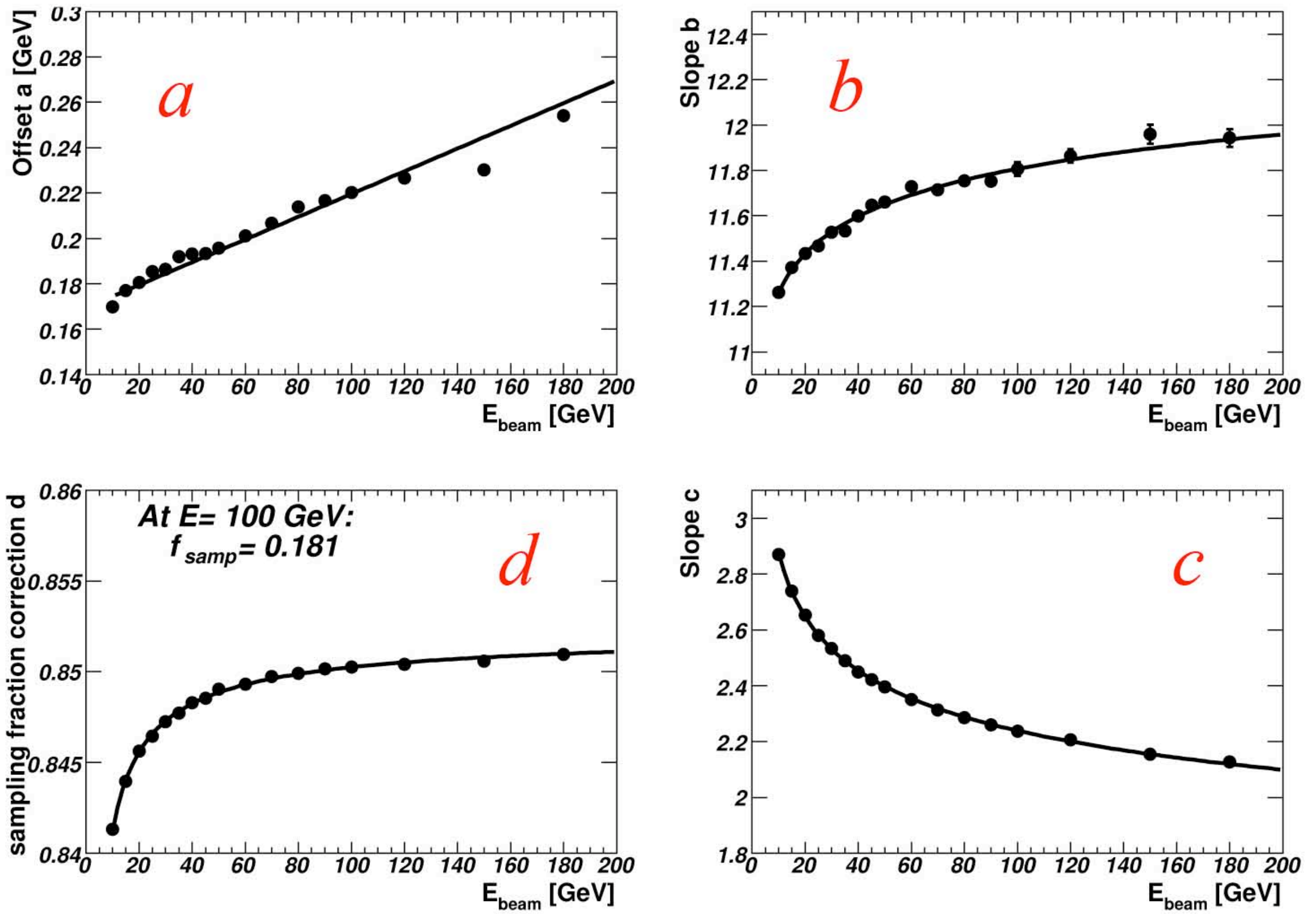


NIM A568 (2006) 601

Depth dependent em sampling fraction



ATLAS: Energy reconstruction ECAL



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

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.

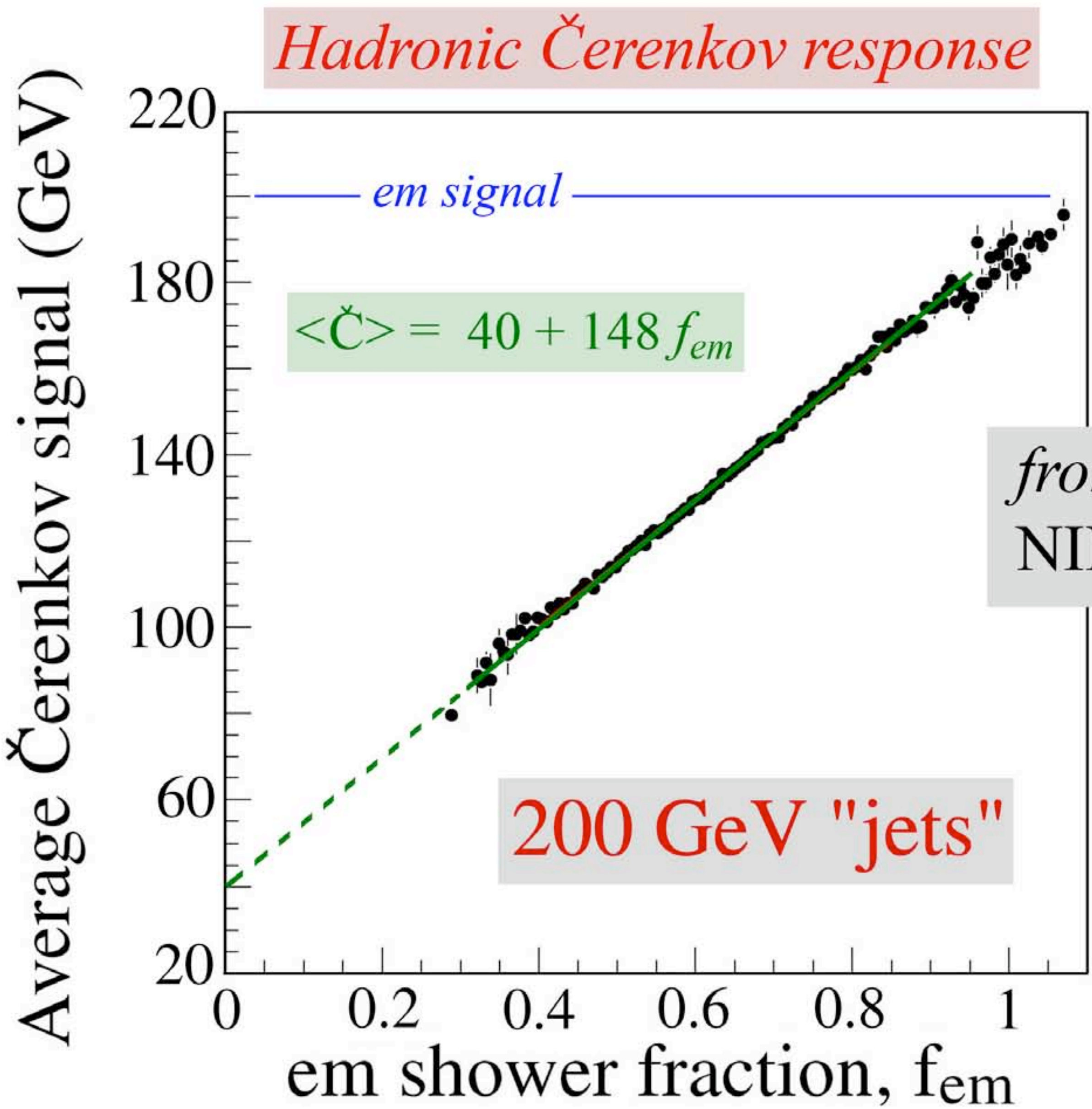
The non-electromagnetic shower component (1)

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



$$R = f_{em} \cdot e + (1\text{-}f_{em}) \cdot h$$
$$= p_0 + p_1 f_{em}$$

from:
NIM A537 (2005) 537

$$f_{em} = 0 \longrightarrow R_h = 0.2\, R_{em}$$
$$< 0.2\, R_{mip}$$

The non-electromagnetic shower component (2)

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

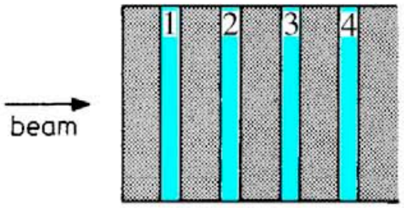
1) Because of the small hadronic signals (i.e. large e/h values) of calorimeters that are blind to these protons.

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

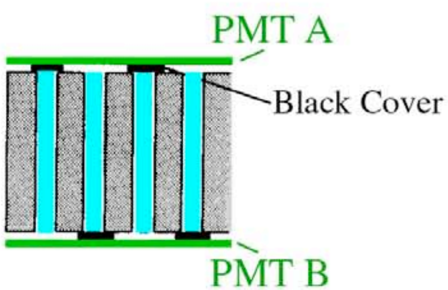
2) Because of the absence of correlations between the signals from adjacent active layers in fine-sampling hadron calorimeters

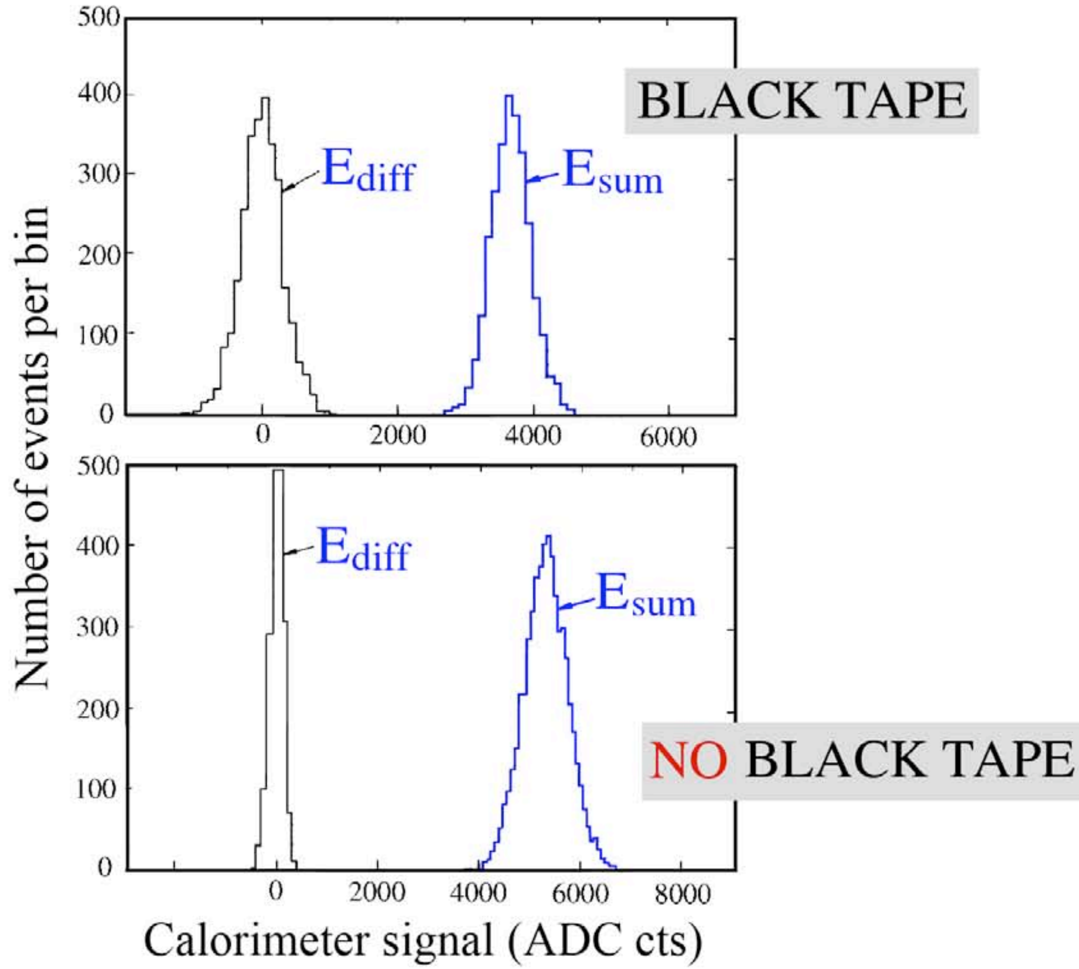
The calorimeter from the example had 0.06 λ_{int} thick sampling layers.
A mip would lose on average 12.7 MeV traversing these layers.

Correlations between signals from different sampling layers



$$E_a = E_1 + E_3 + \ldots$$
$$E_b = E_2 + E_4 + \ldots$$
$$E_{sum} = E_a + E_b$$
$$E_{diff} = E_a - E_b$$





Fluctuations (%)	*10 mm lead / 2.5 mm plastic* Electrons	Pions
σ_A, σ_B	36.0±1.0	60.5±1.0
σ_{sum}	24.5±1.0	43.5±1.0
σ_{diff}	25.8±1.0	42.3±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 ~ 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)

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.

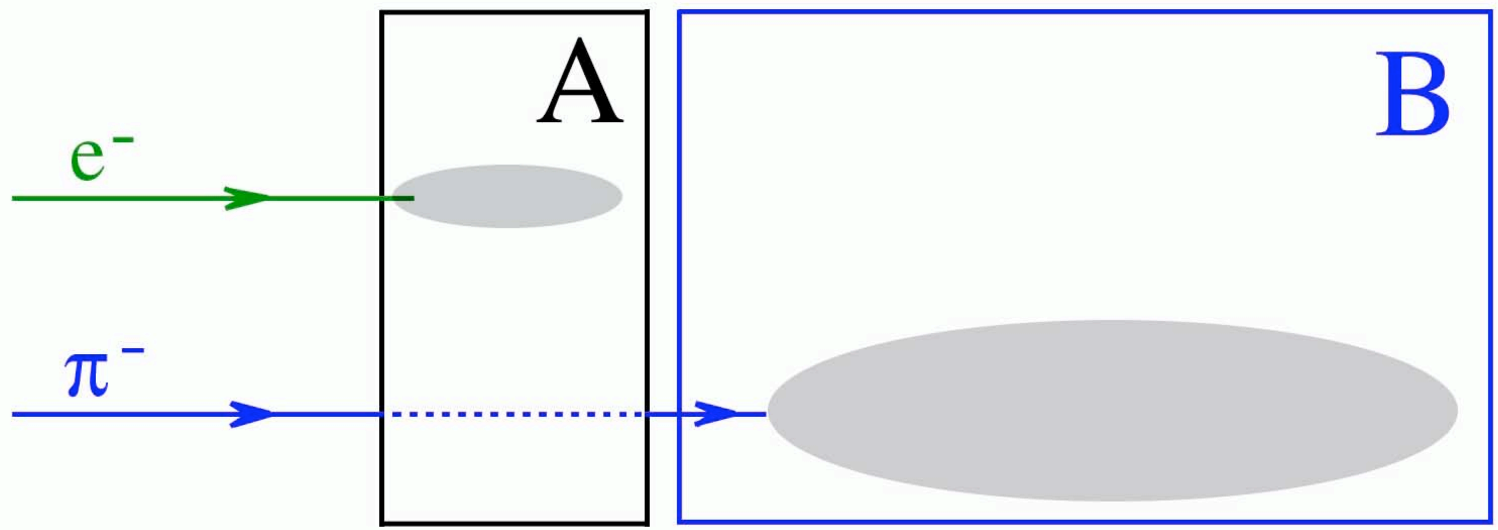
Aspects of the calibration of Calorimeter systems at colliders

(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

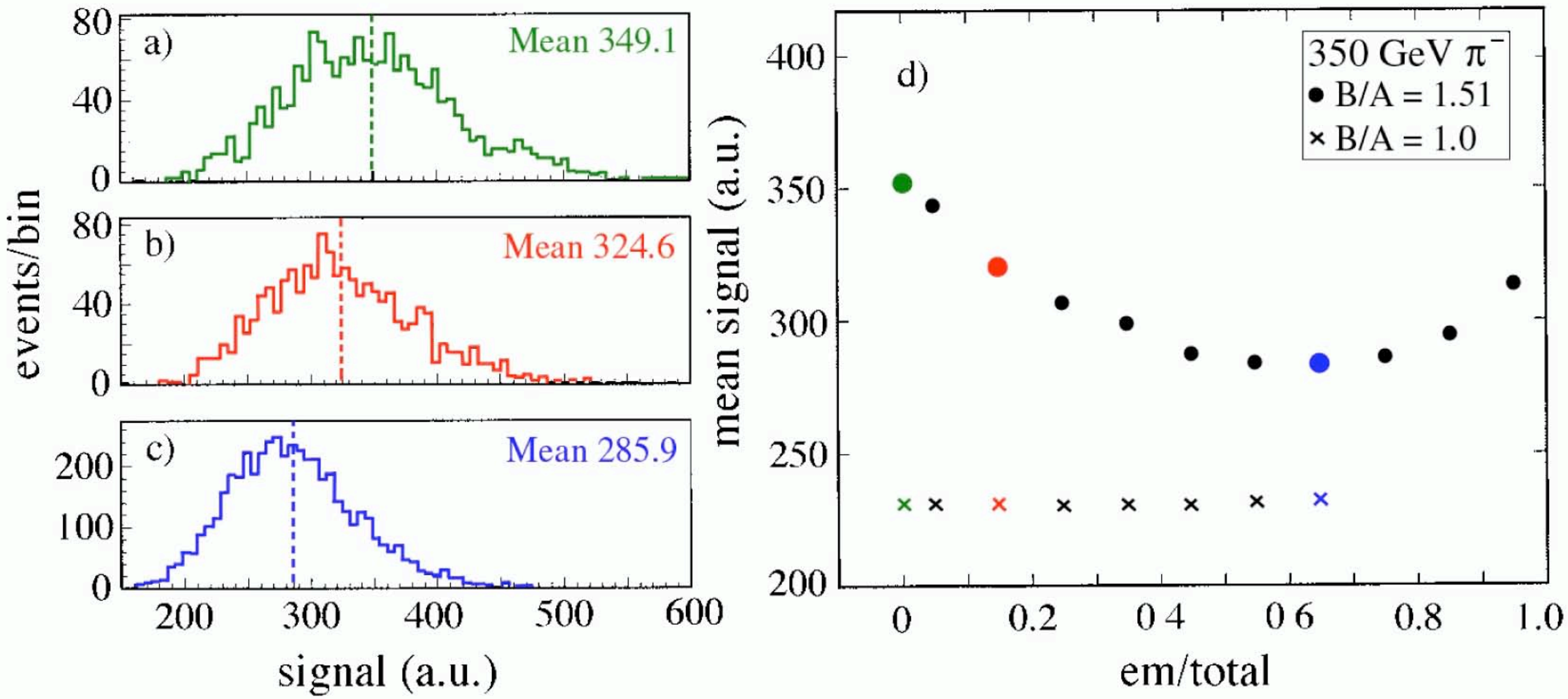


FIG. 6.10. Signal distributions for 350 GeV pion showers in a longitudinally segmented quartz-fiber calorimeter, for events in which different fractions of the (unweighted) shower energy were recorded in the em calorimeter section. Shown are distributions for which this fraction was compatible to zero (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 ≠ 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)

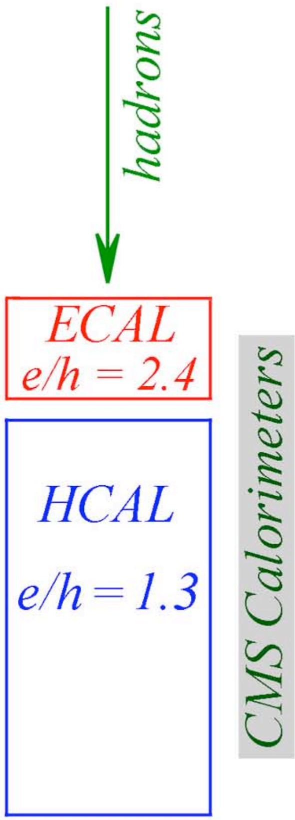
Hadronic response and signal linearity in CMS

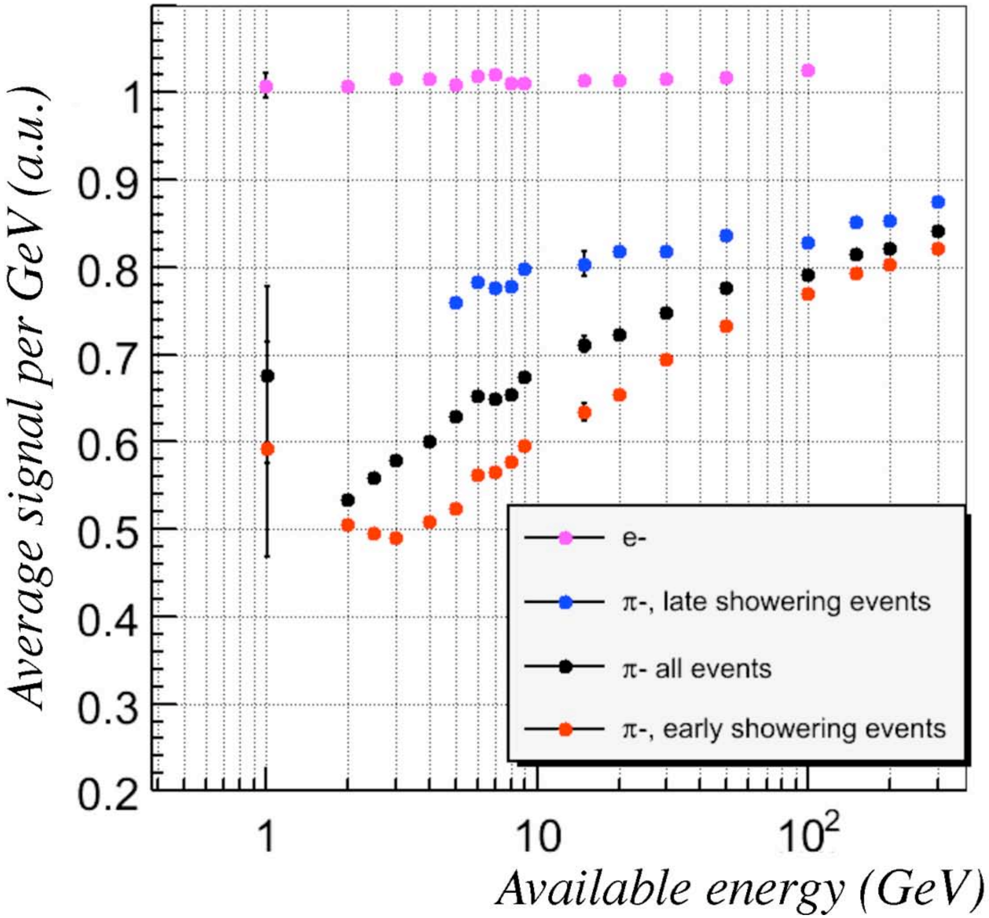
CMS pays a price for its focus on em energy resolution

ECAL has $e/h = 2.4$, while HCAL has $e/h = 1.3$

→ *Response depends strongly on starting point shower*

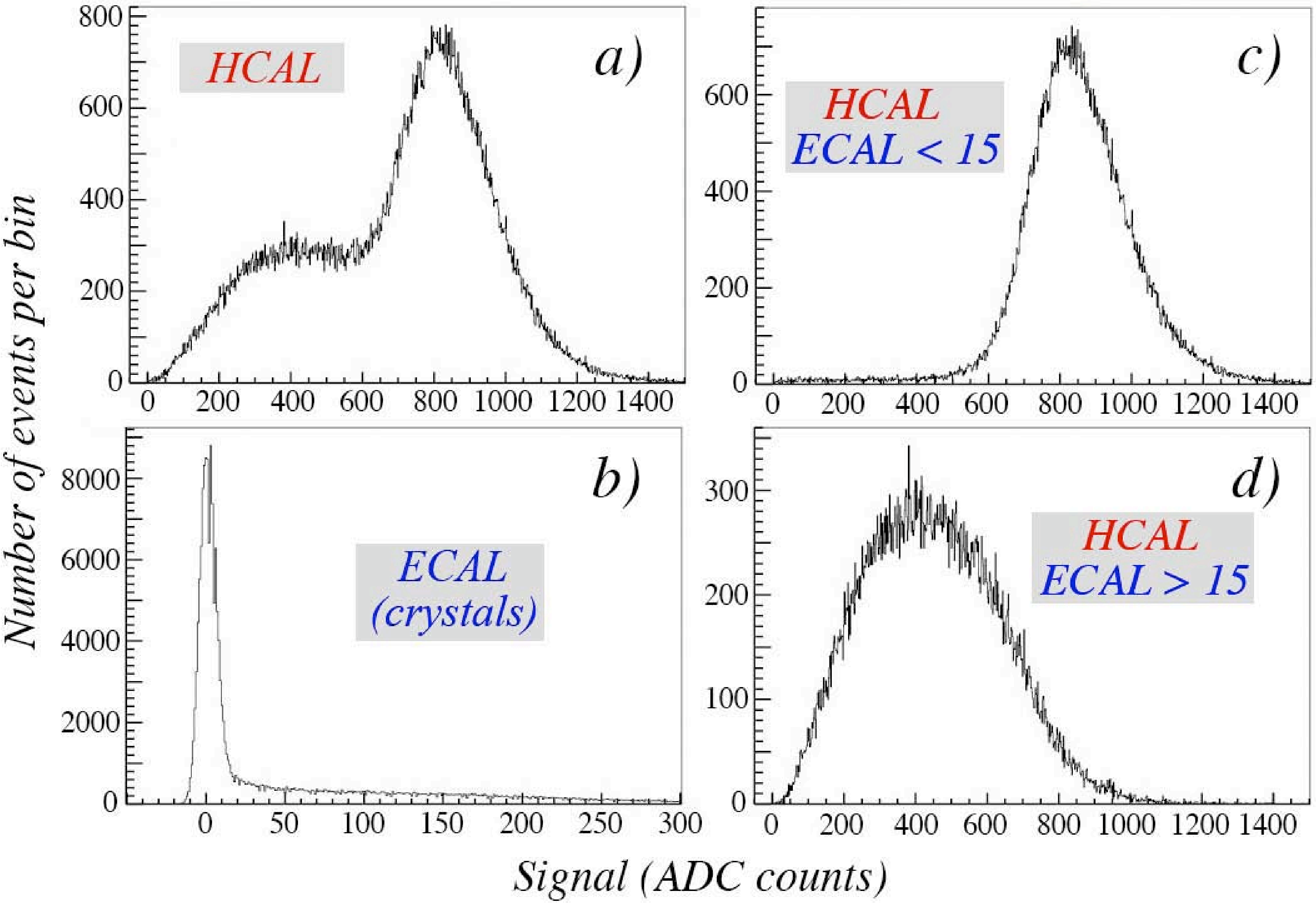
Data from: CMS note 2007/012



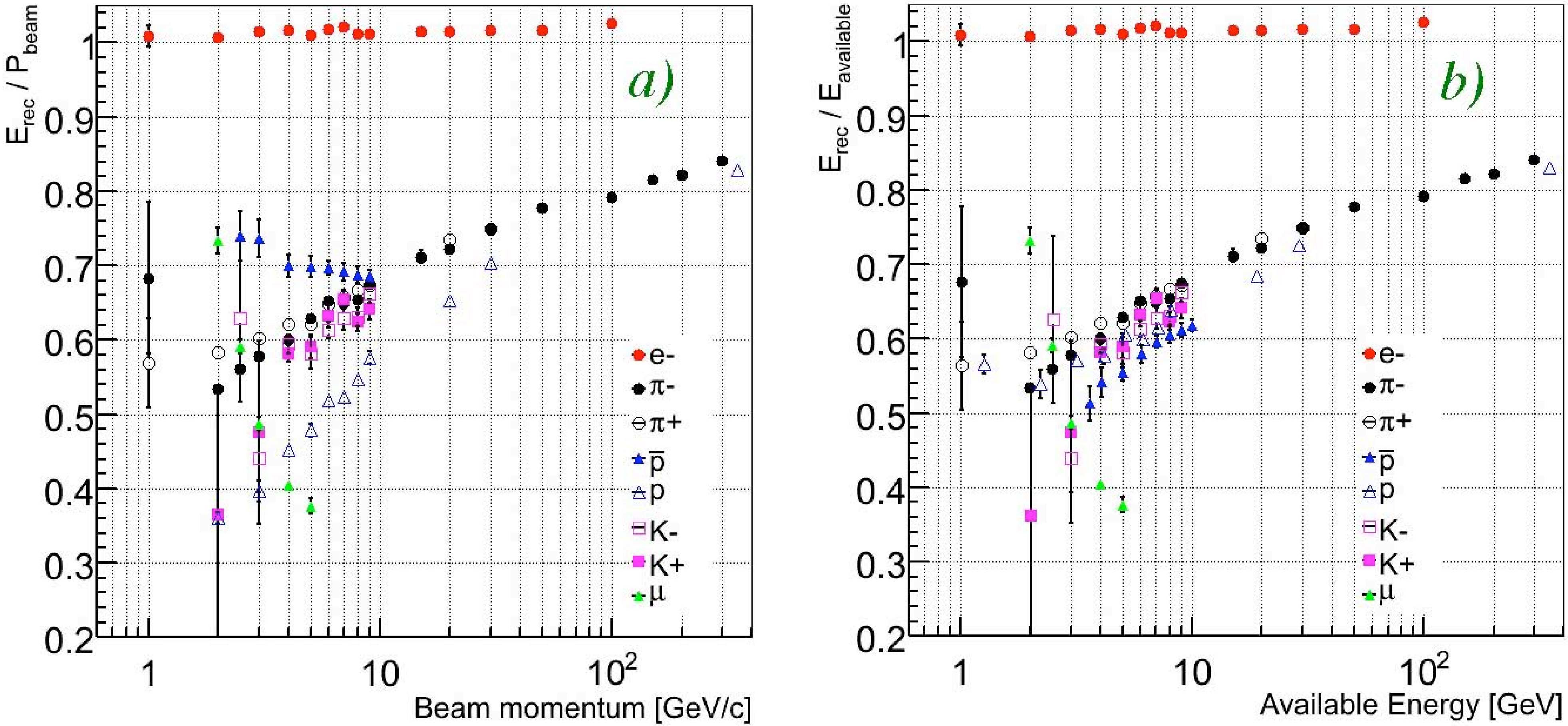


Pion signals in crystal ECAL + scintillator HCAL

100 GeV π^-



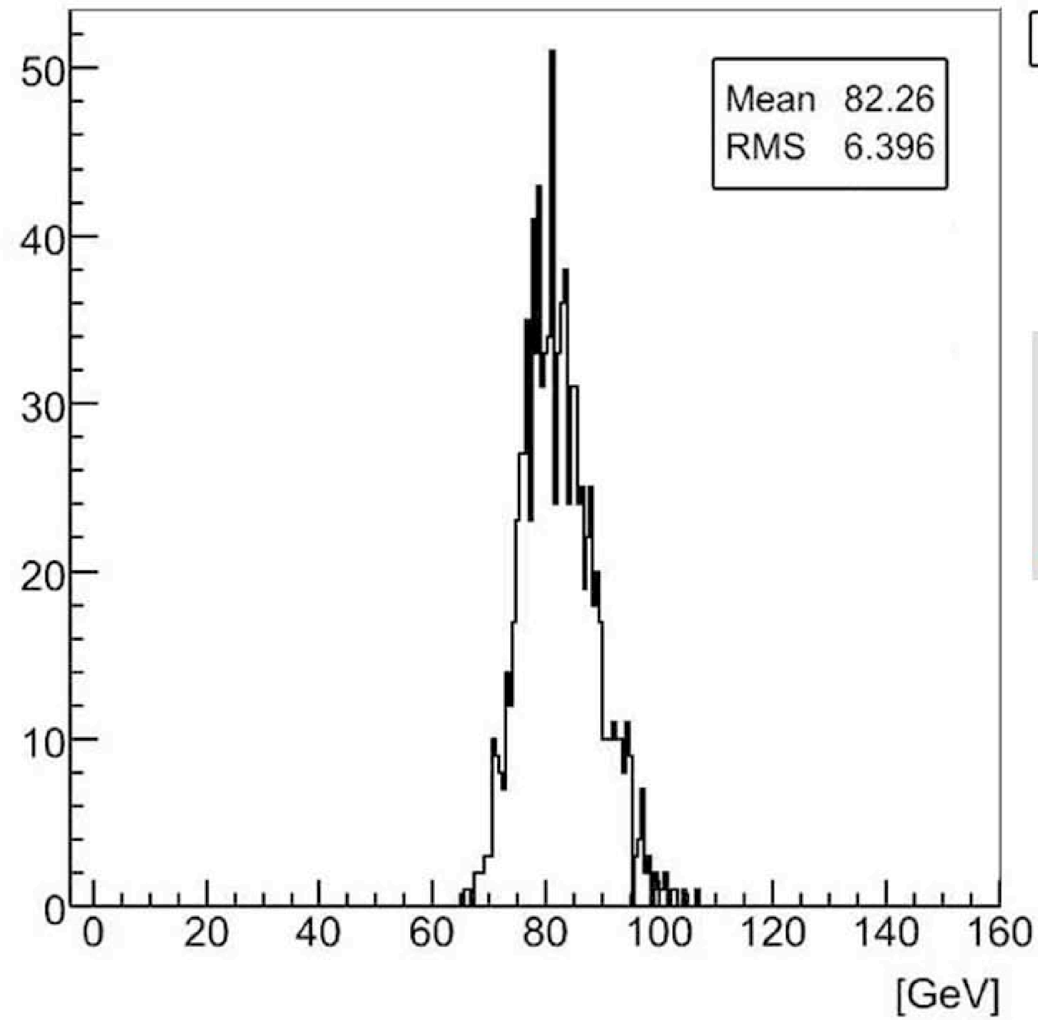
Single particles and jets in the CMS calorimeters



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



Jet signal reconstructed on the basis of the measured signals from its constituents

100 GeV jet: σ/mean = 7.8%

(100 GeV π: 14%)

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

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

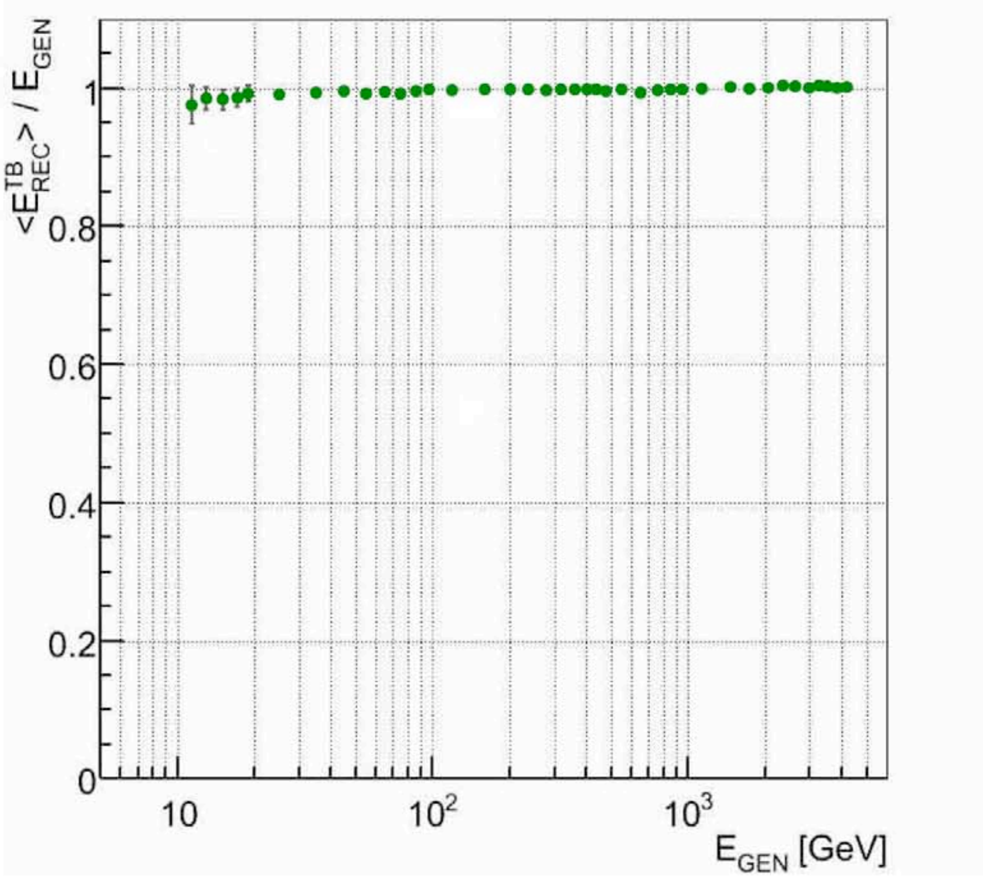


Figure 5.18: Average calorimeter response to jets after the test beam particles were corrected. Almost linear response at 1 confirms the validity of our jet reconstruction based on test beam data.

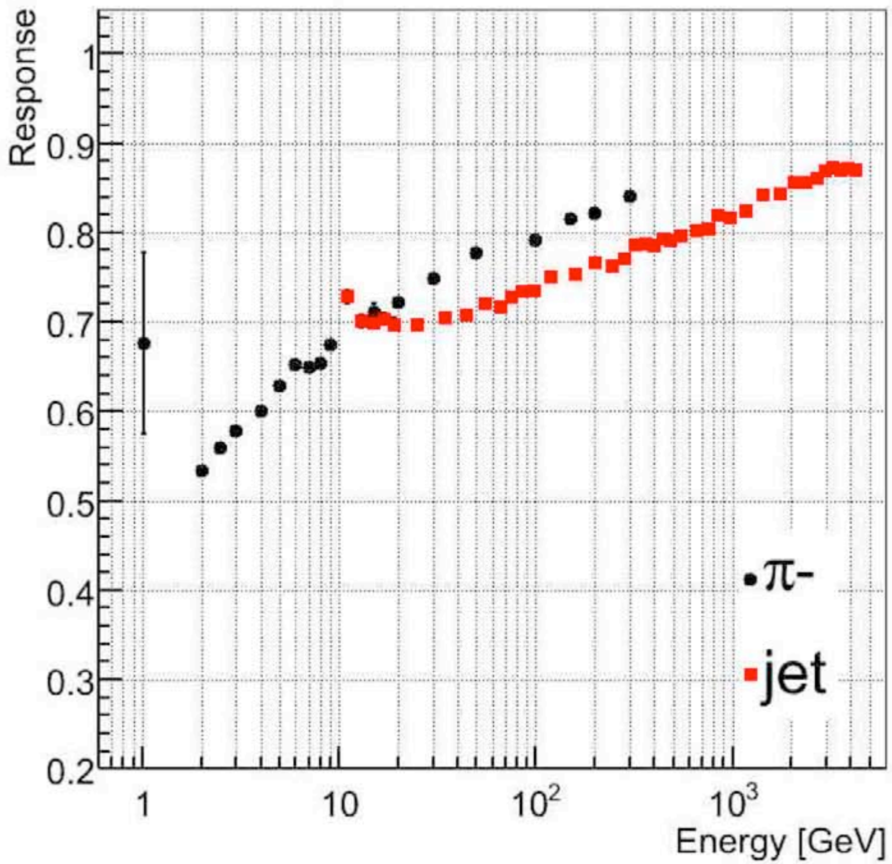


Figure 5.20: The jet response is lower than charged pion response, because a jet consists of mostly low energy (< 10 GeV) particles and the low calorimeter response to these particles reduces the jet response with respect to charged pions.

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

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*

  $Z \rightarrow e^+e^-$ (91.2 GeV/c^2) $J/\psi \rightarrow e^+e^-$ (3.10 GeV/c^2) $\Upsilon \rightarrow e^+e^-$ (9.46 GeV/c^2)

  (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 (minimum-bias) jet/jet invariant mass distributions.
  Argument: QCD background is too high.

- *However, how about* $Z \longrightarrow b\,\bar{b}$ *?*
  CDF, D0, ATLAS, CMS should have samples comparable in size to $Z \longrightarrow e^{+}e^{-}$
  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^{-1} *to get meaningful event sample*

Final comments about longitudinal segmentation & calibration

- *A given fragmenting parton of a certain energy may produce very different types of jets, e.g. jets with a leading π^o or with a leading $\pi^\pm$.*
  With a correction scheme based on averages, such jets will be systematically reconstructed with energies that are either too high (π^o) or too low.
  One could try to use additional information (tracker, energy deposit pattern) to recognize such cases and apply corrections

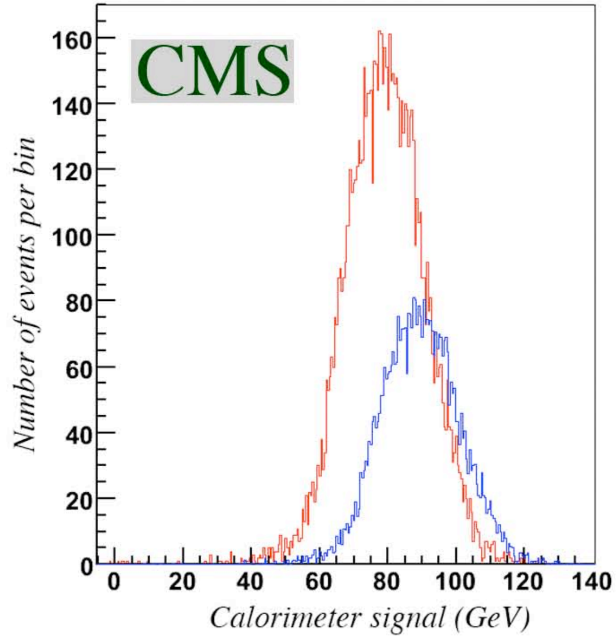
- *Longitudinal segmentation may be very DANGEROUS, since readout elements located in the developing shower may affect the signals in a major way (e.g. the "spikes" in the CMS ECAL)*

- *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*

The future of calorimetry

- *Hadronic calorimetry will become increasingly important, especially if a machine such as CLIC will ever be built. Jet spectroscopy will replace particle spectroscopy, e.g. to distinguish final-state W/Z bosons*



- *Different approaches are followed to develop calorimeter systems that are up to that task:*
  - *Compensating calorimeters*
    Proven technology, current holders of all performance records
  - *Dual-readout calorimeters*
    Try to improve on the performance of compensating calorimeters by eliminating the weak points of the latter
    Many experimental successes have been achieved, goals within reach
  - *Systems based on Particle Flow Analysis*
    Combine the information from a tracking system and a fine-grained calorimeter

Compensating calorimetry

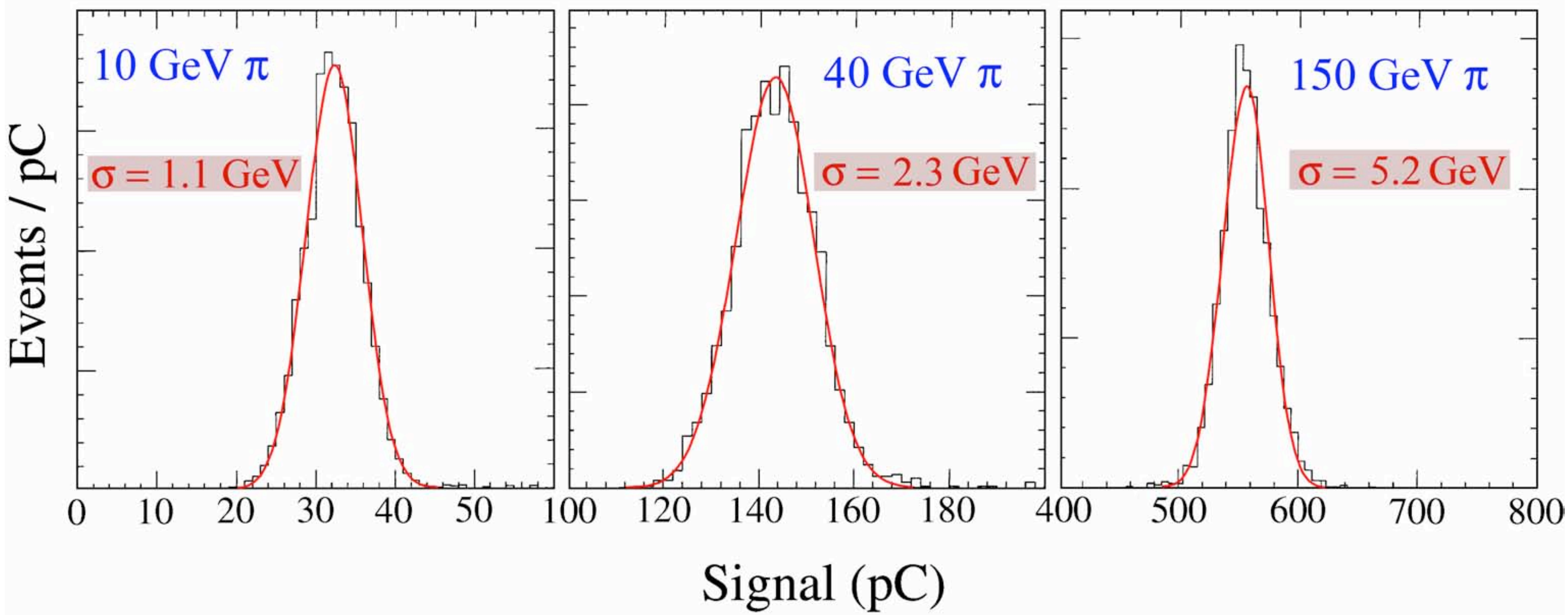
- *Reasons for poor hadronic performance of non-compensating calorimeters understood*

- *Compensation mechanisms fully understood*

^{238}U absorber (fission $\longrightarrow$ compensation for invisible energy loss)
is neither needed nor sufficient

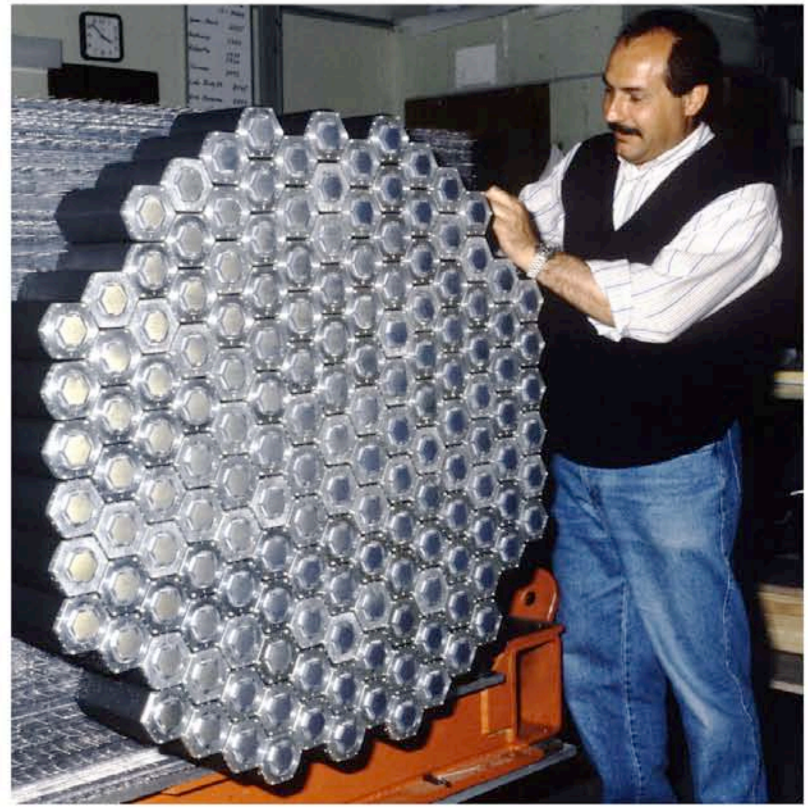
Experimentally demonstrated with Pb/scintillator calorimeters (ZEUS, SPACAL)

Hadronic signal distributions in a compensating calorimeter

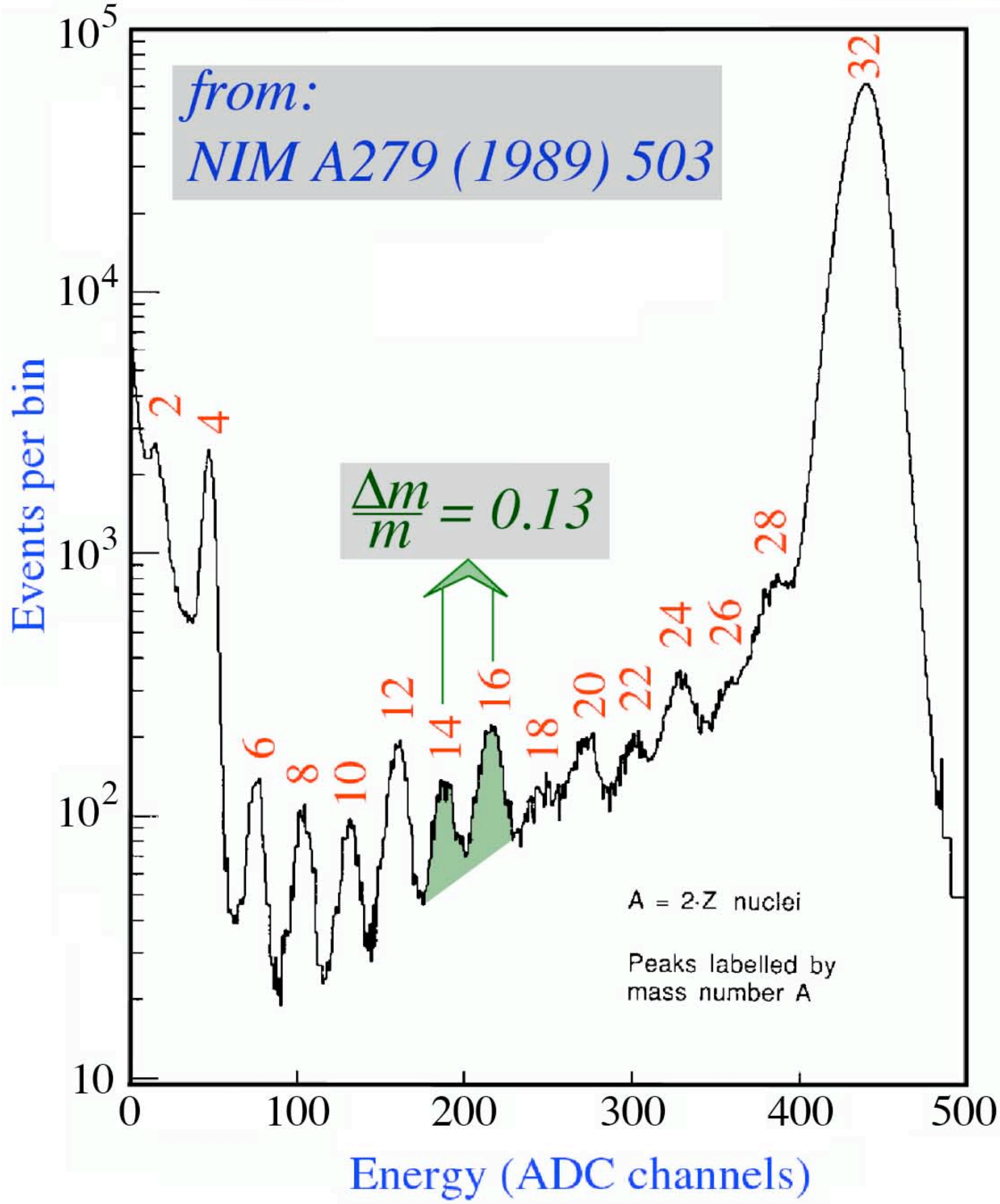


from: NIM A308 (1991) 481

SPACAL 1989



Hadron calorimetry in practice
Energy resolution in a compensating calorimeter



W/Z separation:

$\frac{\Delta m}{m} \sim 0.11$

The WA80 calorimeter as high-resolution spectrometer. Total energy measured with the calorimeter for minimum-bias events revealed the composition of the momentum-selected CERN heavy-ion beam

Pros & Cons of Compensating Calorimeters

Pros

- Same *energy scale* for electrons, hadrons and jets. No ifs, ands or buts.
- *Calibrate* with electrons and you are done.
- Excellent hadronic *energy resolution* (SPACAL: $30\%/\sqrt{E}$).
- *Linearity,* Gaussian *response function* and all that good stuff.
- Compensation fully understood.
  We know how to build these things, even though GEANT doesn't

Cons

- Small sampling fraction (2.4% in Pb/plastic)
  $\longrightarrow$ *em energy resolution limited* (SPACAL: $13\%/\sqrt{E}$, ZEUS: $18\%/\sqrt{E}$)
- Compensation relies on detecting neutrons
  $\longrightarrow$ Large *integration volume*
  $\longrightarrow$ Long *integration time* (~50 ns)

Elements needed to improve the excellent ZEUS/SPACAL performance:

1) *Reduce the contribution of sampling fluctuations to energy resolution*
(THE limiting factor in SPACAL/ZEUS)

2) *Eliminate/reduce effects of fluctuations in "invisible energy"*
→ *calorimeter needs to be efficient in detecting the "nuclear" fraction of the non-em shower component*

3) *Eliminate the effects of fluctuations in the em shower fraction, f_{em}*
in a way that does NOT prevent 1), 2)

→ *Dual-Readout Calorimetry*

An attractive option for improving the quality of hadron calorimetry:

Use Čerenkov light!! *Why?*

Hadron showers < *em* component (π^o) / *non-em* component (mainly soft *p*)

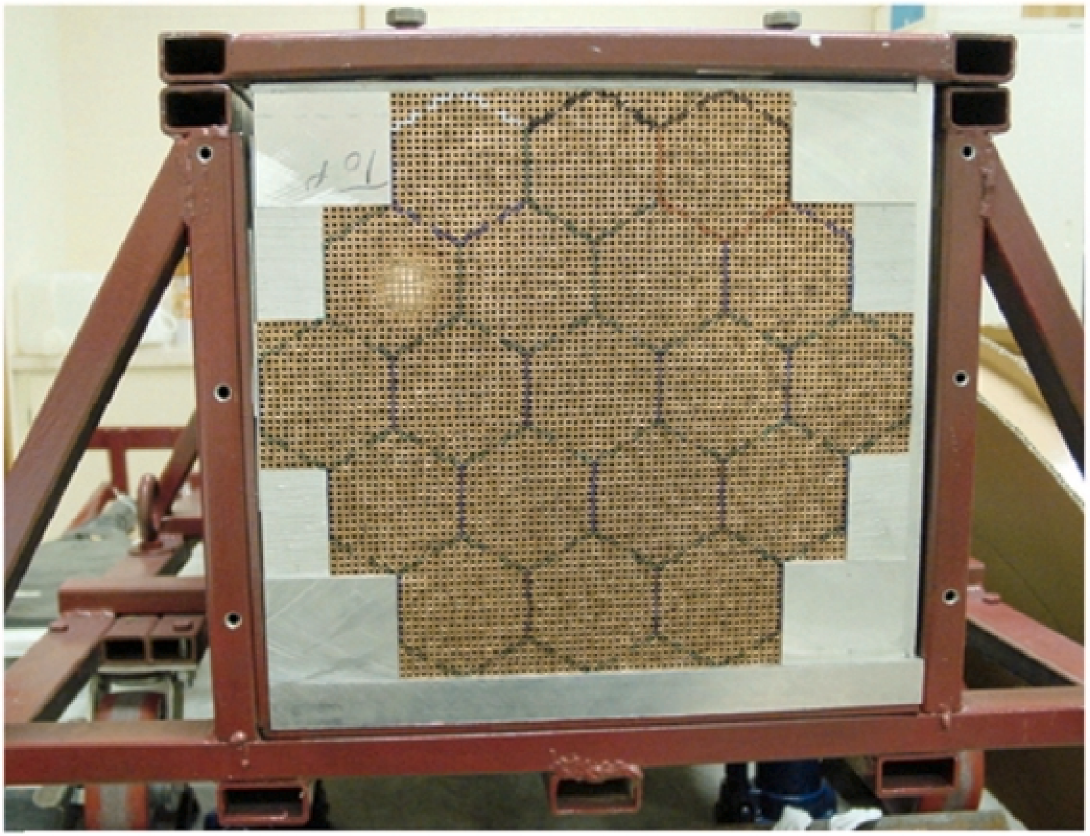
Calorimeter response to these components not the same *(e/h ≠ 1)*

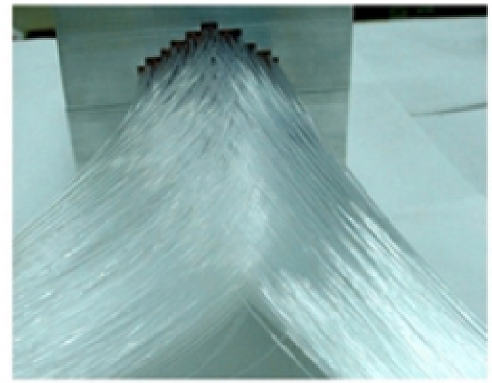
Čerenkov light almost exclusively produced by em component
(~80% of non-em energy deposited by non-relativistic particles)

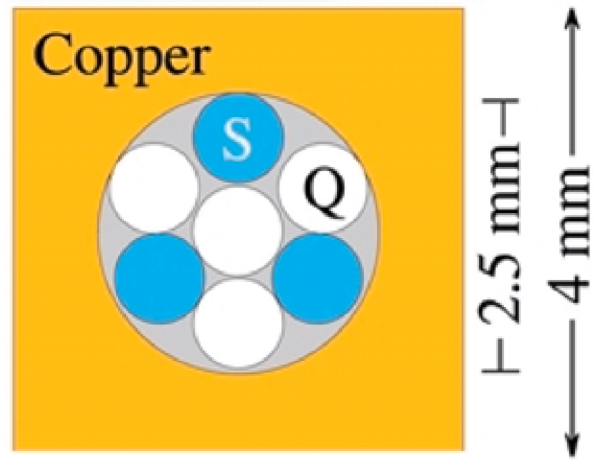
➡ DREAM (Dual REAdout Method) principle:

Measure f_{em} event by event by comparing Č and dE/dx signals

DREAM: Structure

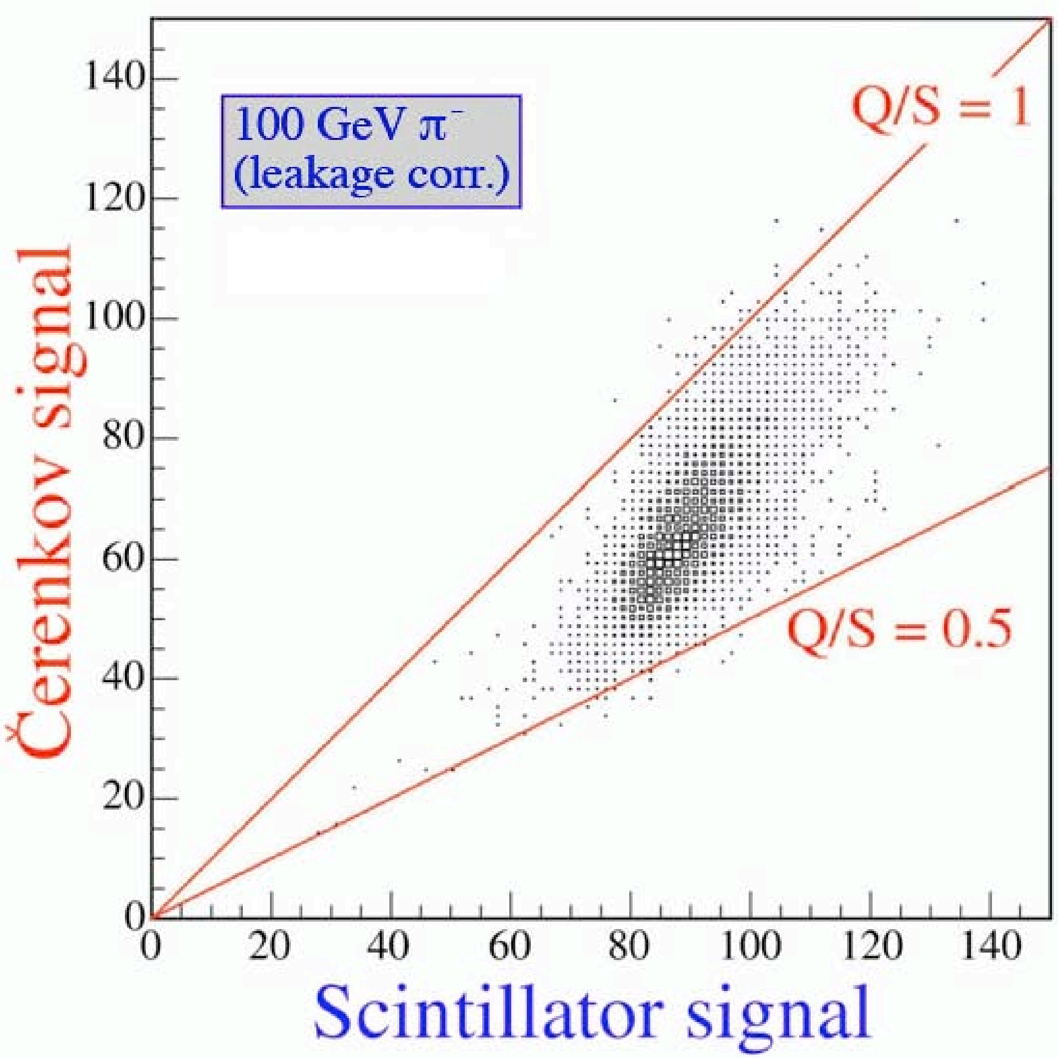






- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

DREAM: How to determine f_{em} and E ?



$$S = E\left[f_{\rm em} + \frac{1}{(e/h)_S}(1 - f_{\rm em})\right]$$

$$Q = E\left[f_{\rm em} + \frac{1}{(e/h)_Q}(1 - f_{\rm em})\right]$$

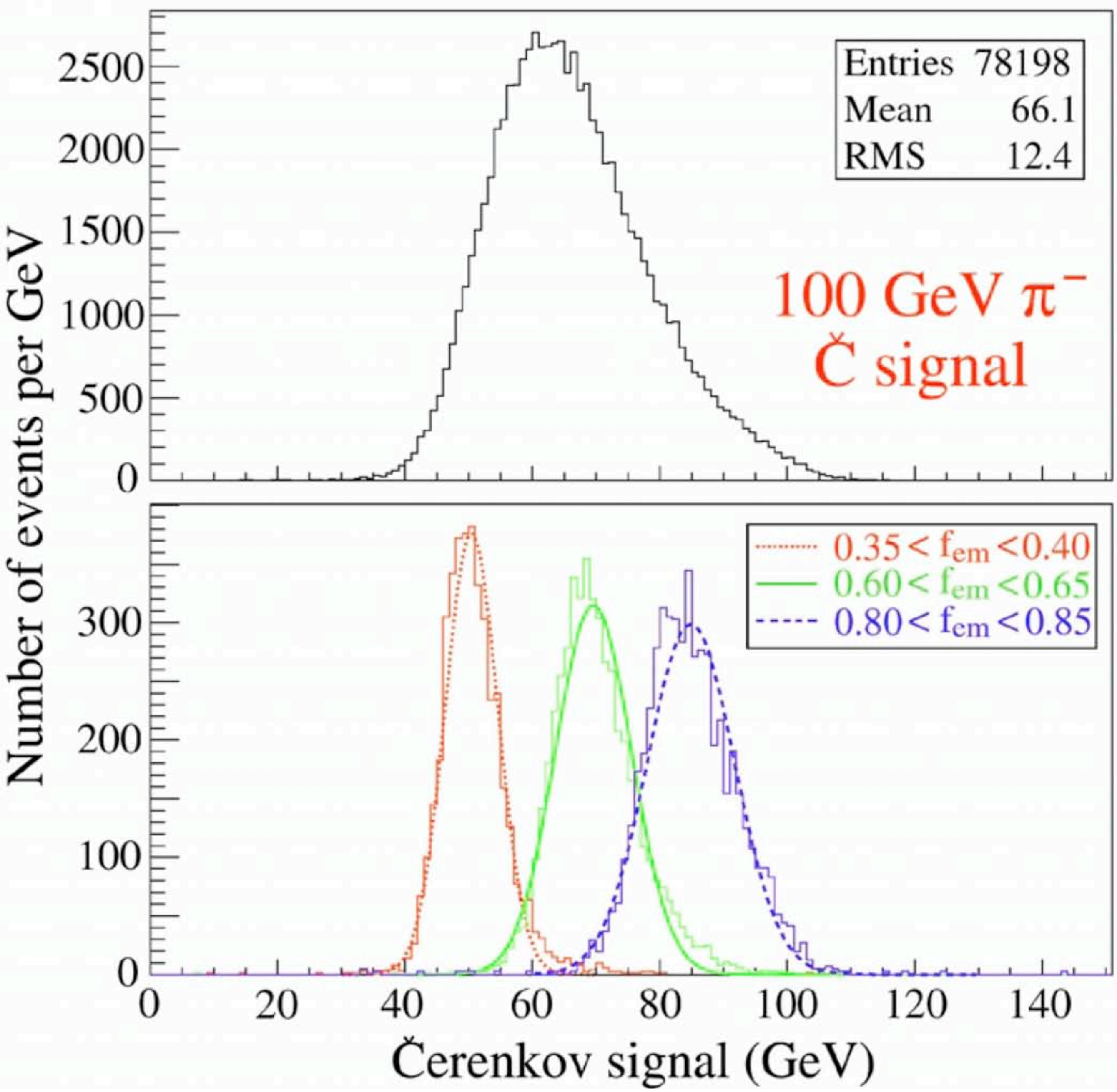
e.g. If $e/h = 1.3\ (S),\ 4.7\ (Q)$

$$\frac{Q}{S} = \frac{f_{em} + 0.21\ (1 - f_{em})}{f_{em} + 0.77\ (1 - f_{em})}$$

$$E = \frac{S - \chi Q}{1 - \chi}$$

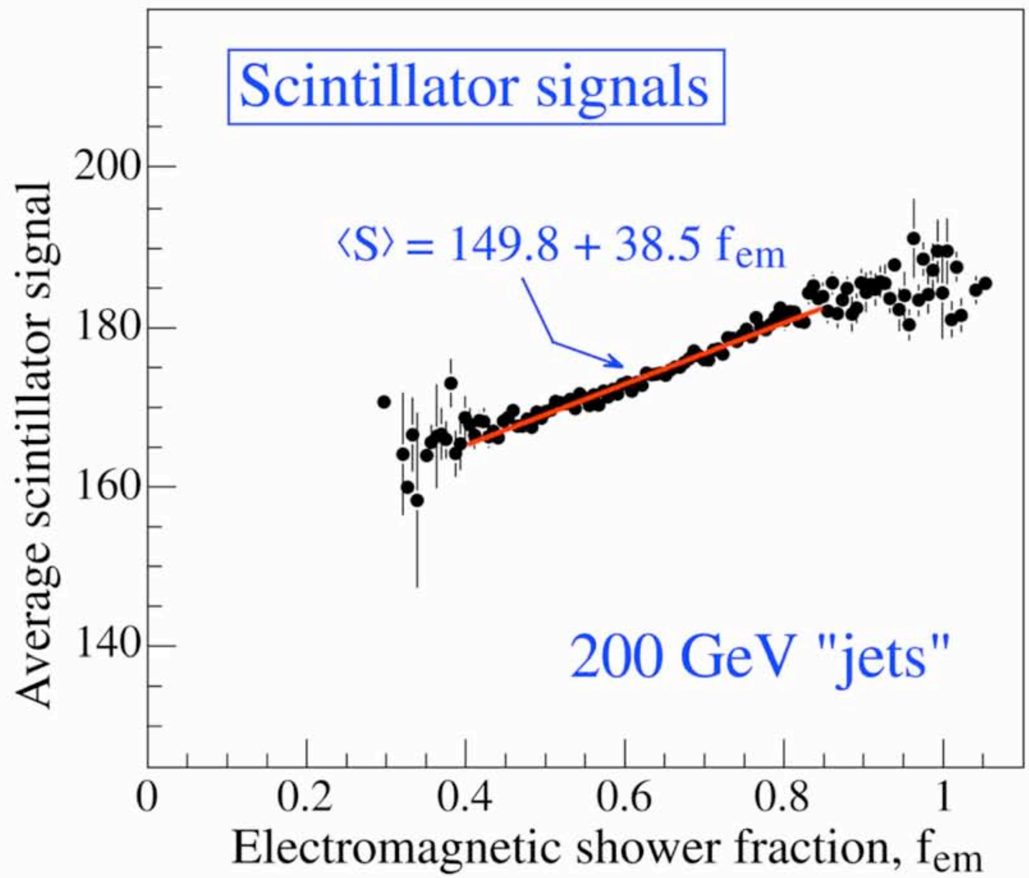
with $\chi = \dfrac{1 - (h/e)_S}{1 - (h/e)_Q} \sim 0.3$

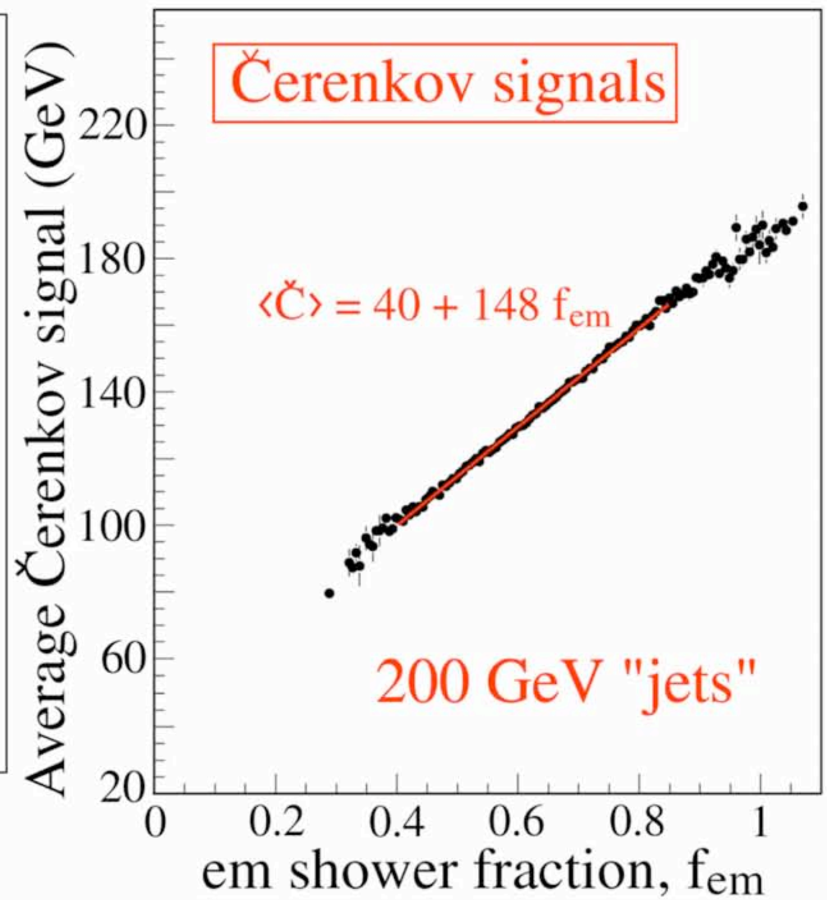
DREAM: Effect of event selection based on f_{em}



From:
NIM A537 (2005) 537

DREAM: Signal dependence on f_{em}



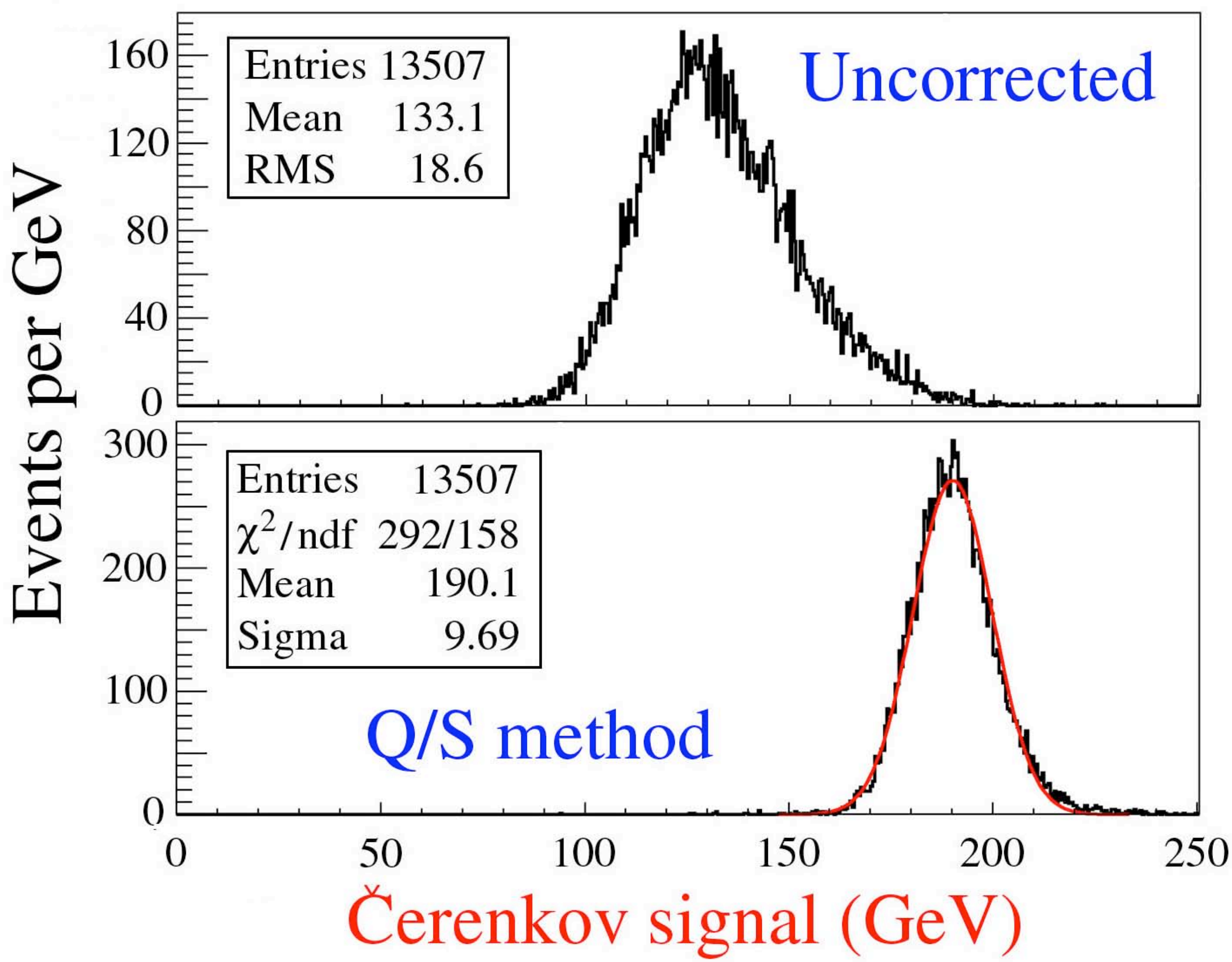


$$R(f_{\text{em}}) = p_0 + p_1 f_{\text{em}}$$ with $$\frac{p_1}{p_0} = e/h - 1$$

Cu/scintillator $e/h = 1.3$ Cu/quartz $e/h = 4.7$

From:
NIM A537 (2005) 537

DREAM: Effect of corrections (200 GeV "jets")



Effects of Q/S corrections on

hadronic signal linearity *and* *jet resolution*

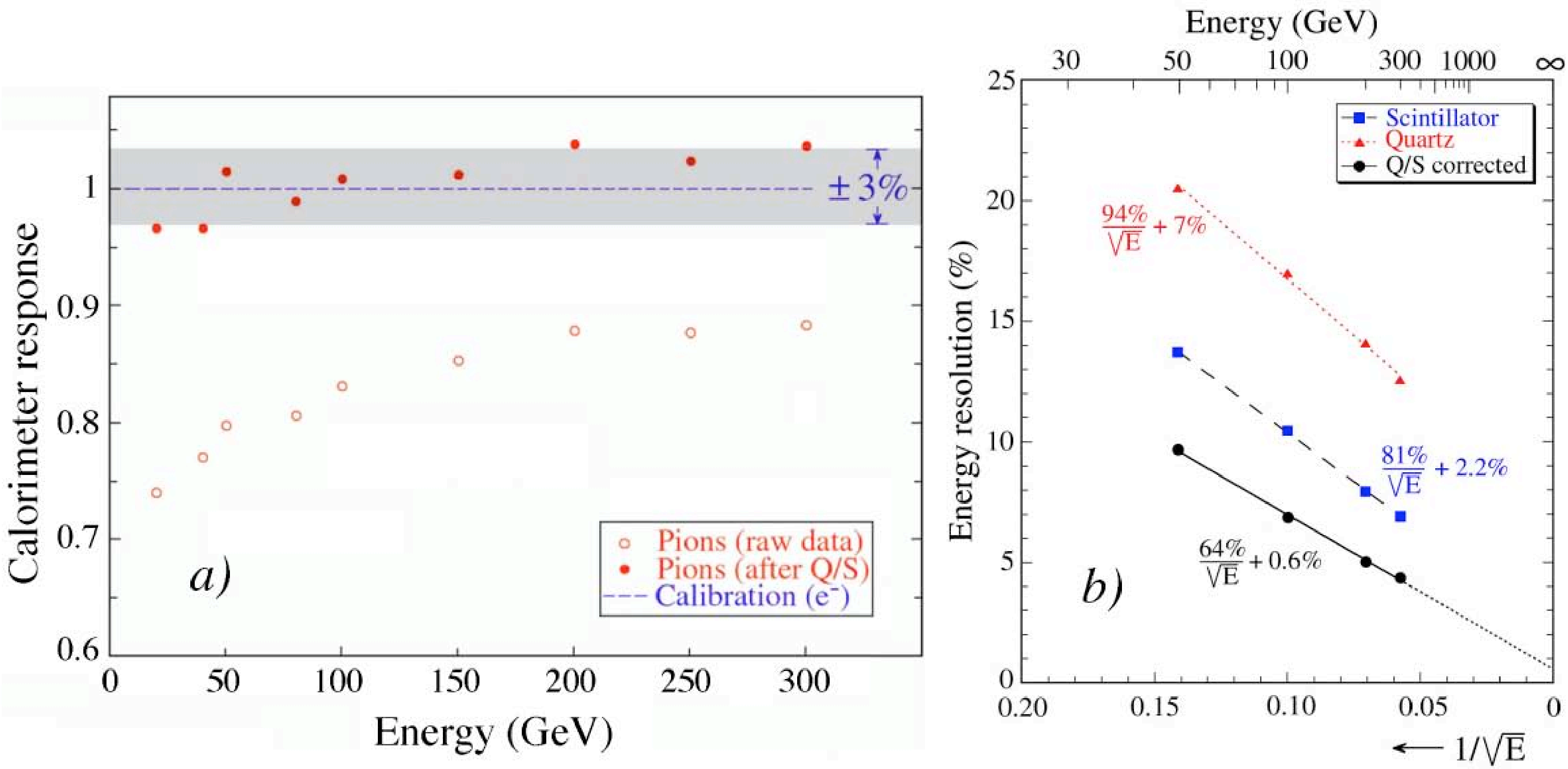


Figure 9: The scintillator response of the DREAM calorimeter to single pions (a) and the energy resolution for "jets" (b), before and after the dual-readout correction procedures were applied to the signals [5].

CONCLUSIONS
from tests of fiber prototype

- DREAM offers a powerful technique to *improve* hadronic calorimeter performance:
  - Correct hadronic energy reconstruction, *in an instrument calibrated with electrons!*
  - Linearity for hadrons and jets
  - Gaussian response functions
  - Energy resolution scales with $1/\sqrt{E}$
  - $\sigma/E < 5\%$ for high-energy "jets", in a detector with a mass of only 1 ton!
    dominated by fluctuations in shower leakage

In other words:
The same advantages as intrinsically compensating calorimeters (e/h = 1)
WITHOUT the limitations (sampling fraction, integration volume, time)

Particle Flow Analysis

- *The basic idea*

  Combine the information of the tracker and the calorimeter system to determine the jet energy

  Momenta of charged jet fragments are determined with the tracker

  Energies of the neutral jet fragments come from the calorimeter

- *This principle has been used successfully to improve the hadronic performance of experiments with poor hadronic calorimetry*

  However, the improvements are fundamentally limited

  In particular, no one has ever come close to separating W/Z this way

- *The problem*

  The calorimeters do not know that the charged jet fragments have already been measured by the tracker. These fragments are also absorbed in the calorimeter. Confusion: Which part of the calorimeter signals comes from the neutral jet fragments?

- *Advocates of this method claim that a fine detector granularity will help solve this problem. Others believe it would only create more confusion.*

  Like with all other issues in calorimetry, this issue has to be settled by means of experiments, NOT by Monte Carlo simulations!!

Conclusions

- *Interpretation of calorimeter signals is crucially important for the jet energy scale*
- *Longitudinal segmentation = asking for (calibration) trouble, especially if the different segments have different e/h values*
- *By calibrating all segments of a longitudinally segmented calorimeter system in the same way, some important problems may be avoided (non-linearity, response dependence on starting point showers,...)*
- *In the past 20 years, the quality of hadron calorimetry has decreased, partly because of the lack of meaningful guidance from MC simulations*
- *In calorimeters, more information does not necessarily lead to better results, but instead to more confusion (cf. thermal calorimeters)*
- *There are major advantages in a calorimeter that has the same response (signal/GeV) to ALL particles, regardless their nature or energy, such as the one DREAM is developing*

Backup slides

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* ⟶ useless as design tool
- *LESSON 6:* If you want to improve hadronic calorimeter performance
  ⟶ *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)

Hadronic signal (non-)linearity: Dependence on e/h

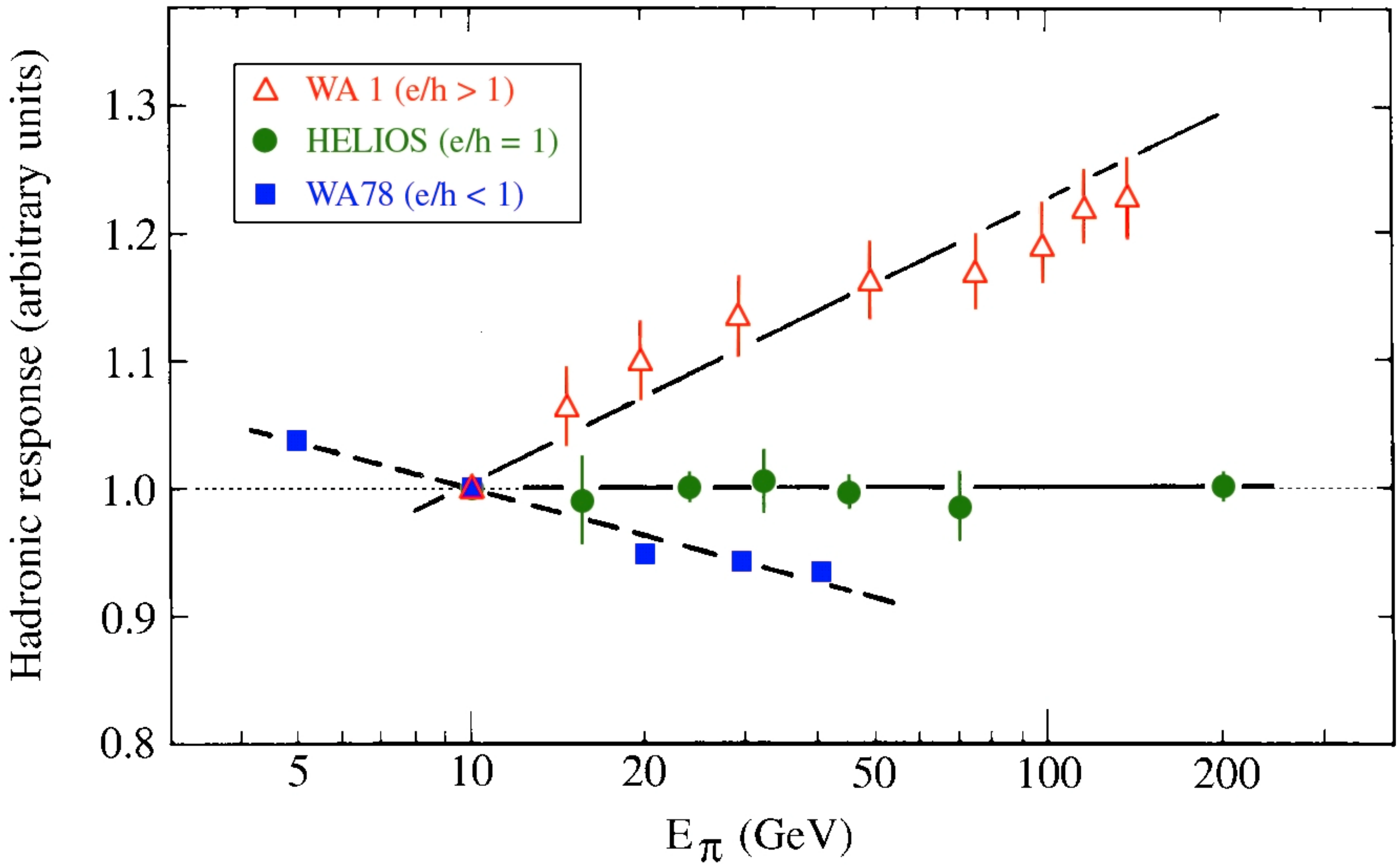


FIG. 3.14. The response to pions as a function of energy for three calorimeters with different e/h values: the WA1 calorimeter ($e/h > 1$, [Abr 81]), the HELIOS calorimeter ($e/h \approx 1$, [Ake 87]) and the WA78 calorimeter ($e/h < 1$, [Dev 86, Cat 87]). All data are normalized to the results for 10 GeV.

Hadronic response function: Effect of e/h

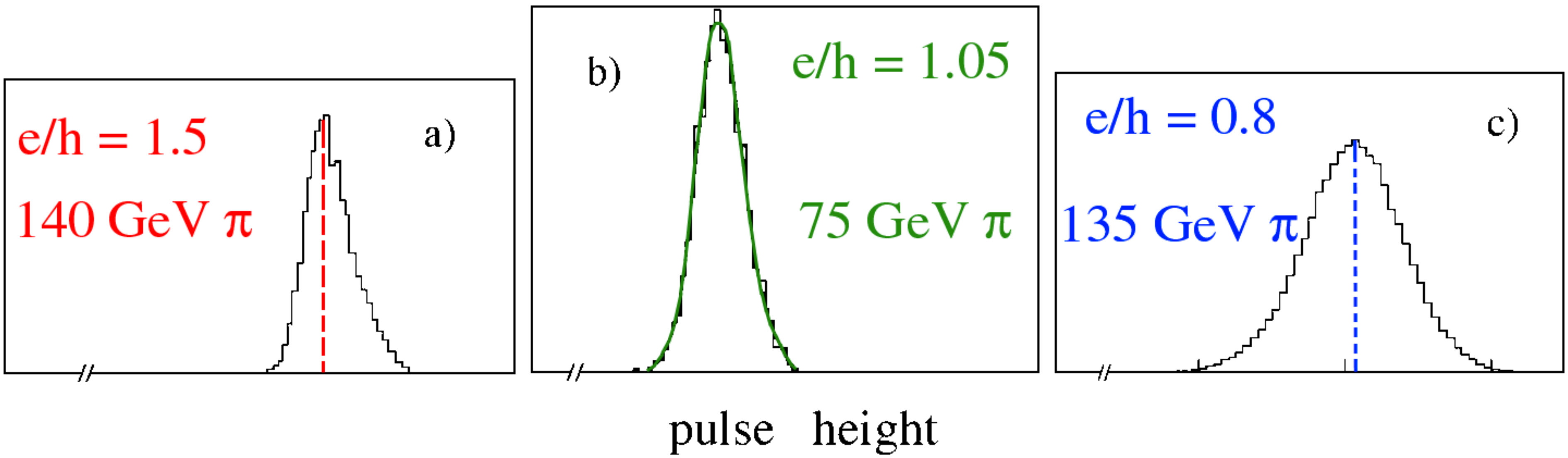


FIG. 7.24. Signal distributions for mono-energetic pions in calorimeters with different e/h values. Data from WA1 [Abr 81], ZEUS [Beh 90] and WA78 [Dev 86].

Hadronic resolution of non-compensating calorimeters

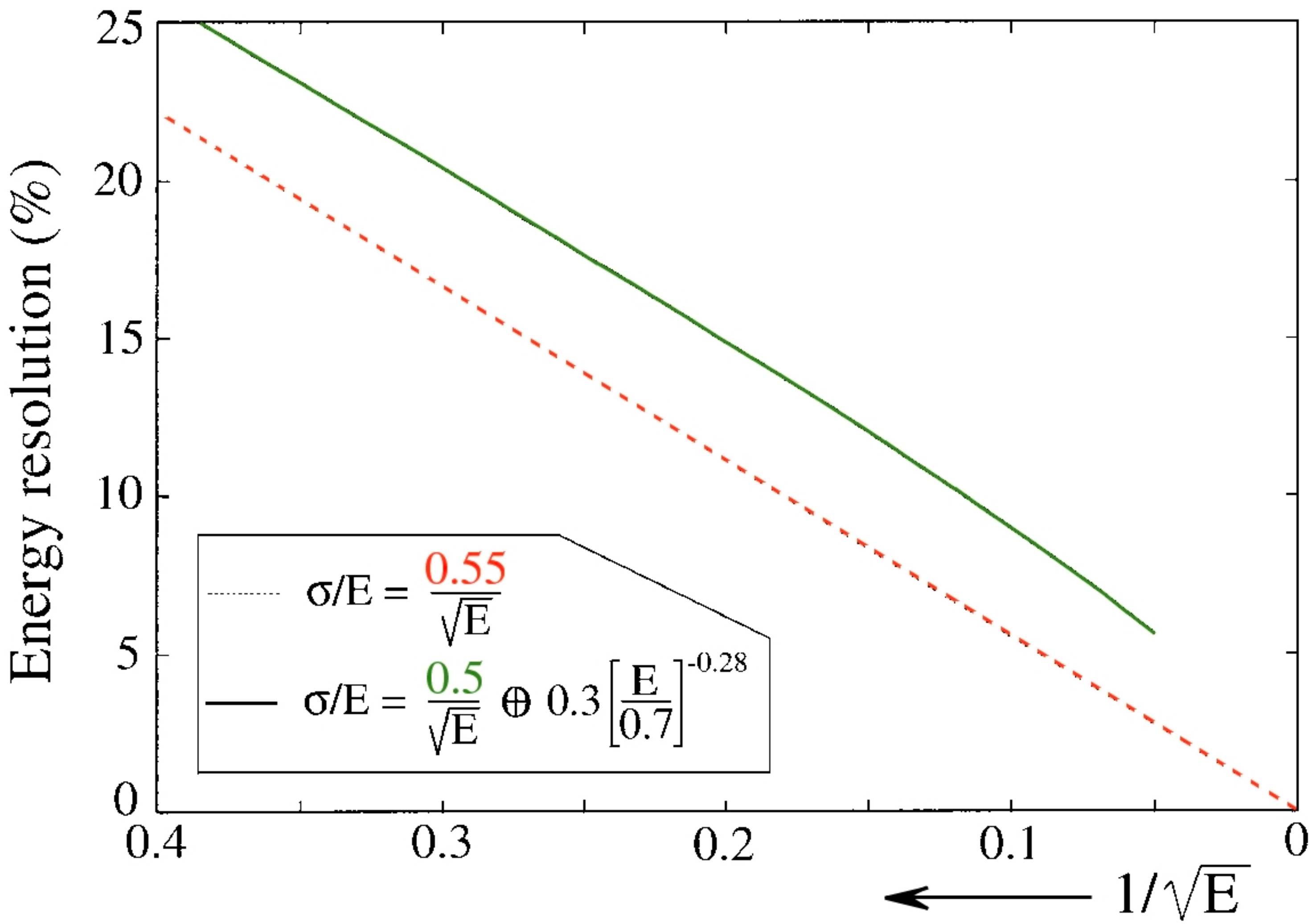
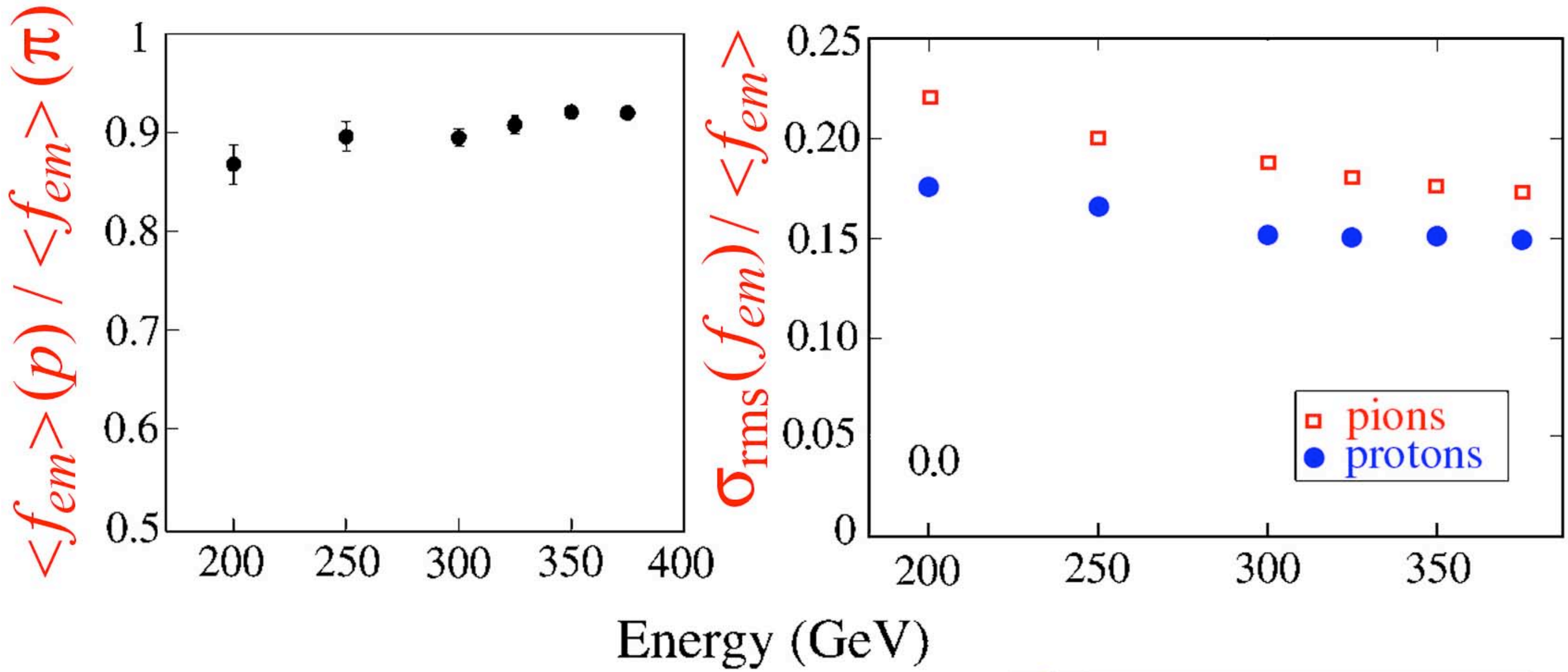


FIG. 4.48. The energy resolution calculated with Equation 4.29 for energies up to 400 GeV (the solid line), and calculated with a sole stochastic term with a slightly larger a_1 value (the dotted line). See text for details.

The em shower fraction, f_{em} (5)

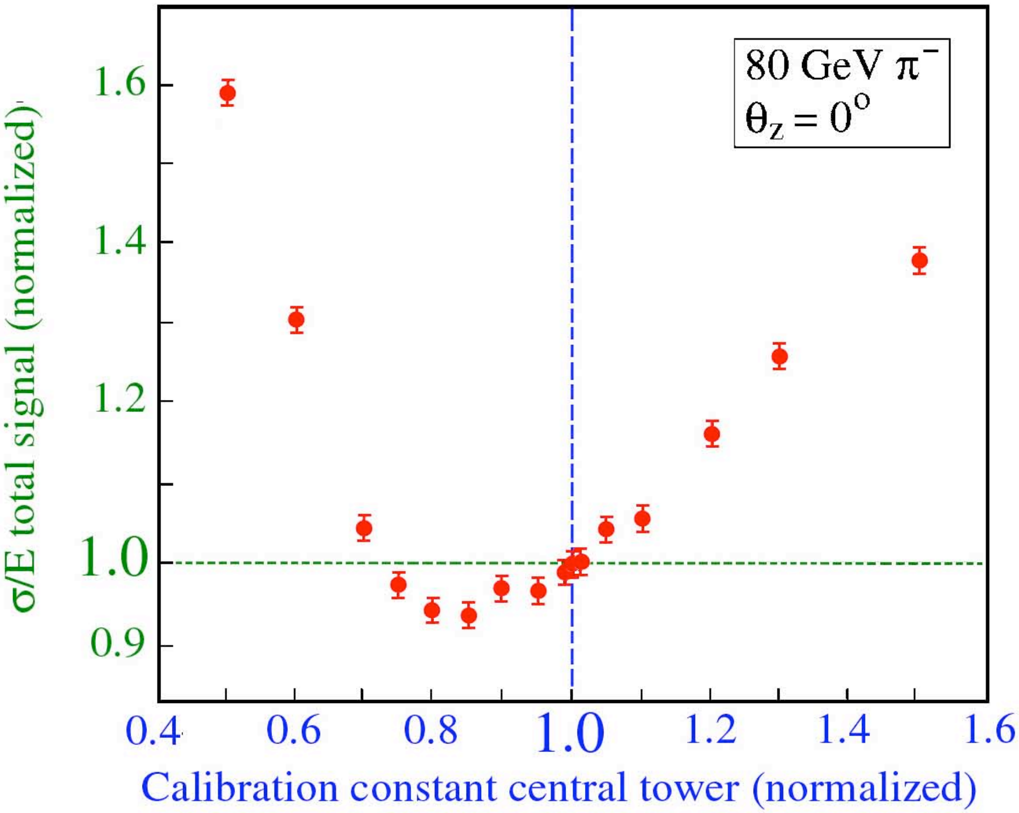


from:
NIM A408 (1998) 380

$\langle f_{em}\rangle$ and the fluctuations in f_{em} are different in π- and *p*-induced showers

Intercalibrating sections by minimizing total signal width

GIVES WRONG RESULTS!



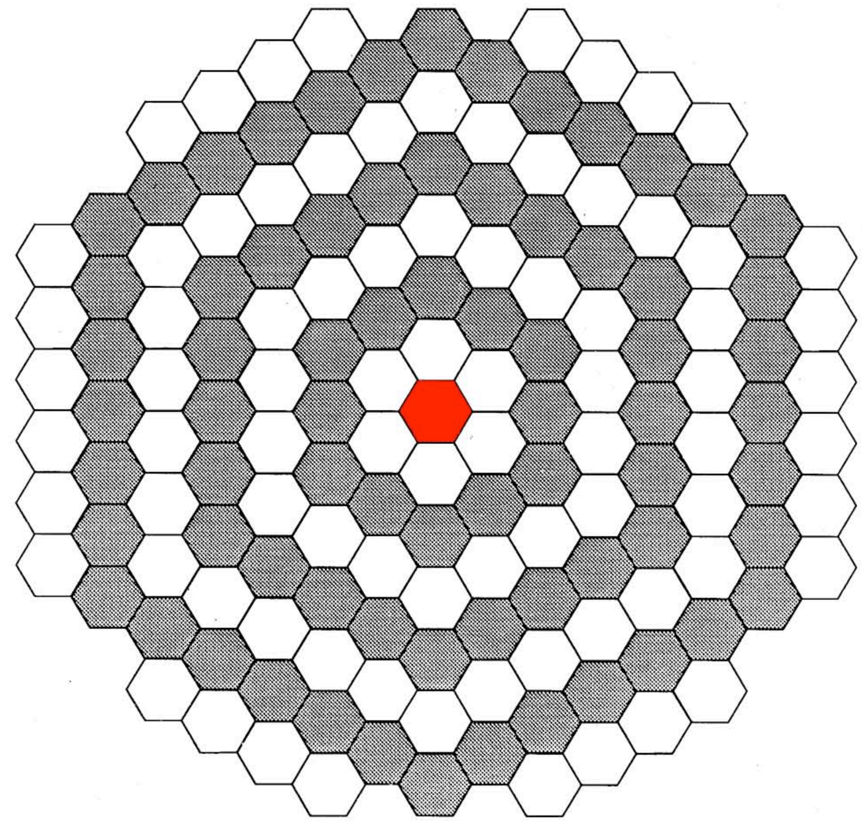
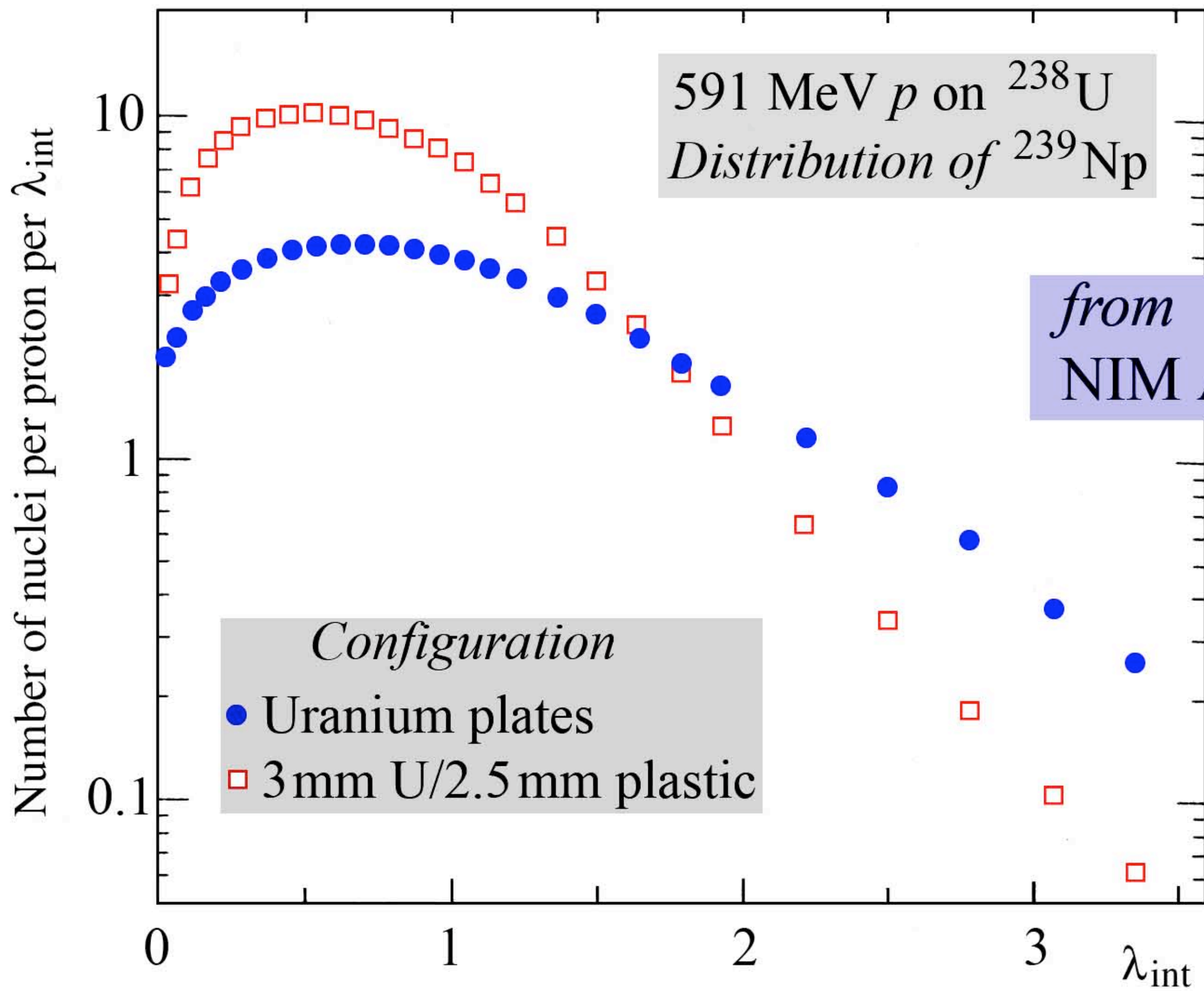


Figure 11: The fractional width, σ/E, of the signal distribution for 80 GeV π^- in the SPACAL detector as a function of the weighting factor applied to signals from the central calorimeter tower into which the pion beam was steered. The calorimeter towers were calibrated with high-energy electrons [7].

From: NIM A485 (2002) 385.

The importance of hydrogen in the absorbing structure



from
NIM A252 (1986) 4

(Nuclear evaporation) neutrons are typically produced with E_{kin} ~ few MeV.
Elastic *n-p* scattering slows these neutrons down.
^{239}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.

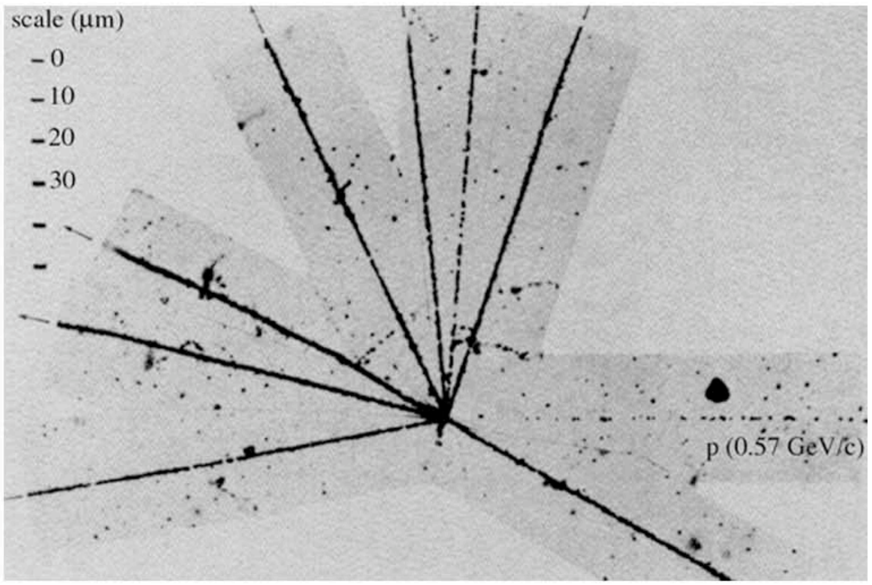
Therefore, the *neutron component may be very efficiently sampled* in such calorimeters. The sampling fraction may be much larger than for the other shower particles .

This is the key element of *compensation*.

Avoid repeating mistakes from the past

- *Don't place readout elements that produce HUGE signals for one particular type of shower particle in the path of the developing shower*

  ("Texas tower" effect)



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.

- *"Digital" calorimetry was tried and abandoned for good reasons (1983)*

Particle identification with calorimeters

e/π separation using time structure signals

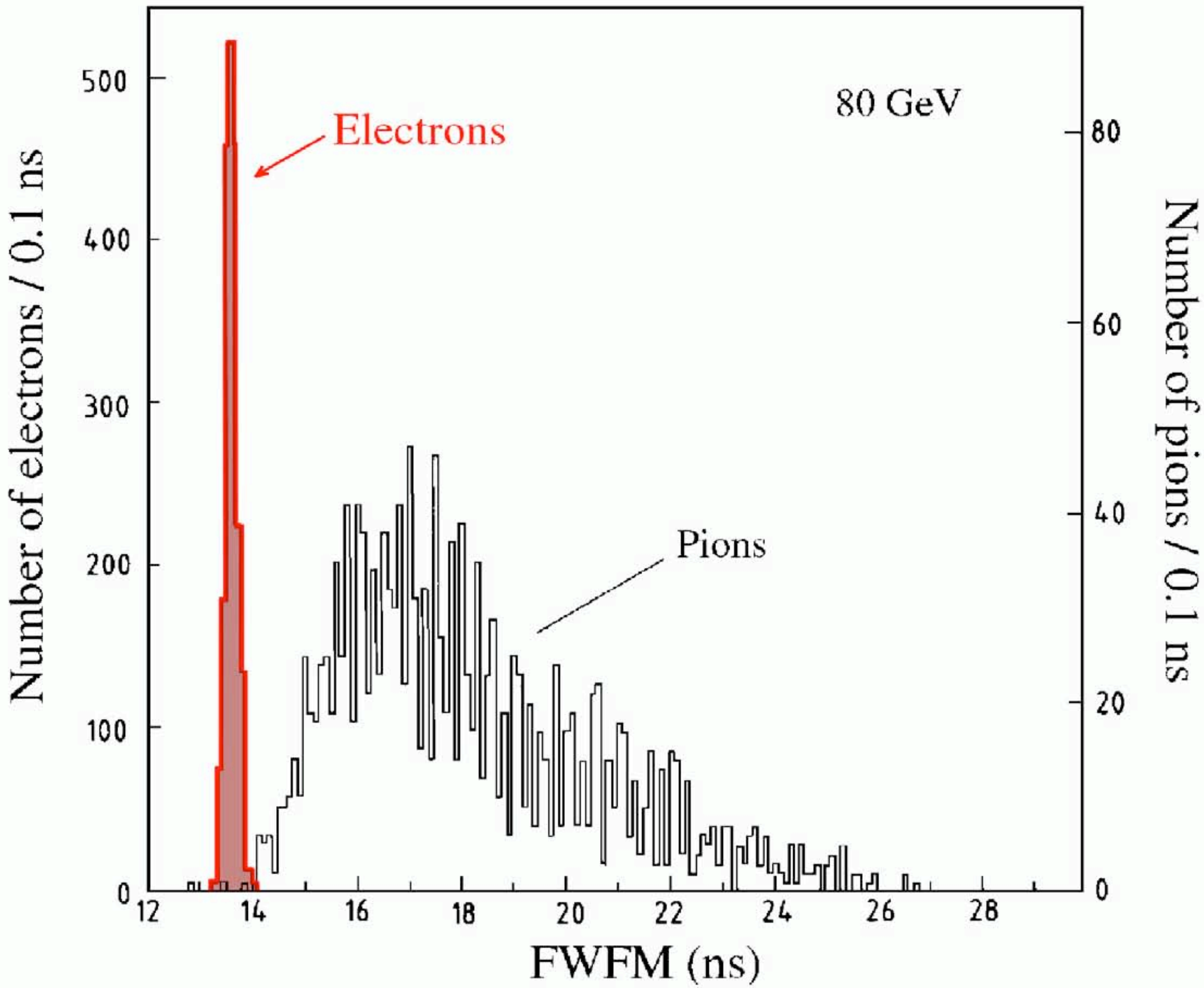


FIG. 7.33. The distribution of the full width at one-fifth maximum (FWFM) for 80 GeV electron and pion signals in SPACAL [Aco 91a].

How to improve DREAM performance

- Build a larger detector ⟶ *reduce effects side leakage*

Expected effect of full shower containment

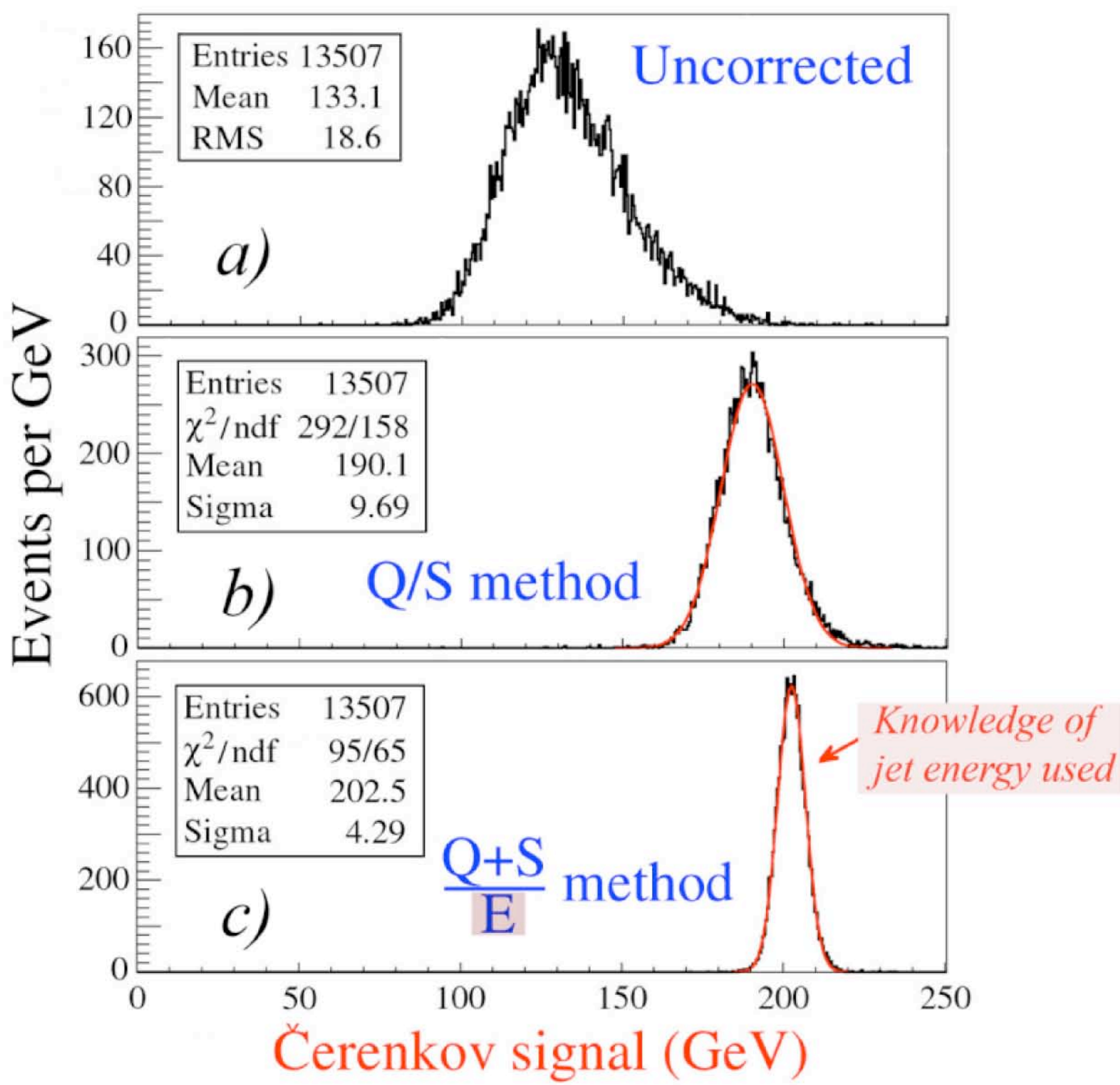


Figure 2: Čerenkov signal distributions for 200 GeV multi-particle events. Shown are the raw data (a), and the signal distributions obtained after application of the corrections based on the measured em shower content, with (c) or without (b) using knowledge about the total "jet" energy [5].

How to improve DREAM performance

- Build a larger detector $\longrightarrow$ *reduce effects side leakage*

- *Increase Čerenkov light yield*
  DREAM: 8 p.e./GeV $\longrightarrow$ fluctuations contribute $35\%/\sqrt{E}$

- *Reduce sampling fluctuations*
  These contributed $\sim 40\%/\sqrt{E}$ to hadronic resolution in DREAM

Homogeneous calorimeters (crystals)

- No reason why DREAM principle should be limited to fiber calorimeters
- *Crystals* have the potential to solve light yield + sampling fluctuations problem
- HOWEVER: *Need to separate the light into its Č, S components*

OPTIONS:

1) Directionality. S light is isotropic, Č light directional
2) Time structure. Č light is prompt, S light has decay constant(s)
3) Spectral characteristics. Č light λ^{-2} , S light depends on scintillator
4) Polarization. Č light polarized, S light not.

Separation of $PbWO_4$:1%Mo signals into S, Č components

From:

NIM A604 (2009) 512

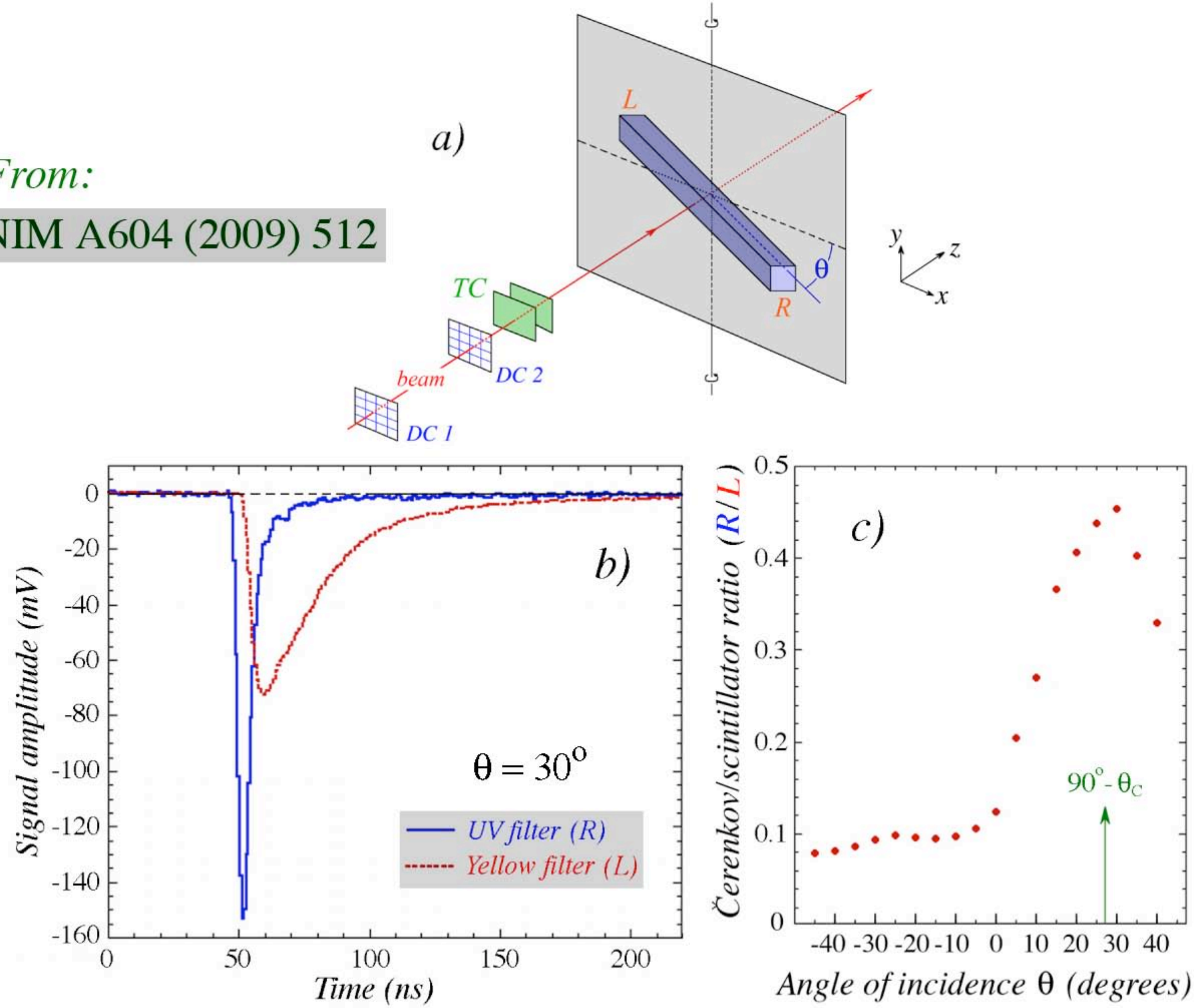
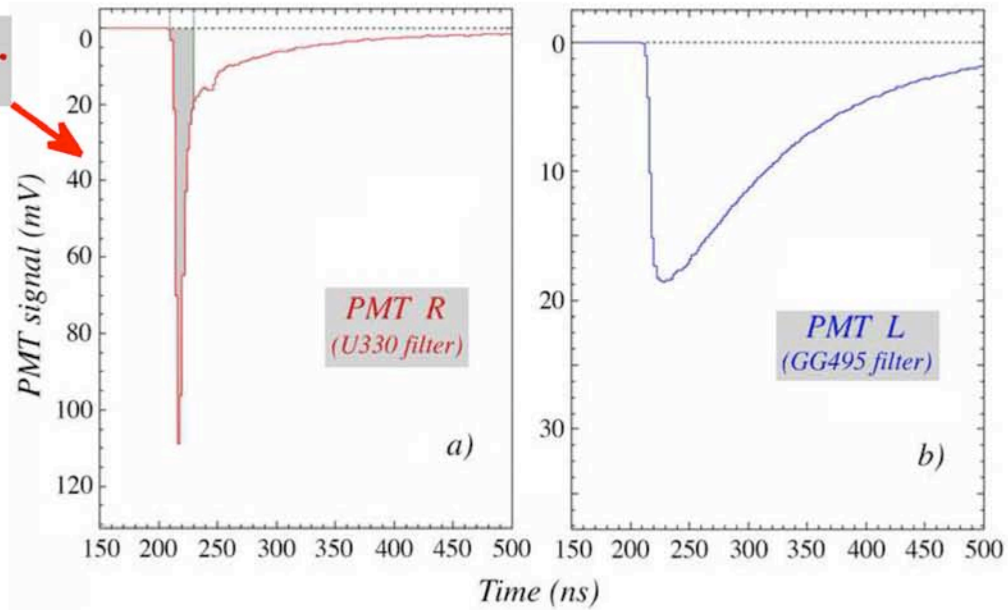
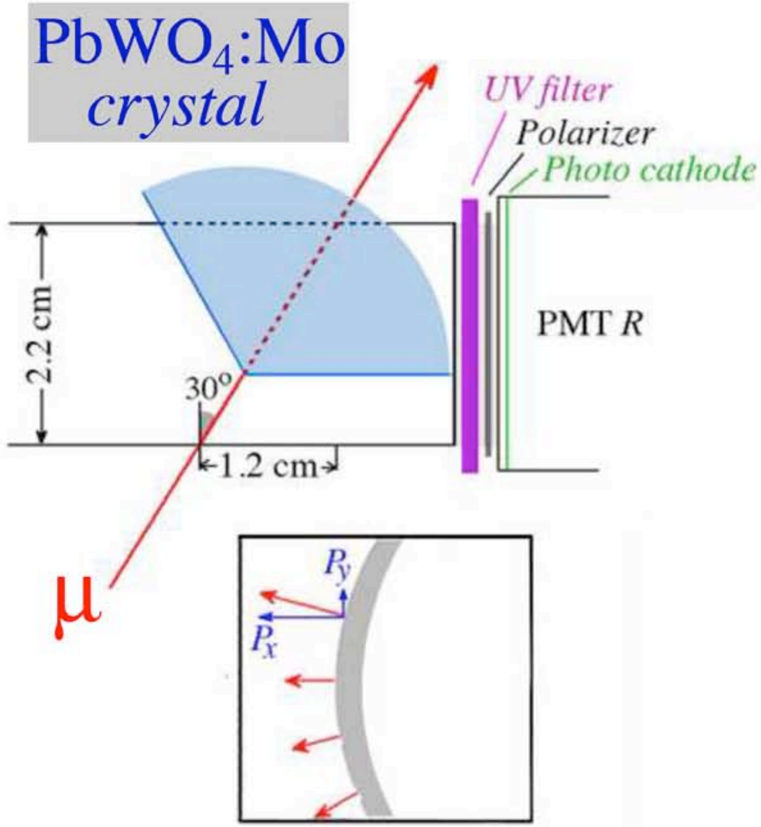


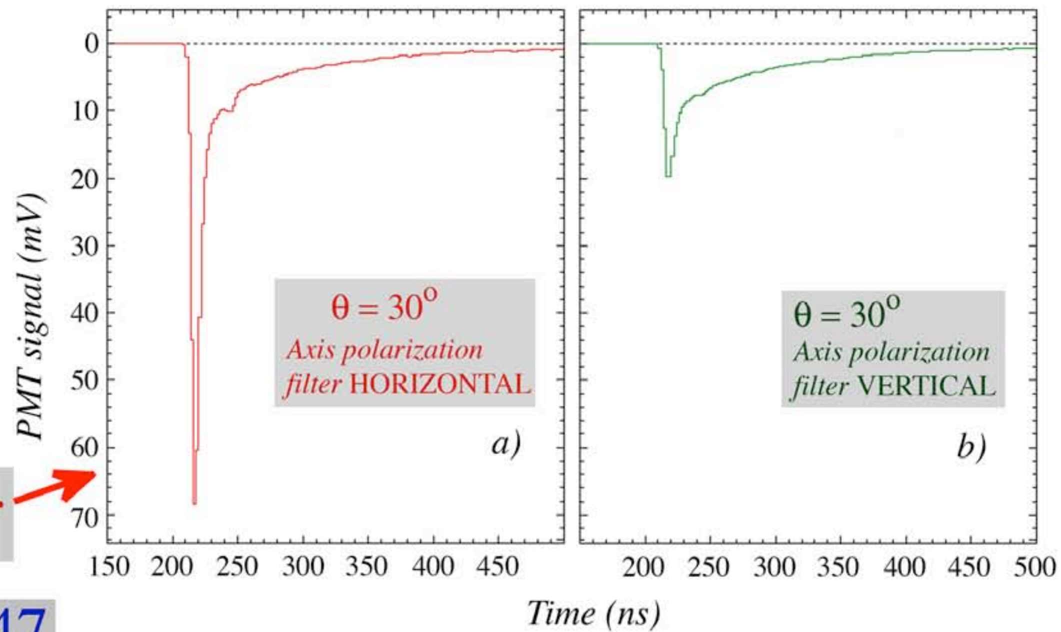
Figure 3: Unraveling of the signals from a Mo-doped $PbWO_4$ crystal into Čerenkov and scintillation components. The experimental setup is shown in diagram a. The two sides of the crystal were equipped with a UV filter (side R) and a yellow filter (side L), respectively. The signals from 50 GeV electrons traversing the crystal are shown in diagram b, and the angular dependence of the ratio of these two signals is shown in diagram c .

Separating the Čerenkov and scintillation components

Effects of the colored filter



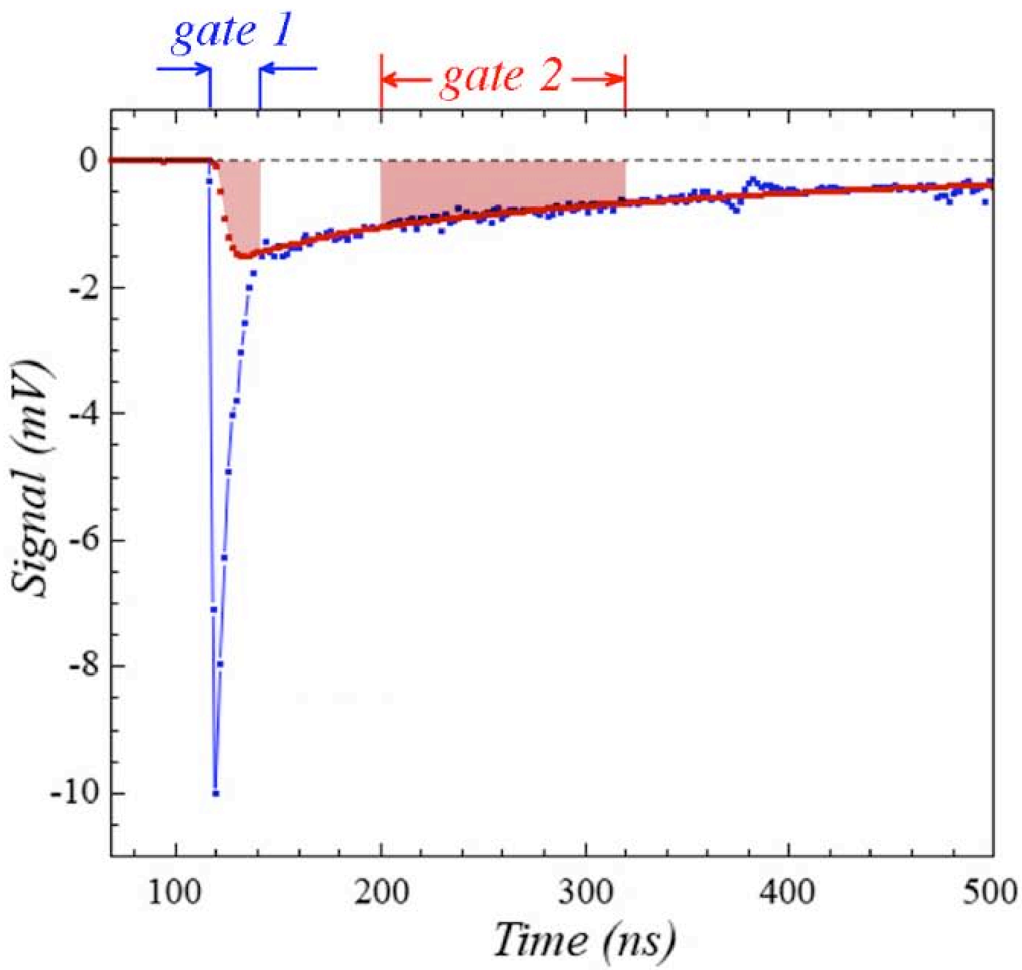




Effects of the polarization filter

from: NIM A638 (2011) 47

Čerenkov and Scintillator information from one signal !



BGO crystal
UG 11 (UV) filter

From:
NIM A595 (2008) 359

Figure 14: The time structure of a typical shower signal measured in the BGO em calorimeter equipped with a UV filter. These signals were measured with a sampling oscilloscope, which took a sample every 0.8 ns. The UV BGO signals were used to measure the relative contributions of scintillation light (gate 2) and Čerenkov light (gate 1)

How to improve DREAM performance

- Build a larger detector ⟶ *reduce effects side leakage*

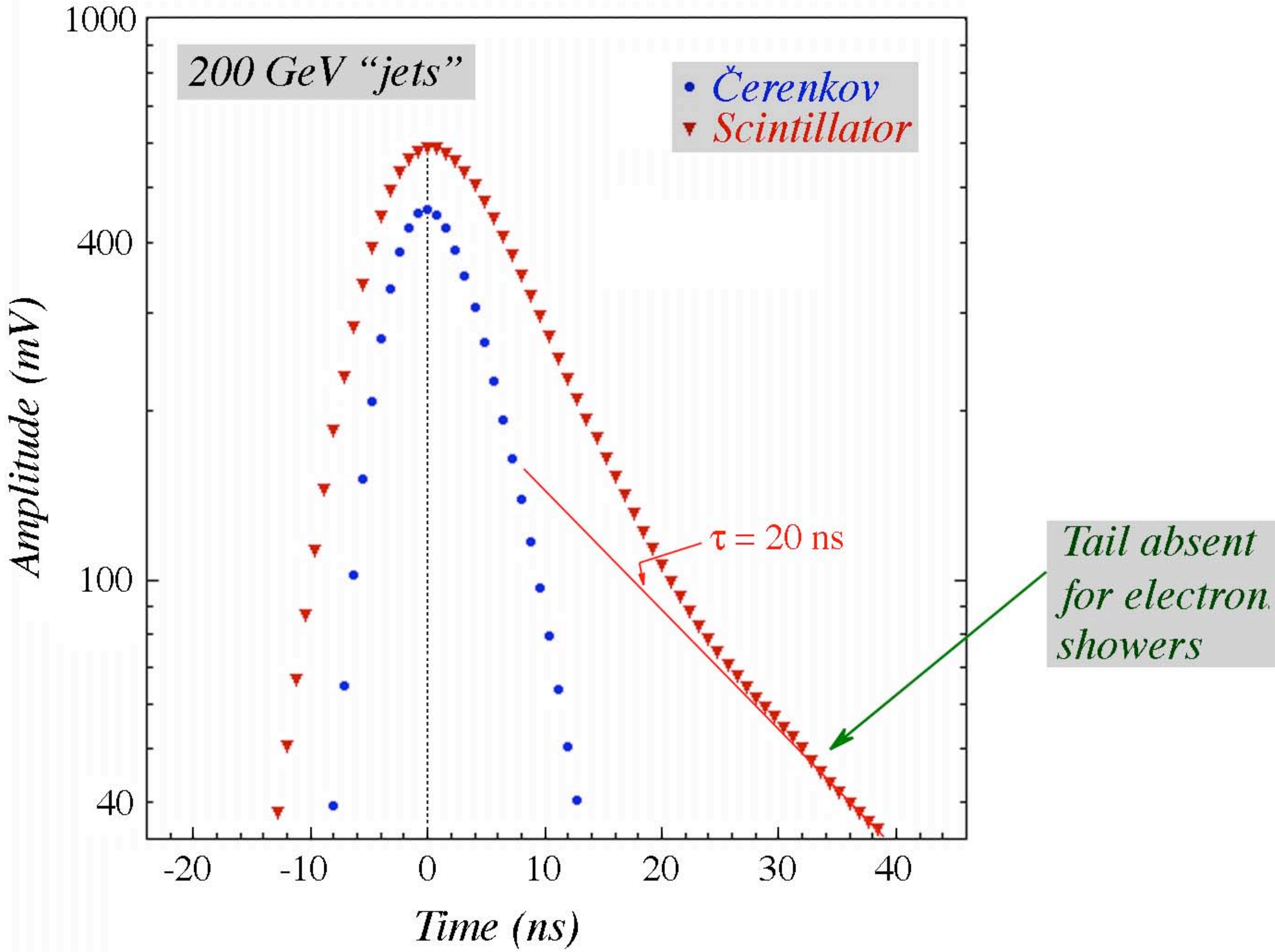
- *Increase Čerenkov light yield*
  DREAM: 8 p.e./GeV ⟶ fluctuations contribute $35\%/\sqrt{E}$

- *Reduce sampling fluctuations*
  These contributed ~ $40\%/\sqrt{E}$ to hadronic resolution in DREAM

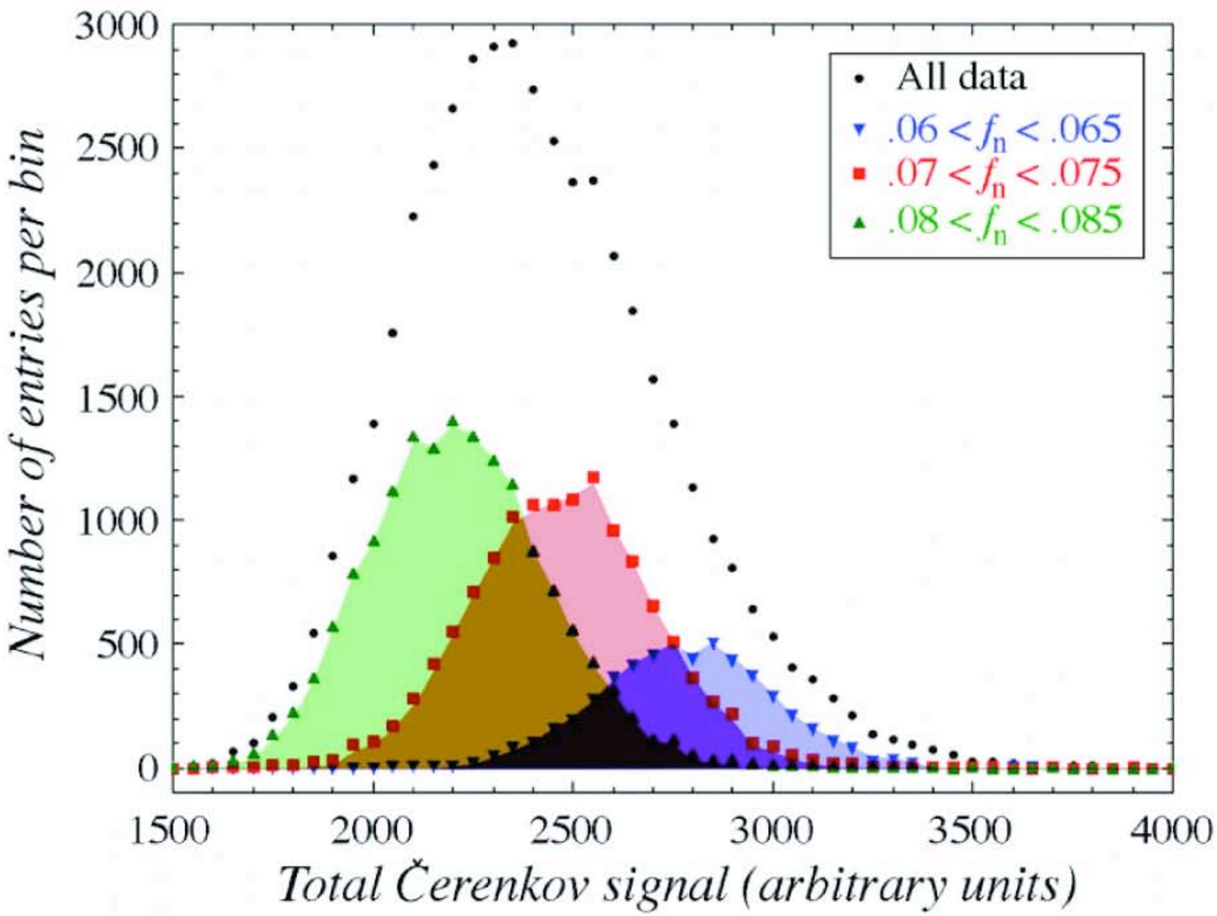
- For ultimate hadron calorimetry ($15\%/\sqrt{E}$): *Measure E_{kin} (neutrons)*
  Is correlated to nuclear binding energy loss (invisible energy)

Can be inferred from the time structure of the signals

Time structure of the DREAM signals: the neutron tail



Probing the total signal distribution with the neutron fraction



From:

NIM A598 (2009) 422

Figure 18: Distribution of the total Čerenkov signal for 200 GeV "jets" and the distributions for three subsets of events selected on the basis of the fractional contribution of neutrons to the scintillator signal .

A critical look at PFA

- *The fact that 65% of the jet energy is measured with excellent precision in the tracker is irrelevant*

In our detectors, the charged tracks are better measured than photon(s) which are themselves better measured than neutral hadron(s)

Resolution on the charged track(s)	$\Delta p/p$	$\sim$ qq 10^{-5}
Resolution on the photon(s)	$\Delta E/E$	$\sim 12\%$
Resolution on the h°	$\Delta E/E$	$\sim 45\%$

$$\underset{\text{fraction}}{E_{jet}} = \underset{65\%}{E_{\text{charged tracks}}} + \underset{26\%}{E_{\gamma}} + \underset{9\%}{E_{h^0}}$$

From: J.C. Brient CALOR 08

What matters for the jet energy resolution are the fluctuations in this 65%.

> In the absence of a calorimeter, one should therefore not expect to be able to measure jet energy resolutions better than 25–30% on the basis of tracker information alone, *at any energy*. And

From: NIM A495 (2002) 107

A critical look at PFA (2)

- *The crucial issue is if one can eliminate the contributions from showering charged hadrons in the calorimeter system, i.e. avoid double counting*

All claims in this respect are based on GEANT4 MC simulations, which

a) have never predicted anything correctly concerning hadron calorimetry

b) are especially wrong in predicting lateral shower shapes (too narrow)

and since the advocates still don't like the results (tails in distribitions), they

c) resort to phony statistics to make them look better

resolution over-emphasises the importance of these tails. In this paper, performance is quoted in terms of rms_{90}, which is defined as the rms in the smallest range of reconstructed energy which contains 90% of the events.

From: NIM A611 (2009) 25

Even for a perfectly Gaussian distribution, $rms_{90} \ll \sigma_{fit}$

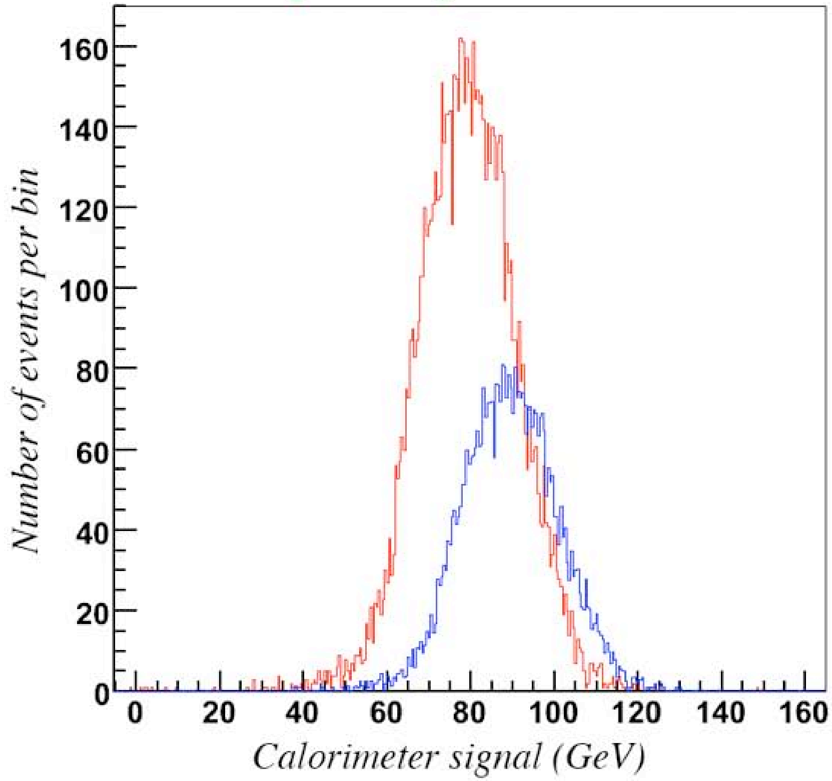
perform the first systematic study of the potential of high granularity PFlow calorimetry. For simulated events in the ILD detector concept, a jet energy resolution of $\sigma_E/E \lesssim 3.8\%$ is achieved for 40–400 GeV jets. This result, which demonstrates that high granularity PFlow calorimetry can meet the challenging

A critical look at PFA (3)

- *Testing claims of how well PFA algorithms are capable of avoiding double counting should be straightforward for the CALICE Collaboration, who have pursued this technique experimentally in the last 10 years*

A jet is a collection of particles, mainly pions and photons. If one has a data base of beam particles of different energies hitting the calorimeter system at different impact points, one could use these experimental data to construct the energy deposit profile for a given jet in many different ways. For each profile, one could apply one's favorite PFA algorithm to eliminate the contributions from charged hadrons and determine the remaining calorimeter energy, which could then be added to the (precisely known) energy of the charged hadrons to give the jet energy → *Jet response function*

Example:
Jet response function CMS



A critical look at PFA (4)

- *Proposed PFA systems consist of millions of readout channels (fine granularity!)*
  Question: How does one want to calibrate these calorimeters?
  (cf. problems discussed earlier)
  Answer (CALICE): DIGITAL calorimetry (energy ∝ # of channels that fired)

This was tried and abandoned in 1983, for good reasons: Particle density in the core of em showers is very high

→ *Non-linearity*

From: NIM 205 (1983) 113