ON WRONG AND CORRECT WAYS
to analyze & interpret calorimeter test beam data

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Trends & Challenges
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GOAL / MESSAGE of this talk

The assessment of the performance of calorimeters is very different from that of other types of particle detectors.

Important performance characteristics:

- *Vertex detector:* *Position resolution*
- *Tracking system:* *Two-track separation*
  Momentum resolution
- *Trigger counter:* *Time resolution*
- *Wire chambers:* *Detection efficiency*

→ *Can all be determined in straightforward and unambiguous ways*

Calorimeter: *Energy resolution* → *Depends on how measurements are done and by whom*

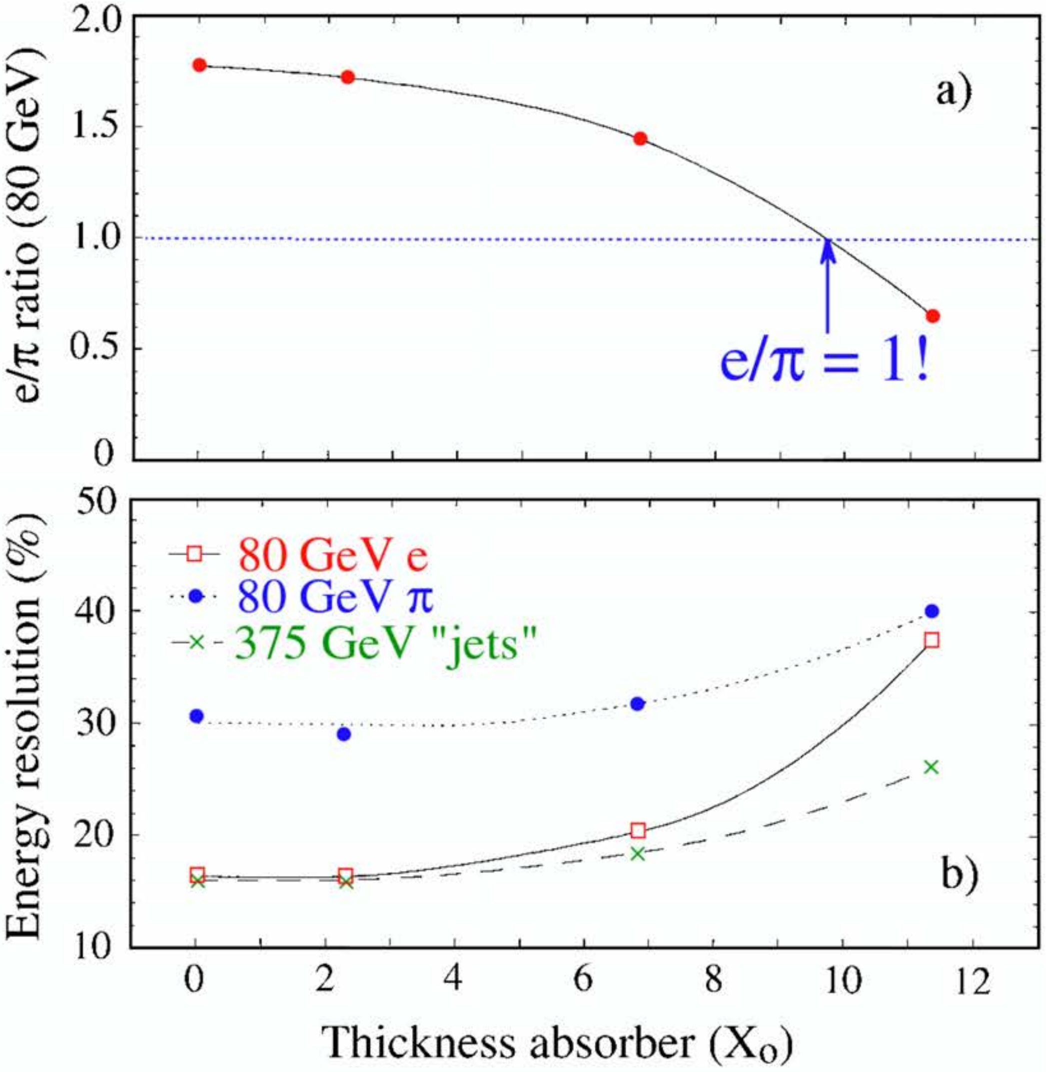
About calorimeter energy resolution

Energy resolution is determined by FLUCTUATIONS

Excluding certain fluctuations (either on purpose or unconscionably) therefore leads to a resolution that seems better than in reality

"Dummy" compensation

NIM A390 (1997) 63, NIM A400 (1997) 267



Energy resolution is determined by fluctuations, NOT by mean values. Therefore, multiplying the signals from one calorimeter section with a constant factor, has NO effects on the resolution.

Extreme example:

Calorimeter with dead material upstream to equalize the response to electrons and pions.

FIG. 4.59. The e/π signal ratio at 80 GeV (a) and the energy resolution (b) of a quartz-fiber calorimeter preceded by dead material (iron), as a function of the thickness of this material [Fer 97]. The energy resolution is given for 80 GeV electrons and pions, and for multi-particle "jets" generated by 375 GeV pions in an upstream target.

About calorimeter energy resolution

Energy resolution is determined by FLUCTUATIONS

Excluding certain fluctuations (either on purpose or unconscionably) therefore leads to a resolution that seems better than in reality

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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

Prologue

1974: *Willis/Radeka build first LAr calorimeters*

1976: ^{238}*U/LAr tested in electron and pion beams* *(4.6 λ deep module)*

Result: NIM 141 (1977) 61

$10\ \mathrm{GeV}\ \pi^- \longrightarrow \sigma/E = 9.6\%\ \ (\text{i.e. } 30\%/\sqrt{E})^*$

It later turned out that the authors had limited the analysis to events whose showers were fully contained inside a limited area of this small calorimeter (radius 1.5λ).
These events had, on average, anomalously high electromagnetic content (π^0), which leads to an anomalously good energy resolution.

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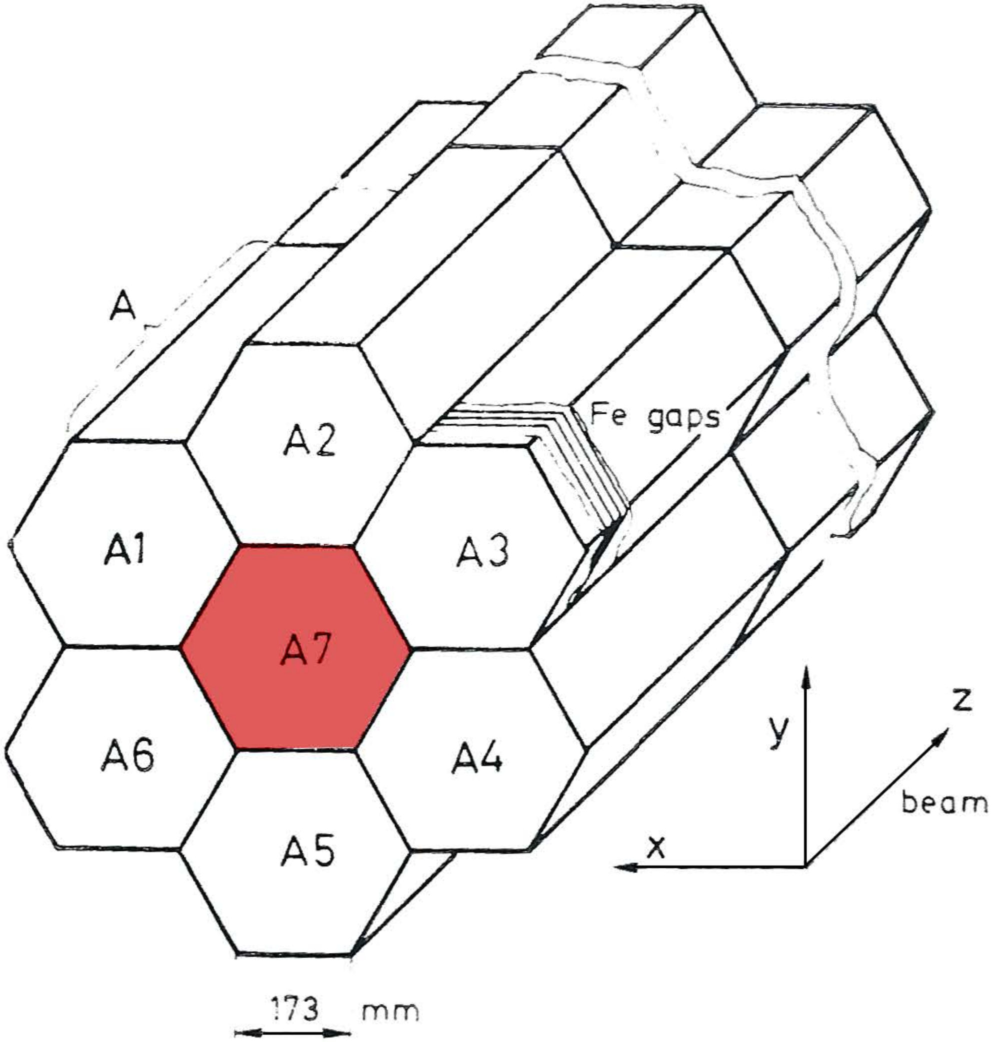
* *This result started a controversy, since other groups who built U/LAr calorimeters (D0 prototypes) found much worse resolutions.*

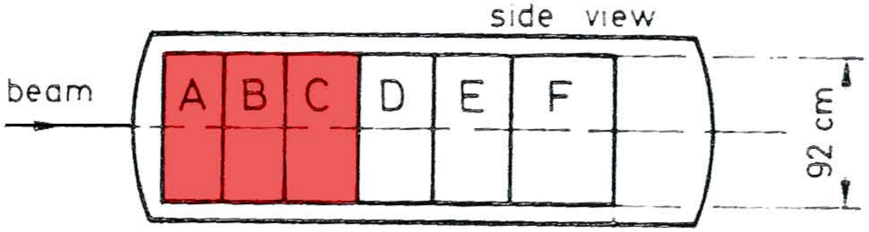
The first ^{238}U/LAr calorimeter

NIM 141 (1977) 61

🟥 *^{238}U/LAr*

The rest: Fe/LAr





Common mistakes in assessing calorimeter performance

ANALYSIS OF TEST BEAM EVENTS

- *Biased event samples*
- *Use of the calorimeter itself to select/eliminate events*
- *MISCALIBRATION*

REPORTING OF THE RESULTS

- *Quoting the energy resolution in terms of* $x\%/\sqrt{E}$
- *Eliminating important contributions to the resolution*
- *Suggesting linearity is not important*
- *Suggesting* $\pi = jet,\ e = \gamma$
- *Deliberate misleading presentation of results*

The use of biased event samples

Most common examples:

- *Select events that are fully contained in the calorimeter*
  No signal in tailcatcher, no signal in lateral leakage counters

- *Select showers with a fixed starting point,*
  e.g. in a preshower detector directly upstream

- *Select showers that start beyond the em calorimeter section*
  and deposit energy only in the hadronic section

Consequences :

- *Energy resolution too optimistic,*
  because certain contributions not taken into account
  (non-uniformity of response, fluctuations in em shower fraction,.....)

- *Mismeasurement of the response (average signal per GeV)*

A biased event sample

(arXiv:1207.4210v1 [physics.ins-det])

(< 20%)

particle type	beam energy [GeV]	all pions	selected pions
π^-	10	440208	84706
π^-	15	127554	24997
π^-	18	52880	10492
π^-	20	342798	67093
π^-	25	201243	39631
π^-	35	272987	54126
π^-	40	472345	93301
π^-	45	325092	63547
π^-	50	304023	59076
π^-	60	647090	121588
π^-	80	741440	139248
π^+	30	155210	30884
π^+	40	307177	60595
π^+	50	159414	30843
π^+	60	449273	86947
π^+	80	272441	52442

Table 1. Summary of the data samples. The total number of pions is the number of events classified as pions, after rejection of empty, noisy and double particle events, and the application of muon rejection and particle identification cuts. The number of selected pions are the events with an identified shower start in the first five layers of the AHCAL, which are used in the present analysis. For most energies, several run periods at different temperatures are combined to maximise statistics.

Use of the calorimeter itself to select / eliminate events

Example:

- *CMS beam tests of ECAL + HCAL*
- *Some fraction of the events taken with π beams had very large signals*
- *It was assumed that these were "double hits" (several simultaneous beam particles), and the events were eliminated from the analysis*
- *When CMS started to operate, it turned out that these were actually real, the so-called "spike events"*

Sometimes it is very tempting

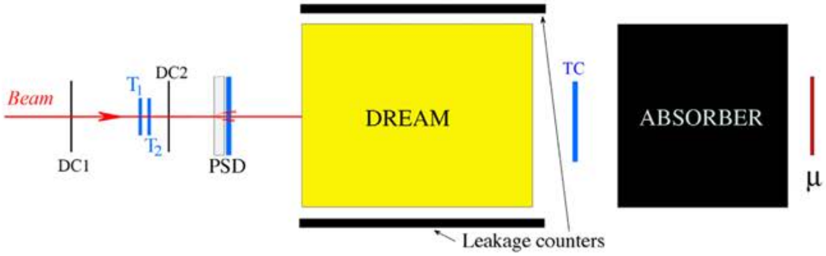


Fig. 4. Schematic overview of the arrangement of the auxiliary detectors that were used to identify the individual beam particles (not to scale). See text for details.

NIM A735 (2014) 120

μ:

mip in PSD
mip in TC
mip in μ

Hadron:

mip in PSD
0 in μ

Electron:

> 2mip in PSD
0 in TC, μ

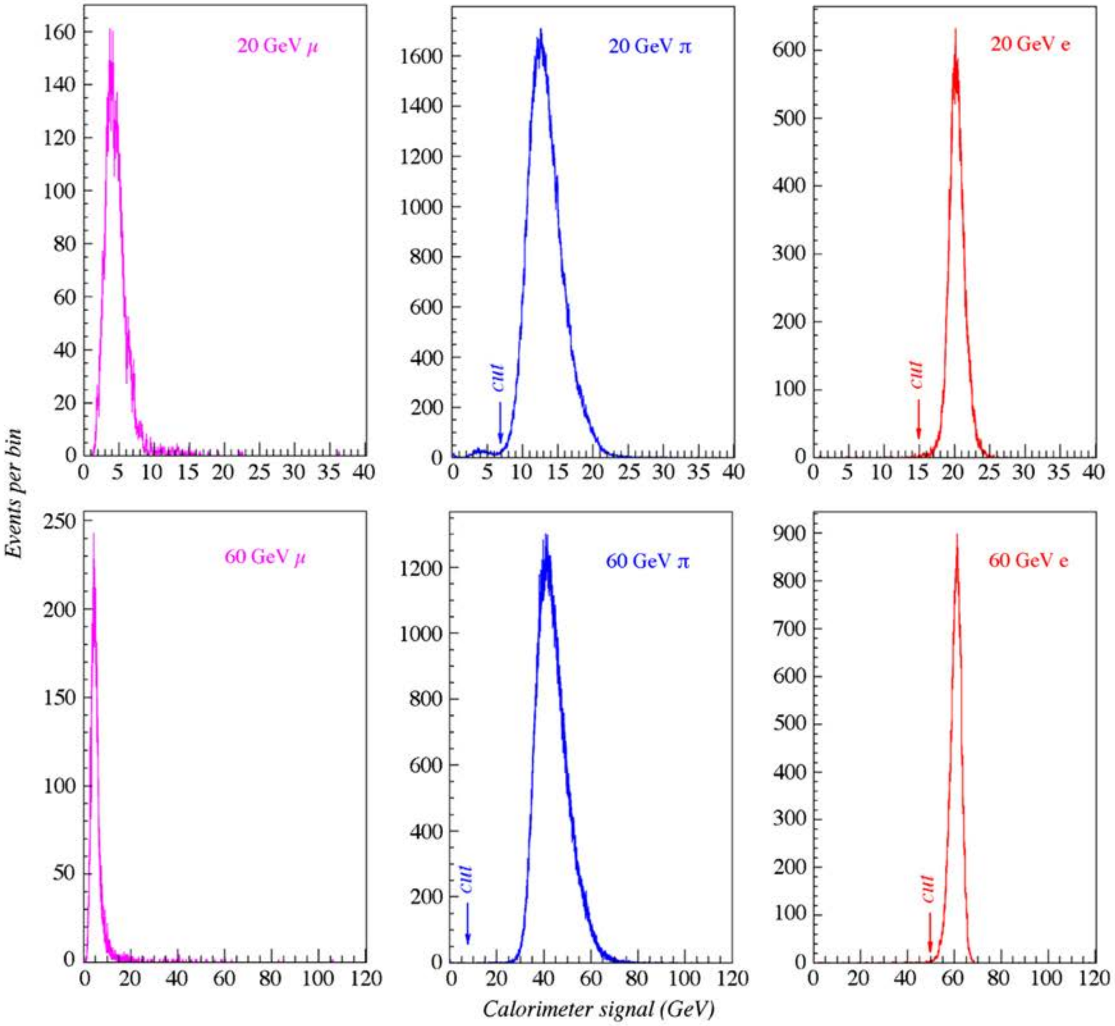
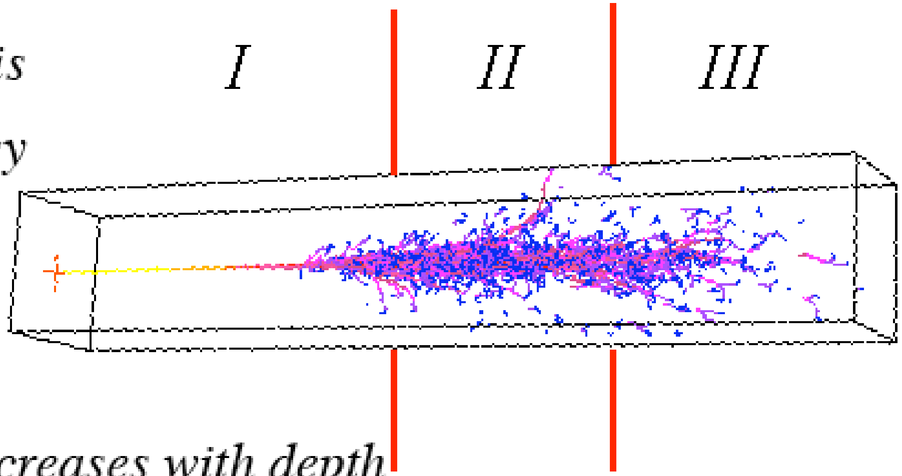


Fig. 5. The calorimeter signal distributions for the pure muon, pion and electron event samples used in the analyses. See text for details.

(Mis) 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*

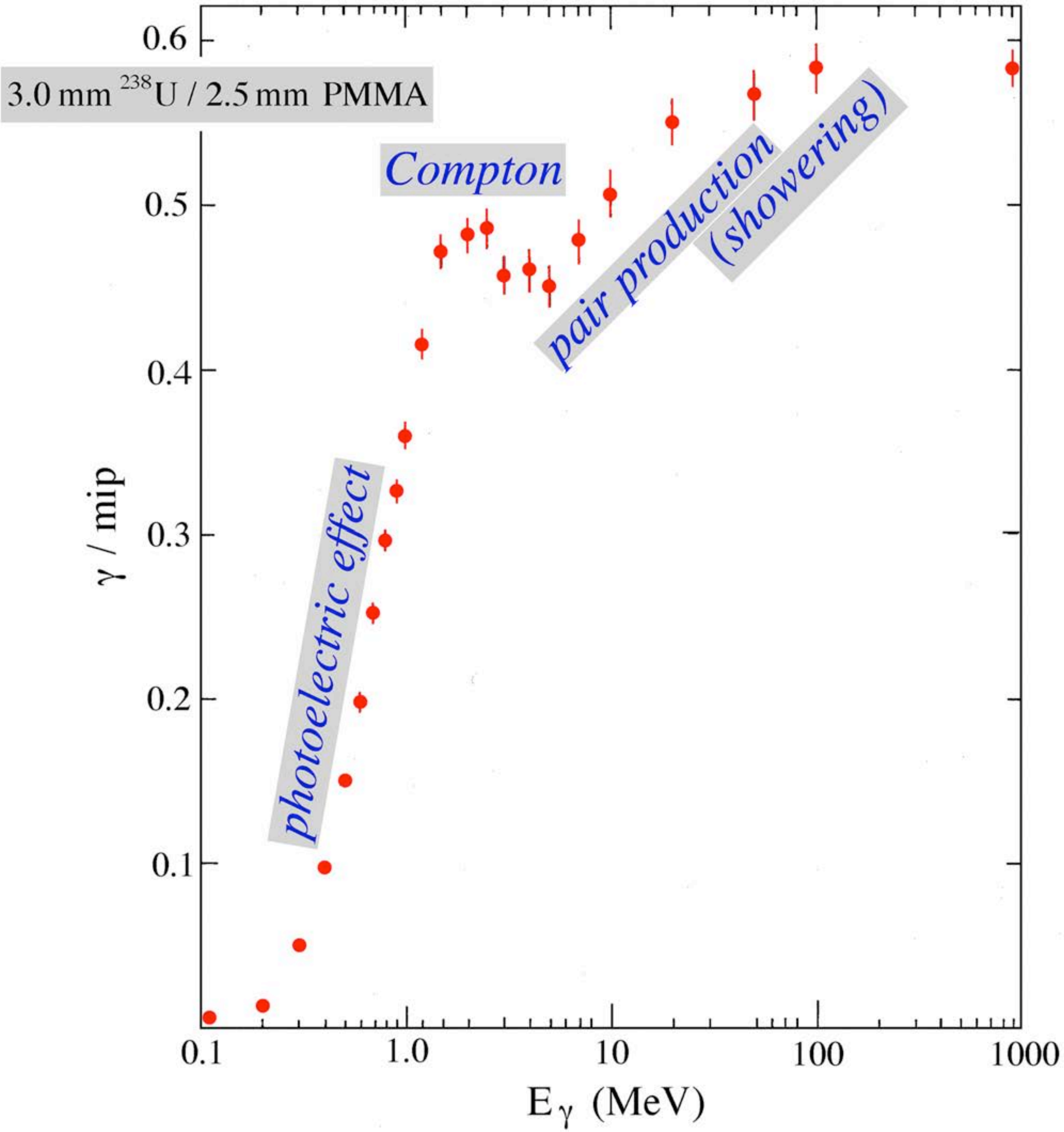
Calibration of calorimeter systems

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

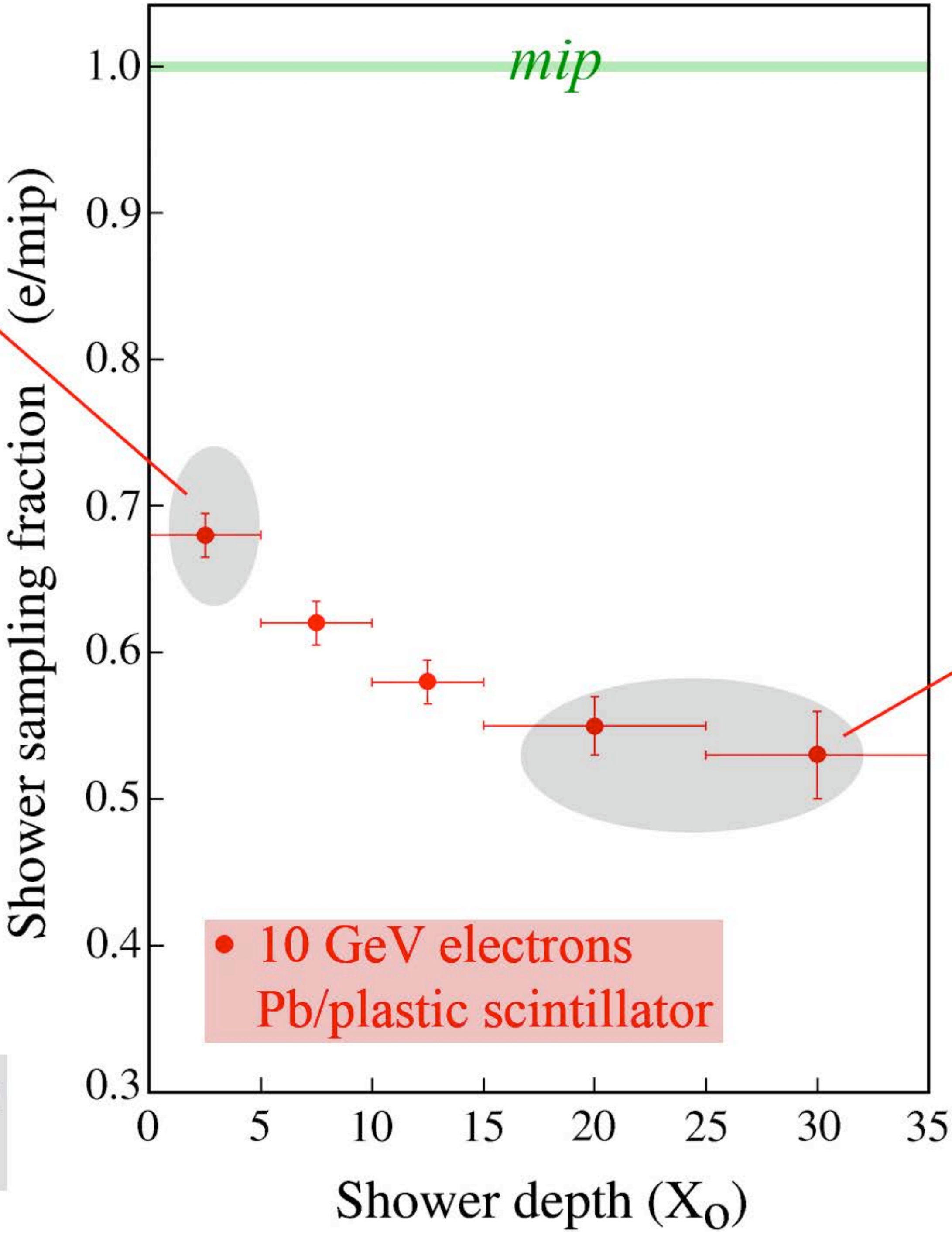
- *Fundamental problem in sampling calorimeters:*
  Different shower components are sampled differently
  Shower composition changes as shower develops
  → *Sampling fraction changes with the shower age* (also E dependent)

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**



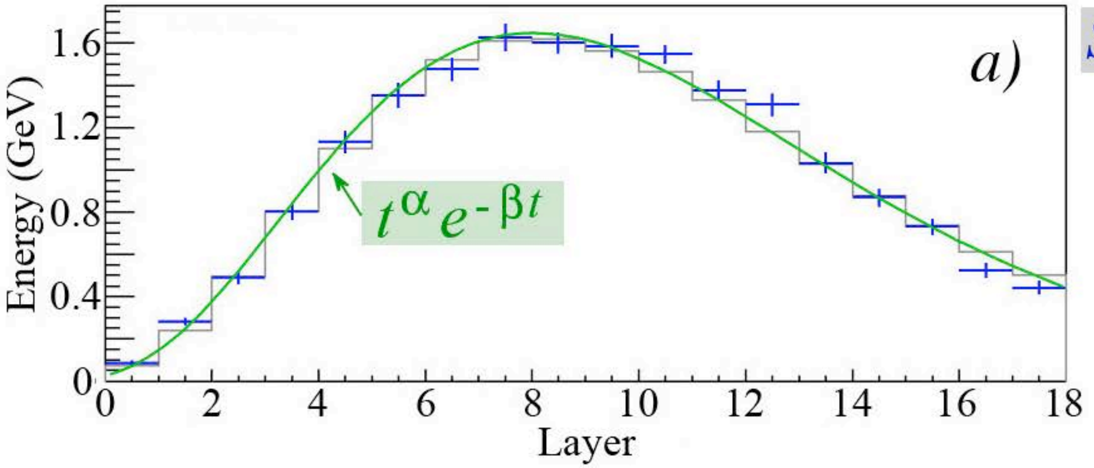
shower dominated by mip's

shower dominated by soft γ's

**By as much as 30%!*

Calibration misery of longitudinally segmented devices

Example: AMS (em showers!)



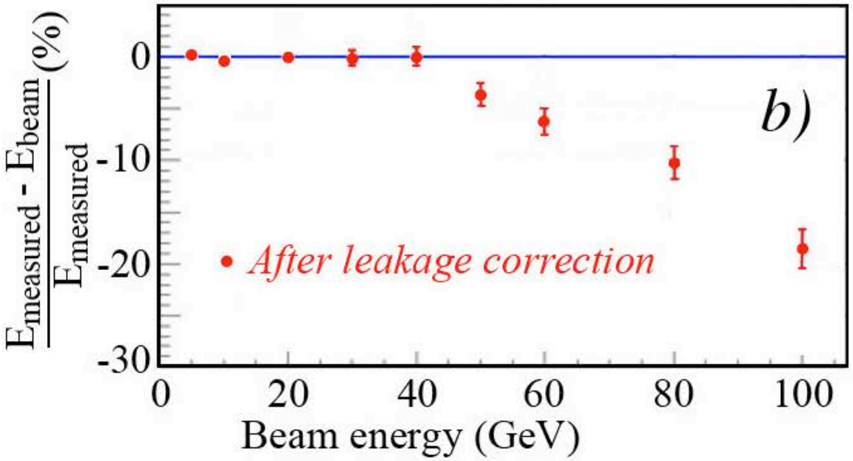
Source: NIM A490 (2002) 132

Pb/scintillating fiber (18 layers)

Calibrated with mip's:
11.7 MeV/layer

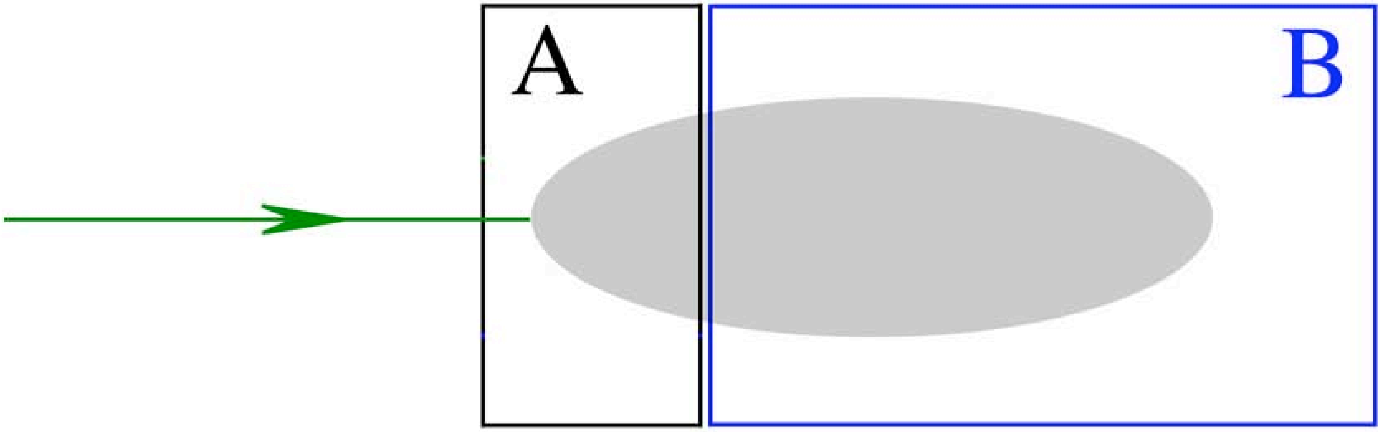
Leakage estimated from fit to measured shower profile

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

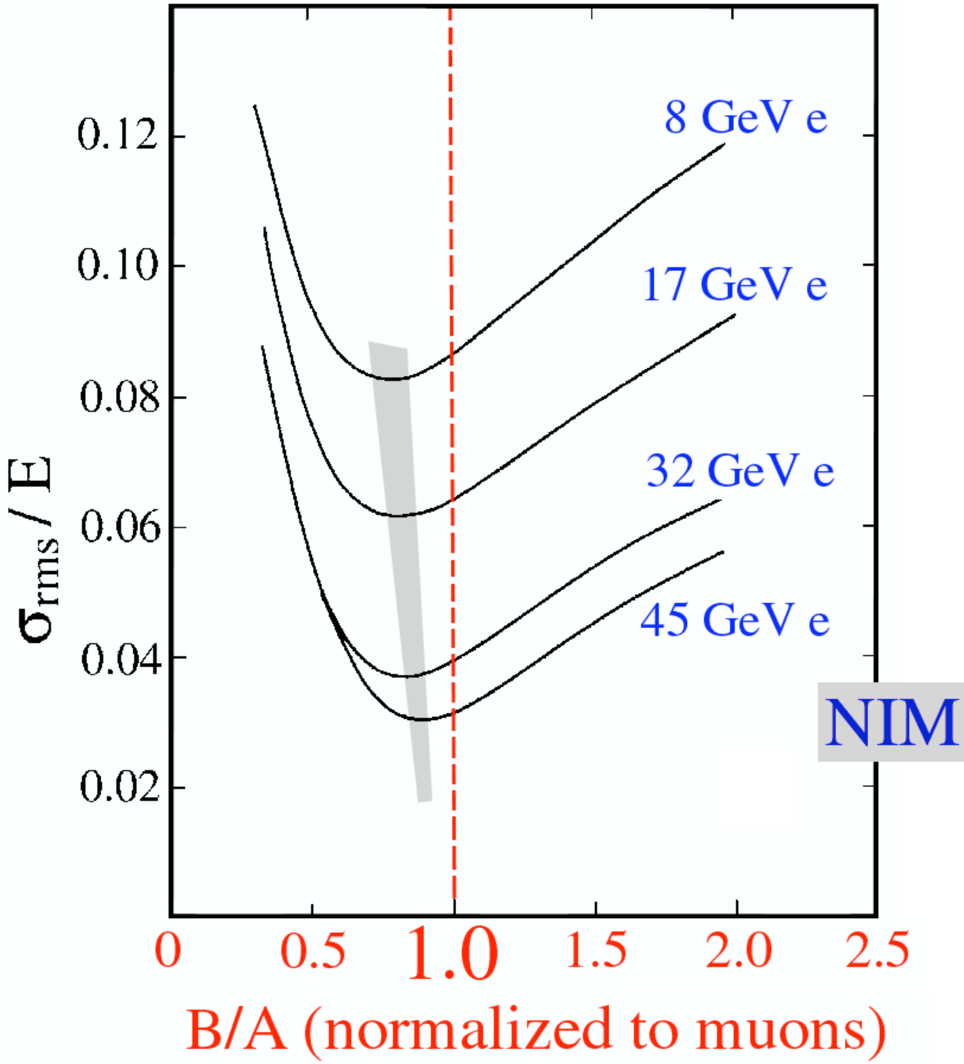
A widely used technique for calibrating segmented devices



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*

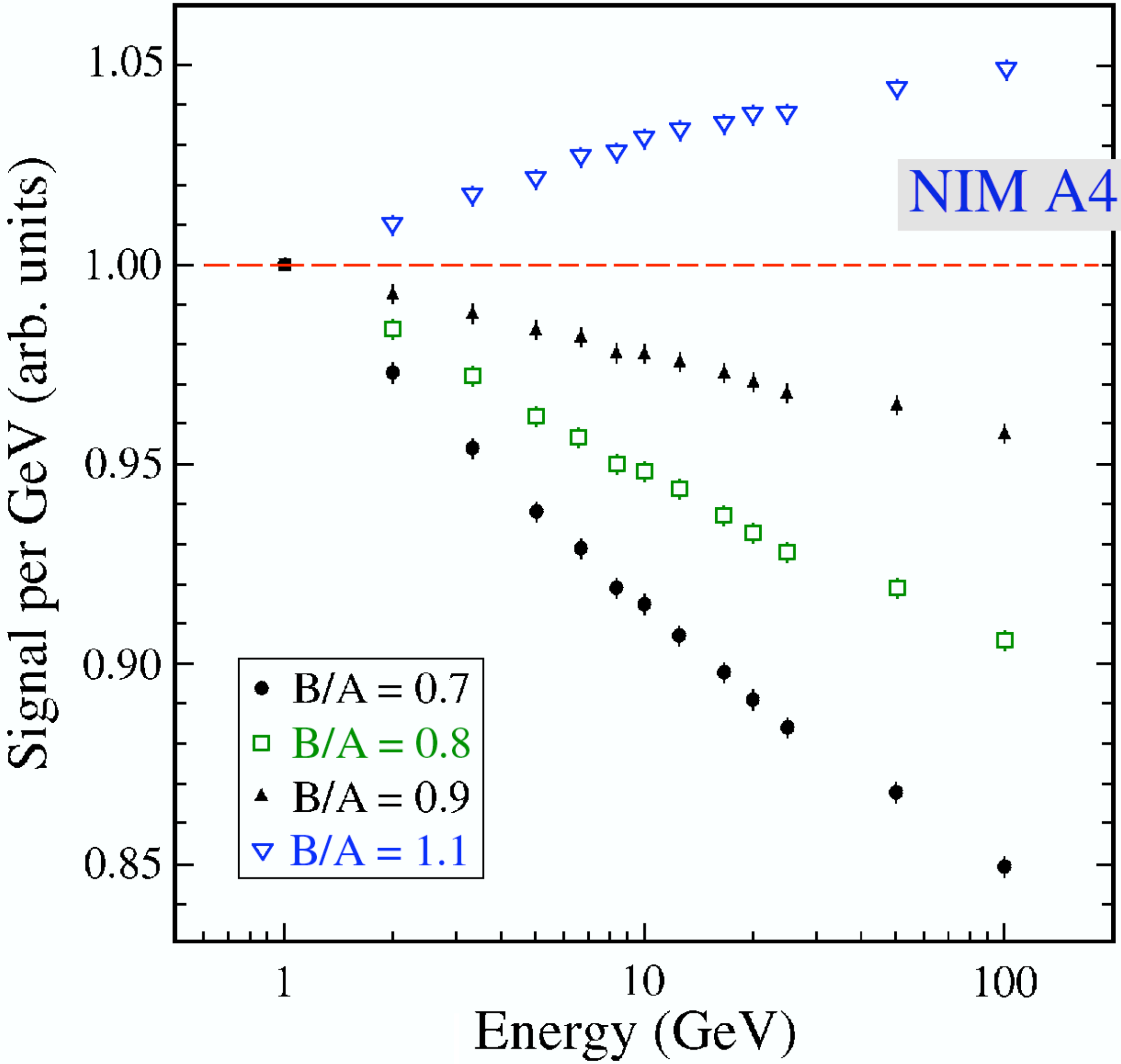
Calibrating longitudinally segmented calorimeters



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

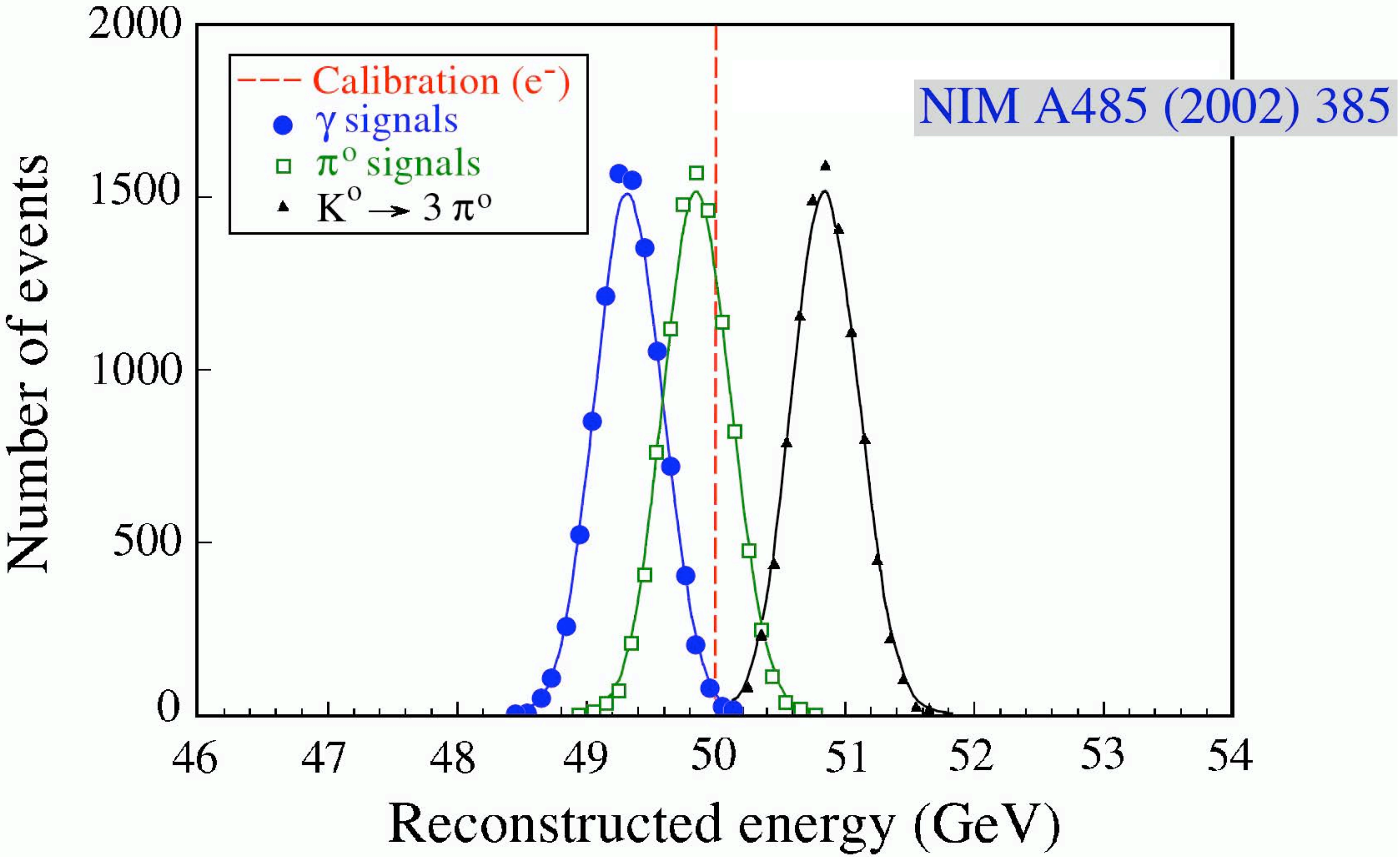


Figure 14: Signal distributions for γs and various hadrons decaying into all-γ final states. All particles have the same nominal energy and the detector, which has an intrinsic resolution of 0.5% for em showers of this energy, was calibrated with electrons using $B/A = 0.8$. See text for details.

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

Intercalibrating sections by minimizing total signal width
GIVES WRONG RESULTS!

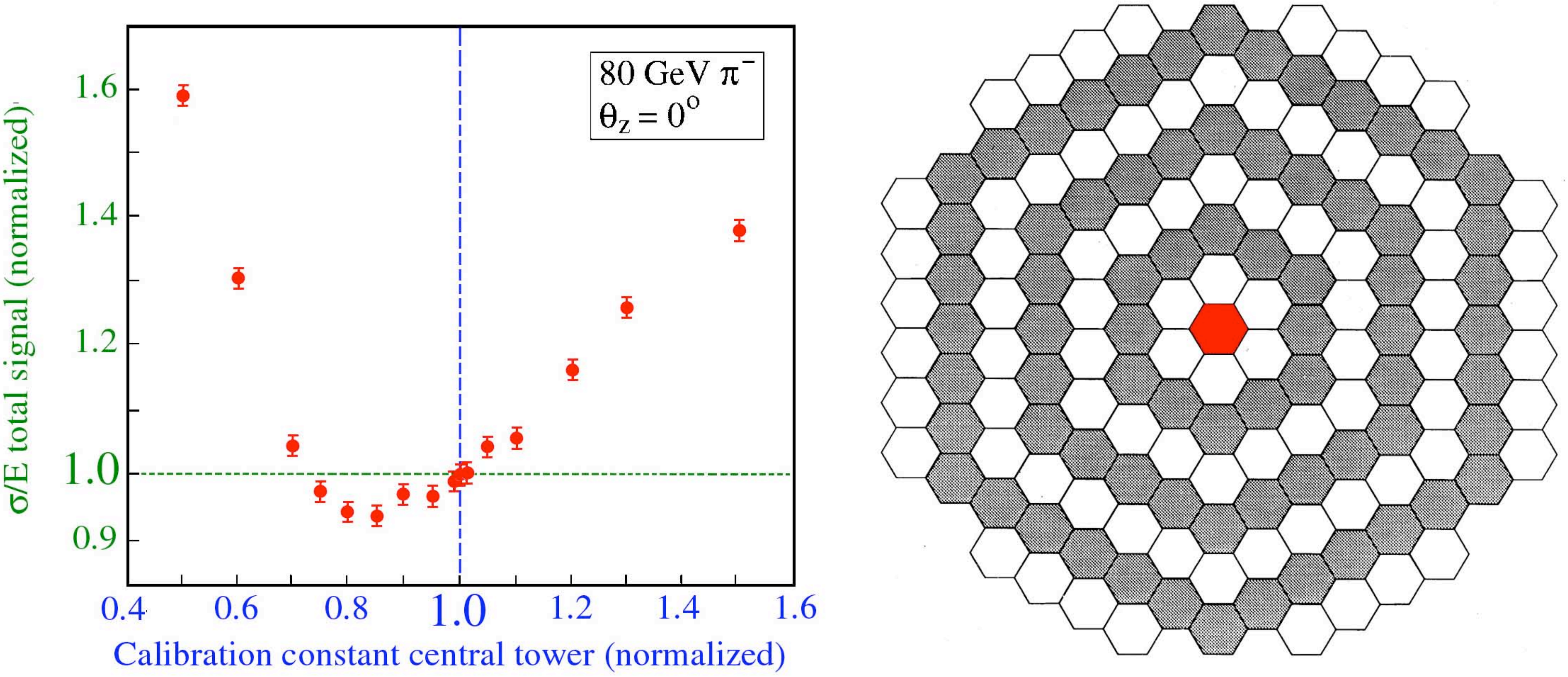


Figure 11: The fractional width, σ/E, of the signal distribution for 80 GeV π^- in the SPACAL detector as a function of the weighting factor applied to signals from the central calorimeter tower into which the pion beam was steered. The calorimeter towers were calibrated with high-energy electrons [7].

From: NIM A485 (2002) 385.

Hadronic showers

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

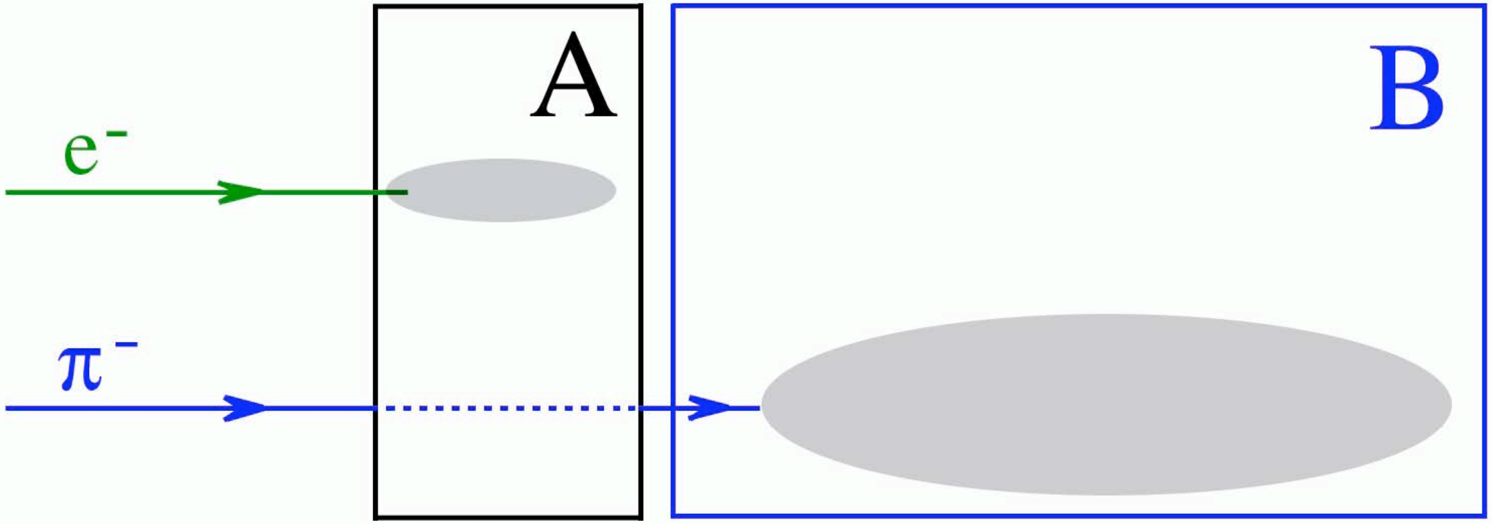
⇛ *Calibration problems even worse than for em calorimeters*

Aspects of the calibration of Calorimeter systems at colliders

- *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

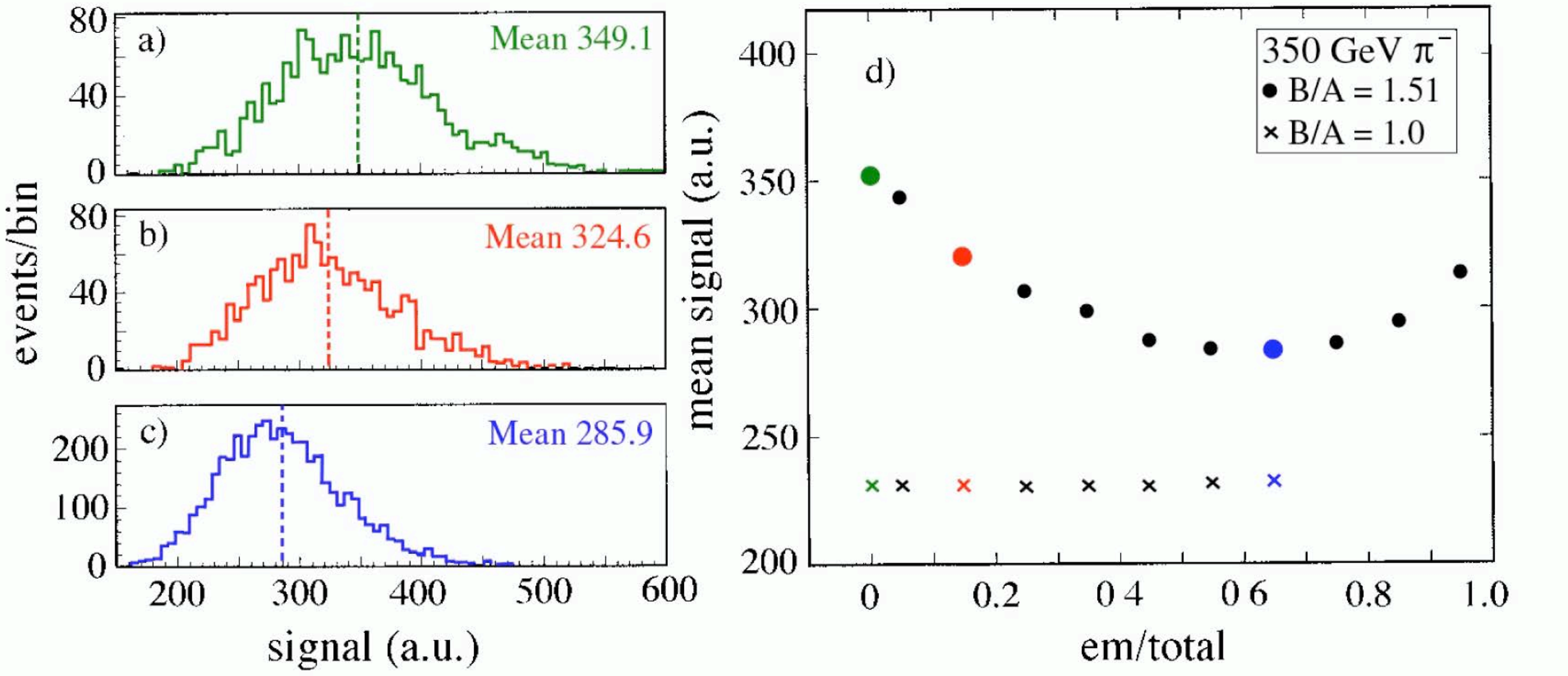


FIG. 6.10. Signal distributions for 350 GeV pion showers in a longitudinally segmented quartz-fiber calorimeter, for events in which different fractions of the (unweighted) shower energy were recorded in the em calorimeter section. Shown are distributions for which this fraction was compatible to zero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

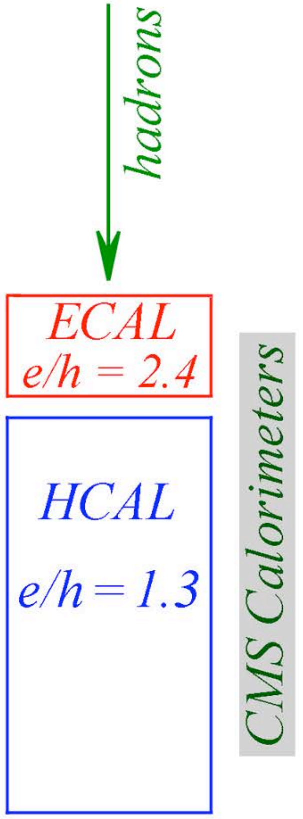
Use the em scale for all sections (B/A = 1)

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*

Data from: CMS note 2007/012

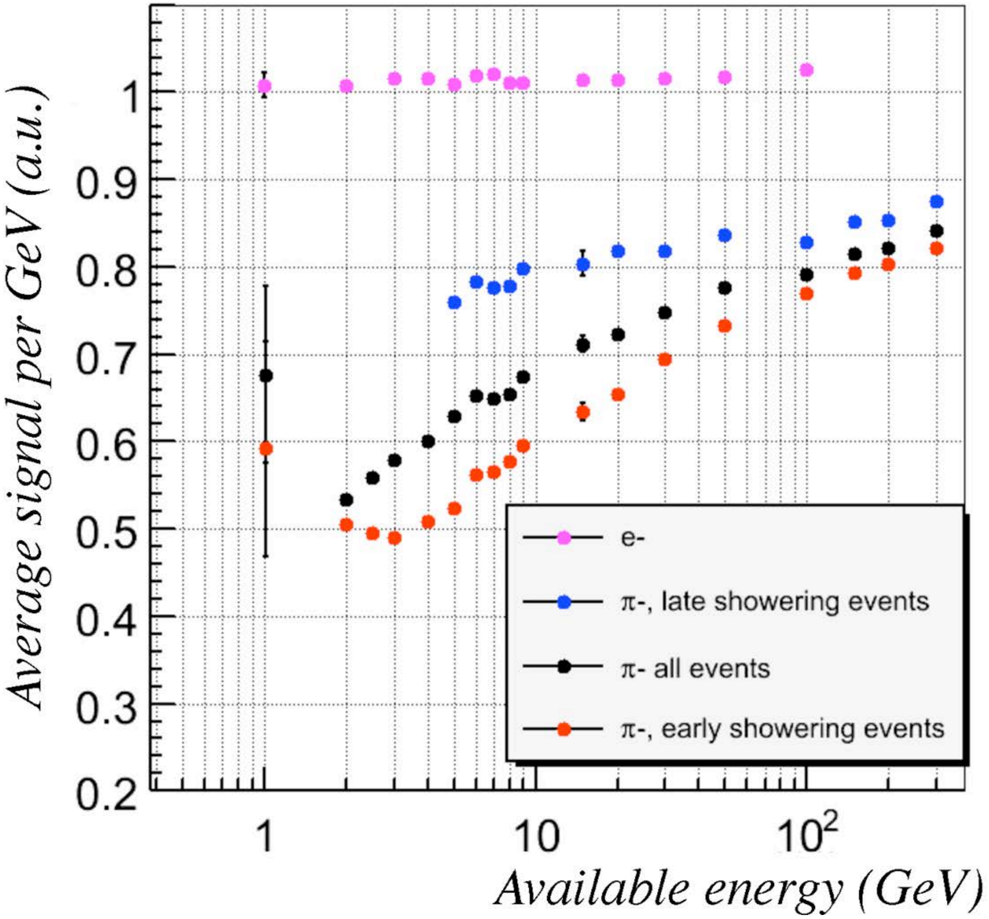


hadrons

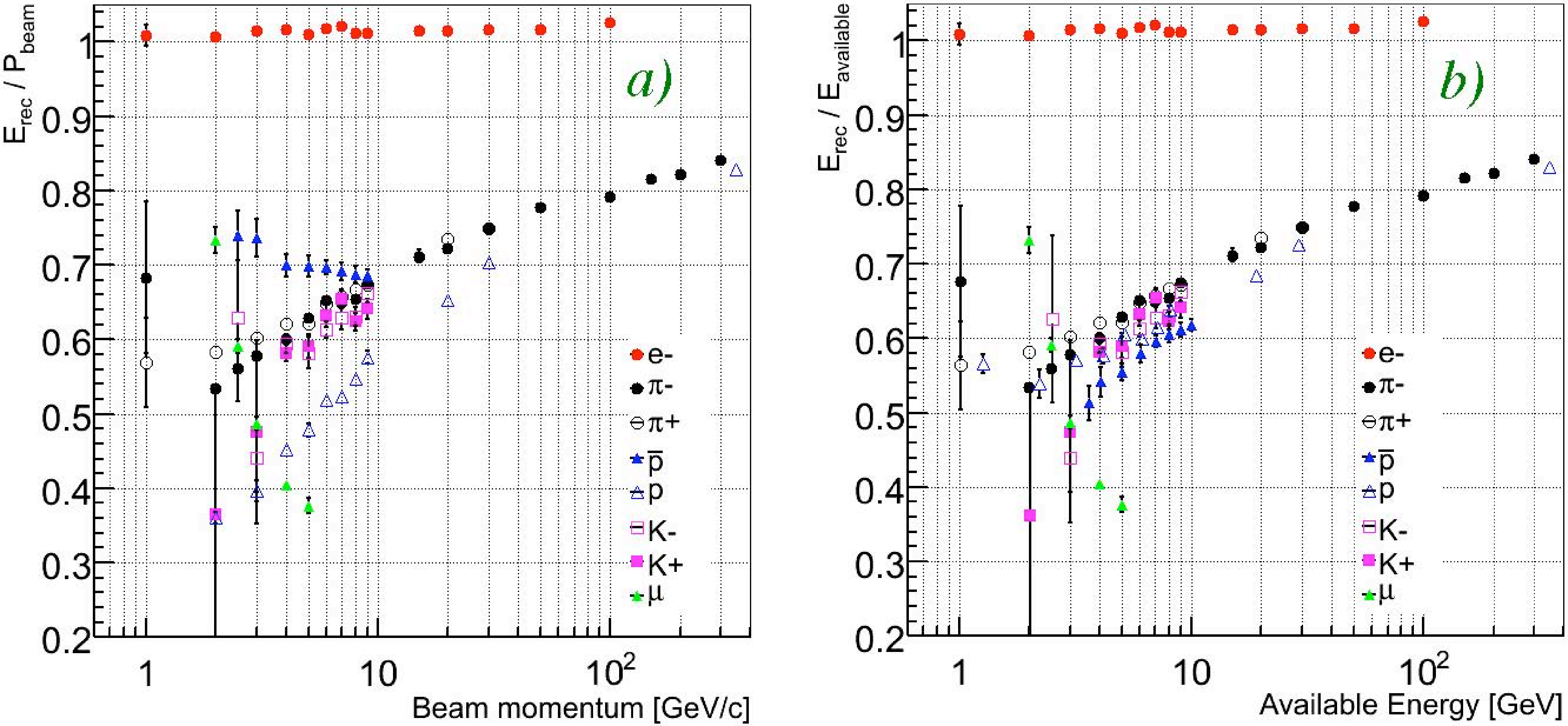
ECAL
$e/h = 2.4$

HCAL
$e/h = 1.3$

CMS Calorimeters



Single particles and jets in the CMS calorimeters



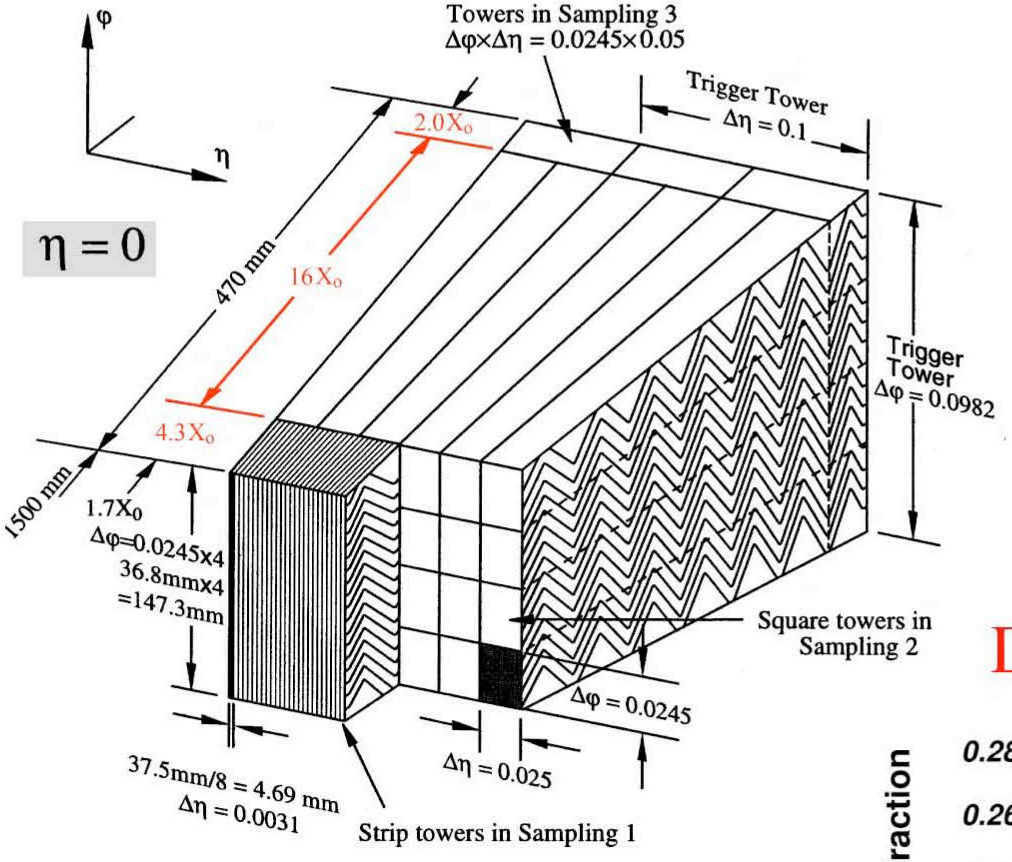
Calorimeter response does not only depend on starting point of the shower, but also on the particle type

So what to do?

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

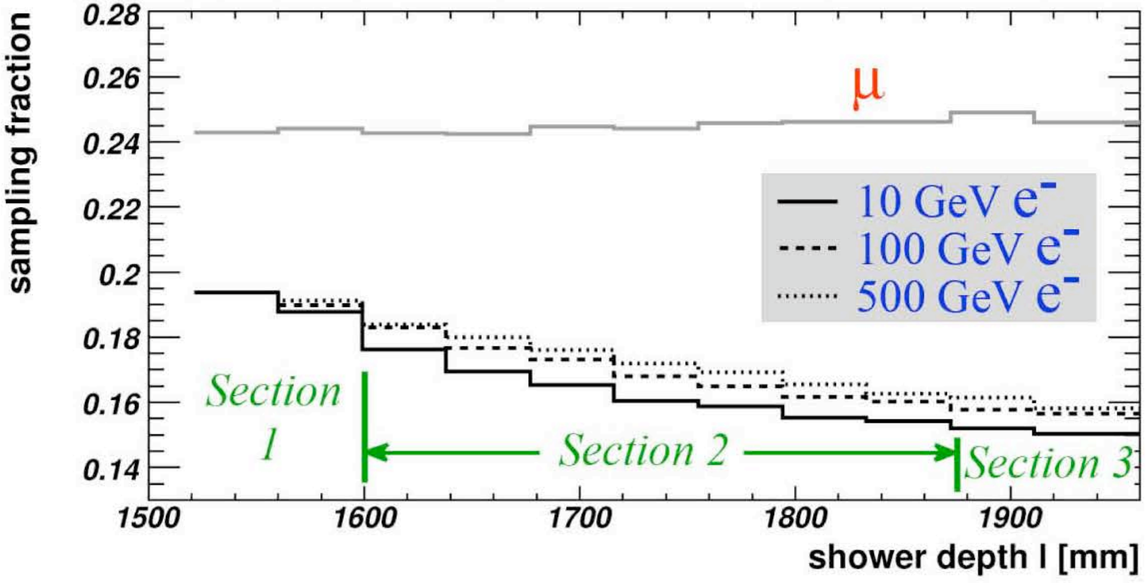
Monte Carlo simulations !!!

ATLAS: The longitudinally segmented (LAr) ECAL

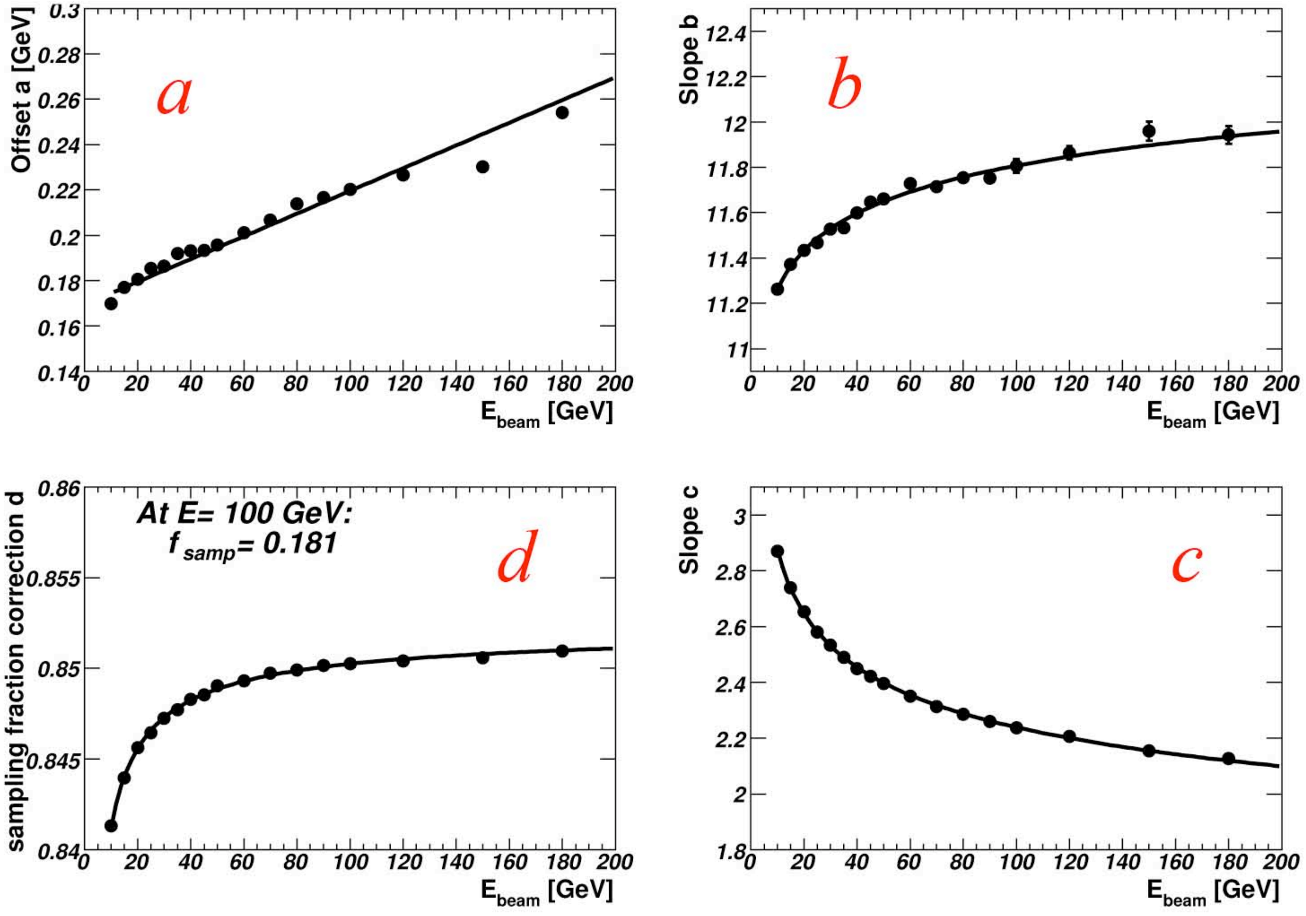


NIM A568 (2006) 601

Depth dependent em sampling fraction



ATLAS: Energy reconstruction ECAL



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

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

MISTAKES IN REPORTING RESULTS

(most of these are deliberate)

Quoting the energy resolution in terms of “$x\%/\sqrt{E}$”

- *The energy resolution is typically affected by several other factors than those determining the stochastic term.*

- *The contributions of these other factors typically have a different energy dependence, and may even dominate in certain energy regions*

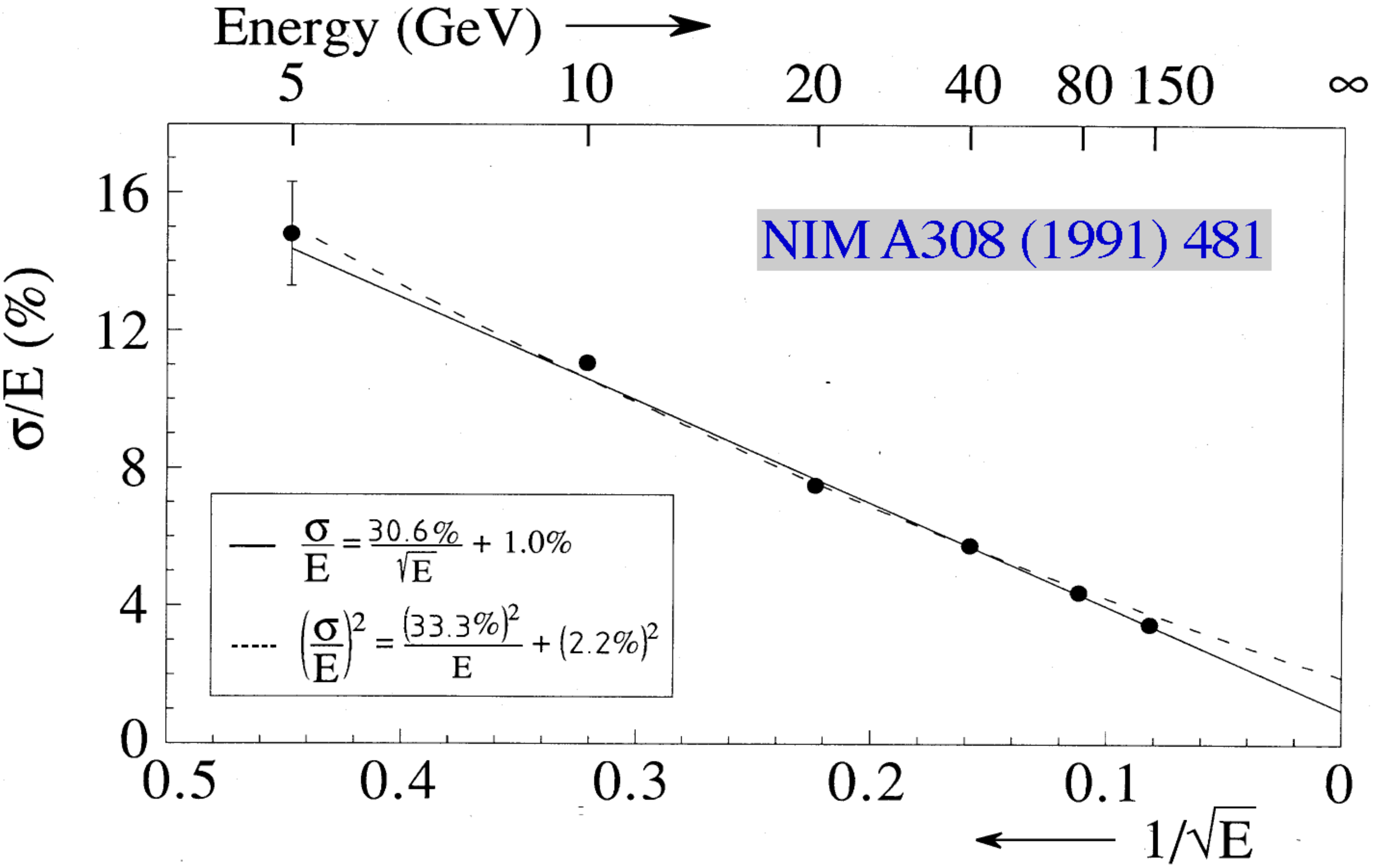
- *An almost universal misunderstanding in this context is that $e/h \neq 1$ (non-compensation) contributes a constant term to the resolution*

  The correct energy dependence is as follows:
  with the degree of non-compensation $0 < x < 1$

$$x \left[\frac{E}{0.7}\right]^{-0.28}$$

- *Quoting the energy resolution (for comparitive purposes) in terms of $x\%/\sqrt{E}$ is a misleading oversimplification of the reality*

The scaling term depends on the type of fit



Linear addition of contributions is suspect

HOWEVER

From:
RW - Calorimetry book

FLUCTUATIONS IN THE ELECTROMAGNETIC SHOWER CONTENT 251

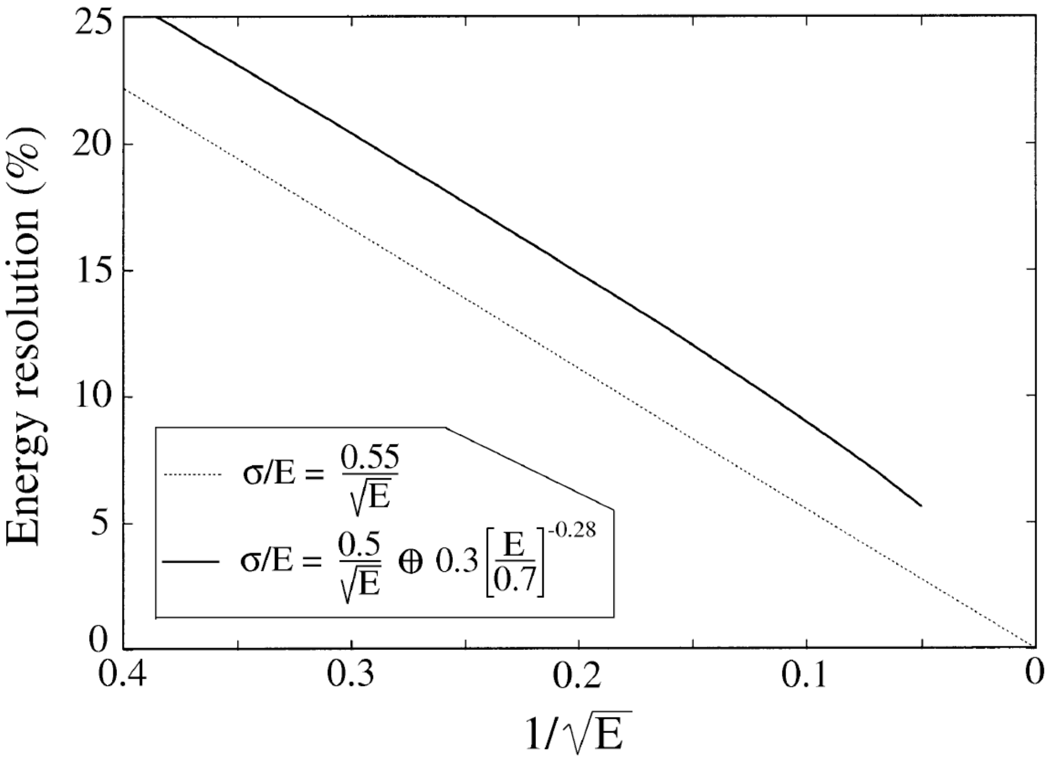


FIG. 4.48. The energy resolution calculated with Equation 4.29 for energies up to 400 GeV (the solid line), and calculated with a sole stochastic term with a slightly larger a_1 value (the dotted line). See text for details.

This means that it is practically impossible to distinguish between fits such as

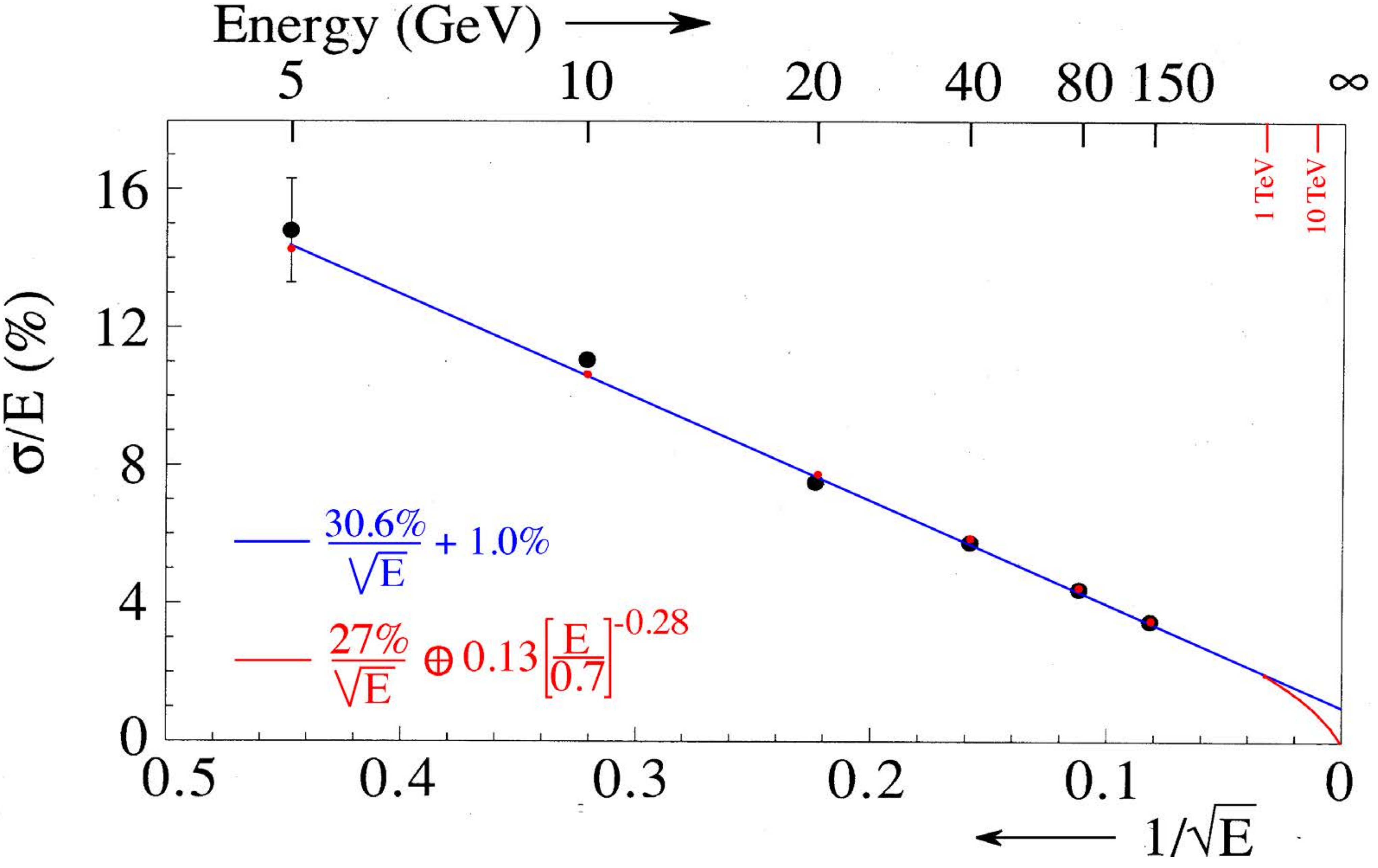
$$\frac{\sigma}{E} = \frac{50\%}{\sqrt{E}} \oplus 30\%\left[\left(\frac{E}{0.7}\right)^{-0.28}\right]$$

and

$$\frac{\sigma}{E} = \frac{55\%}{\sqrt{E}} + 3.5\%$$

in the energy range for which experimental data are available.

Difference only noticeable for E > 1000 GeV



Eliminating important contributions to the energy resolution

- *Often, instrumental effects contribute to the energy resolution*
- *These effects may dominate the resolution in part of the energy range*
- *By eliminating these effects from the quoted resolution, that resolution may look (much) better than in reality*

Examples:

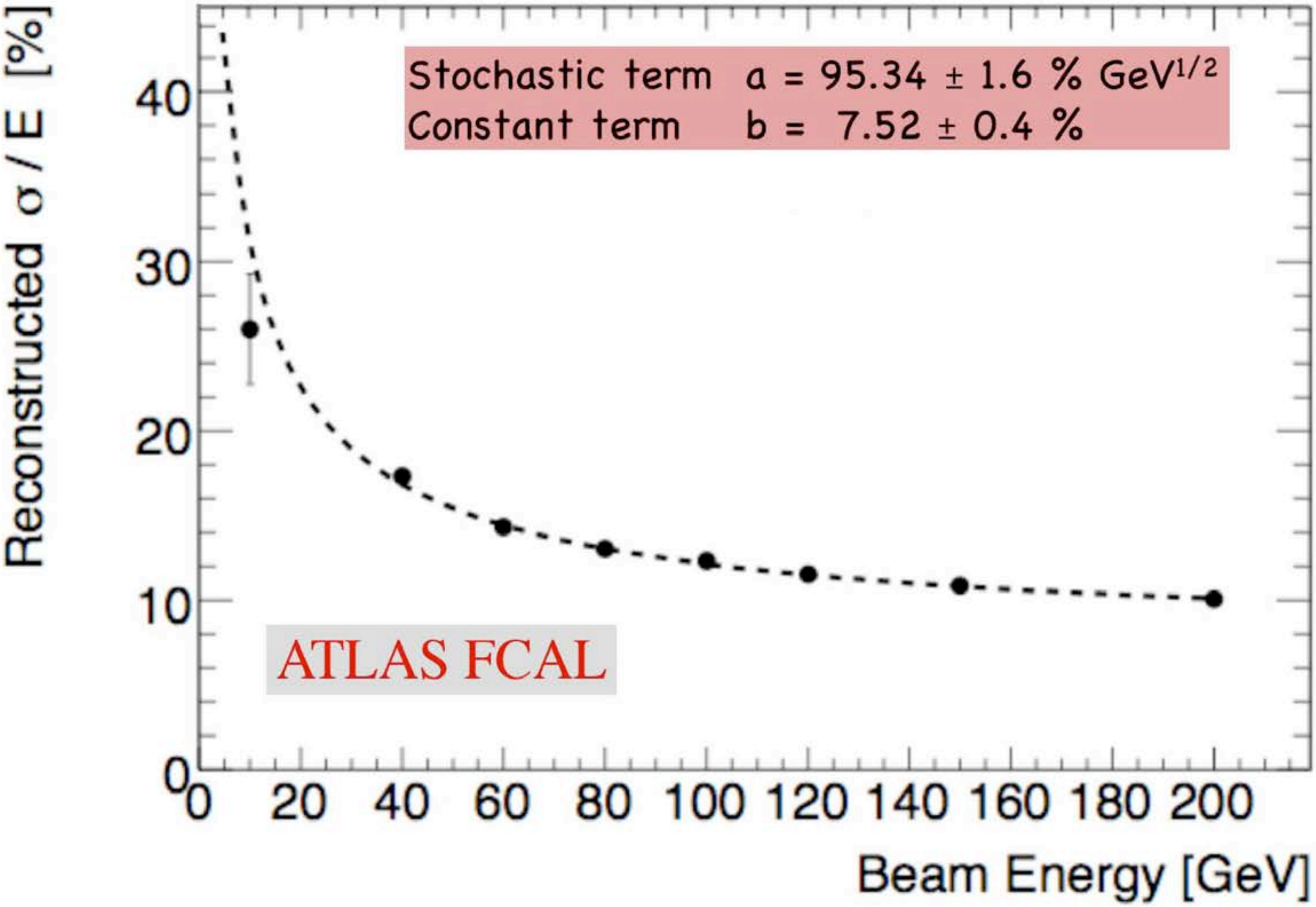
- *Electronic noise*
  Contributes a term 1/E and thus dominates resolution at low energy
- *Light attenuation and other position dependent effects*
  Contributes an energy independent term, thus dominates at high energy
- *Signal saturation*
  May give a very distorted result for the energy resolution

LHC experiments: Performance of the forward calorimeters ATLAS is clearly better than CMS

CMS HF:
a = 280%, b = 11%

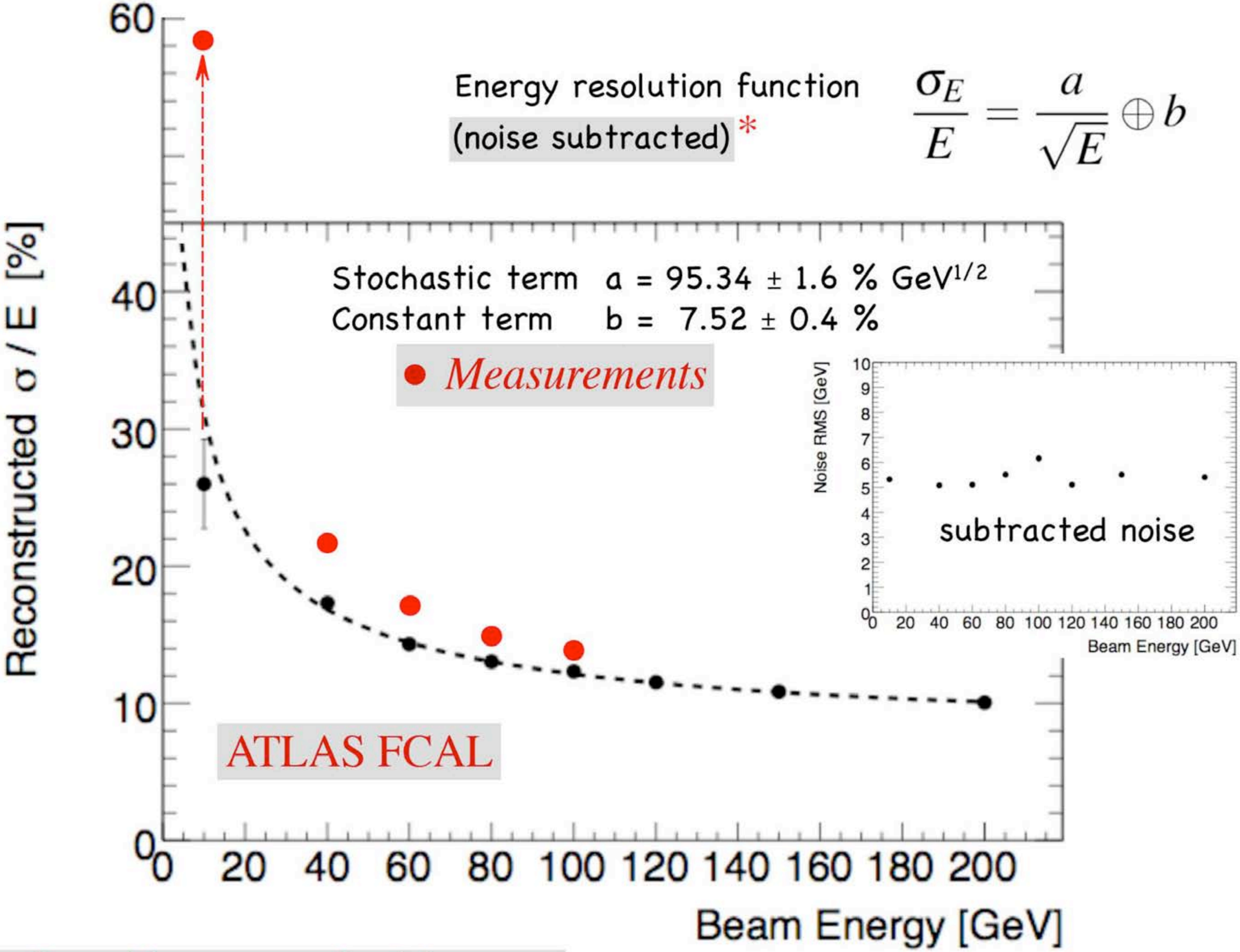
Energy resolution function
(noise subtracted)

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b$$



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

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


Energy resolution function (noise subtracted)*

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b$$

Stochastic term a = 95.34 ± 1.6 % $\mathrm{GeV}^{1/2}$
Constant term b = 7.52 ± 0.4 %

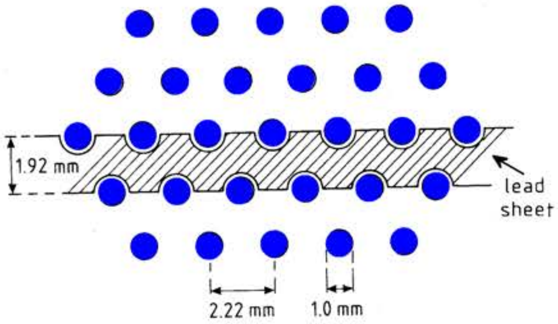
● *Measurements*

ATLAS FCAL

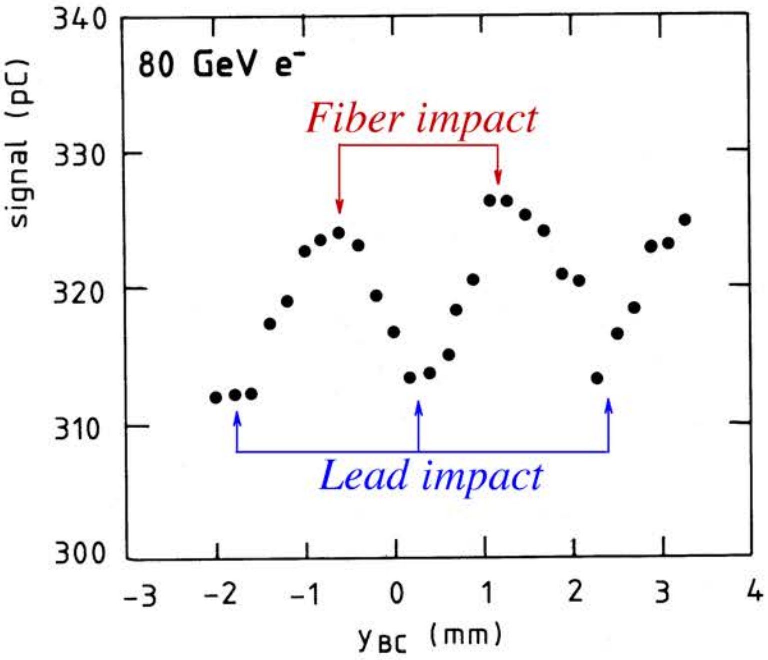
subtracted noise

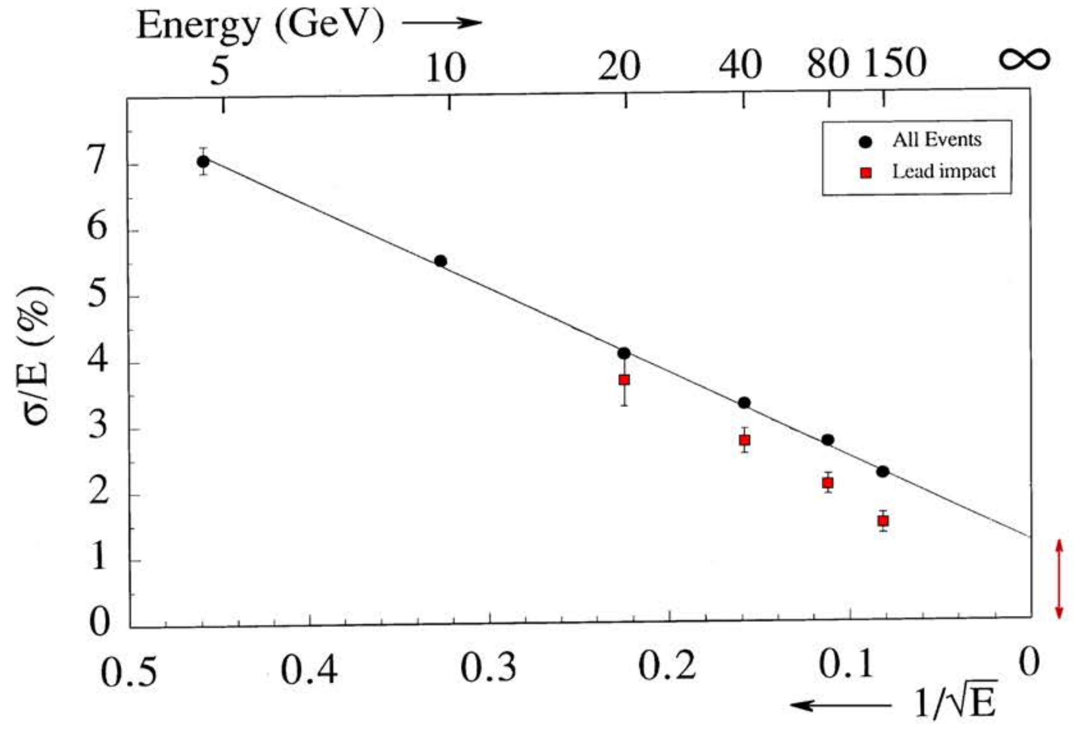
* Not mentioned in summaries/abstracts

SPACAL: Position dependent response to electrons



NIM A308 (1991) 481





constant term
~ 1%

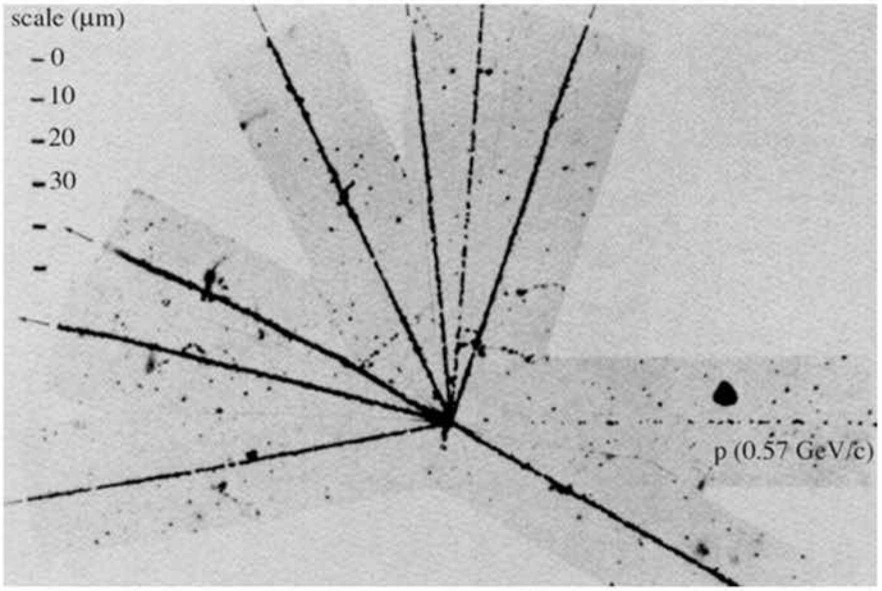
The "Texas tower effect"

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,* $f_{\text{samp}} \sim 10^{-5}$.
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).

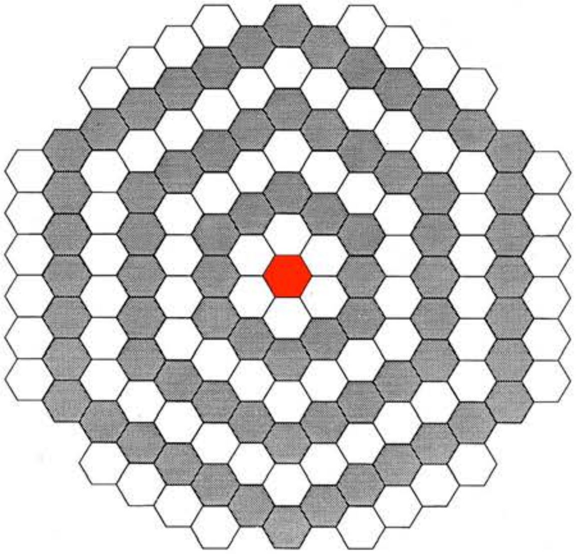
2) *CMS ECAL (lead tungstate crystals read out by Avalanche Photo Detectors*



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.

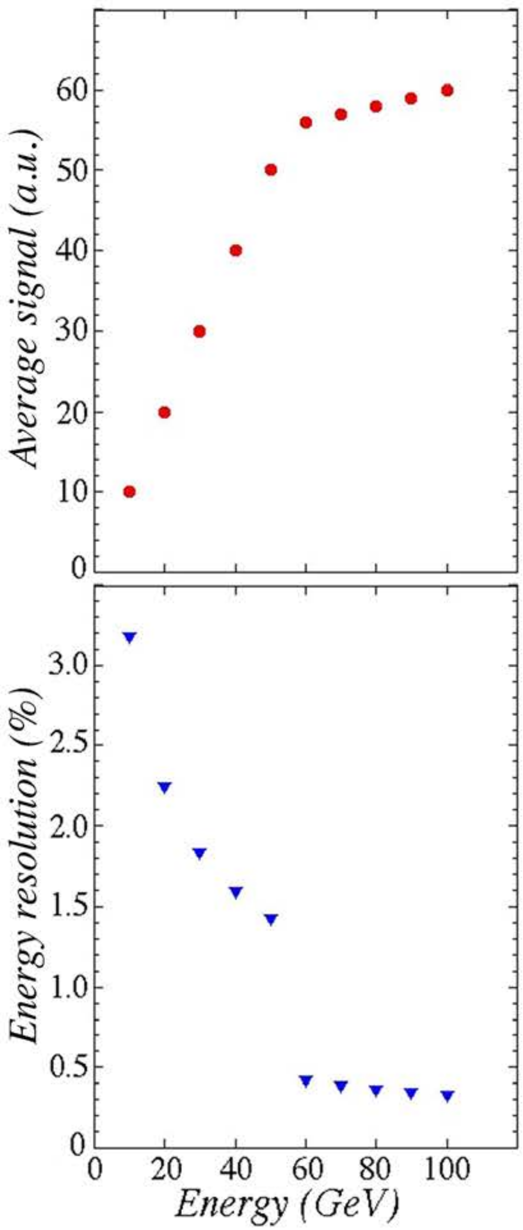
Example: In CMS ECAL, such events may fake energy deposits of tens of GeV.

Signal saturation



Example:

- *One SPACAL tower contains about 90% of electron shower.*



- *During calibration (100 GeV e), the HV of one tower is set too high.*
- *We measure a REALLY good resolution (0.5%) for that tower. This is because the signal in that tower saturates (always the same value). The resolution comes from fluctuations in the 10% that is distributed over the other towers.*
- *This saturation will disappear when lower energy electrons are sent into this tower. Saturation thus manifests itself in the form of signal non-linearity. The response is suppressed for higher energies.*
- *The energy resolution will also become much larger when the saturation is lifted, because fluctuations in the signal from the hit tower (90% of total signal) now also contribute.*

Saturation of signals

The same phenomena also play a role in digital calorimeters

Electromagnetic shower components (e.g. π^o produced in hadronic shower development, are EXTREMELY collimated)

Therefore, many shower particles from such a π^o shower may traverse an individual calorimeter cell. If this cell is digital ("yes" or "no") then one gets the same response, regardless if it is caused by 1,2,3....29 particles.

As a result, an important source of fluctuations is suppressed. Events that would give a distribution of signals in the absence of saturation, now all give the same signal. A Geiger counter has zero resolution

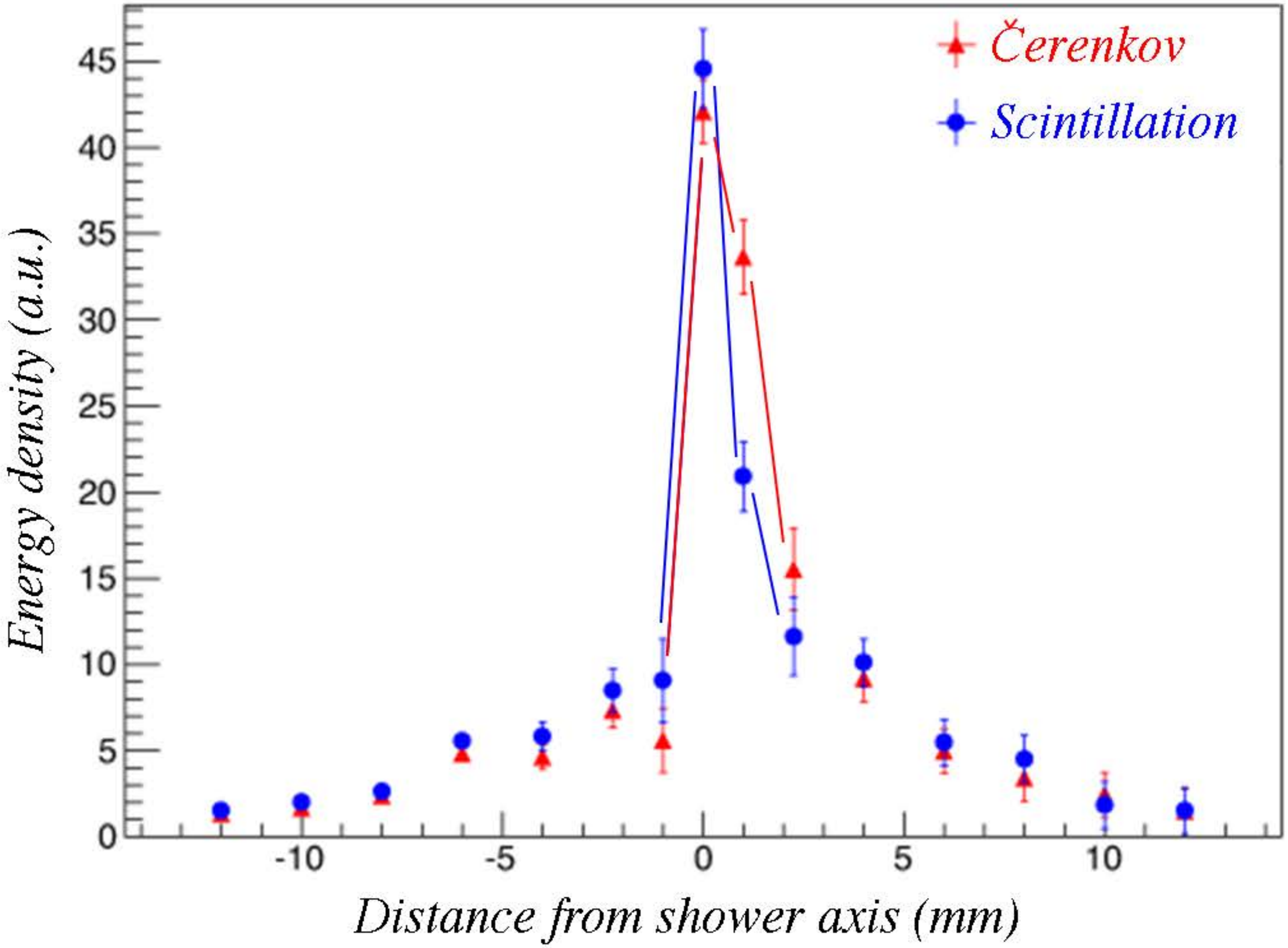
The response and the energy resolution of digital calorimeters are thus completely MEANINGLESS

This was already discovered a long time ago, and the idea to make digital calorimeters was thus abandoned.

NIM 205 (1983) 113

The extremely narrow electromagnetic shower profile

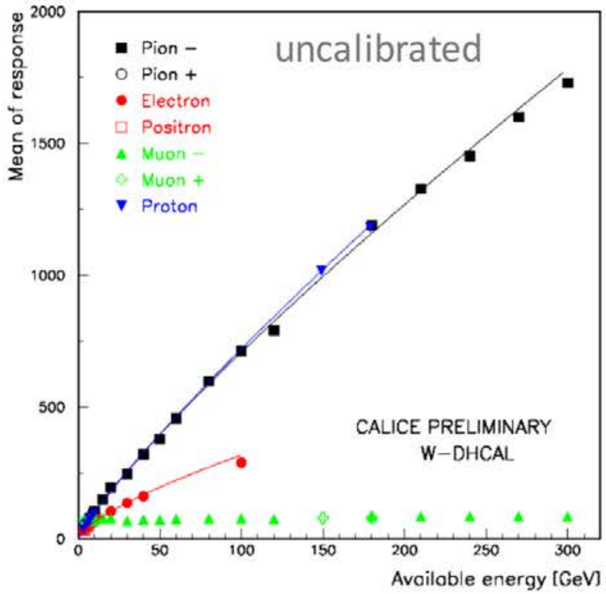
Lateral shower profile



NIM A735 (2014) 130

Response – (Semi) - Digital HCALs

Tungsten – DHCAL



Non-linear response
to both e$^{\pm}$ and hadrons

Both well described by
power law αE^{β}

Badly over-compensating
e/h ~ 0.9 – 0.5
→ need smaller readout pads

Deviations from linear response due to finite readout pad size

Functional form a priori not known, but needed for energy reconstruction

Is linearity mandatory for imaging calorimeters?

Suggesting that linearity is irrelevant

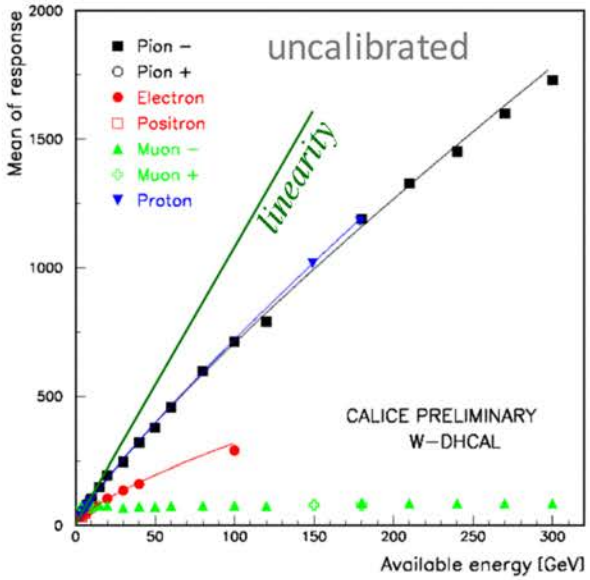
- *If the non-linearity is caused by signal saturation, the measured energy resolution is meaningless (much better than justified)*

- *If the non-linearity is caused by miscalibration, the measured energy depends on the type of particle that causes the signal* (*cf.* γ, π^o, $K^o \rightarrow 3\pi^o$)

- *If the non-linearity is caused by non-compensation, then the signal can be converted to energy by using the proper calibration constants*

Response – (Semi) - Digital HCALs

Tungsten – DHCAL



Non-linear response
to both $e^{\pm}$ and hadrons

Both well described by
power law αE^{β}

Badly over-compensating
e/h ~ 0.9 – 0.5
→ need smaller readout pads

Deviations from linear response due to finite readout pad size

Functional form a priori not known, but needed for energy reconstruction

Is linearity mandatory for imaging calorimeters? YES !!

Signal saturation makes the results MEANINGLESS

Suggesting $e = \gamma$, $\pi = jet$

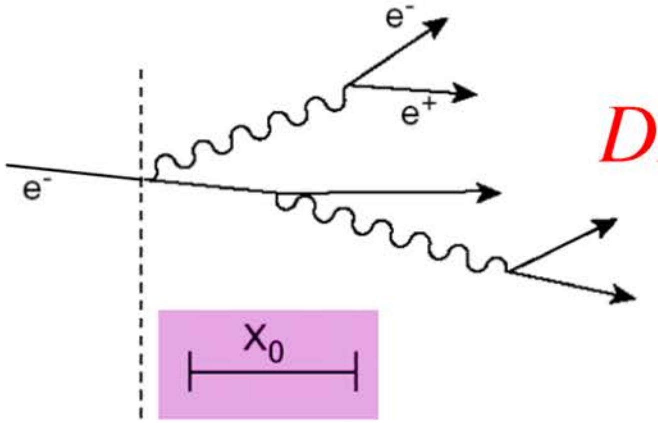
In practice, one wants to use the calorimeter system to measure

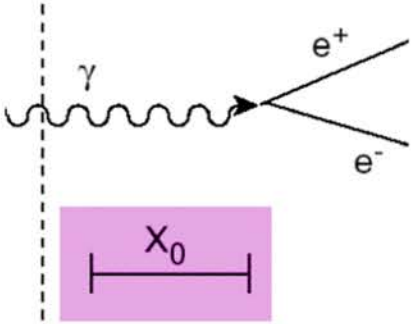
- *Gammas (e.g. to detect the Higgs boson:* $H^{o} \longrightarrow \gamma\gamma$*)*
- *Jets (i.e. fragmenting quarks, gluons)*

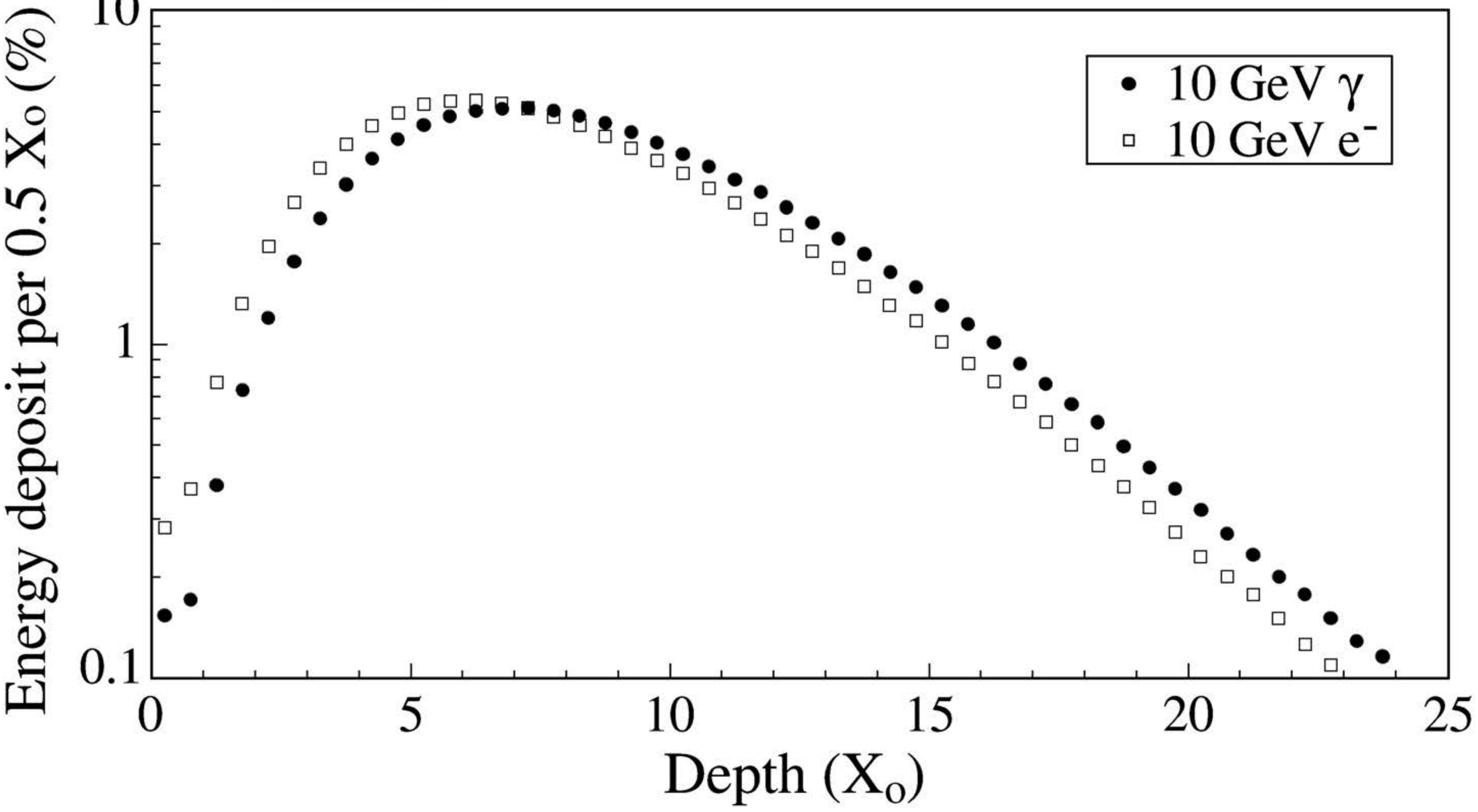
However, the calorimeters are typically tested with beams of electrons and pions

The calorimeter performance is NOT the same for these objects!

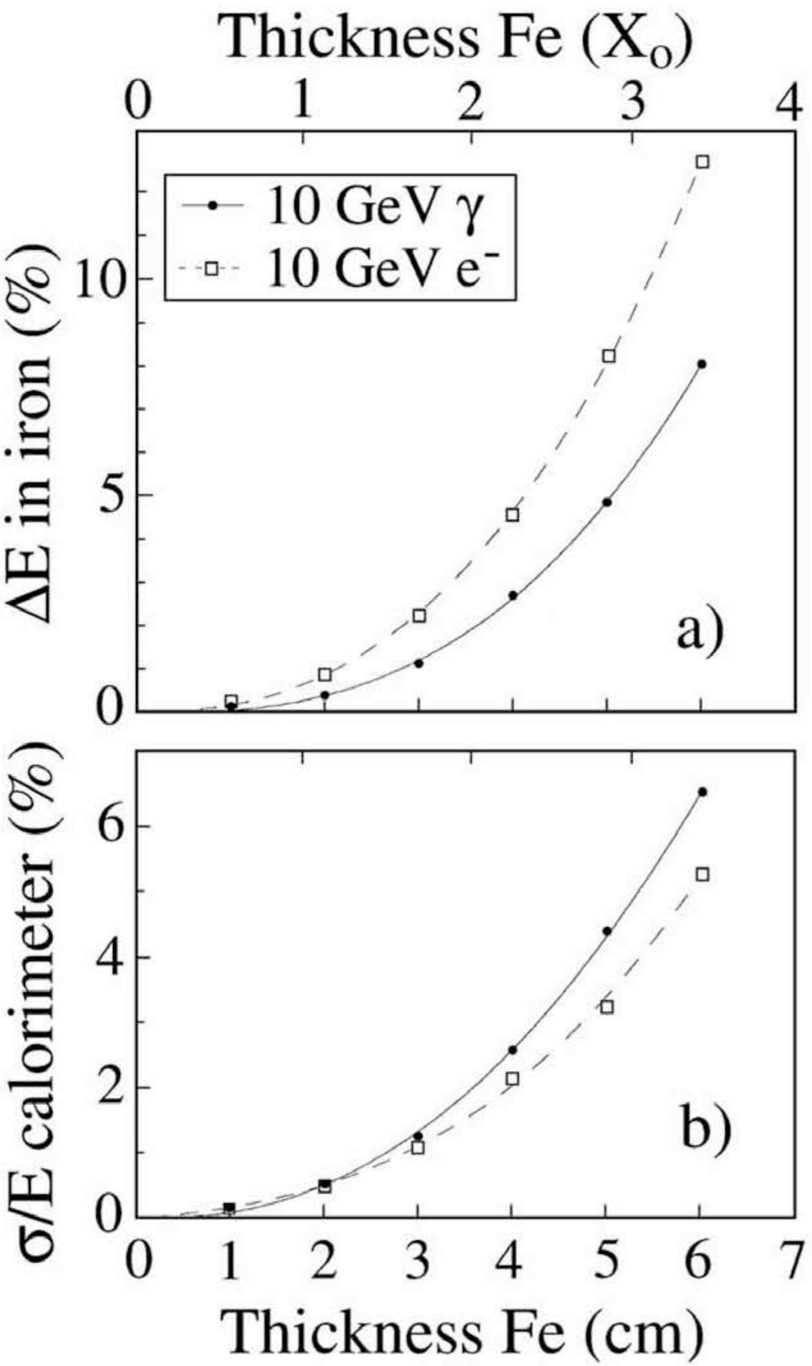
In a calorimeter, showers initiated by electrons and γs DEVELOP DIFFERENTLY







For a calorimeter, e ≠ γ



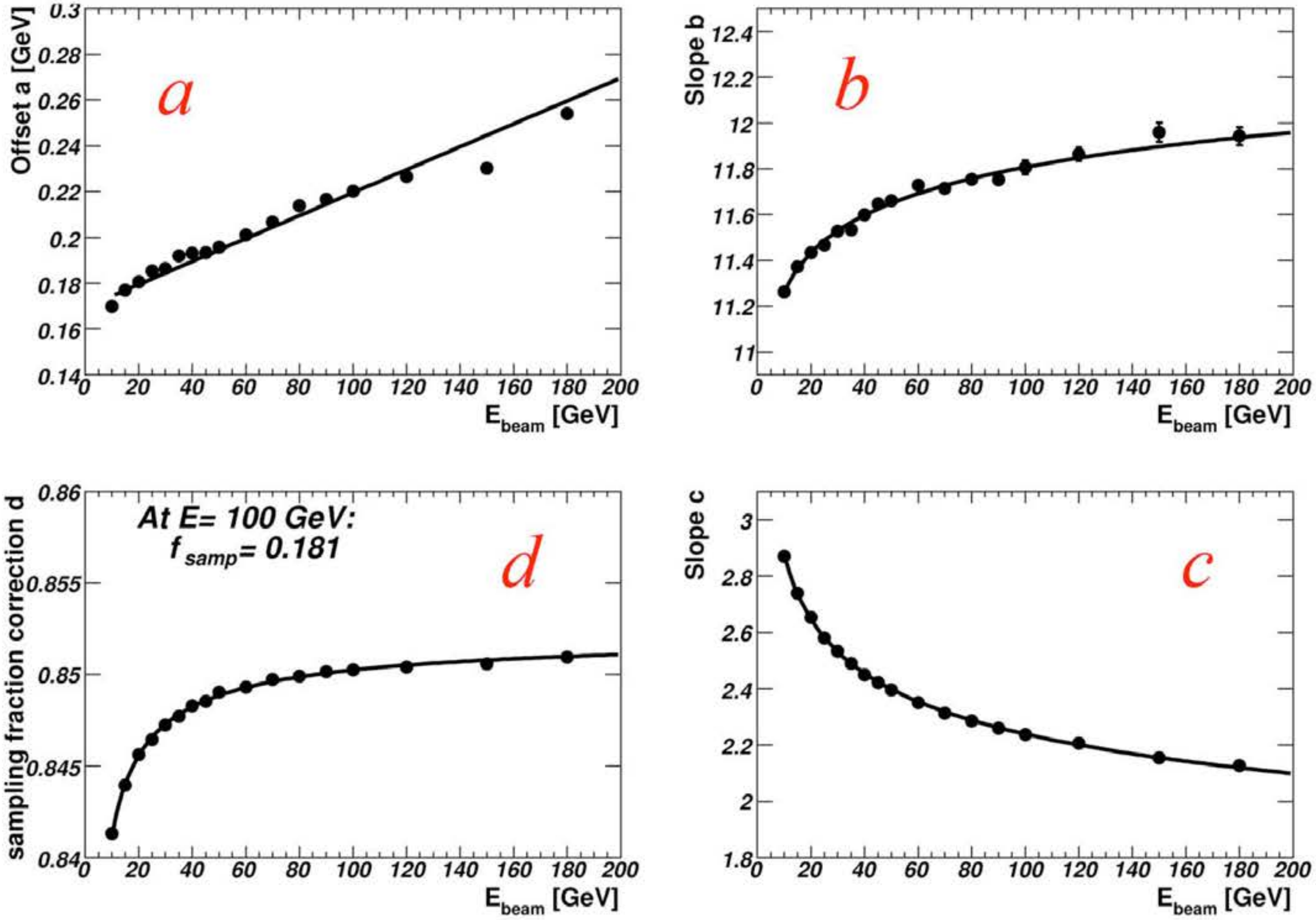
Effects of upstream material

Electrons lose more energy

Energy resolution worst for γ

From: NIM A485 (2002) 385

ATLAS: Energy reconstruction (for electrons) in ECAL



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

THIS WILL GIVE WRONG RESULTS FOR GAMMA’S !!

On pions and jets

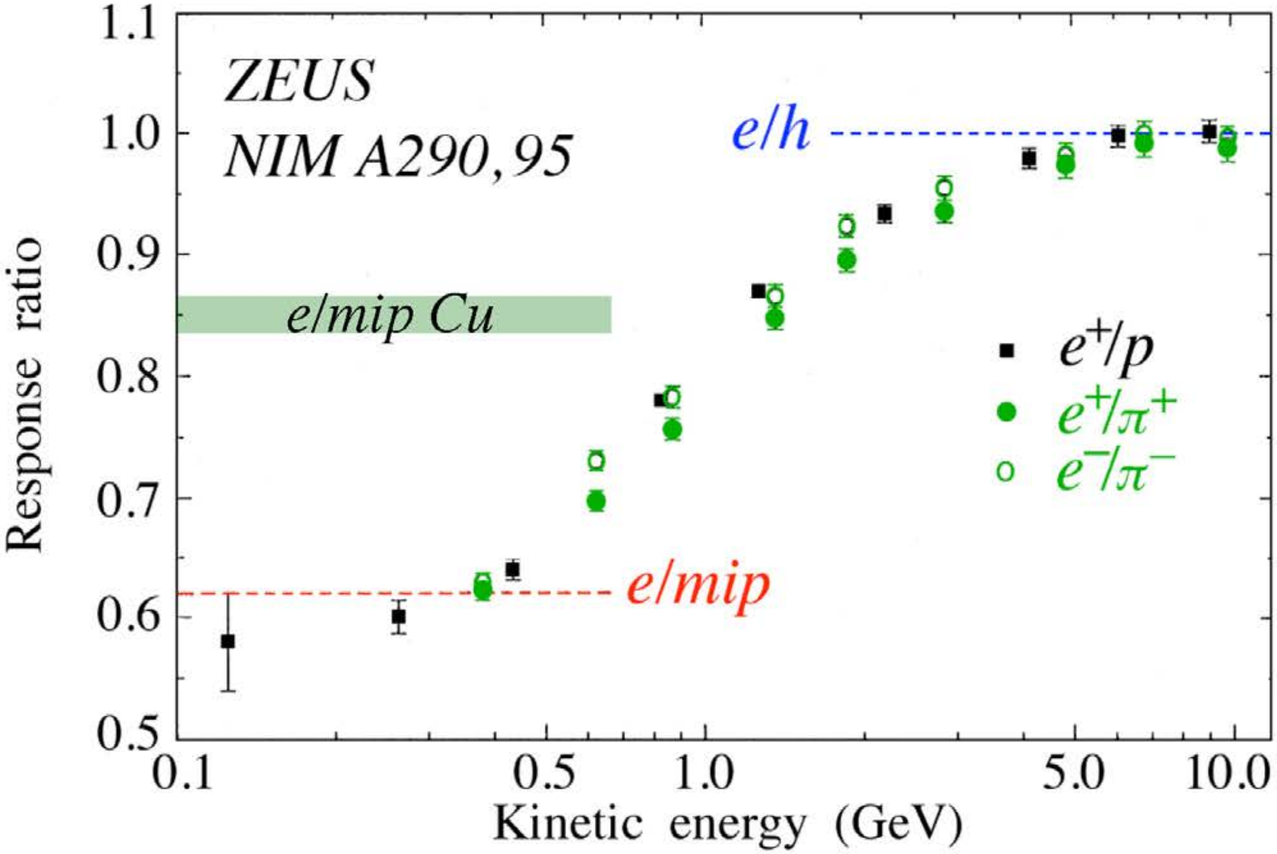
Single-π performance does not guarantee anything for jets

Jets involve ADDITIONAL sources of fluctuations

- *Fluctuations in energy sharing between em and non-em jet components*
- *Fluctuations in the energy sharing between the different non-em jet fragments (response non-linearities very important)*
- *Fluctuations in energy sharing between the different calorimeter sections are not the same as for single pions*

The last issue is the reason why algorithms developed for "offline compensation" based on beam tests with pions did not work well for jets (H1).

In a high-Z compensating calorimeter, jet resolution is not as good as single-π resolution



Signal non-linearities at low energy (< 5 GeV)
due to non-showering hadrons
Many jet fragments fall in this category

A copper or iron based calorimeter would be much better in that respect

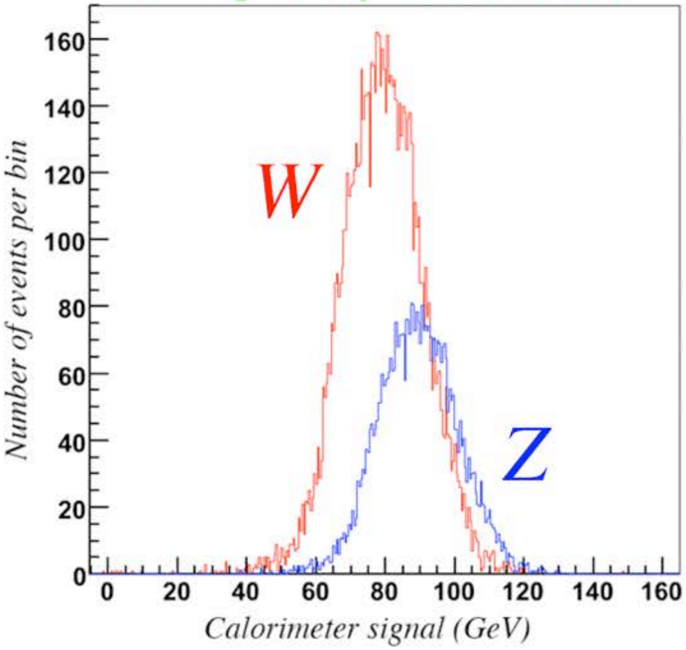
From pions to jets

Correct procedure:

- *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.*

→ *Jet response function*

Example:
Jet response function CMS



- *Testing claims of how well PFA algorithms are capable of avoiding double counting should be straightforward in this way as well. 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.*

Wrong procedure:

Use a black box Monte Carlo simulation that is known to be wrong in reproducing crucial features such as the width of hadronic showers to obtain a jet response function. Then use phony statistics to derive from this a jet resolution value.

Mis-representation of obtained results

Generally accepted definitions of calorimeter performance:

- *Energy resolution*

  The precision with which the energy of a showering object can be determined. Expressed in terms of a standard deviation.

- *Linearity*

  A calorimeter is linear when the signal is proportional to the deposited energy.

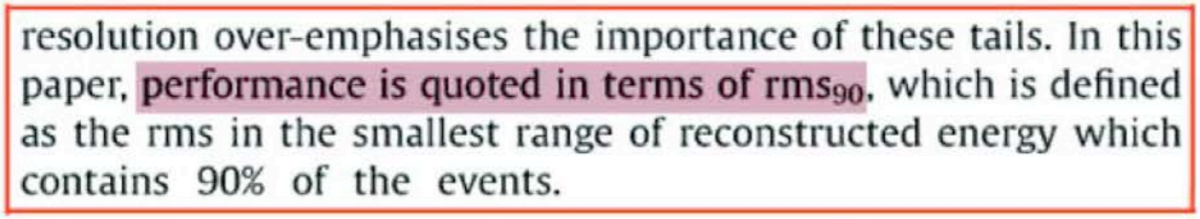
  The average signal per unit energy is in that case constant

Sometimes, these terms are deliberately "redefined" with the purpose to make the performance look better than it is

Redefining "energy resolution"

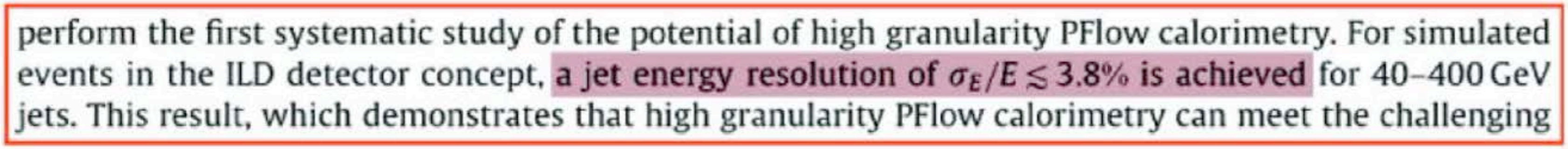
If the signal distributions have tails, some people resort to phony statistics in order to make the results look better than they are

Example : NIM A611 (2009) 25



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.

Even for a perfectly Gaussian distribution, $\mathrm{rms}_{90} \ll \sigma_{\mathrm{fit}}$



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

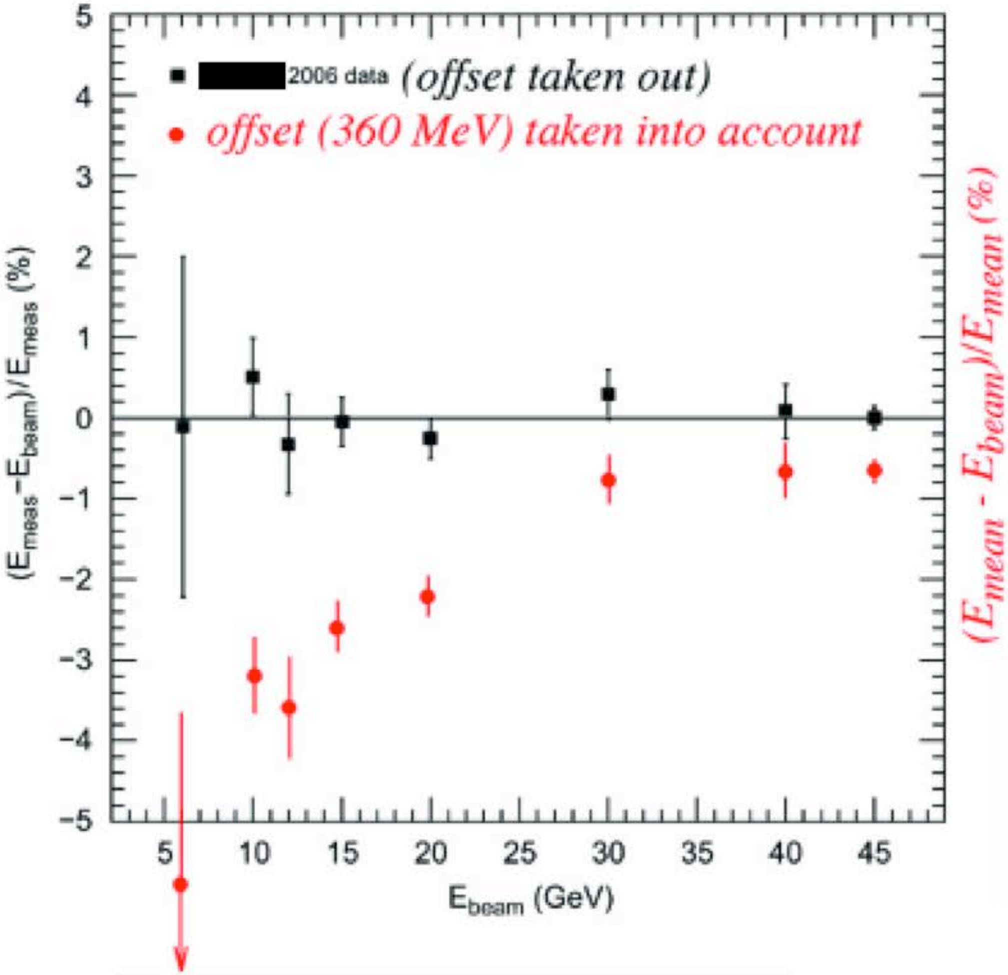
The correct way:

If the distribution is Gaussian, then resolution is given by σ_{fit}

Otherwise, σ_{rms} *should be quoted as the resolution*

Redefining "response linearity"

The fact that a straight line can be drawn through the data points does NOT mean that the calorimeter is linear



Source: NIM A608 (2009) 372

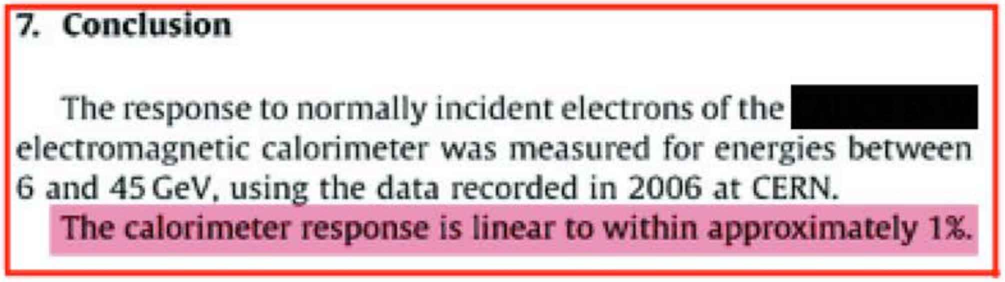
Fit to experimental data (electrons):

$$E_{mean} = \beta \cdot E_{beam} - 360\ \text{MeV}$$

Then, they define:

$$E_{meas} = E_{mean} + 360\ \text{MeV}$$

and conclude:



7. Conclusion

The response to normally incident electrons of the [redacted] electromagnetic calorimeter was measured for energies between 6 and 45 GeV, using the data recorded in 2006 at CERN. The calorimeter response is linear to within approximately 1%.

In reality, they measured a non-linearity of ~5% over less than one decade in energy!

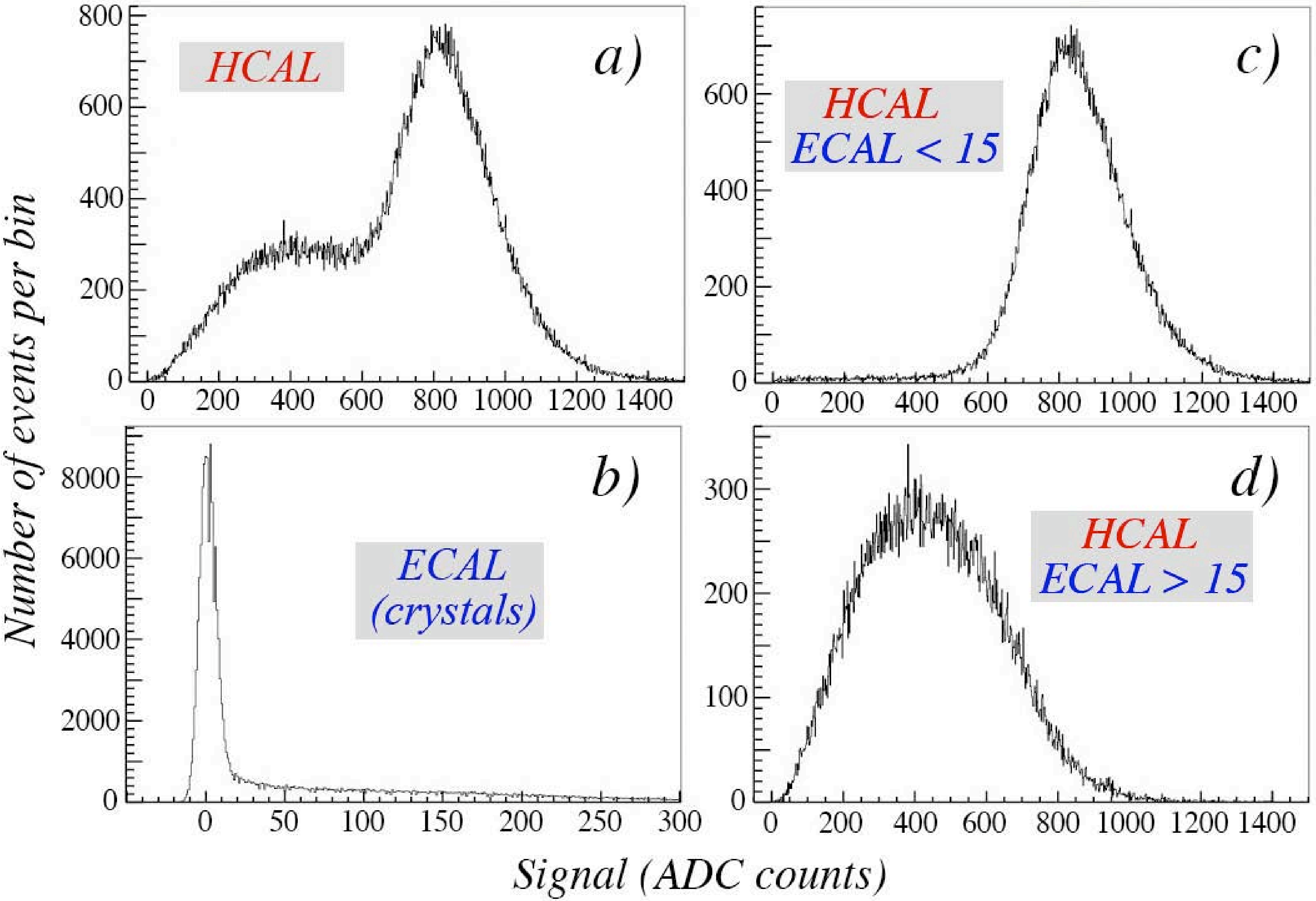
Conclusions

- *Be very careful when comparing calorimeters*
- *Beware for the propaganda and the rhetoric*
  There is a lot of ignorance / incompetence / dishonesty out there
- *As a result, calorimeters built / proposed for modern experiments in particle physics are WORSE than 20 - 30 years ago*

Backup slides

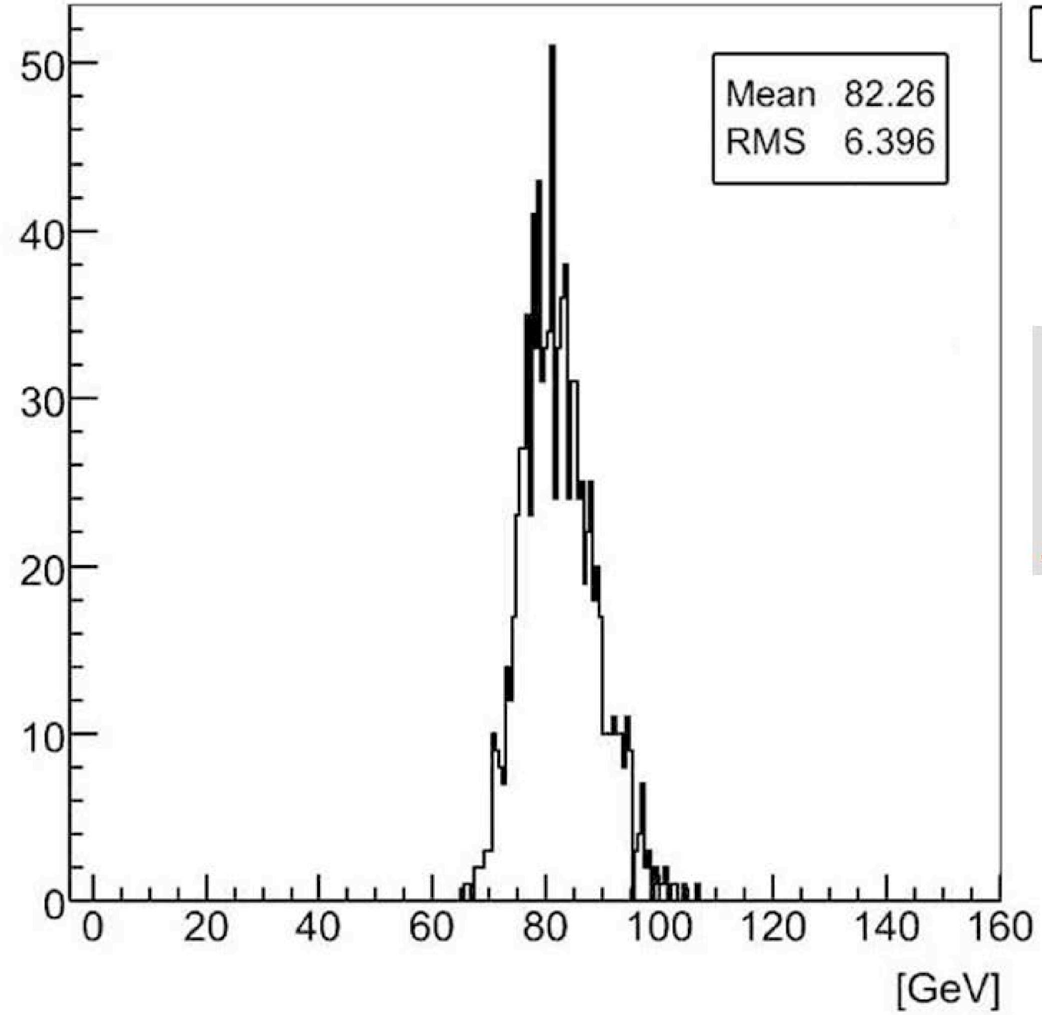
Pion signals in crystal ECAL + scintillator HCAL

100 GeV π^-



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)

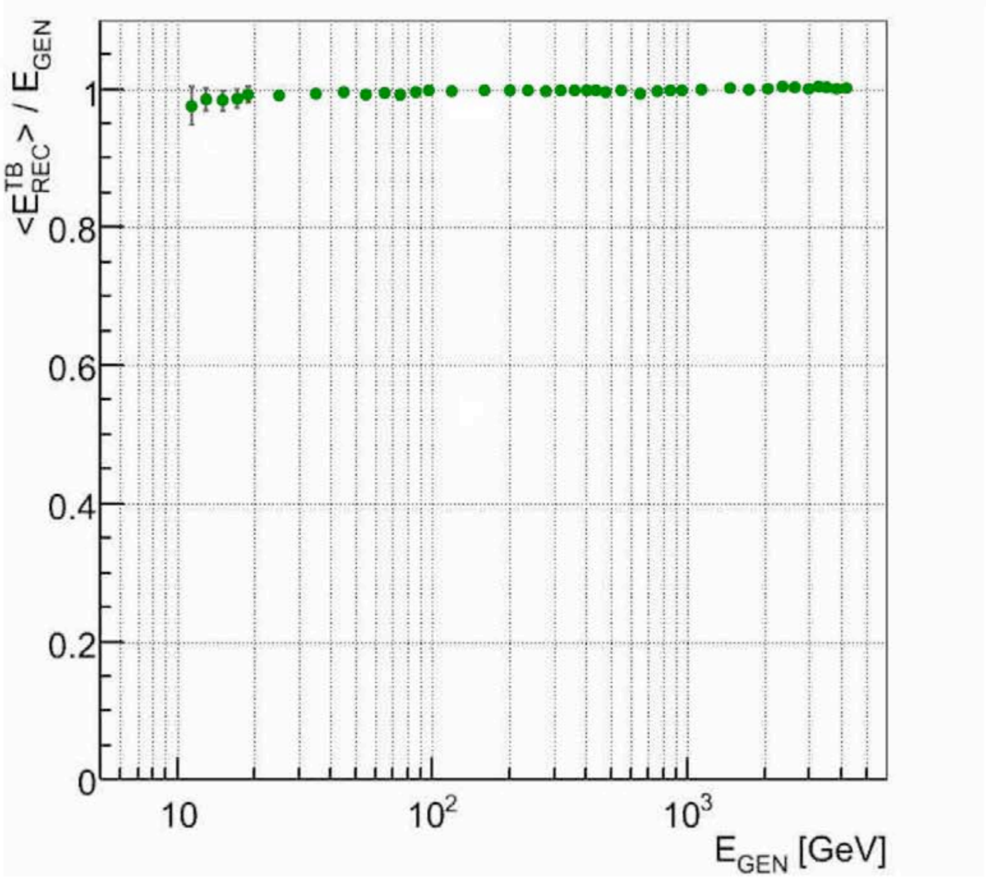


Figure 5.18: Average calorimeter response to jets after the test beam particles were corrected. Almost linear response at 1 confirms the validity of our jet reconstruction based on test beam data.

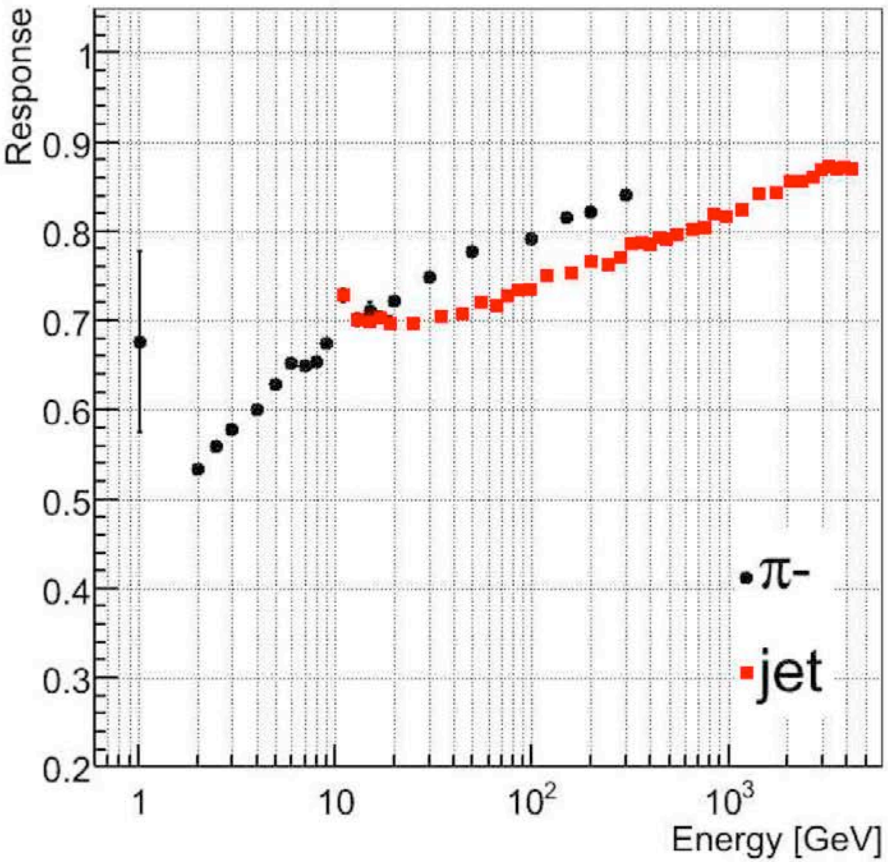


Figure 5.20: The jet response is lower than charged pion response, because a jet consists of mostly low energy (< 10 GeV) particles and the low calorimeter response to these particles reduces the jet response with respect to charged pions.

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*

  $Z \longrightarrow e^+e^-$ (91.2 GeV/c^2)

  $J/\psi \longrightarrow e^+e^-$ (3.10 GeV/c^2)

  $\Upsilon \longrightarrow e^+e^-$ (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 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*

- *General problem with calibration of "jet energy scale" in calorimeters with* $e/h \neq 1$*:*
  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° *vs. jets with leading* $\pi^{\pm}$*)*