CALORIMETRY
at the energy frontier

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Decisions about the future require a good understanding of the past

Outline:

- *What is calorimetry? Why use it in particle physics?*
- *A brief history (50 years) of calorimetric particle detection*
- *Common misconceptions*
- *Options for the future*
- *Conclusions*

Misconceptions about calorimetry

- *A shower is a collection of mips*

  - cause of calibration problems of longitudinally segmented calorimeters
  - catastrophic effects of one shower particle

- *Energy resolution ≡ width of signal distribution*

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

Results of miscalibration: Mass dependence

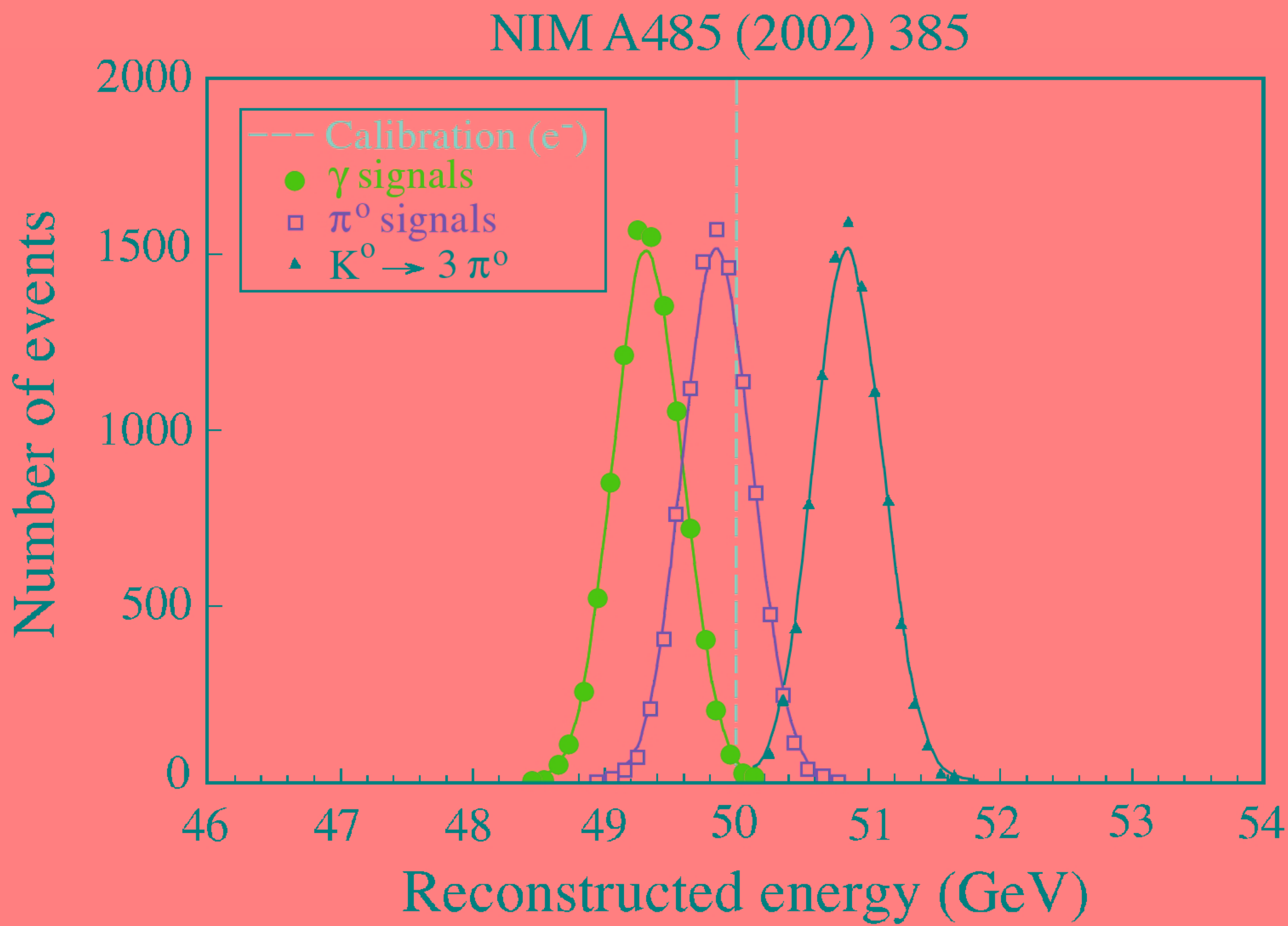

Figure 14: Signal distributions for γs and various hadrons decaying into all-γ final states. All particles have the same nominal energy and the detector, which has an intrinsic resolution of 0.5% for em showers of this energy, was calibrated with electrons using $B/A = 0.8$. See text for details.

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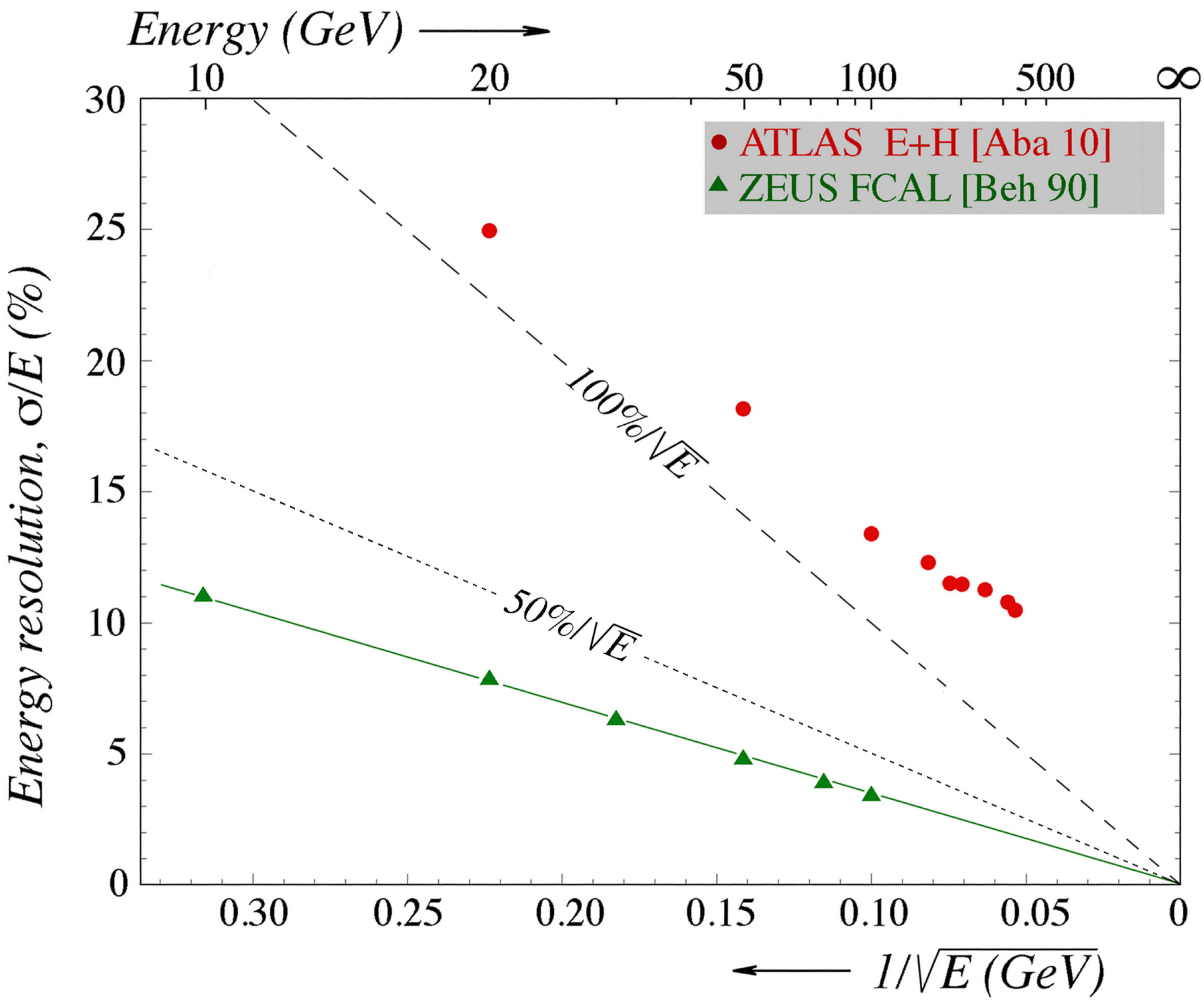
- *Energy resolution scales like* $E^{-1/2}$

Hadronic energy resolution of compensating vs modern calorimeters



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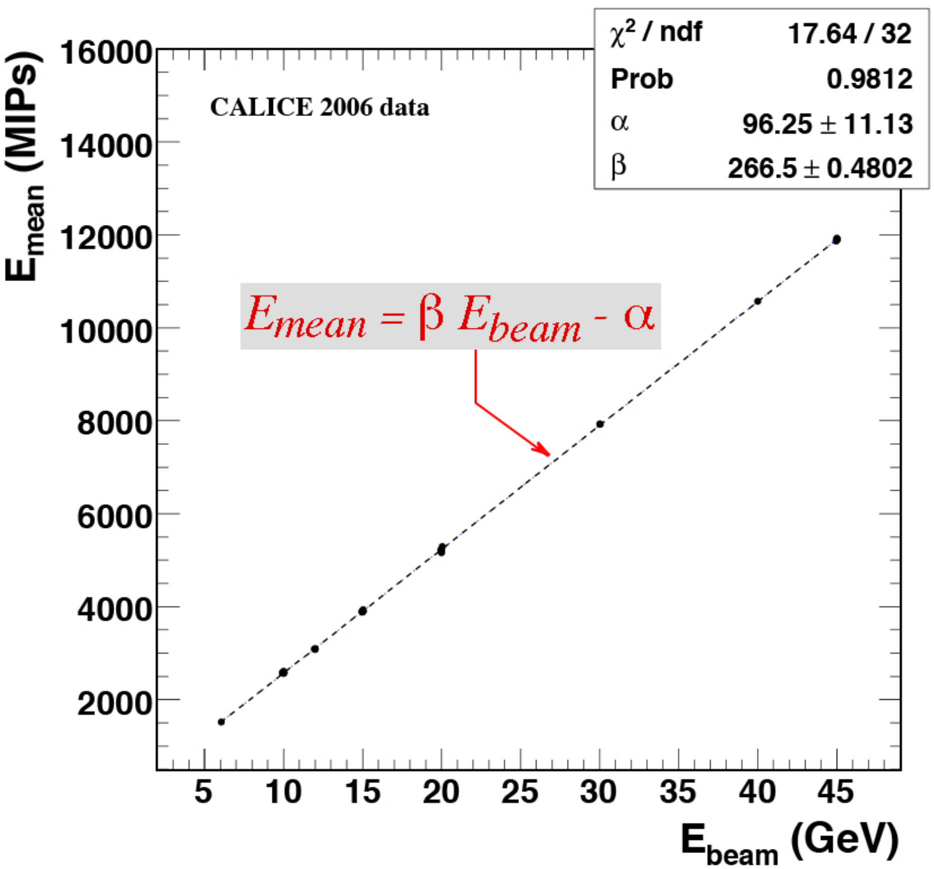
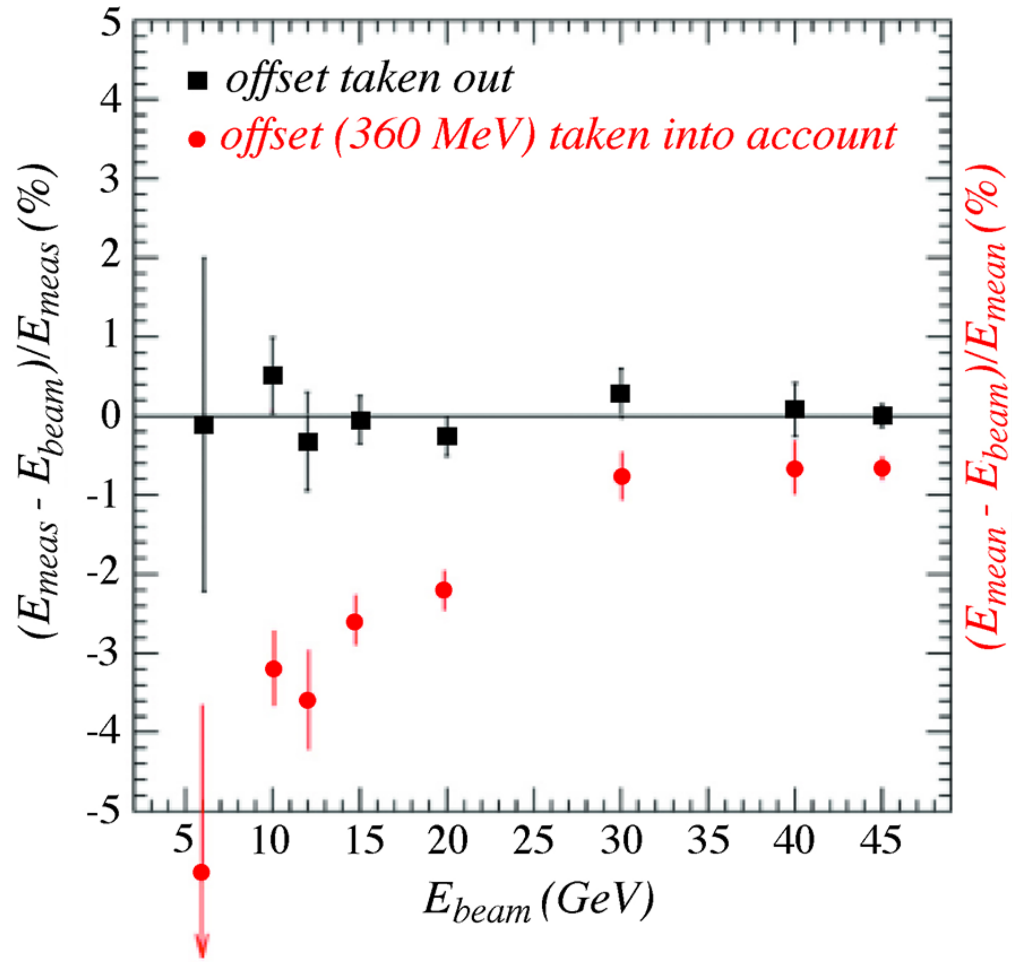
Response non-linearity in CALICE W/Si ECAL

NIM A608 (2009) 372





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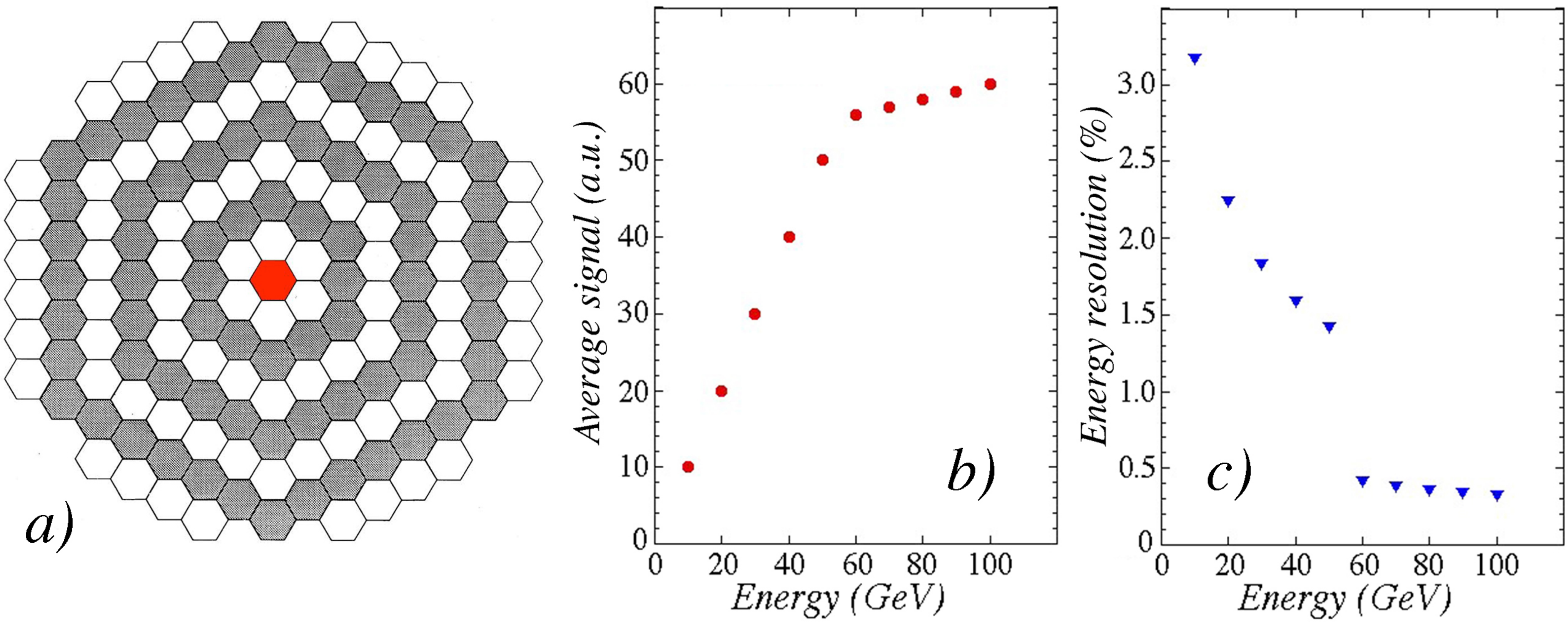
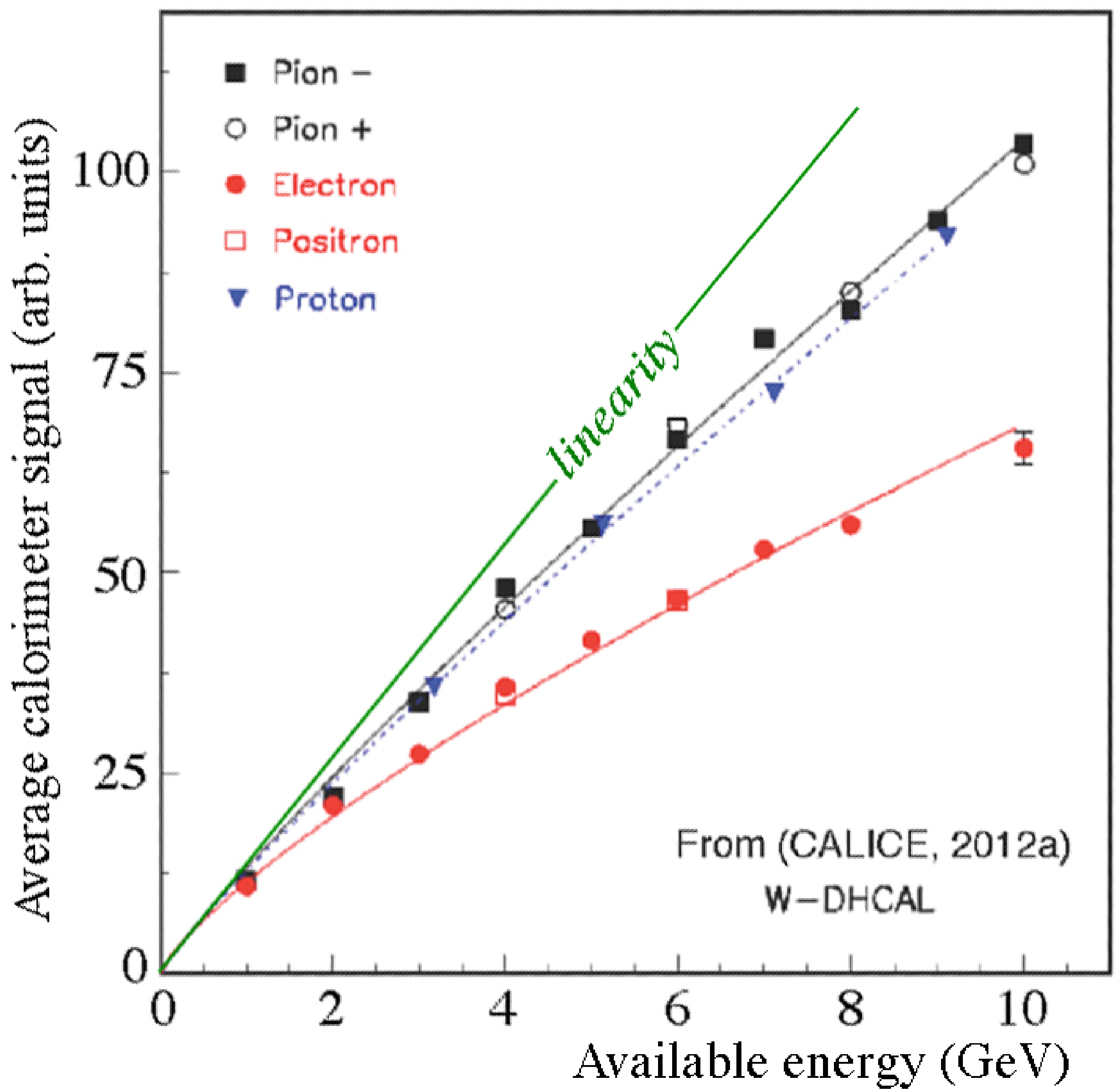
Effects of signal saturation (SPACAL)



Signal saturation in the CALICE DHCAL
(overcompensating @ < 10 GeV)

Rev. Mod. Phys. 88 (2015) 15003



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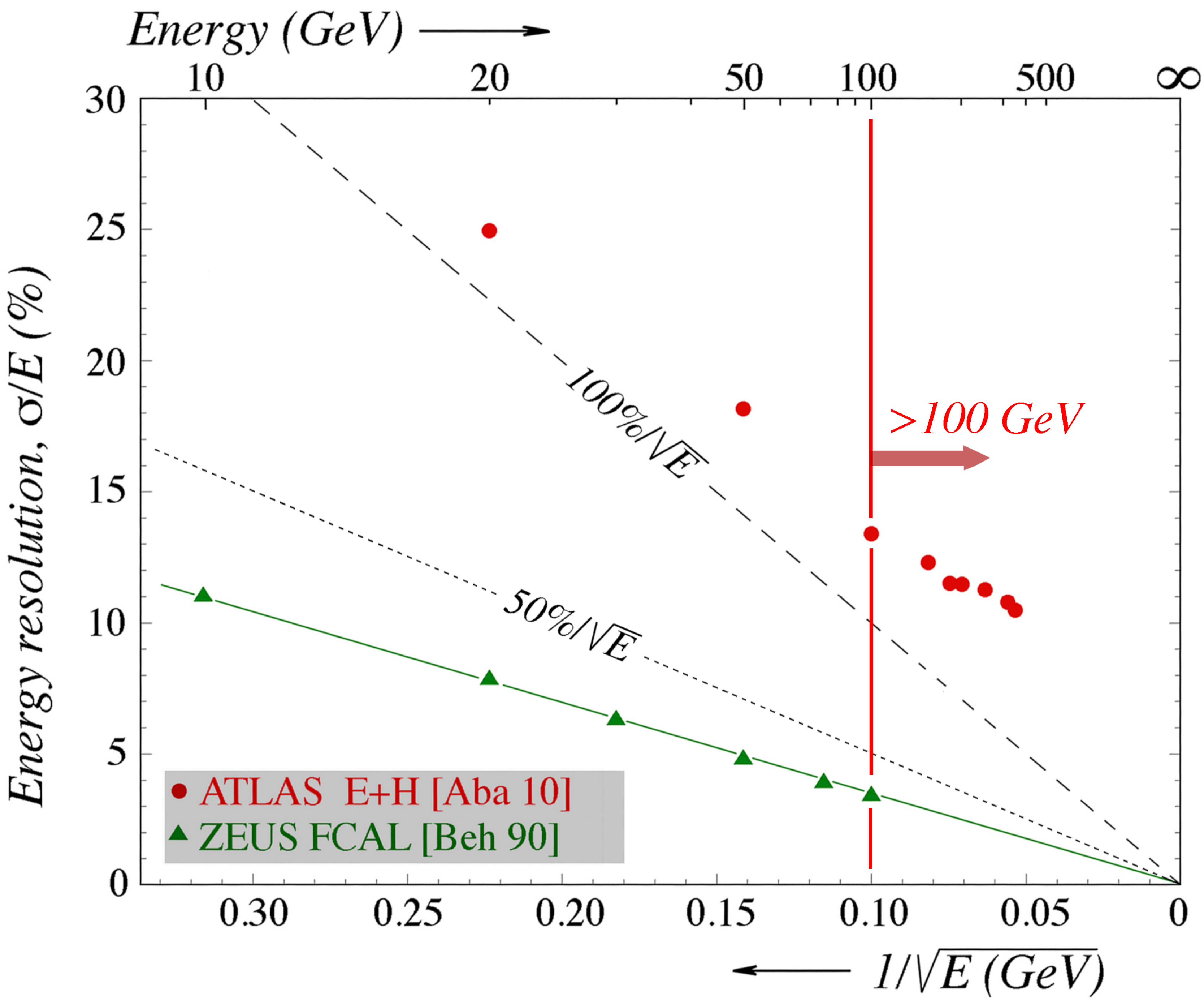

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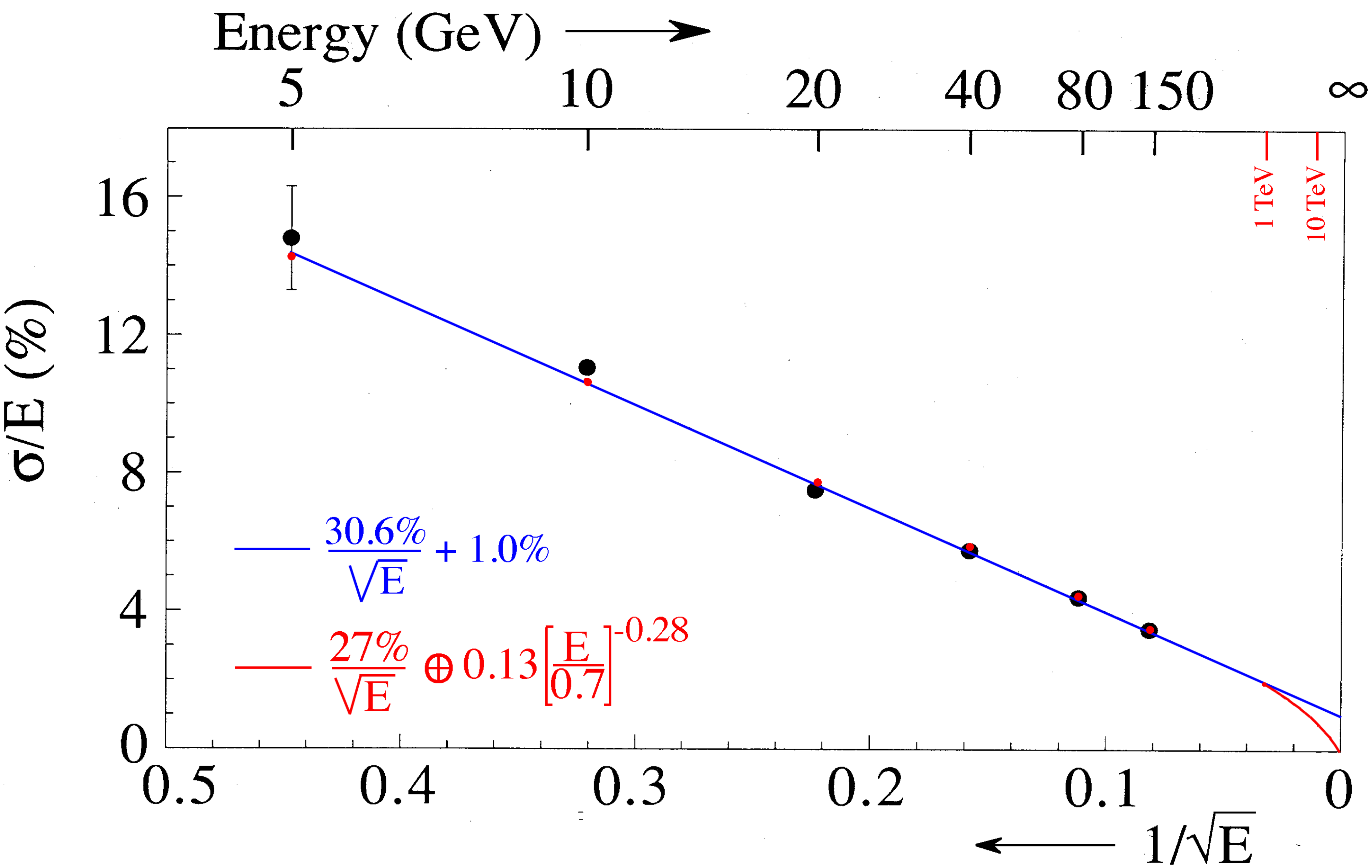
- *The only effect of non-compensation is a constant term in the energy resolution*

Difference only noticeable for E > 1000 GeV



Misconceptions about calorimetry

- *The only effect of non-compensation is a constant term in the energy resolution*

  - *Hadronic signal non-linearity*
  - *Non-Gaussian response functions*
  - *Different average signal for p, π, K*
  - *Calibration problems, especially if e/h (em) ≠ e/h (had)*

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

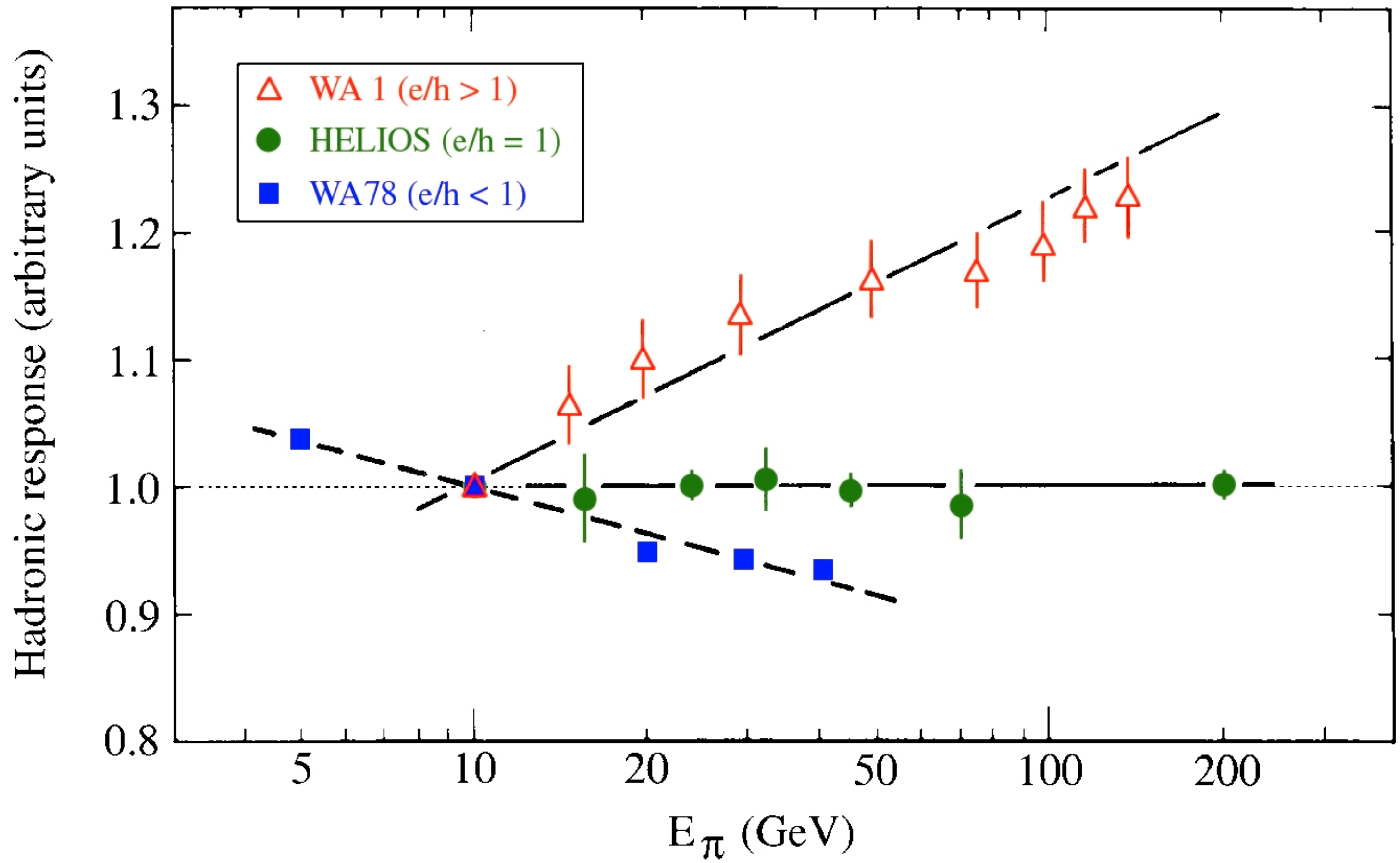
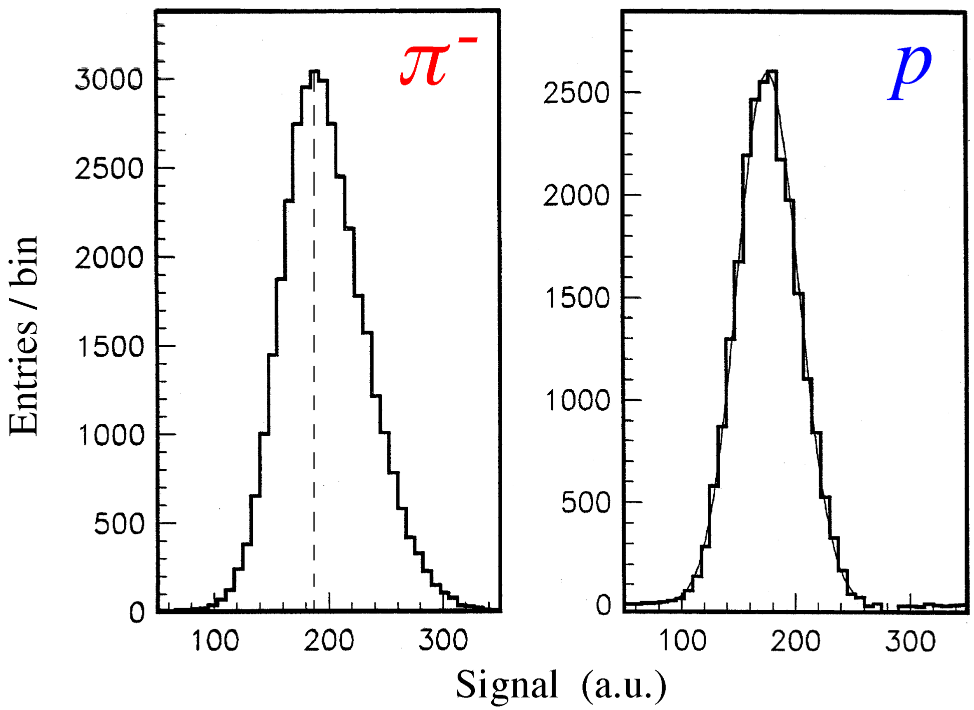
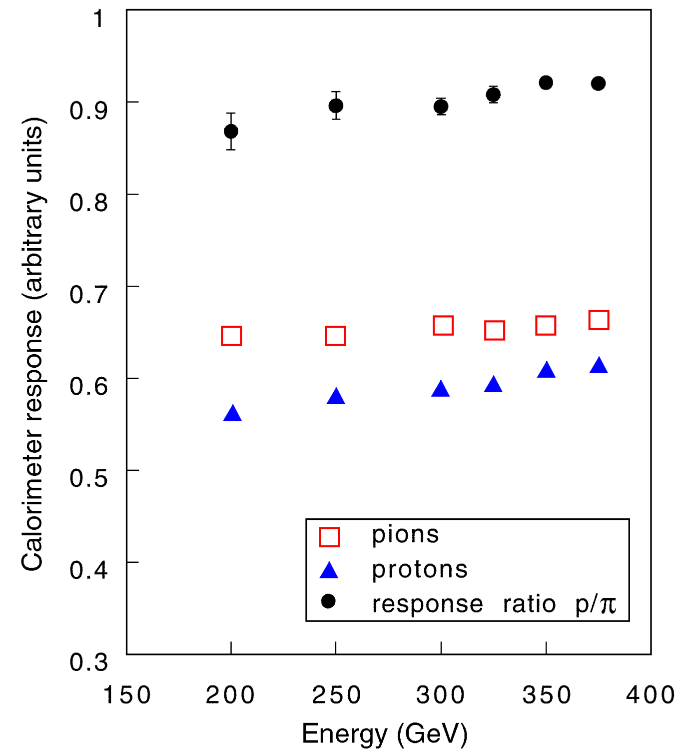
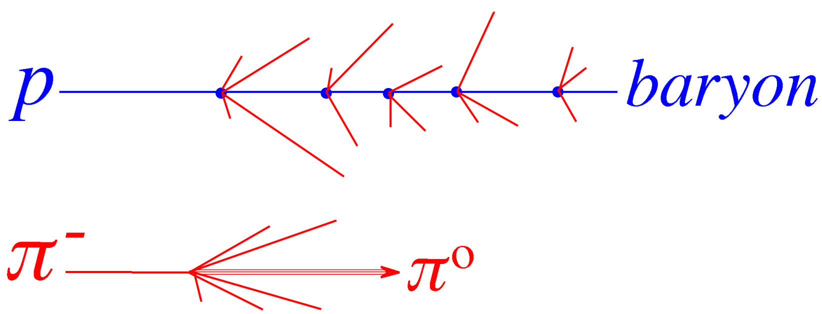


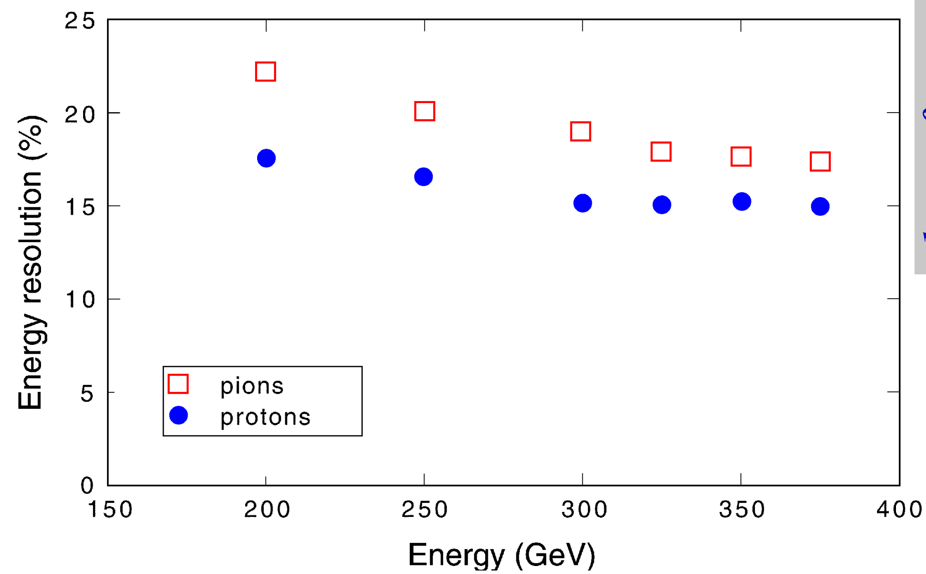
FIG. 3.14. The response to pions as a function of energy for three calorimeters with different e/h values: the WA1 calorimeter ($e/h > 1$, [Abr 81]), the HELIOS calorimeter ($e/h \approx 1$, [Ake 87]) and the WA78 calorimeter ($e/h < 1$, [Dev 86, Cat 87]). All data are normalized to the results for 10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

Proton / pion differences in calorimeter signals
caused by differences in em shower fraction characteristics









data from NIM A408 (1998) 380

em fraction in p showers:
- *smaller*
- *less fluctuations*
- *more symmetric*
- *less concentrated near axis*

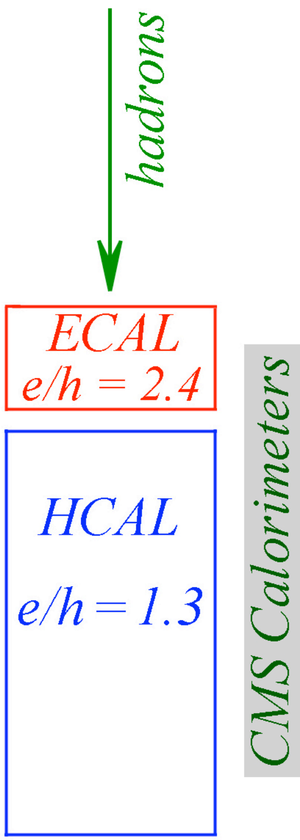
Consequences for LHC calorimeters

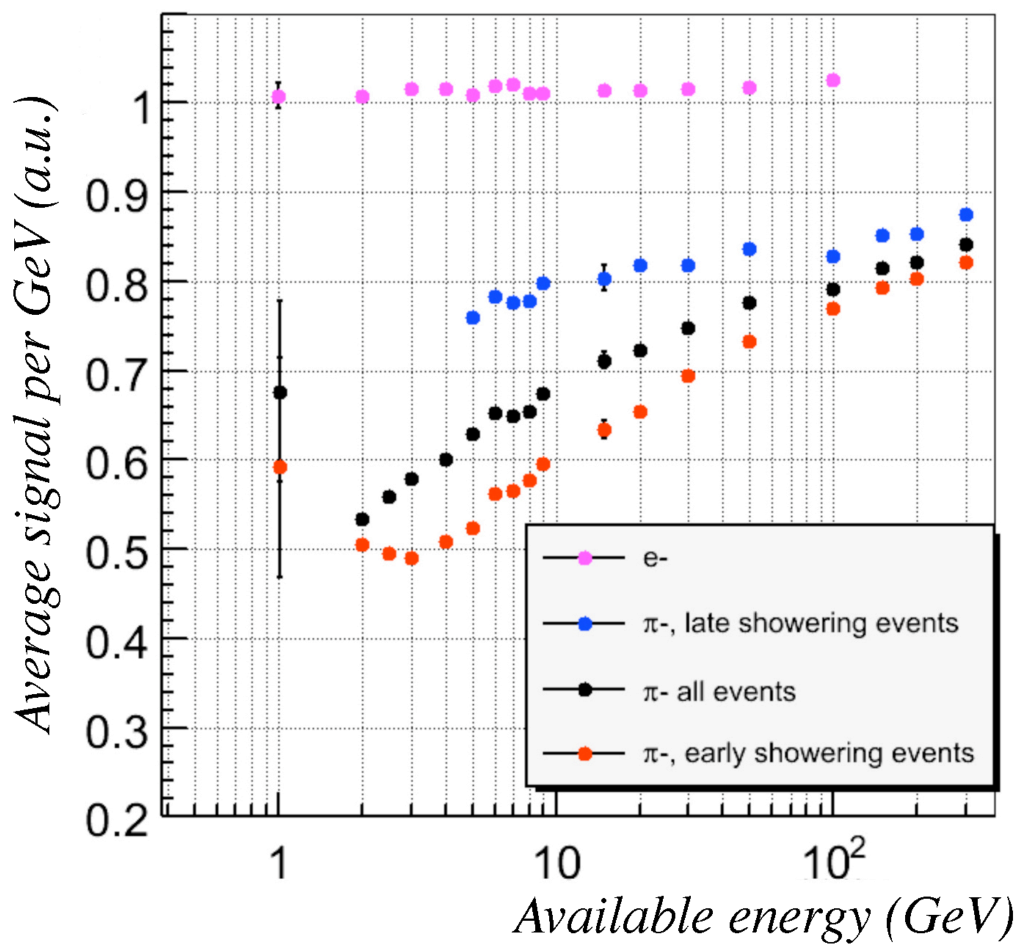
Hadronic response and signal linearity (CMS)

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

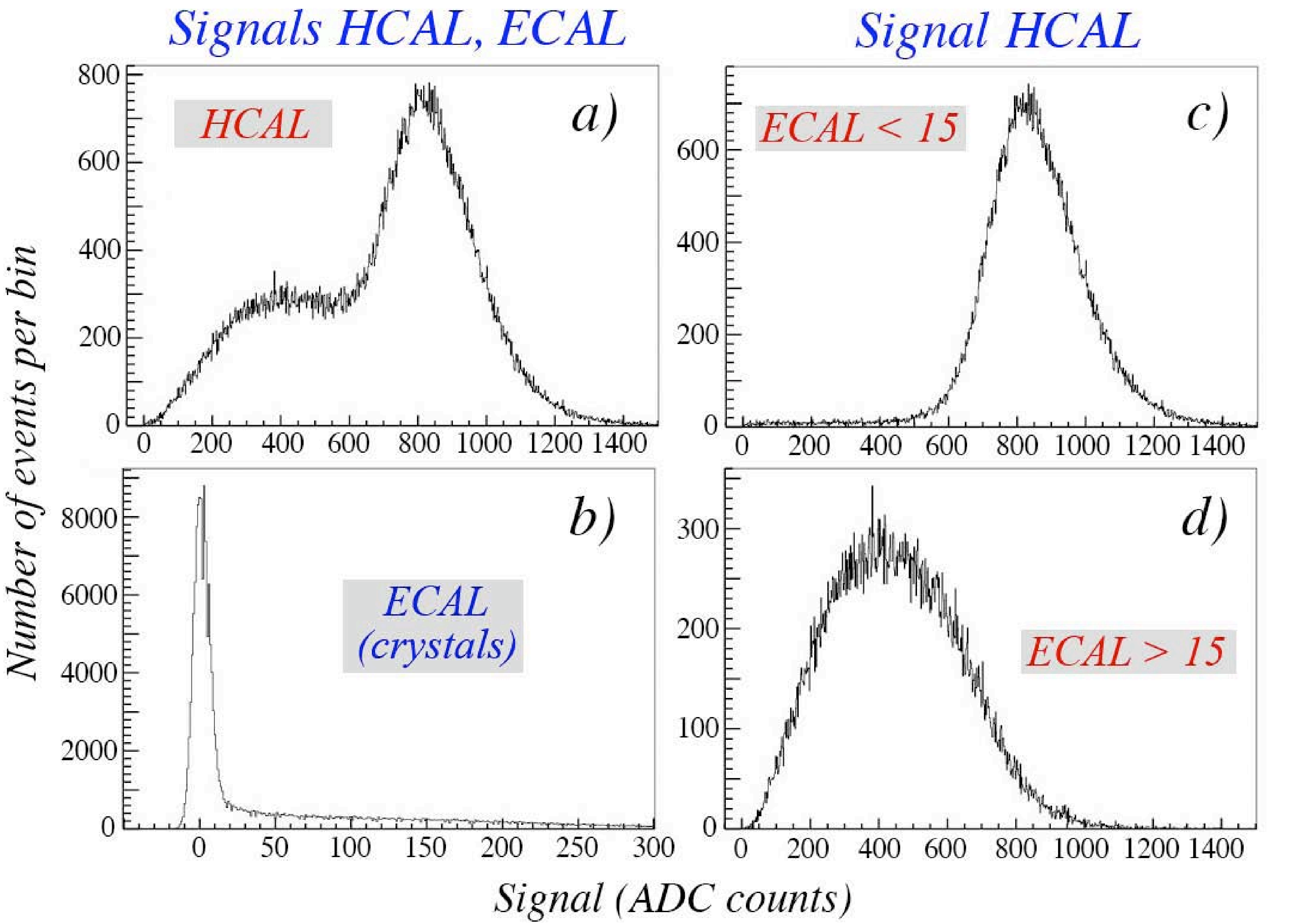
⟶ *Response depends strongly on starting point shower*

Data from: CMS note 2007/012





Pion signals in crystal ECAL + scintillator HCAL



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- *Compensation would be nice, but is not really important*
- *The only effect of non-compensation is a constant term in the energy resolution*
- *ALL CALORIMETER PROBLEMS CAN BE SOLVED OFFLINE*

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

Options for the future

- *Intrinsically compensating calorimeters*
- *Dual-readout calorimeters*
- *Particle Flow Analysis systems*

Intrinsically compensating calorimeters

Fluctuations in the em shower component (f_{em})

- *Why are these important ?*
  - Electromagnetic calorimeter response ≠ non-em response *($e/h \neq 1$)*
  - Event-to-event fluctuations are large and *non-Gaussian*
  - *$\langle f_{em} \rangle$ depends on* shower *energy* and *age*

- *Cause of all common problems in hadron calorimeters*
  - *Energy scale* different from electrons, in energy-dependent way
  - Hadronic *non-linearity*
  - *Non-Gaussian* response function
  - Poor energy *resolution*
  - *Calibration* of the sections of a longitudinally segmented detector

The Uranium remedy!!

- *Around 1985, the idea came up (W. Willis) to use depleted uranium (^{238}U) as absorber material. Nuclear fission in the non-em shower component would (by chance, just) COMPENSATE for the losses in nuclear binding energy.*

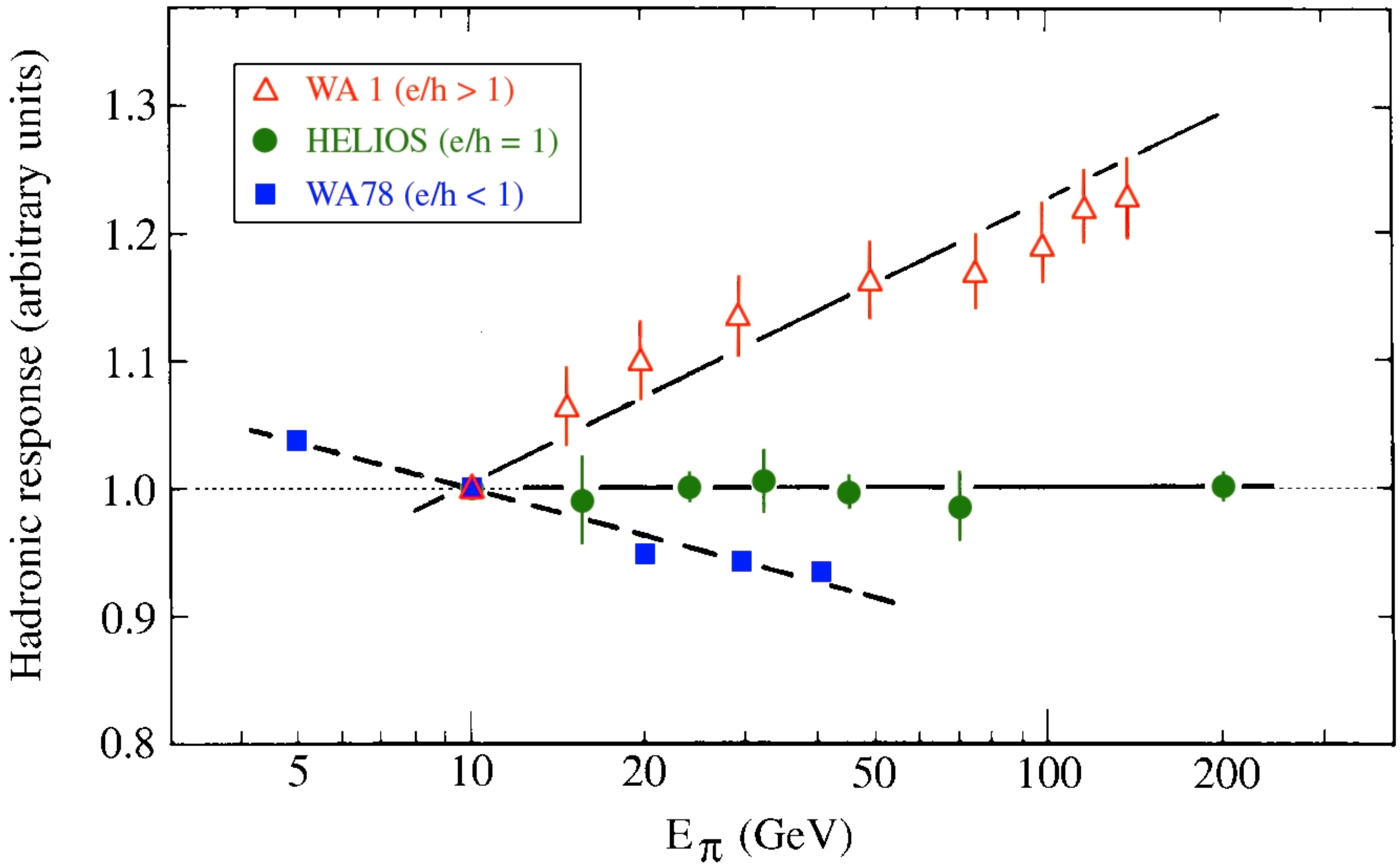
- *Calorimeters with $e/h = 1$ would from now on be known as "compensating" Willis' group built the first such calorimeter for an ISR experiment (^{238}U/plastic scintillator) : Linear response, good energy resolution*

- *However, other attempts were less successful. One uranium calorimeter even gave $e/h \sim 0.8$ ("overcompensating") Others were approximately compensating, but gave poor resolution (e.g. L3)*

- *Around 1985, there was a lot of confusion about the possible merits (or absence thereof) of uranium absorber*

- *L3 data gave a clue to the solution*

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



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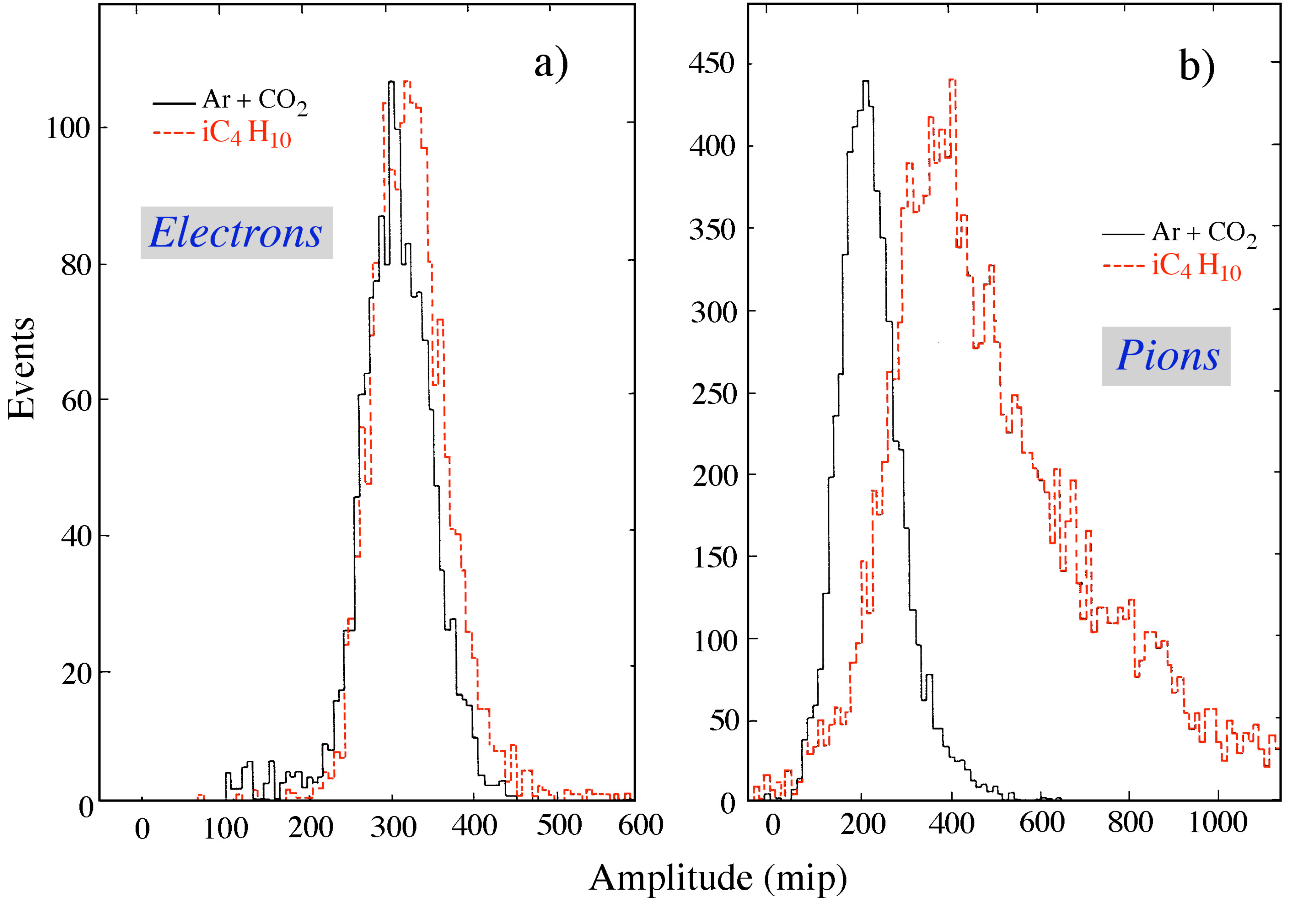
Compensation and energy resolution in L3 hadron calorimeter



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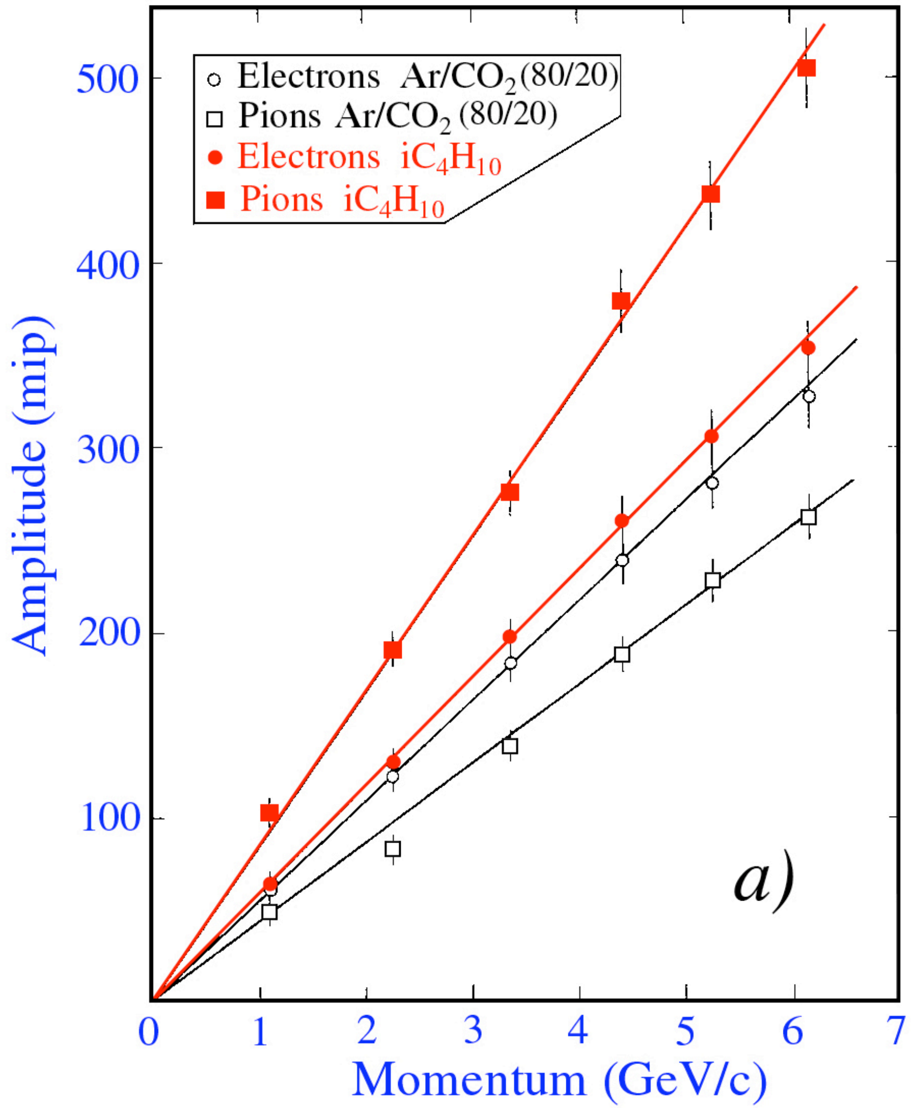
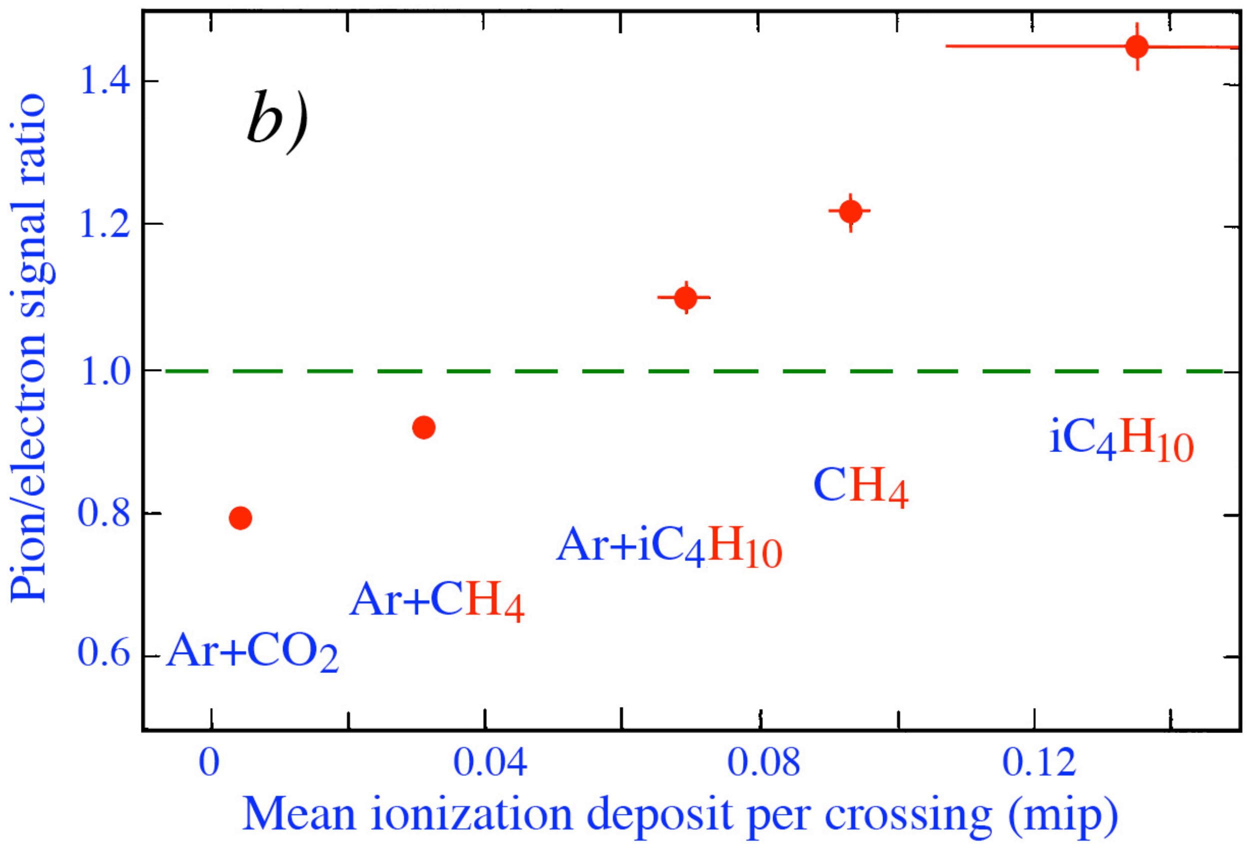
The compensation puzzle solved!

The e/h value is not determined by the absorber, but by active medium

and in particular by its H-content!





The secrets of compensation unraveled

- *Calorimeter signal is the sum of all the signals from the shower particles produced in the absorption process.*

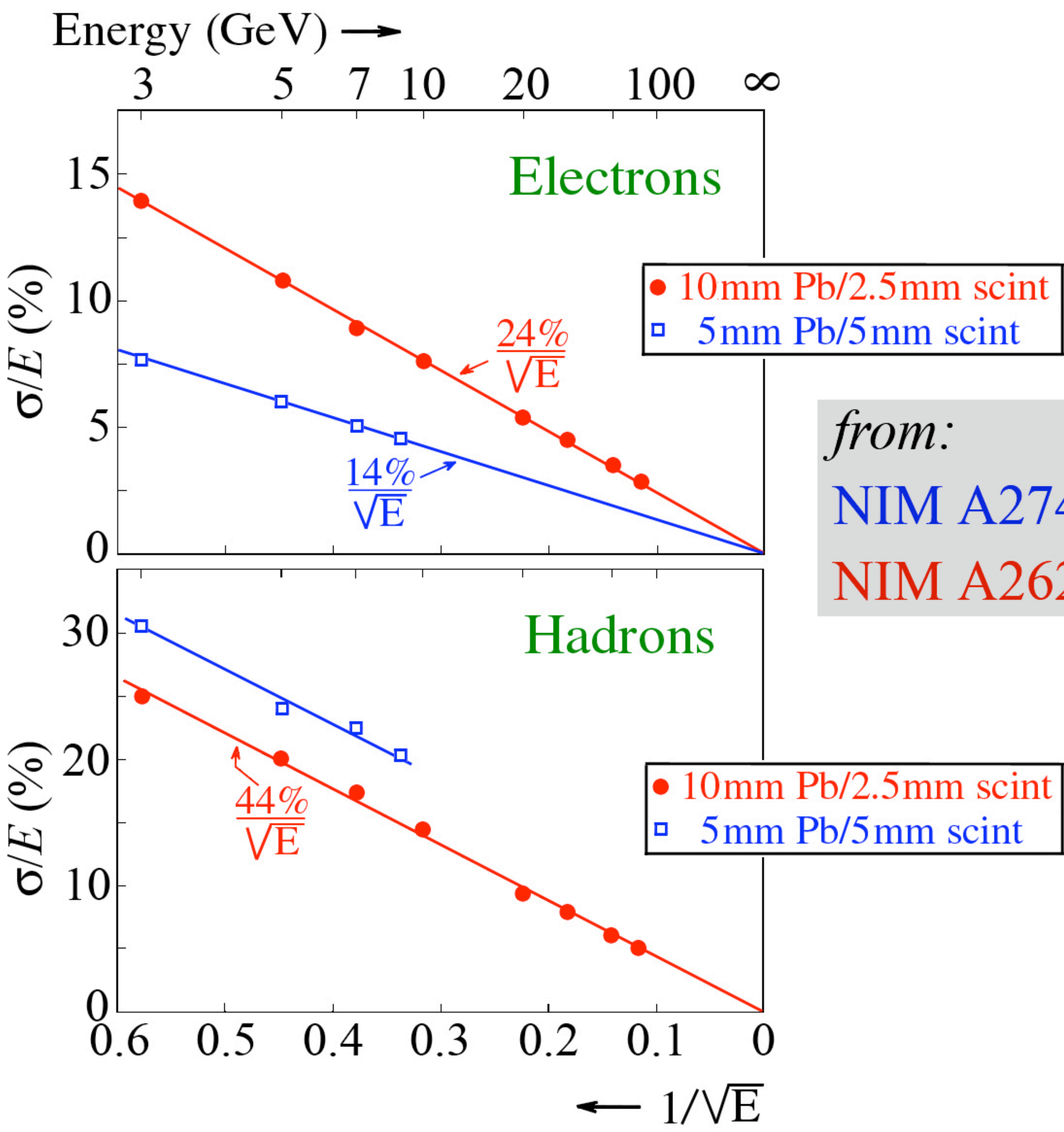
- *Crucial shower particles are sampled in very different ways, depending on the calorimeter structure. Compared to a mip,*
  - *electrons and γs are sampled less efficiently when using high-Z absorber* $(e\downarrow)$
  - *neutrons can be sampled much more efficiently with H-rich active material* $(h\uparrow)$

- *By choosing the optimal sampling fraction, these factors can be tuned to to achieve e/h = 1*

- *Efficient neutron detection also reduces the effects of fluctuations in nuclear binding energy loss on the energy resolution (correlated!)*

- *The use of uranium absorber is neither necessary nor sufficient In fact, the best energy resolutions have been obtained with Pb absorber*

Calorimetric effects of efficient neutron sampling



from:

NIM A274 (1989) 134 $e/h \sim 1.5$

NIM A262 (1987) 229 $e/h = 1.05$

The response to neutrons is increased (relative to the other shower particles) by a factor of 4 in the more crudely sampling calorimeter

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* $(e/h = 1)$.

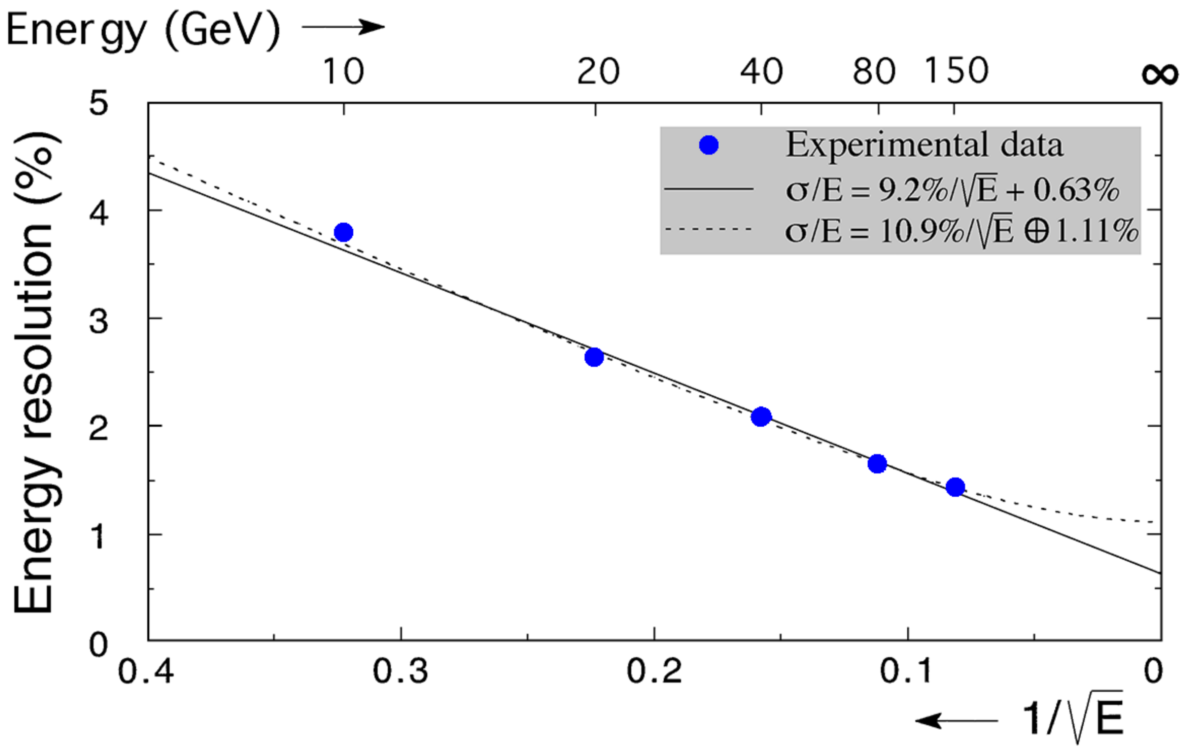
In addition, the total kinetic energy of the neutrons is strongly correlated with the lost nuclear binding energy.
Therefore, efficient neutron detection is crucial for reducing the contribution of fluctuations in "invisible energy" to the resolution.

A good alternative for future e^+e^- collider experiments

(compensating em and had segments)

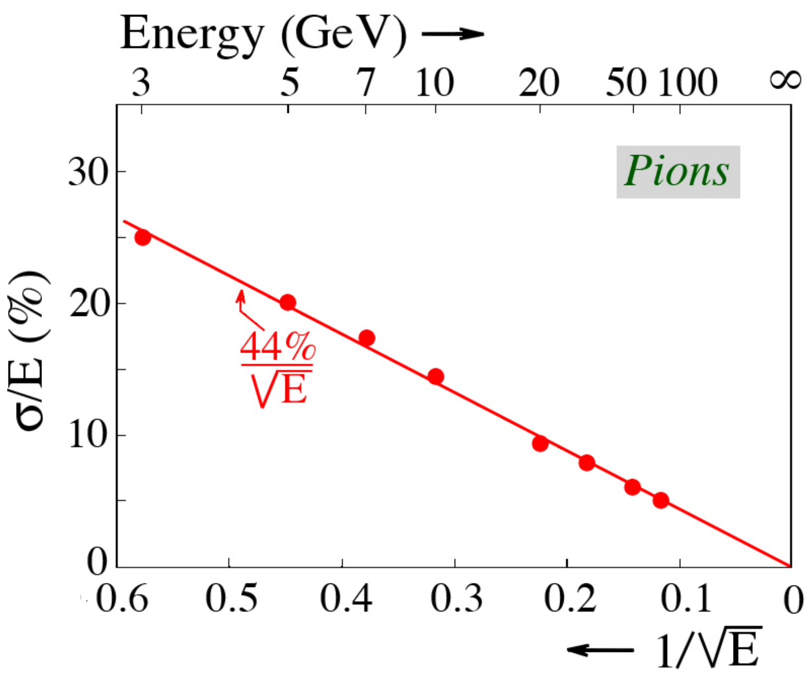
ECAL

● Pb/fiber 4:1, 0.5 mm fibers (RD1)



HCAL

● 10mm Pb/2.5mm scint [Bern87]



NIM A337 (1994) 314

NIM A262 (1987) 229

Pros & Cons of Compensating Calorimeters

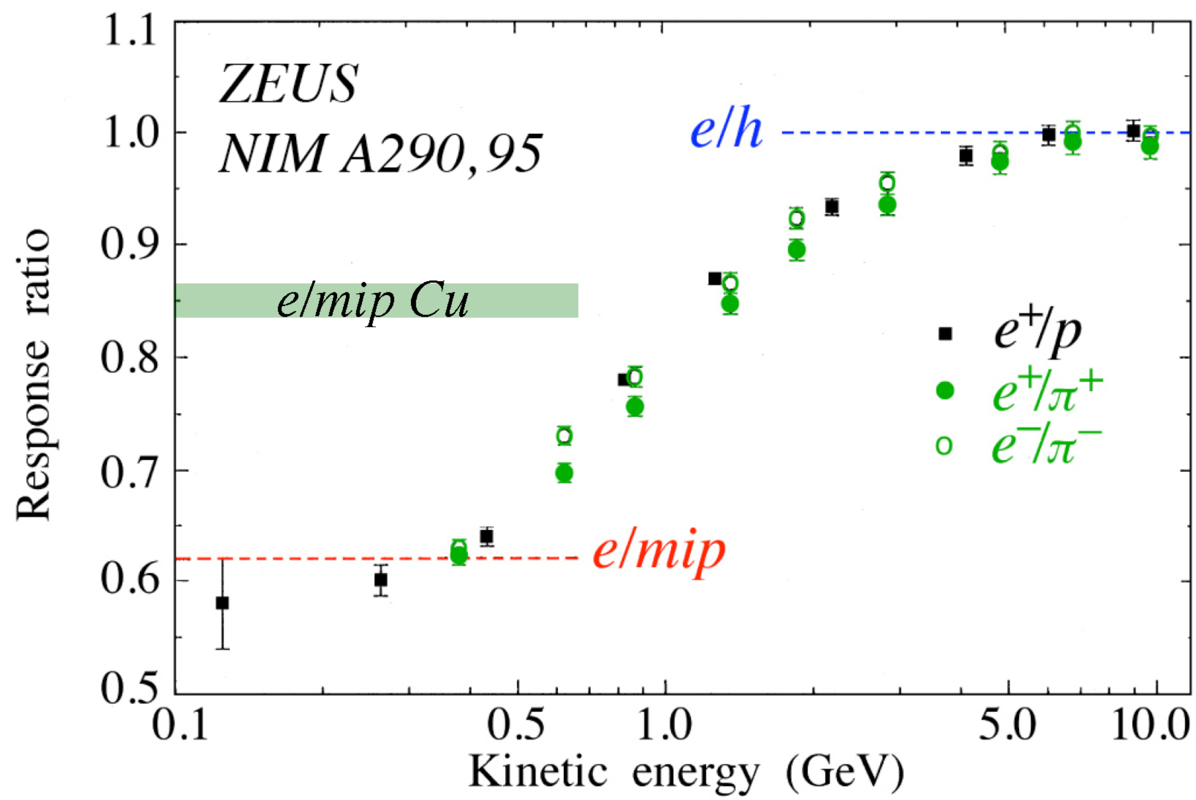
Pros

- 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)
- *Jet* resolution not as good as for single hadrons in Pb,U calorimeters

What is the problem with the jet energy resolution?



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

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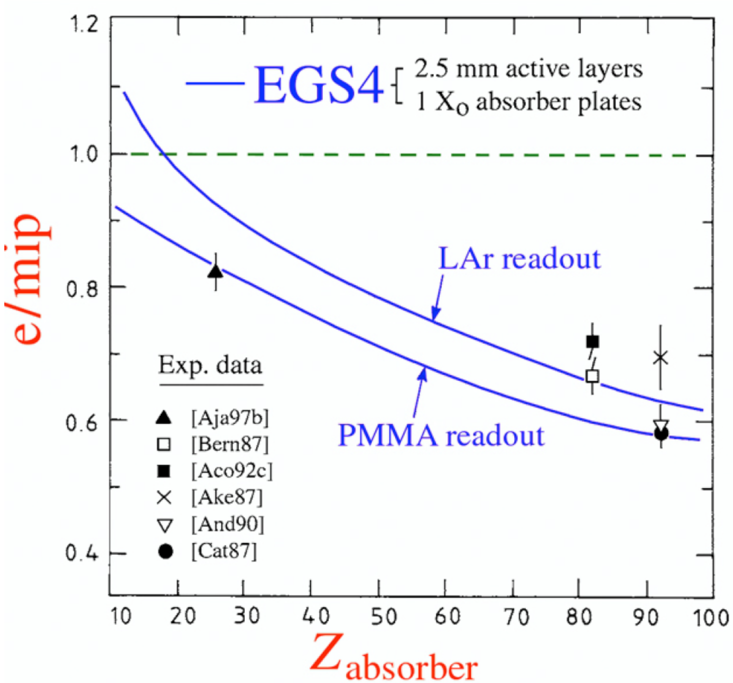

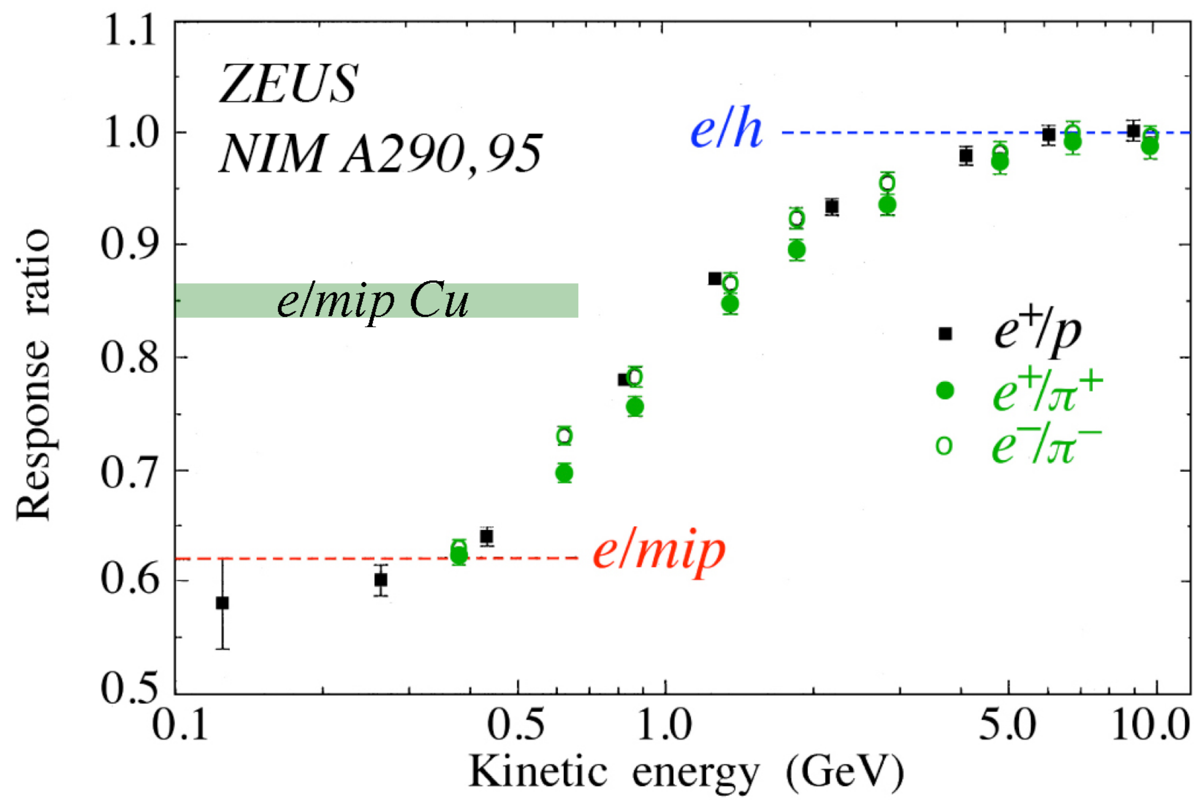

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Many jet fragments fall in this category

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

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) *Use lower-Z absorber material*
   to eliminate / reduce the jet problems

3) *Maintain advantages of compensation*
   (eliminate / reduce effects of fluctuations in f_{em} and invisible energy)

→ *Dual-Readout Calorimetry*

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)

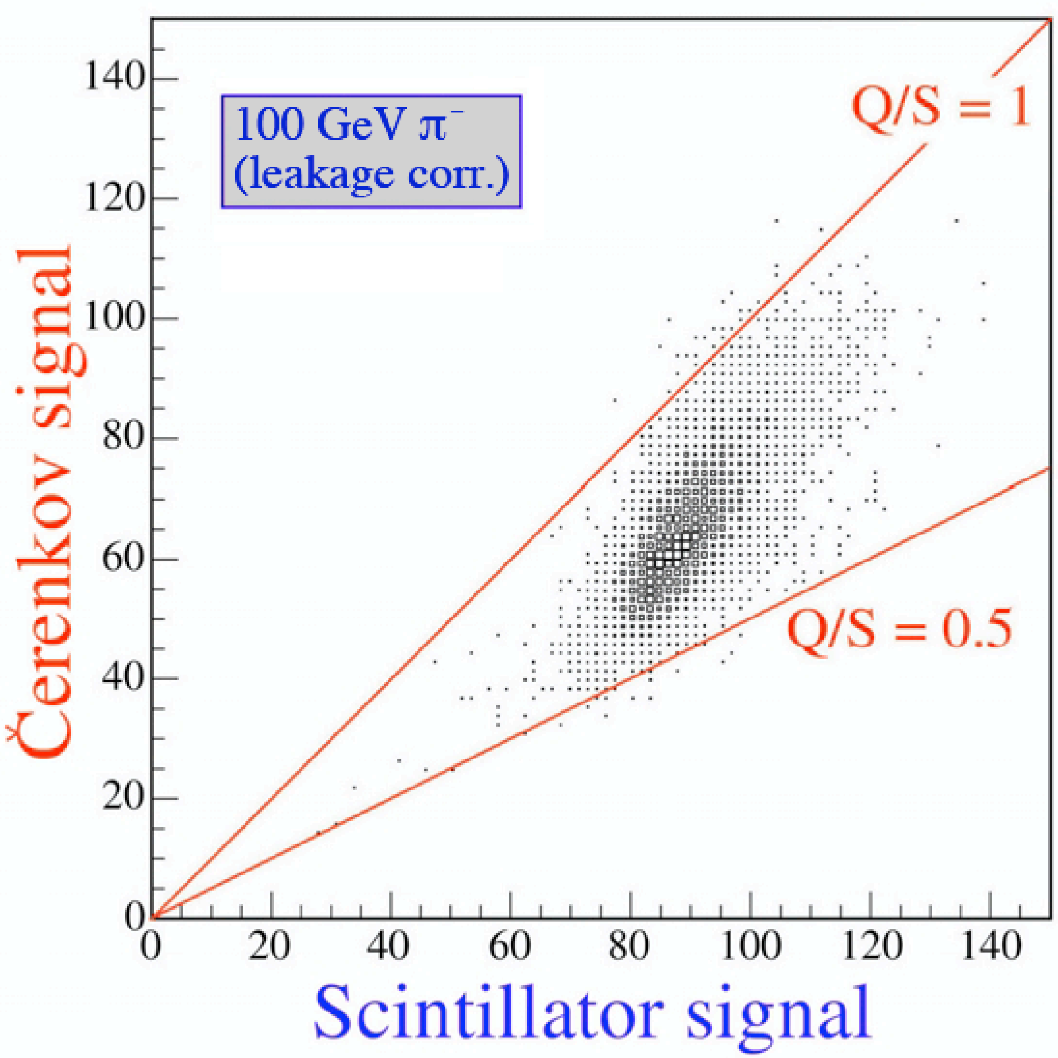
Calorimeter response to these components not the same *(e/h ≠ 1)*

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: How to determine f_{em} and E ?



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

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

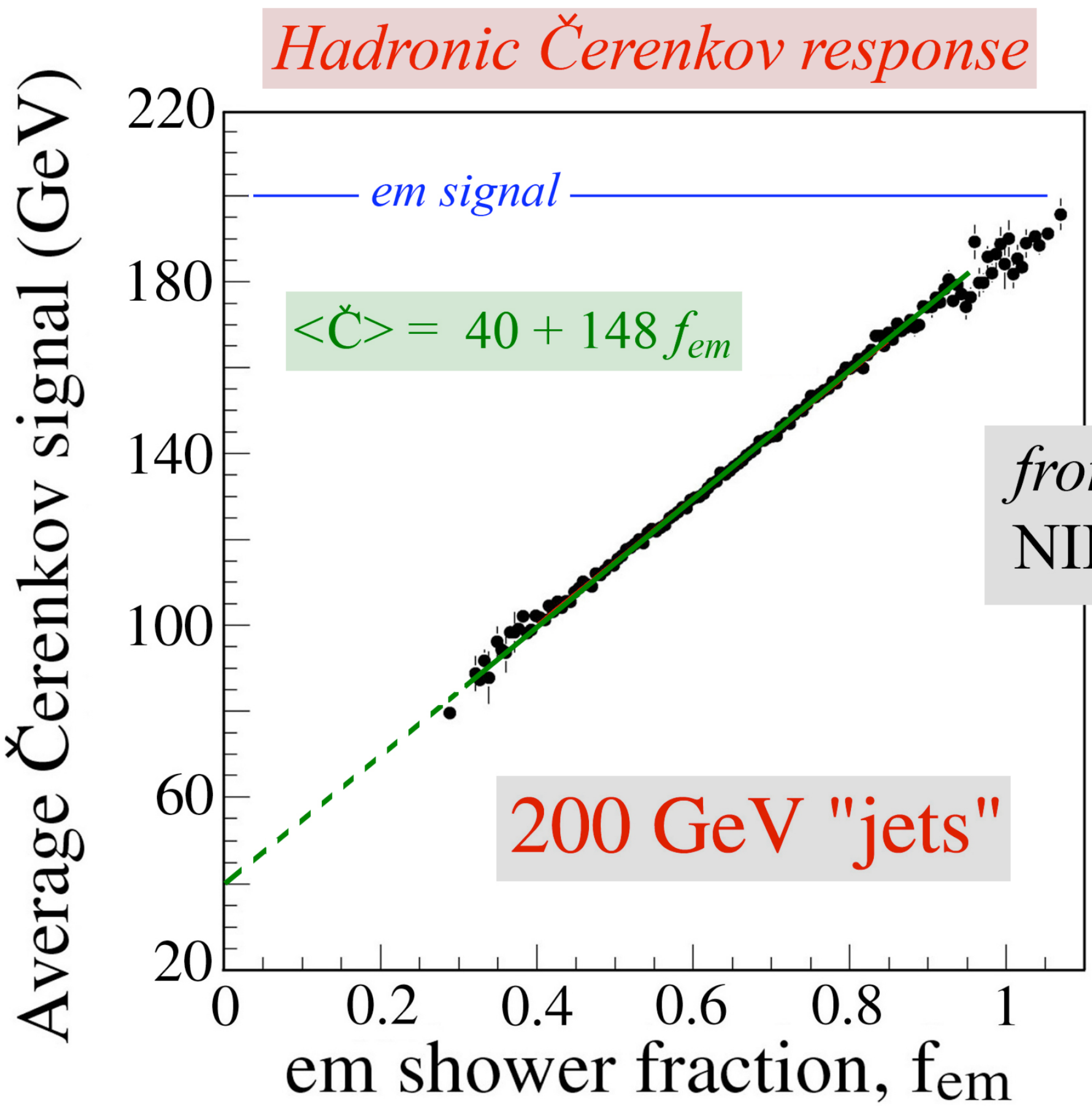
e.g. If $e/h = 1.3$ (S), 4.7 (Q)

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

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

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

The dual-readout method



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

$$e/h = \frac{p_1}{p_0} - 1 = 4.7$$

from:
NIM A537 (2005) 537

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

Experimentally, one measures f_{em} event by event
Scale signal up to $f_{em} = 1$, i.e. the em scale

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)

And this performance can be achieved with a calorimeter consisting of low-Z absorber material!

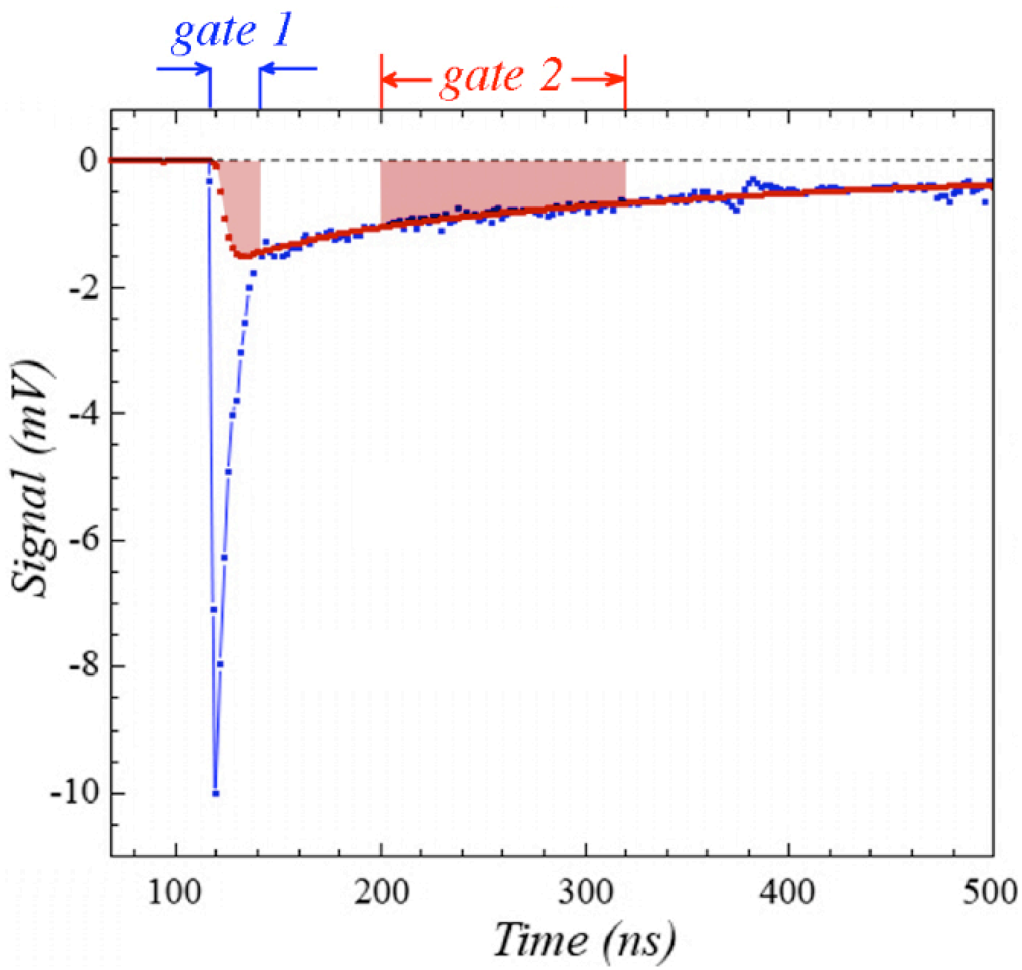
How to improve DREAM performance

- 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 ~ 40%/$\sqrt{E}$ to hadronic resolution in DREAM

Čerenkov and Scintillator information from one signal !



BGO crystal
UG 11 (UV) filter

From:
NIM A595 (2008) 359

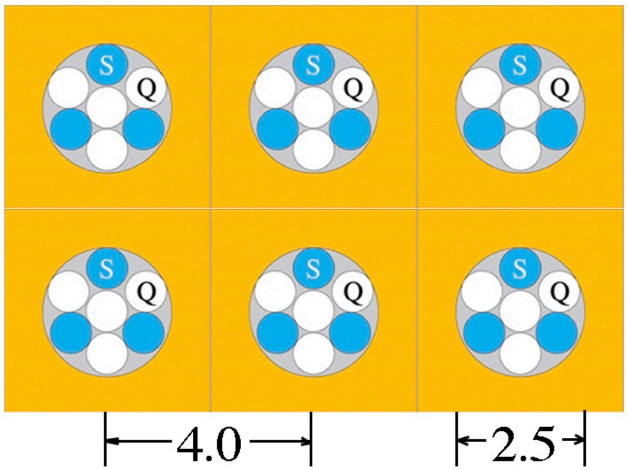
Figure 14: The time structure of a typical shower signal measured in the BGO em calorimeter equipped with a UV filter. These signals were measured with a sampling oscilloscope, which took a sample every 0.8 ns. The UV BGO signals were used to measure the relative contributions of scintillation light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

Cu/fiber dual-readout calorimetry

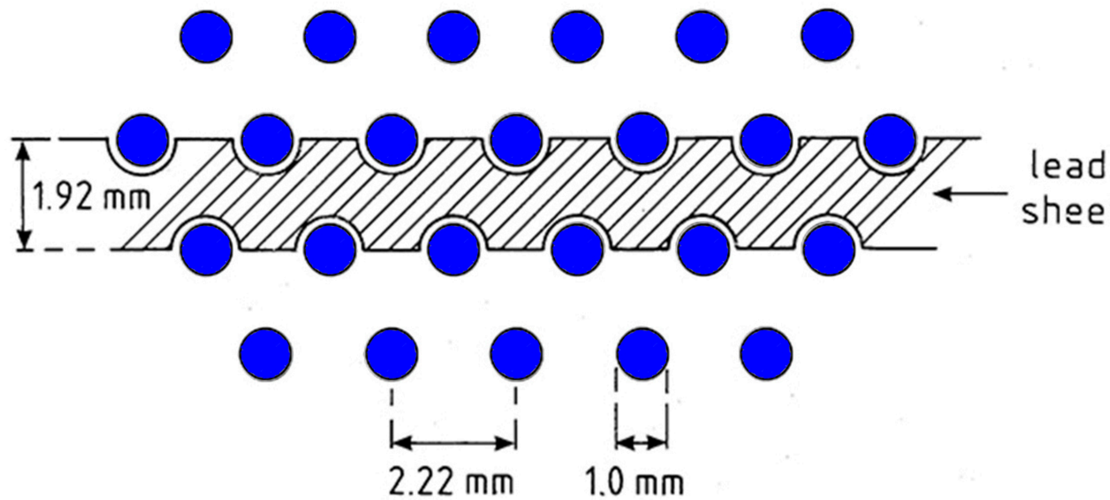
- *Excellent em and hadronic energy resolution*
- *Calibration is trivial*
- *Excellent particle-id in longitudinally unsegmented detector*
- *Ultrafast Cherenkov signals give unique timing options*

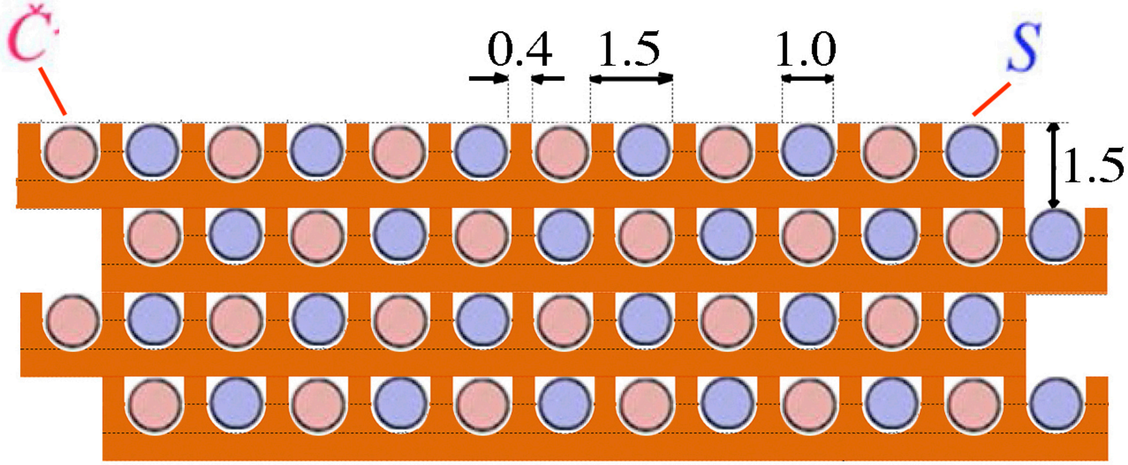
Sampling fraction & frequency

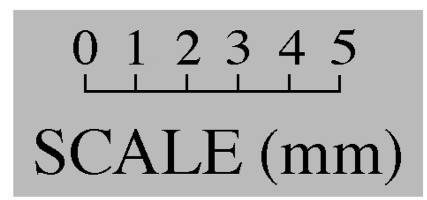
DREAM



SPACAL







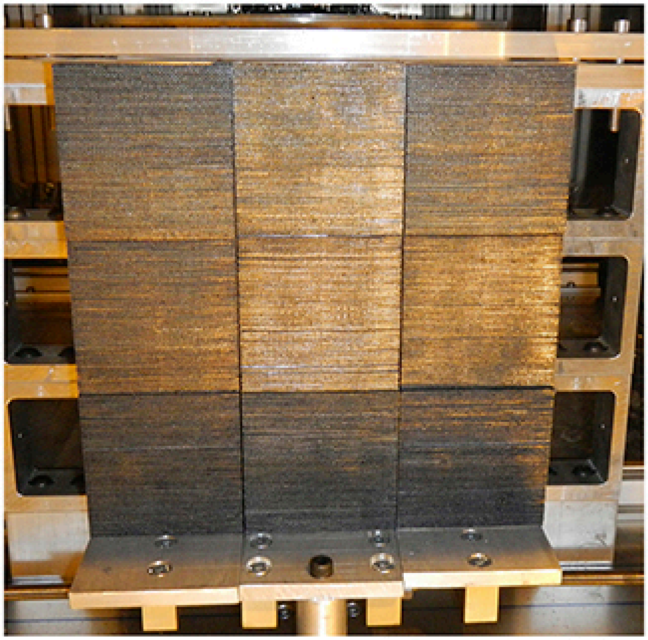
Fiber pattern *RD52*

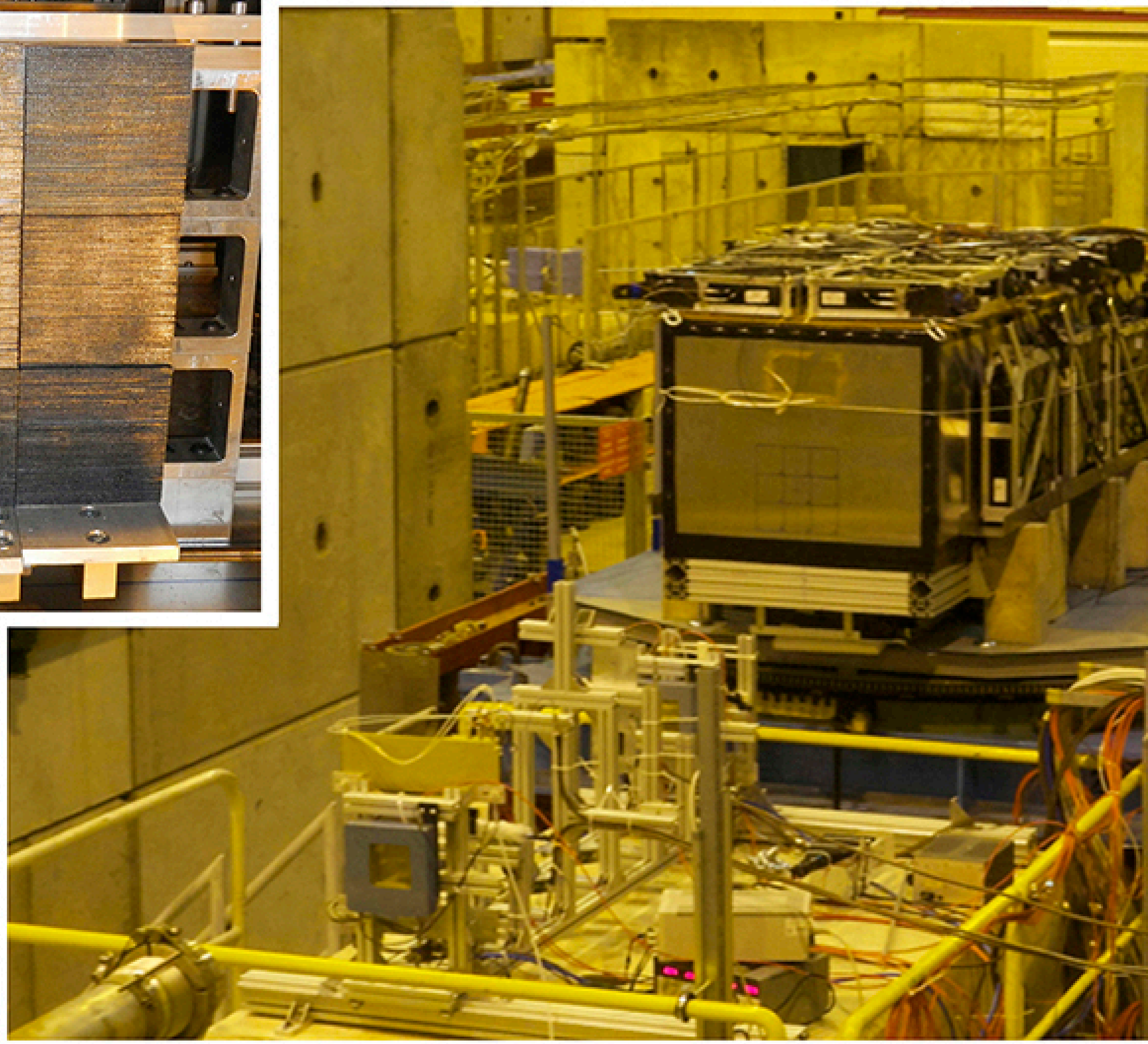
Absorber thickness between sampling layers (Moliere radii):

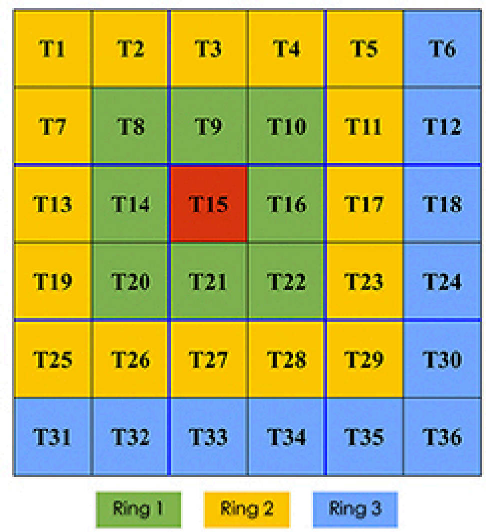
SPACAL 0.071 *DREAM 0.099* *RD52 0.027*

The RD52 lead-based DREAM calorimeter

(1.2 tonnes)

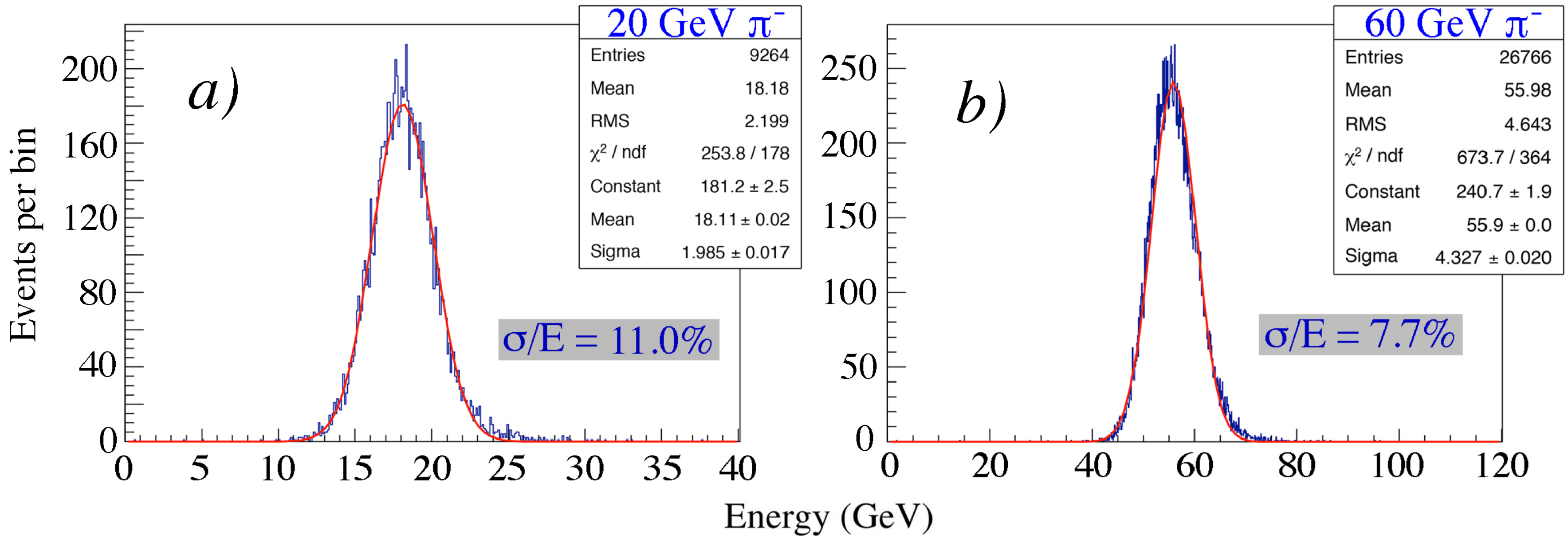






Hadronic performance
(1.2 ton RD52 Pb based calorimeter)

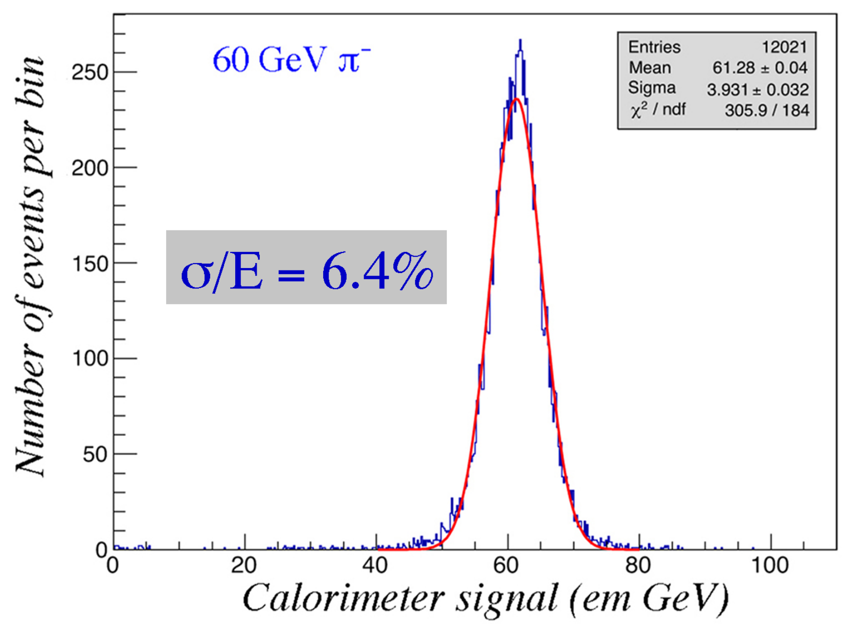
NIM A732 (2013) 475



Including information from leakage counters

(2016 SPSC report RD52)

GEANT4:
Cu absorber +
sufficiently large detector:
$\sigma/E = 4.1\%$



A crucial feature: No longitudinal segmentation

- *Advantages:*
  - *Compact construction*
  - *No intercalibration of sections needed*
  - *Calibrate with electrons and you are done*

- *Possible disadvantages:*
  - *Dealing with pile-up (not an issue at ILC)*
  - *Pointing for neutral particles*
  - *Electron ID*

However, a fine lateral granularity can do wonders

In addition:

- *Time structure of the signals can provide crucial depth information*

Methods to distinguish e/π in longitudinally unsegmented calorimeter

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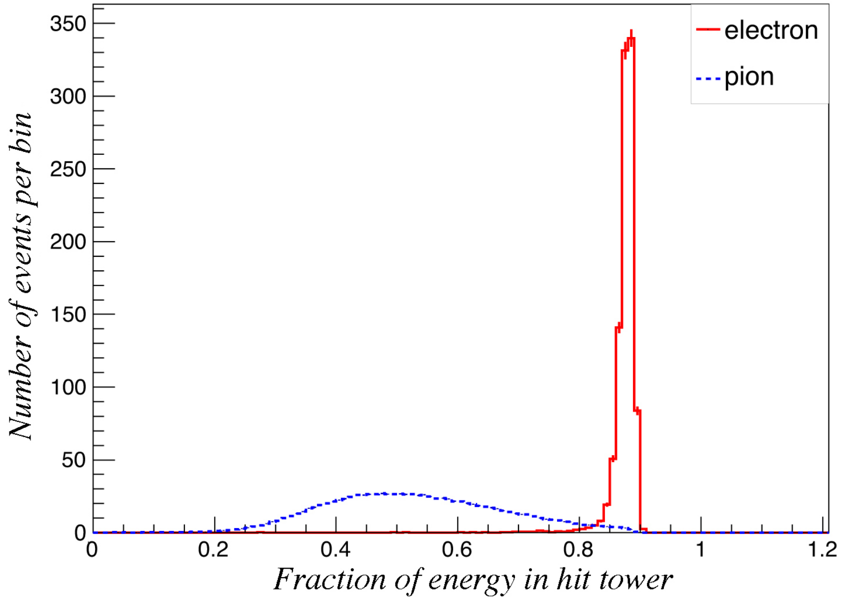
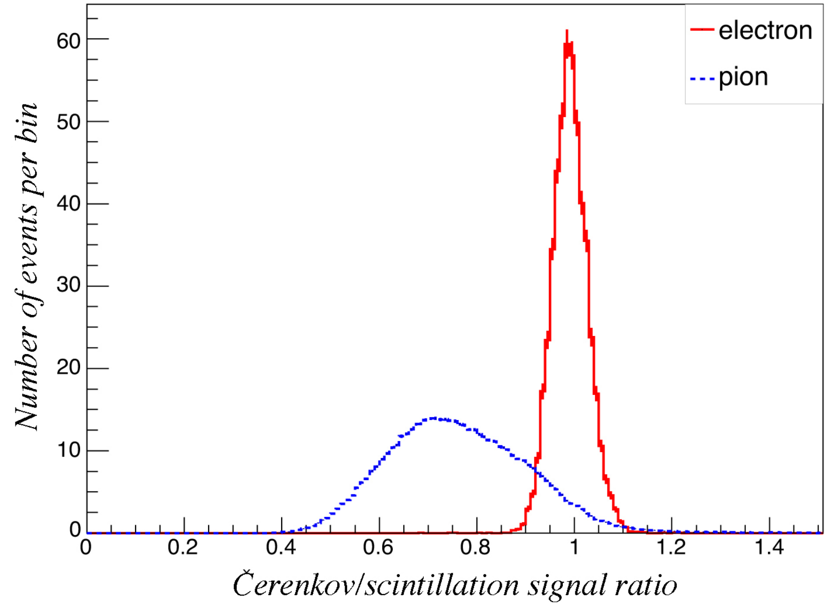
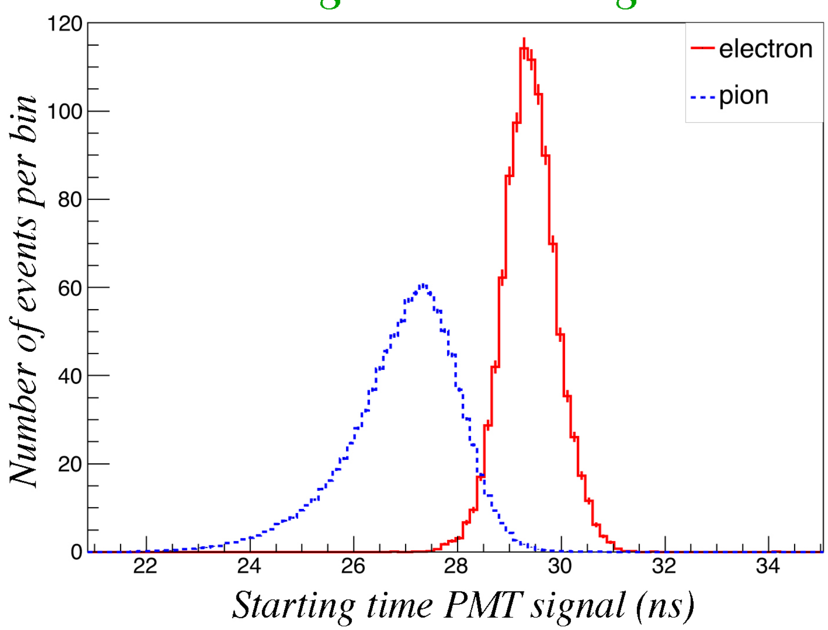
Lateral shower profile



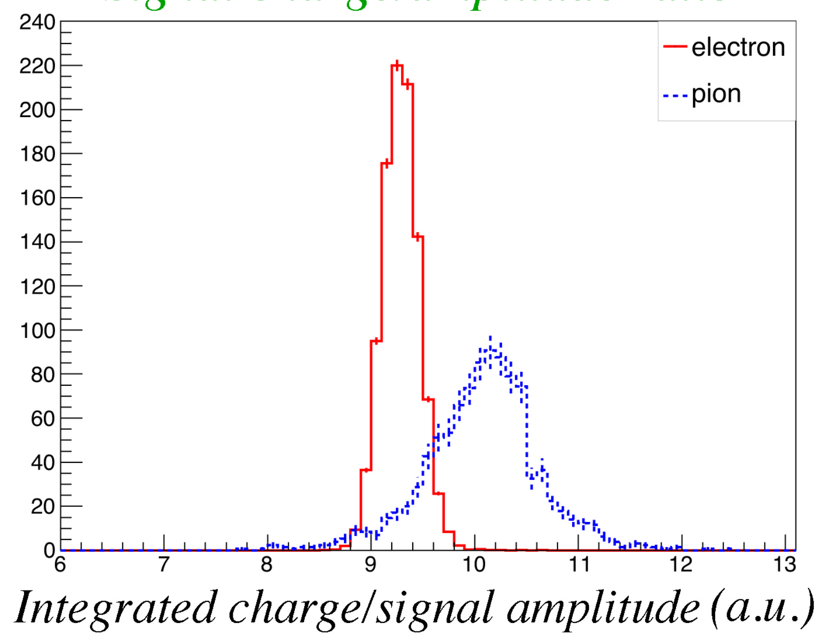
Difference C/S signals



Starting time PMT signal

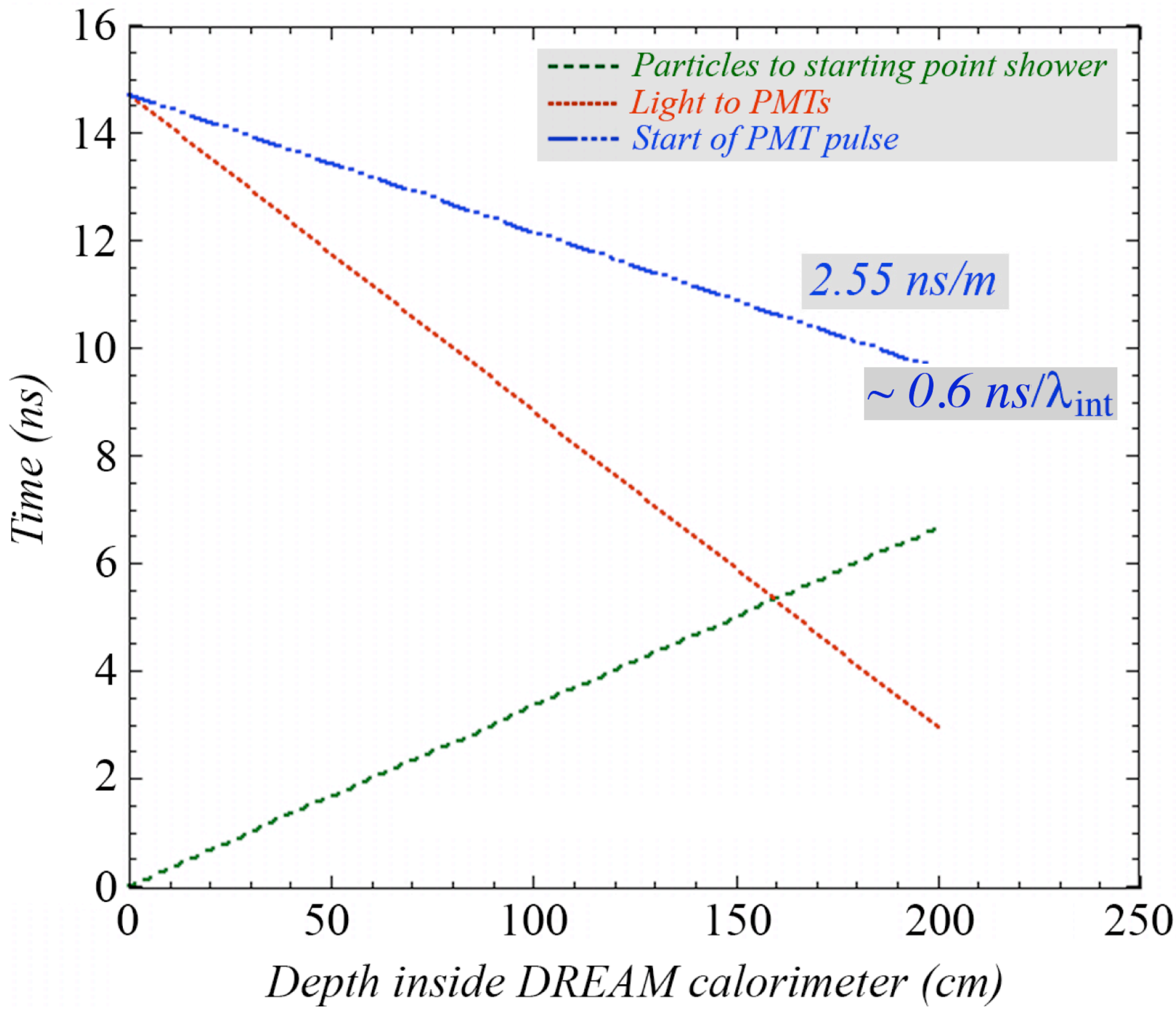


Signal charge/amplitude ratio

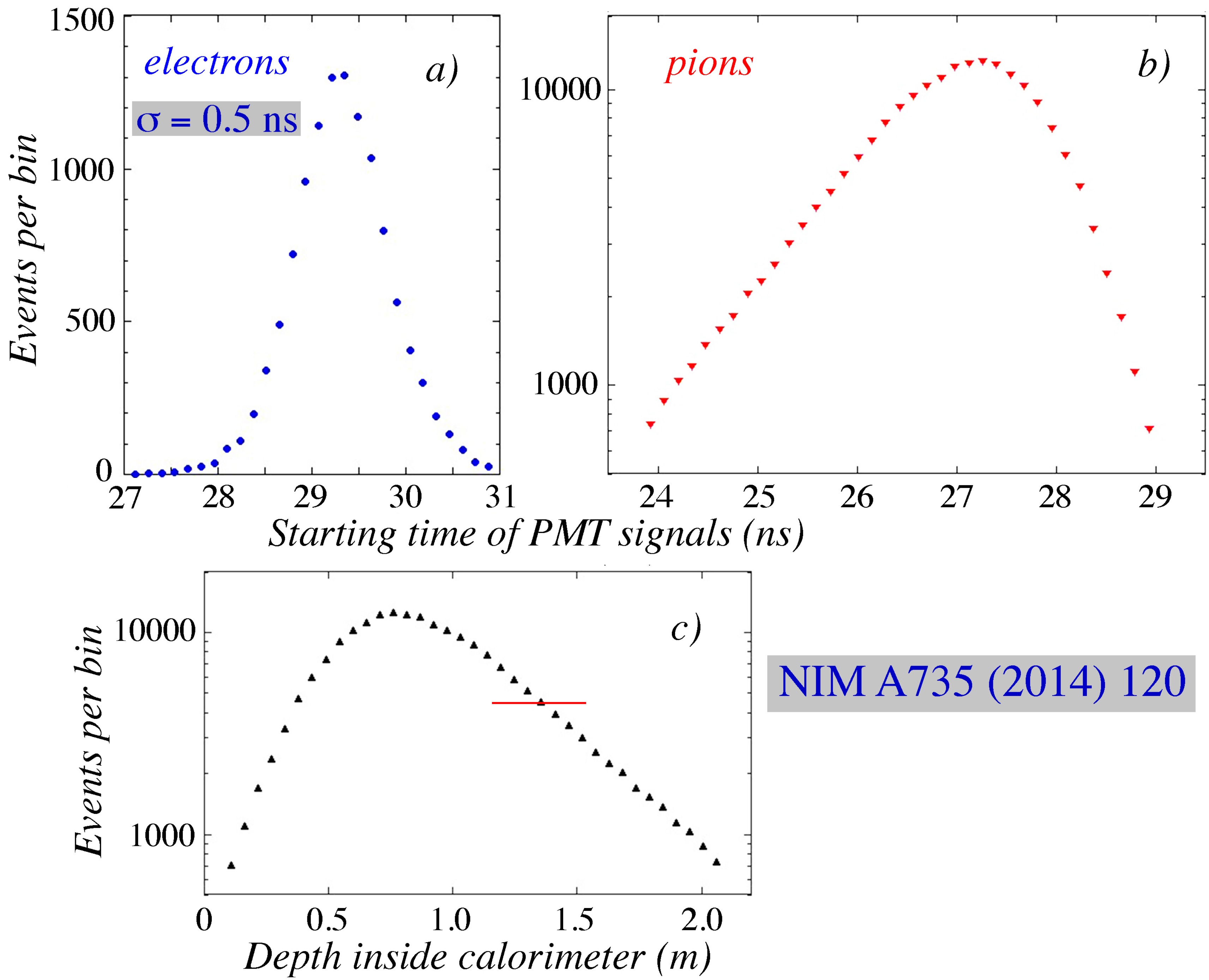


Combination of cuts: >99% electron efficiency, <0.2% pion mis-ID

Depth of the light production and the starting point of the PMT signals



Use starting time PMT signal to determine the depth of the light production and thus identify particle



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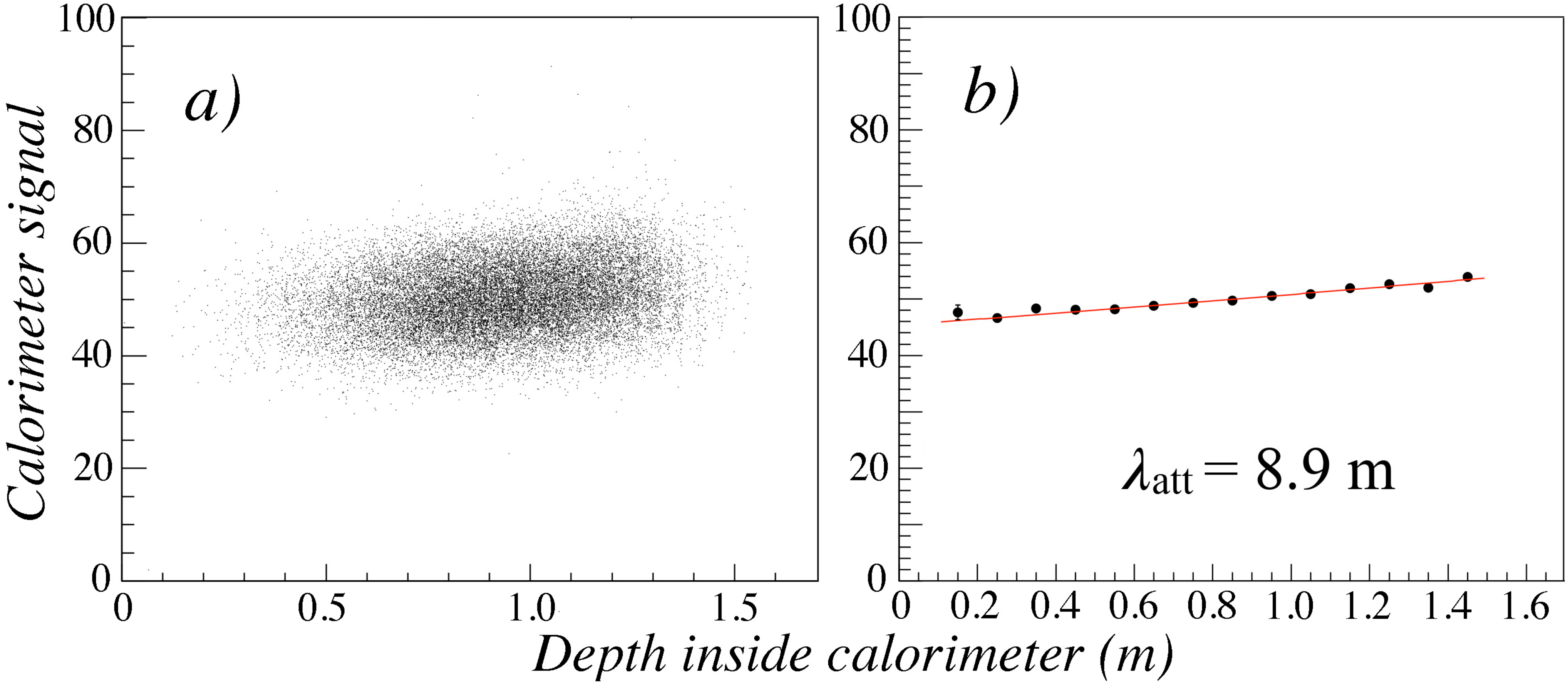
Use depth of light production to correct for light attenuation



Particle Flow Analysis

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*

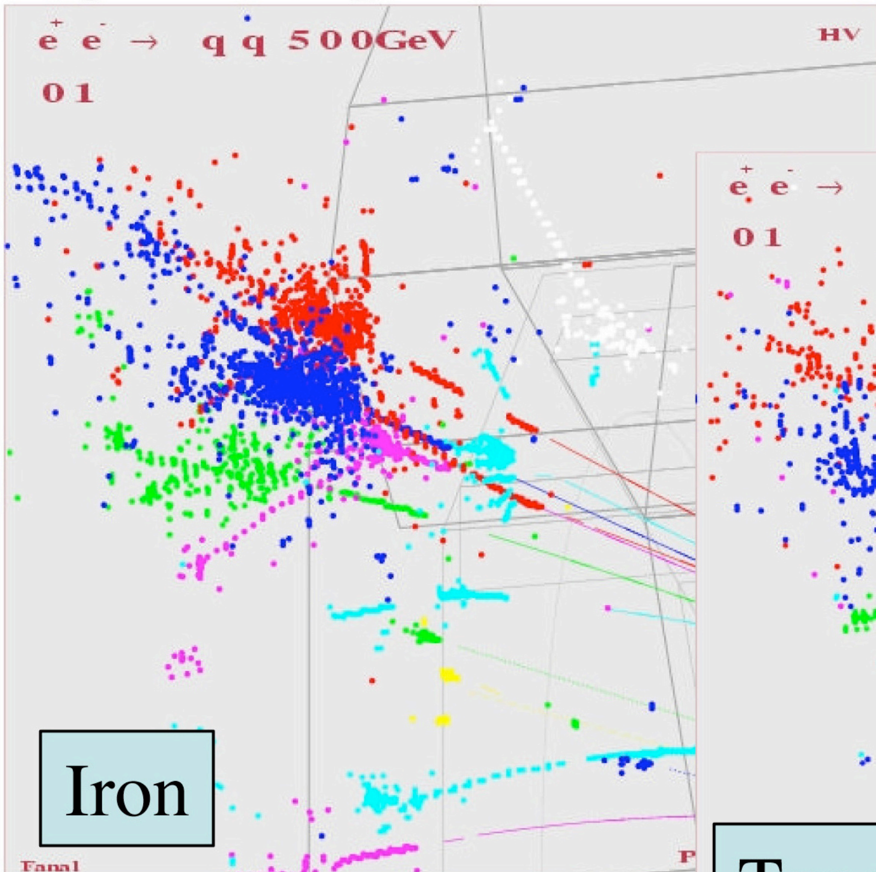
  The calorimeters do not know that the charged jet fragments have already been measured by the tracker. These fragments are also absorbed in the calorimeter. Confusion: Which part of the calorimeter signals comes from the neutral jet fragments?

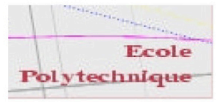
- *Advocates of this method claim that a fine detector granularity will help solve this problem. Others believe it would only create more confusion.*

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

Pink Pion Physics

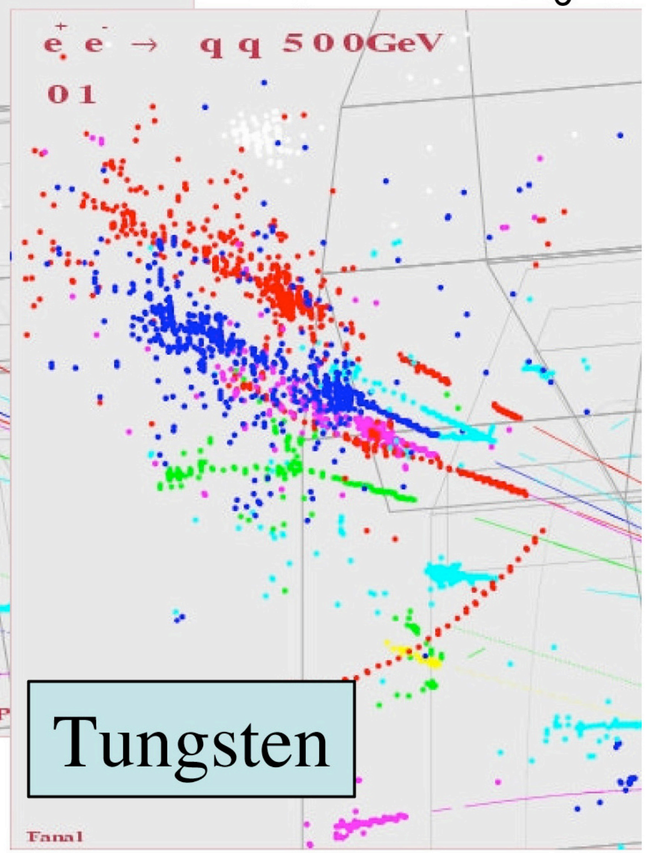
X_0 = 1.8cm, λ_I=17cm

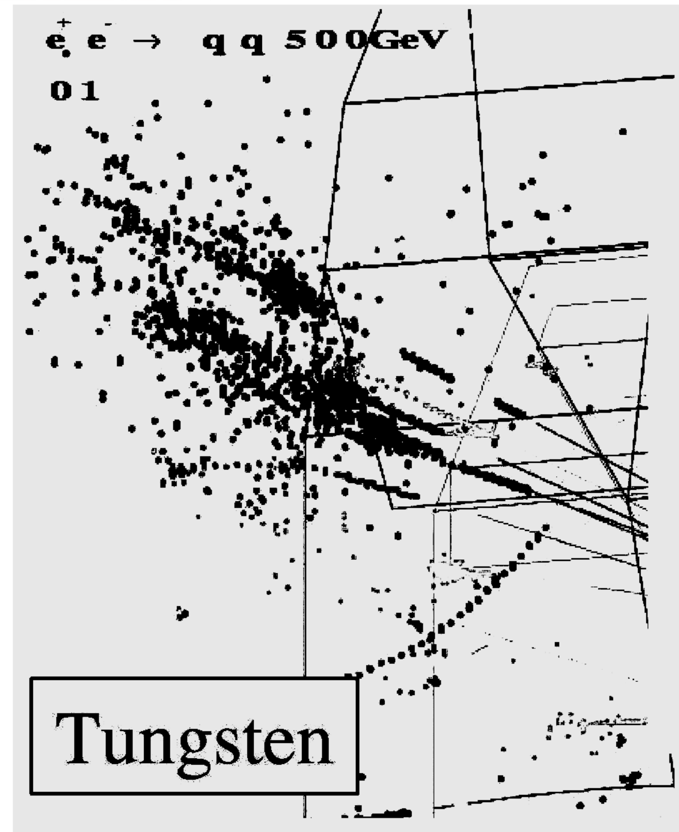




(images courtesy H.Videau)

X_0 = 0.35cm, λ_I=9.6cm





On high-resolution hadron calorimetry

Available online at www.sciencedirect.com
SCIENCE DIRECT
Nuclear Instruments and Methods in Physics Research A 495 (2002) 107–120
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.com/locate/nima

On the energy measurement of hadron jets

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Abstract

The elementary constituents of hadronic matter (quarks, anti-quarks, gluons) manifest themselves experimentally in the form of jets of particles. We investigate the precision with which the energy of these fragmenting objects can be measured. The relative importance of the instrumental measurement precision and of the jet algorithm is assessed. We also evaluate the "energy flow" method, in which the information from a charged-particle tracker is combined with that from a calorimeter in order to improve the jet energy resolution.

PACS: 02.70.Uu; 29.40.Vj

Keywords: Calorimetry; Fluctuations; Jets; Energy flow

From Conclusions:

Both our simulations and the experimental data show that the EFM does offer a beneficial effect. However, this effect should not be exaggerated. The improvement in the energy resolution is typically 30%. Poor calorimeter systems benefit more than good calorimeter systems, and a strong magnetic field also helps.

cf CMS vs ATLAS !!

bosons and decreases at higher energies. Claims that much better results may be achieved for highly granular calorimeter systems, in which the showers generated by the individual jet fragments may be recognized and separated from each other are unsubstantiated. We have shown that for most of the showers in practical detectors, the overlap between the shower profiles rather than the detector granularity is the factor that limits the benefits of this method.

No experimental evidence to the contrary!!

Particle Flow Analysis

A quote from the scientific literature NIM A495 (2002) 107

Important ingredients

- *A large detector (i.e. tracking volume)*
- *A strong magnetic field*
- *An excellent tracker*
- *A poor detector for hadron showers*

→ *PFA may turn poor jet detection into mediocre jet detection*

Check:	*CMS*	*ATLAS*
• *A large detector (i.e. tracking volume)*	√	√
• *A strong magnetic field*	√	×
• *An excellent tracker*	√	×
• *A poor detector for hadron showers*	√	×
	benefits from PFA	*does not benefit*

A frequently used, but misleading argument

- *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°	$\Delta E/E$	$\sim 45\%$

$$E_{jet} = E_{charged\ tracks} + E_{\gamma} + E_{h^0}$$

fraction: charged tracks 65%, γ 26%, h^0 9%

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

Hadronic calorimeter prototype

Vienna Conference on Instrumentation
NIM A732 (2013) 466

Absorber: Tungsten or Steel

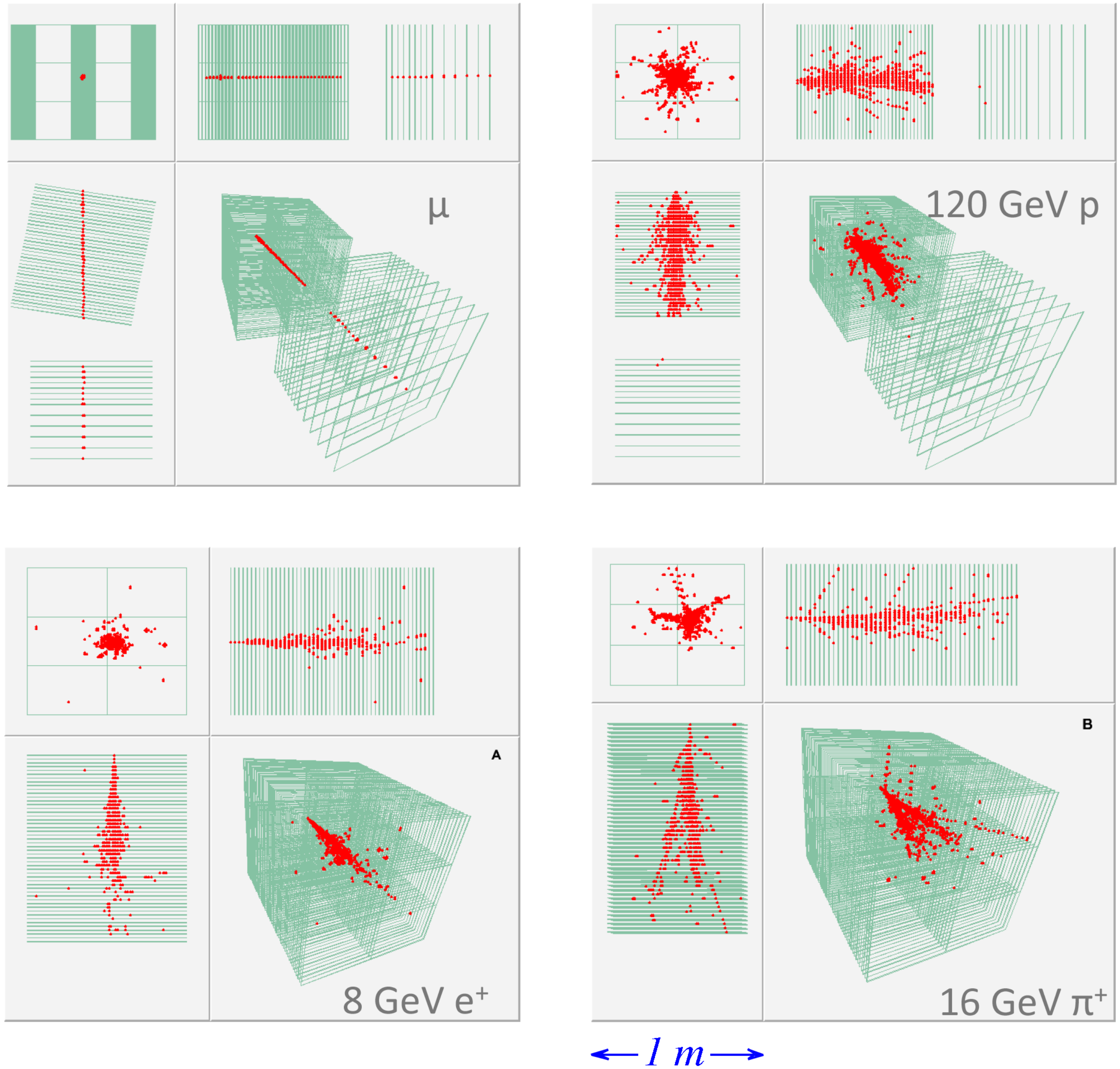
Digital readout: RPCs (1 x 1 cm^2)

Dimensions: 54 layers, 1 x 1 m^2

~500,000 readout channels !!

Tested at CERN/FNAL, e/π 10 - 300 GeV

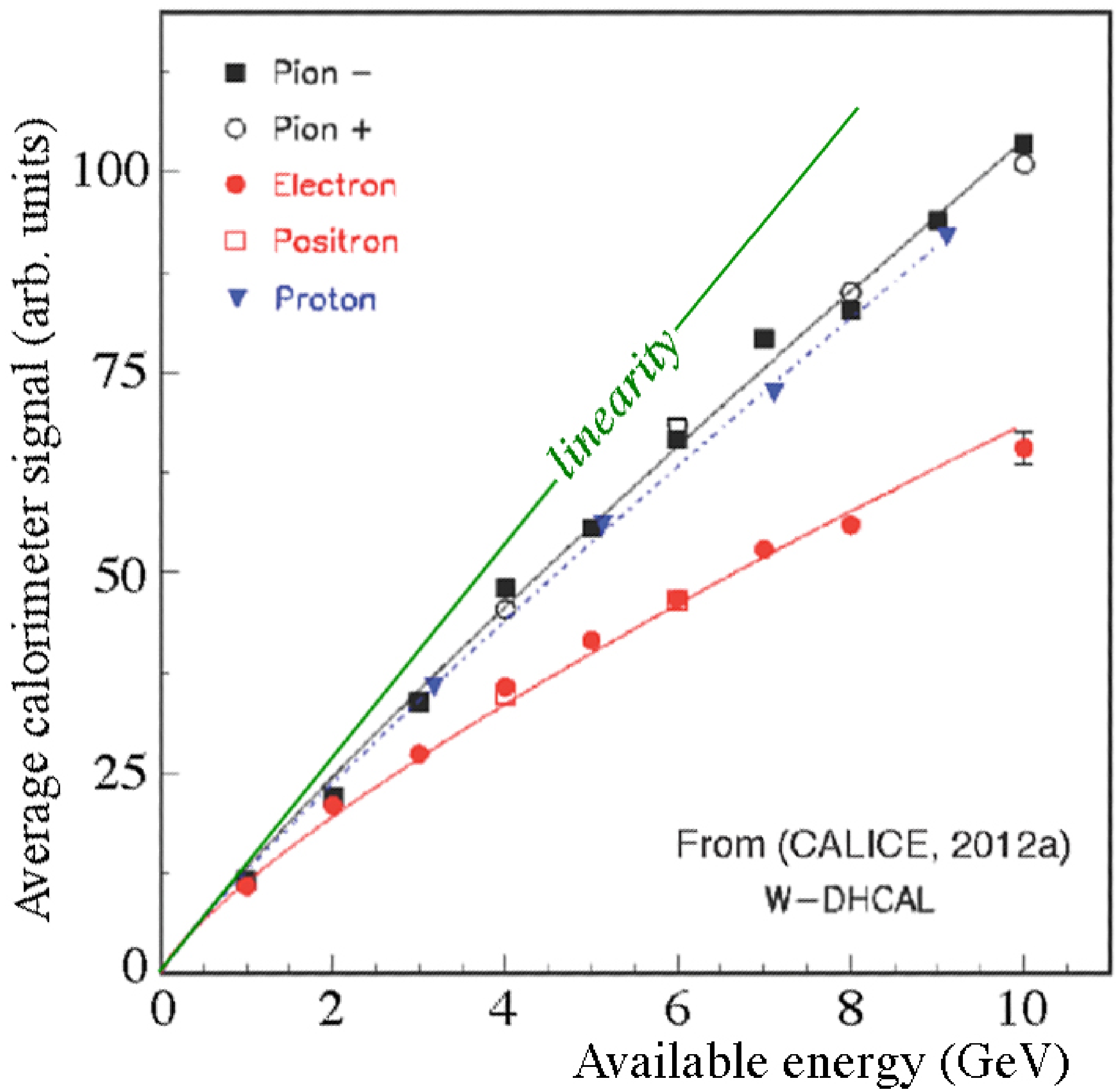
Some events displays of the CALICE DHCAL



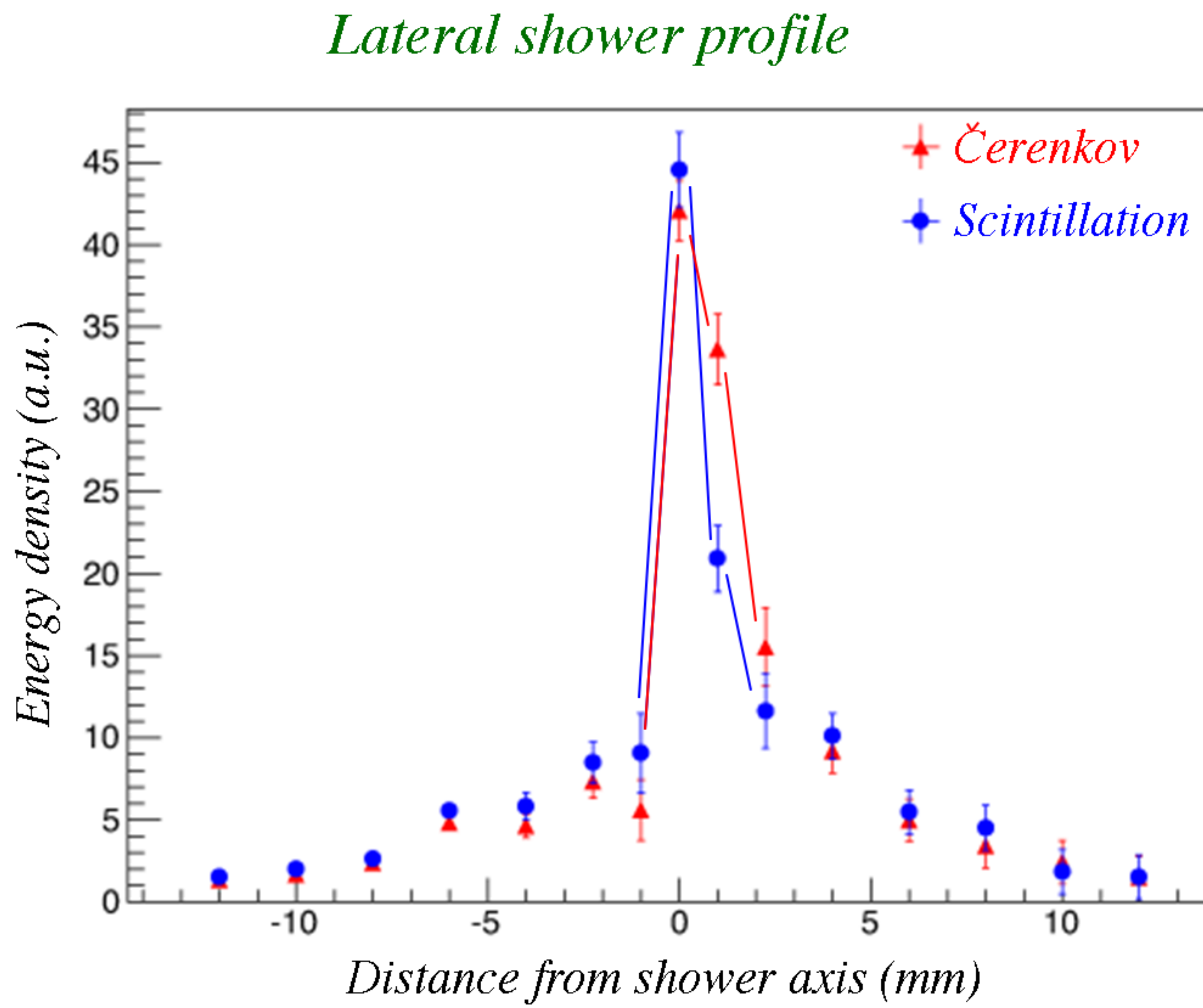
There exists no such thing as a TYPICAL event profile

Signal saturation in the CALICE DHCAL
(overcompensating @ < 10 GeV)

Rev. Mod. Phys. 88 (2015) 15003



The extremely narrow electromagnetic shower profile



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Fundamental problems with PFA

- *Calibration?!*
- *Non-linearity (saturation effects)*
- *Texas towers*

Unfortunately, the proponents of PFA are not interested in these issues, and only study engineering problems

Misconceptions about calorimetry

- *A shower is a collection of mips*
- *Energy resolution ≡ width of signal distribution*
- *Energy resolution scales like* $E^{-1/2}$
- *Linearity ≡ you can fit a straight line through some data points*
- *Signal saturation does not matter*
- *Compensation would be nice, but is not really important*
- *The only effect of non-compensation is a constant term in the energy resolution*
- *ALL CALORIMETER PROBLEMS CAN BE SOLVED OFFLINE*

→ *Pretend everything is OK*
Build those calorimeter systems with 10^8 *channels**
Leave it to future generations to solve the mess

---

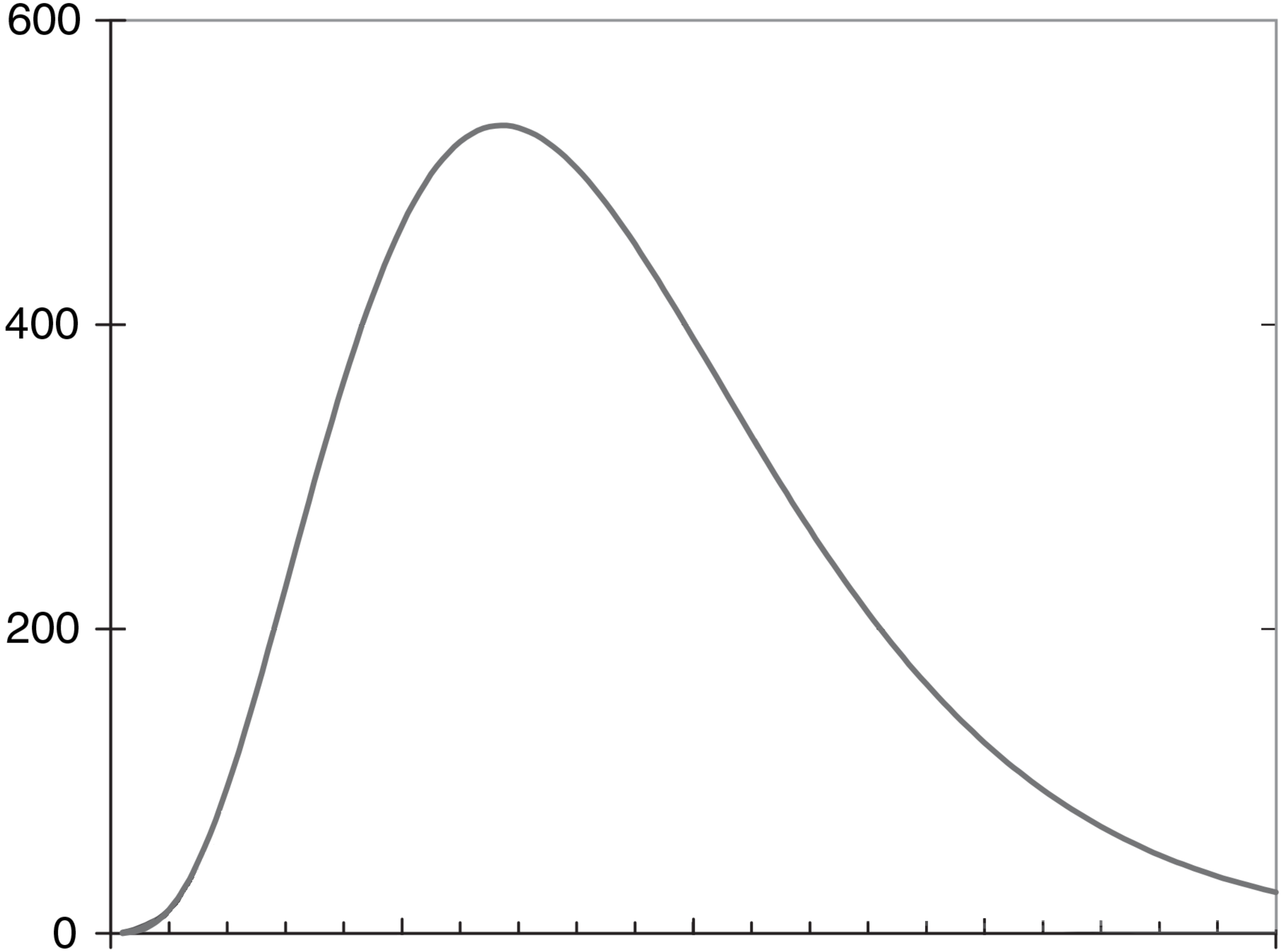
* *Predicted em energy resolution for CMS upgrade: 20 - 24%/*$\sqrt{E}$

The future of calorimetry in high energy physics

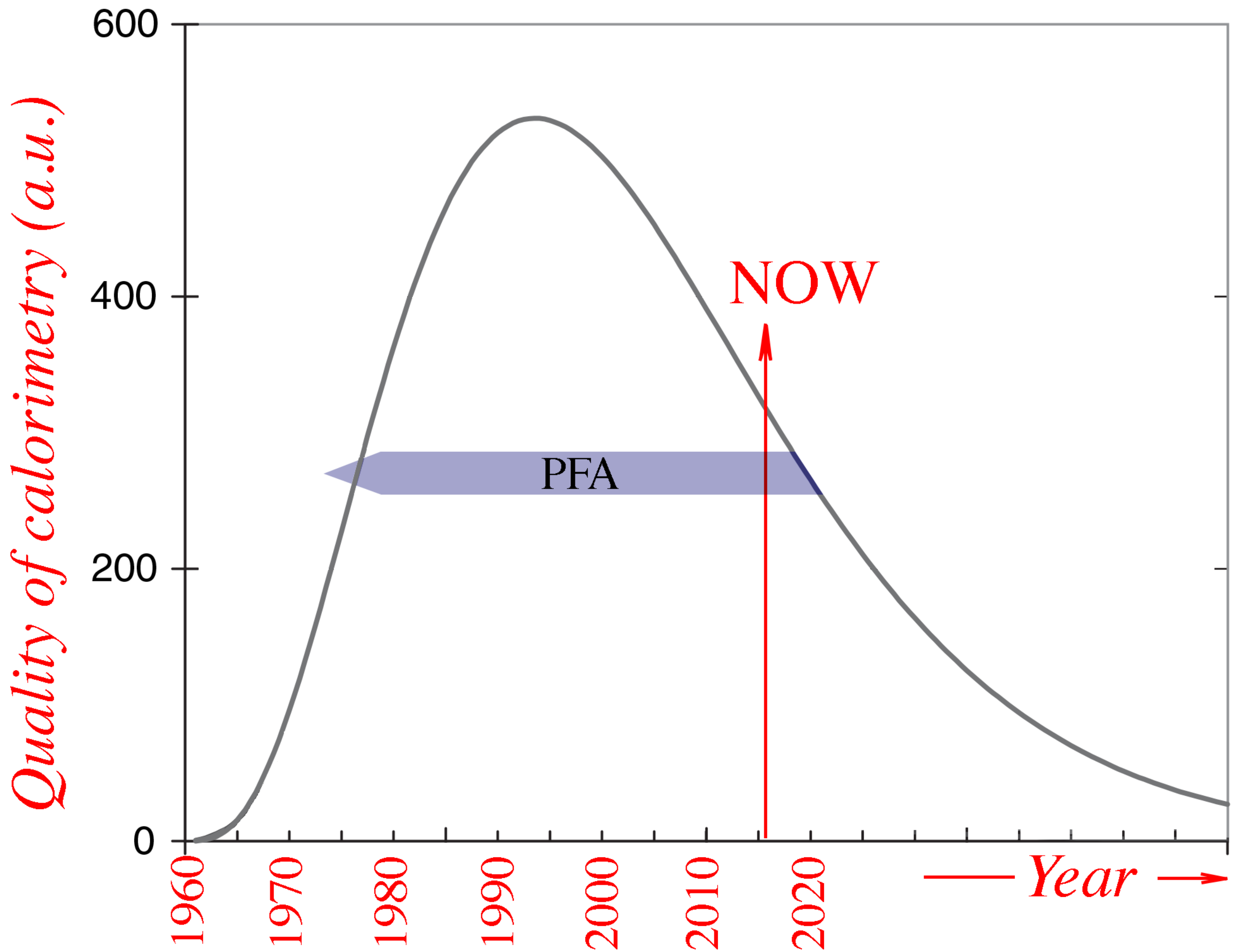
- *No funding available for generic R&D*
- *Ignorance, misconceptions + lack of interest for crucial issues*
- *Belief that all problems can be solved with technology (W, Si, RPC)*

$\Longrightarrow$ *The future looks bleak (imho)*

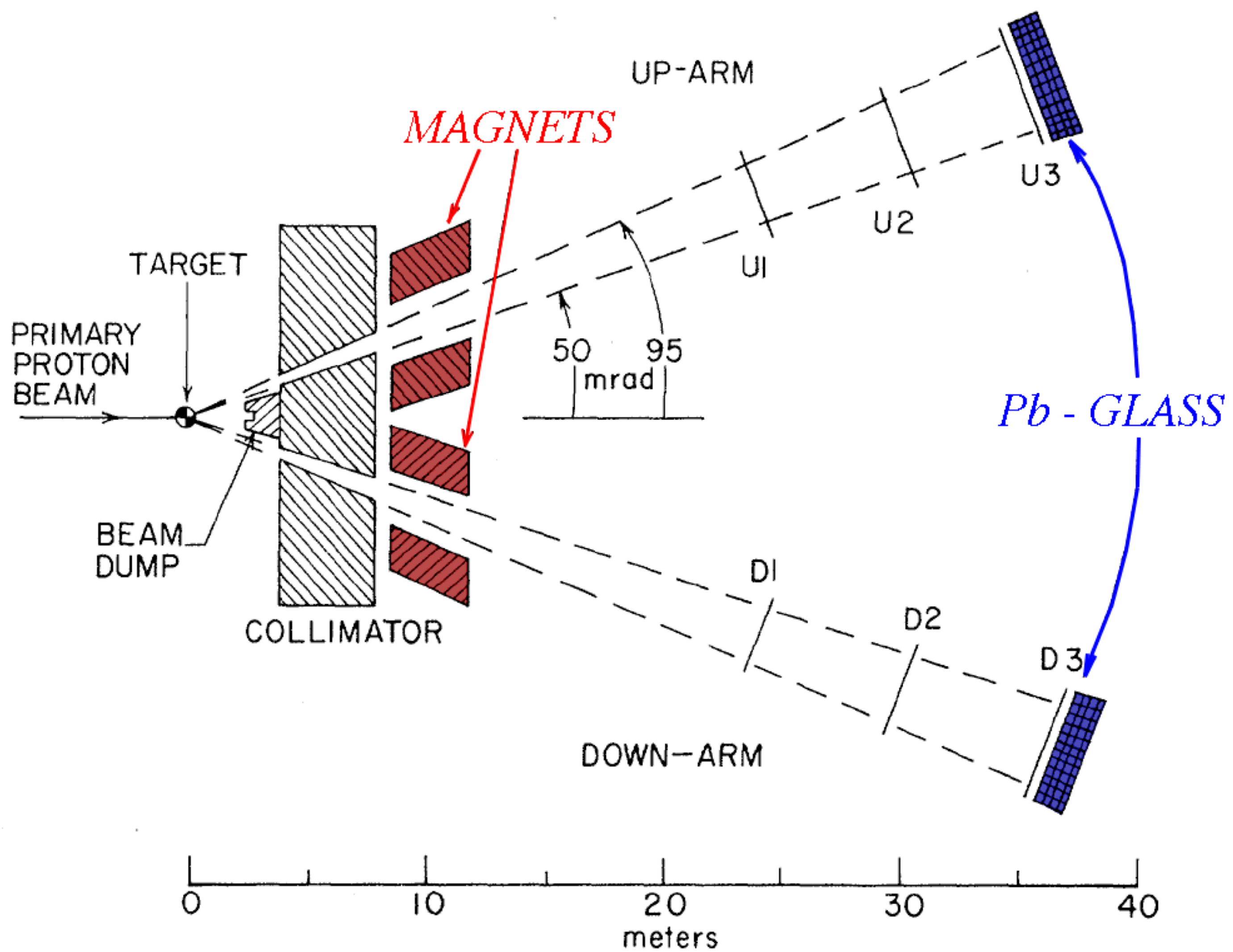
Where do we go from here?



The future of calorimetry in HEP experiments



1970s - Shower counters in magnetic spectrometers



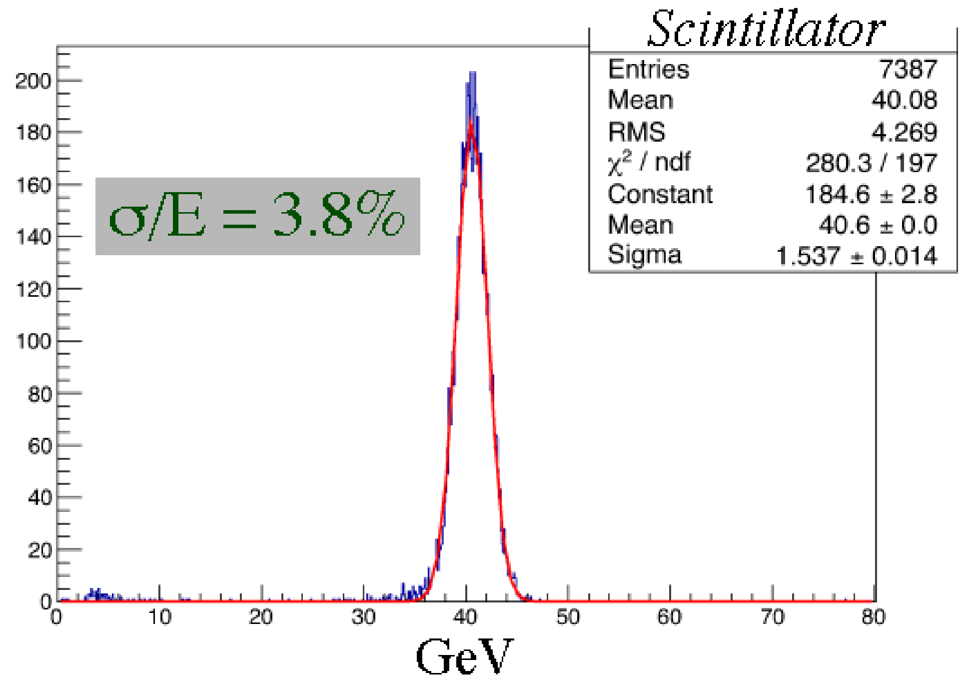
However, in modern 4π experiments the showers start after < 2m, instead of 40m

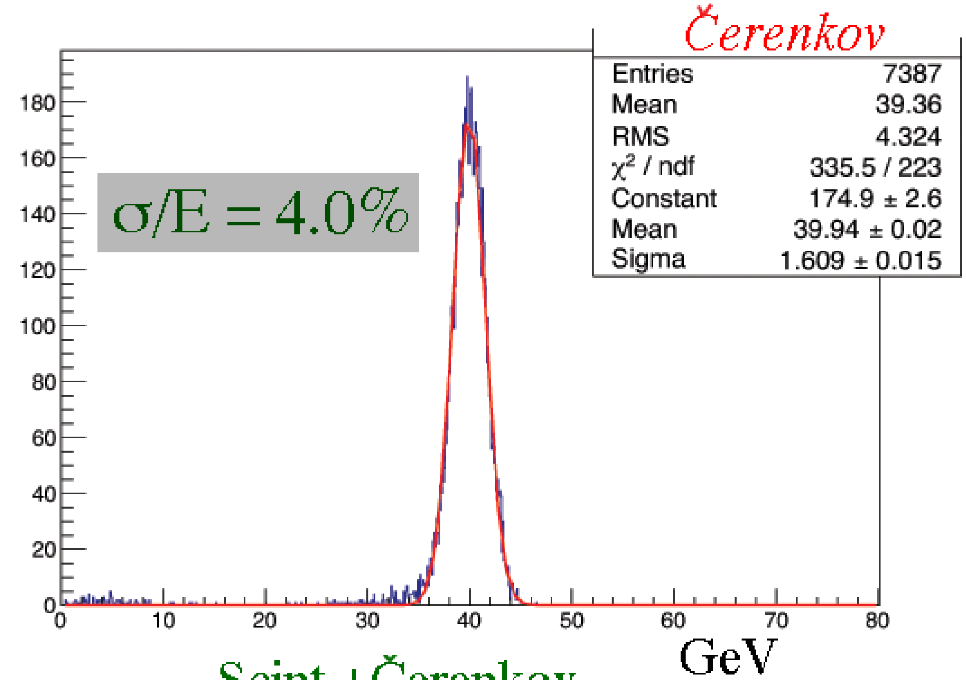
Conclusions

- *In the past 30 years, calorimeters have become the heart and soul of almost any experiment in particle physics, for good reasons*
- *Electromagnetic calorimeters have become precision tools, in stark contrast with hadron calorimeters*
- *The quality of hadron calorimeters has decreased in the last 20 years, partly because of the lack of meaningful MC simulations.*
- *In longitudinally segmented calorimeters, the problem of the jet energy scale may be fundamentally unsolvable, especially when different segments have (very) different e/h values*
  In general: Longitudinal segmentation = asking for (calibration) trouble
- *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

S and Č signals sample the showers independently
Resolution improves by combining





40 GeV electrons
Cu-fiber calorimeter

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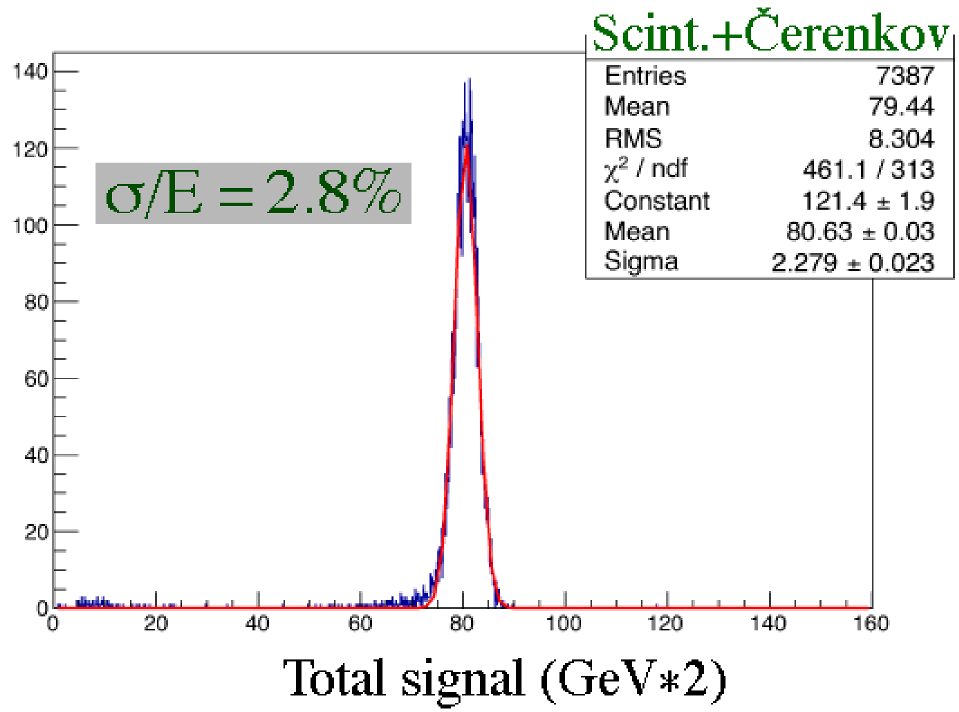
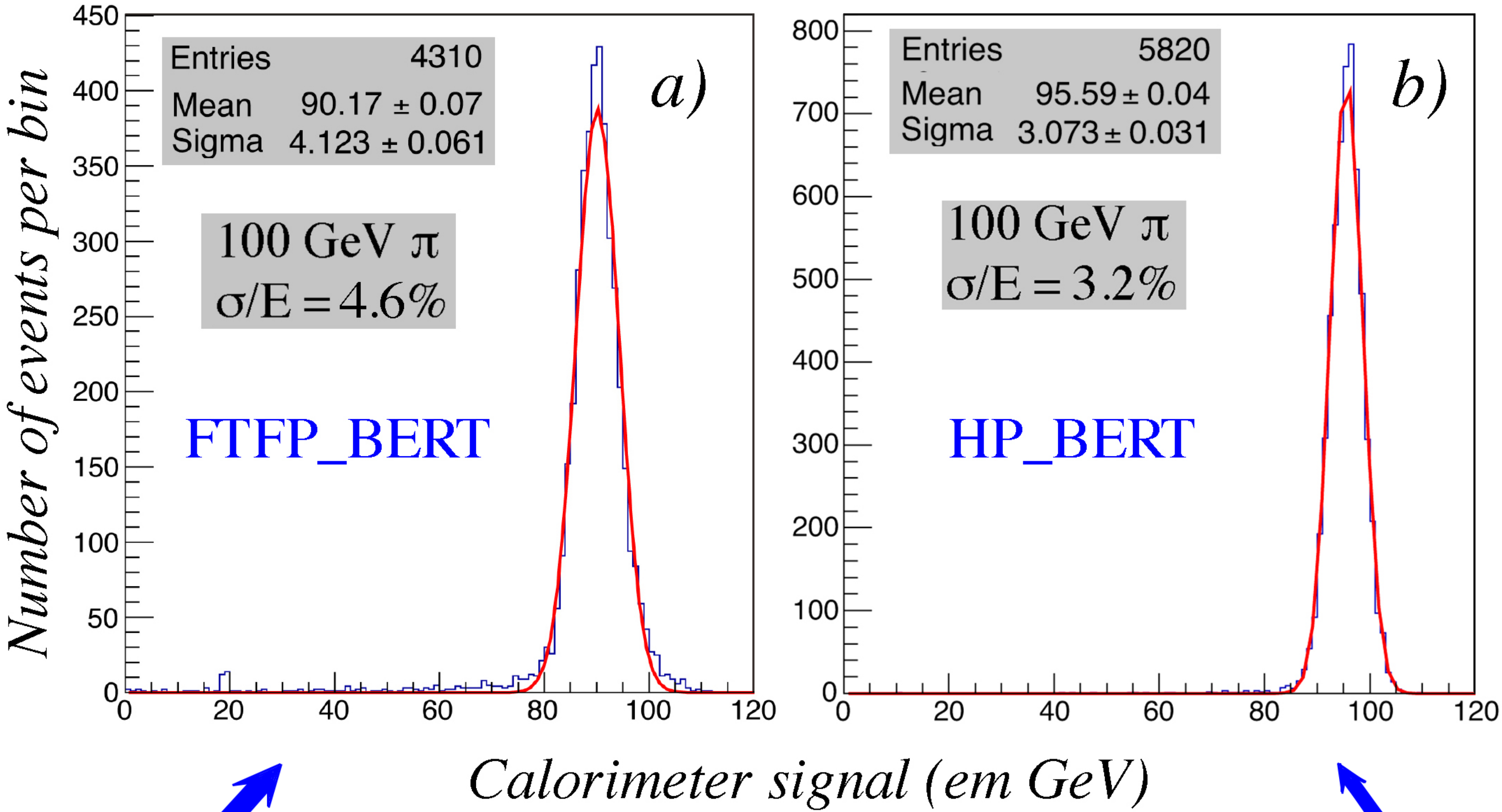


GEANT4 simulations of 100 GeV π

RD52_Cu 65 x 65 cm^2



Standard hadronic shower simulation package

High precision simulation package (neutrons!!)

The energy resolution of compensating calorimeters is dominated by sampling fluctuations

$$\sigma/E = a_{\text{samp}}/\sqrt{E}$$

Published results a_{samp} (%):

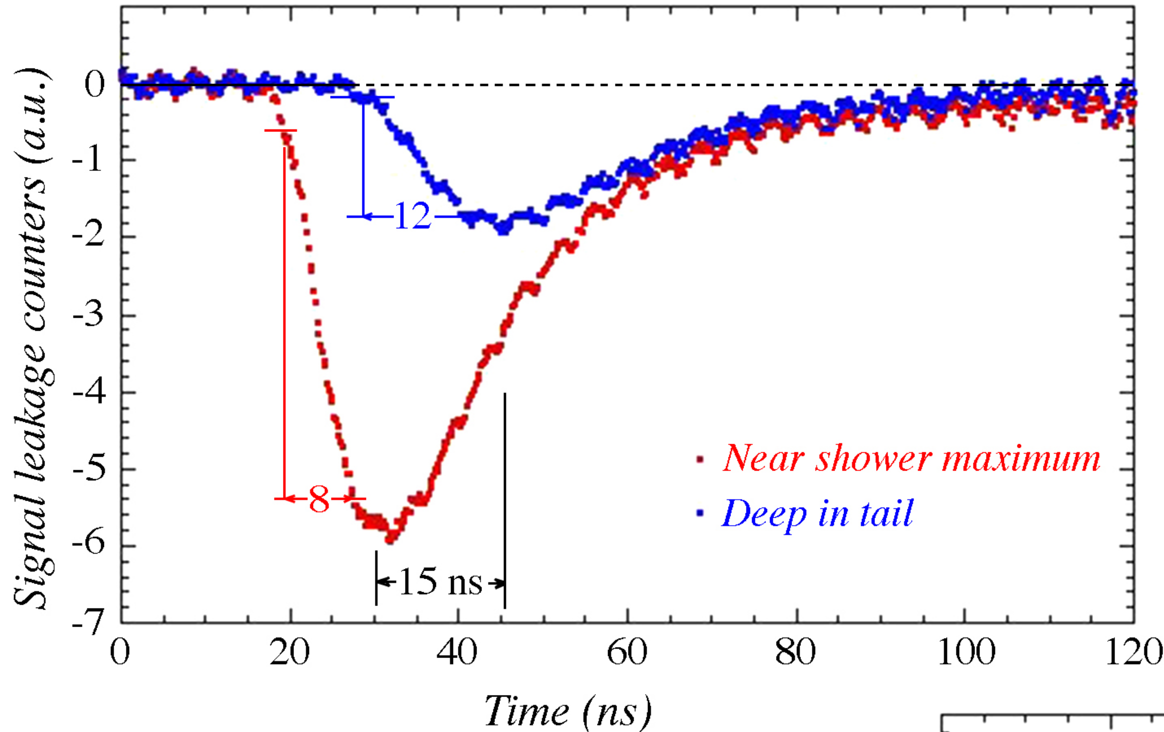
Experiment	Structure	em resolution	hadr. resolution
HELIOS	U/plastic plates	19 - 22	34 - 39
ZEUS	U/plastic plates	16.5	31.1
SPACAL	Pb/fibers	12.9	30.6
ZEUS	Pb/plastic plates	23.5	41.2
RD52	Cu/fibers	8.9 (13.9)	?

8.9: sampling

(13.9): total (incl Č p.e.)

?: GEANT: 32

Comparison signal shapes leakage counters

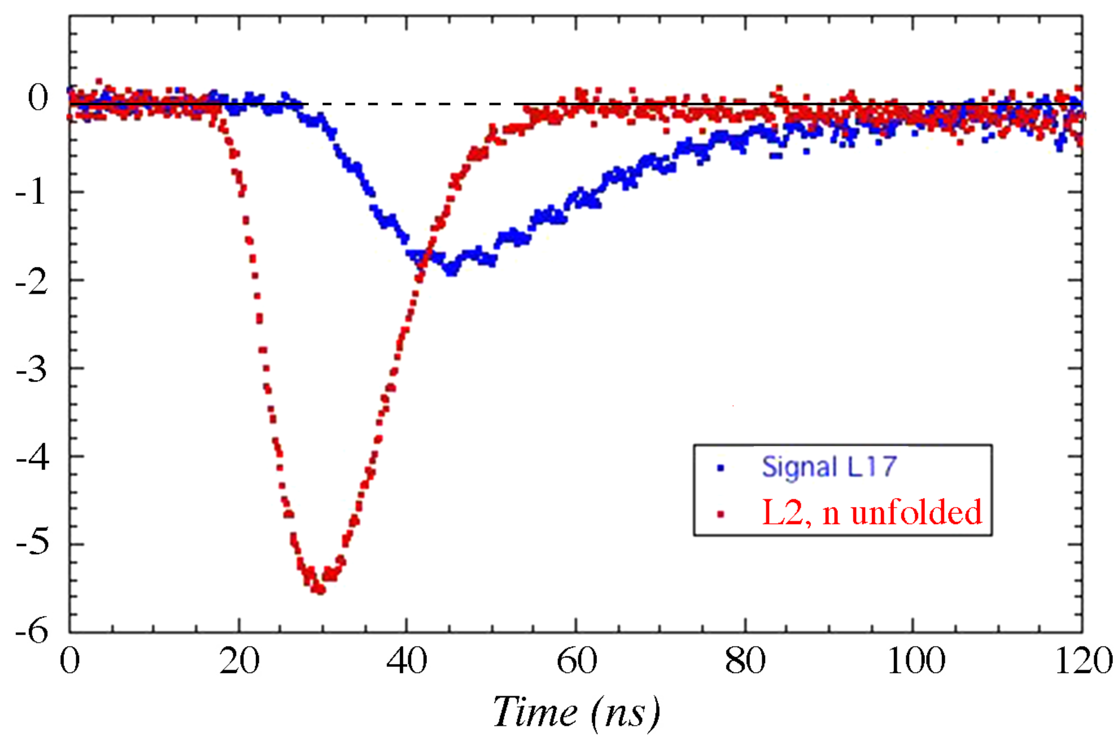


Expected signal contributions:

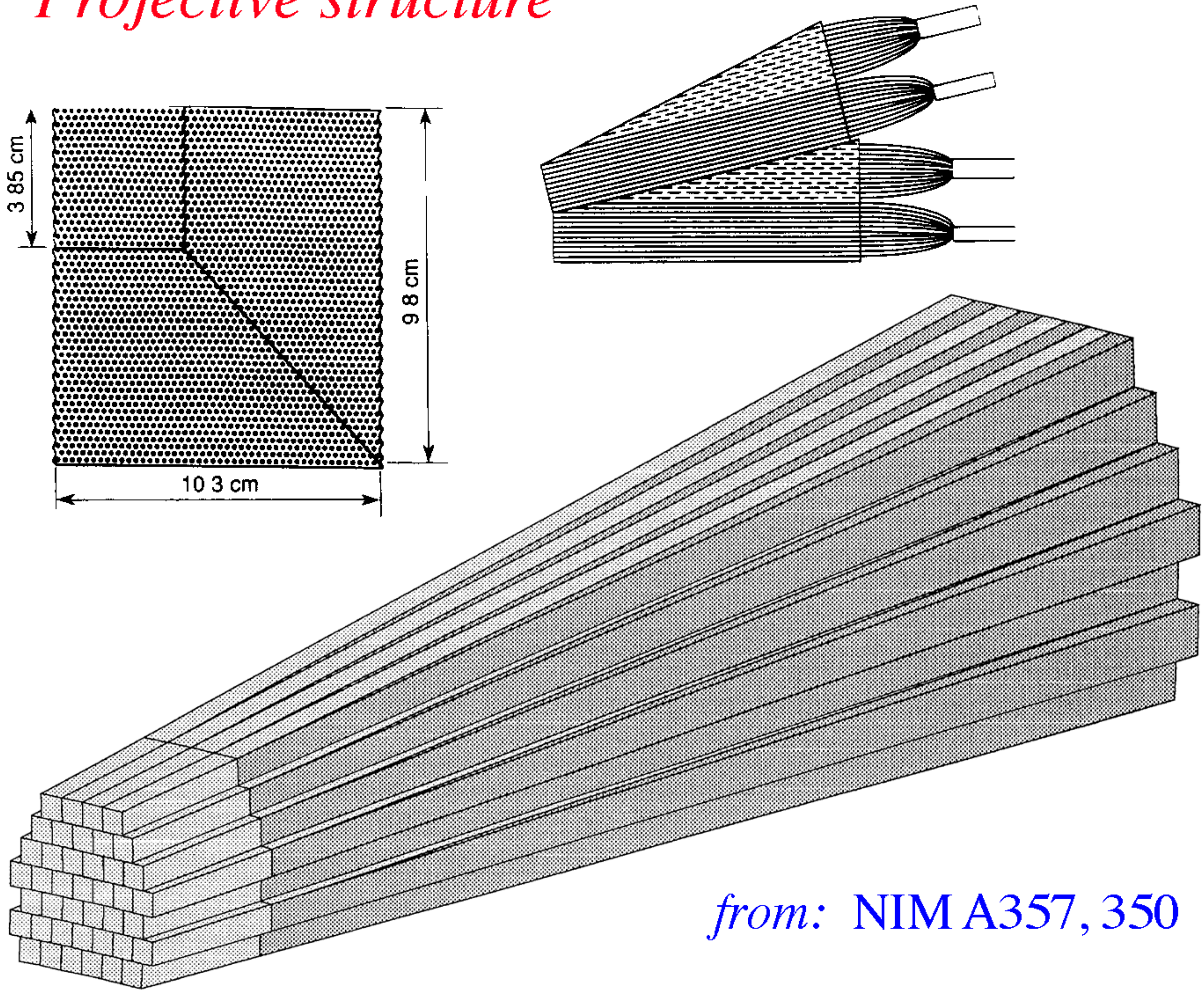
- prompt charged shower particles

- n + p → n + p
(time constant 10 - 20 ns)

n contribution unfolded



Projective structure



from: NIM A357, 350