(HADRON) CALORIMETRY OPTIONS
for future experiments in particle physics

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Trends & Challenges
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Decisions about the future require a good understanding of the past

Outline:

- *A brief history (50 years) of calorimetry*
- *The future: A dream or a nightmare?*
- *Conclusions*

A brief history of calorimetry (used as a particle detection technique)

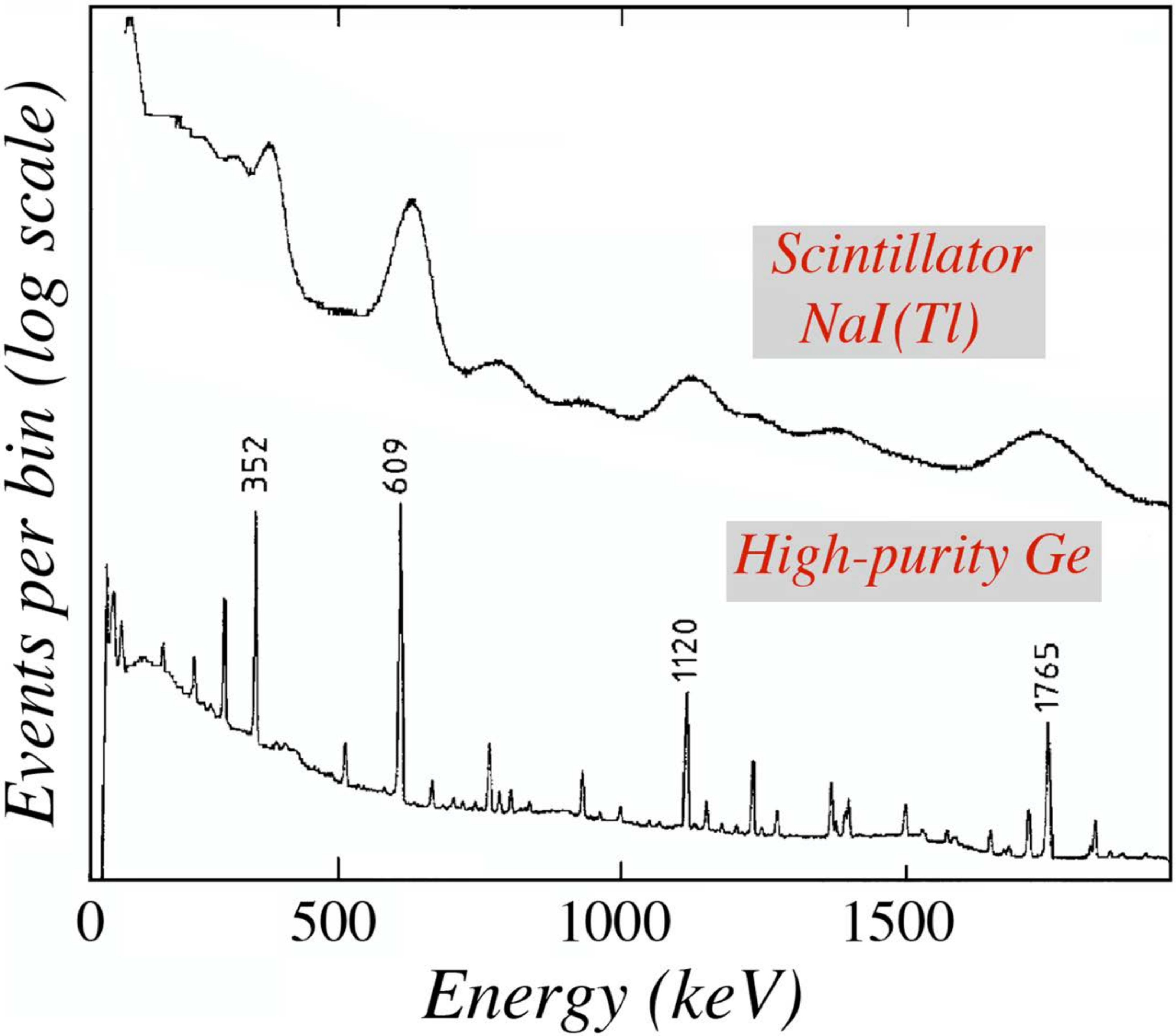
- *In the 1960s, particle physics started to make the transition from the bubble chamber era to experiments based on electronic counters*

- *The detectors basically formed a magnetic spectrometer, in which all charged particles produced in reactions on a fixed target were analyzed:*
  Momentum from effects Lorentz force
  Energy (mass) from time-of-flight or dE/dx

- *For the detection of the neutral reaction products (overwhelmingly γs from π° decay), one used scintillating crystals, developed in the 1950s for nuclear spectroscopy, and called these "shower counters"*

- *Using properly chosen materials (high Z!), even very-high-energy γs can be fully absorbed in detectors of limited length (<30 cm), and be measured with spectacularly good energy resolution*

The importance of good energy resolution

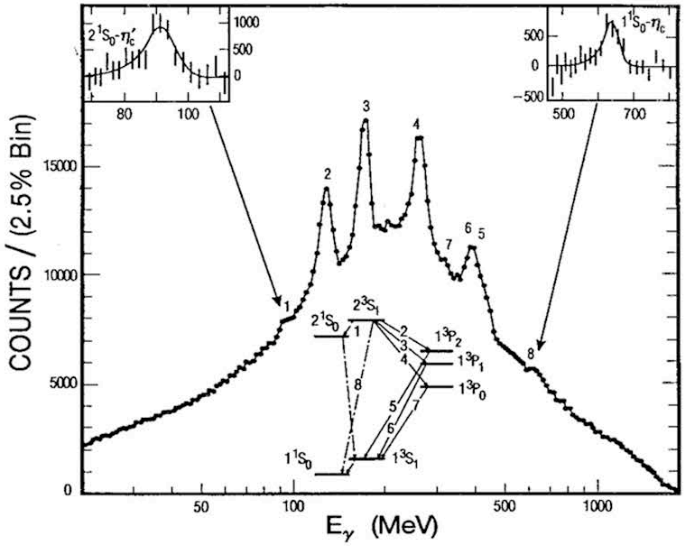


A brief history of calorimetry (2)

- *To save money, large calorimeters were built as sampling devices (functions of absorption and signal generation carried out by different materials).*
- *For active material, one originally used plastic scintillator plates or wire chambers. Later, liquid argon or krypton, scintillating fibers and semiconductor pads were introduced as active material*
  Typically, lead was used as absorber material (short radiation length)
- *Some of these devices also achieved sub-1% energy resolutions for e,γ*
  Examples: NA48 (Pb-LKr), KLOE (Pb-fibers)
- *Other particles also generated signals in these calorimeters.*
  However, the energy resolution was considerably worse
  Even at the highest energies, resolutions better than 10% were hard to achieve. Worse, the detectors were non-linear, and the response also depended on the type of particle (pion, proton)

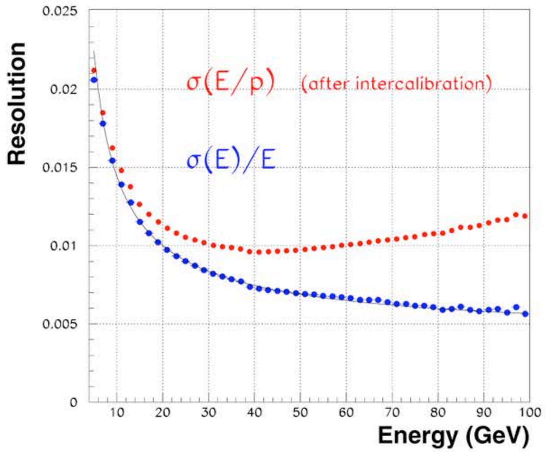
Electromagnetic shower detection in Particle Physics

SPEAR: NaI(Tl) crystals



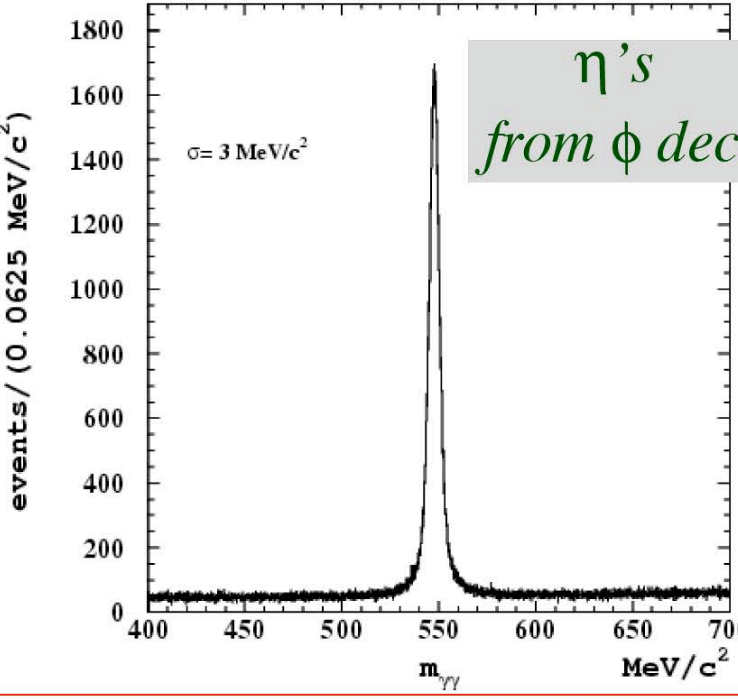
Charmonium spectroscopy (e^+e^-)

NA48 (CP violation in K^0)
LKr calorimeter



KLOE @
DAPHNE
(ϕ factory)

Pb-scifi
calorimeter



η's
from ϕ decay

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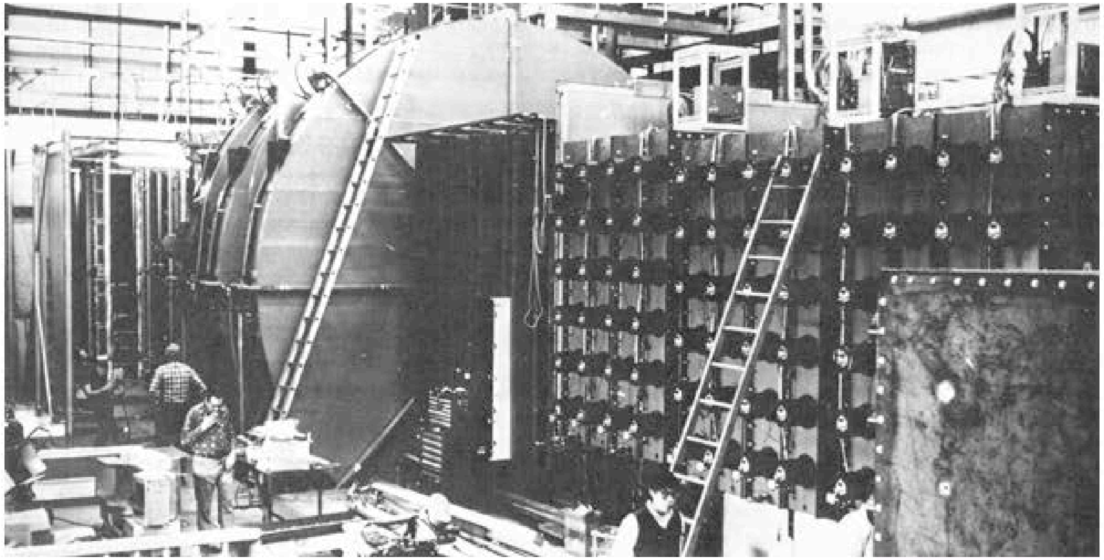
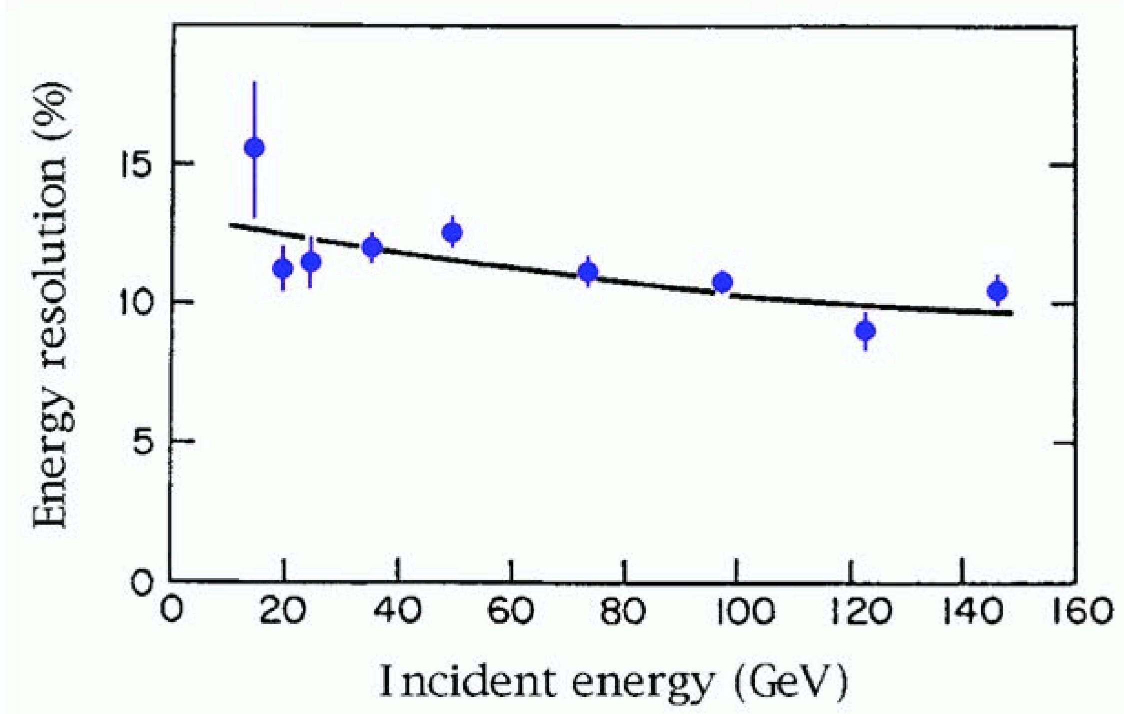
Energy resolution of a homogeneous hadron calorimeter

(60 tonnes of liquid scintillator)





From: NIM 125 (1975) 447

A brief history of calorimetry (3)

- *In the 1970s, calorimeters took on new tasks.*

  → *High-energy neutrino experiments: Target + trigger (total energy)*
  → *Collider experiments (ISR, PETRA): Energy flow (missing E_T , jets)*
  → *General: Particle ID (e,γ,μ,ν)*

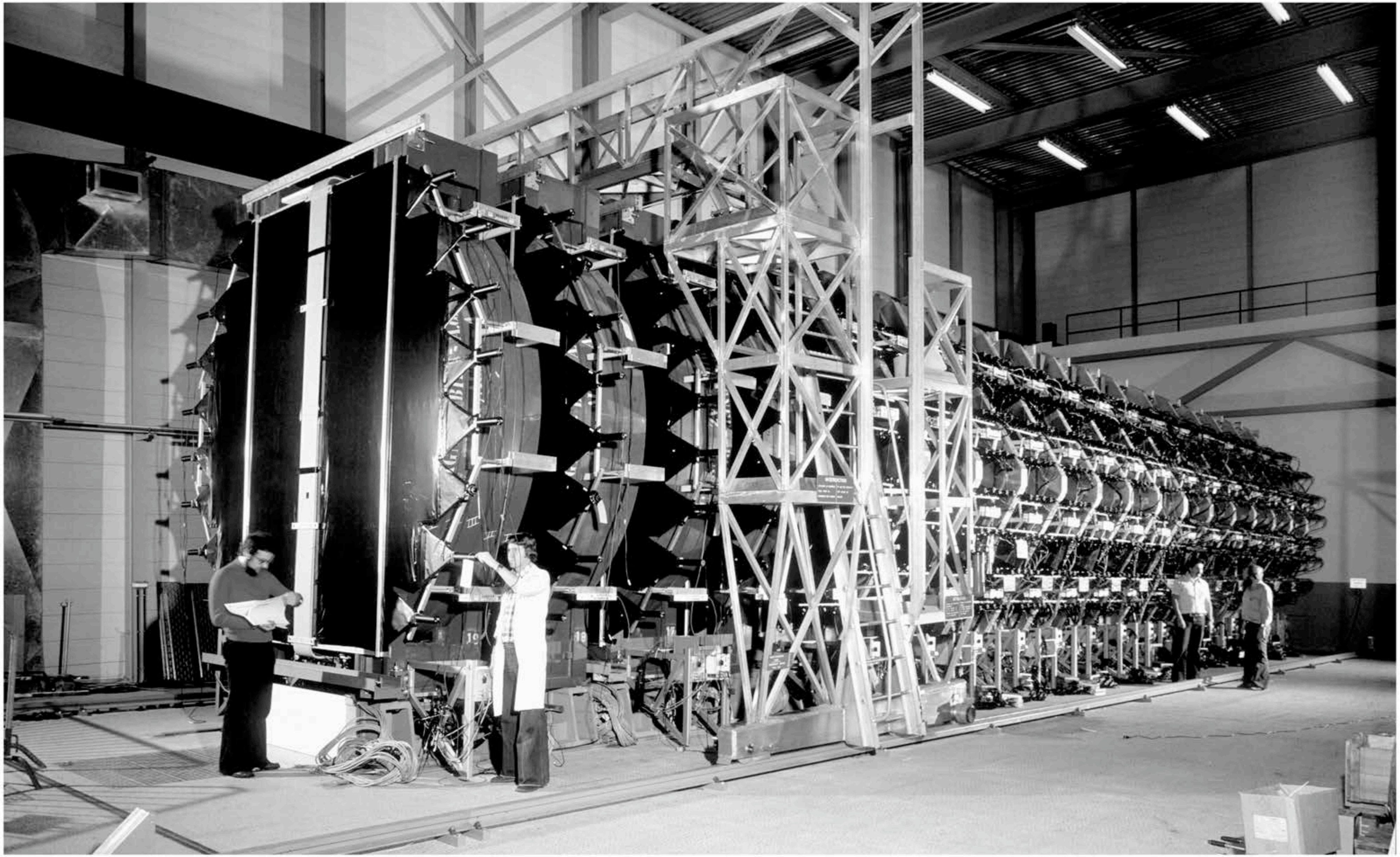
- *Calorimeters turned out to be extremely suitable for such tasks. This is the main reason why they have become the central component of any detector system at accelerator based HEP experiments*

- *However, detailed understanding of the hadronic calorimeter performance was still lacking. Monte Carlo simulations provided little or no guidance.*

- *In many experiments, good hadronic performance was not considered a top priority. Detector choice was therefore determined by other considerations (money, radiation hardness, personal hobbyism .....)*

The WA1 neutrino experiment (1976)

(integrated target, calorimeter, tracker)



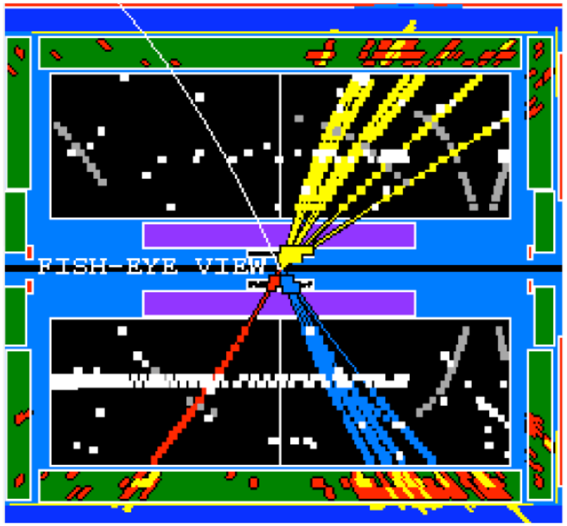
Example of energy flow information

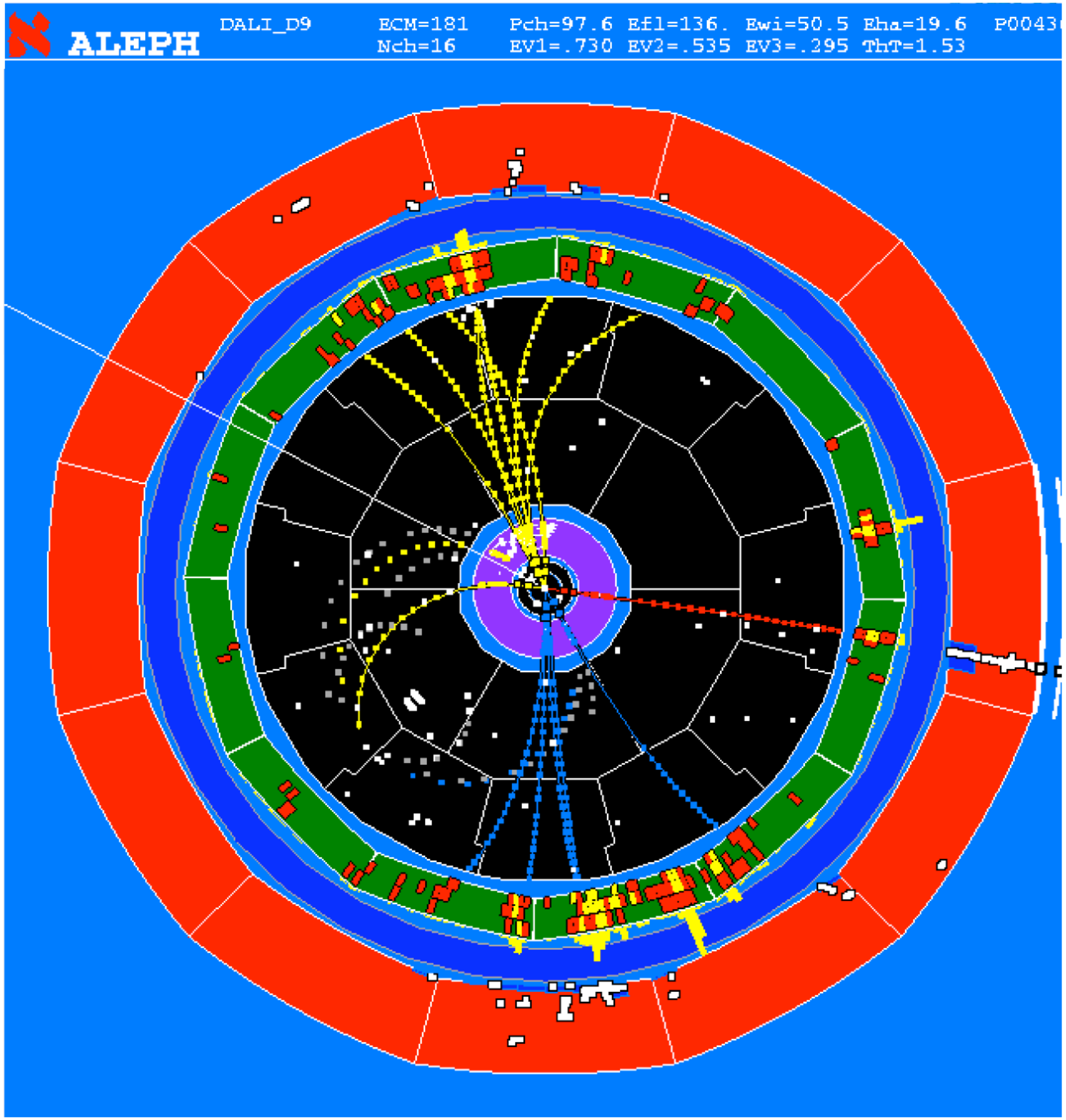
$e^+e^- \rightarrow W^+W^-$
$(\sqrt{s} = 181\ \mathrm{GeV})$

$WW \rightarrow qq\mu\nu_\mu$

In final state:

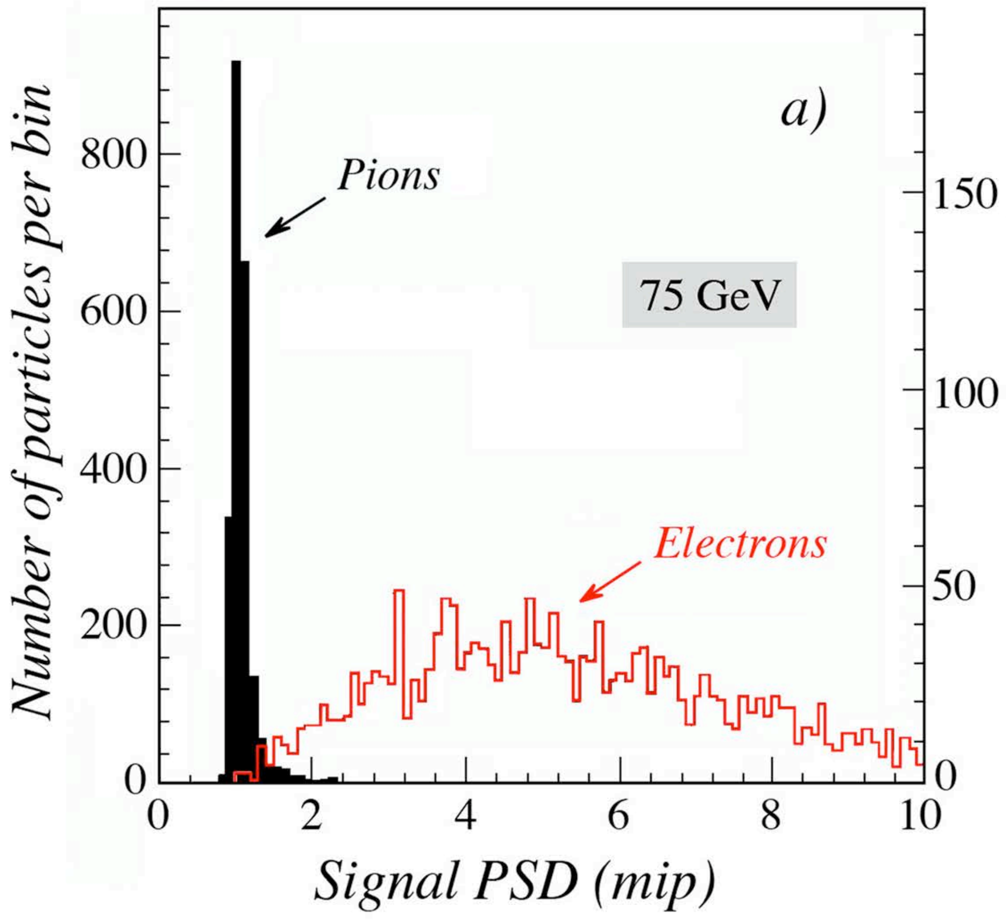
2 hadronic jets
1 energetic muon
missing $E_T\ (\nu_\mu)$



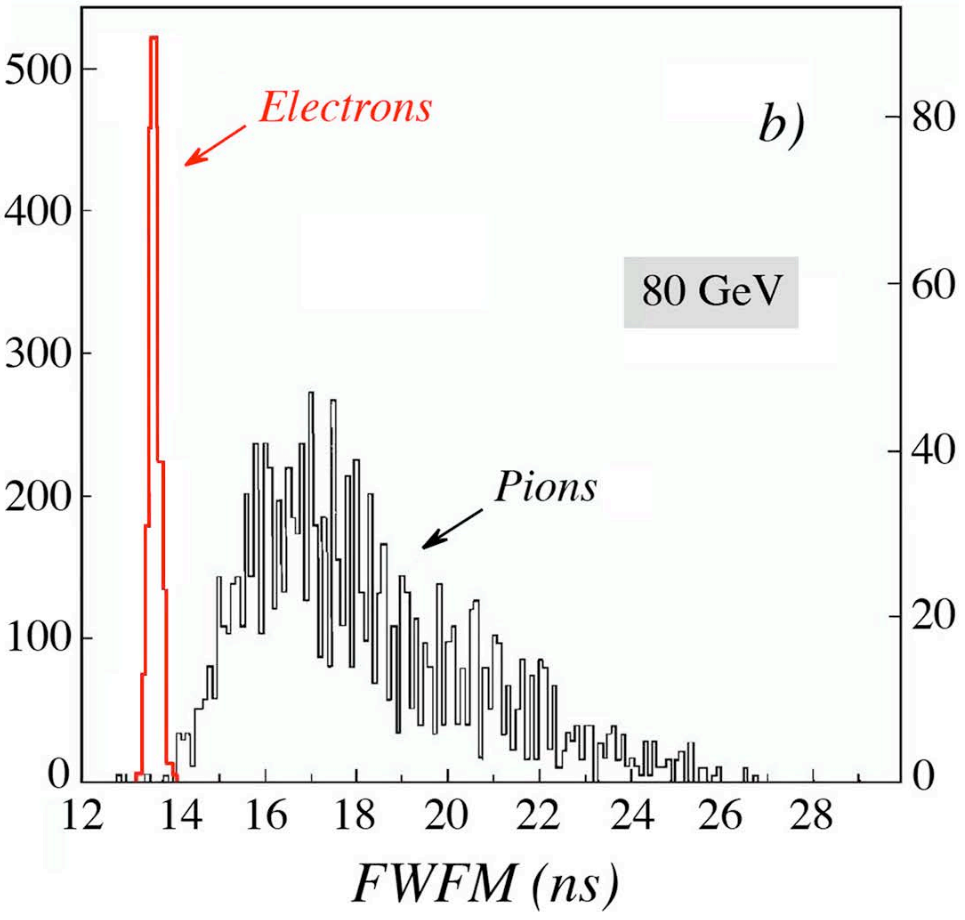


Particle identification with calorimeters

Using shower profile (pre-shower detector)



Using time structure of the signals



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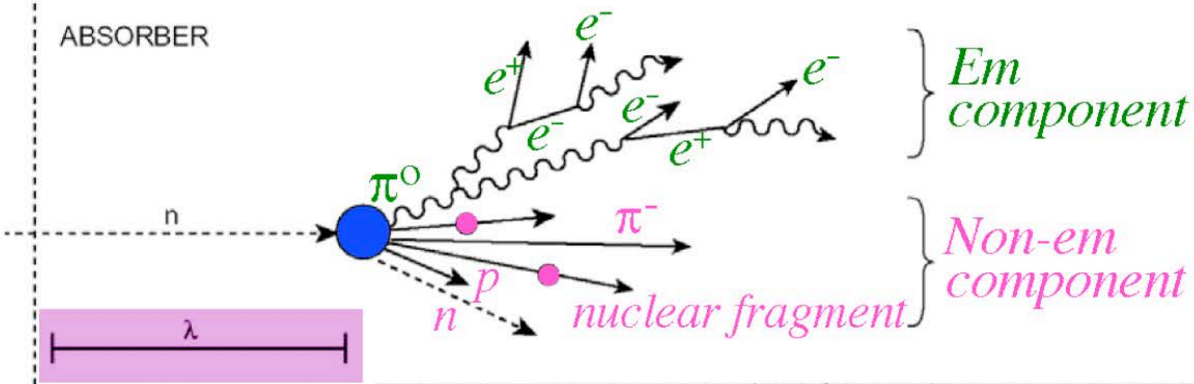
A brief history of calorimetry (4)

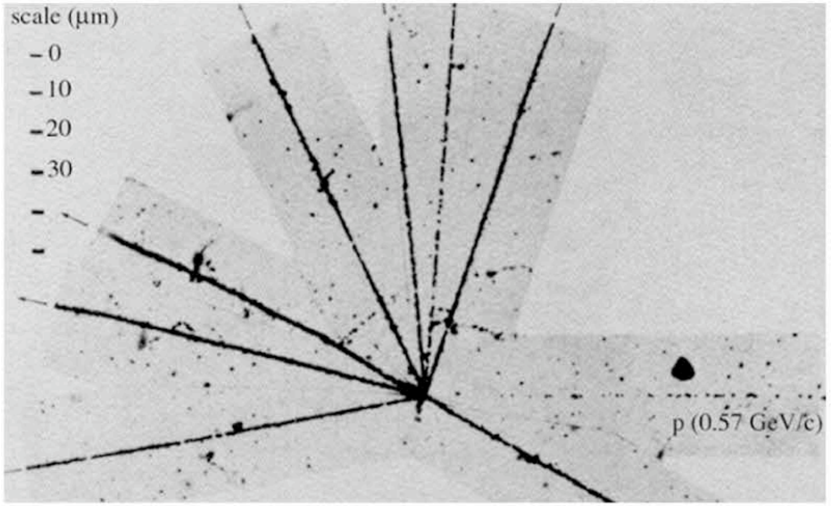
- *Since ~1985, separate efforts have been undertaken to understand (and thus improve!) the performance of hadron calorimeters, both experimentally and at the Monte Carlo level*
- *What has been learned in this respect is almost entirely due to experimental efforts*
- *MC simulations are still not in a state in which they can be considered a useful tool for design and optimization of detectors*
- *As a result, the development of calorimeters for the LHC experiments has proceeded without meaningful guidance from MC simulations.*
  And the experiments pay the price for that.

The physics of hadronic shower development

- *A hadronic shower consists of two components*



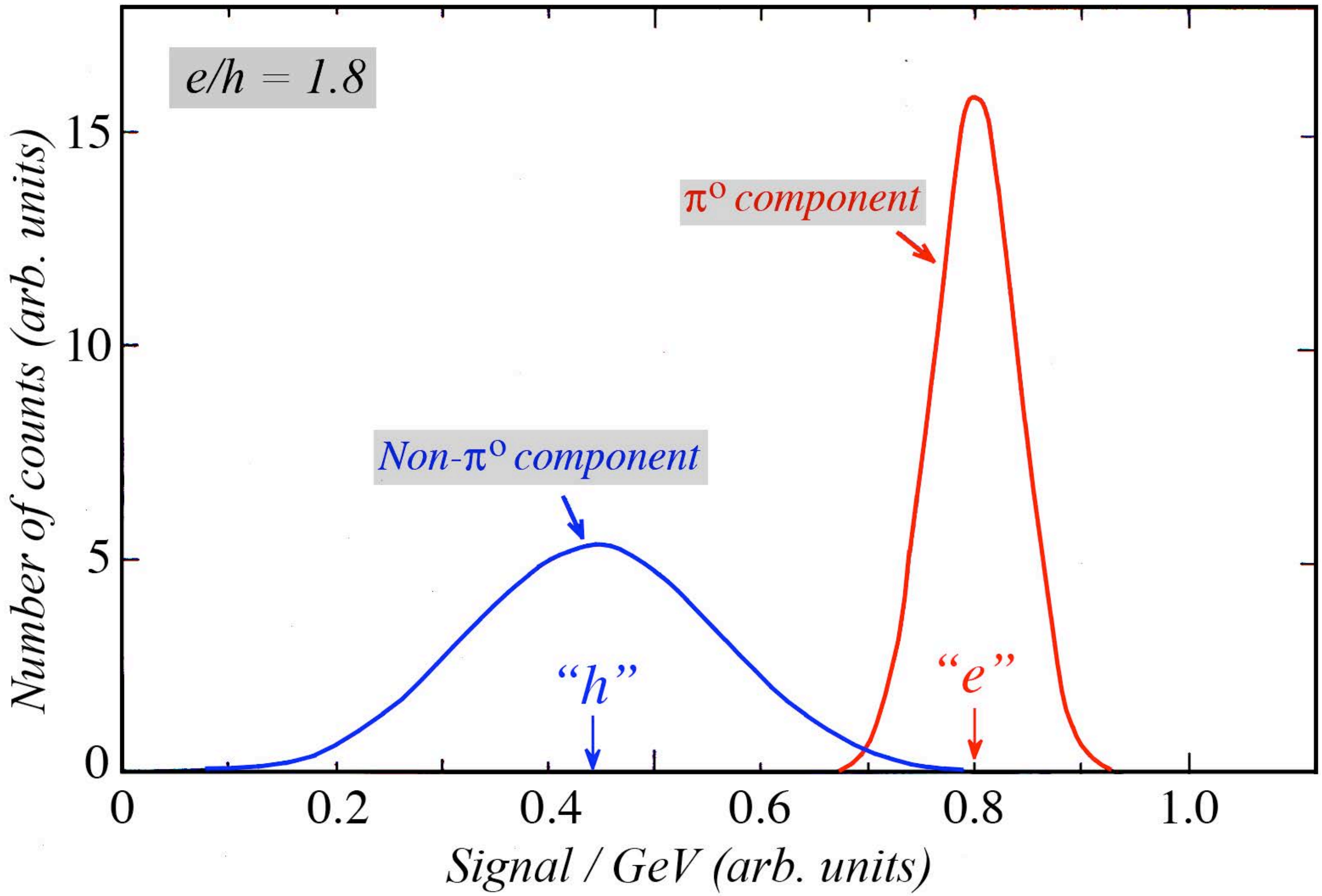
- *Electromagnetic component*
  - electrons, photons
  - neutral pions → 2 γ
- *Hadronic (non-em) component*
  - charged hadrons $\pi^\pm$,$K^\pm$ (20%)
  - nuclear fragments, p (25%)
  - neutrons, soft γ's (15%)
  - break-up of nuclei *("invisible")* (40%)



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

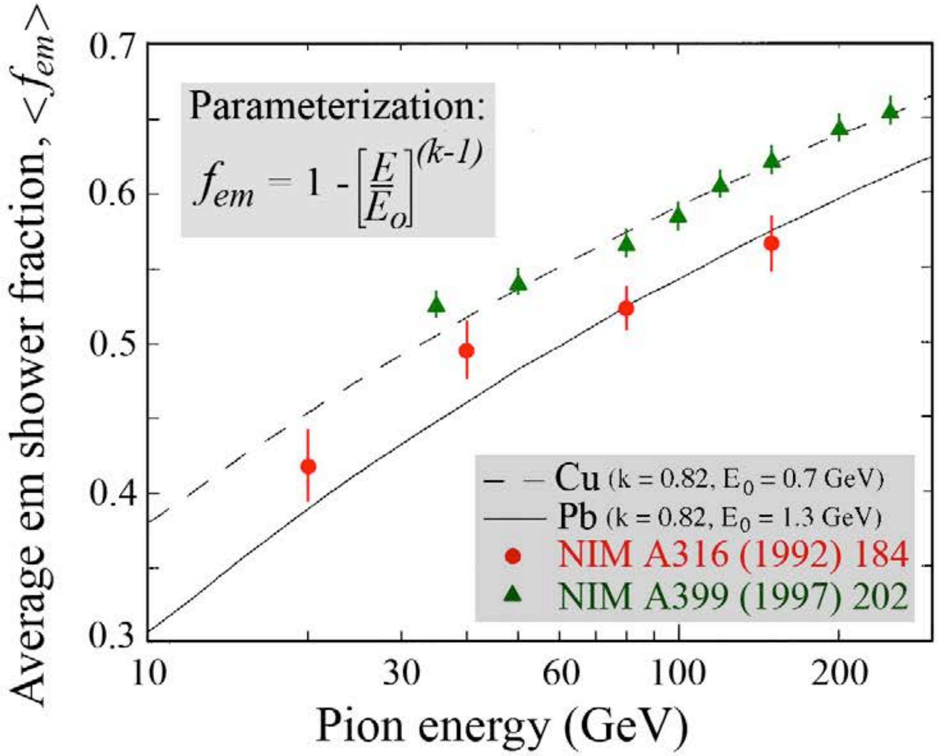
The calorimeter response to the two shower components is NOT the same

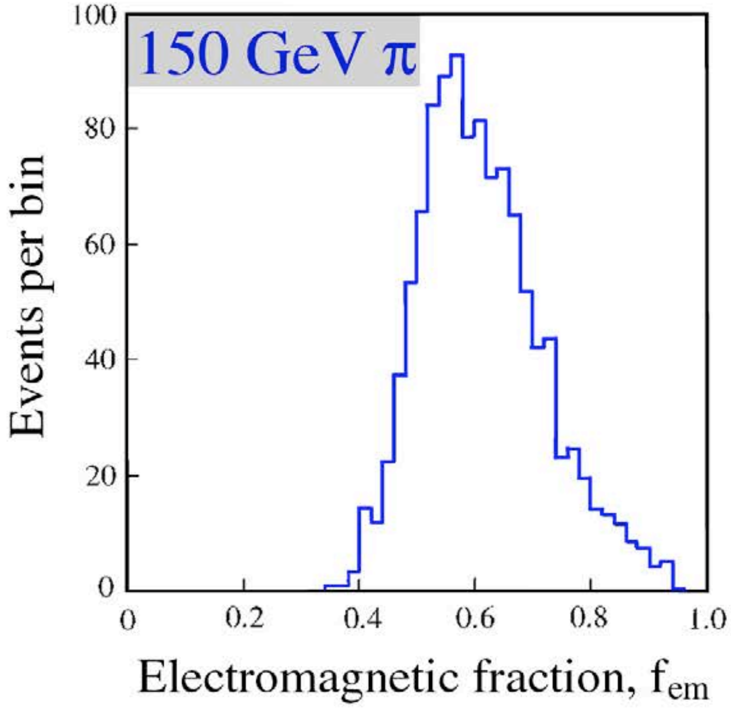
(mainly because of nuclear breakup energy losses in non-π° component)



(Fluctuations in) the electromagnetic shower fraction, f_{em}

i.e. the fraction of the shower energy deposited by π^os





The em fraction is, on average,
large and energy dependent

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

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*
  - *$<f_{em}>$ 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 ~ 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

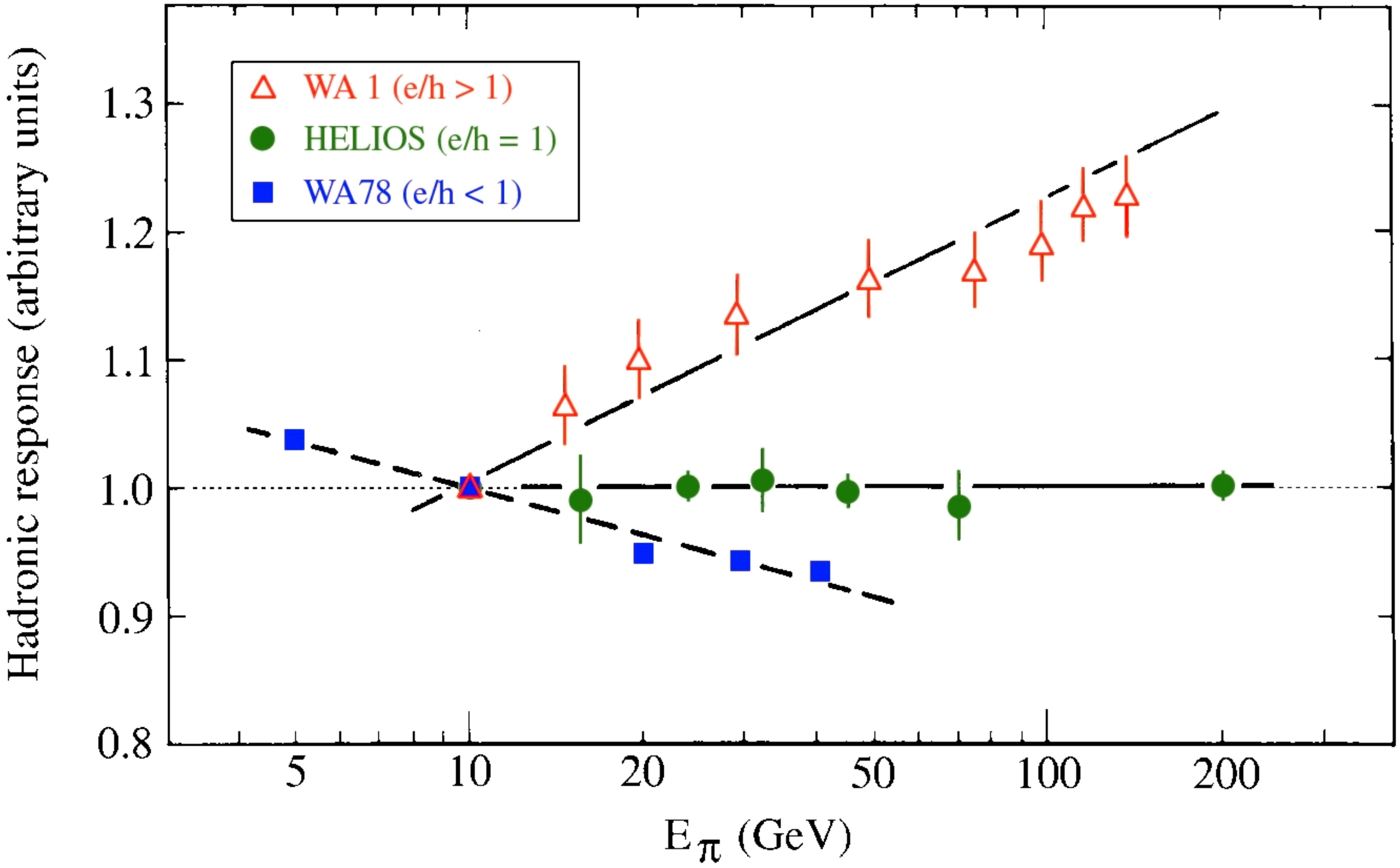
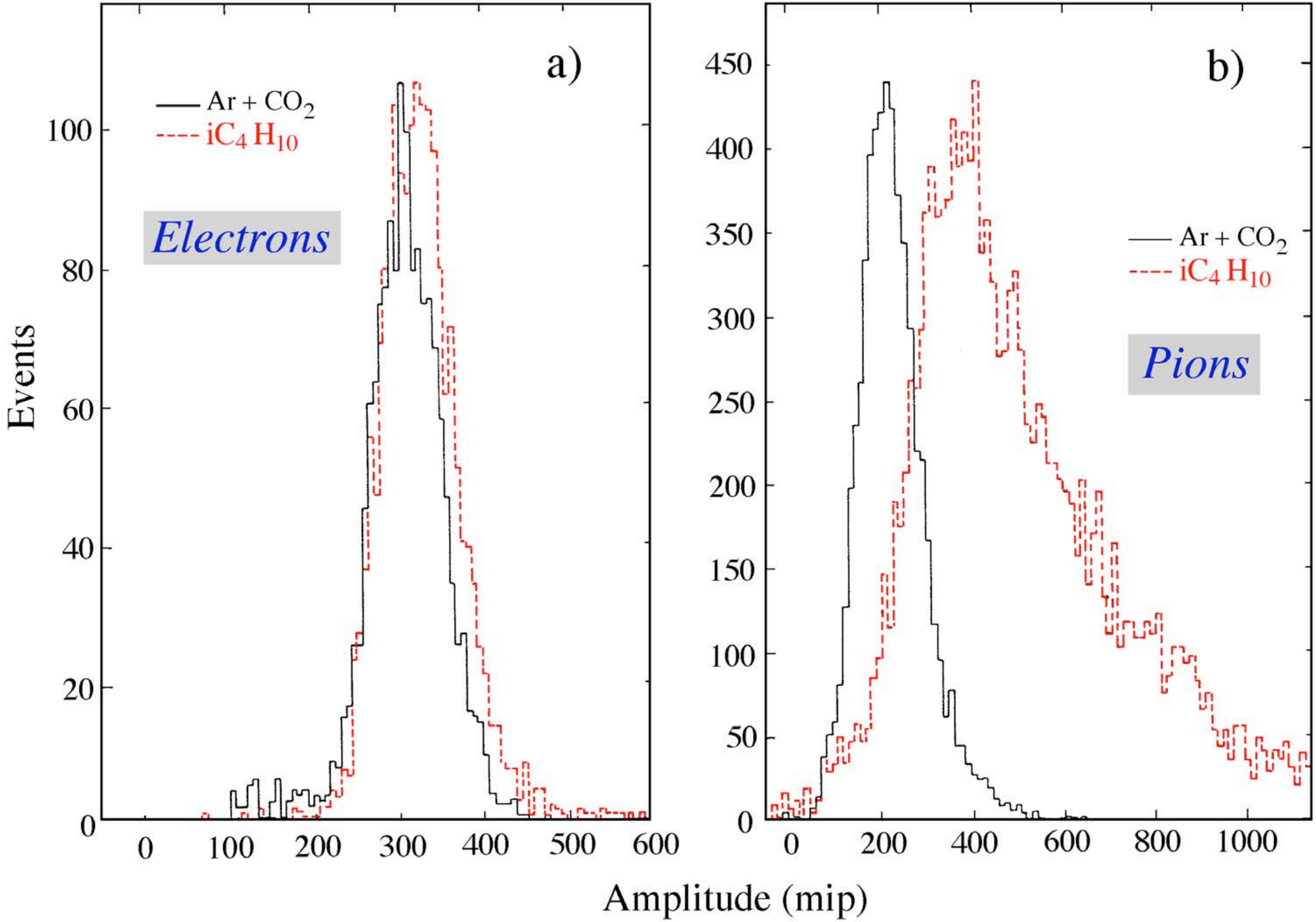


FIG. 3.14. The response to pions as a function of energy for three calorimeters with different e/h values: the WA1 calorimeter ($e/h > 1$, [Abr 81]), the HELIOS calorimeter ($e/h \approx 1$, [Ake 87]) and the WA78 calorimeter ($e/h < 1$, [Dev 86, Cat 87]). All data are normalized to the results for 10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

Compensation and energy resolution in L3 hadron calorimeter



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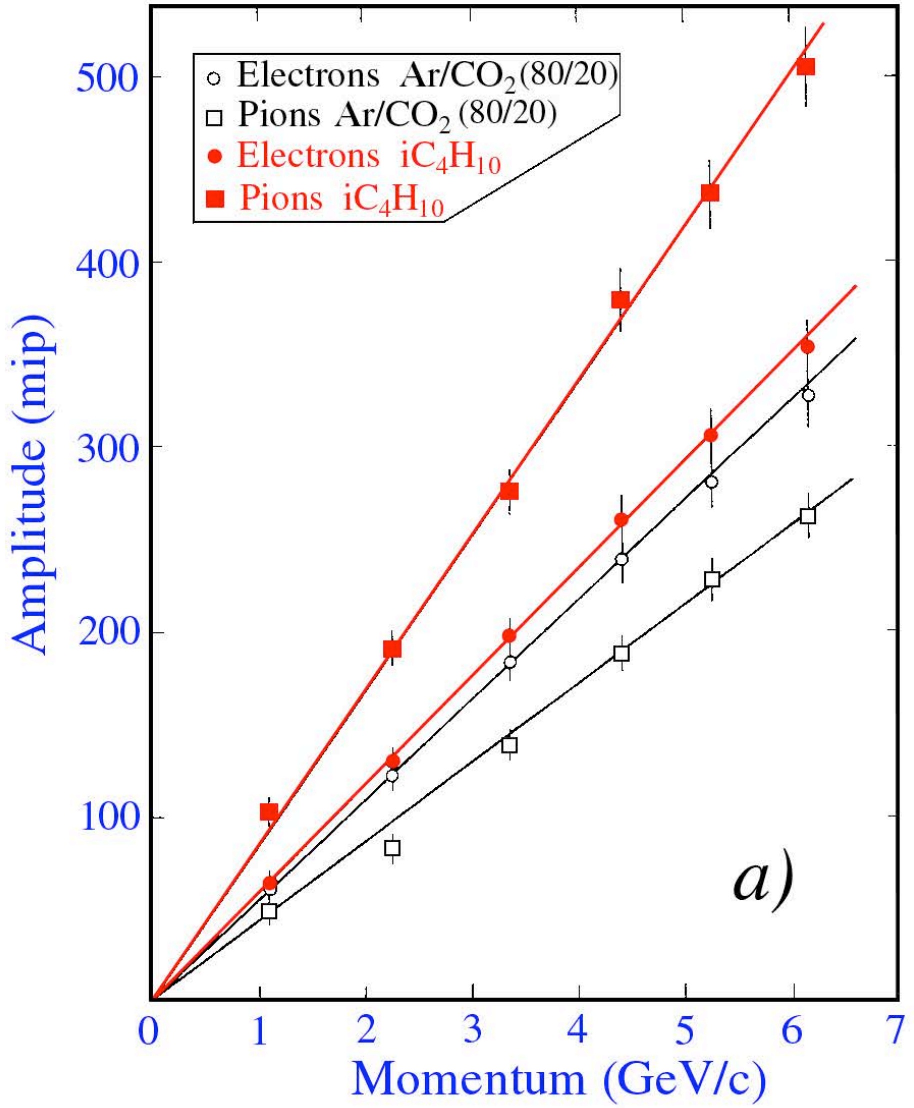
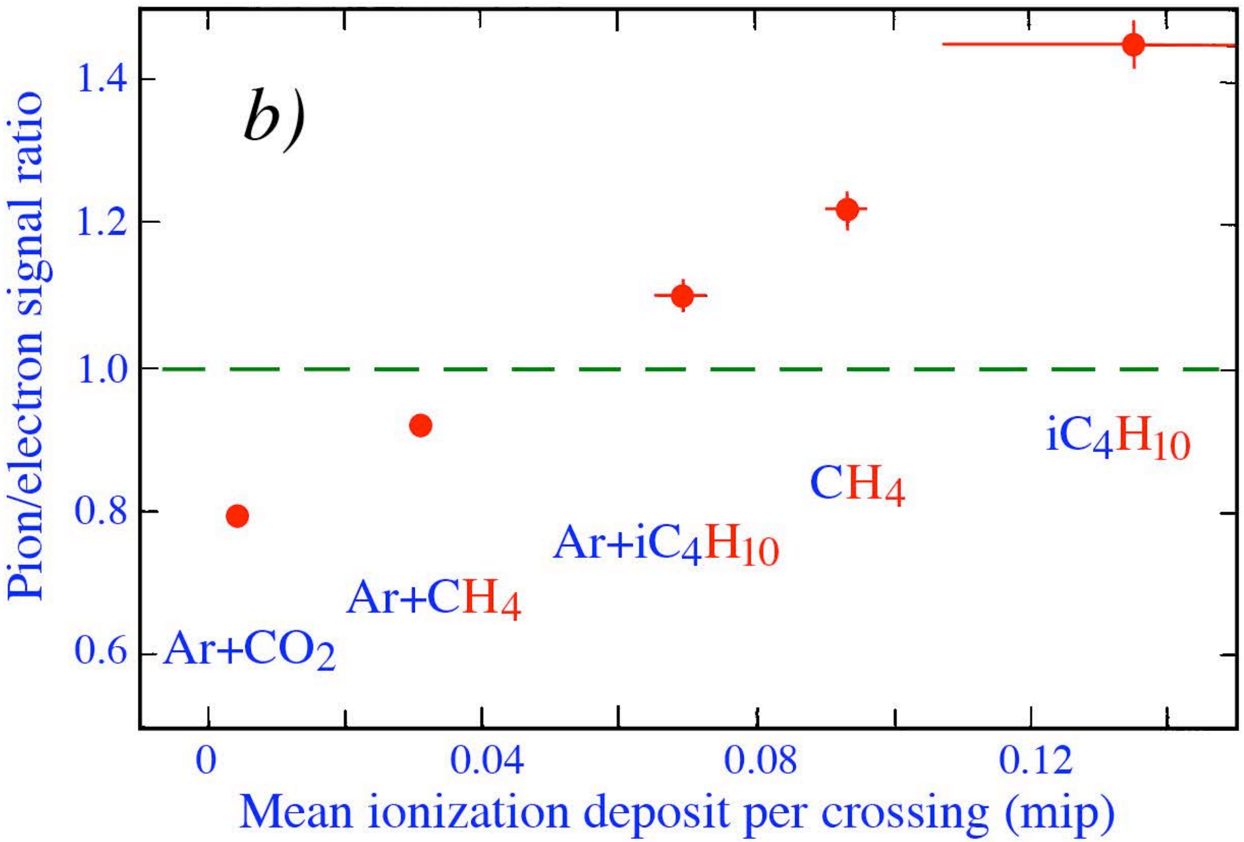
The compensation puzzle solved!

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.

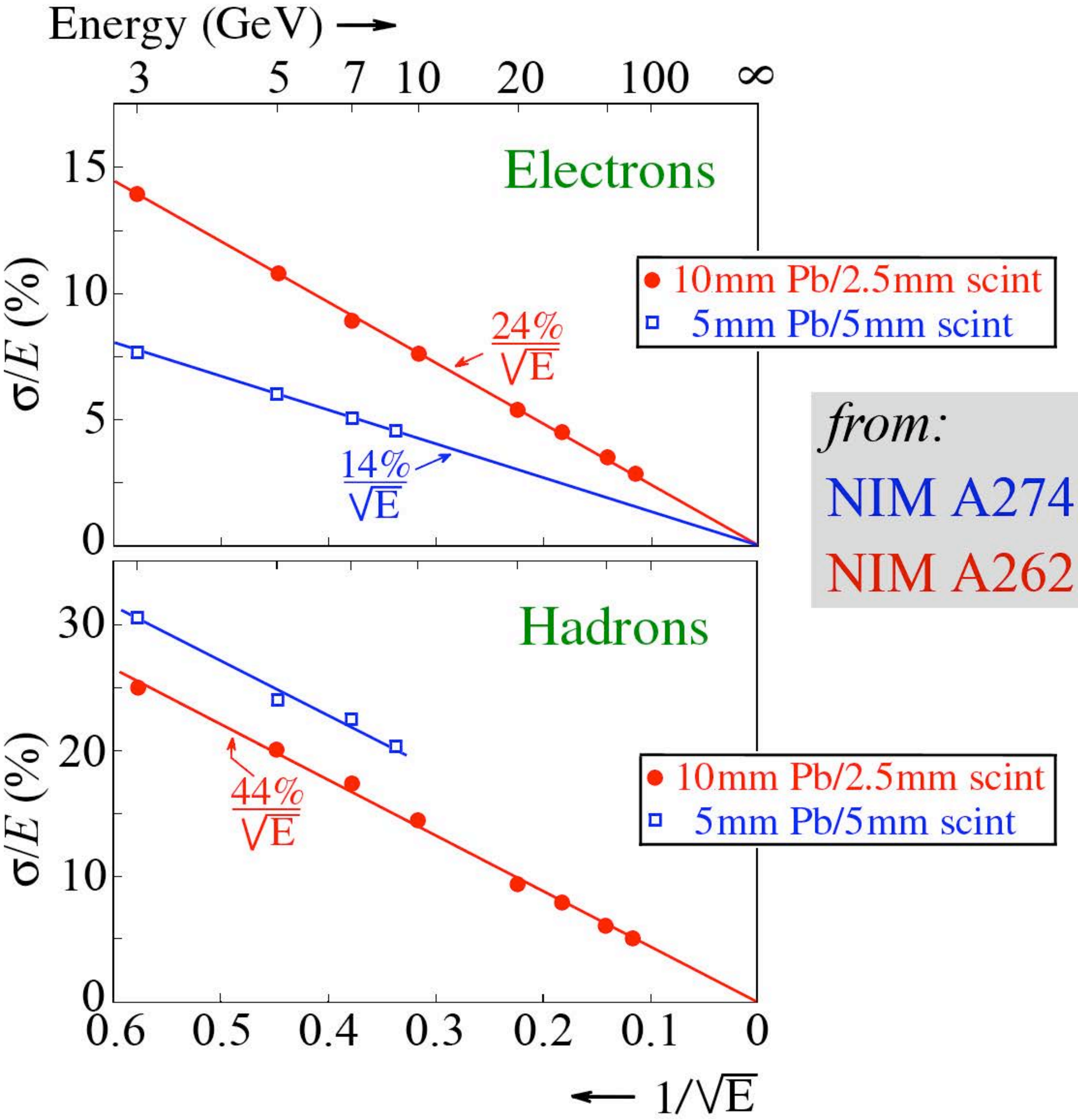
- Crucial shower particles are sampled in very different ways, depending on the calorimeter structure. Compared to a mip,
  - electrons and γs are sampled less efficiently when using high-Z absorber
  - neutrons can be sampled much more efficiently with H-rich active material

- 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* ~ 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.

High resolution hadron calorimetry had become a reality

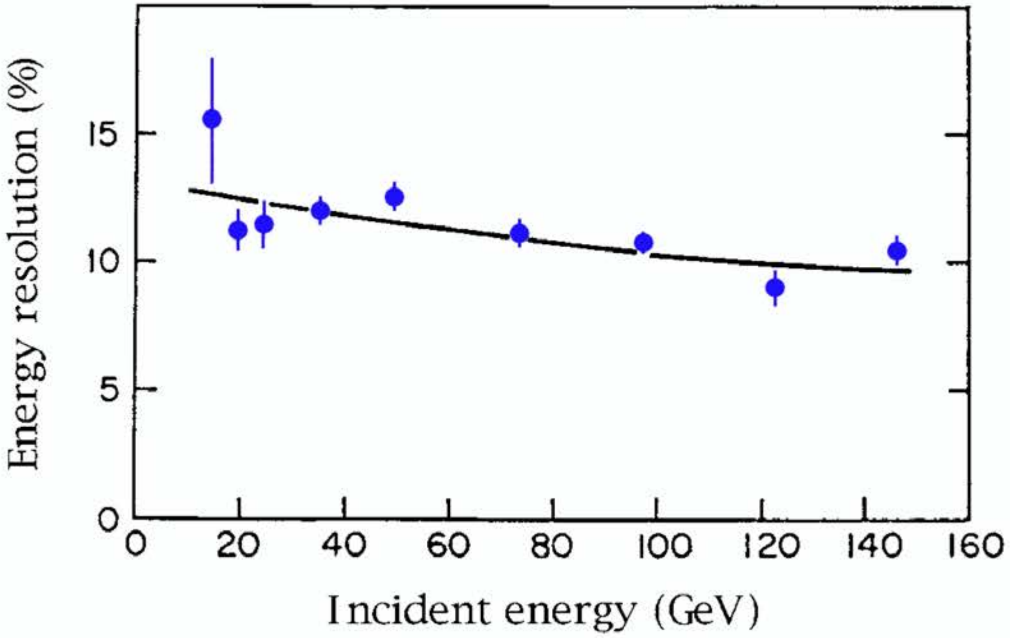
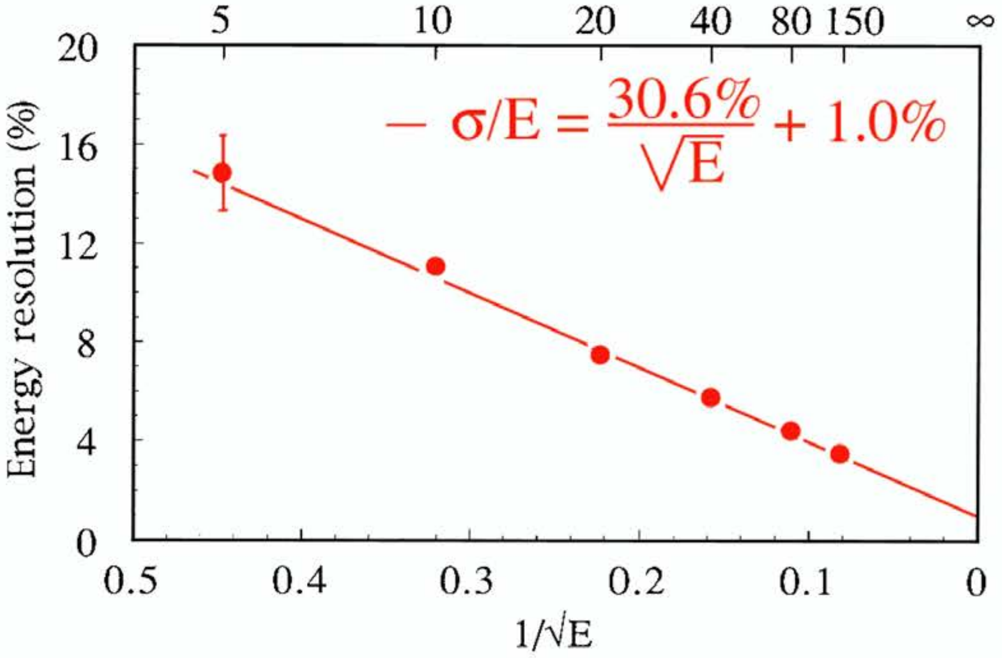


Figure 9: The hadronic energy resolution as a function of energy, for a homogeneous calorimeter consisting of *60 tonnes of liquid scintillator*

NIM 125 (1975) 447



$$\sigma/E = \frac{30.6\%}{\sqrt{E}} + 1.0\%$$

Figure 10: The hadronic energy resolution as a function of energy, for the compensating SPACAL *lead/plastic-scintillator calorimeter (sampling fraction 2%)*

NIM A308 (1991) 481

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. 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.

A brief history of calorimetry (4)

- Since ~1985, separate efforts have been undertaken to understand (and thus improve!) the performance of hadron calorimeters, both experimentally ad at the Monte Carlo level

- What has been learned in this respect is almost entirely due to experimental efforts

- 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

- As a result, the development of calorimeters for the LHC experiments has proceeded without meaningful guidance from MC simulations.

  And the experiments pay the price for that.

Consequences for LHC calorimeters

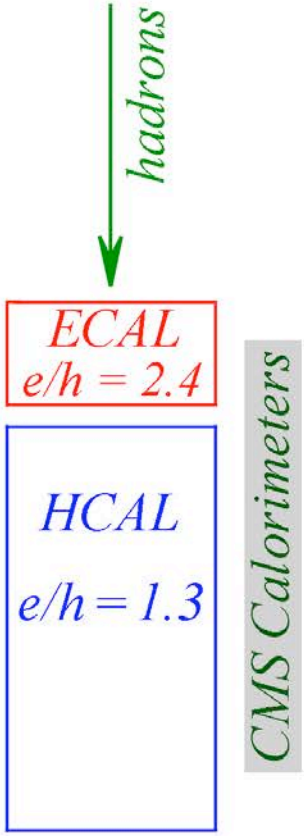
Hadronic response and signal linearity (CMS)

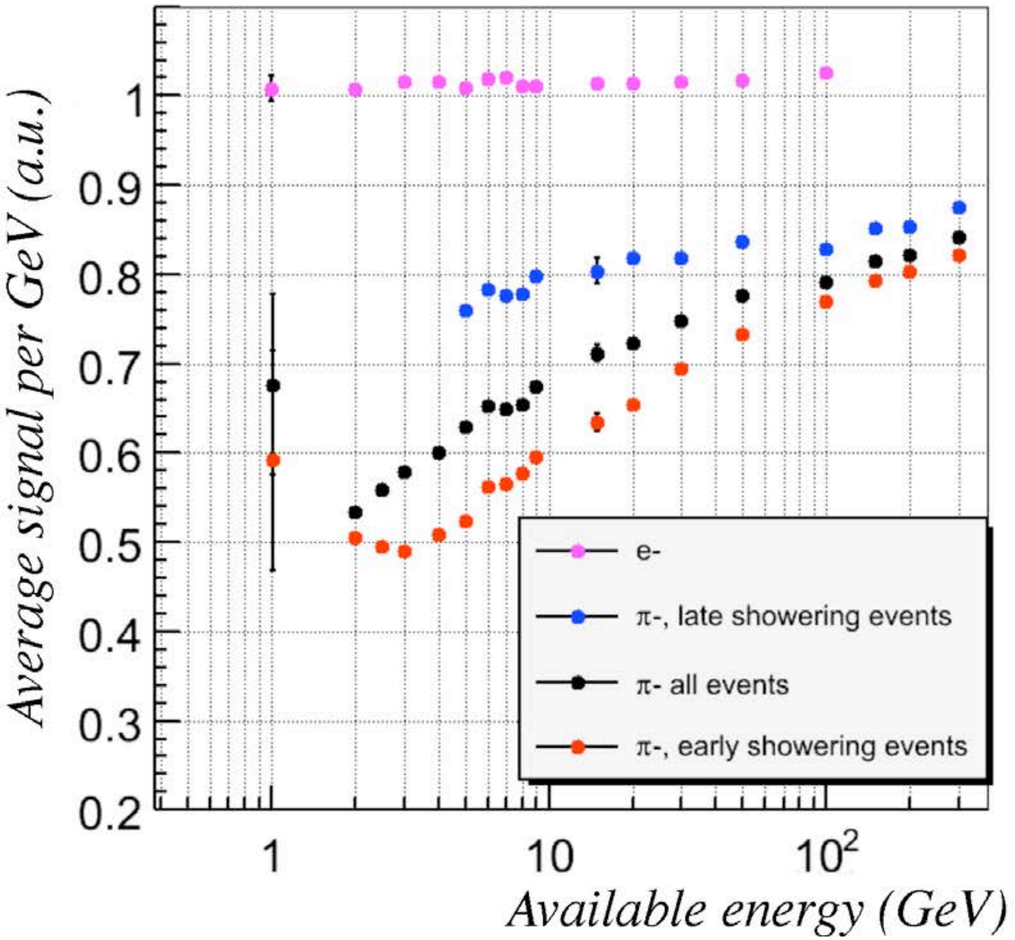
CMS pays a price for its focus on em energy resolution

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

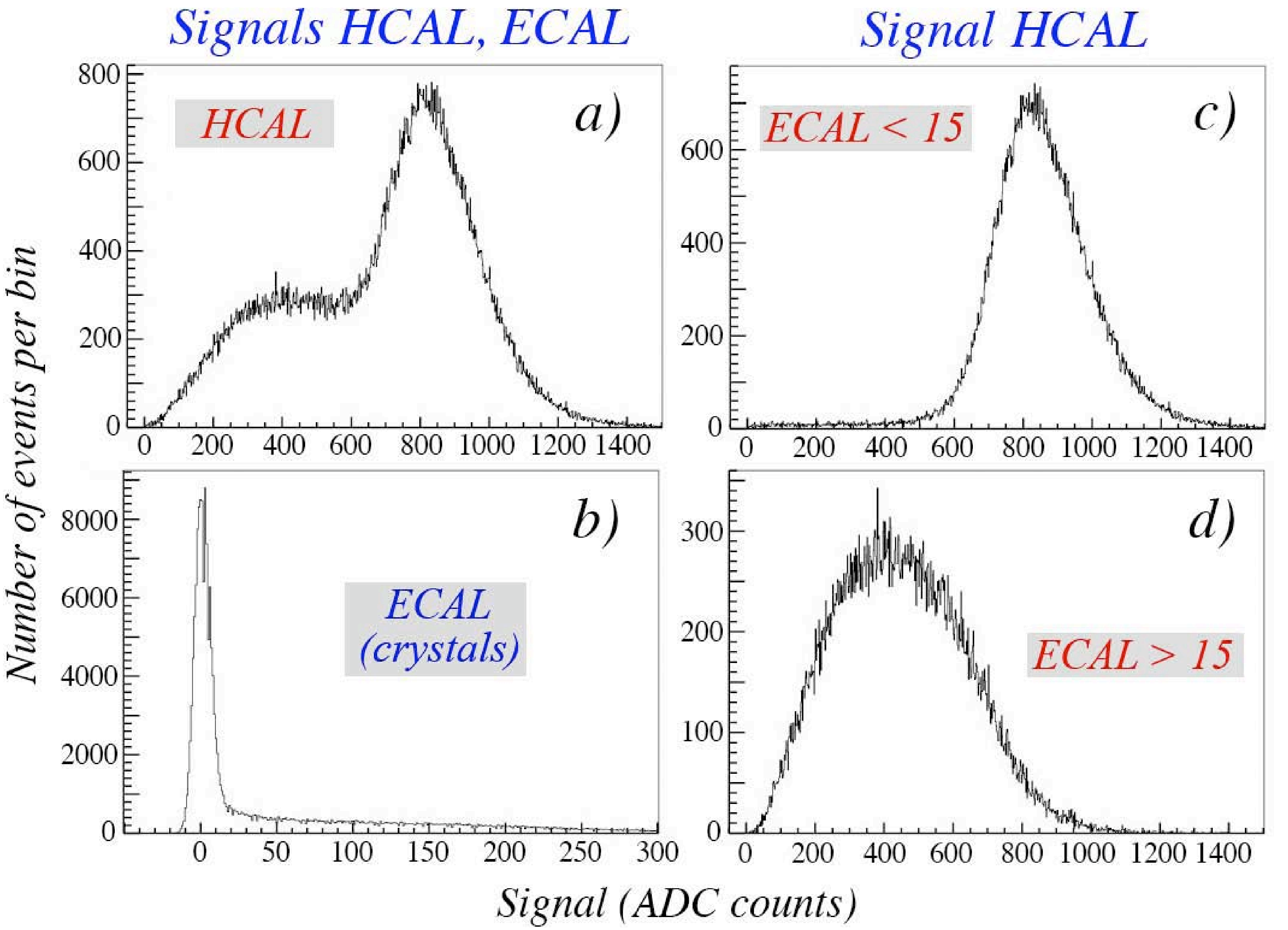
→ *Response depends strongly on starting point shower*

Data from: CMS note 2007/012





Pion signals in crystal ECAL + scintillator HCAL



One area where RELIABLE MC is badly needed: Calibration

The enormous complications that arise when calibrating a longitudinally segmented (sampling) calorimeter

The problem:

- *In the absorption process, the energy is deposited by*
  - *electrons, positrons, photons (em)*
  - *electrons, positrons, photons, pions, protons, neutrons (had)*
- *In a given sampling calorimeter, the sampling fraction is typically very different for these different particles*
  Also, the composition of the shower changes as the shower develops
- *As a result, the relationship between measured signal and deposited energy (calibration constant) varies with depth, and is especially for hadrons in a given detector segment different for each event*

Calorimetry for future experiments

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

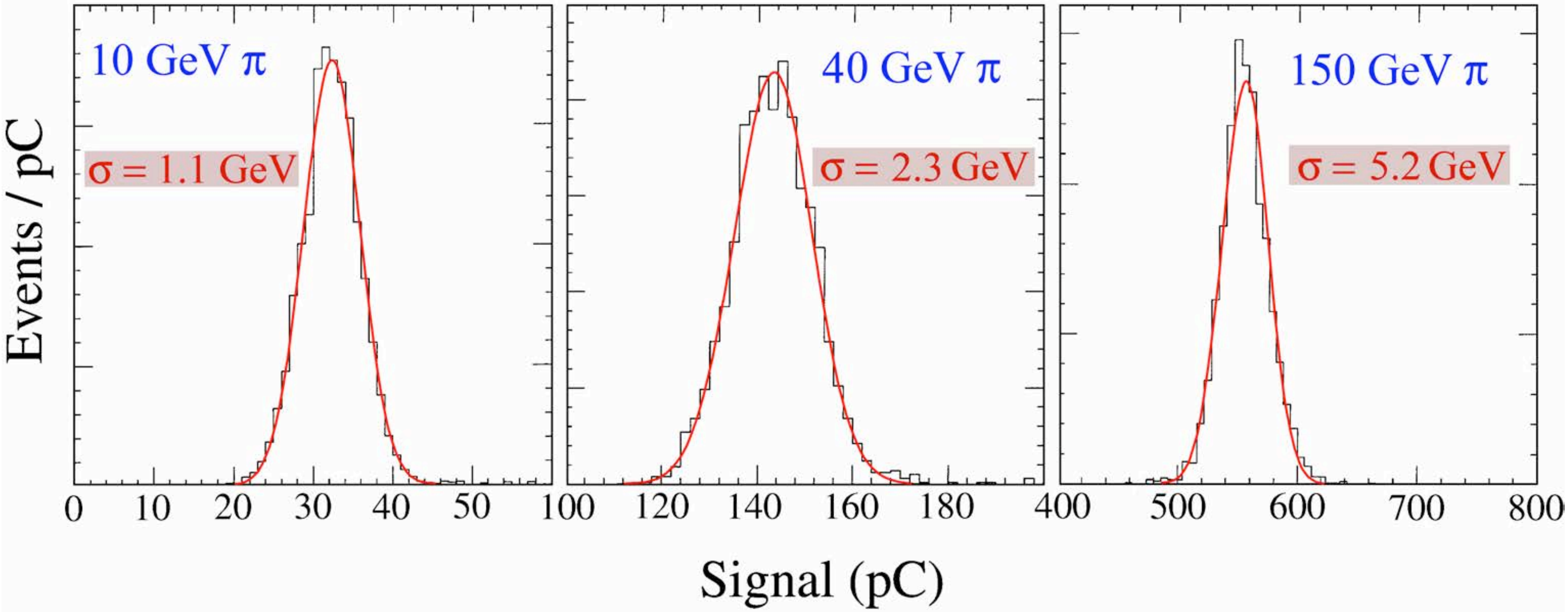
- *Reasons for poor hadronic performance of non-compensating calorimeters understood*

- *Compensation mechanisms fully understood*

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

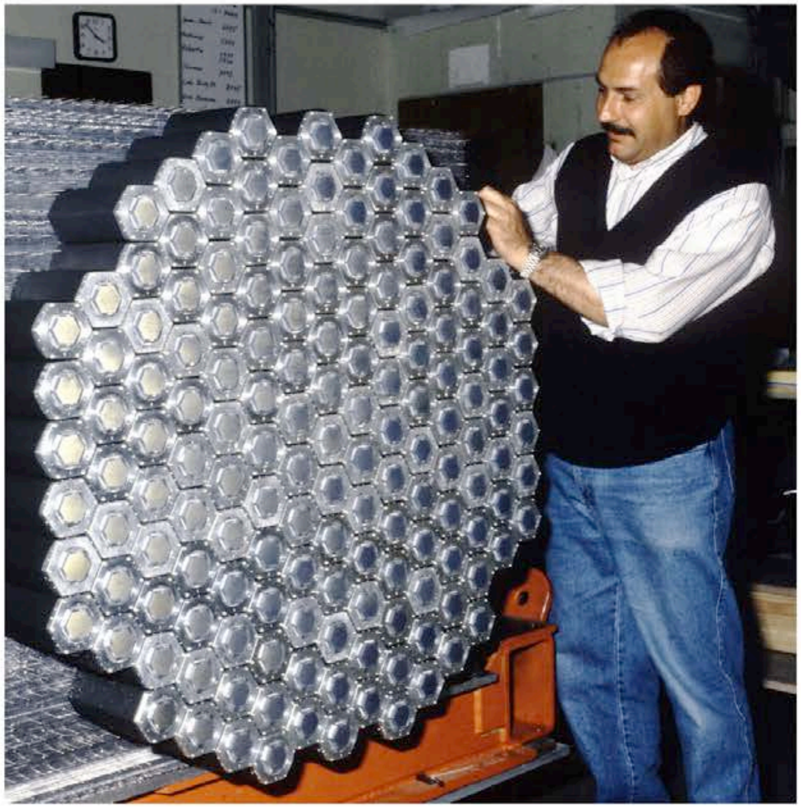
Experimentally demonstrated with Pb/scintillator calorimeters (ZEUS, SPACAL)

Hadronic signal distributions in a compensating calorimeter

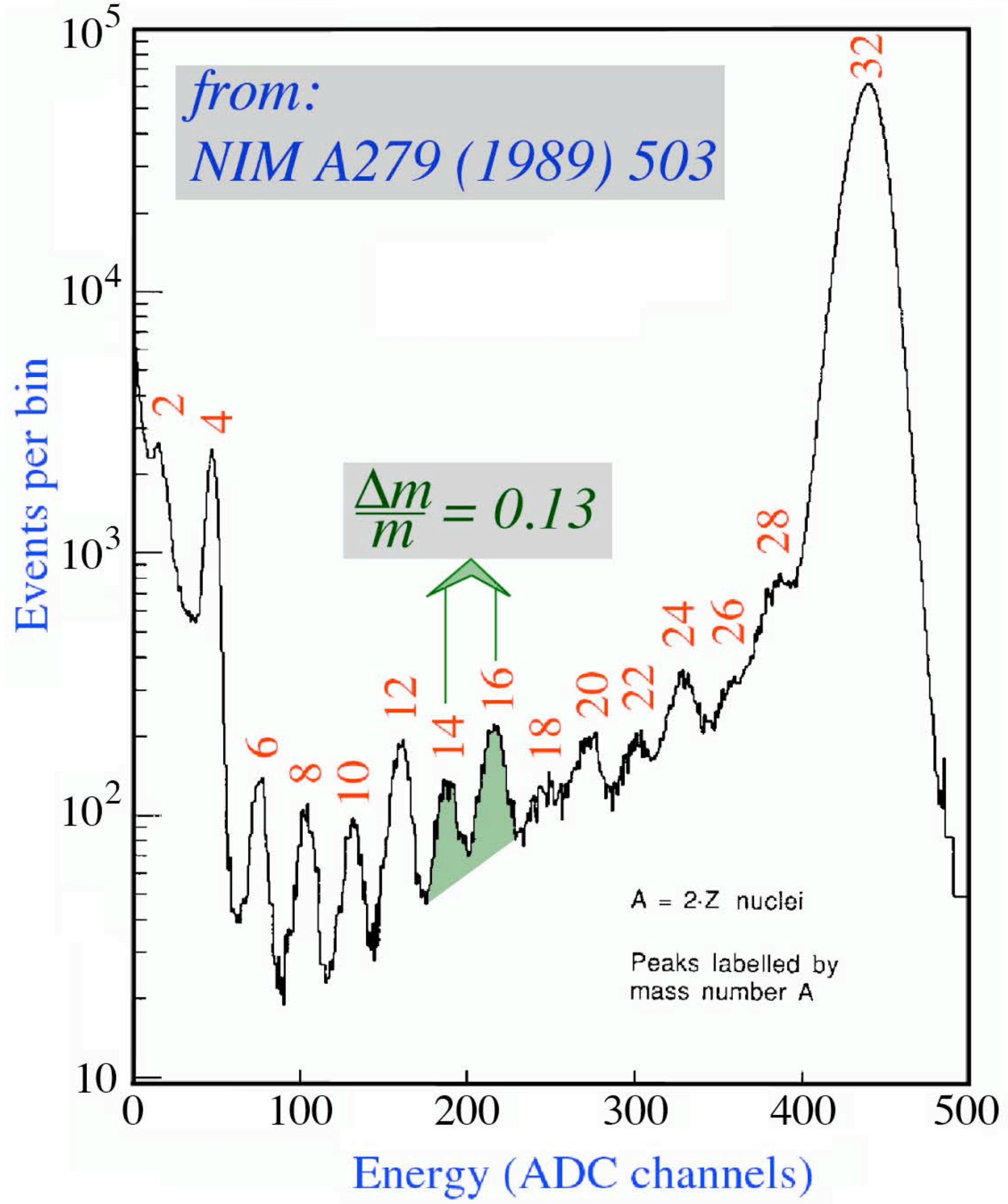


from: NIM A308 (1991) 481

SPACAL 1989



Hadron calorimetry in practice
Energy resolution in a compensating calorimeter



from:
NIM A279 (1989) 503

$\frac{\Delta m}{m} = 0.13$

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

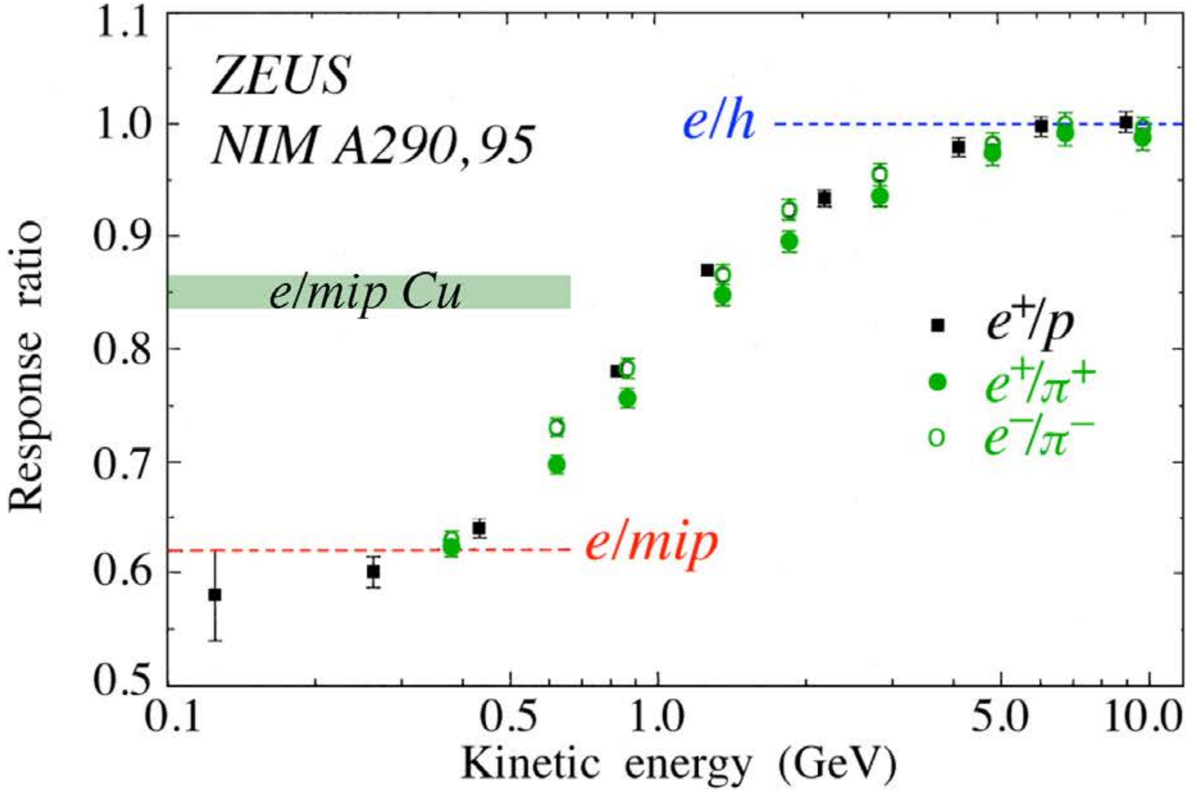
Pros

- 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)
  ⟶ *em energy resolution limited* (SPACAL: $13\%/\sqrt{E}$, ZEUS: $18\%/\sqrt{E}$)
- Compensation relies on detecting neutrons
  ⟶ Large *integration volume*
  ⟶ 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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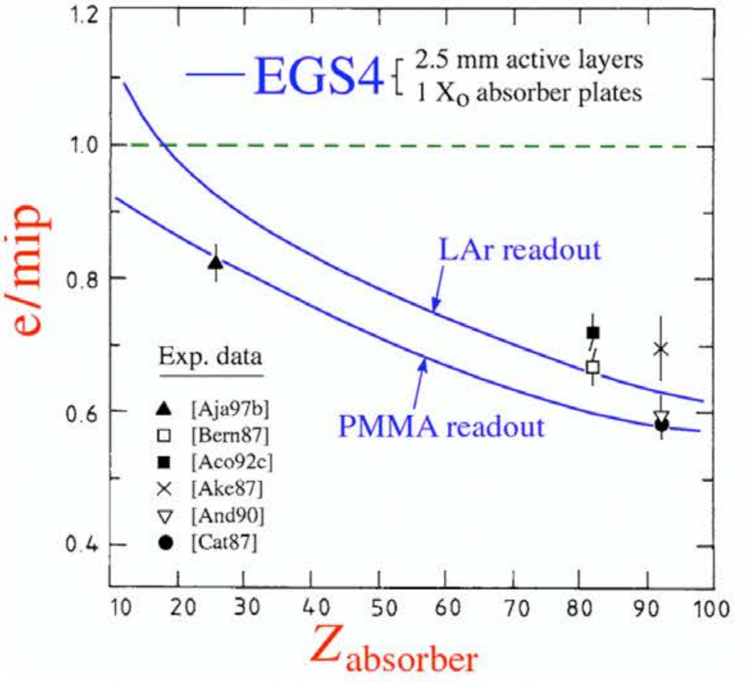

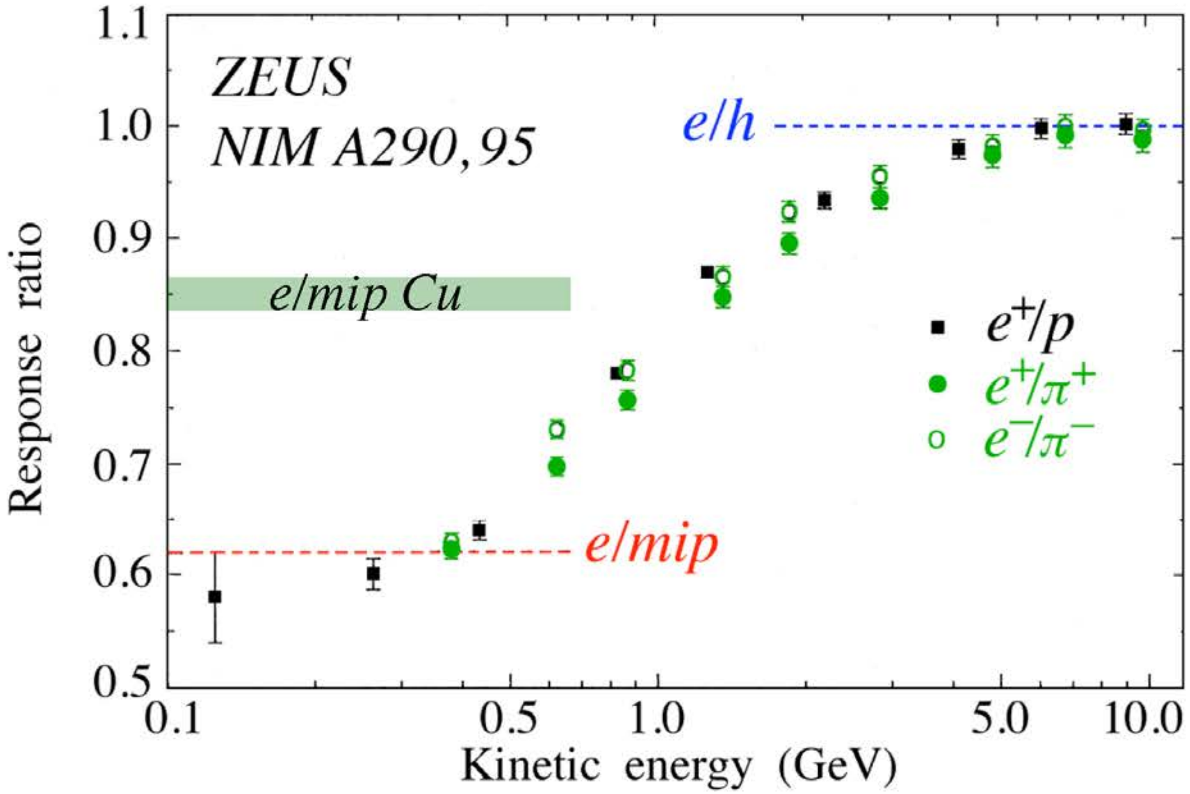

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A copper or iron based calorimeter would be much better in that respect

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?*

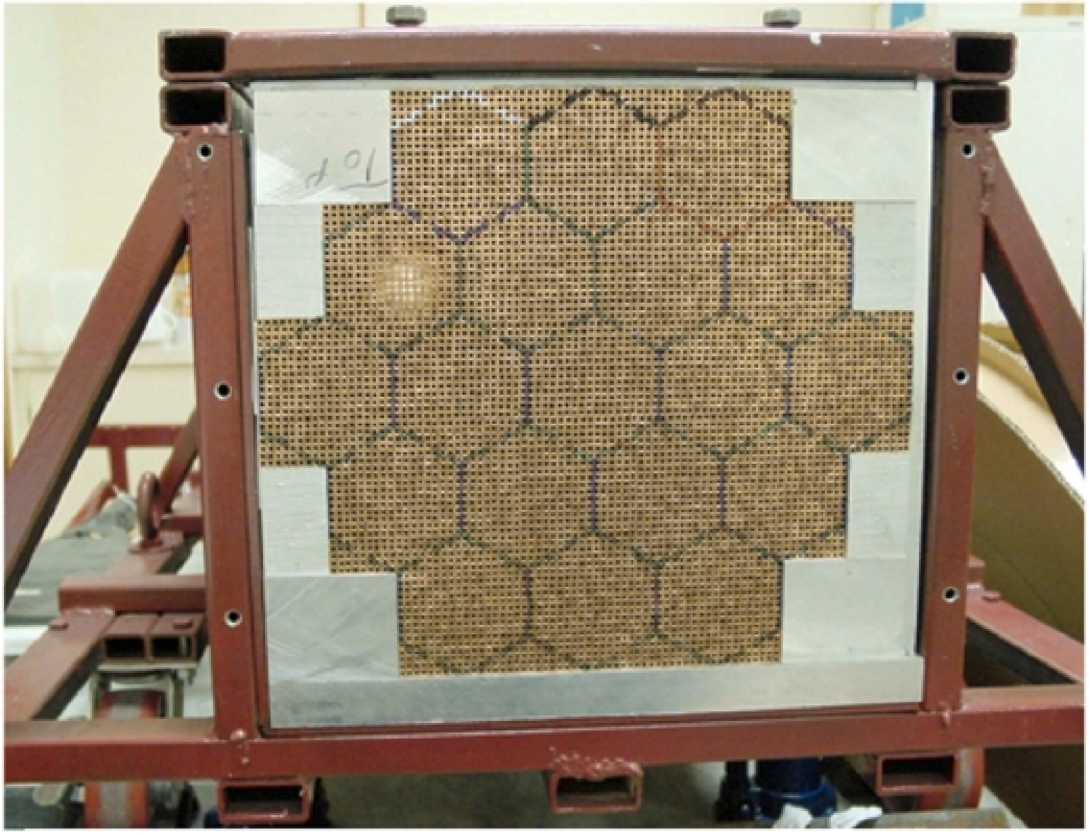
Hadron showers <
em component (π^{o})
non-em component (mainly soft p)

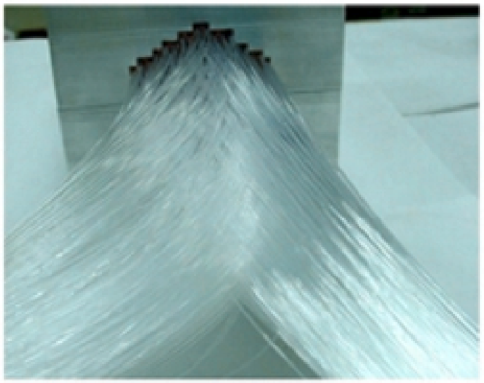
Calorimeter response to these components not the same $(e/h \neq 1)$

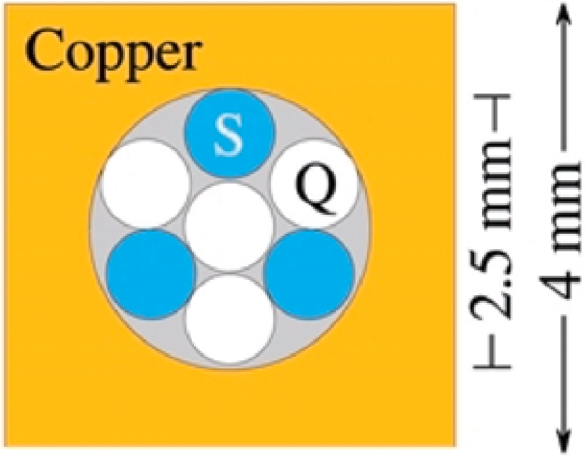
Čerenkov light almost exclusively produced by em component
(~80% of non-em energy deposited by non-relativistic particles)

➡ DREAM (Dual REAdout Method) principle:
Measure f_{em} *event by event by comparing Č and dE/dx signals*

DREAM: Structure

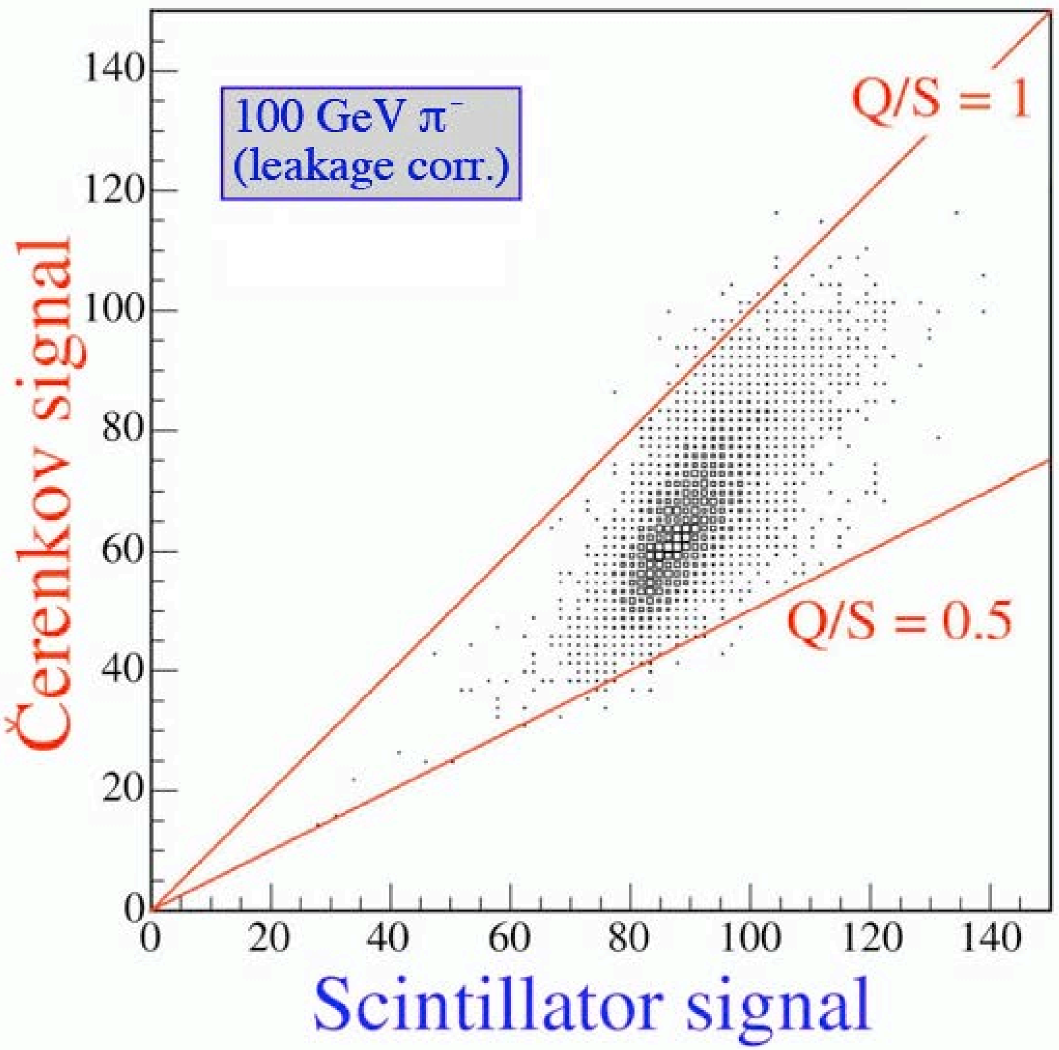






- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

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



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

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

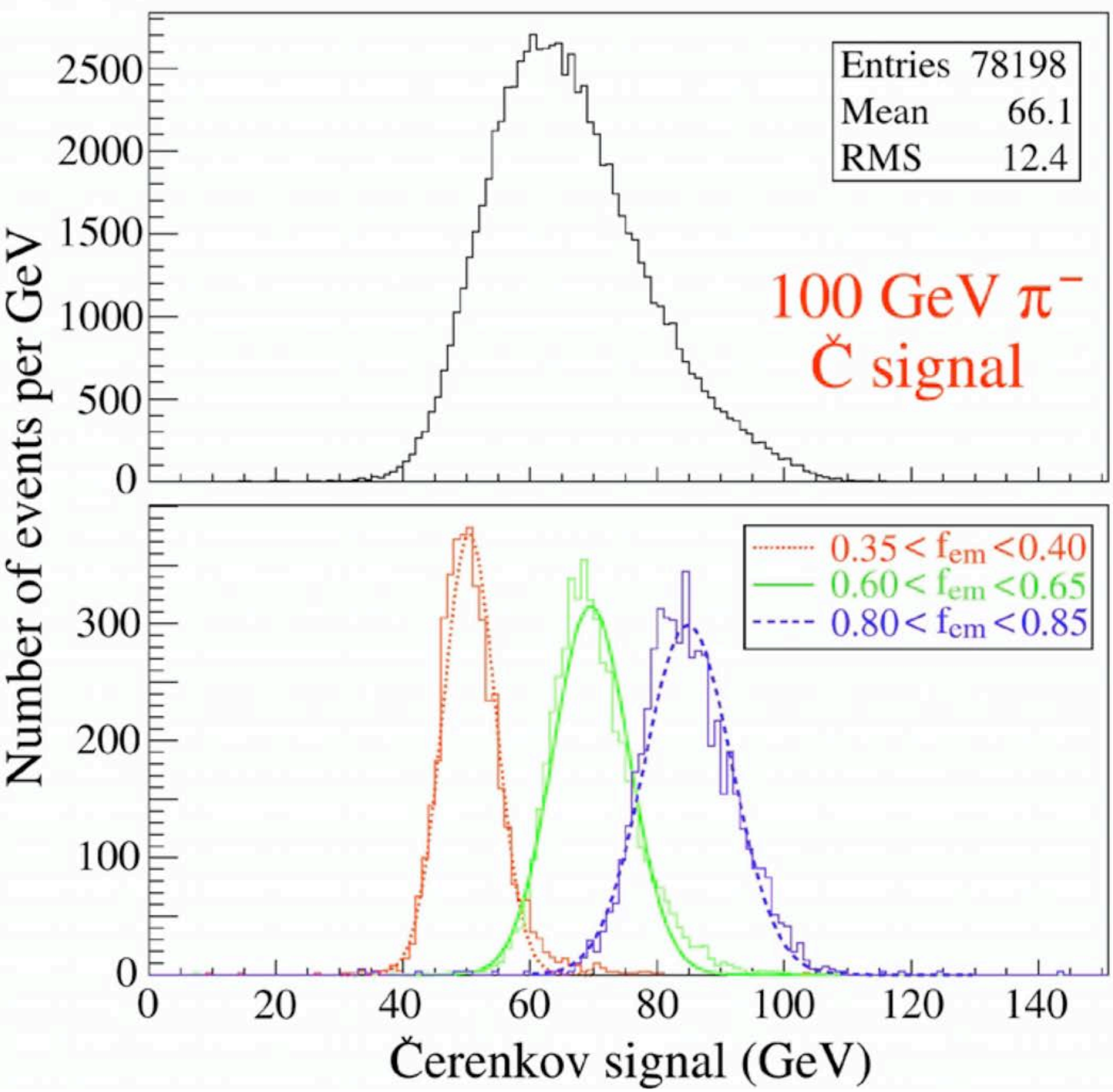
e.g. If $e/h = 1.3$ (S), 4.7 (Q)

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

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

with $\chi = \frac{1 - (h/e)_{\mathrm{S}}}{1 - (h/e)_{\mathrm{Q}}} \sim 0.3$

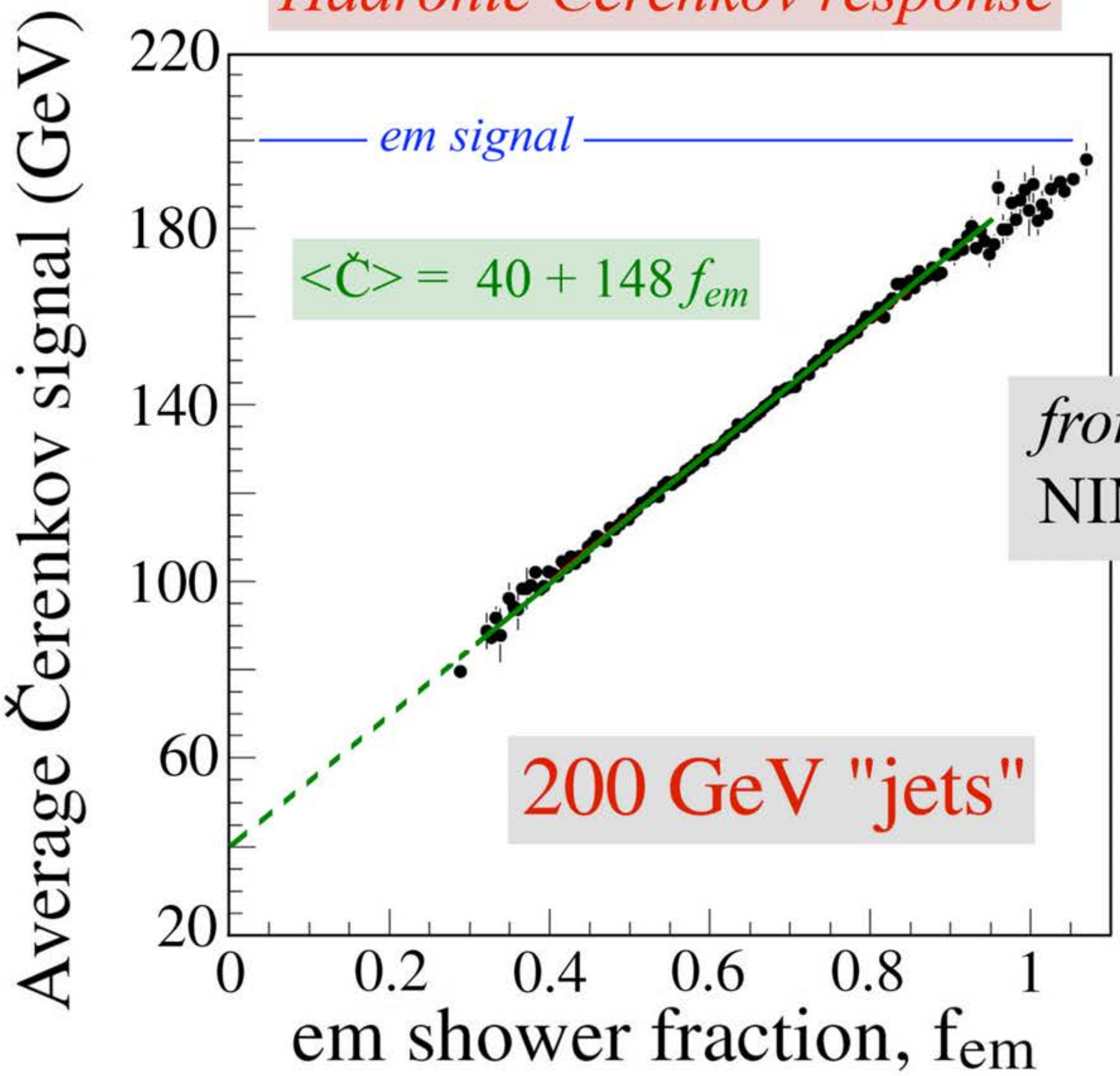
DREAM: Effect of event selection based on f_{em}



From:
NIM A537 (2005) 537

The dual-readout method

Hadronic Čerenkov response



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

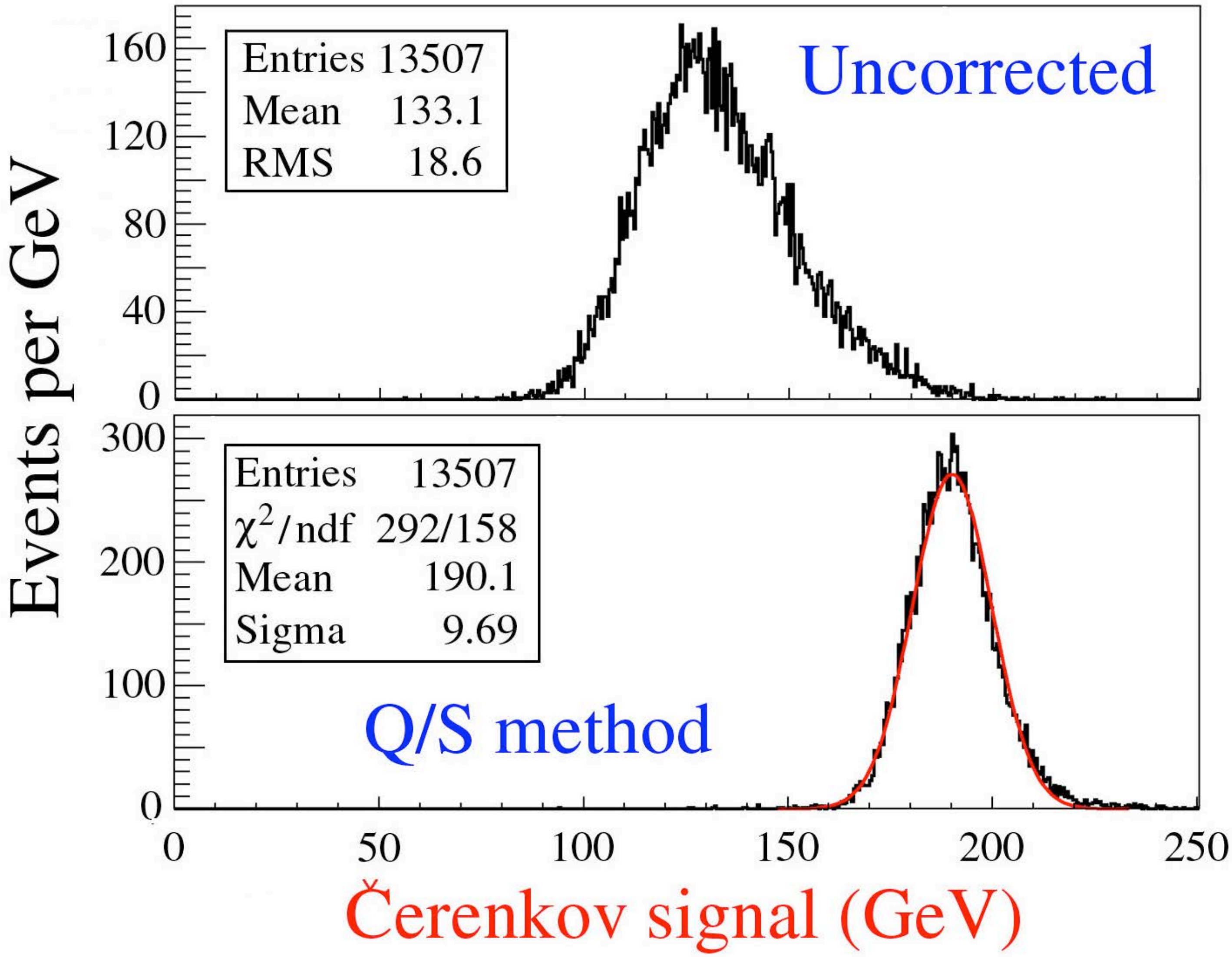
$$e/h = \frac{p_1}{p_0} - 1 = 4.7$$

from:
NIM A537 (2005) 537

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

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

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



Effects of Q/S corrections on hadronic signal linearity and jet resolution

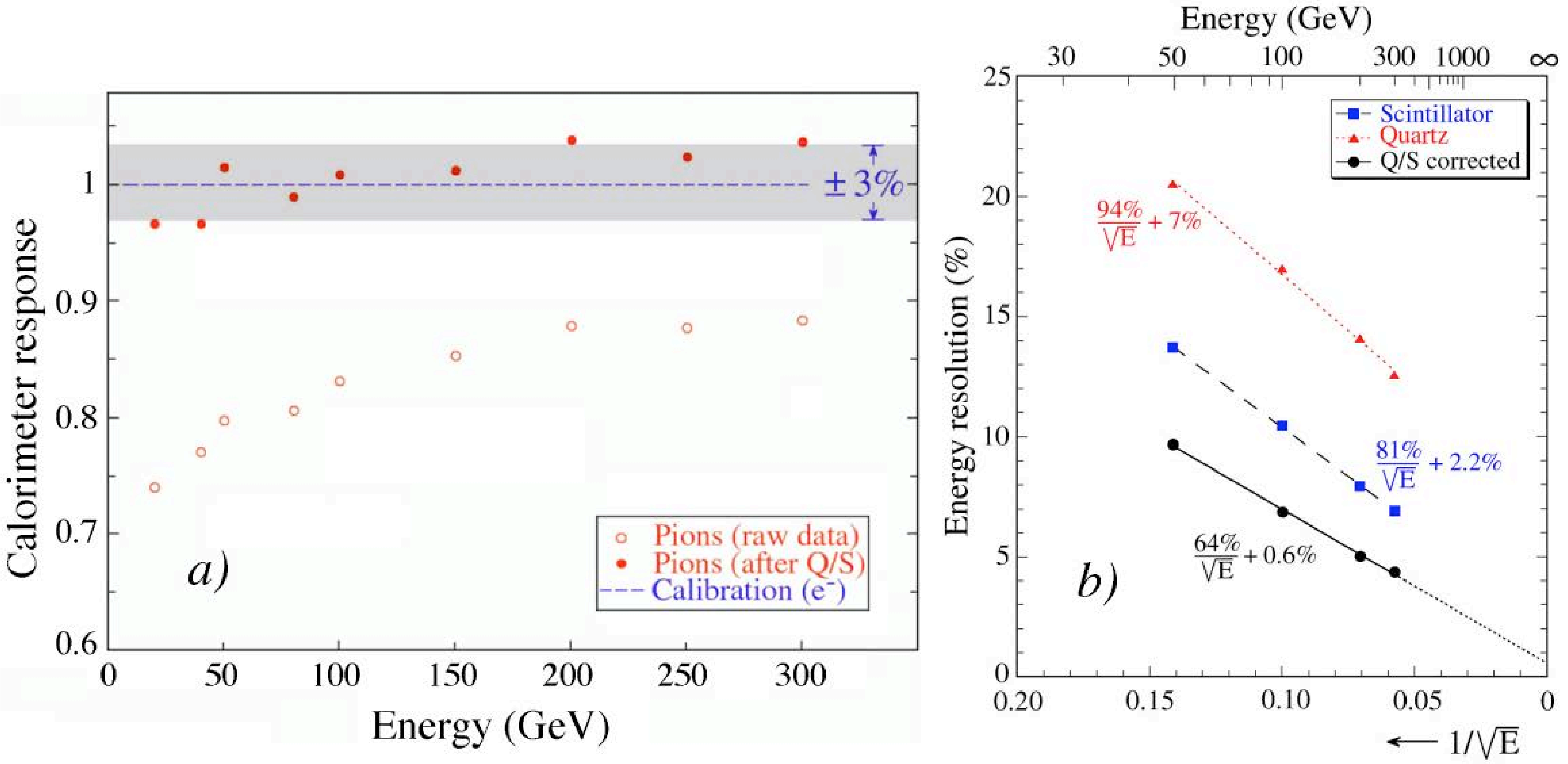


Figure 9: The scintillator response of the DREAM calorimeter to single pions (a) and the energy resolution for "jets" (b), before and after the dual-readout correction procedures were applied to the signals [5].

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 $1/\sqrt{E}$
  - σ/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 ⟶ *reduce effects side leakage*

Expected effect of full shower containment

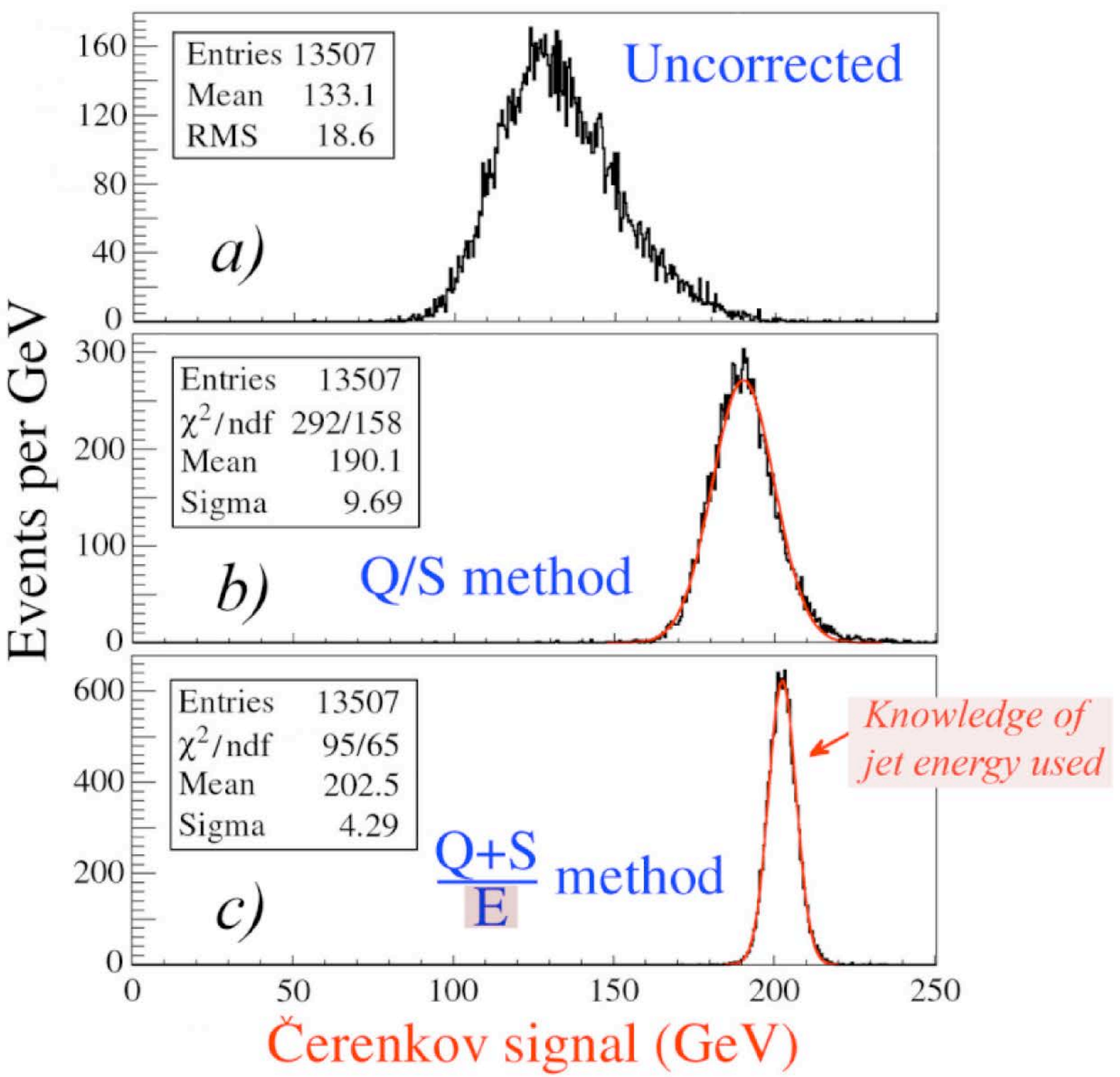


Figure 2: Čerenkov signal distributions for 200 GeV multi-particle events. Shown are the raw data (*a*), and the signal distributions obtained after application of the corrections based on the measured em shower content, with (*c*) or without (*b*) using knowledge about the total "jet" energy [5].

How to improve DREAM performance

- Build a larger detector ⟶ *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

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 PbWO4 :1%Mo signals into S, Č components

From:

NIM A604 (2009) 512

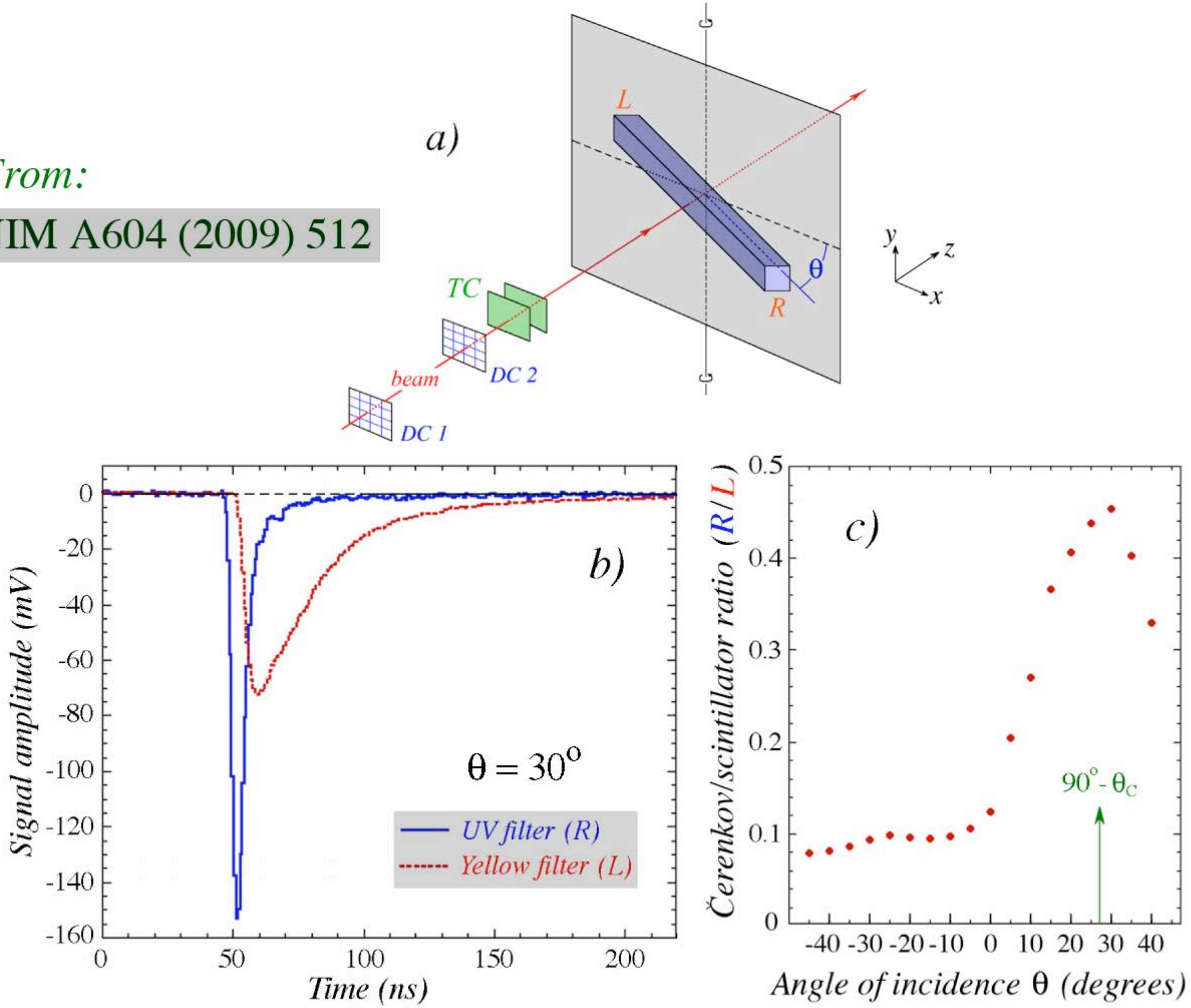
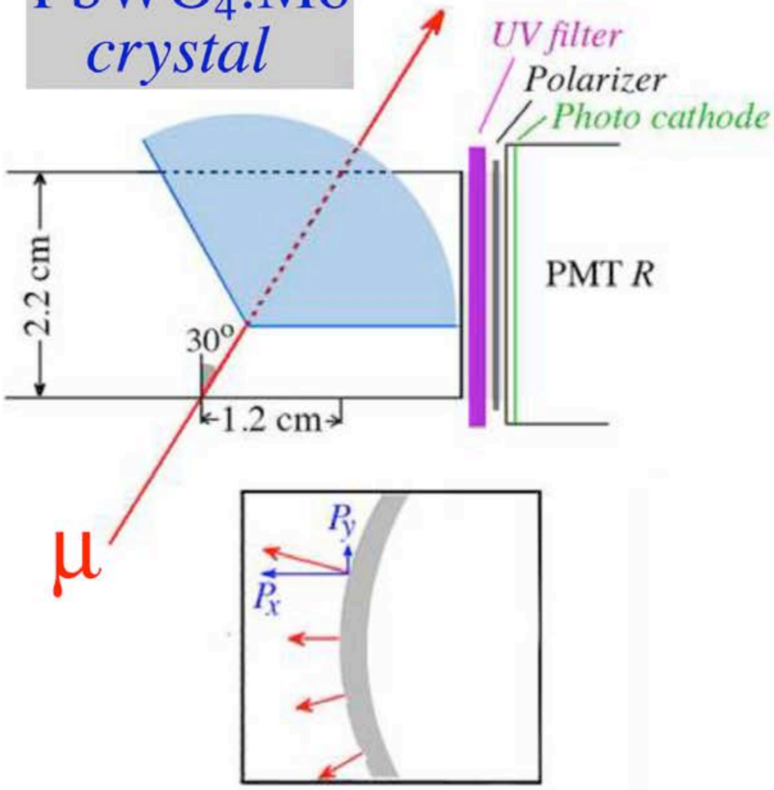


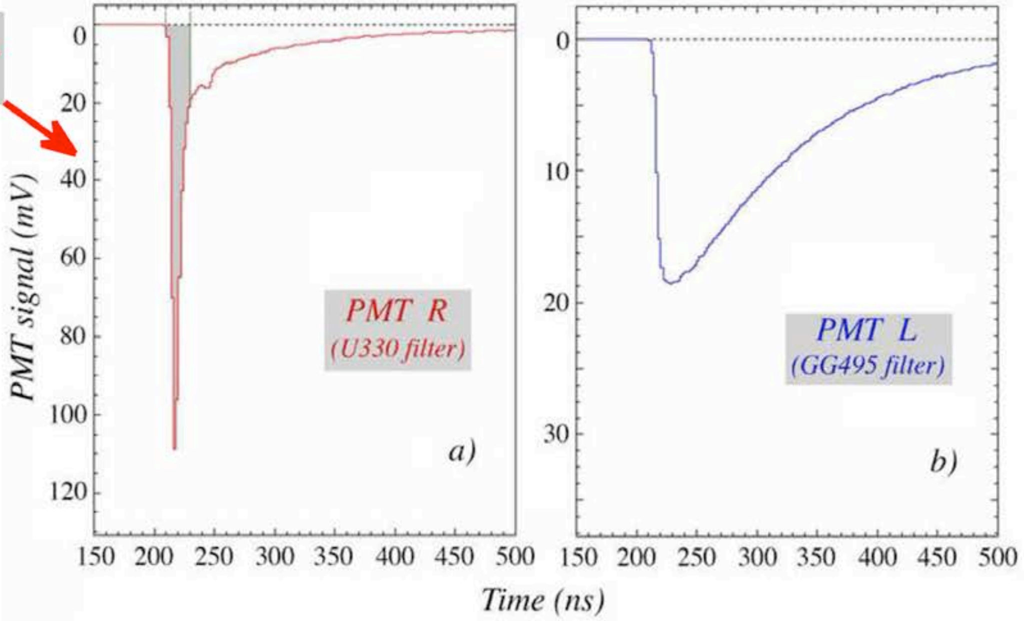
Figure 3: Unraveling of the signals from a Mo-doped $PbWO_4$ crystal into Čerenkov and scintillation components. The experimental setup is shown in diagram *a*. The two sides of the crystal were equipped with a UV filter (side *R*) and a yellow filter (side *L*), respectively. The signals from 50 GeV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

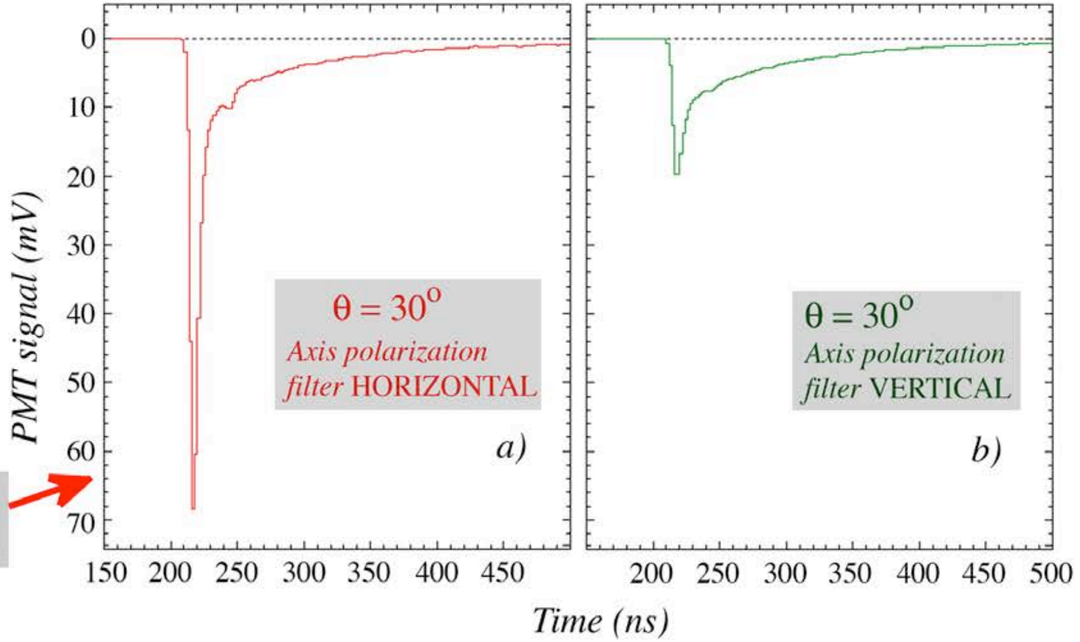
Separating the Čerenkov and scintillation components

Effects of the colored filter

$PbWO_4$:Mo *crystal*

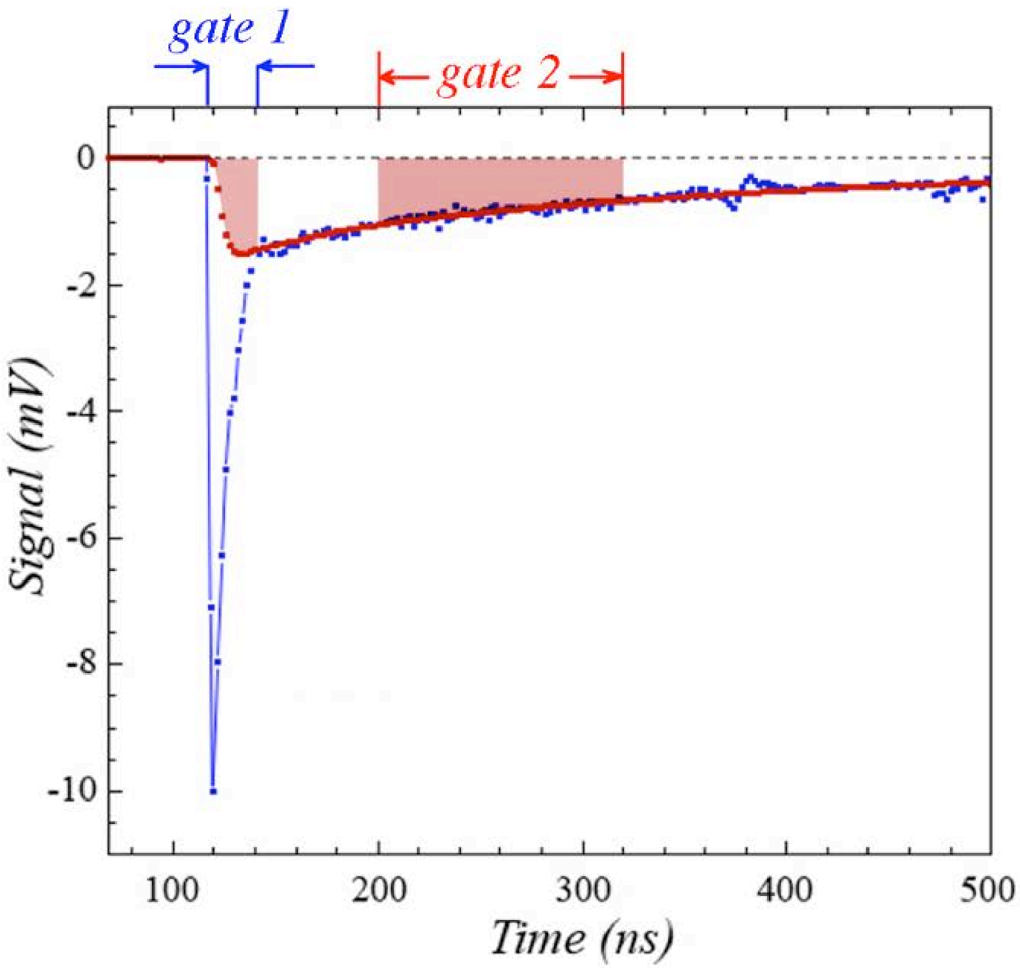






Effects of the polarization filter

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

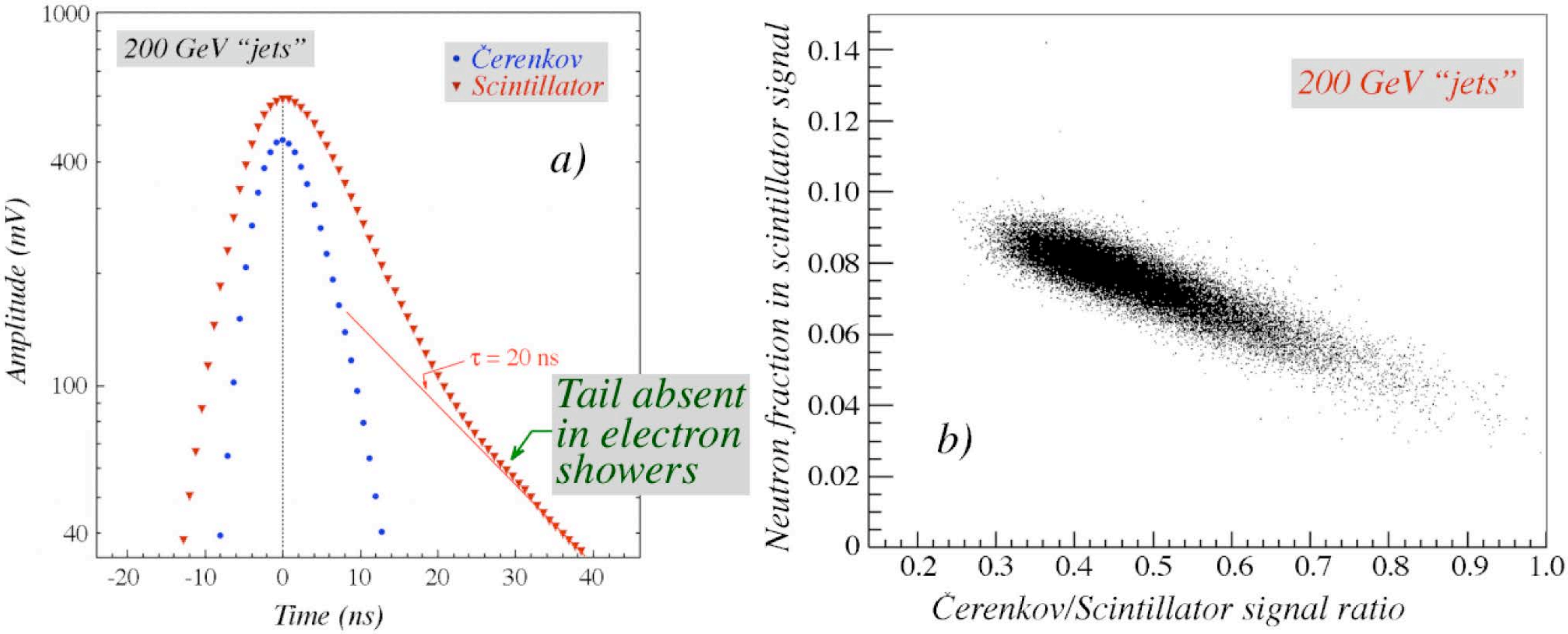
- For ultimate hadron calorimetry ($15\%/\sqrt{E}$): *Measure E_{kin} (neutrons)*

  Is correlated to nuclear binding energy loss (invisible energy)

Can be inferred from the time structure of the signals

High-resolution hadron calorimetry also requires efficient detection of the "nuclear" shower component

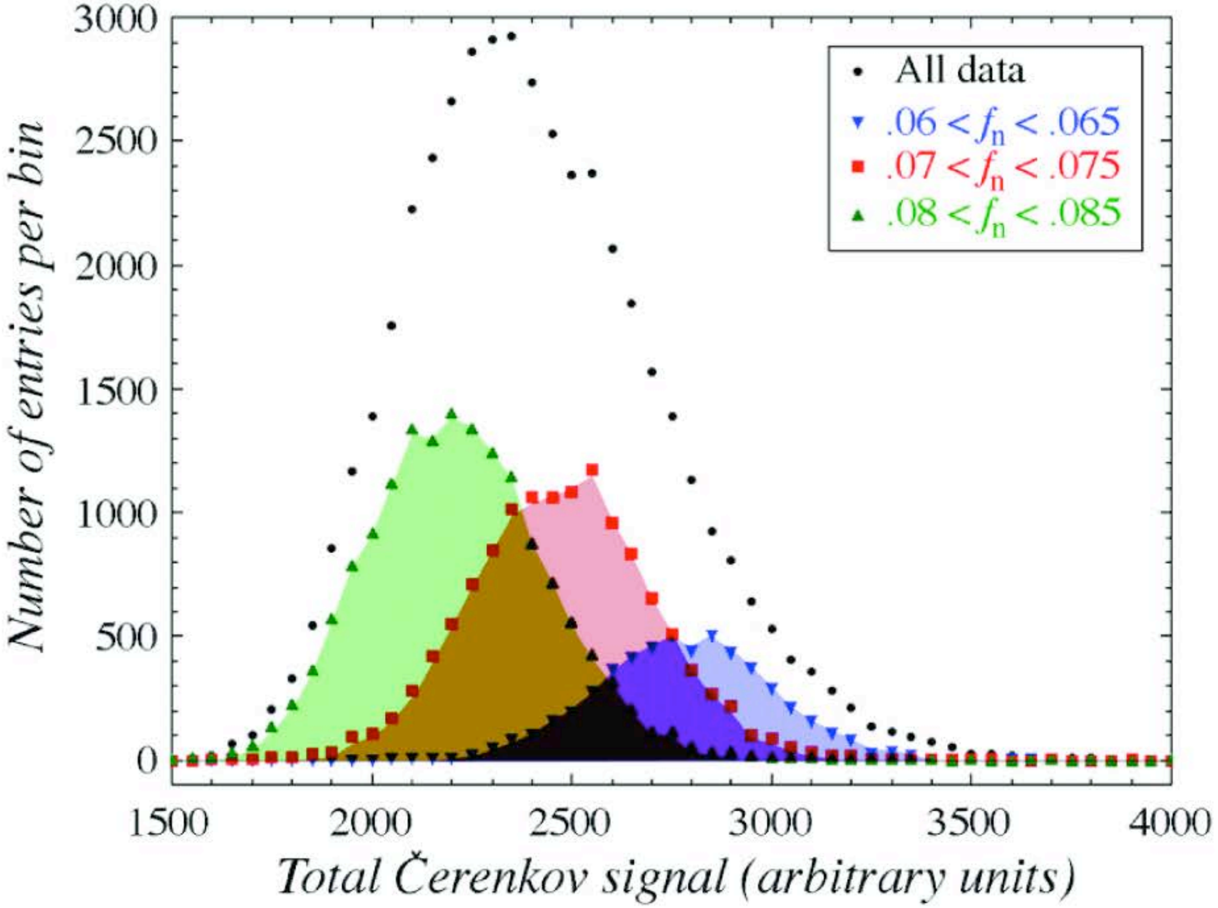
Time structure of the DREAM signals: the neutron tail (anti-correlated with f_{em})



Tail absent in electron showers

Figure 4: The average time structure of the Čerenkov and scintillation signals recorded for 200 GeV "jets" in the fiber calorimeter (a). Scatter plot of the fraction of the scintillation light contained in the (20 ns) exponentional tail versus the Čerenkov/scintillation signal ratio measured in these events (b) [9].

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 .

The follow-up: RD52

- Concentrate on fiber calorimetry
  - *Shower containment >99% , i.e. mass ~ 5 tonnes*
    → *effects of leakage fluctuations negligible*
  - *Preferably copper absorber*

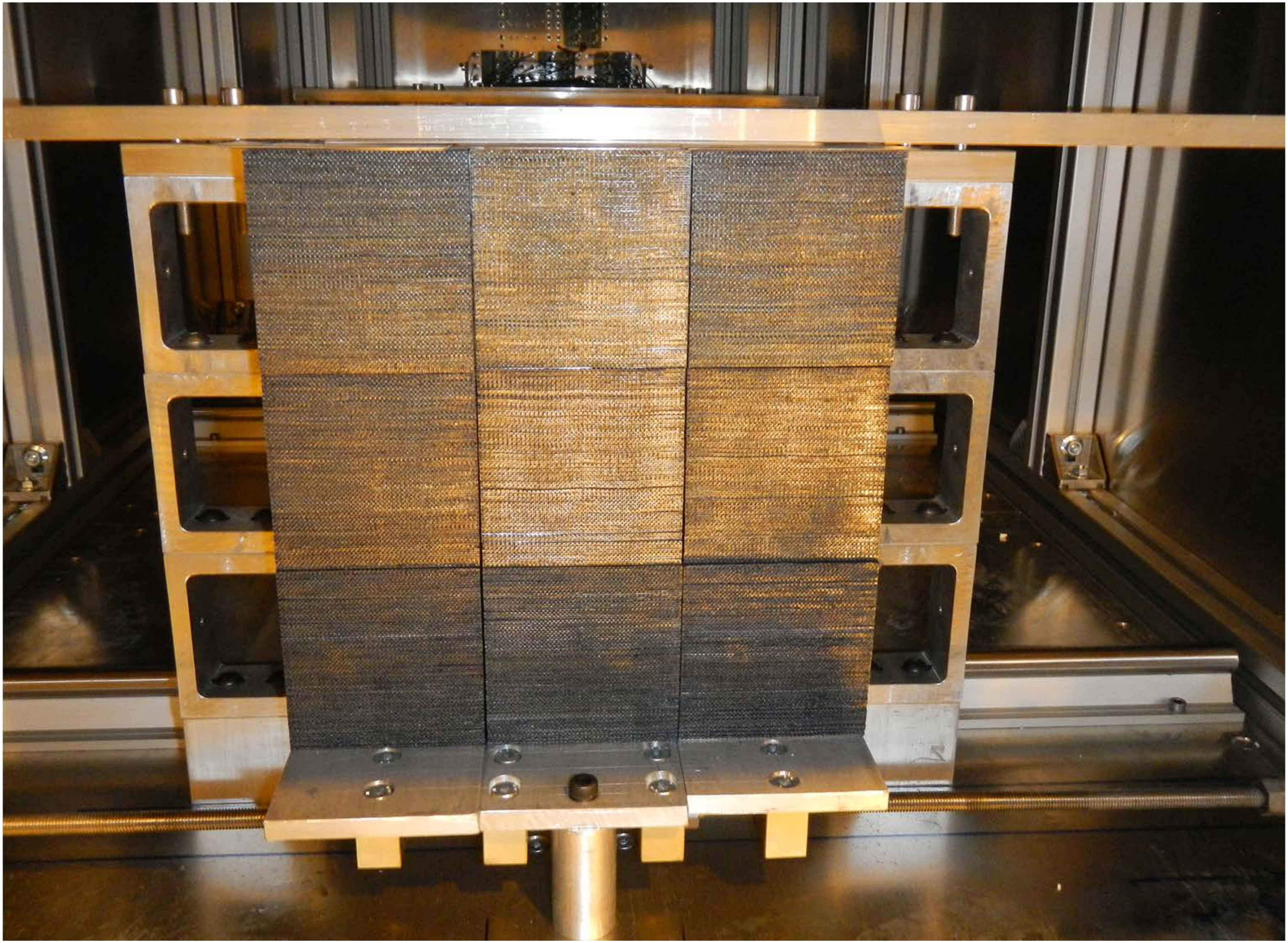
- Other design criteria:
  - *Čerenkov light yield in fiber detector > 100 p.e./GeV (em)*
  - *Sampling fluctuations fiber detector < 10%/$\sqrt{E}$ (em)*

    Achieved sampling fluctuations 8.9%/$\sqrt{E}$, Č light yield 40 p.e./GeV
    Total stochastic term 13.9%/$\sqrt{E}$

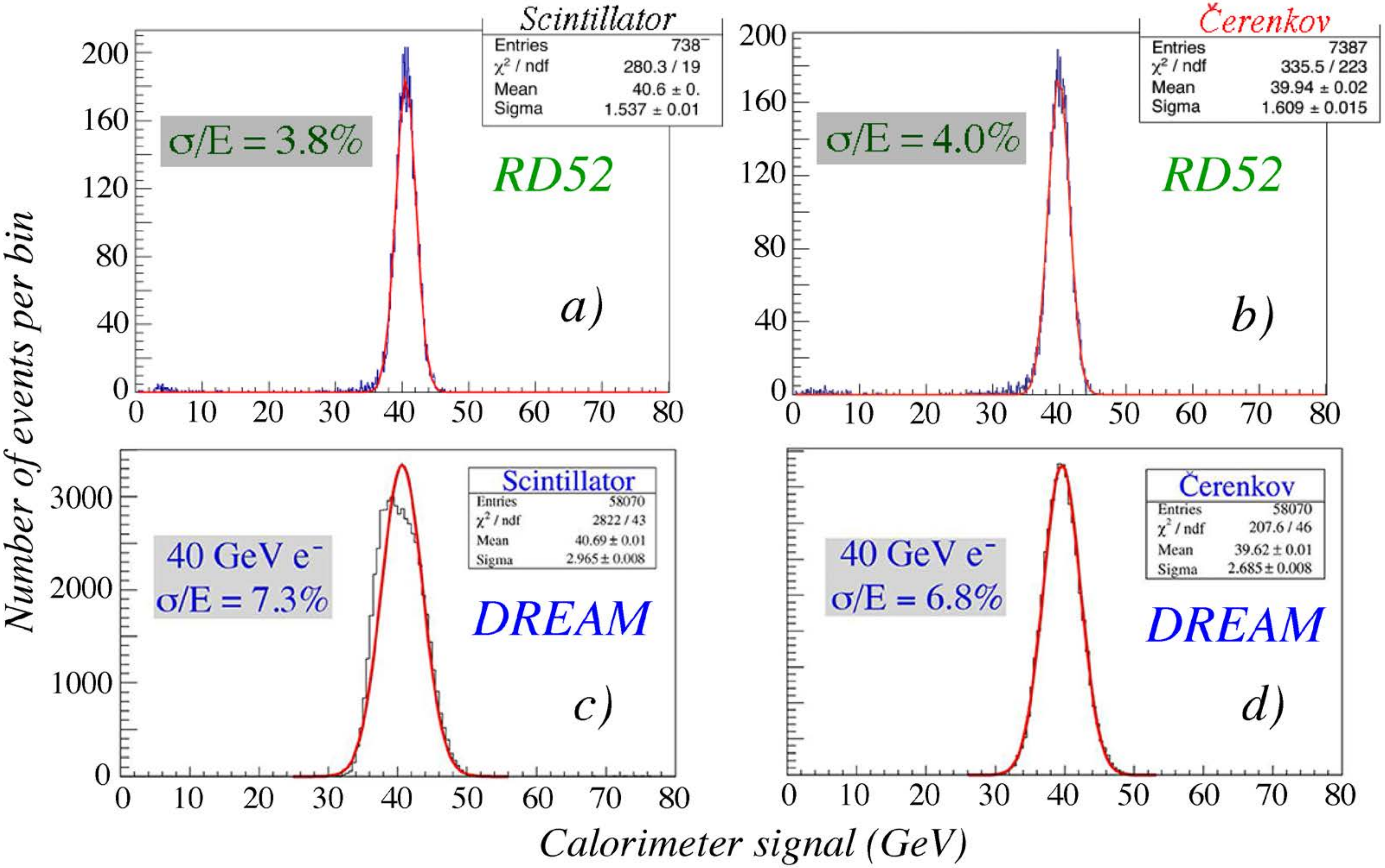
  - *Depth measurement of shower maximum for each event*
  - *Time structure measured for every signal*

    Needed for particle ID, light attenuation corrections

The 3 x 3 module (72 channels) RD52 calorimeter tested 12/2012



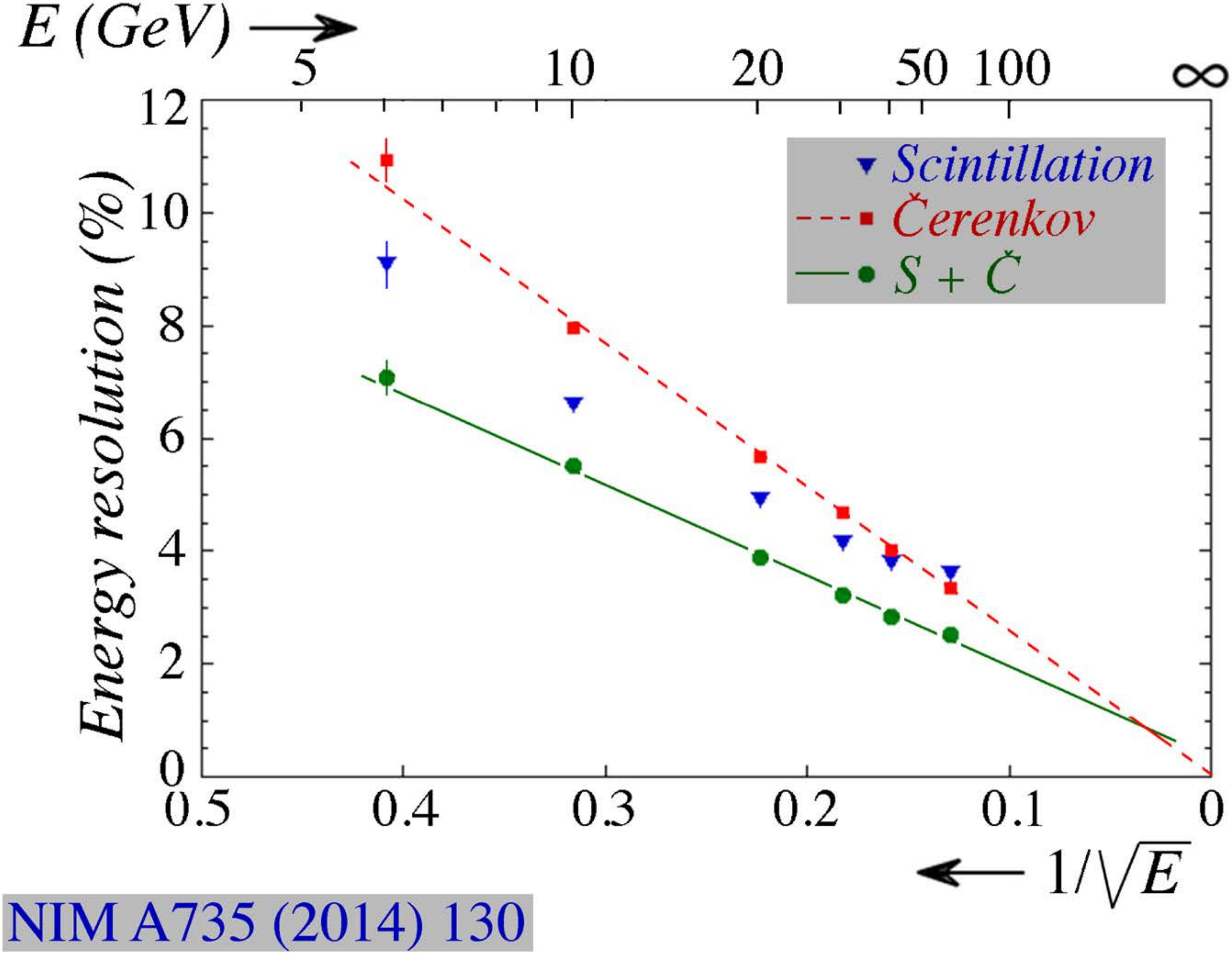
Electromagnetic performance strongly improved in RD52



NIM A735 (2014) 130

Electromagnetic performance RD52 calorimeter

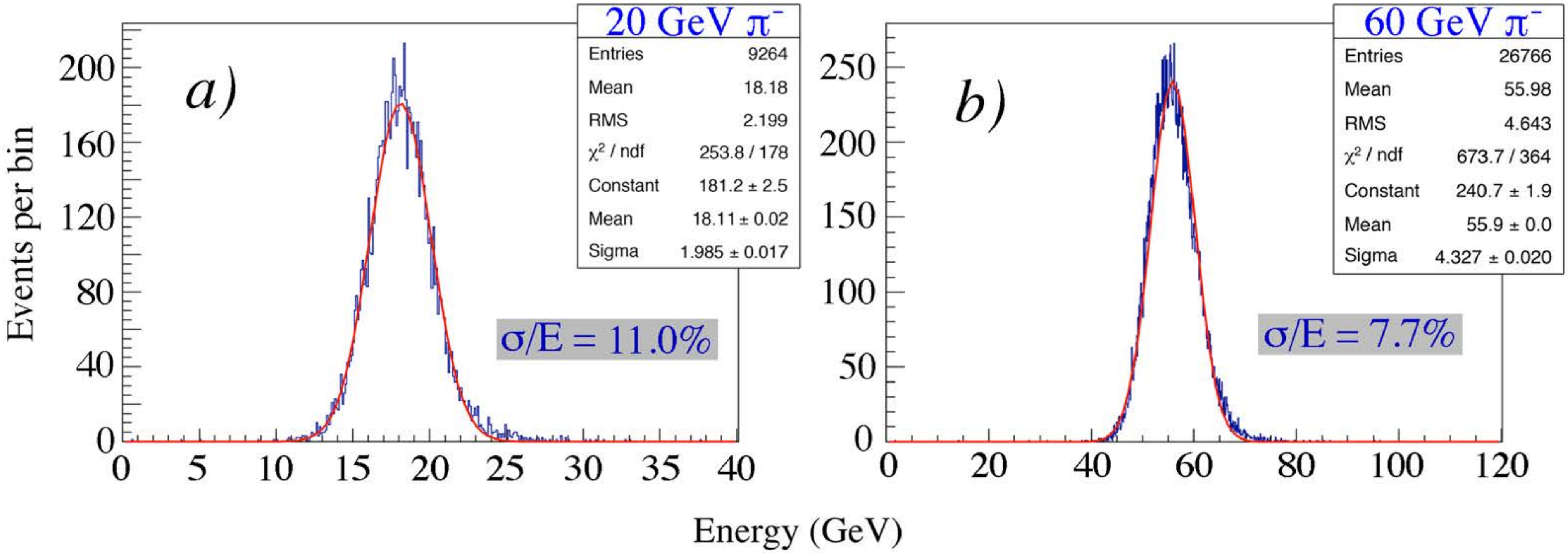
Moreover, combining S and C signals further improves resolution



NIM A735 (2014) 130

Hadronic performance

(1.2 ton RD52 Pb based calorimeter)

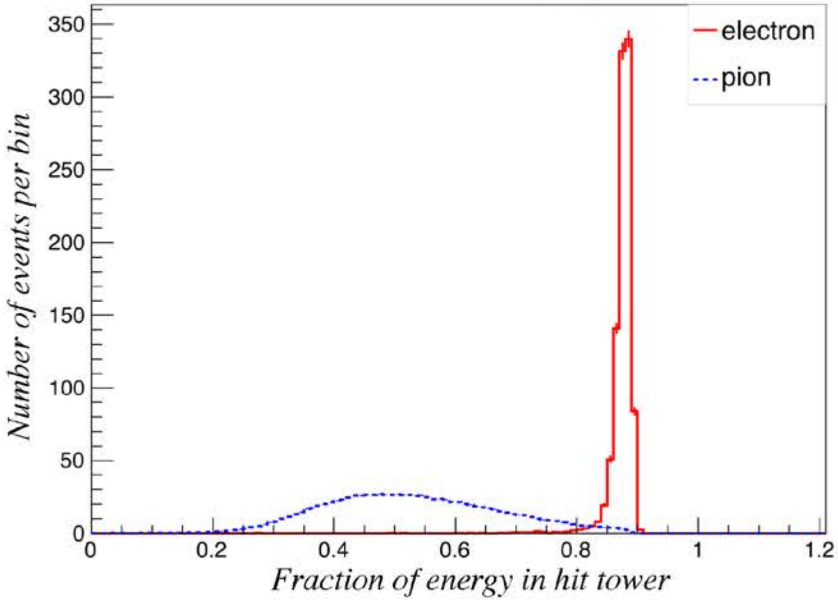


NIM A732 (2013) 475

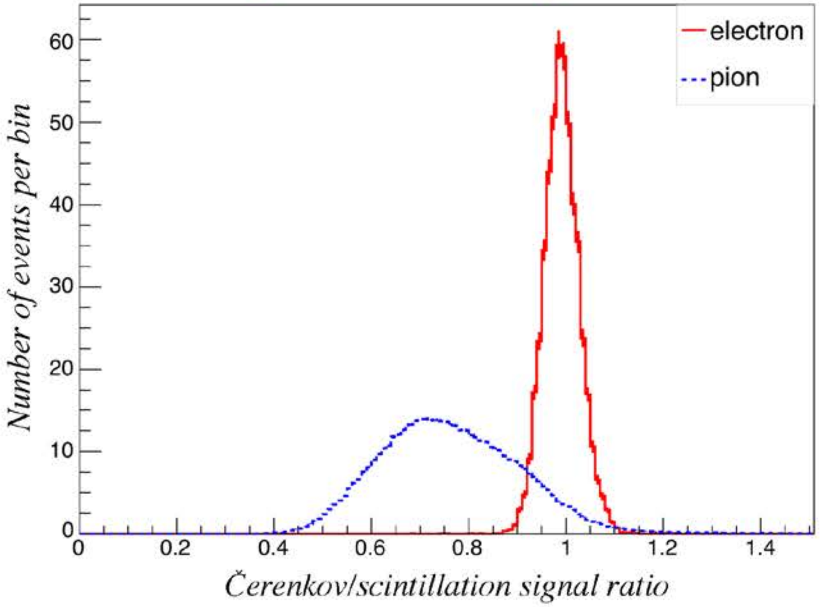
Methods to distinguish e/π in longitudinally unsegmented calorimeter

NIM A735 (2014) 120

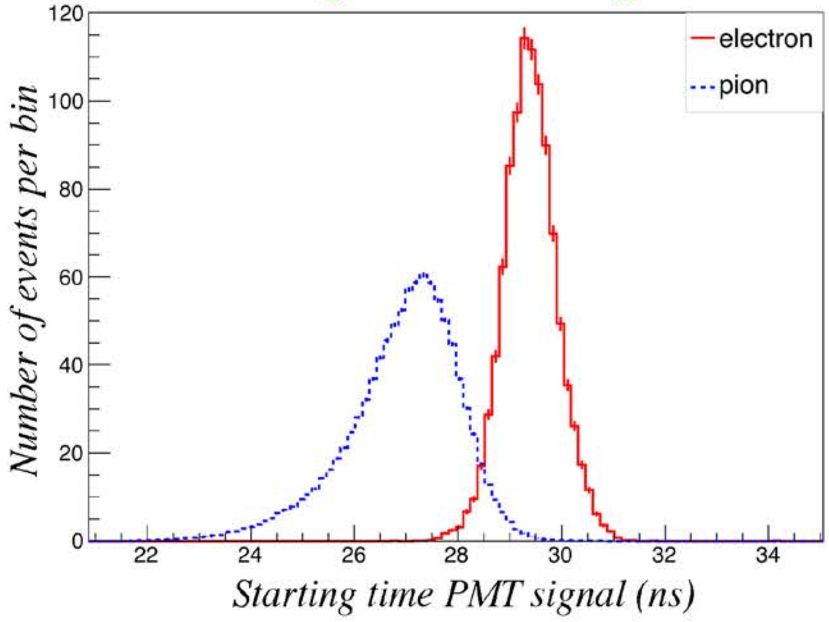
Lateral shower profile



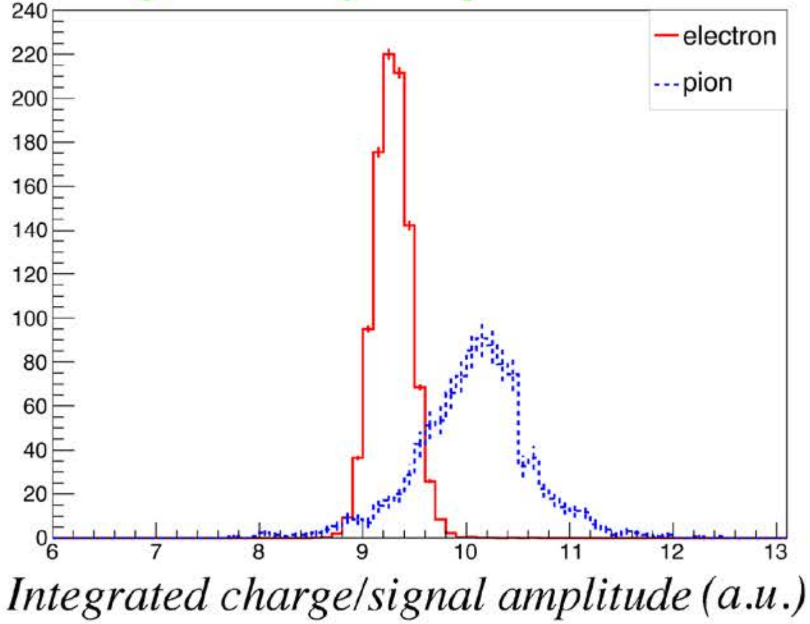
Difference C/S signals



Starting time PMT signal



Signal charge/amplitude ratio



Combination of cuts: Electron ID efficiency >99.8%, pion mis-ID probability <0.2%

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!!

Particle Flow Analysis

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

Important ingredients

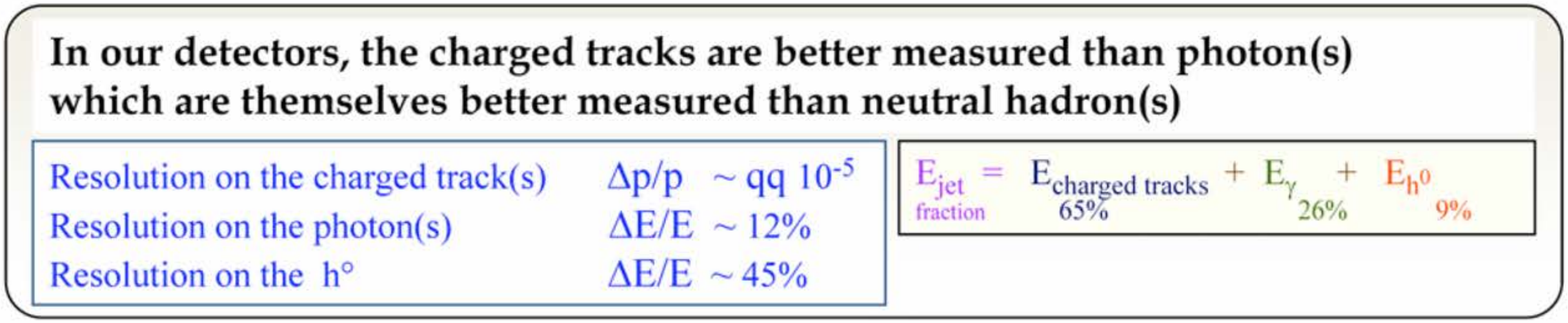
- *A large detector (i.e. tracking volume)*
- *A strong magnetic field*
- *An excellent tracker*
- *A poor detector for hadron showers*

→ *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*



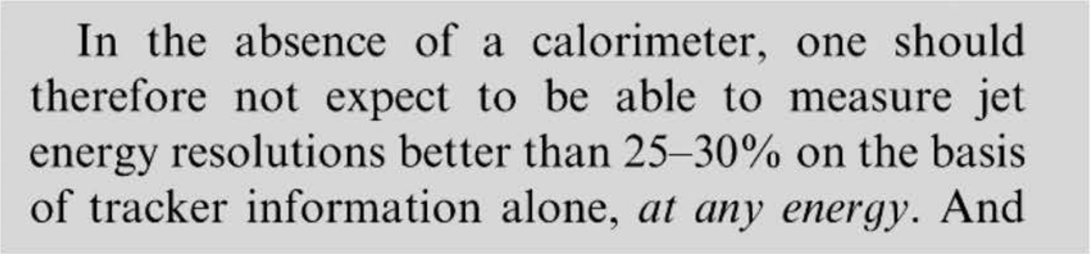
In our detectors, the charged tracks are better measured than photon(s) which are themselves better measured than neutral hadron(s)

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

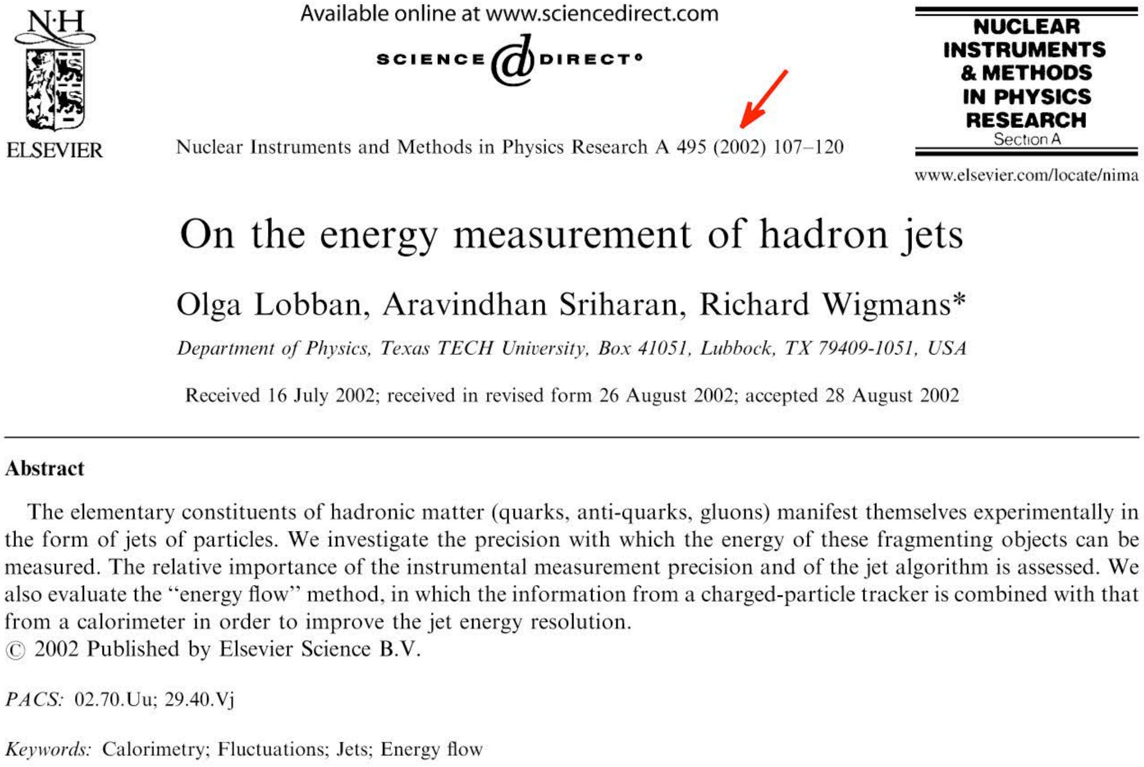
What matters for the jet energy resolution are the fluctuations in this 65%.



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

On high-resolution hadron calorimetry



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On the energy measurement of hadron jets

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Received 16 July 2002; received in revised form 26 August 2002; accepted 28 August 2002

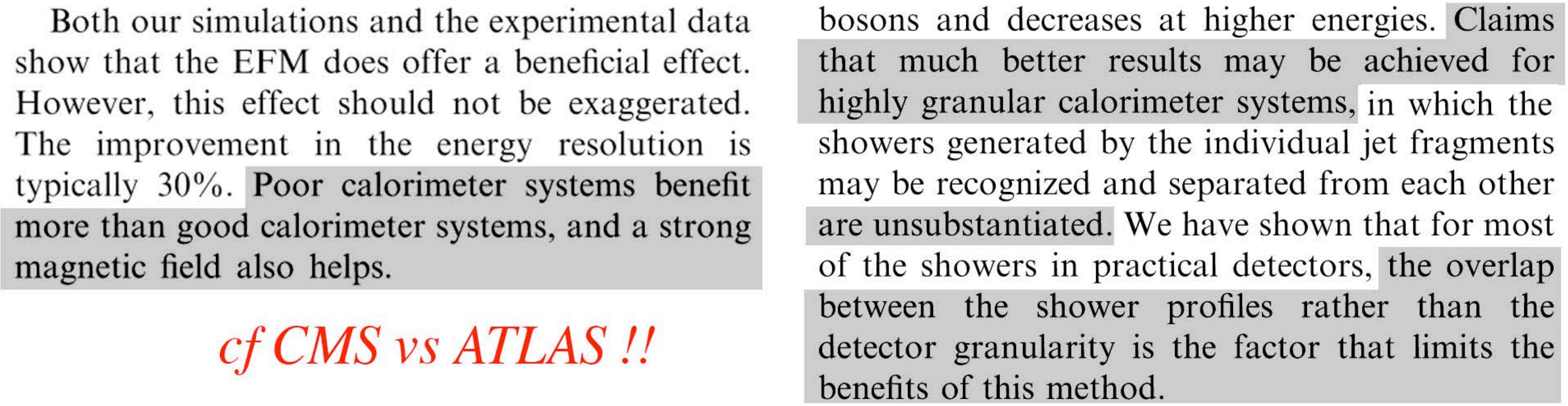
Abstract

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.

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.

cf CMS vs ATLAS !!

No experimental evidence to the contrary!!

Calibration

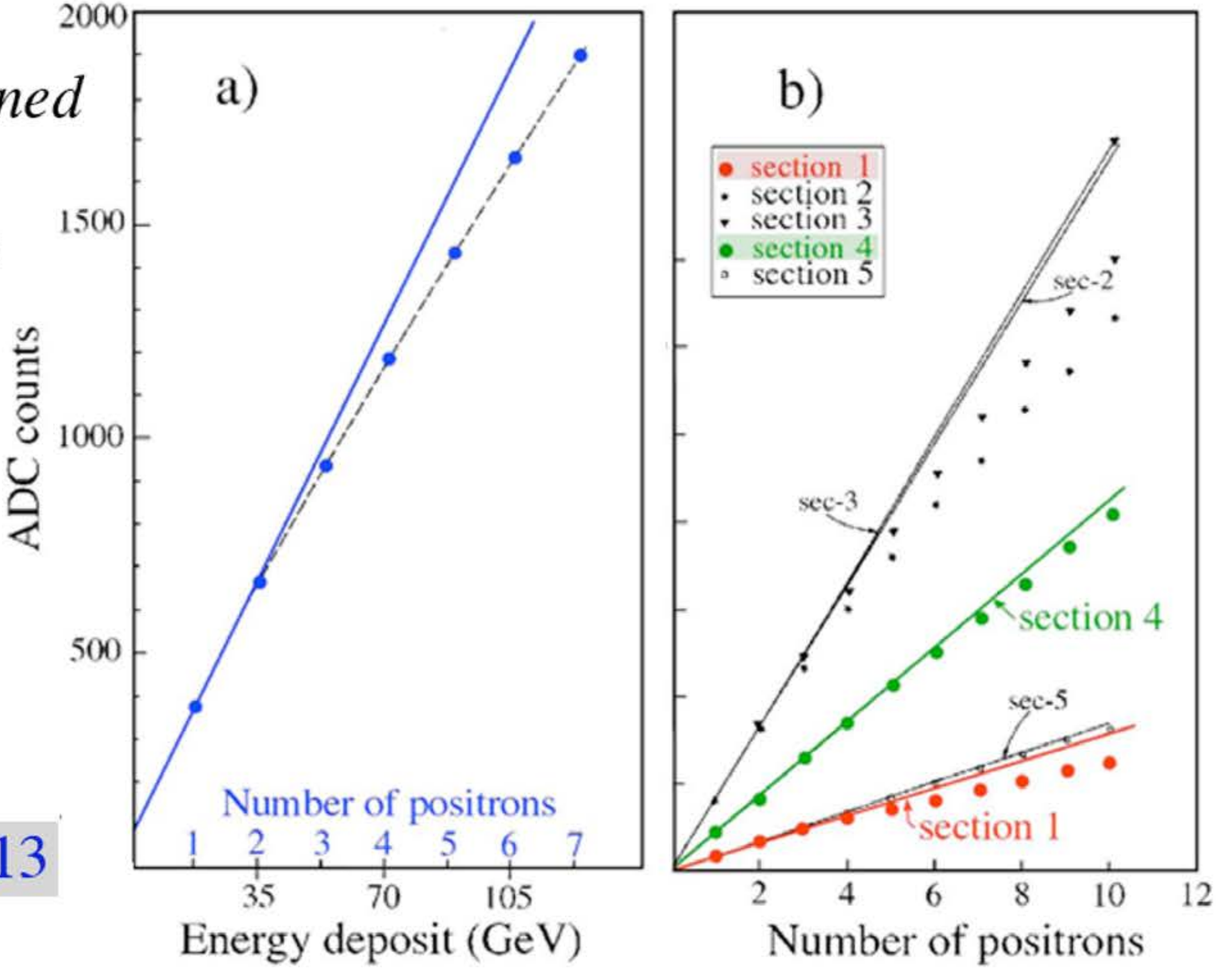
- *Proposed PFA systems consist of millions of readout channels (fine granularity!)*

  Question: How does one want to calibrate these calorimeters?

  Answer (CALICE): DIGITAL calorimetry (energy $\propto$ # of channels that fired)

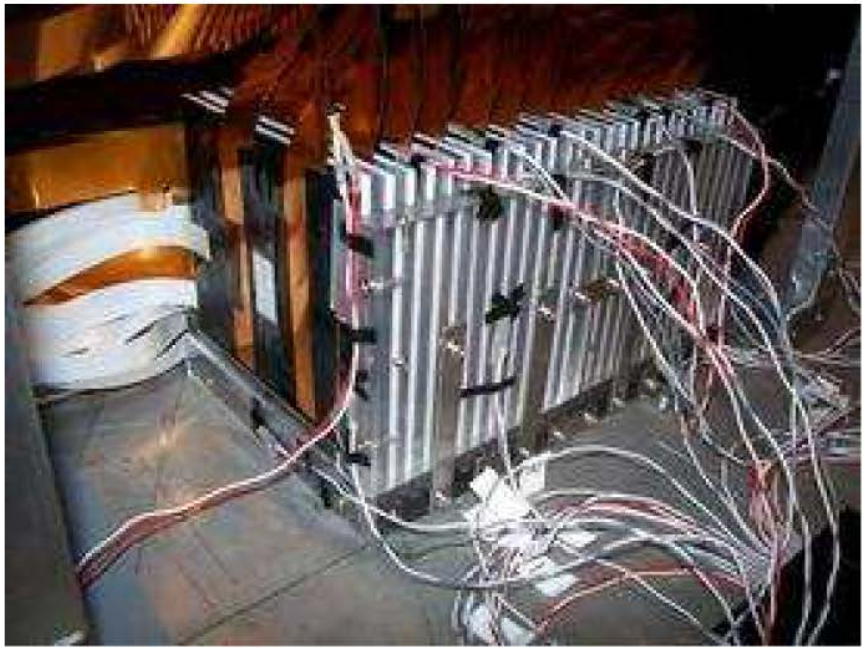
This was tried and abandoned in 1983, for good reasons: Particle density in the core of em showers is very high

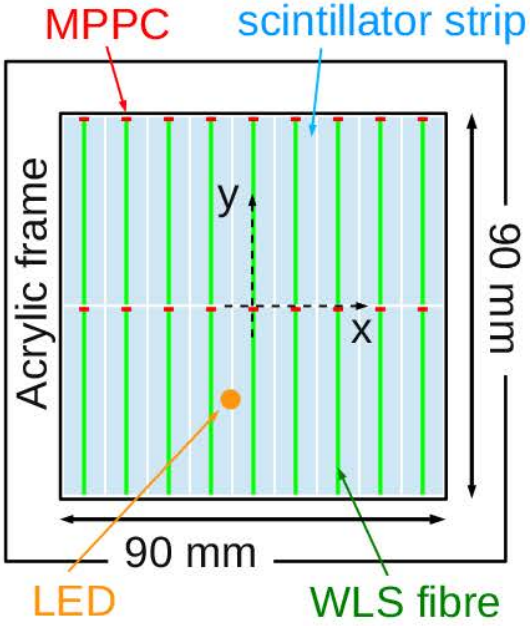
→ *Non-linearity*



From: NIM 205 (1983) 113

CALICE: A few recent results





ECAL prototype:

W/scintillator, MPPC readout.

26 layers, lateral granularity 10 x 10 mm^2

Dimensions: $4.1\ \rho_M \times 4.1\ \rho_M \times 22\ X_o$

Tested at DESY with 1 - 6 GeV/c positrons

The electromagnetic energy resolution

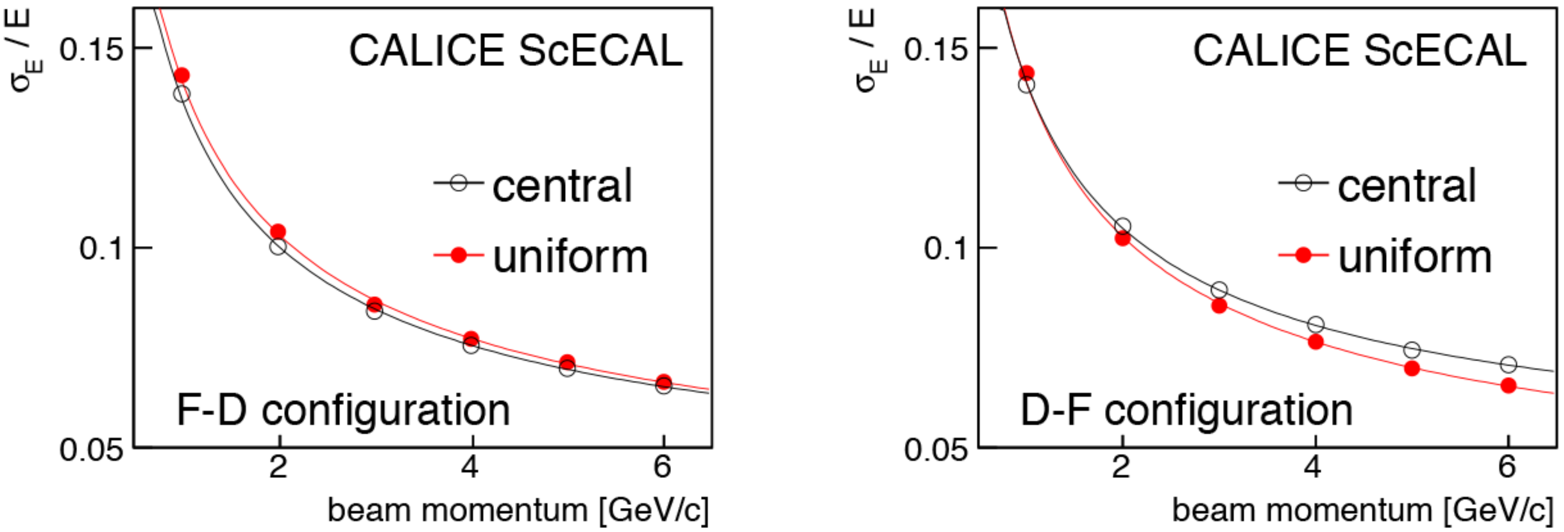


Figure 14: The energy resolutions measured using data taken with 1–6 GeV/c e^+ beams in the central and uniform regions of the two detector configurations. The results of the fits described in the text are also shown.

Fit results:

$$\sigma/E = \frac{(13.2 - 13.8)\%}{\sqrt{E}} \oplus (3.4 - 4.5)\%$$

Hadronic calorimeter prototype

Vienna Conference on Instrumentation
NIM A732 (2013) 466

Absorber: Tungsten or Steel

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

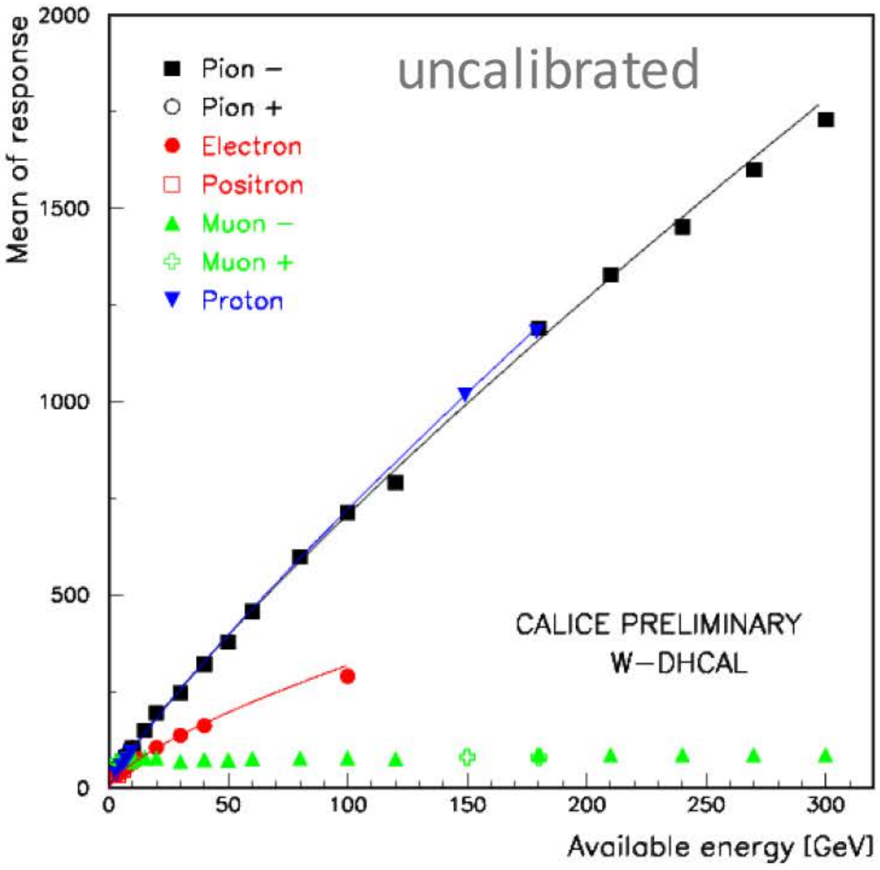
Dimensions: 54 layers, 1 x 1 m^2

~500,000 readout channels !!

Tested at CERN/FNAL, e/π 10 - 300 GeV

Test results digital hadron calorimeter CALICE

Tungsten – DHCAL



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

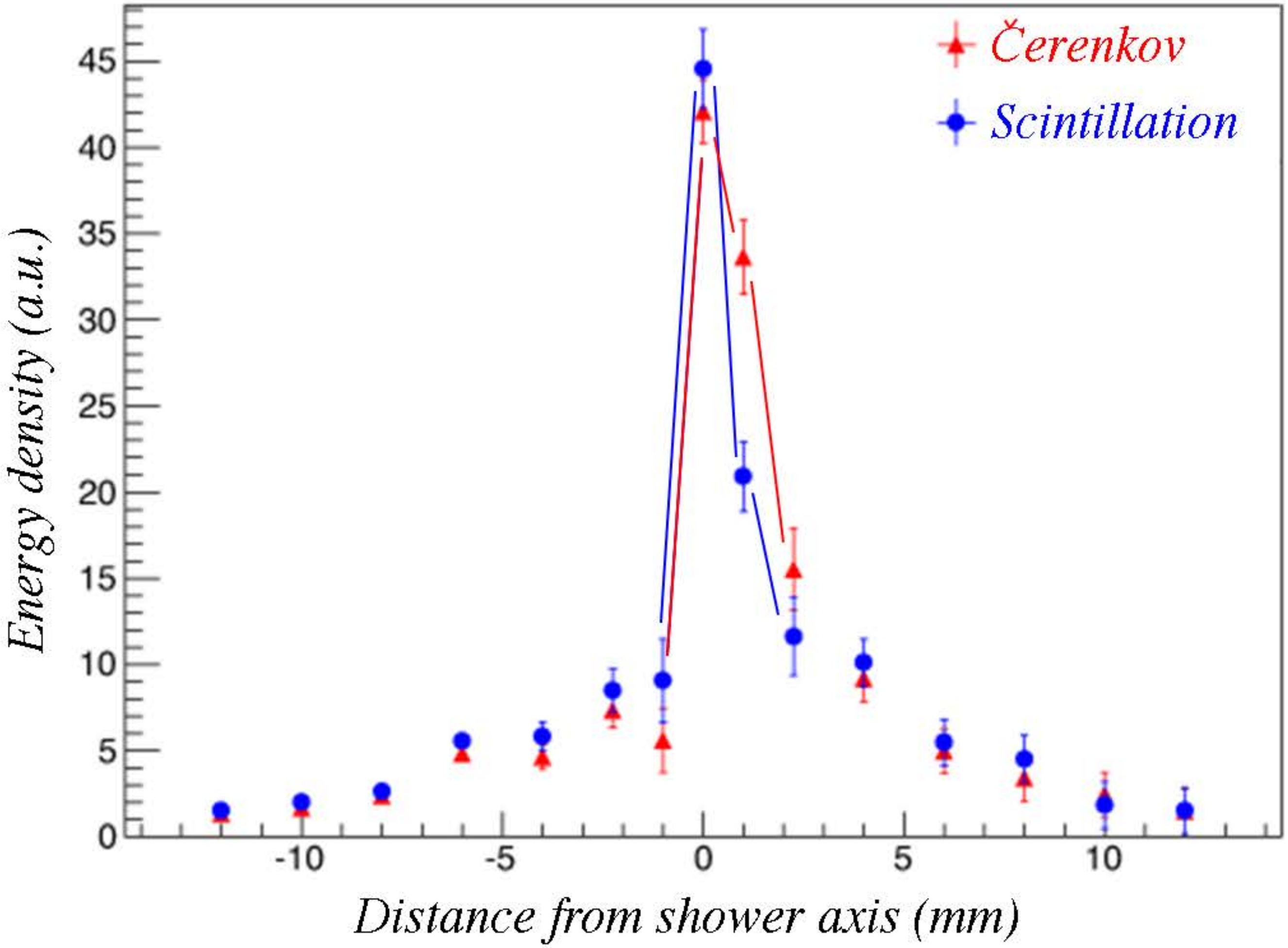
Both well described by
power law αE^{β}

Badly over-compensating
e/h ~ 0.9 – 0.5

→ need smaller readout pads !!!!

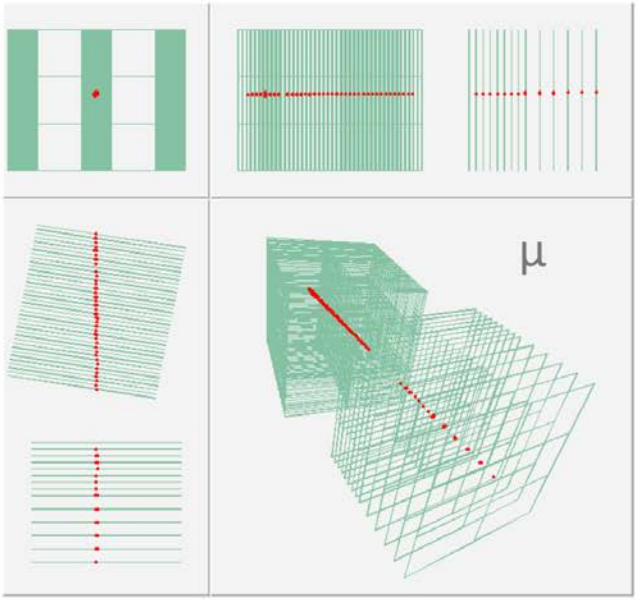
The extremely narrow electromagnetic shower profile

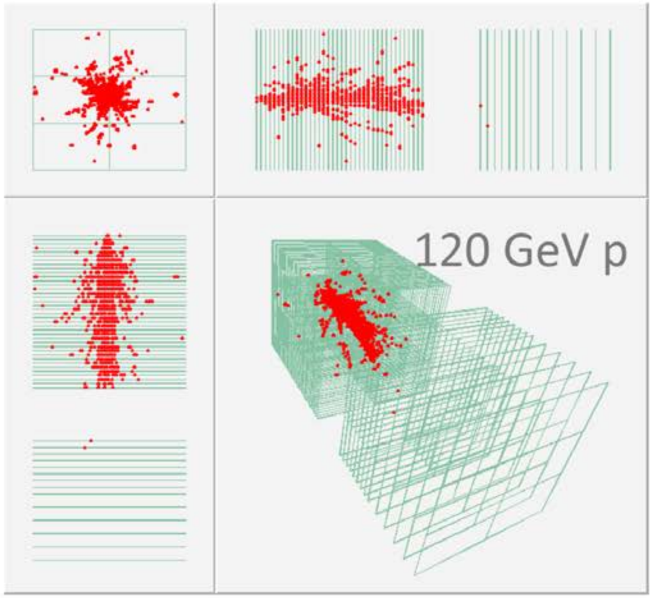
Lateral shower profile

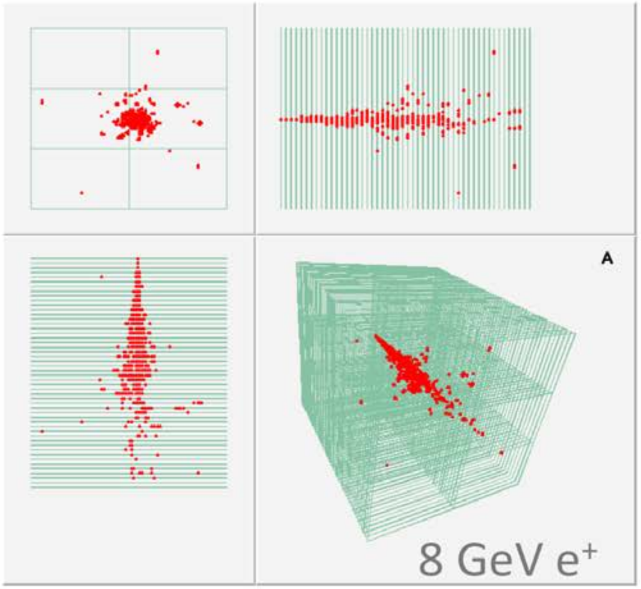


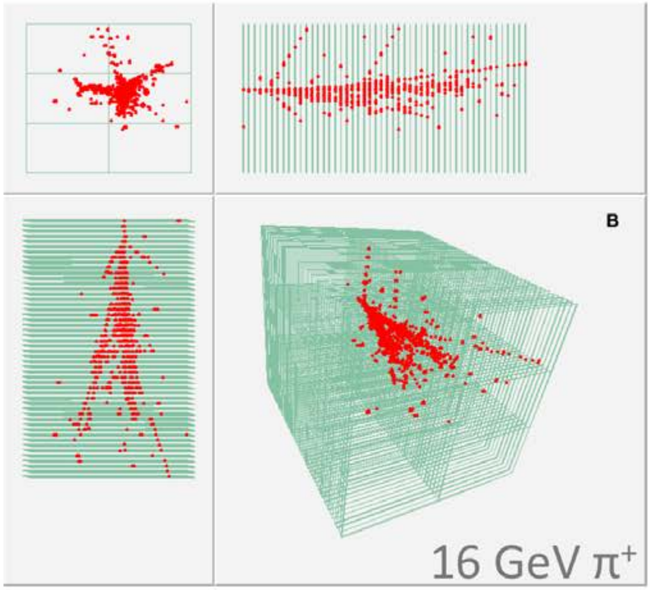
NIM A735 (2014) 130

Some events displays of the CALICE DHCAL









⟵ 1 m ⟶

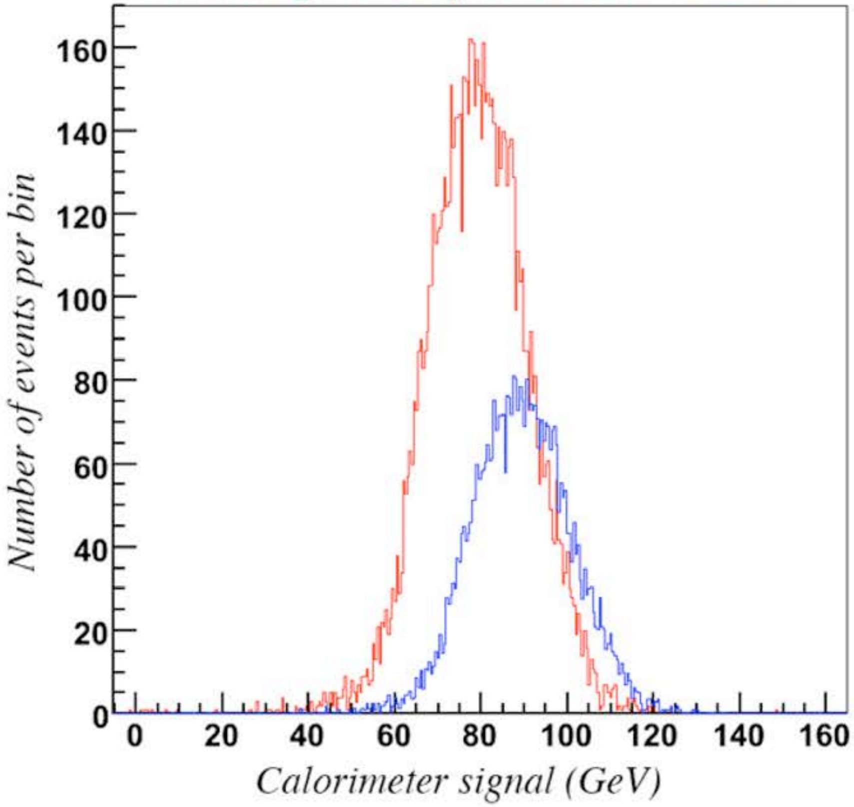
There exists no such thing as a TYPICAL event profile

Experimental tests: The proof is in the pudding

- *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.*

Example:
Jet response function CMS



- *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*

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

Compensation

Naive expectations for hadron calorimeters

Average composition of non-em shower component:

- *Pions, kaons,....*	*20%*	*(relativistic)*
- *Protons*	*25%*	
- *Neutrons*	*15%*	
- *Invisible*	*40%*	

		Exp. value
Cherenkov calorimeter:	$e/h = 1/0.2$	~ 5
Crystal calorimeter:	$e/h = 1/(0.2 + f_1 \,.\, 0.25)$ with $f_1 < 1$	> 2
LAr calorimeter:	$e/h = \frac{e}{mip}/(0.2 + f_1 \,.0.25)$, $0.6 < \frac{e}{mip} < 1$	$1.3\text{-}1.8^{*}$
Plastic-scint. calorimeter	$e/h = \frac{e}{mip}/(0.2 + f_1 \,.0.25 + f_2 \,.\, 0.15)$ with $f_2 > 1$	< 1.5

f_1 *describes signal saturation*

f_2 *the (tuneable) neutron efficiency*

Efficient neutron detection is also very important for hadronic energy resolution because kinetic energy neutrons correlated with invisible energy

Therefore, intrinsic resolution much better in ZEUS,SPACAL than in D0

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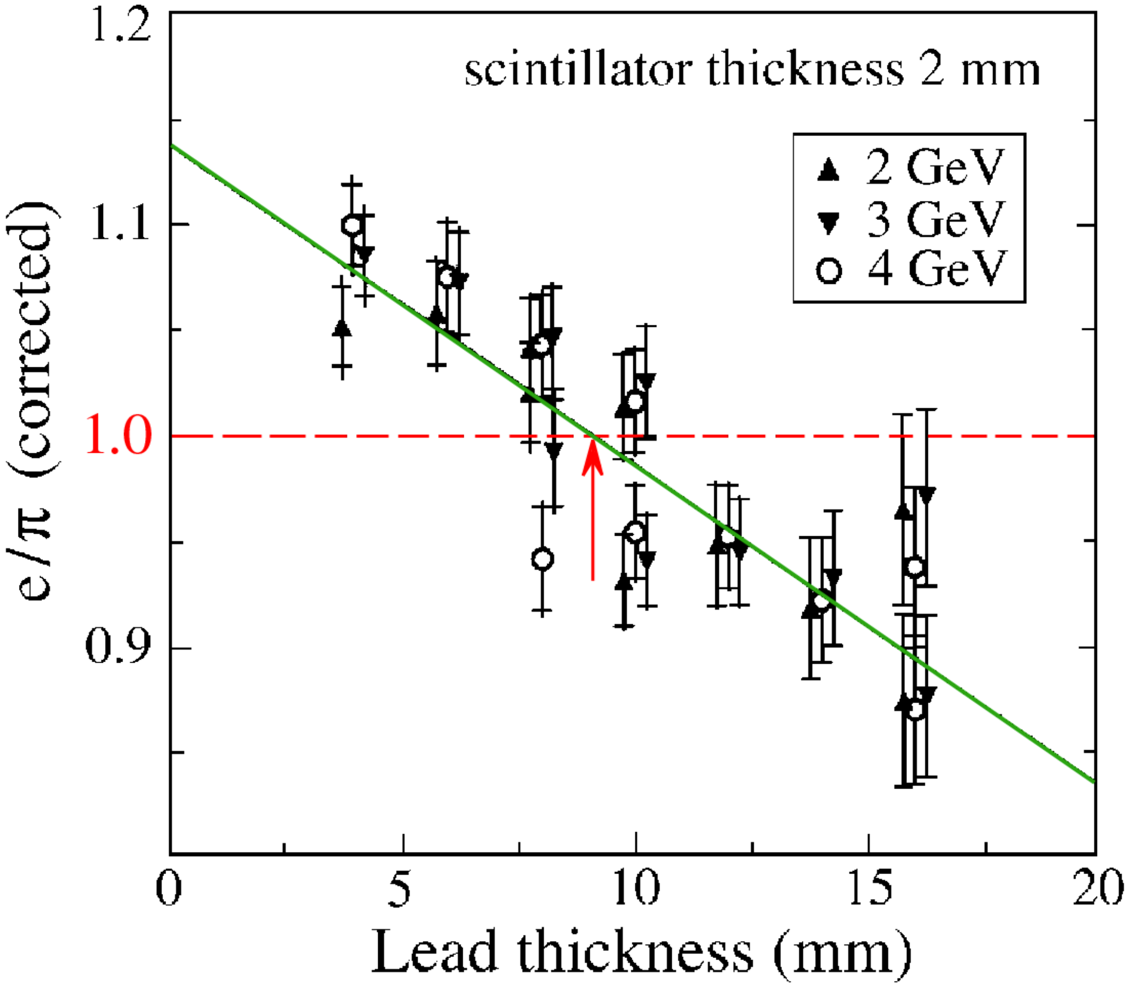
* *Except for uranium absorbers (fission energy)*

High-resolution jet spectroscopy (2)

1. Compensating Pb/scintillator calorimetry

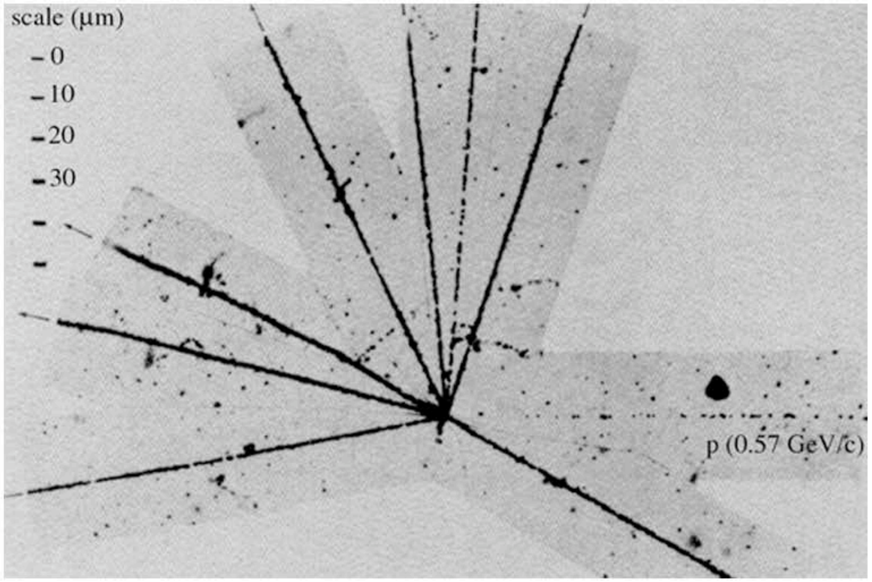
JLC prototype studies: NIM A432 (1999) 48



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.

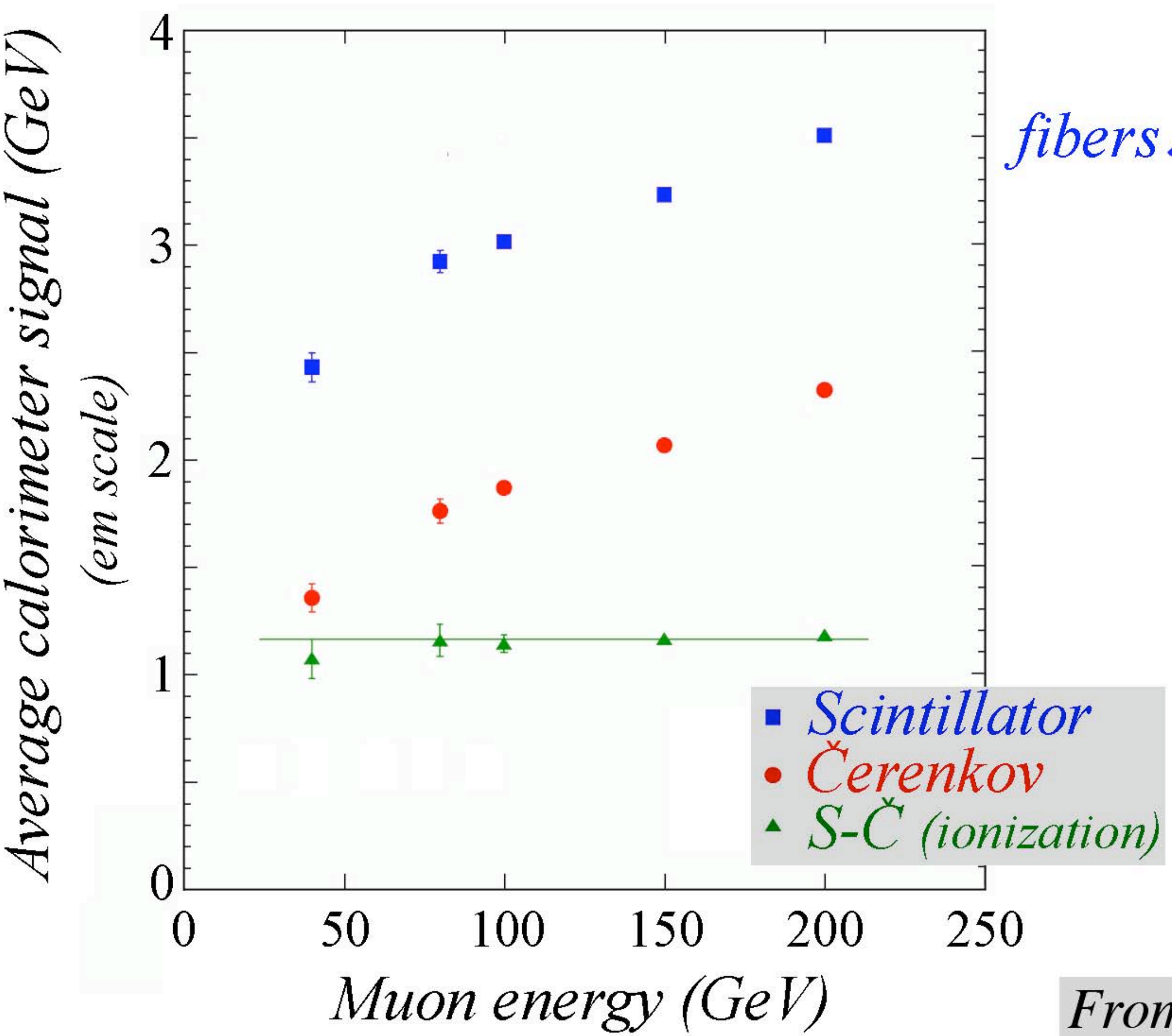
Example: In CMS ECAL, such events may fake energy deposits of tens of GeV.

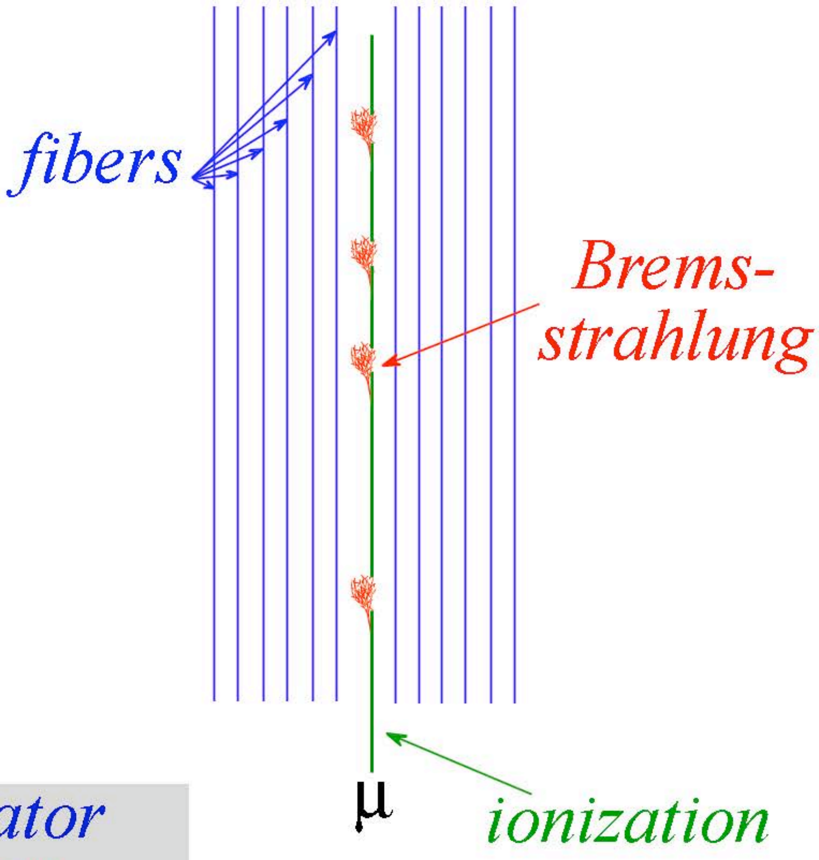
- *"Digital" calorimetry was tried and abandoned for good reasons (1983)*

DREAM

Calorimetric separation of ionization / radiation losses

Muon signals in the DREAM calorimeter

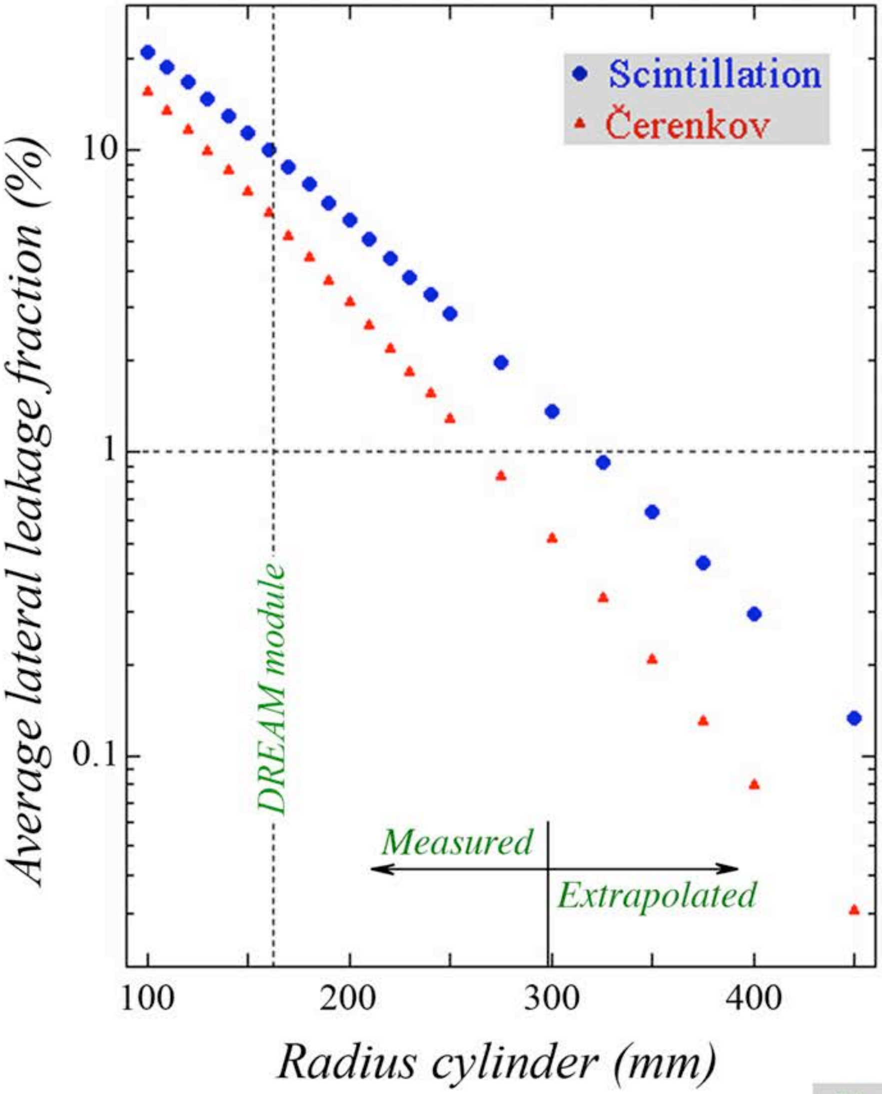


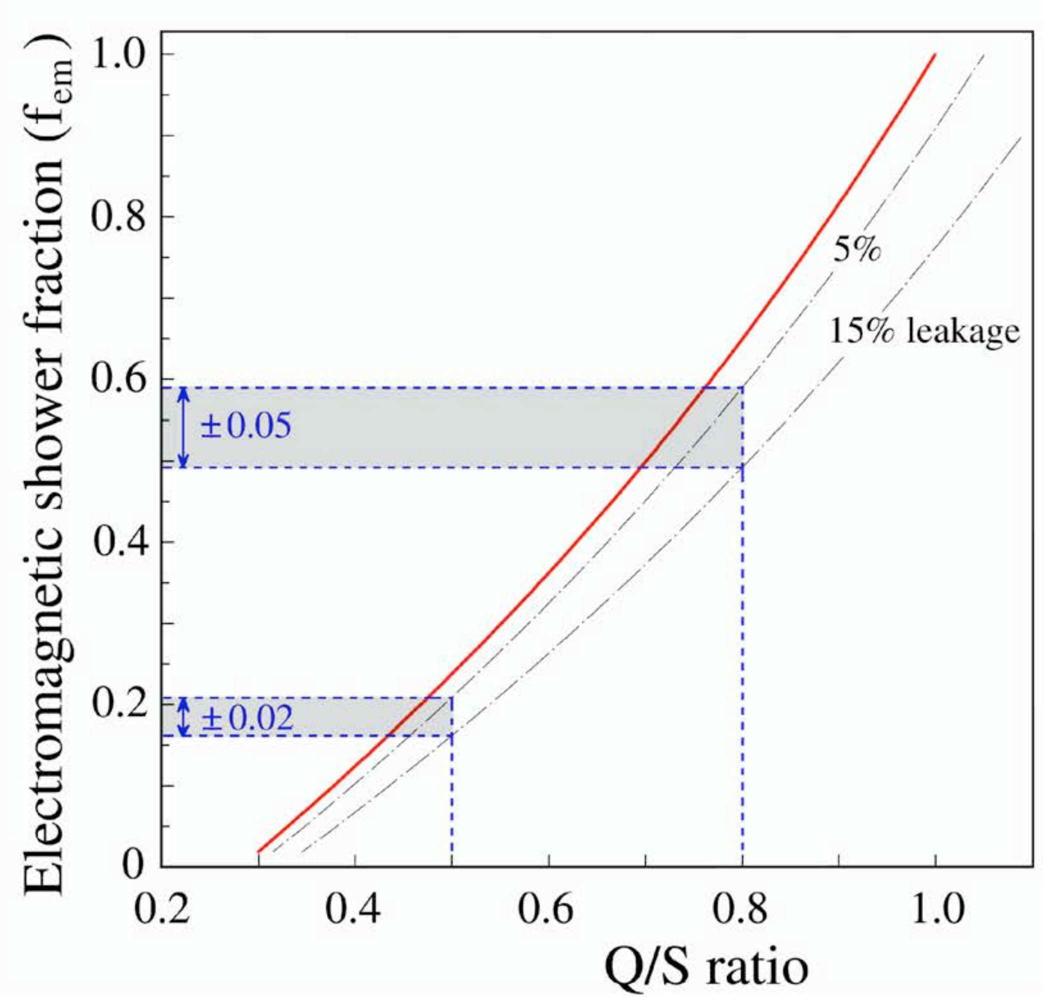


From: NIM A533 (2004)305

DREAM: The importance of leakage and its fluctuations

Lateral shower containment (π)





From:
NIM A584 (2008) 273

Neutron information can be used to improve the response function and the energy resolution

From: NIM A598 (2009) 422

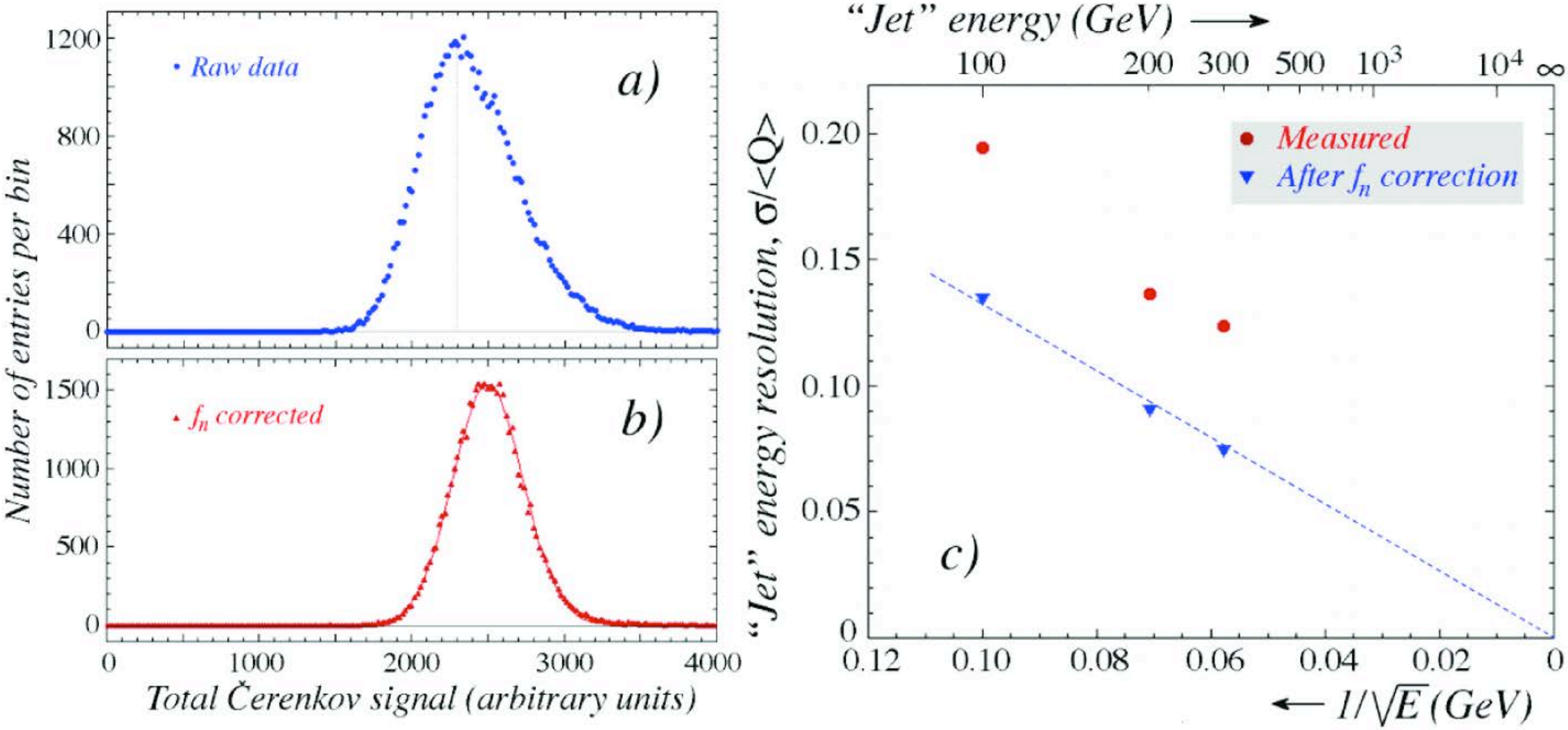
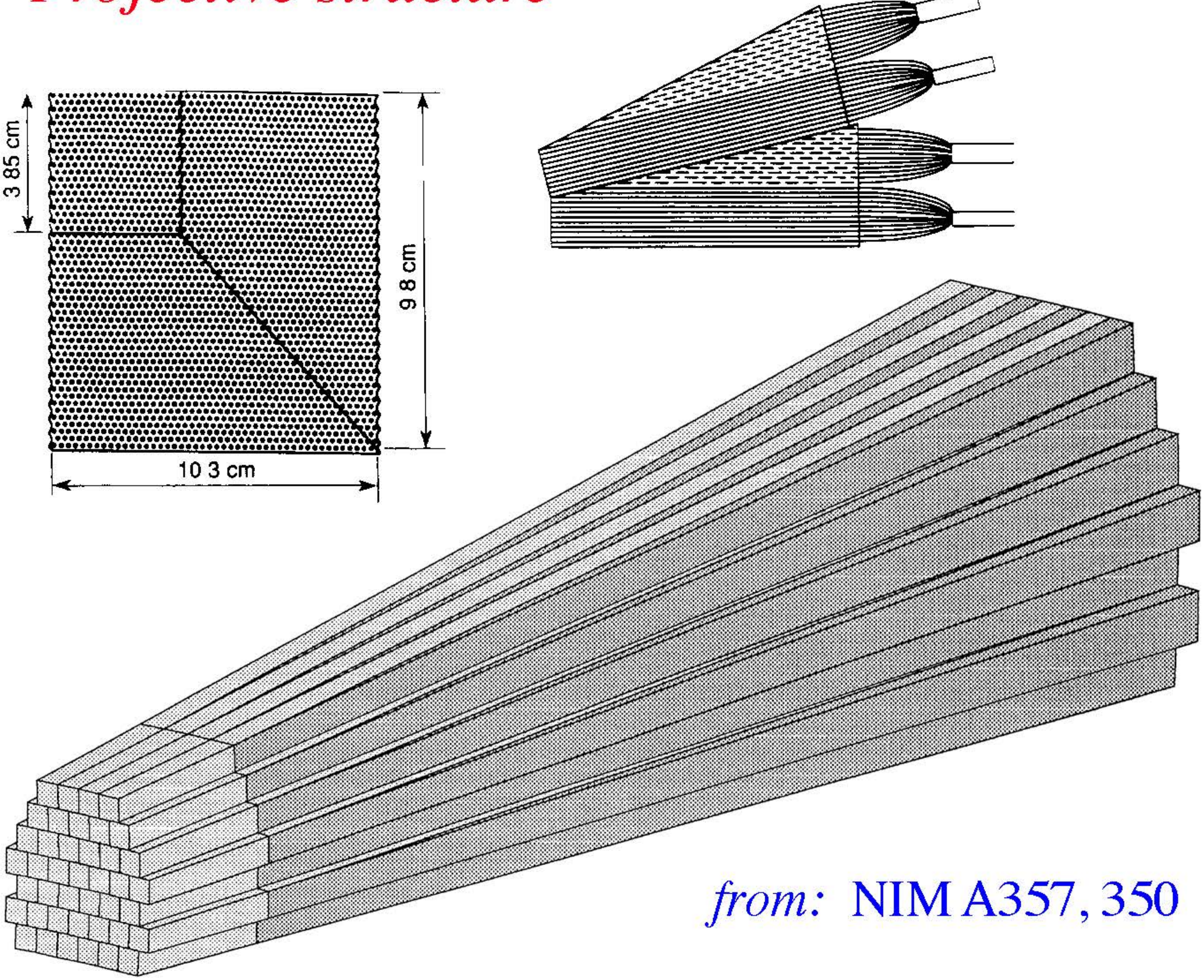


Figure 19: Distribution of the total Čerenkov signal for 200 GeV "jets" before (a) and after (b) applying the correction based on the measured value of f_n, described in the text. Relative width of the Čerenkov signal distribution for "jets" as a function of energy, before and after a correction that was applied on the basis of the relative contribution of neutrons to the scintillator signals (c).

Projective structure



from: NIM A357, 350

A crucial feature: No longitudinal segmentation

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

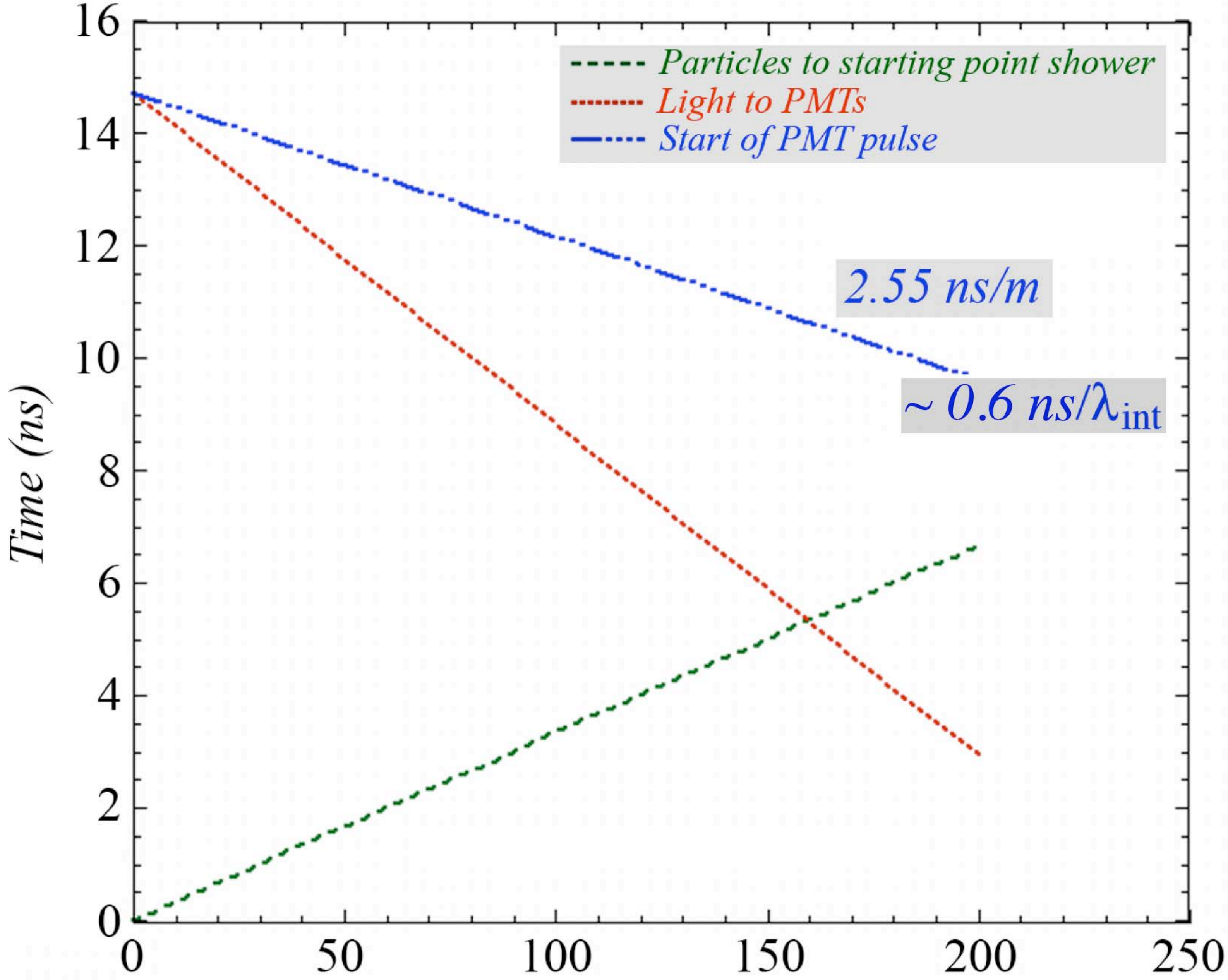
- *Possible disadvantages:*
  - *Dealing with pile-up (not an issue at ILC)*
  - *Pointing for neutral particles*
  - *Electron ID*

However, a fine lateral granularity can do wonders

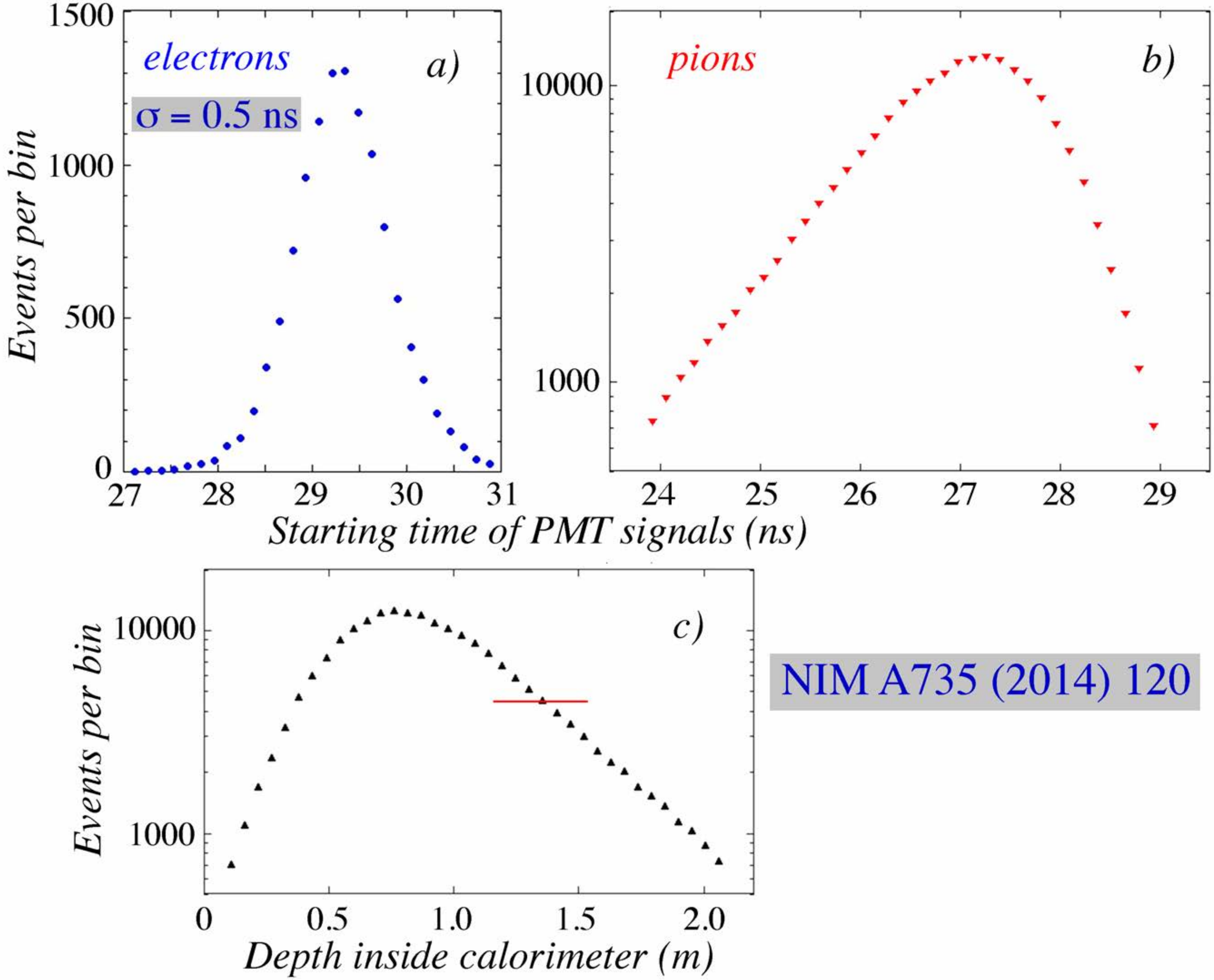
In addition:

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

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

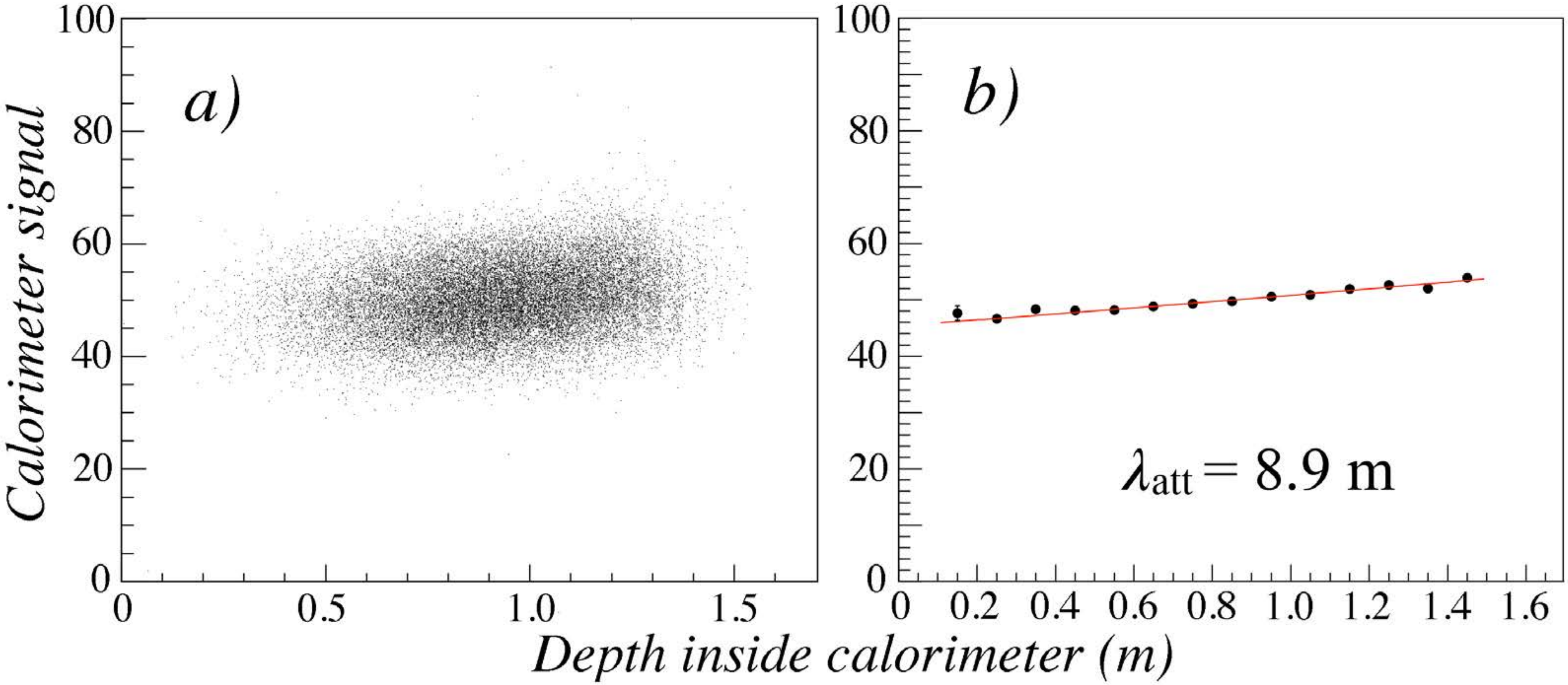


Use starting time PMT signal to determine the depth of the light production and thus identify particle

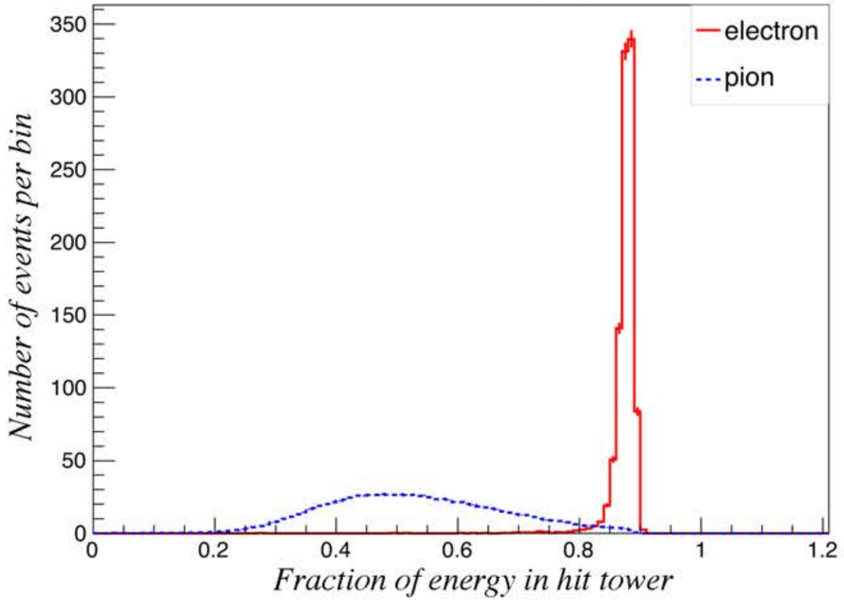


NIM A735 (2014) 120

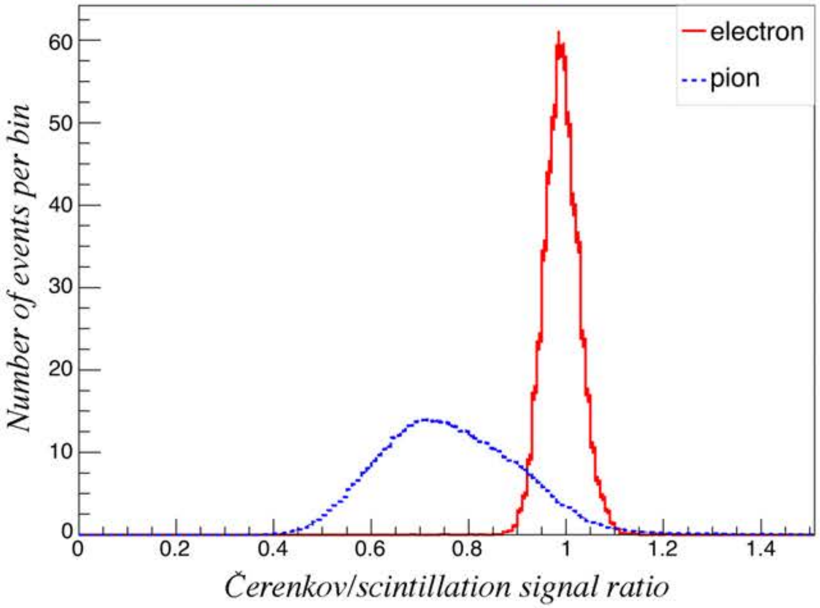
Use depth of light production to correct for light attenuation



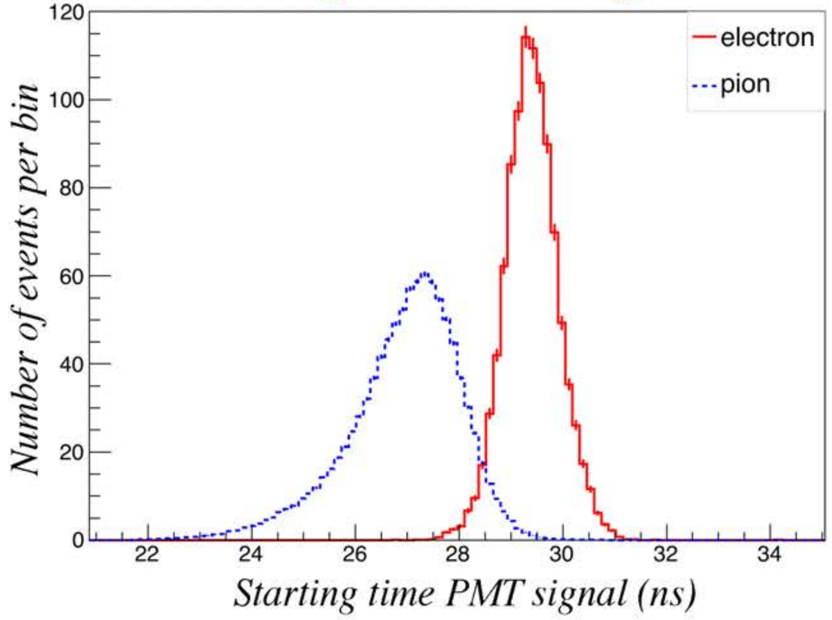
Methods to distinguish e/π in longitudinally unsegmented calorimeter



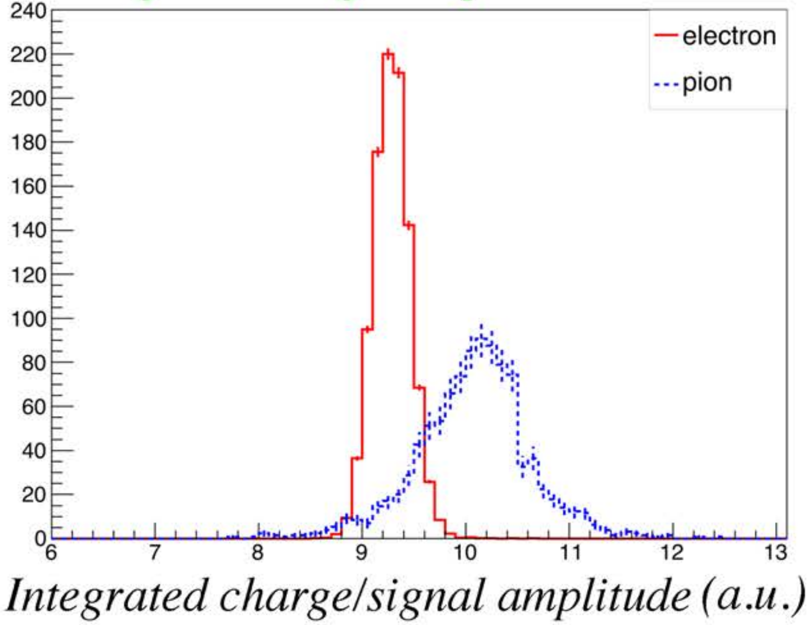
Lateral shower profile



Difference C/S signals



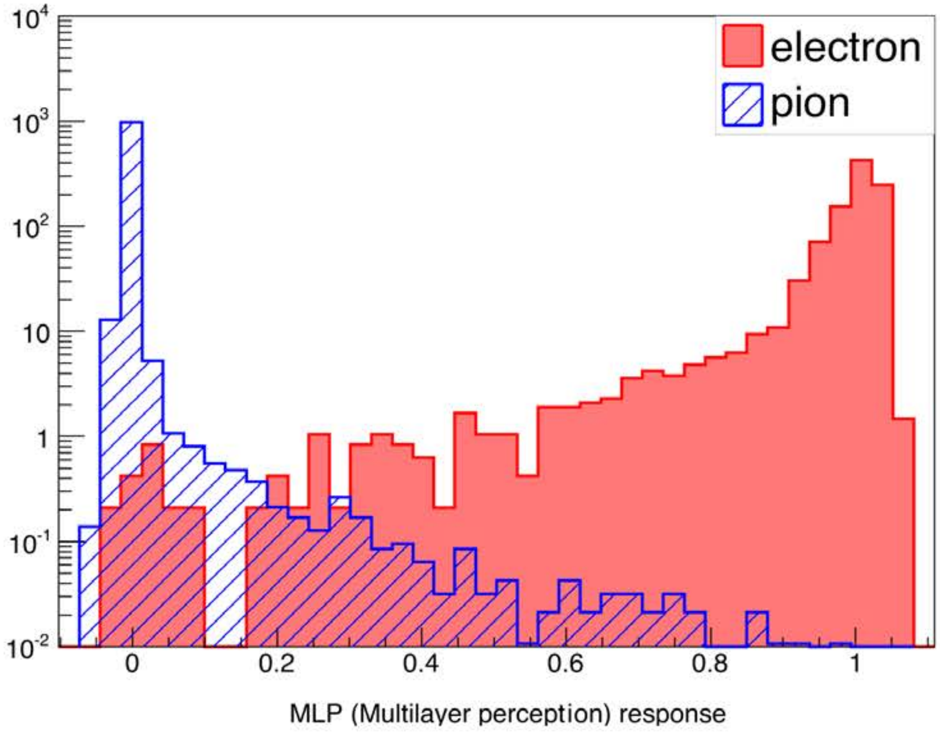
Starting time PMT signal

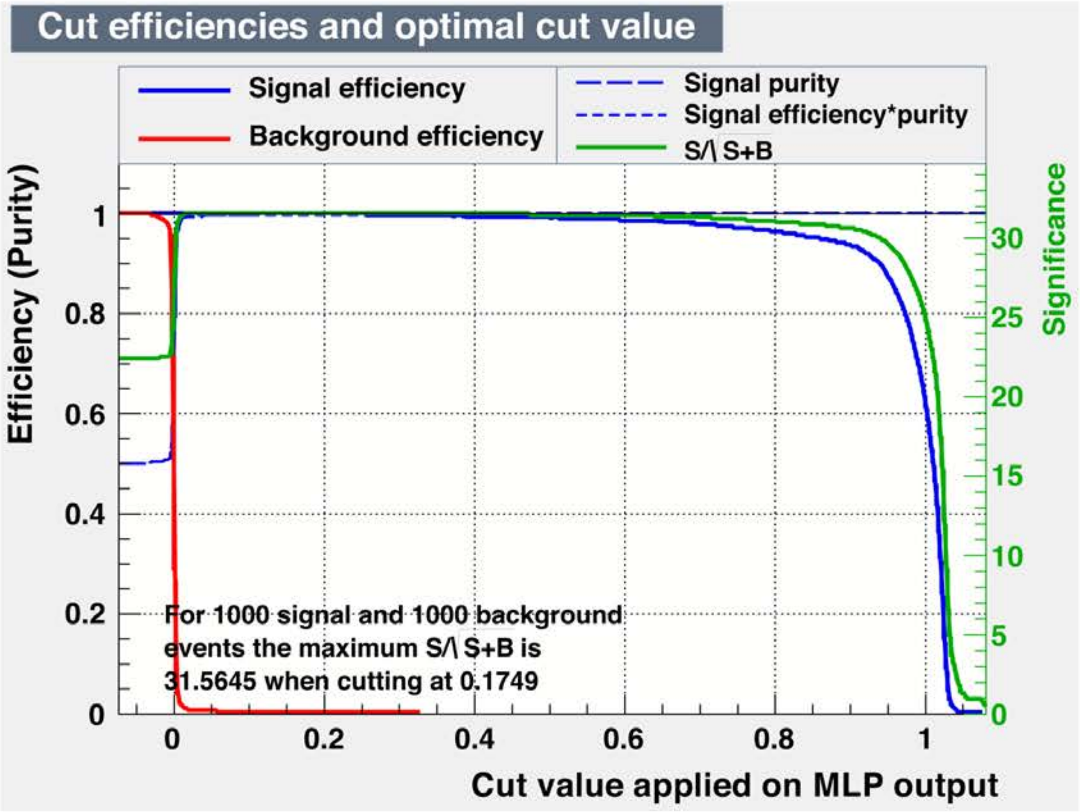


Signal charge/amplitude ratio

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

Neural network analysis 60 GeV e/π separation





for MLP > 0.17 : 99.81% electron ID

0.20% π mis-ID

NIM A735 (2014) 120

Advantages / disadvantages HHCAL concept

Advantages:

- *No sampling fluctuations*
- *Some calibration problems characteristic for sampling calorimeters don’t play a role*

Disadvantages:

- *No sensitivity to neutrons, and thus to invisible energy fluctuations*
- *Light attenuation*
- *Readout*
- *COST*

Monte Carlo

The crucial elements of hadronic shower simulations

The *non-electromagnetic* shower component

A very large fraction (> 80%) of the calorimeter signal from this component is caused by *protons* and other nuclear fragments. Pions and other mips play, at best, only a minor role.

It is, therefore, crucial to simulate the processes in which these protons are being produced, as accurately as possible.

→ *Nuclear breakup* processes determine many aspects of the hadronic calorimeter performance

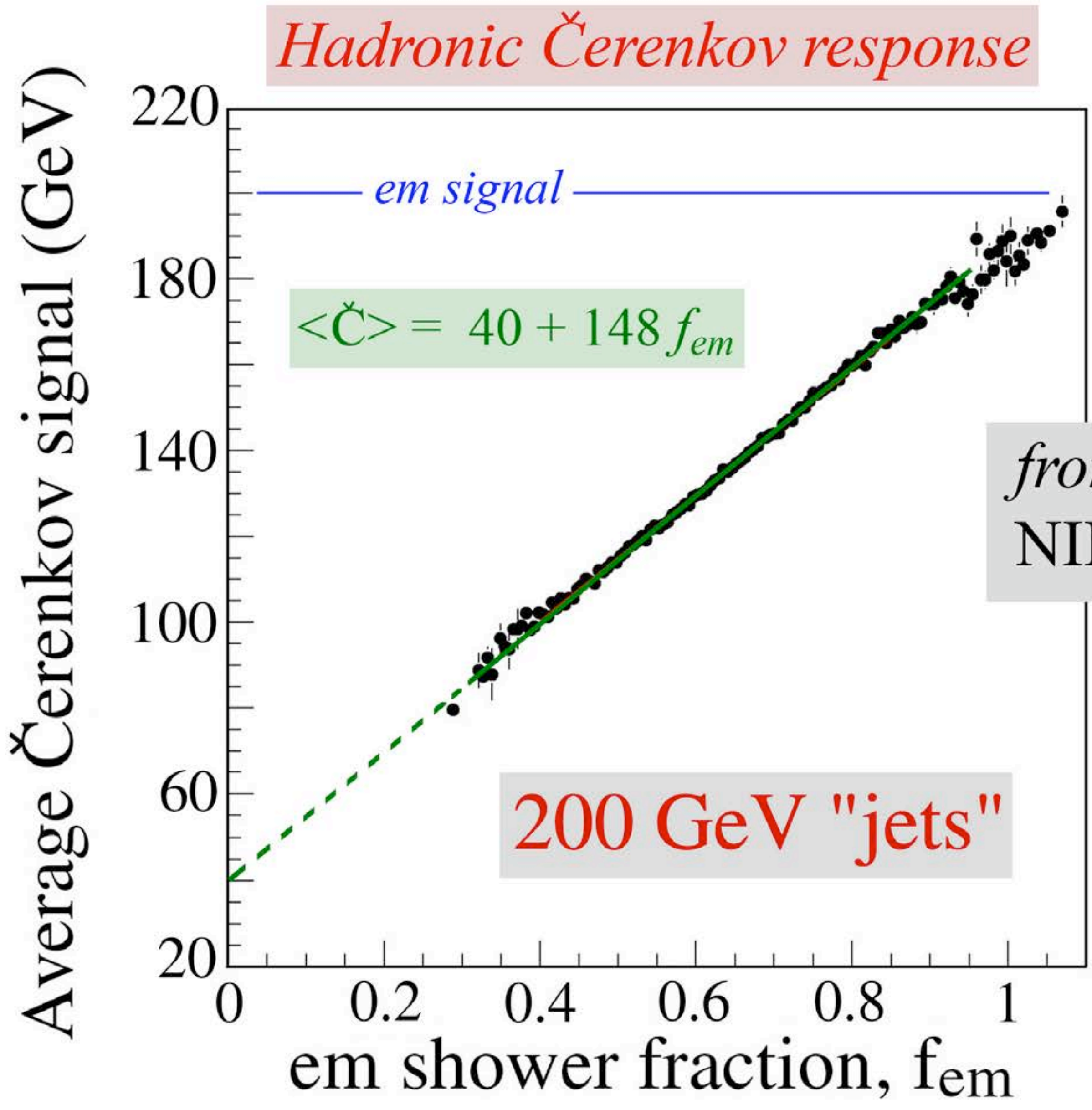
The non-electromagnetic shower component (1)

How do we know that protons dominate non-em signal?

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



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

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 non-em signal?

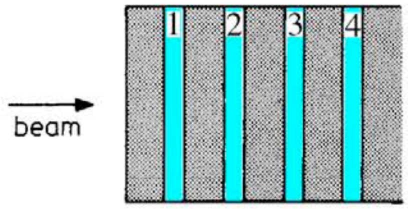
1) Because of the small hadronic signals (i.e. large e/h values) of calorimeters that are blind to these protons.

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

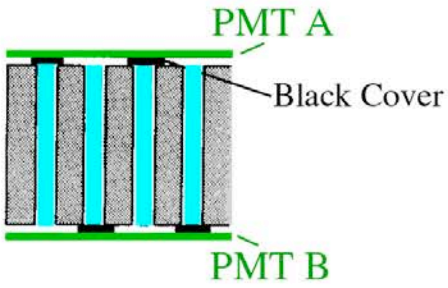
2) Because of the absence of correlations between the signals from adjacent active layers in fine-sampling hadron calorimeters

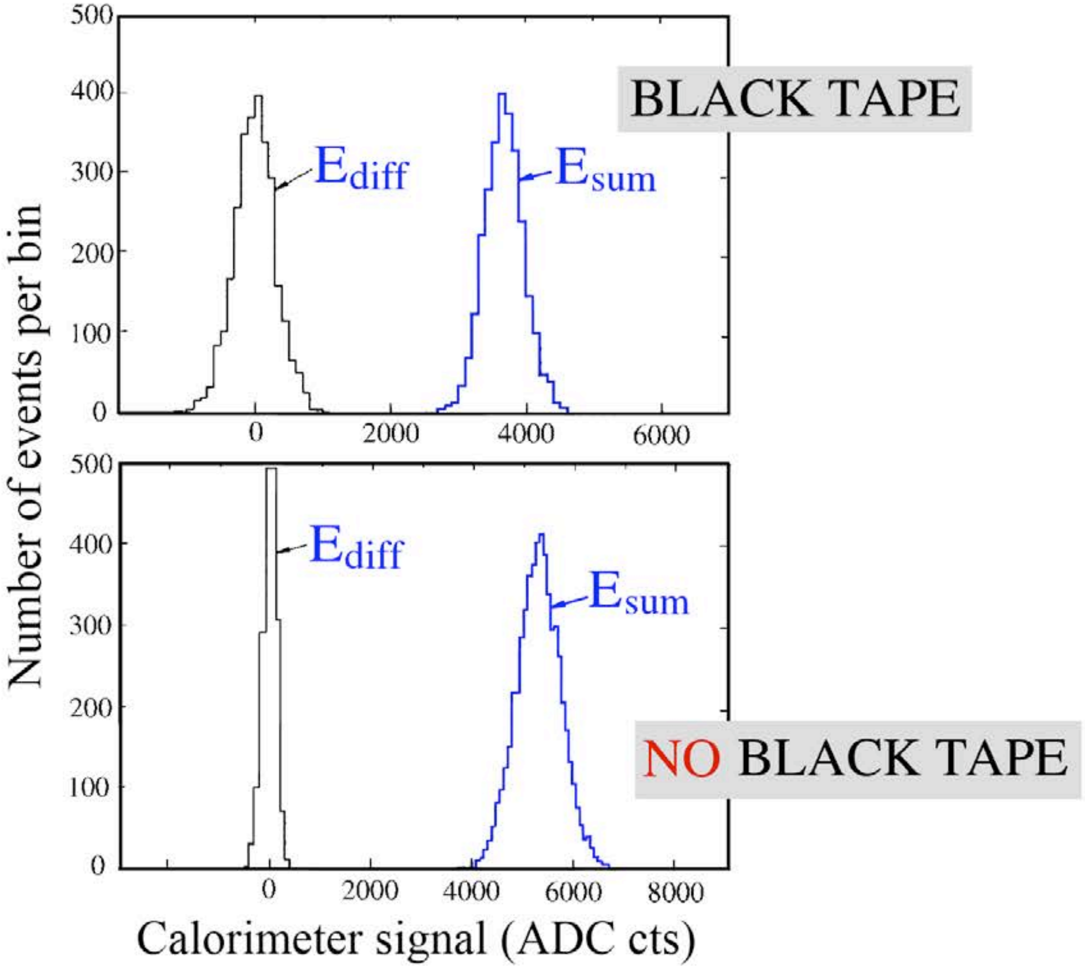
The calorimeter from the example had 0.06 $\lambda_{\rm int}$ thick sampling layers.
A mip would lose on average 12.7 MeV traversing these layers.

Correlations between signals from different sampling layers



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





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.

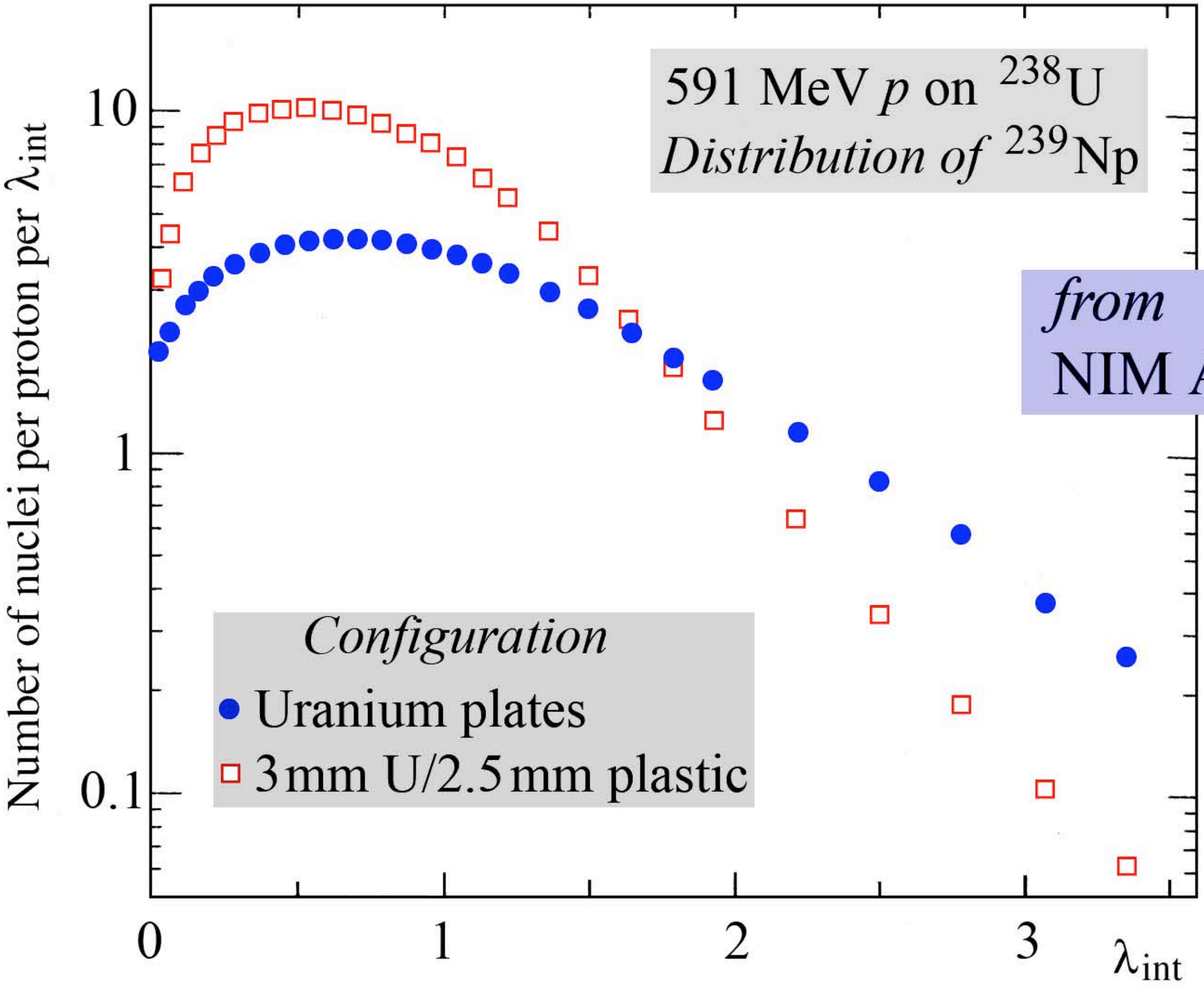
Spallation protons typically carry ~ 100 MeV kinetic energy.
Their range is typically of the order of the thickness of sampling layers in hadron calorimeters.

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)

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

EFM

Resolution improvement expected with EFM

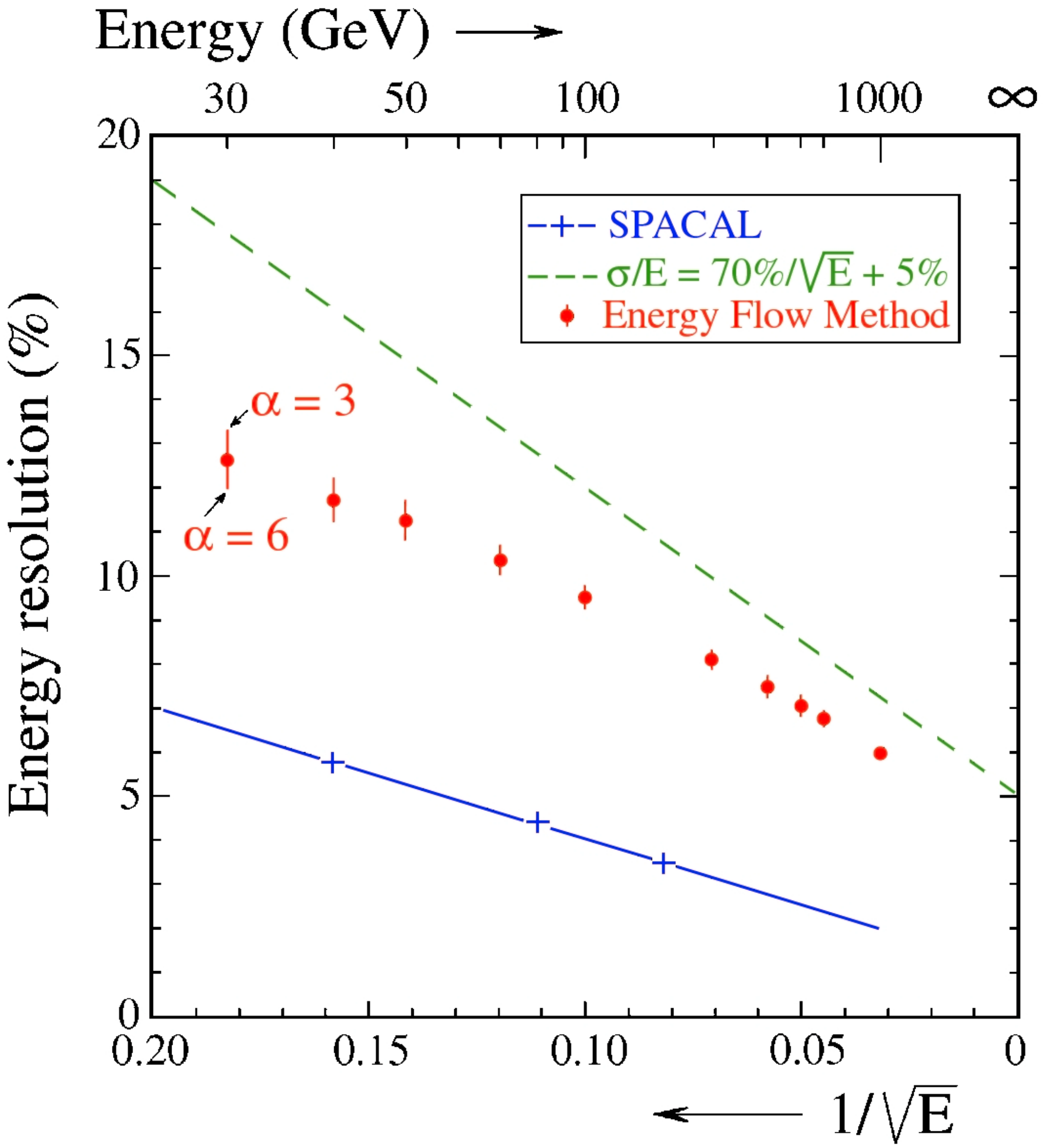


Fig. 11. The jet energy resolution as a function of energy, obtained after applying the Energy Flow Method (the black dots), using simulated data from a calorimeter with a jet resolution given by the dashed curve. For comparison, the jet resolution of a compensating calorimeter is given (SPACAL [7], the dotted curve). From: NIM A495 (2002) 107.