Calorimetry in the 21st century

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Decisions about the future require a good understanding of the past

Outline:

- *A brief history (50 years) of calorimetry*
- *Common misconceptions*
- *Options for the future*
- *Conclusions*

Some milestones in the development of calorimetry

as an experimental technique

in nuclear, particle & astrophysics

in the past 50 years

Milestones

- 1965 - *Quantum leap in signal quanta (e-h pairs in semiconductors)*

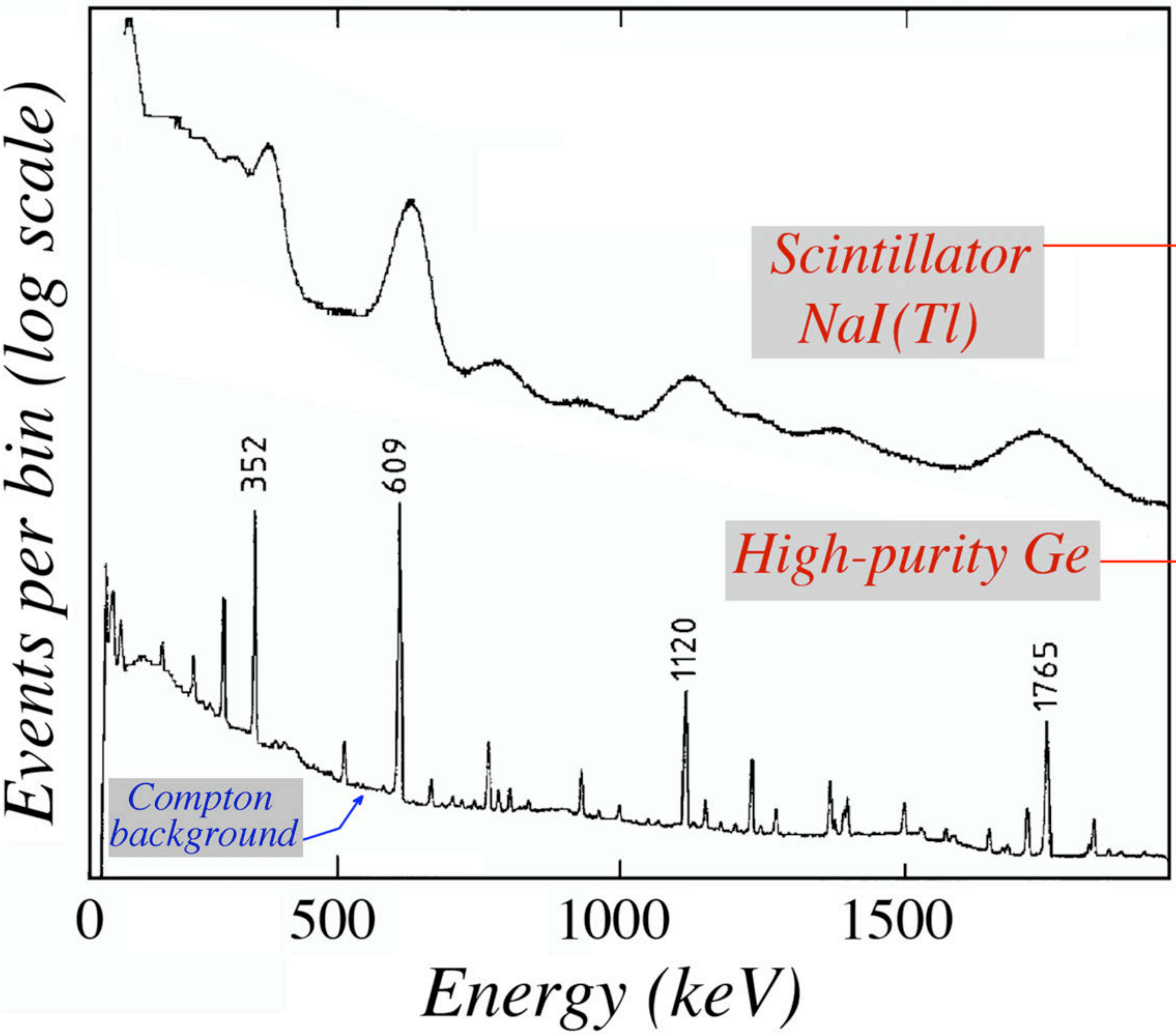
Performance of calorimeters *improves with energy*
(~ $E^{-1/2}$ if statistical processes are the limiting factor)

$$If\ E \propto signal,\ i.e.\ E \propto \#\ signal\ quanta\ n \longrightarrow \sigma(E) \propto \sqrt{n}$$

$$\longrightarrow energy\ resolution\ \frac{\sigma(E)}{E} \propto 1/\sqrt{n} \propto 1/\sqrt{E}$$

Nuclear γ ray detectors

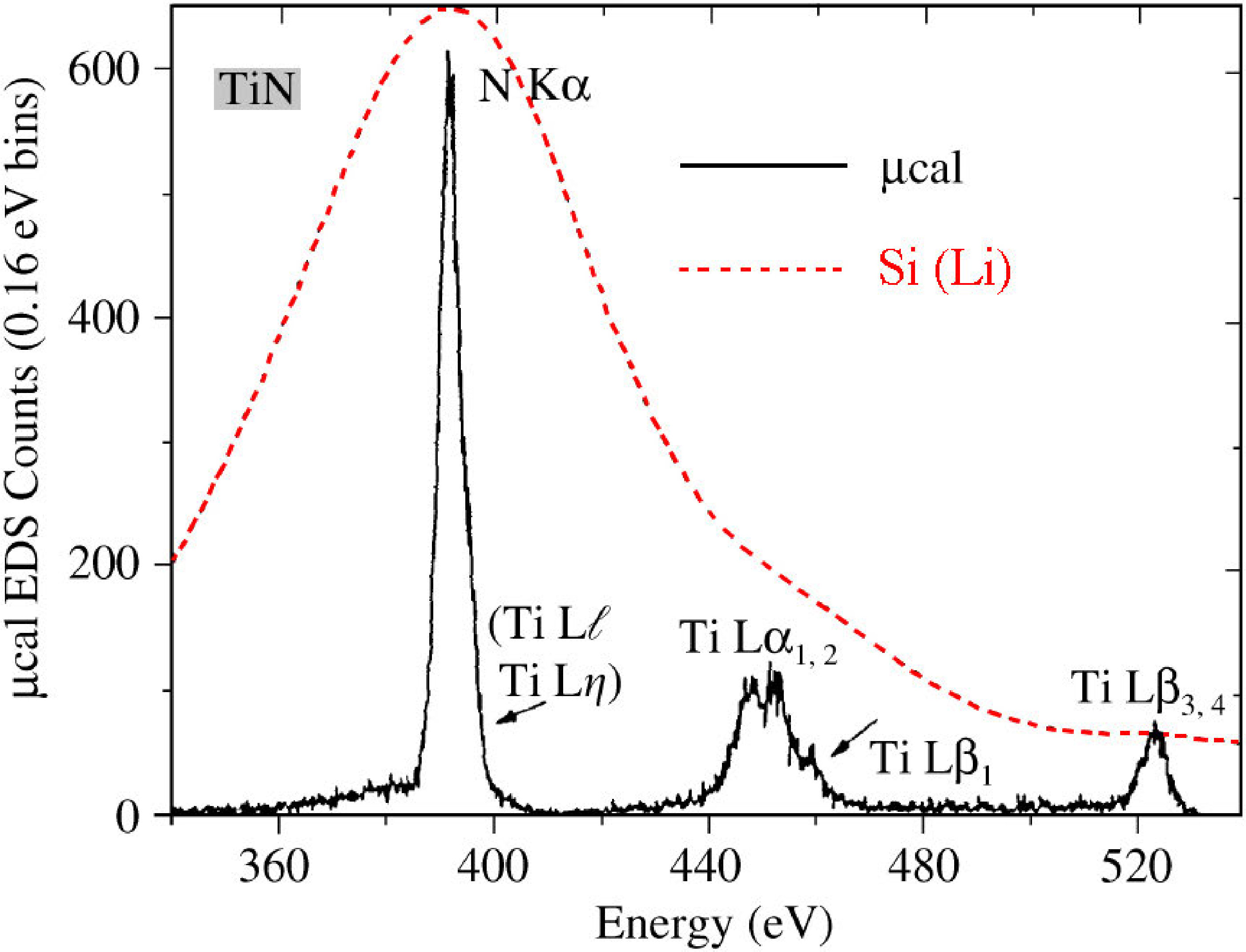
Energy resolution dominated by signal quantum fluctuations (?)



~100 eV per photon
10 000 photons/MeV

2.9 eV per e-h pair
350 000 pairs/MeV
$\sigma/E \sim 0.2\%$

One can do even better in cryogenic calorimeters! *(binding energy Cooper pairs ~ meV)*



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*

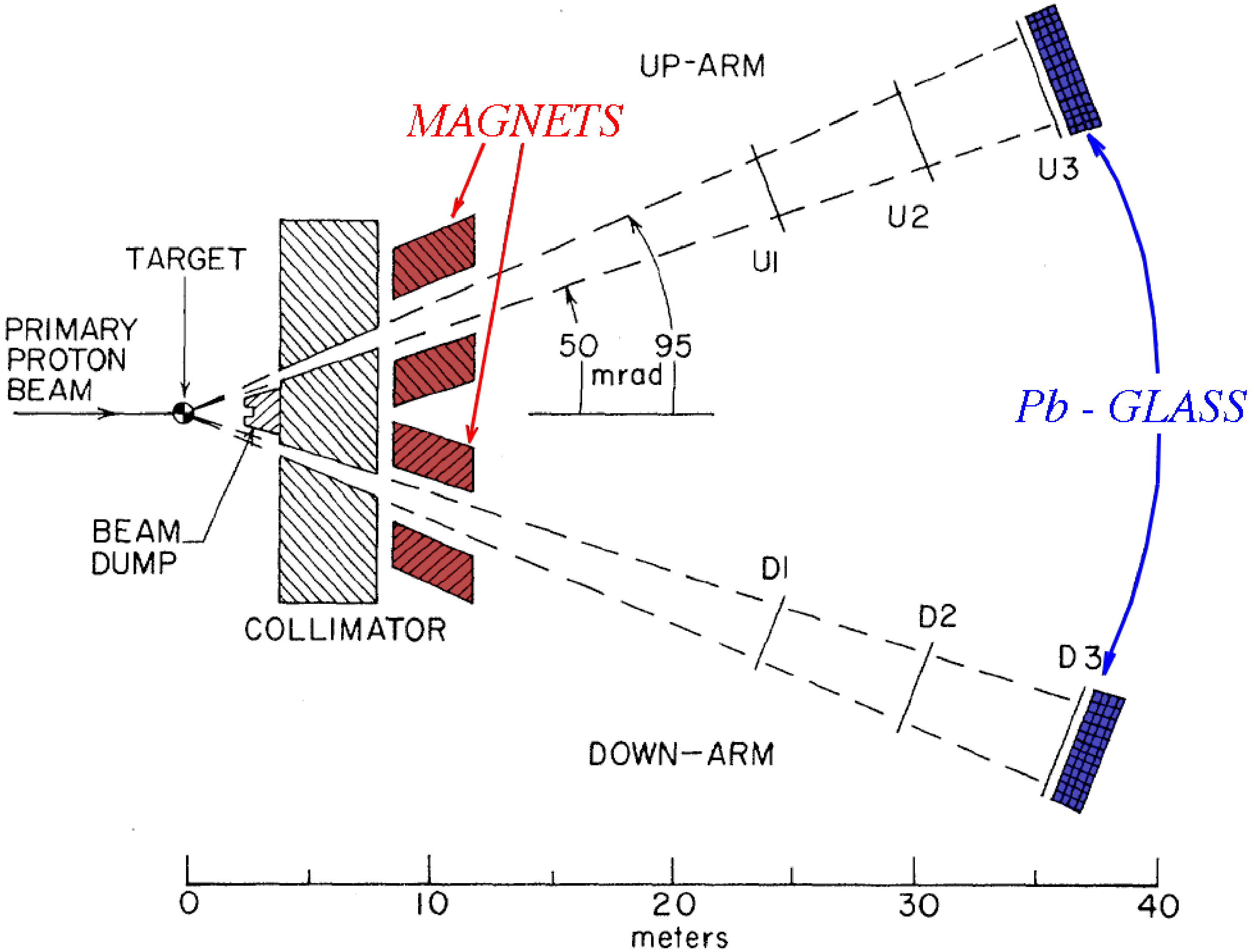
Milestones

- 1965 - *Quantum leap in signal quanta (e-h pairs in semiconductors)*
- 1970 - *Shower counters in HEP (crucial for discovery b-quark)*

1970s - Shower counters in magnetic spectrometers

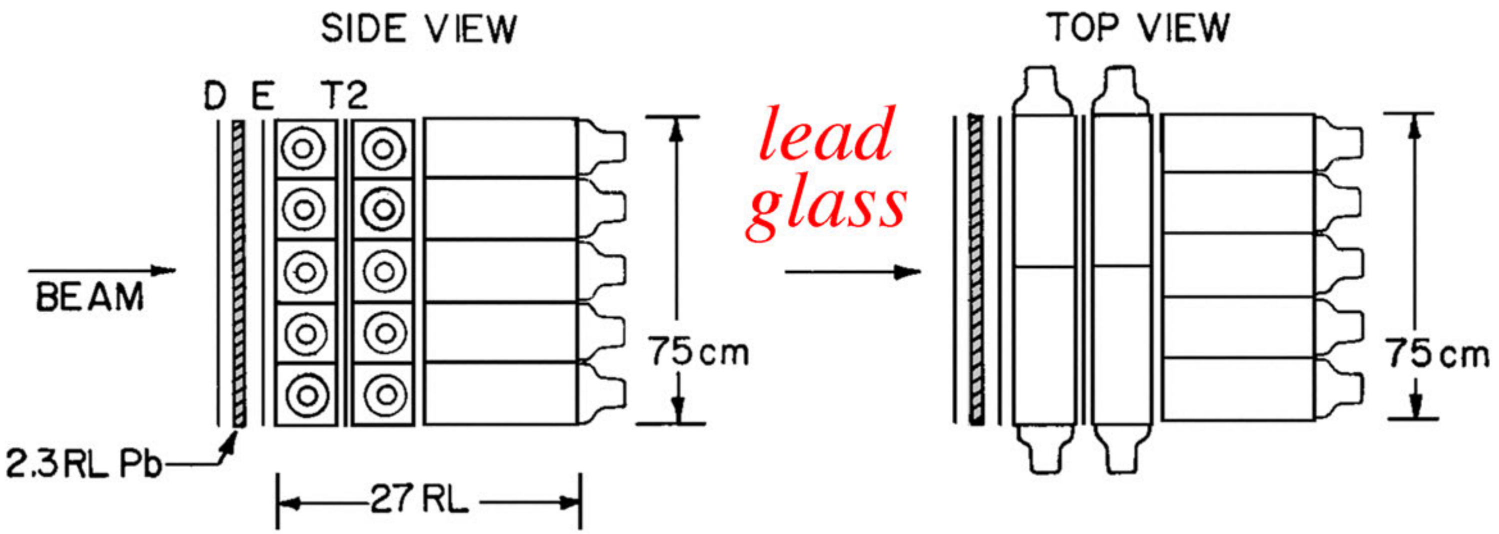
Example: E70 / 288 @ Fermilab

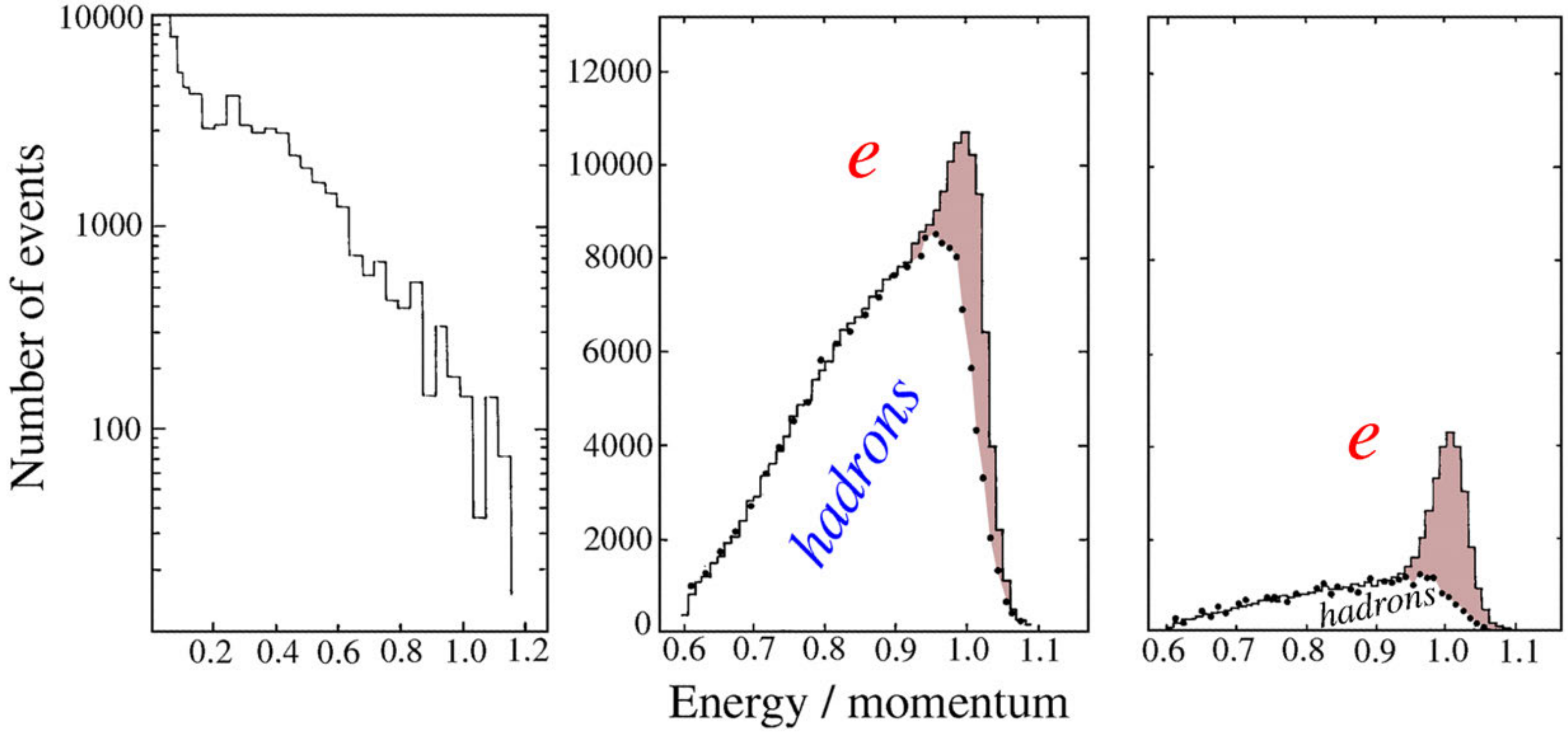
Discovered Upsilon $\rightarrow l^+ l^-$



Shower counters in the 1970s

(electron identification in a fixed-target experiment - NIM 127, 495)



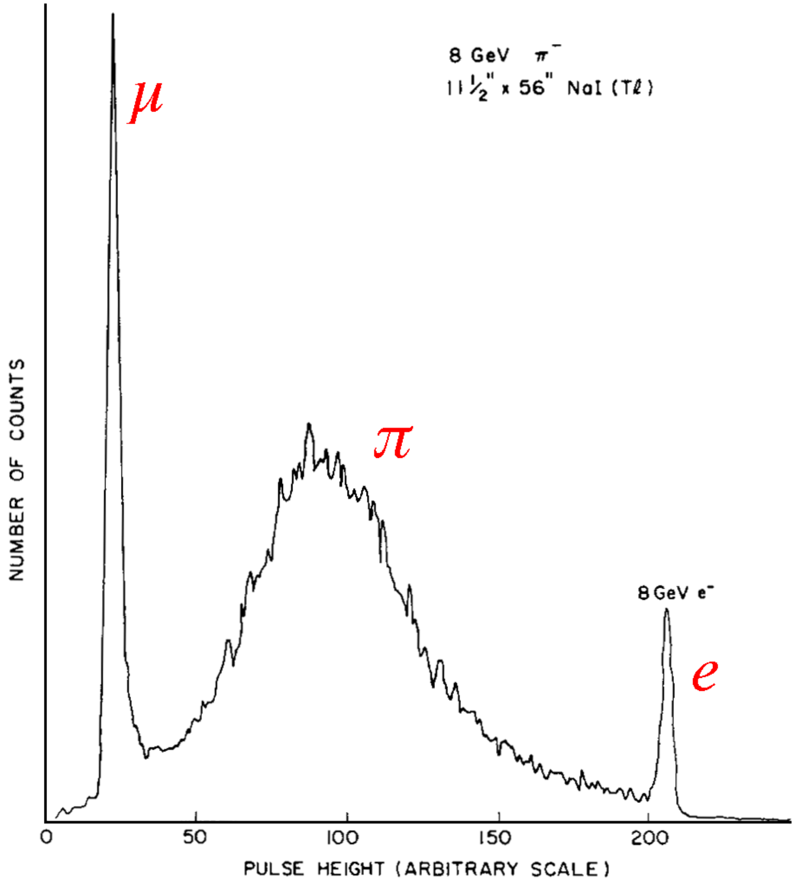


Early indication that hadron calorimetry is different!

NIM 75 (1969) 130

450 kg of NaI (Tl) crystals

Tested with 8 GeV particle beams



Conclusions of authors:

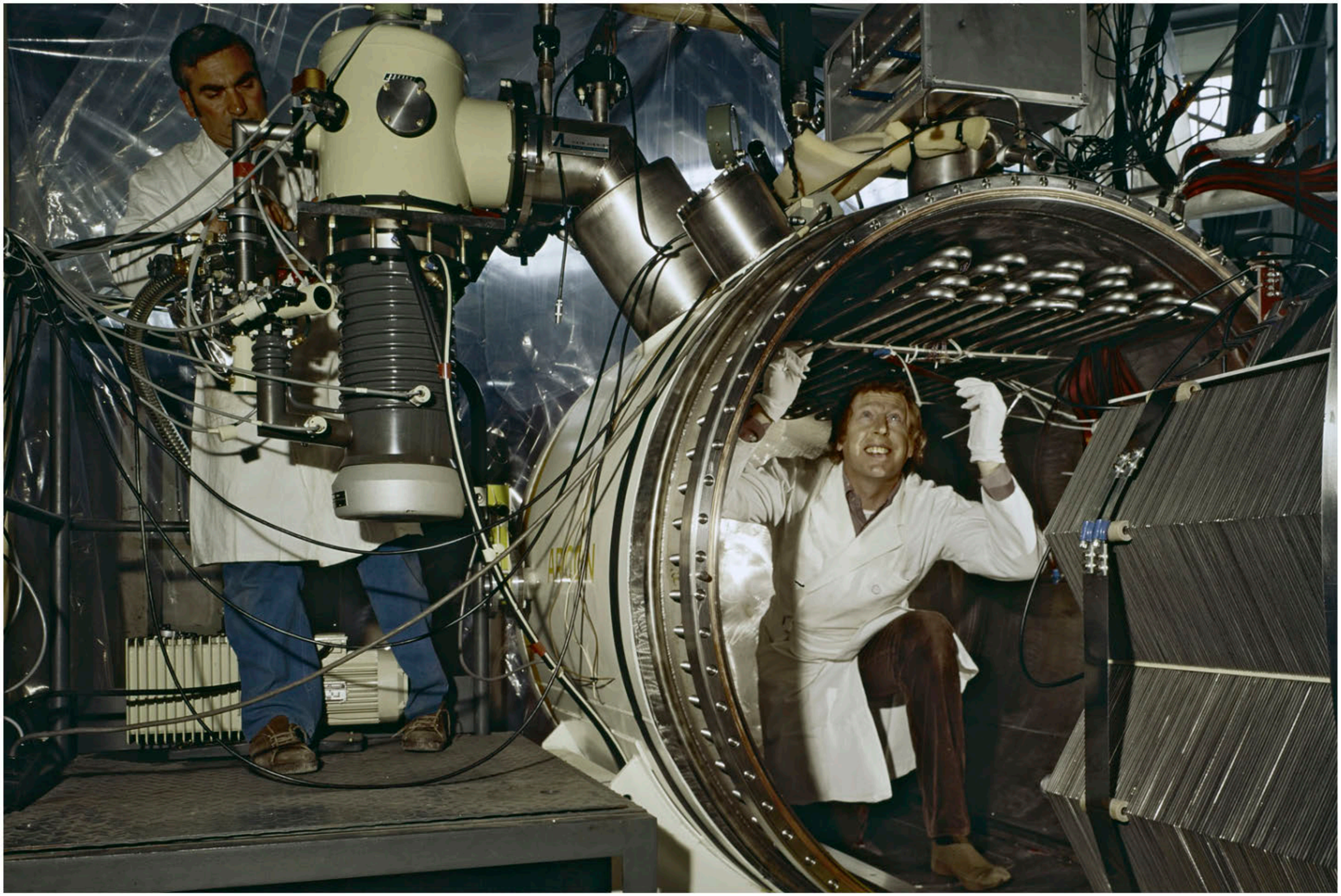
- *50% of energy leaks out*
- *MC: much less leakage*
- *Same results at 4, 12, 16 GeV*
- *Resolution did NOT improve with E*

Milestones

- 1965 - *Quantum leap in signal quanta (e-h pairs in semiconductors)*
- 1970 - *Shower counters in HEP (crucial for discovery b-quark)*
- 1974 - *Liquid argon calorimetry invented*

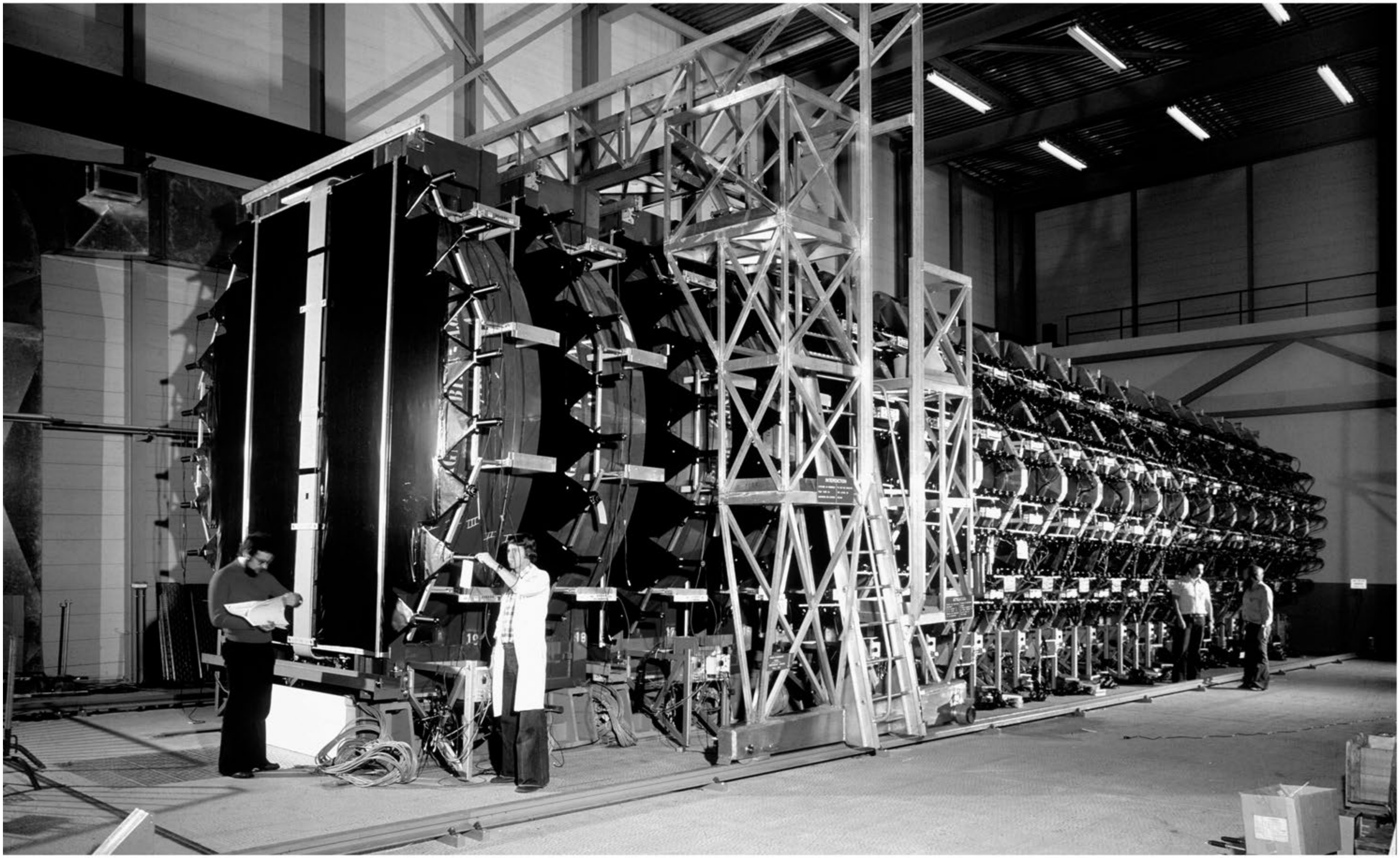
Willis/Radeka Lar calorimeter for an ISR experiment (1974)

Direct collection of ionization charge
in a dense sampling medium



1975 - Calorimeters take on new tasks
(target, trigger counter, tracking, particle ID)

WA1



Milestones

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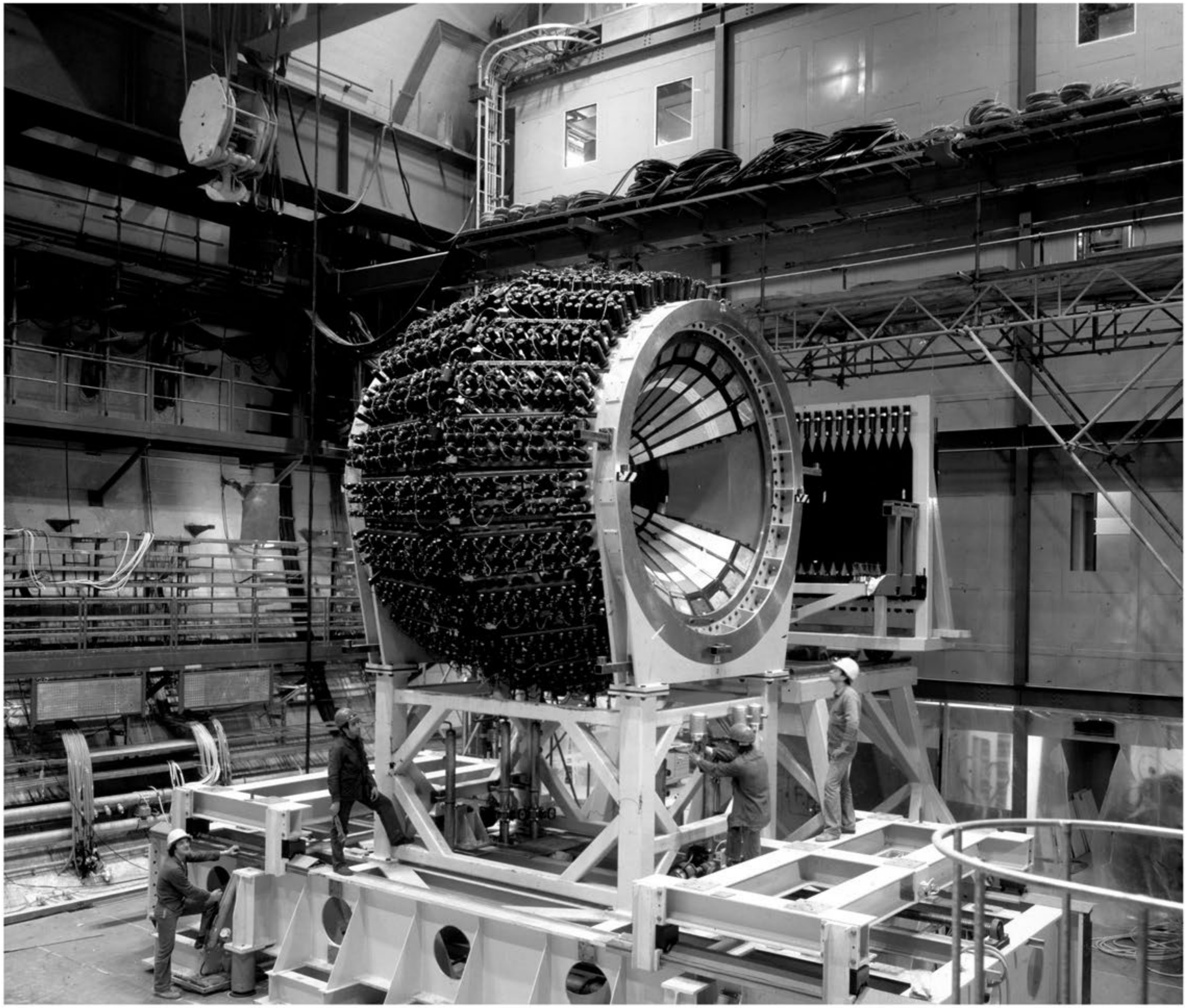
- 1975 - *Liquid argon calorimetry invented*
- 1980 - *4π calorimeters introduced (crucial for discovery W boson)*

1980 - Calorimeters become crucial component of 4π experiments

(event selection: trigger on energy flow parameters such as missing E_T)

Led to discovery of $W \rightarrow e\nu$, $W \rightarrow \mu\nu$

UA2
(CERN)



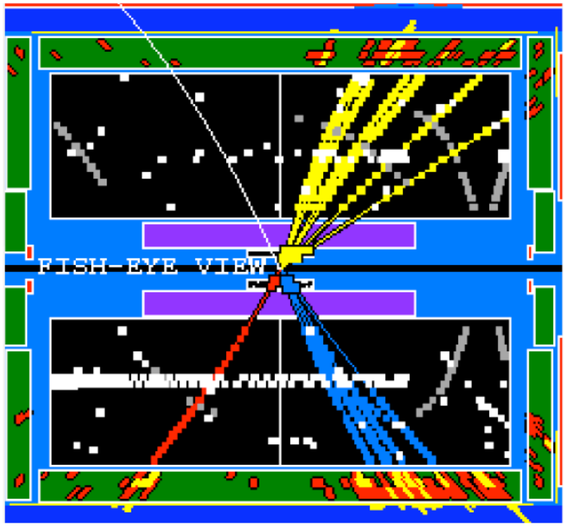
Example of energy flow information

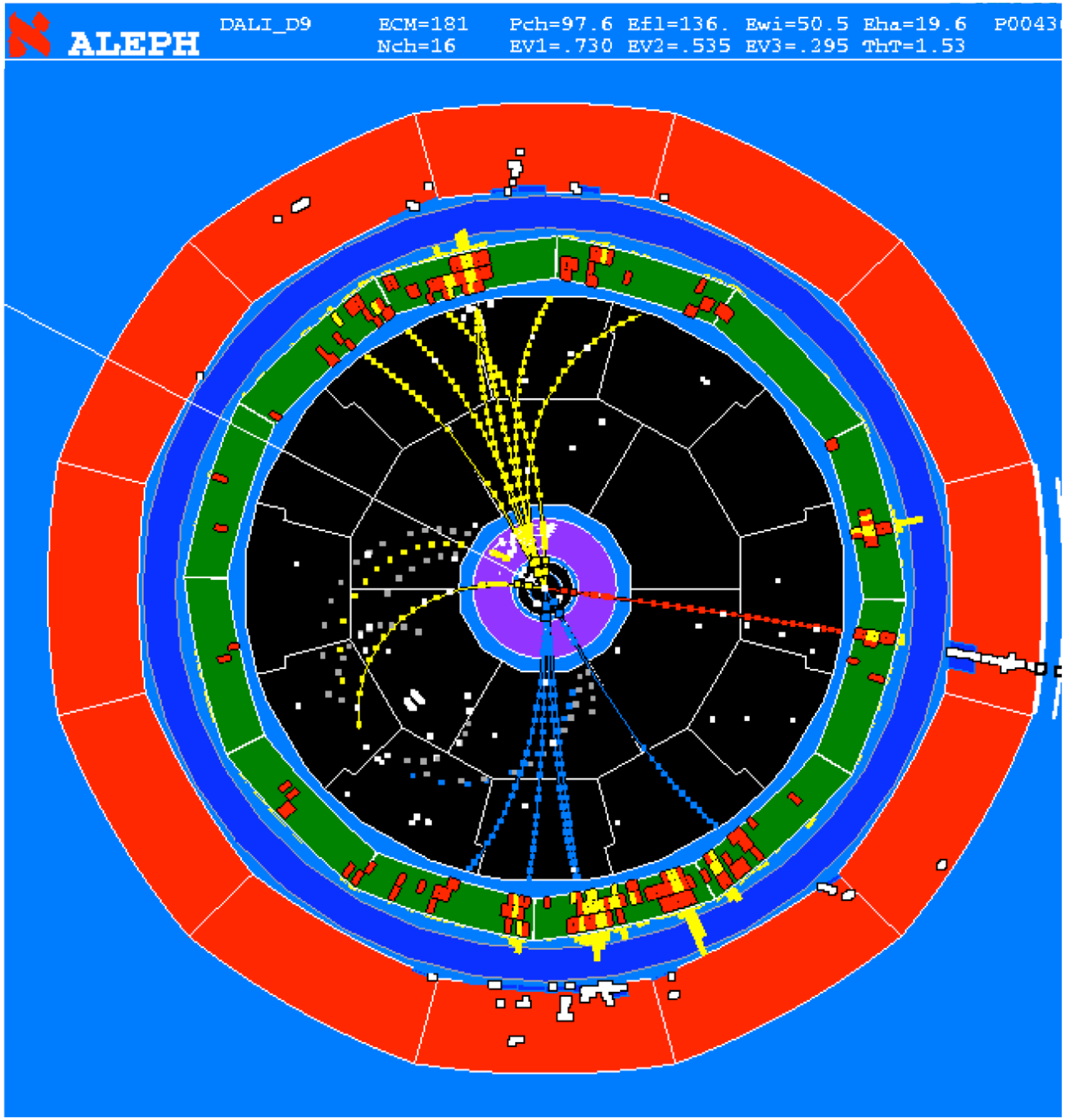
$e^+e^- \rightarrow W^+W^-$
$(\sqrt{s} = 181\ \mathrm{GeV})$

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

In final state:

2 hadronic jets
1 energetic muon
missing E_T (ν_μ)





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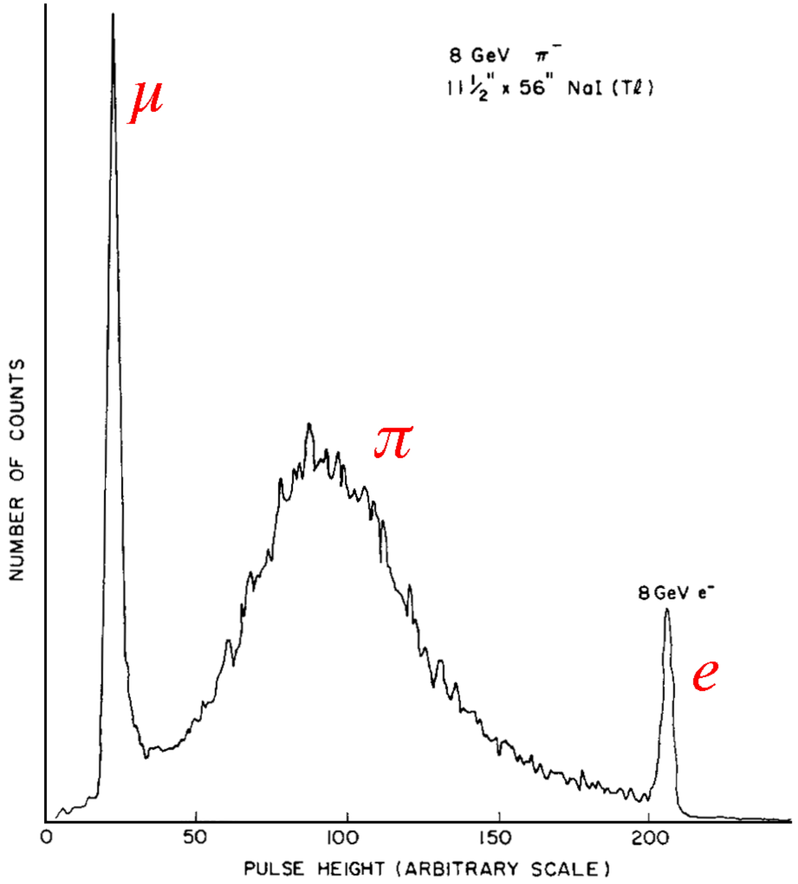

Conclusions of authors:

- *50% of energy leaks out*
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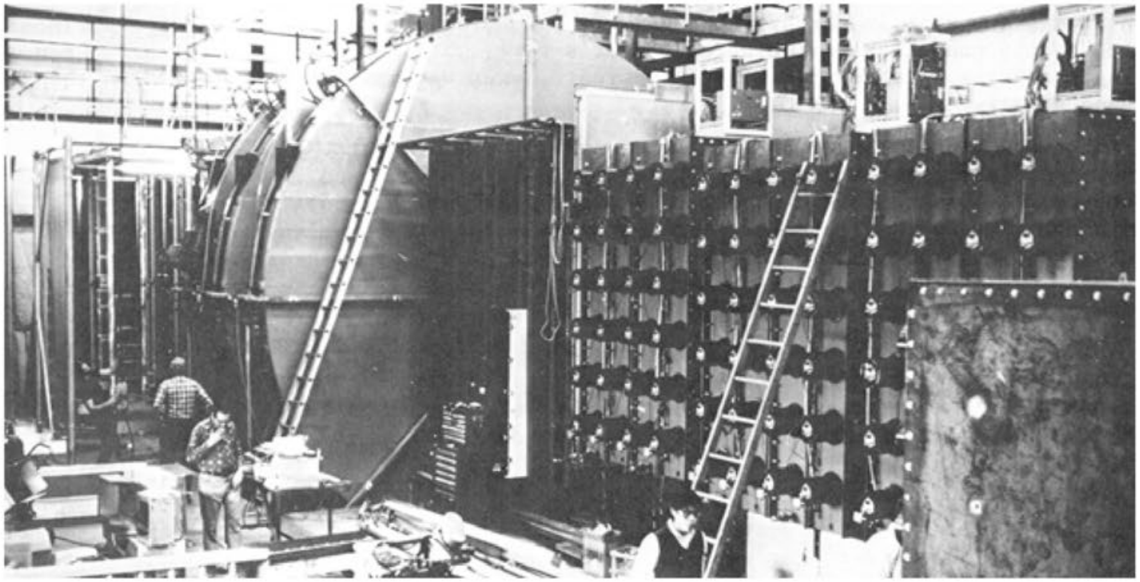
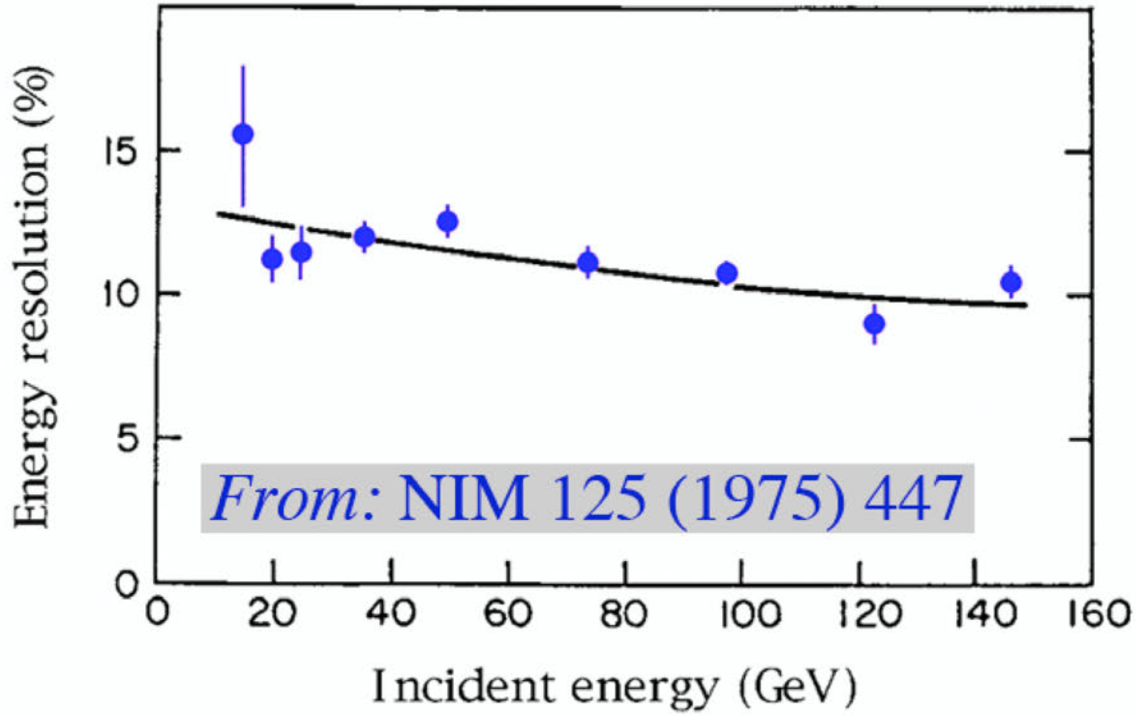
Energy resolution of a homogeneous hadron calorimeter

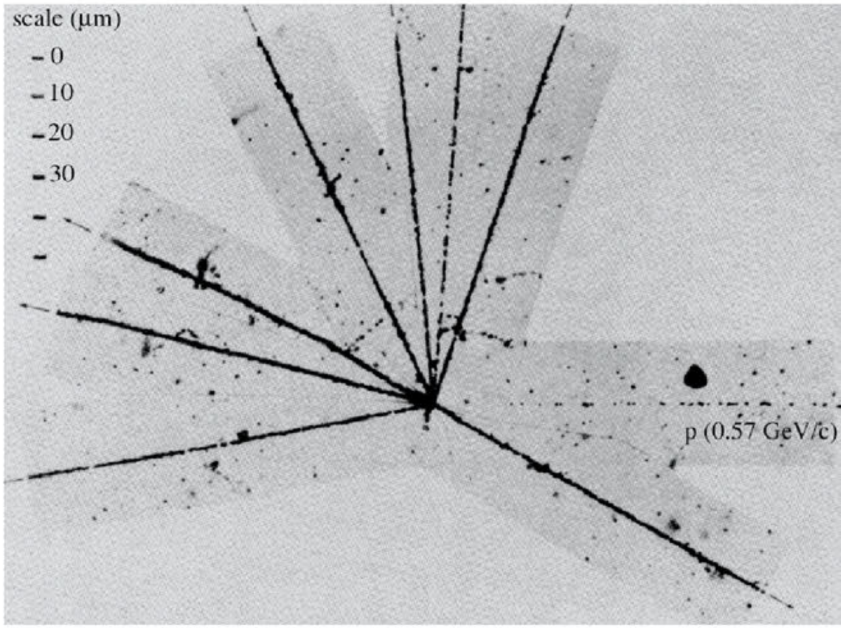
(60 tonnes of liquid scintillator)



Statistical processes are NOT the limiting factor here. Resolution is limited by fluctuations in invisible energy losses in the non-em shower component, e.g. in nuclear interactions



From: NIM 125 (1975) 447



High resolution hadron calorimetry had become a reality

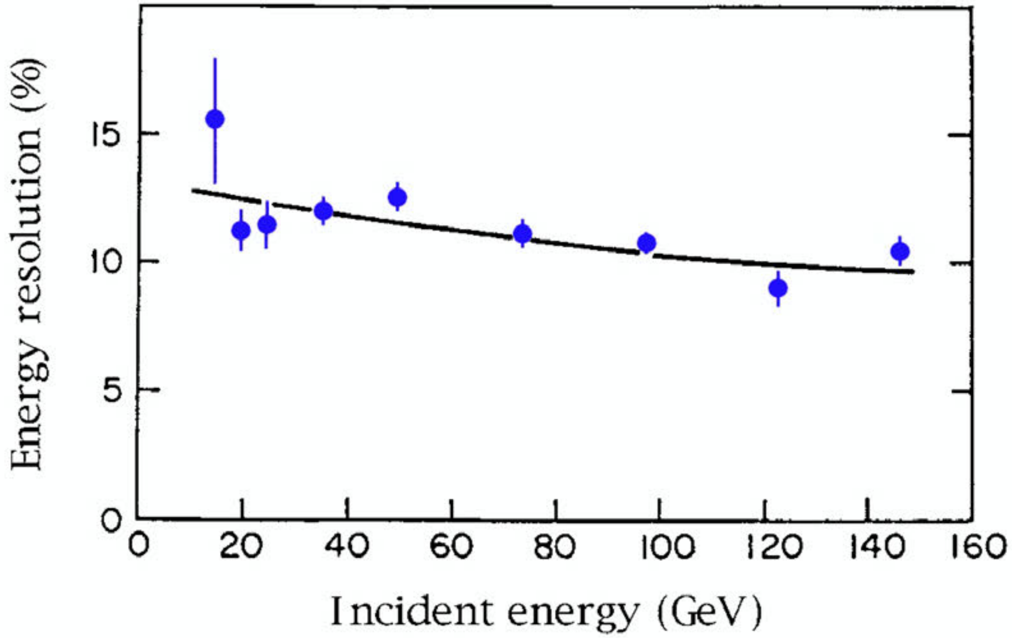
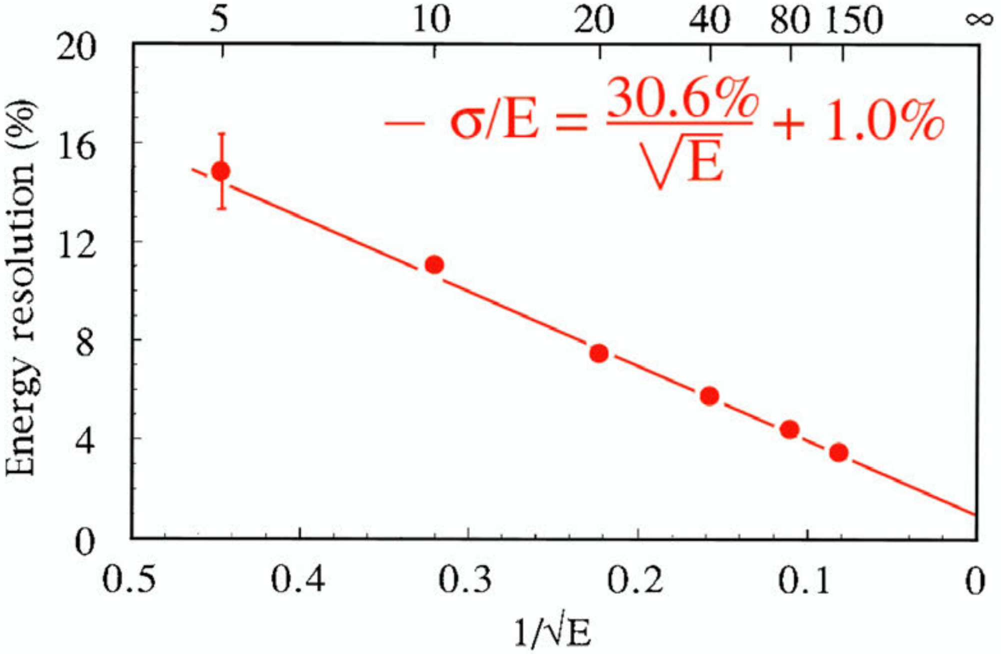


Figure 9: The hadronic energy resolution as a function of energy, for a homogeneous calorimeter consisting of 60 *tonnes of liquid scintillator*

NIM 125 (1975) 447

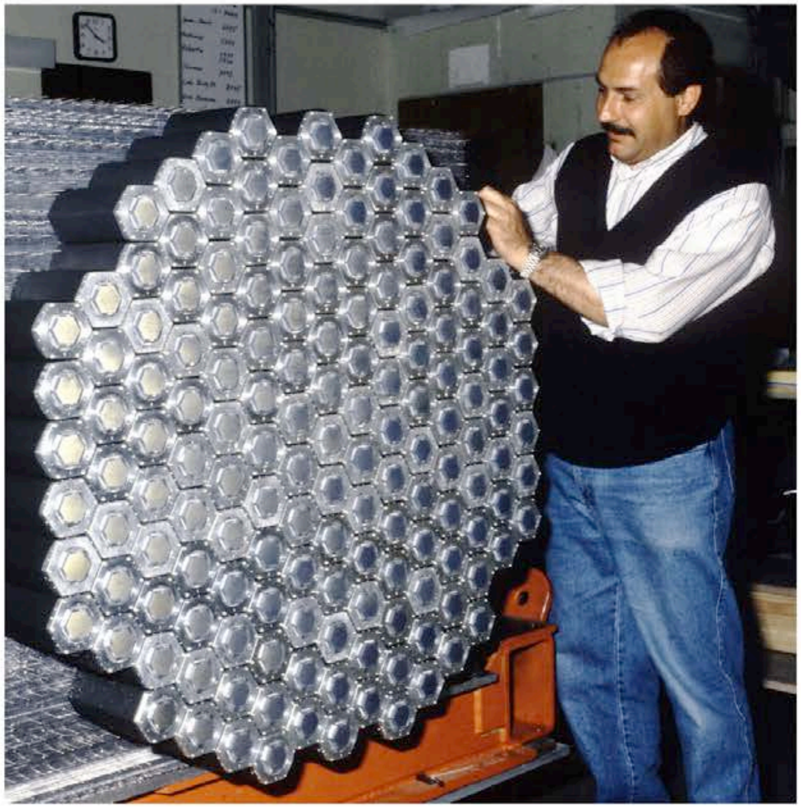


$$-\ \sigma/E = \frac{30.6\%}{\sqrt{E}} + 1.0\%$$

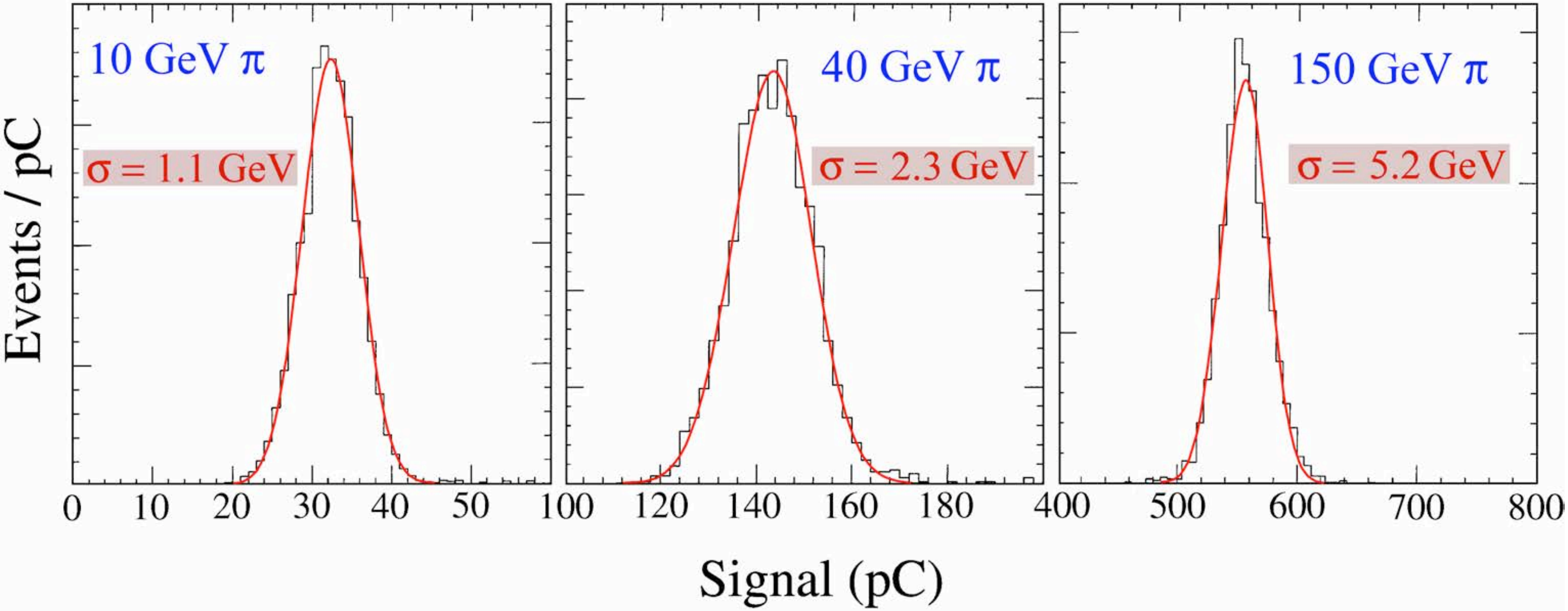
Figure 10: The hadronic energy resolution as a function of energy, for the compensating SPACAL *lead/plastic-scintillator calorimeter (sampling fraction 2%)*

NIM A308 (1991) 481

SPACAL 1989

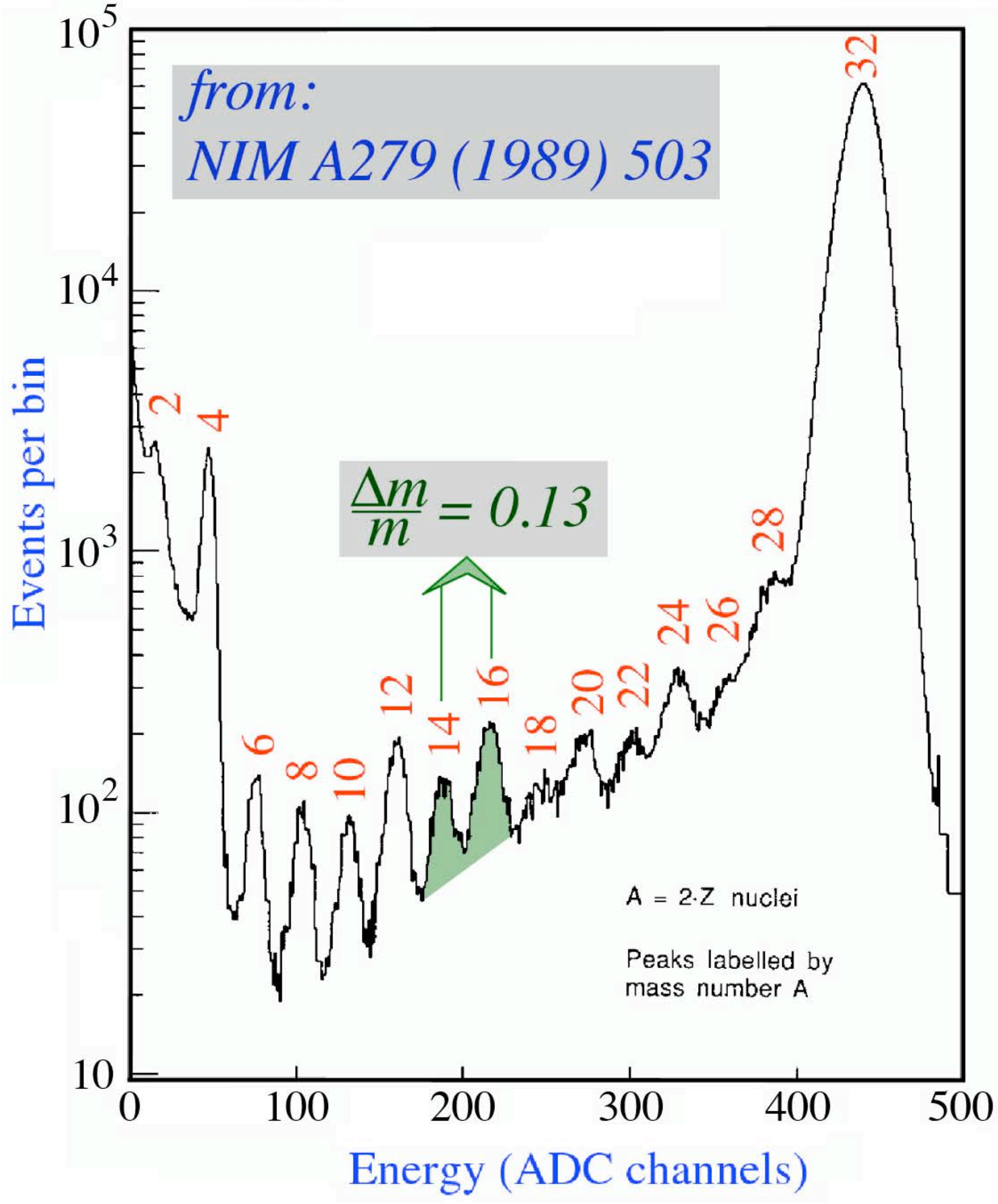


Hadronic signal distributions in a compensating calorimeter



from: NIM A308 (1991) 481

Hadron calorimetry in practice
Energy resolution in a compensating calorimeter



W/Z separation:

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

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

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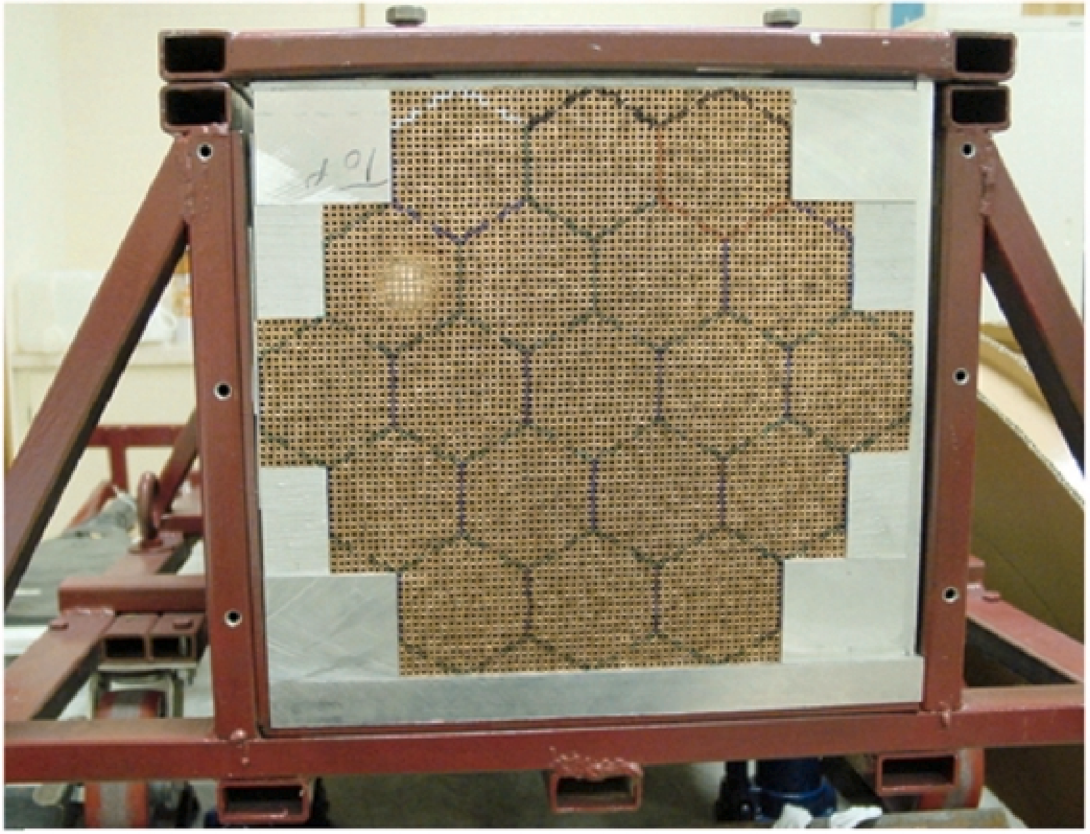
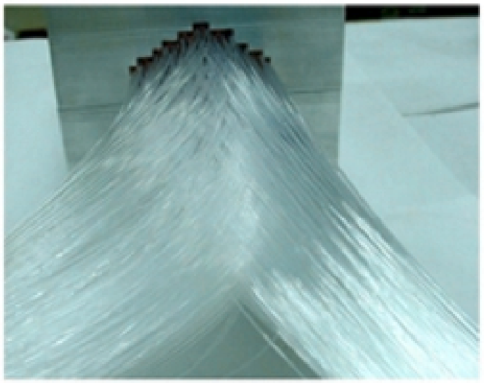
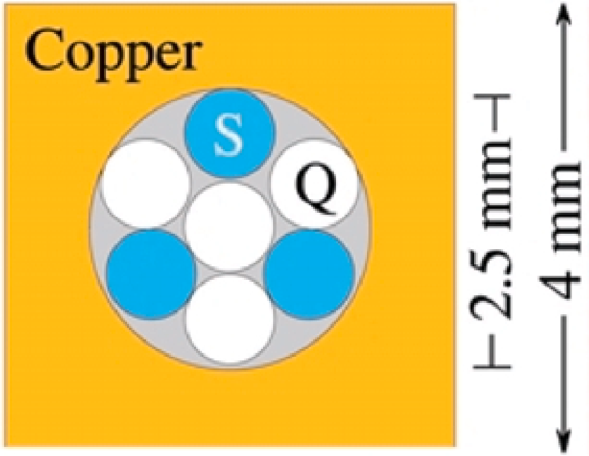
- 1987 - *Compensation mechanism understood*
- 2000 - *Merits of dual-readout calorimetry experimentally demonstrated*

DREAM: Structure

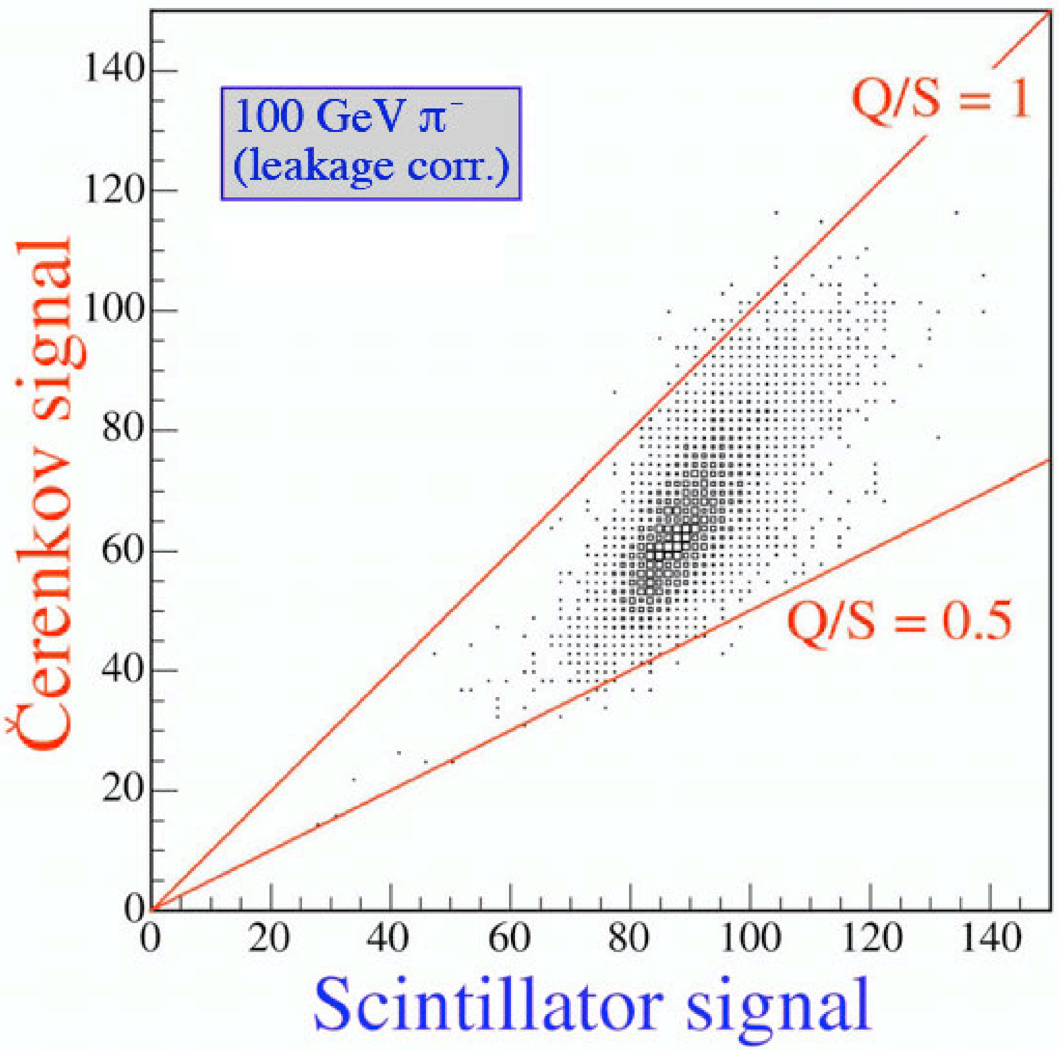






- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length ≈ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

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



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

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

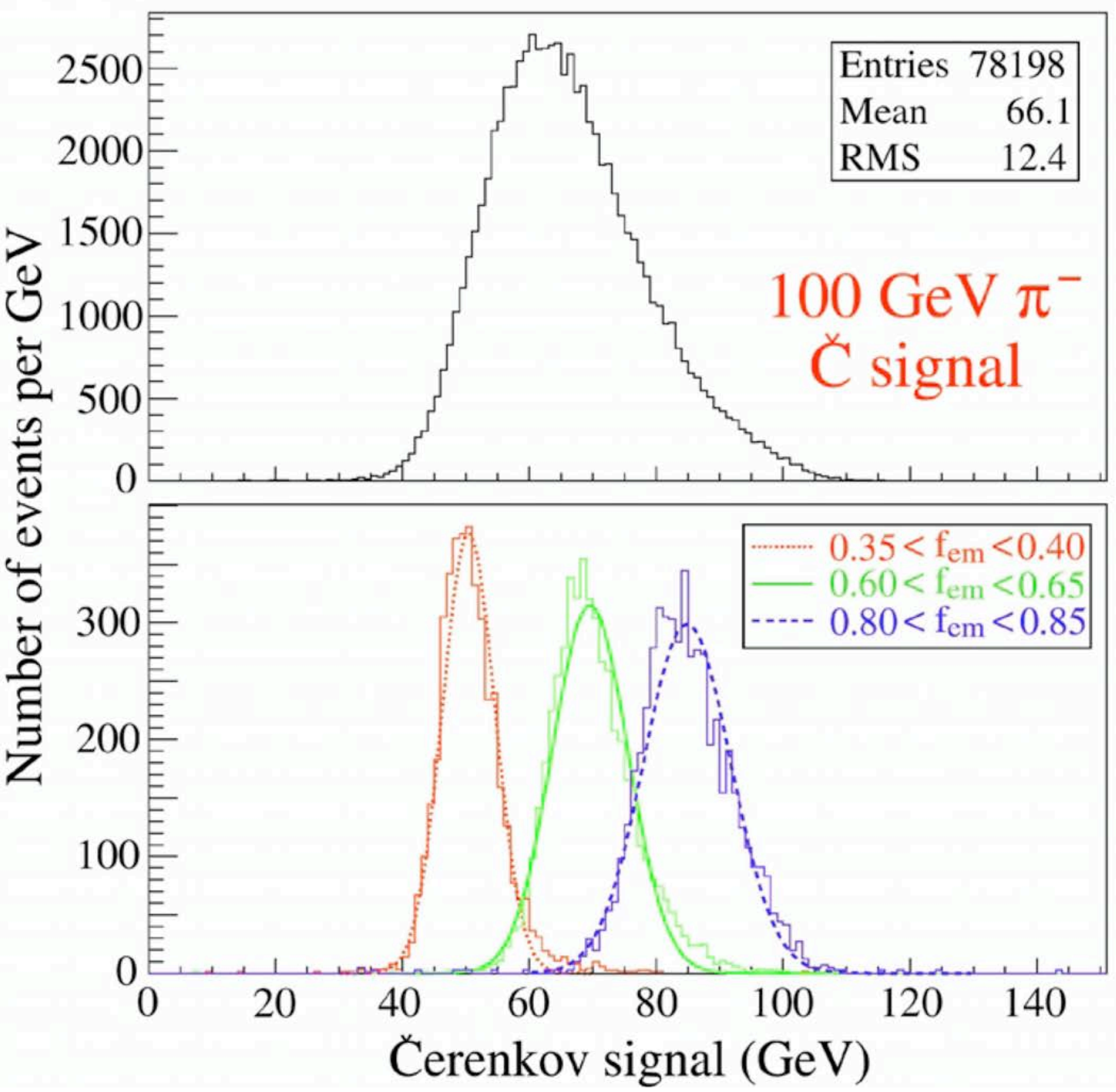
e.g. If $e/h = 1.3$ (S), 4.7 (Q)

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

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

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

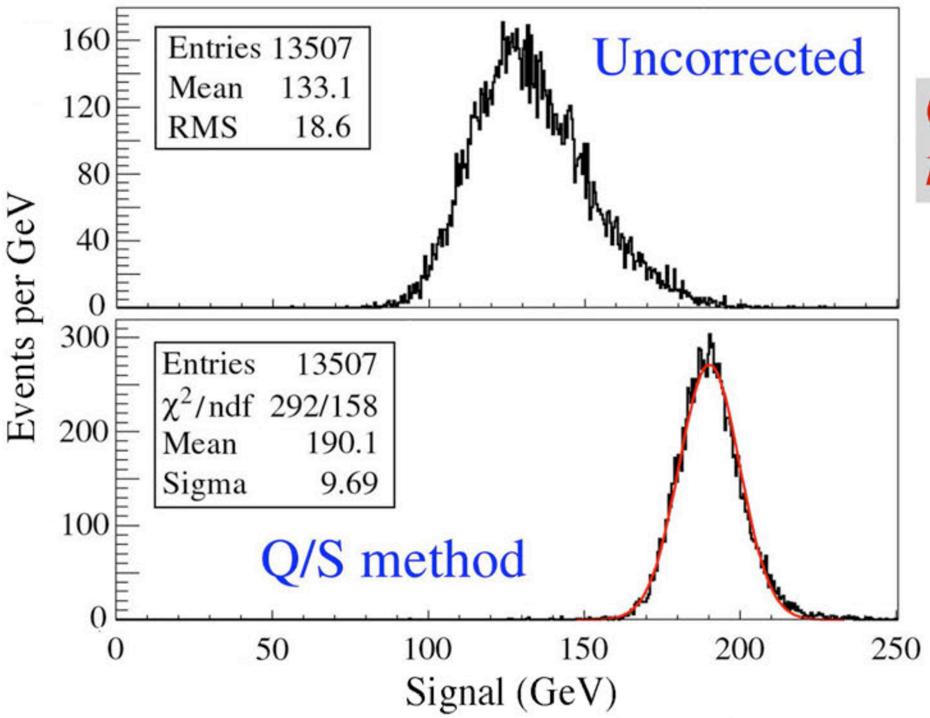
DREAM: Effect of event selection based on f_{em}



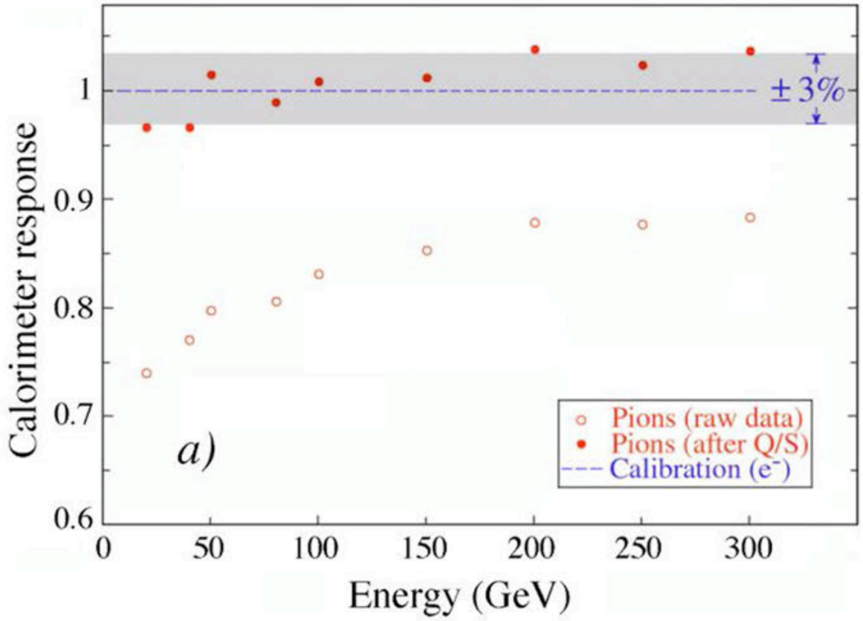
From:
NIM A537 (2005) 537

Effects of Q/S corrections on

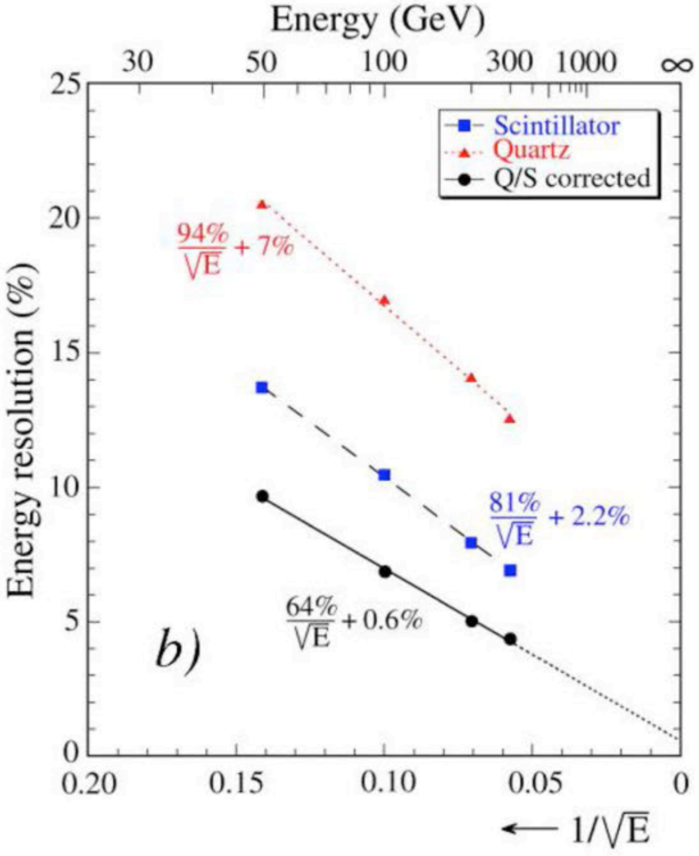
Calorimeter response function



hadronic signal linearity



jet energy resolution



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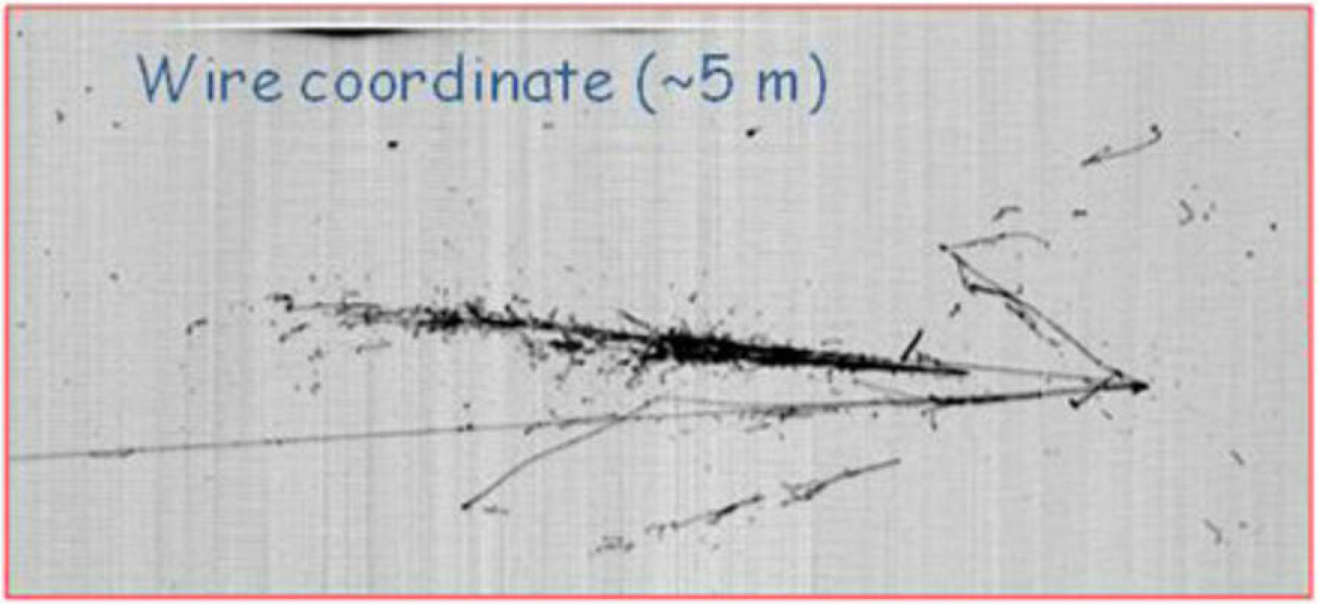
- 2000 - *Merits of dual-readout calorimetry experimentally demonstrated*
- 2005 - *Imaging calorimetry demonstrated (LAr)*

2005 - Imaging calorimetry pioneered by ICARUS (LAr)



CERN to Gran Sasso ν beam ←

Some common (sometimes dangerous)

misconceptions

about calorimetry

Misconceptions about calorimetry

- *A shower is a collection of mips*

A shower is a collection of different shower particles
(e, γ, π, p, n)

In a sampling calorimeter, these are sampled differently

The shower composition changes as the shower develops

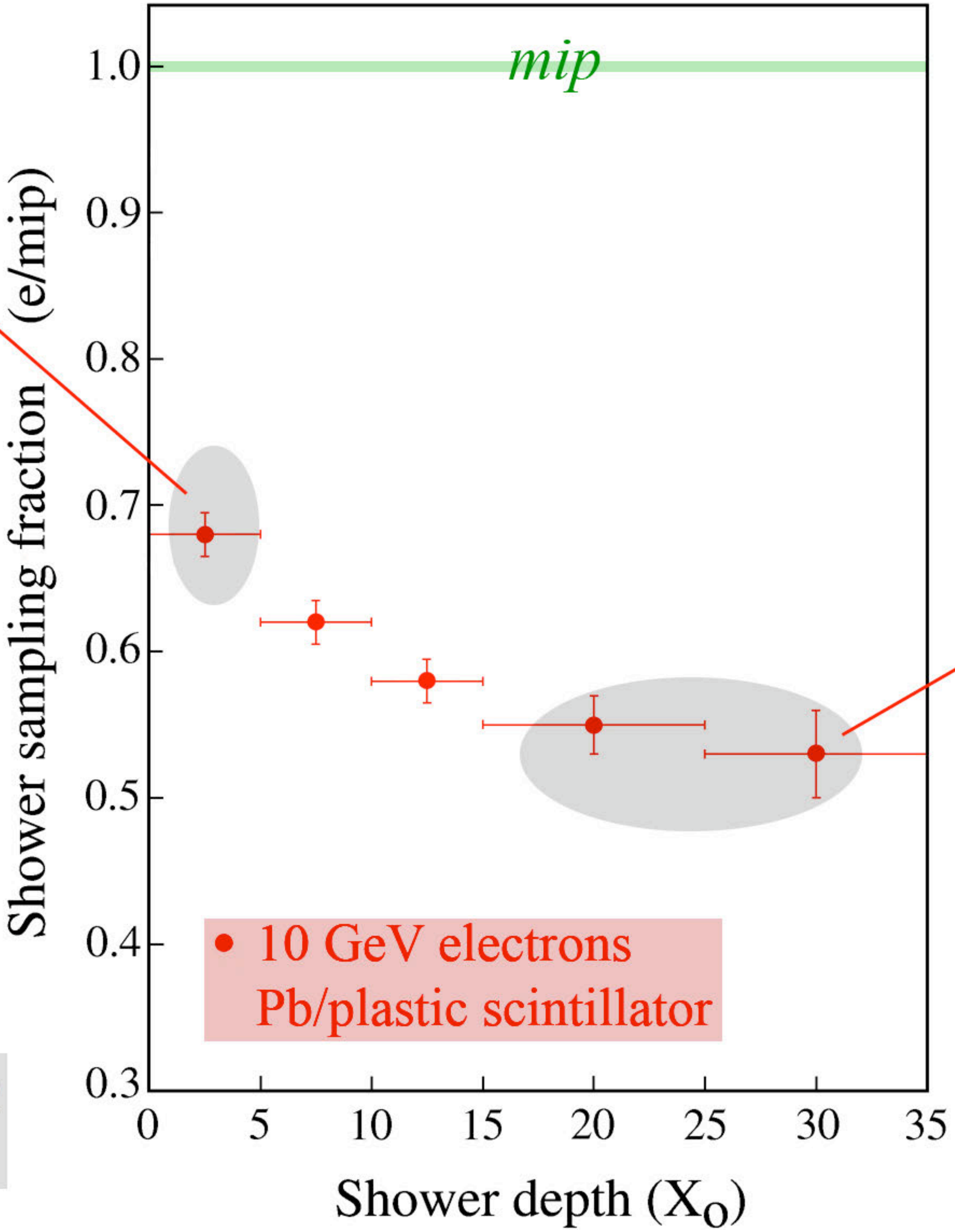
Misconceptions about calorimetry

- *A shower is a collection of mips*

This misconception is

THE SOURCE OF MANY CALIBRATION PROBLEMS

*The sampling fraction changes as shower develops**



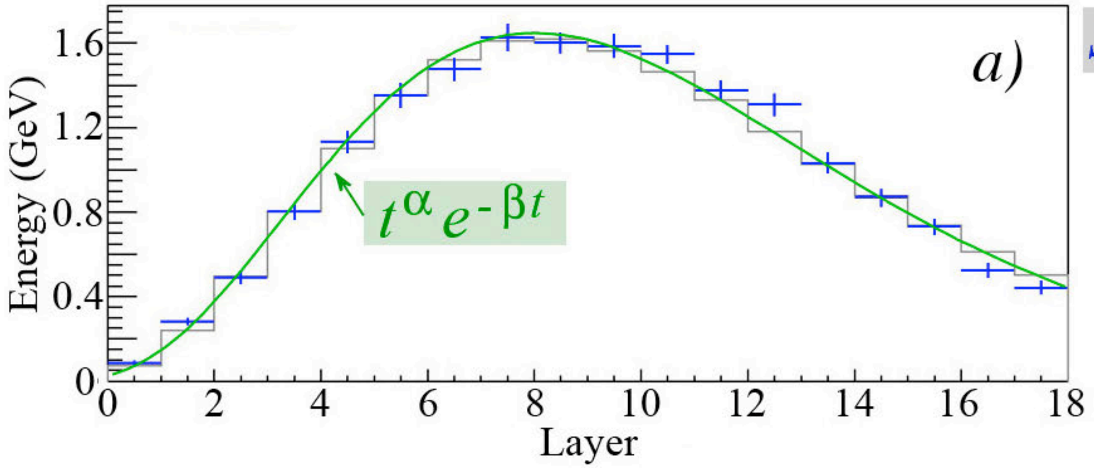
shower dominated by mip's

shower dominated by soft γ's

**By as much as 30%!*

Calibration misery of longitudinally segmented devices

Example: AMS (em showers!)



Source: NIM A490 (2002) 132

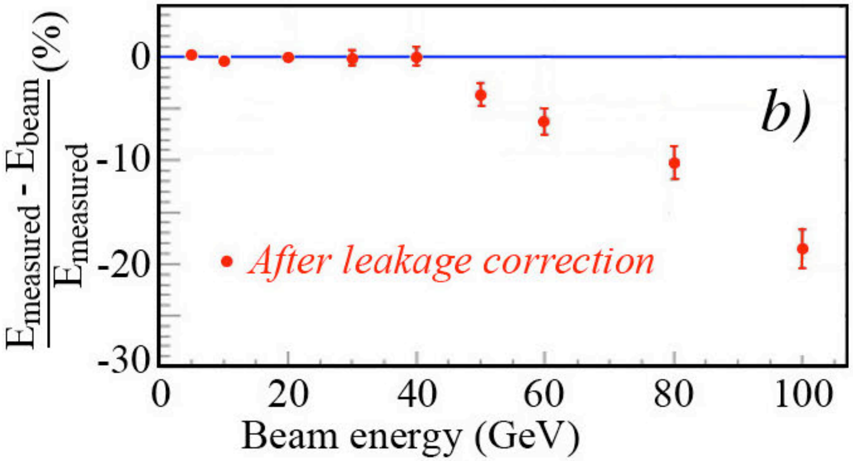
Pb/scintillating fiber (18 layers)

Calibrated with mip's:
11.7 MeV/layer

Leakage estimated from fit to measured shower profile

However:
In em shower, signal per GeV decreases as shower develops

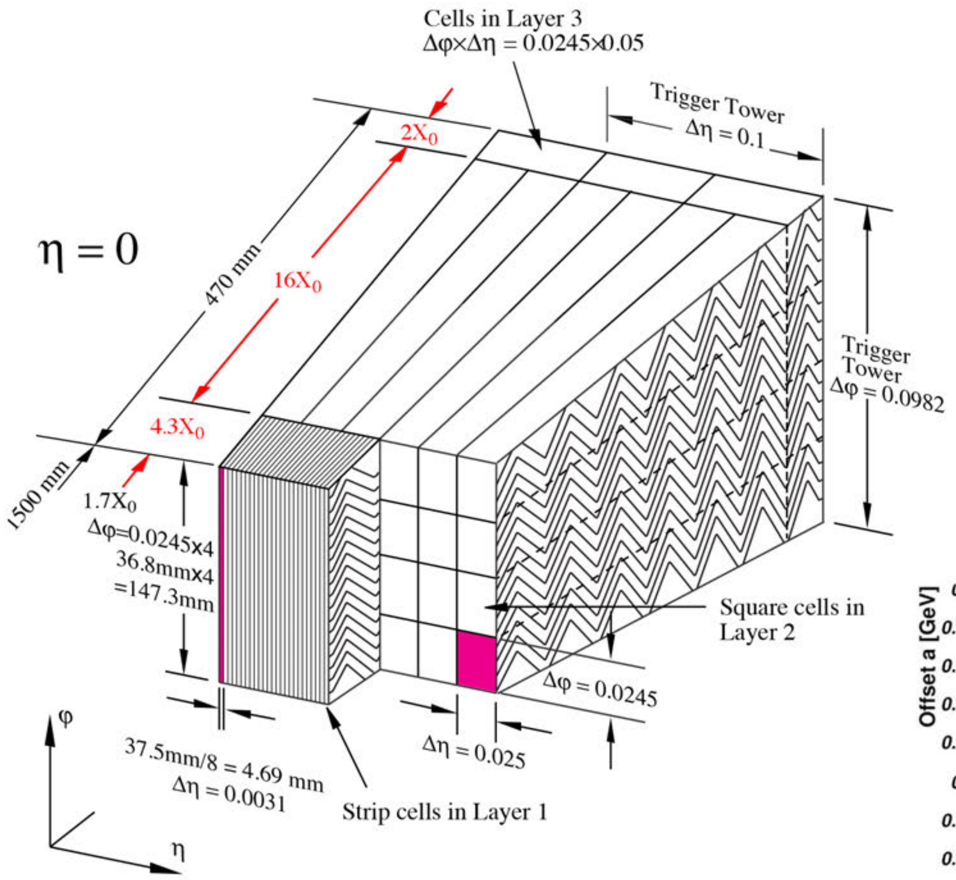
→ *(leakage) energy based on measured signals underestimates reality*

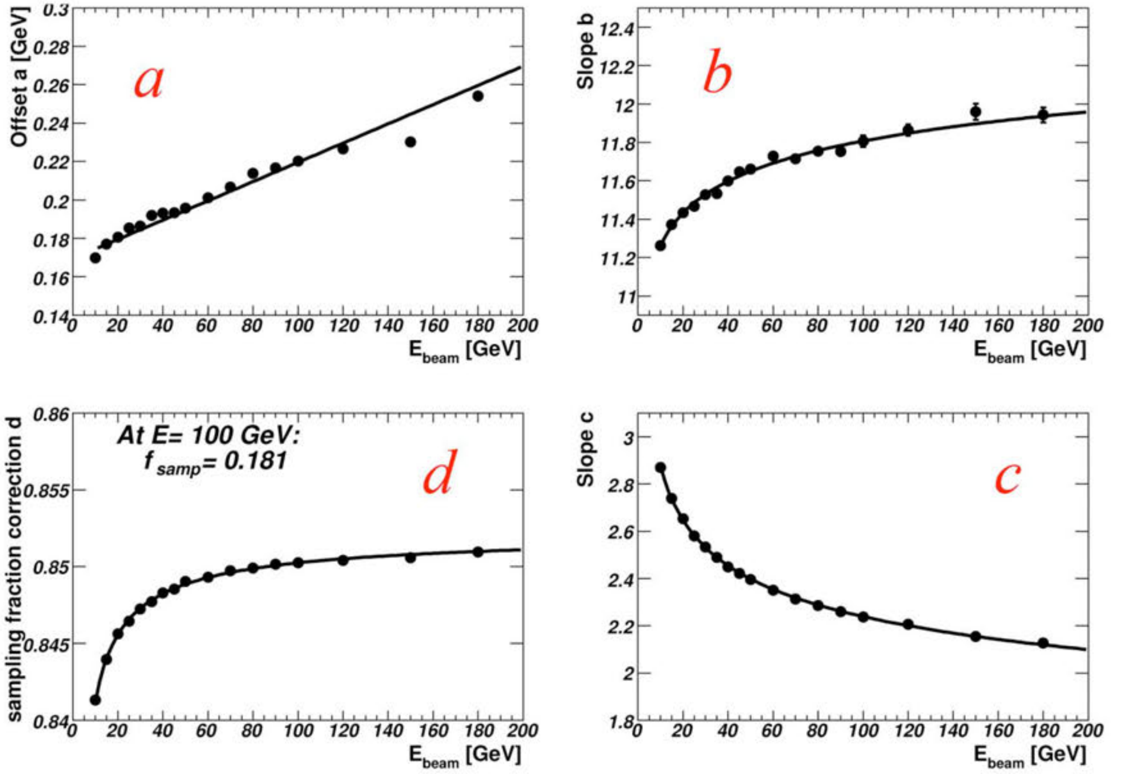


Required very elaborate MC simulations to solve, since effects depend on energy and direction incoming particle

Calibration of the ATLAS ECAL

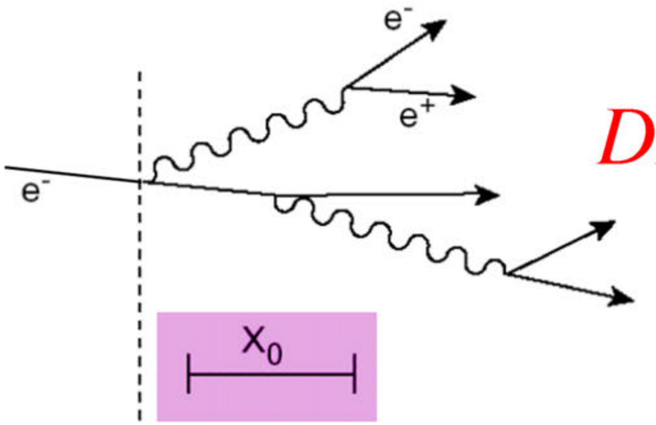
(for electrons, NOT γs)

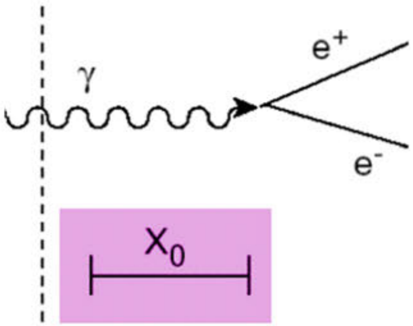


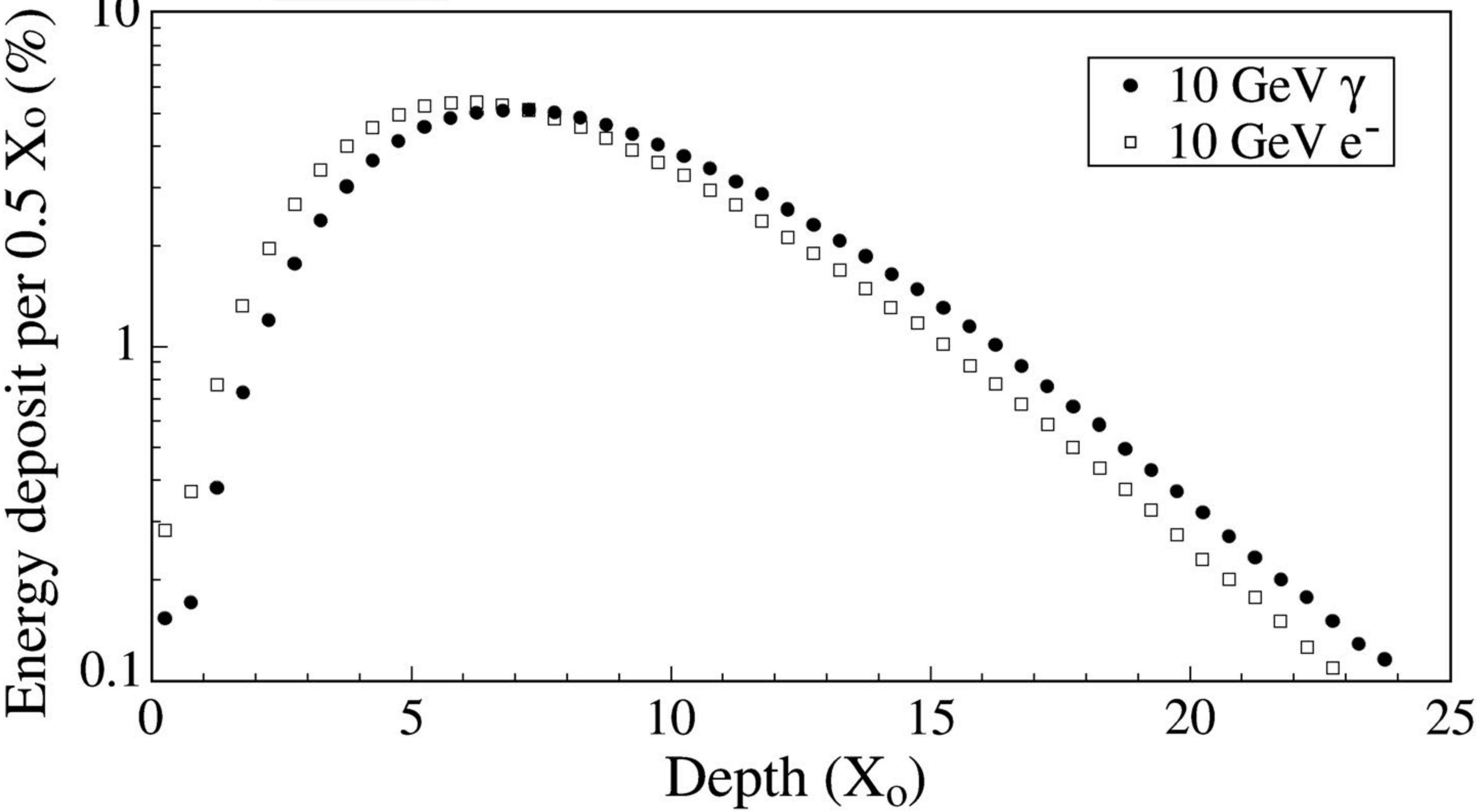


$$E^{rec} = \left(a(E) + b(E)\; E_0^{vis} + c(E)\; (E_0^{vis} \cdot E_1^{vis})^{0.5} + \frac{1}{d(E)\, f_{samp}} \sum_{i=1,3} E_i^{vis} \right) \cdot f_{\text{cell impact}}(\Delta\Phi) \cdot (1 + f_{\text{leakage}})$$

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

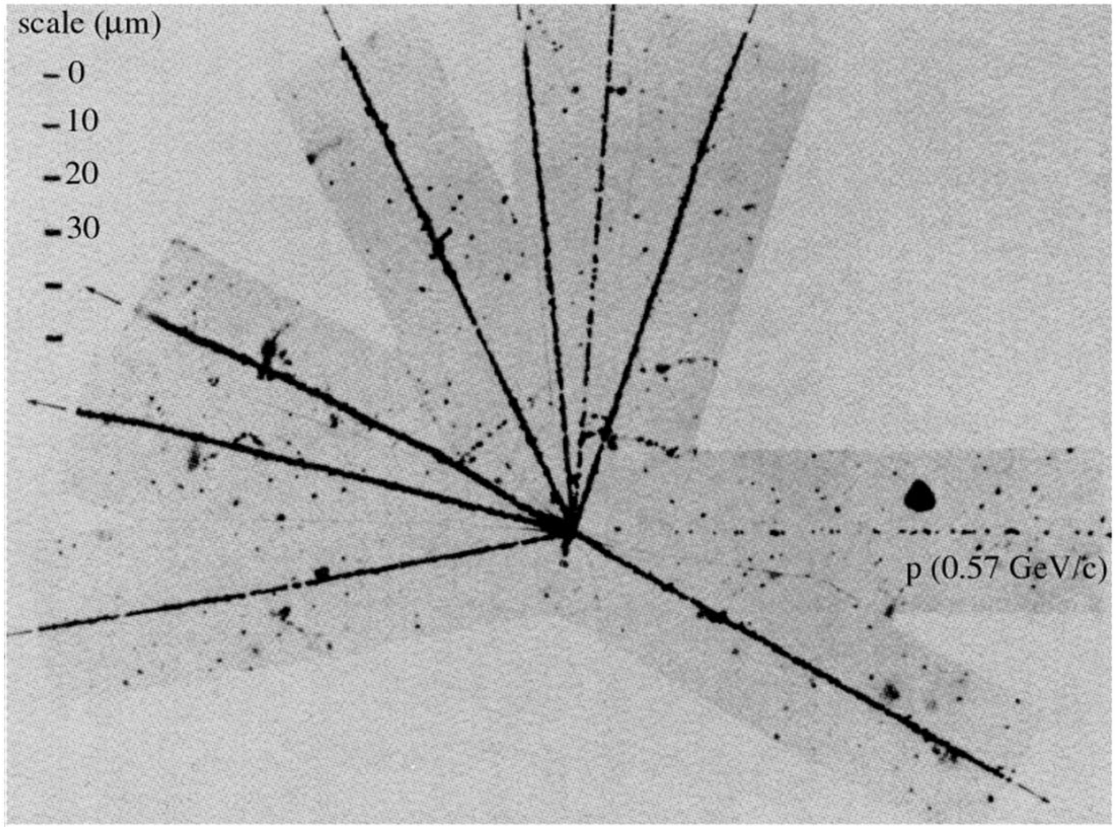






Catastrophic effects of ONE individual shower particle (1)

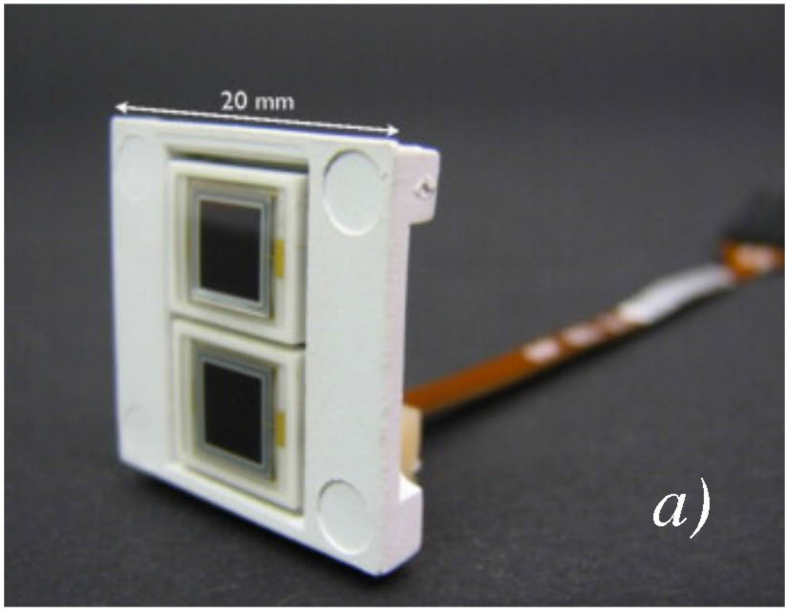
A typical process inside a hadronic shower

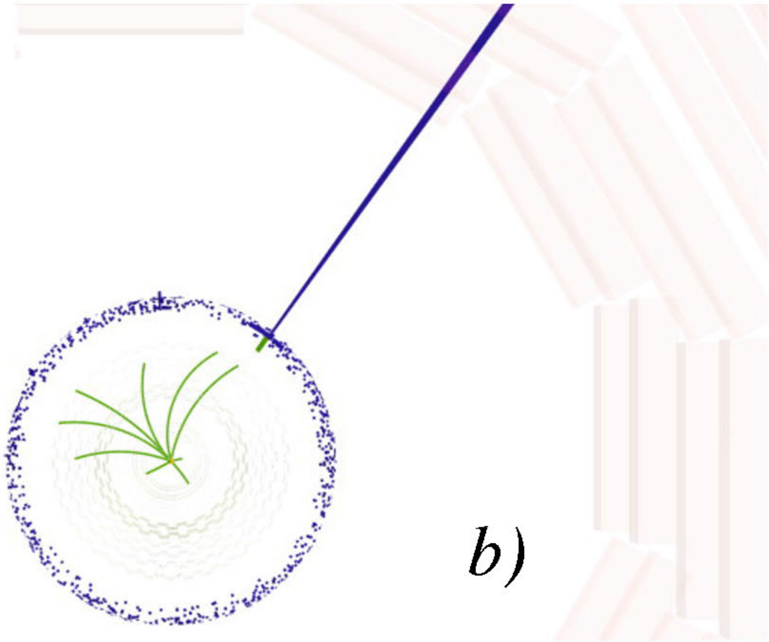


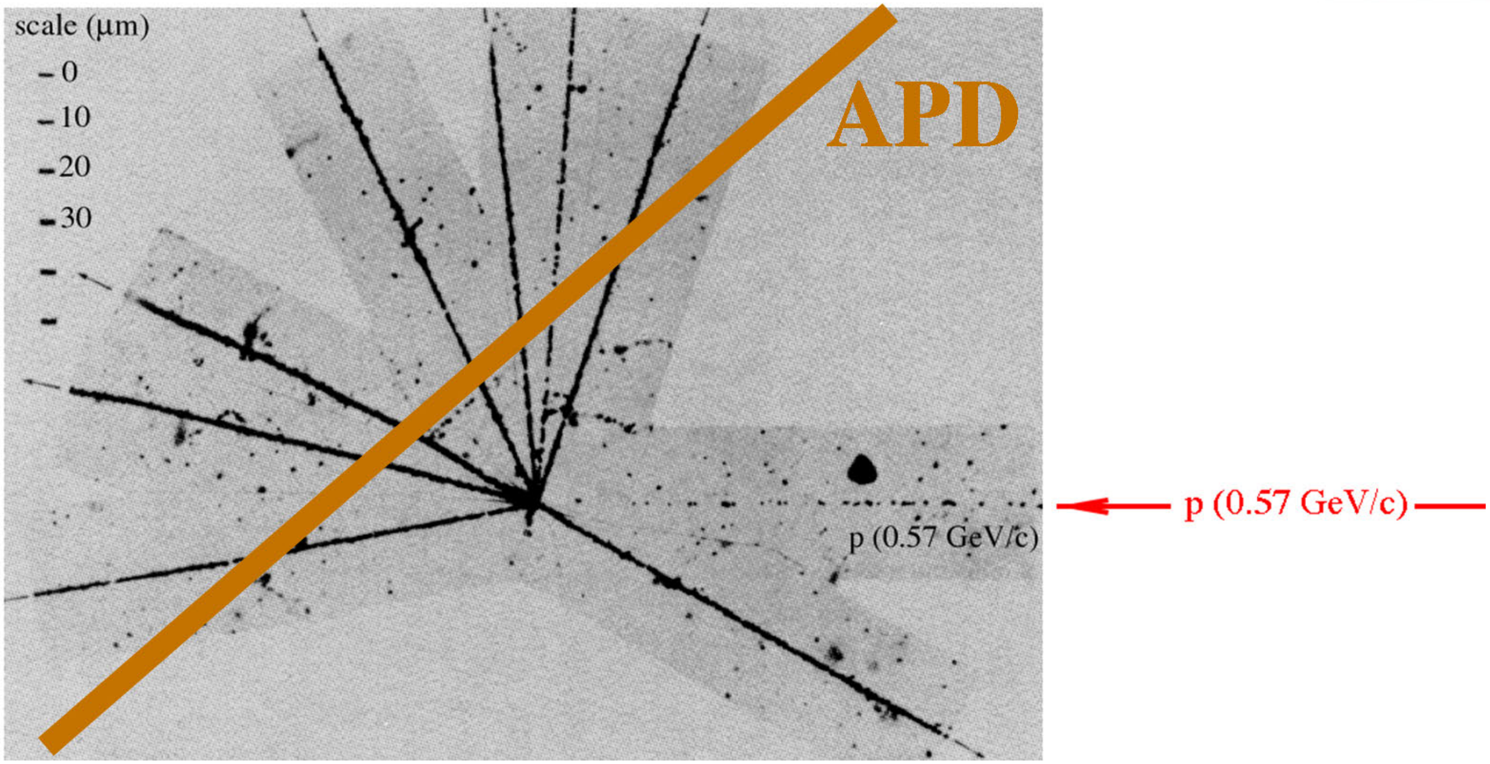
← p (0.57 GeV/c) —

($E_{kin} = 160$ MeV)

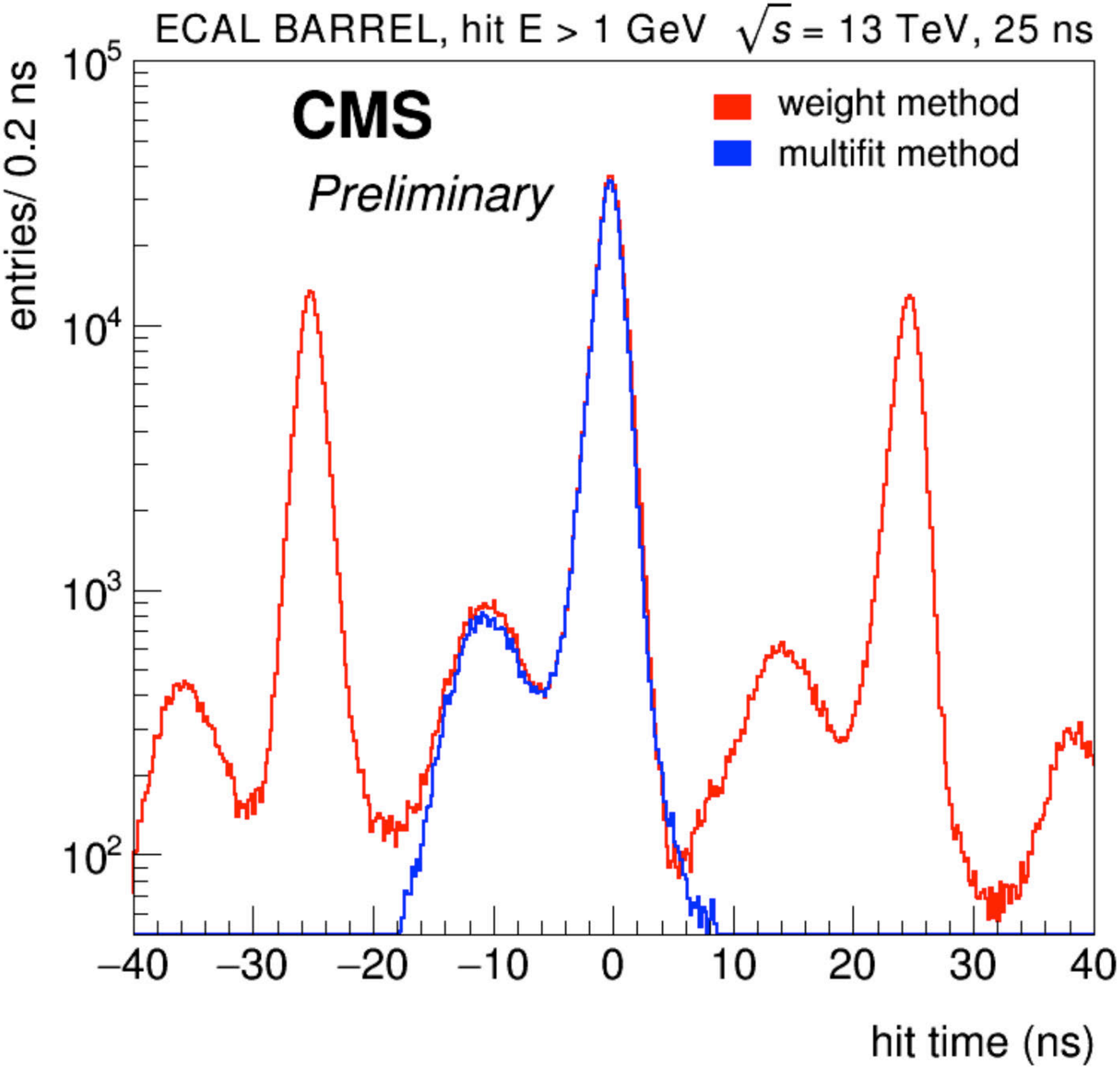
“Spike” events in CMS







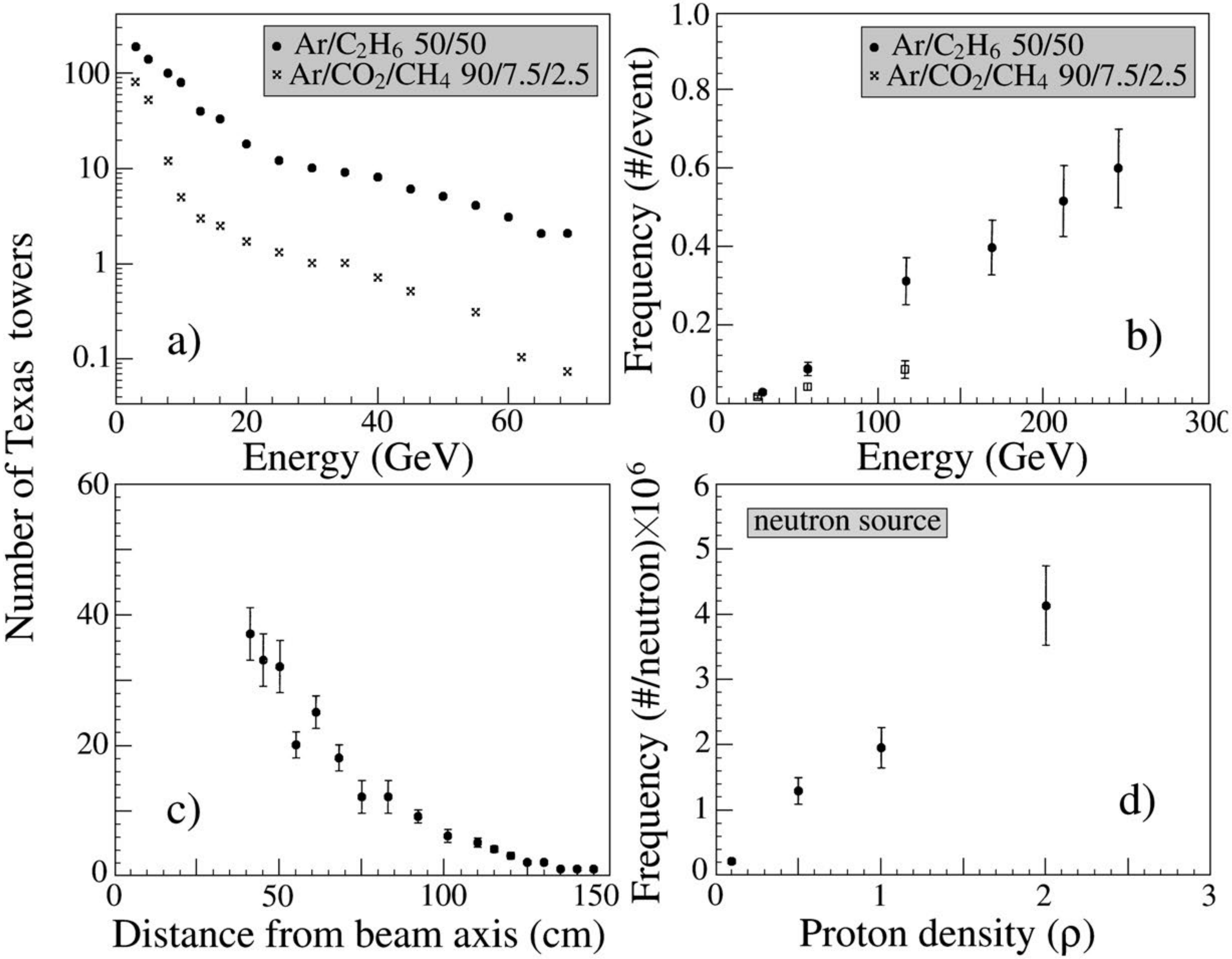
Spikes in CMS ECAL (after Swiss-cross elimination!)



Catastrophic effects of ONE individual shower particle (2)

The Texas Tower effect (CDF, 1988)

Sampling fraction mips = $10^{-5} \longrightarrow$ *100 GeV shower ≡ 1 MeV in gas!*



Catastrophic effects of ONE individual shower particle (3)

(my prediction: bets, anyone?)

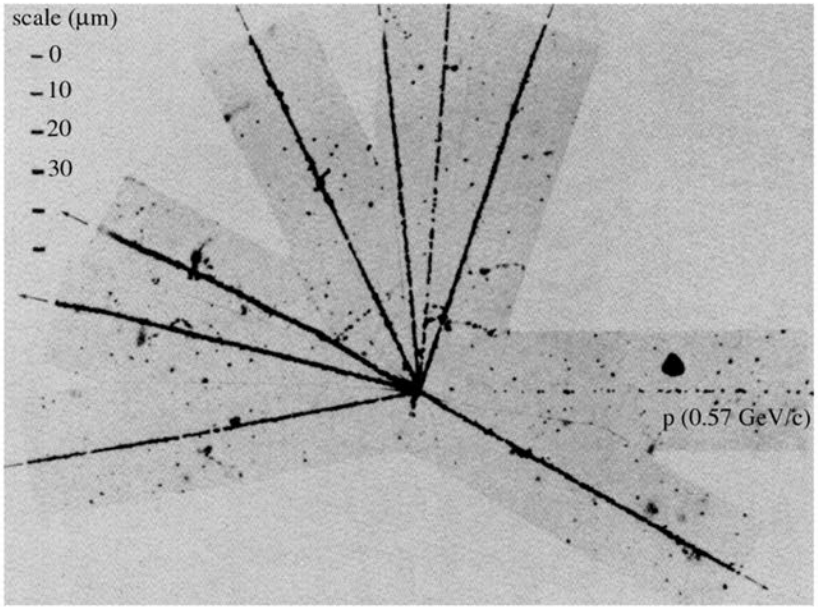
The high-luminosity CMS upgrade of the endcap calorimeter system has a section (FH) consisting of 5 cm thick brass absorber plates, interleaved with 100 μm silicon.

Sampling fraction for mips = $6 \cdot 10^{-4}$

An event such as this one (initiated by a 160 MeV proton) may deposit 30 MeV in one Si layer

No signal saturation!

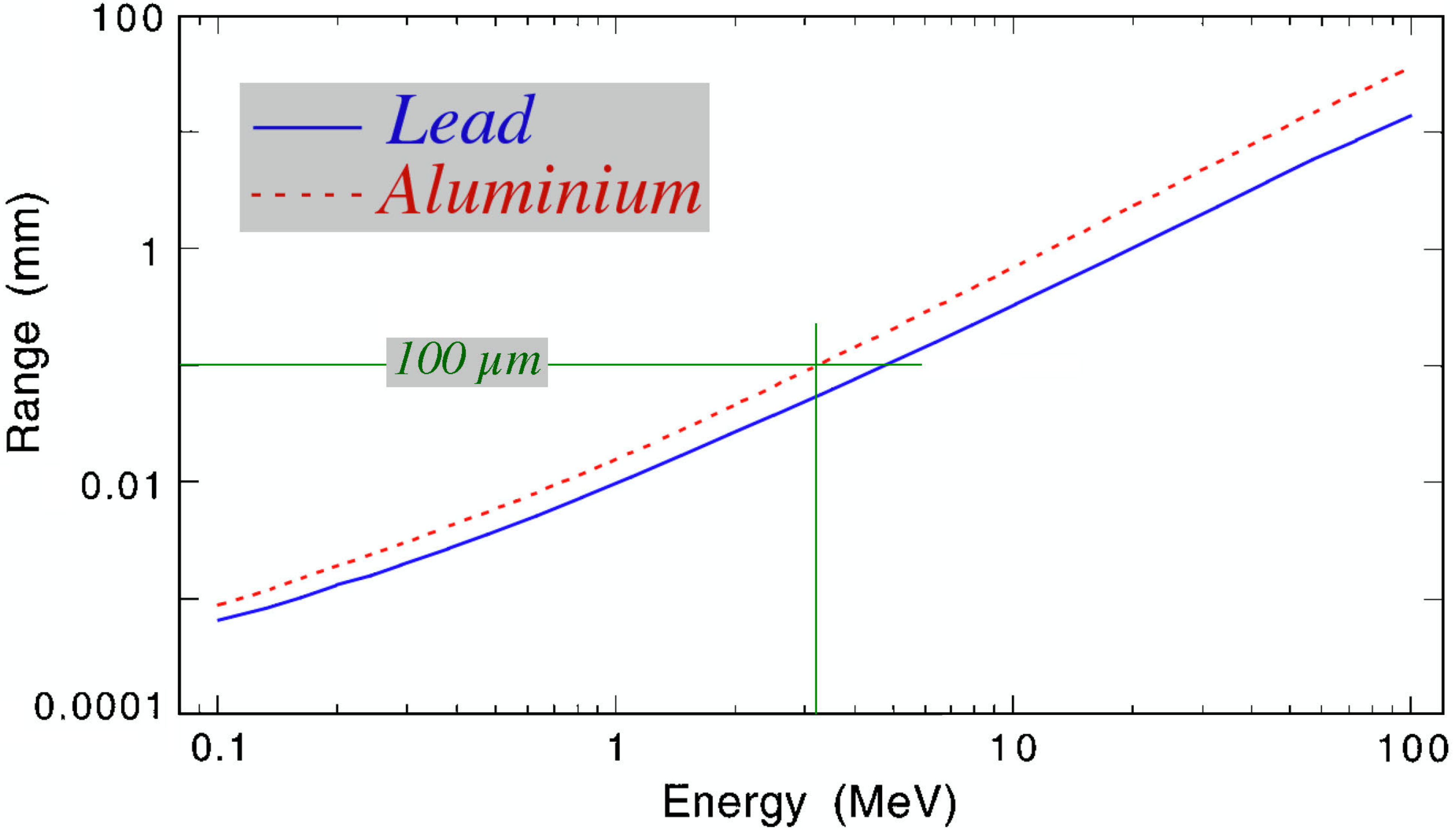
This will be interpreted as a 50 GeV energy deposit!



p (0.57 GeV/c)

(E_{kin} = 160 MeV)

The range of low-energy protons in different materials



Misconceptions about calorimetry

- *A shower is a collection of mips*
- *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

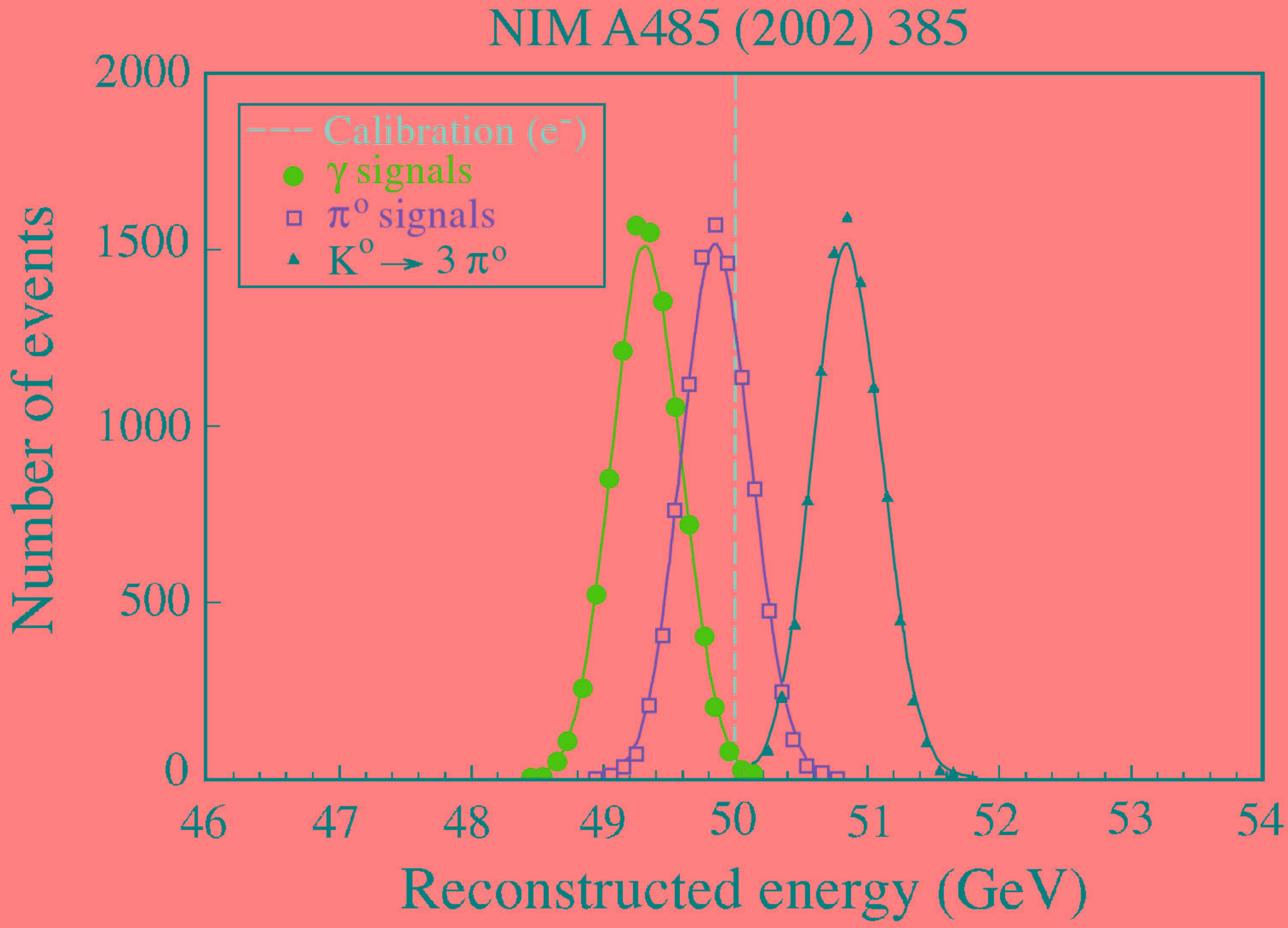
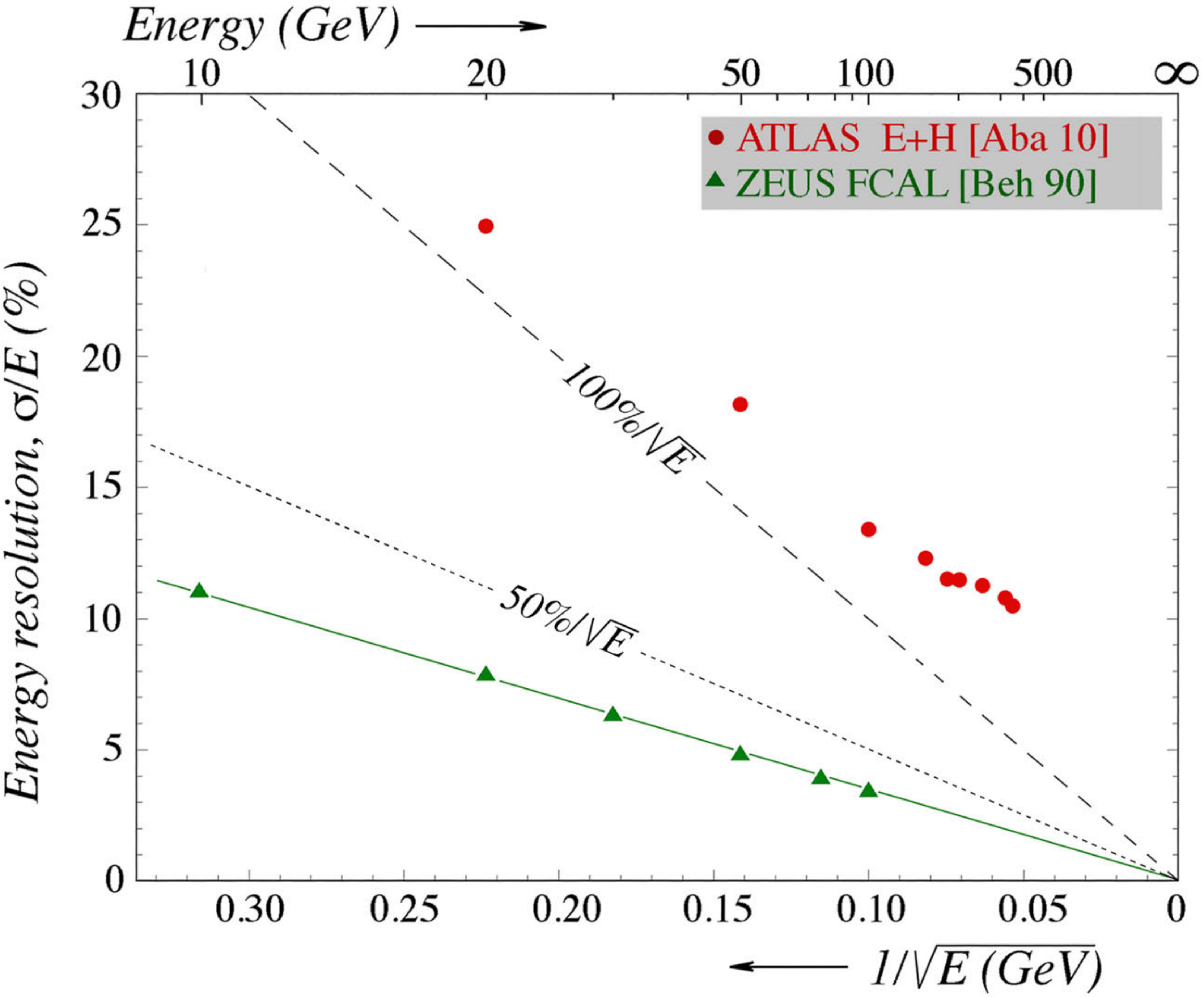


Figure 14: Signal distributions for γs and various hadrons decaying into all-γ final states. All particles have the same nominal energy and the detector, which has an intrinsic resolution of 0.5% for em showers of this energy, was calibrated with electrons using $B/A = 0.8$. See text for details.

Misconceptions about calorimetry

- *A shower is a collection of mips*
- *Energy resolution ≡ width of signal distribution*
- *Energy resolution scales like* $E^{-1/2}$

Hadronic energy resolution of compensating vs modern calorimeters



Misconceptions about calorimetry

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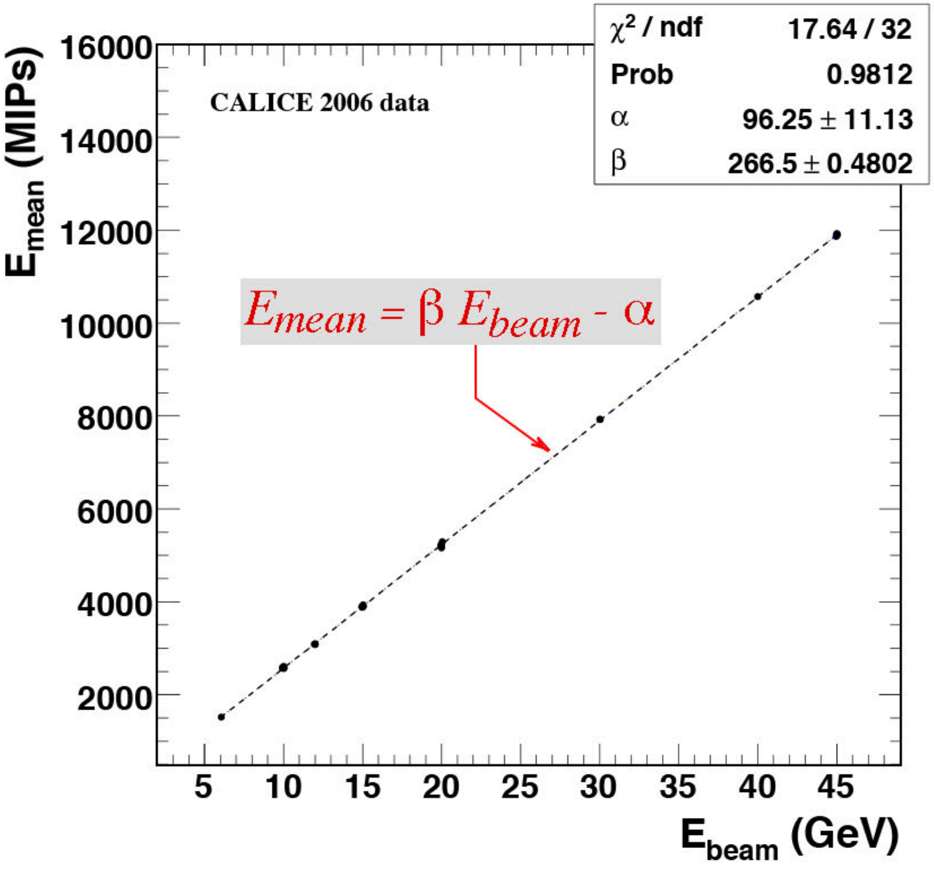
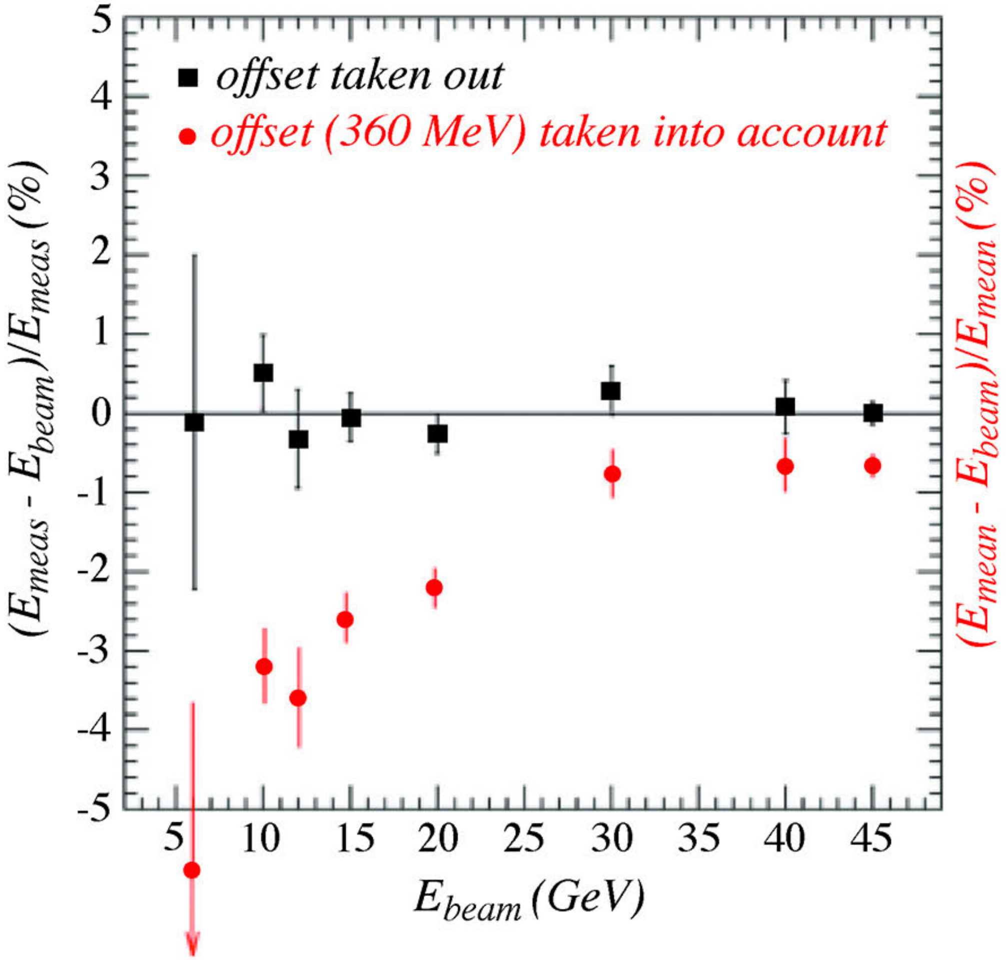
Response non-linearity in CALICE W/Si ECAL

NIM A608 (2009) 372





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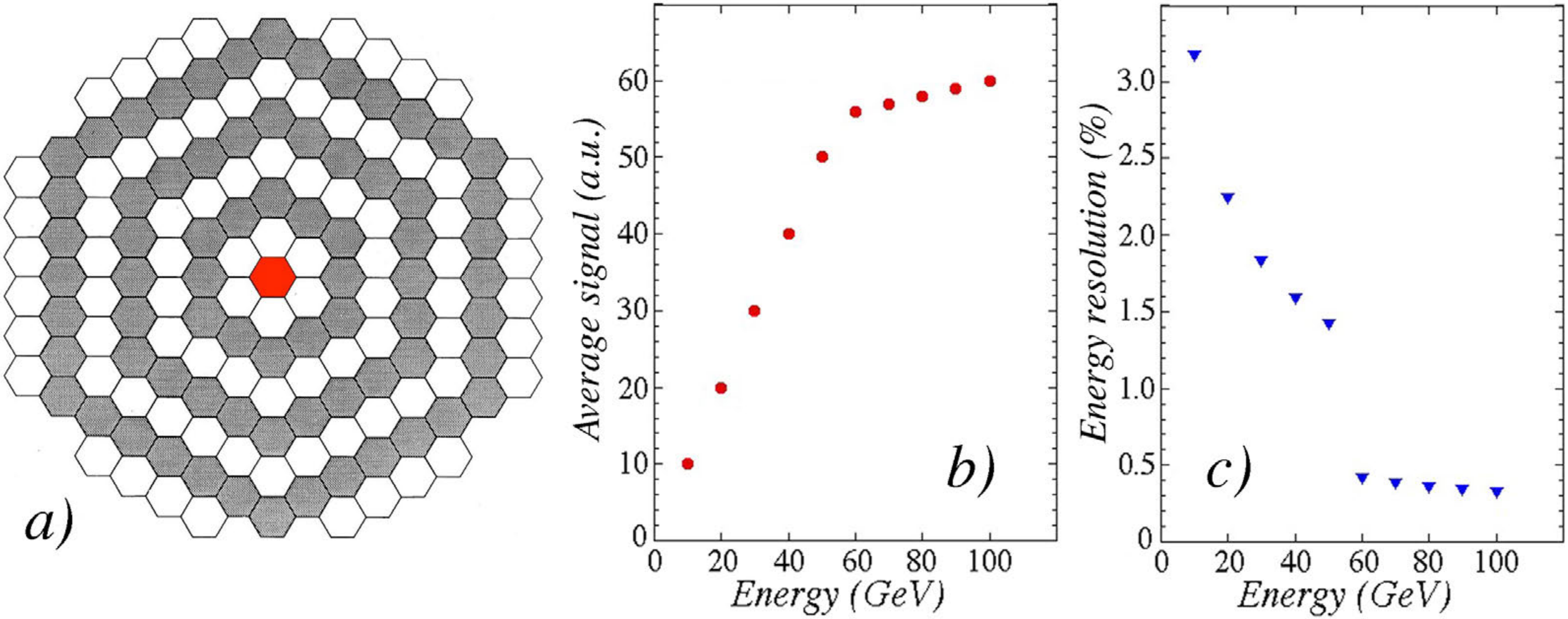
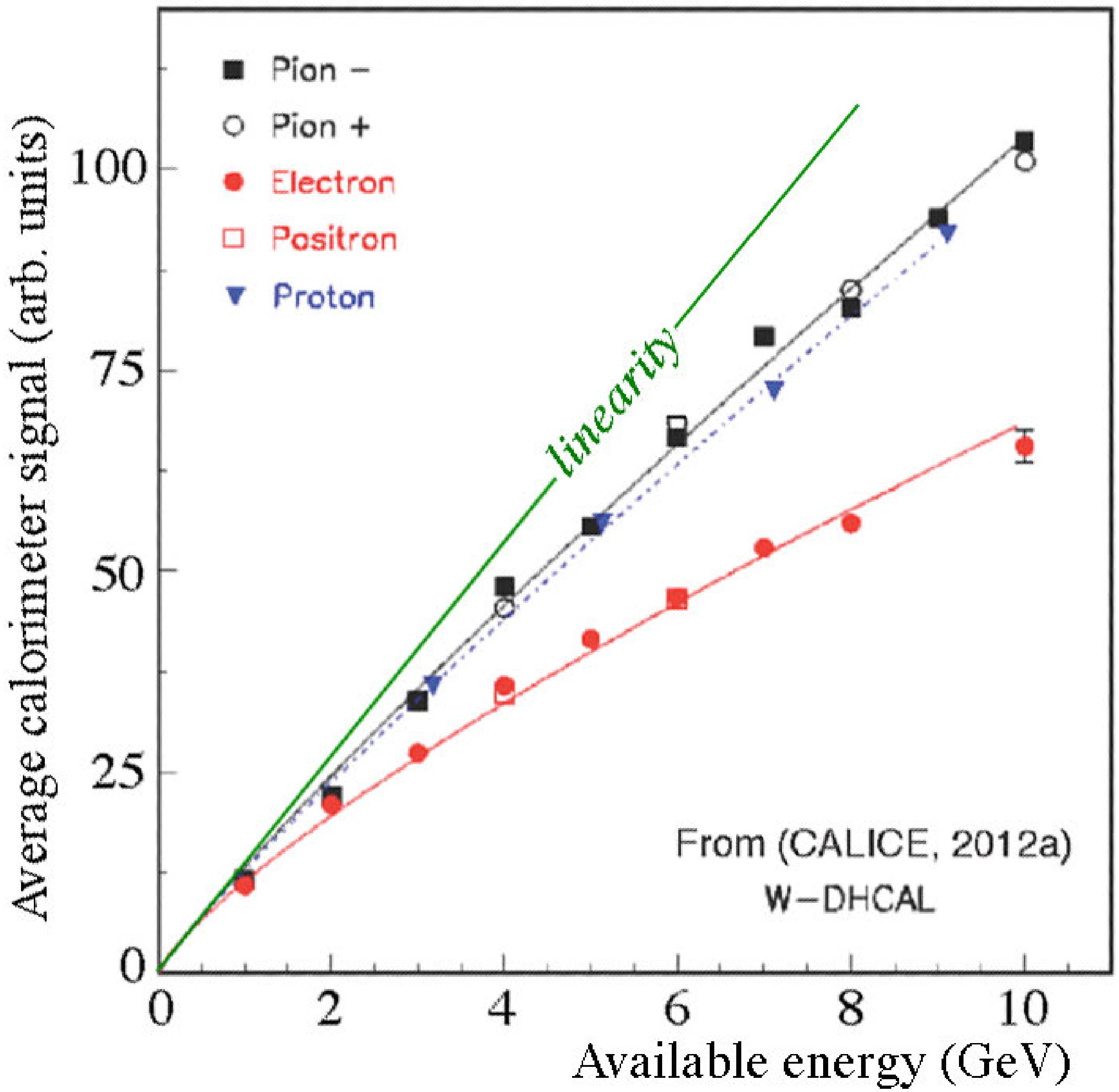
Effects of signal saturation (SPACAL)



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

Rev. Mod. Phys. 88 (2015) 15003



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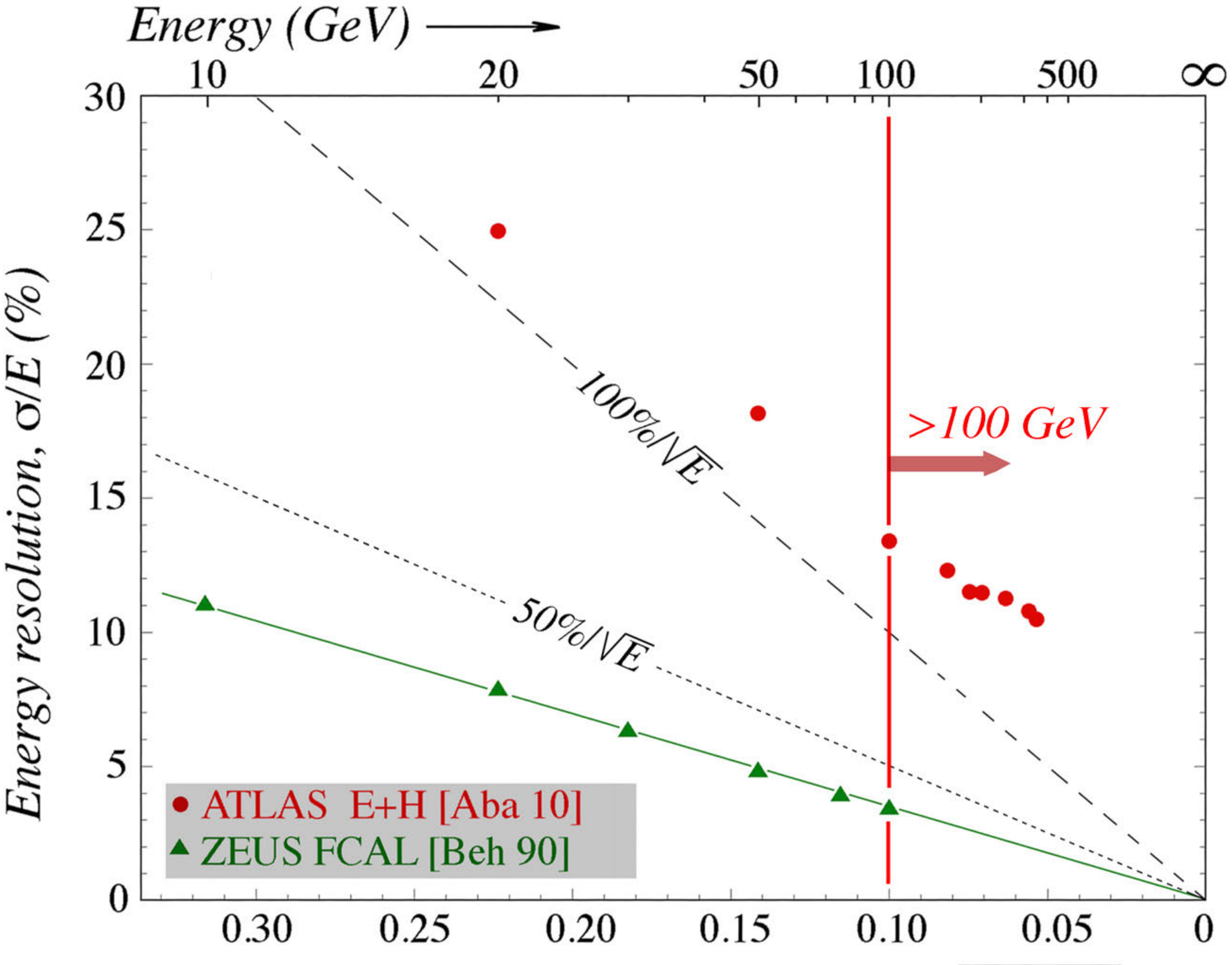

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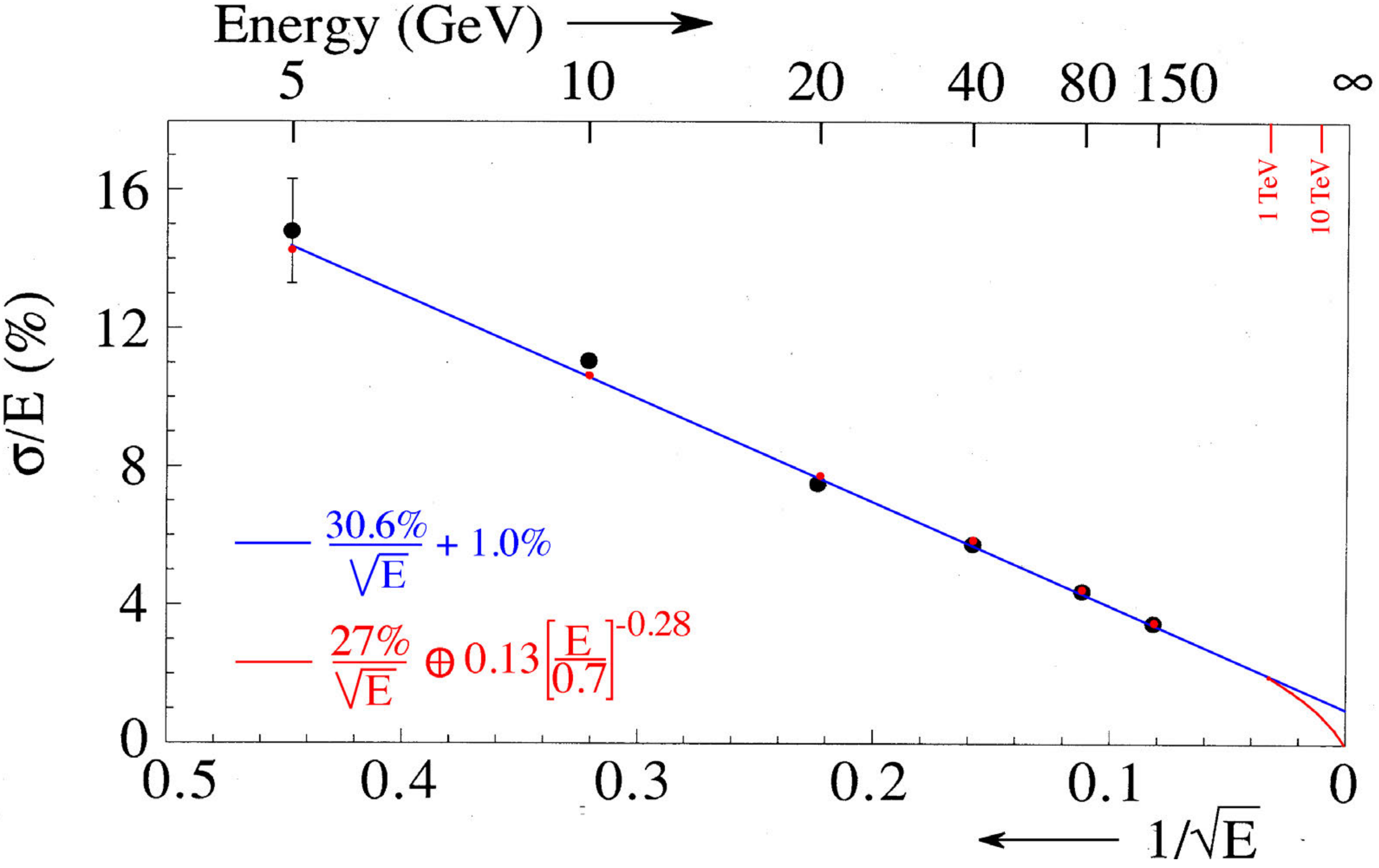
- The only effect of non-compensation is a constant term in the energy resolution

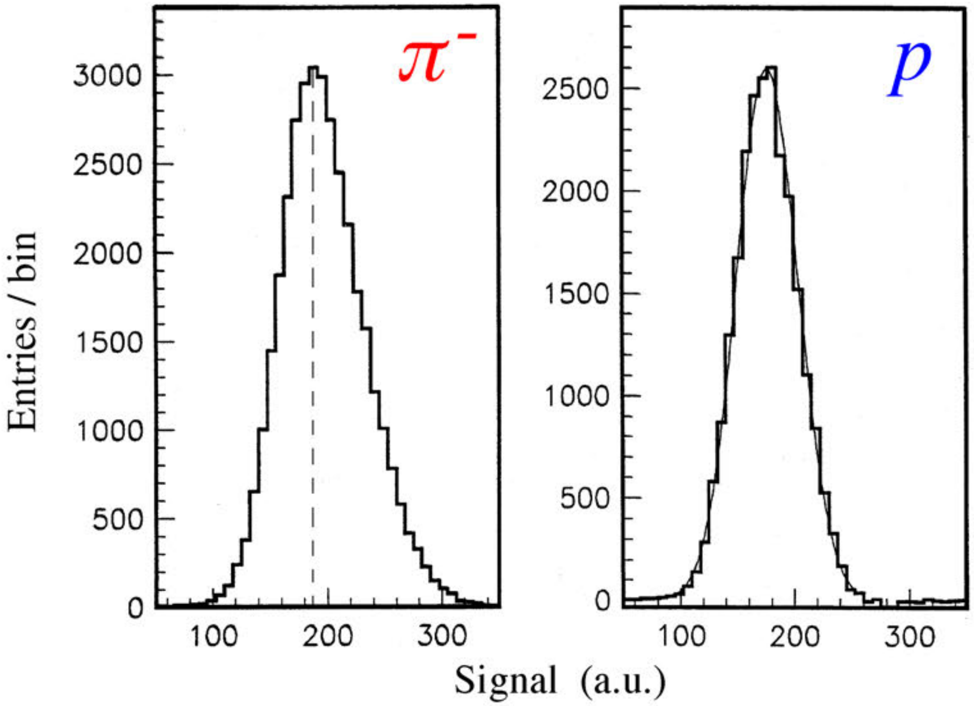
Difference only noticeable for E > 1000 GeV

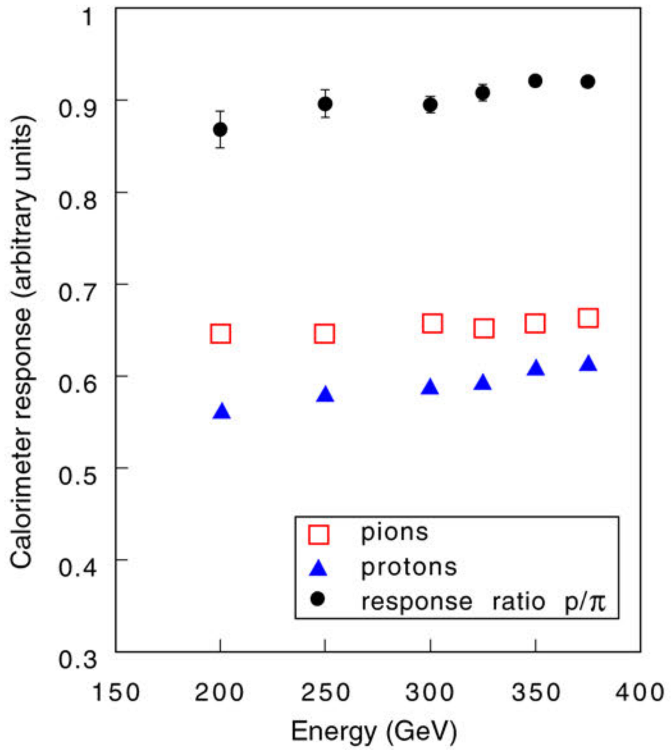


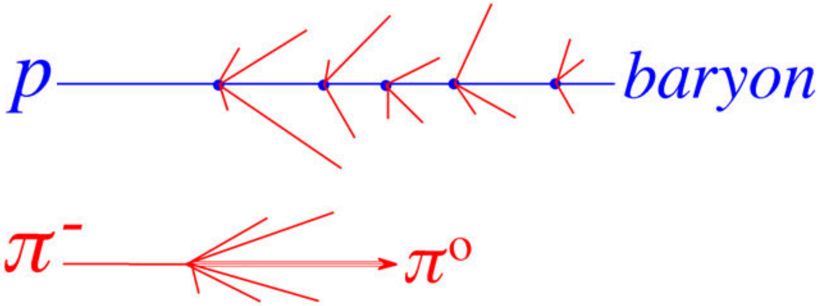
Misconceptions about calorimetry

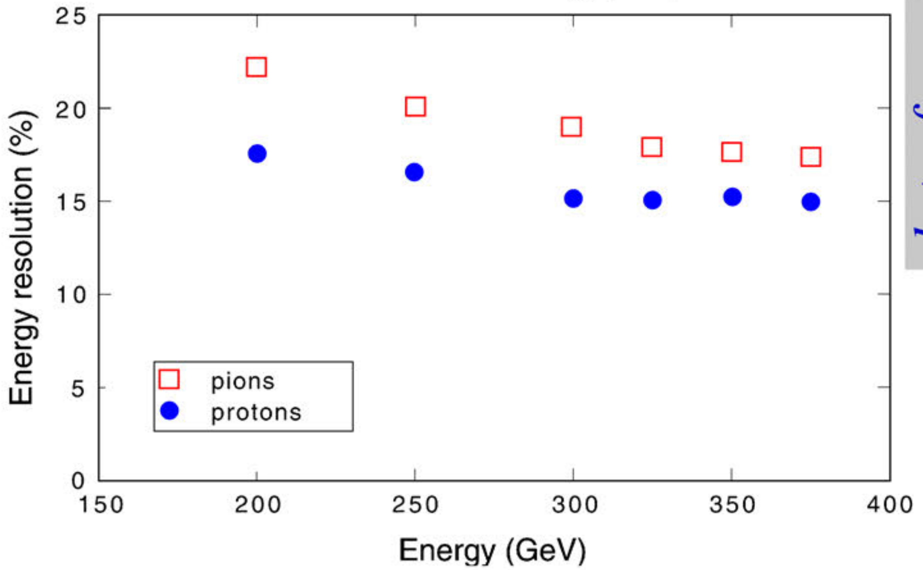
- *The only effect of non-compensation is a constant term in the energy resolution*
  - *Hadronic signal non-linearity*
  - *Non-Gaussian response functions*
  - *Different average signal for p, π, K*
  - *Calibration problems, especially if e/h (em) ≠ e/h (had)*

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









em fraction in p showers:

- *smaller*
- *less fluctuations*
- *more symmetric*
- *less concentrated near axis*

data from NIM A408 (1998) 380

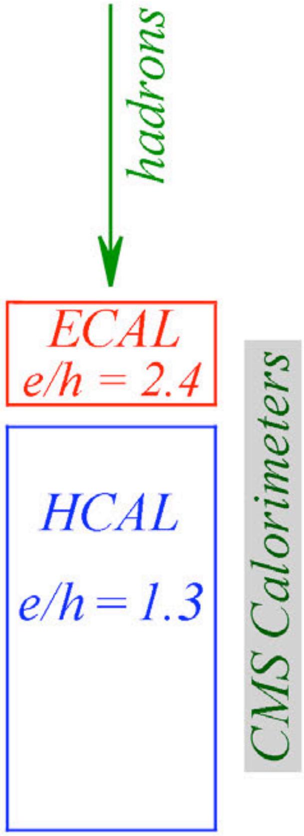
Consequences for LHC calorimeters

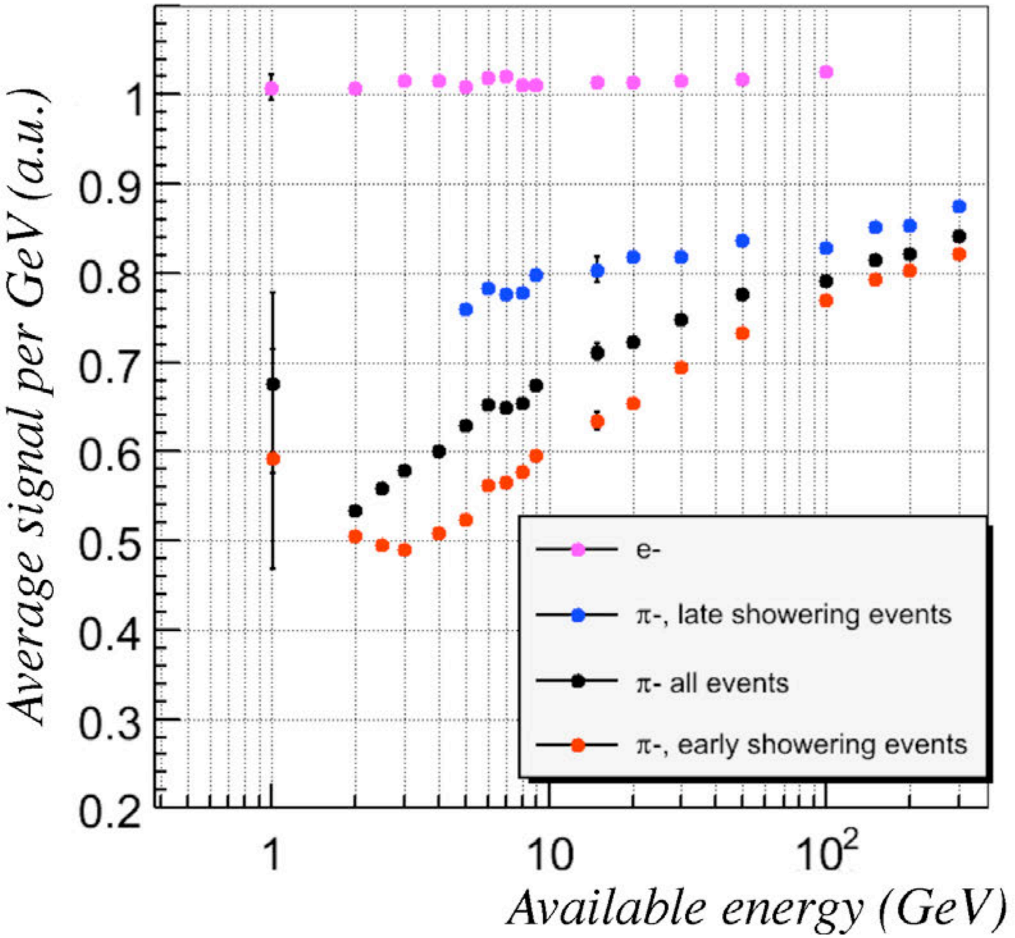
Hadronic response and signal linearity (CMS)

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





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Options for the future

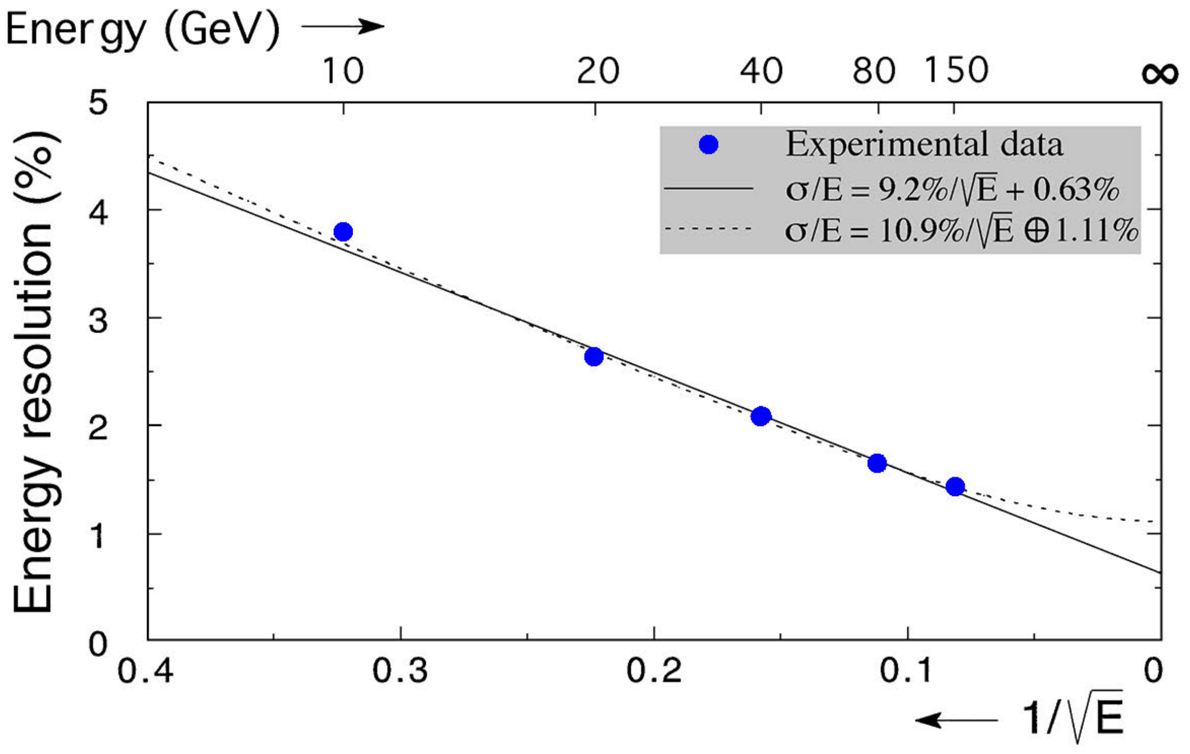
- *Intrinsically compensating calorimeters*
- *Dual-readout calorimeters*
- *Particle Flow Analysis systems*

A good alternative for future collider experiments

(compensating em and had segments)

ECAL

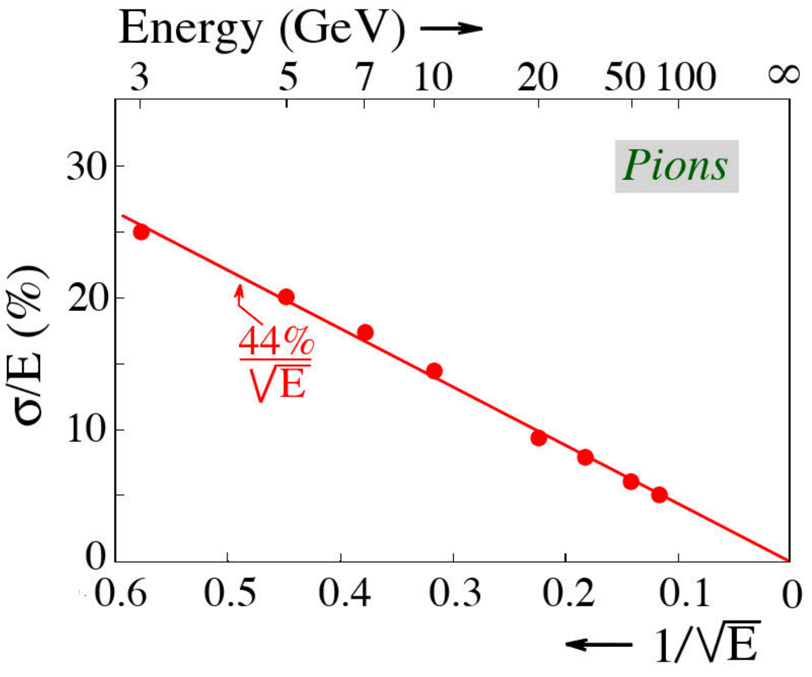
● Pb/fiber 4:1, 0.5 mm fibers (RD1)



NIM A337 (1994) 314

HCAL

● 10mm Pb/2.5mm scint [Bern87]



NIM A262 (1987) 229

Cu/fiber dual-readout calorimetry

- *Excellent em and hadronic energy resolution*

- *Calibration is trivial*

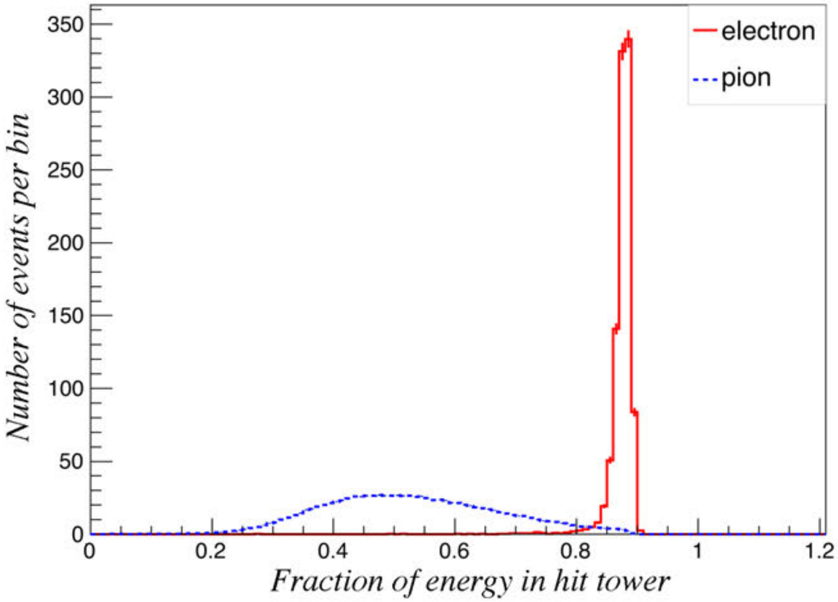
- *Excellent particle-id in longitudinally unsegmented detector*

- *Ultrafast Cherenkov signals give unique timing options*

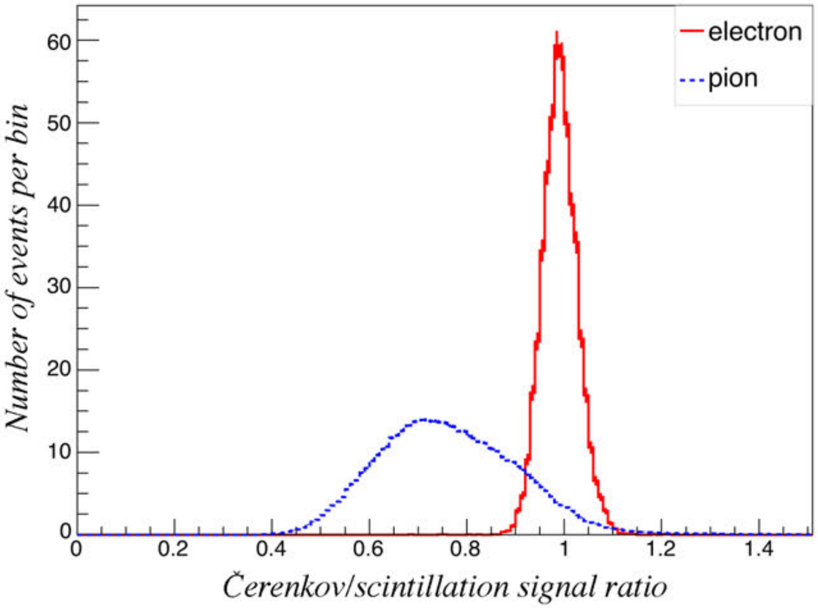
Methods to distinguish e/π in longitudinally unsegmented calorimeter

NIM A735 (2014) 120

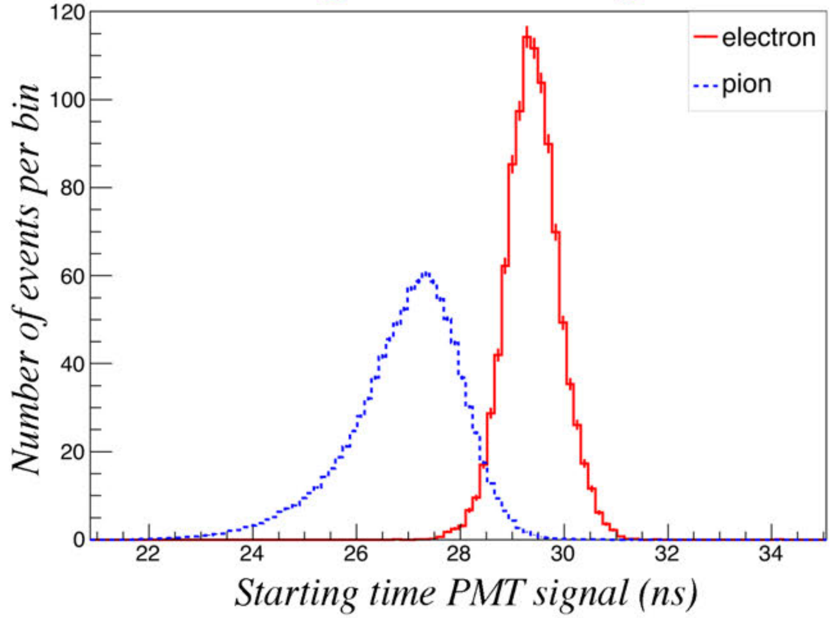
Lateral shower profile



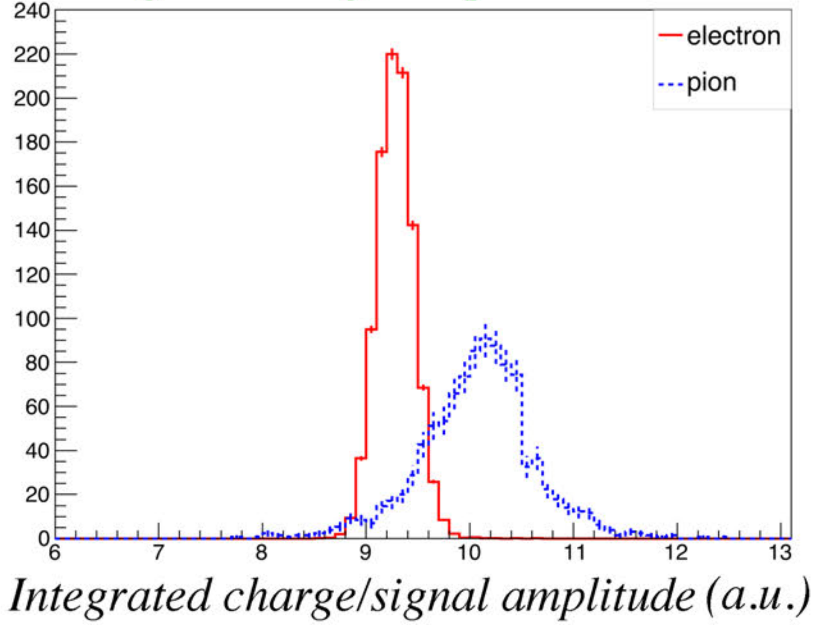
Difference C/S signals



Starting time PMT signal



Signal charge/amplitude ratio



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

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

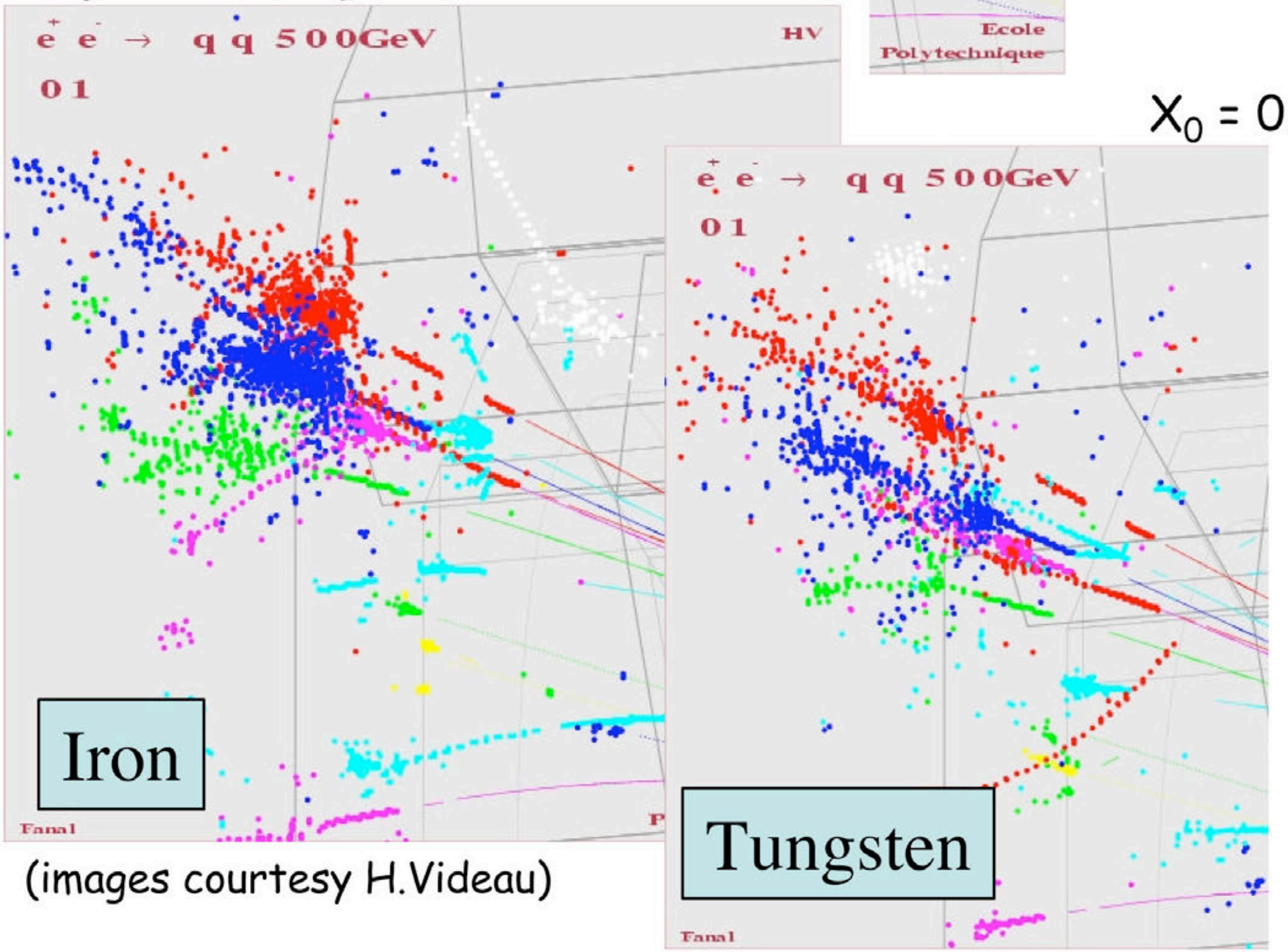
- This principle has been used successfully to improve the hadronic performance of experiments with poor hadronic calorimetry
  However, the improvements are fundamentally limited
  In particular, no one has ever come close to separating W/Z this way

- 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!!

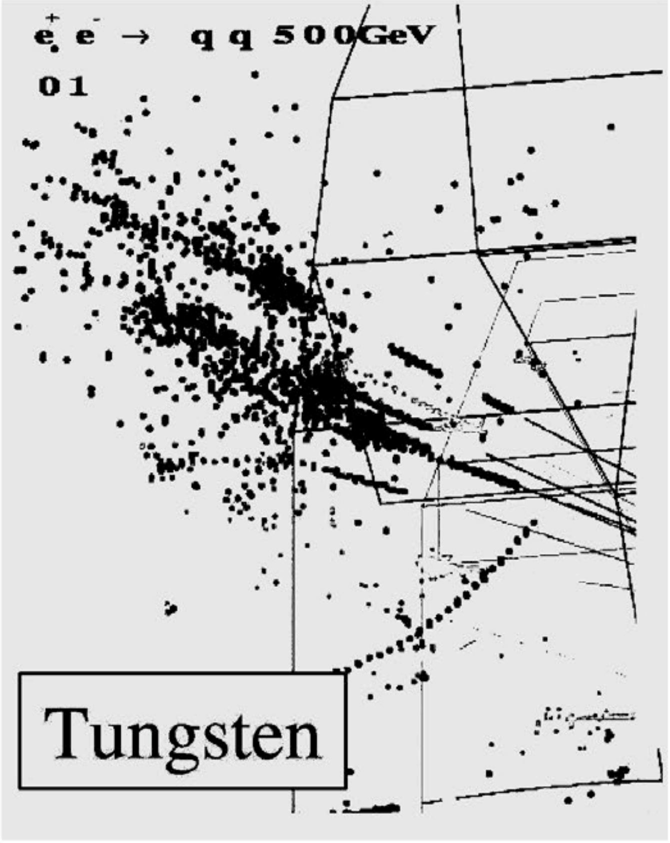
Pink Pion Physics

X_0 = 1.8cm, λ_I=17cm



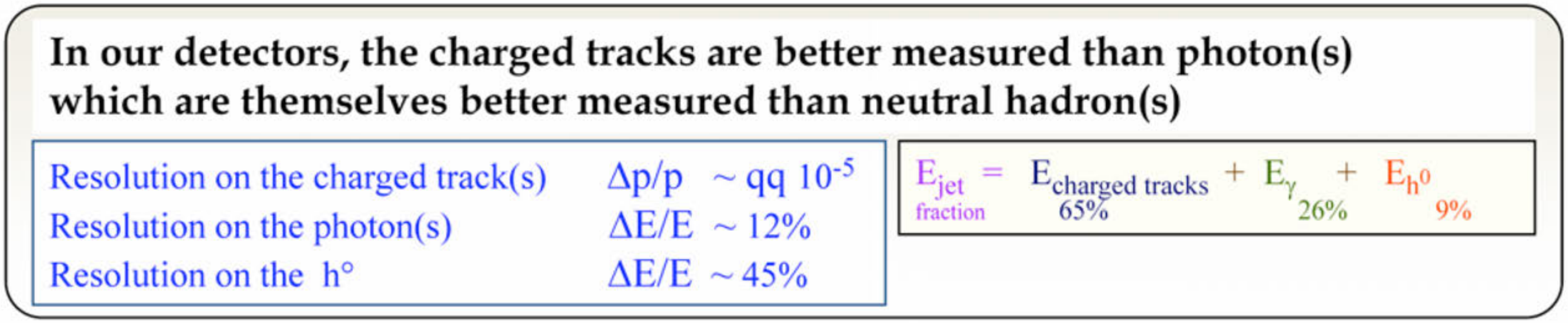
(images courtesy H.Videau)

X_0 = 0.35cm, λ_I=9.6cm



A frequently used, but misleading argument

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



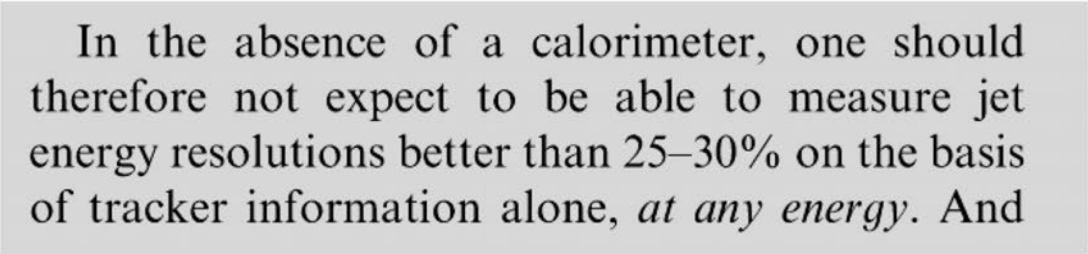
In our detectors, the charged tracks are better measured than photon(s) which are themselves better measured than neutral hadron(s)

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°	$\Delta E/E \sim 45\%$

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

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

Hadronic calorimeter prototype

Vienna Conference on Instrumentation
NIM A732 (2013) 466

Absorber: Tungsten or Steel

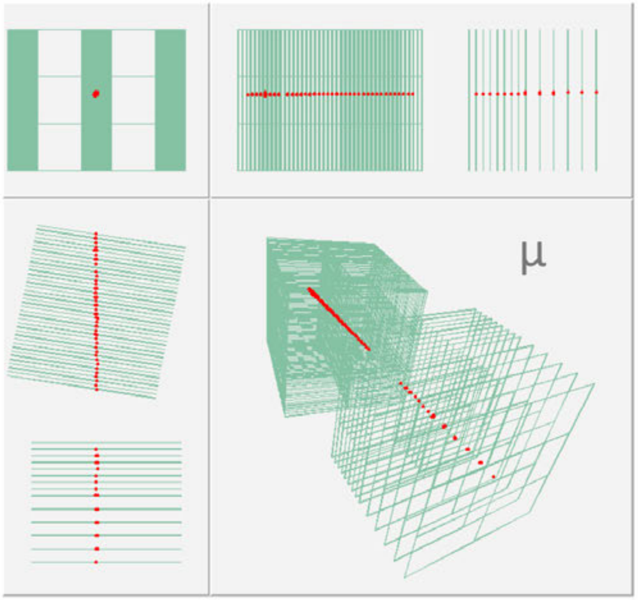
Digital readout: RPCs (1 x 1 cm^2)

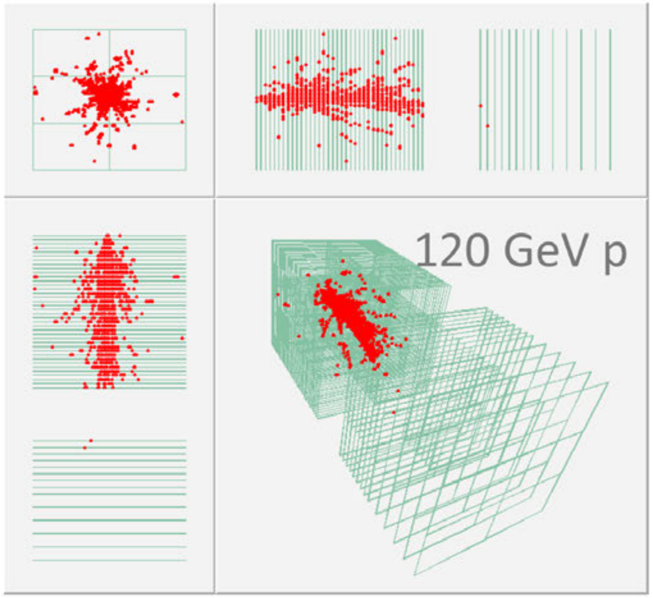
Dimensions: 54 layers, 1 x 1 m^2

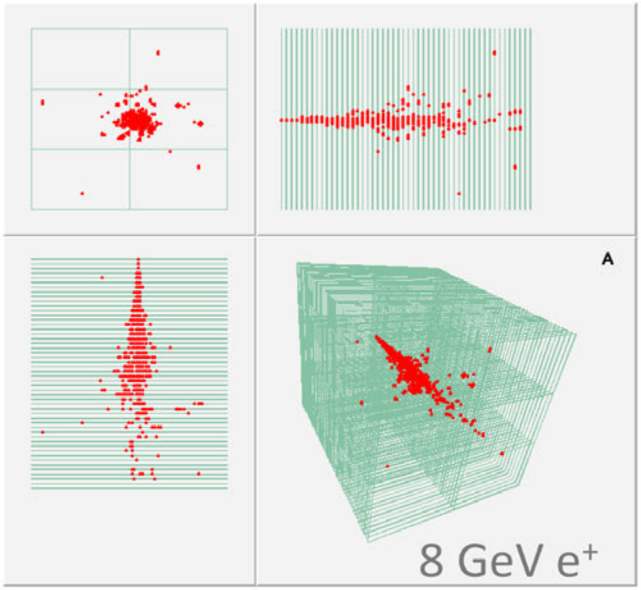
~500,000 readout channels !!

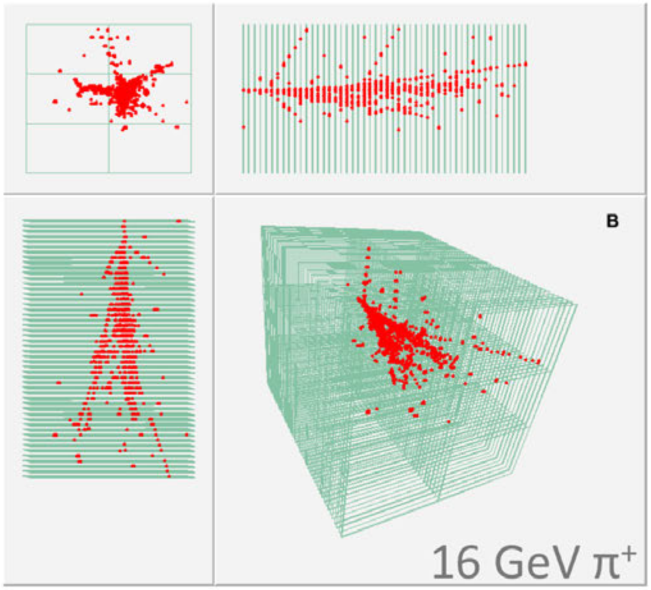
Tested at CERN/FNAL, e/π 10 - 300 GeV

Some events displays of the CALICE DHCAL







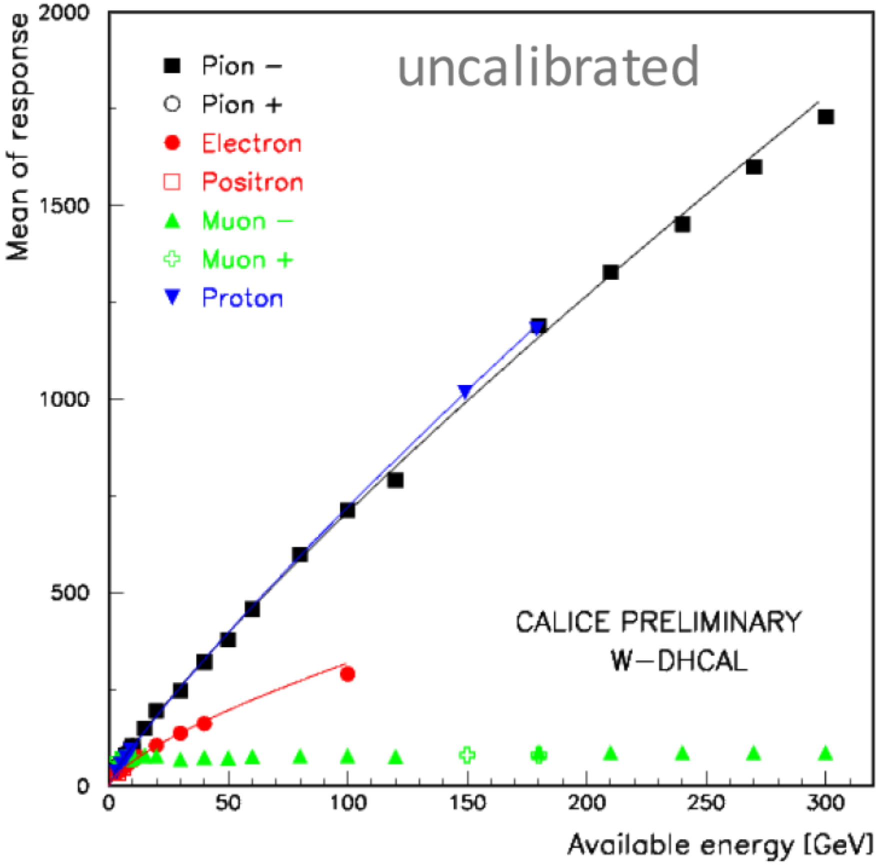


← 1 m →

There exists no such thing as a TYPICAL event profile

Test results digital hadron calorimeter CALICE

Tungsten – DHCAL



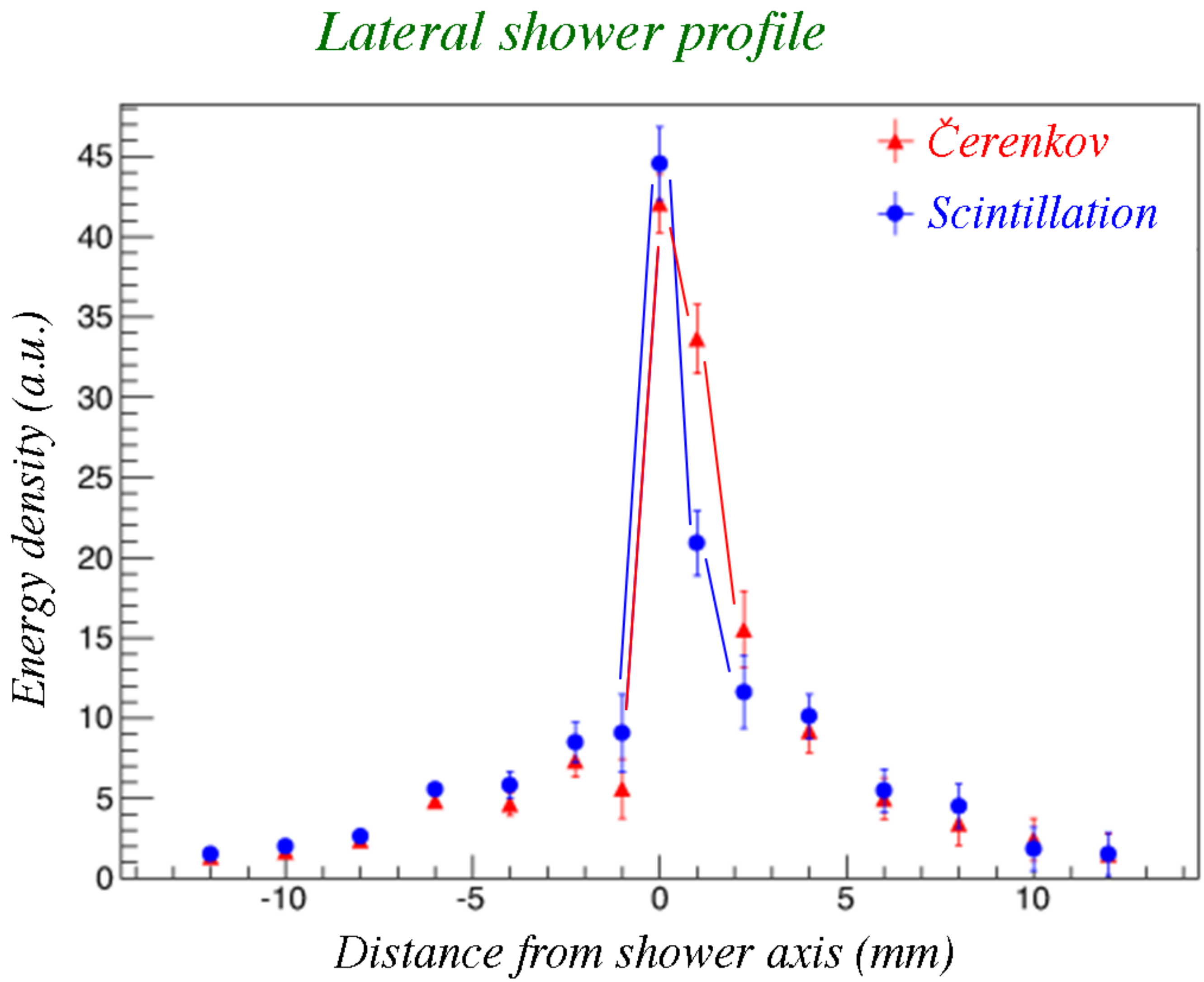
Non-linear response
to both $e^{\pm}$ and hadrons

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



NIM A735 (2014) 130

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

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- *ALL CALORIMETER PROBLEMS CAN BE SOLVED OFFLINE*

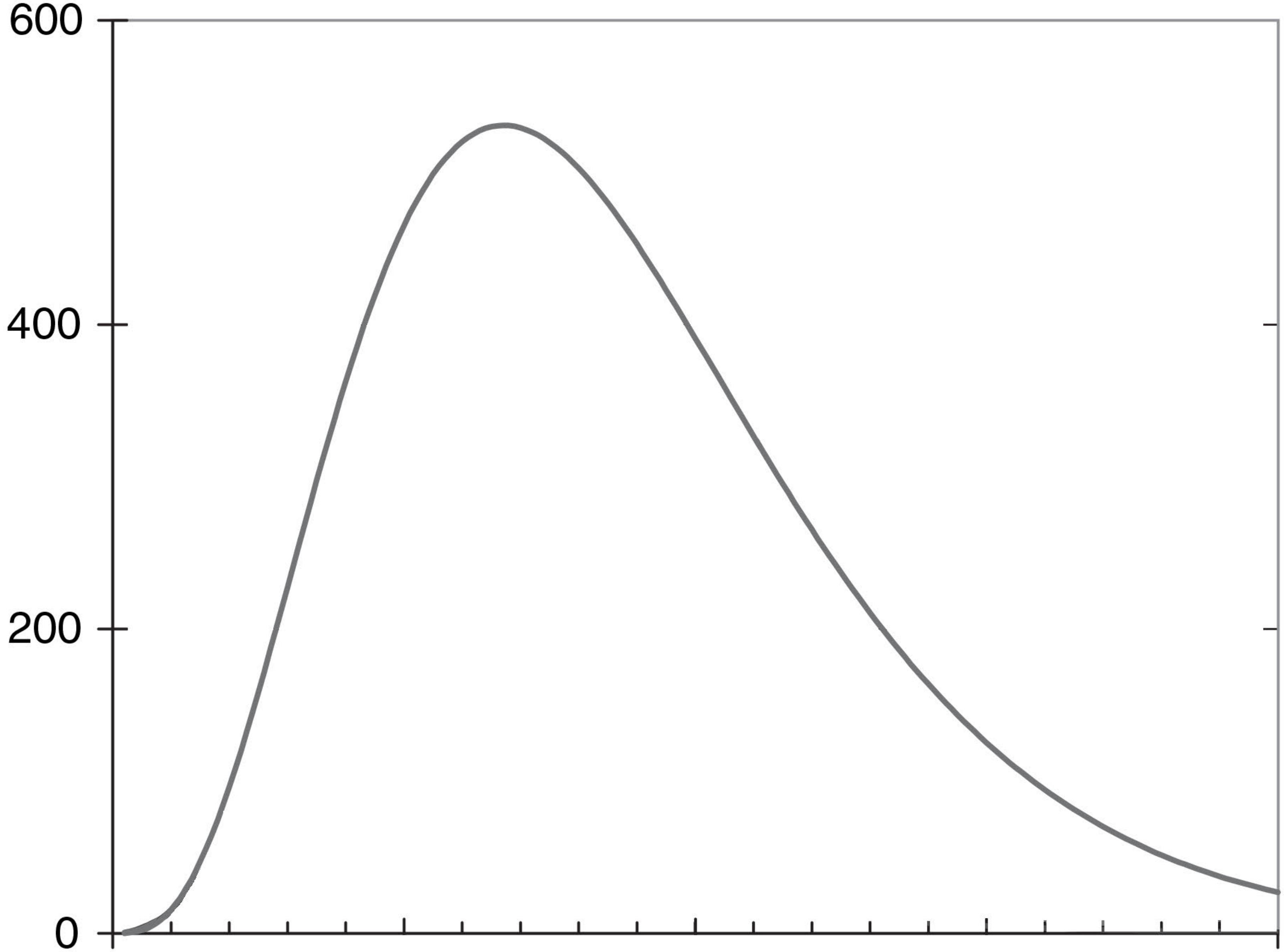
→ *Pretend everything is OK*
Build those calorimeter systems with 10^8 *channels*
Leave it to future generations to solve the mess

The future of calorimetry in high energy physics

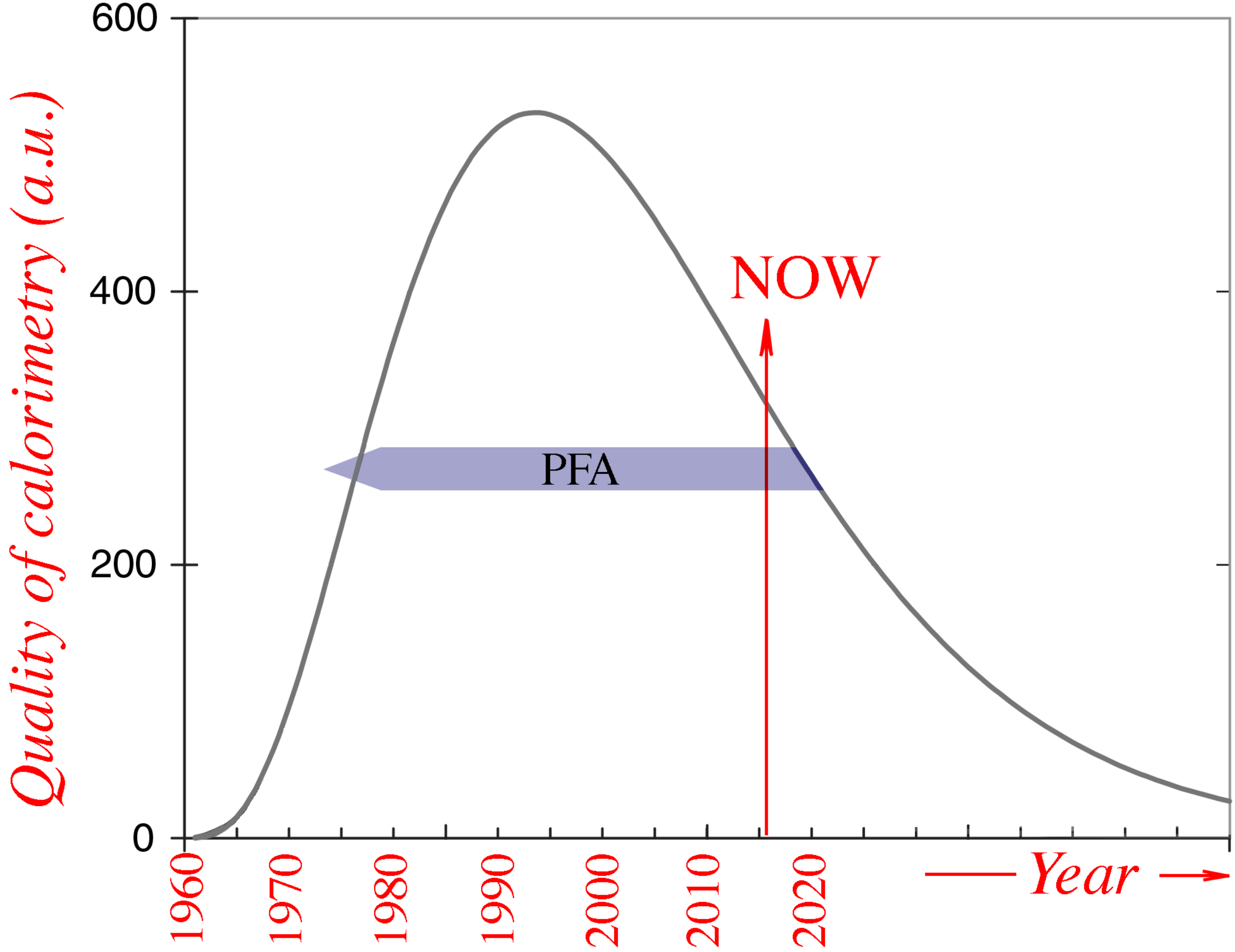
- *No funding available for generic R&D*
- *Ignorance, misconceptions + lack of interest for crucial issues*
- *Belief that all problems can be solved with technology (W, Si, RPC)*

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

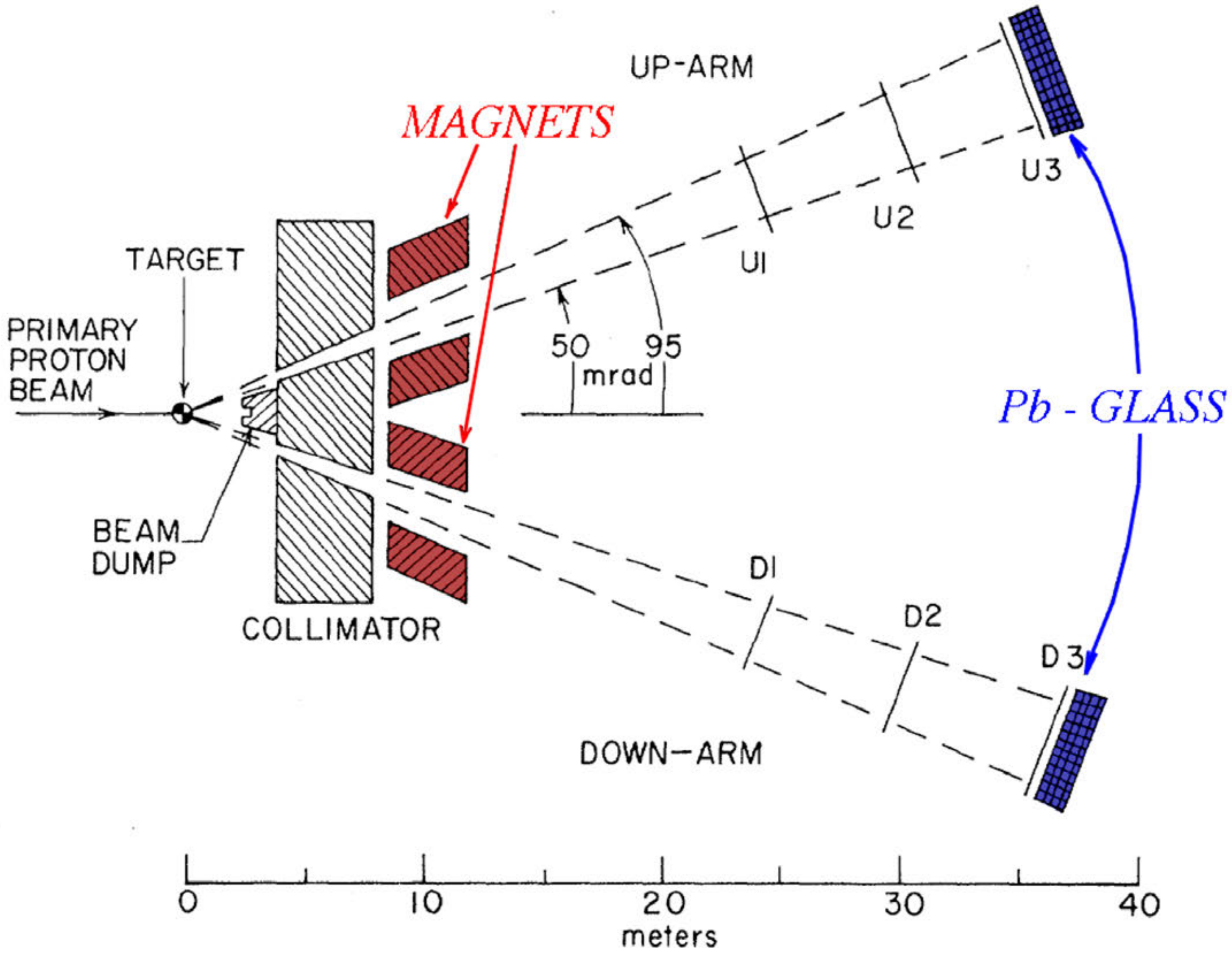
Where do we go from here?



The future of calorimetry in HEP experiments



1970s - Shower counters in magnetic spectrometers

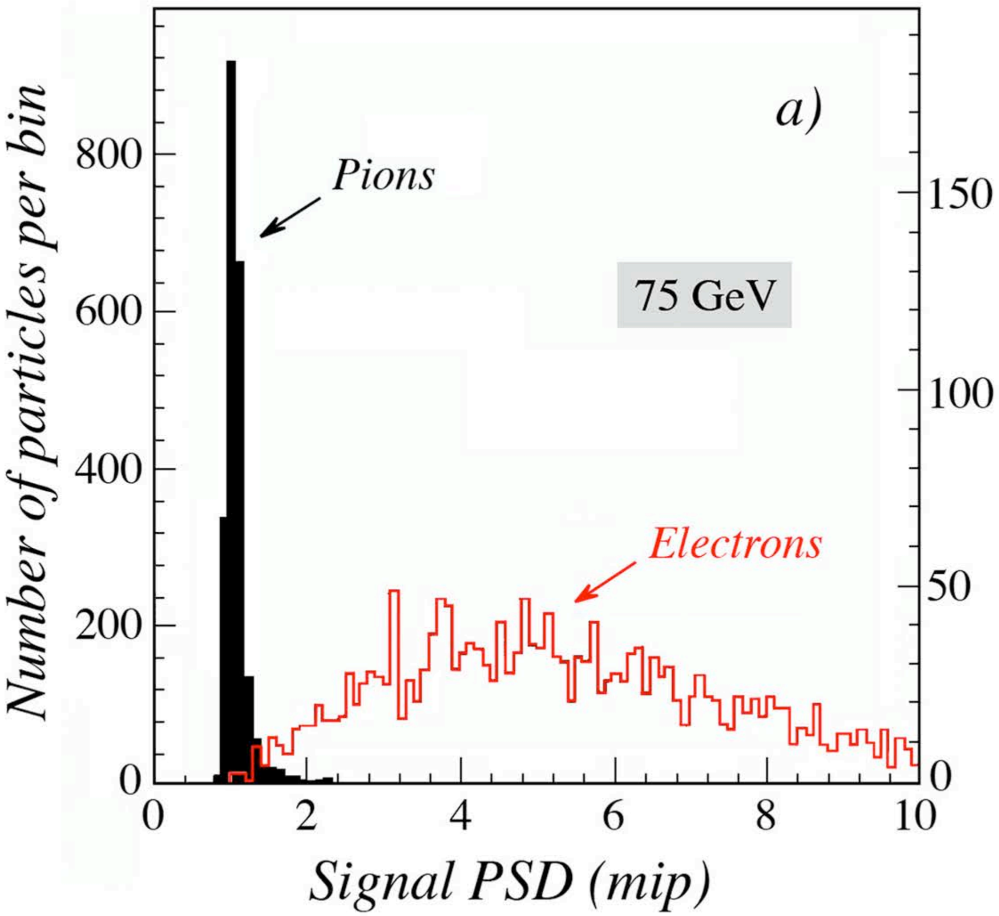


However, in modern 4π experiments the showers start after < 2m, instead of 40m

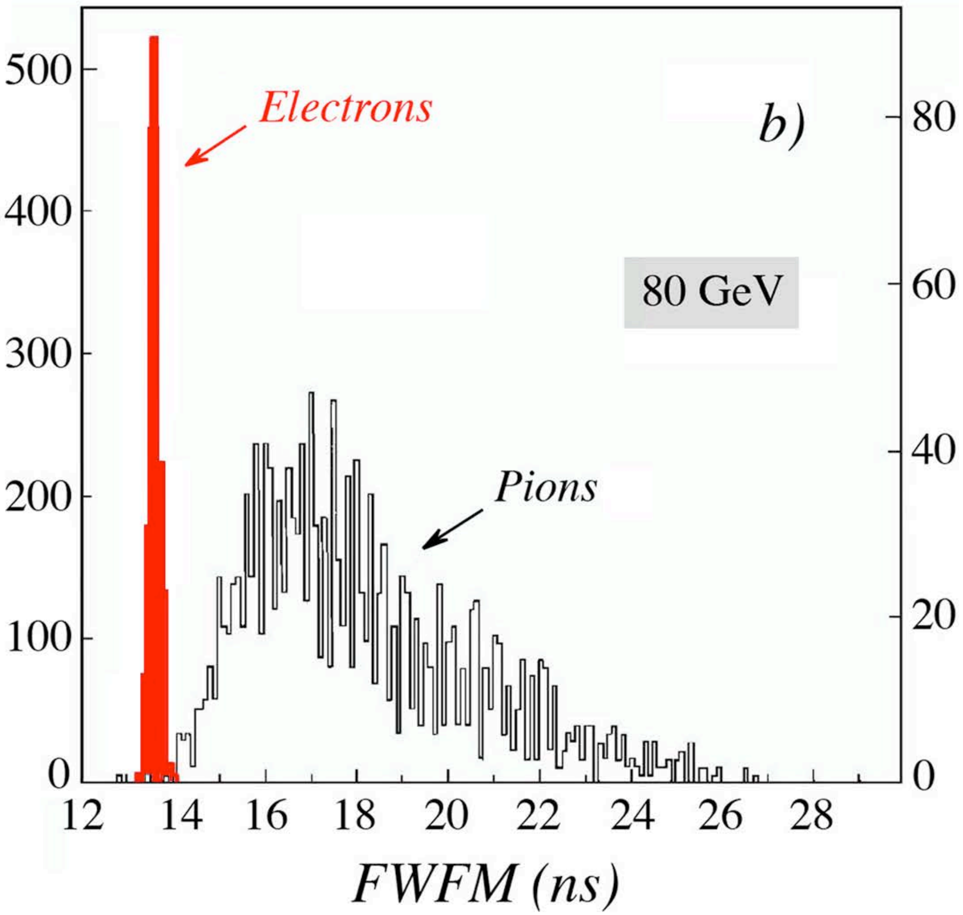
Backup slides

Particle identification with calorimeters

Using shower profile (pre-shower detector)



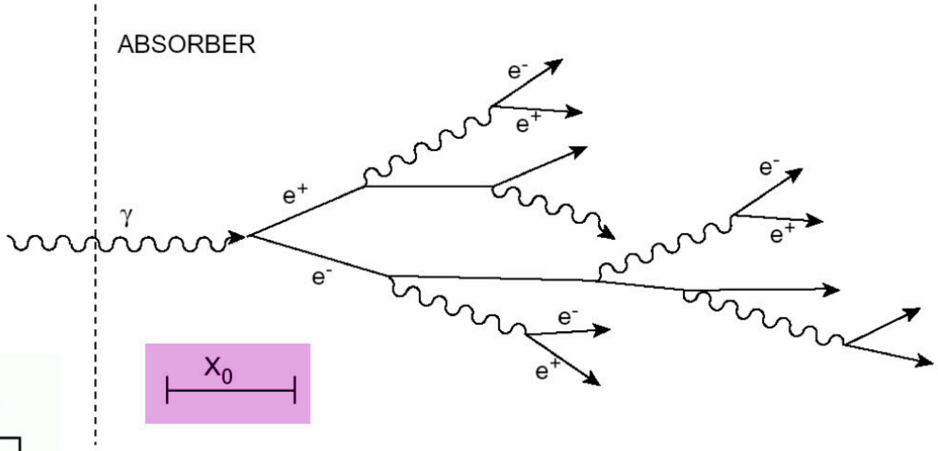
Using time structure of the signals

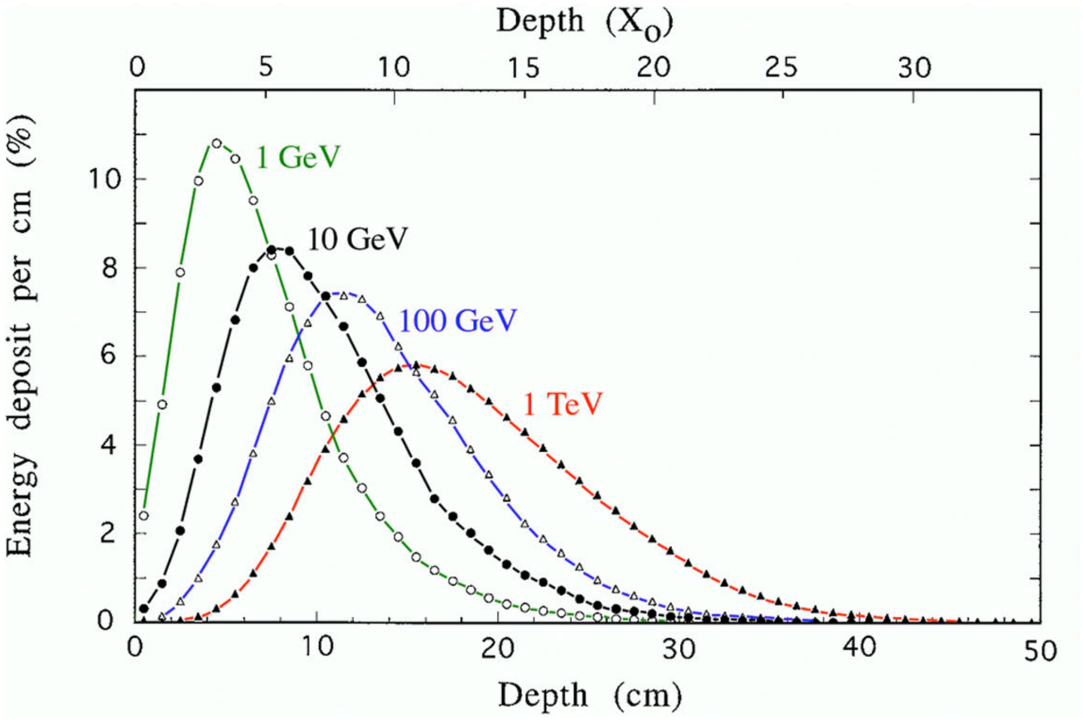


Calorimeters

Electromagnetic shower development

When a high-energy electron or photon enters a calorimeter, its energy is absorbed in a cascade of processes in which many different "shower" particles are produced.



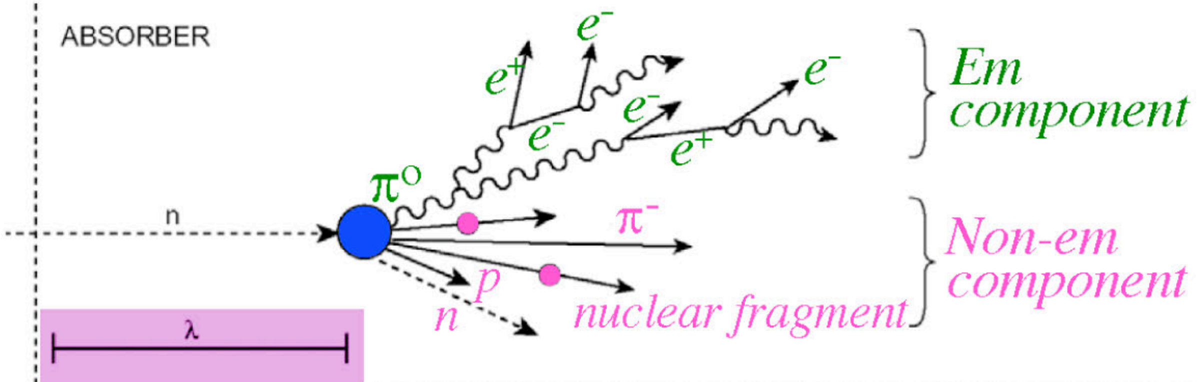


The shower development is governed by the "radiation length" X_o, which is typically ~ 1 cm

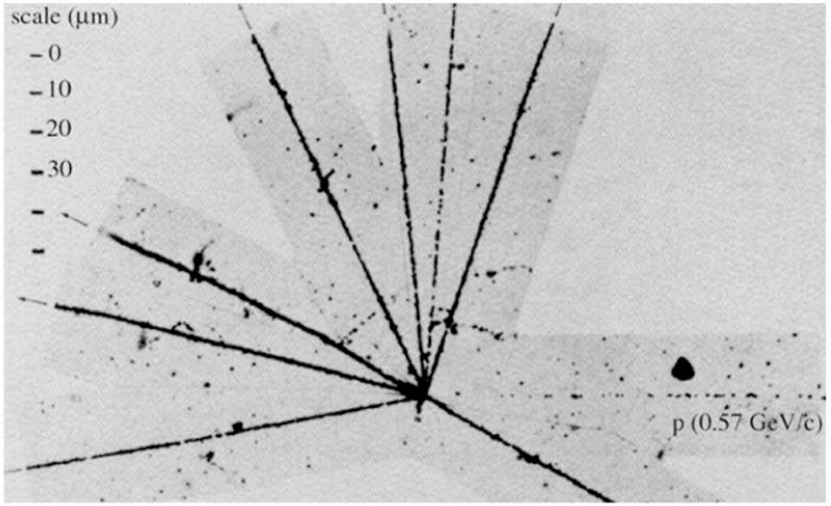
Even very-high-energy particles are absorbed in relatively small detectors (99% of 100 GeV e^- in 10 kg)

The physics of hadronic shower development

- A hadronic shower consists of two components



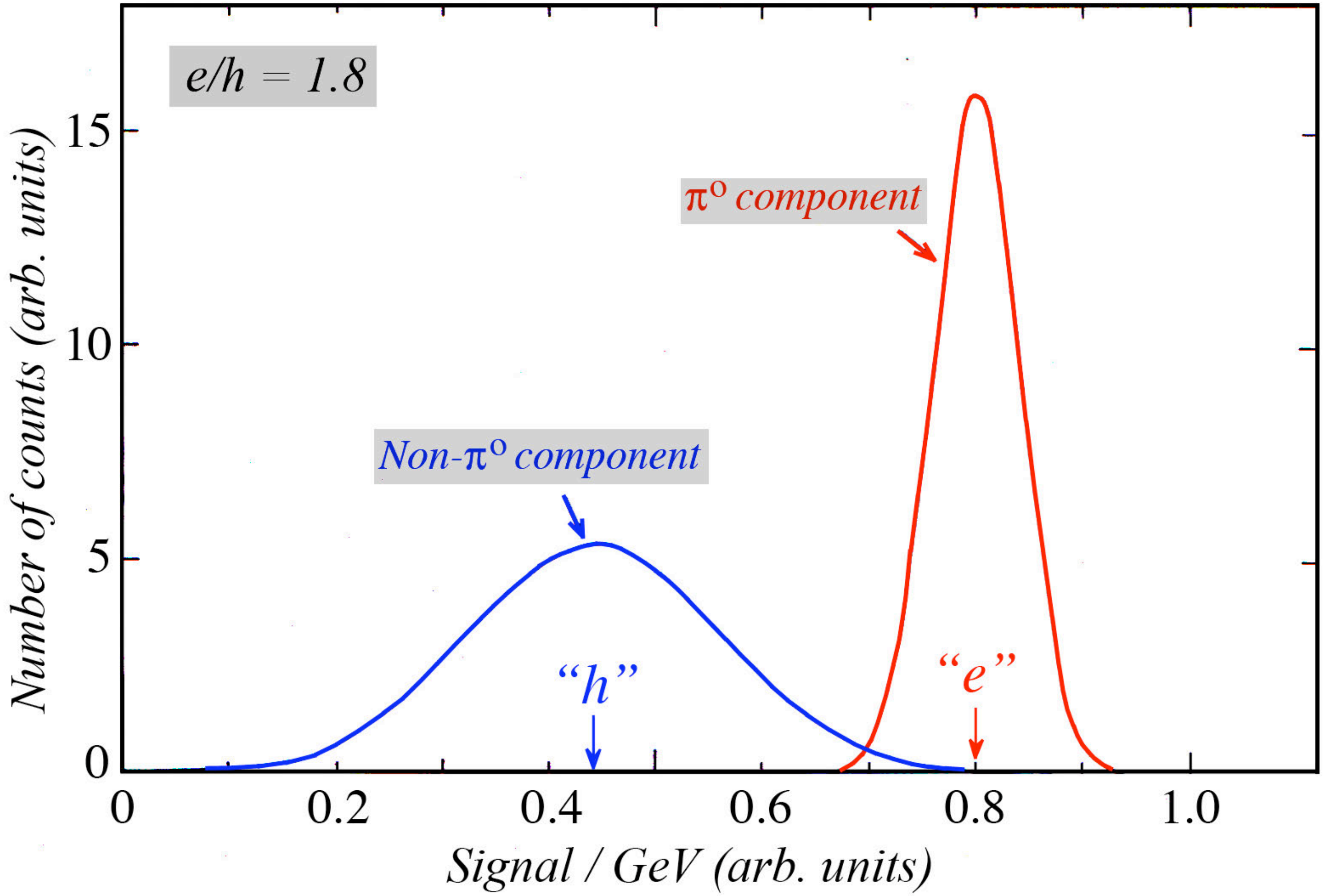
- **Electromagnetic component**
  - electrons, photons
  - neutral pions → 2 γ
- **Hadronic (non-em) component**
  - charged hadrons $\pi^{\pm}$, $K^{\pm}$ (20%)
  - nuclear fragments, p (25%)
  - neutrons, soft γ's (15%)
  - break-up of nuclei (*"invisible"*) (40%)



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

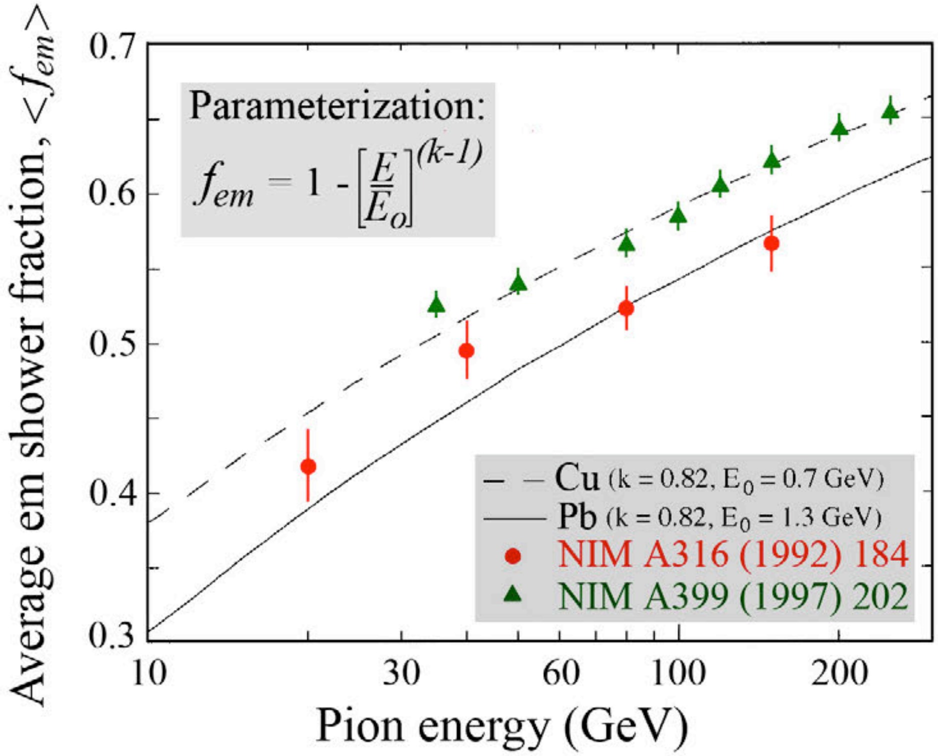
The calorimeter response to the two shower components is NOT the same

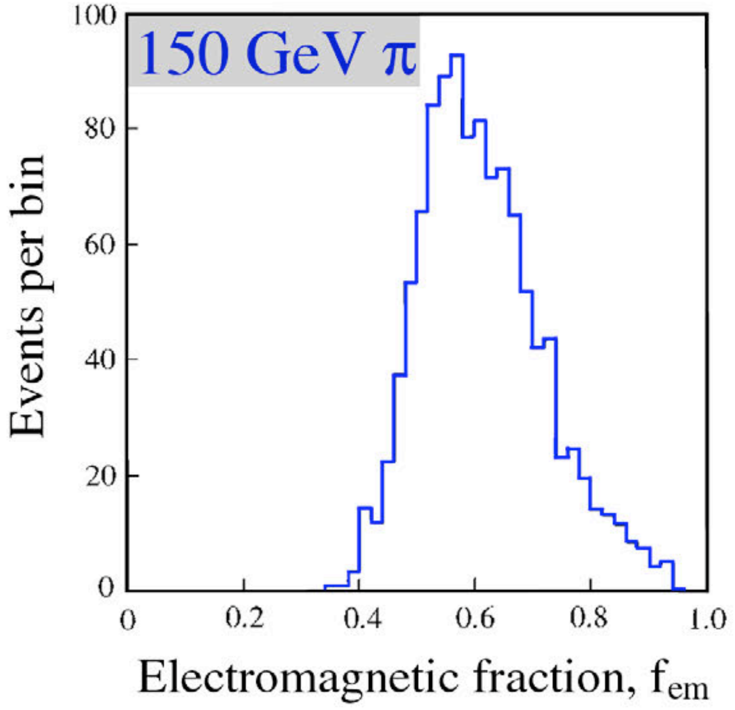
(mainly because of nuclear breakup energy losses in non-π^o component)



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

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

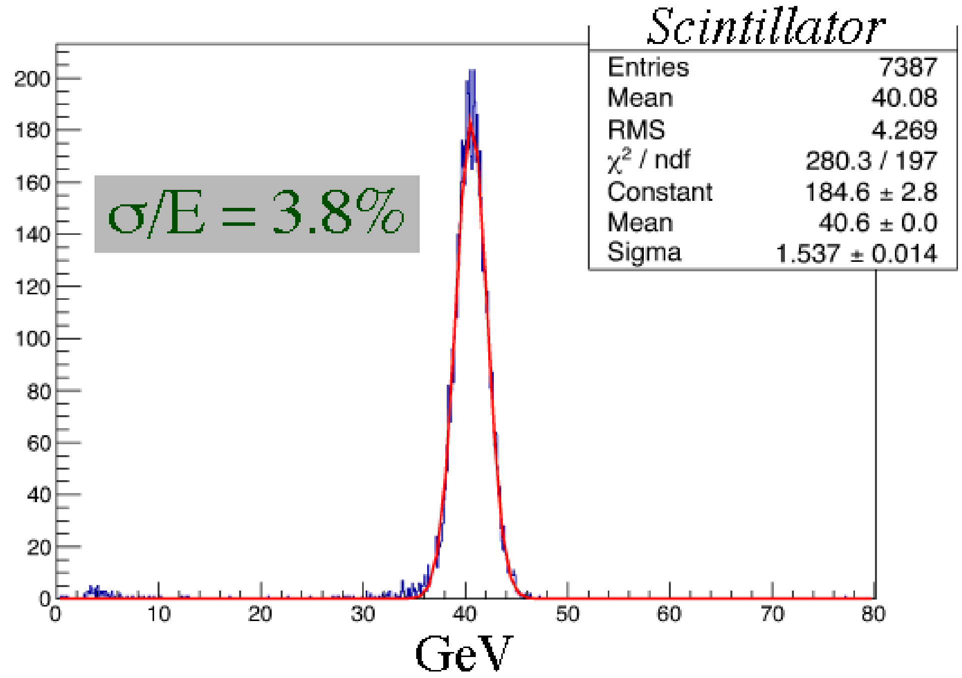


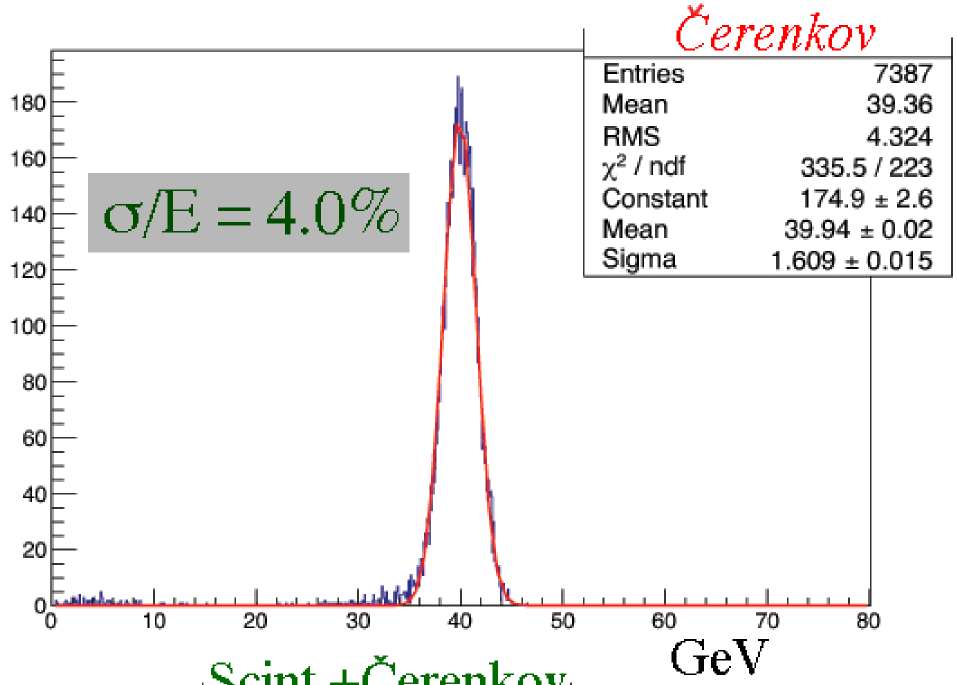


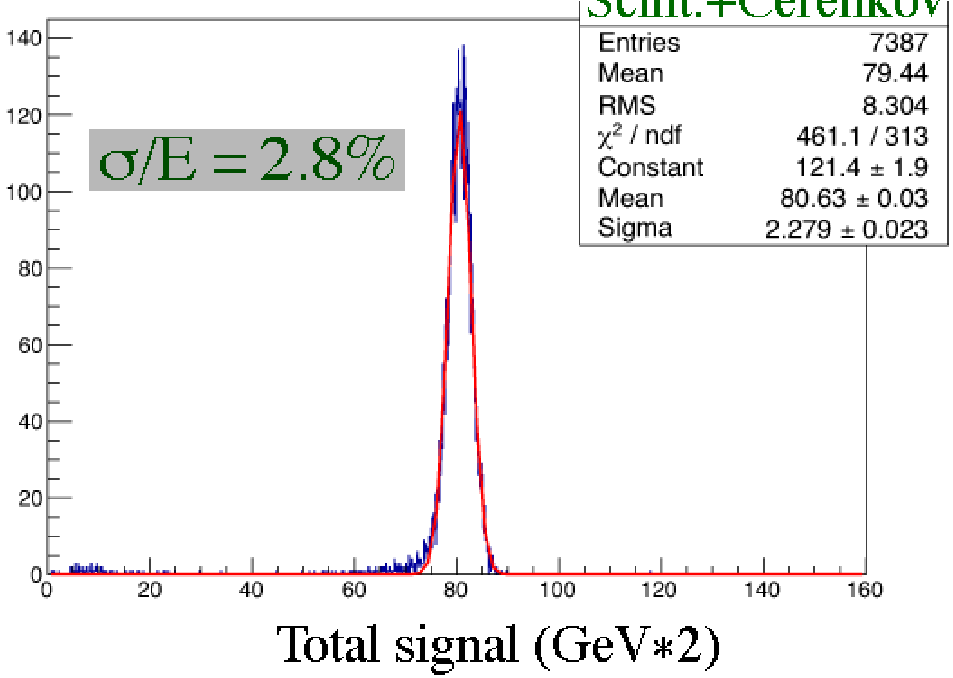
The em fraction is, on average, *large and energy dependent*

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

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



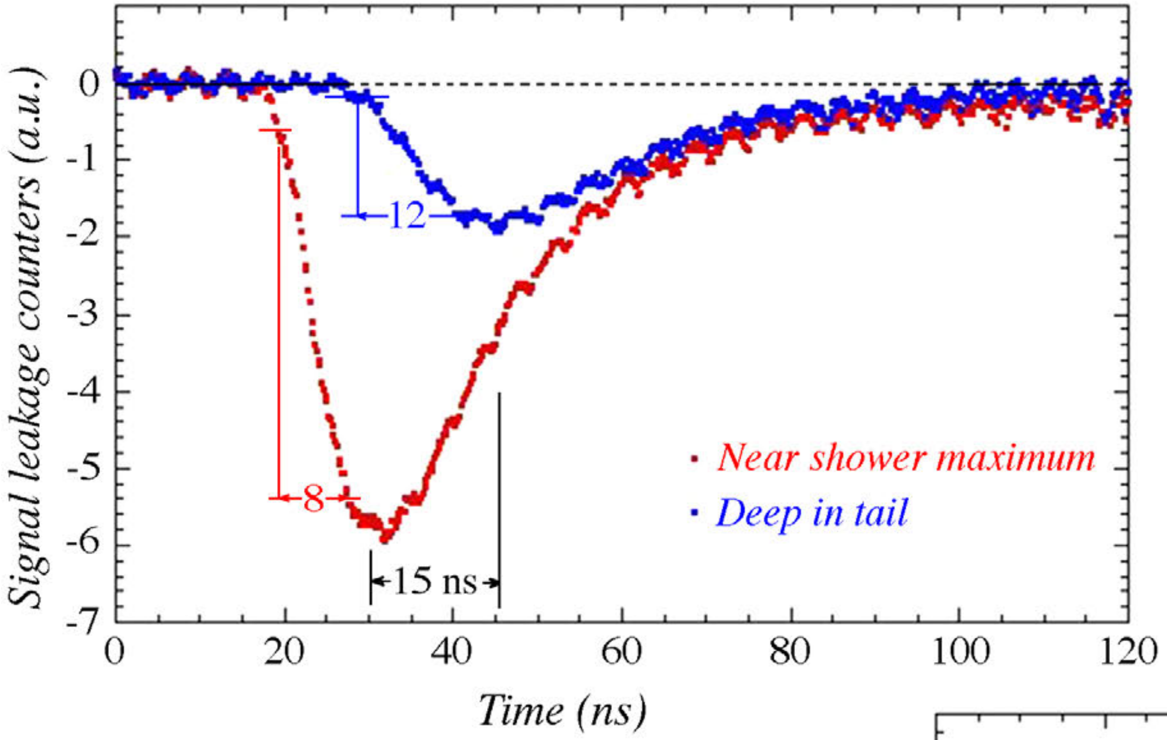




40 GeV electrons
Cu-fiber calorimeter

NIM A735 (2014) 130

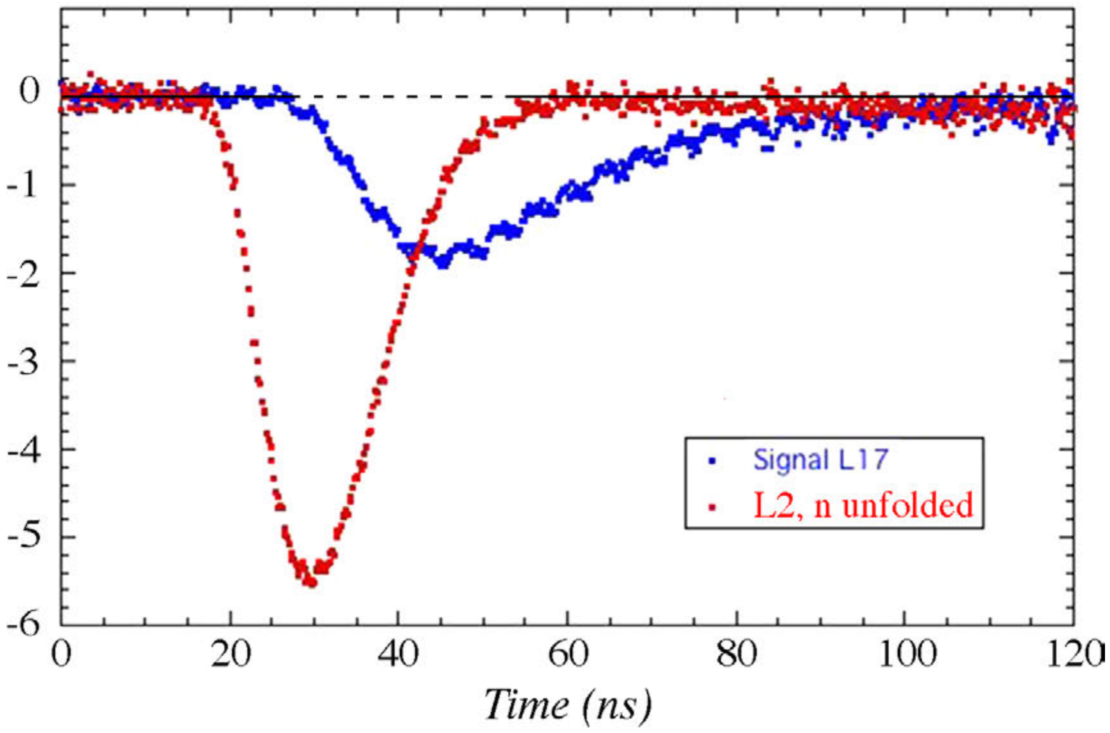
Comparison signal shapes leakage counters



Expected signal contributions:

- *prompt charged shower particles*
- *$n + p \rightarrow n + p$ (time constant 10 - 20 ns)*

n contribution unfolded



The energy resolution of compensating calorimeters is dominated by sampling fluctuations

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

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)	?

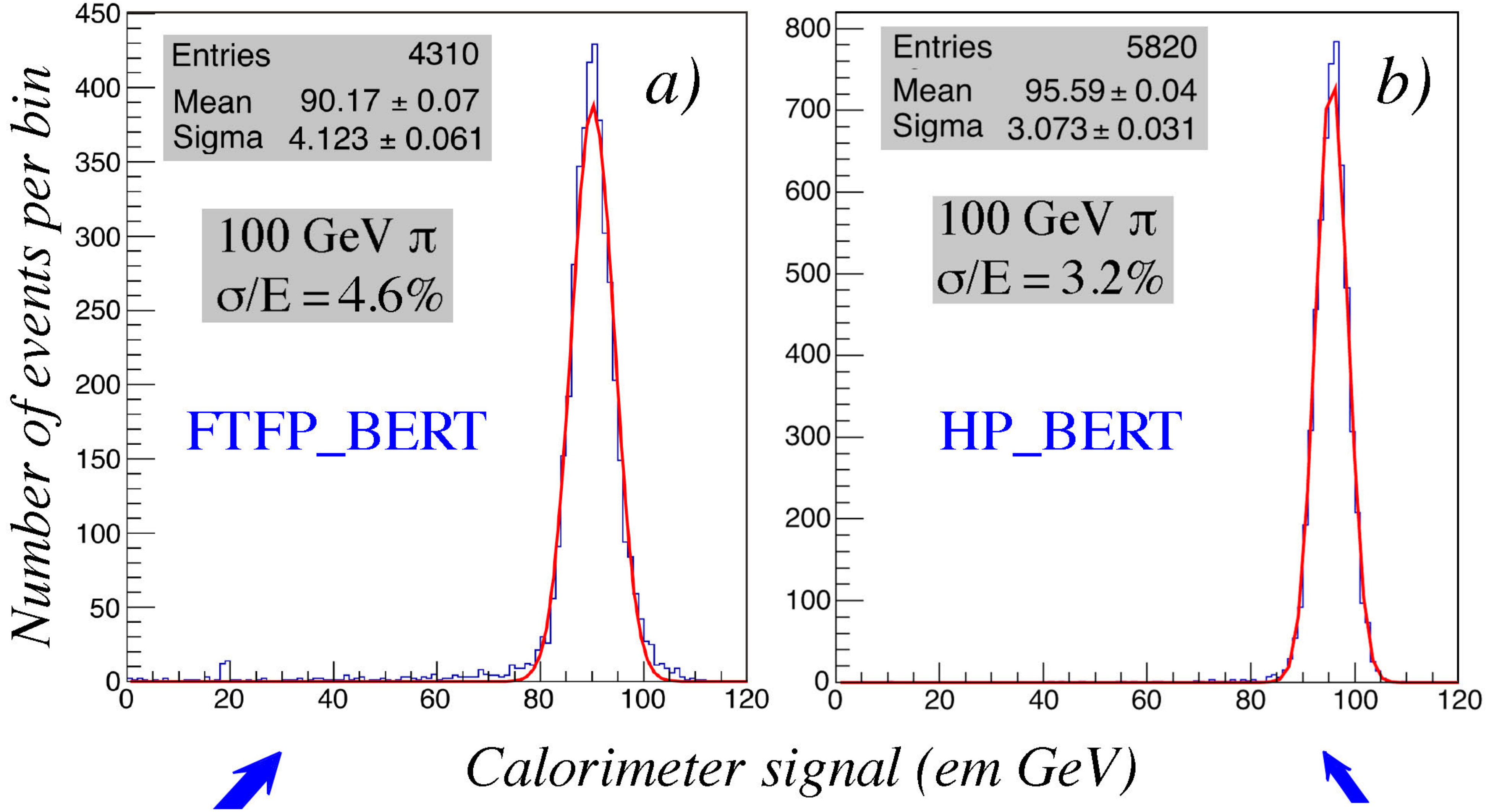
sampling

total
(incl Č p.e.)

GEANT: 32

GEANT4 simulations of 100 GeV π

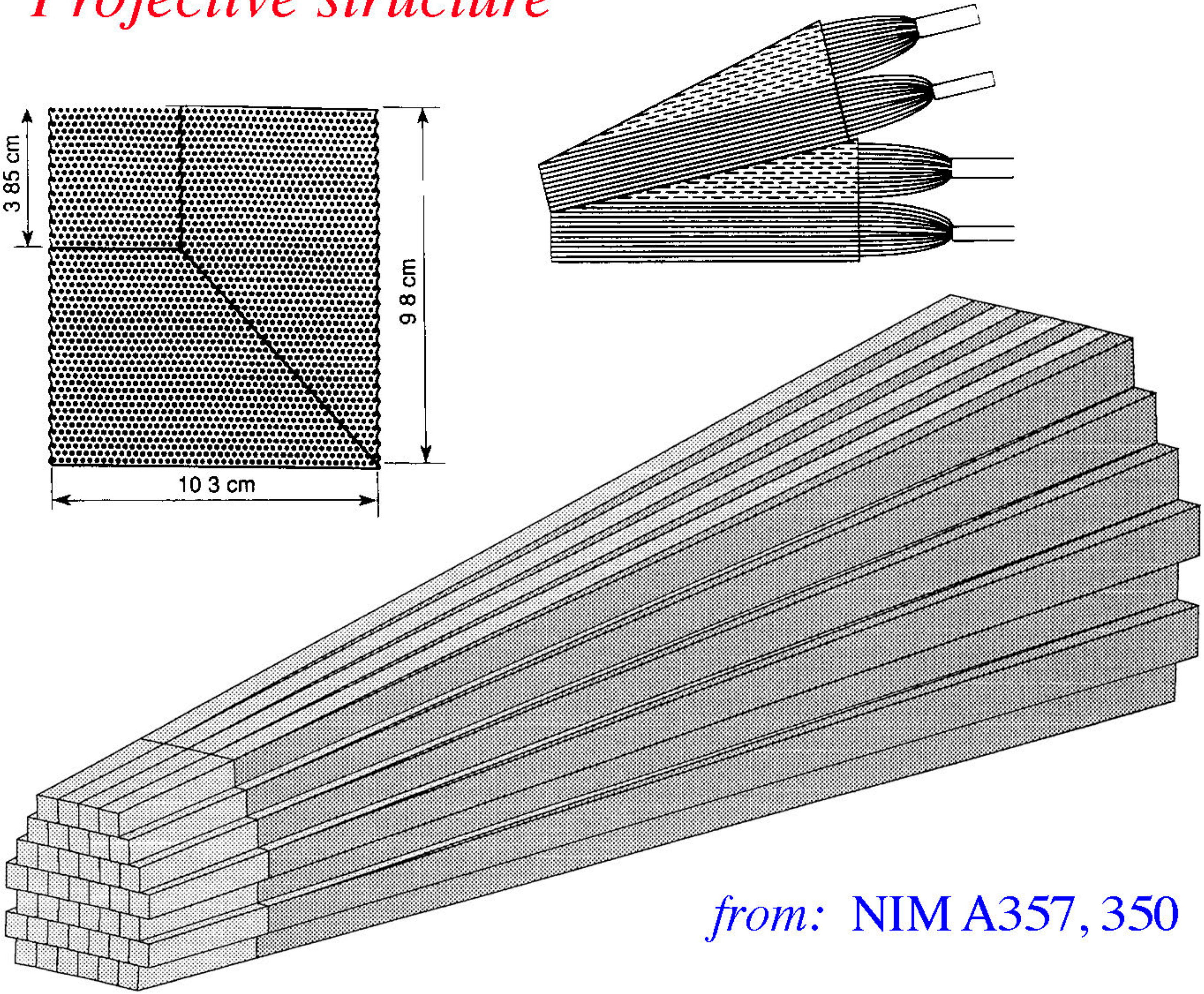
RD52_Cu   65 x 65 cm^2



Standard hadronic
shower simulation
package

High precision
simulation package
(neutrons!!)

Projective structure



from: NIM A357, 350