CALORIMETRY
at the energy frontier

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Lectures at the 44th SLAC Summer Institute
August 16 -17, 2016

Decisions about the future require a good understanding of the past

Outline:

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

Calorimetry: definition

Calorimetry is the measurement of the transfer of energy in a physical process. Energy may or may not be converted from one form into another in this process.

Units:

1 calorie = energy needed to increase the temperature of 1 gram of liquid water by 1 degree Celsius

$1\ cal = 4.18\ Joule$
$= 2.61\ 10^{19}\ eV$

$1\ TeV = 3.83\ 10^{-8}\ cal$

Calorimetry in particle physics

Calorimeters are instruments to measure the energy of individual particles, produced in scattering experiments at accelerators or elsewhere (e.g. cosmic rays absorbed in the Earth's atmosphere)

Reminder: 1 TeV = 3.83 10^{-8} calories
A temperature increase of the detector is therefore not a practical method to measure this energy

Therefore, rather than measuring the increase of the average velocity of the ~10^{23} atoms of which the instrument consists, the effects on atoms in the vicinity of the passing particles are measured in these detectors

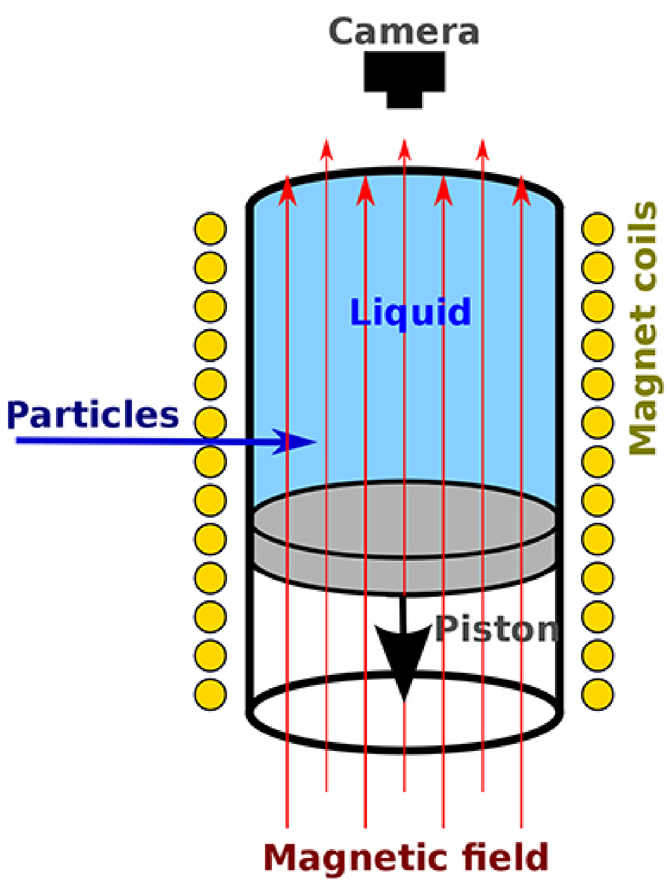
Local thermal effects in a particle detector

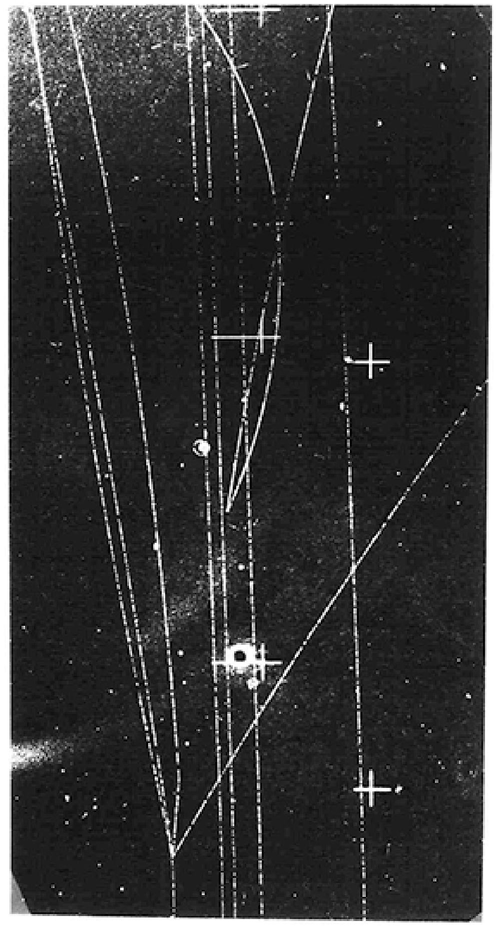
A passing charged particle heats the liquid along its track, causing it to boil. The trajectory of the particles is thus indicated by tracks of gas bubbles in this BUBBLE CHAMBER

The particle momentum is determined from bending in the magnetic field

NB This is NOT considered a calorimeter

Only a fraction of the energy carried by the particles is absorbed





Calorimeters for particle physics experiments

- *In particle physics, a calorimeter is a (massive) detector in which the particles to be detected are completely STOPPED*

  The absorption process is usually referred to as "shower development"

- *The signals may be provided by:*
  - *Scintillator: The total amount of light produced in the absorption process is a measure for the energy of the incoming particle*
  - *Liquid argon: The charge liberated in the stopping process provides the signals*
  - *Water: The Čerenkov light serves as the source of information*

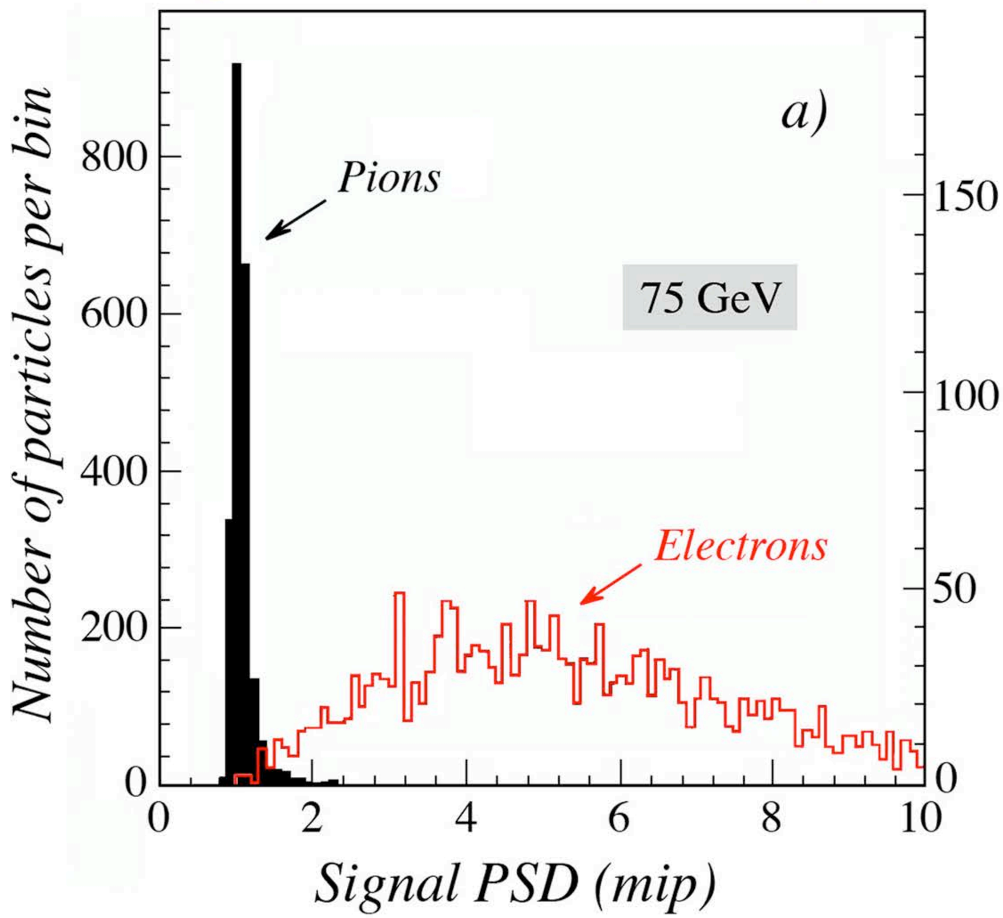
- *The segmentation of the instrumented volume makes it possible to determine the momentum vector of the particles.*

  The signals in the different calorimeter "towers" indicate the shower axis, and thus the direction of the incoming particle.

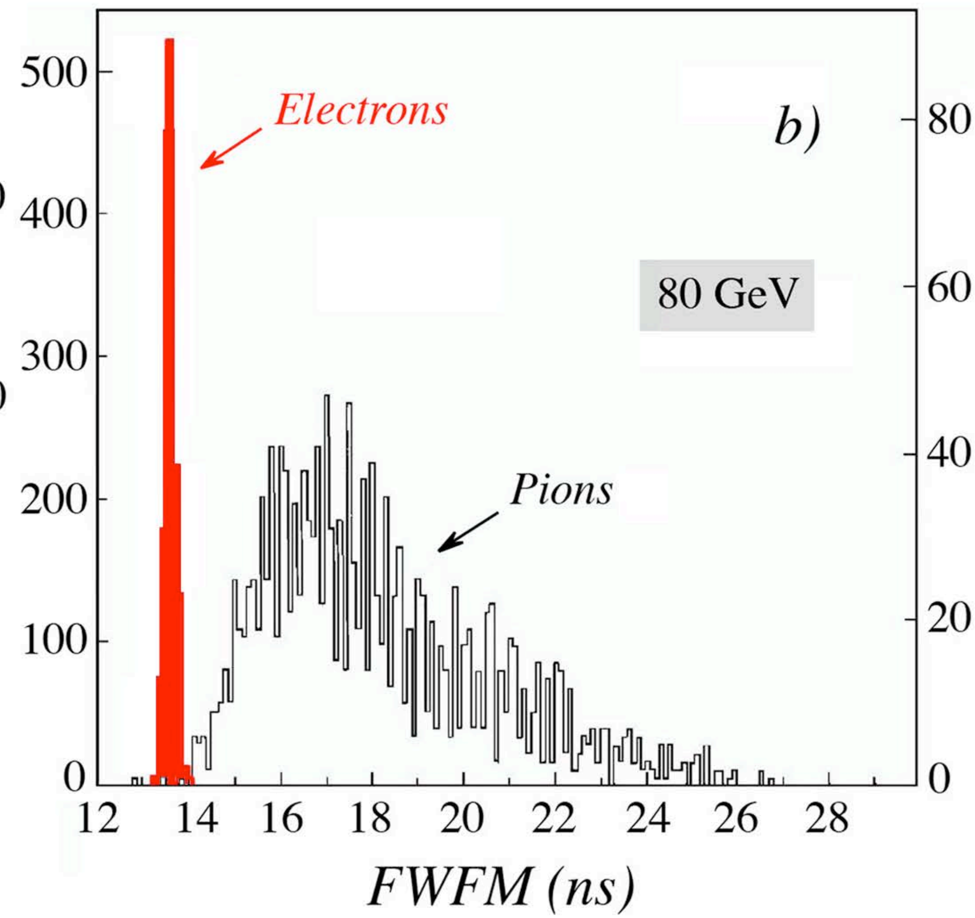
- *The particle type may be derived from the shower profile, the time structure of the signals, ...*

Particle identification with calorimeters

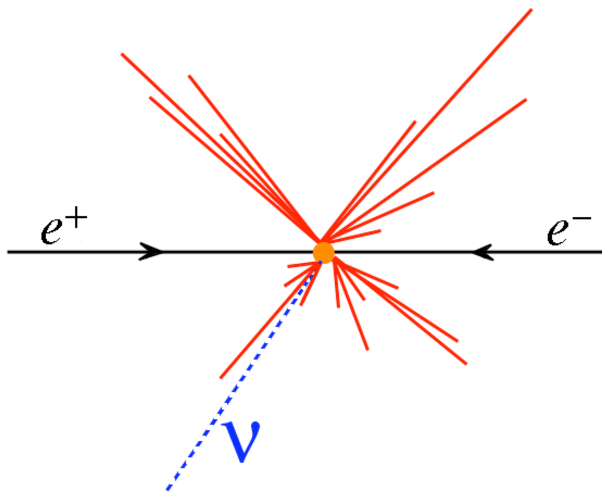
Using shower profile (pre-shower detector)



Using time structure of the signals



Why calorimetry?

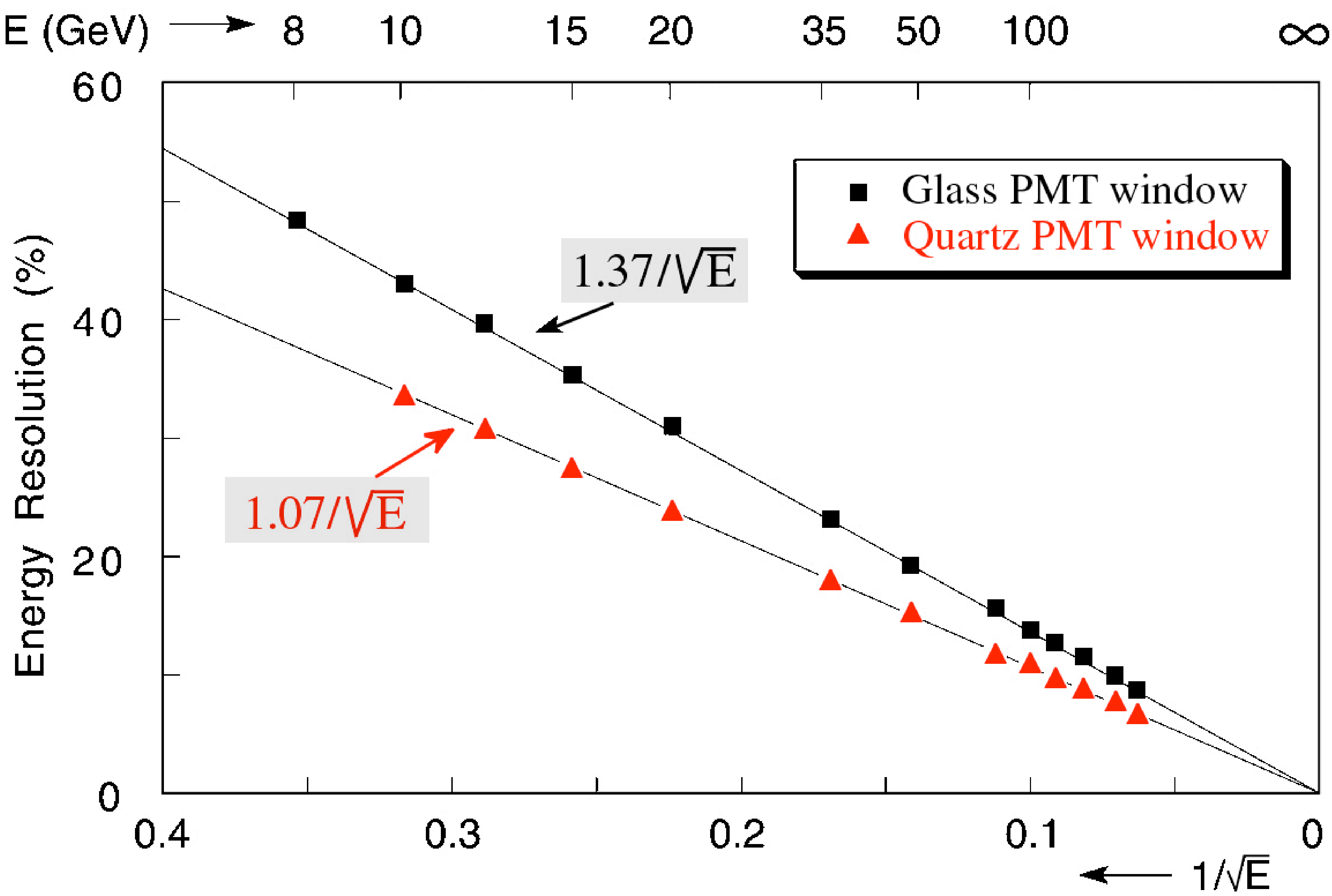


- Measure *charged + neutral* particles
- Obtain information on *energy flow*: Total (missing) transverse energy, jets, *etc.*
- Obtain information *fast* → recognize and select interesting events in real time *(trigger)*
- Performance of calorimeters *improves with energy* (~ $E^{-1/2}$ if statistical 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* $\dfrac{\sigma(E)}{E} \propto 1/\sqrt{n} \propto 1/\sqrt{E}$

In an ideal calorimeter, resolution scales as $E^{-1/2}$



Some milestones in the development of calorimetry

as an experimental technique

in nuclear, particle & astrophysics

in the past 50 years

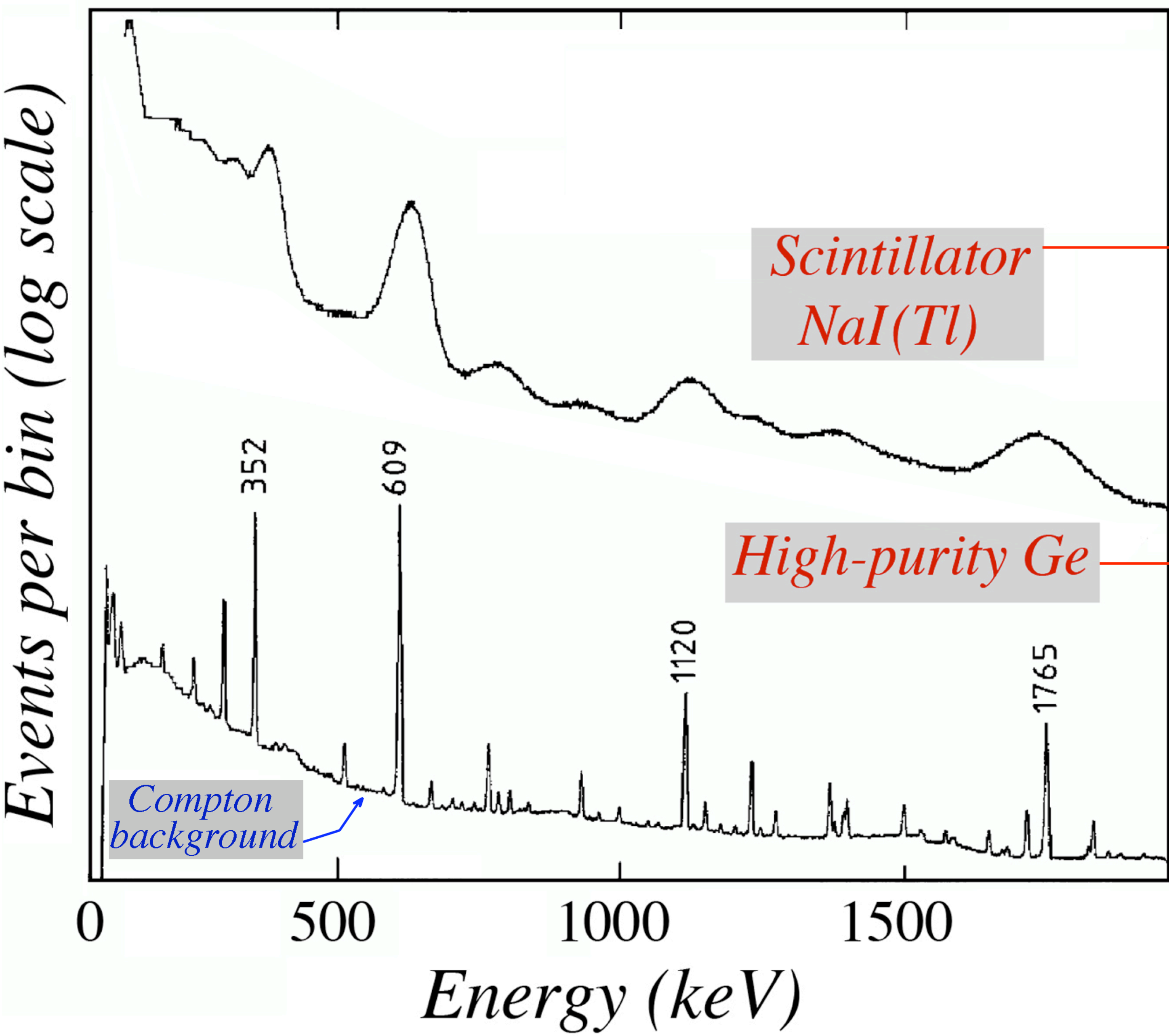
Milestones

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

This turned out to be very important for nuclear γ ray spectroscopy

Nuclear γ ray detectors

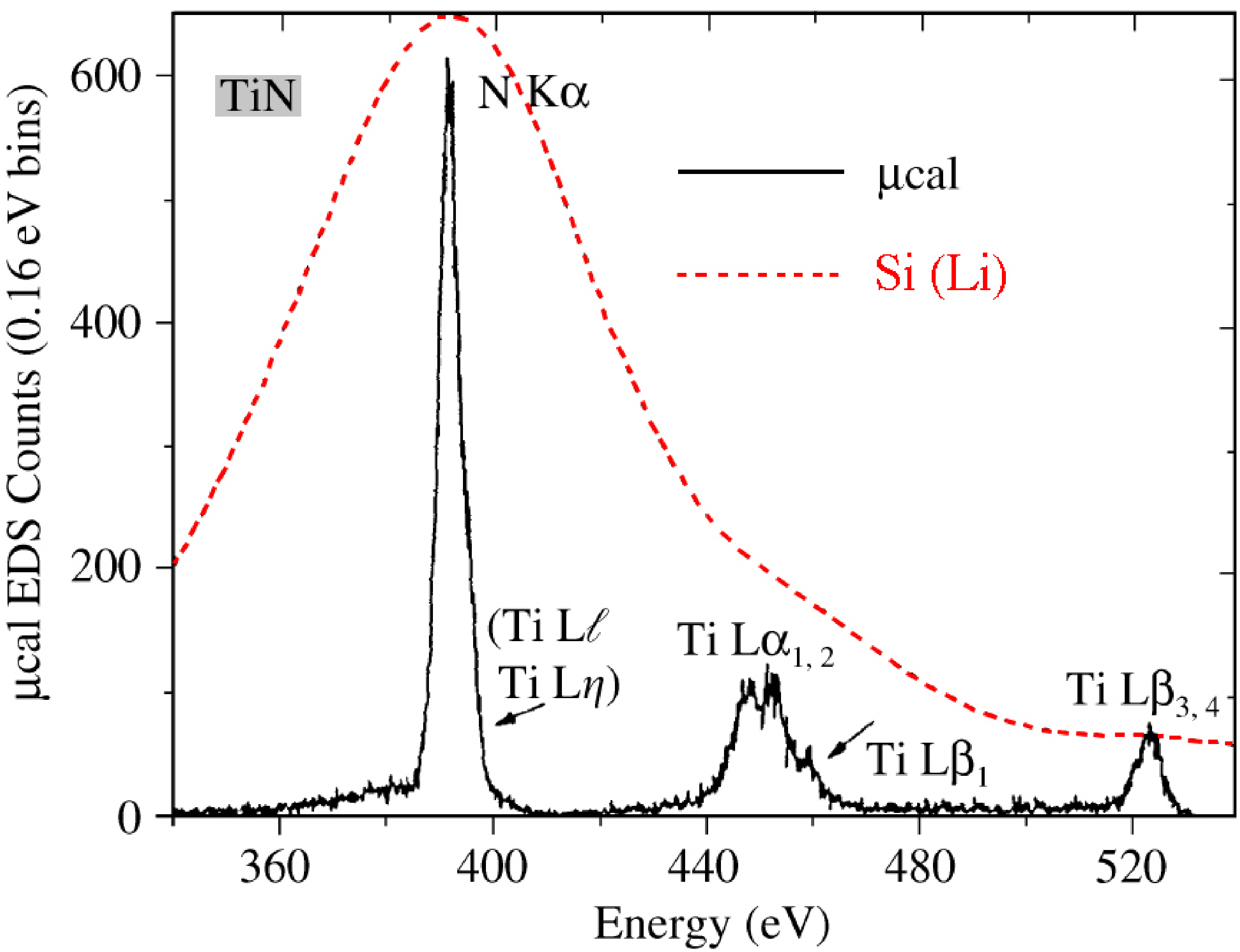
Energy resolution dominated by signal quantum fluctuations (?)



~100 eV per photon
10 000 photons/MeV

2.9 eV per e-h pair
350 000 pairs/MeV
σ/E ~ 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

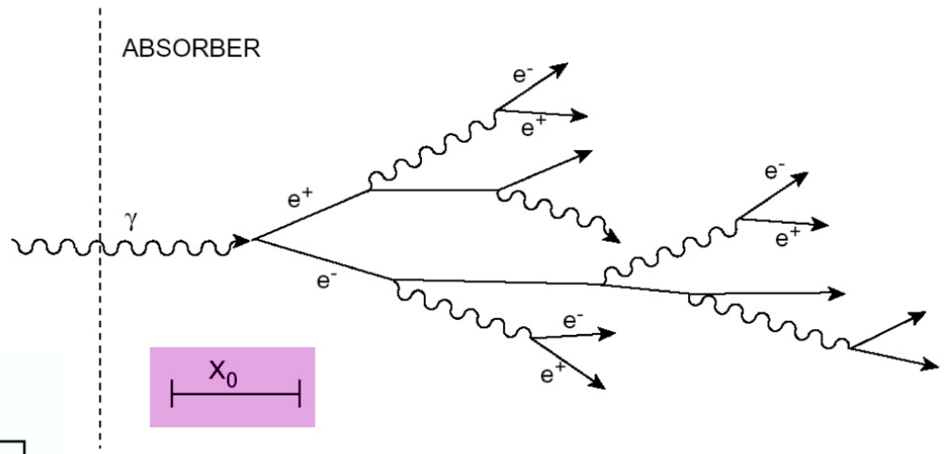
- *For the detection of the neutral reaction products (overwhelmingly γs from π° decay), one used scintillating crystals, developed in the 1950s for nuclear spectroscopy, and called these "shower counters"*

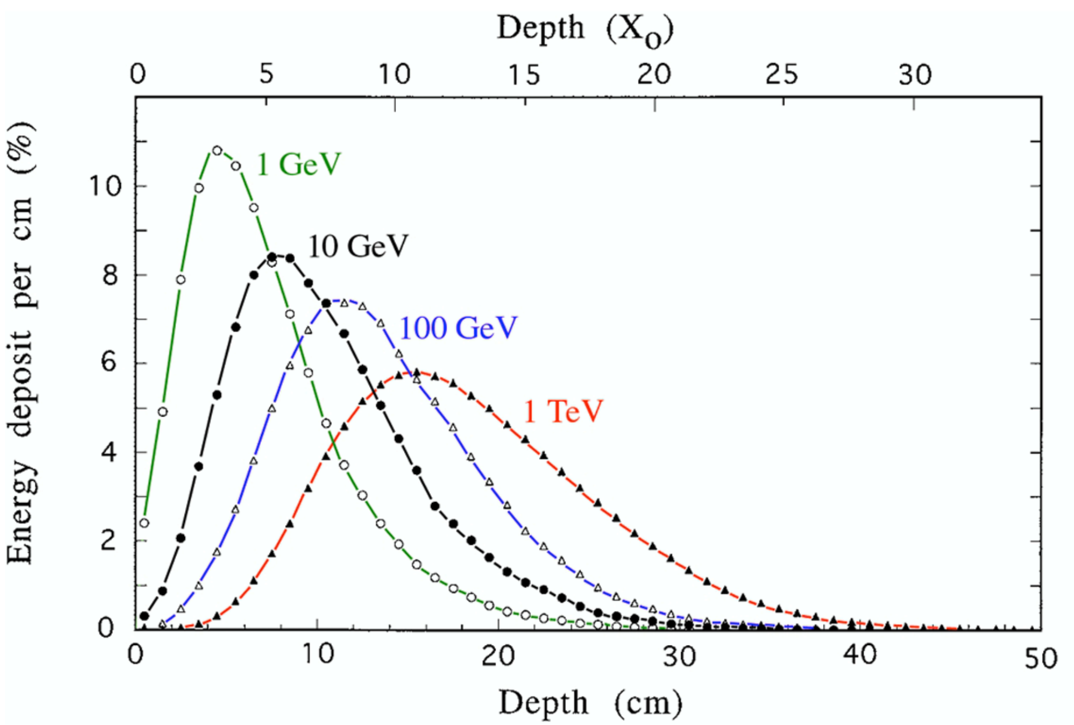
- *Using properly chosen materials (high Z!), even very-high-energy γs can be fully absorbed in detectors of limited length (<30 cm), and be measured with spectacularly good energy resolution*

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.



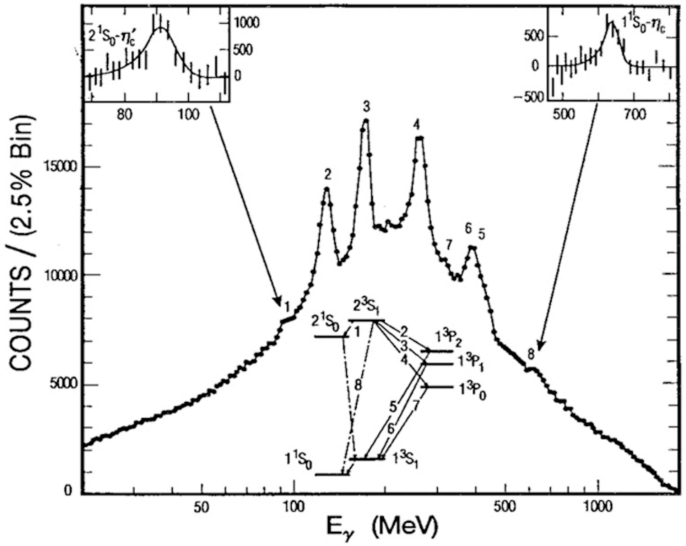


The shower development is governed by the "radiation length" X_o, which is typically ~ 1 cm

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

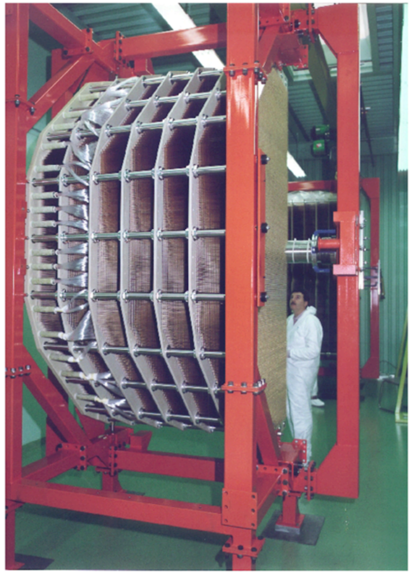
Electromagnetic shower detection in Particle Physics

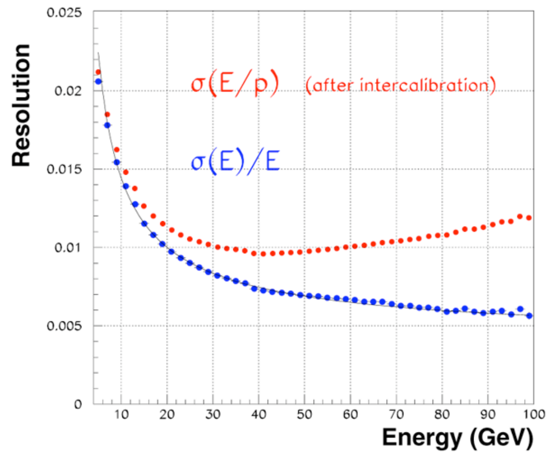
SPEAR: NaI(Tl) crystals



Charmonium spectroscopy (e^+e^-)

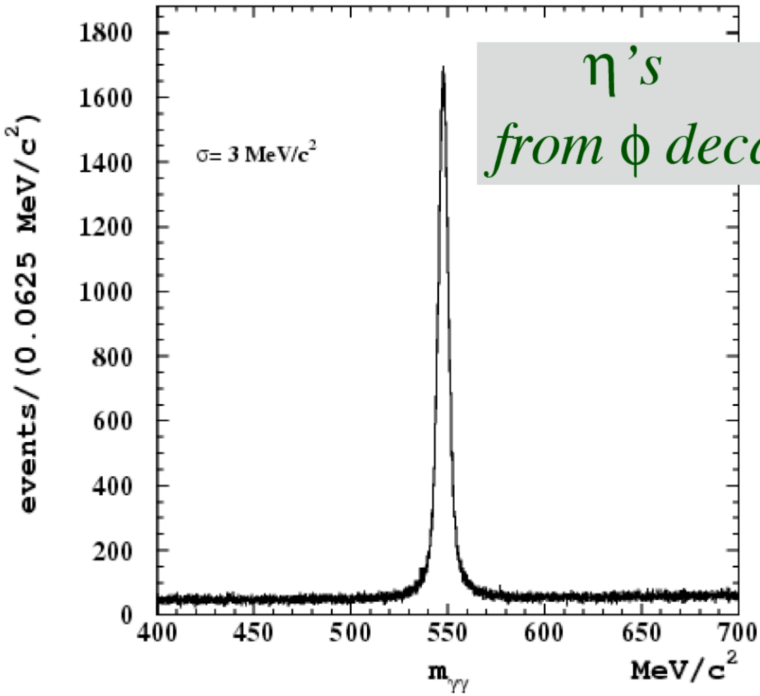
NA48 (CP violation in K^0)
LKr calorimeter





KLOE @ DAPHNE (φ factory)

Pb-scifi calorimeter



η's from φ decay

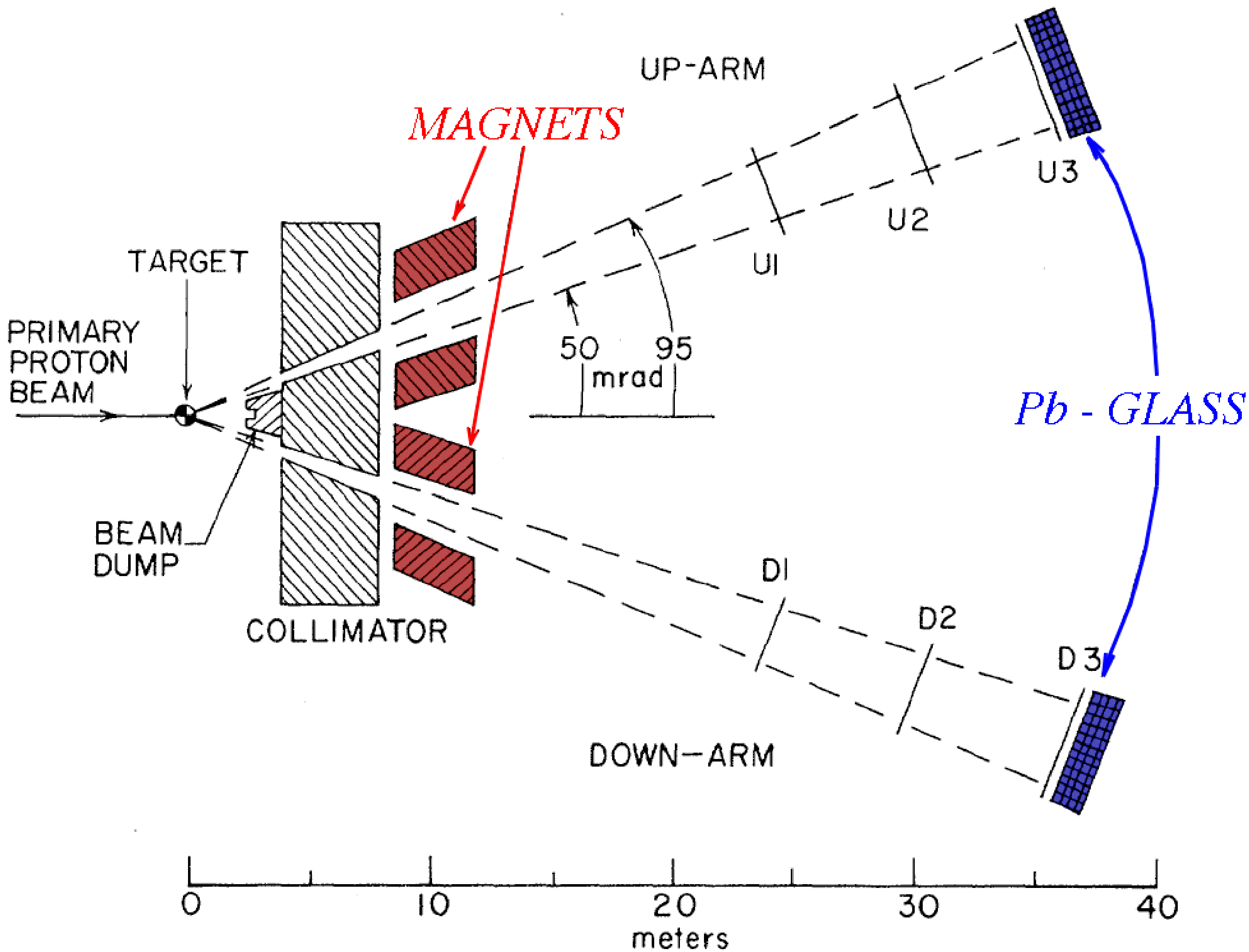
Milestones

- 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

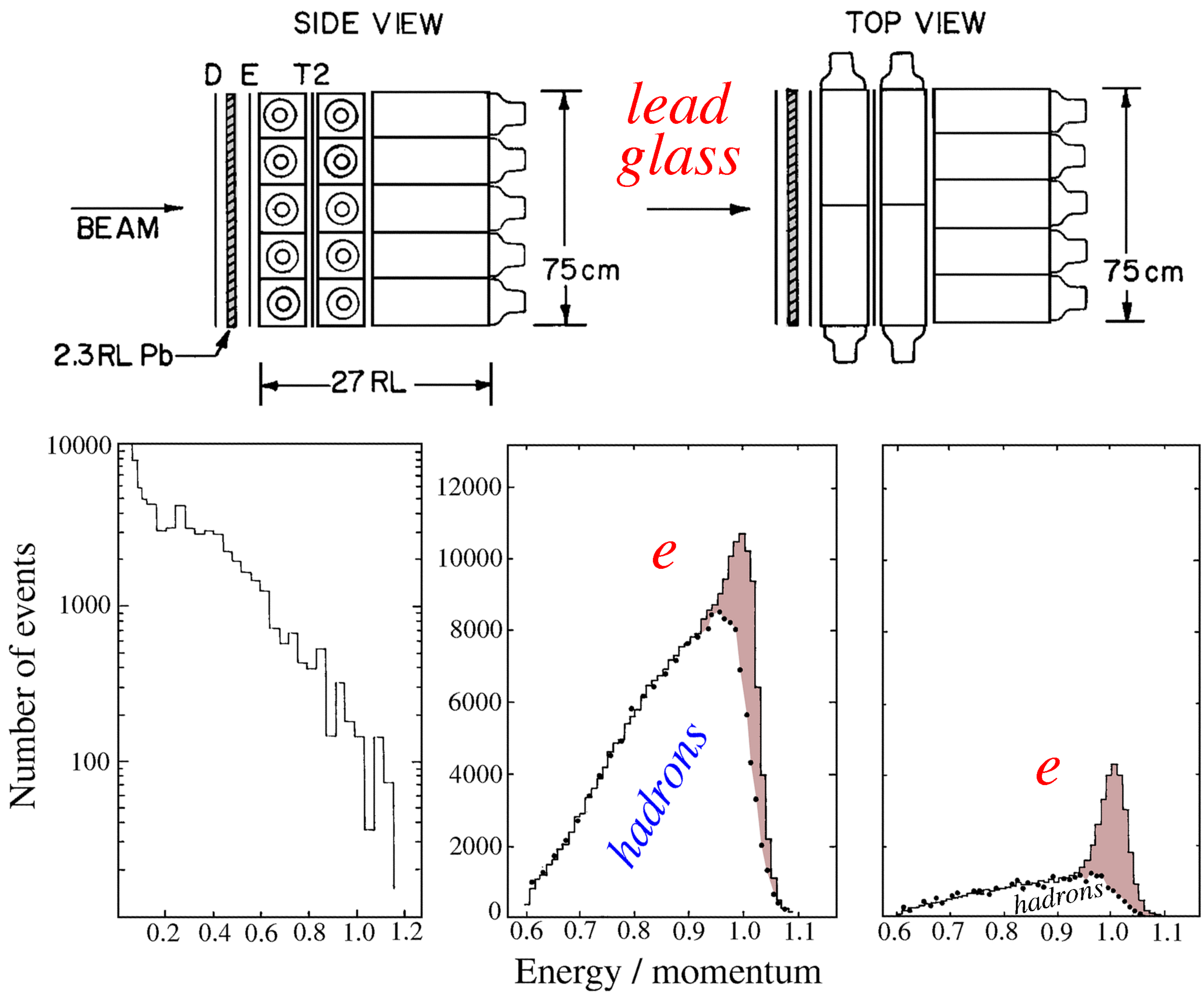
Example: E70 / 288 @ Fermilab

Discovered Upsilon → $l^+ l^-$



Shower counters in the 1970s

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

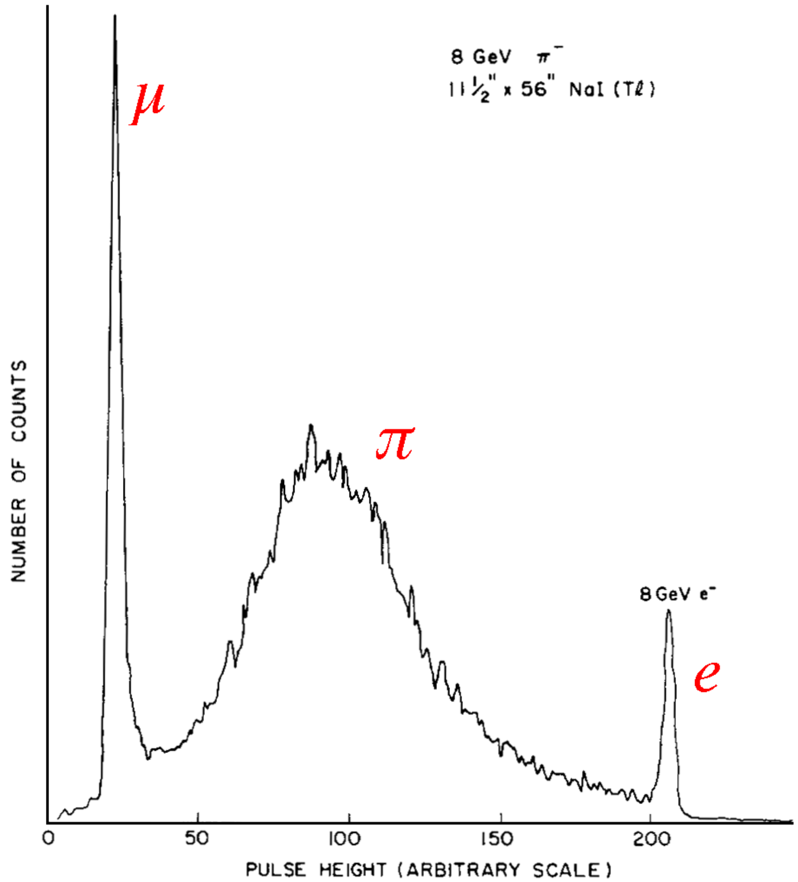


Early indication that hadron calorimetry is different!

NIM 75 (1969) 130

450 kg of NaI (Tl) crystals

Tested with 8 GeV particle beams



Conclusions of authors:

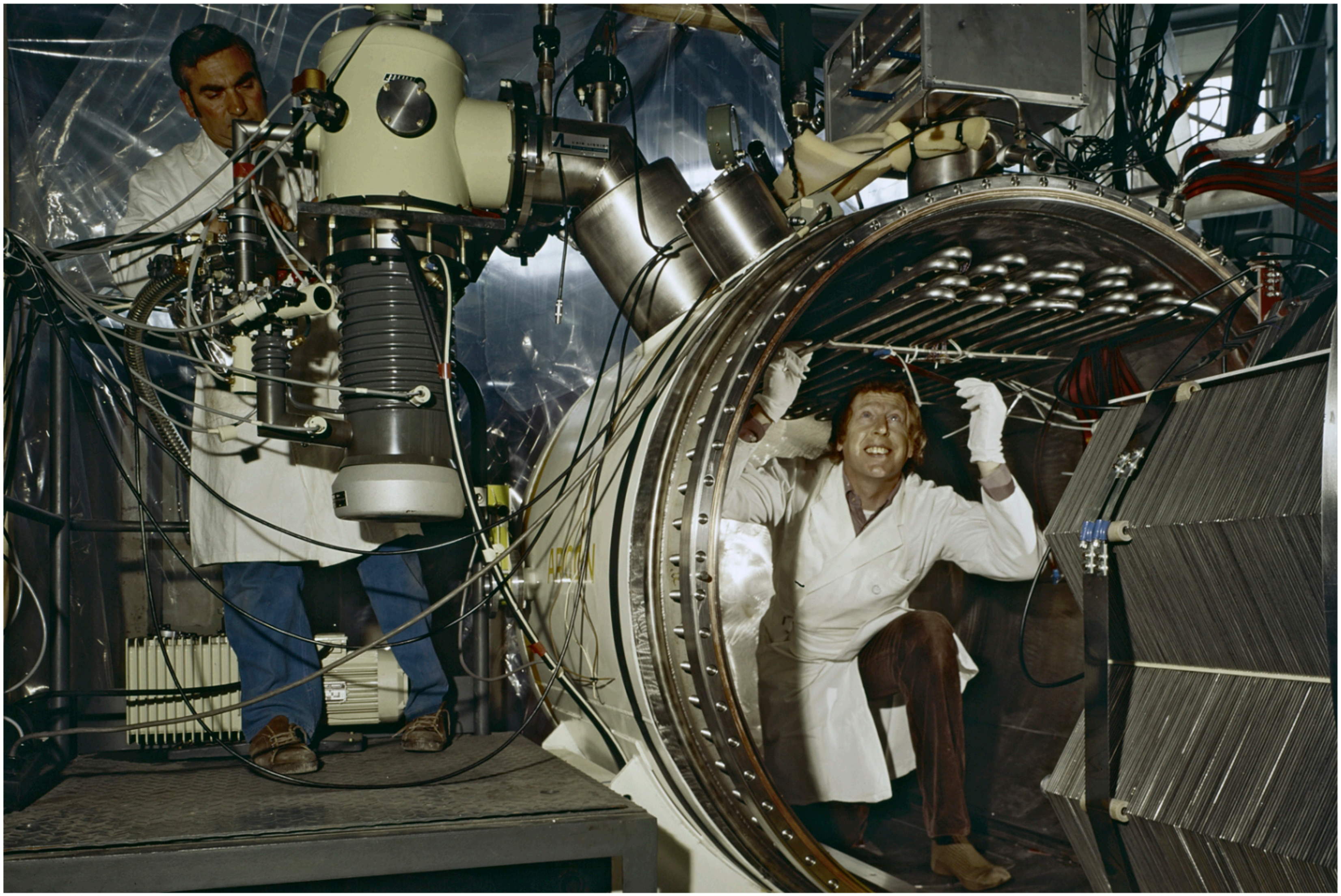
- *50% of energy leaks out*
- *MC: much less leakage*
- *Same results at 4, 12, 16 GeV*
- *Resolution did NOT improve with E*

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



A brief history of calorimetry (3)

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

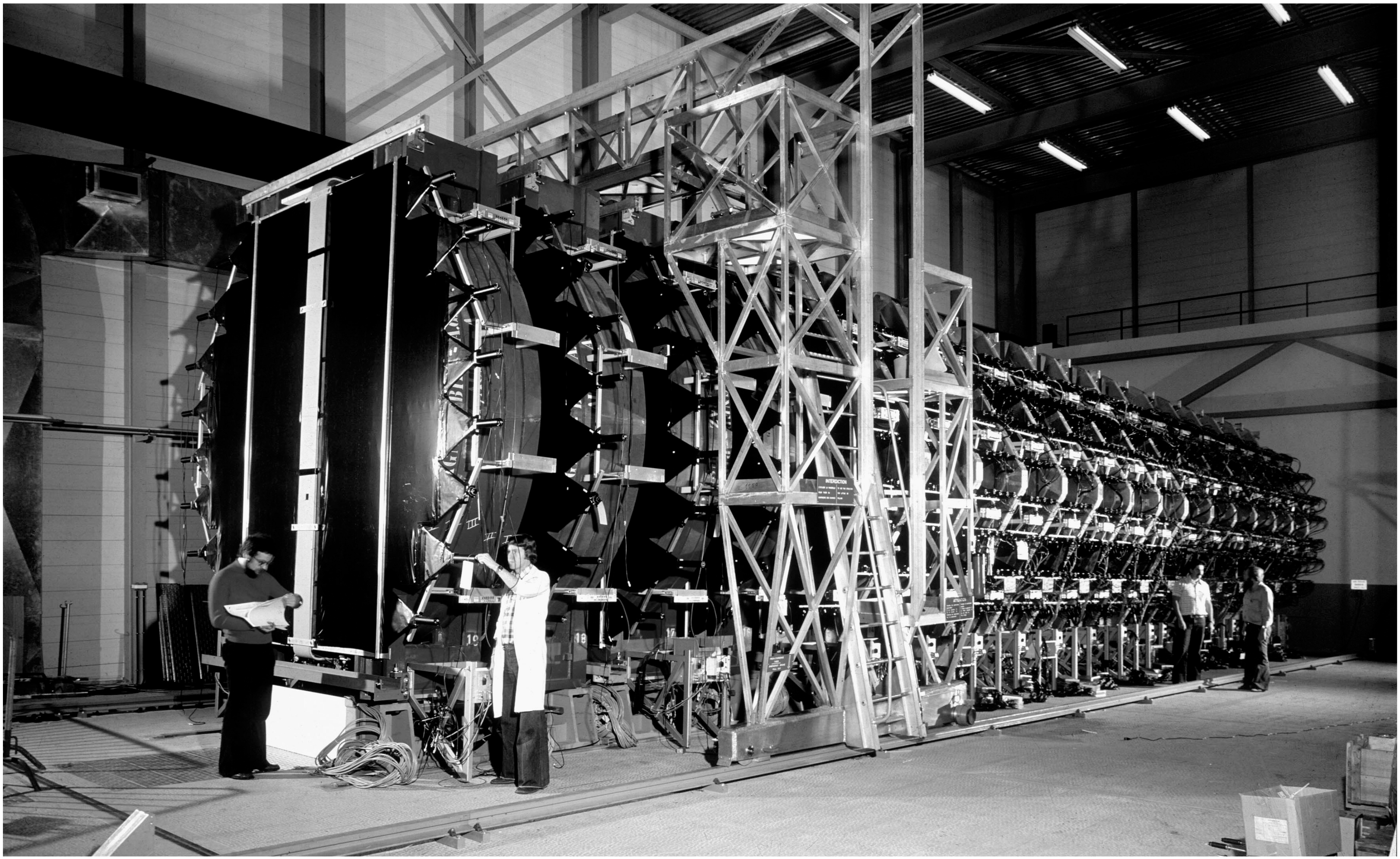
  → *High-energy neutrino experiments: Target + trigger (total energy)*

  → *Collider experiments (ISR, PETRA): Energy flow (missing E_T, jets)*

  → *General: Particle ID (e, γ, μ, ν)*

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

WA1



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- *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.*

Milestones

- 1965 - *Quantum leap in signal quanta (e-h pairs in semiconductors)*
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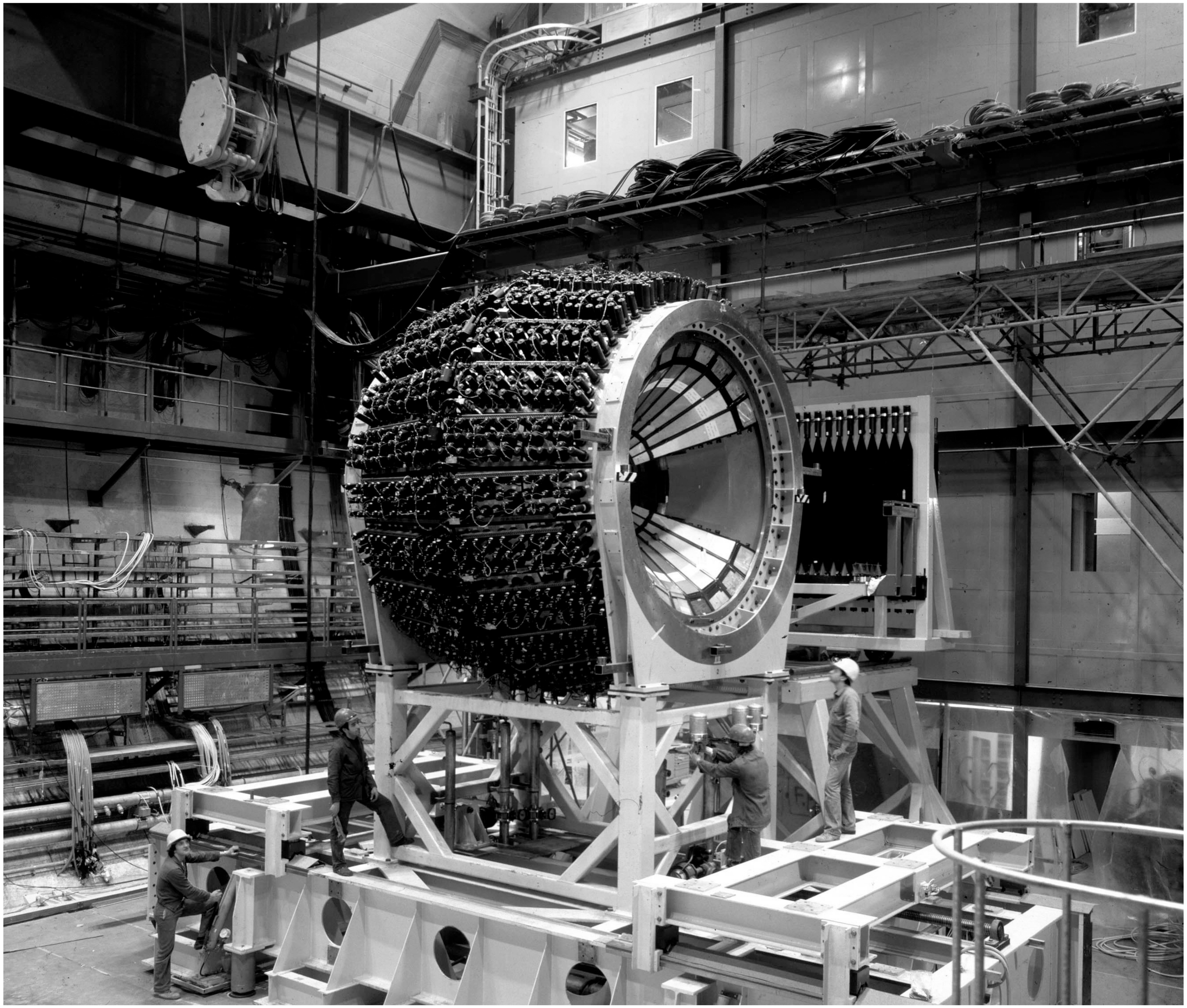
- 1975 - *Liquid argon calorimetry invented*
- 1980 - *4π calorimeters introduced (crucial for discovery W boson)*

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)

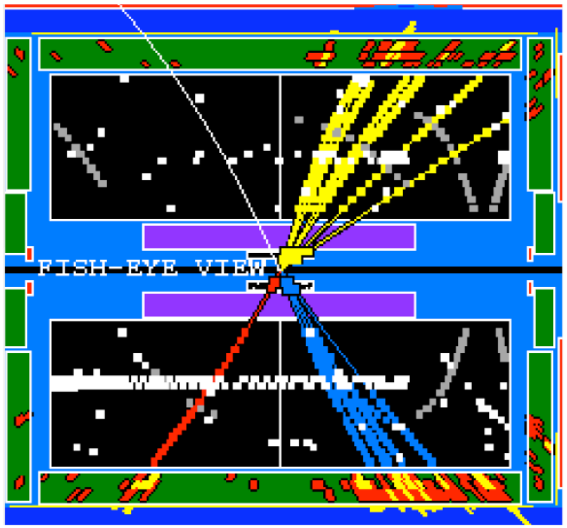


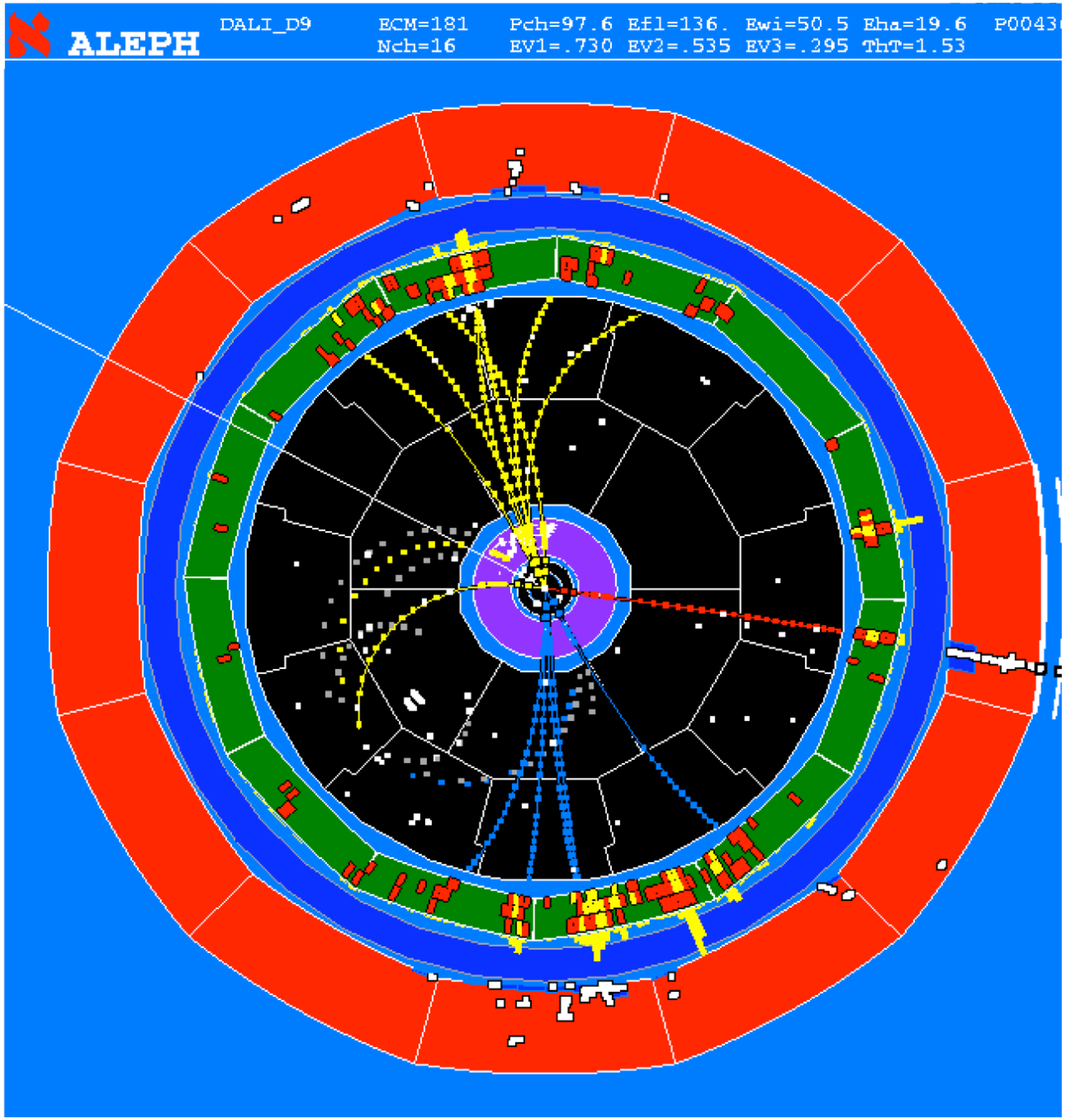
Example of energy flow information

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

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

In final state:
2 hadronic jets
1 energetic muon
missing E_T (ν_μ)





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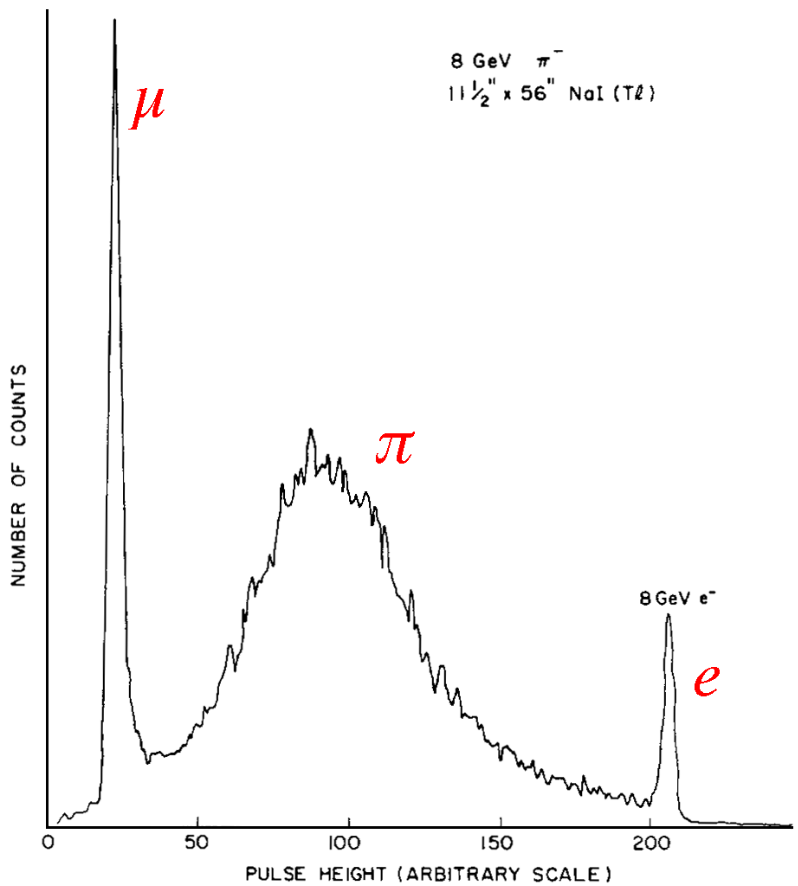

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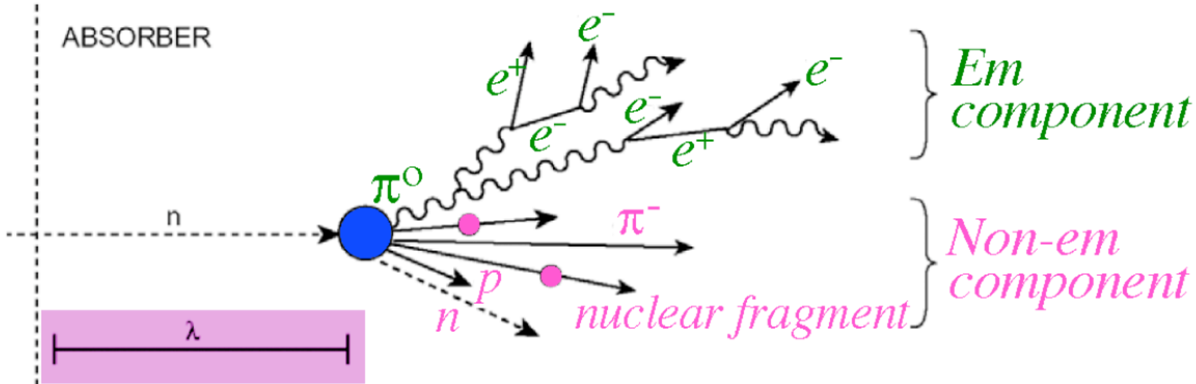
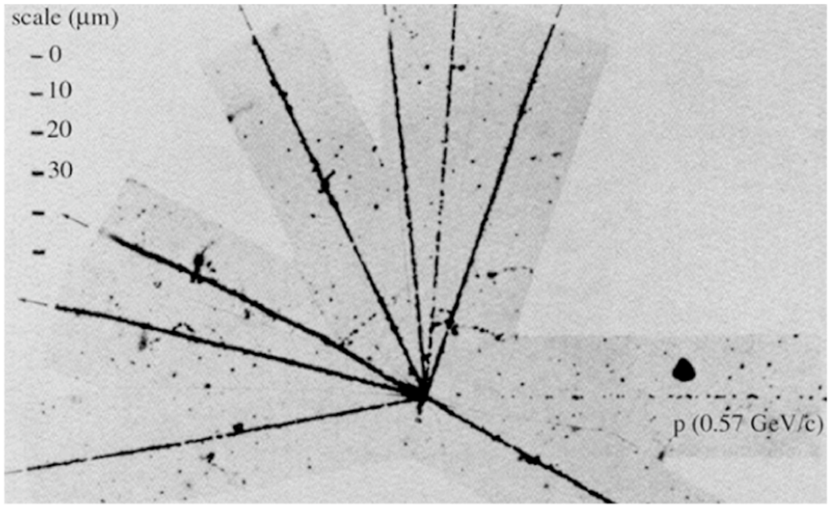
The physics of hadronic shower development

- *A hadronic shower consists of two components*



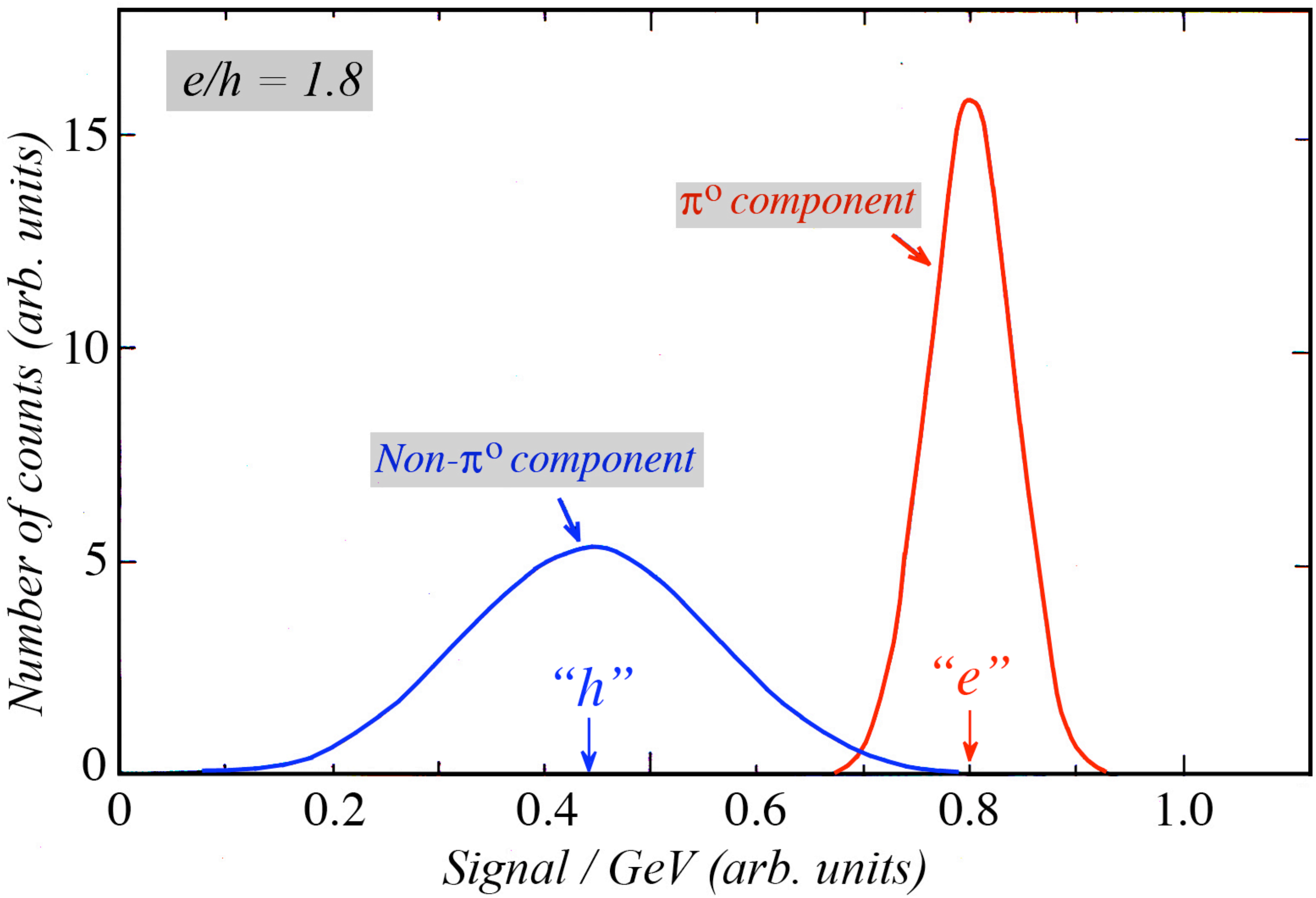
  - *Electromagnetic component*
    - electrons, photons
    - neutral pions → 2 γ
  - *Hadronic (non-em) component*
    - charged hadrons $\pi^{\pm}$, $K^{\pm}$ (20%)
    - nuclear fragments, p (25%)
    - neutrons, soft γ's (15%)
    - break-up of nuclei *("invisible")* (40%)



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

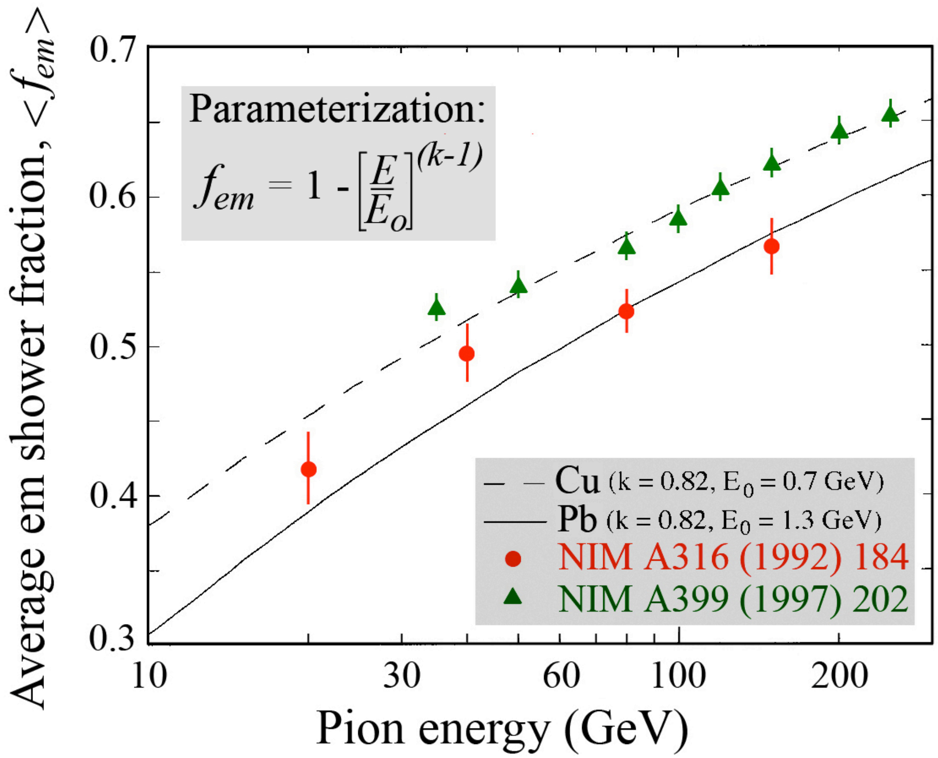
The calorimeter response to the two shower components is NOT the same

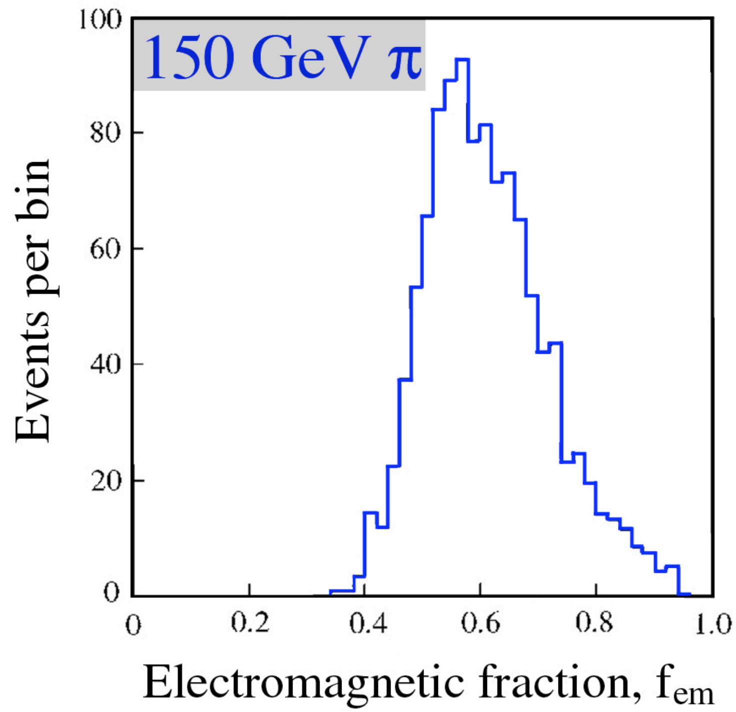
(mainly because of nuclear breakup energy losses in non-π° component)



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

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

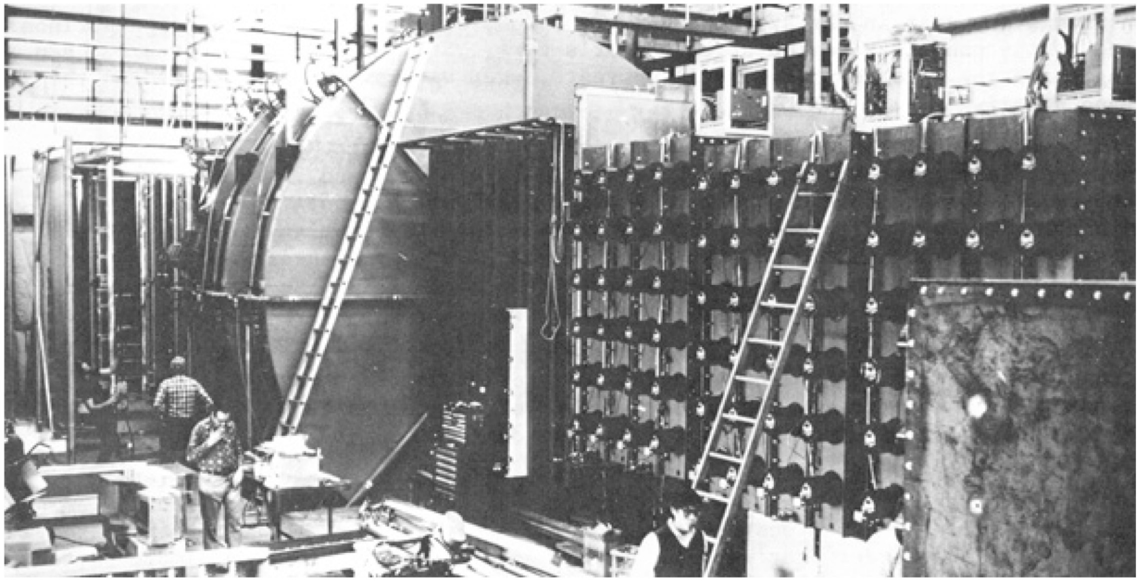




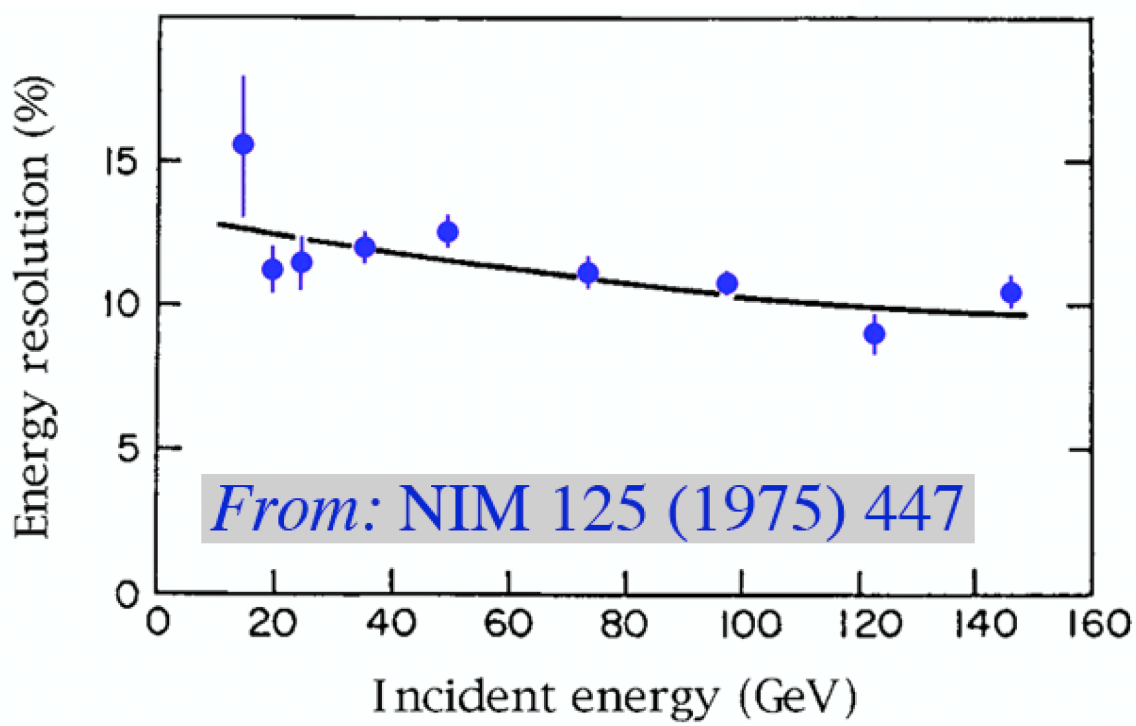
The em fraction is, on average, *large and energy dependent*

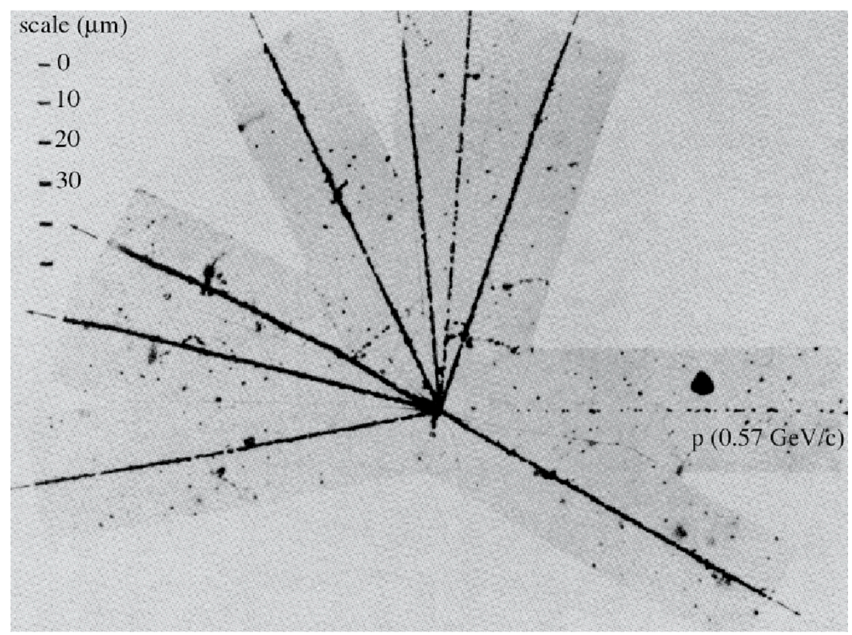
Fluctuations in f_{em} are *large and non-Poissonian*

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



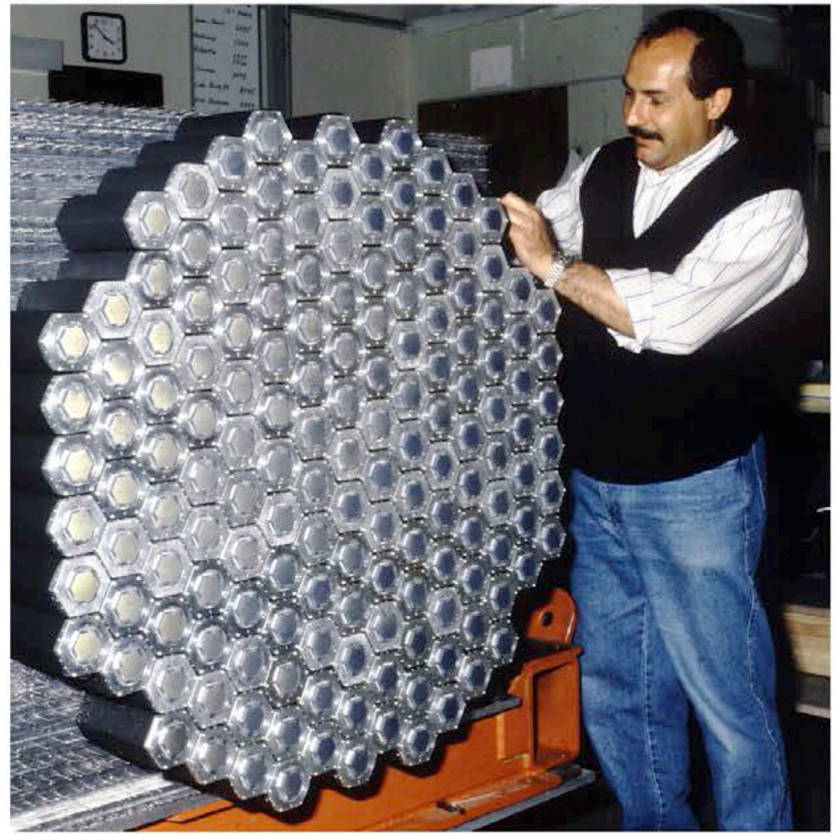


Intrinsically compensating calorimeters

are designed in such a way that e/h = 1

→ *effects of fluctuations in f_{em} eliminated*

SPACAL 1989



High resolution hadron calorimetry had become a reality

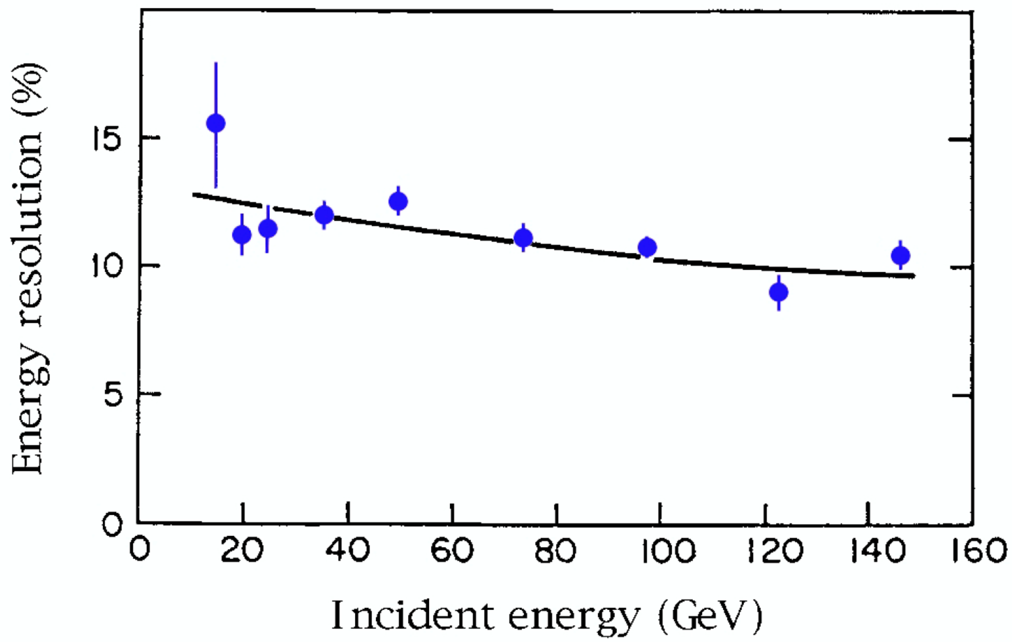


Figure 9: The hadronic energy resolution as a function of energy, for a homogeneous calorimeter consisting of *60 tonnes of liquid scintillator*

NIM 125 (1975) 447

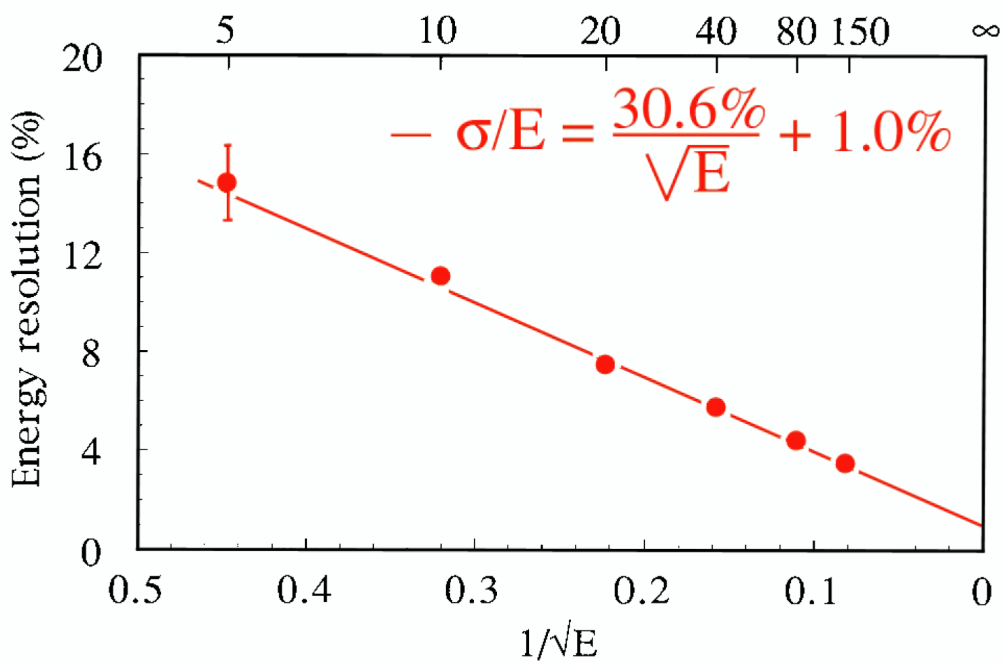
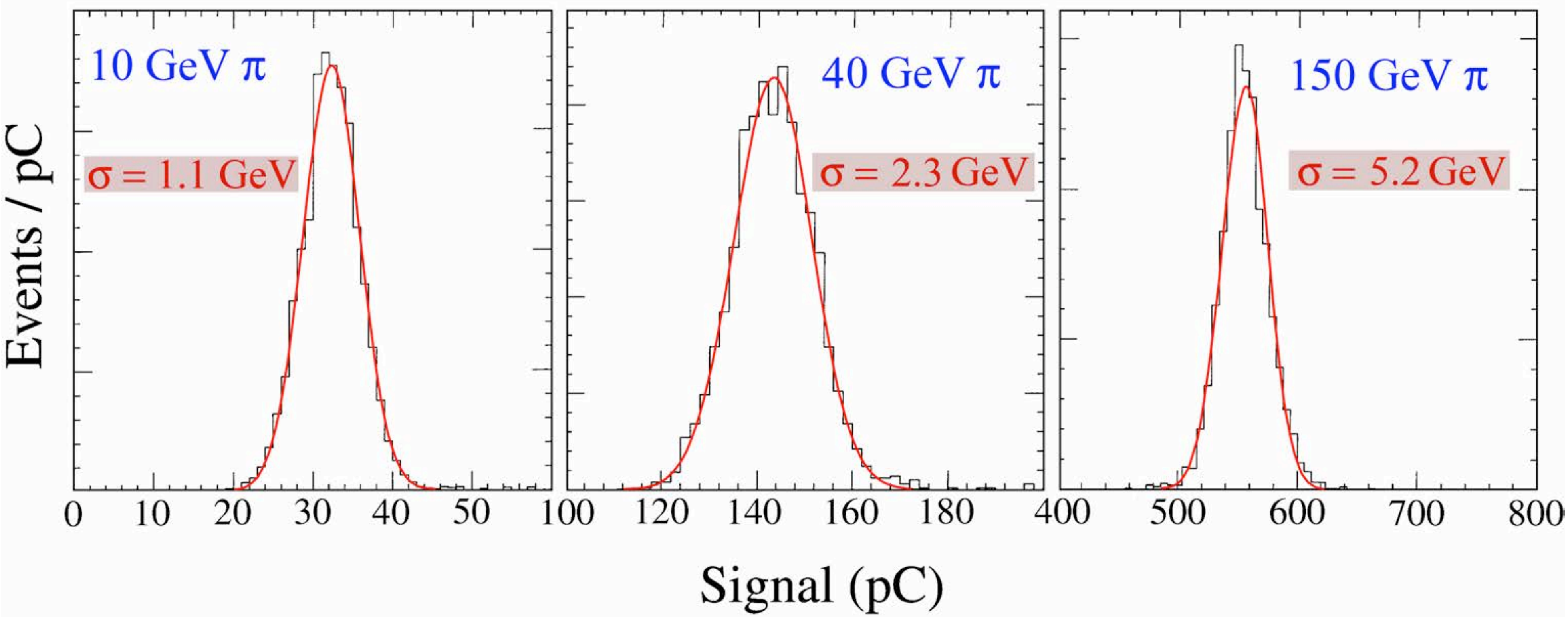


Figure 10: The hadronic energy resolution as a function of energy, for the compensating SPACAL *lead/plastic-scintillator calorimeter (sampling fraction 2%)*

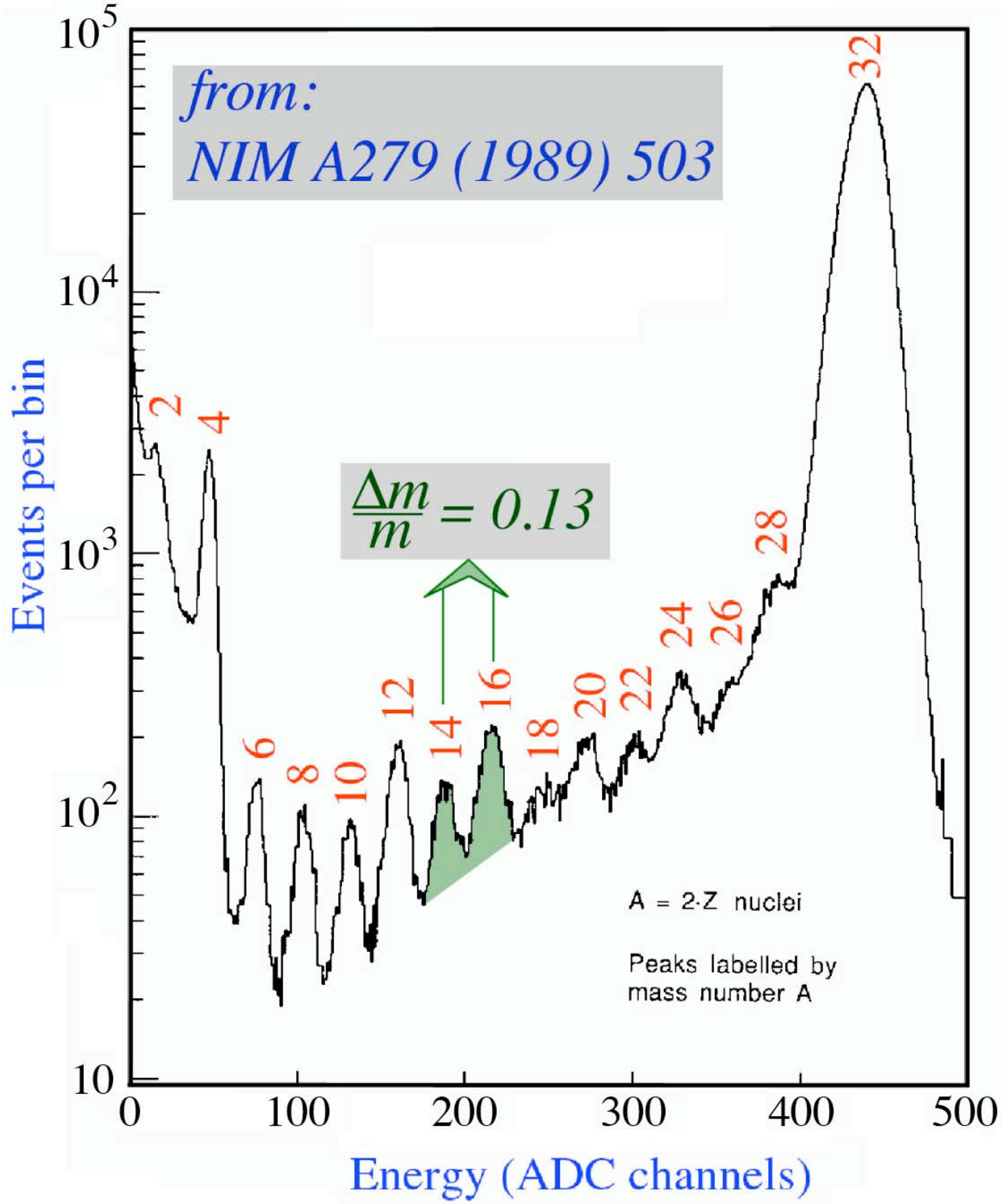
NIM A308 (1991) 481

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

Milestones

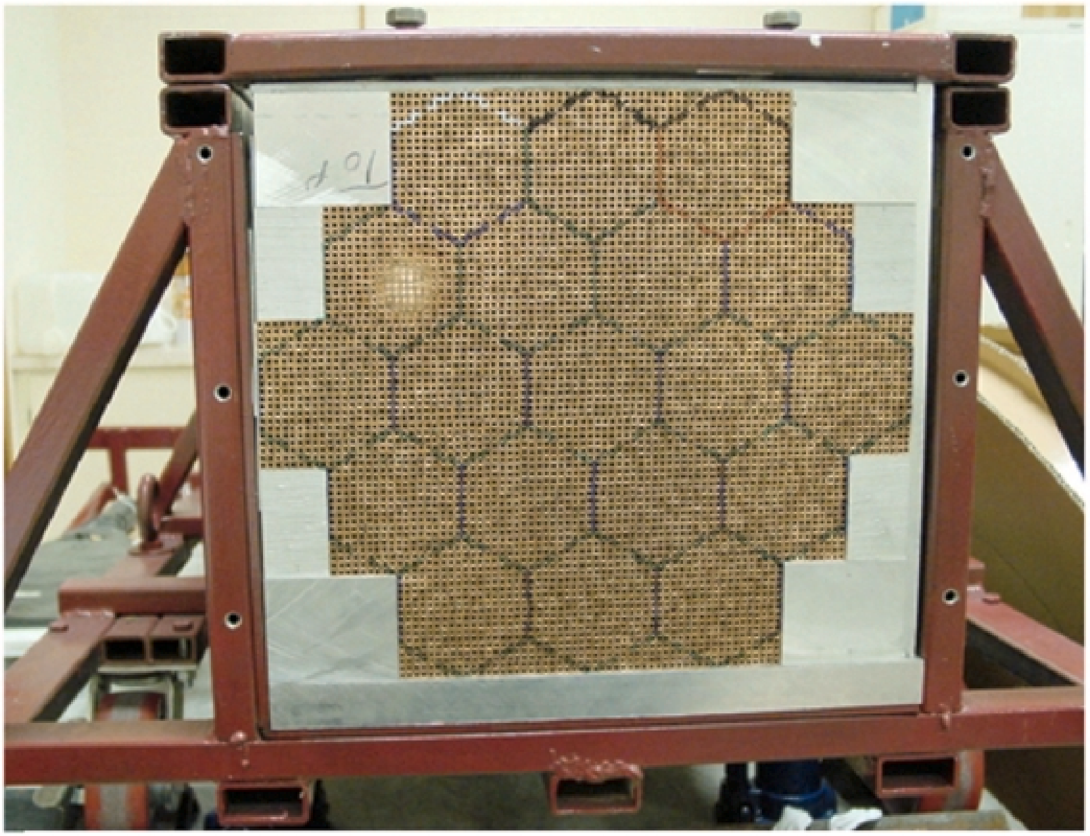
- 1965 - *Quantum leap in signal quanta (e-h pairs in semiconductors)*
- 1970 - *Shower counters in HEP (crucial for discovery b-quark)*
- 1975 - *Liquid argon calorimetry invented*
- 1980 - *4π calorimeters introduced (crucial for discovery W boson)*
- 1987 - *Compensation mechanism understood*
- 2000 - *Merits of dual-readout calorimetry experimentally demonstrated*

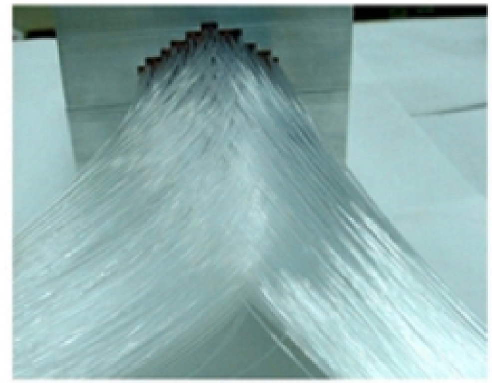
Dual-readout calorimetry

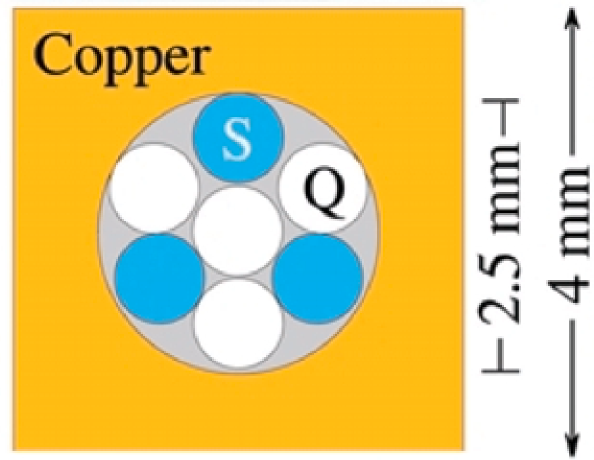
Measure the em shower fraction f_{em} event by event

$\longrightarrow$ *eliminate effects of fluctuations in f_{em} on the calorimeter performance*

DREAM: Structure

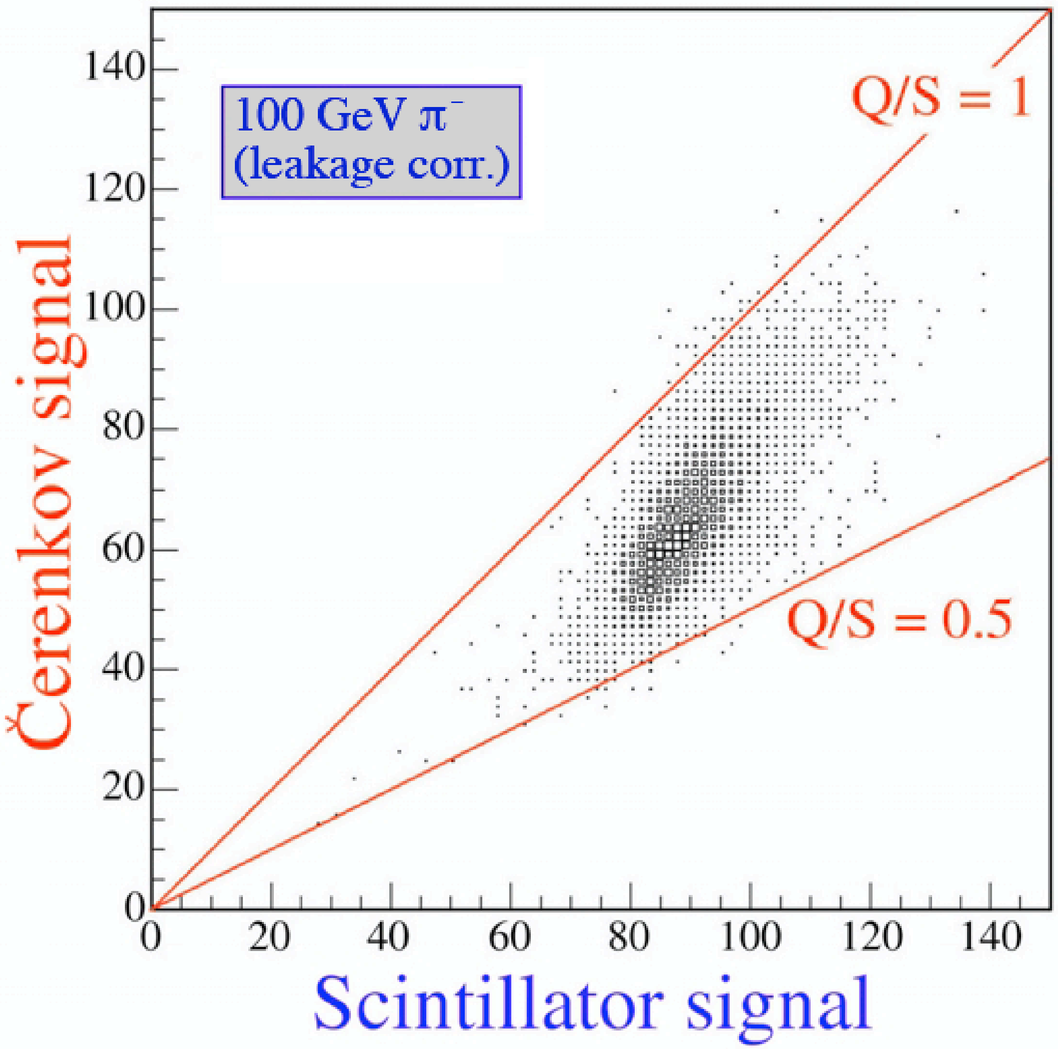






- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

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



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

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

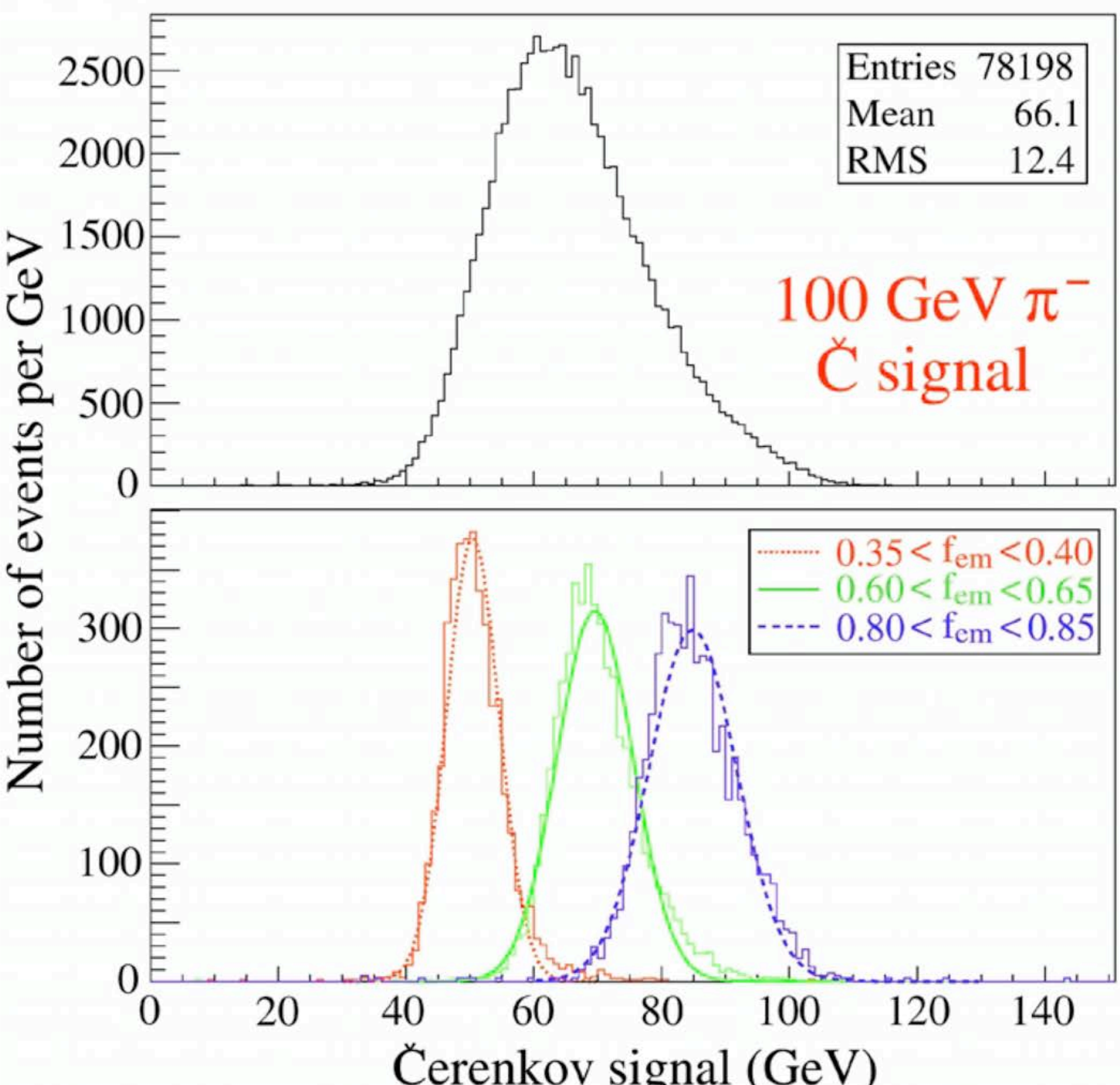
e.g. If $e/h = 1.3$ (S), 4.7 (Q)

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

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

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

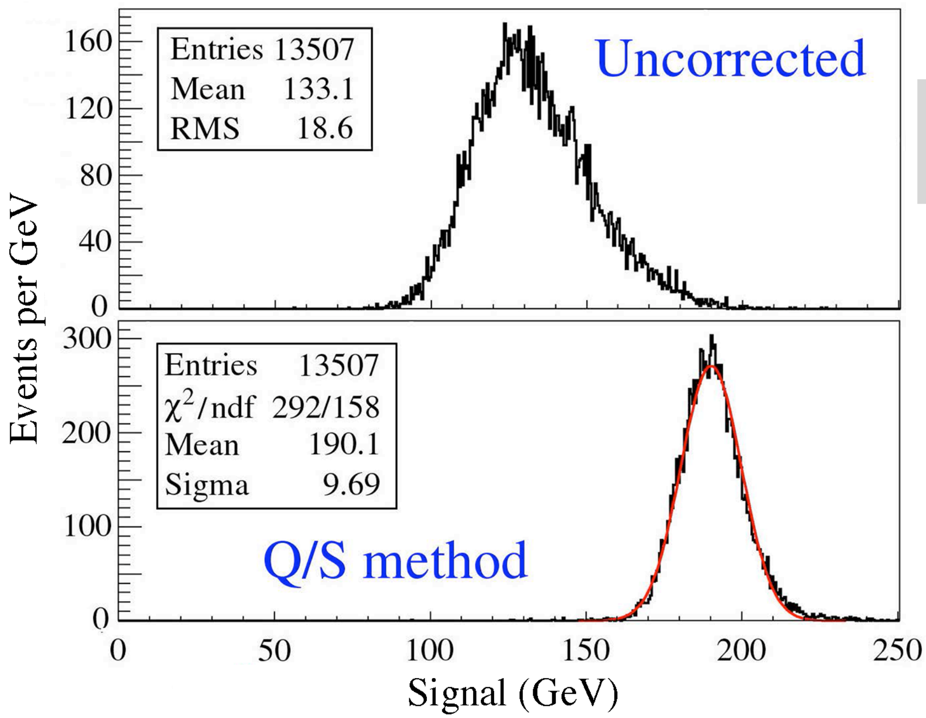
DREAM: Effect of event selection based on f_{em}



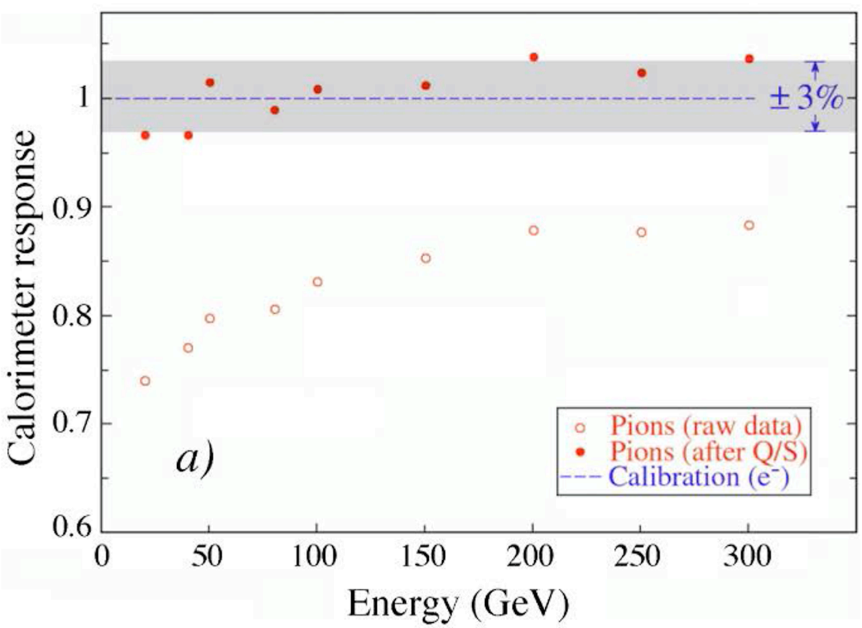
From:
NIM A537 (2005) 537

Effects of Q/S corrections on

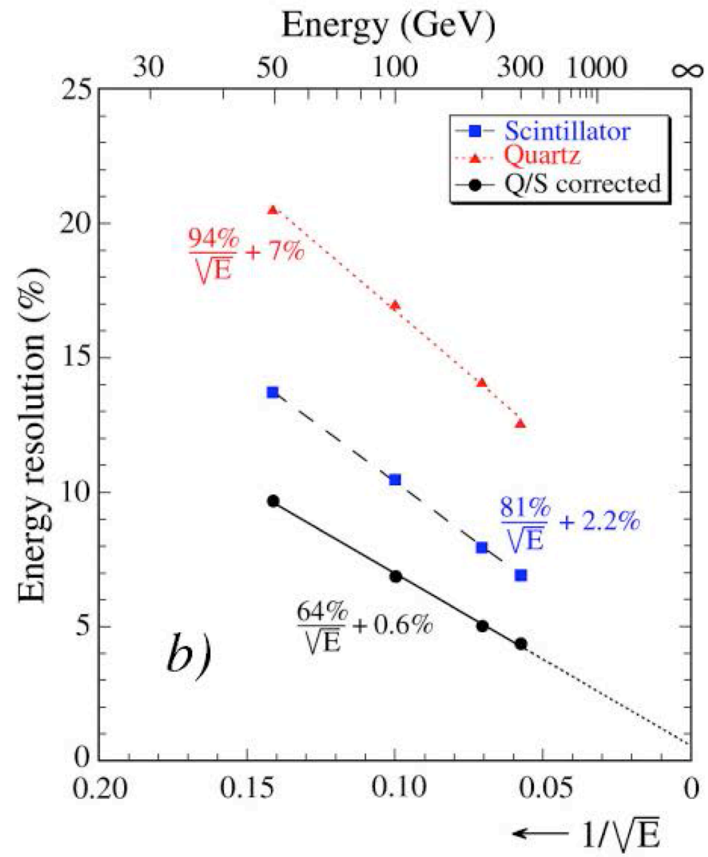
Calorimeter response function



hadronic signal linearity



jet energy resolution



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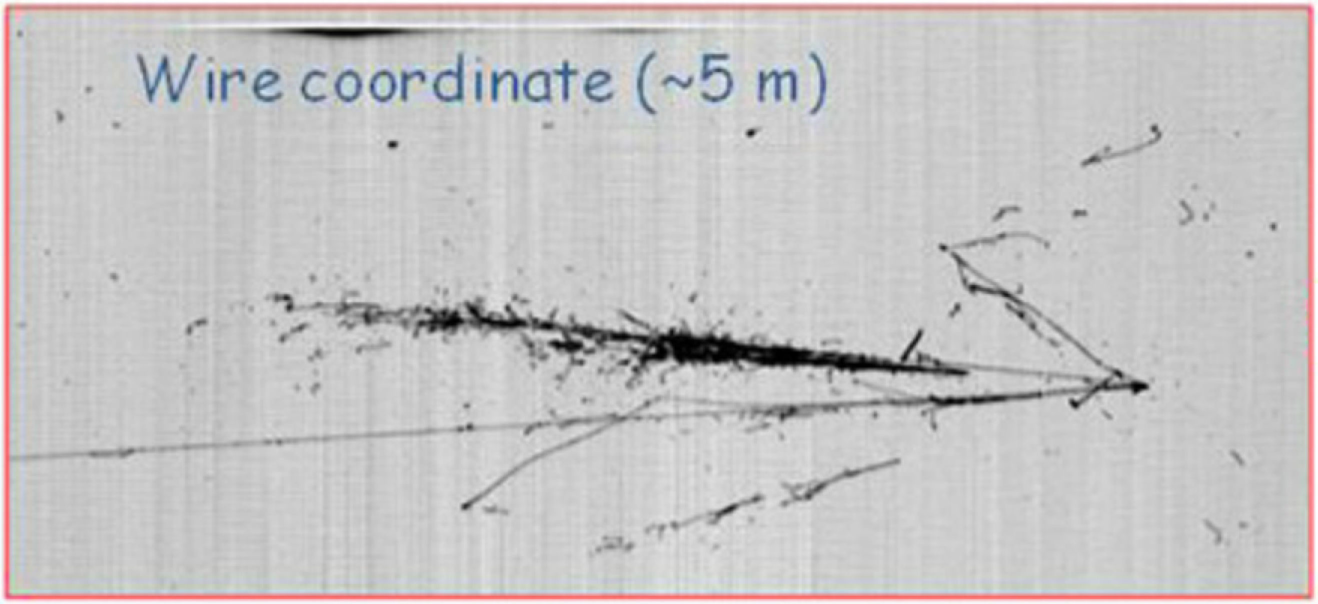
- 1980 - *4π calorimeters introduced (crucial for discovery W boson)*
- 1987 - *Compensation mechanism understood*
- 2000 - *Merits of dual-readout calorimetry experimentally demonstrated*
- 2005 - *Imaging calorimetry demonstrated (LAr)*

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

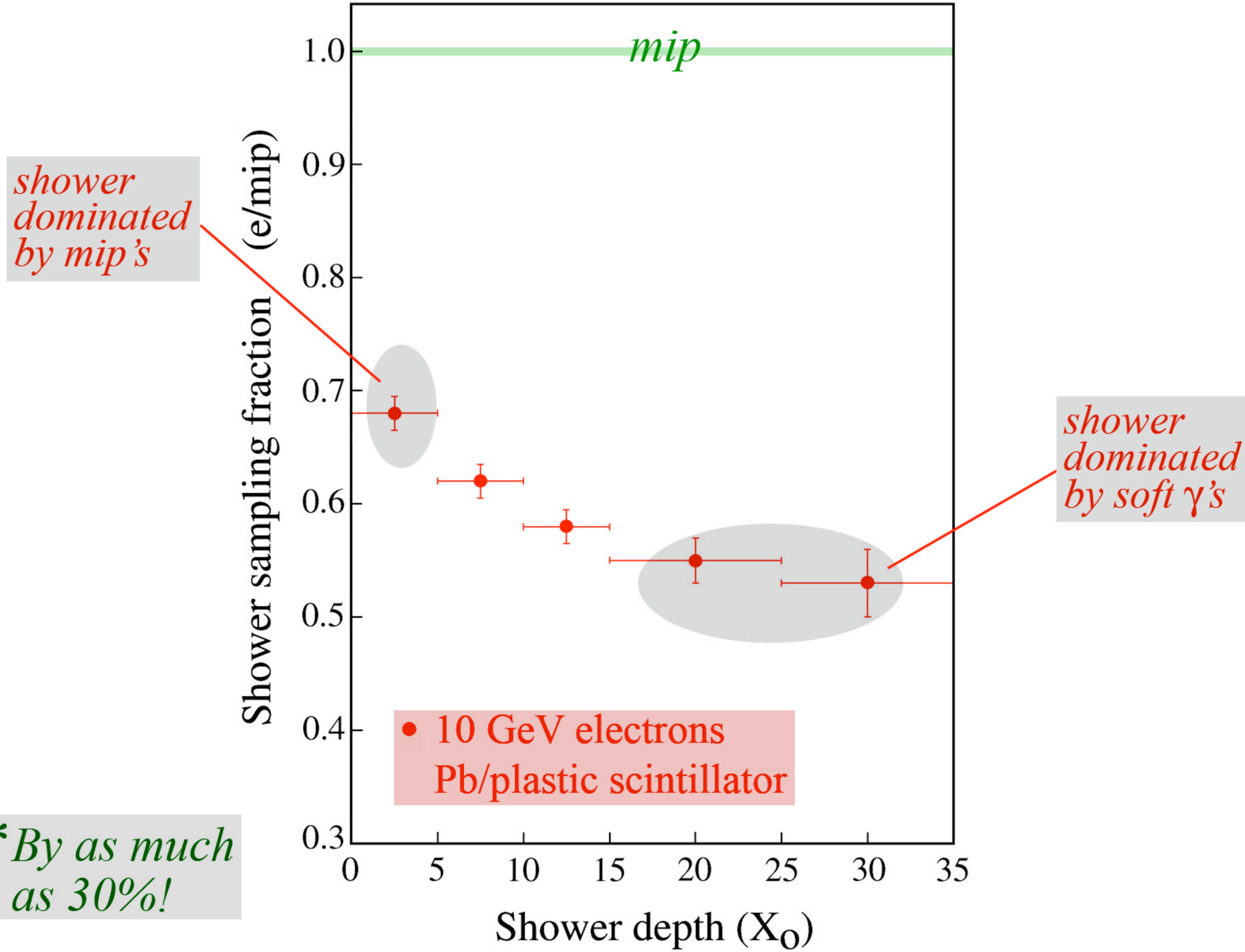
Misconceptions about calorimetry

- *A shower is a collection of mips*

This misconception is

THE SOURCE OF MANY CALIBRATION PROBLEMS

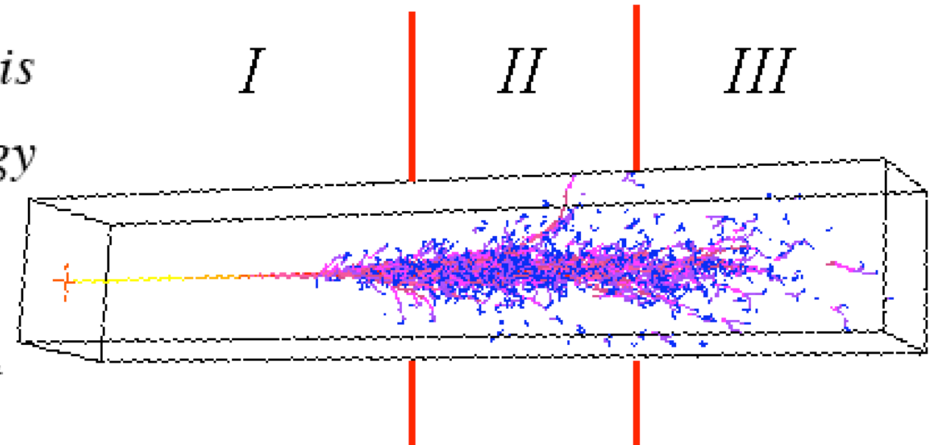
*The sampling fraction changes as shower develops**



**By as much as 30%!*

Calibration of longitudinally segmented devices

- *Imagine a Cherenkov calorimeter, e.g. lead glass*
- *High-energy electrons develop showers in this*
- *On average, 10 p.e. per GeV deposited energy*
  100 GeV e gives a signal of 1000 p.e.,
  20 GeV e gives a signal of 200 p.e., etc.



- *Shower particles < 0.3 MeV give NO Č light*
- *The relative contribution of such particles increases with depth*
- *If this detector is cut into 3 parts, the relationship between deposited energy and resulting signal is then, e.g.*

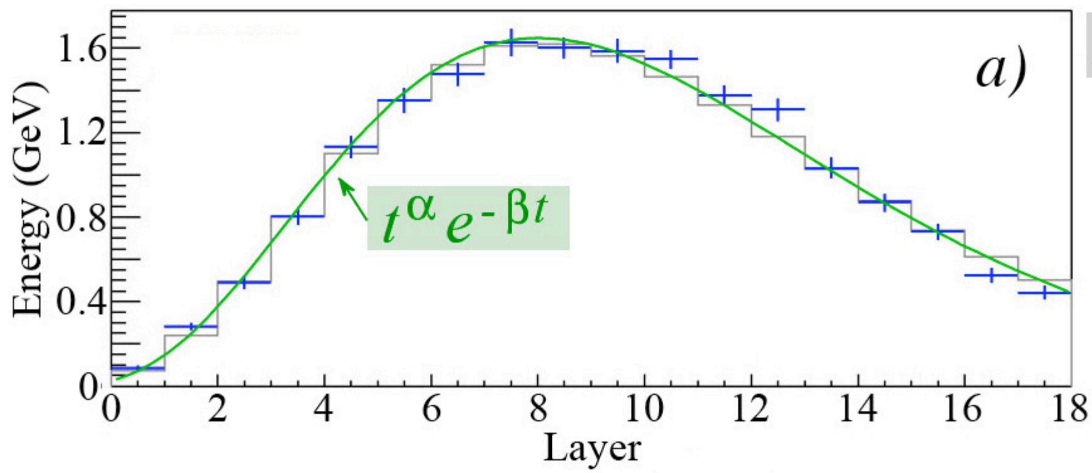
  I: 15 p.e./GeV II: 10 p.e./GeV III: 5 p.e./GeV

  These constants have been derived for 100 GeV e, which deposit, on average, 30/40/30% in these 3 parts, and thus give, on average, a signal of 1000 p.e., as before
- *However, a low-energy shower deposits most of its energy in part I. Based on these calibration constants, its energy is UNDERESTIMATED*
- *And for an em shower starting in section III (e.g. γ from π° decay), the energy is systematically OVERESTIMATED*

→ *Non-linearity + energy dependence on starting point shower*

Calibration misery of longitudinally segmented devices

Example: AMS (em showers!)



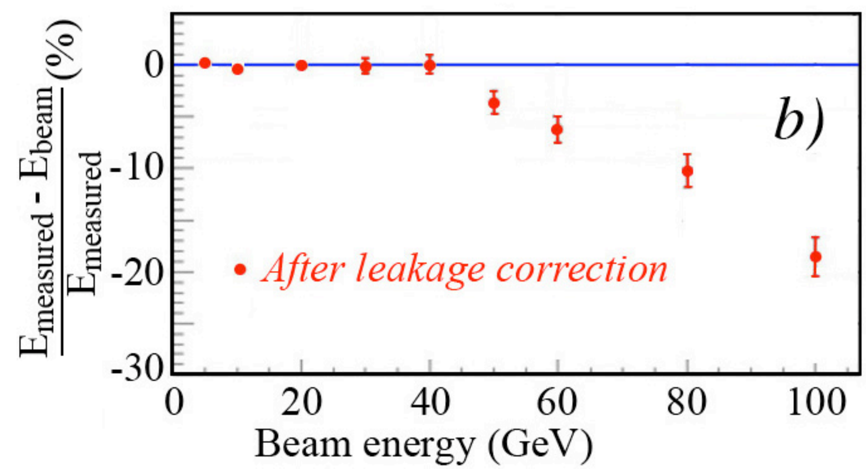
Source: NIM A490 (2002) 132

Pb/scintillating fiber (18 layers)

Calibrated with mip's: 11.7 MeV/layer

Leakage estimated from fit to measured shower profile

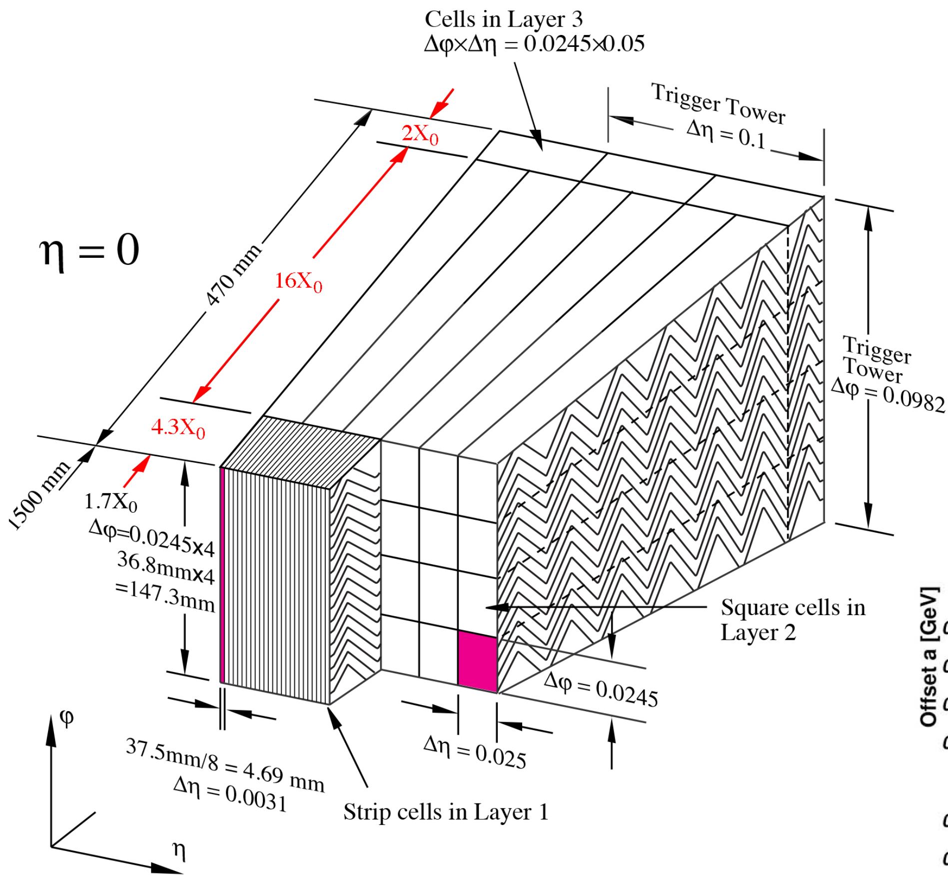
However:
In em shower, signal per GeV decreases as shower develops
→ (leakage) energy based on measured signals underestimates reality

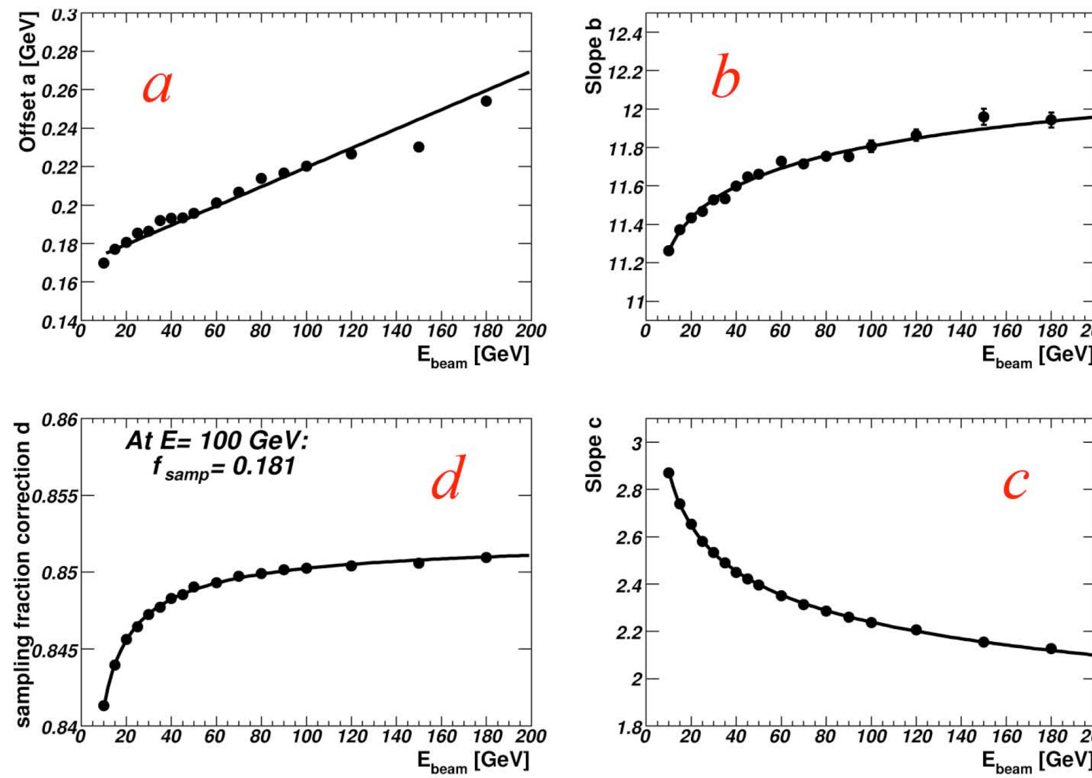


Required very elaborate MC simulations to solve, since effects depend on energy and direction incoming particle

Calibration of the ATLAS ECAL

(for electrons, NOT γs)



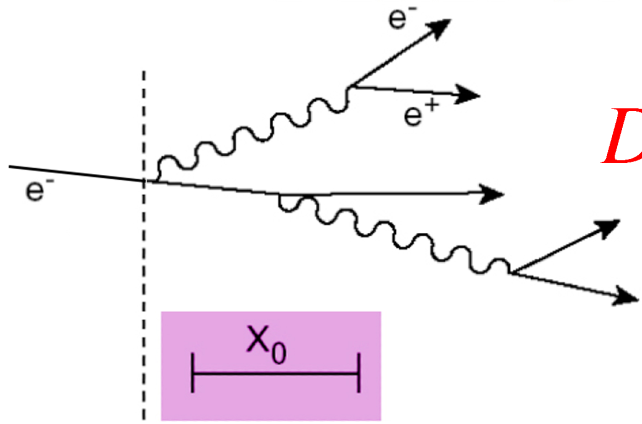


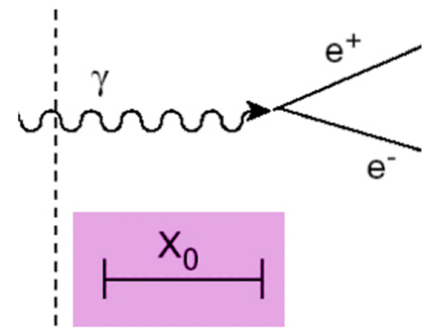
$$E^{rec} = \left(a(E) + b(E)\ E_0^{vis} + c(E)\ (E_0^{vis} \cdot E_1^{vis})^{0.5} + \frac{1}{d(E)\, f_{samp}} \sum_{i=1,3} E_i^{vis} \right) \cdot f_{\text{cell impact}}(\Delta\Phi) \cdot (1 + f_{\text{leakage}})$$

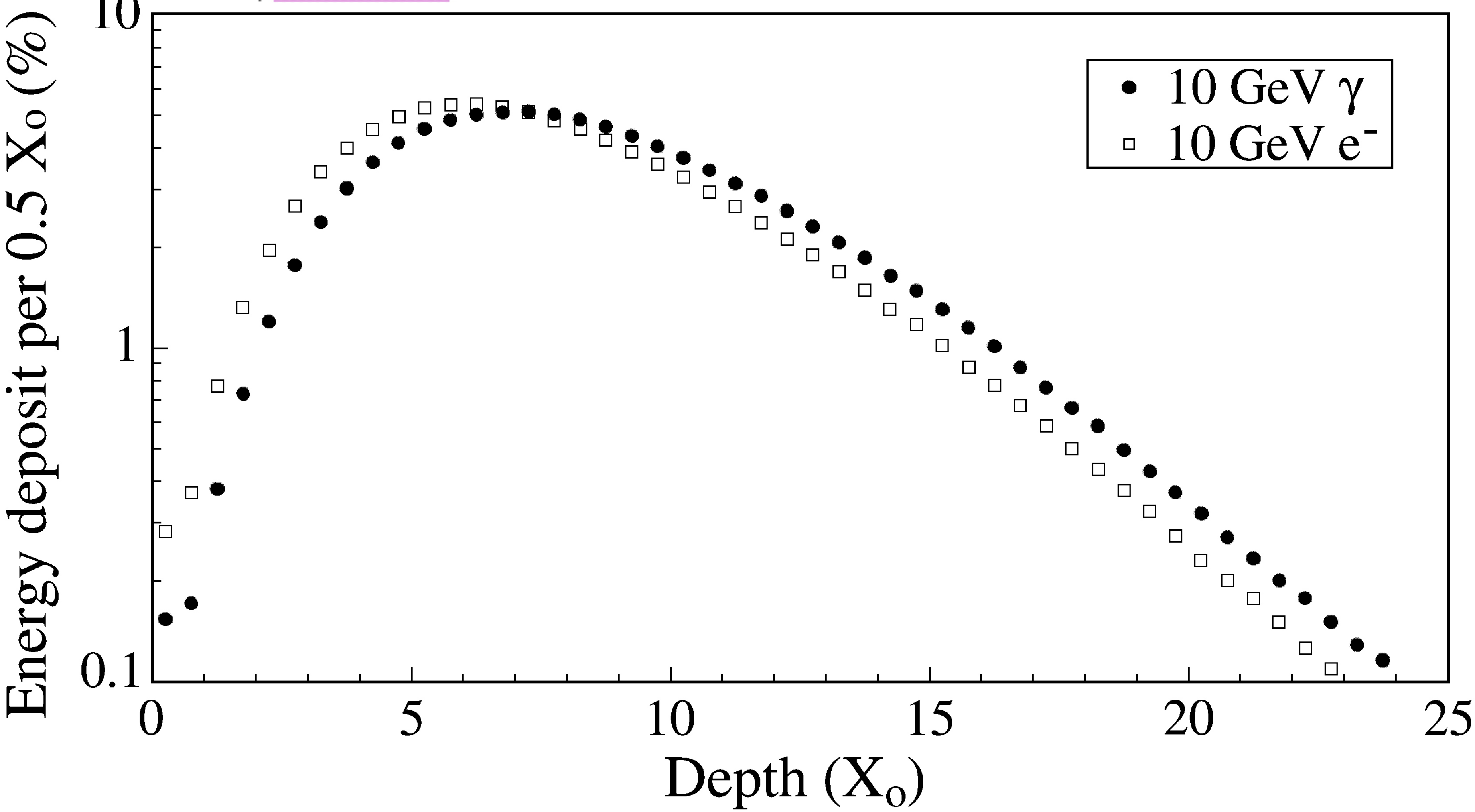
In a calorimeter, showers initiated by electrons and γs

DEVELOP

DIFFERENTLY

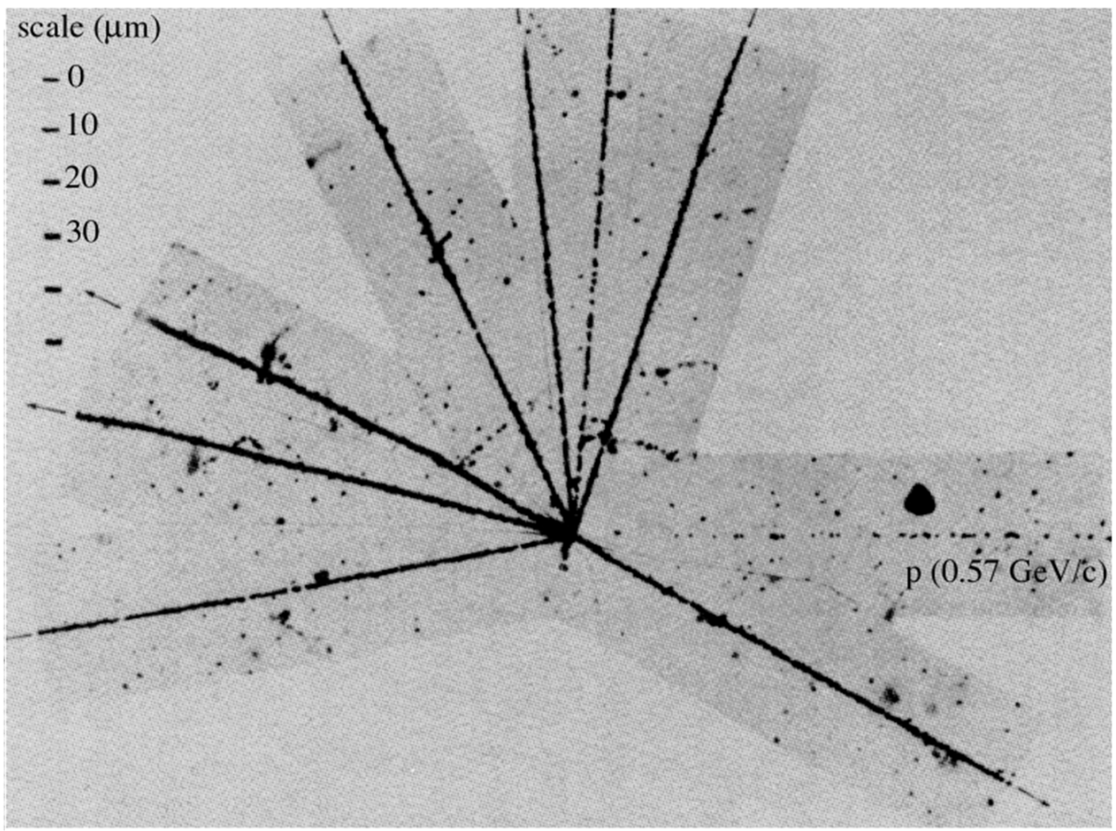






Catastrophic effects of ONE individual shower particle (1)

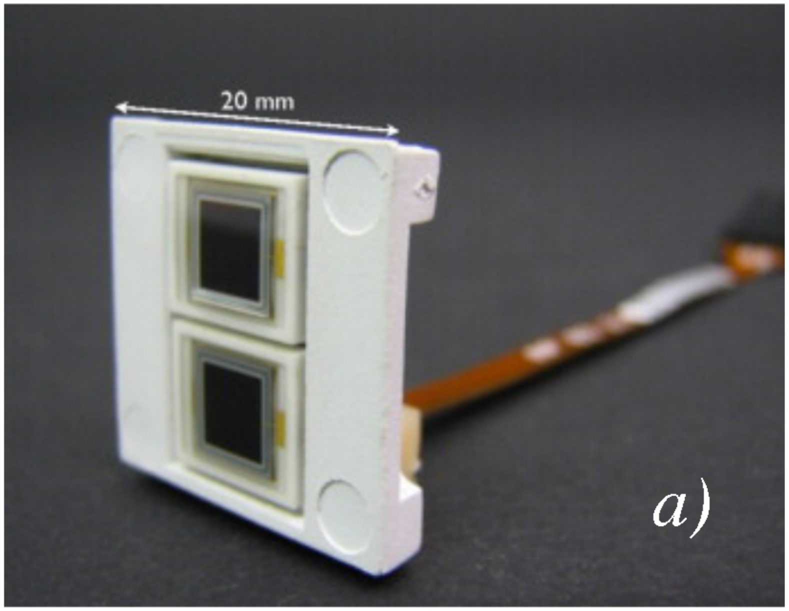
A typical process inside a hadronic shower

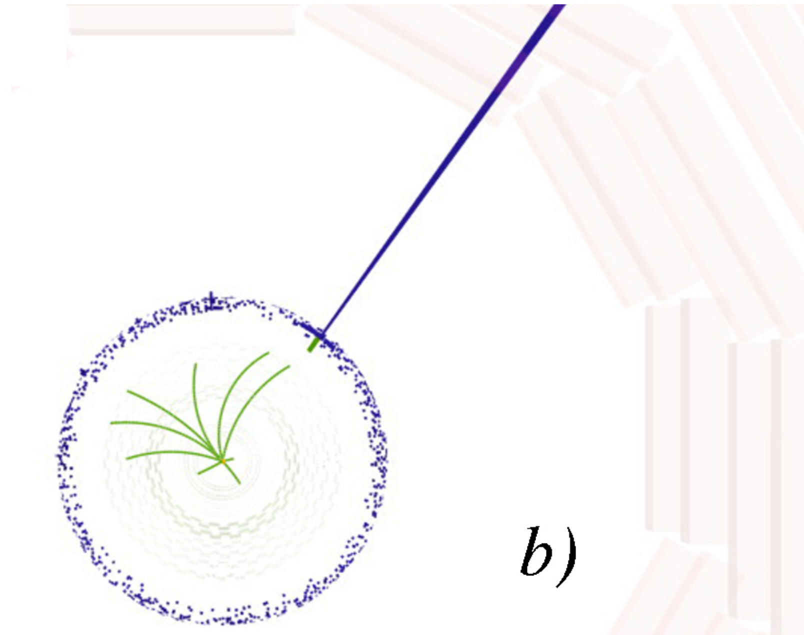


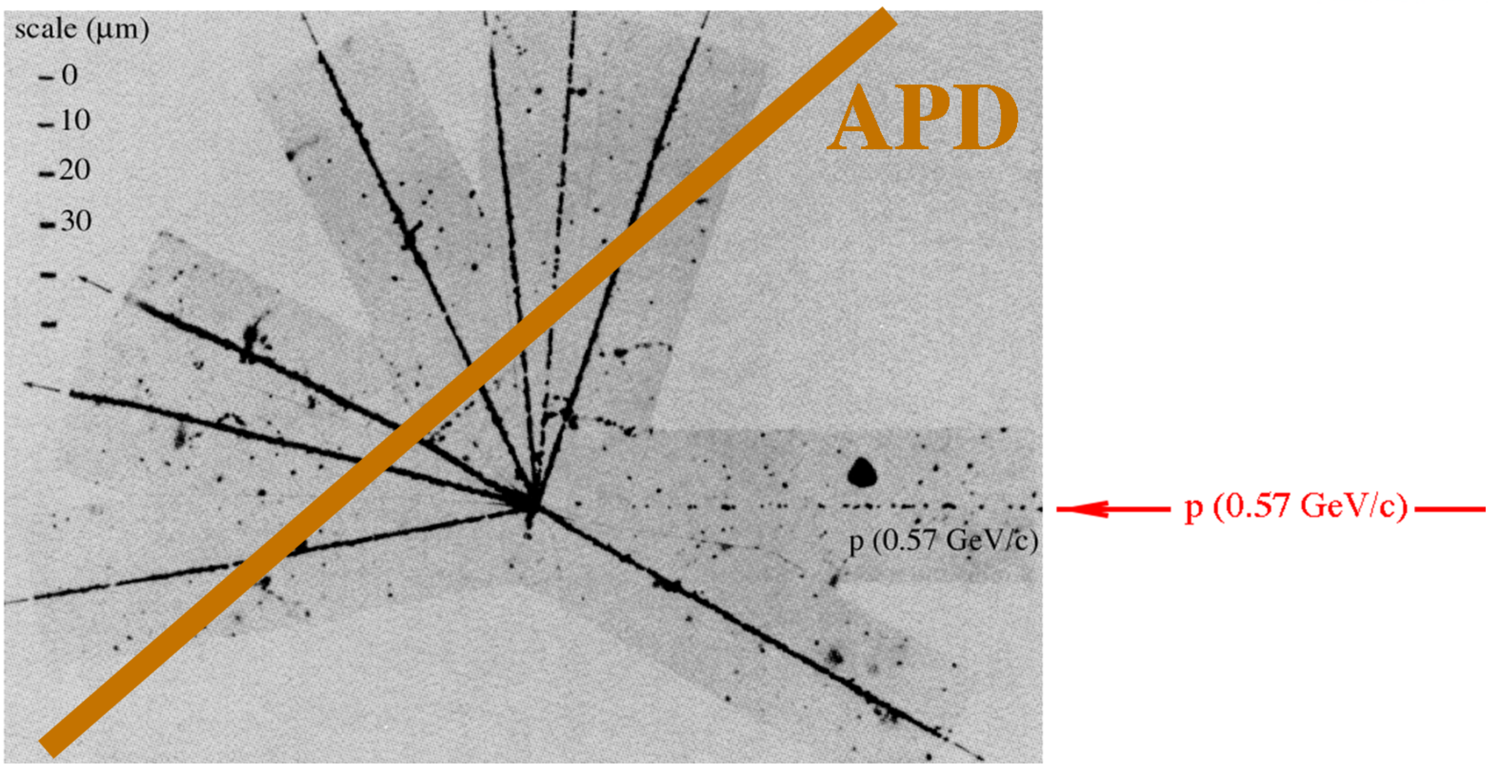
p (0.57 GeV/c)

(E_{kin} = 160 MeV)

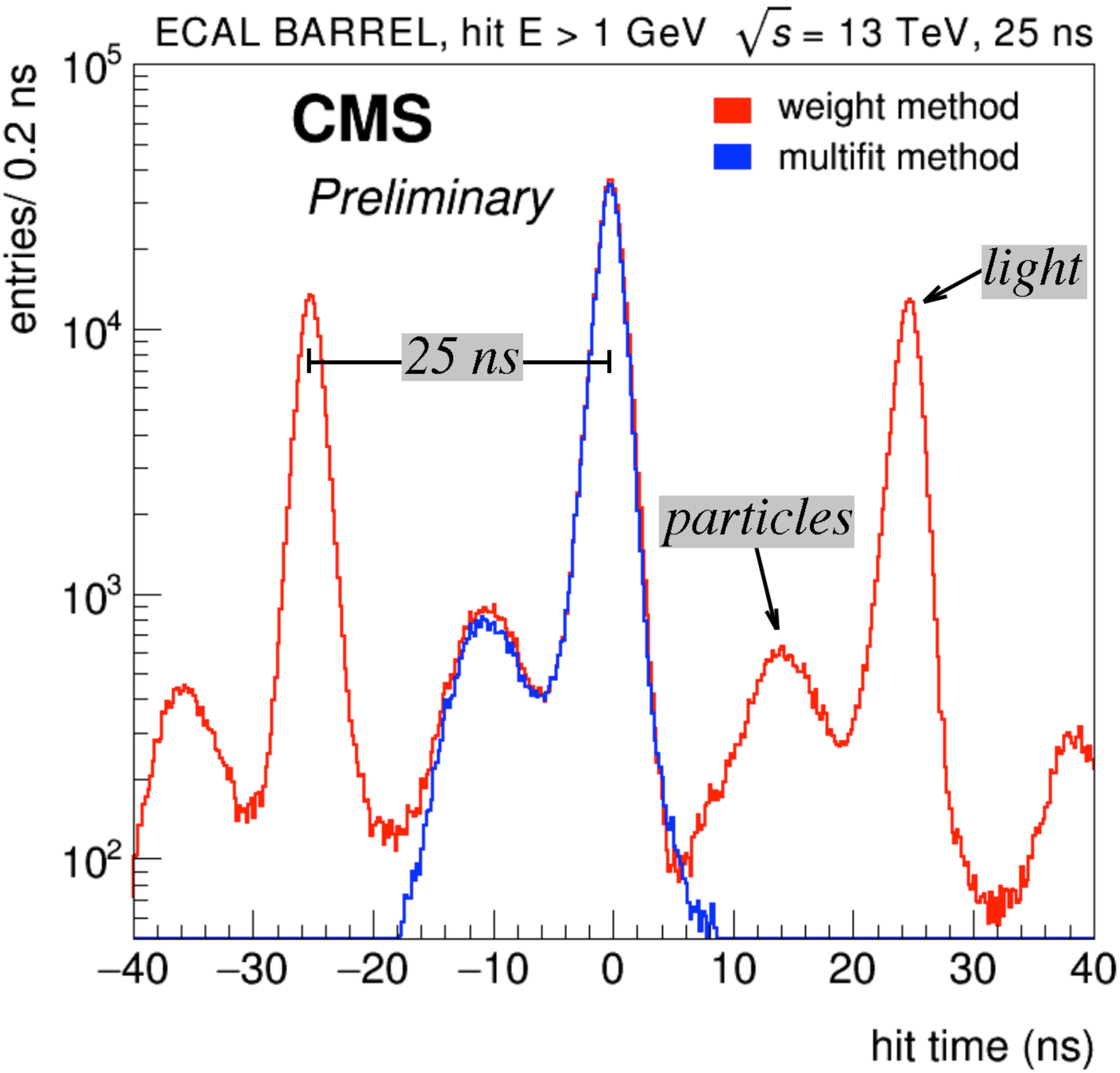
“Spike” events in CMS

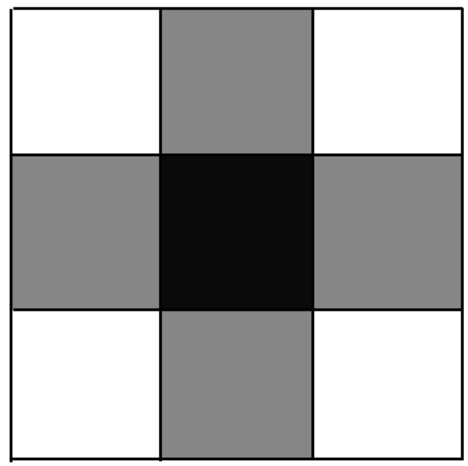






Spikes in CMS ECAL (after Swiss-cross elimination!)

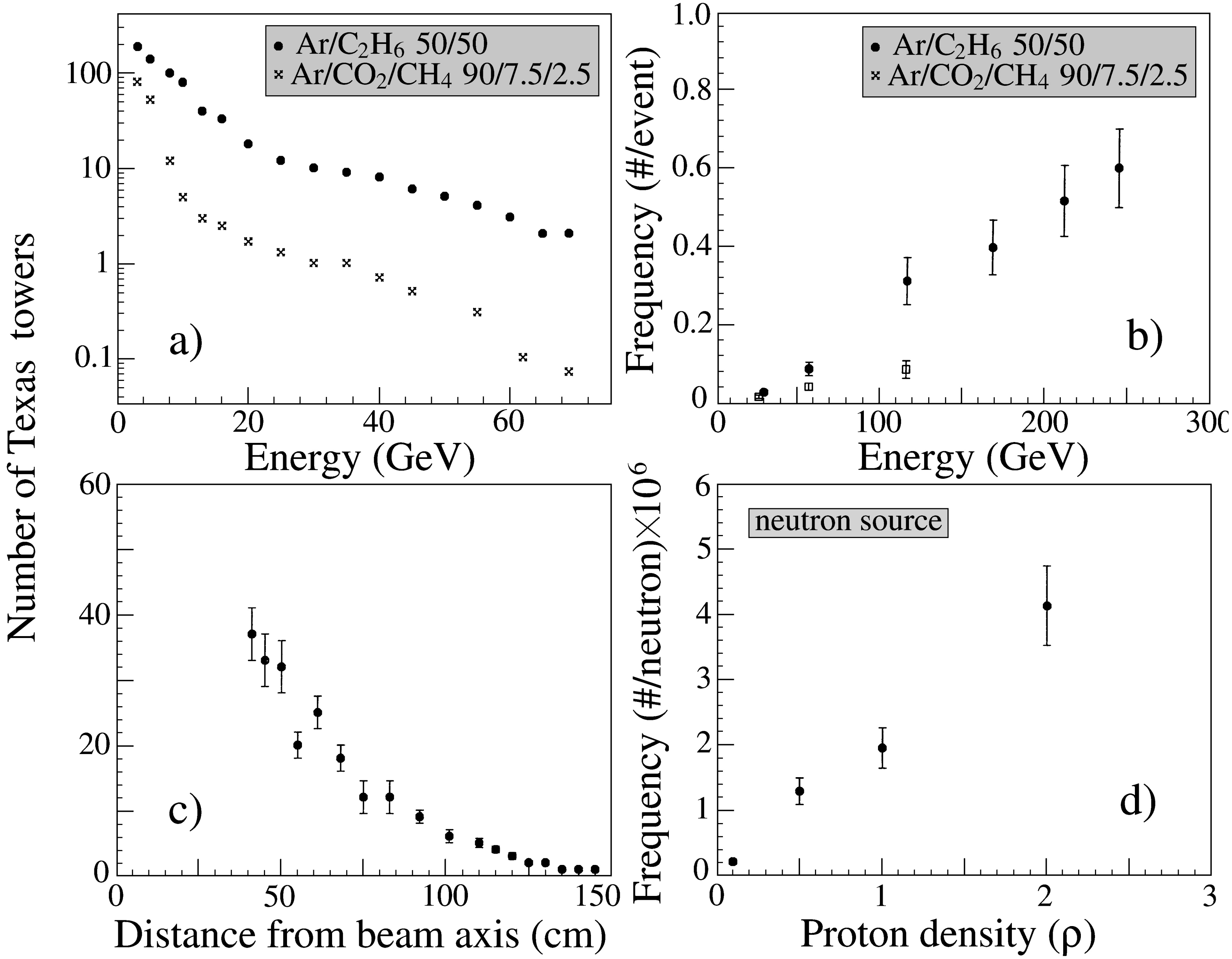




Catastrophic effects of ONE individual shower particle (2)

The Texas Tower effect (CDF, 1988)

Sampling fraction mips = 10^{-5} ⟶ 100 GeV shower ≡ 1 MeV in gas!



Catastrophic effects of ONE individual shower particle (3)

(my prediction: bets, anyone?)

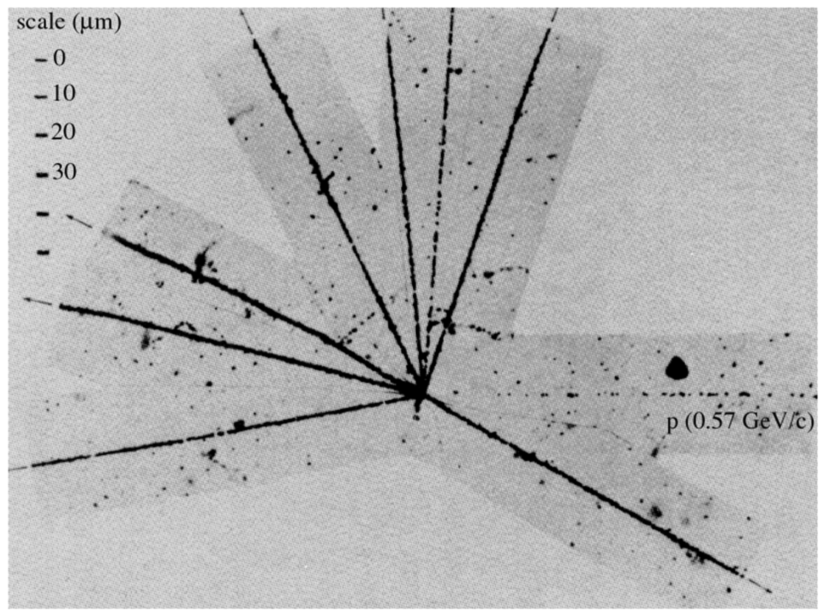
The high-luminosity CMS upgrade of the endcap calorimeter system has a section (FH) consisting of 5 cm thick brass absorber plates, interleaved with 100 μm silicon.

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

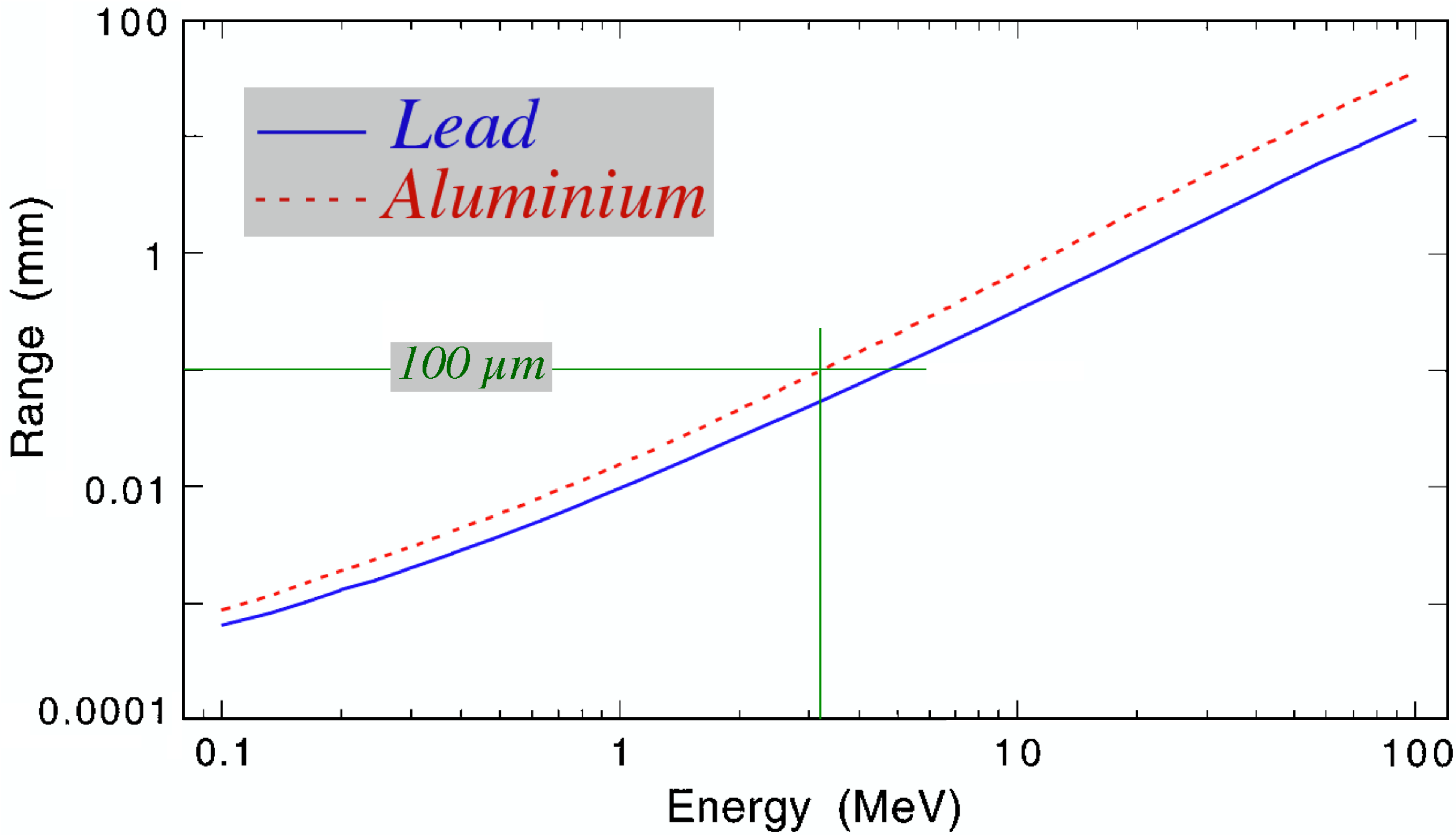
No signal saturation!

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

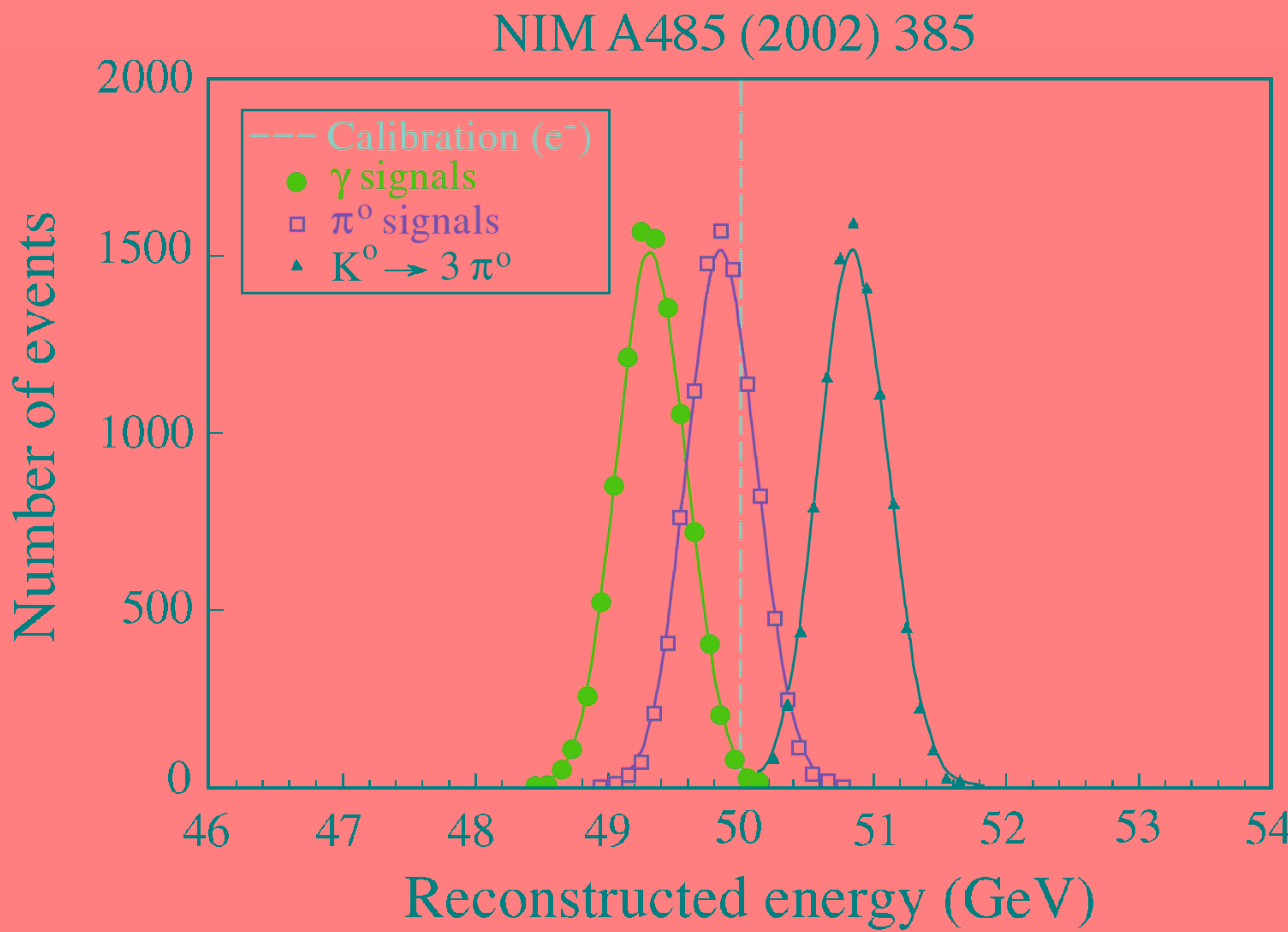


Figure 14: Signal distributions for γs and various hadrons decaying into all-γ final states. All particles have the same nominal energy and the detector, which has an intrinsic resolution of 0.5% for em showers of this energy, was calibrated with electrons using $B/A = 0.8$. See text for details.

Misconceptions about calorimetry

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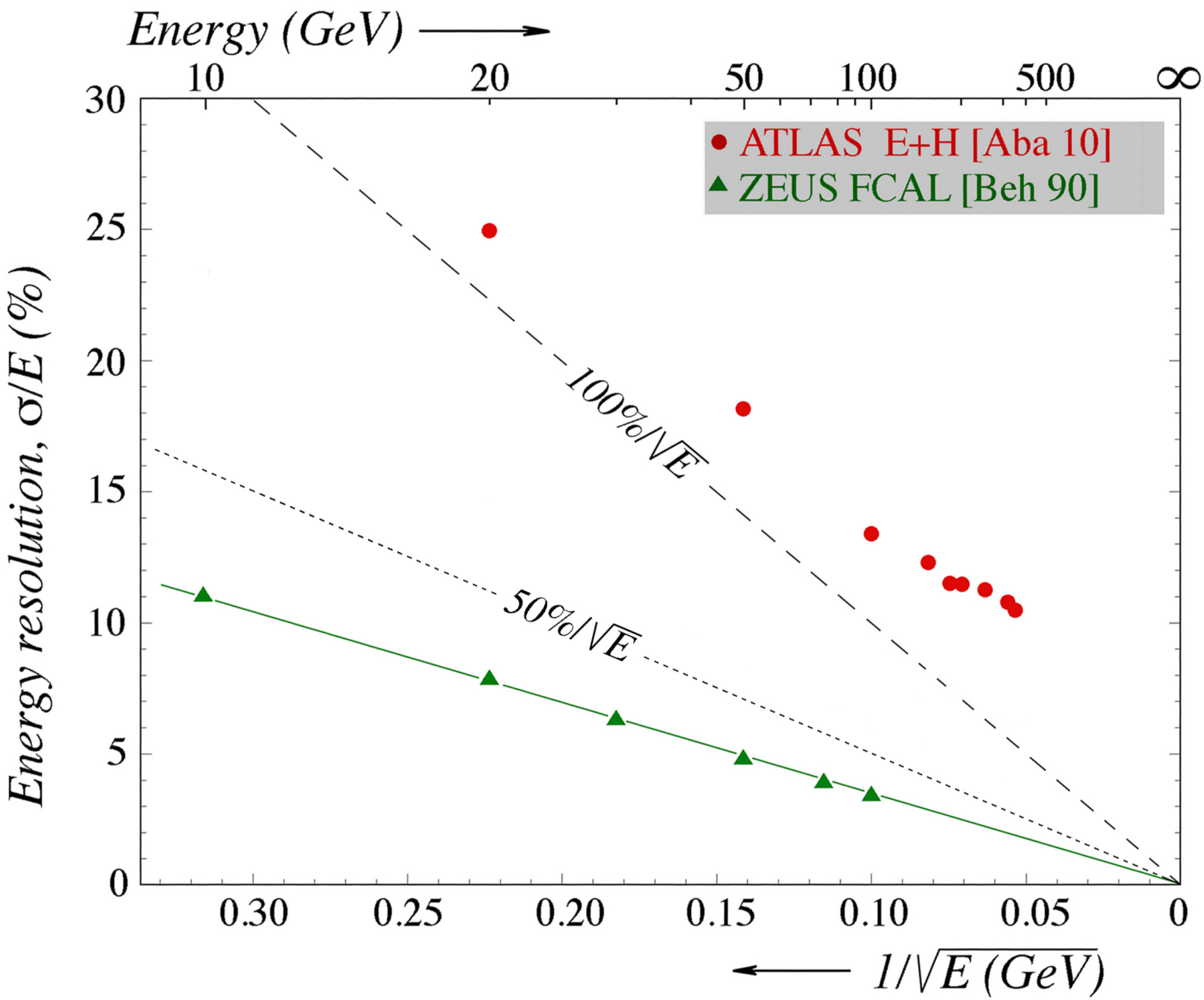
- *Energy resolution scales like* $E^{-1/2}$

Hadronic energy resolution of compensating vs modern calorimeters



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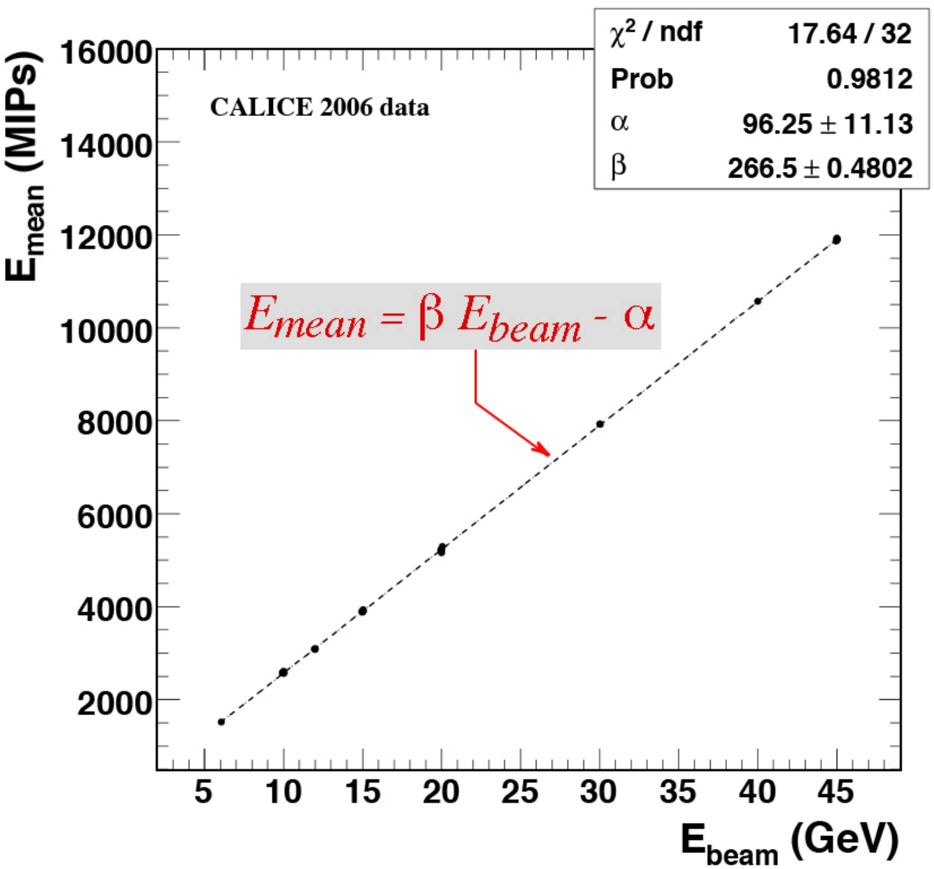
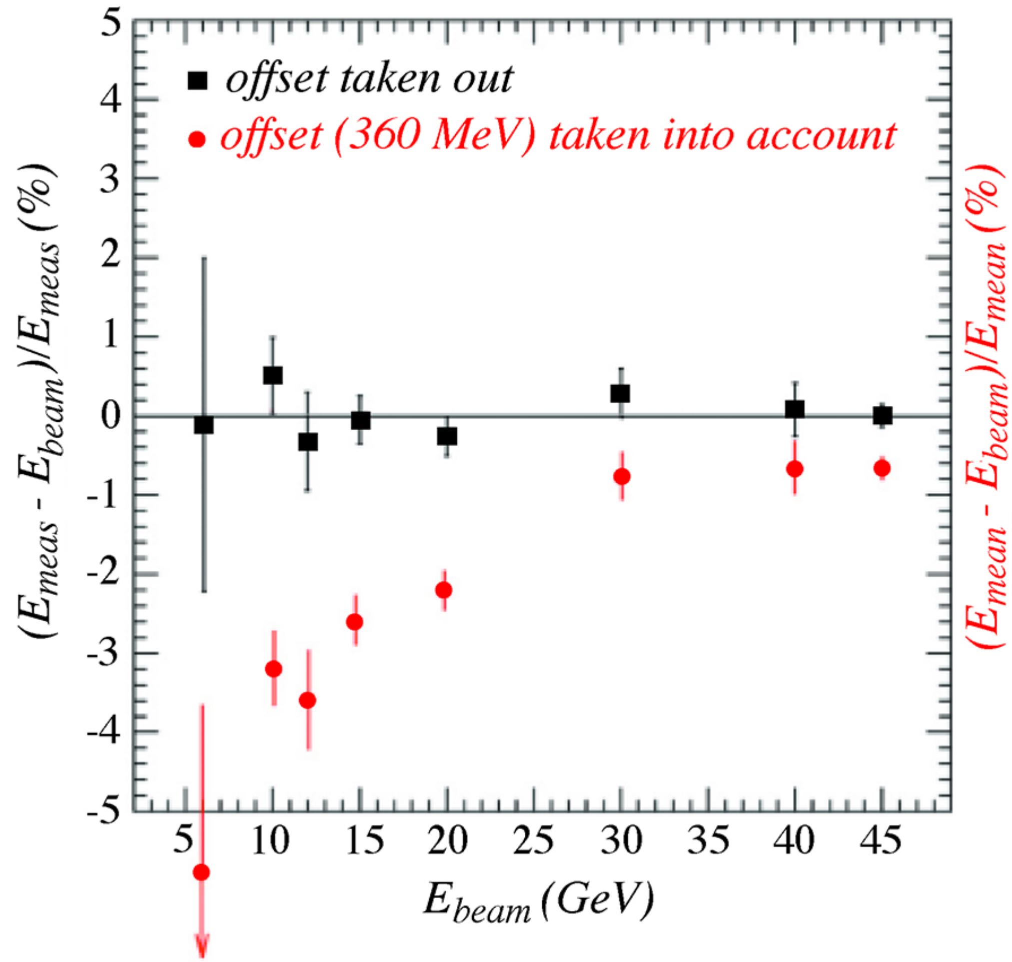
Response non-linearity in CALICE W/Si ECAL

NIM A608 (2009) 372





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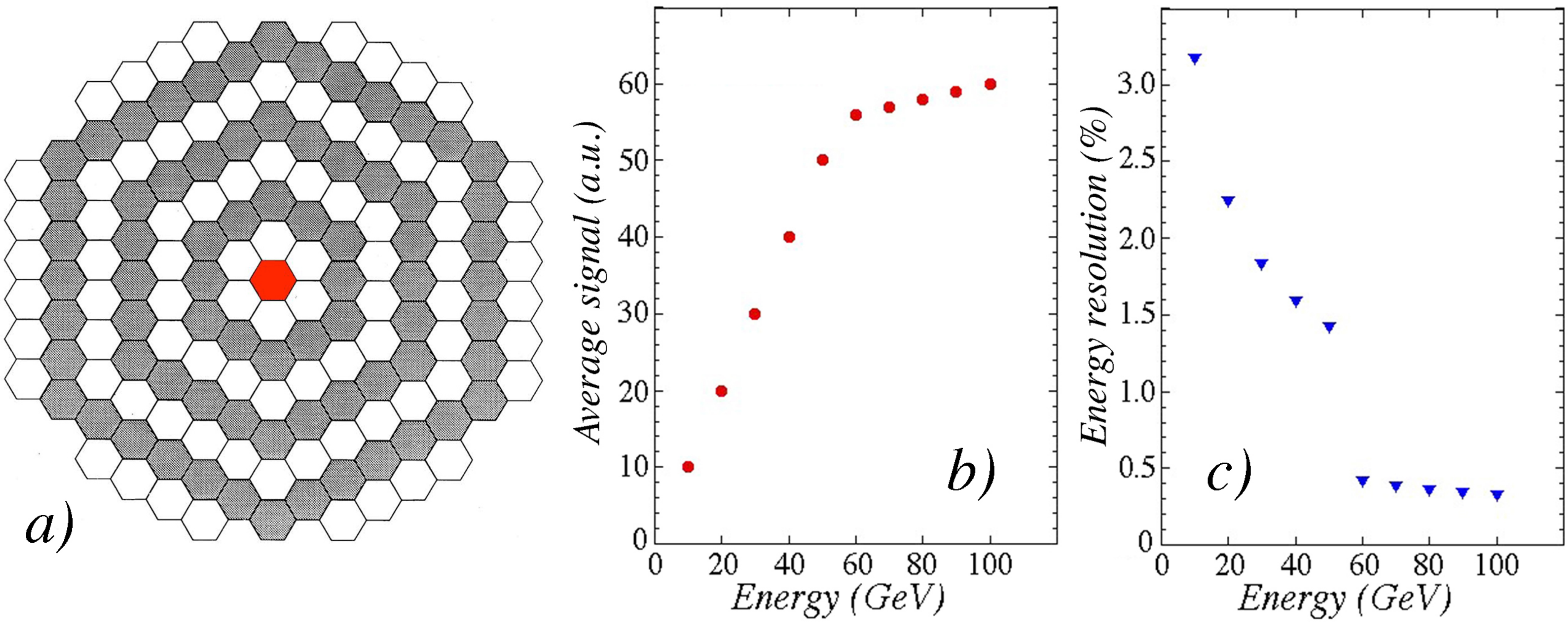
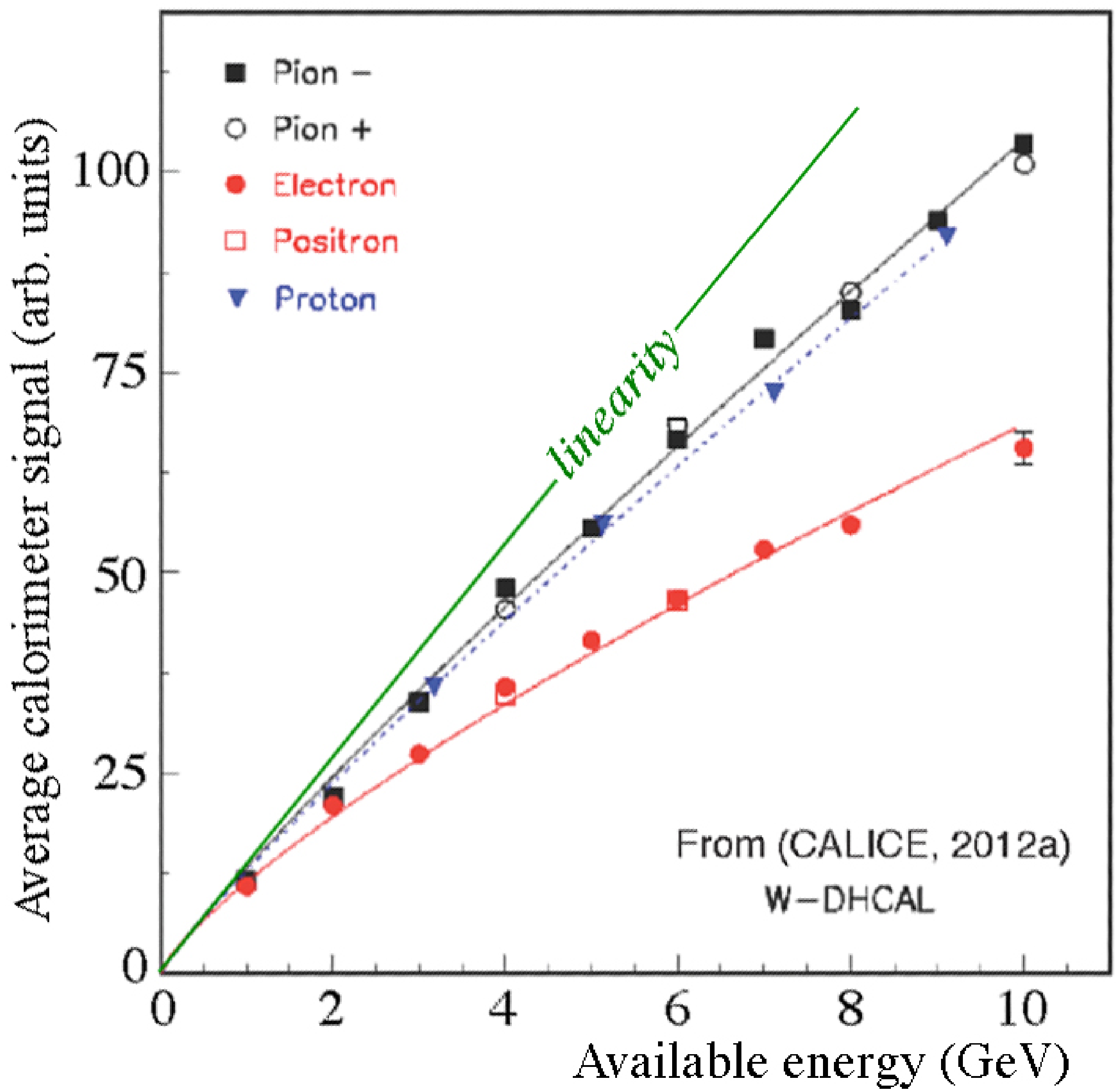
- *Signal saturation does not matter*

Effects of signal saturation (SPACAL)



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

Rev. Mod. Phys. 88 (2015) 15003



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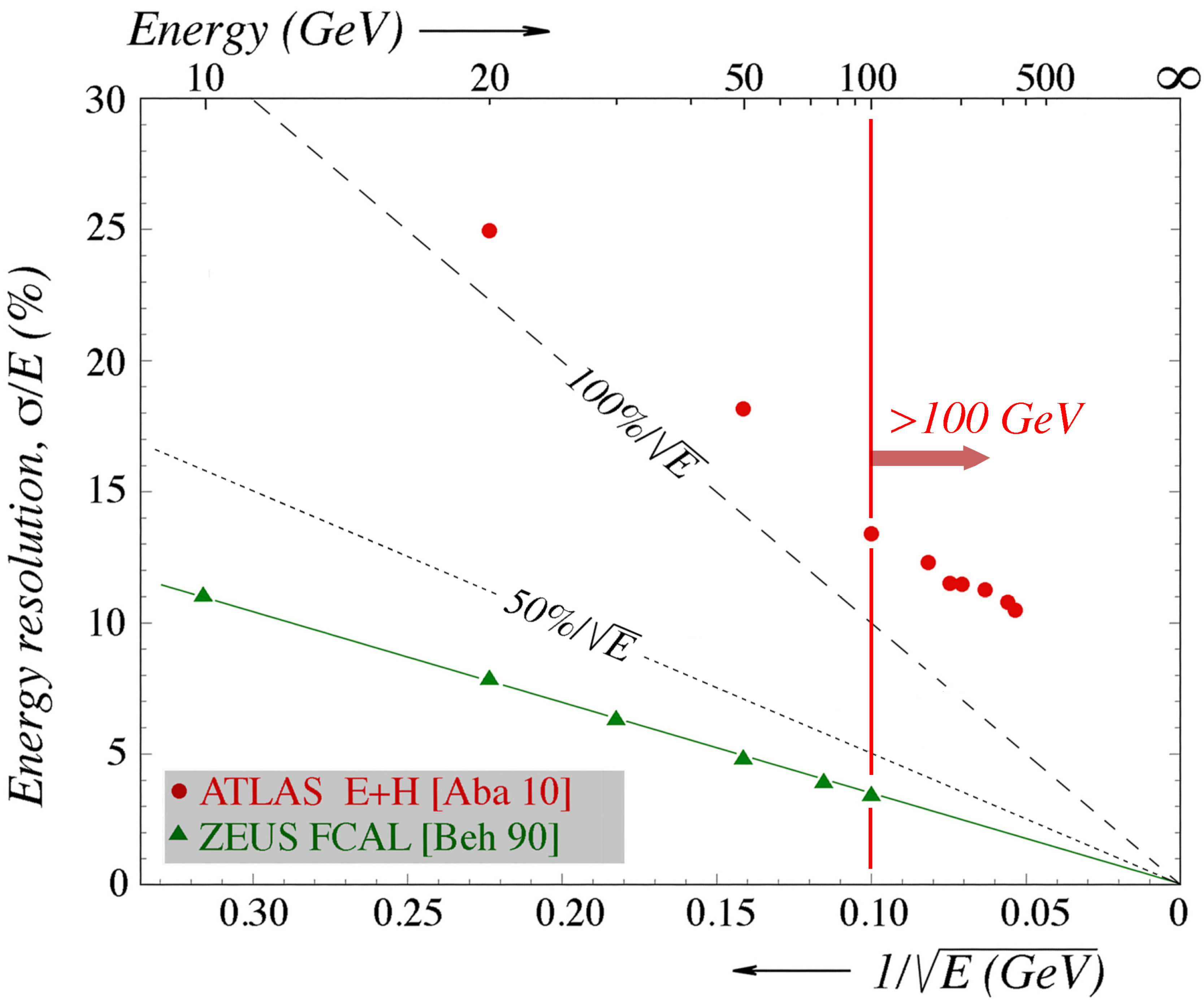
Hadronic energy resolution of compensating vs modern calorimeters



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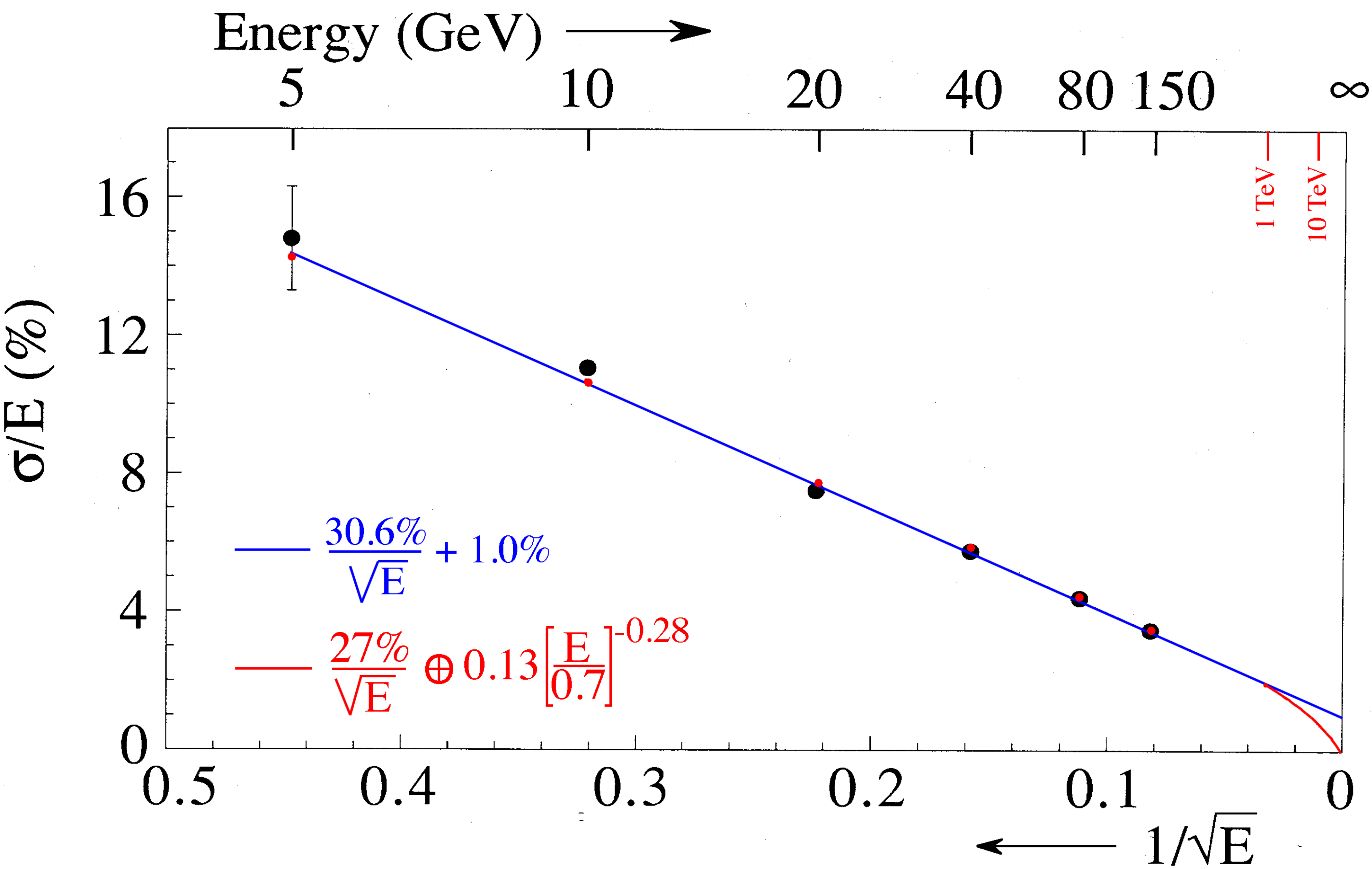
- *Compensation would be nice, but is not really important*
- *The only effect of non-compensation is a constant term in the energy resolution*

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) $\neq$ e/h (had)*

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

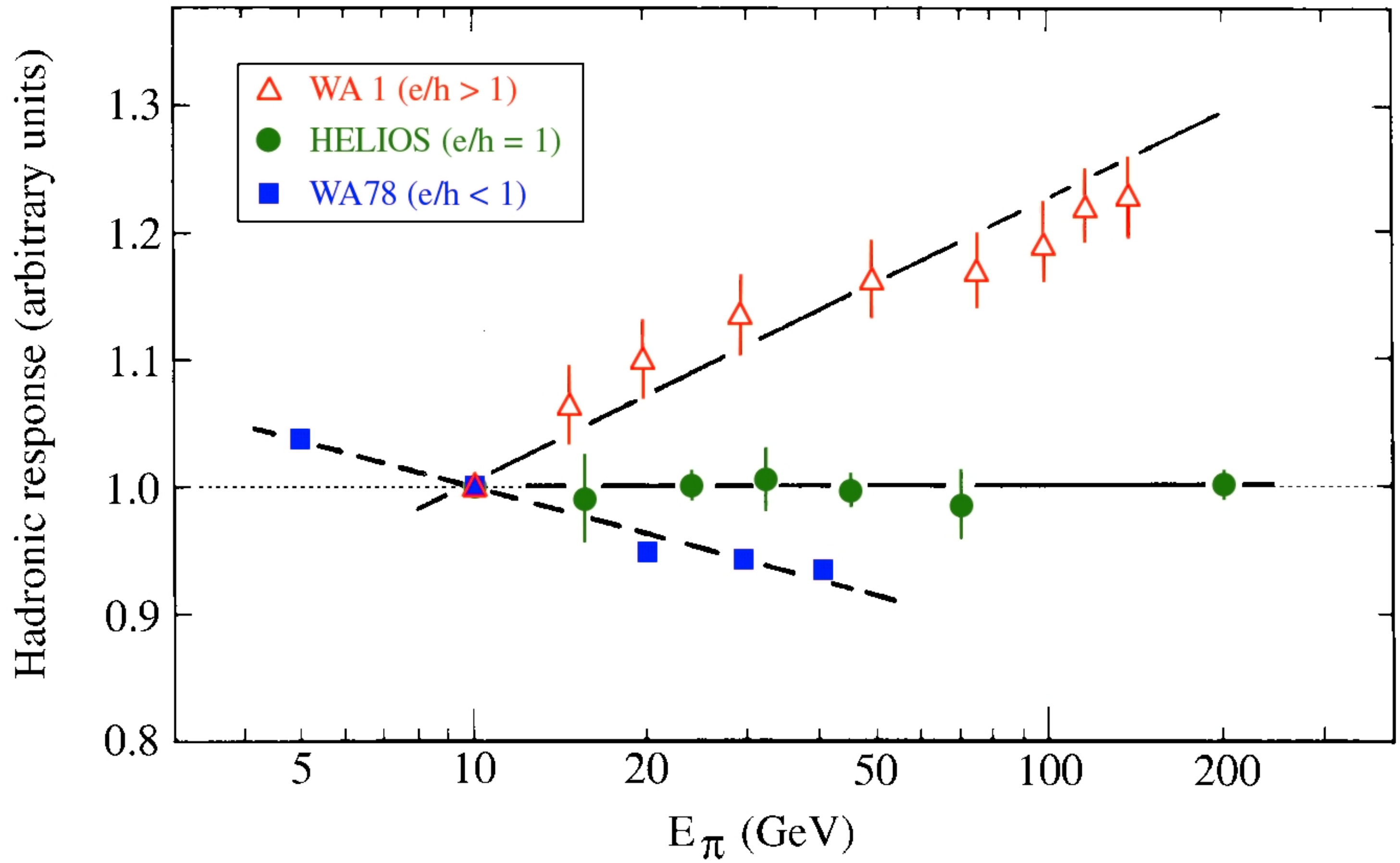
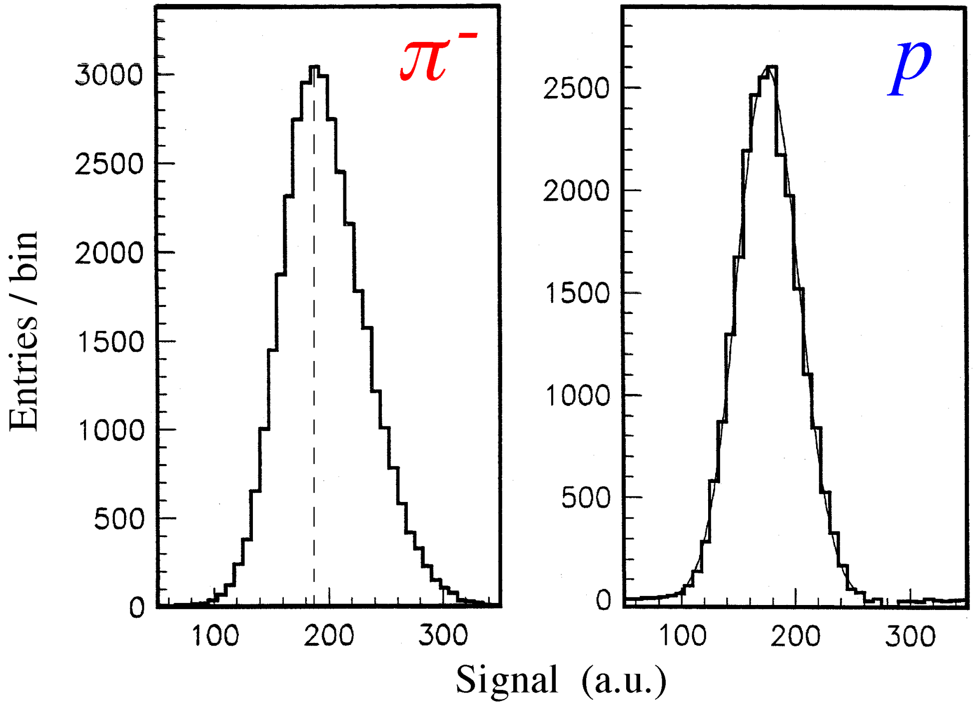
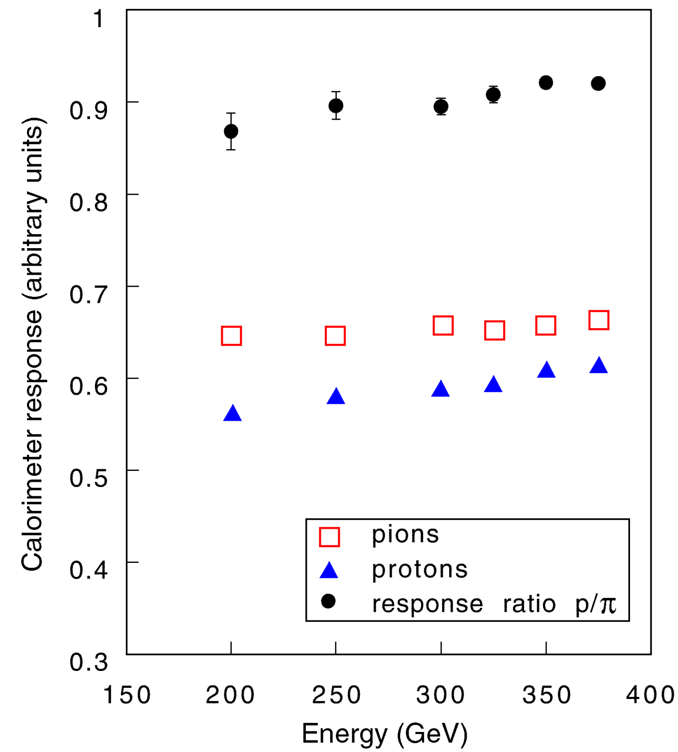


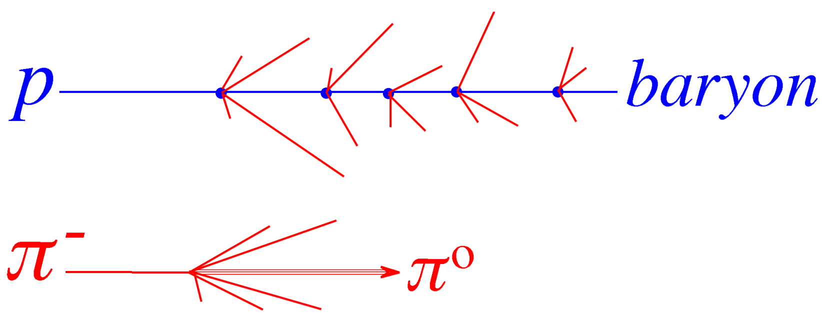
FIG. 3.14. The response to pions as a function of energy for three calorimeters with different e/h values: the WA1 calorimeter ($e/h > 1$, [Abr 81]), the HELIOS calorimeter ($e/h \approx 1$, [Ake 87]) and the WA78 calorimeter ($e/h < 1$, [Dev 86, Cat 87]). All data are normalized to the results for 10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

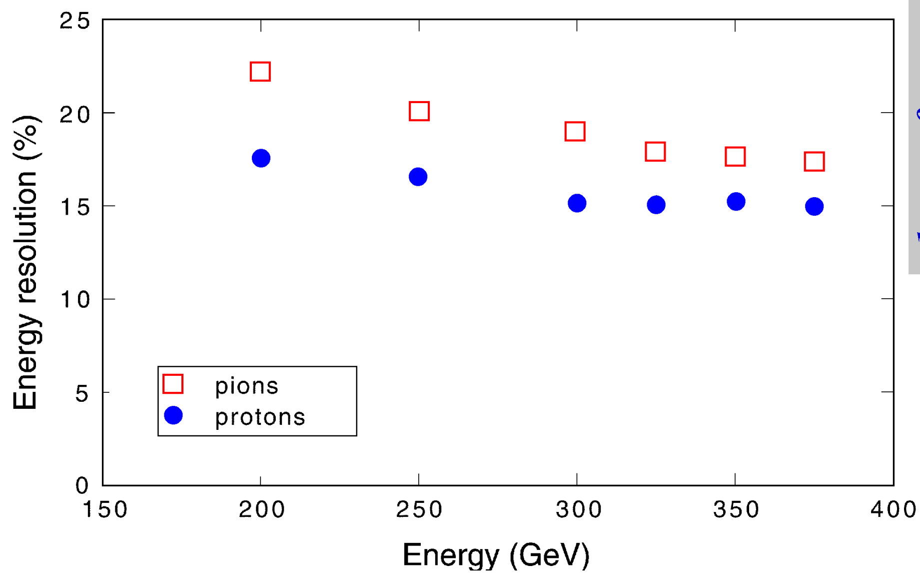
Proton / pion differences in calorimeter signals

caused by differences in em shower fraction characteristics









data from NIM A408 (1998) 380

em fraction in p showers:

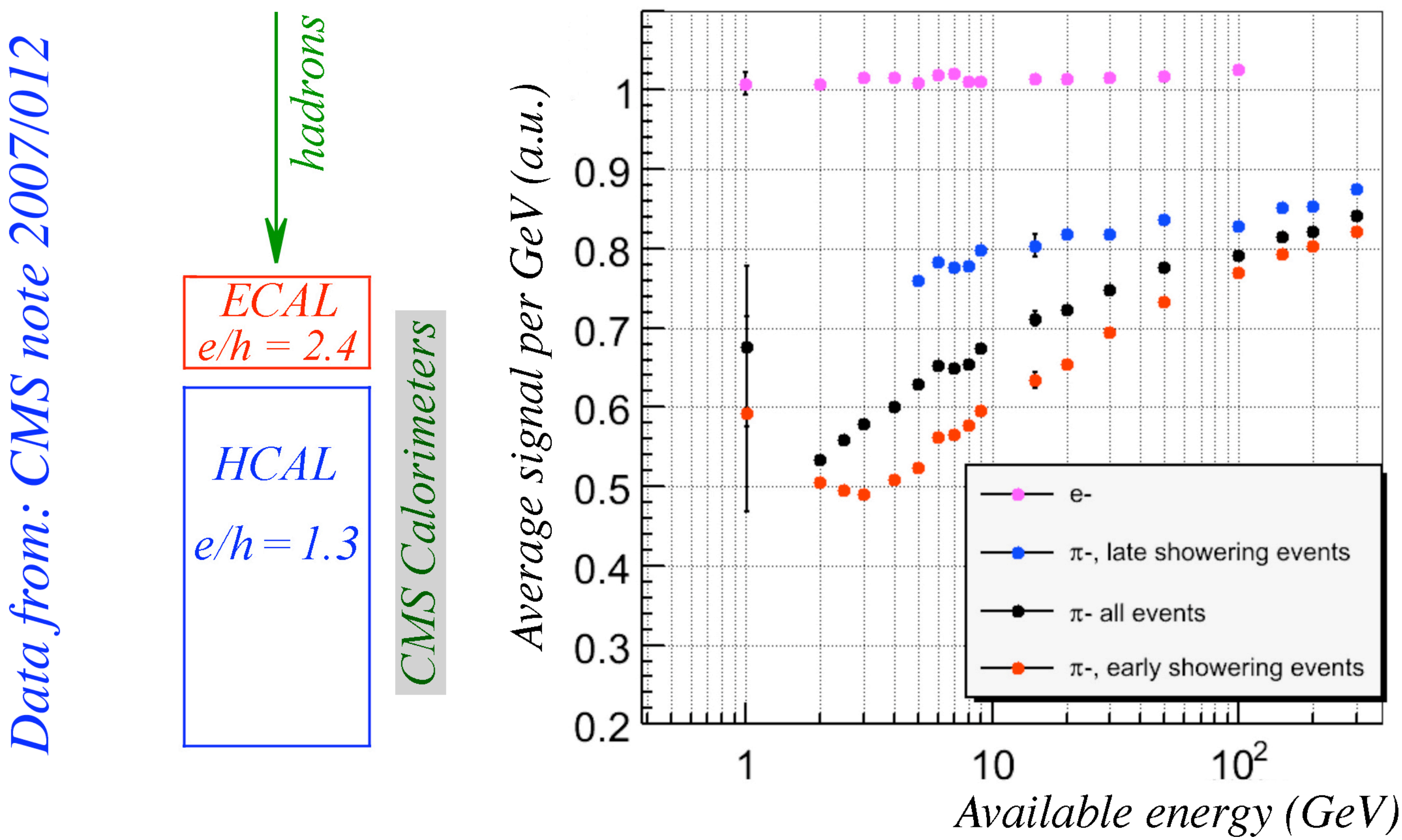
- *smaller*
- *less fluctuations*
- *more symmetric*
- *less concentrated near axis*

Consequences for LHC calorimeters

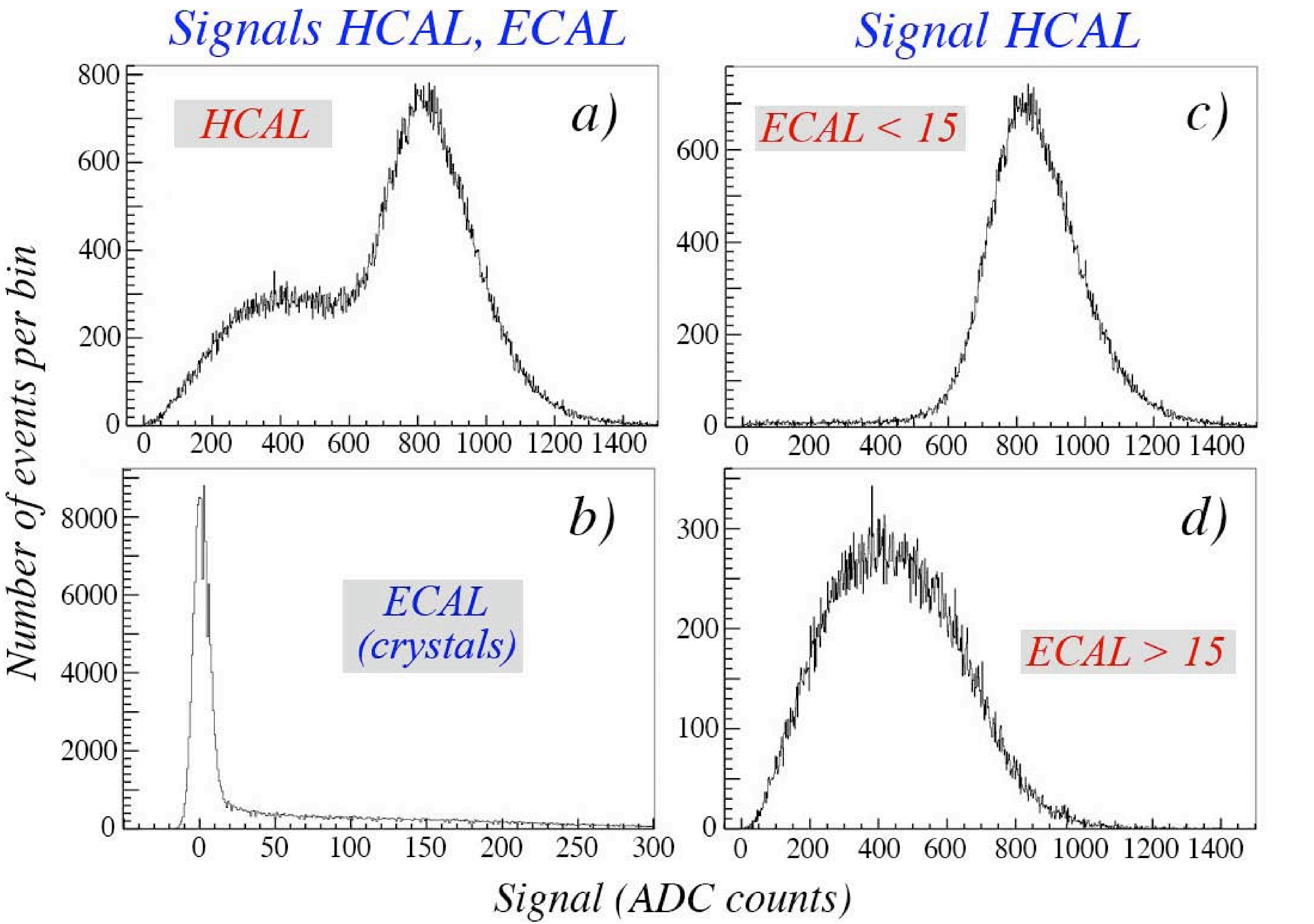
Hadronic response and signal linearity (CMS)

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

→ *Response depends strongly on starting point shower*



Pion signals in crystal ECAL + scintillator HCAL



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- *The only effect of non-compensation is a constant term in the energy resolution*
- *ALL CALORIMETER PROBLEMS CAN BE SOLVED OFFLINE*

End of lecture 1