Calorimetry in the 21st century

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Outline

Day 1

- *Calorimetry in the 20th century (a brief history)*
- *The basics of calorimetry*
- *Electromagnetic calorimetry*
- *The fundamental problems of hadron calorimetry*
- *Methods to improve hadron calorimeter performance*

Outline

Day 2

- *Experience with operating calorimeters*
  - Calibration and non-linearity
  - Catastrophic effects caused by a single shower particle
  - Signals from external sources
- *Misconceptions and their consequences*
- *Particle Flow Analysis*
- *Energy resolution*
- *Options for future experiments*
- *Conclusions*

Want to know more?

- *New developments in calorimetric particle detection*
  arXiv:1807.03853 (preprint J. Progr. Part. Nucl. Phys. 2018)

- *Calorimetry - energy measurement in particle physics*
  Monographs on Physics, vol. 168, Oxford University Press (2017)

- *Dual-readout calorimetry*
  Rev. Mod. Phys. 90 (2018) 025002

A brief history

of design philosophy in particle physics experiments

- $\lesssim$1970: Bubble Chamber Era : *Target* $\equiv$ *detector*

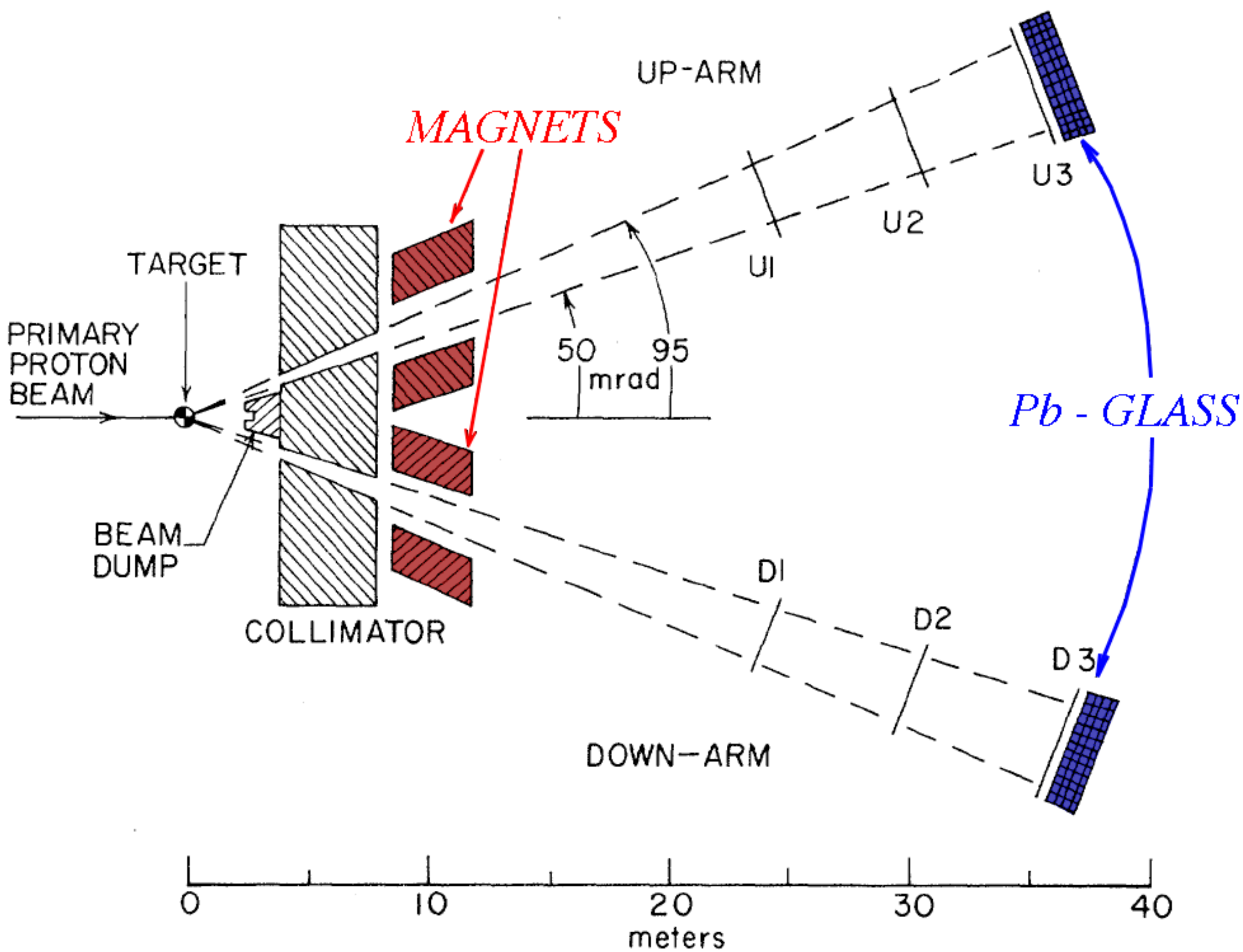
- 1965 - 1985: "Electronic Bubble Chambers" *(fixed-target exp.)*

  Momenta of charged particles: Tracking in magnetic field
  Particle ID: TOF, dE/dx, Č counters
  Muon ID: Absorber
  Photons: "Shower counters"

1970s - Shower counters in magnetic spectrometers

Example: E70 / 288 @ Fermilab

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



A brief history

of design philosophy in particle physics experiments

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- 1965 - 1985: "Electronic Bubble Chambers" *(fixed-target exp.)*

  Momenta of charged particles: Tracking in magnetic field
  Particle ID: TOF, dE/dx, Č counters
  Muon ID: Absorber
  Photons: "Shower counters"

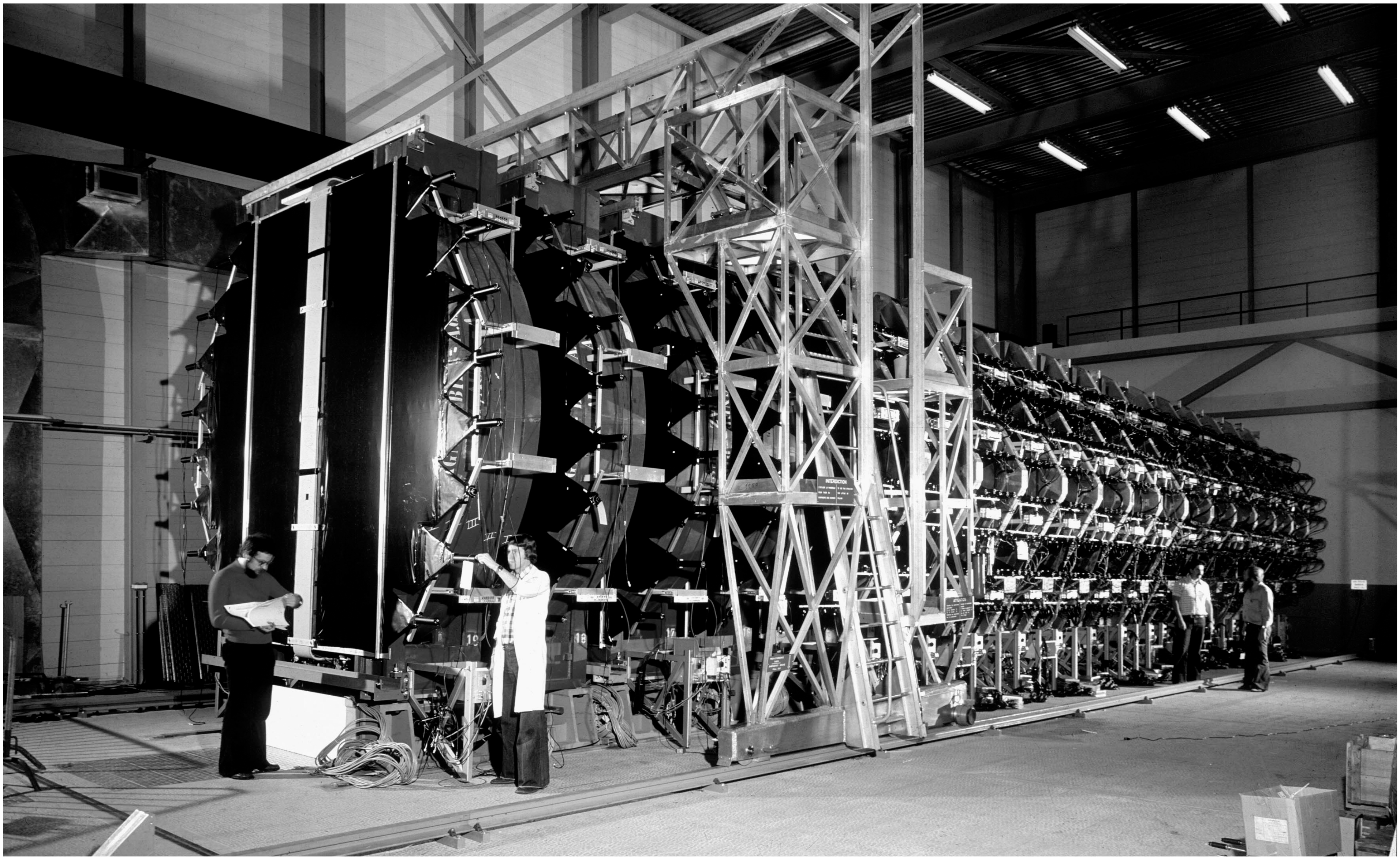
- 1980 - now: Calorimeter system cornerstone *(collider exp.)*

  Strong emphasis on electromagnetic calorimetry (exception: HERA)
  Magnetic field optional (UA2, D0)

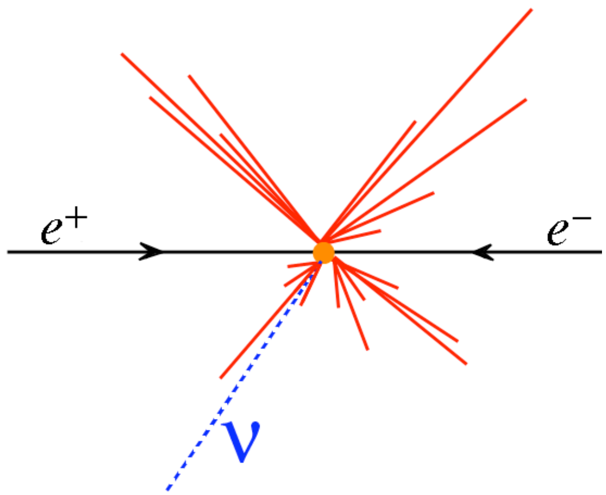
1975 - Calorimeters take on new tasks

(target, trigger counter, tracking, particle ID)

WA1



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* ($\sim E^{-1/2}$ if statistical processes are the limiting factor)

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

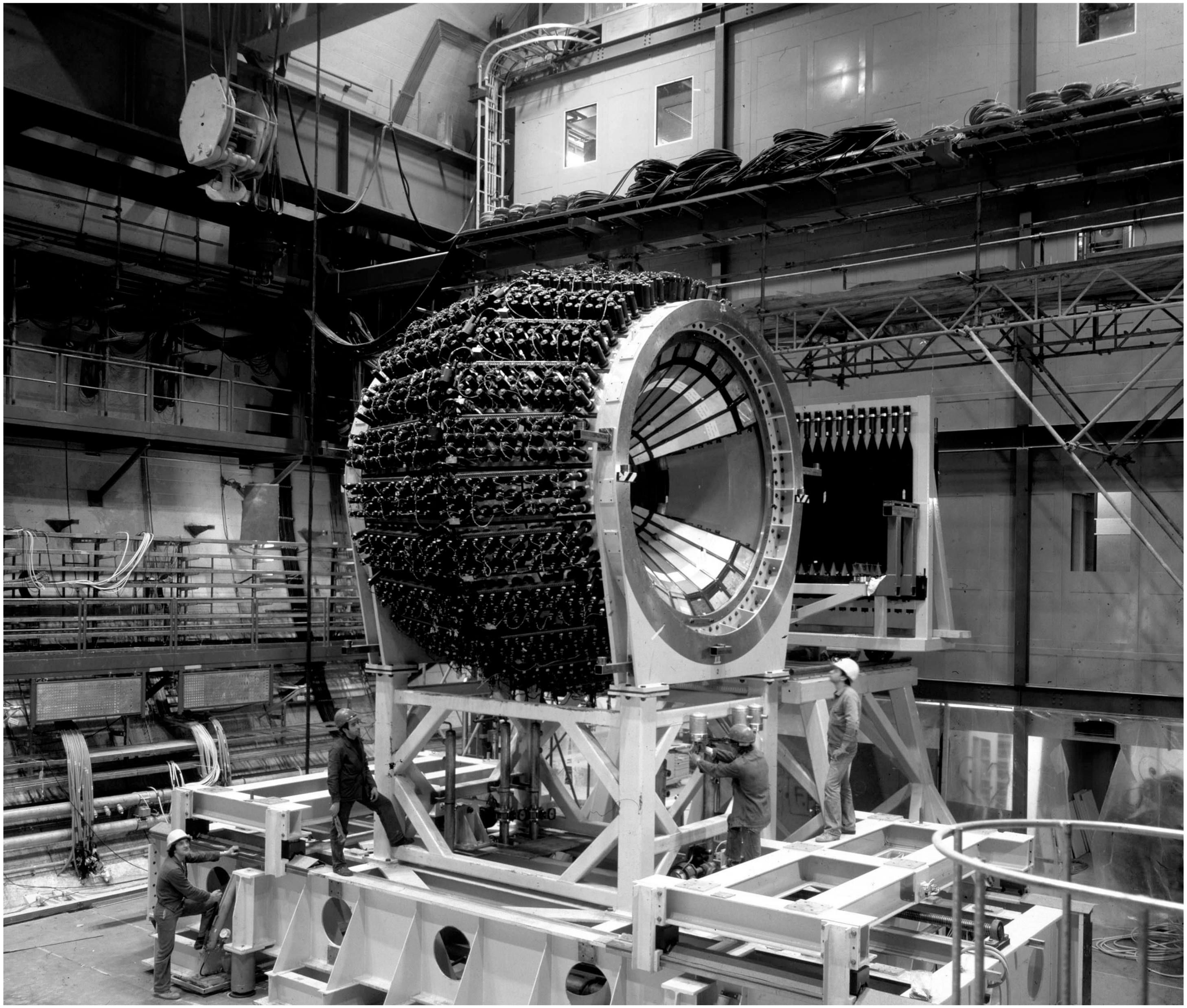
→ energy resolution $\frac{\sigma(E)}{E} \propto 1/\sqrt{n} \propto 1/\sqrt{E}$

1980 - Calorimeters become crucial component of 4π experiments

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

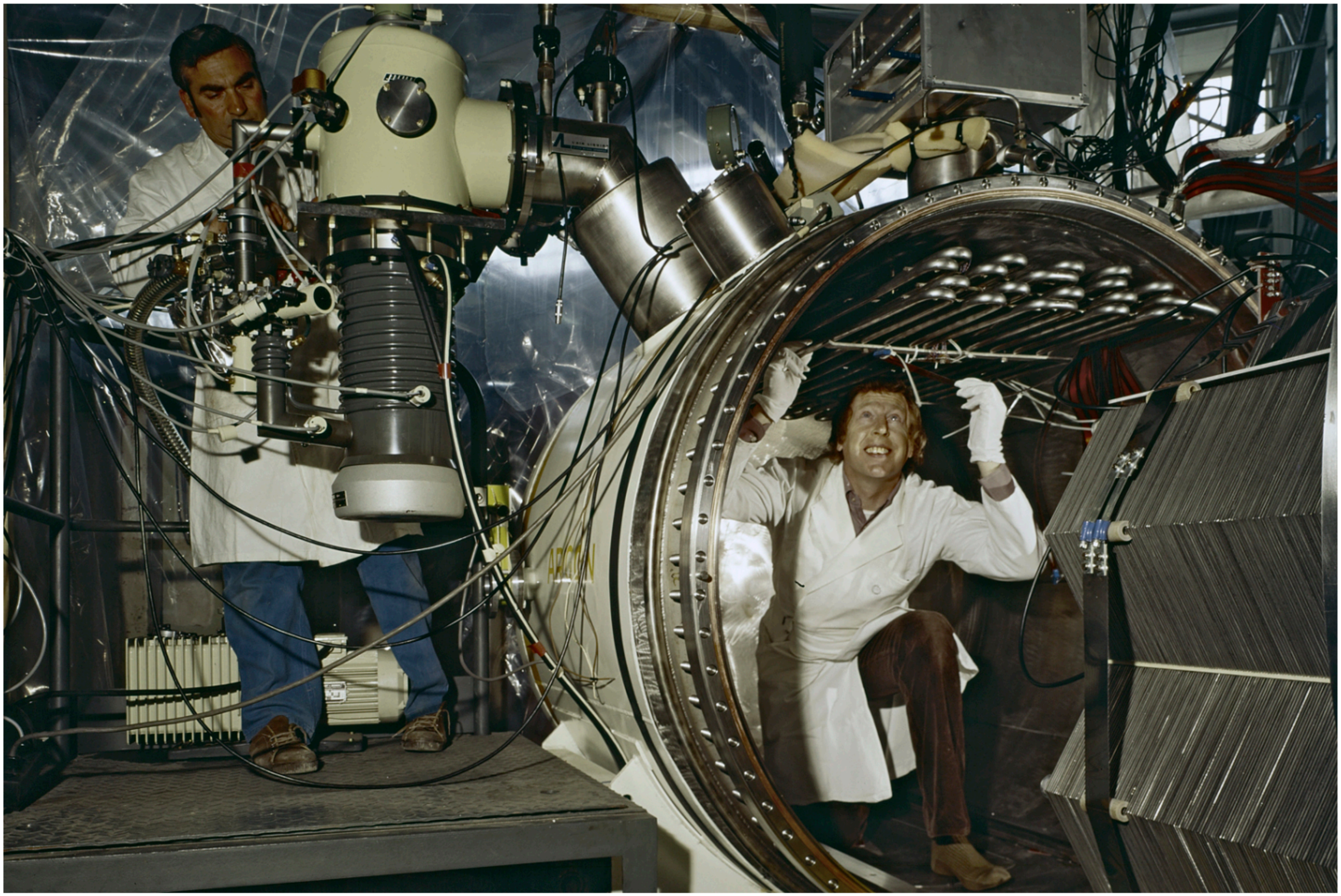
Led to discovery of $W \rightarrow e\nu$, $W \rightarrow \mu\nu$

UA2 (CERN)



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

Direct collection of ionization charge
in a dense sampling medium

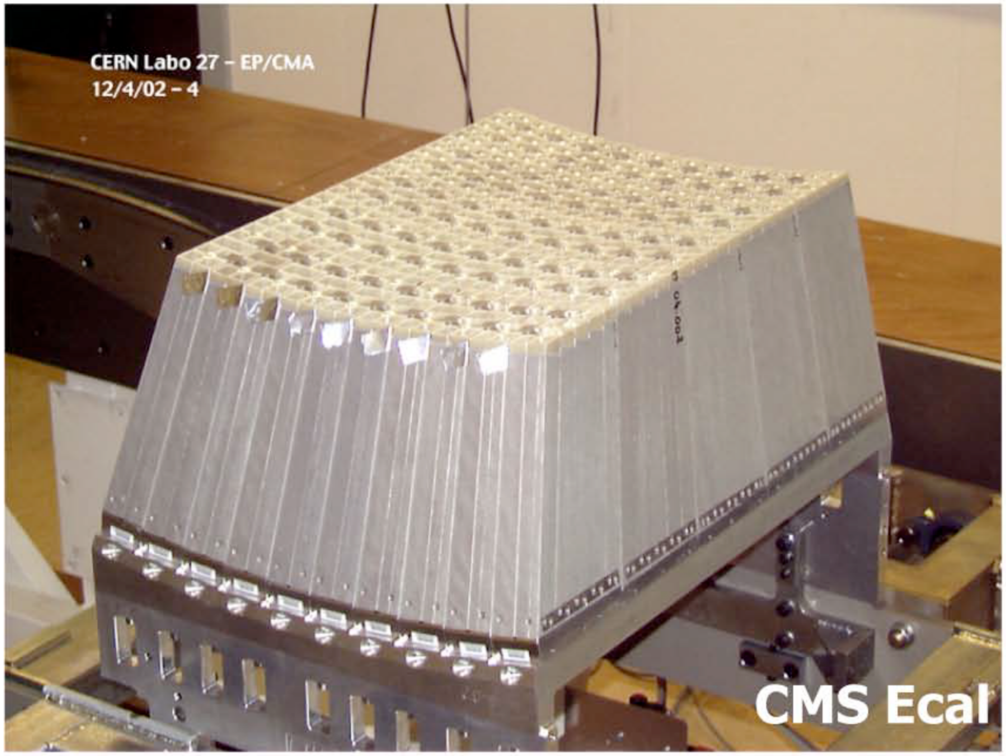


Types of calorimeters

Homogeneous calorimeters

Absorber material = detector material

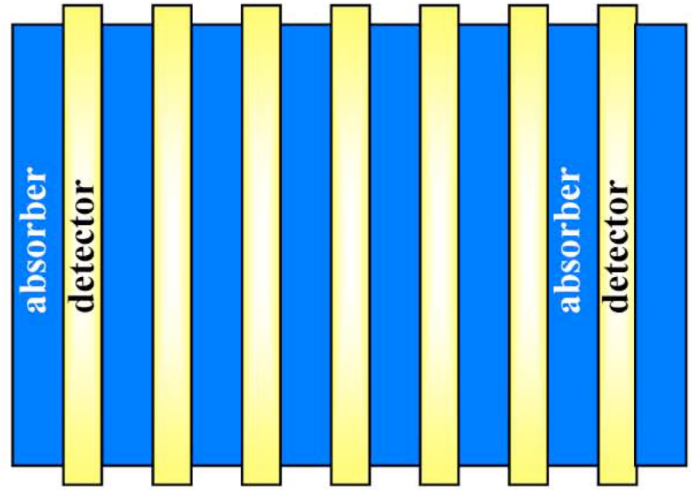
- *High-density crystals used as electromagnetic calorimeters*
  Example: CMS ECAL, $PbWO_4$. Density 8.3 g/cm^3, radiation length 8.9 mm.

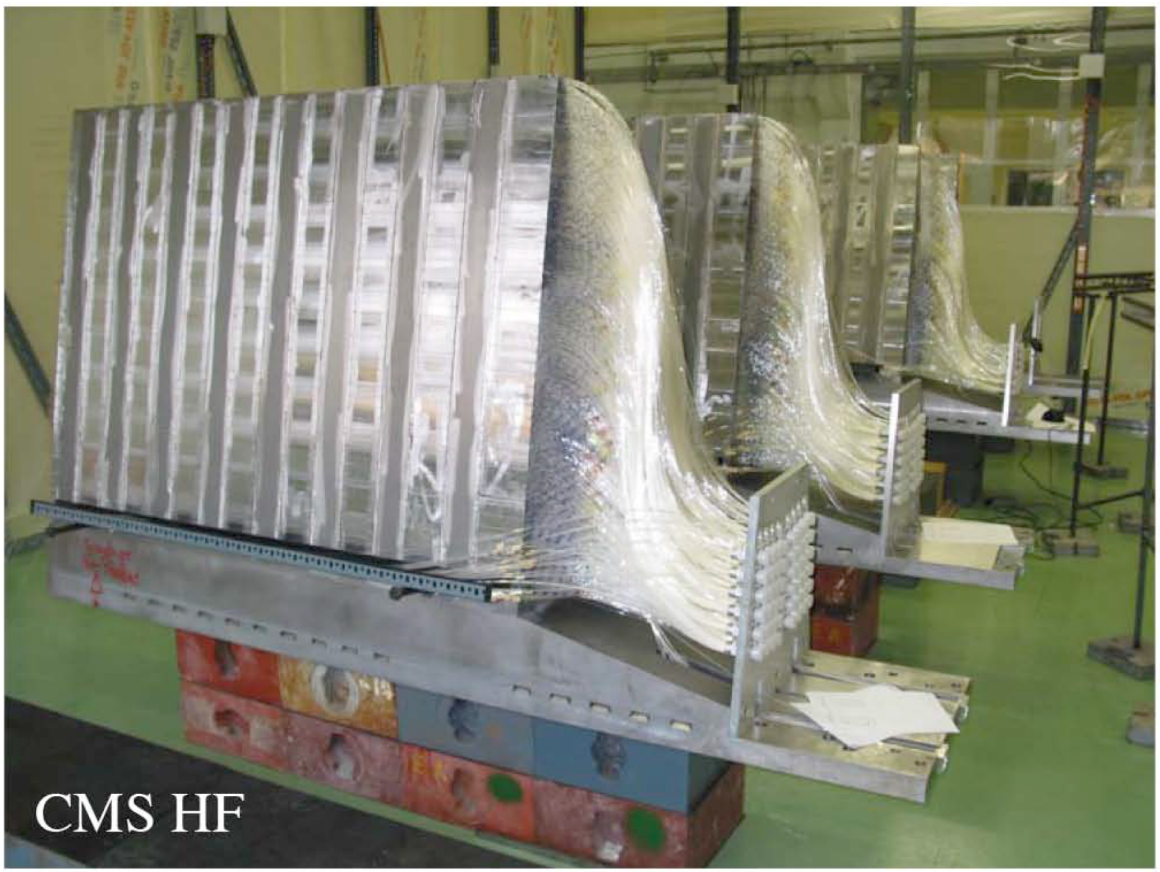


- *Very good energy resolution*
- *Very expensive*
- *Radiation damage a problem*
- *Other crystals:*
  NaI(Tl), CsI, BGO, BaF_2

Sampling calorimeters

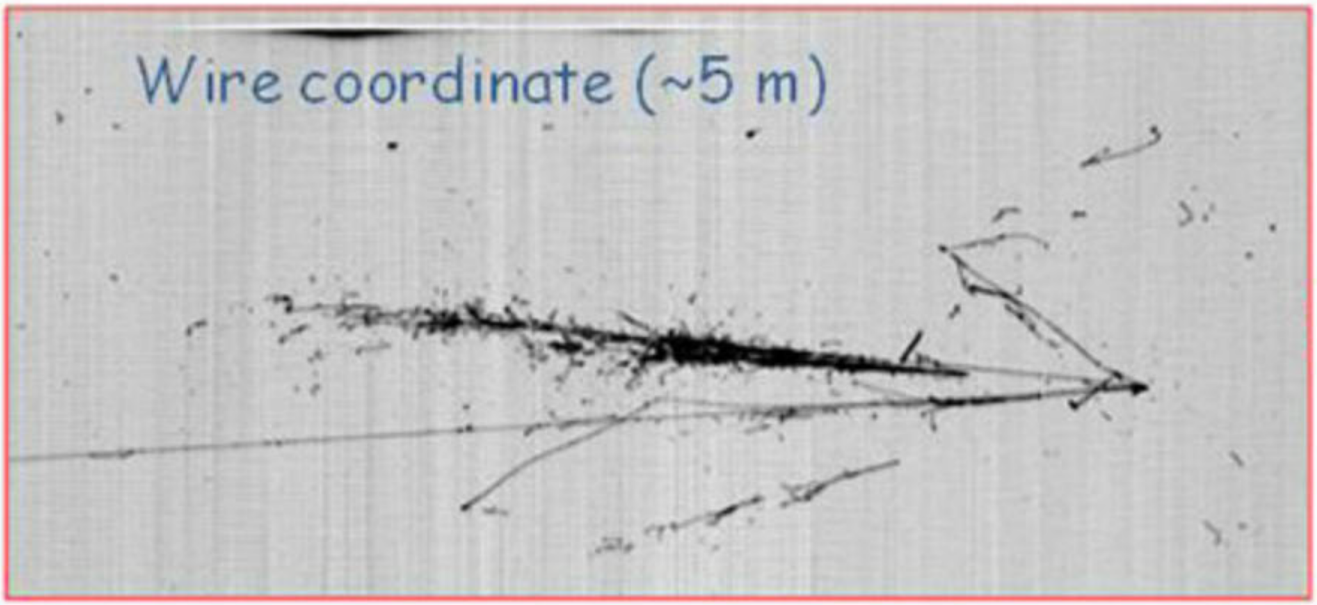
- *Different absorber and detector materials*
- *Absorber media: Fe, Cu, Pb, U, W*
- *Active media: Scintillator, LAr, gas…*





Imaging calorimeters

Pioneered by ICARUS (Gran Sasso Lab)



← *CERN to Gran Sasso ν beam*

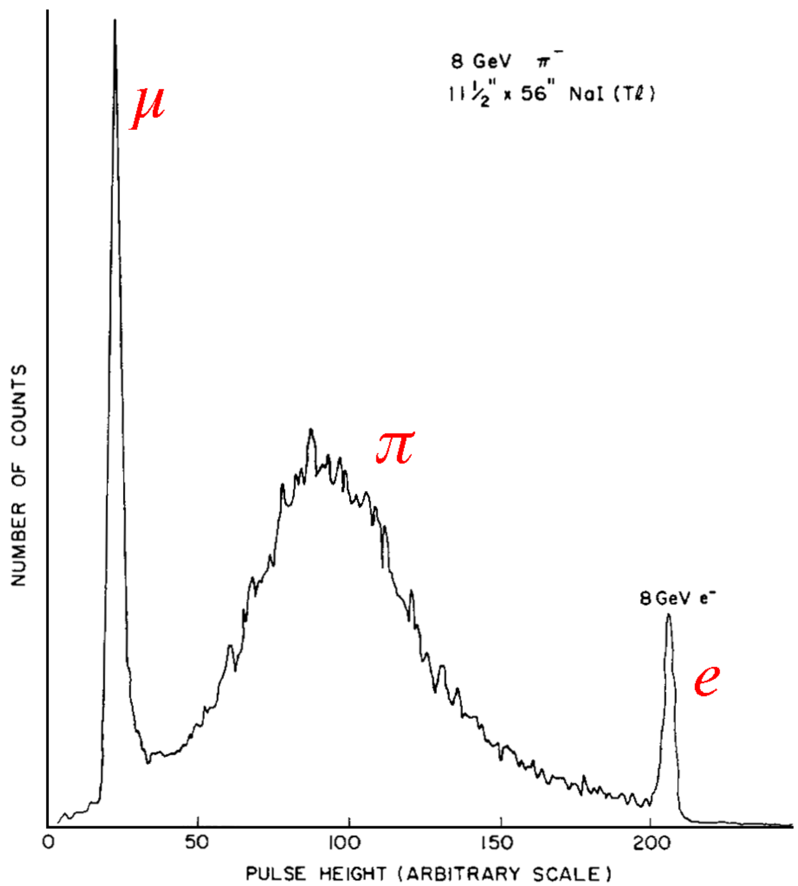
Hadron detection with calorimeters

Early indication that hadron calorimetry is different!

NIM 75 (1969) 130

450 kg of NaI (Tl) crystals

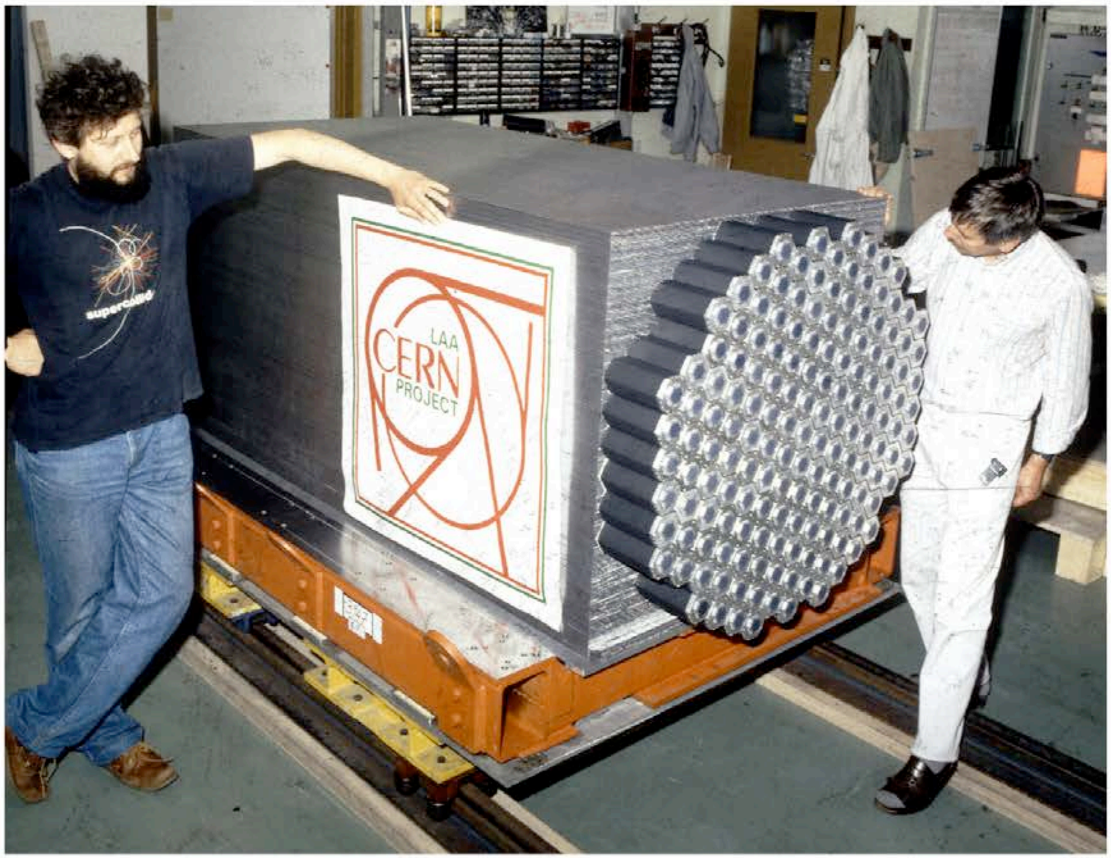
Tested with 8 GeV particle beams

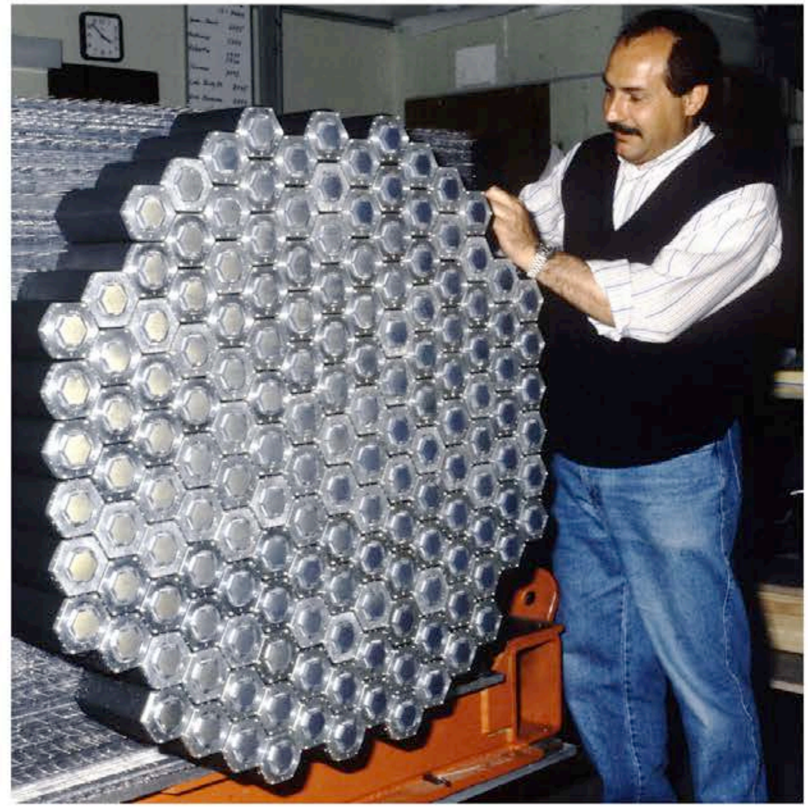


Conclusions of authors:

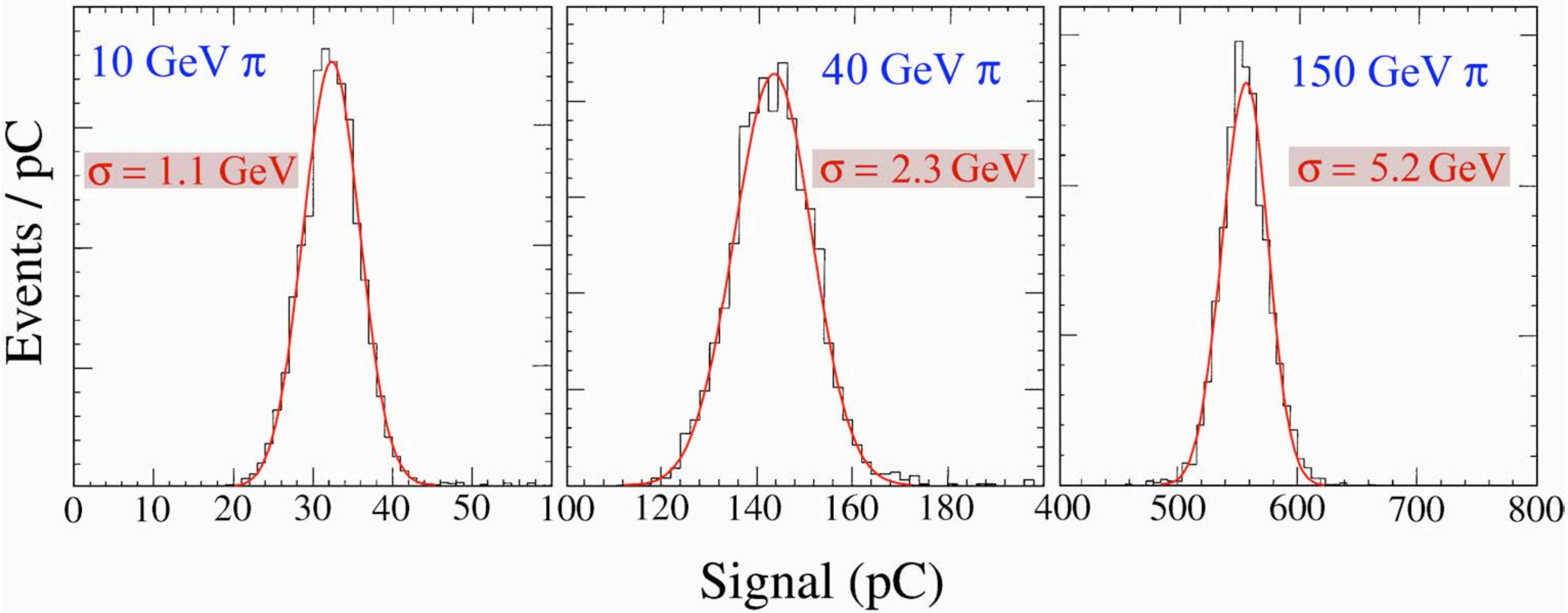
- *50% of energy leaks out*
- *MC: much less leakage*
- *Same results at 4, 12, 16 GeV*
- *Resolution did NOT improve with E*

SPACAL 1989



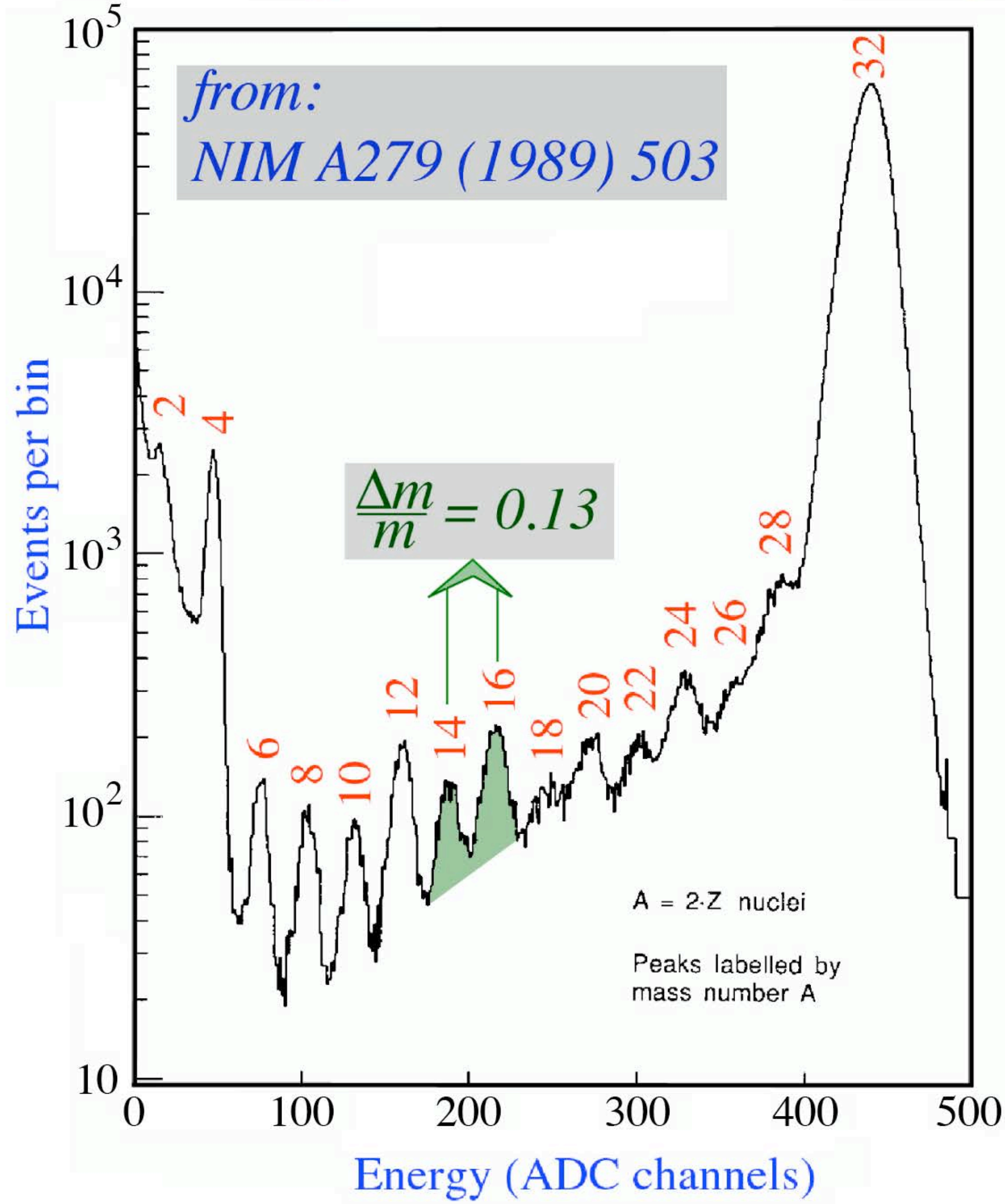


Hadronic signal distributions in a compensating calorimeter



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

The basics of calorimetry

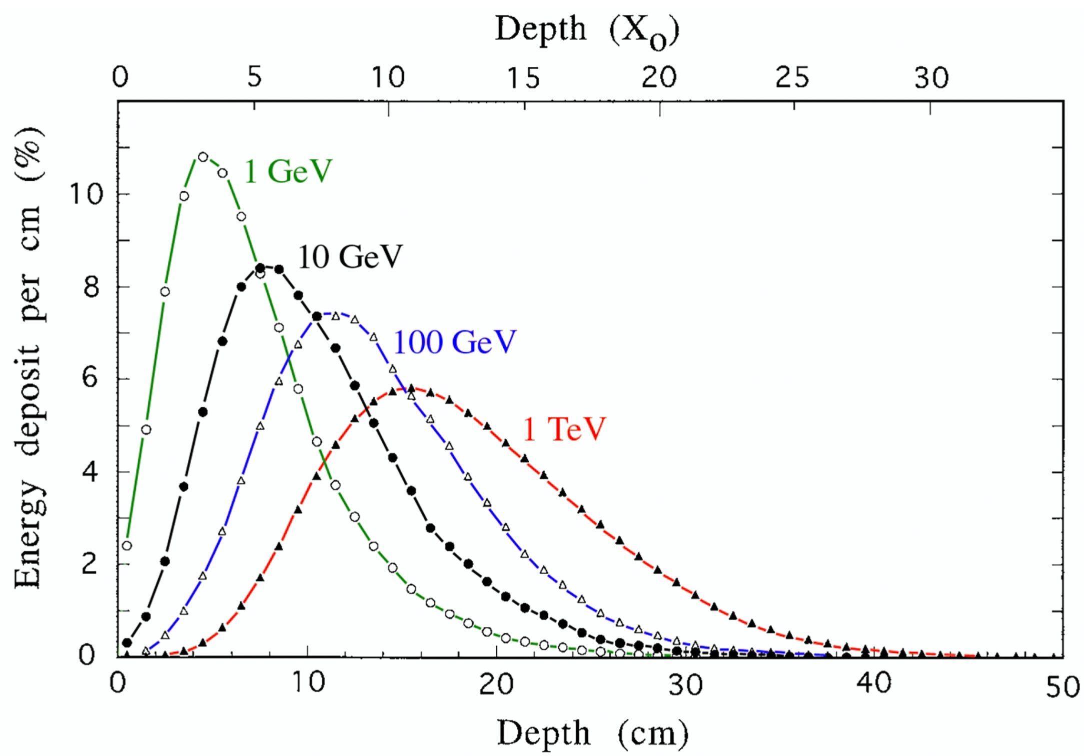
with emphasis on features important for sampling calorimetry

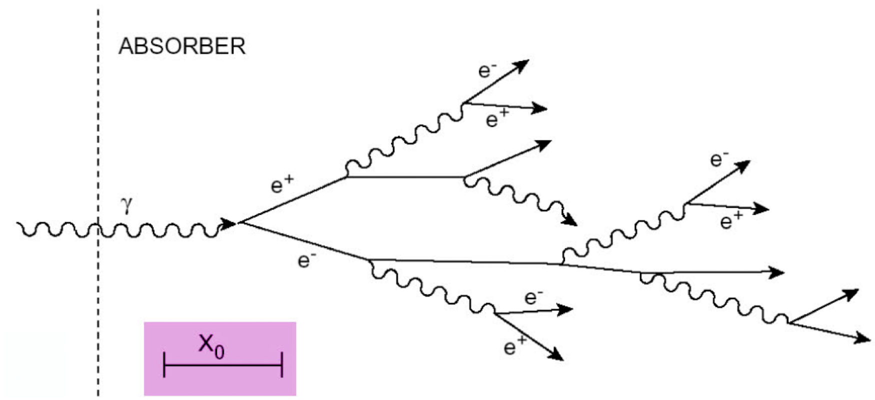
Shower development

Absorption of high-energy particle takes place in large number of steps

Eventually, low-energy shower particles deposit their kinetic energy by ionizing or exciting the atoms of the absorber material

Electromagnetic showers:
Initially $\gamma \to e^+e^-$, $e \to \gamma$ *(particle multiplication)*
After shower maximum: $\gamma \to e^-$, *electrons range out*

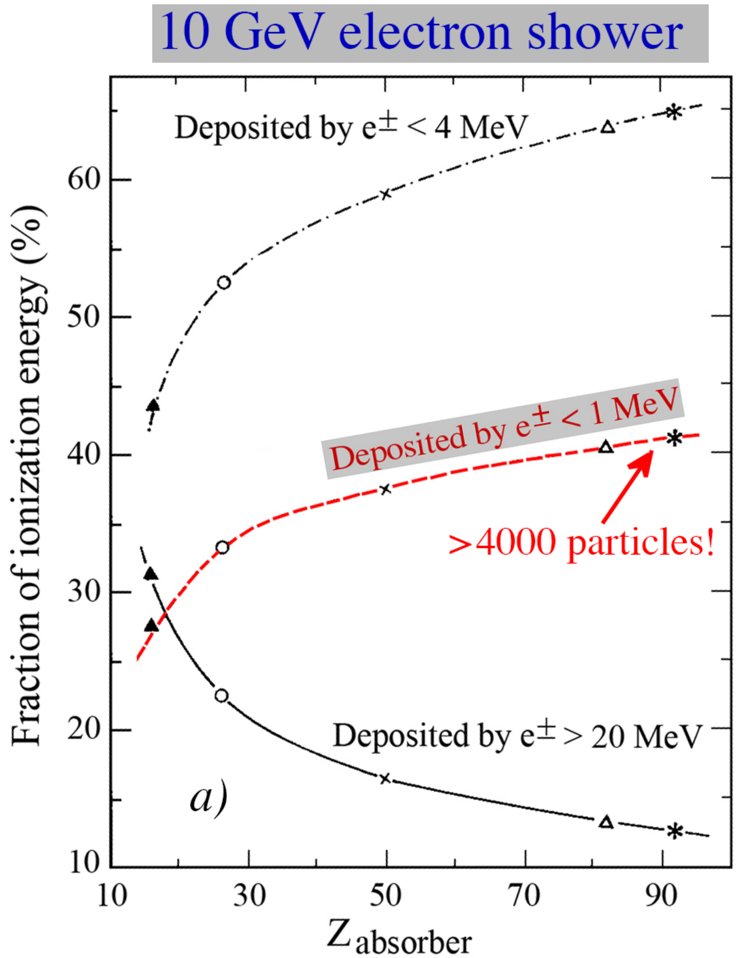


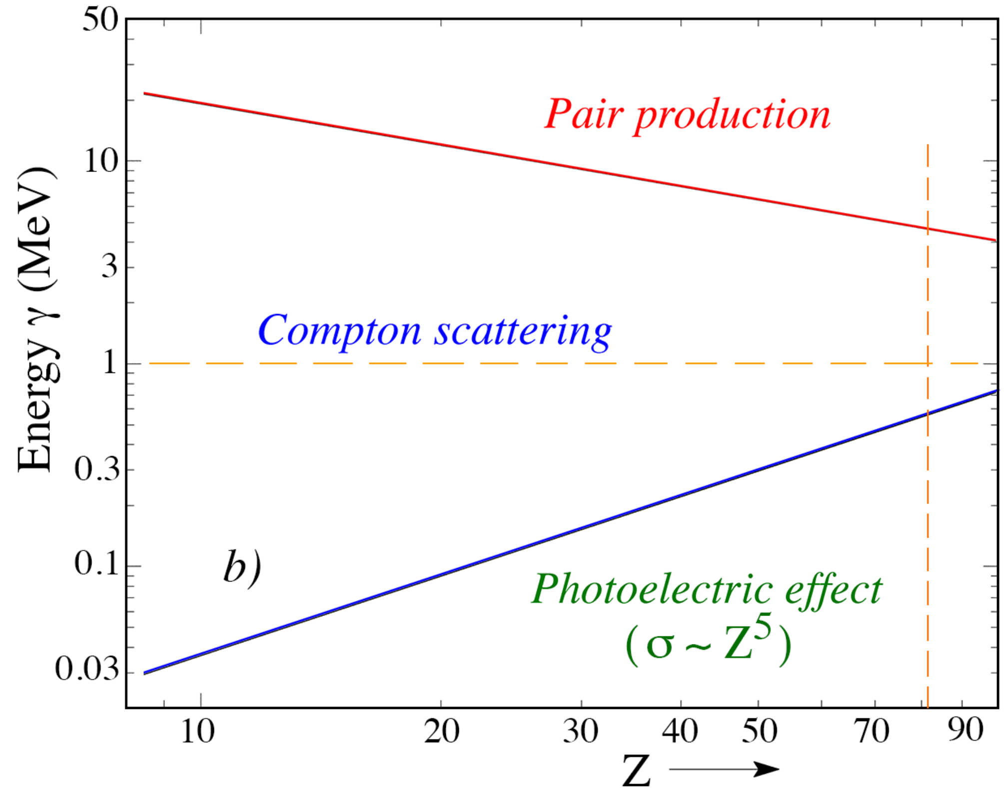


The shower development is governed by the "radiation length" X_o*, which is typically ~ 1 cm*

Hadron showers: *Nuclear reactions* → *protons, neutrons very important*

Calorimeter properties determined by last stages of shower development



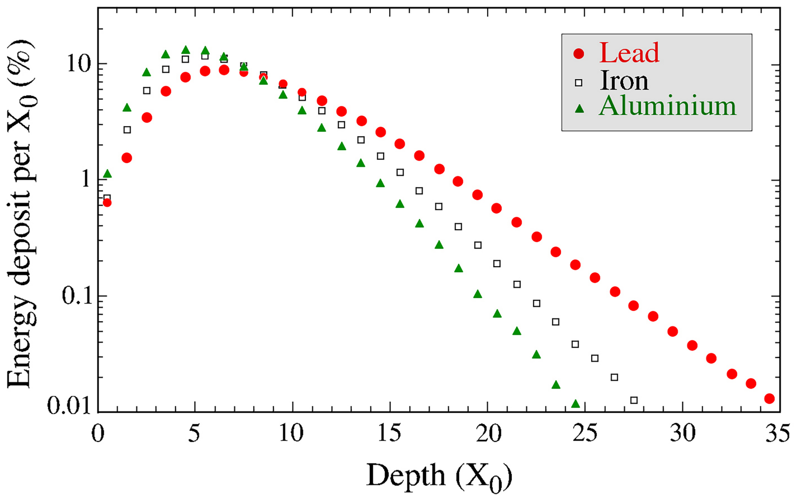


Consequences:

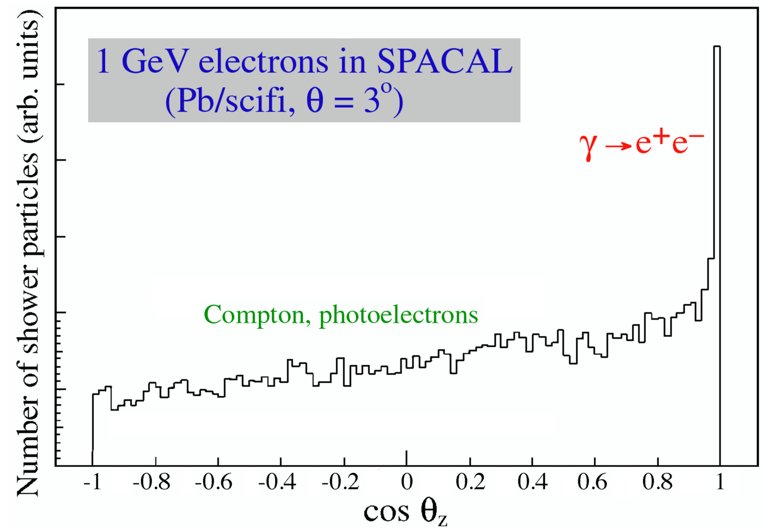
- *Radiation length not a material independent scaling variable*
- *Orientation active layers in sampling calorimeter does not matter*
- *Sampling fraction changes as function of depth (age) of shower*

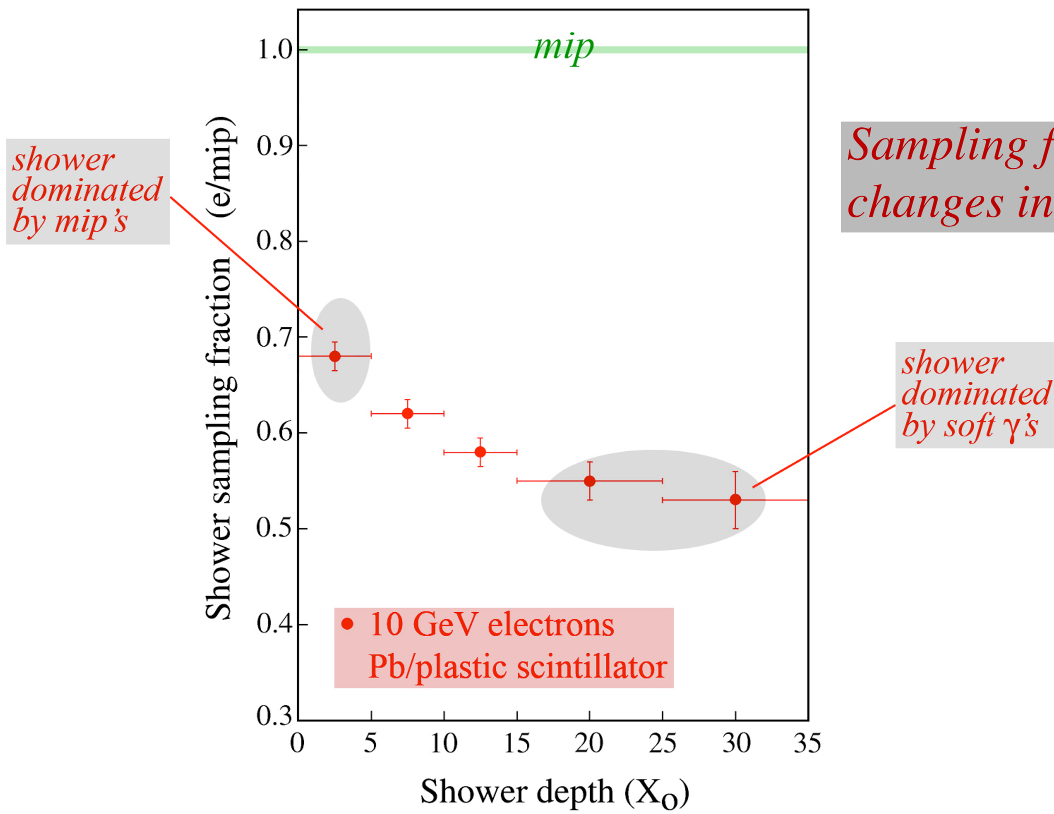
Examples of effects of soft, late-stage shower particles

X_0 not good scaling variable



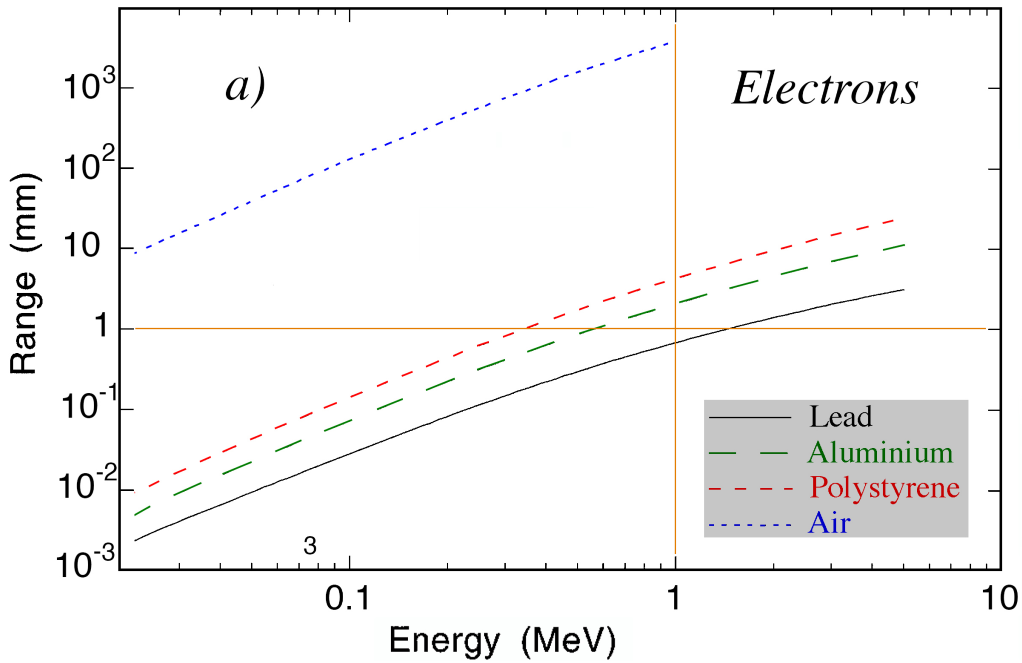
Orientation active layers not important



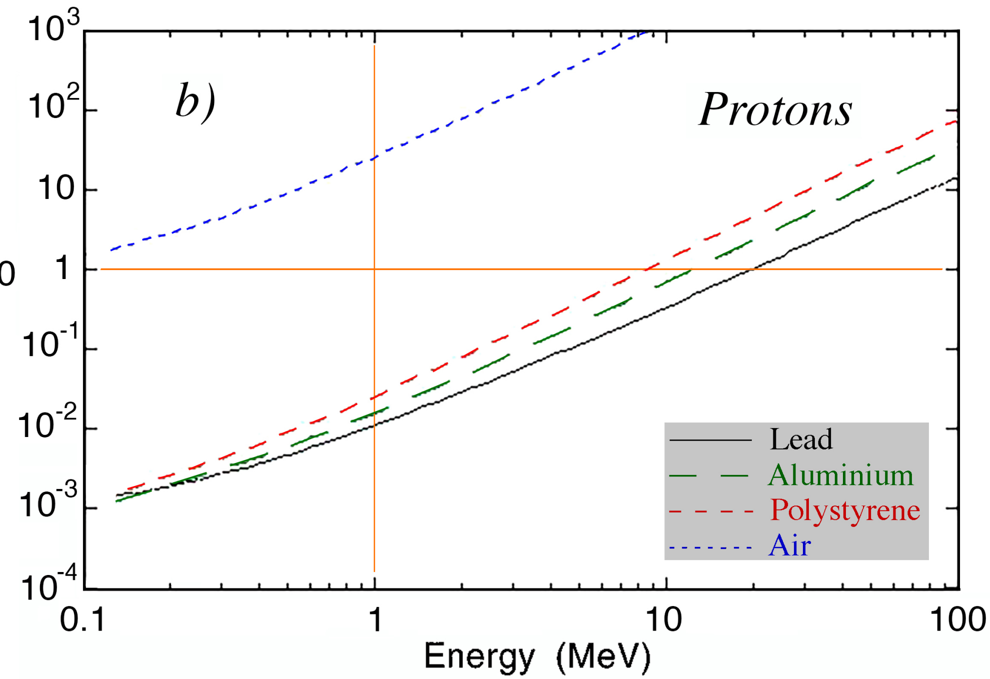


Sampling fraction changes in developing shower

The range of typical shower particles



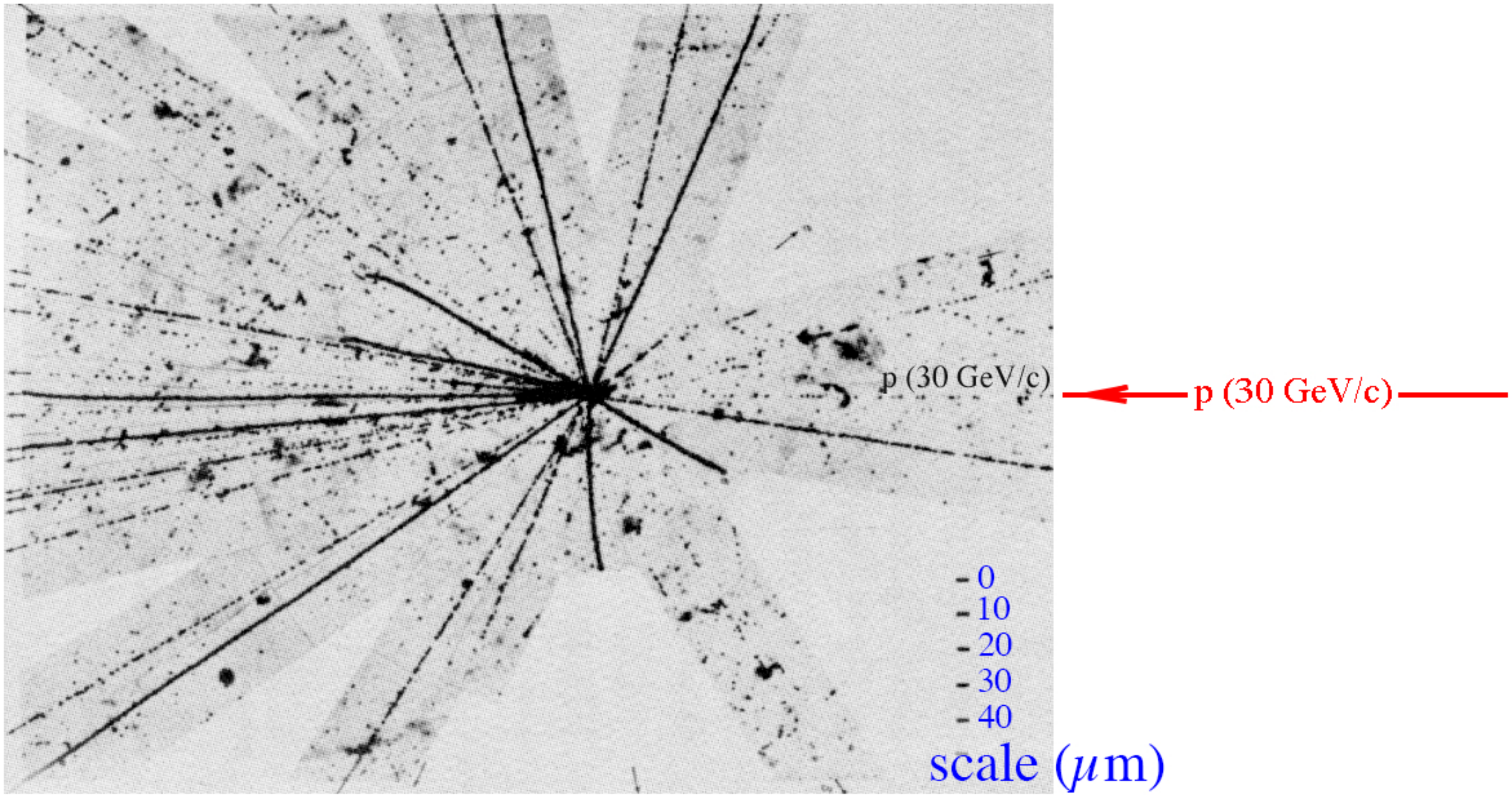
Nuclear binding energy 6-8 MeV/nucleon



Electrons: 40% < 1 MeV

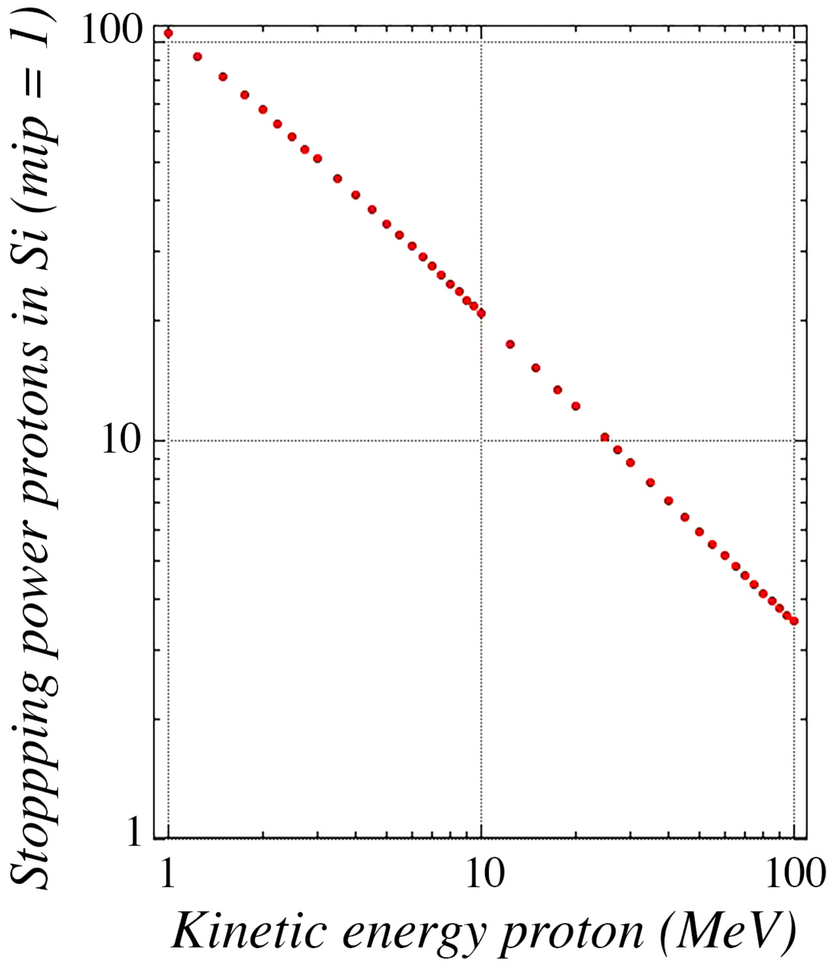
Therefore, a typical shower particle travels a distance that is smaller than the distance between consecutive active layers in a sampling calorimeter and thus contributes only to the signal from ONE layer (or, more often, ZERO)

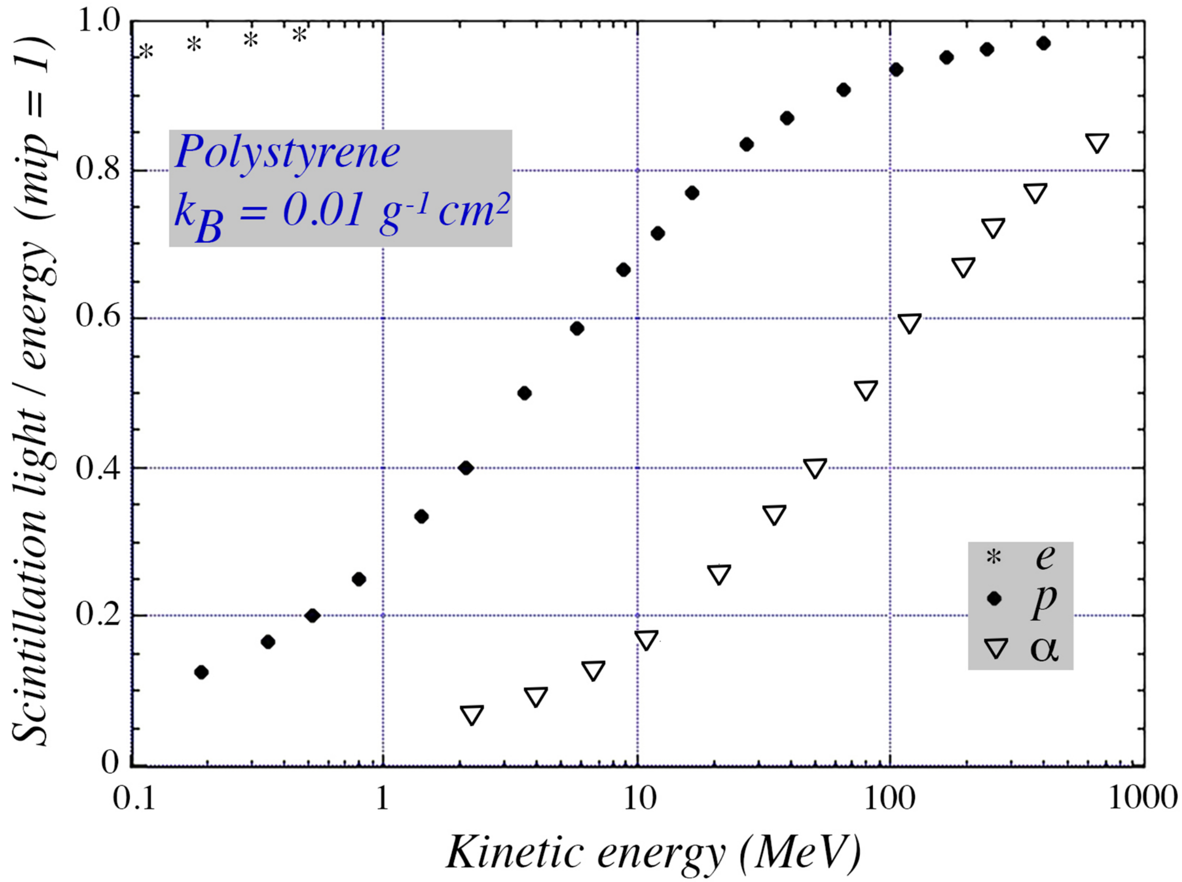
When nuclear reactions get involved



Calorimeter signal quenching

(densely ionizing particles)





Plastic scintillator. liquid argon: Important quenching effects

Gaseous readout, silicon: No quenching effects

Signal saturation and calorimeter performance

Distinguish between:

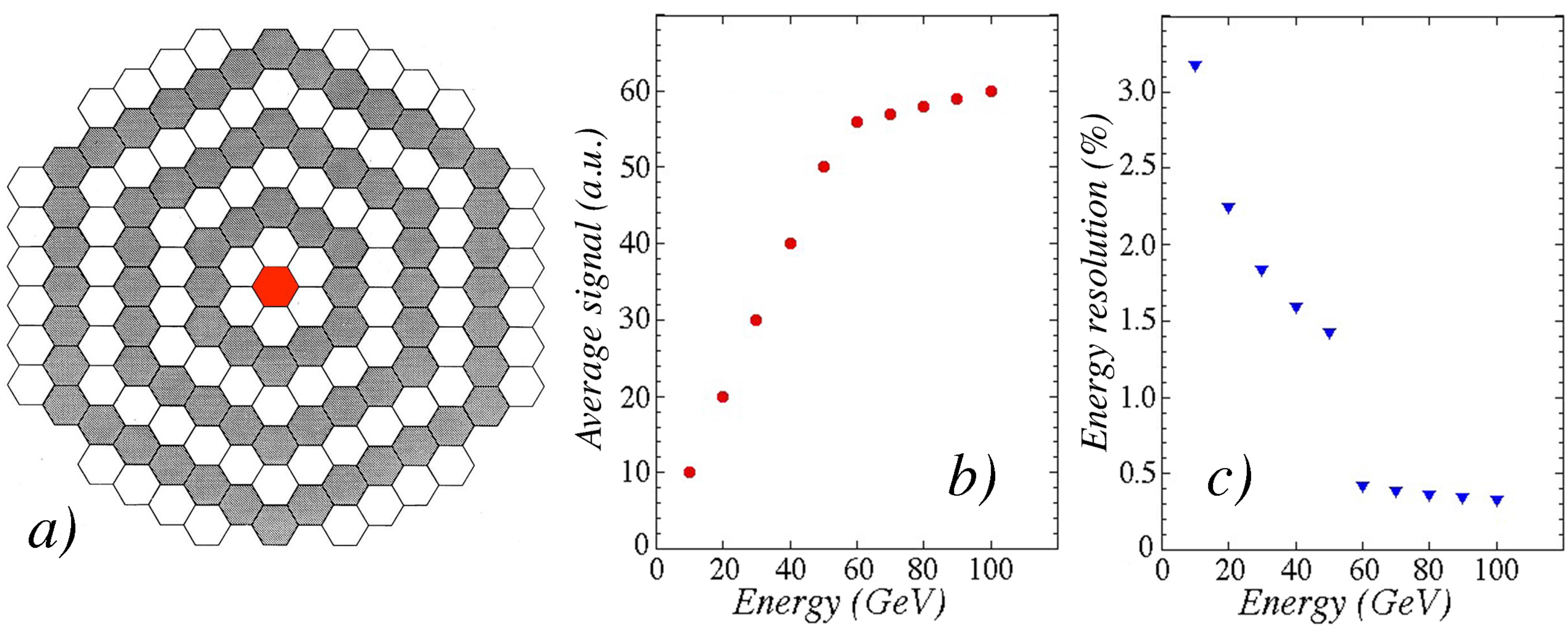
1) Saturation of active calorimeter medium
(signal not proportional to deposited energy)

Typically, this leads to bad, non-recoverable effects (non-linearity, meaningless resolution)
Example: “digital” calorimeters (SiPM, RPC)

2) Saturation of the readout electronics

Effects are similar, but recoverable: Non-linearity, overestimated energy resolution

Example: SPACAL

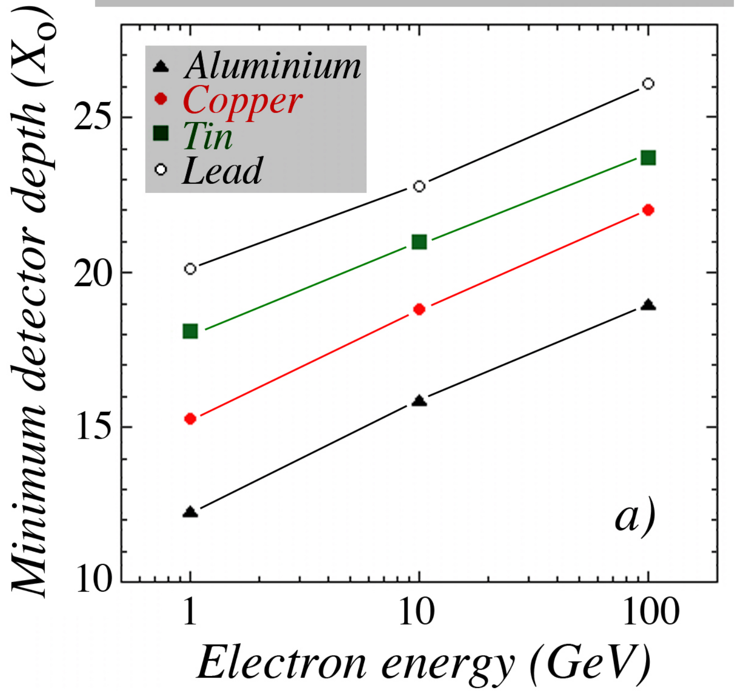


Properties of electromagnetic calorimeters

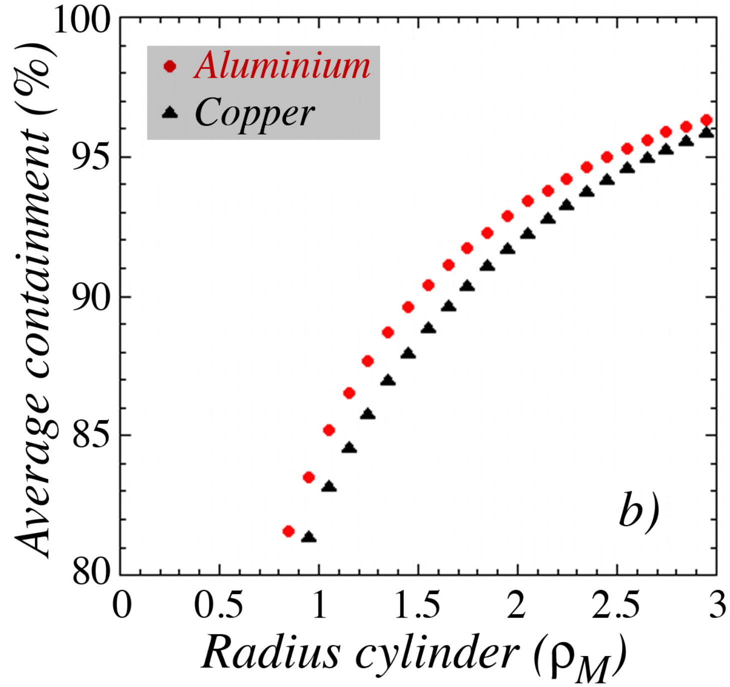
- *How big (effects shower leakage on performance)*
- *Energy resolution*
- *Shower profiles*

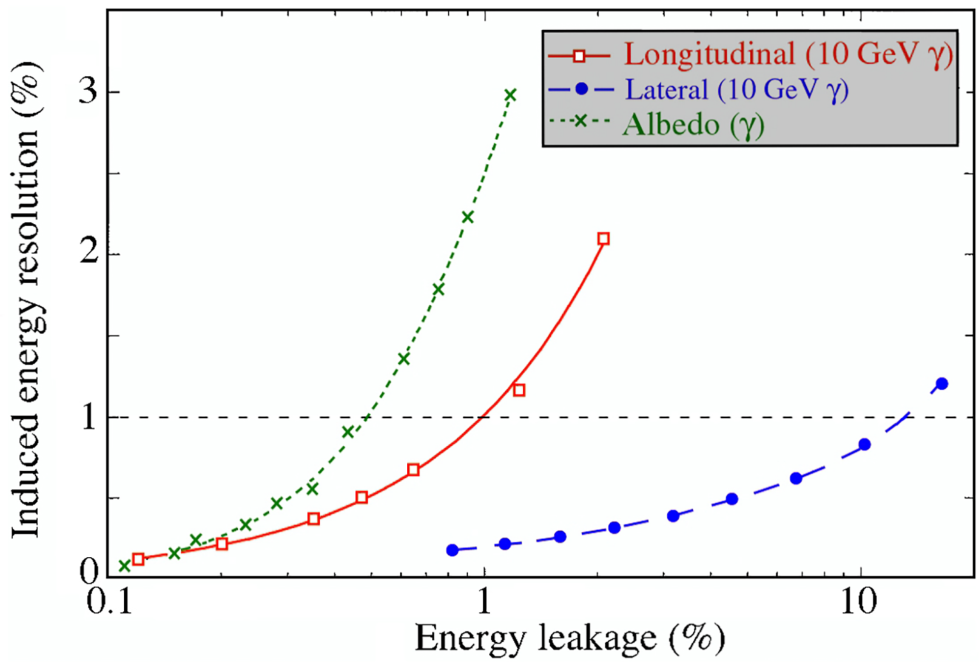
How big should an em calorimeter be?

99% longitudinal containment



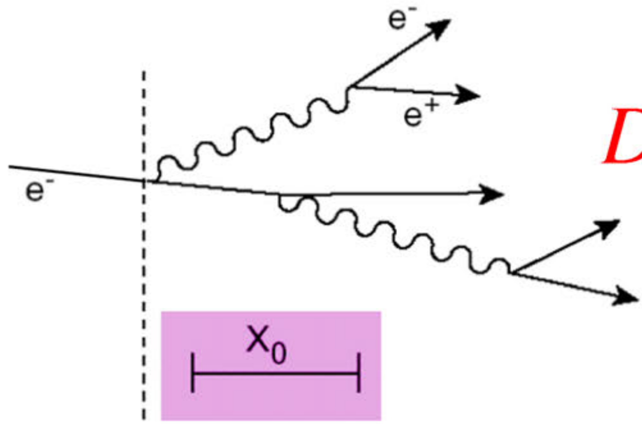
Lateral shower containment

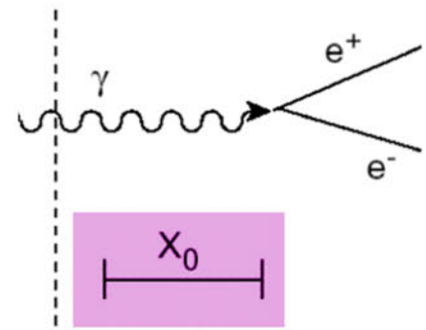


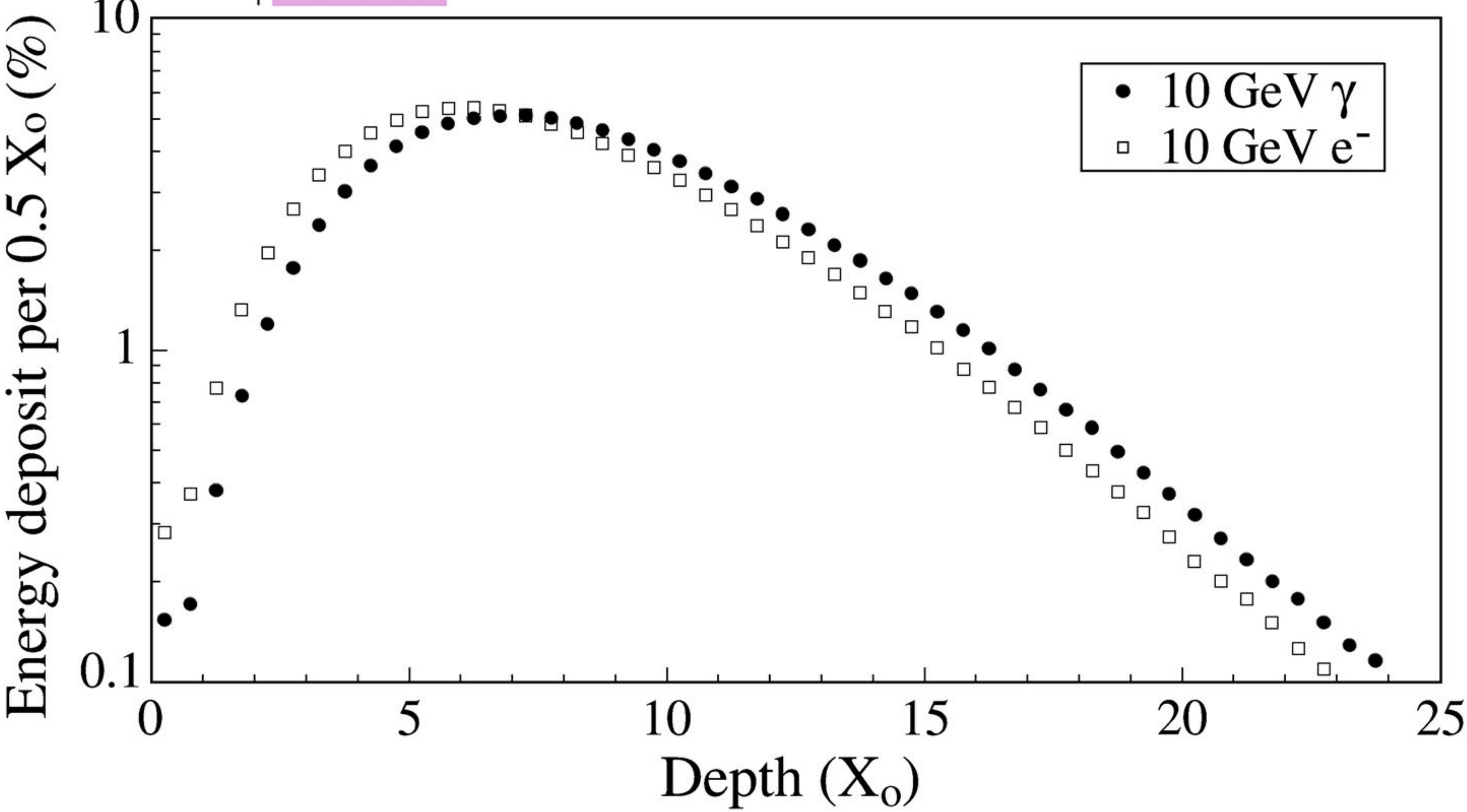


Effect of shower leakage on the em energy resolution

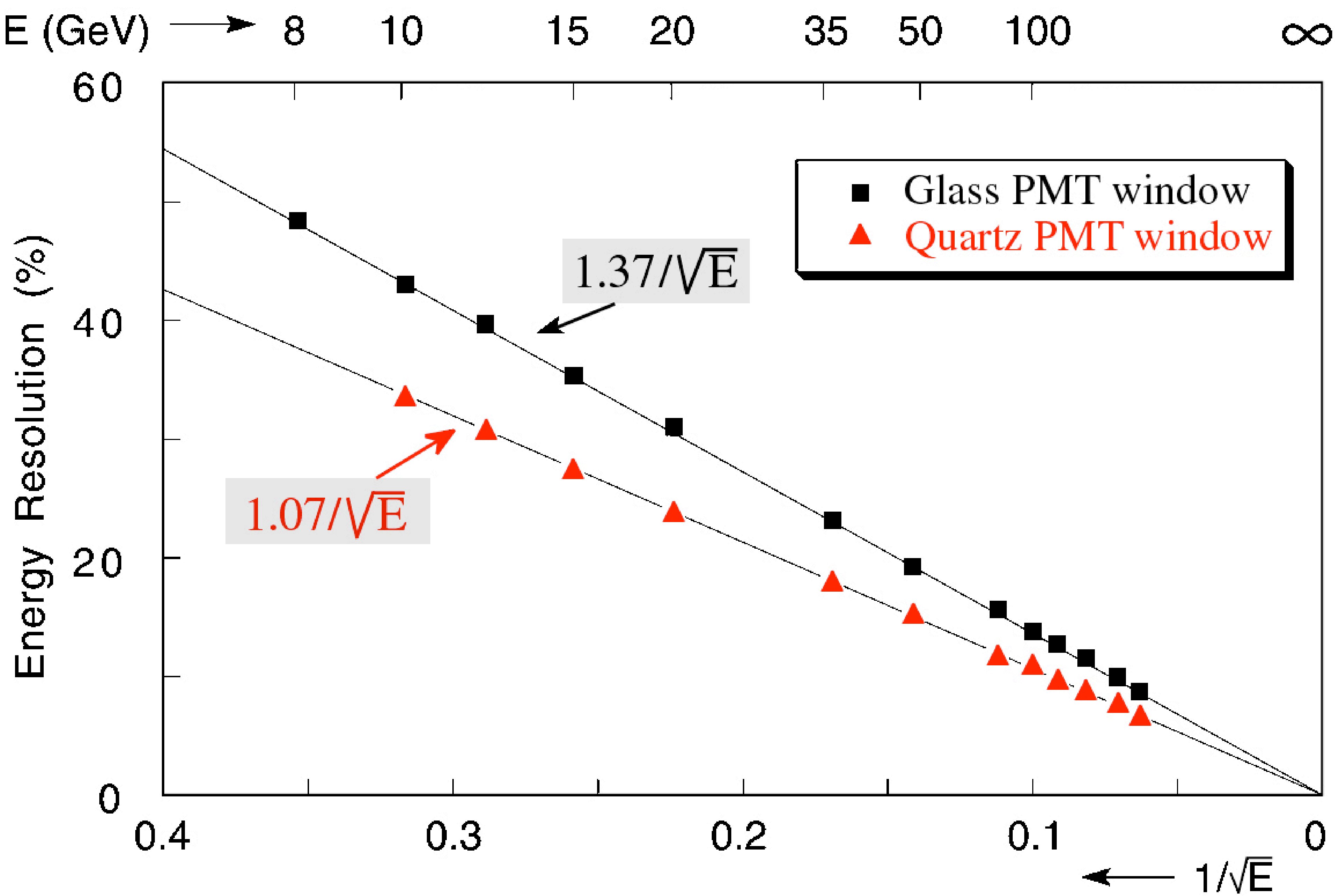
In a calorimeter, showers initiated by electrons and γs DEVELOP DIFFERENTLY







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



Non-stochastic contributions to the energy resolution

- *Electronic noise (contributes as 1/E)*

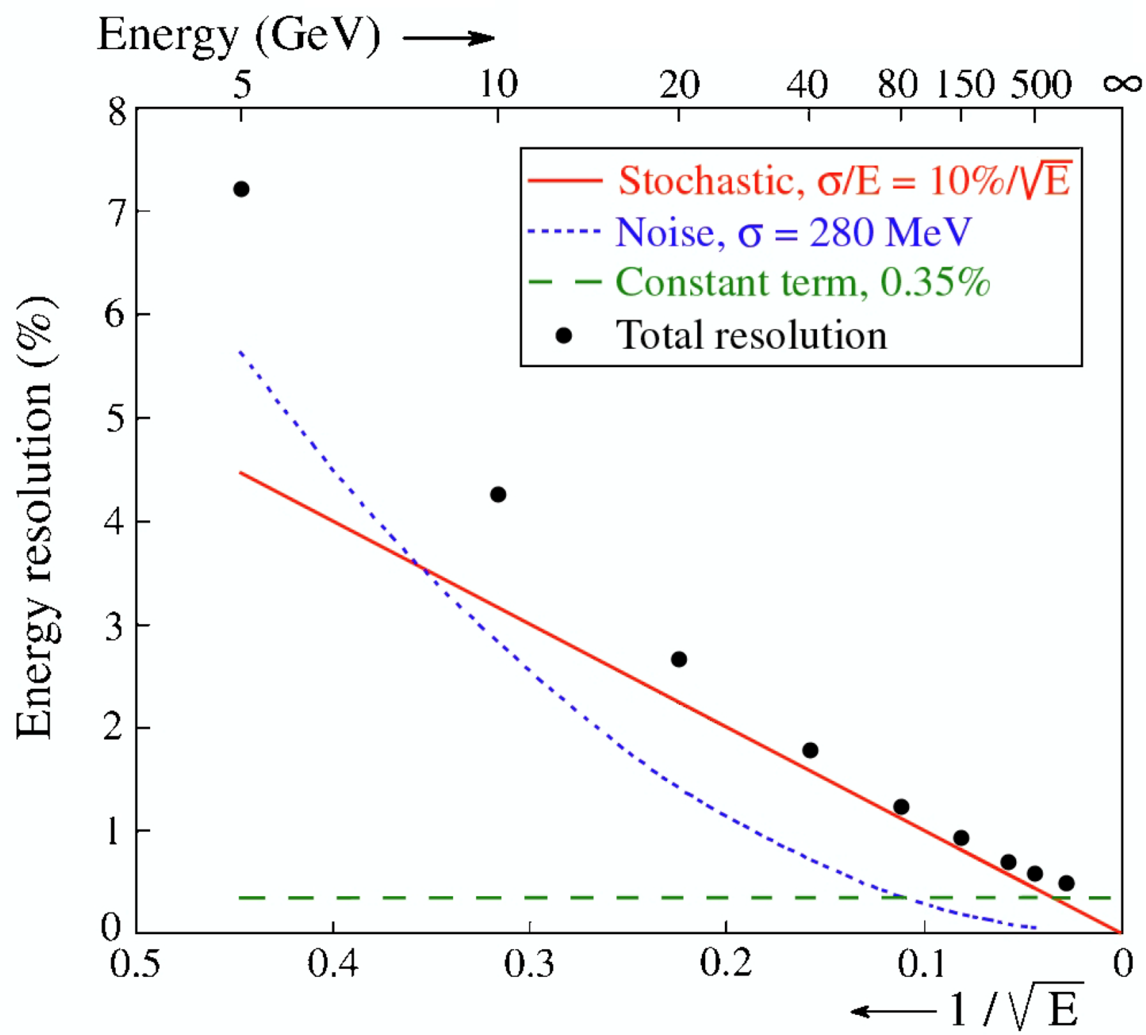
- *Instrumental effects (energy independent contribution)*
  - *- non-uniformity of structure*
  - *- light attenuation*
  - *- position dependence of the response*
  - *- ......*

- *Shower leakage (contributions different for longitudinal/lateral)*

- *Catastrophic effects, such as the "spikes" in CMS ECAL*

- *In hadron calorimeters: Effects of non-compensation*

The em energy resolution of the ATLAS calorimeter

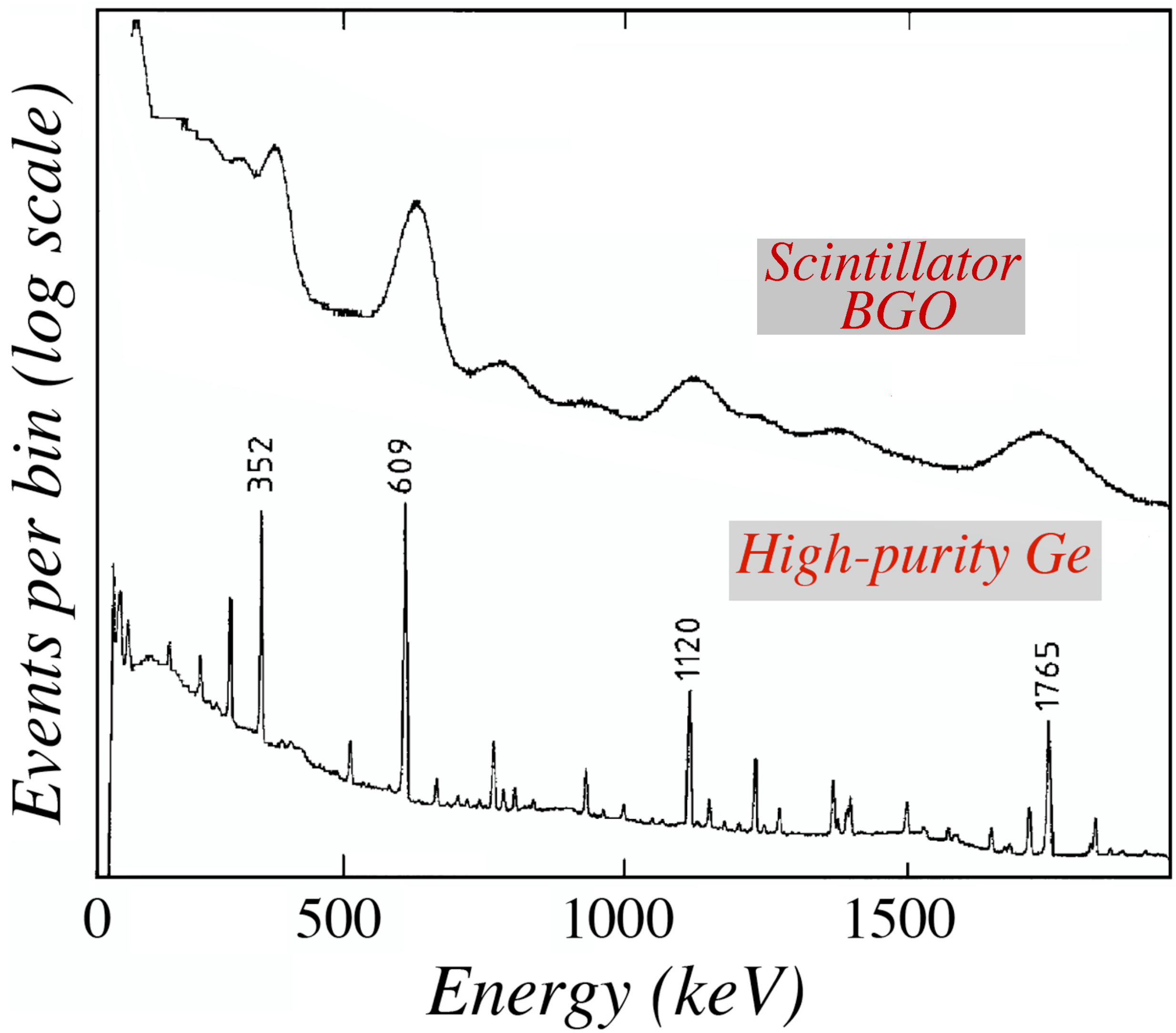


Add in quadrature:

$$\sigma_{tot}^2 = \sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \sigma_4^2 \ldots$$

FIG. 9.30. The em energy resolution and the separate contributions to it, for the em barrel calorimeter, at $\eta = 0.28$ [Gin 95].

The best em energy resolutions are achieved with homogeneous calorimeters

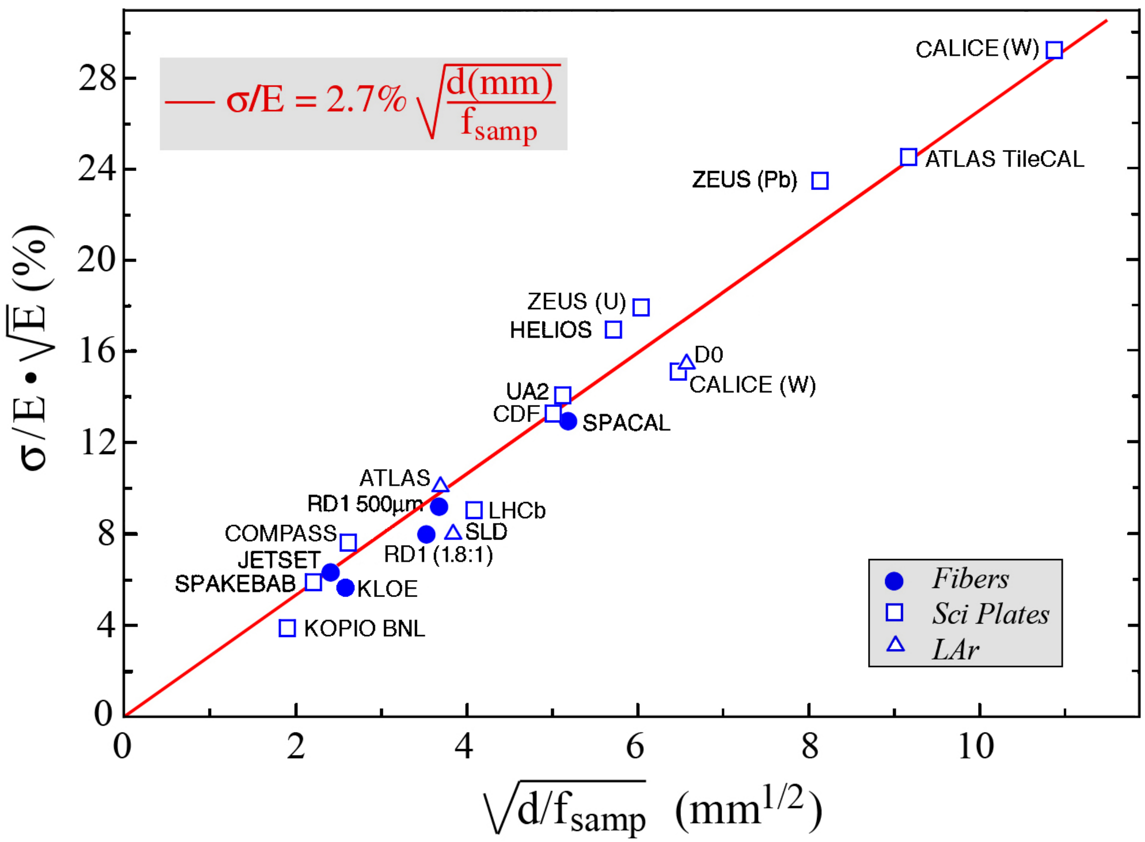


Energy resolution determined/limited by fluctuations in the number of signal quanta

Semiconductors: 2 eV/electron-hole pair ⟶ *500,000/MeV* ⟶ $\sigma/E = 0.14\%$

Em energy resolution in sampling calorimeters

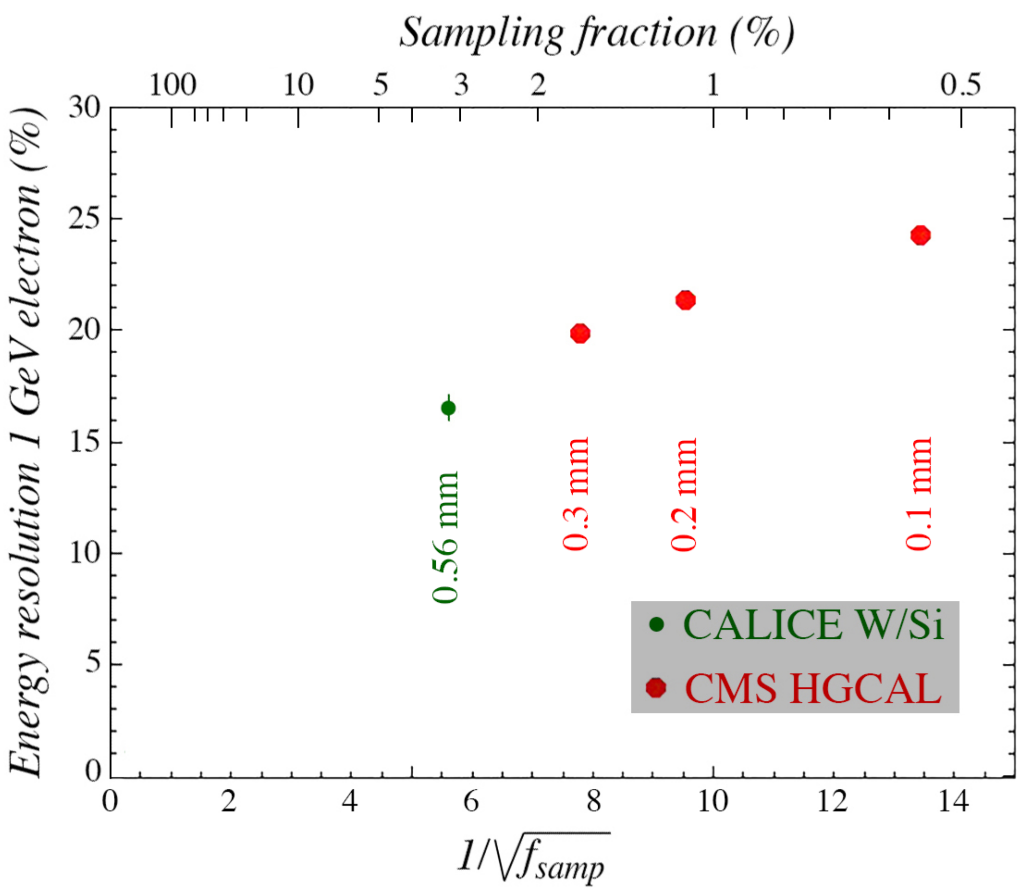
determined by fluctuations in number of shower particles that contribute to the signals

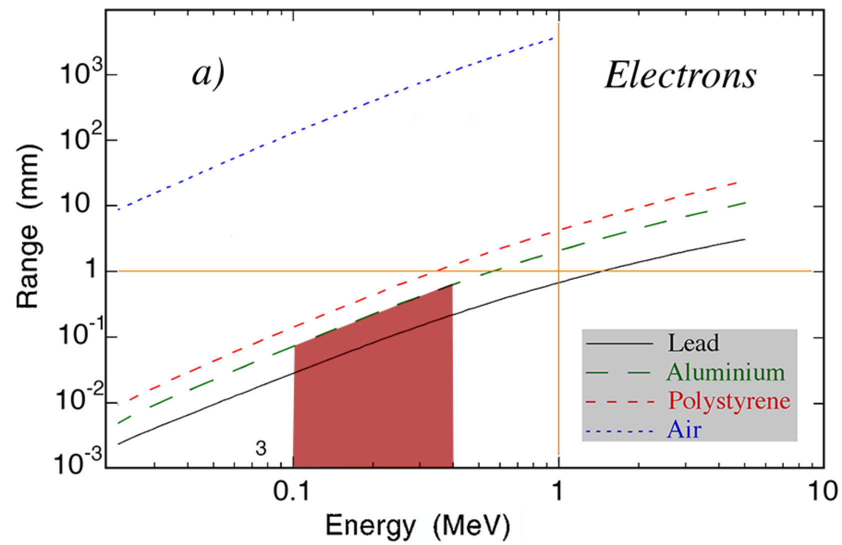


i.e. the total surface area of the border between active and passive calorimeter media, in the region where the shower develops

Both the sampling fraction (f_{samp}) and the sampling frequency (d) are important in that context

When the active layers are very thin (gas, Si)
then fluctuations in the path length of the (very soft) shower particles
give an additional contribution to the em energy resolution



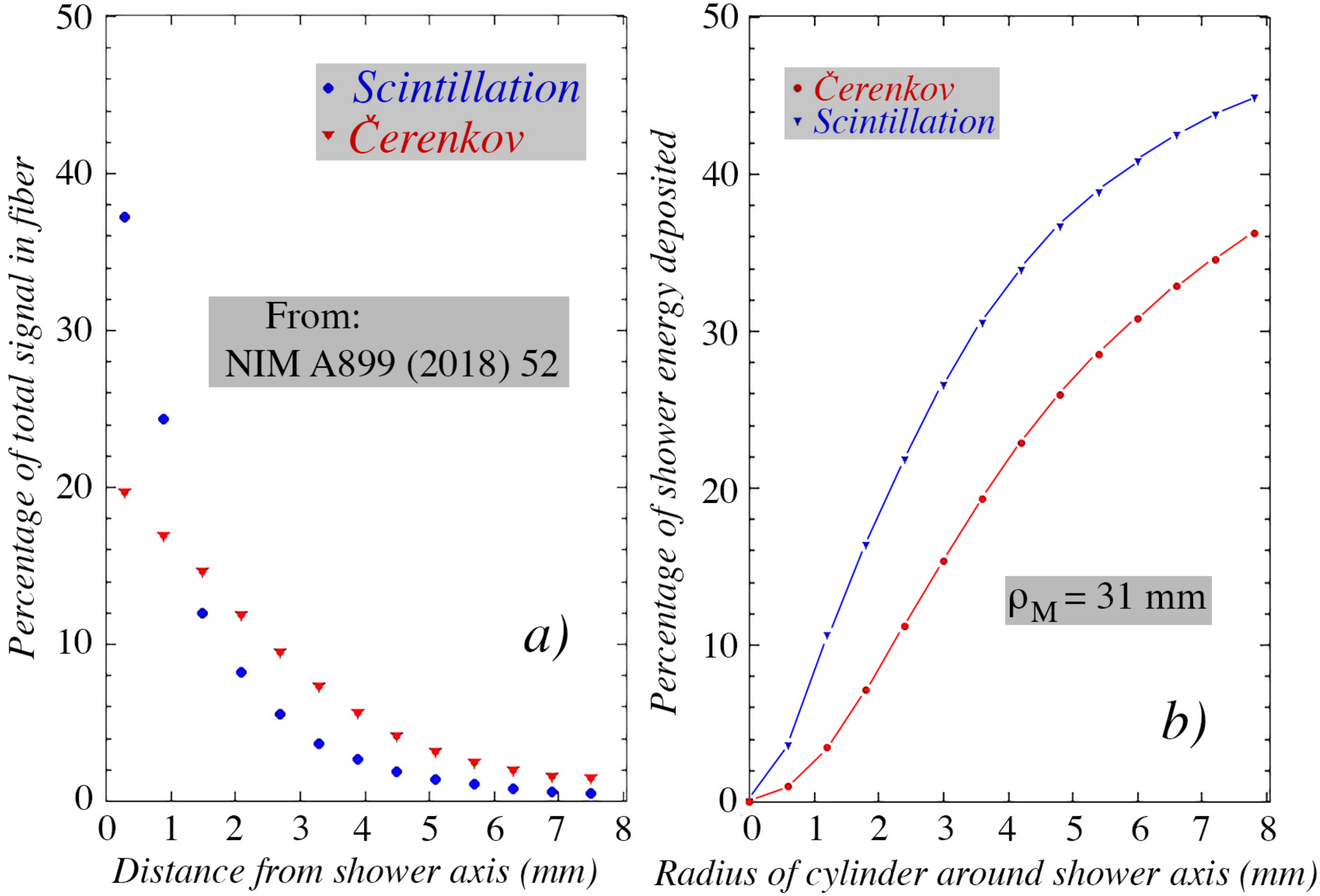


Electrons: 40% < 1 MeV

100 μm Si: 115 keV e
500 μm Si: 330 keV e

The trajectory of such very soft electrons thus determined the calorimeter signal

Lateral and radial profiles of em showers measured with a very-fine-grained calorimeter (SiPM readout)

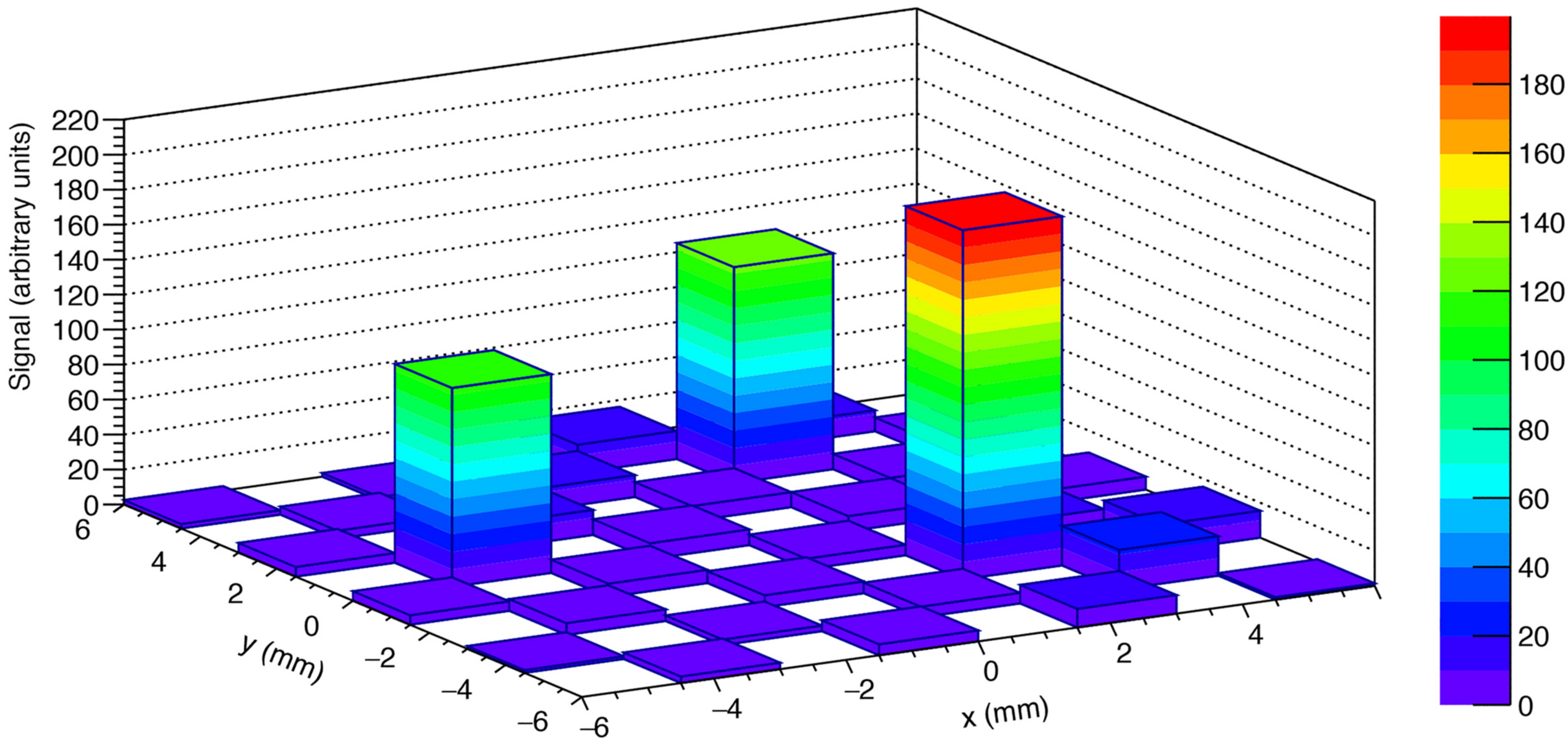


Differences between measurements with scintillation and Cherenkov light (later)

IMPORTANT!!

Shower profile characteristics make it possible to recognize different em showers developing in very close proximity

This plot represents a measurement with a calorimeter with a lateral cross section of 1.2 x 1.2 cm^2 *(0.4 x 0.4* ρ_M^2*)*

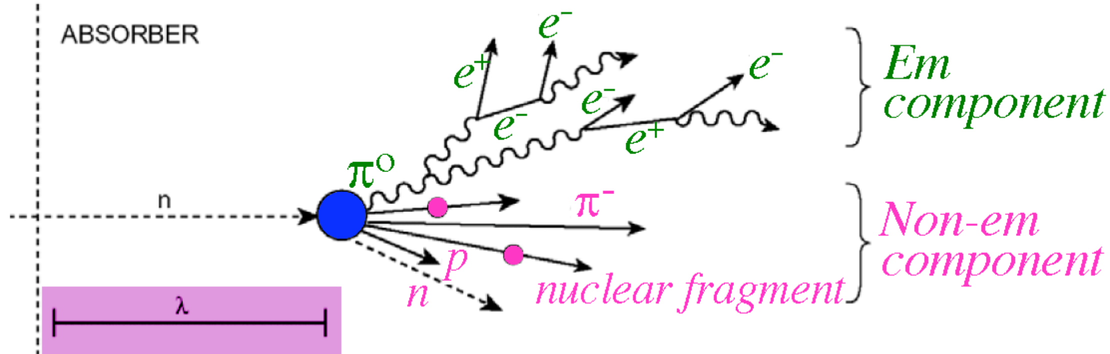


A (very short) primer in the essence of

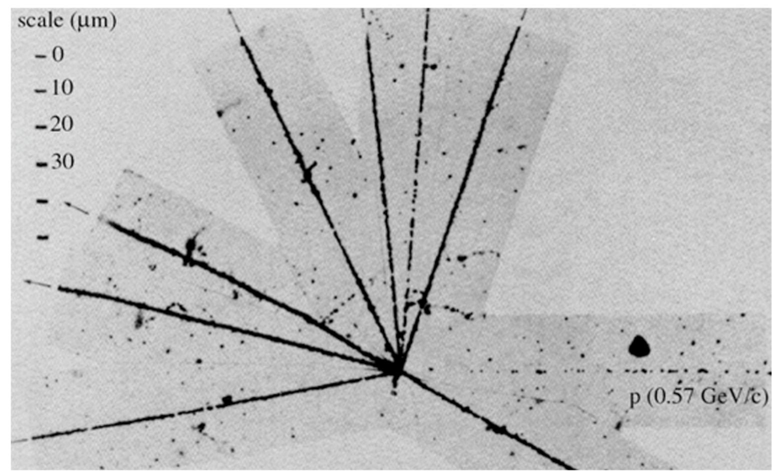
HADRON CALORIMETRY

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%)

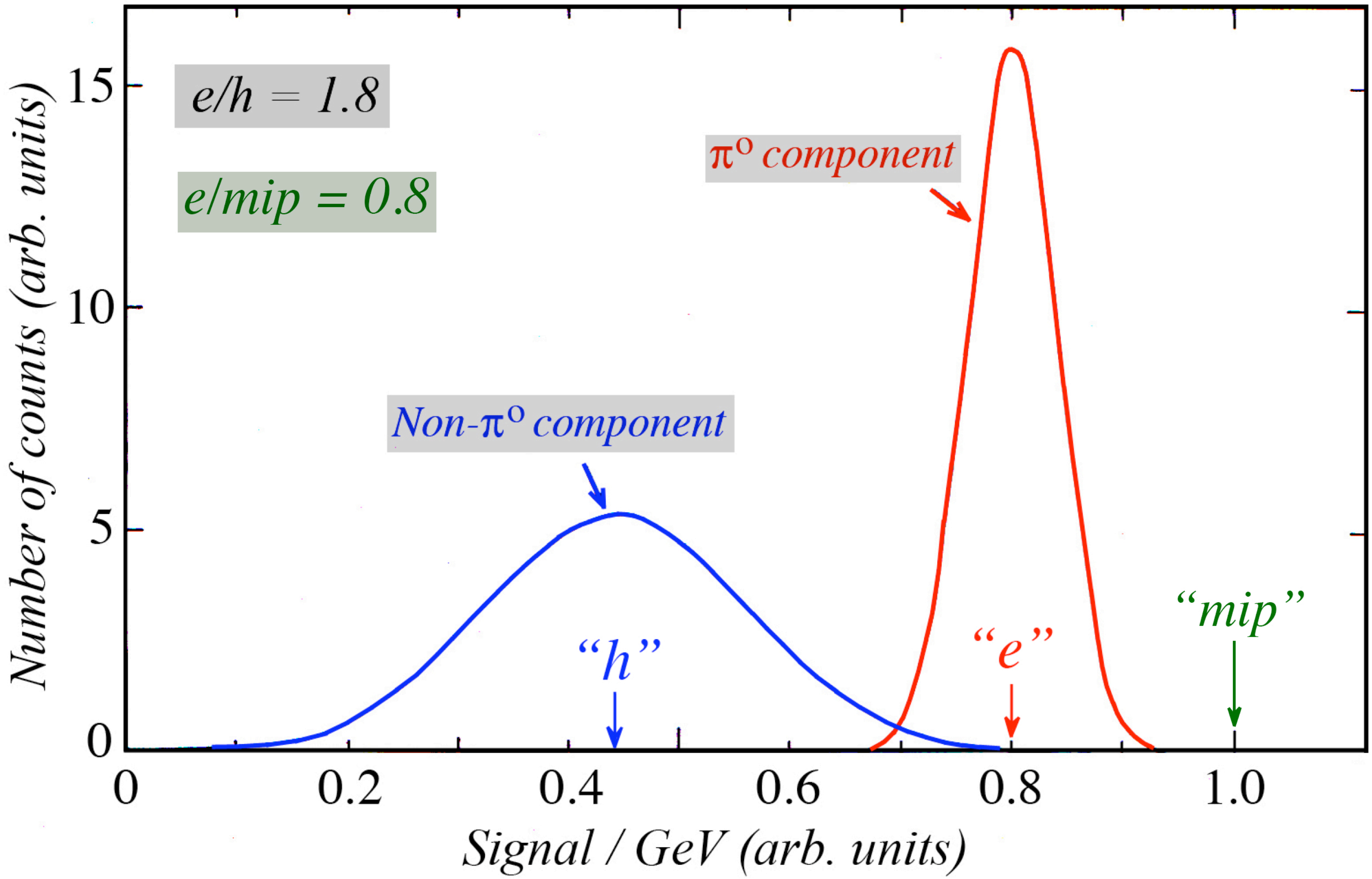


- *Important characteristics for hadron calorimetry:*
  - *Large, non-Gaussian fluctuations in energy sharing em/non-em*
  - *Large, non-Gaussian fluctuations in "invisible" energy losses*

  (e.g. 100 GeV π: energy resolution ZEUS 3.5%, D0 7%)

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

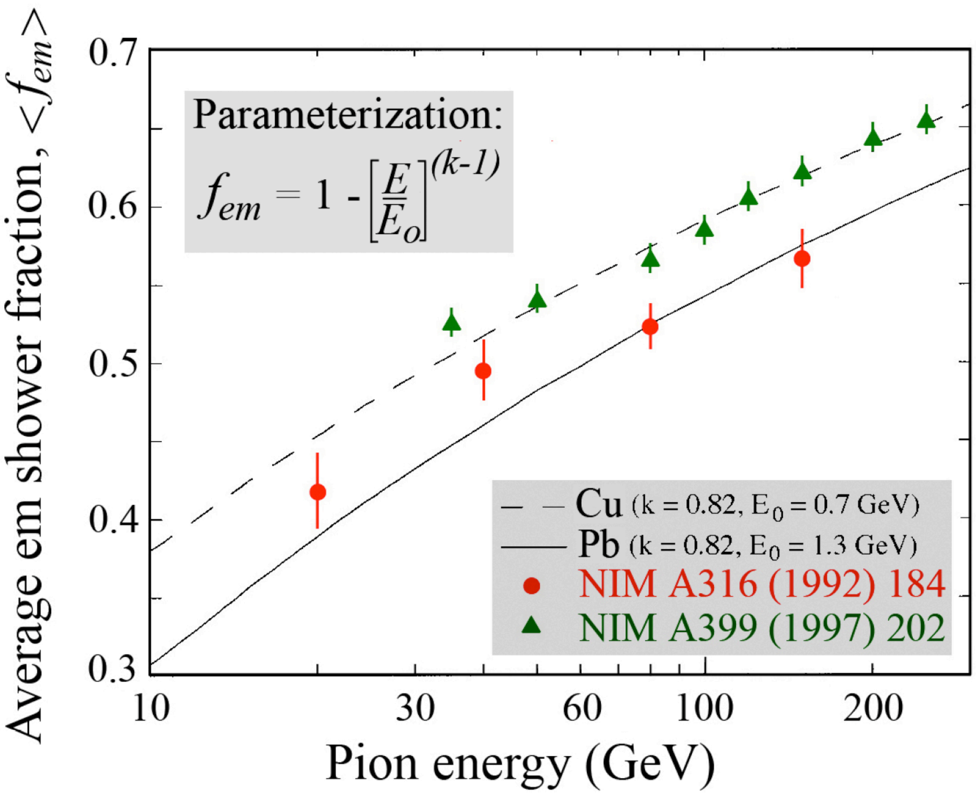
(mainly because of nuclear breakup energy losses in non-π^o component)

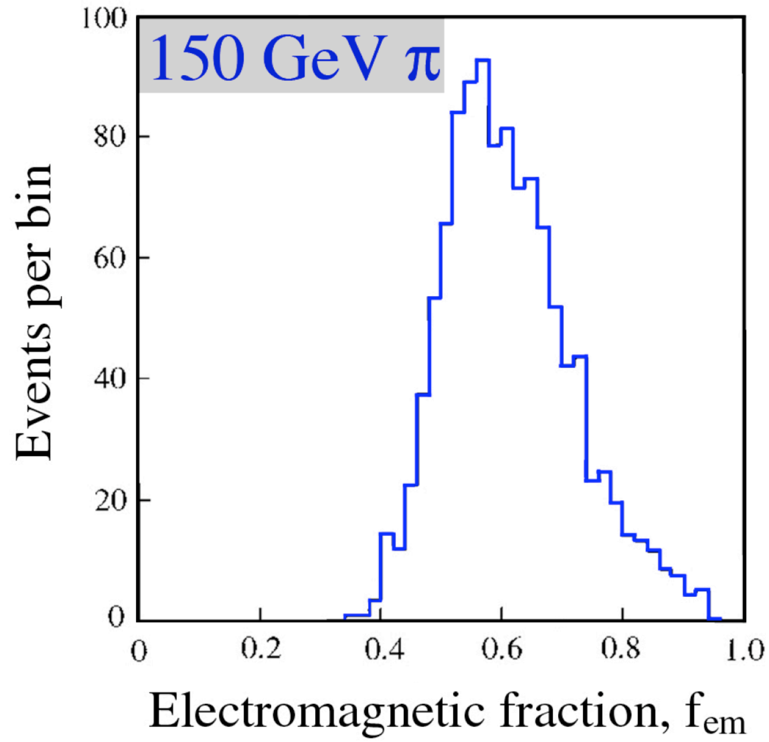


This effect is quantified by the e/h ratio. For example, in crystal calorimeters, e/h ~ 2, i.e. 50% of the non-em energy deposit is invisible

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

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

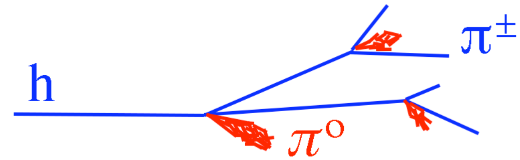




The em fraction is, on average, *large and energy dependent*

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

π^o production is a "one-way street"



Consequences for hadron calorimetry

- *Additional contribution to the hadronic energy resolution (no $1/\sqrt{E}$ scaling). NOT a constant term!!*

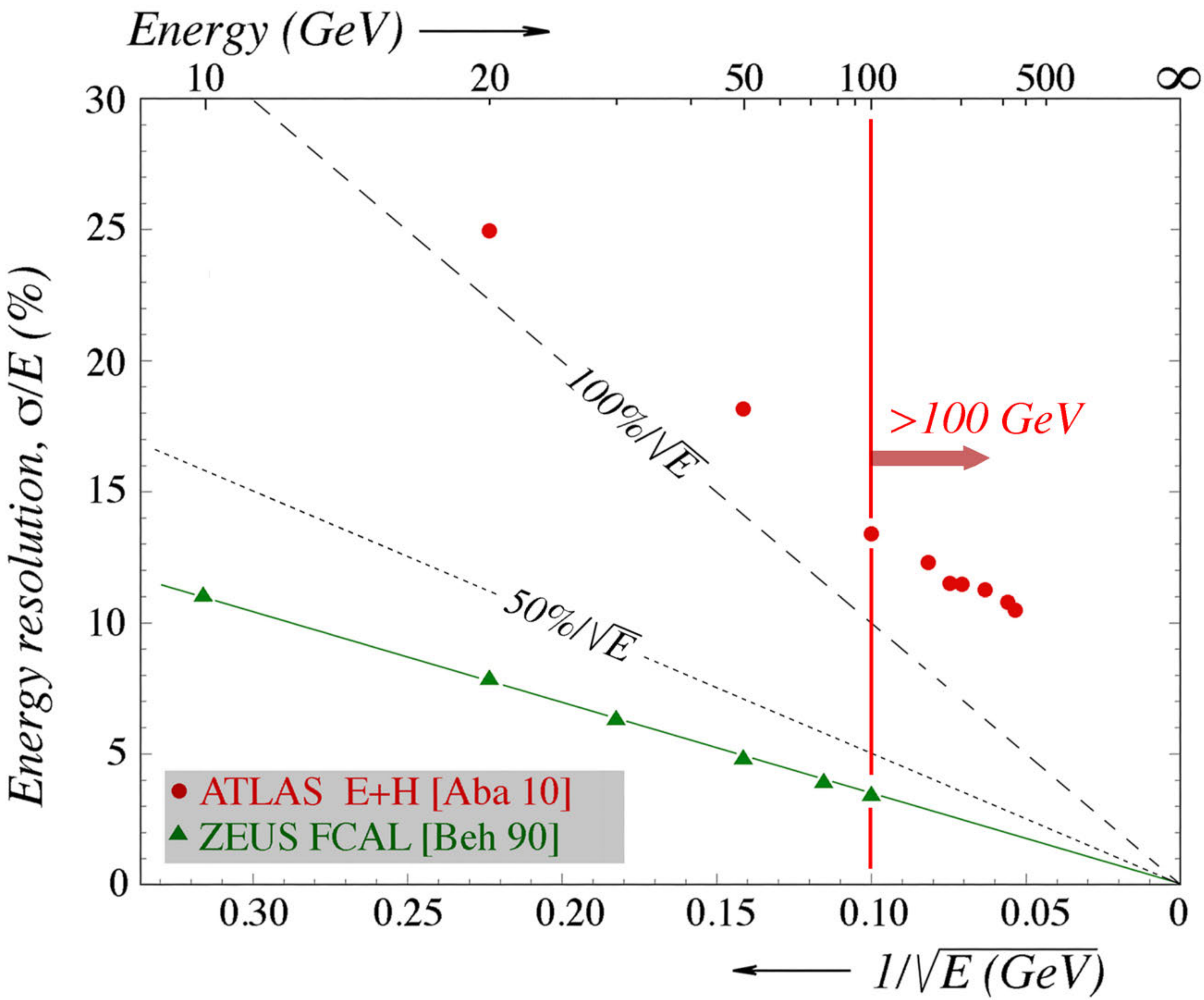
- *Hadronic signal non-linearity*

- *Non-Gaussian response functions*

- *Different average signal for p, π, K*

- *Calibration problems, especially if e/h (em) ≠ e/h (had)*

Hadronic energy resolution of compensating vs modern calorimeters



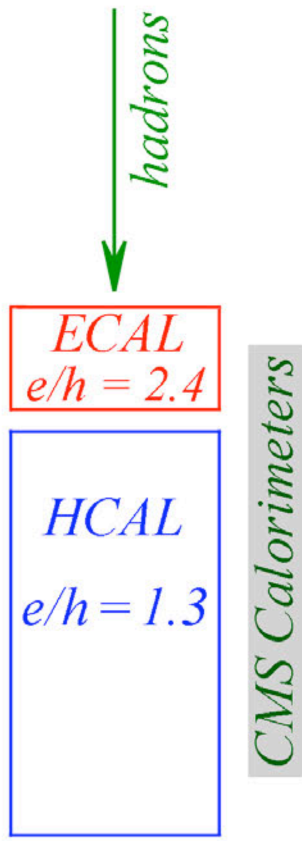
Consequences for LHC calorimeters

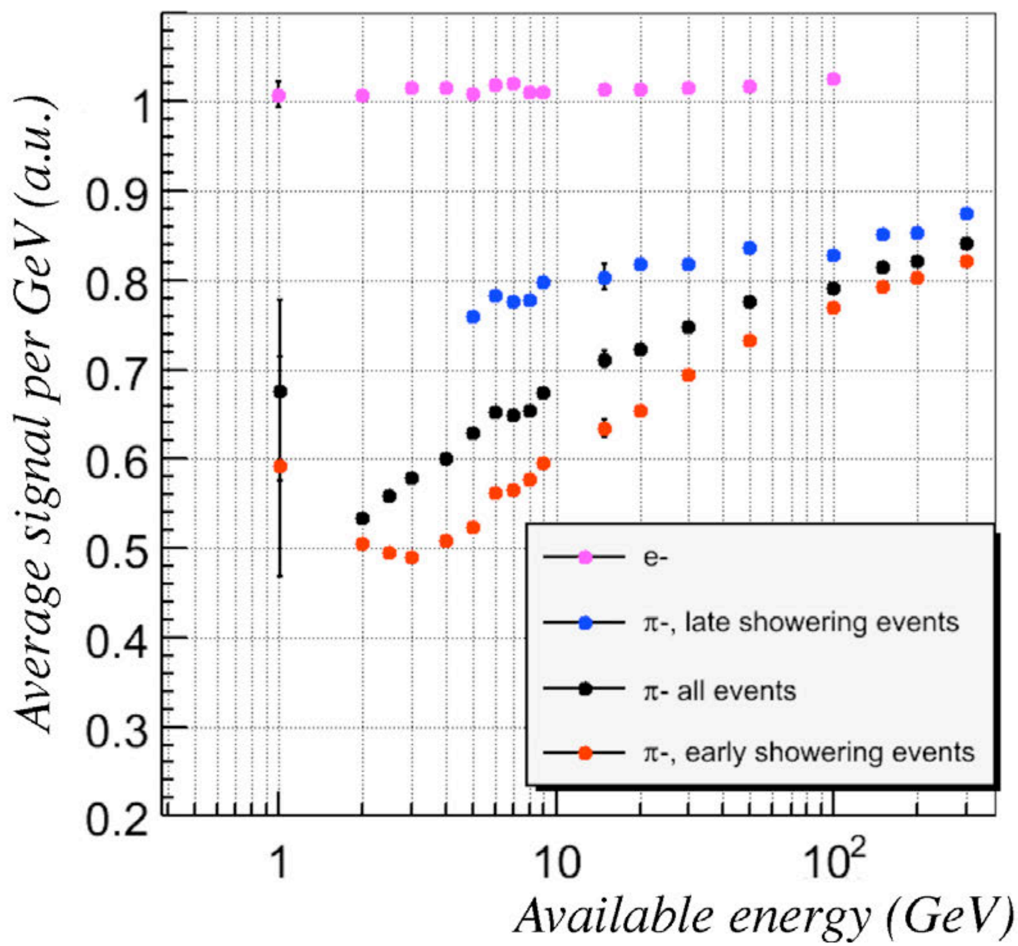
Hadronic response and signal linearity (CMS)

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

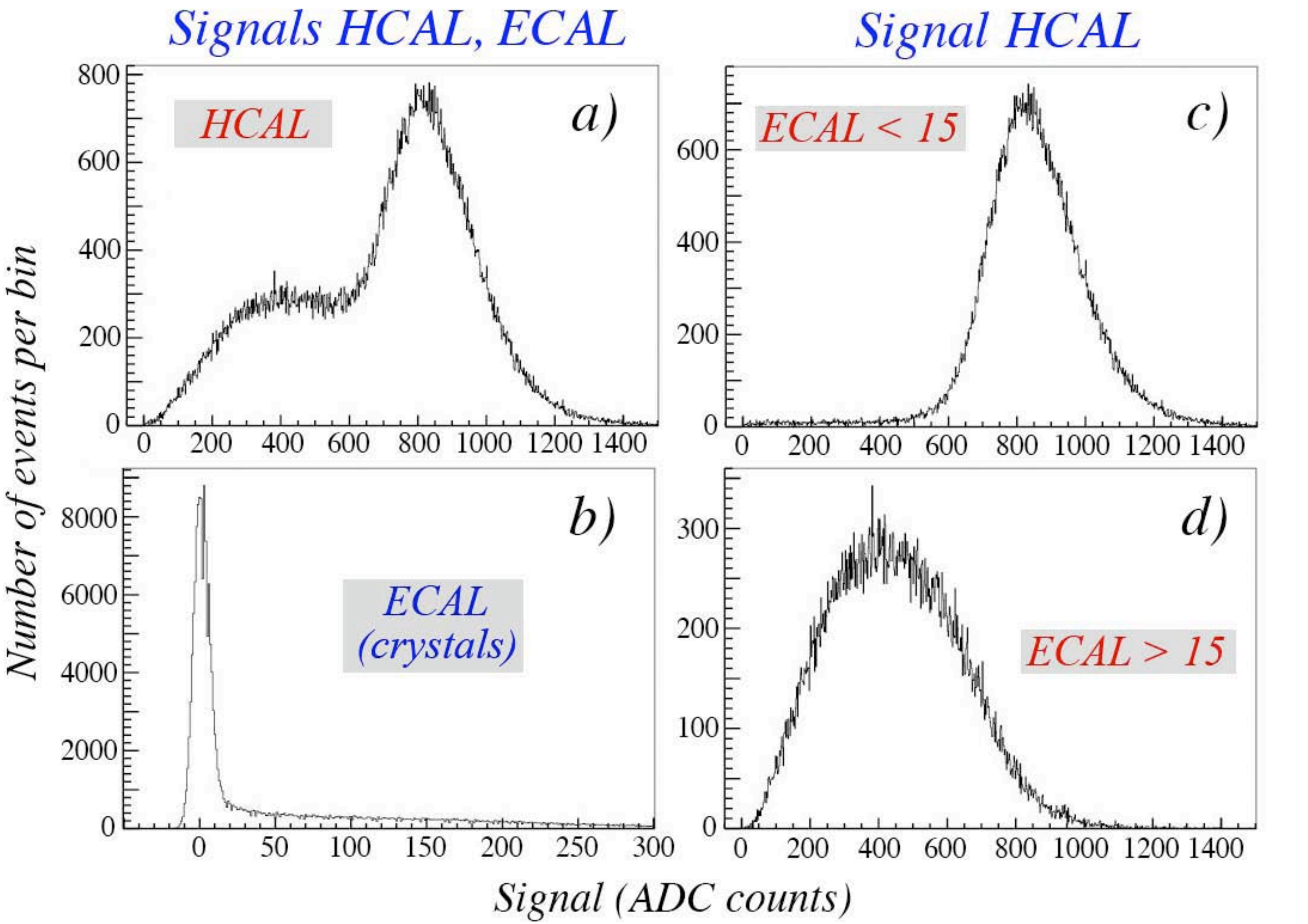
→ *Response depends strongly on starting point shower*

Data from: CMS note 2007/012

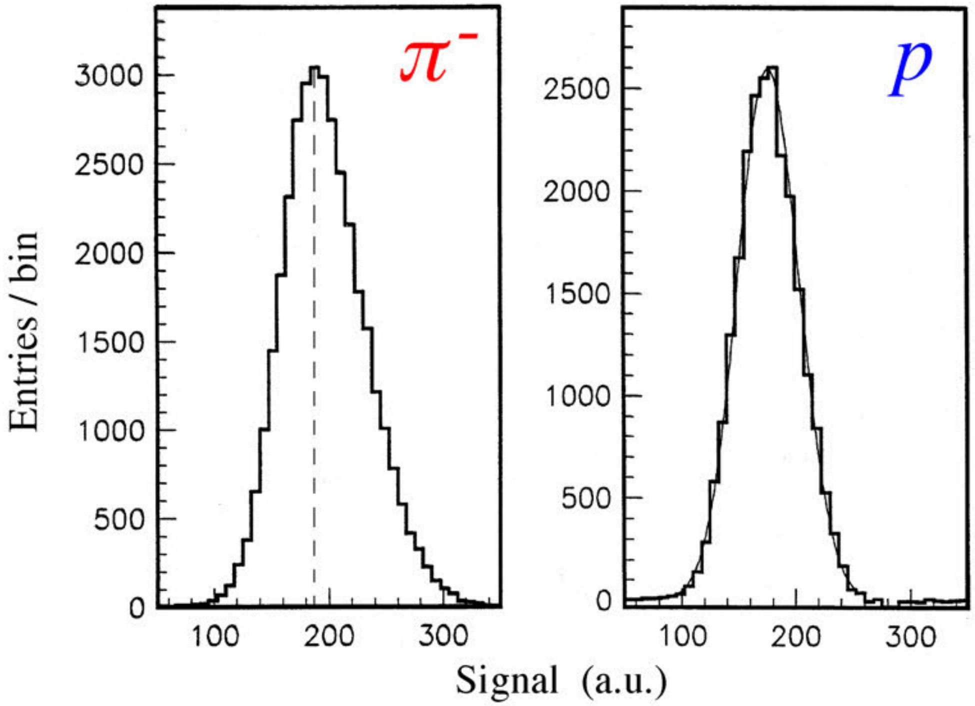


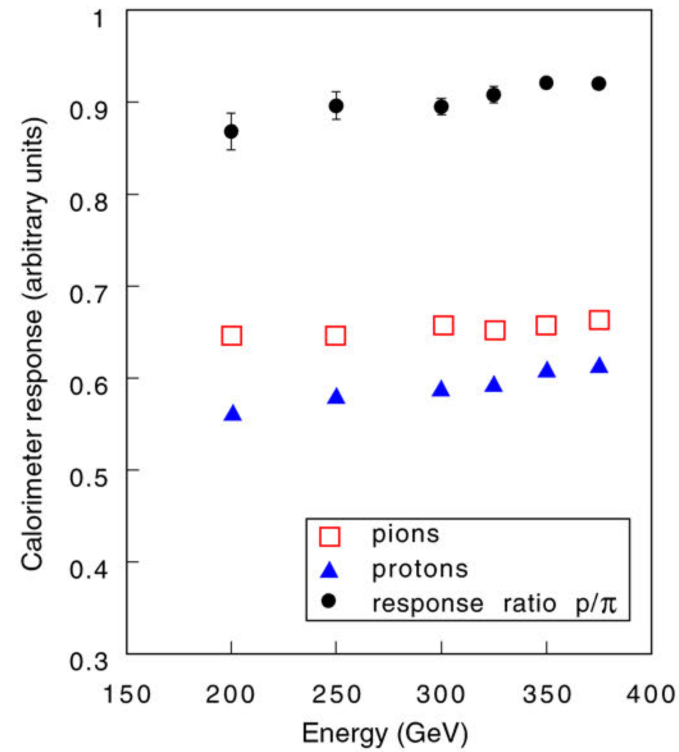


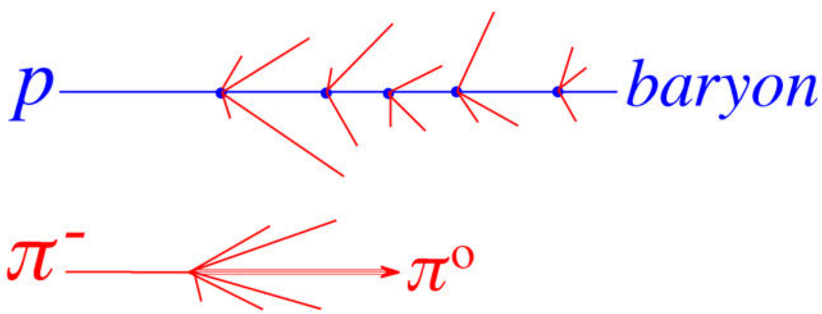
Pion signals in crystal ECAL + scintillator HCAL

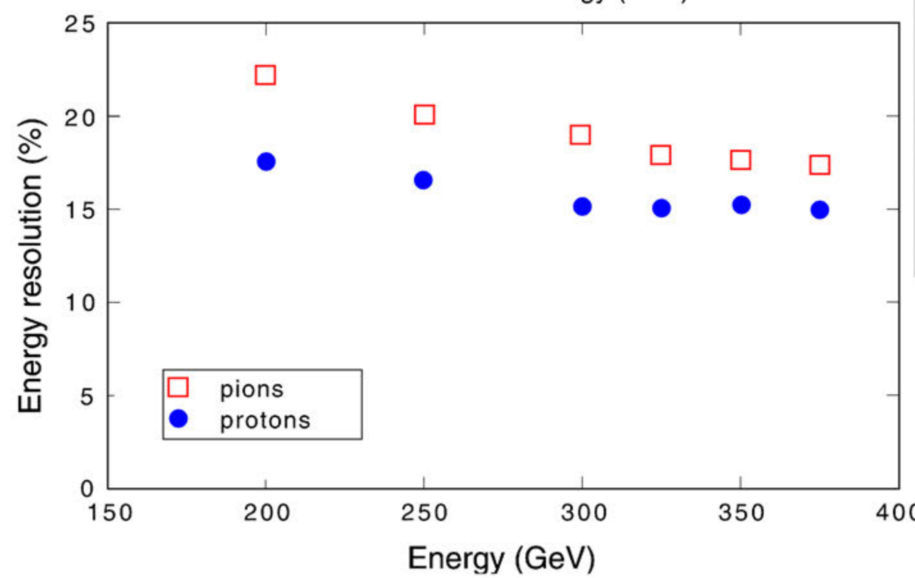


Proton / pion differences in calorimeter signals
caused by differences in em shower fraction characteristics









em fraction in p showers:

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

data from NIM A408 (1998) 380

How to improve hadronic calorimeter performance?

Exploit a measurable quantity that is correlated to the nuclear binding energy losses

- *Total kinetic energy of neutrons produced in shower development ("compensation")*

- *Total non-em energy component ("dual-readout")*

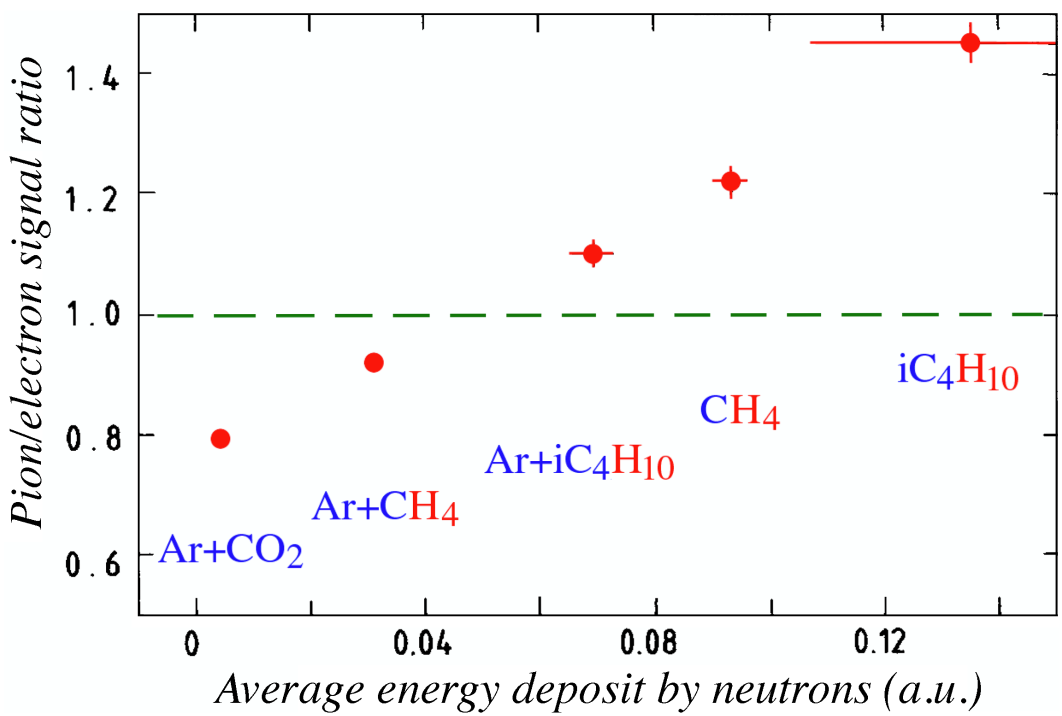
Compensation

Exploit the fact that neutrons may be sampled much more efficiently than mips

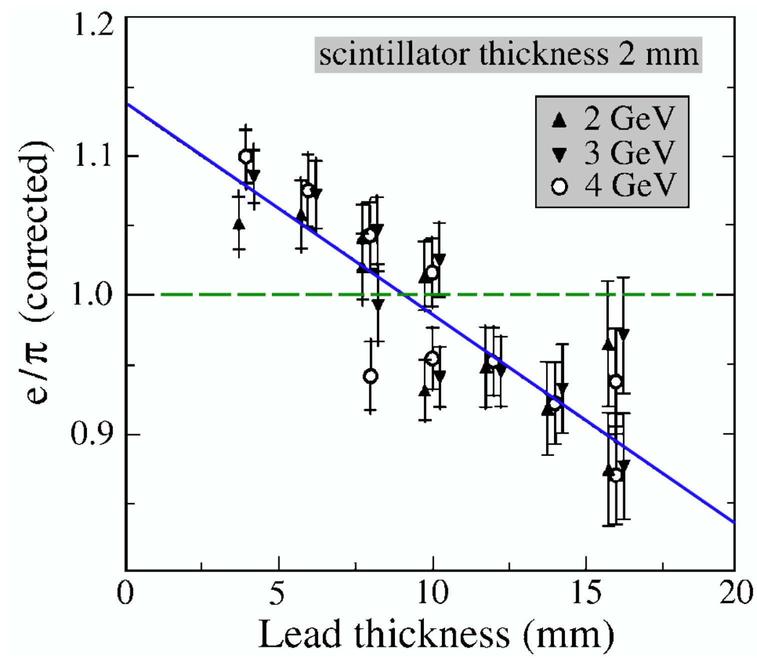
Ingredients: high-Z absorber, hydrogen-rich active material

Need very specific (small) sampling fraction to get e/h = 1.0 (e.g. thickness ratio ~5/1 for lead/plastic-scintillator)

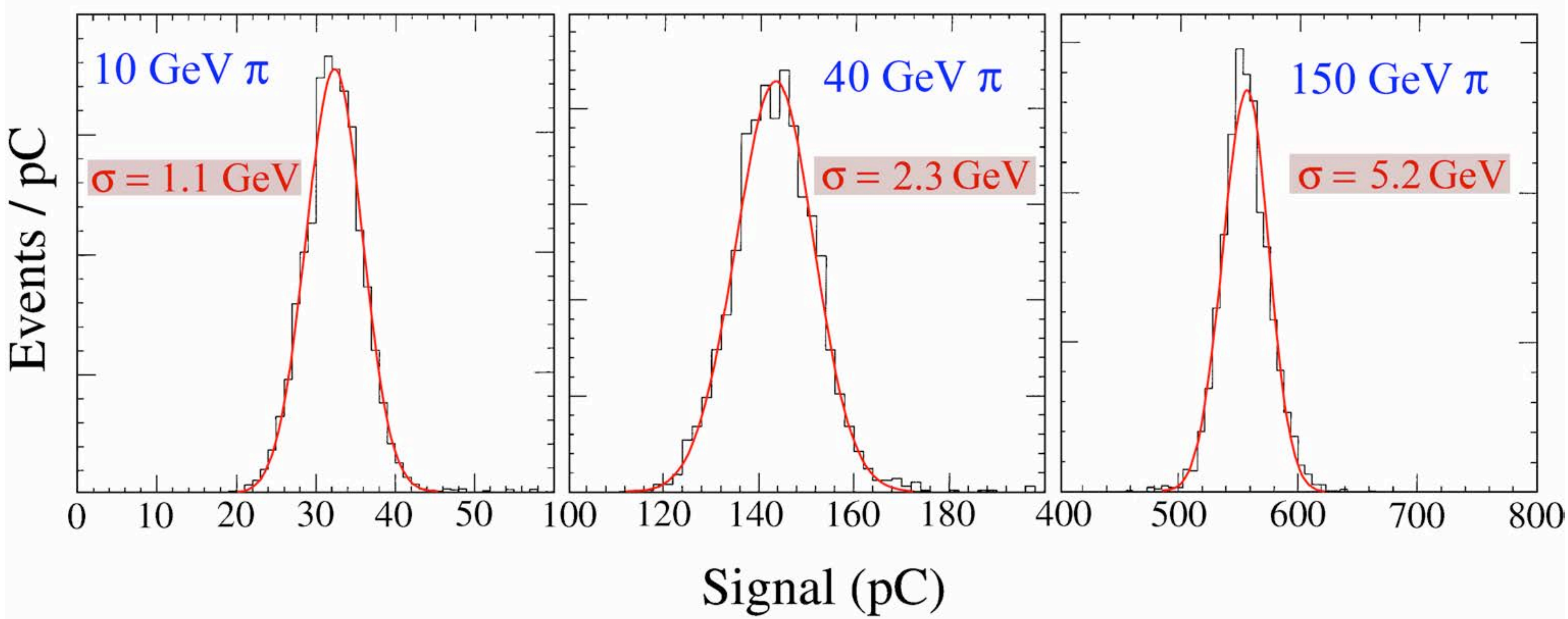
Uranium / gas (L3)



Pb/plastic-scintillator (KEK)



Hadronic signal distributions in a compensating calorimeter



from: NIM A308 (1991) 481

Advantages compensation:

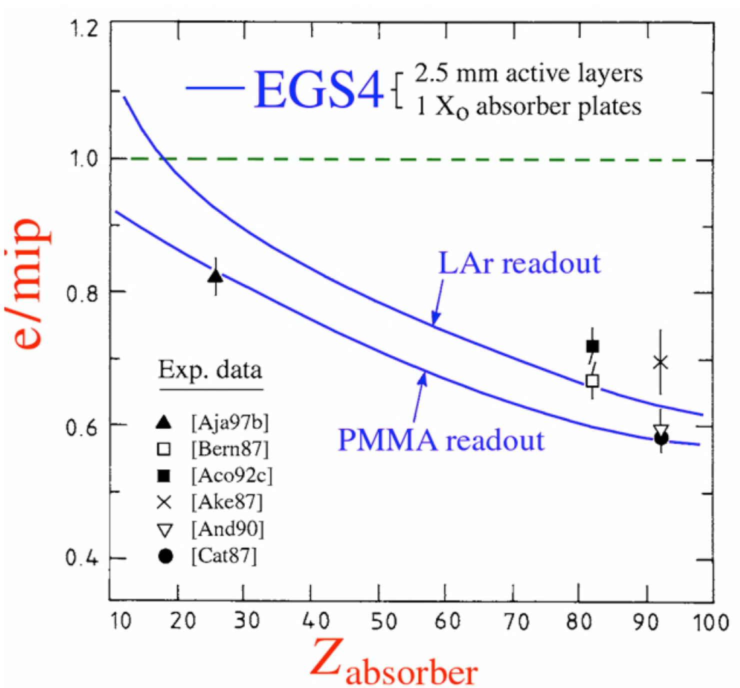
- *Same response to electrons and hadrons (e/h = 1)*
- *Gaussian response functions*
- *Linear response (average signal proportional to energy*

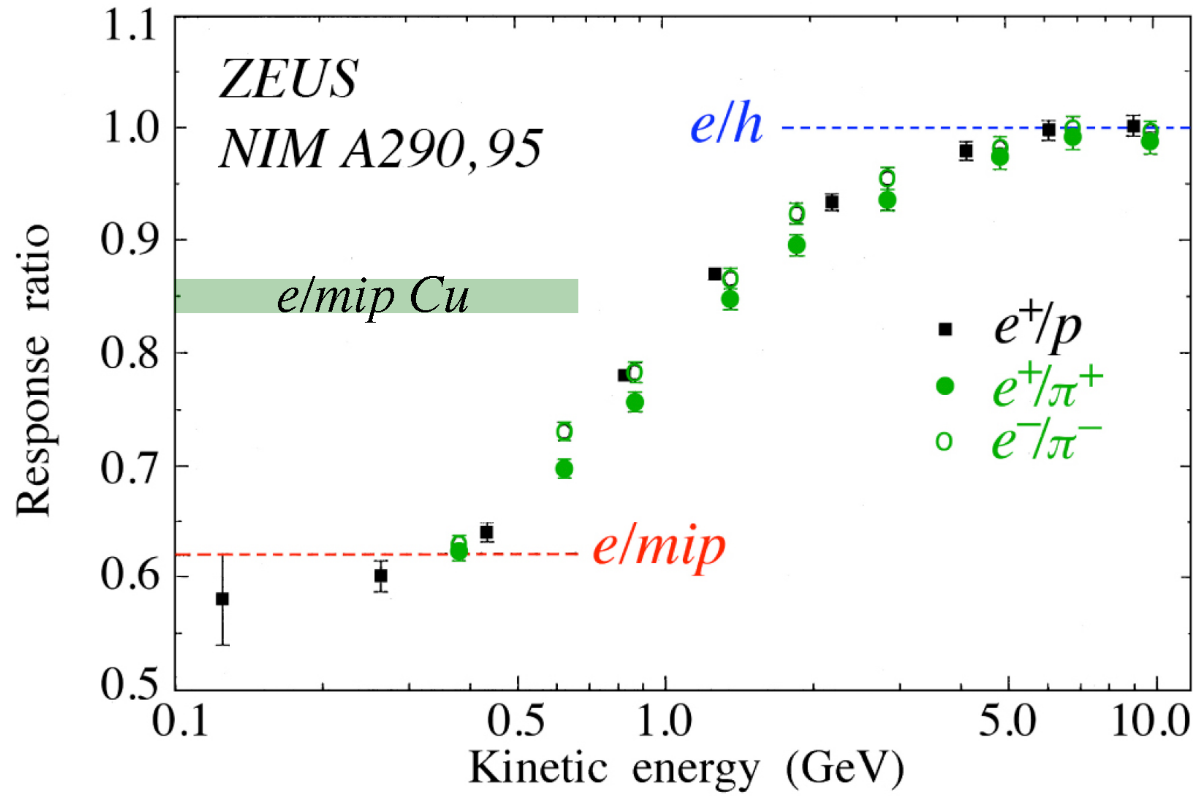
Disadvantages compensation:

- *Small sampling fraction (limits em energy resolution)*
- *Long signal integration time (~30 ns)*
- *Large integration volume*
- *Jet energy resolution limited by e/mip*

Jet energy resolution is typically worse than for single hadrons

What is the problem with the jet energy resolution?

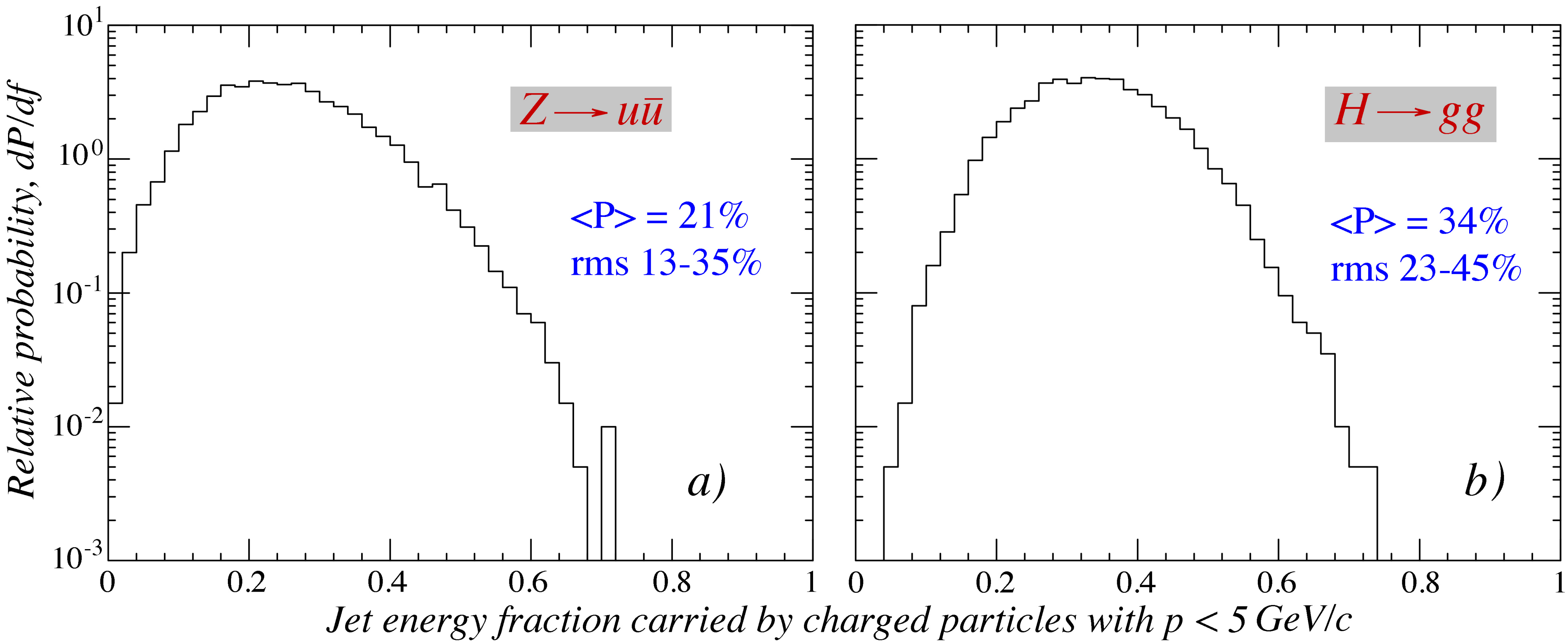




Signal non-linearities at low energy (< 5 GeV)
due to non-showering hadrons
Many jet fragments fall in this category

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

Jet energy fraction carried by hadrons with $p < 5$ GeV/c *



* *From B. Webber (Cambridge Univ.)*

DUAL-READOUT CALORIMETRY

- *Dual-readout Method (DREAM):*

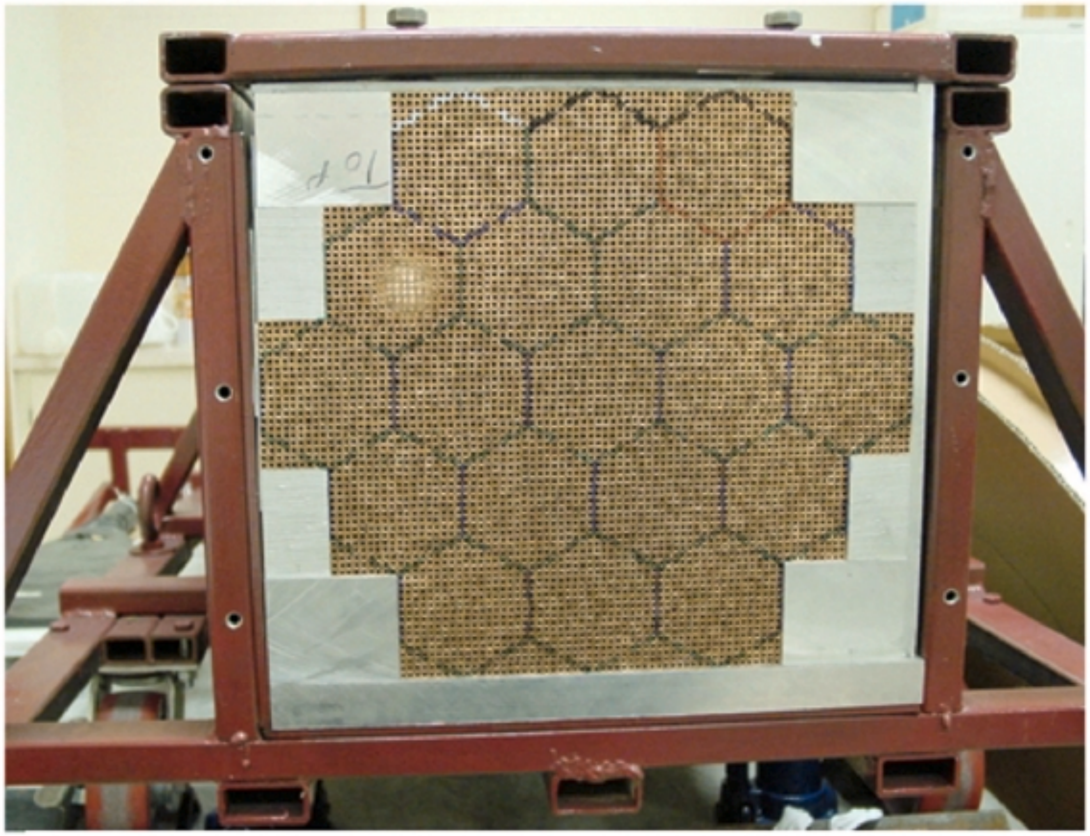
  Simultaneous measurement of scintillation light (dE/dx) and Čerenkov light produced in shower development makes it possible to measure the em fraction of hadron showers event by event.
  The effects of fluctuations in this fraction on the calorimeter performance can thus be eliminated

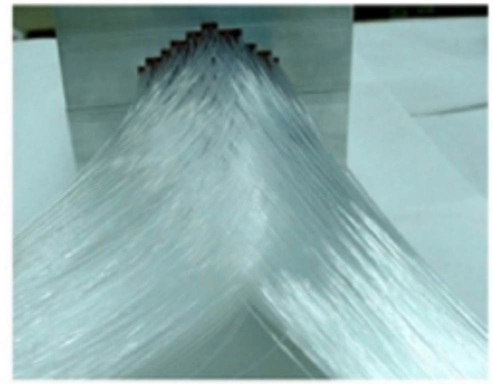
- *This method exploits the fact that the (e/h) values of a sampling calorimeter based on scintillation light and Čerenkov light are very different (e.g. protons from the h component contribute to the S, but not to the Č signals)*

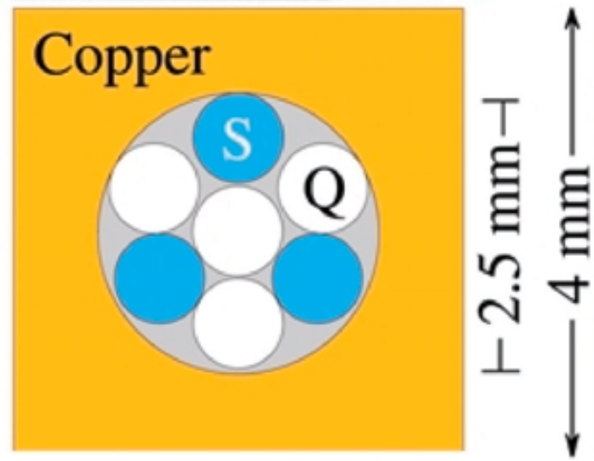
- *In this way, the same advanges are obtained as for intrinsically compensating calorimeters (e/h = 1), WITHOUT the limitations (sampling fraction, integration volume, time)*

  - *Correct hadronic energy reconstruction, in an instrument calibrated with electrons*
  - *Linearity + excellent energy resolution for hadrons & jets*
  - *Gaussian response functions*

DREAM: Structure

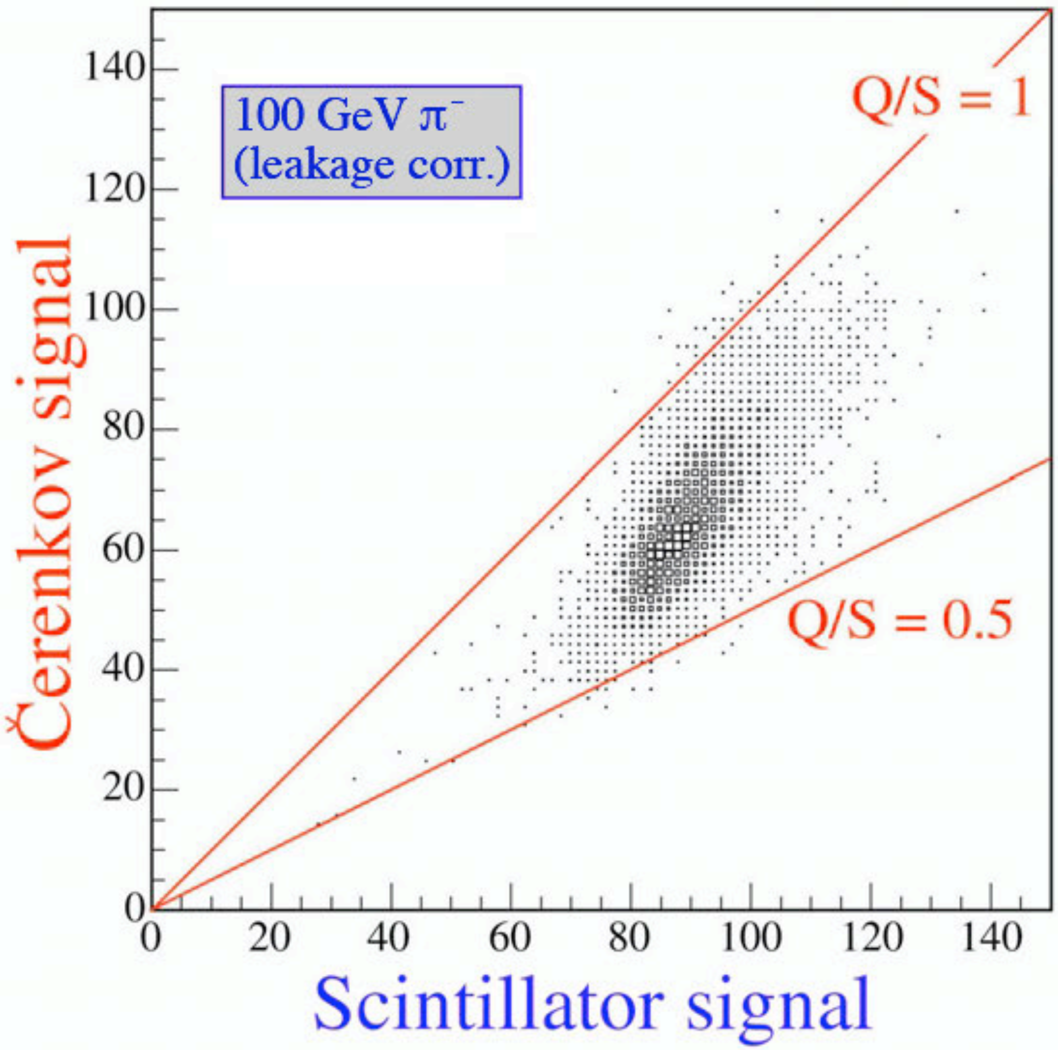






- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

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



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

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

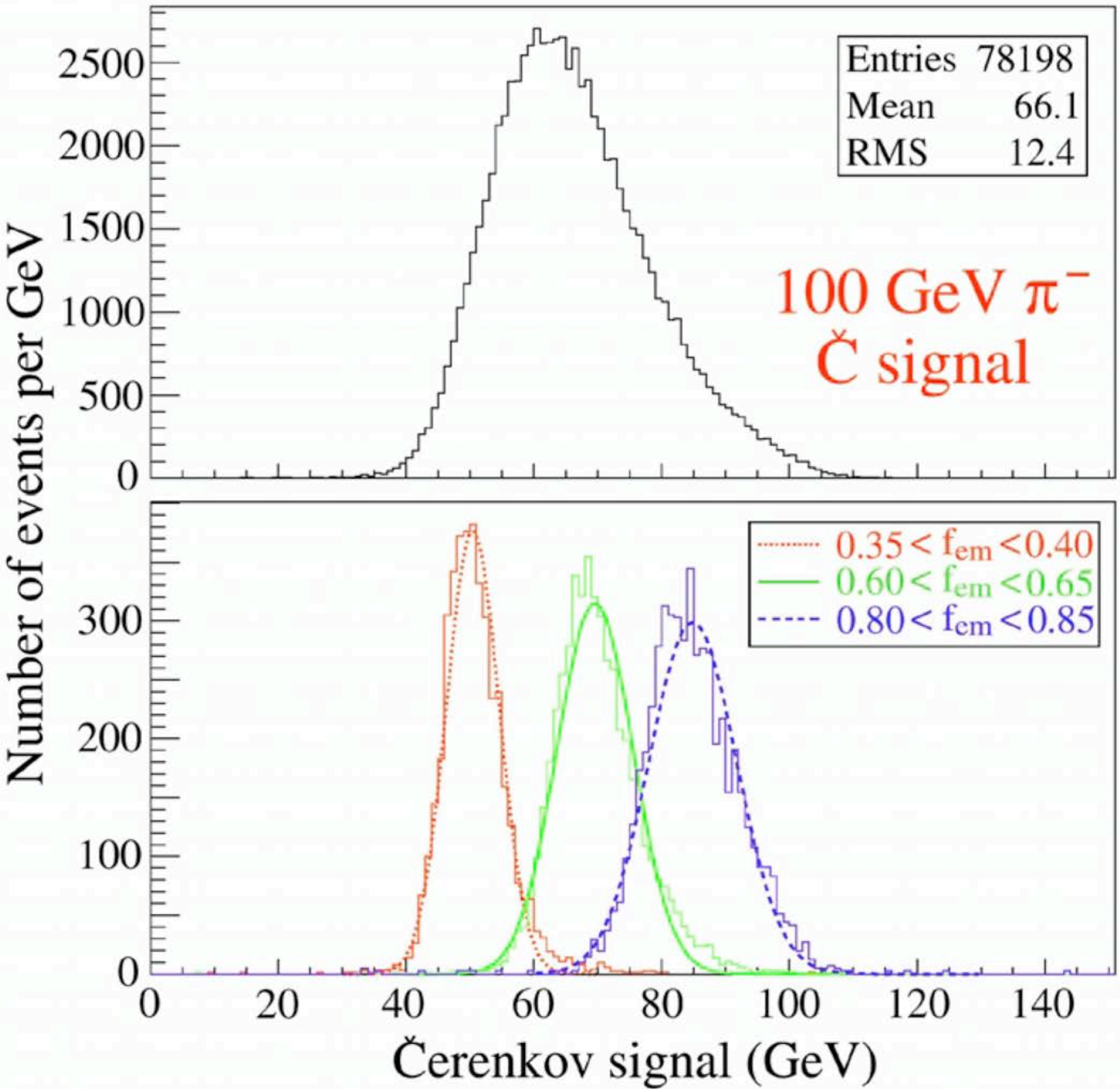
e.g. If $e/h = 1.3$ (S), 4.7 (Q)

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

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

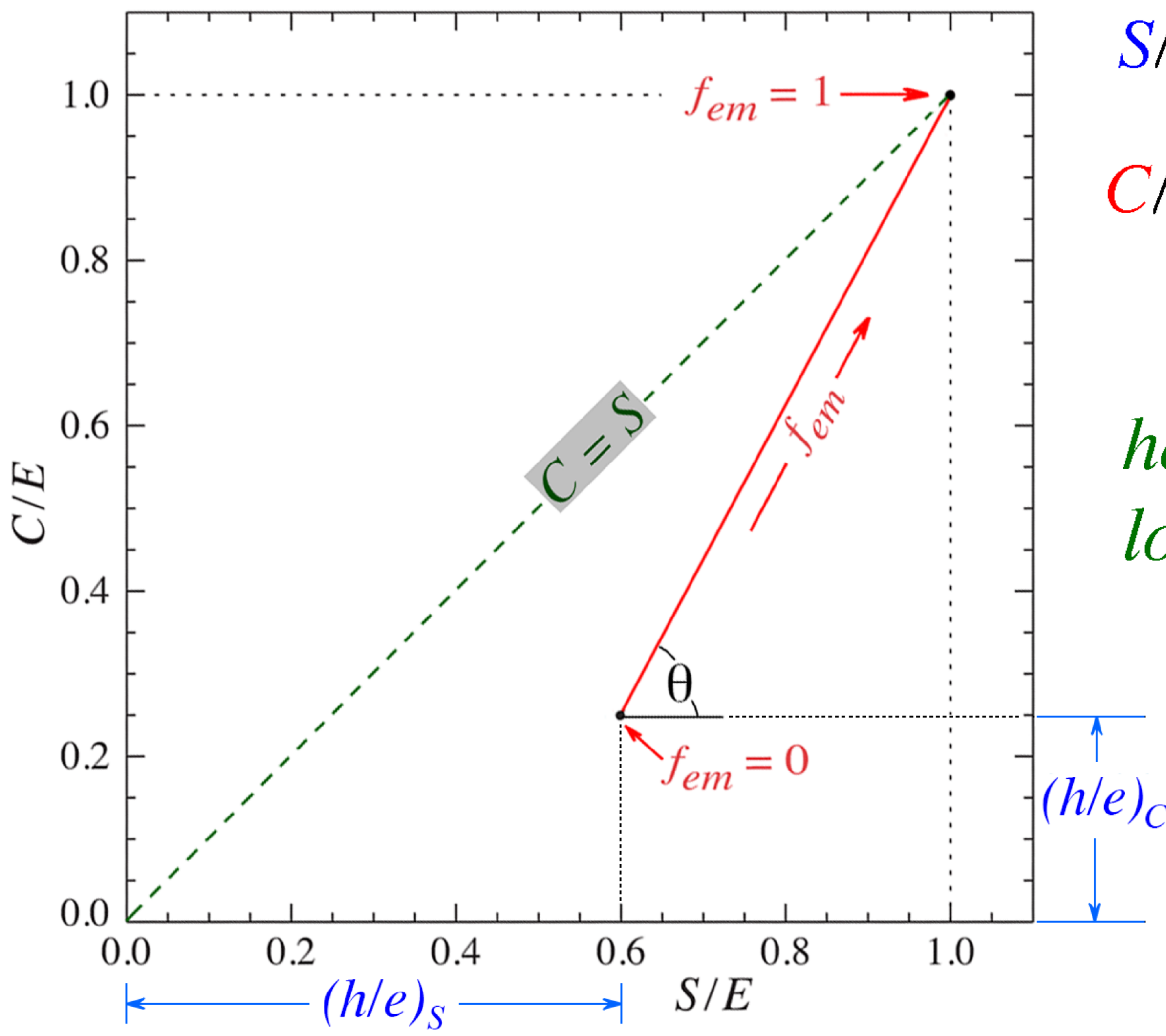
with $\chi = \frac{1 - (h/e)_S}{1 - (h/e)_Q} \sim 0.3$

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



From:
NIM A537 (2005) 537

Principles of dual-readout calorimetry (1)

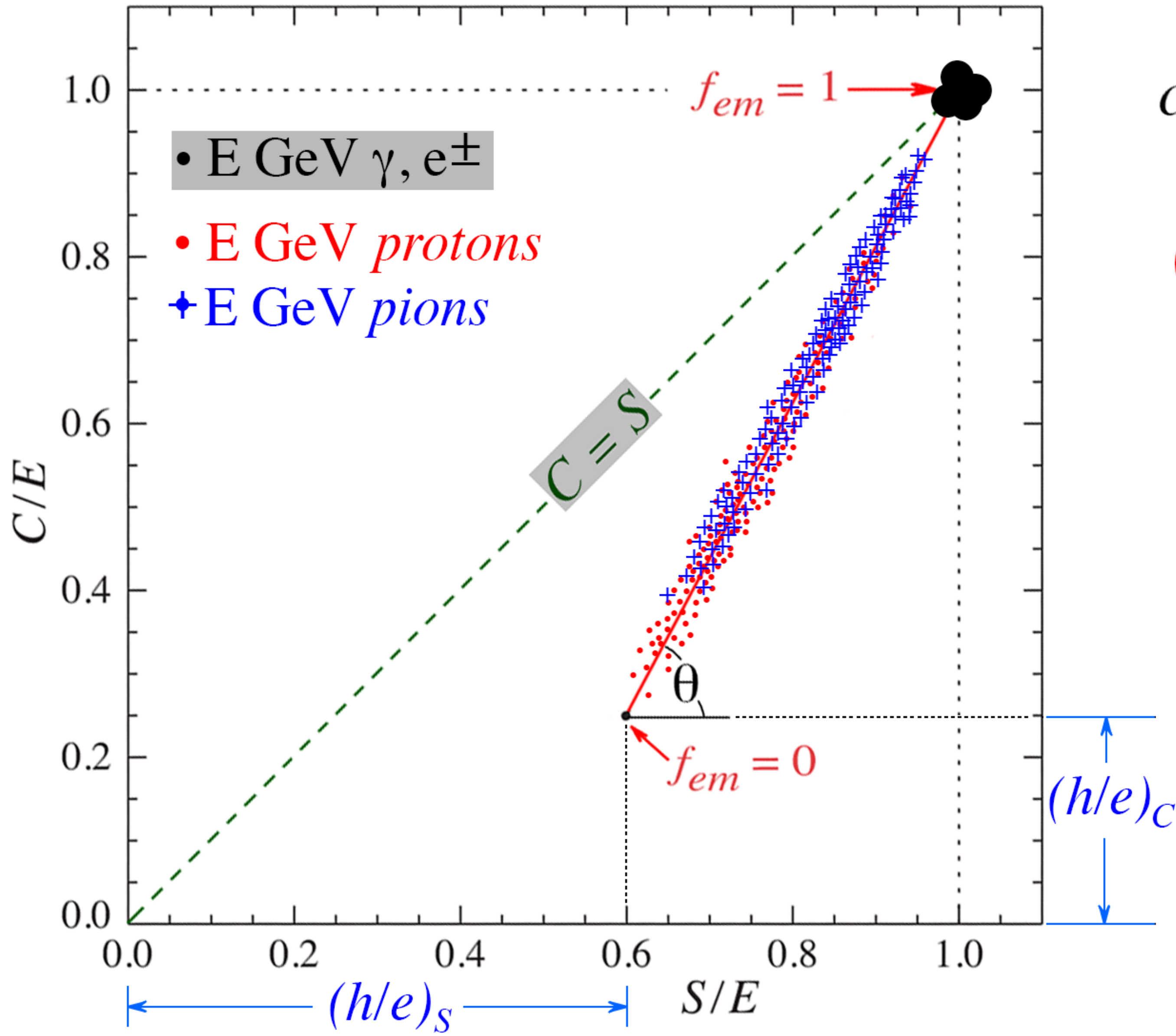


$$S/E = (h/e)_S + f_{em}\,[1 - (h/e)_S]$$

$$C/E = (h/e)_C + f_{em}\,[1 - (h/e)_C]$$

hadronic data points (S,C) located on straight (red) line

Principles of dual-readout calorimetry (2)



$$cotg\,\theta = \frac{1-(h/e)_S}{1-(h/e)_C} = \chi$$

θ,χ are independent of energy!!

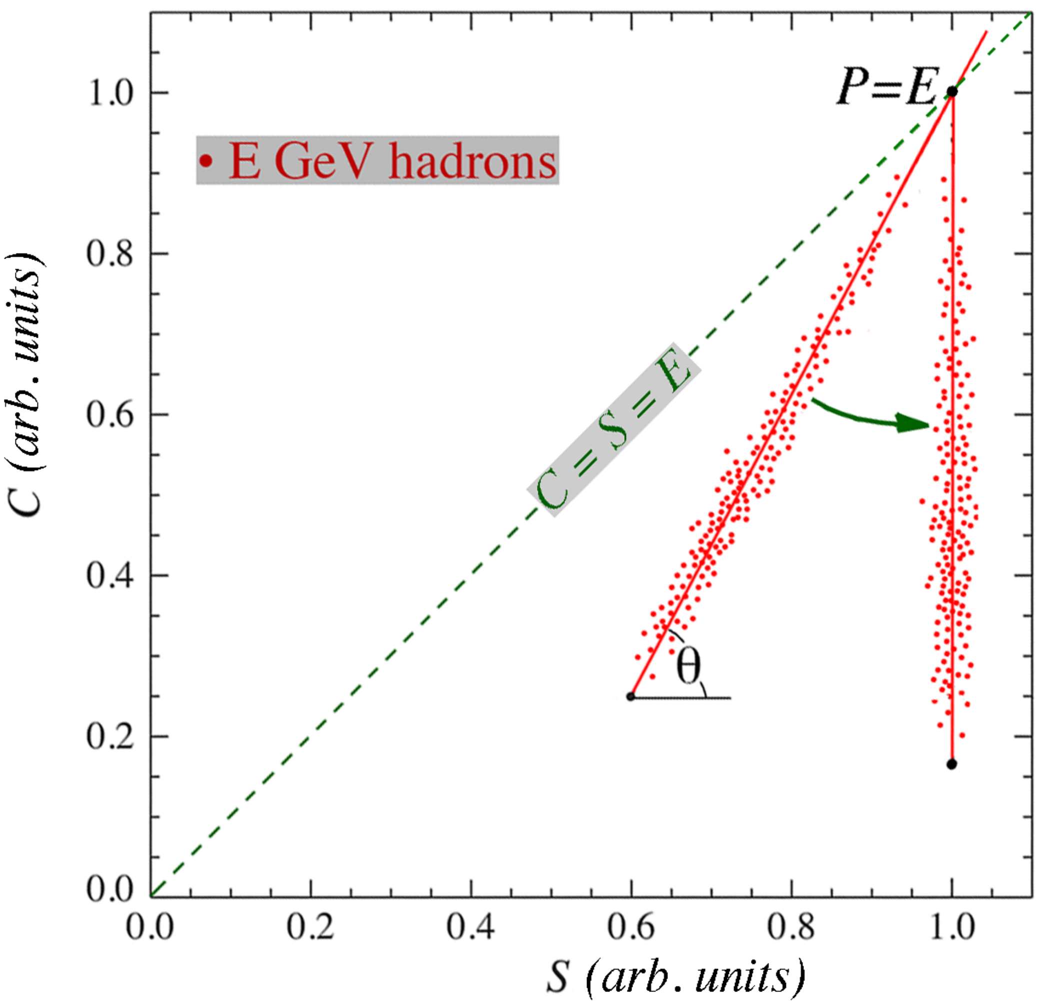
and also independent of the type of hadron!!

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

is universally valid

Principles of dual-readout calorimetry (3)

The rotation method

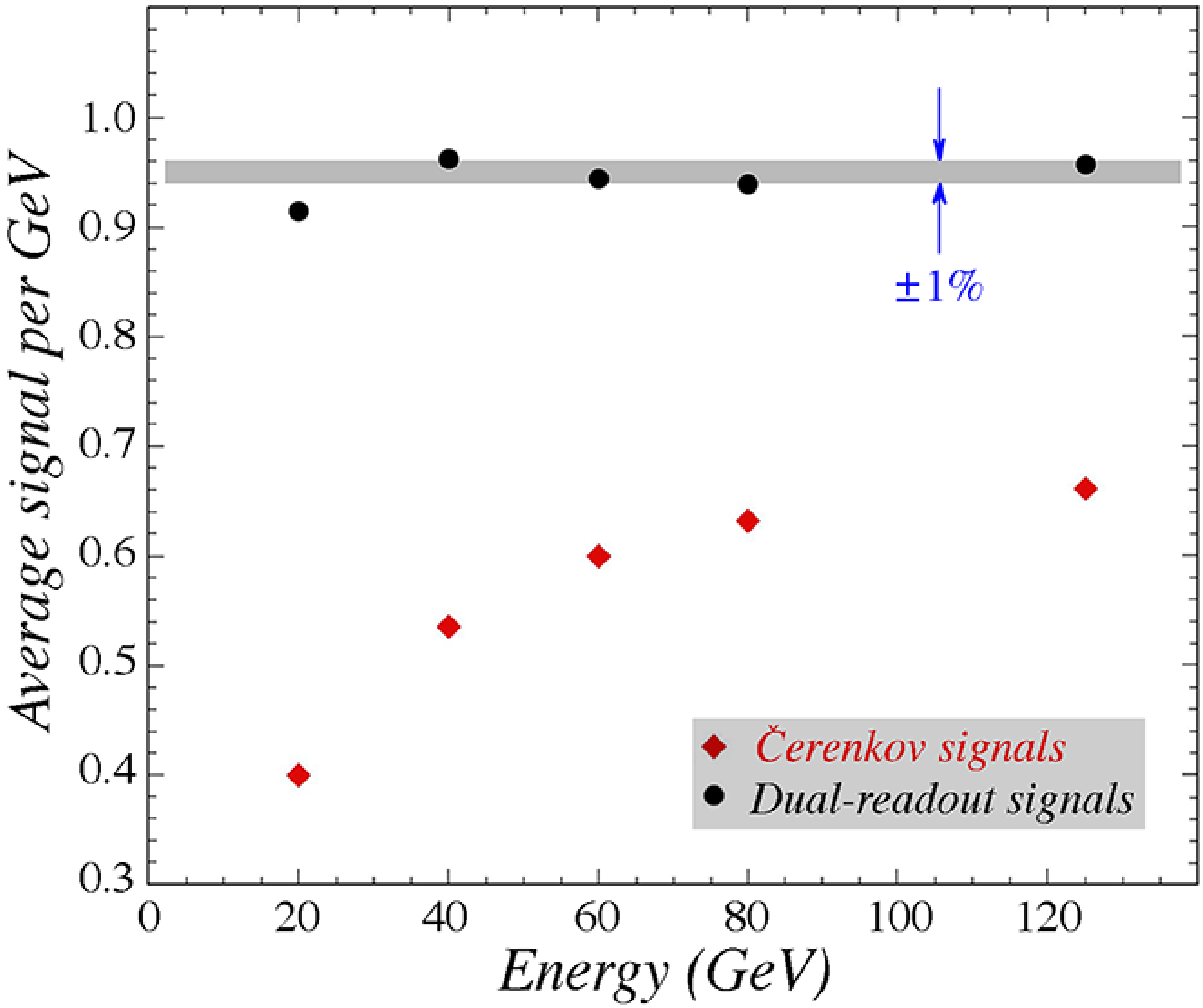


- *Fit experimental data with a straight line*
- *Determine coordinates of P (intersection with C=S line)*
- *Rotate data points about P over angle ($90^{\circ} - \theta$)*
- *Project data points on horizontal (S) axis*

θ is independent of E and particle type!!
→ Don't need this info!!

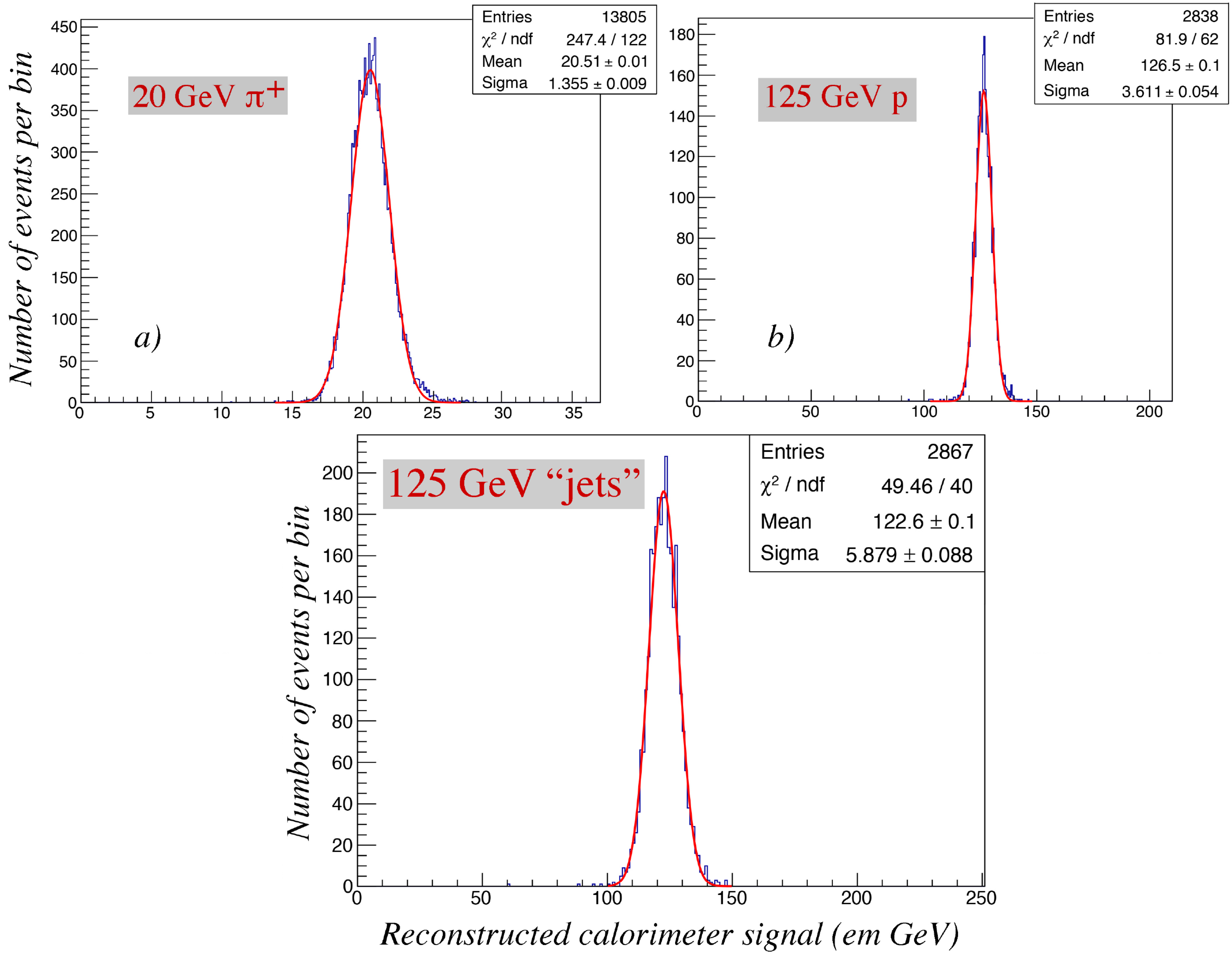
Effects of the dual-readout method

Signal linearity

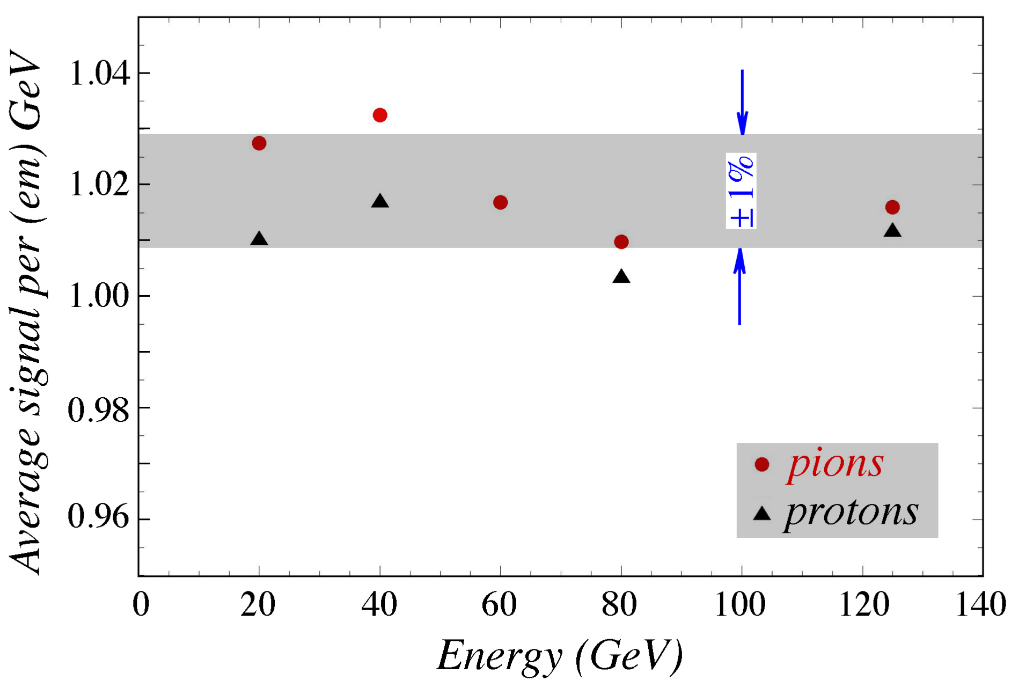


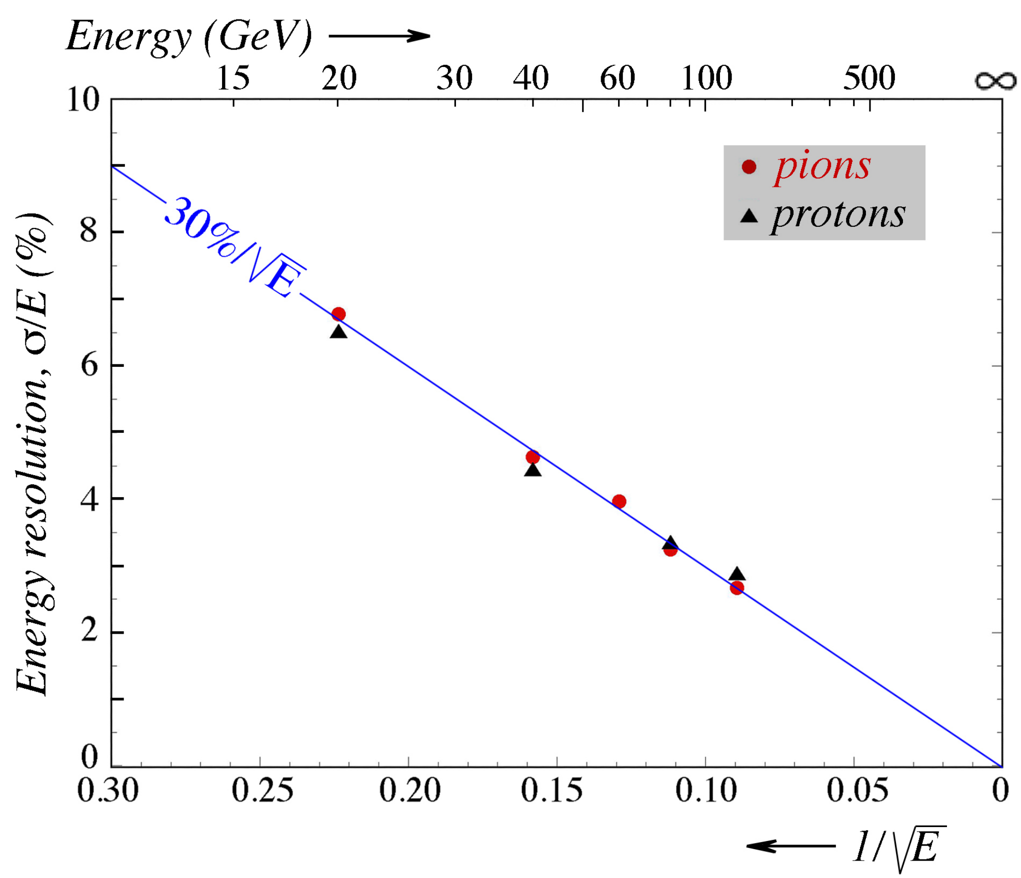
Signal distributions obtained with 1-ton DR fiber calorimeter

(π, p, multi-particle events)



Hadronic signal linearity and energy resolution achieved with the dual-readout method





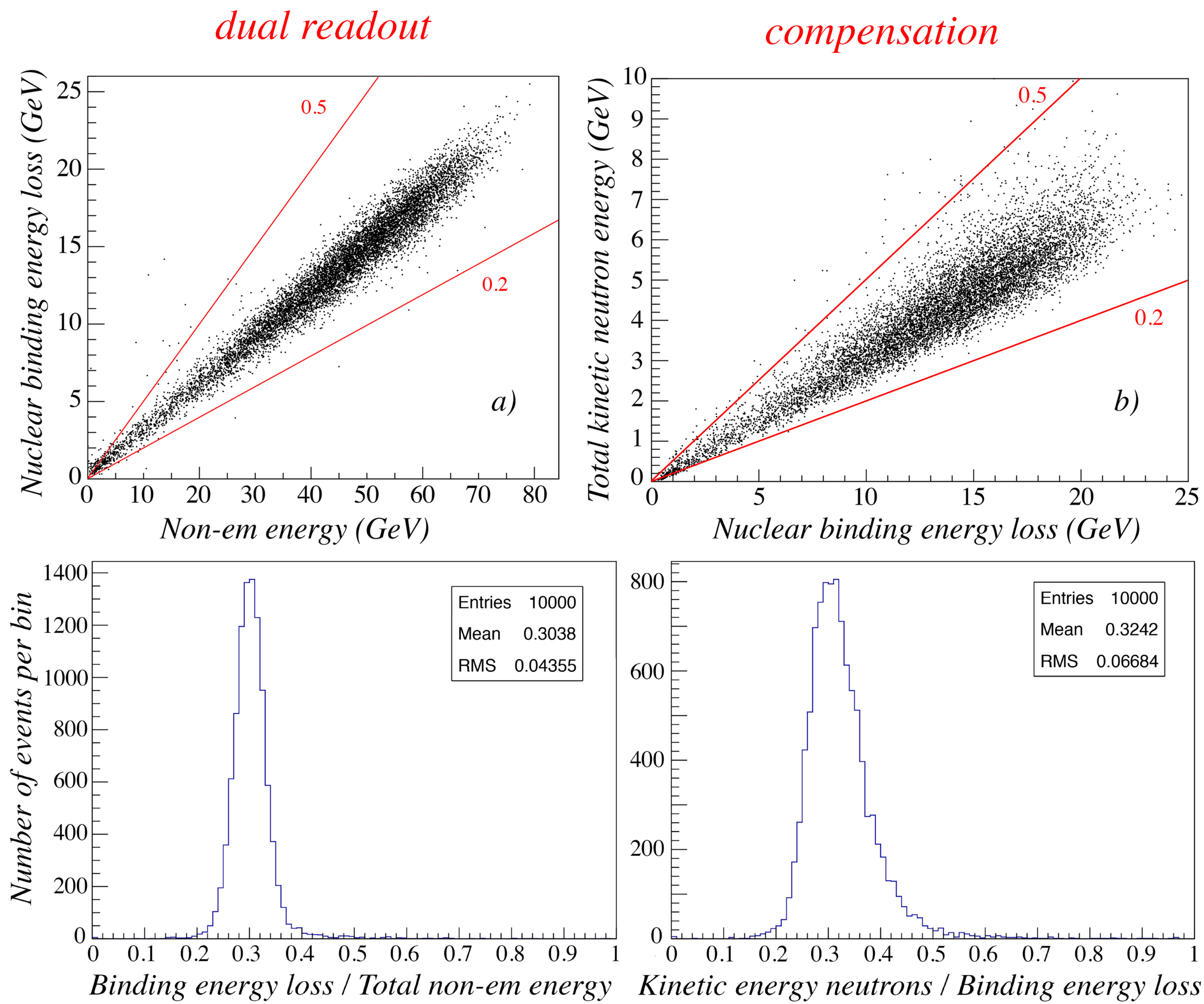
Dual-readout vs Compensation

Both measure a quantity that is correlated to the invisible energy loss

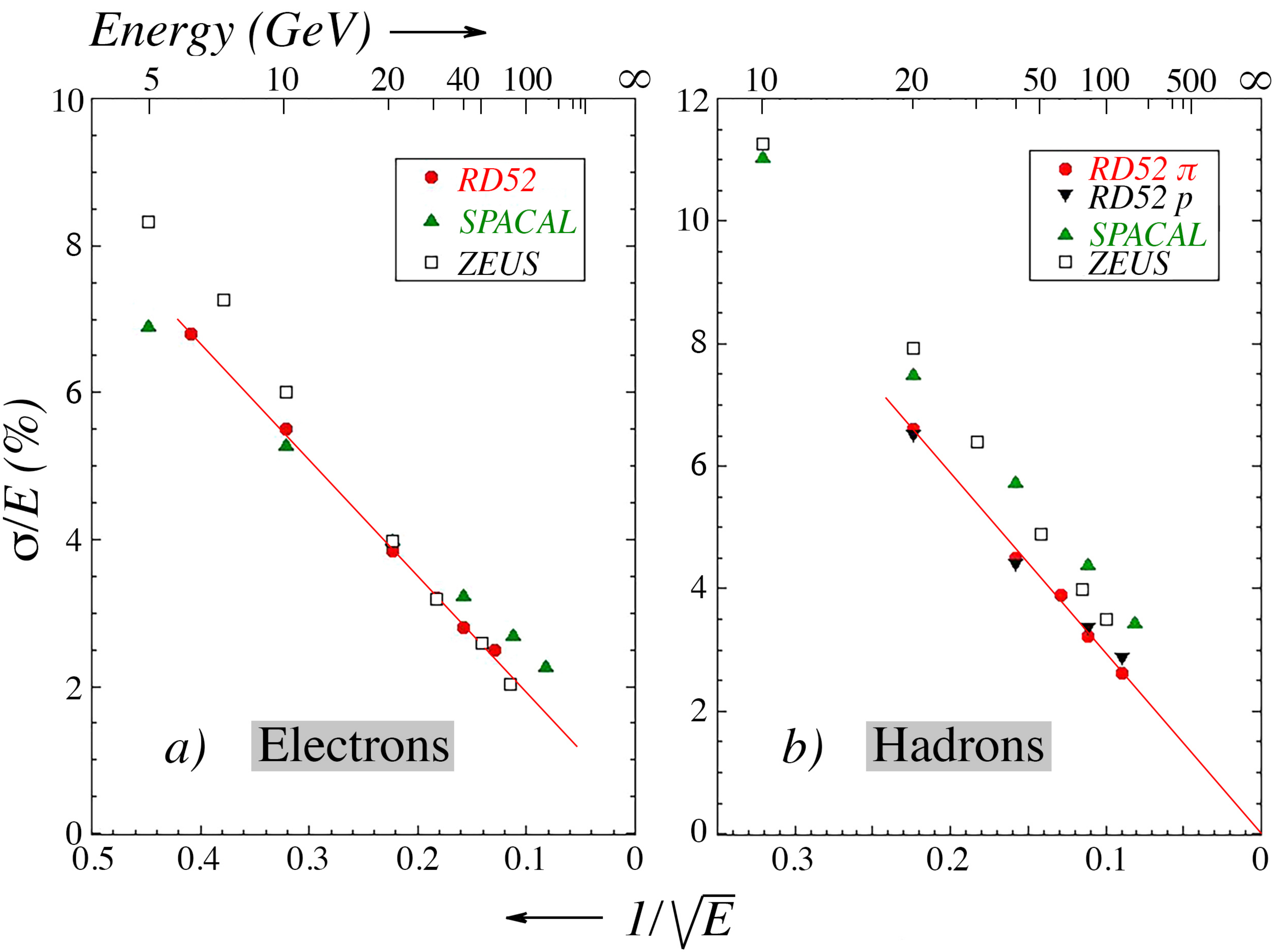
Dual-readout: em shower fraction
Compensation: total kinetic neutron energy

Which correlation is better?

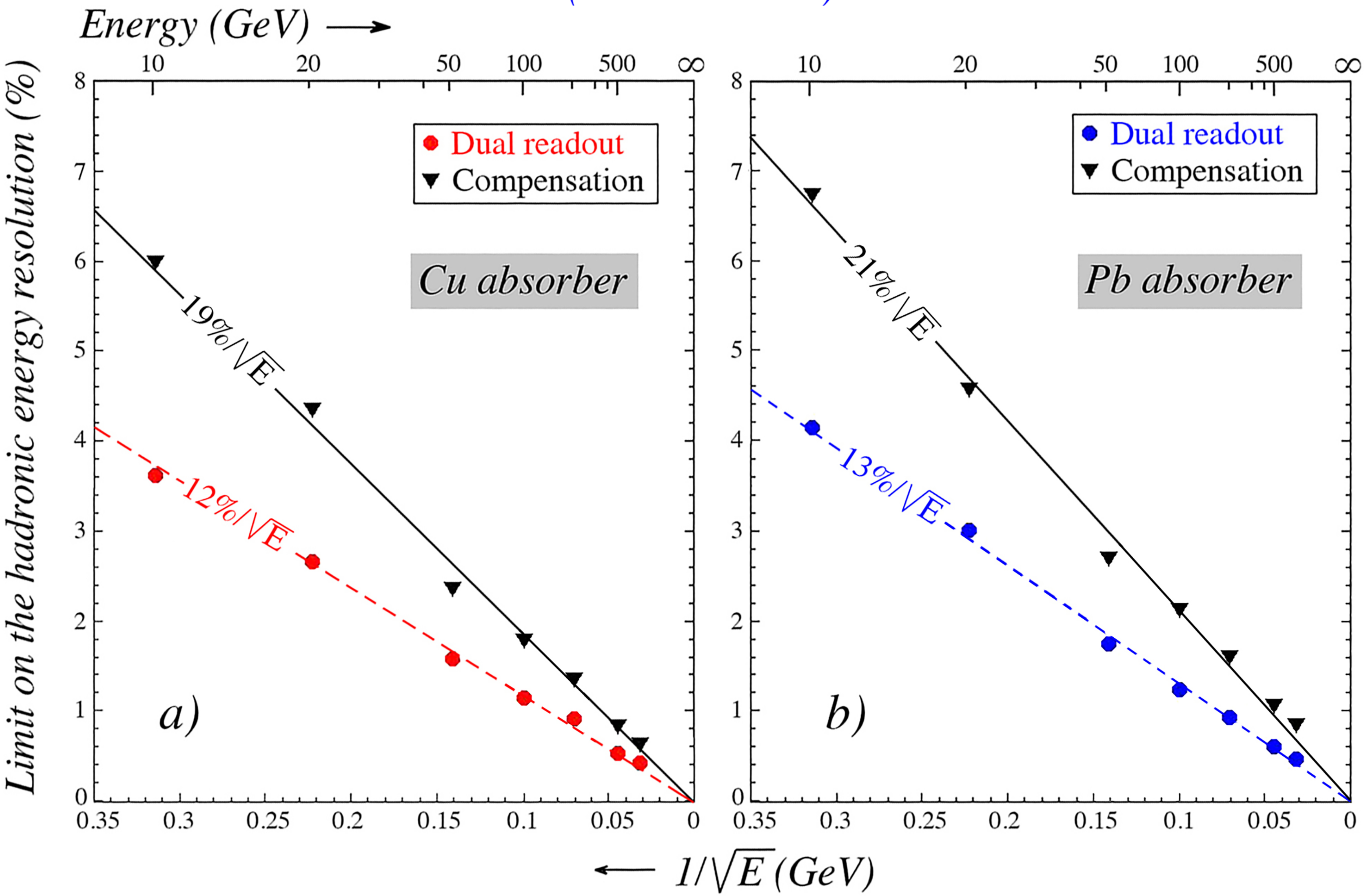
Correlation with invisible energy (100 GeV pion showers)



Dual-readout vs Compensation: Comparison experimental results



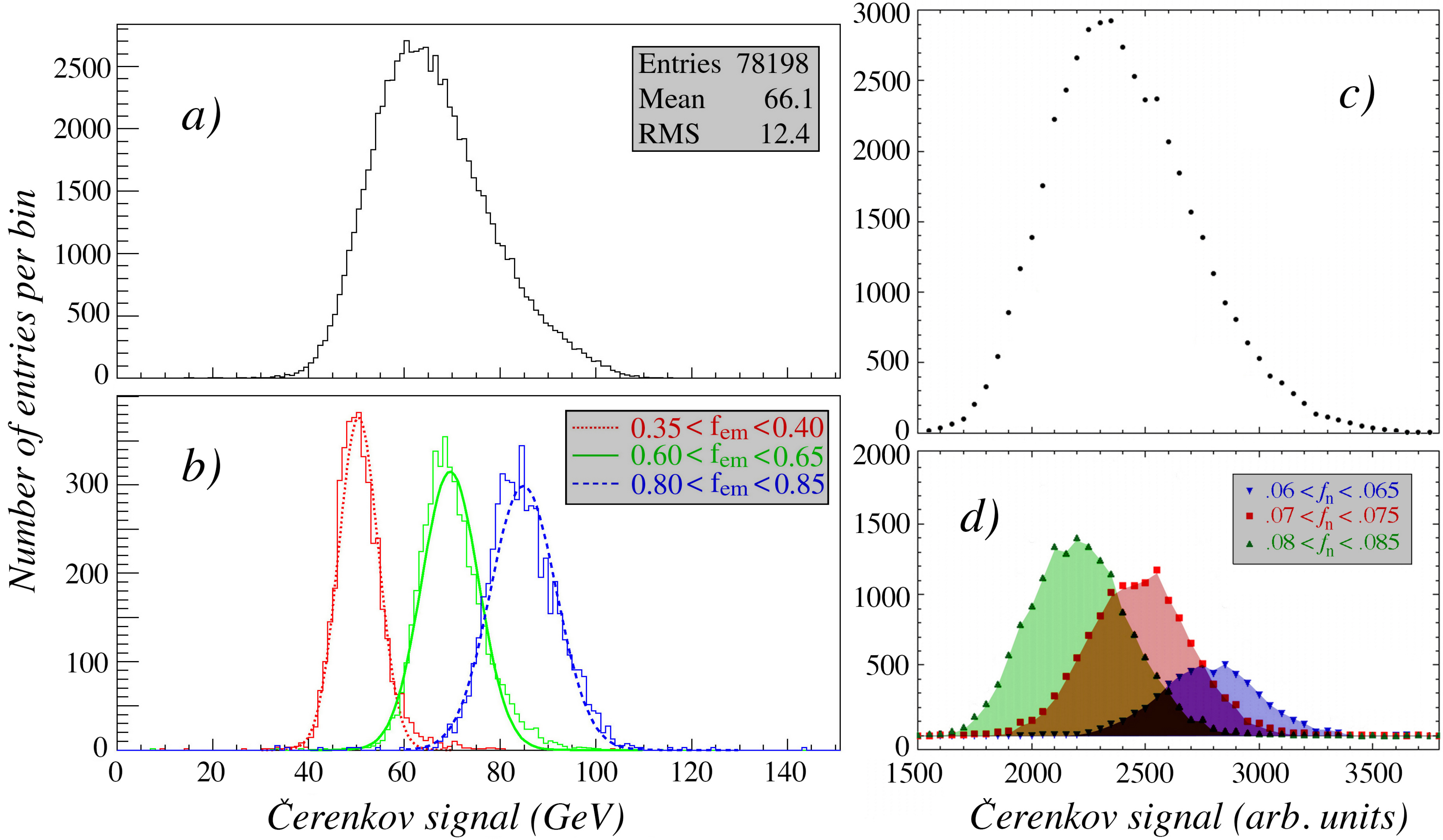
Lower limits on hadronic energy resolution (Monte Carlo)



Comparison dual-readout/compensation with experimental data

em shower fraction

neutrons (time structure)



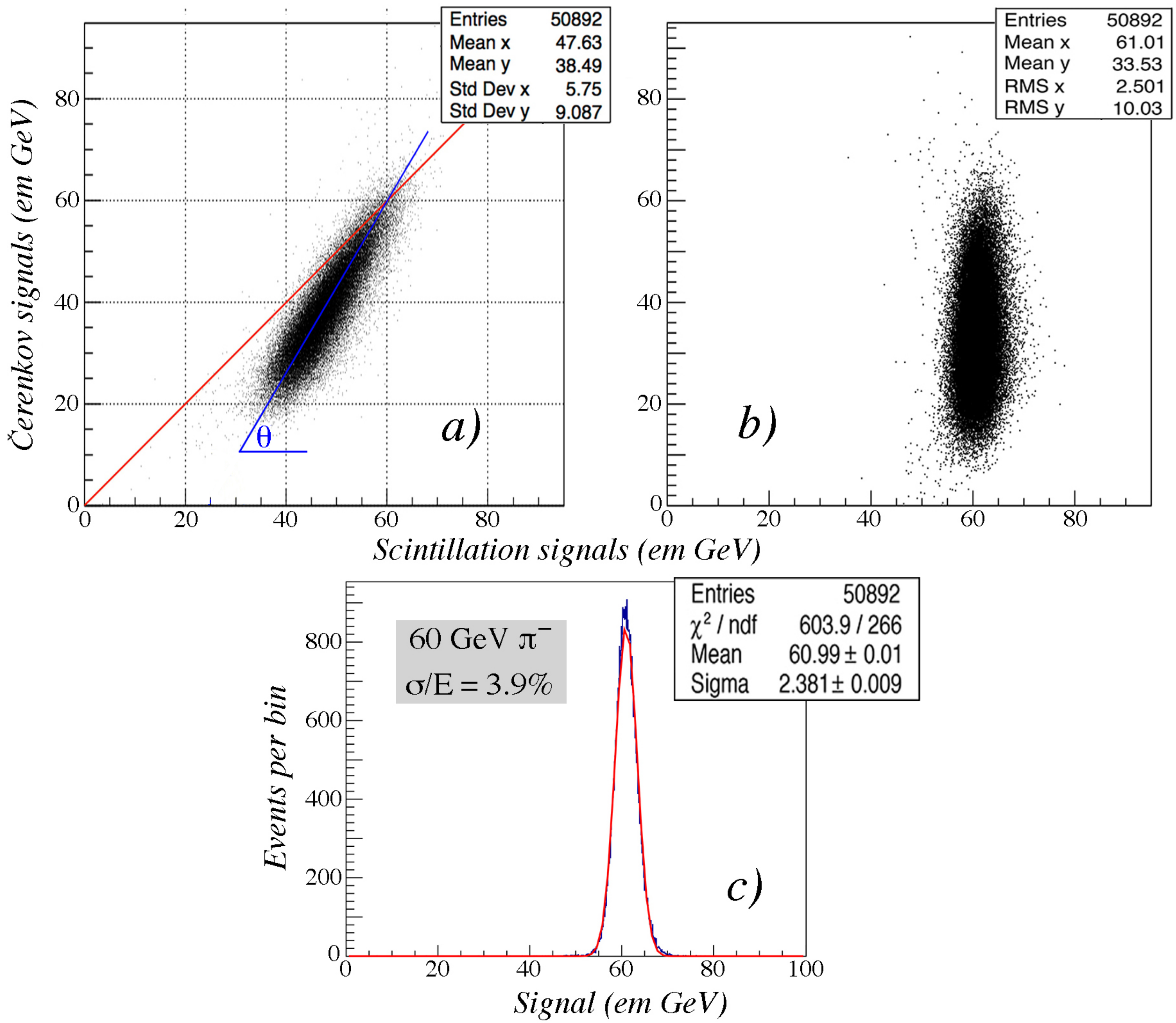
Backup slides

Some applications of the rotation method

hadron data taken October 2015
with the lead based RD52 fiber calorimeter

Applications of the DR rotation method (1)

60 GeV π^-



Applications of the DR rotation method (2)

80 GeV π^+ / p