

Dual-Readout Method Calorimetry (DREAM)

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A brief history of calorimetry (1)

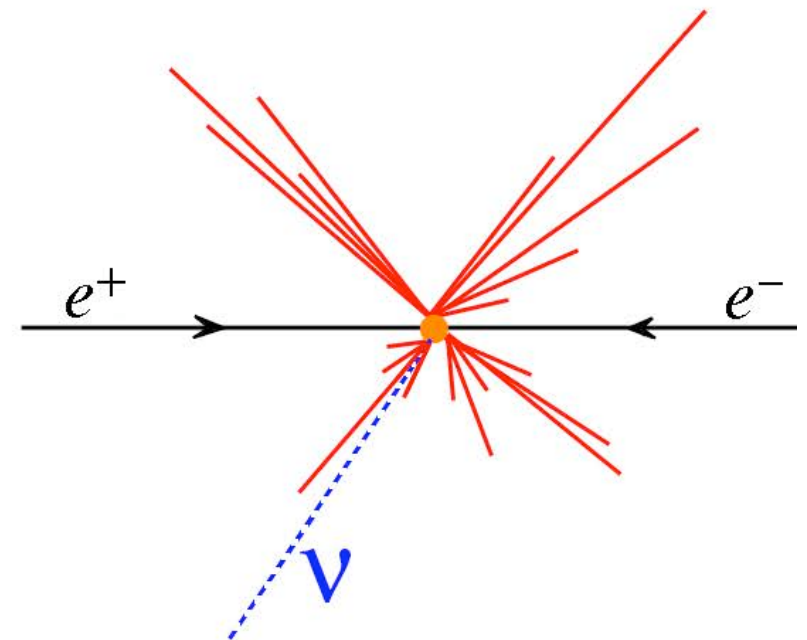
- Particle detection using calorimeter was pioneered in nuclear physics shortly after World War II.
- In **1960s**:
 - the **transition** from the **bubble chamber** era to experiments based on **electronic counters**.
 - In **nuclear spectroscopy**, high **Z** material: **good energy resolution for γ s**. (e.g. NaI(Tl), Ge)
- **Sampling calorimeters**: the construction of large calorimeters.
 - e.g. absorber: Pb (short radiation length), active material: plastic scintillator, LAr, LKr.
 - NA48 (Pb-LKr): $3.5\%/\sqrt{E}$, KLOE (Pb-fibers): $4.8\%/\sqrt{E}$ (Good energy resolution for e, γ) — 1990s.

A brief history of calorimetry (2)

- In **1970s**, the new tasks of calorimeter: the **measurement of jet energy** and **missing E_T** at the collider experiments (ISR, PETRA) and **particle ID** (e , γ , μ , ν).
- **Calorimeters** worked nicely for such tasks and **became the main detector** at accelerator based particle physics experiments.
- However, **the energy resolution of hadrons** was considerably **worse than** that of **e and γ** . The understanding of hadron calorimeter performance was not good enough.
- Since **~ 1985** , the **efforts to understand the performance of hadron calorimeters** has been doing both experimentally and at the Monte Carlo level.

Why Calorimetry?

- Energy measurement: **charge** and **neutral** particles
- Provide **energy flow** information:
 - total amount of energy in an event
 - Missing E_T (geometric imbalances)
 - Jet production
- **Fast information**: event selection in real time (trigger)



Performance of Calorimeter

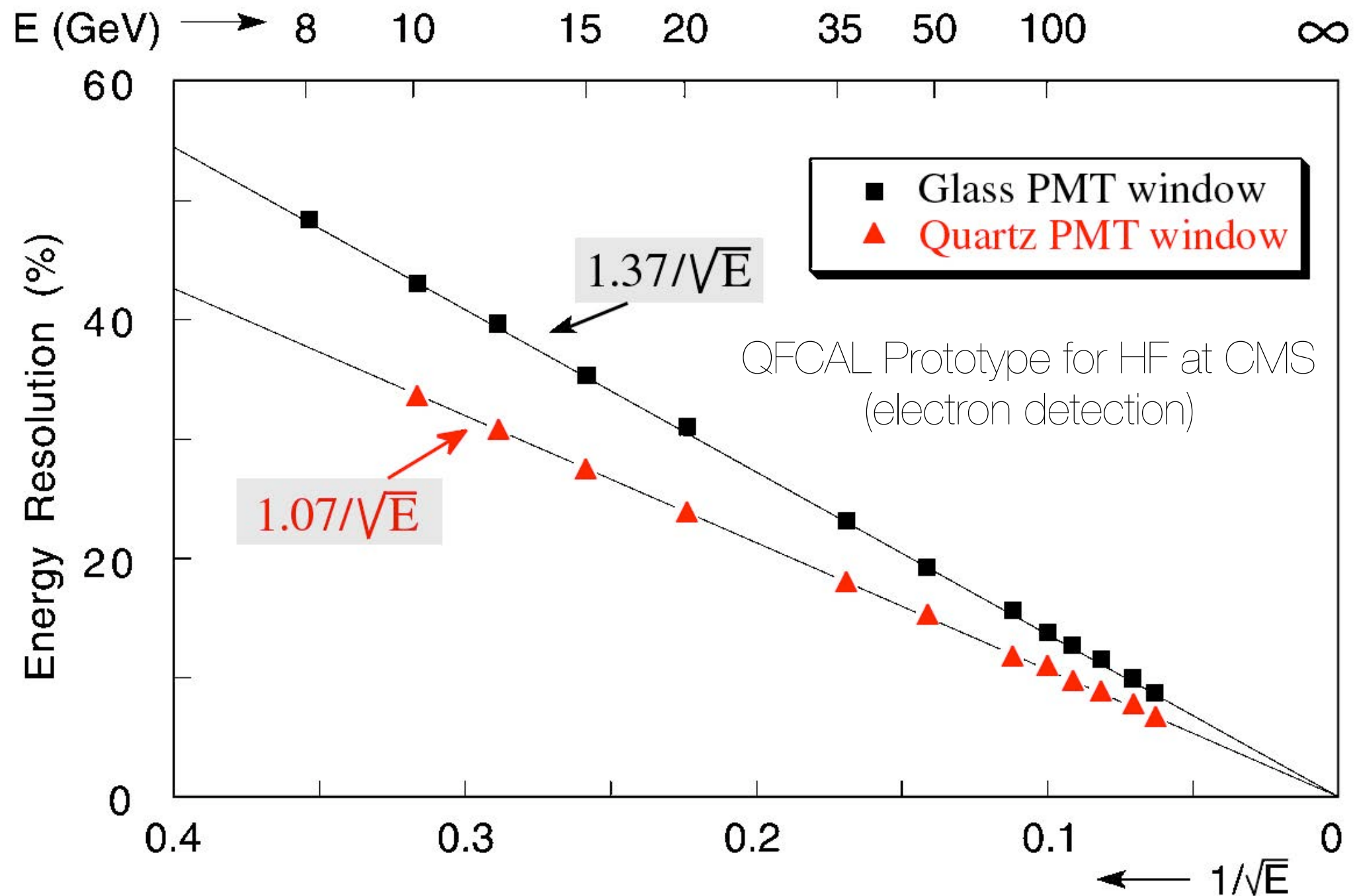
- improves as energy increases
 - Energy resolution follows Poisson statistics
 - If a particle with energy E create signal,

$$E \propto n \text{ (\# of signal quanta)} \rightarrow \sigma \propto \sqrt{n}$$

$$\text{Energy resolution } (\sigma/E) \propto 1/\sqrt{n} \propto 1/\sqrt{E}$$

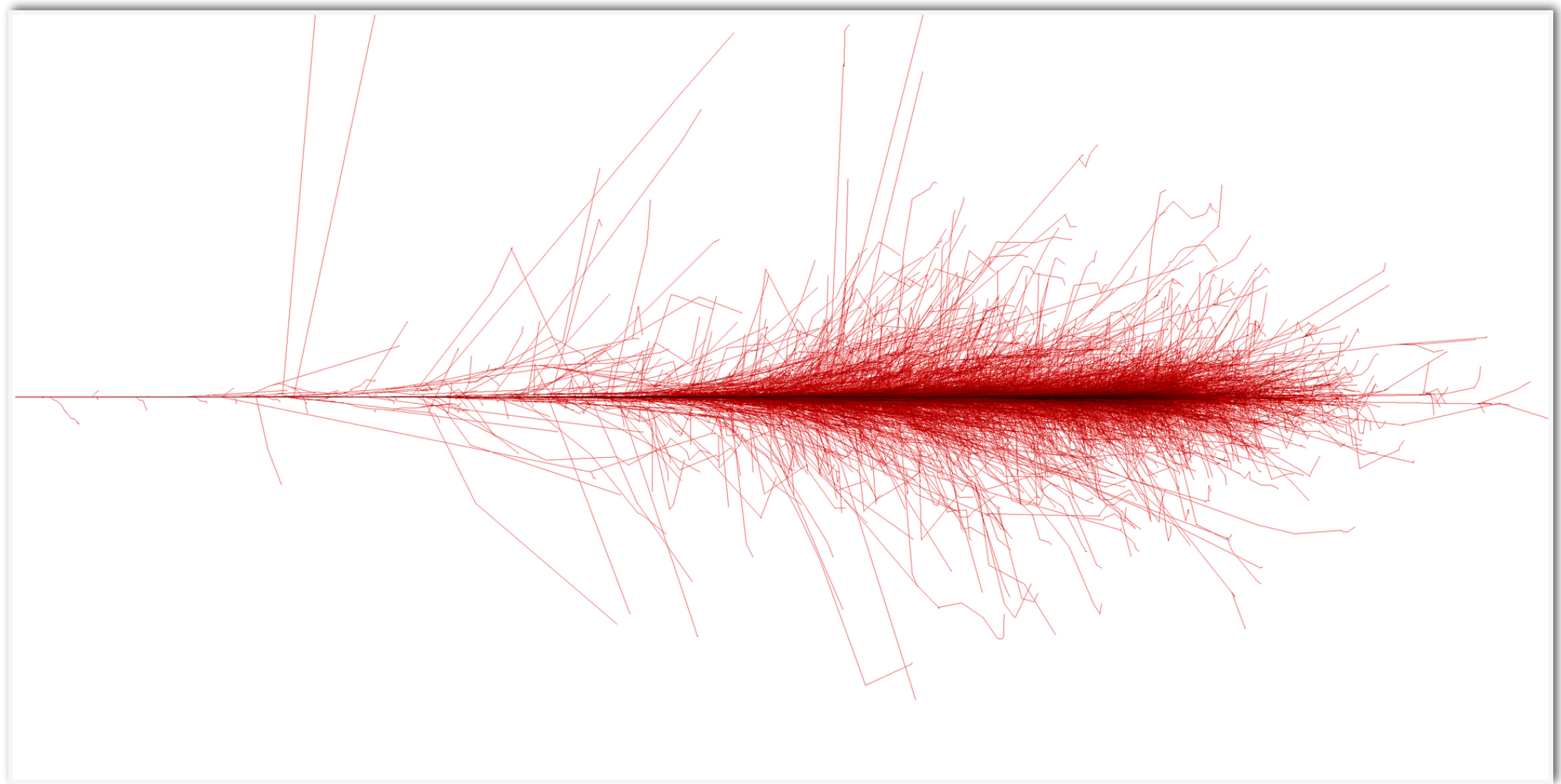
Ideal Calorimeter

Energy Resolution Scales as $1/\sqrt{E}$



Electromagnetic Shower (e, γ)

100 GeV Photon

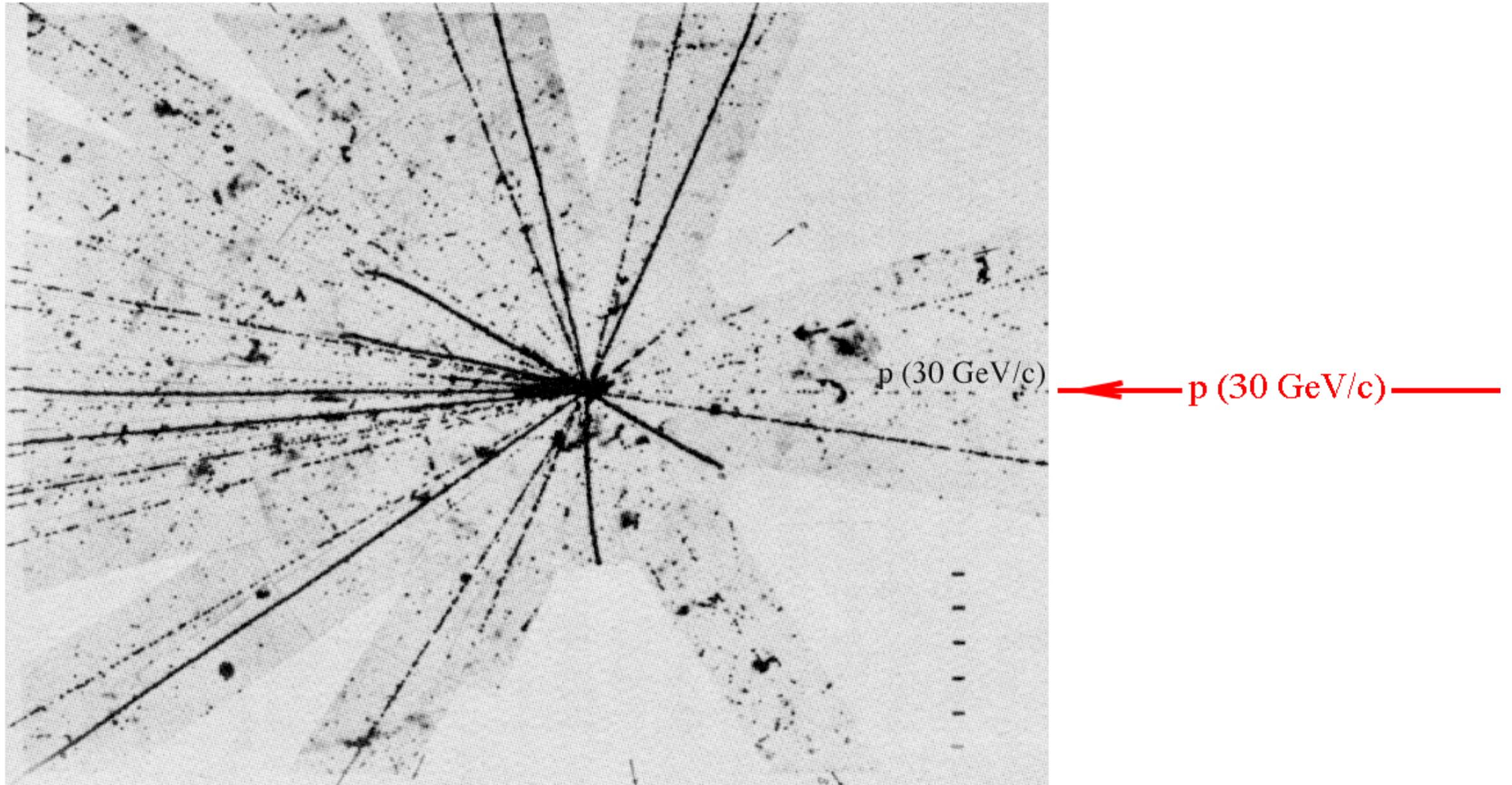


Calorimeter signal is directly proportional to the energy of incoming particles

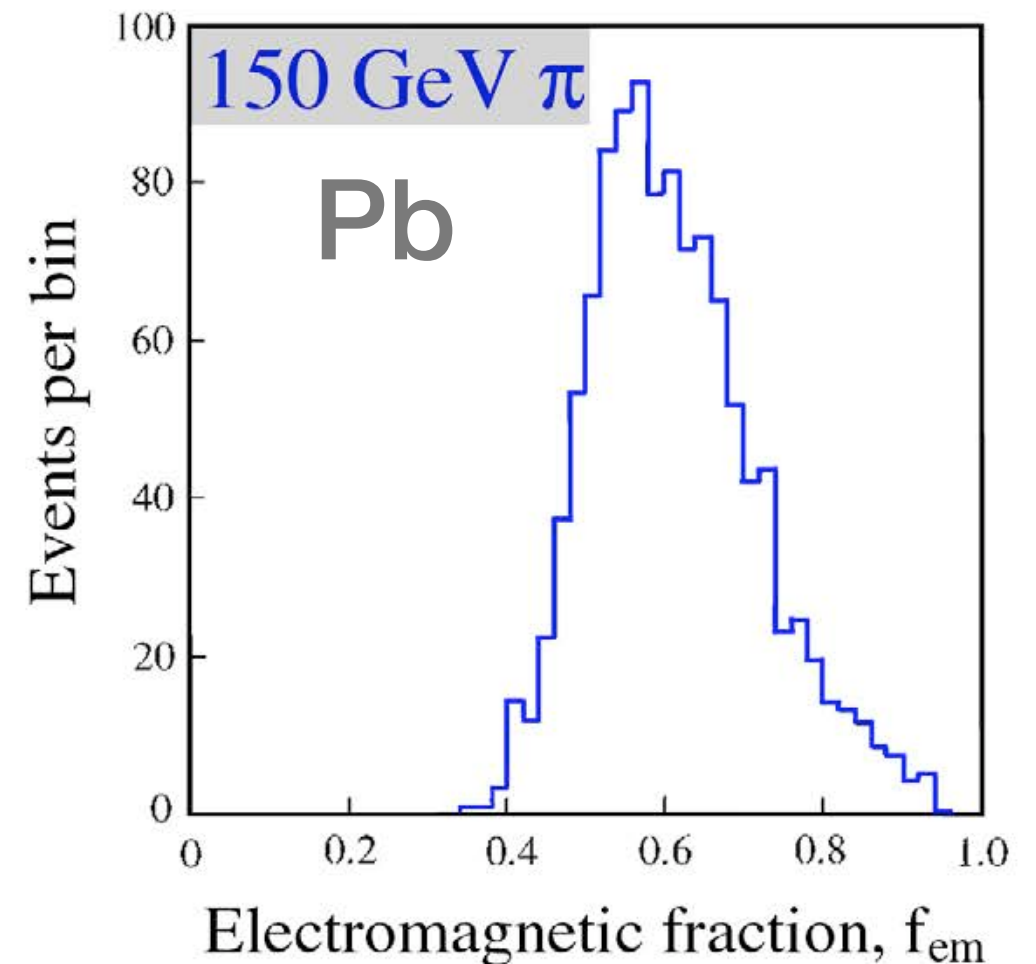
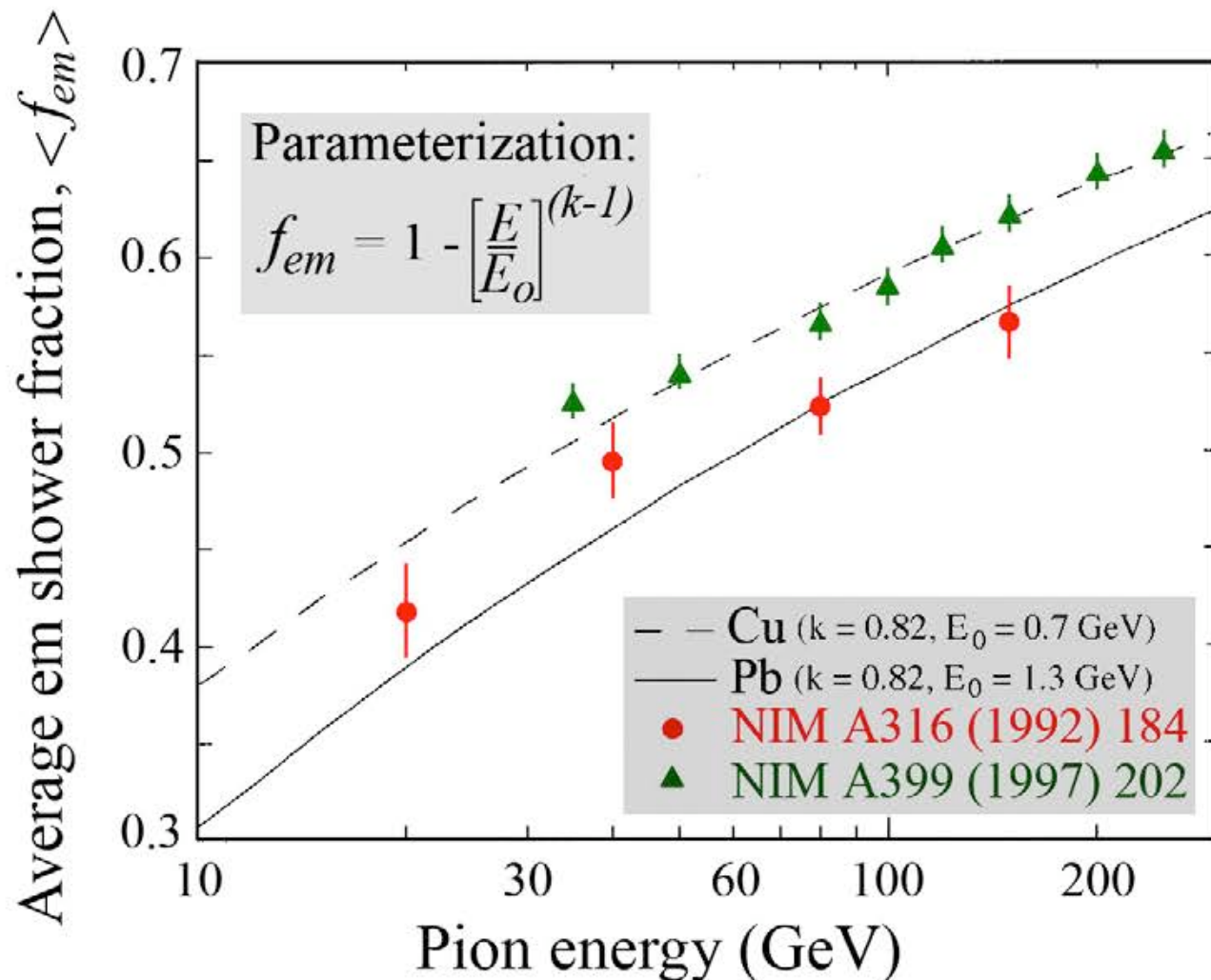
Electromagnetic calorimeters are well understood and offer very precise energy measurement (e, γ detection)

“Hadron Calorimeters are usually far from ideal”

Hadron Shower



Fluctuations of the electromagnetic shower fraction (f_{em})



The em fraction depends on (on average):

- pion energy
- the type of absorber material

Event-to-event fluctuation

Non-Gaussian, Asymmetric

Consequence of Main Fluctuations in Hadron Showers

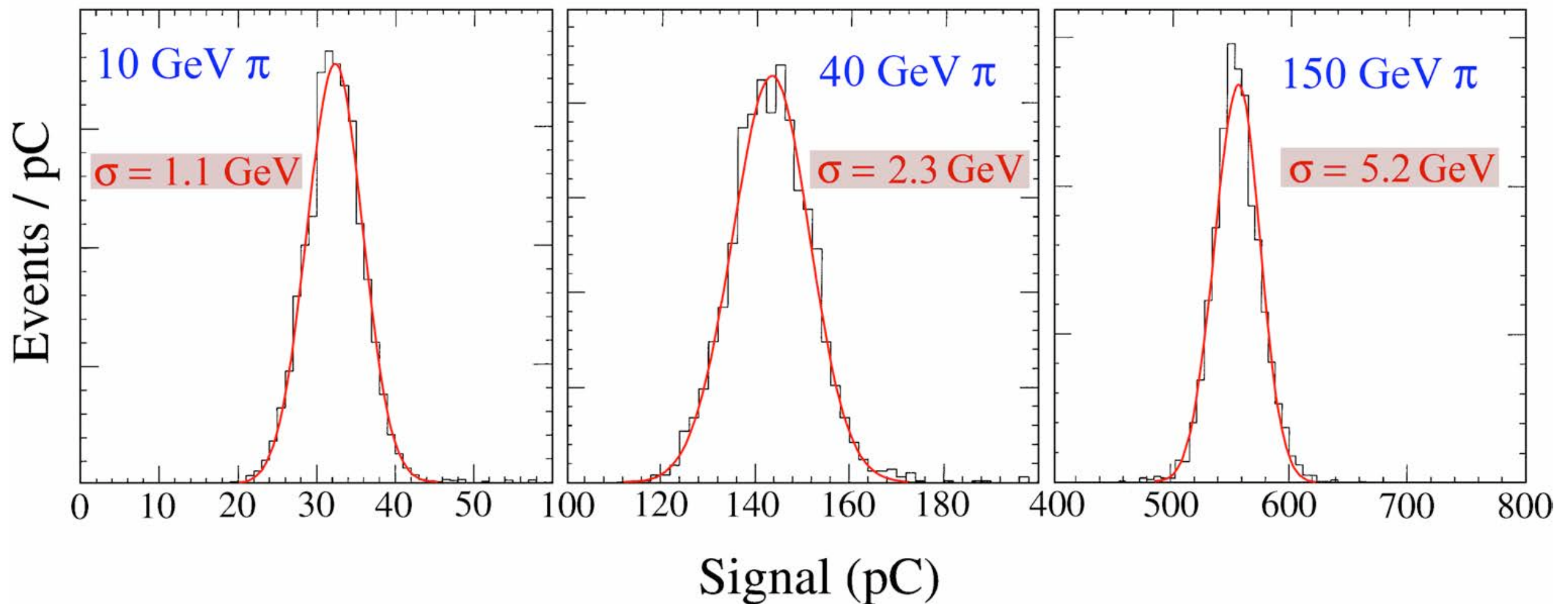
- **Energy Scale** is different from electron, energy dependent
- **Non-linearity**
- **Non-Gaussian** response function
- **Poor energy resolution**

Different Approaches to improve hadronic calorimetry

- Compensating calorimeters
 - designing em and non-em responses are equal ($e/h = 1$)
 - hadronic energy resolution of SPACAL: $30\%/\sqrt{E}$
- Dual-Readout calorimeters
 - measuring f_{em} event by event using Cerenkov light
 - this approach has been proved experimentally last 15 years

SPACAL (Pb/Scintillator Calorimeter)

Hadronic signal distributions in a compensating calorimeter



from: NIM A308 (1991) 481

Pros & Cons of Compensating Calorimeter

- Pros

- Same energy scale for electrons, hadrons and jets.
- Calibrate with electrons and you are done.
- Excellent hadronic energy resolution (SPACA: $30\%/\sqrt{E}$)
- Linearity, Gaussian response function.

- Cons

- Small sampling fraction (2.4% in Pb/plastic)
 - ➔ limited em energy resolution
- Compensating relies on detecting neutrons
 - ➔ Large integration volume
 - ➔ Long integration time (~ 50 ns)

How can we improve the performance of hadron calorimeters?

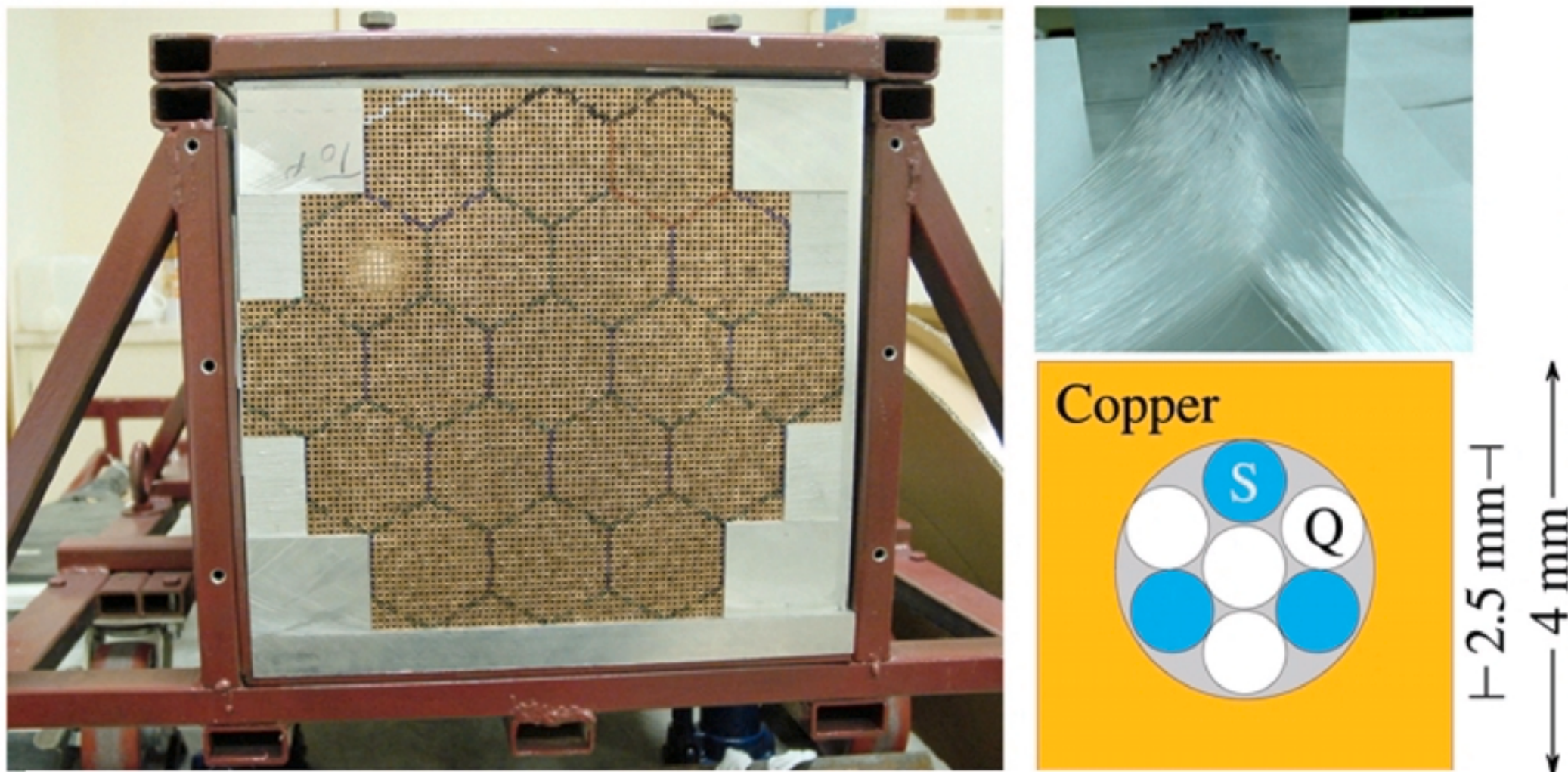
- Dominant fluctuation: f_{em}
 - EM shower component almost exclusively produces Cerenkov light
 - 80 % of non-em energy deposited by non-relativistic particle (non-em component: mainly soft proton)

Dual-REAdout Method (DREAM)

Measure f_{em} event-by-event with Cerenkov and Scintillation signals

The Prototype DREAM Detector

DREAM: Structure



- *Some characteristics of the DREAM detector*

- **Depth** 200 cm ($10.0 \lambda_{\text{int}}$)
- Effective **radius** 16.2 cm ($0.81 \lambda_{\text{int}}$, $8.0 \rho_M$)
- **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

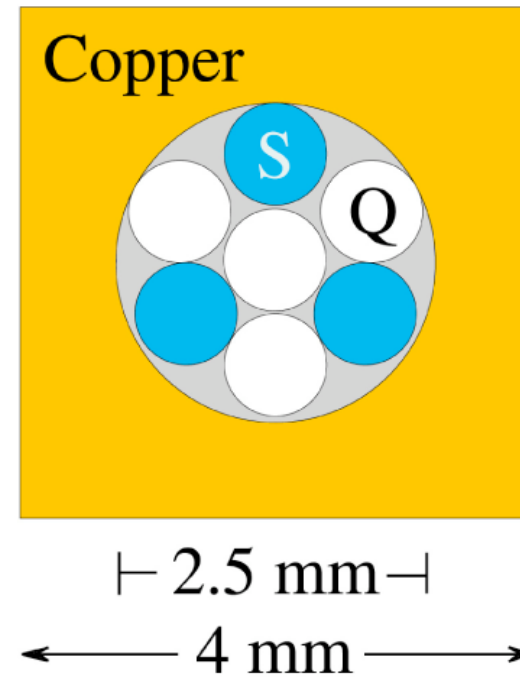


Figure 5: The basic building block of the DREAM detector is a $4 \times 4 \text{ mm}^2$ extruded hollow copper rod of 2 meters length, with a 2.5 mm diameter central hole. Seven optical fibers (4 undoped and 3 scintillating fibers) with a diameter of 0.8 mm each are inserted in this hole, as shown.

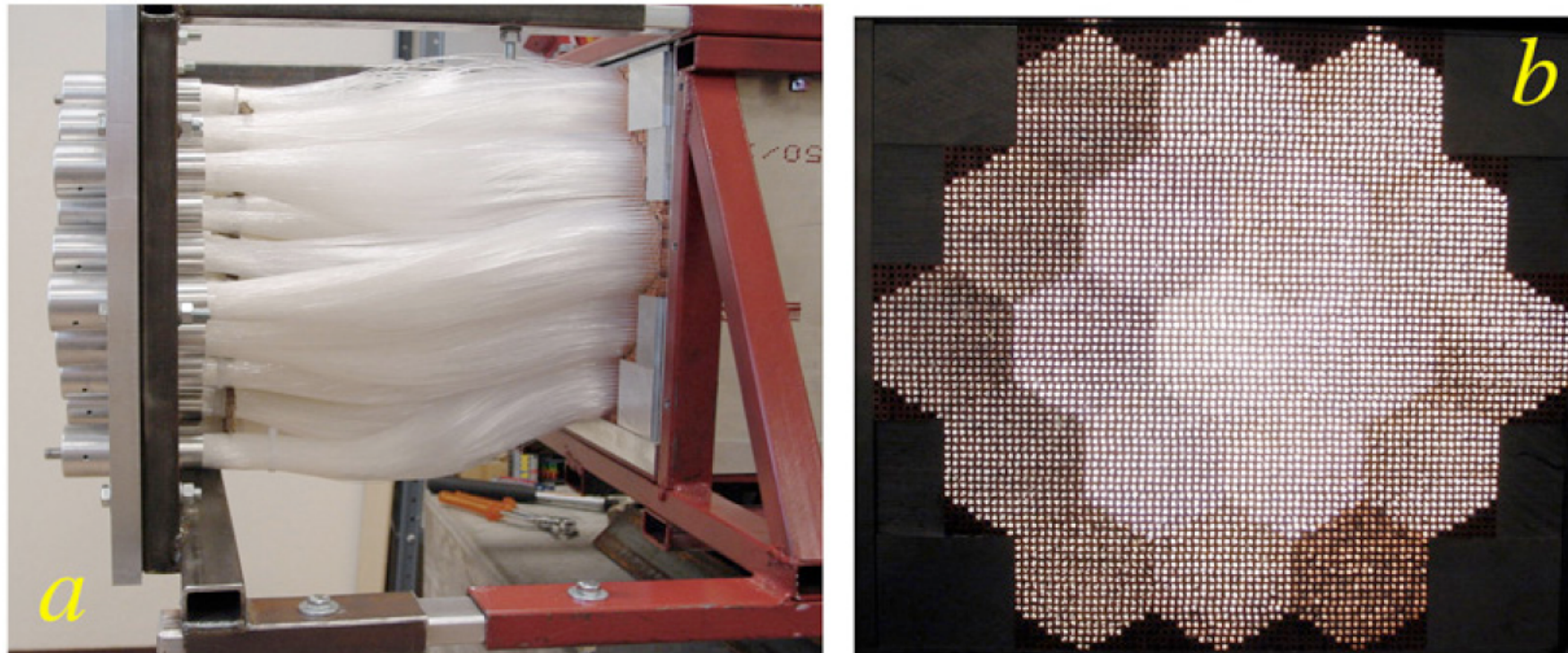


Figure 6: The DREAM detector. Shown are the fiber bunches exiting from the rear face of the detector (*a*) and a picture taken from the front face while the rear end was illuminated (*b*). The hexagonal readout structure is made visible this way.

Muon Detection

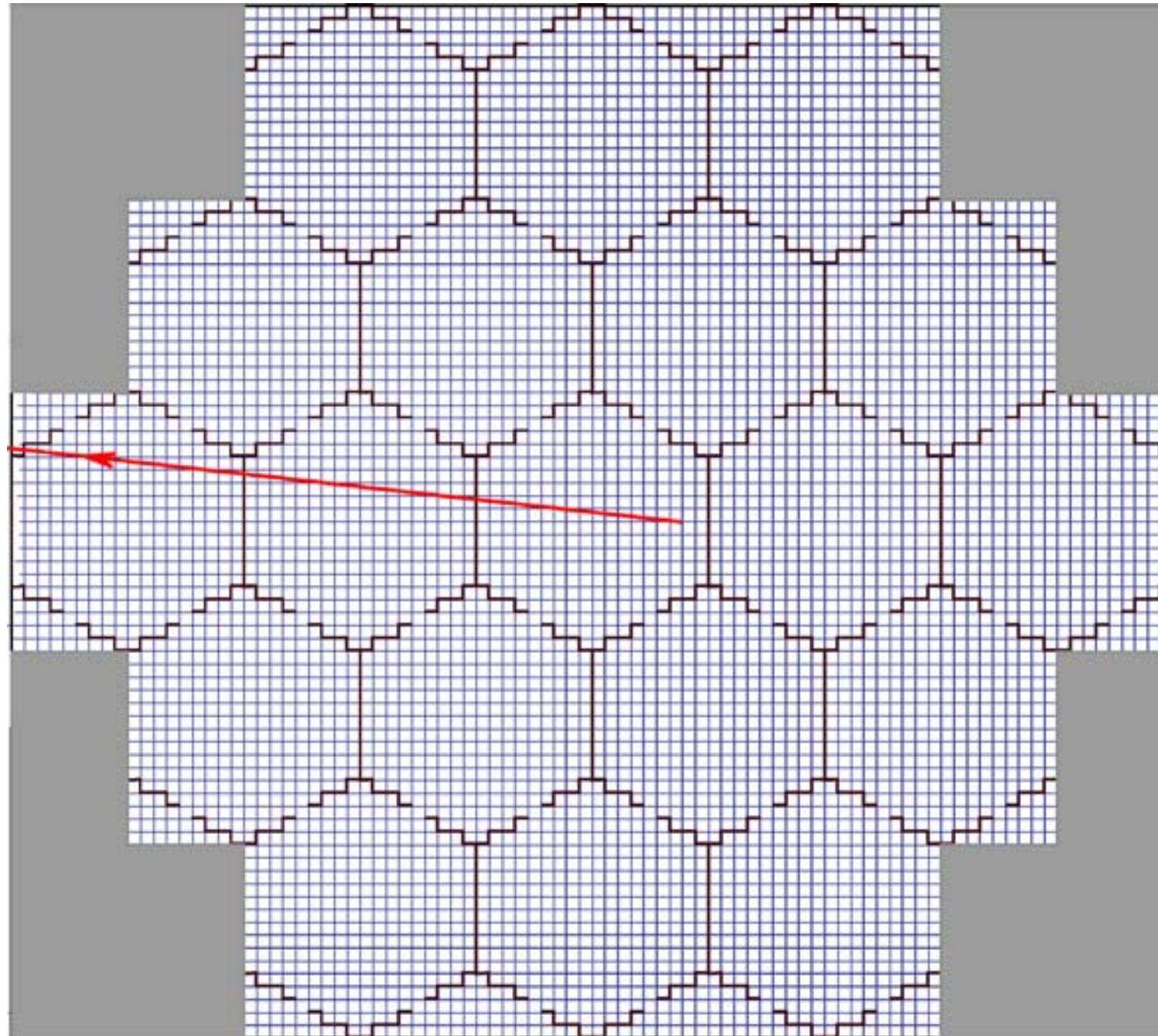
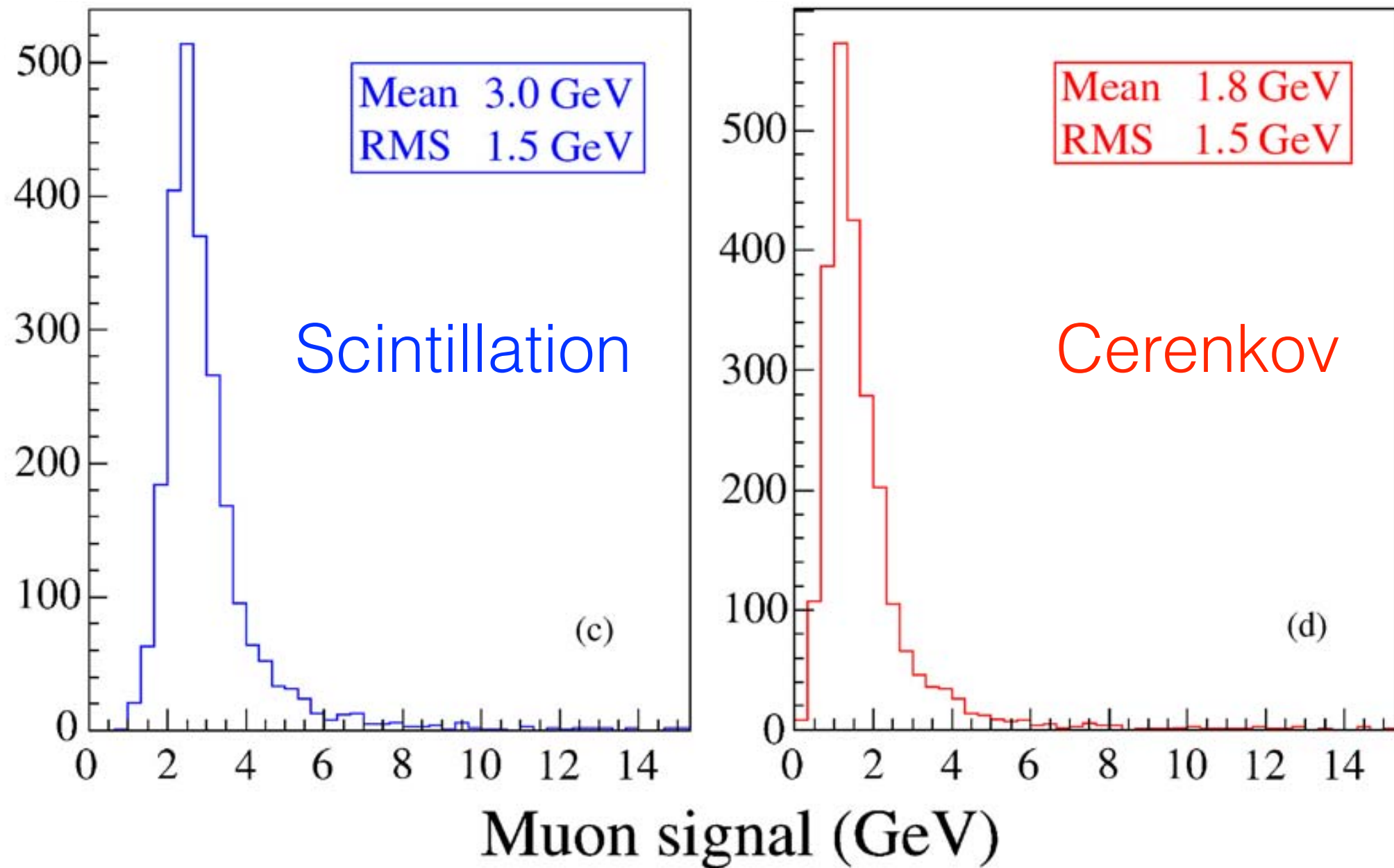


Fig. 2. Layout of the DREAM calorimeter. The detector consists of 19 hexagonal towers. A central tower is surrounded by two hexagonal rings, the Inner Ring (6 towers) and the Outer Ring (12 towers). The towers are not longitudinally segmented. The arrow indicates the (projection of the) trajectory of a muon traversing the calorimeter oriented in position $D(6^\circ, 0.7^\circ)$.

Distributions of the measured energy loss of 100 GeV muons



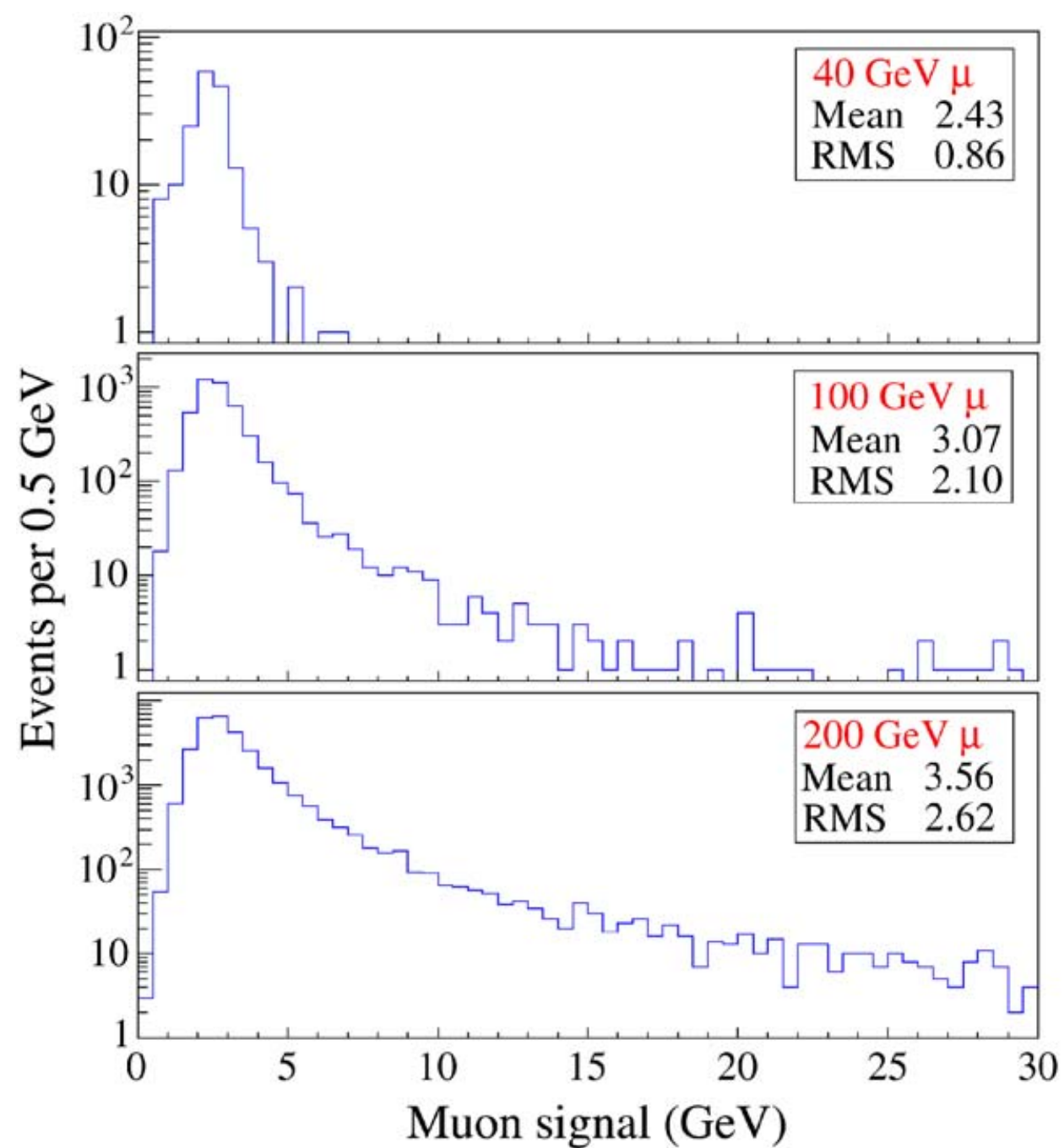


Fig. 14. Signal distributions for 40, 100 and 200 GeV muons, measured with the scintillating fibers in the DREAM calorimeter.

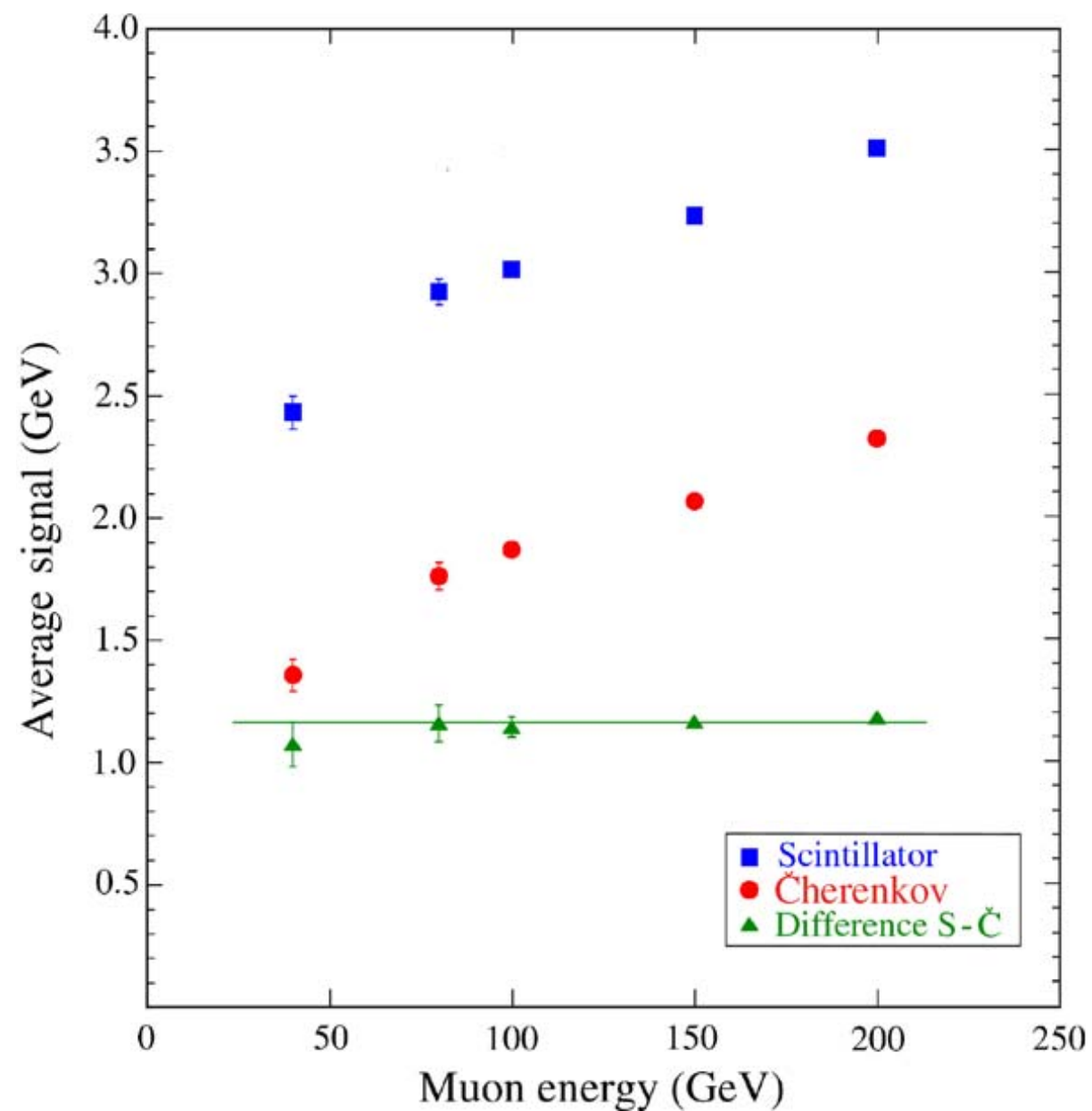


Fig. 18. Average signal from muons traversing the DREAM calorimeter, as a function of the muon energy. The detector was oriented in position D(6° , 0.7°). Results are given separately for the scintillating and the Cherenkov fibers. Also shown is the *difference* between the average signal values from both media.

Electron Detection



Fig. 4. Schematic view of the experimental setup in the beam line in which the DREAM detector was tested with electrons (see text for details).

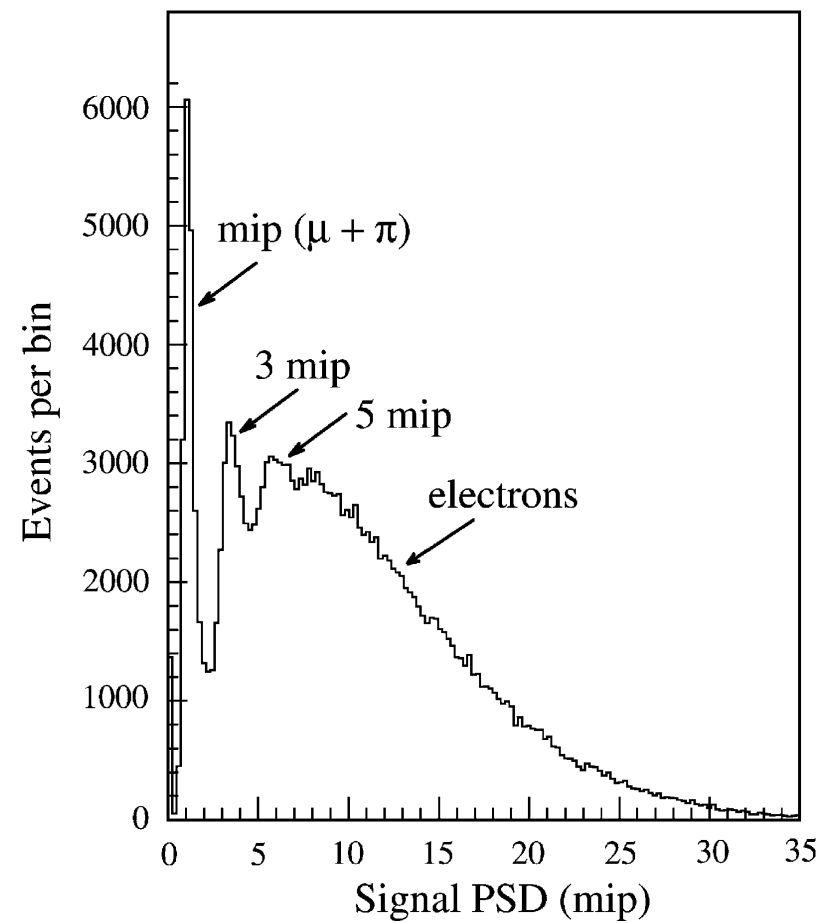


Fig. 5. Signal distribution for events recorded in the PSD for the 100 GeV electron beam. See text for details.

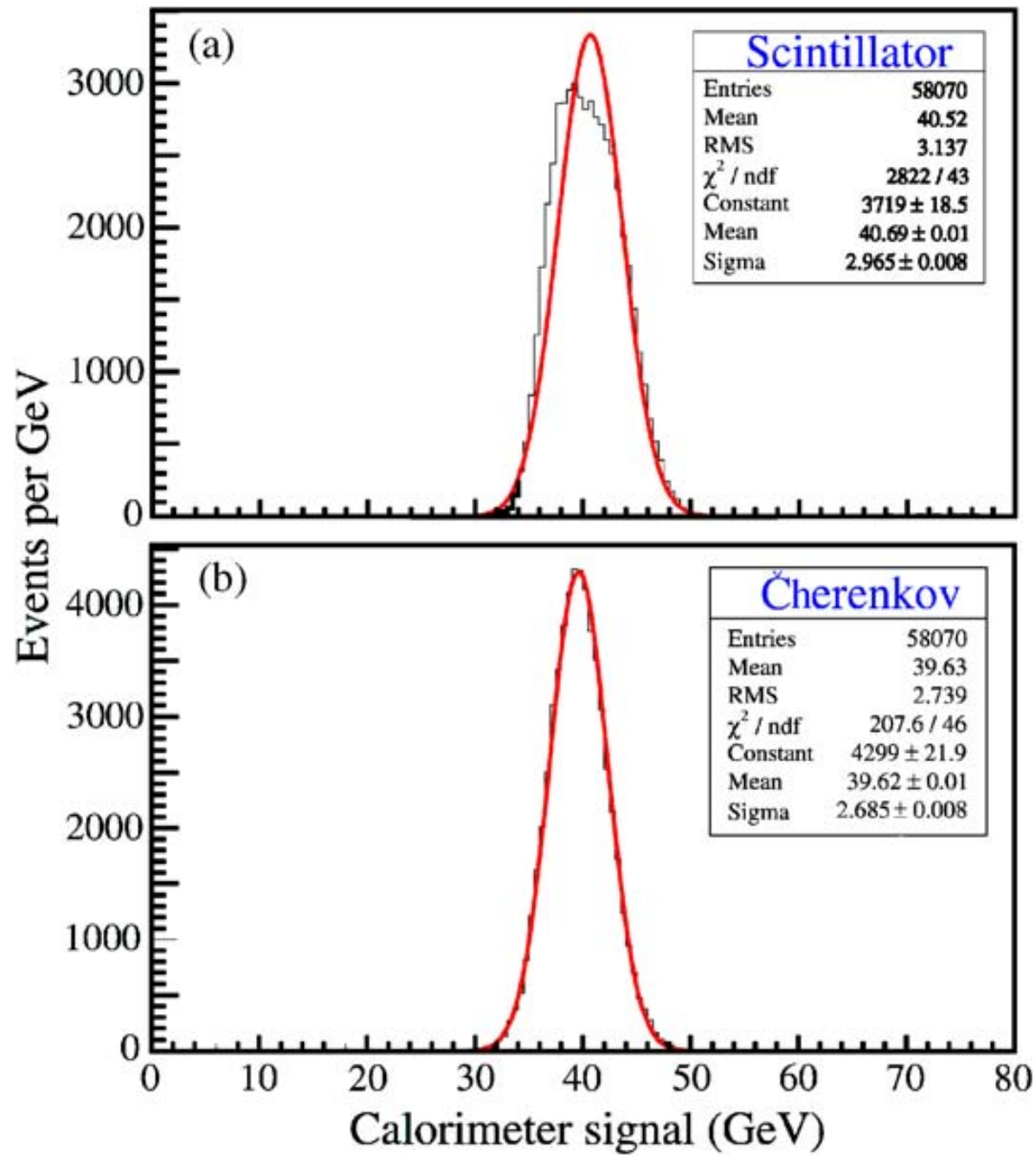


Fig. 7. Signal distributions for 40 GeV electrons, recorded from the scintillating (a) and the Cherenkov (b) fibers, with the DREAM calorimeter in the untilted position, A(2°, 0.7°).

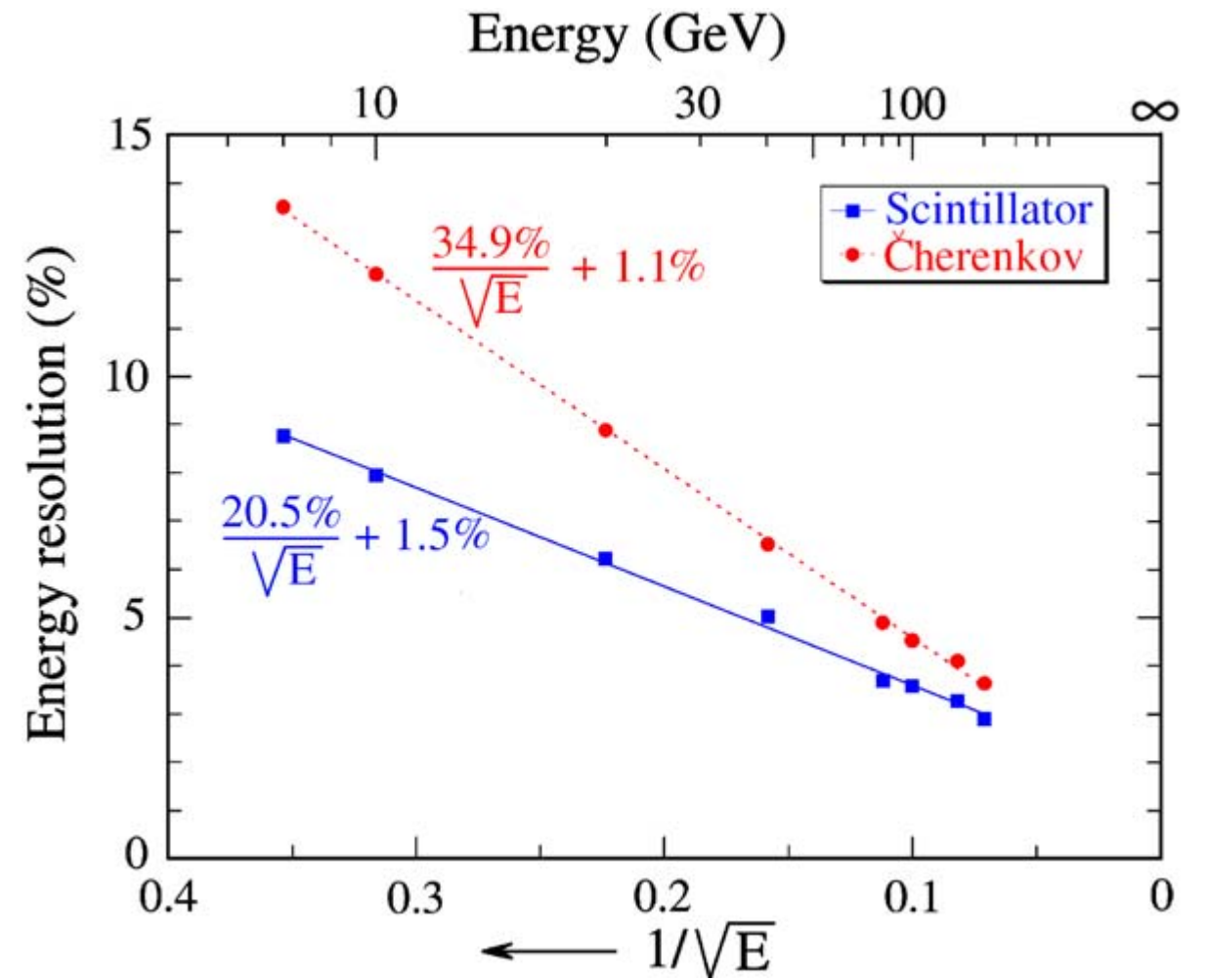


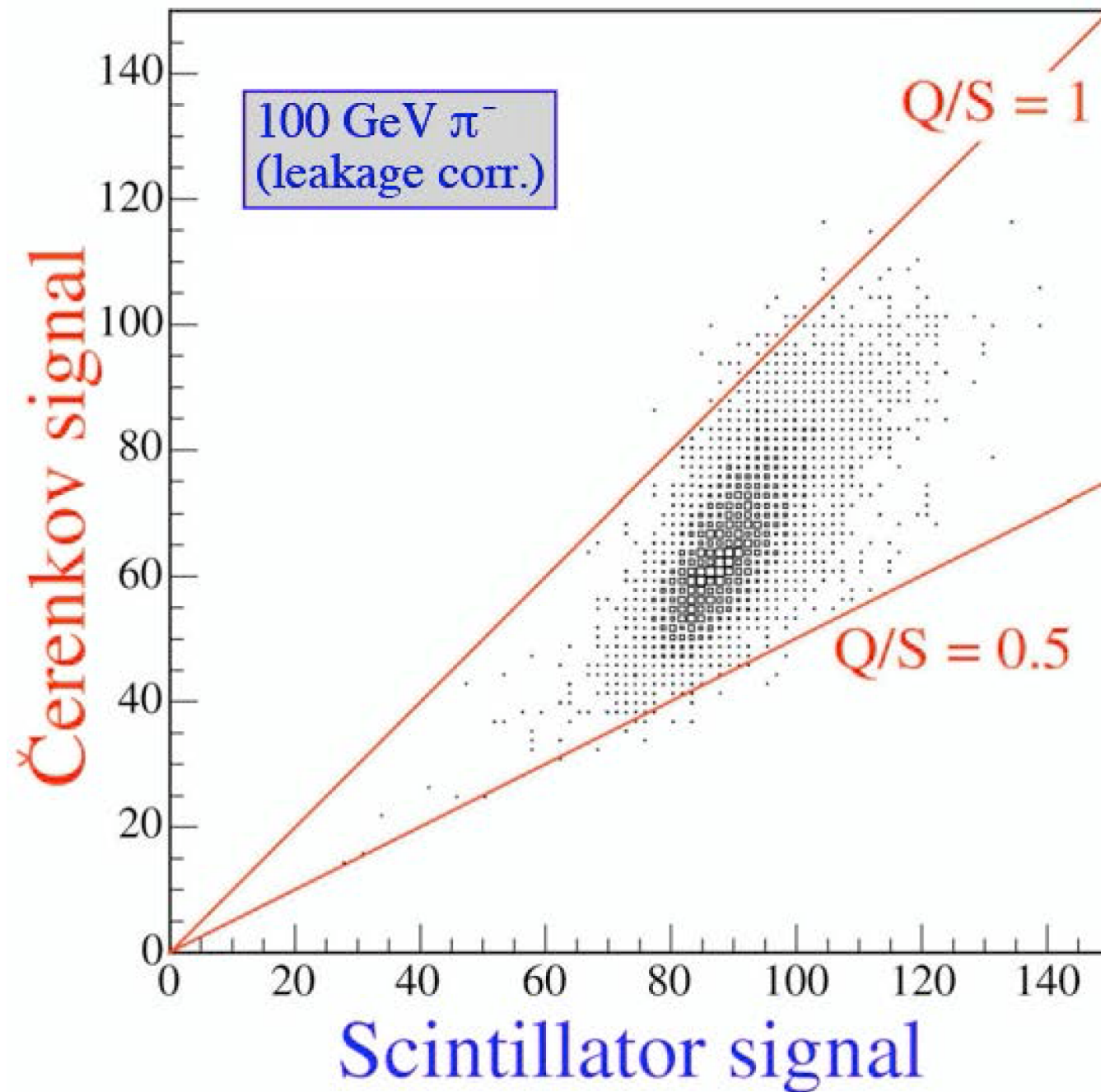
Fig. 20. The energy resolution as a function of energy, measured with the scintillating (squares) and Cherenkov fibers (circles), for electrons entering the calorimeter in the tilted position, B(3°, 2°).

Hadron and Jet detection



Fig. 4. Schematic view of the experimental setup in the beam line in which the DREAM detector was tested.

DREAM Principle



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

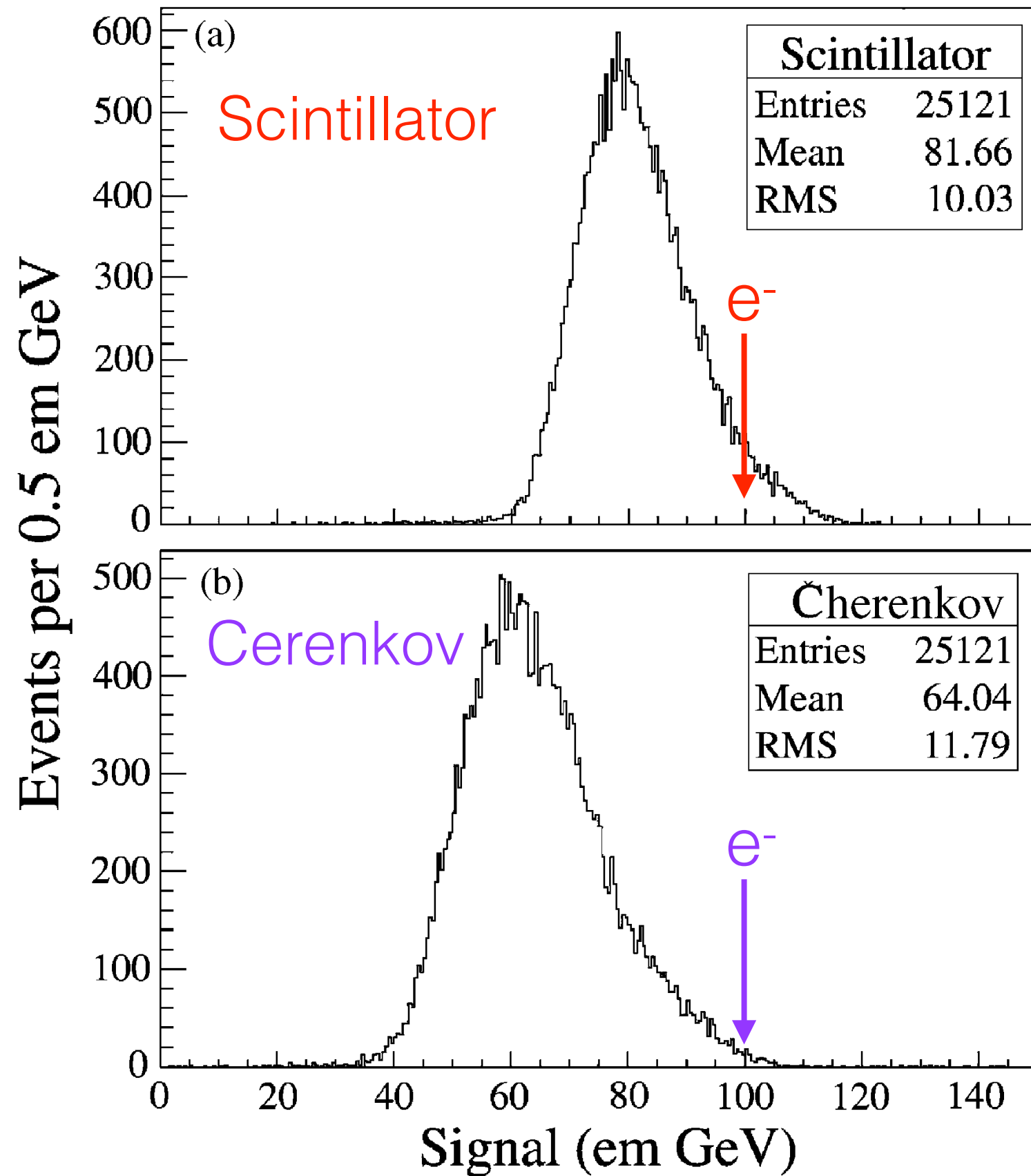
$$Q = E \left[f_{\text{em}} + \frac{1}{(e/h)_Q} (1 - f_{\text{em}}) \right]$$

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

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

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

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



DREAM
Raw signals
(100 GeV π^-)

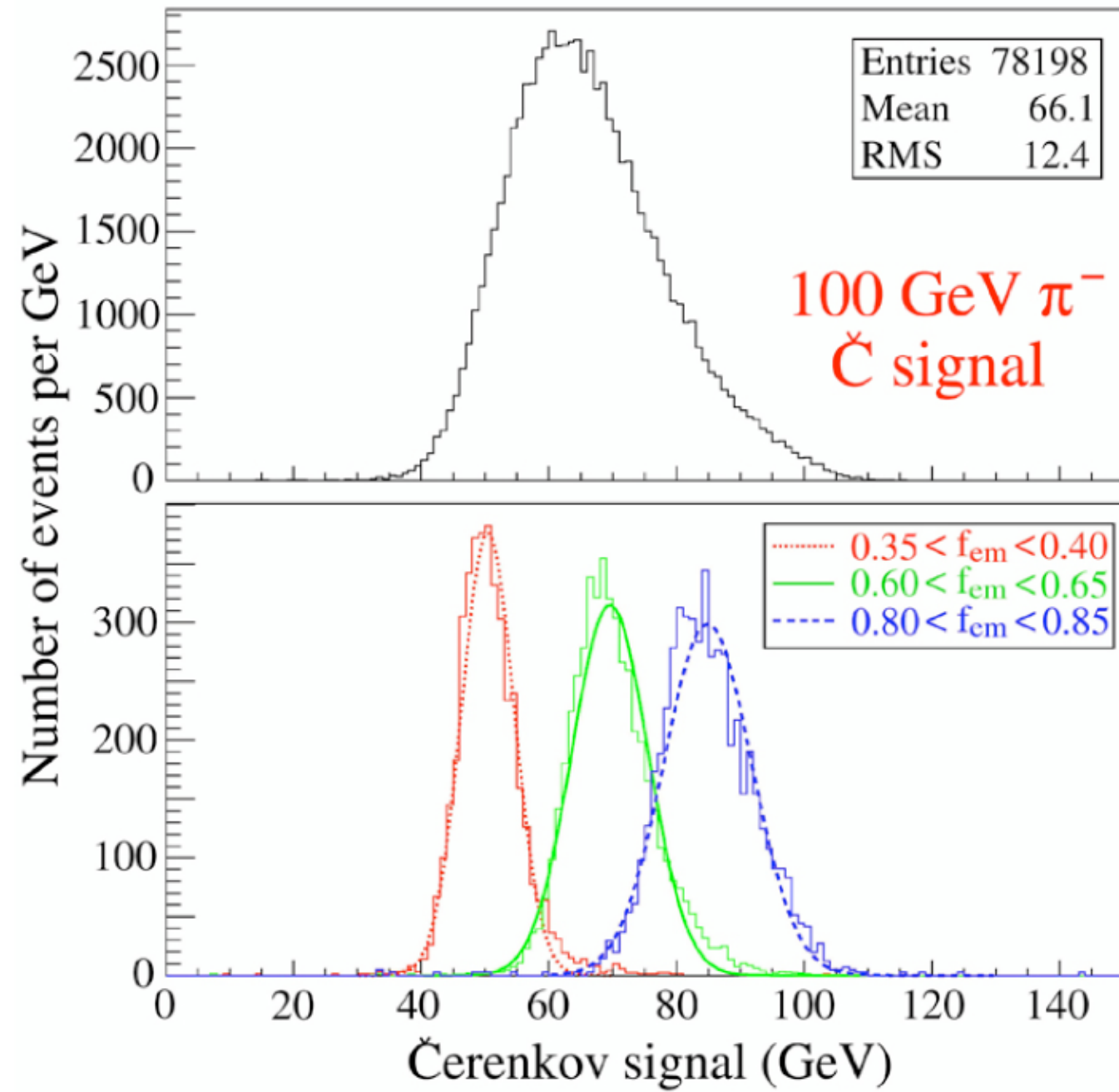


Figure 1: Čerenkov signal distributions for 100 GeV π^- . Shown are all events (top) and samples selected on the basis of their electromagnetic shower content (bottom) [5].

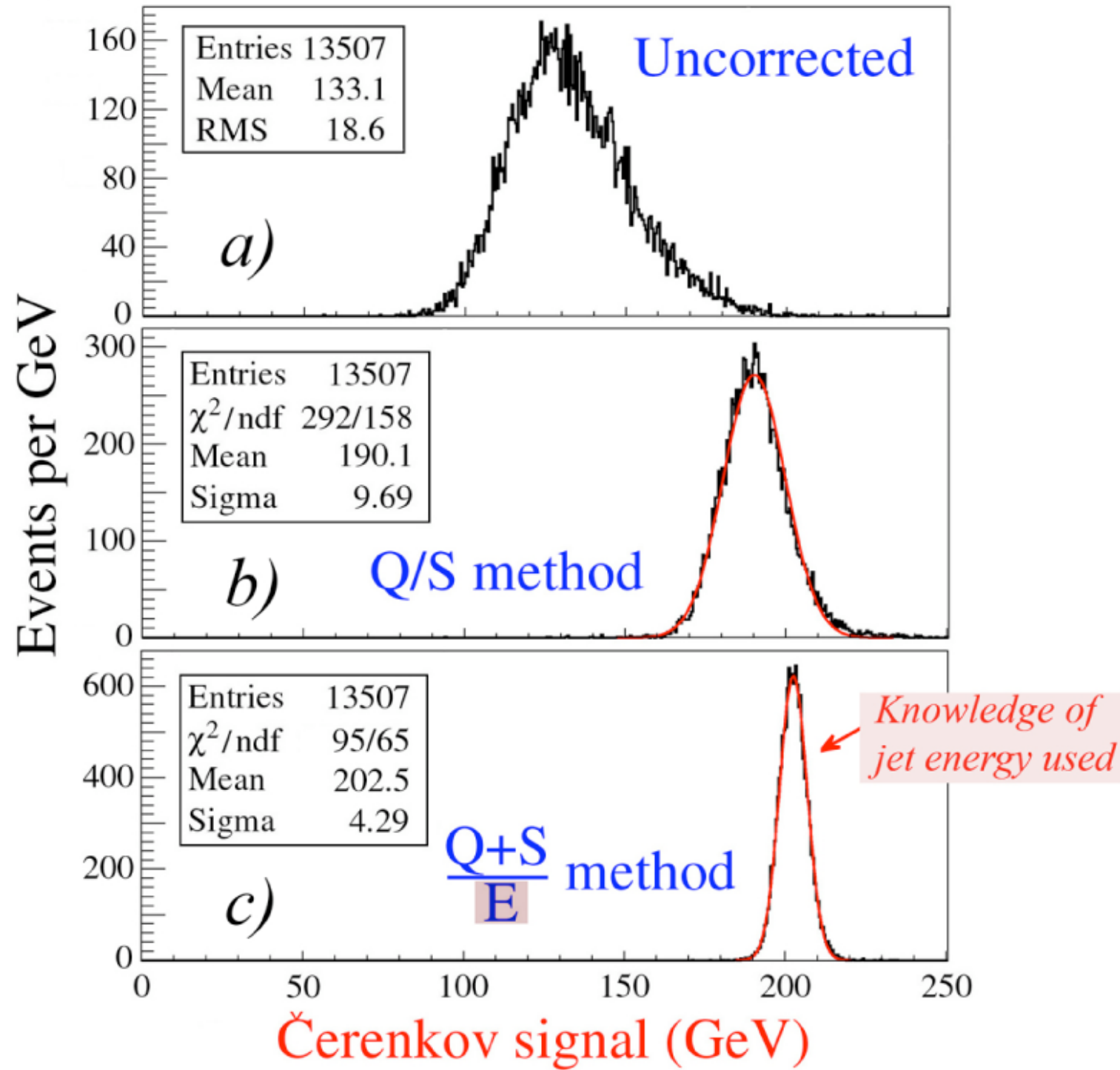


Figure 2: Čerenkov signal distributions for 200 GeV multi-particle events. Shown are the raw data (*a*), and the signal distributions obtained after application of the corrections based on the measured em shower content, with (*c*) or without (*b*) using knowledge about the total “jet” energy [5].

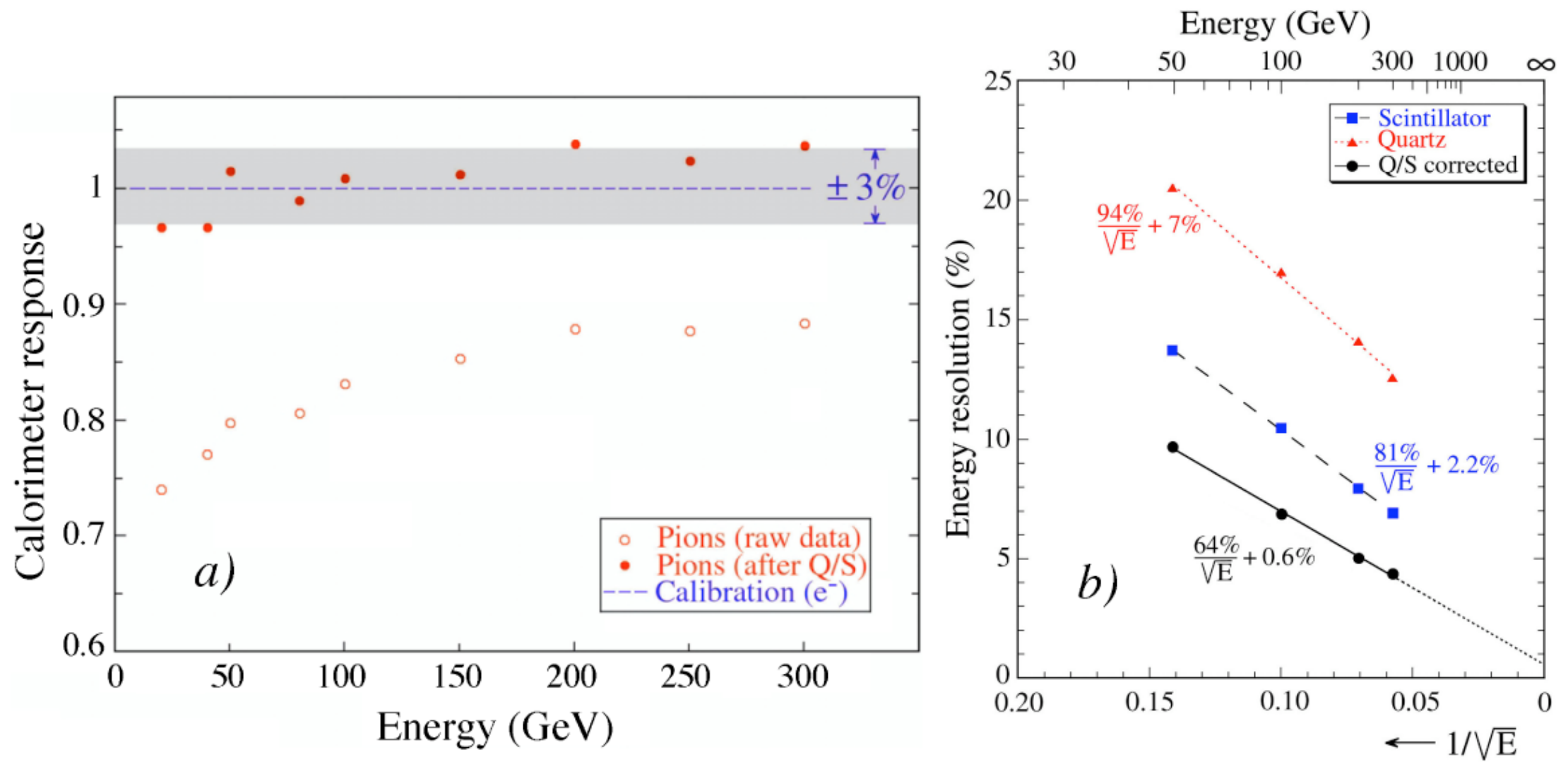


Figure 9: The scintillator response of the DREAM calorimeter to single pions (a) and the energy resolution for “jets” (b), before and after the dual-readout correction procedures were applied to the signals [5].

What we learned from tests with the prototype DREAM detector

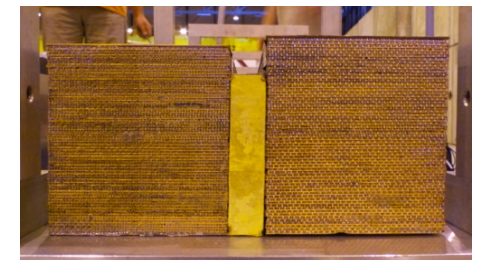
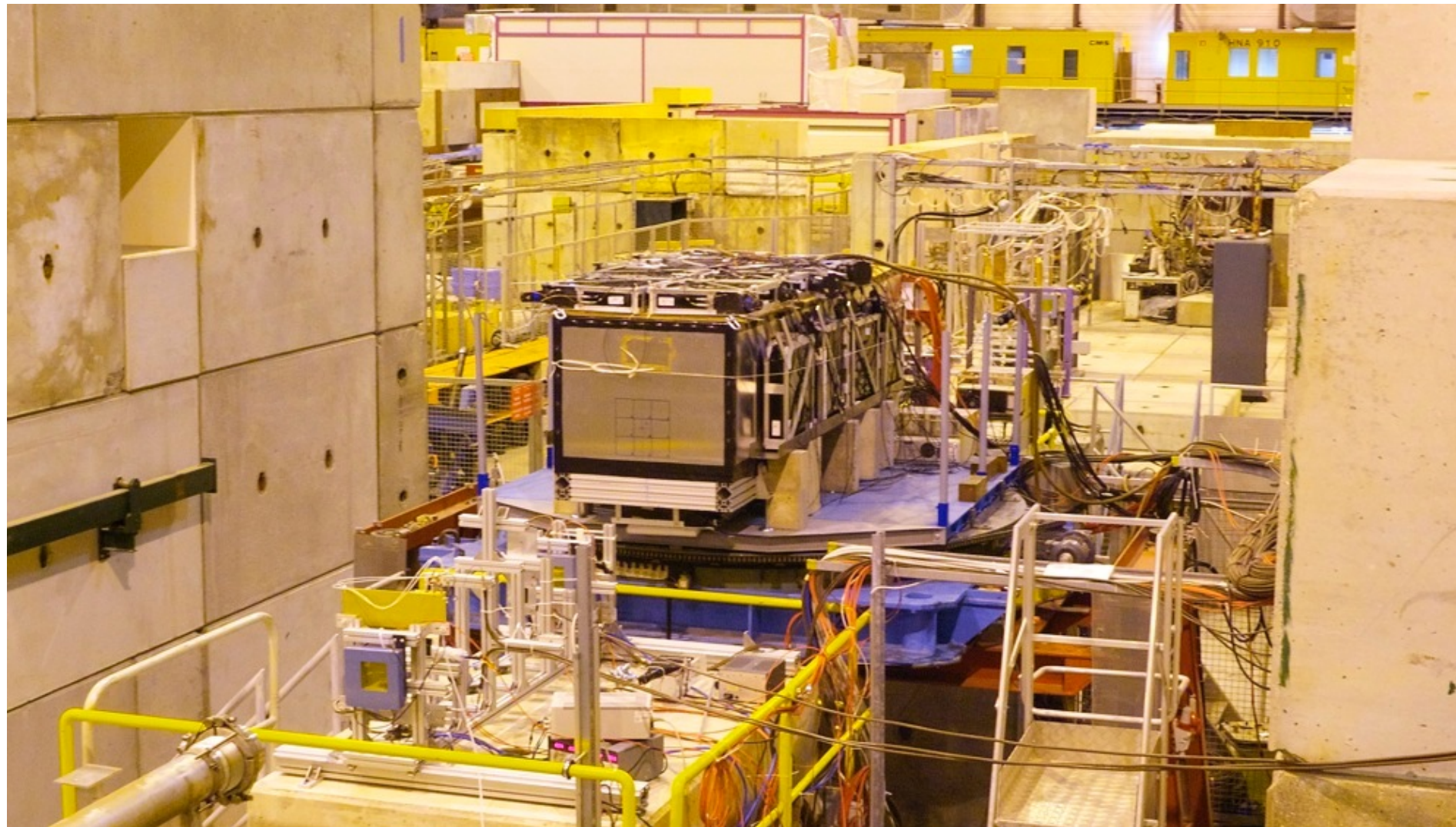
- Calibration with electrons, and then **correct hadronic energy** reconstruction
- Restore **linear calorimeter response** for single hadrons and jets
- **Gaussian response function**
- **Energy resolution** well described by **$1/\sqrt{E}$** scaling
- **$\sigma/E = \sim 5\%$ for 200 GeV “jets”** by the detection with only 1 ton Cu/fiber calorimeter. **Shower leakage fluctuations are dominant** in this case

Dual-REAout Fiber calorimeter is **free** from the **limitations (sampling fraction, integration volume, time)** of intrinsically compensating calorimeters ($e/h=1$)

Additional factors to improve DREAM performance

- Reduction of shower leakage (leakage fluctuations) → Build larger detector
- Increase Cerenkov light yield
 - Prototype DREAM: 8 p.e./GeV → light yield fluctuations contribute by $35\%/\sqrt{E}$
- Reduction of sampling fluctuations → Put more fibers
 - contribute $\sim 40\%/\sqrt{E}$ to hadronic resolution (single pions)

Test Beam with the new DREAM modules



Al 4	Al 3	Cu 4	Cu 3
Al 1	Al 2	Cu 1	Cu 2

T1	T2	T3	T4	T5	T6
T7	T8	T9	T10	T11	T12
T13	T14	T15	T16	T17	T18
T19	T20	T21	T22	T23	T24
T25	T26	T27	T28	T29	T30
T31	T32	T33	T34	T35	T36

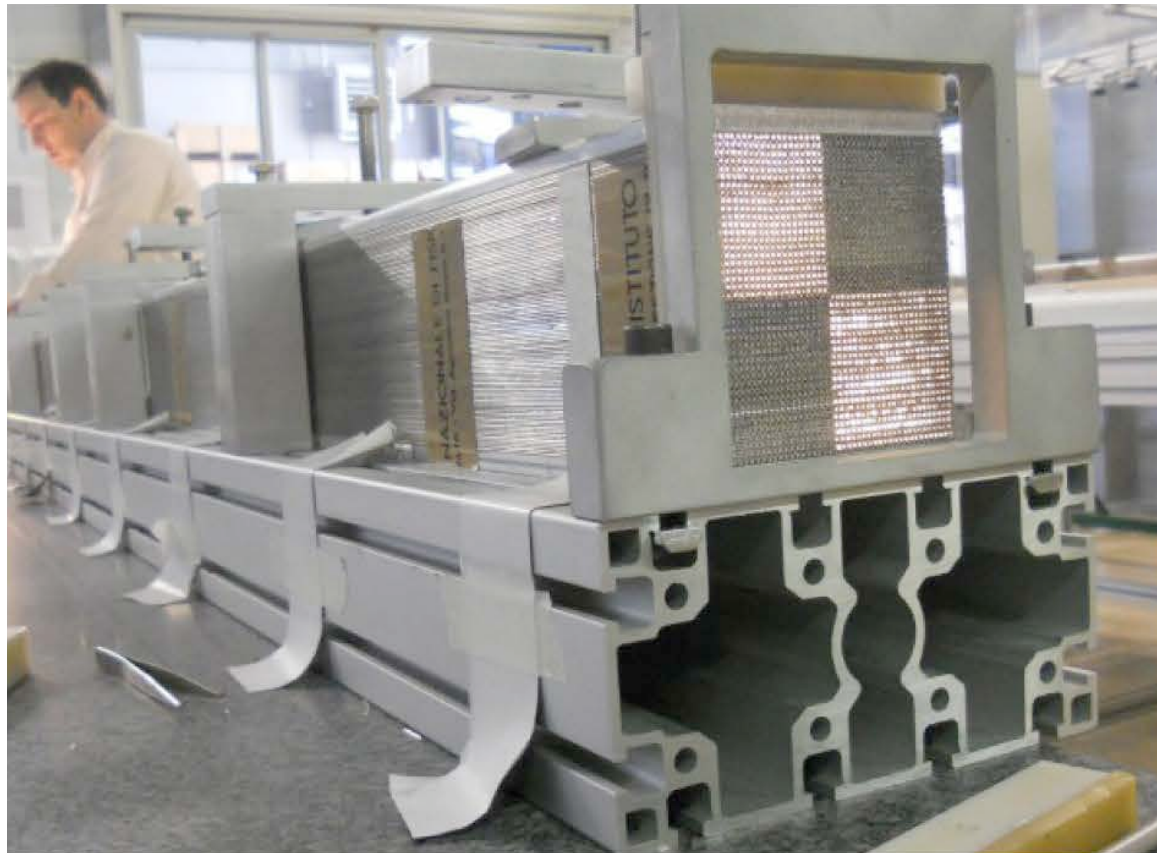
Ring 1 Ring 2 Ring 3



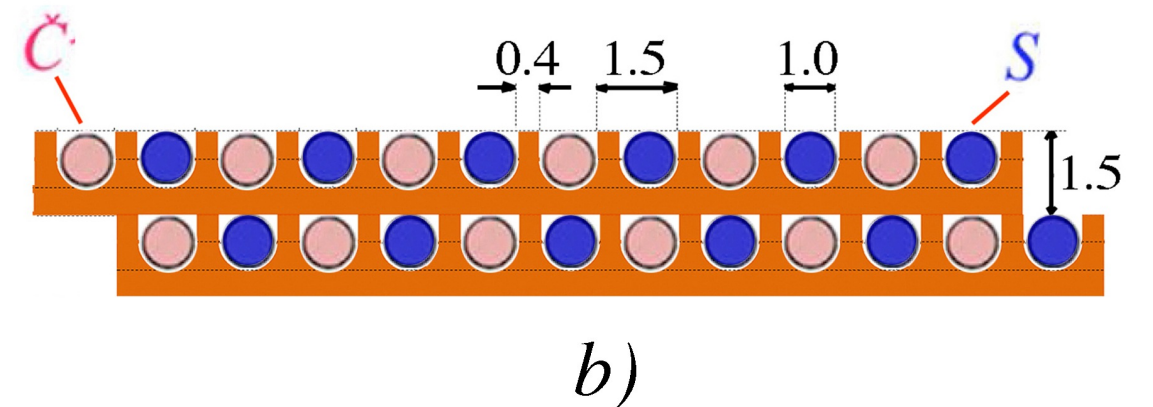
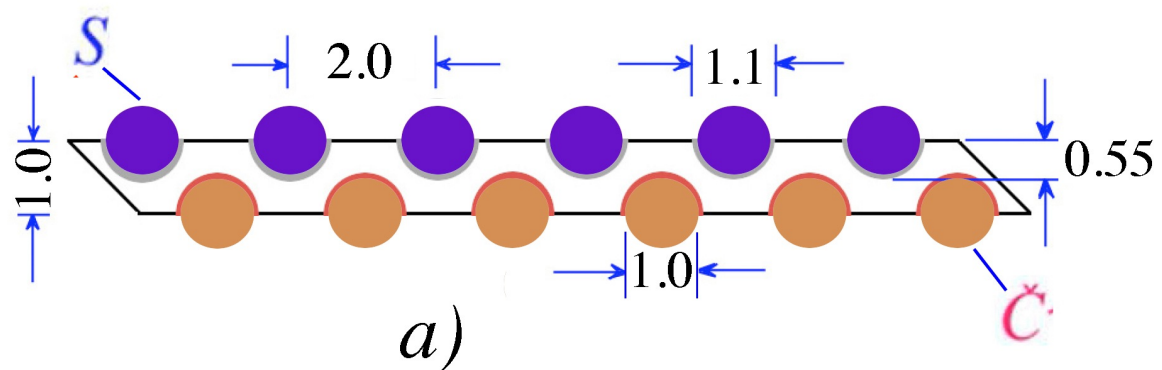
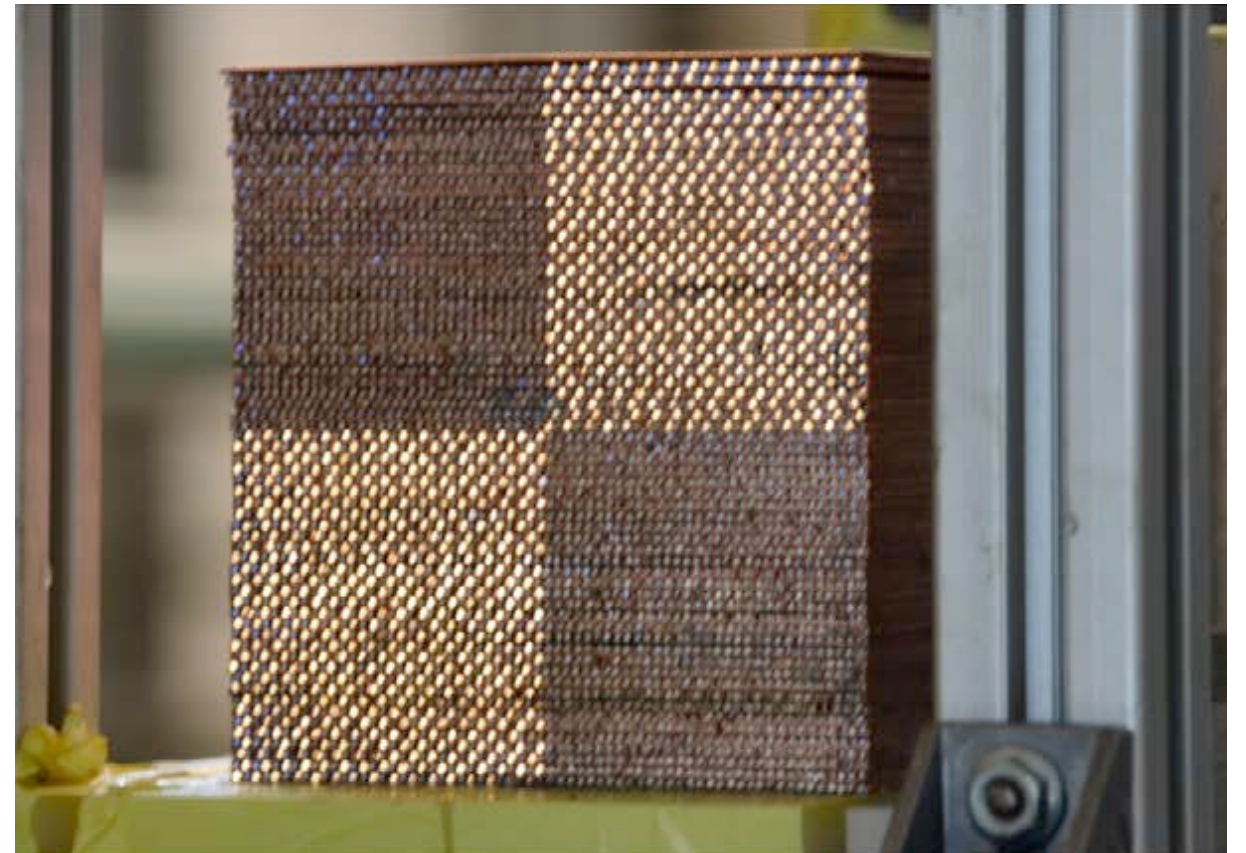
9 Pb modules (36 towers, 72 channels), 2 Cu modules (8 towers), 20 leakage counters (Plastic scintillator)

The structures of **Pb** and **Cu** modules

Pb

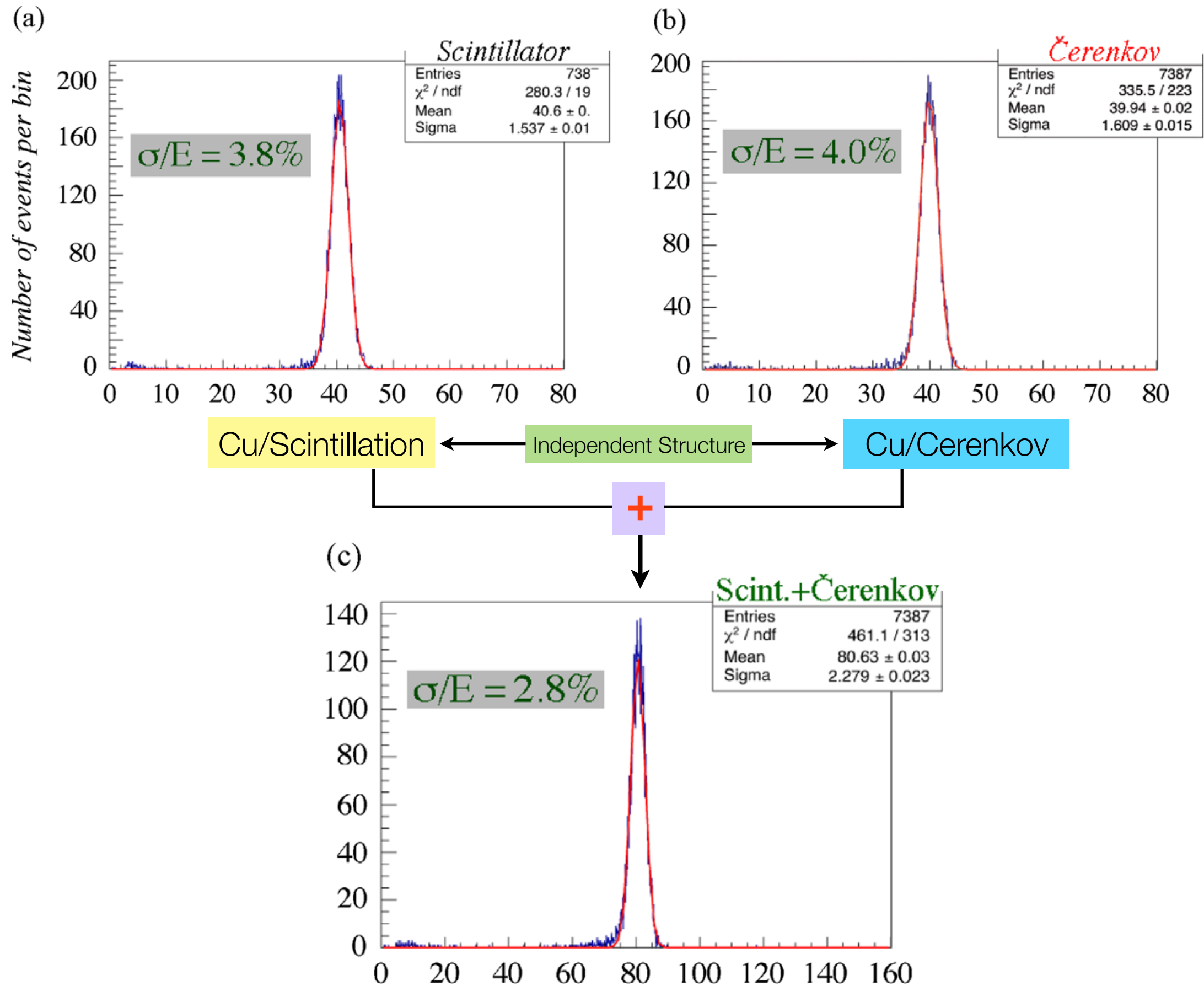


Cu

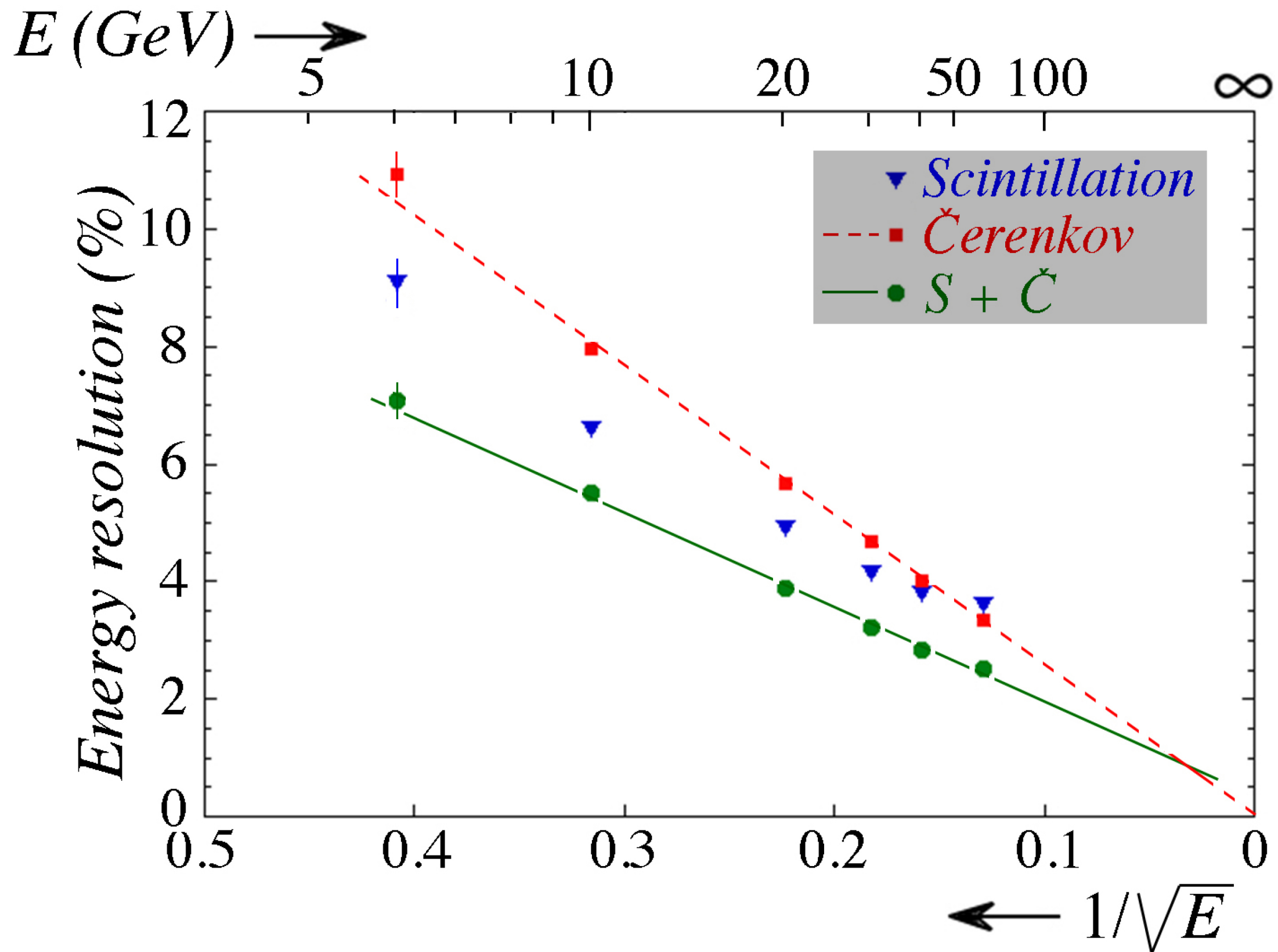


Electromagnetic Performance

The electromagnetic performance for 40 GeV e^- (Cu/fiber)



The energy resolution for electrons (Cu/fiber)



Hadronic Performance

The hadronic performance (Pb/fiber)

Dual-REAdout Method

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

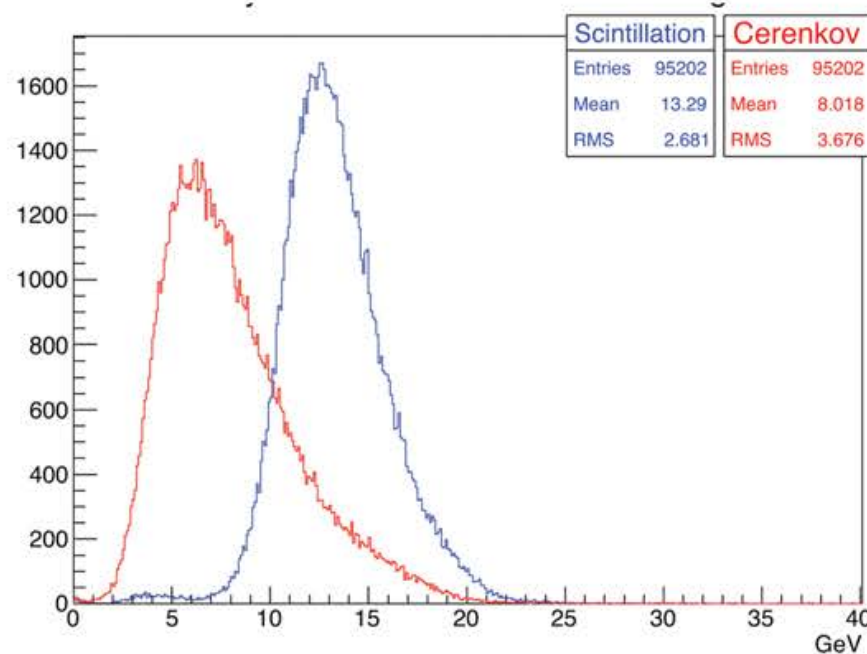
$$Q = E \left[f_{\text{em}} + \frac{1}{(e/h)_Q} (1 - f_{\text{em}}) \right]$$



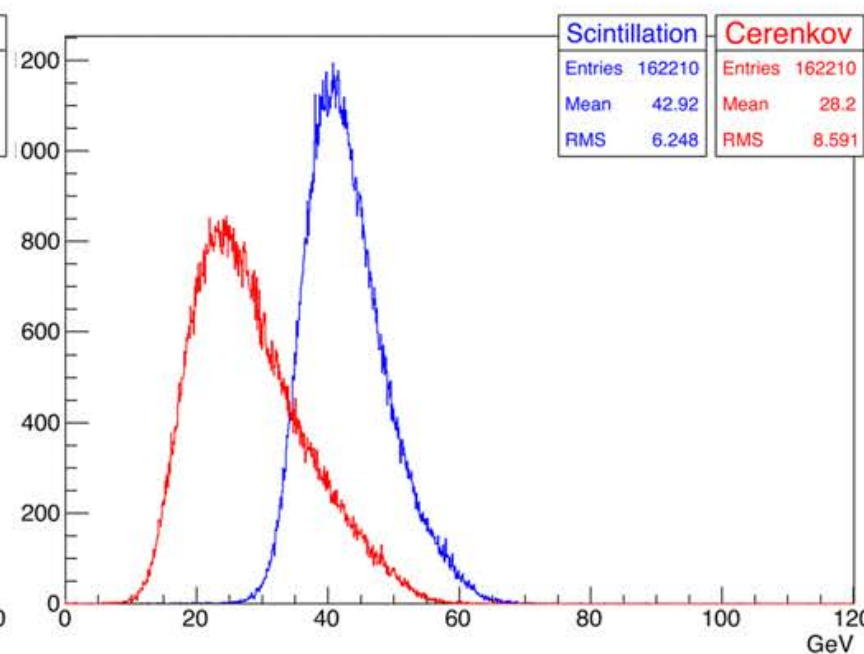
$$E = \frac{S - \chi Q}{1 - \chi}$$

with $\chi = \frac{1 - (h/e)_S}{1 - (h/e)_Q} = 0.45$

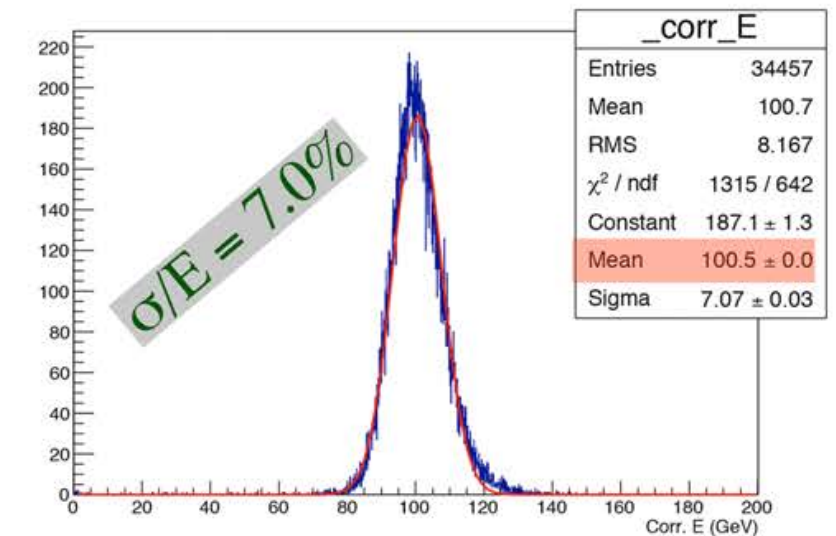
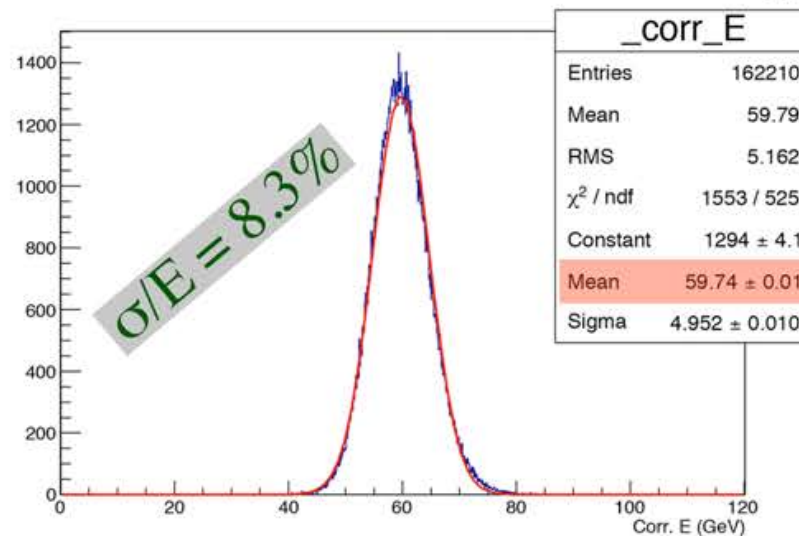
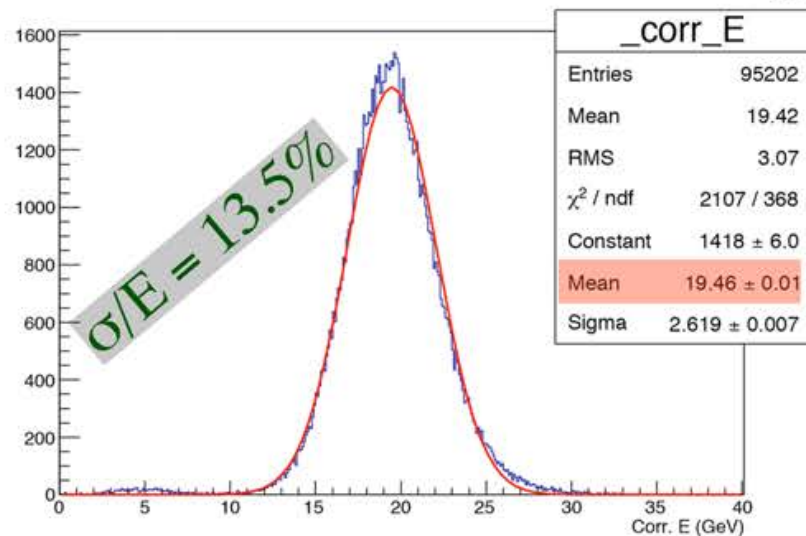
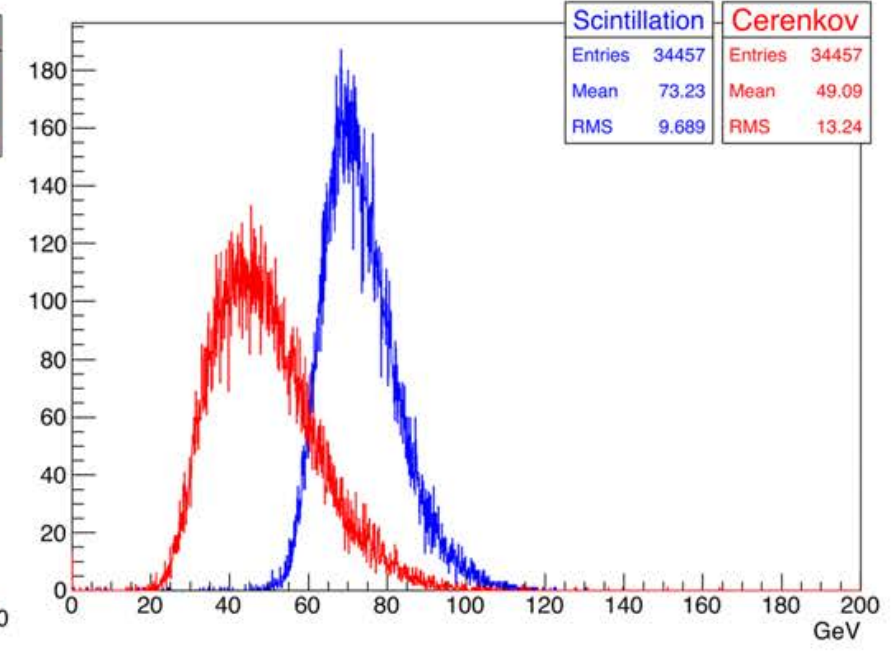
20 GeV π^-



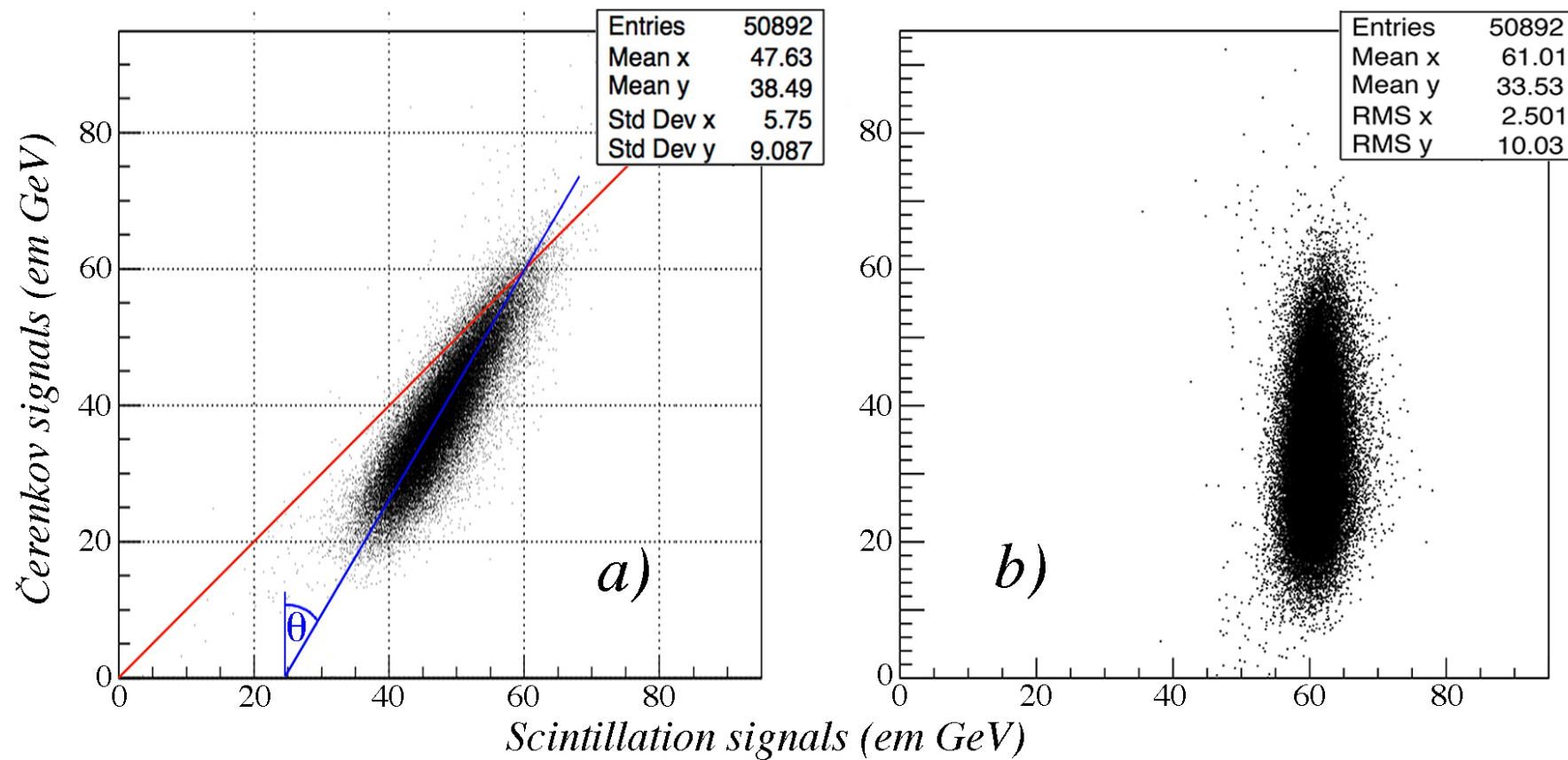
60 GeV π^-



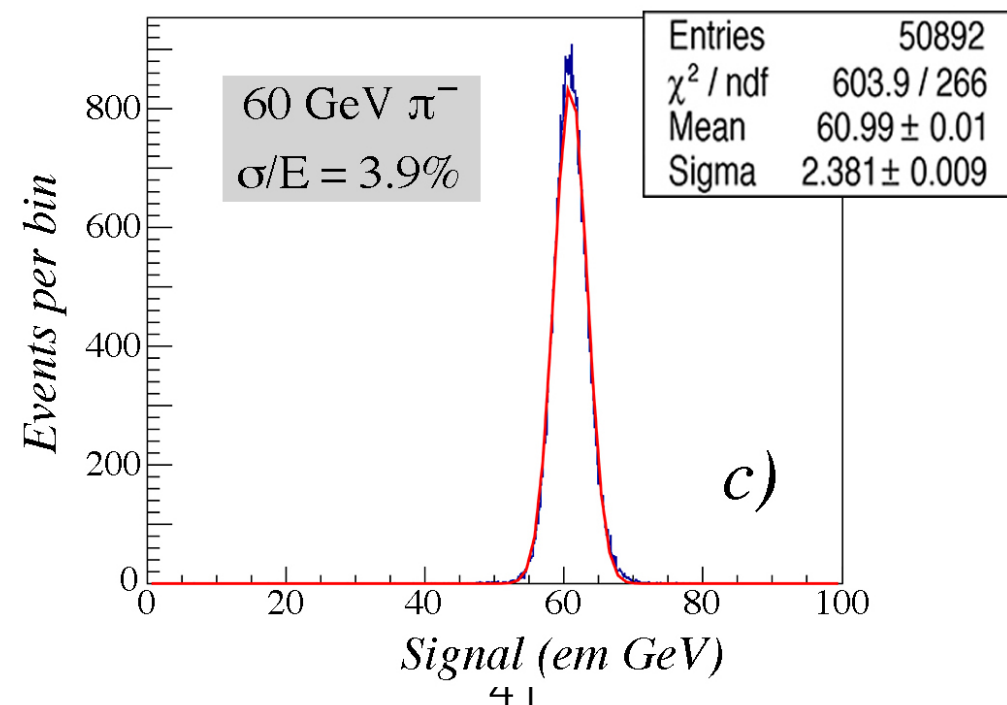
100 GeV π^-



The Rotation Method

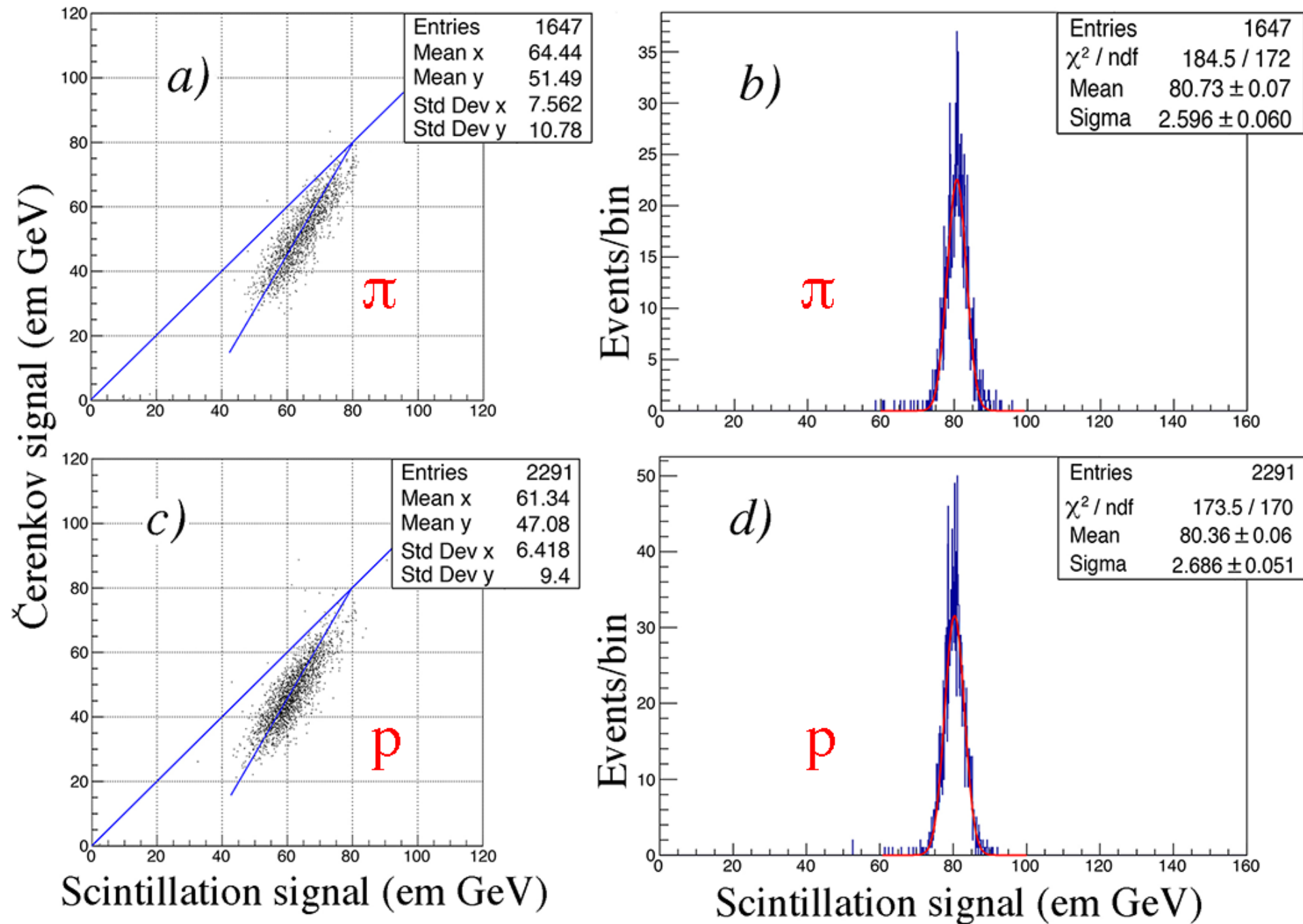


60 GeV π^-

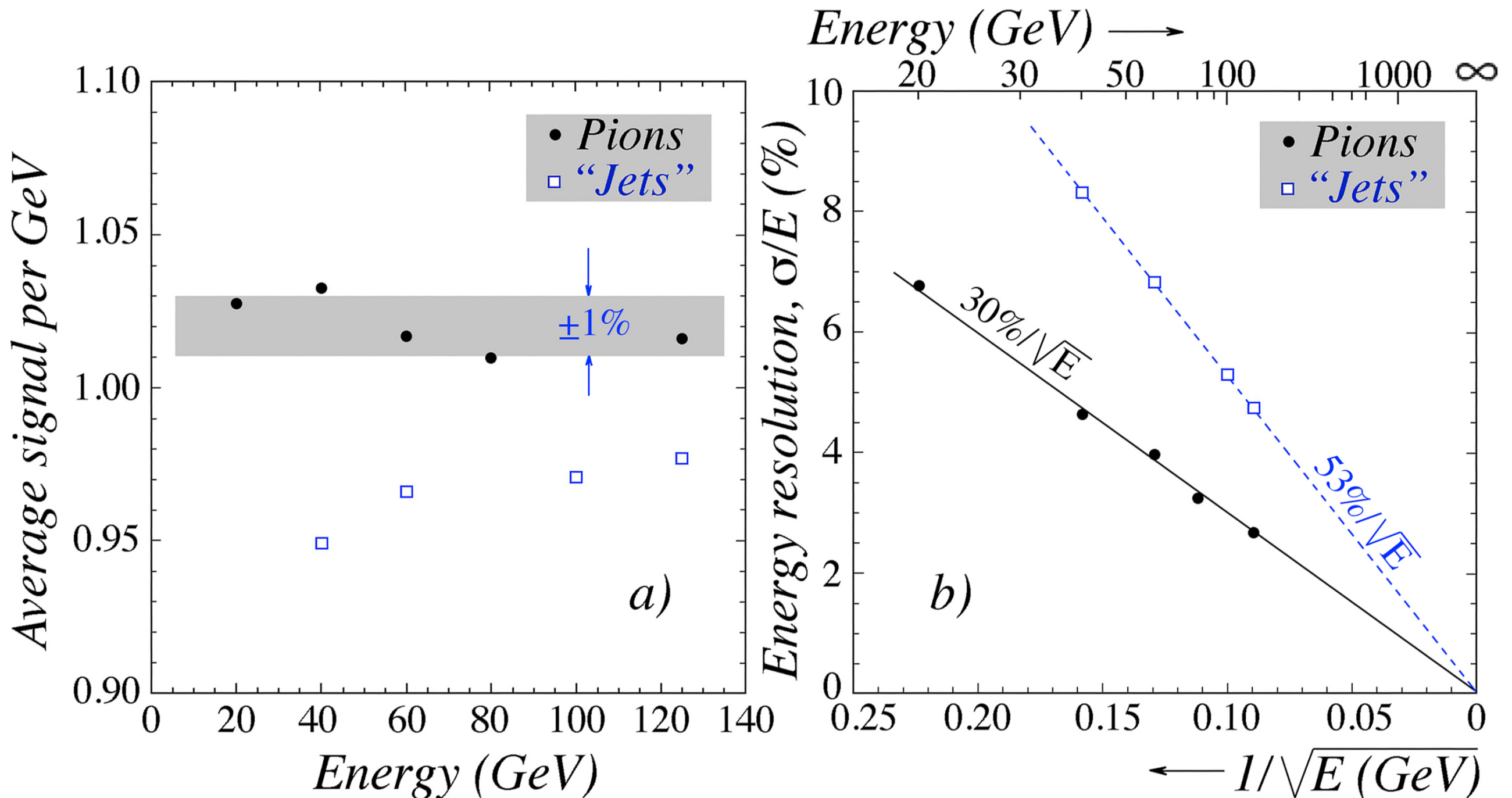


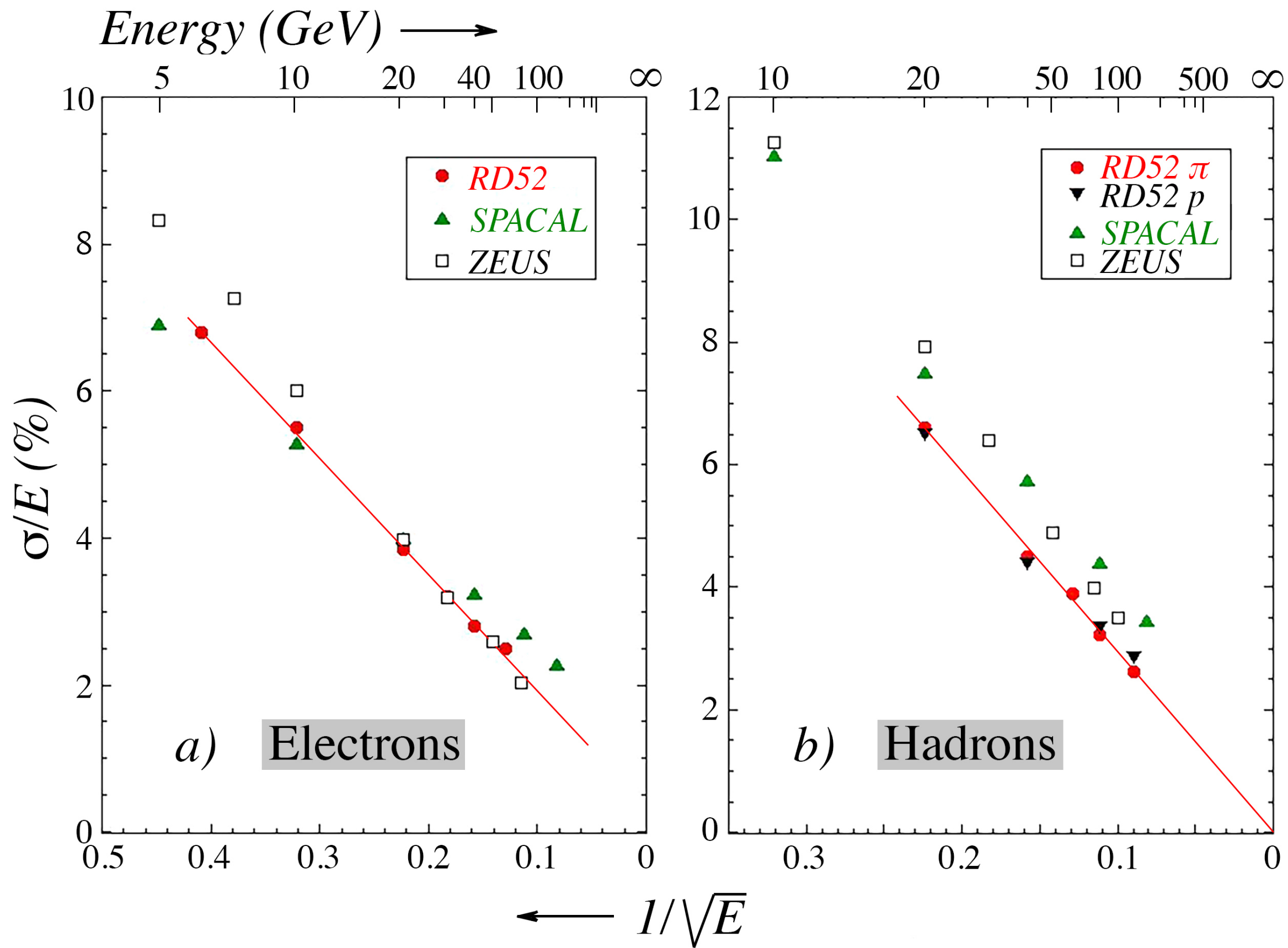
The Rotation Method

80 GeV π^+ / p



The Rotation Method





Achievements and Plans

- We have proved that DREAM calorimeter can achieve **the excellent energy resolutions for both EM and hadrons experimentally**.
- More results such as **particle identification, muon detection, crystal study for DREAM calorimetry** and so on:
 - <http://www.phys.ttu.edu/~dream/results/publications/publications.html>
- For last 15 years, **DREAM** principle has been proved with experimental data and **31 papers** were published.
- In July, a summary paper for **15-year R&D results** was submitted to ***Reviews of Modern Physics*** and is under review.
- Based on these R&D results, **Korea-Italy-China** started **simulation efforts to design the calorimeter for the CEPC project** in the beginning of 2017 (**C**onceptual **D**esign **R**eport).
- RD52 (DREAM) project will be newly proposed to CERN in the next year, which is associated with the future collider projects.

Backup

Definitions

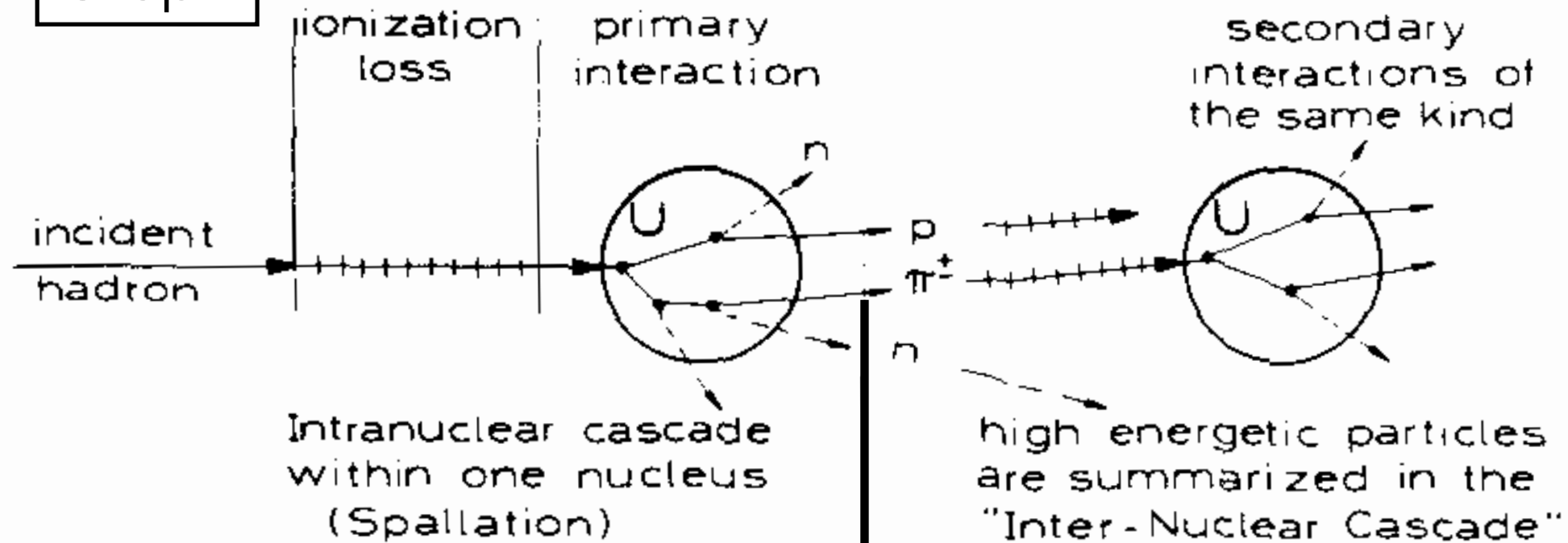
- Thermodynamics:
 - Calorimetry: Determining the specific heat of water or other substances.
 - Calorimeters: the thermally isolated boxes containing the substance of our study.
- Nuclear and Particle Physics:
 - **Calorimetry**: the detection of particles, and measurement of their properties, through total absorption in a block of matter (In the absorption process, almost all particle's energy eventually converted into heat).
 - Calorimeter: a block of matter

Hadron Shower

Spallation

NIM A 263 (1988) 136

Step I

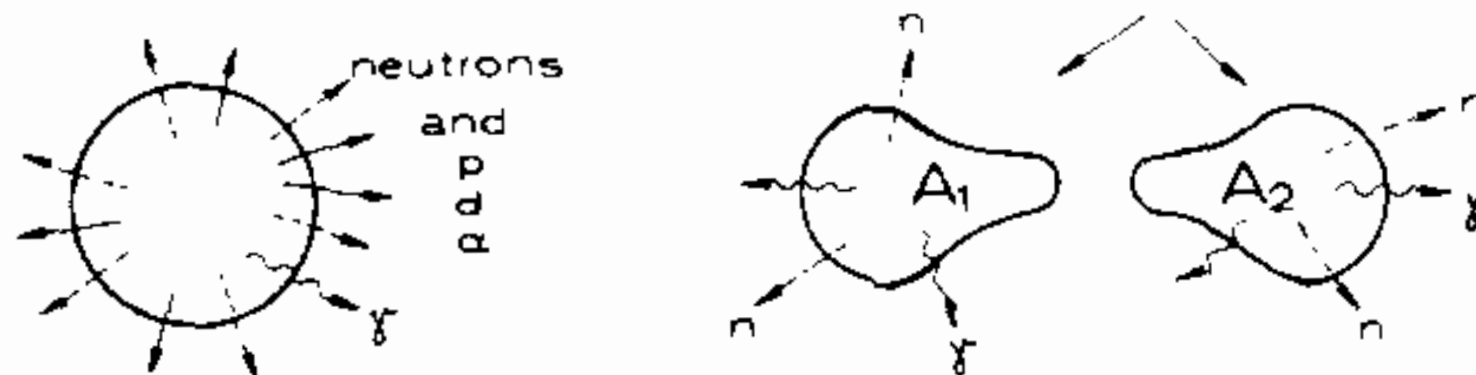


Step II

The highly excited nuclei might:

either evaporate many particles

or undergo a fission process



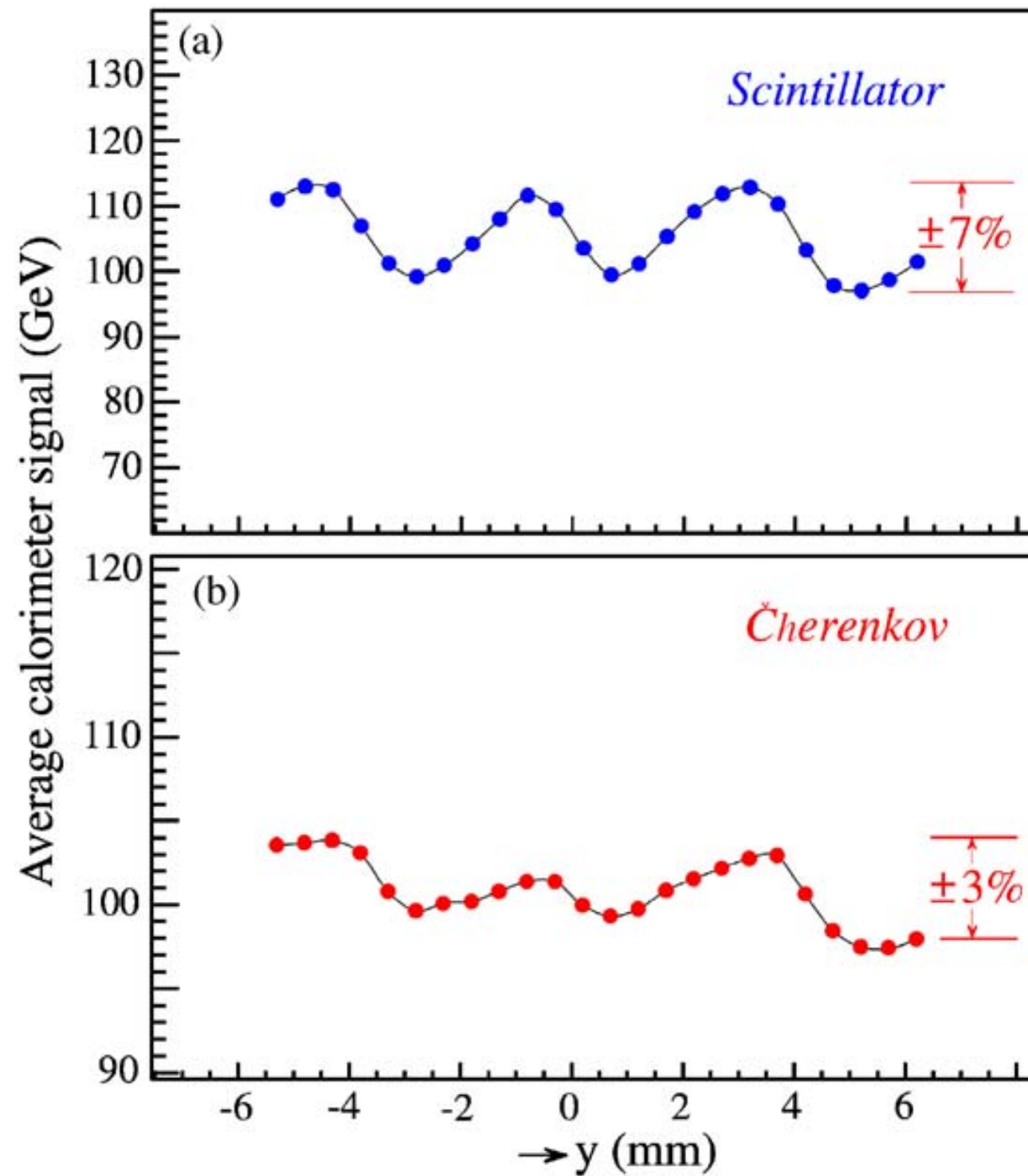
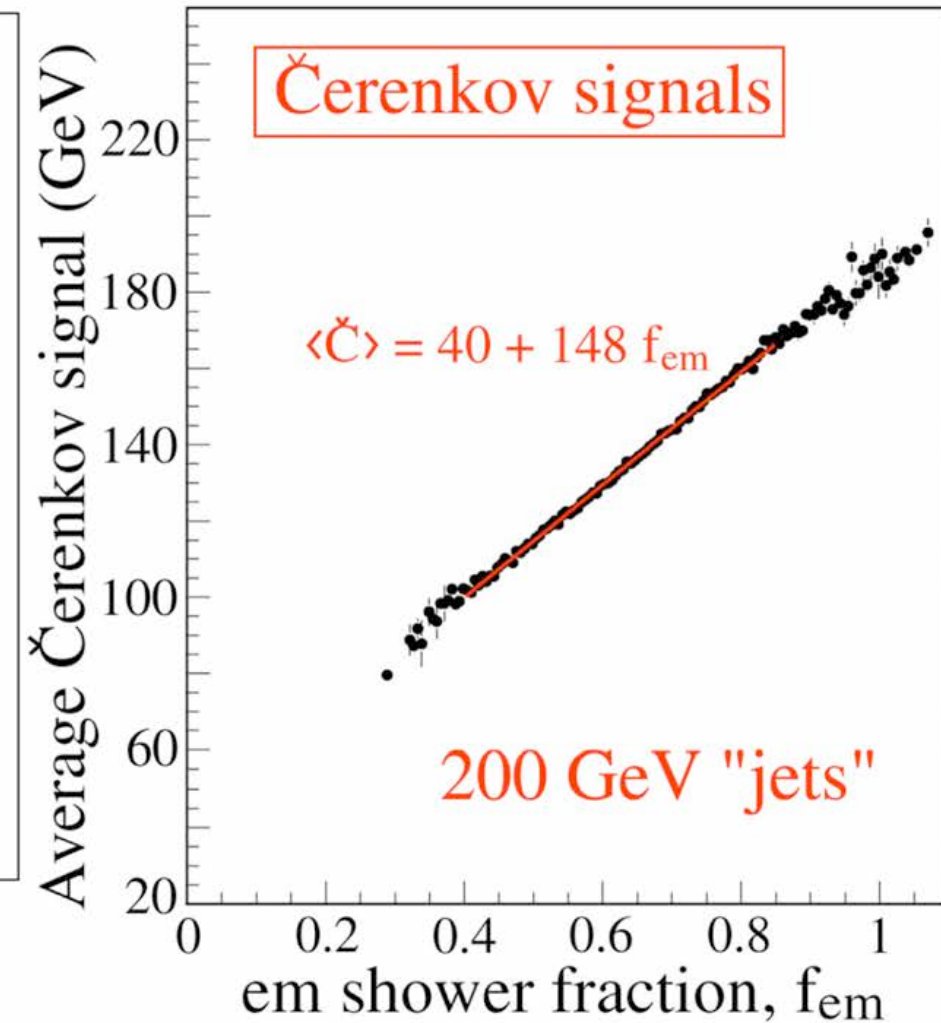
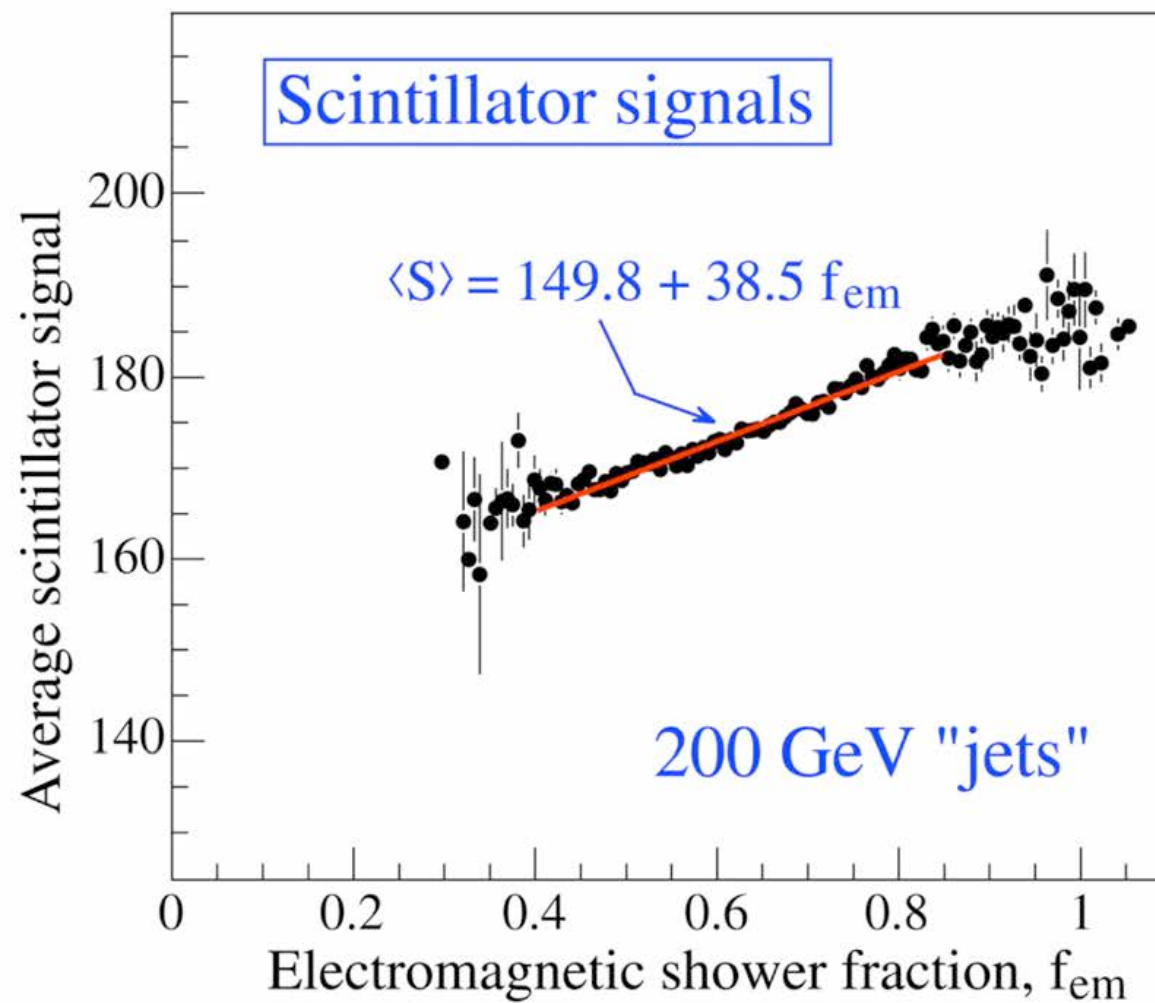


Fig. 11. Average calorimeter signal as a function of the y -coordinate of the impact point, for the scintillator (a) and Cherenkov (b) signals from 100 GeV electrons entering the DREAM calorimeter oriented in the untilted position, $A(2^\circ, 0.7^\circ)$. Note the different vertical scales.

Signal Dependence on f_{em}



$$R(f_{em}) = p_0 + p_1 f_{em}$$

with

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

Cu/scintillator $e/h = 1.3$

Cu/quartz $e/h = 4.7$

From:

NIM A537 (2005) 537

Table 2

Results of the fits of expressions of the types $\sigma/E = aE^{-1/2} + b$ and $\sigma/E = AE^{-1/2} \oplus B$ to the measured experimental energy resolutions

Coefficient	<i>Untilted, A(2°, 0.7°)</i>		<i>Tilted, B(3°, 2°)</i>	
	S	C	S	C
a	14.0 ± 0.2	38.2 ± 0.4	20.5 ± 0.3	34.9 ± 0.4
b	5.6 ± 0.1	0.8 ± 0.1	1.5 ± 0.2	1.1 ± 0.2
χ^2/N_{dof}	22/6	94/6	373/6	125/6
A	23.8 ± 0.3	40.0 ± 0.6	23.7 ± 0.3	37.5 ± 0.5
B	6.7 ± 0.2	2.2 ± 0.3	2.8 ± 0.2	2.6 ± 0.2
χ^2/N_{dof}	137/6	26/6	910/6	47/6

All numbers are given in %. The χ^2 values were calculated on the basis of statistical errors only.

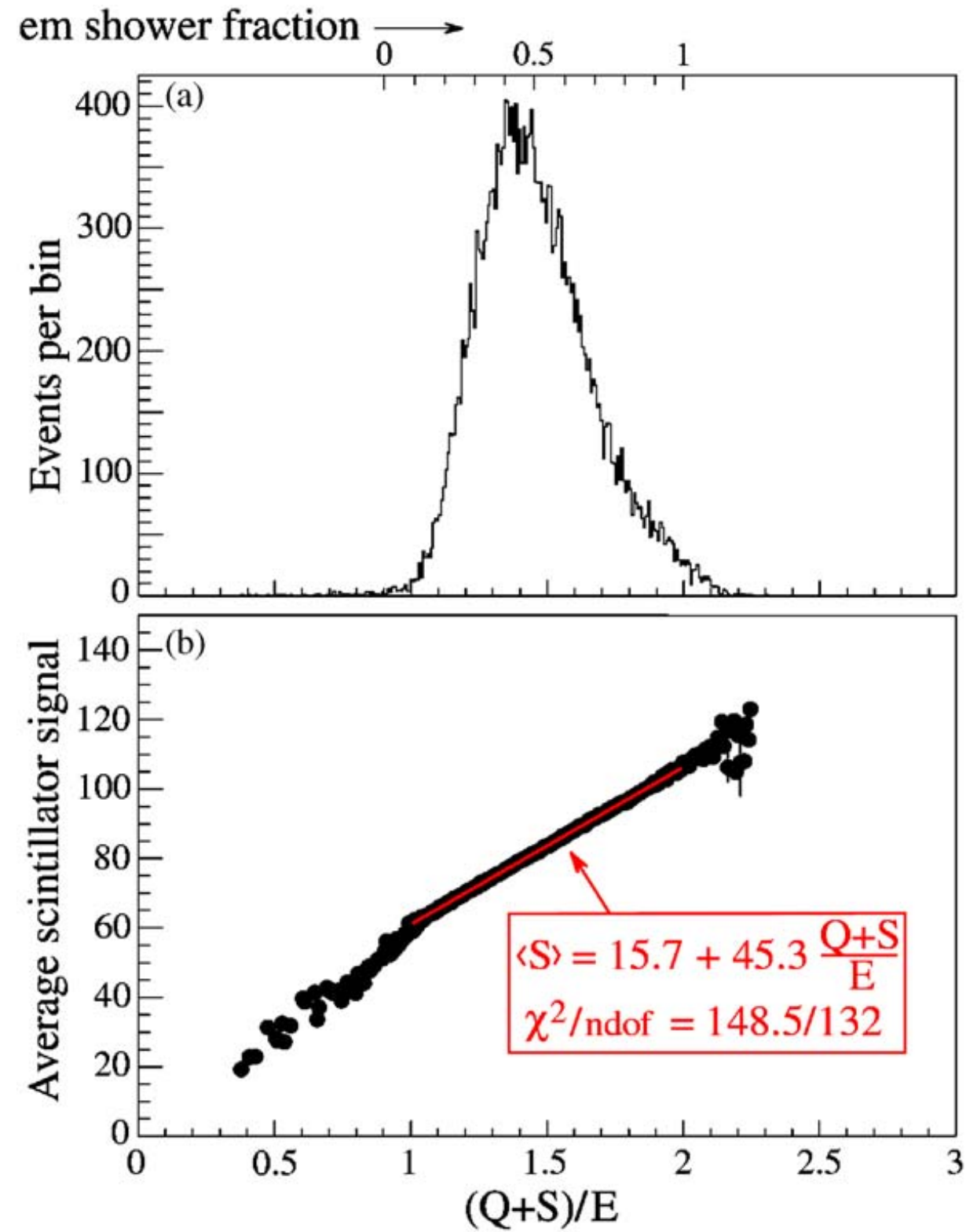


Fig. 14. Distribution of the variable $(Q + S)/E$, and of the em shower fraction derived on the basis of Eq. (2), for 100 GeV π^- showering in the DREAM calorimeter (a). The average scintillator signal for 100 GeV π^- , as a function of $(Q + S)/E$ (b).