What we learned from the prototype DREAM calorimeter

(Everything you always wanted to know about the original DREAM module)

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Jan. 14, 2016

IAS 2016 at HKUST

Why Dual-REAdout Method (DREAM) calorimeter?

A brief history of calorimetry (1)

- 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 γs**. (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).

A brief history of calorimetry (2)

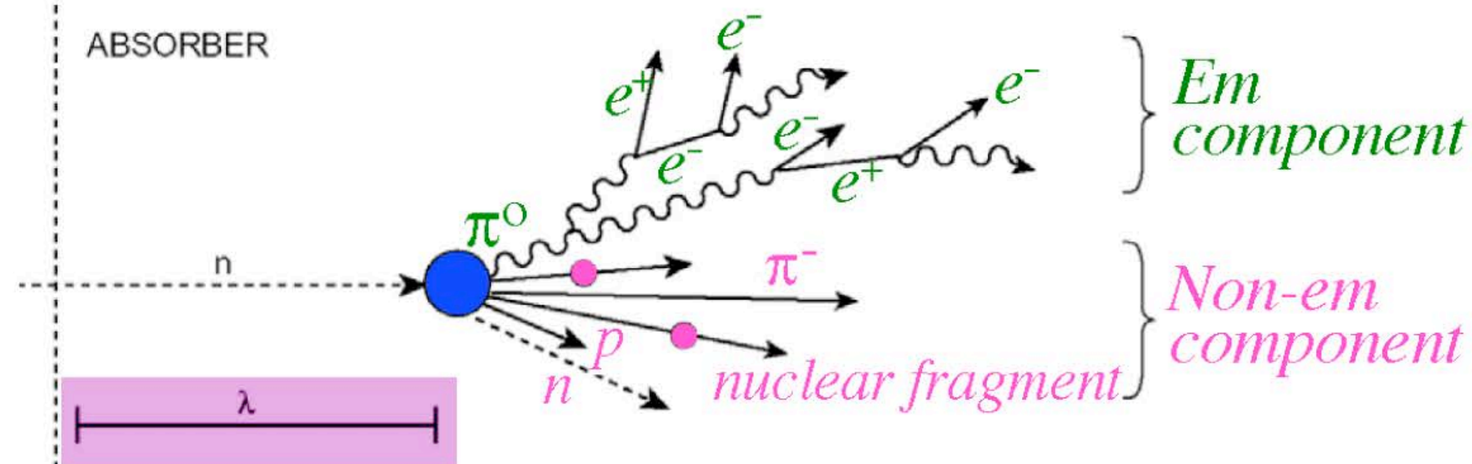
- In **1970s**, the new tasks of calorimeter: the **measurement of jet energy** and **missing E_T** at the collider experiments (ISR, PETRA) and **particle ID** (e, γ, μ, ν).
- **Calorimeters** worked nicely for such tasks and **became the main detector** at accelerator based particle physics experiments.
- 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.

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

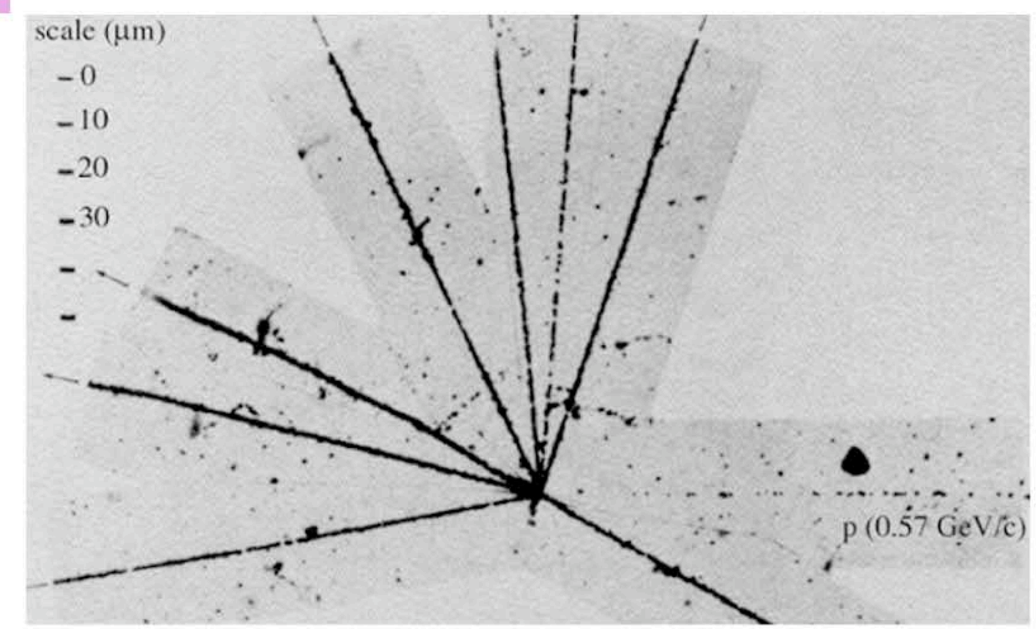
“Hadron Calorimeters are usually far from ideal”

Hadron Shower

- *A hadronic shower consists of two components*

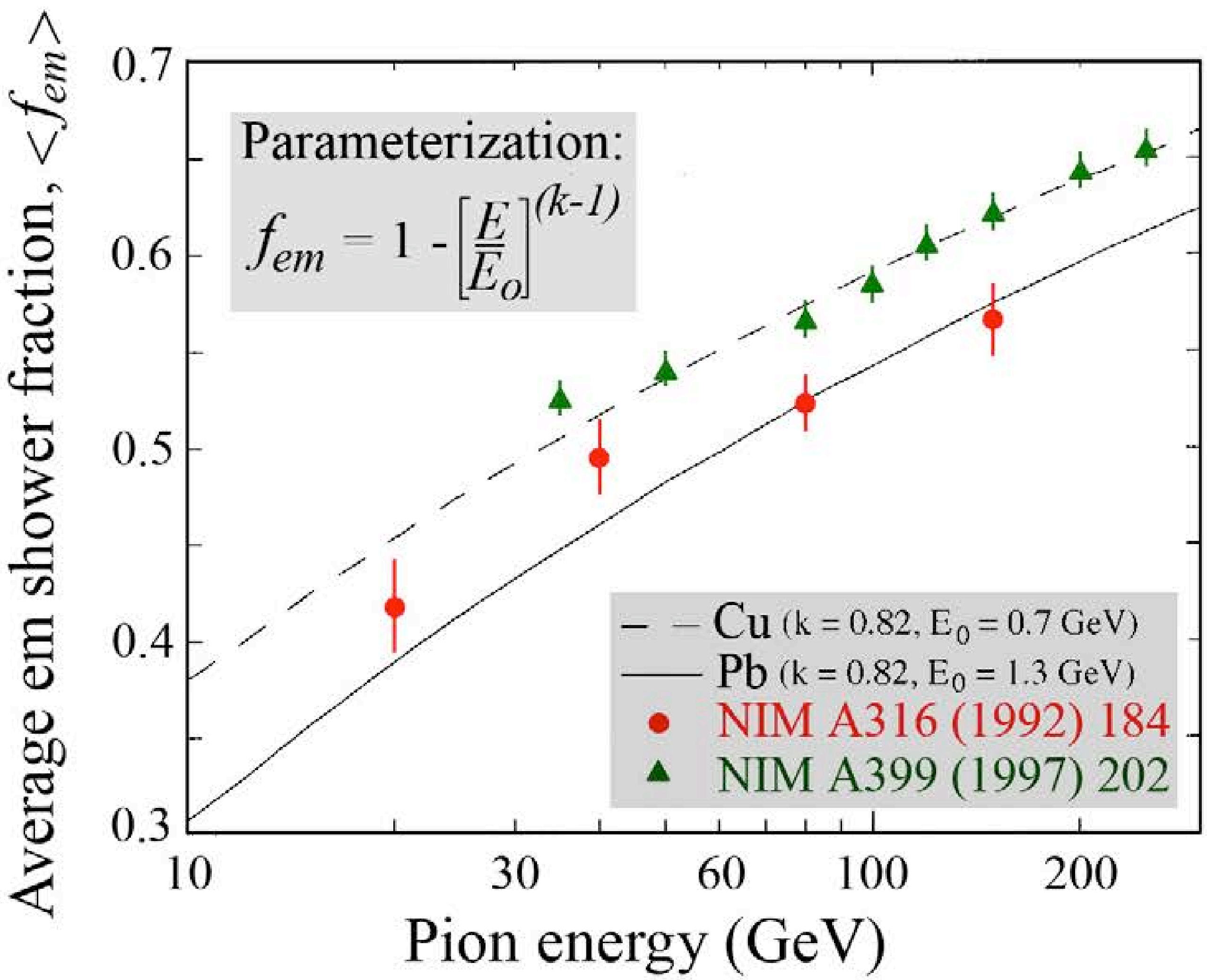


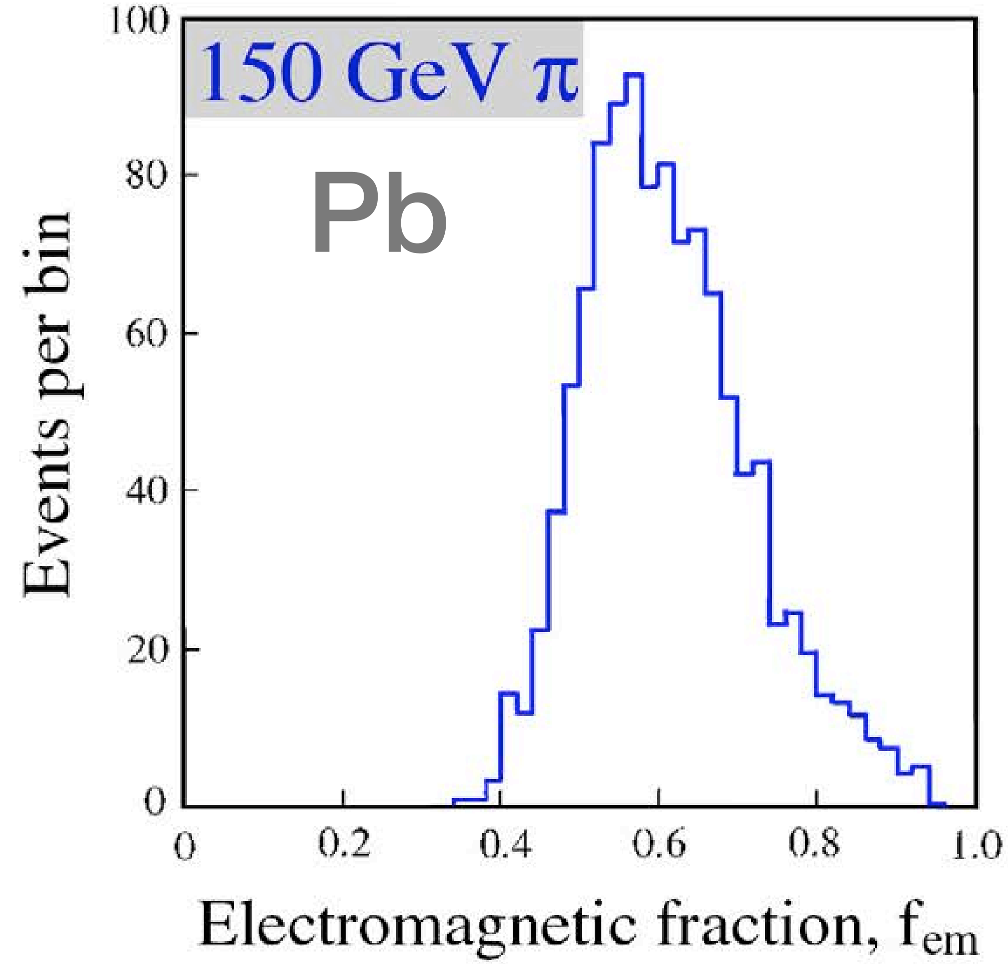
- *Electromagnetic component*
  - electrons, photons
  - neutral pions → 2 γ
- *Hadronic (non-em) component*
  - charged hadrons $\pi^{\pm}$,$K^{\pm}$ (20%)
  - nuclear fragments, p (25%)
  - neutrons, soft γ's (15%)
  - break-up of nuclei (*"invisible"*) (40%)



- Main fluctuations in hadron calorimetry:
  - Large, non-Gaussian **electromagnetic component fluctuation**
  - Large, non-Gaussian fluctuation in nuclear binding energy loss ("invisible")

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

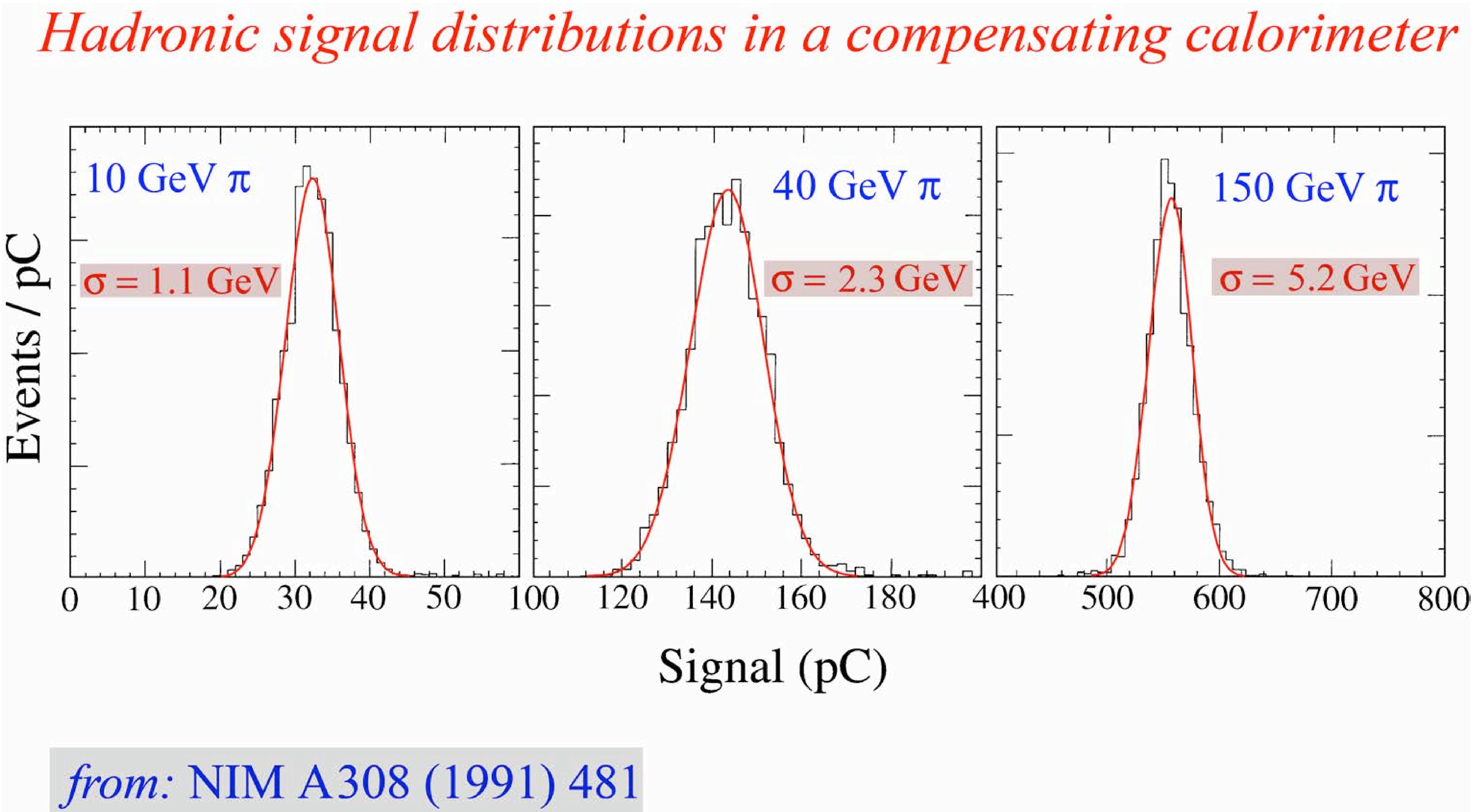
Consequence of Main Fluctuations in Hadron Showers

- 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 ($e/h = 1$) (SPACAL)
  - 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 10 years

SPACAL (Pb/Scintillator Calorimeter)



How can we improve the performance of hadron calorimeters?

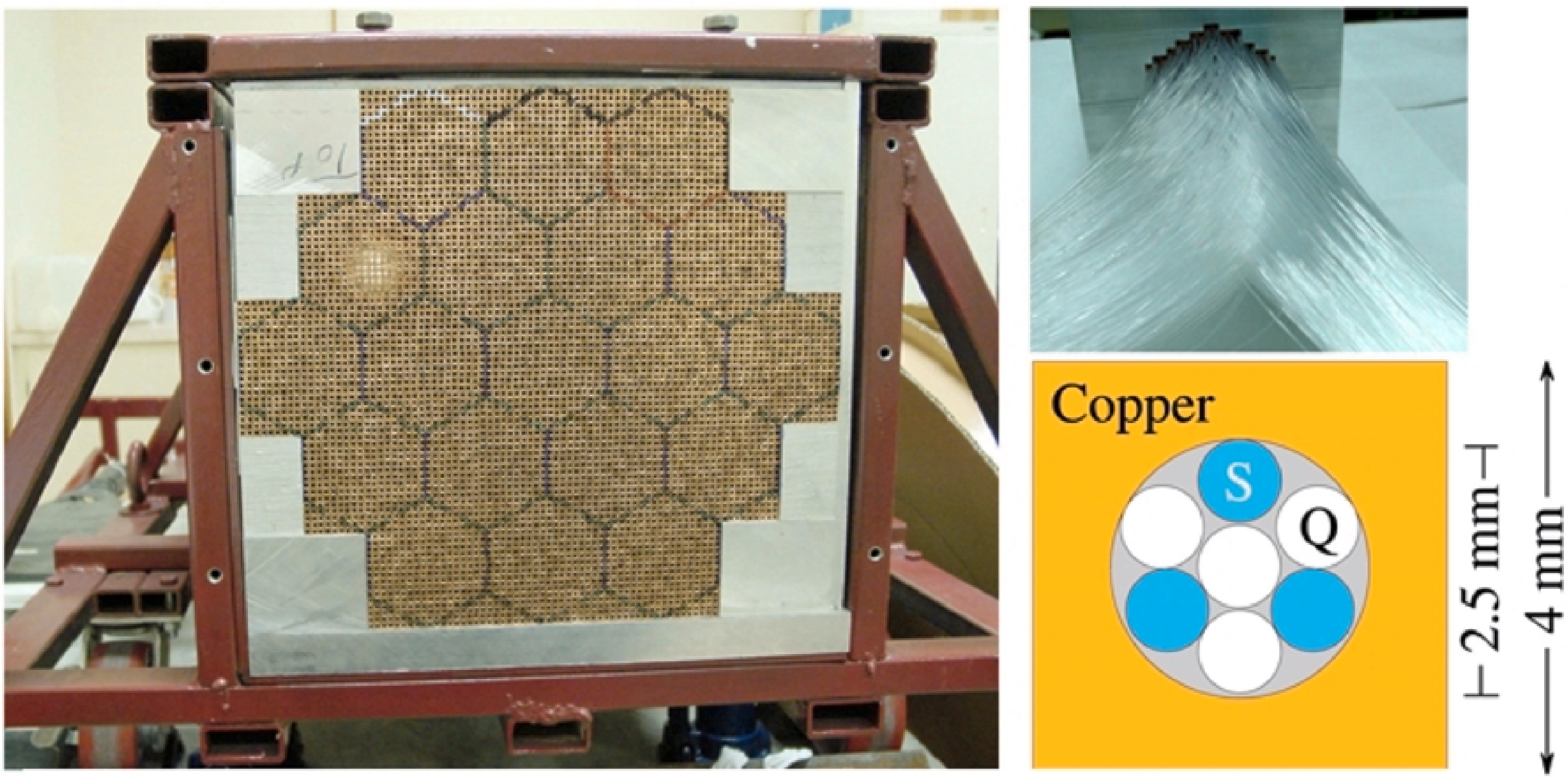
- Dominant fluctuation: f_{em}
  - EM shower component almost exclusively produces Cerenkov light
  - 80 % of non-em energy deposited by non-relativistic particle (non-em component: mainly soft proton)

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 $\lambda_{\rm int}$)
  - Effective radius 16.2 cm (0.81 $\lambda_{\rm int}$, 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

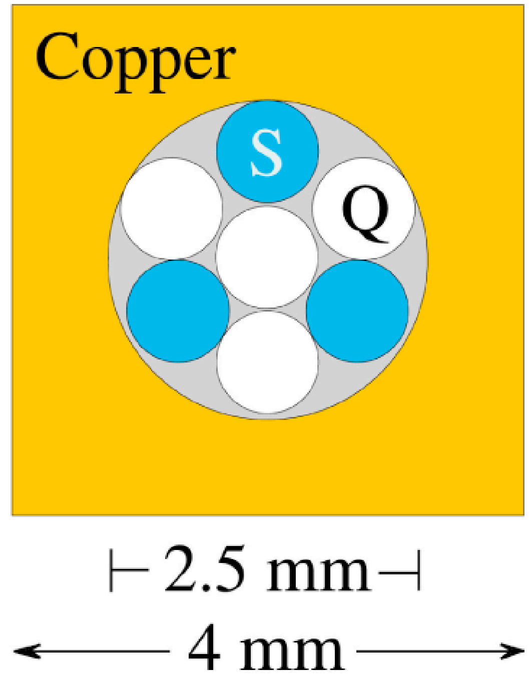


Figure 5: The basic building block of the DREAM detector is a 4×4 mm^2 extruded hollow copper rod of 2 meters length, with a 2.5 mm diameter central hole. Seven optical fibers (4 undoped and 3 scintillating fibers) with a diameter of 0.8 mm each are inserted in this hole, as shown.

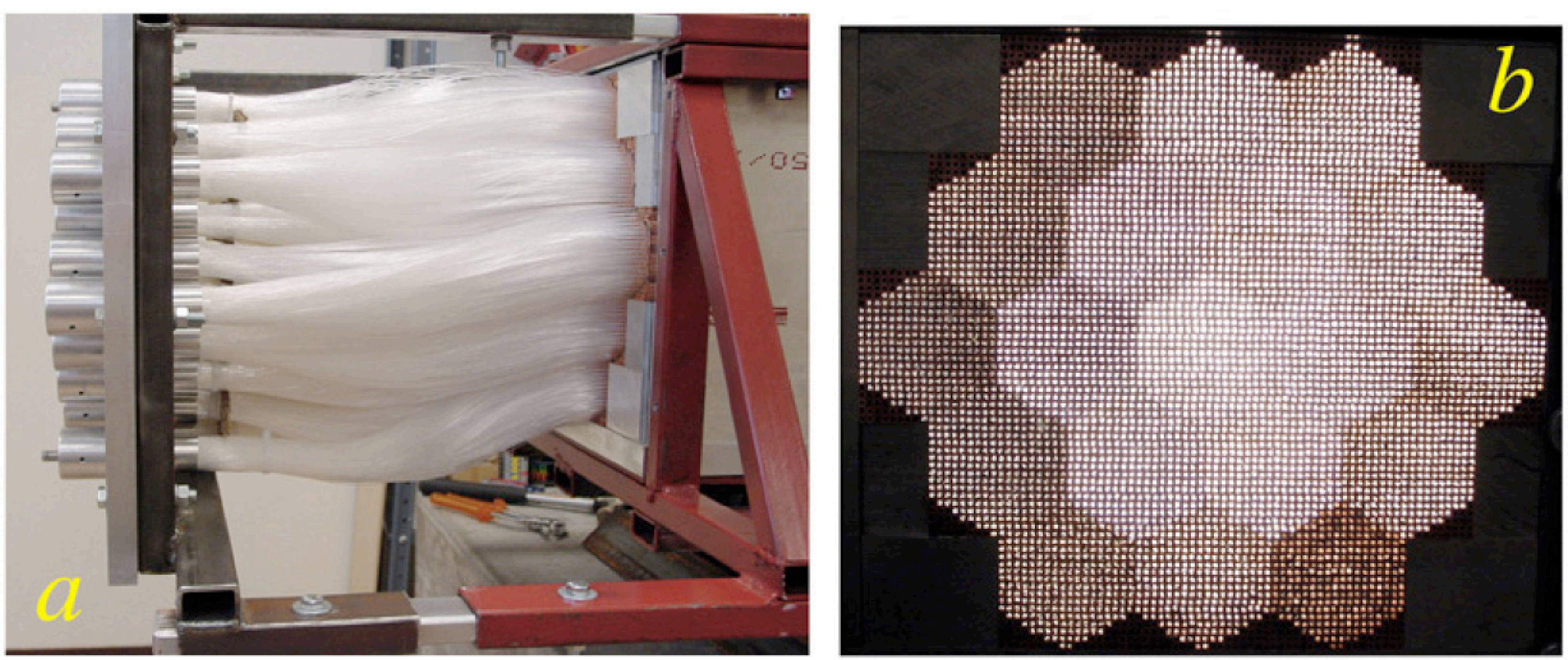


Figure 6: The DREAM detector. Shown are the fiber bunches exiting from the rear face of the detector (a) and a picture taken from the front face while the rear end was illuminated (b). The hexagonal readout structure is made visible this way.

Muon Detection

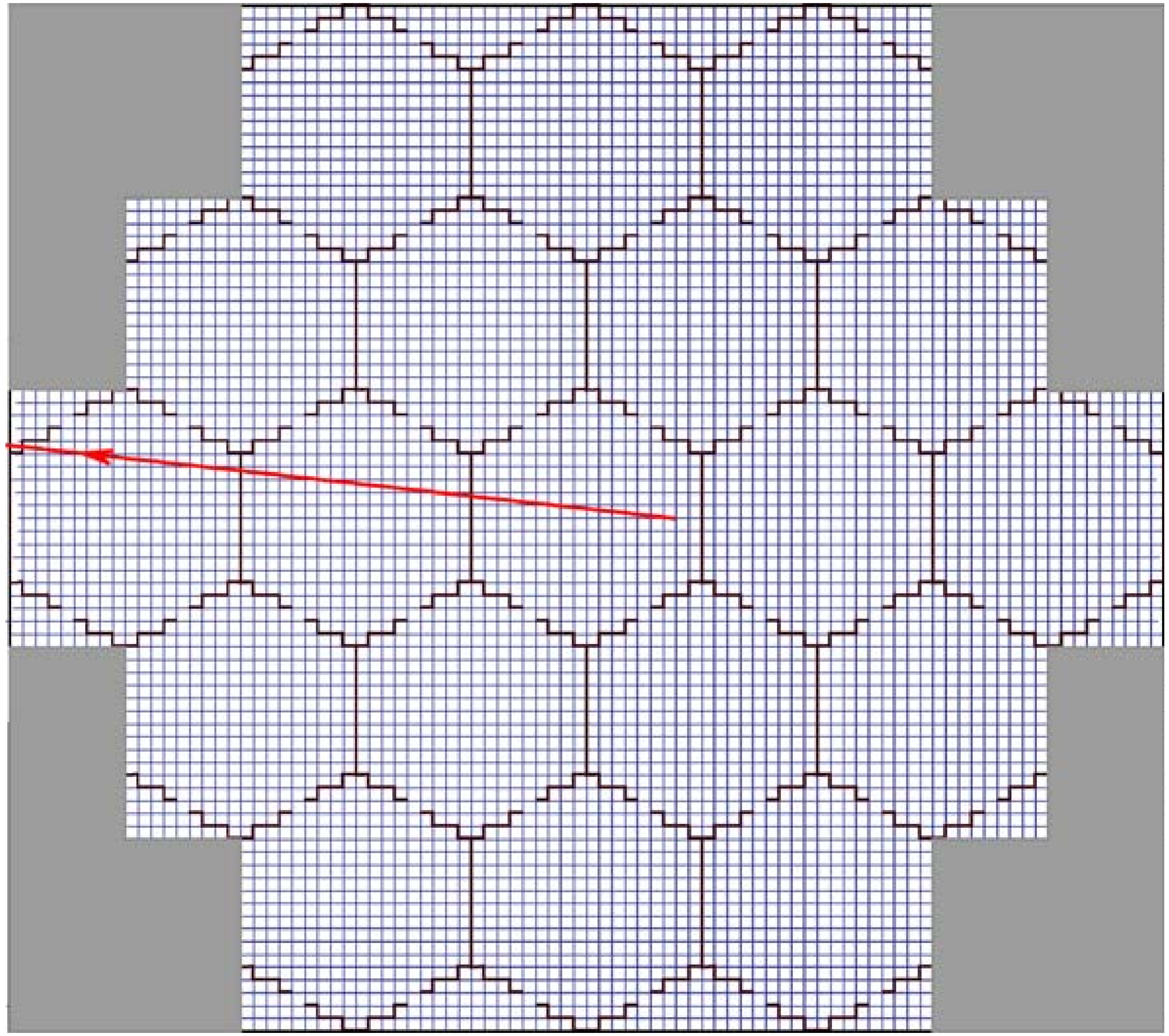
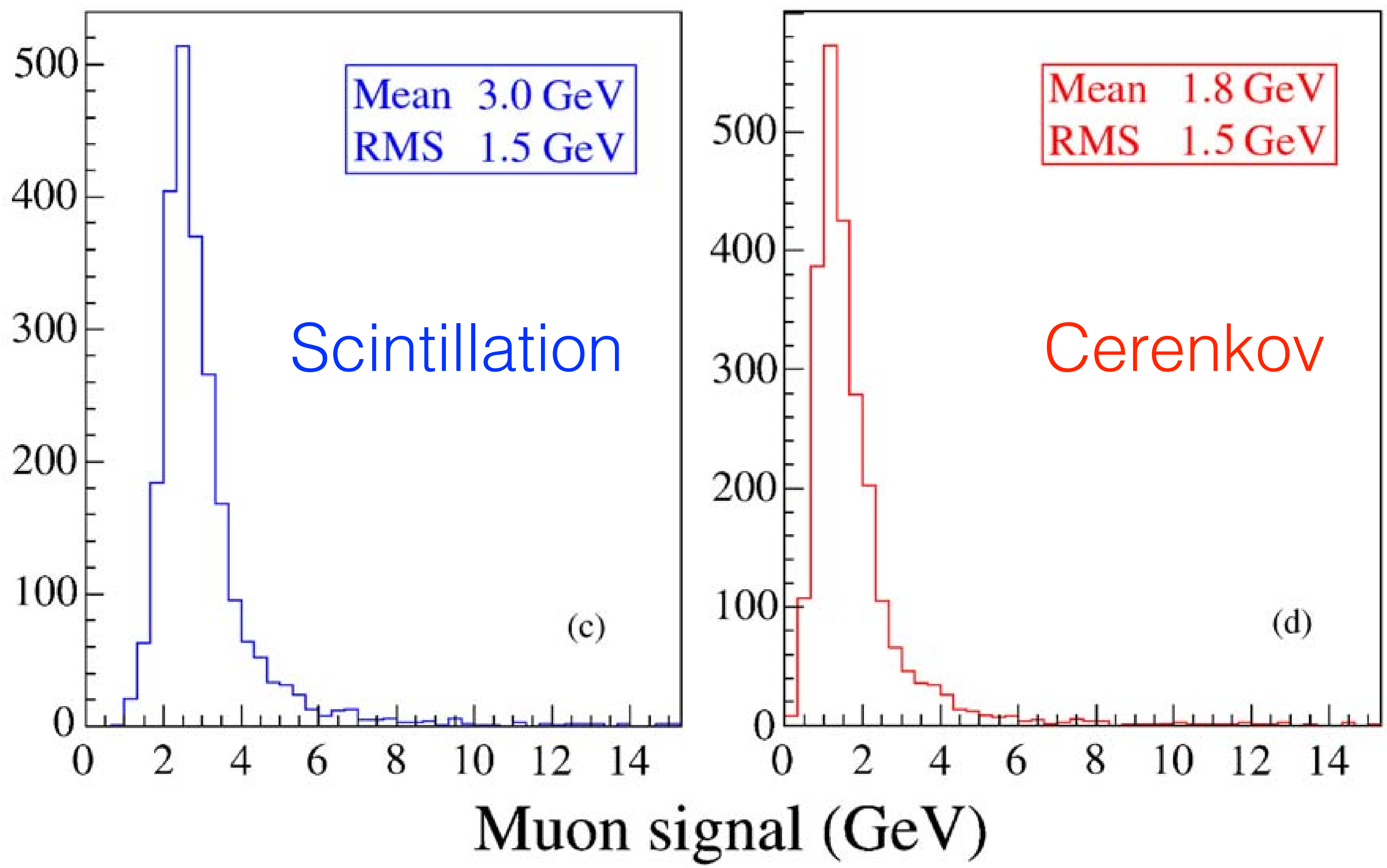


Fig. 2. Layout of the DREAM calorimeter. The detector consists of 19 hexagonal towers. A central tower is surrounded by two hexagonal rings, the Inner Ring (6 towers) and the Outer Ring (12 towers). The towers are not longitudinally segmented. The arrow indicates the (projection of the) trajectory of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

Distributions of the measured energy loss of 100 GeV muons



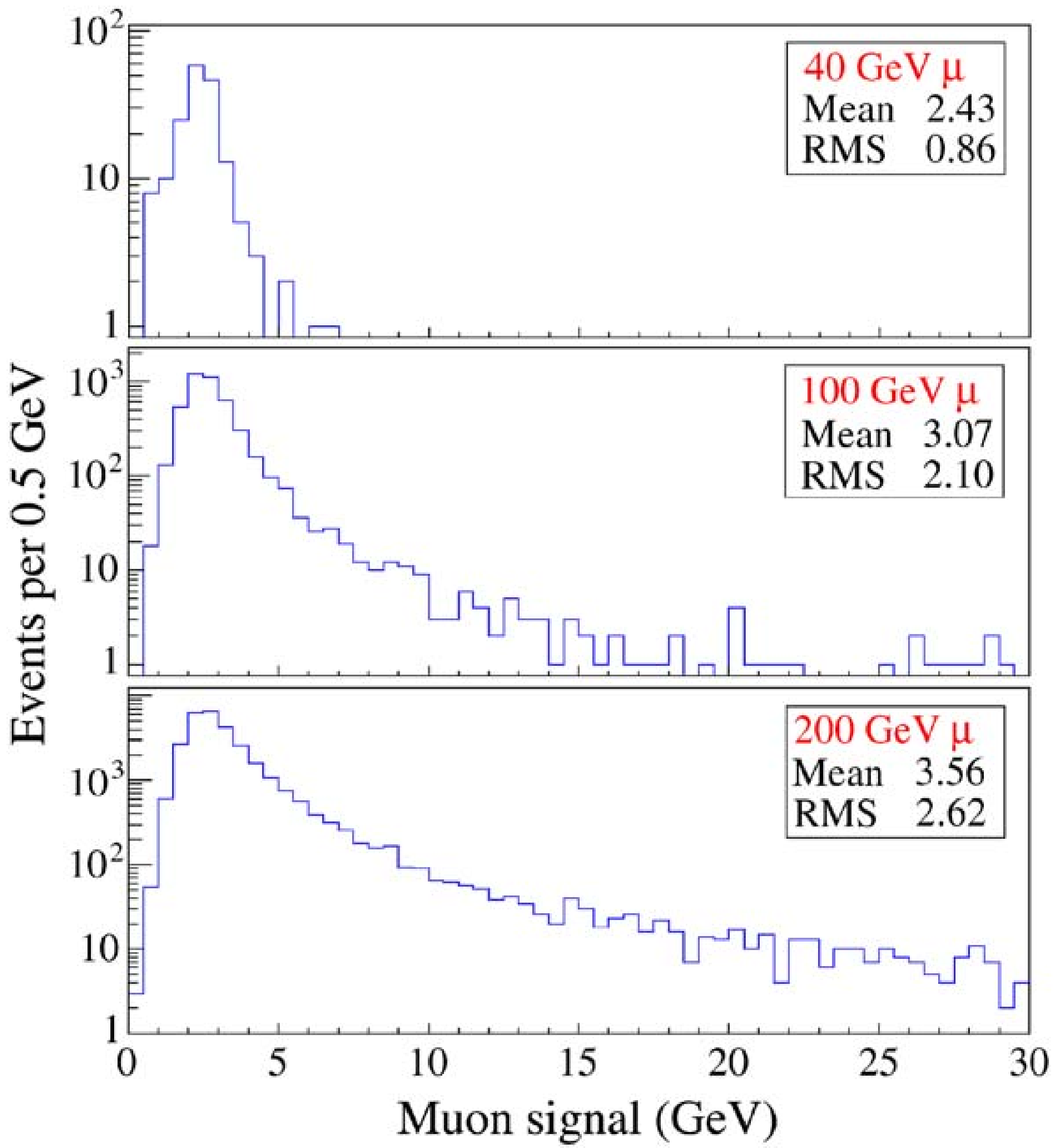


Fig. 14. Signal distributions for 40, 100 and 200 GeV muons, measured with the scintillating fibers in the DREAM calorimeter.

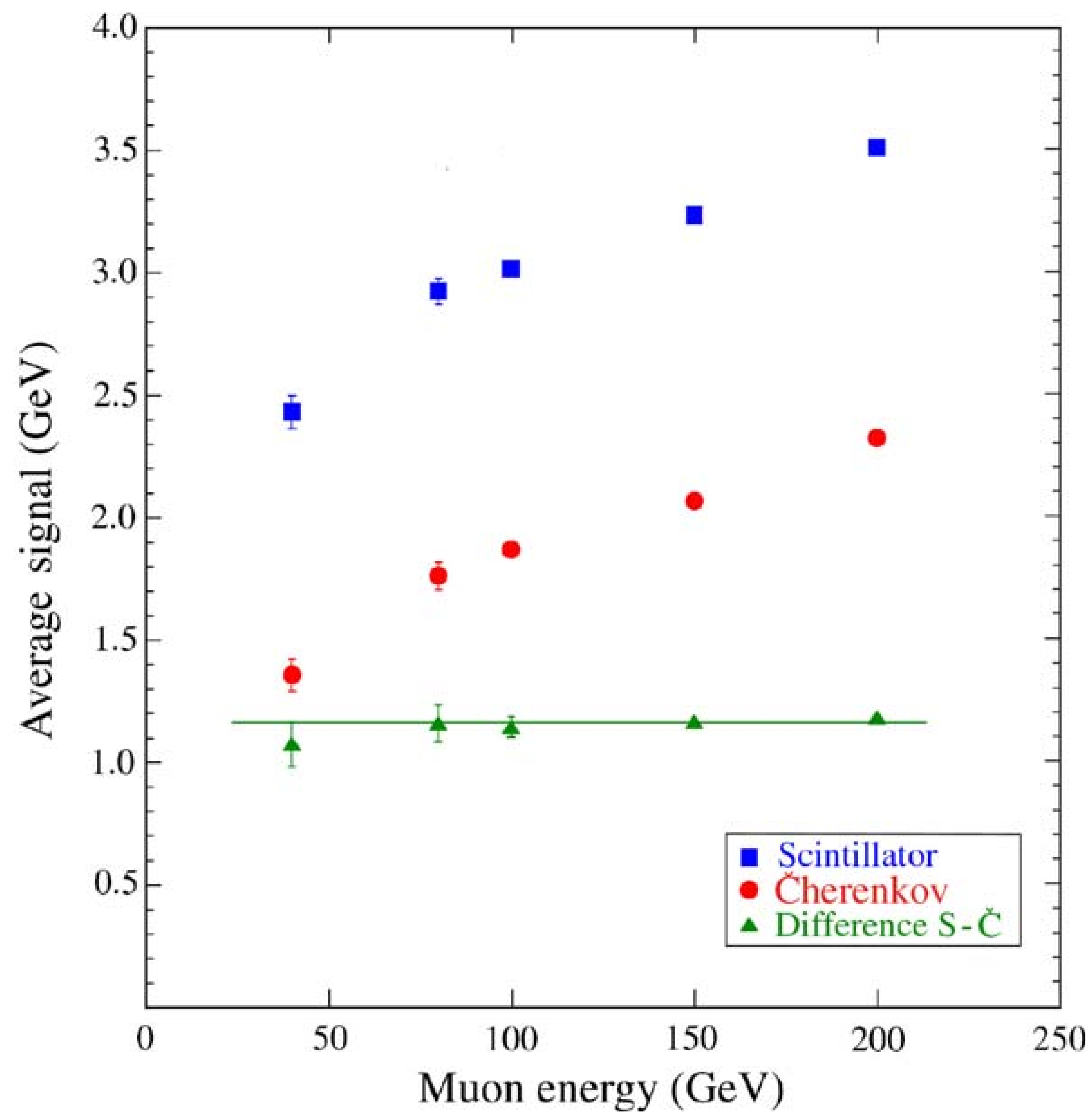


Fig. 18. Average signal from muons traversing the DREAM calorimeter, as a function of the muon energy. The detector was oriented in position D(6°, 0.7°). Results are given separately for the scintillating and the Cherenkov fibers. Also shown is the *difference* between the average signal values from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

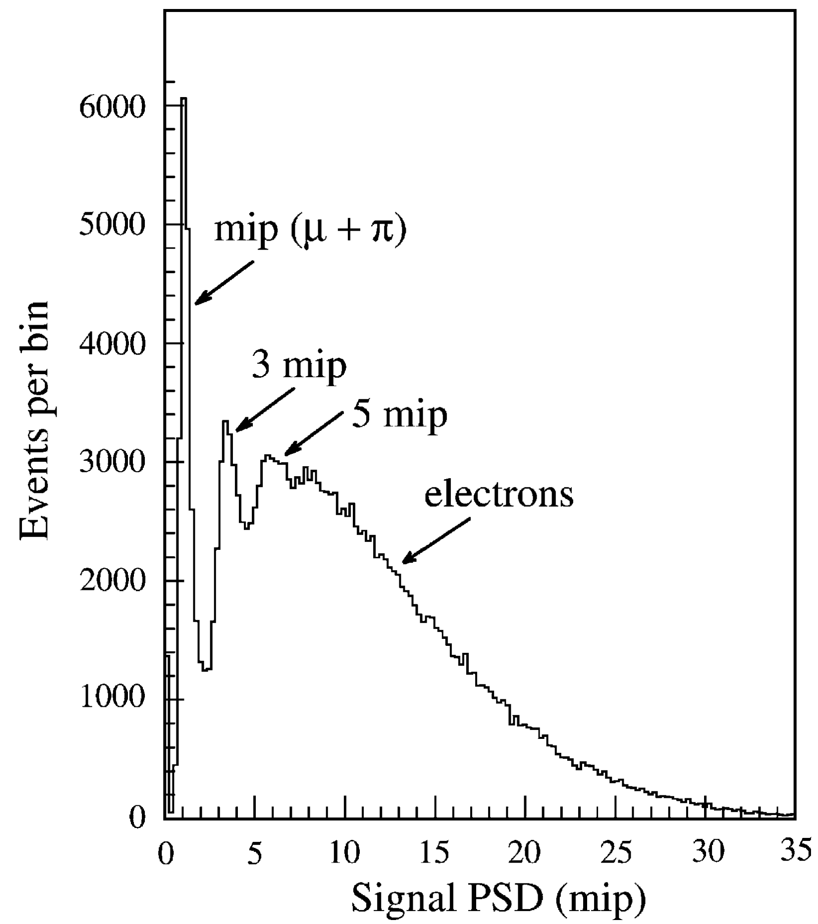


Fig. 5. Signal distribution for events recorded in the PSD for the 100 GeV electron beam. See text for details.

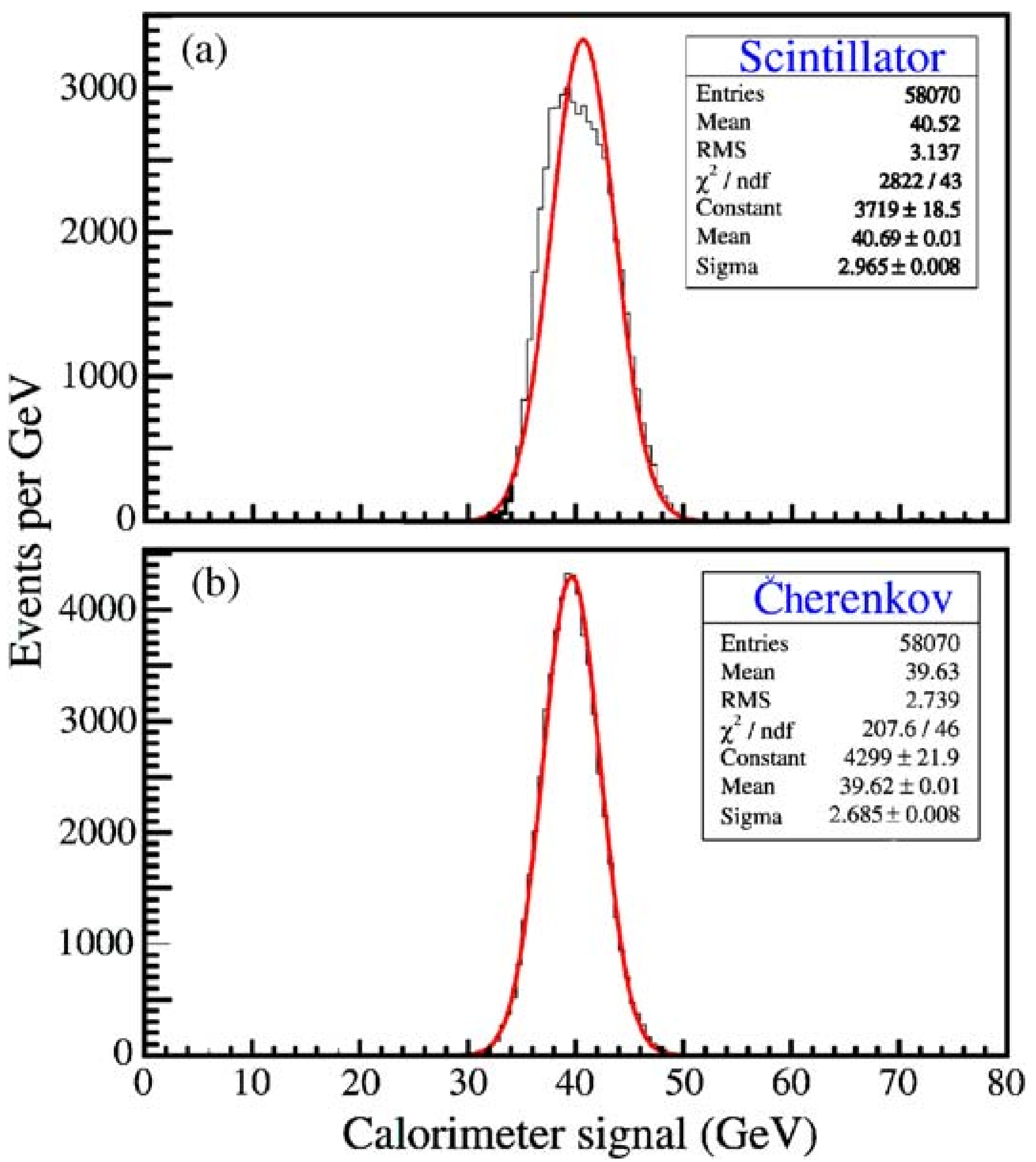


Fig. 7. Signal distributions for 40 GeV electrons, recorded from the scintillating (a) and the Cherenkov (b) fibers, with the DREAM calorimeter in the untilted position, A(2°, 0.7°).

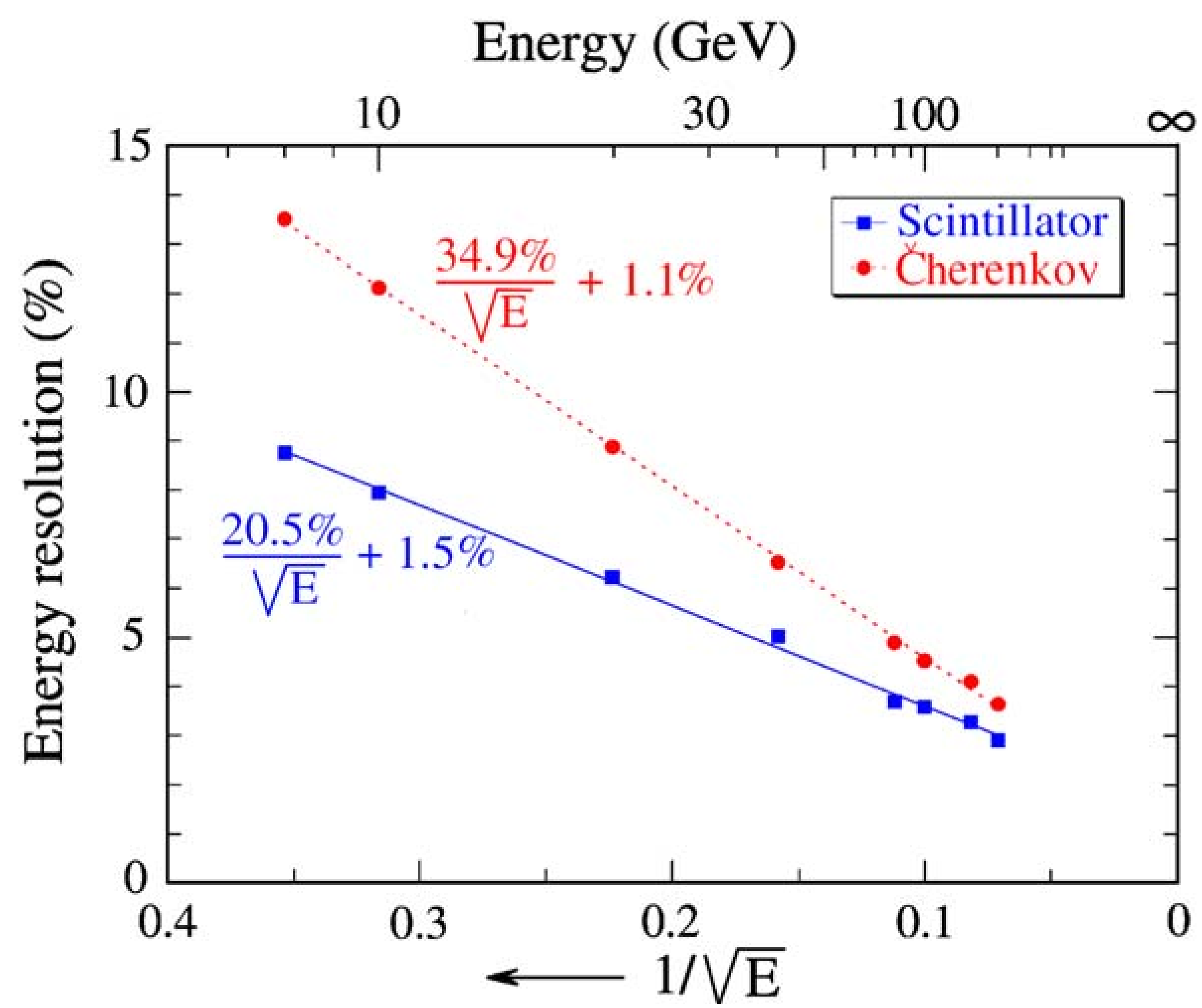
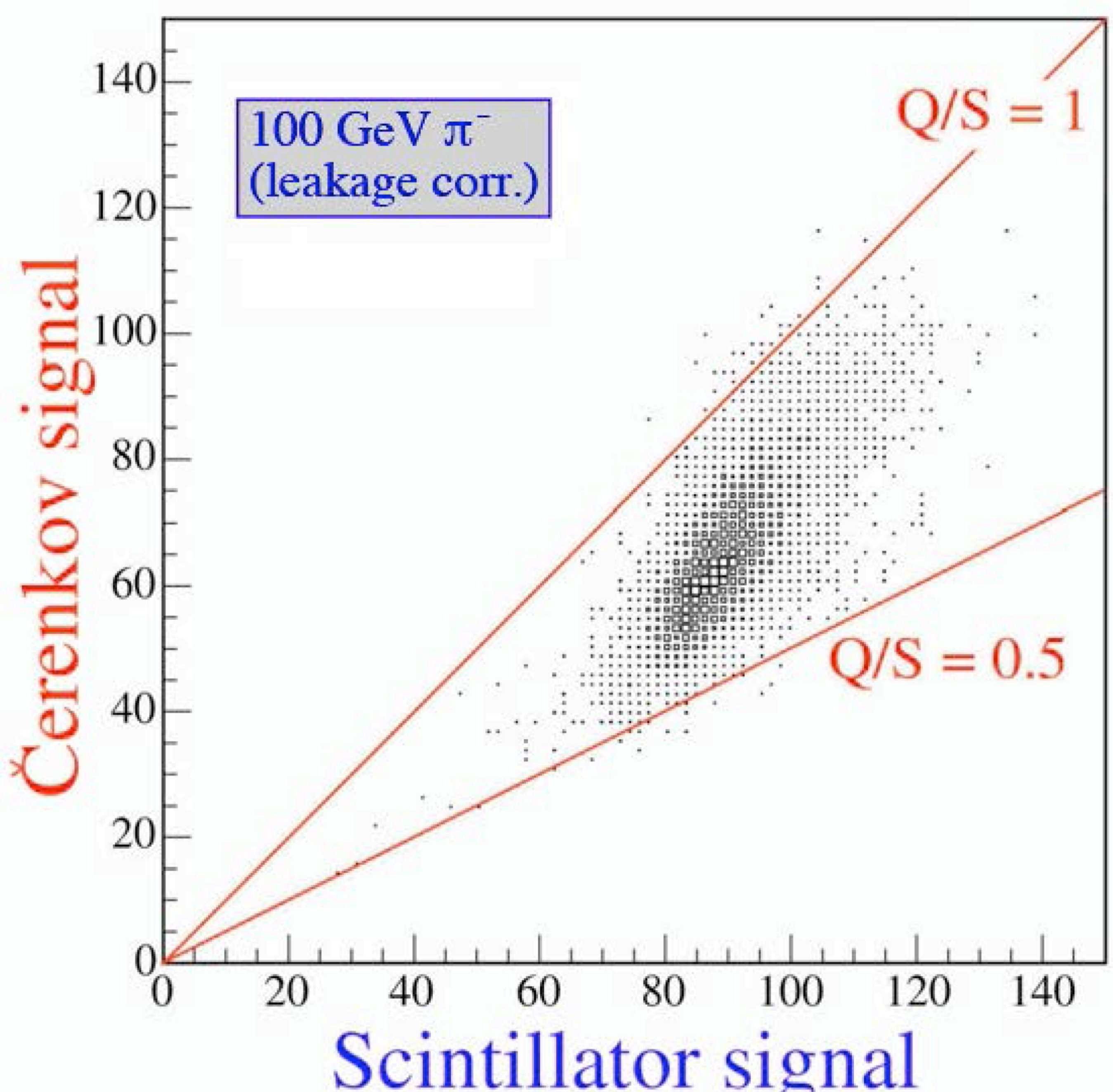


Fig. 20. The energy resolution as a function of energy, measured with the scintillating (squares) and Cherenkov fibers (circles), for electrons entering the calorimeter in the tilted position, B(3°, 2°).

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



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

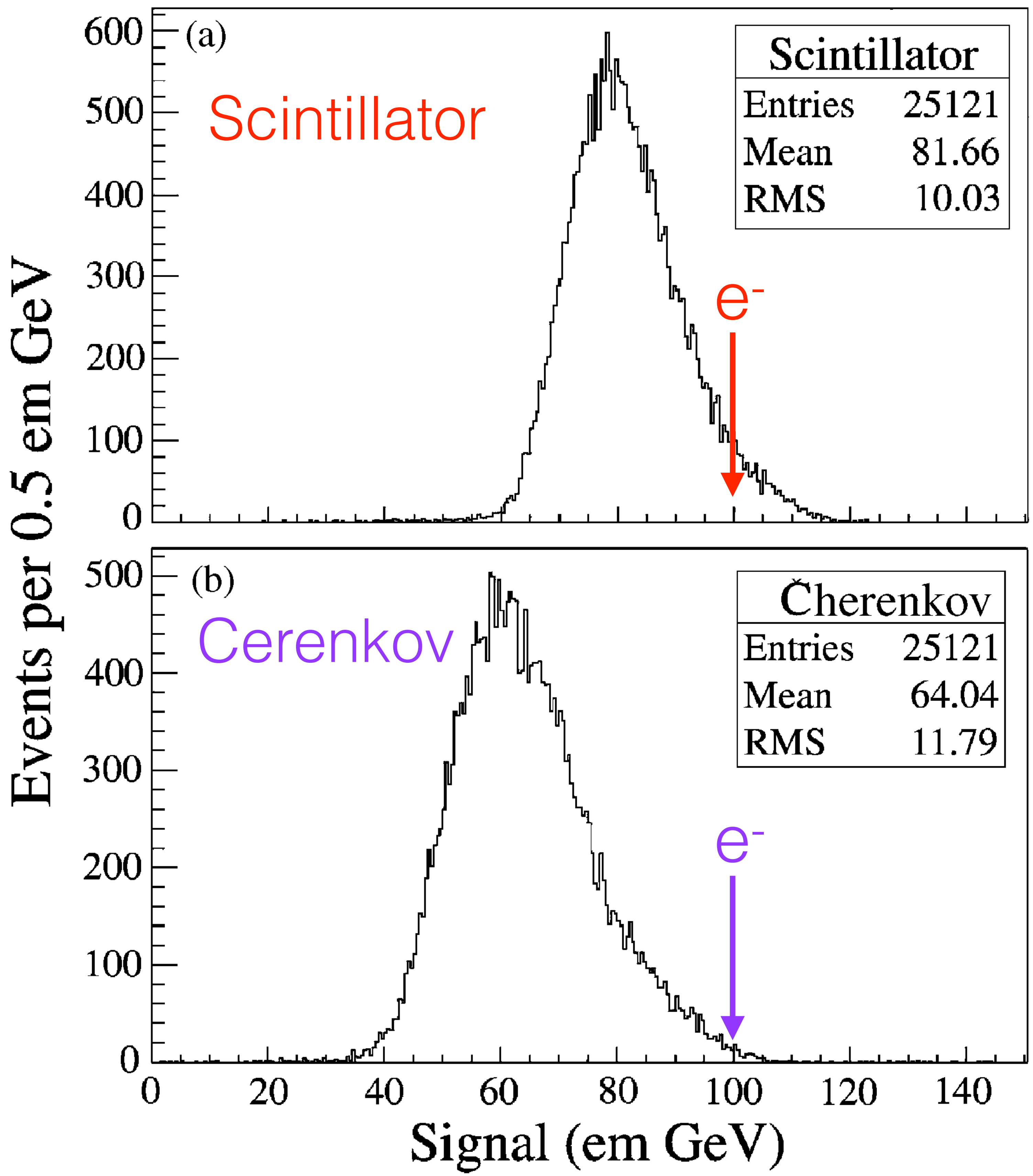
$$Q = E\left[f_{\rm em} + \frac{1}{(e/h)_Q}(1 - f_{\rm em})\right]$$

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

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

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

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



DREAM Raw signals (100 GeV π^-)

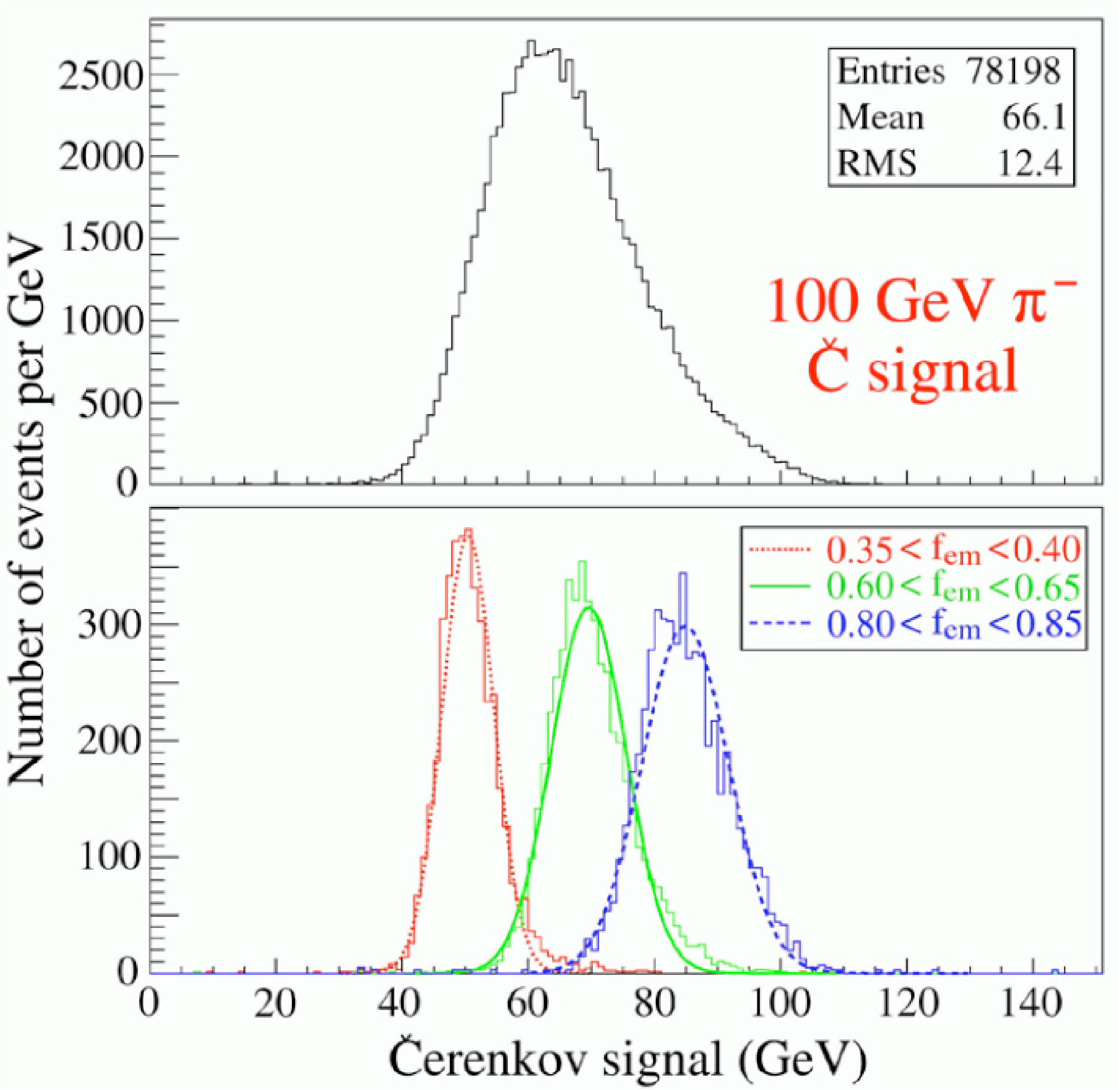
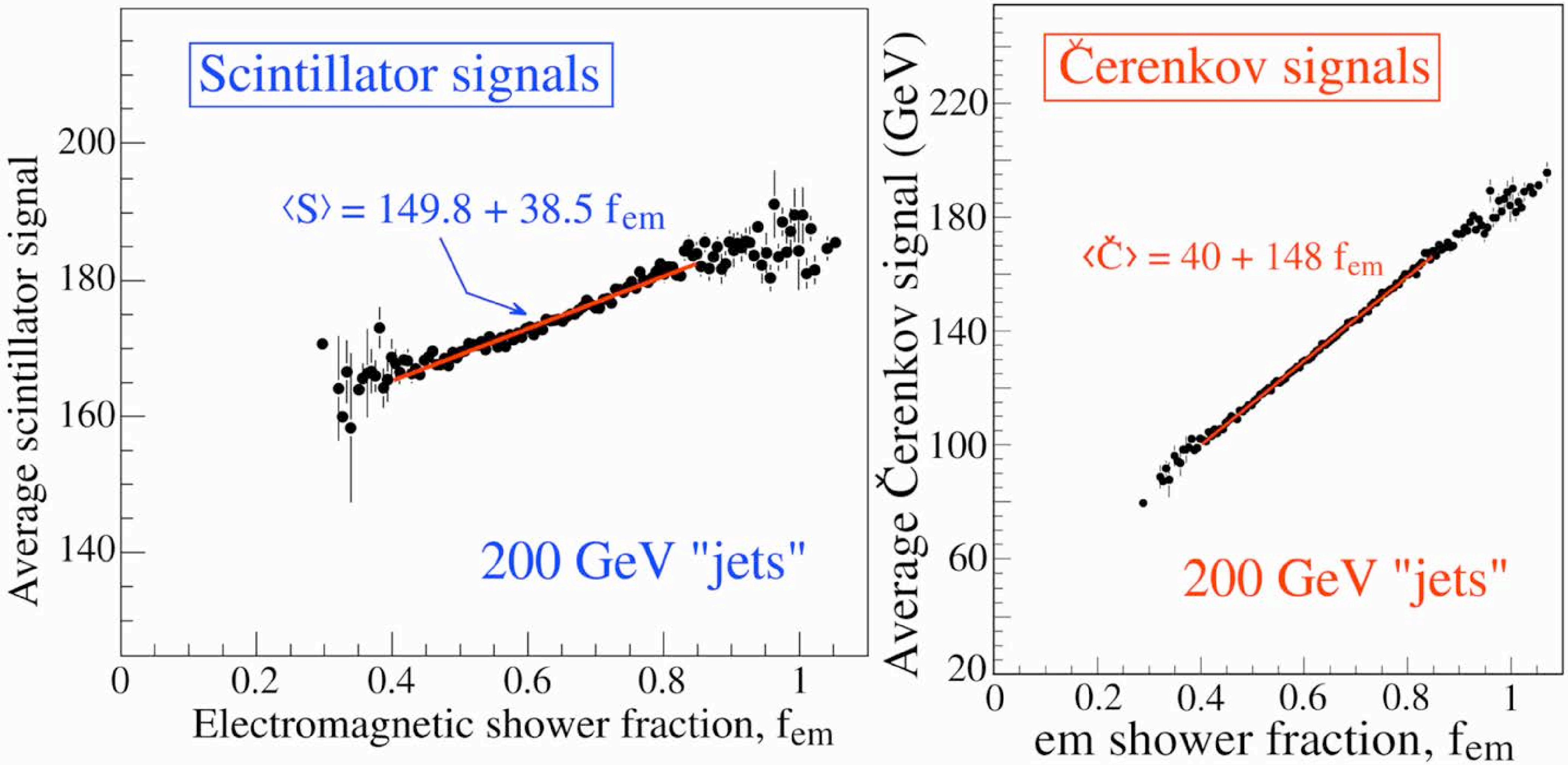


Figure 1: Čerenkov signal distributions for 100 GeV π^-. Shown are all events (top) and samples selected on the basis of their electromagnetic shower content (bottom) [5].

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

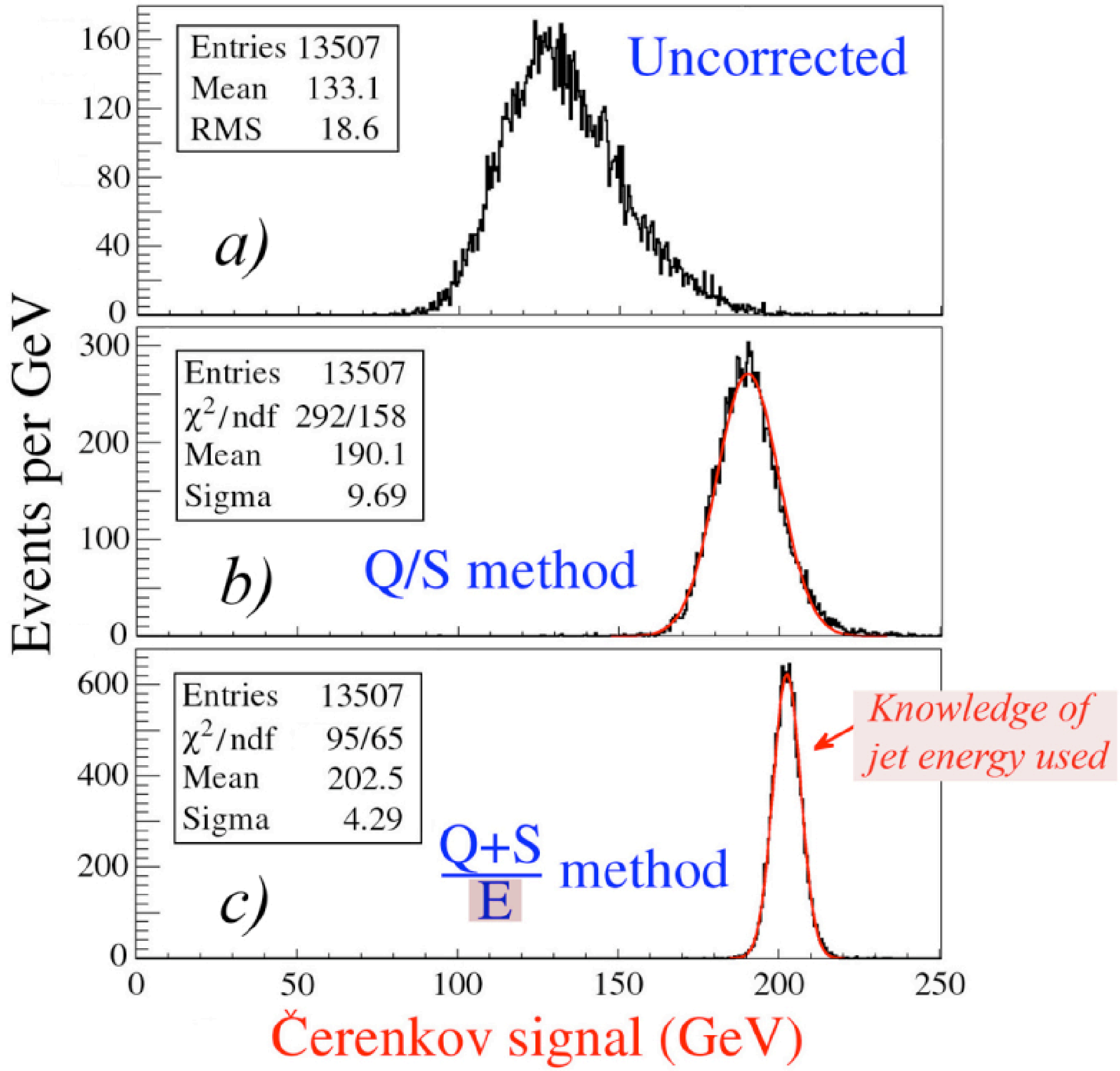


Figure 2: Čerenkov signal distributions for 200 GeV multi-particle events. Shown are the raw data (a), and the signal distributions obtained after application of the corrections based on the measured em shower content, with (c) or without (b) using knowledge about the total "jet" energy [5].

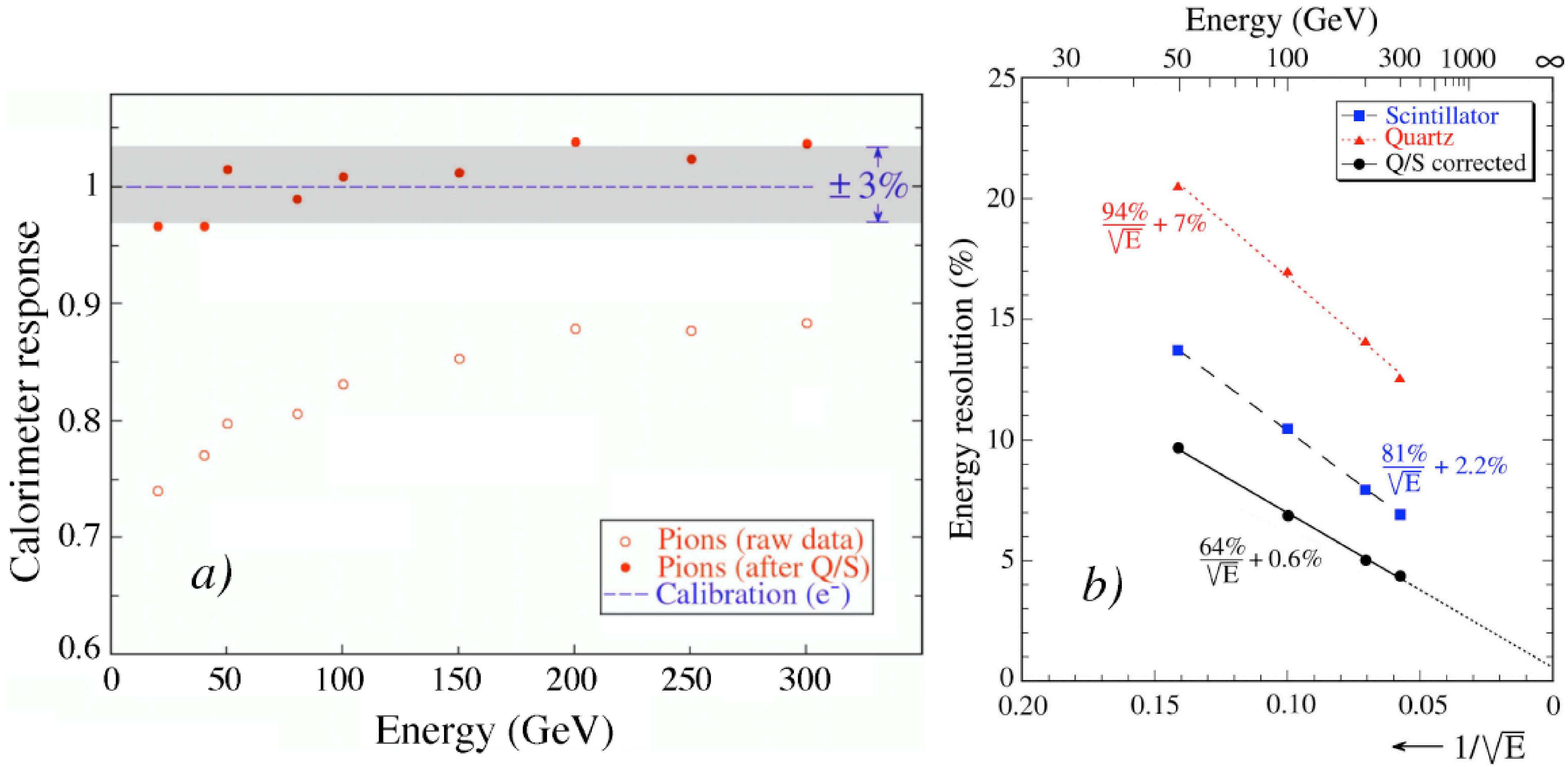


Figure 9: The scintillator response of the DREAM calorimeter to single pions (*a*) and the energy resolution for "jets" (*b*), before and after the dual-readout correction procedures were applied to the signals [5].

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

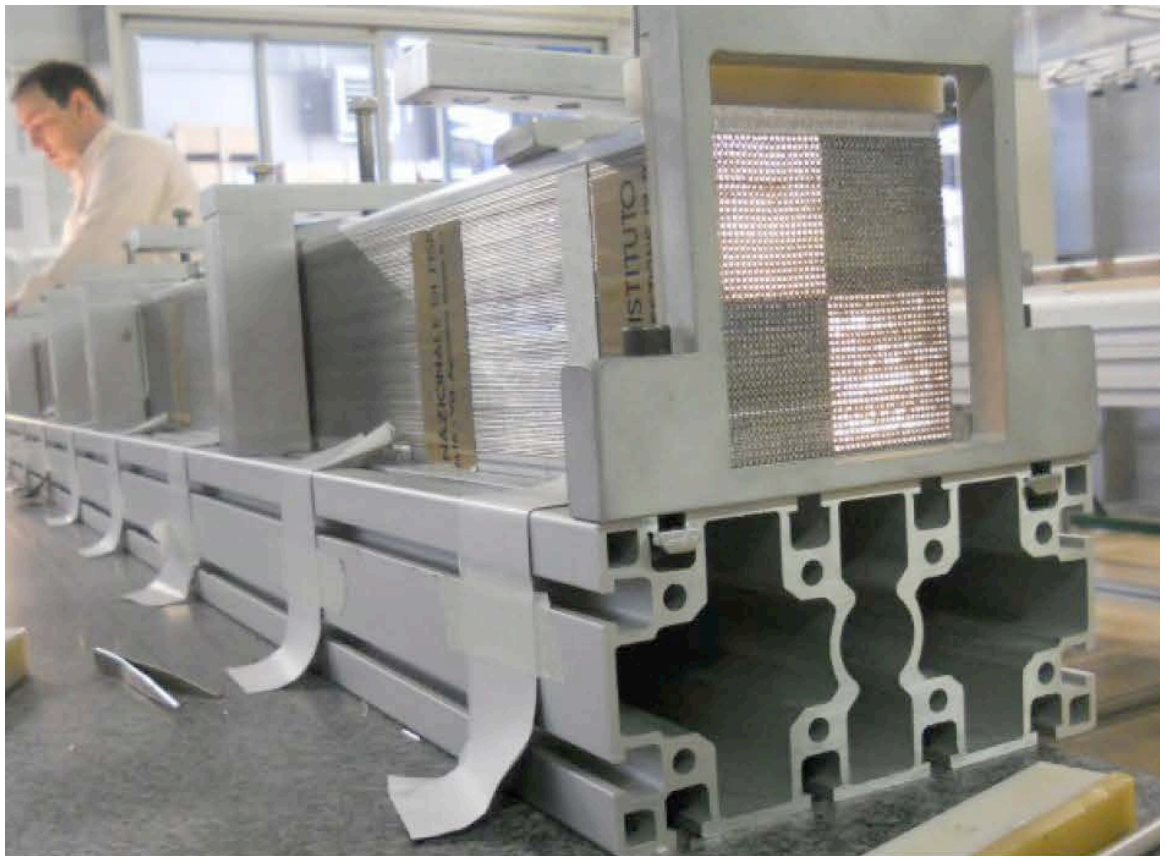
Dual-REAout Fiber calorimeter is free from the limitations (sampling fraction, integration volume, time) of intrinsically compensating calorimeters (e/h=1)

Additional factors to improve DREAM performance

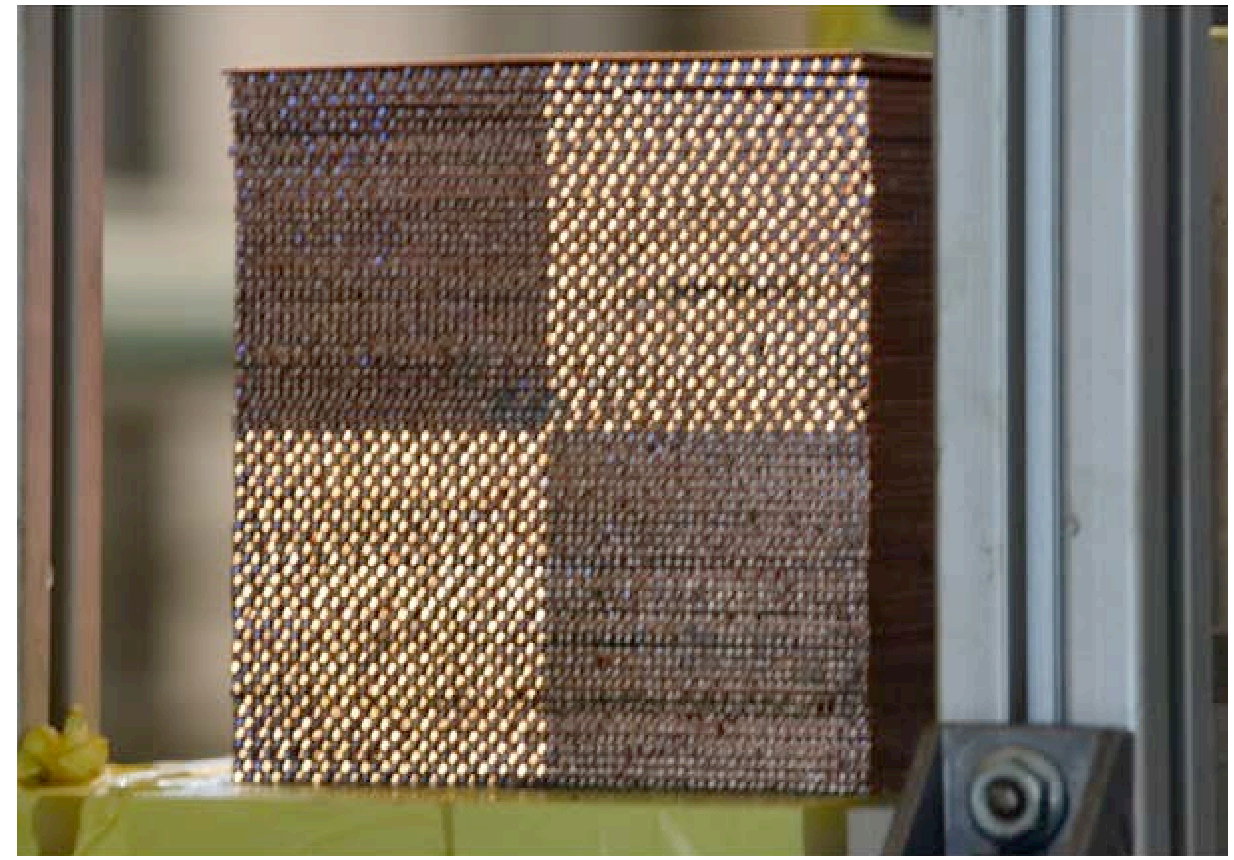
- Reduction of shower leakage (leakage fluctuations) → Build larger detector
- Increase Cerenkov light yield
  - Prototype DREAM: 8 p.e./GeV → light yield fluctuations contribute by 35%/$\sqrt{E}$
- Reduction of sampling fluctuations → Put more fibers
  - contribute ~40%/$\sqrt{E}$ to hadronic resolution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

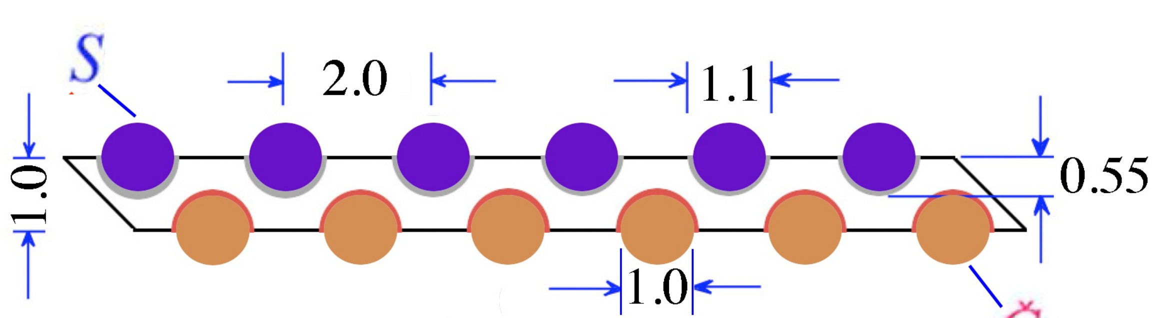
The structures of Pb and Cu modules

Pb

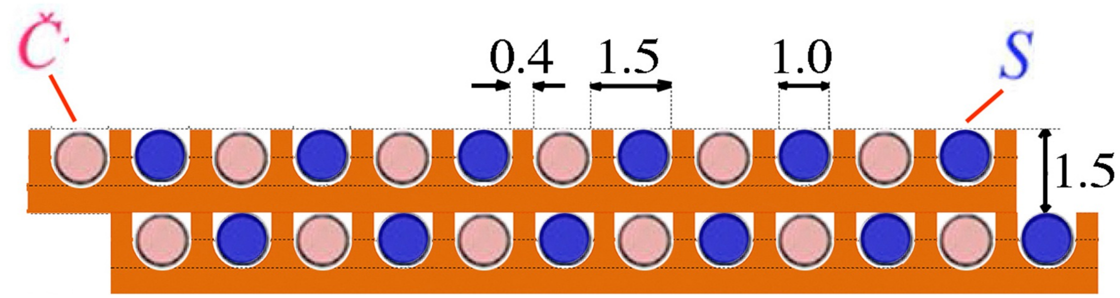


Cu



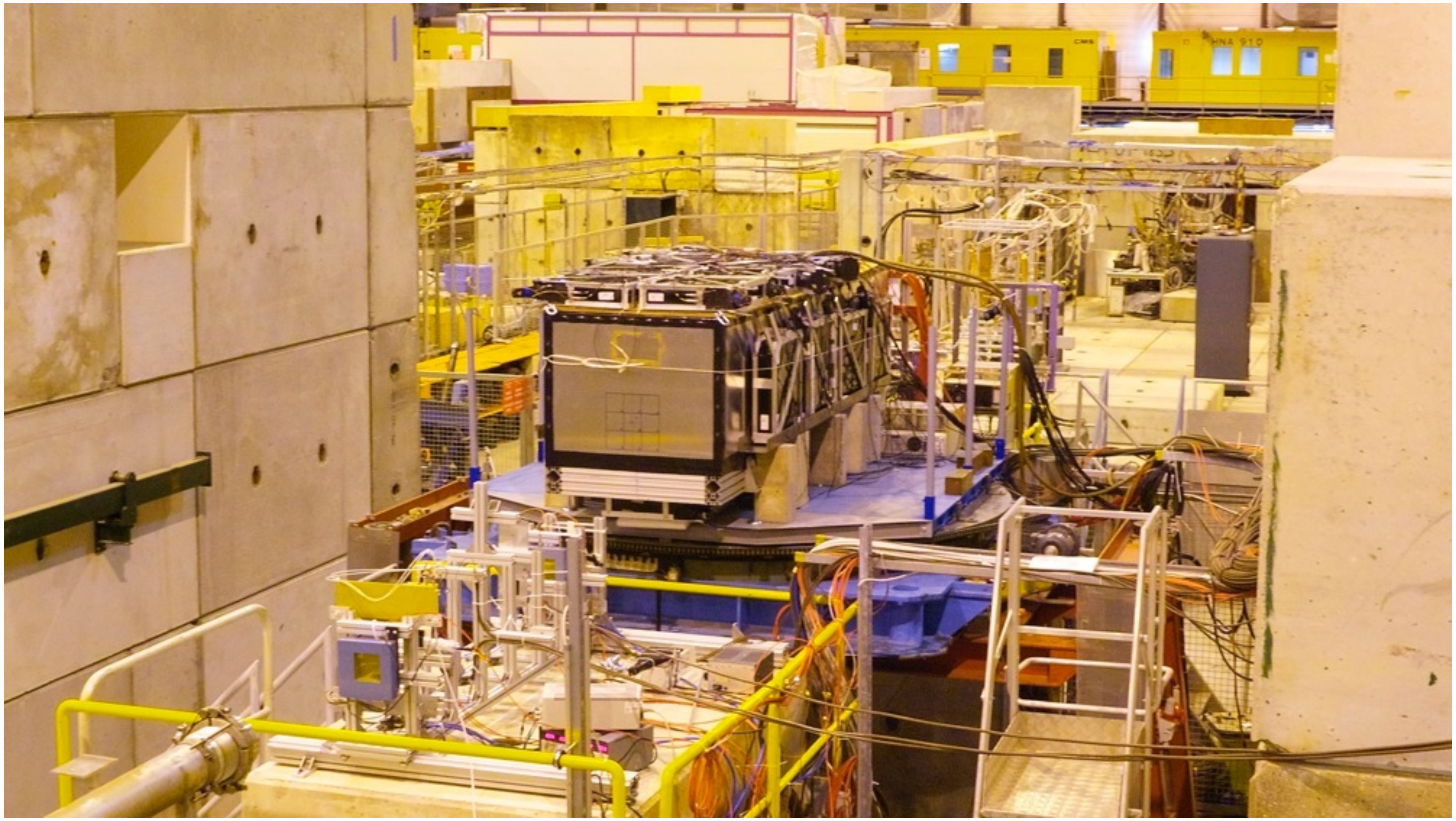


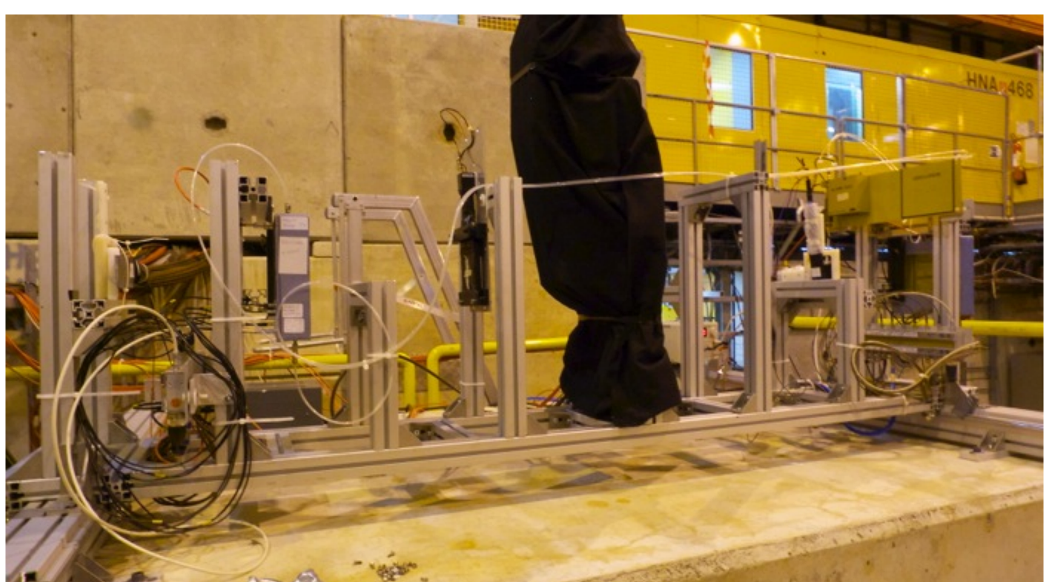
a)

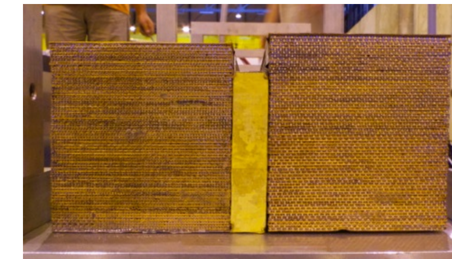


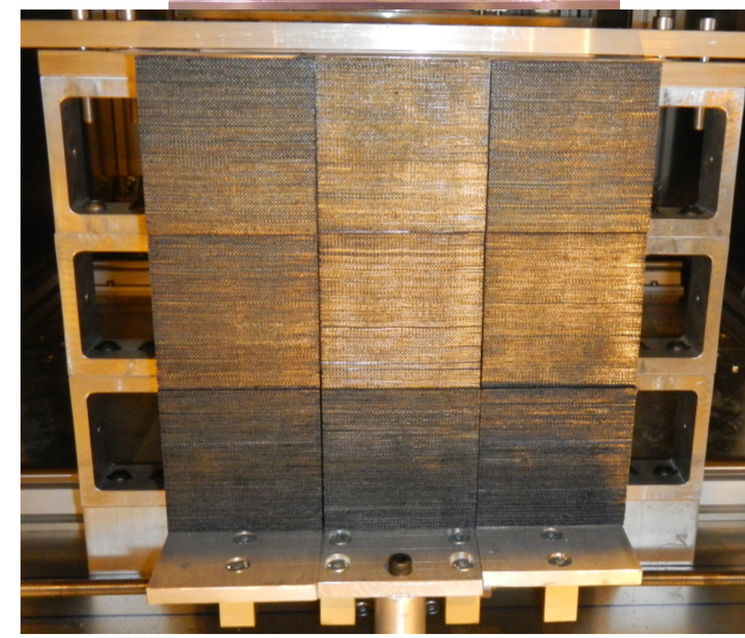
b)

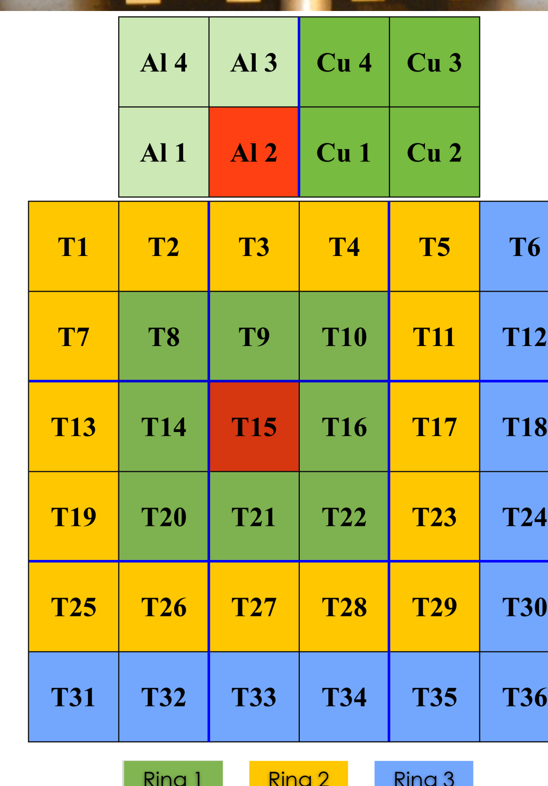
Test Beam with the new DREAM modules







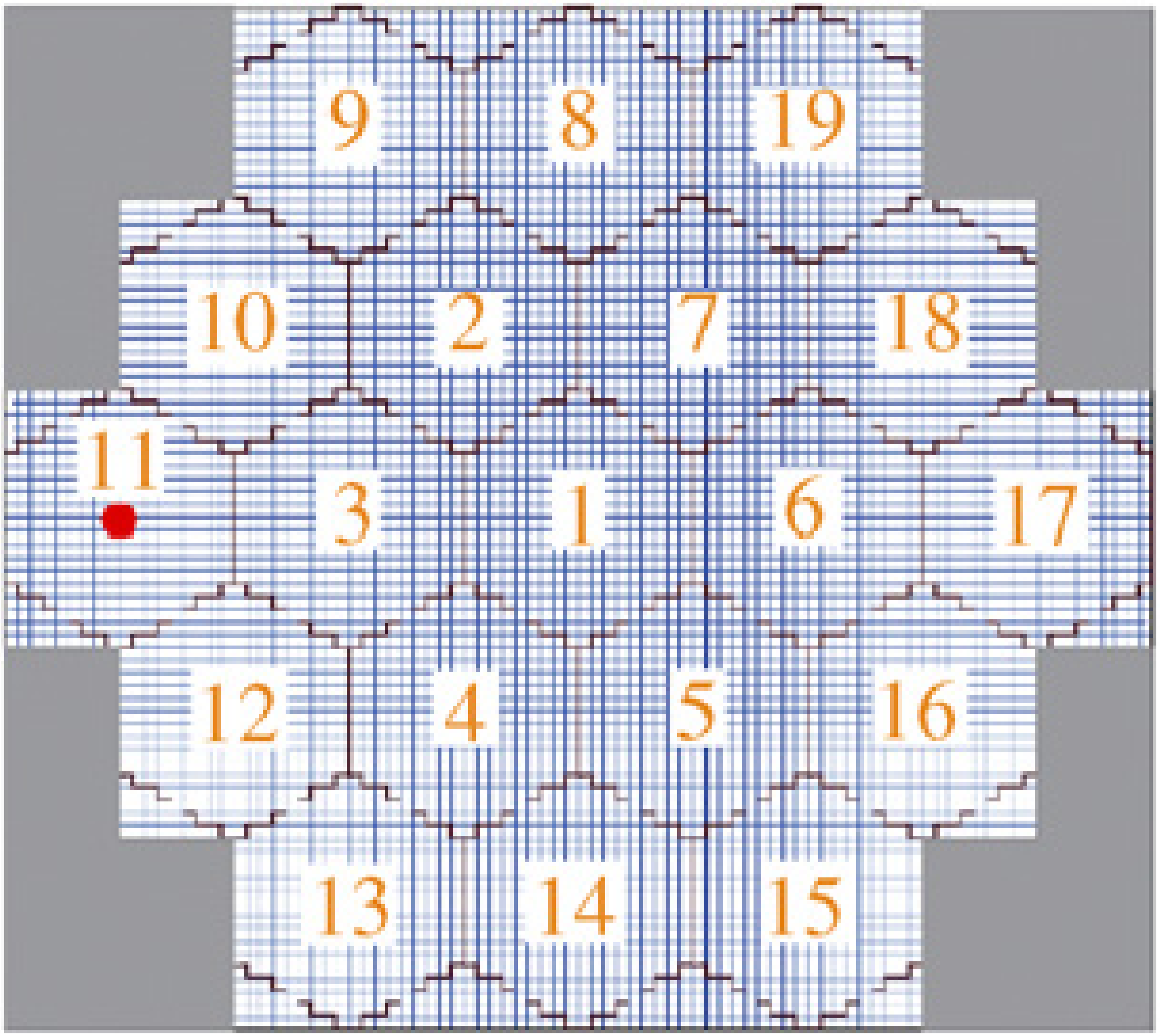




9 Pb modules (36 towers, 72 channels), 2 Cu modules (8 towers), 20 leakage counters (Plastic scintillator)

The results about the new DREAM calorimeters will be shown in the conference week

Backup



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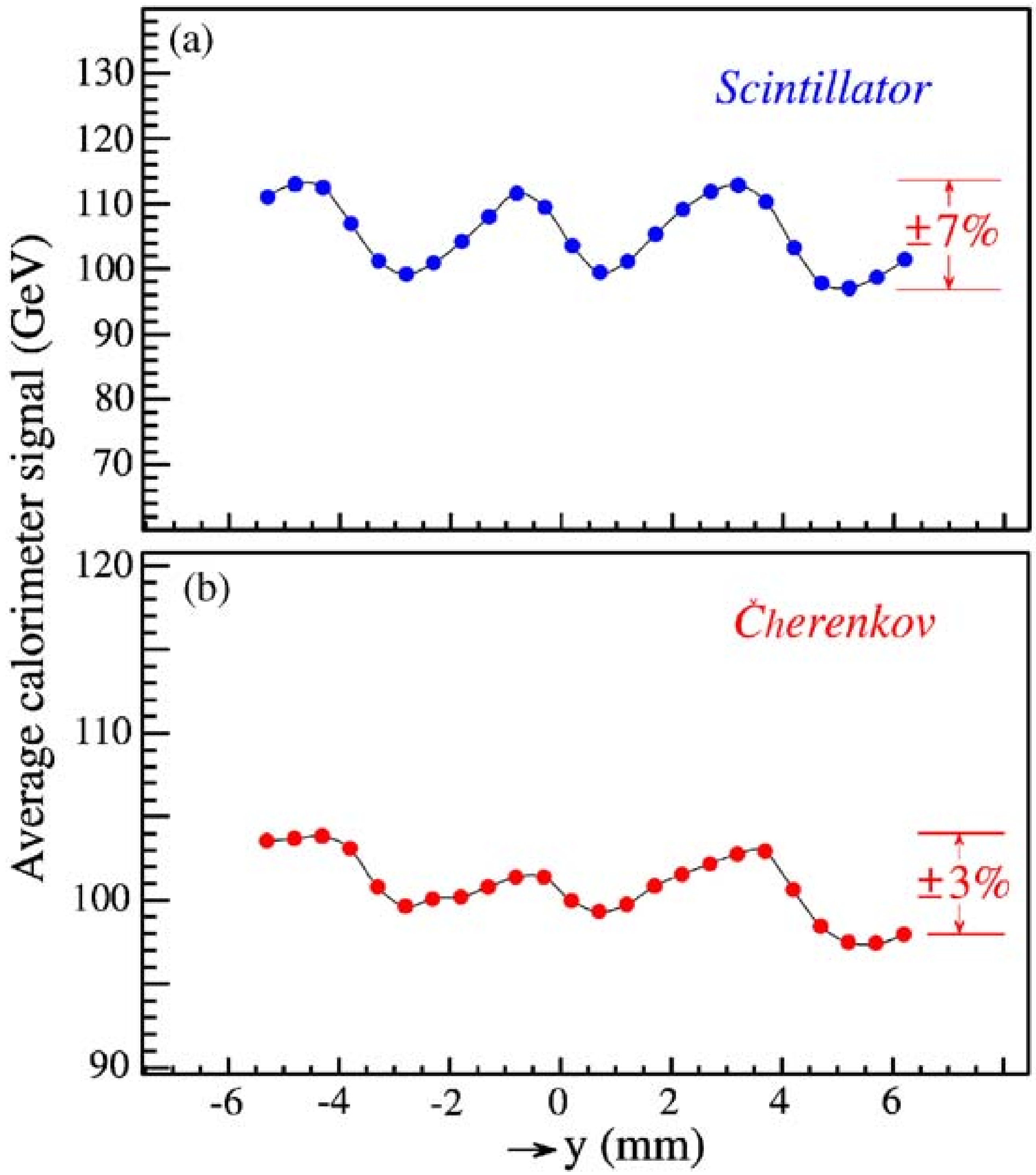

Fig. 11. Average calorimeter signal as a function of the *y*-coordinate of the impact point, for the scintillator (a) and Cherenkov (b) signals from 100 GeV electrons entering the DREAM calorimeter oriented in the untilted position, A(2°, 0.7°). Note the different vertical scales.

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	*Untilted*, A(2°, 0.7°)		*Tilted*, B(3°, 2°)	
	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.

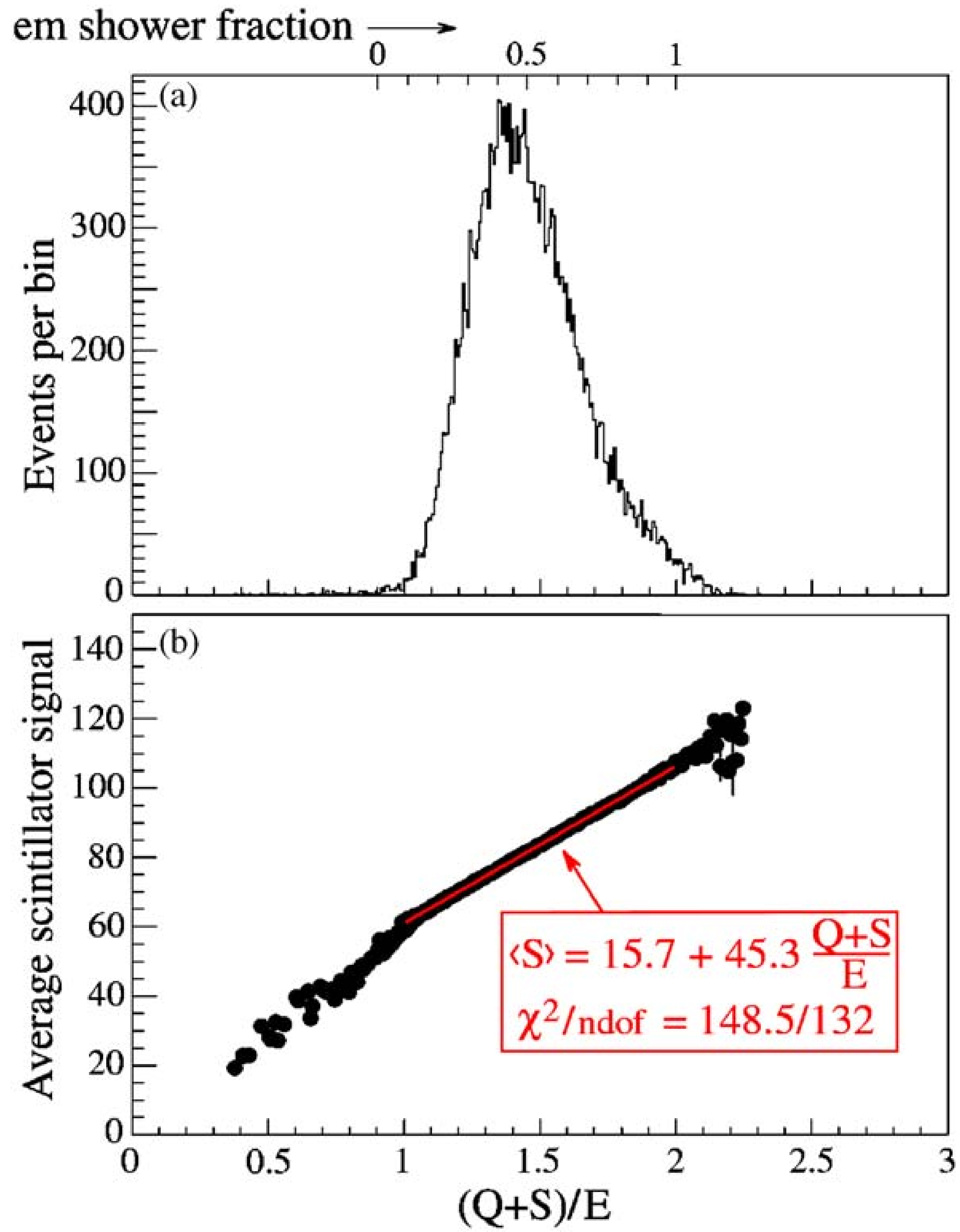

Fig. 14. Distribution of the variable $(Q+S)/E$, and of the em shower fraction derived on the basis of Eq. (2), for 100 GeV π^- showering in the DREAM calorimeter (a). The average scintillator signal for 100 GeV π^-, as a function of $(Q+S)/E$ (b).