HADRON CALORIMETRY
How to meet the ILC requirements

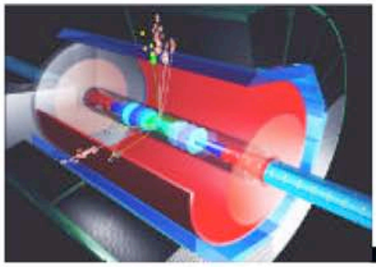
Richard WIGMANS

Snowmass, 8/18/2005

- Lessons from 25 years of R&D
- The DREAM solution
- Results & plans

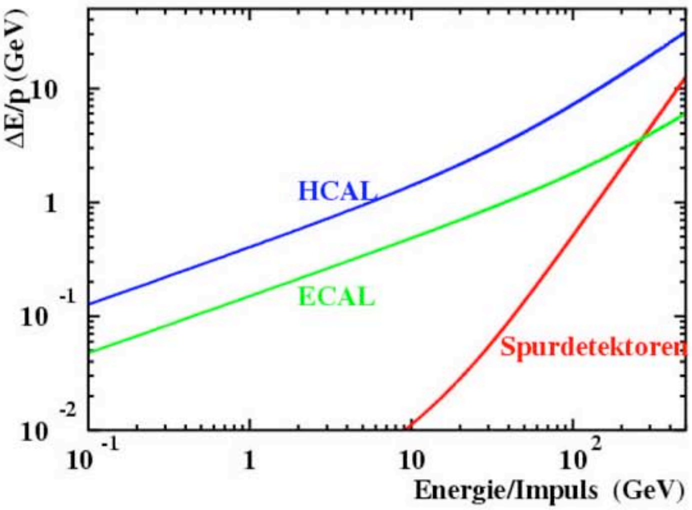
LESSONS FROM 25 YEARS OF R&D

- *LESSON 1:* Energy resolution is determined by *fluctuations*,
  not by average values



Particle Flow Algorithms

- Best jet energy resolution with minimum calorimetry
  - tracking detectors to measure energy of charged particles (**65%** of the typical jet energy)
  - EM calorimeter for photons (**25%**)
  - EM and HAD calorimeter for neutral hadrons (**10%**)



$$E_{\text{jet}} = E_{\text{charged}} + E_{\text{photons}} + E_{\text{neut. had.}}$$

$$\sigma^2_{E\text{jet}} = \sigma^2_{E\text{charged}} + \sigma^2_{E\text{photons}} + \sigma^2_{E\text{neut.had.}} + \sigma^2_{\text{confusion}}$$

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  Consequence for PFA: $\Sigma E_\pi = (30 \pm 5)\%$ much better than $(60 \pm 20)\%$
  The relevant fluctuations are *large* and almost *energy independent*

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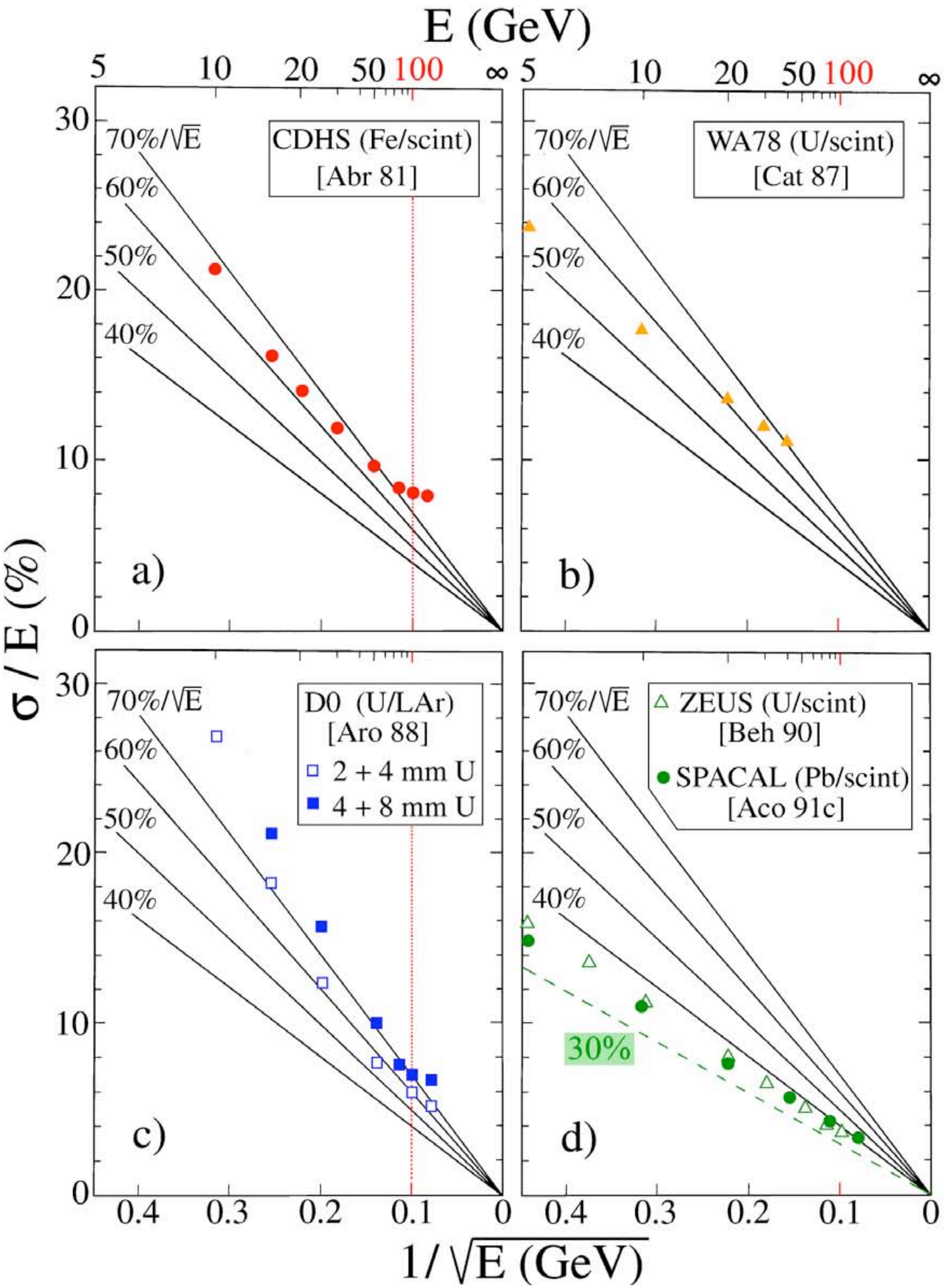
  Resolution goal should be stated as: $\sigma \approx 3$ GeV @ 80 - 90 GeV



Hadronic energy resolution does ***NOT*** scale with $1/\sqrt{E}$

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Saturation in "digital" calorimeters (wire chamber readout)

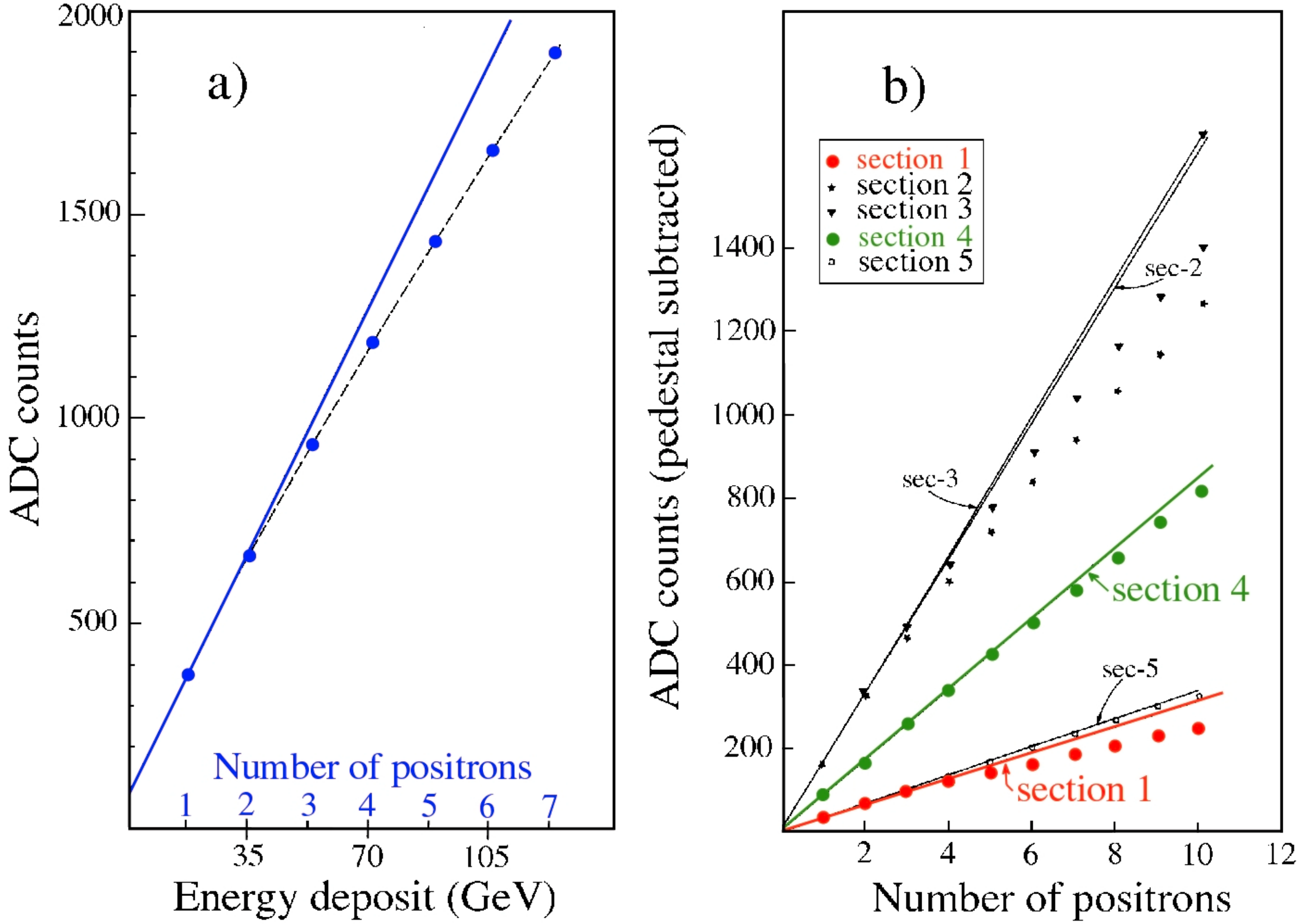

FIG. 3.2. Average em shower signal from a calorimeter read out with gas chambers operating in a "saturated avalanche" mode, as a function of energy. From: NIM 205 (1983) 113.

Hadronic shower profiles: Fluctuations!

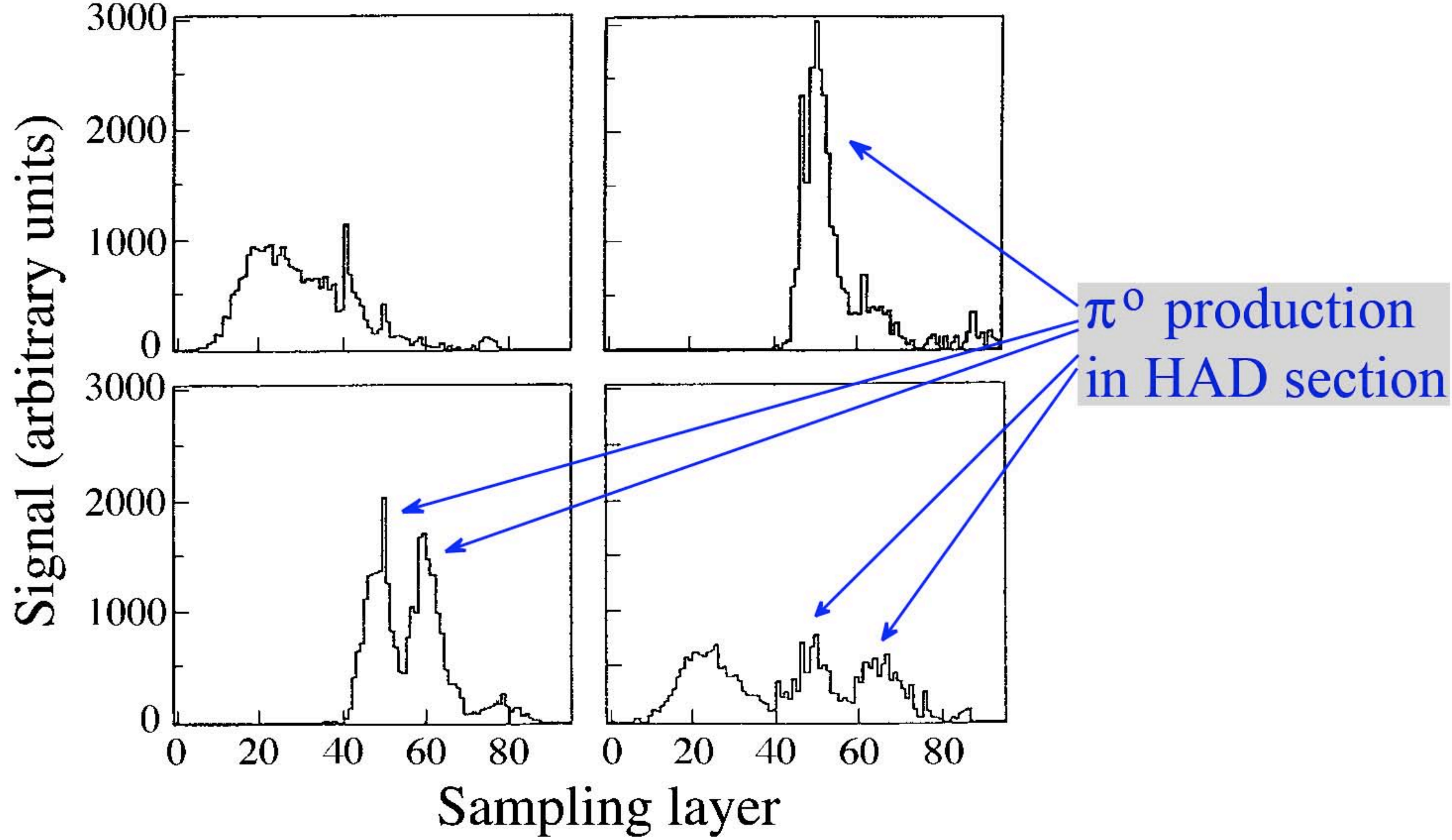

FIG. 2.35. Longitudinal profiles for 4 different showers induced by 270 GeV pions in a lead/iron/plastic-scintillator calorimeter. Data from [Gre 94].

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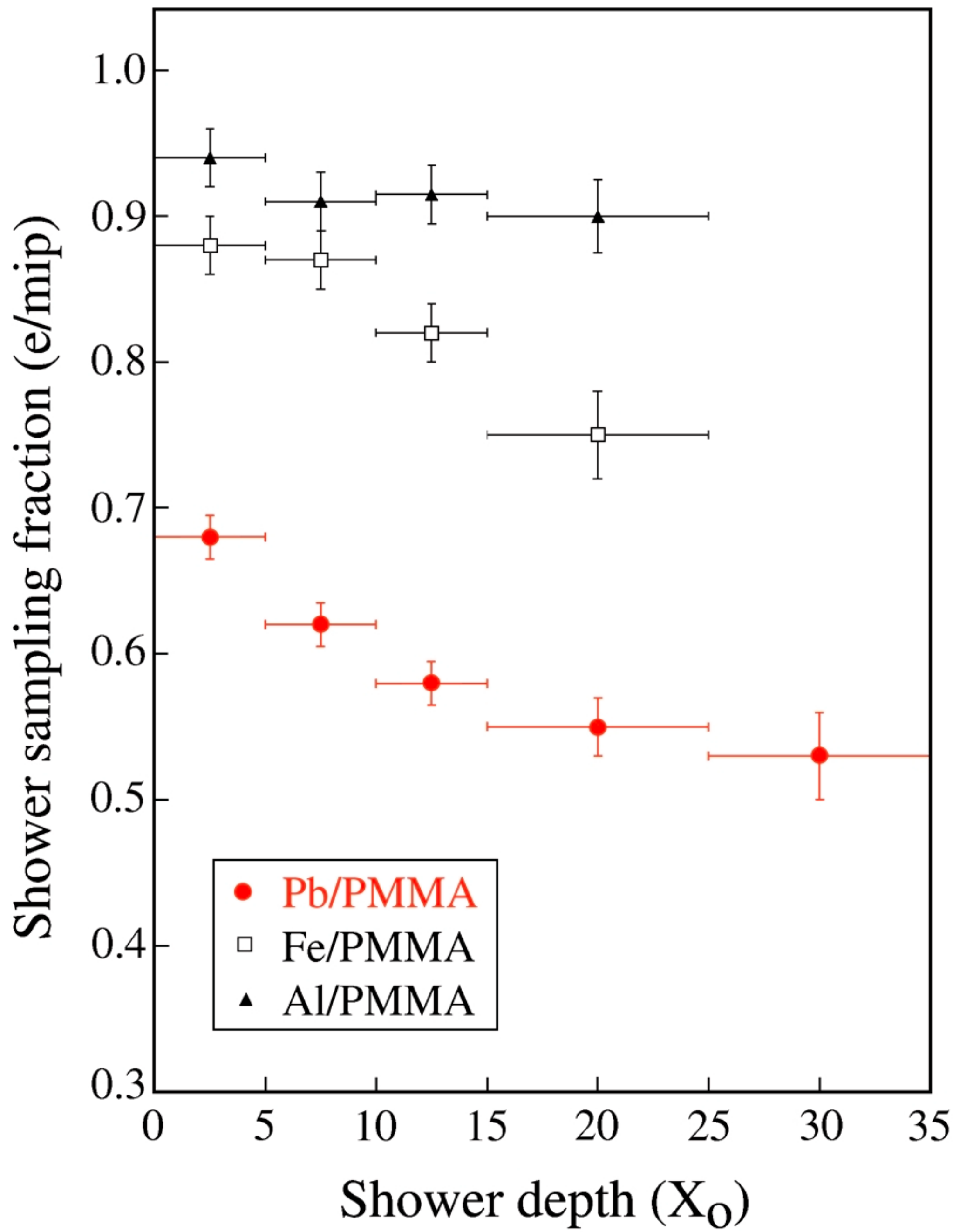
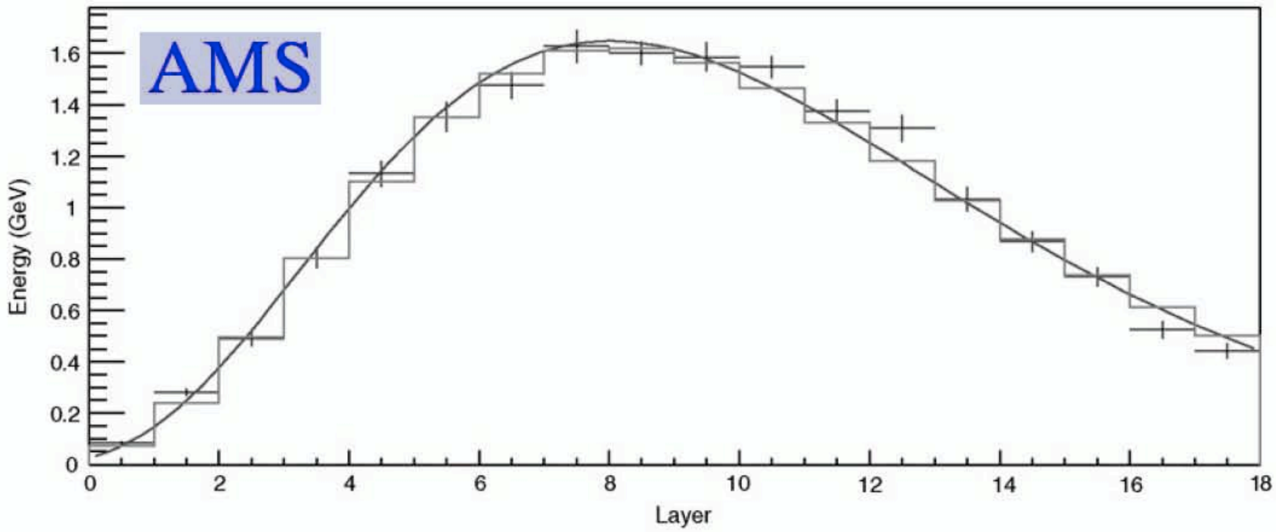
  Correct energy scale is at least as as important as good resolution

LESSON 4b: *Longitudinal segmentation means asking for trouble*

The sampling fraction changes with depth!



Consequences of depth dependence sampling fraction



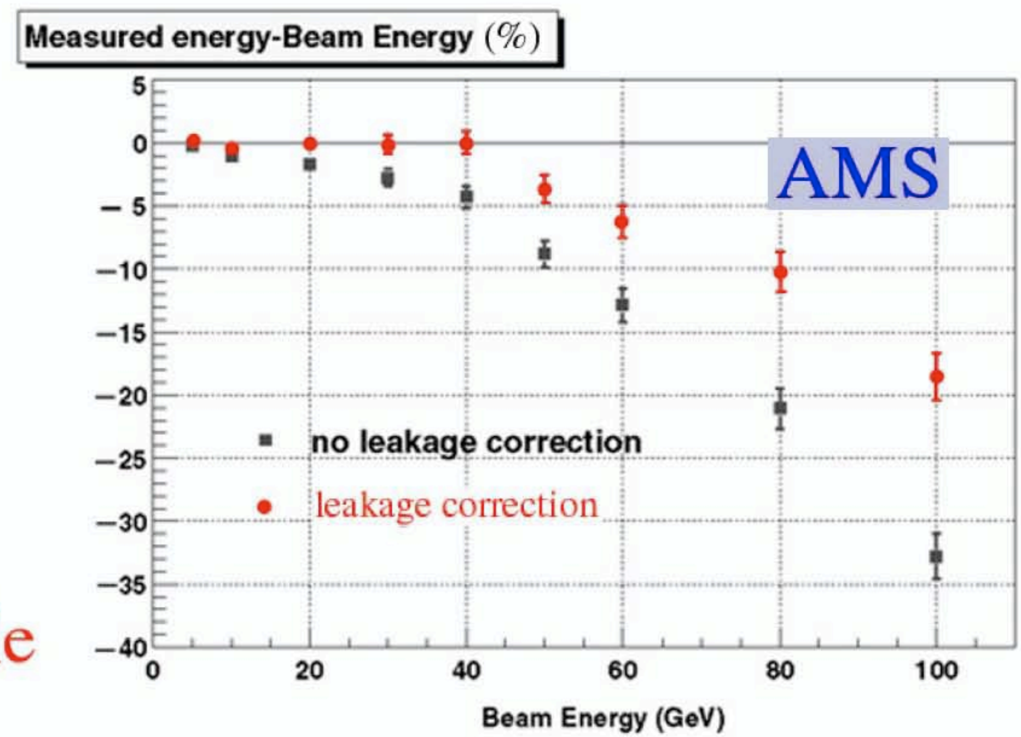
NIM A490, 132 (2002)

Pb/scintillating fiber

18 layers (17 X_0)

Calibrated with mip's:
11.7 MeV/layer

Shower leakage:
(under)estimated on basis of fit to longitudinal profile



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- *LESSON 5:* GEANT based MC simulations of hadronic shower development
  are *fundamentally flawed* ⟶ useless as design tool

LESSONS FROM 25 YEARS OF R&D

- *LESSON 6:* If you want to improve hadronic calorimeter performance

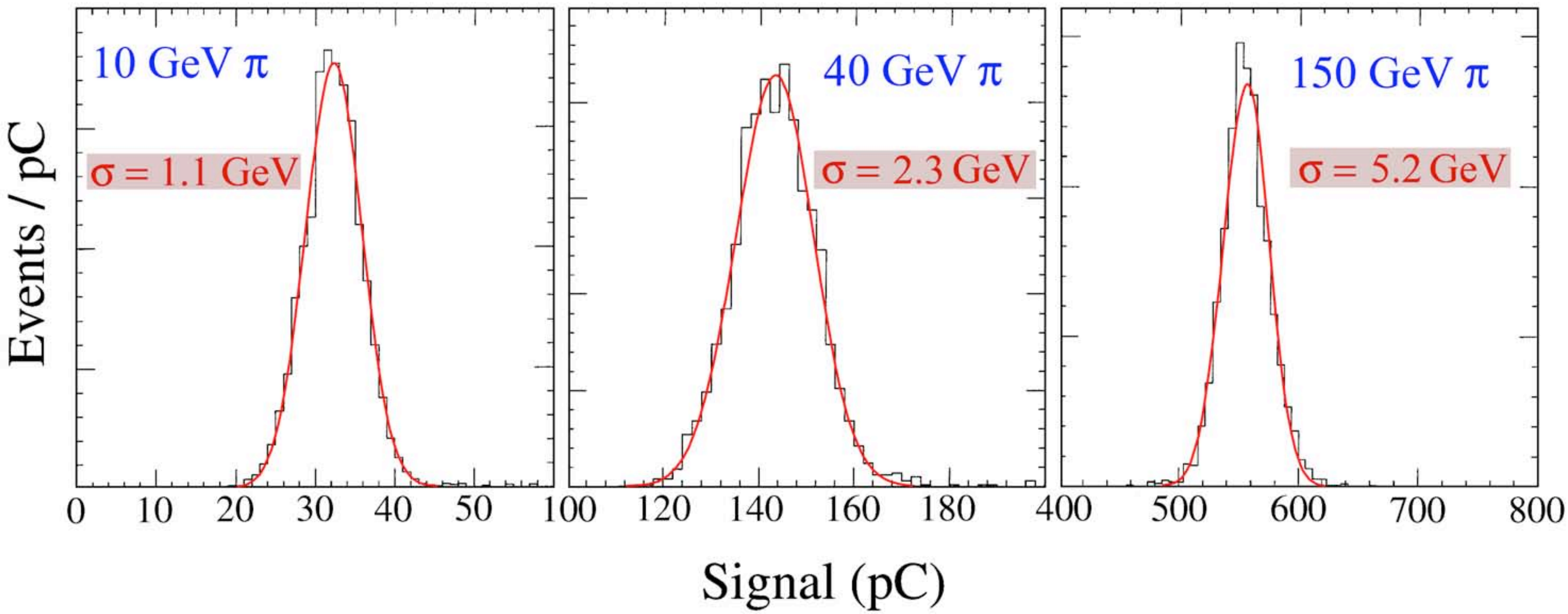
⟶ *reduce/eliminate the (effects of) fluctuations that dominate the performance*

1) Fluctuations in the em shower fraction, f_{em}

2) Fluctuations in visible energy (nuclear binding energy losses)

This can be done
ILC requirements were already met 15 years ago

Hadronic signal distributions in compensating calorimeter



from: NIM A308 (1991) 481

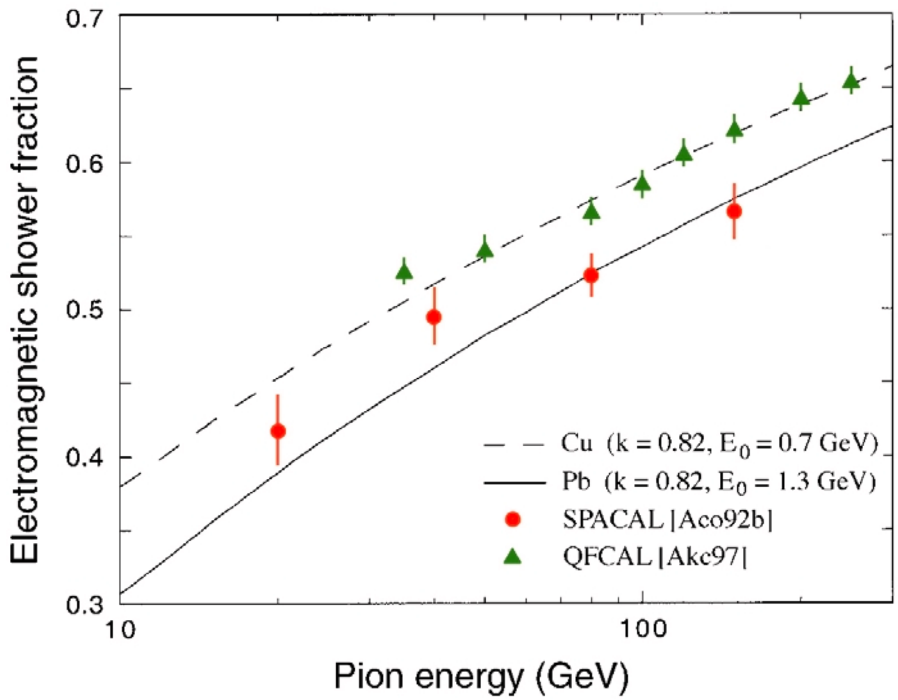
Fluctuations in the em shower component (f_{em})

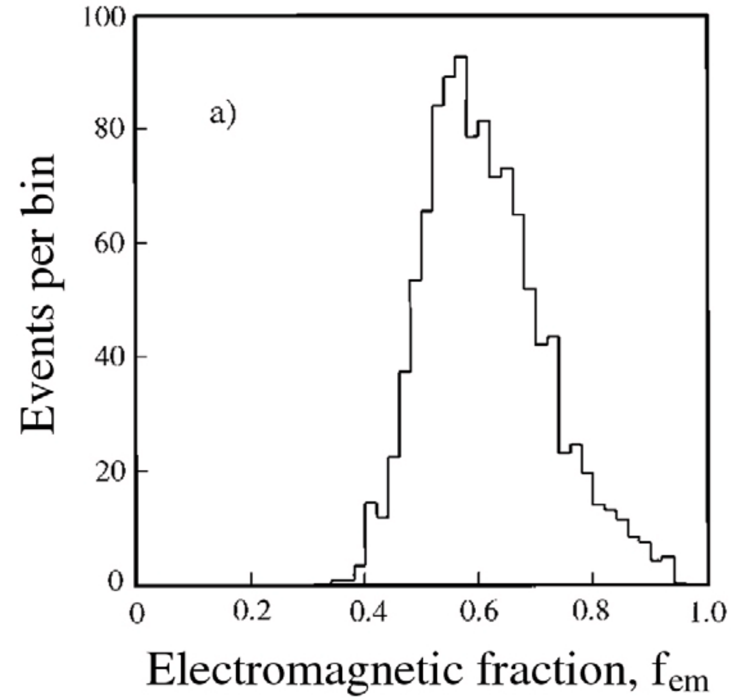
- *Why are these important ?*
  - Electromagnetic calorimeter response ≠ non-em response *($e/h \neq 1$)*
  - Event-to-event fluctuations are large and *non-Gaussian*
  - *$\langle f_{em} \rangle$ depends on* shower *energy* and *age*

- *Cause of all common problems in hadron calorimeters*
  - *Energy scale* different from electrons, in energy-dependent way
  - Hadronic *non-linearity*
  - *Non-Gaussian* response function
  - Poor energy *resolution*
  - *Calibration* of the sections of a longitudinally segmented detector

- *Solutions*
  - *Compensating* calorimeters ($e/h = 1$), *e.g.* Pb/plastic scintillator
  - Measure *f_{em} event-by-event*

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





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

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

The DREAM principle

- *Quartz fibers are only sensitive to em shower component!*
  - CMS prototype: e/h ~ 5 NIM A399 (1997) 202

  ➡ Use dual-readout system:

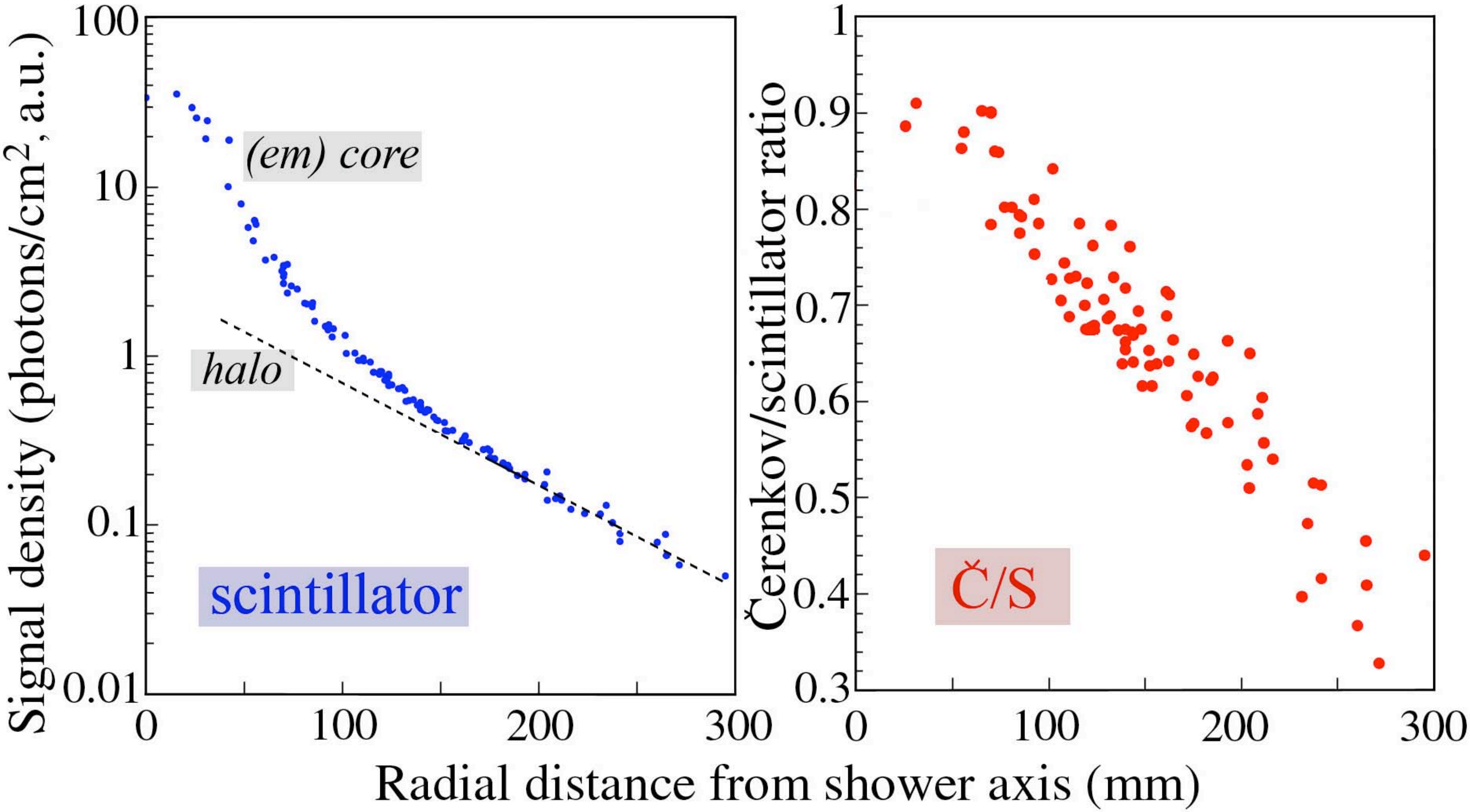
  - Regular readout (scintillator, LAr,...) measures *visible* energy
  - Quartz fibers measure em shower component E_{em}
  - Combining both results makes it possible to determine f_{em} and the energy E of the showering hadron
  - *Eliminate dominant source of fluctuations*

DREAM = Dual REAdout Module

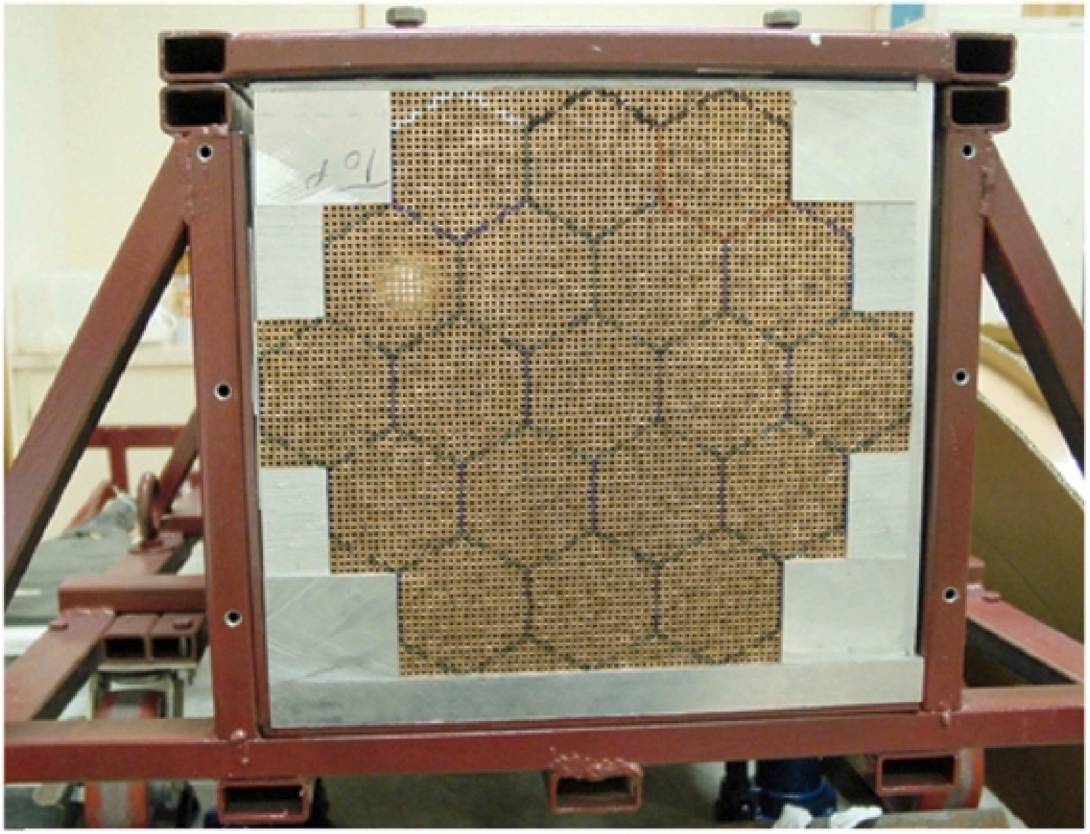
- *The DREAM Collaboration:*

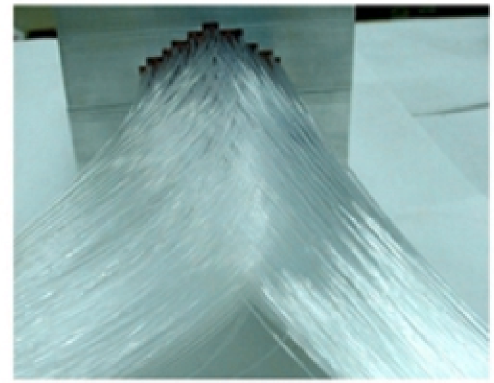
N. Akchurin, K. Carrell, H. Kim, R. Thomas, R. Wigmans (TTU)
O. Atramentov, J. Hauptman (IASU), H.P. Paar (UCSD), A. Penzo (Trieste)

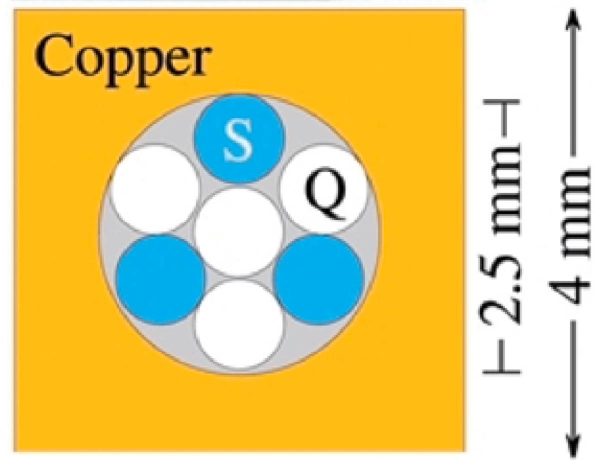
Radial hadron shower profiles (DREAM)



DREAM: Structure

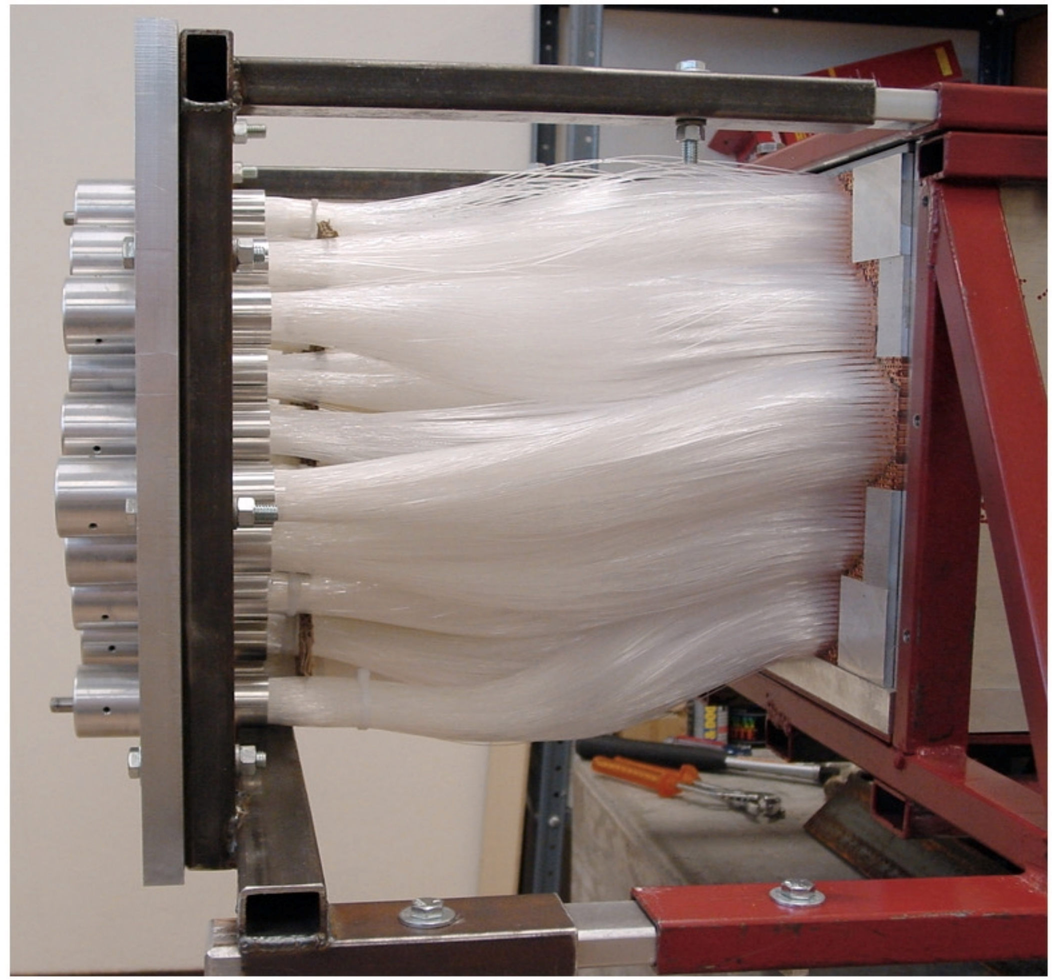


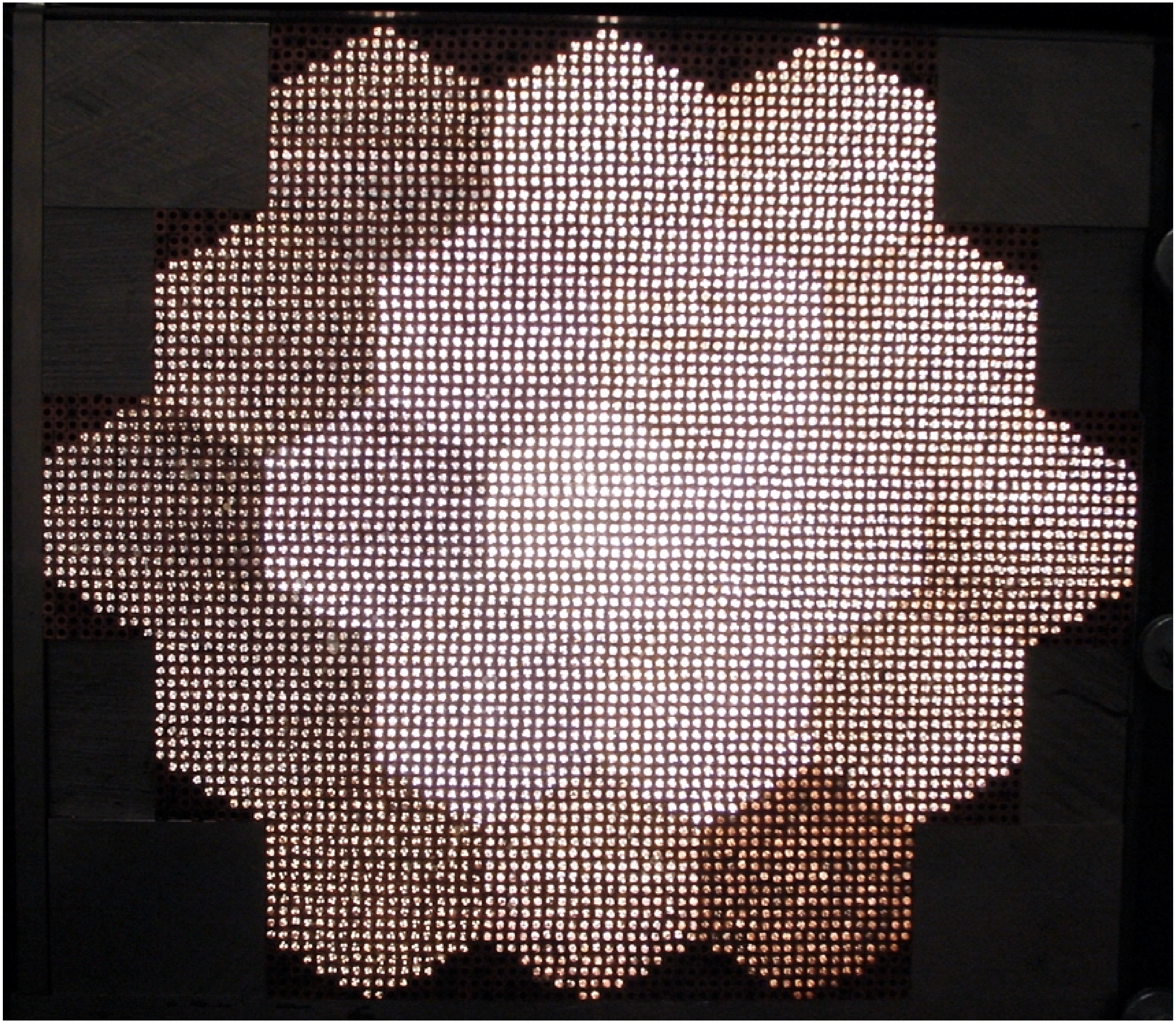




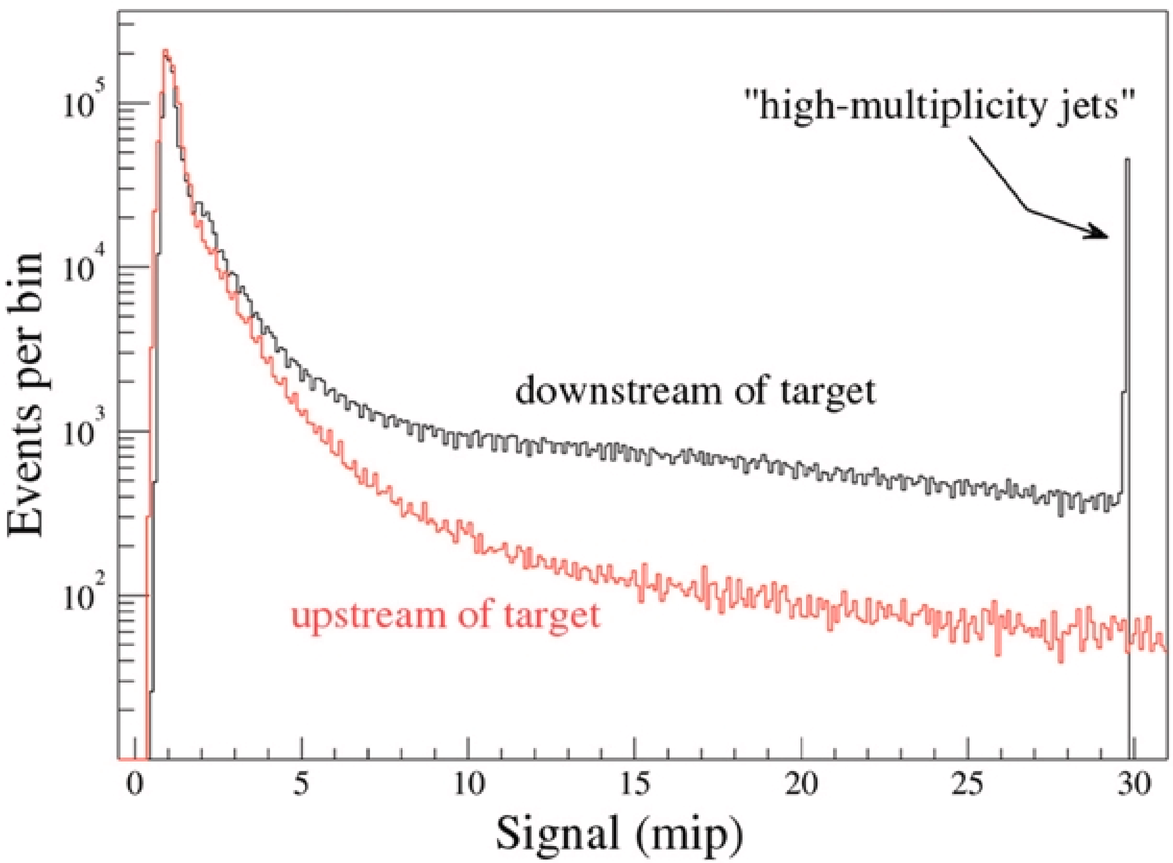
- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

DREAM readout



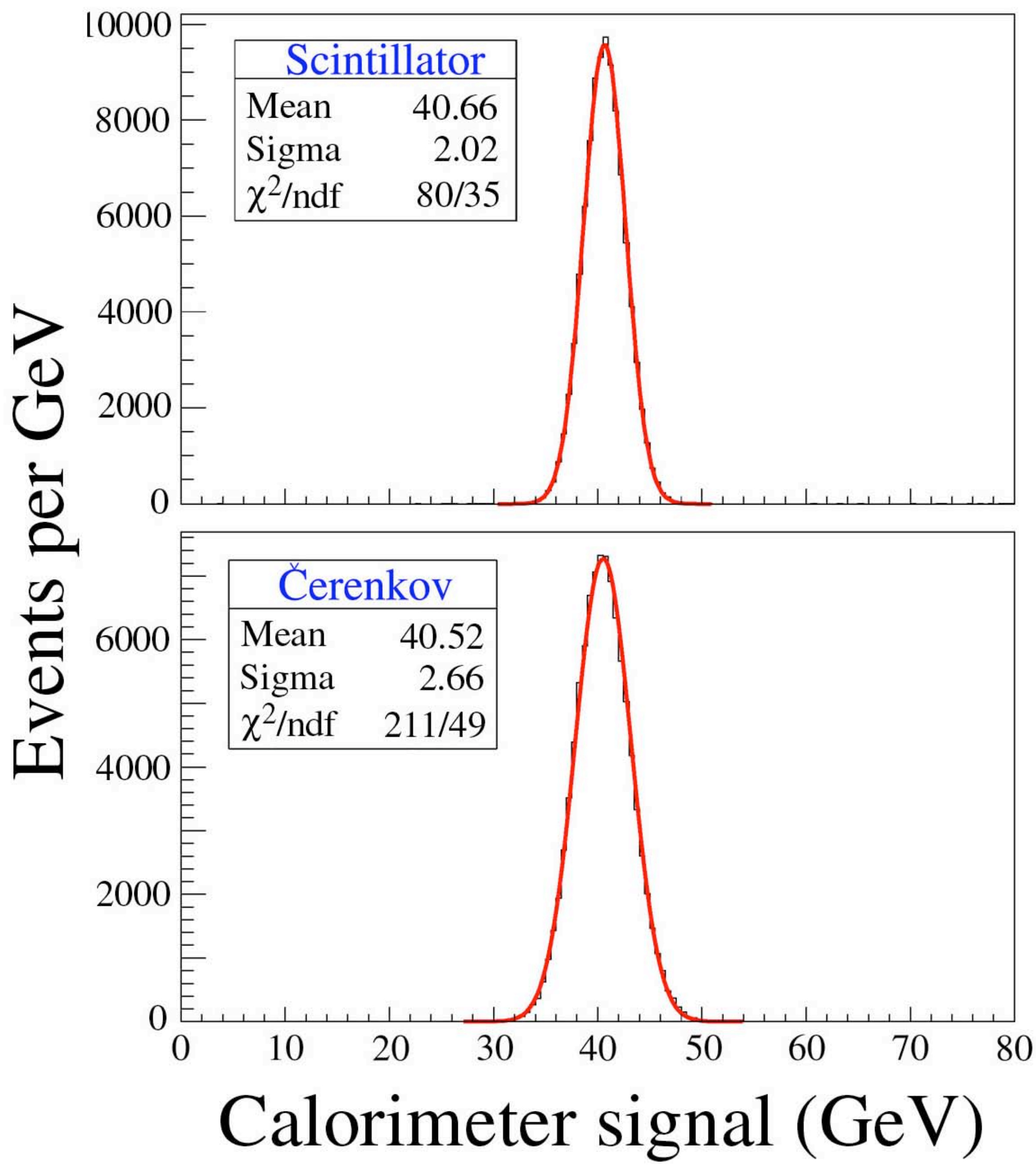


Experimental setup for DREAM beam tests

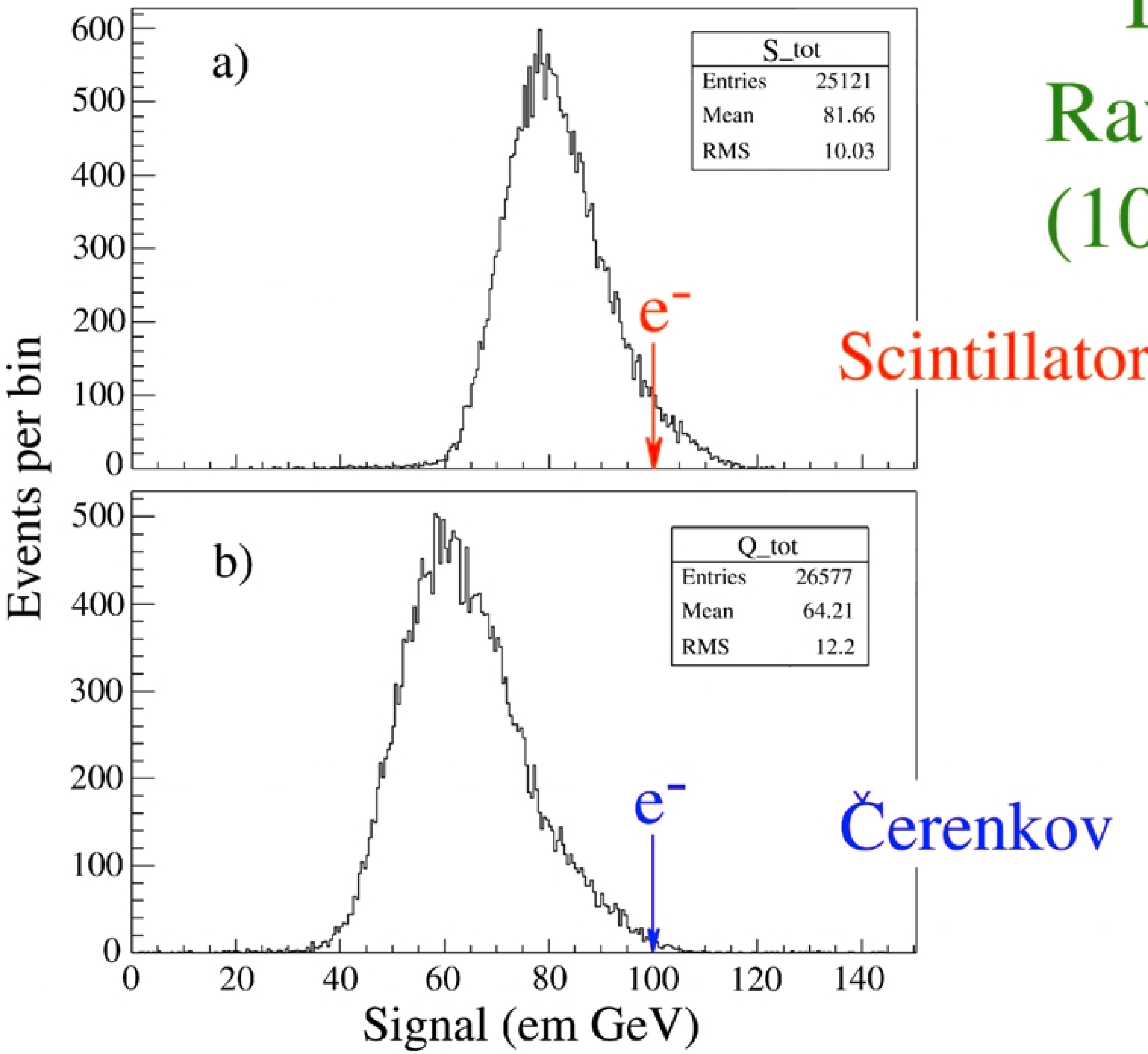


"JET" Measurements

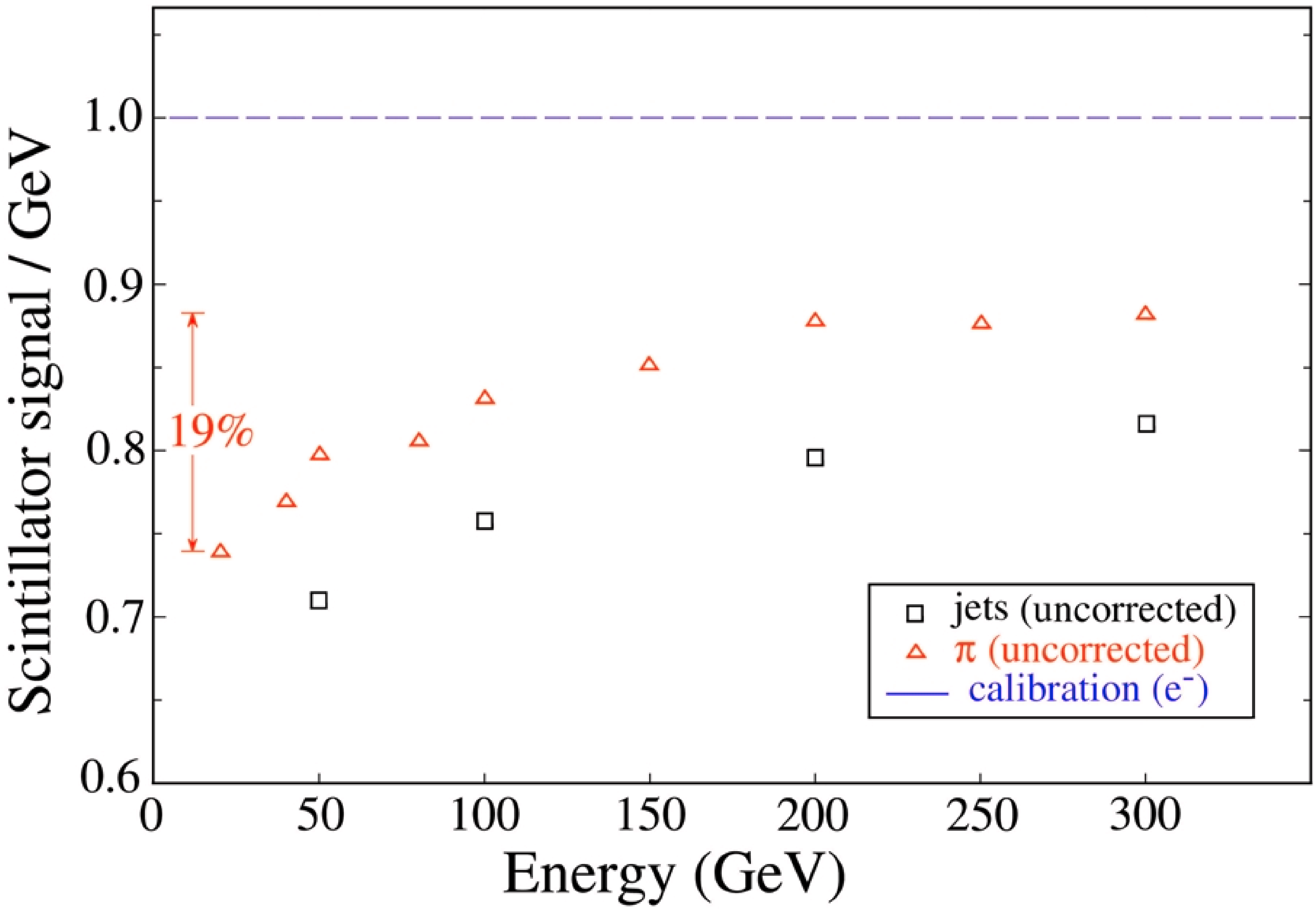
Calibration with 40 GeV electrons (tilt 2^o)



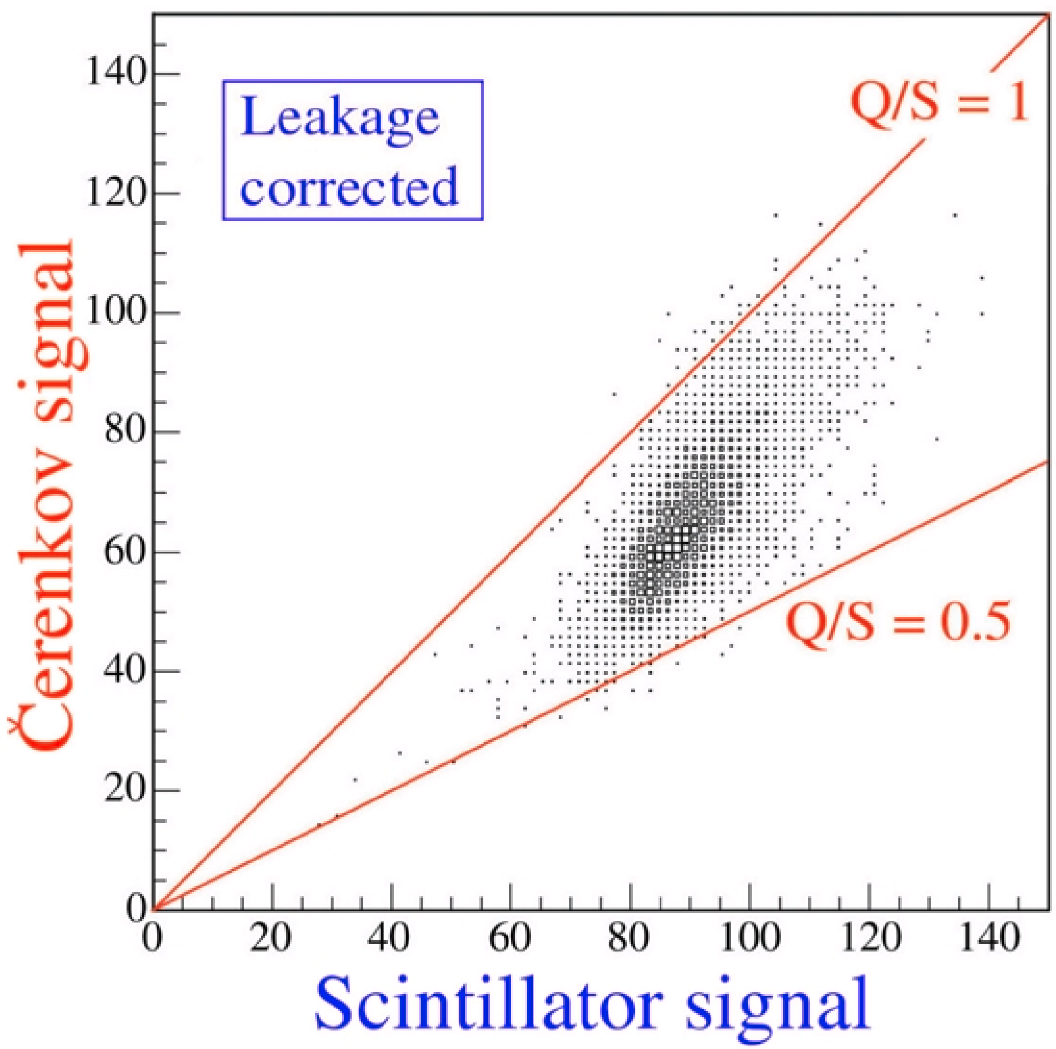
DREAM
Raw signals
(100 GeV π^-)



DREAM: Hadronic response (non-linearity)



DREAM: The (energy-independent) Q/S method



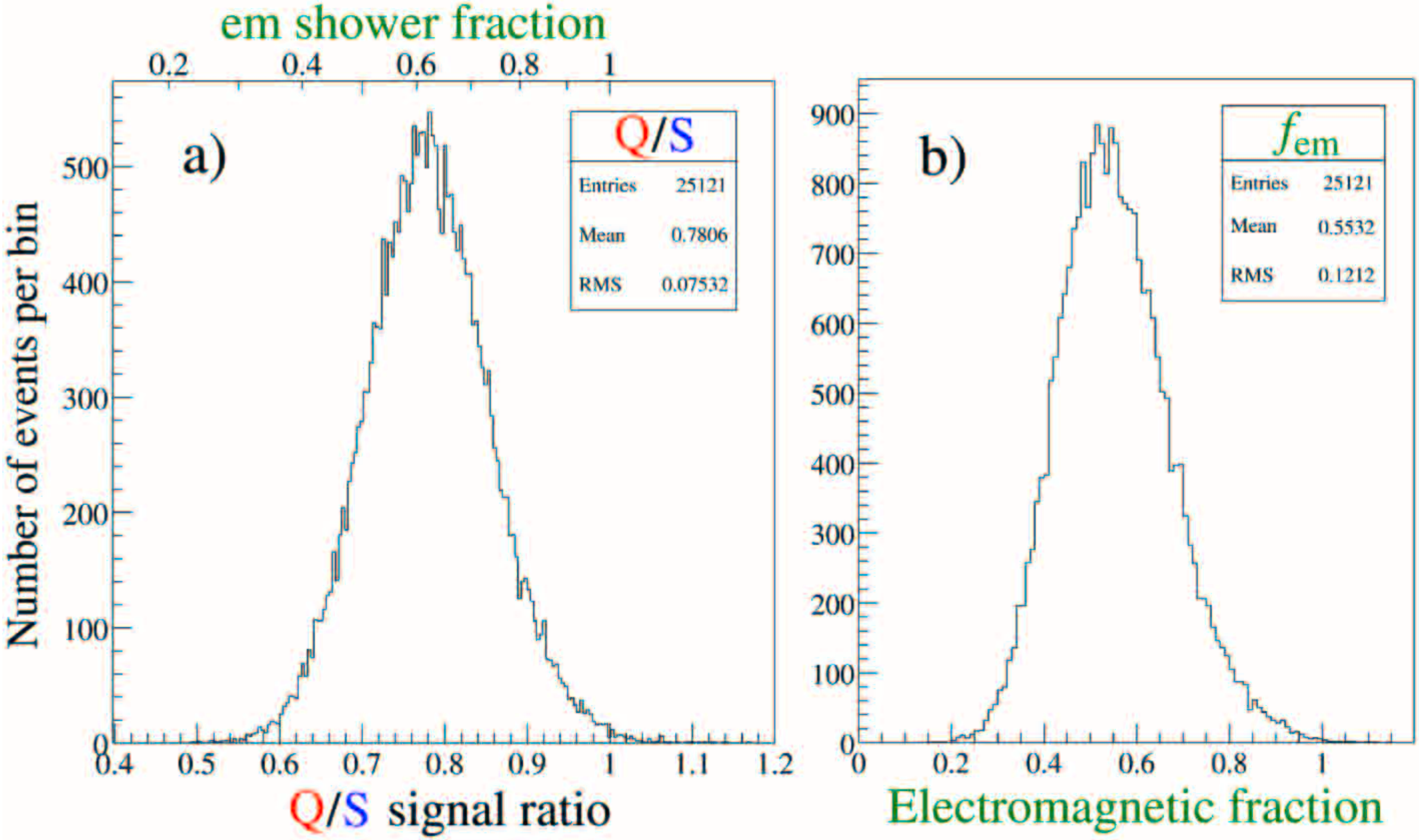
$$S = E\left[f_{\rm em} + \frac{1}{(e/h)_{\rm S}}(1 - f_{\rm em})\right]$$

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

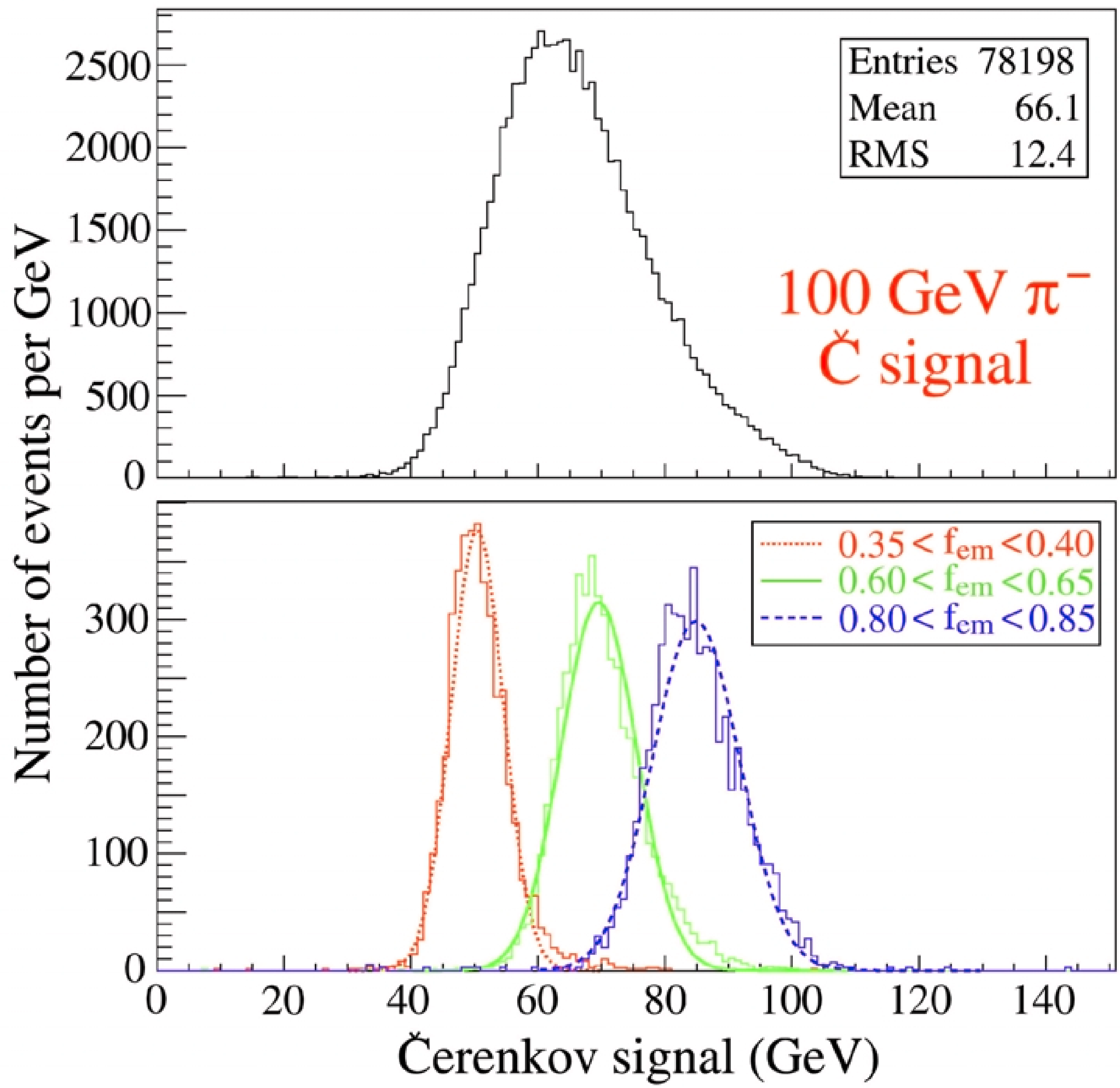
$e/h = 1.3$ (S), 5 (Q)

$$\frac{Q}{S} = \frac{f_{\rm em} + 0.20\,(1 - f_{\rm em})}{f_{\rm em} + 0.77\,(1 - f_{\rm em})}$$

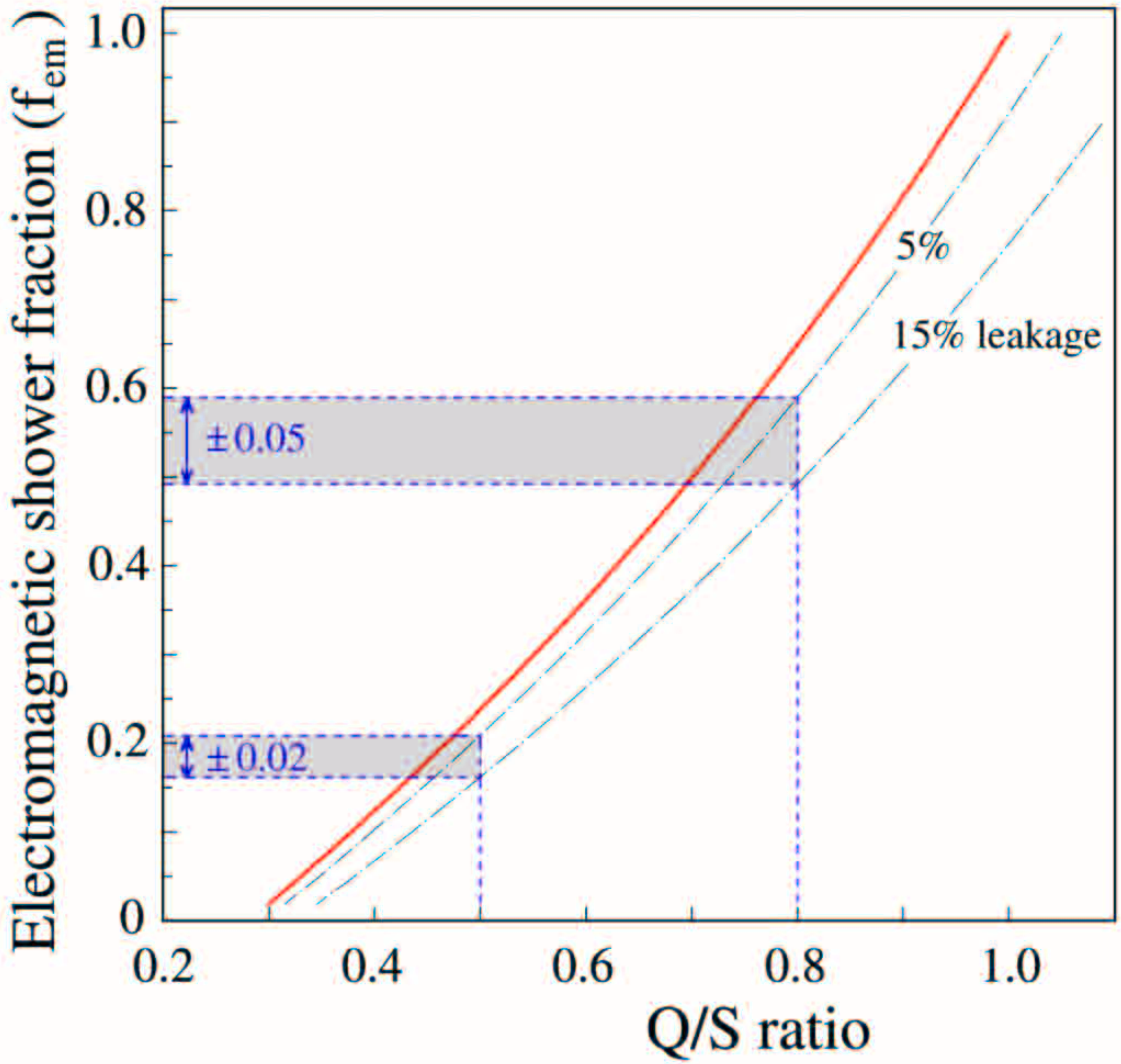
DREAM: relationship between Q/S ratio and f_{em}



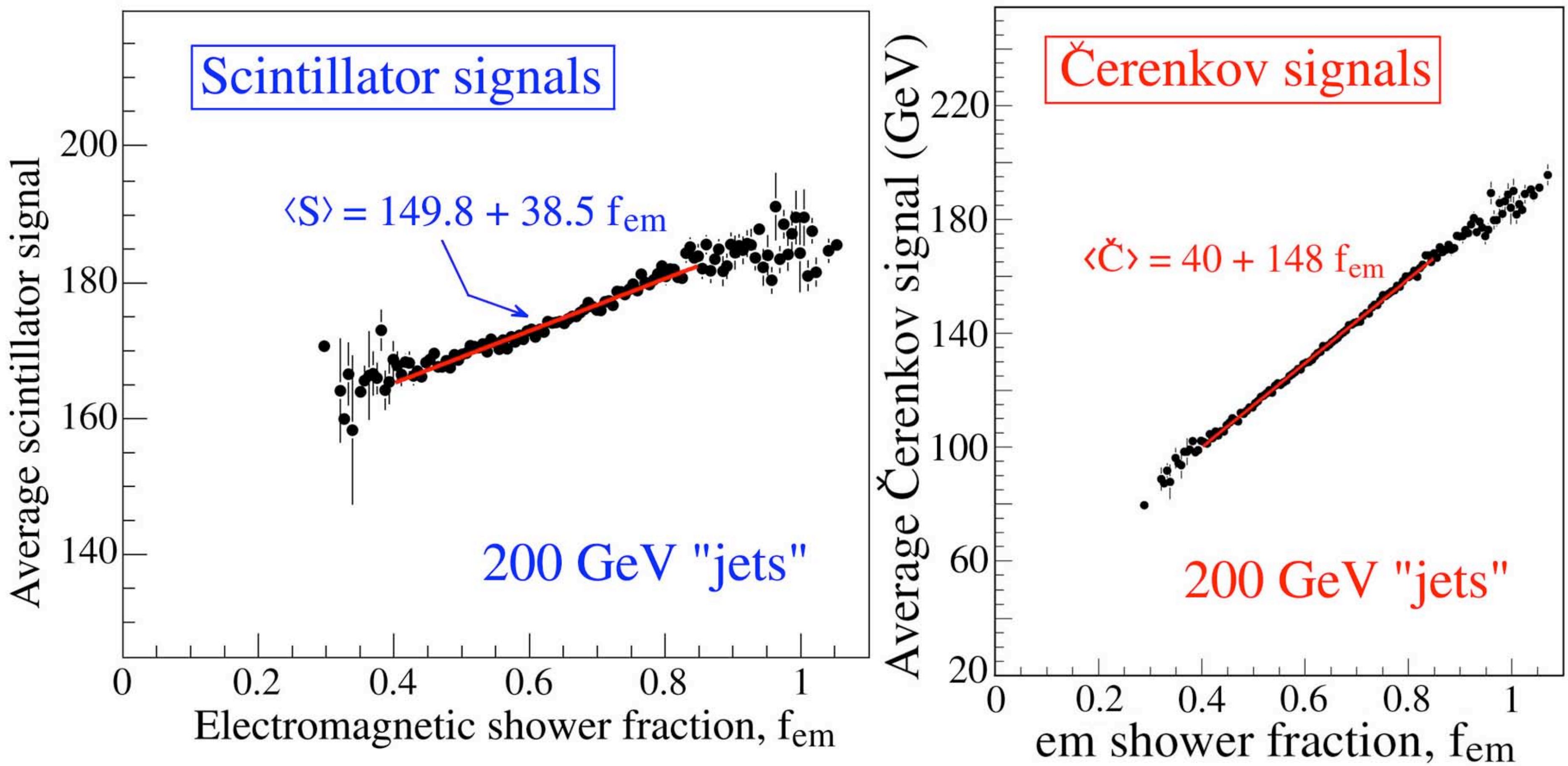
DREAM: Effect of event selection based on f_{em}



DREAM: Relationship between Q/S and f_{em}



DREAM: Signal dependence on f_{em}



$$R(f_{\rm em}) \;=\; p_0 \;+\; p_1\; f_{\rm em} \quad \text{with} \quad \frac{p_1}{p_0} \;=\; e/h \;-\; 1$$

Cu/scintillator e/h = 1.3 Cu/quartz e/h = 4.7

Dual-Readout Calorimetry in Practice

The (energy-independent) Q/S method

- Hadronic response (normalized to electrons):

$$R(f_{\rm em}) \;=\; f_{\rm em} \;+\; \frac{1}{e/h}\,\Big[1 \;-\; f_{\rm em}\Big], \qquad e/h = 1.3\ (\mathrm{S}),\;\; 5\ (\check{\mathrm{C}})$$

- Q/S response *ratio* related to $f_{\rm em}$ value $\rightarrow$ find $f_{\rm em}$ from Q/S:

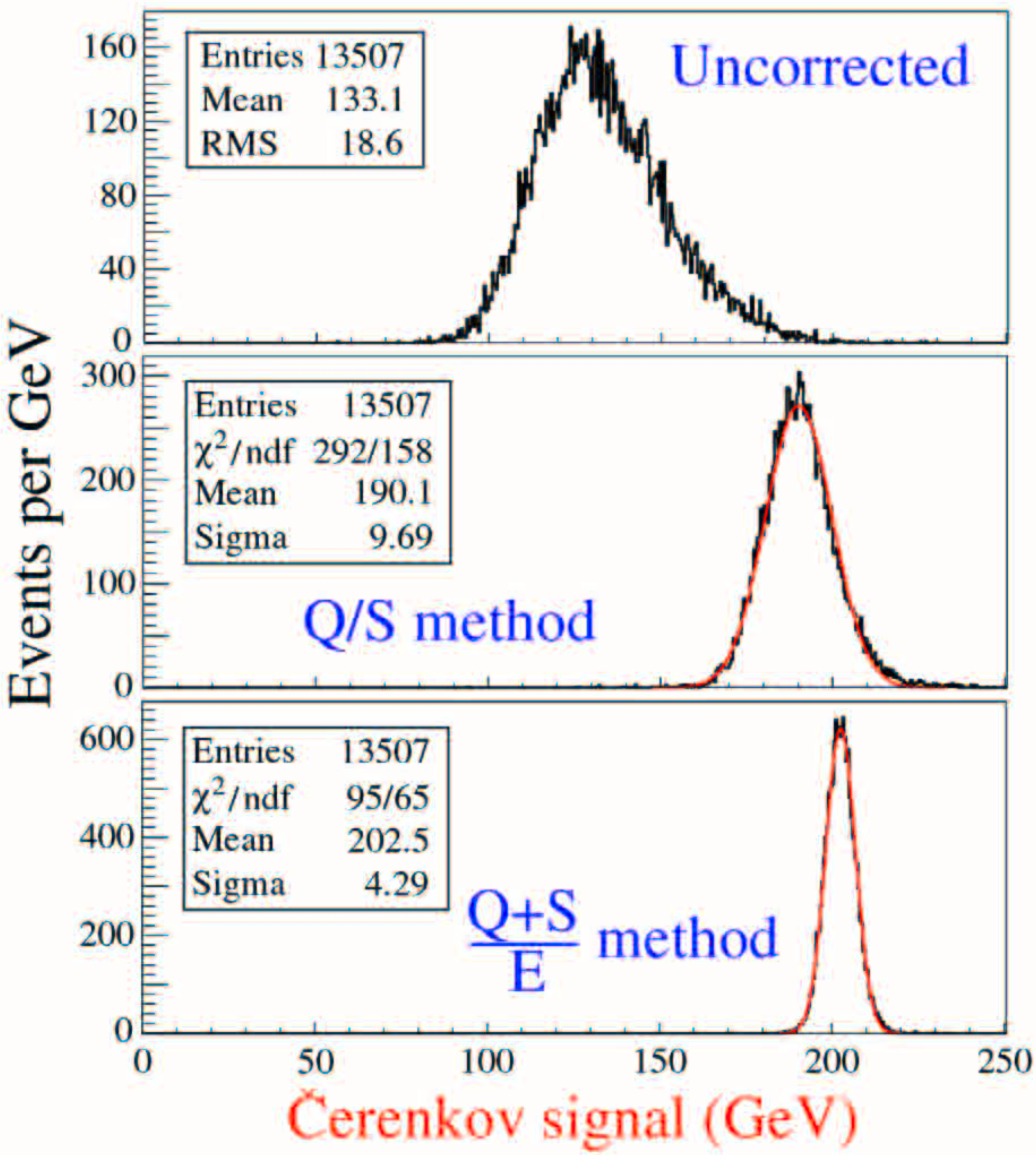
$$\boxed{\frac{Q}{S} \;=\; \frac{R_Q}{R_S} \;=\; \frac{f_{\rm em} + 0.20\ (1 - f_{\rm em})}{f_{\rm em} + 0.77\ (1 - f_{\rm em})}}$$

- Correction to measured signals (regardless of energy):

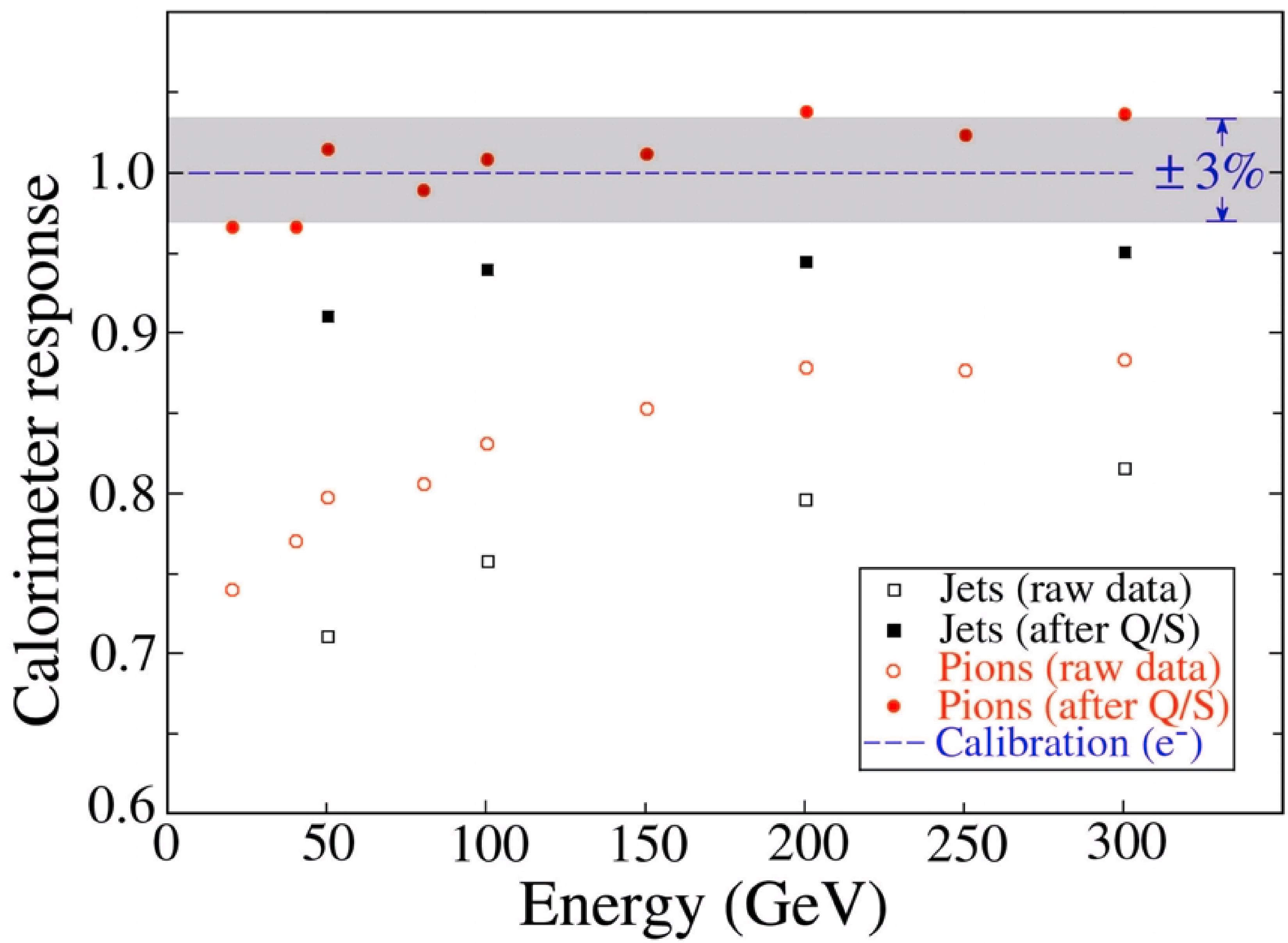
$$\boxed{S_{\rm corr} \;=\; S_{\rm meas}\left[\frac{1 + p_1/p_0}{1 + f_{\rm em}\cdot p_1/p_0}\right]}\;, \qquad \text{with} \quad \frac{p_1}{p_0} \;=\; (e/h)_S \;-\; 1$$

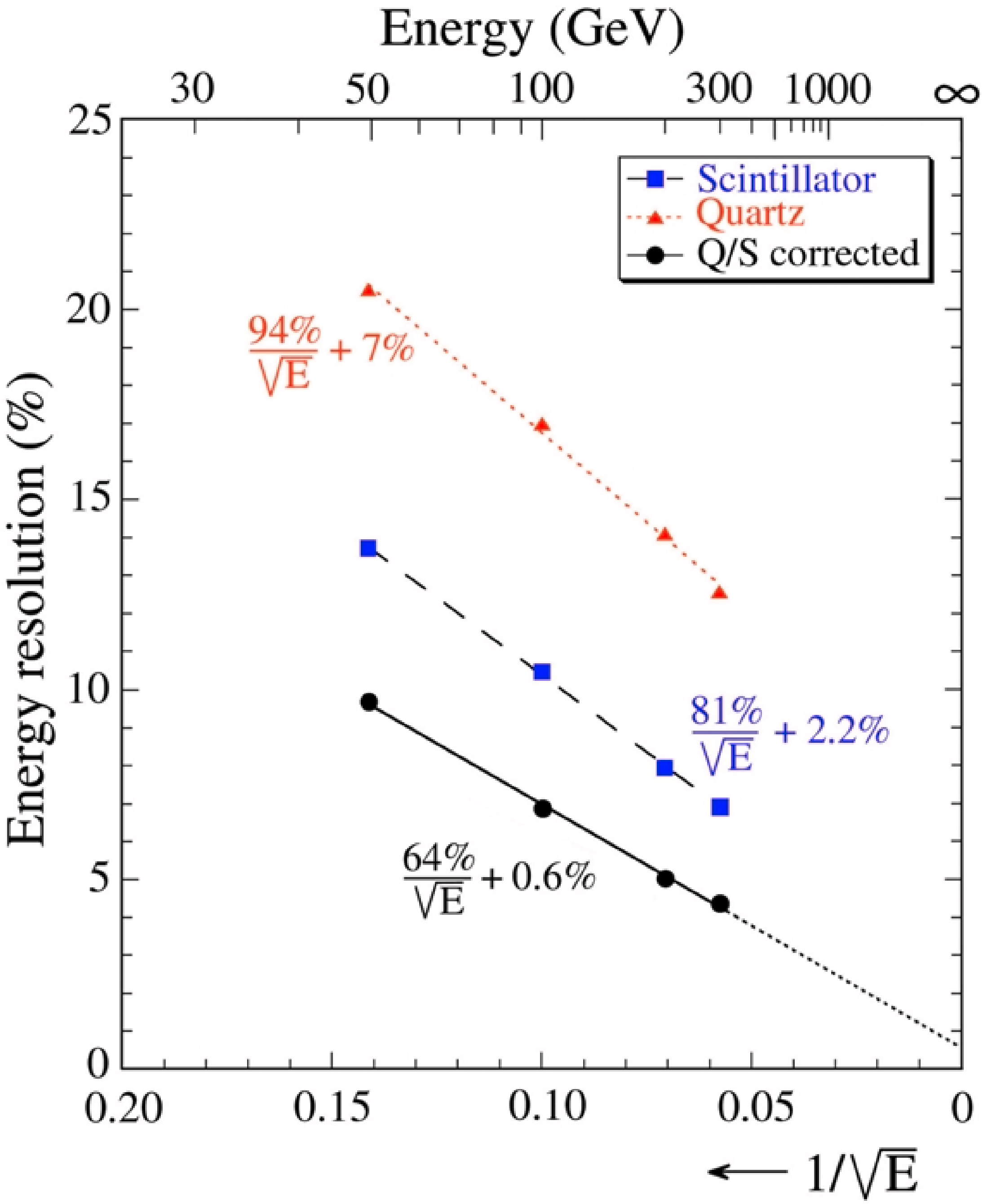
$$\boxed{Q_{\rm corr} \;=\; Q_{\rm meas}\left[\frac{1 + p_1/p_0}{1 + f_{\rm em}\cdot p_1/p_0}\right]}\;, \qquad \text{with} \quad \frac{p_1}{p_0} \;=\; (e/h)_{\check{C}} \;-\; 1$$

DREAM: Effect of corrections (200 GeV "jets")



Hadronic response: Effect Q/S correction





DREAM

Energy resolution "jets"

CONCLUSIONS
from tests

- DREAM offers a powerful technique to *improve* hadronic calorimeter performance:
  - Correct hadronic energy reconstruction, *in an instrument calibrated with electrons!*
  - Linearity for hadrons and jets
  - Gaussian response functions
  - Energy resolution scales with $1/\sqrt{E}$
  - $\sigma/E < 5\%$ for high-energy "jets", in a detector with a mass of only 1 ton!
    dominated by fluctuations in shower leakage

- These, and many other, experimental results are described in 3 papers:

Hadrons & jets:	Nucl. Instr. & Meth. A537 (2005) 537
Electrons:	Nucl. Instr. & Meth. A536 (2005) 29
Muons:	Nucl. Instr. & Meth. A533 (2004) 305

ILC Calorimetry

What is needed?	DREAM
1) Correct hadronic energy reconstruction	√
2) Separate W from Z ⟶ $\sigma \sim 3$ GeV	

DREAM prototype resolution (σ~7 GeV) *limited by*	*Needed*
• *Leakage fluctuations (mass 1 ton)*	*$*
• *Light yield (Quartz fibers: 8 Č.p.e./GeV* ⟶ $35\%/\sqrt{E}$*)*	*more light*
• *Fluctuations in visible energy*	TREAM

More Light

- Use fibers with *larger numerical aperture*

  (e.g. clear acrylic plastic fibers: 18 Č.p.e./GeV)

- *Increase* fiber *packing fraction and/or quantum efficiency*

  (this would necessitate different readout, e.g. SiPM)

- Use *homogeneous medium*

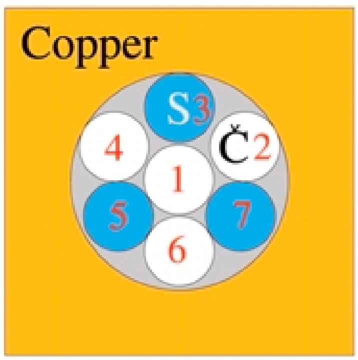
  There is absolutely no reason why DREAM principles should be limited to fibers

  These principles can be used in any optical calorimeter whose signals can be separated into scintillation and Čerenkov components

$\Longrightarrow$ DREAM 2

DREAM 2

- To what extent can light from an optical calorimeter be separated into its scintillaton and Čerenkov components?
- *Modified* the DREAM calorimeter

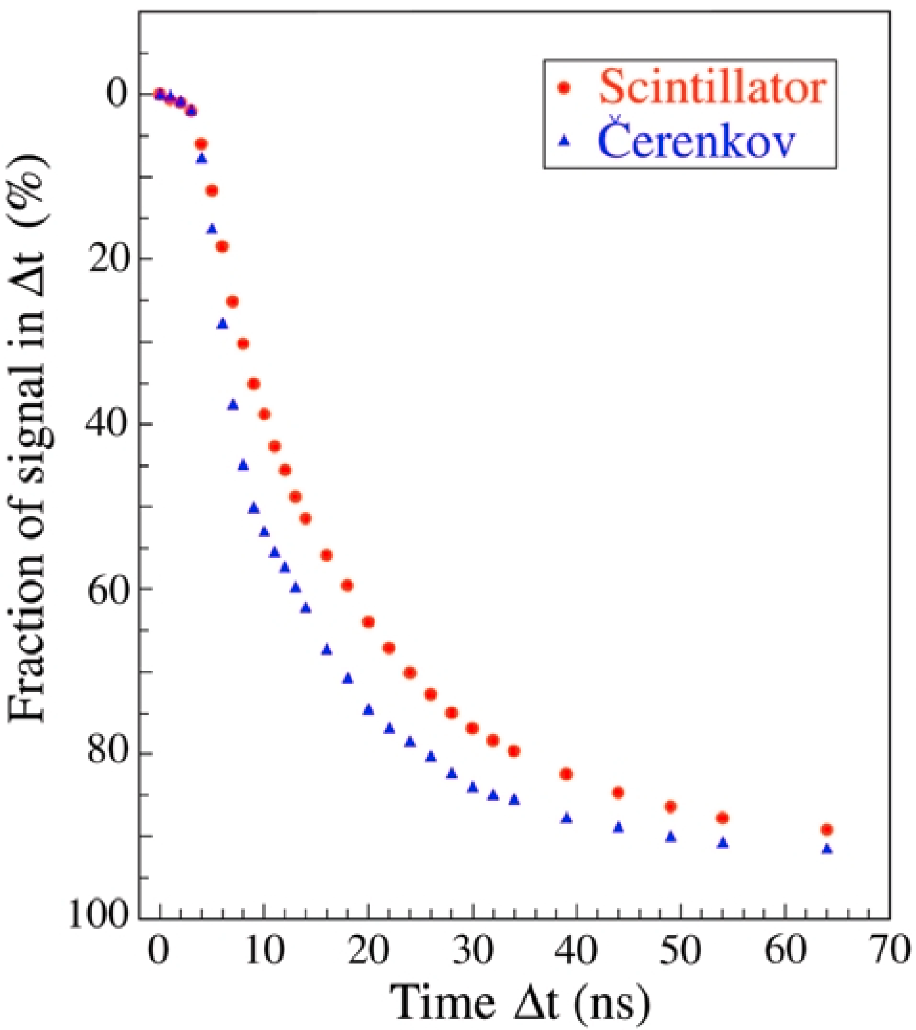


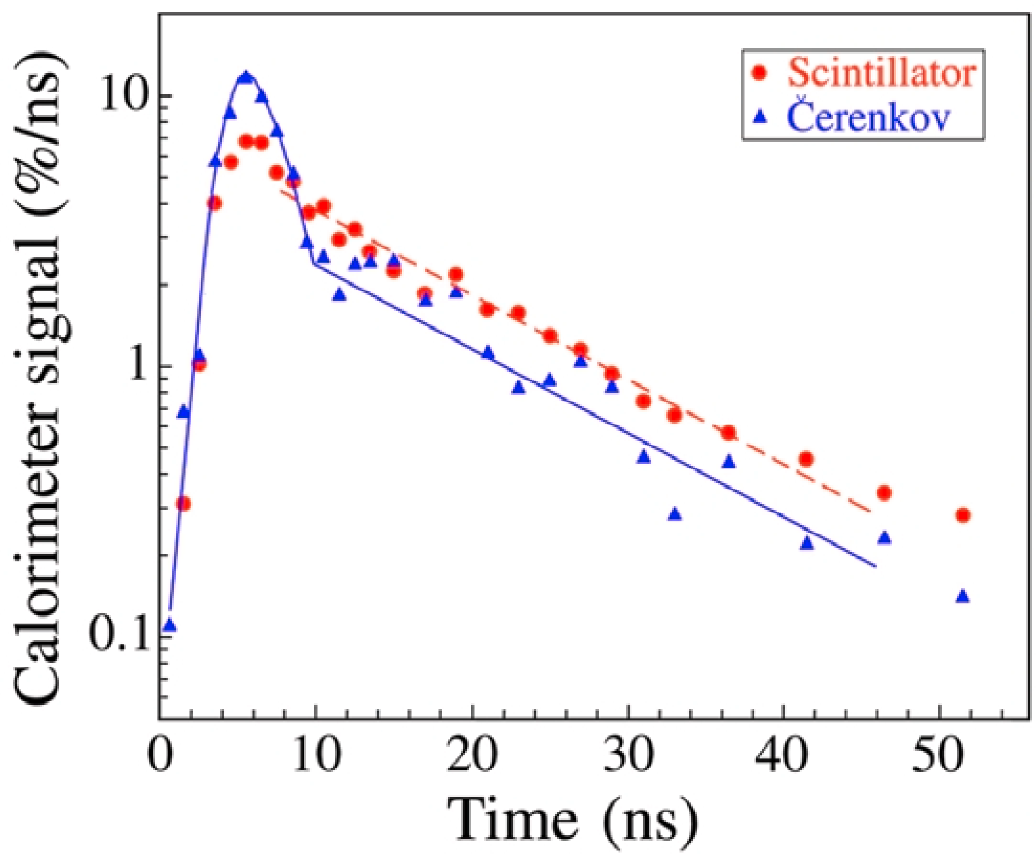
5+7	PMT1 (S)
2+4	PMT2 (Č)
1+3+6	PMT3 (mixed)

Also:
Fibers read out from both ends

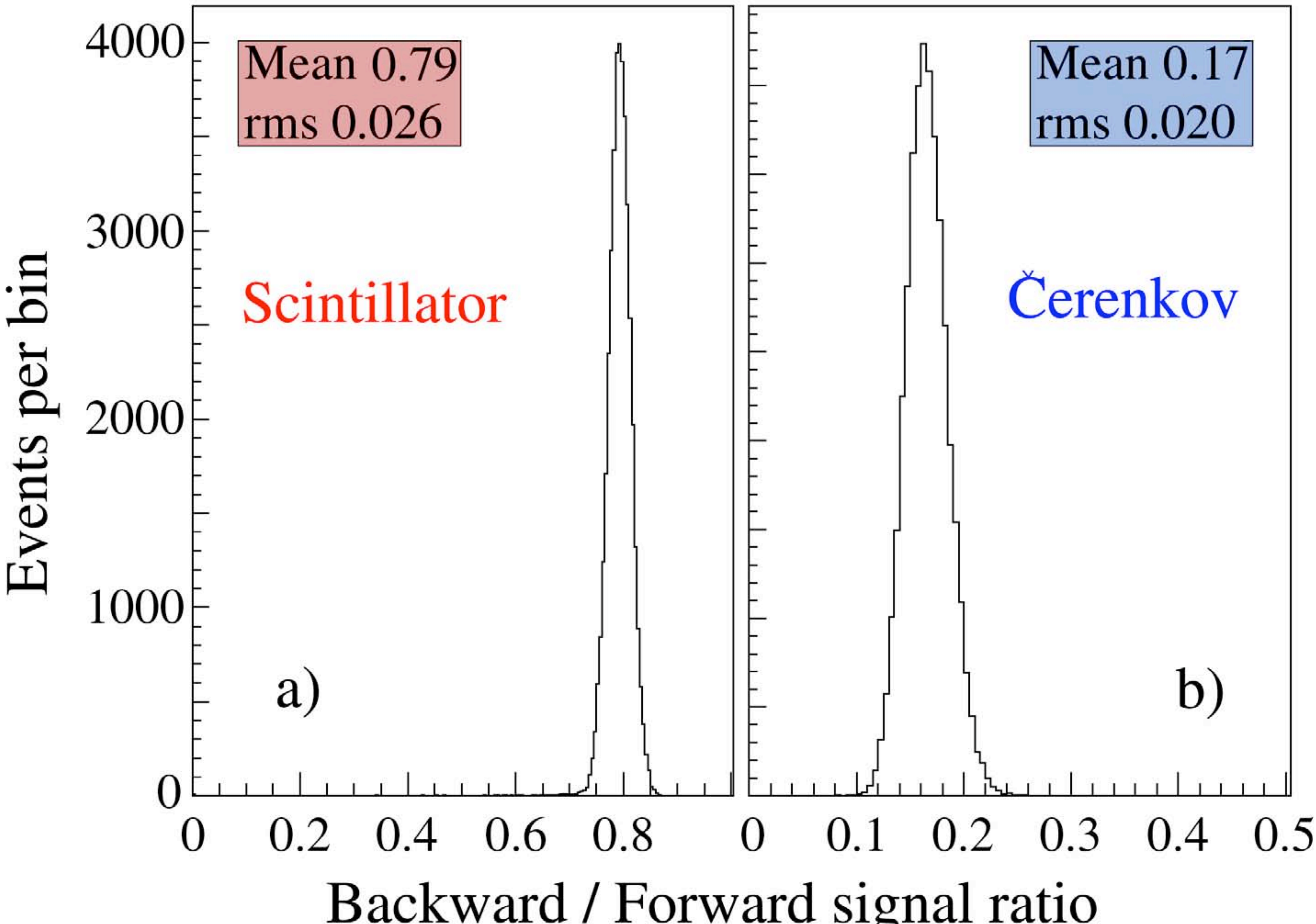
- Separation methods based on differences in:
  - Time structure of signals
  - Light directionality
  - Optical spectra
  - Polarization

DREAM - Differences in time structure





DREAM - Light directionality



Ultimate Hadron Calorimetry

- Having eliminated all other effects, fluctuations in nuclear binding energy losses ($f_{\Delta B}$) are the main remaining challenge
- ΔB is correlated with the total kinetic energy carried by neutrons
  Efficient detection of neutrons can reduce intrinsic resolution of hadron calorimeters to $\sim 15\%/\sqrt{E}$
- TREAM ⟶ measure that kinetic energy event by event
  (triple readout)

TREAM

- A third type of fibers will make it possible to measure E(n) and thus reduce the effects of fluctuations in ΔB

- Two options are being studied:

  - Replace every second scintillating fiber in DREAM with a non-hydrogenous scintillating fiber (*e.g.* doped quartz)
    E(n) can be determined from a comparison of signals from hydrogenous and non-hydrogenous fibers

  - Develop dedicated fibers
    that are specifically sensitive to MeV-type neutrons

DREAM/ILC R&D Program

- *Investigate issues relevant for DREAM-based ILC calorimeter*
  - Build and test larger prototype, with SiPM readout
  - Build homogeneous EM section, test in conjunction
  - Build test module with neutron sensitive fibers
  - *etc.*

- *International collaboration is being formed*
  - Original DREAM institutes (TTU, IASU, UCSD, Trieste)
  - Several Italian institutes have expressed interest to join
  - Others are welcome

CONCLUSIONS

- D(T)REAM seems capable of meeting / exceeding ILC hadronic calorimeter performance requirements
- Bonus: Em resolution $< 5\%/\sqrt{E}$
- And: The entire detector can be calibrated with electrons!

Monte Carlo simulations and hadron calorimetry

- *Hadron calorimetry*

GEANT/GEISHA/FLUKA .... *have not contributed anything* to our fundamental understanding of hadron calorimetry

Progress in understanding has been made *despite* these programs

Simulations are *flawed at fundamental levels*, *e.g.* π^0 production and neutron contributions to the signals, which are crucial for understanding hadron calorimetry

Benchmark data for tests of MC simulations:

- E. Bernardi *et al.*, NIM **A262** (1987) 229
- G. d'Agostini *et al.*, NIM **A274** (1989) 134
- N. Akchurin *et al.*, NIM **A408** (1998) 380.

Benchmark data for hadronic Monte Carlo

Test of π^0 production modelling

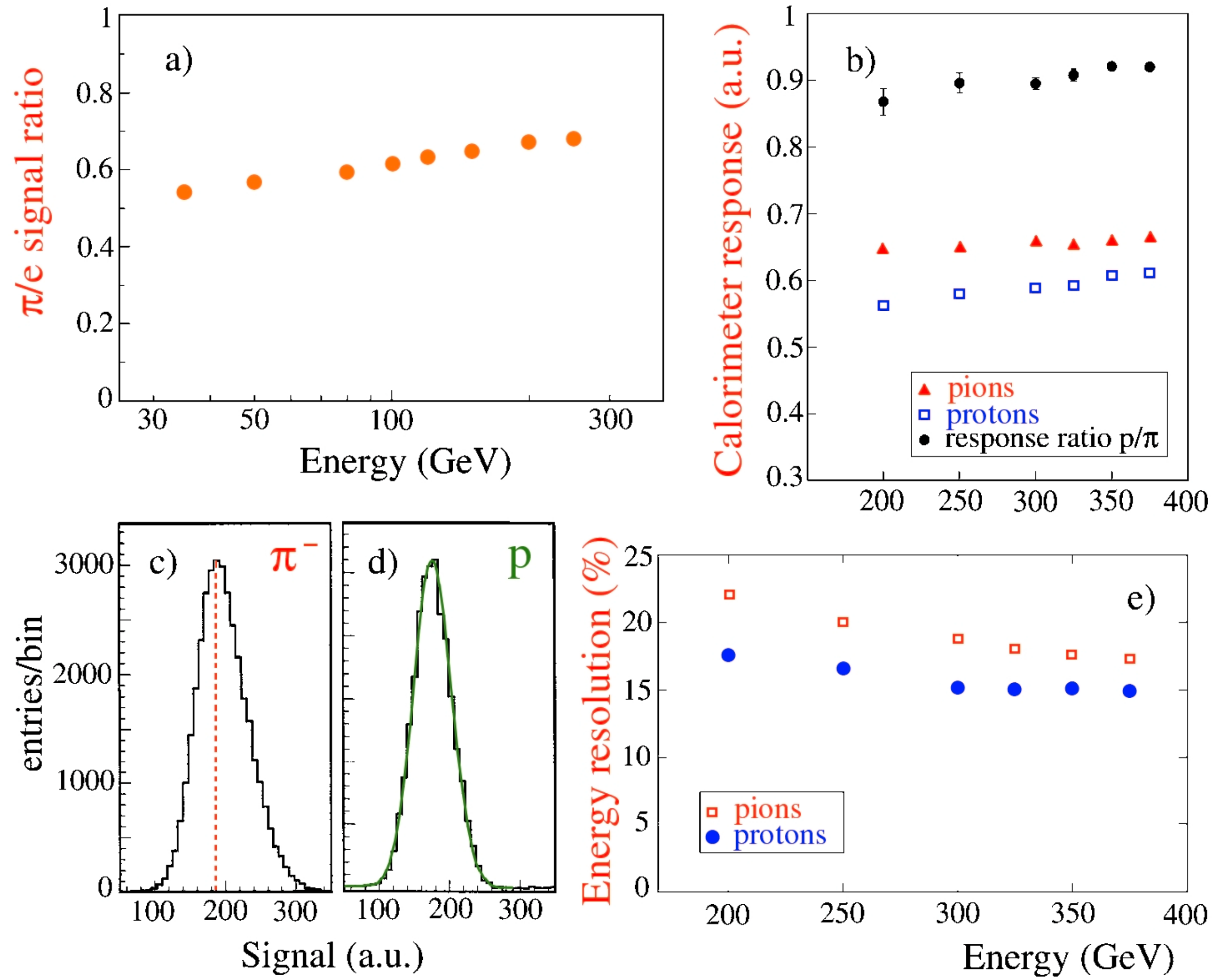


FIG. 8.27. Calorimeter benchmark data for testing the correct implementation of π^0 production in Monte Carlo simulations of hadronic shower development. Experimental data from a copper/quartz-fiber calorimeter, showing the π/e signal ratio as a function of energy (a), the response to protons and pions, as well as the ratio of these responses, as a function of energy (b), the response functions to 300 GeV pions (c) and protons (d), and the energy resolutions for pions and protons as a function of energy (e) [Akc 97].

Benchmark data for hadronic Monte Carlo

Test of description neutron effects

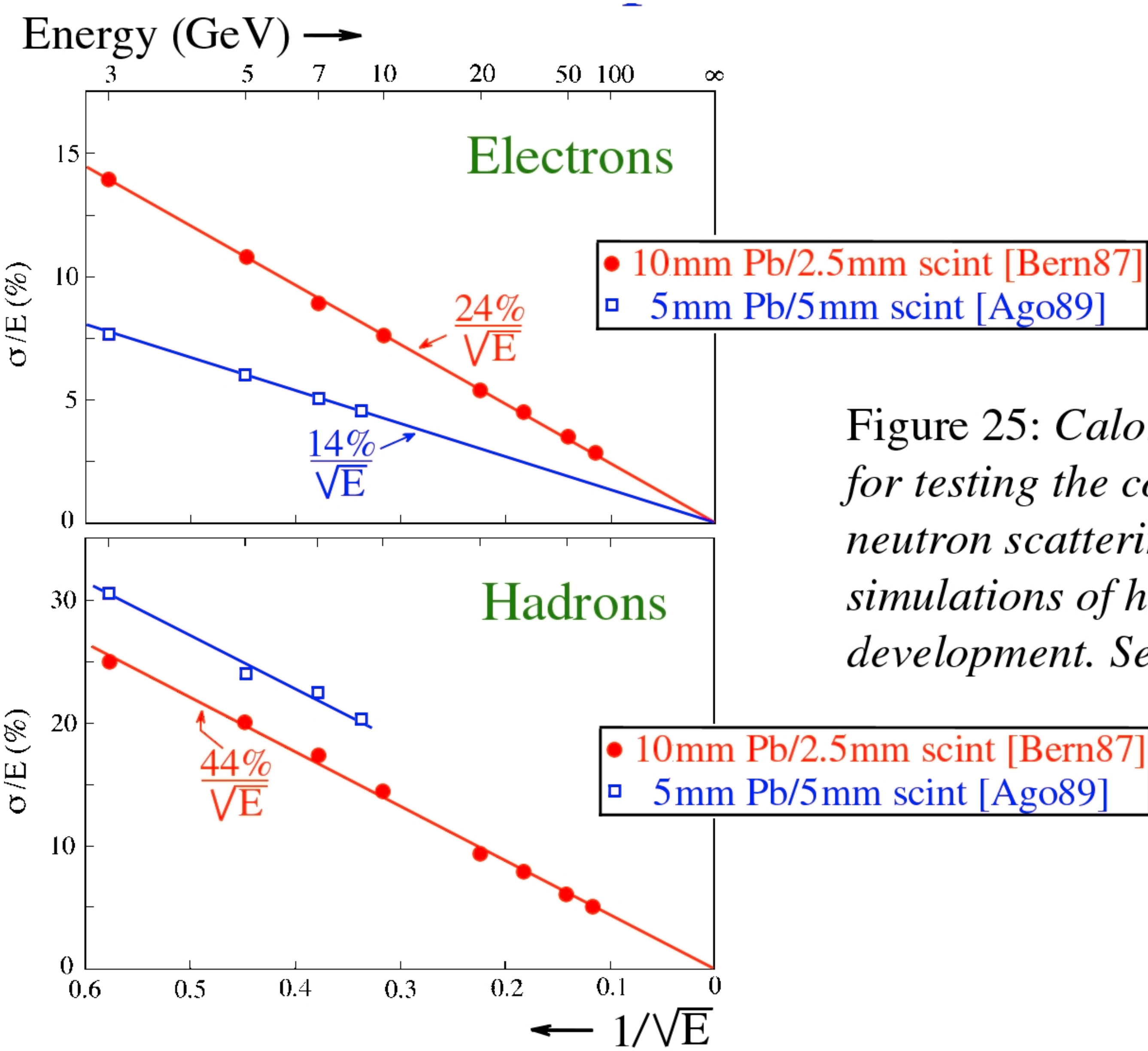


Figure 25: *Calorimeter benchmark data for testing the correct implementation of neutron scattering data in Monte Carlo simulations of hadronic shower development. See text for details.*