D R E A M
about high-resolution jet spectroscopy

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Frascati, March 9, 2004

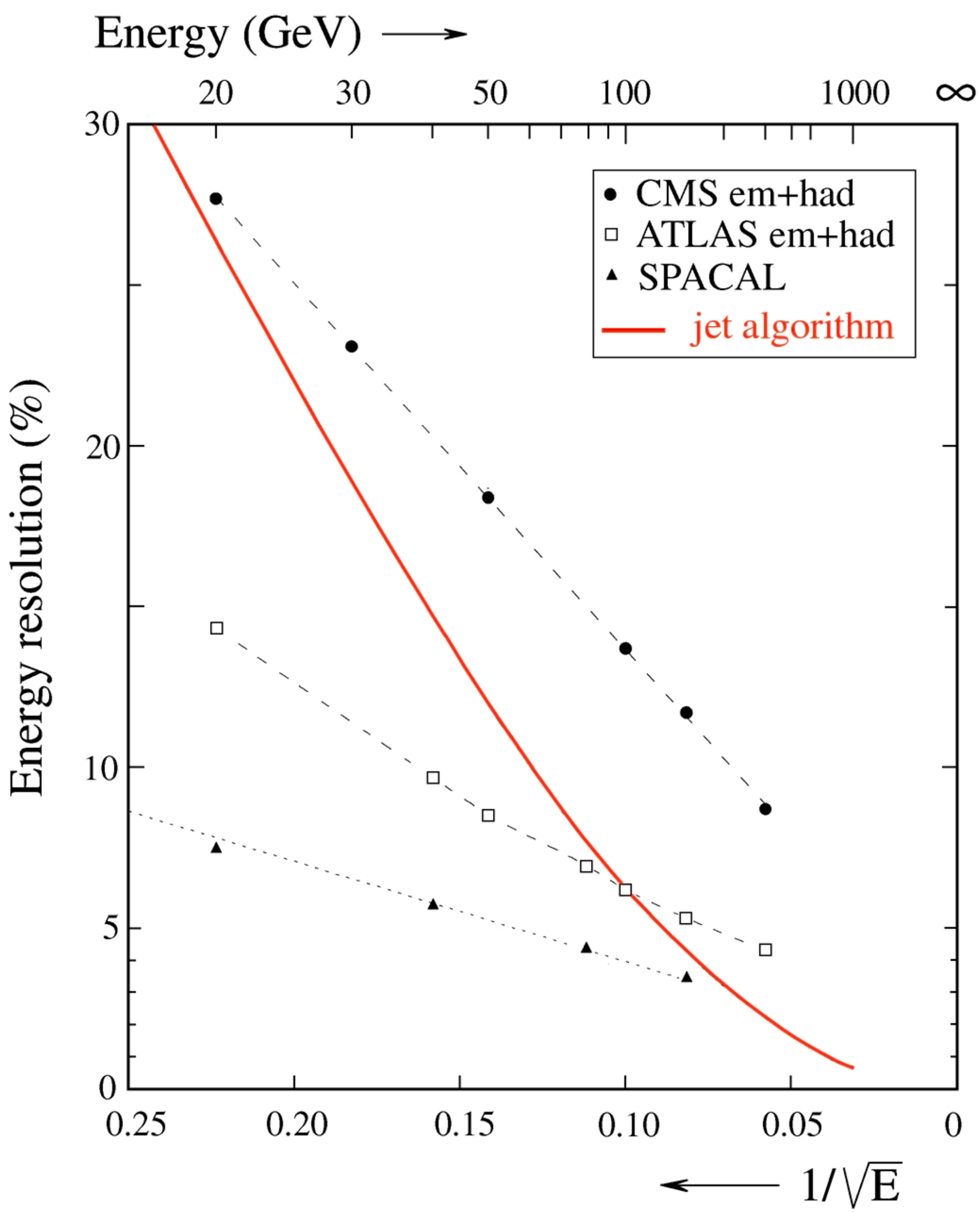
Outline:

- The importance of high-resolution jet spectroscopy
- Different approaches to achieve this goal
- Why DREAM?
- Beam tests of the DREAM detector
- What next?

High-resolution hadron calorimetry
(for jet spectroscopy)

- *Very relevant for Linear high-energy* e^+e^- *colliders*
  - Uncertainties due to jet algorithms/underlying event small
  - No constrained fits as in LEP

➡ Intrinsic detector properties limiting factor



CALORIMETRIC JET DETECTION

High-resolution hadron calorimetry

- *Common problems in hadron calorimeters*
  - Energy scale different from electrons, in energy-dependent way
  - Hadronic non-linearity
  - Non-Gaussian response function
  - Poor energy resolution

- *Why?*
  - Electromagnetic calorimeter response $\neq$ non-em response *($e/h \neq 1$)*
  - Large event-to-event fluctuations in em shower content *(f_{em})*

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

High-resolution hadron calorimetry

- *No solution*

  There is *no merit* in "offline compensation" (e/π by weighting)

  Resolution is determined by *fluctuations, not* by mean values

  Side effects: Increased signal non-linearity, response depends on starting point shower, ... See NIM A487 (2002) 381

"Dummy" compensation

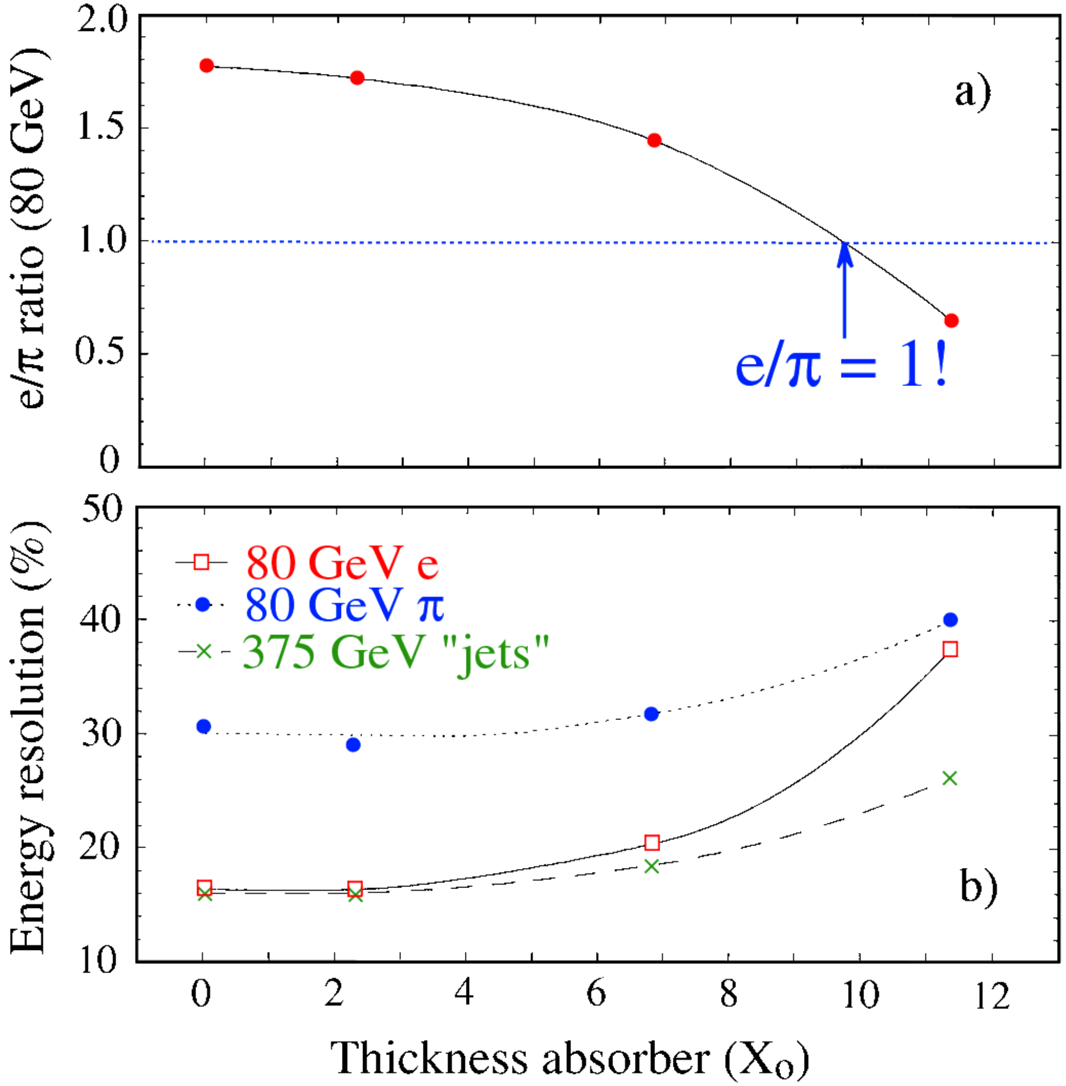
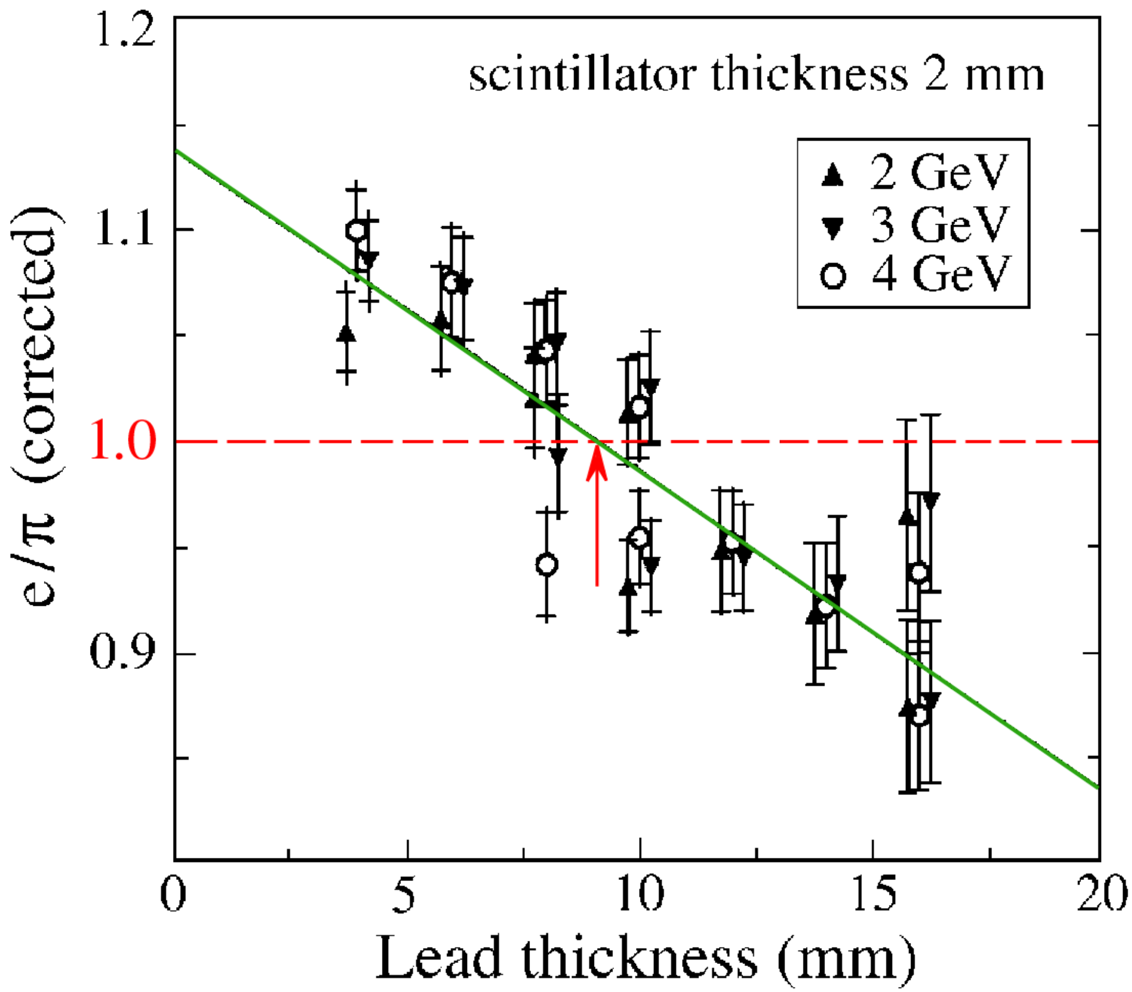


FIG. 4.59. The e/π signal ratio at 80 GeV (a) and the energy resolution (b) of a quartz-fiber calorimeter preceded by dead material (iron), as a function of the thickness of this material [Fer 97]. The energy resolution is given for 80 GeV electrons and pions, and for multi-particle "jets" generated by 375 GeV pions in an upstream target.

High-resolution jet spectroscopy (2)

1. Compensating Pb/scintillator calorimetry

JLC prototype studies: NIM A432 (1999) 48



What compensation does and does not do for you

- Compensation does *not guarantee* high resolution.
  Fluctuations in f_{em} are eliminated, but others may be very large.
  Example: Texas Tower effect.

- Compensation has some *drawbacks*
  - Small sampling fraction required $\rightarrow$ em resolution limited
  - Relies on neutrons $\rightarrow$ calorimeter signals have to be integrated over large volume and time. SPACAL's $30\%/\sqrt{E}$ needed 15 tonnes and 50 ns. Not always possible in practice.

Compensation in a Uranium/gas calorimeter

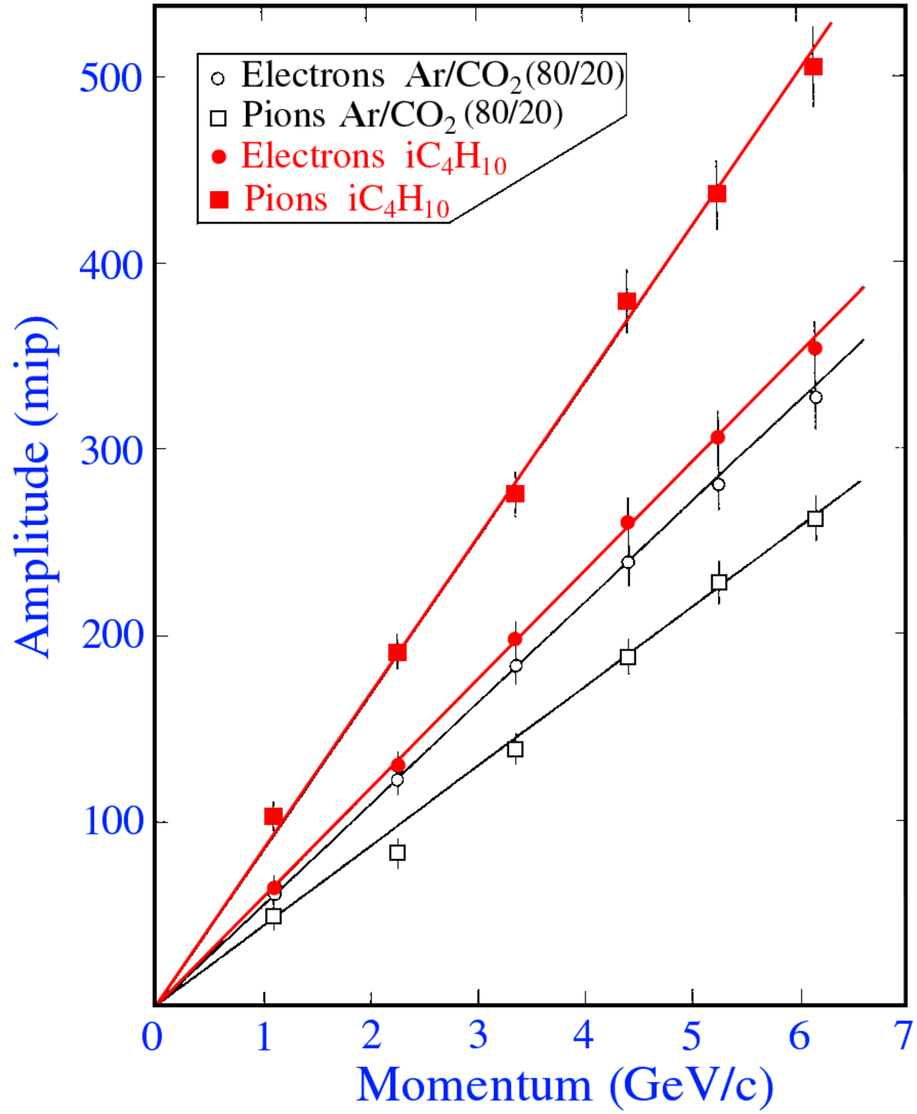


FIG. 3.31. The average signals for electrons and pions, measured with the uranium/gas calorimeter of the L3 Collaboration, for two different choices of gas with which the proportional wire chambers were operated. From: NIM A251 (1986) 258.

Compensation in gas calorimeters
Hadronic response function

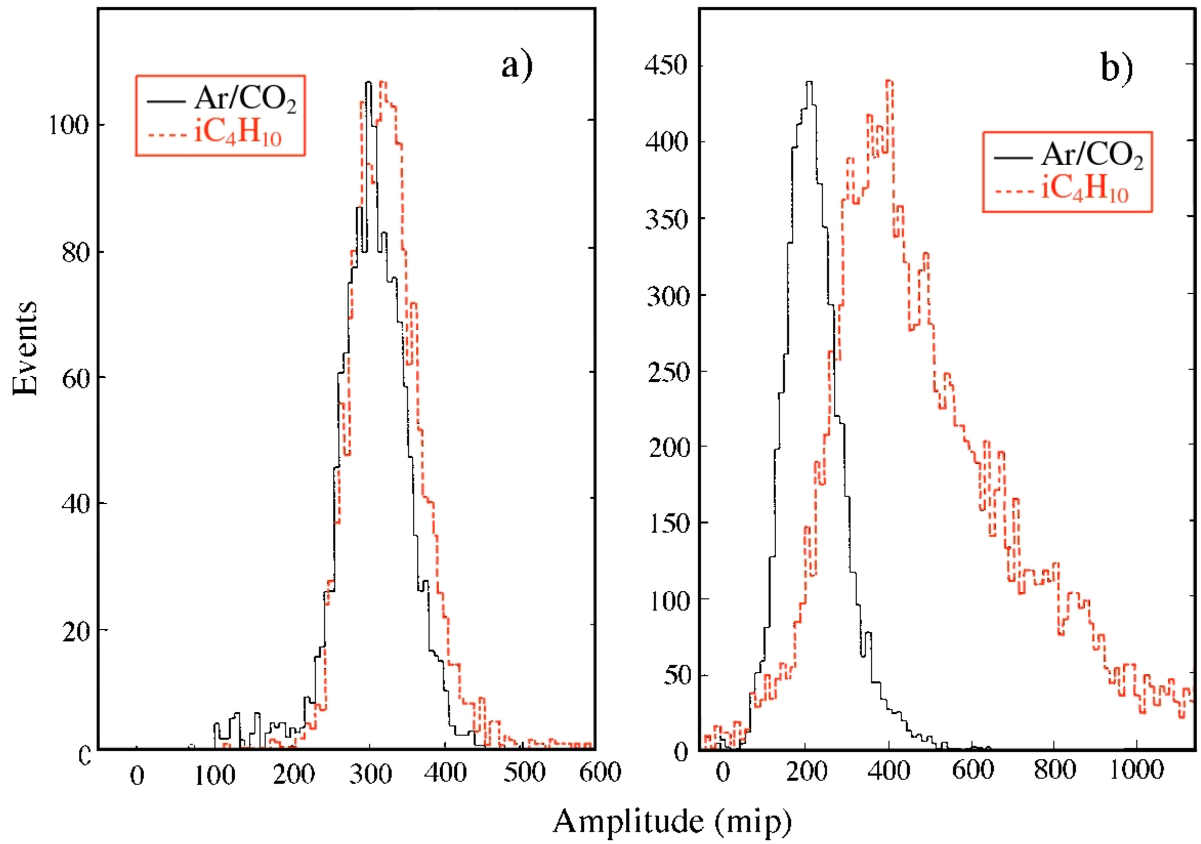


FIG. 4.57. Signal distributions recorded with the L3 ^{238}U/gas calorimeter, for 6 GeV electrons (a) and 6 GeV pions (b), with two different gas choices. The solid histograms were obtained with a mixture of argon (80%) and CO_2 (20%), the dashed histograms with isobutane. From: NIM A251 (1986) 258.

Compensation requires large integration volume!

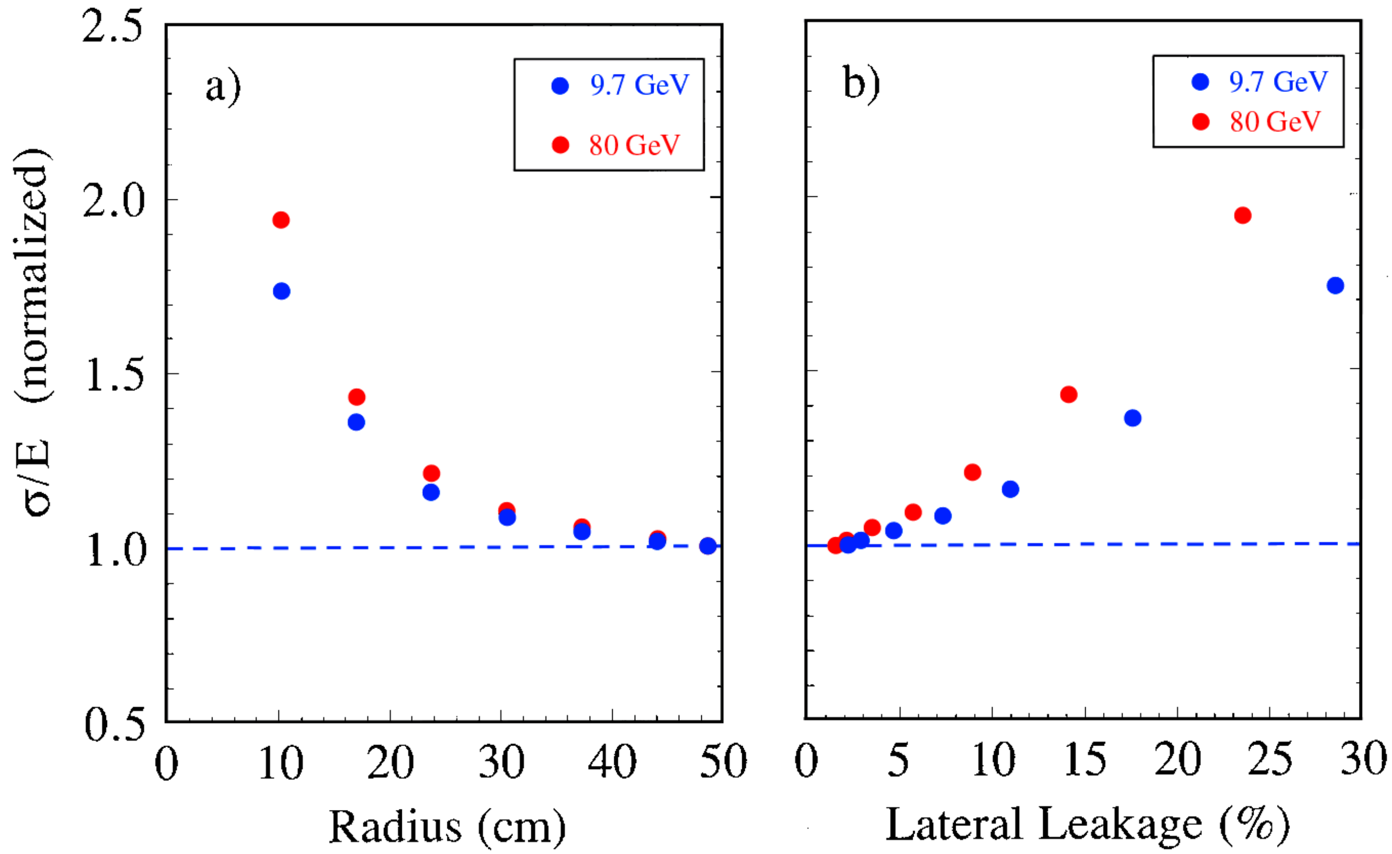


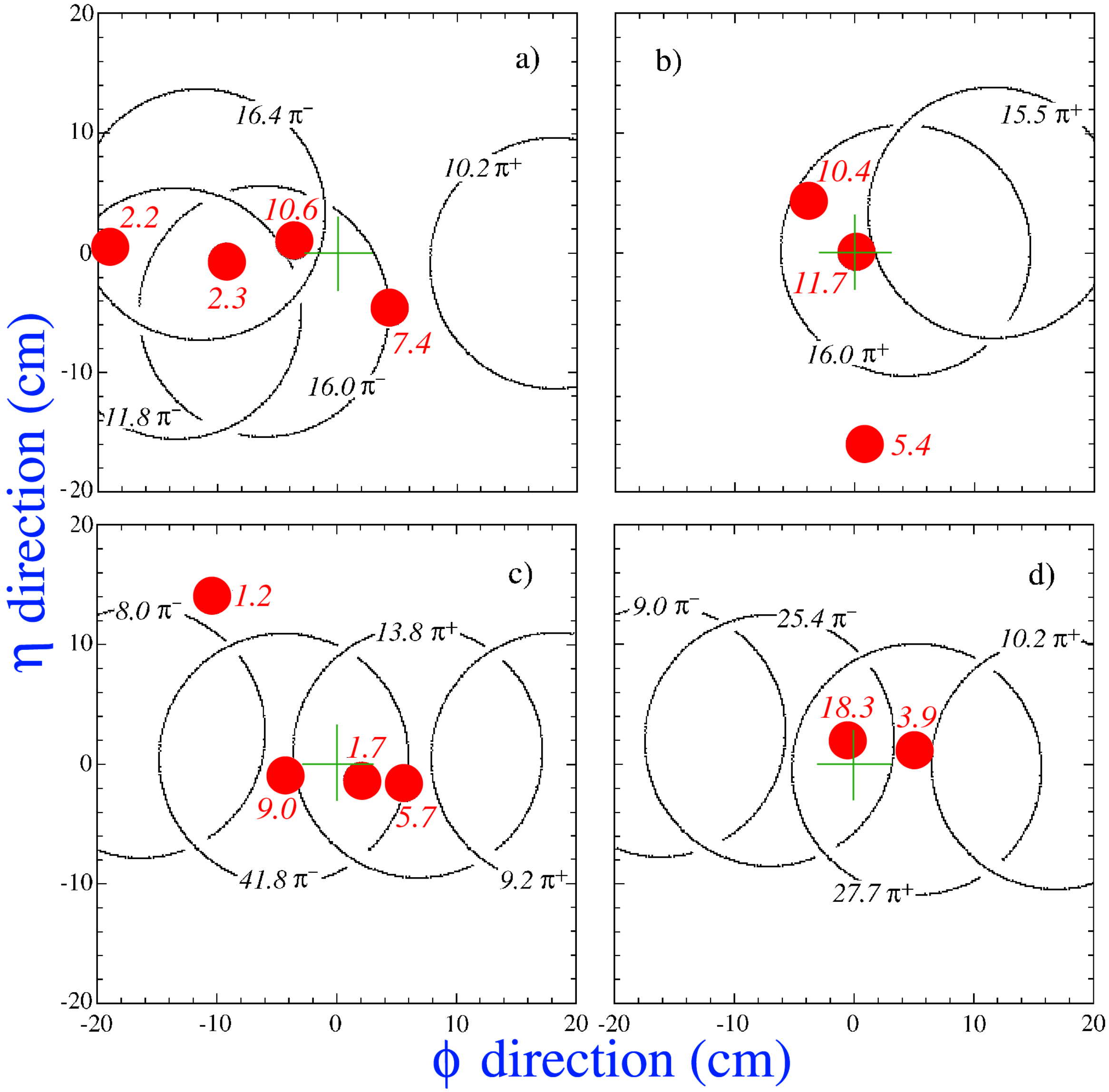
FIG. 4.30. The hadronic energy resolution as a function of the effective radius of the area over which the calorimeter signals were integrated. The energy resolutions have been normalized to the value for the complete SPACAL detector. Results for 9.7 and 80 GeV π^- that entered the calorimeter at an angle of 3° with the fiber axis (a). The same data as a function of the lateral shower leakage fraction (b). From: NIM A308 (1991) 481.

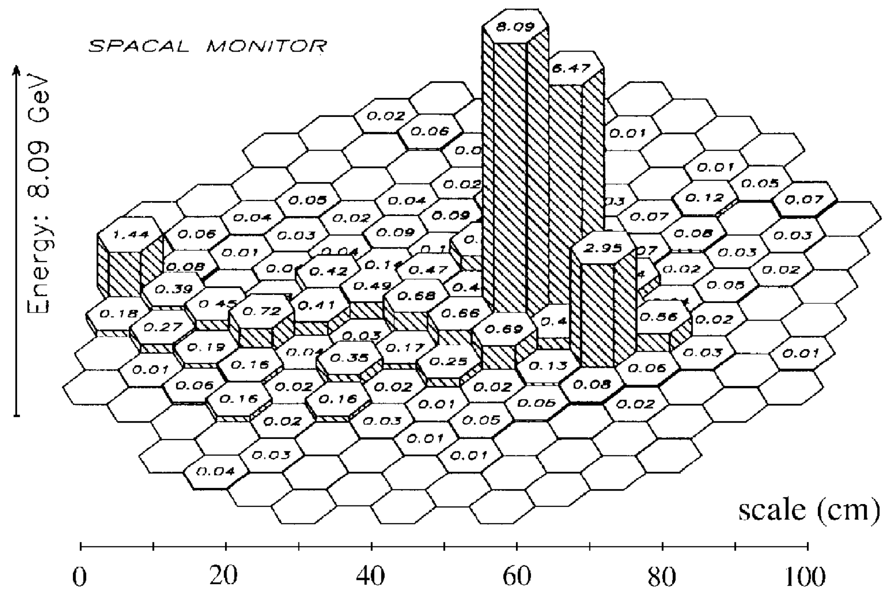
High-resolution jet spectroscopy (3)

2. Energy Flow Method

- Measure charged particles with tracker
  photons, neutral hadrons with calorimeter
- Fluctuations in jet composition are large.
  If only charged jet components measured $\rightarrow (\sigma/E)_{\rm jet} \sim 25 - 30\%$
  (independent of jet energy) $\rightarrow$ calorimetry essential!
- The problem with this method is *shower overlap*
  One needs to deconvolute the contributions from showering charged particles to the total energy deposit profile in the calorimeter.
- This problem is *not* solvable with a finer granularity
  The showers have certain transverse dimensions and exhibit large fluctuations in all dimensions.
  Larger distance vertex-calorimeter and larger **B**-field would help
- NIM A495 (2002) 107: Method may give improvement of $\sim 30\%$

Energy Flow Method: "π" jet





Typical energy deposit profile in (SPACAL) calorimeter

Resolution improvement expected with EFM

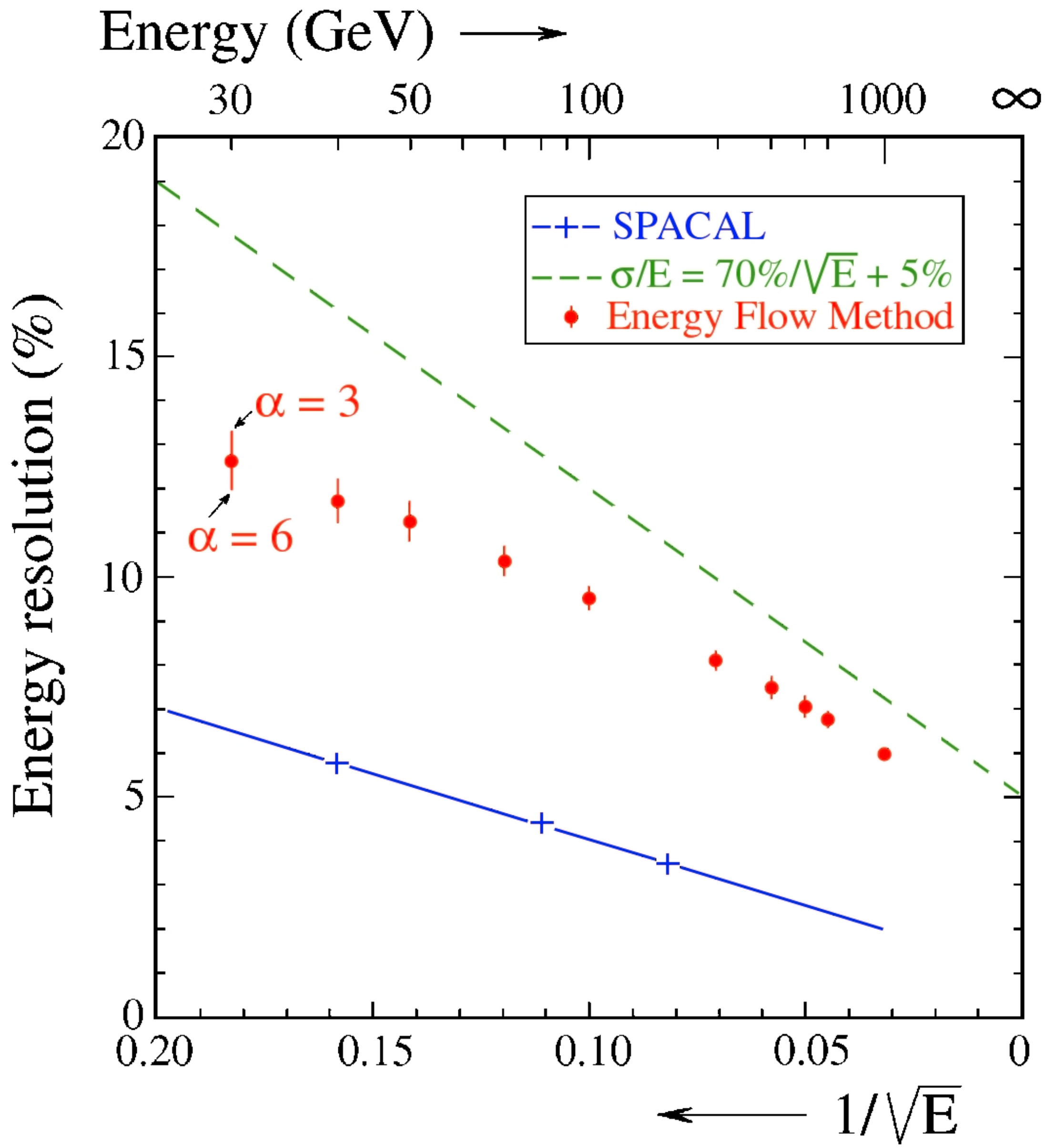
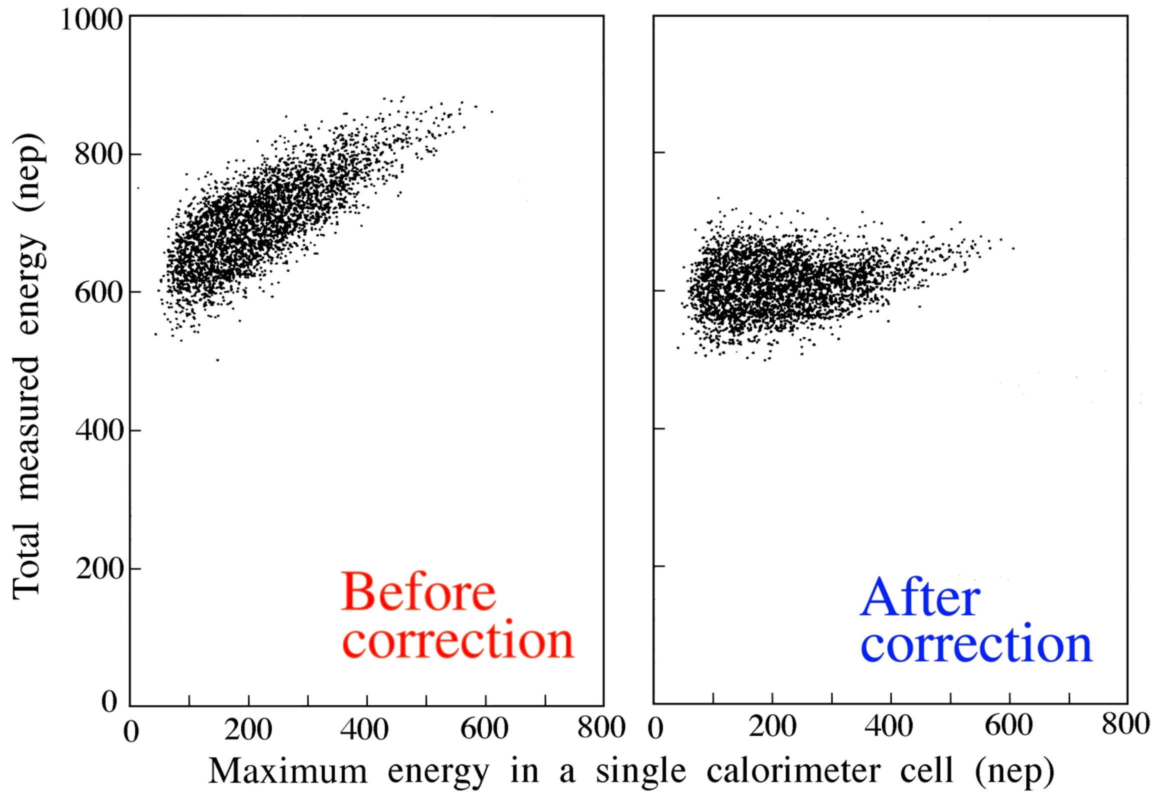


Fig. 11. The jet energy resolution as a function of energy, obtained after applying the Energy Flow Method (the black dots), using simulated data from a calorimeter with a jet resolution given by the dashed curve. For comparison, the jet resolution of a compensating calorimeter is given (SPACAL [7], the dotted curve). From: NIM A495 (2002) 107.

Measuring the electromagnetic shower content

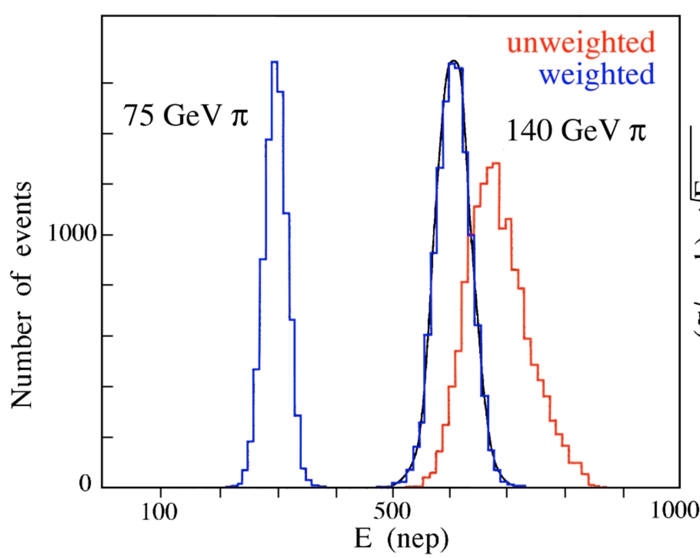
- *Measure f_{em} event by event*
  - Pioneered by WA1 around 1980
  - Used characteristics of energy deposit profile to disentangle em/non-em shower components
  - Works better as energy increases
  - Does *not* work for jets (collection of γs, πs showering simultaneously in the same area)

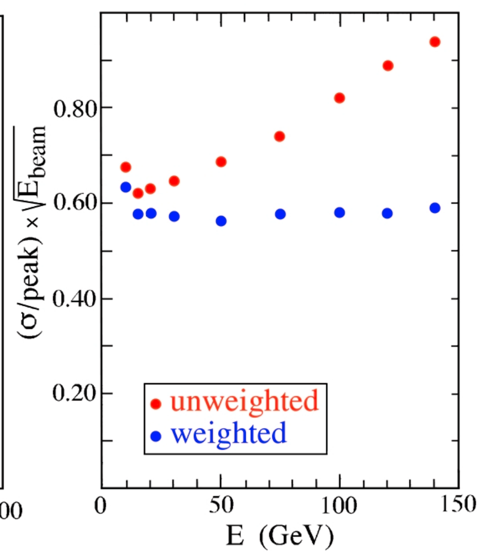
WA1: Determine f_{em} event by event



From:

NIM 180 (1981) 429





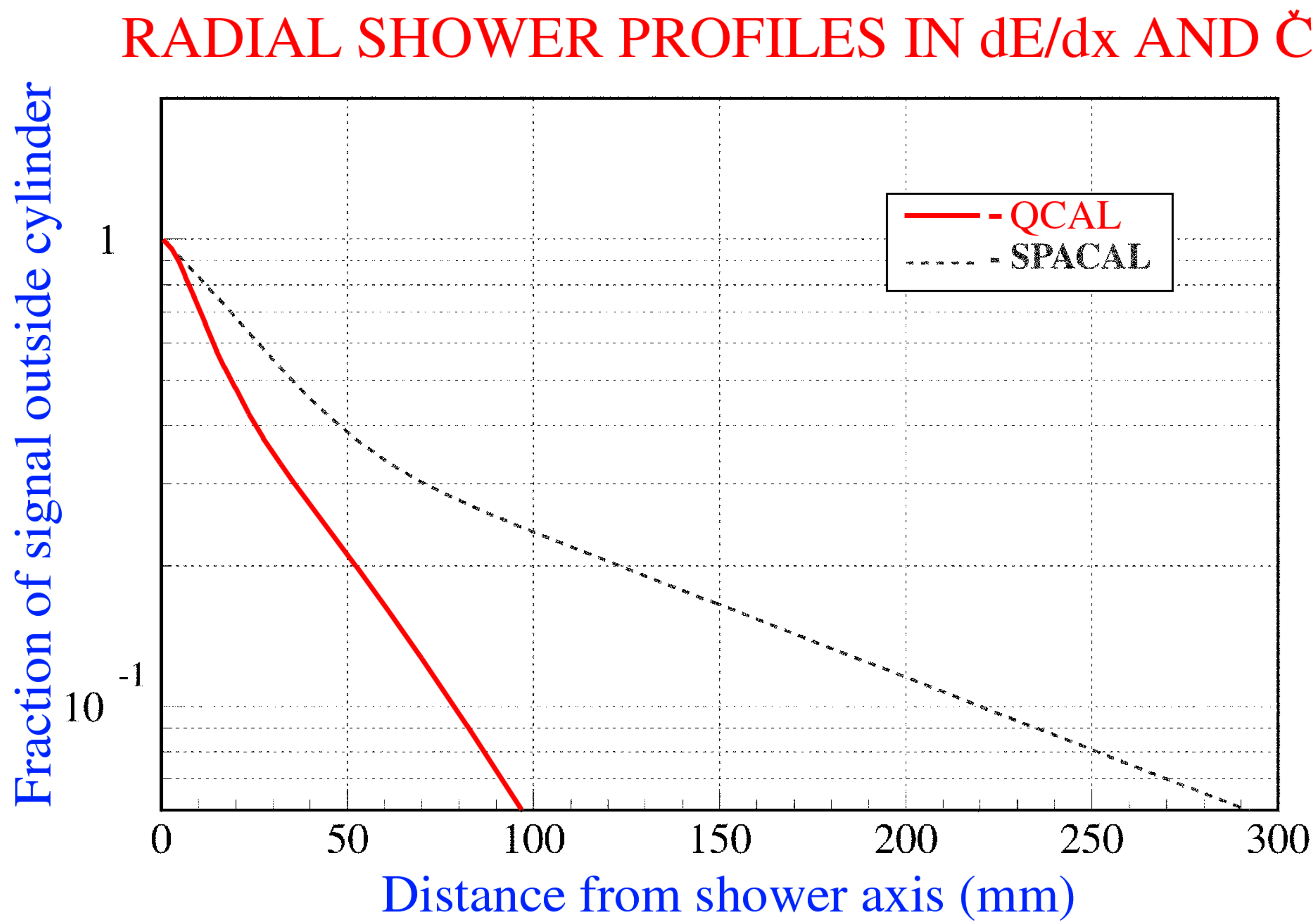
The DREAM principle

- *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

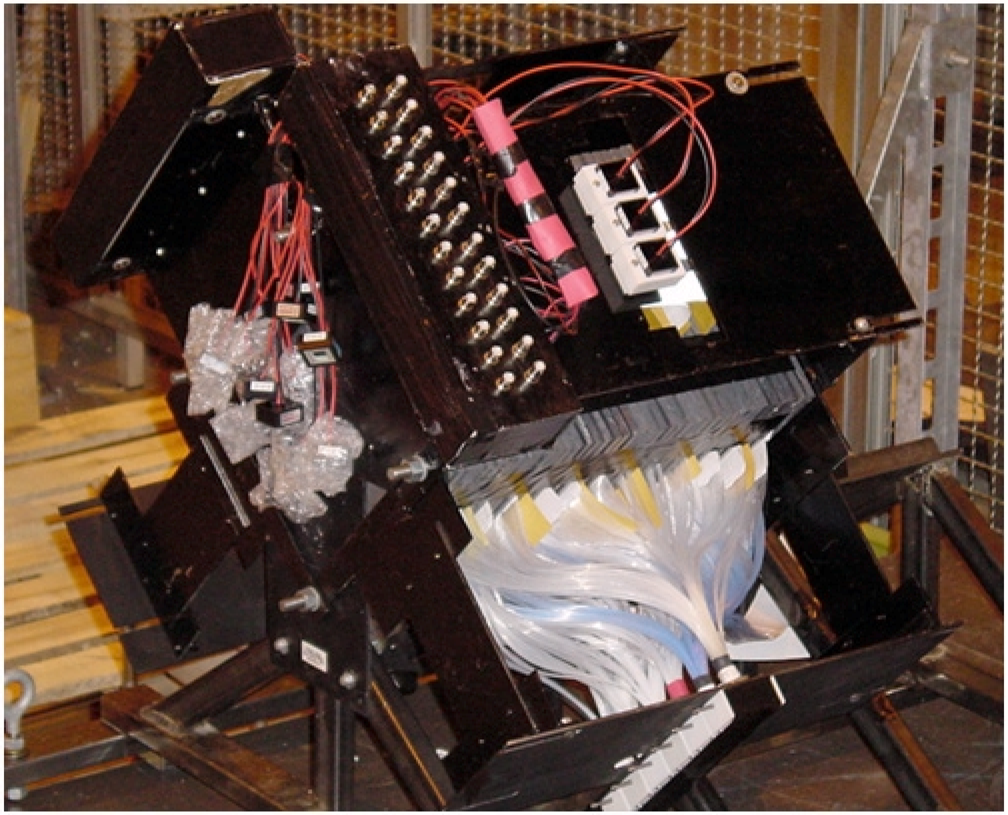


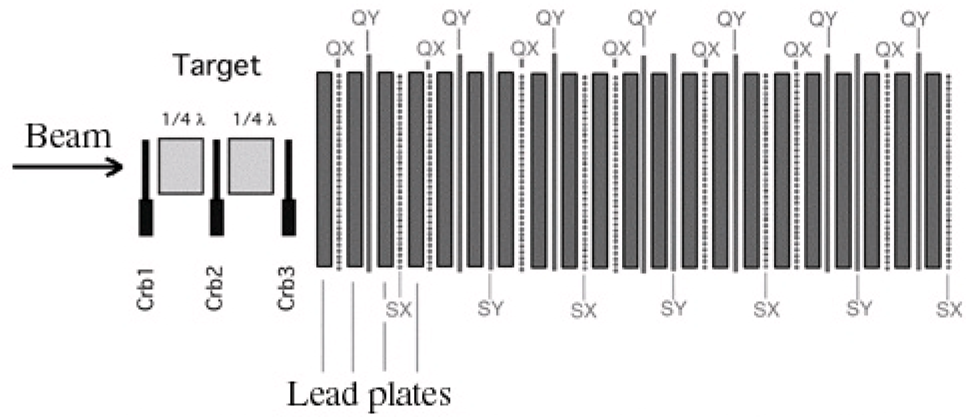
RADIAL SHOWER PROFILES IN dE/dx AND Č
QCAL
SPACAL
1
10 -1
0
50
100
150
200
250
300
Fraction of signal outside cylinder
Distance from shower axis (mm)

Dual-Readout Calorimetry: ACCESS
(NIM A462 (2001) 411)

- ACCESS: How to do a reasonable energy measurement of PeV ions in a 1 - 2 λ_{int} deep calorimeter?
  - Energy resolution dominated by *leakage fluctuations*
    $\rightarrow$ need event-to-event leakage information to improve resolution
  - *Hypothesis*: Leakage correlated with π^0 production in calorimeter. Large (small) fraction of energy incoming ion going into π^0s
    $\rightarrow$ small (large) fraction of energy leaks out of thin device
  - Compare signals from scintillating fibers/quartz fibers for same events: *Q/S* is indeed measure for leakage, that can be used to improve energy resolution.

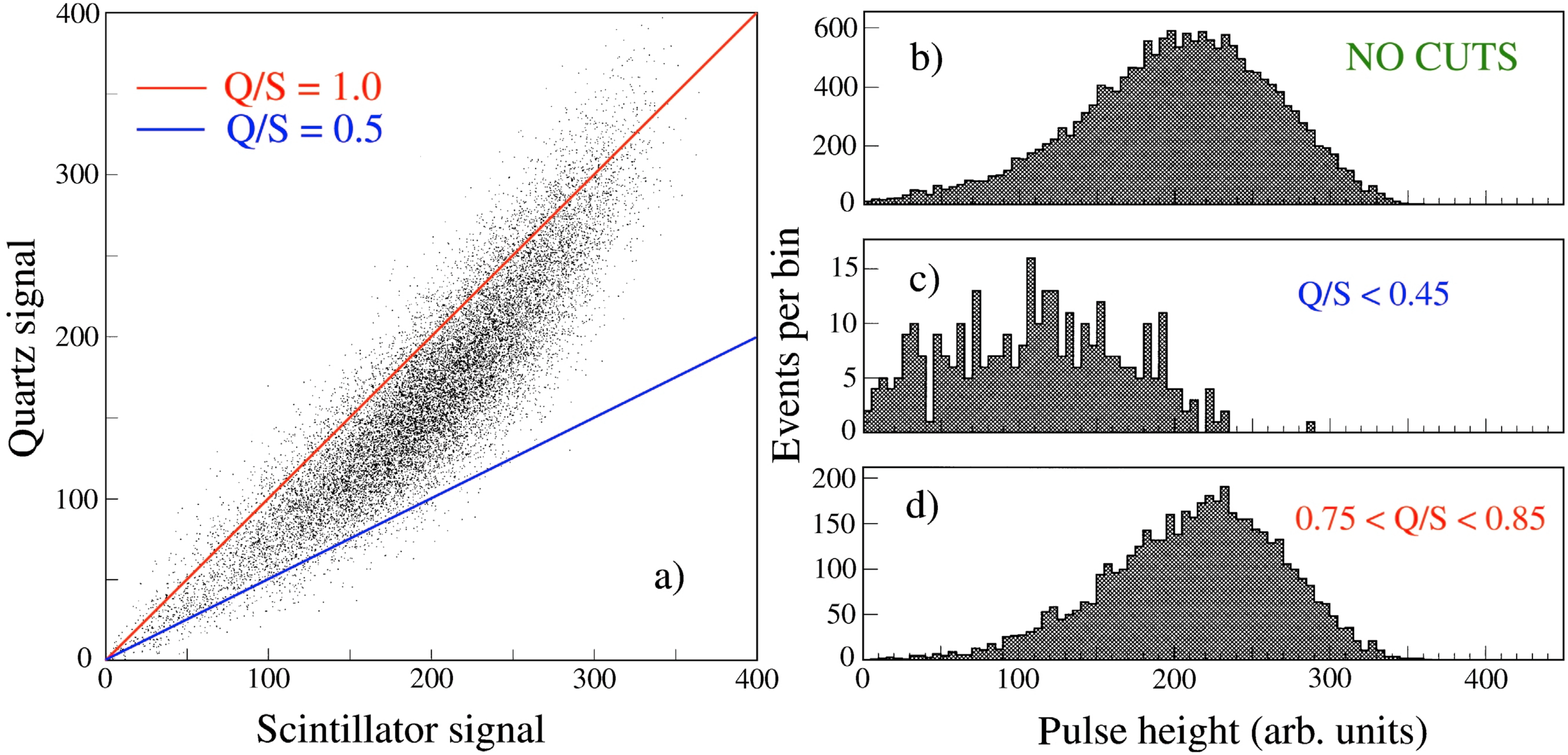
ACCESS Dual-Readout Prototype calorimeter





ACCESS: Proof of principle

NIM A462 (2001) 411



Dual-Readout Calorimetry: DREAM

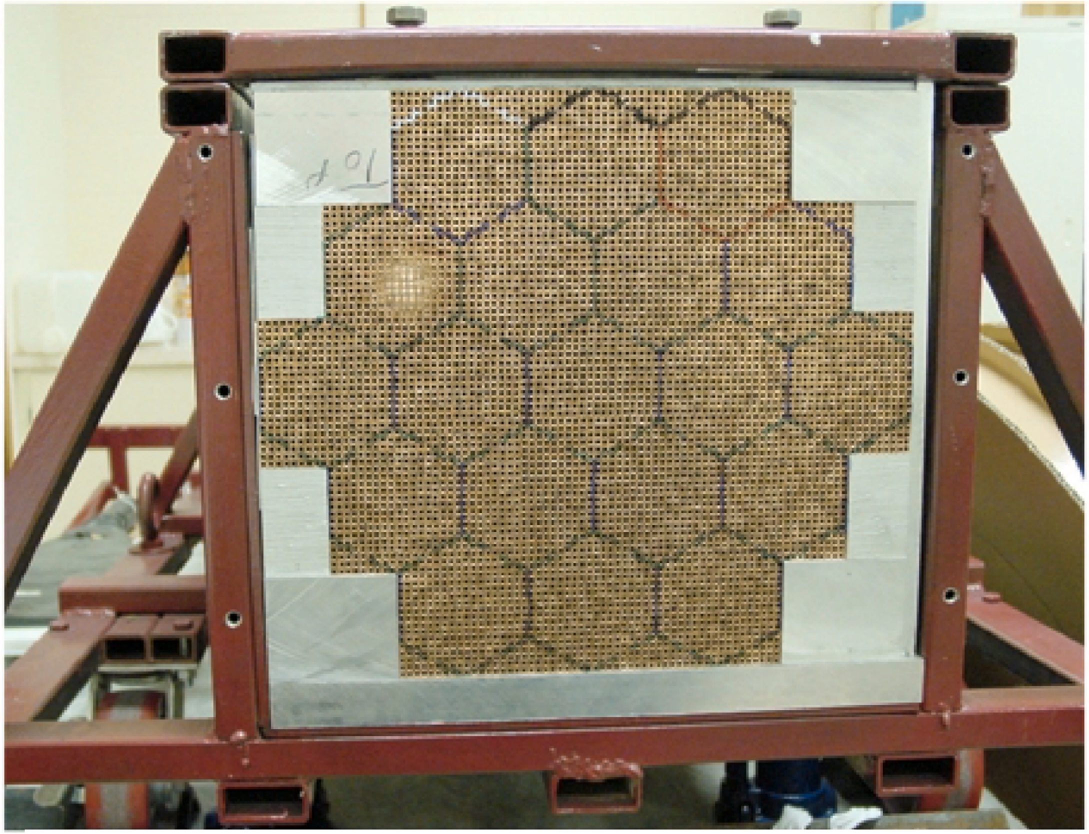
- Since Dual-Readout method works already so well for very thin devices, we built a 10 $\lambda_{\rm int}$ deep calorimeter to explore its full potential.

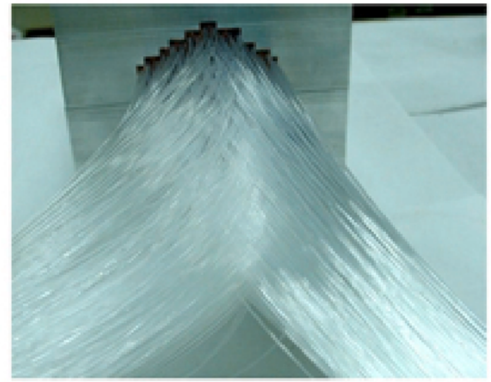
  Composition DREAM detector:

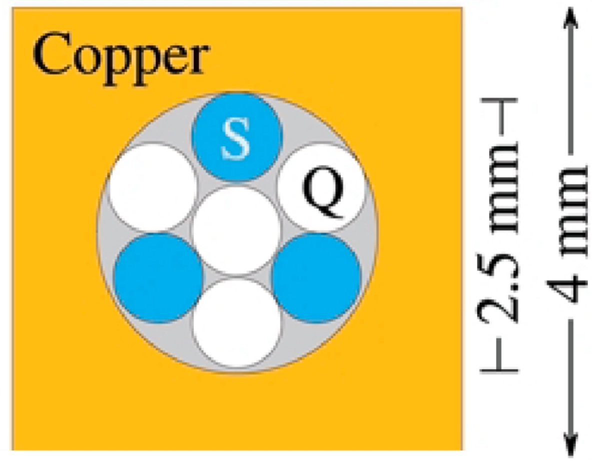
  Cu : scintillator : Čerenkov fibers : air = 69.3 : 9.4 : 12.6 : 8.7

  Filling fraction (active material/absorber) = 31.7%

DREAM: Structure

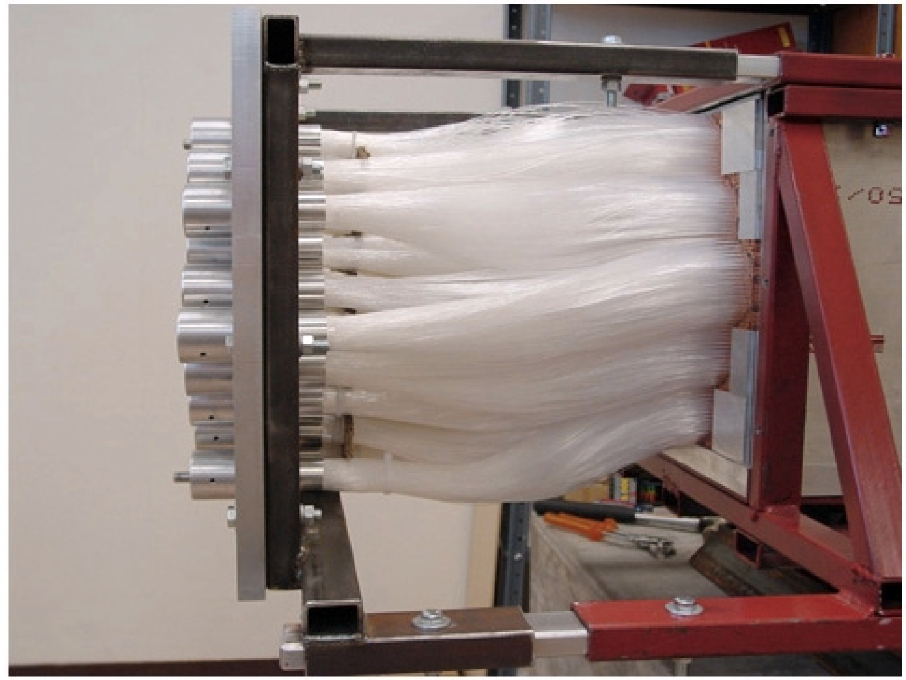


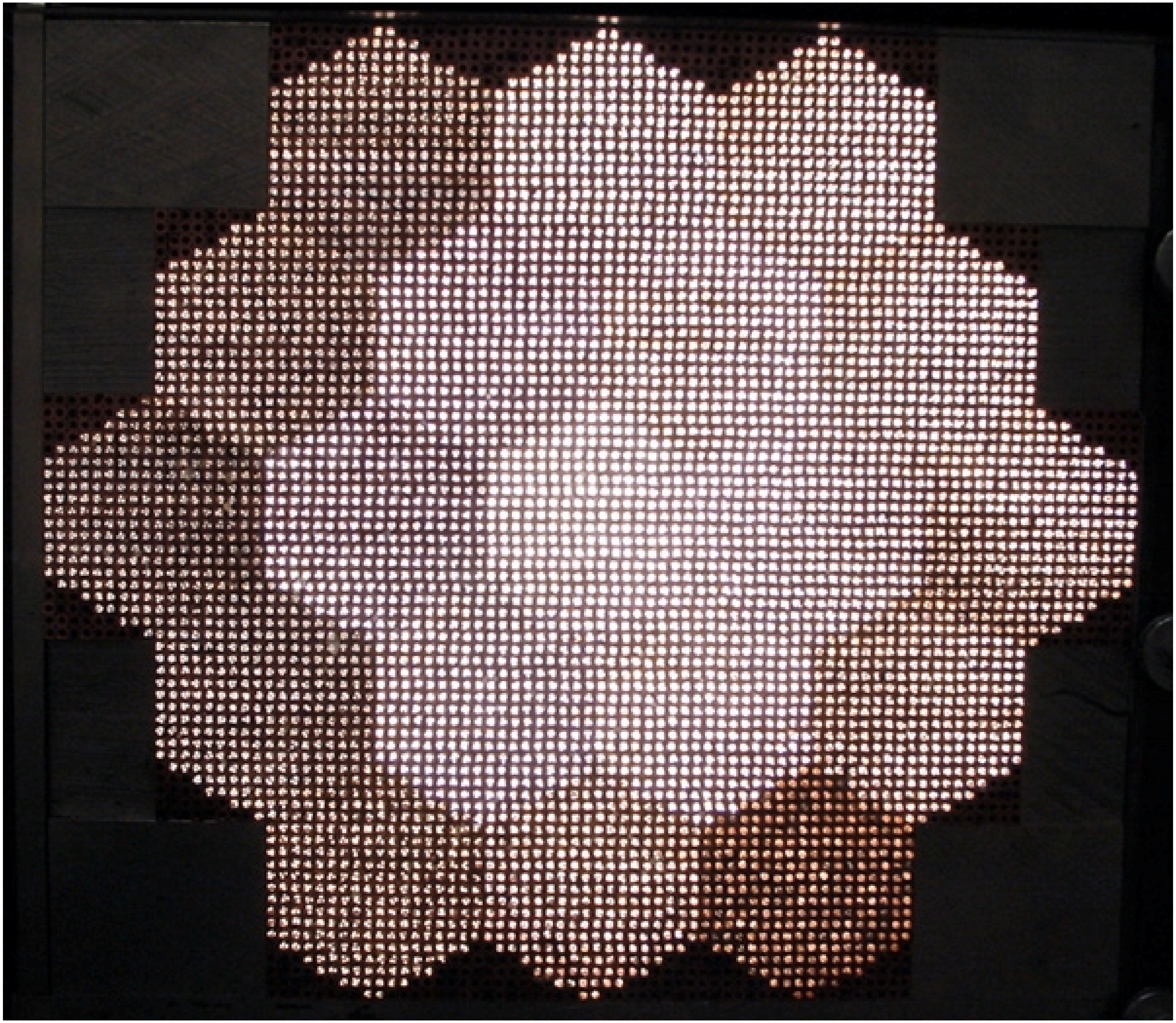


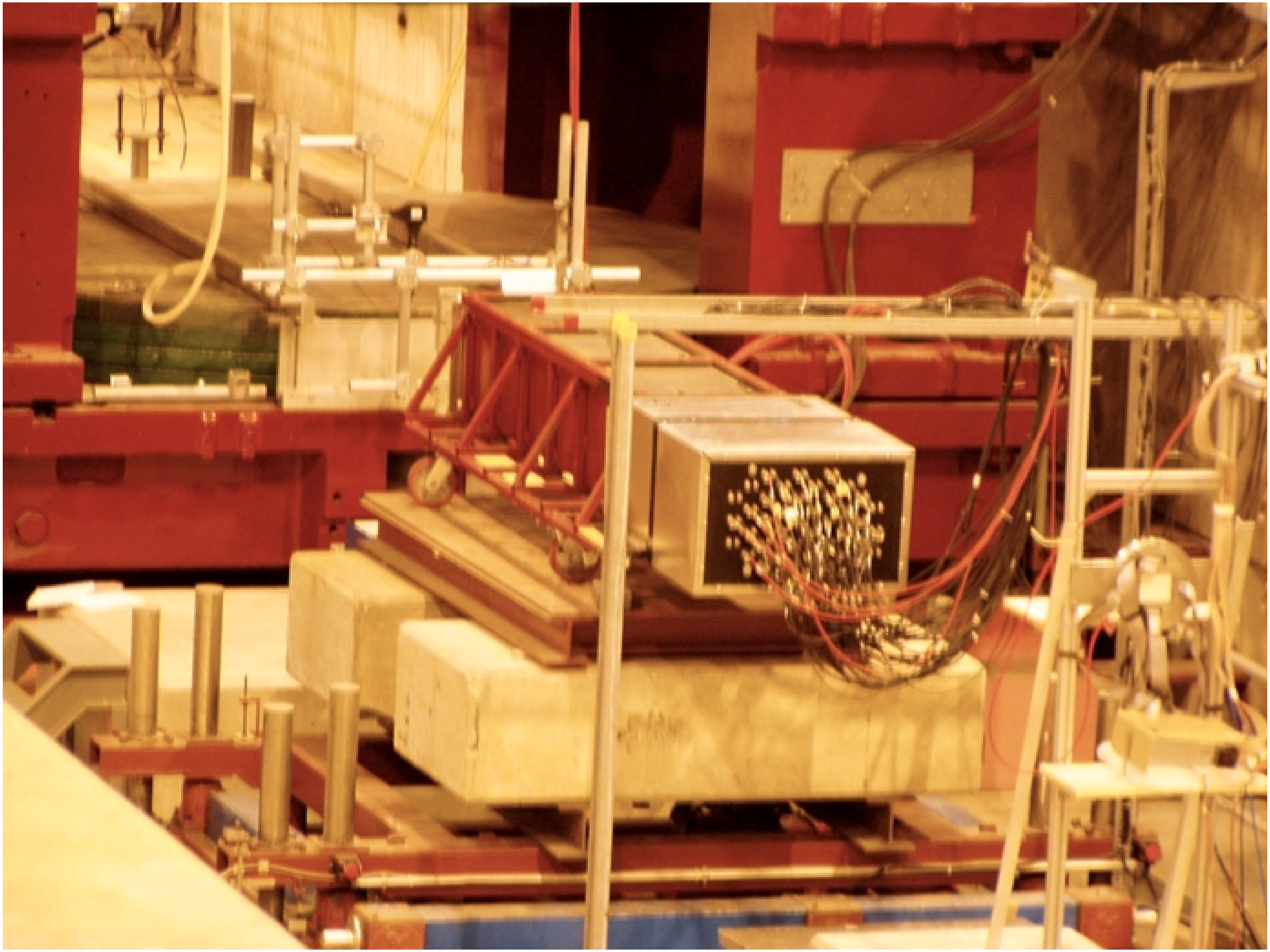


- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

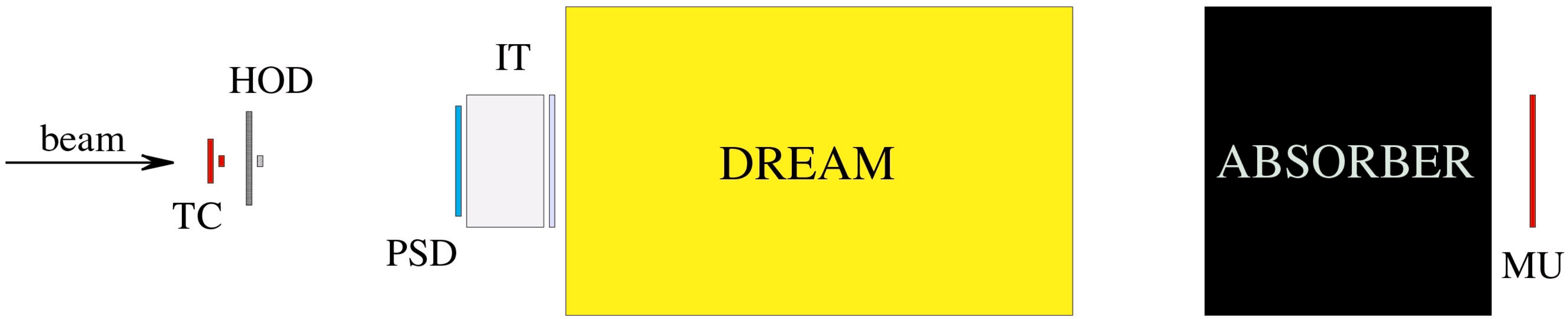
DREAM: Readout

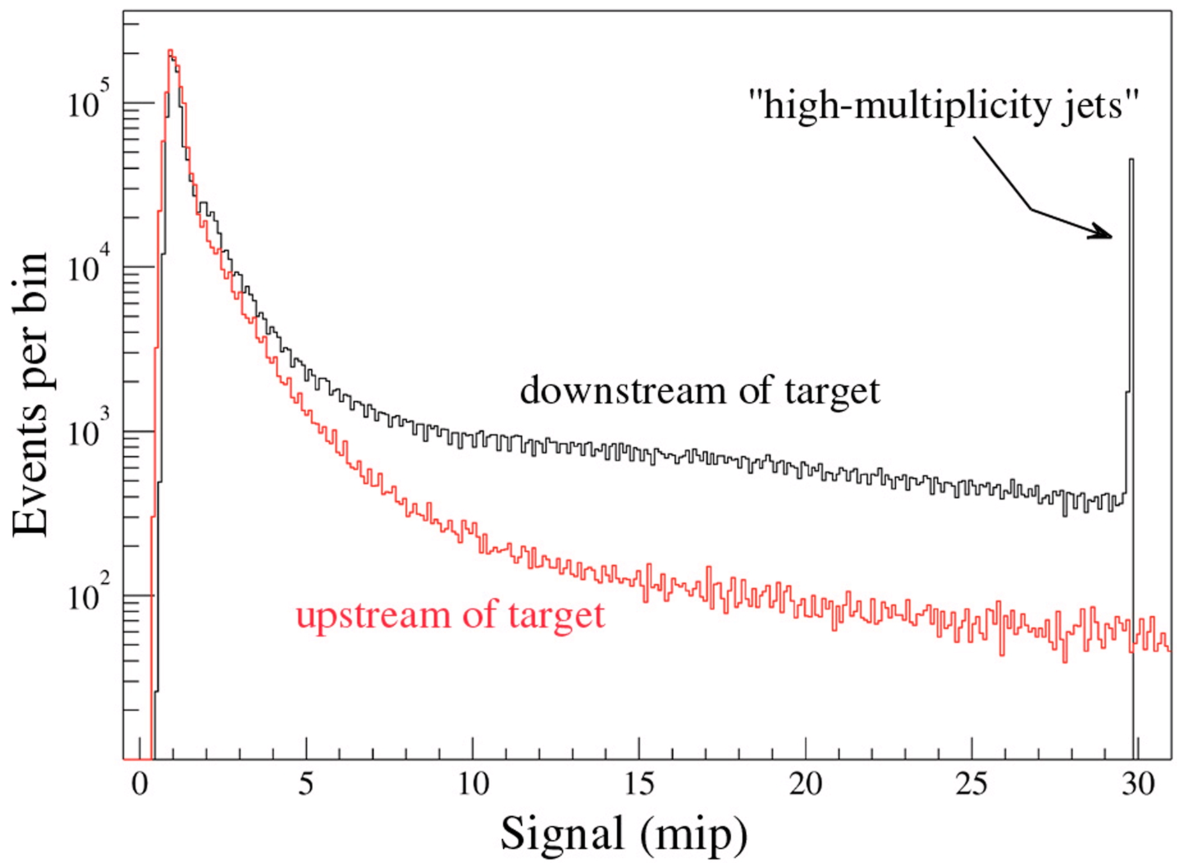






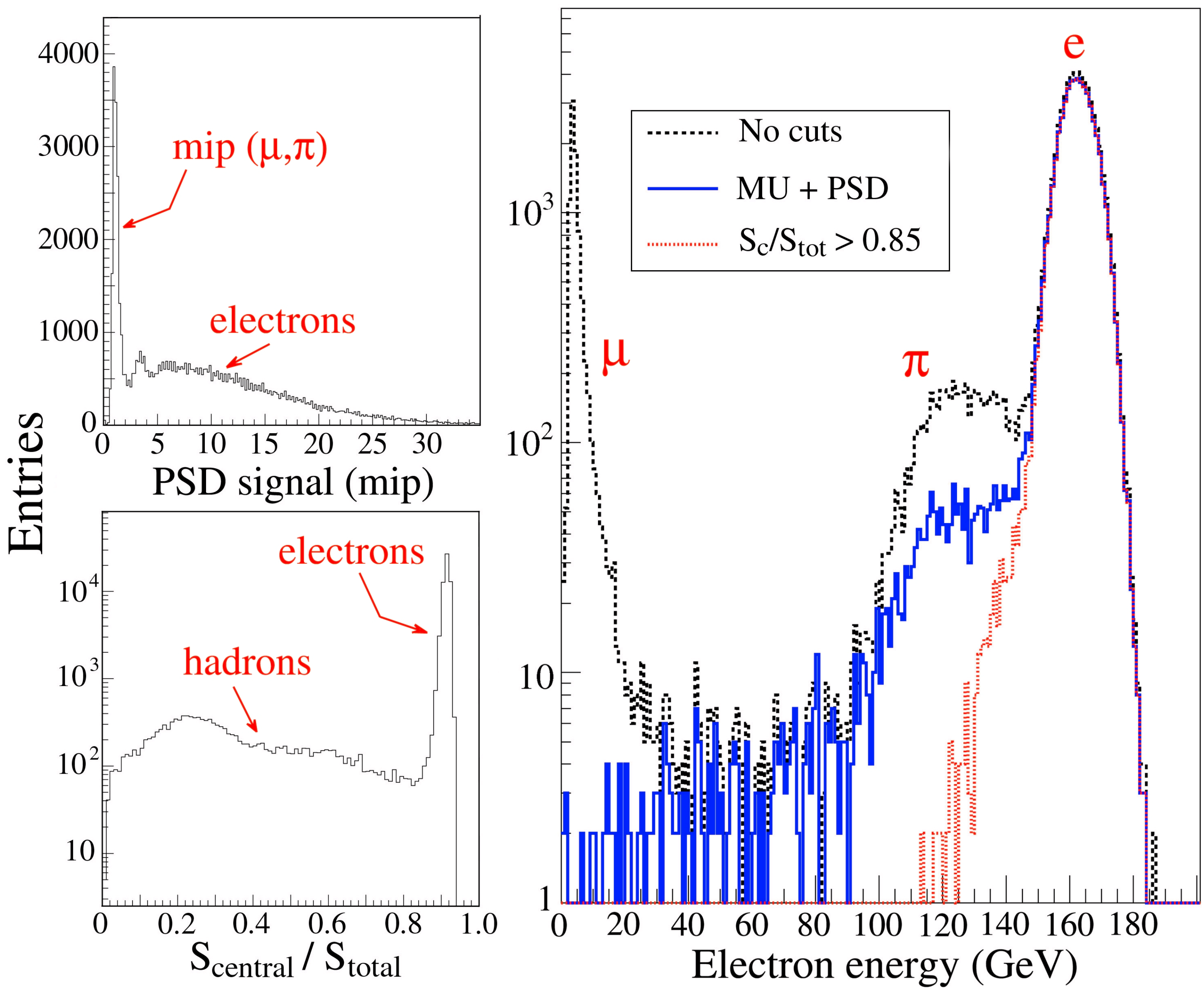
Experimental setup for DREAM beam tests



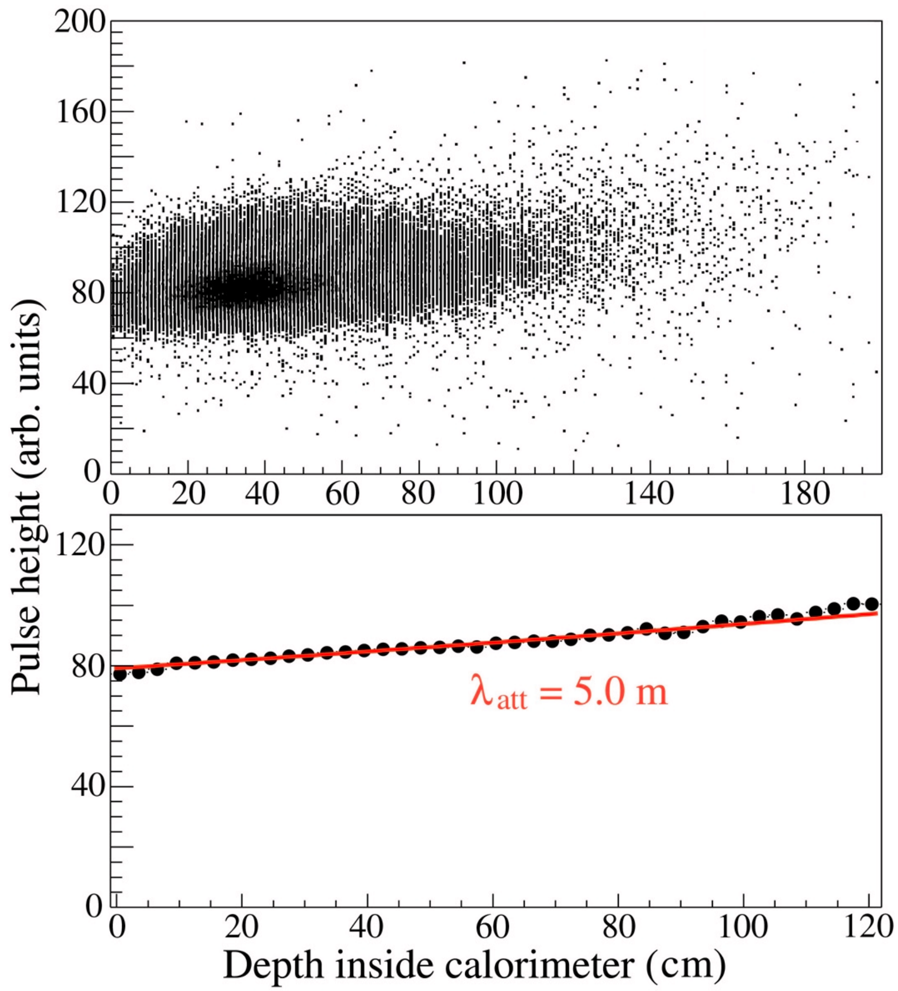


"JET" Measurements

Sample purity: Benefits of the PSD



DREAM: Benefits of the hodoscope



Depth z of light production:

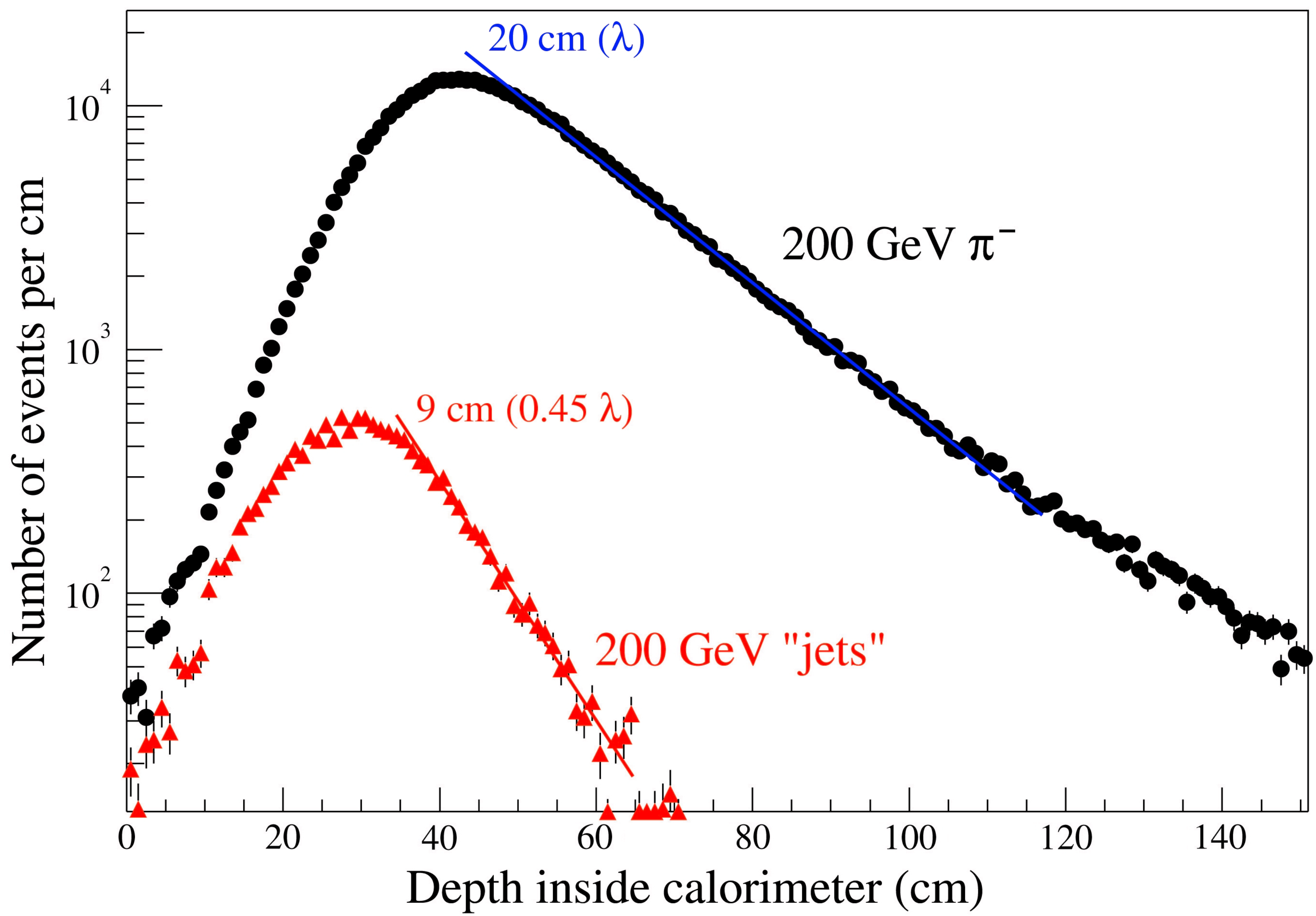
$$z = \frac{x_{cal} - x_{hod}}{\sin \theta}$$

Light attenuation in fibers

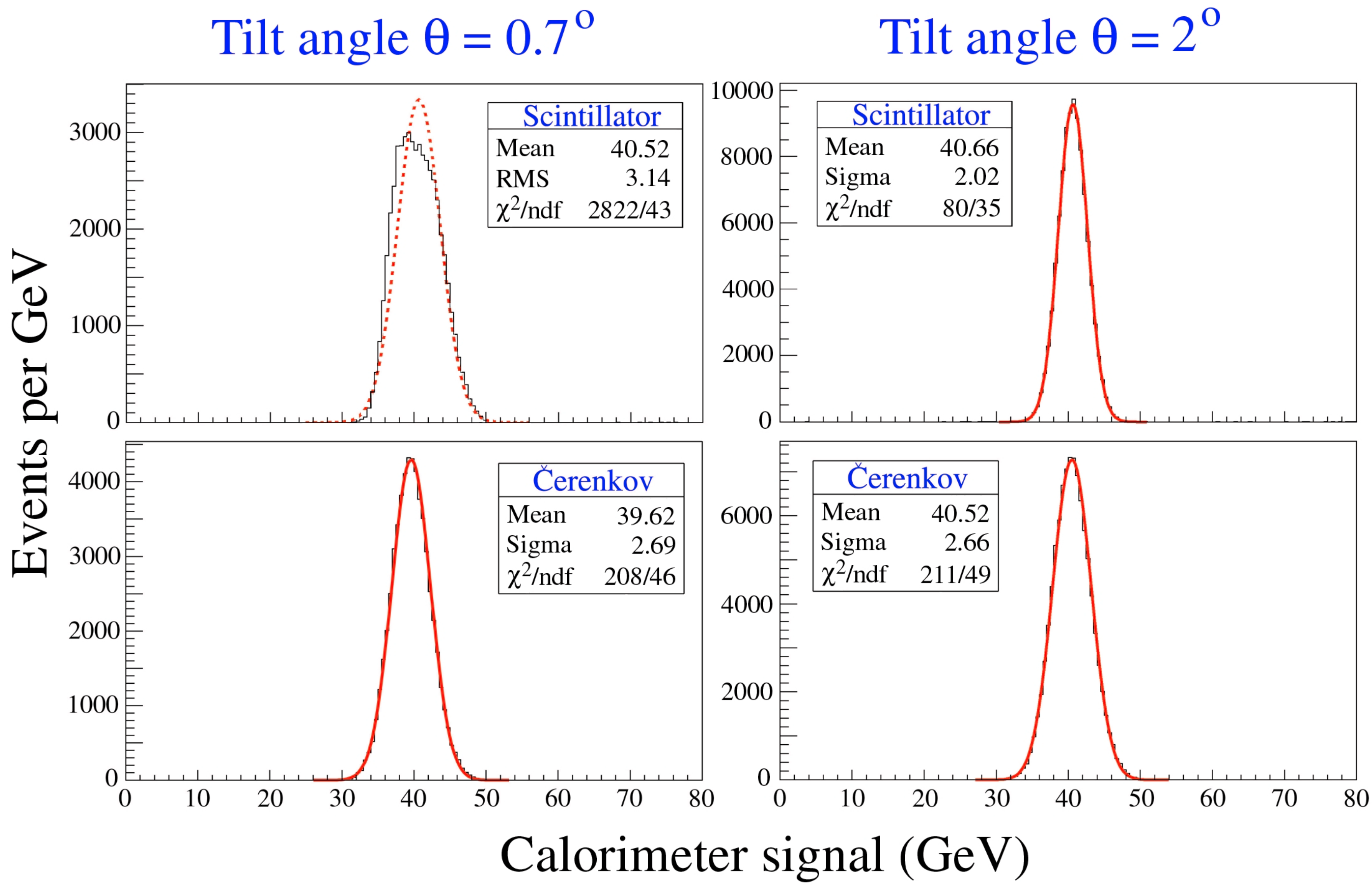
Correction:

$$S_{corr} = S_{meas} \exp\left[-(z - 30)/500\right]$$

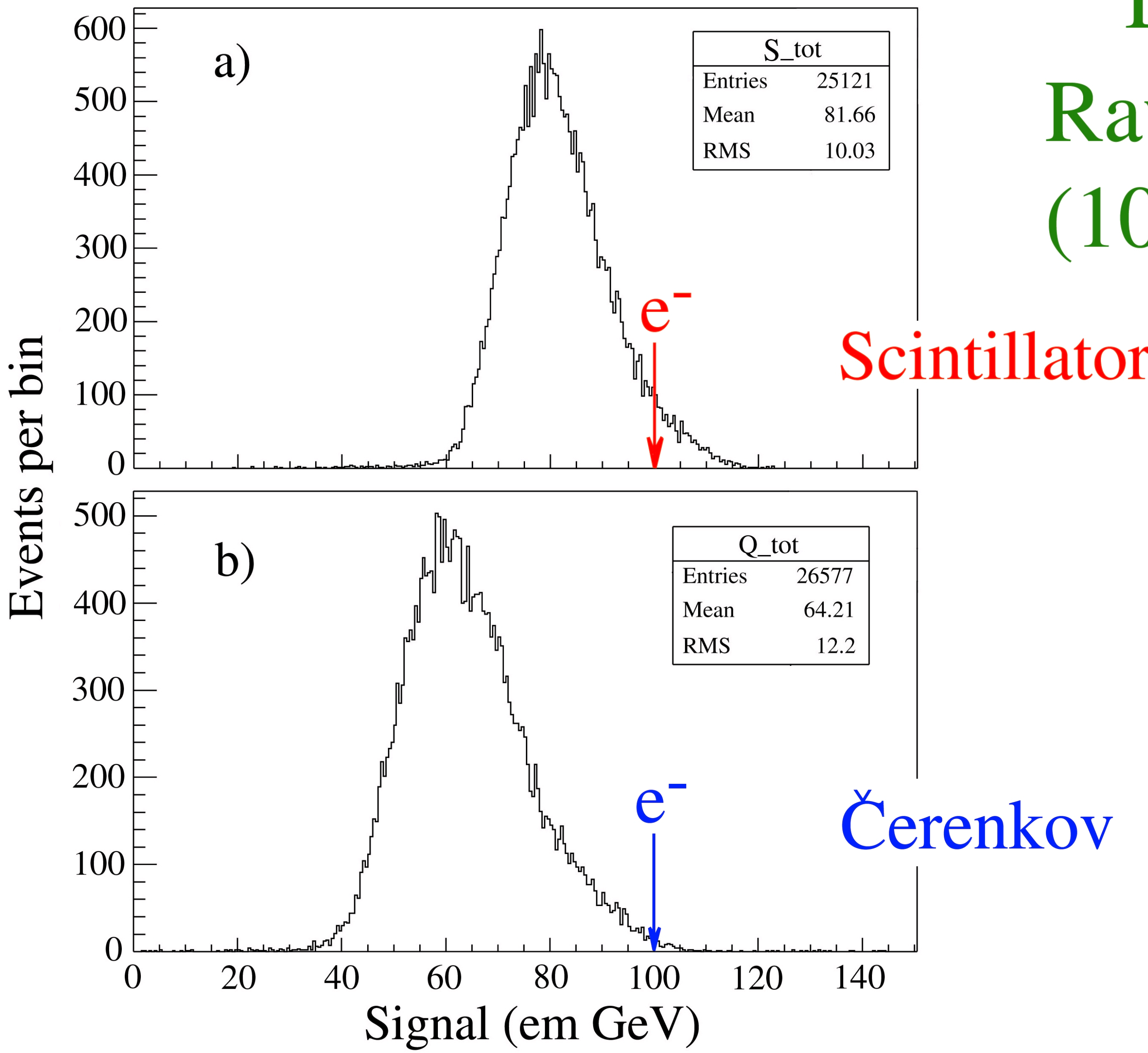
Jets vs. single particles: *z* of light production



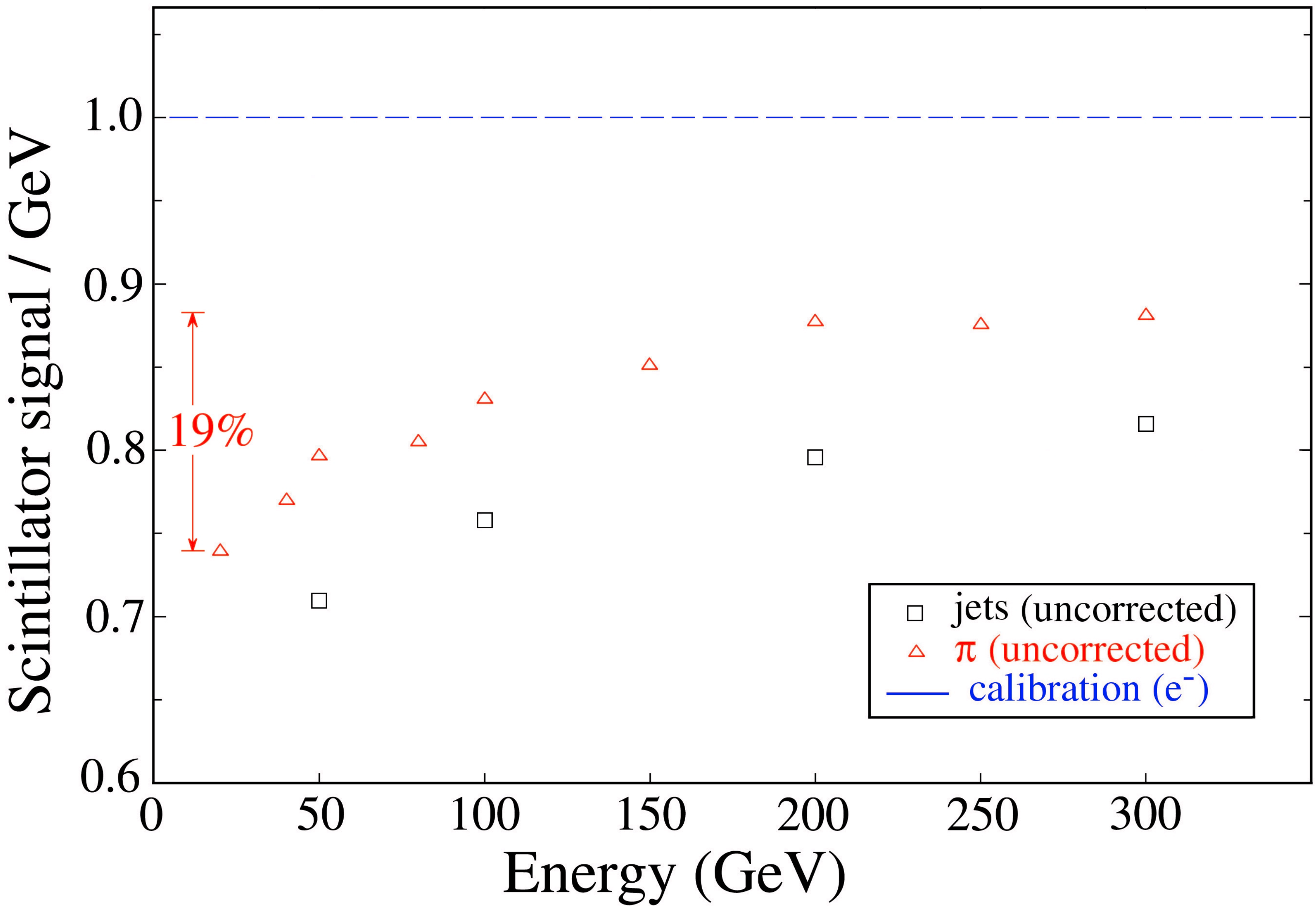
DREAM: Electromagnetic response function (40 GeV e⁻)



DREAM Raw signals (100 GeV π^-)

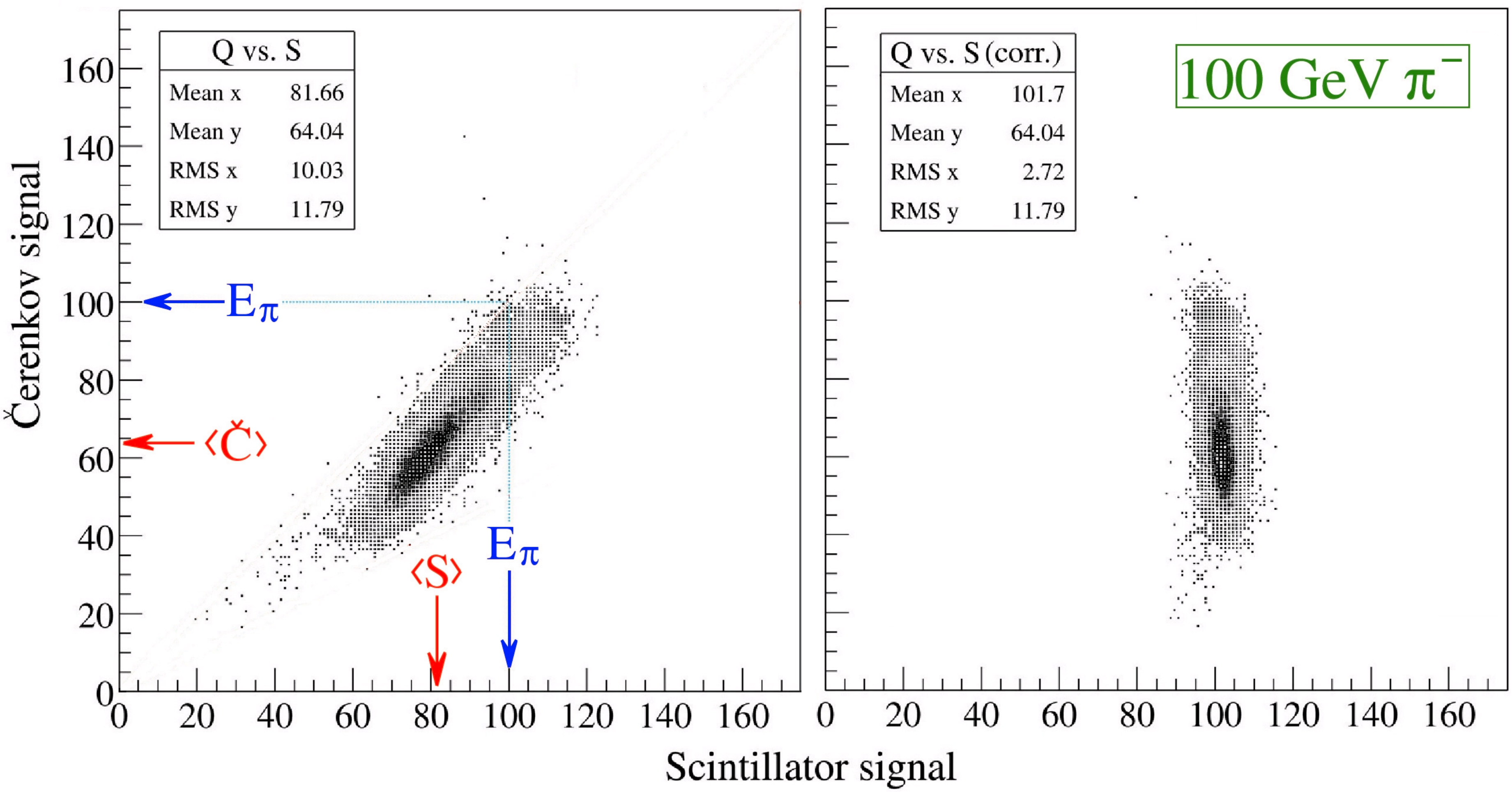


DREAM: Hadronic response (non-linearity)

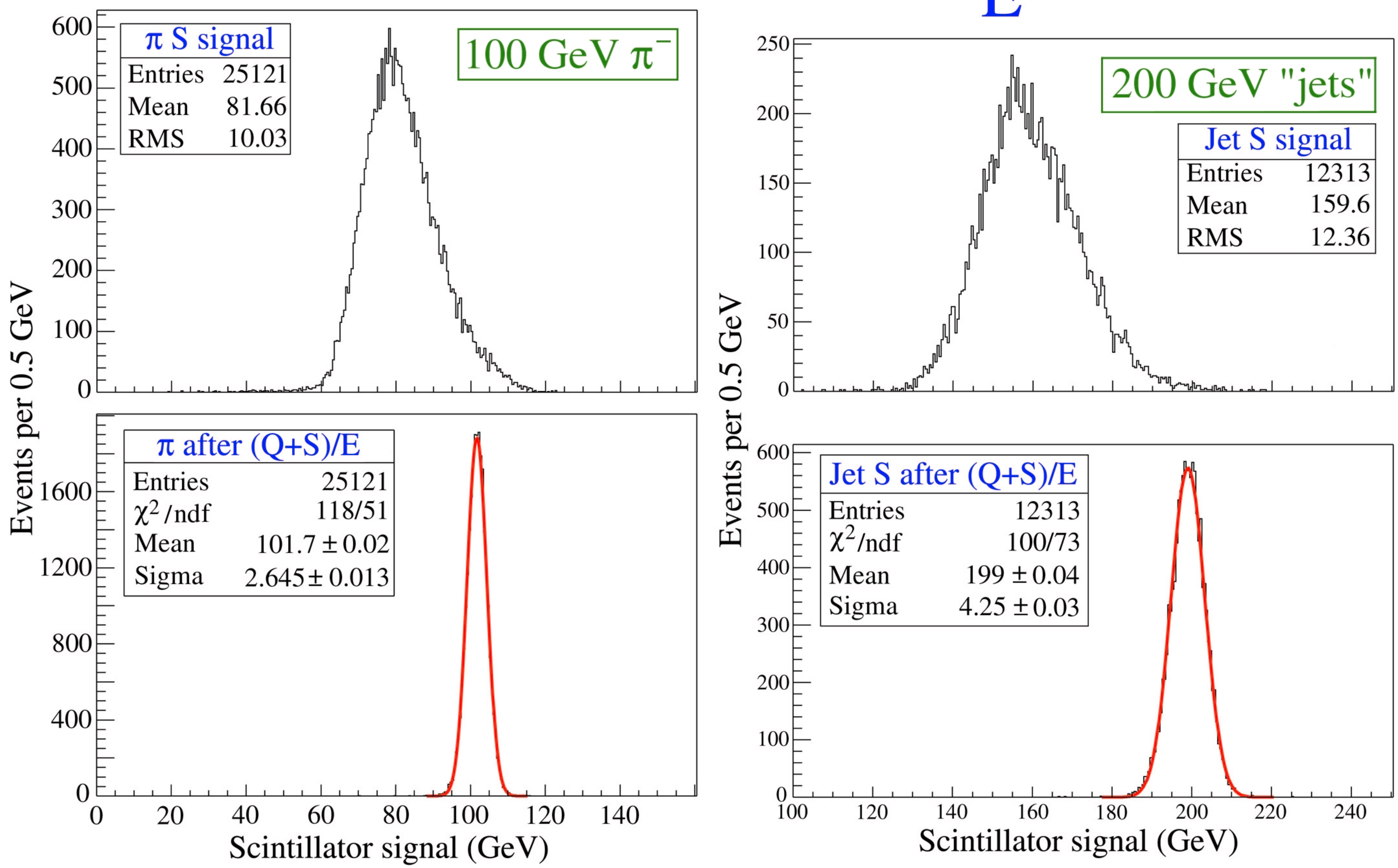


DREAM: Hadronic corrections on the basis of (Q+S)/E

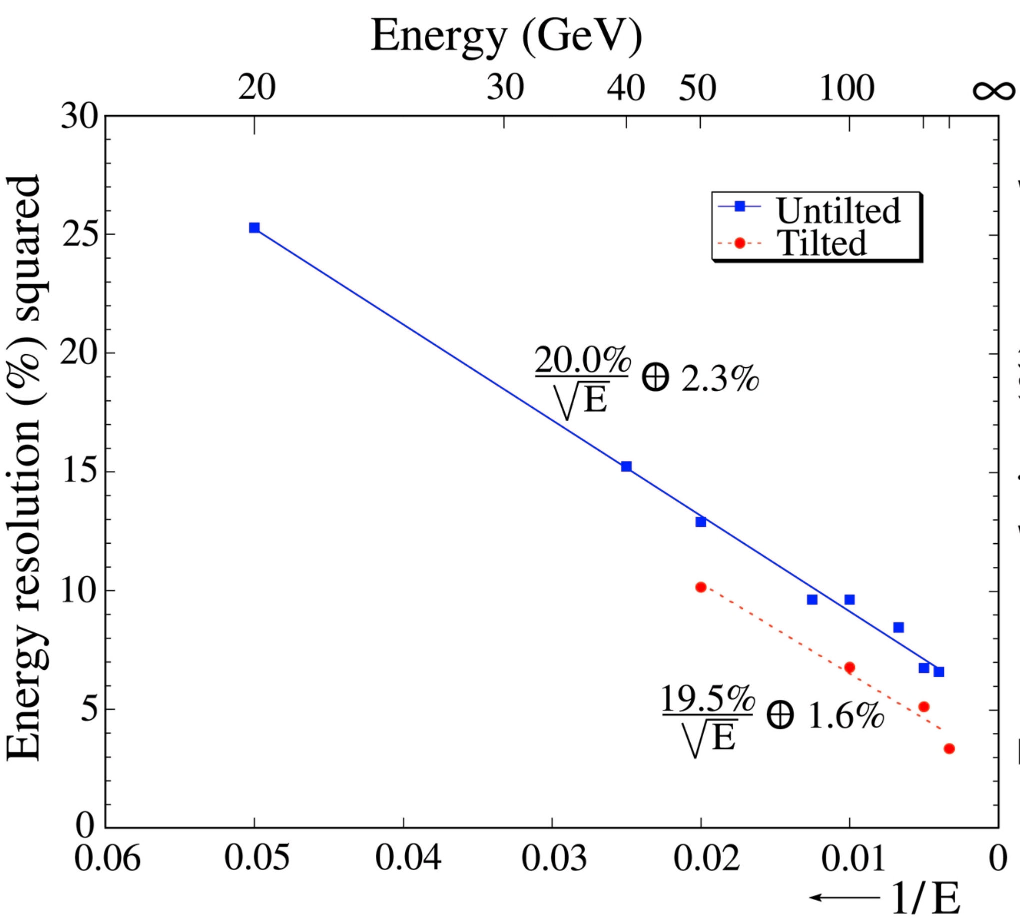
$$\left(\frac{S}{E}\right)_{\text{corr}} = \left(\frac{S}{E}\right)_{\text{meas}} + 0.453\left[1.9 - \frac{(Q+S)_{\text{meas}}}{E}\right]$$

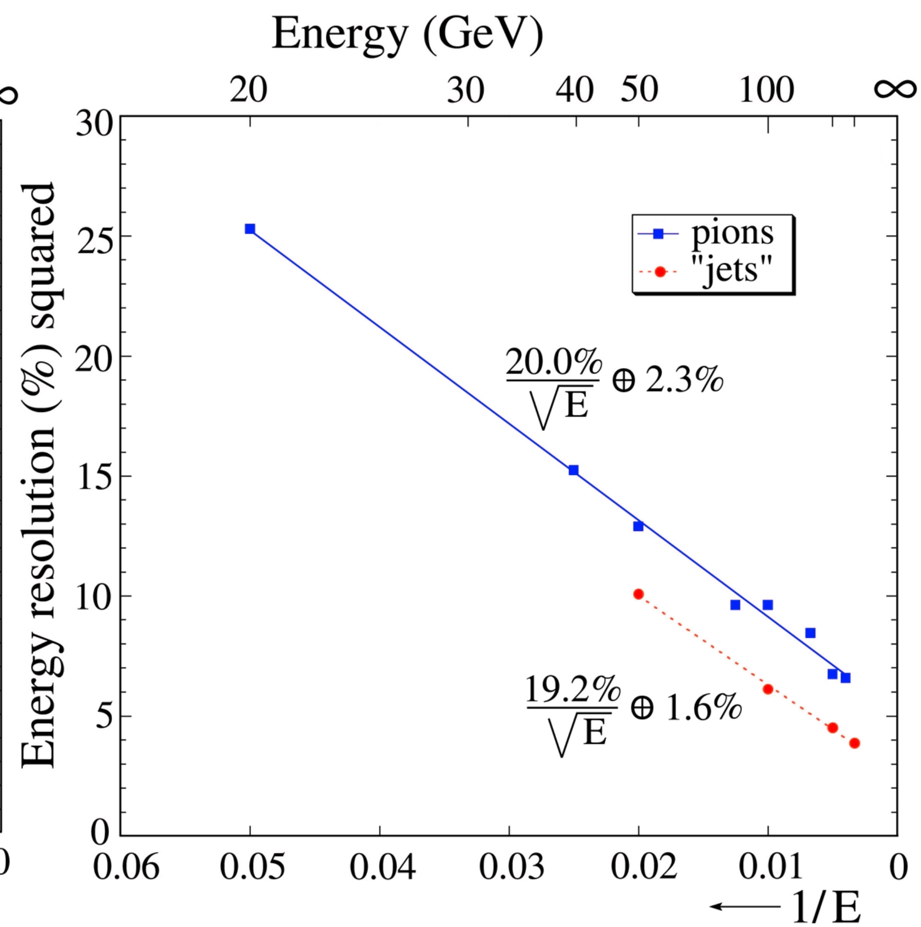


Hadronic resolution: Effect of $\frac{Q+S}{E}$ correction

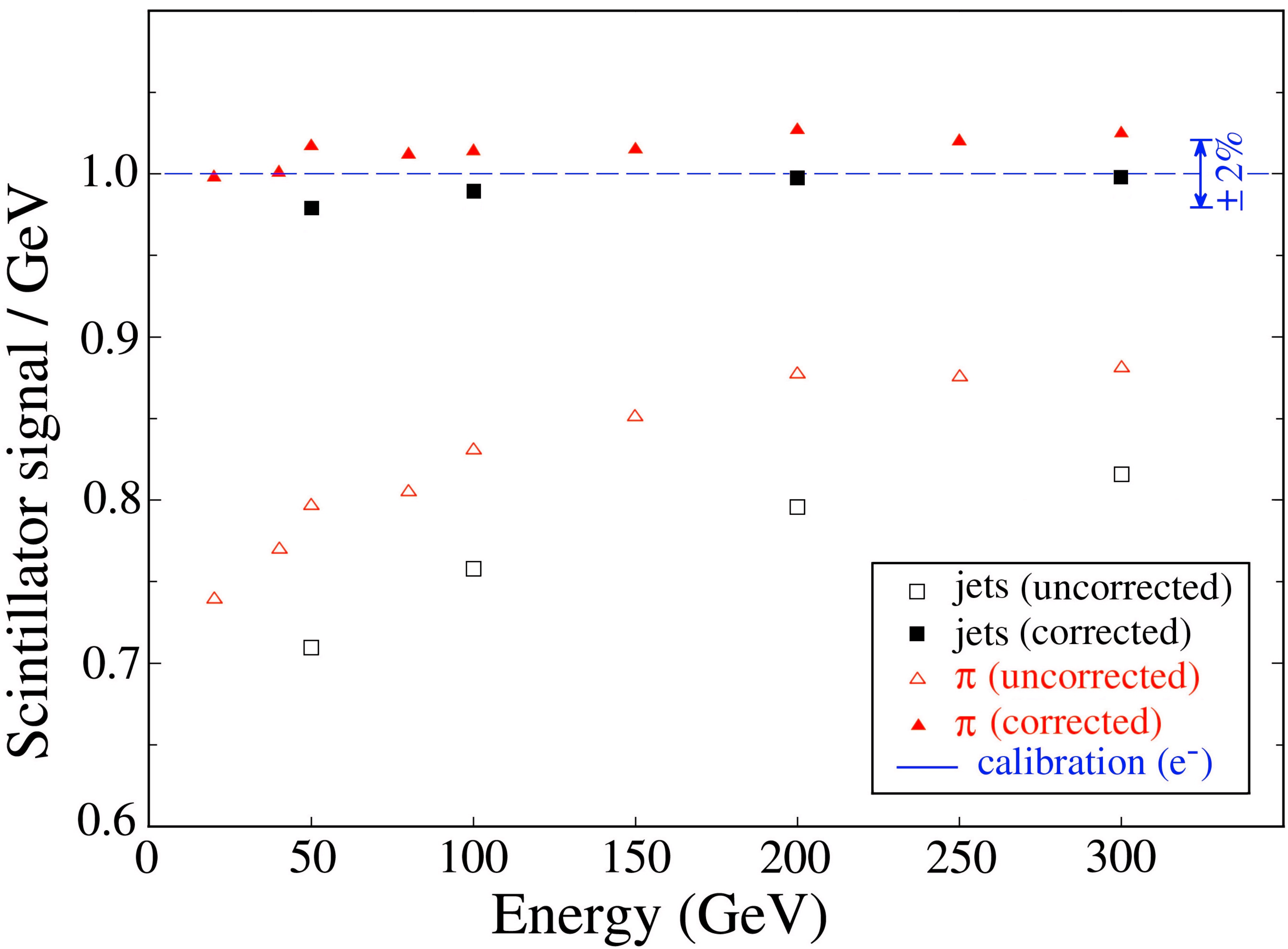


Hadronic resolution: Effect $\frac{Q+S}{E}$ correction





Hadronic response: Effect of $\frac{Q+S}{E}$ correction



On fluctuations and corrections

- Energy resolution determined by
  a) Photoelectron statistics
  b) Sampling fluctuations
  c) Leakage fluctuations
  d) Fluctuations in em shower fraction (f_{em})

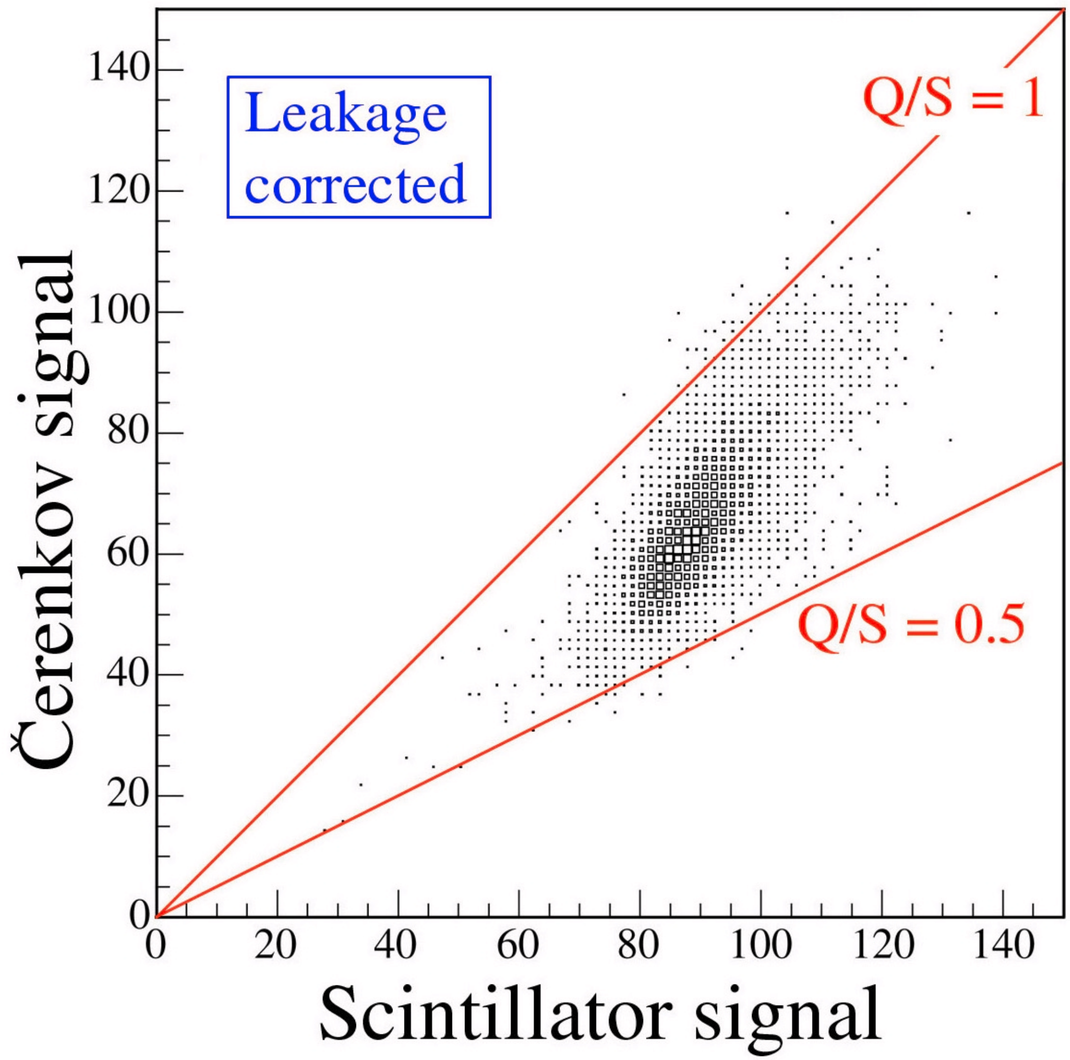
- When we assume knowledge of $E \rightarrow$ leakage fluctuations eliminated

  ➡ **(Q+S)/E** method only leaves contributions from a) and b)

- Energy-independent method: Based on measured **Q/S** signal ratio

  Small detector $\rightarrow$ S signals corrected for side leakage (average 10%)

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



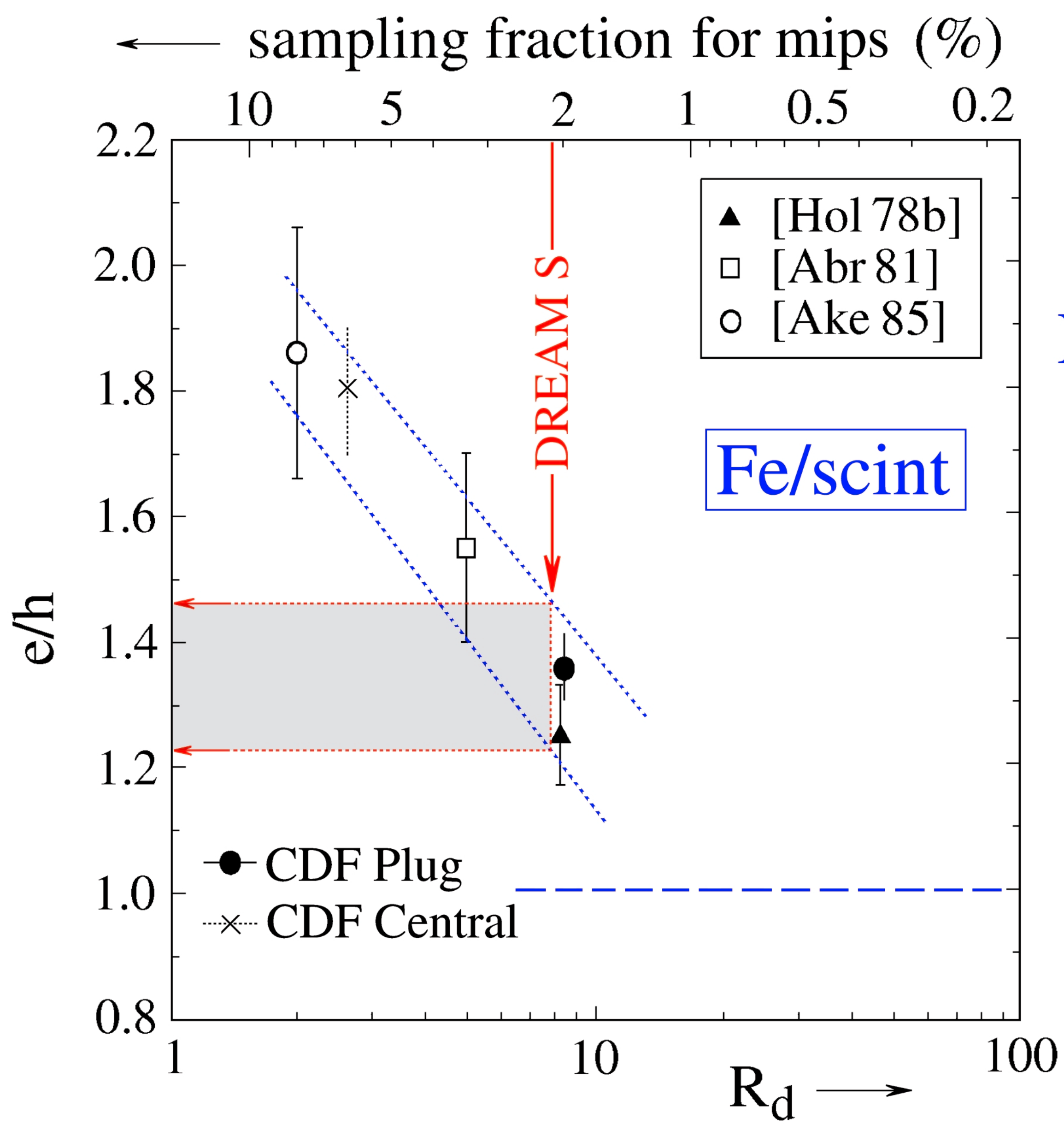
$$S = E\left[f_{\rm em} + \frac{1}{(e/h)_{\rm S}}(1 - f_{\rm em}) \right]$$

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

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

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

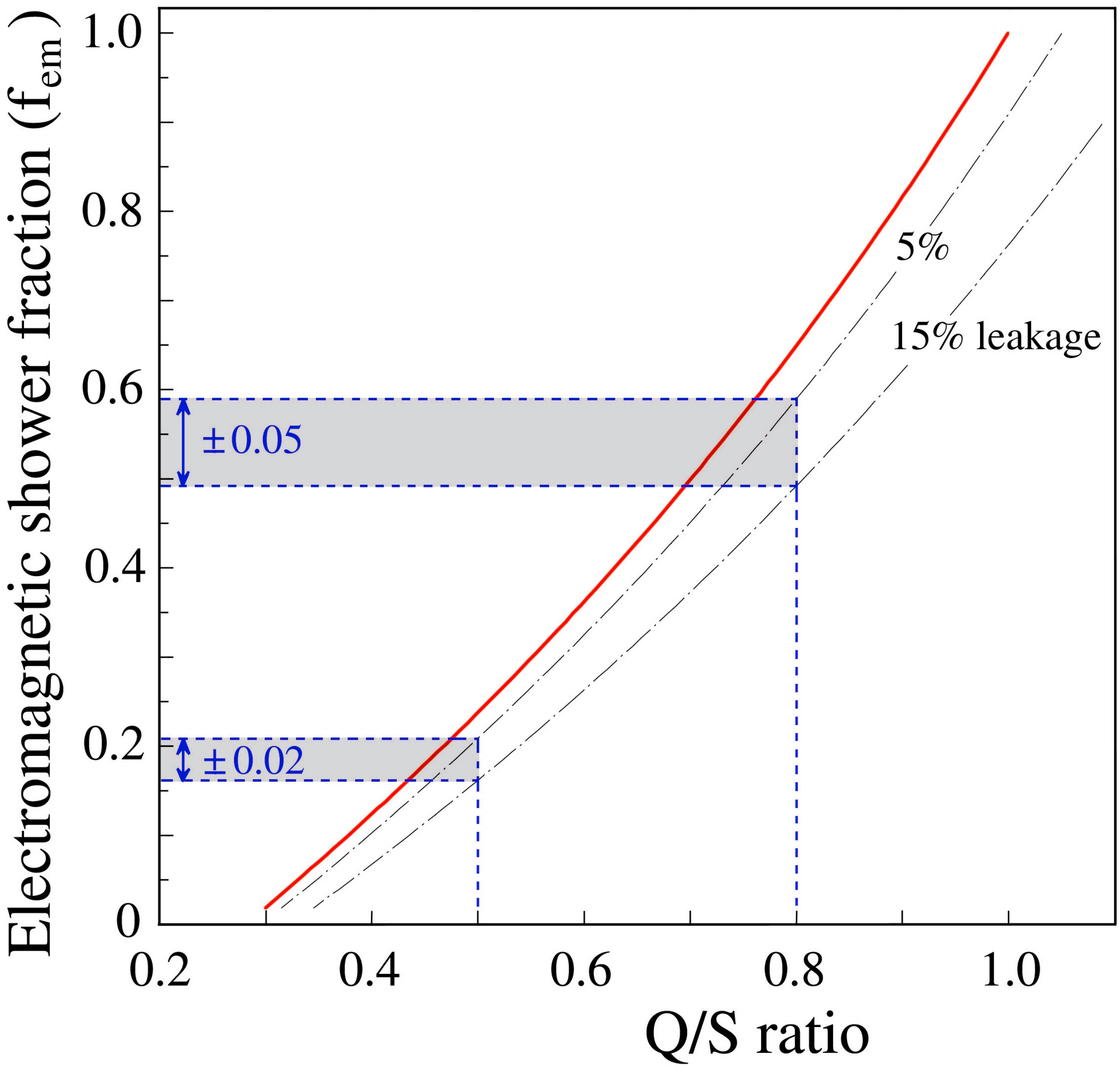
DREAM: estimate e/h in S channel



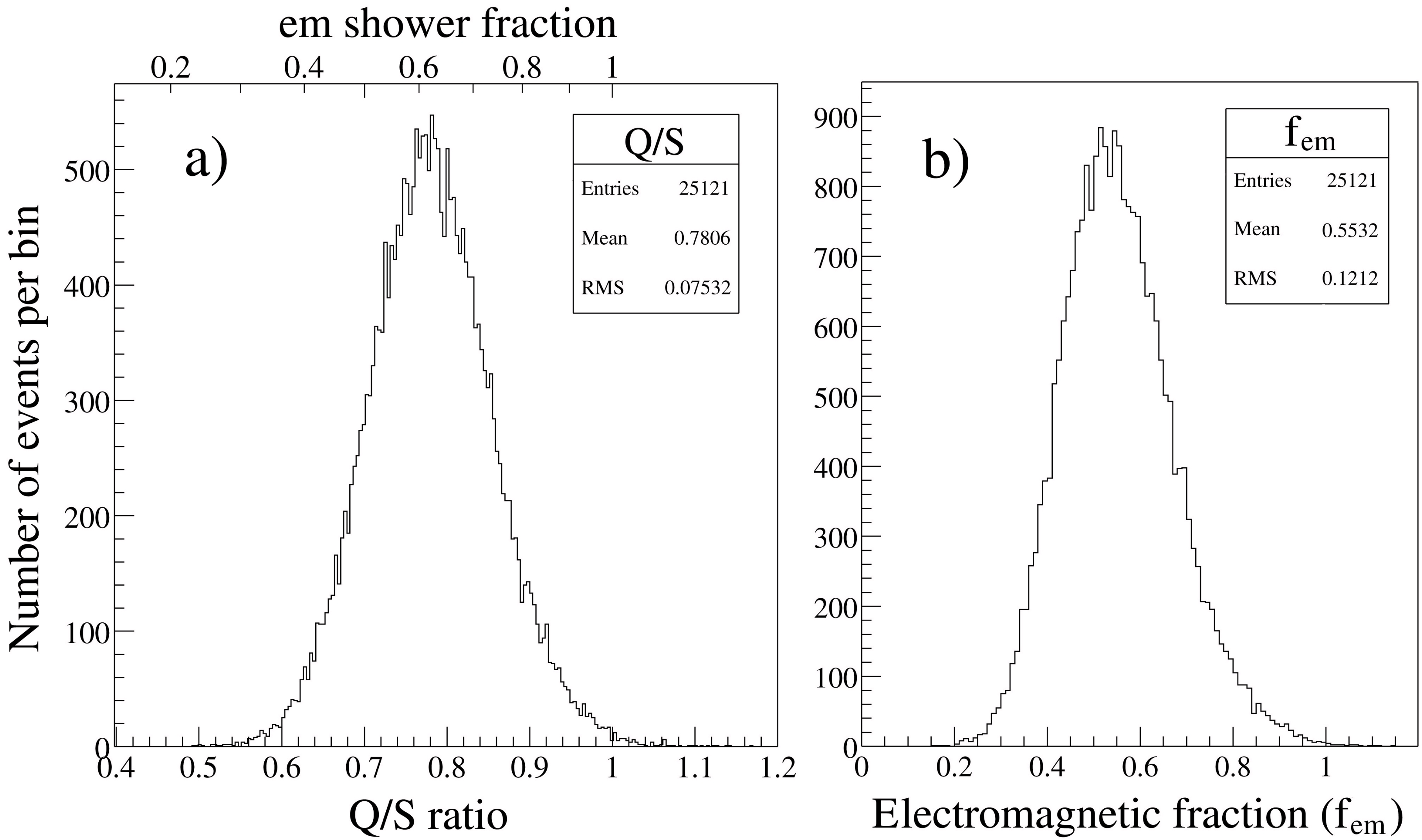
From:

NIM A457 (2002) 381

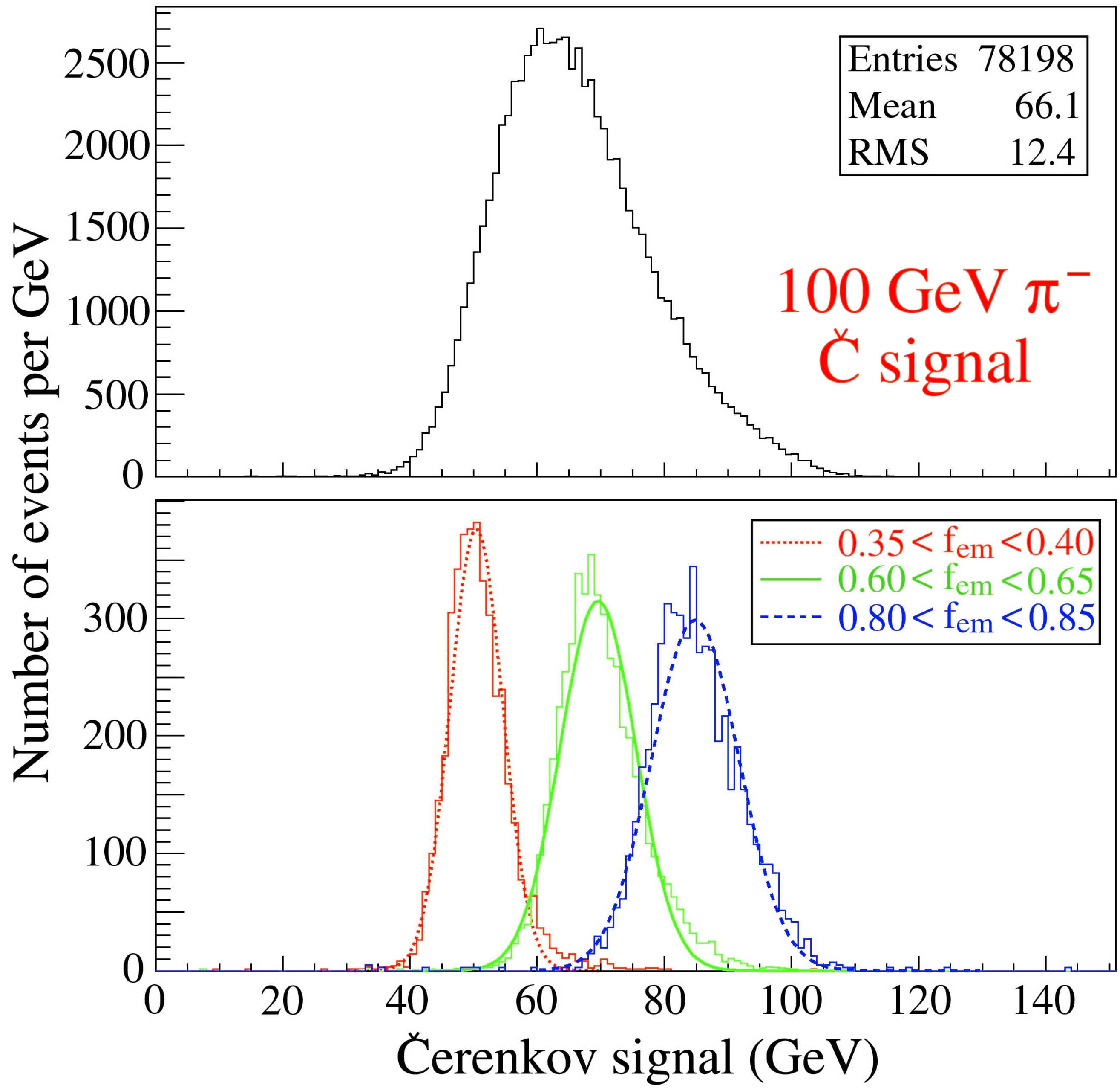
DREAM: Relationship between Q/S and f_{em}



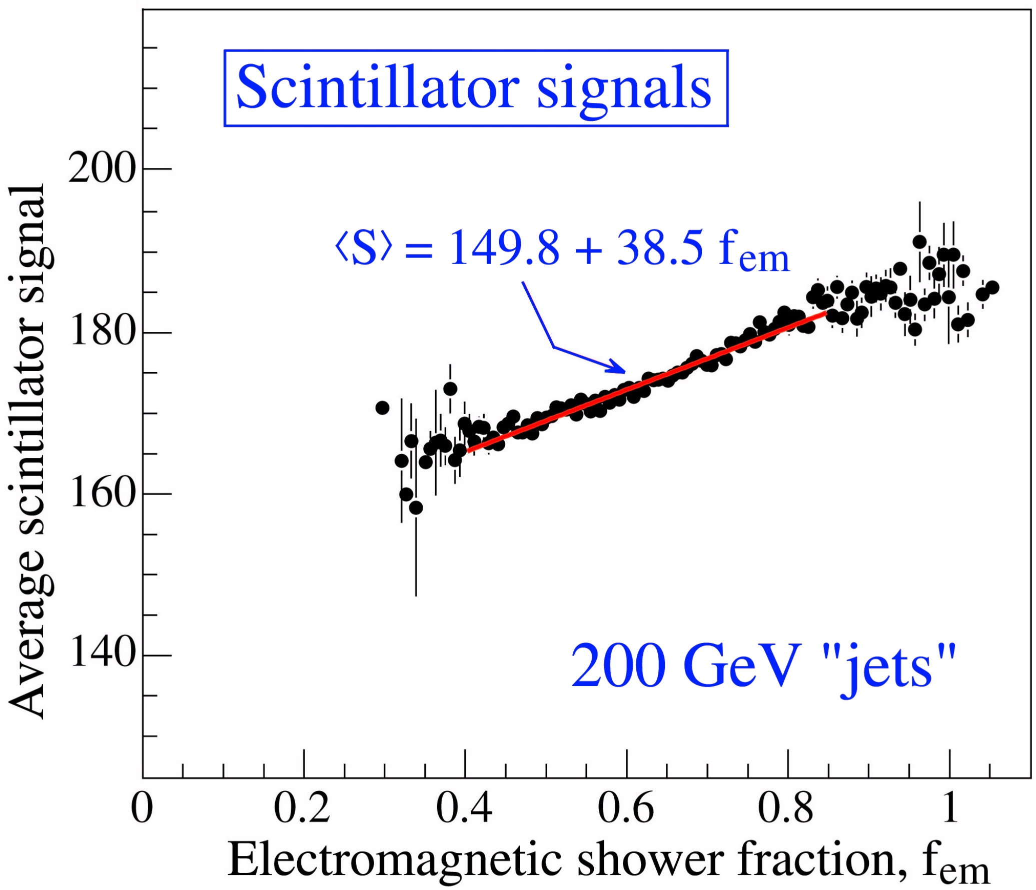
DREAM: relationship between Q/S ratio and f_{em}

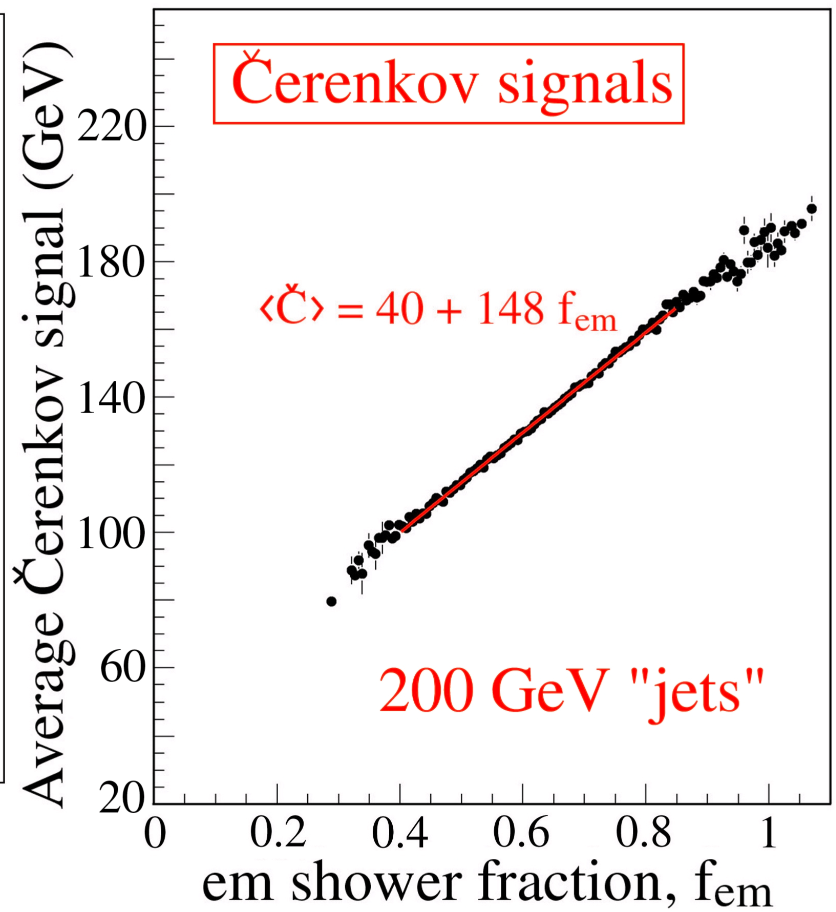


DREAM: Effect of event selection based on f_{em}



DREAM: Signal dependence on f_{em}





Finally, a way to measure *e/h*

The hadronic calorimeter response (average signal per unit energy):

$$R(f_{\rm em}) \;=\; f_{\rm em} \;+\; \frac{1}{e/h}\,(1 - f_{\rm em})$$

Normalized $\rightarrow R = 1$ for electrons.

The (average) signal thus depends on $f_{\rm em}$ as:

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

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

Therefore, the $f_{\rm em}$ dependence of the average signal tells e/h:

DREAM: 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):

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

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

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

- Correction to measured signals (regardless of energy):

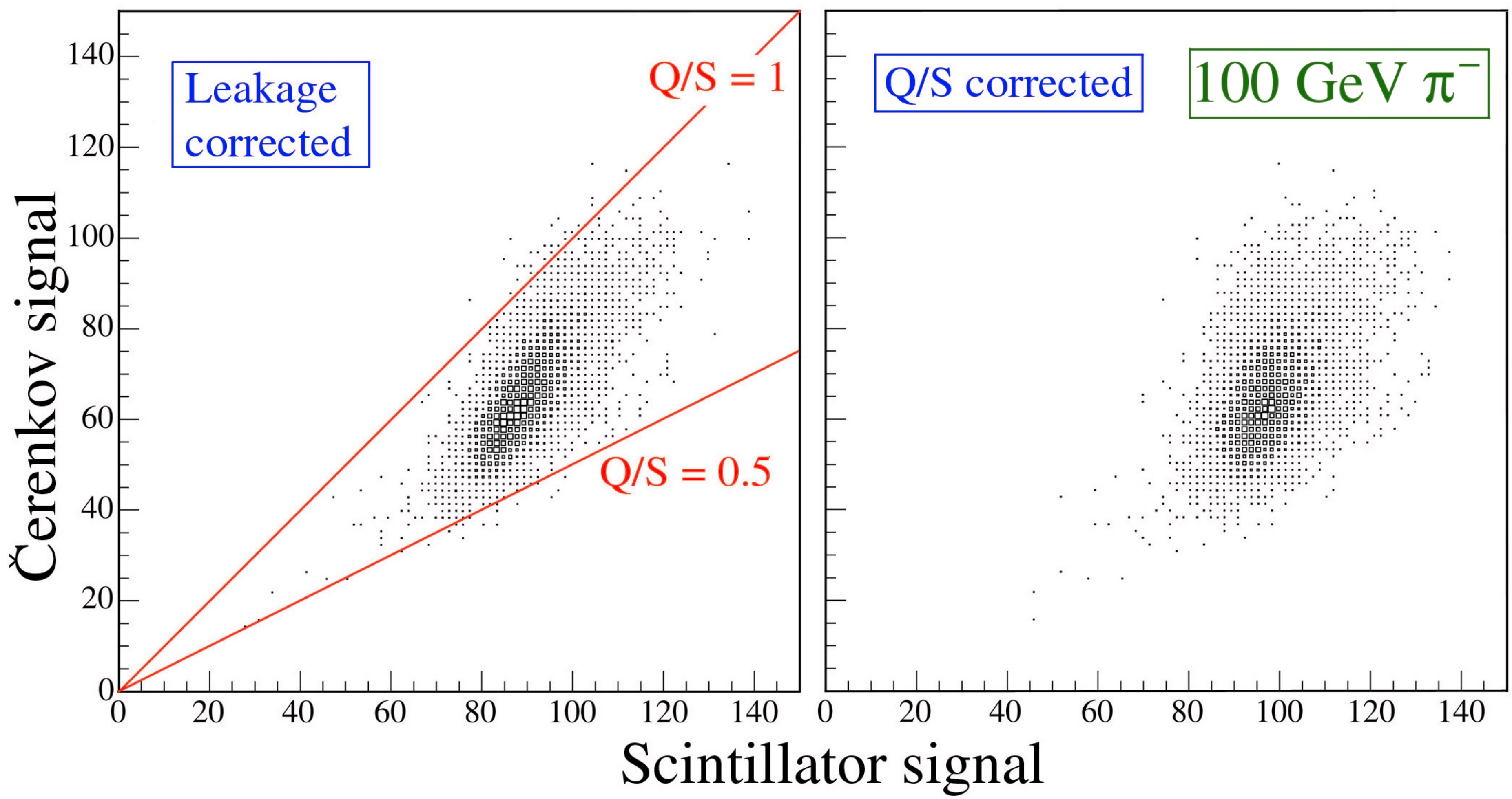
$$S_{\rm corr} \;=\; S_{\rm meas}\left[\frac{1 + p_1/p_0}{1 + f_{\rm em}\cdot p_1/p_0}\right], \qquad \text{with} \quad \frac{p_1}{p_0} \;=\; (e/h)_S \;-\; 1$$

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

DREAM: Hadronic corrections on the basis of Q/S

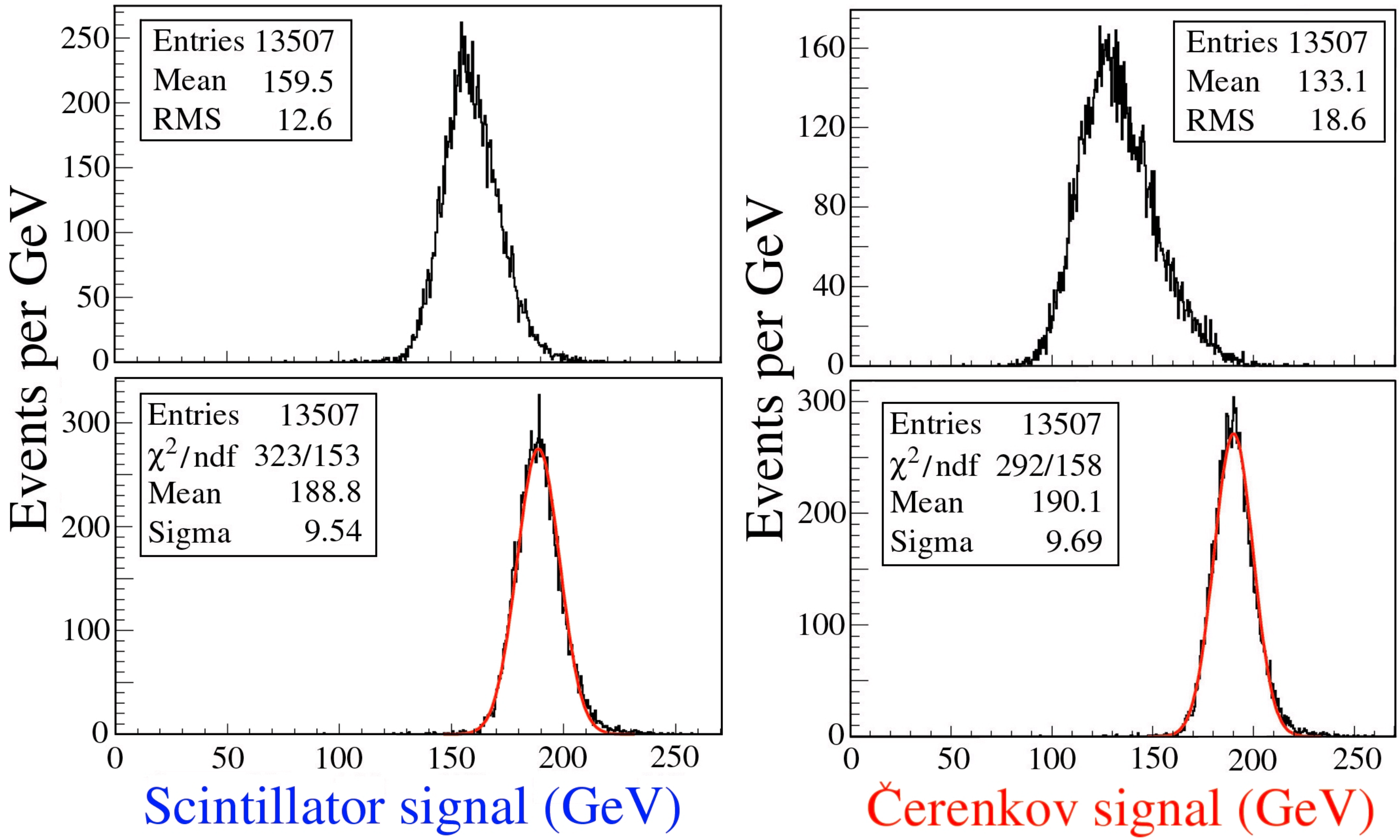
$$\frac{Q}{S} = \frac{f_{\rm em} + 0.20\,(1 - f_{\rm em})}{f_{\rm em} + 0.77\,(1 - f_{\rm em})}$$

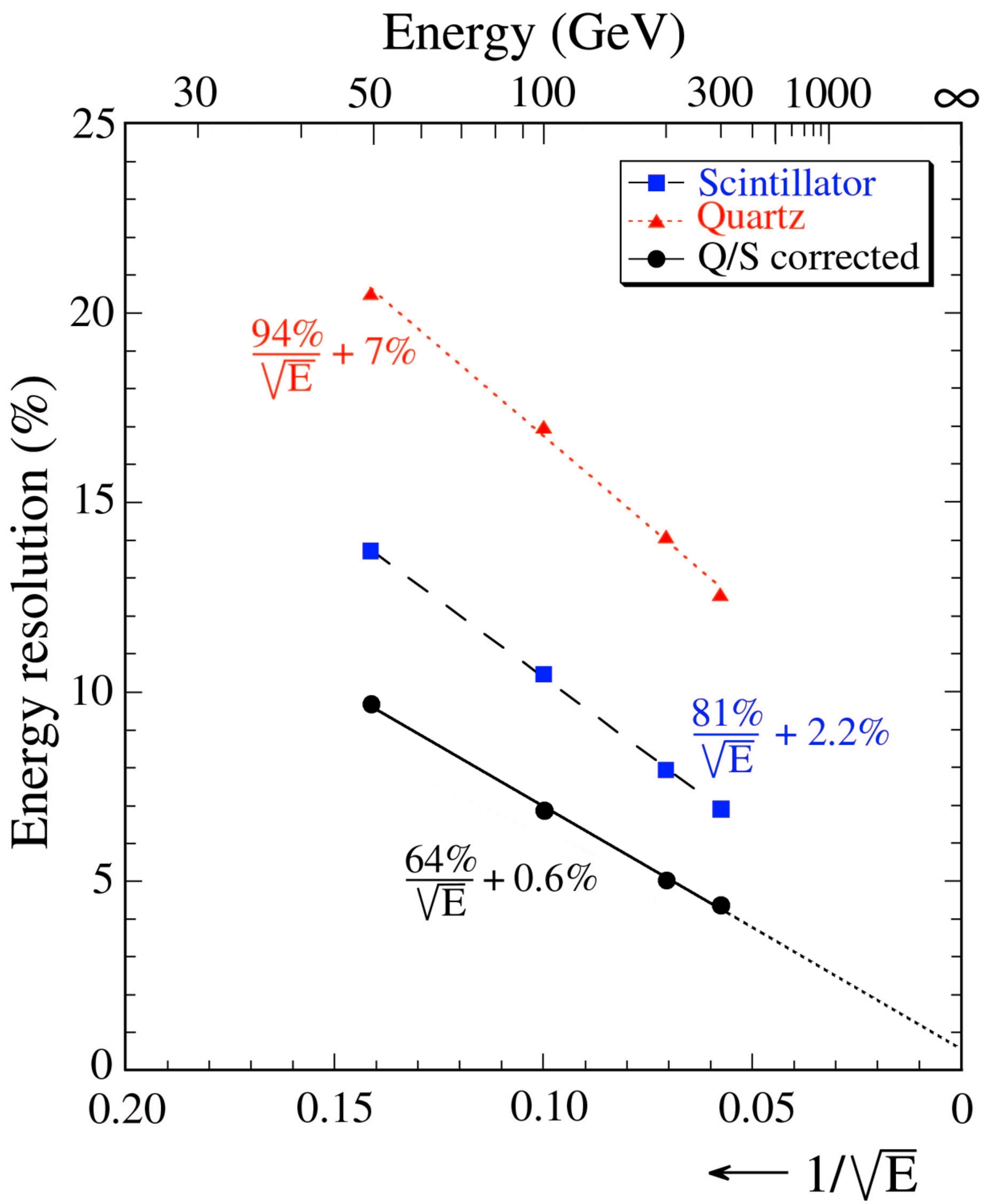
$$S_{\rm corr} = S_{\rm meas}\left[\frac{1 + p_1/p_0}{1 + f_{\rm em}\cdot p_1/p_0}\right] \quad \text{with} \quad \frac{p_1}{p_0} = \frac{e}{h} - 1$$



DREAM: Effect of Q/S based corrections

(200 GeV "jets")

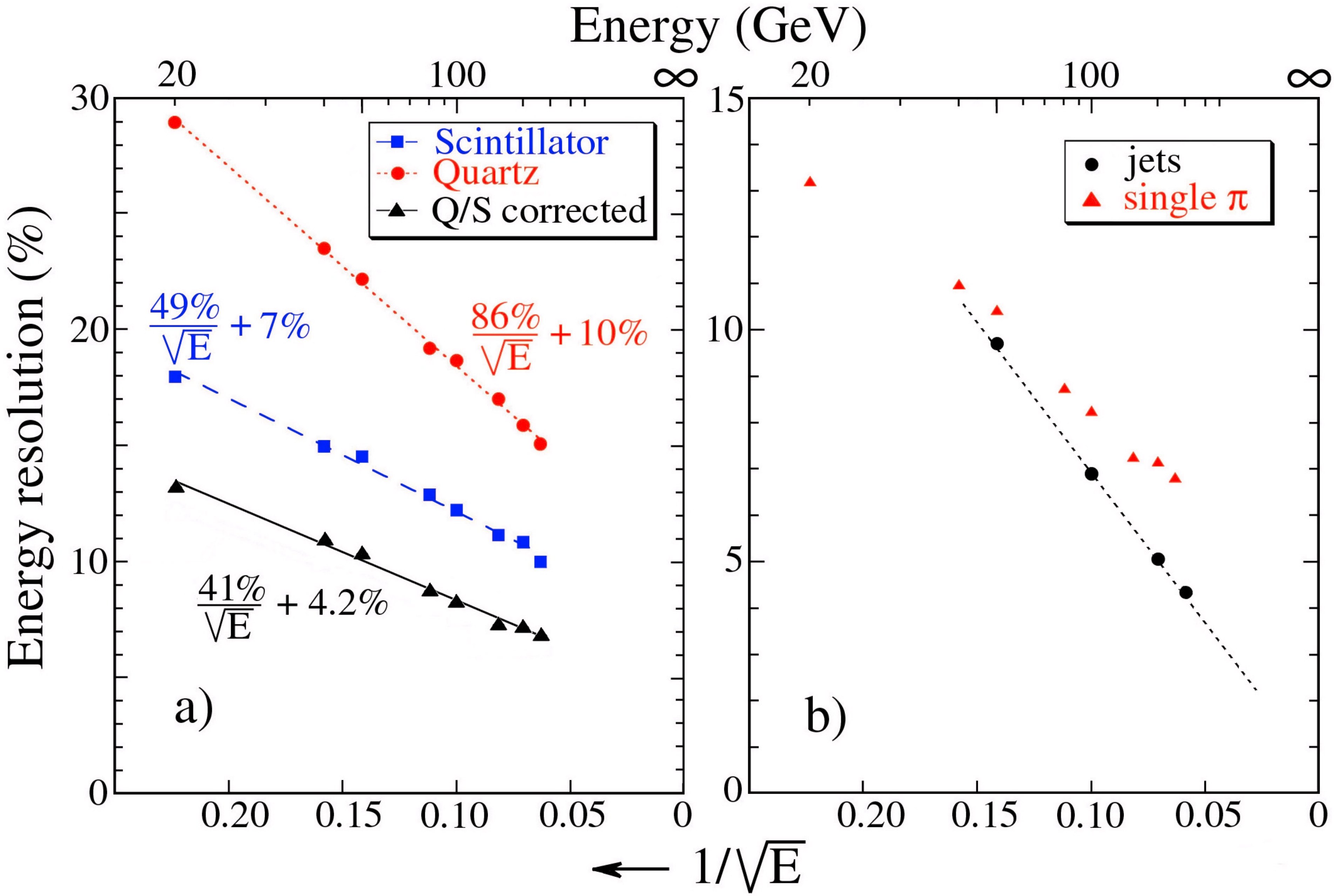




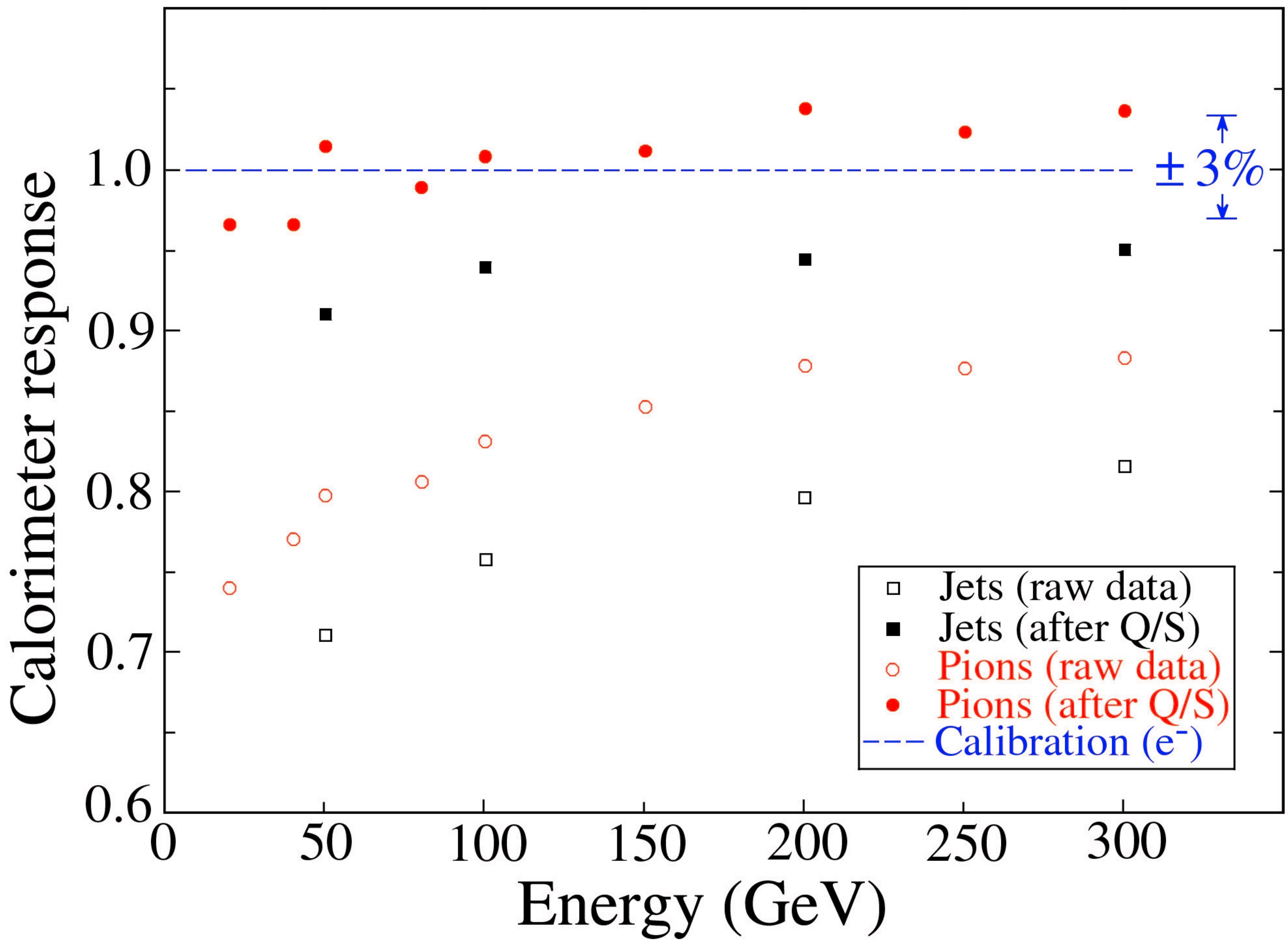
DREAM

Energy resolution "jets"

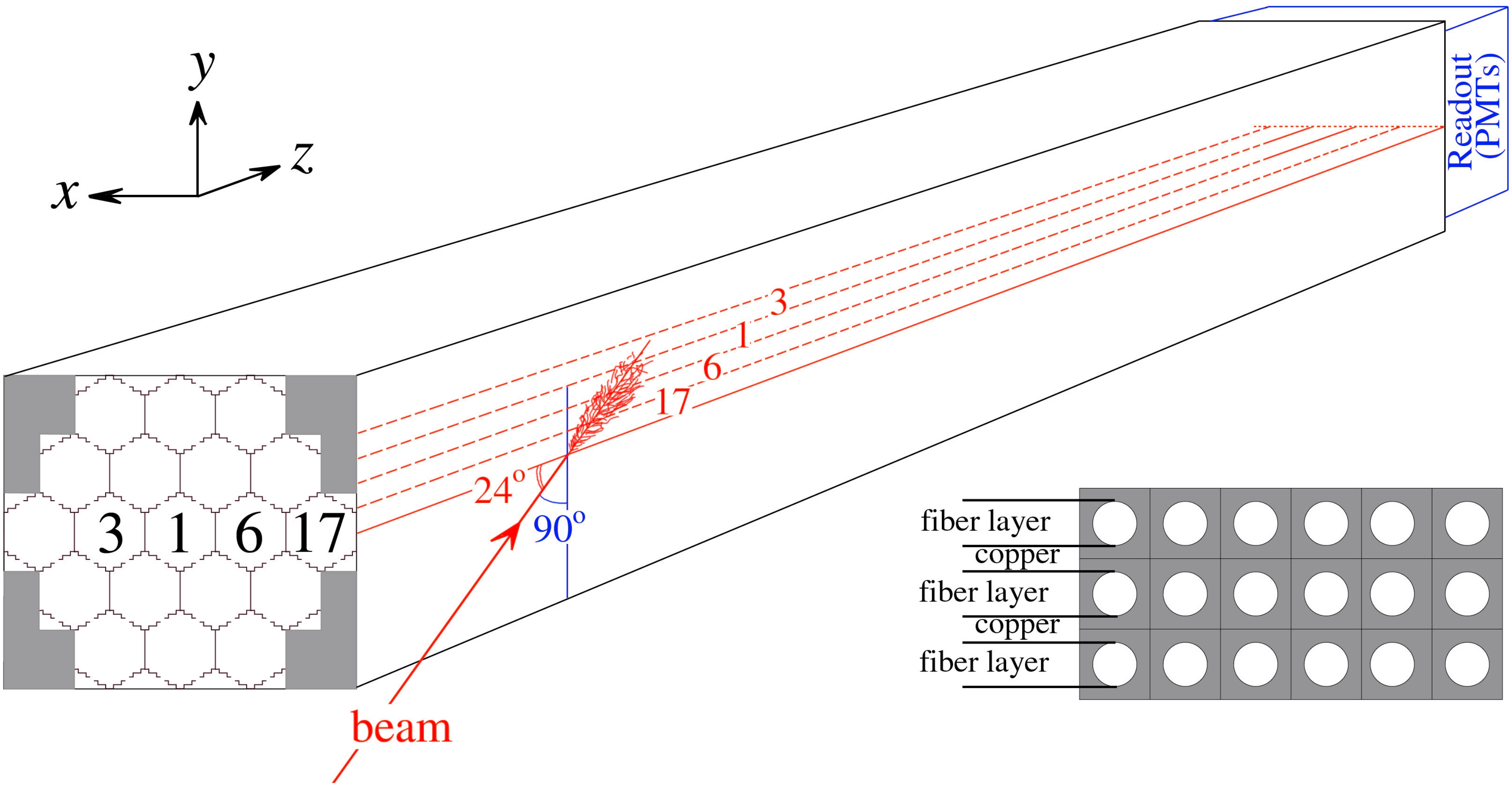
Energy resolution pions: Effect Q/S correction



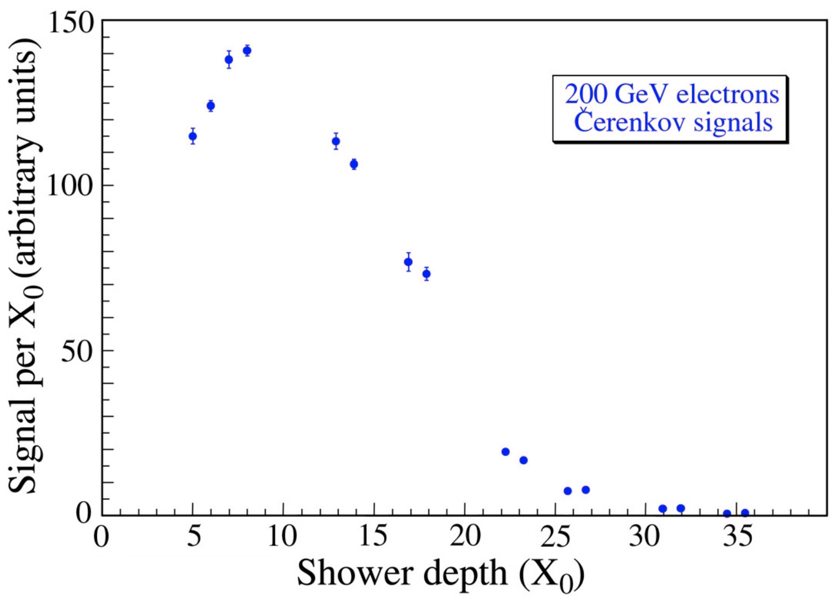
Hadronic response: Effect Q/S correction

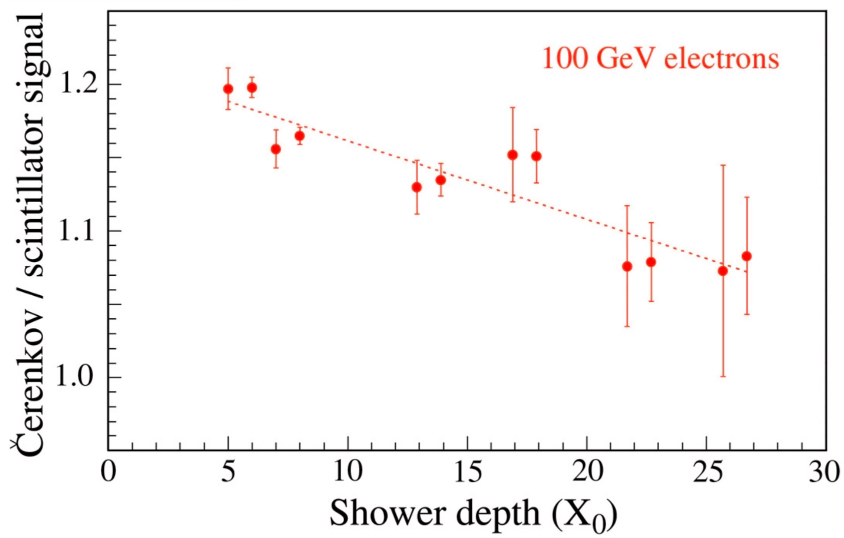


DREAM: z-scan position

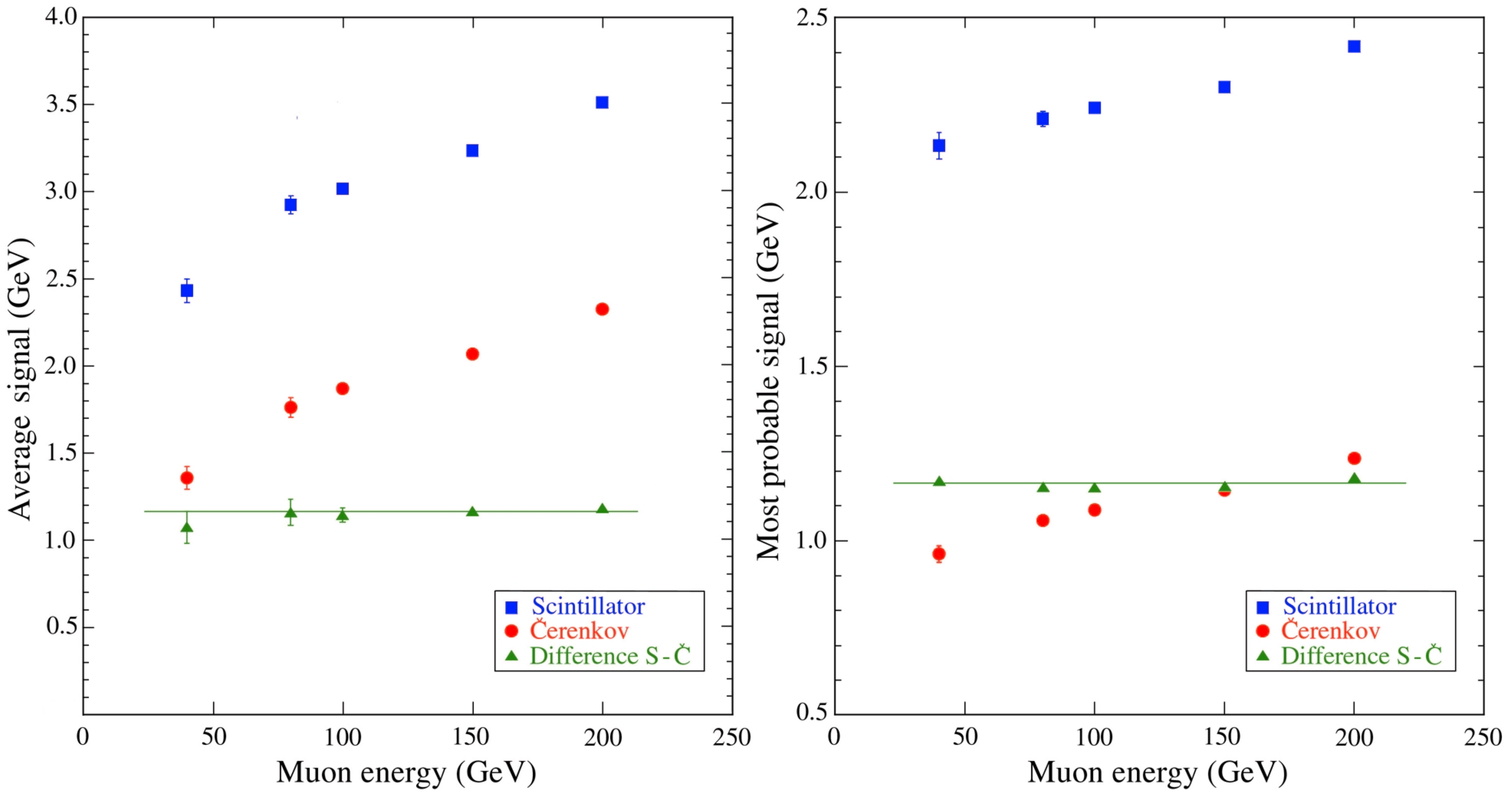


DREAM - Longitudinal EM shower profile

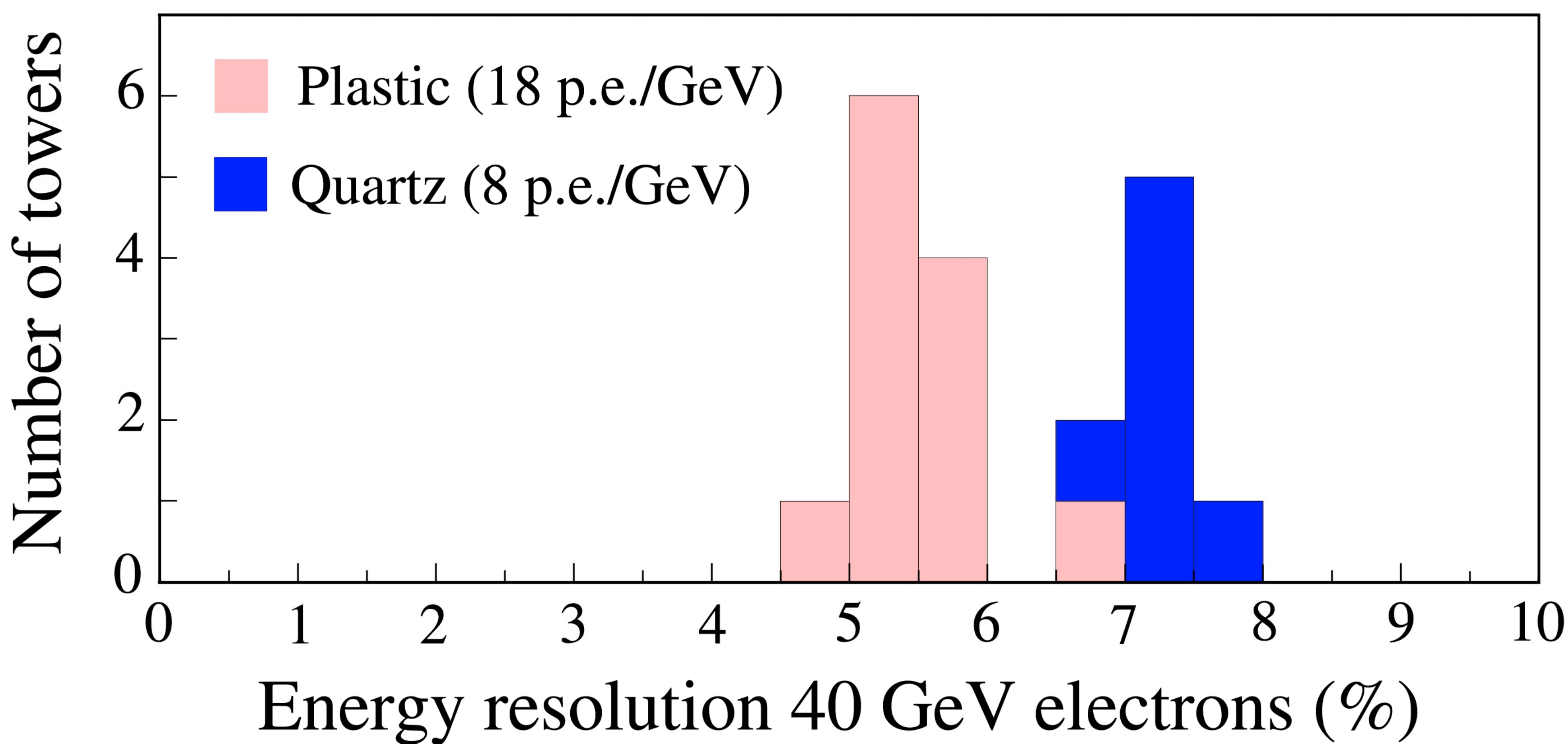




Muon signals in the DREAM calorimeter



Čerenkov fibers: Quartz vs. plastic



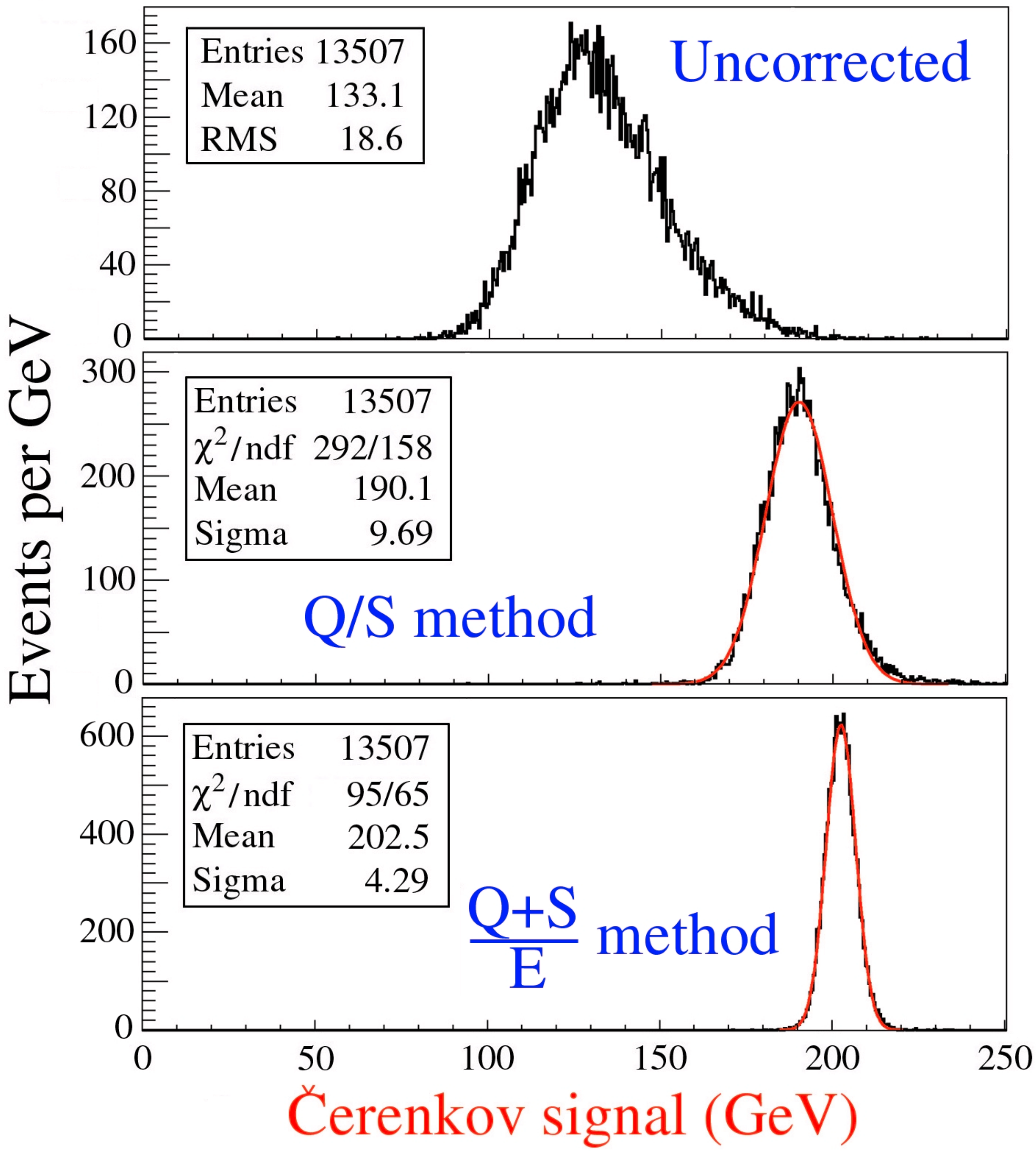
CONCLUSIONS

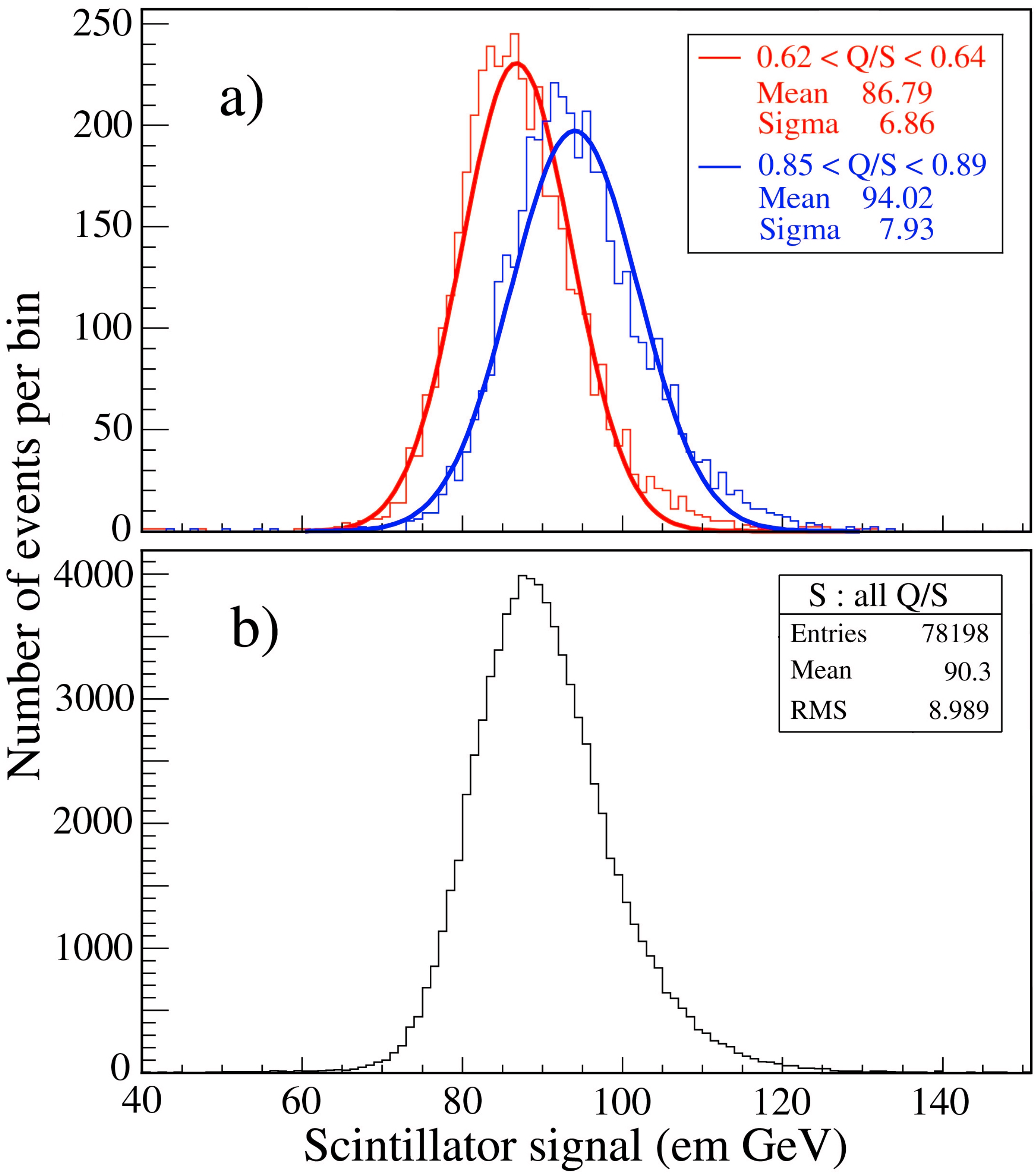
- DREAM offers a powerful technique to improve hadronic calorimeter performance:
  - Correct hadronic energy reconstruction, in an instrument calibrated with electrons!
  - Linearity for hadrons and jets
  - Gaussian response functions
  - Energy resolution scales with $1/\sqrt{E}$
  - $\sigma/E < 5\%$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

- Next logical step: *Separate scintillation from Čerenkov light in one medium producing both*
  - *Tools*: time structure signals, optical spectra, polarization, directionality, ...

- If this works:
  - Use DREAM in combination with crystal em calorimeter as excellent jet detector
  - *Remember*: Typically, $\sim$ half of jet energy ends up in em section, with huge fluctuations

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



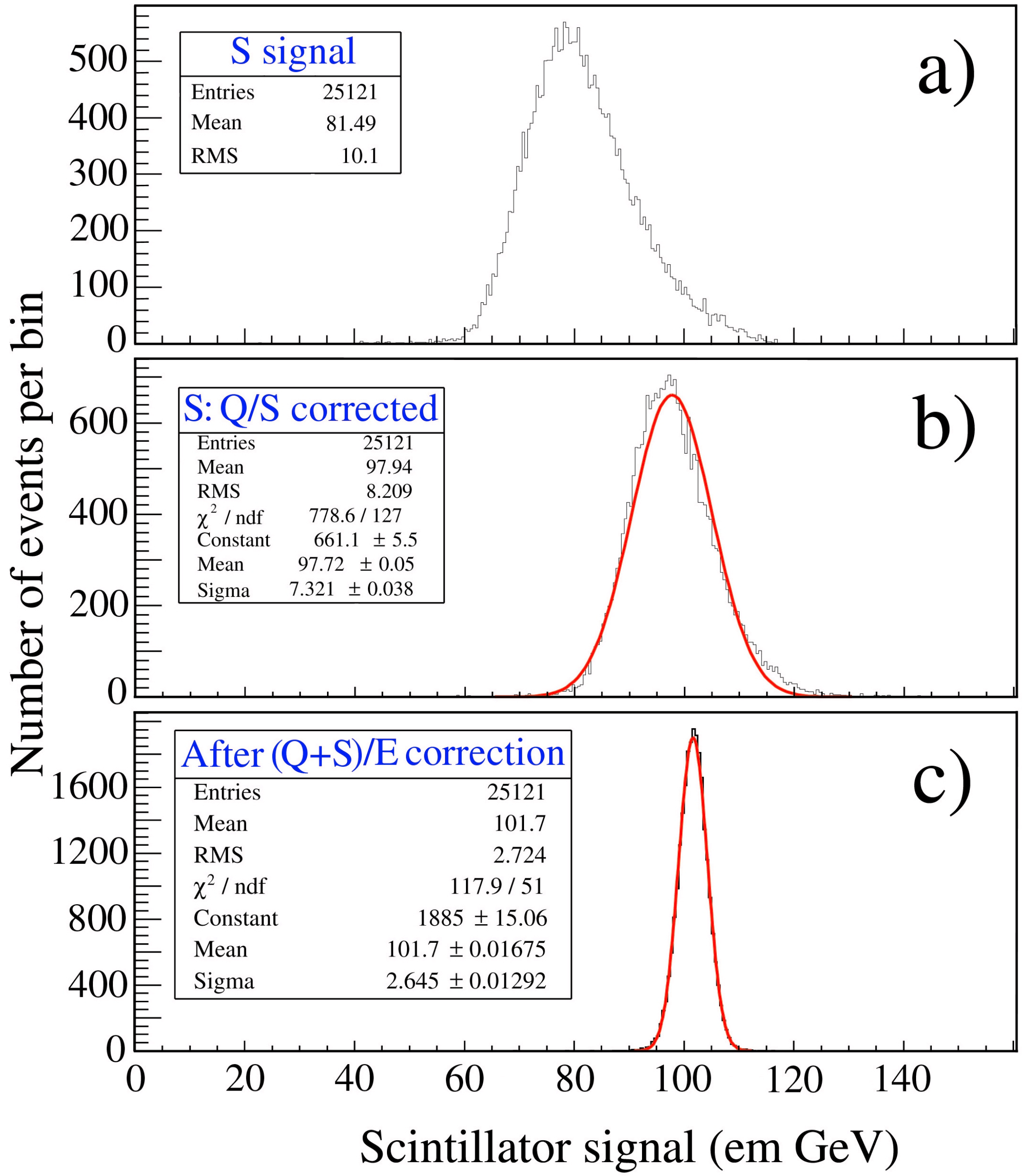


DREAM

Signal distributions for different Q/S bins

DREAM

Effects corrections on signal distributions



Saturation in "digital" calorimeters (wire chamber readout)

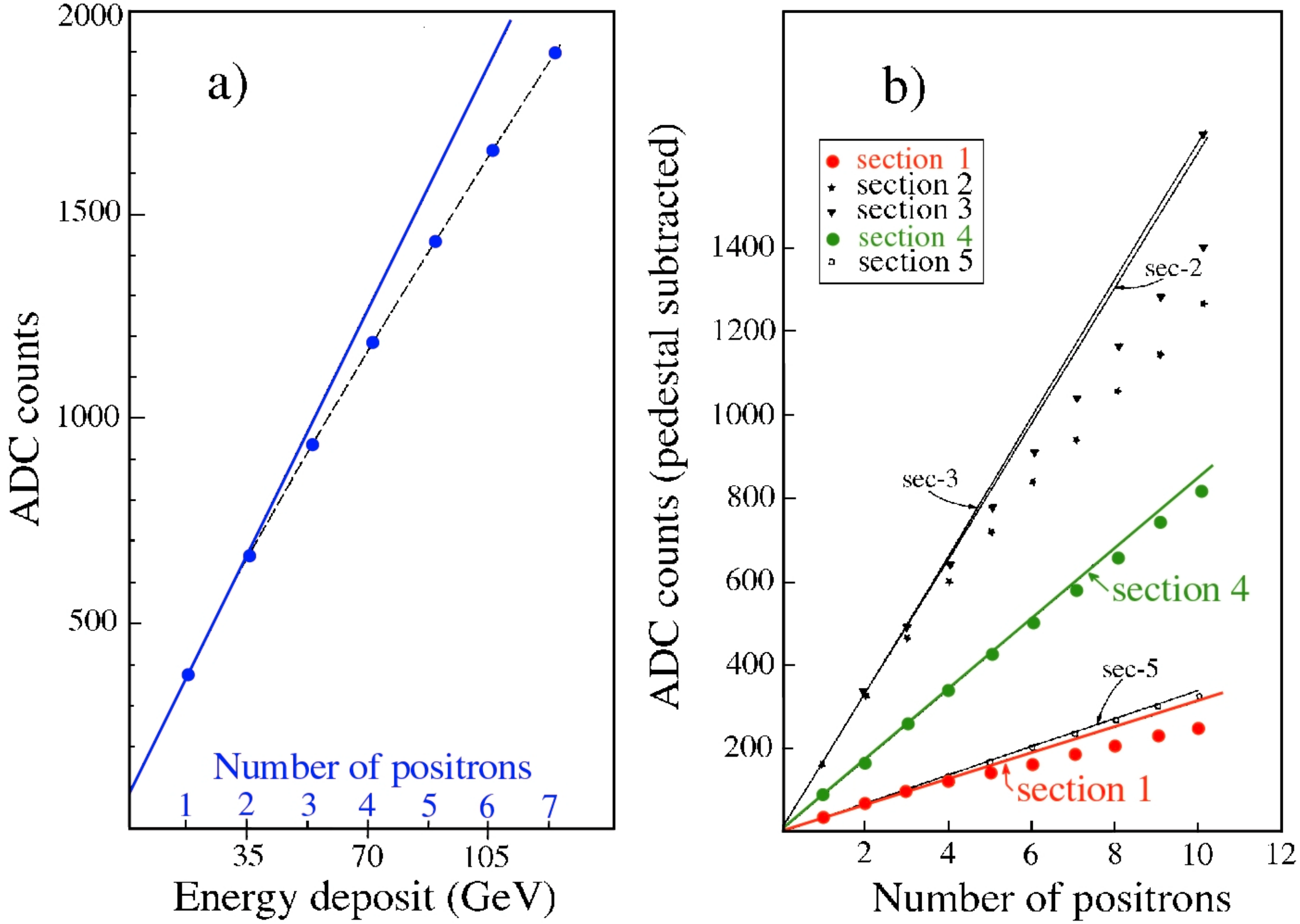


FIG. 3.2. Average em shower signal from a calorimeter read out with gas chambers operating in a "saturated avalanche" mode, as a function of energy. From: NIM 205 (1983) 113.