CALORIMETRY

The challenges of future experiments

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CERN, March 15, 2006

Outline:

- A brief history
- Challenges of future experiments (LHC/SLHC, ILC/CLIC)
- Possible solutions / Lessons from the past
- Recent R&D results

A brief history

of design philosophy in particle physics experiments

- $\lesssim$ 1970: Bubble Chamber Era : *Target ≡ 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"

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

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

- $\gtrsim$ 2000: Return to the past? Particle Flow Analysis

  Use tracking, particle ID and calorimeter information
  to measure 4-vectors of jets

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

Important calorimeter features

- Energy resolution
- Position resolution (need 4-vectors for physics)
- Signal speed
- Particle ID capability

The importance of (hadronic) energy resolution

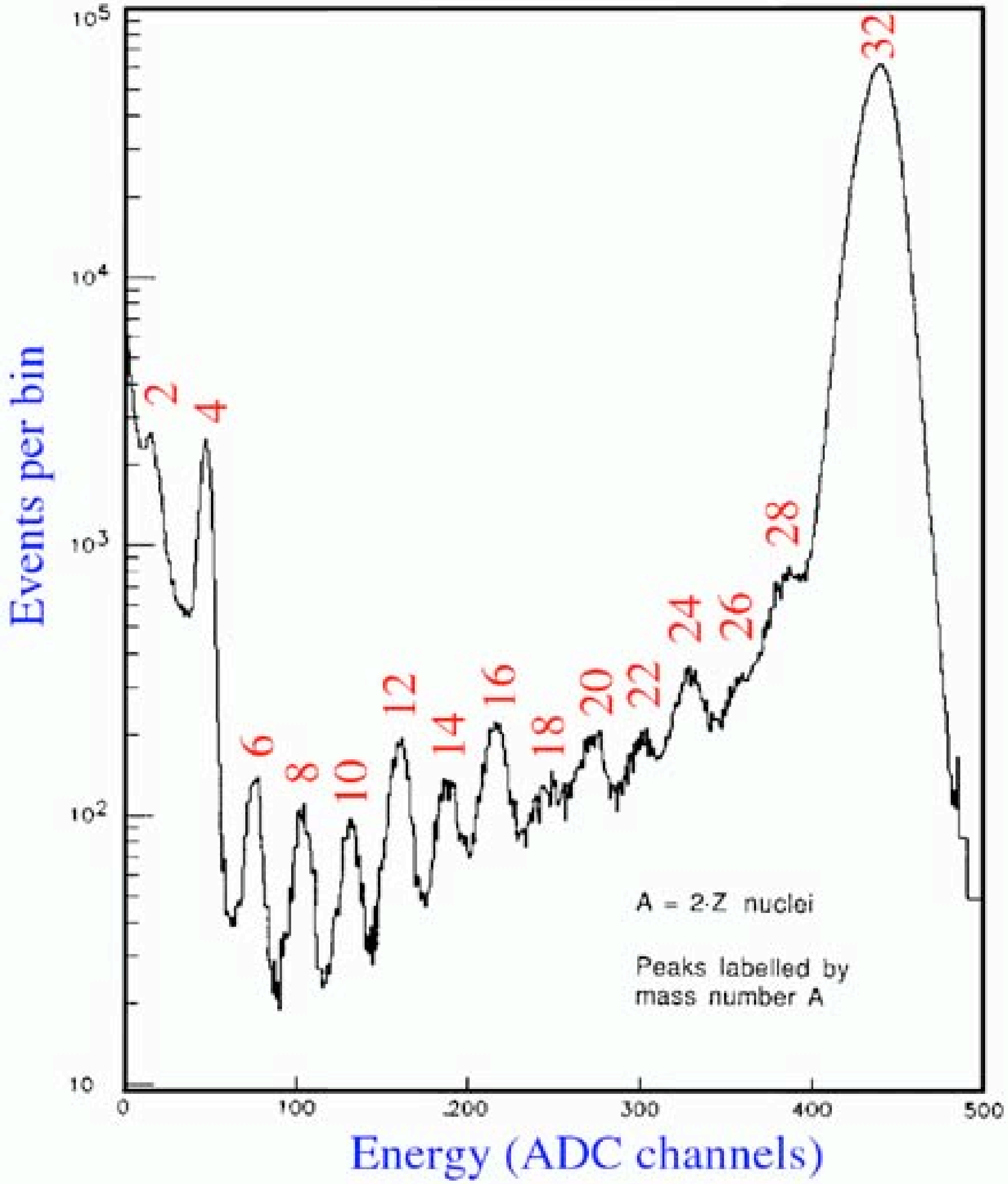


FIG. 7.51. The WA80 calorimeter as a high-resolution spectrometer. Total energy measured with the calorimeter for minimum-bias events revealed the composition of the momentum-selected CERN heavy-ion beam [You 89].

The importance of (hadronic) energy resolution (2)

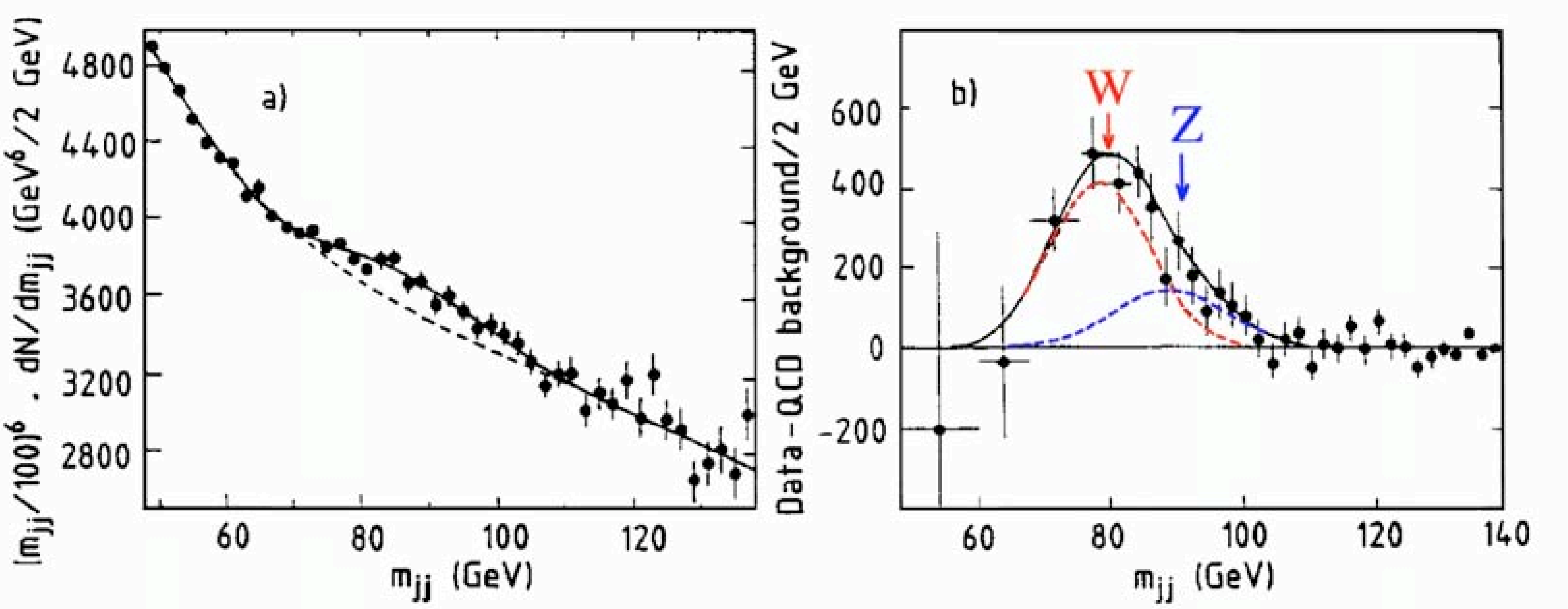


FIG. 7.50. Two-jet invariant mass distributions from the UA2 experiment [Alit 91]. Diagram a) shows the measured data points, together with the results of the best fits to the QCD background alone (*dashed curve*), or including the sum of two Gaussian functions describing $W, Z \rightarrow q\bar{q}$ decays. Diagram b) shows the same data after subtracting the QCD background. The data are compatible with peaks at $m_W = 80$ GeV and $m_Z = 90$ GeV. The measured width of the bump, or rather the standard deviation of the mass distribution, was 8 GeV, of which 5 GeV could be attributed to non-ideal calorimeter performance [Jen 88].

The importance of signal speed

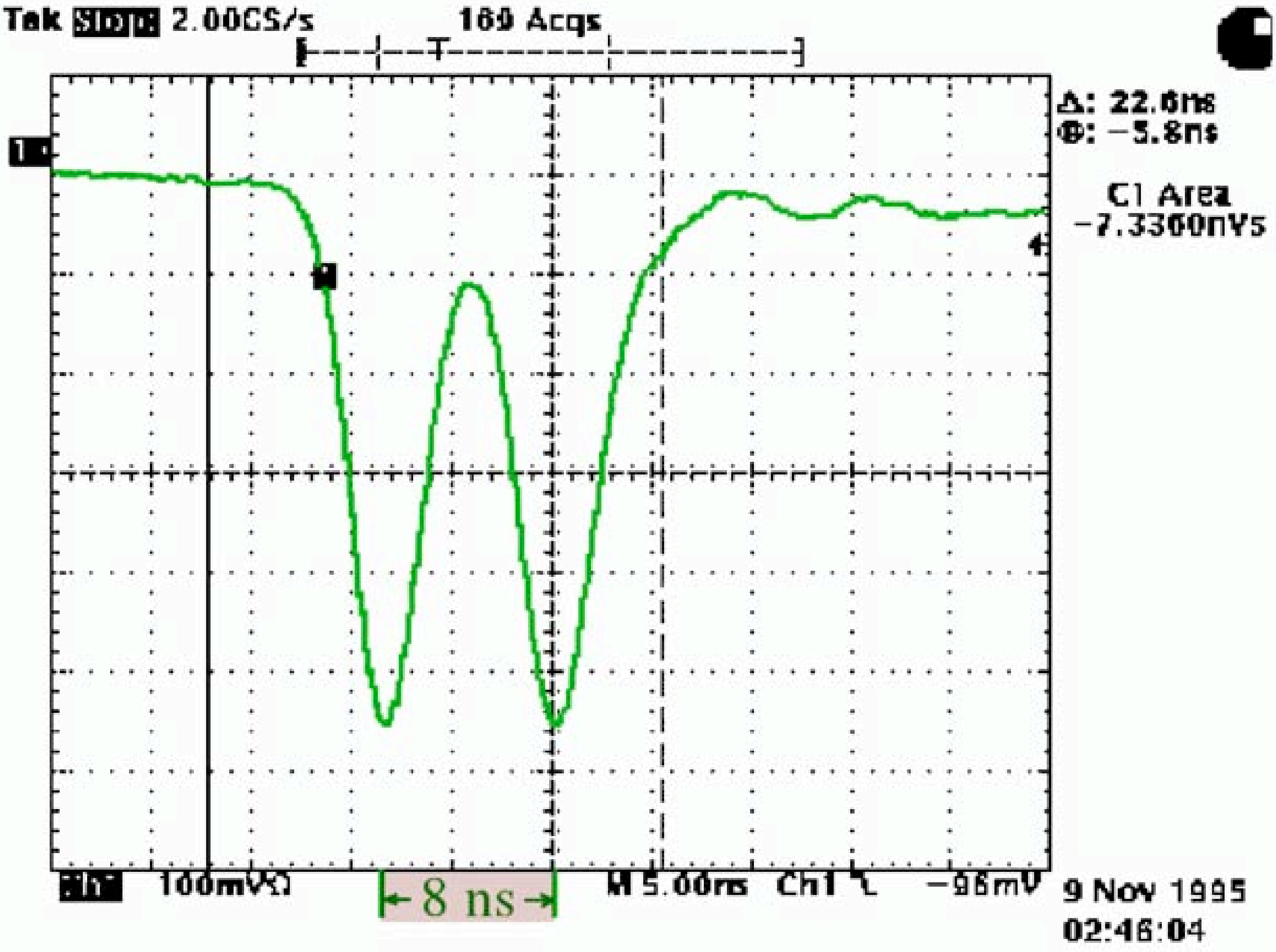


FIG. 7.19. Oscilloscope picture of two events separated by 8 ns in the Zero Degree Quartz Fiber Calorimeter of the NA50 experiment in the CERN heavy-ion beam [Arn 98].

Particle ID does NOT require segmentation!

e/π separation using time structure signals

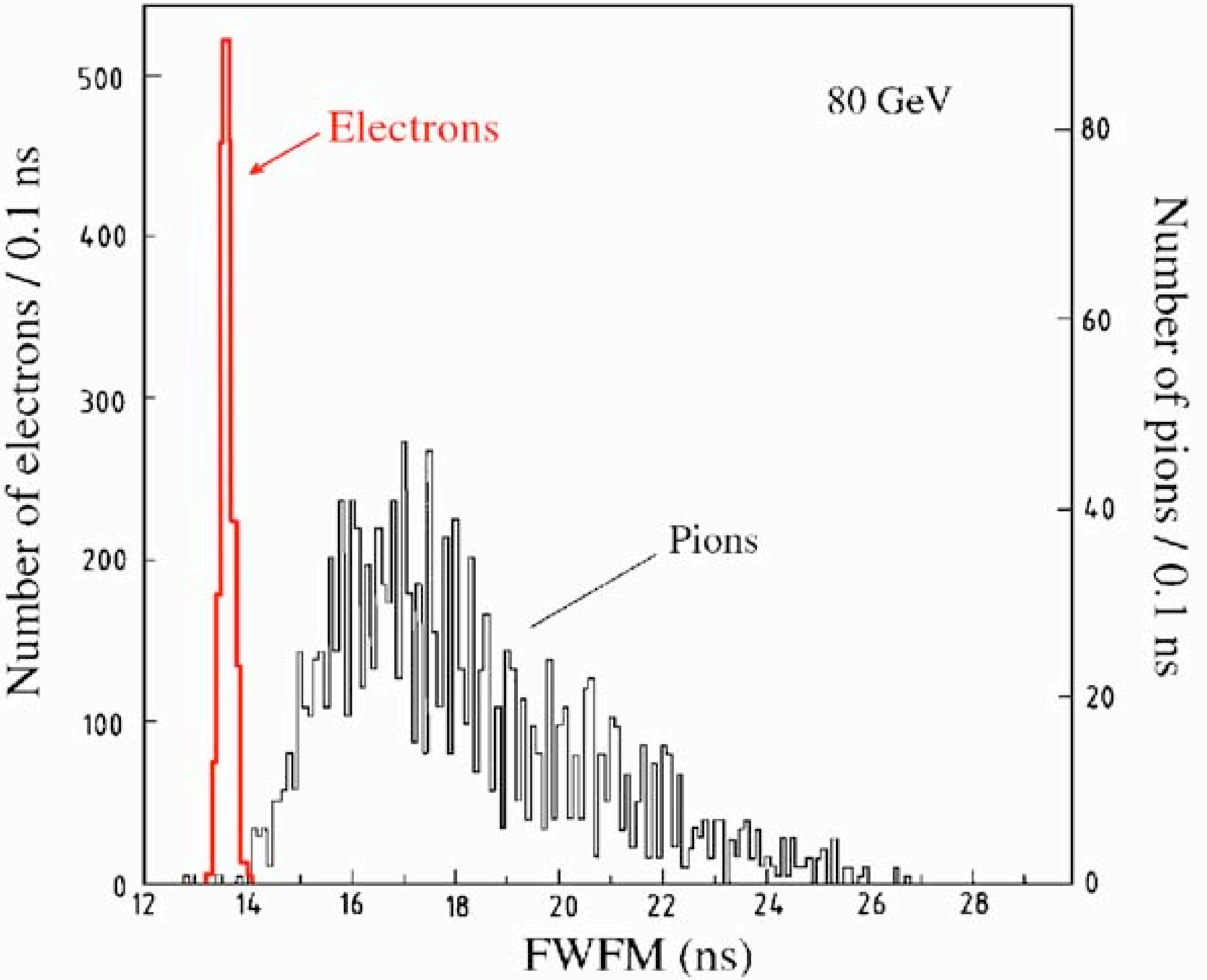


FIG. 7.33. The distribution of the full width at one-fifth maximum (FWFM) for 80 GeV electron and pion signals in SPACAL [Aco 91a].

Important calorimeter features

- Energy resolution
- Position resolution (need 4-vectors for physics)
- Signal speed
- Particle ID capability

but also

- *Gaussian response function* (avoid bias for steeply falling distributions)
- *Signal linearity*, or at least
- Well known relationship between signal & energy *(reliable calibration)*

Most hadron calorimeters fall short in this respect

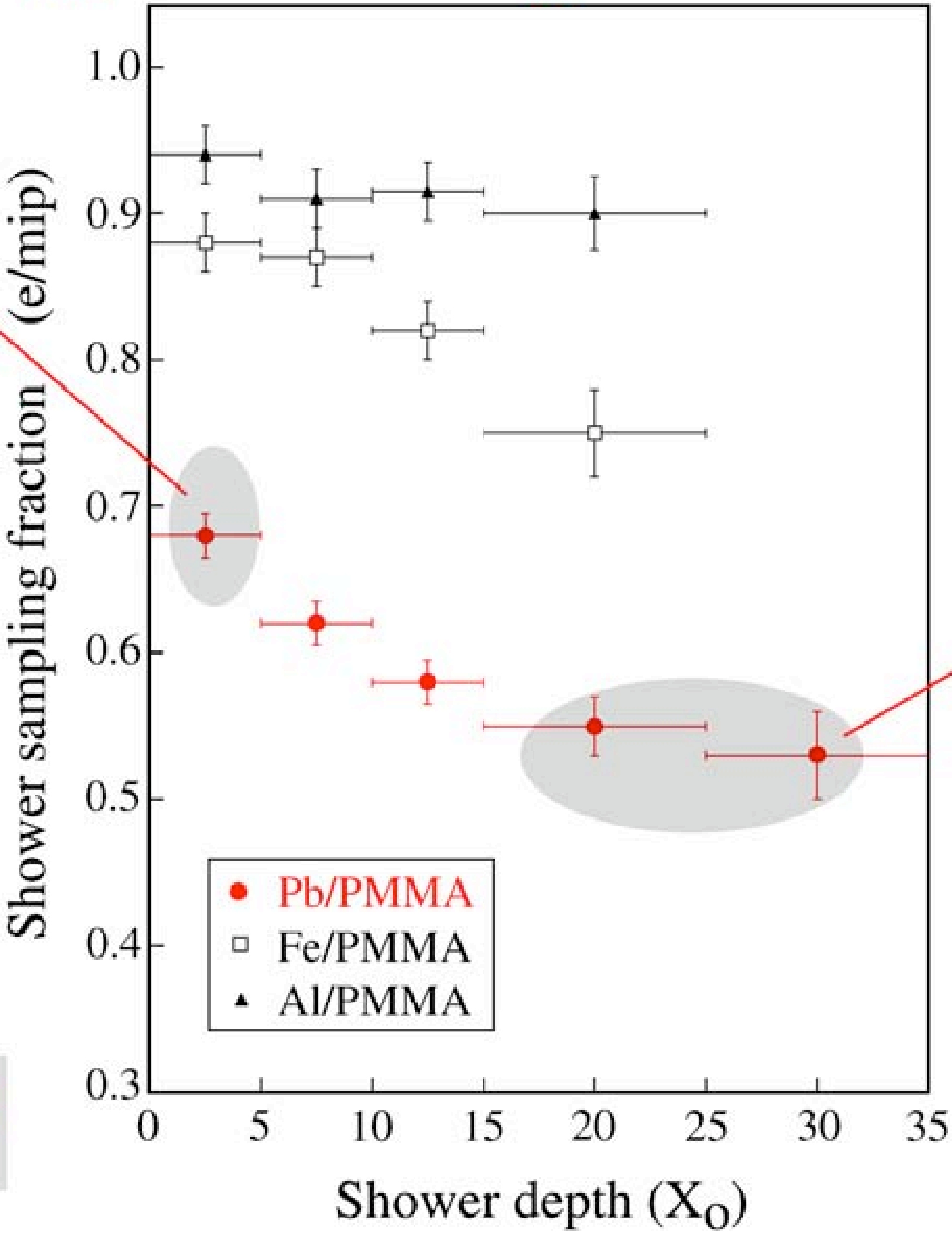
Calibration of calorimeter systems

- Determine relationship between *signal* (pC, p.e.) and *energy* (GeV)

- *Fundamental problem in sampling calorimeters:*
  Different shower components are sampled differently
  Shower composition changes as shower develops
  → *Sampling fraction changes with the shower age* (also E dependent)

How to intercalibrate the sections
of a longitudinally segmented calorimeter?

*The sampling fraction changes as shower develops**



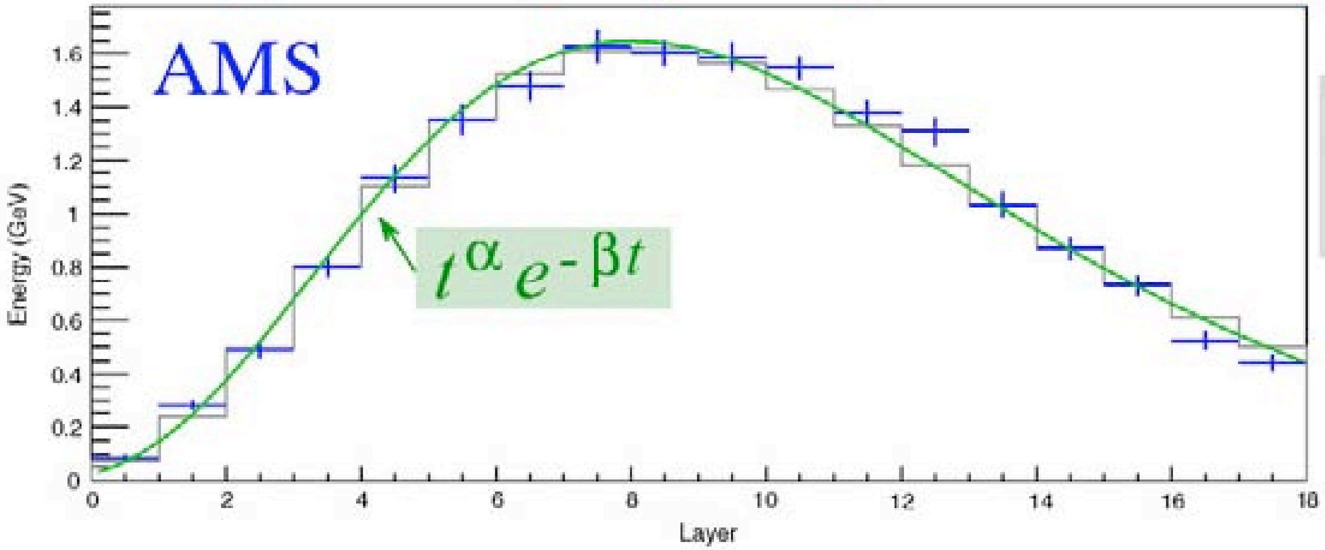
shower dominated by mip's

shower dominated by soft γ's

**By as much as 30%!*

CALIBRATION MISERY

Consequences of depth dependence sampling fraction



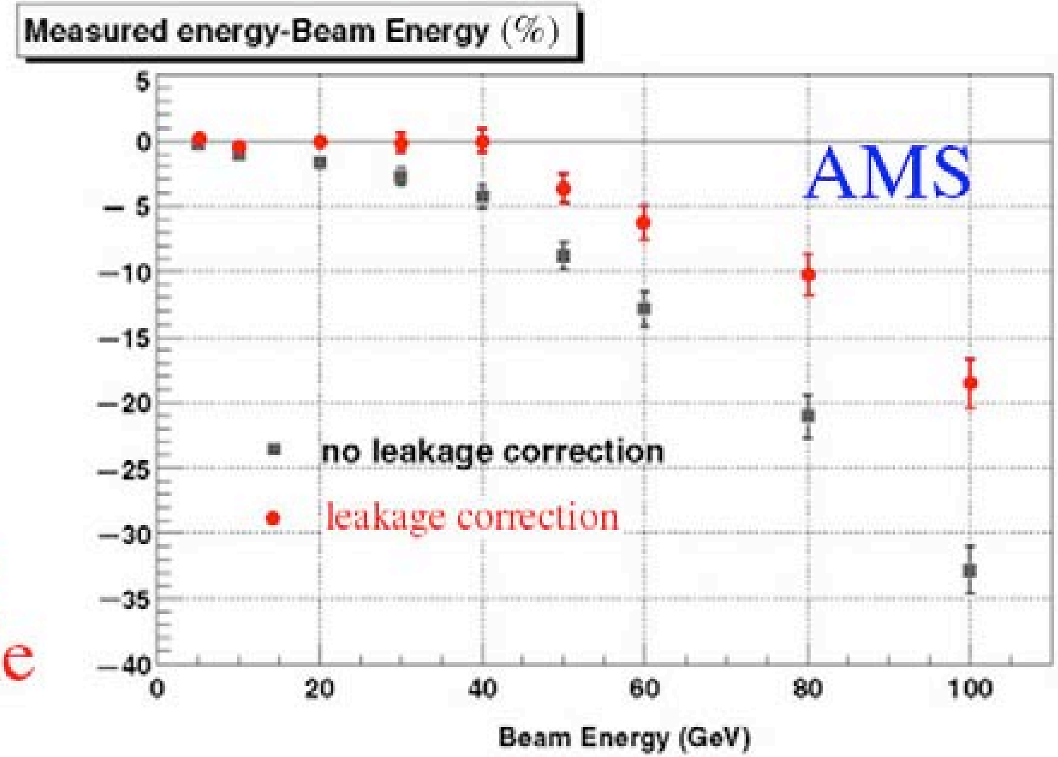
NIM A490, 132 (2002)

Pb/scintillating fiber

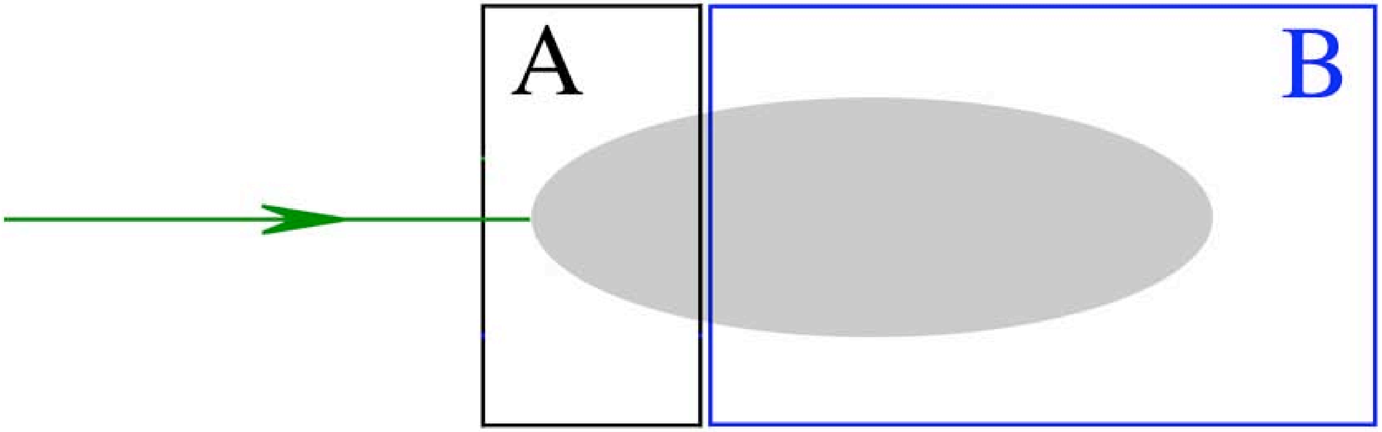
18 layers (17 X_0)

Calibrated with mip's:
11.7 MeV/layer

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



A widely used technique for calibrating segmented devices



Minimize $Q = \sum_{j=1}^{N}\left[E - A\sum_{i=1}^{n} S_{ij}^{\mathrm{A}} - B\sum_{i=1}^{n} S_{ij}^{\mathrm{B}}\right]^2$

→ *Determine A,B*

Calibrating a segmented calorimeter by minimizing total signal width

GIVES WRONG RESULTS!

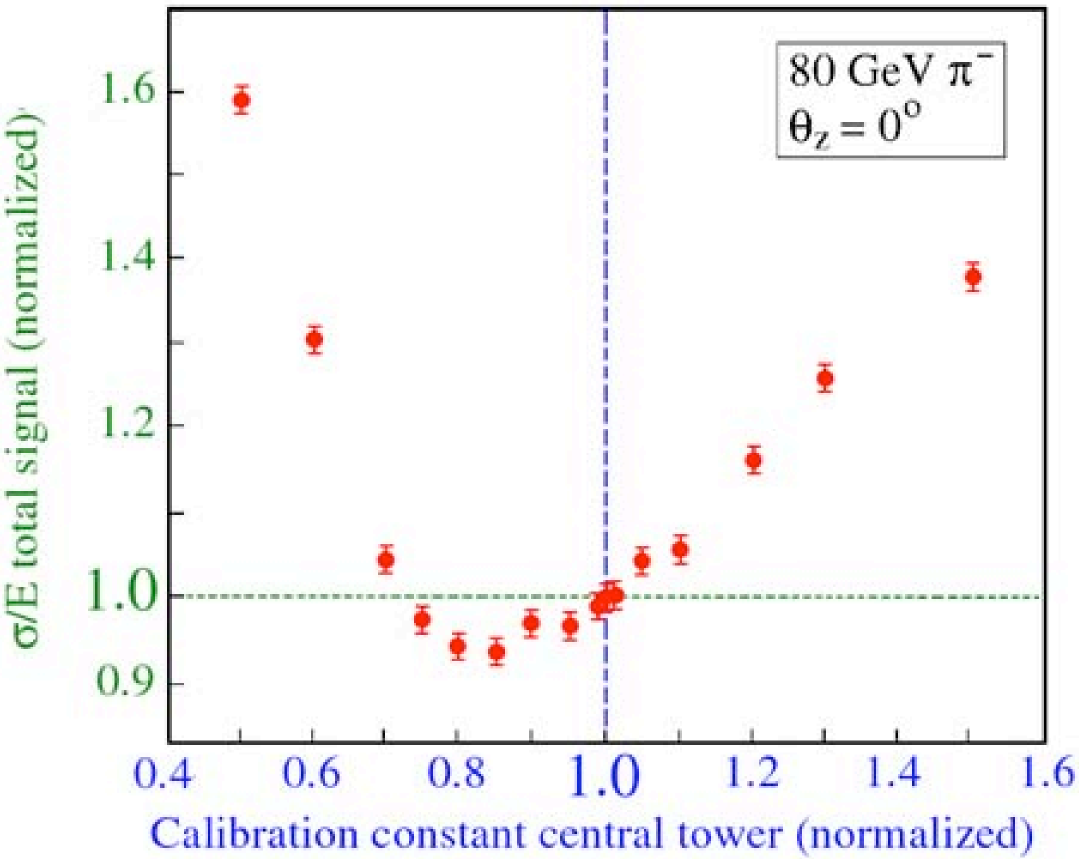


Figure 11: The fractional width, σ/E, of the signal distribution for 80 GeV π^- in the SPACAL detector as a function of the weighting factor applied to signals from the central calorimeter tower into which the pion beam was steered. The calorimeter towers were calibrated with high-energy electrons [7].

From: NIM A485 (2002) 385.

Calibration of calorimeter systems

- Determine relationship between *signal* (pC, p.e.) and *energy* (GeV)

- *Fundamental problem in sampling calorimeters:*
  Different shower components are sampled differently
  Shower composition changes as shower develops
  → *Sampling fraction changes with the shower age* (also E dependent)

  How to intercalibrate the sections
  of a longitudinally segmented calorimeter?

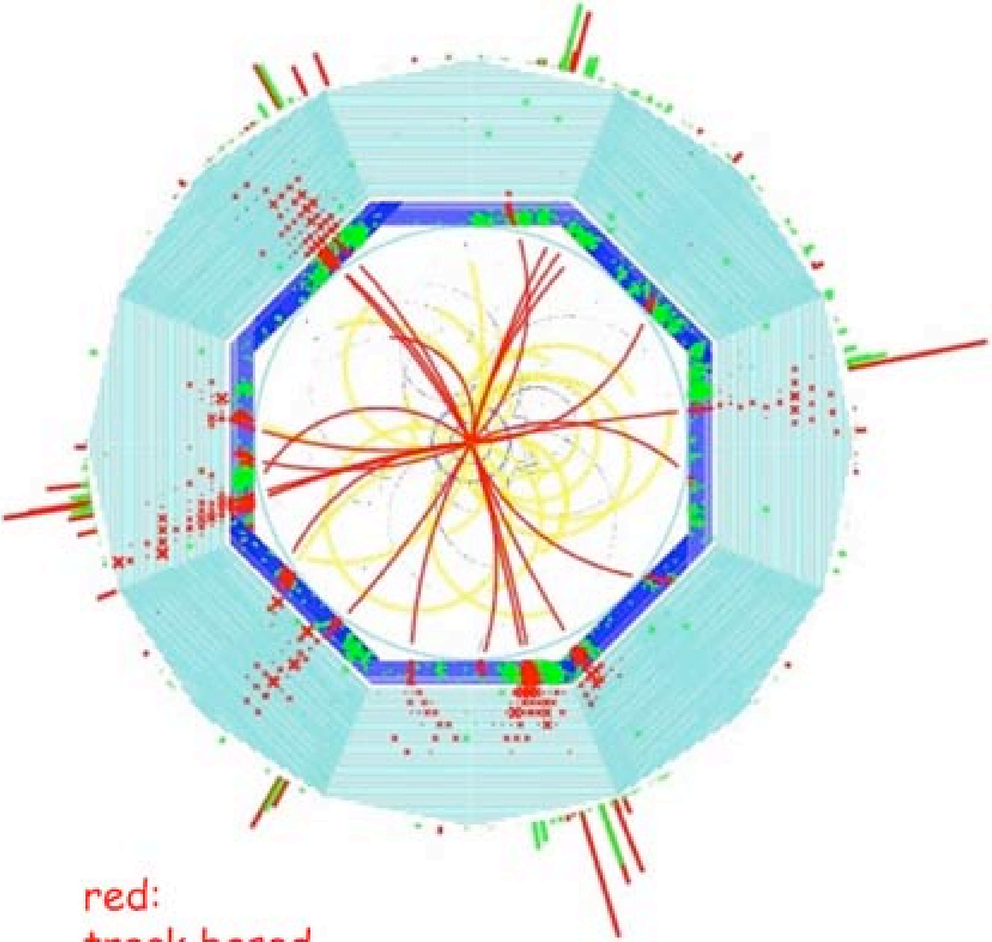
- How do you know if the calibration is correct?
  - Electromagnetic: $Z, J/\Psi \rightarrow e^{+}e^{-}$, $\pi^{0}, \eta \rightarrow \gamma\gamma$
  - Hadronic: ??? $W,Z \rightarrow q\bar{q}$ ‘γ – *jet balancing*’ ???

Particle Flow Analysis (Energy Flow Method)

- Use *tracking, particle ID and calorimetry* to measure 4-vectors of jets
- Charged particles represent typically ~ *65%* of the jet energy

  However, if only charged jet components are measured:
  $(\sigma/E)_{jet} = 25\text{-}30\%$
  (independent of jet energy)

  → *Calorimetry essential !*
- The problem with this method is *shower overlap*. Need to deconvolute contributions from showering charged particles to avoid *double counting*



red:
track based

green:
calorimeter based

ZHH → qqbbbb

Example of PFA at LEP: ALEPH

Attempt to reconstruct hadronic event structure using particle identification and software compensation

Cleaning
select tracks/clusters

↓

Track cluster matching:
Calorimeter Objects (CO)

↓

Remove electrons from COs
subtract from clusters

↓

Remove muons from COs
subtract from clusters

↓

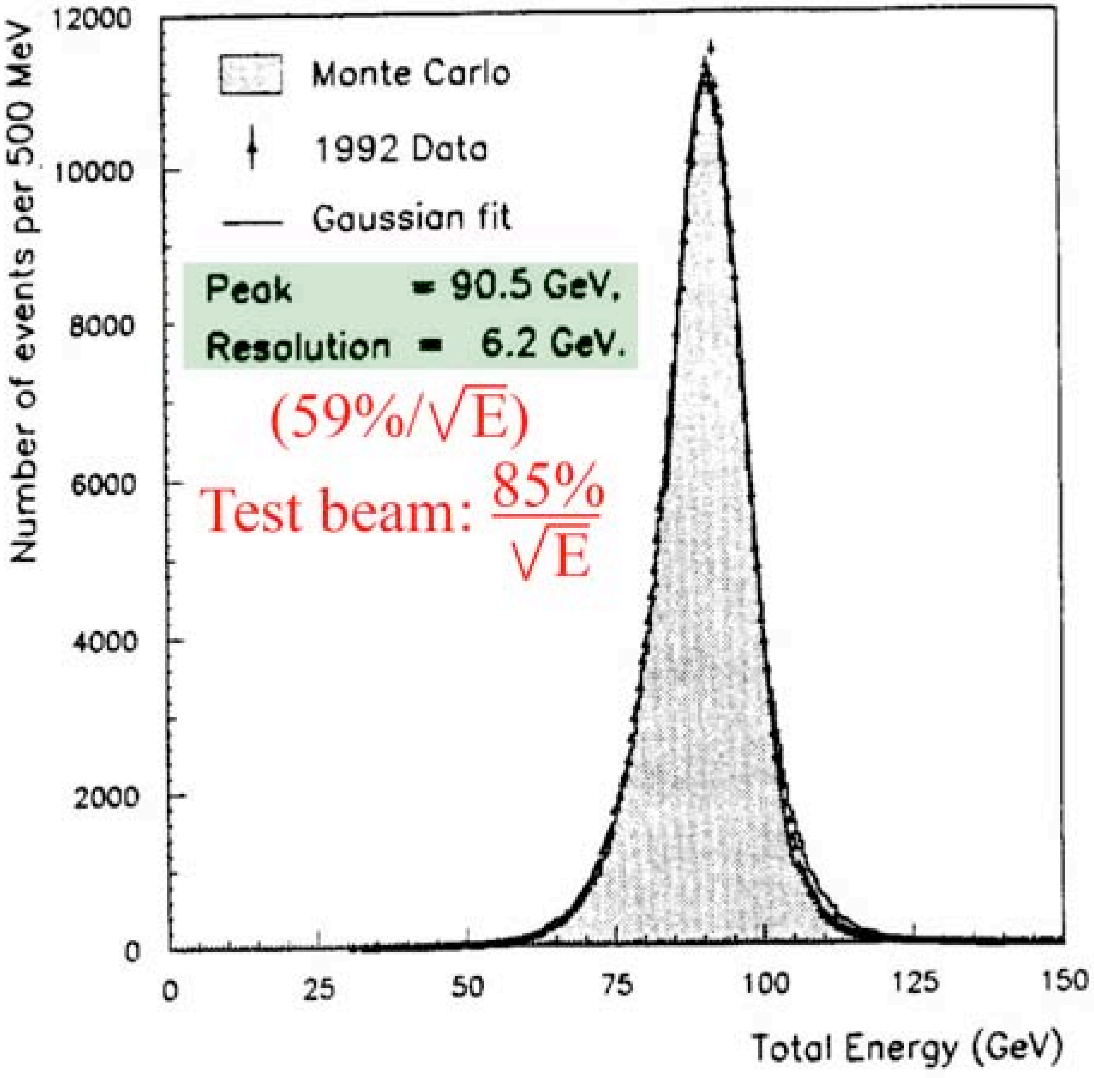
Remove photon and neutral
pion clusters from COs

↓

Scale remaining ECAL
clusters in 3 storeys
(software compensation)

↓

Subtract associated charged
particle tracks:
Neutral hadron cluster



Peak = 90.5 GeV.
Resolution = 6.2 GeV.

$(59\%/\sqrt{E})$

Test beam: $\frac{85\%}{\sqrt{E}}$

NIM A360 (1995) 481

PFA at a Hadron Collider

(no kinematic constraints as at LEP)

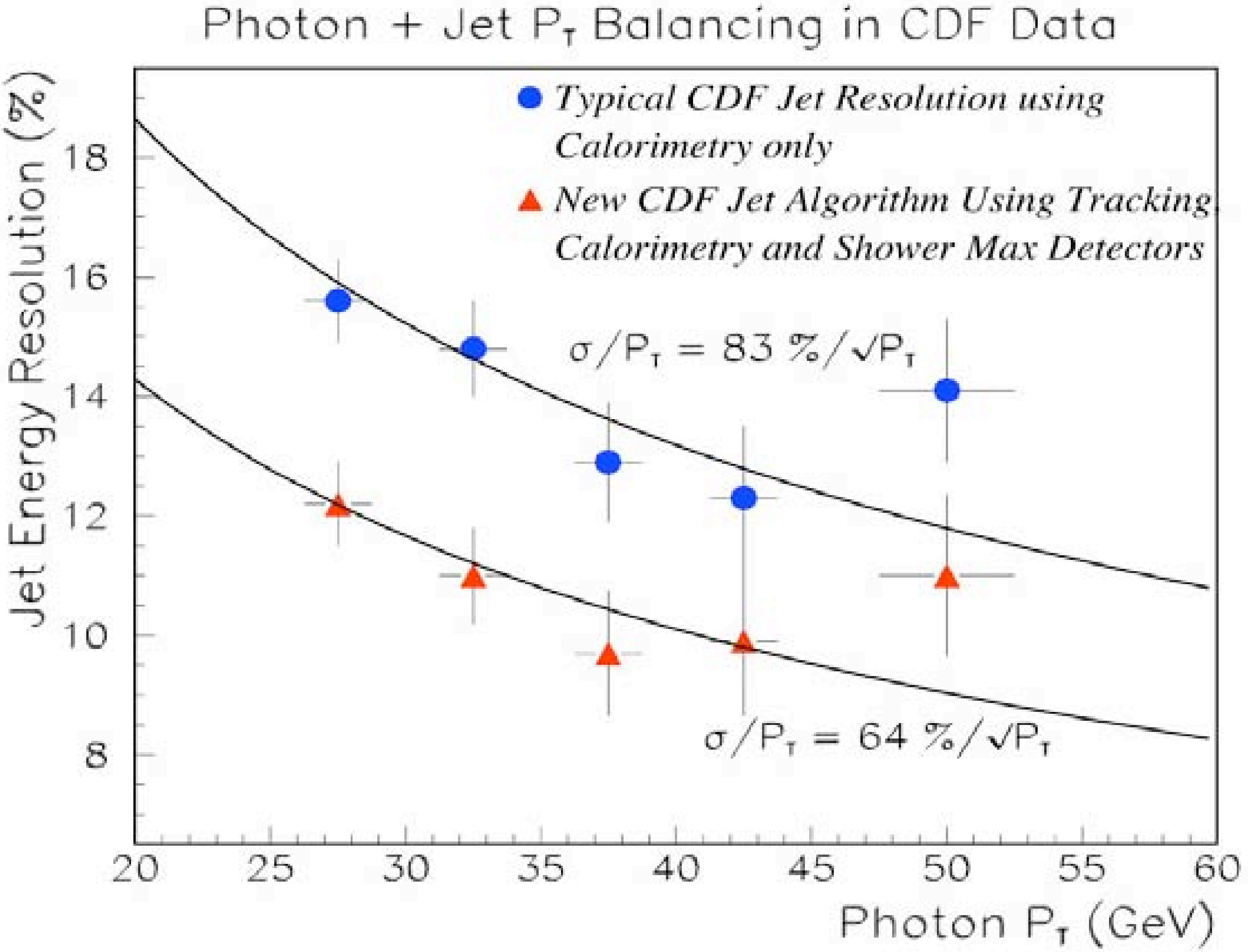


Figure 4: *The central detector resolution σ_D is plotted as a function of P_T^γ for the two methods.*

From: CDF note 5005 (2000)

Improvement of energy resolution expected with EFM (PFA)

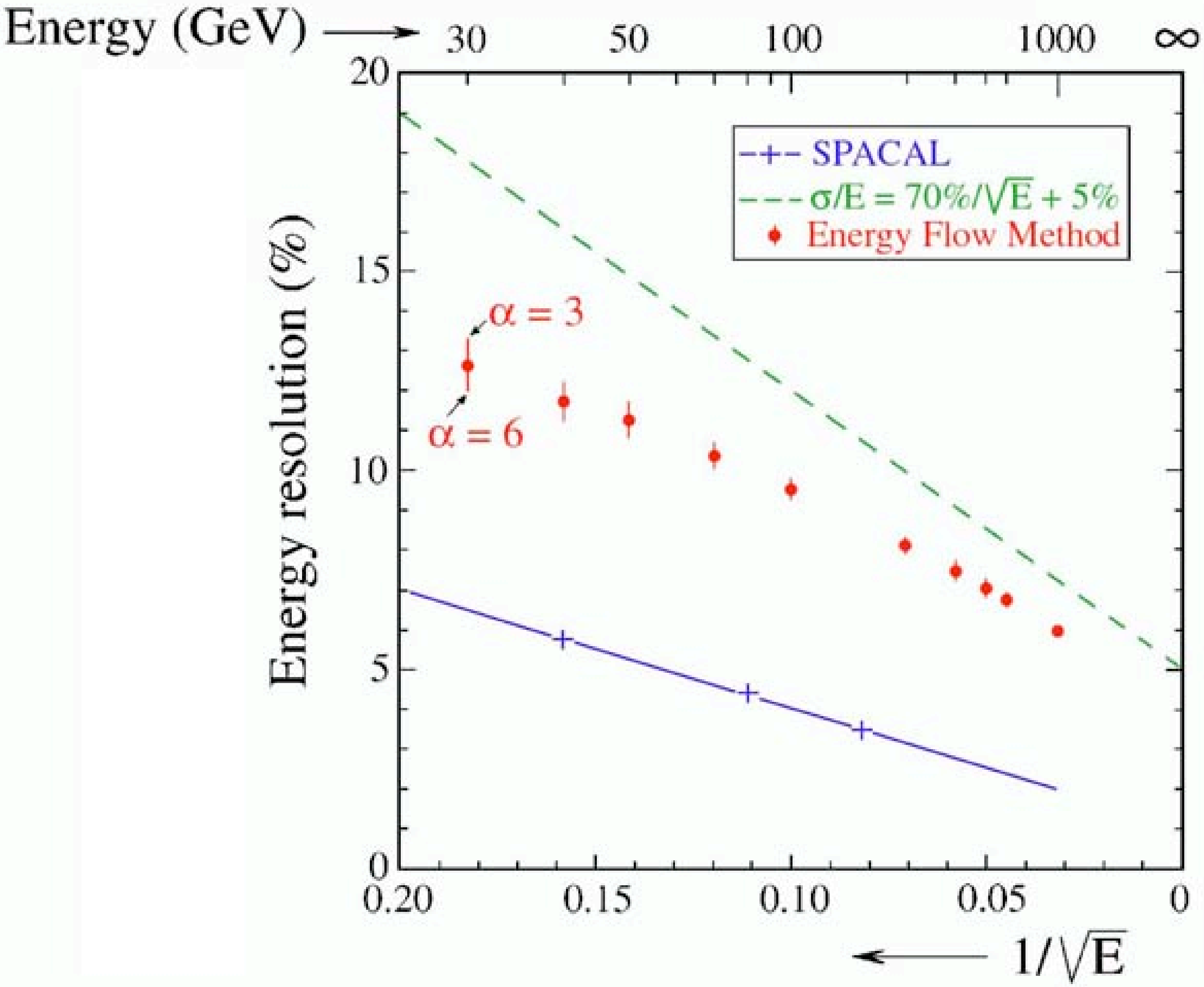


Fig. 11. The jet energy resolution as a function of energy, obtained after applying the Energy Flow Method (the dots), using simulated data from a calorimeter with a jet resolution given by the dashed curve. For comparison, the jet resolution of a compensating calorimeter is given (SPACAL [7]). From: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

Challenges in future experiments (1)

LHC (ATLAS, CMS)

- Em: Calorimeters designed to be sensitive to $H^{o} \longrightarrow \gamma\gamma$
  Challenge: Maintain stability

- Hadrons/jets:
  Challenge: The energy scale (segments with different e/h)
  Recommendation: Approach calibration in a very systematic way, understood by all users, do not rely on fudge factors. Well documented.
  Example: NIM A487 (2002) 381

Challenges in future experiments (2)

SLHC (ATLAS, CMS)

Assuming that bunch spacing does not become smaller:
Effects of increased number of underlying events: Trivial extrapolation
Main challenge: The effects of radiation

- *Radiation damage of scintillators and quartz (CMS)*
  H_2 build-up in LAr (ATLAS) } *affects performance*
- *Activation of detector materials* → *access/service problematic*
- *Cooling of forward calorimeters.*

The calorie becomes a relevant unit for calorimeters: 1 cal = 2.6 10^{10} GeV
CMS: 100 GeV per min. bias event deposited in Forward Calorimeters

@10^{34} cm^{-2} s^{-1}: 12 J/s (W)
@10^{35} cm^{-2} s^{-1}: 120 W

Challenges in future experiments (3)

ILC / CLIC

- *Need to measure 4-vectors of jets with excellent precision.*
  Physics program relies heavily on final states with (several) bosons: W,Z,H
  Necessary to reconstruct W,Z through their hadronic decay modes.

  Hadronic energy resolution very important for this multi-jet spectroscopy.

- *The same argument can also be made for SLHC.*
  For example, study of multi-boson couplings is statistics limited
  if one only would consider leptonically decaying W,Z.

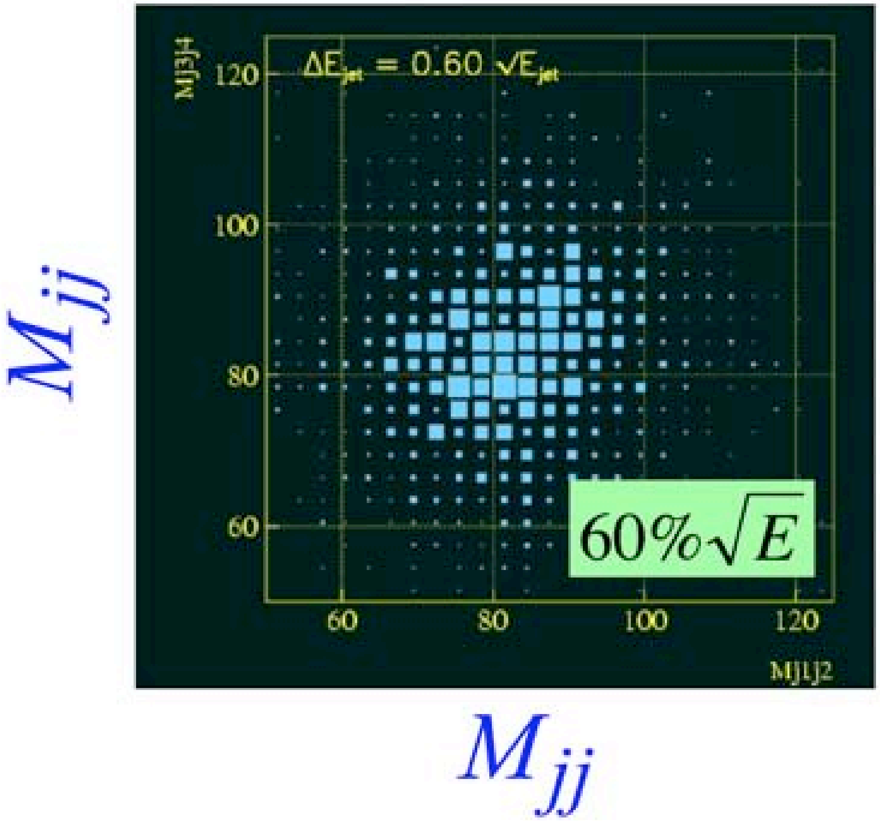
  → *SLHC physics program might benefit from improved hadron calorimetry*

- *The issue of $H^{o} \rightarrow \gamma\gamma$ will presumably be settled during LHC running.*
  Therefore, it is conceivable to replace the calorimeter system by one
  with strongly improved hadronic performance for SLHC era.

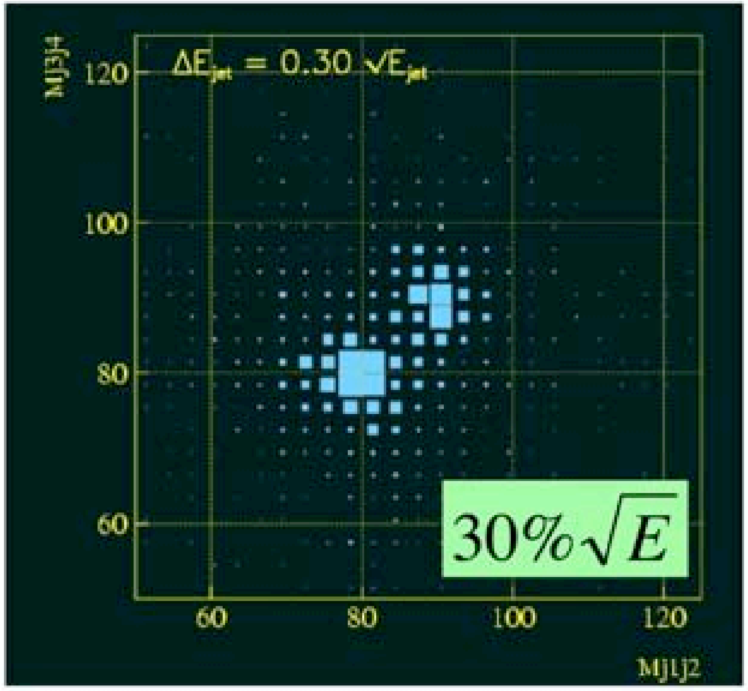
Design goal ILC/CLIC: separate $W,Z \rightarrow q\bar{q}$

- *Hadronic energy resolution very important for this multi-jet spectroscopy.*

LEP-like detector



LC design goal

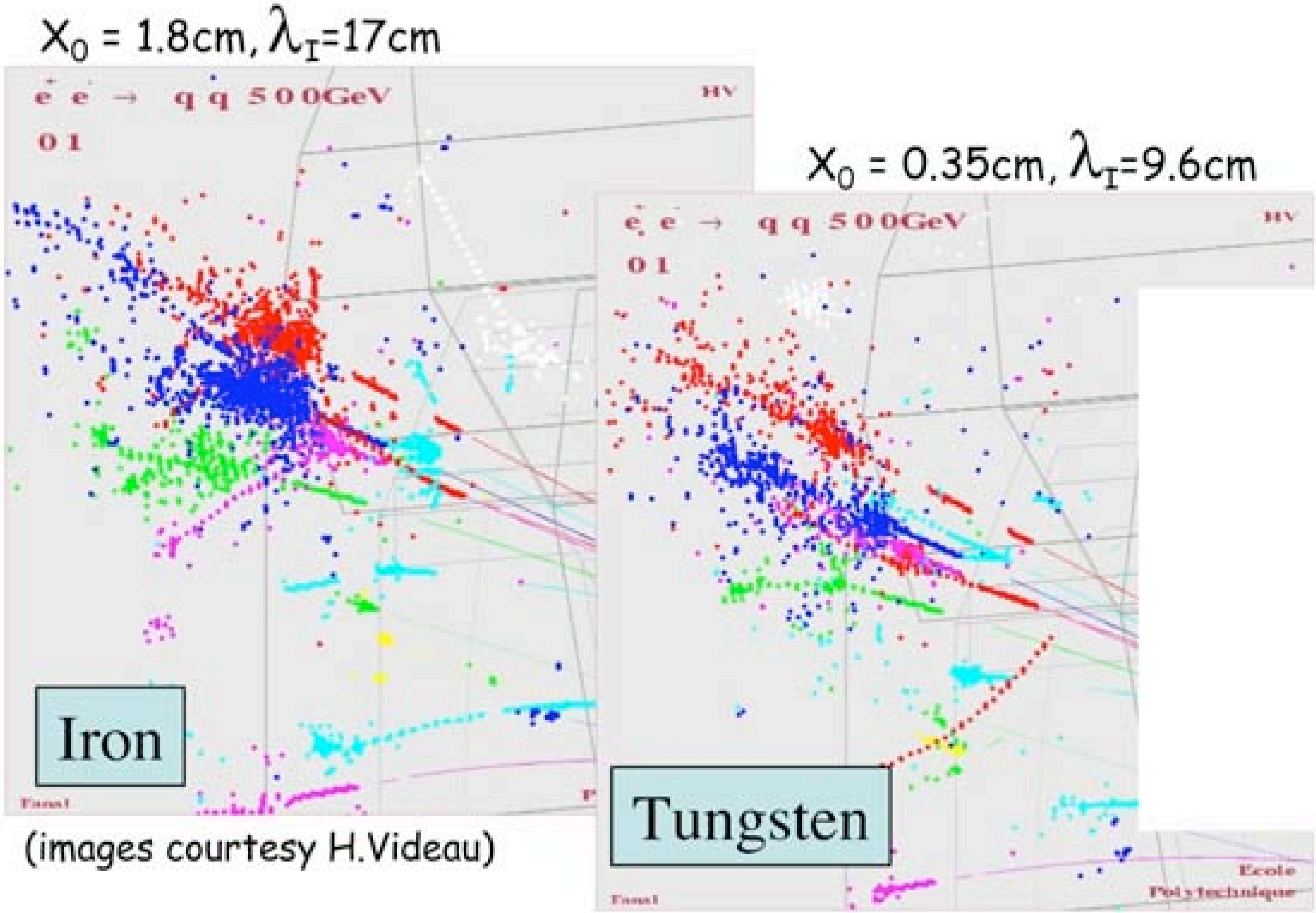


- *No kinematic constraints as in LEP (beamstrahlung)*

PFA @ ILC: High Density + Fine Granularity

- In order to reduce the problems of shower overlap, ILC R&D focuses on *reducing the shower dimensions* and *decreasing the calorimeter cell size*

(Alternatively, one could increase shower separation through $\vec{B}$, radius calorimeter)



X_0 = 1.8cm, λ_I=17cm

X_0 = 0.35cm, λ_I=9.6cm

(images courtesy H.Videau)

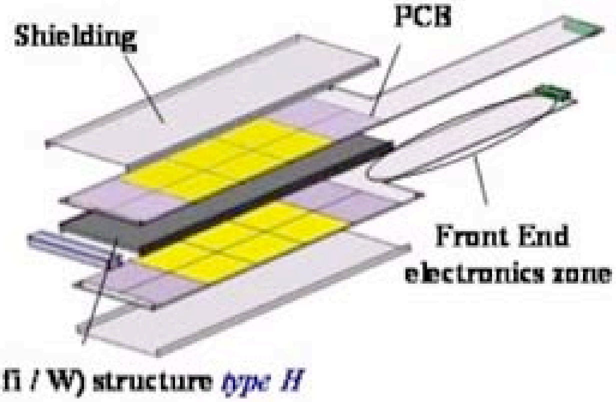
- *How about calibration??*

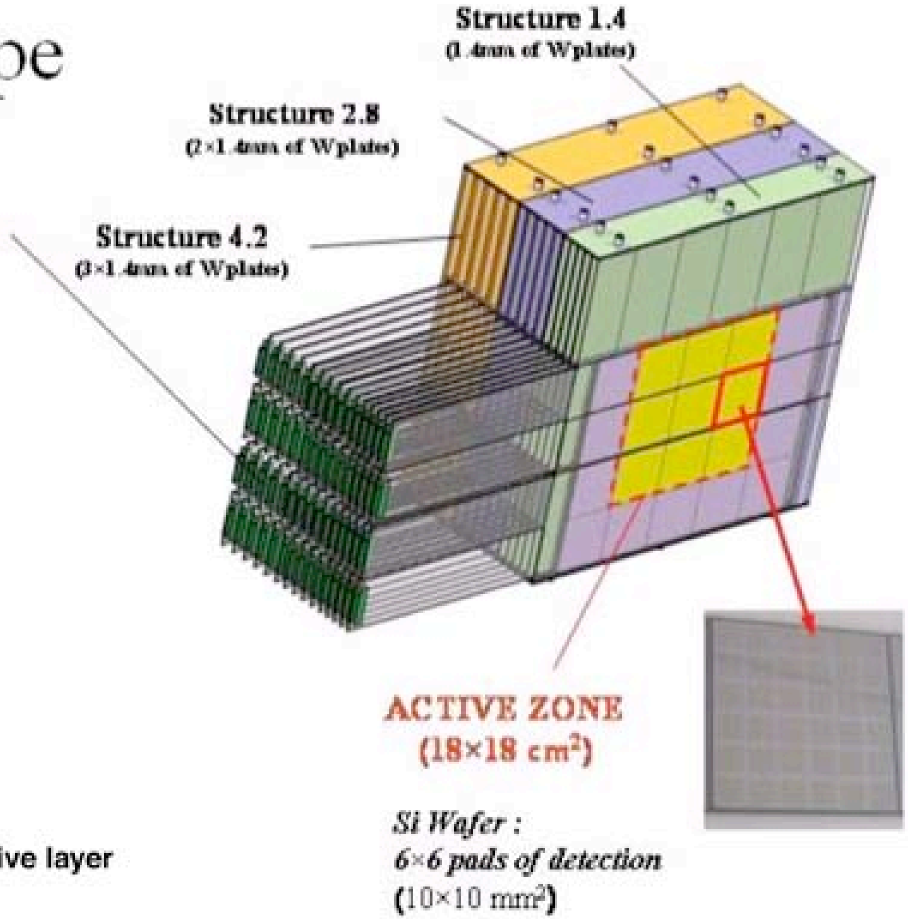
ILC R&D example (PFA): CALICE

164 Physicists, 28 Institutes, 9 Countries: 3 Regions

- ECAL and HCAL together, different options
- electron and hadron beams, start end 2004 at DESY

CALICE ECAL prototype





full Si/W prototype (24 X_0)

- ▹ 30 layers × 18 cm × 18 cm interleaved with 0.5 mm Si pads
- ▹ W absorber, 10+10+10 layers, 1.4 mm:2.8 mm:4.2 mm thick per respective layer
- ▹ readout by **1 × 1 cm^2 cells, total: 9720 channels**

LESSONS FROM 25 YEARS OF R&D

- *LESSON 1:* Energy resolution is determined by *fluctuations*,
  not by average values
- *LESSON 2:* Digital calorimetry has been tried *and abandoned,* for good reasons
- *LESSON 3a:* A narrow signal distribution is useless if the mean value is incorrect
  Correct energy scale is at least as as important as good resolution

  LESSON 3b: *Longitudinal segmentation means asking for trouble*
- *LESSON 4:* GEANT based MC simulations of hadronic shower development
  are *fundamentally flawed* ⟶ useless as design tool
- *LESSON 5:* If you want to improve hadronic calorimeter performance
  ⟶ *reduce/eliminate the (effects of) fluctuations*
  that dominate the performance :

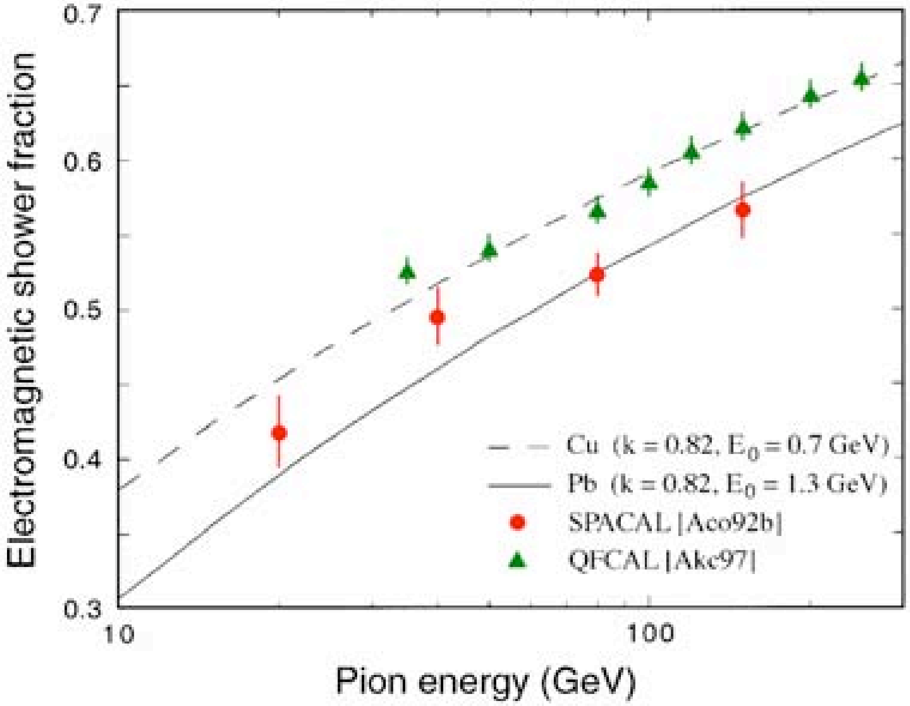
  i) Fluctuations in the em shower graction, f_{em}
  ii) Fluctuations in visible energy (nuclear binding energy losses)

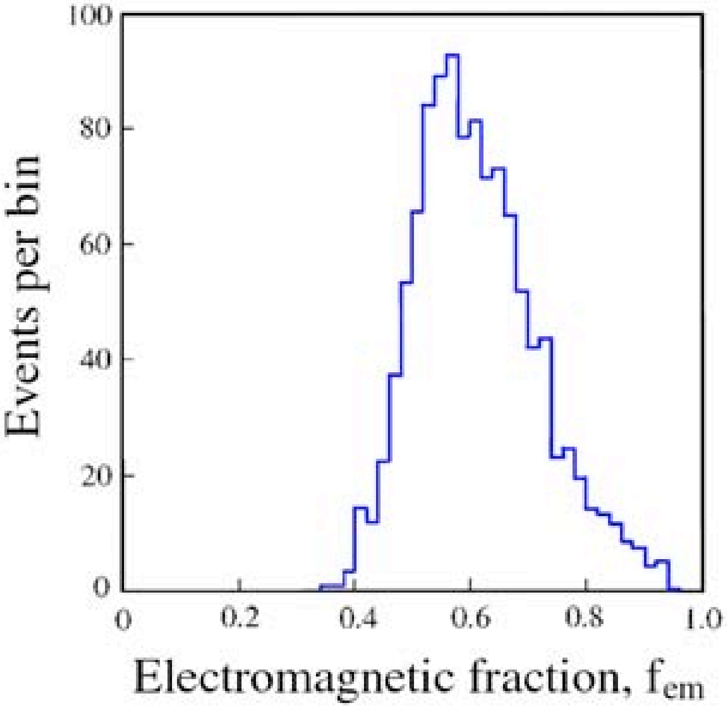
Fluctuations in the em shower component (f_{em})

- *Why are these important ?*
  - Electromagnetic calorimeter response ≠ non-em response *($e/h \neq 1$)*
  - Event-to-event fluctuations are large and *non-Gaussian*
  - *$<f_{em}>$ 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

(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*

LESSONS FROM 25 YEARS OF R&D

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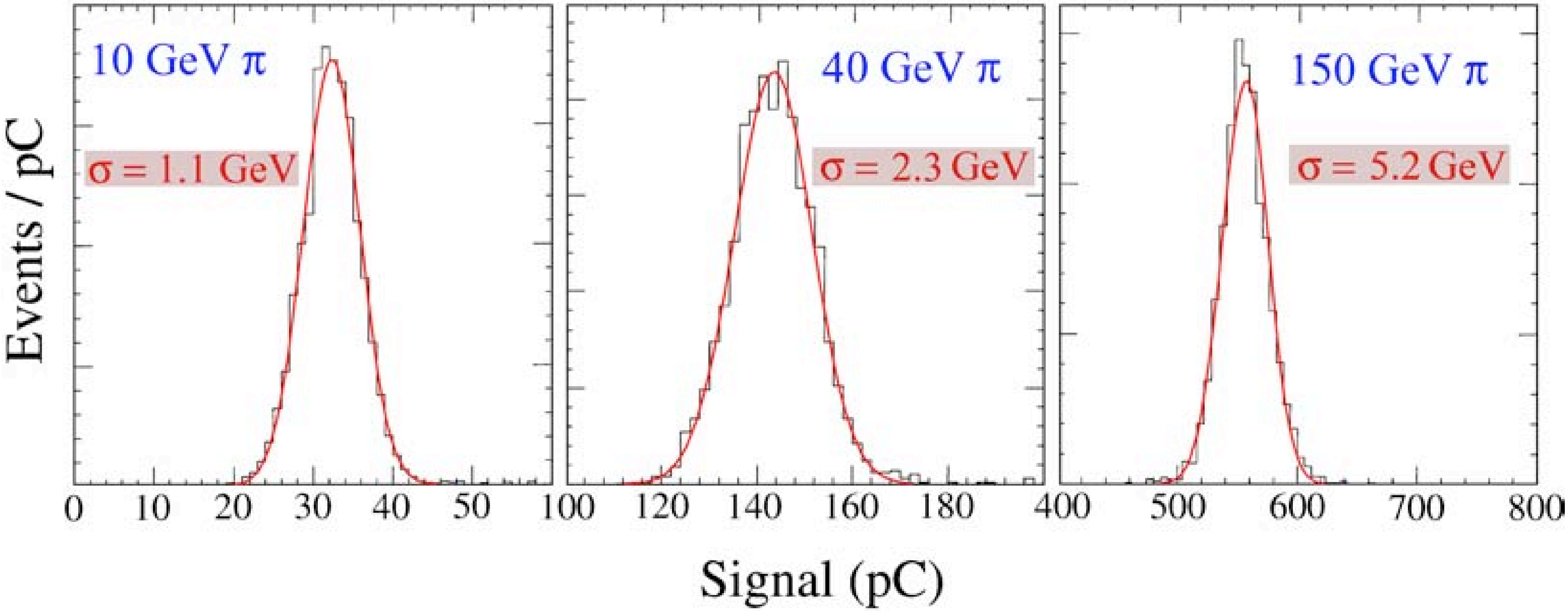
  i) Fluctuations in the em shower graction, f_{em}
  ii) Fluctuations in visible energy (nuclear binding energy losses)

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

Hadronic signal distributions in a compensating calorimeter



from: NIM A308 (1991) 481

Pros & Cons of Compensating Calorimeters

Pros

- Same *energy scale* for electrons, hadrons and jets. No ifs, ands or buts.
- *Calibrate* with electrons and you are done.
- Excellent hadronic *energy resolution* (SPACAL: 30%/$\sqrt{E}$).
- *Linearity,* Gaussian *response function* and all that good stuff.
- Compensation fully understood.
  We know how to build these things, even though GEANT doesn't

Cons

- Small sampling fraction (2.4% in Pb/plastic)
  ⟶ *em energy resolution limited* to 10-15%/$\sqrt{E}$
- Compensation relies on detecting neutrons
  ⟶ Large *integration volume*
  ⟶ Long *integration time* (~50 ns)

The DREAM principle

- *Quartz fibers are only sensitive to em shower component!*

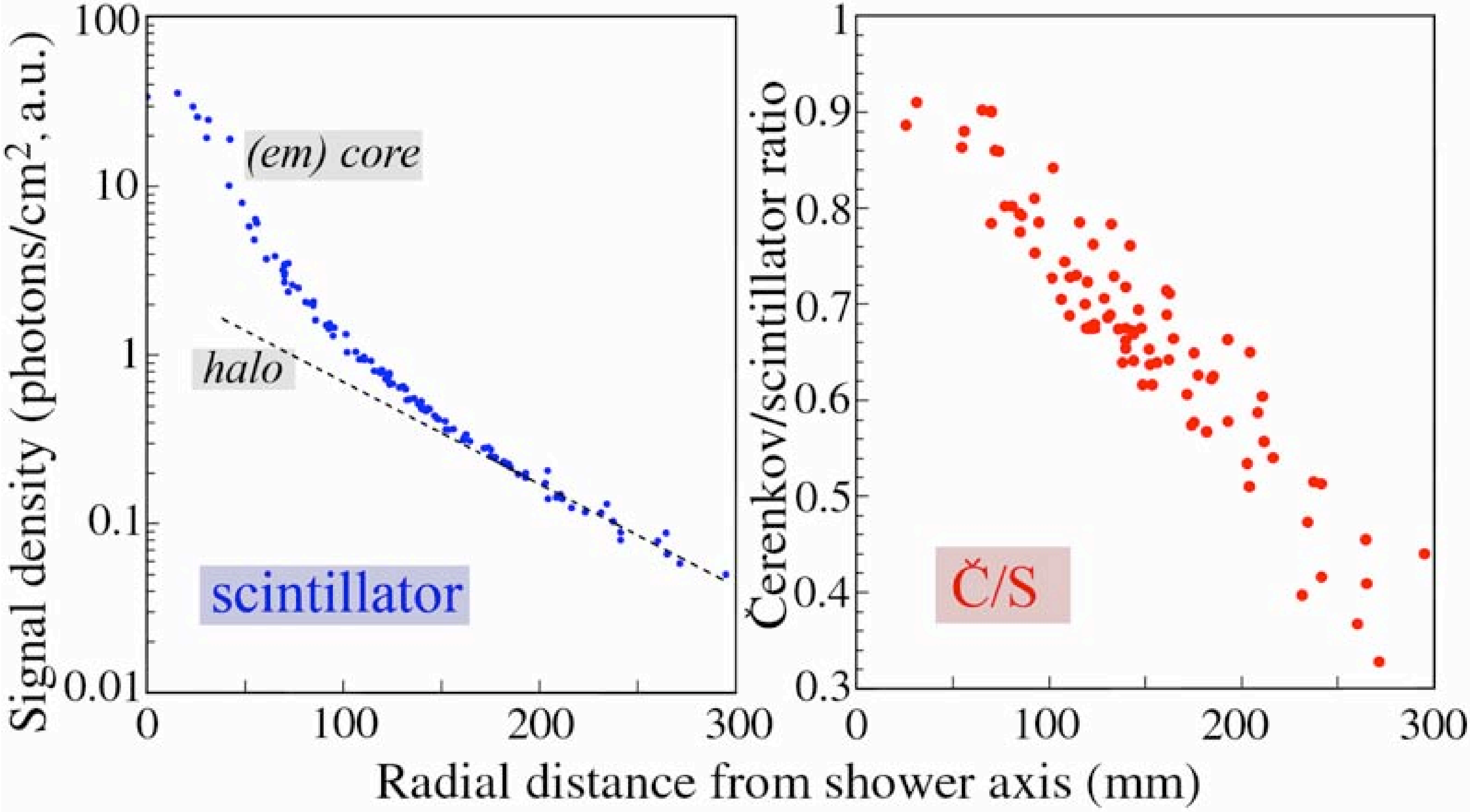
- CMS prototype: e/h ~ 5 NIM A399 (1997) 202

➡ Use dual-readout system:

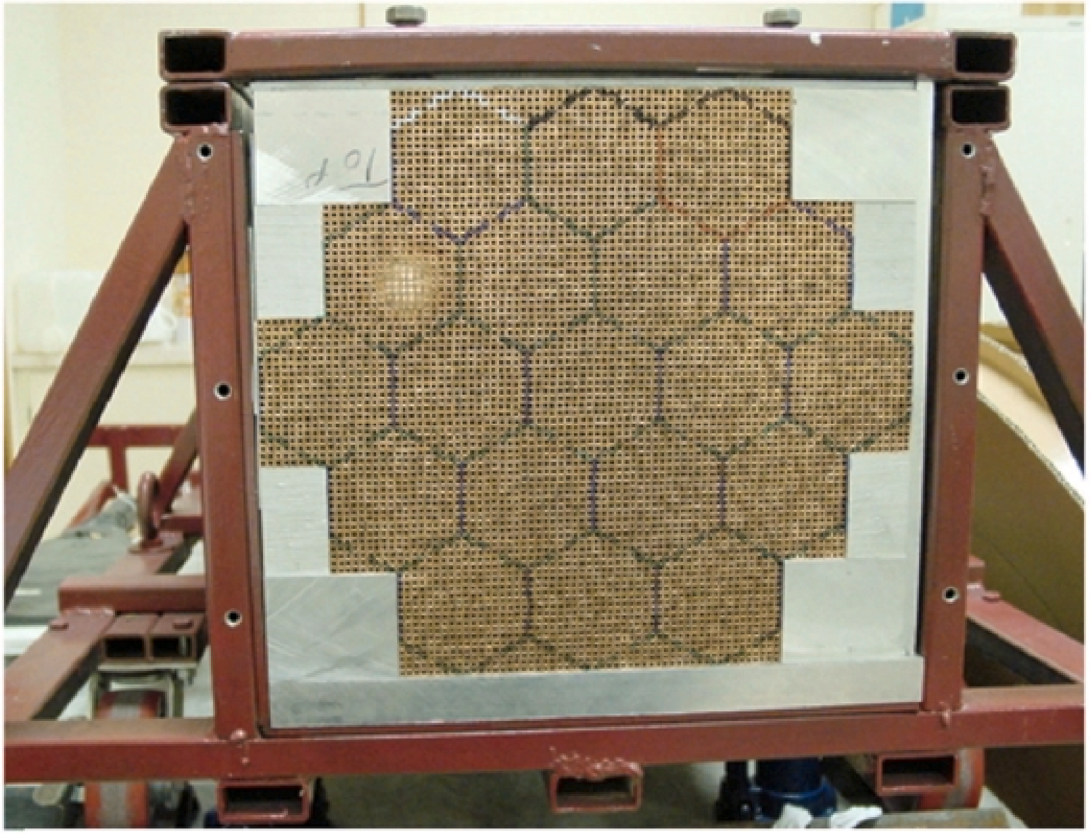
- Regular readout (scintillator, LAr,...) measures *visible* energy
- Quartz fibers measure em shower component E_{em}
- Combining both results makes it possible to determine f_{em} and the energy E of the showering hadron
- *Eliminate dominant source of fluctuations*

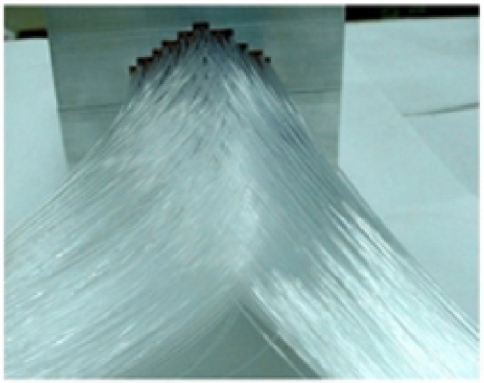
DREAM = Dual REAdout Module

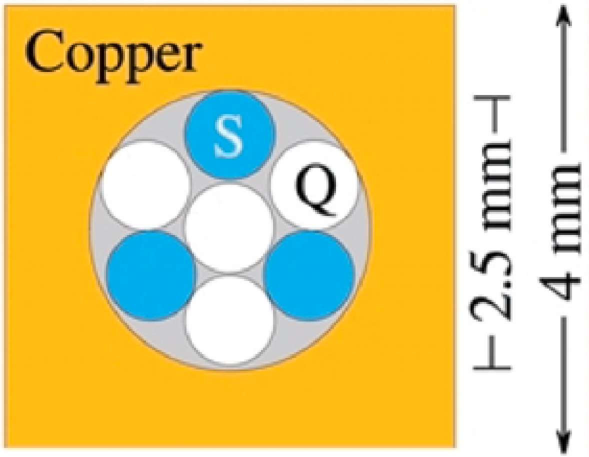
Radial hadron shower profiles (DREAM)



DREAM: Structure

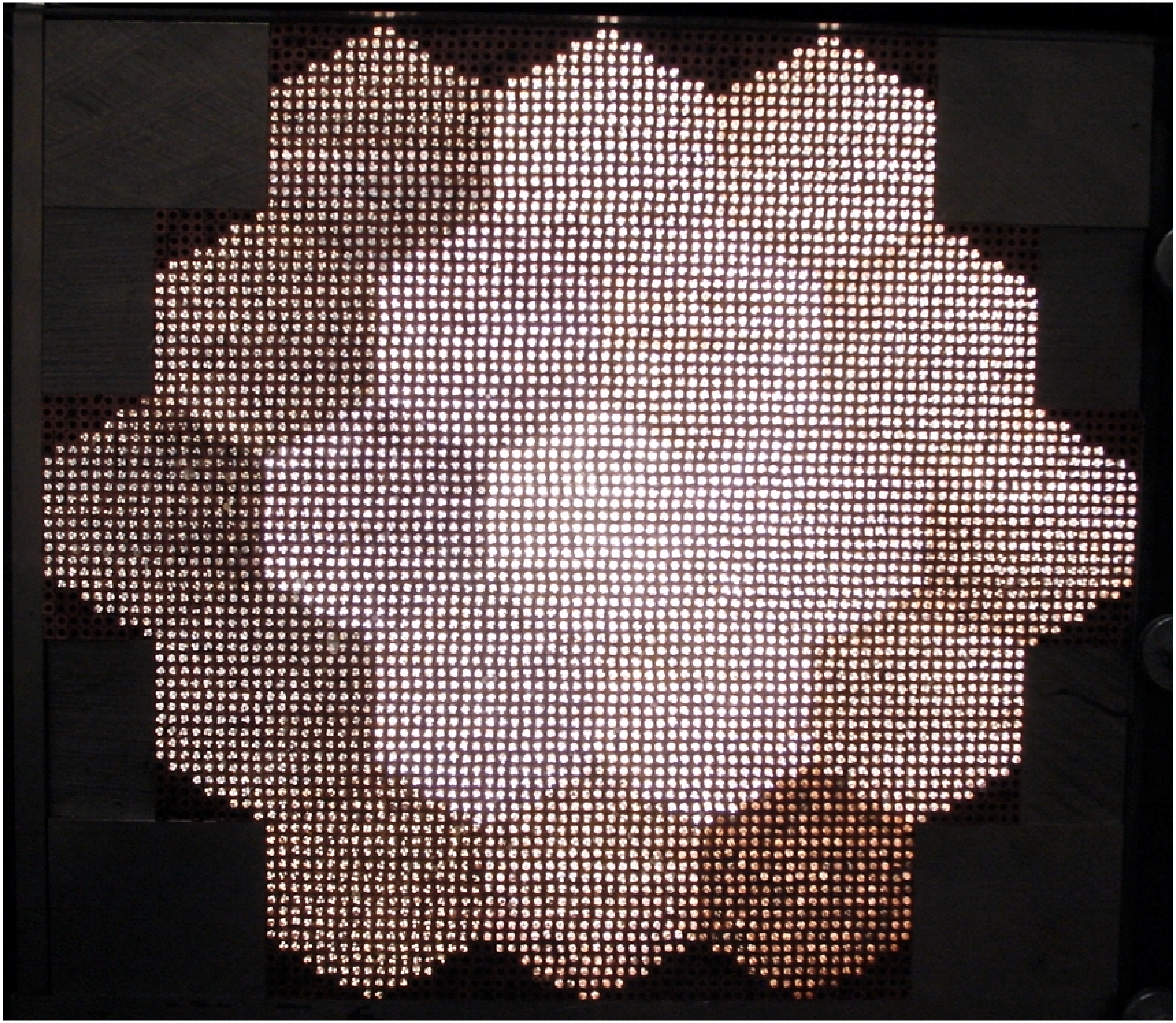




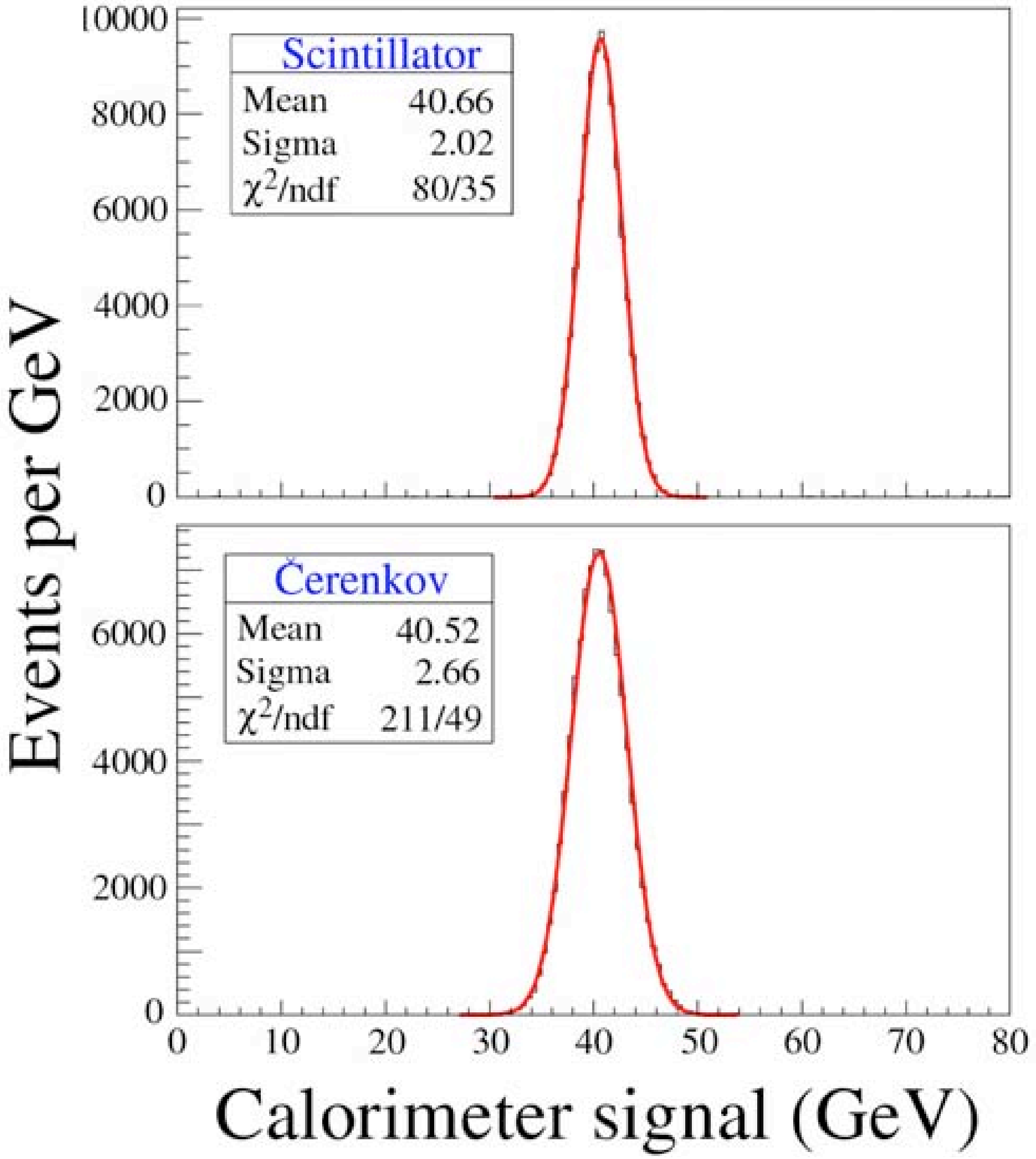


- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

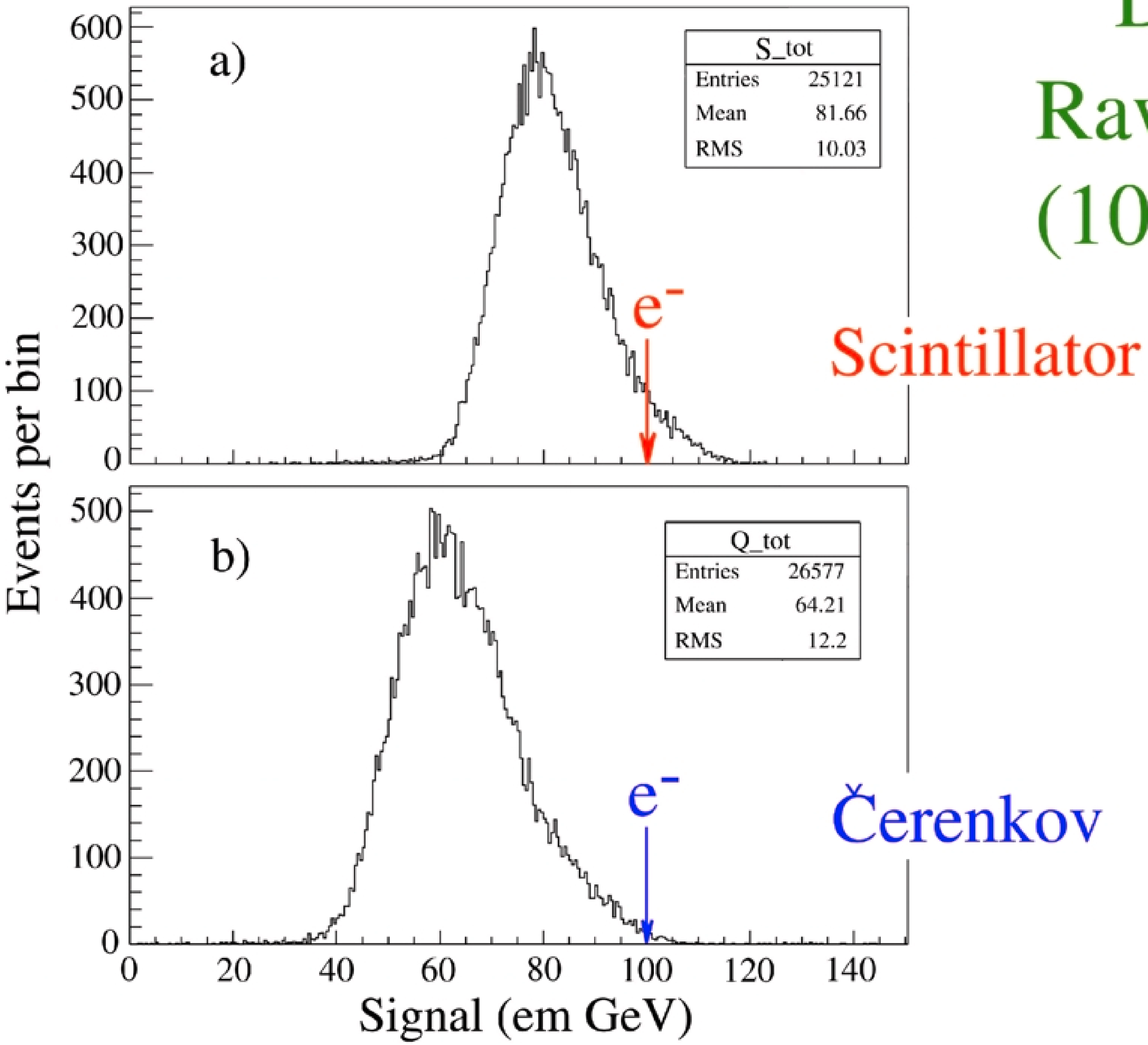
DREAM readout



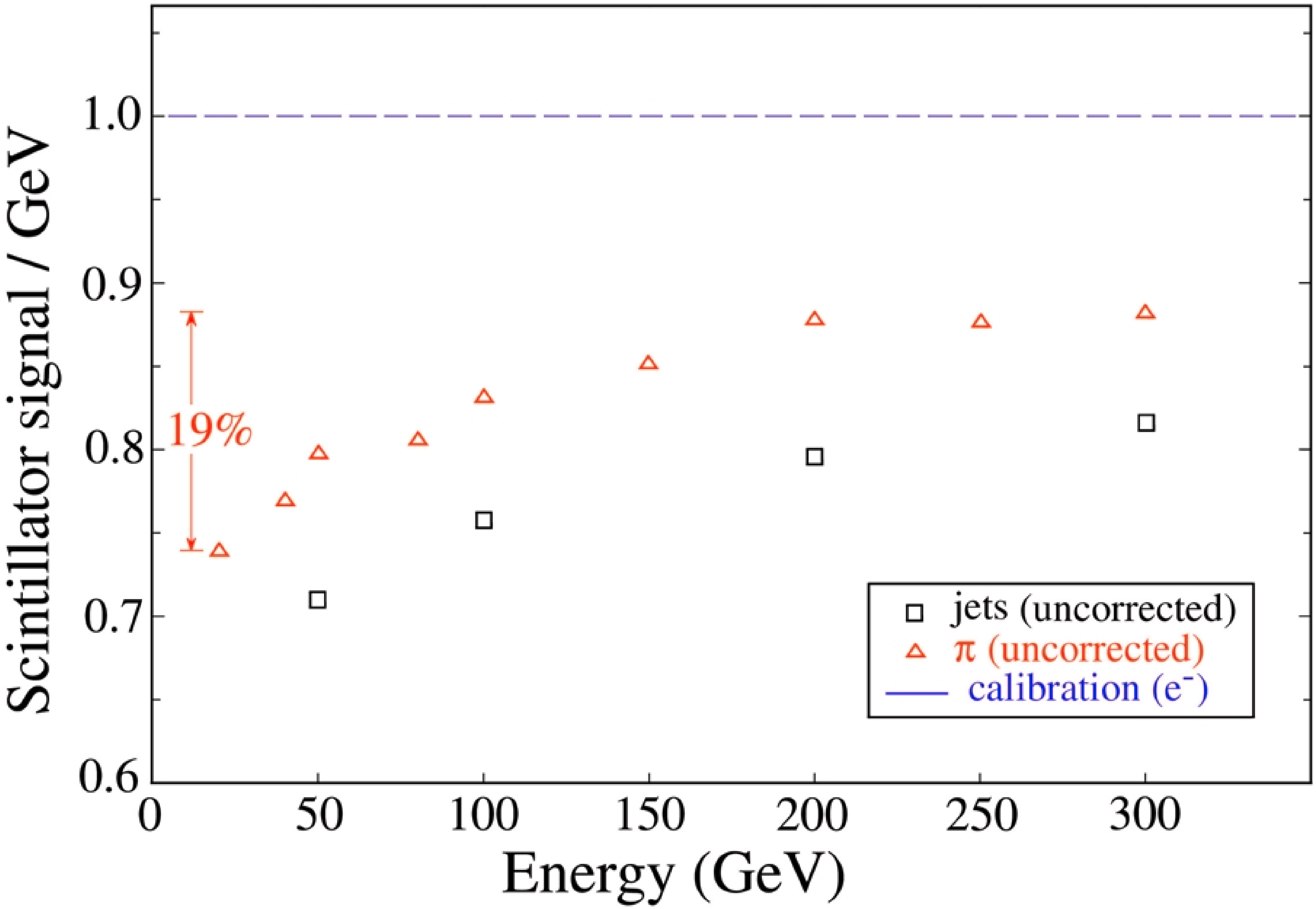
Calibration with 40 GeV electrons (tilt 2°)



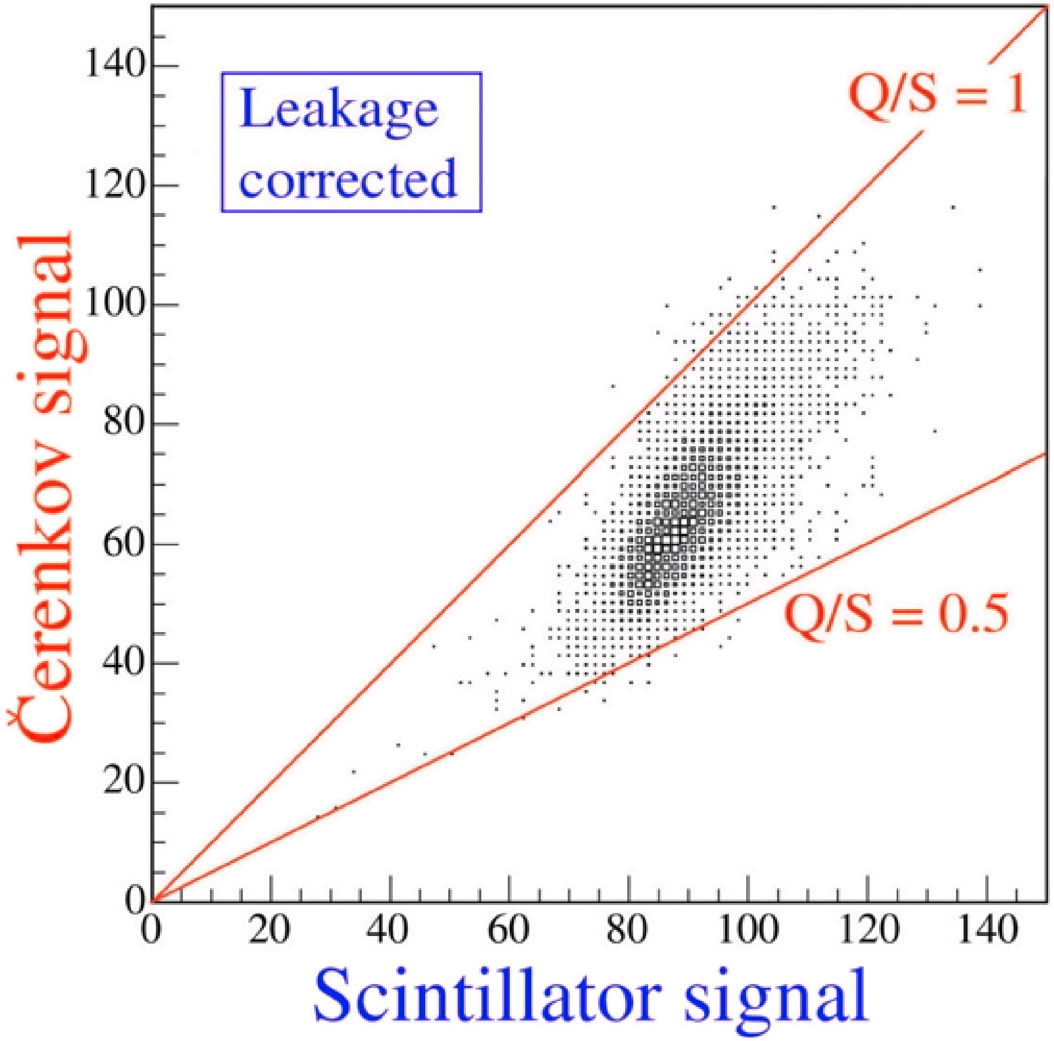
DREAM
Raw signals
(100 GeV π^-)



DREAM: Hadronic response (non-linearity)



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



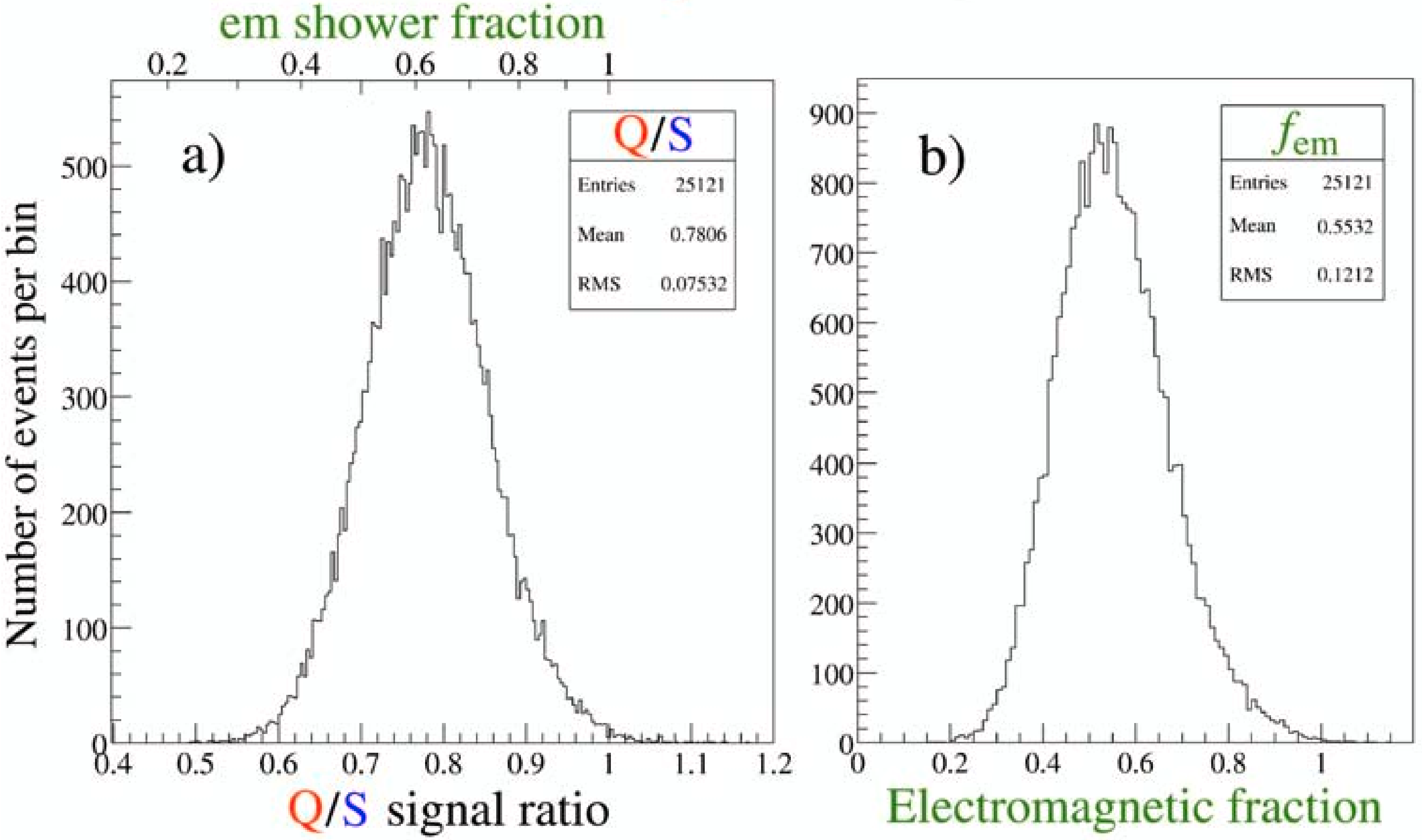
$$S = E\left[f_{\mathrm{em}} + \frac{1}{(e/h)_{\mathrm{S}}}(1 - f_{\mathrm{em}})\right]$$

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

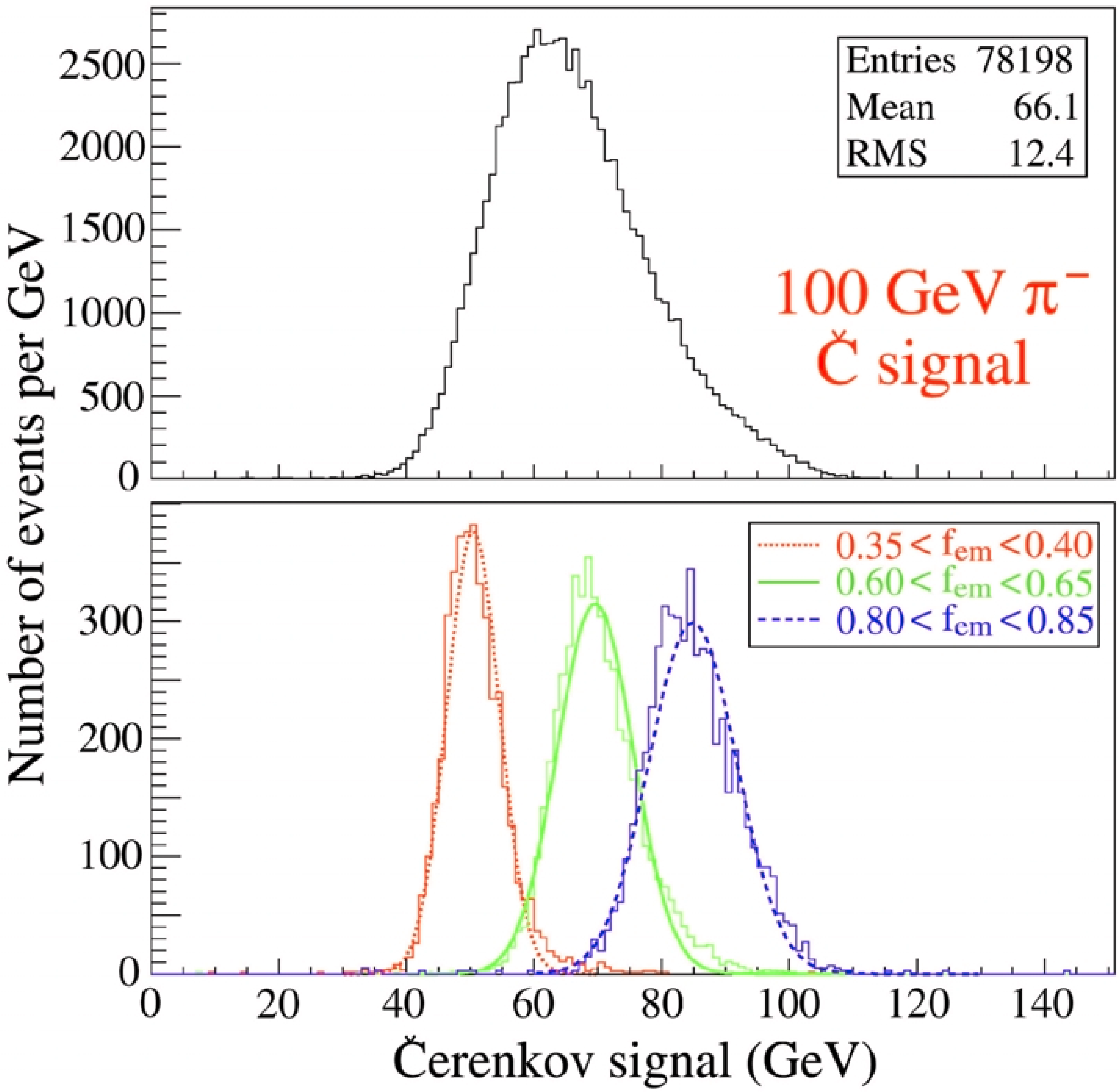
$e/h = 1.3$ (S), 5 (Q)

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

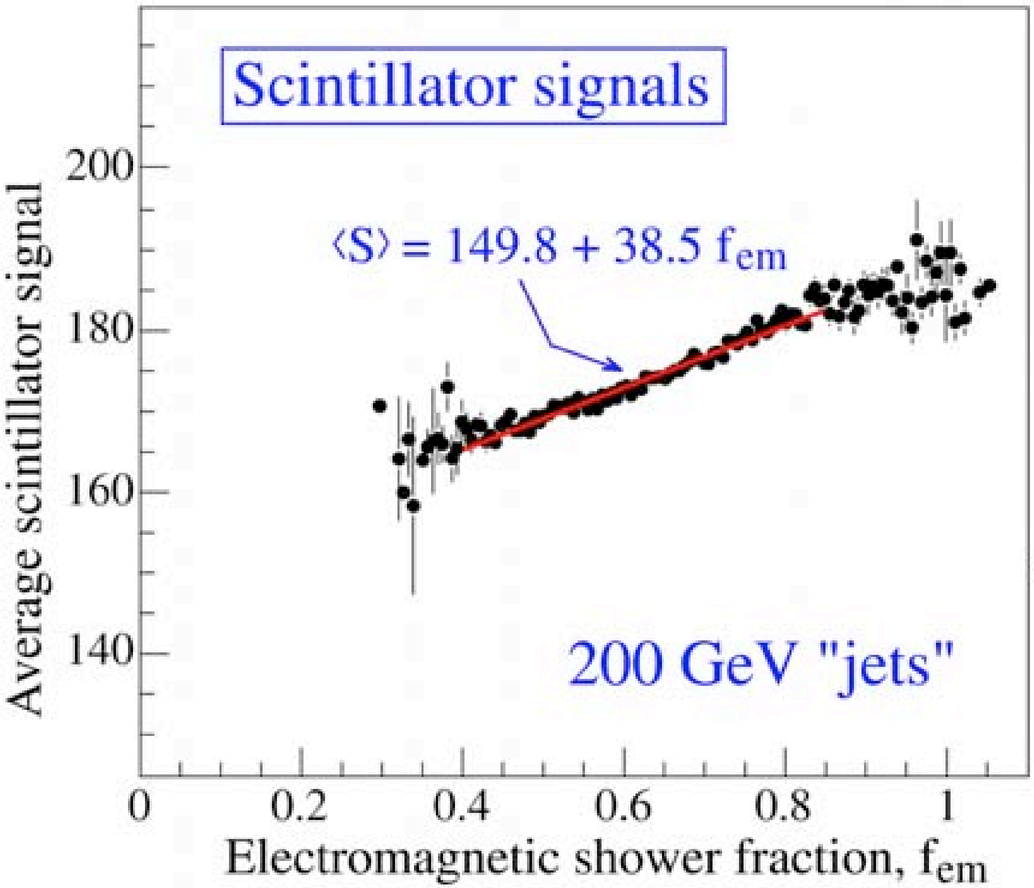
DREAM: relationship between Q/S ratio and f_{em}

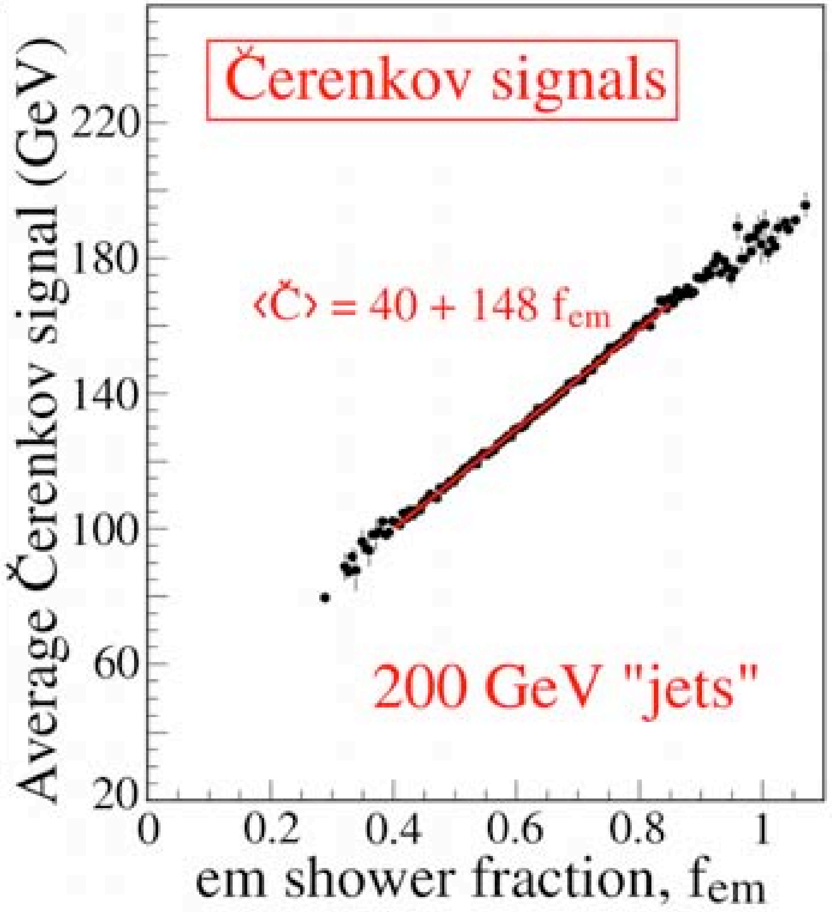


DREAM: Effect of event selection based on f_{em}



DREAM: Signal dependence on f_{em}





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

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):

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

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

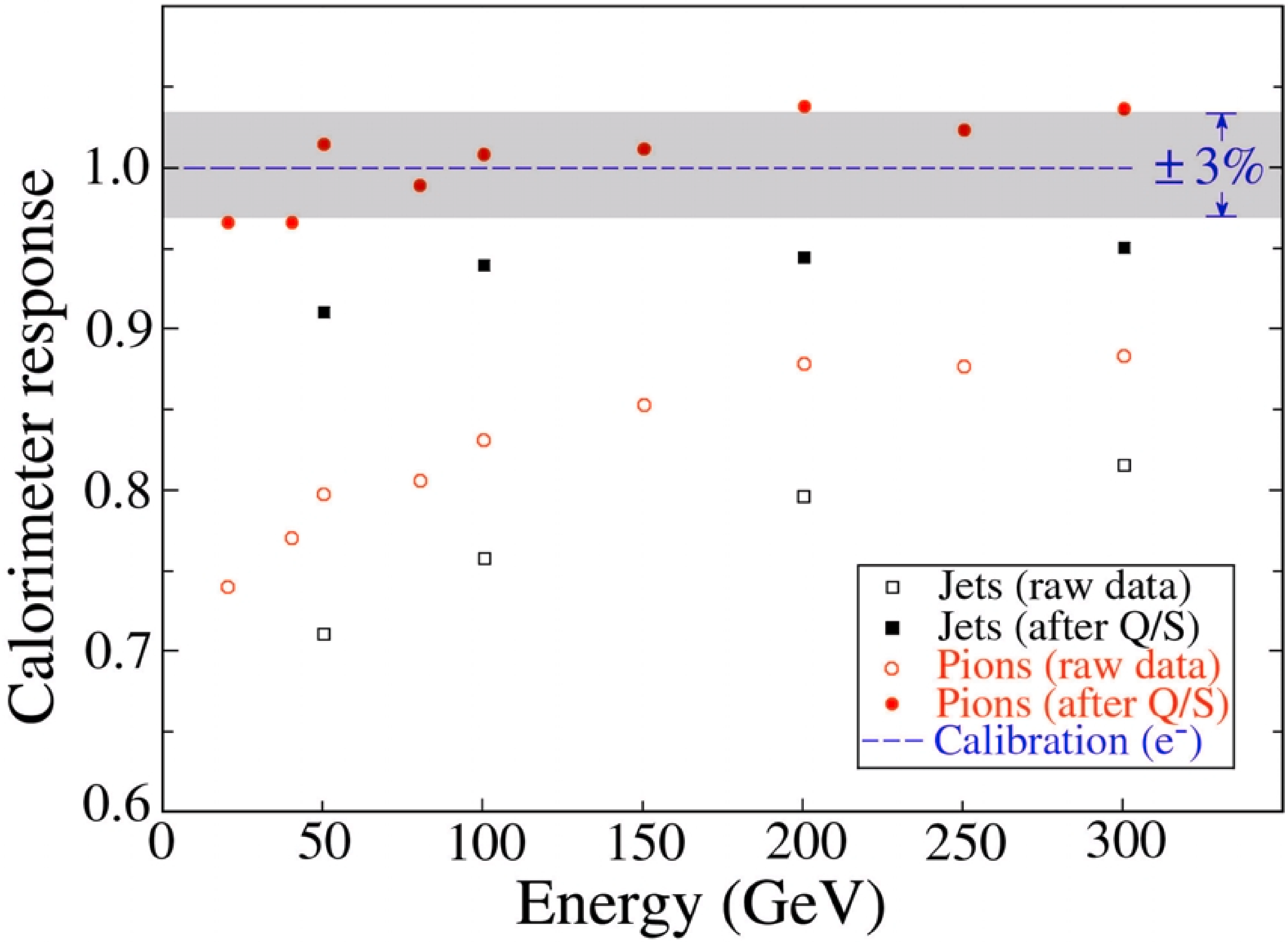
$$\boxed{\frac{Q}{S} \;=\; \frac{R_Q}{R_S} \;=\; \frac{f_{\rm em} + 0.20\ (1 - f_{\rm em})}{f_{\rm em} + 0.77\ (1 - f_{\rm em})}}$$

- Correction to measured signals (regardless of energy):

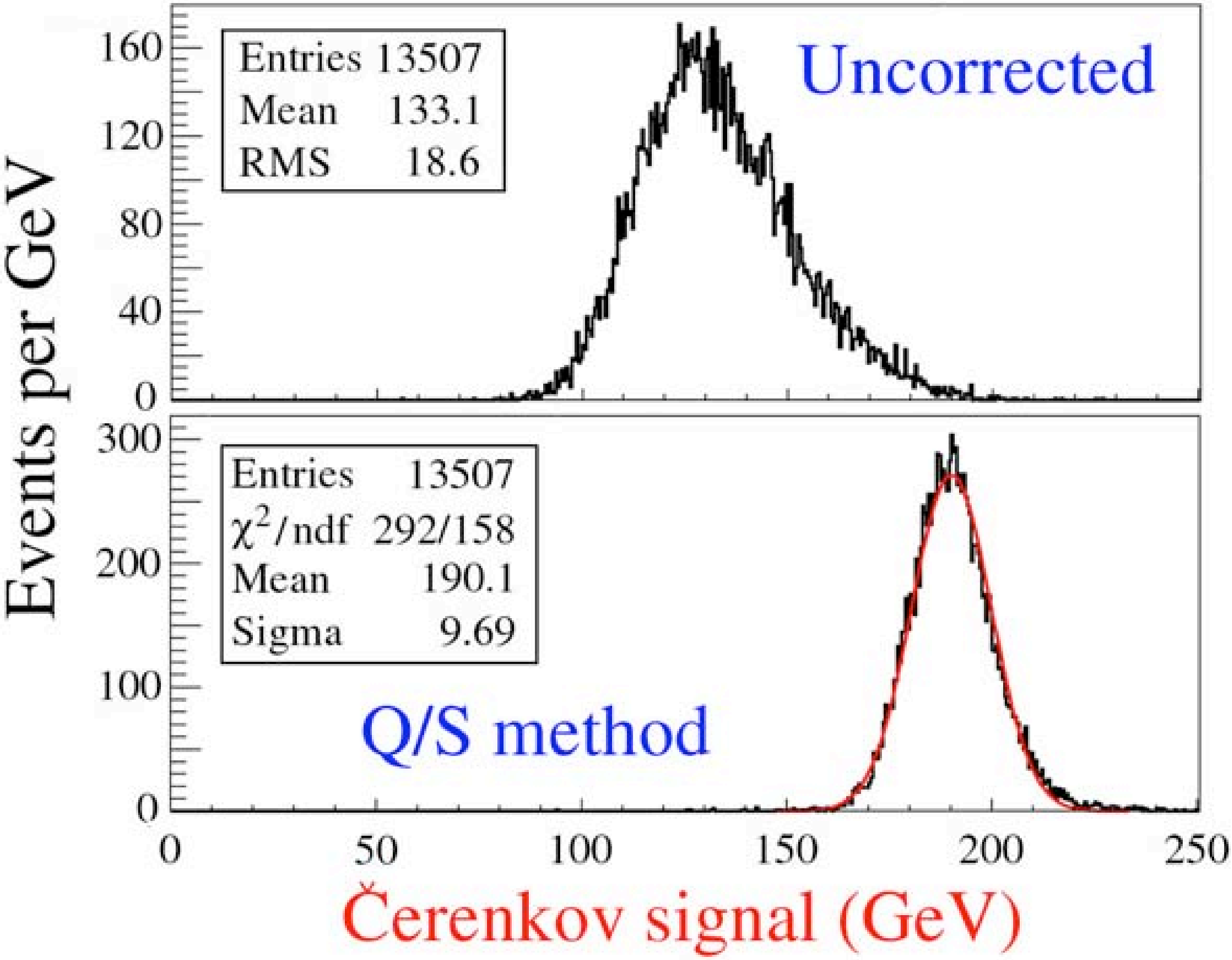
$$\boxed{S_{\rm corr} \;=\; S_{\rm meas}\left[\frac{1 + p_1/p_0}{1 + f_{\rm em}\cdot p_1/p_0}\right]} \;, \qquad {\rm with} \quad \frac{p_1}{p_0} \;=\; (e/h)_S \;-\; 1$$

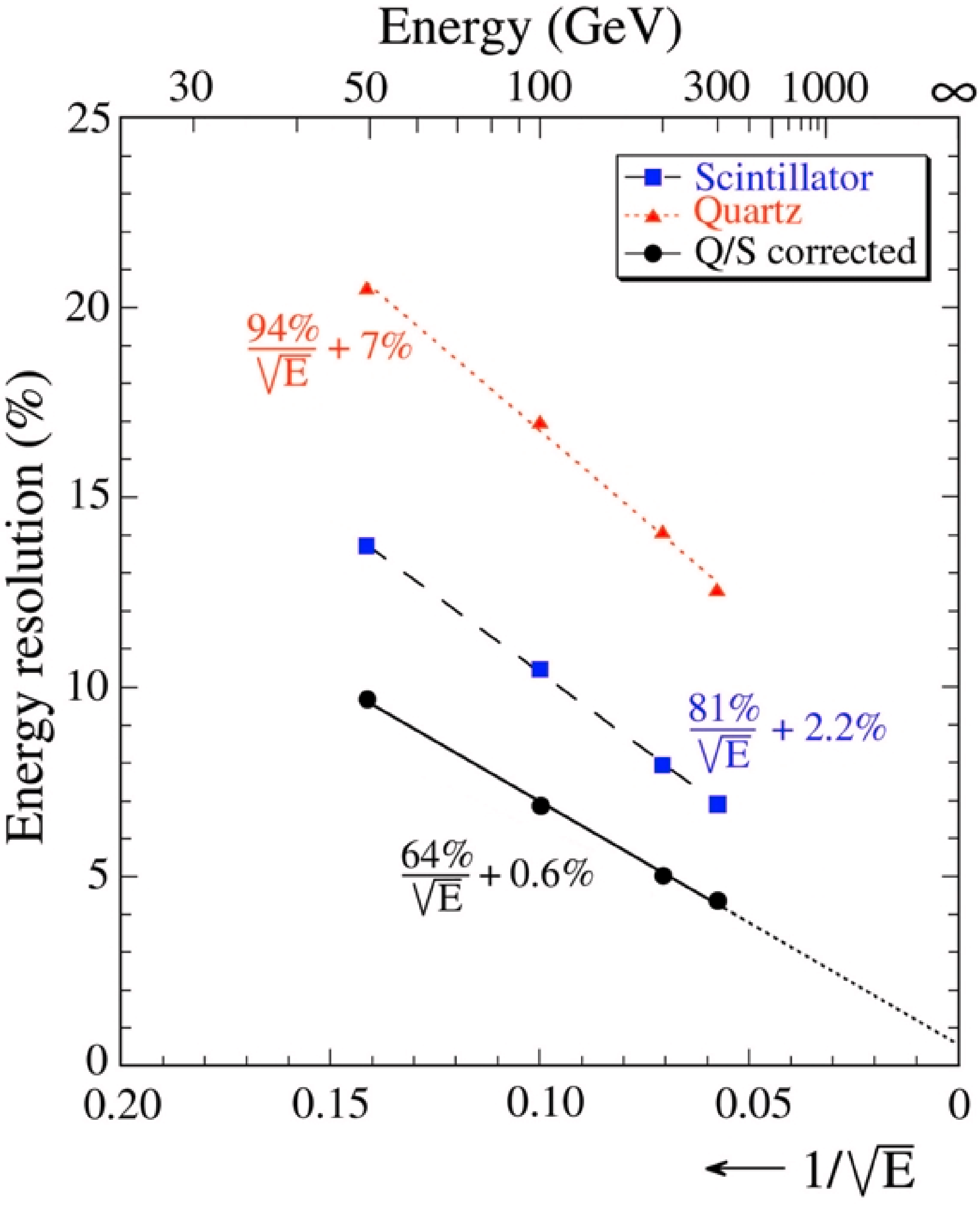
$$\boxed{Q_{\rm corr} \;=\; Q_{\rm meas}\left[\frac{1 + p_1/p_0}{1 + f_{\rm em}\cdot p_1/p_0}\right]} \;, \qquad {\rm with} \quad \frac{p_1}{p_0} \;=\; (e/h)_{\check{C}} \;-\; 1$$

Hadronic response: Effect Q/S correction



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





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

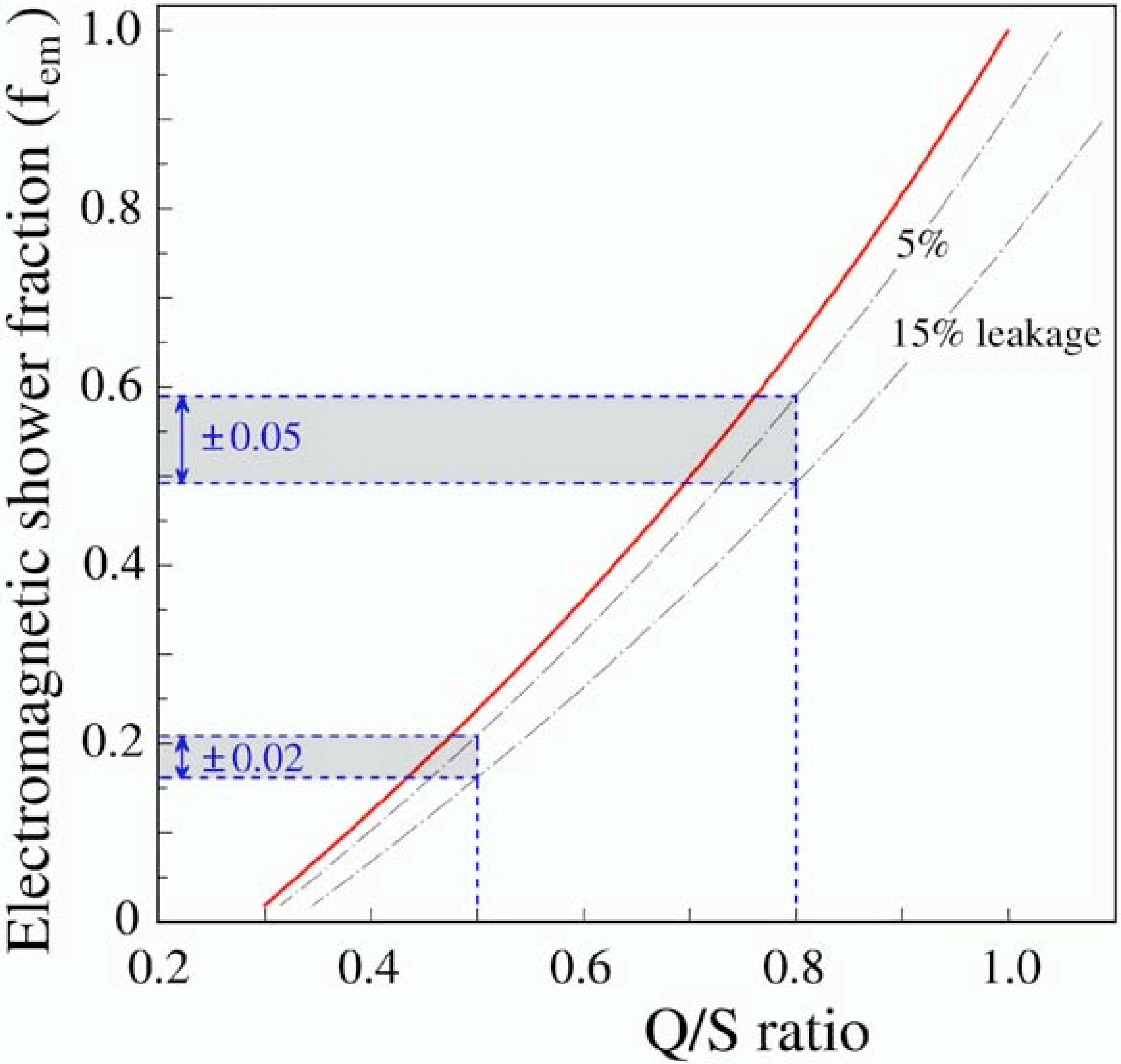
- These, and many other, experimental results are described in 3 papers:

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

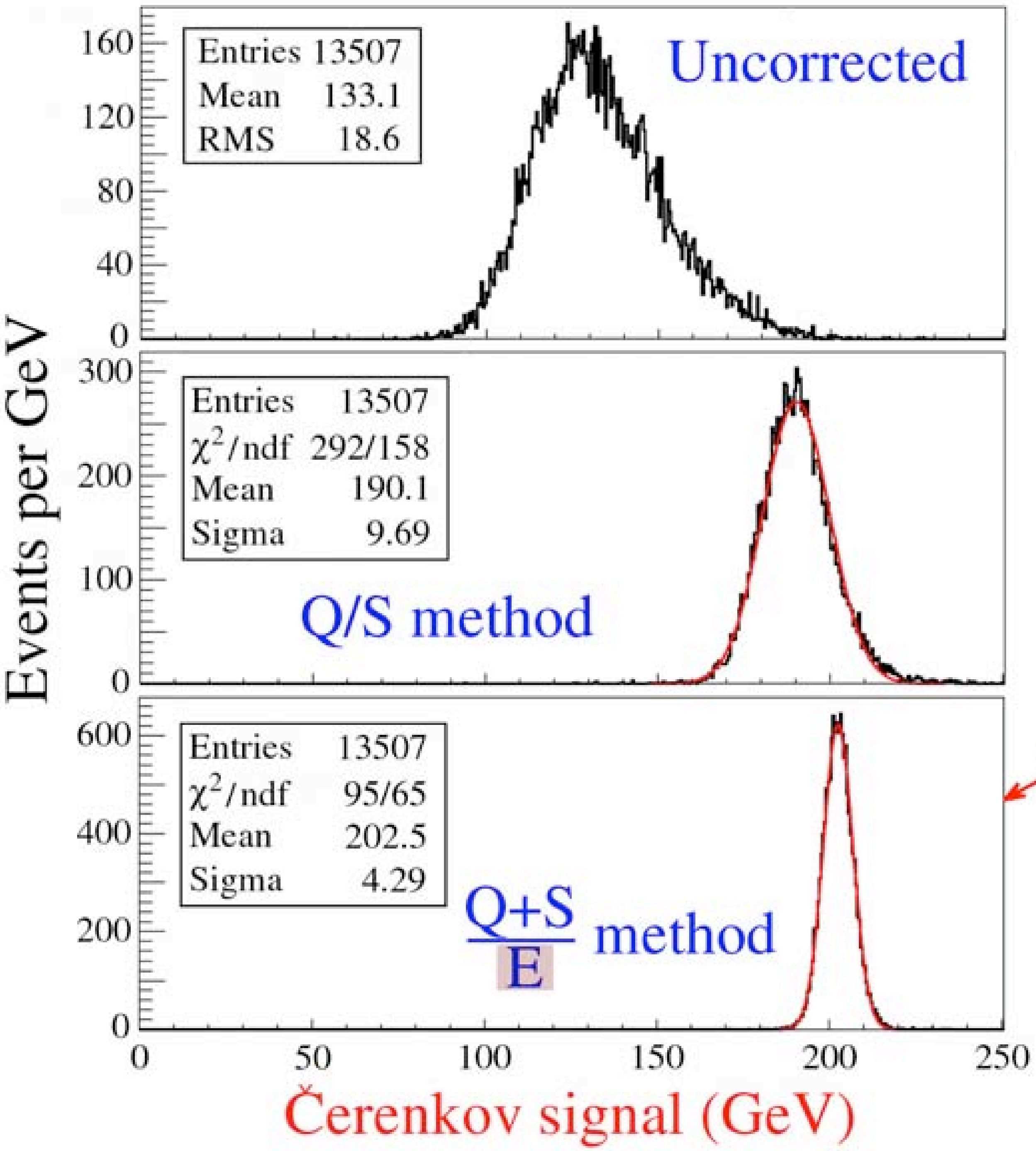
How to improve DREAM performance

- Build a larger detector ⟶ *reduce effects side leakage*

DREAM: The importance of leakage and its fluctuations



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



Knowledge of jet energy used

How to improve DREAM performance

- Build a larger detector ⟶ *reduce effects side leakage*

- *Increase Čerenkov light yield*

  DREAM: 8 p.e./GeV ⟶ fluctuations contribute 35%/$\sqrt{E}$

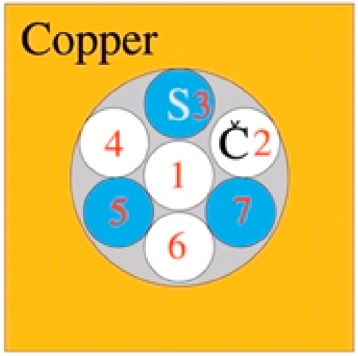
  No reason why DREAM principle is limited to fiber calorimeters

  Homogeneous detector ?!

  ⟶ *Need to separate the light into its Č, S components*

DREAM 2

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



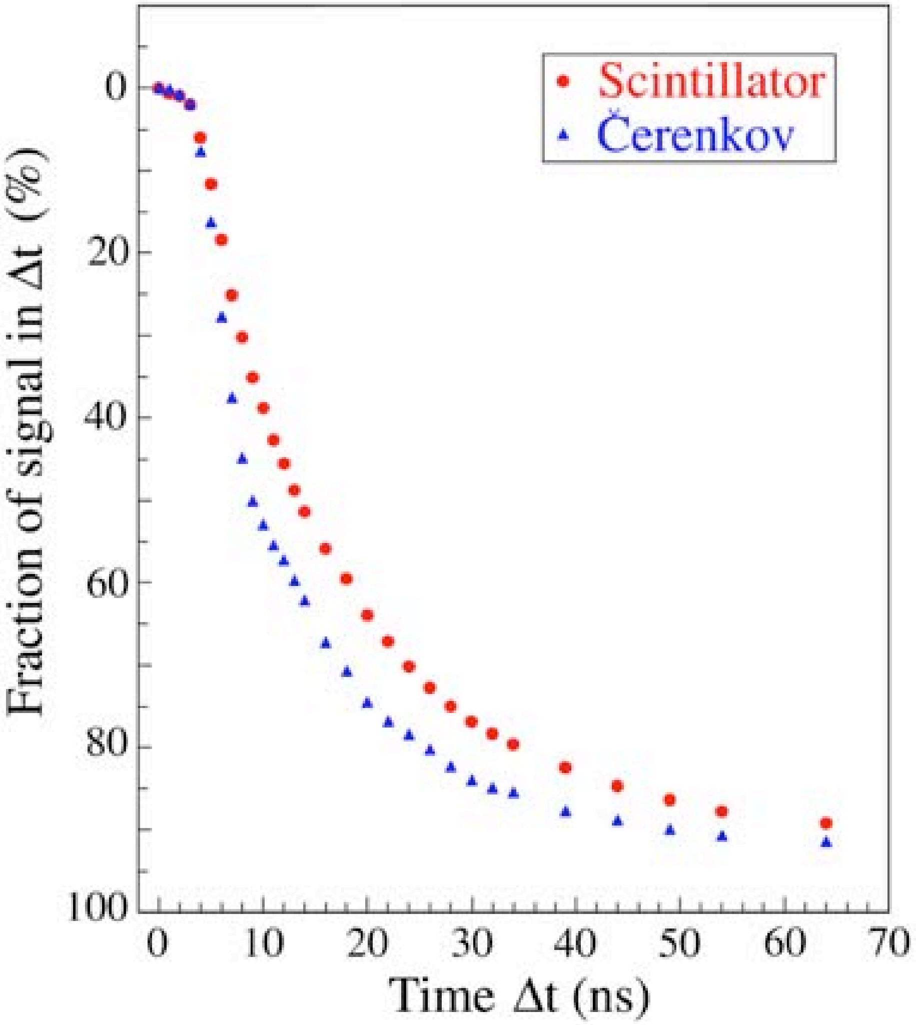
5+7	PMT1 (S)
2+4	PMT2 (Č)
1+3+6	PMT3 (mixed)

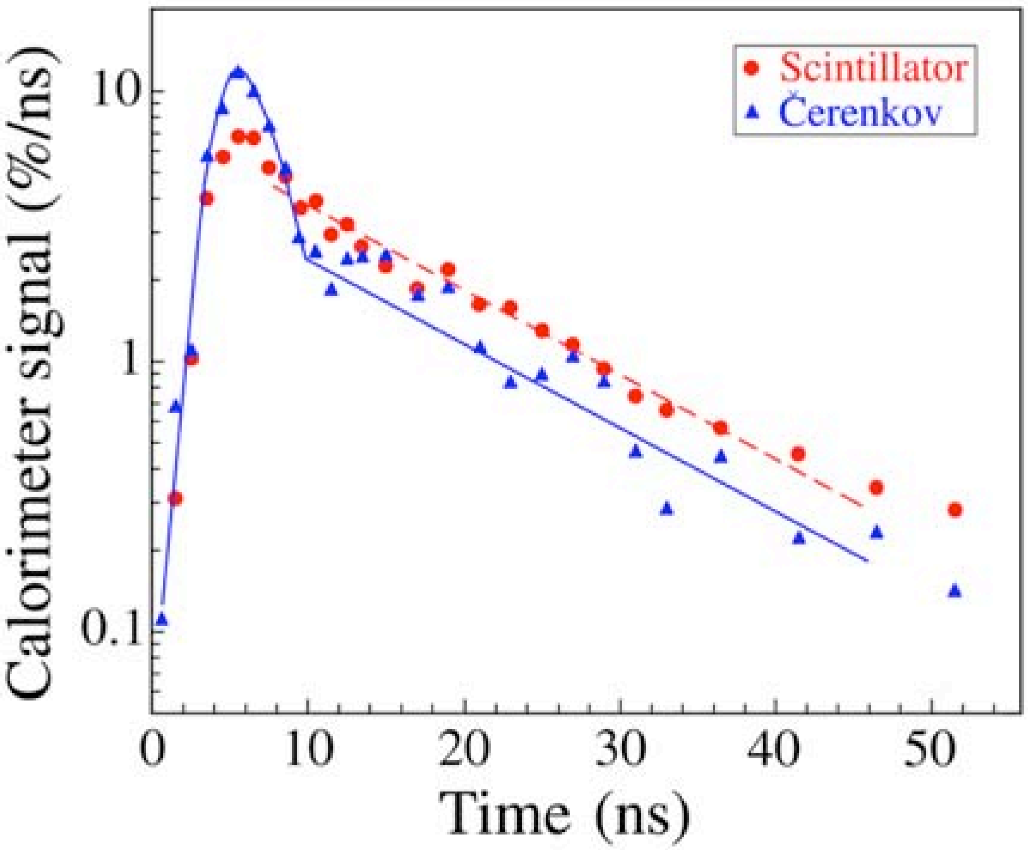
Also:

Fibers read out from both ends

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

DREAM - Differences in signal time structure

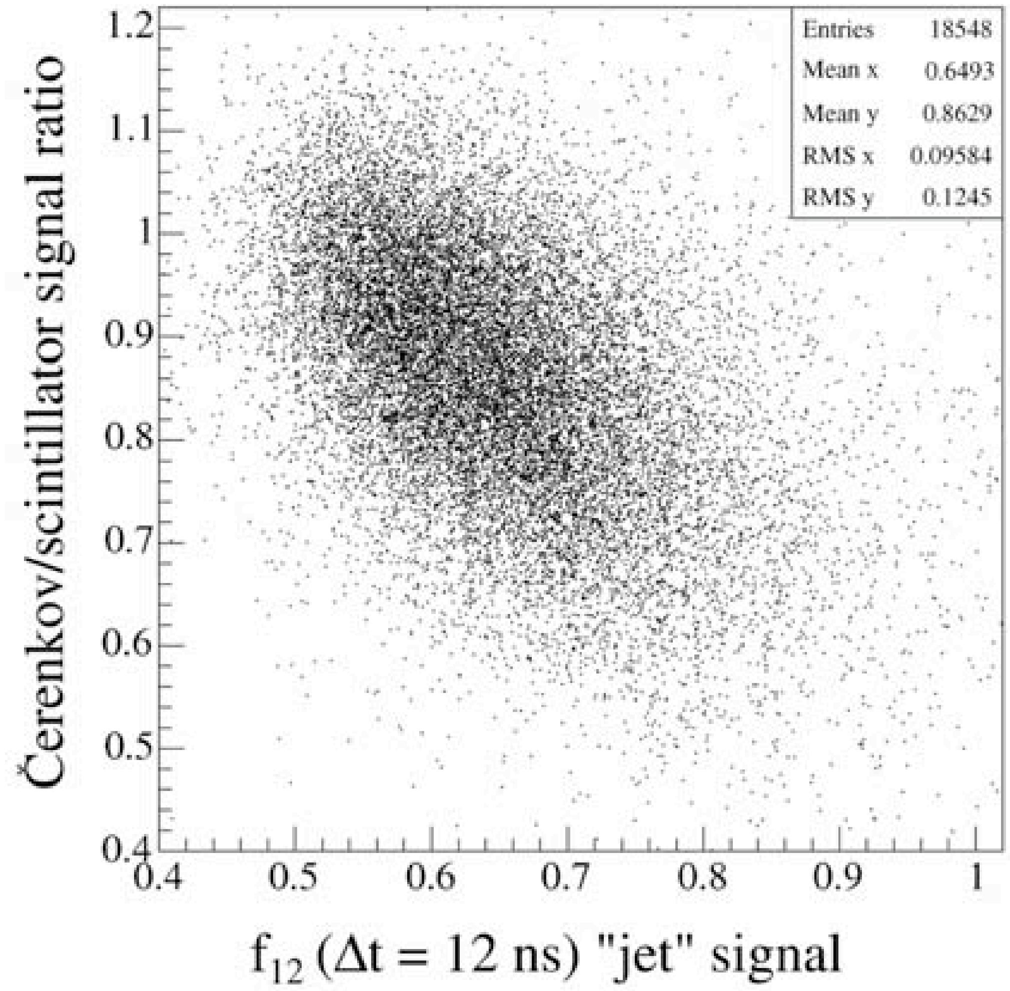




NIM A550 (2005) 185

DREAM: Separation of mixed signal into Č/S components

Use time structure event by event



Fraction of signal observed in first 12 ns is measure for Čerenkov/Scintillator ratio

Limiting factor:
Čerenkov light yield
(8 p.e./GeV)

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How to improve DREAM performance

- Build a larger detector ⟶ *reduce effects side leakage*

- *Increase Čerenkov light yield*

  DREAM: 8 p.e./GeV ⟶ fluctuations contribute 35%/$\sqrt{E}$

  No reason why DREAM principle is limited to fiber calorimeters

  Homogeneous detector ?!

  ⟶ *Need to separate the light into its Č, S components*

- For ultimate hadron calorimetry (15%/$\sqrt{E}$): *Measure E_{kin} (neutrons)*

  Is correlated to nuclear binding energy loss (invisible energy)

  Can be measured with third type of fiber : TREAM

Summary

- New developments in calorimetry are primarily driven by ILC/CLIC. Some of the R&D results may be useful for SLHC.
- Calorimeter design of ATLAS/CMS was driven by $H^{\text{o}} \rightarrow \gamma\gamma$. May not be the same choice for the SLHC era. Redesign calorimeter system with focus on hadronic performance?
- Increased luminosity will have major consequences for calorimeters, in terms of radiation damage and operating conditions.
- The DREAM approach seems to combine the advantages of compensation with a reasonable amount of design flexibility.

(pet pief) Longitudinal segmentation is asking for trouble,
GEANT is (unfortunately) useless for hadron calorimetry

Backup slides

1) Digital calorimetry
2) Fluctuations in hadron showers
3) Monte Carlo benchmark p/pi
4) Monte Carlo benchmark n
5) Calibration CDF

Saturation in "digital" calorimeters (wire chamber readout)

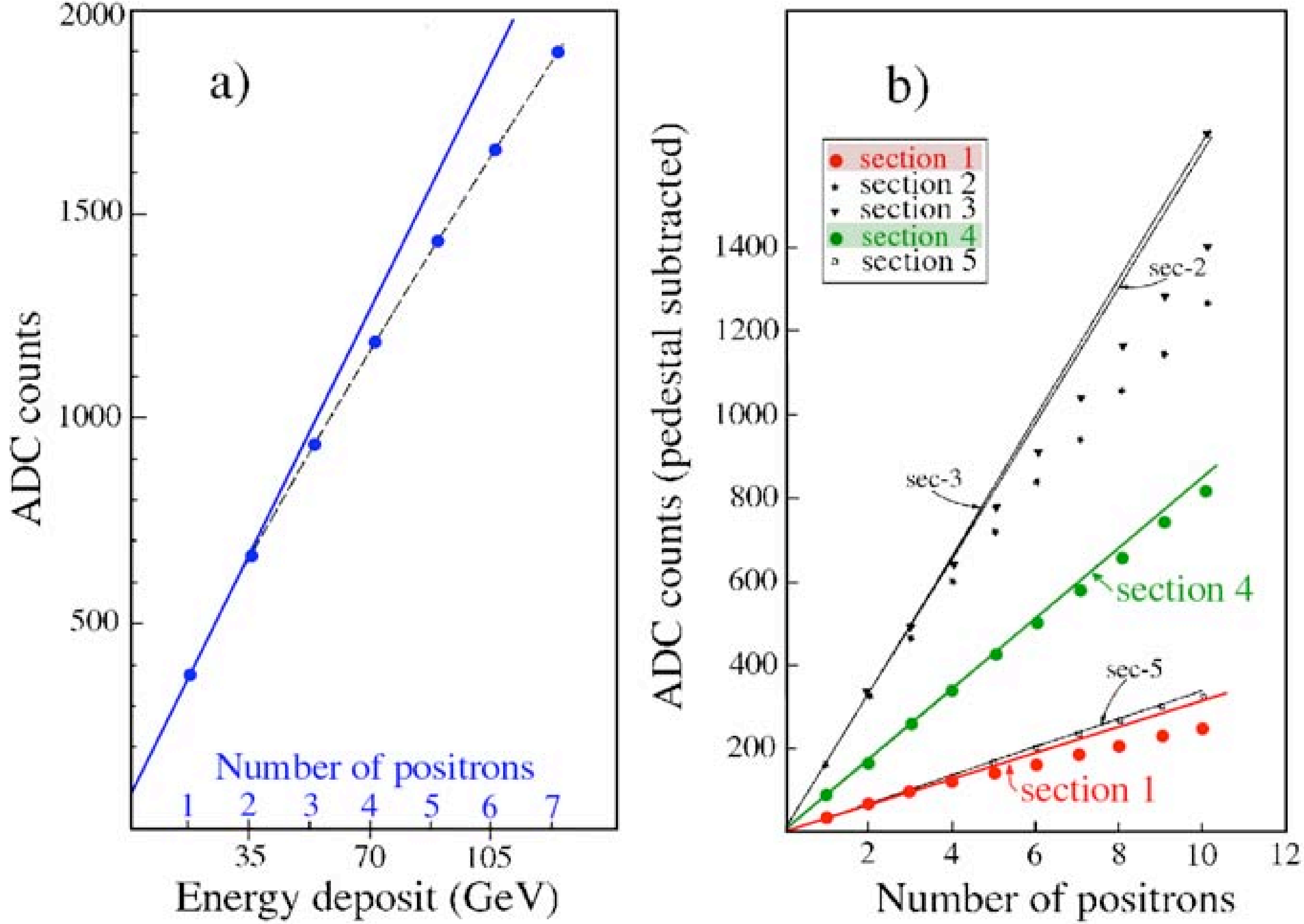
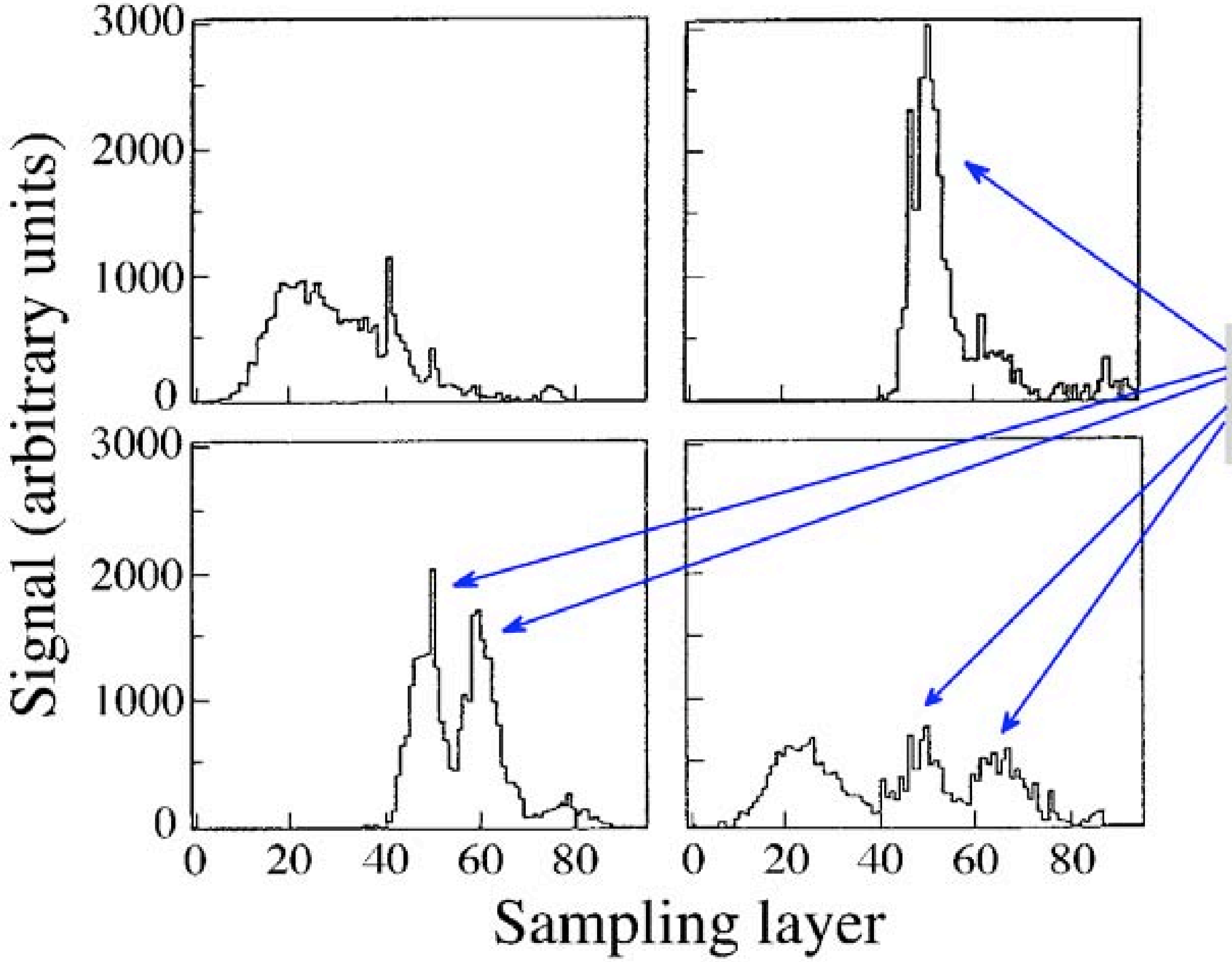


FIG. 3.2. Average em shower signal from a calorimeter read out with gas chambers operating in a "saturated avalanche" mode, as a function of energy. From: NIM 205 (1983) 113.

Hadronic shower profiles: Fluctuations!



π° production
in HAD section

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].

Benchmark data for hadronic Monte Carlo

Test of π^0 production modelling

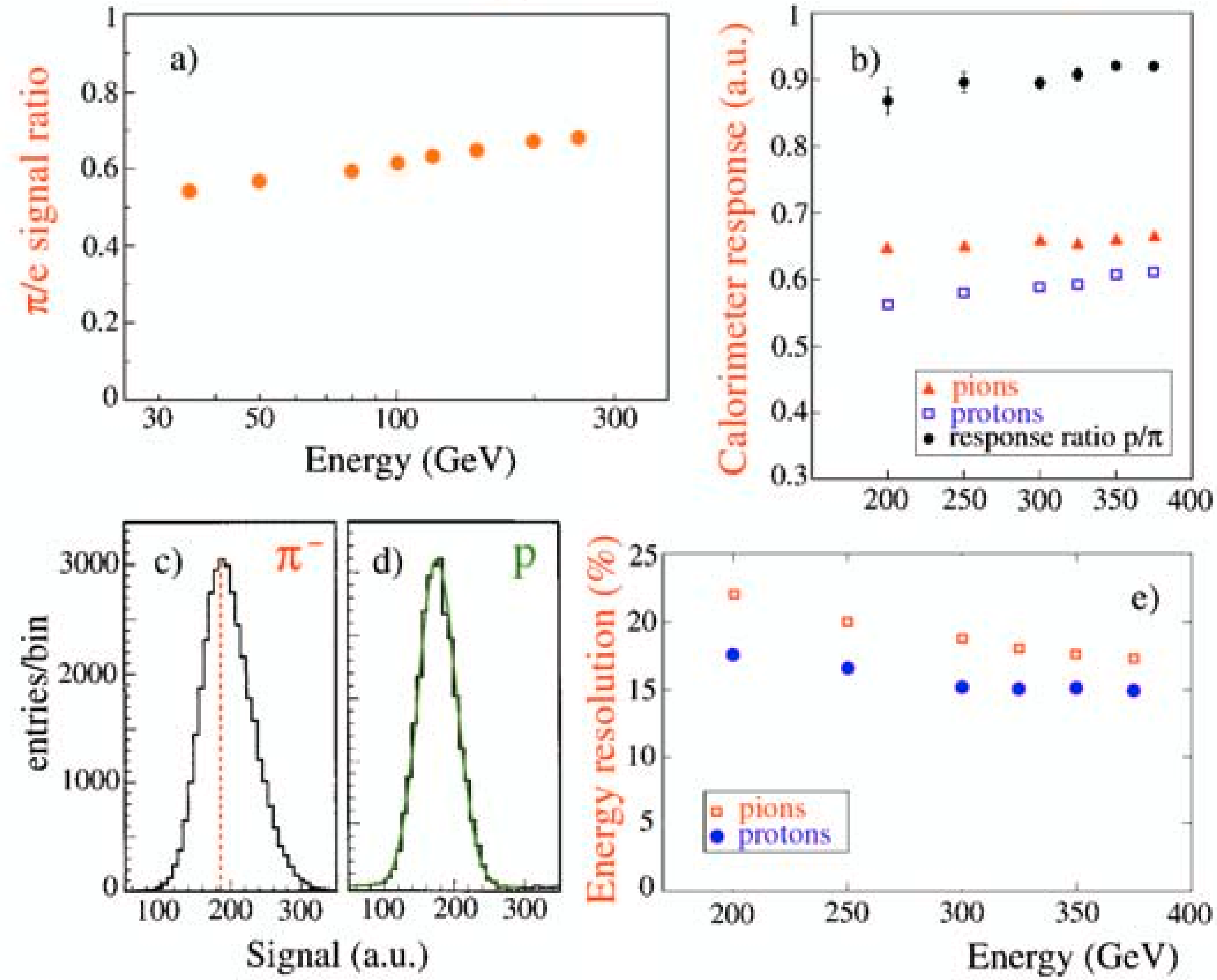


FIG. 8.27. Calorimeter benchmark data for testing the correct implementation of π^0 production in Monte Carlo simulations of hadronic shower development. Experimental data from a copper/quartz-fiber calorimeter, showing the π/e signal ratio as a function of energy (a), the response to protons and pions, 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

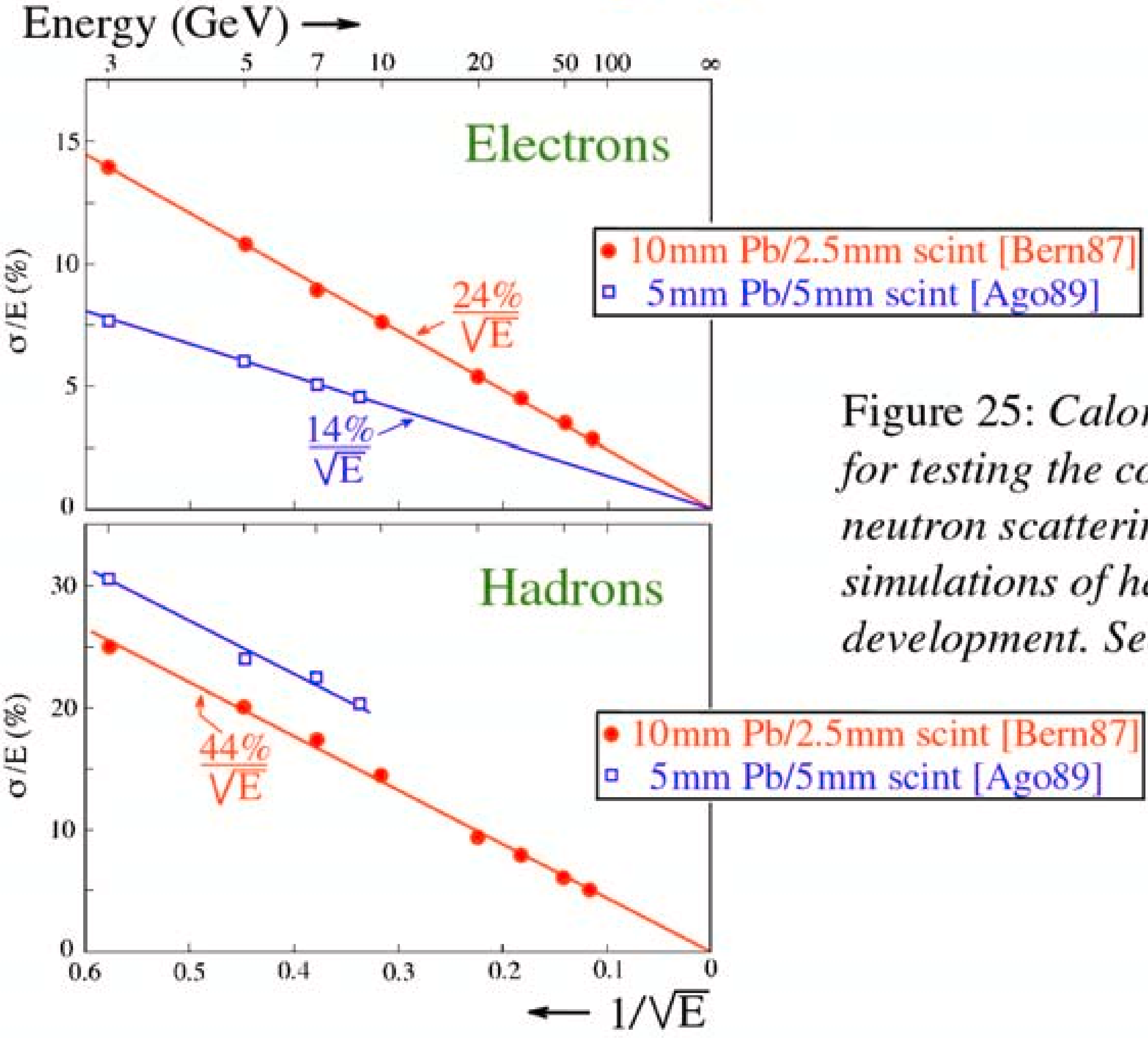


Figure 25: *Calorimeter benchmark data for testing the correct implementation of neutron scattering data in Monte Carlo simulations of hadronic shower development. See text for details.*

Effects of miscalibration: Mass reconstruction

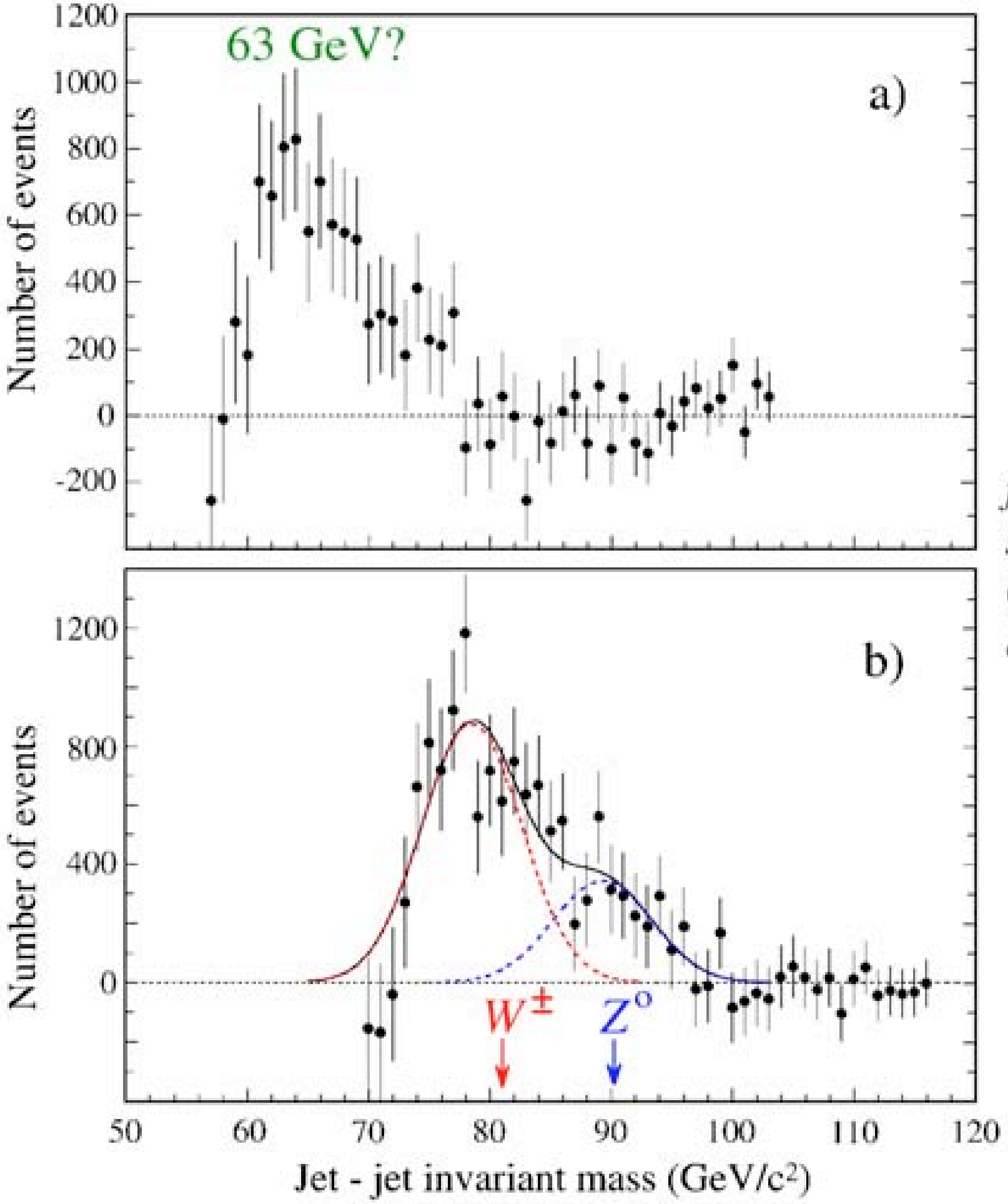


Figure 9: *The jet-jet invariant mass distribution for CDF Run Ic. The background has been subtracted. Results are shown for the standard CDF calbration constants* (a) *and for our alternative calibration scheme* (b).

From CDF note 6530 (2002)