HADRON CALORIMETRY

What have we learned since CALOR 1 from DREAM and other projects?

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Hadron Calorimetry

What have we learned since CALOR 1?

Outline:

- *The status-quo in 1990*
- *What has been learned since?*
- *How to make further progress?*
- *Summary*

The status quo in 1990

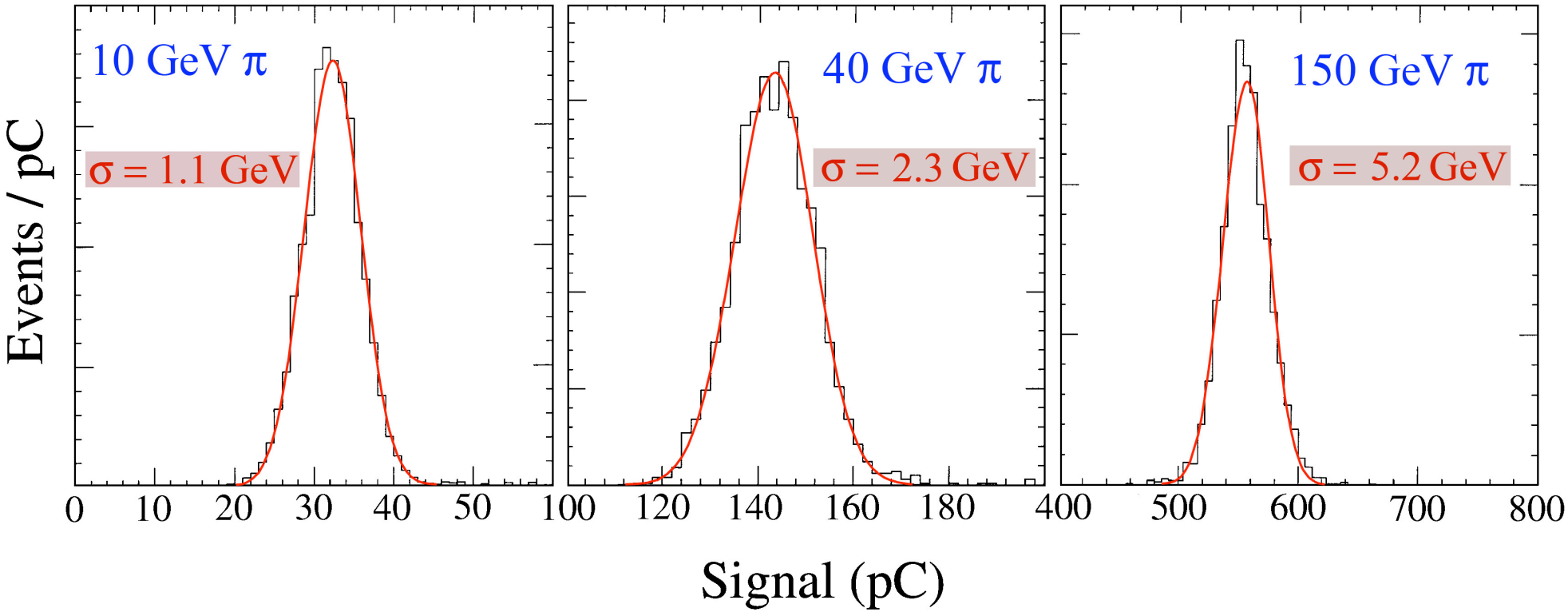
- *Reasons for poor hadronic performance of non-compensating calorimeters understood*

- *Compensation mechanisms fully understood*

  ^{238}U absorber (fission $\longrightarrow$ compensation for invisible energy loss)
  is neither needed nor sufficient

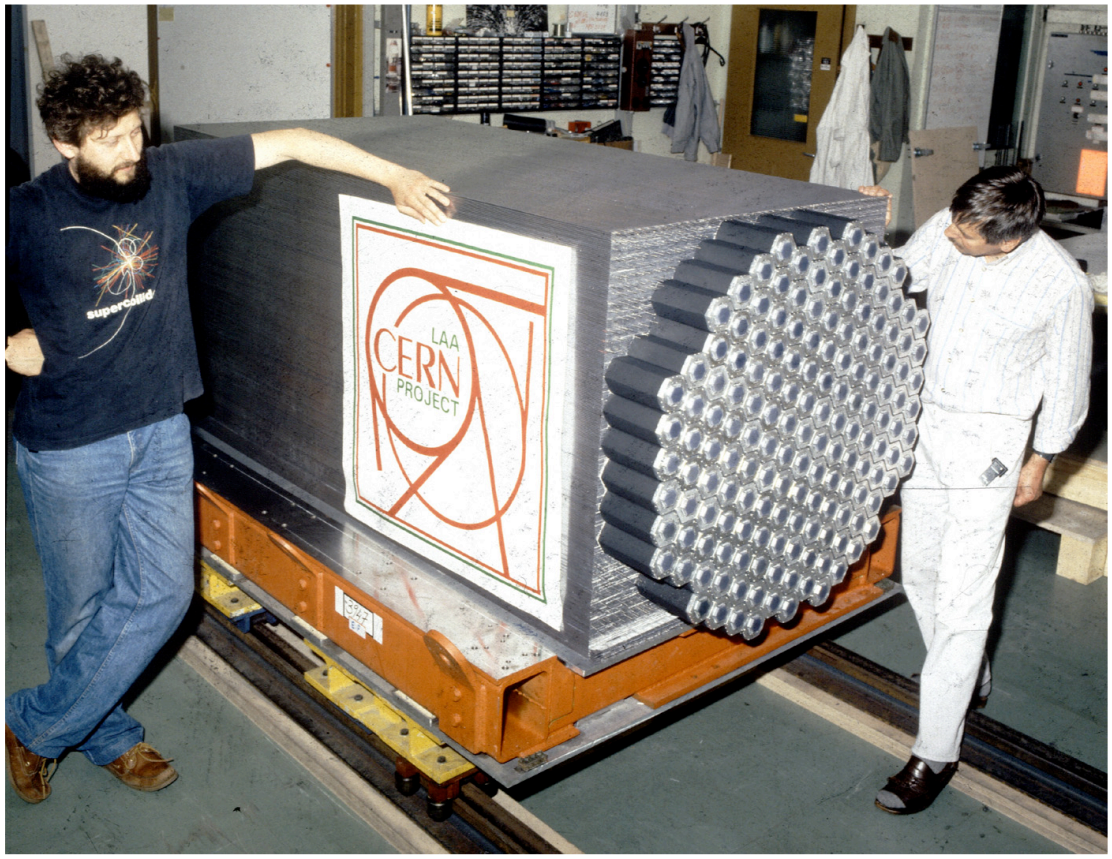
  Experimentally demonstrated with Pb/scintillator calorimeters (ZEUS, SPACAL)

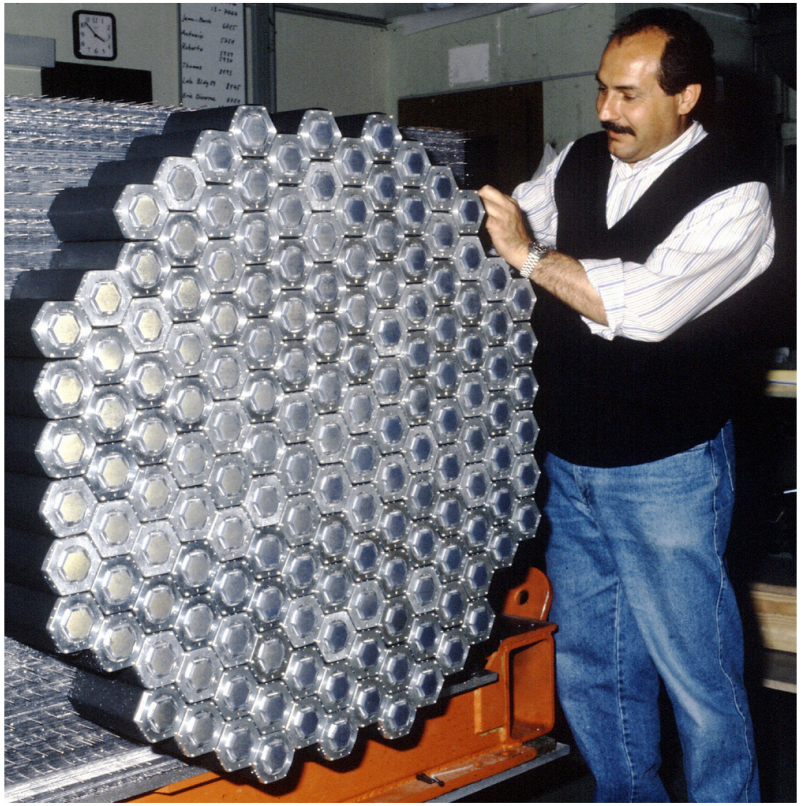
Hadronic signal distributions in a compensating calorimeter



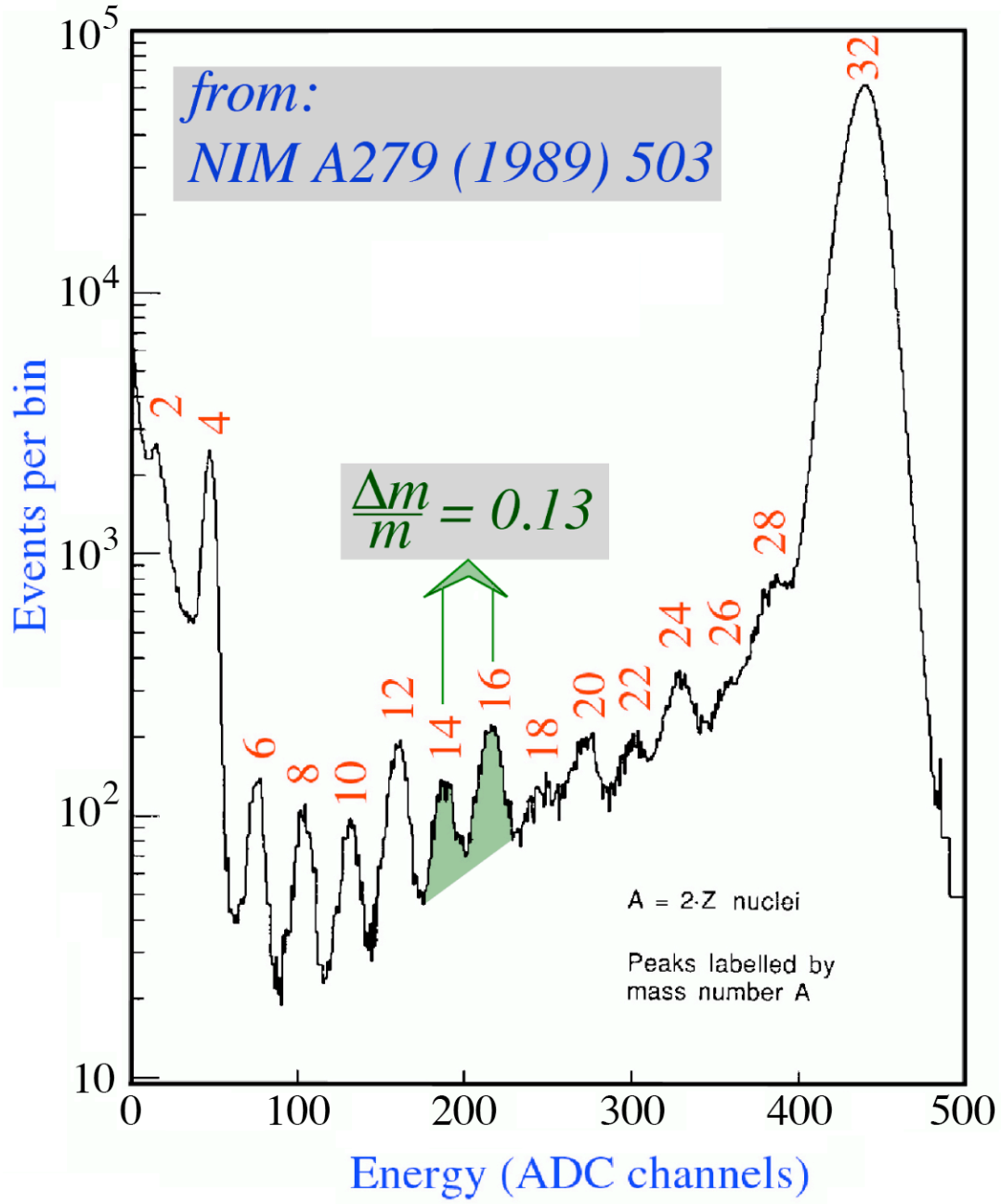
from: NIM A308 (1991) 481

SPACAL 1989





Hadron calorimetry in practice
Energy resolution in a compensating calorimeter



W/Z separation:

$\frac{\Delta m}{m} \sim 0.11$

The WA80 calorimeter as high-resolution spectrometer. Total energy measured with the calorimeter for minimum-bias events revealed the composition of the momentum-selected CERN heavy-ion beam

Hadron calorimetry in practice
Energy resolution for a non-compensating calorimeter

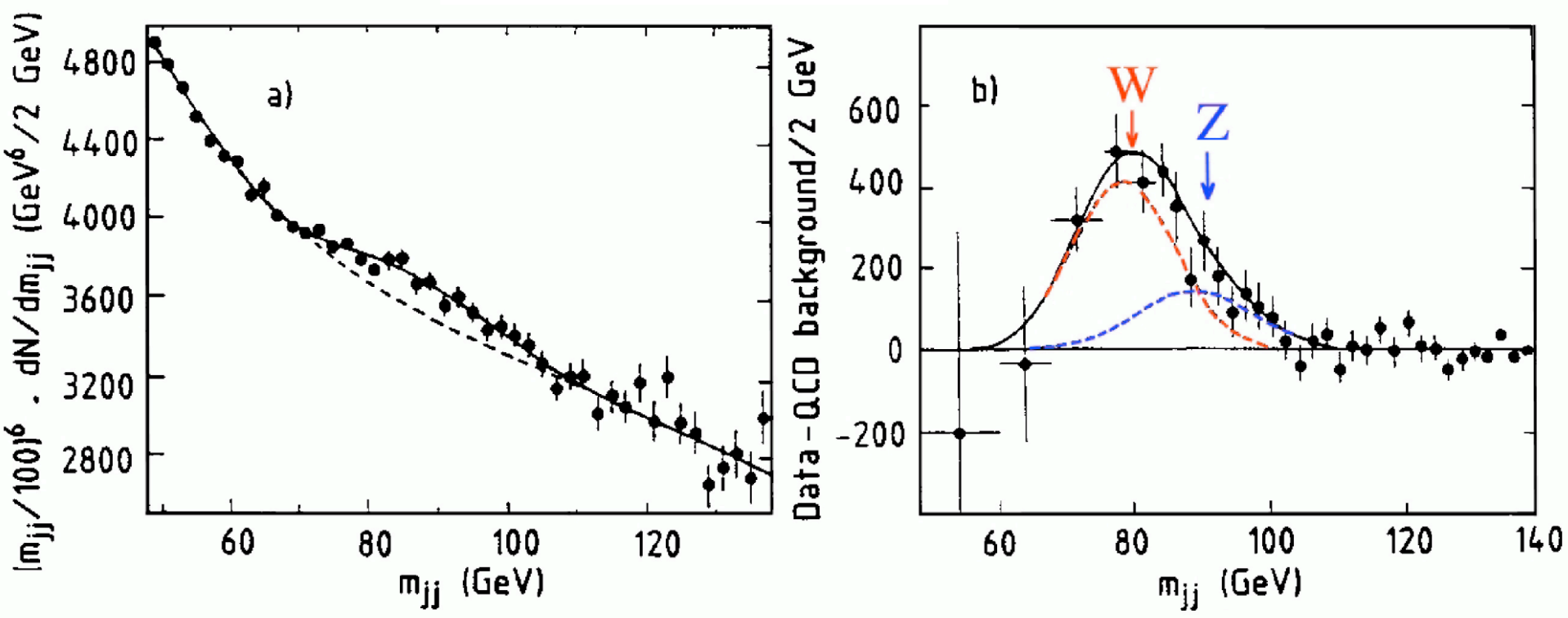


FIG. 7.50. Two-jet invariant mass distributions from the UA2 experiment [Alit 91]. Diagram *a*) shows the measured data points, together with the results of the best fits to the QCD background alone (*dashed curve*), or including the sum of two Gaussian functions describing $W, Z \rightarrow q\bar{q}$ 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].

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* (SPACAL: $13\%/\sqrt{E}$, ZEUS: $18\%/\sqrt{E}$)
- Compensation relies on detecting neutrons
  → Large *integration volume*
  → Long *integration time* (~50 ns)

The DREAM project was started with the goal

to IMPROVE these results!

i.e.

- *Better em energy resolution*
- *Smaller integration volume*
- *Faster charge collection*

- *All this while maintaining (or further improving) the excellent hadronic performance*

The status quo in 1990

- *Reasons for poor hadronic performance of non-compensating calorimeters understood*

- *Compensation mechanisms fully understood*

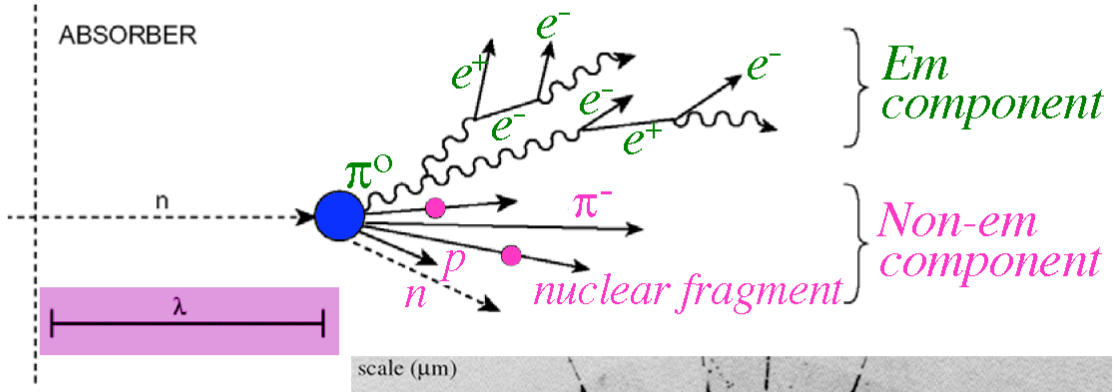
  ^{238}U absorber (fission $\longrightarrow$ compensation for invisible energy loss) is neither needed nor sufficient

  Experimentally demonstrated with Pb/scintillator calorimeters (ZEUS, SPACAL)

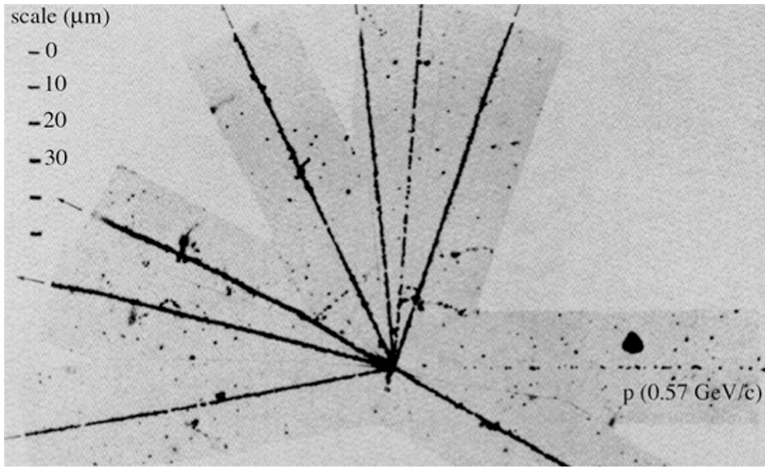
- ***Monte Carlo simulations had provided some clues (T. Gabriel et al.)***
  e.g. suppression of em response (e/mip < 1),
  importance of nuclear reactions in absorption process

The physics of hadronic shower development

- *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%)

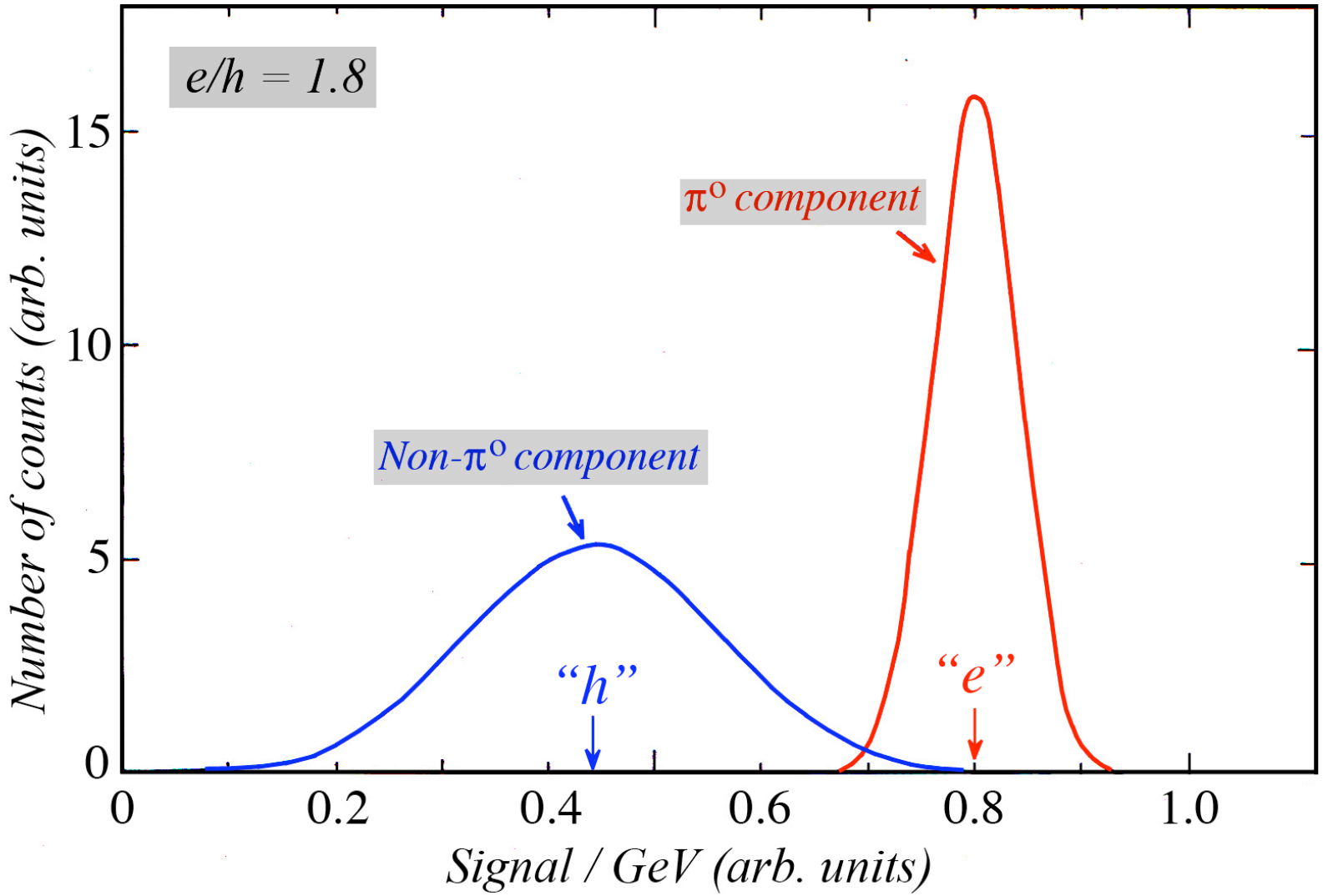


- *Important characteristics for hadron calorimetry:*
  - *Large, non-Gaussian fluctuations in energy sharing em/non-em*
  - *Large, non-Gaussian fluctuations in "invisible" energy losses*

(e.g. 100 GeV π: energy resolution ZEUS 3.5%, D0 7%)

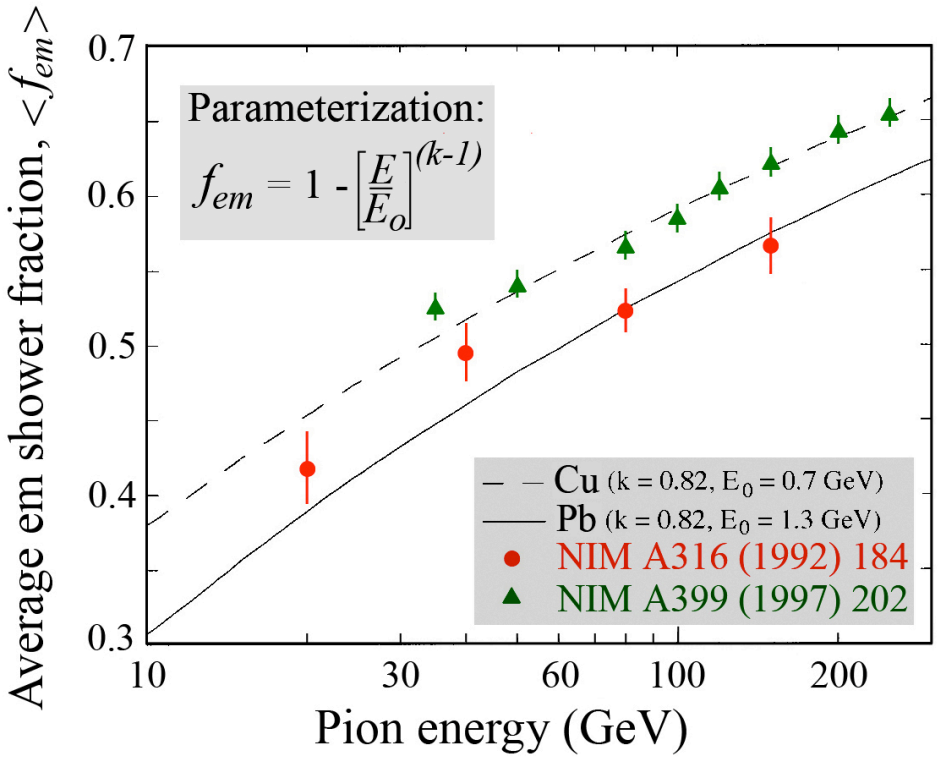
The calorimeter response to the two shower components is NOT the same

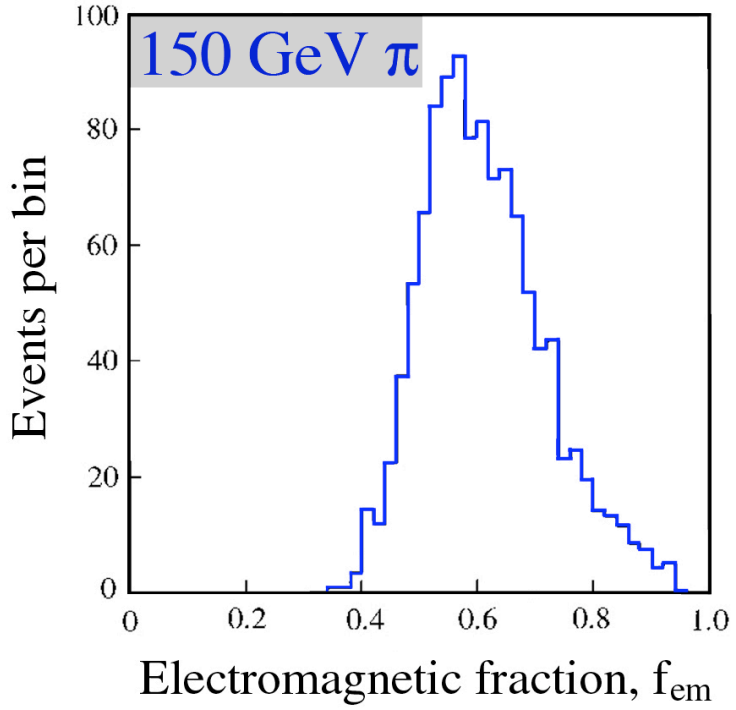
(mainly because of nuclear breakup energy losses in non-π^o component)



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

i.e. the fraction of the shower energy deposited by π^os





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

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

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

- *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*, *which does NOT scale as* $(\sqrt{E})^{-1}$
  - *etc*.
  -

What has been learned since 1990?

What has been learned since 1990?

From Monte Carlo simulations:

NOTHING

(of meaningful importance)*

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* *Monte Carlo simulations of em shower development were, for example, crucial for solving complicated calibration problems in ATLAS, AMS*

Monte Carlo simulations of hadronic shower development did, for example, NOT foresee the "spike" problems in the CMS ECAL

GEANT4 simulations of hadron showers

A few recent quotes from the published literature:

On pion detection in ATLAS: NIM A607 (2010) 372

> The measurements were compared to simulated results obtained using Geant 4. The simulation predicts a larger response and a lower energy resolution than what was measured.

On hadronic shower profiles (ATLAS):
NIM A615 (2010) 158

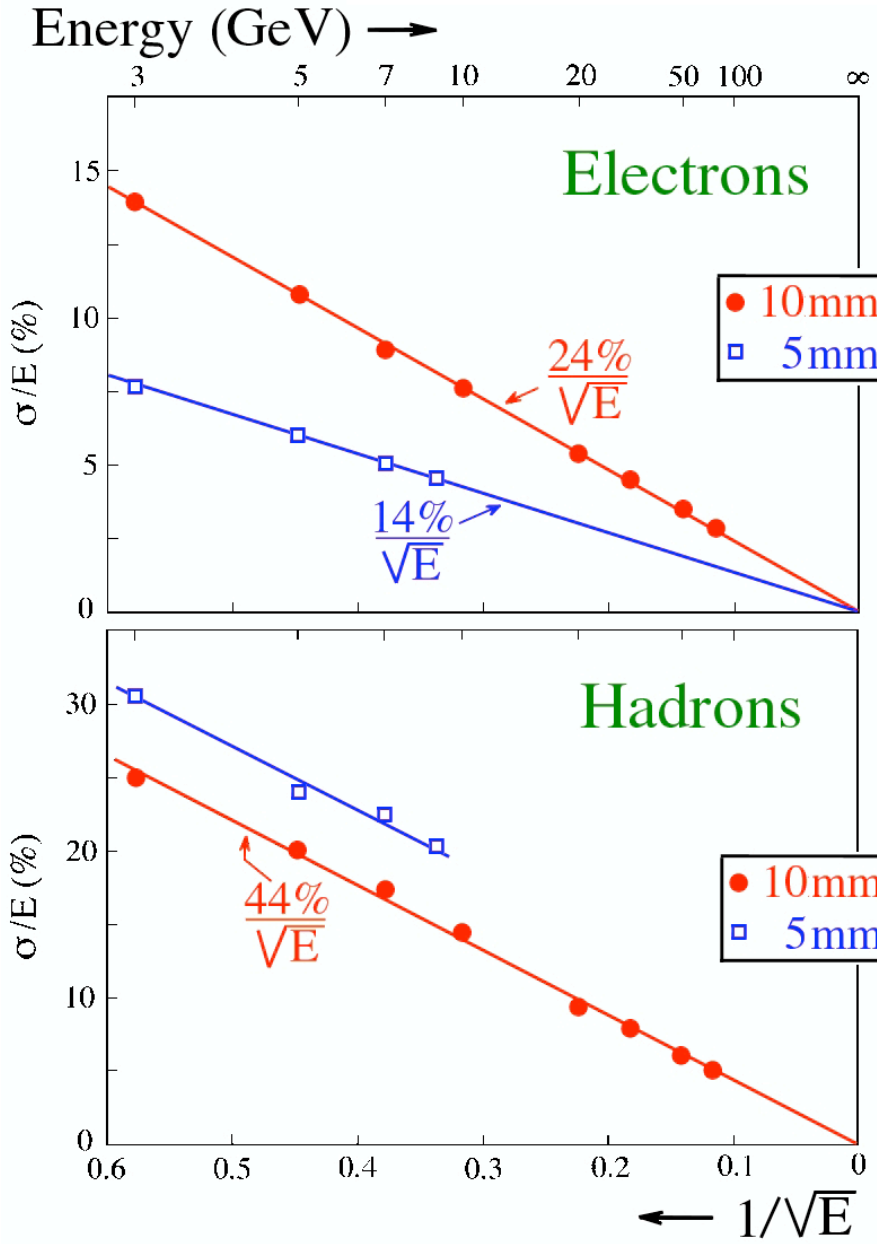
> The experimental data have been compared with the results of GEANT4 simulation, using two basic physics lists, LHEP and QGSP, as well as extensions where the Bertini intra-nuclear cascade is used. Neither of these physics lists is able to reproduce the data in the whole energy range satisfactorily.

See also talks by R. Poeshl & F. Simon at this conference

Benchmark data for hadronic shower MC simulations

Sensitive test for correct implementation of nuclear effects

(~80% of non-em sector!)



Experimental data from ZEUS:

NIM A262 (1987) 229

NIM A274 (1989) 134

NO GEANT simulation has even come close to reproducing these data

What have we learned since 1990?

As a result,
development of the hadron calorimetry for the LHC experiments took place

without meaningful guidance from MC simulations

and consequences had to be expected

Consequences for LHC calorimeters

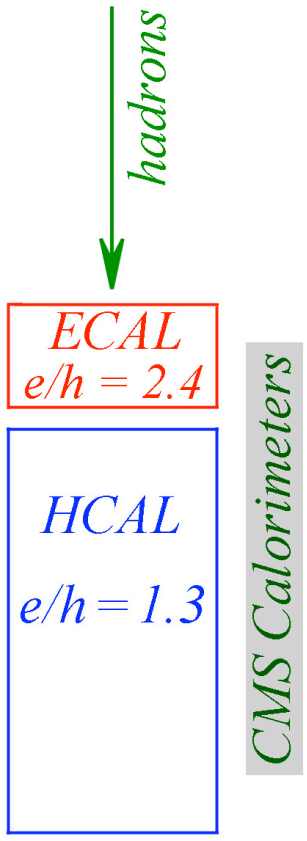
Hadronic response and signal linearity (CMS)

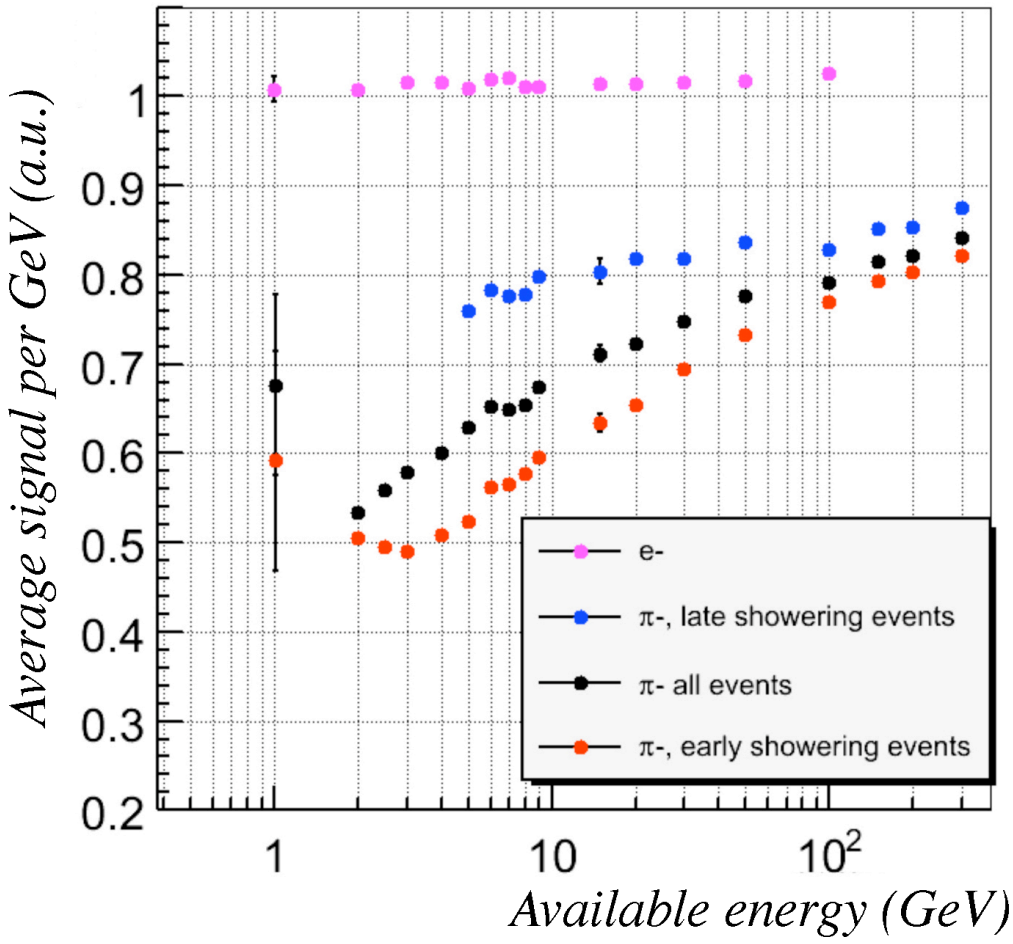
CMS pays a price for its focus on em energy resolution

ECAL has $e/h = 2.4$, while HCAL has $e/h = 1.3$

→ *Response depends strongly on starting point shower*

Data from: CMS note 2007/012





What has been learned since 1990?

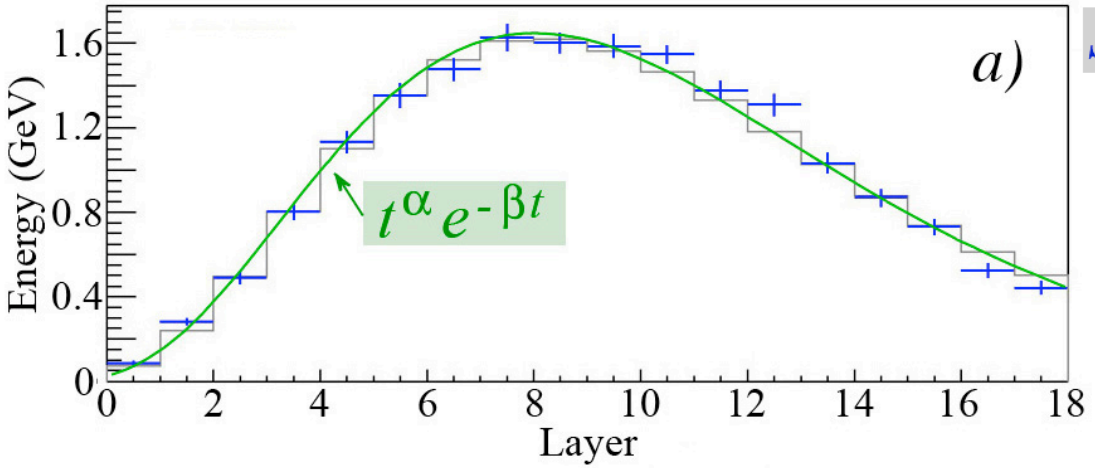
The enormous complications that arise when calibrating a longitudinally segmented (sampling) calorimeter

The problem:

- *In the absorption process, the energy is deposited by*
  - *electrons, positrons, photons (em)*
  - *electrons, positrons, photons, pions, protons, neutrons (had)*
- *In a given sampling calorimeter, the sampling fraction is typically very different for these different particles*
  Also, the composition of the shower changes as the shower develops
- *As a result, the relationship between measured signal and deposited energy (calibration constant) varies with depth, and is especially for hadrons in a given detector segment different for each event*

Calibration misery of longitudinally segmented devices

Example: AMS (em showers!)



Source: NIM A490 (2002) 132

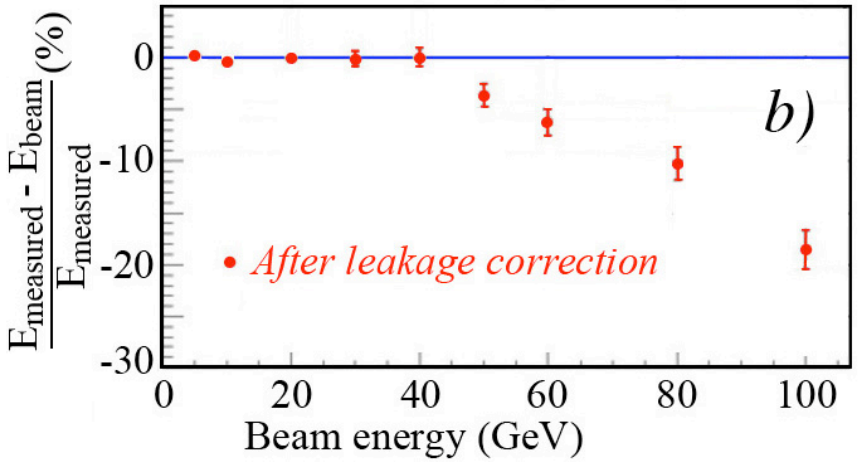
Pb/scintillating fiber (18 layers)

Calibrated with mip's:
11.7 MeV/layer

Leakage estimated from fit to measured shower profile

However:
In em shower, signal per GeV decreases as shower develops

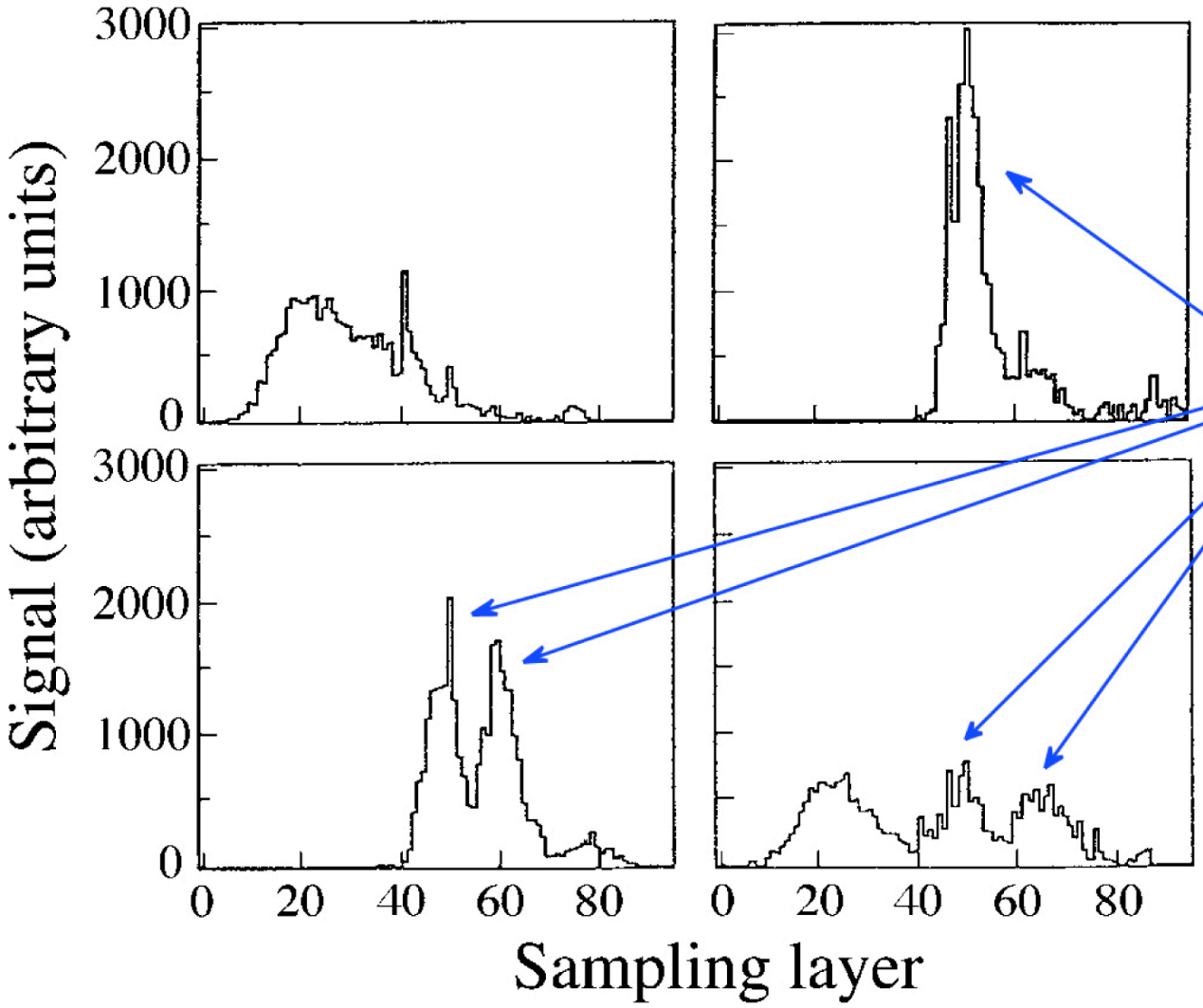
→ *(leakage) energy based on measured signals underestimates reality*



Required very elaborate MC simulations to solve, since effects depend on energy and direction incoming particle

Calibration problems for hadronic shower detection

π^0 production may take place anywhere in the absorber



270 GeV π in Pb/Fe/scint. (hanging-file calorimeter)

π^0 production in HAD section

The em shower component is sampled more efficiently than the non-em one

The calibration constant of each individual sampling layer thus depends on the type of event.

What has been learned since 1990?

The enormous complications that arise when calibrating a longitudinally segmented (sampling) calorimeter

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  Also, the composition of the shower changes as the shower develops
- *As a result, the relationship between measured signal and deposited energy (calibration constant) varies with depth, and is especially for hadrons in a given detector segment different for each event*

- ***These problems may be avoided in longitudinally unsegmented calorimeters and (to some extent) in homogeneous detectors***

Elements needed to improve the excellent ZEUS/SPACAL performance:

1) *Reduce the contribution of sampling fluctuations to energy resolution*
   (THE limiting factor in SPACAL/ZEUS)

2) *Eliminate/reduce effects of fluctuations in "invisible energy"*
   → *calorimeter needs to be efficient in detecting the "nuclear" fraction of the non-em shower component*

3) *Eliminate the effects of fluctuations in the em shower fraction, f_{em}*
   in a way that does NOT prevent 1), 2)

→ *Dual-Readout Calorimetry*

An attractive option for improving the quality of hadron calorimetry:

Use Čerenkov light!! *Why?*

Hadron showers < *em* component (π^0)
non-em component (mainly soft *p*)

Calorimeter response to these components not the same *(e/h ≠ 1)*

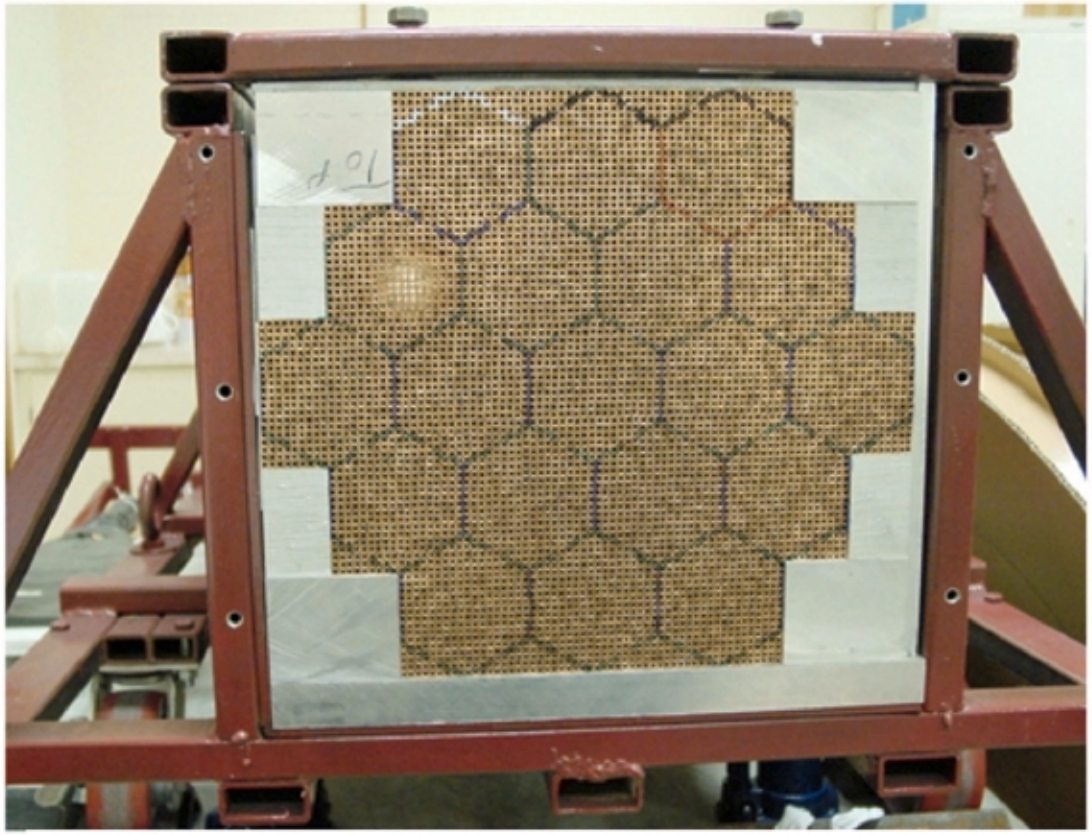
Čerenkov light almost exclusively produced by em component *
(~80% of non-em energy deposited by non-relativistic particles)

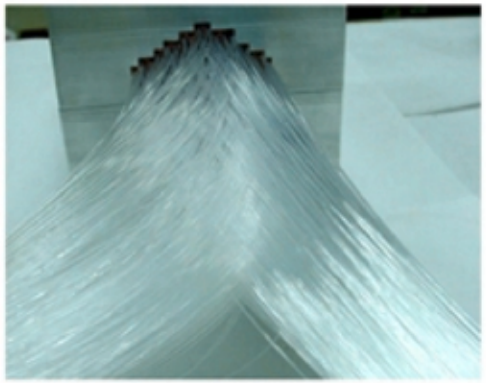
➡ DREAM (Dual REAdout Method) principle:
Measure f_{em} event by event by comparing Č and dE/dx signals

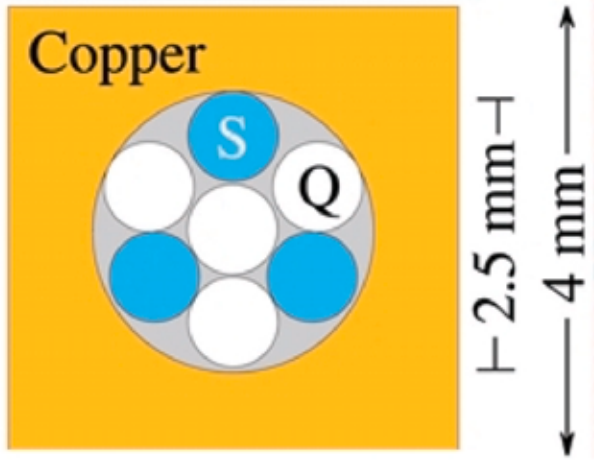
* How do we know this?

- CMS HF: *e/h* ~ 5
- Lateral profiles of hadronic showers

DREAM: Structure

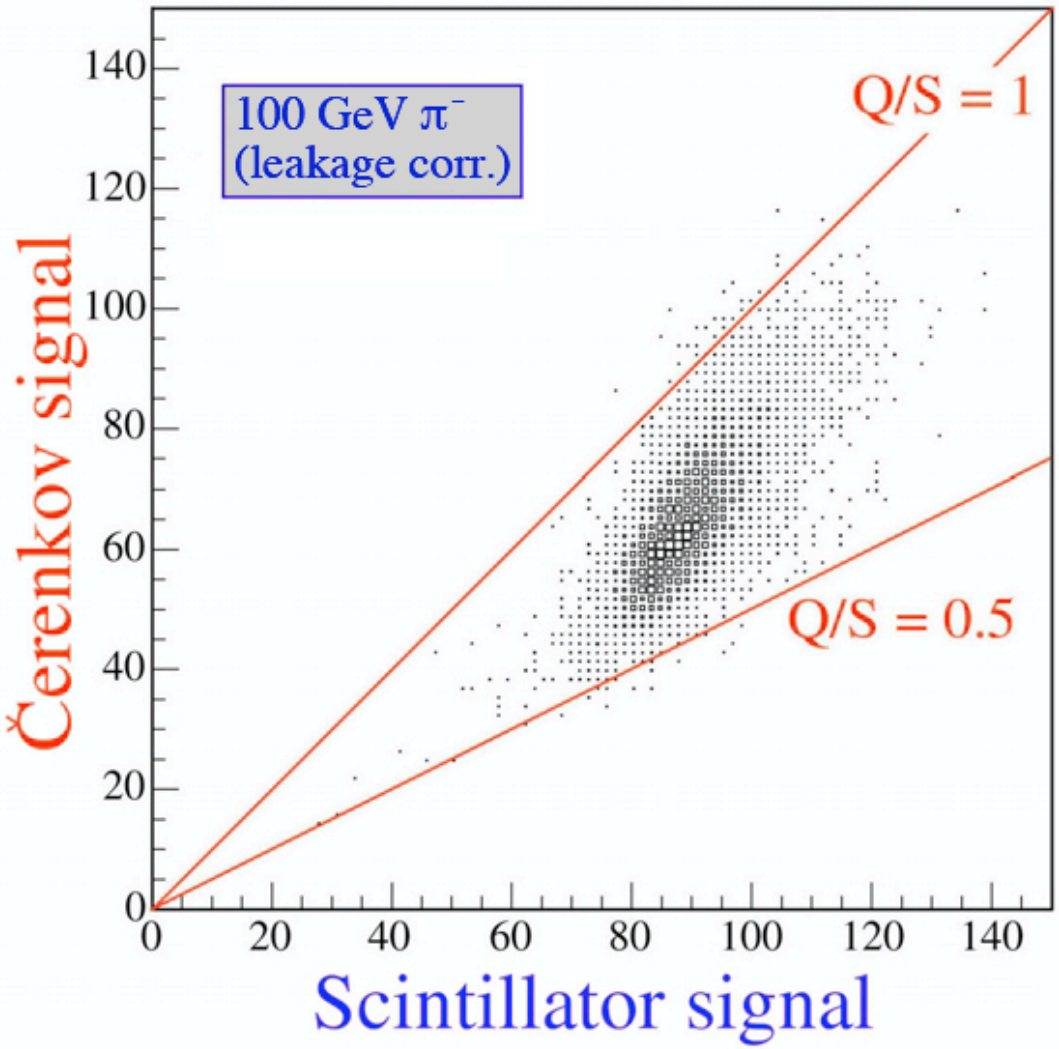






- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

DREAM: How to determine f_{em} and E?



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

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

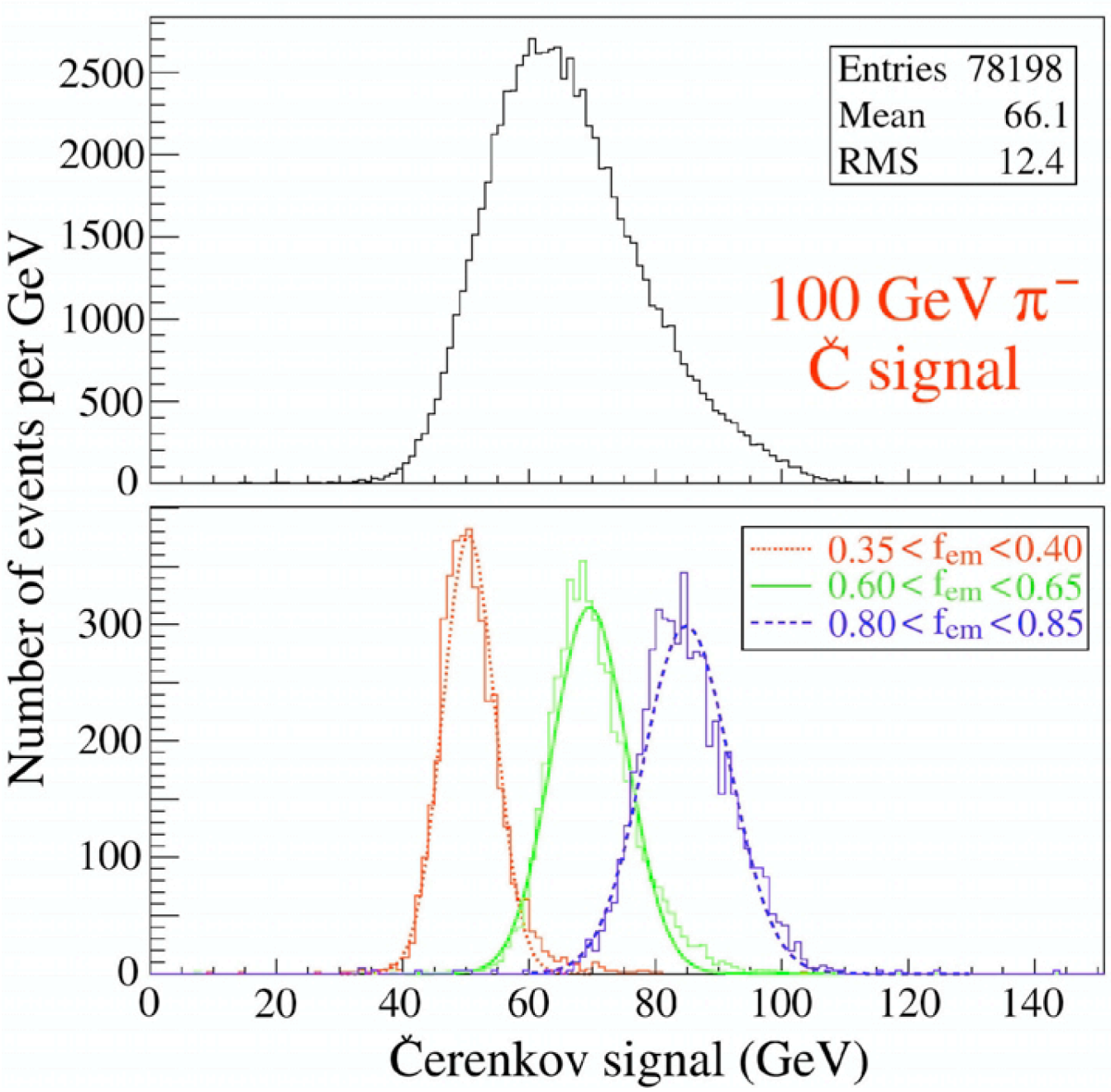
e.g. If $e/h = 1.3$ (S), 4.7 (Q)

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

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

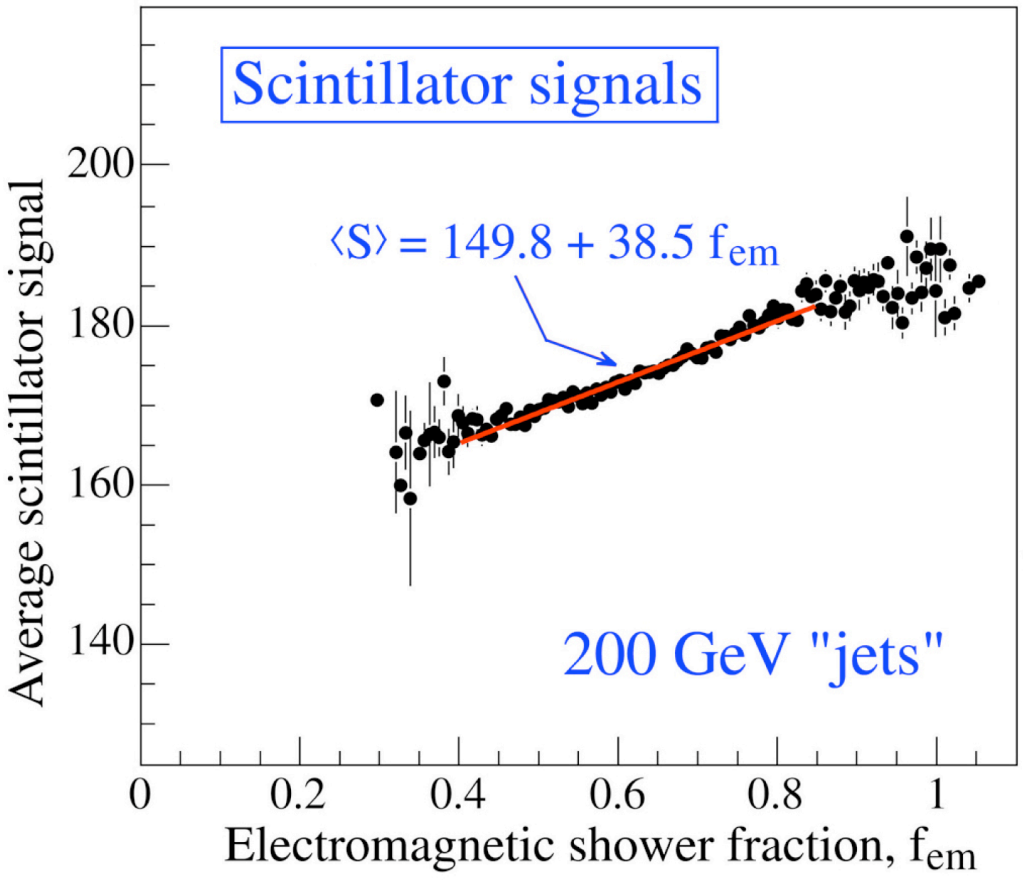
with $\chi = \dfrac{1 - (h/e)_S}{1 - (h/e)_Q} \sim 0.3$

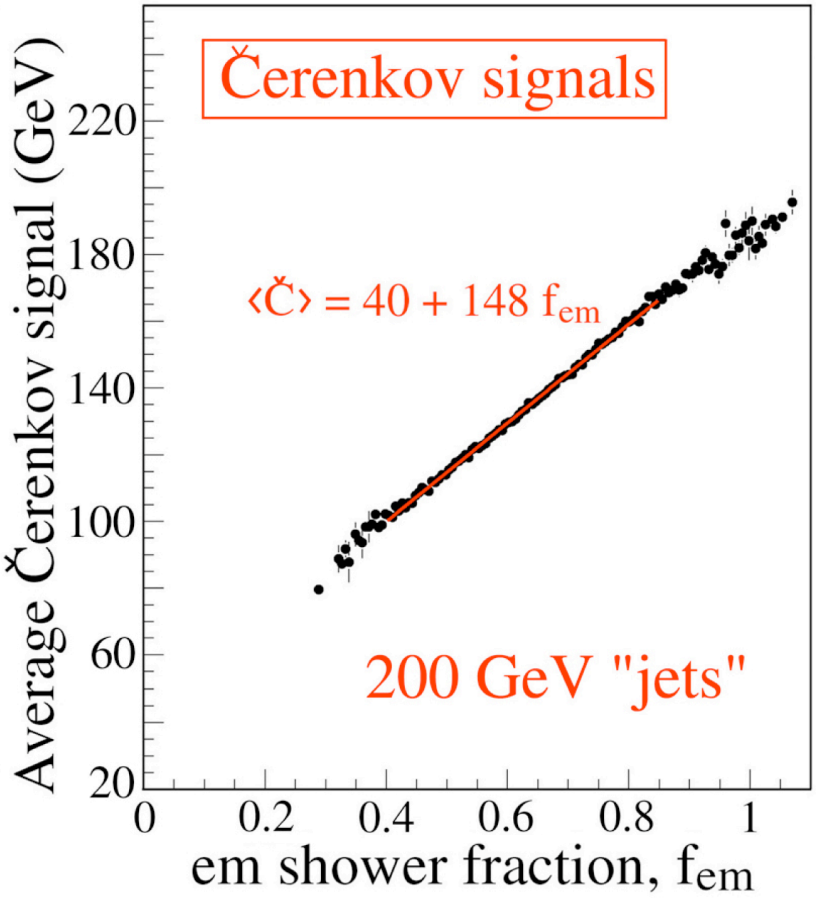
DREAM: Effect of event selection based on f_{em}



From:
NIM A537 (2005) 537

DREAM: Signal dependence on f_{em}



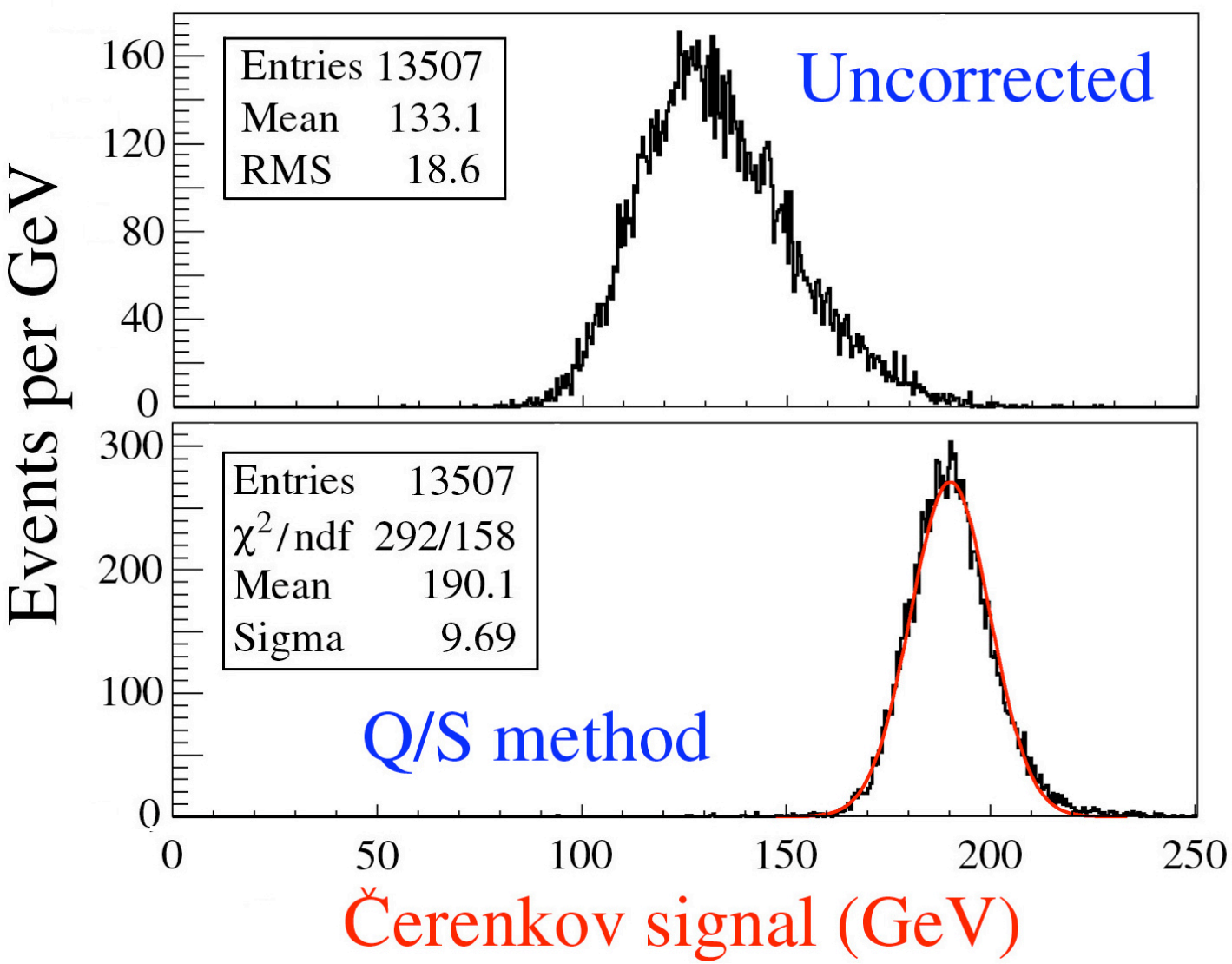


$$R(f_{\rm em}) = p_0 + p_1 \, f_{\rm em} \quad \text{with} \quad \frac{p_1}{p_0} = e/h - 1$$

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

From:
NIM A537 (2005) 537

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



Effects of Q/S corrections on

hadronic signal linearity *and* *jet resolution*

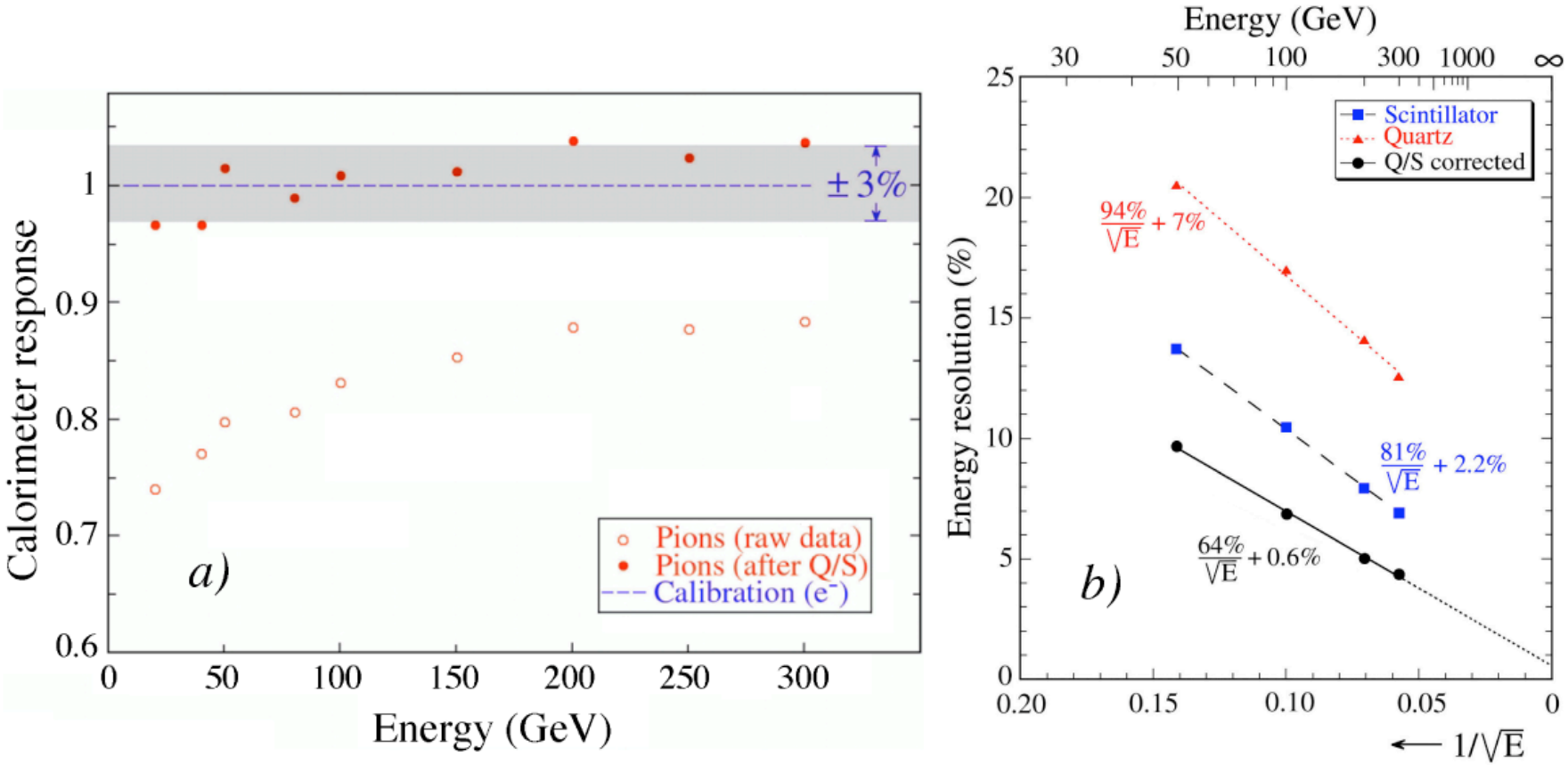


Figure 9: The scintillator response of the DREAM calorimeter to single pions (a) and the energy resolution for "jets" (b), before and after the dual-readout correction procedures were applied to the signals [5].

CONCLUSIONS
from tests of fiber prototype

- 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

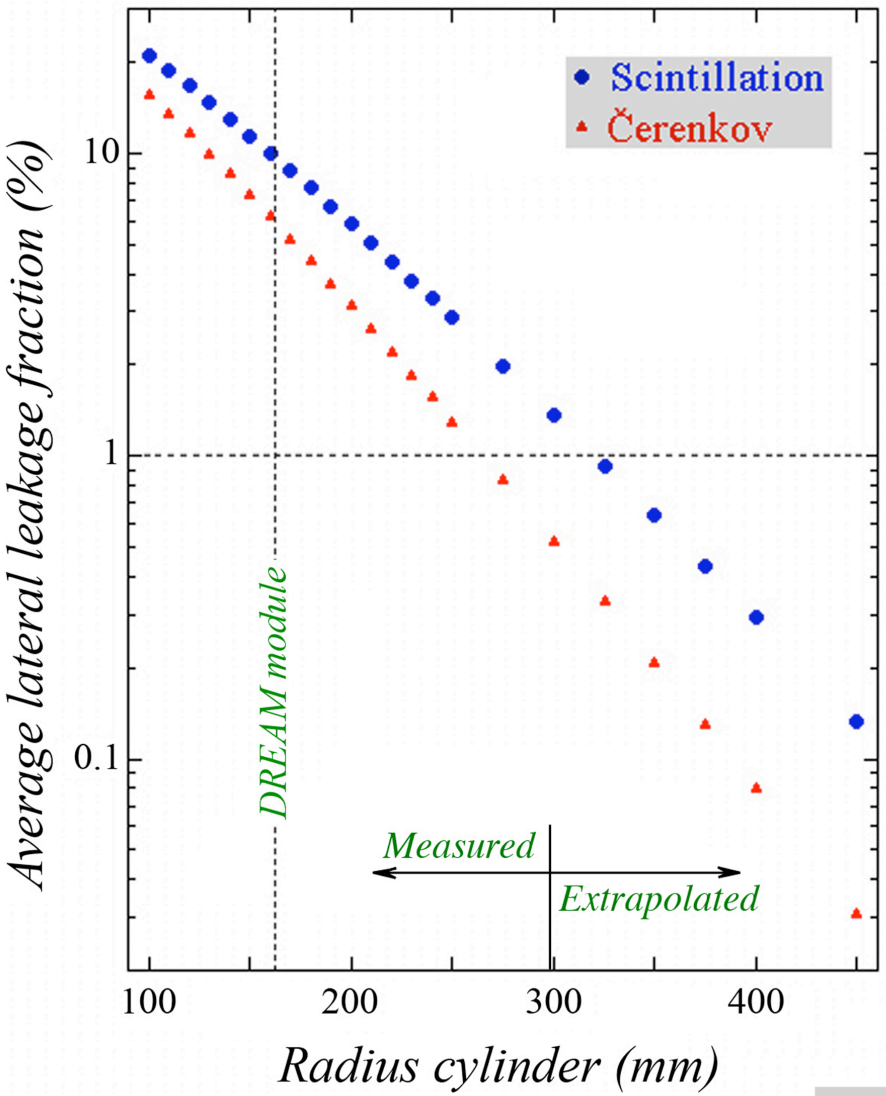
In other words:
The same advantages as intrinsically compensating calorimeters (e/h = 1)
WITHOUT the limitations (sampling fraction, integration volume, time)

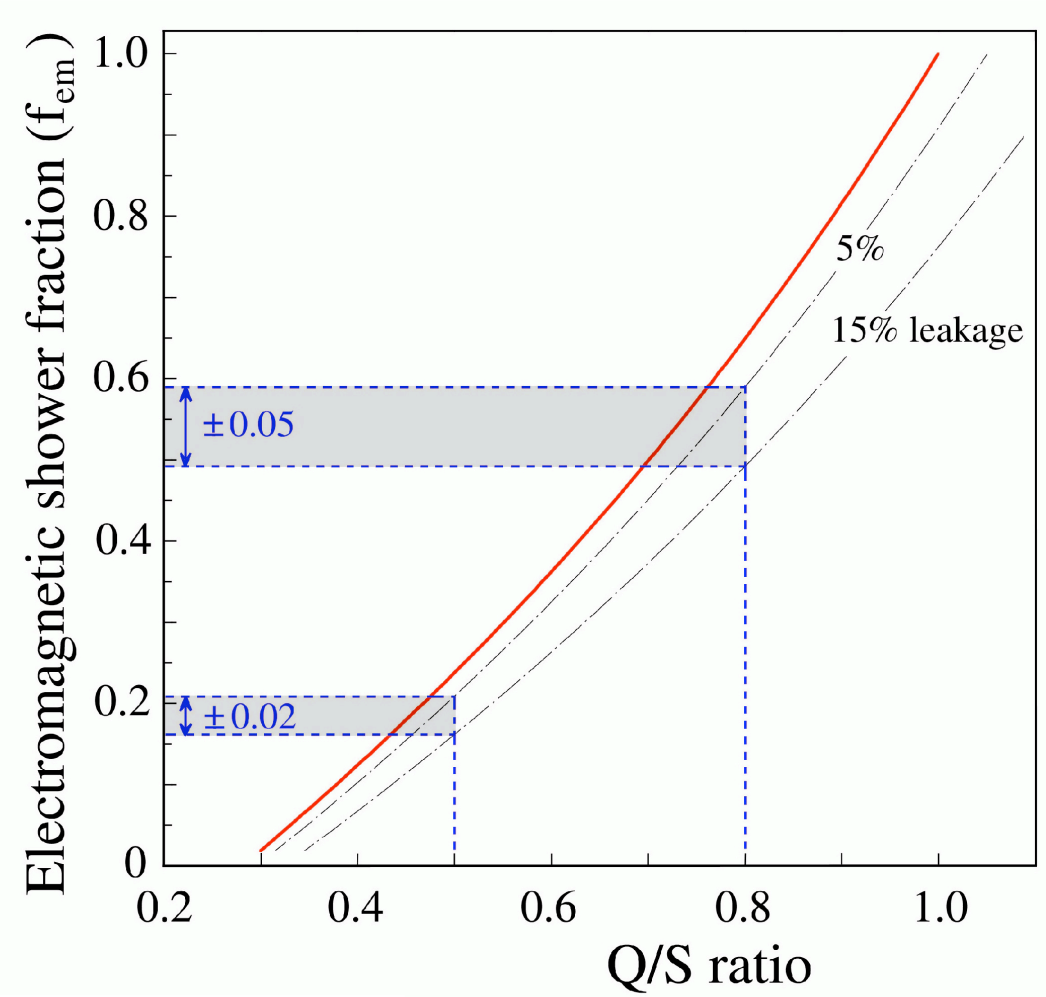
How to improve DREAM performance

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

DREAM: The importance of leakage and its fluctuations

Lateral shower containment (π)





From:
NIM A584 (2008) 273

Expected effect of full shower containment

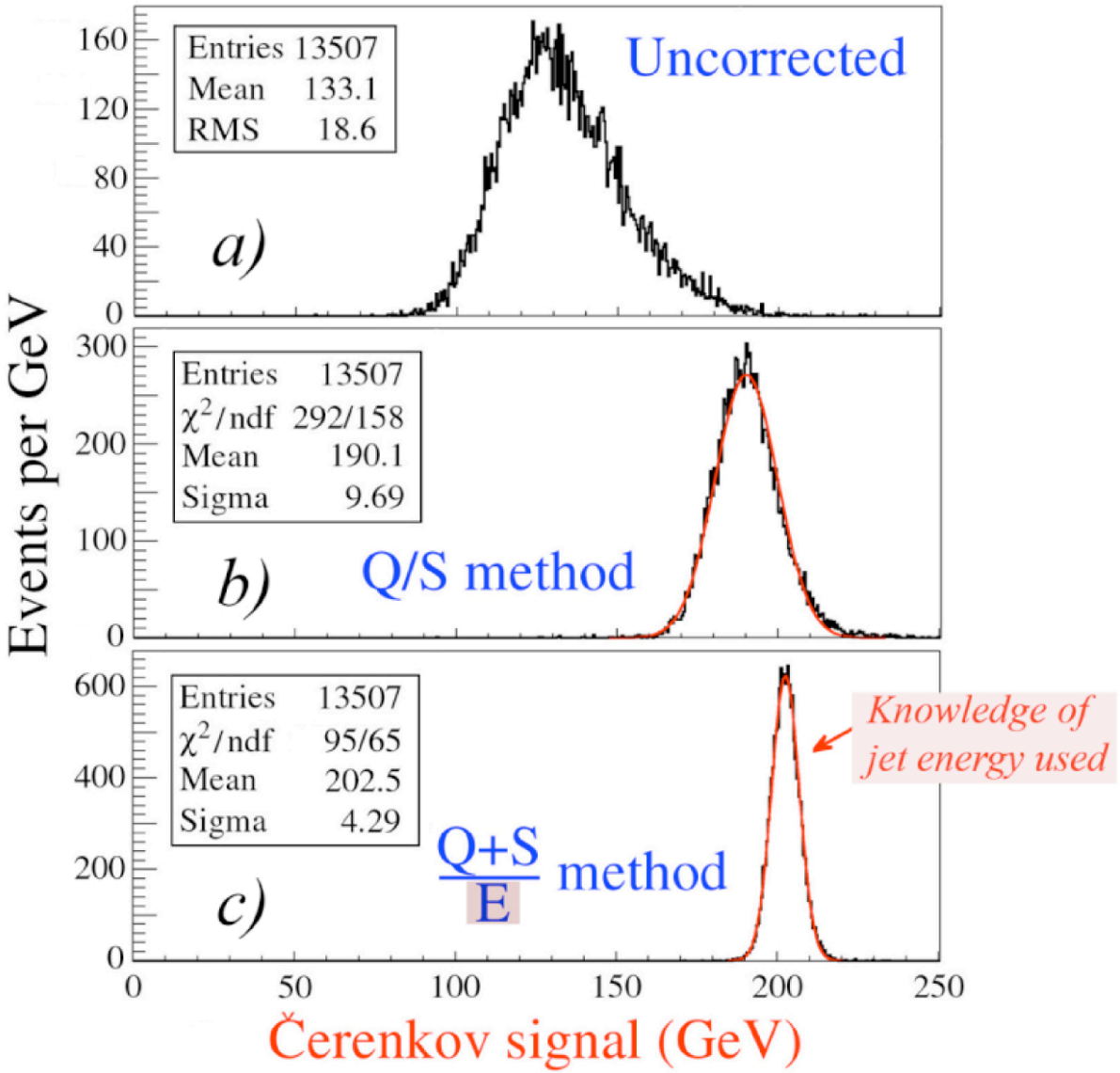


Figure 2: Čerenkov signal distributions for 200 GeV multi-particle events. Shown are the raw data (a), and the signal distributions obtained after application of the corrections based on the measured em shower content, with (c) or without (b) using knowledge about the total "jet" energy [5].

How to improve DREAM performance

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

- *Increase Čerenkov light yield*
  DREAM: 8 p.e./GeV ⟶ fluctuations contribute $35\%/\sqrt{E}$

- *Reduce sampling fluctuations*
  These contributed ~ $40\%/\sqrt{E}$ to hadronic resolution in DREAM

Homogeneous calorimeters (crystals)

- No reason why DREAM principle should be limited to fiber calorimeters
- *Crystals* have the potential to solve light yield + sampling fluctuations problem
- HOWEVER: *Need to separate the light into its Č, S components*

OPTIONS:

1) Directionality. S light is isotropic, Č light directional

2) Time structure. Č light is prompt, S light has decay constant(s)

3) Spectral characteristics. Č light λ^{-2} , S light depends on scintillator

4) Polarization. Č light polarized, S light not.

Separation of $PbWO_4$:1%Mo signals into S, Č components

From:

NIM A604 (2009) 512

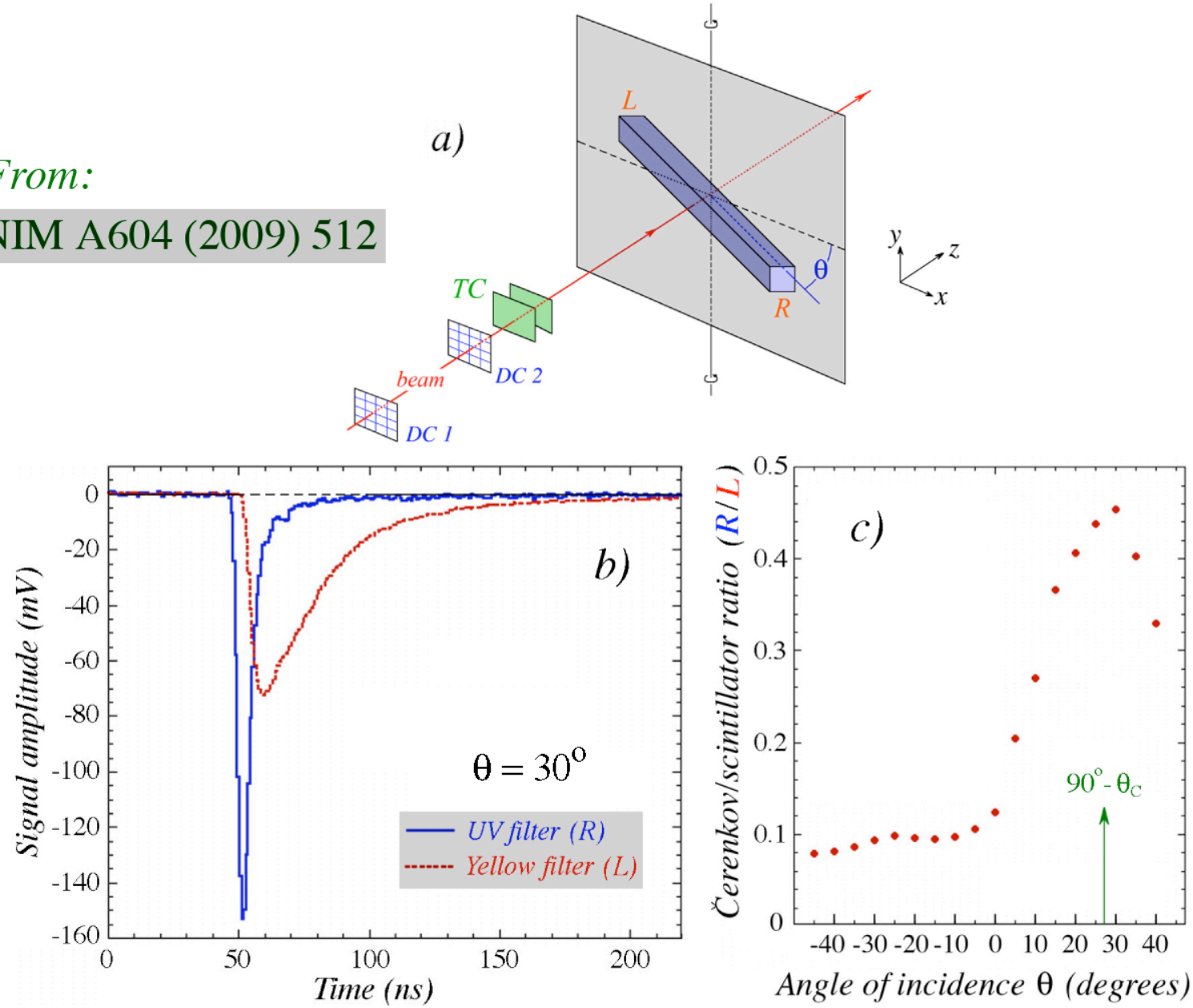
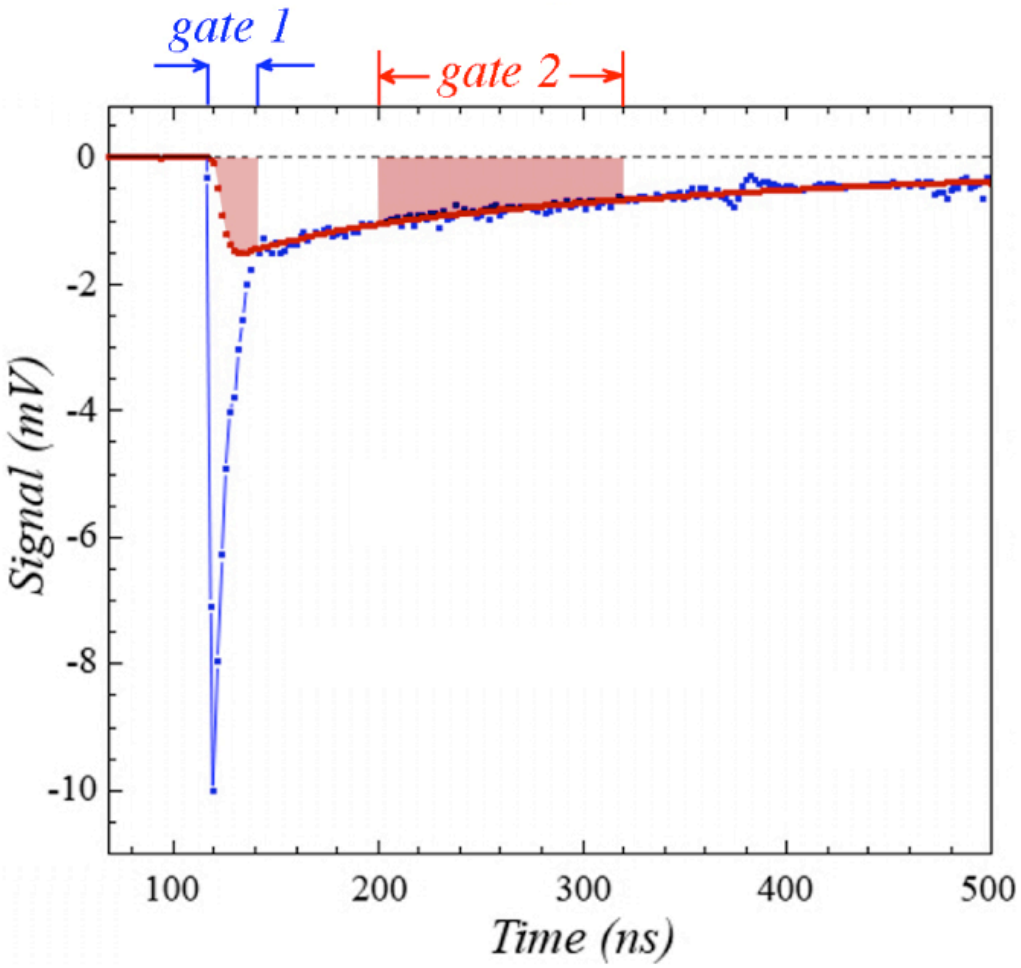


Figure 3: Unraveling of the signals from a Mo-doped $PbWO_4$ crystal into Čerenkov and scintillation components. The experimental setup is shown in diagram *a*. The two sides of the crystal were equipped with a UV filter (side *R*) and a yellow filter (side *L*), respectively. The signals from 50 GeV electrons traversing the crystal are shown in diagram *b*, and the angular dependence of the ratio of these two signals is shown in diagram *c* .

Čerenkov and Scintillator information from one signal !



BGO crystal
UG 11 (UV) filter

From:
NIM A595 (2008) 359

Figure 14: The time structure of a typical shower signal measured in the BGO em calorimeter equipped with a UV filter. These signals were measured with a sampling oscilloscope, which took a sample every 0.8 ns. The UV BGO signals were used to measure the relative contributions of scintillation light (gate 2) and Čerenkov light (gate 1)

Test setup hybrid calorimeter system (BGO + fibers)

Figure 15: The calorimeter during installation in the H4 test beam, which runs from the bottom left corner to the top right corner in this picture. The 100-crystal BGO matrix is located upstream of the fiber calorimeter, and is read out by 4 PMTs on the left (small end face) side.

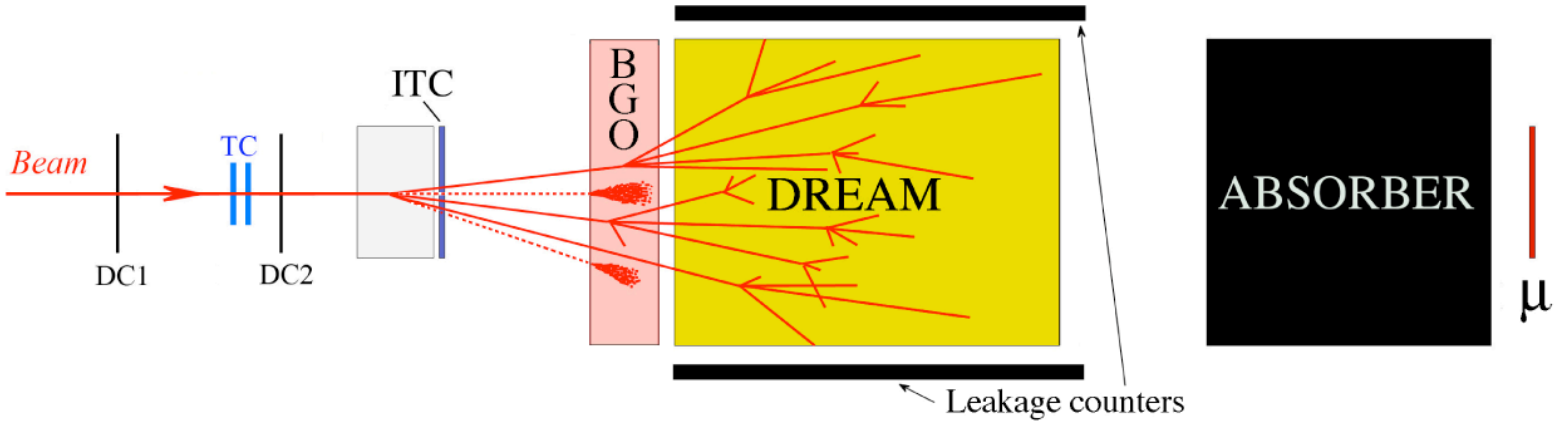
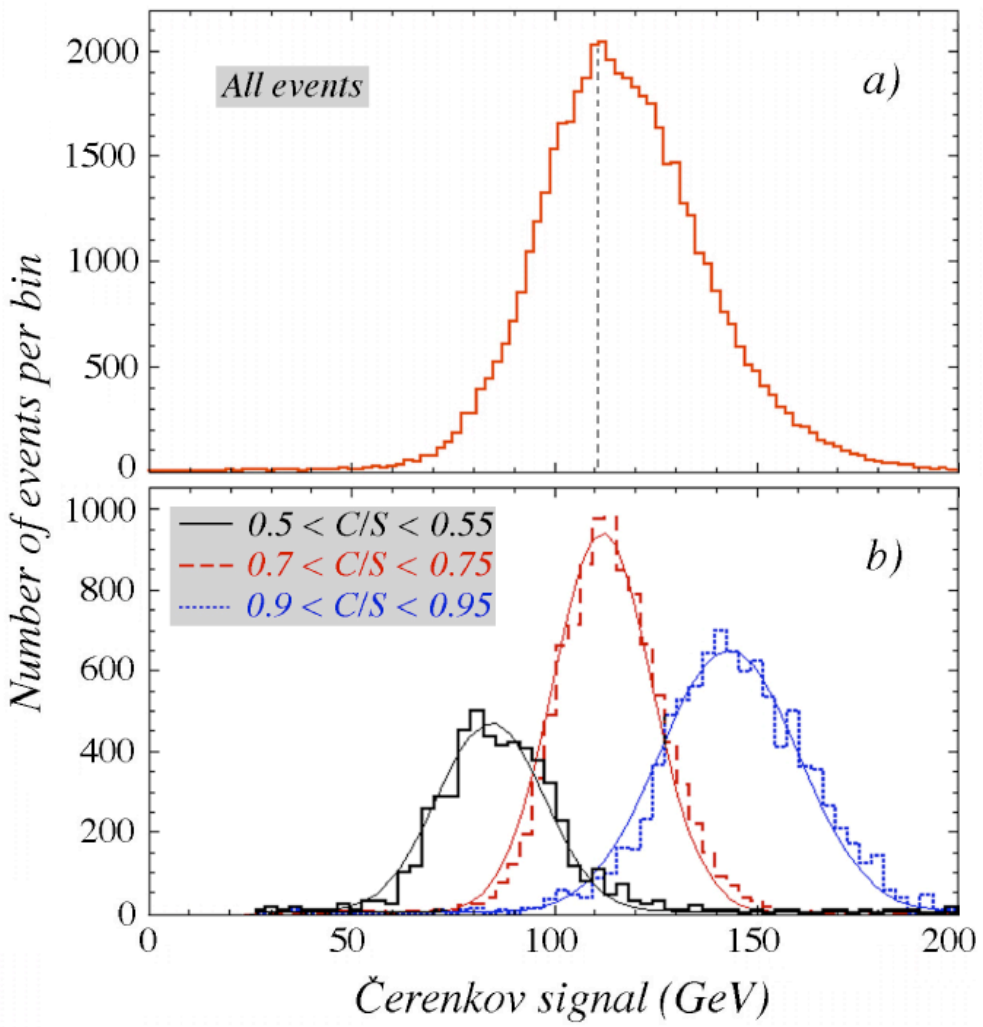


Figure 16: Schematic of the experimental setup in the beam line in which the hybrid calorimeter system was tested (see text for details). Also shown is the occurrence and development of a multi-particle event ("jet") originating in the upstream target [17].

Čerenkov/scintillator ratio also measures f_{em} for jets in hybrid!



On average,
~50% of the "jet" energy
deposited in BGO matrix

from
NIM A610 (2009) 488

Figure 17: The Čerenkov signal distribution for 200 GeV "jet" events detected in the BGO + fiber calorimeter system (a) together with the distributions for subsets of events selected on the basis of the ratio of the total Čerenkov and scintillation signals in this detector combination (b).

How to improve DREAM performance

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

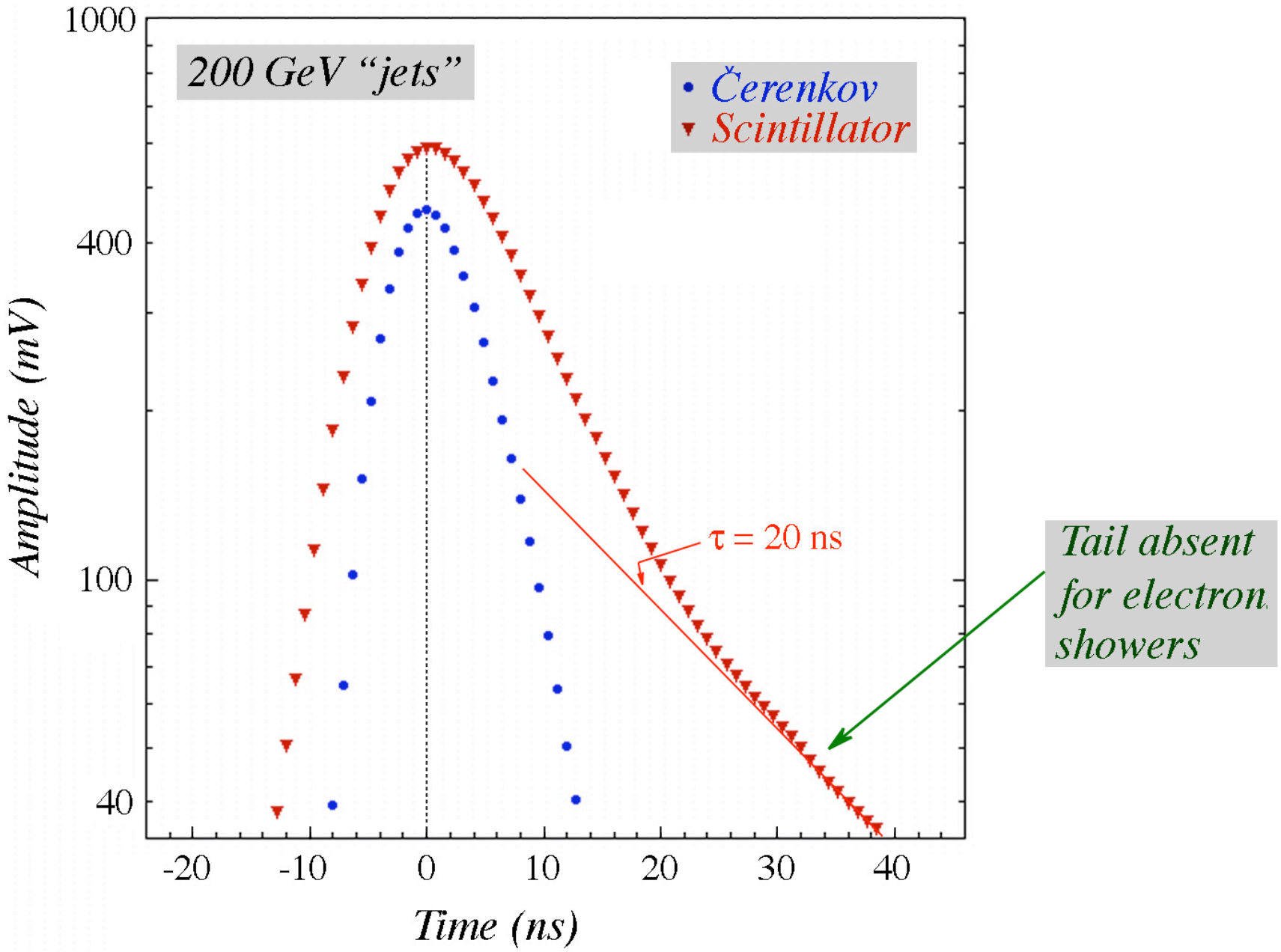
- *Increase Čerenkov light yield*
  DREAM: 8 p.e./GeV ⟶ fluctuations contribute 35%/$\sqrt{E}$

- *Reduce sampling fluctuations*
  These contributed ~ 40%/$\sqrt{E}$ to hadronic resolution in DREAM

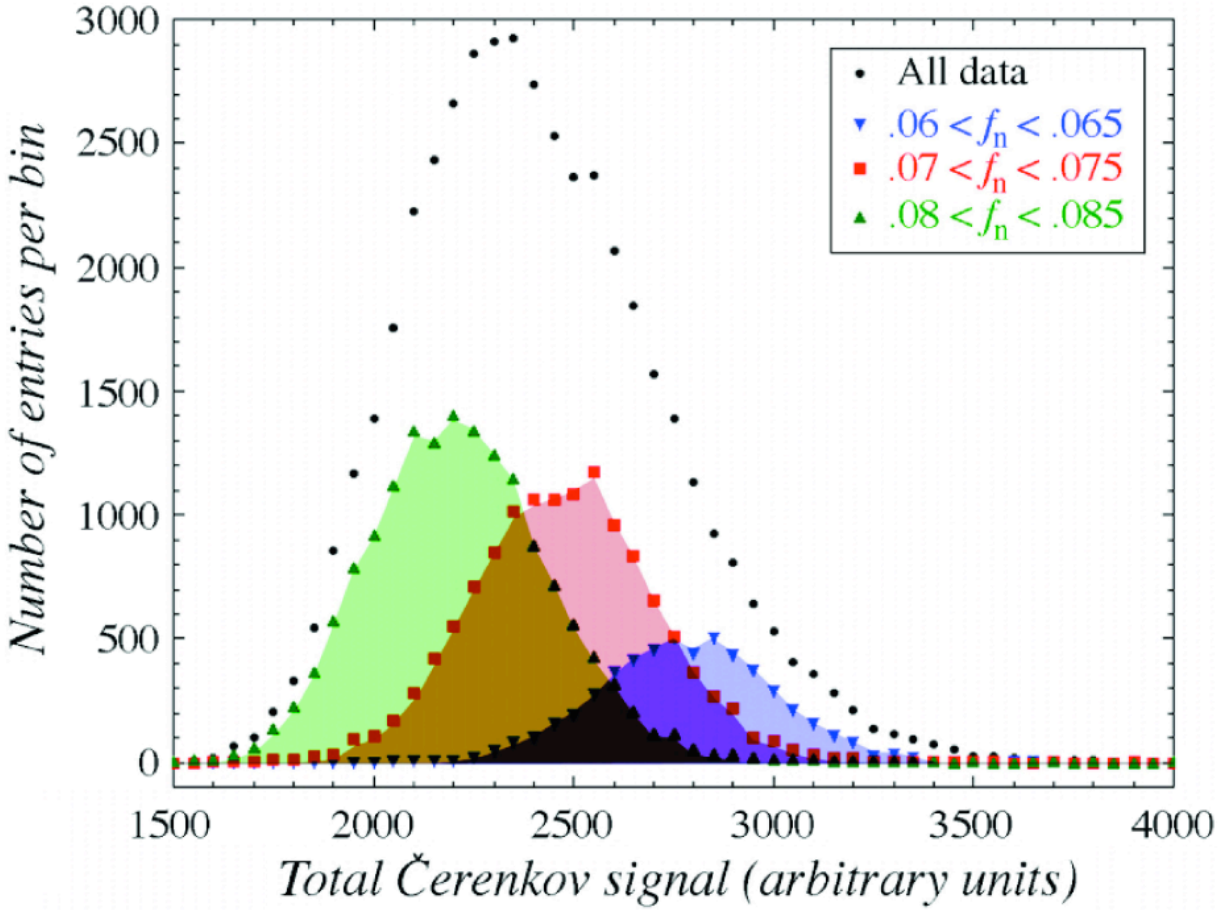
- For ultimate hadron calorimetry (15%/$\sqrt{E}$): *Measure E_{kin} (neutrons)*
  Is correlated to nuclear binding energy loss (invisible energy)

Can be inferred from the time structure of the signals

Time structure of the DREAM signals: the neutron tail



Probing the total signal distribution with the neutron fraction



From:

NIM A598 (2009) 422

Figure 18: Distribution of the total Čerenkov signal for 200 GeV "jets" and the distributions for three subsets of events selected on the basis of the fractional contribution of neutrons to the scintillator signal.

Neutron information can be used to improve the response function and the energy resolution

From: NIM A598 (2009) 422

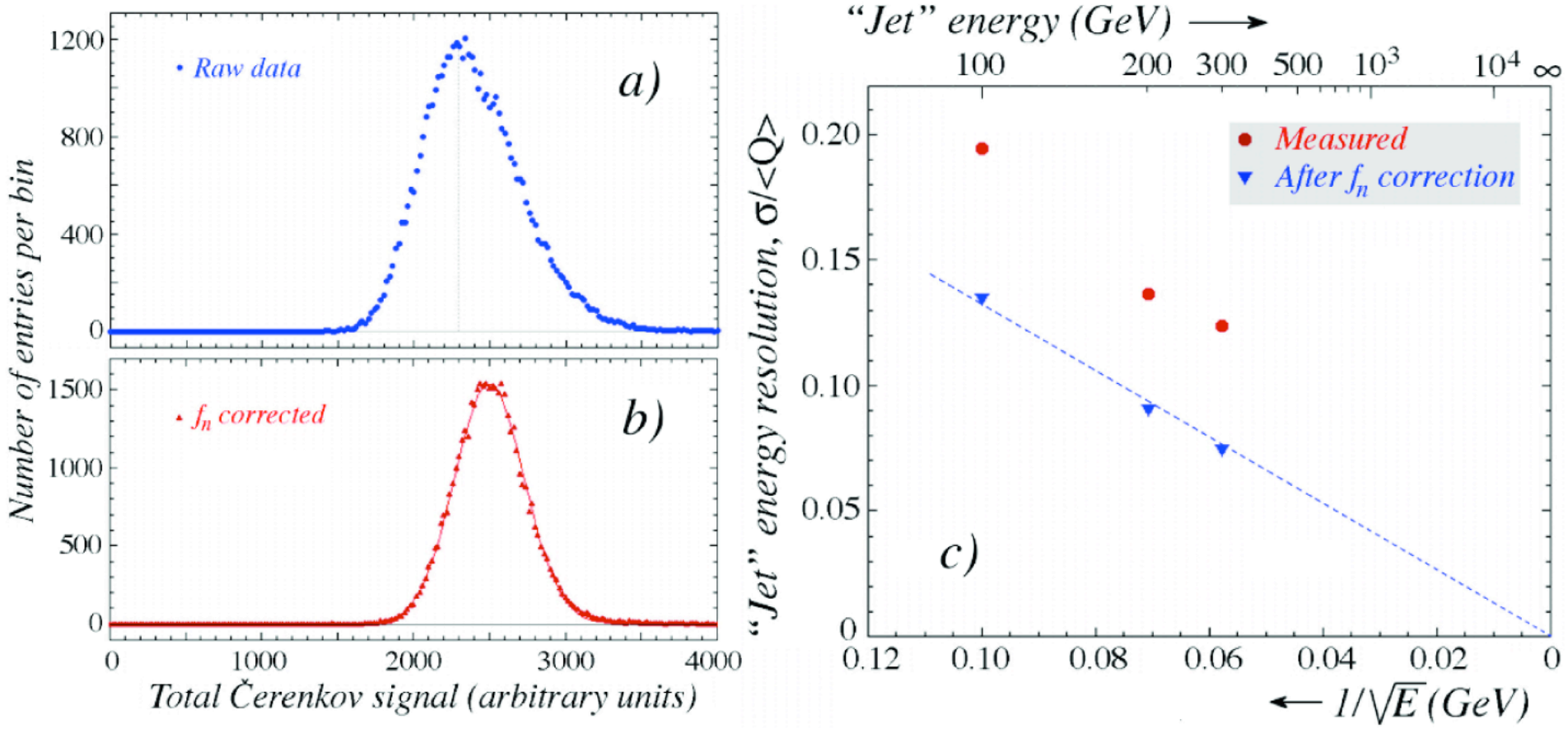


Figure 19: Distribution of the total Čerenkov signal for 200 GeV "jets" before (a) and after (b) applying the correction based on the measured value of f_n, described in the text. Relative width of the Čerenkov signal distribution for "jets" as a function of energy, before and after a correction that was applied on the basis of the relative contribution of neutrons to the scintillator signals (c).

Future research plans

We have now reached the point where we believe that we have all the ingredients in hand to build the perfect calorimeter system, or at least a calorimeter system that meets and exceeds the performance requirements of experiments at the ILC and CLIC. We propose to prove this statement by building and testing such a detector.

(from proposal to funding agencies)

Crucial aspects of proposal

- Build two detectors, and test these separately and together
  - *Fiber calorimeter, 5 tonnes* ← (FIRST PRIORITY)
  - *Dedicated dual-readout crystal matrix (em section)*
- Shower containment >99% → *effects of leakage fluctuations negligible*
- Other design criteria:
  - *Čerenkov light yield in fiber detector > 100 p.e./GeV (em)*
  - *Sampling fluctuations fiber detector < 10%/√E (em)*
  - *Depth measurement of shower maximum for each event (attenuation!)*
  - *Time structure measured for every signal*
- *For details, see CERN-SPSC 2010-012*
  Expect results at next CALOR conference(s)

How (NOT) to make further progress?

Further progress

Just like in the past 30+ years, in the absence of reliable MC simulations, progress depends on experimental verification of new ideas

Apart from DREAM, these ideas are:

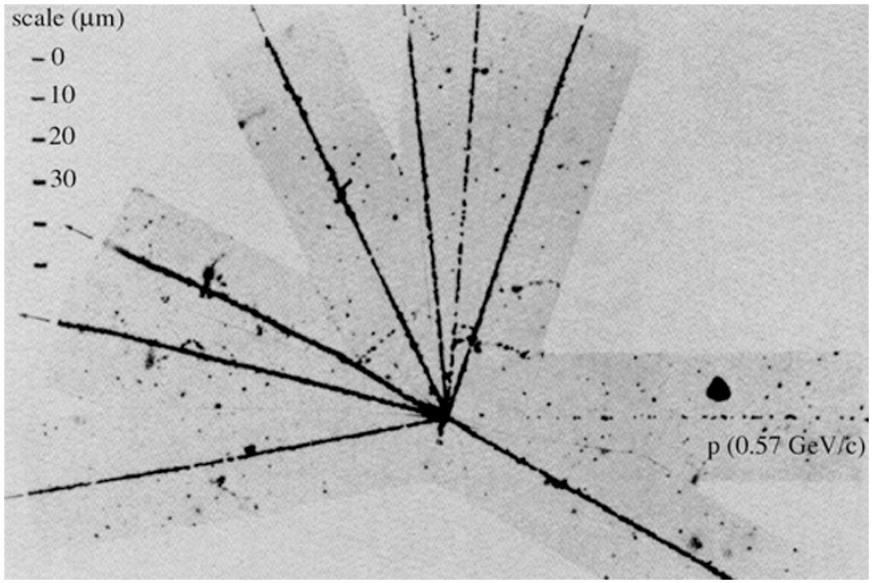
- Homogeneous dual-readout calorimeter
  - *Potential advantages: No sampling fluctuations, excllent em energy resolution*
  - *Potential problems: No handle on "nuclear" fluctuations, Č light attenuation, readout, COST*
- Particle Flow Analysis
  - *Potential advantages: Additional information from tracker is used to measure jets*
  - *Potential problems: Double counting, calibration of fine-grained calorimeter*

It is also crucial to test new devices in conditions that approach the application for which they are designed AS CLOSELY AS POSSIBLE.

That is, using either multiparticle events, or generated jets.
NOT single-particle test beams, where one has many possibilities to make results look good that are not applicable for jets.

Avoid repeating mistakes from the past

- *Don't place readout elements that produce HUGE signals for one particular type of shower particle in the path of the developing shower*
  ("Texas tower" effect)



Charged nuclear fragments may be 100 - 1000 times minimum ionizing. When traversing an APD, they may create a signal 100,000 times larger than that from a scintillation photon.

Example: In CMS ECAL, such events may fake energy deposits of tens of GeV.

- *"Digital" calorimetry was tried and abandoned for good reasons (1983)*

Saturation in "digital" calorimeters (wire chamber readout)

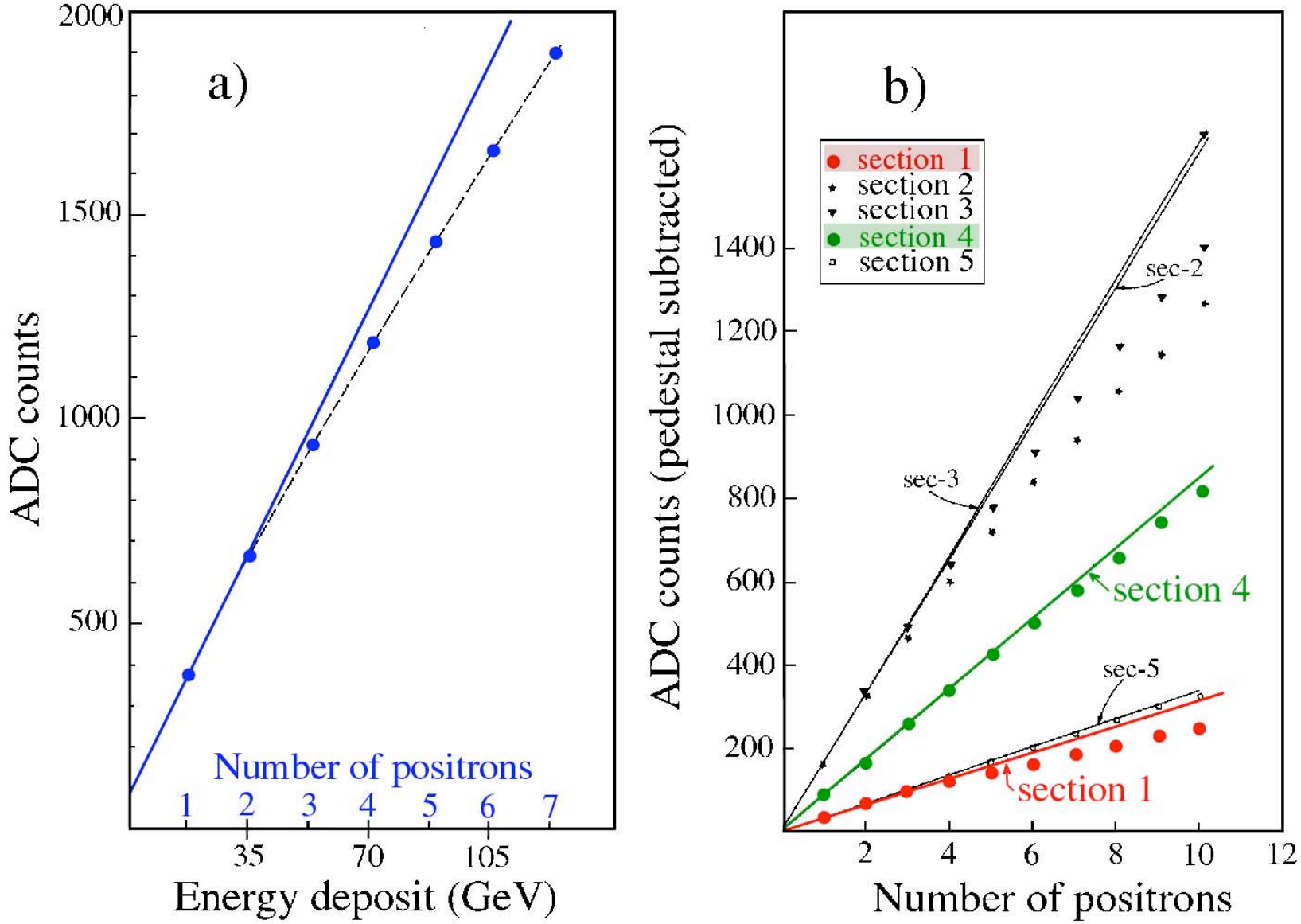
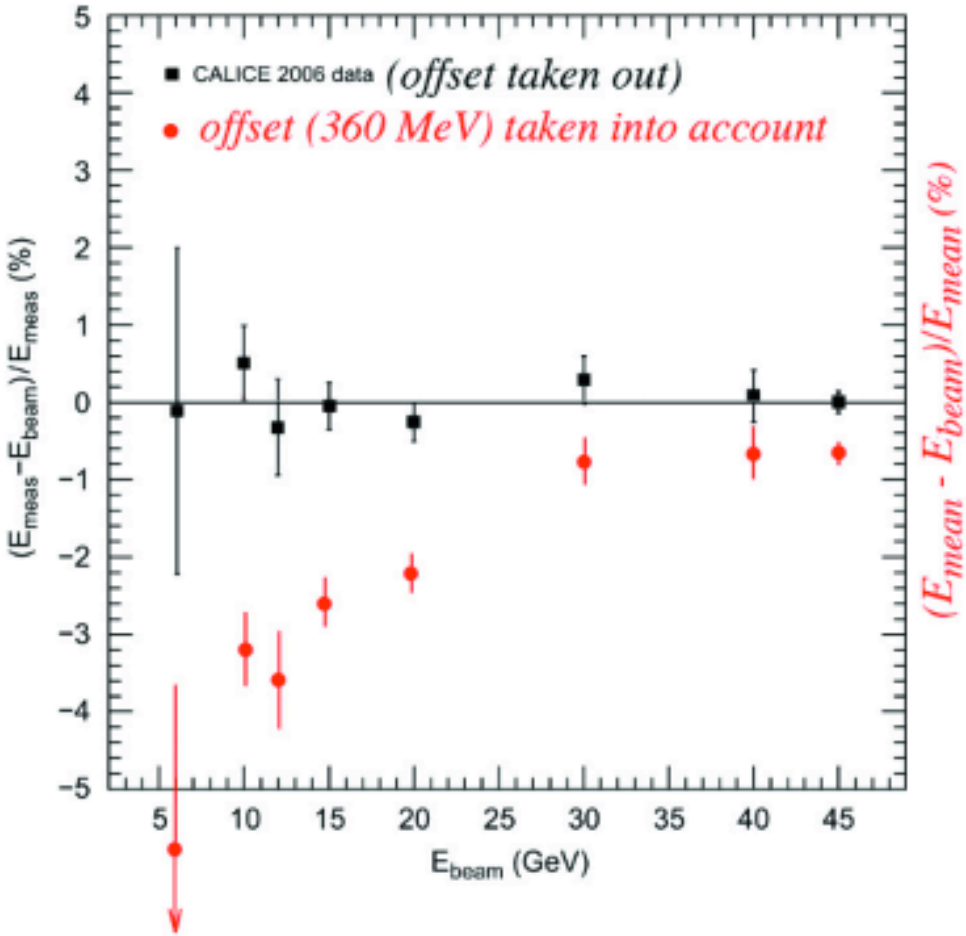


FIG. 3.2. Average em shower signal from a calorimeter read out with gas chambers operating in a "saturated avalanche" mode, as a function of energy. From: NIM 205 (1983) 113.

Dishonesty in reporting results

Misrepresent what was measured experimentally



Source: NIM A608 (2009) 372

CALICE:

Fit to experimental data (electrons):

$$E_{mean} = \beta \cdot E_{beam} - 360\ MeV$$

Then, they define:

$$E_{meas} = E_{mean} + 360\ MeV$$

and conclude:

7. Conclusion

The response to normally incident electrons of the CALICE Si-W electromagnetic calorimeter was measured for energies between 6 and 45 GeV, using the data recorded in 2006 at CERN.
The calorimeter response is linear to within approximately 1%.

In reality, they measured a non-linearity of ~5% over less than one decade in energy!

Dishonesty in reporting results
Phony statistics

resolution over-emphasises the importance of these tails. In this paper, performance is quoted in terms of rms_{90}, which is defined as the rms in the smallest range of reconstructed energy which contains 90% of the events.

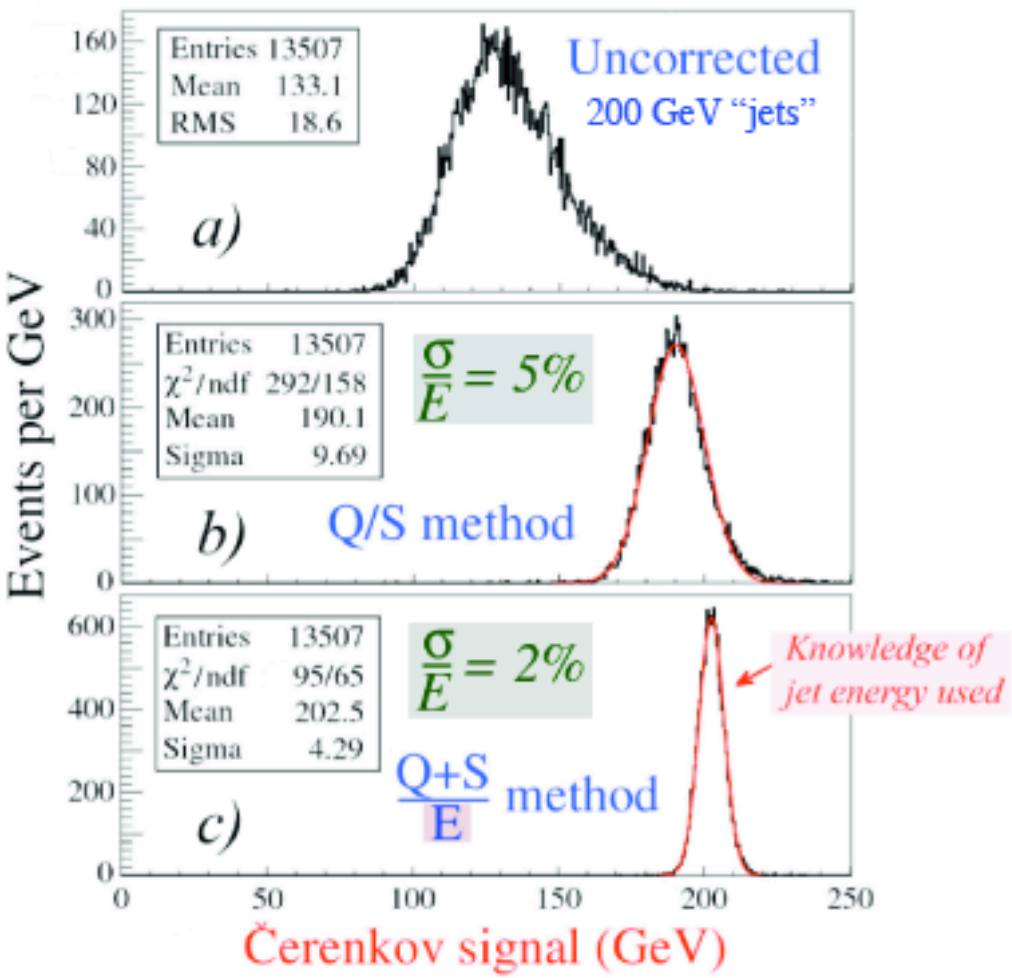
Even for a perfectly Gaussian distribution, $rms_{90} << \sigma_{fit}$

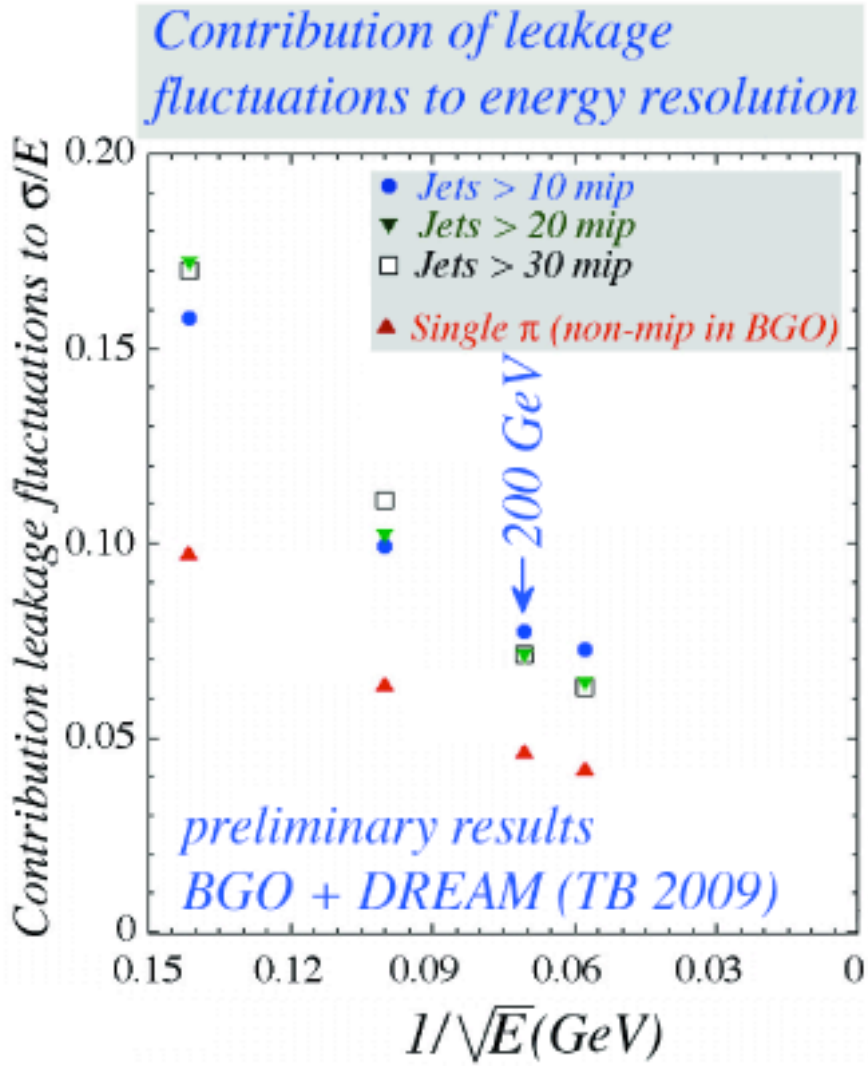
perform the first systematic study of the potential of high granularity PFlow calorimetry. For simulated events in the ILD detector concept, a jet energy resolution of $\sigma_E/E \lesssim 3.8\%$ is achieved for 40–400 GeV jets. This result, which demonstrates that high granularity PFlow calorimetry can meet the challenging

Source: NIM A611 (2009) 25

Honesty in reporting results (DREAM)

Source: NIM A537 (2005) 537





It is very tempting (but incorrect) to claim that DREAM has measured 200 GeV jets with an energy resolution of 2%

How NOT to make further progress

Pretend that MC simulations represent THE TRUTH

From the above study it is concluded that, for 45–250 GeV jets, the jet energy resolution obtained from PFlow calorimetry as implemented in PandoraPFA does not depend strongly on the hadronic shower model; the observed differences are $< 5\%$. This is an important statement; it argues strongly against the need for a test beam based demonstration of PFlow calorimetry (the design of such an experiment would be challenging). *

Source: NIM A611 (2009) 25

* *N.B. Such tests would be straightforward with CALICE*

How NOT to make further progress

Move this topic from the realm of science to religion

> It is widely believed [1)] that the most promising strategy for achieving the ILC jet energy goal [2)] is the Particle Flow (PFlow) approach to calorimetry using a highly granular detector.

From: NIM A611 (2009) 25

Notes:

1) Except by people who know the scientific literature and who do understand hadron calorimetry

2) This goal was already achieved 20 years ago (see earlier slides)

Summary

- *It is, and has been for 20 years, possible to build calorimeters that can separate hadronically decaying intermediate vector bosons (W,Z)*
- *Calibrating a longitudinally segmented calorimeter continues to be a very complicated and usually grossly underestimated job*
- *The DREAM approach combines the advantages of compensating calorimetry with a reasonable amount of design flexibility*
- *The dominating factors that limited the hadronic resolution of compensating calorimeters (ZEUS, SPACAL) to* $30 - 35\%/\sqrt{E}$ *can be eliminated, and the theoretical resolution limit for hadron calorimeters* $(15\%/\sqrt{E})$ *seems within reach*
- *The DREAM project holds the promise of high-quality calorimetry for* ***all*** *types of particles, with an instrument that can be calibrated with electrons*
- *Rhetoric + academic dishonesty is NOT helpful for further progress*

Backup slides

Particle identification with calorimeters

e/π separation using time structure signals

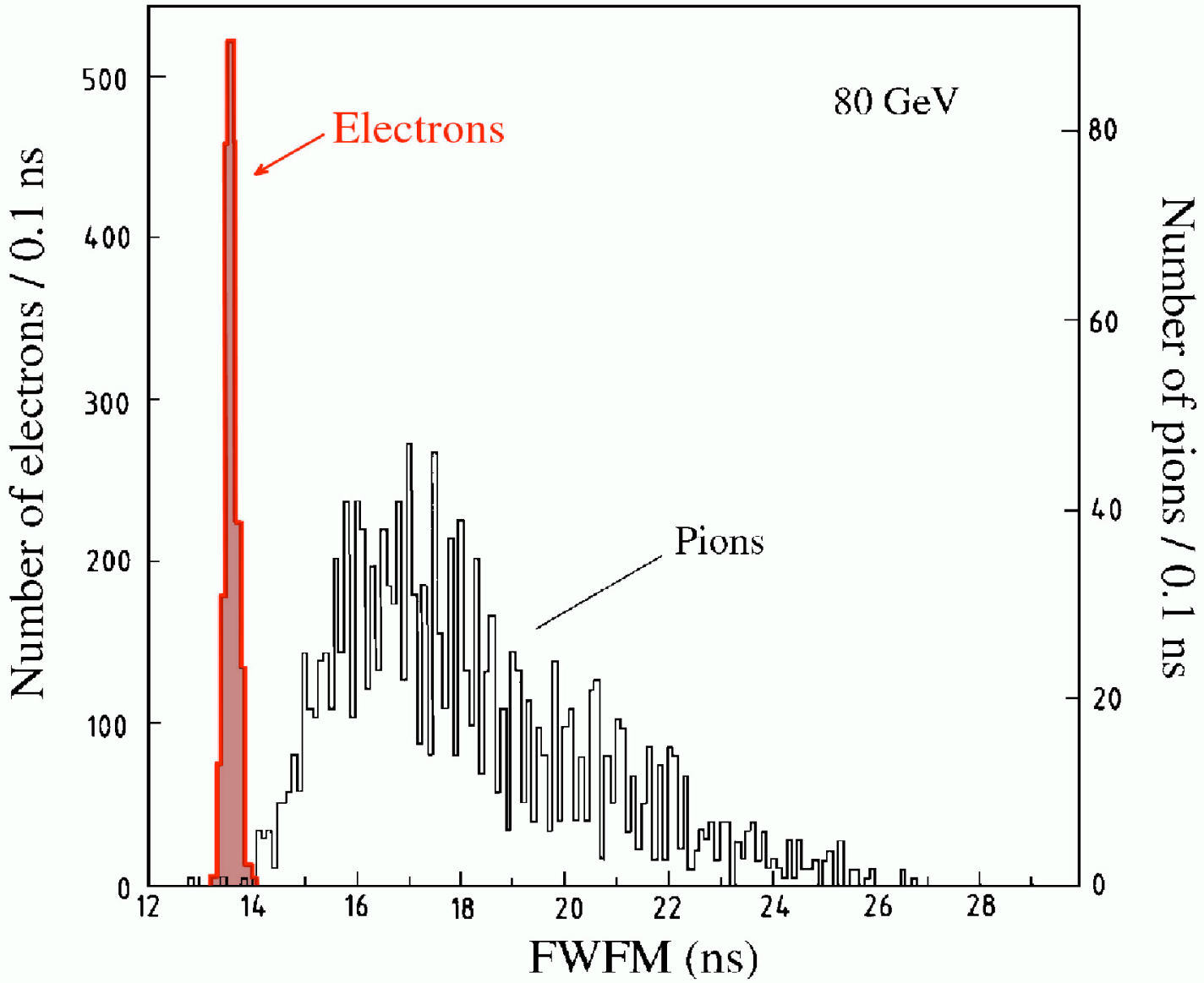
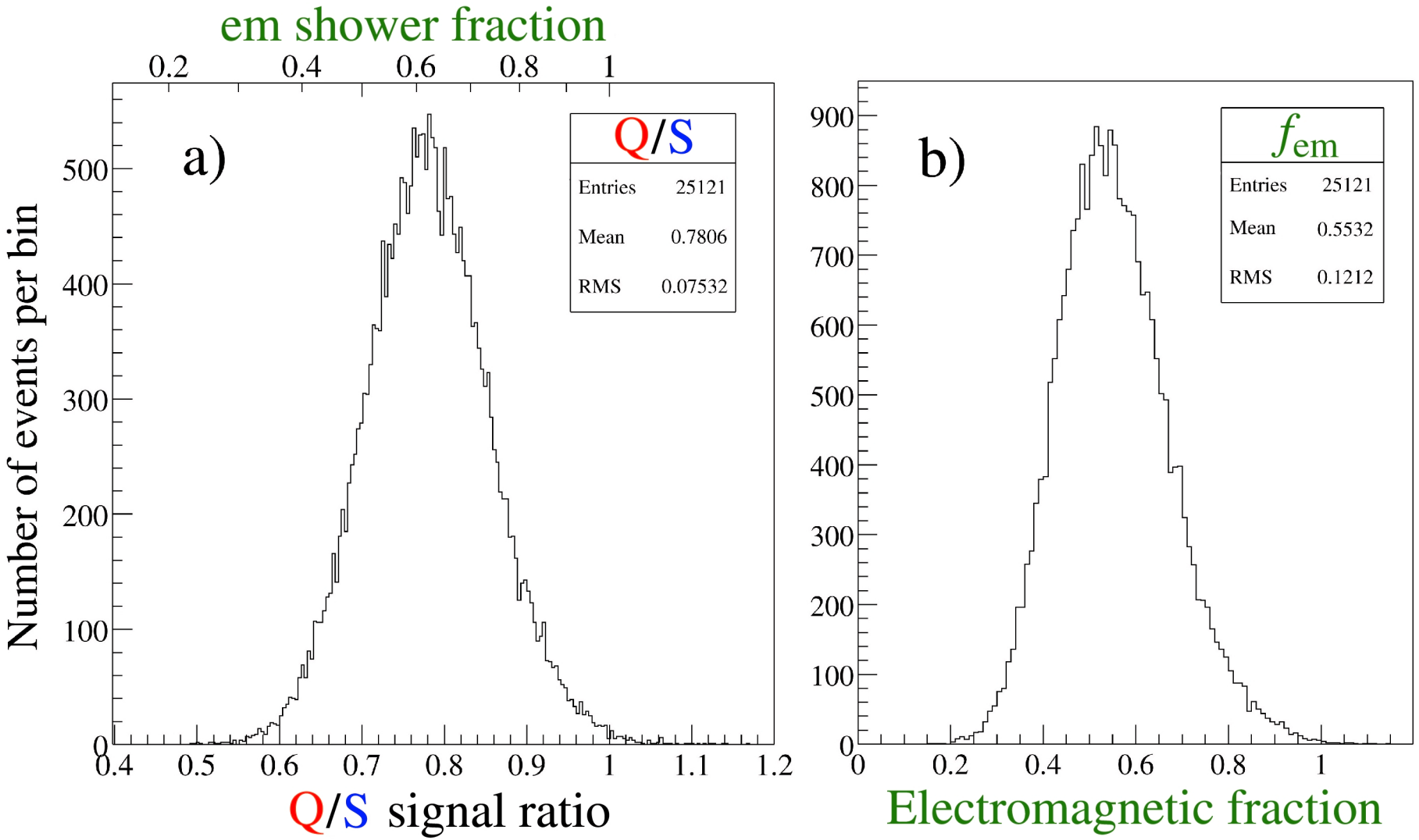


FIG. 7.33. The distribution of the full width at one-fifth maximum (FWFM) for 80 GeV electron and pion signals in SPACAL [Aco 91a].

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



Contribution leakage fluctuations to energy resolution (BEFORE dual-readout corrections!)

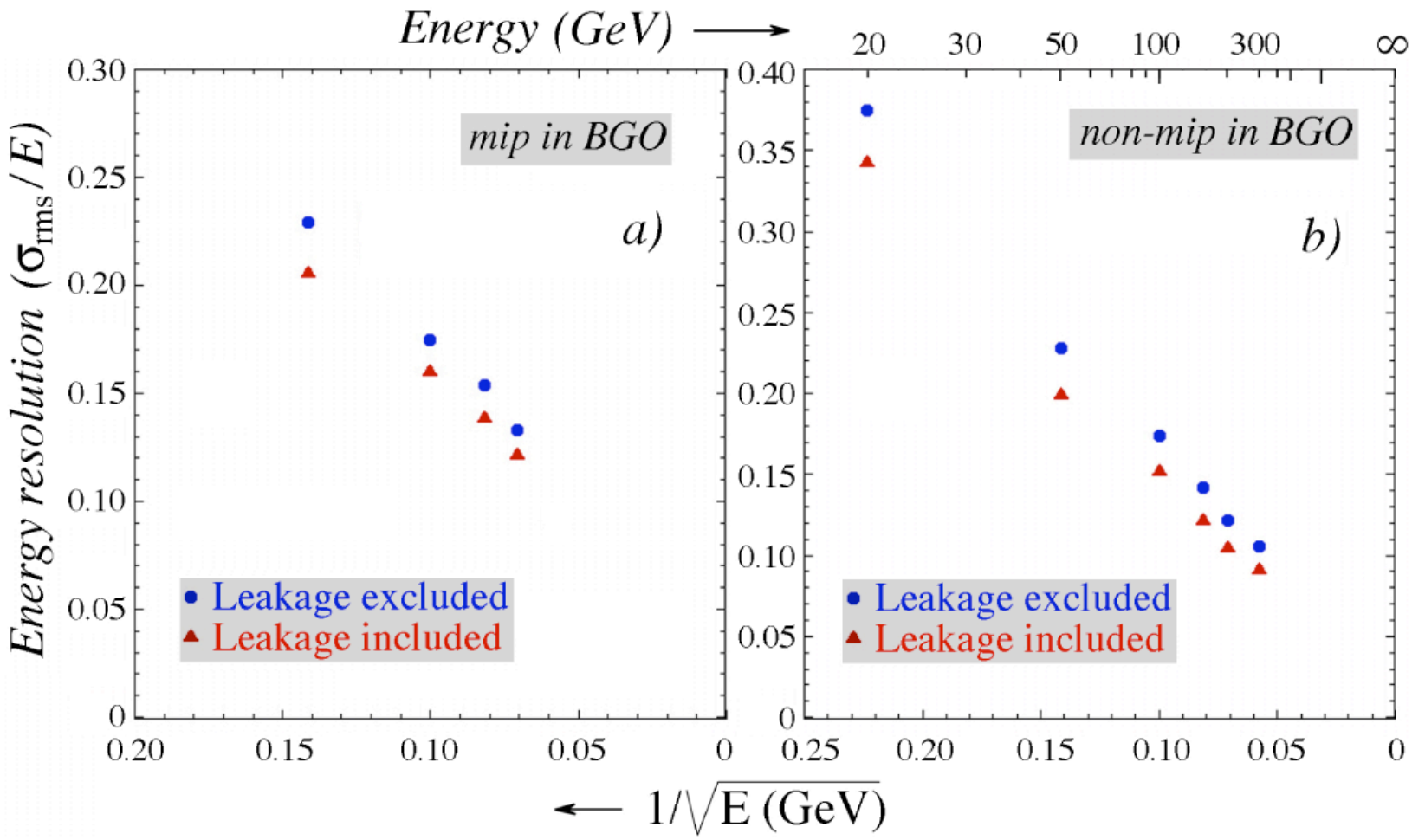


Figure 21: Energy resolution for single pions that penetrated the BGO ECAL without starting a shower, measured with the scintillation signals alone. Results are given with and without taking into account the signals from the leakage counters (*a*). Energy resolution for single pions that started their shower in the BGO ECAL, measured with the scintillation signals alone. Also here, results are given with and without taking into account the signals from the leakage counters (*b*) [17].

Sampling considerations

Sampling fluctuations and the e.m. energy resolution

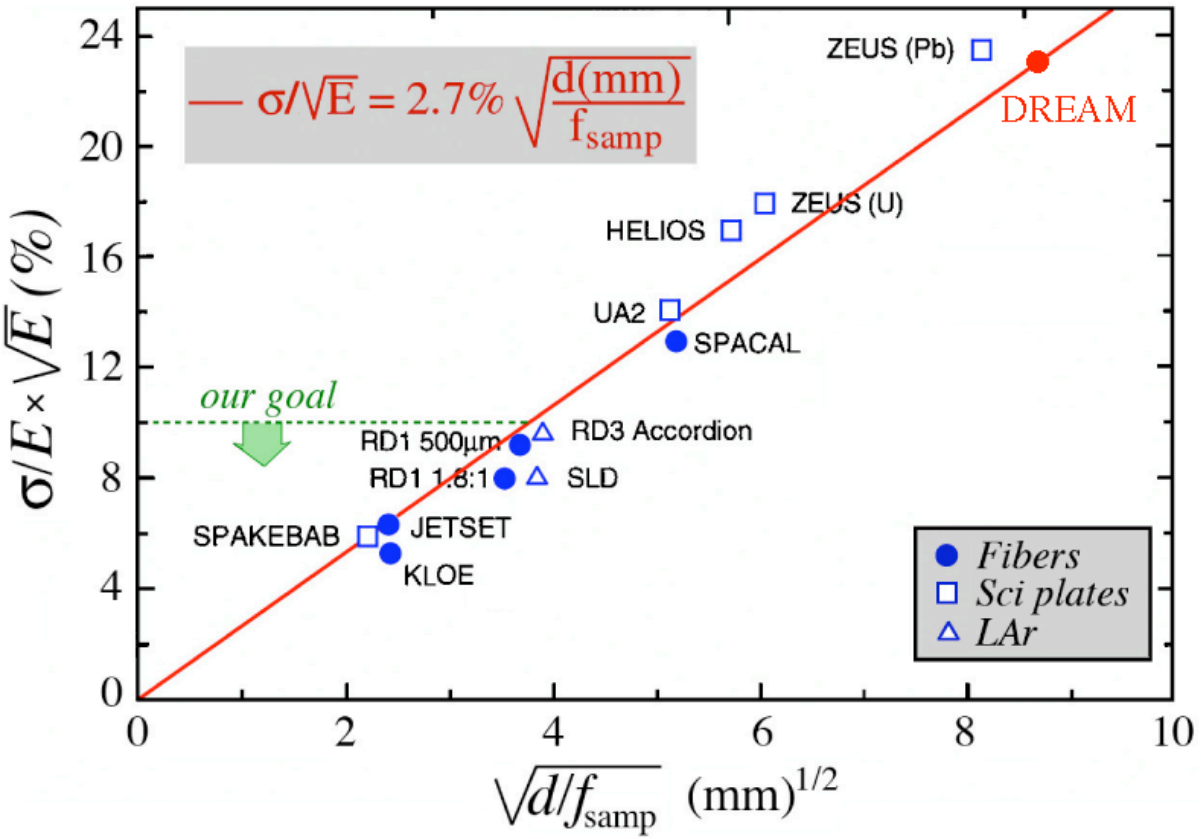


Figure 23: The em energy resolution of sampling calorimeters as a function of the parameter $(d/f_{\rm samp})^{1/2}$, in which d is the thickness of an active sampling layer (*e.g.* the diameter of a fiber or the thickness of a liquidargon gap), and $f_{\rm samp}$ the sampling fraction for mips [20].

Sampling fluctuations

DREAM fiber module: 21%/√E (em), twice as large for hadrons

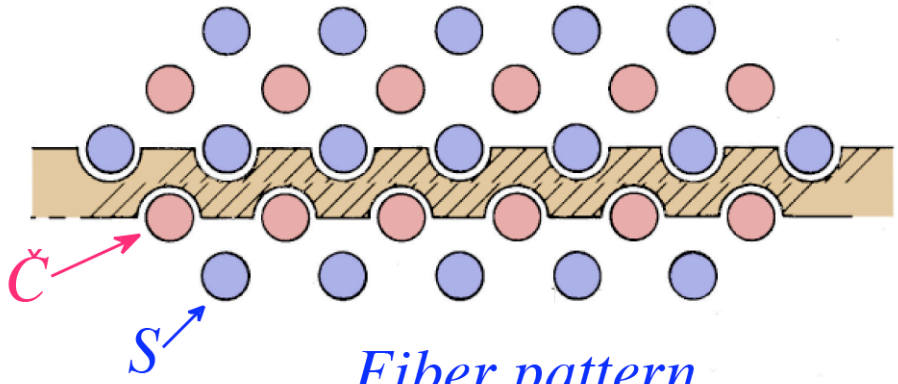
Decrease the sampling fluctuations as follows:

- *Embed fibers individually in metal structure, instead of bunches*
  Reduces to 15%/√E

- *Increase the overall fiber filling fraction*
  (from 22% in original fiber module to 43%. PMTs should fit in "shadow")
  Reduces to 11%/√E

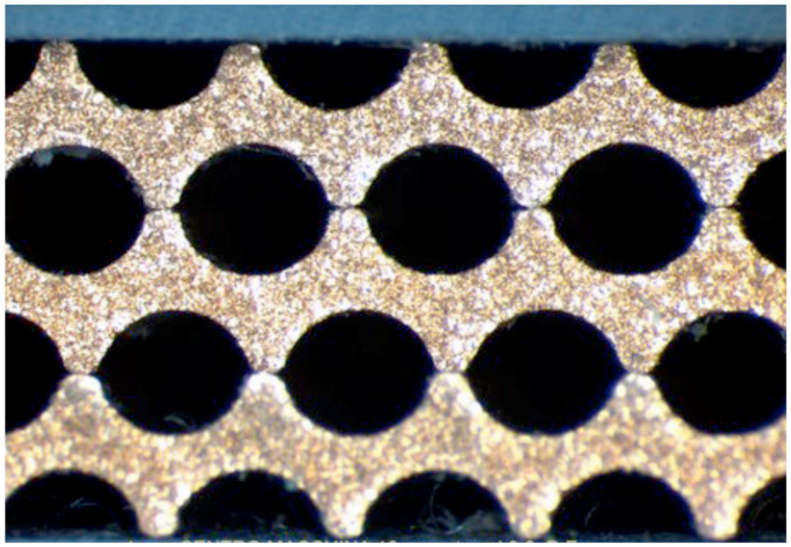
Combine C + S signals for em showers: 8%/√E

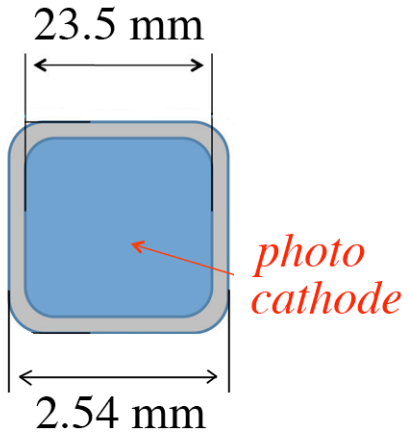
Learn from KLOE and SPACAL!



Fiber pattern

- *interaction length 25 cm*
- *Moliere radius 2.6 cm*
- *10 λ deep*
- *radiation length 2.8 cm*





Hamamatsu R8900
pc: 85%!

(Čerenkov) light yield

Čerenkov light yield in fiber calorimeter

In original DREAM module:

8 photoelectrons/GeV for quartz fibers (N.A. = 0.33)

18 photoelectrons/GeV for plastic fibers (N.A. = 0.50)

Increase by:

- *Using fibers with larger numerical aperture* x 2
  (multi-clad plastic, NA=0.72)

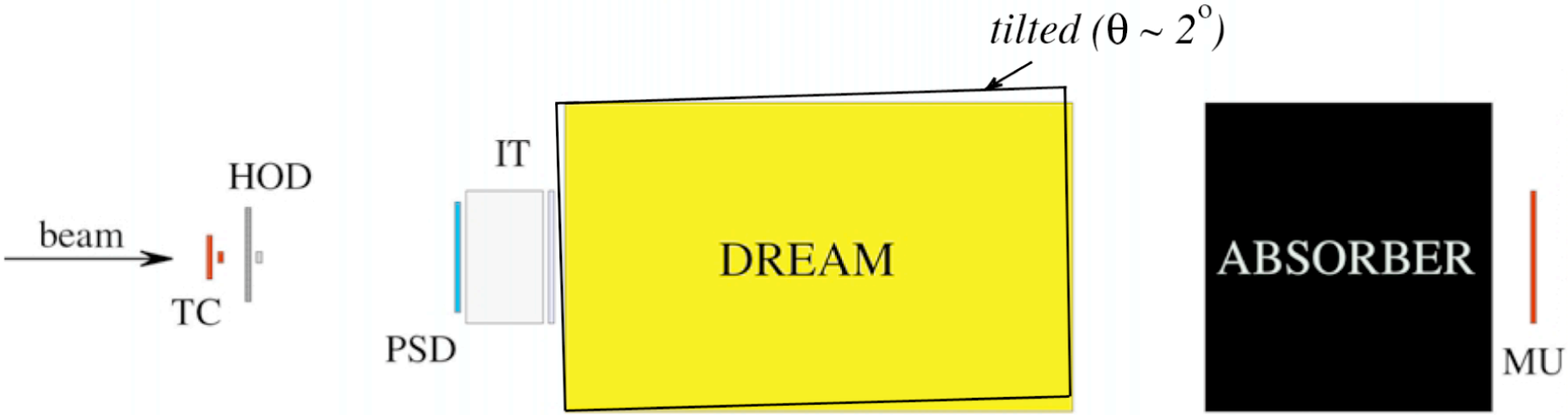
- *Increasing the (Čerenkov) sampling fraction* x 2

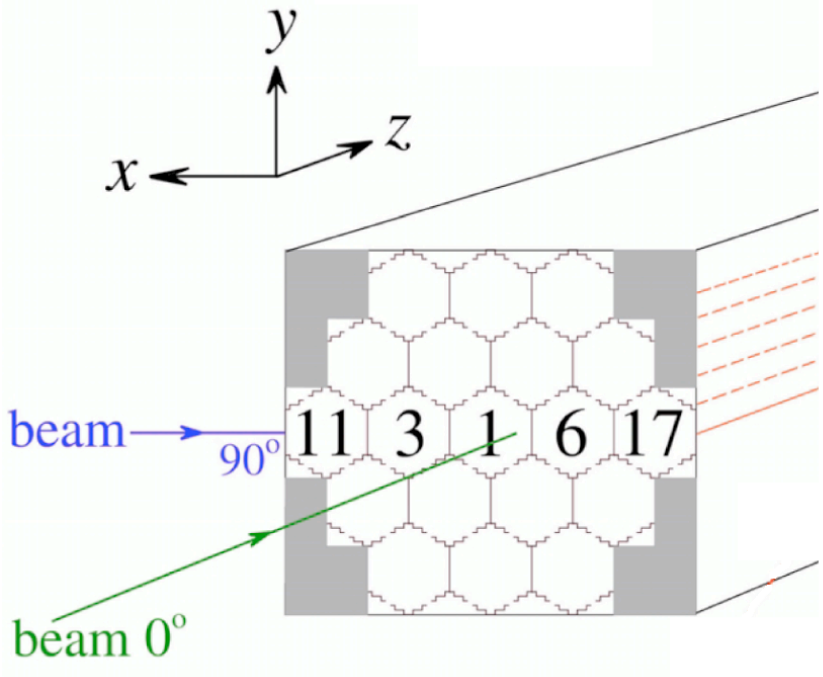
- *Using PMTs with a larger quantum efficiency* x 1.5

Expect to reach > 100 p.e./GeV

Light attenuation

Experimental setup for DREAM beam tests





$\theta = 2^{\circ}$: *The deeper the light is produced, the more the center-of-gravity of the shower shifts to Tower 6*

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

Importance of measuring the depth of the shower maximum event by event

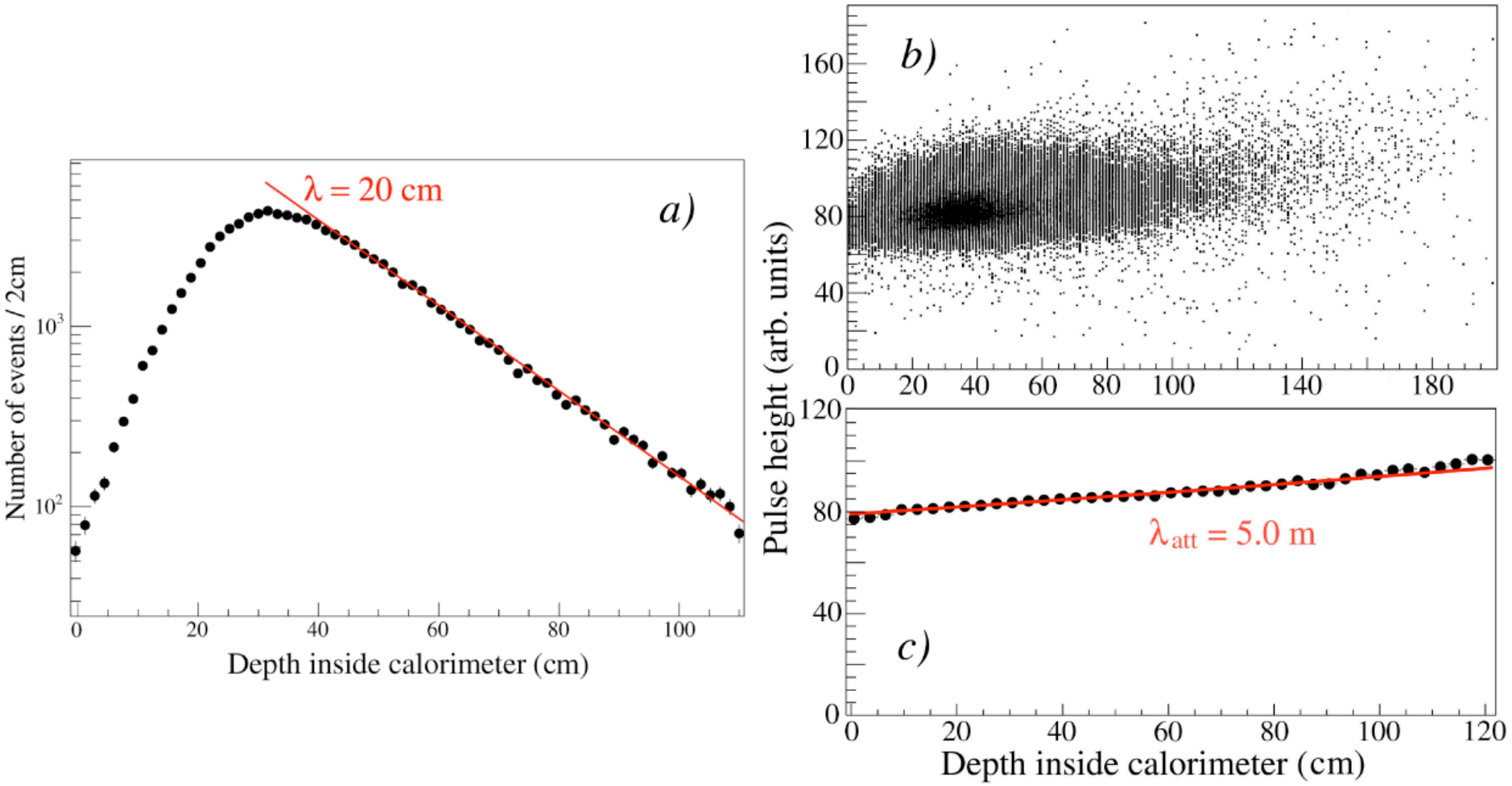


Figure 26: Distribution of the average depth at which the scintillation light is produced in the DREAM calorimeter by showering hadrons (a). Scatter plot showing the total scintillator signal versus the average depth of the light production (a) and the average size of the total scintillator signal as a function of that depth (b), for events induced by 100 GeV π^- mesons. [5].

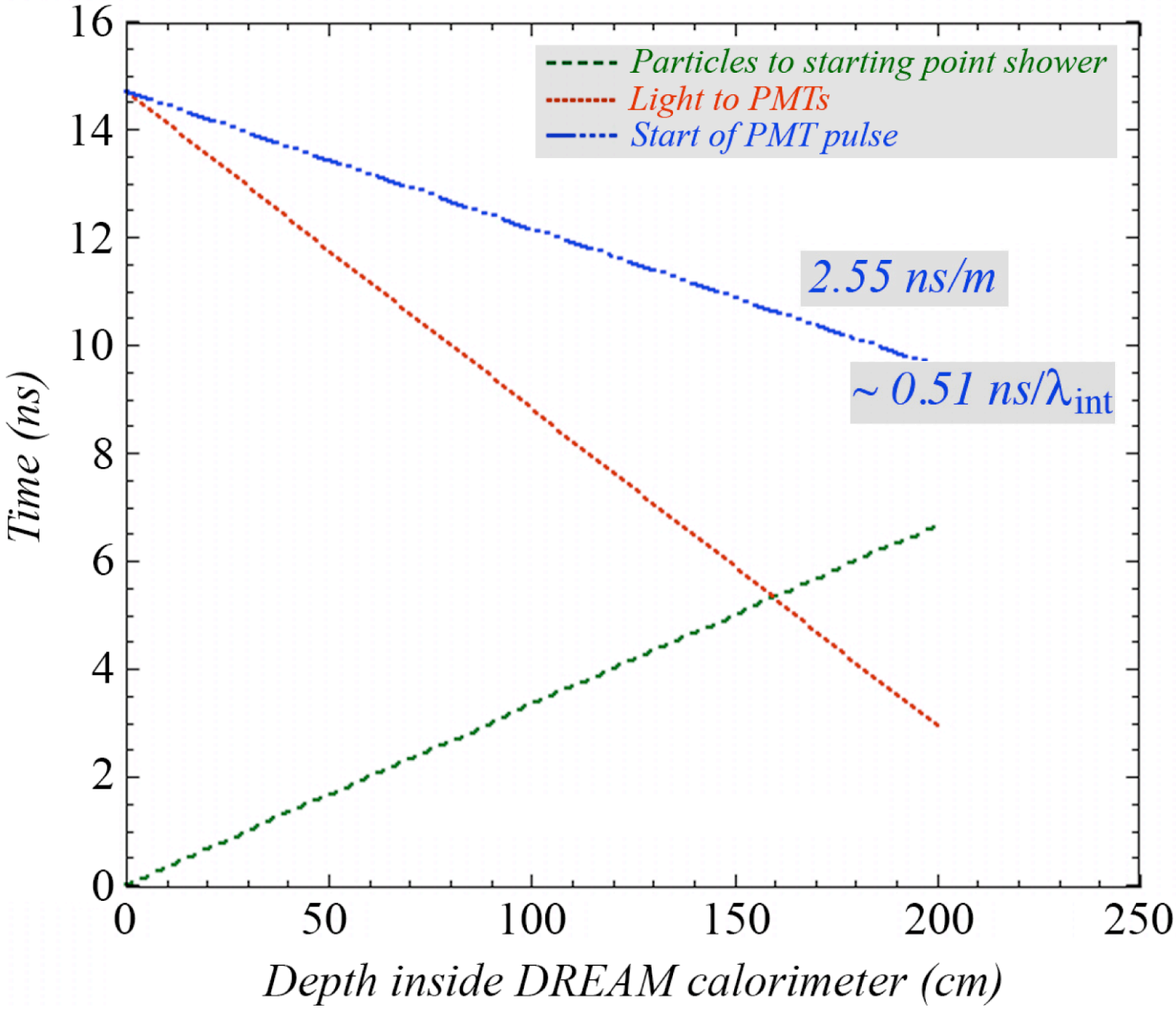
An alternative method to measure shower depth

Disadvantages of described method:

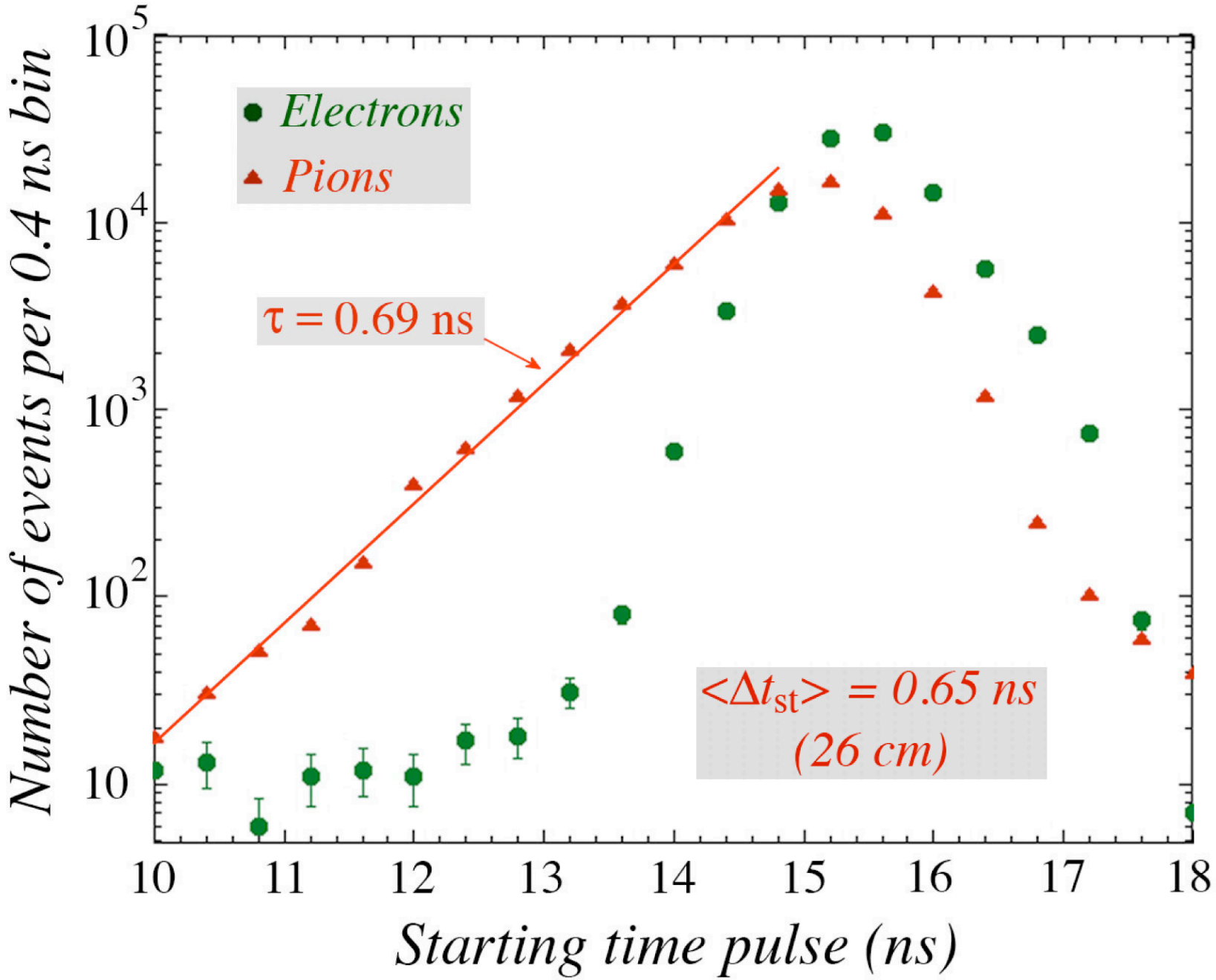
- *Does not work for neutral particles*
- *Does not work for jets*
- *Non-projective calorimeter impractical*

Alternative makes use of the fact that light in fibers travels at $v = c/n$, while particles producing the light travel at $v \sim c$

Depth of the light production and the starting point of the PMT signals



Precise measurement of starting point signal gives depth of the light production!!



Time structure signals

Fiber calorimeter: needed for neutron tail of S signals

Crystals: needed to separate C and S signals

*We plan to use a data acquisition system based on the DRS chip** *(Domino Ring Sampler) developed at PSI.*
An array of 1024 switching capacitors samples the input signal, at a frequency of 2 GHz (DRS-IV).
Read out by pipeline 12-bit ADC.

* *See* NIM A518 (2004) 407

Crystals

Čerenkov and Scintillator information from one signal !

from: NIM A604 (2009) 512

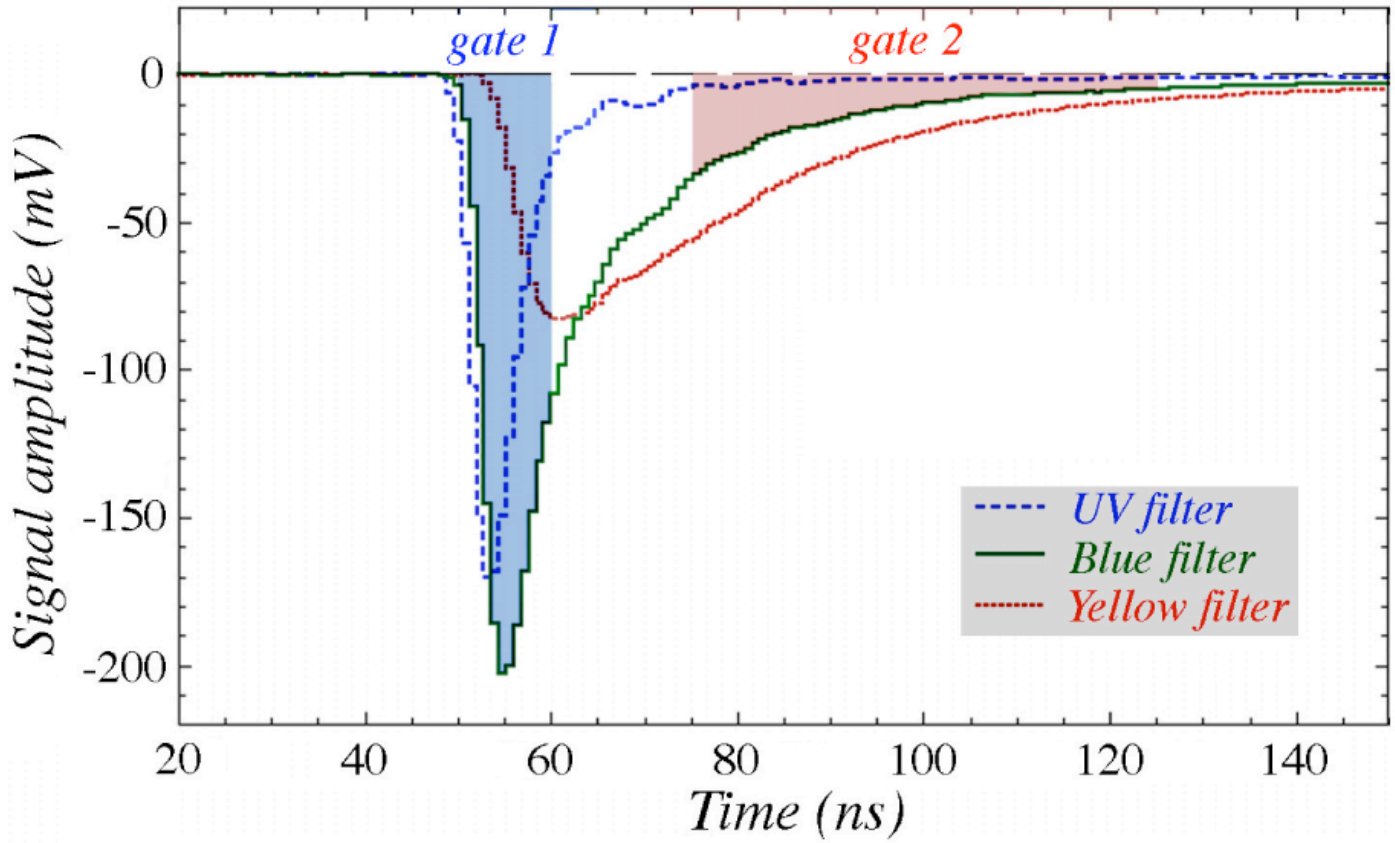


Figure 27: Average structure of the signals from a $PbWO_4$ crystal doped with 1% of molybdenum. The light generated in this crystal by 50 GeV electrons was transmitted either through a UV, a blue or a yellow filter.