Dual-Readout Calorimetry *

Excellent measurement precision for ALL particles and NO calibration issues!!

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Texas Tech University

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EPS Stockholm, July 2013

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* *DREAM (RD52) Collaboration:*
Cagliari, Cosenza, Lisbon, Pavia, Pisa, Roma, Iowa State, TTU

The ideal calorimeter

- *Excellent energy resolution for ALL particles* ($e,\gamma,q,g,h,\not{E}_T$)
- *Easy, trivial calibration*
- *Helpful tool in particle ID*
- *Compact, fast, cheap,...........*

How to achieve excellent hadronic energy resolution?

- *In most hadron calorimeters, fluctuations in f_{em} dominate*

  - Eliminate by: Compensation ($e/h = 1$)
    Measuring f_{em} event by event (DREAM)

- *Fluctuations in VISIBLE ENERGY (nuclear binding energy loss, ΔB)*

  - Non-em signal is dominated by "nuclear" component: p,n
  - Correlation between "nuclear signal" and ΔB determines ultimate limit on hadronic energy resolution (ZEUS *vs* D0)
  - Crystals disfavored in this respect

- *STOCHASTIC fluctuations (sampling, light yield ...)*

  - Limiting factor for electromagnetic energy resolution

An attractive option for improving the quality of hadron calorimetry:

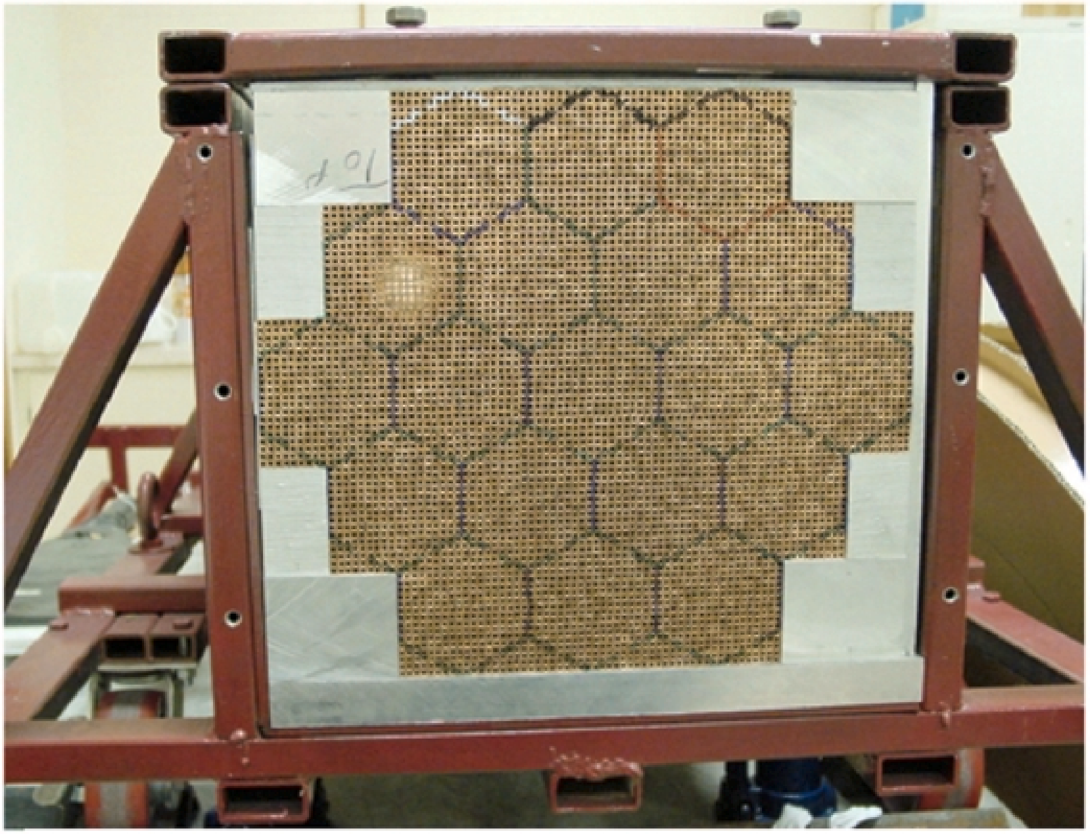
Use Čerenkov light!! *Why?*

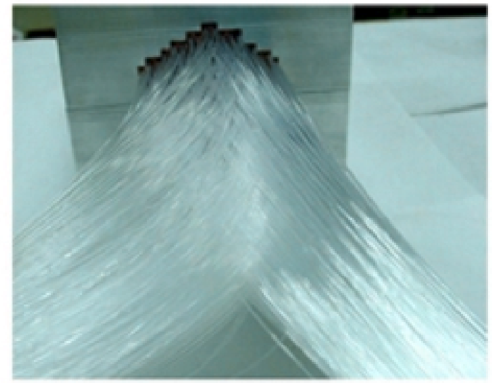
Čerenkov light almost exclusively produced by em shower component
(~80% of non-em energy deposited by non-relativistic particles)

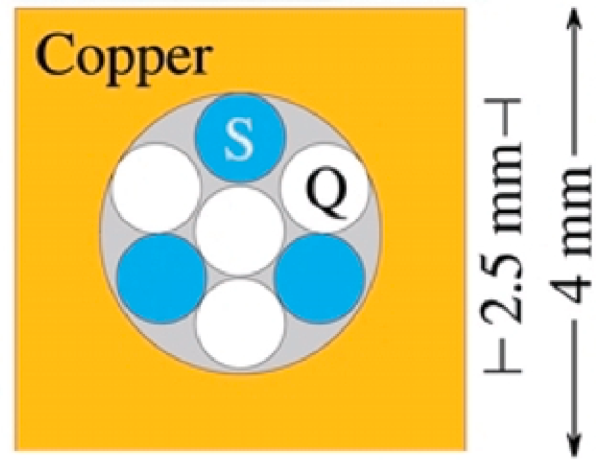
➡ DREAM (Dual REAdout Method) principle:

Measure f_{em} event by event by comparing Č and dE/dx signals

DREAM: Structure

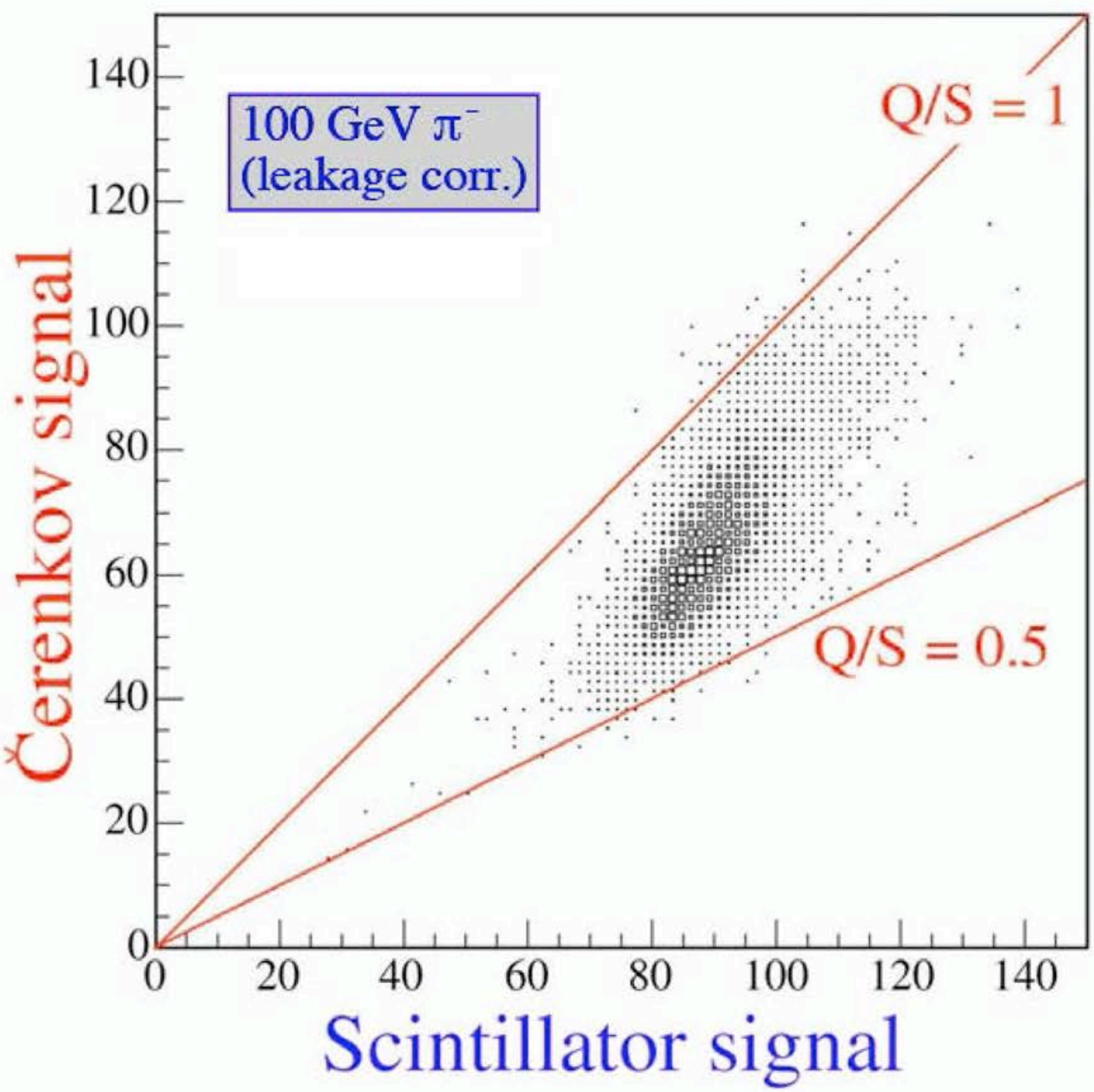






- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 $\lambda_{\rm int}$)
  - Effective radius 16.2 cm (0.81 $\lambda_{\rm int}$, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read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

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



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

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

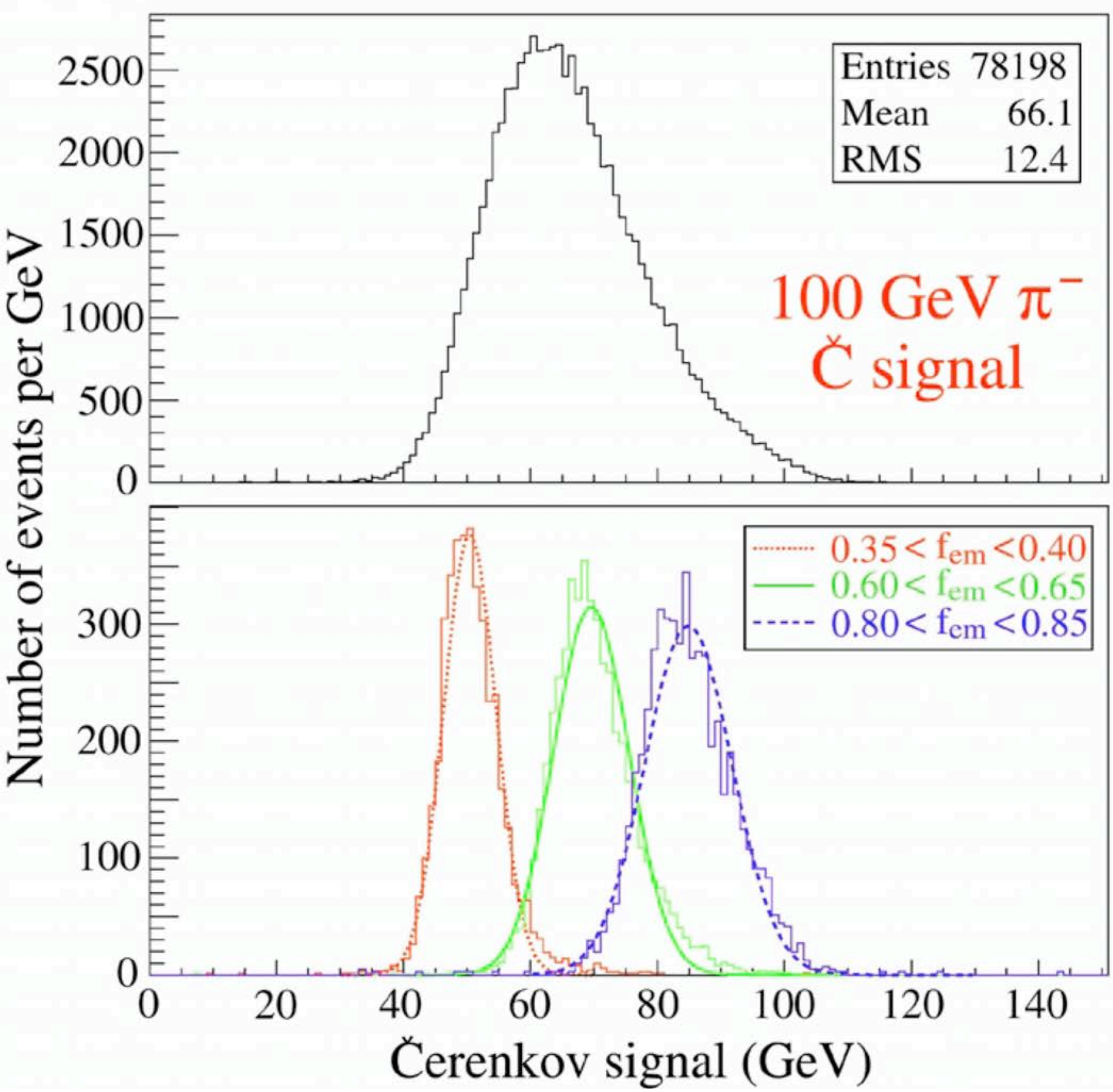
e.g. If $e/h = 1.3$ (S), 4.7 (Q)

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

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

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

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



From:
NIM A537 (2005) 537

The new dual-readout fiber calorimeter built by the RD52 Collaboration

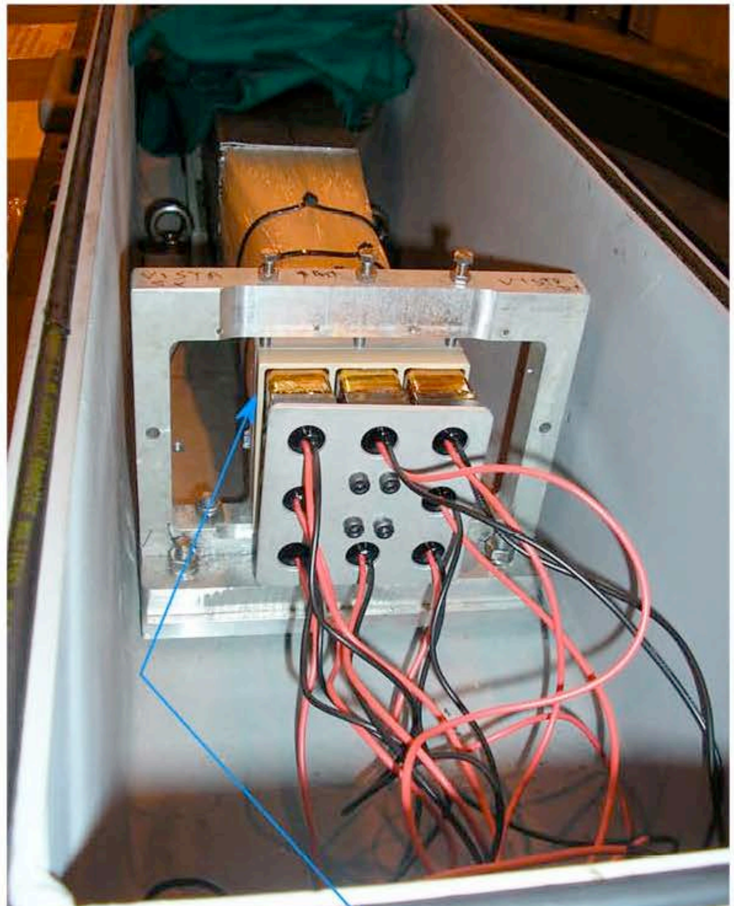
- *Fluctuations in f_{em} eliminated*
  Fluctuations in effects of ΔB minimized (estimate $15\%/\sqrt{E}$)

- *Improve on stochastic fluctuations*
  - *Sampling fluctuations*
  - *Čerenkov light yield*

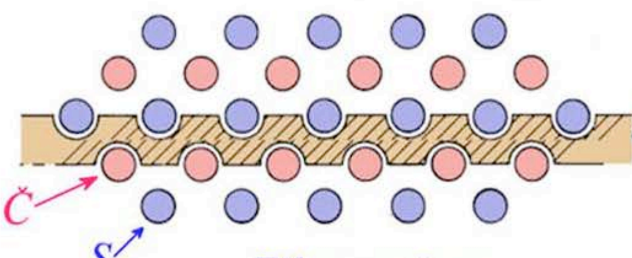
  Both contributed ~$35\%/\sqrt{E}$ to DREAM results

- *Test effect of improvements with electron showers, since the em resolution is limited by stochastic fluctuations*

The first SuperDREAM module tested at CERN

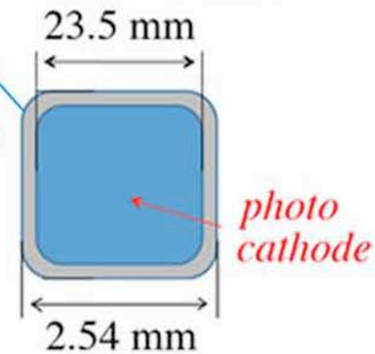


Pb absorber
9.3 x 9.3 x 250 cm
150 kg
4 towers, 8 PMTs
2 x 2048 fibers

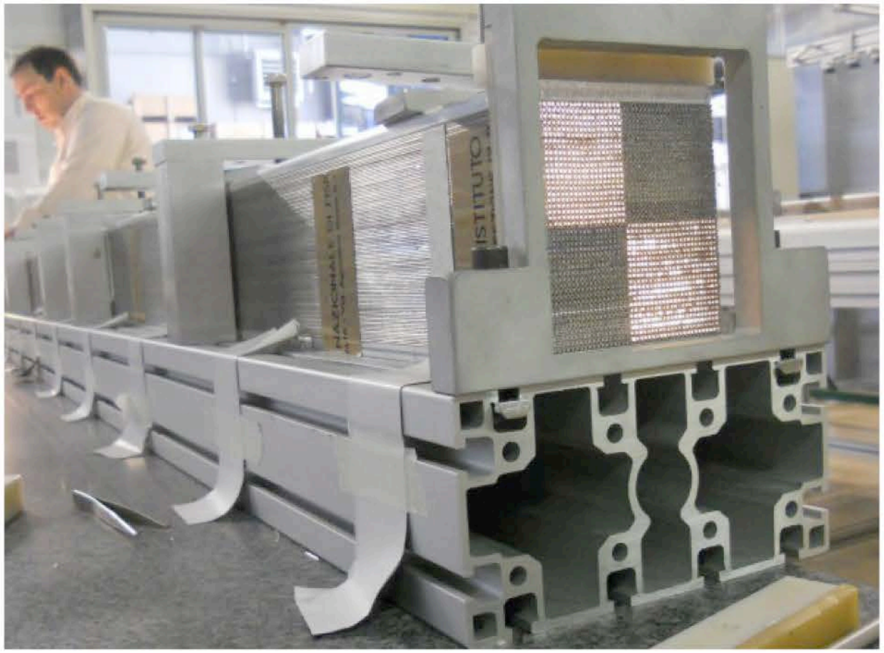


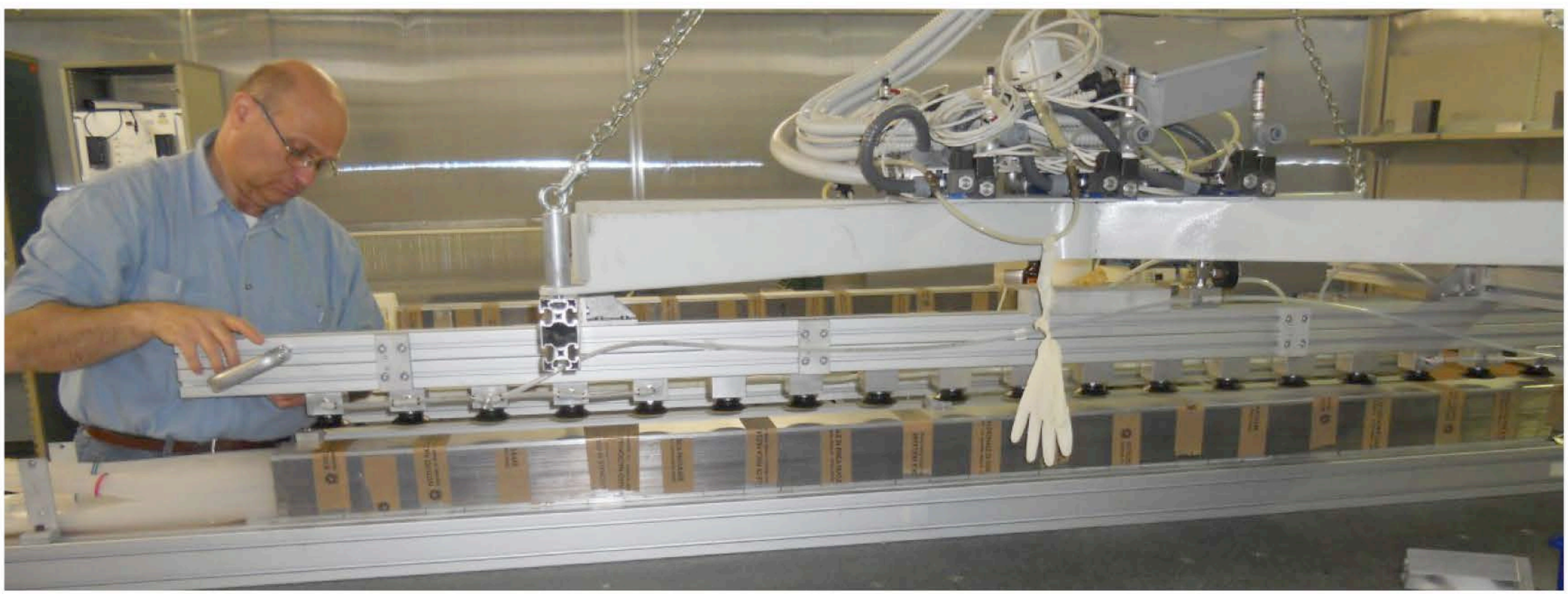
Fiber pattern

Hamamatsu R8900
pc: 85%!

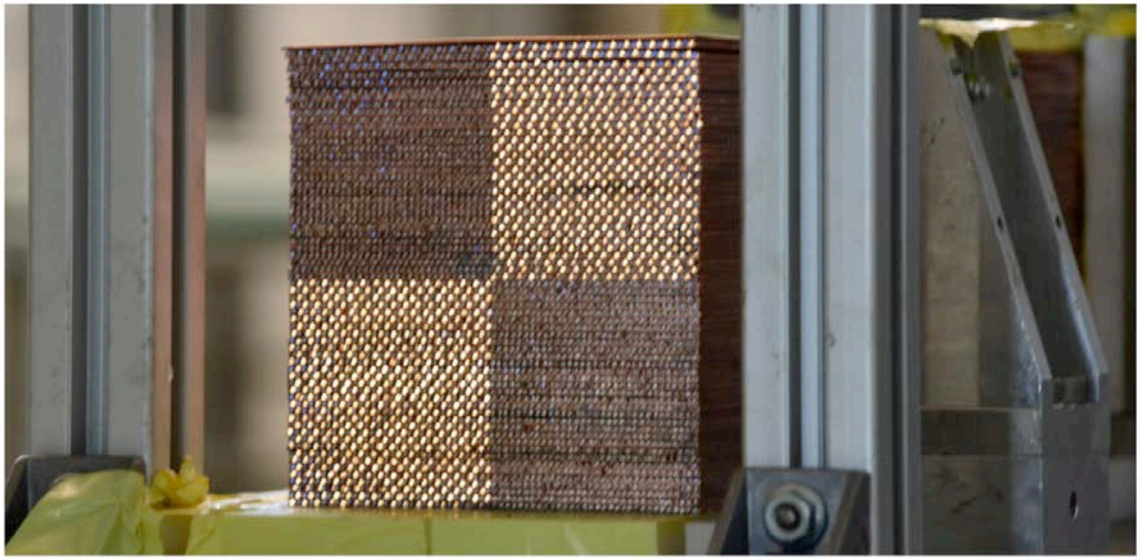


Production of Pb based SuperDREAM modules



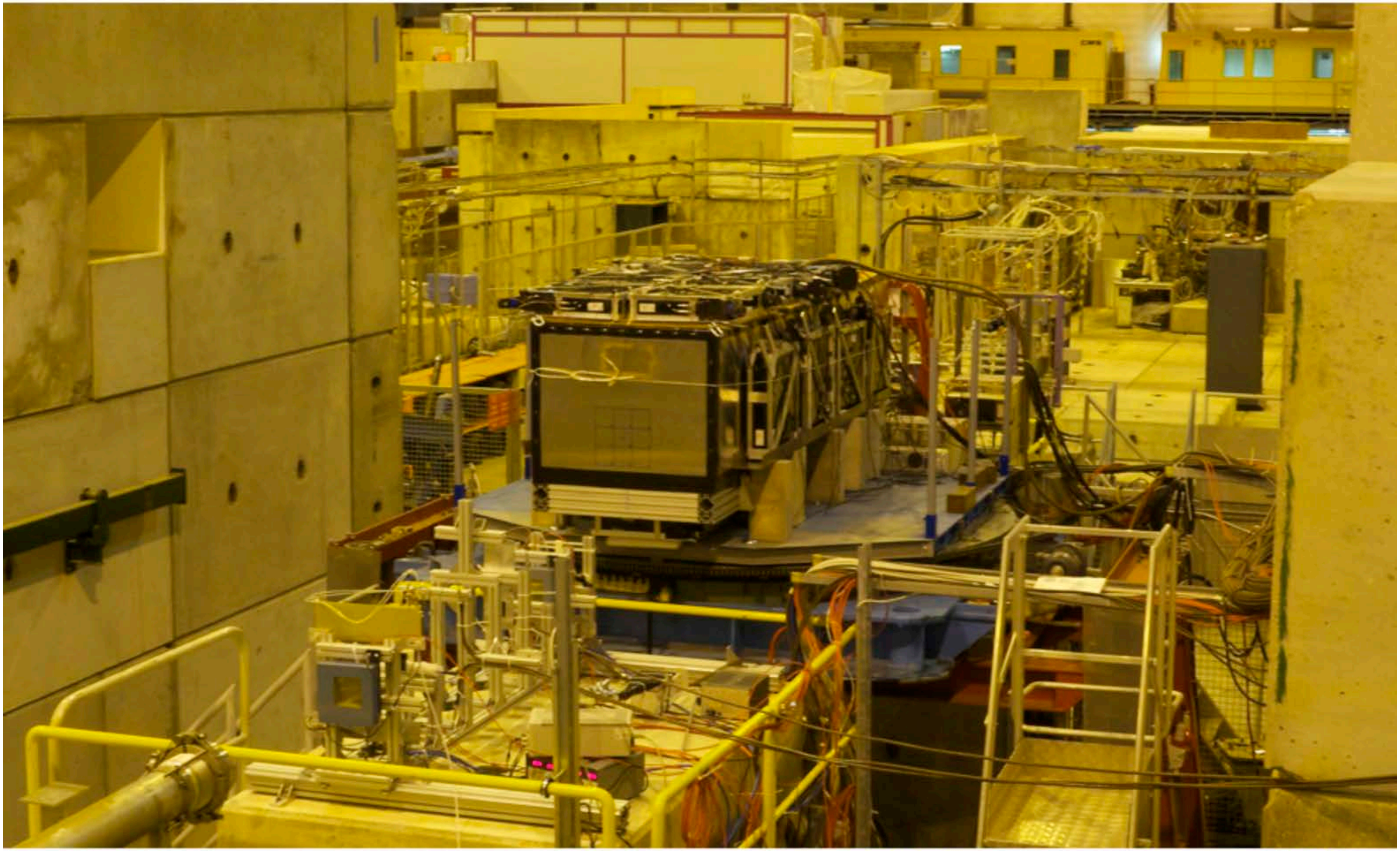


The first copper module



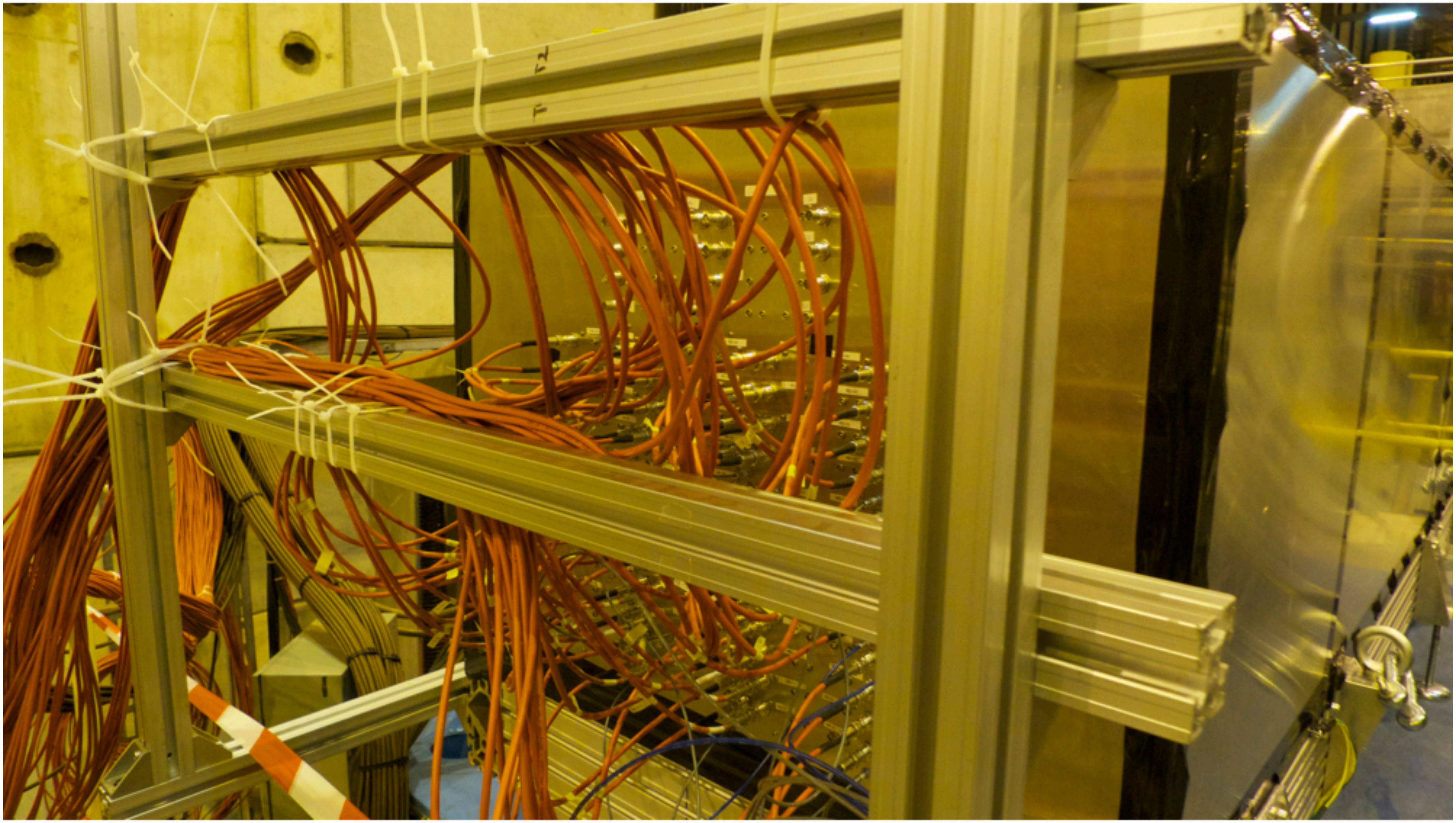
The new SuperDREAM fiber module tested at CERN

(December 2012)

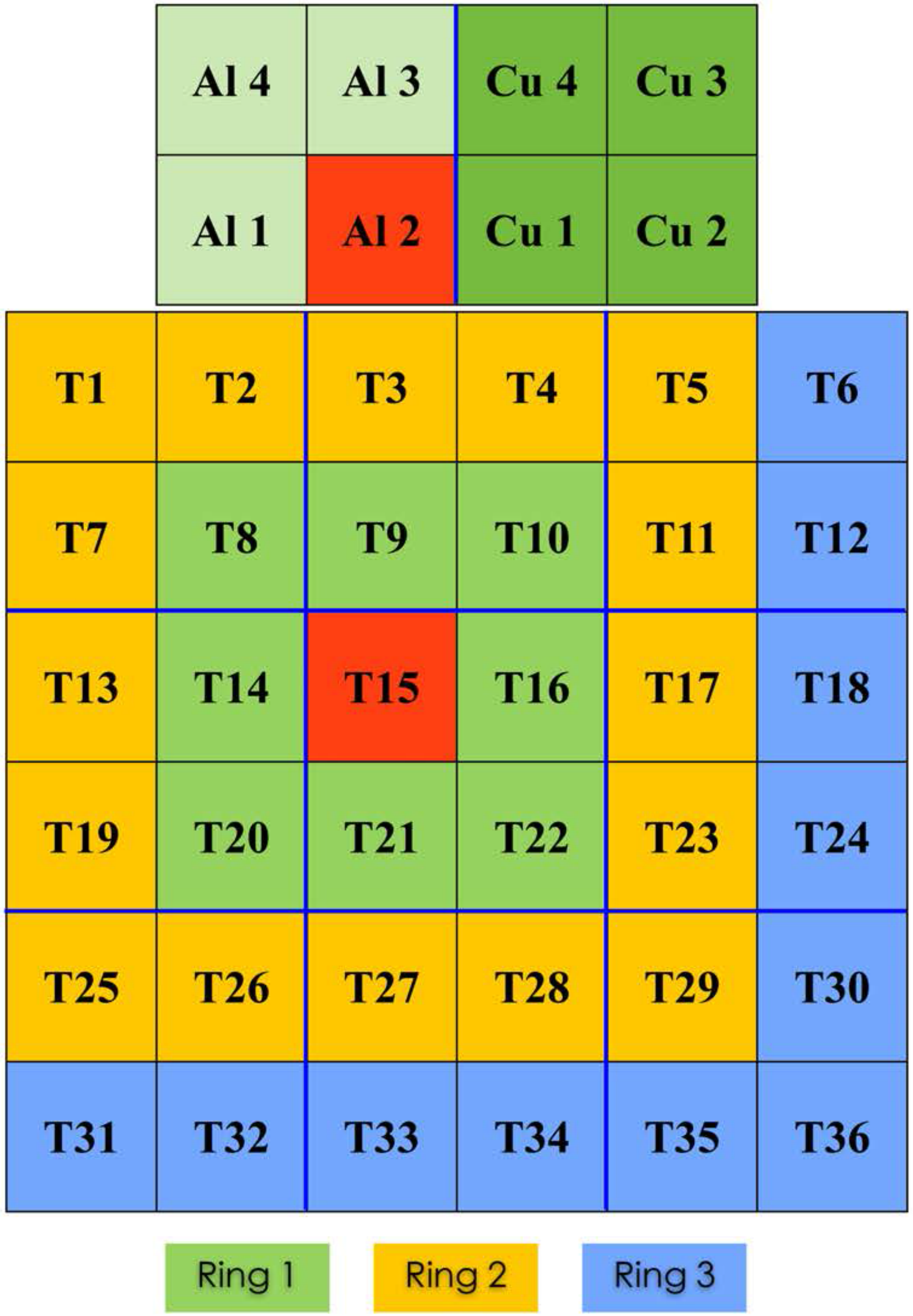


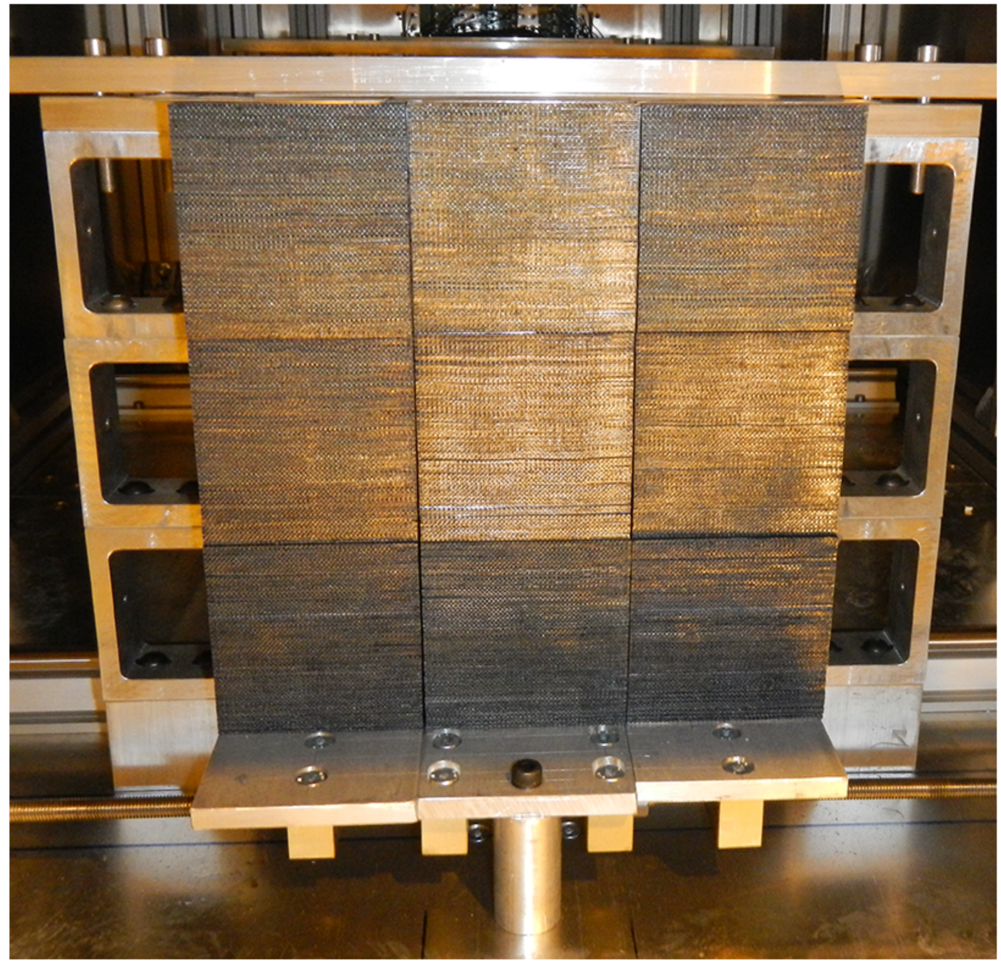
9 modules (36 towers, 72 signals), 1.4 tonnes Pb/fiber + 2 modules Cu/fiber
20 leakage modules (500 kg plastic scintillator)

Rear side of the new SuperDREAM module

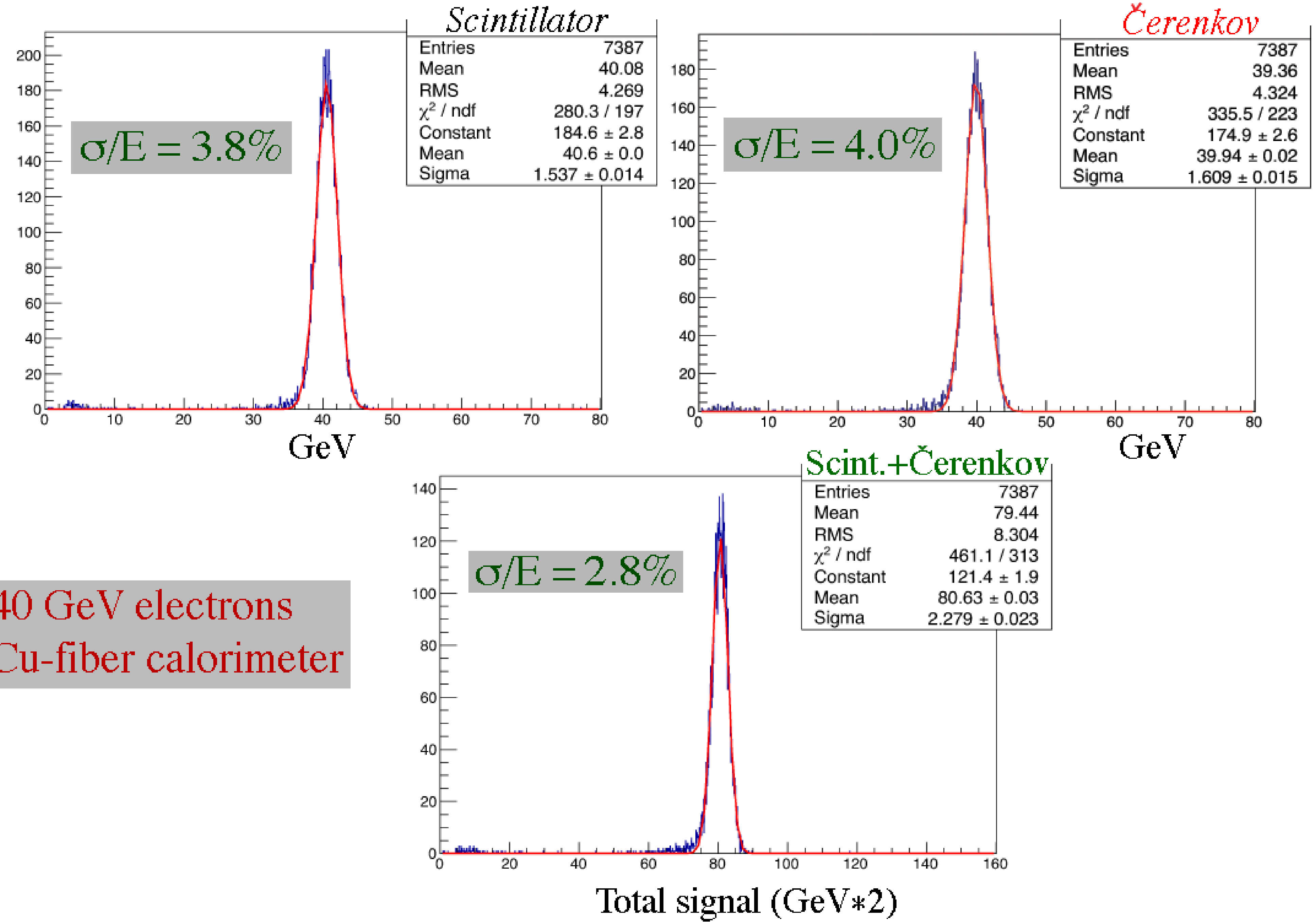


The RD52 fiber calorimeter tested in November 2012





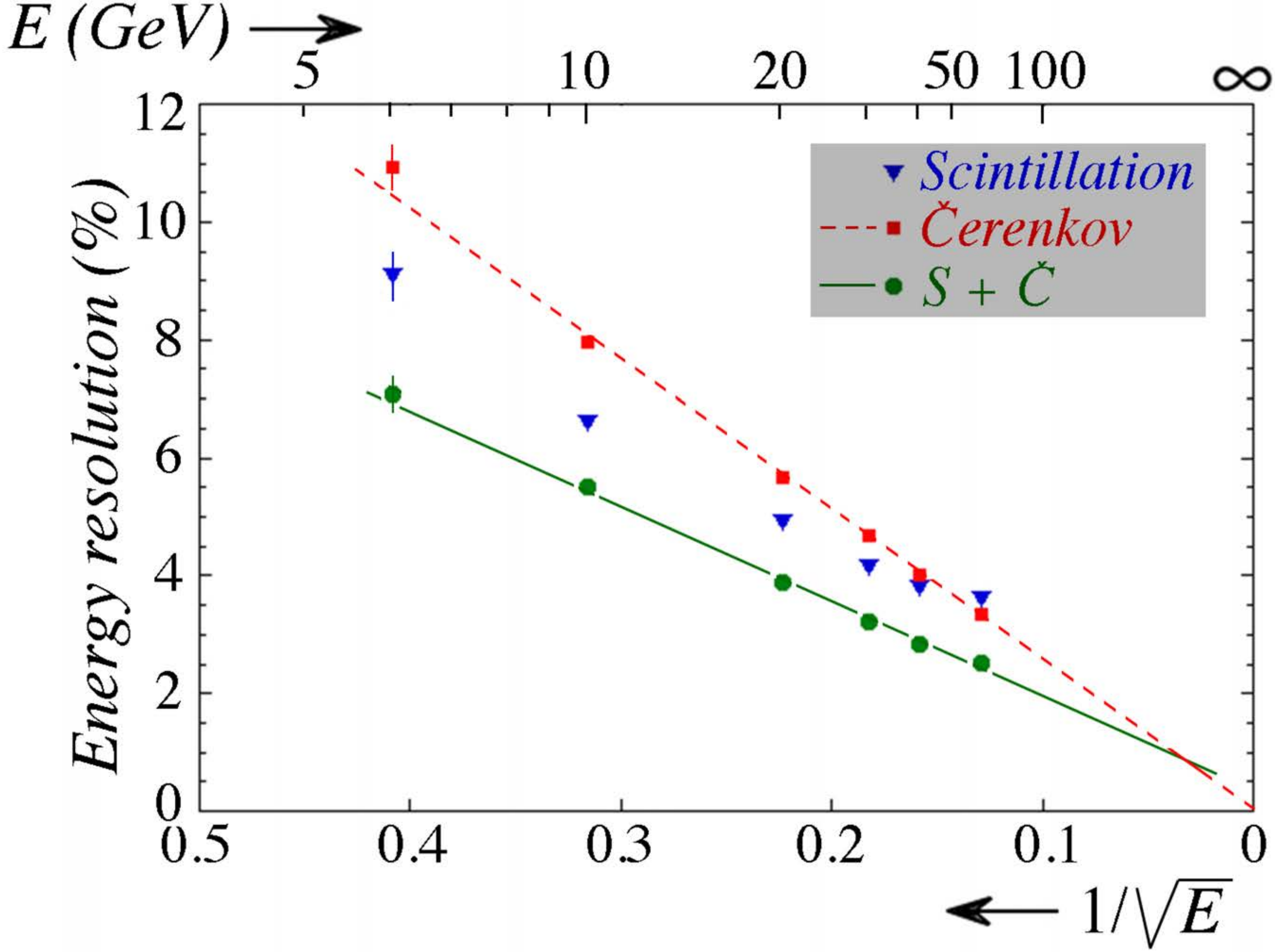
S and Č signals sample the showers independently
Resolution improves by combining



40 GeV electrons
Cu-fiber calorimeter

Combining signals from two fiber types improves resolution

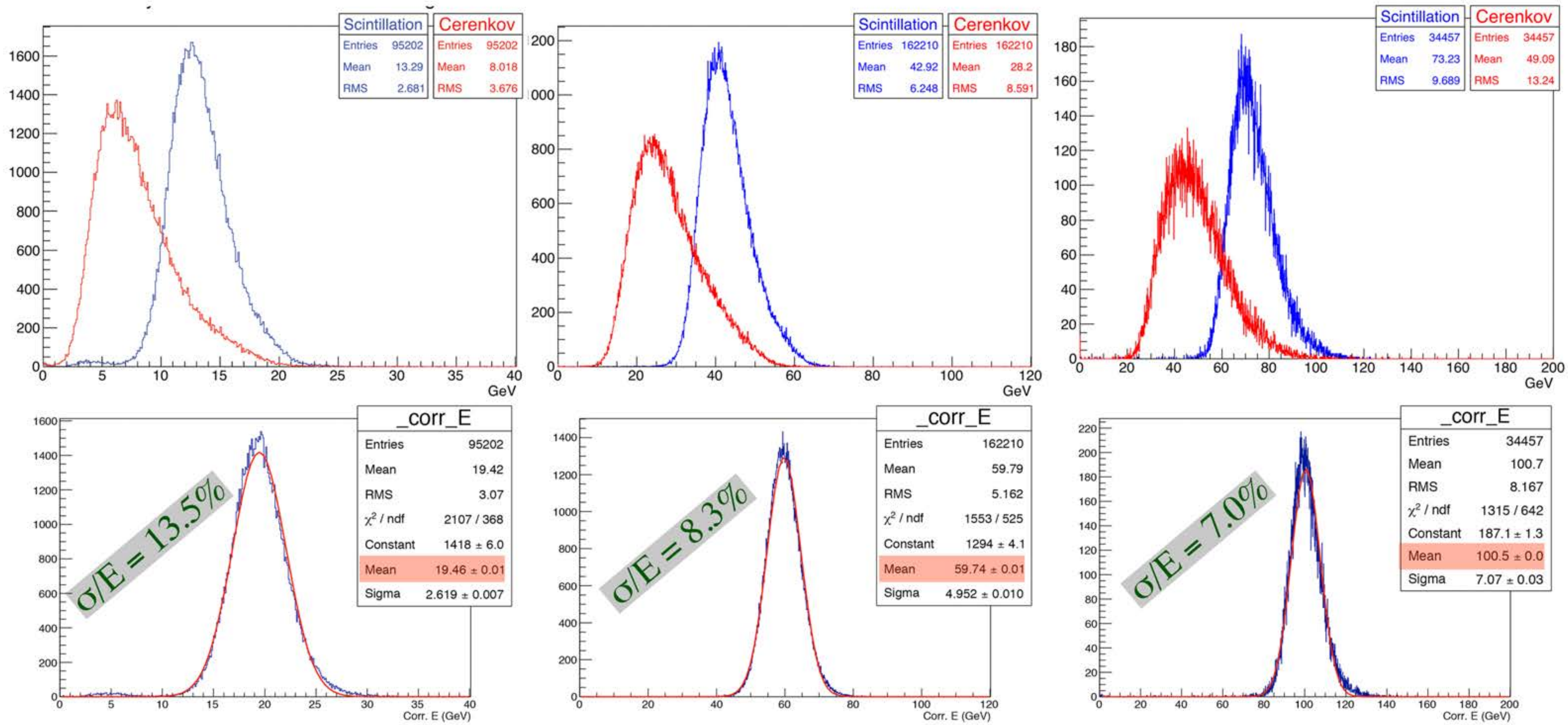
→ Stochastic term dominates



Hadron detection with a dual-readout calorimeter

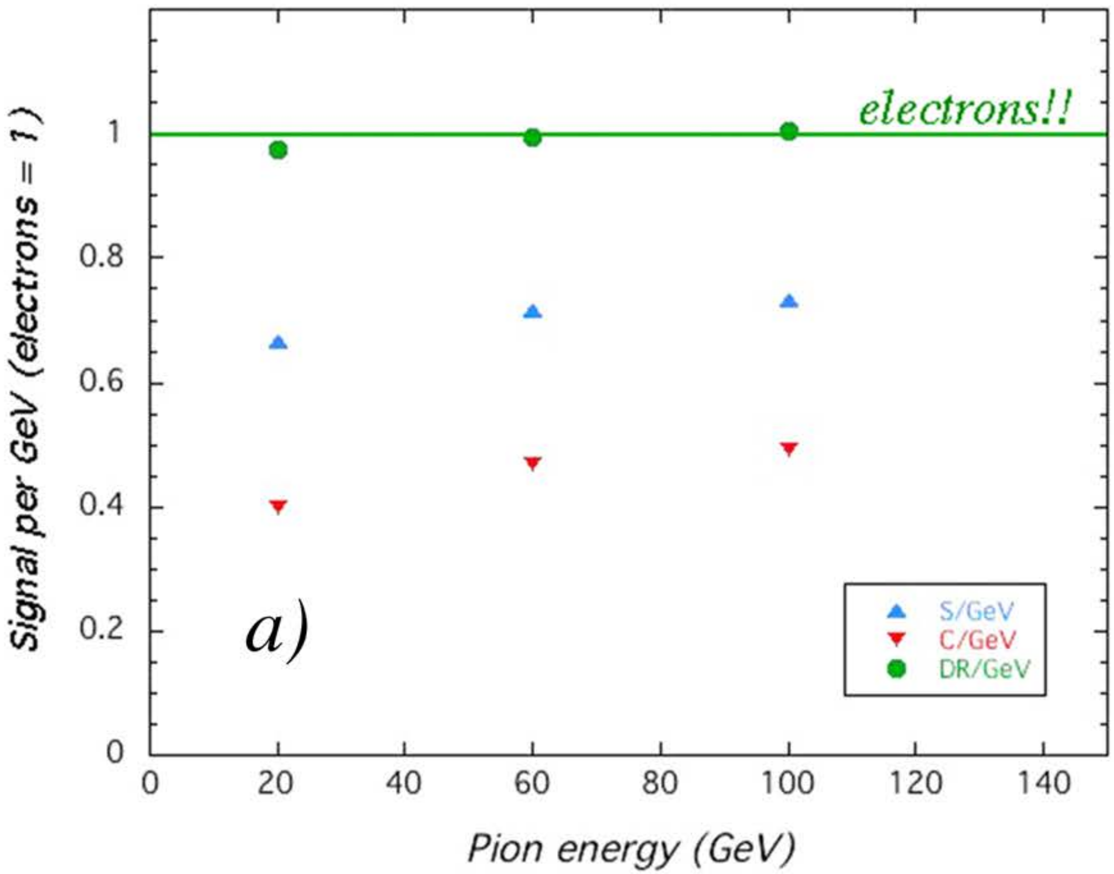
$$E = \frac{S - \chi C}{1 - \chi} \quad \textit{with} \quad \chi = \frac{1 - (h/e)_S}{1 - (h/e)_C} = 0.45$$

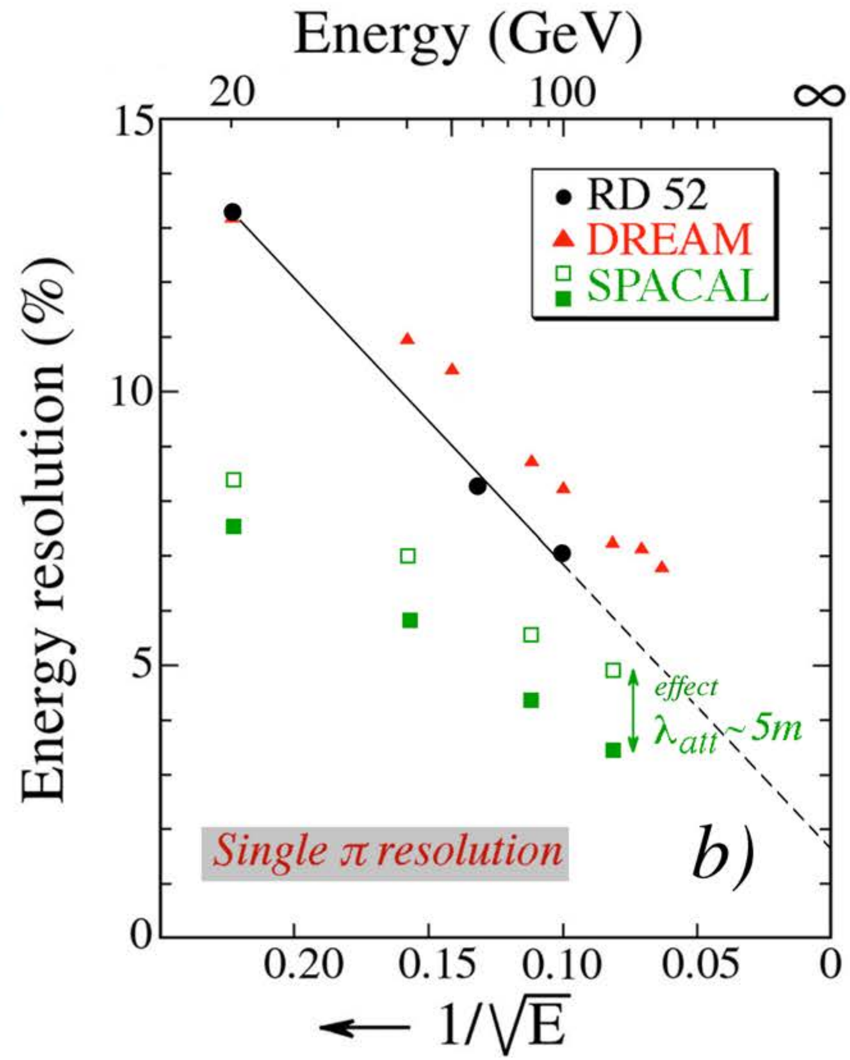
20 GeV π^- | 60 GeV π^- | 100 GeV π^-



The calorimeter response and energy resolution for single pions

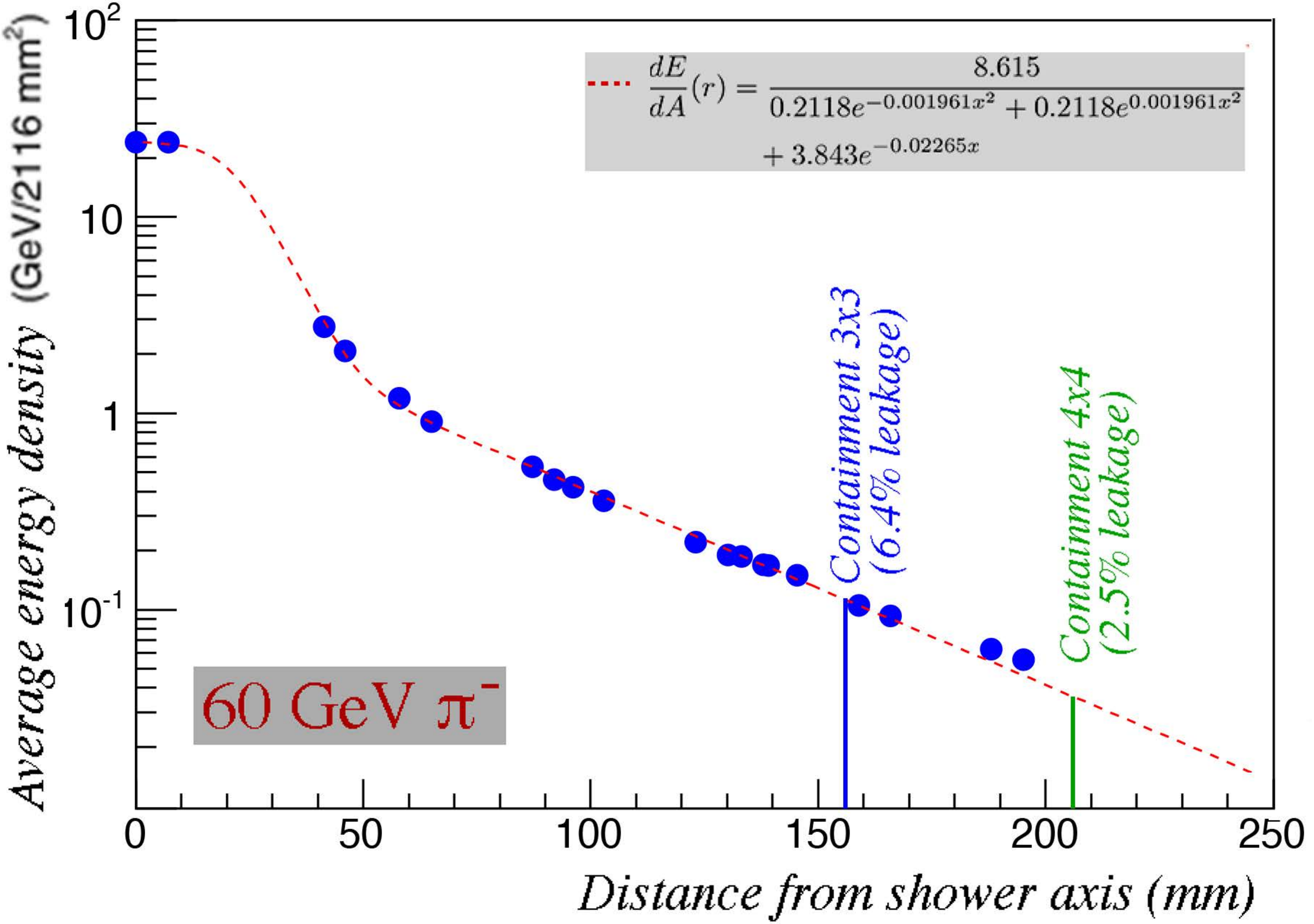
Electron energy scale well reproduced by DR!!





Note: RD52 pion data still preliminary (e.g., no light attenuation corrections)

Radial profile and hadronic shower containment



A crucial feature: No longitudinal segmentation

- *Advantages:*
  - *Compact construction*
  - *No intercalibration of sections needed*
  - *Calibrate with electrons and you are done*

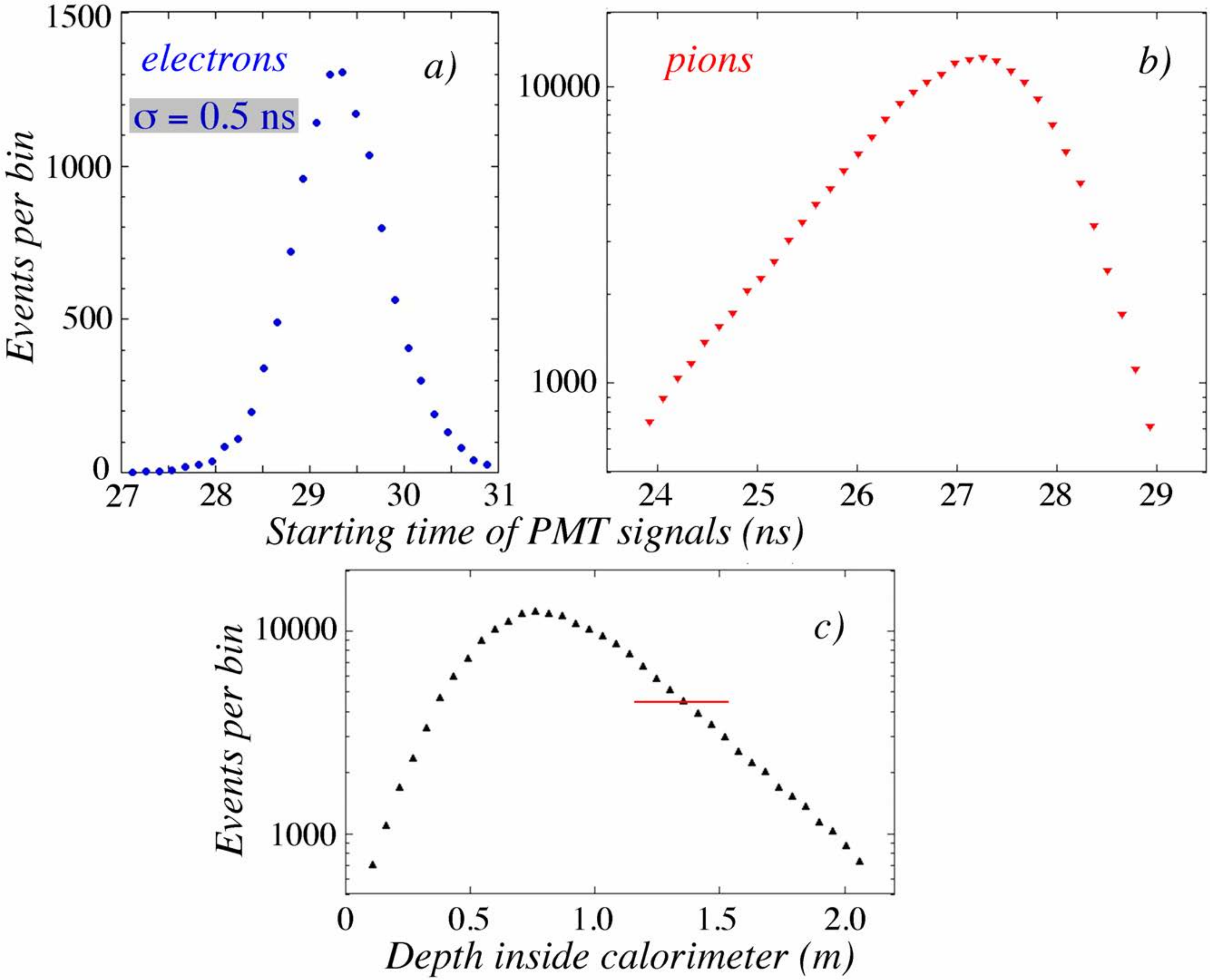
- *Possible disadvantages:*
  - *Dealing with pile-up (not an issue at ILC)*
  - *Pointing for neutral particles*
  - *Electron ID*

However, a fine lateral granularity can do wonders

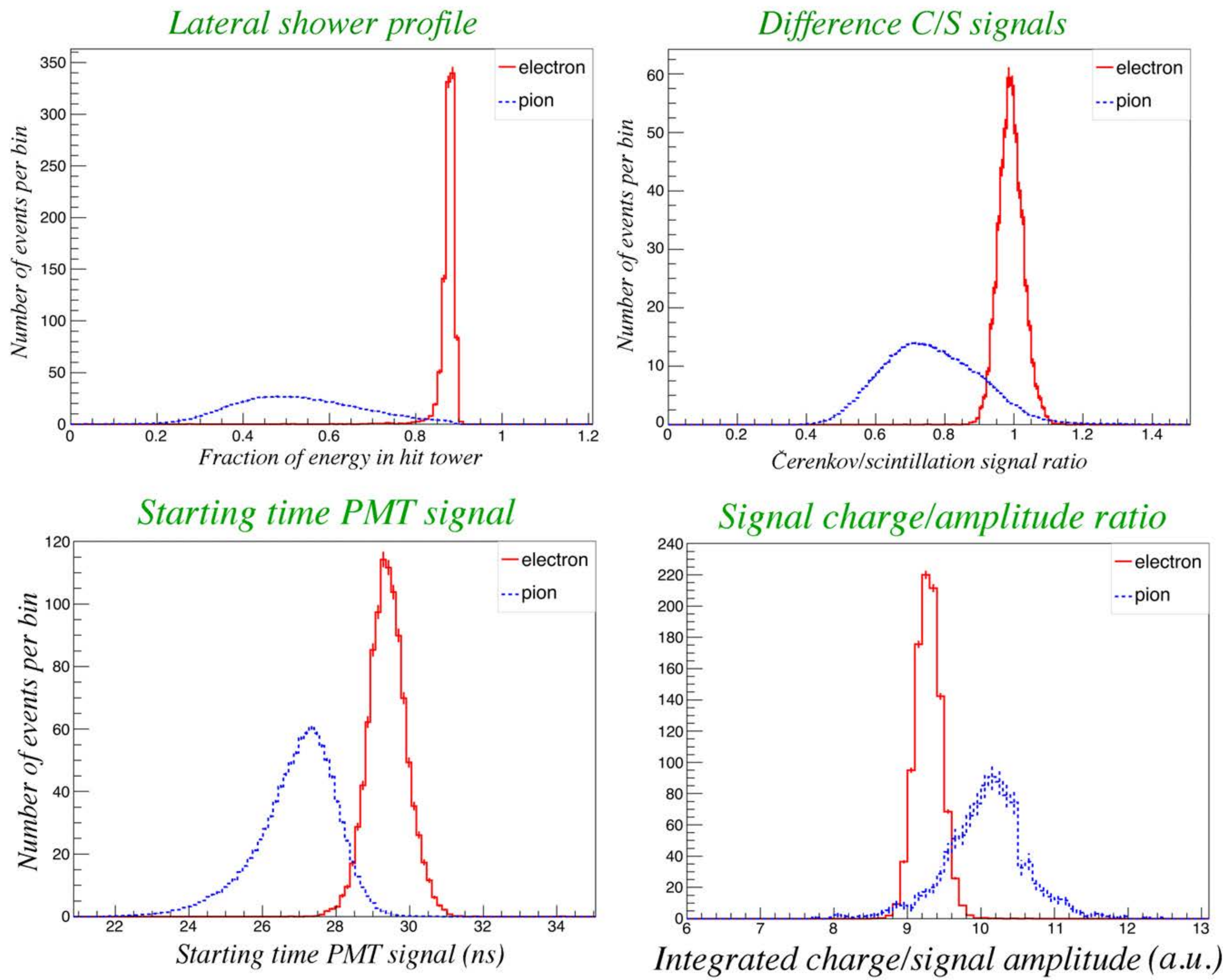
In addition:

- *Time structure of the signals can provide crucial depth information*

Use starting time PMT signal to determine the depth of the light production and thus identify particle

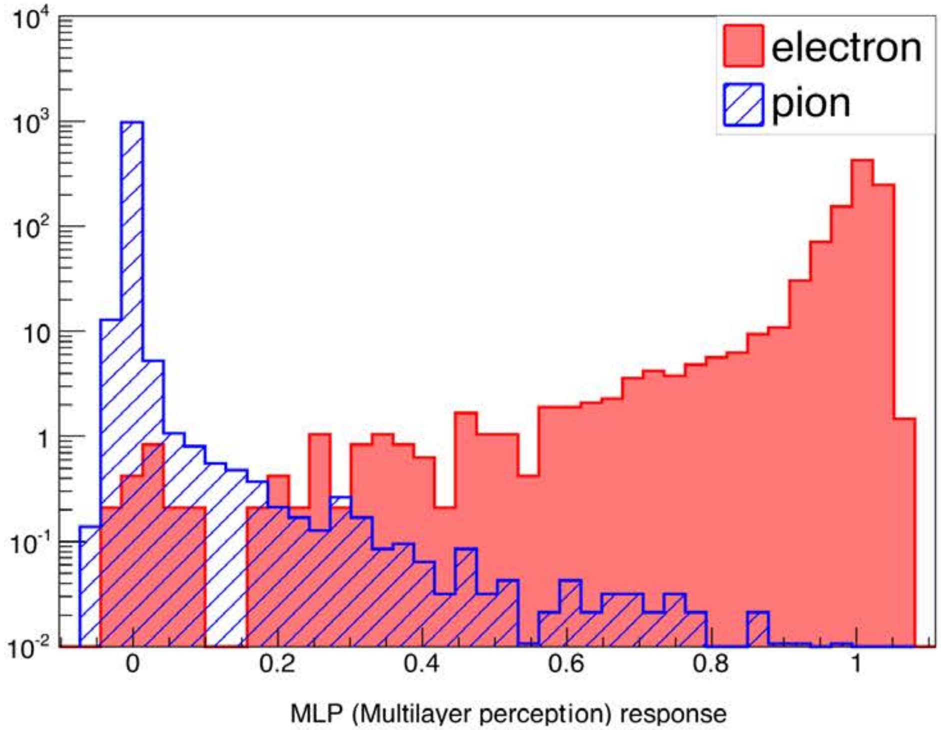


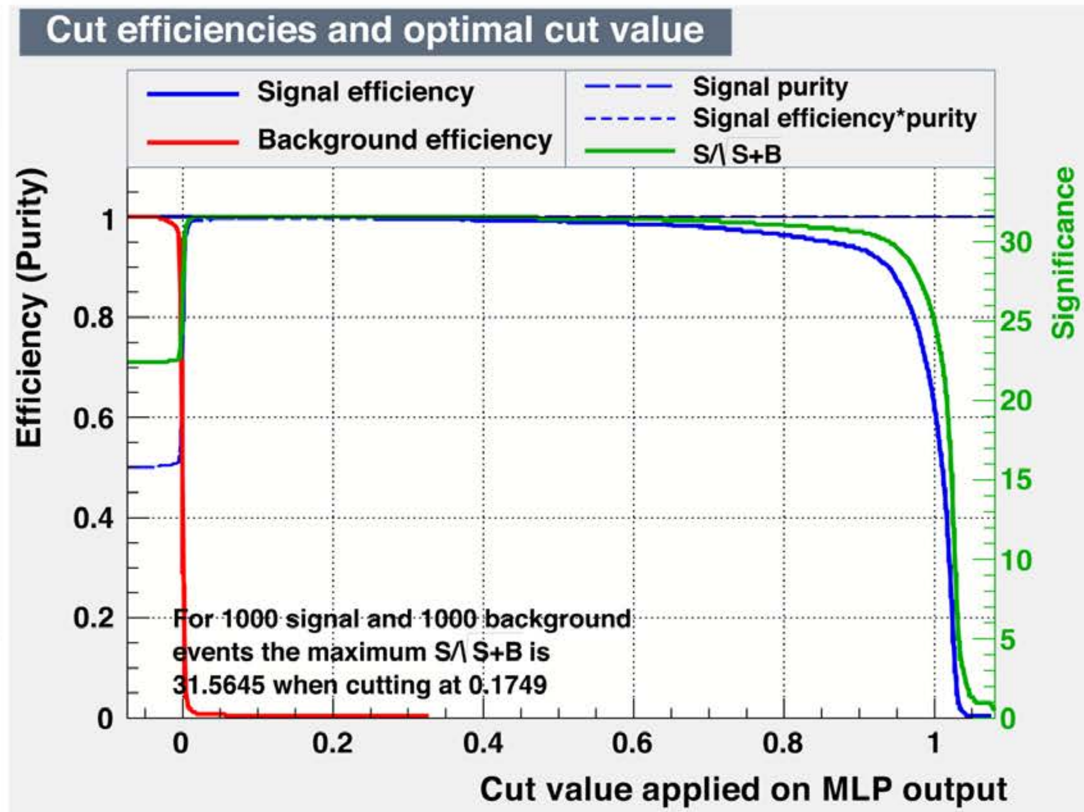
Methods to distinguish e/π in longitudinally unsegmented calorimeter



Combination of cuts: >99% electron efficiency, <0.2% pion mis-ID

Neural network analysis 60 GeV e/π separation





for MLP > 0.17 : 99.81% electron ID
0.20% π mis-ID

Longitudinally segmented vs. unsegmented calorimeters

Arguments for segmentation

- *Electron ID*
- *Optimize em section for high-resolution measurements*

However

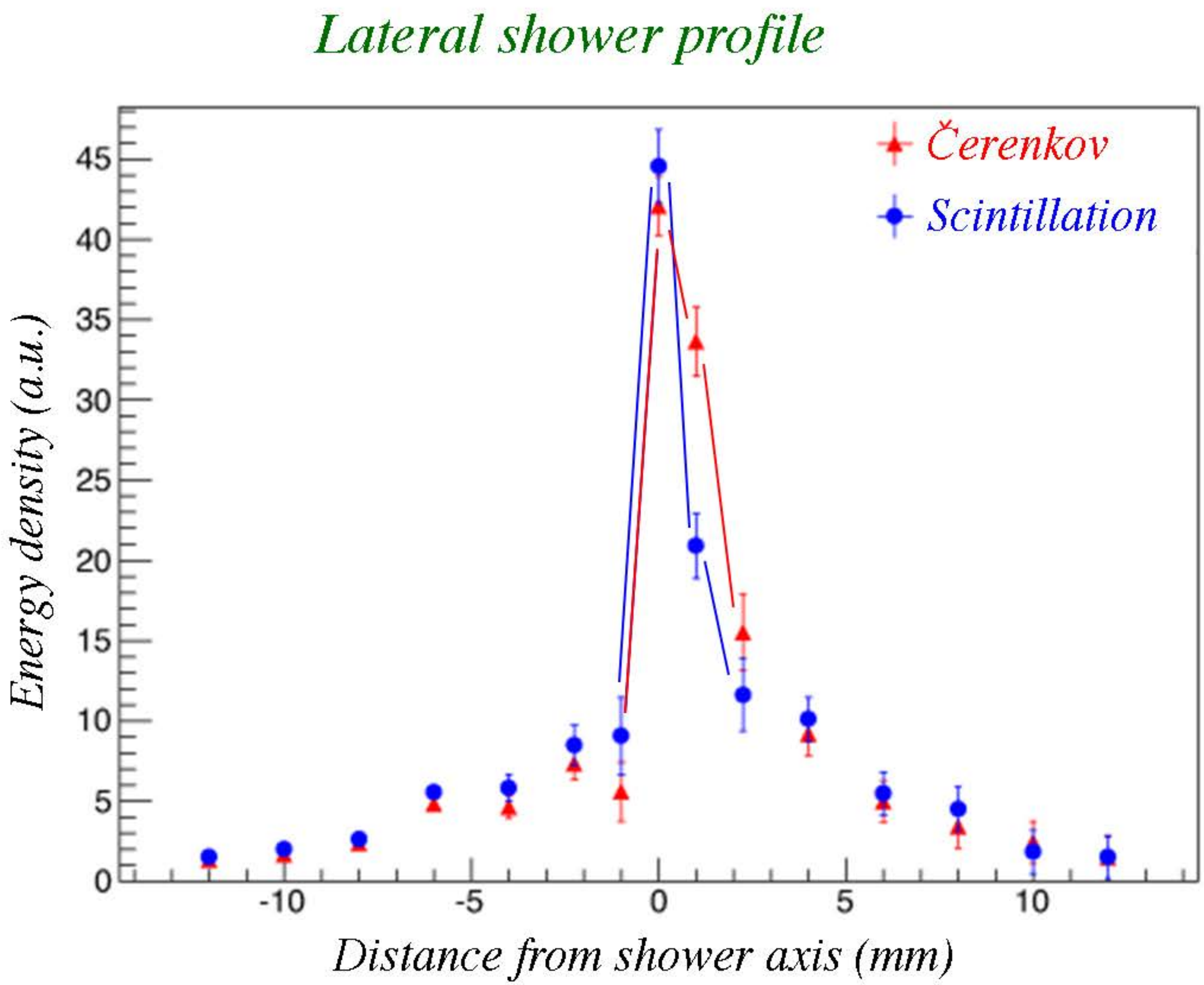
- *Intercalibration segments problematic, to say the least (jet energy scale)*

Attractive features of longitudinally UNSEGMENTED calorimeters

- *Uniform structure throughout detector, crucial for avoiding calibration problems*
- *Excellent resolution, for all particles (needed in ILC experiments) provided resolution is limited by sampling fluctuations*
- *Possibility to make very fine LATERAL granularity*
  - ⟶ *electron ID no problem*
  - ⟶ *recognize electron in vicinity of other showering particles*
  - ⟶ *separate closely spaced particles*

The RD52 calorimeter offers almost unlimited possibilities in that respect

The extremely narrow electromagnetic shower profile



Conclusions

- *A fine-sampling Cu-fiber dual-readout calorimeter offers the best and, in my opinion the only, possibility to measure jets with energy resolutions at the 1% level*
- *Resolutions needed to separate hadronically decaying W/Z bosons are achievable with this instrument*
- *The same detector measures electrons and* γs *with* $E > 50$ *GeV with resolutions better than 2%*
- *The RD52 calorimeter is linear for all particles and easy to calibrate*
- *It offers excellent identification of electrons, both in isolation and as part of a jet*
- *The RD52 Collaboration expects to complete the proof of these statements experimentally, which is the only way to prove anything concerning hadron calorimetry*

Backup slides

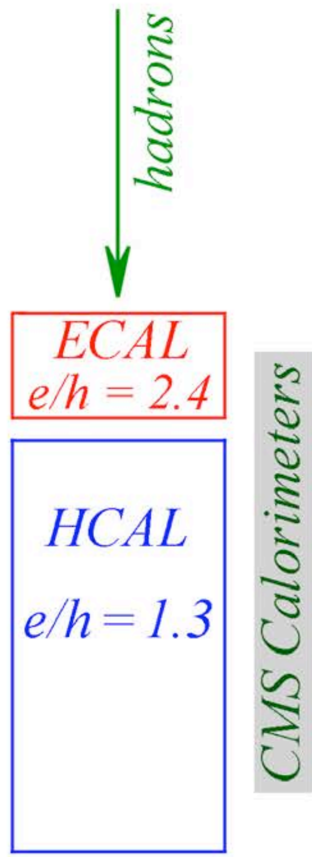
Calorimeter calibration issues

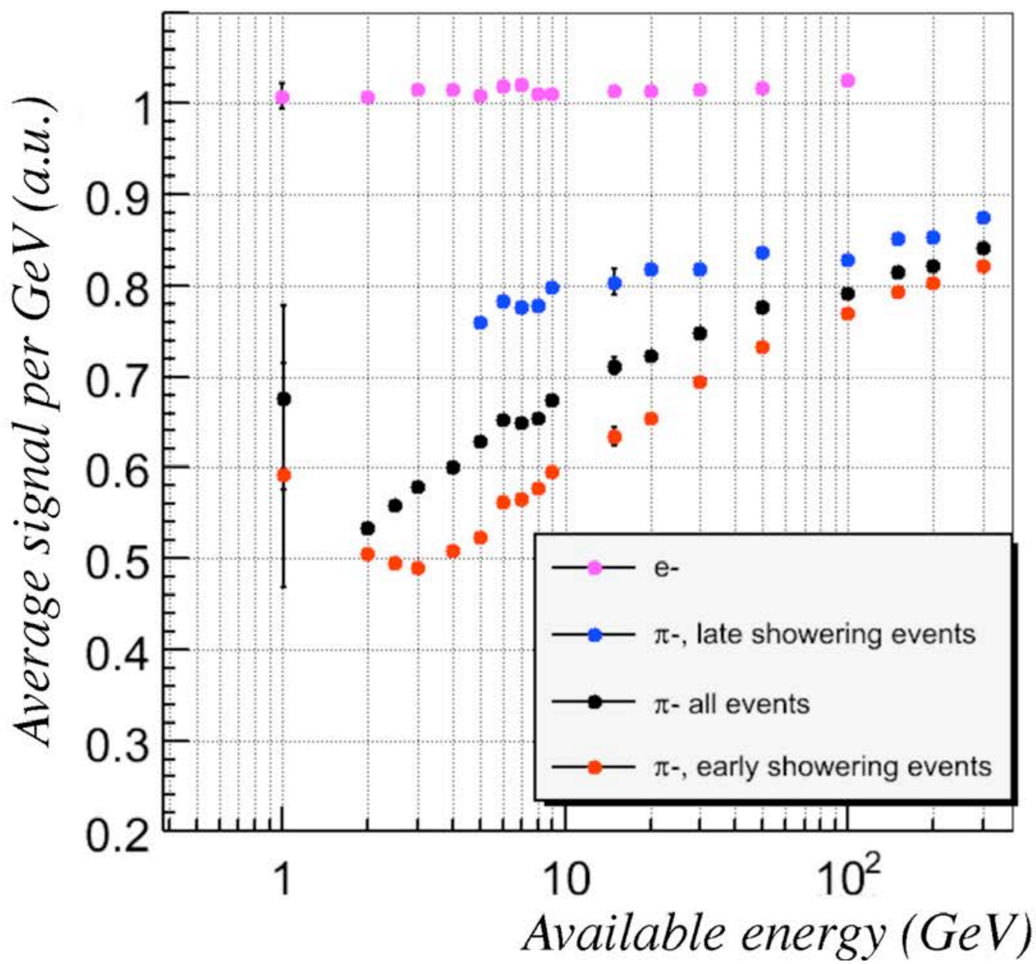
Hadronic response and signal linearity (CMS)

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





How to achieve the excellent hadronic energy resolution needed for experiments at the ILC?

Distinguish between hadronically decaying W,Z bosons
$\longrightarrow$ requires jet energy resolution $\lesssim 4\%$

- *Energy resolution is determined by FLUCTUATIONS*
  - The fact that 65% of jet energy is carried by charged particles (PFA) is *IRRELEVANT*.

On the importance of the calorimeter for PFA

Table 1
The total energy carried by the charged fragments of jets and the fluctuations in this energy ($\sigma_{rms}/E_{charged}$) are listed for jet energies ranging from 10–1000 GeV. Results are given for two different values of the fragmentation function parameter α

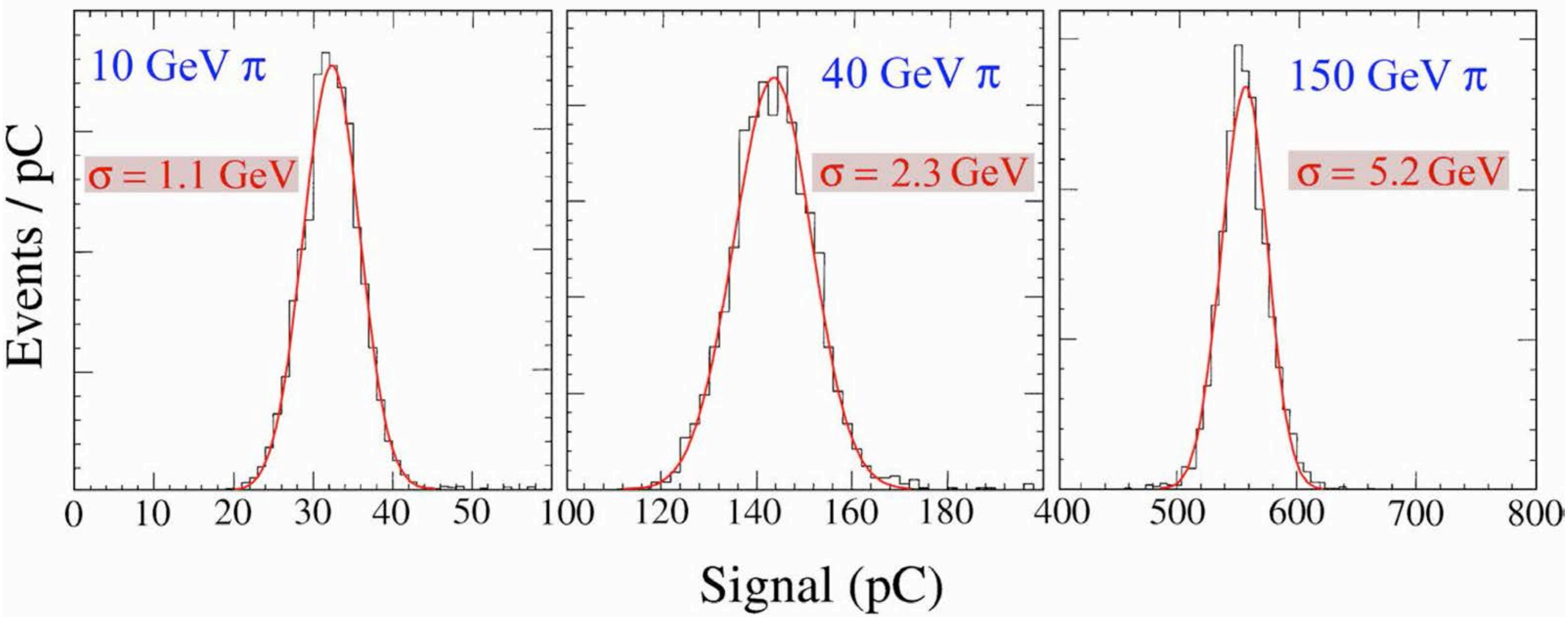
Jet energy (GeV)	$\alpha = 3$		$\alpha = 6$	
	Charged fragments	Fluctuations (%)	Charged fragments	Fluctuations (%)
10	6.83 ± 2.06	30.1	6.88 ± 1.68	24.3
20	13.2 ± 4.13	33.6	13.6 ± 3.27	24.2
30	19.8 ± 6.13	32.6	20.2 ± 4.89	24.2
40	26.5 ± 8.10	30.6	26.9 ± 6.46	24.0
50	33.4 ± 10.0	30.0	33.5 ± 8.10	24.2
100	66.6 ± 19.9	30.4	66.6 ± 16.3	24.4
200	133 ± 40.1	30.2	133 ± 32.0	24.1
300	200 ± 59.8	29.9	200 ± 48.4	24.2
400	266 ± 80.4	30.3	266 ± 64.2	24.2
500	332 ± 99.9	30.1	332 ± 80.5	24.2
1000	663 ± 201	30.3	665 ± 160	24.1

In the absence of a calorimeter, one should therefore not expect to be able to measure jet energy resolutions better than 25–30% on the basis of tracker information alone, *at any energy*. And

From: NIM A495 (2002) 107

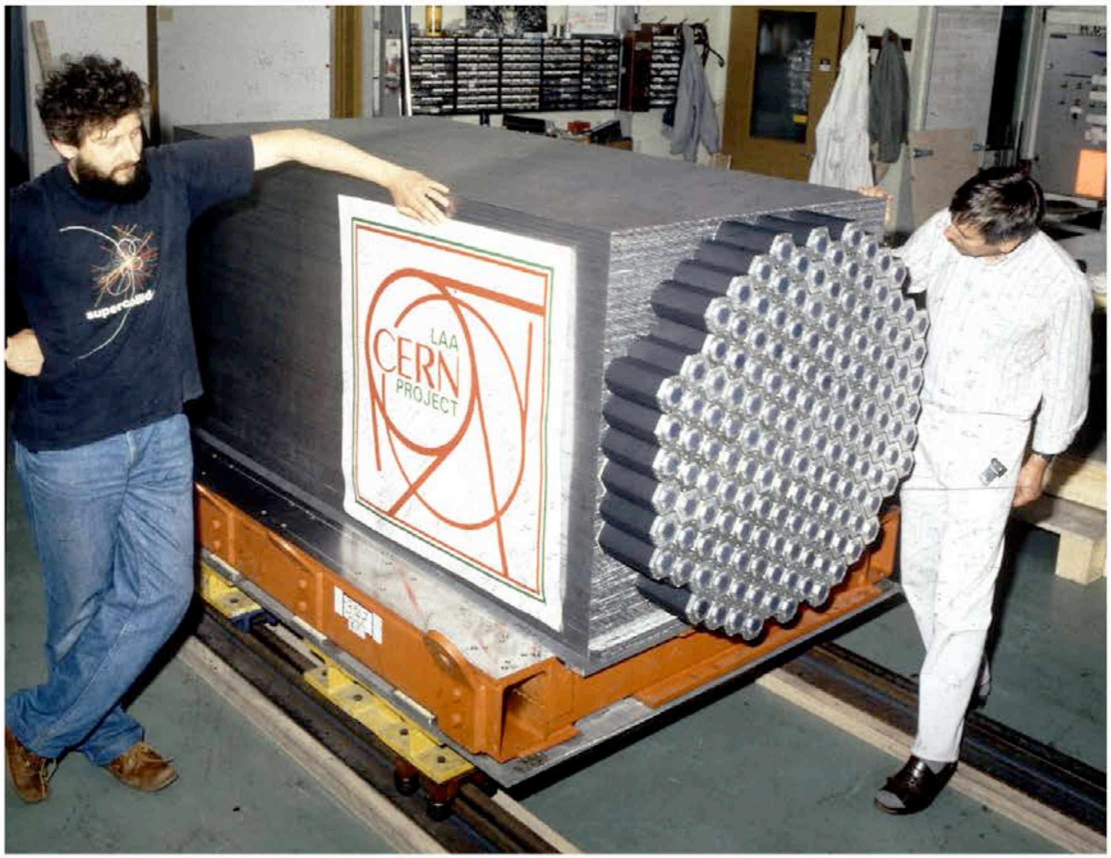
ILC requirements were already met 20 years ago by compensating calorimeters (SPACAL, ZEUS)

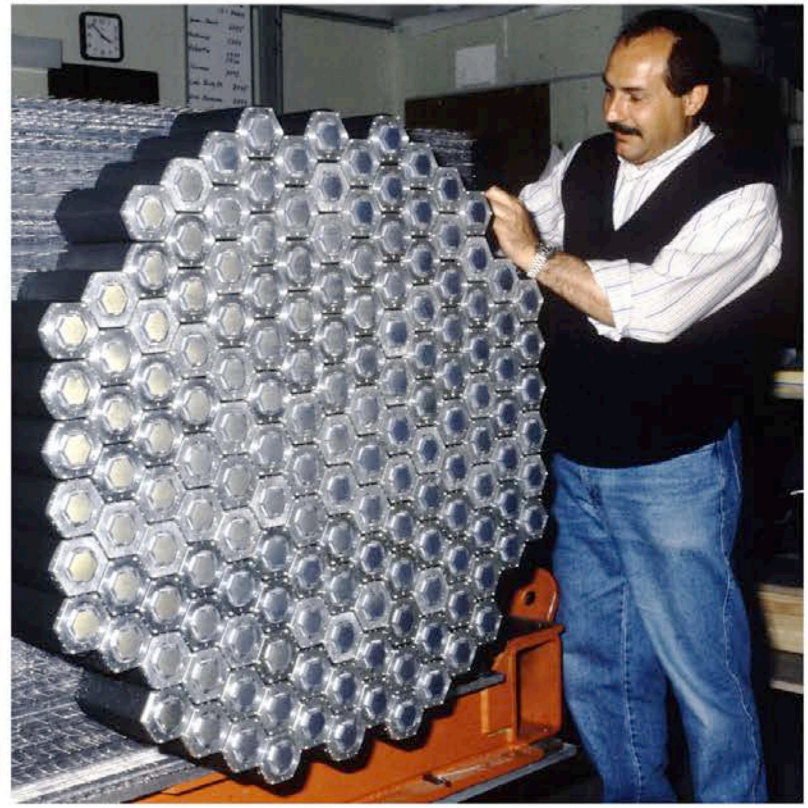
Hadronic signal distributions in a compensating calorimeter



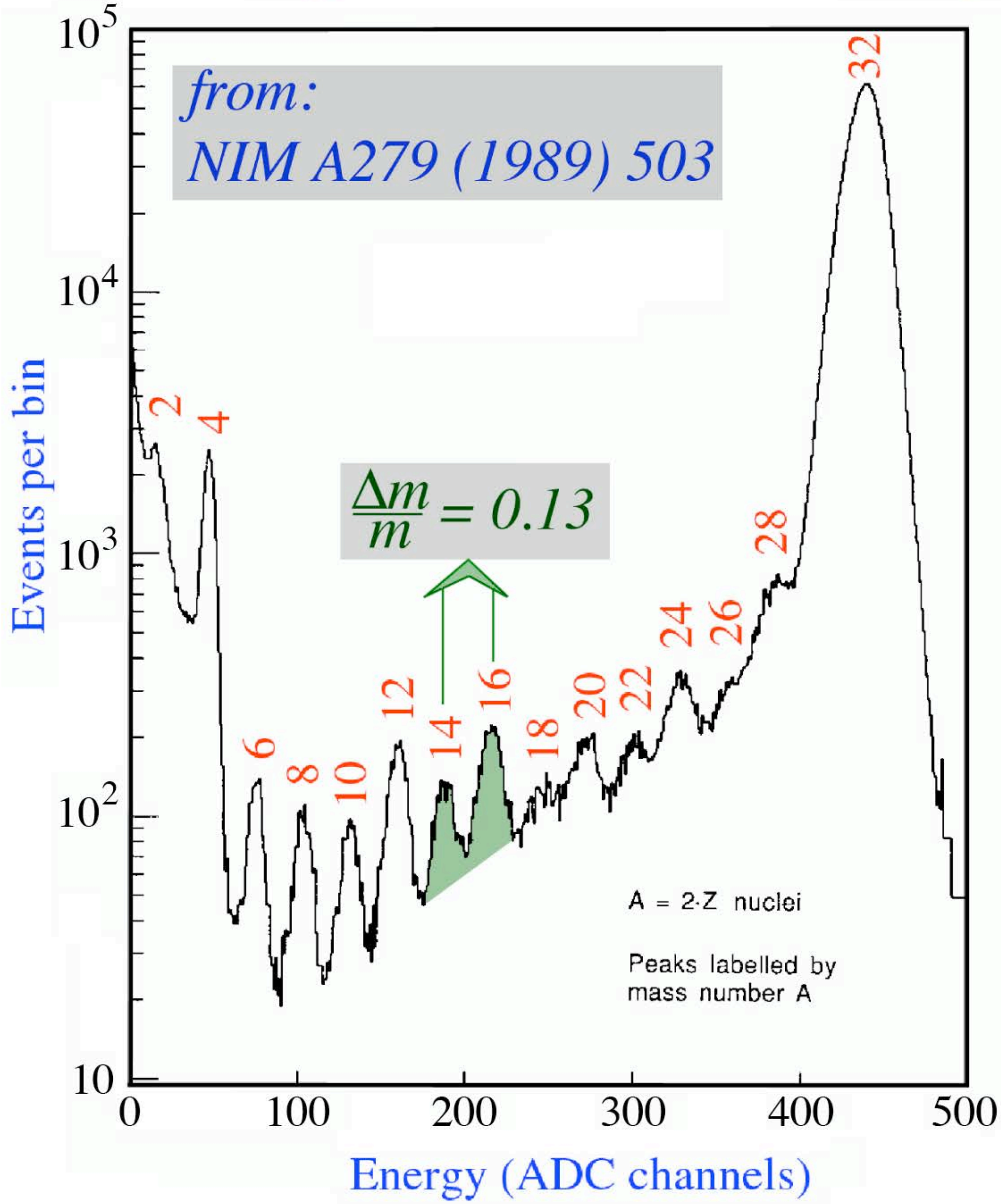
from: NIM A308 (1991) 481

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

Pros & Cons of Compensating Calorimeters

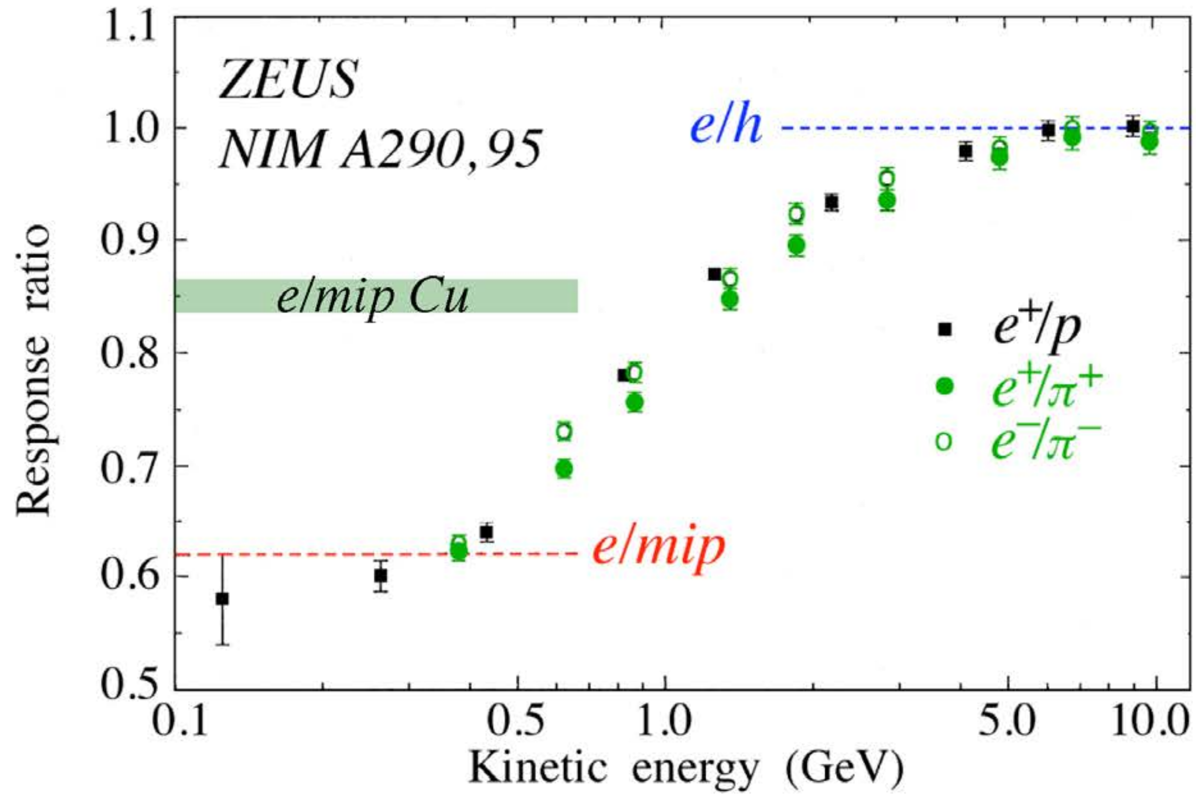
Pros

- 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

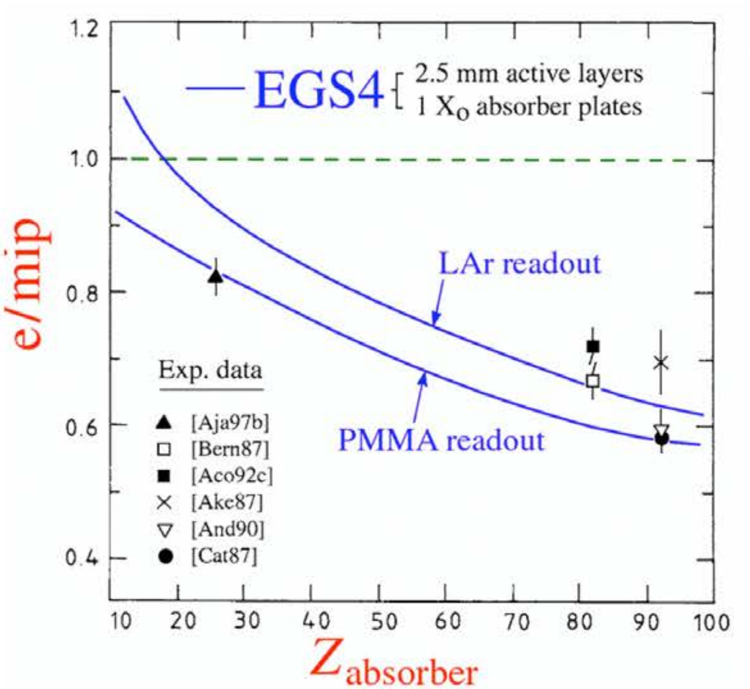
- Small sampling fraction (2.4% in Pb/plastic)
  ⟶ *em energy resolution limited* (SPACAL: 13%/$\sqrt{E}$, ZEUS: 18%/$\sqrt{E}$)
- Compensation relies on detecting neutrons
  ⟶ Large *integration volume*
  ⟶ Long *integration time* (~50 ns)
- *Jet* resolution not as good as for single hadrons in Pb,U calorimeters

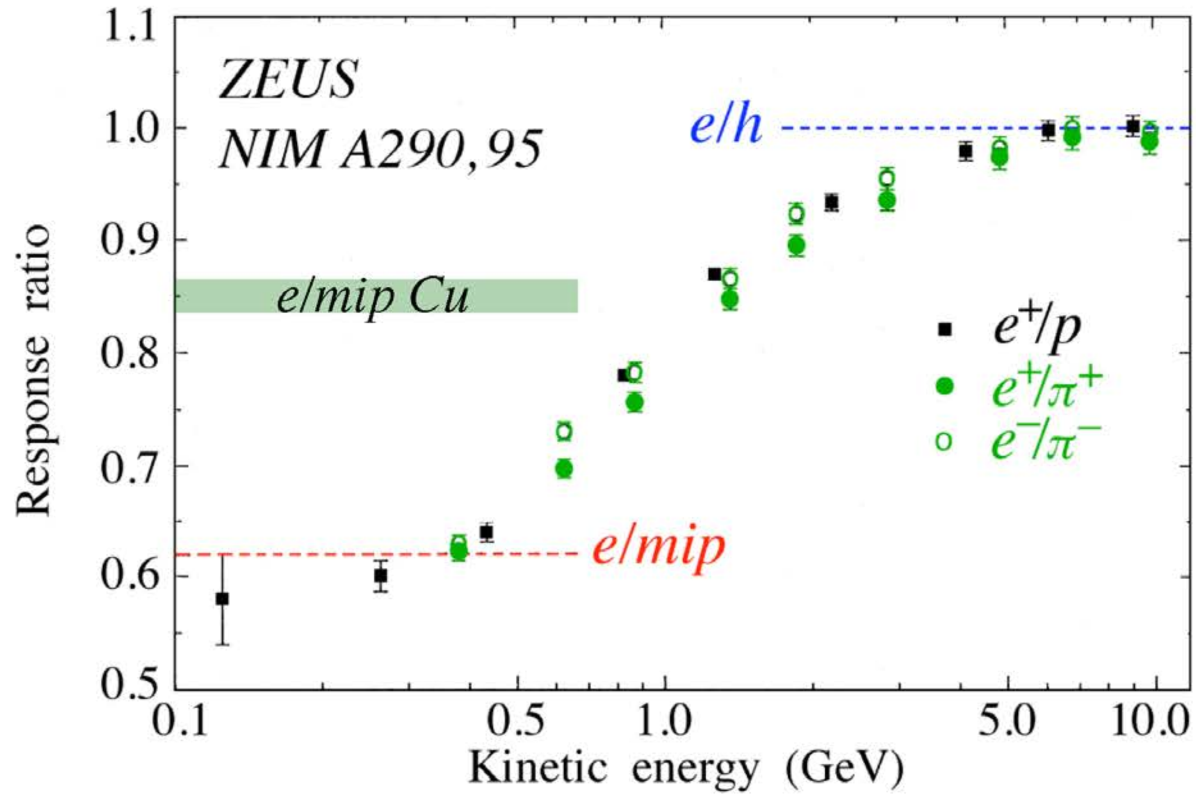
What is the problem with the jet energy resolution?



Signal non-linearities at low energy (< 5 GeV)
due to non-showering hadrons
Many jet fragments fall in this category

What is the problem with the jet energy resolution?

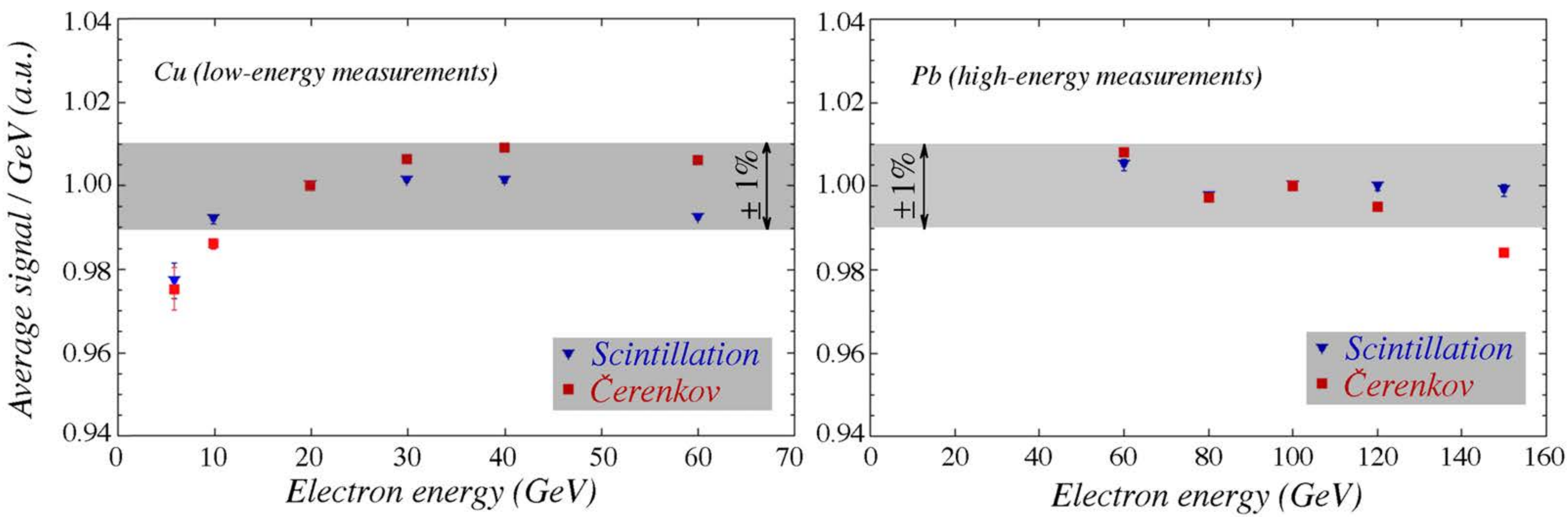




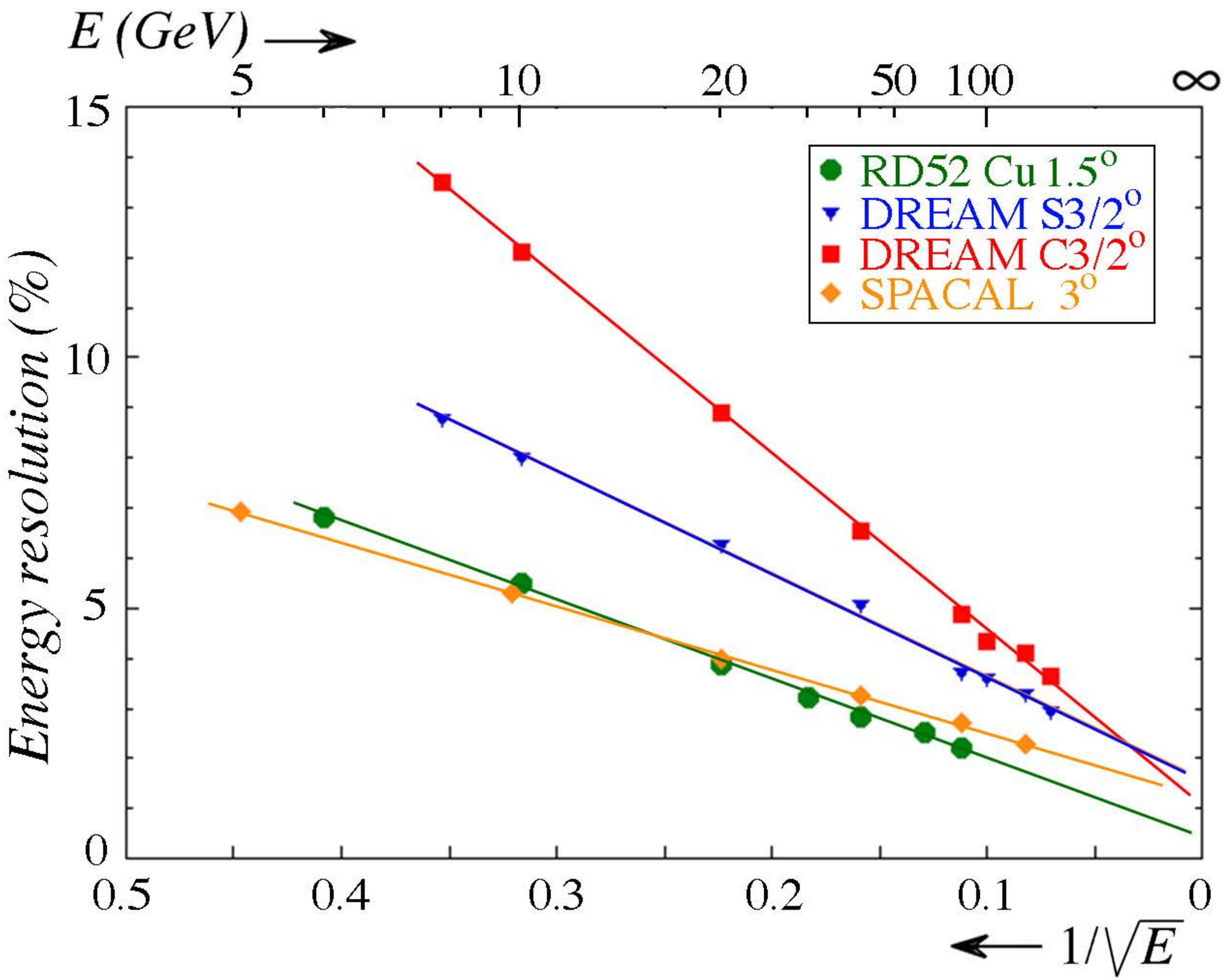
Signal non-linearities at low energy (< 5 GeV)
due to non-showering hadrons
Many jet fragments fall in this category

A copper or iron based calorimeter would be much better in that respect

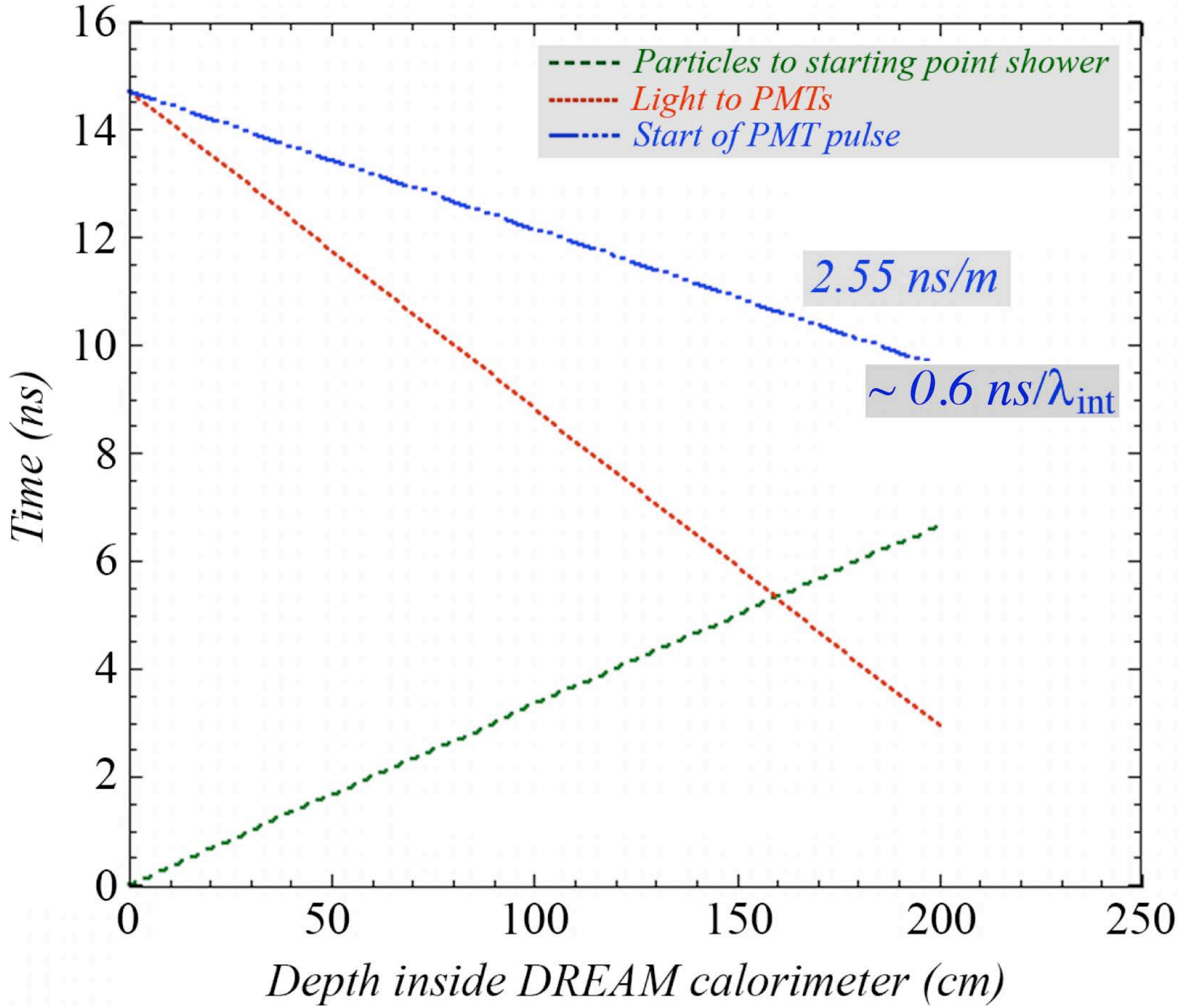
Linearity measurements for em showers



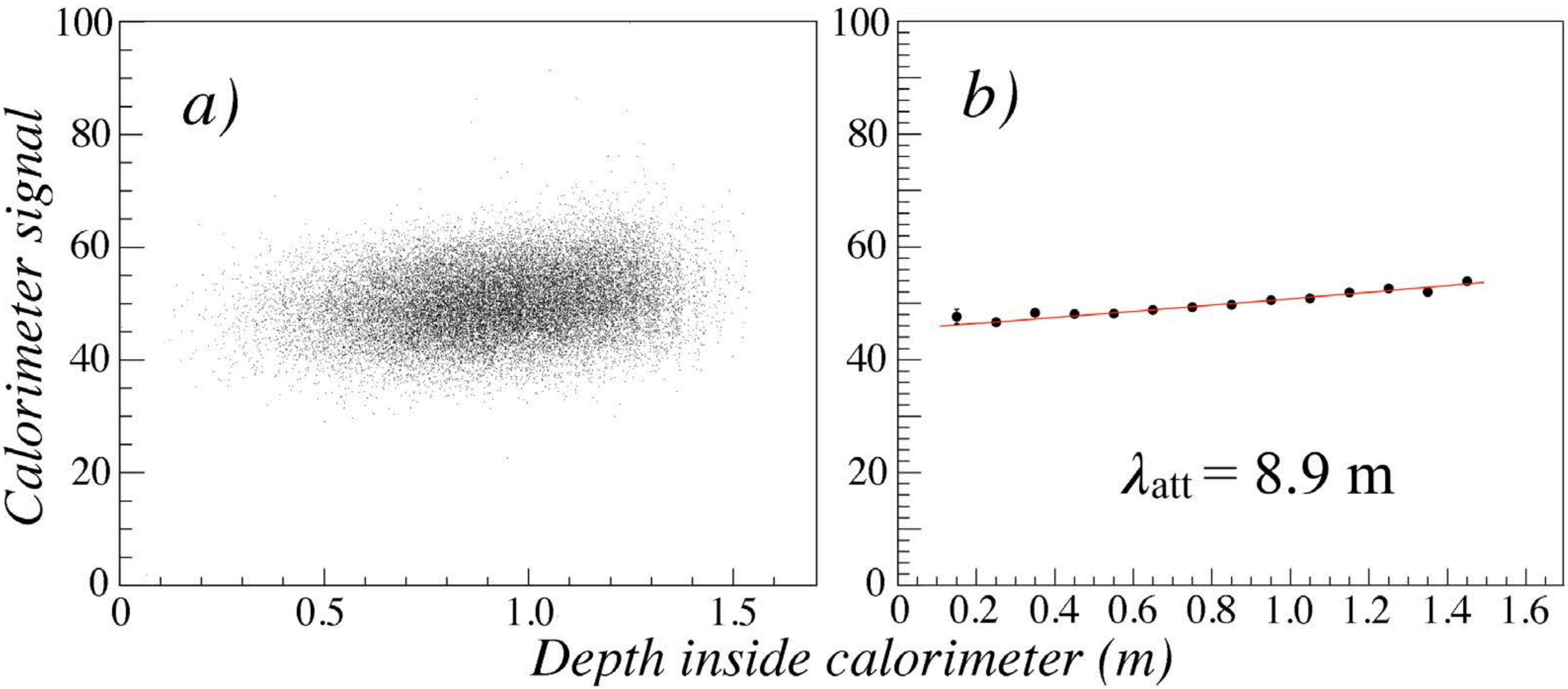
Em resolution RD52 compared to other fiber calorimeters



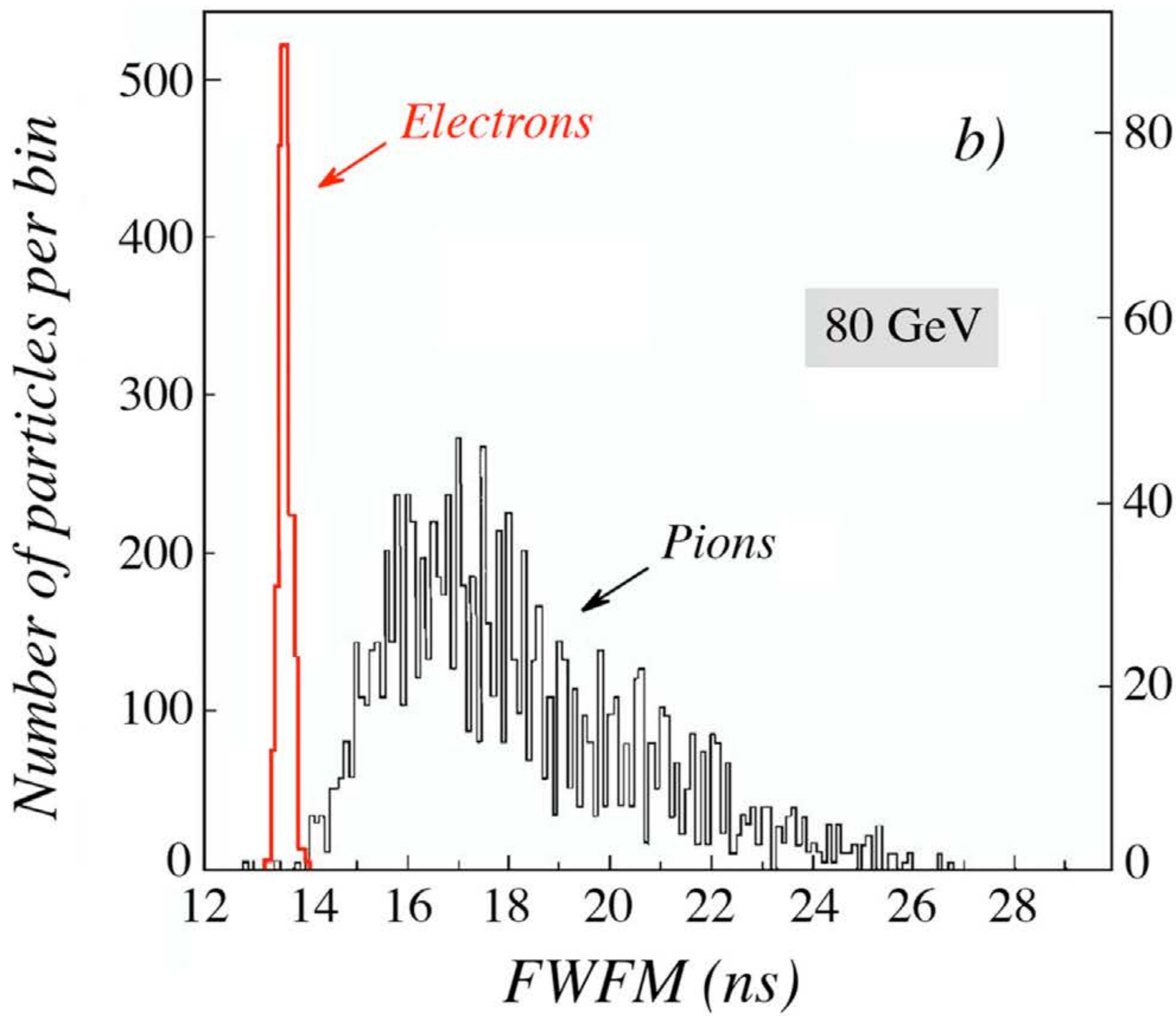
Depth of the light production
and the starting point of the PMT signals



Use depth of light production to correct for light attenuation



Particle ID using the time structure of the signals in the longitudinally unsegmented SPACAL calorimeter

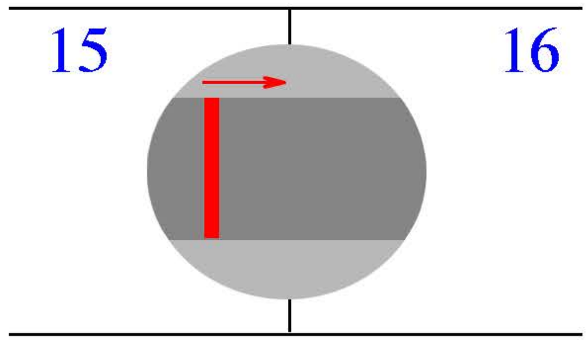


From: NIM A302 (1991) 36

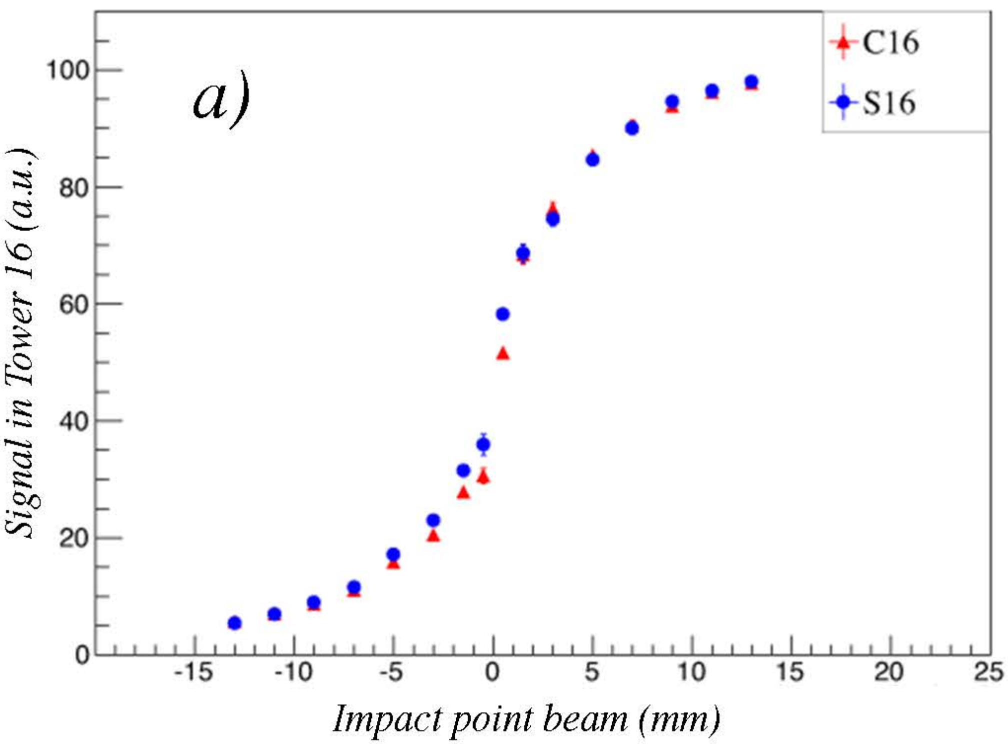
NB: Upstream fiber ends were reflective (aluminized)

The extremely narrow electromagnetic shower profile

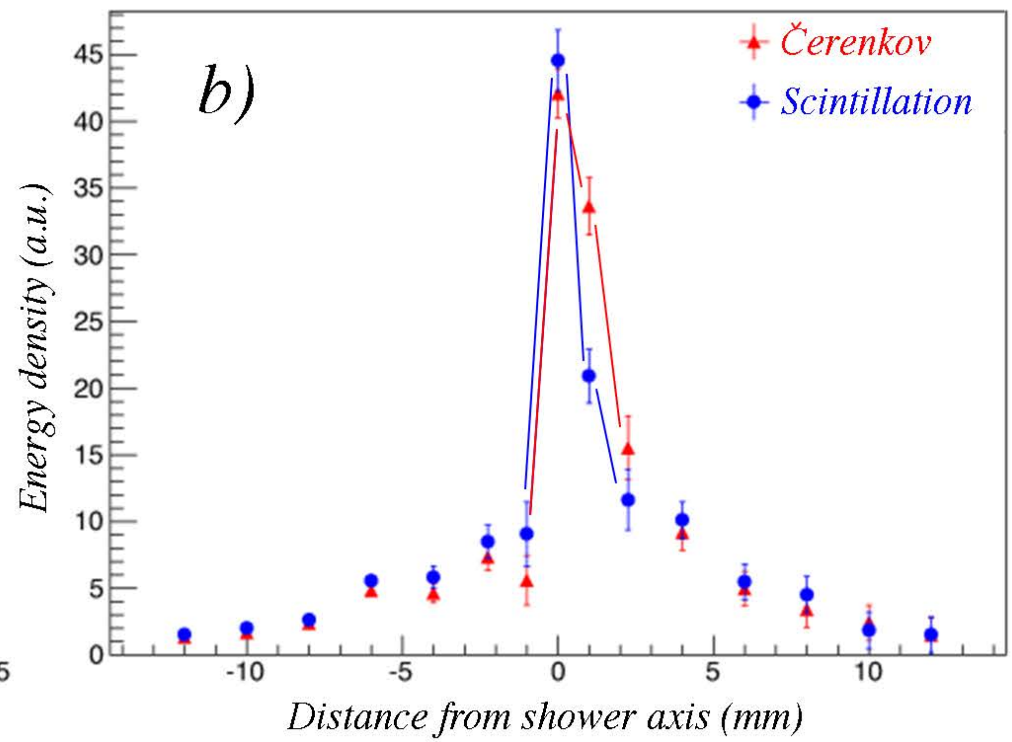
Move small beam spot across tower boundary



Horizontal scan with 1 mm wide beam

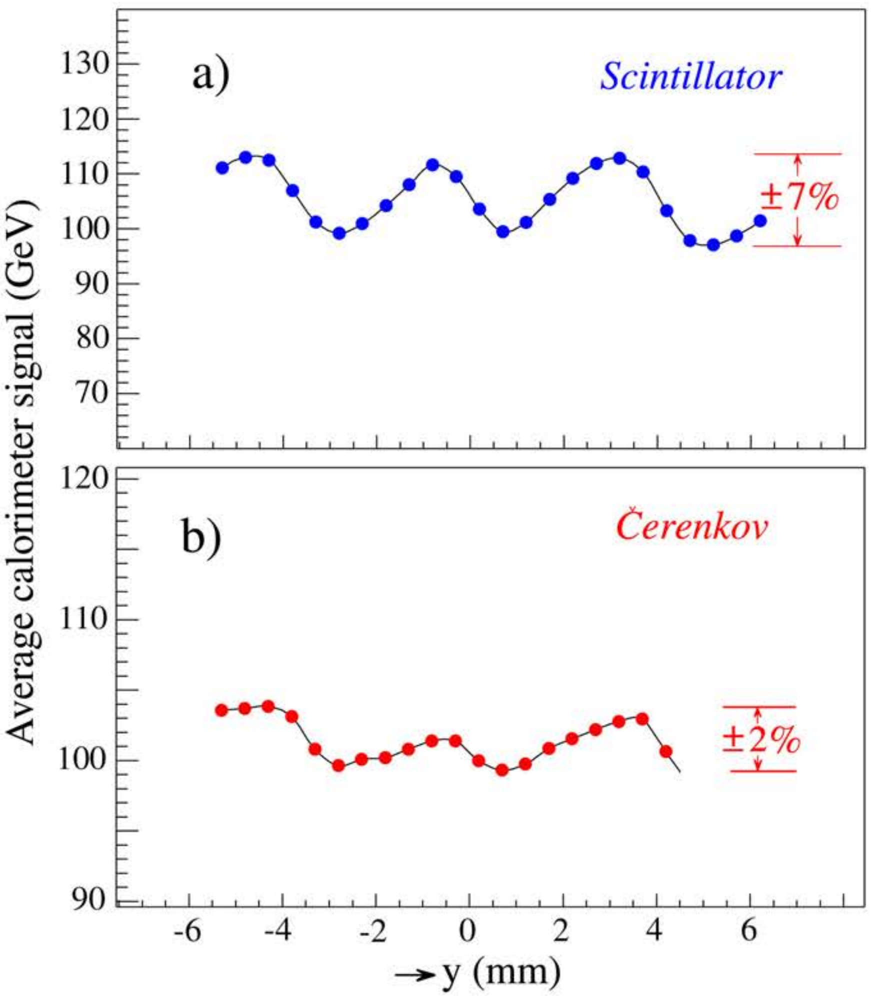


Lateral shower profile

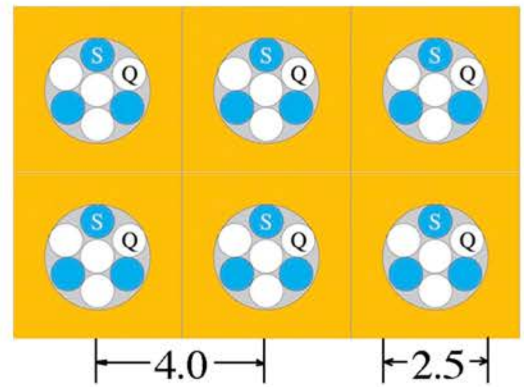


Channeling effects in fiber calorimeters

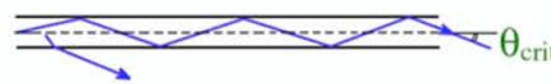
From NIM A536, 29



DREAM

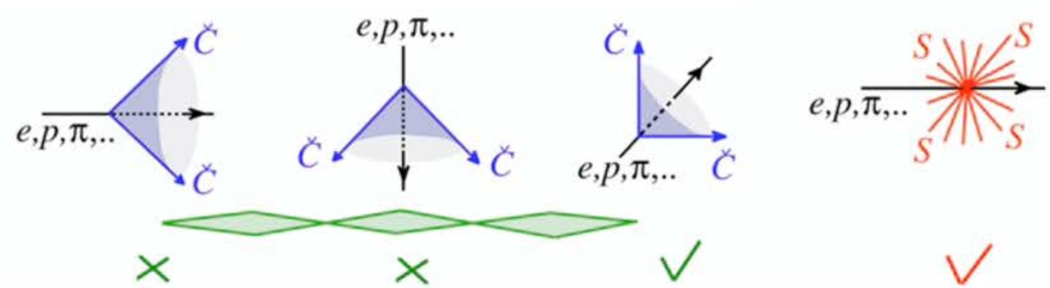


- *Optical fibers* only trap light emitted within the *numerical aperture*



$\theta_{crit} \sim 20^{o}$ for quartz fibers

- Comparison of *Čerenkov* light (directional) and *scintillation* light (isotropic) produced in fiber calorimeters

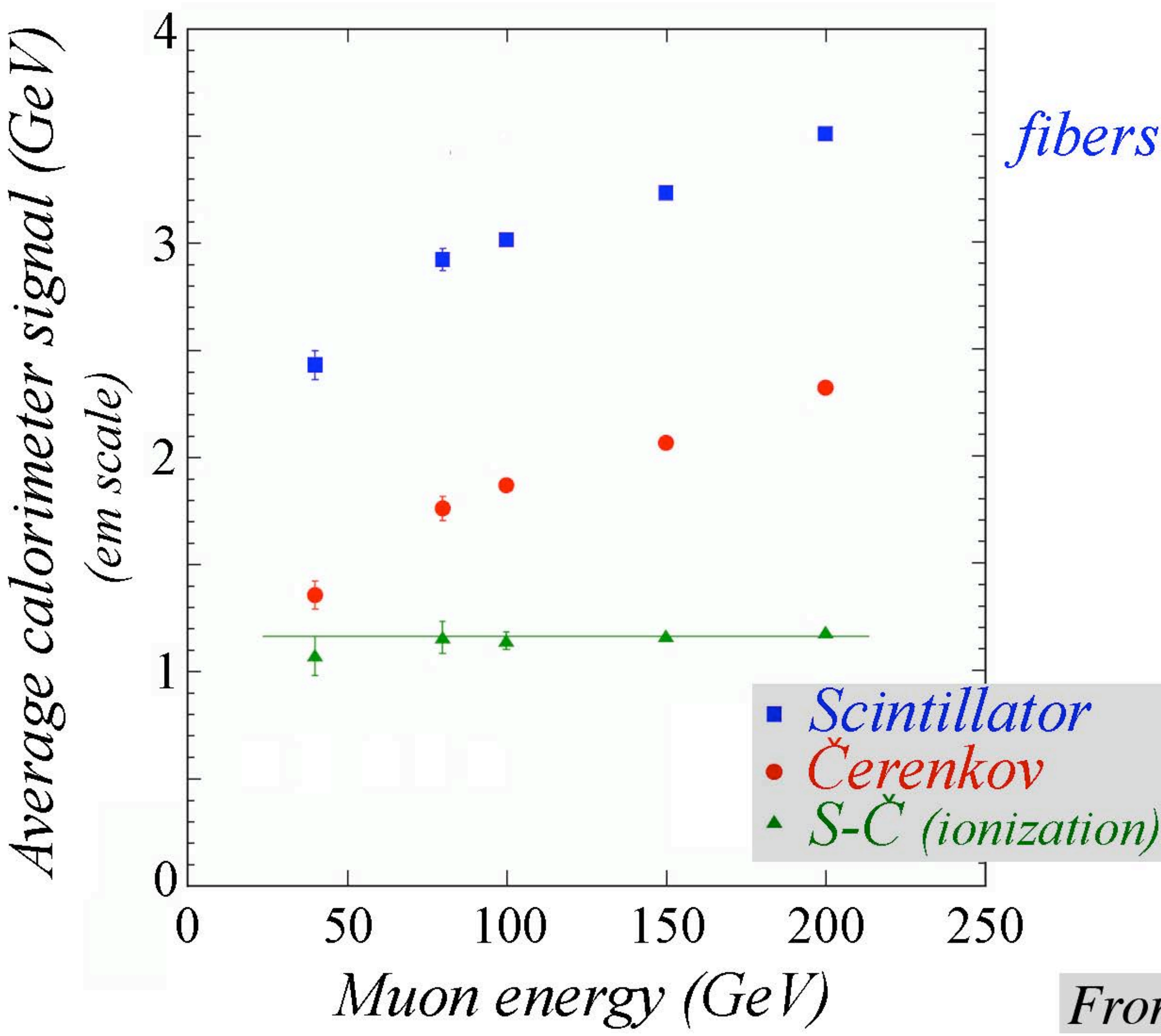


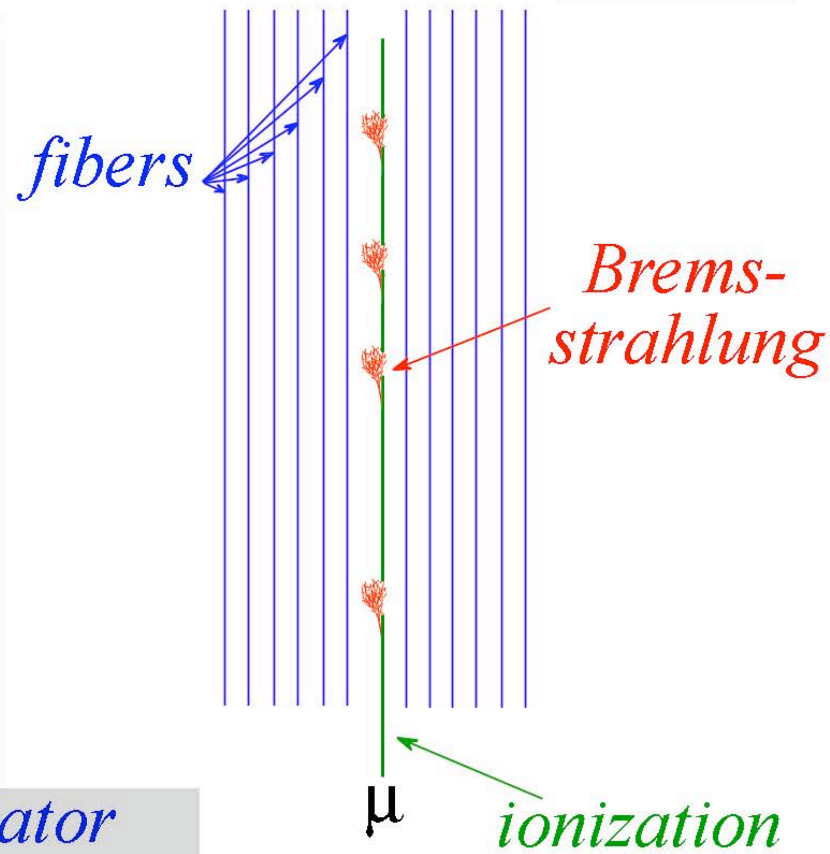
The early, highly collimated em shower component leads to a position dependent response

This component does NOT contribute to the Čerenkov calorimeter signals!

Calorimetric separation of ionization / radiation losses

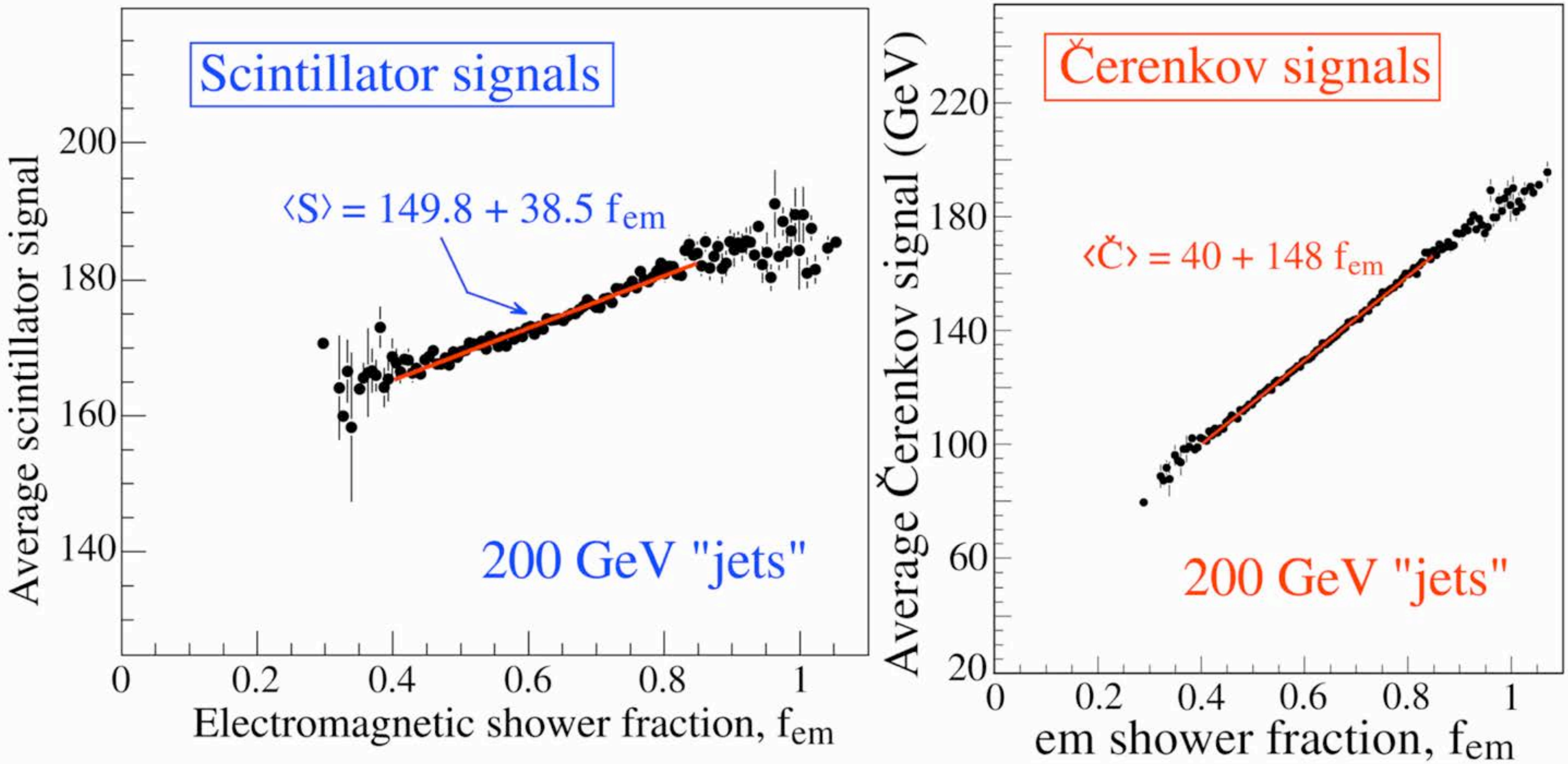
Muon signals in the DREAM calorimeter





From: NIM A533 (2004)305

DREAM: Signal dependence on f_{em}



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

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

From:
NIM A537 (2005) 537

High-resolution hadron calorimetry also requires efficient detection of the "nuclear" shower component

Time structure of the DREAM signals: the neutron tail (anti-correlated with f_{em})

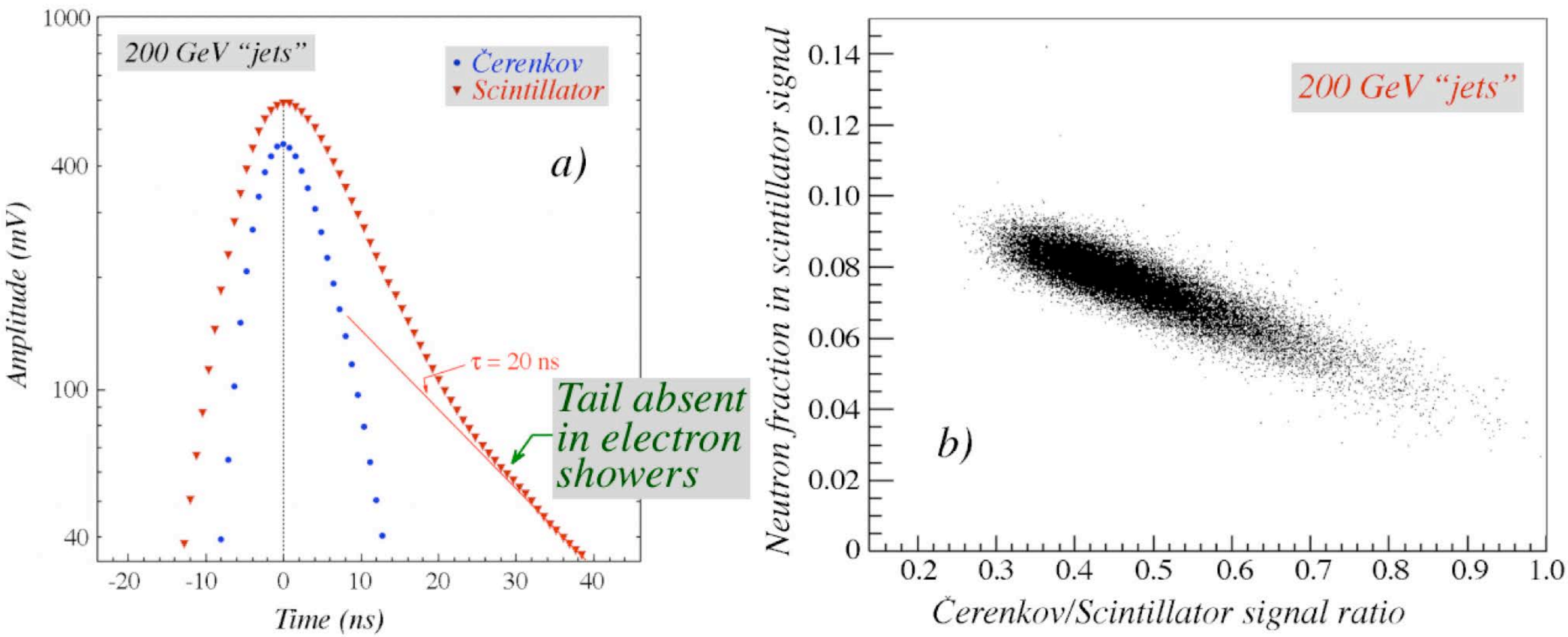
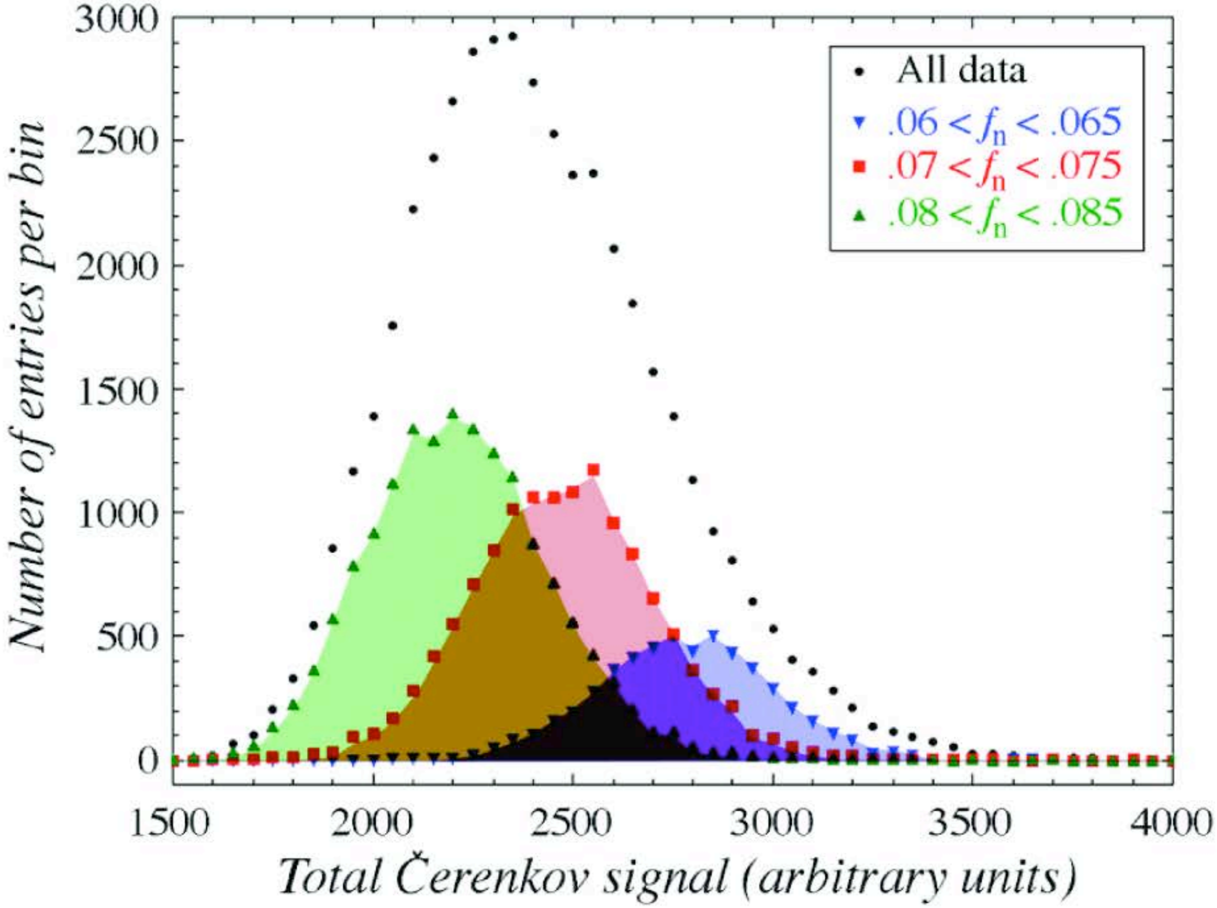


Figure 4: The average time structure of the Čerenkov and scintillation signals recorded for 200 GeV "jets" in the fiber calorimeter (a). Scatter plot of the fraction of the scintillation light contained in the (20 ns) exponentional tail versus the Čerenkov/scintillation signal ratio measured in these events (b) [9].

Probing the total signal distribution with the neutron fraction



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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 .

On high-resolution hadron calorimetry

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On the energy measurement of hadron jets

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Abstract

The elementary constituents of hadronic matter (quarks, anti-quarks, gluons) manifest themselves experimentally in the form of jets of particles. We investigate the precision with which the energy of these fragmenting objects can be measured. The relative importance of the instrumental measurement precision and of the jet algorithm is assessed. We also evaluate the "energy flow" method, in which the information from a charged-particle tracker is combined with that from a calorimeter in order to improve the jet energy resolution.

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Keywords: Calorimetry; Fluctuations; Jets; Energy flow

From Conclusions:

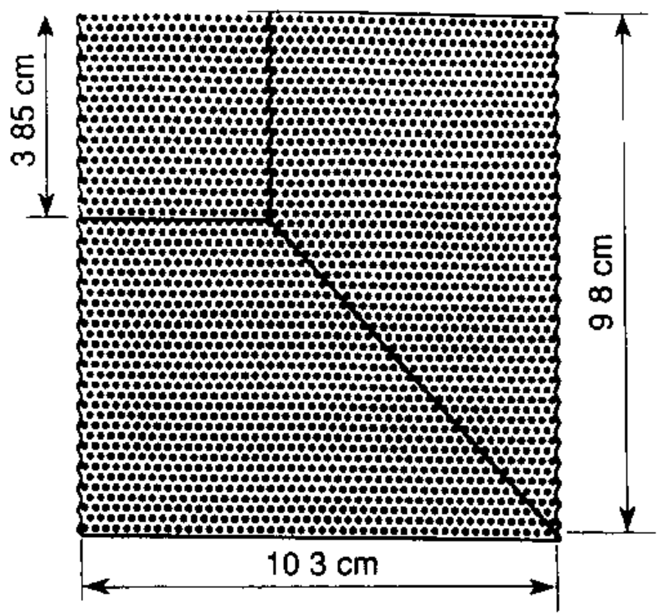
Both our simulations and the experimental data show that the EFM does offer a beneficial effect. However, this effect should not be exaggerated. The improvement in the energy resolution is typically 30%. Poor calorimeter systems benefit more than good calorimeter systems, and a strong magnetic field also helps.

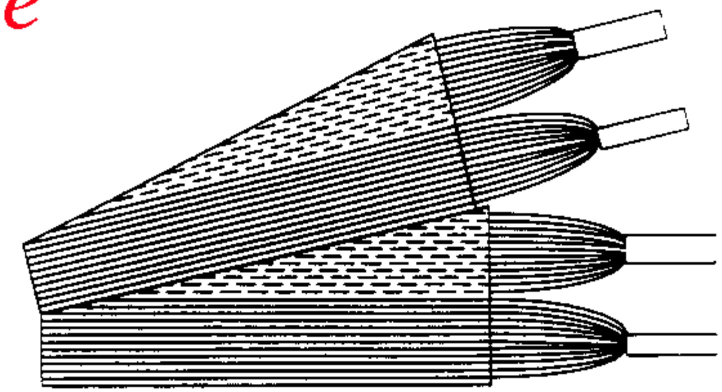
cf CMS vs ATLAS !!

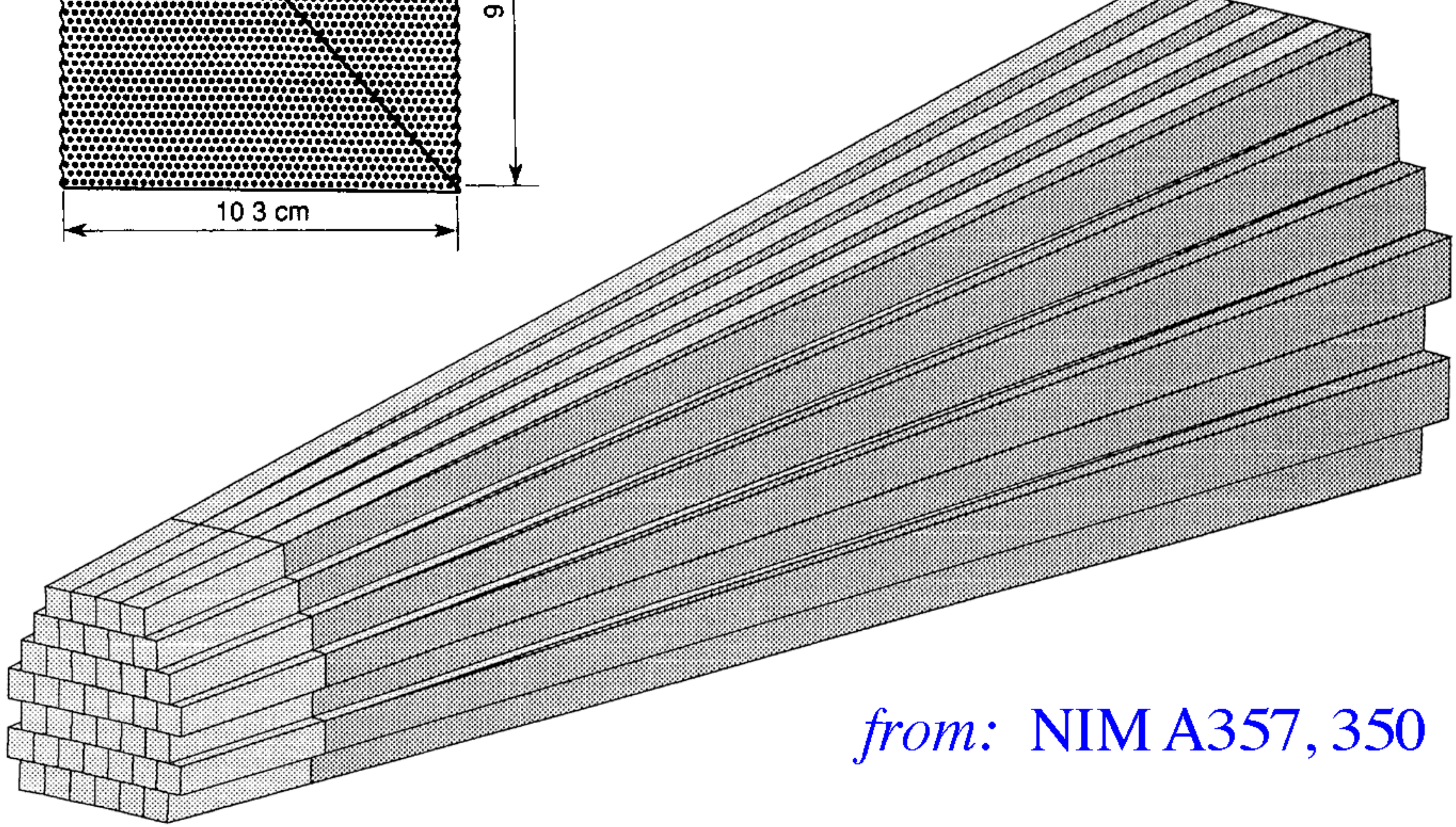
bosons and decreases at higher energies. Claims that much better results may be achieved for highly granular calorimeter systems, in which the showers generated by the individual jet fragments may be recognized and separated from each other are unsubstantiated. We have shown that for most of the showers in practical detectors, the overlap between the shower profiles rather than the detector granularity is the factor that limits the benefits of this method.

No experimental evidence to the contrary!!

Projective structure







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