

# Dual-Readout Calorimetry\*

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

Richard Wigmans  
Texas Tech University

Como, May 17, 2013

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\* *DREAM (RD52) Collaboration:*

*Cagliari, Cosenza, Lisbon, Pavia, Pisa, Roma, Iowa State, TTU*

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

*Distinguish between hadronically decaying W,Z bosons  
→ 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 ( $\sigma_{\text{rms}}/E_{\text{charged}}$ ) are listed for jet energies ranging from 10–1000 GeV. Results are given for two different values of the fragmentation function parameter  $\alpha$

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

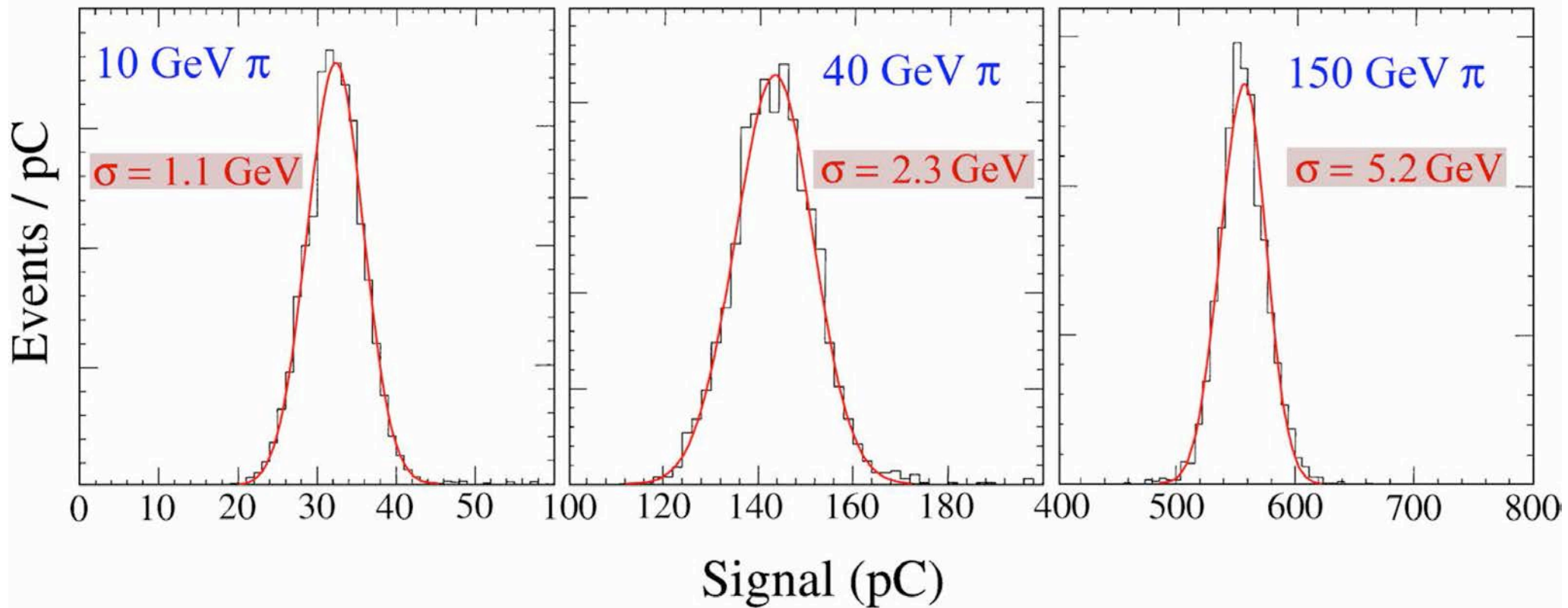
In the absence of a calorimeter, one should therefore not expect to be able to measure jet energy resolutions better than 25–30% on the basis of tracker information alone, *at any energy*. And

# *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,  $\Delta B$ )*
  - Non-em signal is dominated by “nuclear” component:  $p, n$
  - Correlation between “nuclear signal” and  $\Delta B$  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

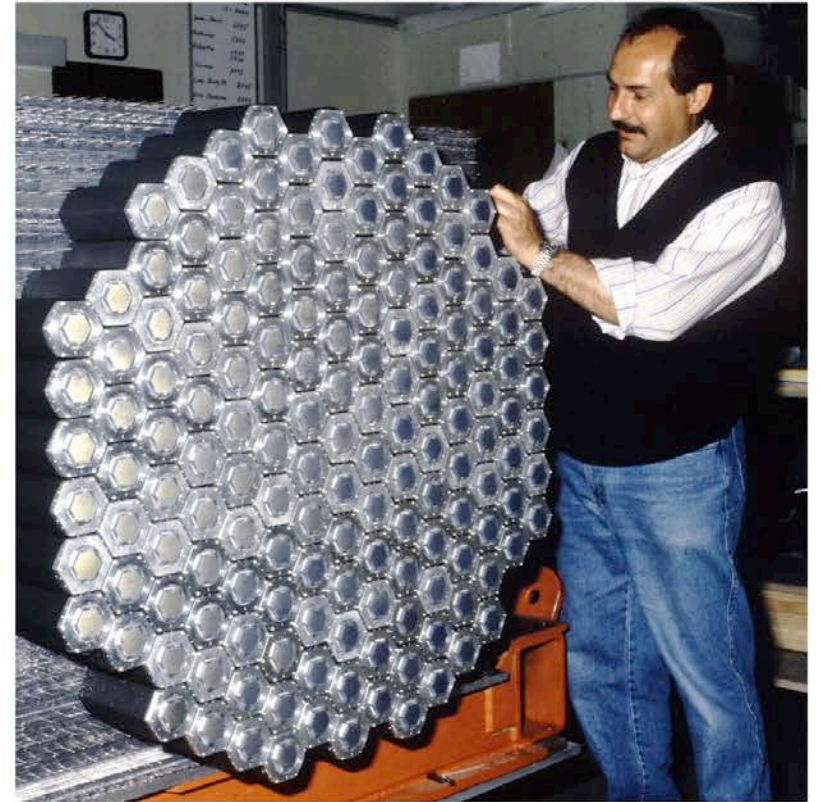
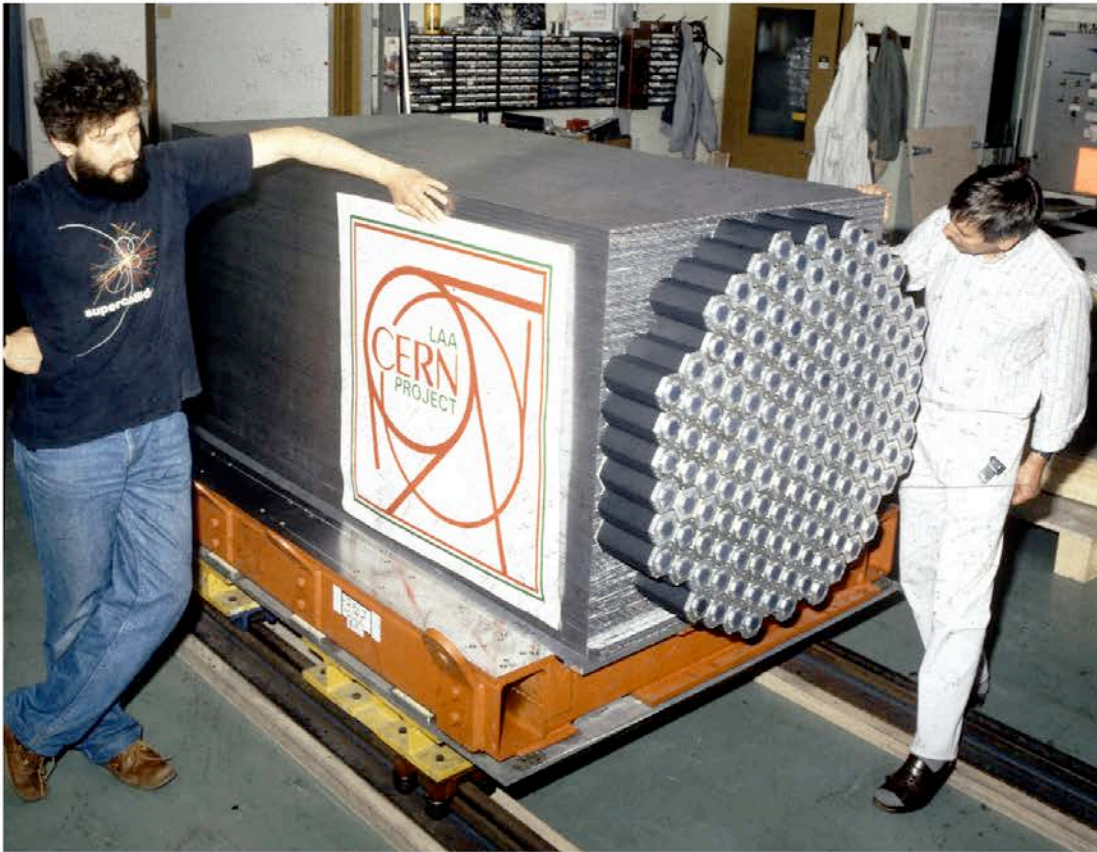
*ILC requirements were already met 20 years ago  
by compensating calorimeters (SPACAL, ZEUS)*

*Hadronic signal distributions in a compensating calorimeter*



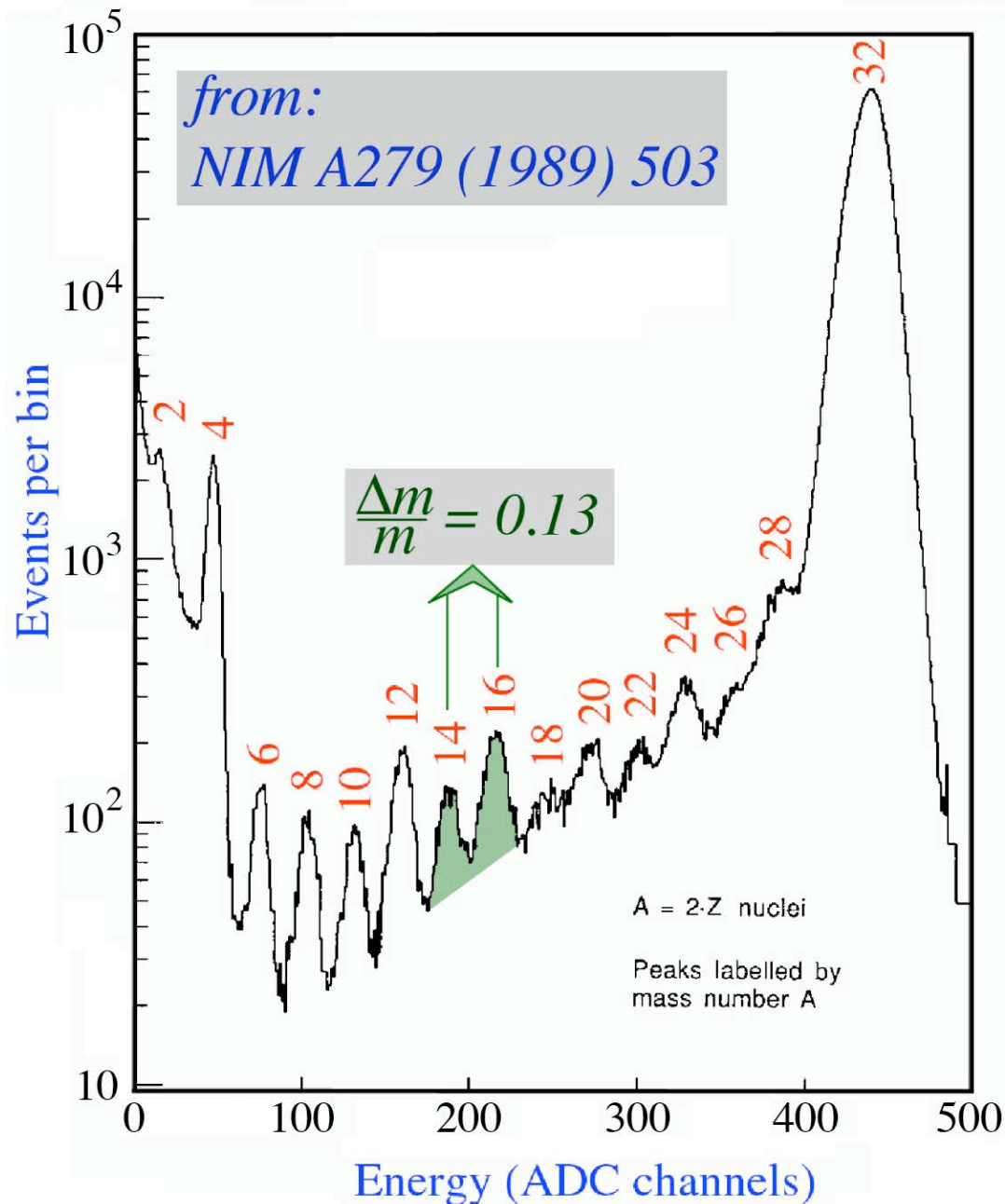
*from: NIM A308 (1991) 481*

## *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

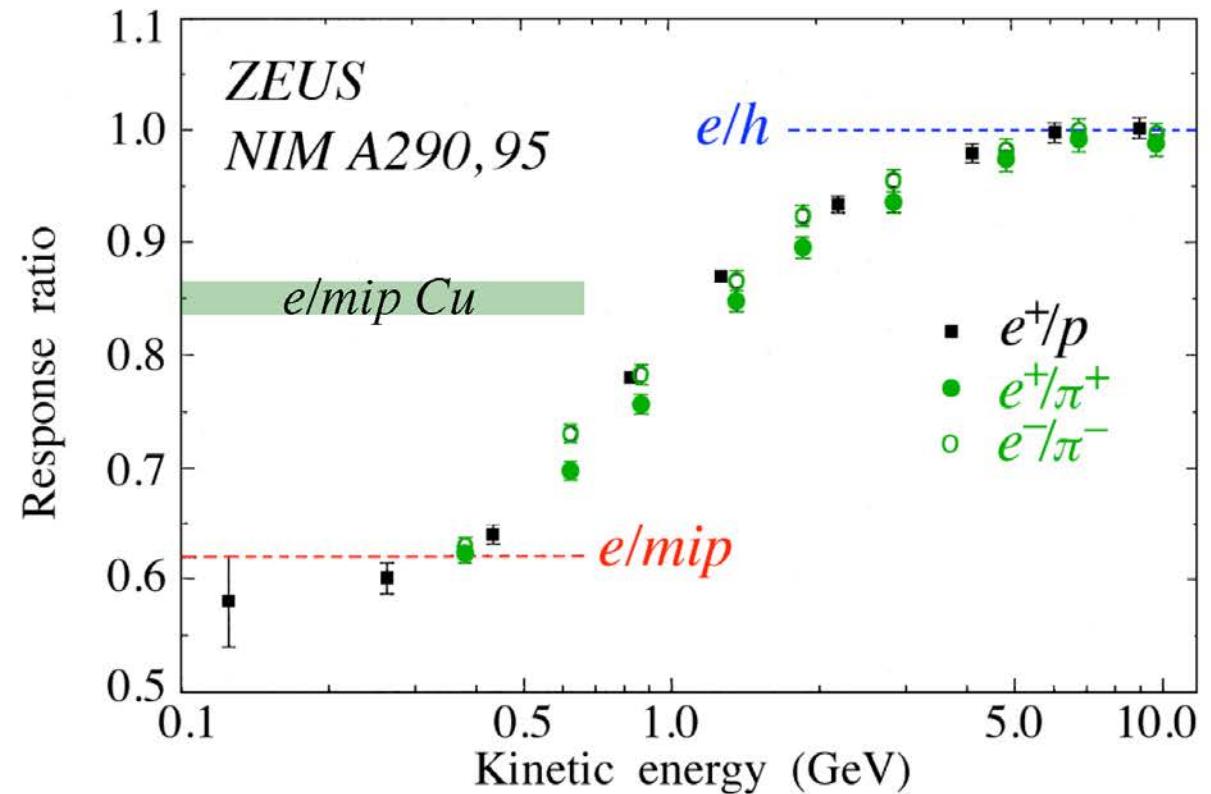
- Same *energy scale* for electrons, hadrons and jets. No ifs, ands or buts.
- *Calibrate* with electrons and you are done.
- Excellent hadronic *energy resolution* (SPACAL:  $30\%/√E$ ).
- *Linearity*, Gaussian *response function* and all that good stuff.
- Compensation fully understood.  
*We know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

## Cons

- Small sampling fraction (2.4% in Pb/plastic)  
→ *em energy resolution limited* (SPACAL:  $13\%/√E$ , ZEUS:  $18\%/√E$ )
- 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

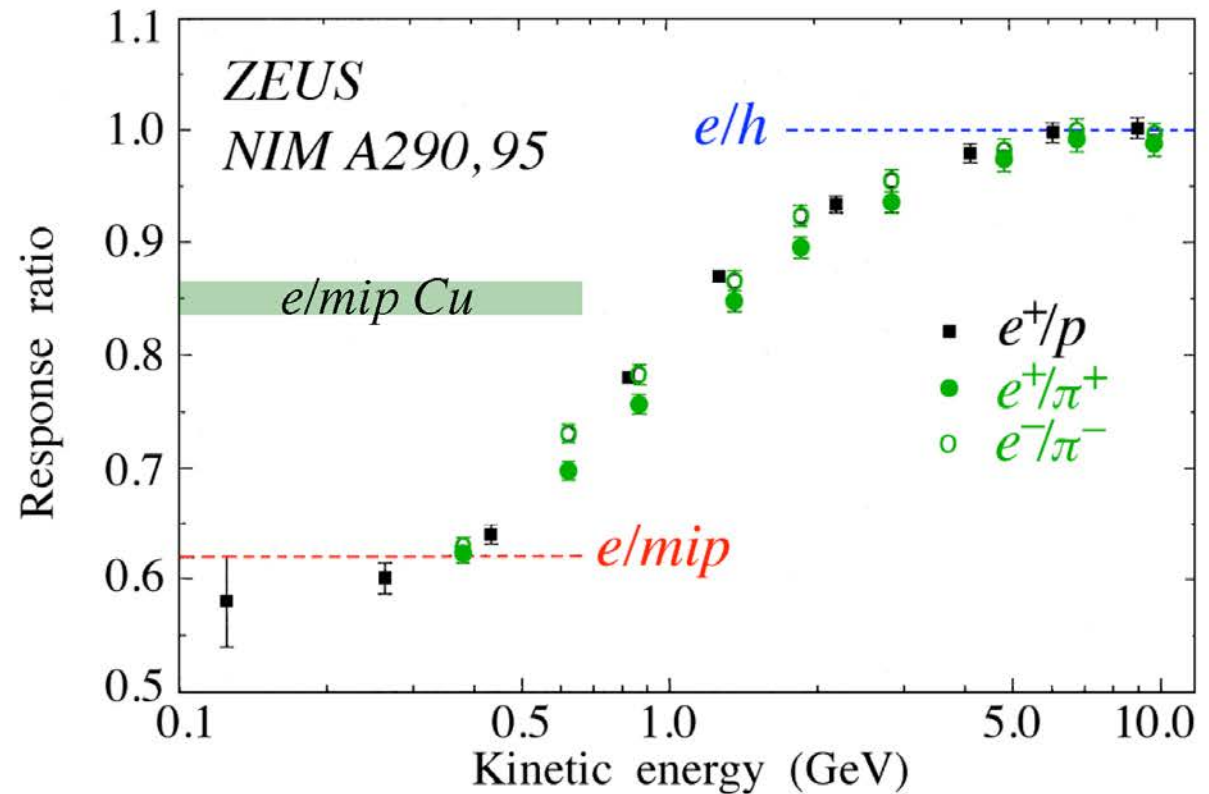
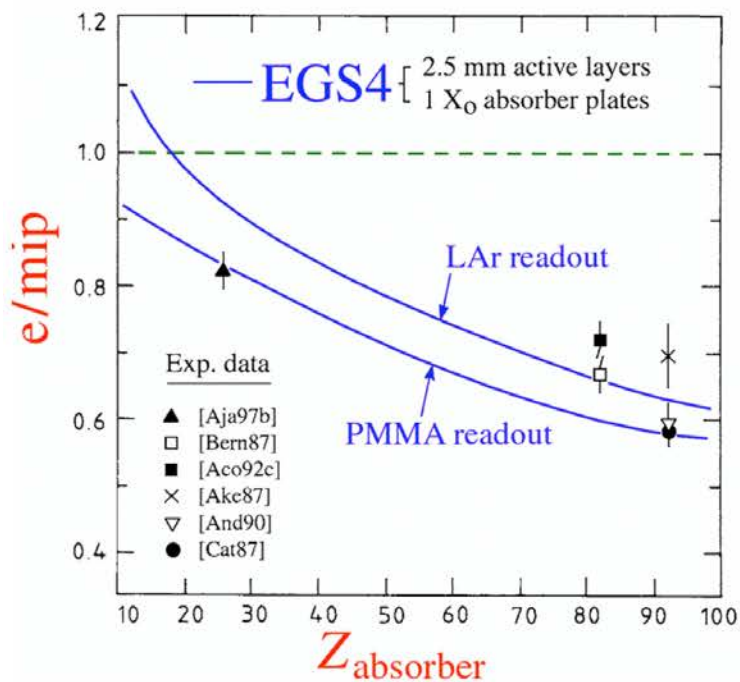


## What is the problem with the jet energy resolution?



*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

*An attractive option for improving the quality of hadron calorimetry:*

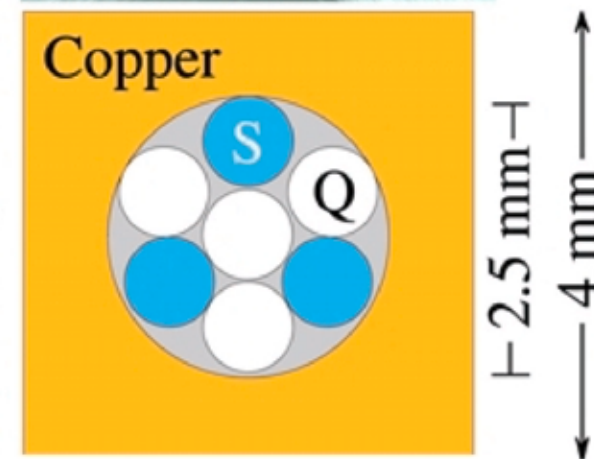
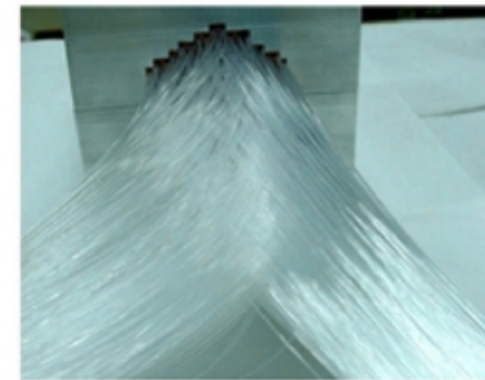
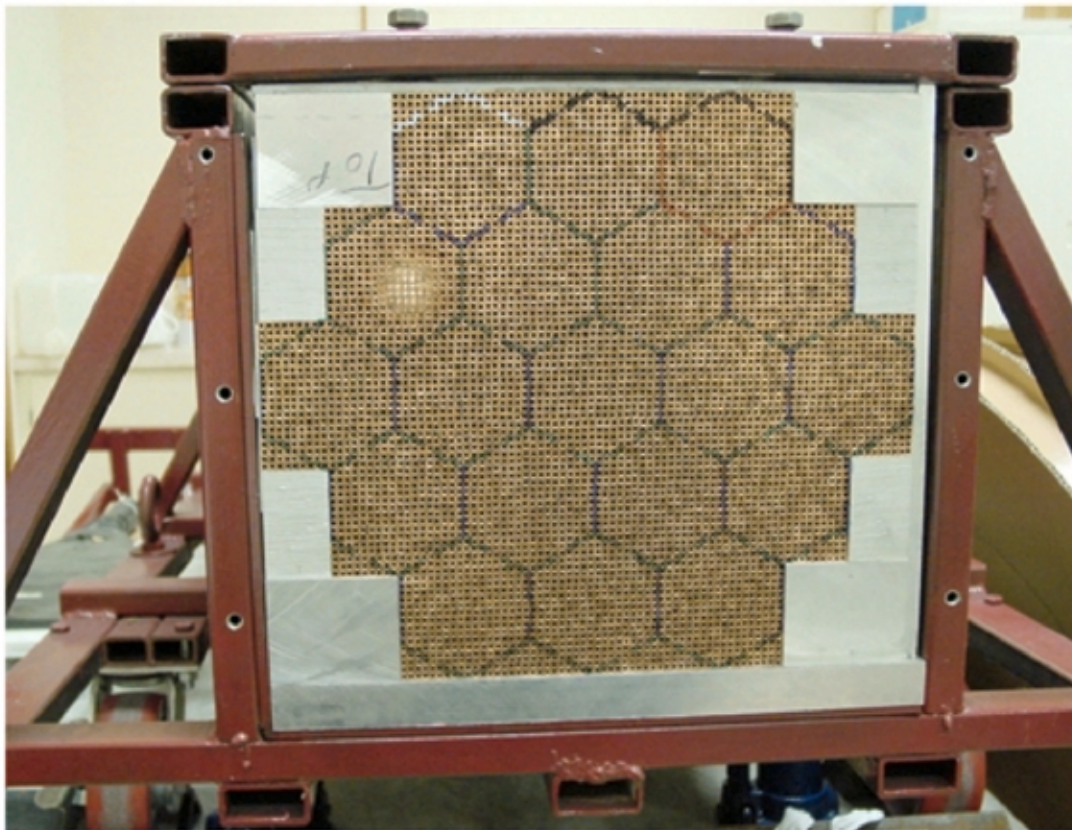
*Use Čerenkov light!! Why?*

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*

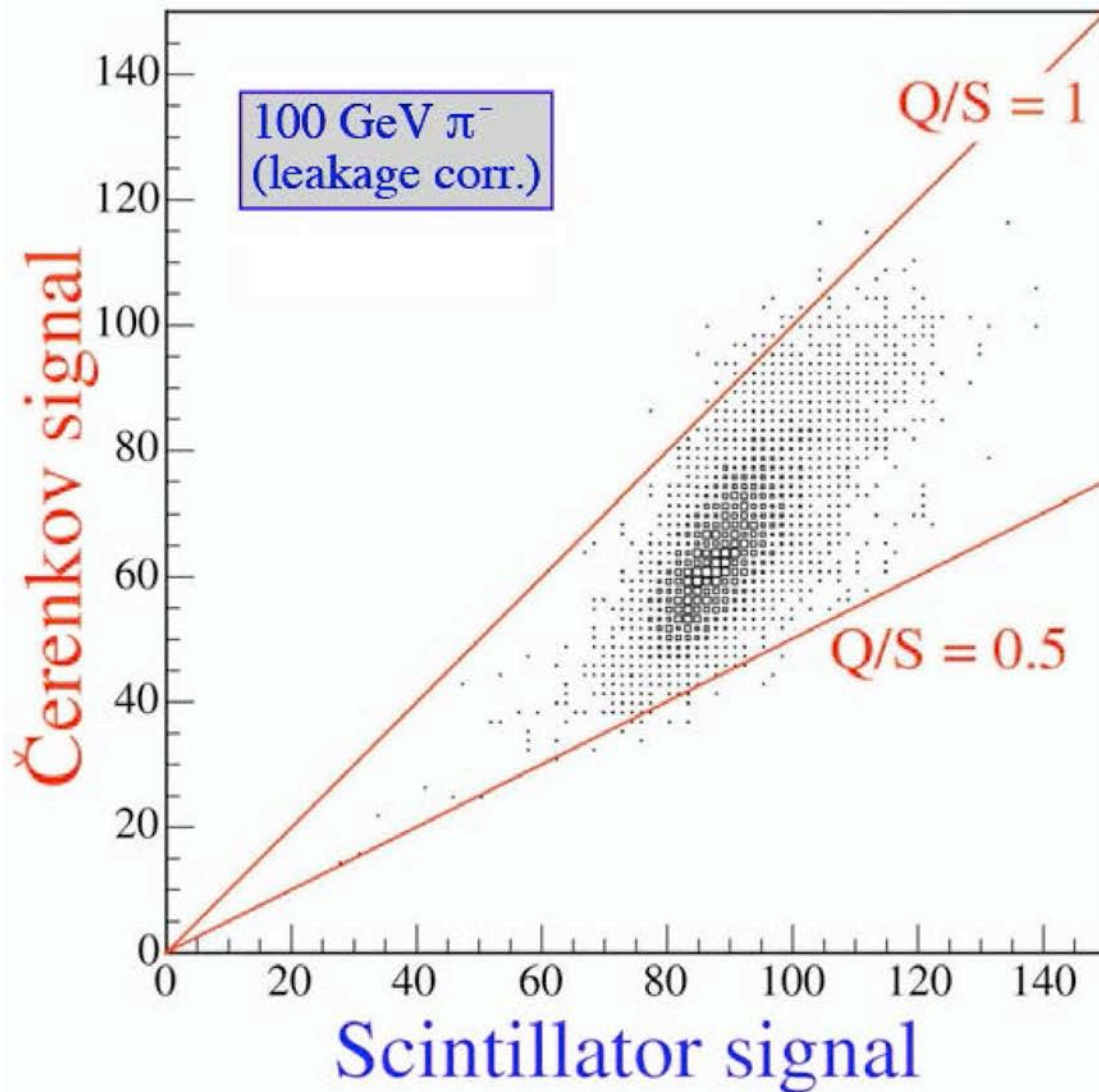
## DREAM: Structure



- *Some characteristics of the DREAM detector*

- **Depth** 200 cm ( $10.0 \lambda_{\text{int}}$ )
- Effective **radius** 16.2 cm ( $0.81 \lambda_{\text{int}}$ ,  $8.0 \rho_M$ )
- **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 $E$ ?



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

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

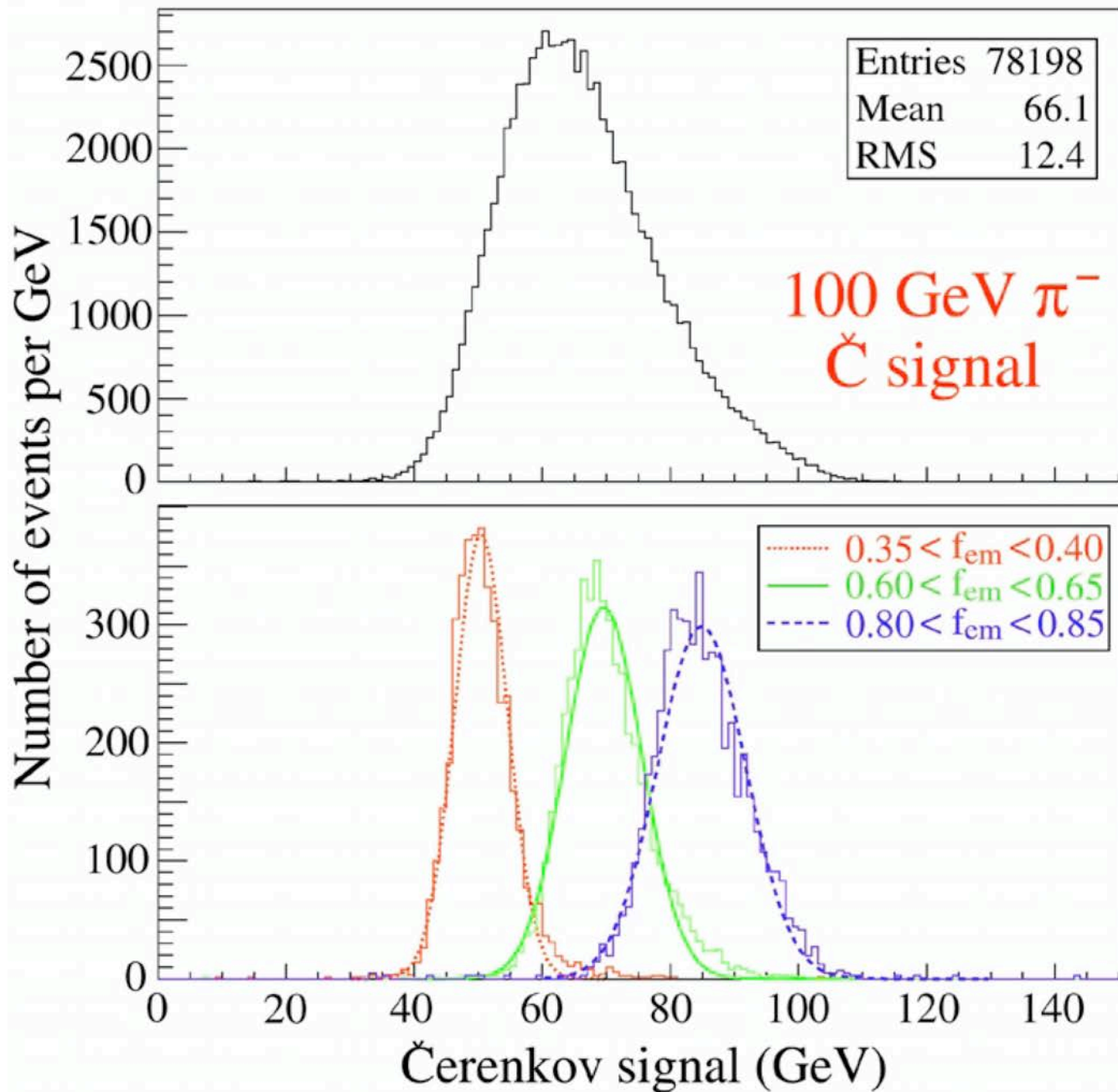
e.g. If  $e/h = 1.3$  (S),  $4.7$  (Q)

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

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

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

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



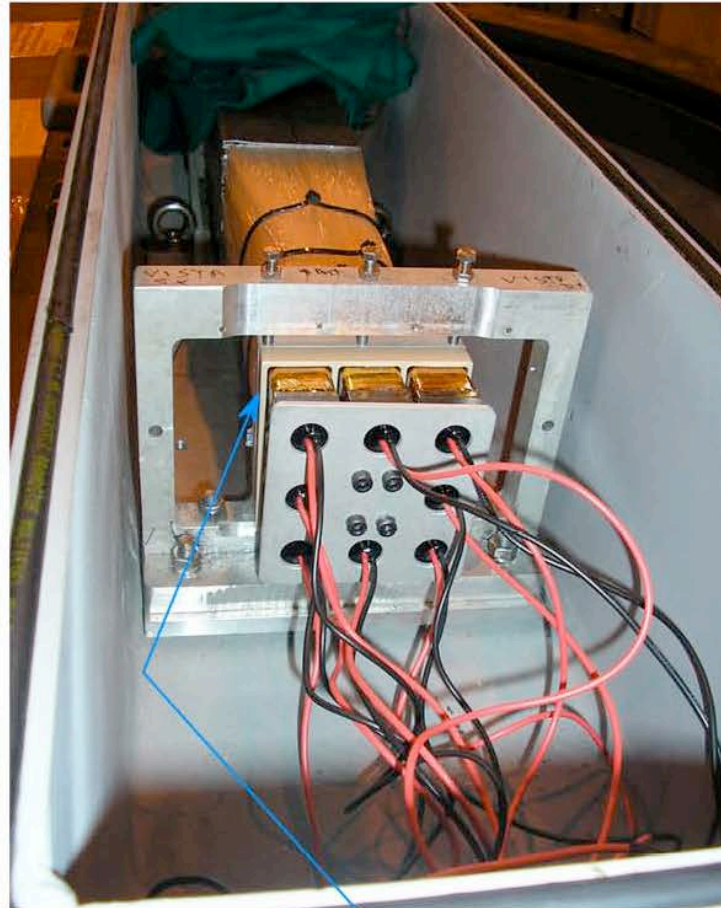
*From:*  
NIM A537 (2005) 537

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

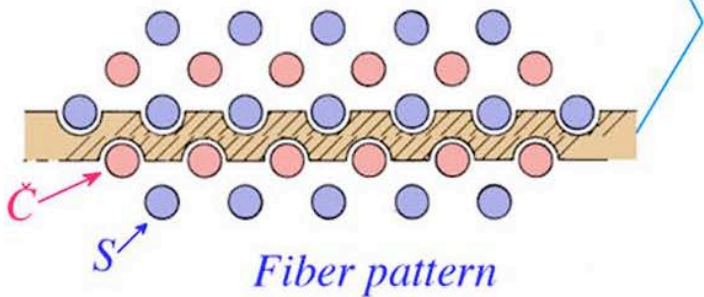
- *Fluctuations in  $f_{em}$  eliminated*  
*Fluctuations in effects of  $\Delta B$  minimized (estimate  $15\%/\sqrt{E}$ )*
- *Improve on stochastic fluctuations*
  - *Sampling fluctuations*
  - *Čerenkov light yield*

*Both contributed  $\sim 35\%/\sqrt{E}$  to DREAM results*
- *Test effect of improvements with electron showers,  
since the em resolution is limited by stochastic fluctuations*

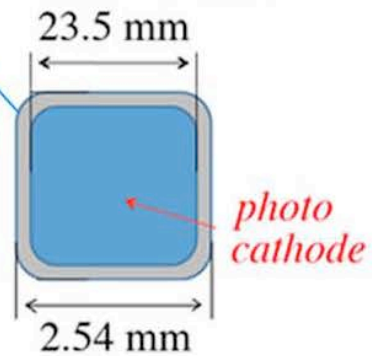
# The first SuperDREAM module tested at CERN



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

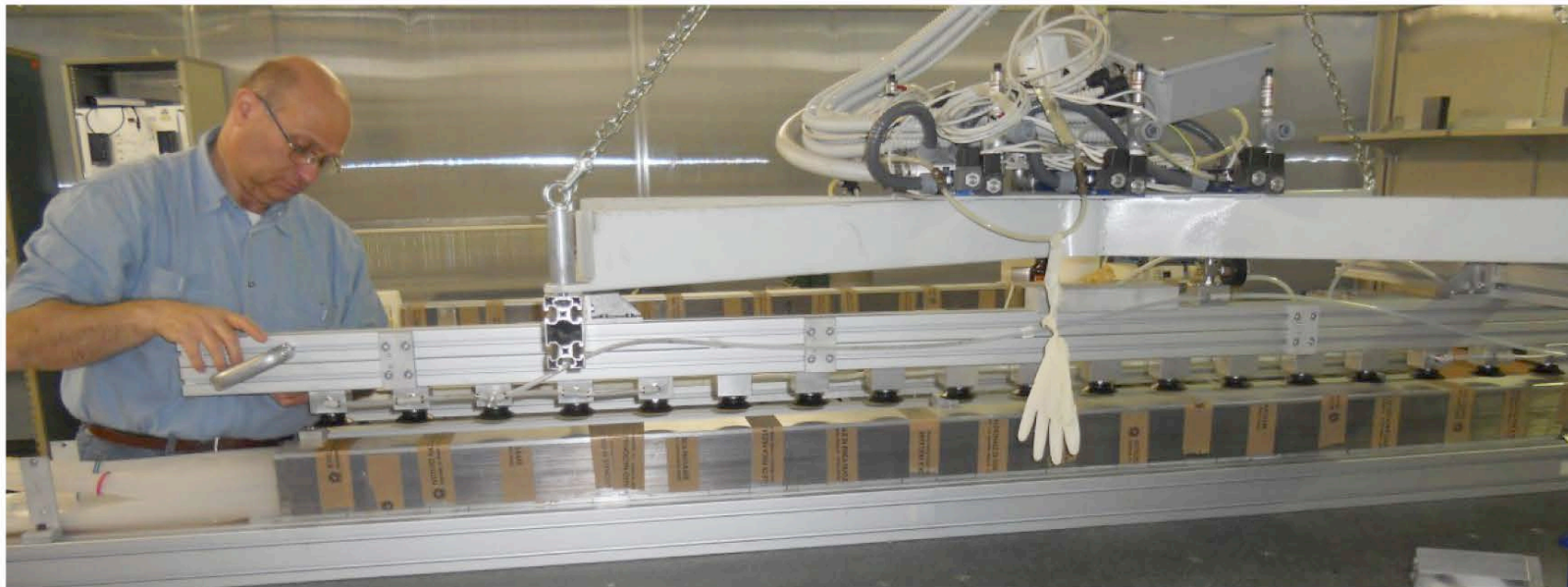
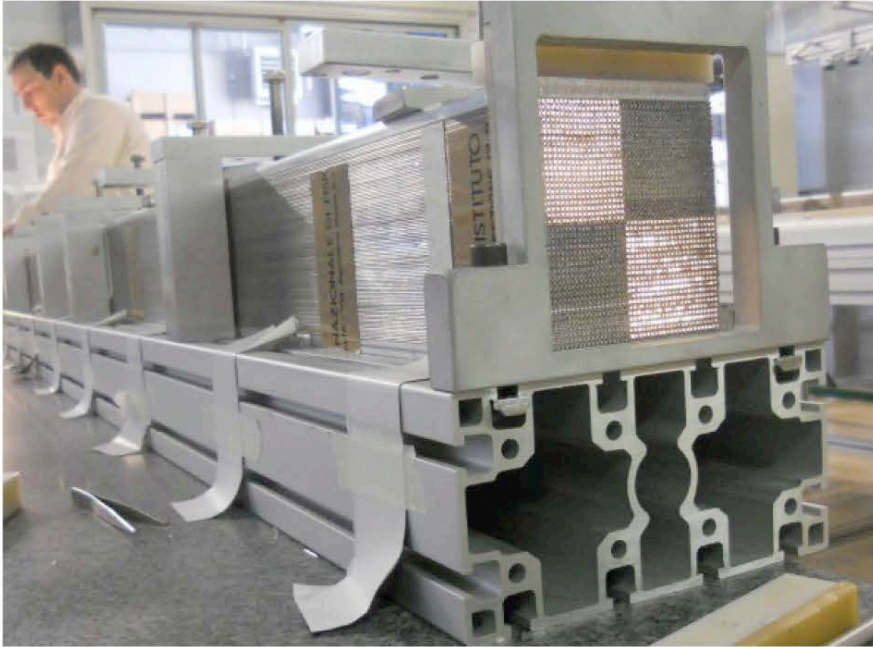


*Hamamatsu R8900  
pc: 85%!*

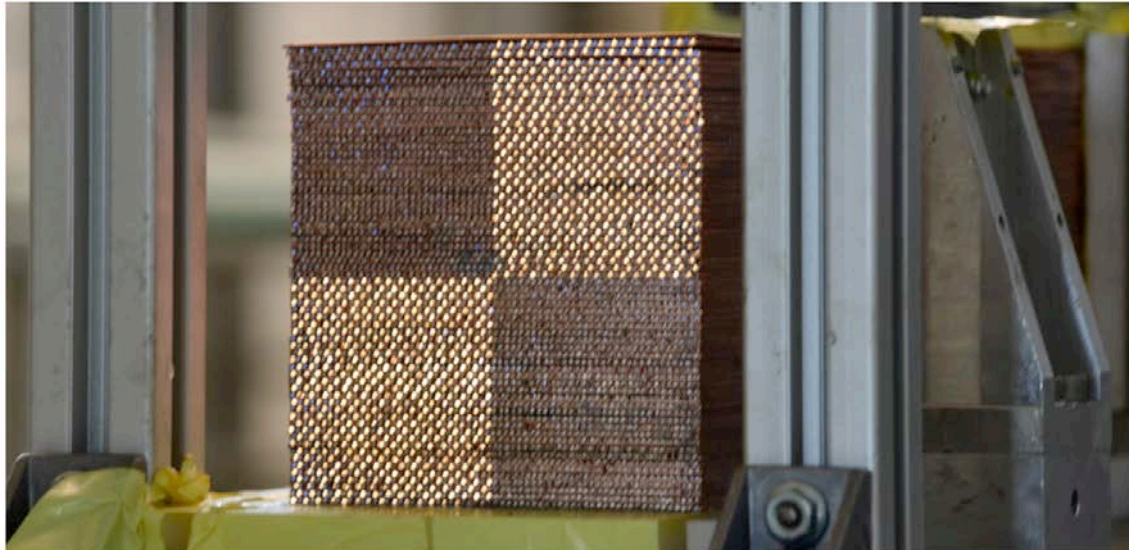




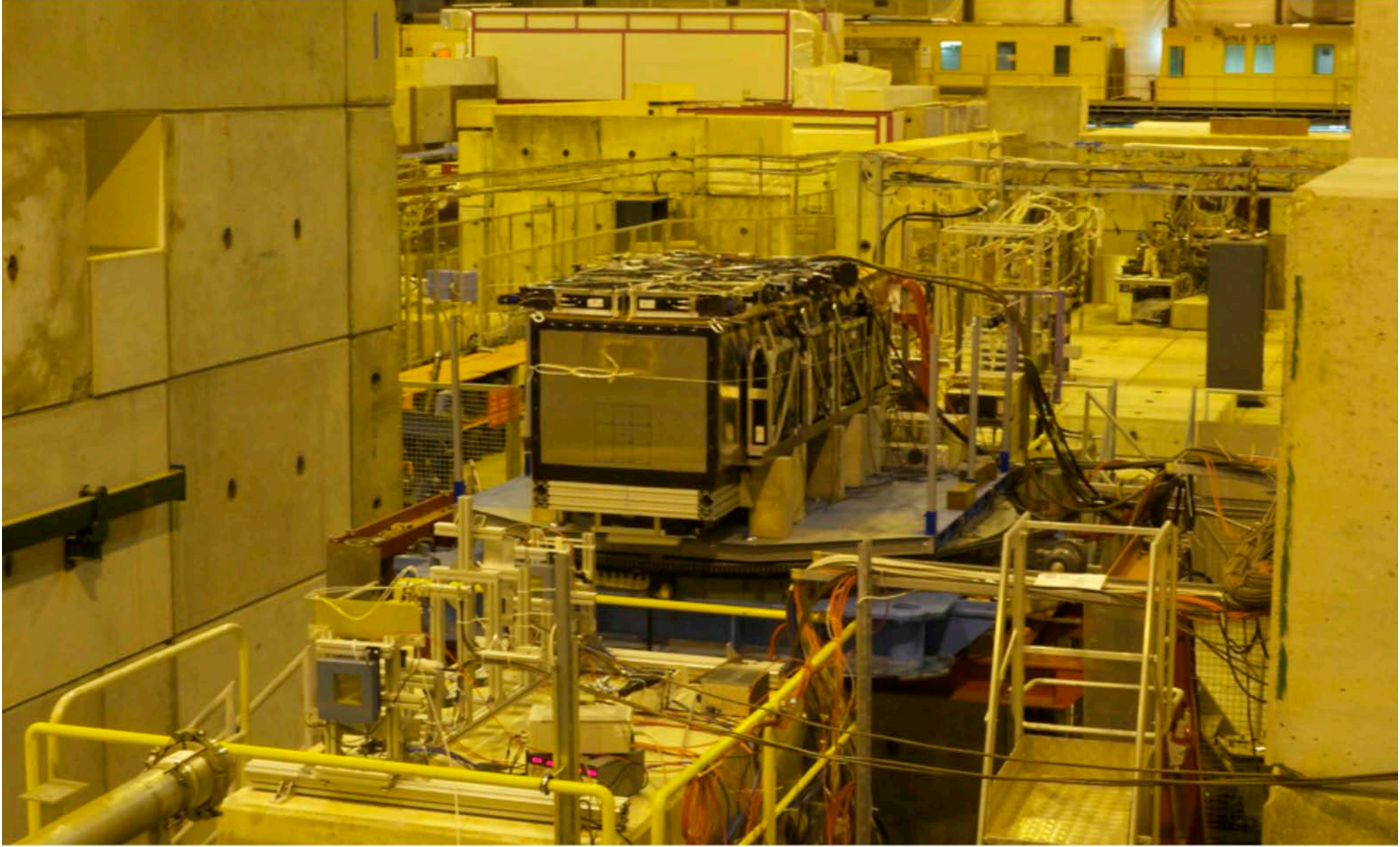
# *Production of Pb based SuperDREAM modules*



# *The first copper module*

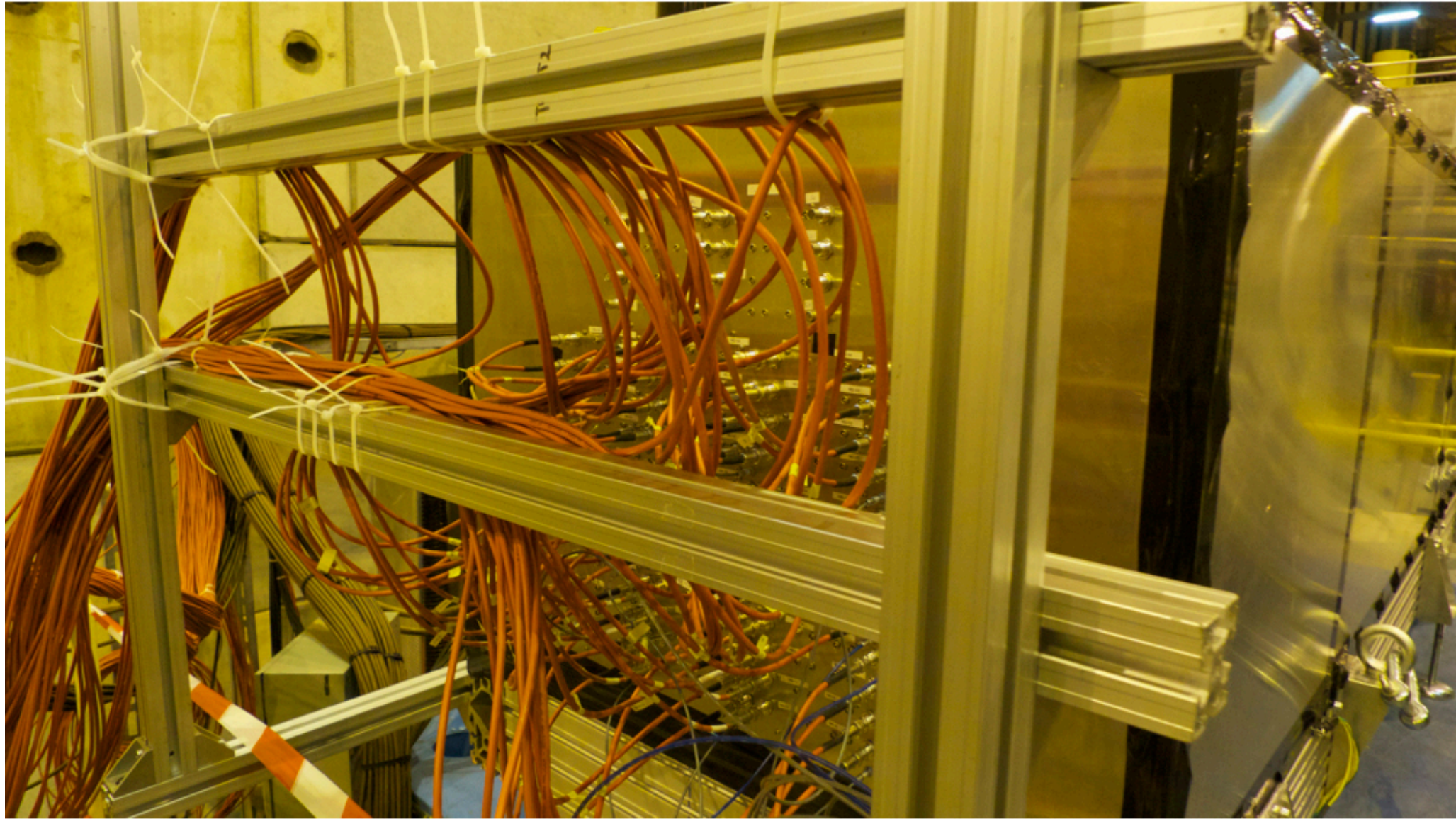


*The new SuperDREAM fiber module tested at CERN  
(December 2012)*

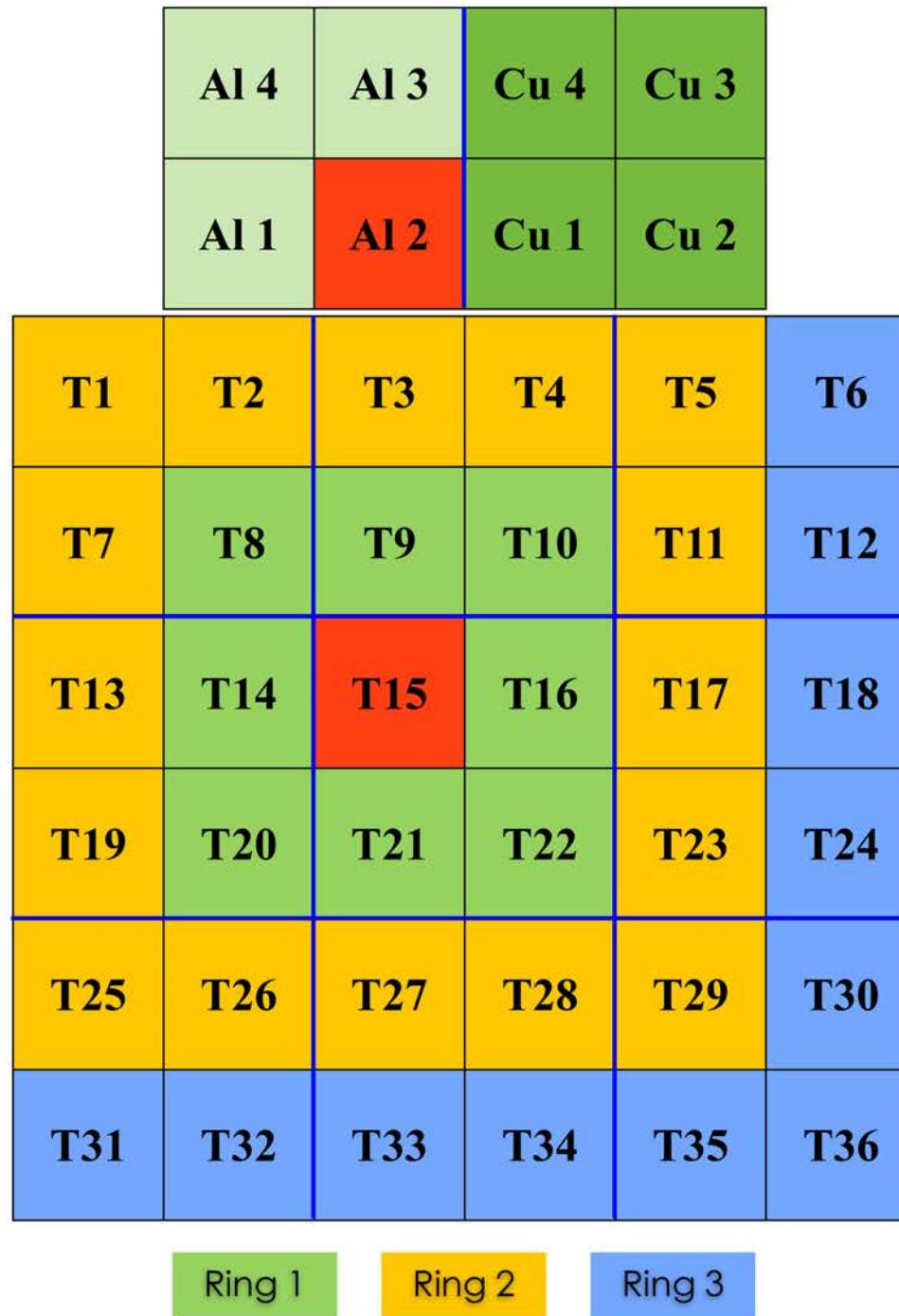


*9 modules (36 towers, 72 signals), 1.4 tonnes Pb/fiber + 2 modules Cu/fiber  
20 leakage modules (500 kg plastic scintillator)*

*Rear side of the new SuperDREAM module*

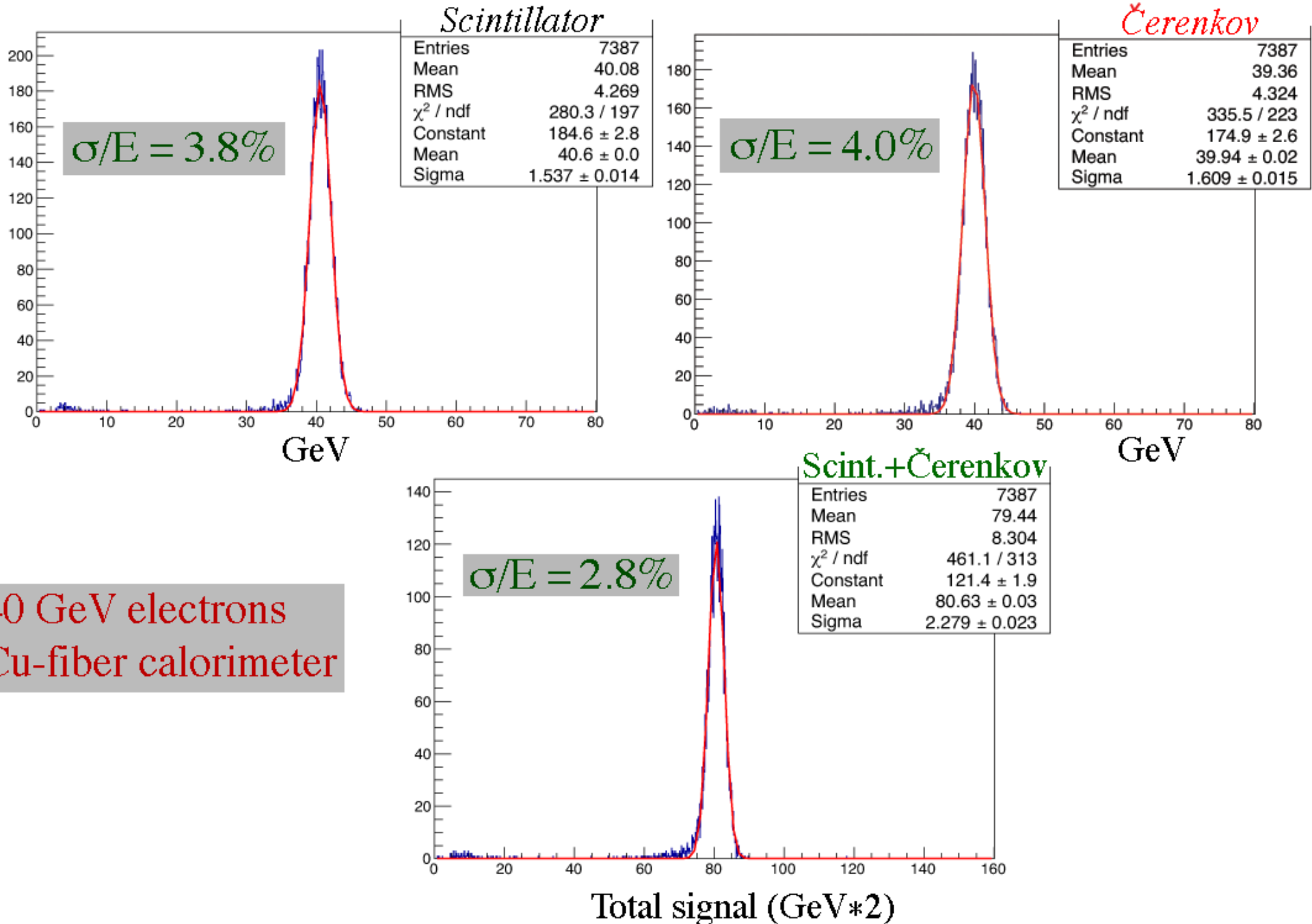


# *The RD52 fiber calorimeter tested in November 2012*



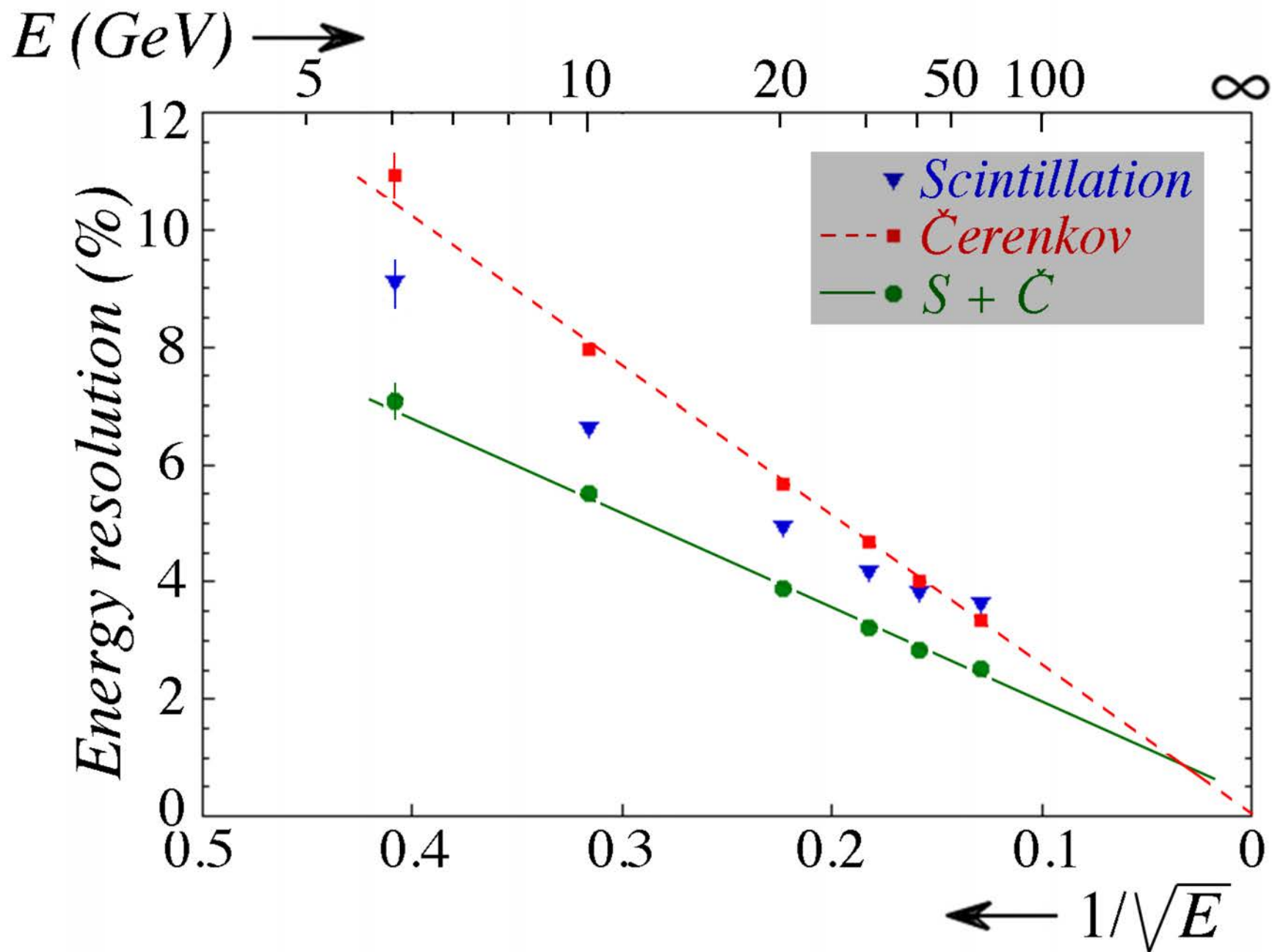
# *S and Č signals sample the showers independently*

## *Resolution improves by combining*

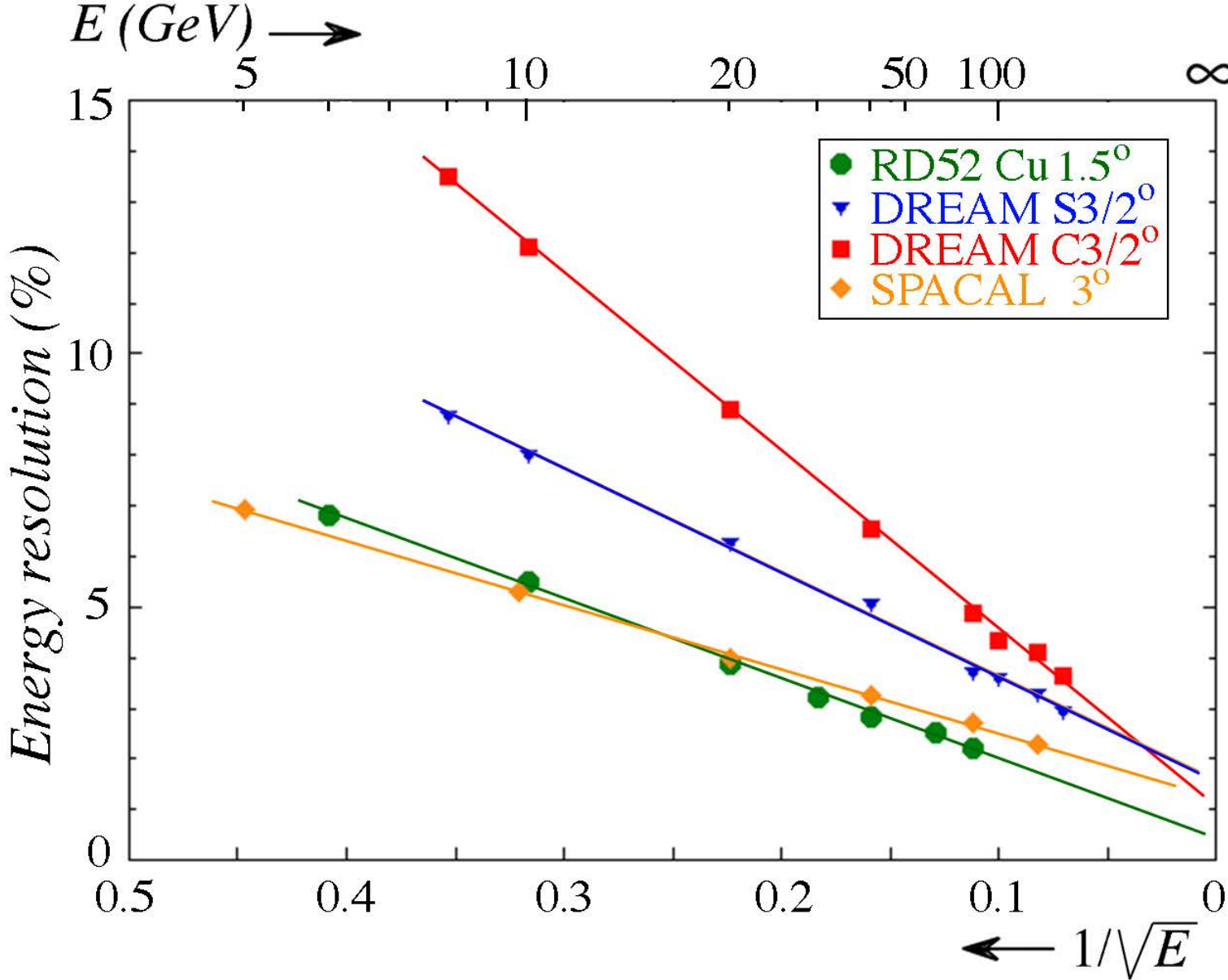


# Combining signals from two fiber types improves resolution

→ Stochastic term dominates



# Em resolution RD52 compared to other fiber calorimeters

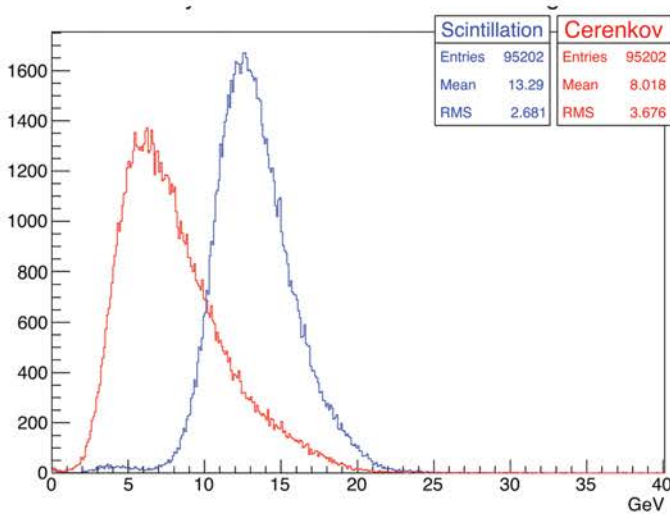




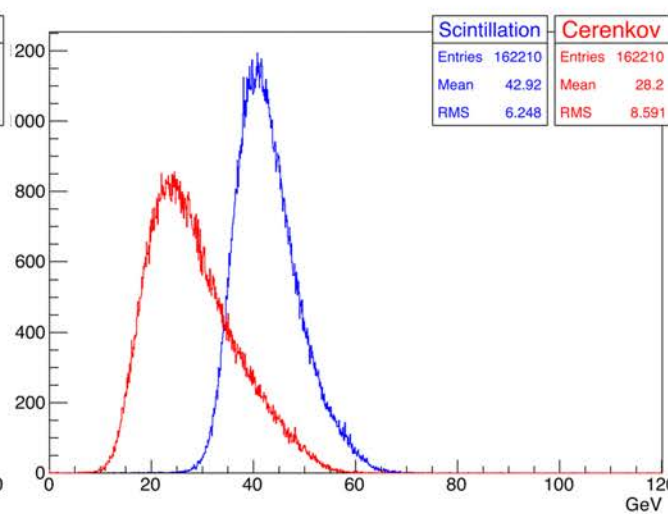
# Hadron detection with a dual-readout calorimeter

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

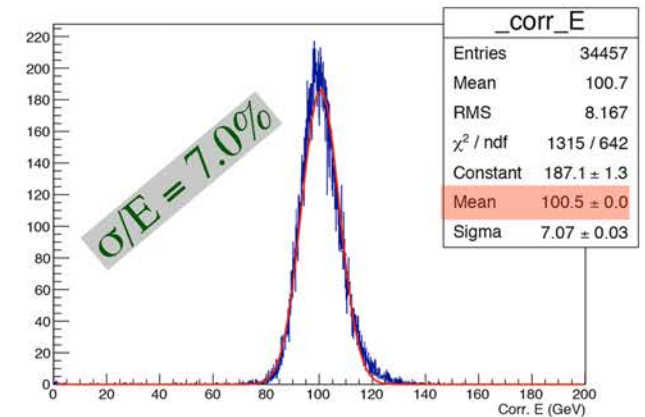
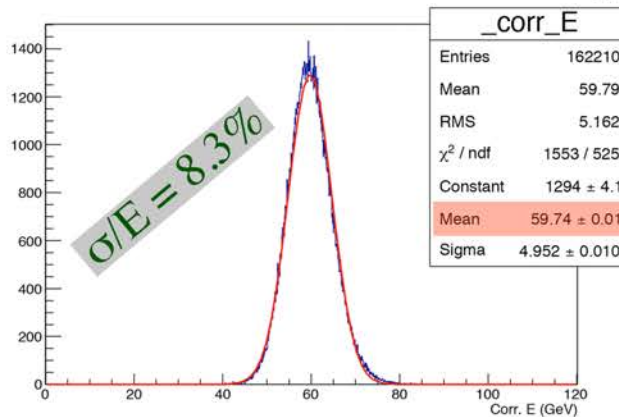
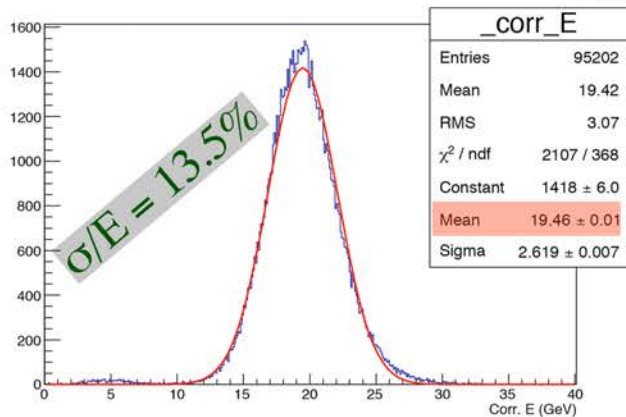
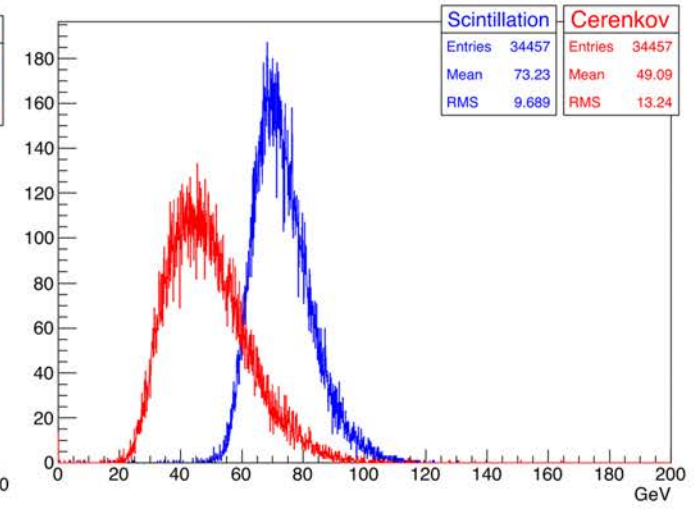
20 GeV  $\pi^-$



60 GeV  $\pi^-$

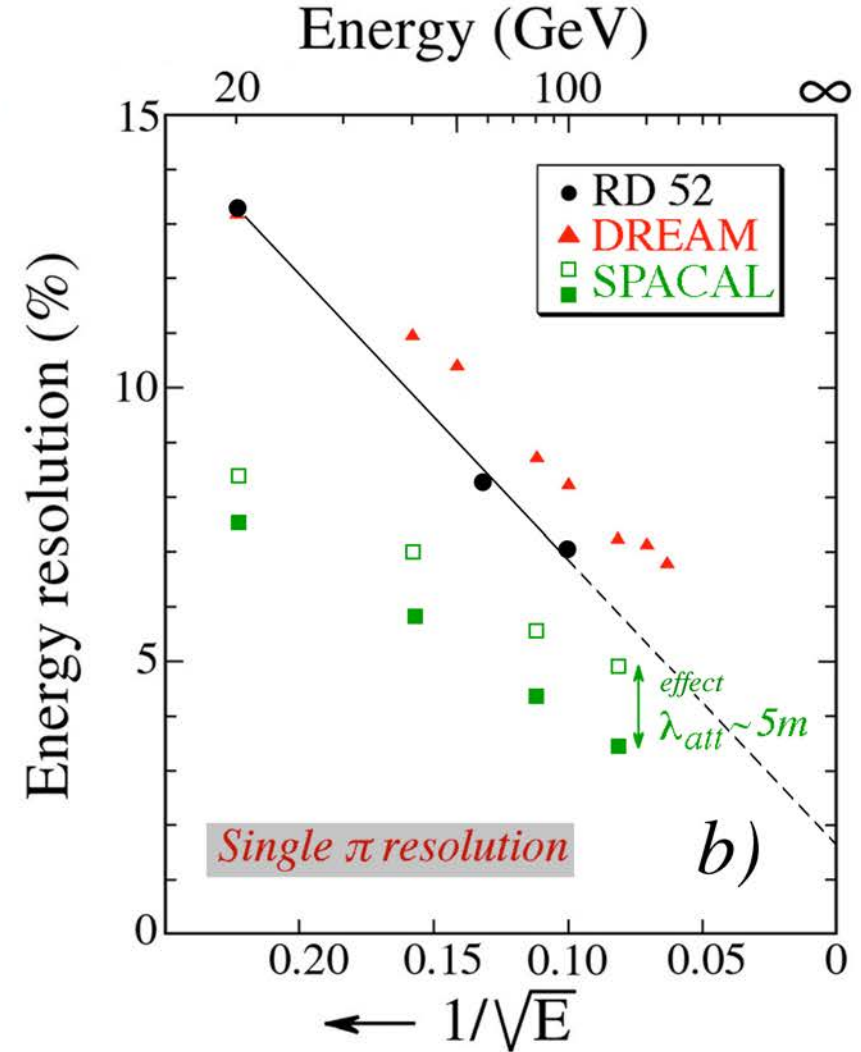
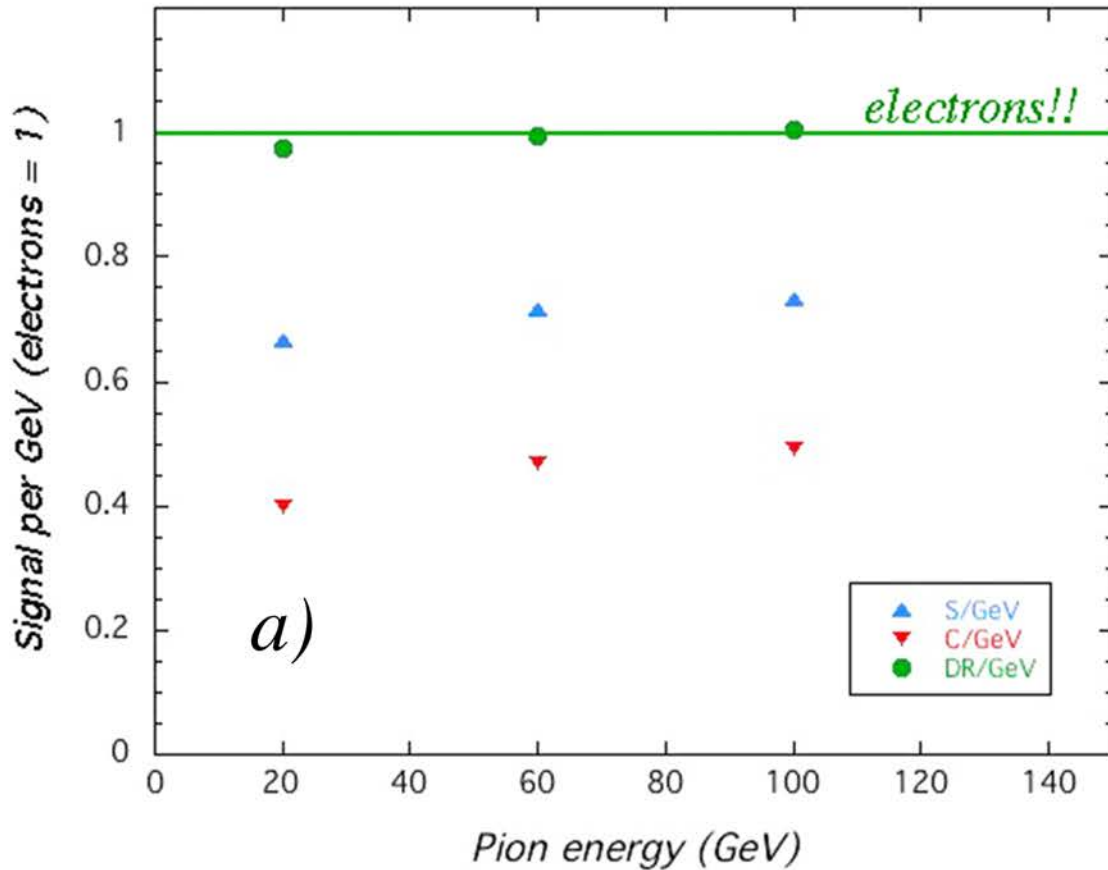


100 GeV  $\pi^-$



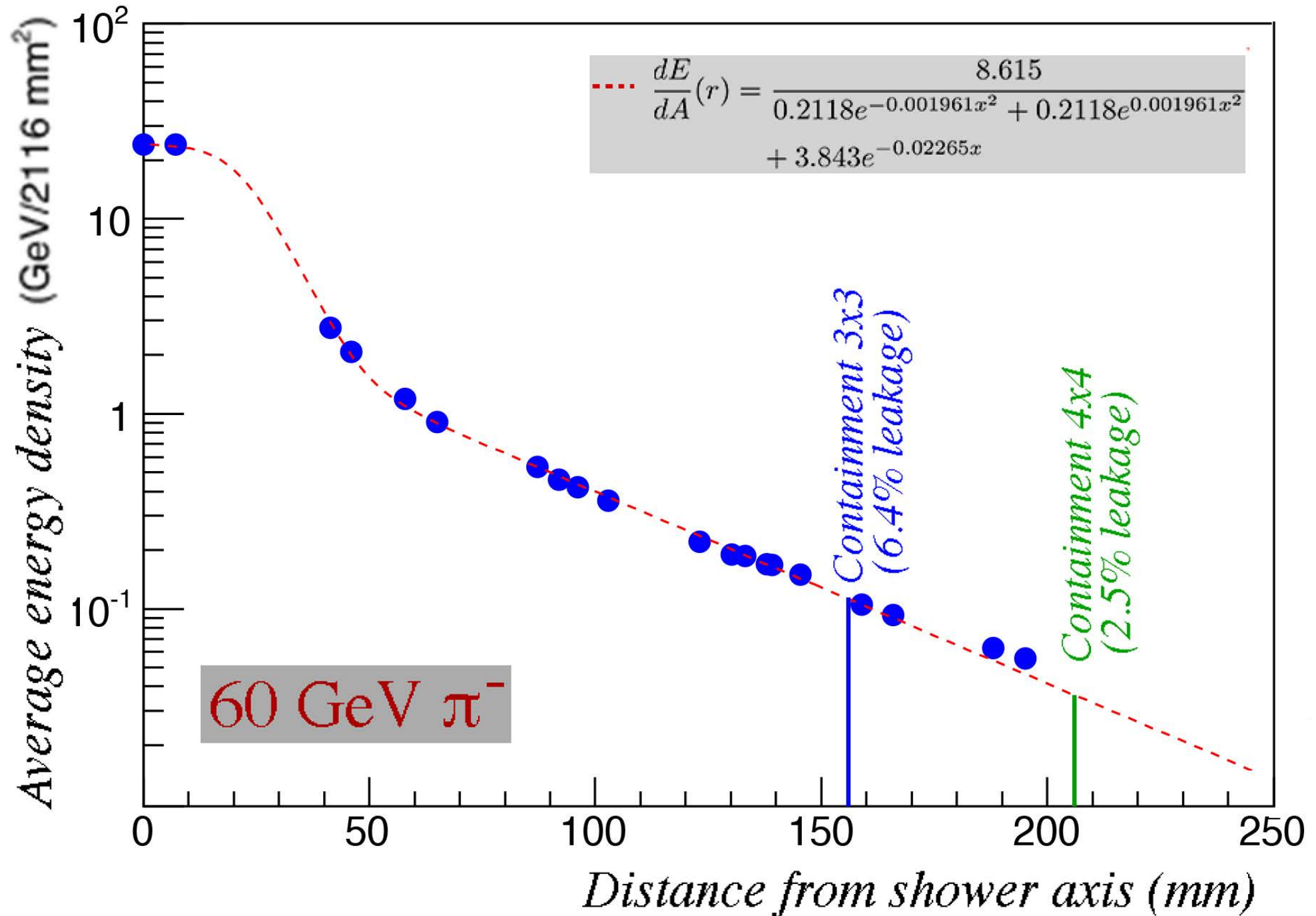
# The calorimeter response and energy resolution for single pions

*Electron energy scale well reproduced by DR!!*

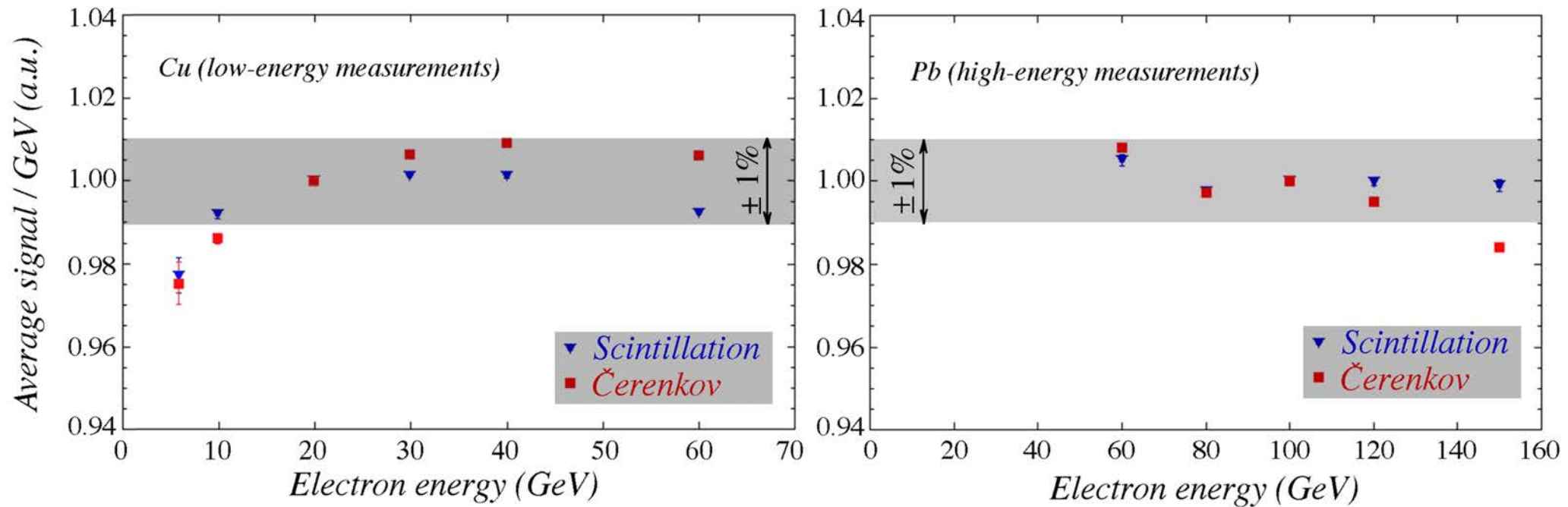


*Note: RD52 pion data still preliminary (e.g., no light attenuation corrections)*

# Radial profile and hadronic shower containment

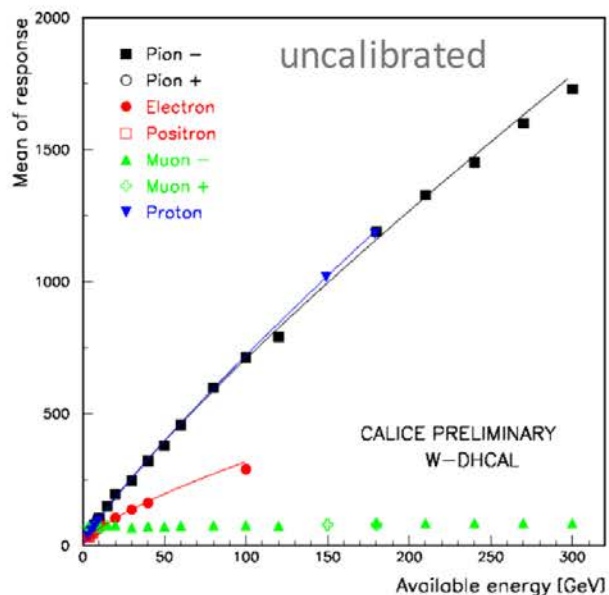


# Linearity measurements for em showers



# Response – (Semi) - Digital HCALs

## Tungsten – DHCAL



Non-linear response  
to both  $e^\pm$  and hadrons

Both well described by  
power law  $\alpha E^\beta$

**Badly over-compensating**

$e/h \sim 0.9 - 0.5$

→ need smaller readout pads

Deviations from  
linear response  
due to finite  
readout pad  
size

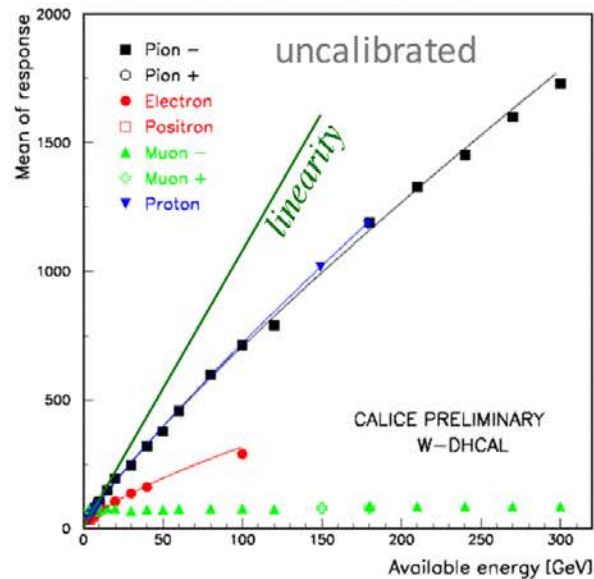
**Functional form a priori not known, but needed for energy reconstruction**

Is linearity mandatory for imaging calorimeters?



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Functional form a priori not known, but needed for energy reconstruction

Is linearity mandatory for imaging calorimeters?

**YES !!**

*e.g.*  $K_L^0 \rightarrow \pi^0 \pi^0 \pi^0$



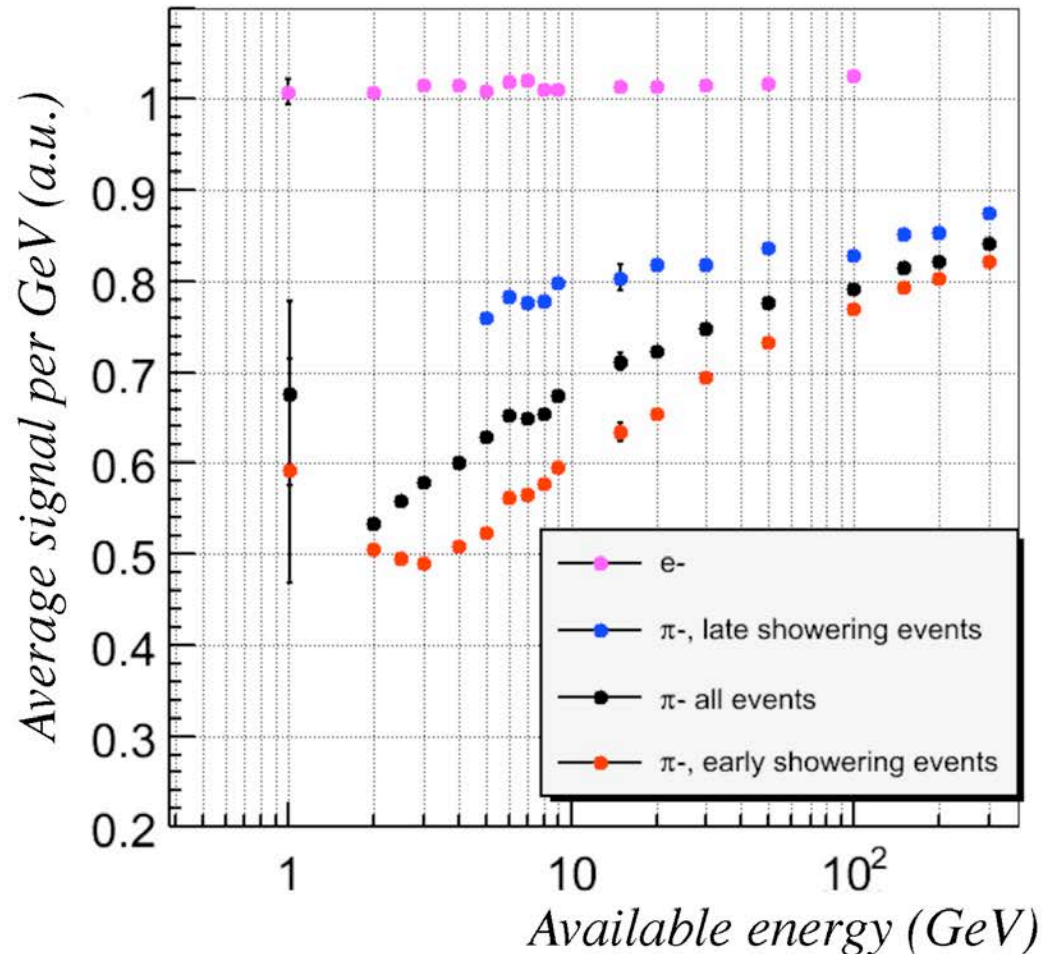
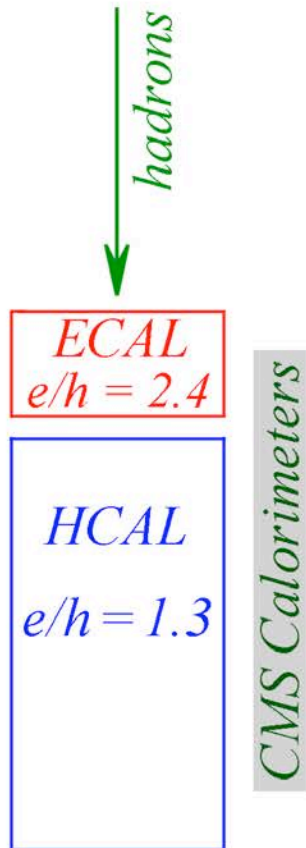
# Calorimeter calibration issues

## *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*



## *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*

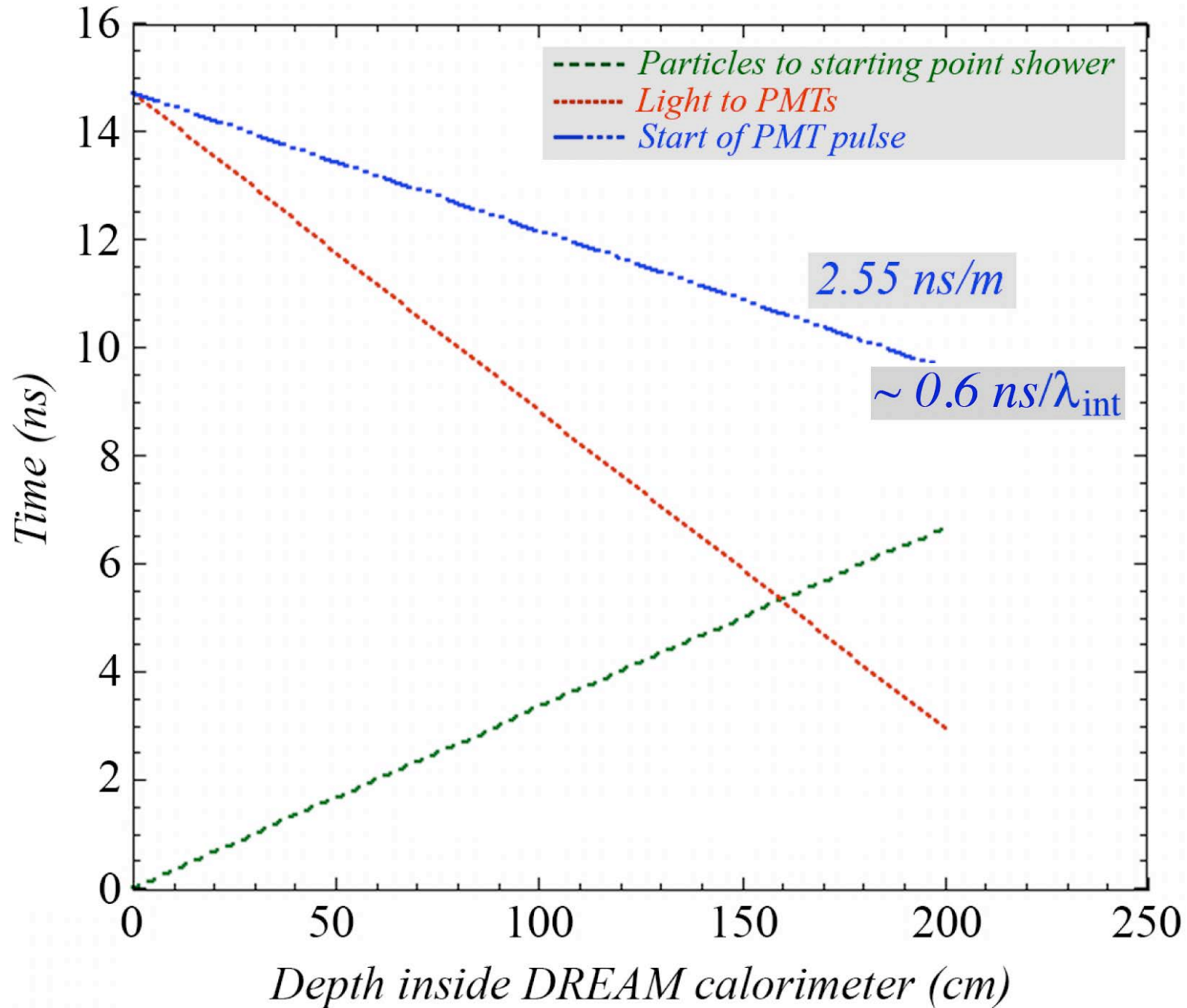
*However, a fine lateral granularity can do wonders*

*In addition:*

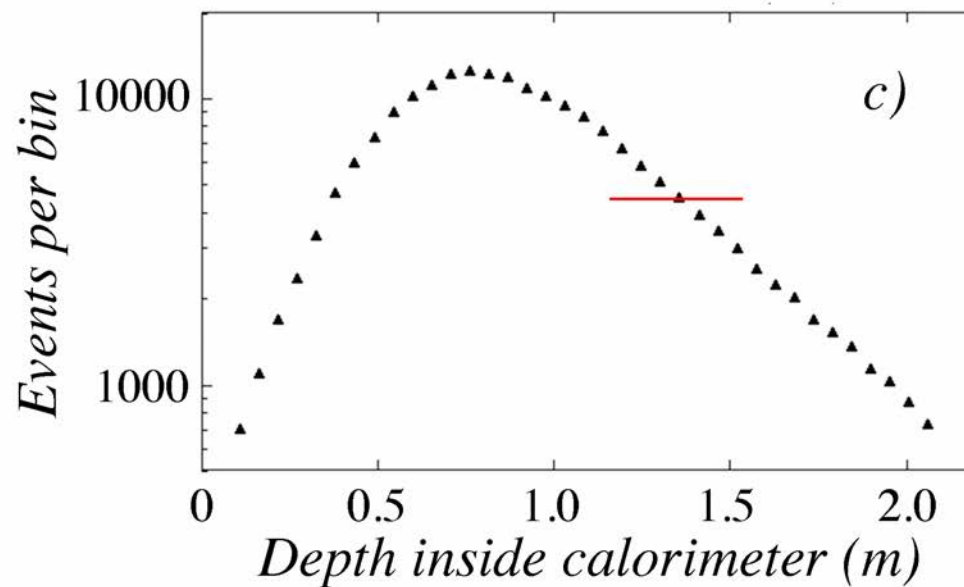
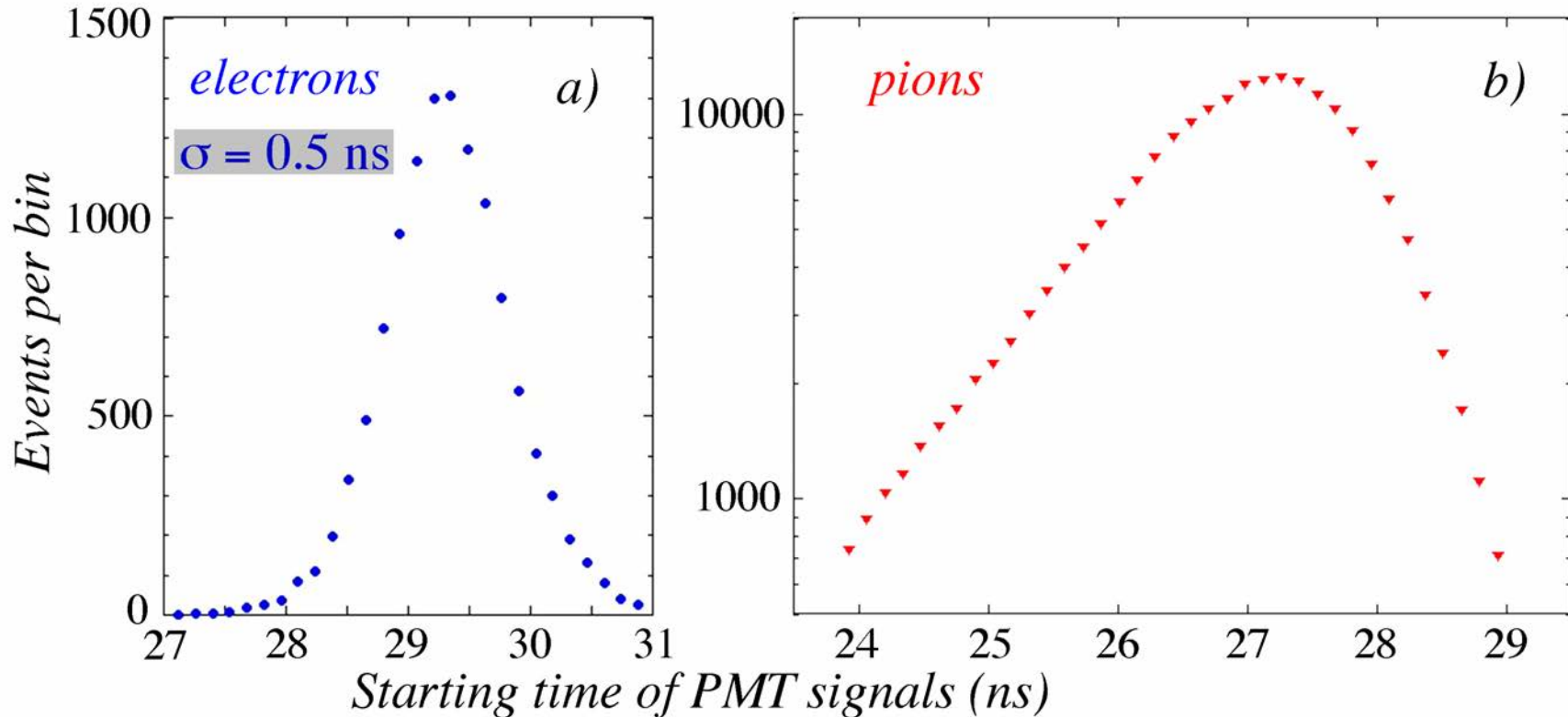
- *Time structure of the signals can provide crucial depth information*



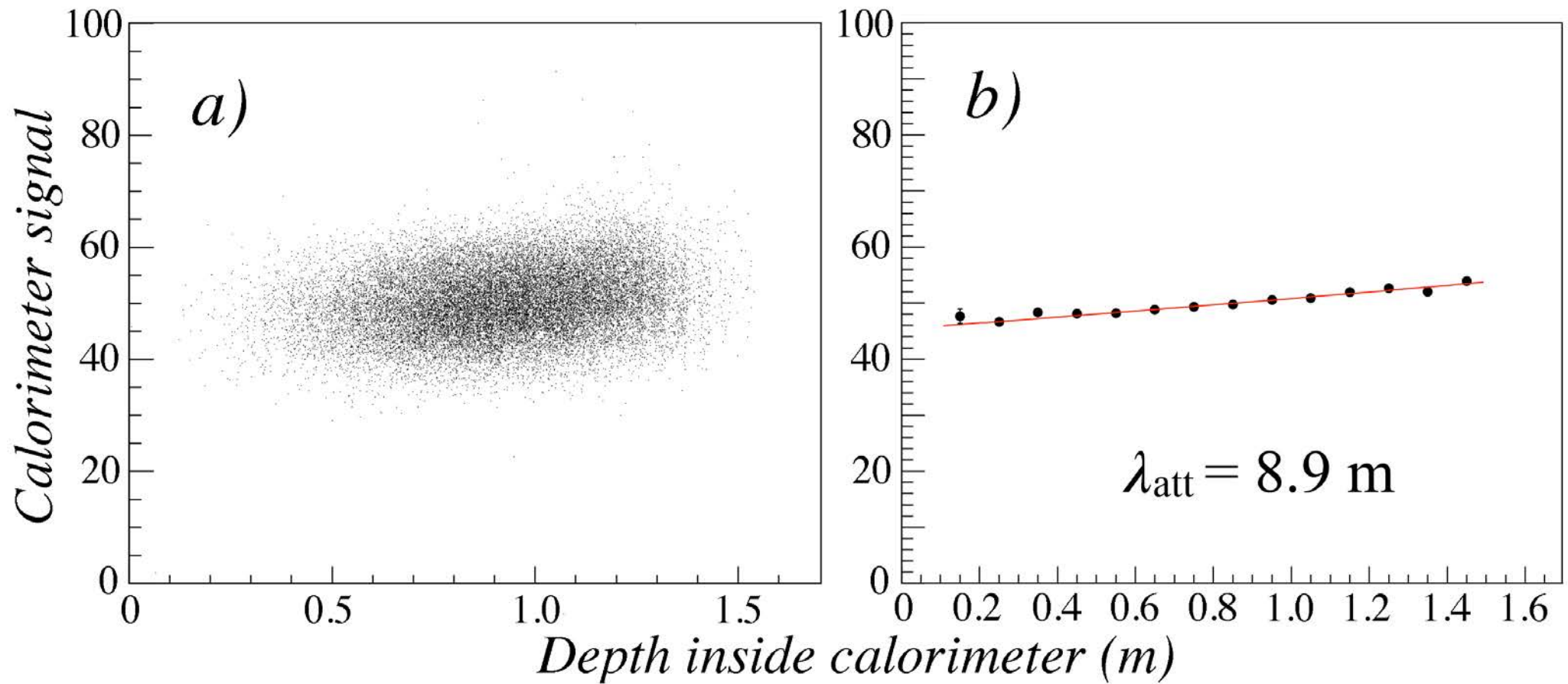
*Depth of the light production  
and the starting point of the PMT signals*



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

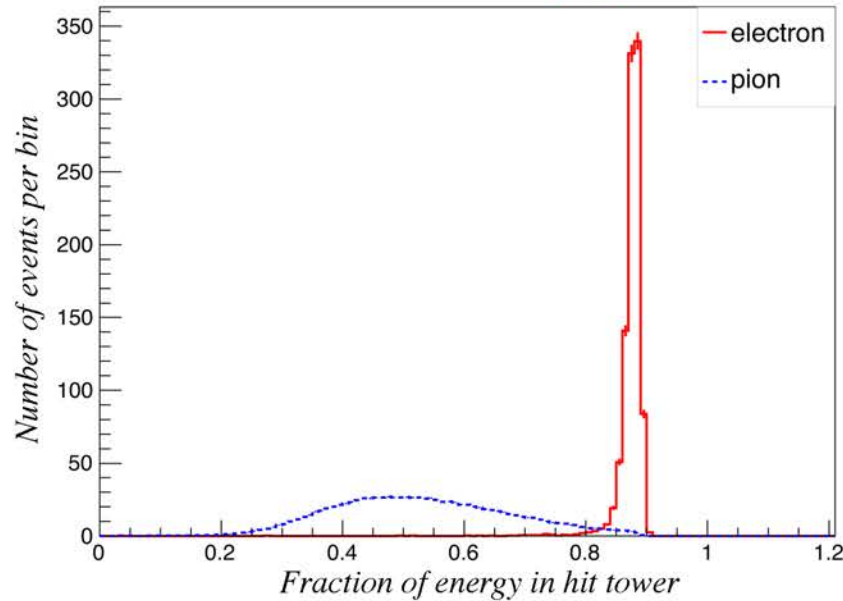


*Use depth of light production to correct for light attenuation*

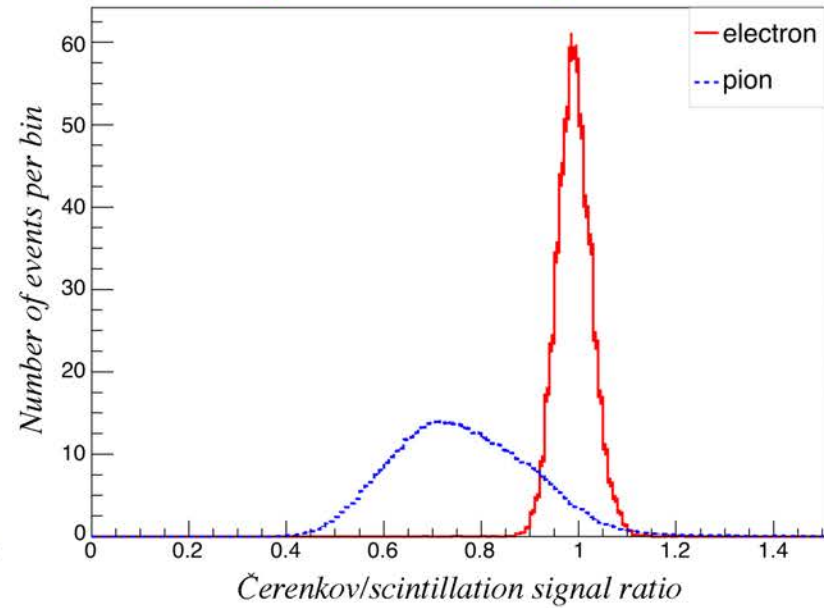


# Methods to distinguish $e/\pi$ in longitudinally unsegmented calorimeter

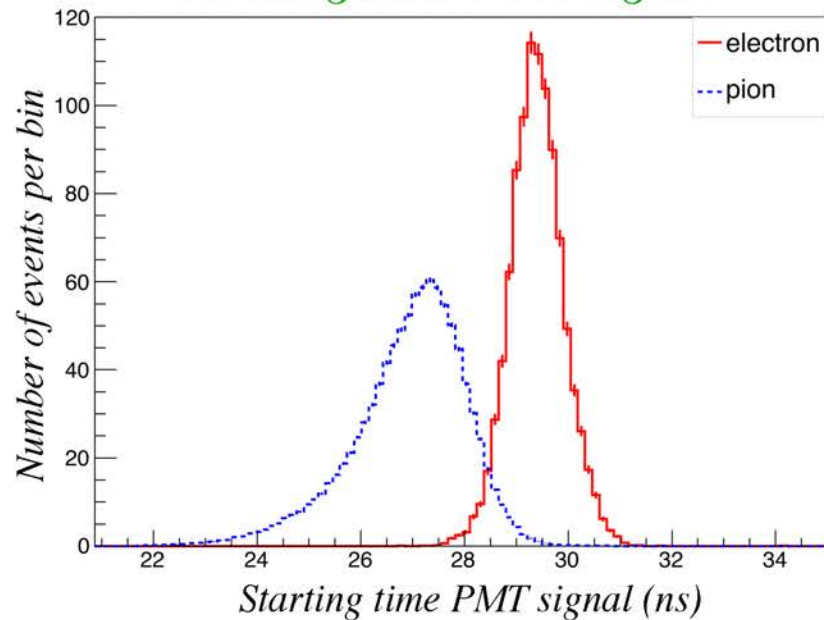
## Lateral shower profile



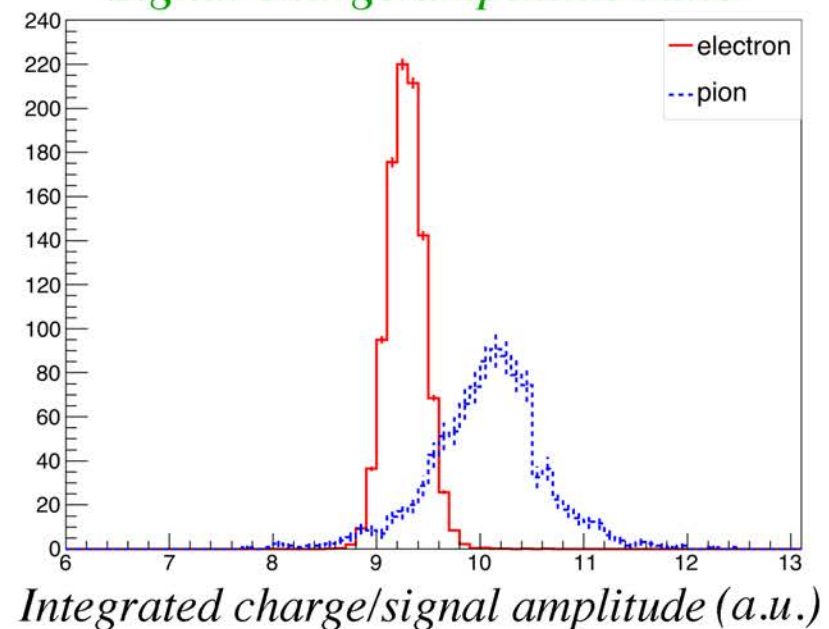
## Difference C/S signals



## Starting time PMT signal

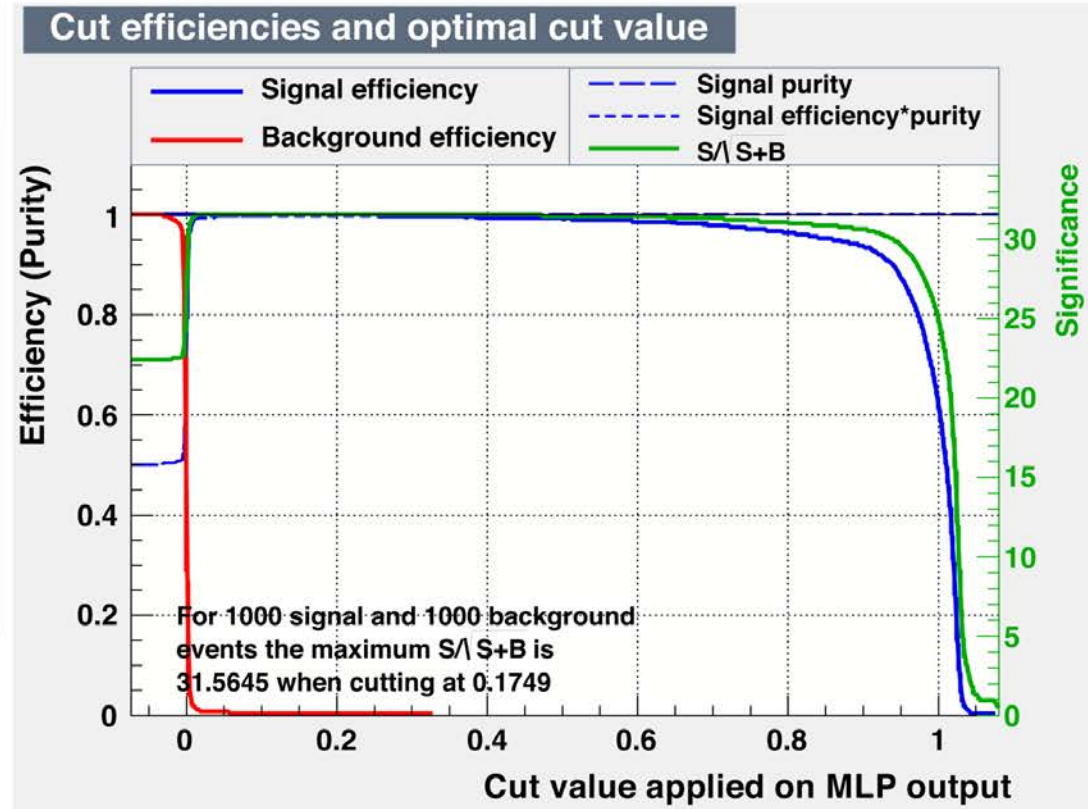
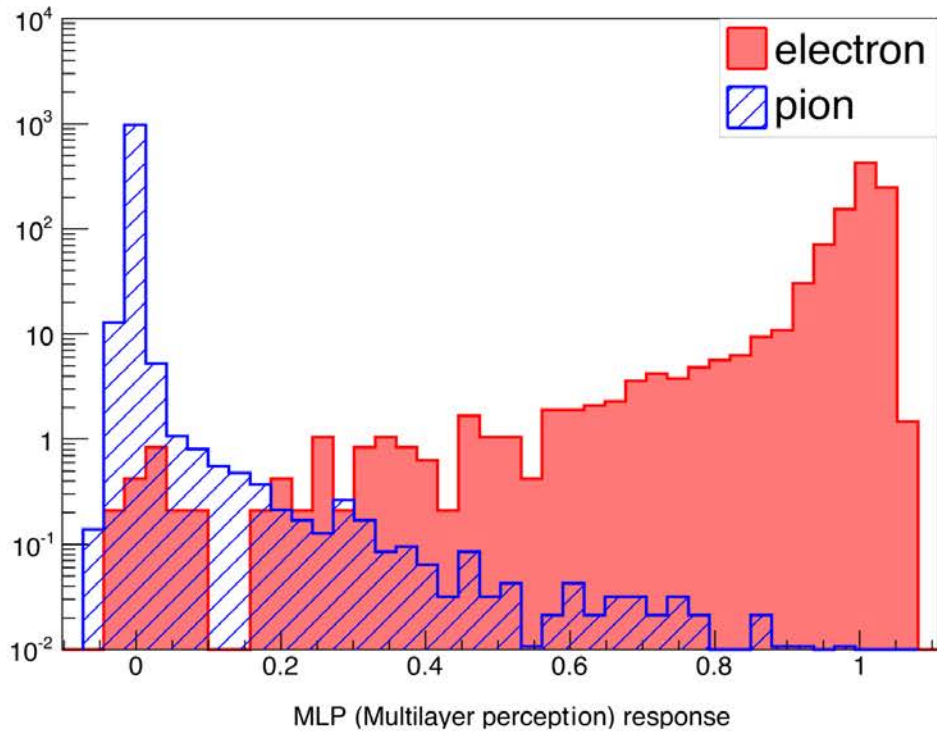


## Signal charge/amplitude ratio



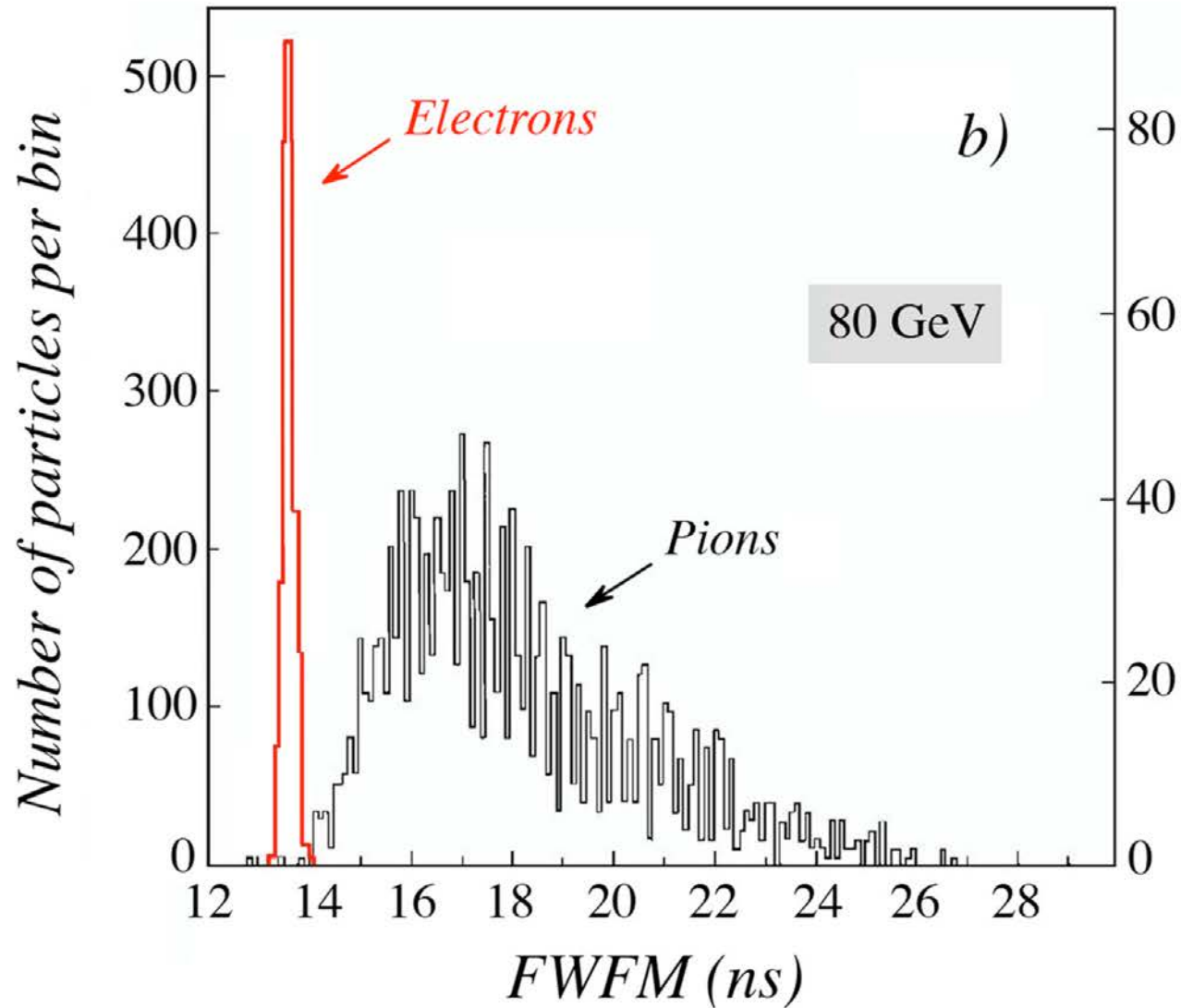
Combination of cuts:  $>99\%$  electron efficiency,  $<0.2\%$  pion mis-ID

# Neural network analysis 60 GeV $e/\pi$ separation



*for MLP > 0.17 : 99.81% electron ID  
0.20%  $\pi$  mis-ID*

*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)*

# *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)*

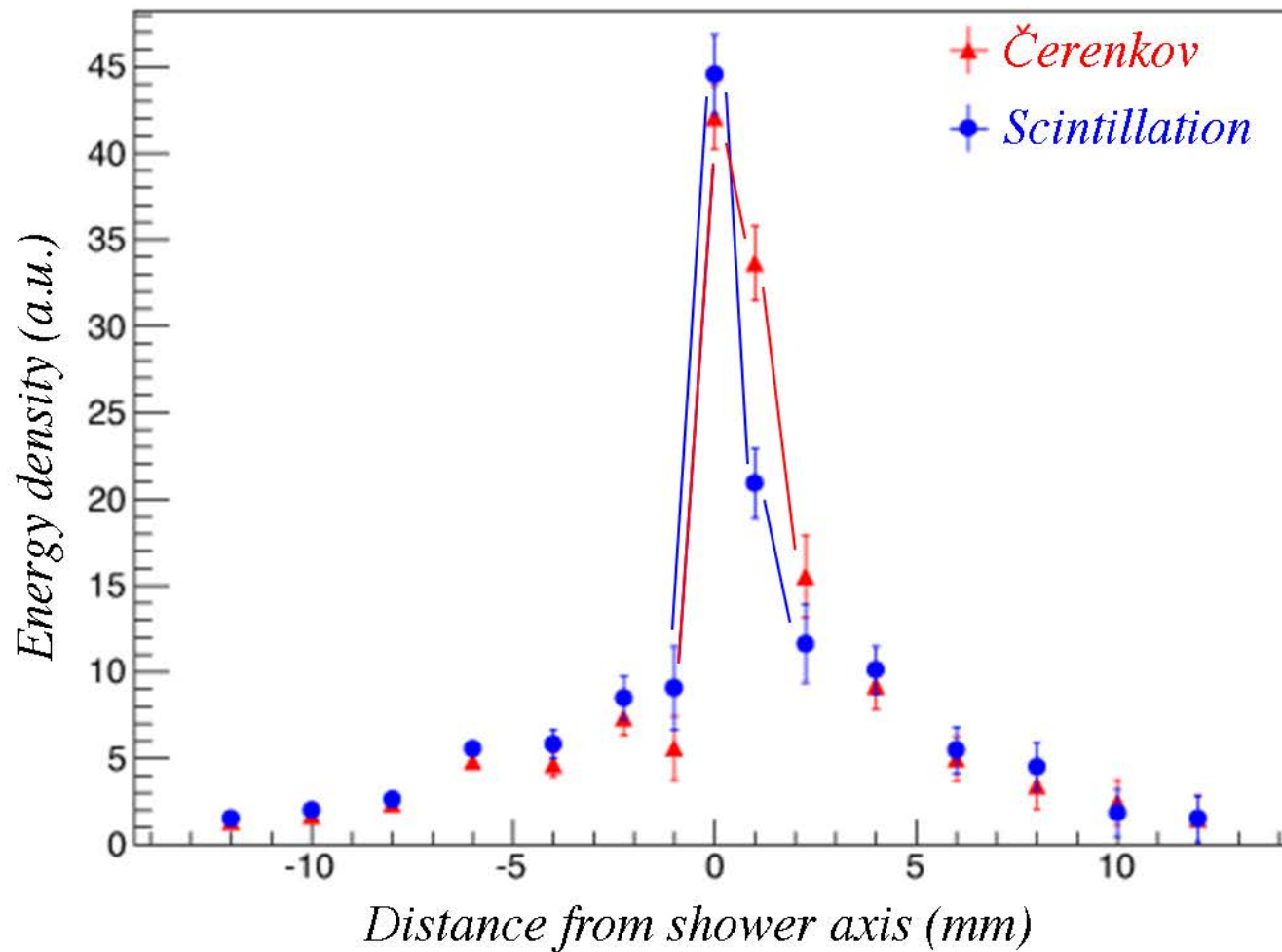
## *Attractive features of longitudinally UNSEGMENTED calorimeters*

- *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

*Lateral shower profile*





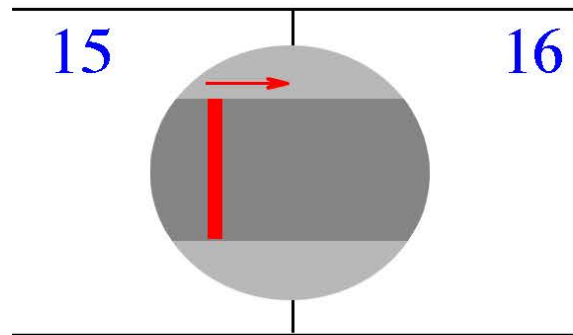
# Conclusions

- *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  $\gamma$ s 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*
- *Italian scientists have made major contributions to this project.. I hope that that can continue to be the case in the context of ILC*

*Backup slides*

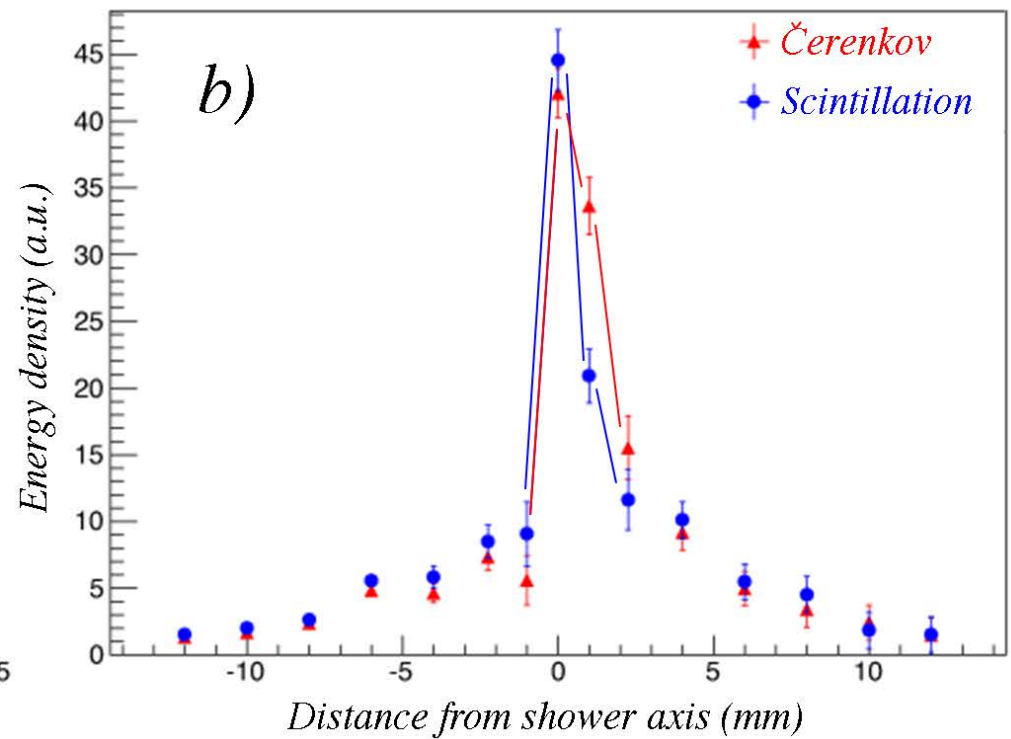
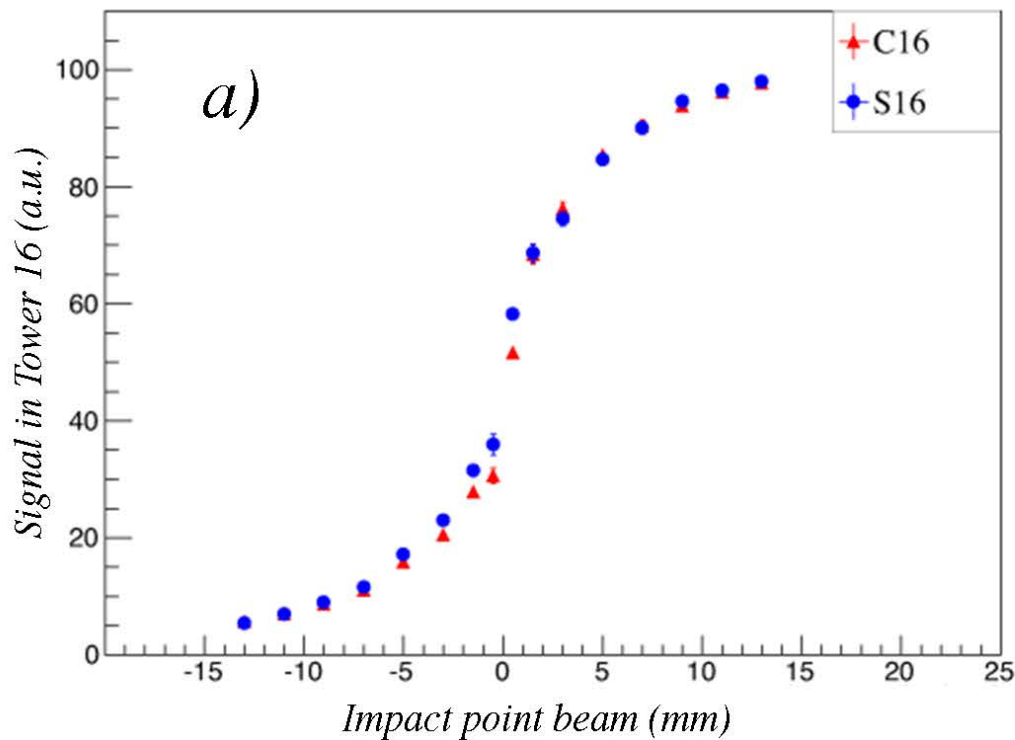
# The extremely narrow electromagnetic shower profile

Move small beam spot across tower boundary



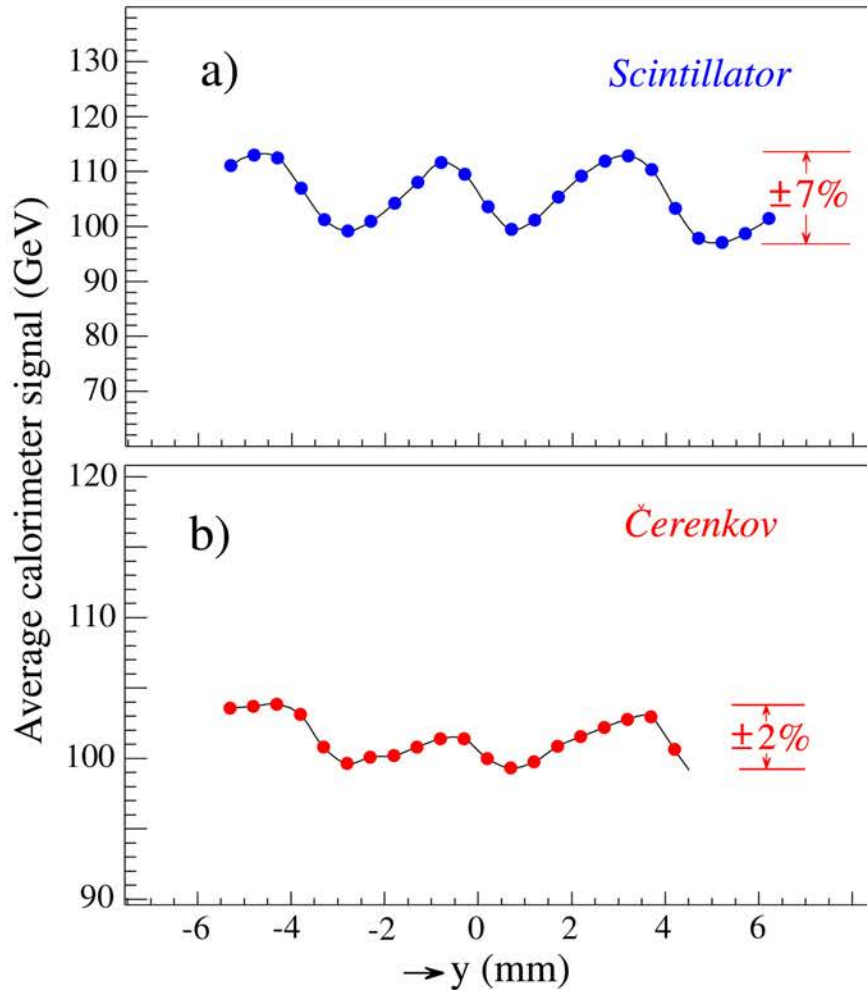
Horizontal scan with 1 mm wide beam

Lateral shower profile

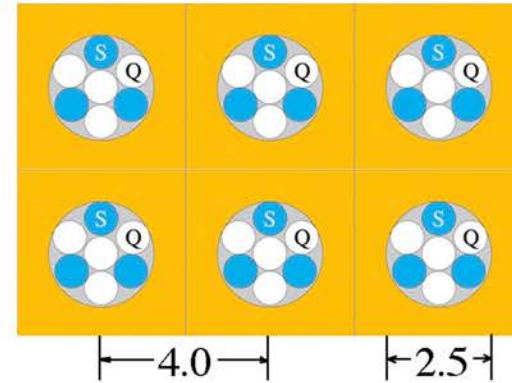


# Channeling effects in fiber calorimeters

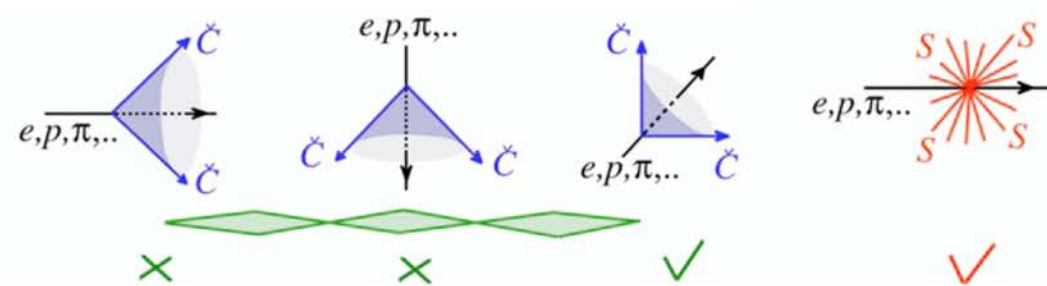
From NIM A536, 29



## DREAM



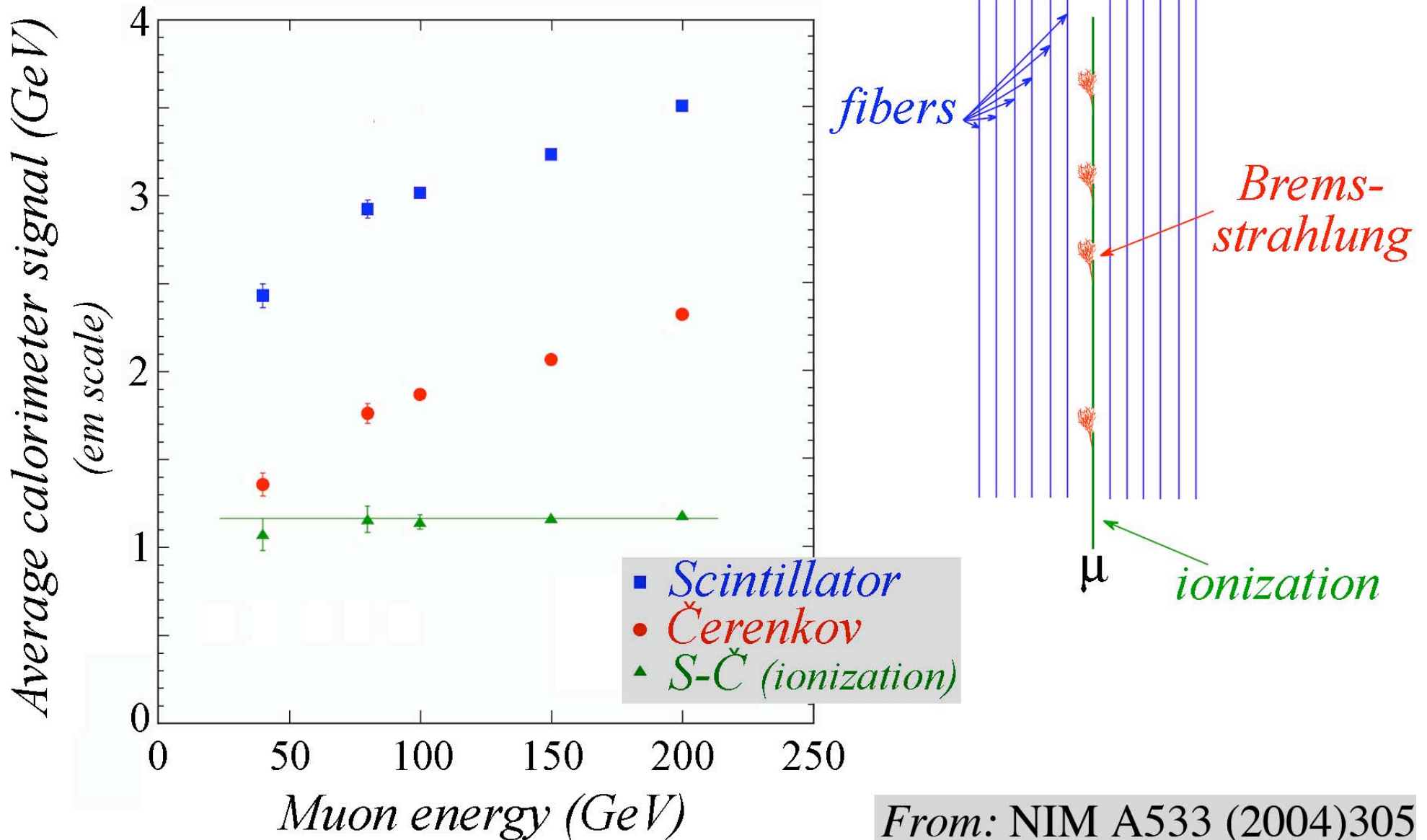
- *Optical fibers* only trap light emitted within the *numerical aperture*  
 $\theta_{\text{crit}} \sim 20^\circ$  for quartz fibers
- Comparison of *Čerenkov* light (directional) and *scintillation* light (isotropic) produced in fiber calorimeters



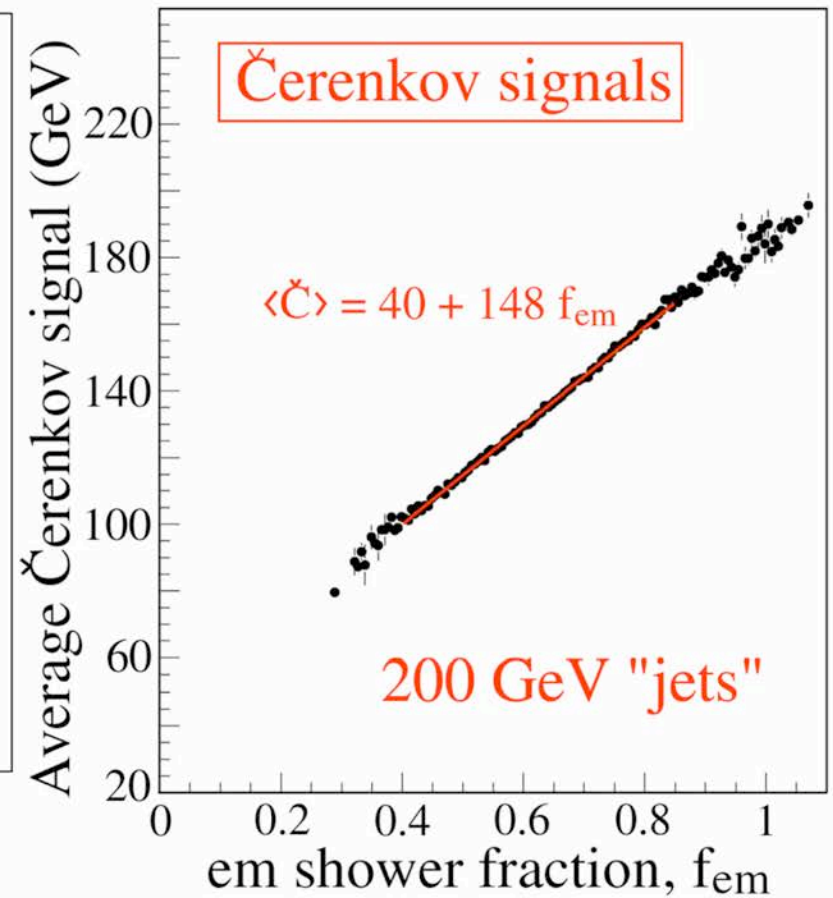
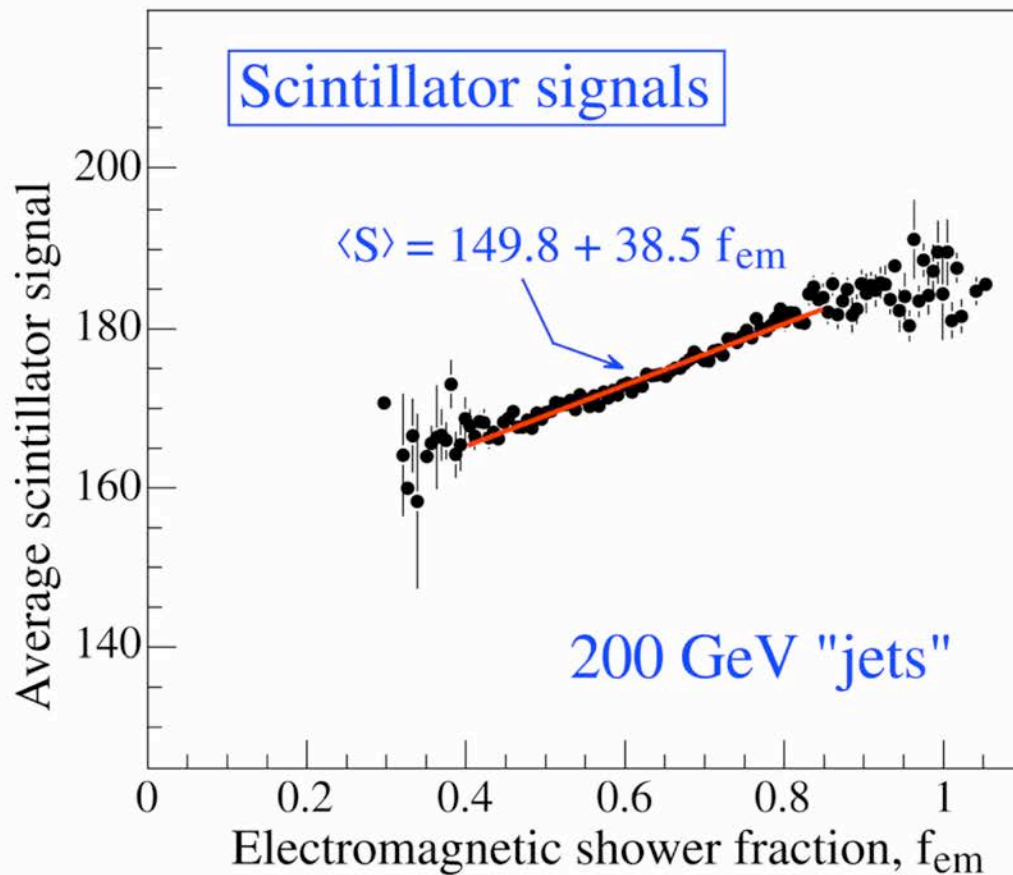
*The early, highly collimated em shower component leads to a position dependent response*  
*This component does NOT contribute to the Čerenkov calorimeter signals!*

# Calorimetric separation of ionization / radiation losses

## Muon signals in the DREAM calorimeter



# DREAM: Signal dependence on $f_{em}$



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

with

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

Cu/scintillator  $e/h = 1.3$

Cu/quartz  $e/h = 4.7$

From:

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*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  $f_{em}$ )*

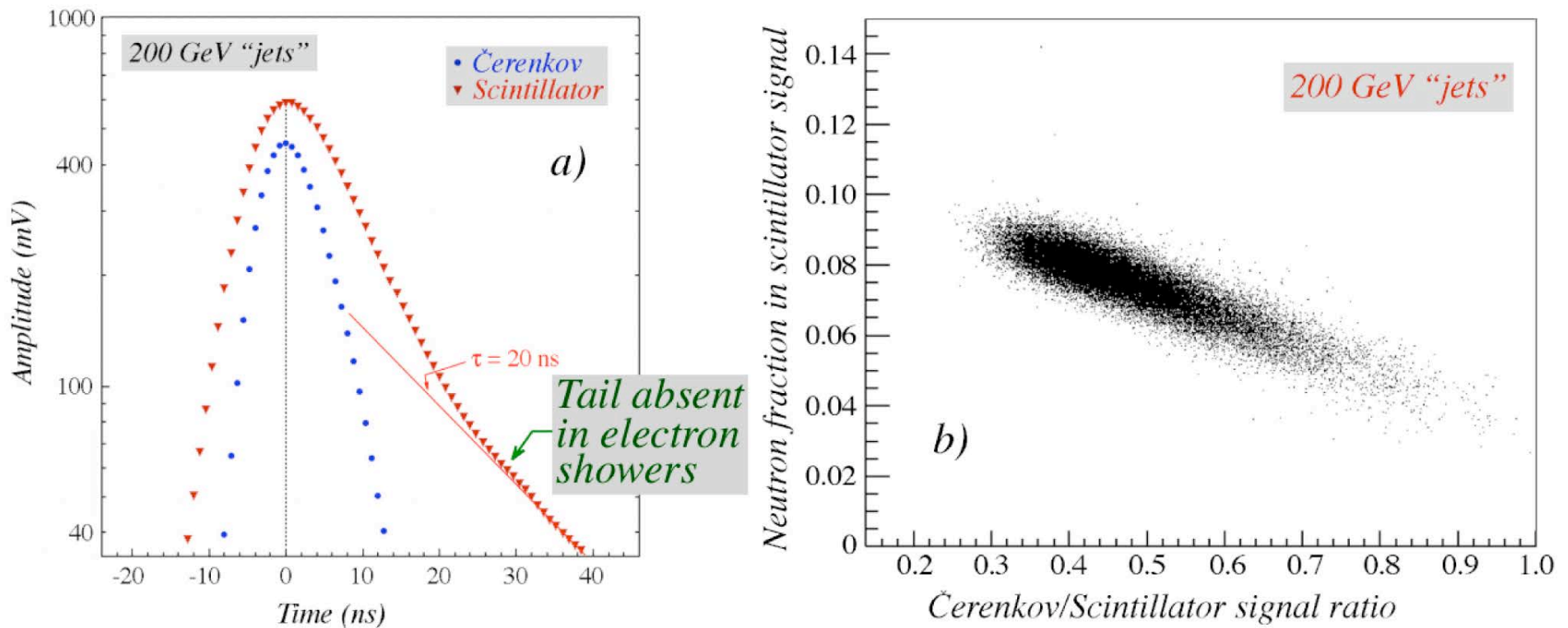
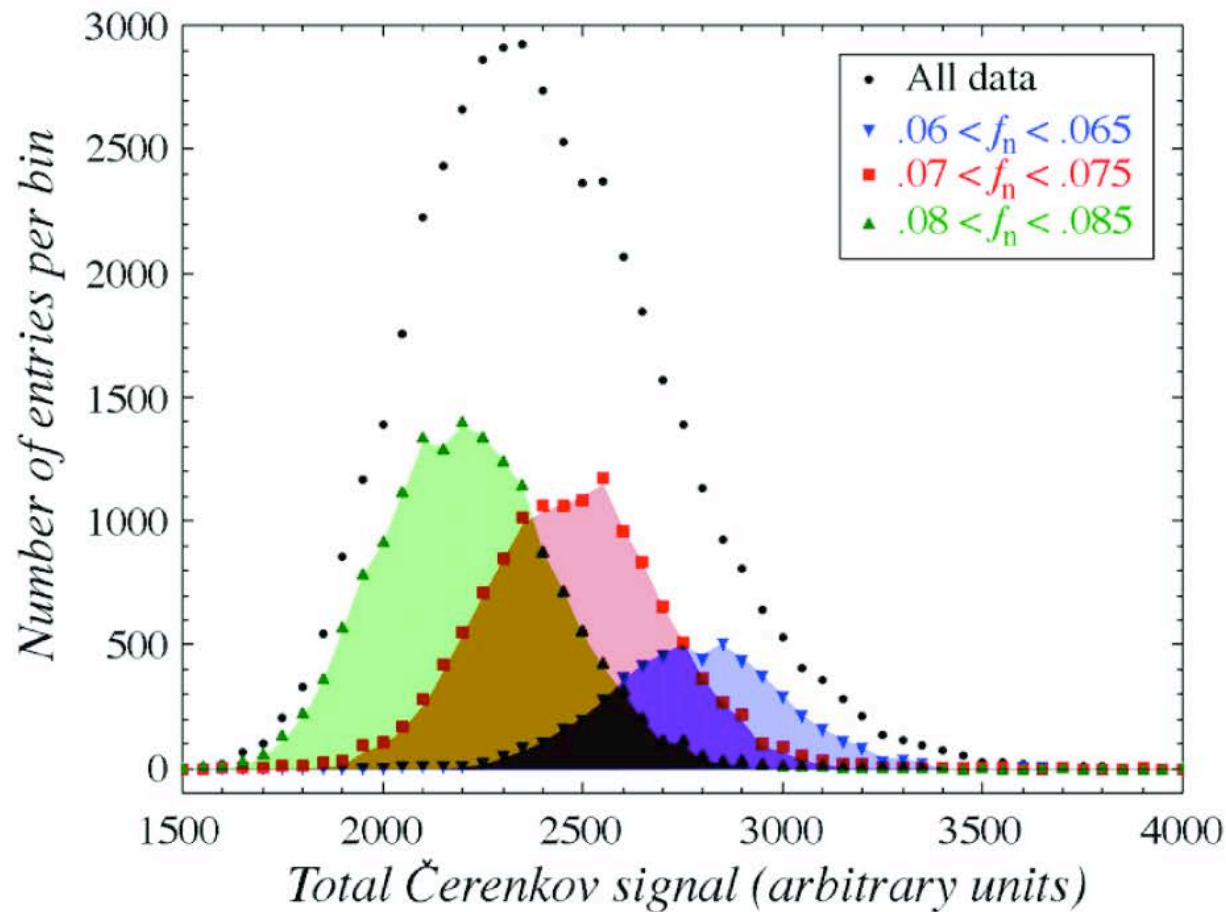


Figure 4: The average time structure of the Čerenkov and scintillation signals recorded for 200 GeV “jets” in the fiber calorimeter (a). Scatter plot of the fraction of the scintillation light contained in the (20 ns) exponential tail versus the Čerenkov/scintillation signal ratio measured in these events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

# 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.



# 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!!*