The Dual-Readout approach to hadron calorimetry

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Outline:

- (Limitations of) calorimeter measurements in particle physics
- Dual-readout calorimetry
- Recent R&D results
- Future plans
- Conclusions

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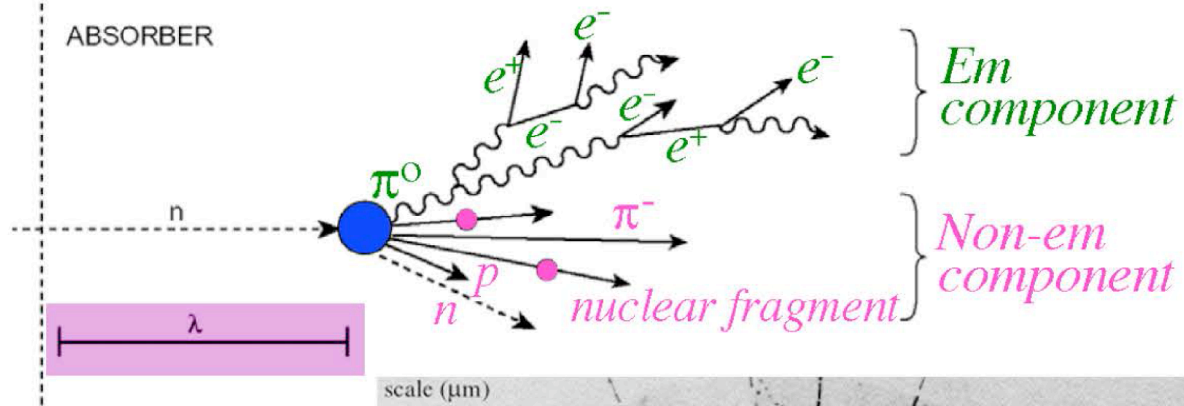
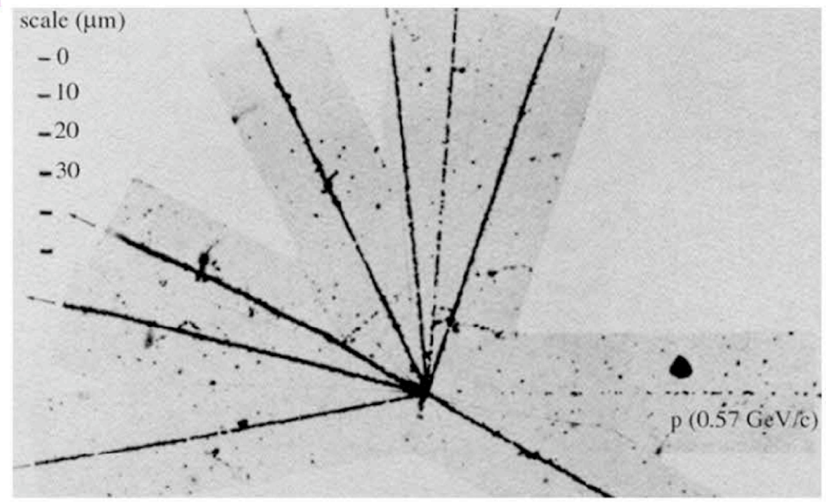
* *DREAM (RD52) Collaboration:*
Cagliari, Cosenza, Pavia, Pisa, Roma, Iowa State, TTU, Lisbon

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:*
  - *Calorimeter response functions for em/non-em shower components are very different ($e/h \neq 1$)*
  - *Large, non-Gaussian fluctuations in energy sharing em/non-em*
  - *Large, non-Gaussian fluctuations in "invisible" energy losses*

An attractive option for improving the quality of hadron calorimetry:

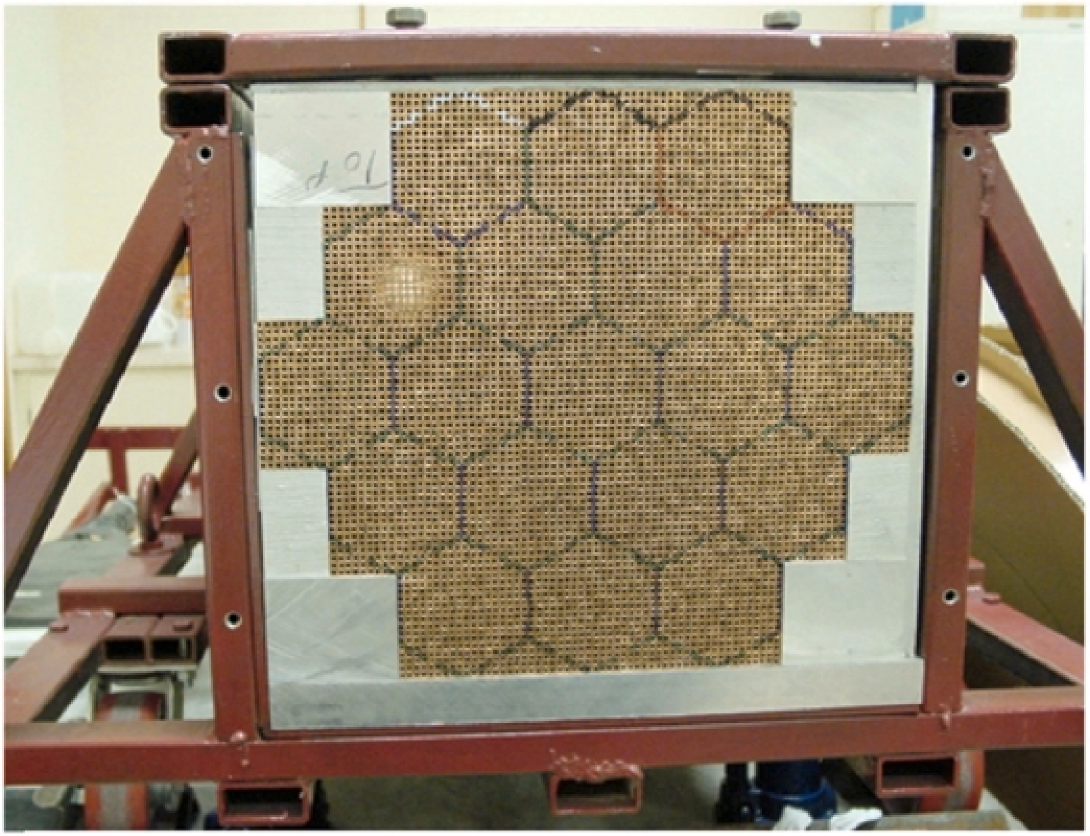
Use Čerenkov light!! *Why?*

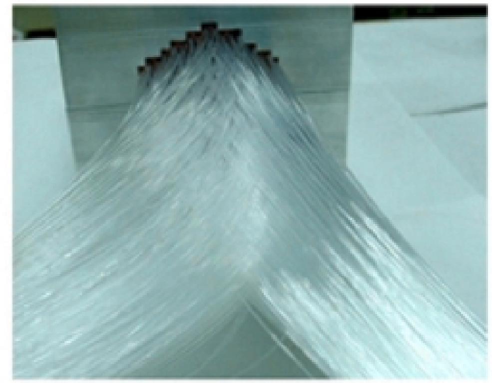
Čerenkov light almost exclusively produced by em shower component (~80% of non-em energy deposited by non-relativistic particles)

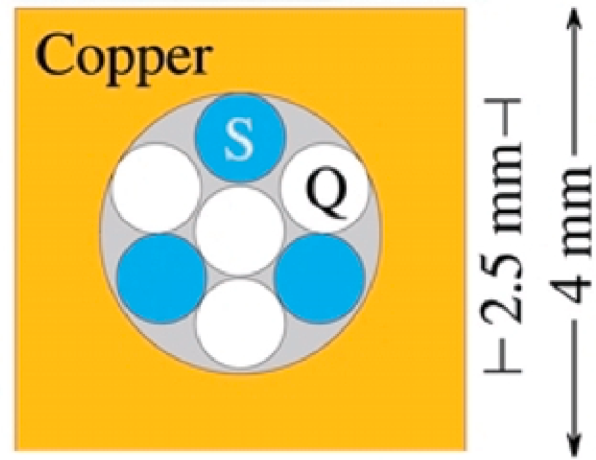
➡ DREAM (Dual REAdout Method) principle:

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

DREAM: Structure

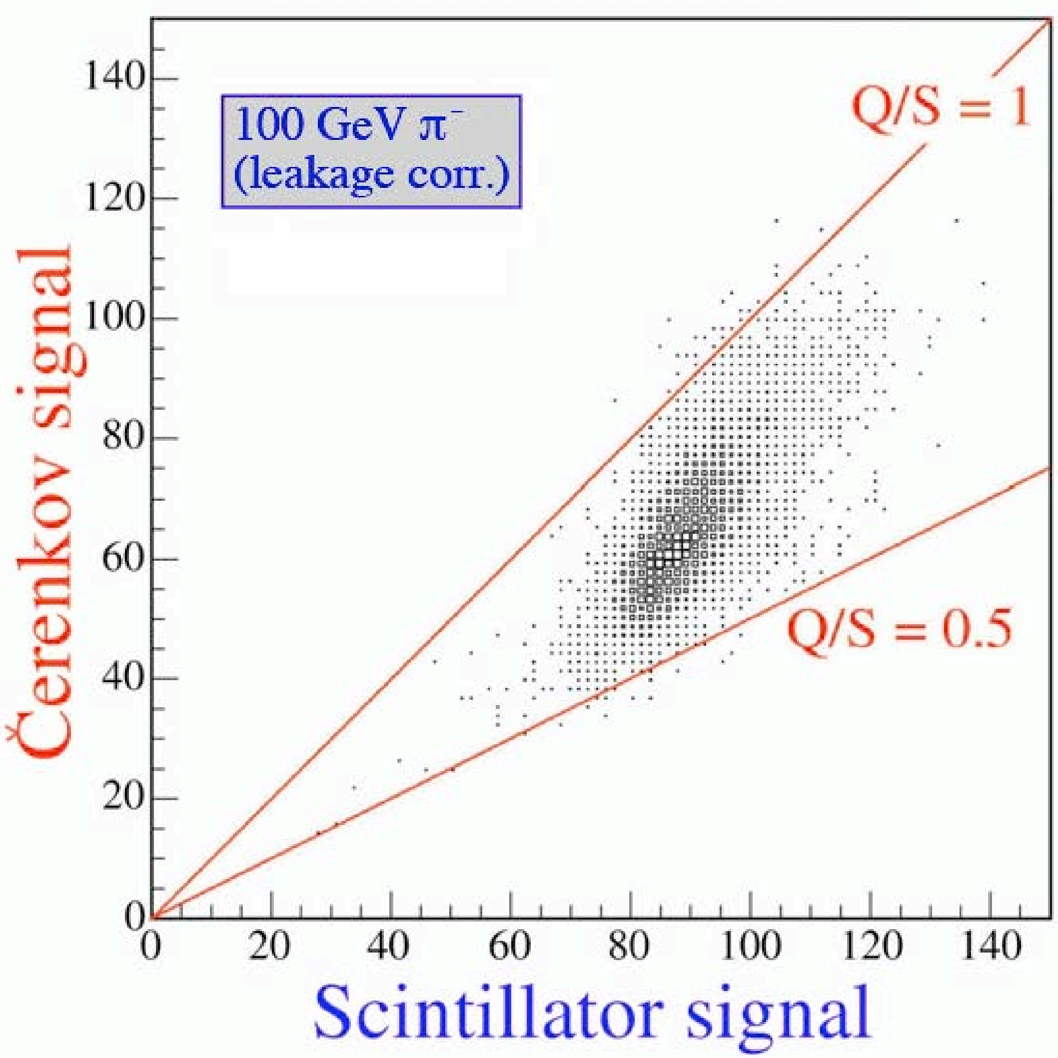






- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 $\lambda_{\rm int}$)
  - Effective radius 16.2 cm (0.81 $\lambda_{\rm int}$, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read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

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



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

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

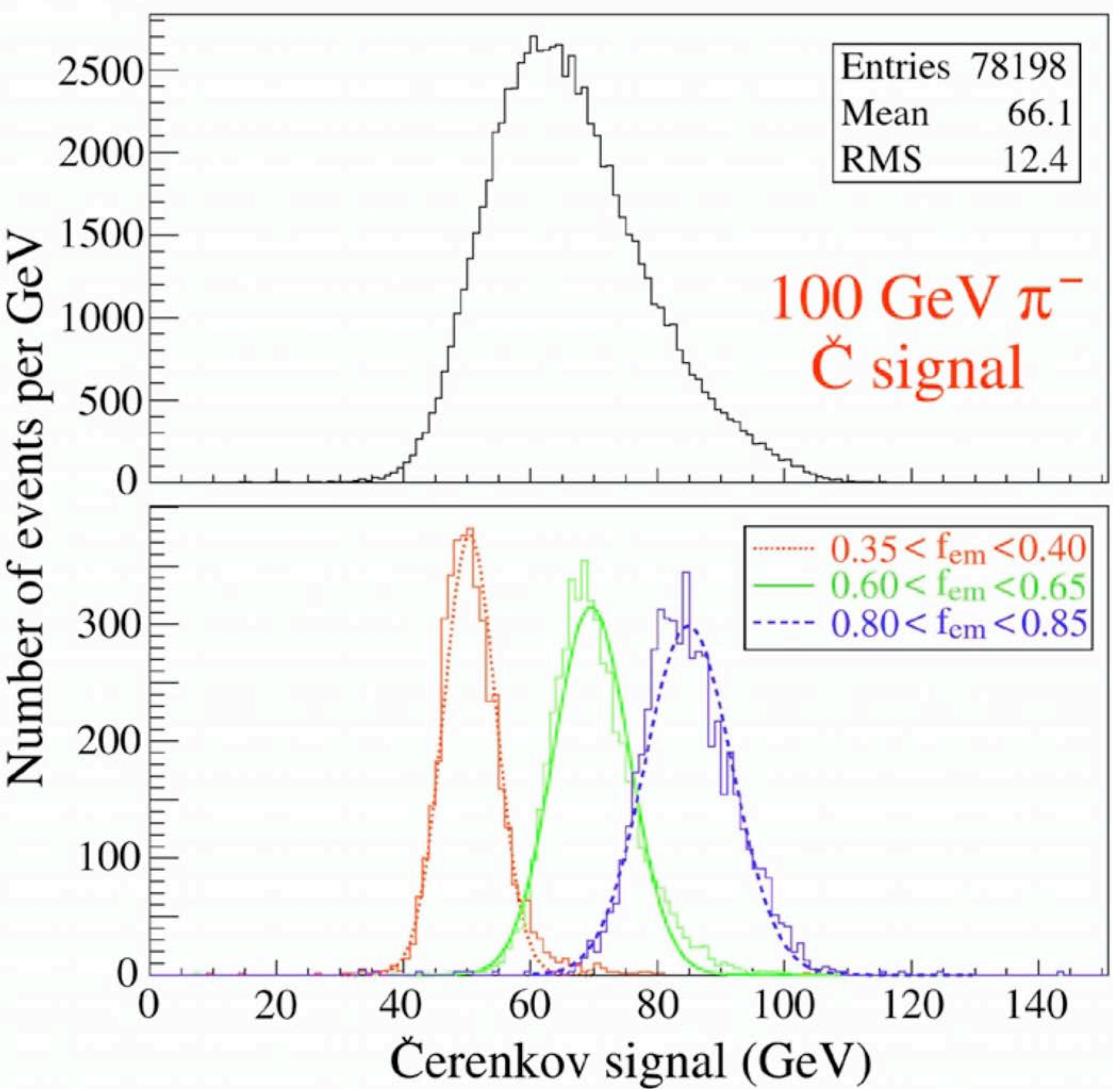
e.g. If $e/h = 1.3$ (S), 4.7 (Q)

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

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

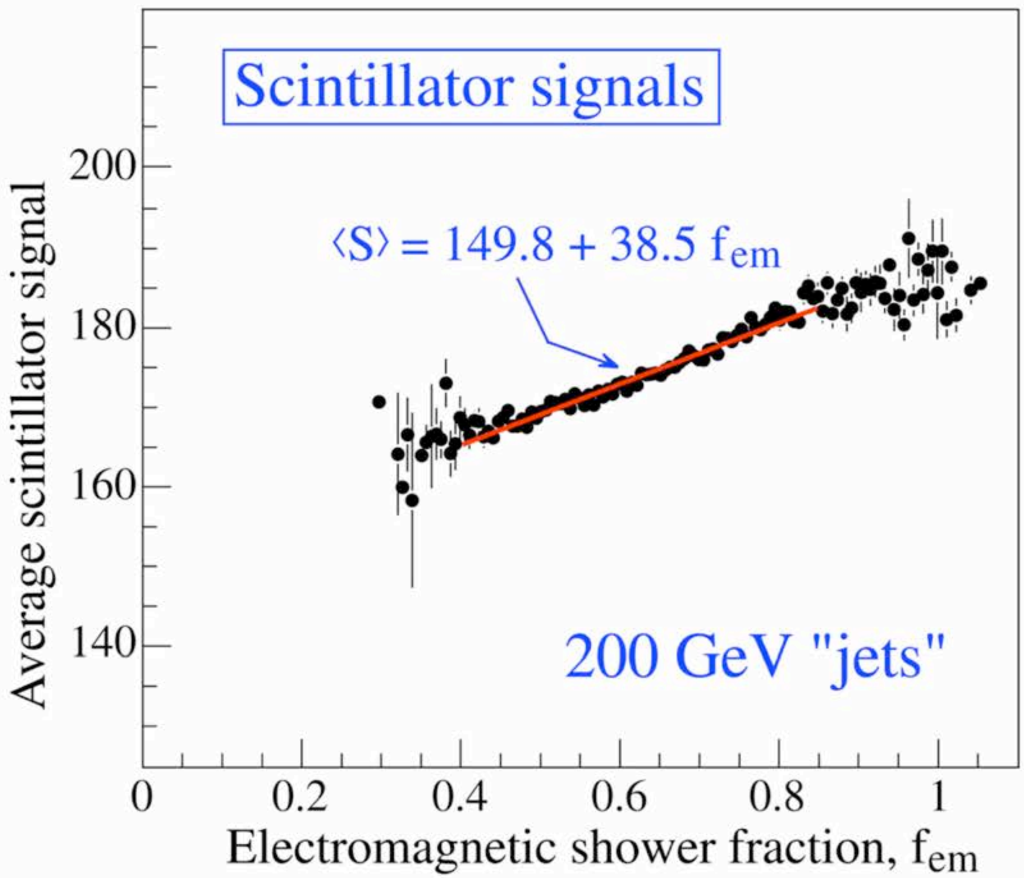
with $\chi = \frac{1 - (h/e)_S}{1 - (h/e)_Q} \sim 0.3$

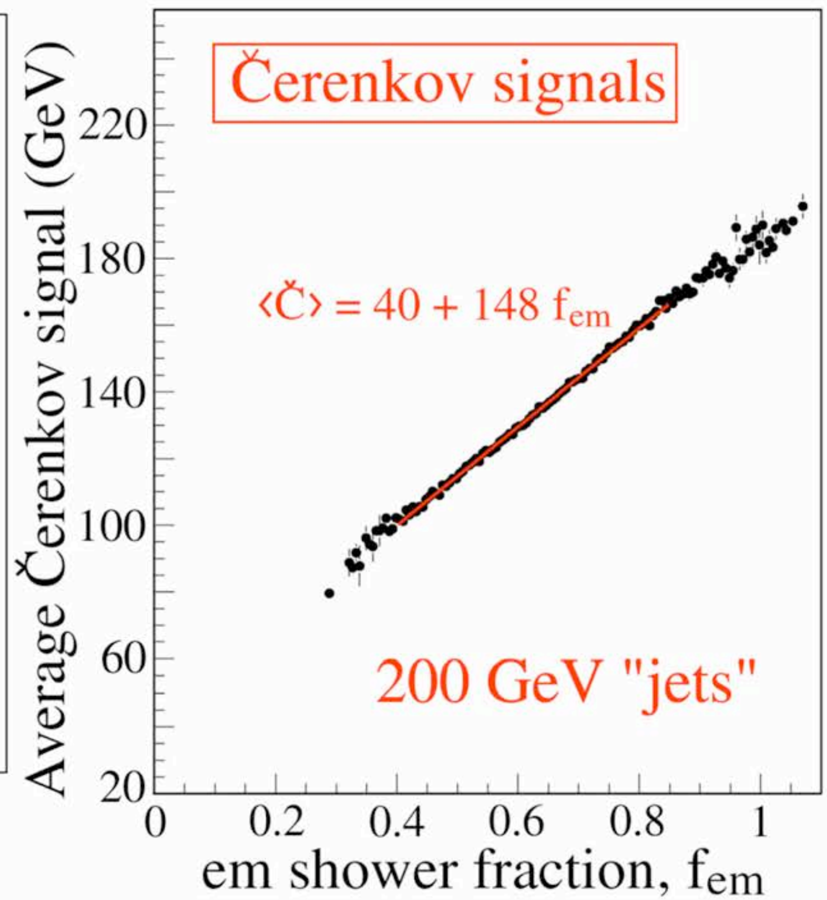
DREAM: Effect of event selection based on f_{em}



From:
NIM A537 (2005) 537

DREAM: Signal dependence on f_{em}





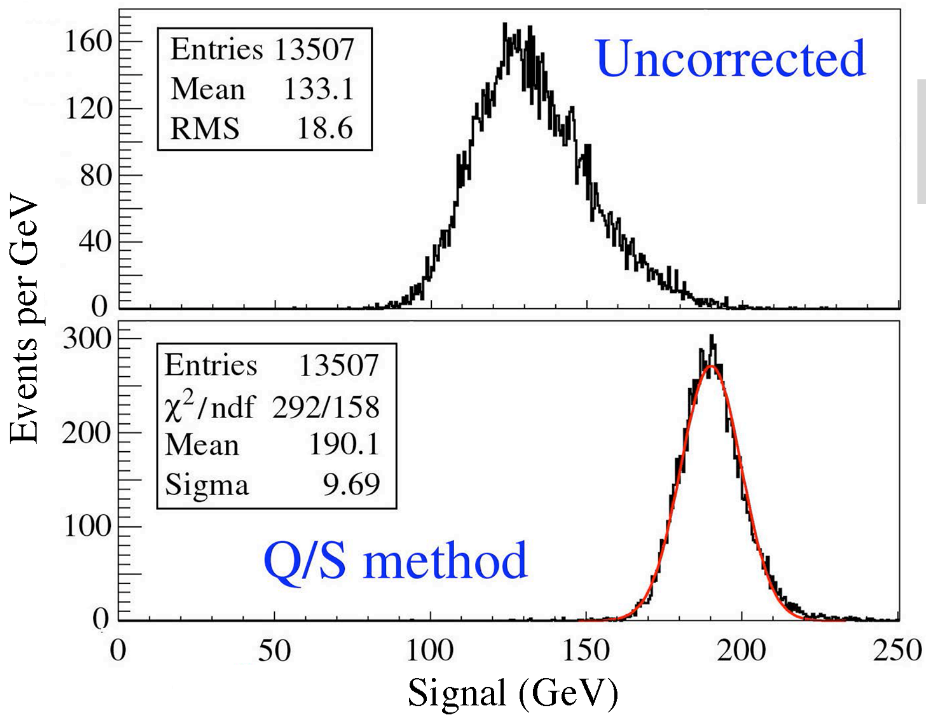
$$R(f_{\rm em}) = p_0 + p_1 \, f_{\rm em}$$ with $$\frac{p_1}{p_0} = e/h - 1$$

Cu/scintillator   e/h = 1.3

Cu/quartz   e/h = 4.7

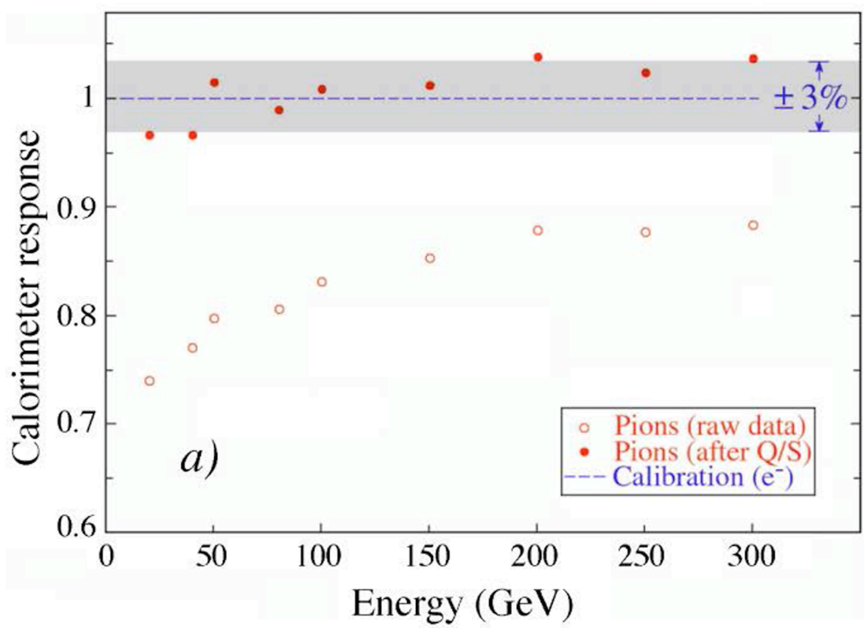
From:
NIM A537 (2005) 537

Effects of Q/S corrections on

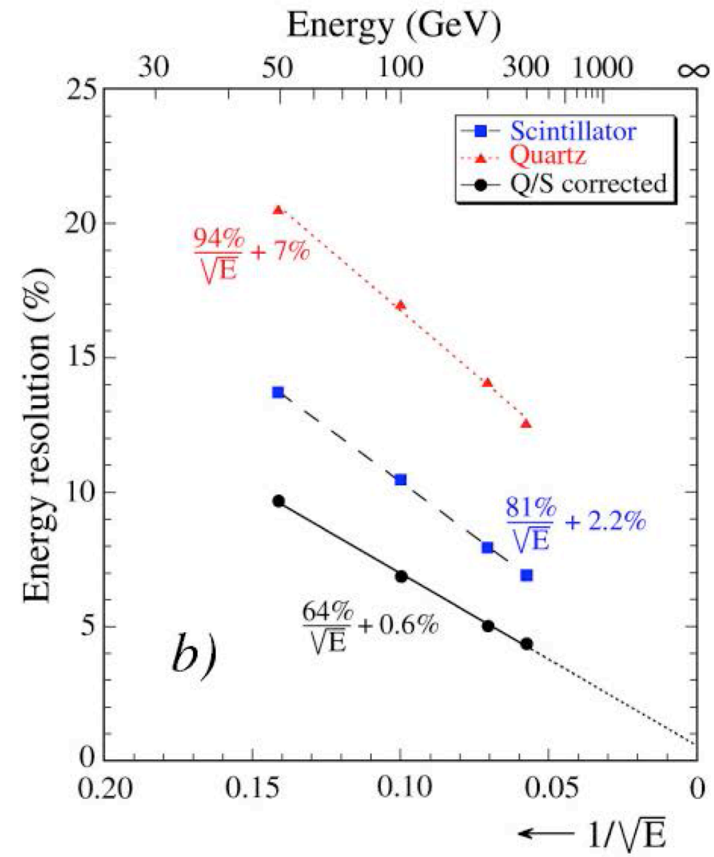


Calorimeter response function

hadronic signal linearity



jet energy resolution



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*

- *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

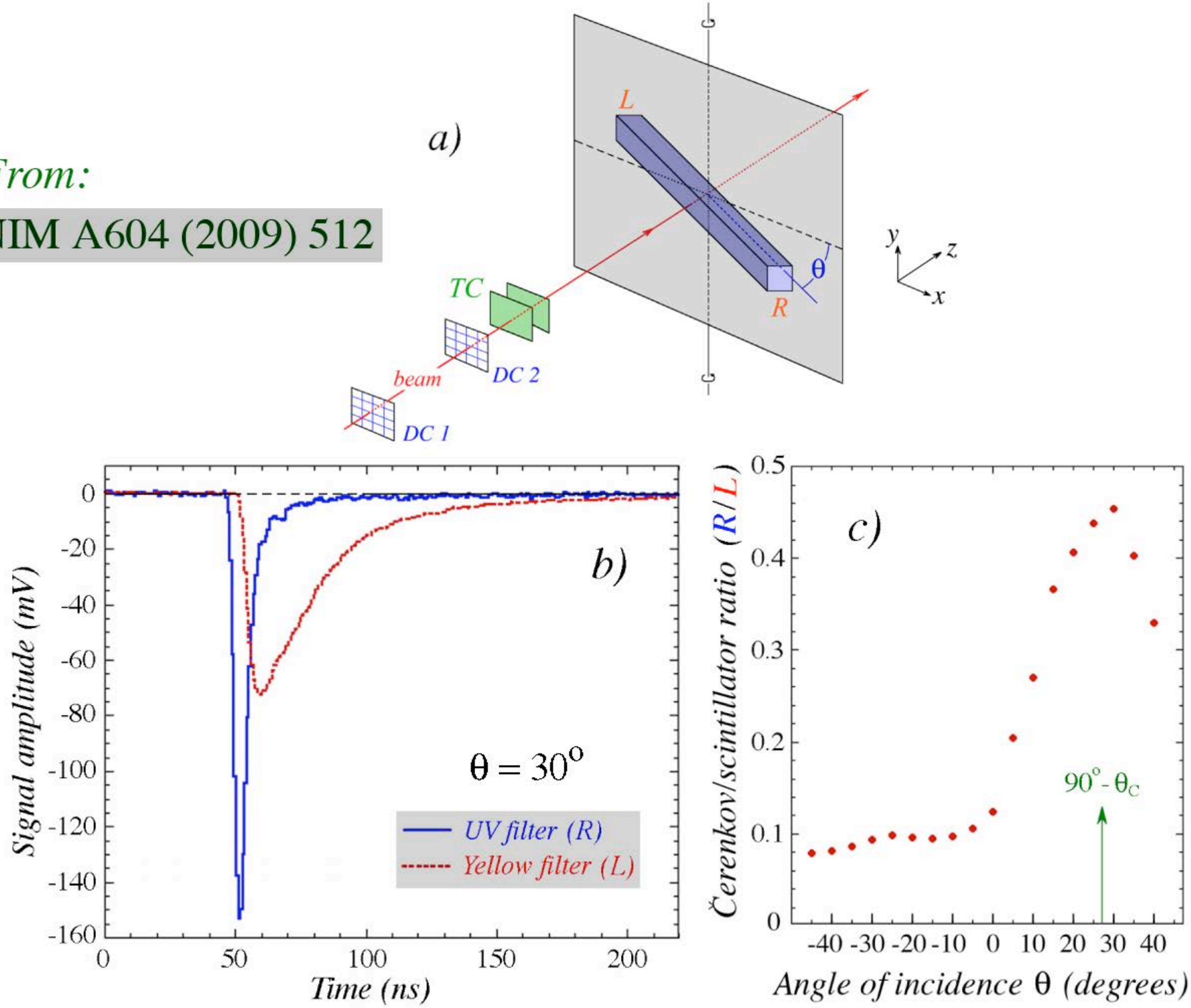


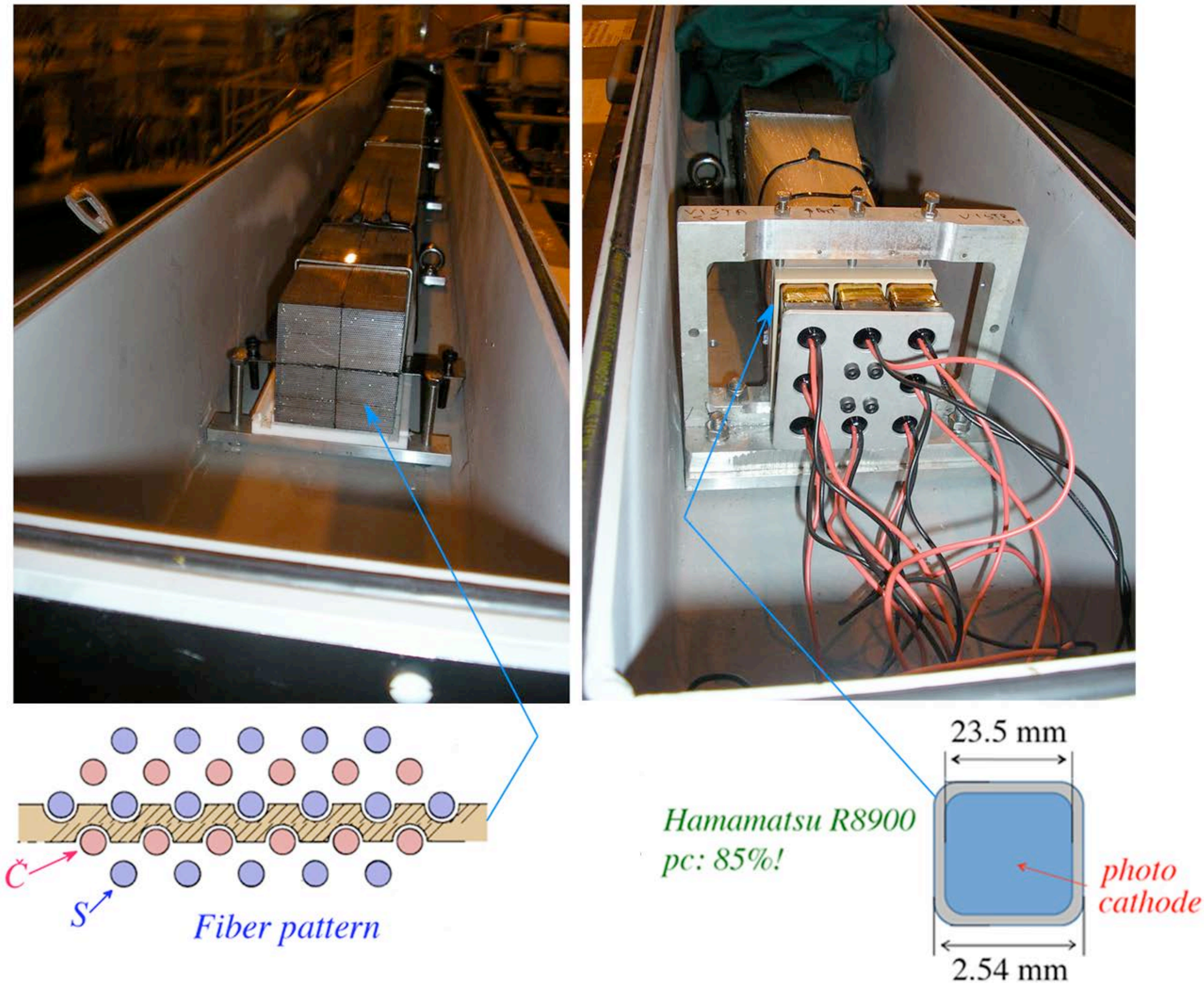
Figure 3: Unraveling of the signals from a Mo-doped $PbWO_4$ crystal into Čerenkov and scintillation components. The experimental setup is shown in diagram a. The two sides of the crystal were equipped with a UV filter (side R) and a yellow filter (side L), respectively. The signals from 50 GeV electrons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

The follow-up: RD52

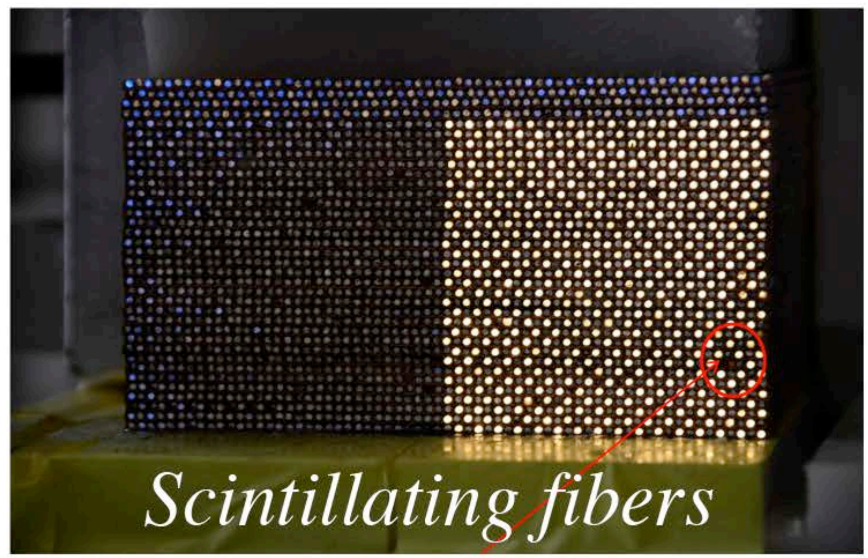
- Concentrate on fiber calorimetry
  - *Shower containment >99%, i.e. mass ~ 5 tonnes*
    → *effects of leakage fluctuations negligible*
  - *Preferably copper absorber*

- 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*

The first SuperDREAM module at H8

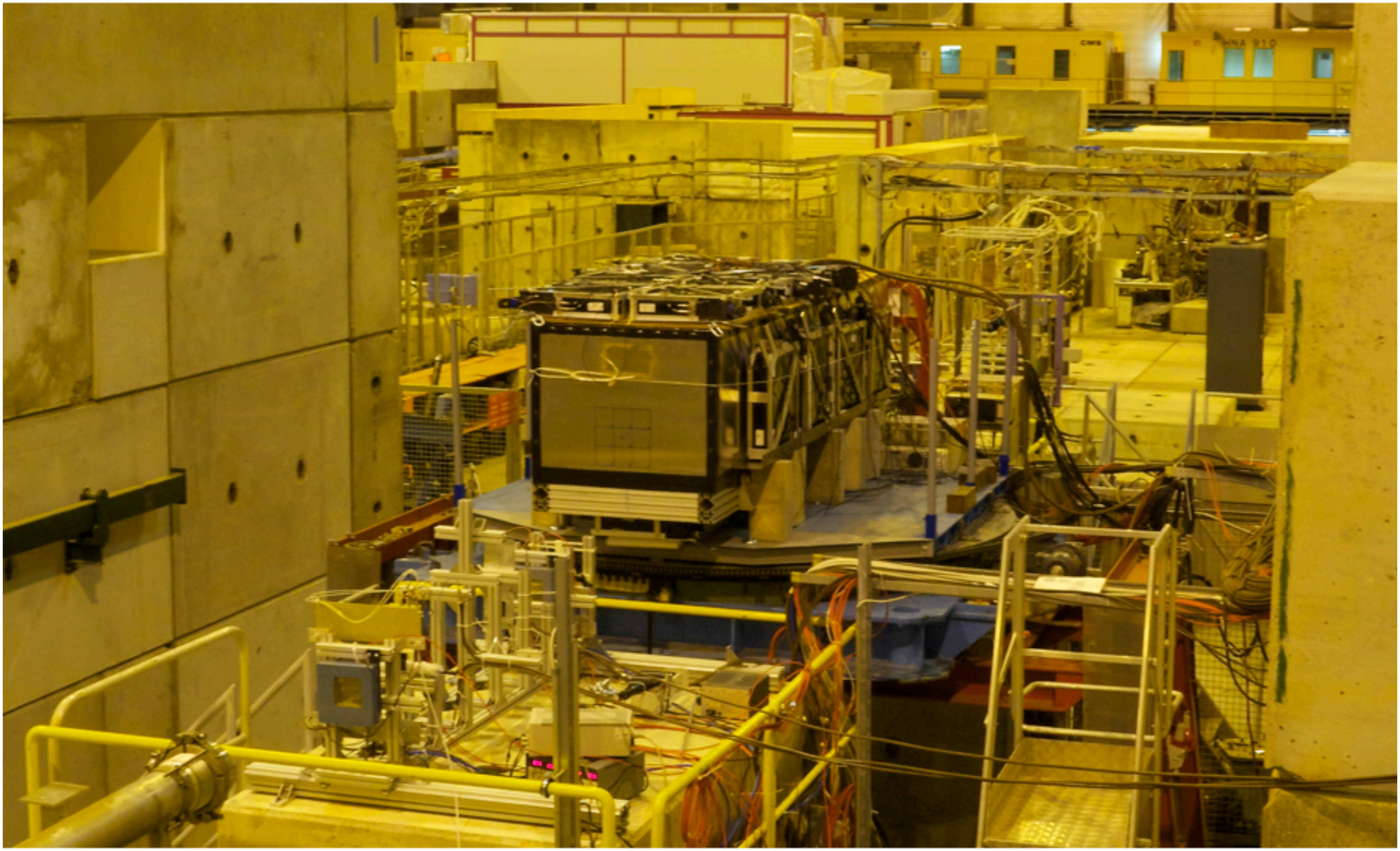


The first copper module



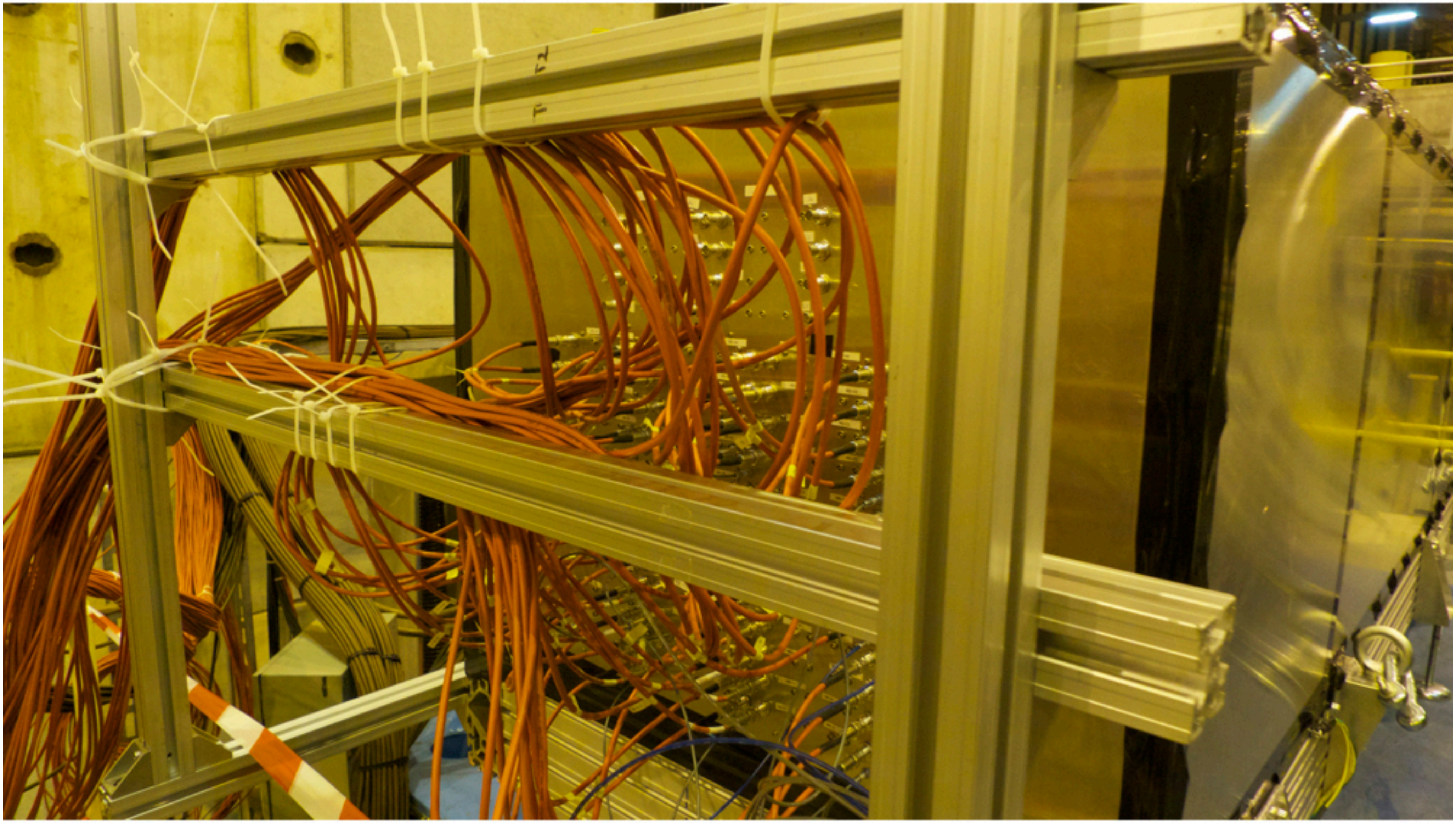
The new SuperDREAM fiber module tested at CERN

(December 2012)



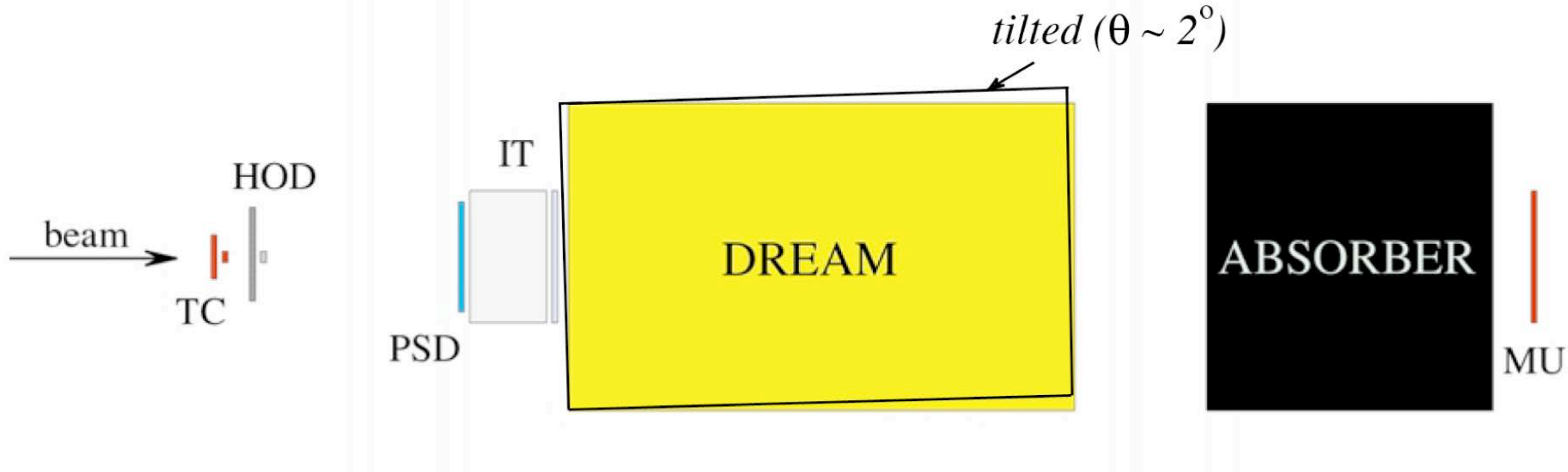
9 modules (36 towers, 72 signals), 1.4 tonnes Pb/fiber + 2 modules Cu/fiber
20 leakage modules (500 kg plastic scintillator)

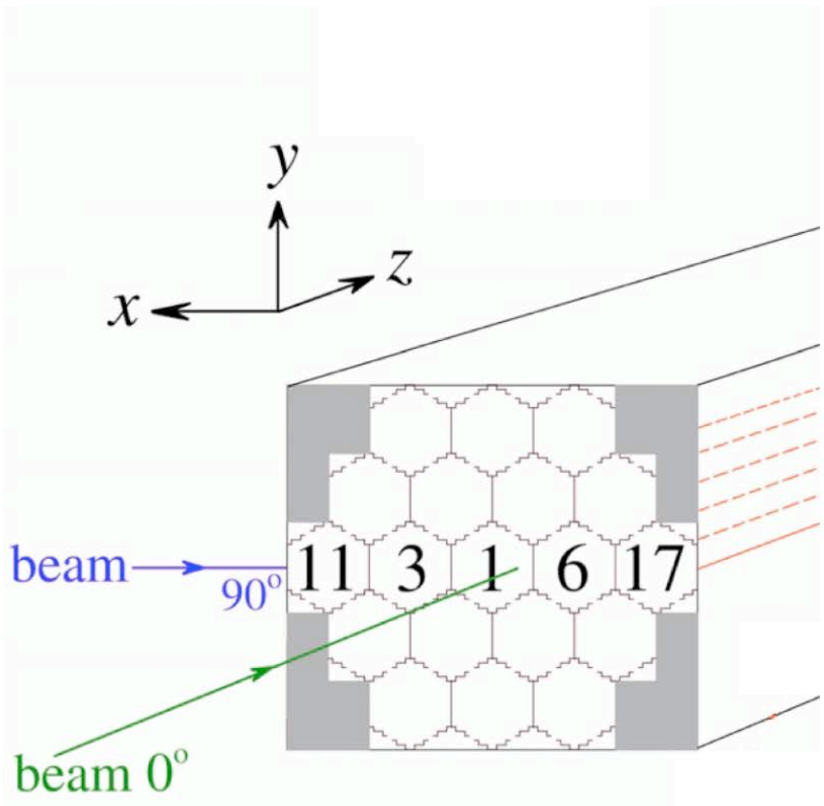
Rear side of the new SuperDREAM module



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*

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

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

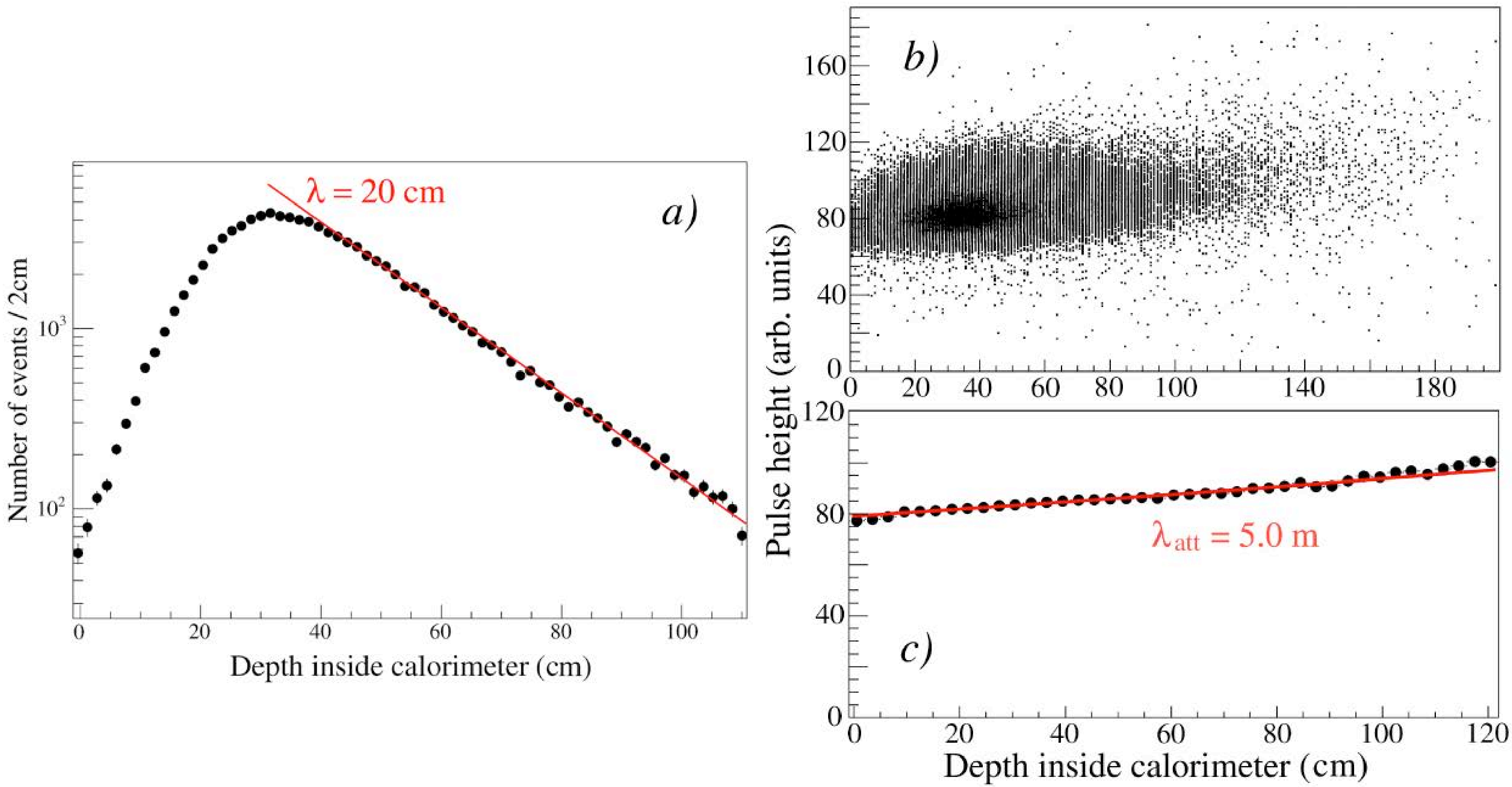


Figure 26: Distribution of the average depth at which the scintillation light is produced in the DREAM calorimeter by showering hadrons (a). Scatter plot showing the total scintillator signal versus the average depth of the light production (a) and the average size of the total scintillator signal as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

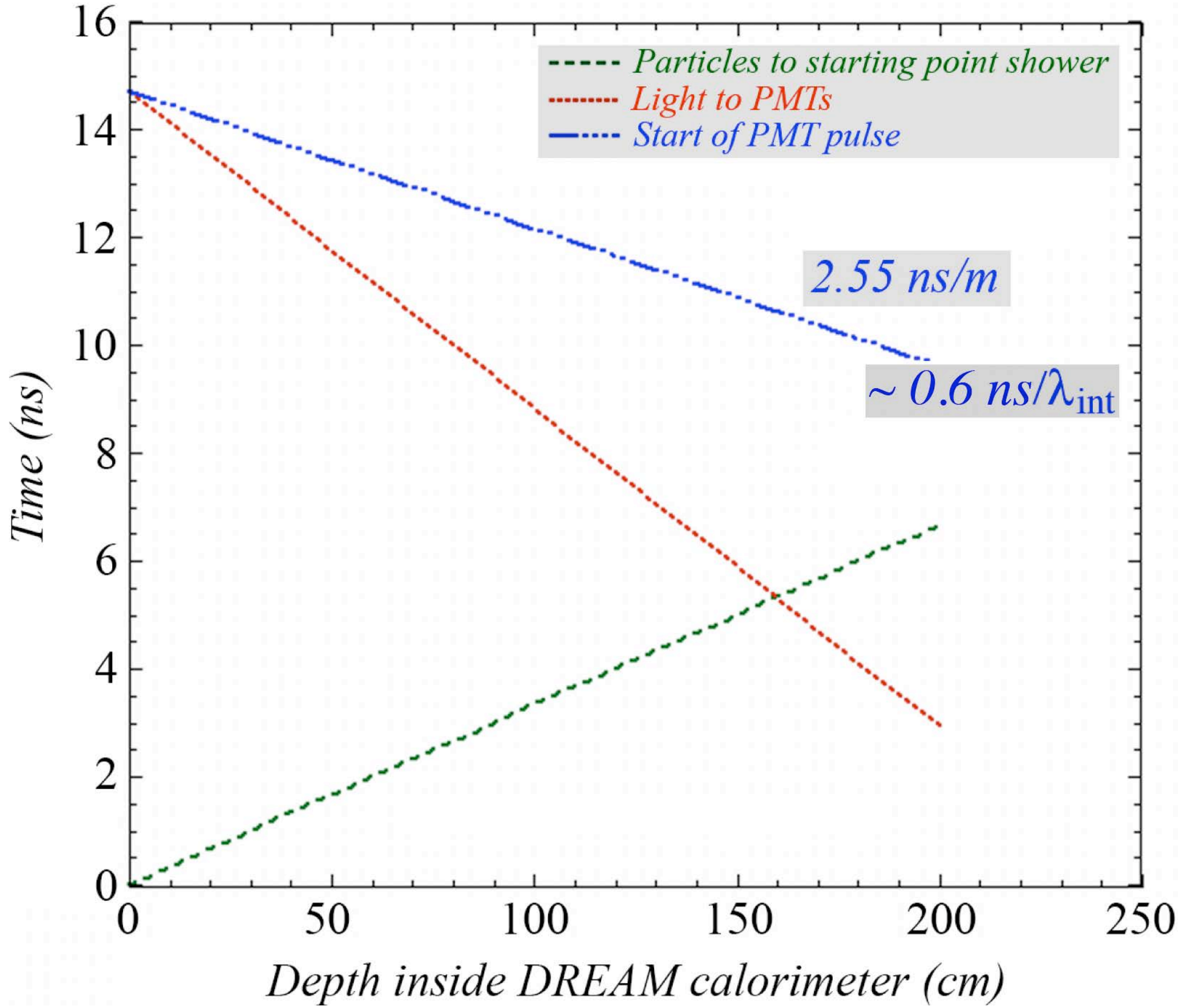
An alternative method to measure shower depth

Disadvantages of described method:

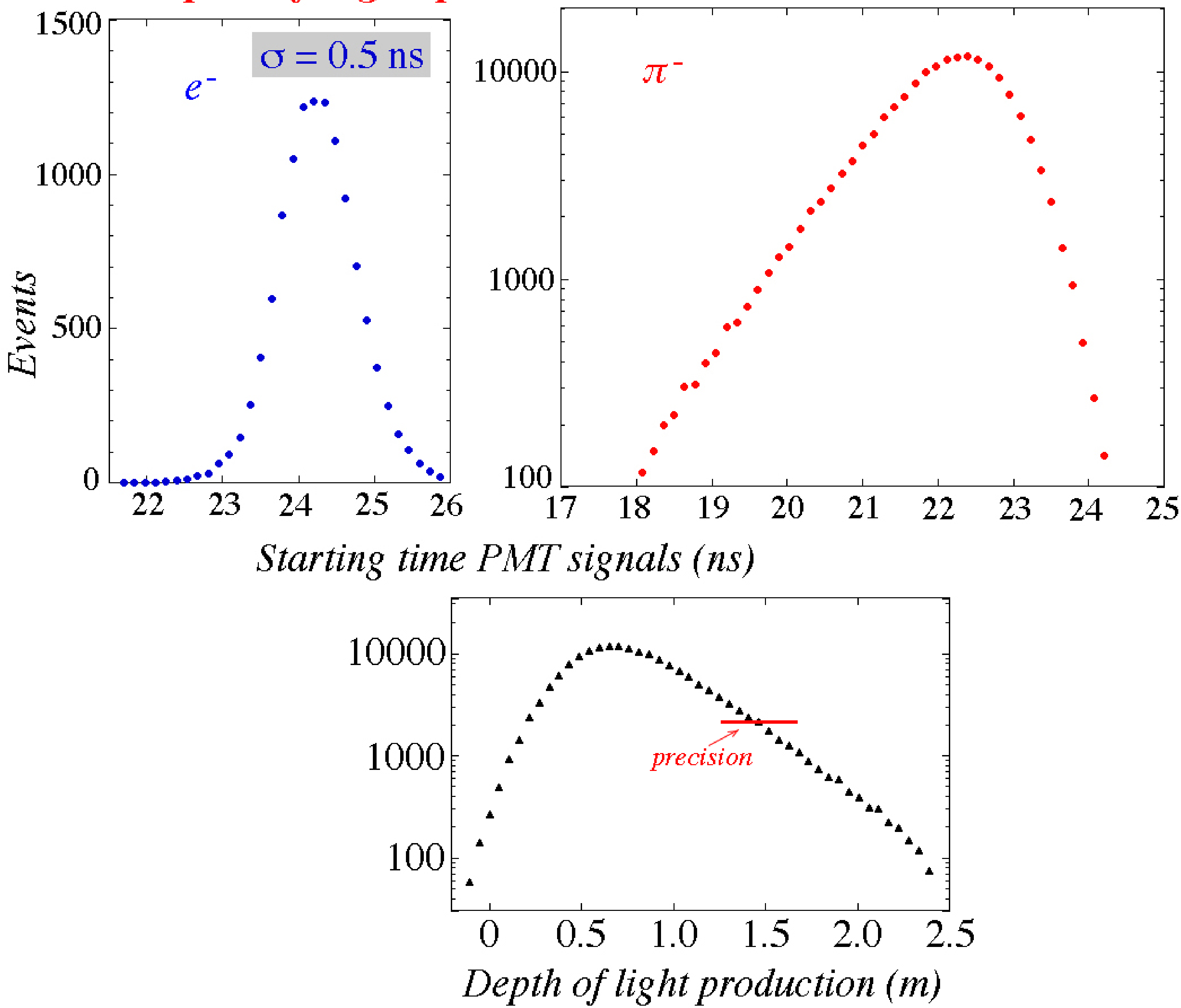
- *Does not work for neutral particles*
- *Does not work for jets*
- *Non-projective calorimeter impractical*

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

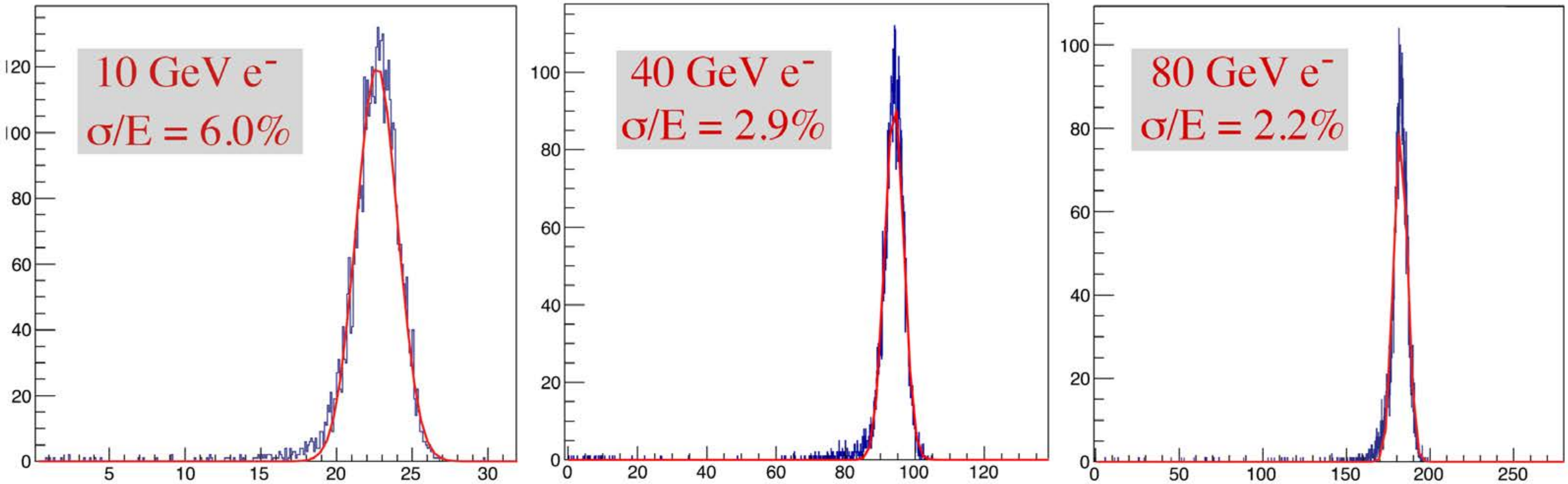
Depth of the light production and the starting point of the PMT signals



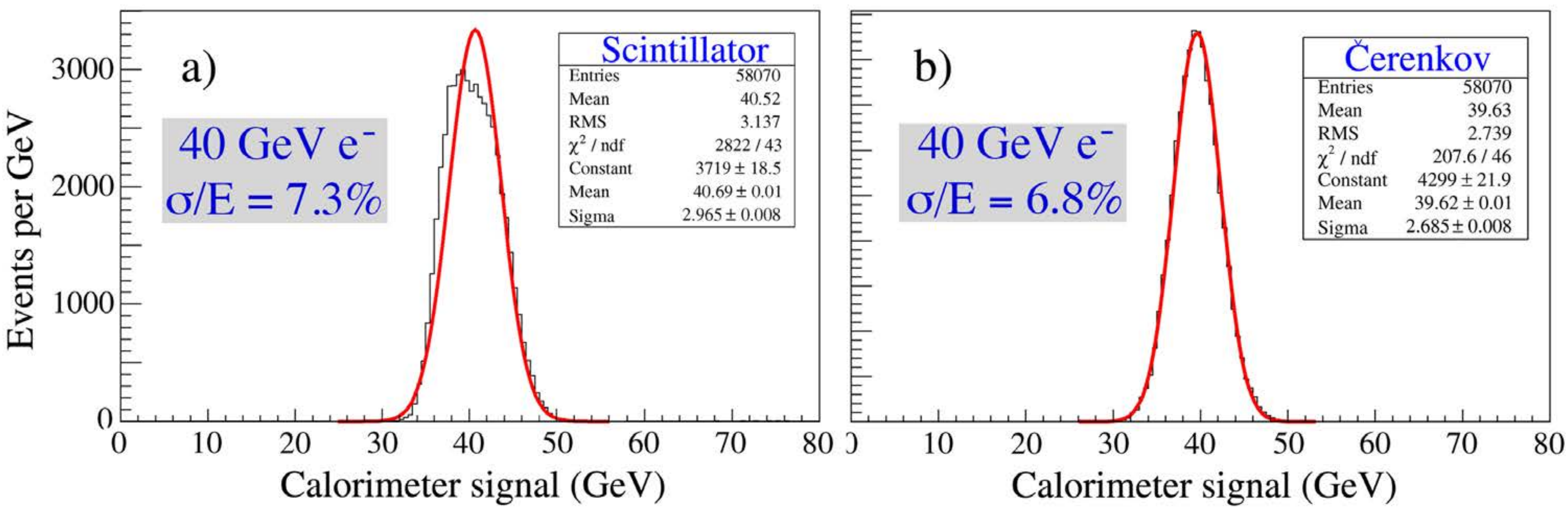
Depth of light production inside calorimeter

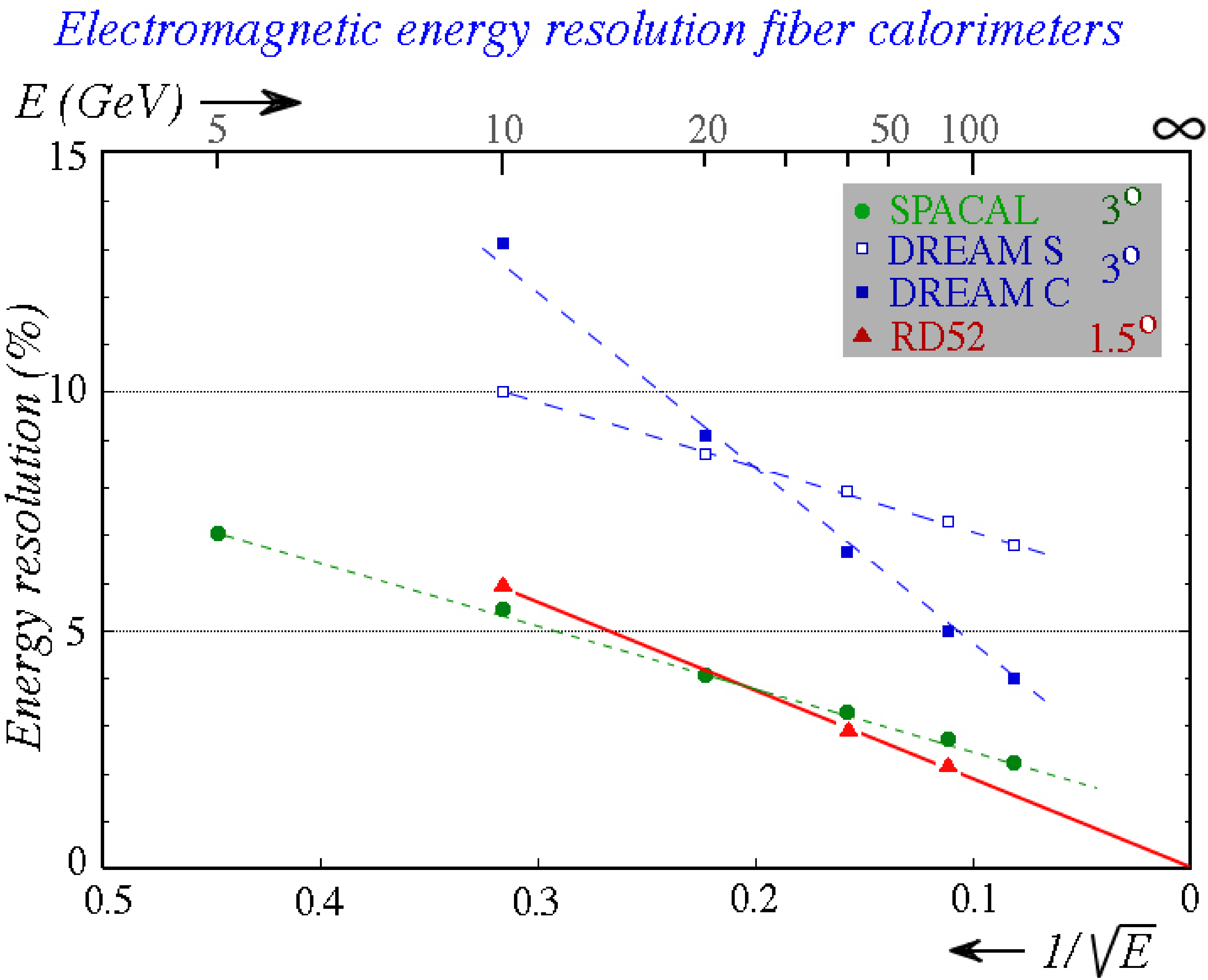


Electrons in new fiber calorimeter (on-line results, i.e. uncalibrated)



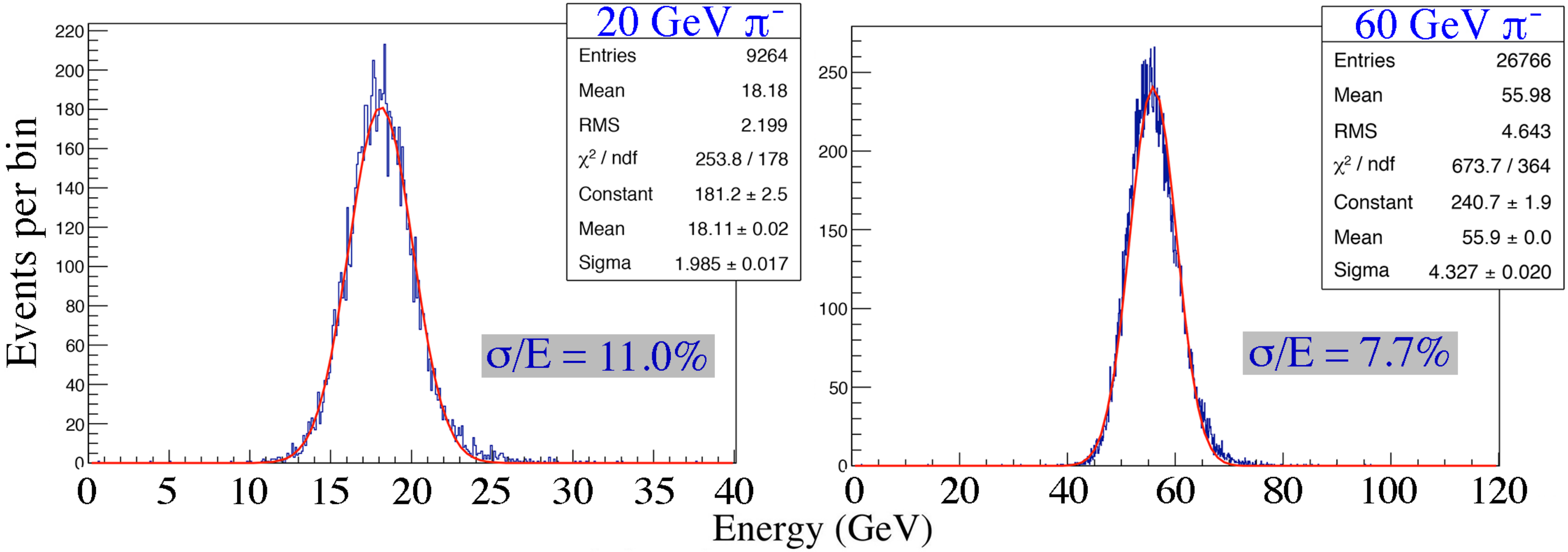
Compared with original DREAM results (NIM A536, 29)





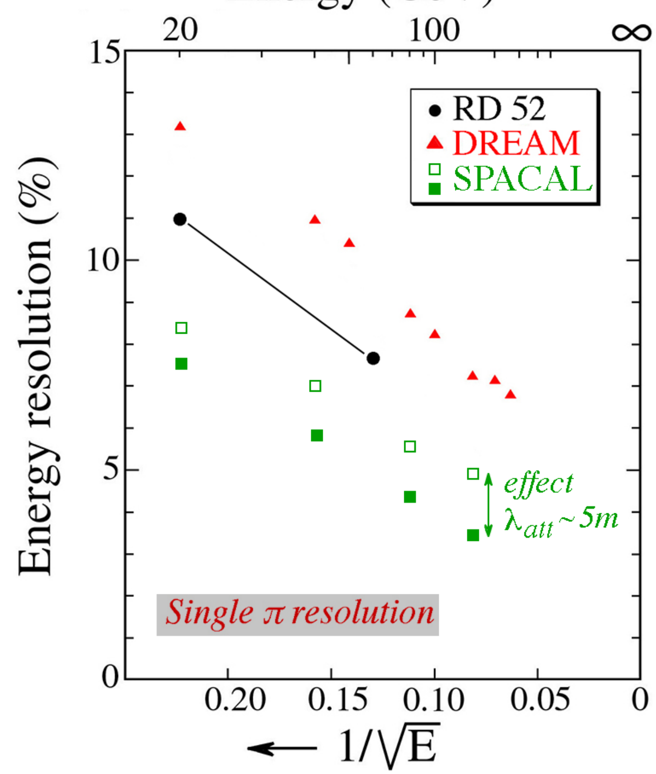
Electromagnetic energy resolution fiber calorimeters
E (GeV)
5
10
20
50
100
∞
15
10
5
0
Energy resolution (%)
SPACAL 3°
DREAM S
DREAM C 3°
RD52 1.5°
0.5
0.4
0.3
0.2
0.1
0
1/√E

Single-pion energy resolution



RD52 results are PRELIMINARY !

No corrections yet for effects light attenuation, shower leakage, etc.



DREAM data published in NIM A537 (2005) 537

SPACAL data published in NIM A308 (1991) 481

Future research plans

Study issues related to implementing DREAM calorimeters in practice

- *Readout: Get rid of rear fiber forests (SiPM)*
- *Shorter effective interaction length (W?)*
- *Projective geometry*

Conclusions (R&D)

- The DREAM approach combines the advantages of compensating calorimetry with a reasonable amount of design flexibility

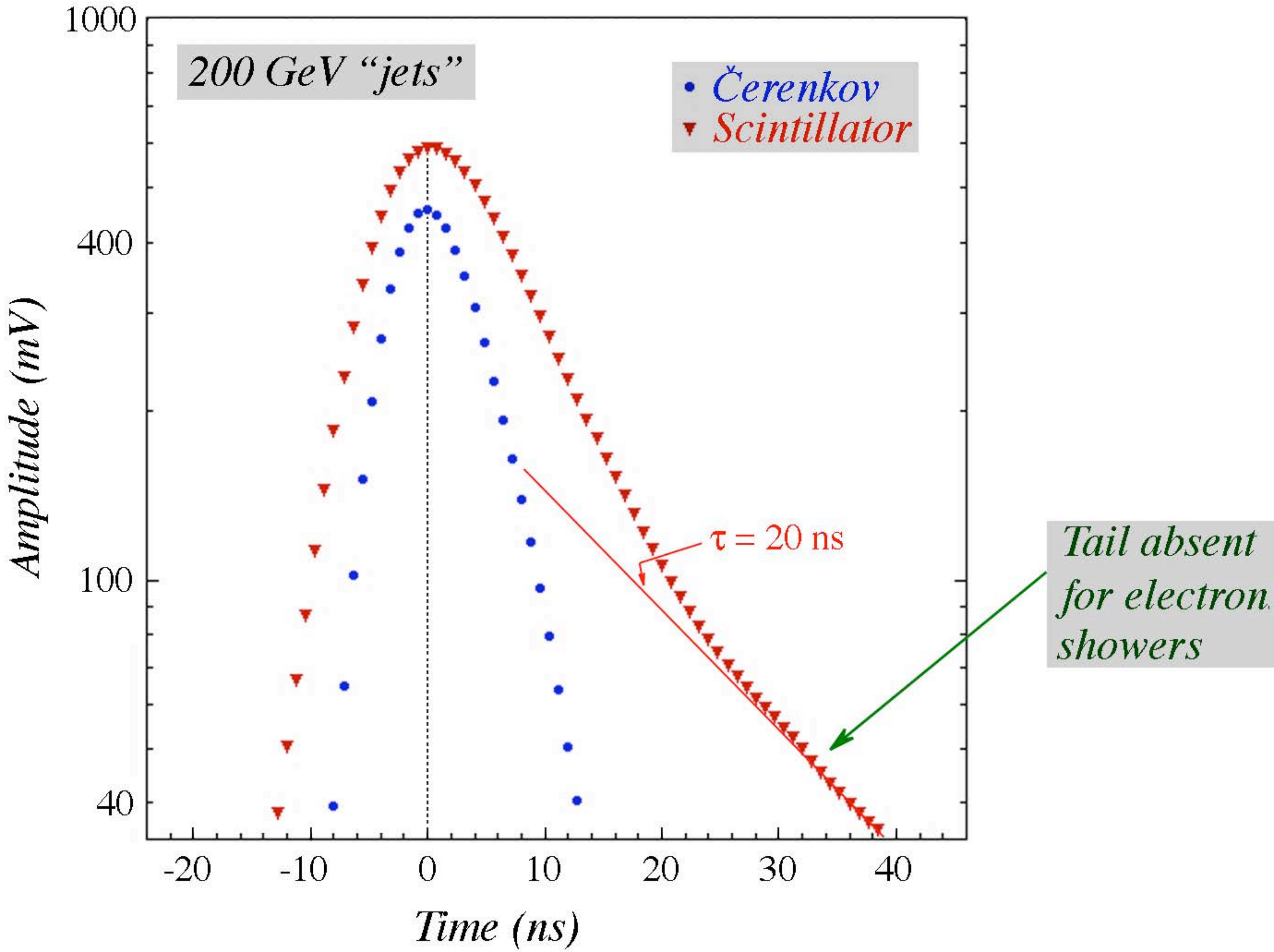
- The dominating factors that limited the hadronic resolution of compensating calorimeters (ZEUS, SPACAL) to 30 - 35%/$\sqrt{E}$ can be eliminated

- The theoretical resolution limit for hadron calorimeters (15%/$\sqrt{E}$) seems within reach

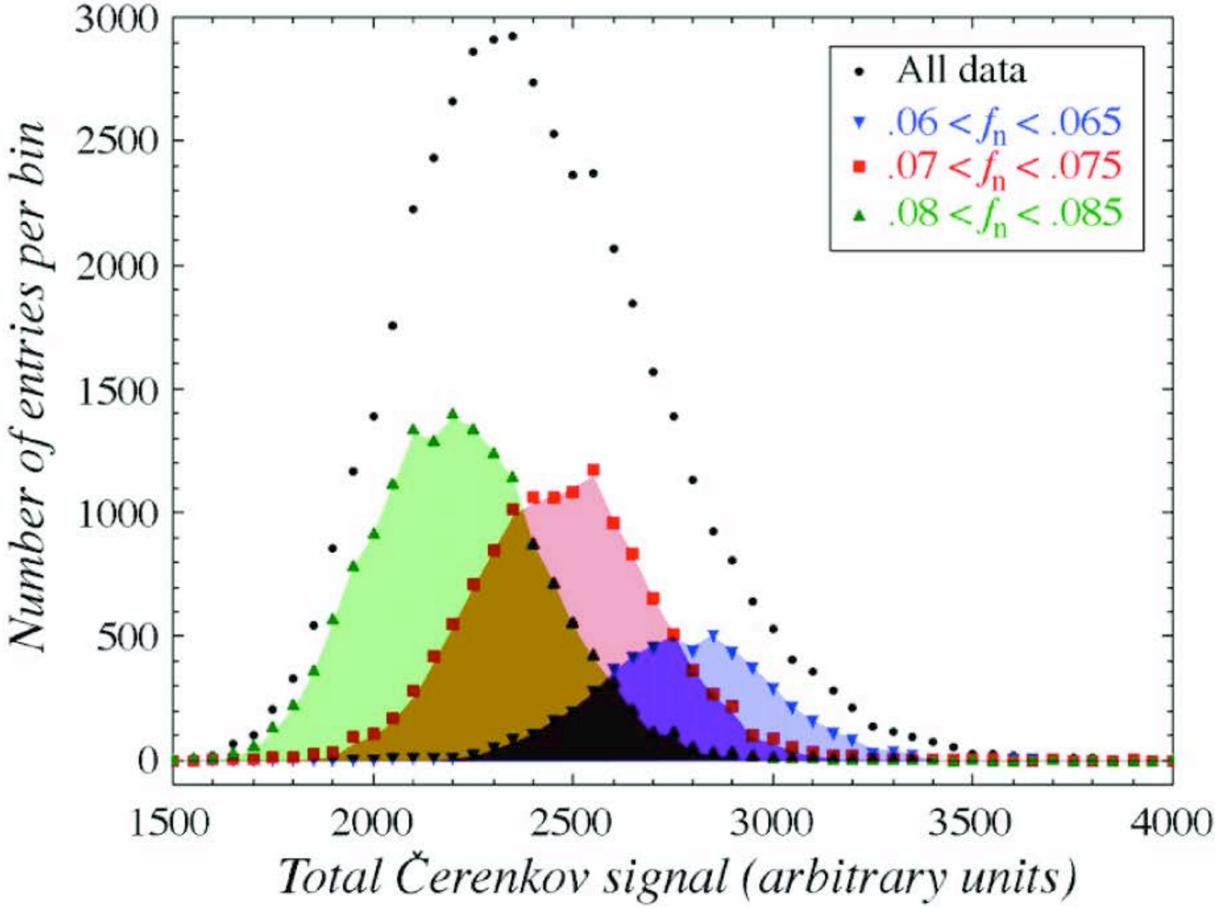
- The DREAM project holds the promise of high-quality calorimetry for *all* types of particles, with an instrument that can be calibrated with electrons

Backup slides

Time structure of the DREAM signals: the neutron tail



Probing the total signal distribution with the neutron fraction

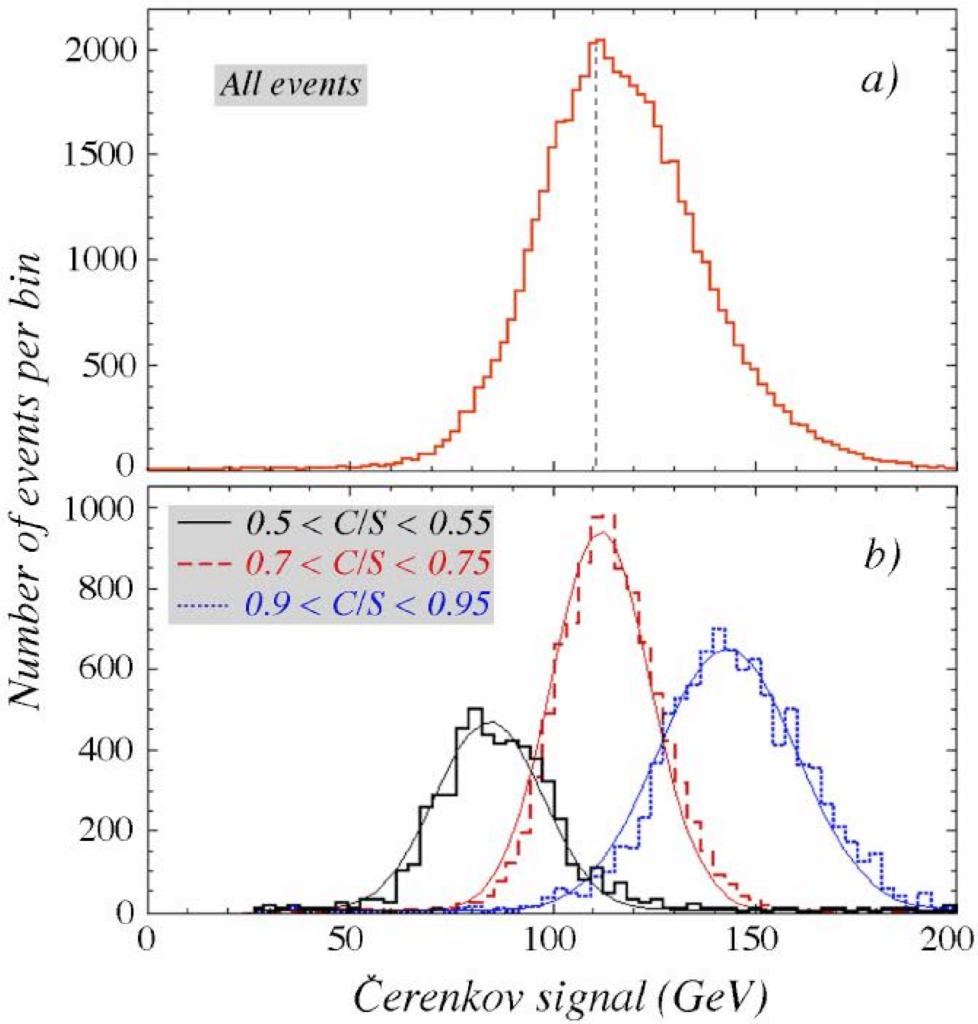


From:

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 .

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



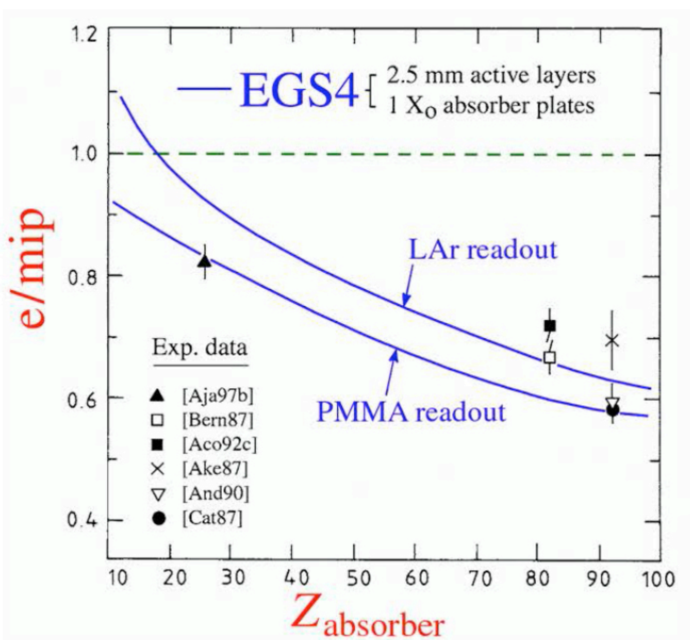
On average,
~50% of the "jet" energy deposited in BGO matrix

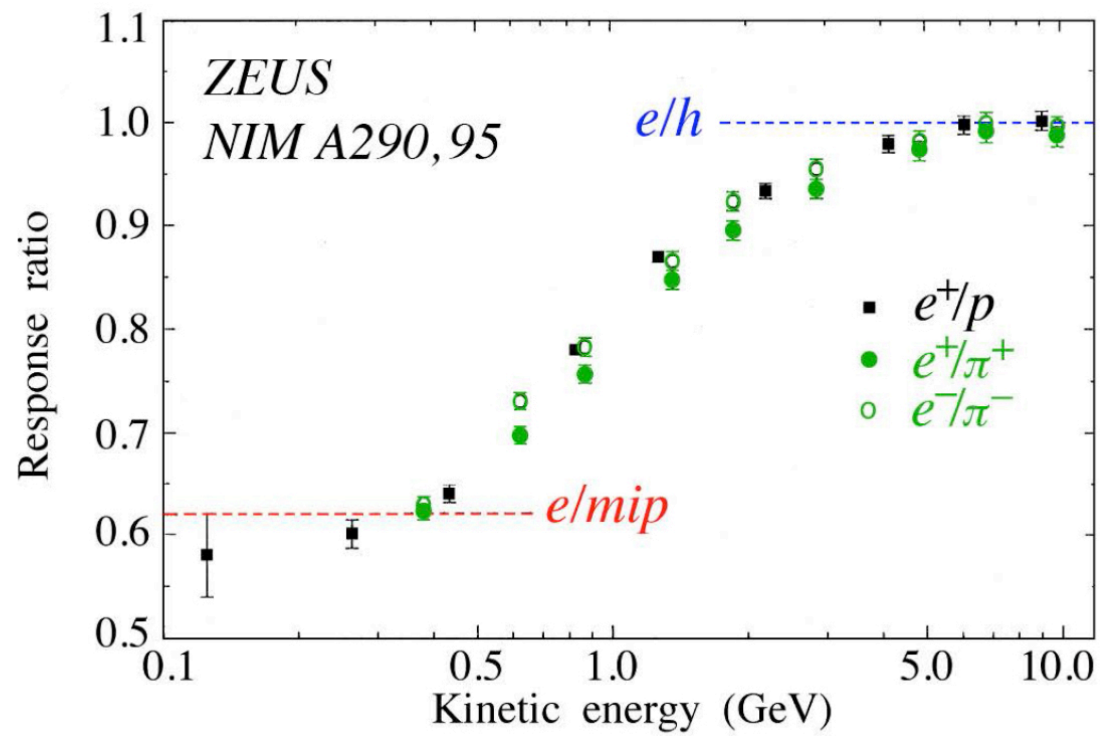
from
NIM A610 (2009) 488

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).

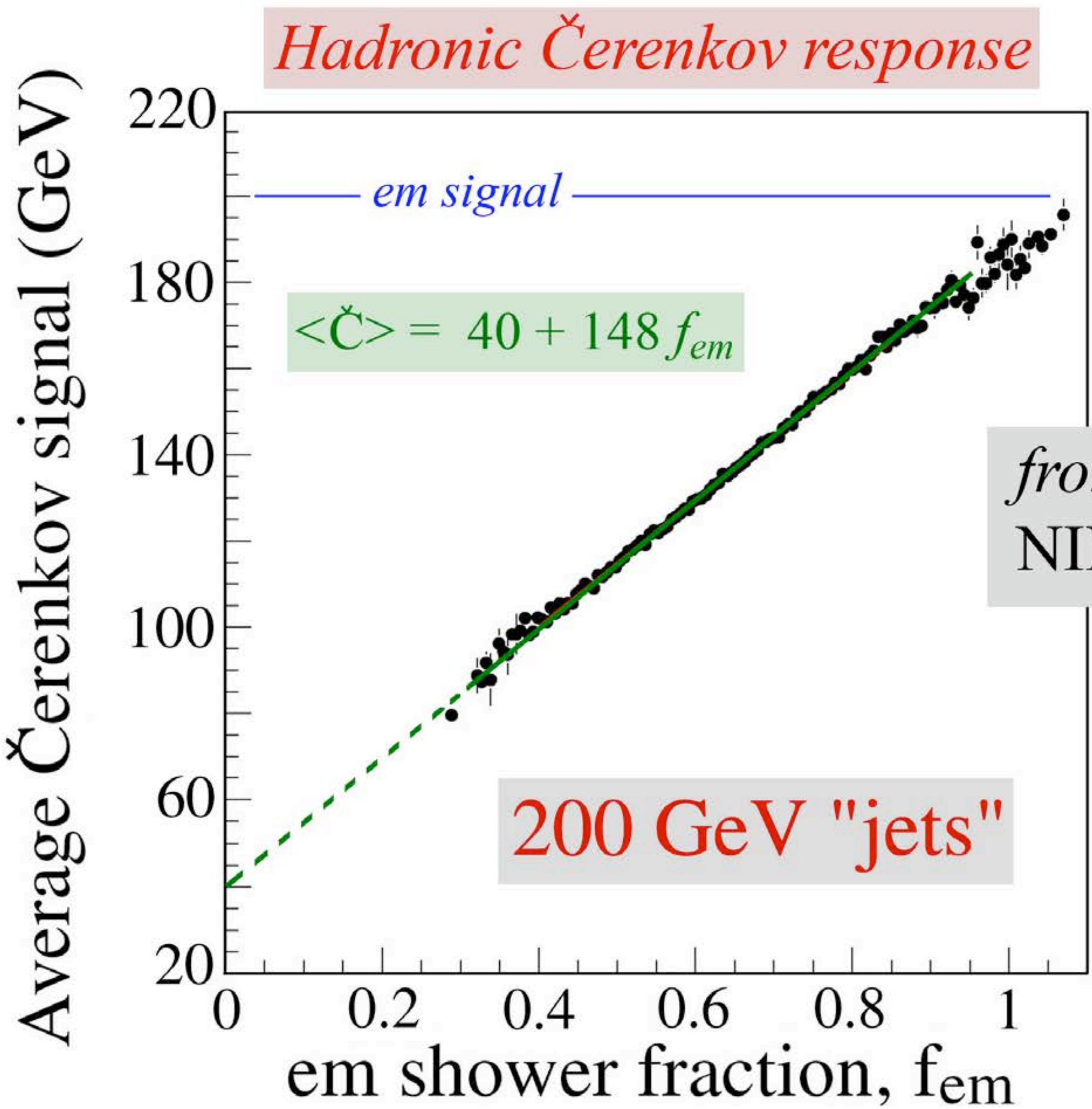
Absorber choice: Cu vs Pb

- *Detector mass:* λ_{Cu} *= 15.1 cm,* λ_{Pb} *= 17.0 cm*
  Mass 1λ^3 *: Cu/Pb = 0.35 , mass detector Cu/Pb = 0.56*
- *e/mip* ⟶ *Čerenkov light yield Cu/Pb ~ 1.4*
  (Showers inefficiently sampled in calorimeters with high-Z absorber)
- *Non-linearity at low energy in calorimeters with high-Z absorber*
  Important for jet detection





DREAM: Measure f_{em} event-by-event



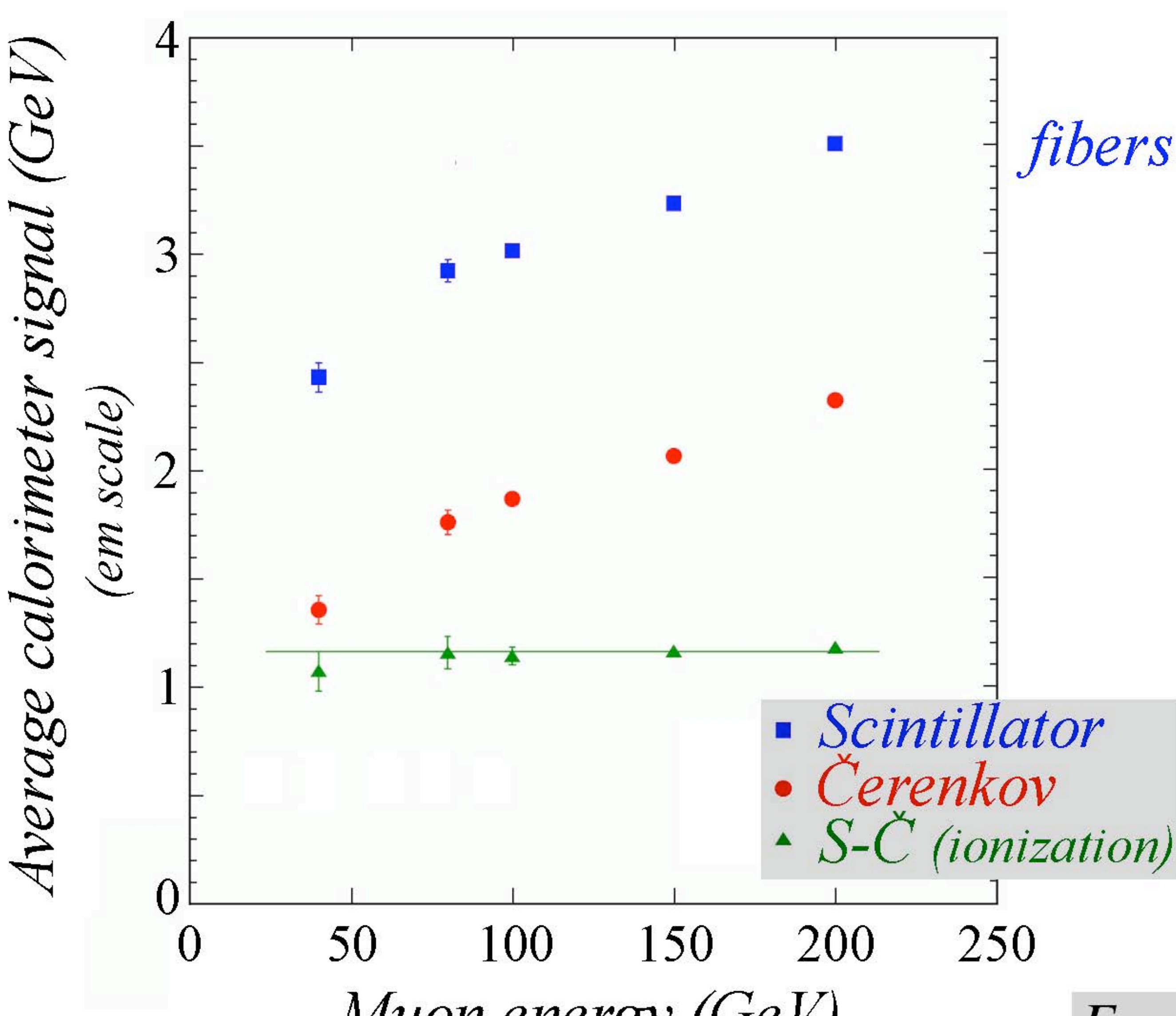
$$R = f_{em} \cdot e + (1 - f_{em}) \cdot h$$
$$= p_0 + p_1 f_{em}$$

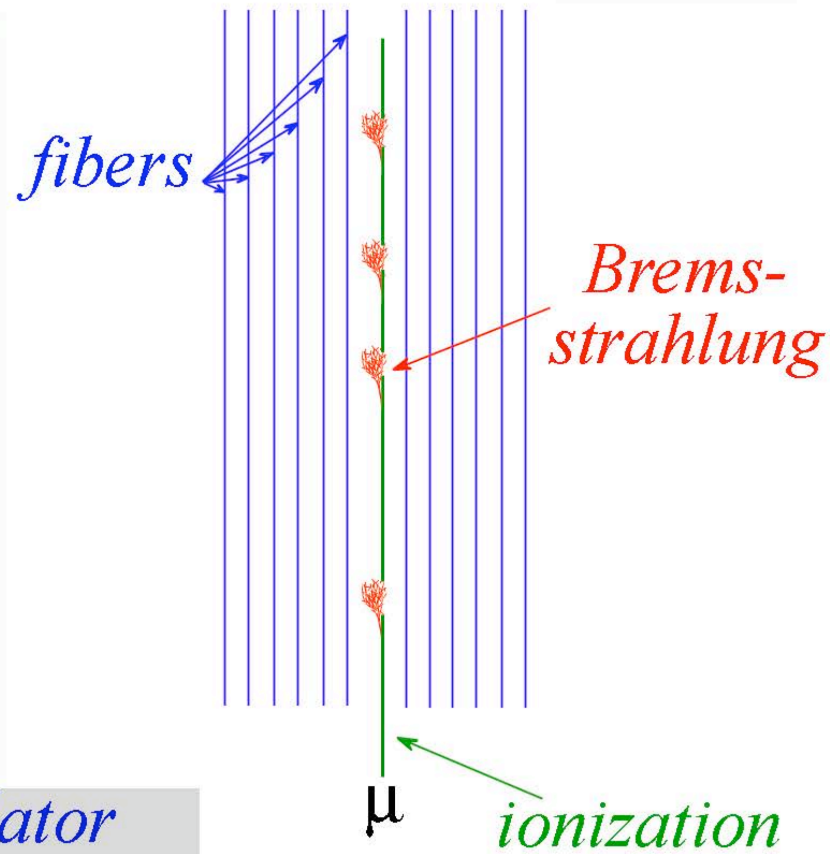
from:
NIM A537 (2005) 537

$$f_{em} = 0 \longrightarrow R_h = 0.2\ R_{em}$$
$$< 0.2\ R_{mip}$$

Calorimetric separation of ionization / radiation losses

Muon signals in the DREAM calorimeter





From: NIM A533 (2004)305

Angular dependence of the Č/S signal ratio in fiber calorimeter