Dual-Readout Calorimetry
for High-Quality Energy Measurements

*New results from the RD52 (DREAM) Collaboration**

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* *DREAM (RD52) Collaboration:*
Cagliari, Cosenza, CERN, UCL, Pavia, Pisa, Roma, Iowa State, TTU, Korea University

RD52 is a *generic* detector R&D project *not* linked to any experiment

Goals:

- *Investigate & eliminate the factors that prevent us from measuring hadrons and jets with similar precision as electrons, photons*
- *Build a calorimeter that is better than anything that has ever been built or conceived before, and up to the challenges of future HEP experiments*

- *N.B. Our calorimeters are intended to actually measure the energy of the objects produced in particle collisions, as well as E_T, $\not{E}_T$ etc. (unlike the multi-million channel PFA calorimeters)*

Outline:

- *Improve what, and how?*
- *Recent, unpublished results*
- *Plans for the future*

State-of-the-art in hadron calorimetry

< 1985   Performance dominated by fluctuations in em shower content ($e/h \neq 1$)

1985 - 1990 Mysteries of compensation solved ($e/h = 1$)
Need proper calorimeter response to shower neutrons

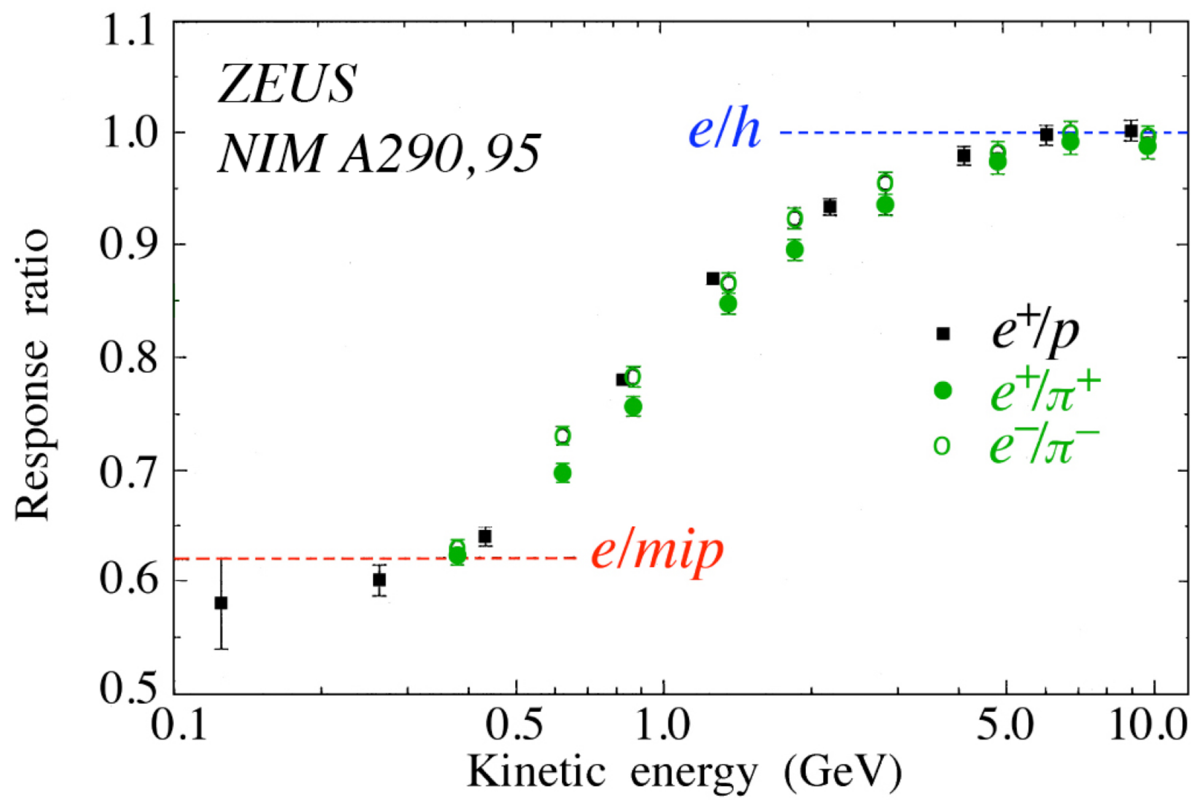
1990 - 1995 ZEUS and SPACAL built compensating hadron calorimeters that were very linear, with resolution of 30-35%/$\sqrt{E}$ for single hadrons

Problems:

1) *Detector mass (Pb,U) much larger than for same # λ_{int} of Fe,Cu*
2) *Small sampling fraction (Pb, 2.4%) limits the em energy resolution*
3) *Jet performance worse than for single hadrons*

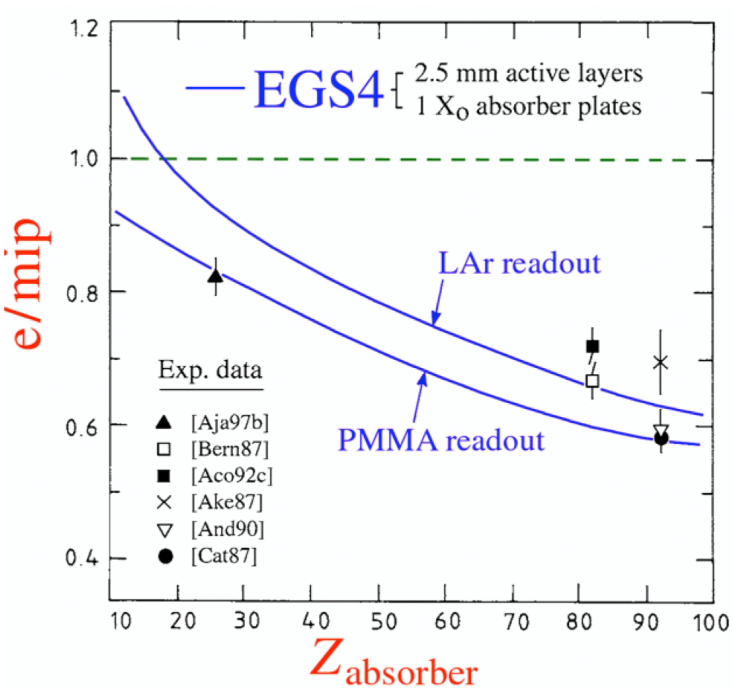
> 2004   DREAM/RD52 intends to reduce/eliminate these problems

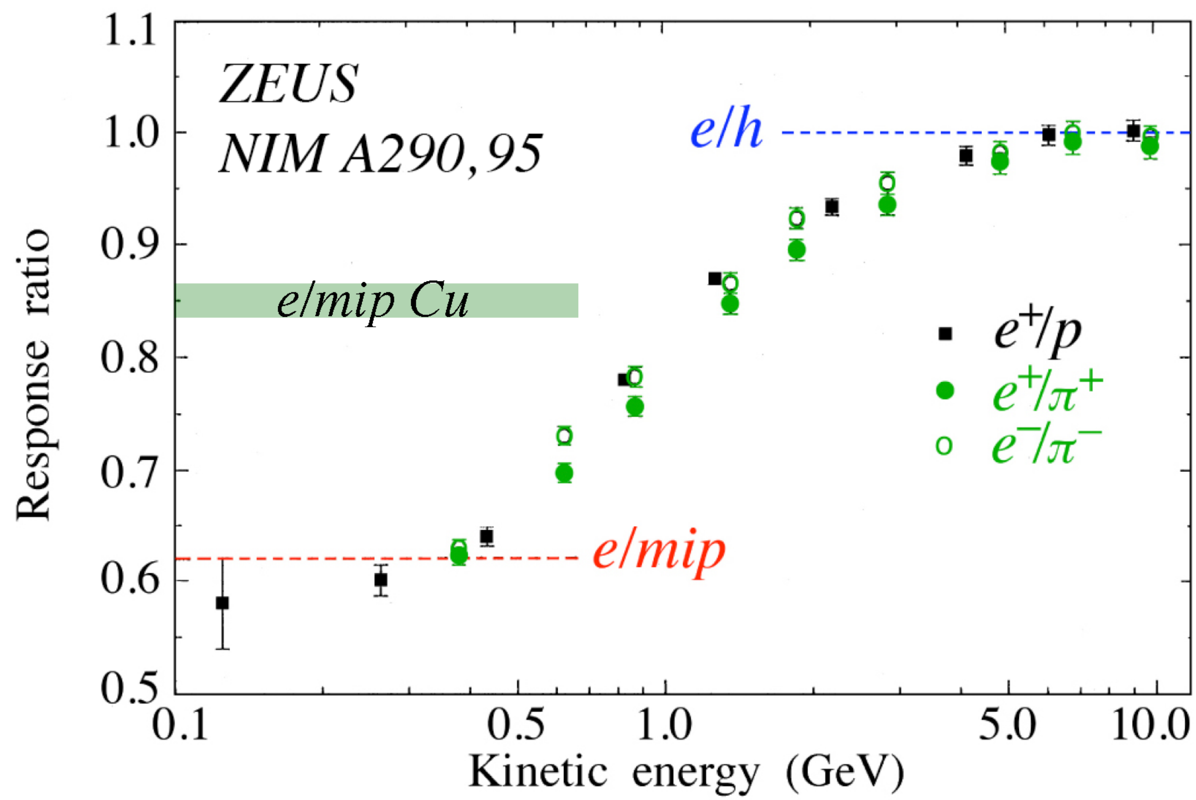
What is the problem with the jet energy resolution?



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

DUAL-READOUT CALORIMETRY

- *Dual-readout Method (DREAM):*

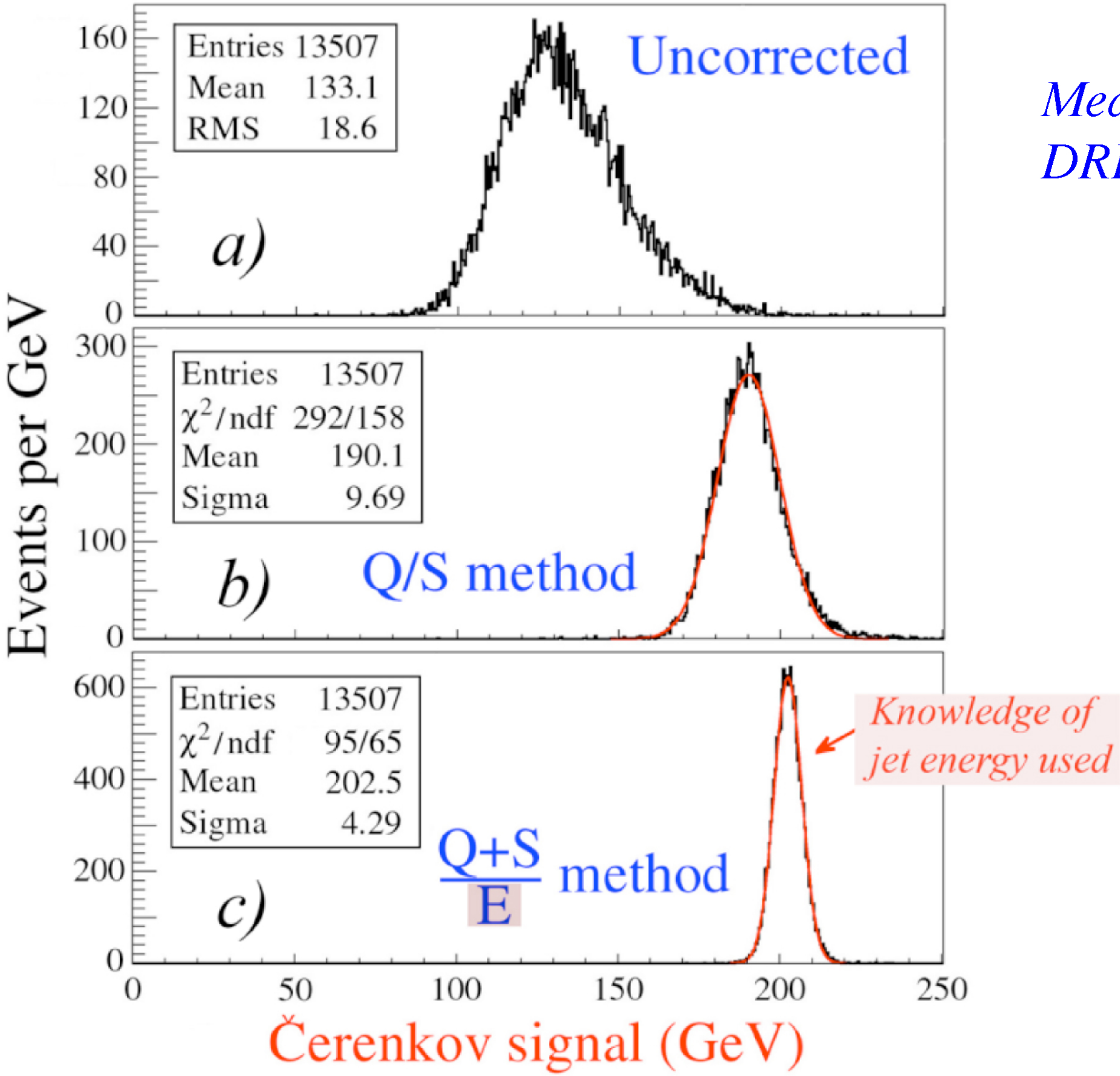
  Simultaneous measurement of scintillation light (dE/dx) and Čerenkov light produced in shower development makes it possible to measure the em fraction of hadron showers event by event.
  The effects of fluctuations in this fraction can thus be eliminated

- *In this way, the same advanges are obtained as for intrinsically compensating calorimeters (e/h = 1), WITHOUT the limitations (sampling fraction, integration volume, time)*

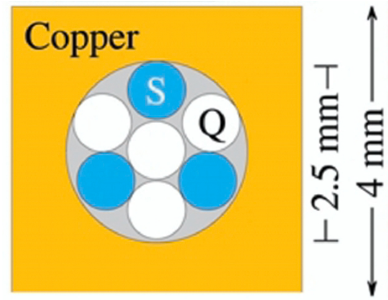
  - *Correct hadronic energy reconstruction, in an instrument calibrated with electrons*
  - *Linearity + excellent energy resolution for hadrons & jets*
  - *Gaussian response functions*

Hadronic performance

Experimental effects of the DREAM procedures (200 GeV "jets")



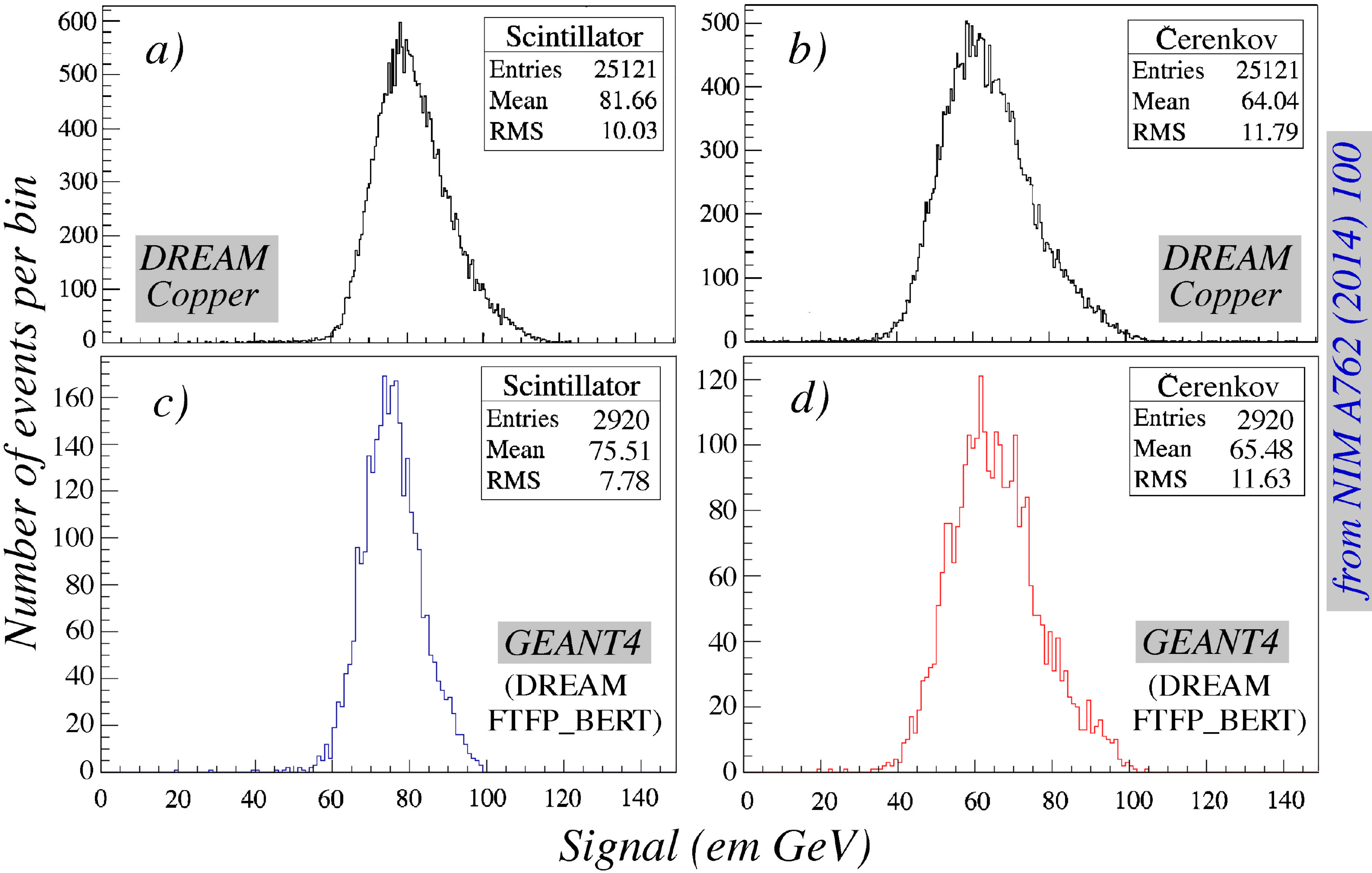
Measured with crudely sampling DREAM module (1030 kg)



(6000 tubes like this)

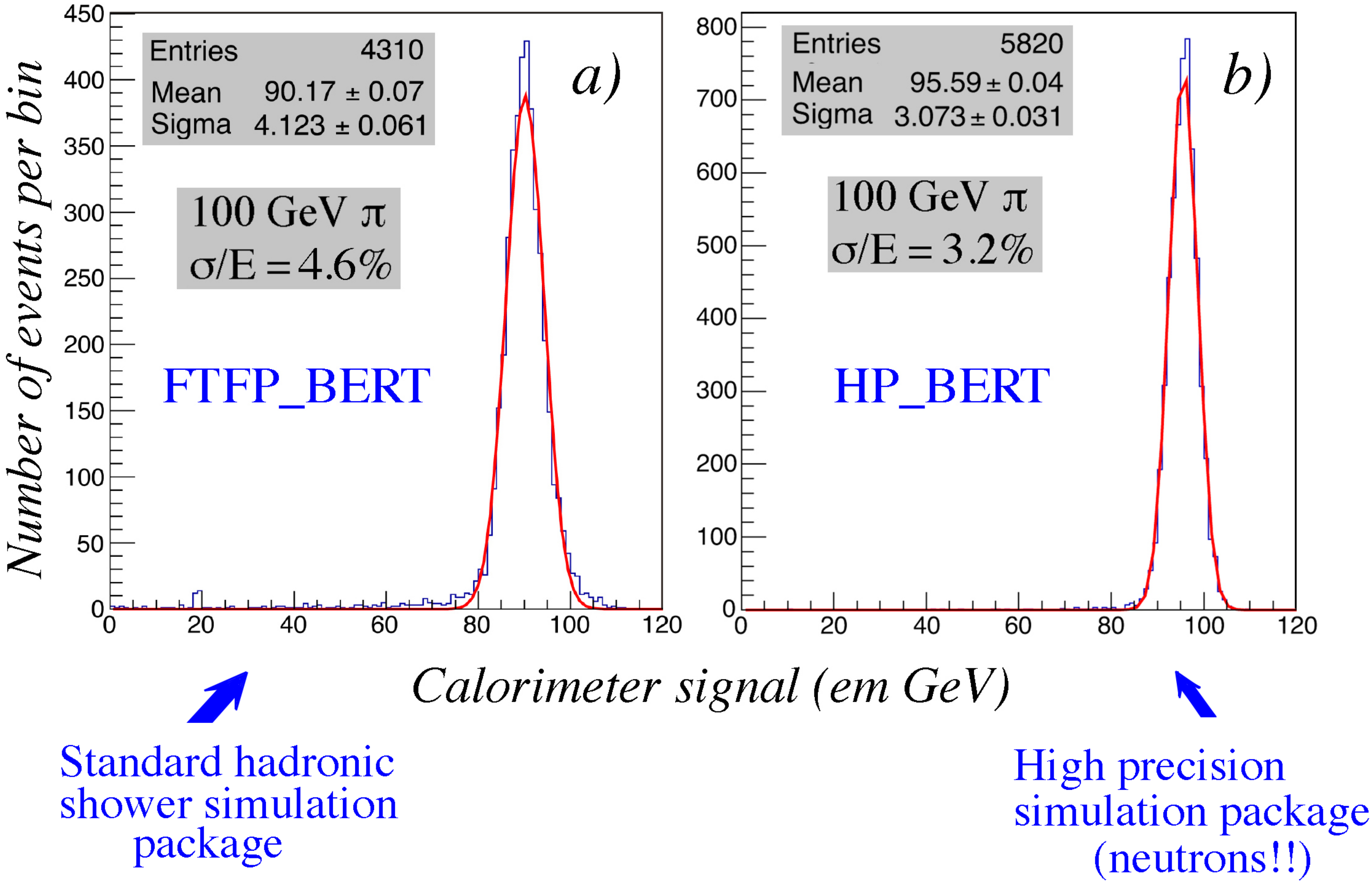
Figure 2: Čerenkov signal distributions for 200 GeV multi-particle events. Shown are the raw data (a), and the signal distributions obtained after application of the corrections based on the measured em shower content, with (c) or without (b) using knowledge about the total "jet" energy [5].

Hadronic response functions of the DREAM Cu-fiber calorimeter (comparison experiment/Monte Carlo)

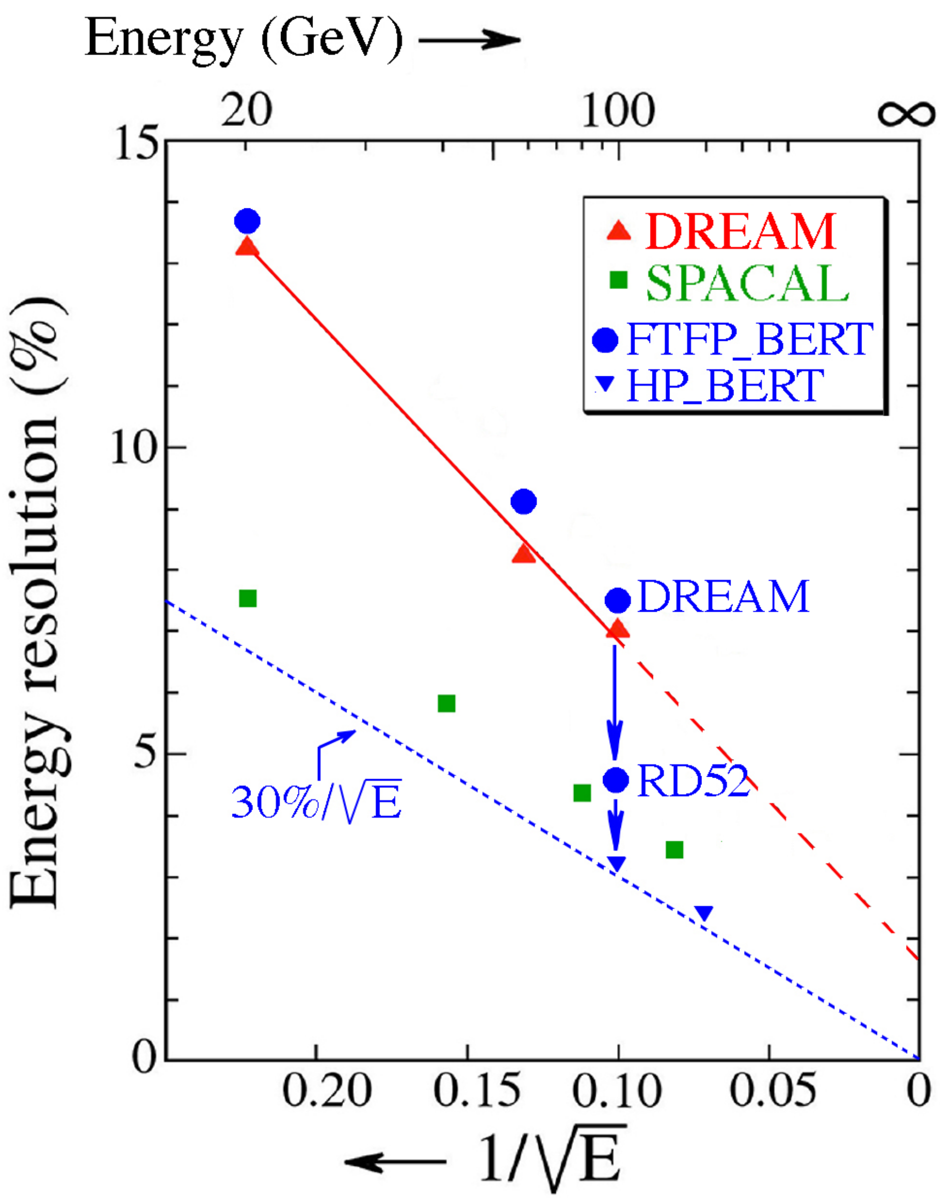


GEANT4 simulations of 100 GeV π

RD52_Cu 65 x 65 cm^2

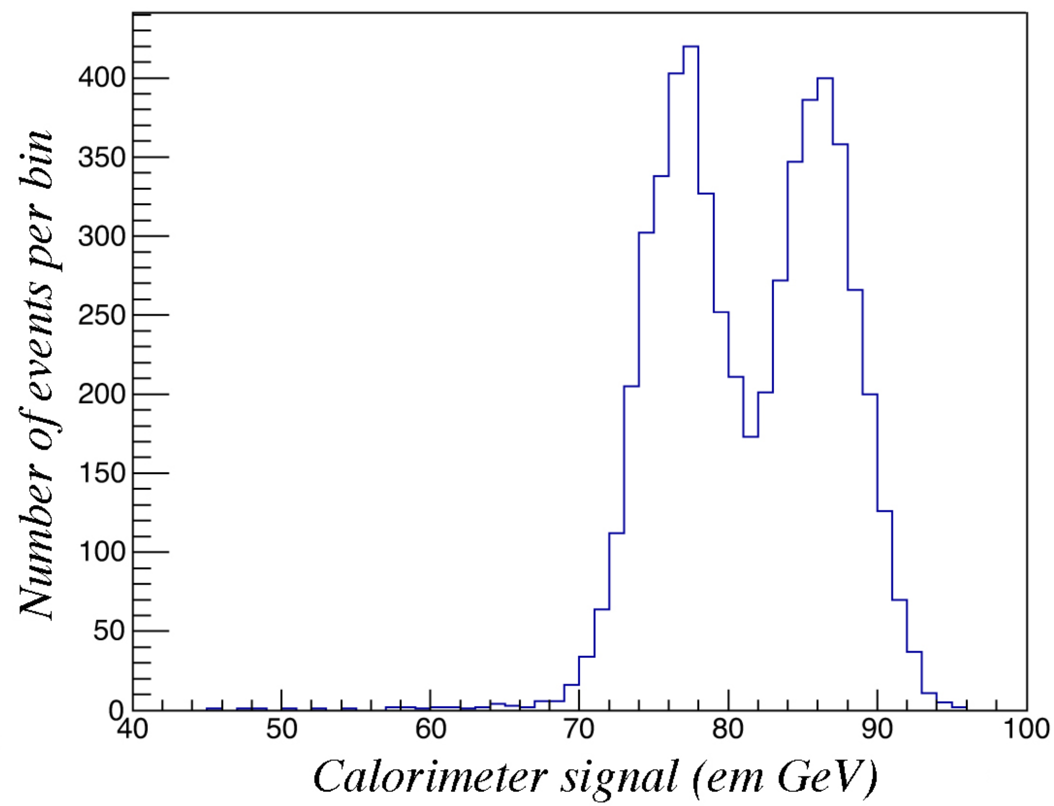


Hadronic energy resolution dual-readout Cu-fiber calorimeter

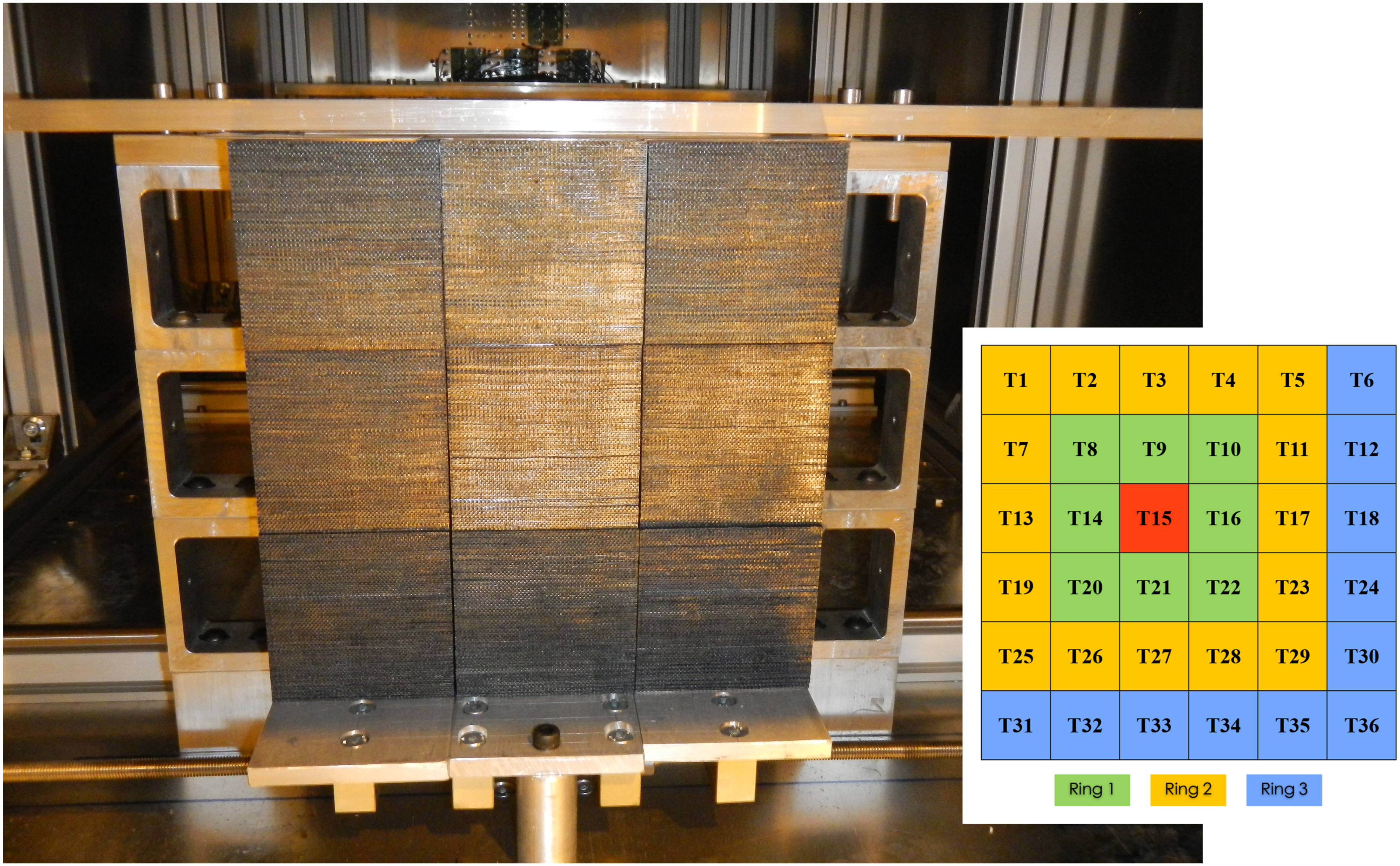


W/Z separation

(high-precision GEANT4)

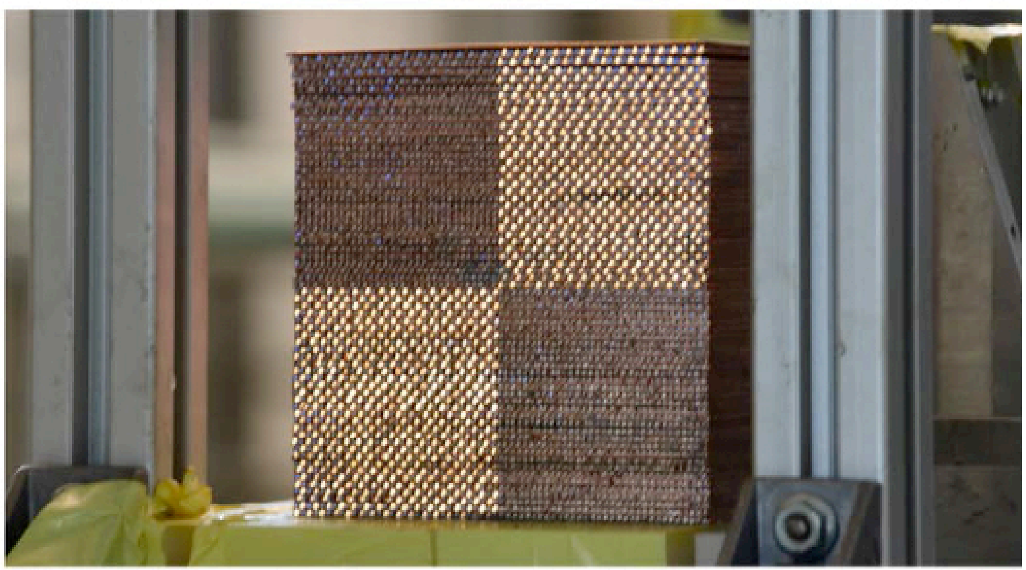


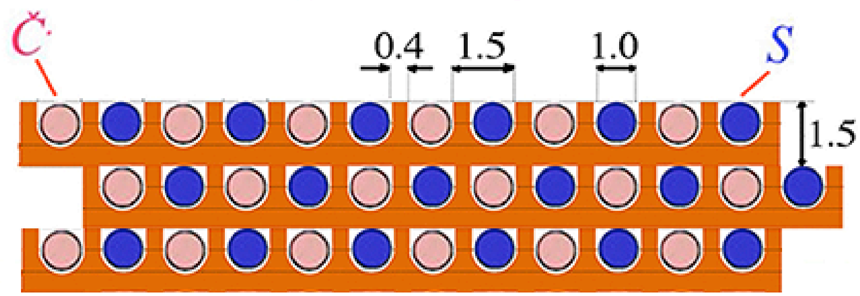
The RD52 Pb-fiber calorimeter



28 x 28 x 250 cm^3 , 1300 kg, 72 electronic channels

The first RD52 Cu-fiber module

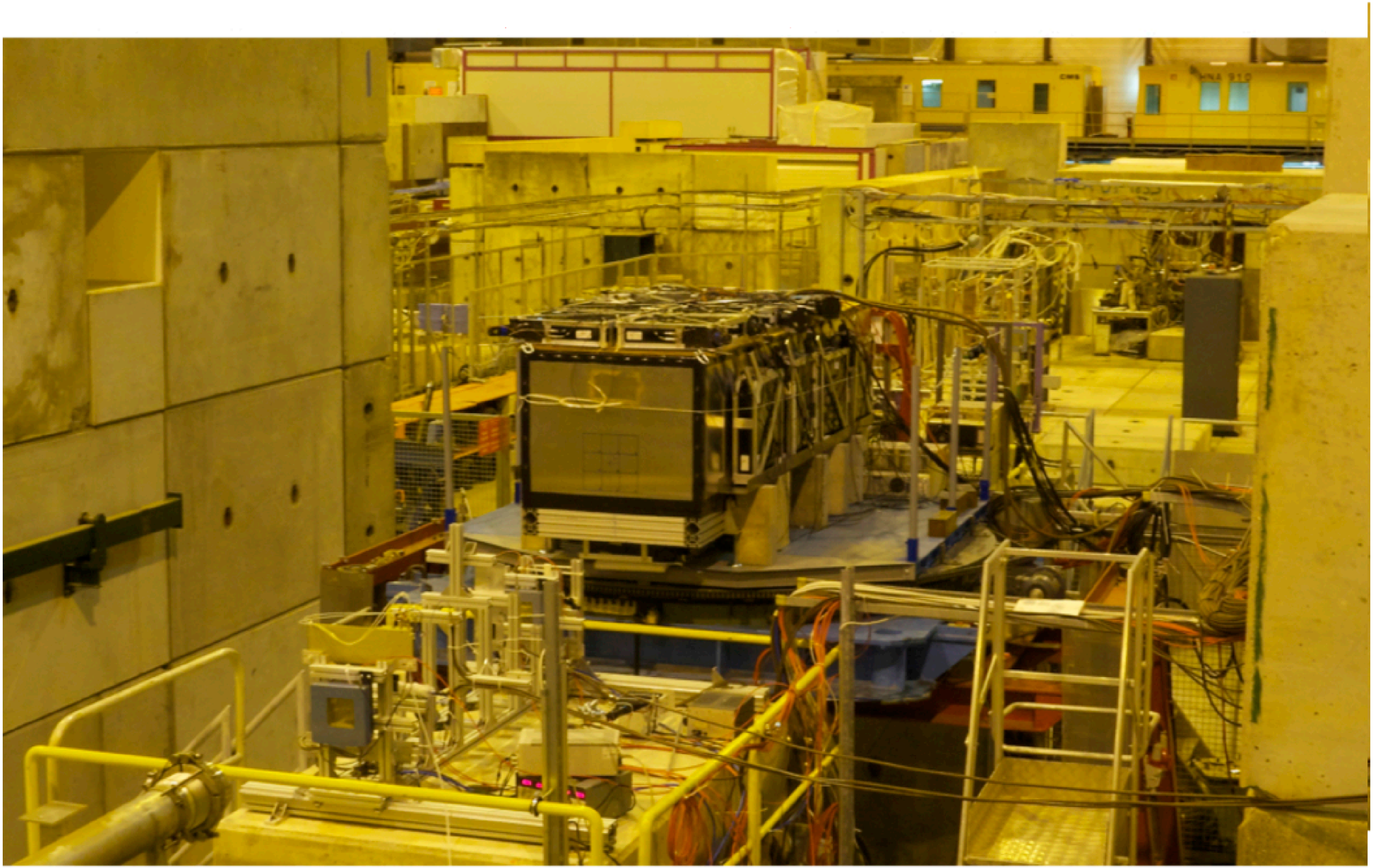




Fiber pattern

2048 S + 2048 Č fibers

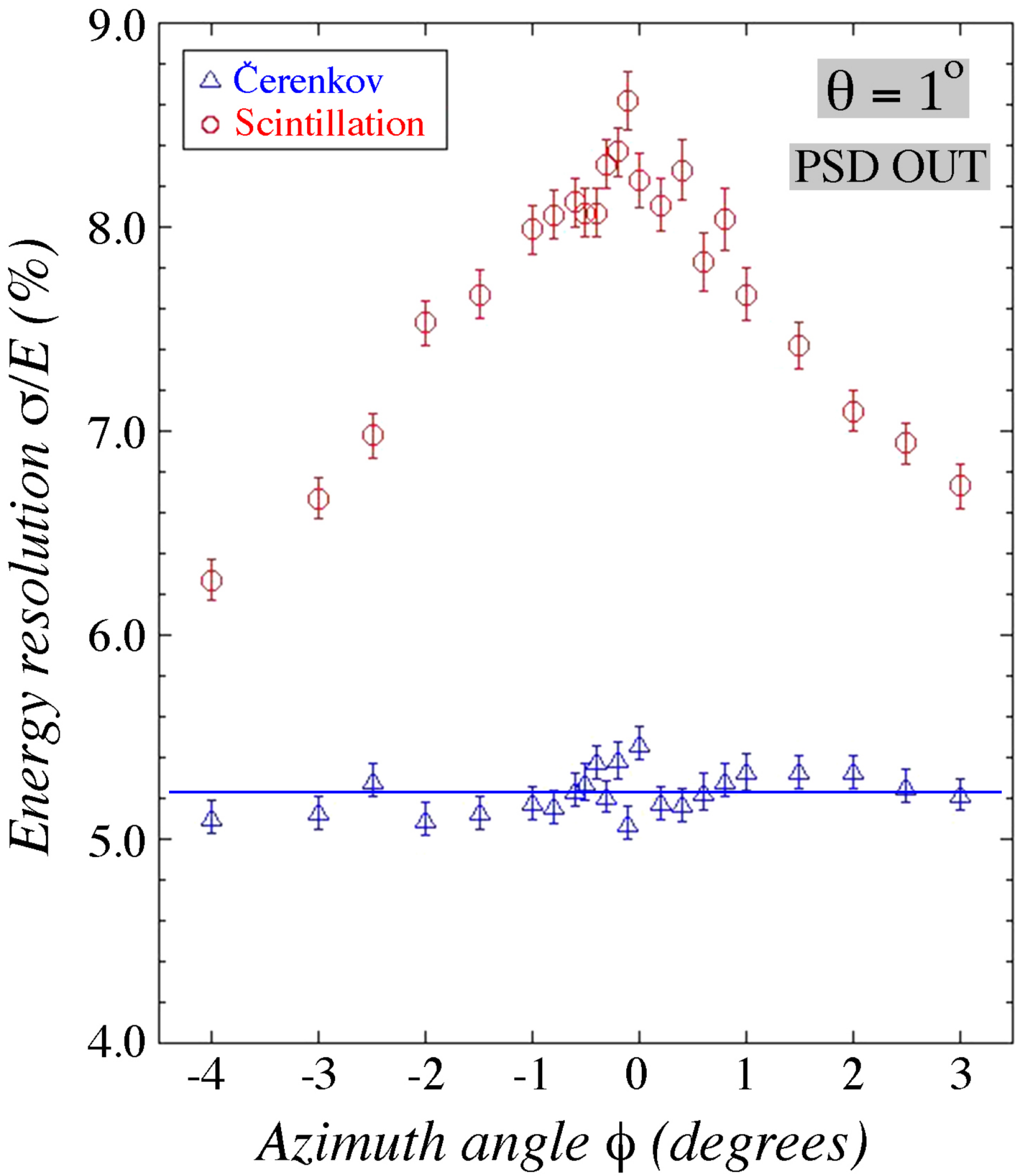
The RD52 test area in the H8 beam line



Electromagnetic performance

20 GeV positrons in the RD52 Cu-fiber calorimeter entering the detector at very small angles i.e. almost parallel to the fibers

The energy resolution for 20 GeV e^+ as a function of the angle of incidence

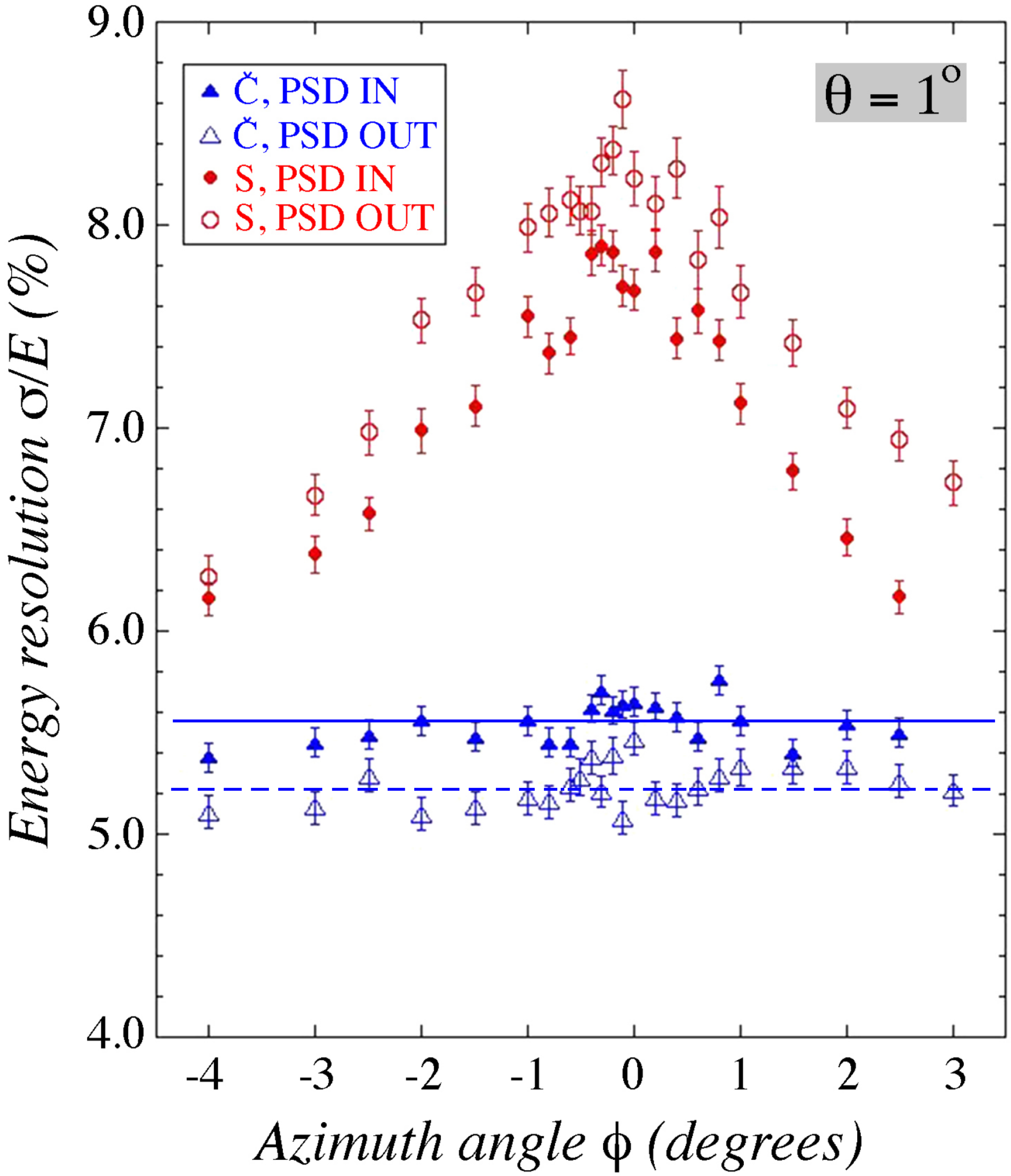


- *em showers are very narrow, especially early on. The sampling fraction of this early shower component depends on impact point (in fiber or in between fibers)*

- *This dependence disappears when particles enter at an angle with the fibers*

- *This effect does NOT play a role for Čerenkov signals, since early part of shower does not contribute to signal (numerical aperture of fibers)*

Effect of upstream absorber (1 X_0) on the em energy resolution

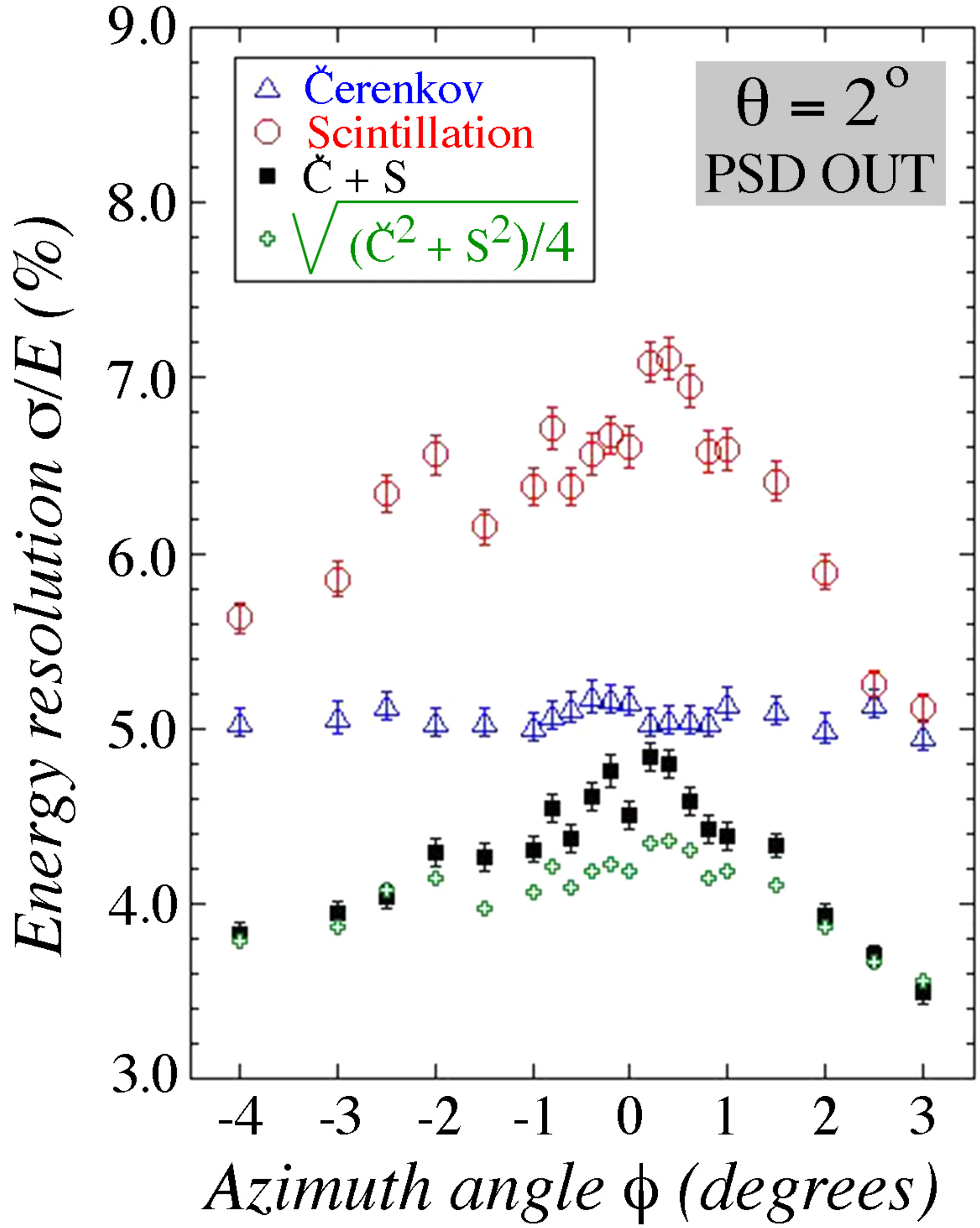


Effects of absorber:

It widens the shower and thus reduces impact point dependence of the response

Fluctuations in energy loss lead to a worse energy resolution

S + Č signals provide independent shower sampling → em energy resolution improves by adding signals



ZEUS: 4.3%

SPACAL: 4.1%

GEANT4: 2.8%

(8.3%/$\sqrt{E}$, 30 Cpe/GeV)

NB: 20 x 30 = 600 Cpe

$\sqrt{600}/600 = 4.1\%$

Other new experimental results

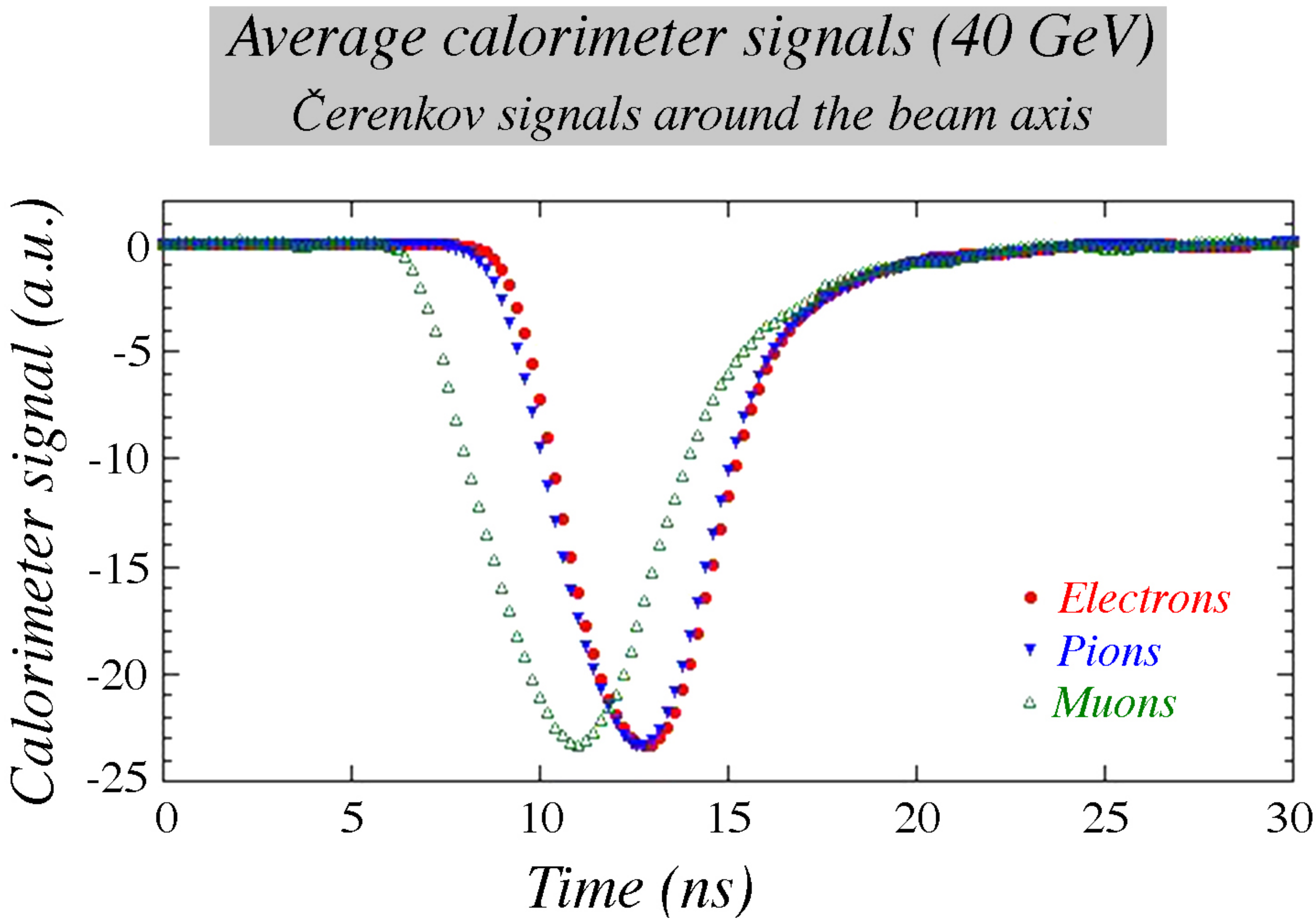
Time structure of calorimeter signals

- *Detailed time structure measurement of calorimeter signals*

  (40 GeV mixed e, π, μ beam, signals digitized at 5 Gs/s)
  Beam steered into Tower 15 of the lead calorimeter

  Study differences that derive from the fact that light travels at c/n (17 cm/ns) in the fibers, while the particles that generate the light travel at ~c (30 cm/ns)
  (except the neutrons!)

  This leads to a depth dependent effect of 2.5 ns/m on the calorimeter signals



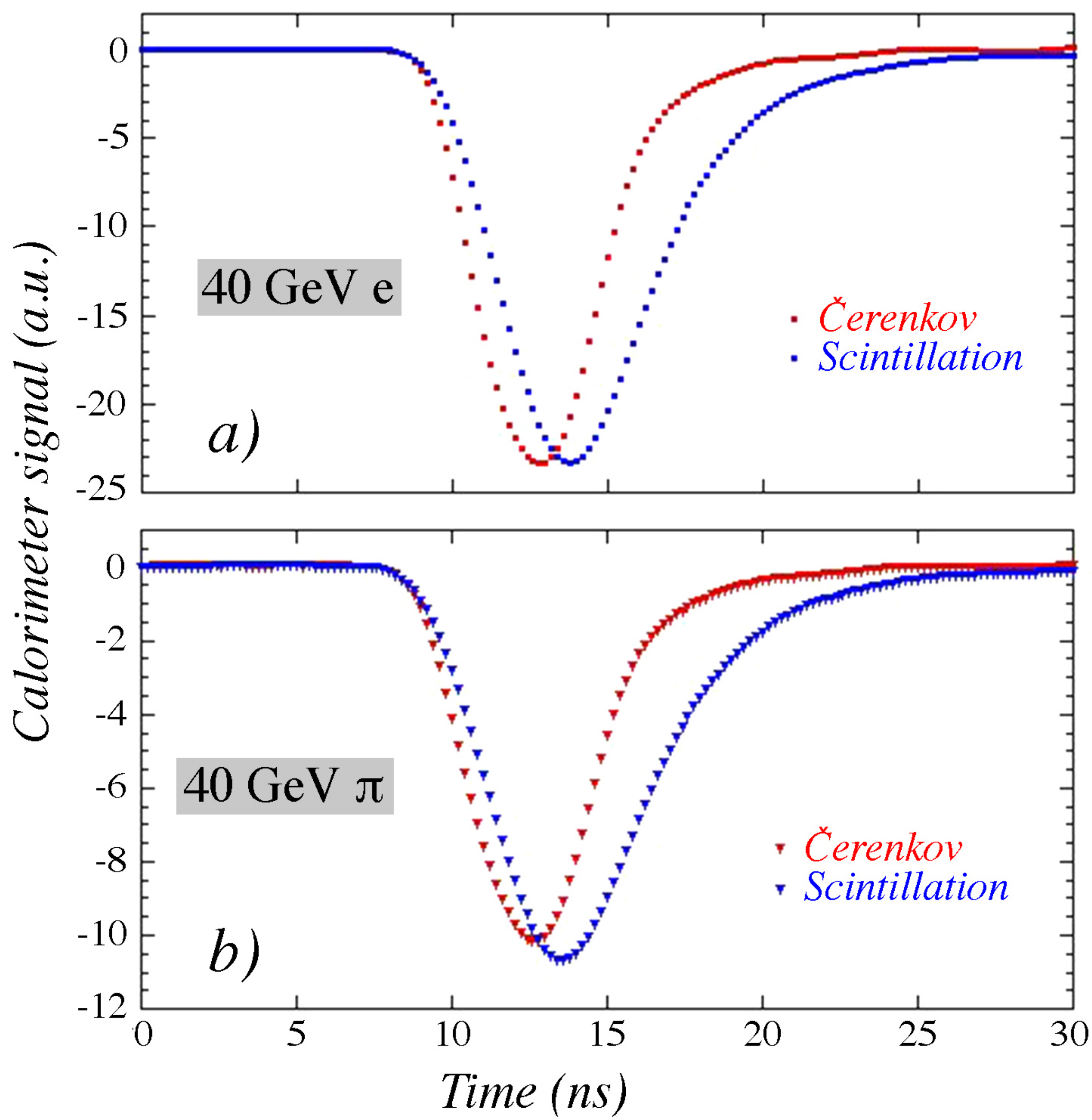
Where is Č light produced?

Electrons: depth shower maximum ~5 cm

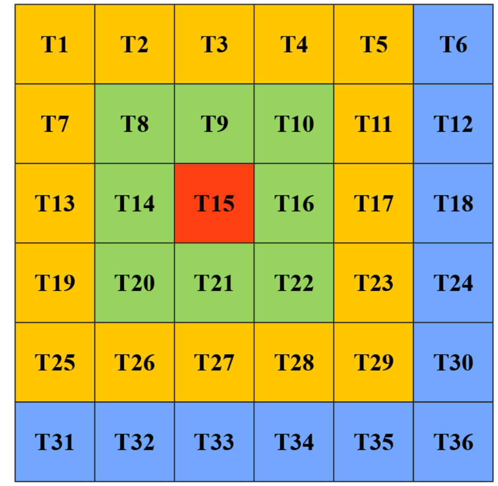
Pions: depth shower maximum ~ 25 cm

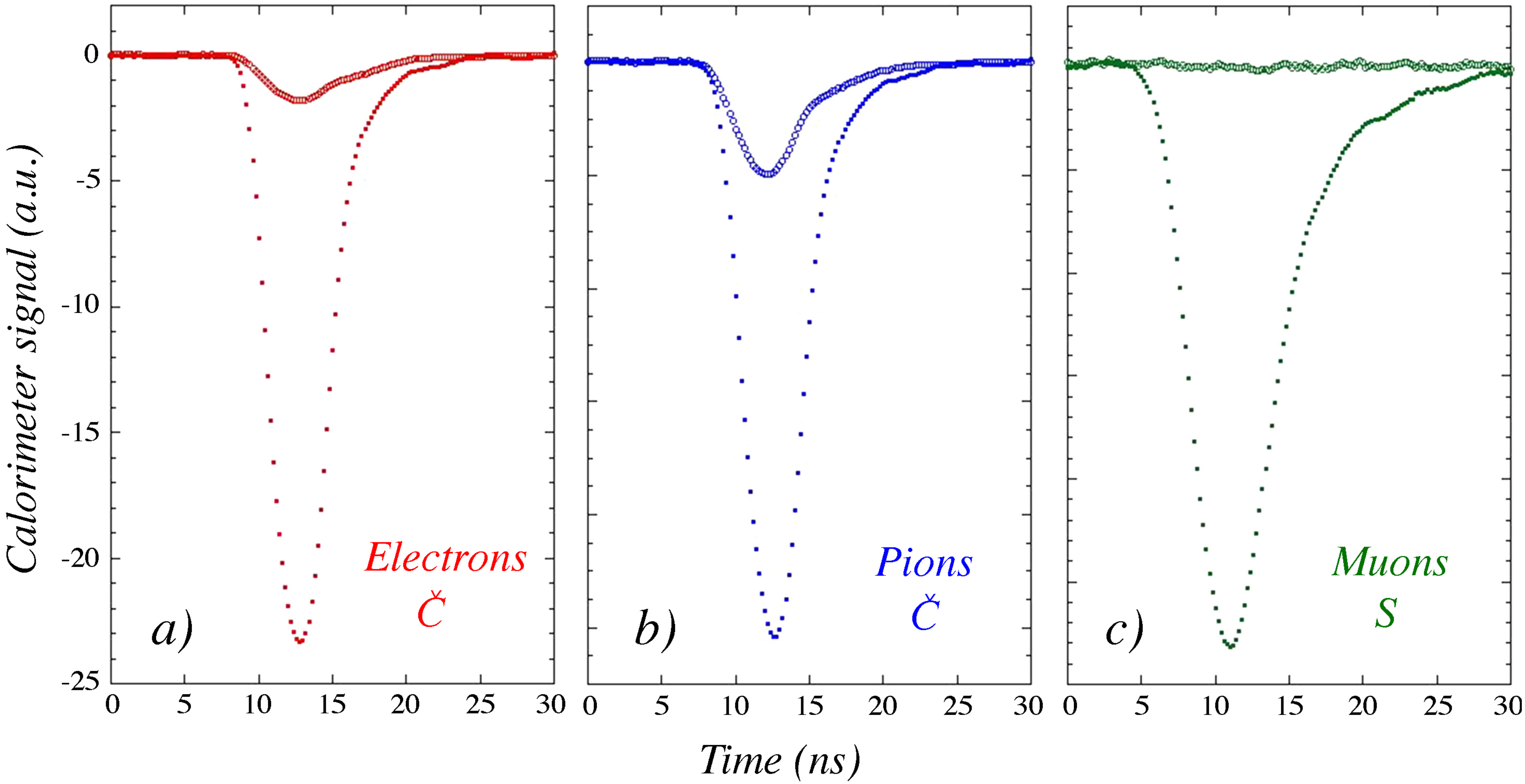
Muons: average depth light production ~125 cm

Comparison Čerenkov / Scintillation signals (around shower axis)

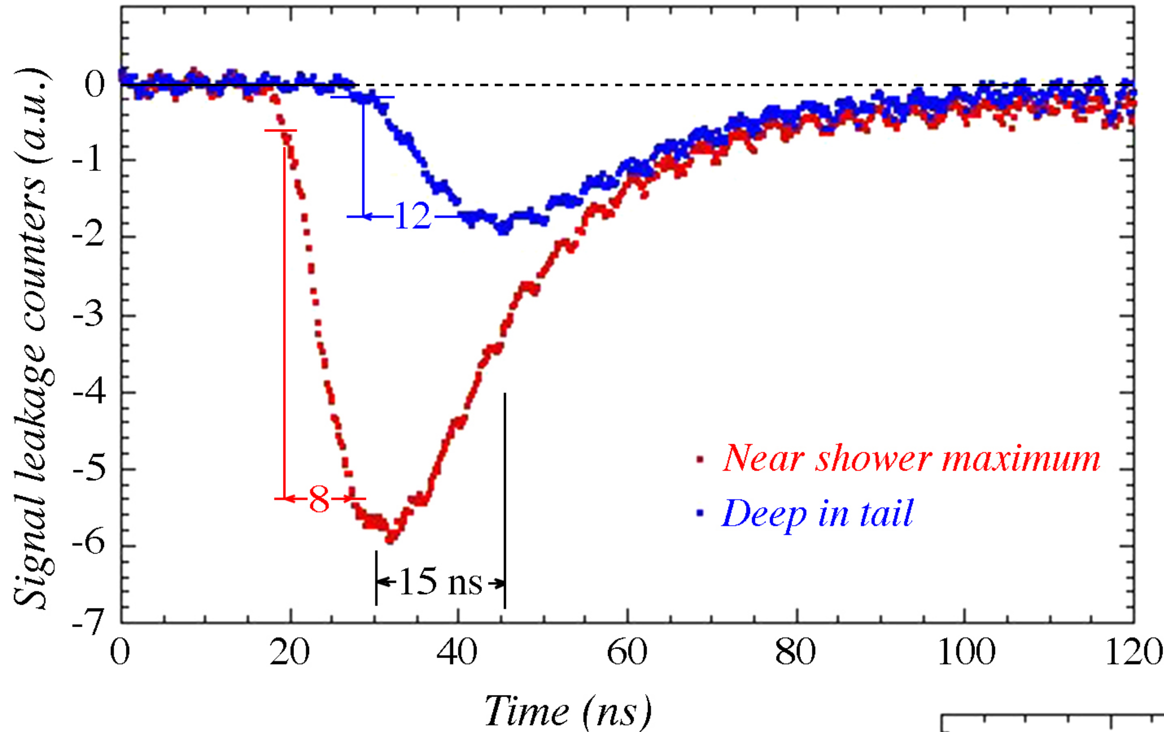


Comparison on-axis / off-axis calorimeter signals
Tower 15 / Tower 21





Comparison signal shapes leakage counters

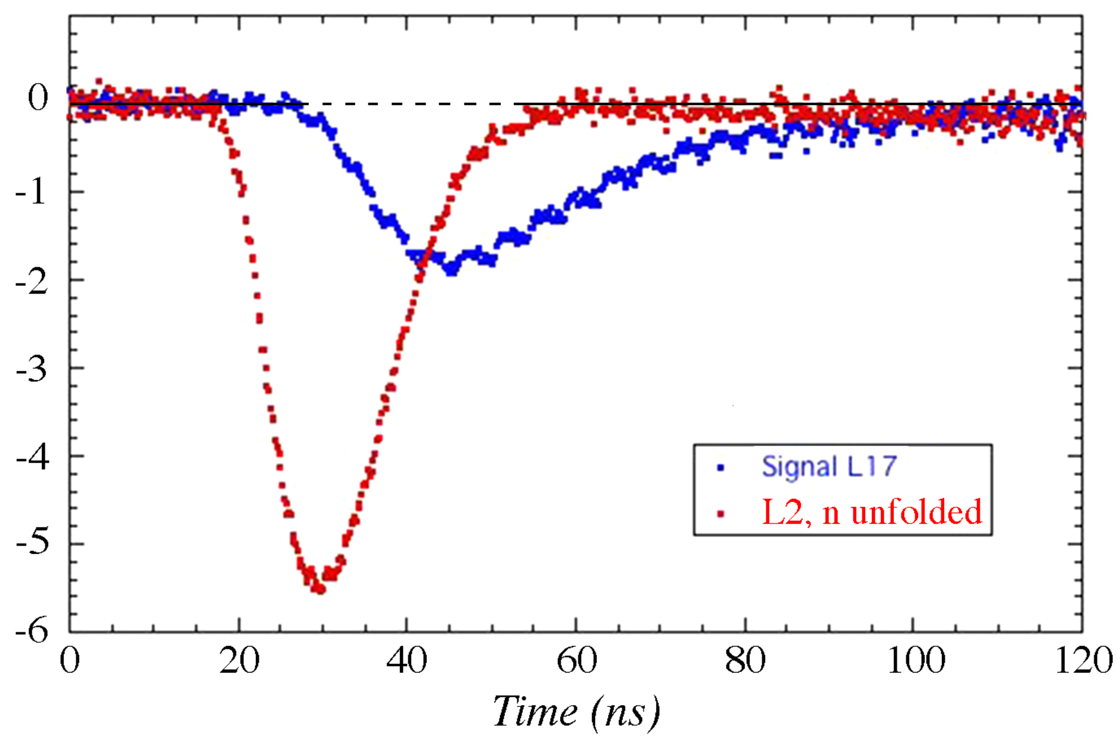


Expected signal contributions:

- prompt charged shower particles

- $n + p \rightarrow n + p$
(time constant 10 - 20 ns)

n contribution unfolded



Plans for the near future

Time structure of the signals

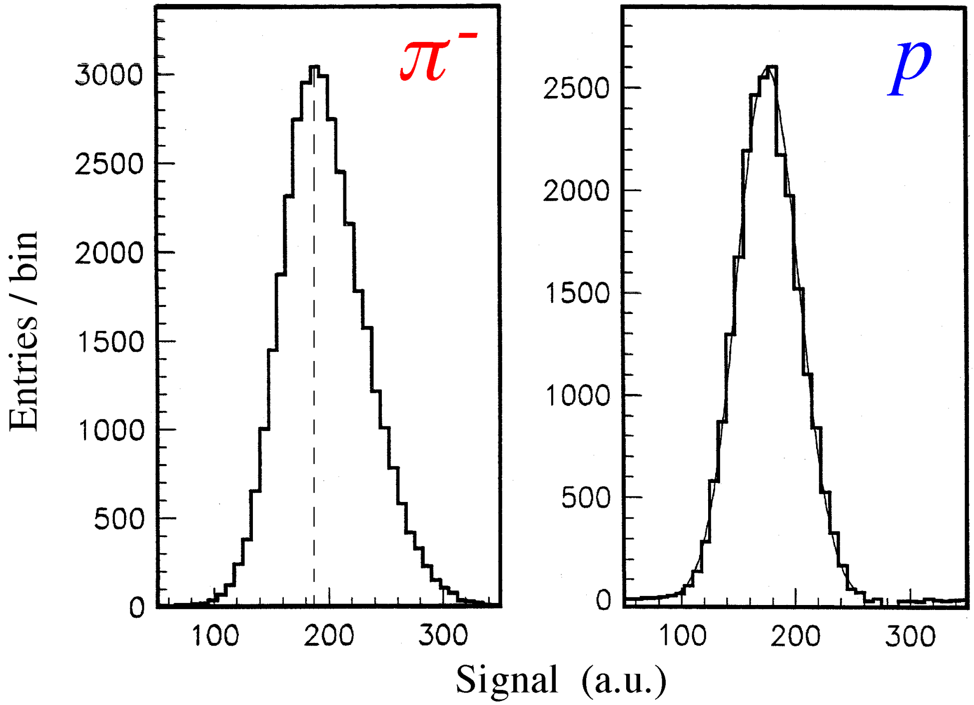
- *Analysis of data has just started.*
  Results shown here concern averages of few thousand events

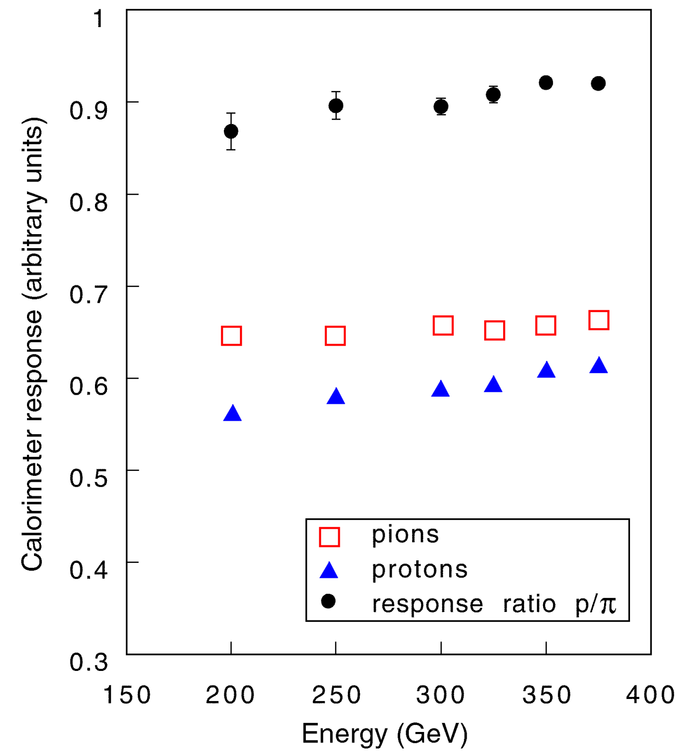
- *Individual events:*
  - *where was light produced?* → *correct for light attenuation.*
  - *what fraction of signal is due to neutrons?* → *improve resolution.*
  - *recognize non-showering particles (μ)* → *particle ID*
  - *multiple peaks in time structure may be caused by pileup* → *resolve.*
    can be studied with reflected light from aluminized front face fibers.

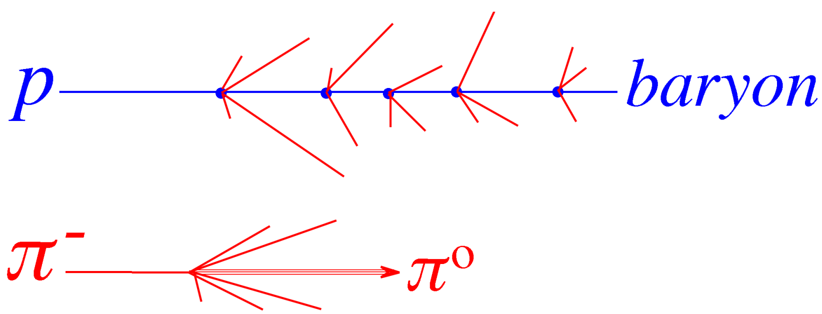
- *All these issues will benefit from faster light detector, especially for Čerenkov signals.*
  New MCP-PMT is much faster than our dynode based PMTs

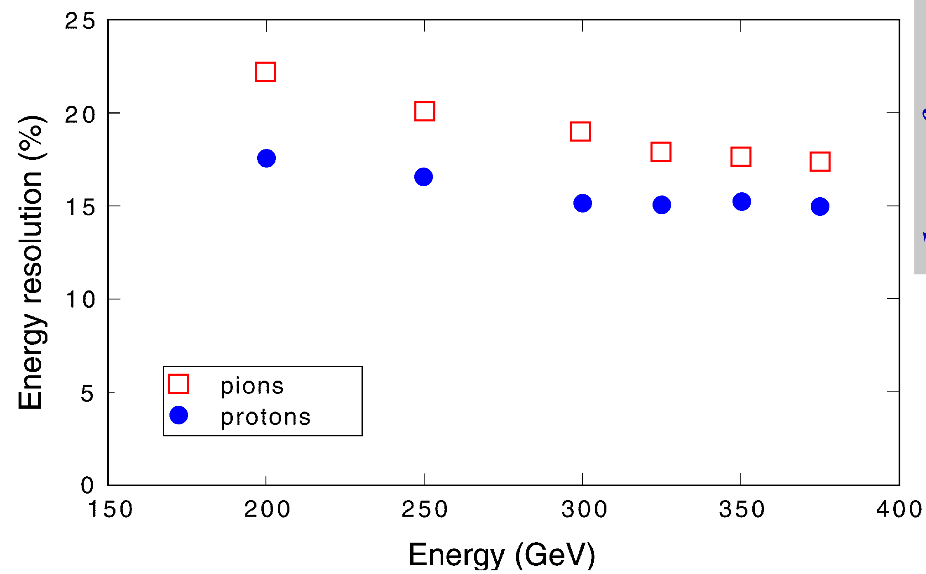
Proton / pion differences in calorimeter signals

caused by differences in em shower fraction characteristics









em fraction in p showers:

- *smaller*
- *less fluctuations*
- *more symmetric*
- *less concentrated near axis*

data from NIM A408 (1998) 380

Summary & Conclusions

- *A dual-readout Cu based fiber calorimeter has better performance characteristics than anything else that has been built or conceived so far*
  - *Excellent signal linearity*
  - *Excellent energy resolution for em and hadronic showers*
  - *No problems with jet energy resolution as in ZEUS (e/mip 0.84 vs 0.61)*
  - *Excellent particle ID possibilities in longitudinally unsegmented detector*
  - *Very fast signals*
  - *Straightforward to calibrate (electrons)*

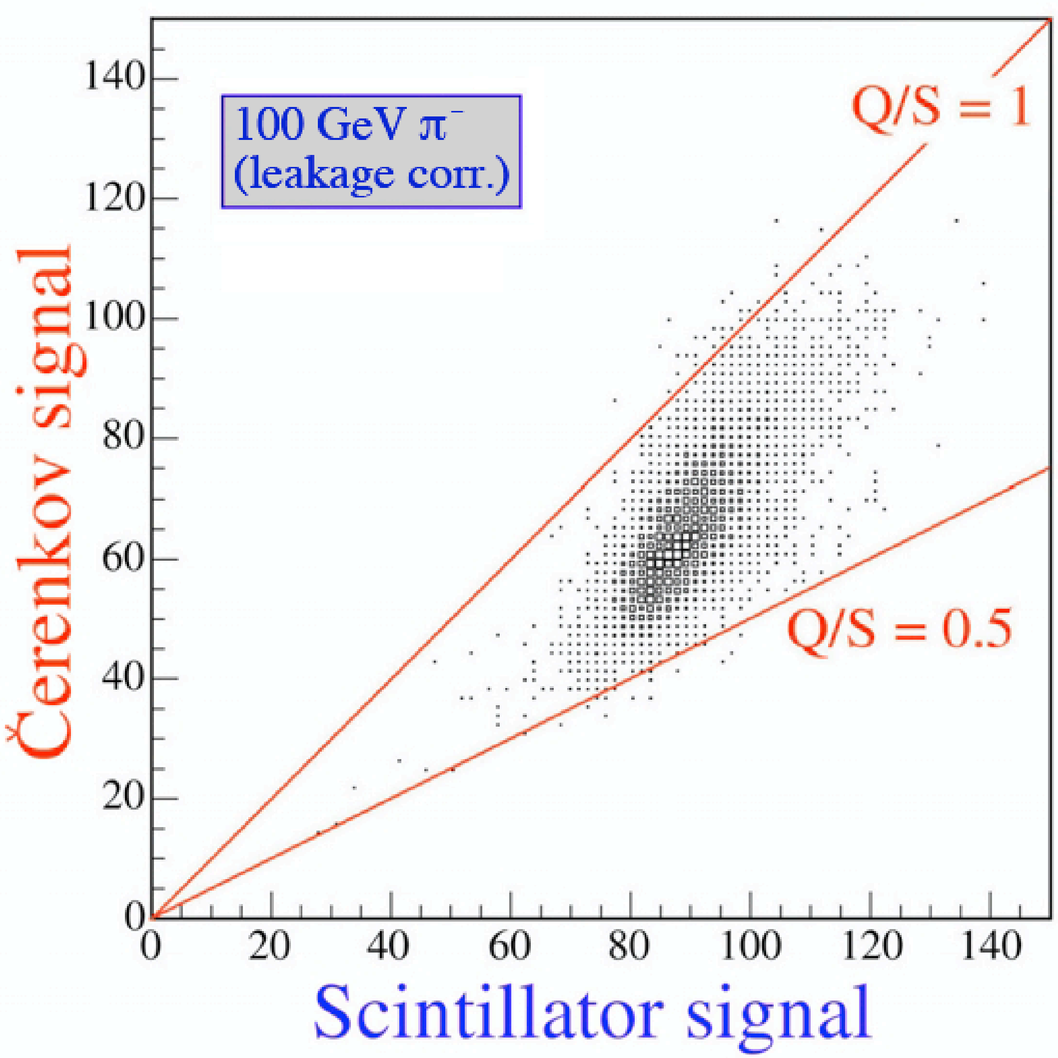
- *New results indicate that performance is also good at very small angles*

  Time structure measurements of signals may further extend possibilities (pileup, particle ID, ...)

- *The DREAM/RD52 project is documented in 27 NIM papers (and counting)*

Backup slides

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



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

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

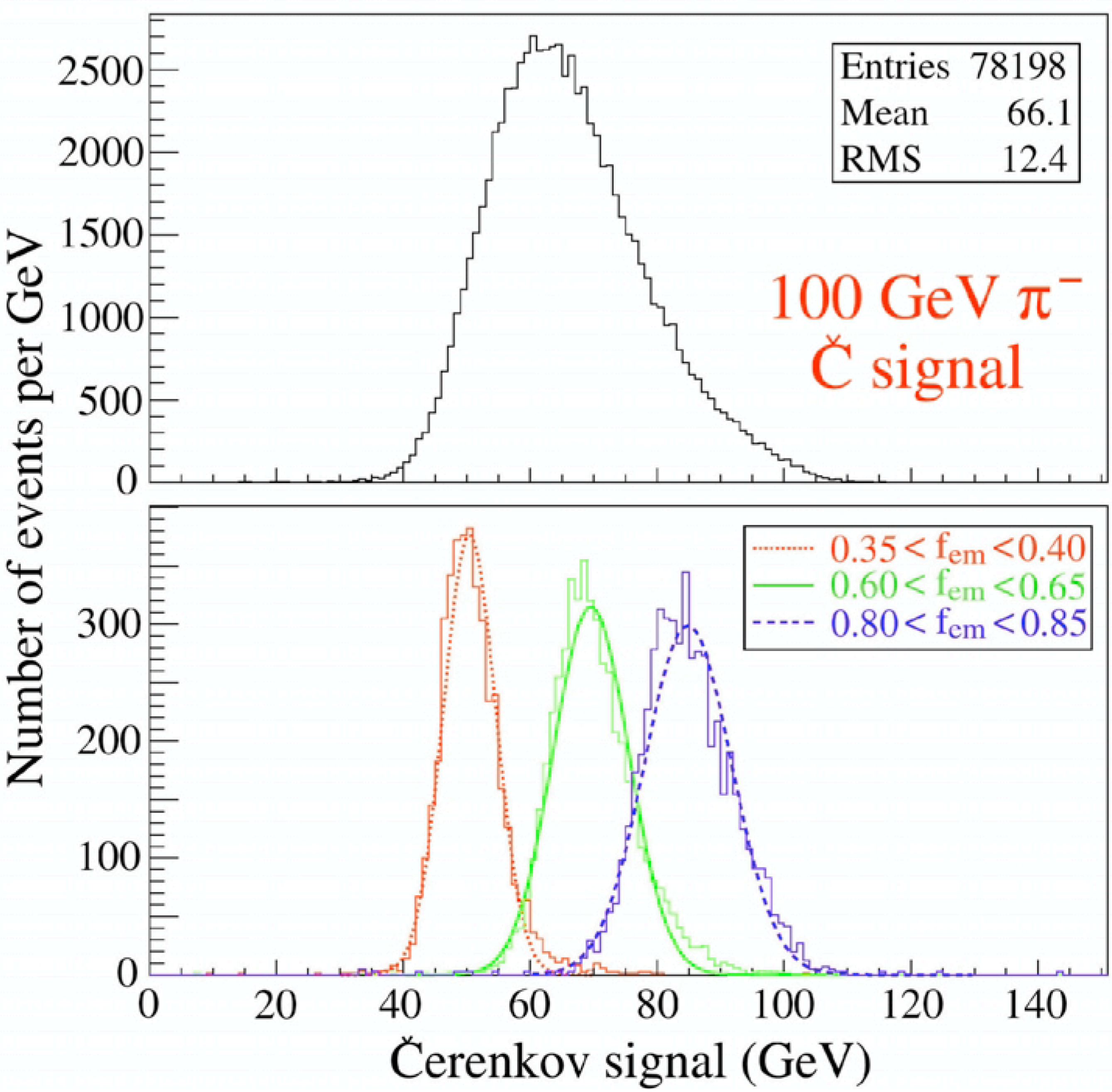
e.g. If $e/h = 1.3$ (S), 4.7 (Q)

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

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

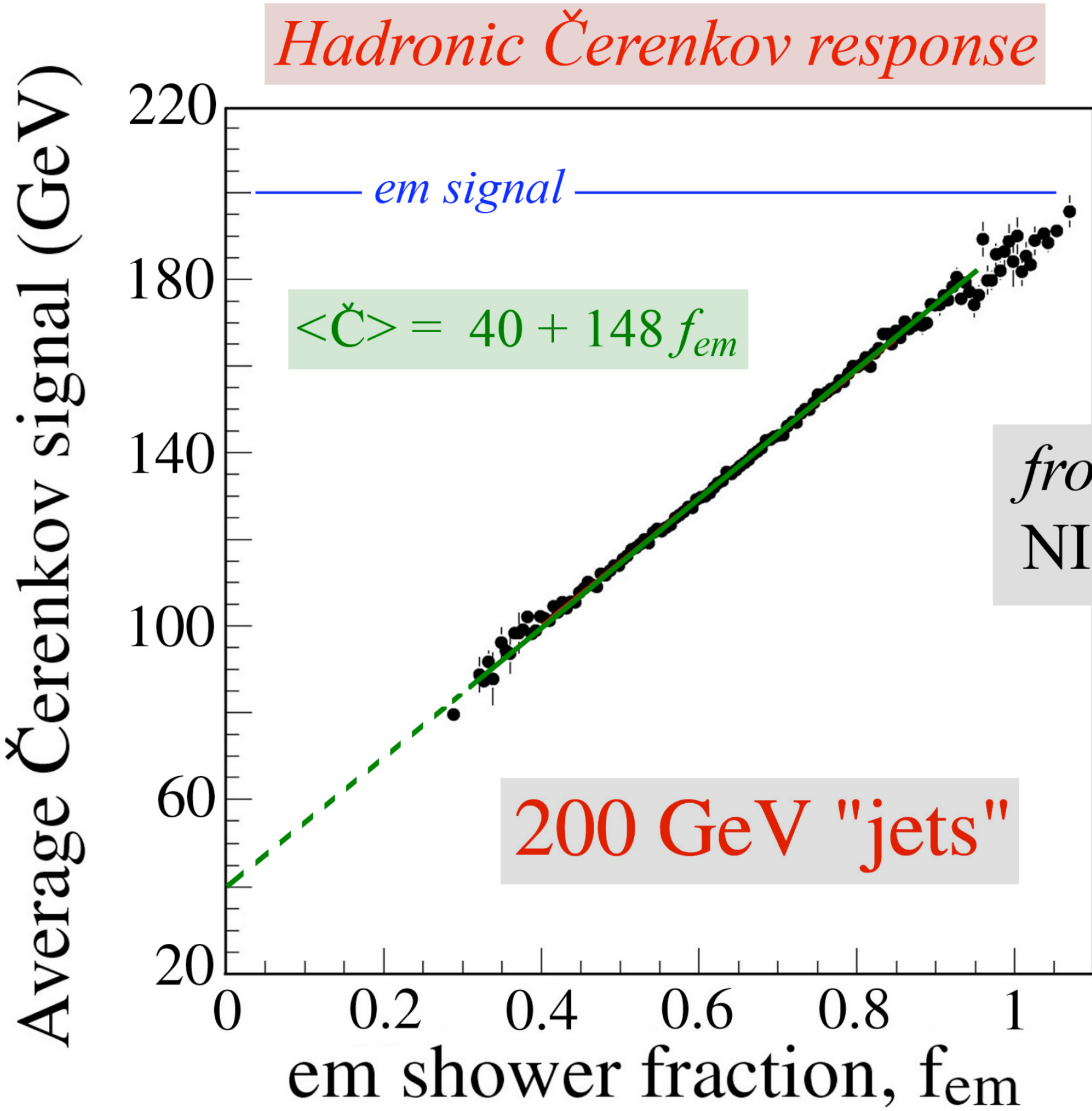
with $\chi = \frac{1 - (h/e)_S}{1 - (h/e)_Q} \sim 0.3$

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



From:
NIM A537 (2005) 537

The dual-readout method



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

$e/h = \frac{p_1}{p_0} + 1 = 4.7$

from:
NIM A537 (2005) 537

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

Experimentally, one measures f_{em} event by event
Scale signal up to $f_{em} = 1$, i.e. the em scale