Dual-Readout Calorimetry
for High-Quality Energy Measurements

*Status report of the RD52 (DREAM) Collaboration**

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CERN, April 14, 2015

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

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

Goal:
Investigate + eliminate the factors that prevent us from measuring hadrons and jets with similar precision as electrons, photons

And thus develop a calorimeter that is up to the challenges of future experiments in particle physics

Outline:

- *New experimental results (6 days in December 2014)*
- *New and improved Monte Carlo simulations*
- *Plans for the future*

D U A L - R E A D O U T   C A L O R I M E T R Y

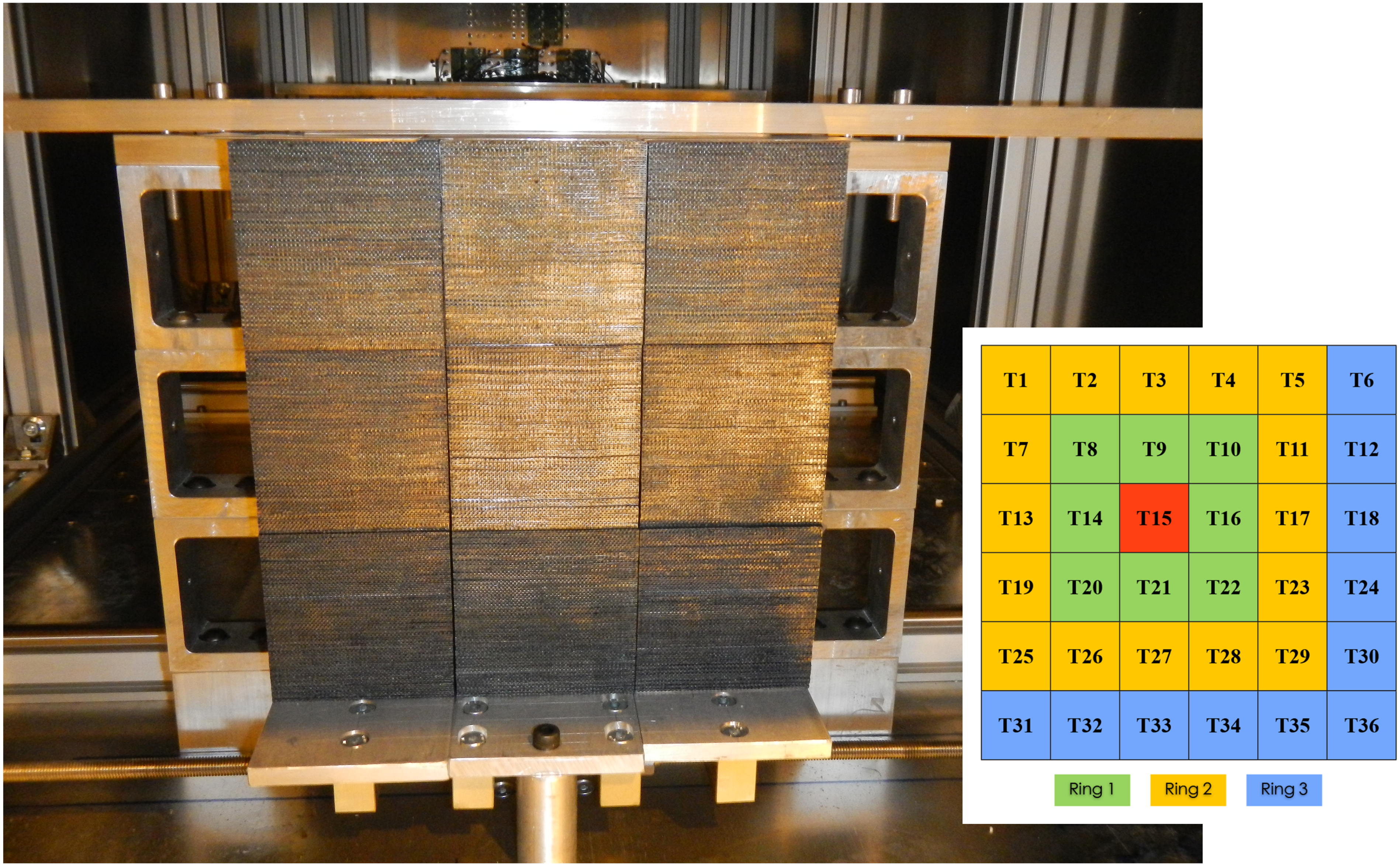
- *Dual-readout Method (DREAM):*

  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)*

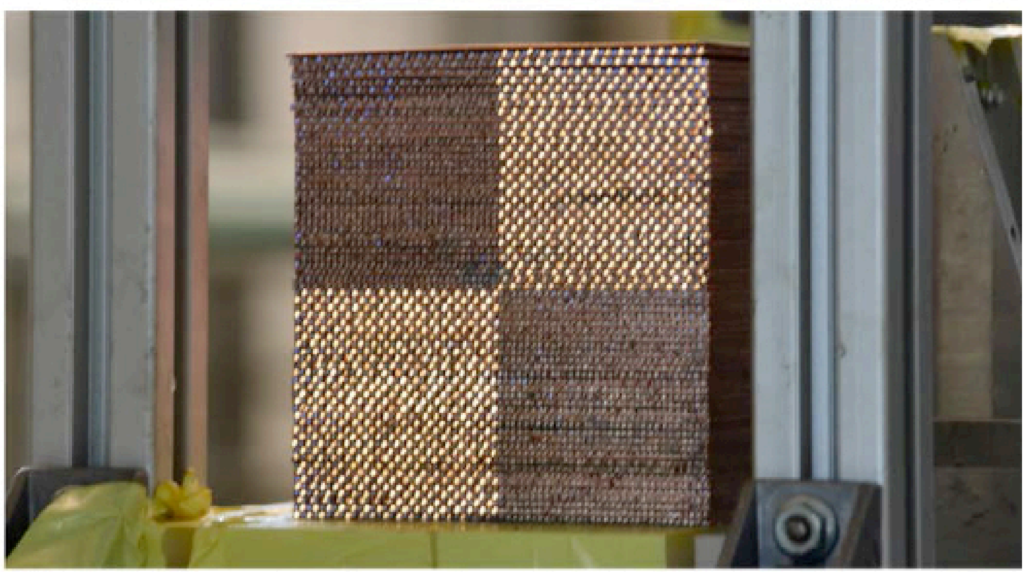
  - *Correct hadronic energy reconstruction, in an instrument calibrated with electrons*
  - *Linearity + excellent energy resolution for hadrons & jets*
  - *Gaussian response functions*

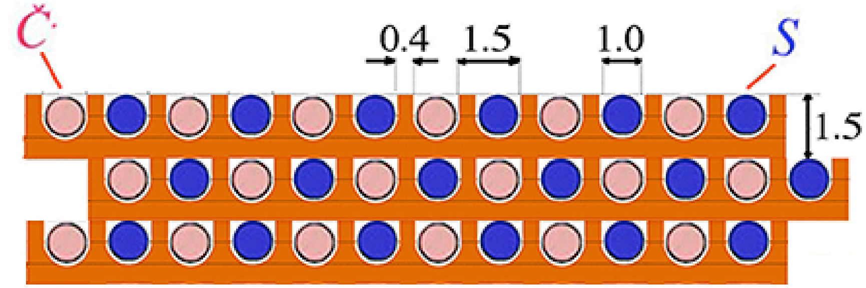
The Pb-fiber calorimeter



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

The first copper module

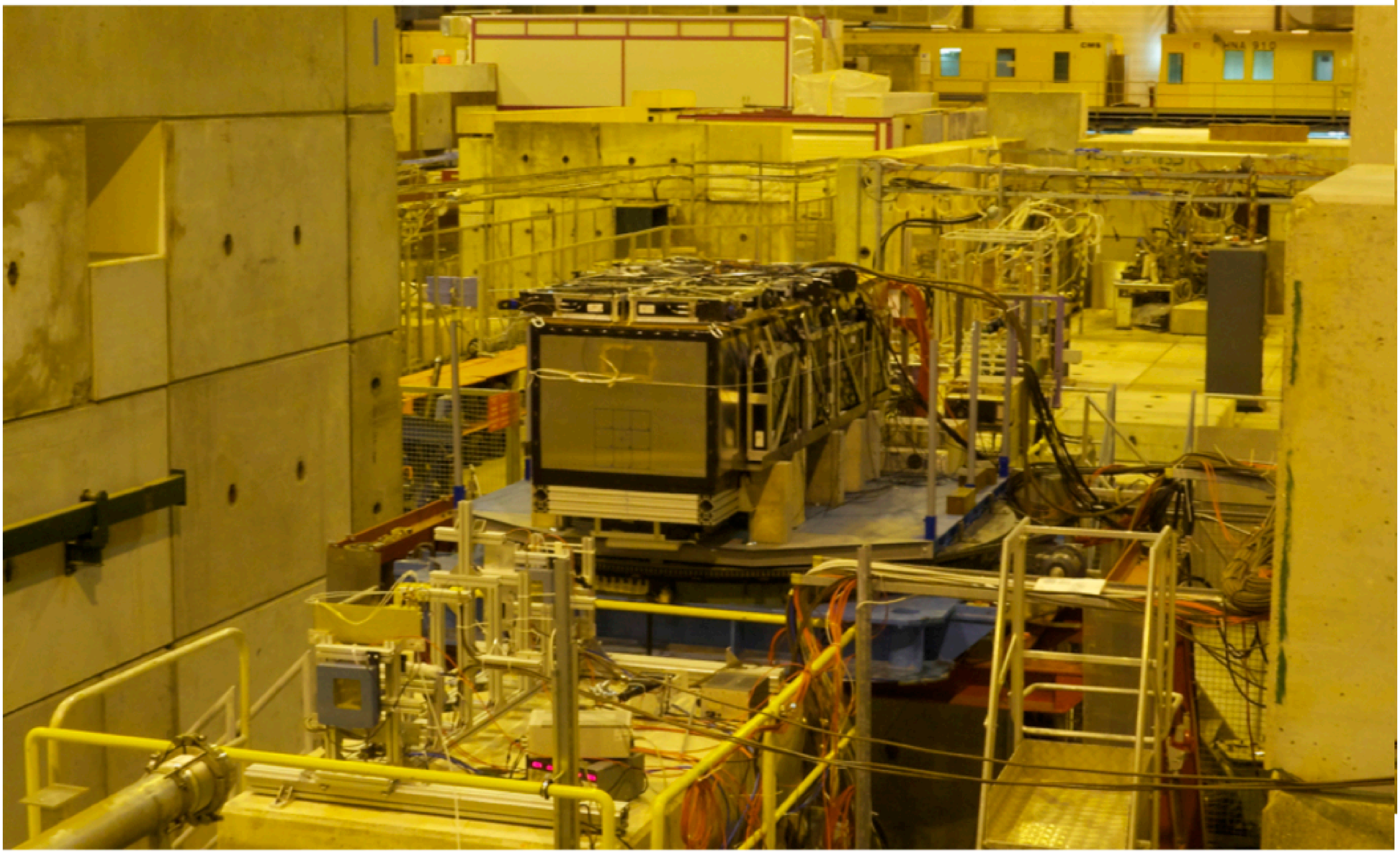




Fiber pattern

2048 S + 2048 Č fibers

The RD52 test area in the H8 beam line



RD52 data taken in December 2014 (6 days)

- *Angular scans with 20 GeV e^+ in the Cu module (-5 to +5 degrees, in 23 steps, 20 kevts/point)**
  - *with and without a $1X_o$ upstream absorber (preshower detector)*
  - *at two different tilt angles*

- *Time structure measurements of e, π, μ in the Pb calorimeter Signals digitized at 5 Gs/s at 30 different locations inside the detector*
  - *100 kevents @ 180 GeV*
  - *100 kevents @ 125 GeV*
  - *100 kevents @ 100 GeV*
  - *100 kevents @ 80 GeV*
  - *100 kevents @ 60 GeV*
  - *100 kevents @ 40 GeV*
  - *80 kevents @ 20 GeV*
  - *70 kevents @ 15 GeV*

** Thanks to rotating table with mrad precisison provided by I. Efthymiopoulos, M. Jeckel*

New experimental results (6 days in December 2014)

- *The performance for electrons at very small angles of incidence (20 GeV e^+ in Cu calorimeter)*

The small-angle performance of a dual-readout fiber calorimeter

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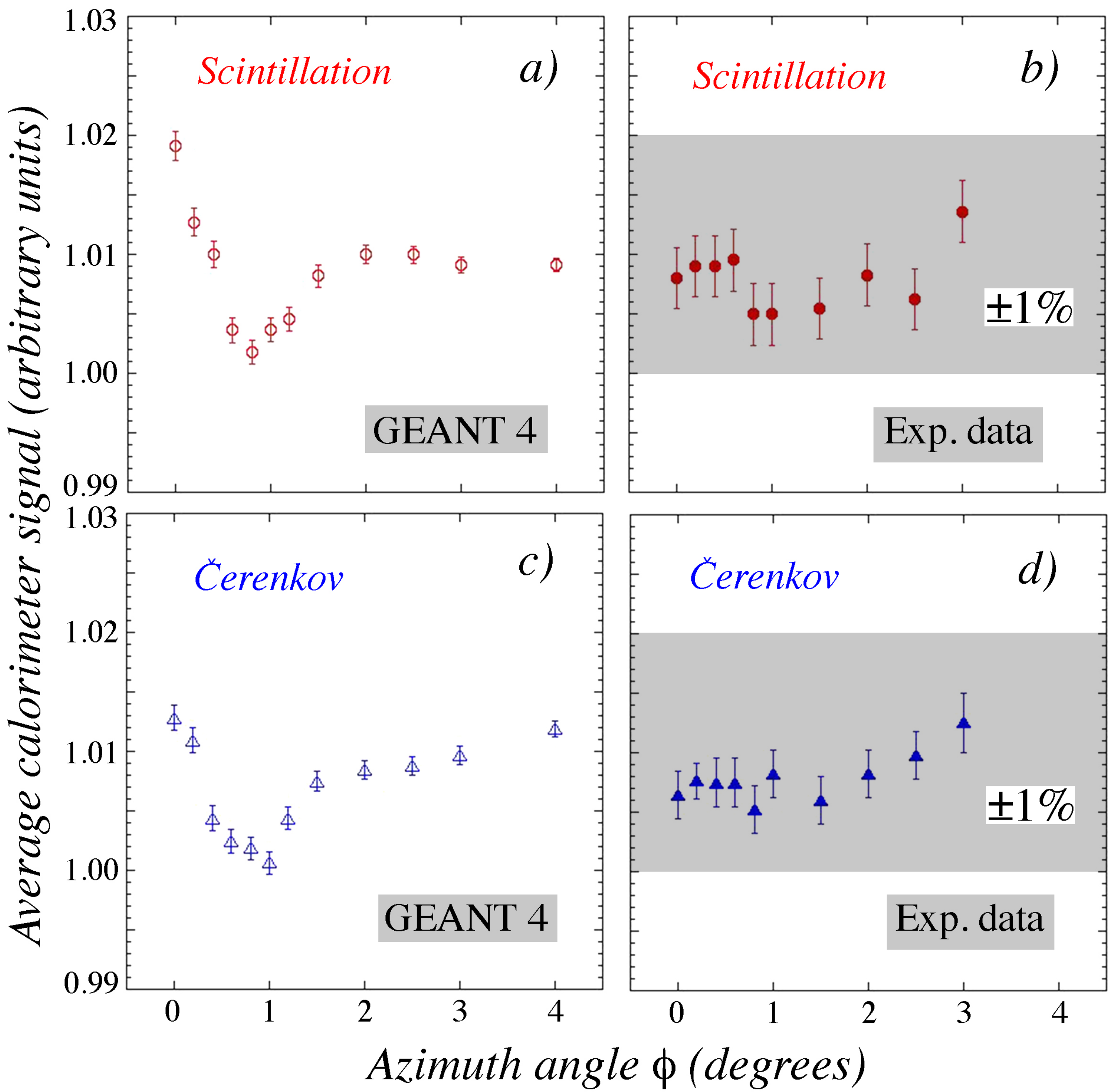
Abstract

The performance of the RD52 dual-readout calorimeter is measured for very small angles of incidence between the 20 GeV electron beam particles and the direction of the fibers that form the active elements of this calorimeter. The calorimeter response is observed to be independent of the angle of incidence for both the scintillating and the Čerenkov fibers, whereas significant differences are found between the angular dependence of the energy resolution measured with these two types of fibers. The experimental results are on crucial points at variance with the predictions of GEANT4 Monte Carlo simulations.

PACS: 29.40.Ka, 29.40.Mc, 29.40.Vj

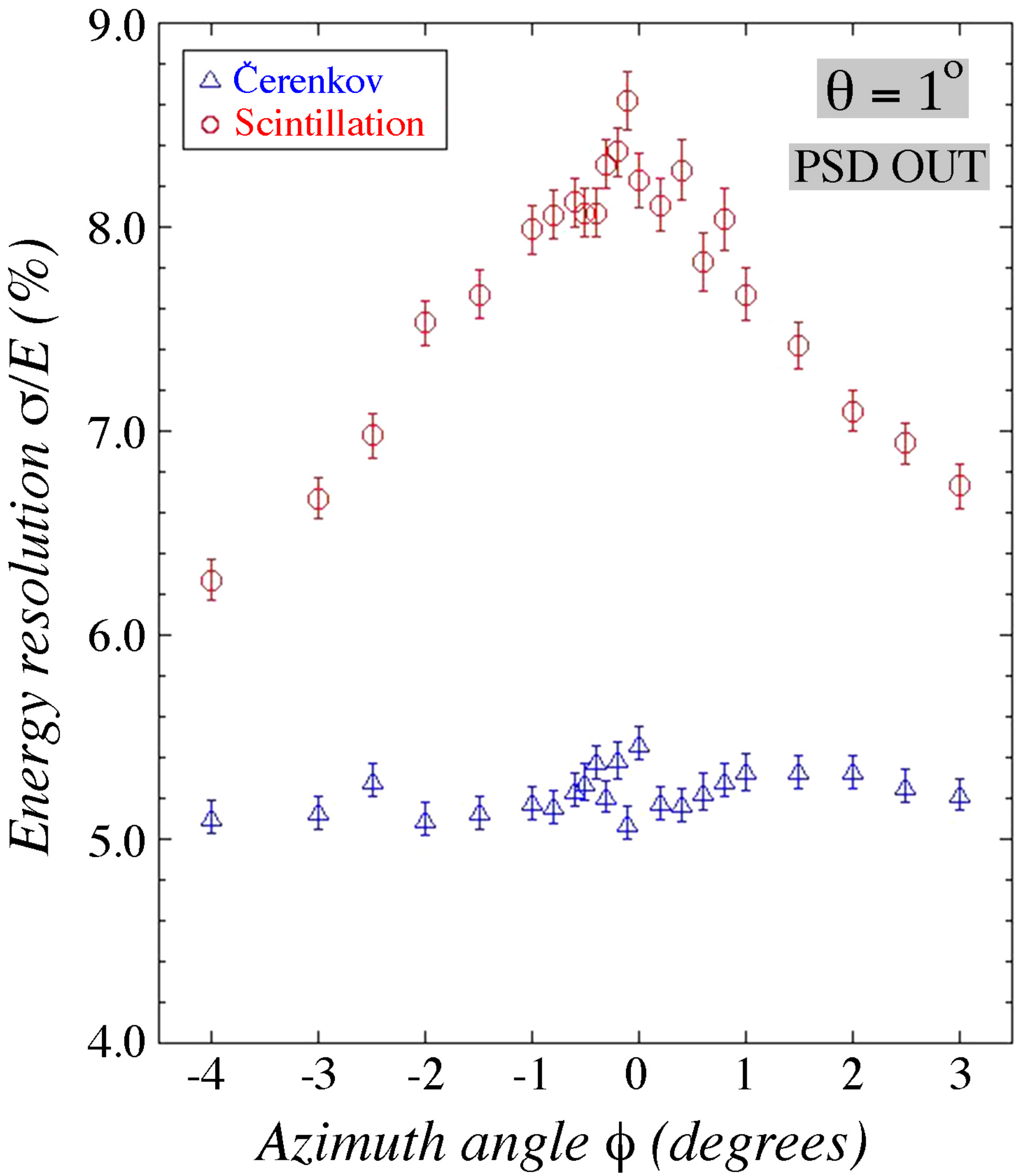
Key words: Dual-readout calorimetry, Čerenkov light, optical fibers

Does the calorimeter response depend on the angle of incidence?



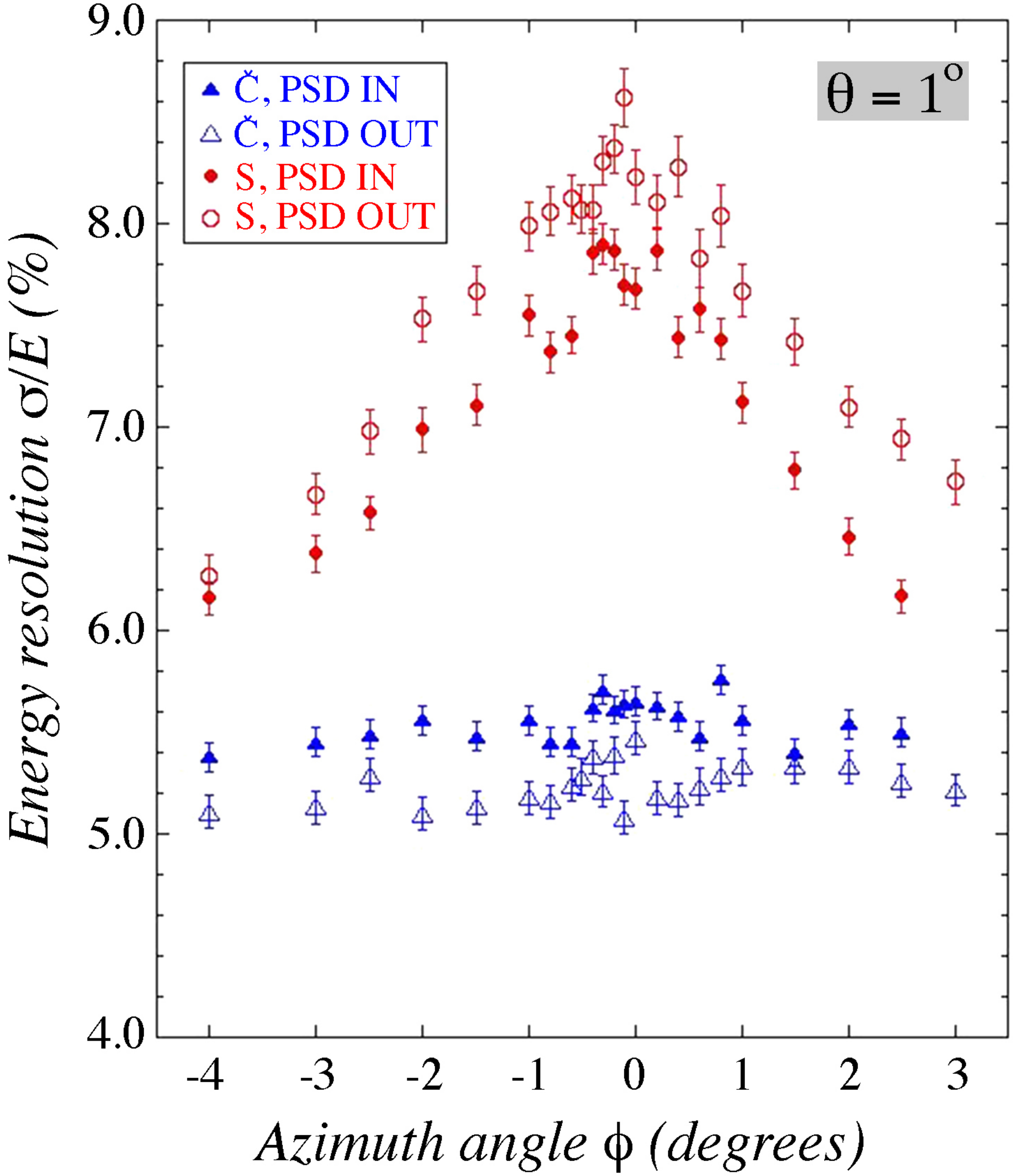
NB: GEANT4 predictions are for lead absorber!
(published in NIM A762,100)

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_O) on the em energy resolution

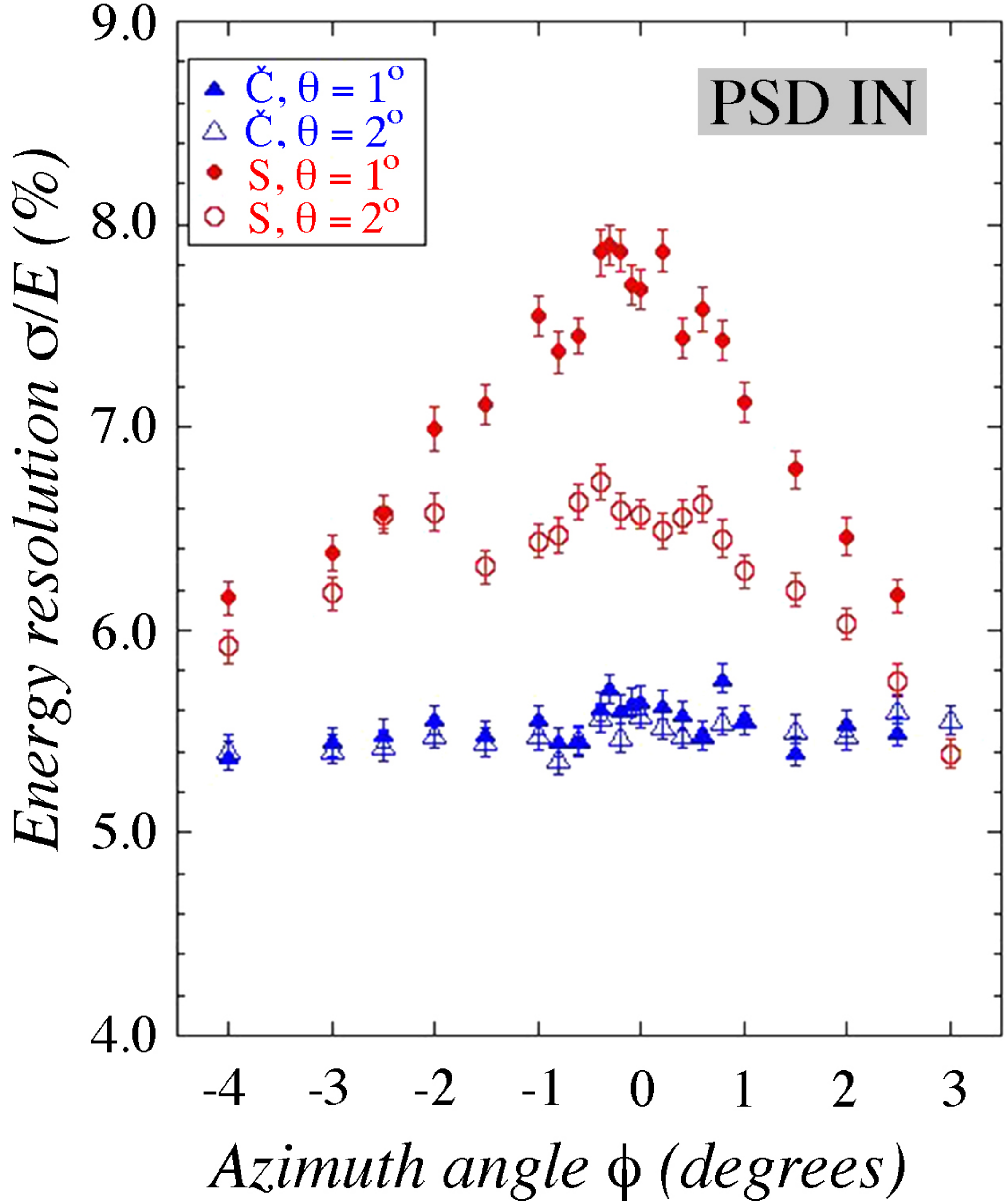


Effects of absorber:

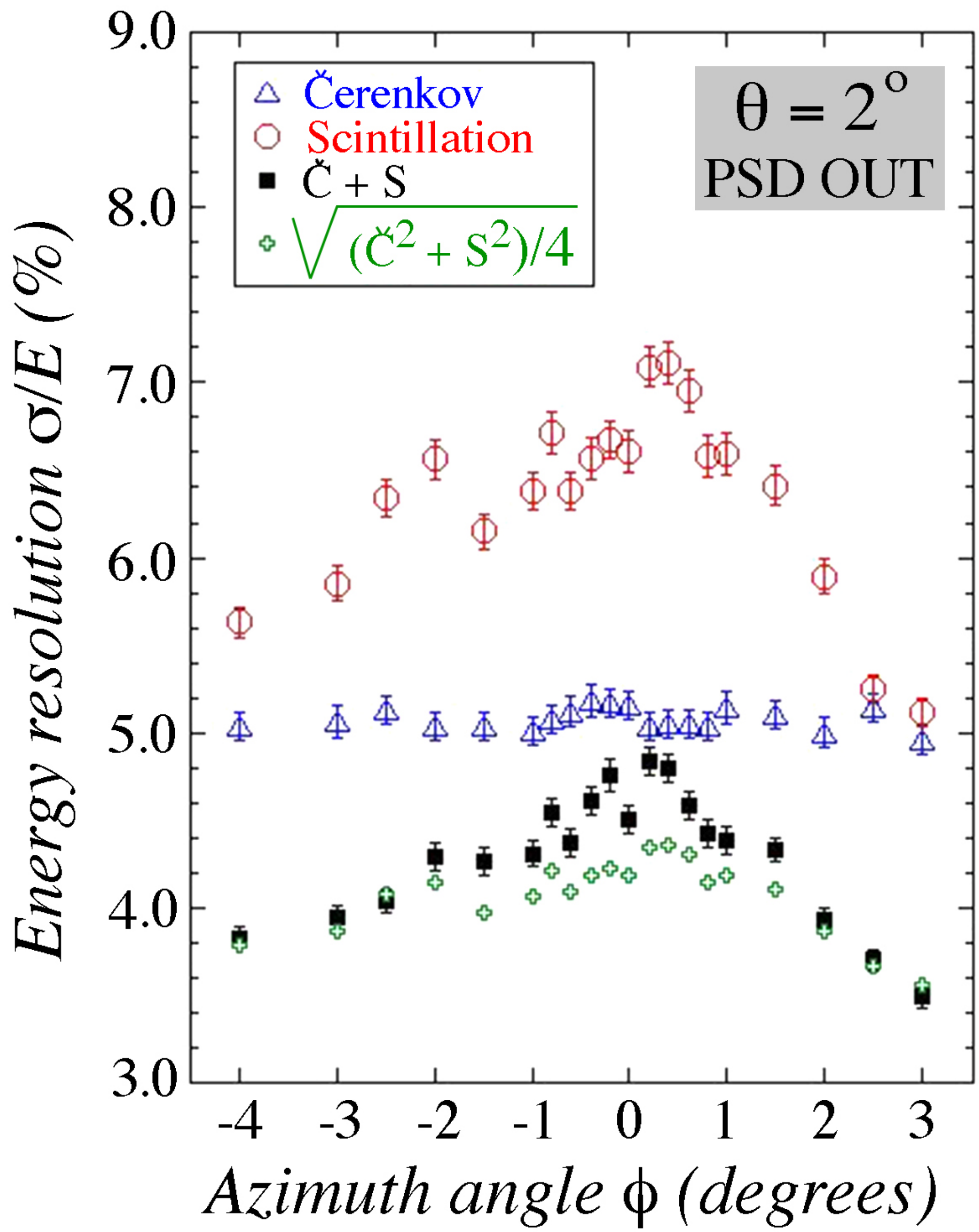
It widens the shower and thus reduces impact point dependence of the response

Fluctuations in energy loss lead to a worse energy resolution

Effect of a change in the tilt angle on the energy resolution (20 GeV e^+)



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

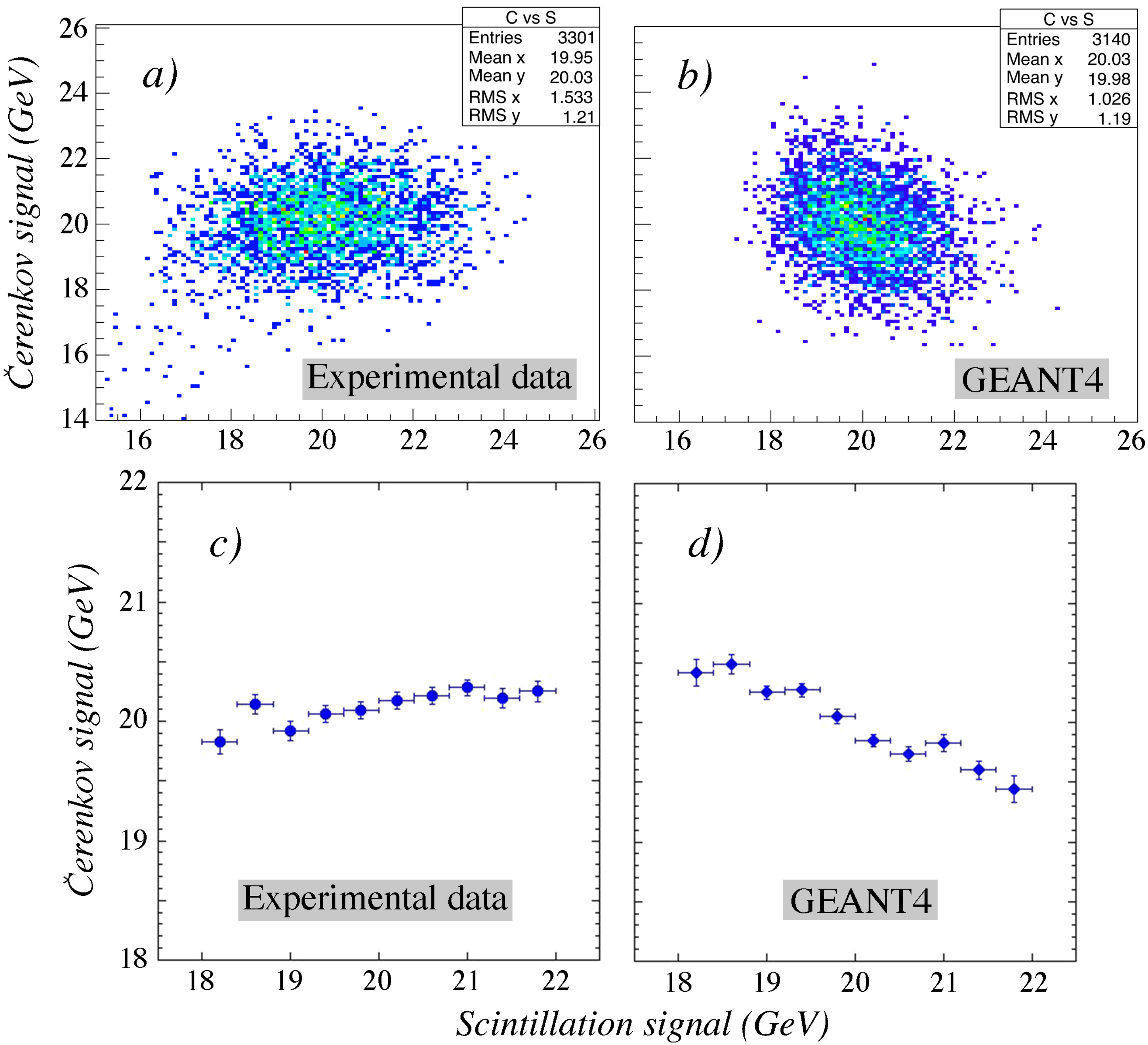


ZEUS: 4.3%
SPACAL: 4.1%

GEANT4: 2.8%
(8.3%/$\sqrt{E}$, 30 Cpe/GeV)

NB: 20 x 30 = 600 Cpe
$\sqrt{600}/600 = 4.1\%$

Is there an anti-correlation between the two types of calorimeter signals?



New experimental results
(6 days in December 2014)

- *Detailed time structure measurement of calorimeter signals*

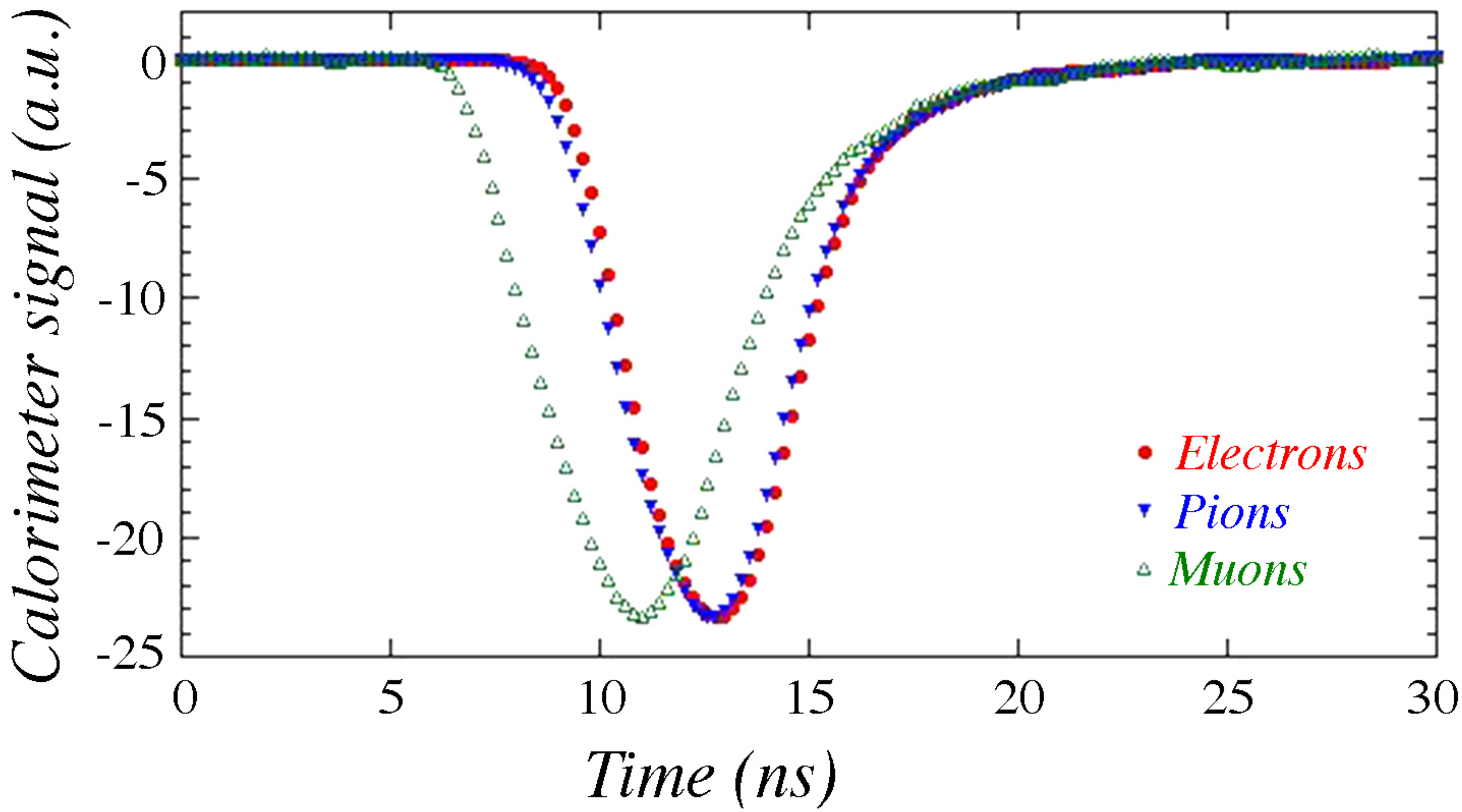
(40 GeV mixed e, π, μ beam, signals digitized at 5 Gs/s)
Beam steered into Tower 15 of the lead calorimeter

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

Average calorimeter signals (40 GeV)

Čerenkov signals around the beam axis



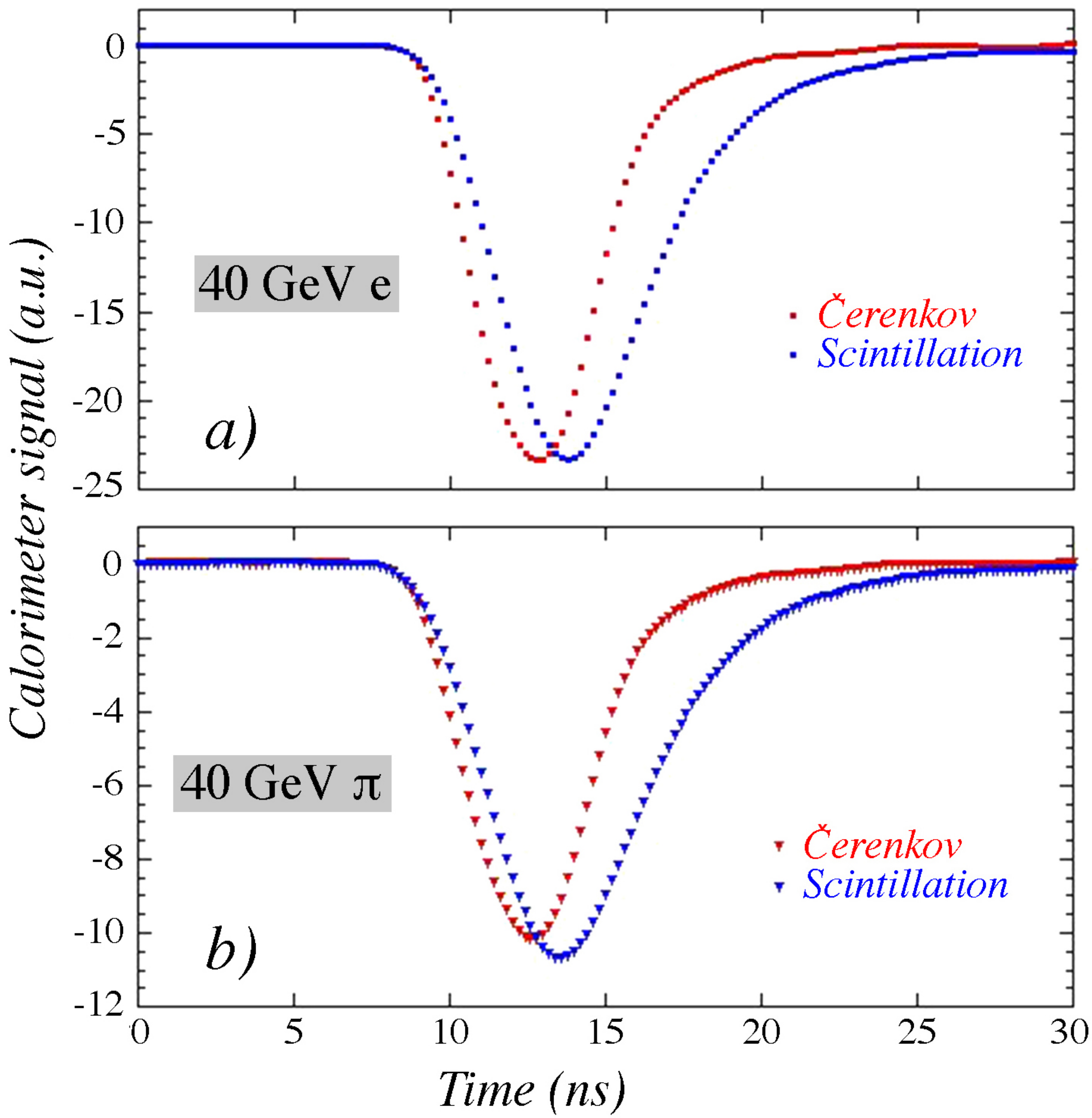
Where is Č light produced?

Electrons: depth shower maximum ~5 cm

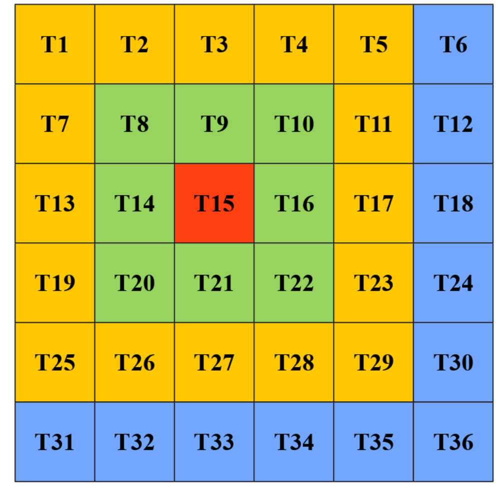
Pions: depth shower maximum~ 25 cm

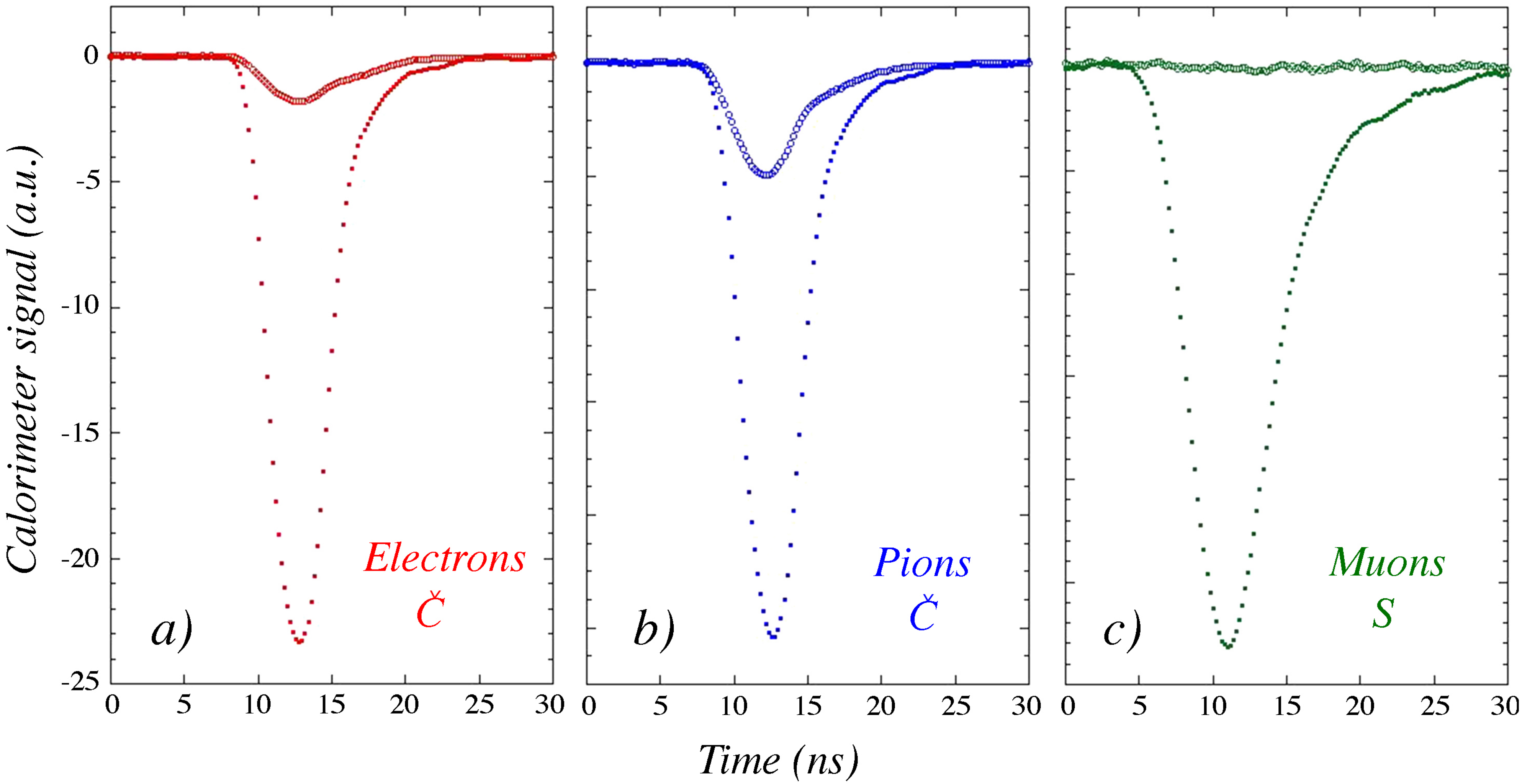
Muons: average depth light production ~125 cm

Comparison Čerenkov / Scintillation signals (around shower axis)

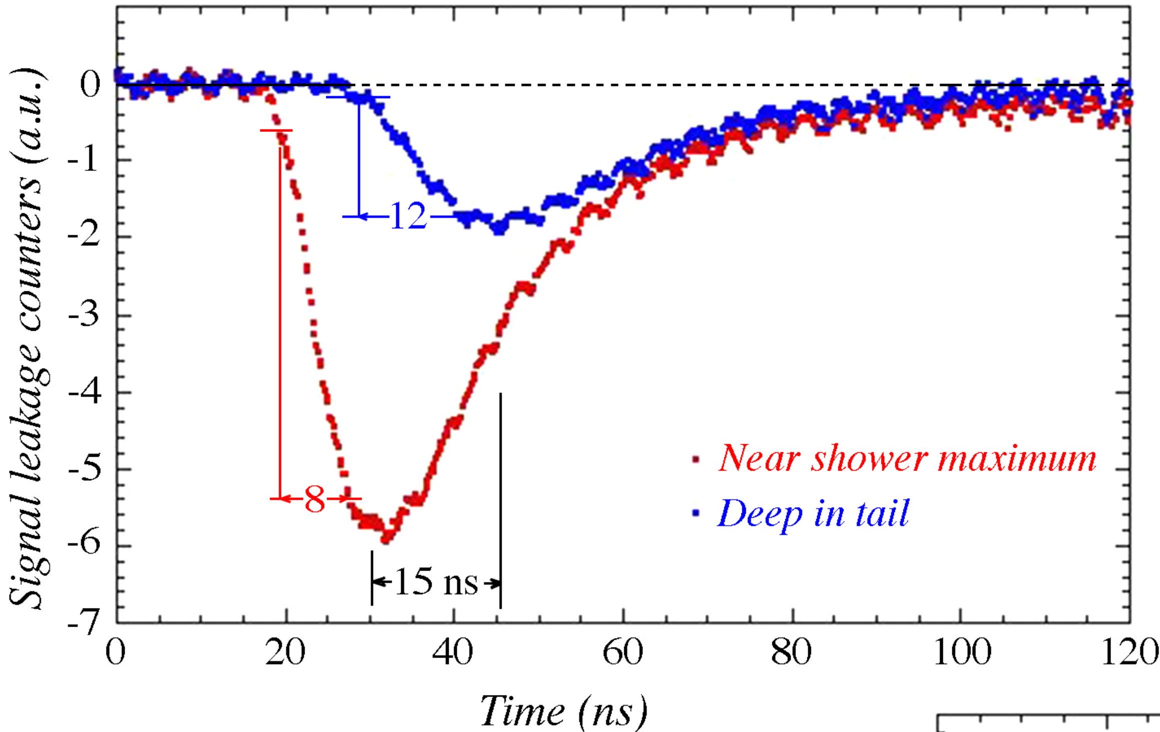


Comparison on-axis / off-axis calorimeter signals
Tower 15 / Tower 21





Comparison signal shapes leakage counters

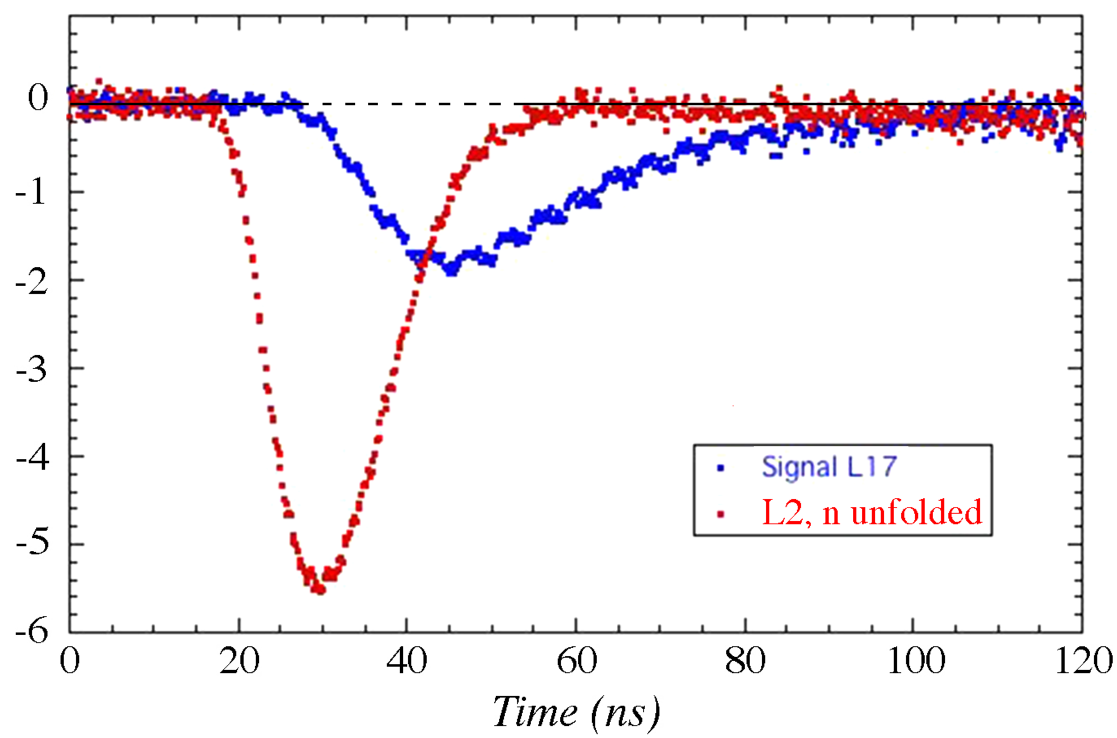


Expected signal contributions:

- prompt charged shower particles

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

n contribution unfolded



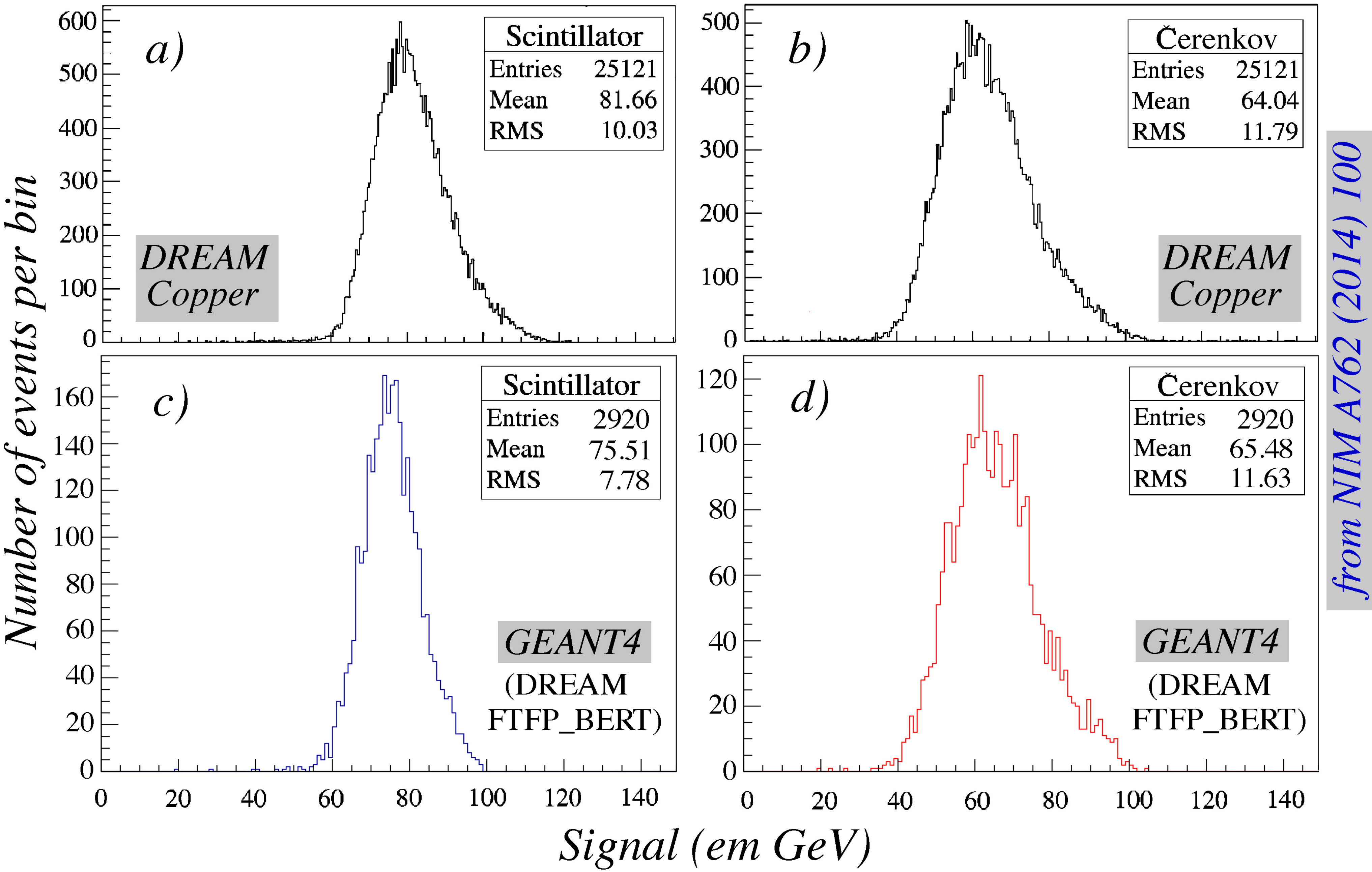
New, improved hadronic Monte Carlo simulations

- *2014 paper: Nucl. Instr. Meth. A762 (2014) 100*
  - *How well is measured hadronic shower performance described?*
  - *How well does the DREAM method work in GEANT4?*
  - *What improvement is expected for a full size Cu based calorimeter?*

- *Repeated some of these simulations with high-precision version of hadronic shower development package (neutrons followed in detail)*

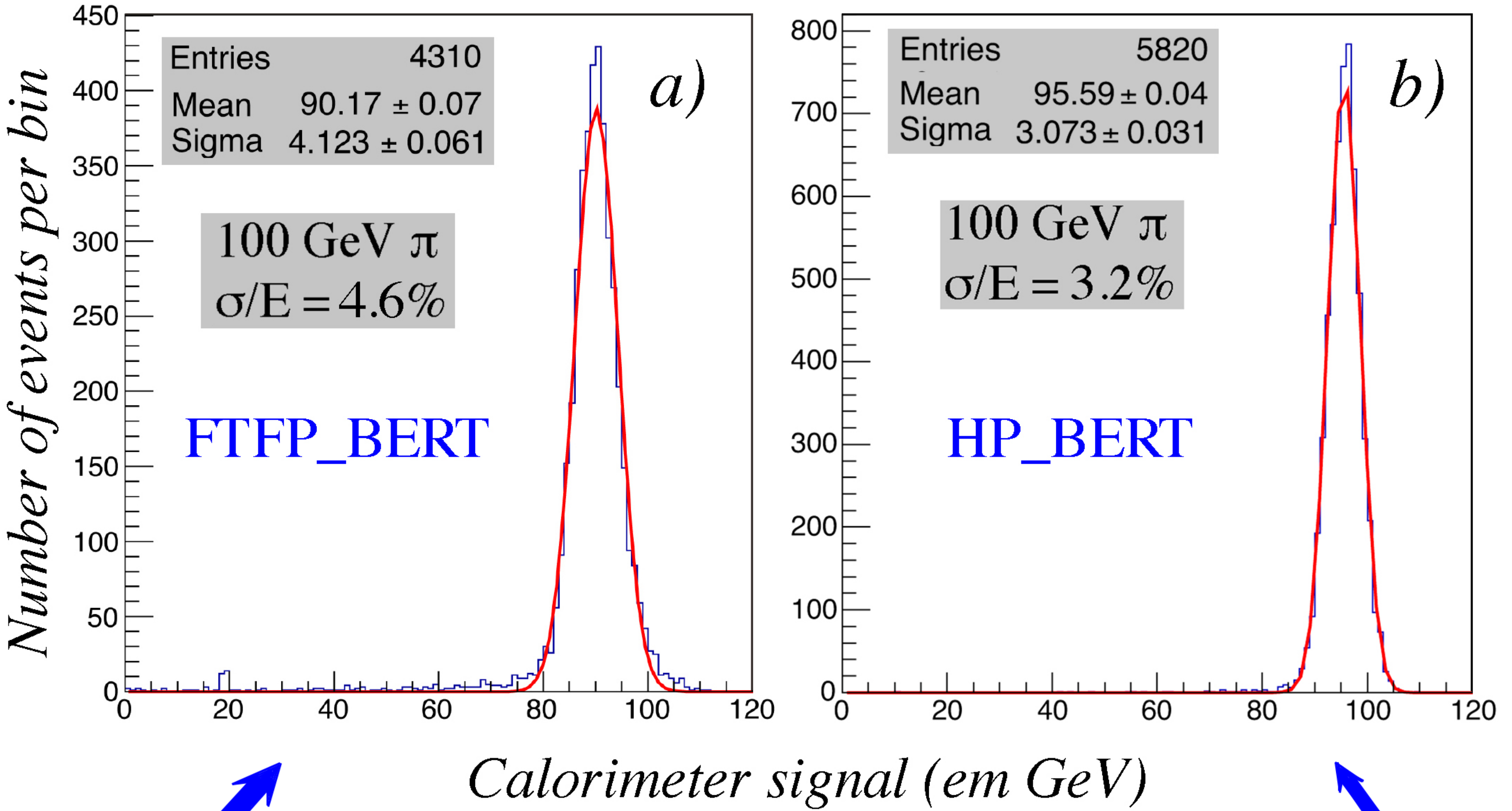
  Extremely CPU time consuming

Hadronic response functions of the DREAM Cu-fiber calorimeter



GEANT4 simulations of 100 GeV π

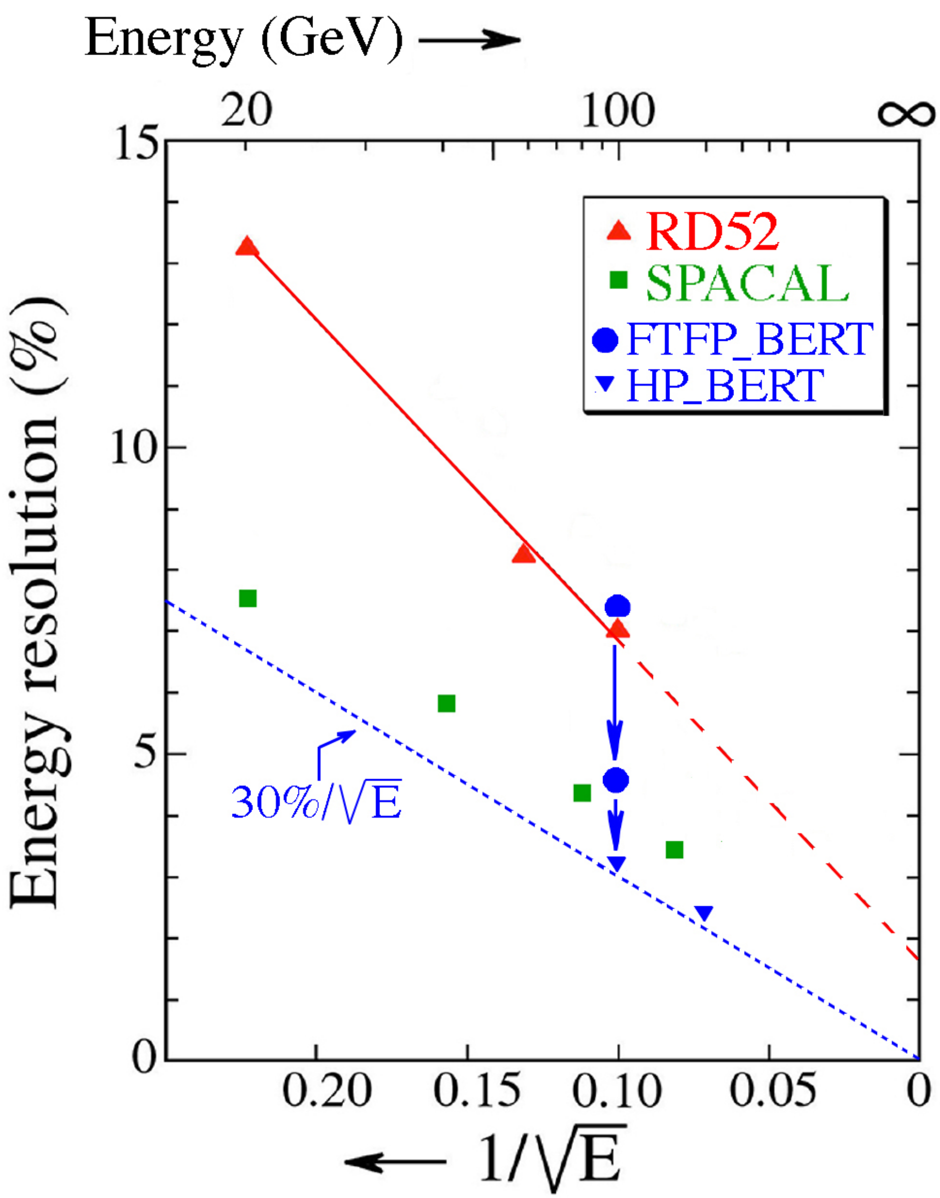
RD52_Cu   65 x 65 cm^2



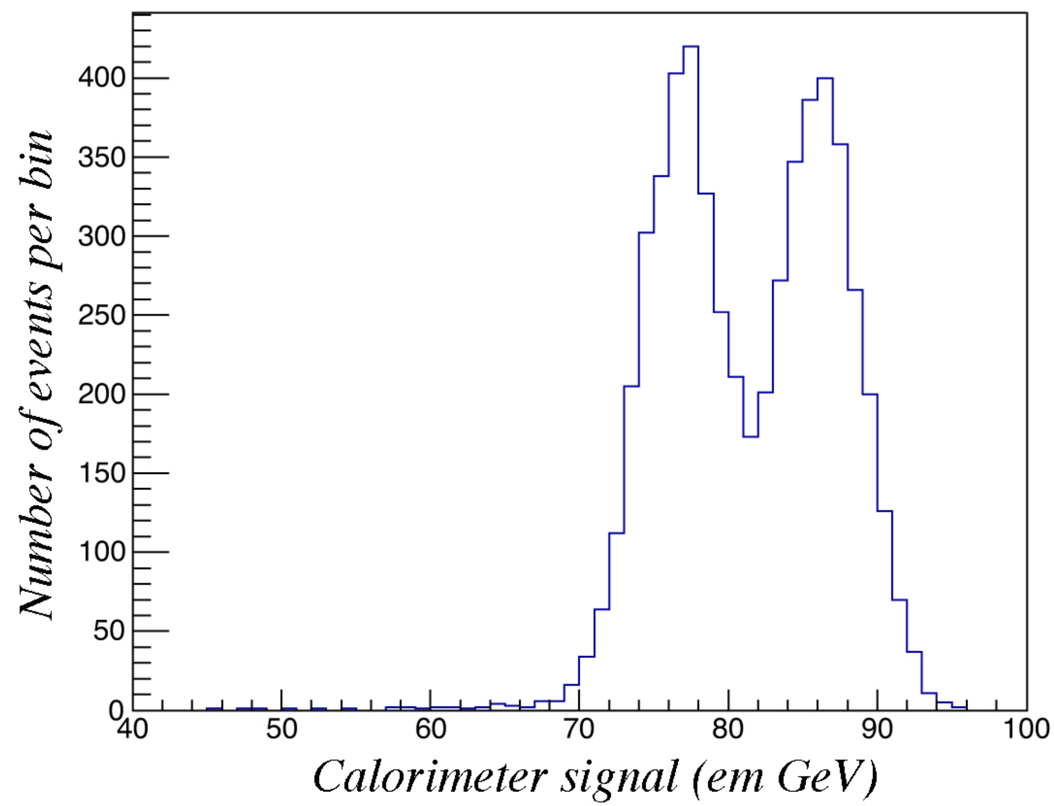
Standard hadronic shower simulation package

High precision simulation package (neutrons!!)

Hadronic energy resolution dual-readout Cu-fiber calorimeter



W/Z separation (high-precision GEANT4)



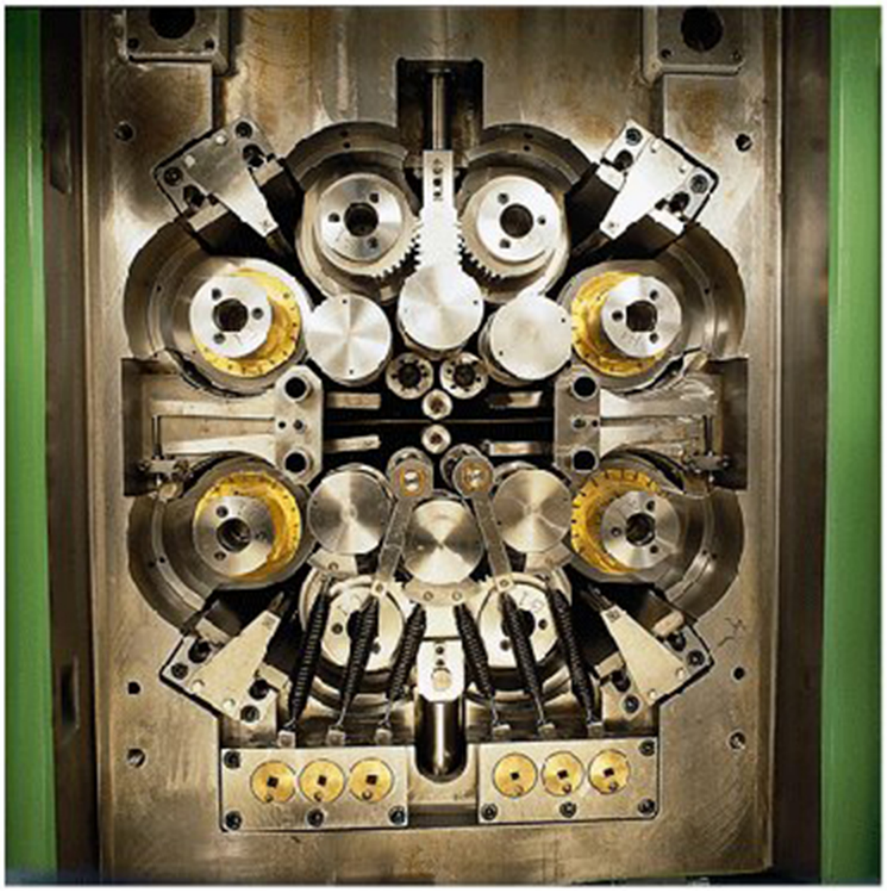
Our plans for the future

- *Important problem: No new funding*
  RD52 has been reduced to a " coalition of the willing" with few resources

- *Another problem: Mass production of Cu absorber structure*
  Copper is a particularly nasty material. However, rolling looks promising

Copper rolling for the new dual-readout Cu-fiber calorimeter

(PMX, ISU, Ames Lab)

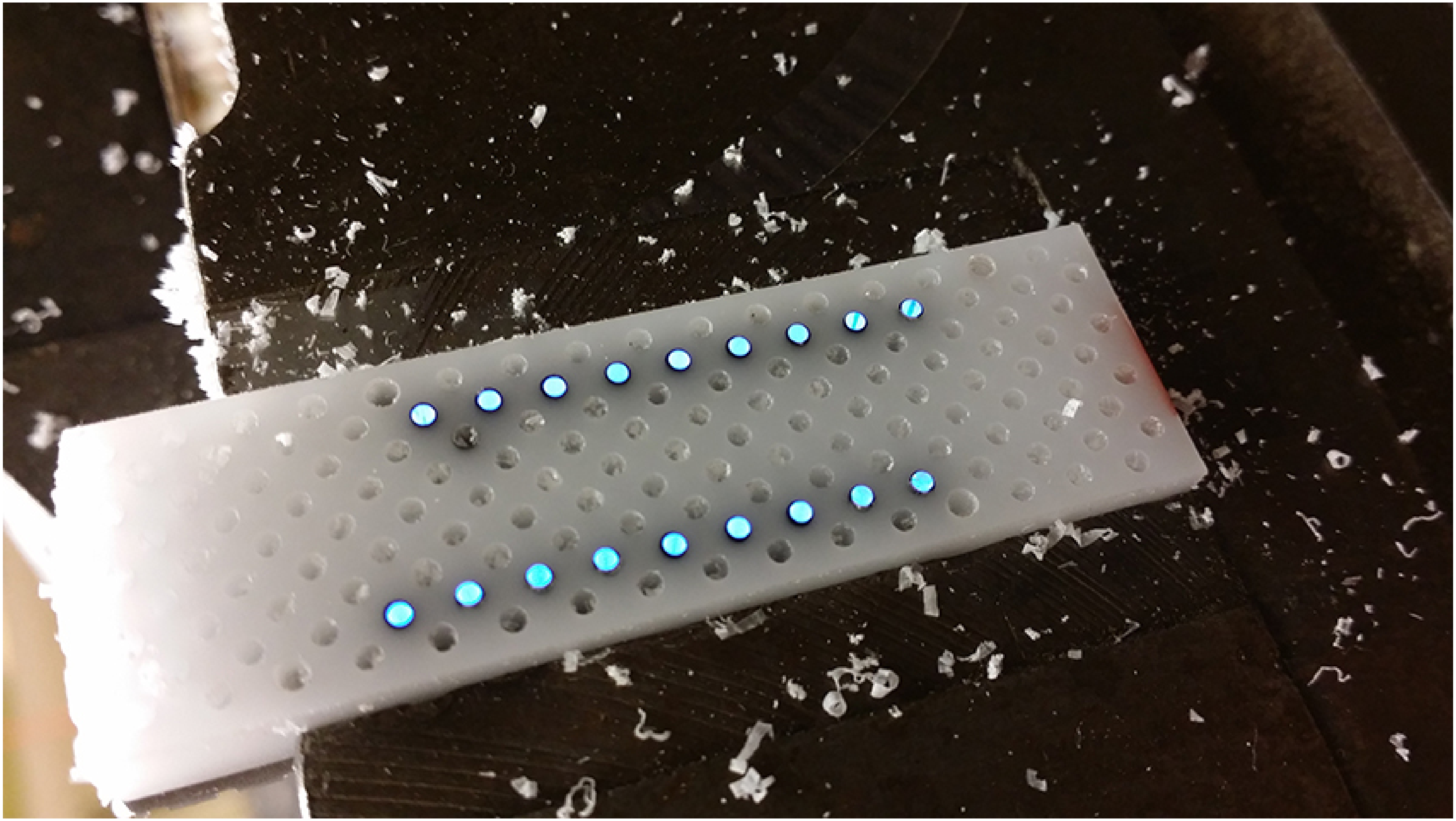


a)

b)

Preparation of new Cu-fiber module

Fiber studies at ISU



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- *We are ready (and have the resources) to build a 3-4 ton fiber calorimeter as soon as copper of acceptable quality becomes available*

- *Plans for 2015:*
  - *Time structure measurements with much faster light detector (MCP-PMT, rise time 0.5 ns, transit time spread 35 ps)*
  - *Measurements of differences between proton/pion/kaon (?) induced showers Čerenkov characteristics, time structure differences*
  - *For this part of our program we request 2 weeks of beam time in H8C*
    If the large new calorimeter becomes available, we need 2 additional weeks
    However, 2016 is more realistic for that part of the program

Time structure of the signals

- *Analysis of 2014 data has just started.*
  Results shown here concern averages of few thousand events

- *Individual events:*
  - where was light produced?→ correct for light attenuation.

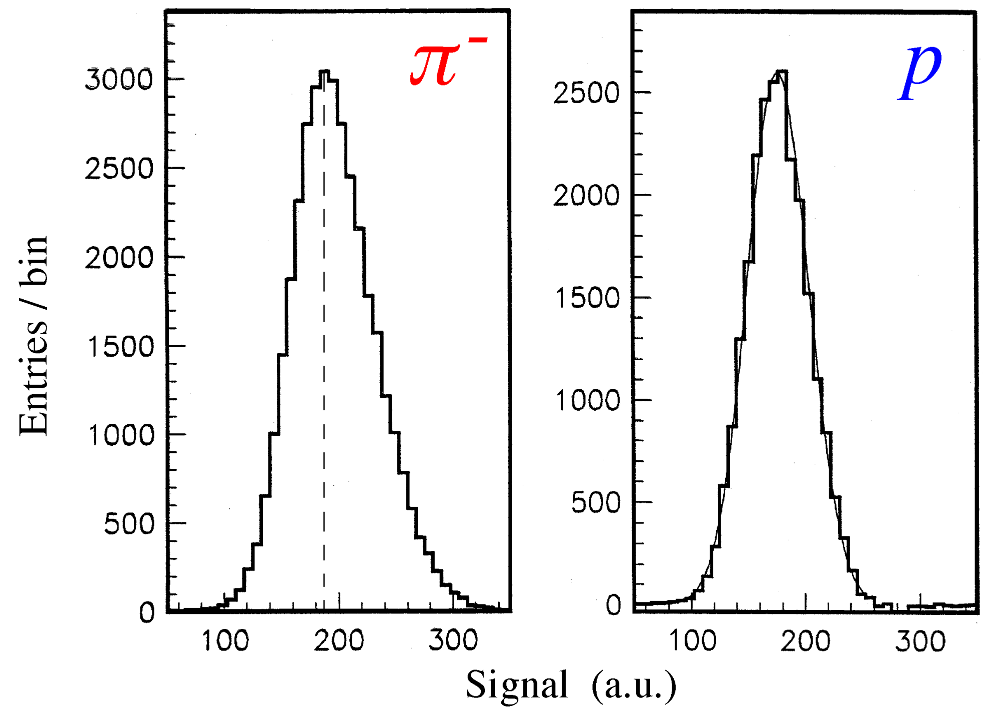
  - what fraction of signal is due to neutrons?→ improve resolution.

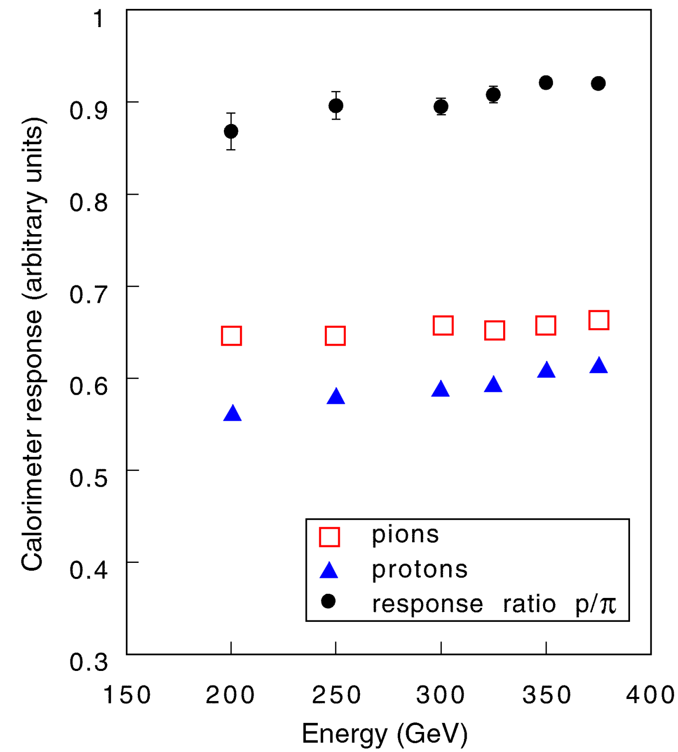
  - recognize non-showering particles (μ) → particle ID

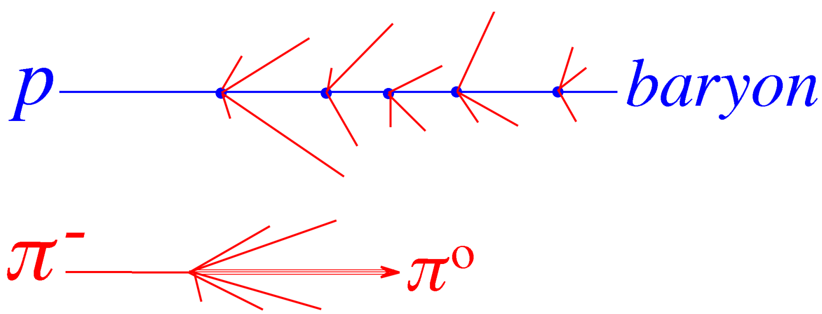
  - multiple peaks in time structure may be caused by pileup → resolve.
  can be studied with reflected light from aluminized front face fibers.

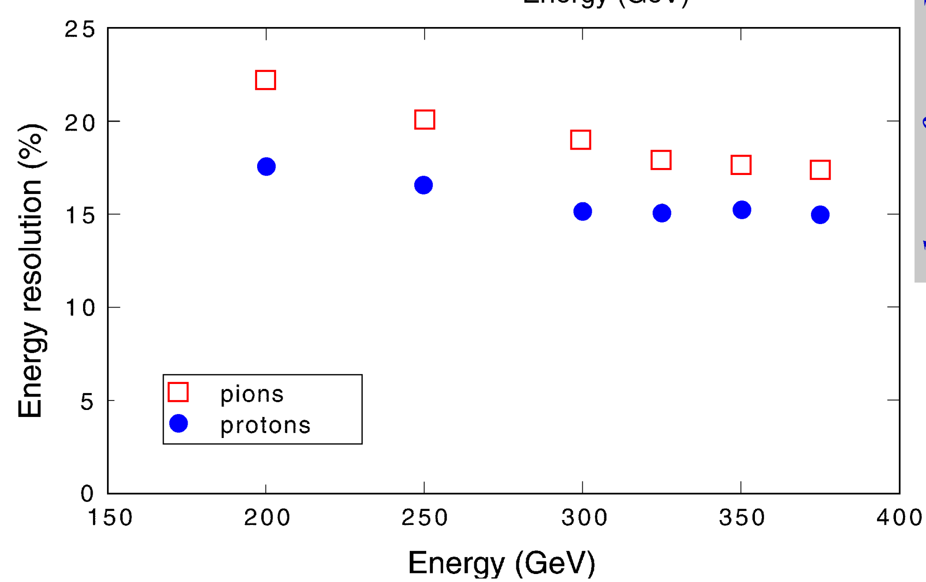
- *All these issues will benefit from faster light detector, especially for Čerenkov signals.*
  New MCP-PMT is much faster than our dynode based PMTs

Proton / pion differences in calorimeter signals
caused by differences in em shower fraction characteristics









data from NIM A408 (1998) 380

em fraction in p showers:
- *smaller*
- *less fluctuations*
- *more symmetric*
- *less concentrated near axis*

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*

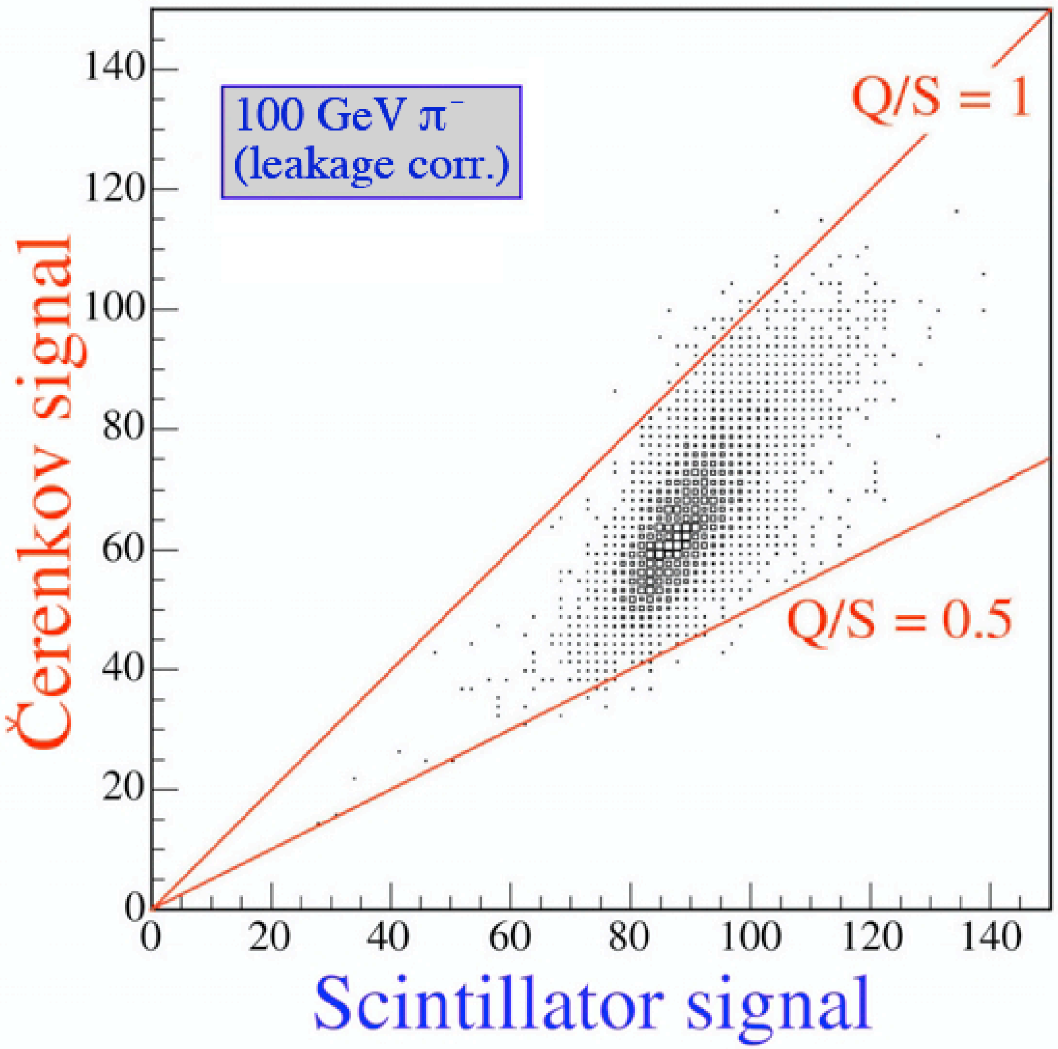
  Time structure measurements of signals may further extend possibilities (pileup, particle ID, ...)

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

- *Thanks to SPS staff who have supported us over the years*

Backup slides

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



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

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

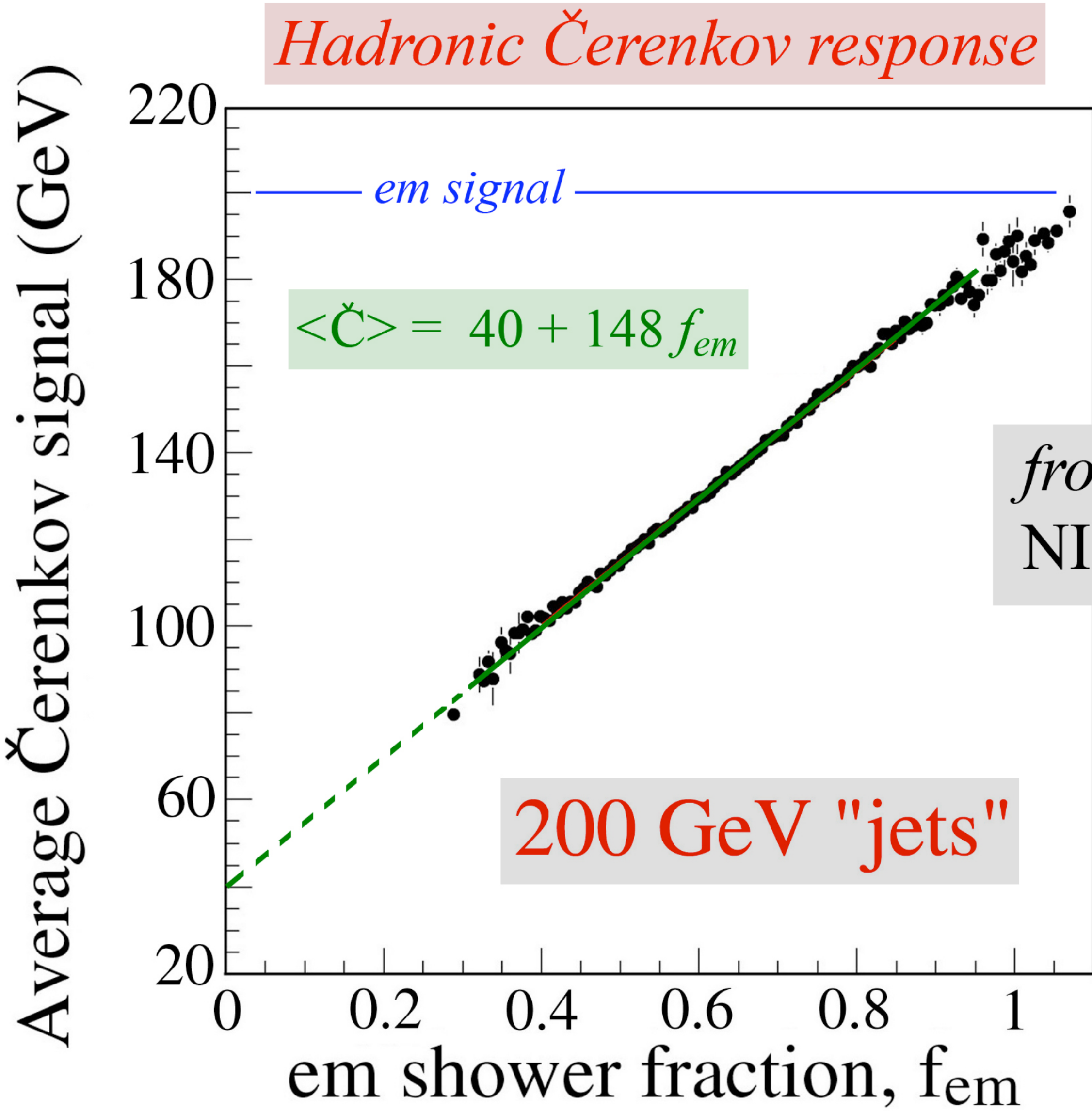
e.g. If $e/h = 1.3$ (S), 4.7 (Q)

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

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

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

The dual-readout method



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

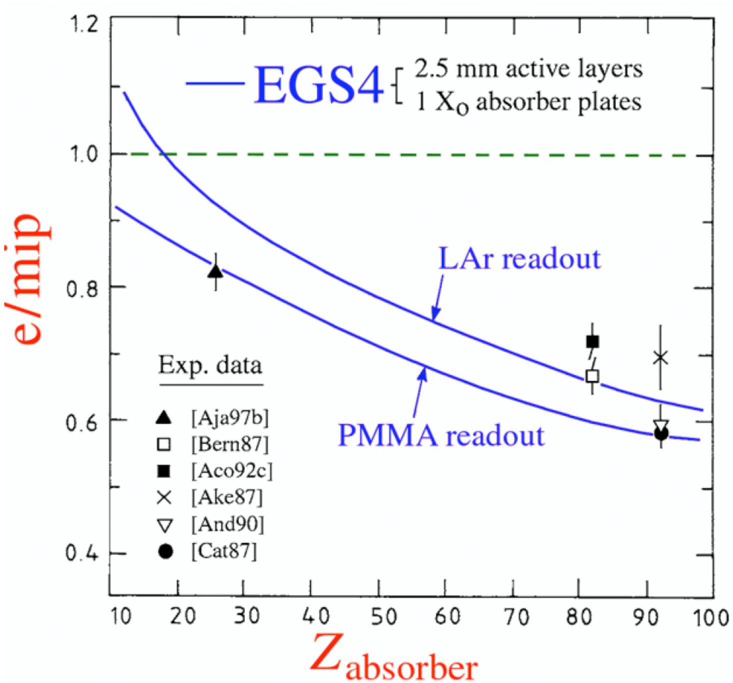
$$e/h = \frac{p_1}{p_0} + 1 = 4.7$$

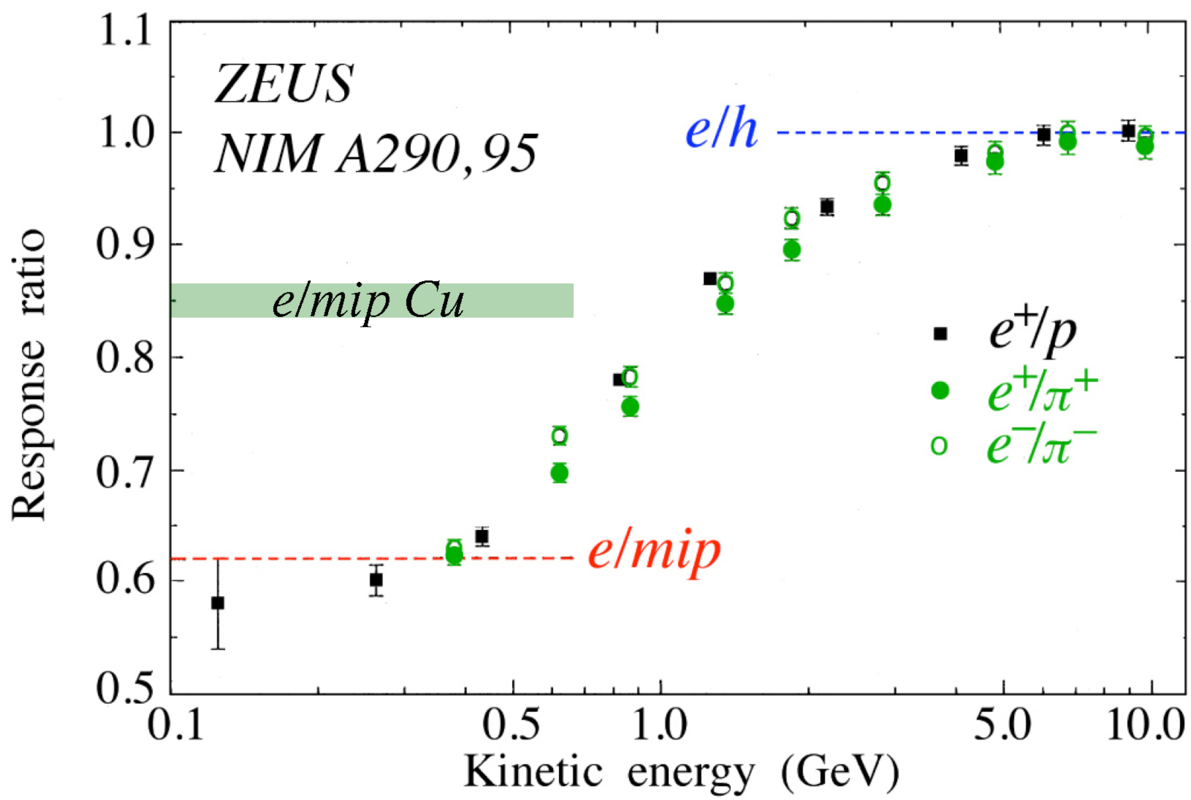
from:
NIM A537 (2005) 537

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

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

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