Dual-Readout Calorimetry
for High-Quality Energy Measurements

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

Richard Wigmans

CERN, April 19, 2016

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* *DREAM (RD52) Collaboration:*
Cagliari, Cosenza, Lisbon, Pavia, Pisa, 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:

- *Papers published in 2015*
- *New experimental results (2 weeks in November 2015)*
- *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*

New RD52 papers published since SPSC 2015 presentation*

Nuclear Instruments and Methods in Physics Research A 808 (2016) 41–53

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

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

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ARTICLE INFO

Article history:
Received 1 July 2015
Received in revised form 30 October 2015
Accepted 3 November 2015
Available online 12 November 2015

Keywords:
Dual-readout calorimetry
Čerenkov light
Optical fibers

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.

1. Introduction

Sampling calorimeters based on large numbers of optical fibers embedded in a metal absorber structure offer some distinct advantages compared to other detectors of high-energy particles. Since the fibers act at the same time as the active medium in which the signals are produced and as a wave guide transporting the signals to the outside world, it is possible to construct hermetic detector structures, which is very important in modern colliding-beam experiments. Also, the very frequent shower sampling allowed by a fiber configuration strongly reduces the effects of sampling fluctuations. Such fluctuations tend to dominate the energy resolution of electromagnetic sampling calorimeters. Several particle physics experiments have taken advantage of these features, *e.g.*, CHORUS [1], KLOE [2], DELPHI [3], WA89 [4], H1 and CMS [5].

In dual-readout calorimeters, two different types of signals are produced by the showering particles. These two types of signals, which represent the total energy deposit by ionization (dE/dx) and the Čerenkov light produced by the relativistic shower products, provide complementary information, which makes it for example possible to determine the electromagnetic fraction of each hadronic shower. The fluctuations in that fraction typically dominate the hadronic energy resolution of calorimeters, and dual-readout calorimeters thus offer the possibility to eliminate the effects of these fluctuations and obtain excellent hadronic performance [6,7].

In the calorimeter discussed in this paper, signals are generated in scintillating fibers, which measure the deposited energy, and in clear plastic fibers, which measure the relativistic shower particles, by means of the Čerenkov light generated by these. A large

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http://dx.doi.org/10.1016/j.nima.2015.11.005

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Nuclear Instruments and Methods in Physics Research A ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

New results from the RD52 project

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On behalf of the RD52 (DREAM) Collaboration

ARTICLE INFO

Keywords:
Calorimetry
Dual-readout
Čherenkov light

ABSTRACT

Simultaneous detection of the Čerenkov light and scintillation light produced in hadron showers makes it possible to measure the electromagnetic shower fraction event by event and thus eliminate the detrimental effects of fluctuations in this fraction on the performance of calorimeters. In the RD52 (DREAM) project, the possibilities of this dual-readout calorimetry are investigated and optimized. In this talk, the latest results of this project will be presented. These results concern tests of a dual-readout fiber calorimeter with electrons at very small angles of incidence, detailed measurements of the time structure of hadron showers in this detector, as well as elaborate comparisons of various aspects of the calorimeter performance with GEANT4 simulations.

1. Introduction

The ideas that formed the basis for the RD52 project, as well as the detectors constructed by the DREAM Collaboration, were already presented at the previous Elba conference [1]. In our detectors, fluctuations in the electromagnetic shower component (f_{em}), which limit the performance of almost all calorimeters used in modern high-energy physics experiments, are eliminated by simultaneous measurements of the energy deposit dE/dx and the fraction of that energy carried by relativistic charged shower particles. We have experimentally demonstrated that this makes it possible to measure f_{em} event by event [2]. We use scintillation light and Čherenkov light as signals for the stated purposes. Therefore, this method has become known as the Dual REAdout Method (DREAM). It provides in practice the same advantages as intrinsically compensating calorimeters ($e/h = 1$), but are not subjected to the limitations of the latter devices: sampling fraction, signal integration time and volume, and especially the choice of absorber material. This has important consequences for the precision of jet measurements.

During most of the time since the previous conference, the CERN accelerator complex has been shut down because of LHC upgrade activities. We have used this period to carry out an extensive program of Monte Carlo simulations, both for electromagnetic and hadronic showers developing in our, in many ways, very unusual calorimeters. Many results of this work have been summarized in a recent paper [3]. At this conference, we report on results of new simulations with different hadronic shower packages. We also present new experimental data on the performance of our copper-fiber calorimeter for showers induced by electrons entering at very small angles with the fiber direction. These studies were inspired by GEANT4 predictions of unexpected phenomena. Finally, we also show very recent results on the time structure of the signals in our dual-readout lead-fiber calorimeter.

2. Hadronic performance

In our recent Monte Carlo paper, we showed that "standard" hadronic shower simulations gave a reasonable description of the response functions for 100 GeV π^- in the original DREAM copper-fiber calorimeter [3]. Especially the Čherenkov response function was well described by these simulations. On the other hand, the scintillation distribution was more narrow, less asymmetric and peaked at a lower value than for the experimental data. From additional analyses, we established that the non-relativistic component of the shower development, which is completely dominated by processes at the nuclear level, is rather poorly described by GEANT4, at least by the FTFP_BERT hadronic shower development package, which is the standard used by the ATLAS and CMS collaborations. Both the average size of this component, as well as its event-to-event fluctuations, are at variance with the experimental data. This non-relativistic shower component only plays a role for the scintillation signals, *not* for the Čherenkov ones.

Yet, some aspects of hadronic shower development that are important for the dual-readout application were found to be in good agreement with the experimental data, *e.g.*, the shape of the Čherenkov response function and the radial shower profiles.

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http://dx.doi.org/10.1016/j.nima.2015.09.069

Please cite this article as: R. Wigmans, Nuclear Instruments & Methods in Physics Research A (2015), http://dx.doi.org/10.1016/j.nima.2015.09.069

*These results were presented in SPSC 2015 meeting

RD52 data taken in November 2015

- *Measurements with 80 GeV e^+ in Cu module oriented perpendicular to the beam ($\pm$30 degrees)*

  - *Comparison shower profiles measured with S/C fibers*
  - *Measuring light attenuation and reflection coefficients in fibers*

- *High statistics measurements with 20 - 180 GeV hadrons in Pb calorimeter oriented along the beam line*

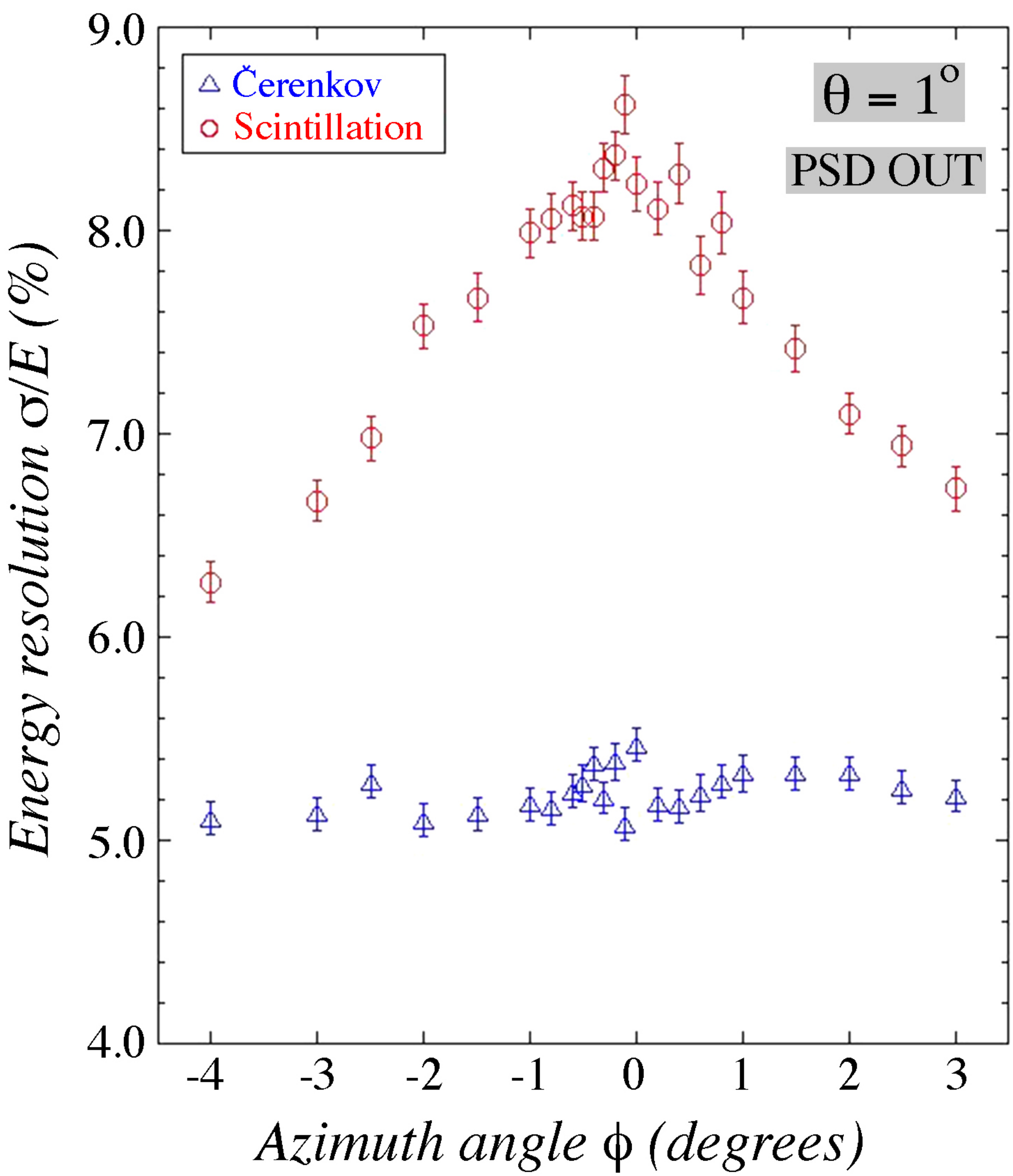
  - *Studies of effect leakage counters on energy resolution*
  - *Studies of pion/proton differences*

Setup in H8 for Cu module measurements

9.6 x 9.6 x 250 cm^3

2048 S fibers, 2048 Č fibers

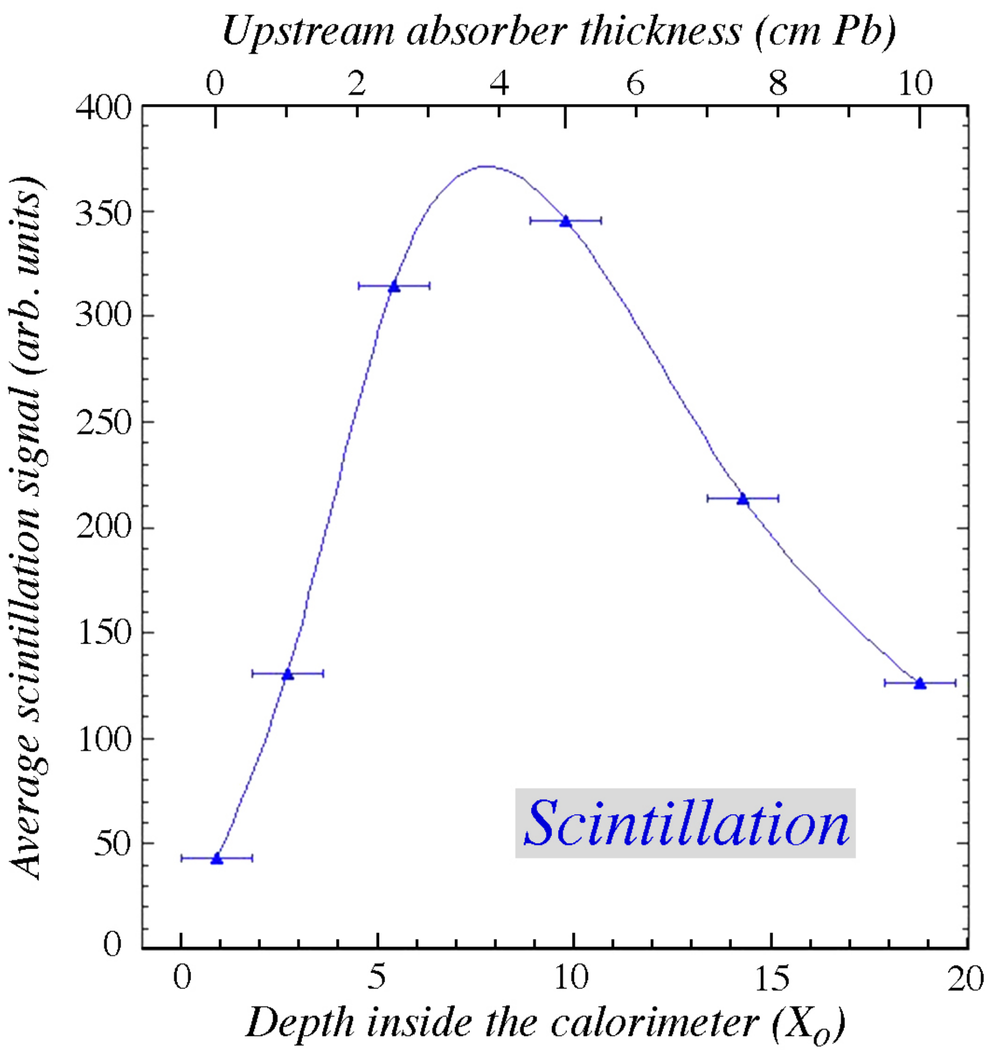
The energy resolution for 20 GeV e^+ as a function of the angle of incidence

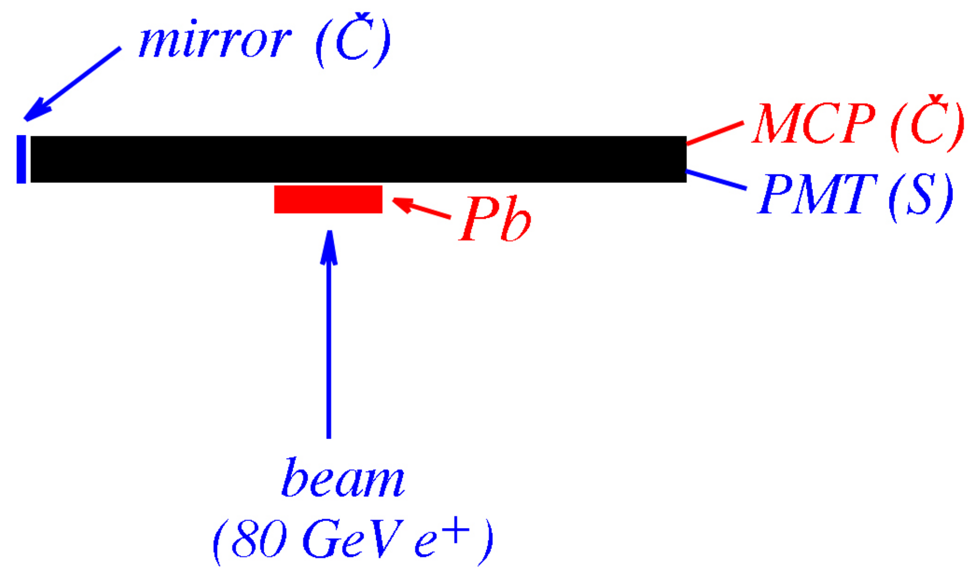


- *em showers are very narrow, especially early on. The sampling fraction of this early shower component depends on impact point (in fiber or in between fibers)*
- *This dependence disappears when particles enter at an angle with the fibers*
- *This effect does NOT play a role for Čerenkov signals, since early part of shower does not contribute to signal (numerical aperture of fibers)*

Shower profile measurements (1)

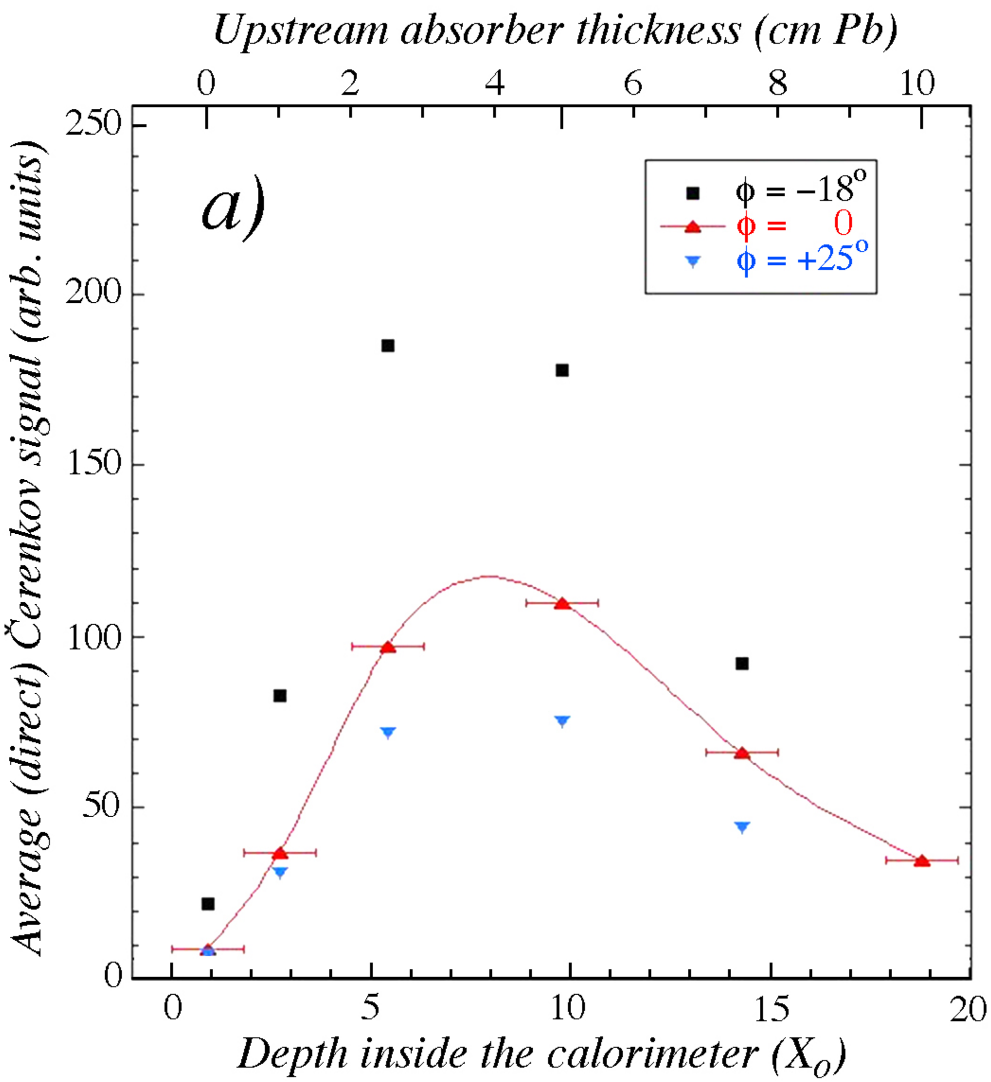
Shower profile measurements @ 90°

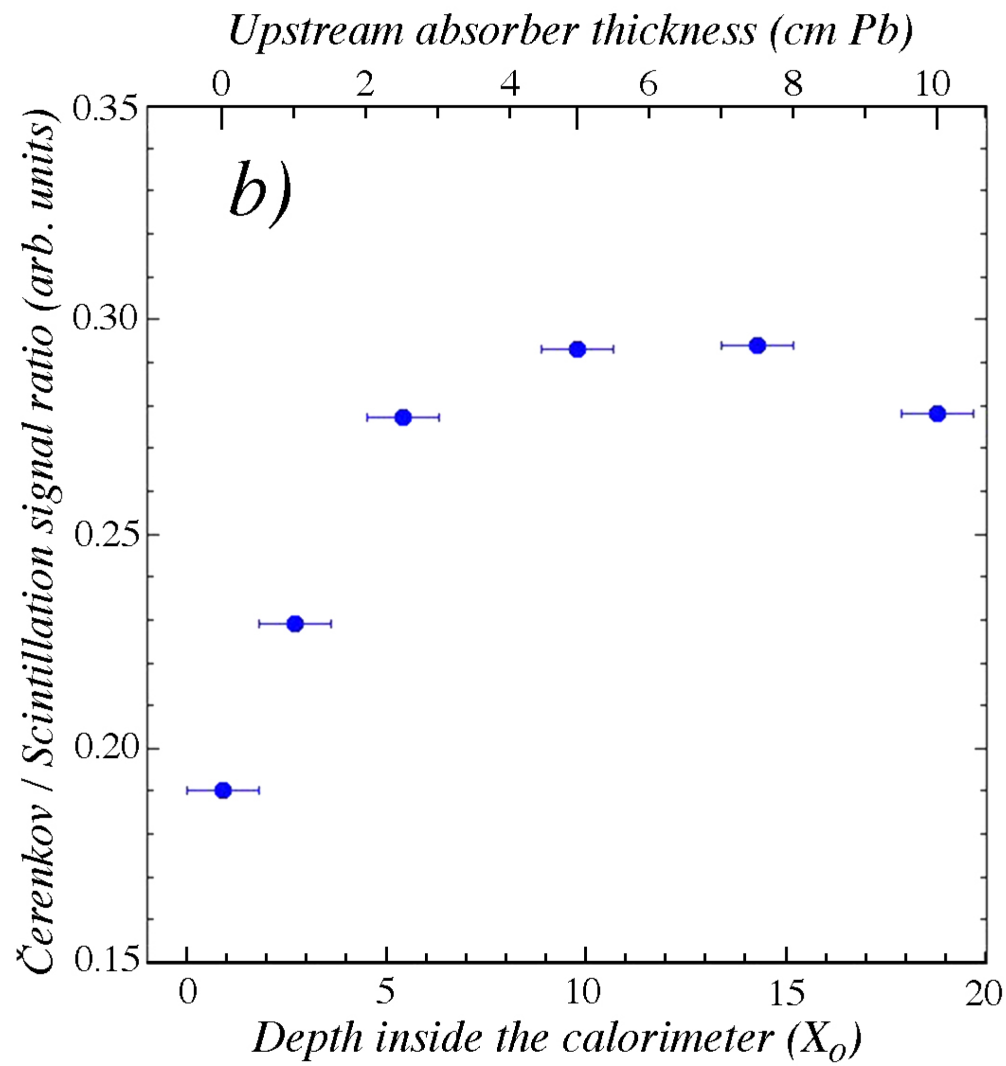




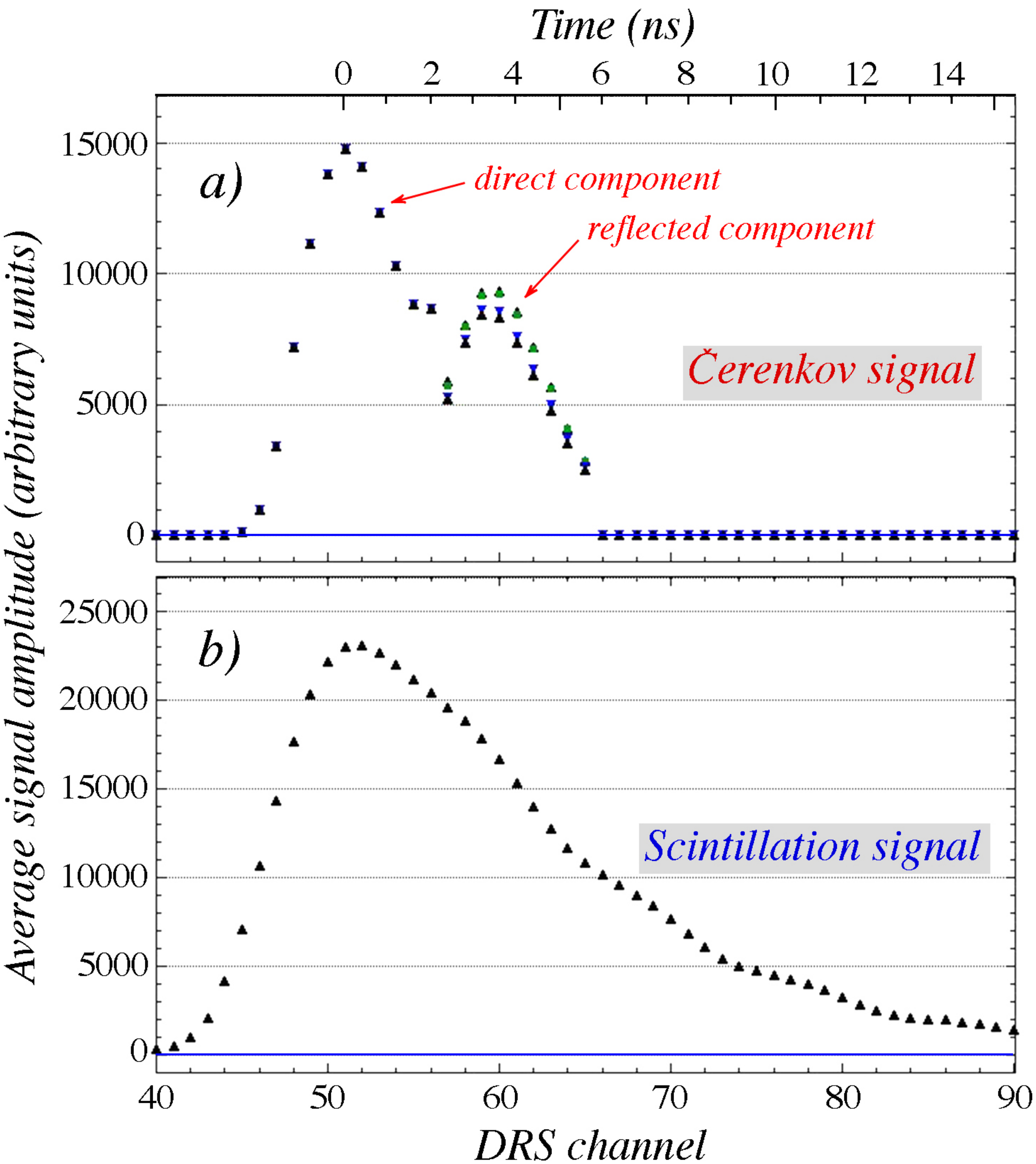
Shower profile measurements (2)

Čerenkov profile & Č/S profile ratio

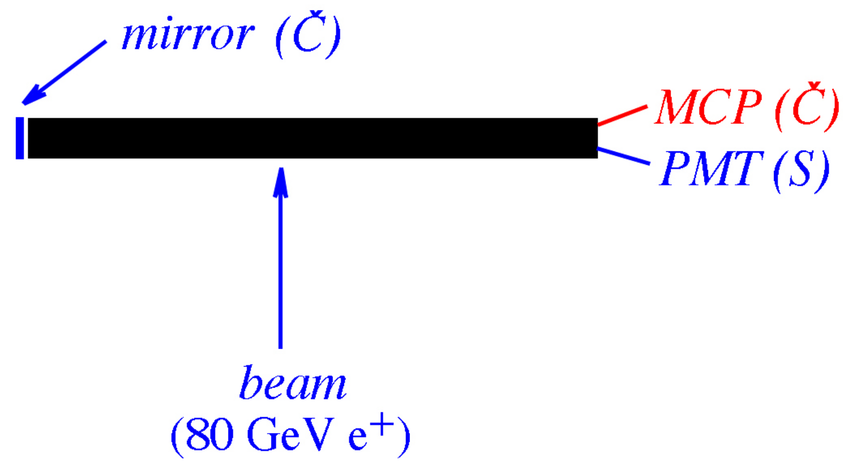




Used MCP-PMT (Photonis Planacon) for fast signals

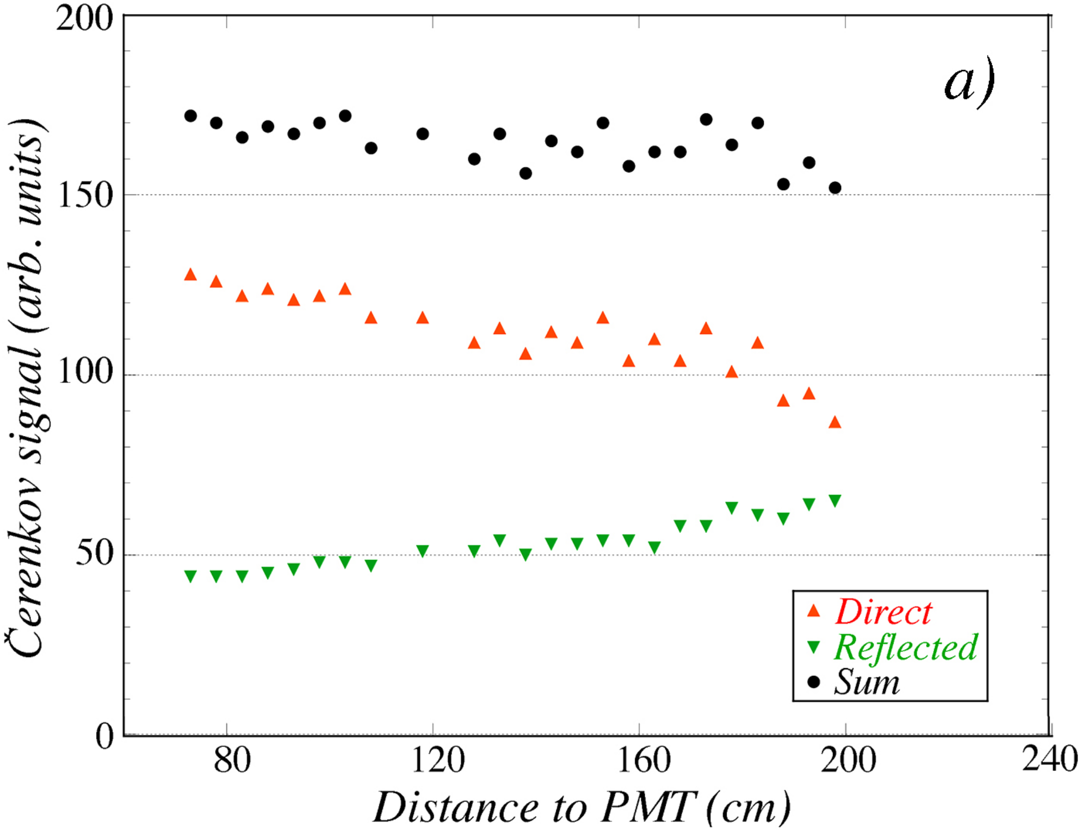


MCP readout



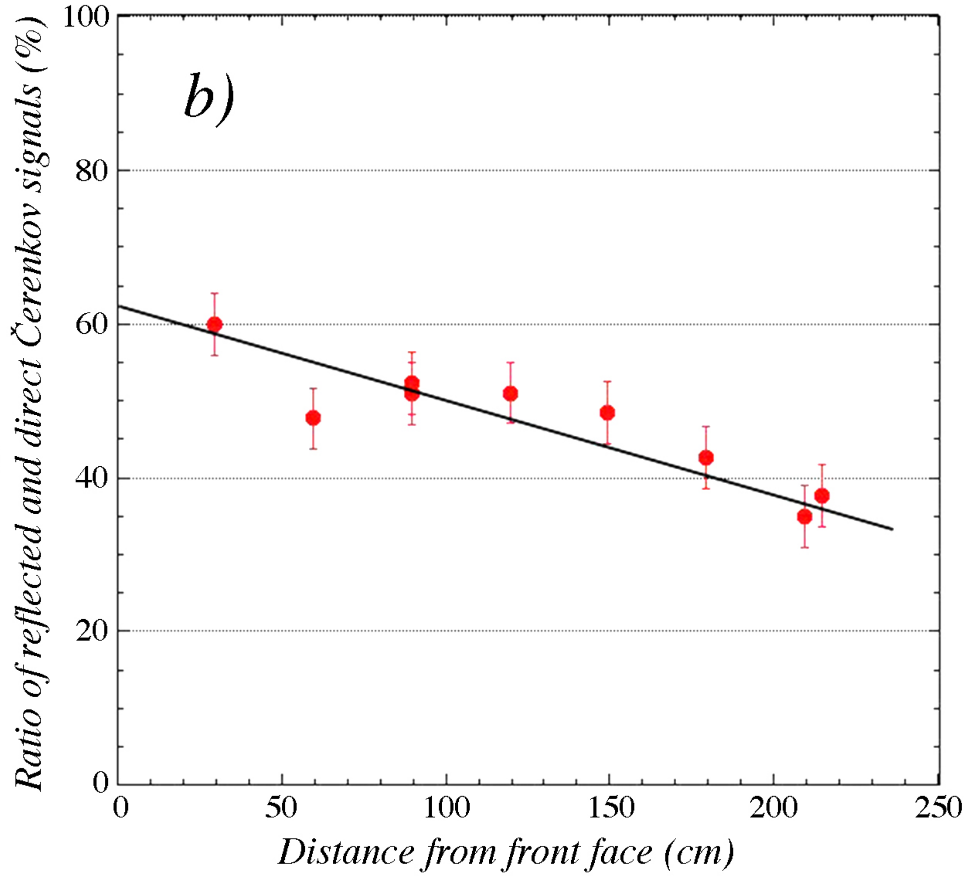
Measurement of light attenuation and reflection in Č fibers

Light attenuation

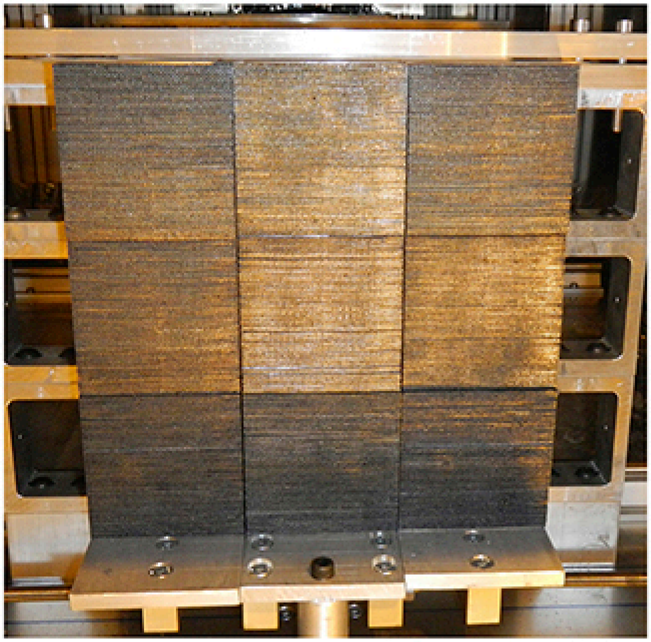


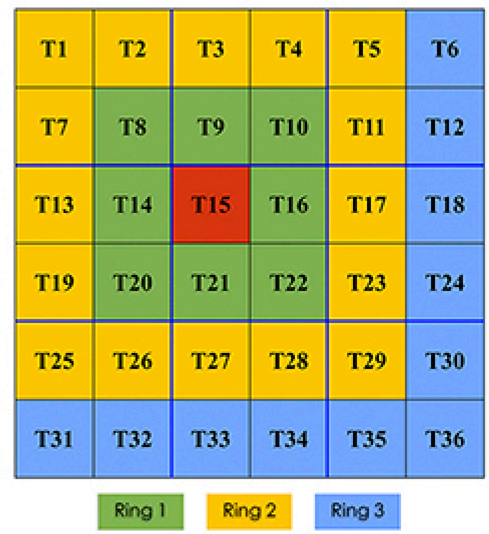
80 GeV e^+

& reflection



Setup in H8 for measurements Pb calorimeter



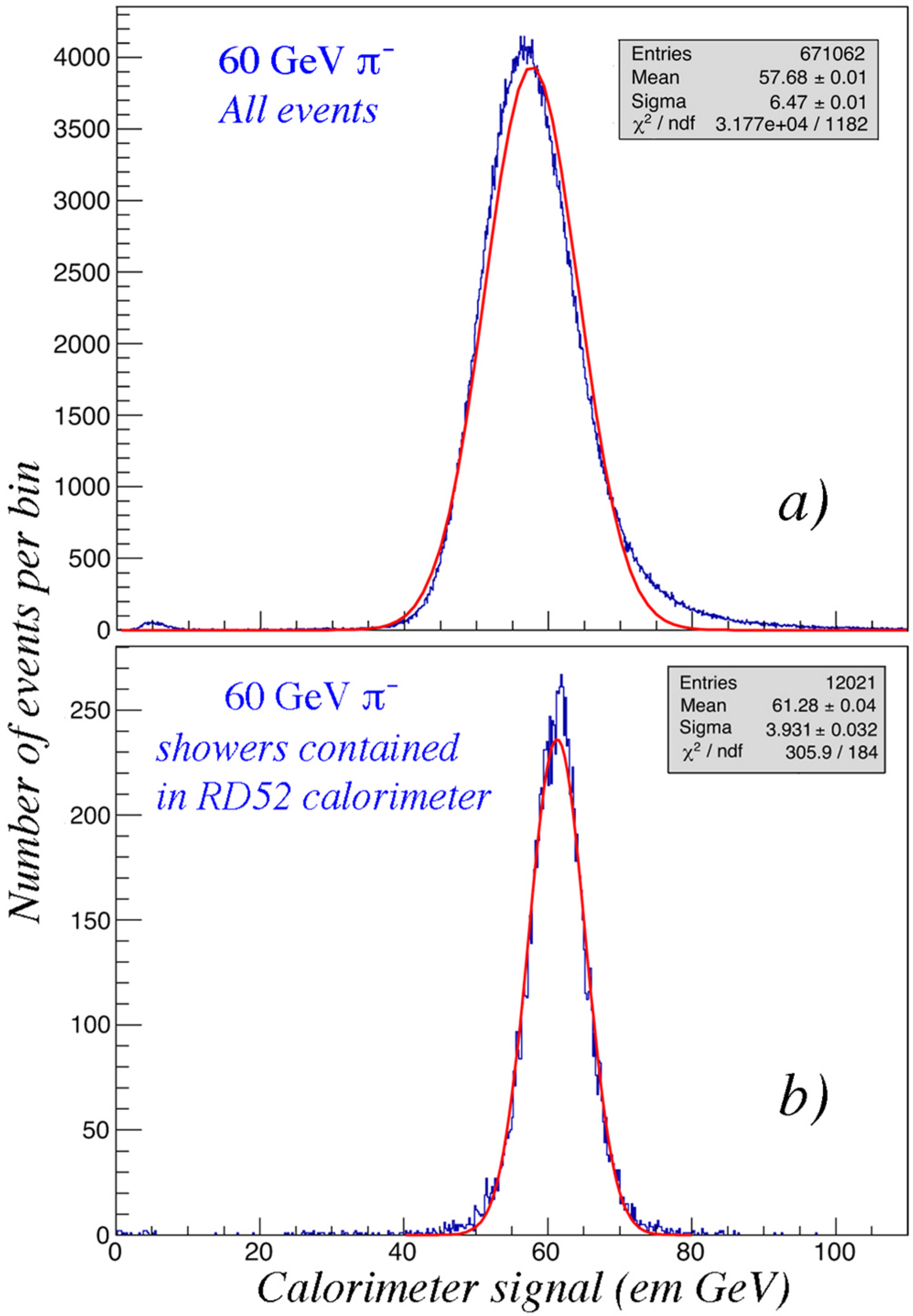


20 x 20 x 250 cm^3

1300 kg

72 channels

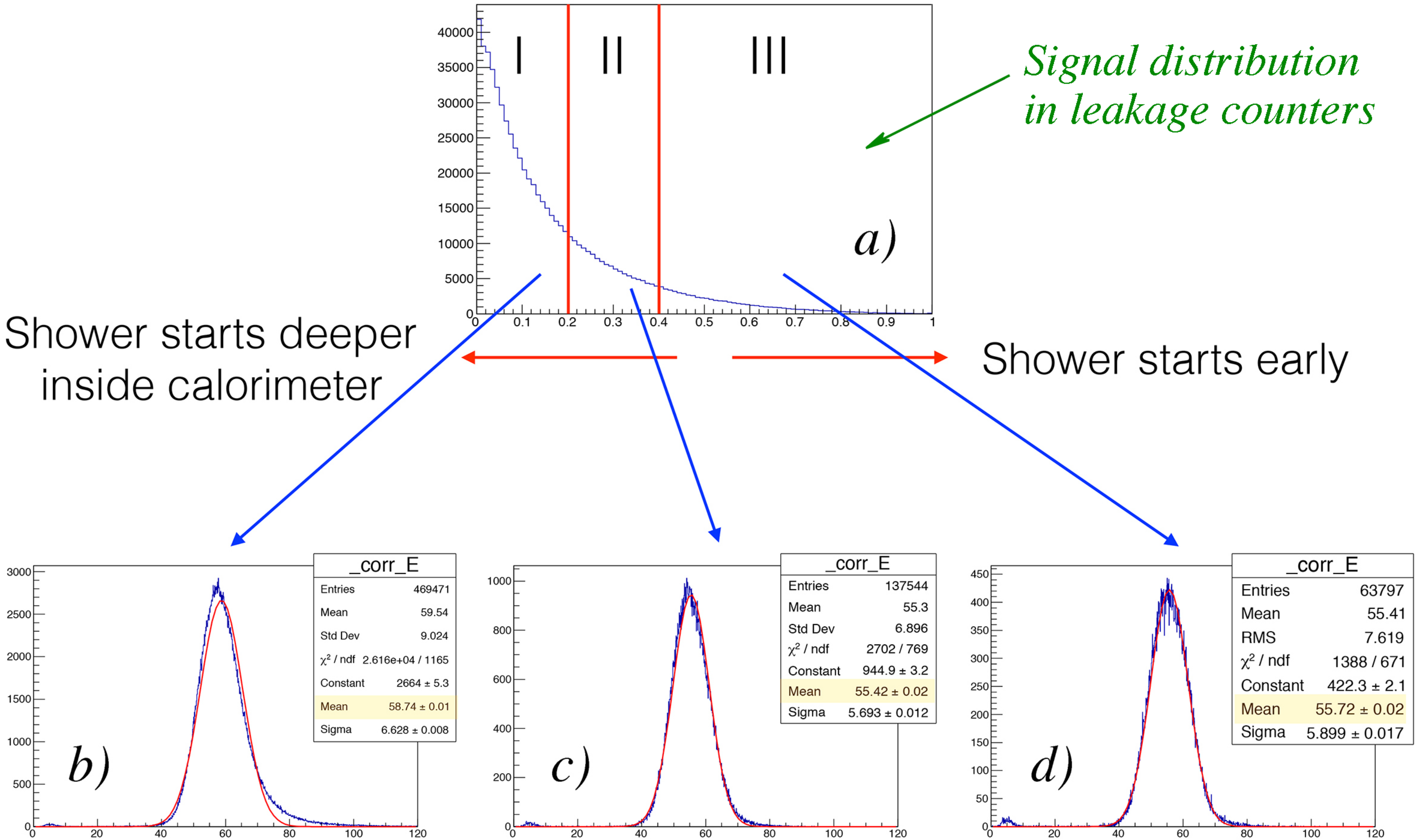
Hadron tests Pb module



Energy resolution hadrons is dominated by

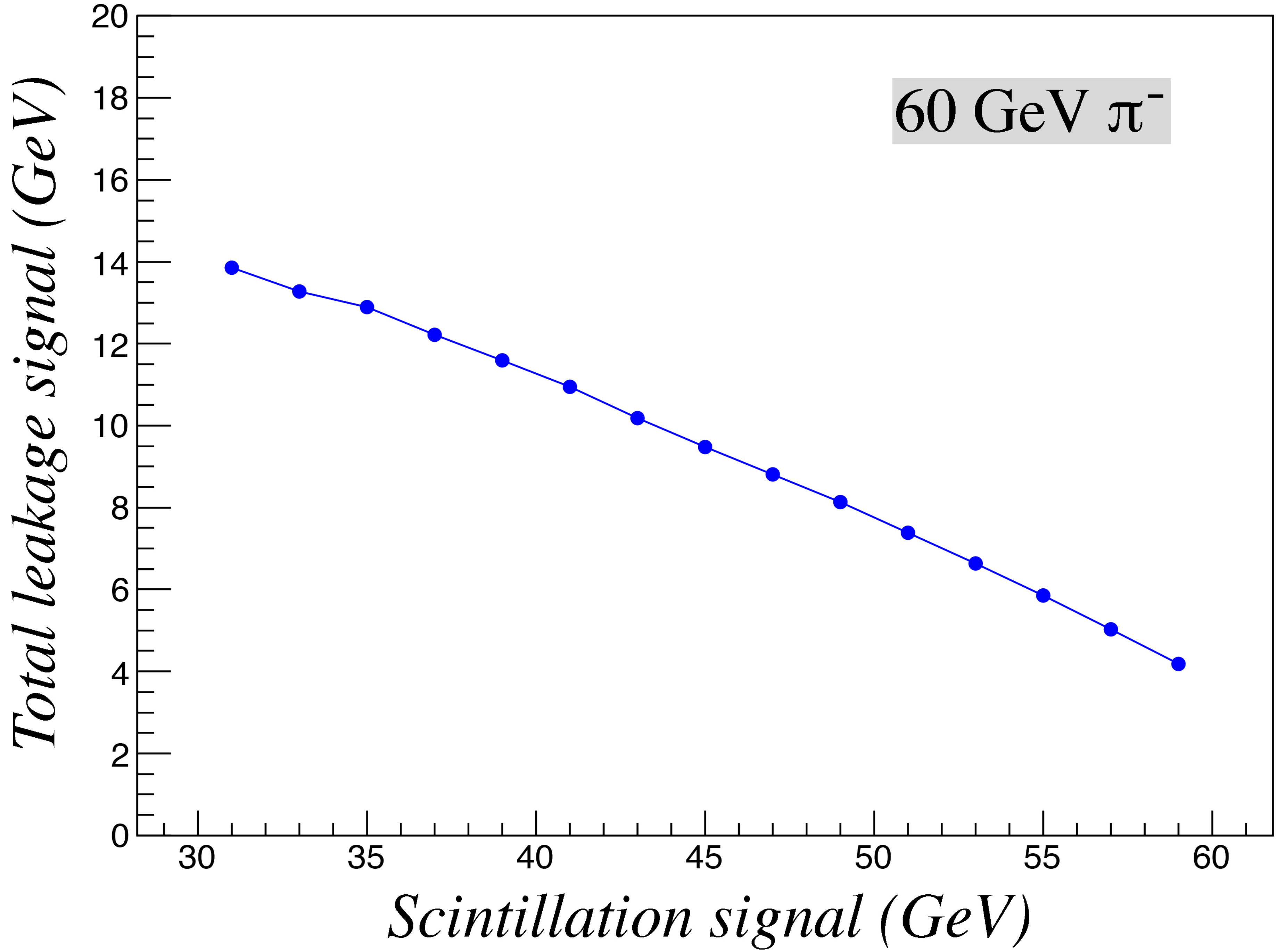
- *Lateral leakage fluctuations*
- *Light attenuation (S)*

Signals are affected by light attenuation in S fibers

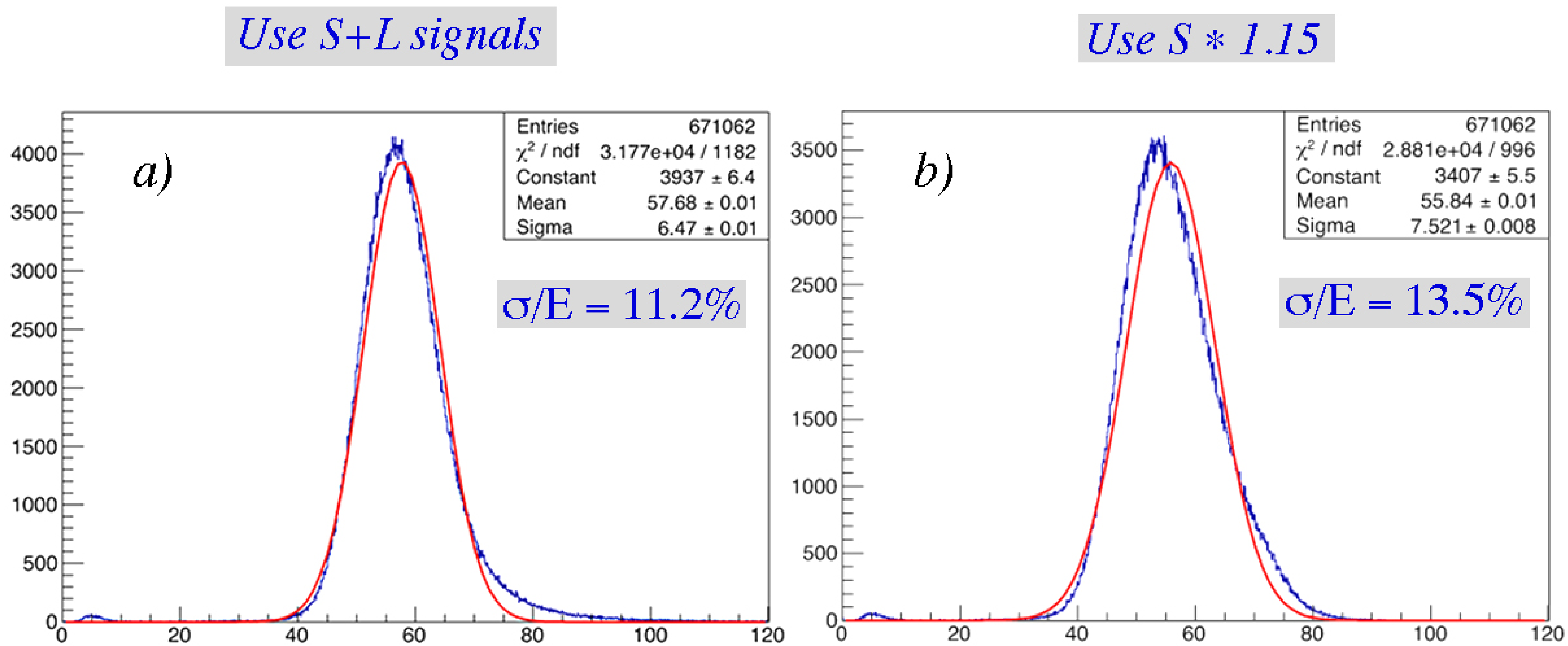


Dual-readout calorimeter signal for 60 GeV pions

Do leakage counters work?

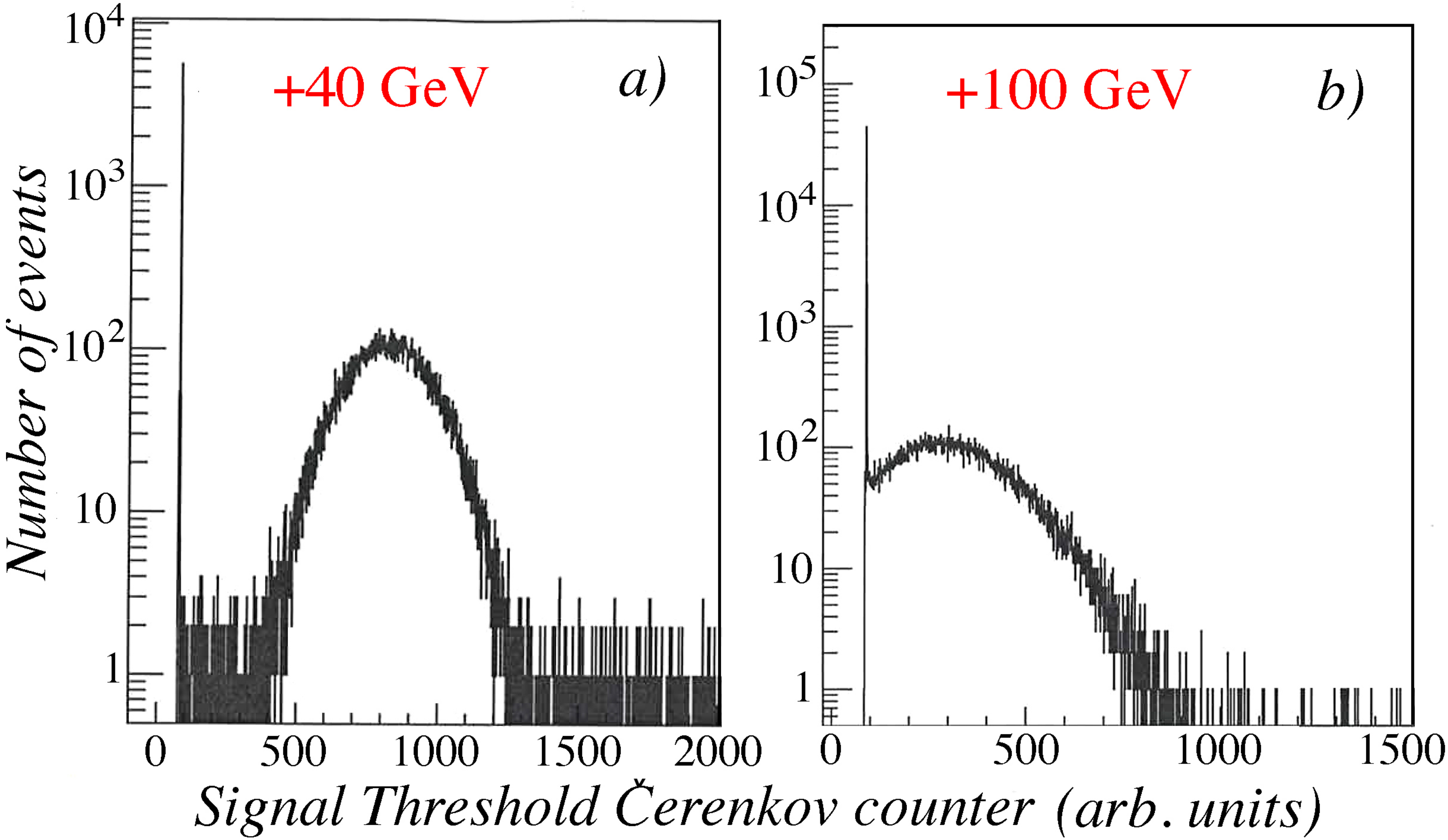


Can leakage counter info be used to improve resolution?

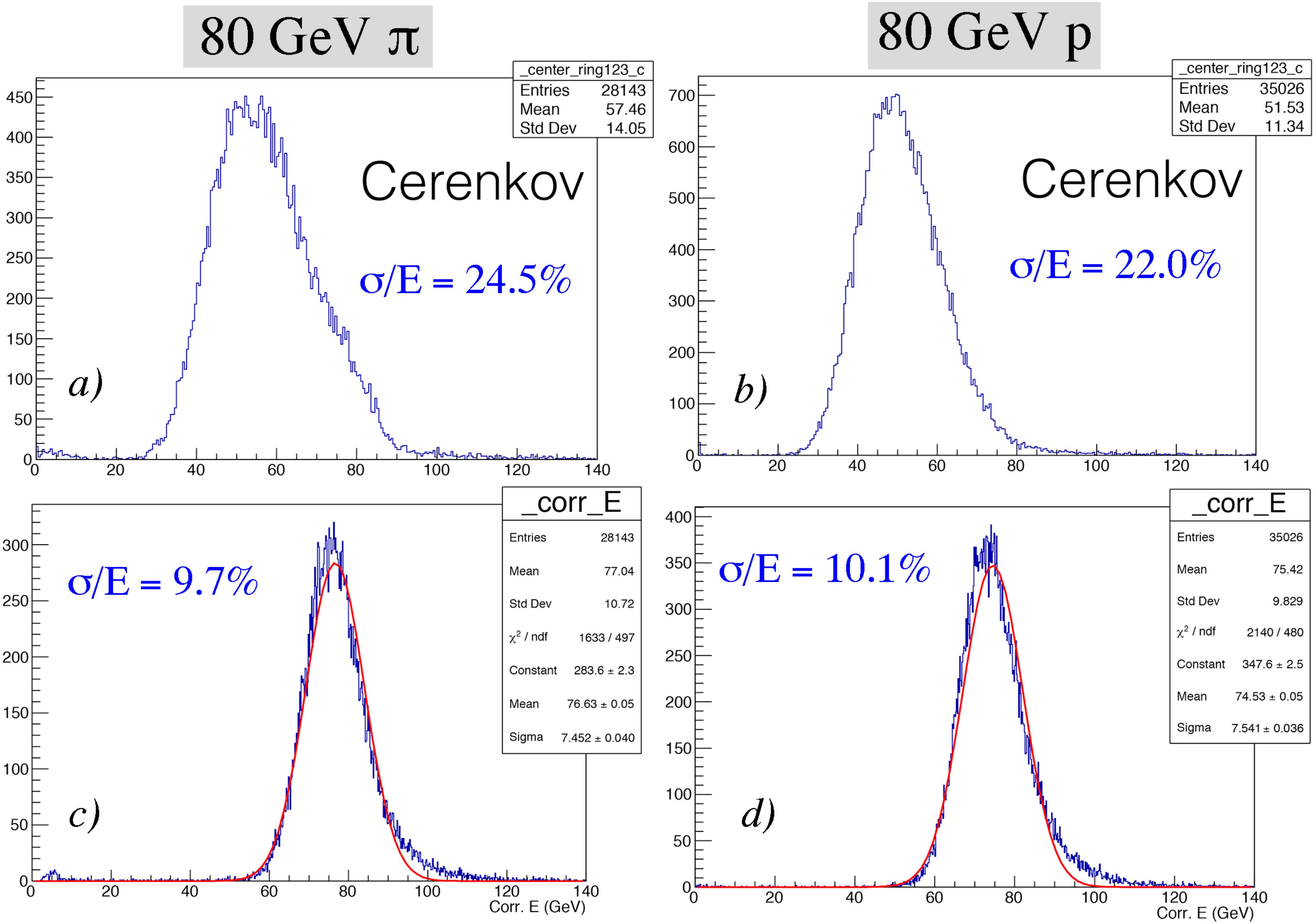


Dual-readout calorimeter signal for 60 GeV pions (GeV)

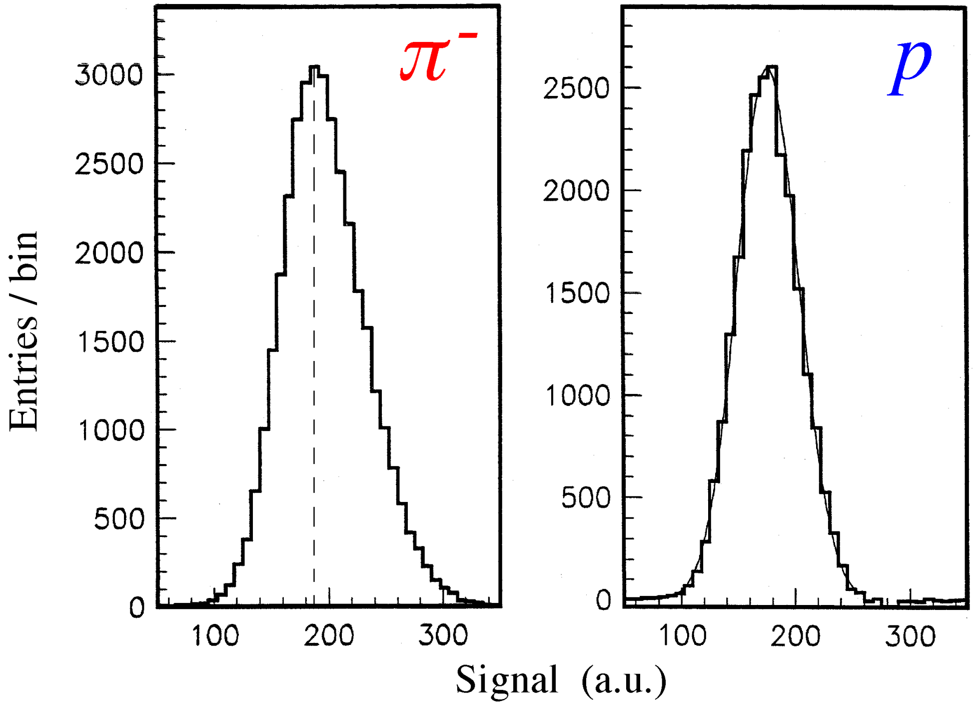
p/π separation with Threshold Čerenkov counters

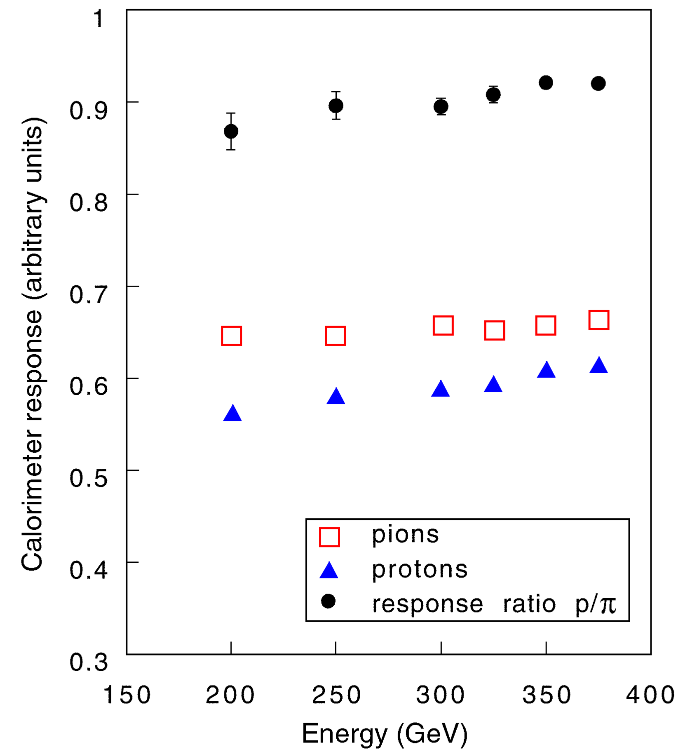


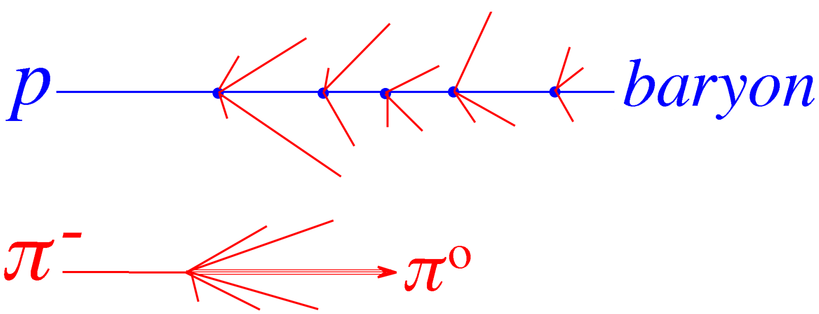
Proton/pion comparison

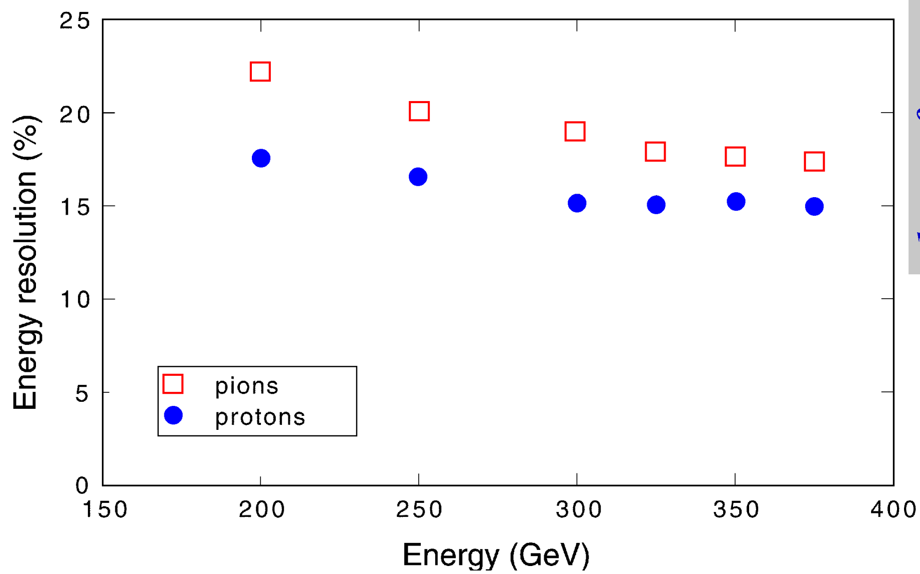


Proton / pion differences in calorimeter signals
caused by differences in em shower fraction characteristics









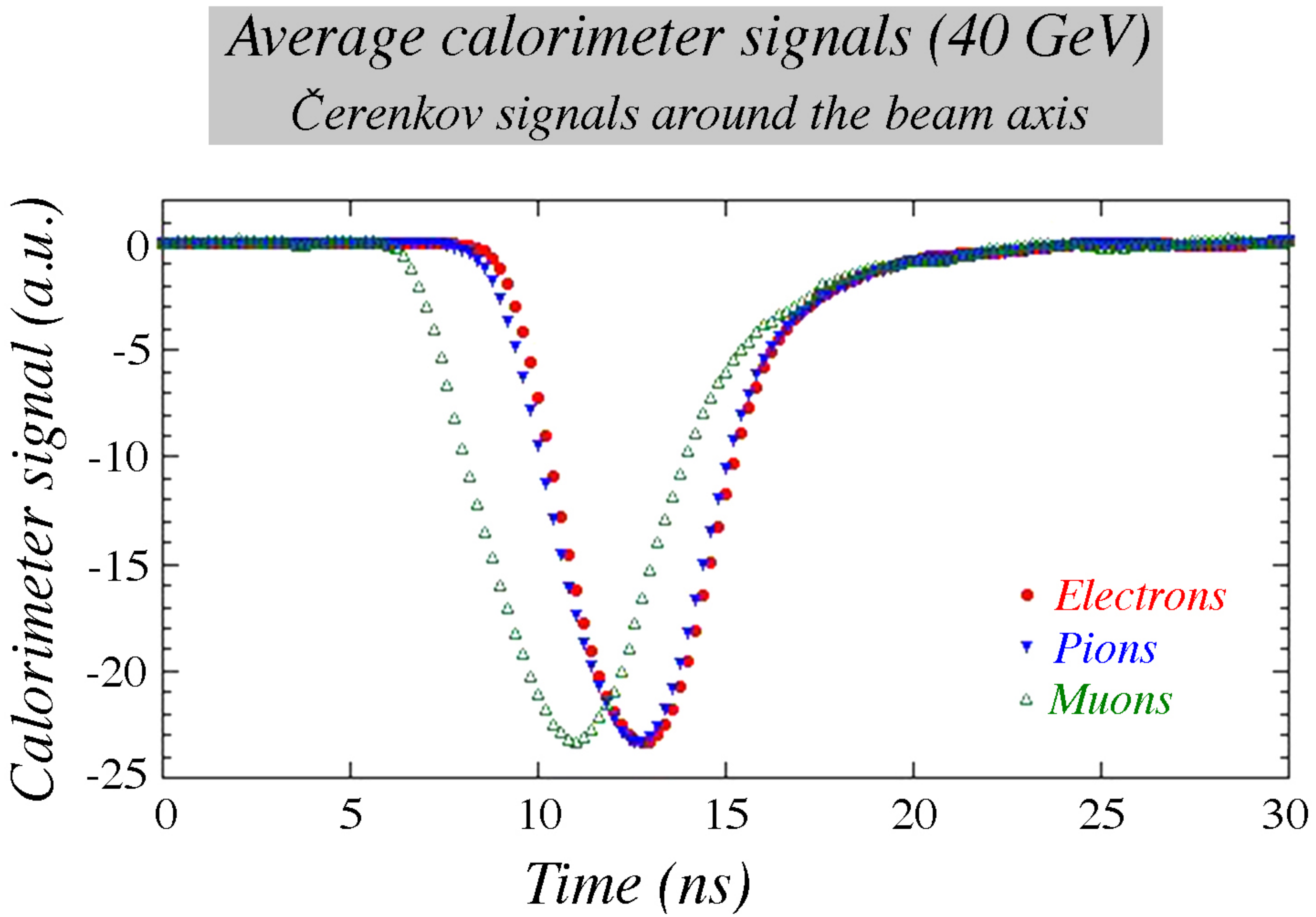
em fraction in p showers:

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

data from NIM A408 (1998) 380

Our plans for the future

- *Plans for 2016:*
  - *Can calorimeter data be used to identify p/π event by event? (time structure events). π^{o} production characteristics quite different*



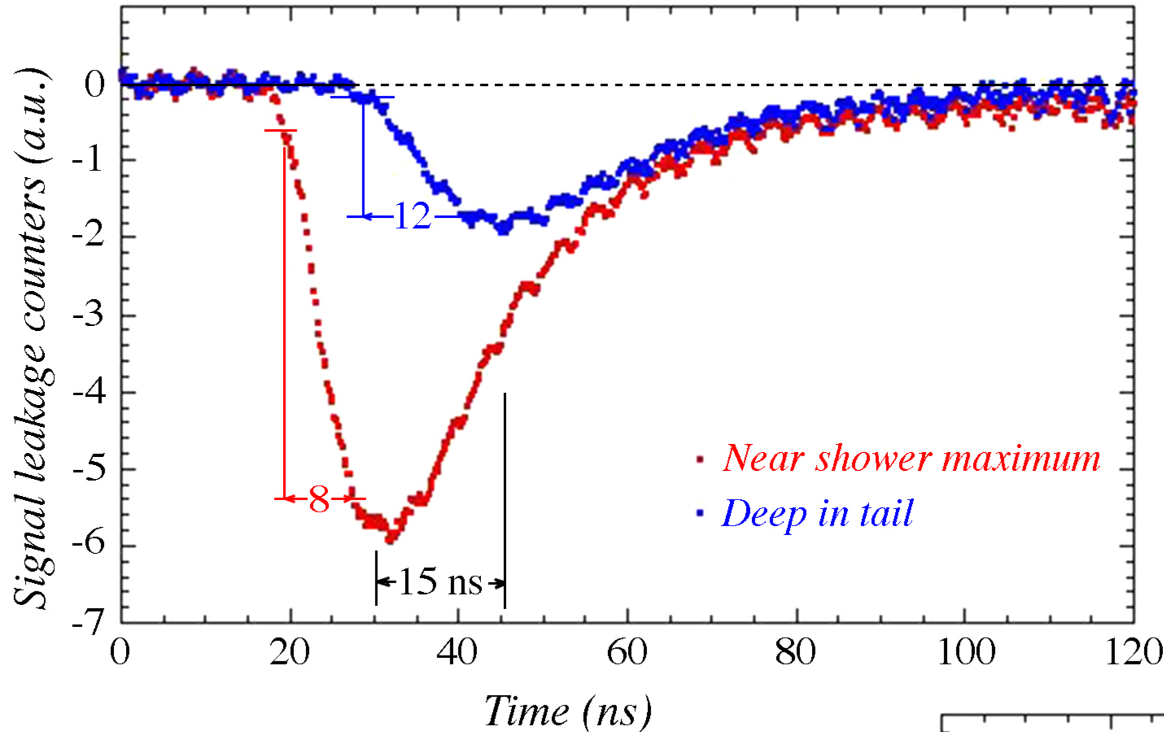
Where is Č light produced?

Electrons: depth shower maximum ~5 cm

Pions: depth shower maximum~ 25 cm

Muons: average depth light production ~125 cm

Comparison signal shapes leakage counters

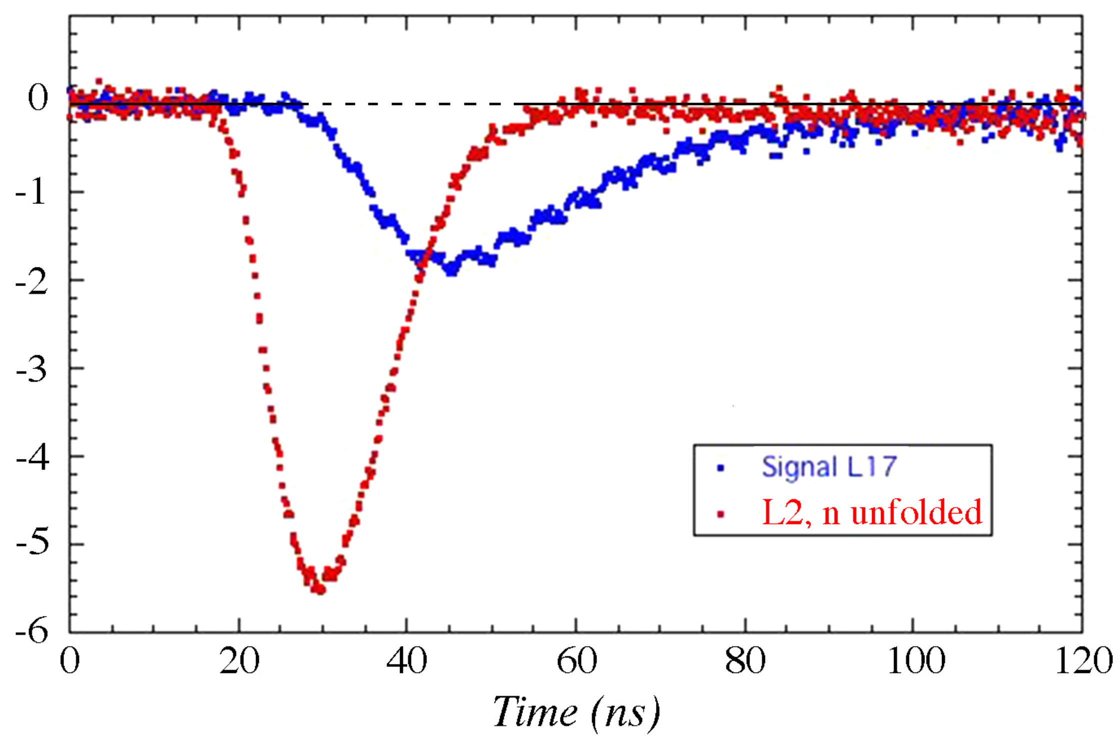


Expected signal contributions:

- prompt charged shower particles

- n + p → n + p
(time constant 10 - 20 ns)

n contribution unfolded



Our plans for the future

- *Plans for 2016:*
  - *Can calorimeter data be used to identify p/π event by event? (time structure events). π^o production characteristics quite different*
  - *Test SiPM readout on a new, em copper module (get rid of fiber forest sticking out from the rear of detector)*

SiPM readout of dual-readout calorimeters

Why bother?

- *Readout can be squeezed into 2 cm instead of 50 cm*
  $\longrightarrow$ *gain precious real-estate*
  $\longrightarrow$ *eliminate antennas for μ,n detection*
  $\longrightarrow$ *creates an option for longitudinal segmentation*

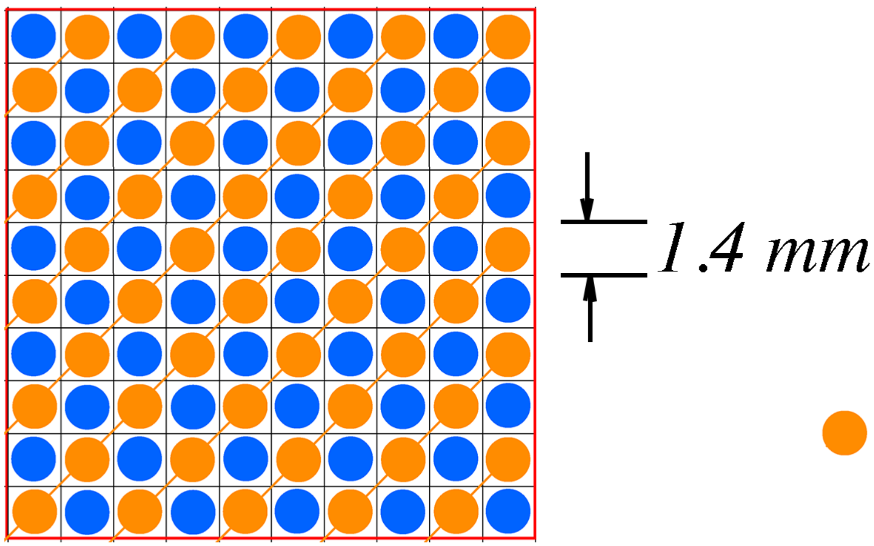
- *Possibility to operate in a magnetic field*

These are issues that are relevant for application of this detector technology in a 4π experiment.

We would like to deliver the proof of principle that this can be done.

SiPM readout of dual-readout calorimeters

Practical problem:
Need to read out 2 types of fibers with very different light yield



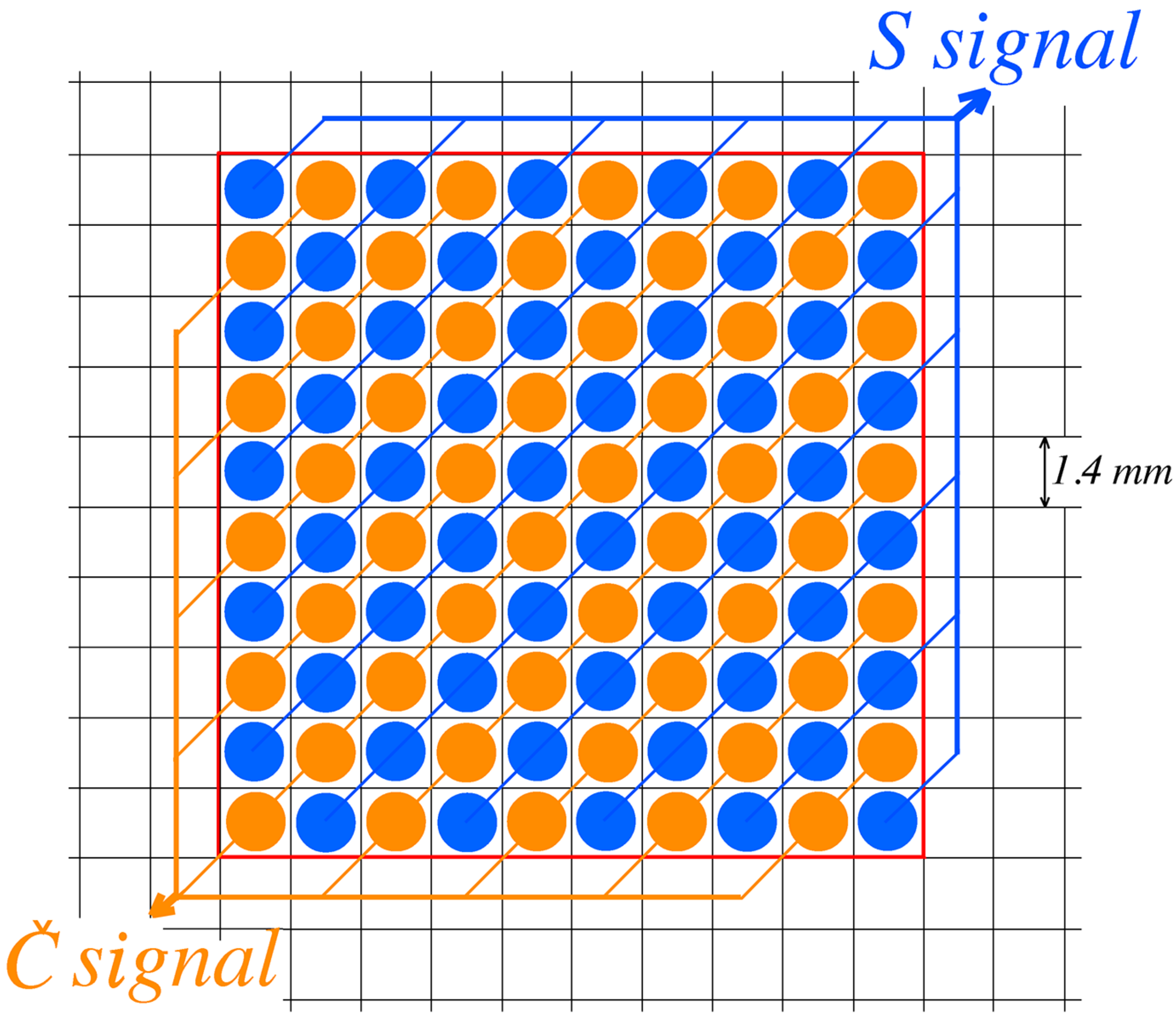
- *Cherenkov: ~50 p.e./GeV*
- *Scintillation: ~1000 p.e./GeV*

- *Need large efficiency,*
  i.e. large pixels (50 μm, 400/mm²)

- *Need large dynamic range,*
  i.e. small pixels (10 μm, 10000/mm²)

SiPM readout for dual-readout calorimeters

A possible option - 1 mm² pixel for each fiber



SiPM readout for dual-readout calorimeters

What are our plans?

- *We have 70 m of copper plates, 1.4 mm thick, 10 grooves/plate*

  ISU is building 7 em calorimeter modules of 14 x 14 mm, 30 X0 deep (J. Hauptman)

- *Hamamatsu is selling of-the-shelf 8x8 matrices of 1 mm^2 SiPM spaced by 0.2 mm*

  In a 0th-order approach we will use these to read out these modules (each fiber separately)

  Test saturation features with electron beams of different energy, at different angles

- *We have requested from Hamamatsu the time scale + cost of a custom made array*

  M. Caccia (Como) is in charge of SiPM readout activities RD52

- *Hopefully this will allow us to do meaningful tests in October*

  If it looks as if we cannot meet this goal, we will ask SPSC coordinator to postpone these tests to 2017

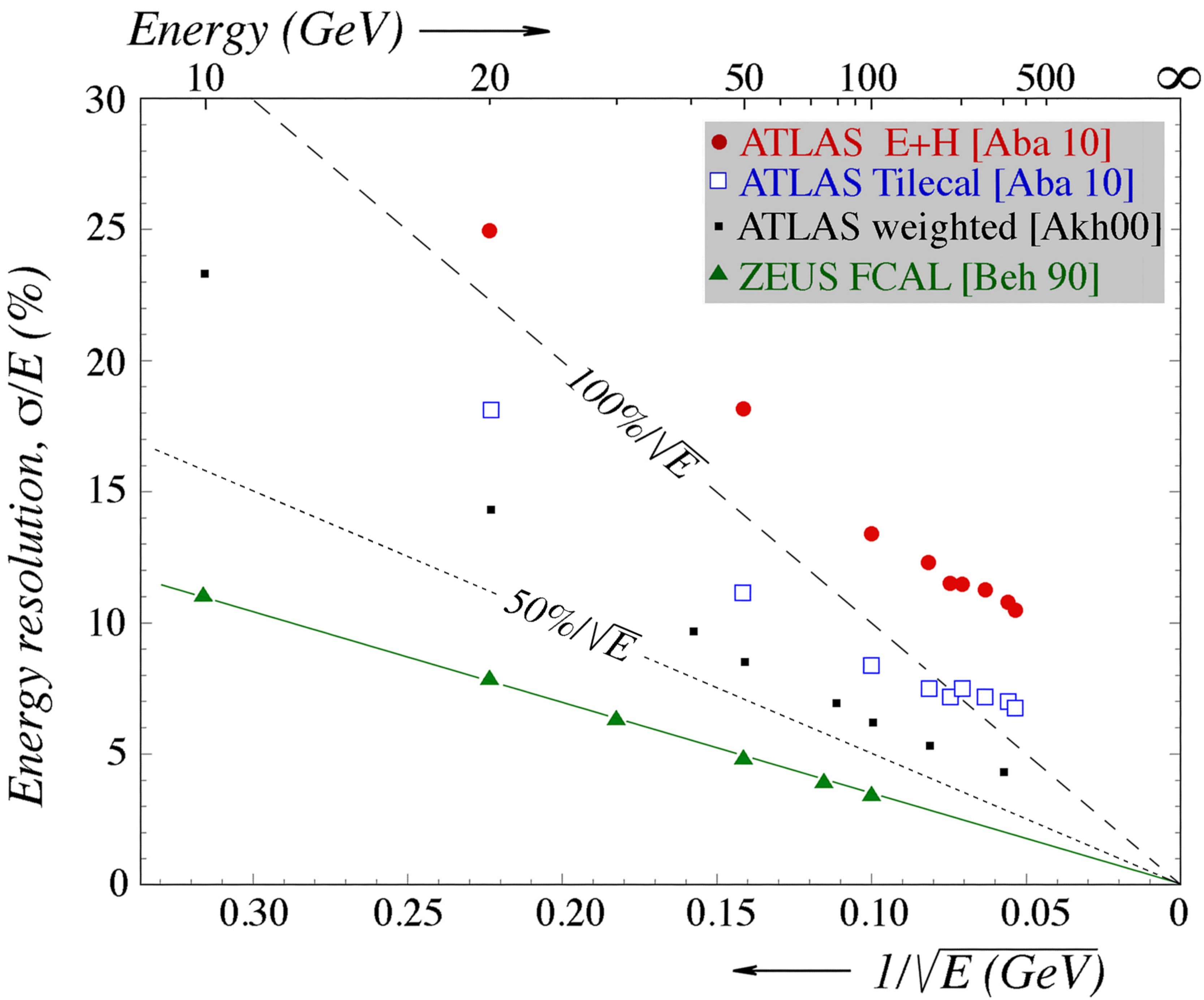
Long term plans

- *Build Cu detector large enough to fully (>99%) contain hadron showers and test expected performance.*

Need 5 tonnes.

Remember:
This detector was designed to have the same advantages as compensating calorimeters (e.g. very good hadronic energy resolution)
plus some others (good em performance, jet resolution, particle ID, ...)

Hadronic energy resolution of compensating vs modern calorimeters



The energy resolution of compensating calorimeters is dominated by sampling fluctuations

$$\sigma/E = a_{\text{samp}}/\sqrt{E}$$

Published results a_{samp} (%):

Experiment	Structure	em resolution	hadr. resolution
HELIOS	U/plastic plates	19 - 22	34 - 39
ZEUS	U/plastic plates	16.5	31.1
SPACAL	Pb/fibers	12.9	30.6
ZEUS	Pb/plastic plates	23.5	41.2
RD52	Cu/fibers	8.9 (13.9)	?

8.9 ← sampling

(13.9) ← total (incl Č p.e.)

? ← GEANT: 32

Long term plans

- *Build Cu detector large enough to fully (>99%) contain hadron showers and test expected performance.*

  Need 5 tonnes.

  Remember:
  This detector was designed to have the same advantages as compensating calorimeters (e.g. very good hadronic energy resolution)
  plus some others (good em performance, jet resolution, particle ID, ...)

- *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. Machining only option that works.
  Cost needs to come down by an order of magnitude to be affordable for a generic R&D project such as ours

- *A future experiment interested in dual-readout calorimetry could complete this part of the job*

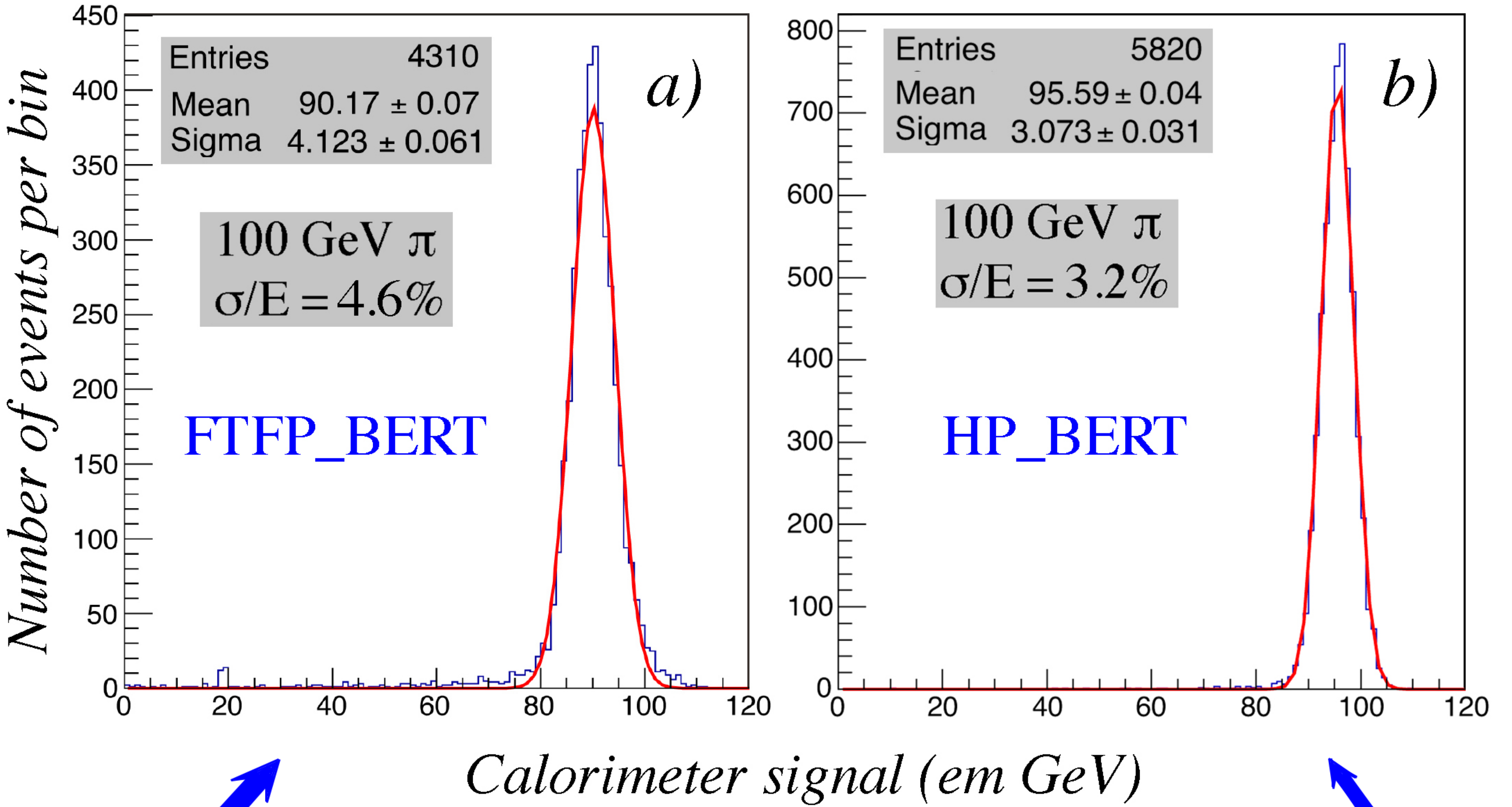
Summary & Conclusions

- *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*
  - *- Better jet energy resolution than ZEUS (e/mip 0.84 vs 0.61)*
  - *- Excellent particle ID possibilities in longitudinally unsegmented detector*
  - *- Very fast signals*
  - *- Straightforward to calibrate (electrons)*
- *Time structure measurements of signals may further extend possibilities (pileup, particle ID, ...)*
- *SiPM readout may eliminate fiber forest and make detector more compact + independent of magnetic field + makes longitudinal segmentation possible*
- *The DREAM/RD52 project is documented in 29 NIM papers (and counting)*
- *Thanks to SPS staff who have supported us over the years*

Backup slides

GEANT4 simulations of 100 GeV π

RD52_Cu   65 x 65 cm^2



Standard hadronic shower simulation package

High precision simulation package (neutrons!!)