25 Years of Dual-Readout Calorimetry

Richard WIGMANS

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Quartz Fibers and the Prospects for Hadron Calorimetry at the 1% Resolution Level[1]

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1 Introduction

In previous talks at this conference, we have heard a lot about quartz fiber calorimeters. These detectors have many interesting properties indeed. However, excellent energy resolution does not seem to be one of those properties. Yet, I will try to convince you that the application of quartz fibers may bring substantial improvements to a variety of aspects of hadron calorimetry, including measurement of the energy of hadron showers with unprecedented accuracy.

Before elaborating on this point, I will first briefly review the various factors contributing to and limiting the performance of calorimeters.

From: Proceedings of the 7th CALOR conference, Tucson 1997

Another excerpt from the Tucson proceedings

In these practical situations, the dual-readout systems discussed here might well offer a major improvement compared to classical calorimeters. The signal contributions of neutrons are of little importance in this case. The dual-readout system provides a measurement of the energy *and of the nature of this energy* in the (small) volume available for the measurement. Because of this additional information, the precision of the results obtained in this way is very likely to rival that obtainable with one type of readout in a considerably larger detector volume.

I am convinced that resources for a dedicated R&D program to investigate these possibilities may turn out to be extremely well spent.

Developments in the preceding decade (1987 - 1997)

Critical issues important for hadron calorimetry became fully understood

- Hadron showers consist of an em and a non-em component
- The non-em component involves nuclear reactions, the nuclear binding energy of nucleons released does NOT contribute to signals: invisible energy
- Energy resolution is determined by event-to-event fluctuations in invisible energy
- The relative effect of such fluctuations does not become smaller as $1/\sqrt{E}$ at increasing energy, as in em calorimeters (sampling fluctuations, # signal quanta)
- The average value of the em shower fraction increases with energy $\longrightarrow$ nonlinearity
- A crucial calorimeter performance parameter is e/h , the ratio of the calorimeter response (average signal/GeV) to the em and non-em shower components
  Typically, $e/h > 1$, because of invisible energy.
  If $e/h = 1$, a major performance improvement can be obtained.

How to improve hadron calorimeter performance?

Compensation

- *Design a calorimeter so that e/h = 1.*
  This works ONLY in sampling calorimeters

- *In sampling calorimeters, different classes of shower particles may be sampled very differently.*
  *In the em component, electrons and positrons are sampled according to dE/dx**
  In the non-em component, neutrons produced in nuclear breakup may be sampled MUCH (10 - 100 times) more efficiently, when the active calorimeter medium contains hydrogen. There is no competition for elastic n-p scattering in that case

- *The total kinetic neutron energy is correlated with the invisible energy loss, especially in high-Z materials*

- *Choose amplification factor for neutron signals such that it compensates for the invisible energy losses: e/h = 1*
  Amplification factor is determined by the sampling fraction for charged shower particles: e.g. ~2% for Pb/plastic scintillator, ~6% for U/plastic scintillator

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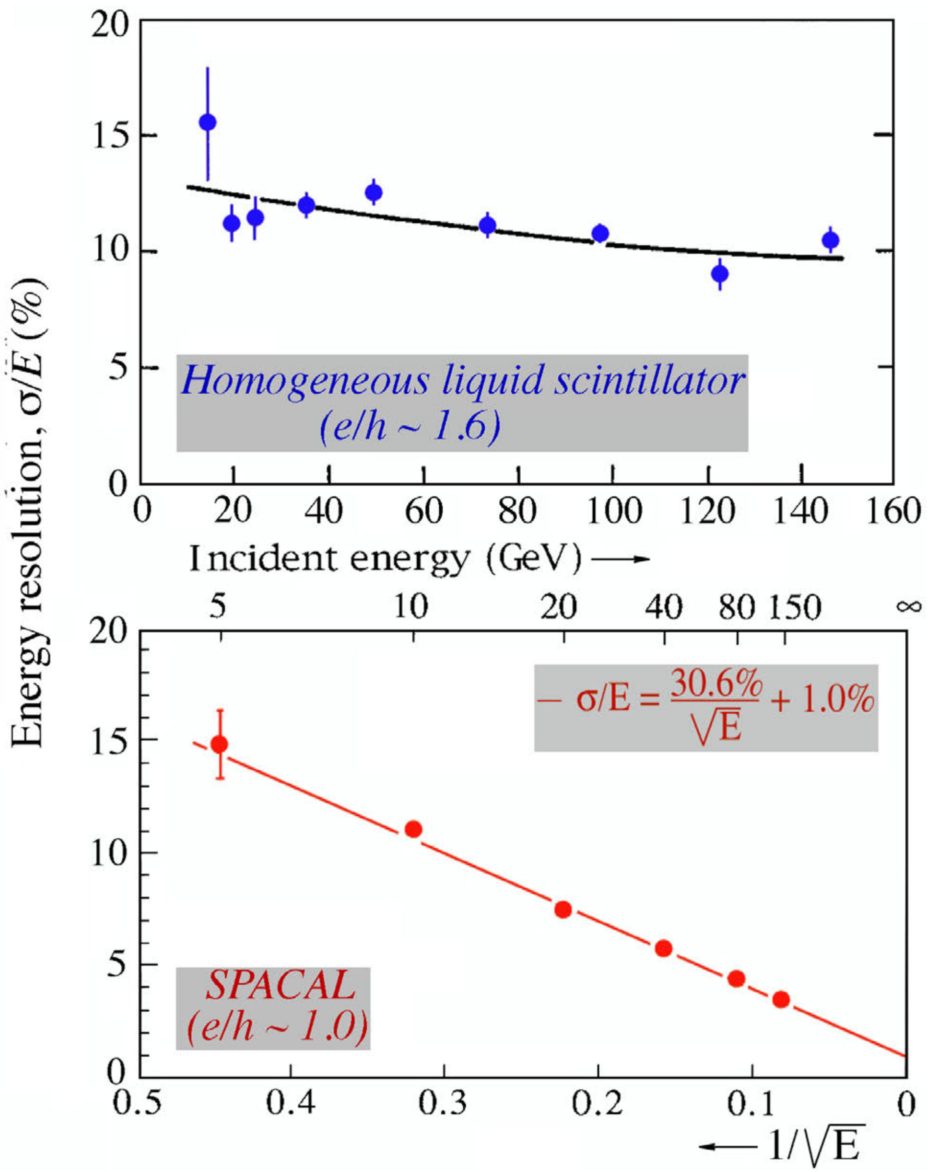
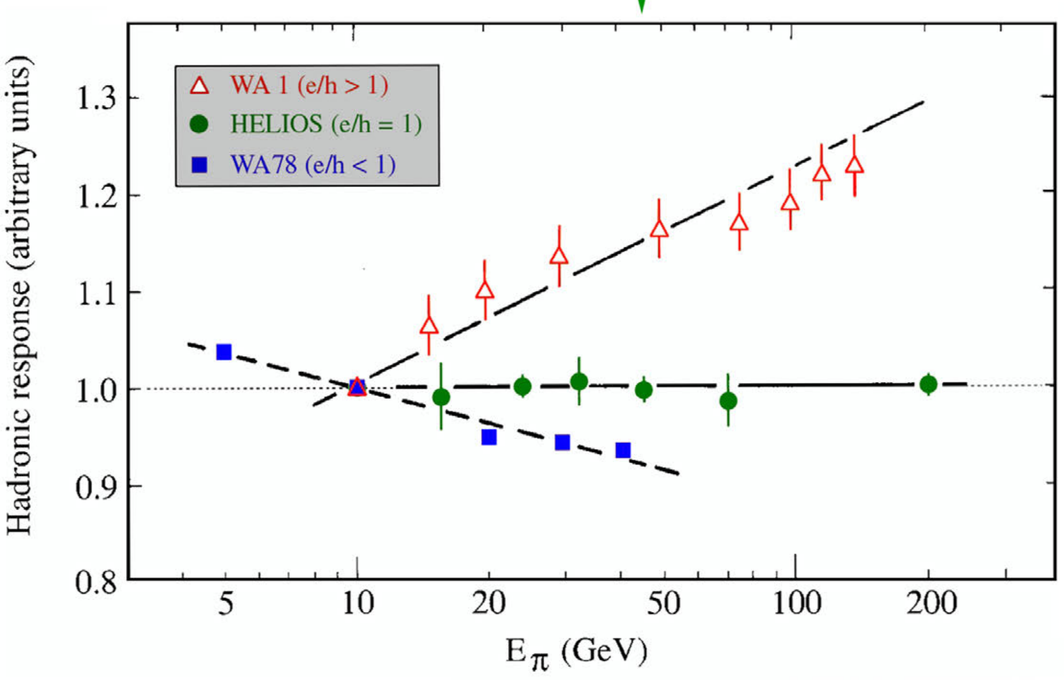
** Sampling of soft shower photons depends on Z value absorber* ⟶ *e/mip typically < 1*

Effects of compensation on

the hadron energy resolution



hadron signal linearity



Pros & Cons of Compensating Calorimeters

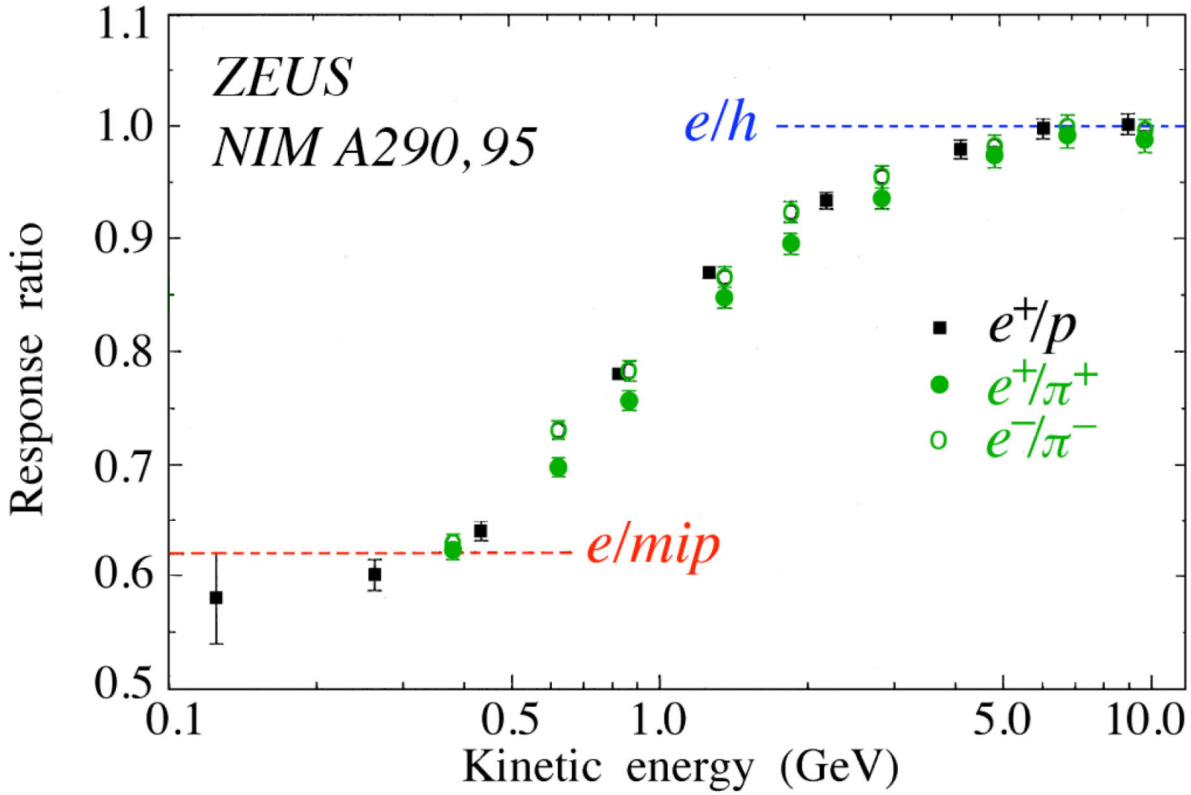
Pros

- 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%/$\sqrt{E}$).
- *Linearity,* Gaussian *response function* and all that good stuff.
- Compensation fully understood.
  We know how to build these things, long before GEANT

Cons

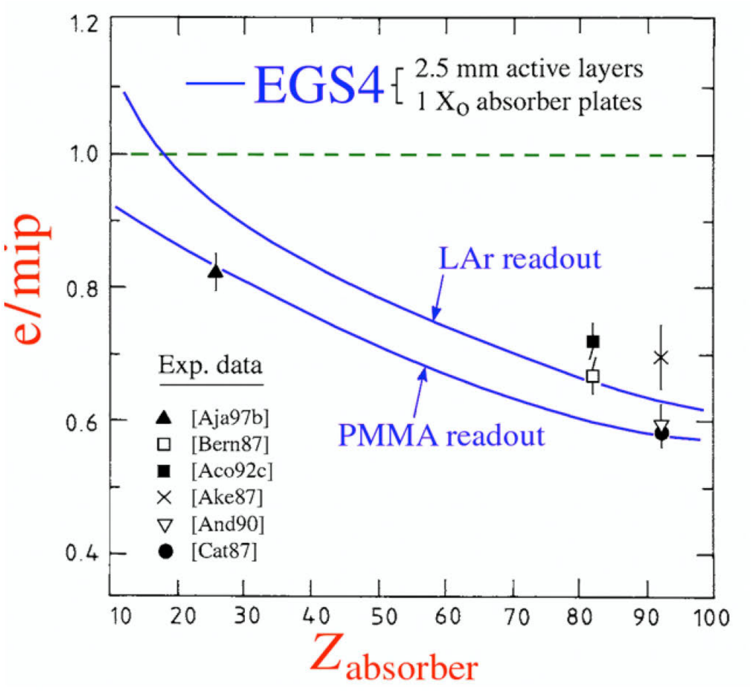
- Small sampling fraction (2.4% in Pb/plastic)
  ⟶ *em energy resolution limited* (SPACAL: 13%/$\sqrt{E}$, ZEUS: 18%/$\sqrt{E}$)
- Compensation relies on detecting neutrons
  ⟶ Large *integration volume*
  ⟶ Long *integration time* (~50 ns)
- *Jet* resolution not as good as for single hadrons in Pb,U calorimeters

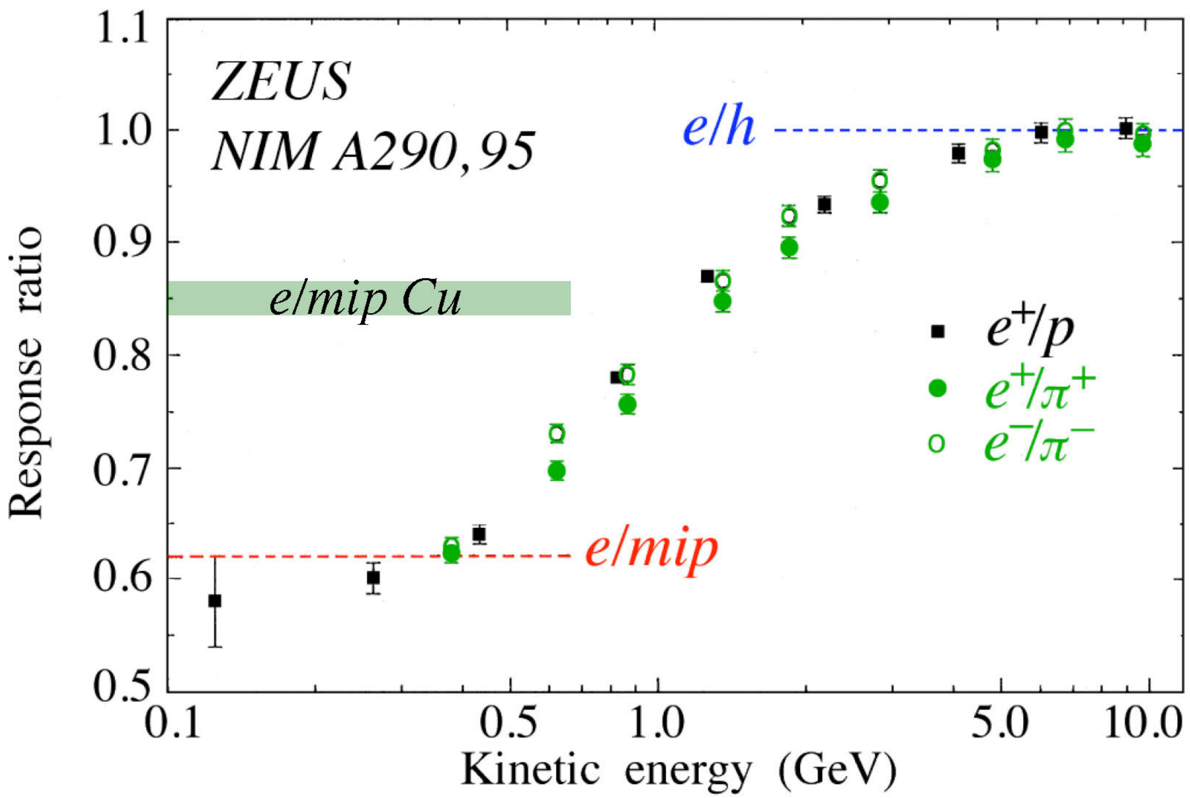
What is the problem with the jet energy resolution?



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

Elements needed to improve the excellent ZEUS/SPACAL performance:

1) *Reduce the contribution of sampling fluctuations to energy resolution*
   (THE limiting factor in SPACAL/ZEUS)

2) *Use lower-Z absorber material**
   to eliminate / reduce the jet problems

3) *Maintain advantages of compensation*
   (eliminate / reduce effects of fluctuations in f_{em} and invisible energy)

⟶ *Dual-Readout Calorimetry*

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* *This may also reduce the weight and volume of the calorimeter*

Dual Readout Calorimetry

An attractive option for improving the quality of hadron calorimetry:

Use Čerenkov light!! *Why?*

Hadron showers < *em* component (π^0)
non-em component (mainly soft *p*)

Calorimeter response to these components not the same *(e/h ≠ 1)*

Čerenkov light almost exclusively produced by em 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*

This idea needed EXPERIMENTAL confirmation

(Monte Carlo simulations of hadron shower development not very reliable in 1997)

In came NASA, with the ACCESS project*
Detection of very-high-energy (up to the PeV regime) cosmic rays, at the ISS
Needed a calorimeter with large aperture, modest energy resolution (~10%),
but most importantly, a SMALL MASS (< 2 nuclear interaction lengths)

The properties of such a calorimeter are completely dominated by leakage fluctuations

Unless you get a handle on that leakage, event-by-event, no good performance expected

Dual-readout may help, as follows:
In the first nuclear interaction some fraction of the energy goes into π° production
If that fraction is large ⟶ relatively little leakage ⟶ relatively large signal
If that fraction is small ⟶ relatively much leakage ⟶ relatively small signal
The C/S signal ratio tells how large that fraction is!!

Does it work in practice?

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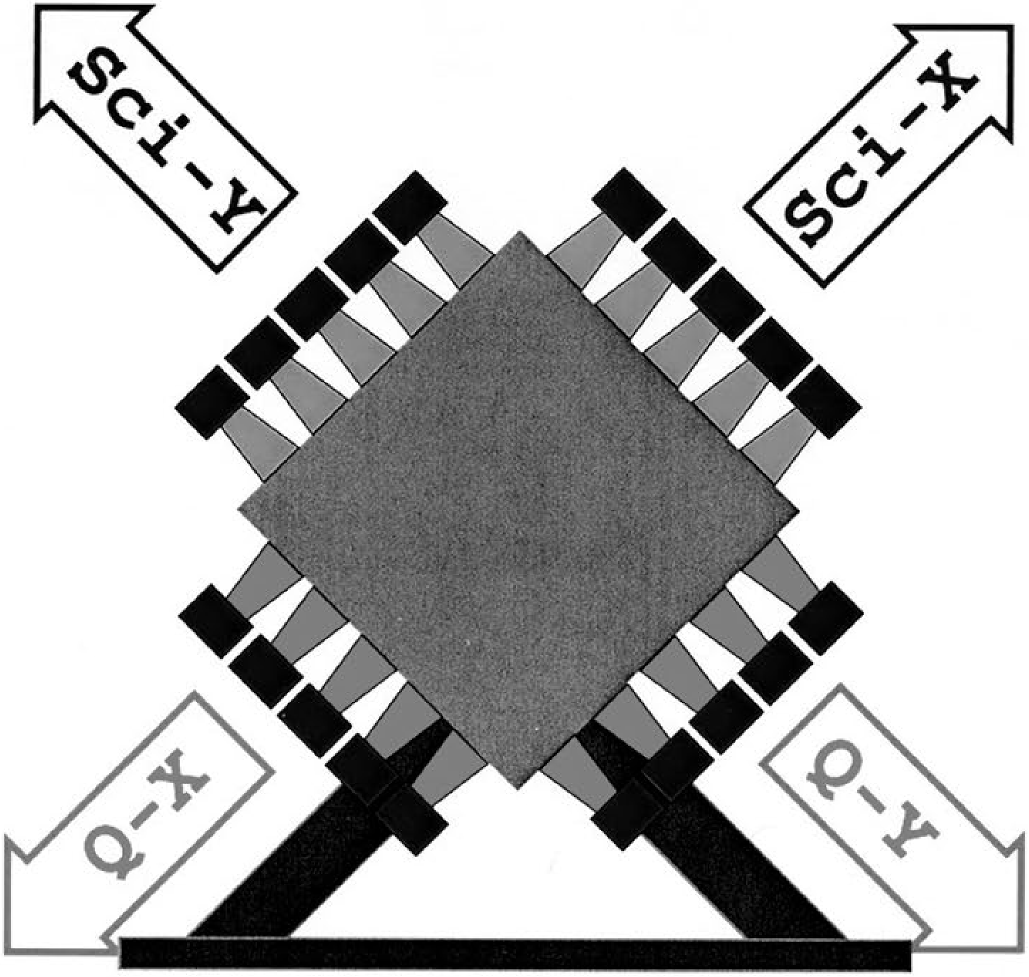
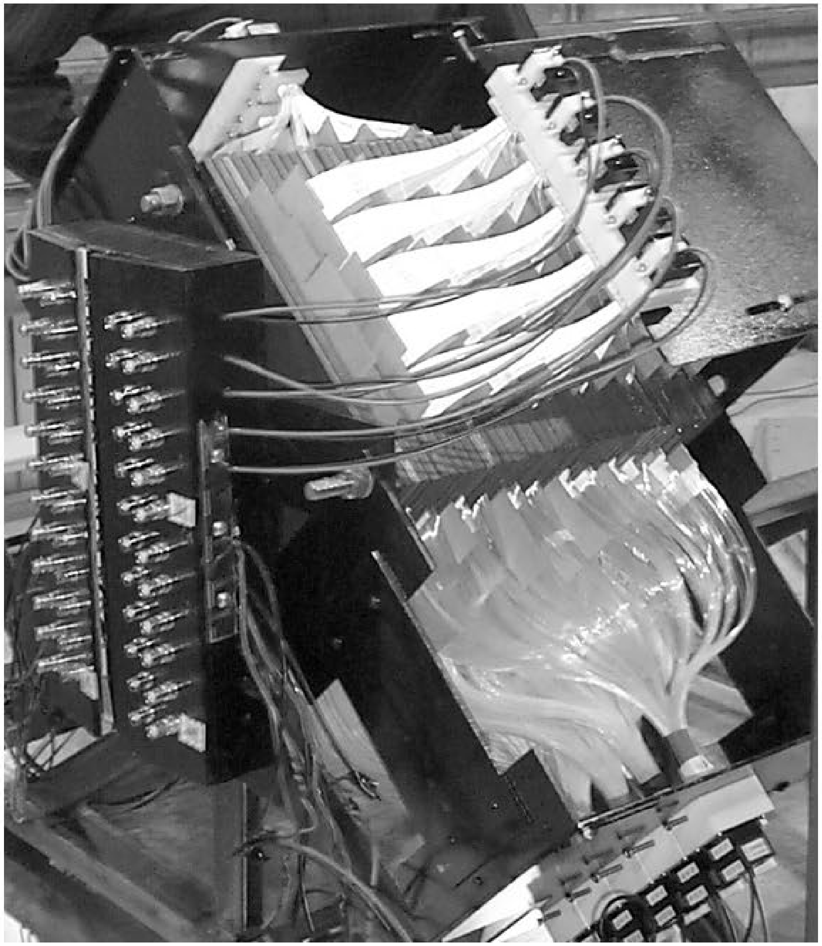
* This project was canceled in 2003, after the accident with the Columbia Space Shuttle

The ACCESS dual-readout calorimeter

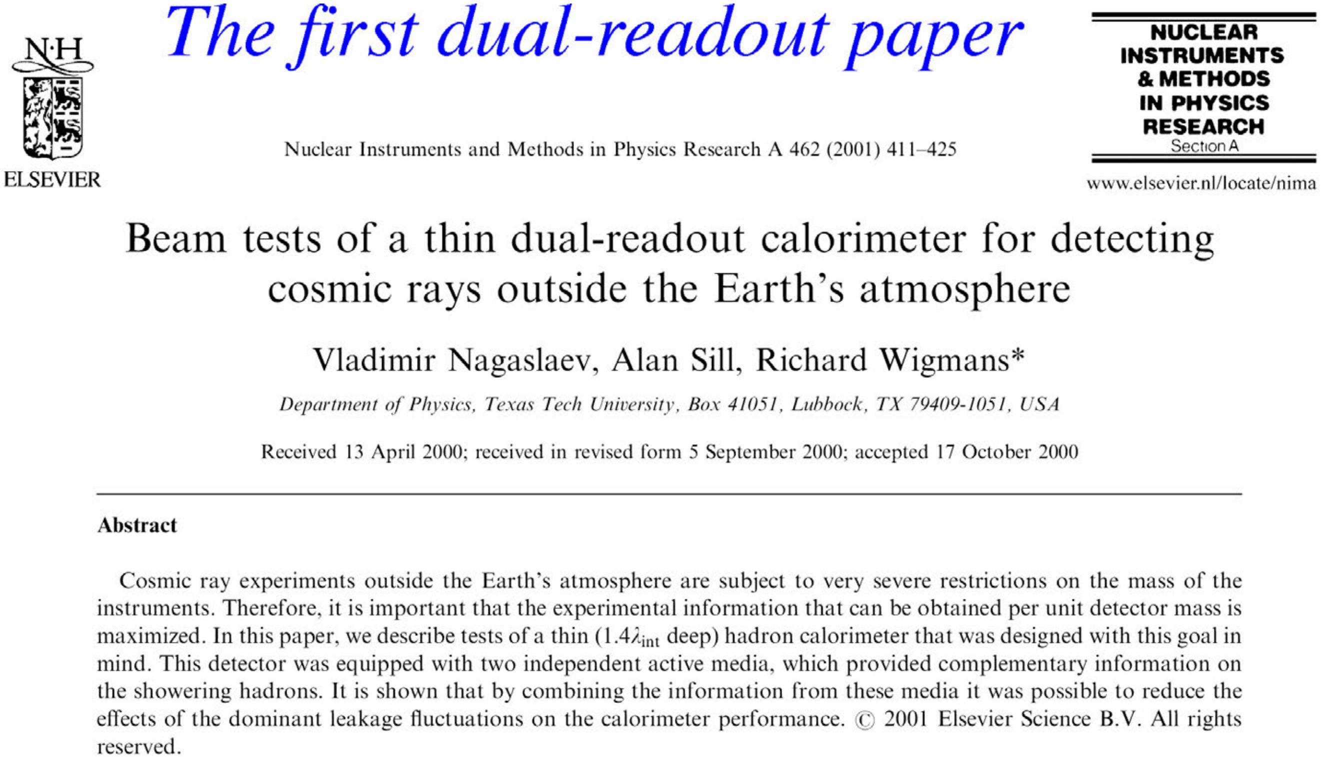
Absorber: 39 Pb plates, 6.4 mm thick (1.4 λ_{int} total depth)
Active: alternating ribbons of plastic scintillator, quartz

Tested with high-energy (up to 375 GeV) pions at CERN





The first dual-readout paper



Nuclear Instruments and Methods in Physics Research A 462 (2001) 411–425

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Beam tests of a thin dual-readout calorimeter for detecting cosmic rays outside the Earth's atmosphere

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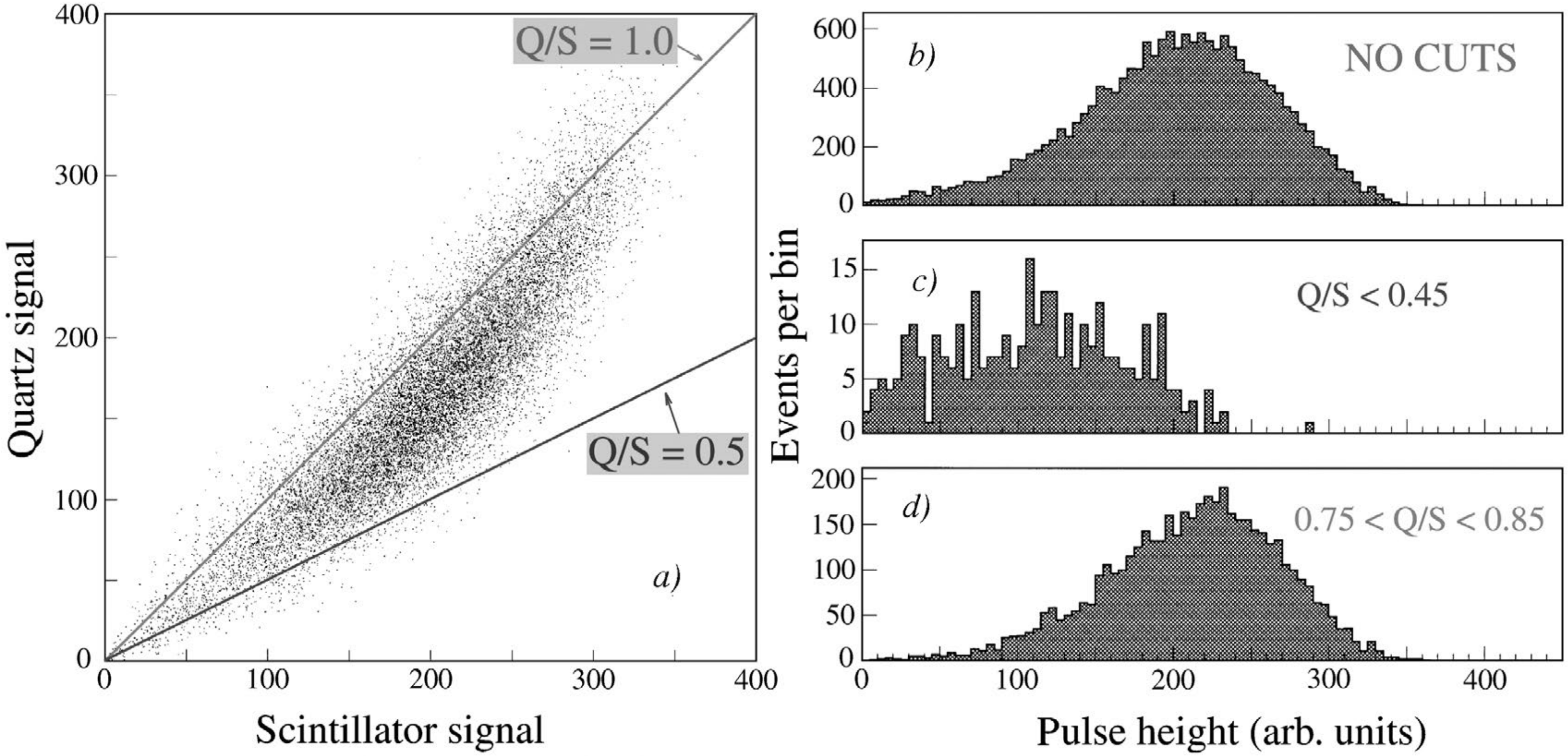
Abstract

Cosmic ray experiments outside the Earth's atmosphere are subject to very severe restrictions on the mass of the instruments. Therefore, it is important that the experimental information that can be obtained per unit detector mass is maximized. In this paper, we describe tests of a thin ($1.4\lambda_{\mathrm{int}}$ deep) hadron calorimeter that was designed with this goal in mind. This detector was equipped with two independent active media, which provided complementary information on the showering hadrons. It is shown that by combining the information from these media it was possible to reduce the effects of the dominant leakage fluctuations on the calorimeter performance. © 2001 Elsevier Science B.V. All rights reserved.



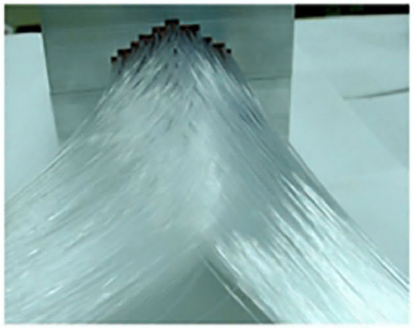
The DREAM project

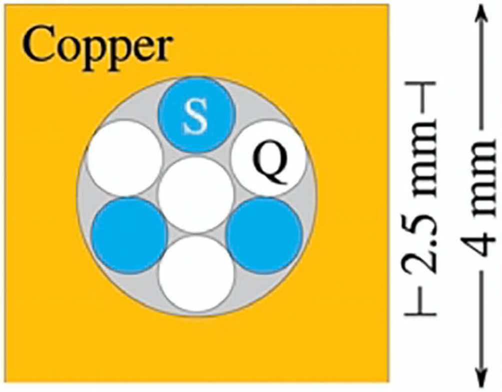
Encouraged by these results, we started to plan for a much larger instrument intended for particle physics experiments.
To contain high-energy hadron showers, it needed to be at least 10 λ_{int} *deep*
We chose copper absorber, which has many advantages over lead (lighter, machinability, e/mip ratio,....)

We managed to convince US-DOE to give us some money for this project ($160,000)
To save money, we used as much material from previous projects as possible (e.g. quartz fibers from CMS HFCAL, photomultipliers, etc.)

The DREAM calorimeter was built at TTU in 2003, and tested at the CERN SPS with high-energy electrons, pions and muons, by a small group of TTU people, with help from some friends (Hans Paar, John Hauptman, Aldo Penzo)

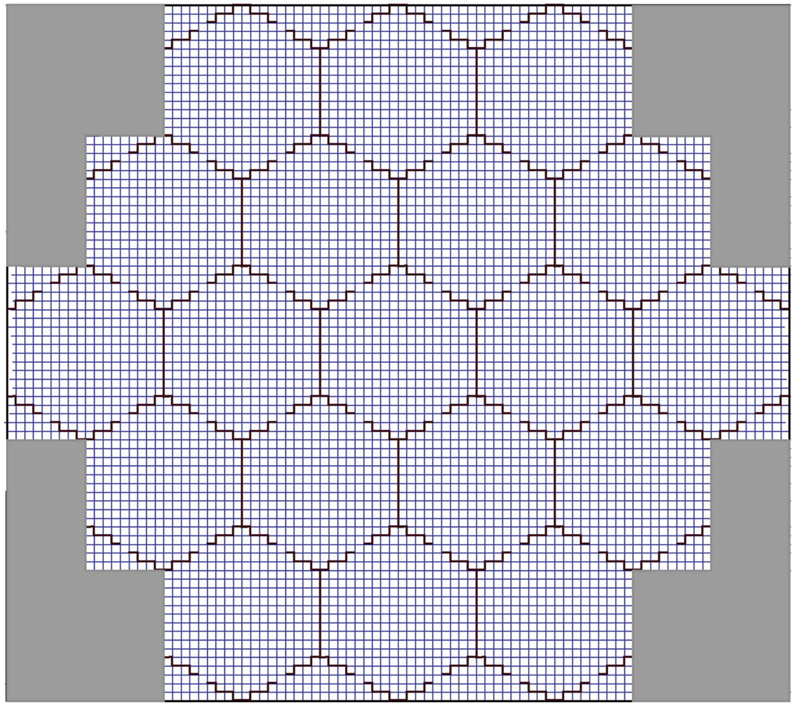
The DREAM calorimeter

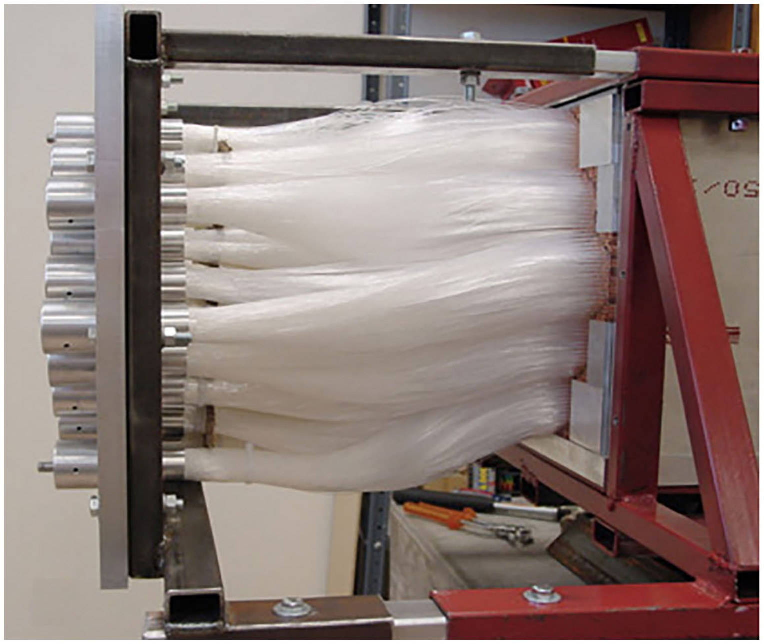




Basic building block: 2 m long copper rod, with a 4 x 4 mm^2 cross section with a 2.5 mm central hole in it.
In this hole were inserted 7 optical fibers, 3 scintillating, 4 undoped (quartz in the central region of the detector, PMMA in the periphery)

The calorimeter consisted of 5,130 such rods, arranged in a pattern of 19 hexagonal cells

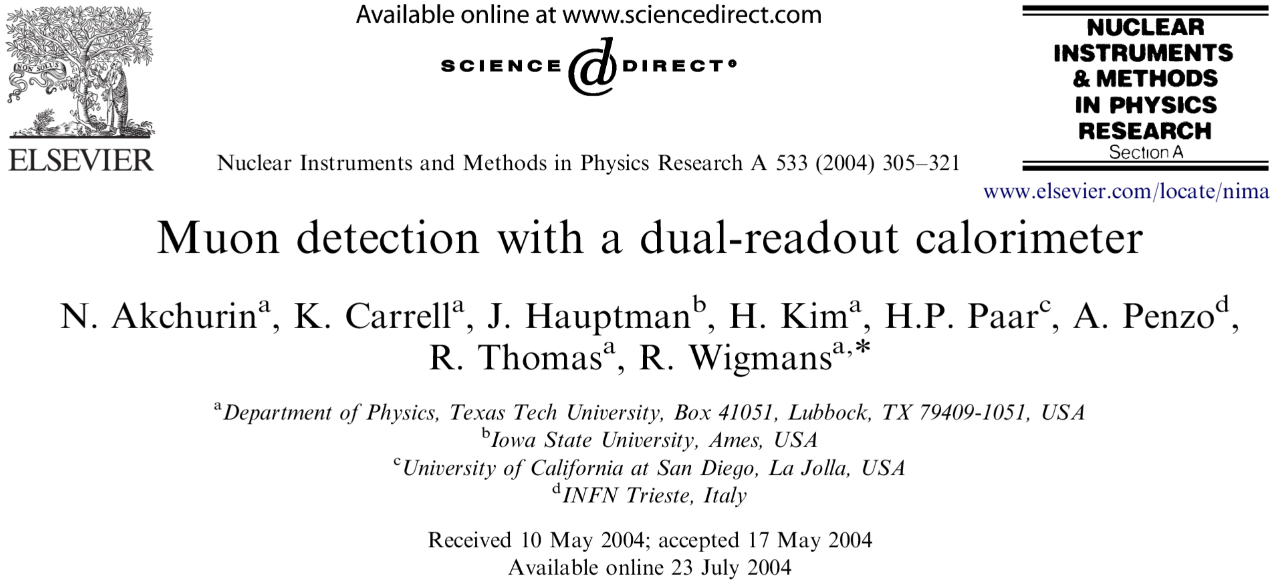




The fibers from each cell were split into 2 bunches, for the S and C fibers. Each bunch was connected to a PMT, so that there were thus 2x 19 =38 signals recorded for every shower developing in this instrument

Total fiducial detector mass was 1,030 kg
(cf SPACAL was ~20,000 kg)

The first DREAM paper, and the first surprise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Muon detection with a dual-readout calorimeter

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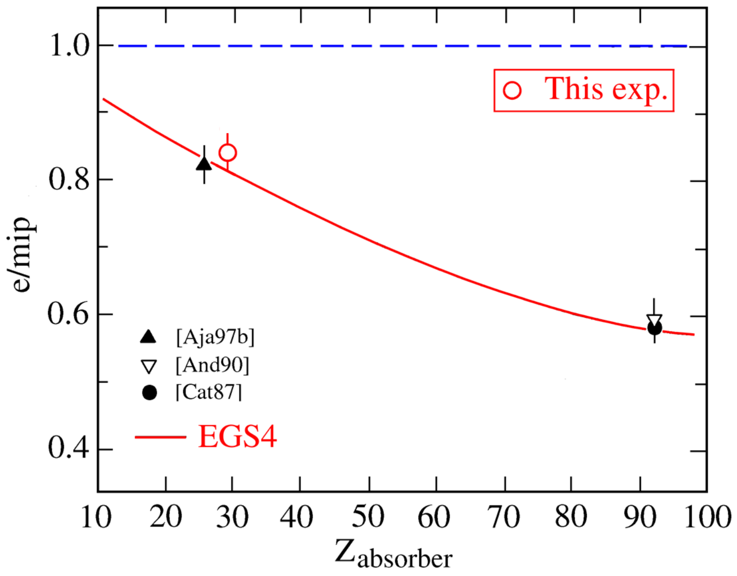
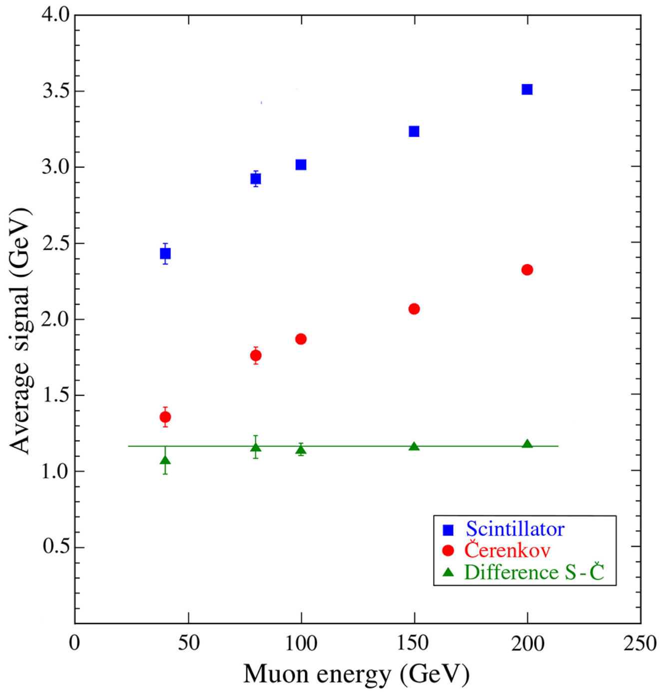
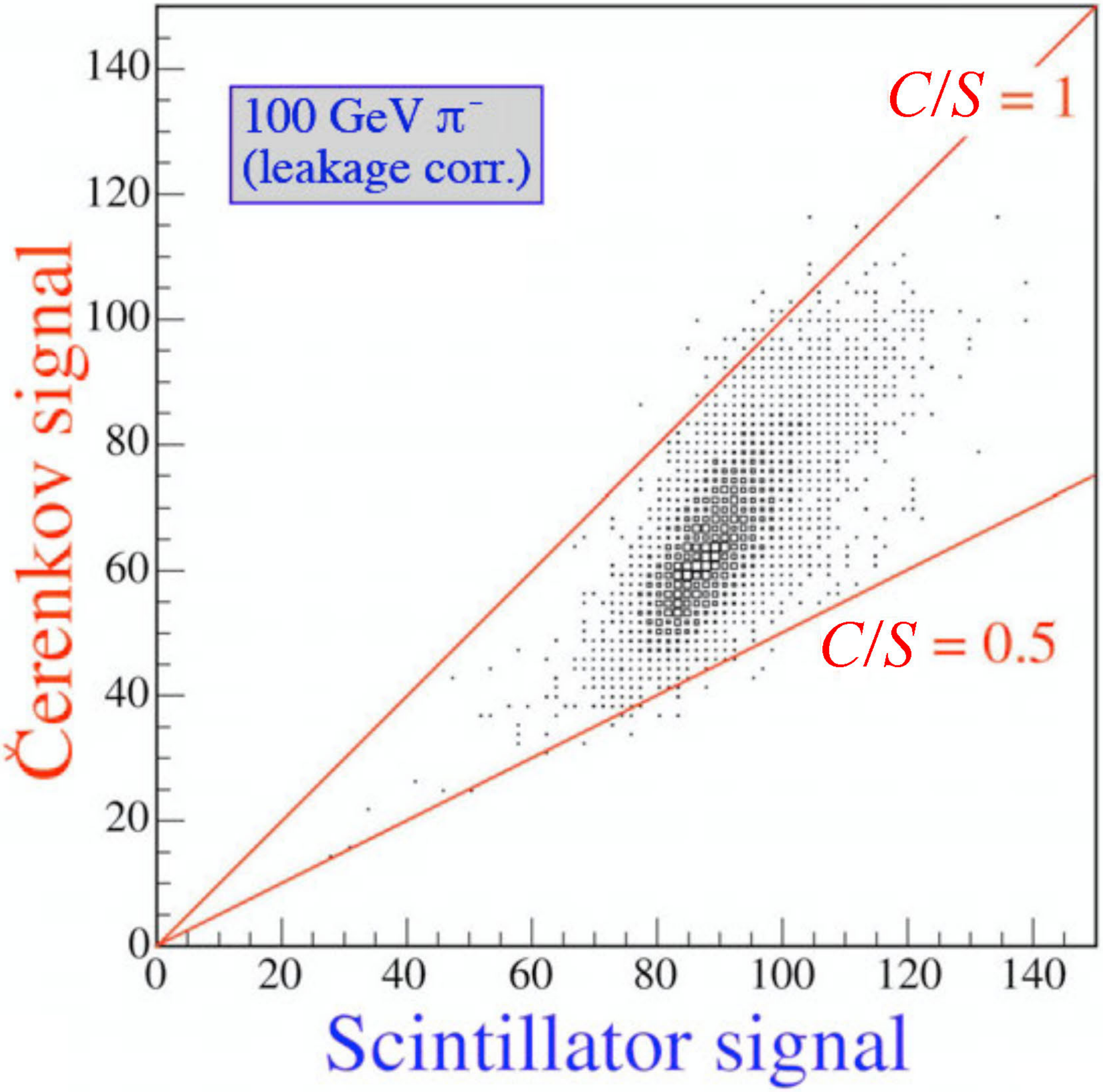


e/mip is indeed much closer to 1.0 for Cu than for Pb/U



The C fibers ONLY detect a signal from the radiative energy losses of the muon traversing the calorimeter

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



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

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

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

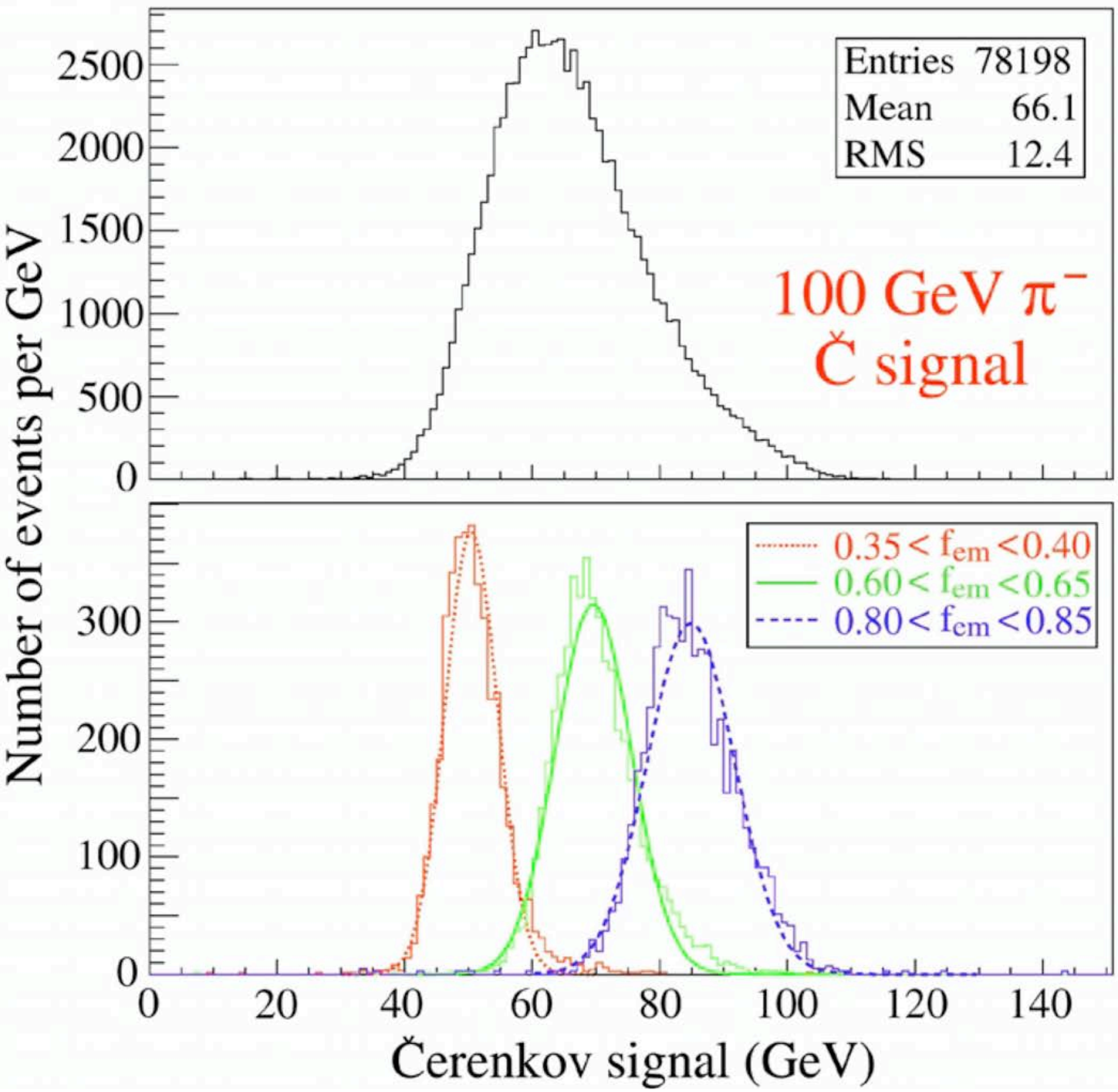
$$\boxed{\frac{C}{S} = \frac{f_{\mathrm{em}} + 0.21\,(1 - f_{\mathrm{em}})}{f_{\mathrm{em}} + 0.77\,(1 - f_{\mathrm{em}})}}$$

$$\boxed{E = \frac{S - \chi C}{1 - \chi}}$$

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

$$\boxed{f_{em} = \frac{(h/e)_C - C/S\,(h/e)_S}{C/S\,[1 - (h/e)_S] - [1 - (h/e)_C]}}$$

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



From:
NIM A537 (2005) 537

Effects of C/S corrections on

hadronic signal linearity and jet resolution

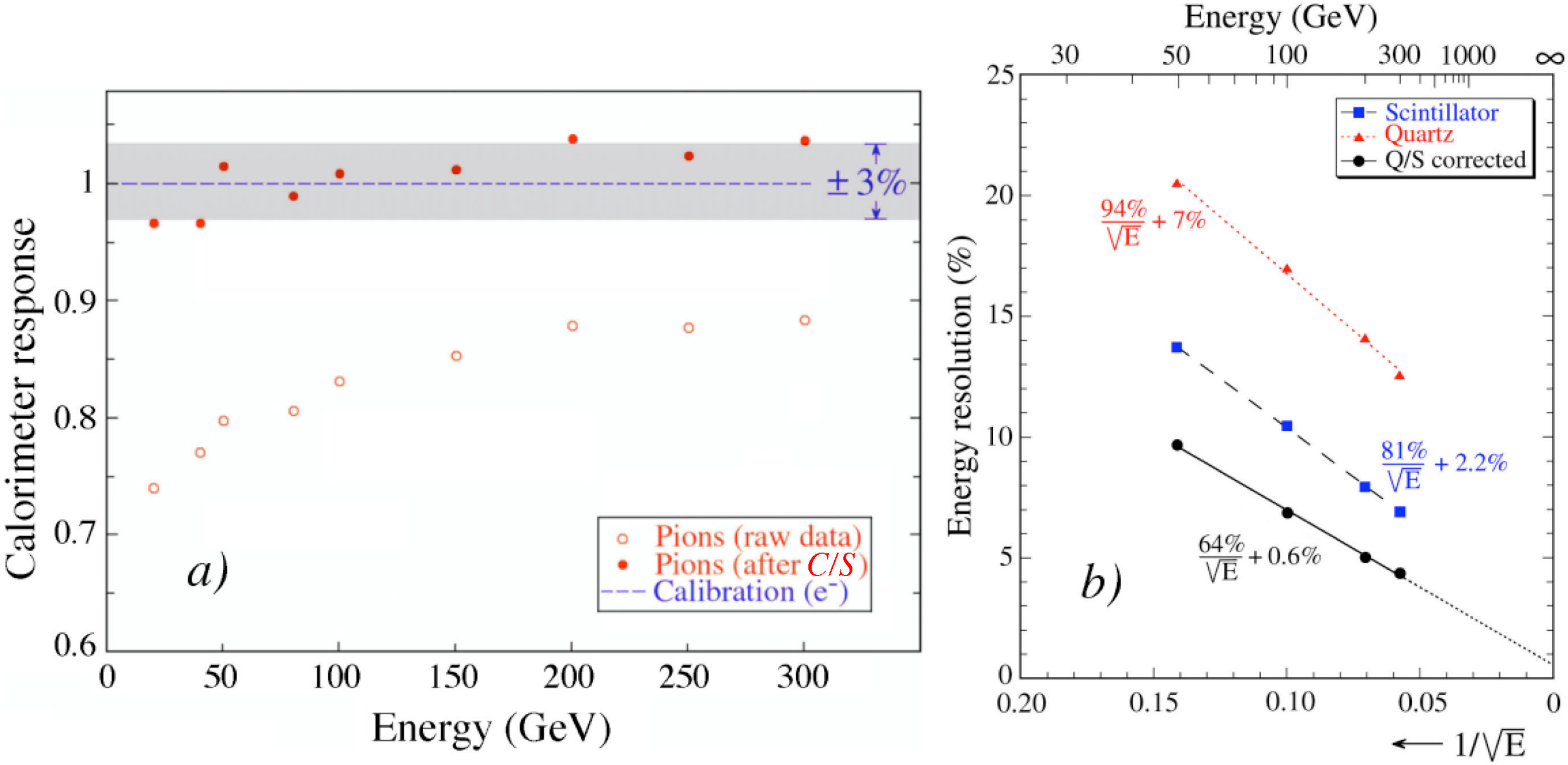


Figure 9: The scintillator response of the DREAM calorimeter to single pions (*a*) and the energy resolution for "jets" (*b*), before and after the dual-readout correction procedures were applied to the signals [5].

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

To study these issues, the RD52 Collaboration was formed (2006)
TTU, ISU (from the USA), Pavia, Pisa, Roma, Cosenza, Cagliari (Italy)

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

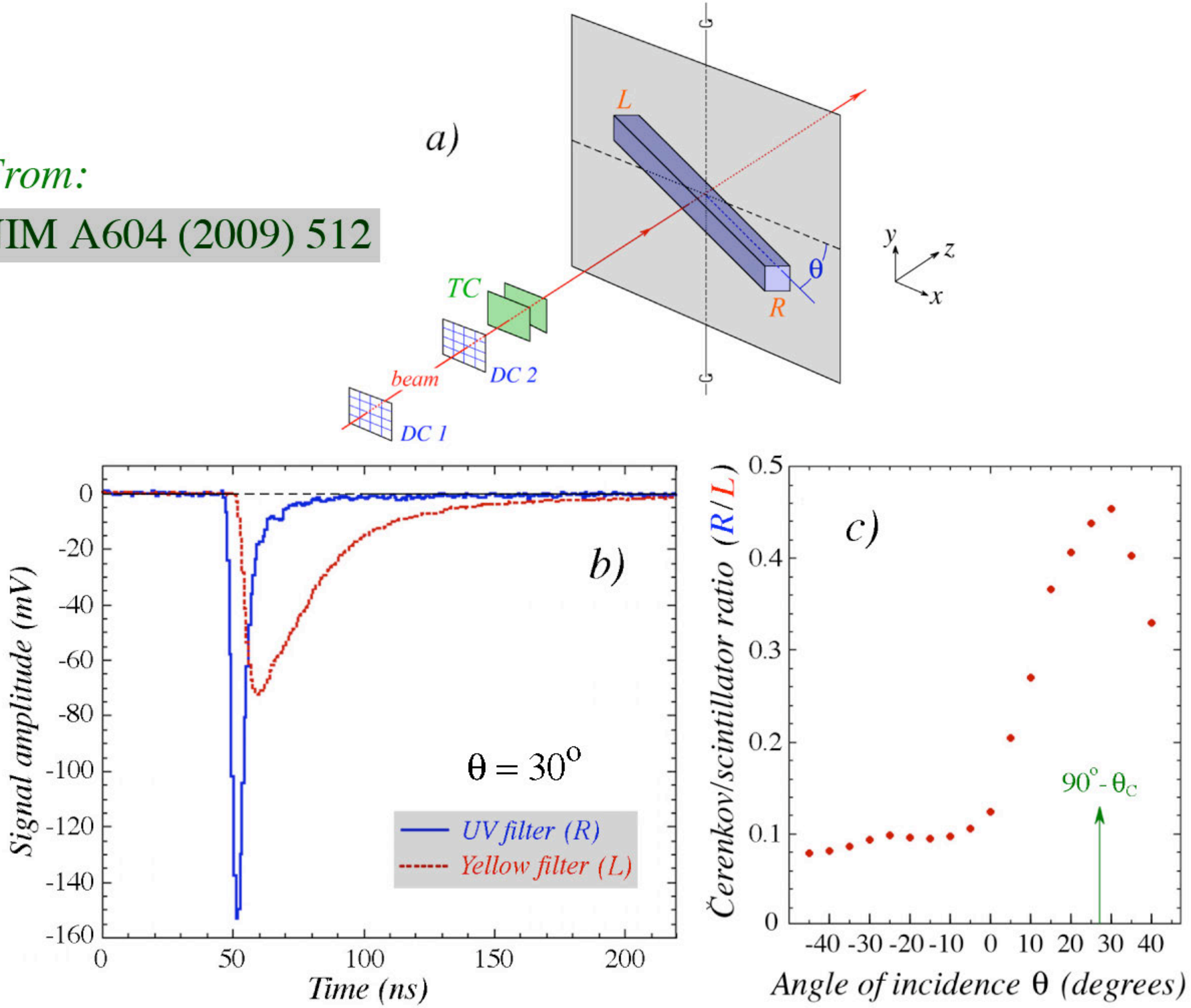
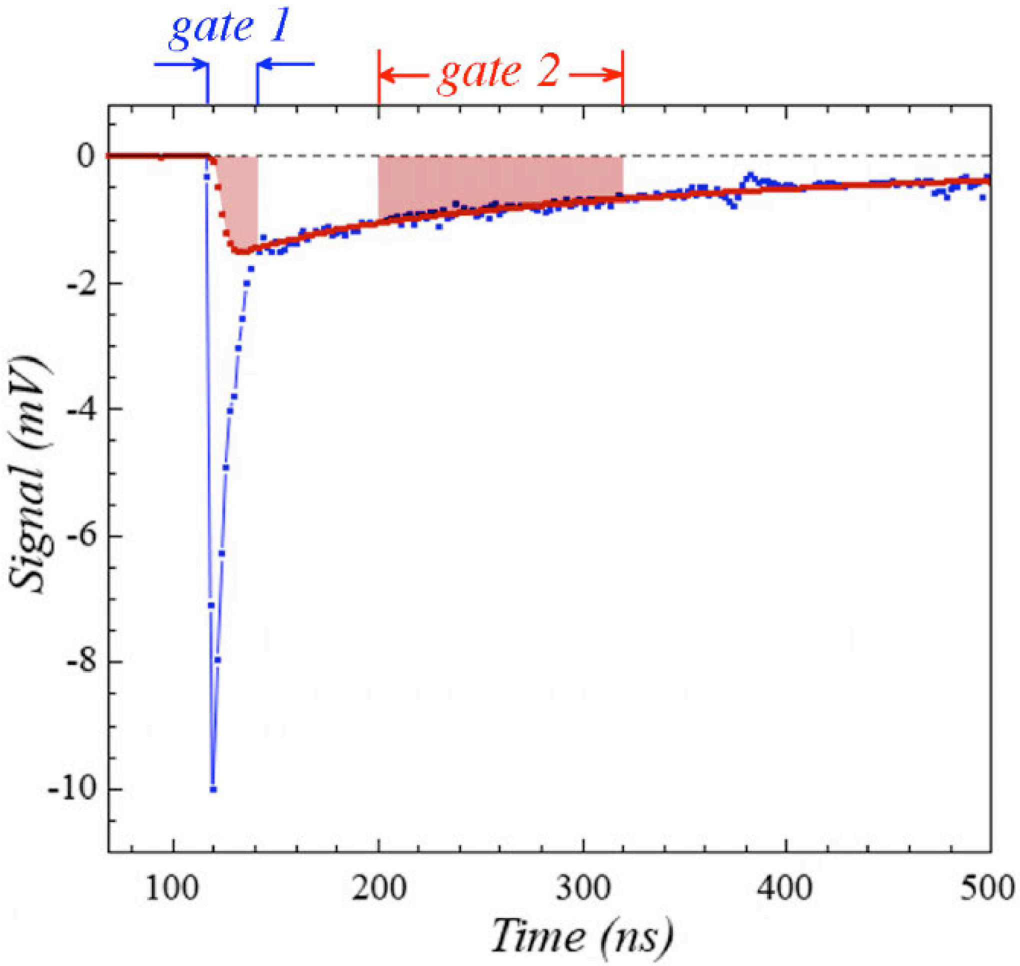


Figure 3: Unraveling of the signals from a Mo-doped $PbWO_4$ crystal into Čerenkov and scintillation components. The experimental setup is shown in diagram *a*. The two sides of the crystal were equipped with a UV filter (side *R*) and a yellow filter (side *L*), respectively. The signals from 50 GeV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

Čerenkov and Scintillator information from one signal !



BGO crystal
UG 11 (UV) filter

From:
NIM A595 (2008) 359

Figure 14: The time structure of a typical shower signal measured in the BGO em calorimeter equipped with a UV filter. These signals were measured with a sampling oscilloscope, which took a sample every 0.8 ns. The UV BGO signals were used to measure the relative contributions of scintillation light (gate 2) and Čerenkov light (gate 1)

How to improve DREAM performance

- Build a larger detector → *reduce effects side leakage*

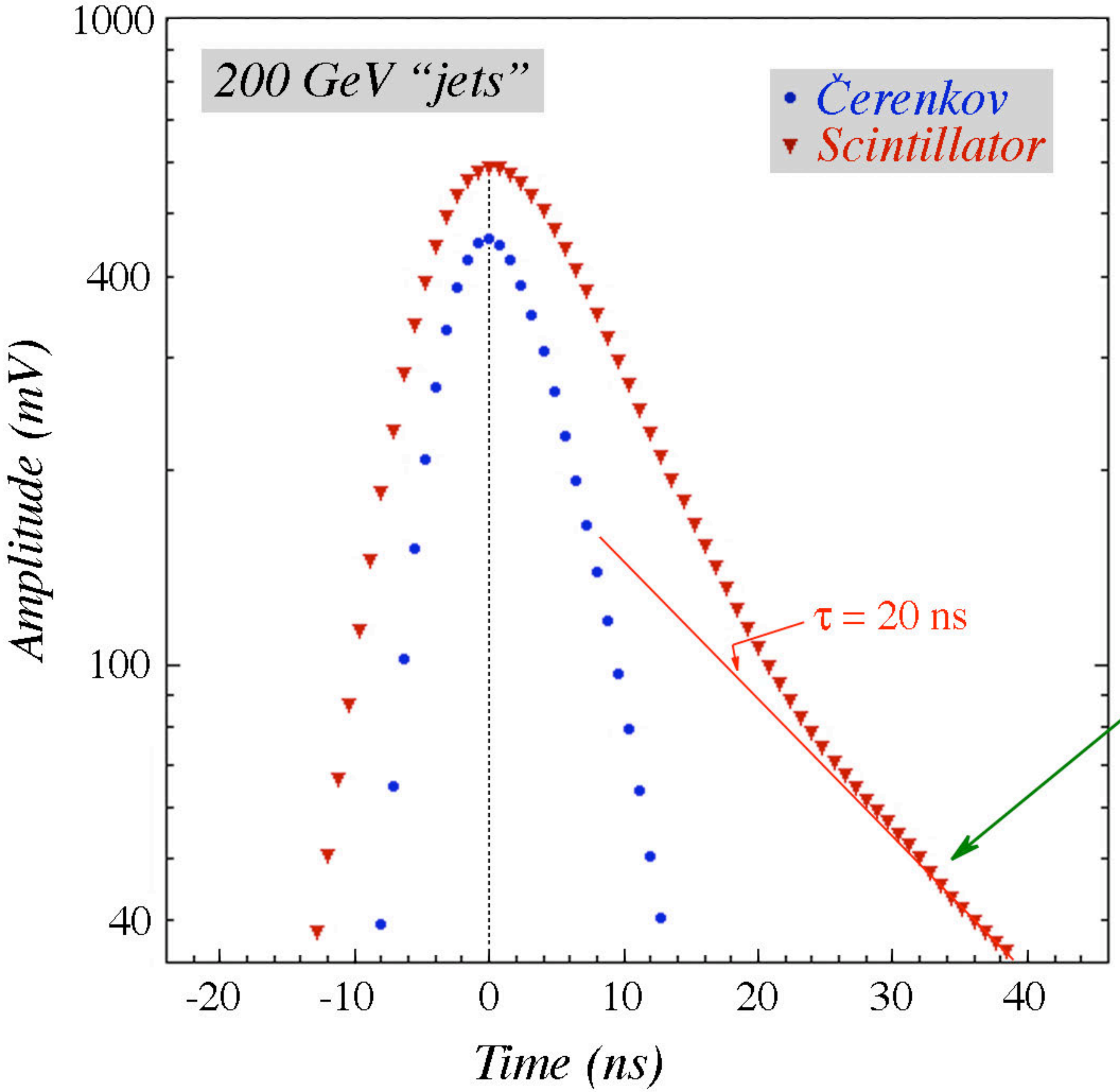
- *Increase Čerenkov light yield*
  DREAM: 8 p.e./GeV → fluctuations contribute 35%/$\sqrt{E}$

- *Reduce sampling fluctuations*
  These contributed ~ 40%/$\sqrt{E}$ to hadronic resolution in DREAM

- For ultimate hadron calorimetry (15%/$\sqrt{E}$): *Measure E_{kin} (neutrons)*
  Is correlated to nuclear binding energy loss (invisible energy)

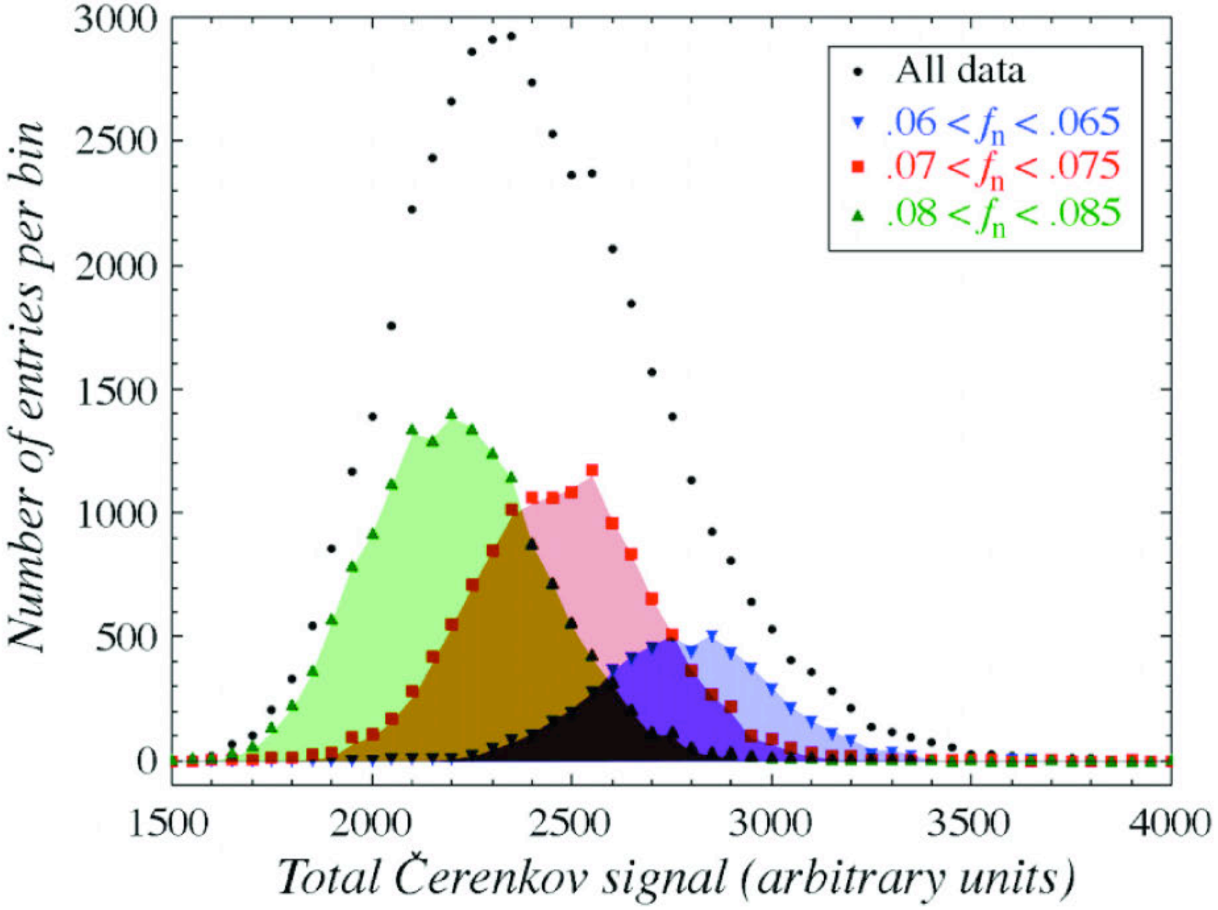
Can be inferred from the time structure of the signals

Time structure of the DREAM signals: the neutron tail



Tail absent for electron showers

Probing the total signal distribution with the neutron fraction

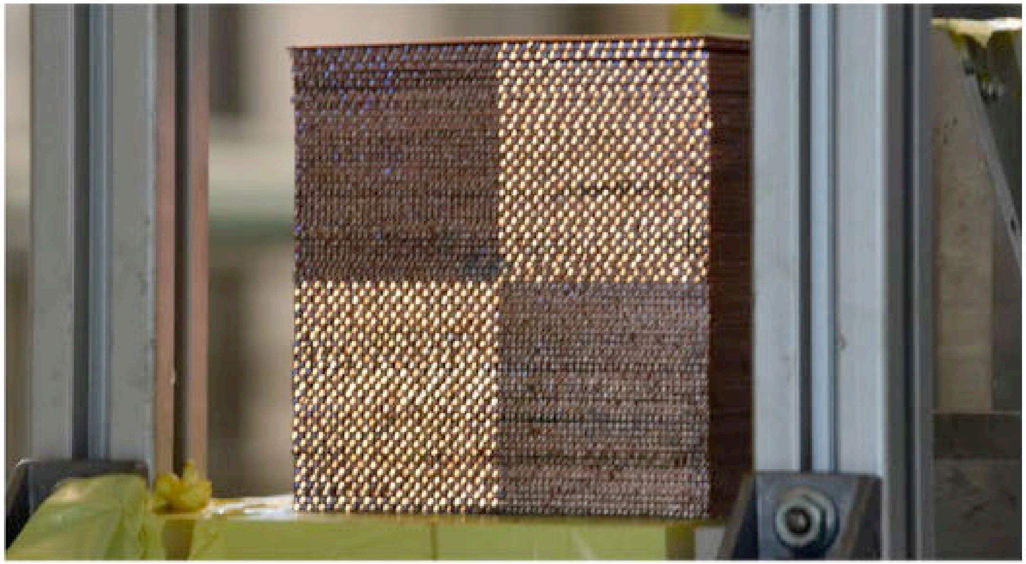


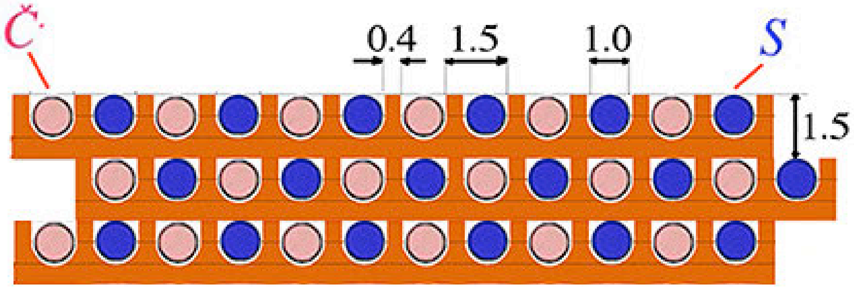
From:

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 .

The first copper module

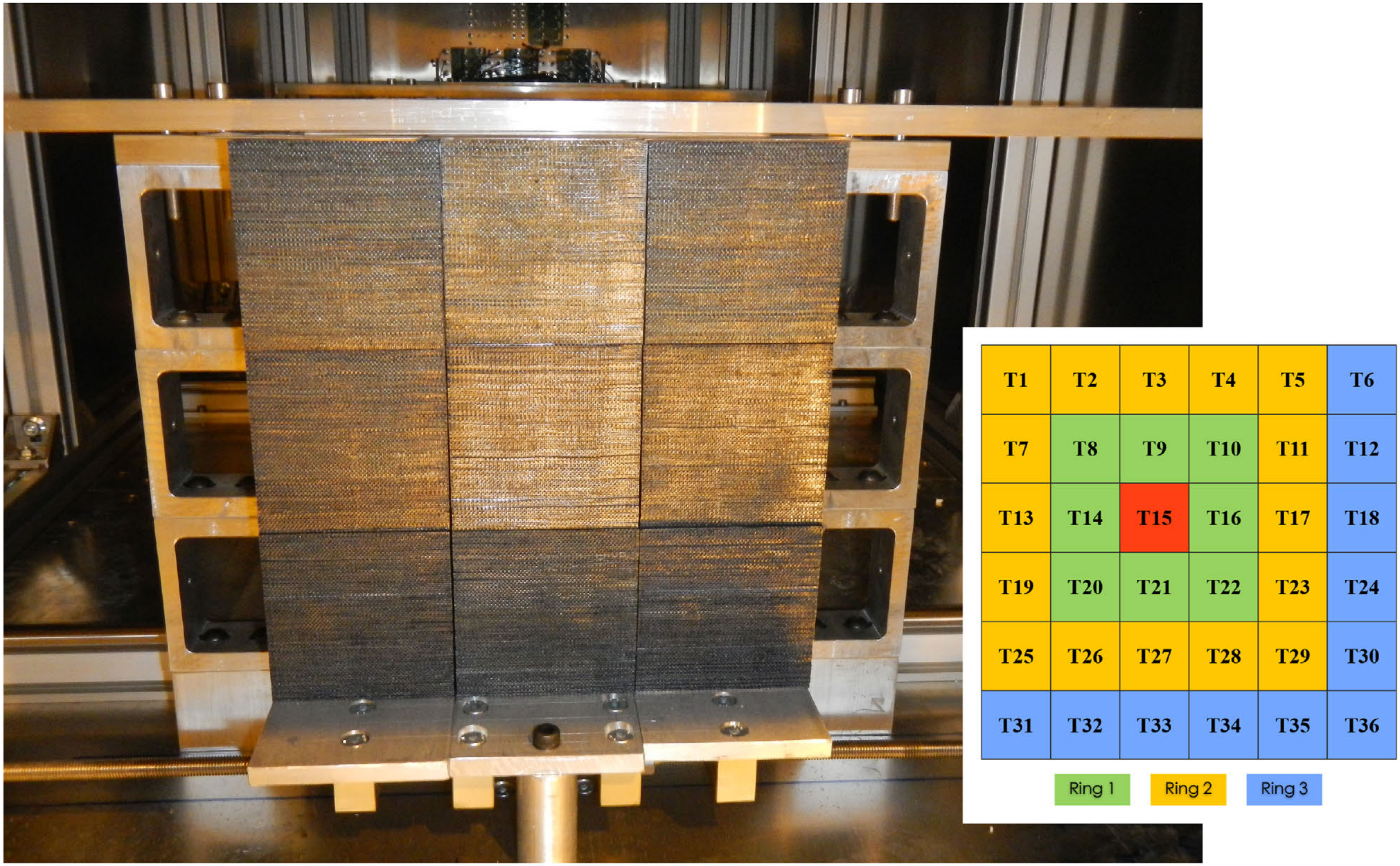




Fiber pattern

2048 S + 2048 Č fibers

The RD52 fiber calorimeter

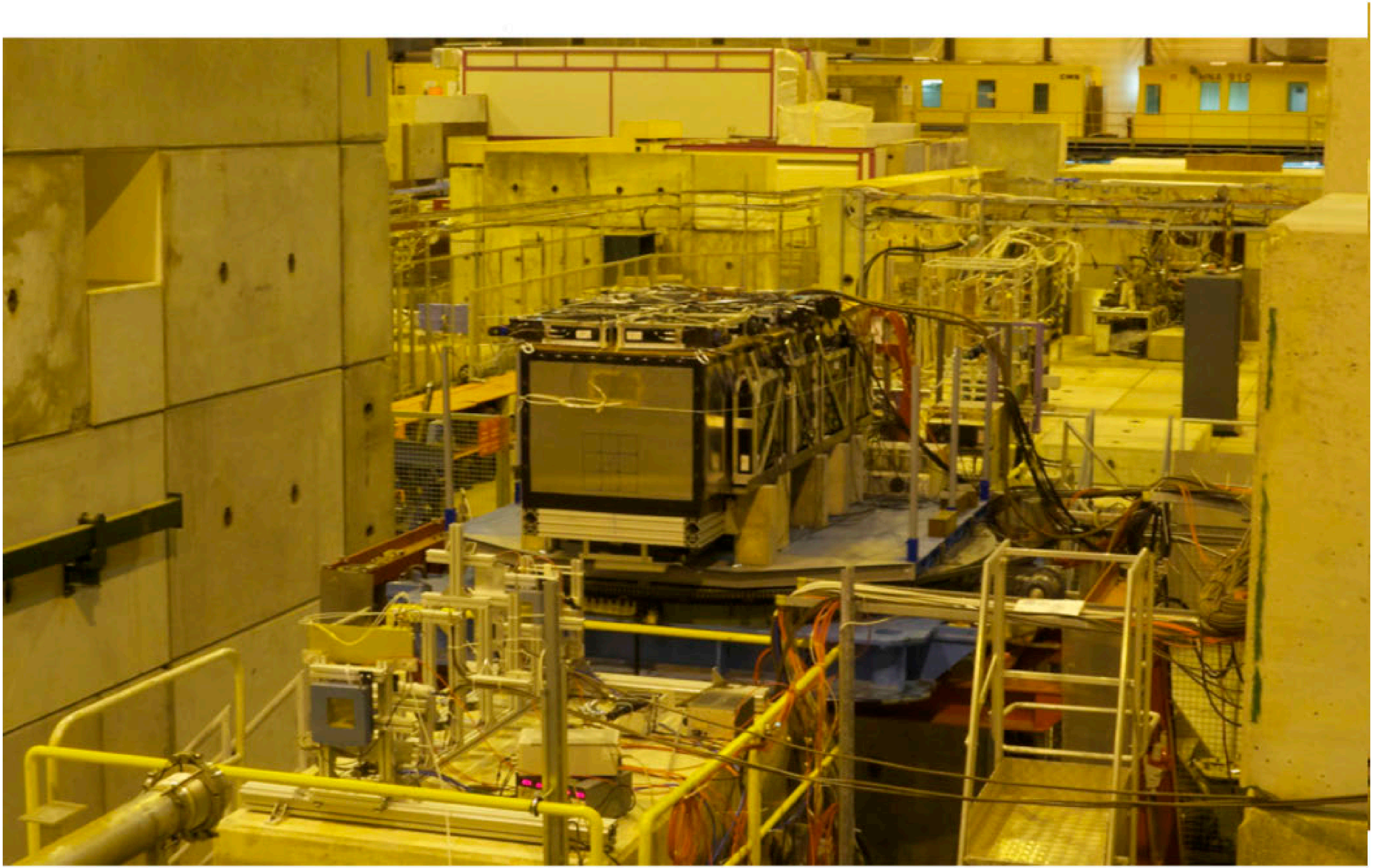


T1	T2	T3	T4	T5	T6
T7	T8	T9	T10	T11	T12
T13	T14	T15	T16	T17	T18
T19	T20	T21	T22	T23	T24
T25	T26	T27	T28	T29	T30
T31	T32	T33	T34	T35	T36

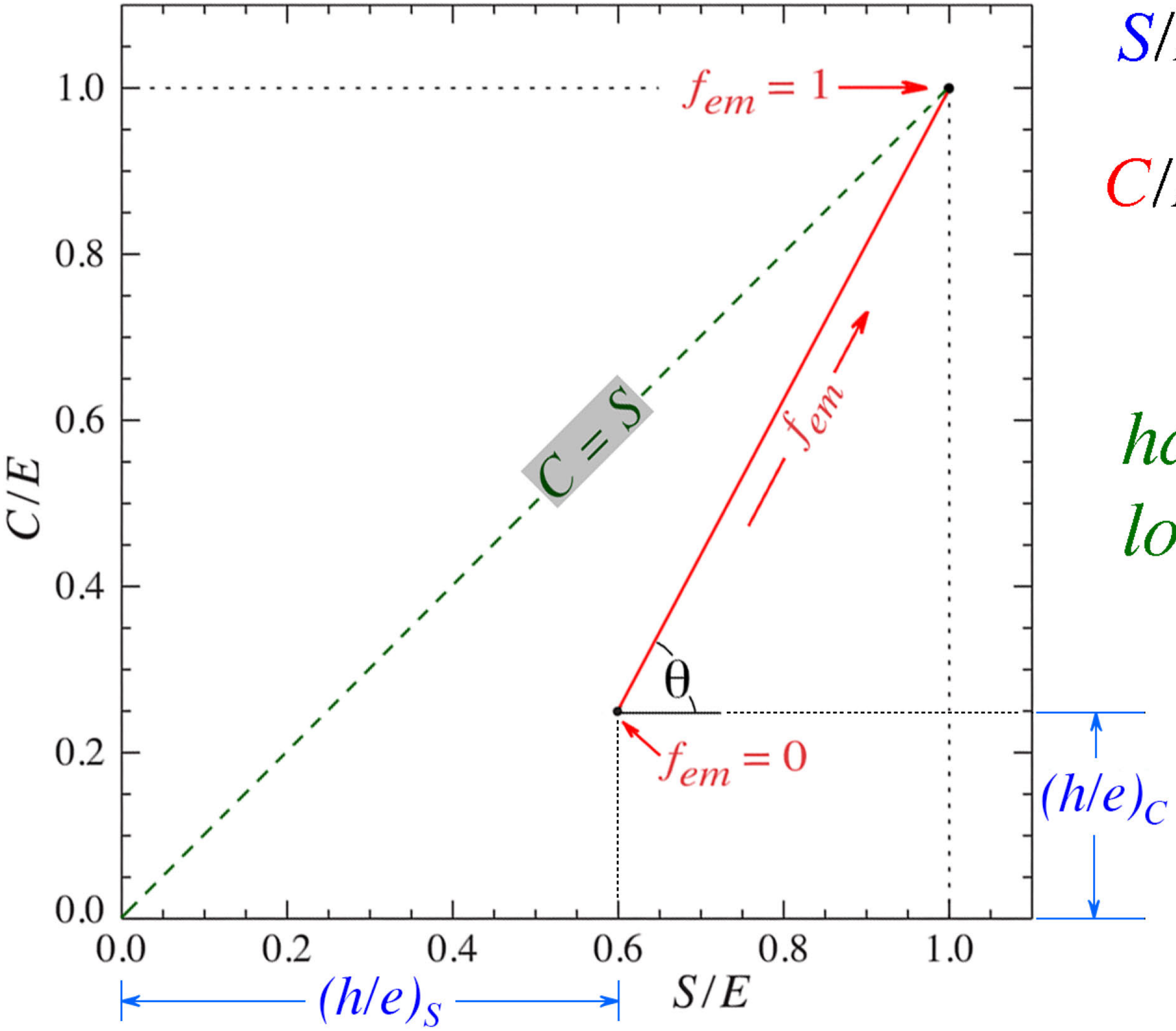
🟩 Ring 1 🟨 Ring 2 🟦 Ring 3

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

The RD52 test area in the H8 beam line



Principles of dual-readout calorimetry (1)

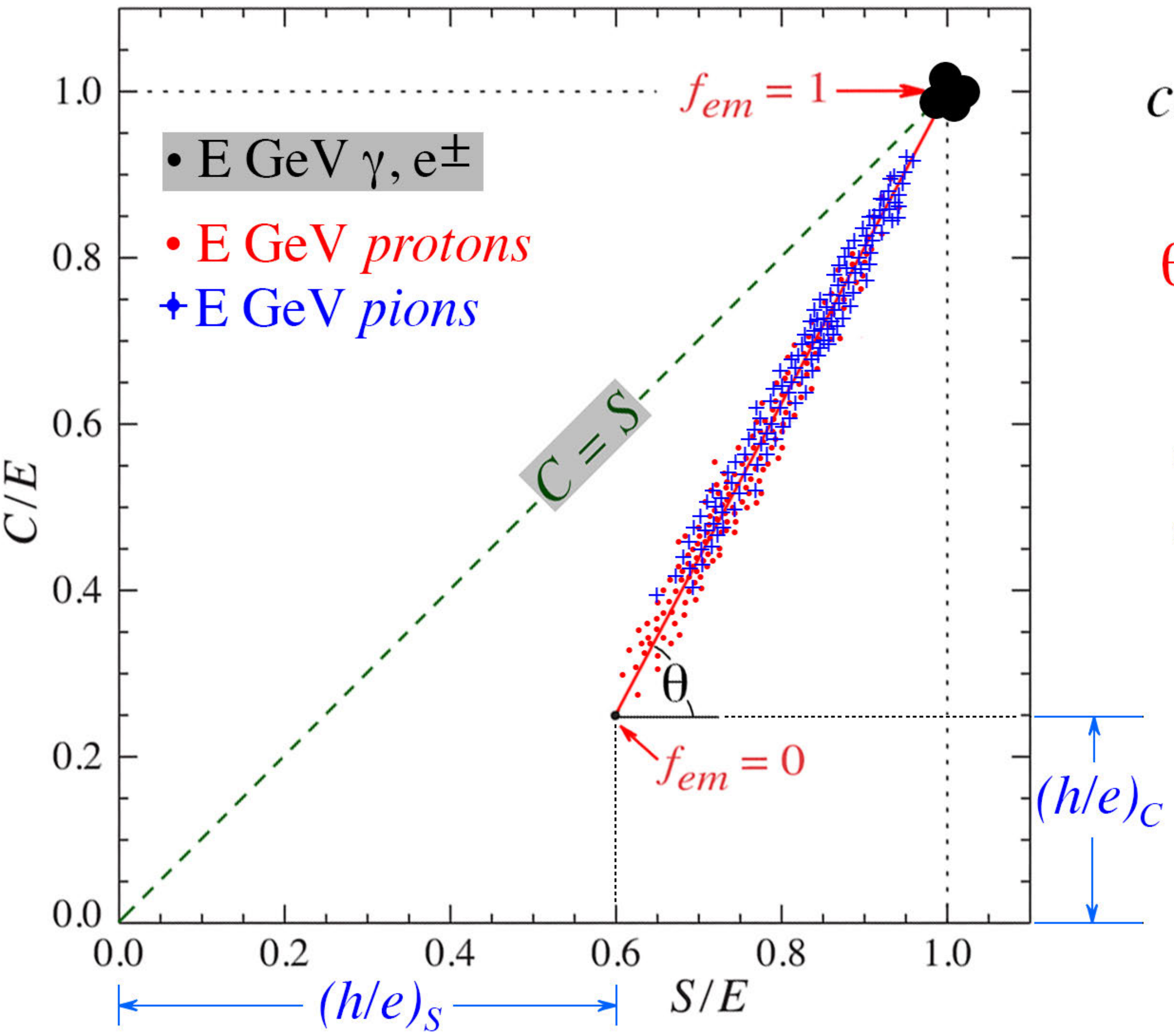


$$S/E = (h/e)_S + f_{em}\,[1 - (h/e)_S]$$

$$C/E = (h/e)_C + f_{em}\,[1 - (h/e)_C]$$

hadronic data points (S,C) located on straight (red) line

Principles of dual-readout calorimetry (2)



$$cotg\,\theta = \frac{1-(h/e)_S}{1-(h/e)_C} = \chi$$

θ,χ are independent of energy!!

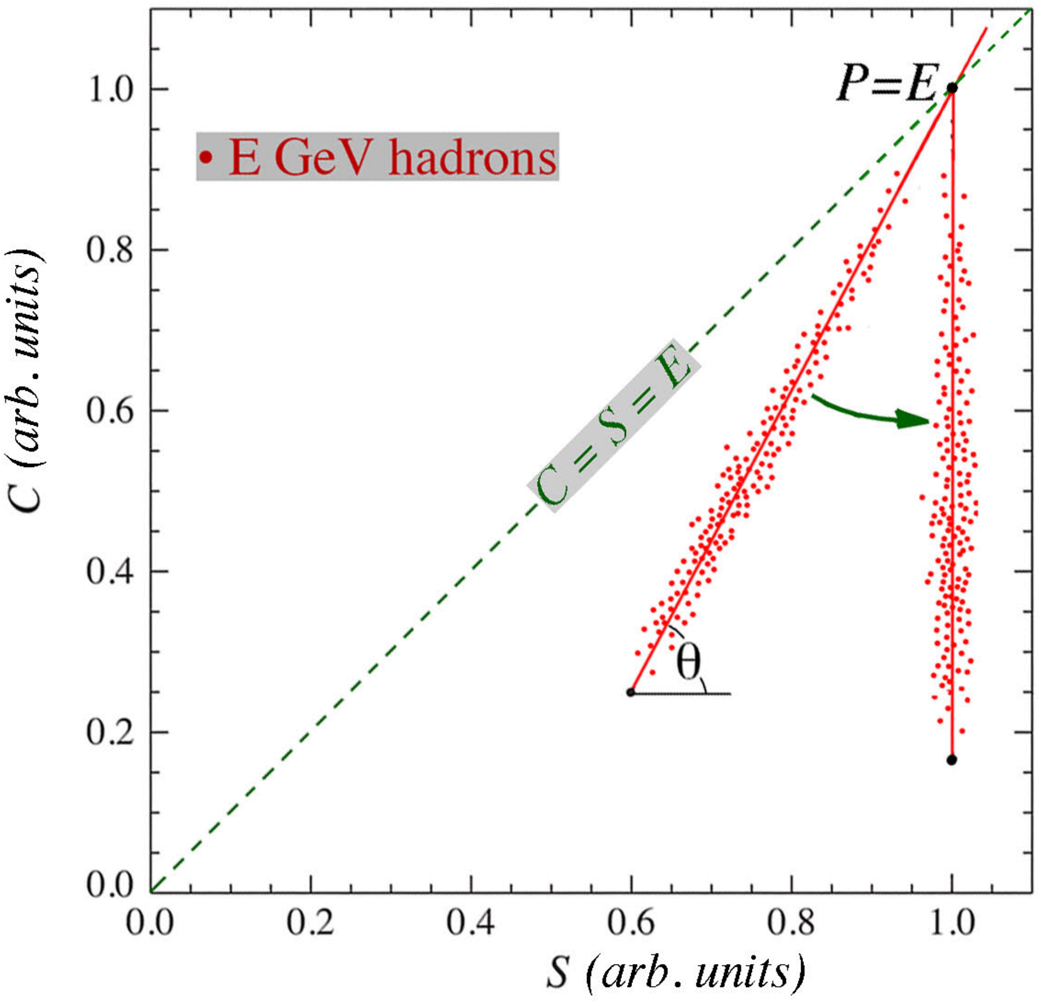
and also independent of the type of hadron!!

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

is universally valid

Principles of dual-readout calorimetry (3)

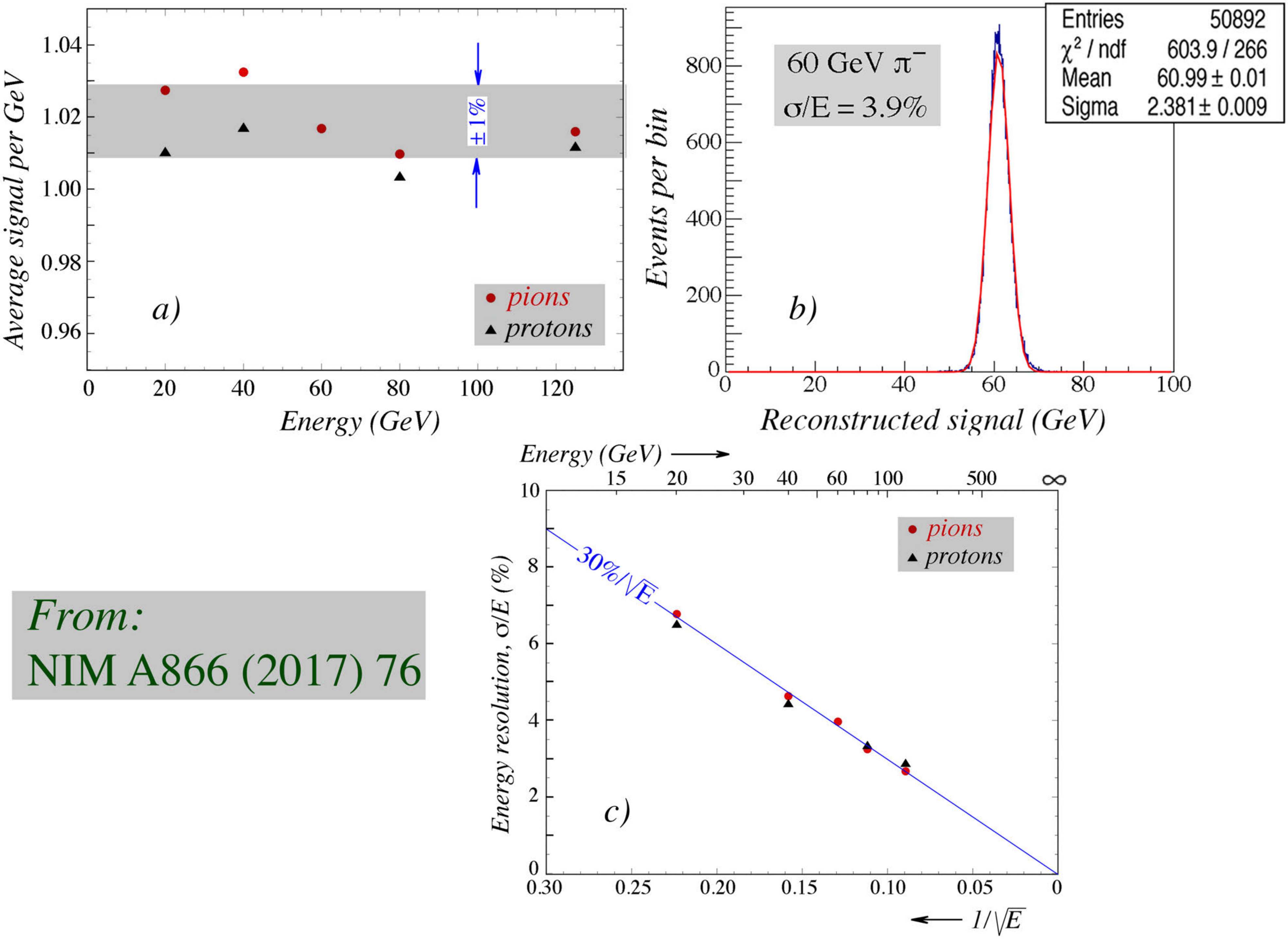
The rotation method



- *Fit experimental data with a straight line*
- *Determine coordinates of P (intersection with C=S line)*
- *Rotate data points about P over angle ($90^o - \theta$)*
- *Project data points on horizontal (S) axis*

θ is independent of E
and particle type!!
→ Don't need this info!!

Hadron results obtained with a dual-readout fiber calorimeter



From:
NIM A866 (2017) 76

A crucial feature: No longitudinal segmentation

- *Advantages:*
  - *Compact construction*
  - *No intercalibration of sections needed*
  - *Calibrate with electrons and you are done*

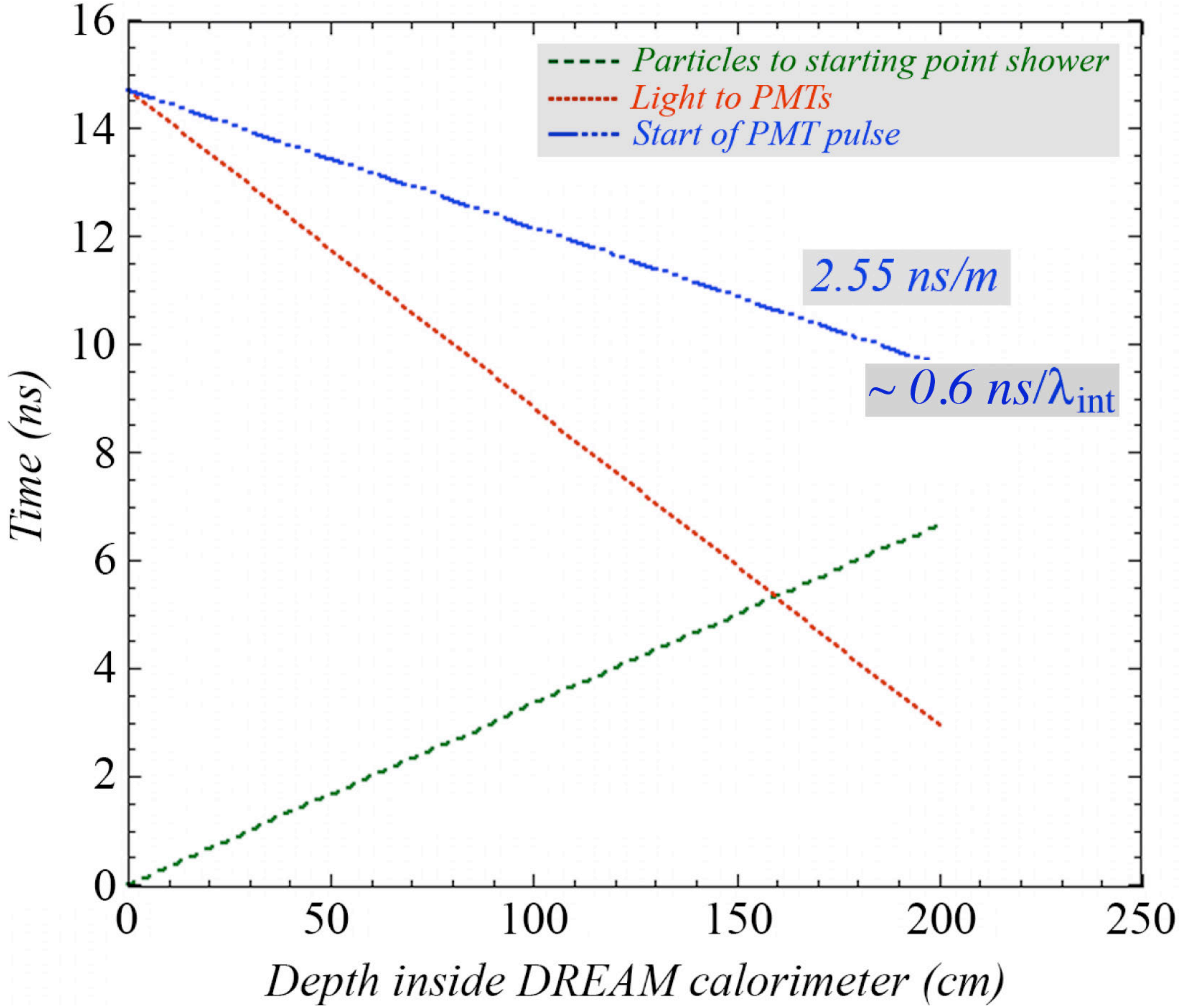
- *Possible disadvantages:*
  - *Dealing with pile-up (not an issue at ILC)*
  - *Pointing for neutral particles*
  - *Electron ID*

However, a fine lateral granularity can do wonders

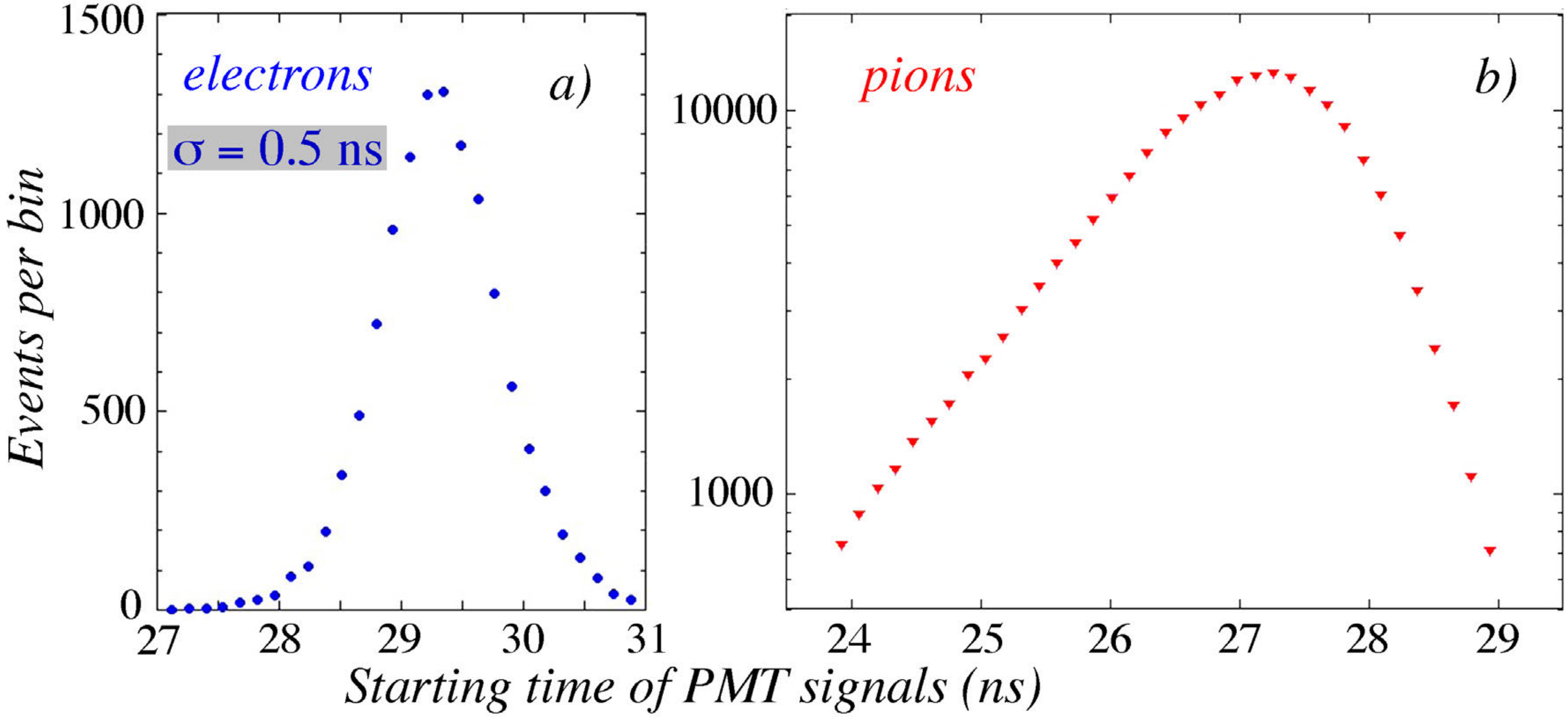
In addition:

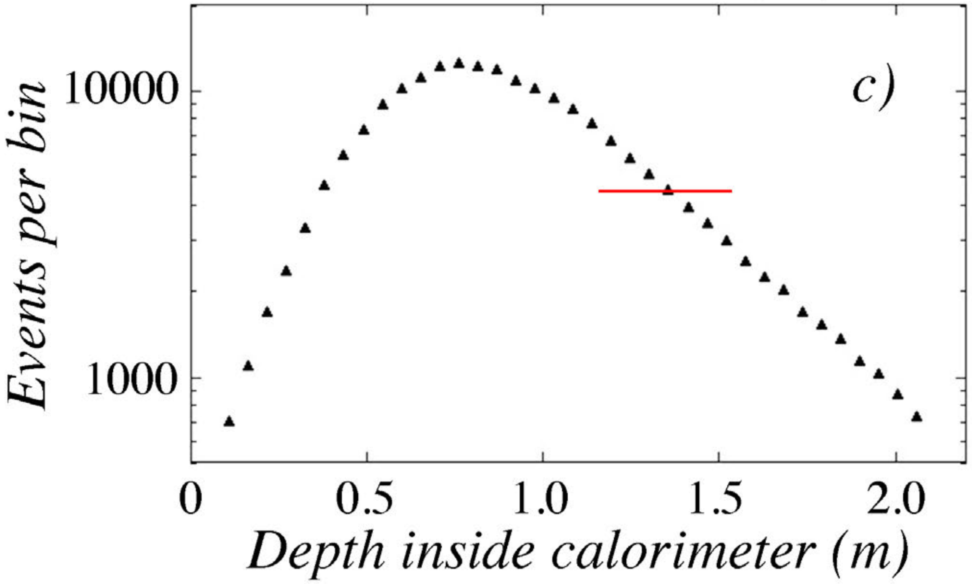
- *Time structure of the signals can provide crucial depth information*

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





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Methods to distinguish e/π in longitudinally unsegmented calorimeter

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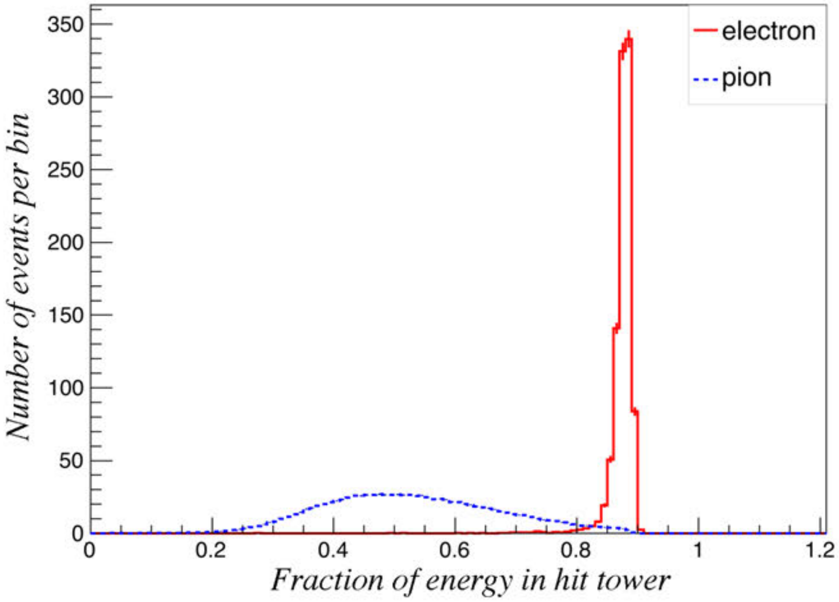
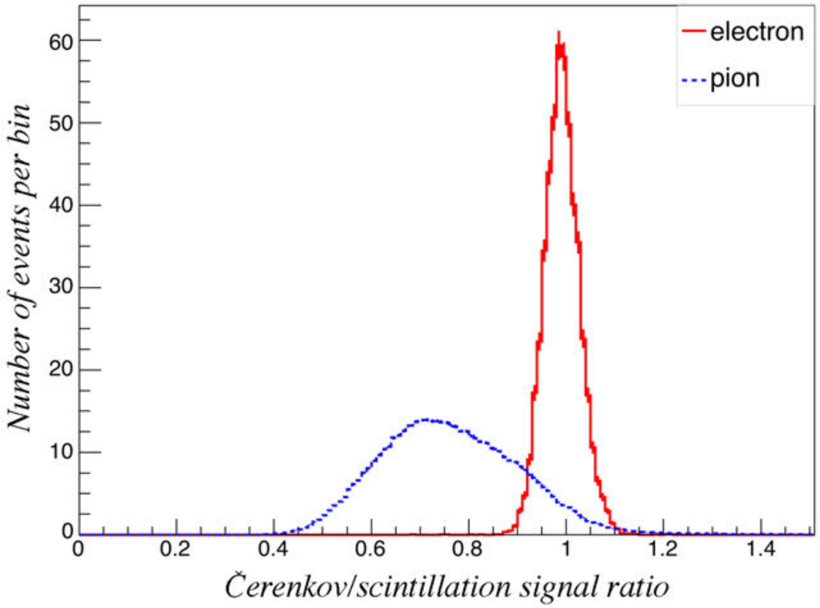
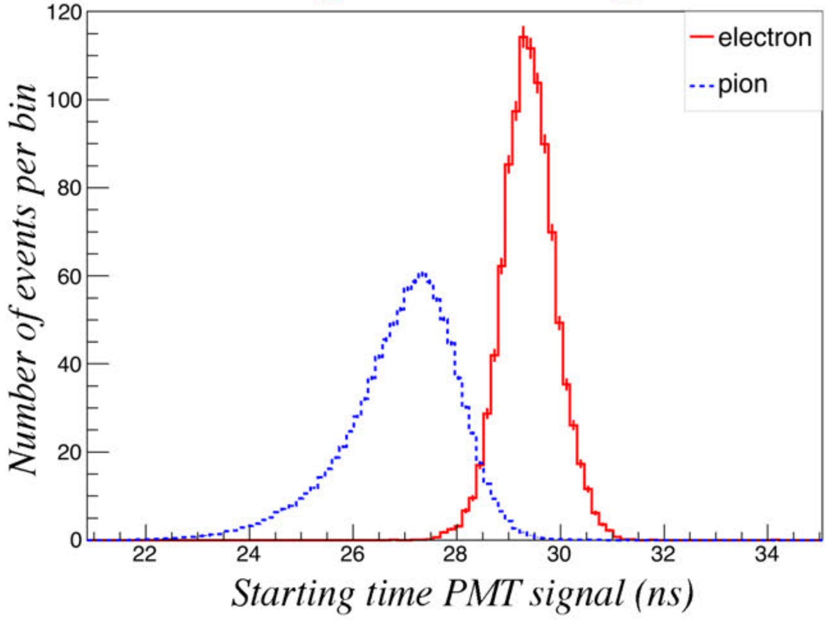
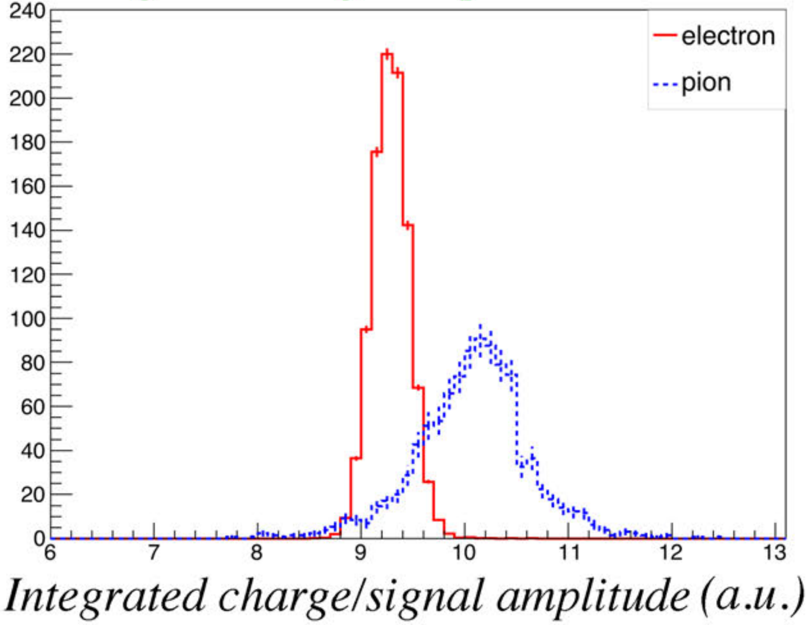

Lateral shower profile


Difference C/S signals


Starting time PMT signal


Signal charge/amplitude ratio

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

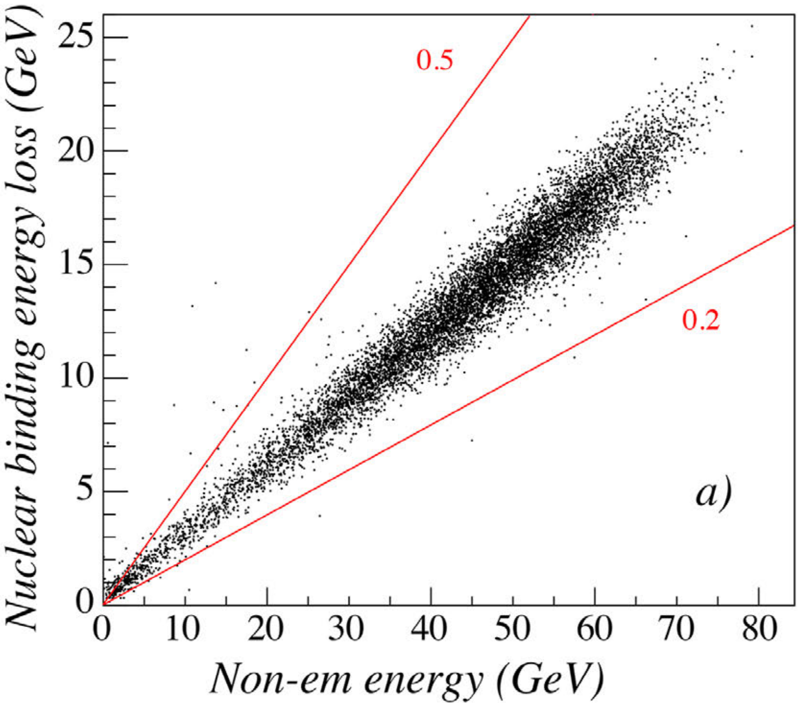
Monte Carlo simulations

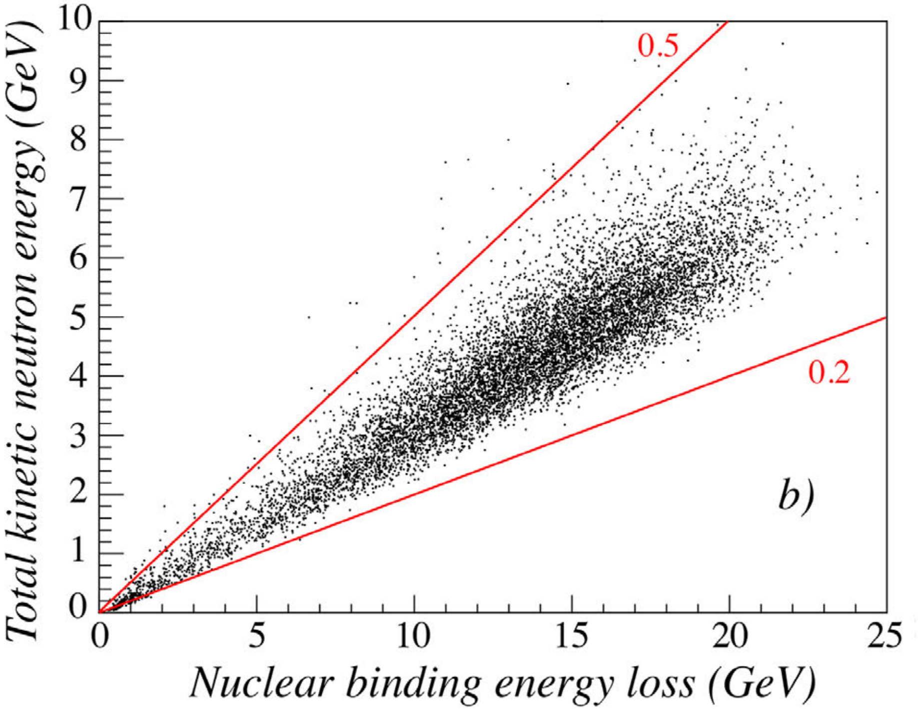
to determine the limits of hadronic performance for calorimeters based on compensation and on dual-readout techniques

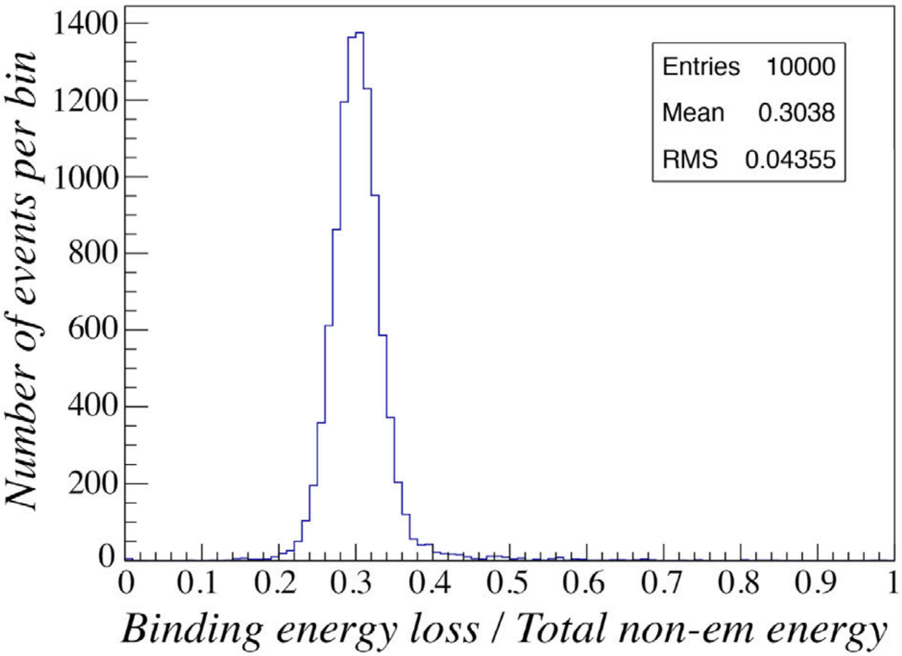
Correlation with invisible energy (100 GeV pion showers)

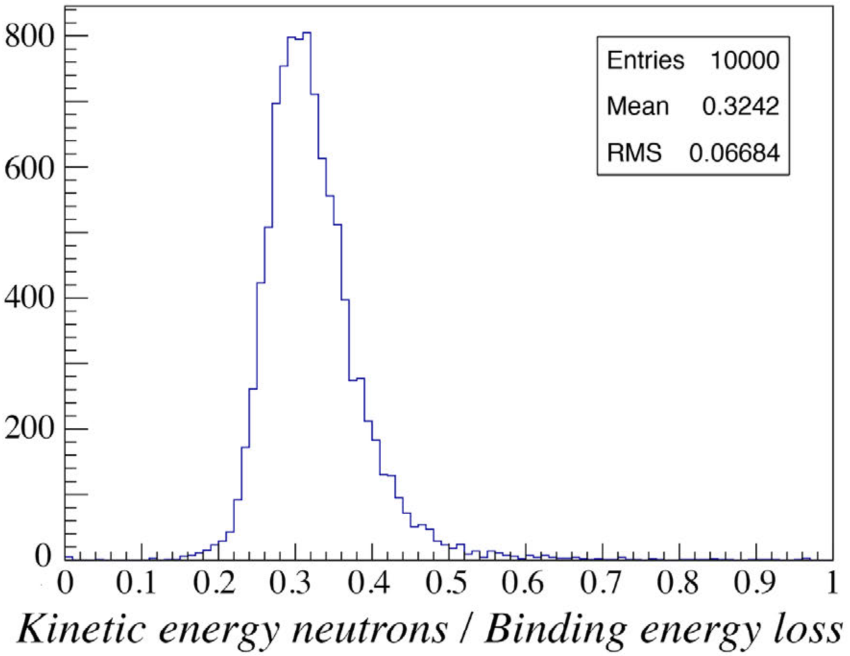
dual readout

compensation



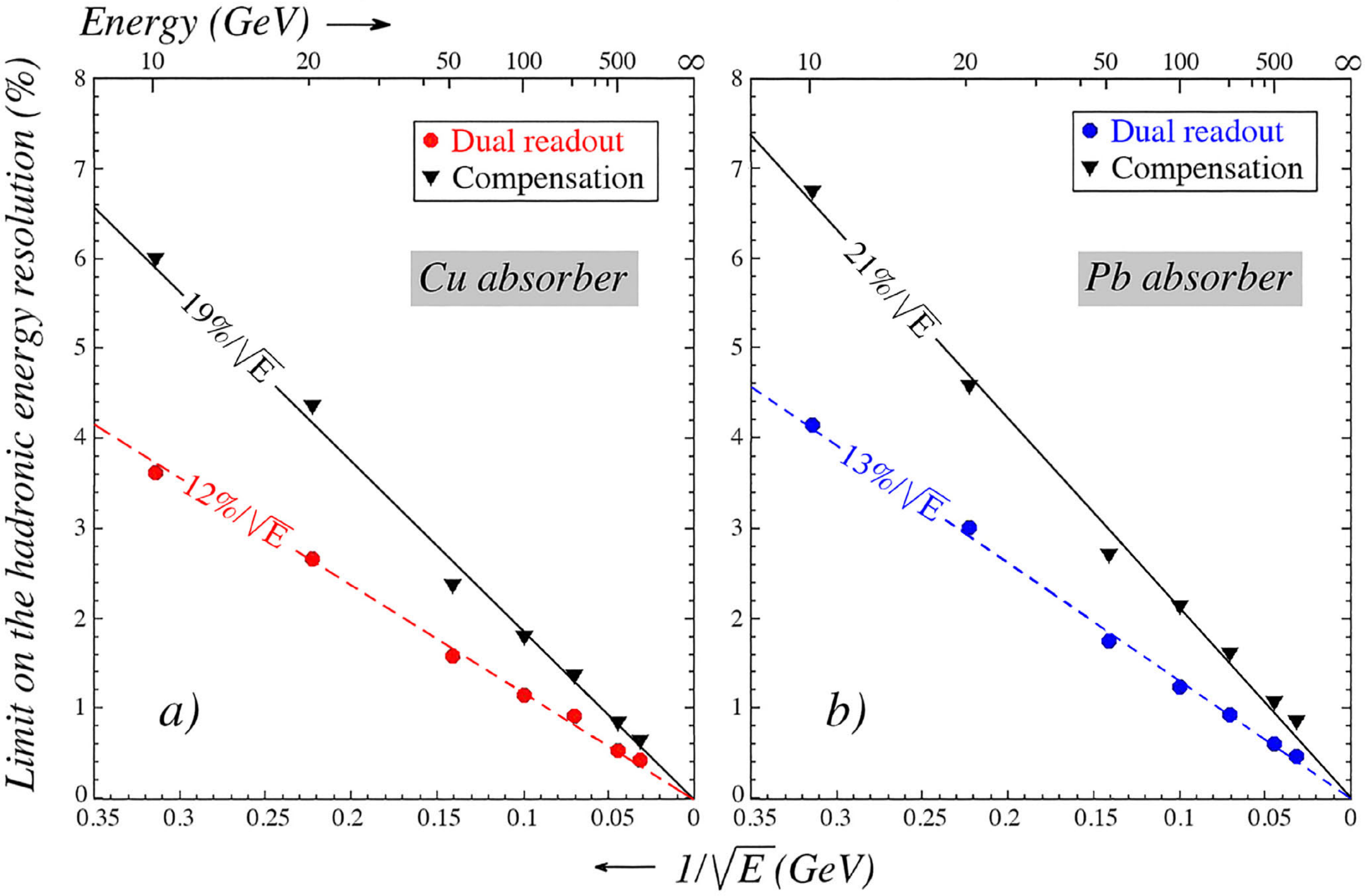






Lower limits on hadronic energy resolution

(MC results described in: NIM A882 (2018) 148)



DUAL-READOUT CALORIMETRY

- *Dual-readout Method (DREAM):*

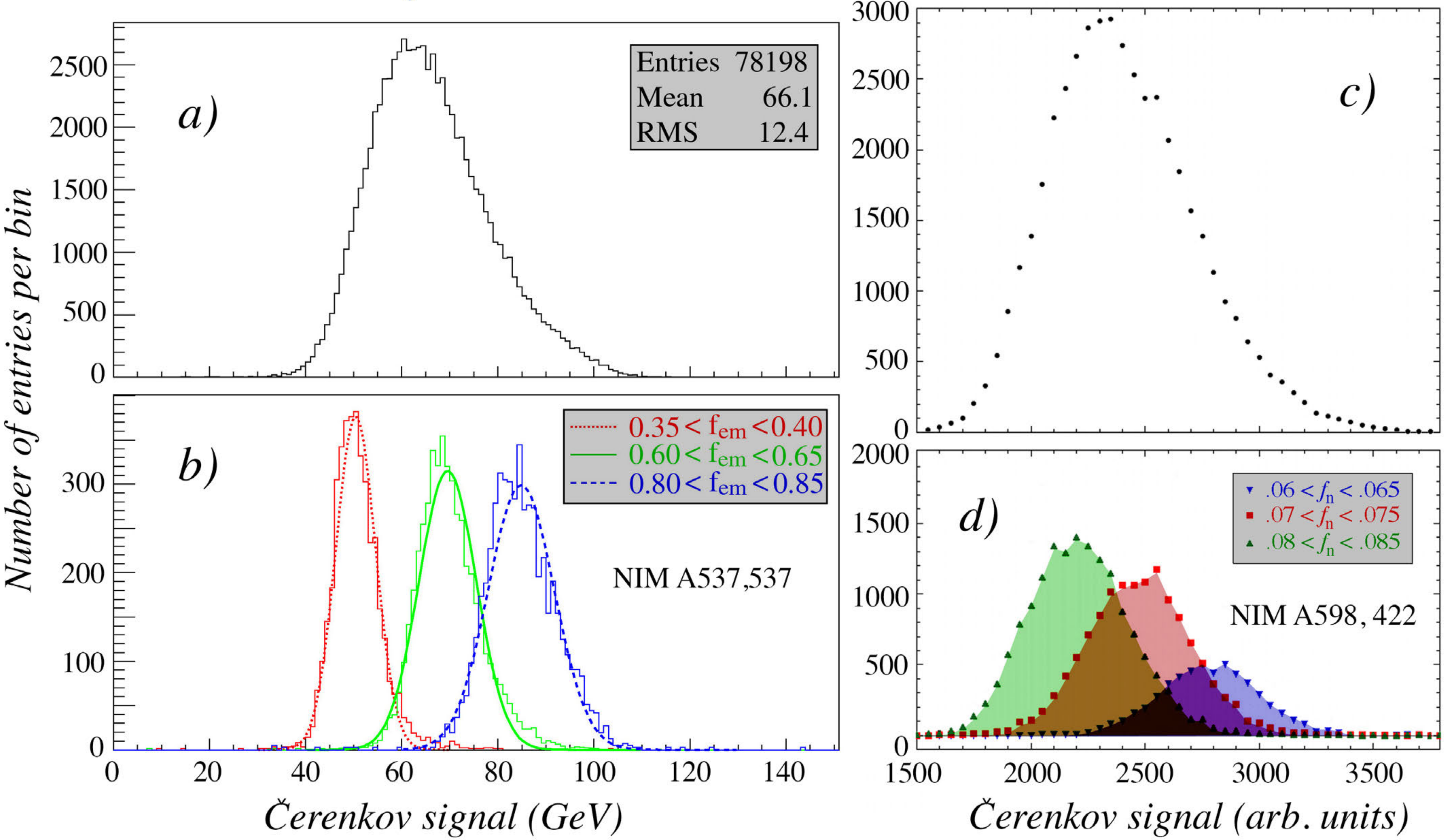
  Simultaneous measurement of scintillation light (dE/dx) and Čerenkov light produced in shower development makes it possible to measure the em fraction of hadron showers event by event.
  The effects of fluctuations in this fraction on the calorimeter performance can thus be eliminated

- *This method exploits the fact that the (e/h) values of a sampling calorimeter based on scintillation light and Čerenkov light are very different (e.g. protons from the h component contribute to the S, but not to the Č signals)*

- *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*

A hadronic signal distribution is a superposition of signal distributions for events with the same

em fraction *neutron content*



Cu/fiber dual-readout calorimetry

- *Excellent em and hadronic energy resolution*
- *Calibration is trivial*
- *Excellent particle-id in longitudinally unsegmented detector*
- *Ultrafast Cherenkov signals give unique timing options*

Selected publications on dual-readout calorimetry

The beginning of Dual-Readout Calorimetry:

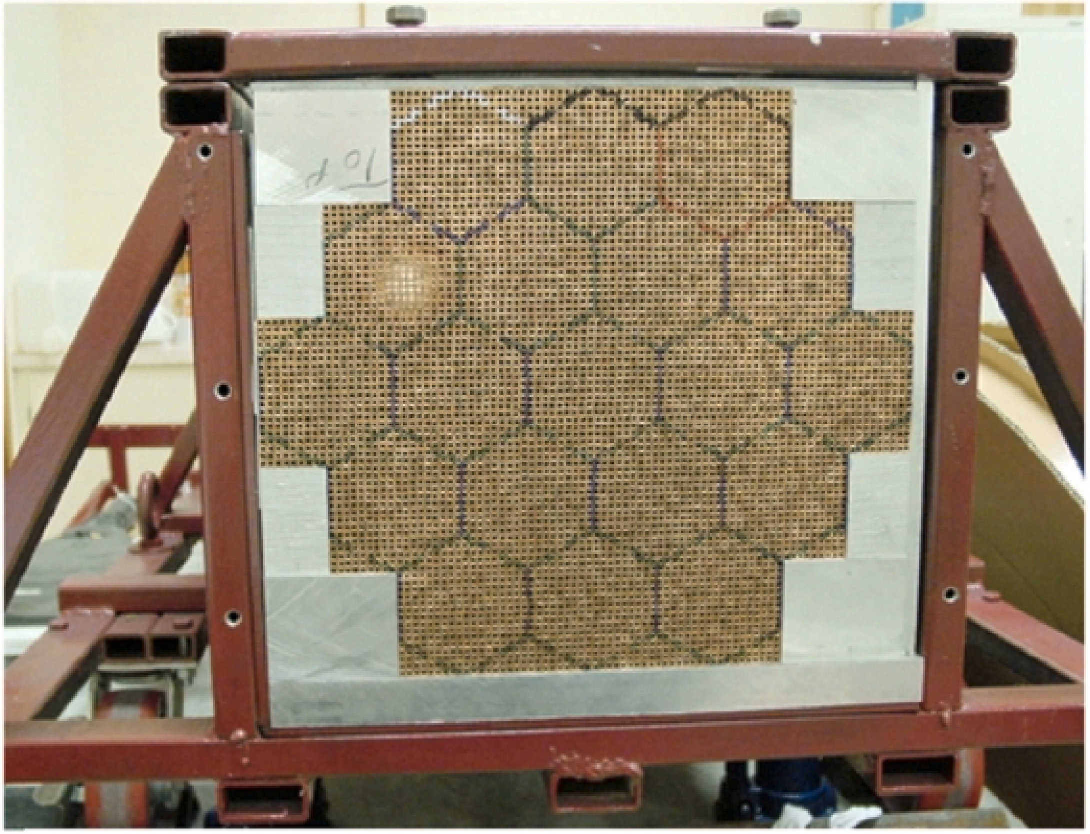
- *Quartz Fibers and the Prospects for Hadron Calorimetry at the 1% Resolution Level*, R. Wigmans, Proceedings of the 7th International Conference on Calorimetry in High Energy Physics, Tucson (AZ), Nov. 9-14, 1997.

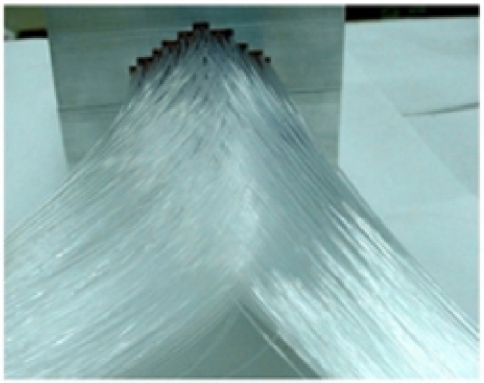
Selected papers in the refereed literature:

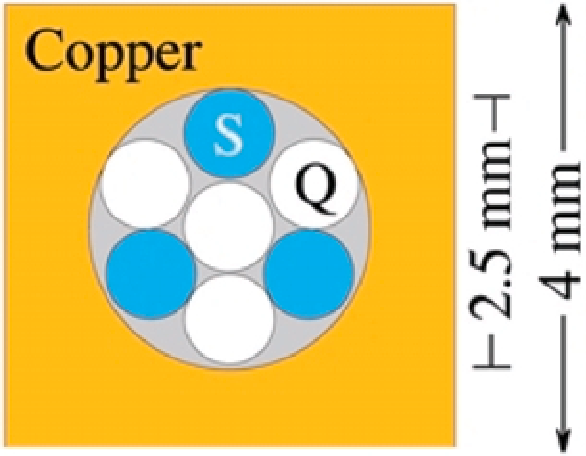
- *Beam Tests of a Thin Dual-Readout Calorimeter for Detecting Cosmic Rays Outside the Earth's Atmosphere*, V. Nagaslaev, A. Sill and R. Wigmans, Nucl. Instr. and Meth. **A462** (2001) 411–425.
- *Muon Detection with a Dual-Readout Calorimeter*, N. Akchurin *et al.*, Nucl. Instr. and Meth. **A533** (2004) 305–321.
- *Hadron and Jet Detection with a Dual-Readout Calorimeter*, N. Akchurin *et al.*, Nucl. Instr. and Meth. **A537** (2005) 537 – 561.
- *Dual-Readout Calorimetry with Crystal Calorimeters*, N. Akchurin *et al.*, Nucl. Instr. and Meth. **A598** (2009) 710 - 721.
- *Particle identification in the longitudinally unsegmented RD52 calorimeter*, N. Akchurin *et al.*, Nucl. Instr. and Meth. **A735** (2014) 120 - 129.
- *The electromagnetic performance of the RD52 fiber calorimeter*, N. Akchurin *et al.*, Nucl. Instr. and Meth. **A735** (2014) 130 - 144.
- *Lessons from Monte Carlo simulations of a dual-readout fiber calorimeter*, N. Akchurin *et al.*, Nucl. Instr. and Meth. **A762** (2014) 100 - 118.
- *Hadron detection with a dual-readout fiber calorimeter*, S. Lee *et al.*, Nucl. Instr. and Meth. **A866** (2017) 76 - 90.
- *On the limit of the hadronic energy resolution of calorimeters*, S. Lee, M. Livan and R. Wigmans, Nucl. Instr. and Meth. **A882** (2018) 148 - 157.
- *Dual-readout calorimetry*, S. Lee, M. Livan and R. Wigmans, Rev. Mod. Phys. **90** (2018) 025002.
- *New Developments in Calorimetric Particle Detection*, R. Wigmans, J. Progr. Part. Nucl. Phys. **103** (2018) 109 - 161

Backup slides

DREAM: Structure

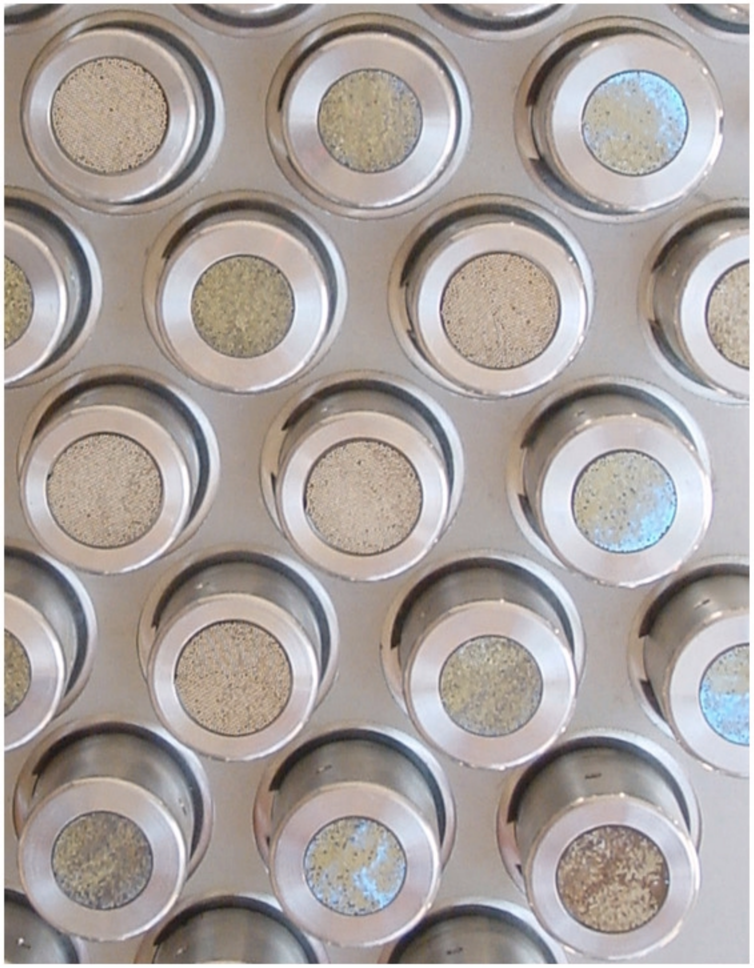


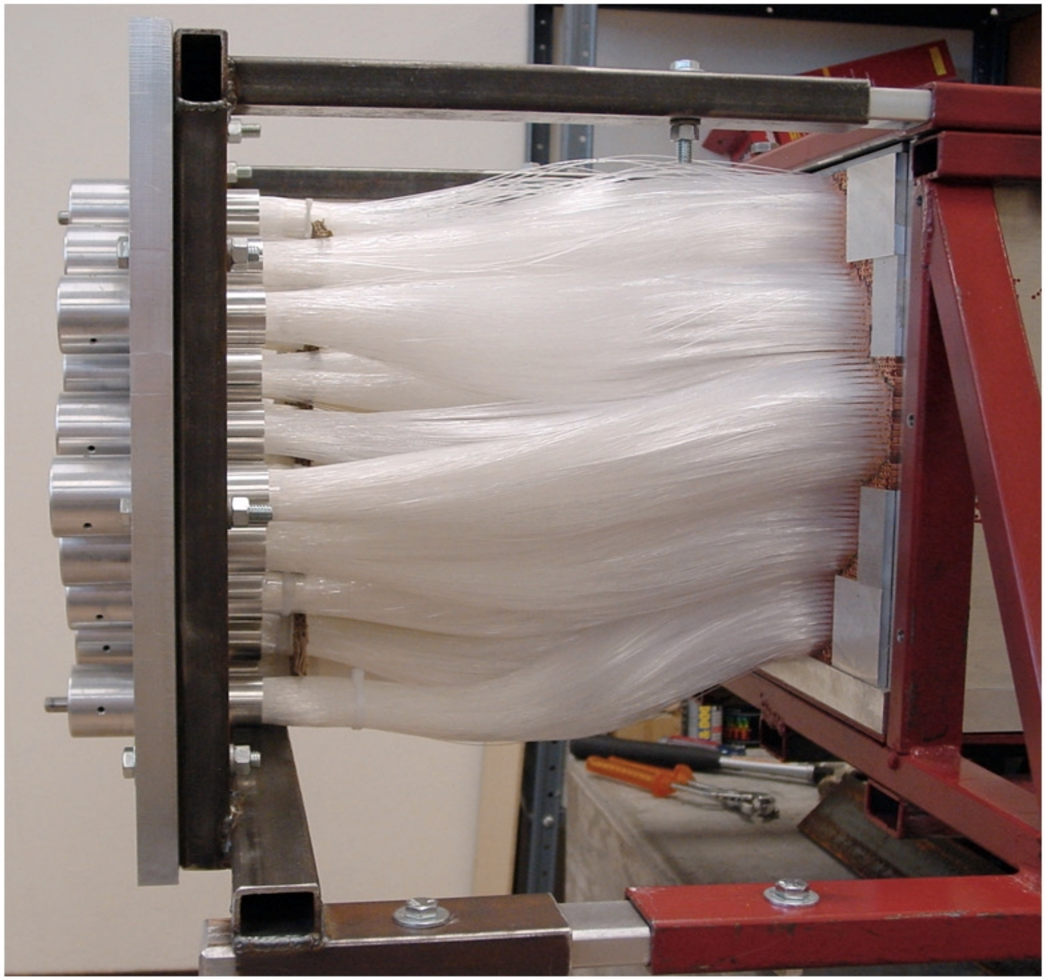


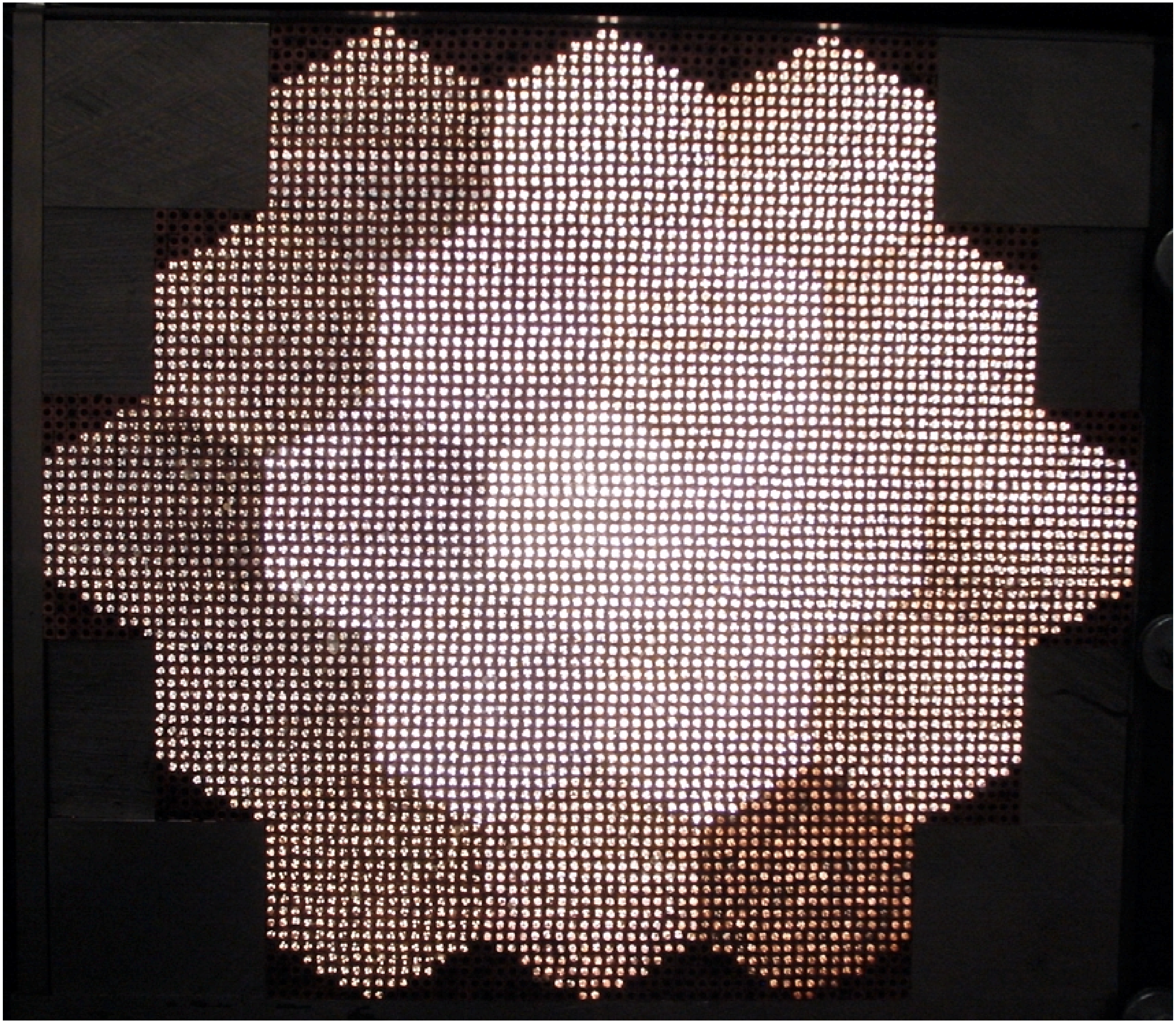


- *Some characteristics of the DREAM detector*
    - Depth 200 cm (10.0 λ_{int})
    - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
    - Mass instrumented volume 1030 kg
    - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
    - Hexagonal towers (19), each read out by 2 PMTs

DREAM readout



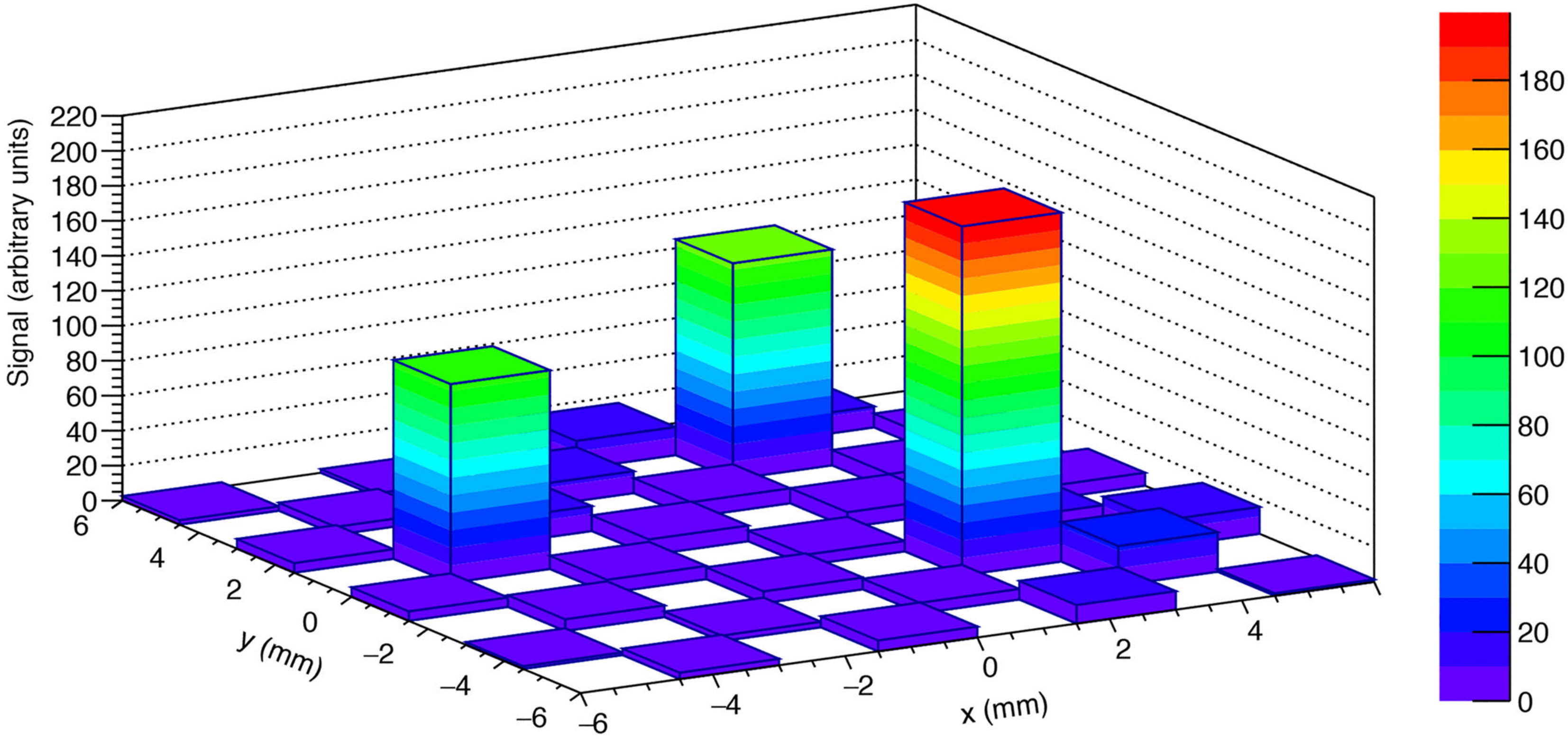




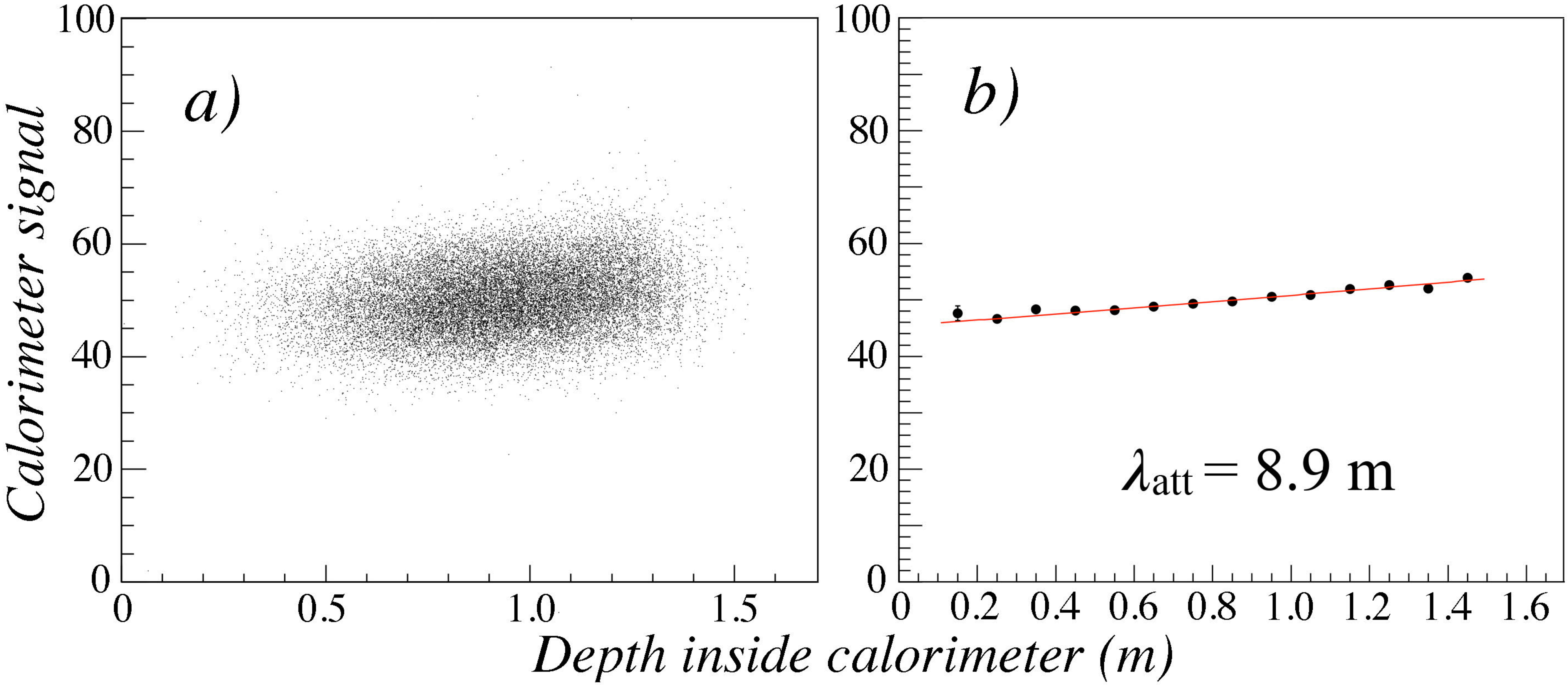
Electron detection with a Cu-fiber DR calorimeter

Thanks to shower profile characteristics, it is also possible to recognize electrons inside a jet if lateral granularity is adequate

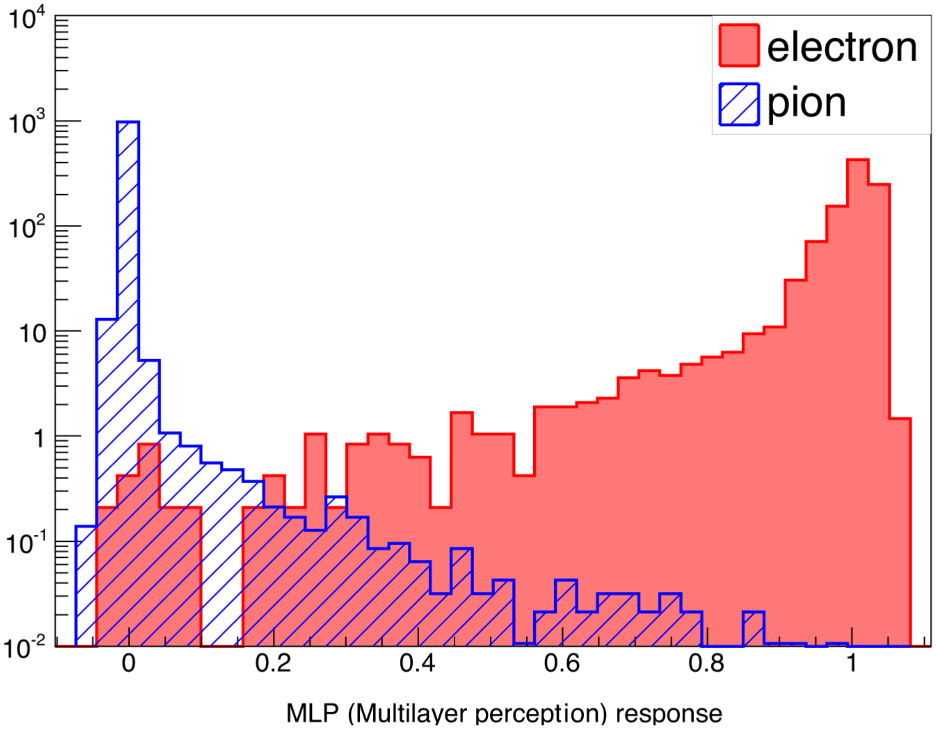
This plot represents a measurement with a calorimeter with a lateral cross section of 1.2 x 1.2 cm^2 (0.4 x 0.4 ρ_M^2)

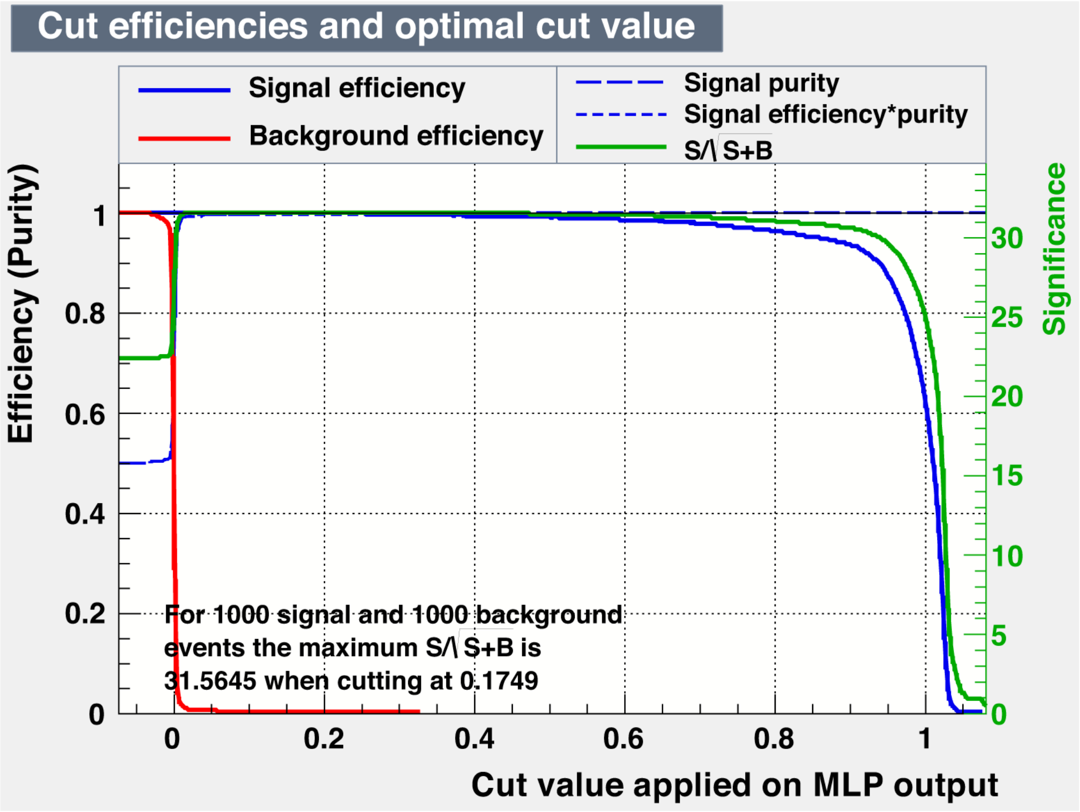


Use depth of light production to correct for light attenuation



Neural network analysis 60 GeV e/π separation





For 1000 signal and 1000 background events the maximum S/\ S+B is 31.5645 when cutting at 0.1749

for MLP > 0.17 : 99.81% electron ID
0.20% π mis-ID

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