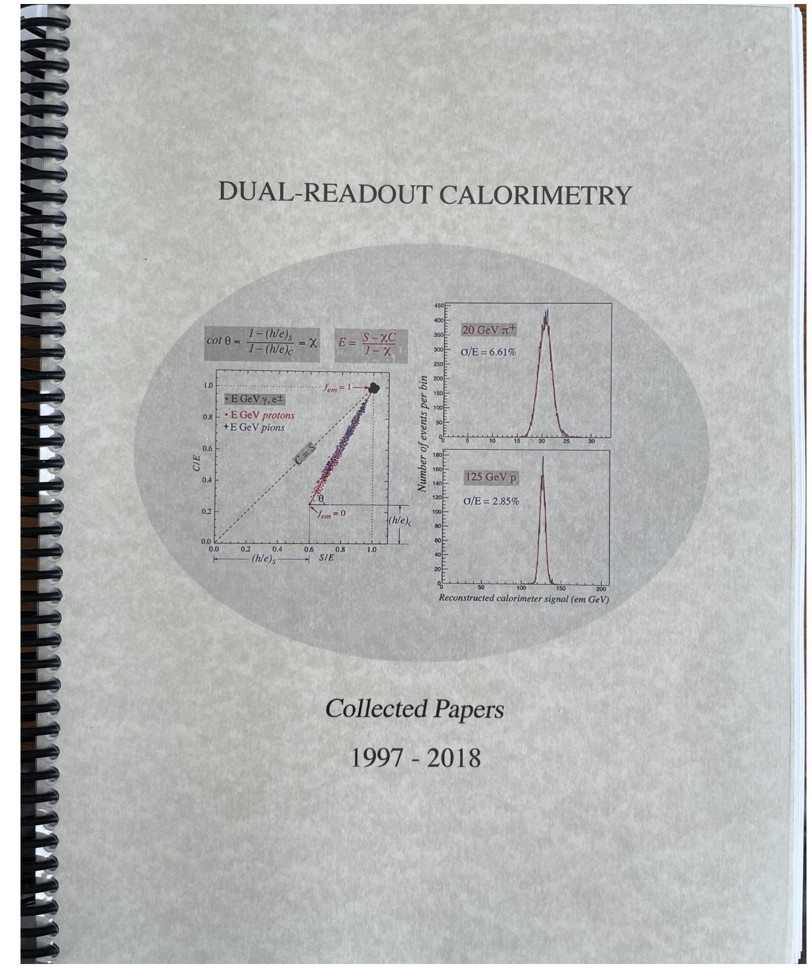
Dual-Readout Calorimetry



Sehwook Lee (Kyungpook National University)
on behalf of **Korean Dual-Readout Calorimeter Collaboration**

2nd PSQ@EIC Meeting: Precision Studies on QCD at EIC
Hilton Gyeong-ju, South Korea and Zoom
July 20, 2021

20 years R&D for Dual-Readout Calorimetry

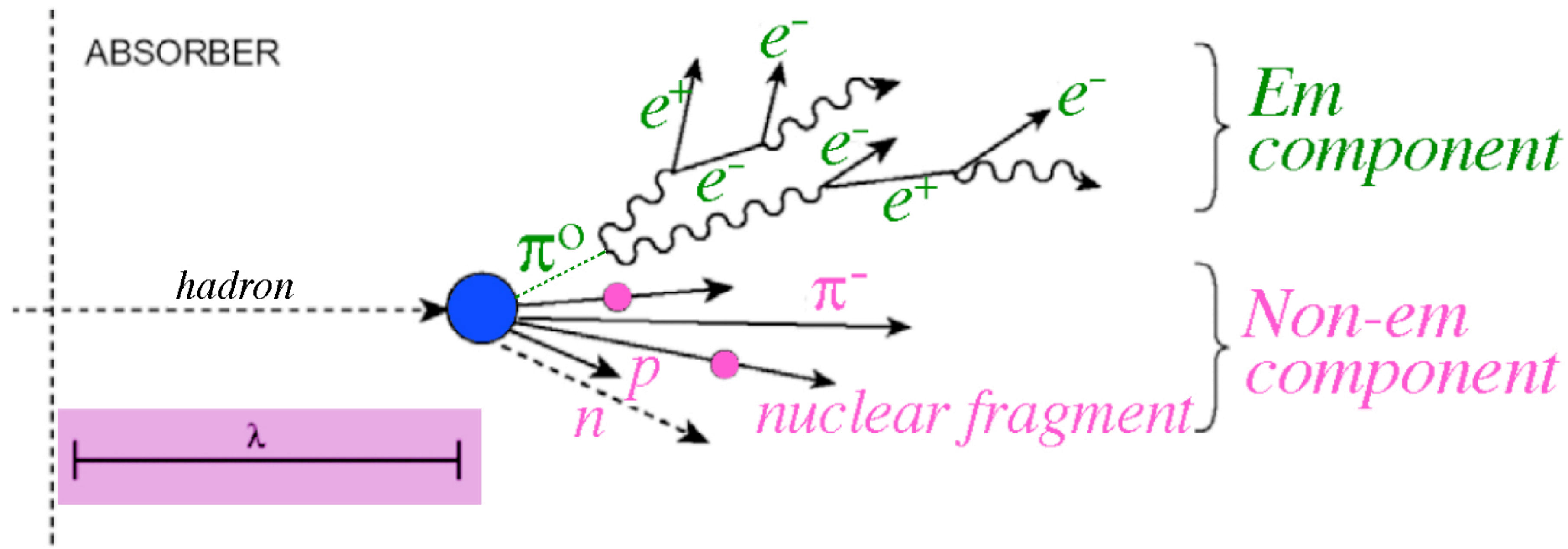
- Richard Wigmans: Quartz fiber and the prospects for hadron calorimetry at the 1% resolution level, CALOR 1997, Tucson USA

- The first paper on a dual-readout calorimeter was published in 2001

- Total 35 papers were published by 2018: http://www.phys.ttu.edu/~dream/results/publications/publications.html

- 20 years R&D results were summarized in Rev. Mod. Phys. 90 (2018) 025002

The Physics of Hadron Shower Development



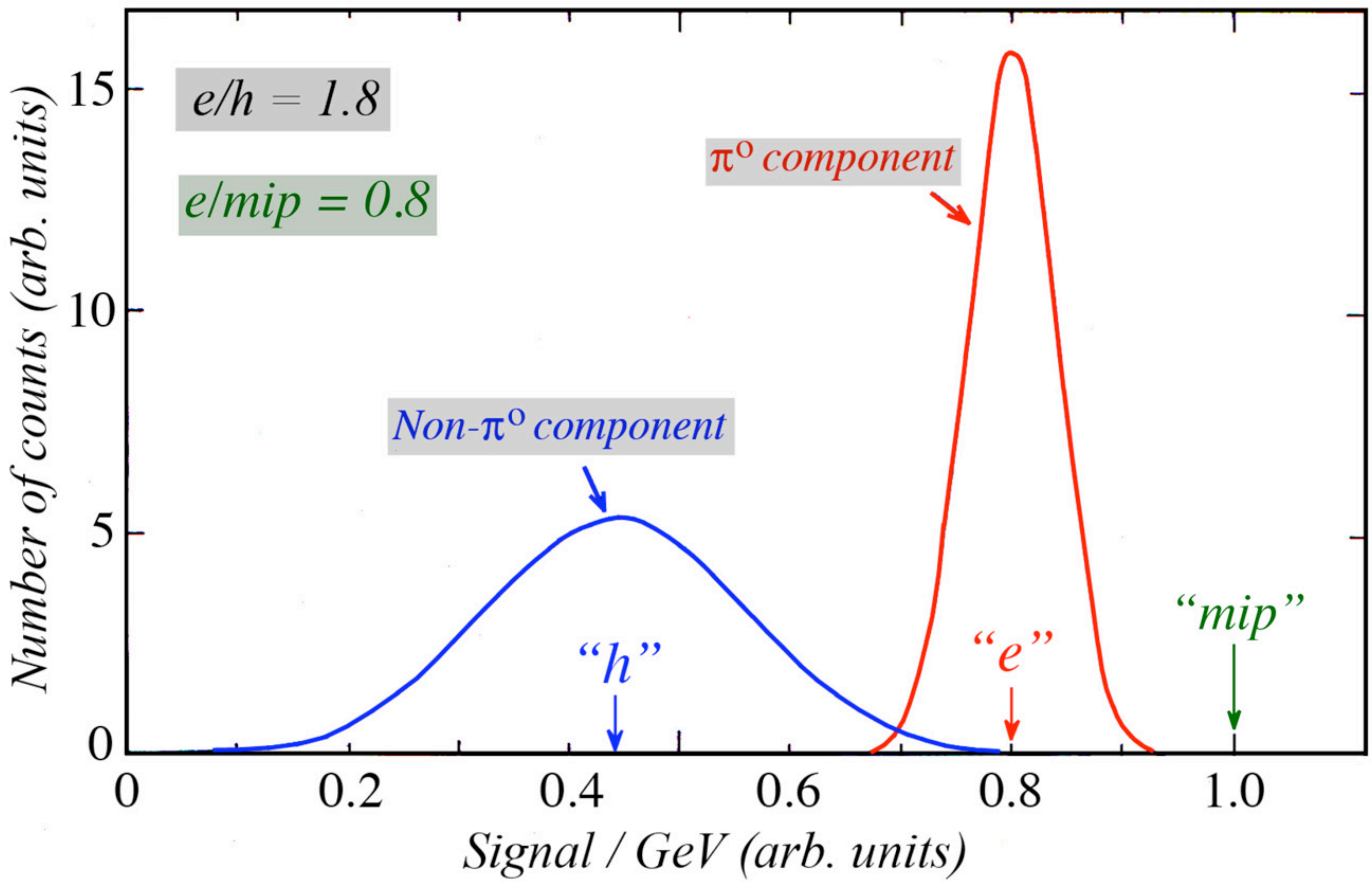
- *Electromagnetic component*
  - electrons, photons
  - neutral pions → 2 γ

- *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%)

- ***Large, non-Gaussian fluctuations of EM component***
- ***Large, non-Gaussian fluctuations of invisible energy losses***

- ***Responsible for the Fluctuations of Hadron Showers***

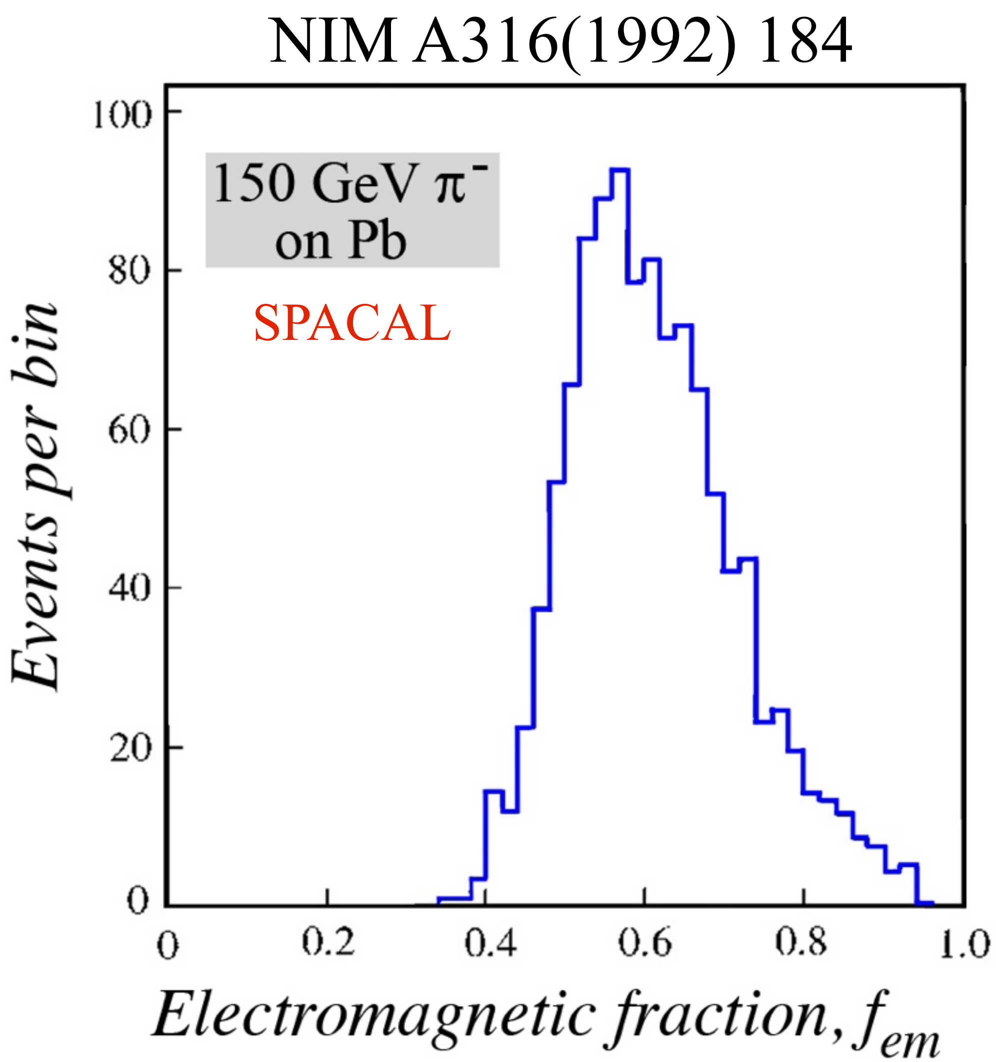
The Calorimeter Response

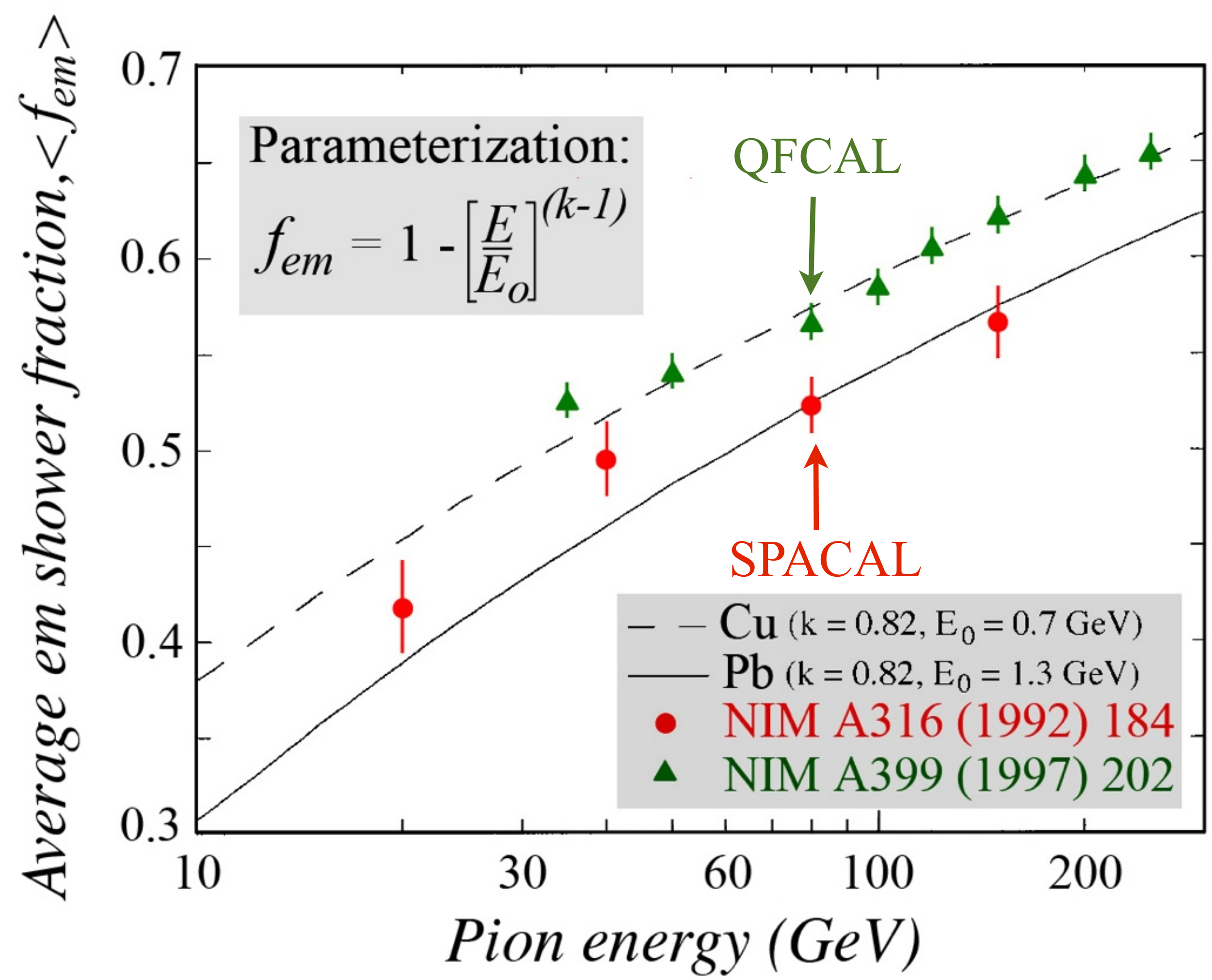


The calorimeter responses to the em and non-em components of hadron showers

Fluctuations of electromagnetic shower fraction

NIM A316(1992) 184

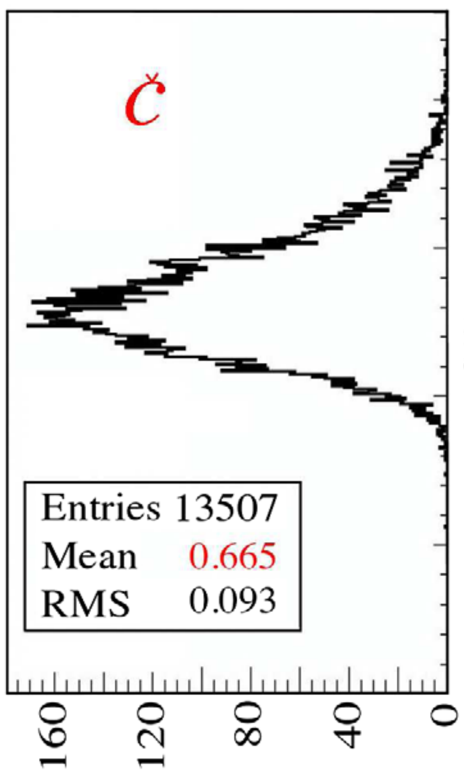


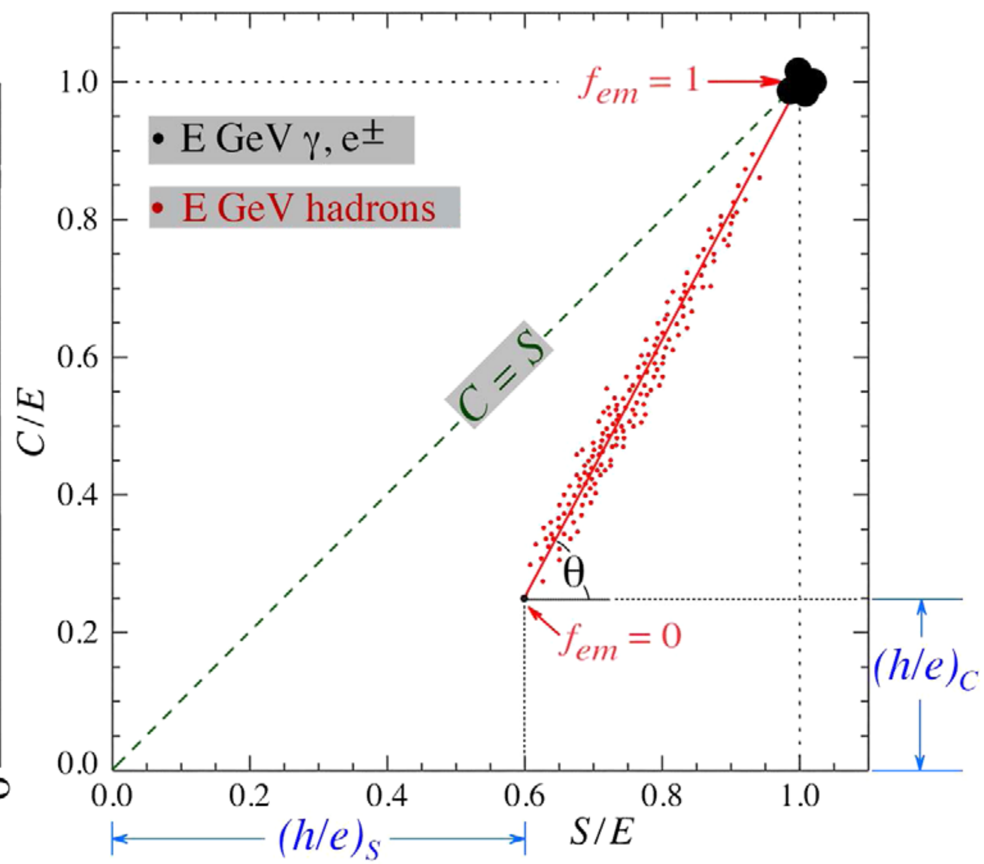


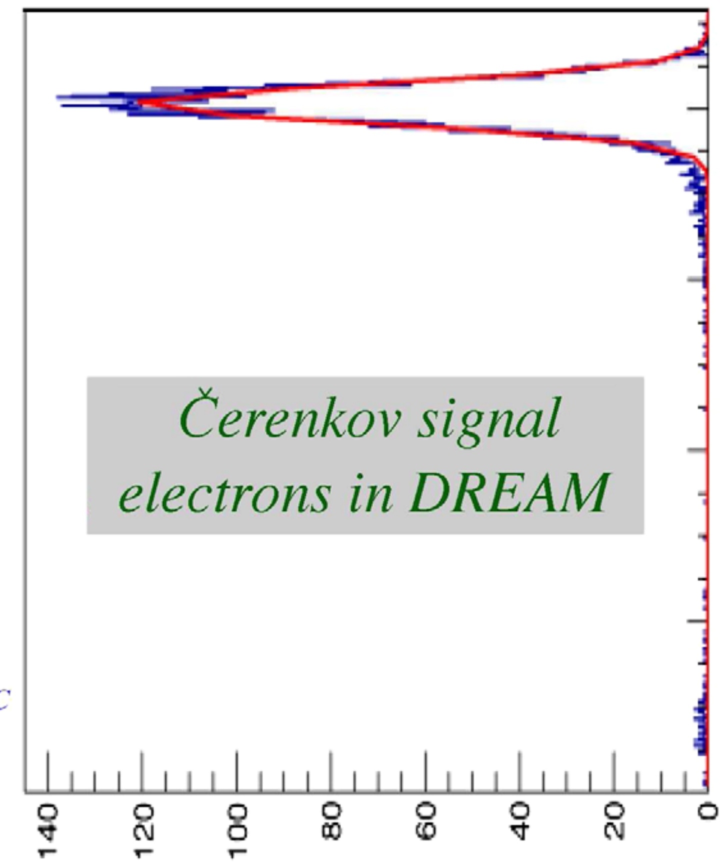
Large, non-Gaussian fluctuations in f_{em}

The em shower fraction (f_{em}) depends on the energy of pion and the type of absorber material

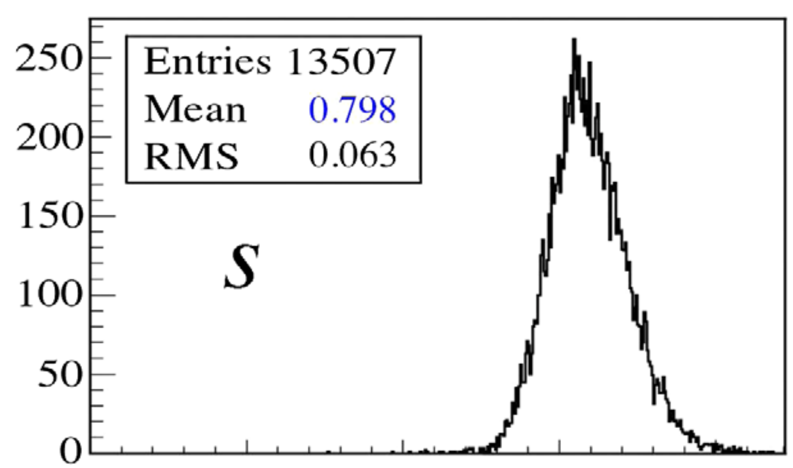
Dual-Readout Method (1)







200 GeV "jets"
in DREAM



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

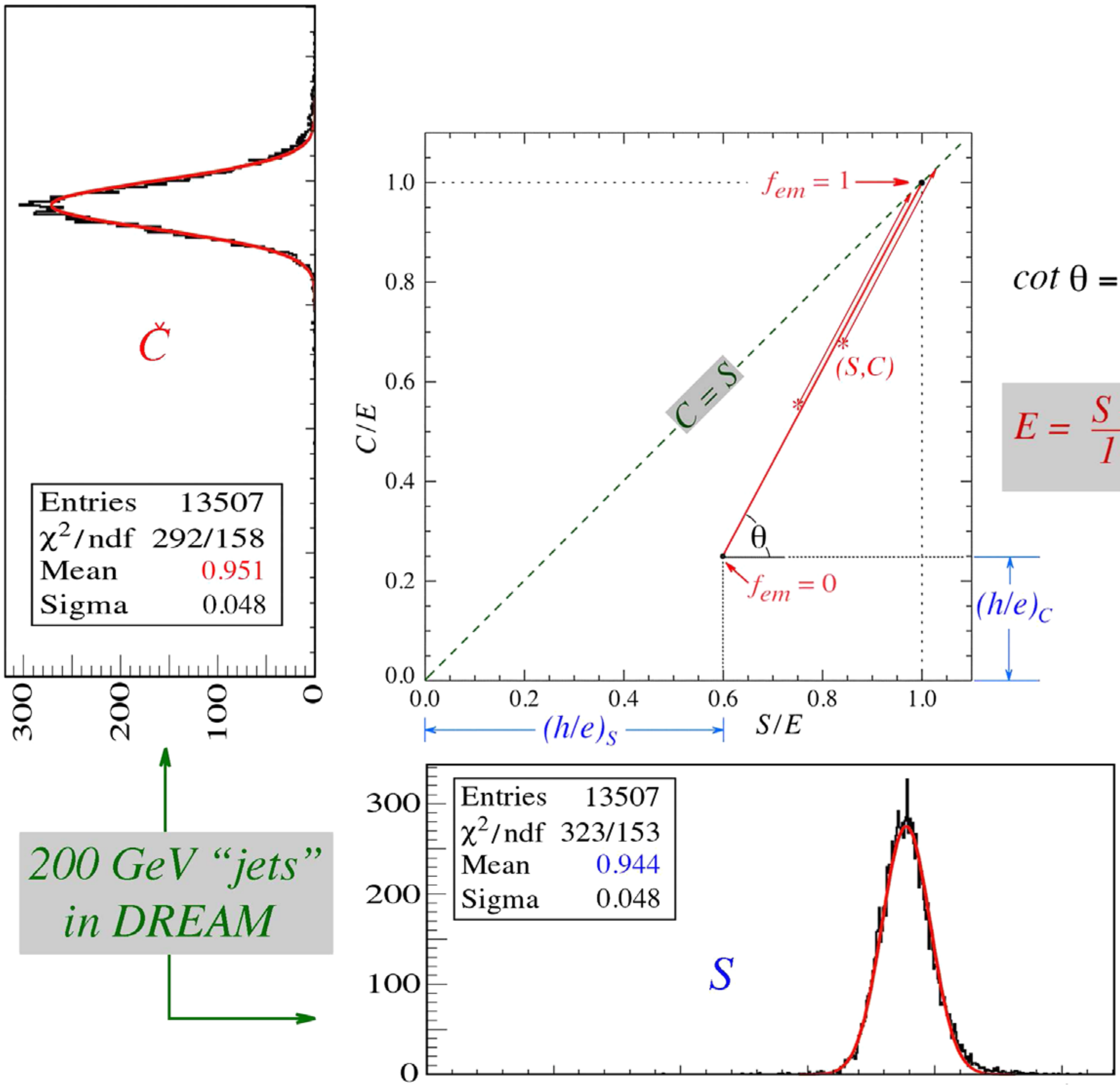
$$C = E\left[f_{\rm em} + \frac{1}{(e/h)_C}(1 - f_{\rm em})\right]$$

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

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

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

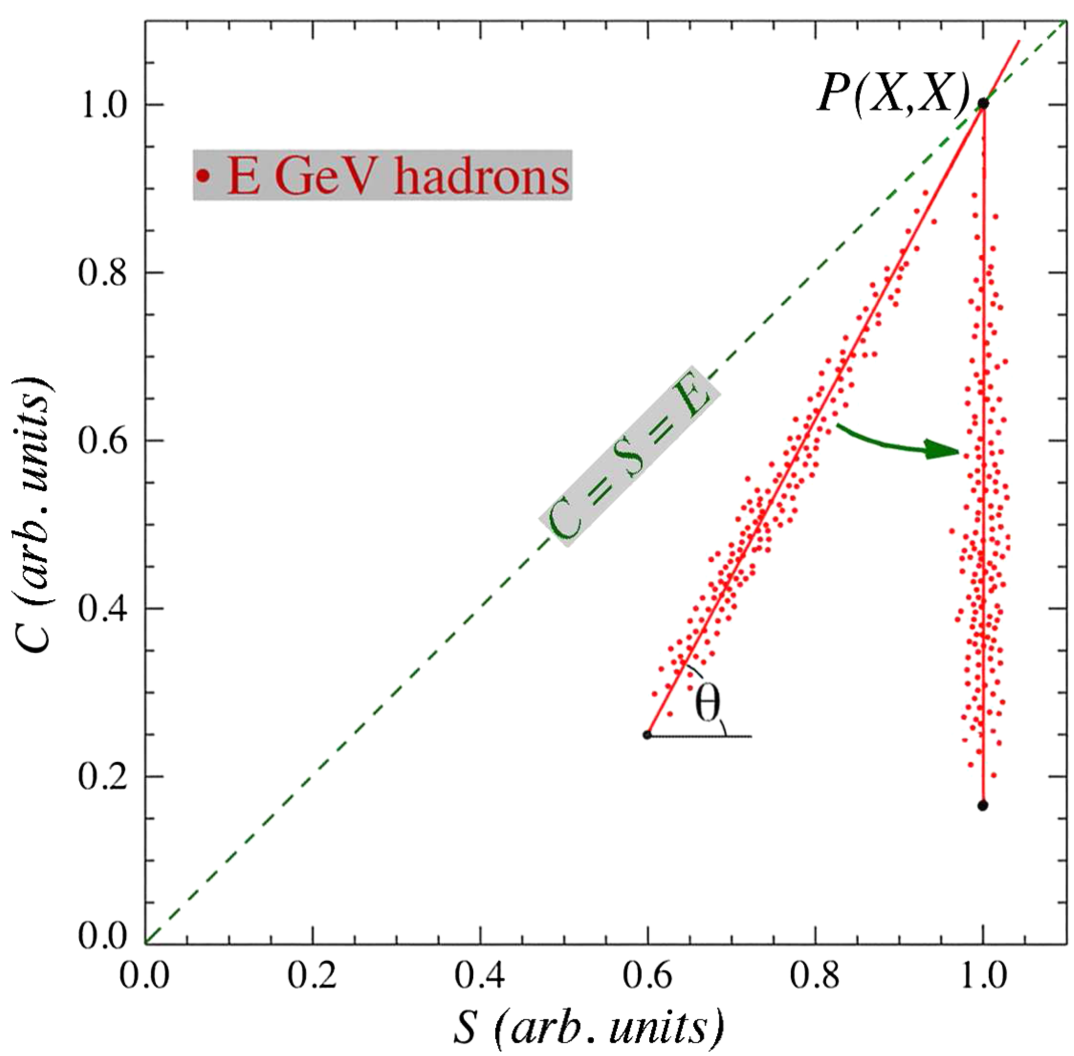
Dual-Readout Method



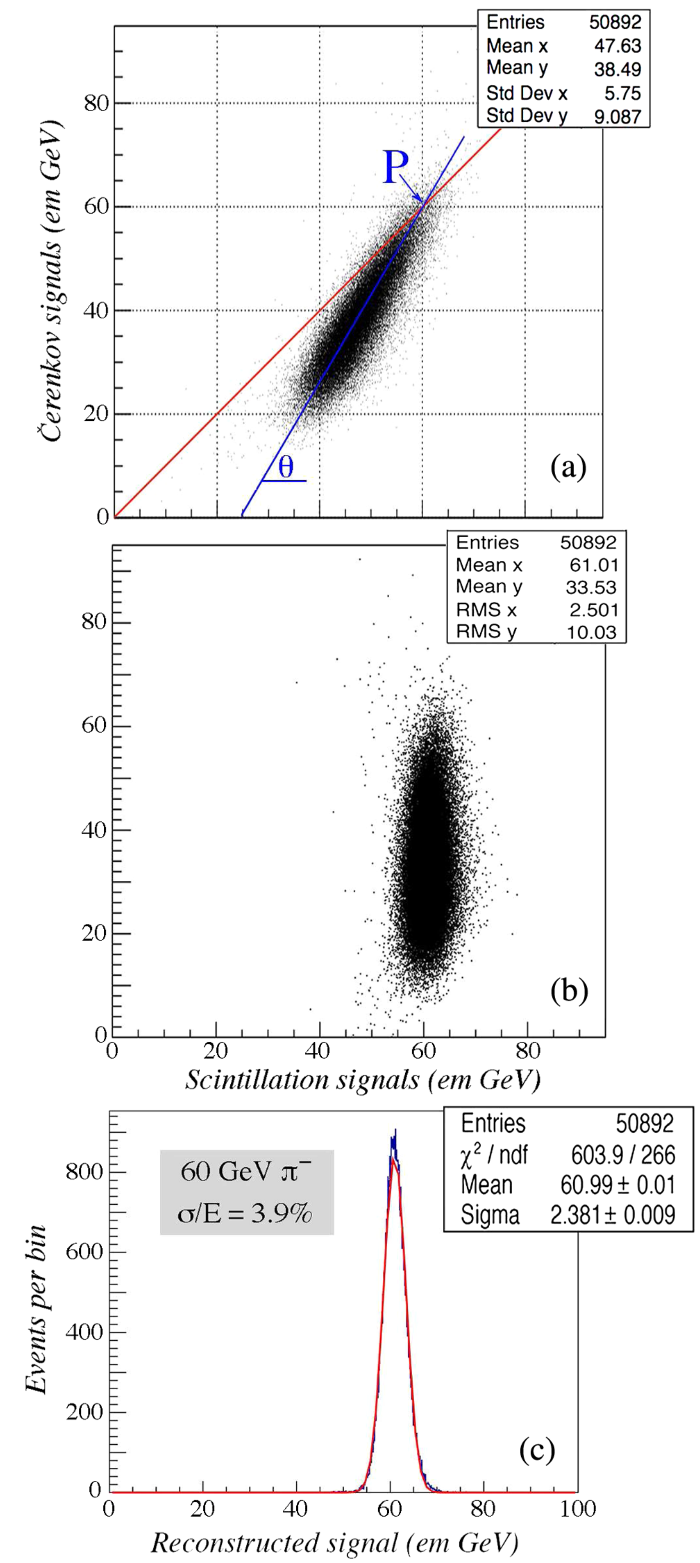
$$\cot\theta = \frac{1-(h/e)_S}{1-(h/e)_C} = \chi$$

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

Rotation Method

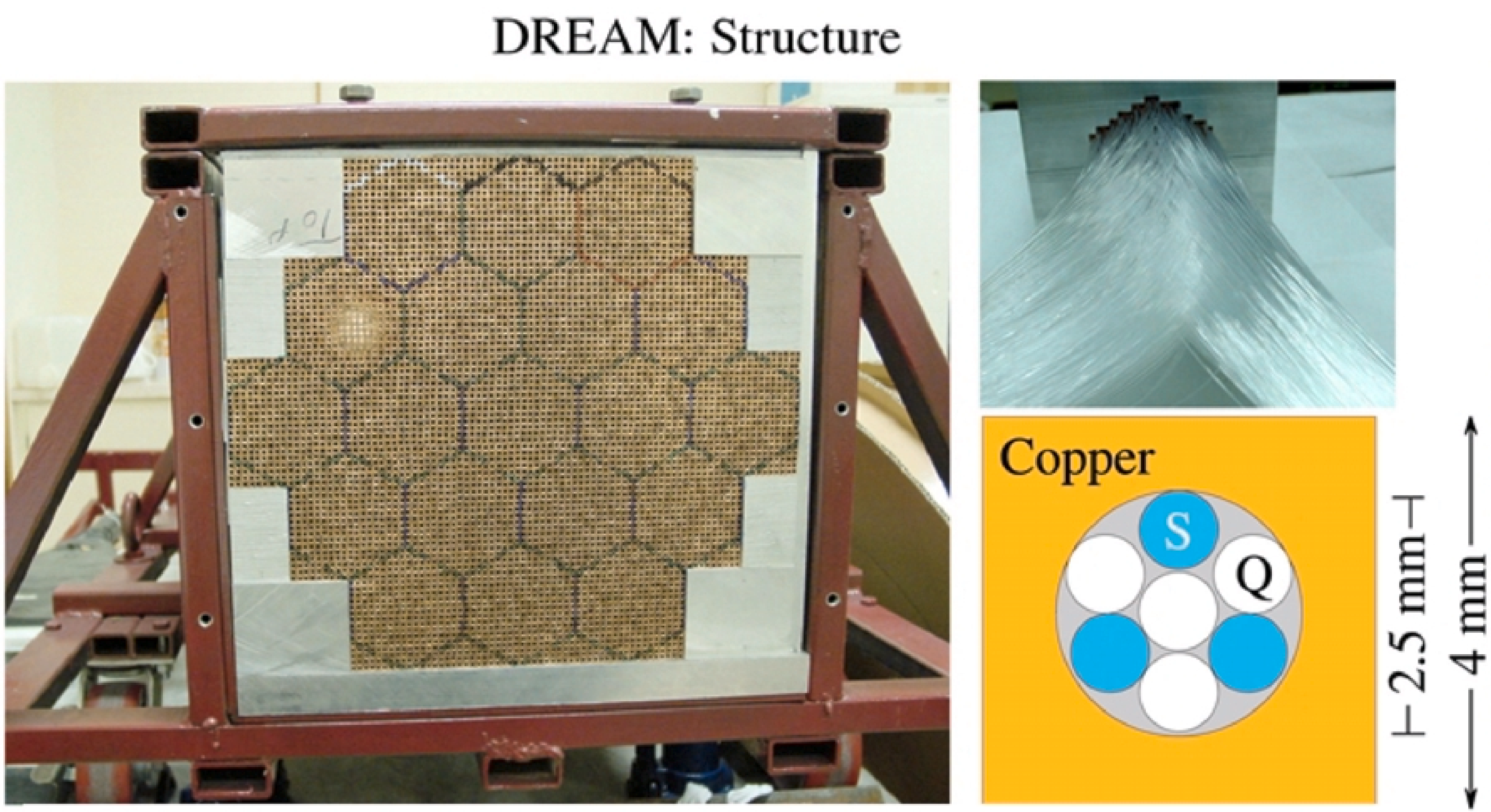


$$\begin{pmatrix} S' \\ C' \end{pmatrix} = \begin{pmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{pmatrix} \begin{pmatrix} S \\ C \end{pmatrix}$$



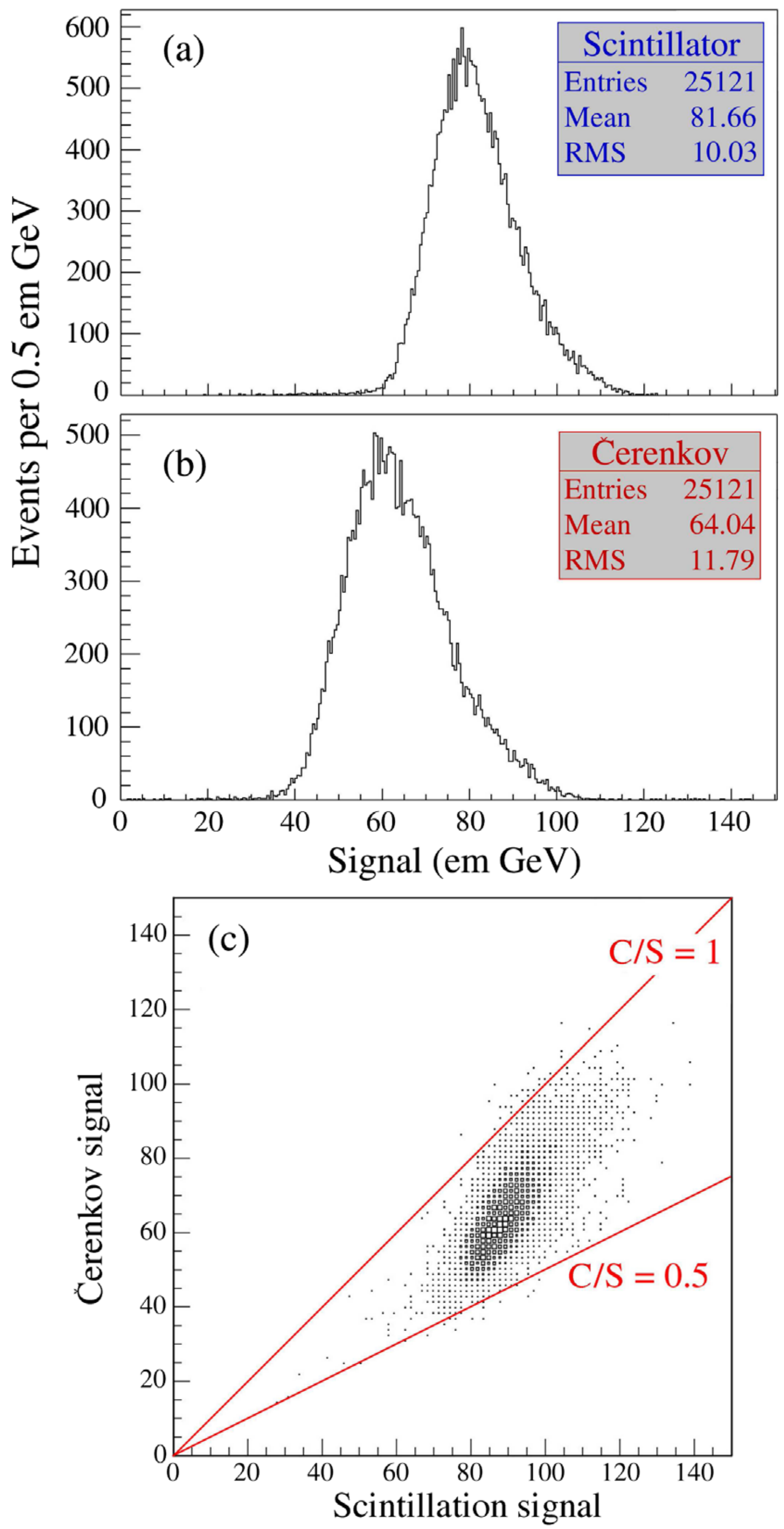
THE DREAM PROJECT

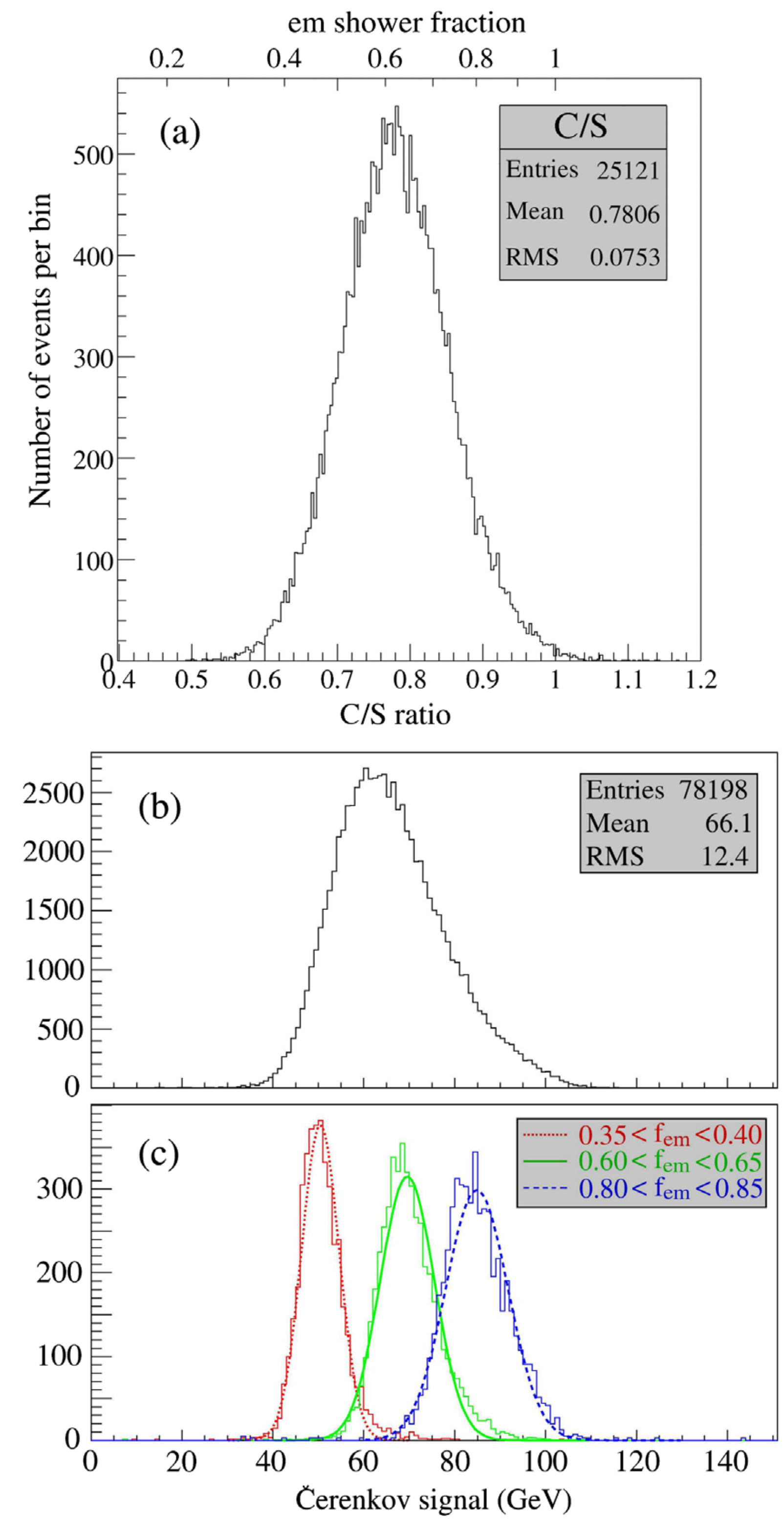
Prototype Dream Calorimeter



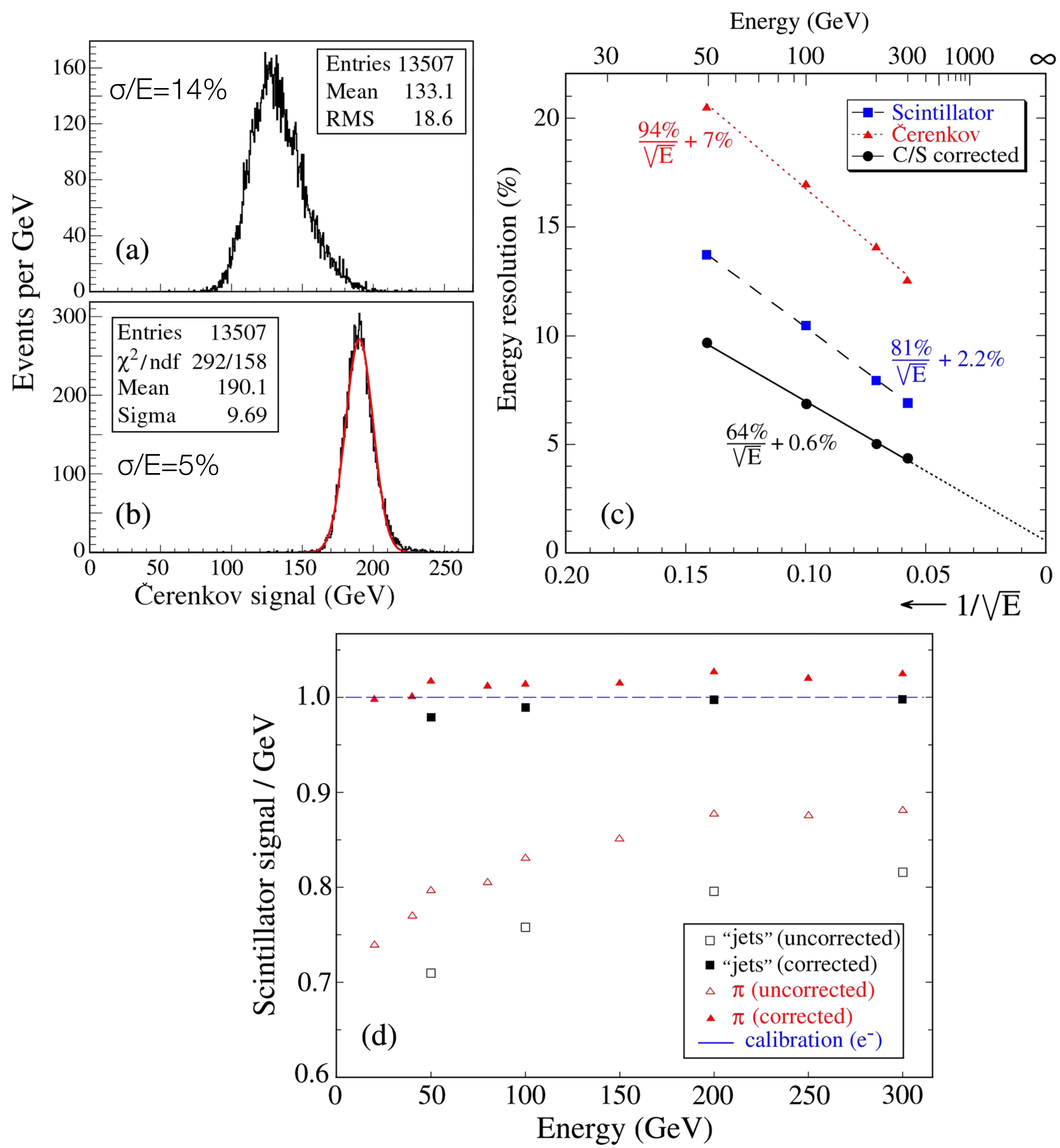
- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

Prototype Dream Calorimeter (100 GeV π)





Prototype Dream Calorimeter (200 GeV jets)



What we learned from tests with the prototype DREAM detector

- Calibration with electrons, and then correct hadronic energy reconstruction
- Restore linear calorimeter response for single hadrons and jets
- Gaussian response function
- Energy resolution well described by $1/\sqrt{E}$ scaling
- $\sigma/E = \sim 5$ % for 200 GeV "jets" by the detection with only 1 ton Cu/fiber calorimeter. Shower leakage fluctuations are dominant in this case

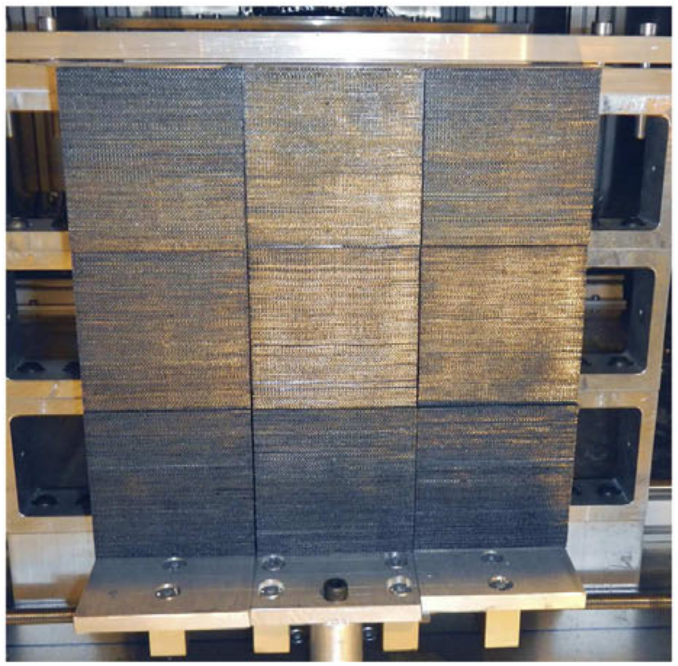
Dual-REAout Fiber calorimeter is free from the limitations (sampling fraction, integration volume, time) of intrinsically compensating calorimeters (e/h=1)

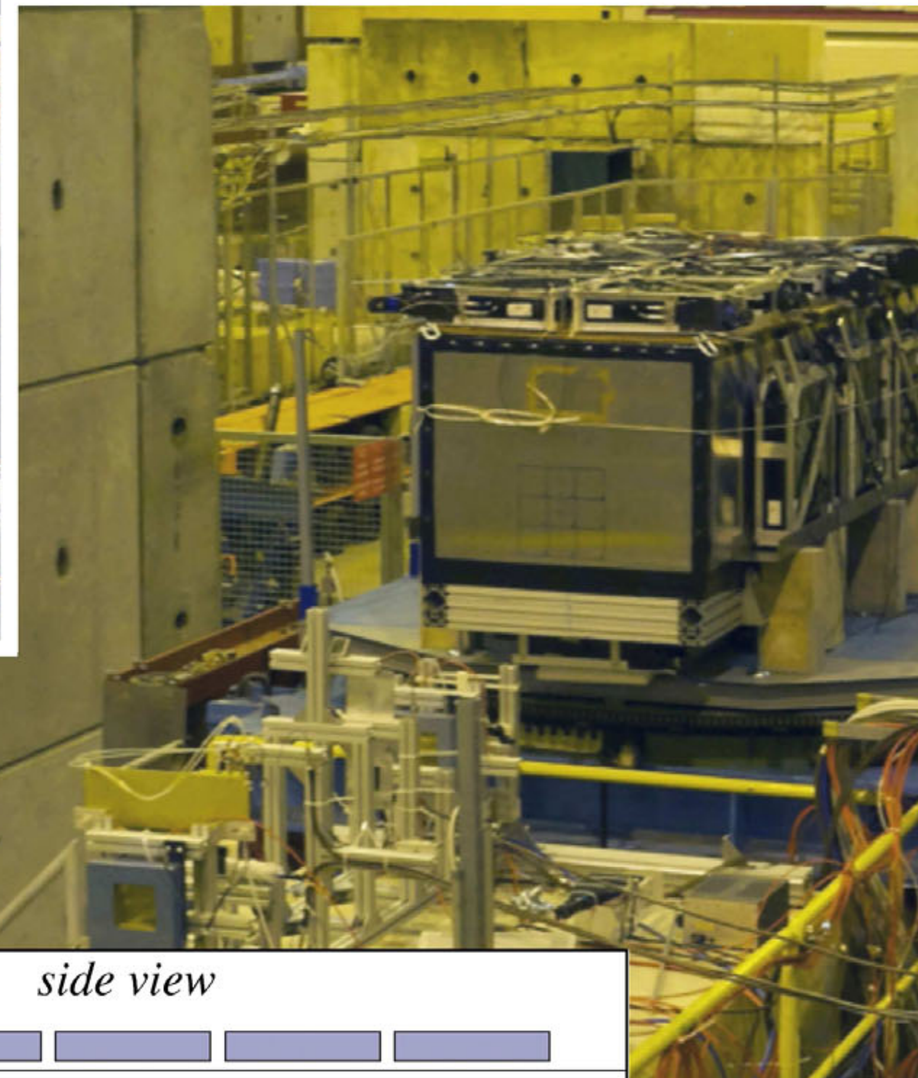
Additional factors to improve DREAM performance

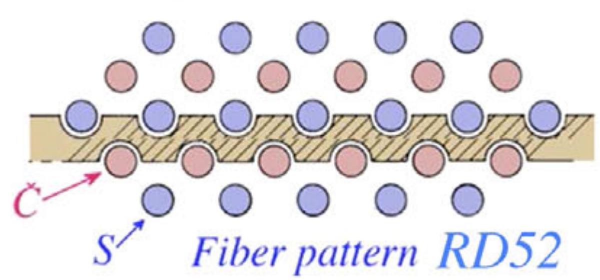
- Reduction of shower leakage (leakage fluctuations) → Build larger detector
- Increase Cerenkov light yield
  - Prototype DREAM: 8 p.e./GeV → light yield fluctuations contribute by 35%//$\sqrt{E}$ (Numerical aperture of quartz fiber: 0.33)
- Reduction of sampling fluctuations
  - contribute ~40%/$\sqrt{E}$ to hadronic resolution (single pions)

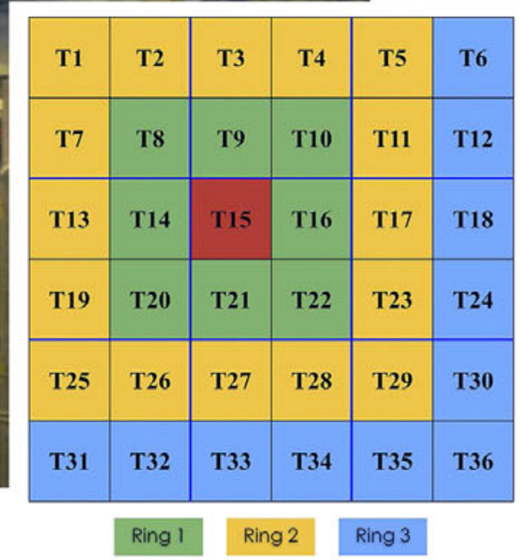
THE RD52 PROJECT OF CERN

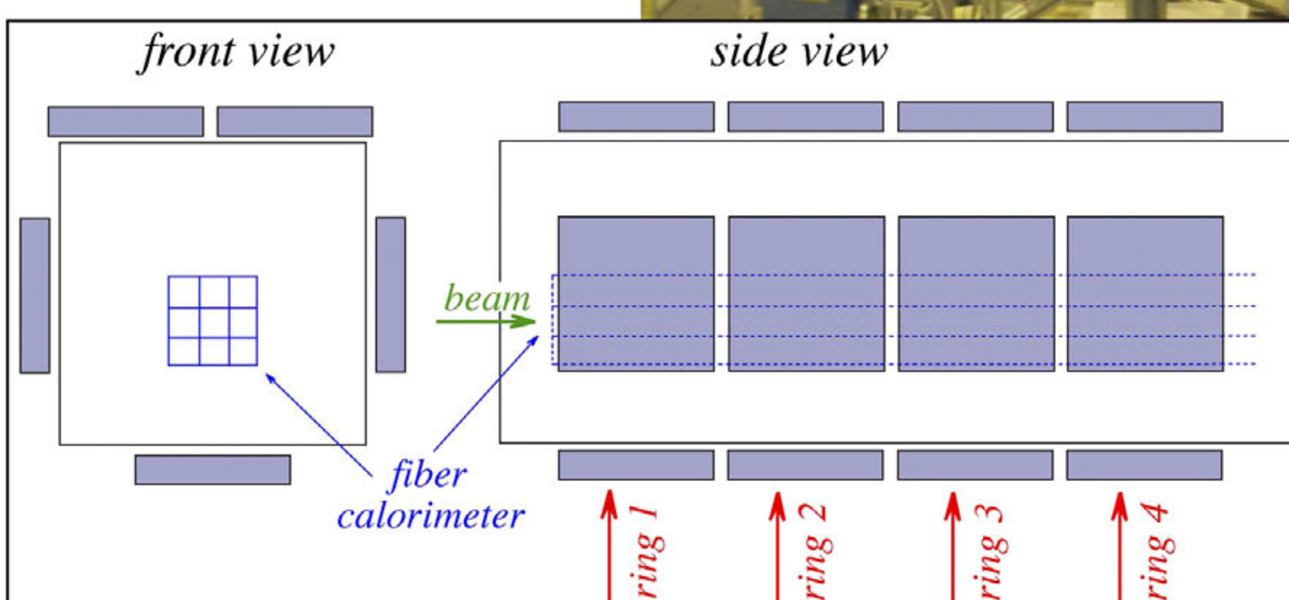
RD52 Pb-fiber Calorimeter





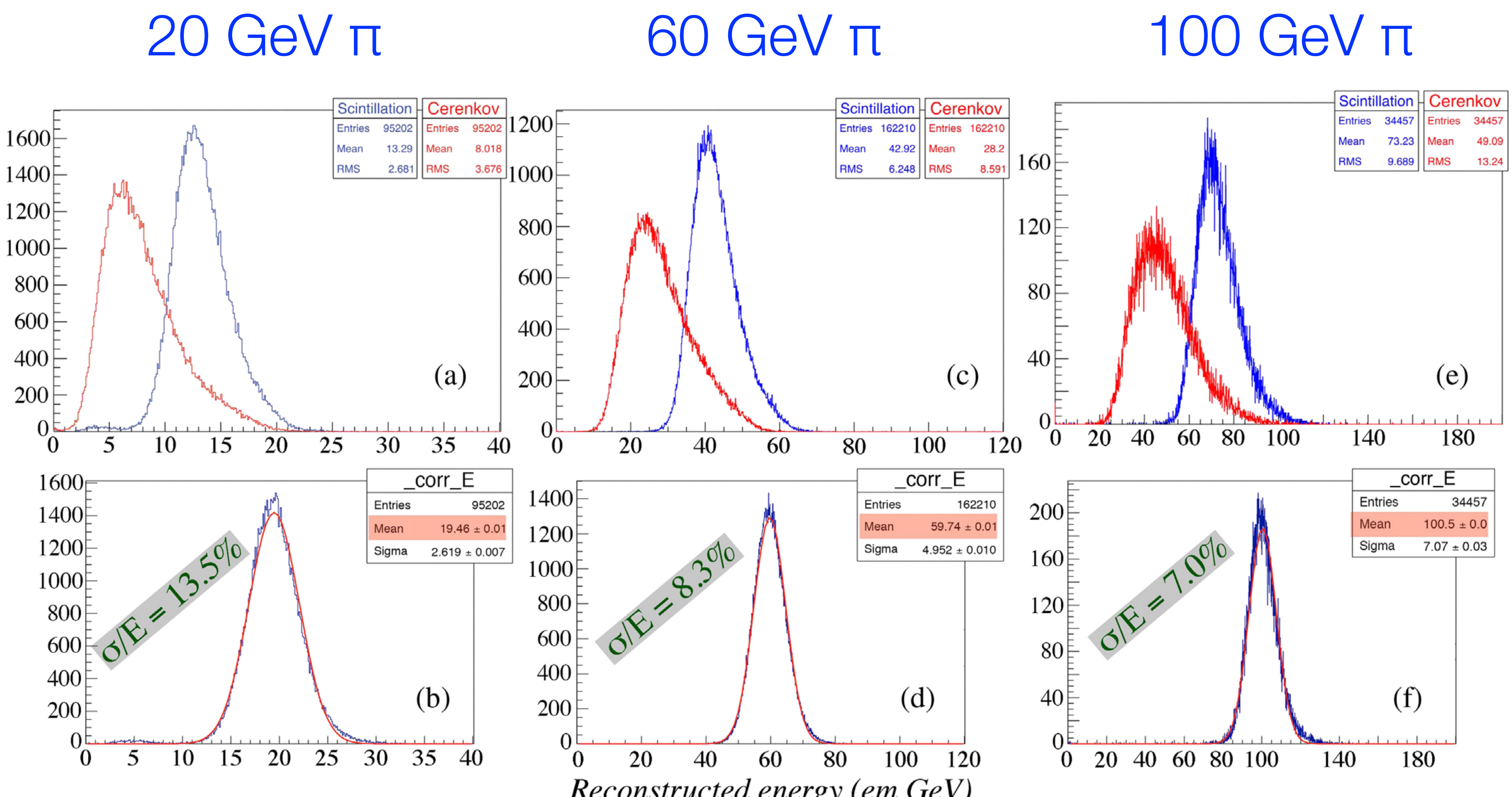






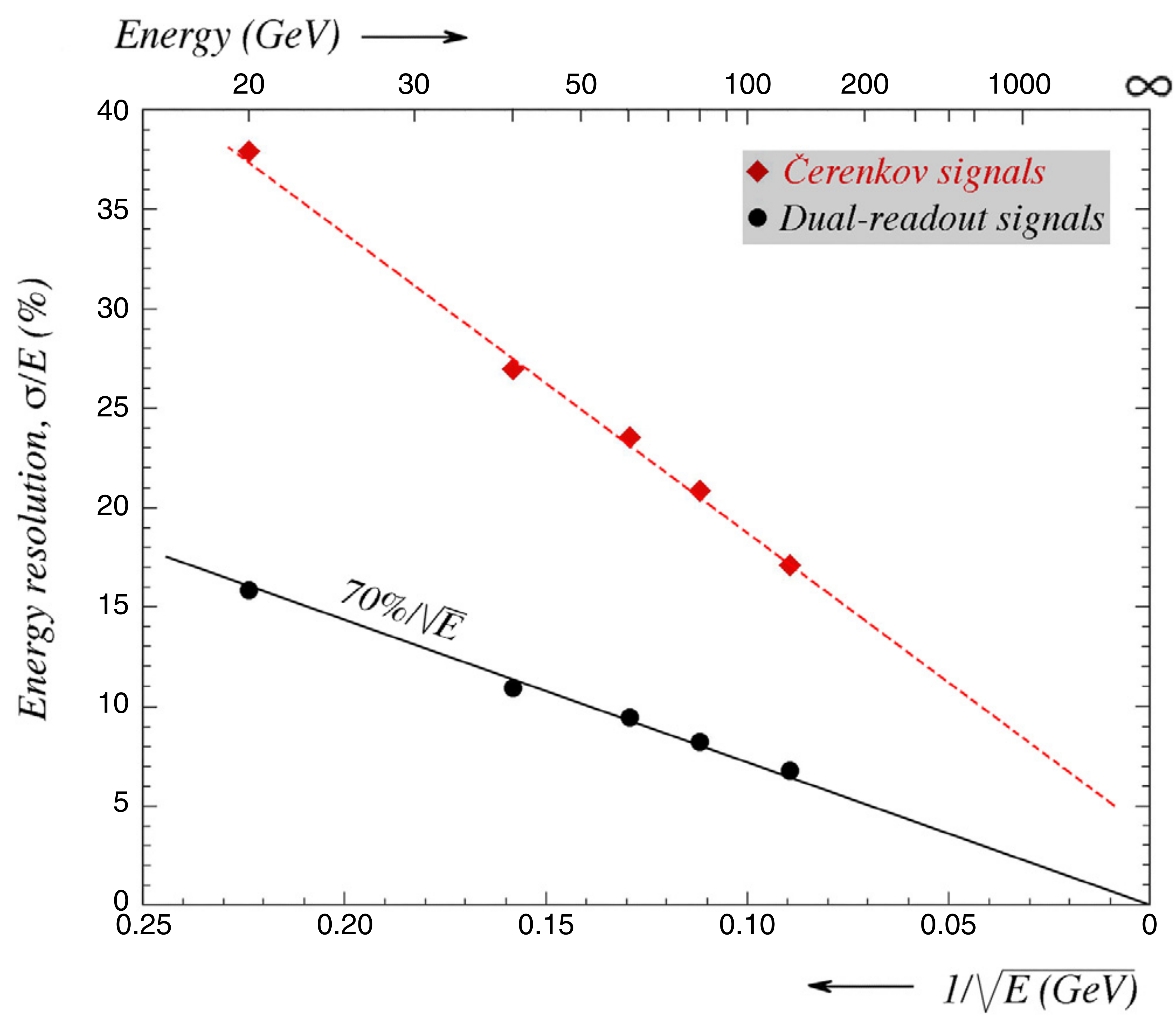
Leakage counters

Hadronic Performance (Dual-Readout Method)

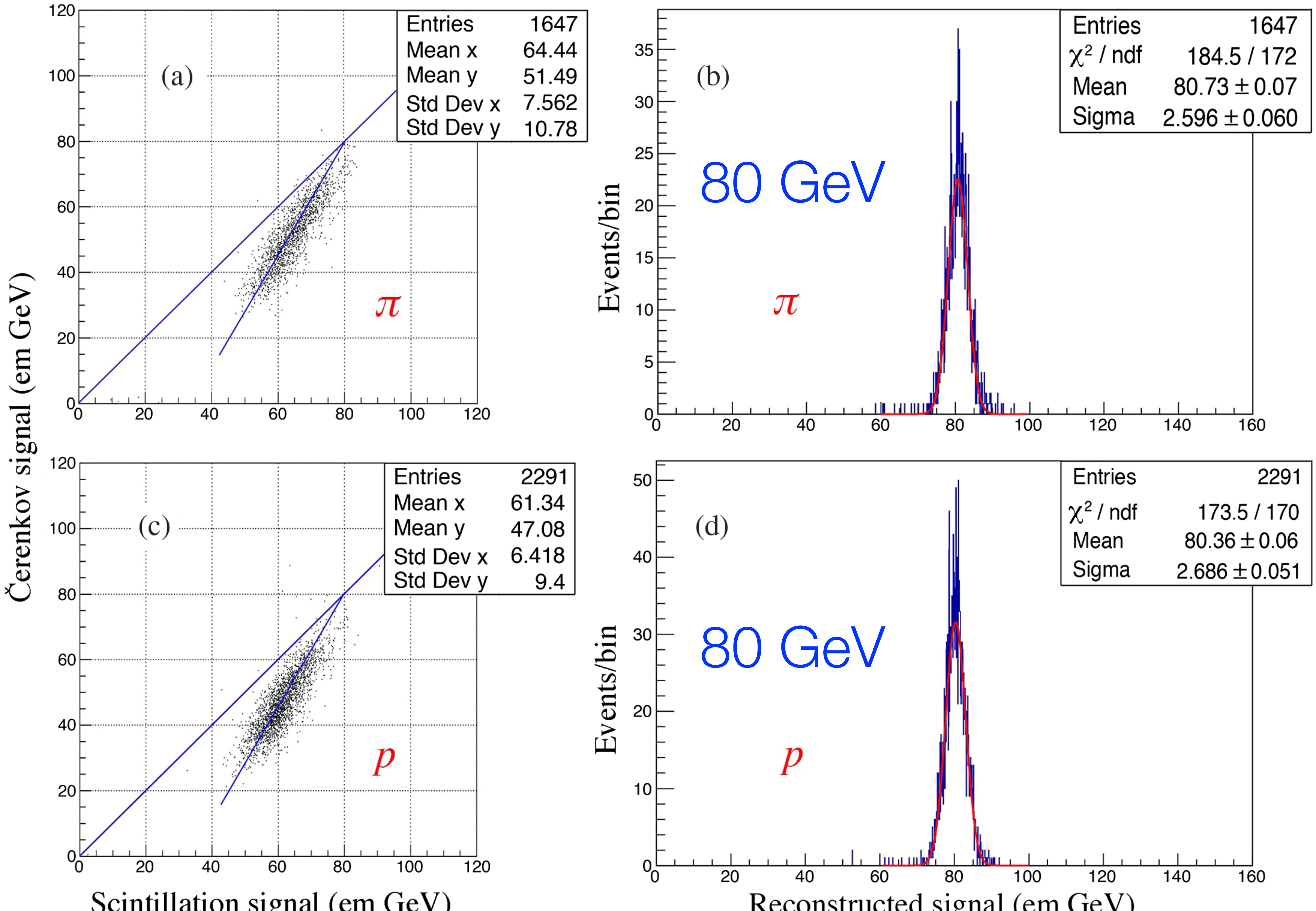


$$E = \frac{S - \chi C}{1 - \chi}, \quad \chi = 0.45.$$

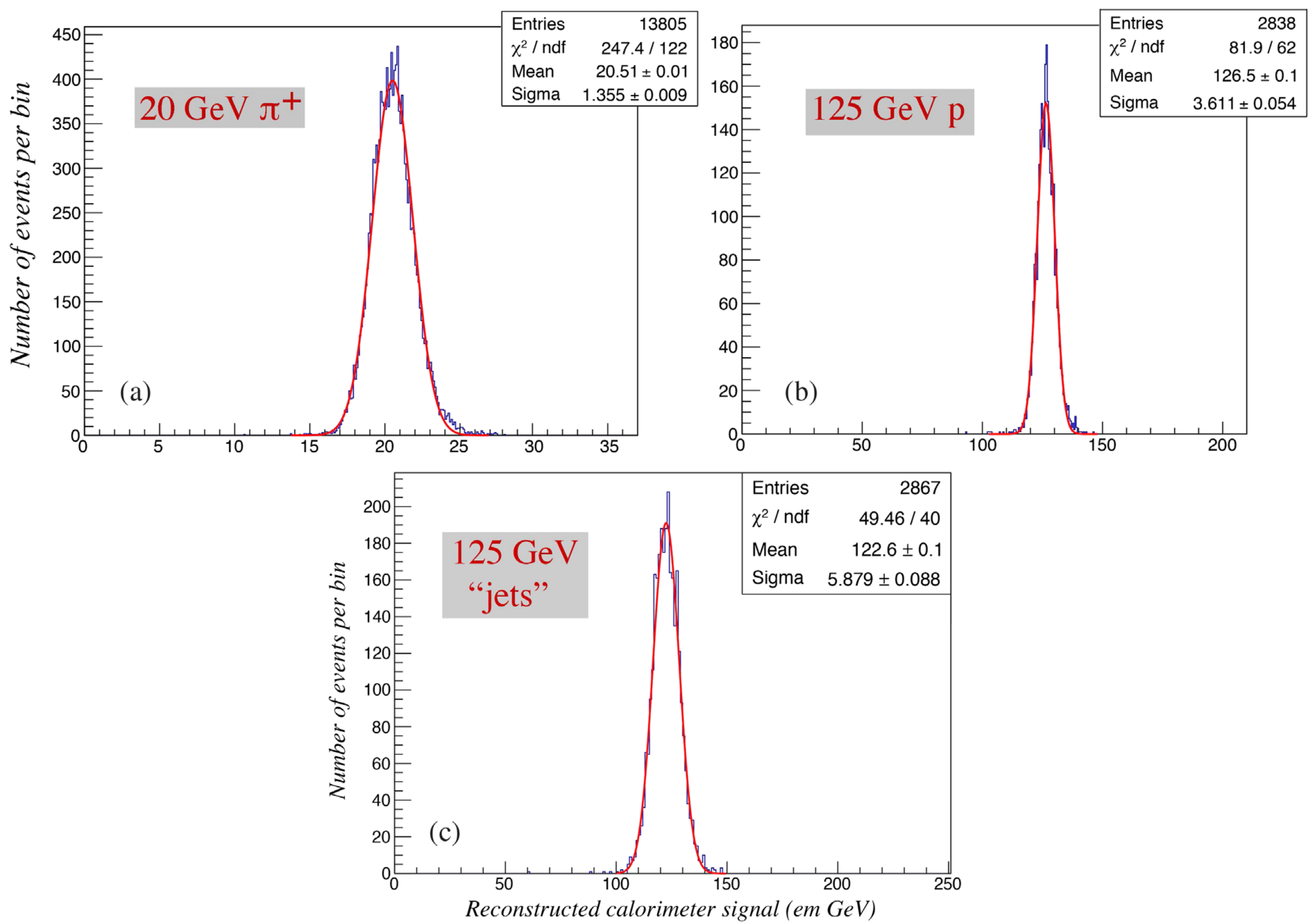
Hadronic Performance (Dual-Readout Method)



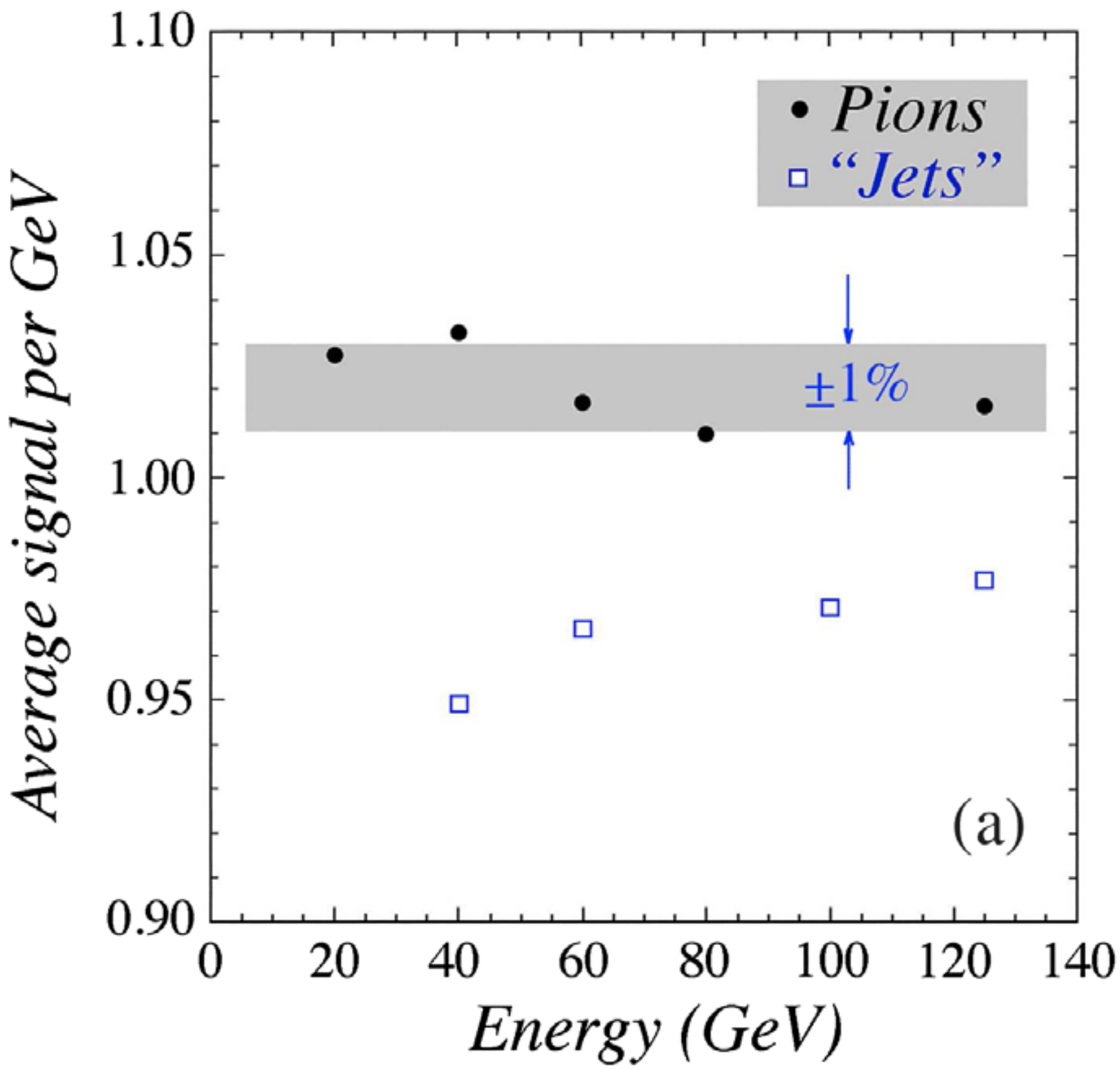
RD52 Pb-fiber Calorimeter (Rotation Method)

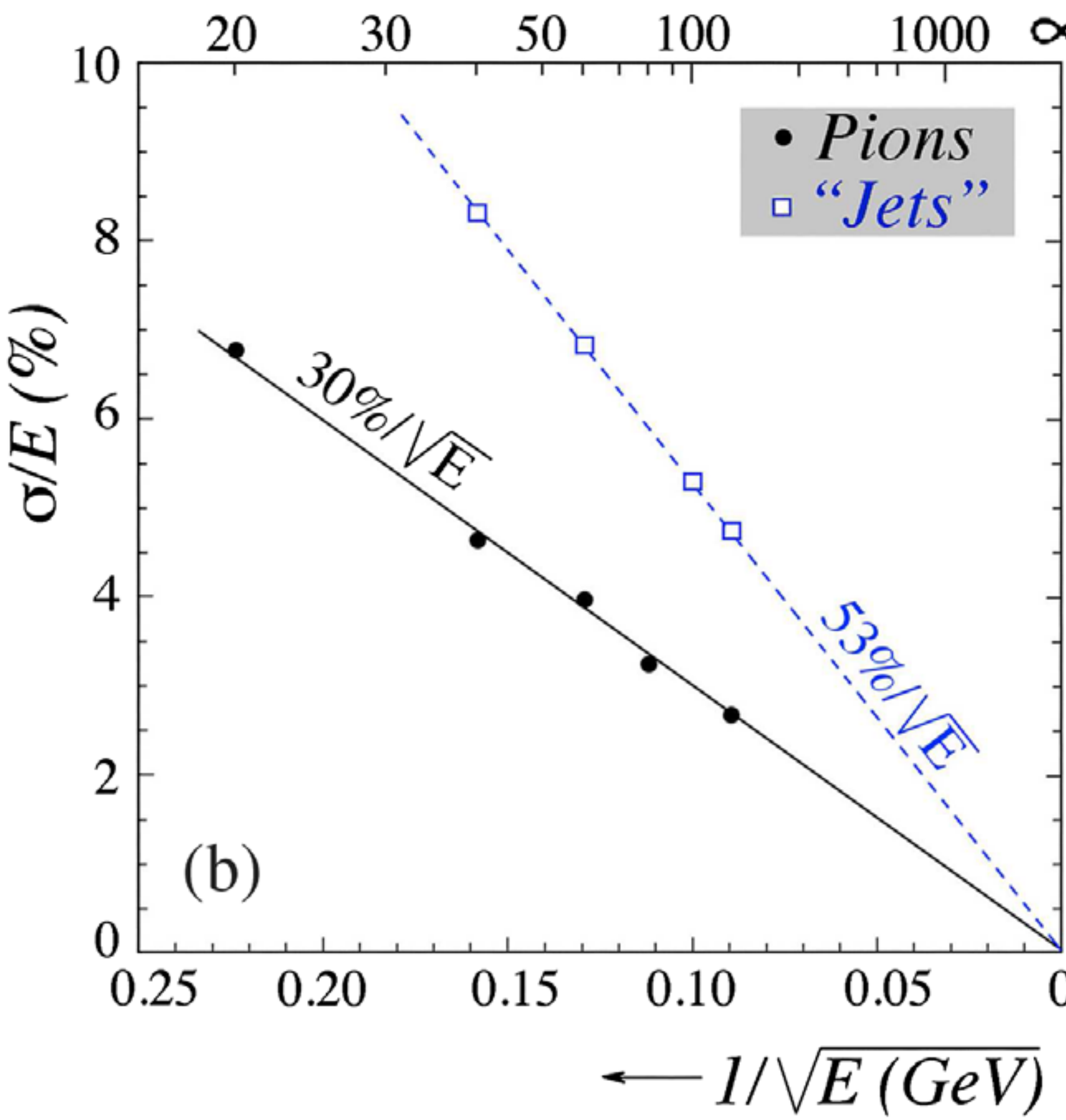


RD52 Pb-fiber Calorimeter (Rotation Method)



RD52 Pb-fiber Calorimeter (Rotation Method)



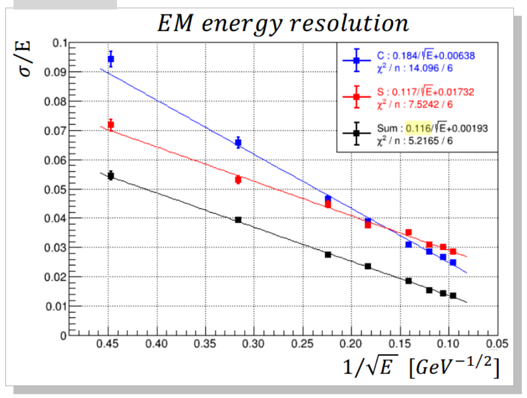


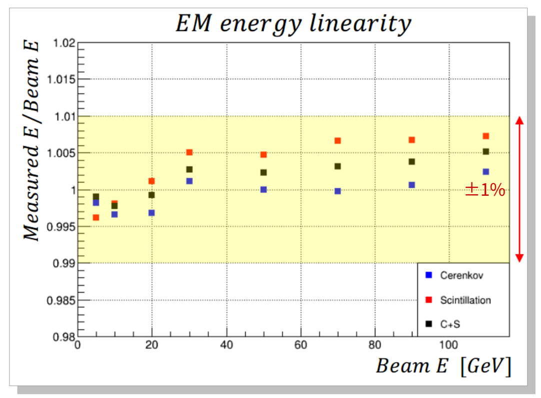
R&D of Korean Dual-Readout Calorimeter Collaboration

Goal: study the hadronic performance with a large detector (10 λ_{int}, 97.5% hadron shower containment)

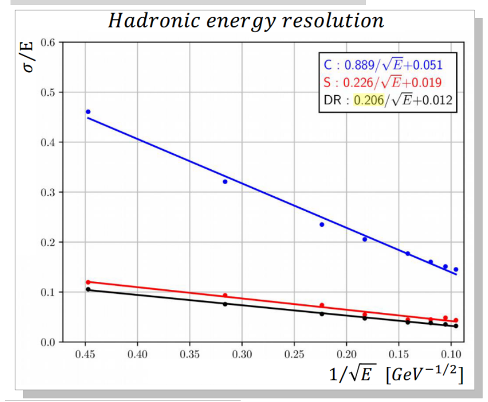
- Simulations for the future lepton collider experiments

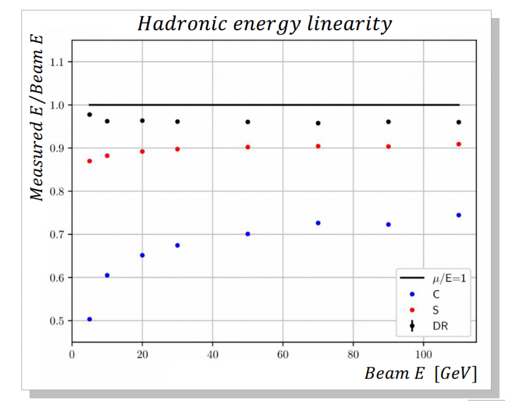
EM

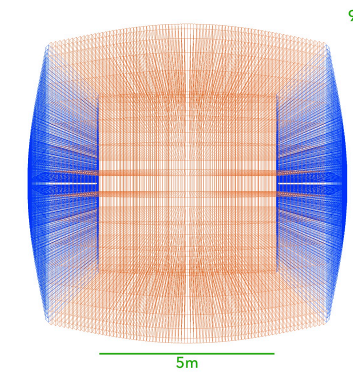




Single hadron

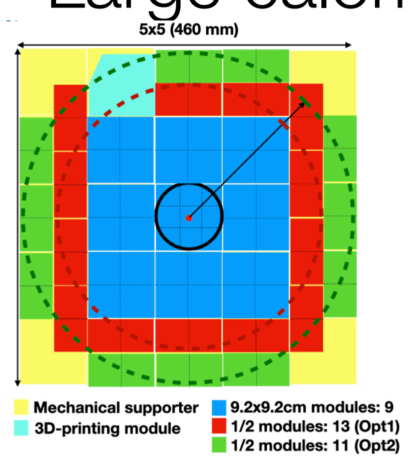


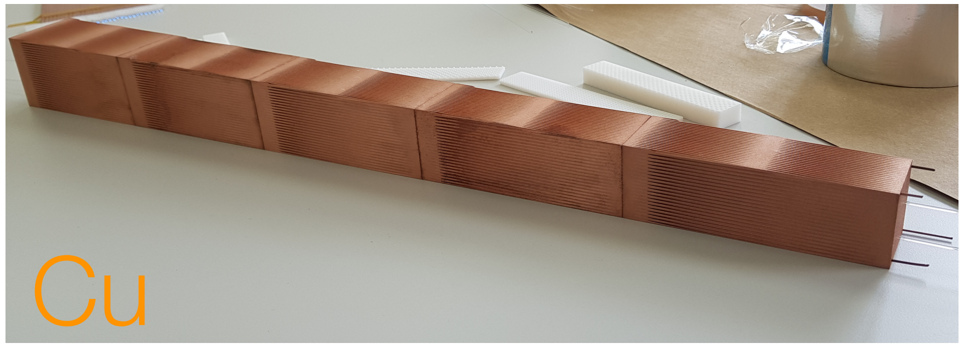


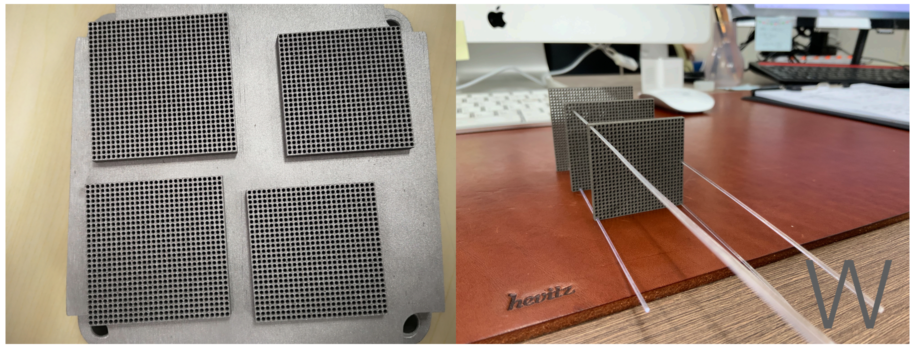


ECCE Calorimeter Working group meeting (June 8): Sanghyun's talk
https://indico.bnl.gov/event/11918/contributions/50512/attachments/35032/56968/210608_shKo_EIC.pdf

- Large calorimeter and projective tower structure with 3D printing







ECCE Calorimeter Working group meeting (June 1): Hwidong's talk
https://indico.bnl.gov/event/11917/contributions/50327/attachments/34872/56681/HDYOO_EICcal_06012021.pdf

Summary

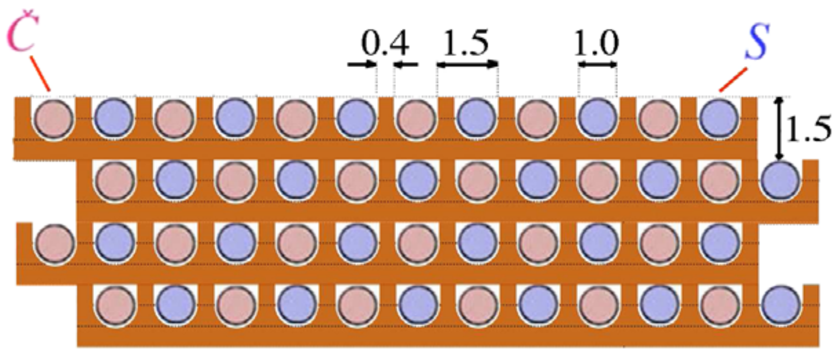
- DREAM and RD 52 Collaborations has proved the dual-readout principles and the good performance in the energy measurement of hadrons

- Ingredients to apply the dual-readout calorimeter to future experiments are on our hands

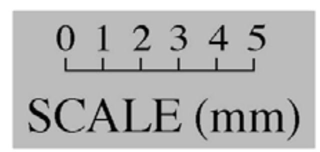
- We are working to prove the performance of the dual-readout calorimeter with a large size of calorimeter which can contain 97.5% of hadron shower energy

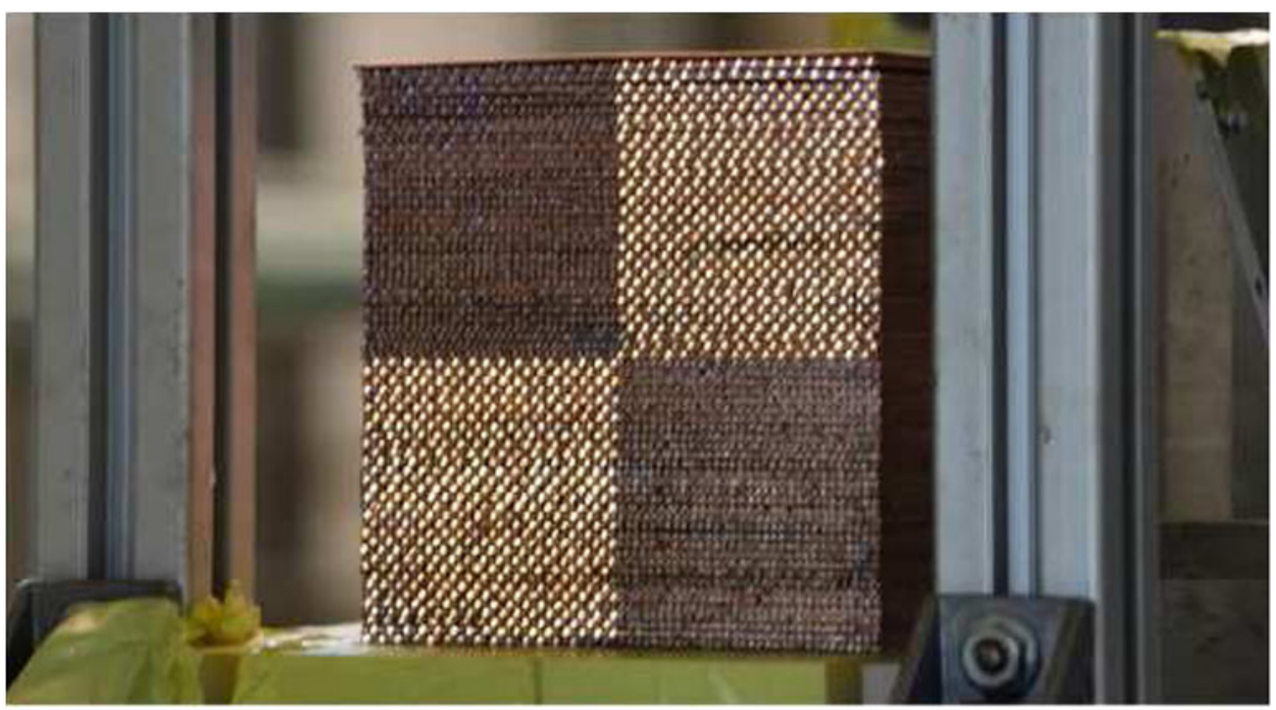
Electromagnetic Performance

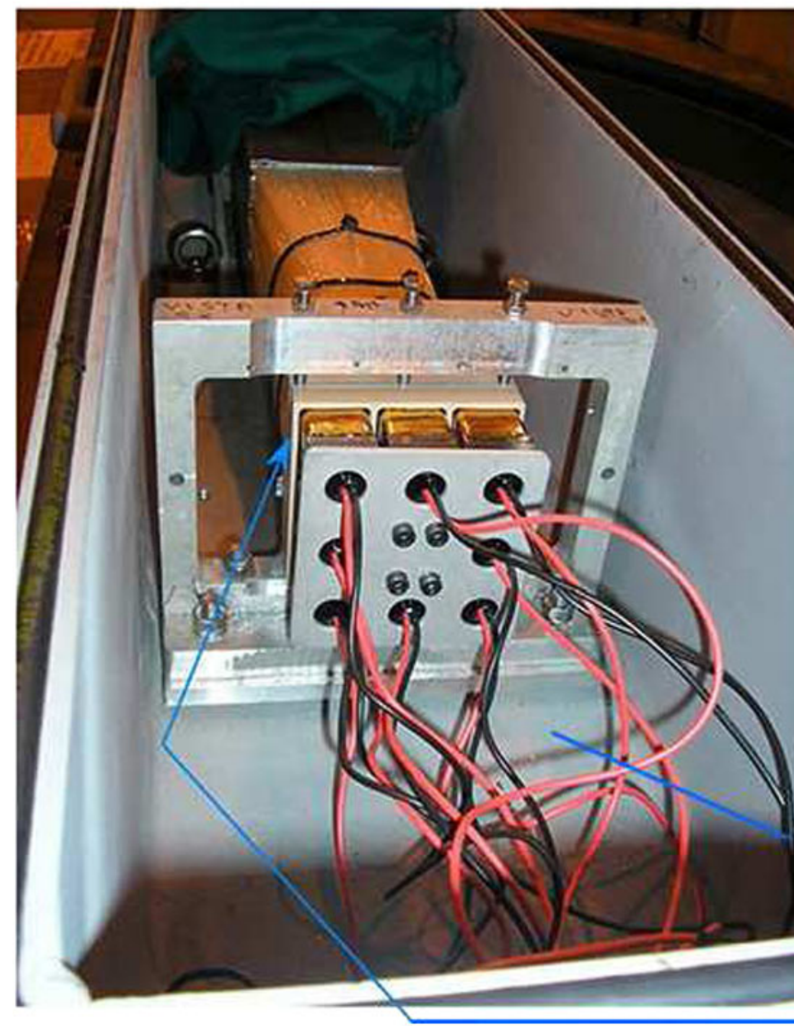
RD52 Cu-fiber Calorimeter



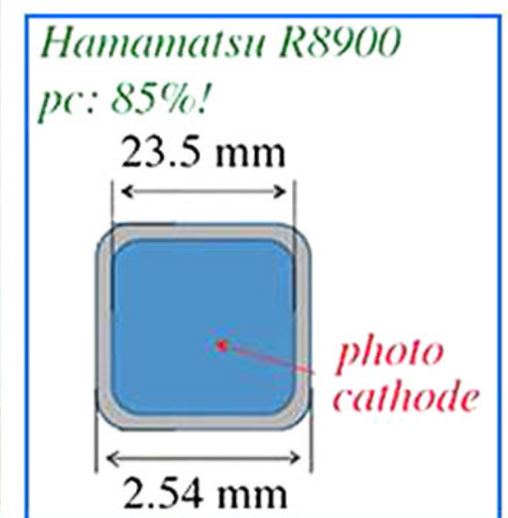
Fiber pattern RD52





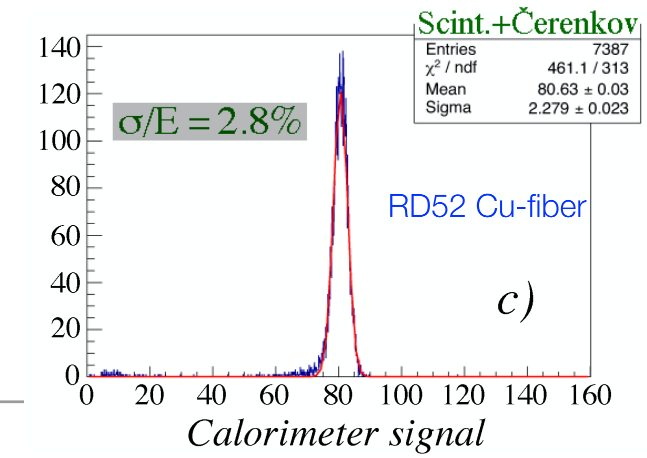


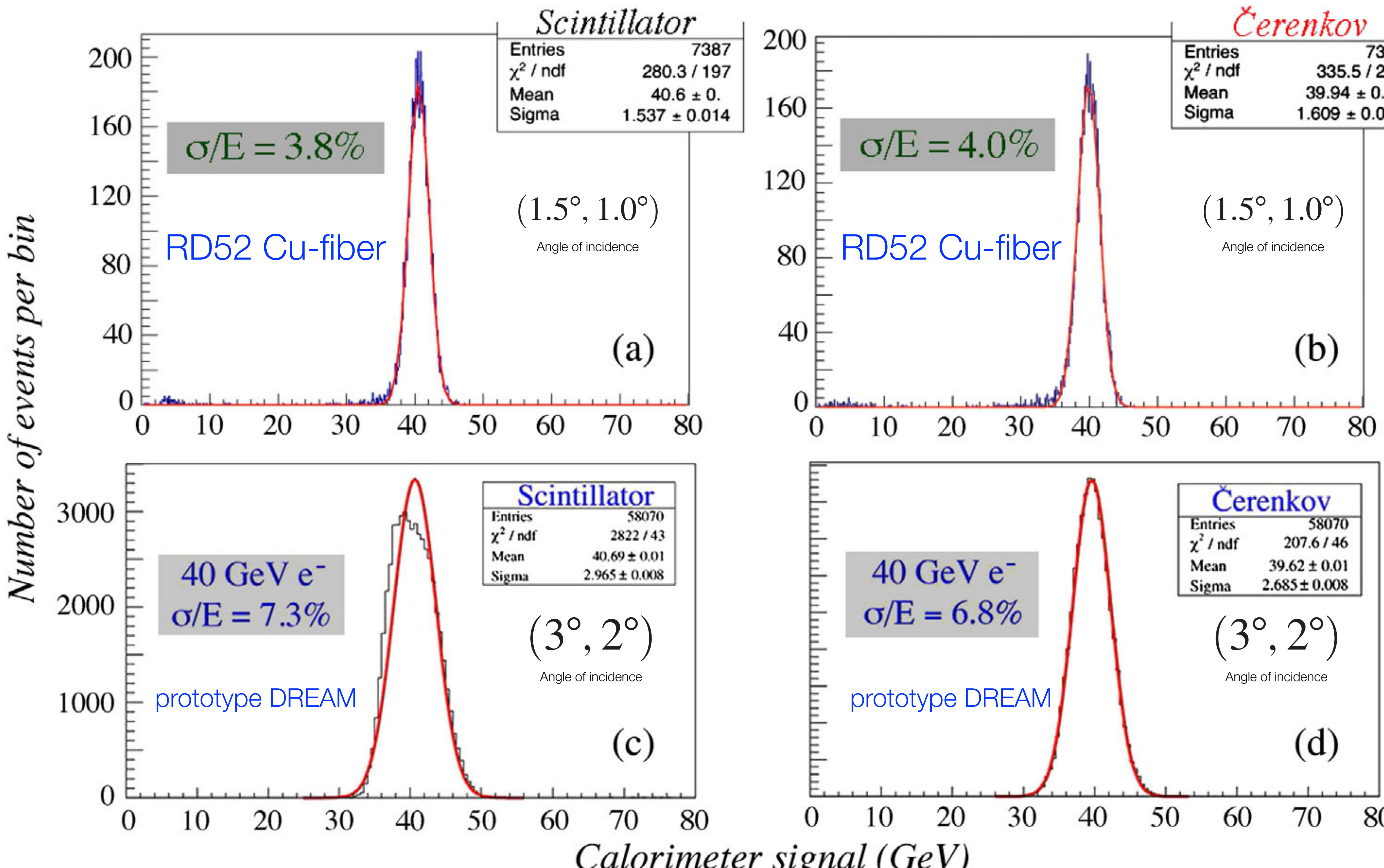
9.3 x 9.3 x 250 cm
150 kg
4 towers, 8 PMTs
2 x 2048 fibers



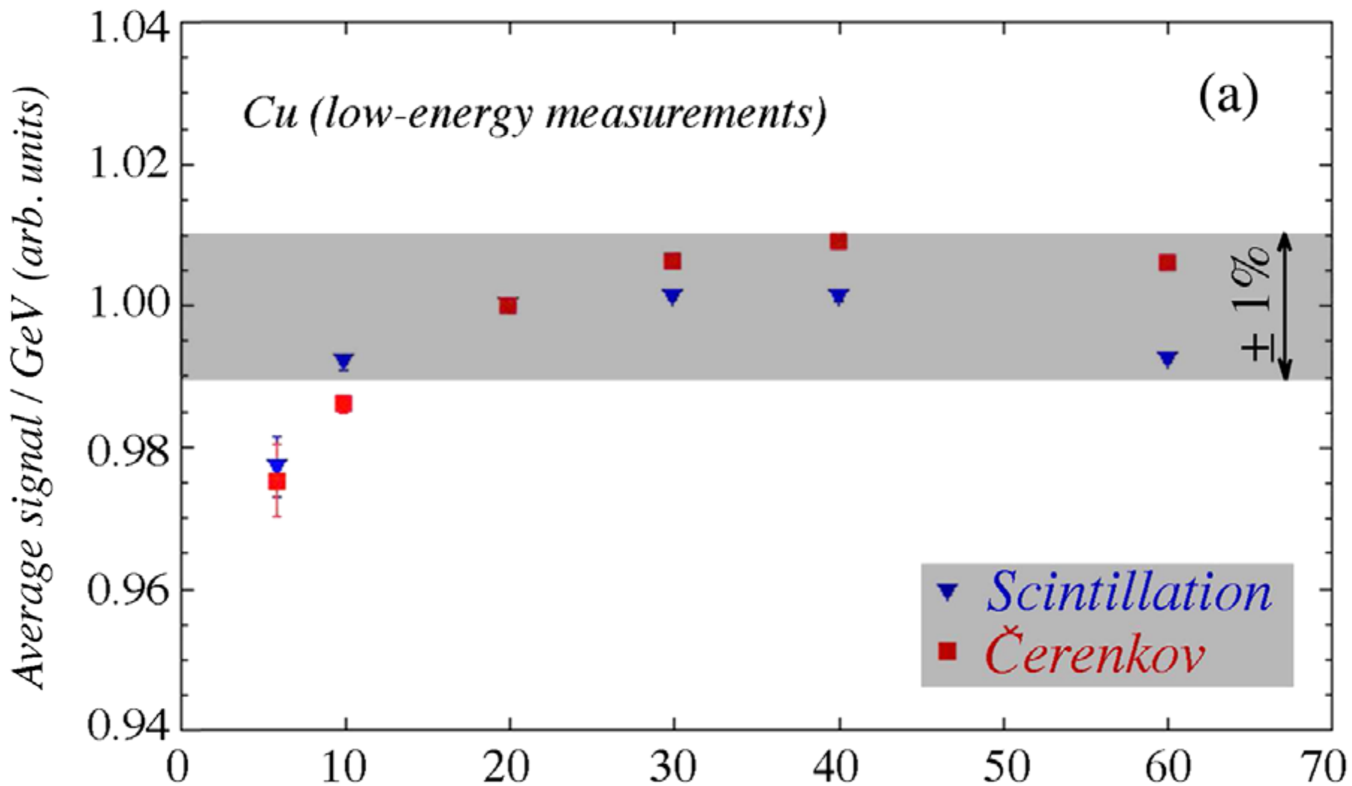
Electromagnetic Performance

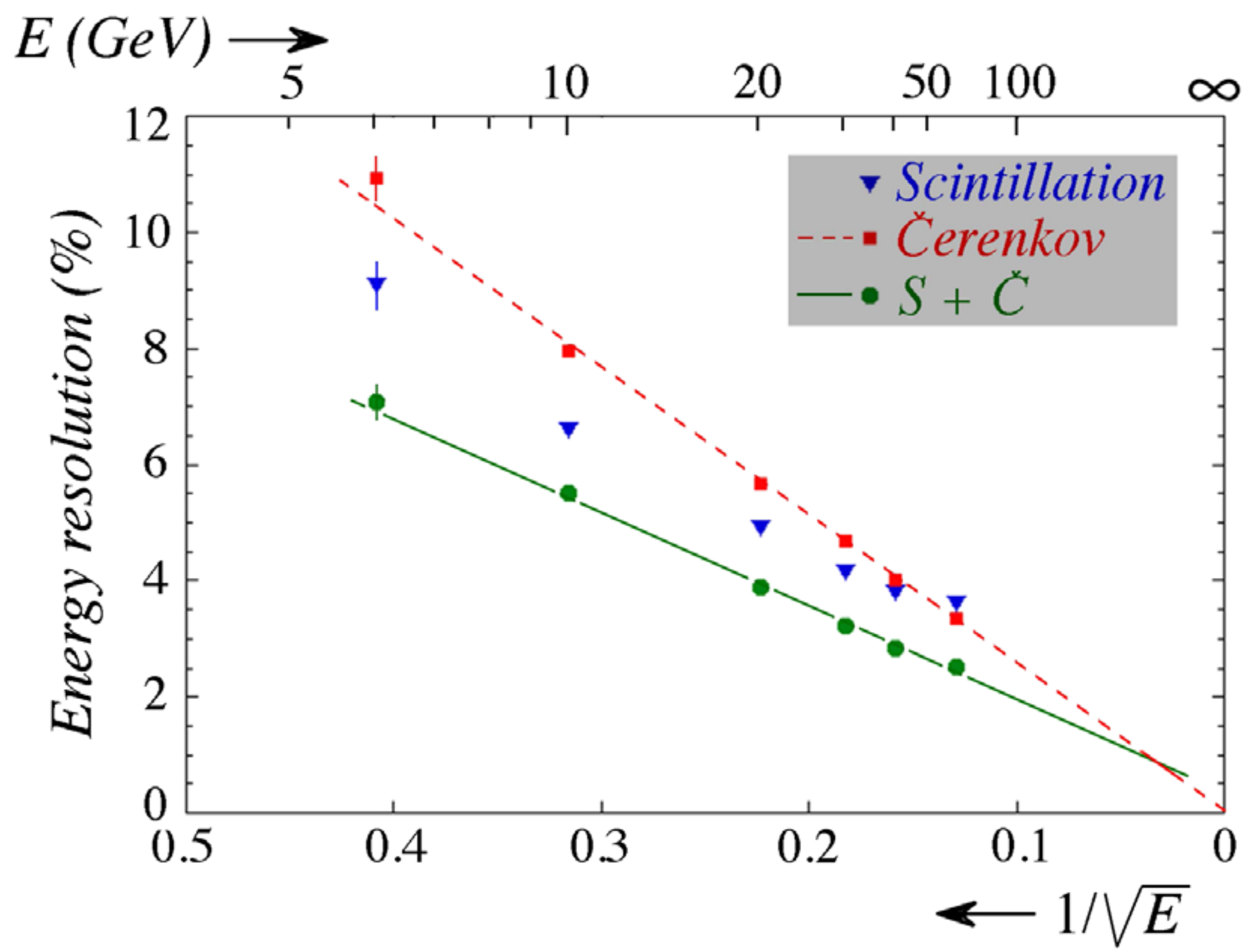
(RD52 vs DREAM calorimeters)



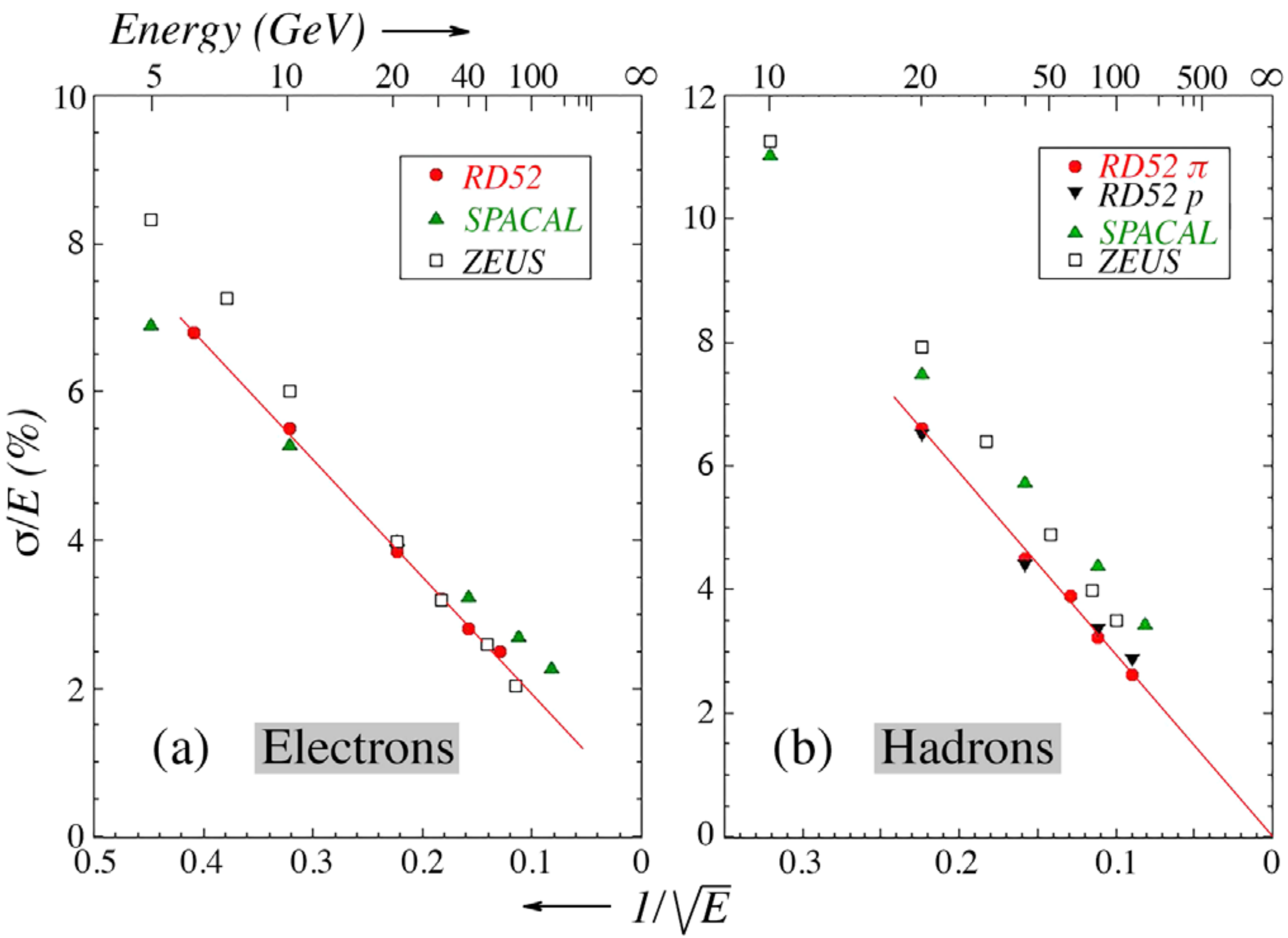


RD52 Cu-fiber Calorimeter



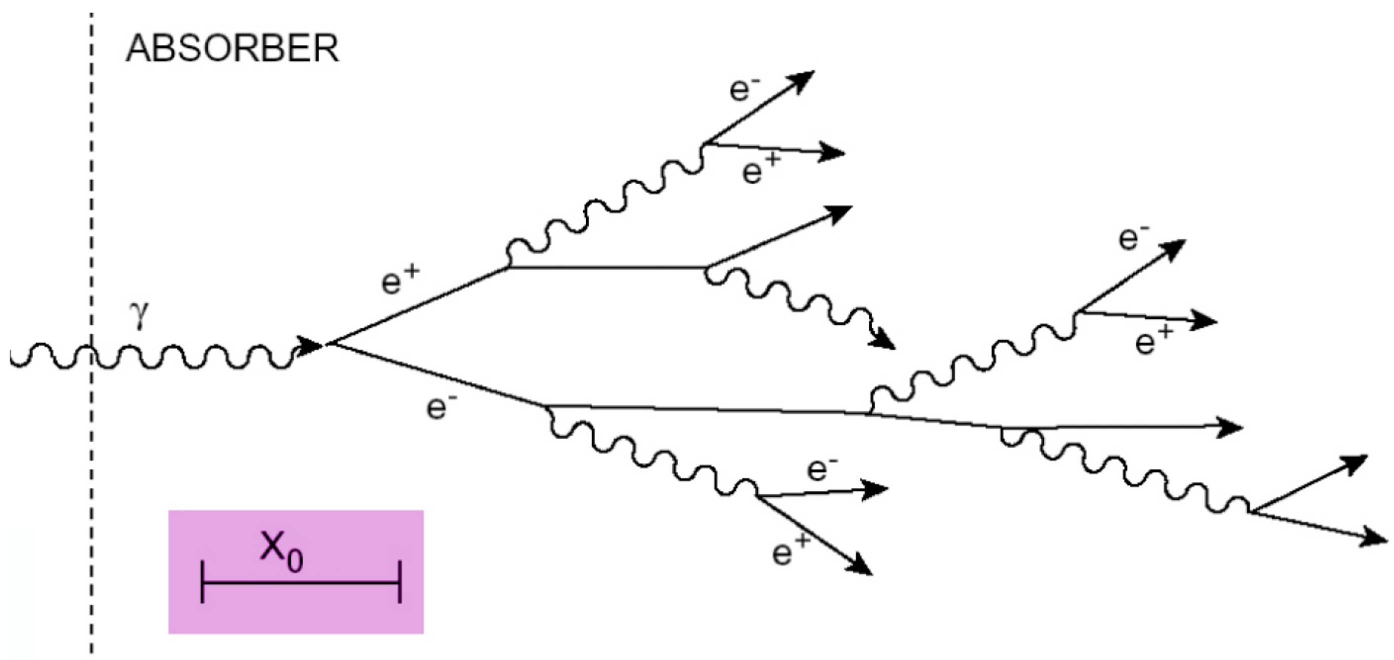


Electromagnetic and Hadronic Performances



Backup

Electromagnetic Calorimeter

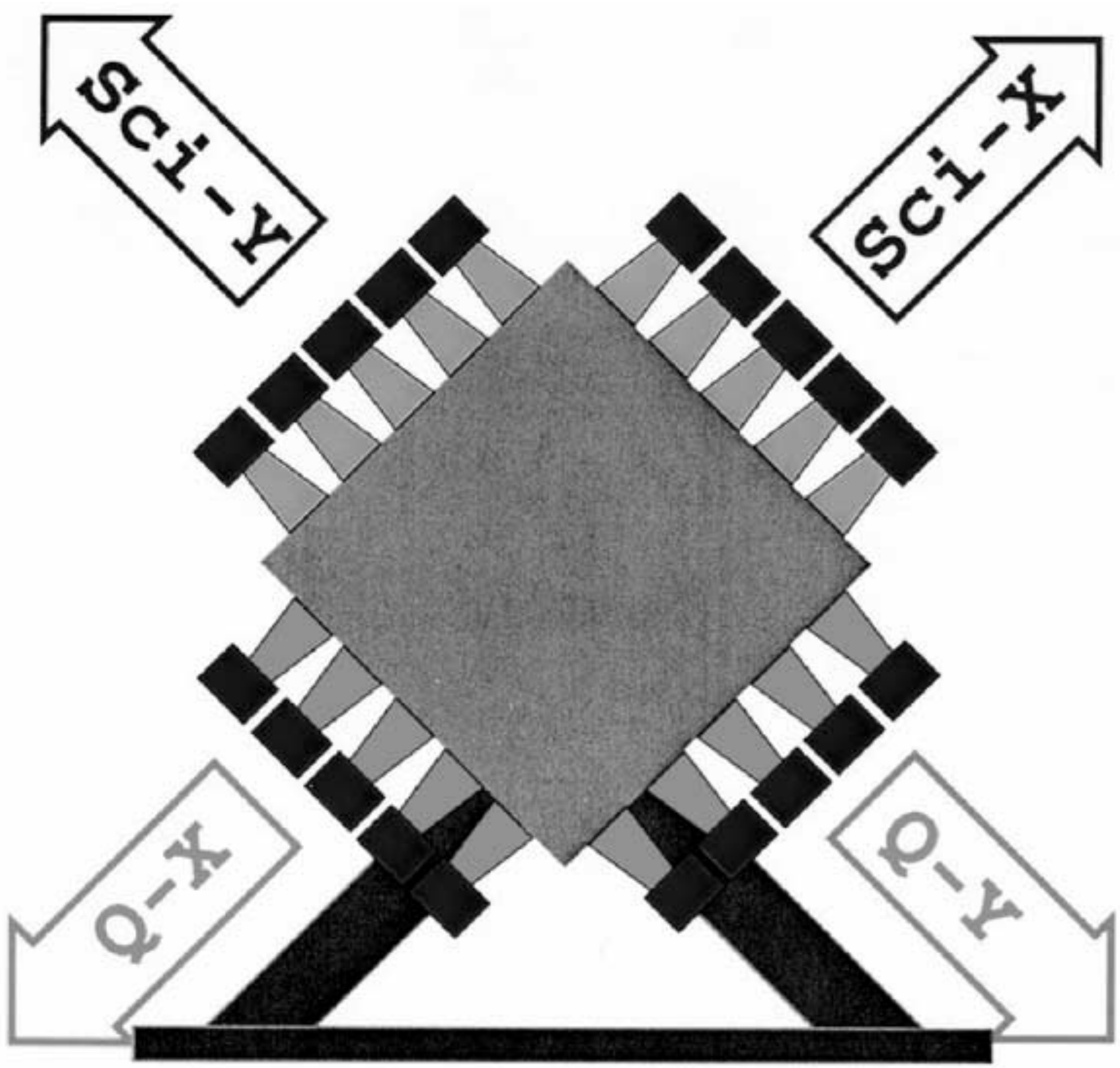


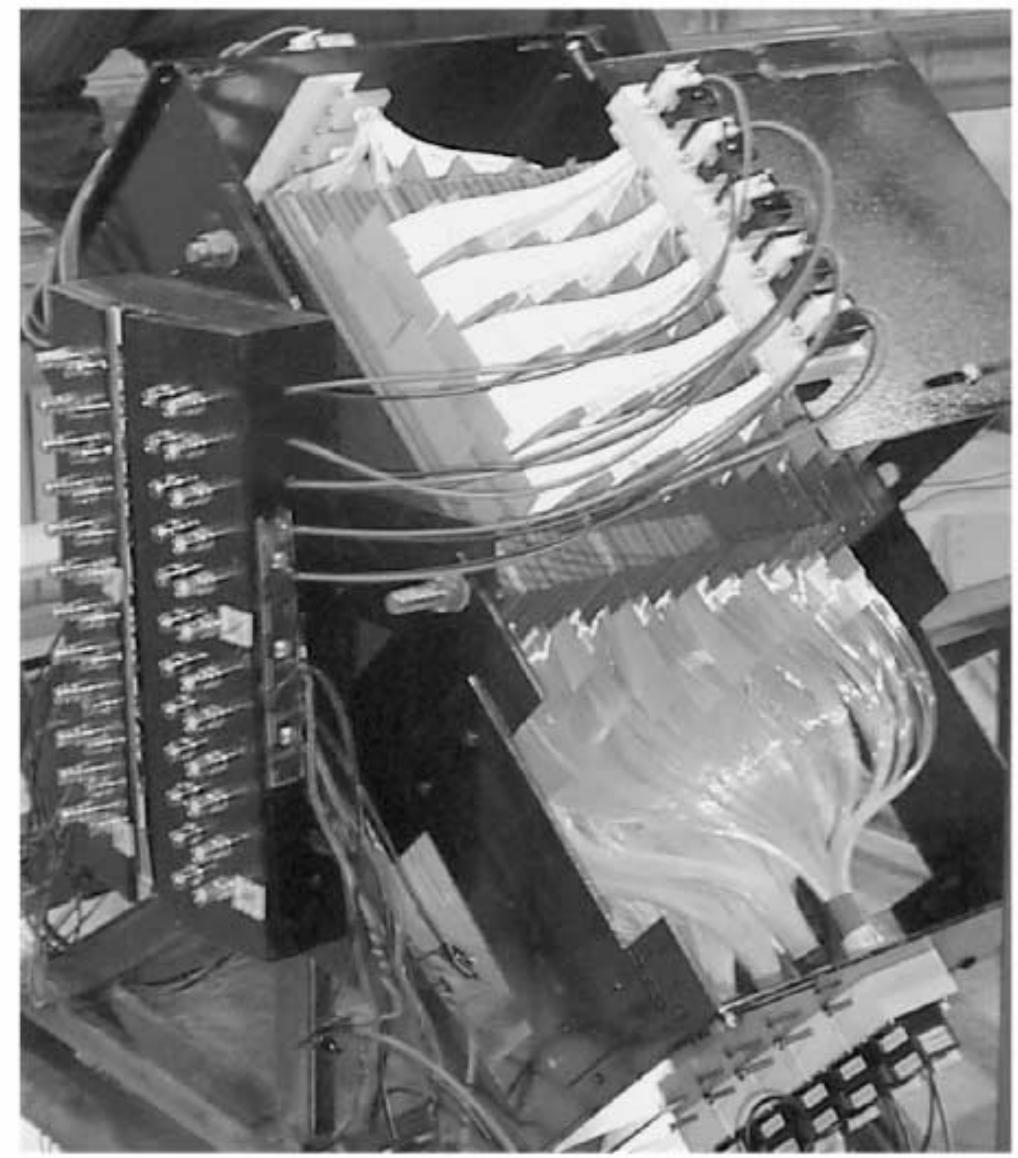
- Electromagnetic shower physics is well understood
- Calorimeter signal is directly proportional to the energy of incoming particles
- It offers very precise energy measurement for e, γ detection

ACCESS

- High-energy cosmic-ray experiment for the International Space Station
- The application of the complementary information from scintillation and Cerenkov light
- The prototype consists of a 1.4 λ_{int} deep lead absorber and two types of optical fibers (scintillation and quartz)
- The calorimeter response to high-energy hadrons is determined by leakage fluctuation
- It distinguishes between events with relatively small and large shower leakage

ACCESS

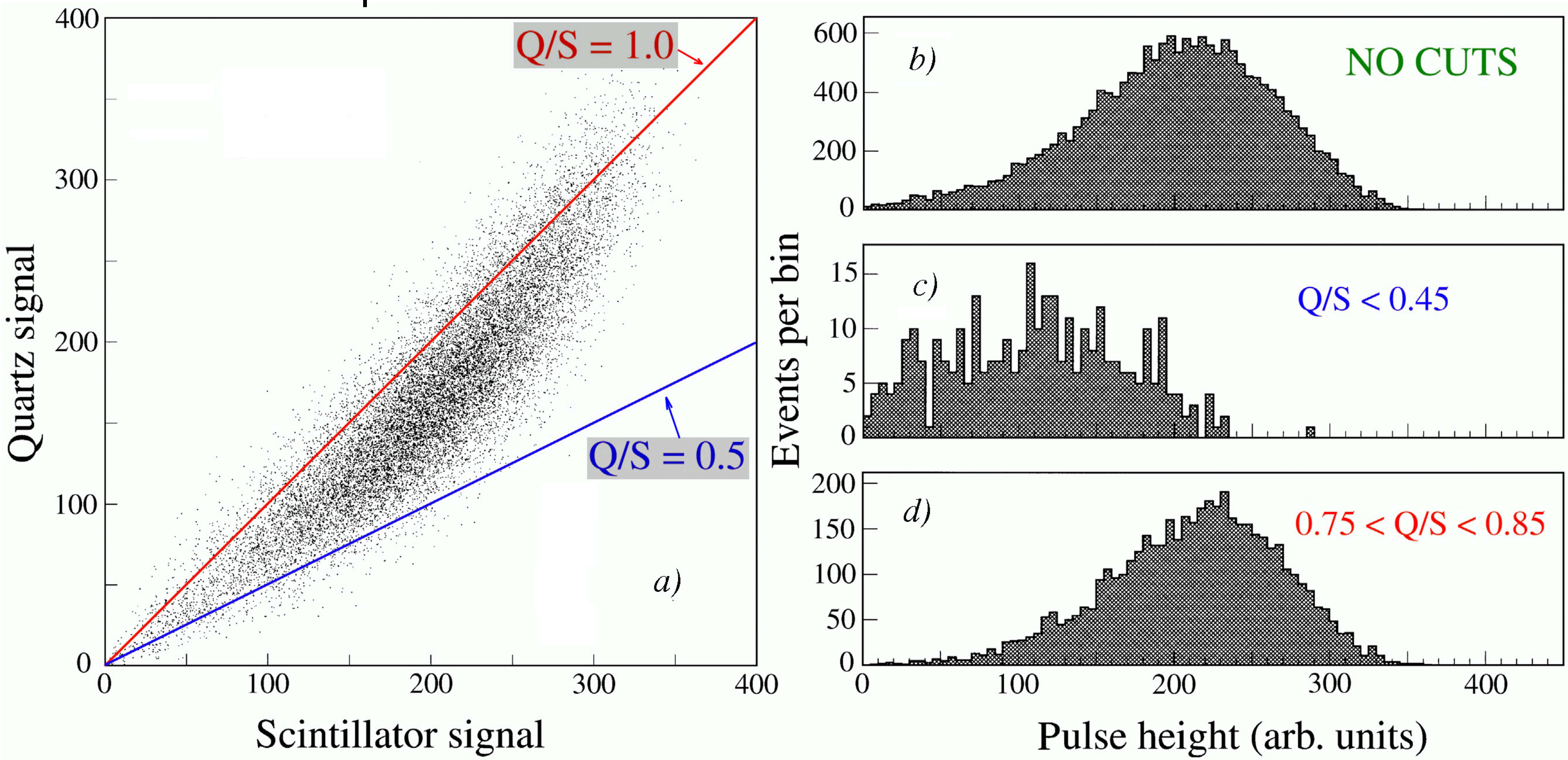




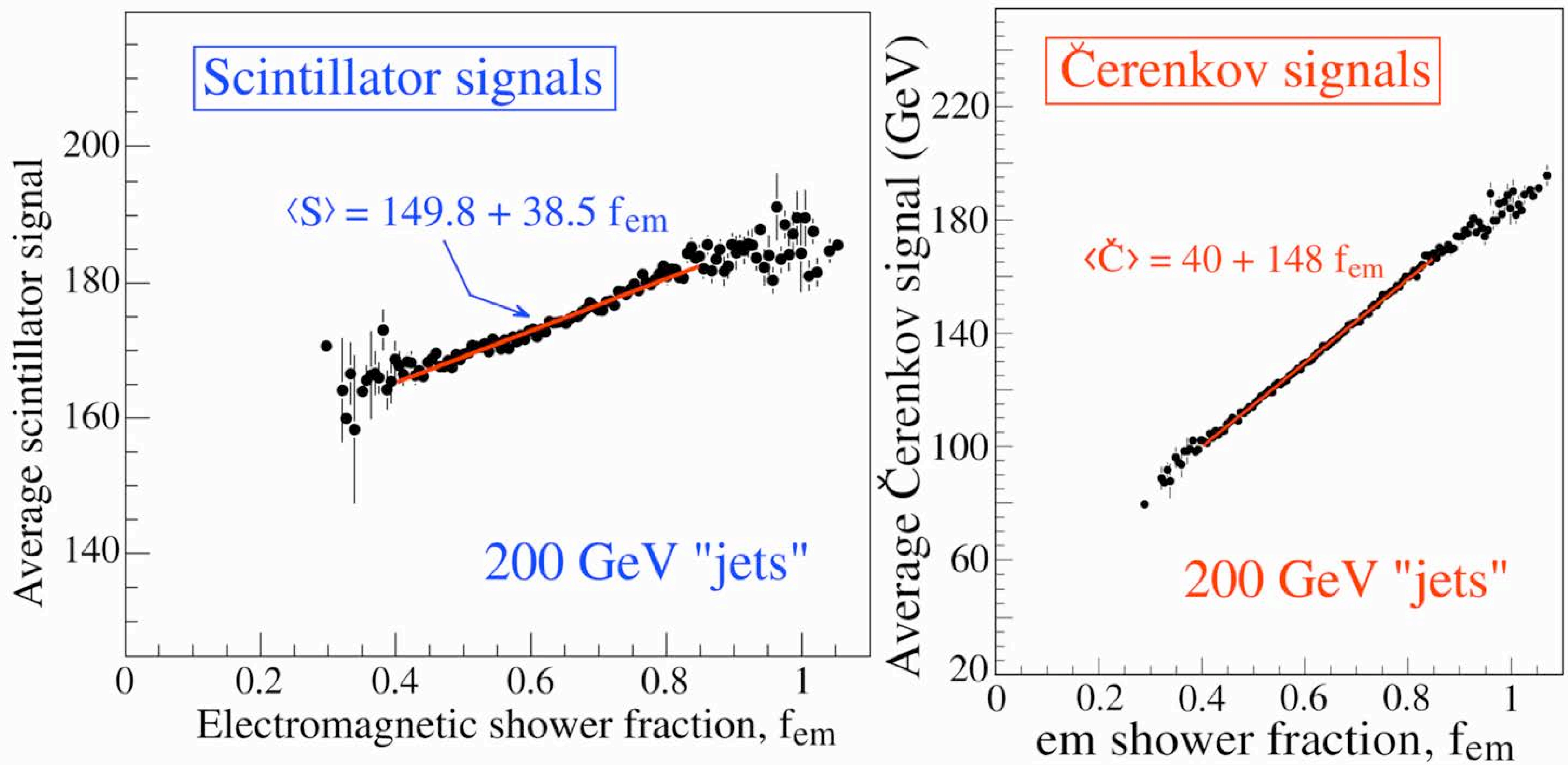
Thin lead plates were interleaved with 4 cm wide ribbons of scintillating and Cerenkov fibers

ACCESS

375 GeV pions



Signal Dependence on f_{em}

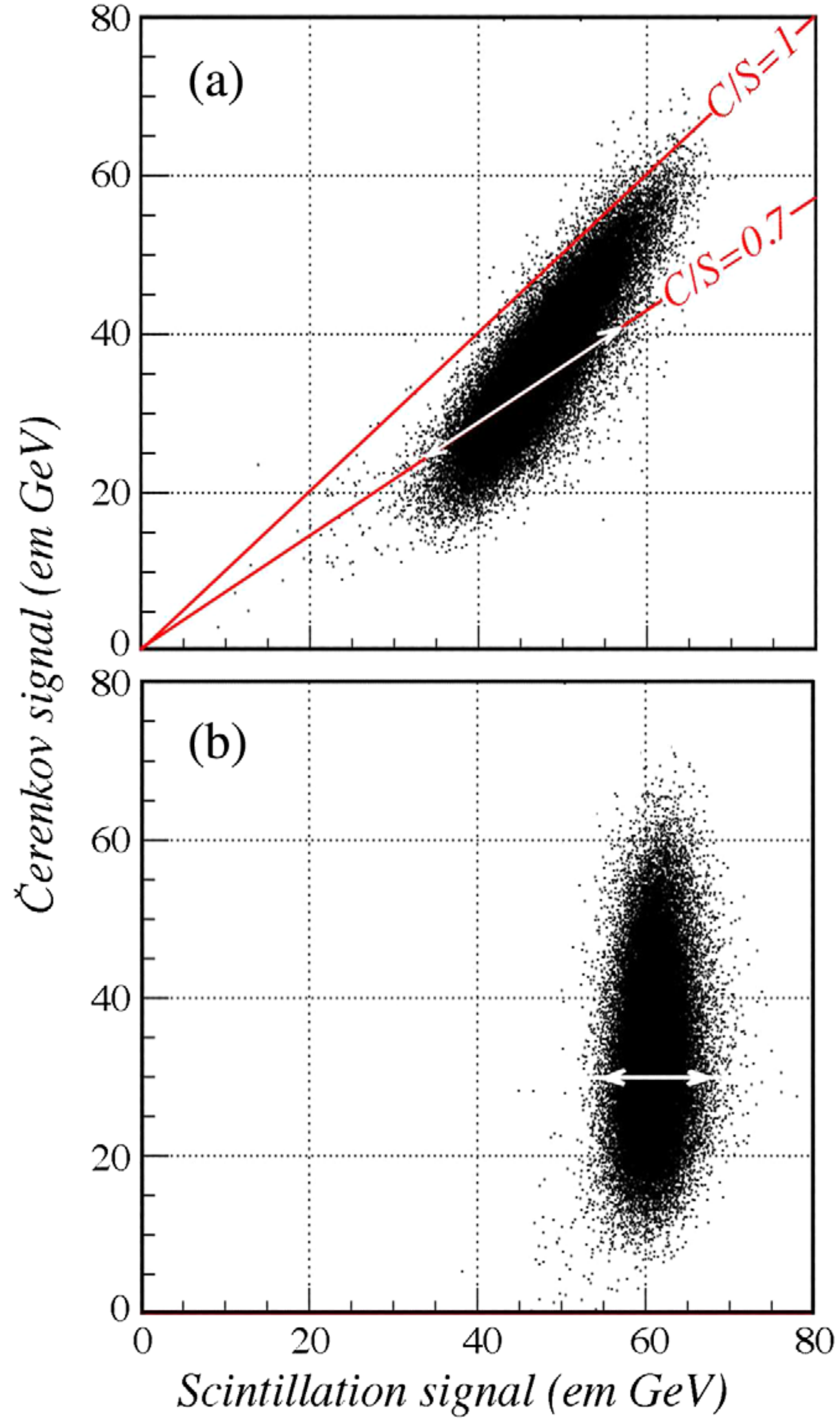


$$R(f_{em}) = p_0 + p_1\ f_{em}$$ with $$\frac{p_1}{p_0} = e/h - 1$$

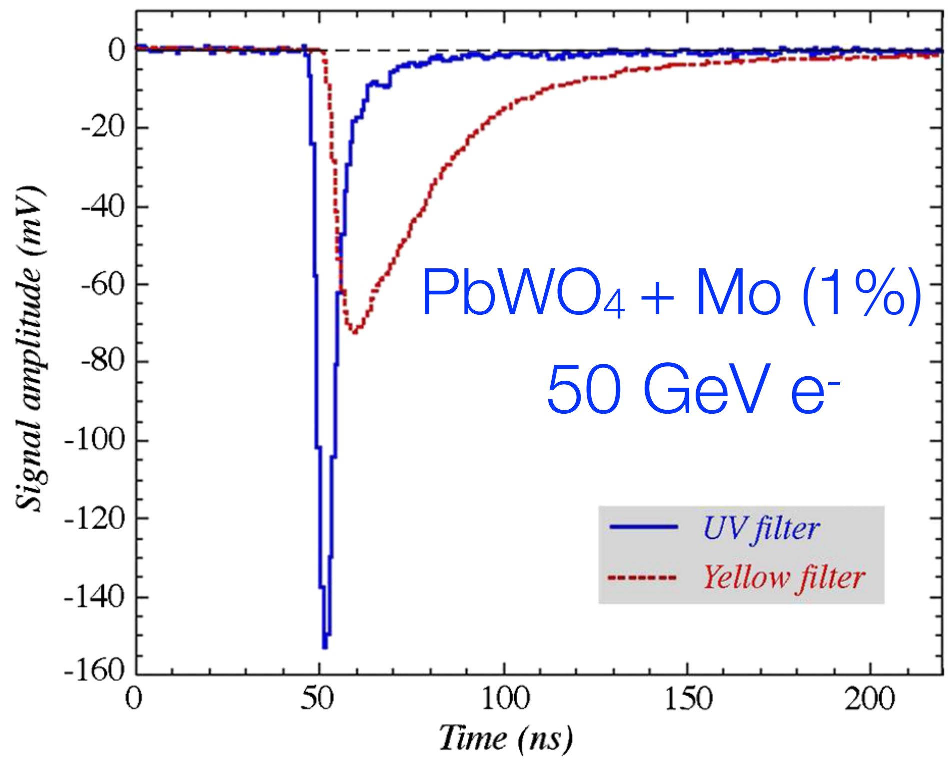
Cu/scintillator e/h = 1.3 Cu/quartz e/h = 4.7

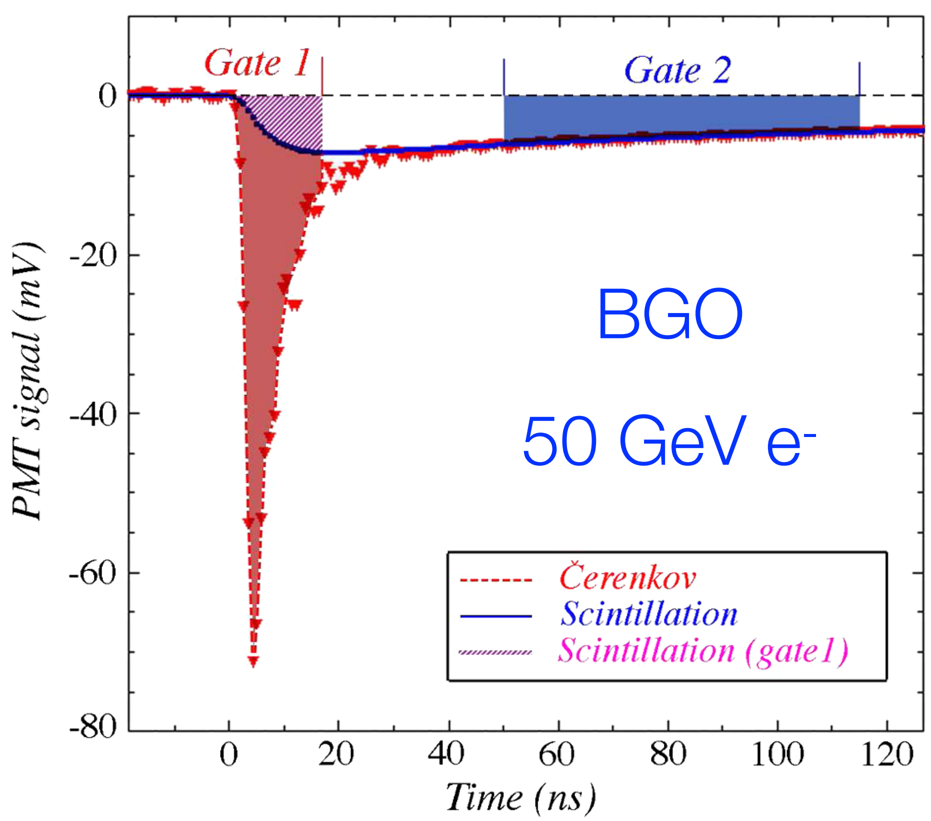
From:
NIM A537 (2005) 537

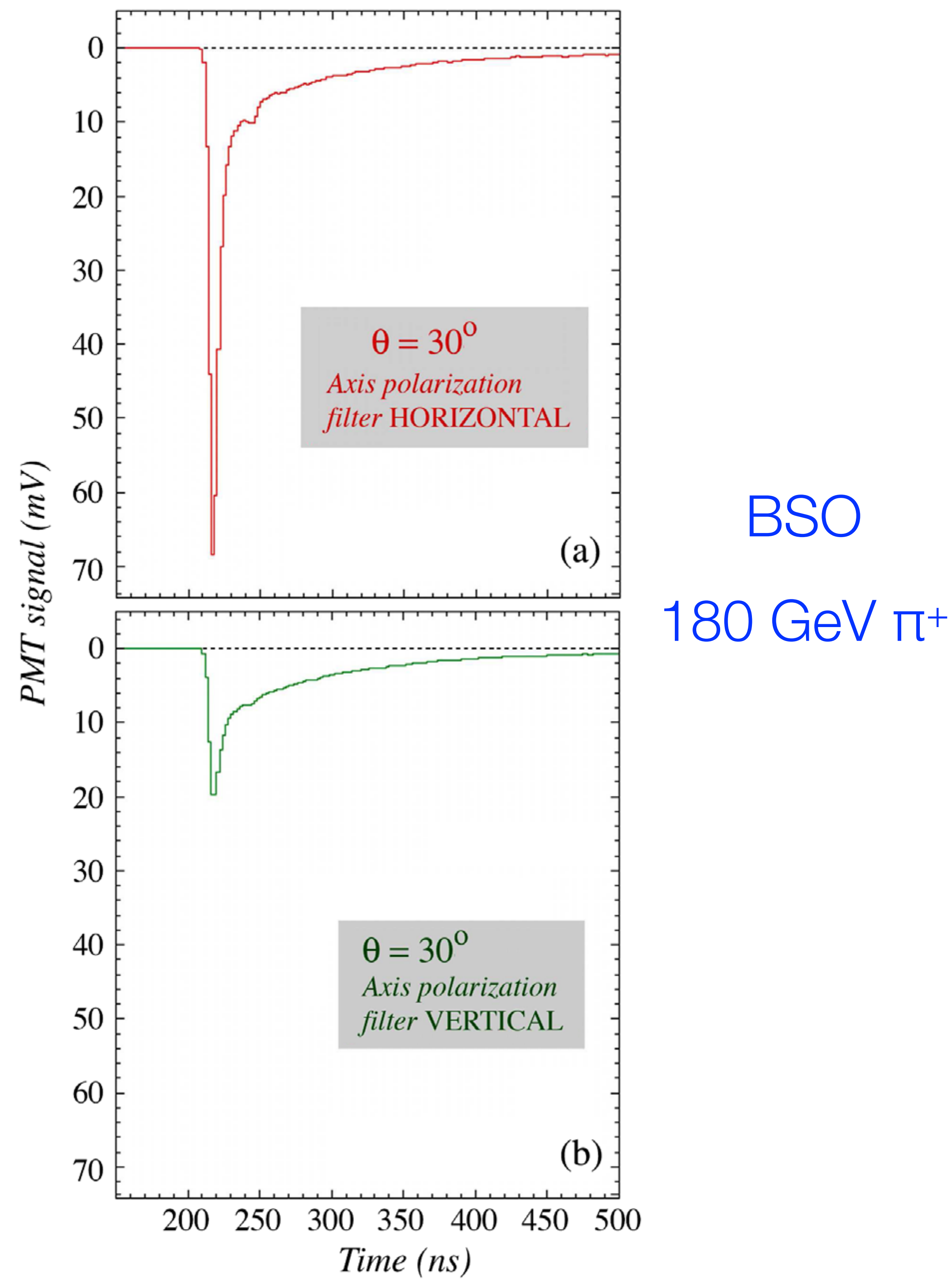
Difference between dual-readout and rotation methods



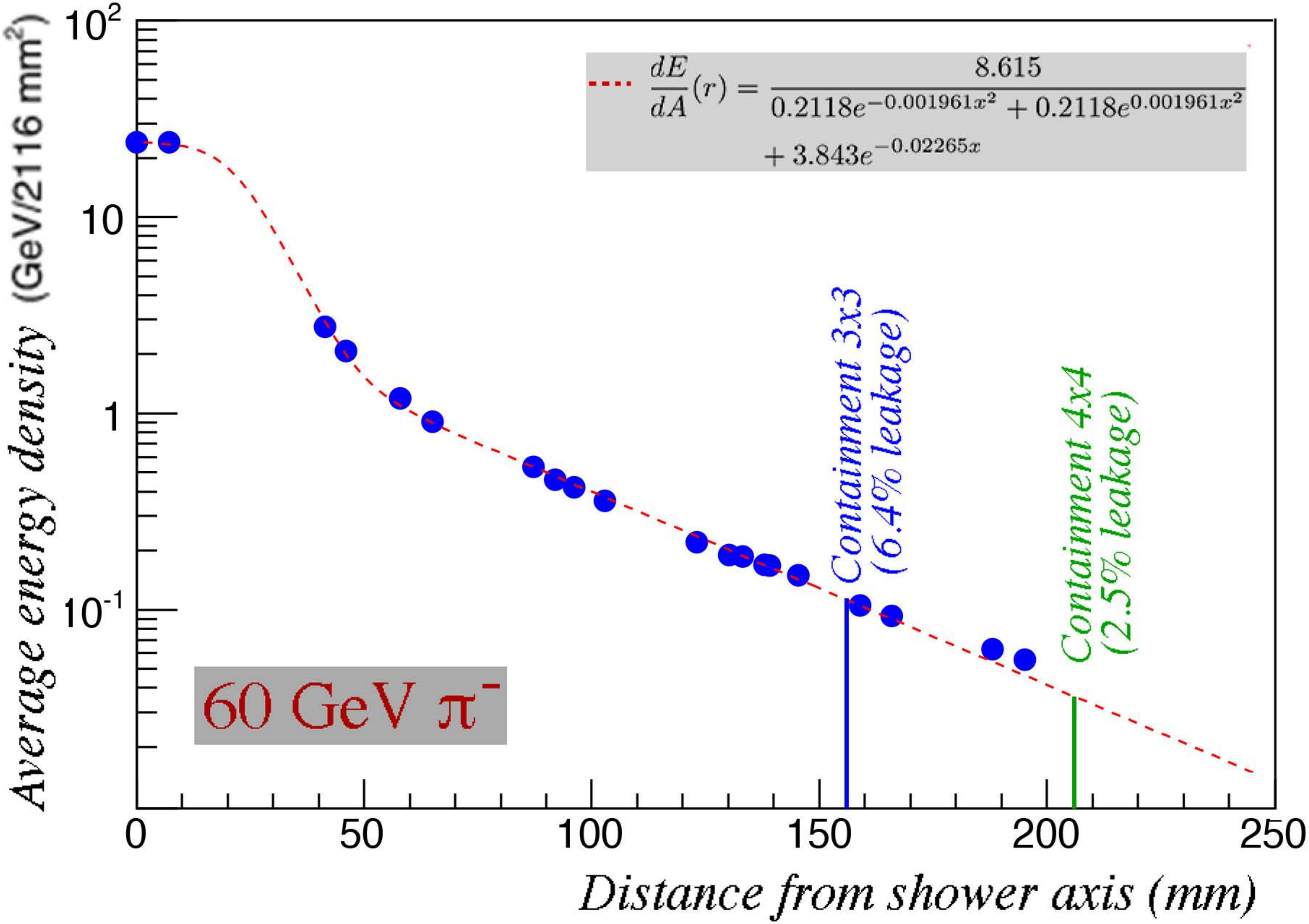
Crystals for Dual-Readout Calorimetry





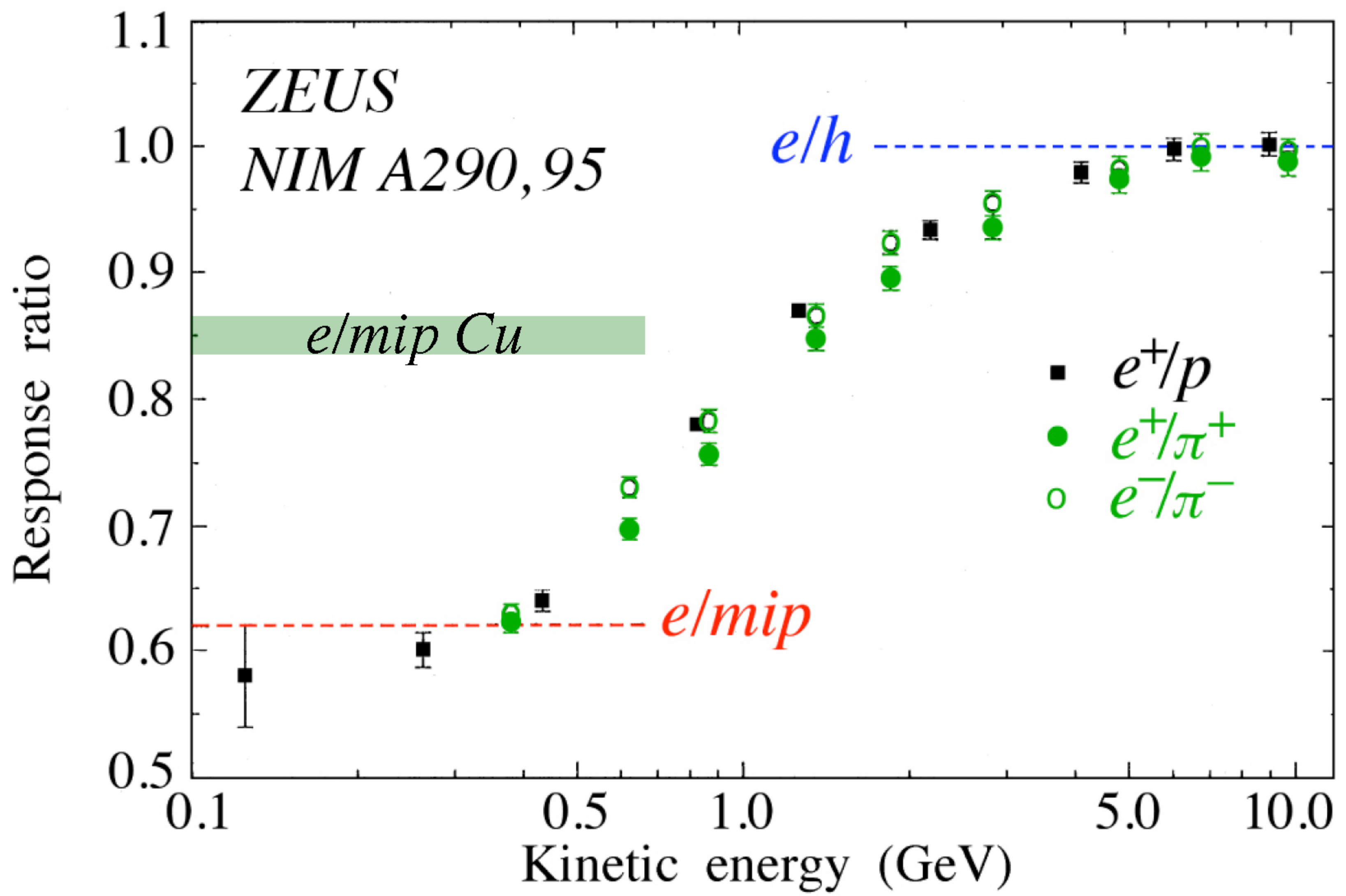


Radial shower profile (Pb/fiber)



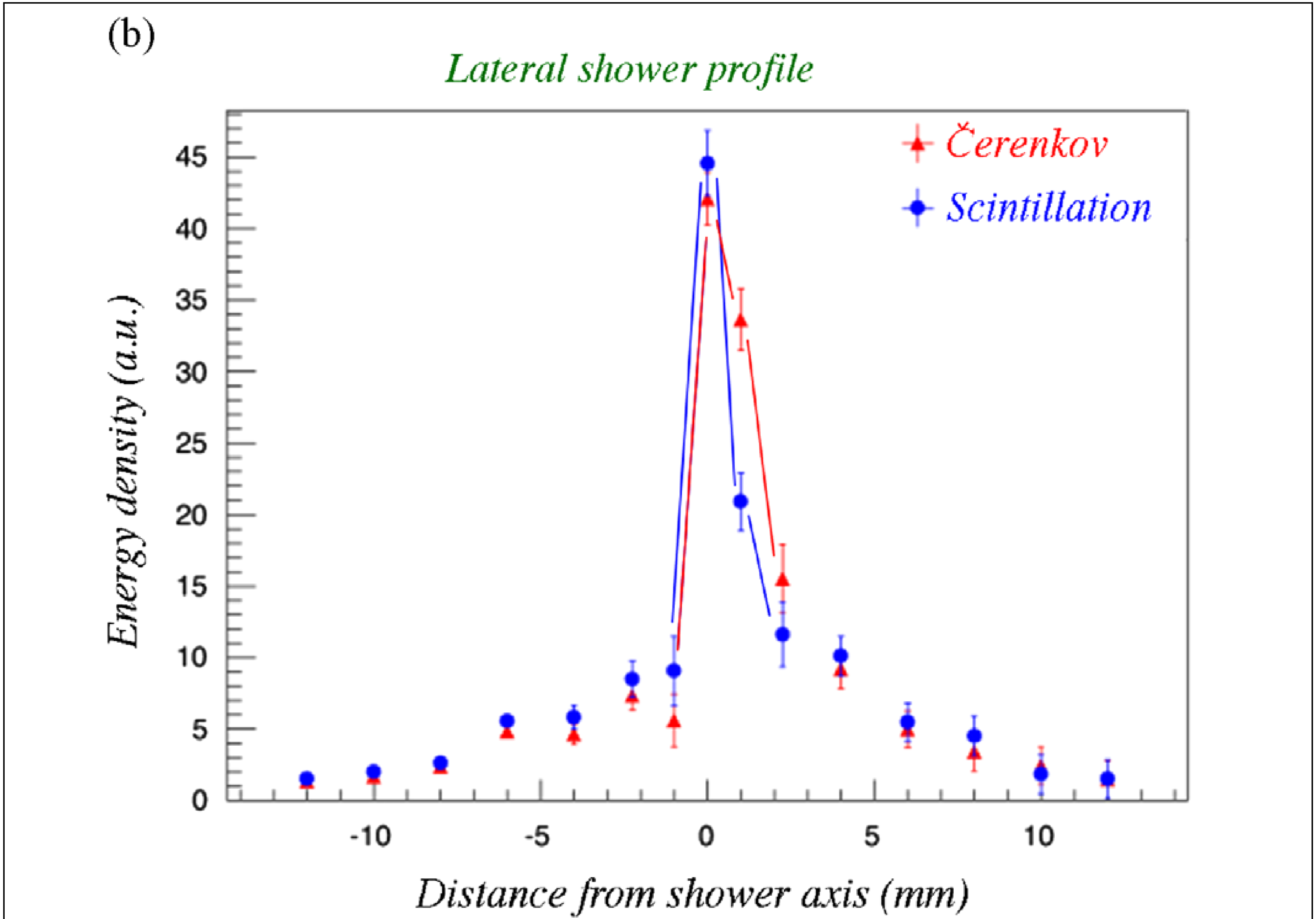
By the way, jet energy resolution is not as good as single pion in Pb, U Calorimeters

^{238}U/Plastic scintillator Calorimeter

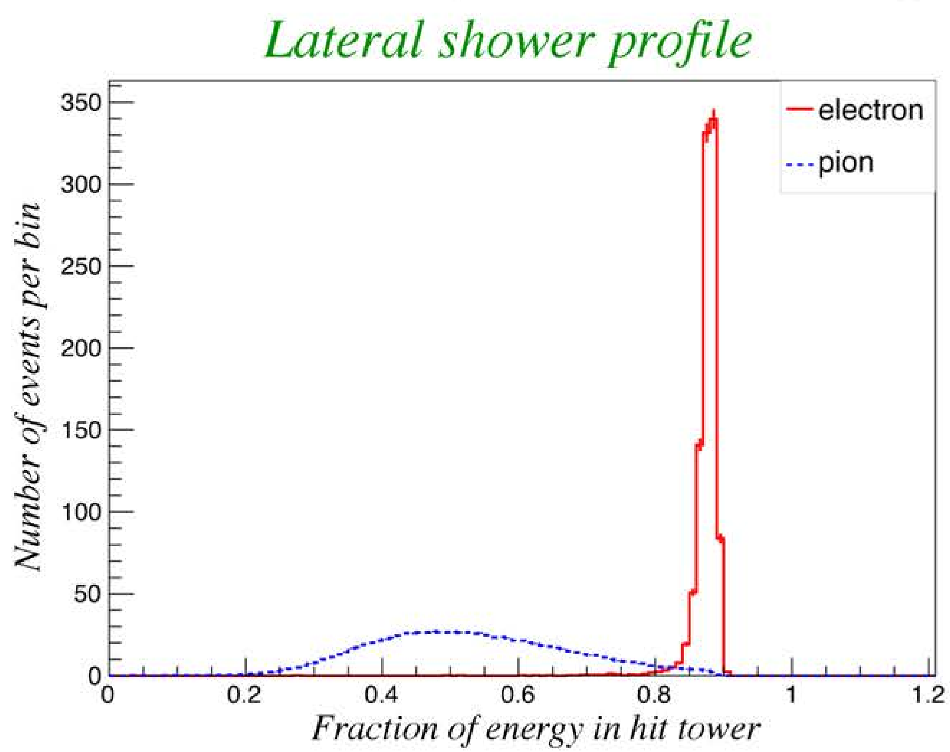


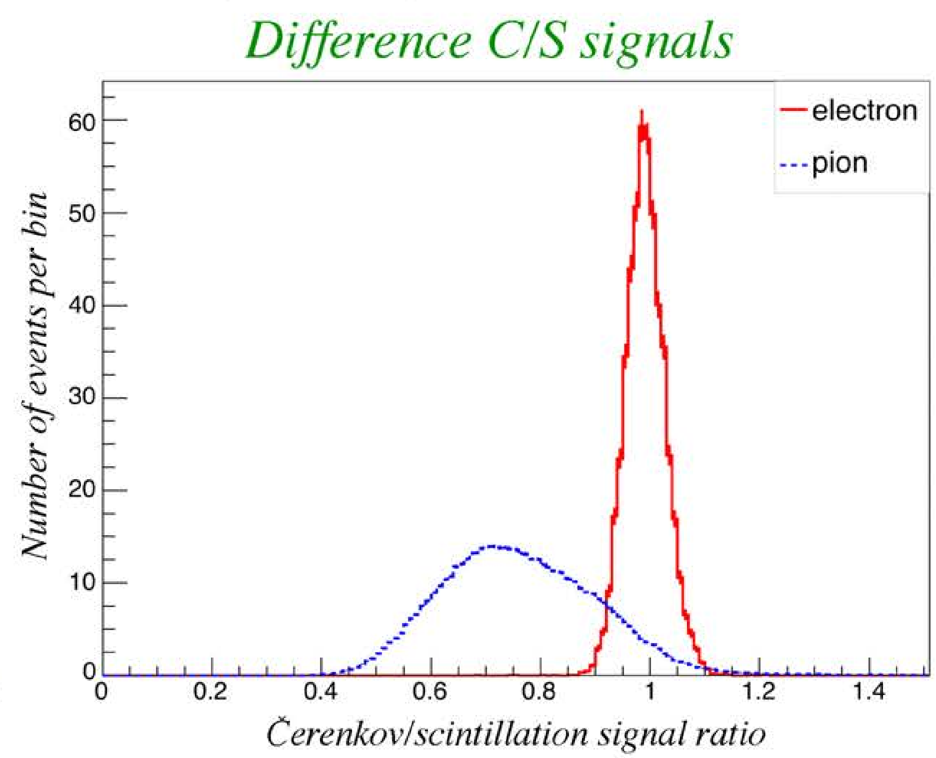
- Non-showering hadrons cause non-linear signal at low energy (<5 GeV)
- Many hadrons from quark, gluon fragmentation fall in the range of energy
- Copper is much better choice for an absorber material

Lateral shower profile of electrons

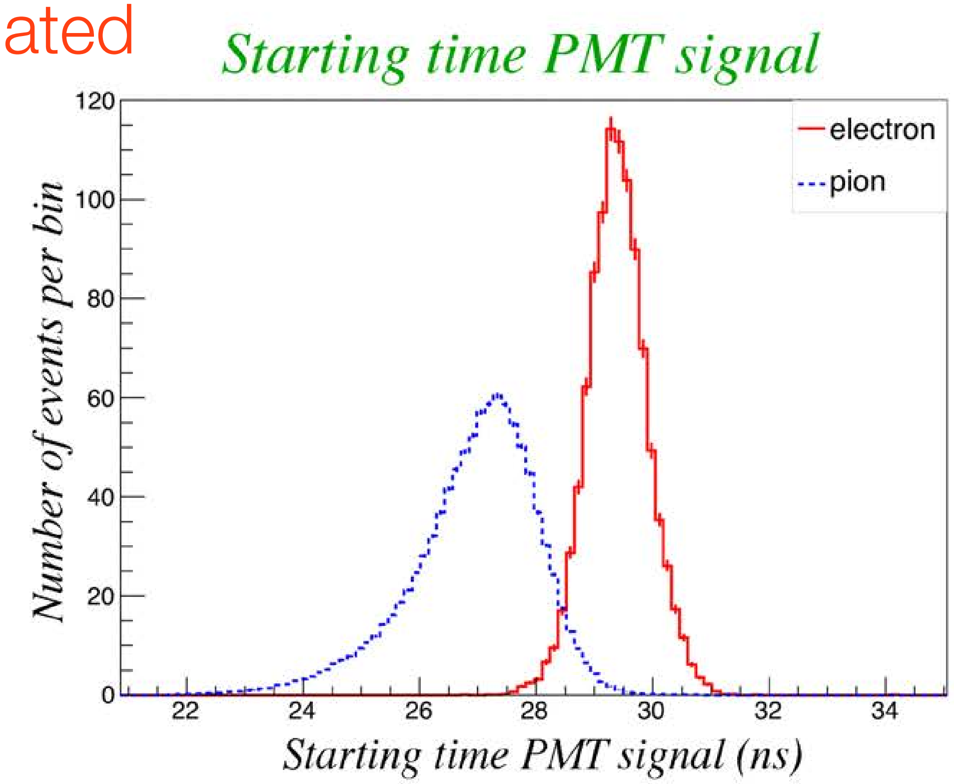


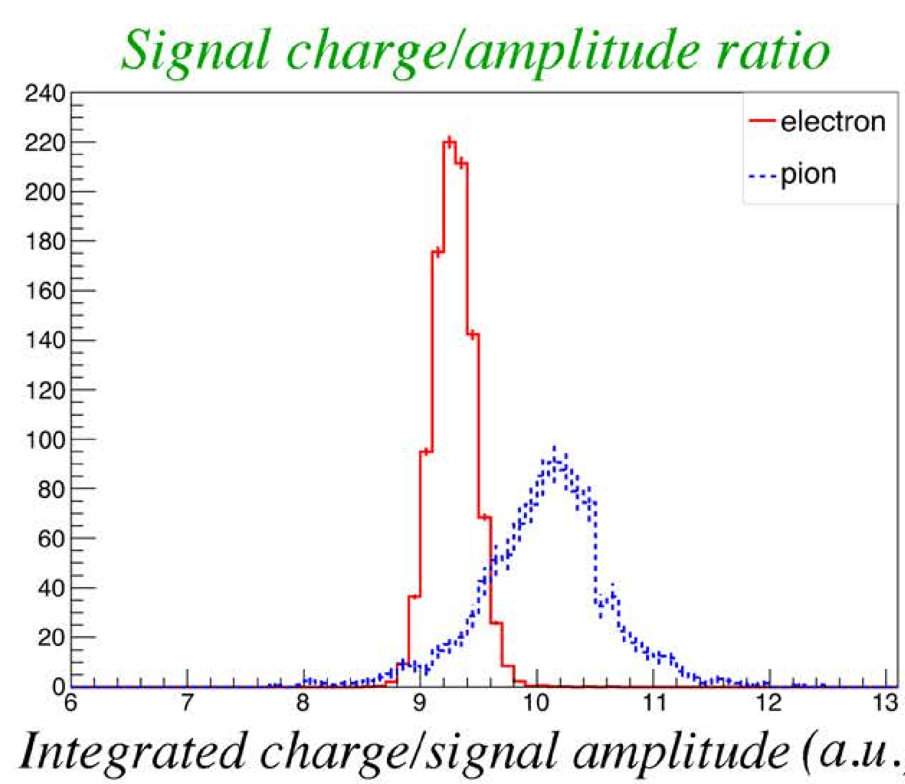
Particle ID (60 GeV)





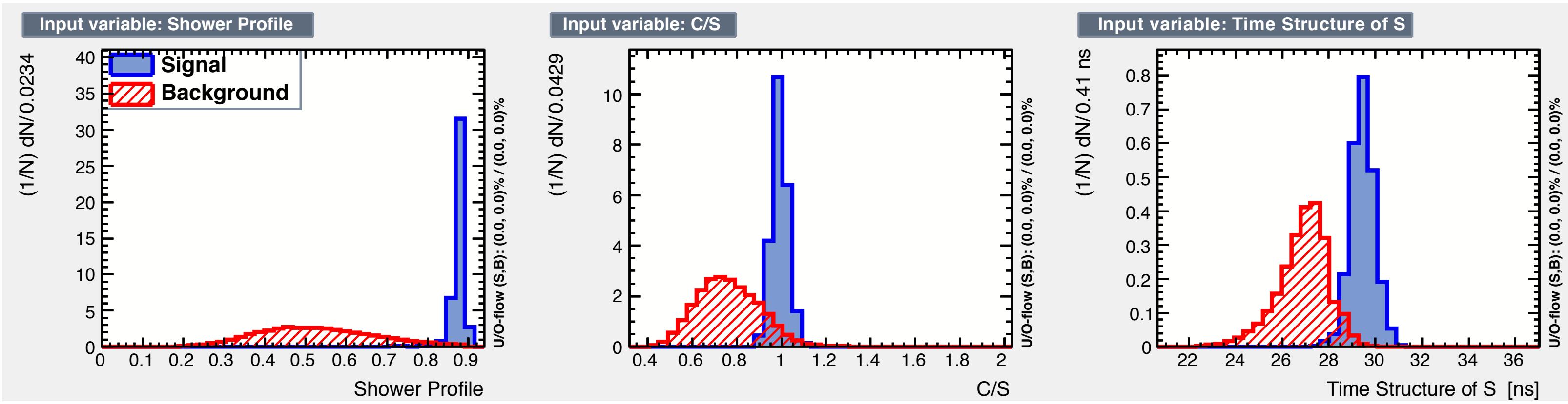
Uncorrelated



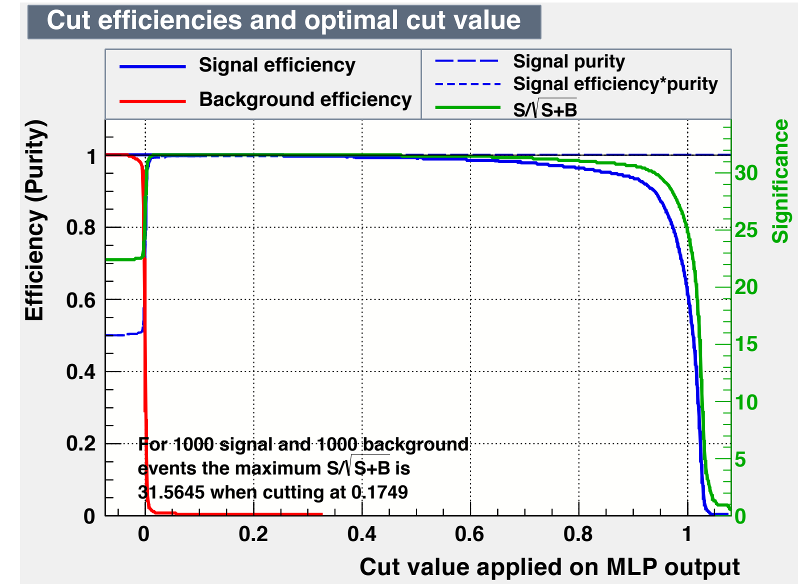


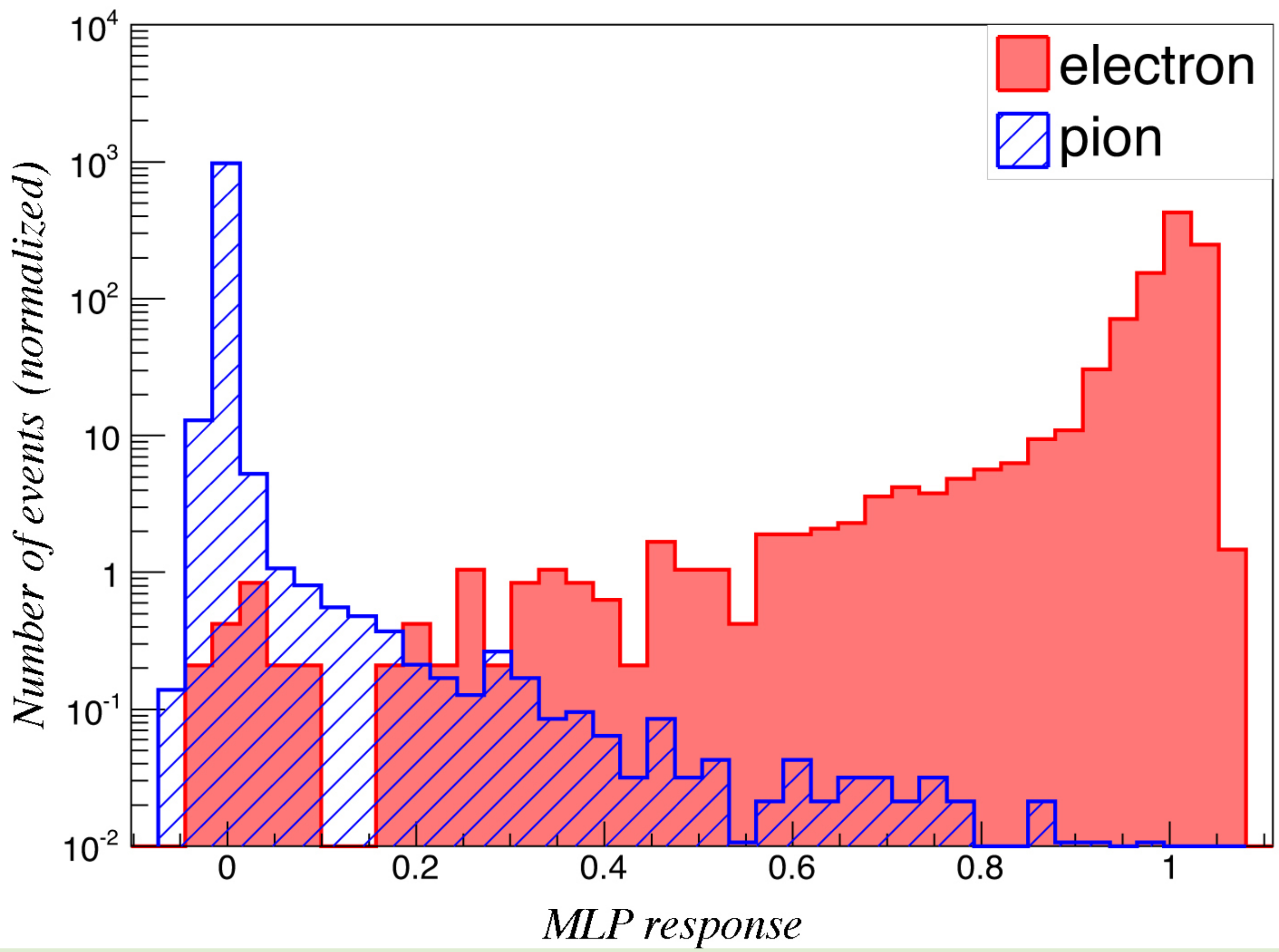
(Lateral shower profile > 0.7, t_s > 28.0 ns): 99.1 % electron ID, 0.5 % pion mis-ID

Input variables for 60 GeV e⁻ and π⁻



Optimal cut





99.8 % electron ID, 0.2 % pion mis-ID for MLP > 0.17

The limits of the hadronic energy resolution

Nuclear binding energy losses

↓

The Poor Performance of Hadron Calorimeter

Two approaches to improve the hadronic performance

1. Compensation

- *the total kinetic energy of neutrons*

2. Dual-Readout

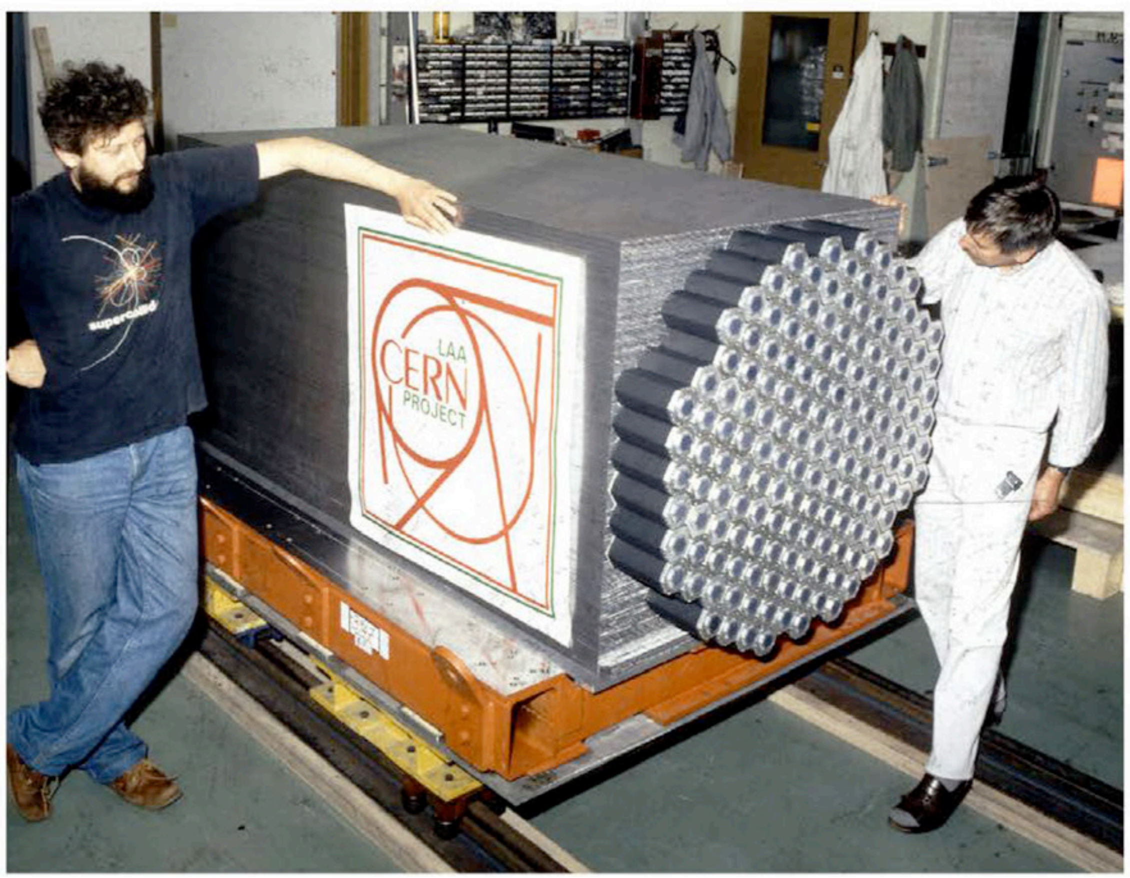
- *the electromagnetic shower fraction*

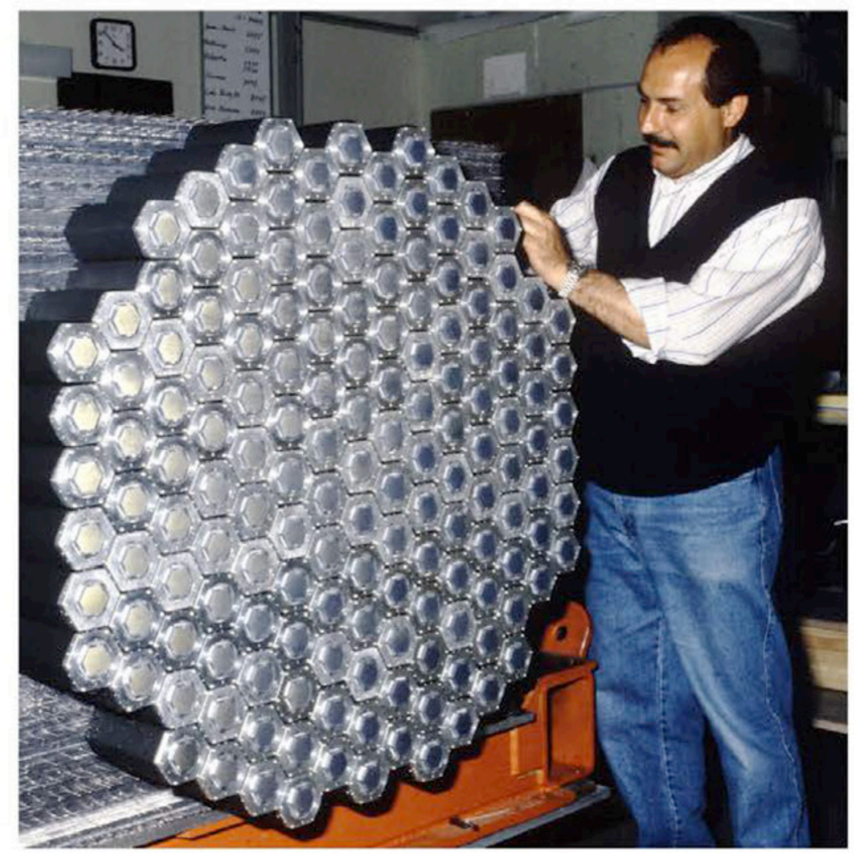
These are measurable quantities that are correlated to the binding energy losses

Compensation

Boosting the signal contributed by the MeV-type neutrons by means of adjusting the sampling fraction achieves e/h=1

SPACAL 1989





Pb - plastic fibers
(4:1 volume ratio)

Dual-Readout Calorimetry

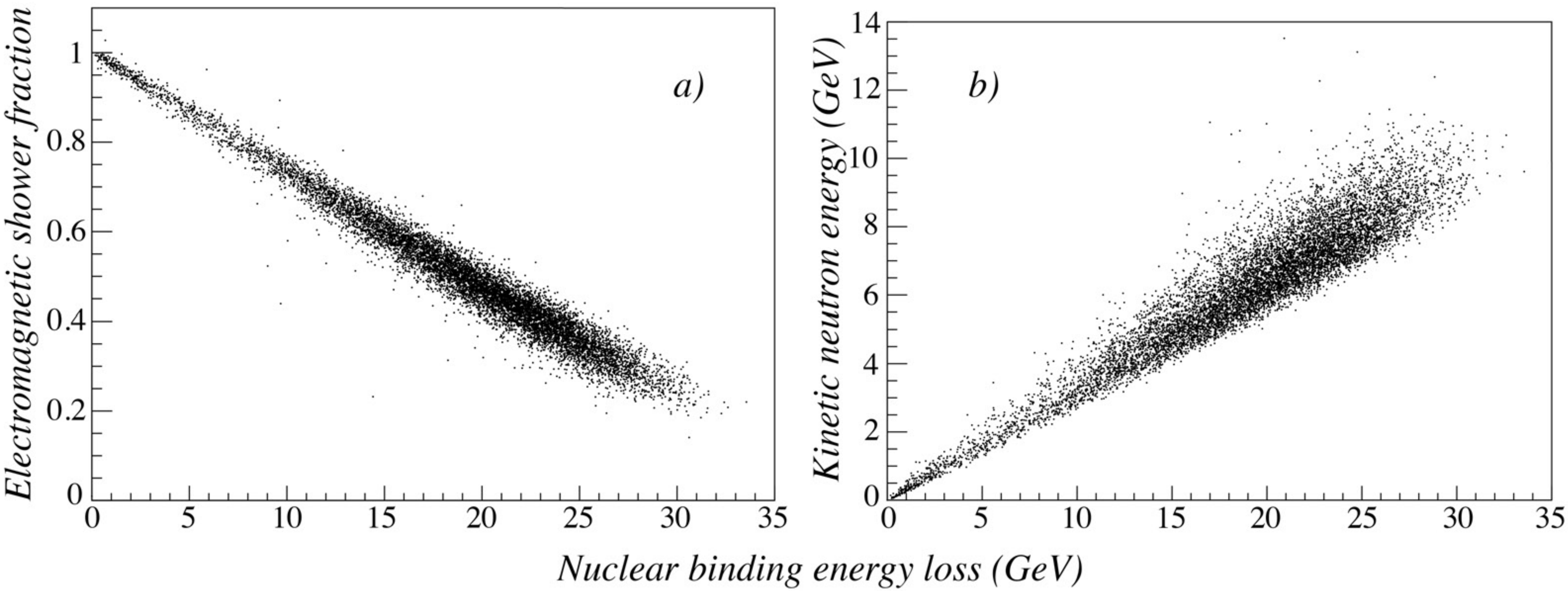
- Dual-readout method (DREAM)
  - The electromagnetic shower fraction is measured by means of comparing scintillation (dE/dx) and Cerenkov signals event by event. The fluctuations in f_{em} can be eliminated.

- e/h=1 can be achieved without the limitations
  - the small sampling fraction
  - a large detector volume
  - a long signal integration time

Prediction of the limits of the hadronic energy resolution

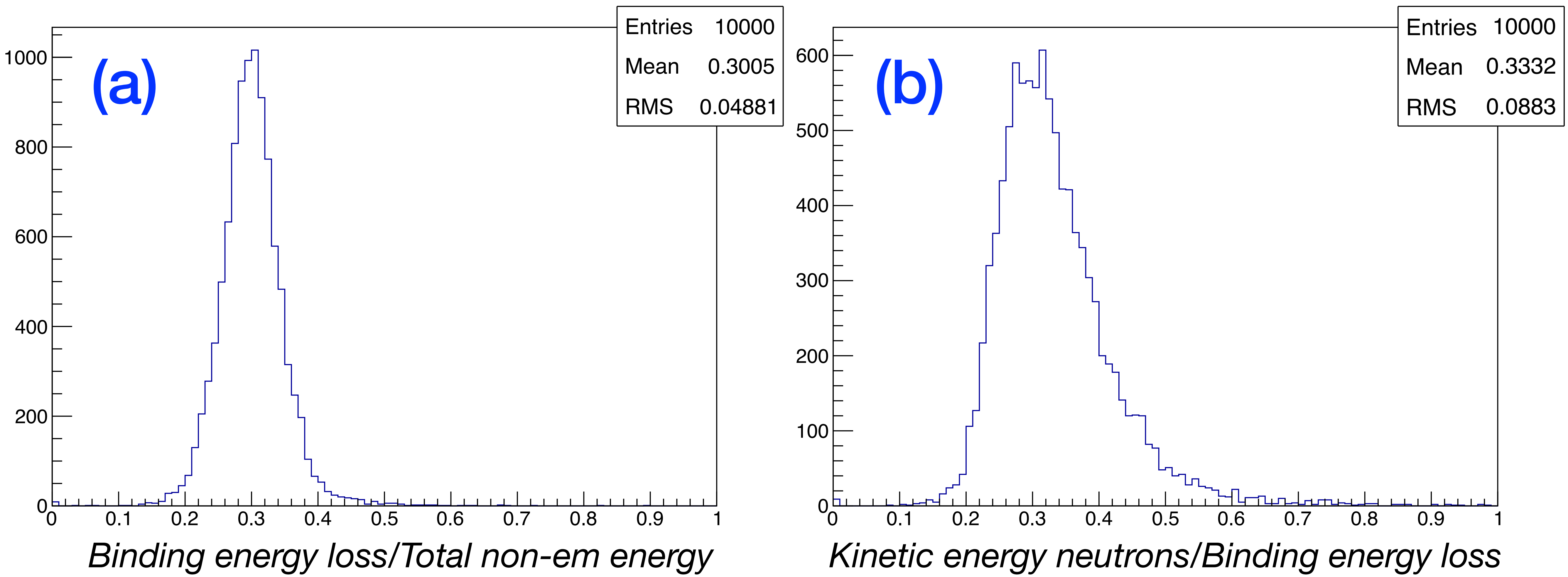
- GEANT 4.10.3-patch2
- FTFP_BERT physics list
- Very large absorber to contain the entire hadron shower
- 10, 20, 50, 100, 200, 500, 1000 GeV π^- sent to Cu and Pb (10,000 events)
- Obtained information in each event:
  - The em shower fraction
  - The total nuclear binding energy loss
  - The total kinetic energy of the neutrons

Correlation between binding energy loss and f_{em} (a) and kinetic energy of neutrons(b)



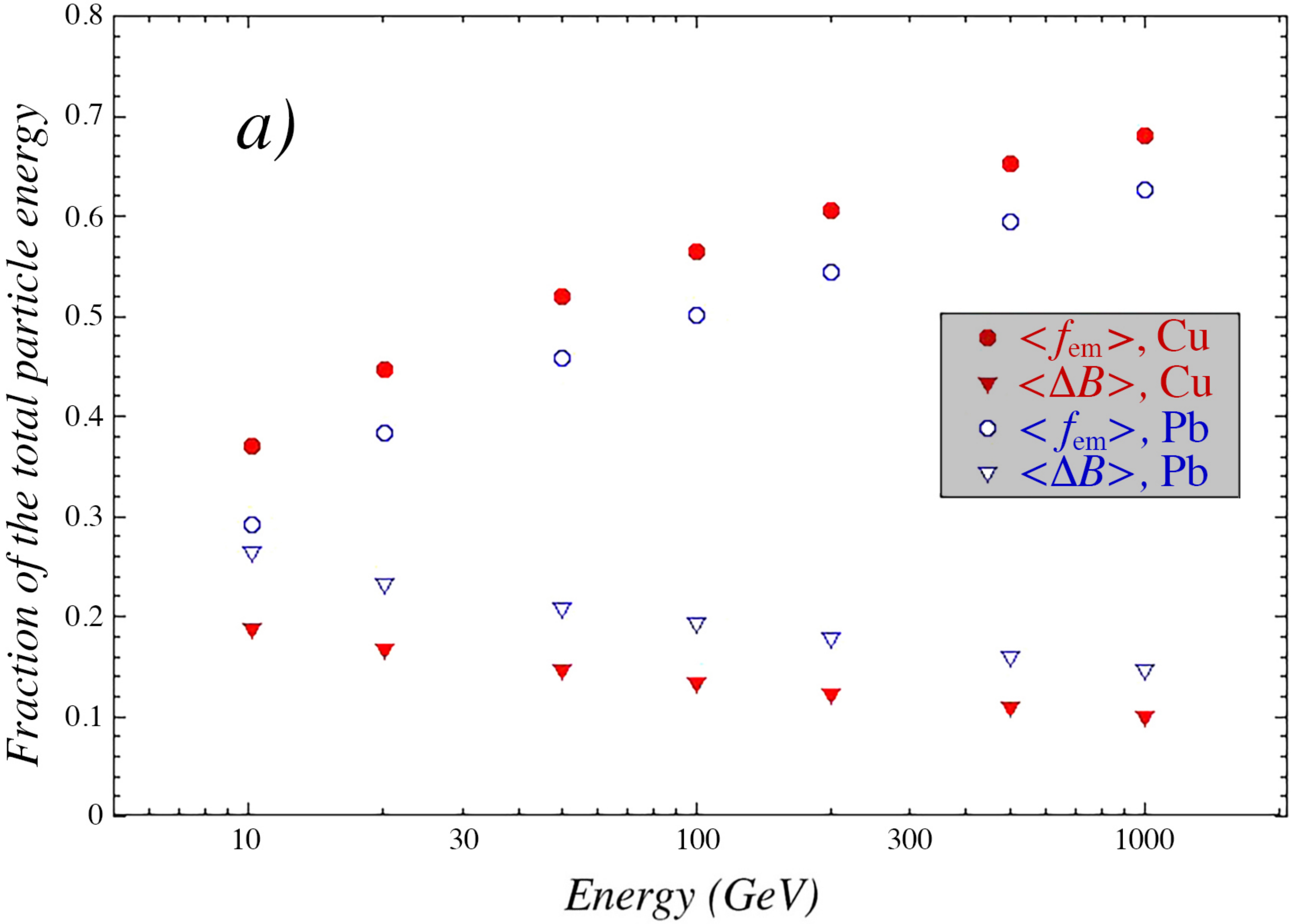
Results are for 100 GeV π- in lead absorber

Correlation between binding energy loss and non-em energy (a) and kinetic energy of neutrons(b)

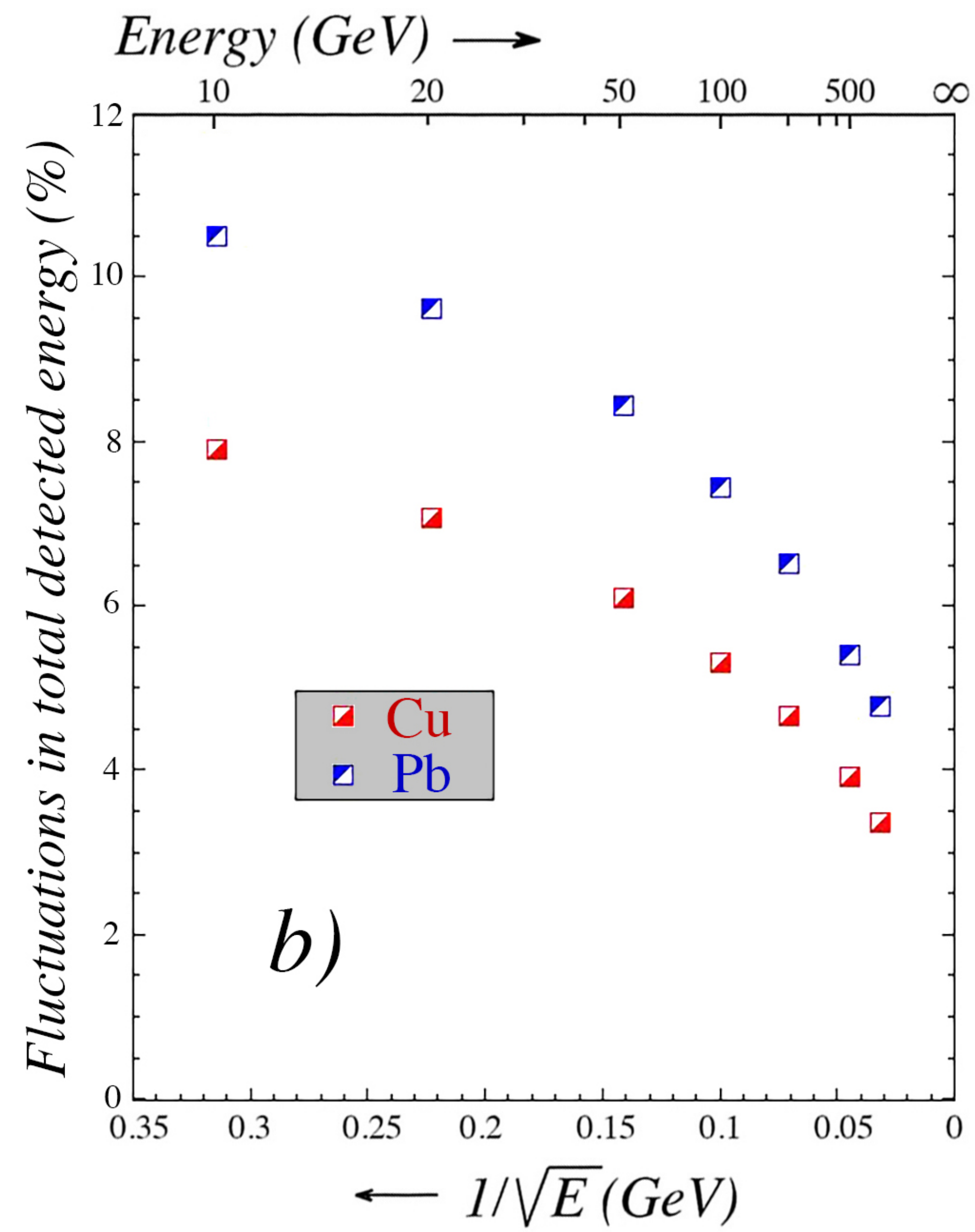


20 GeV π^- in copper

<EM Shower fraction> and <Binding Energy Loss>



Limit on the hadronic energy resolution in the absence of DR or compensation



Limits on the hadronic energy resolution