Dual-Readout Calorimetry

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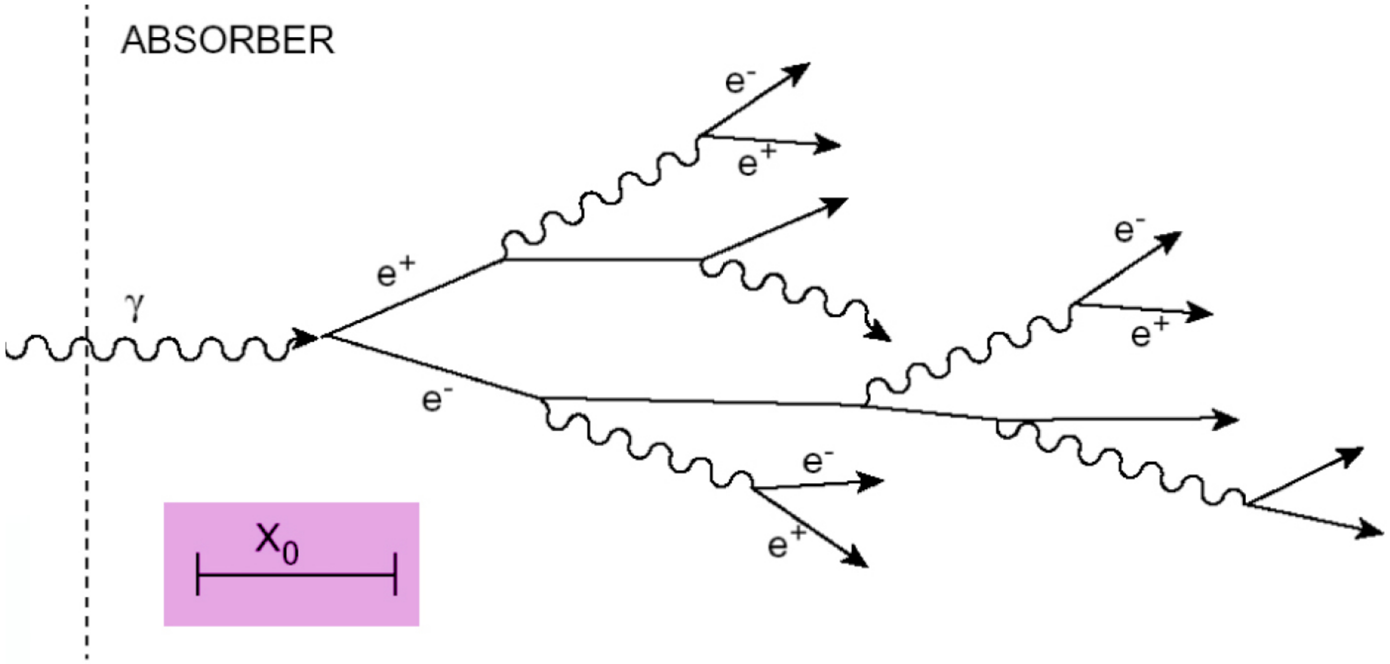
on behalf of RD52 collaboration

Topical Workshop on the CEPC Calorimetry
Institute of High Energy Physics, Beijing
March 13, 2019

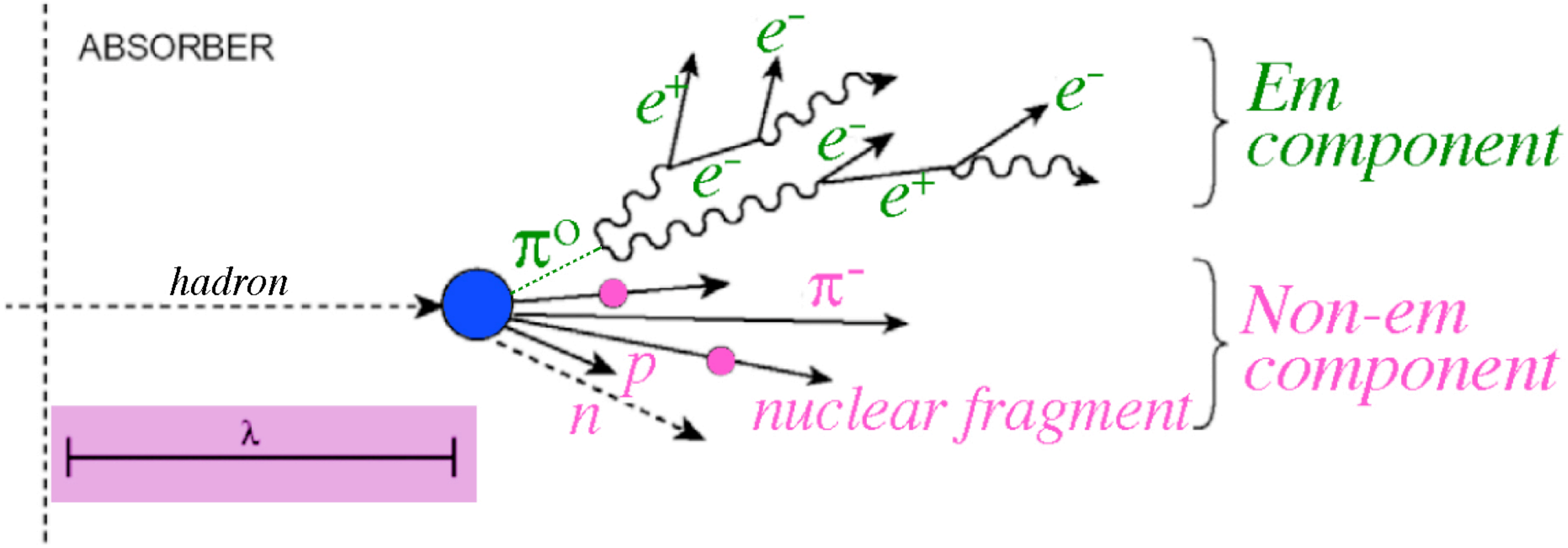
Electromagnetic Calorimeter



- 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

Hadron calorimeters are usually far from ideal

The Physics of Hadron Shower Development



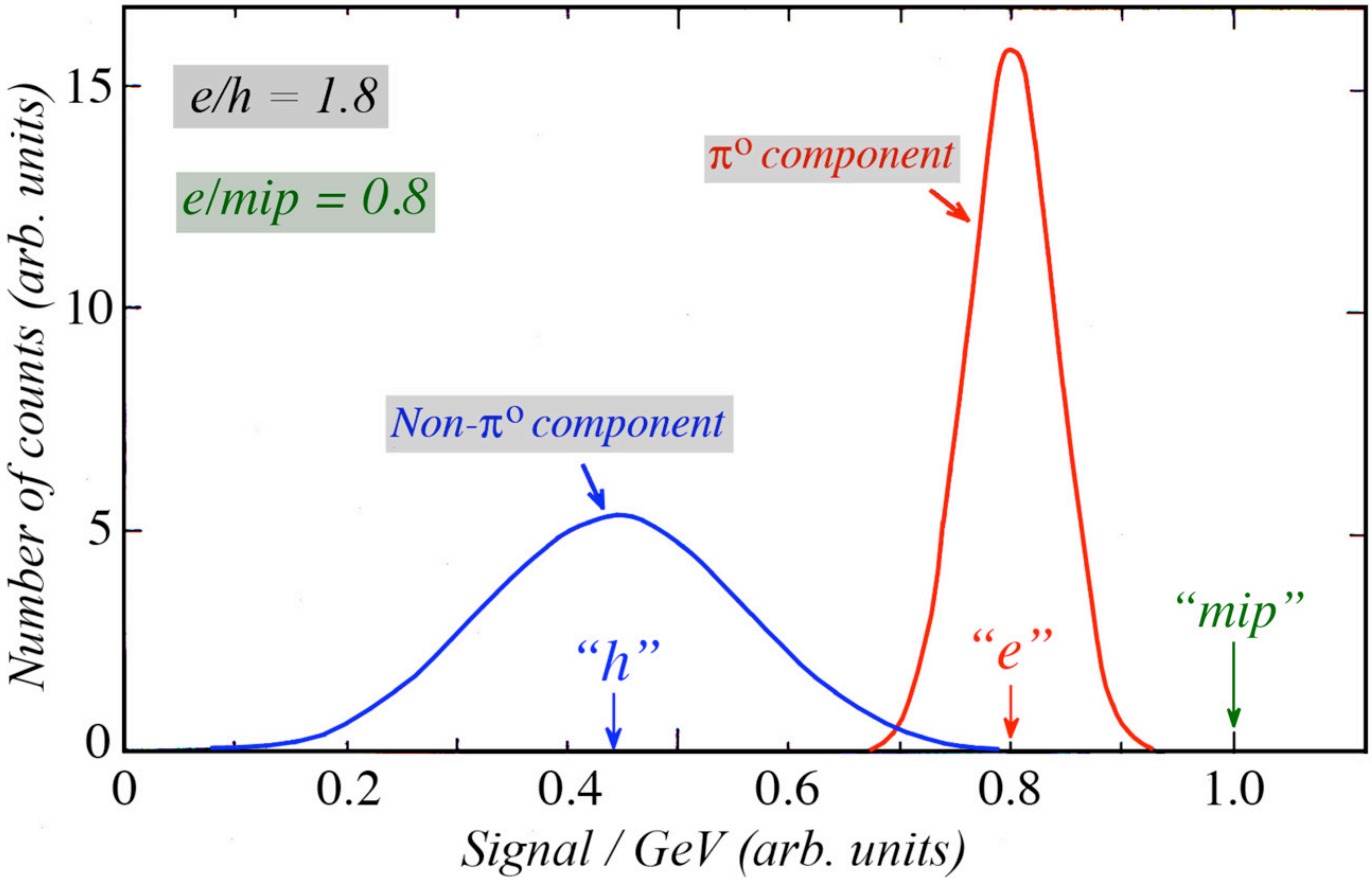
- **Electromagnetic component**
  - electrons, photons
  - neutral pions → 2 γ

- **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***

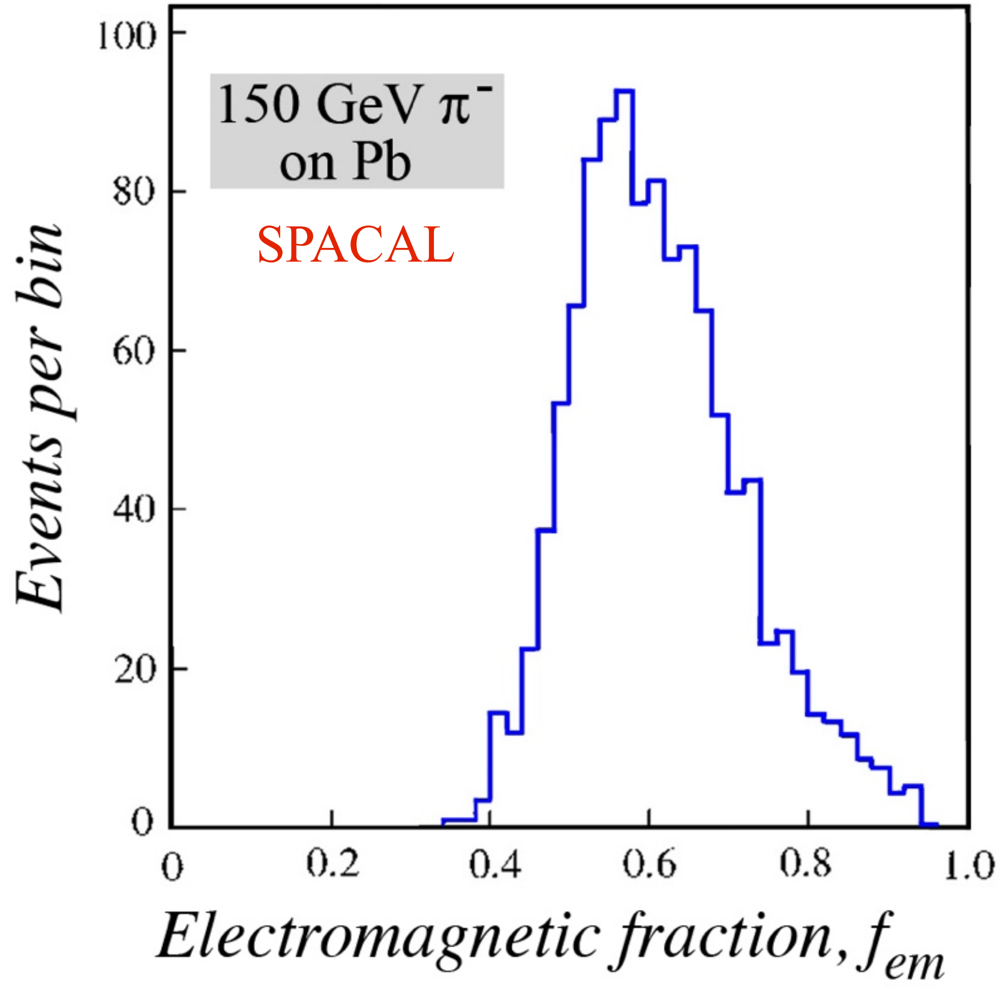
The Calorimeter Response

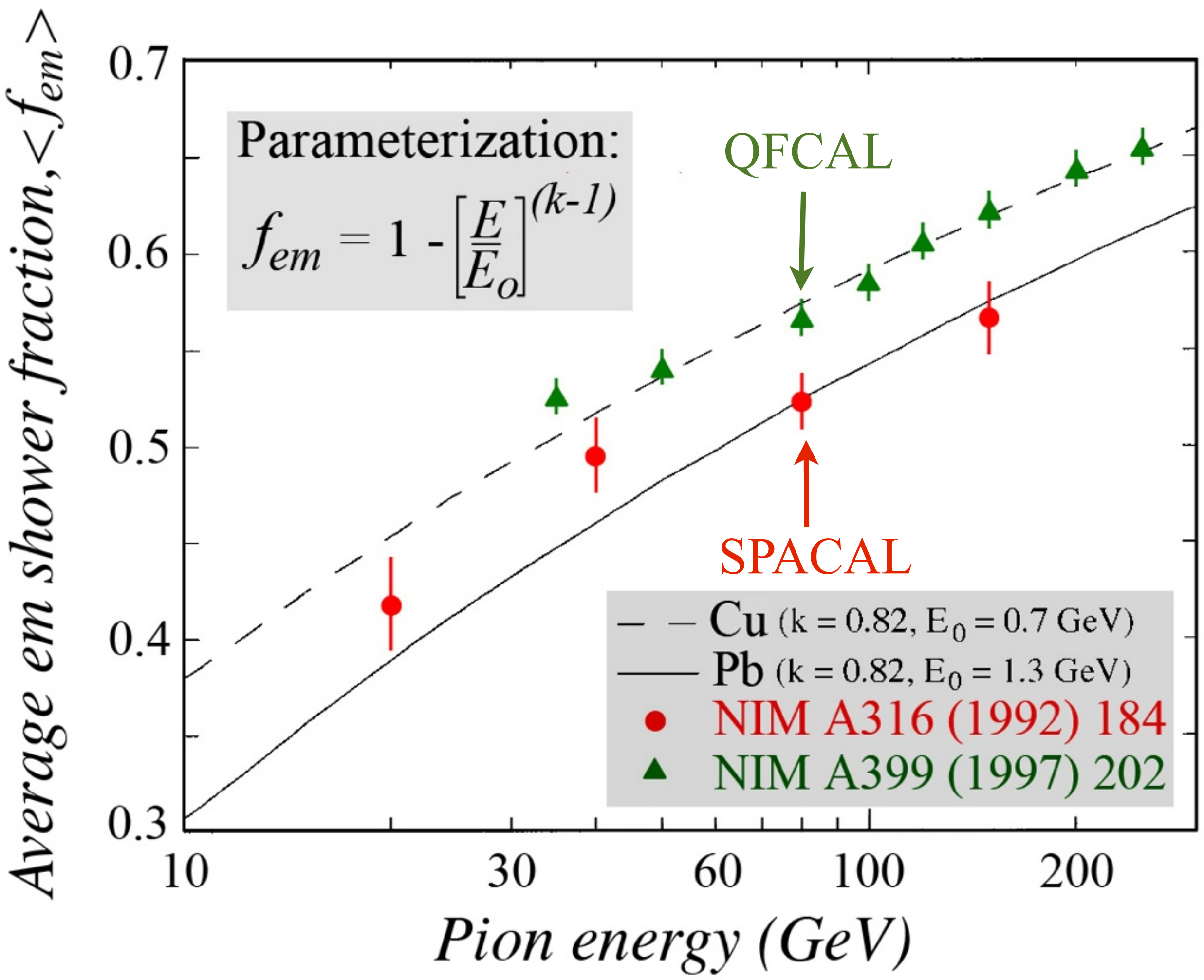


The calorimeter responses to the em and non-em components of hadron showers

Fluctuations of electromagnetic shower fraction

NIM A316(1992) 184





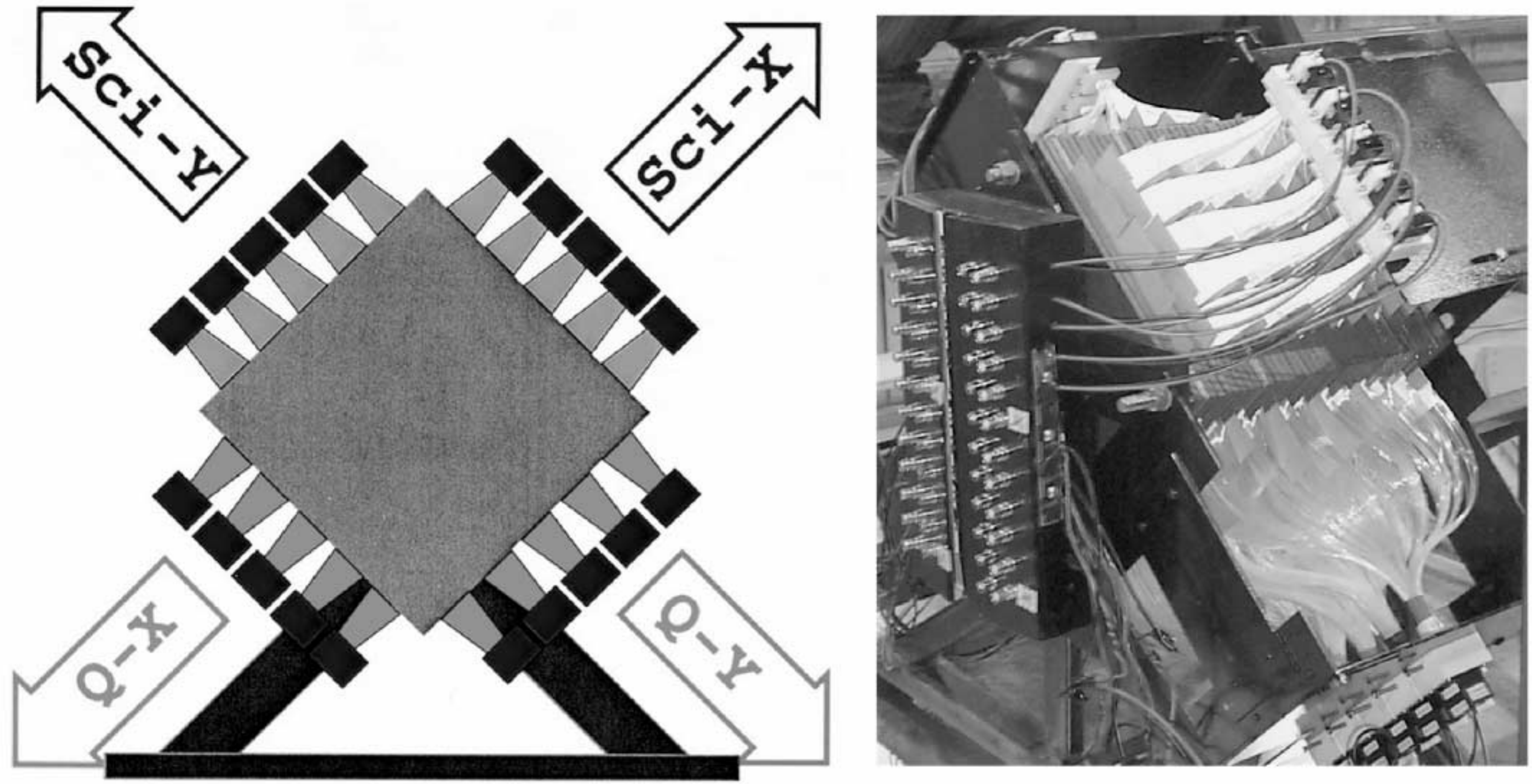
Large, non-Gaussian fluctuations in f_{em}

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

ACCESS

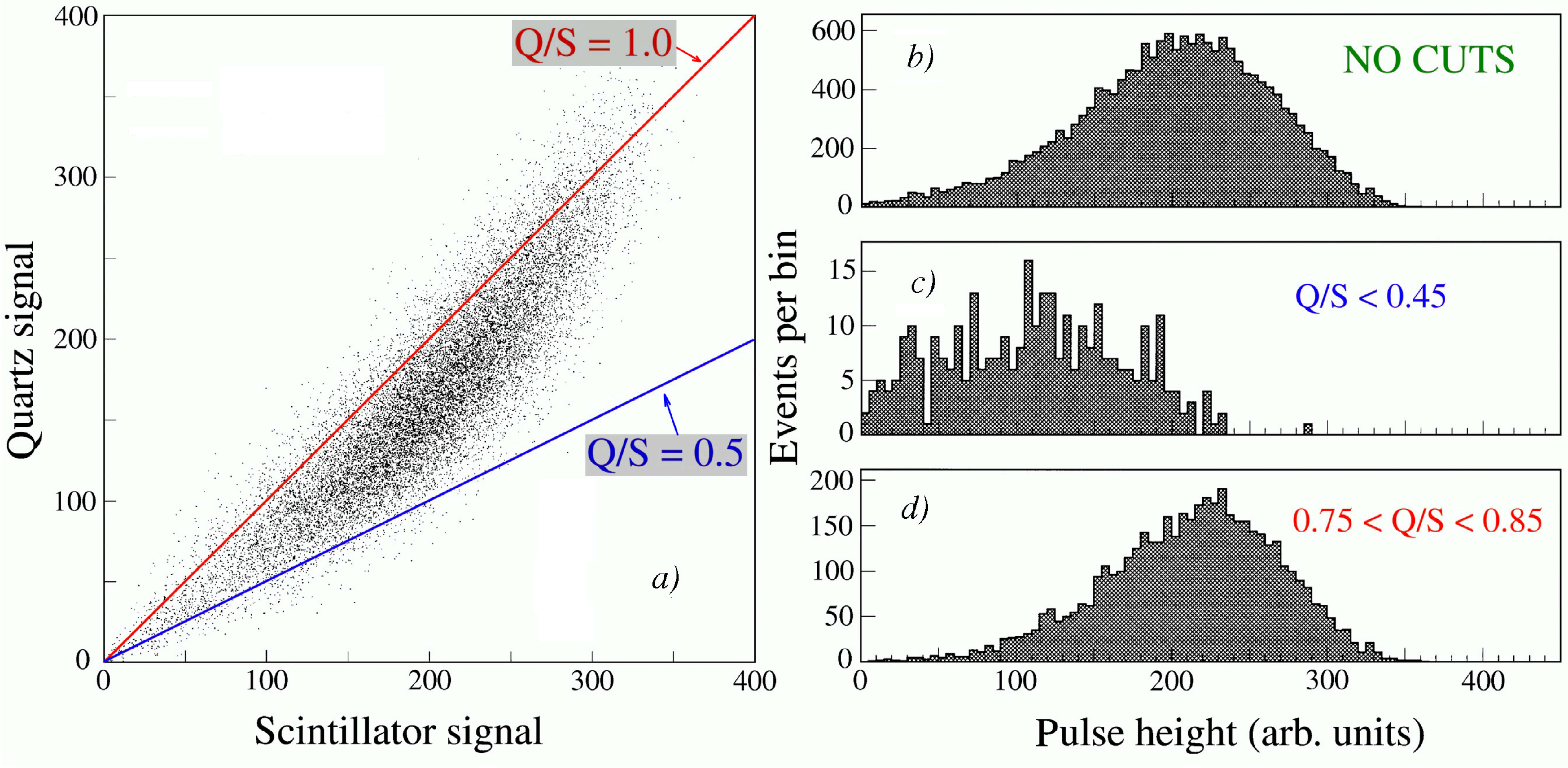
- High-energy cosmic-ray experiment for the International Space Station
- The application of the complementary information from scintillation and Cerenkov light
- Thickness: less than 2 λ_{int}
- The prototype consists of a 1.4 λ_{int} deep lead absorber and two types of optical fibers (scintillation 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



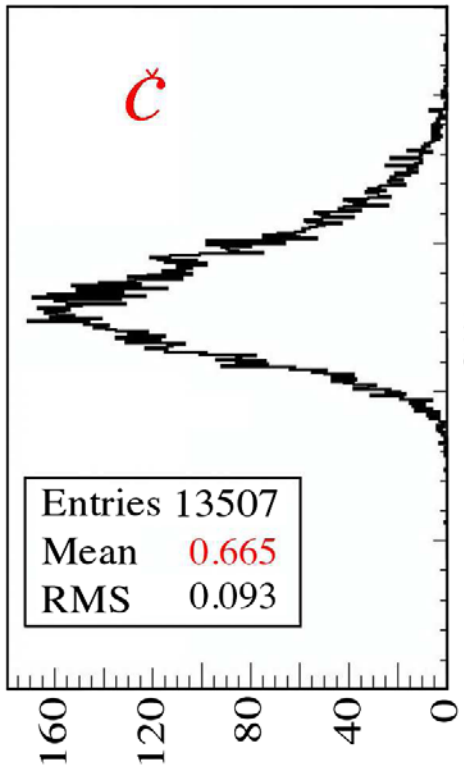
Thin lead plates were interleaved with 4 cm wide ribbons of scintillating and Cerenkov fibers

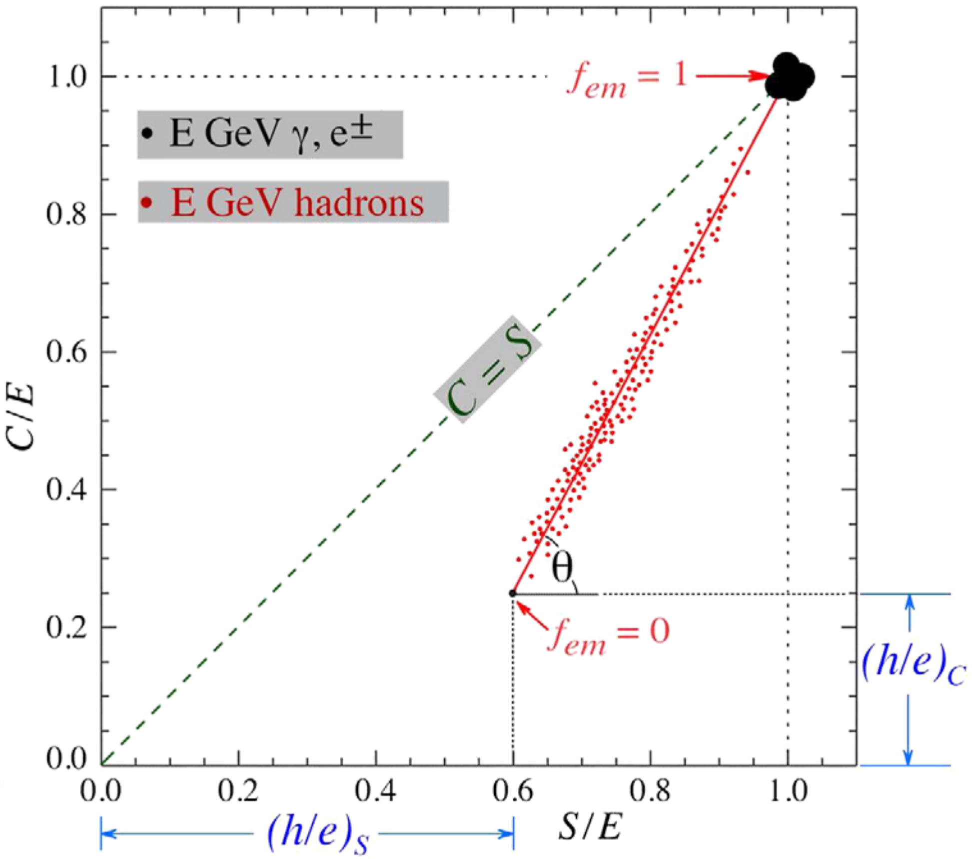
ACCESS

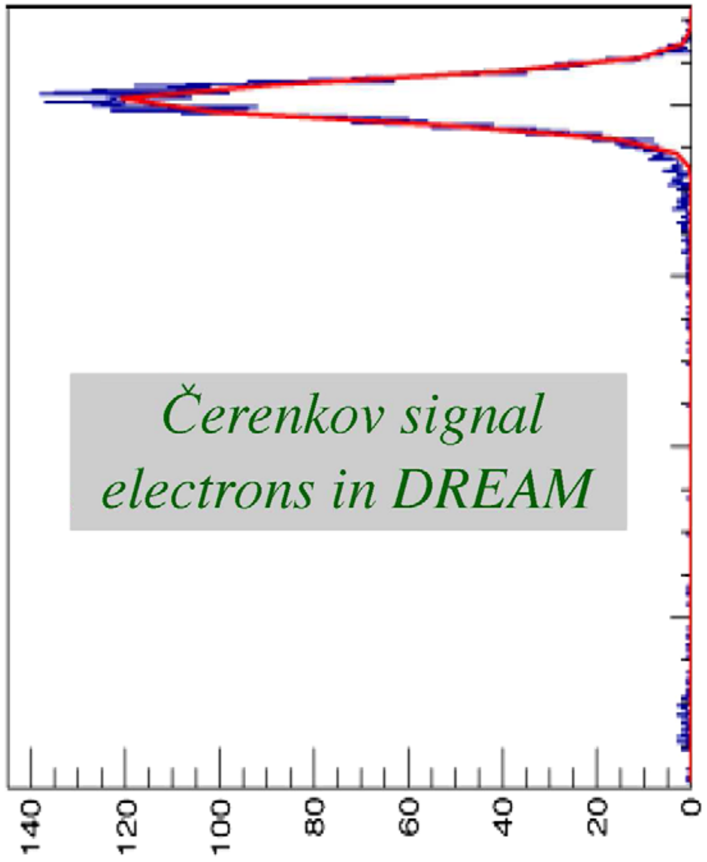


Q/S = 1.0
Q/S = 0.5
Quartz signal
Scintillator signal
a)
0
100
200
300
400
b)
NO CUTS
600
c)
Q/S < 0.45
15
10
5
d)
0.75 < Q/S < 0.85
150
50
Events per bin
Pulse height (arb. units)

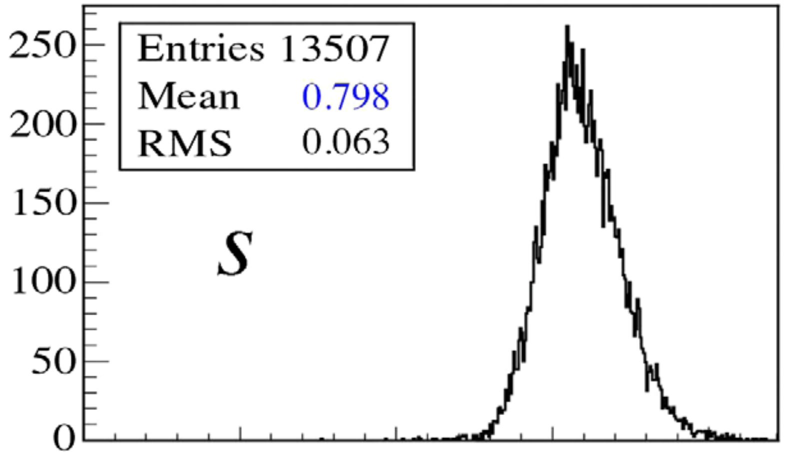
Dual-Readout Method (1)







200 GeV "jets" in DREAM



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

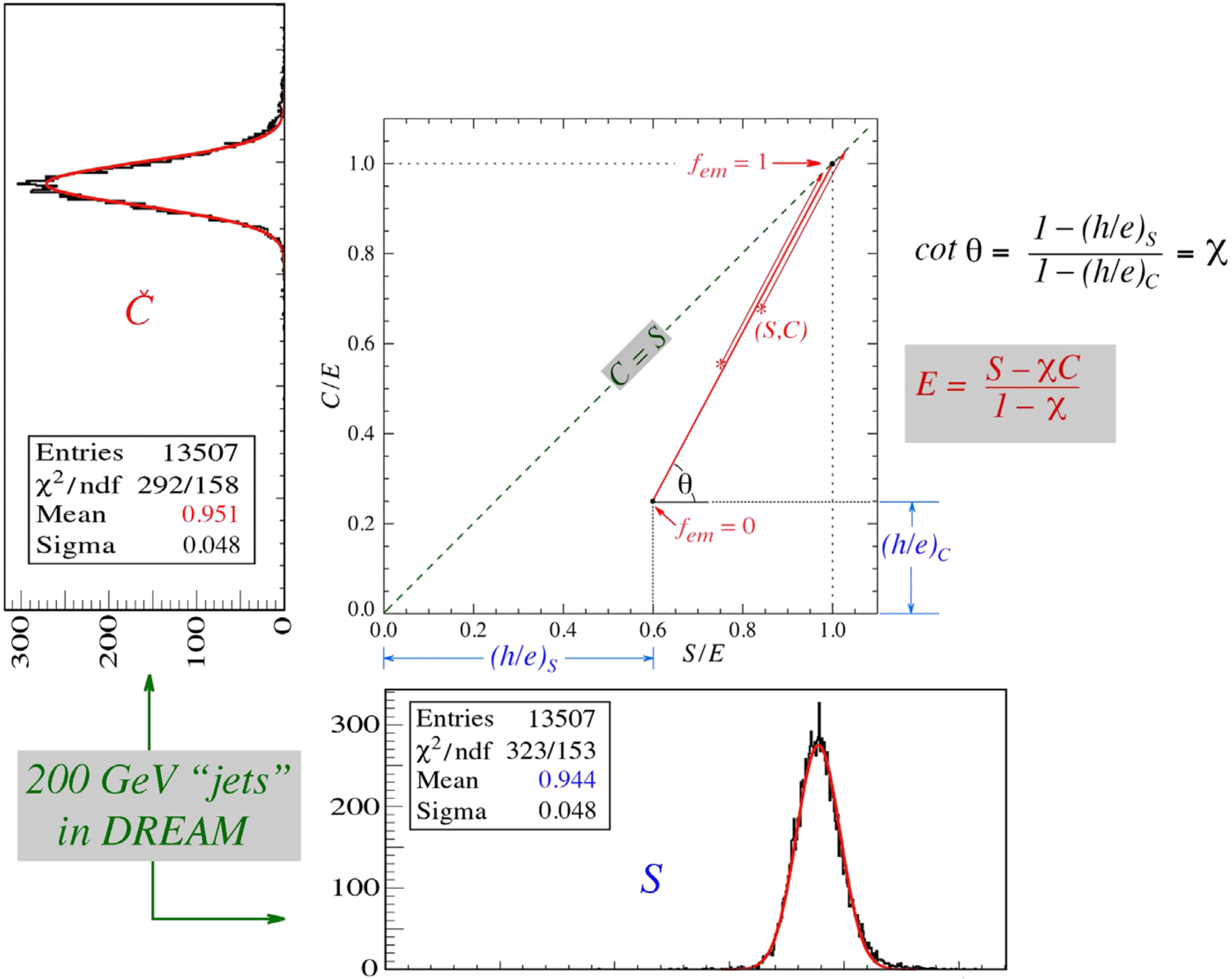
$$C = E\left[f_{\mathrm{em}} + \frac{1}{(e/h)_C}(1 - f_{\mathrm{em}})\right]$$

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

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

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

Dual-Readout Method

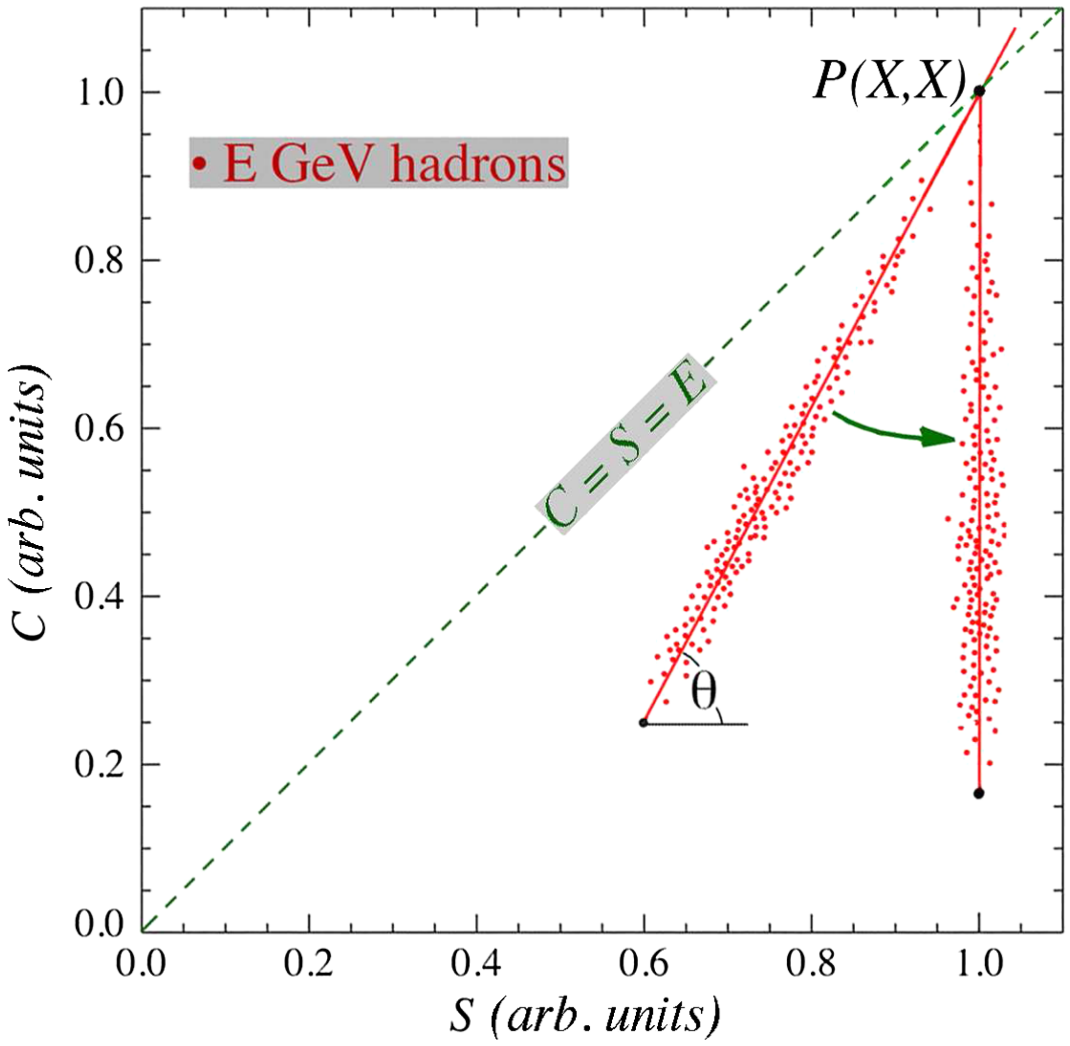


200 GeV "jets" in DREAM

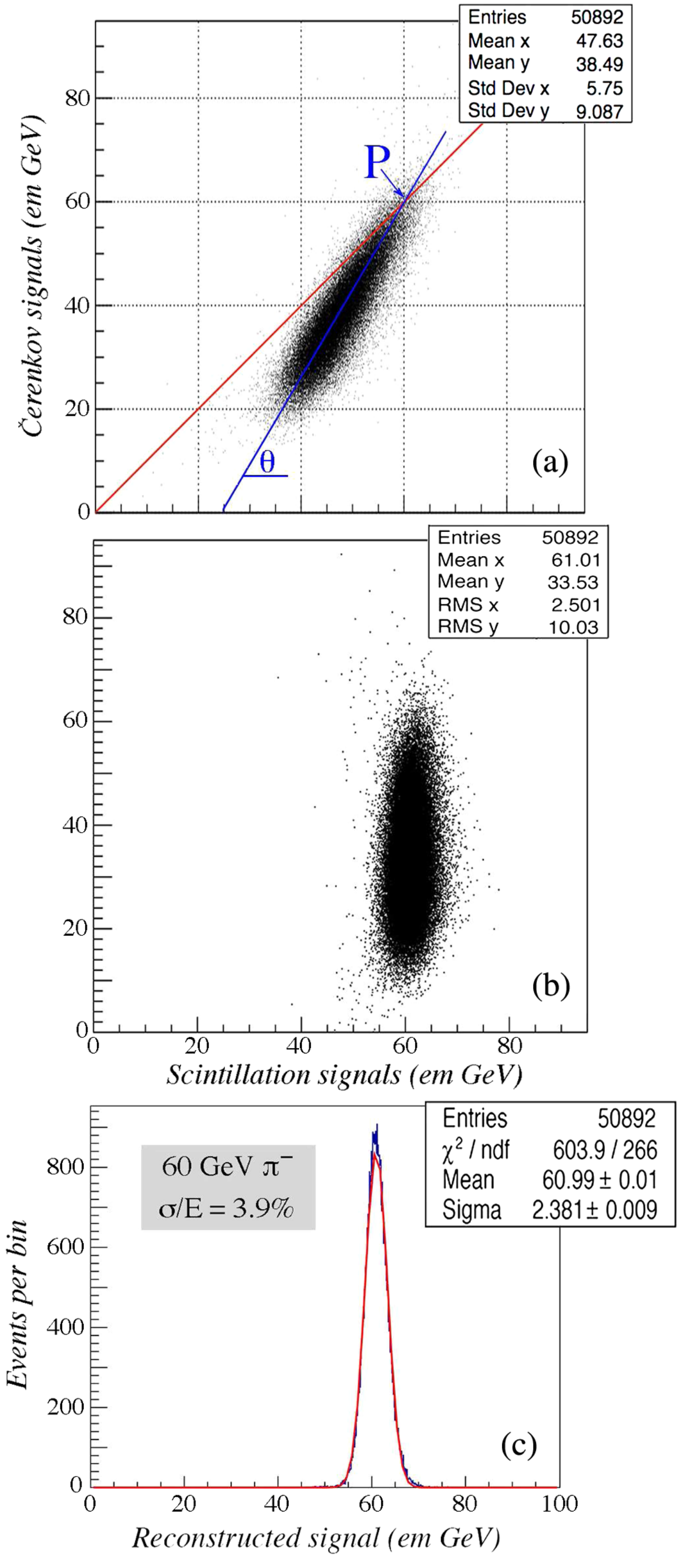
$$\cot\theta = \frac{1-(h/e)_S}{1-(h/e)_C} = \chi$$

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

Rotation Method



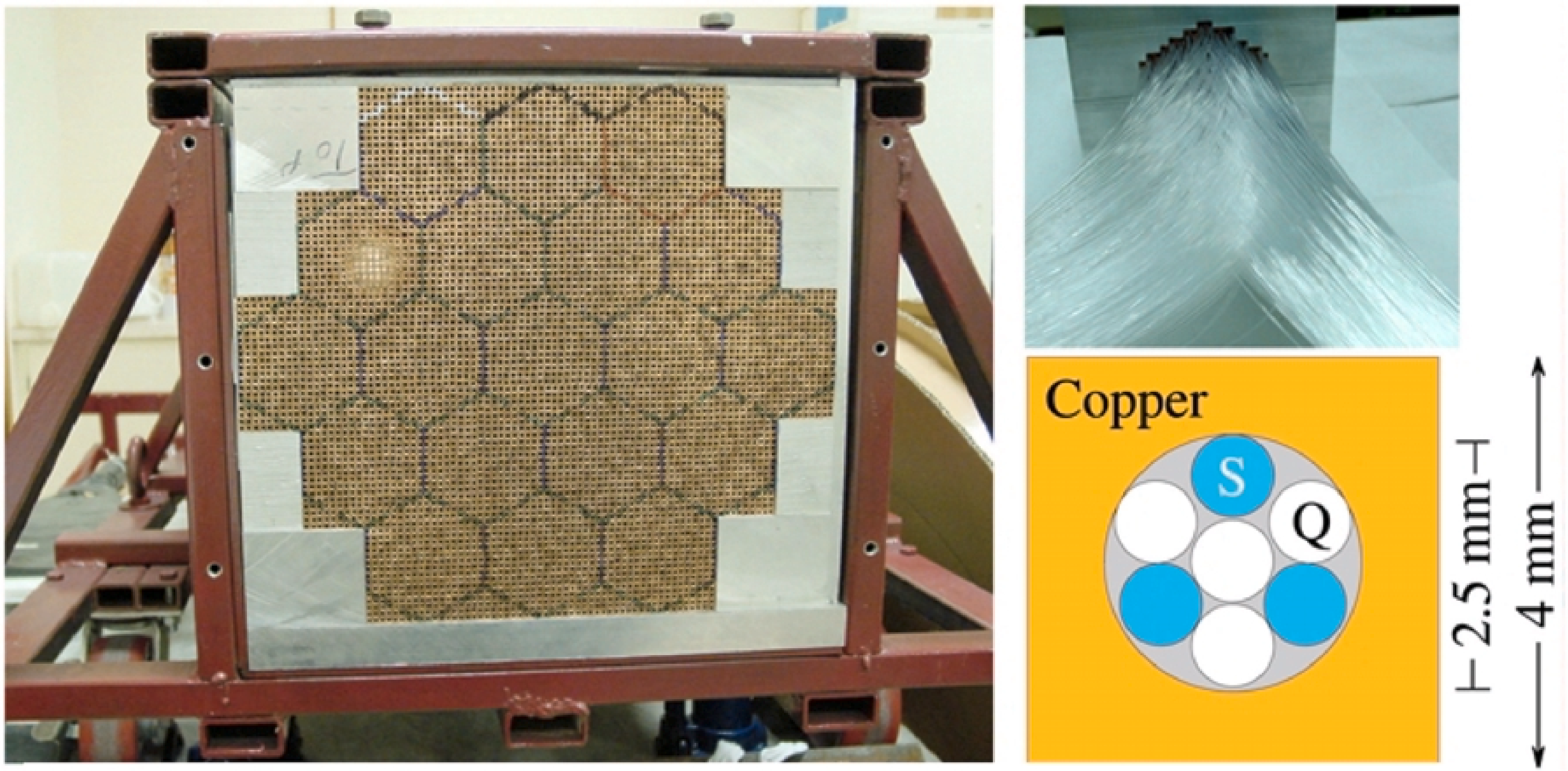
$$\begin{pmatrix} S' \\ C' \end{pmatrix} = \begin{pmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{pmatrix} \begin{pmatrix} S \\ C \end{pmatrix}$$



Hadronic Performance

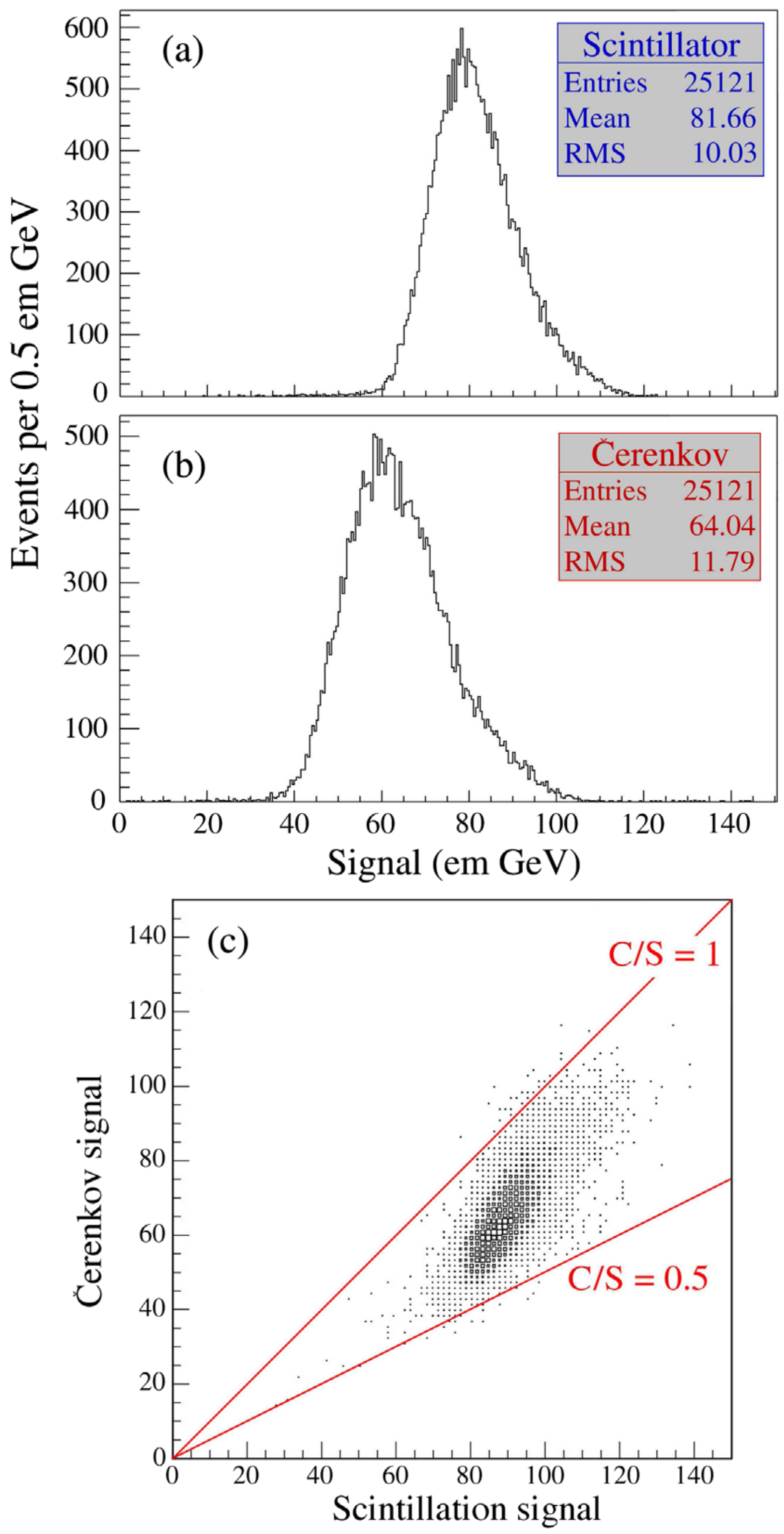
Prototype Dream Calorimeter

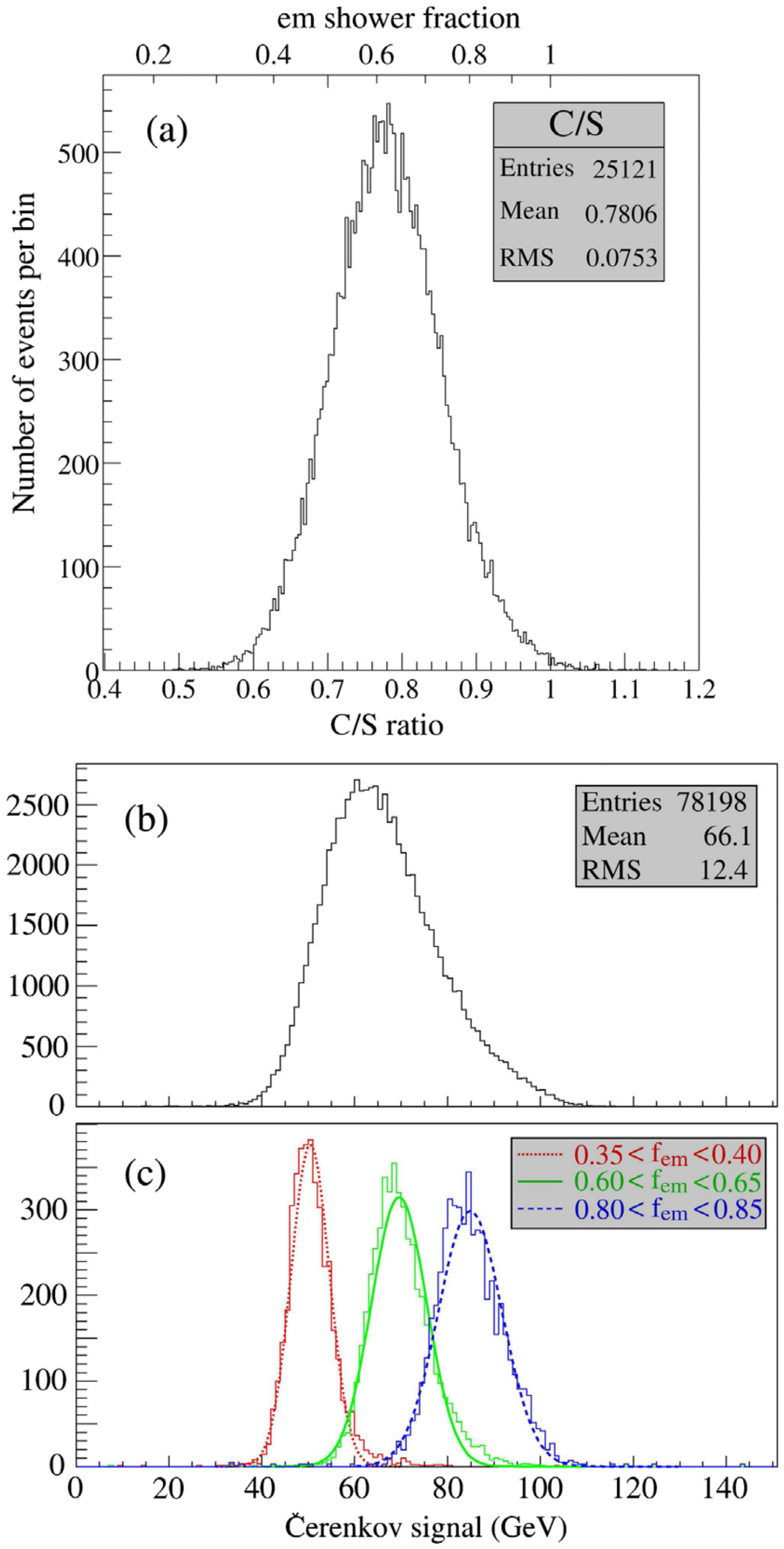
DREAM: Structure



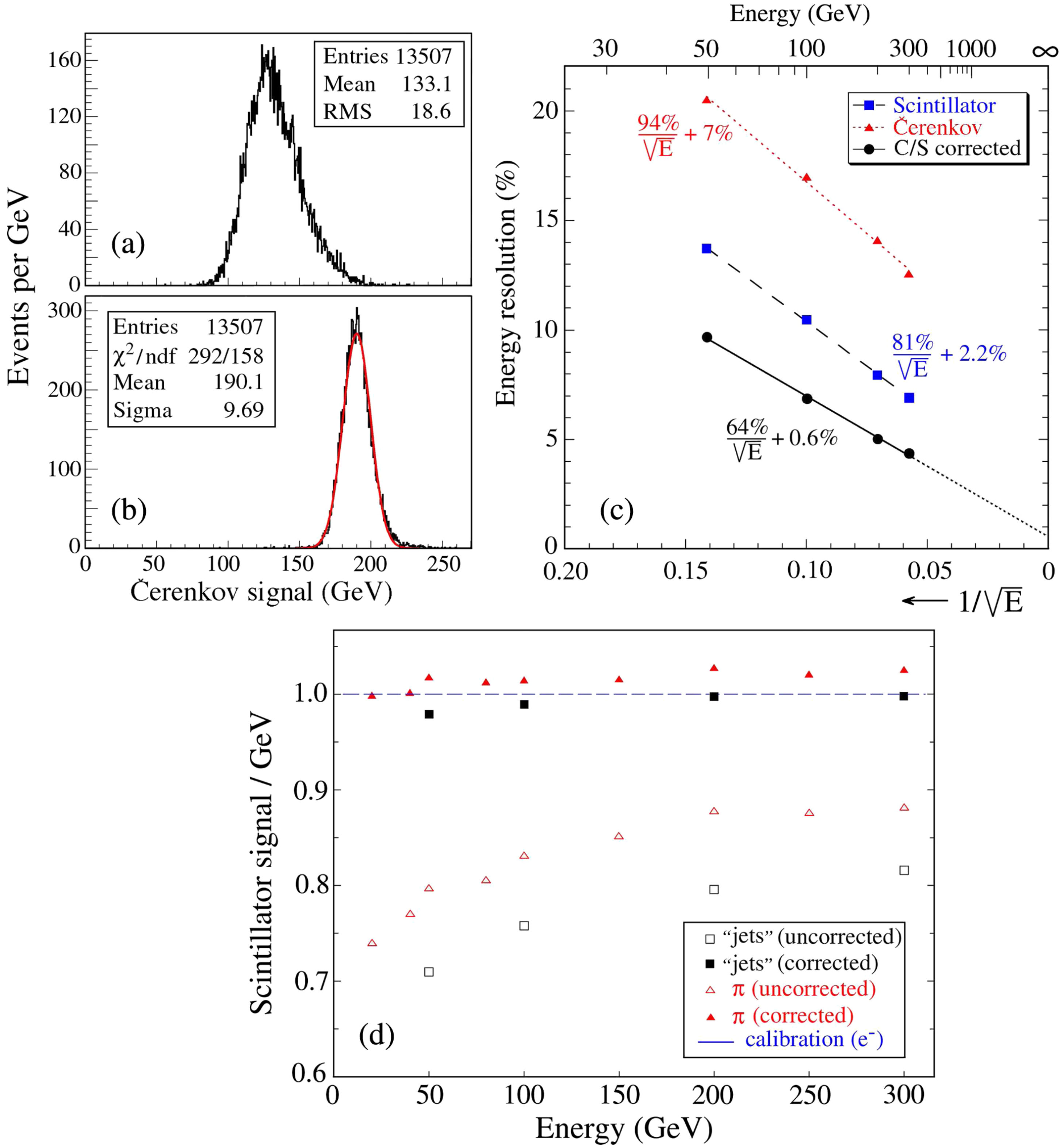
- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

Prototype Dream Calorimeter (100 GeV π)

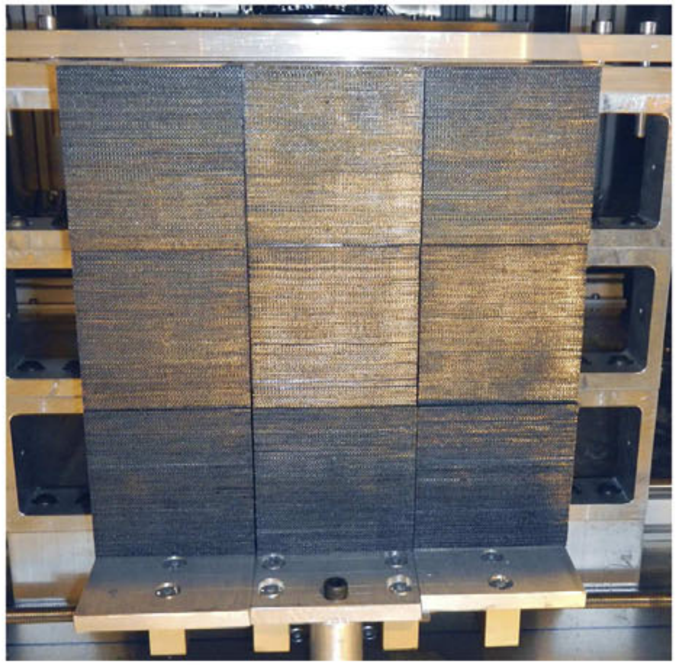


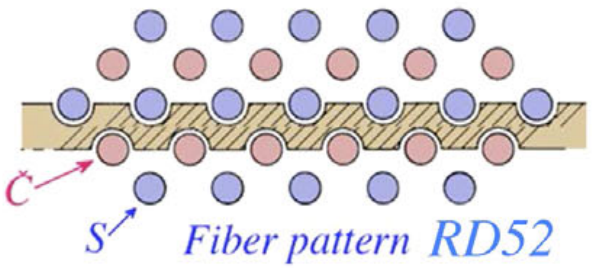


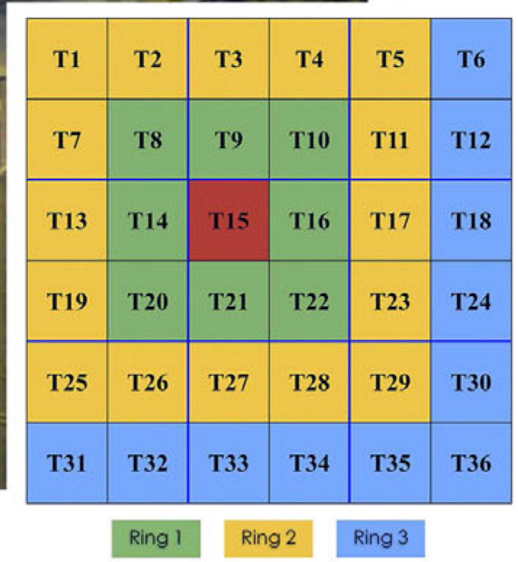
Prototype Dream Calorimeter (200 GeV jets)



RD52 Pb-fiber Calorimeter

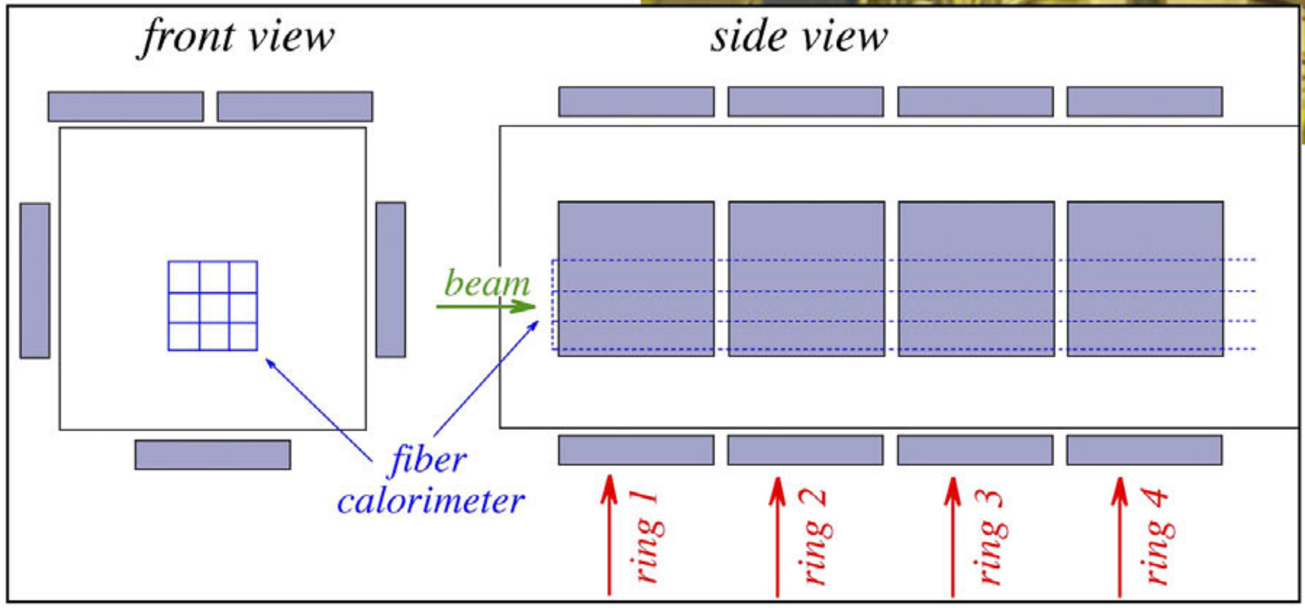






T1	T2	T3	T4	T5	T6
T7	T8	T9	T10	T11	T12
T13	T14	T15	T16	T17	T18
T19	T20	T21	T22	T23	T24
T25	T26	T27	T28	T29	T30
T31	T32	T33	T34	T35	T36

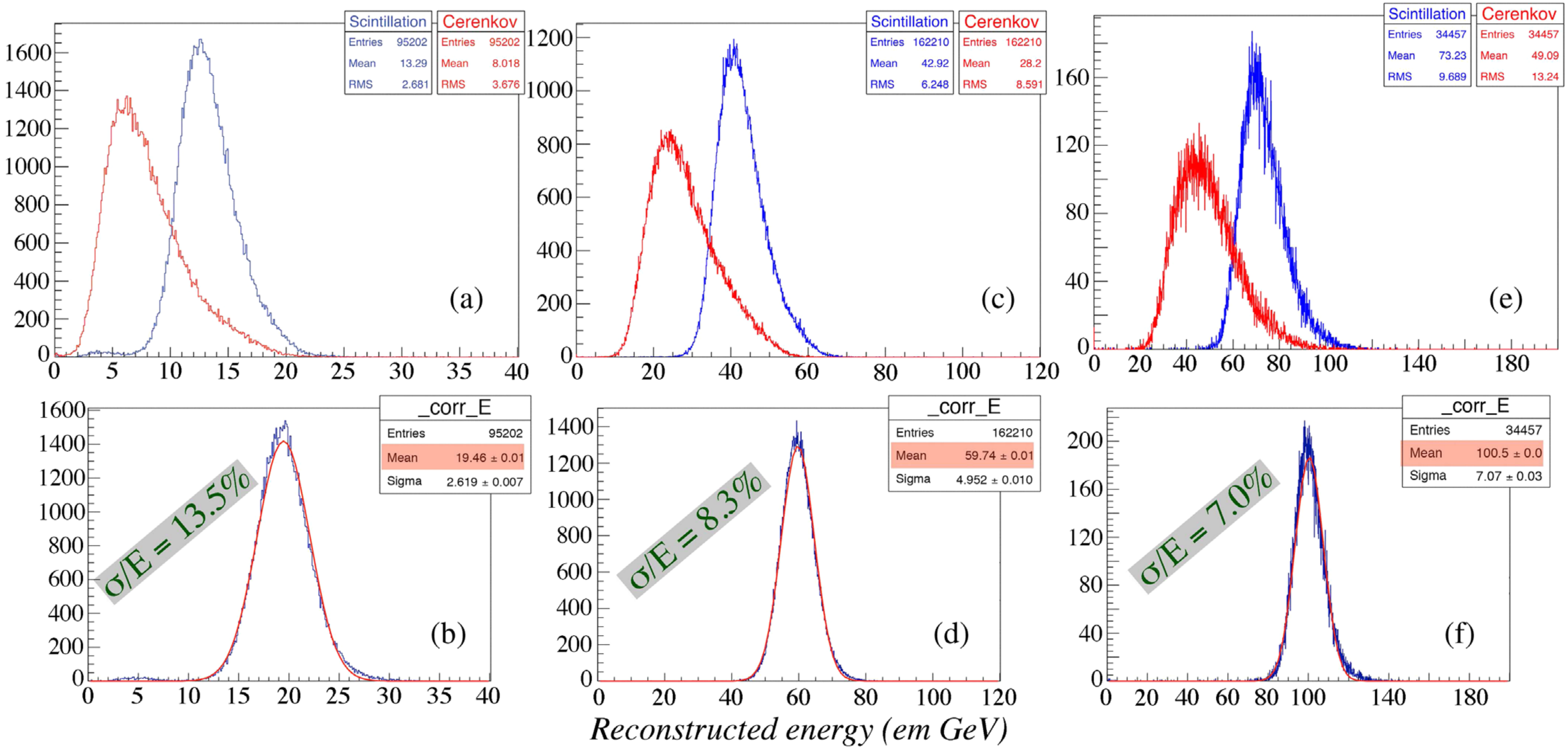
Ring 1 Ring 2 Ring 3



Leakage counters

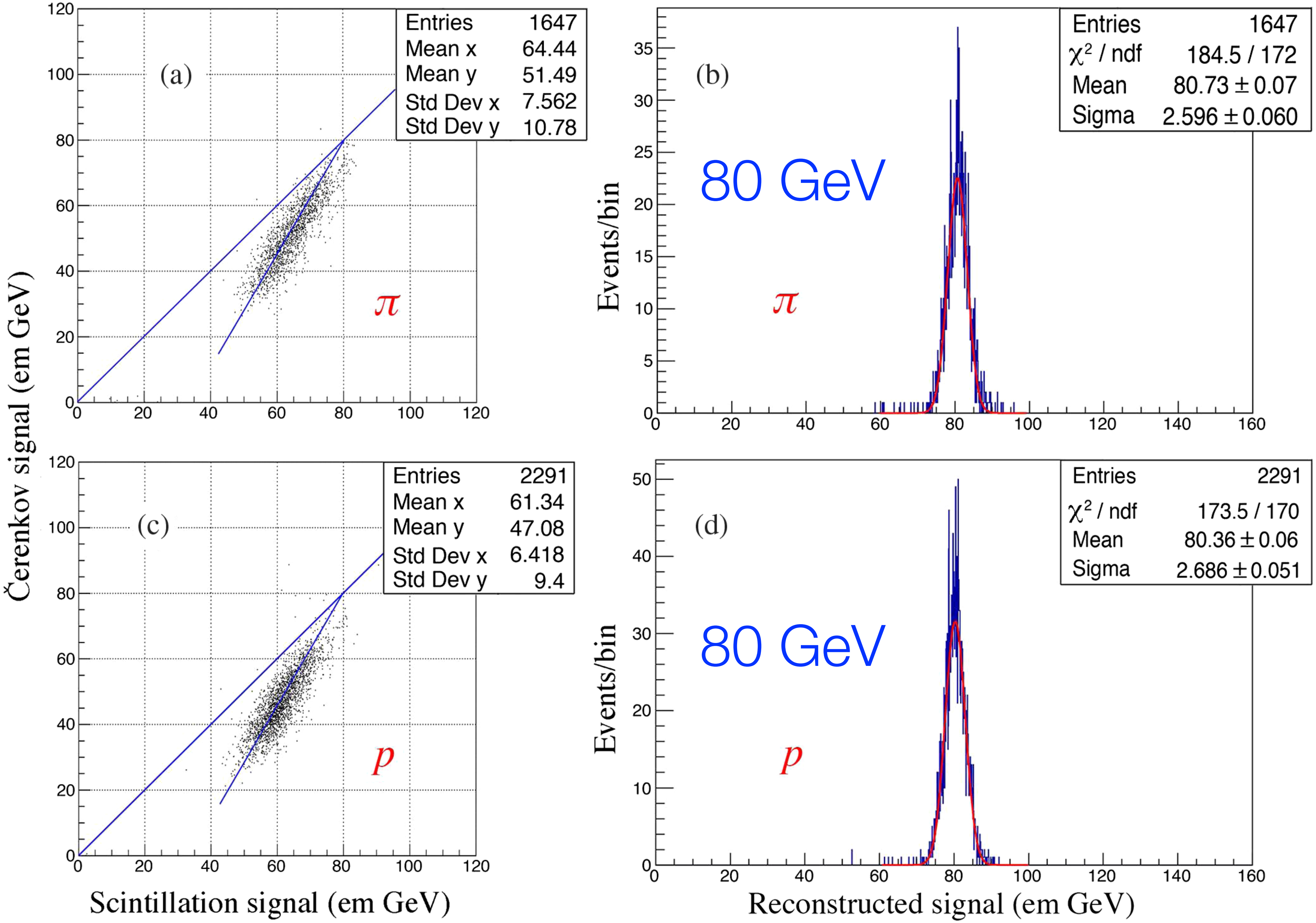
RD52 Pb-fiber Calorimeter (Dual-Readout Method)

20 GeV π   60 GeV π   100 GeV π

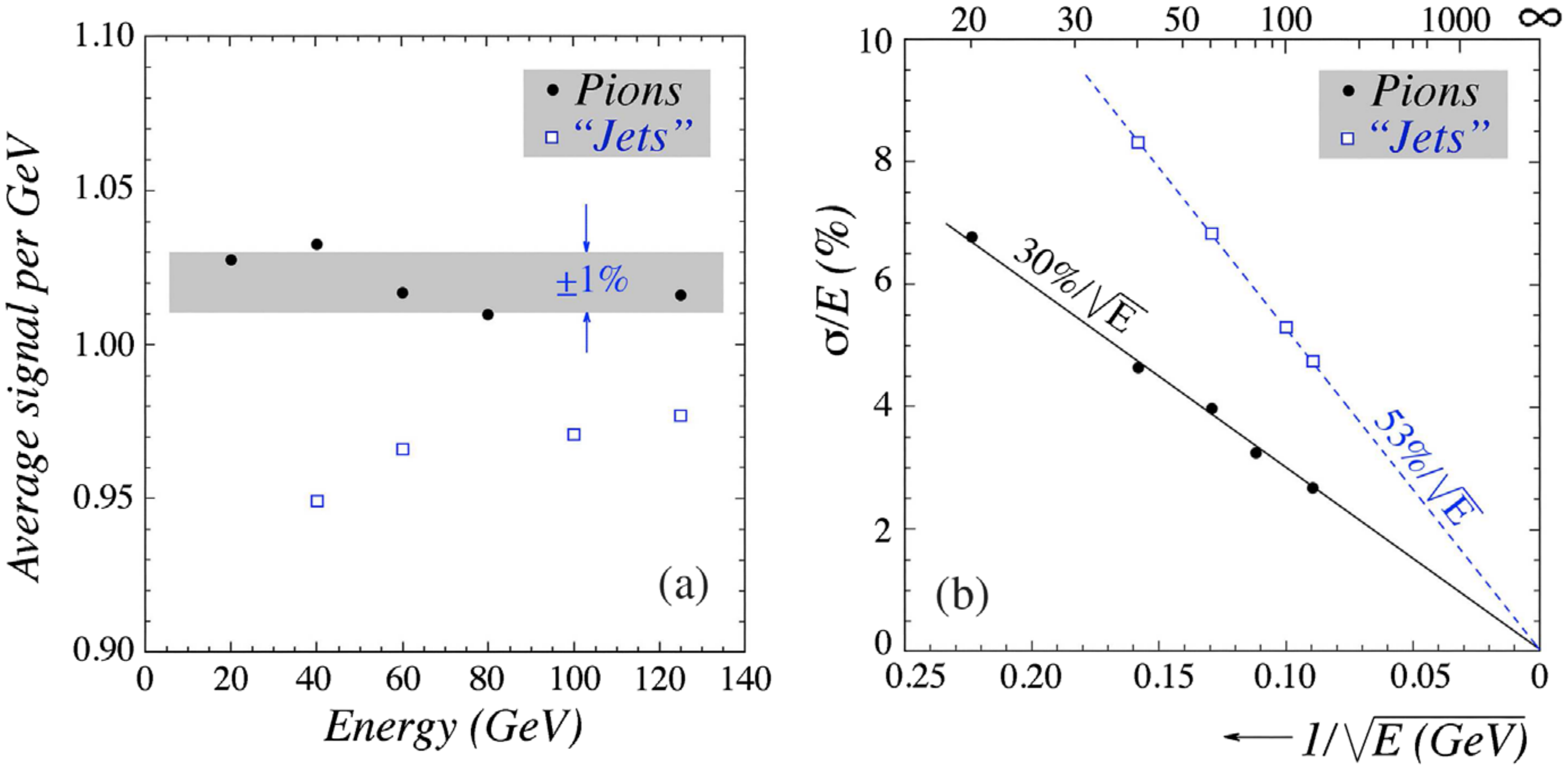


$$E = \frac{S - \chi C}{1 - \chi}, \quad \chi = 0.45.$$

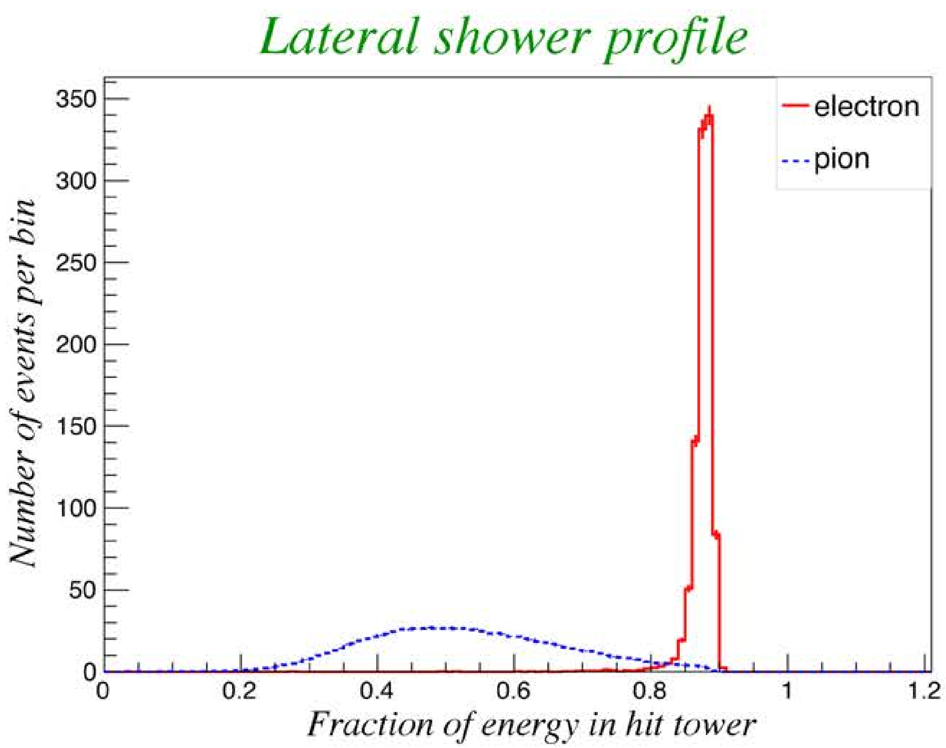
RD52 Pb-fiber Calorimeter (Rotation Method)

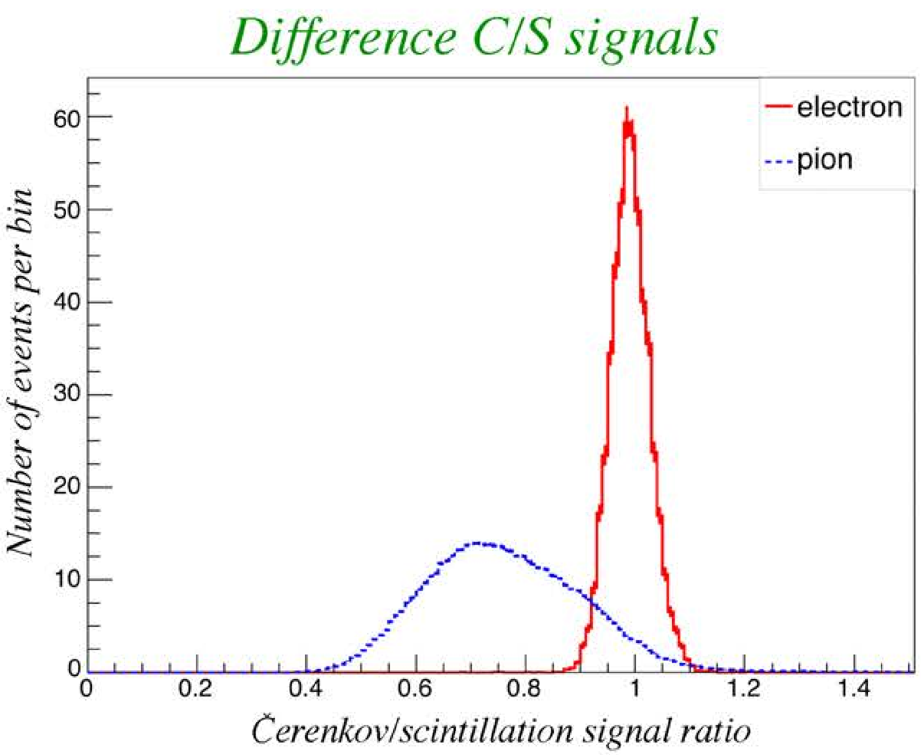


RD52 Pb-fiber Calorimeter (Rotation Method)

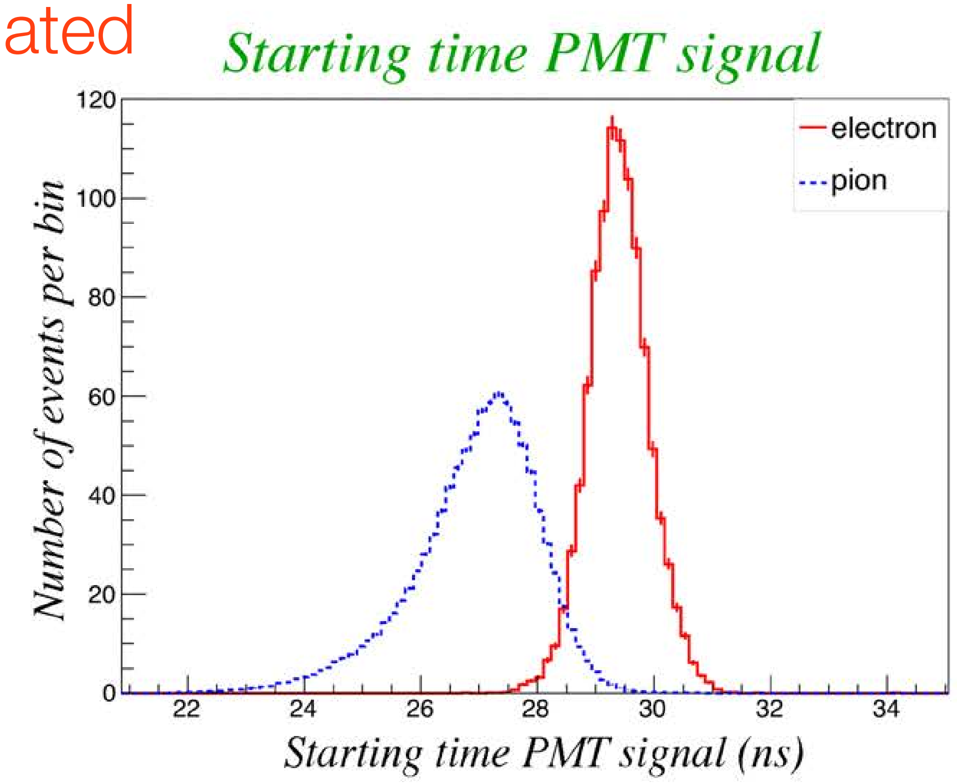


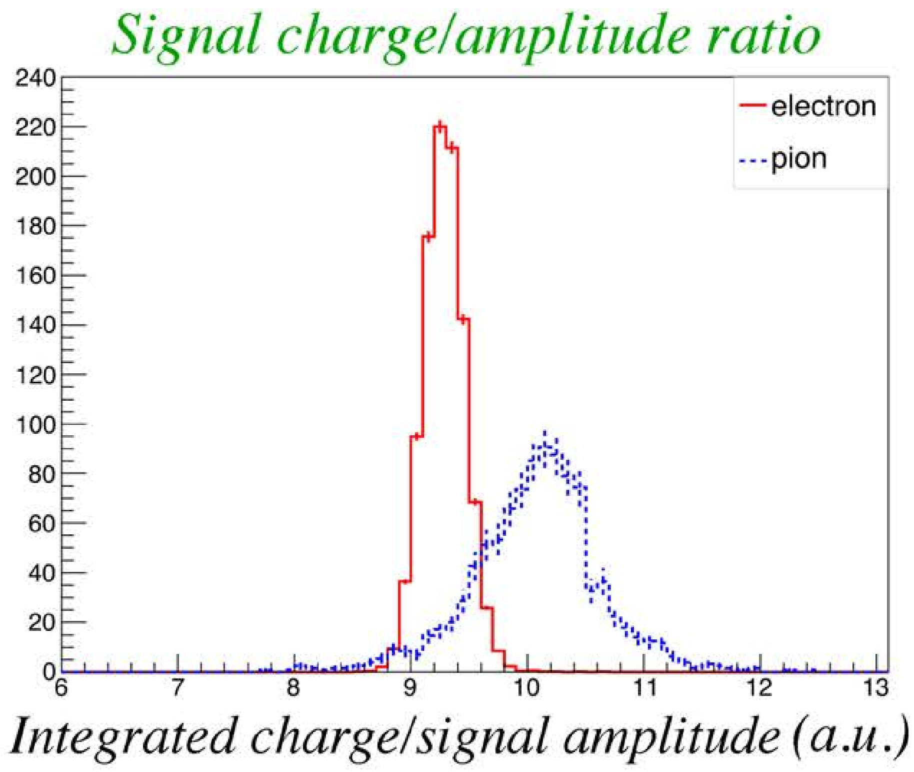
Particle ID (60 GeV)


Lateral shower profile


Difference C/S signals

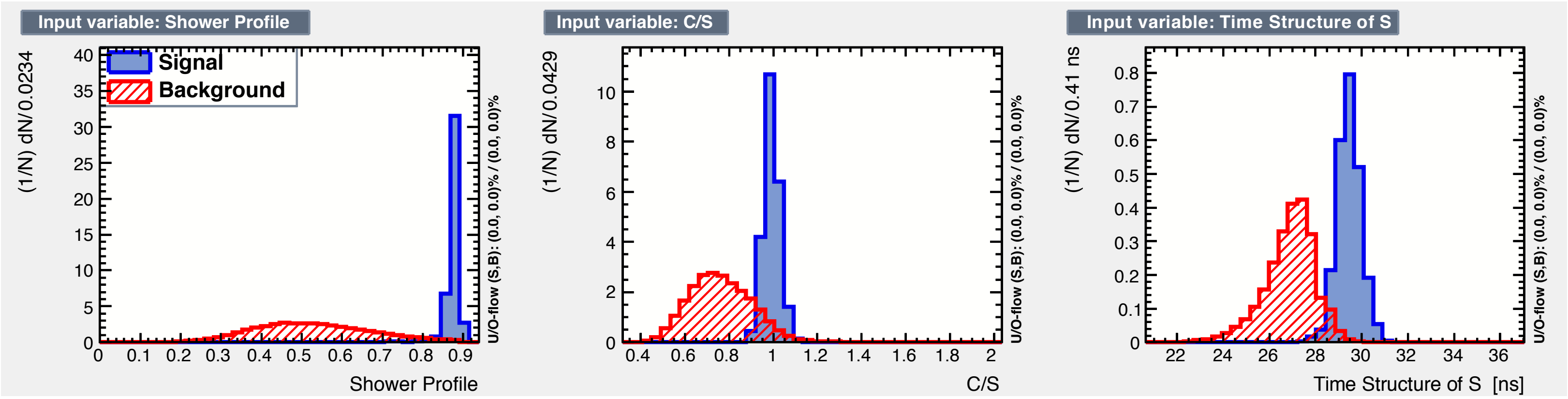
Uncorrelated


Starting time PMT signal

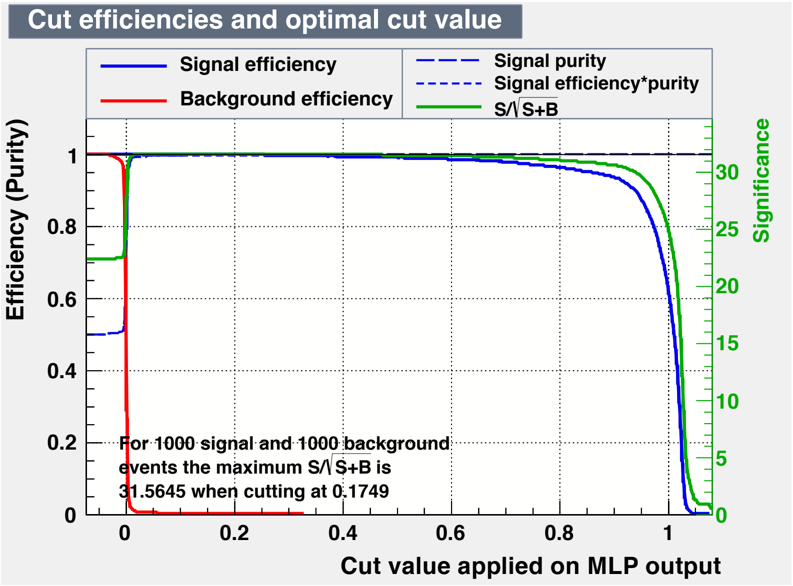

Signal charge/amplitude ratio

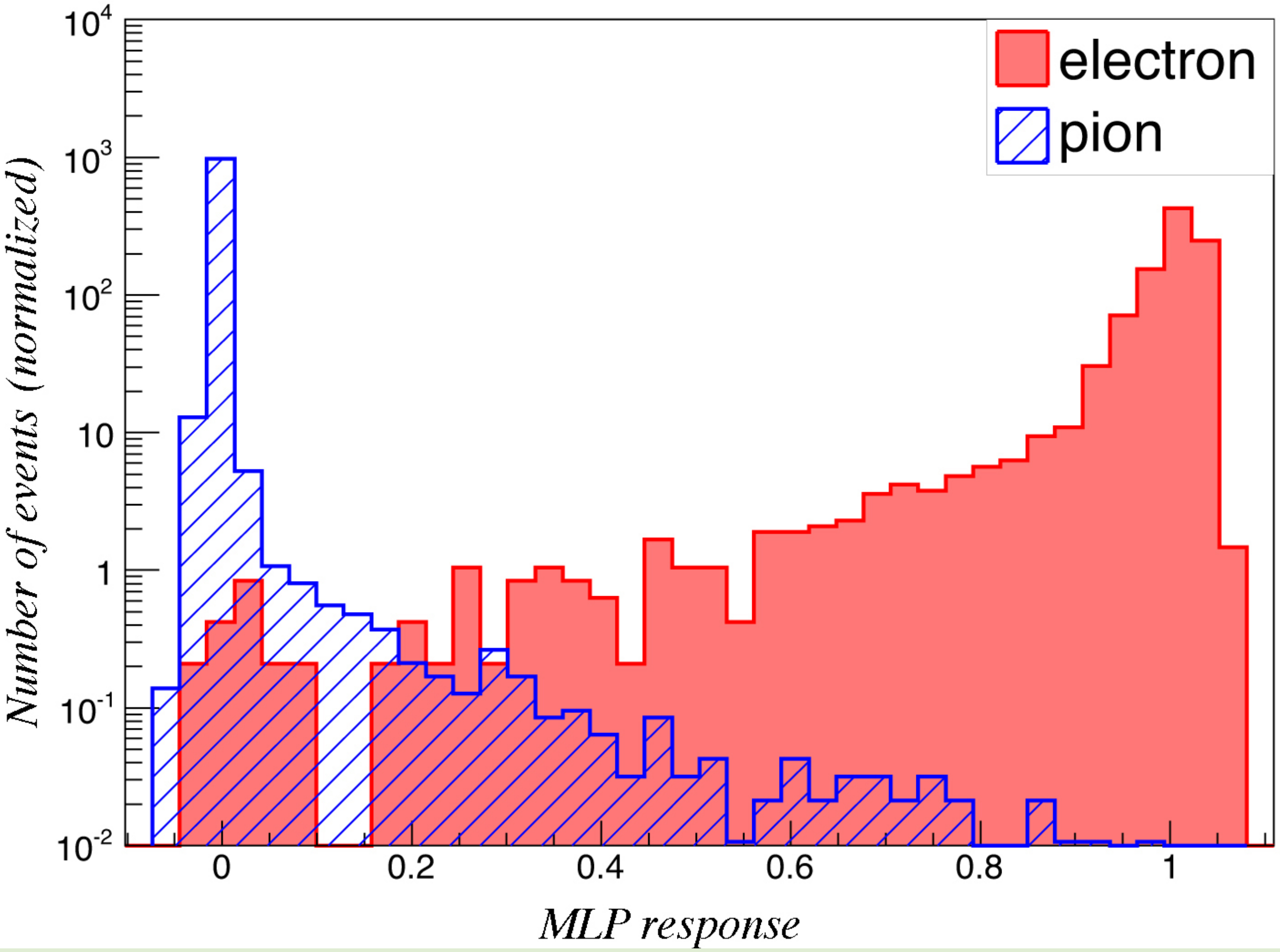
(Lateral shower profile > 0.7, t_s > 28.0 ns): 99.1 % electron ID, 0.5 % pion mis-ID

Input variables for 60 GeV e^- and π^-



Optimal cut

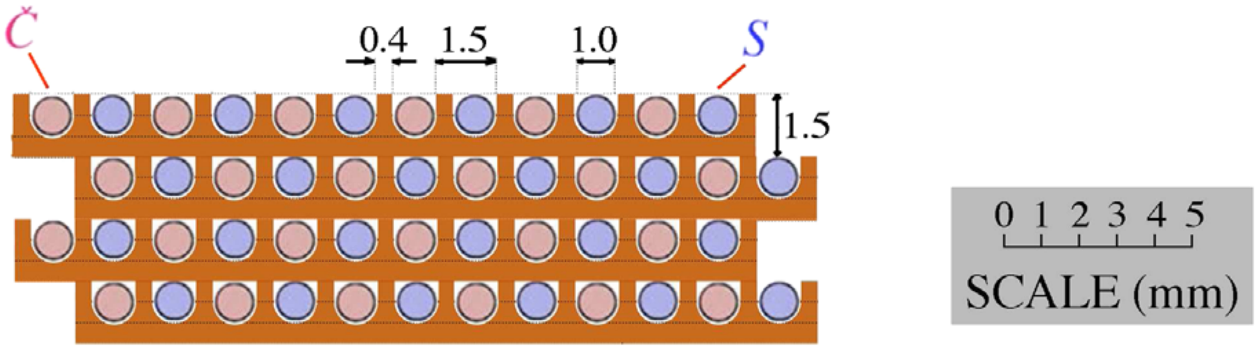




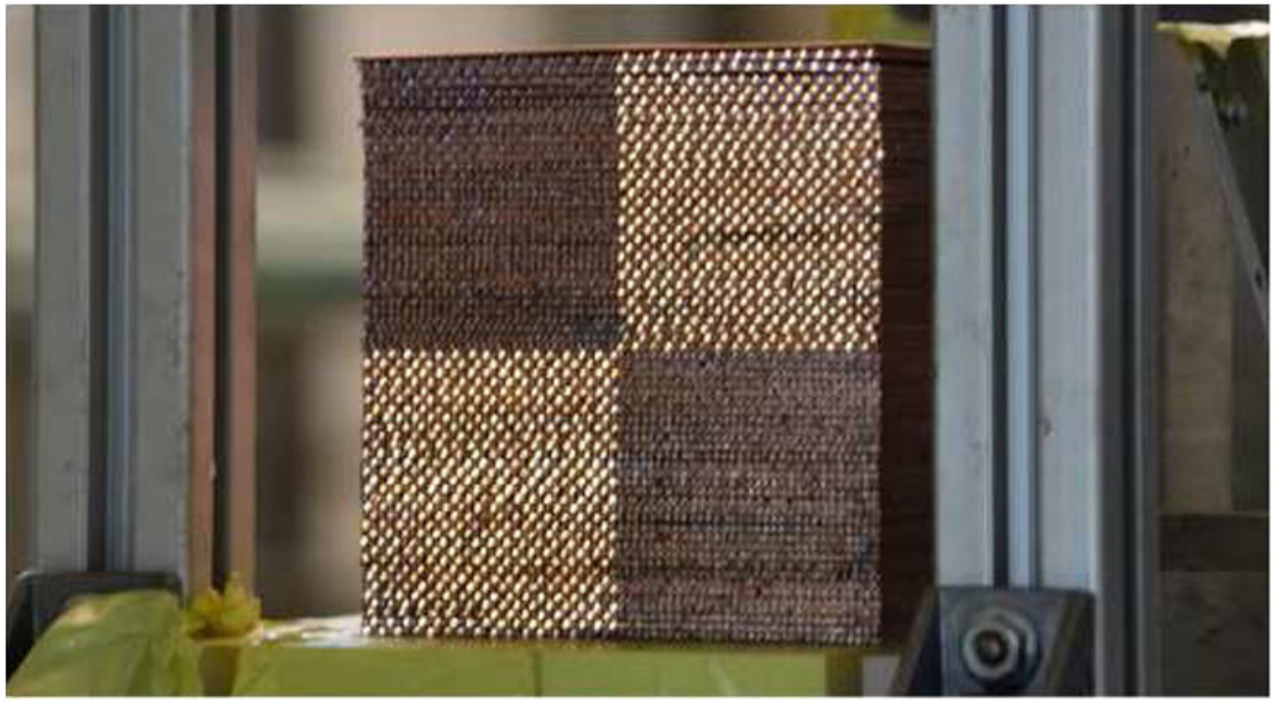
99.8 % electron ID, **0.2 % pion mis-ID** for MLP > 0.17

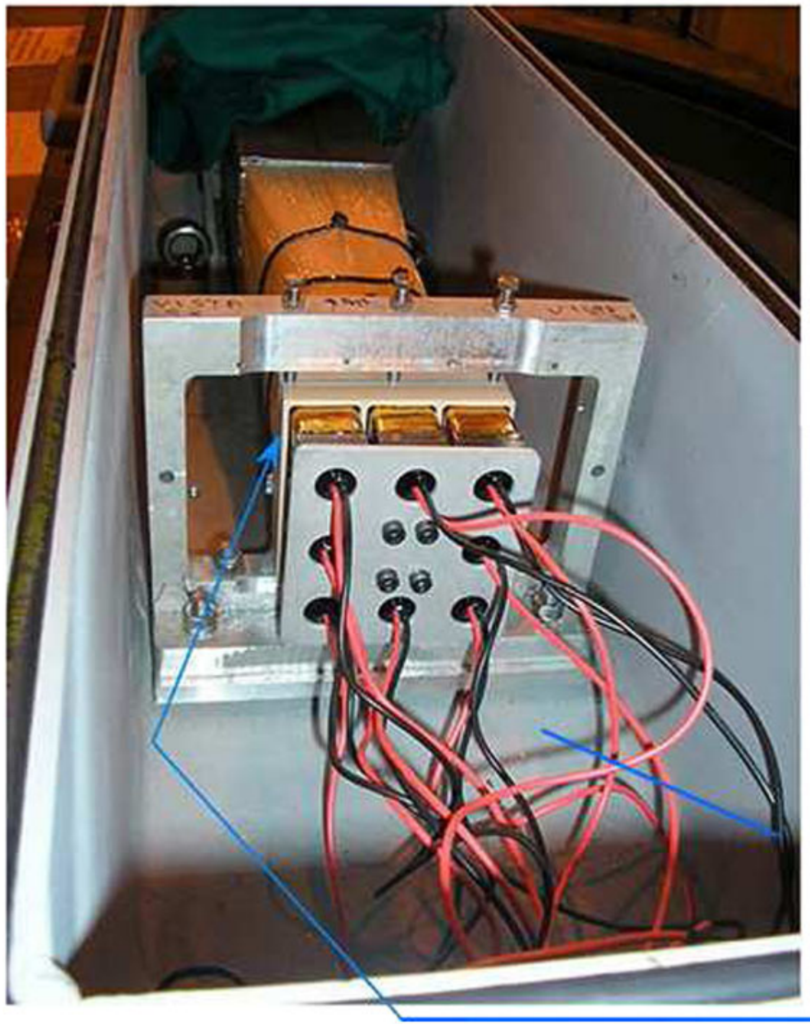
Electromagnetic Performance

RD52 Cu-fiber Calorimeter

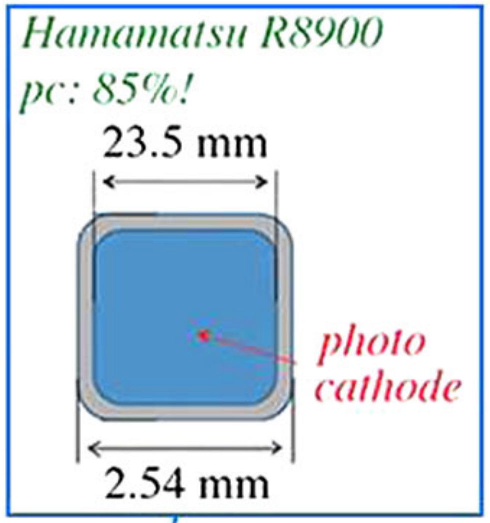


Fiber pattern RD52

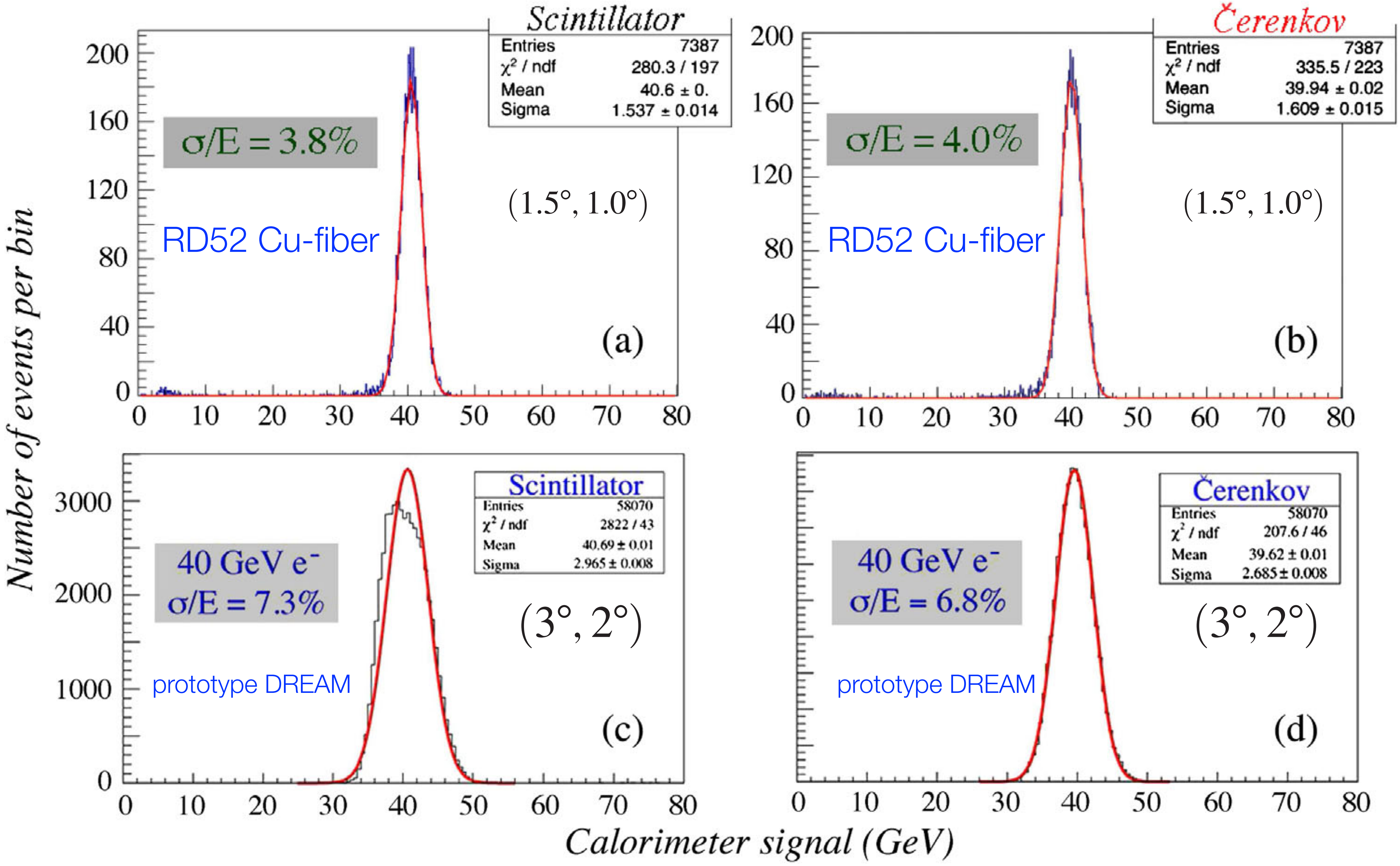




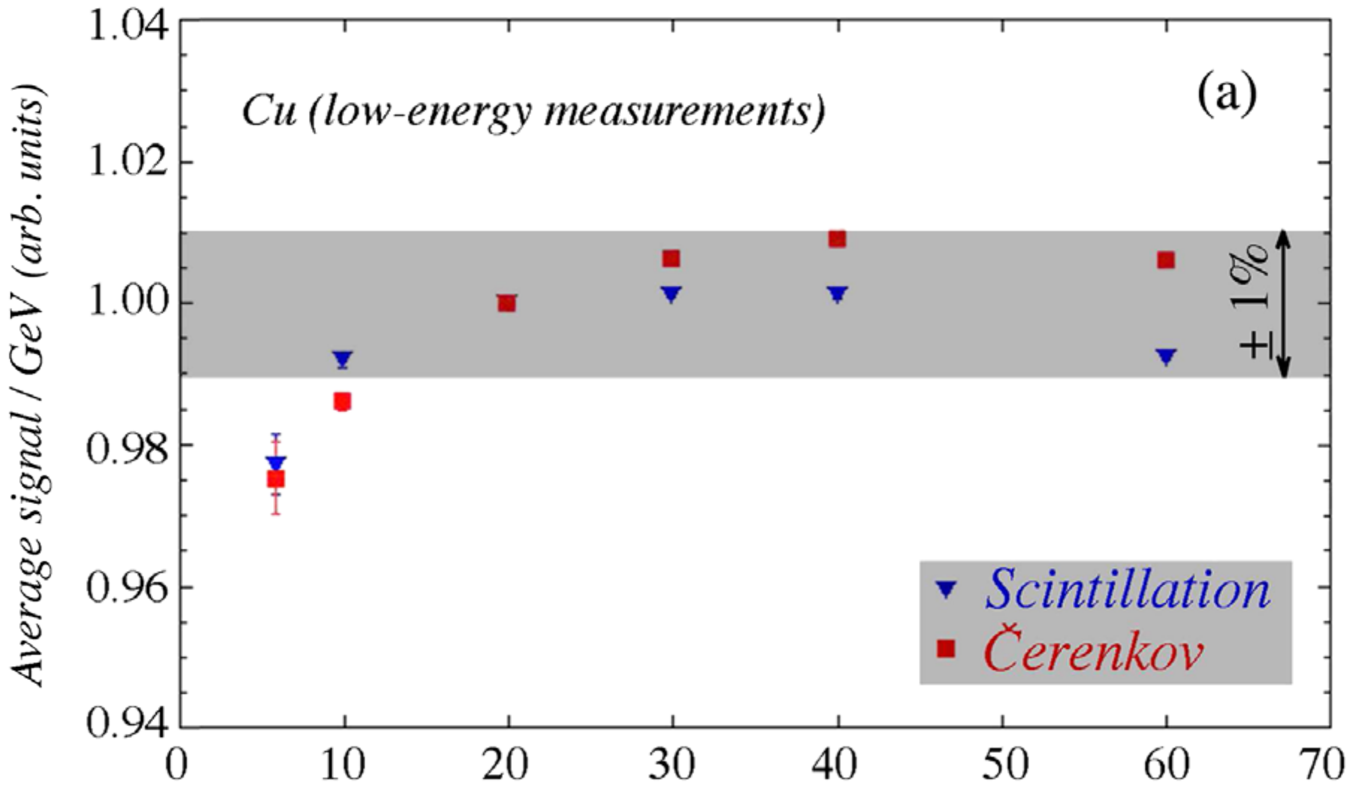
9.3 x 9.3 x 250 cm
150 kg
4 towers, 8 PMTs
2 x 2048 fibers

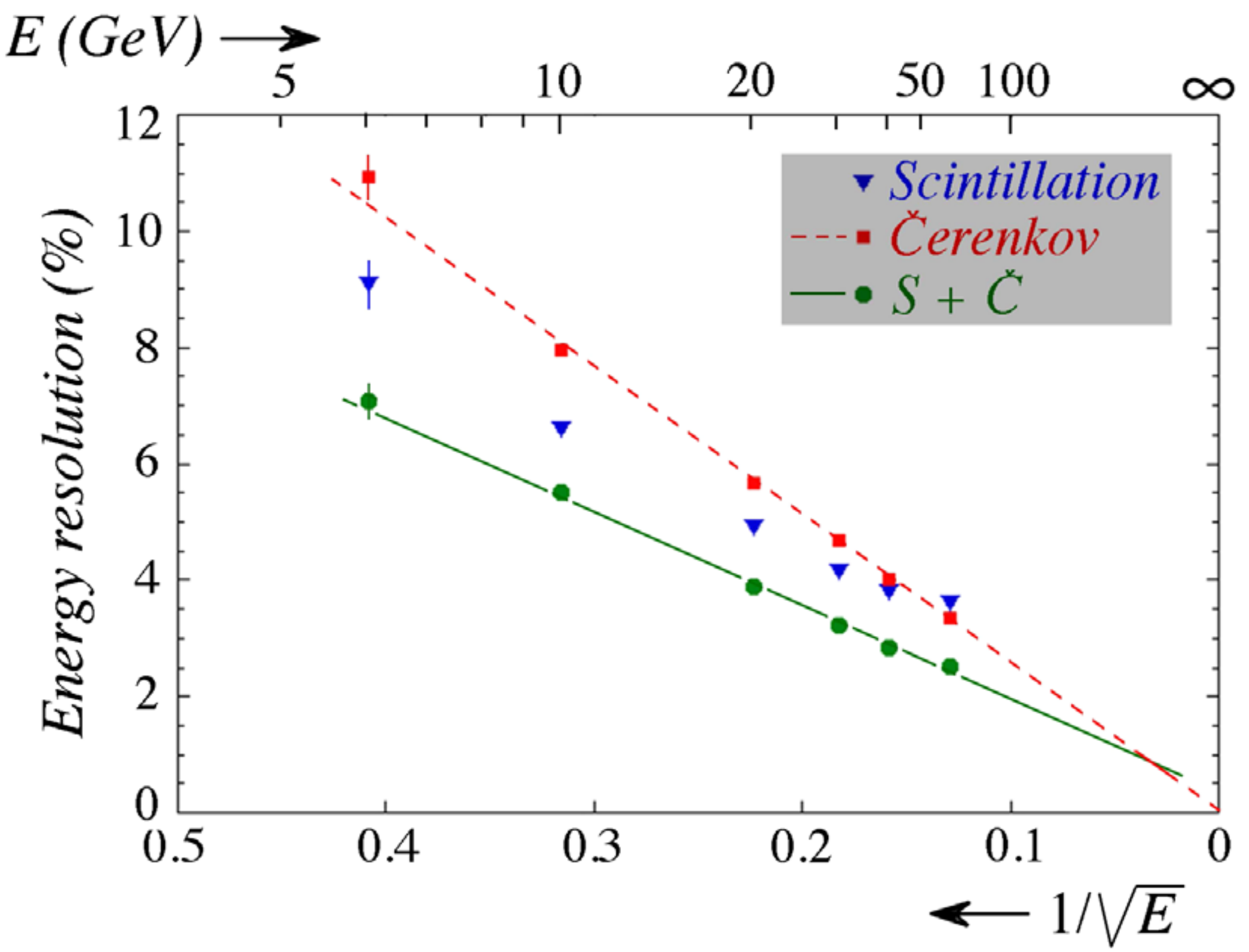


Electromagnetic Performance

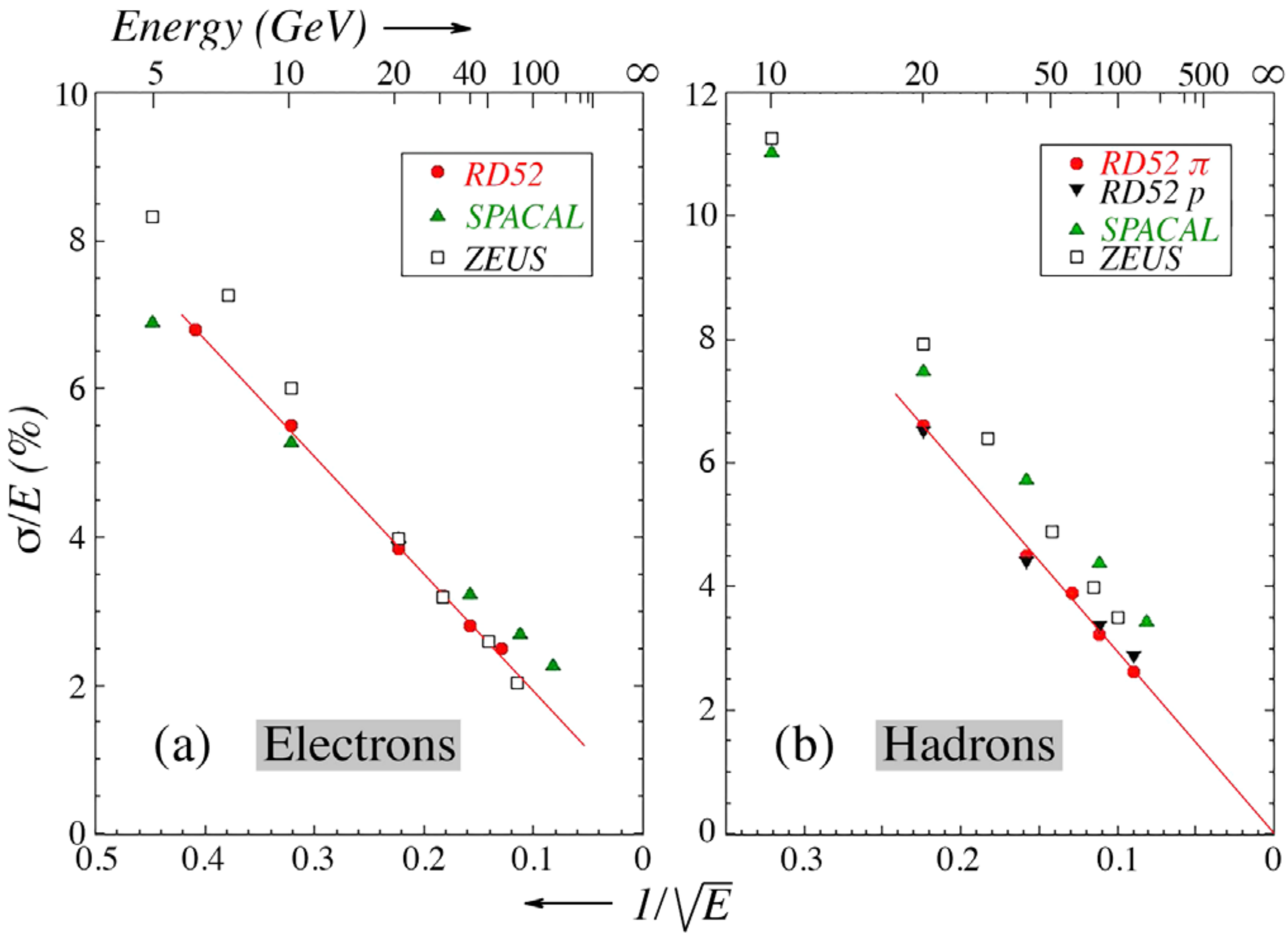


RD52 Cu-fiber Calorimeter

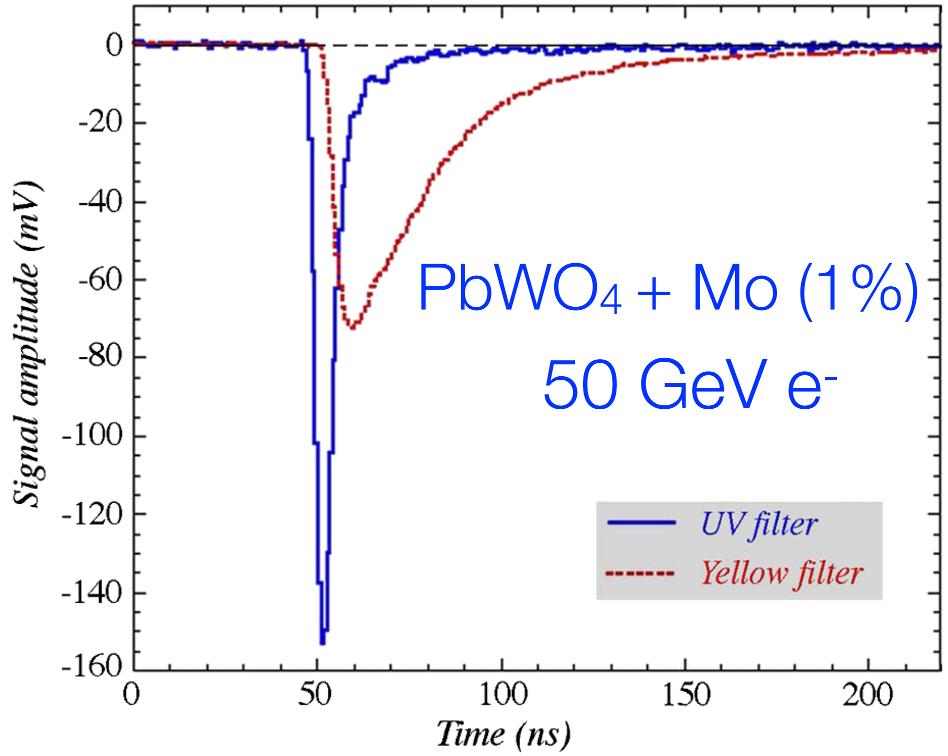




Electromagnetic and Hadronic Performances

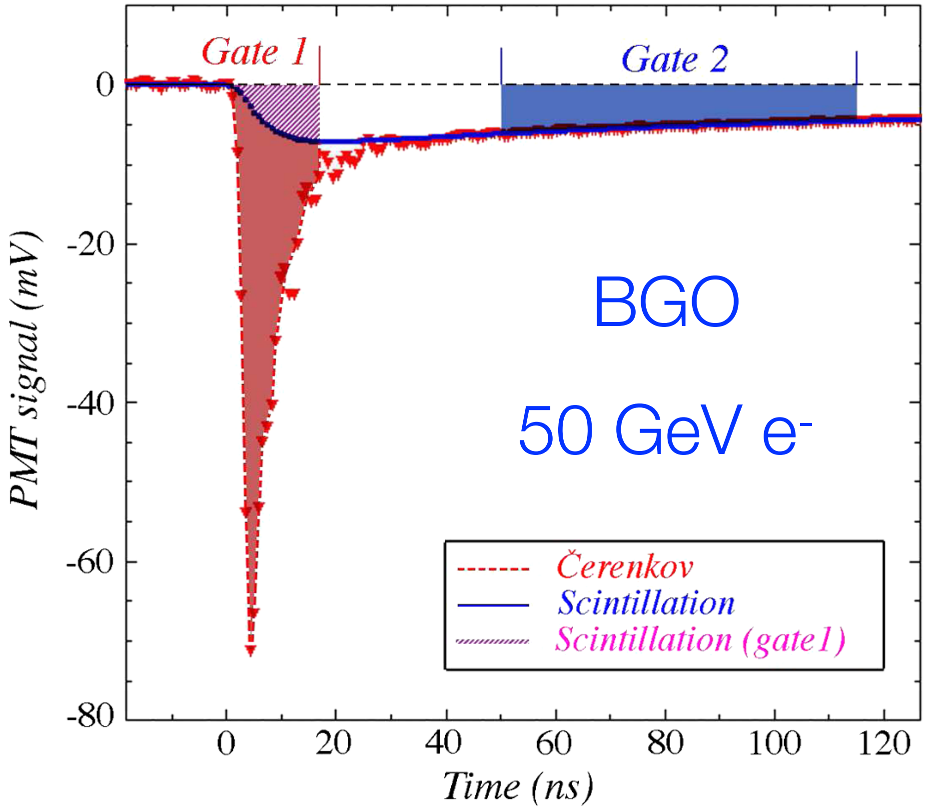


Crystals for Dual-Readout Calorimetry



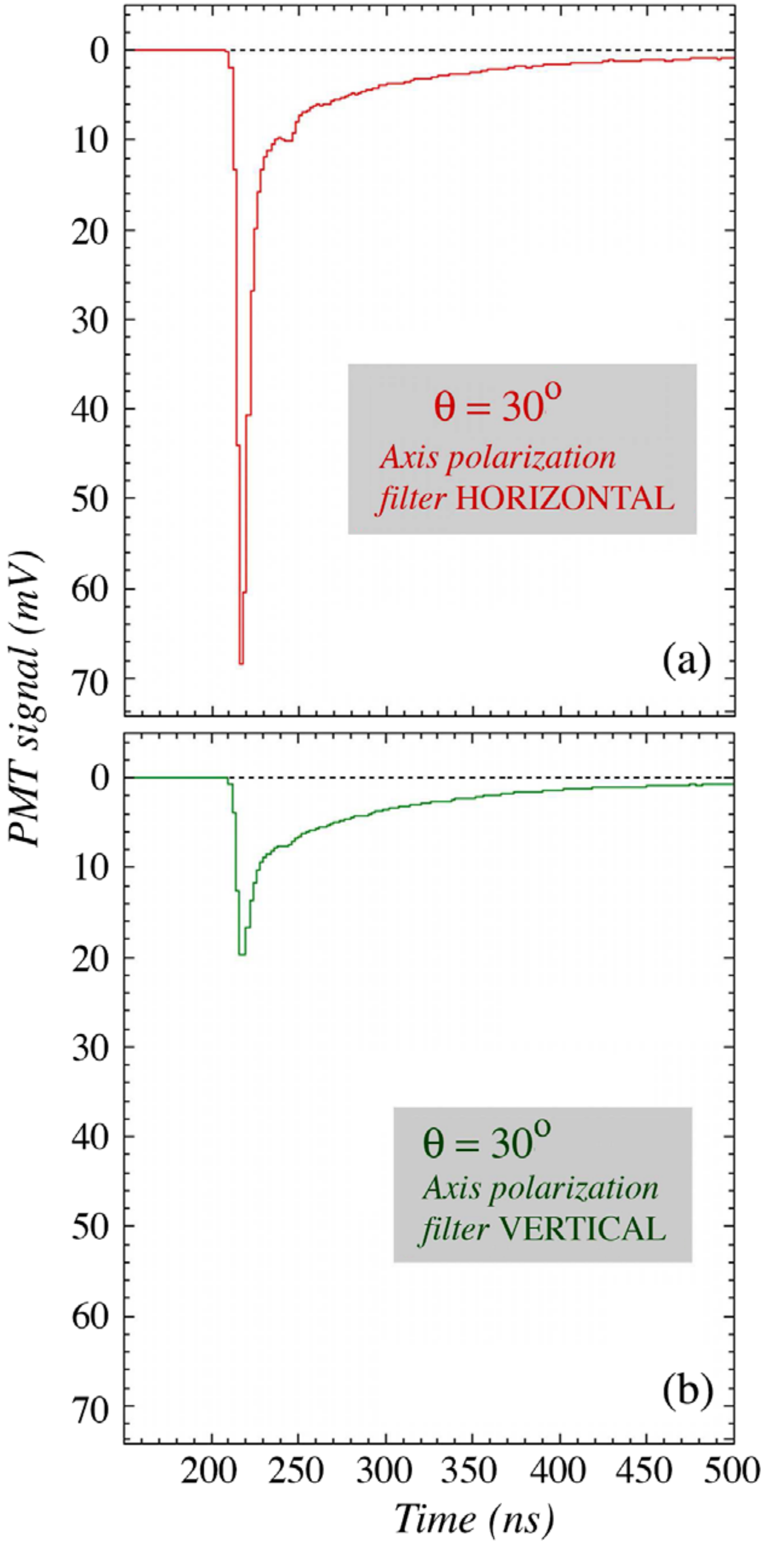
PbWO$_4$ + Mo (1%)

50 GeV e$^-$



BGO

50 GeV e$^-$



BSO

180 GeV π$^+$

The limits of the hadronic energy resolution

Nuclear binding energy losses

↓

The Poor Performance of Hadron Calorimeter

Two approaches to improve the hadronic performance

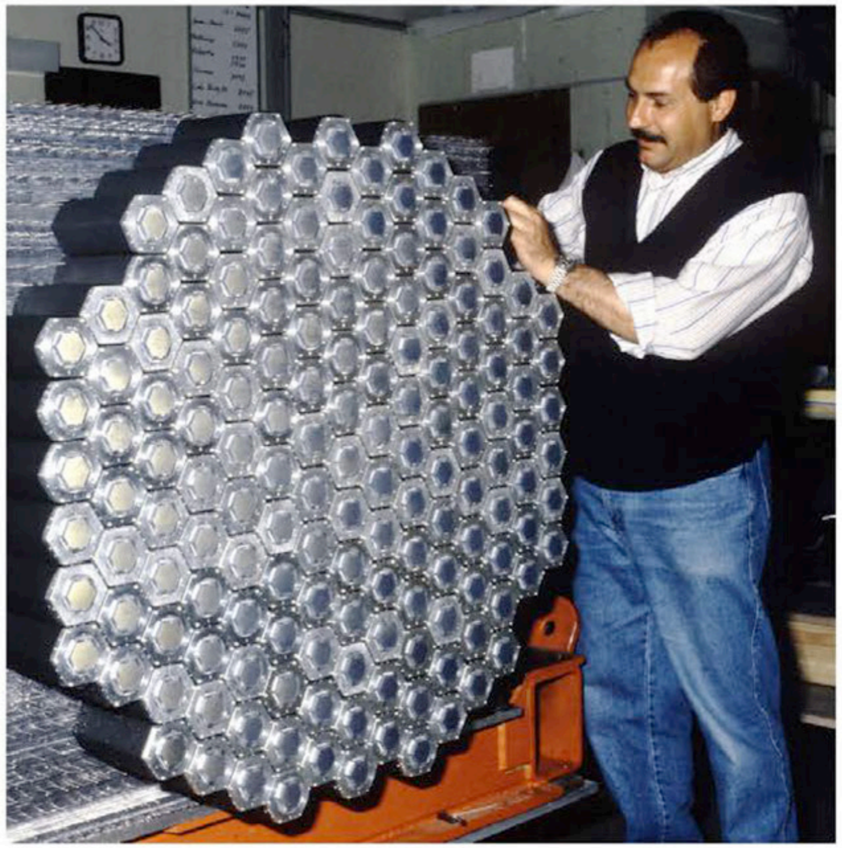
1. ***Compensation***
   - *the total kinetic energy of neutrons*
2. ***Dual-Readout***
   - *the electromagnetic shower fraction*

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)

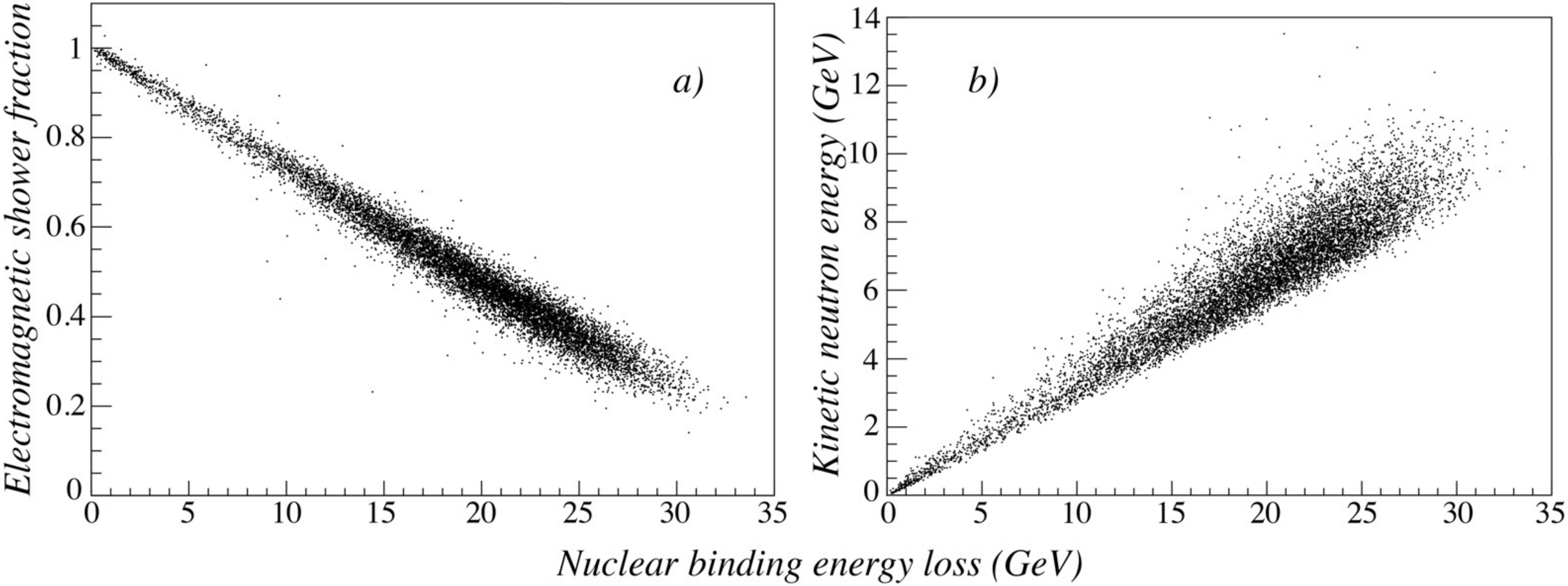
Dual-Readout Calorimetry

- 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

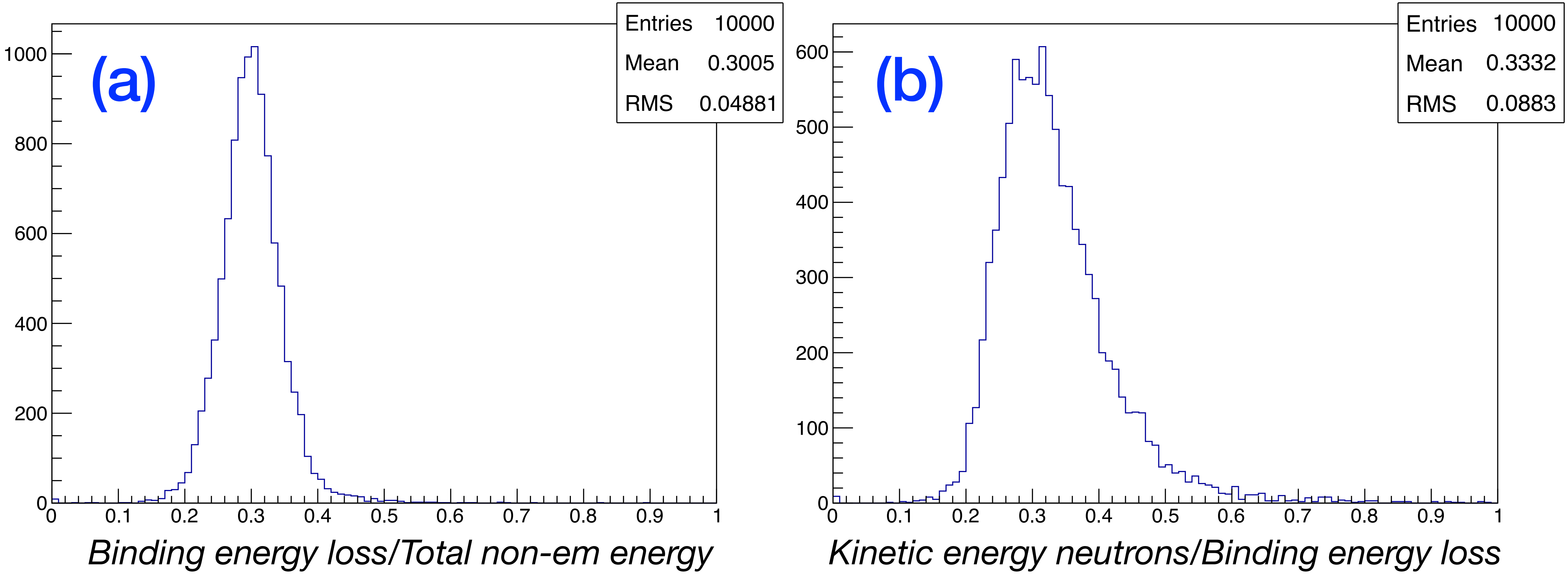
- GEANT 4.10.3-patch2
- FTFP_BERT physics list
- Very large absorber to contain the entire hadron shower
- 10, 20, 50, 100, 200, 500, 1000 GeV π^- sent to Cu and Pb (10,000 events)
- Obtained information in each event:
  - The em shower fraction
  - The total nuclear binding energy loss
  - The total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

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



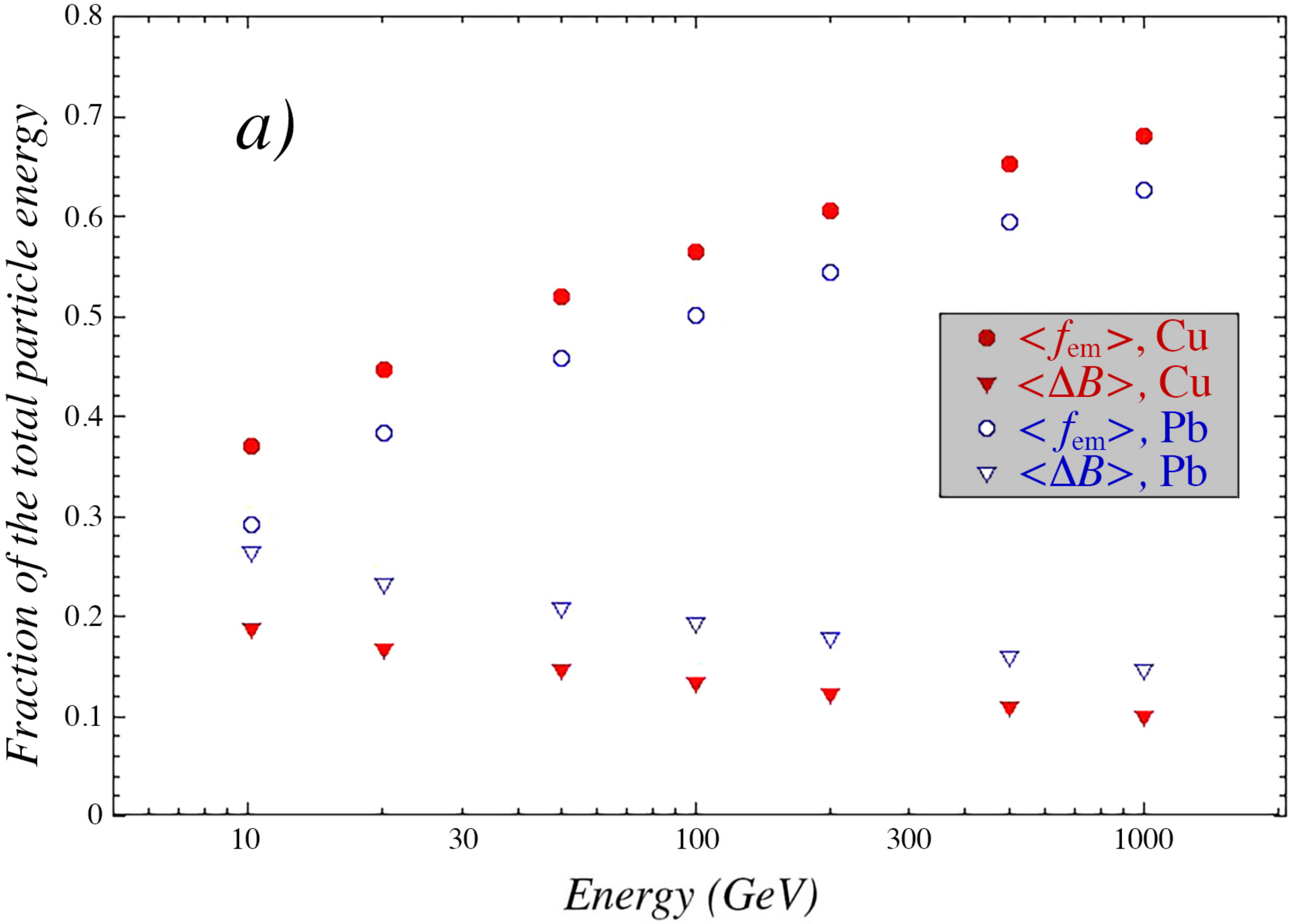
Results are for 100 GeV π- in lead absorber

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

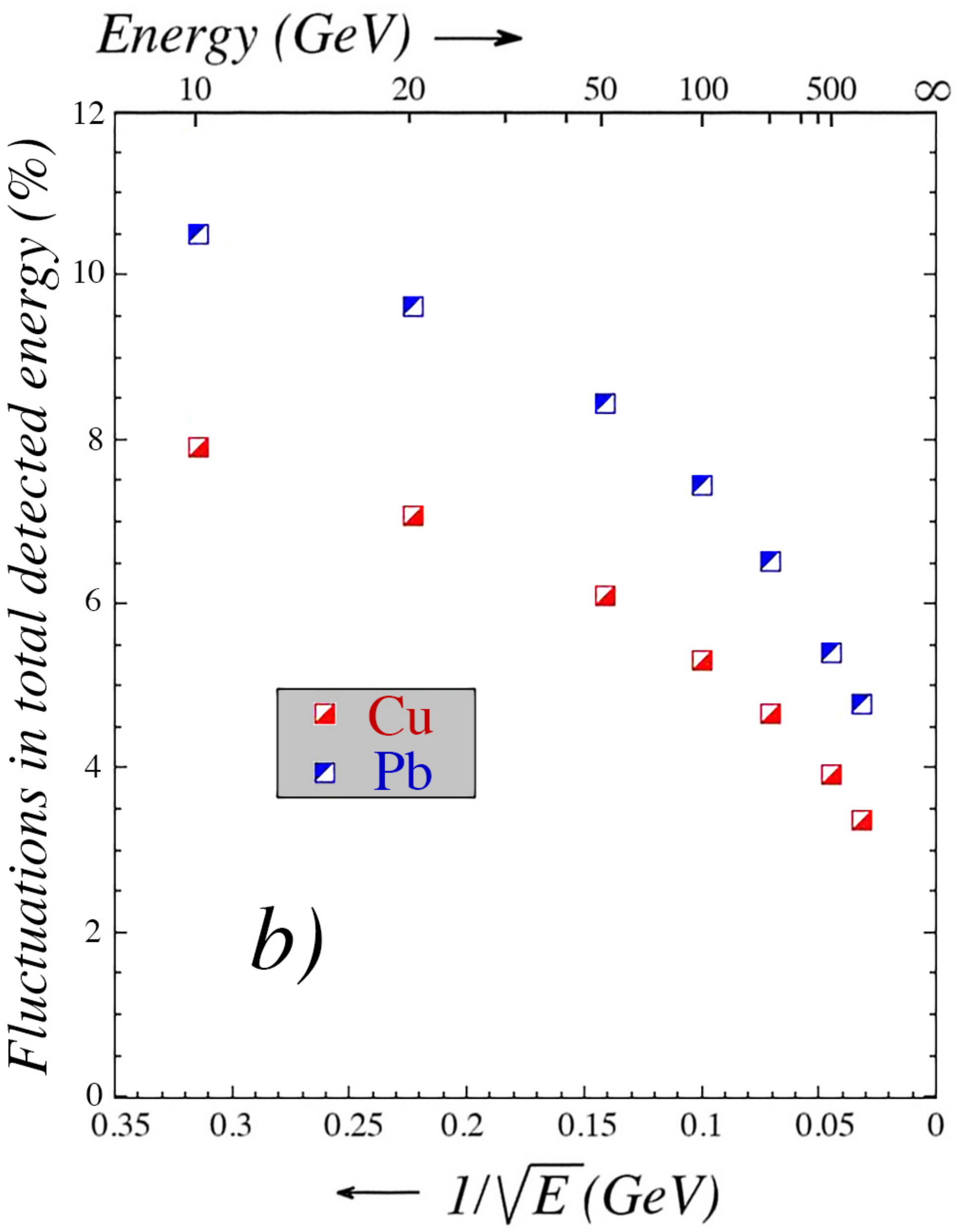


20 GeV π^- in copper

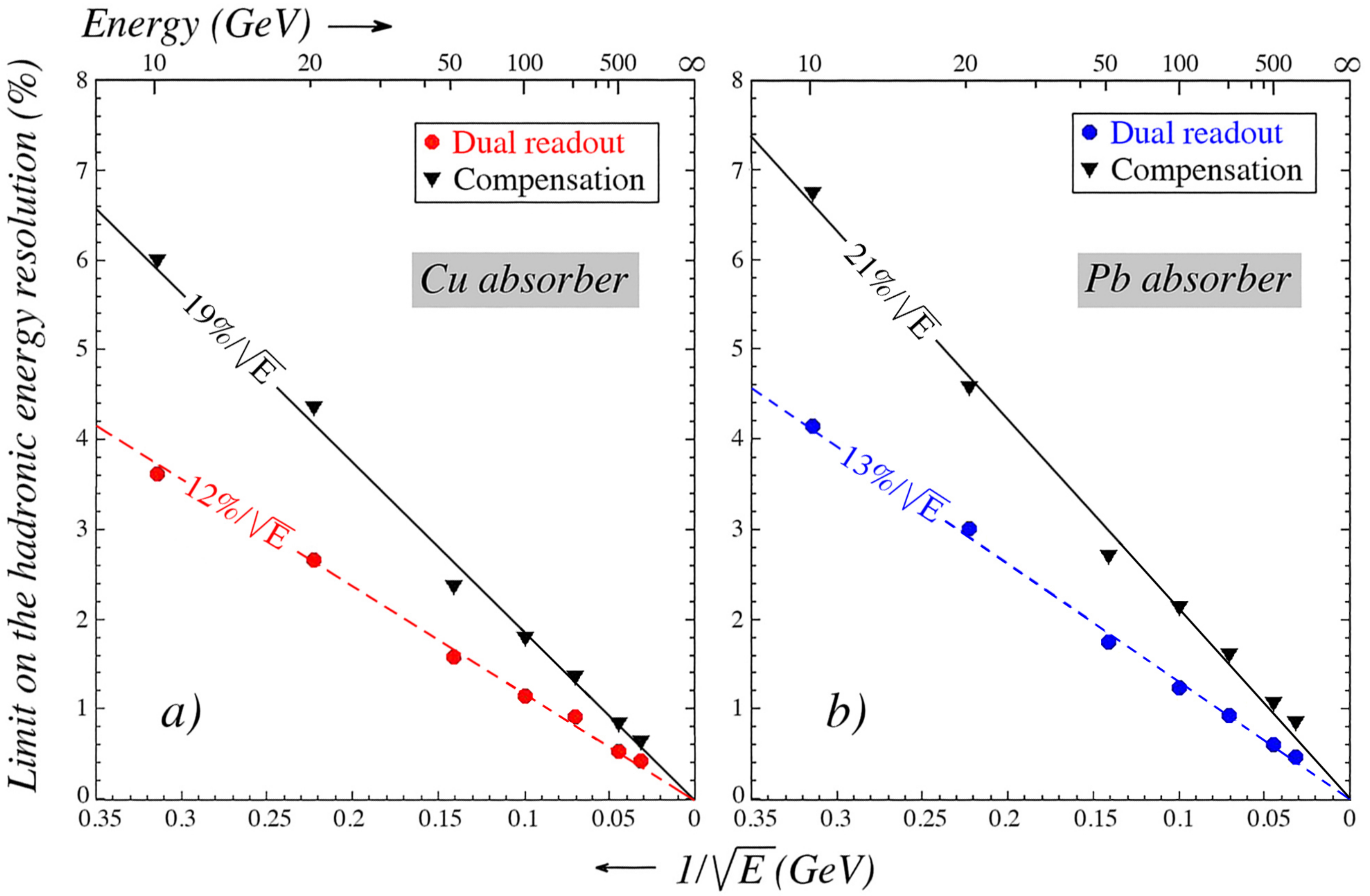
<EM Shower fraction> and <Binding Energy Loss>



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



Limits on the hadronic energy resolution



Summary

- RD 52 Collaboration has proved the Dual-Readout principles and the good performance in the energy measurement of electromagnetic particles and hadrons.

- All published results for last 20 years R&D are at: http://www.phys.ttu.edu/~dream/results/publications/publications.html

- The simulation results showed the limits of the hadron energy resolution with Dual-Readout method are 12% and 13%/$\sqrt{E}$ for Cu and Pb for single hadrons.

  - In reality, we can reach better than 30%/$\sqrt{E}$ for single hadrons using the Dual-Readout method.

Backup

RD52 Pb-fiber Calorimeter (Rotation Method)