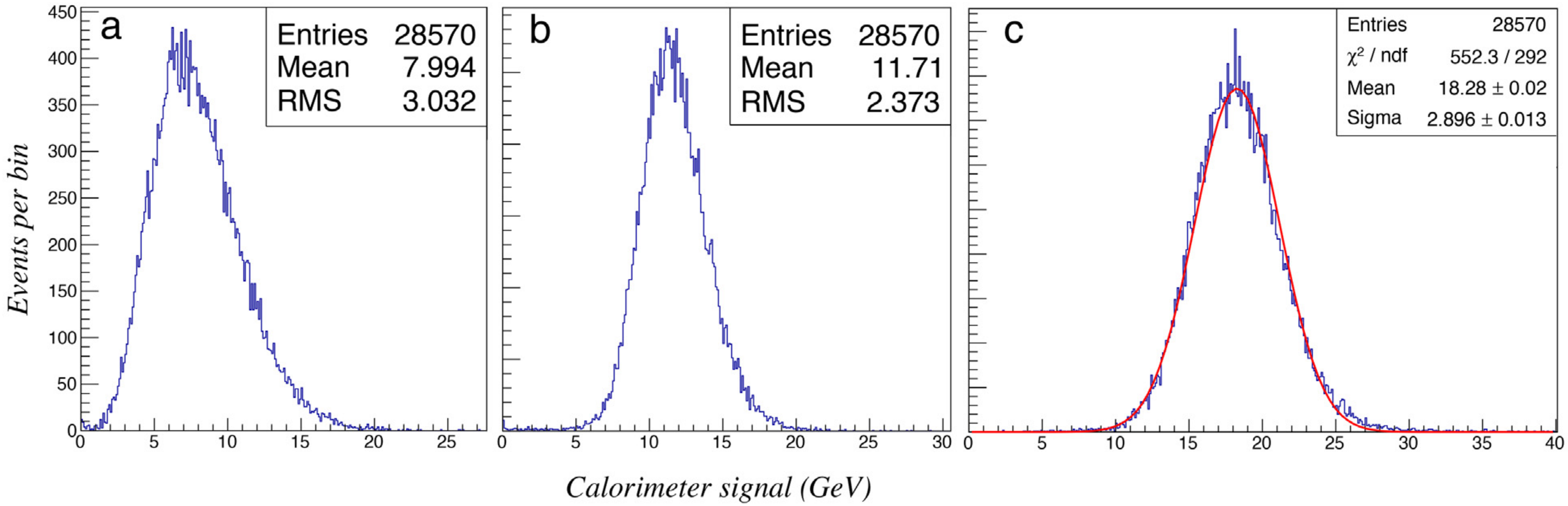


Fig. 11. Signal distributions for 20 GeV π^- particles. Shown are the measured Čerenkov (a) and scintillation (b) signal distributions as well as the signal distribution obtained by combining the two signals according to Eq. (2), using $\chi = 0.45$ (c).

On the limits of the hadronic energy resolution of calorimeters

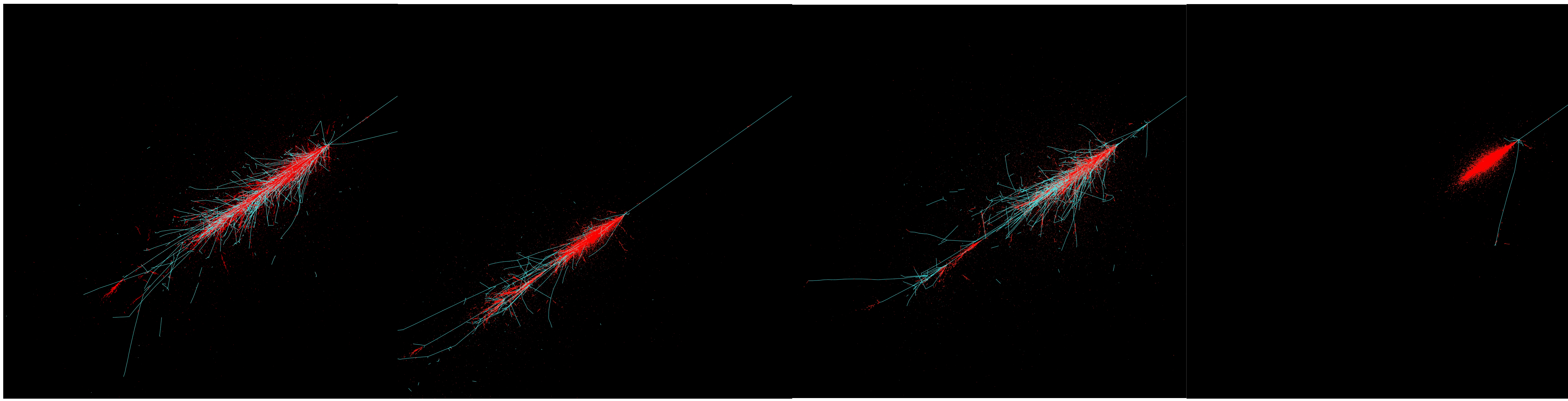
Sehwook Lee
Kyungpook National University

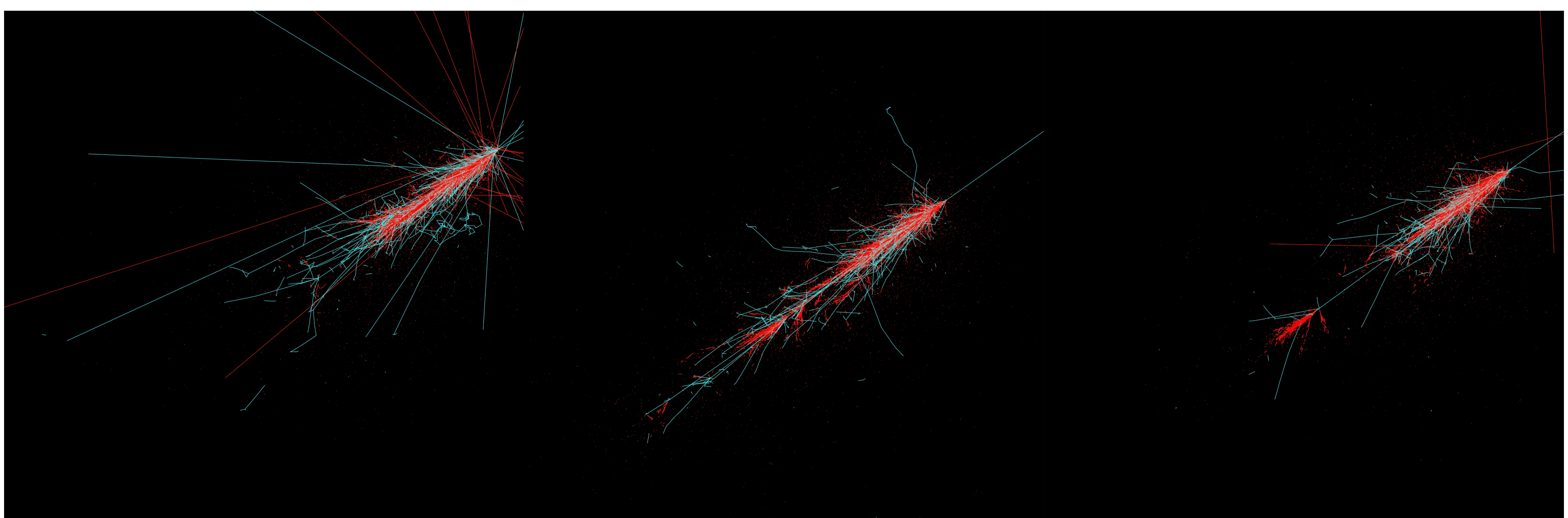
AFAD 2018, Daejeon, January 29 2018

Fluctuations of Hadron Showers

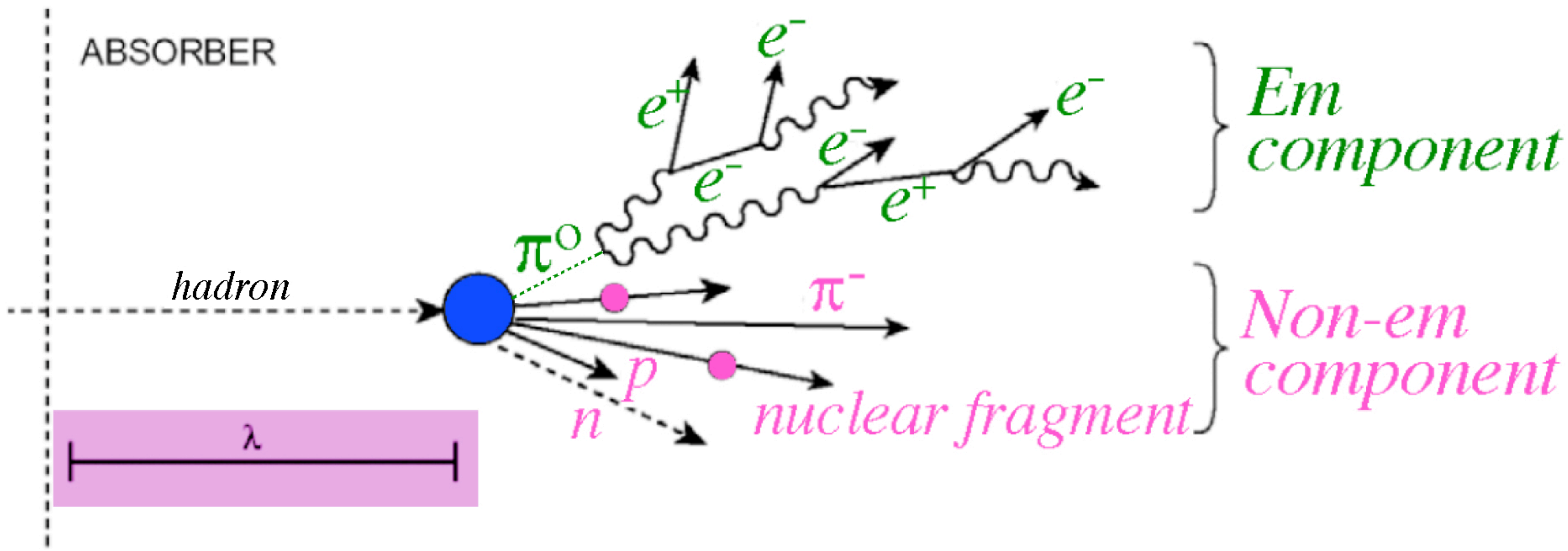
500 GeV Pions, Cu absorber

Red: e^-, e^+ ***Cyon: Other Charged Particles***





The Physics of Hadron Shower Development

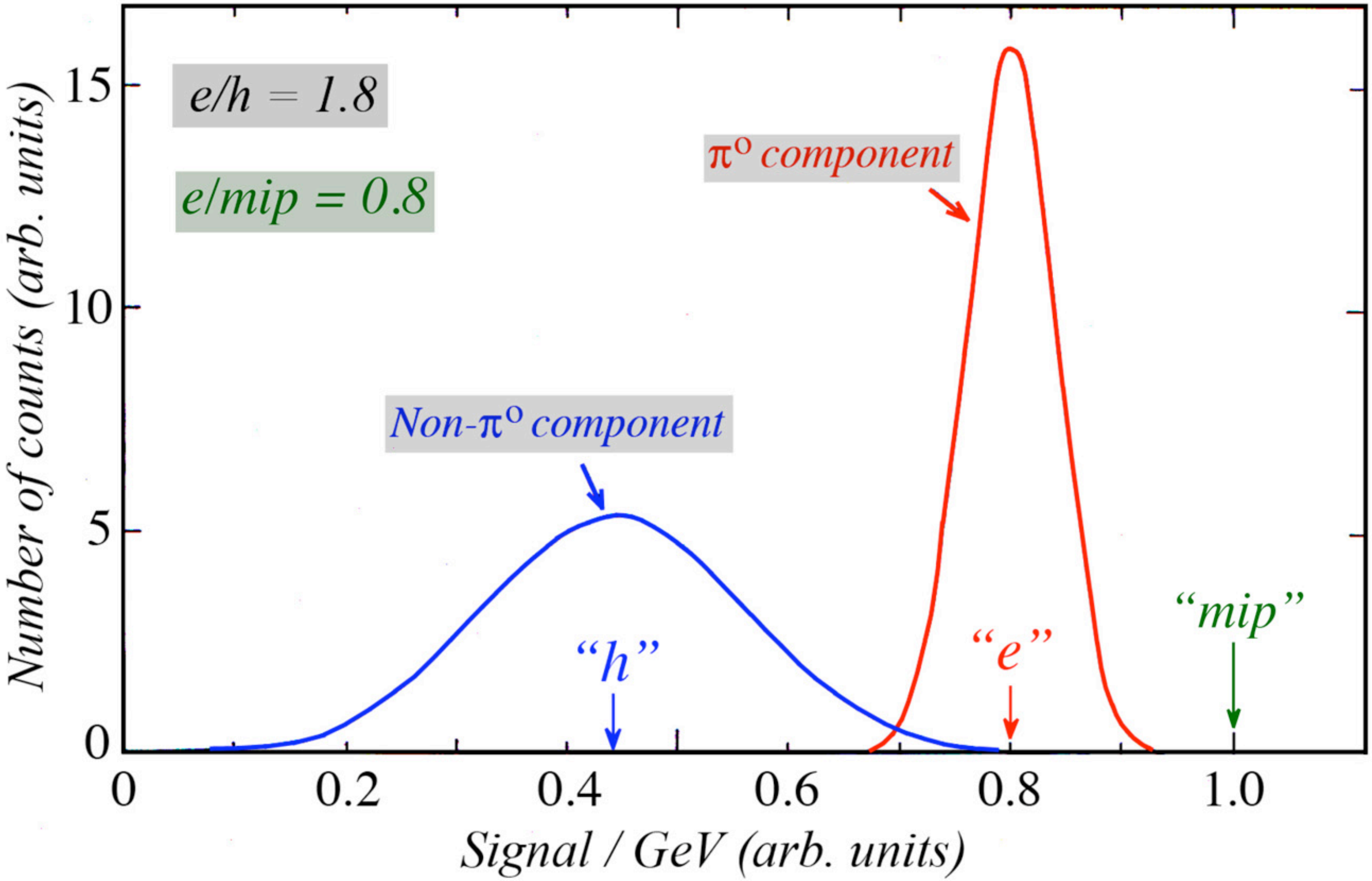


- *Electromagnetic component*
  - electrons, photons
  - neutral pions → 2 γ
- *Hadronic (non-em) component*
  - charged hadrons $\pi^{\pm}$,$K^{\pm}$ (20%)
  - nuclear fragments, p (25%)
  - neutrons, soft γ's (15%)
  - break-up of nuclei (*"invisible"*) (40%)

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

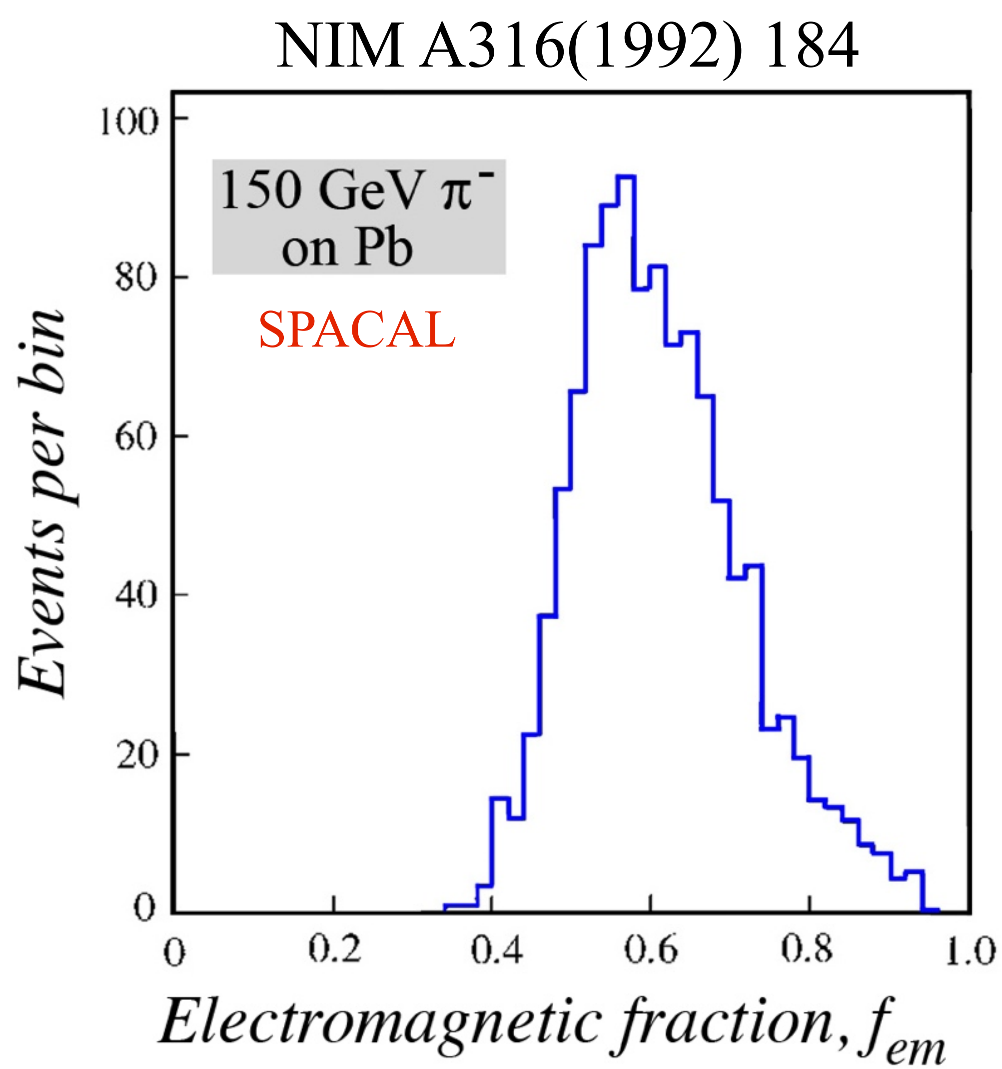
- ***Responsible for the Fluctuations of Hadron Showers***

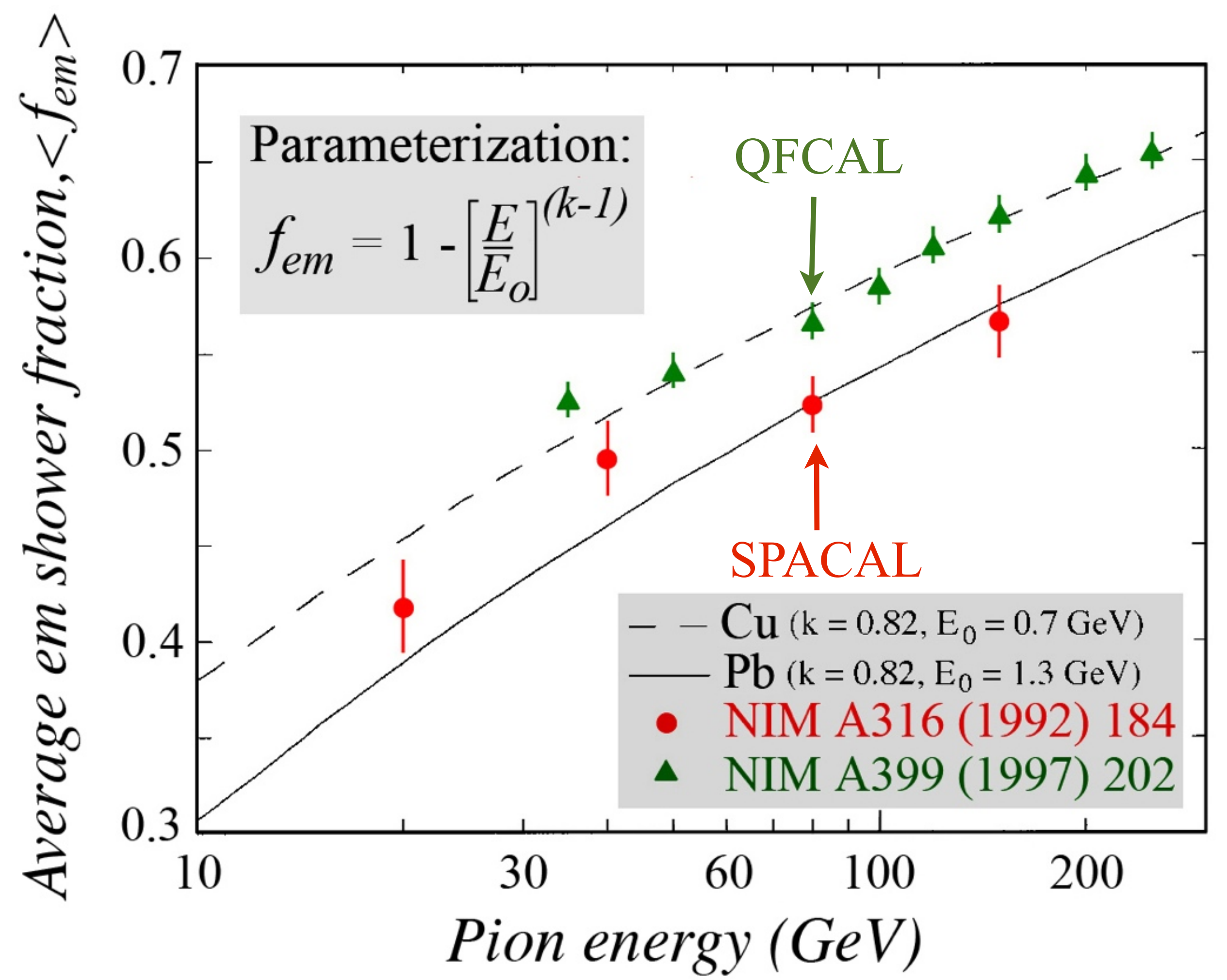
The Calorimeter Response



The calorimeter response to the two components are different. The e/h ratio quantifies the degree of the calorimeter response difference between two components.
For example, e/h=2 meant 50% of the non-em component is invisible.

Fluctuations of electromagnetic shower fraction





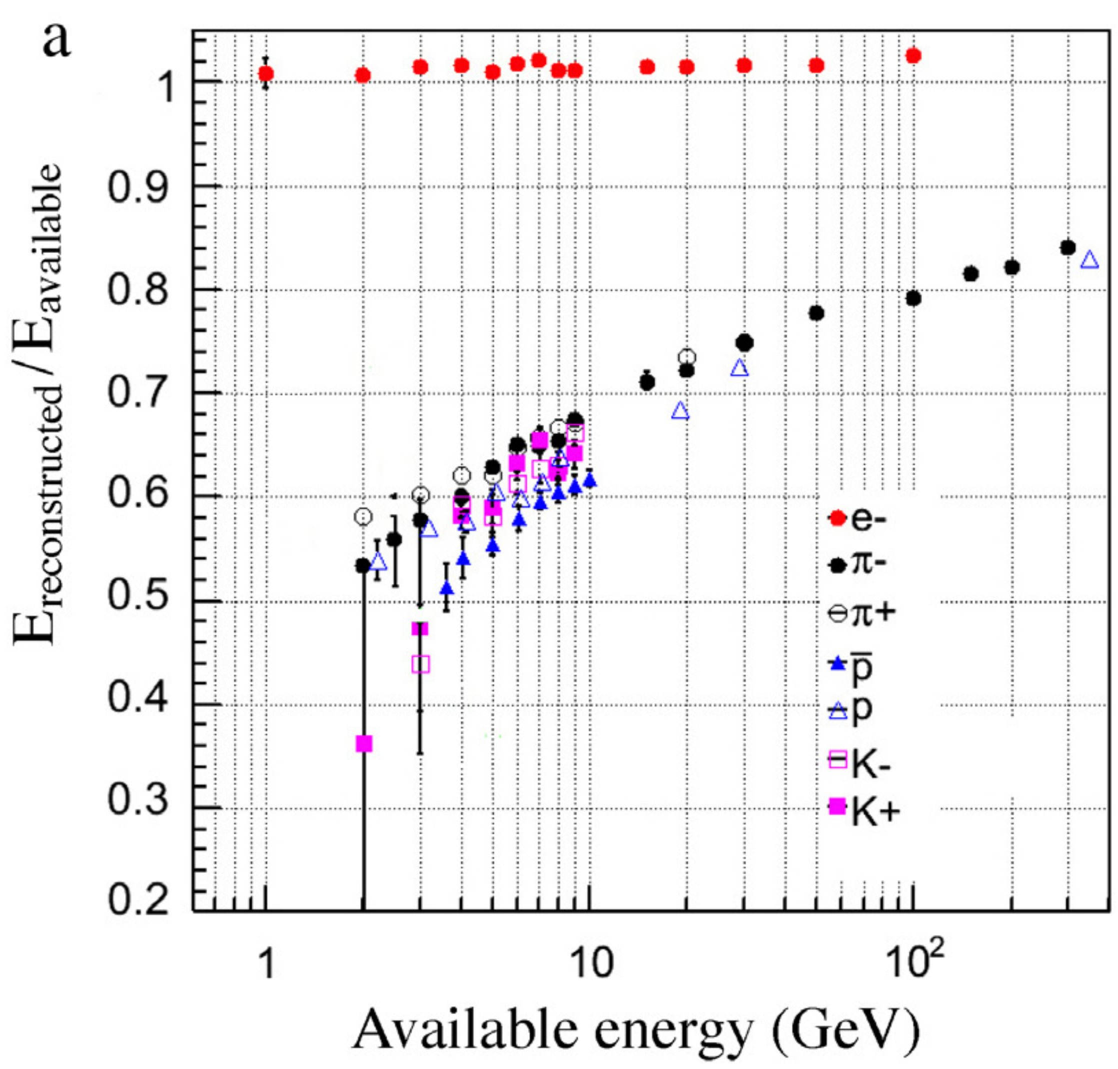
Large, non-Gaussian fluctuations in f_{em}

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

The hadronic performance of non-compensating calorimeter (e/h ≠1)

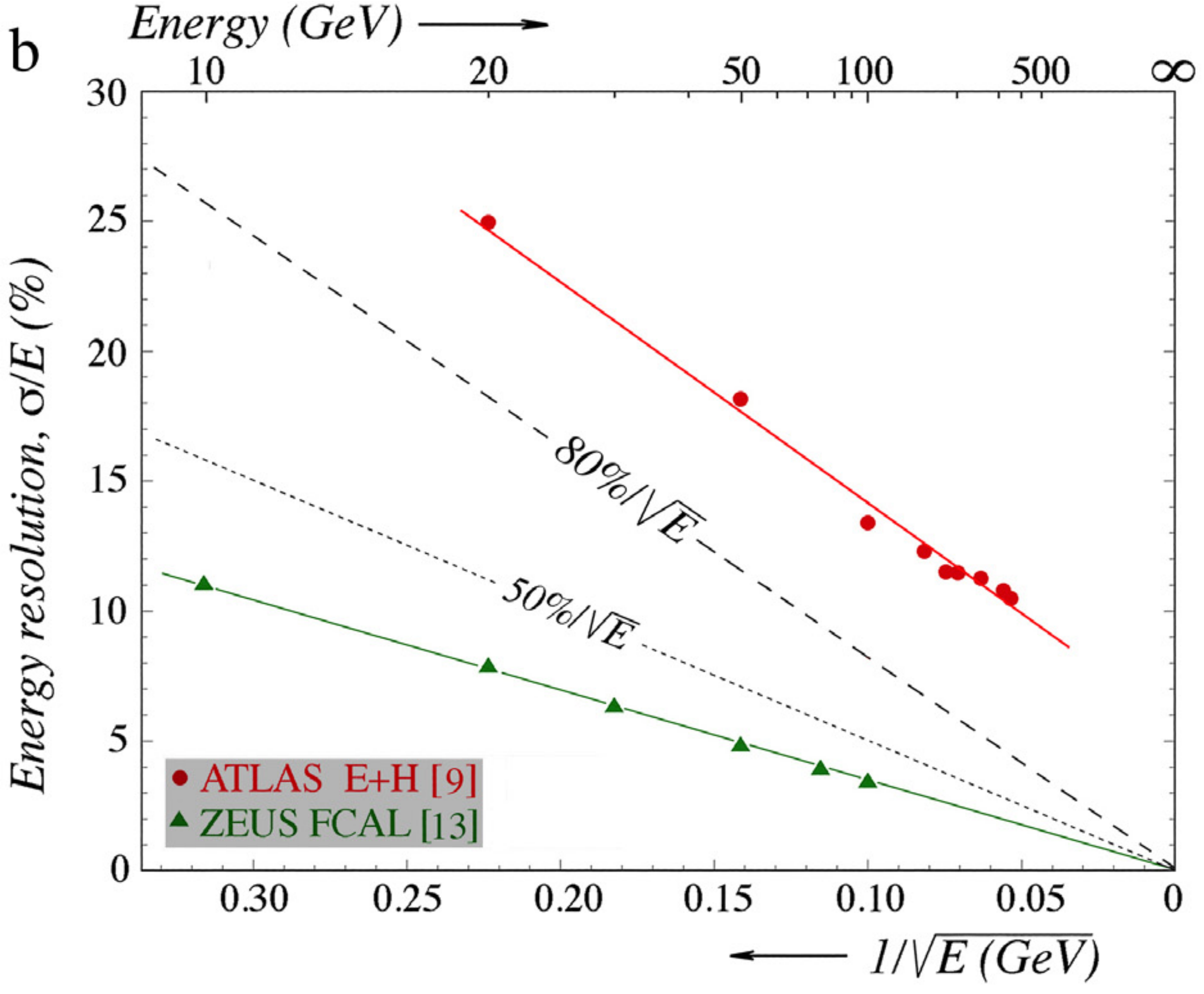
Non-linear response to hadrons

CMS Calorimeter



Deviation from 1/√E scaling in hadronic energy resolution

ATLAS Calorimeter



The Poor Performance of Hadron Calorimeter

↑

Nuclear binding energy losses (root cause)

Methods to remedy the poor hadronic performance

1. Compensation

- *the total kinetic energy of neutrons*

2. Dual-Readout

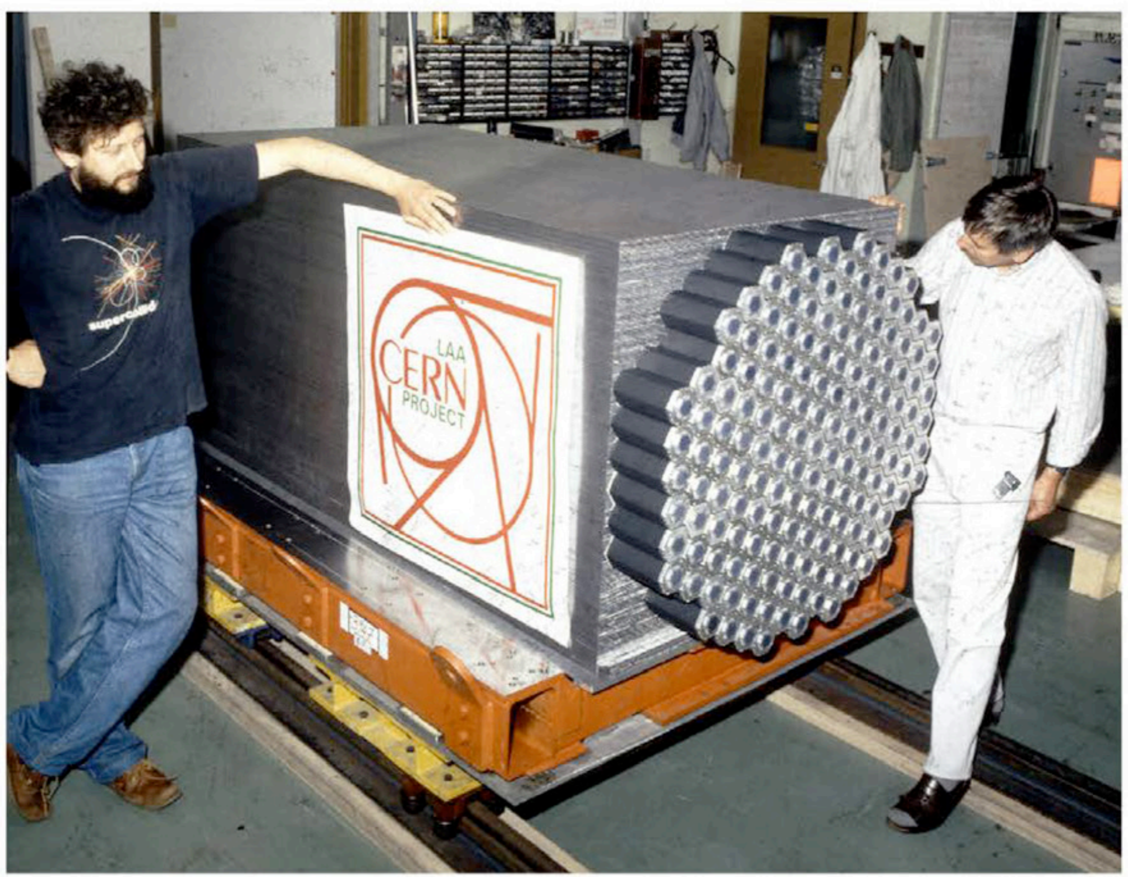
- *the electromagnetic shower fraction*

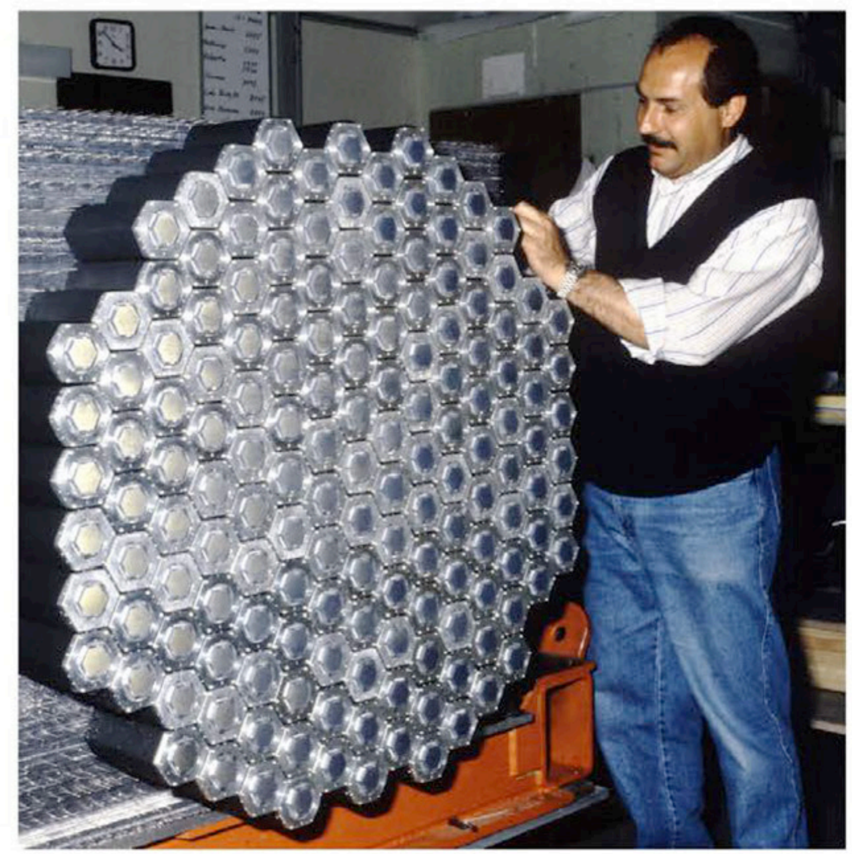
These are measurable quantities that are correlated to the binding energy losses

Compensation

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

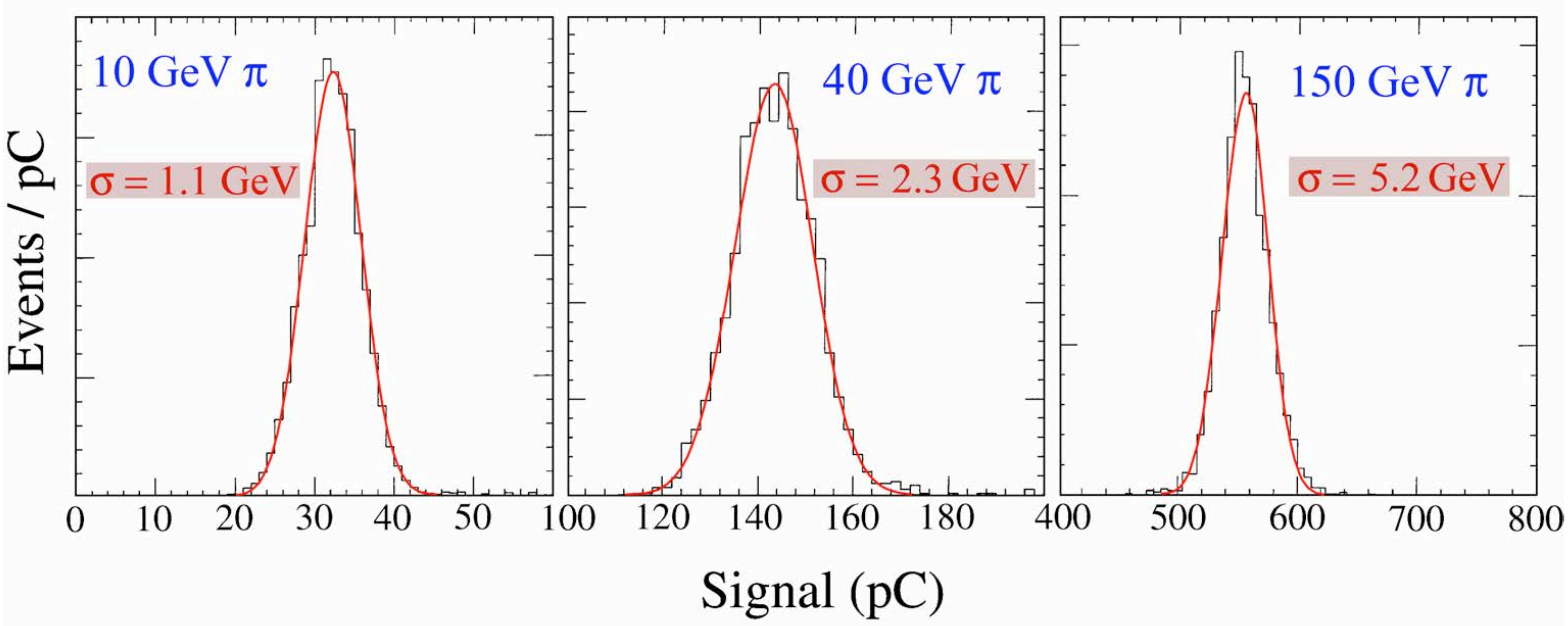
SPACAL 1989





Pb - plastic fibers
(4:1 volume ratio)

Hadronic signal distributions measured with SPACAL (Pb-Scintillation fiber) (Compensating Calorimeter)

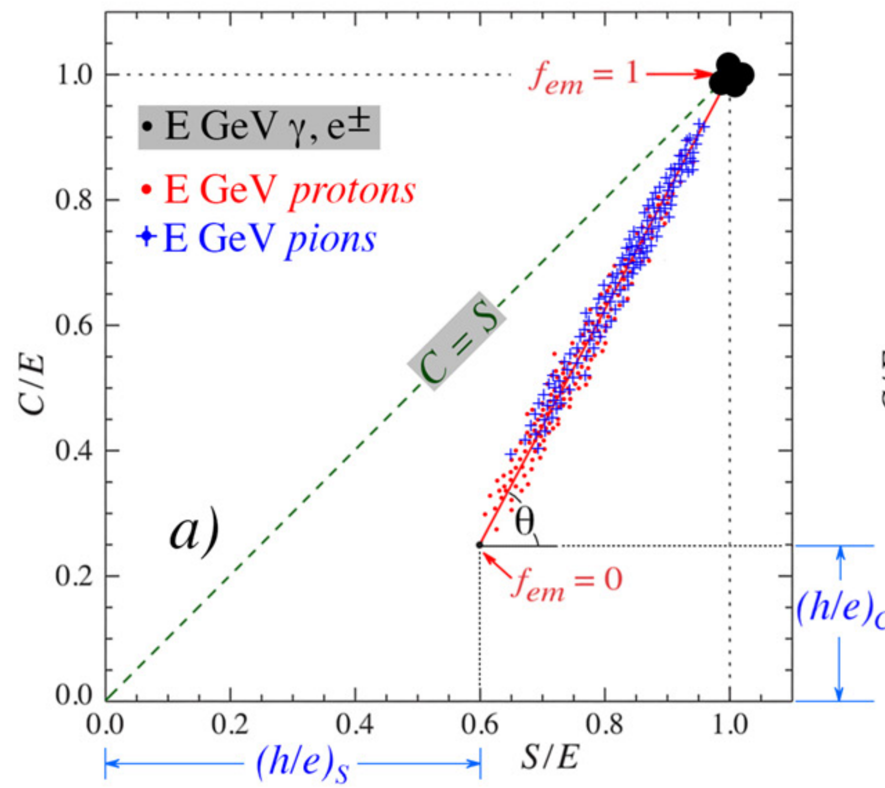


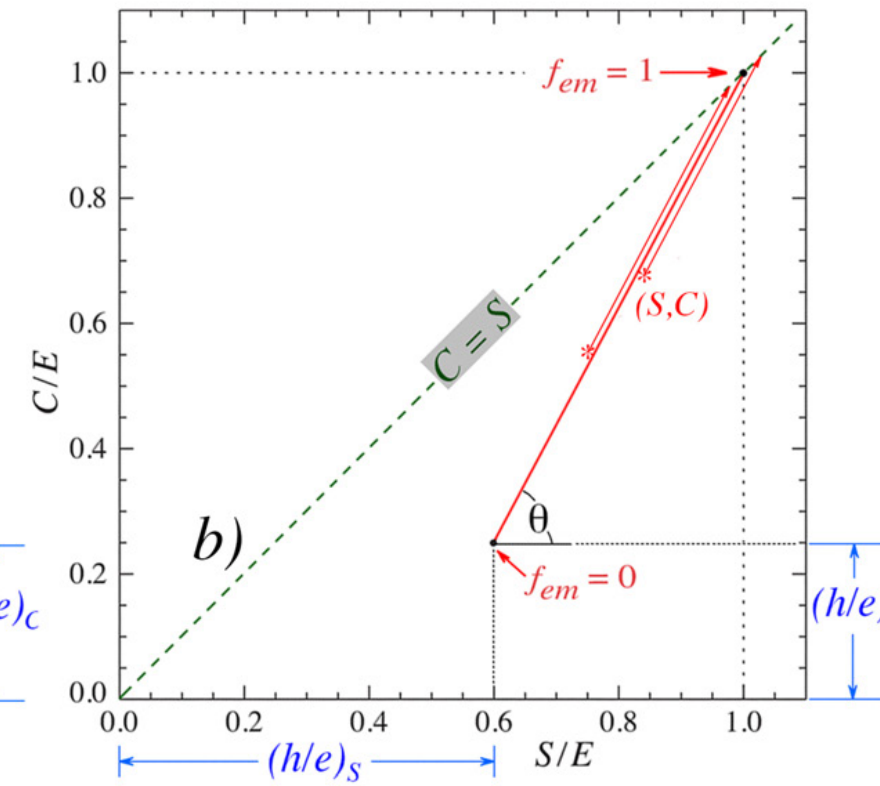
from: NIM A308 (1991) 481

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 such as the small sampling fraction, a large detector volume and a long signal integration time.

Dual-Readout Method



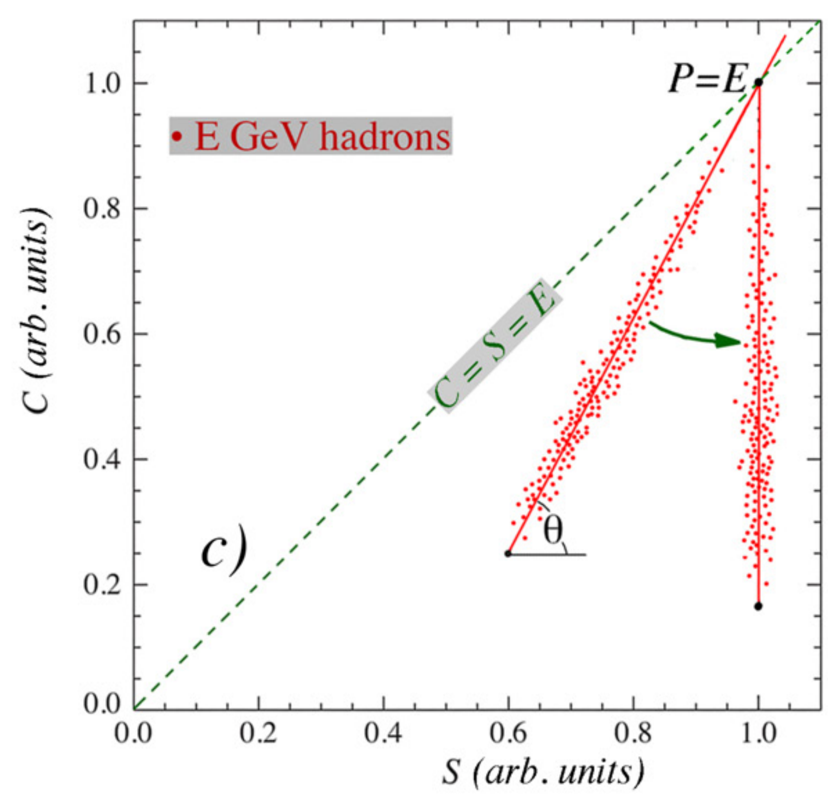


$$S = E\left[f_{\mathrm{em}} + \frac{1}{(e/h)_S}(1 - f_{\mathrm{em}})\right]$$

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

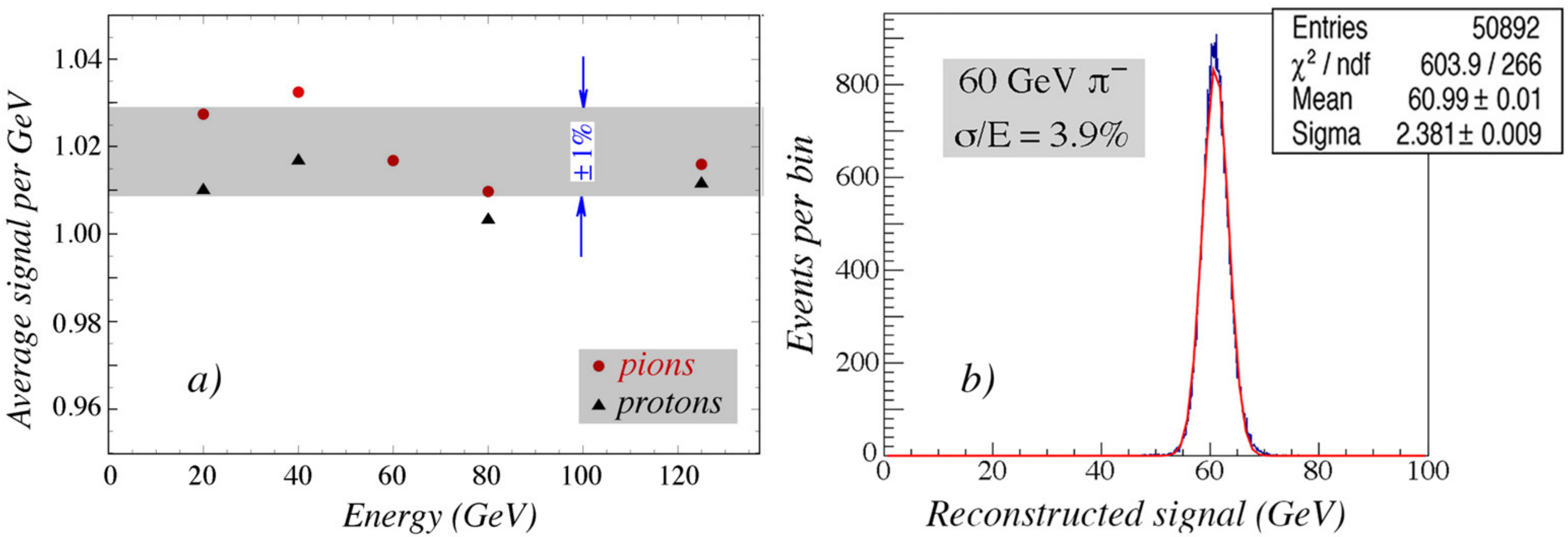
$$cotg\,\theta = \frac{1-(h/e)_S}{1-(h/e)_C} = \chi$$

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

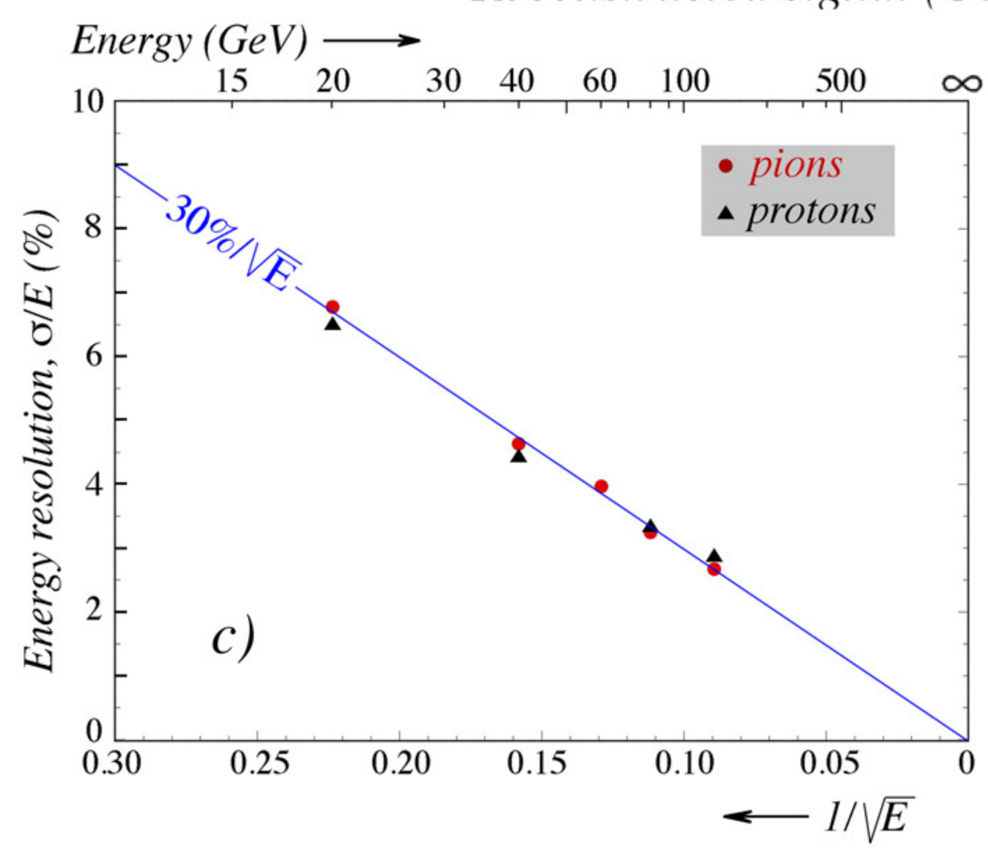


From: NIM A866 (2017) 76

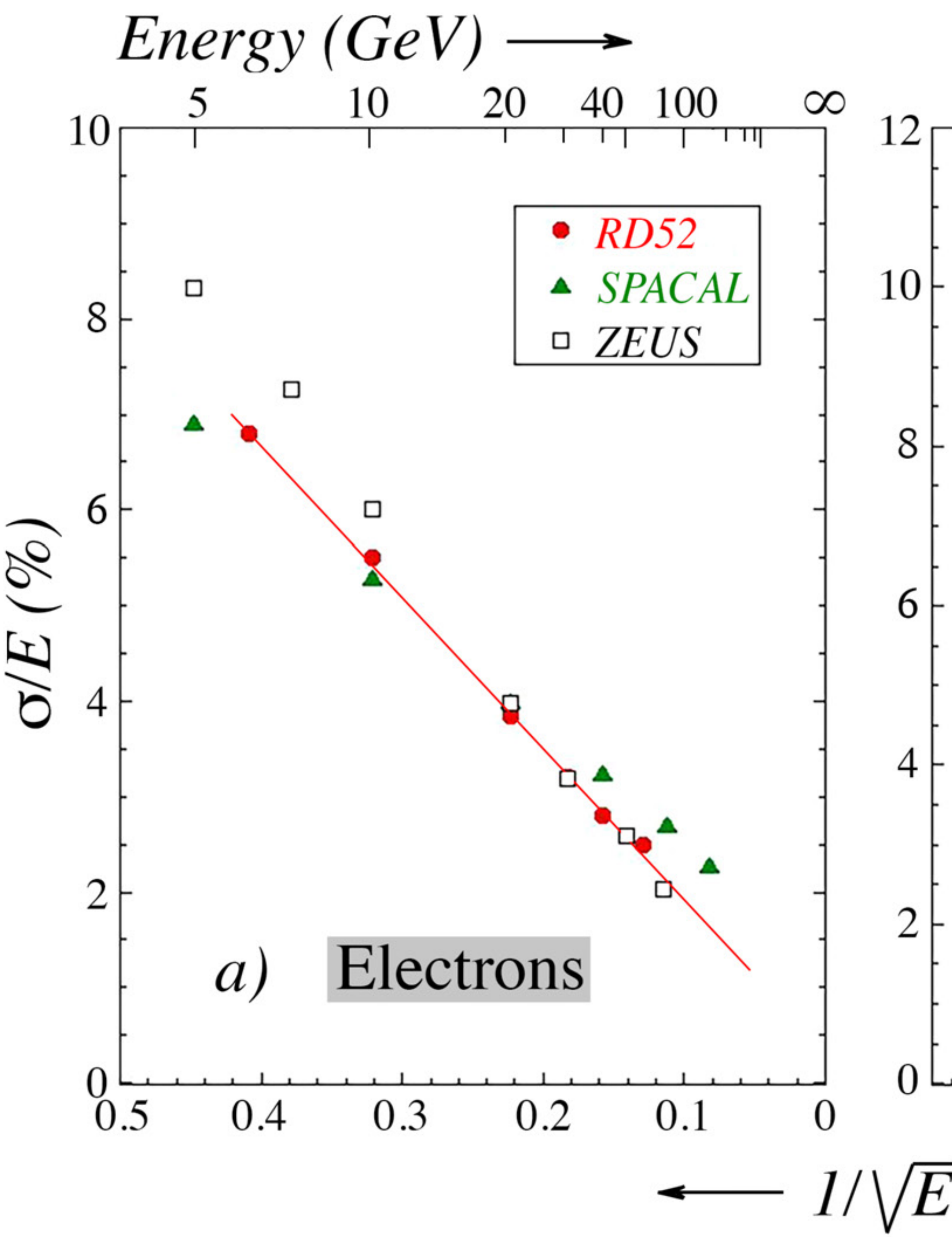
Hadronic Performance of a Dual-Readout Fiber Calorimeter



From:
NIM A866 (2017) 76



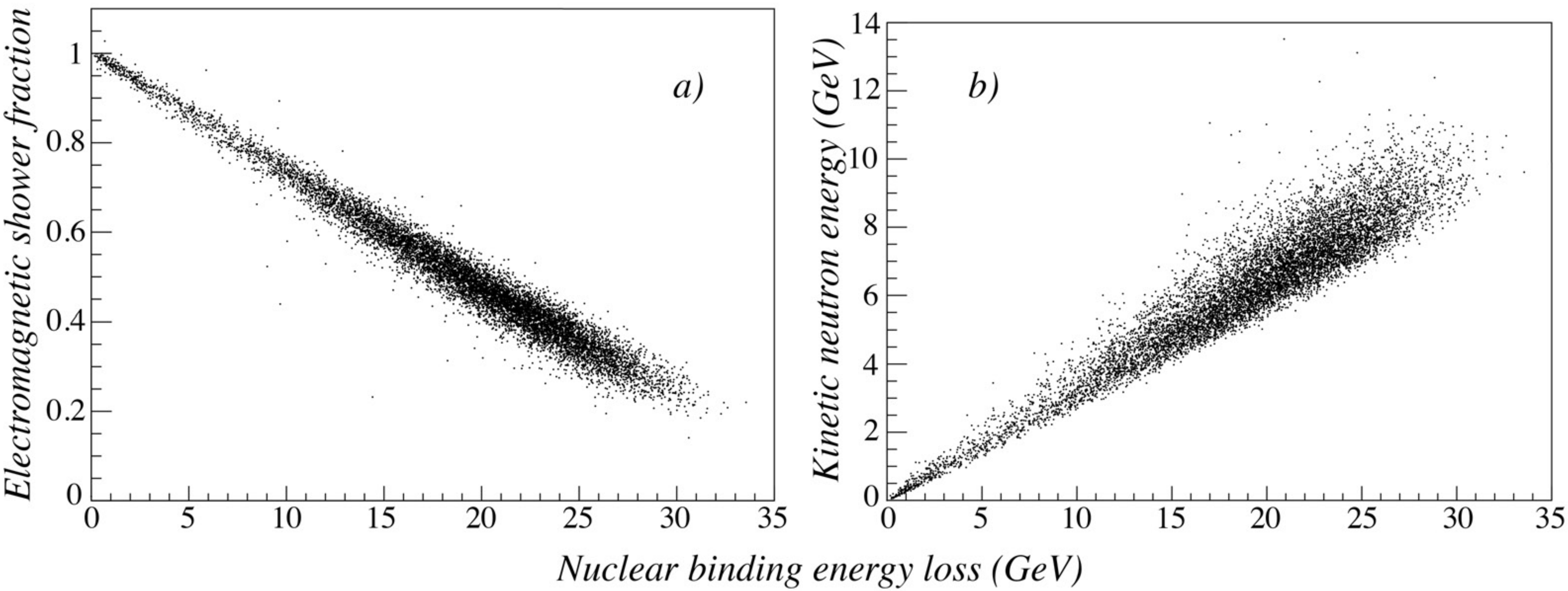
Comparison of Dual-Readout and Compensation



Prediction of the ultimate hadronic energy resolution

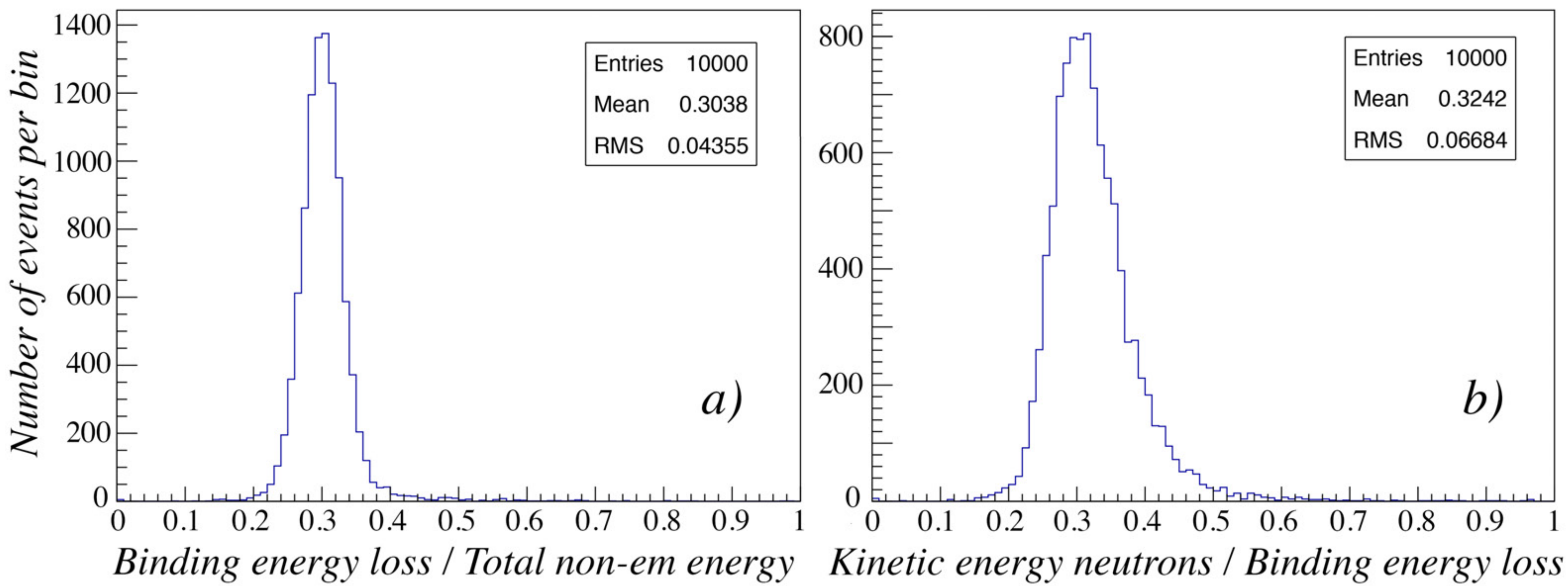
- GEANT 4.10.3-patch2
- FTFP_BERT physics list
- Very large absorber to contain the entire hadron shower
- 10, 20, 50, 100 GeV π^- sent to Cu and Pb (10,000 events)
- Obtained information in each event:
  - The em shower fraction
  - The total nuclear binding energy loss
  - The total kinetic energy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

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



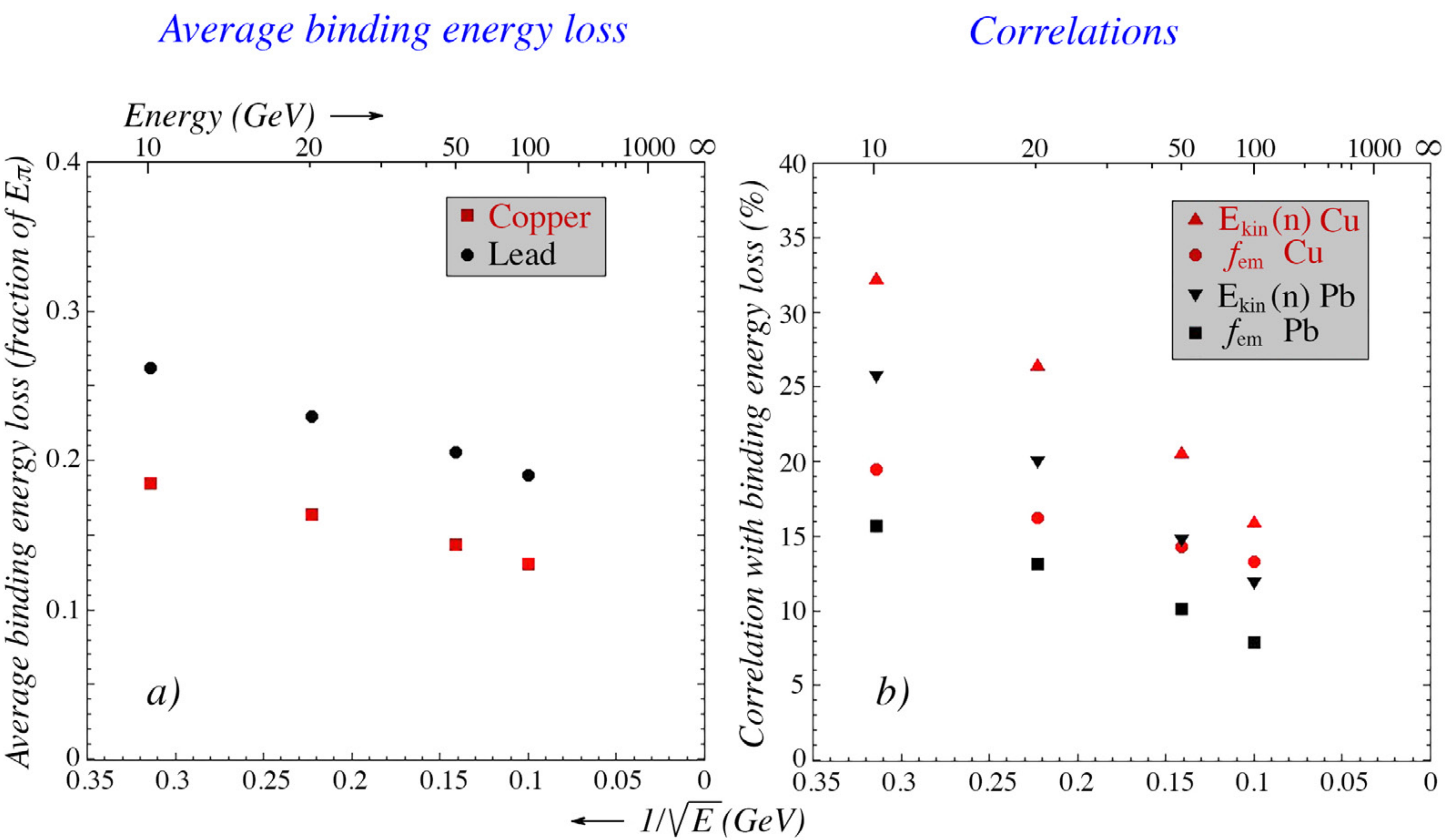
Results are for 100 GeV π- in lead absorber

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

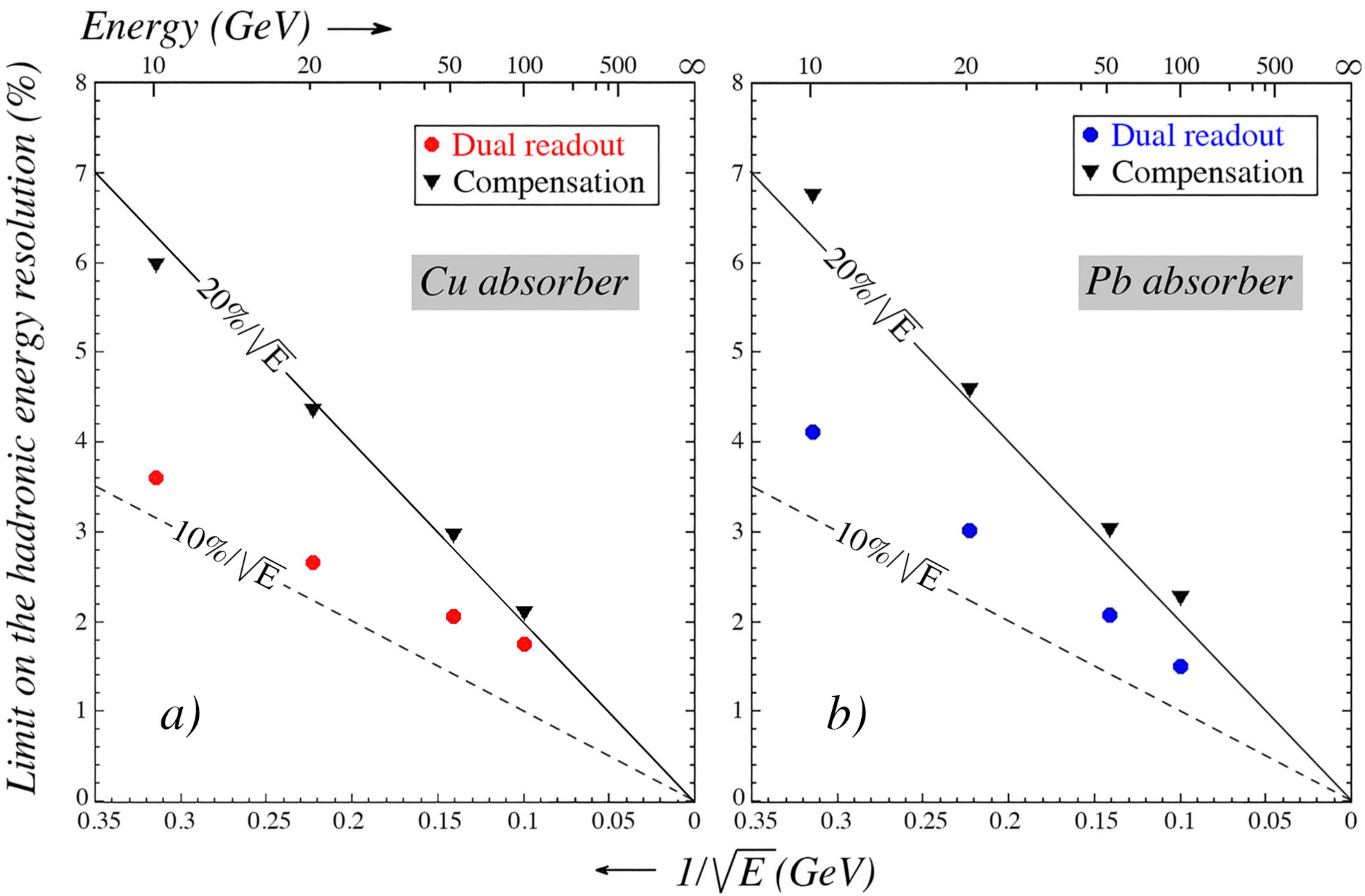


Results are for 50 GeV π^- in copper

Energy dependence



Limit on the ultimate hadronic energy resolution



Conclusion

- Dual-readout and compensation approaches remedy the poor hadronic performance caused by fluctuations of the invisible energy losses

- The good energy resolution, signal linearity, Gaussian response functions and the same calorimeter response to electrons, pions and protons are the characteristic of these two methods in the hadron calorimetry

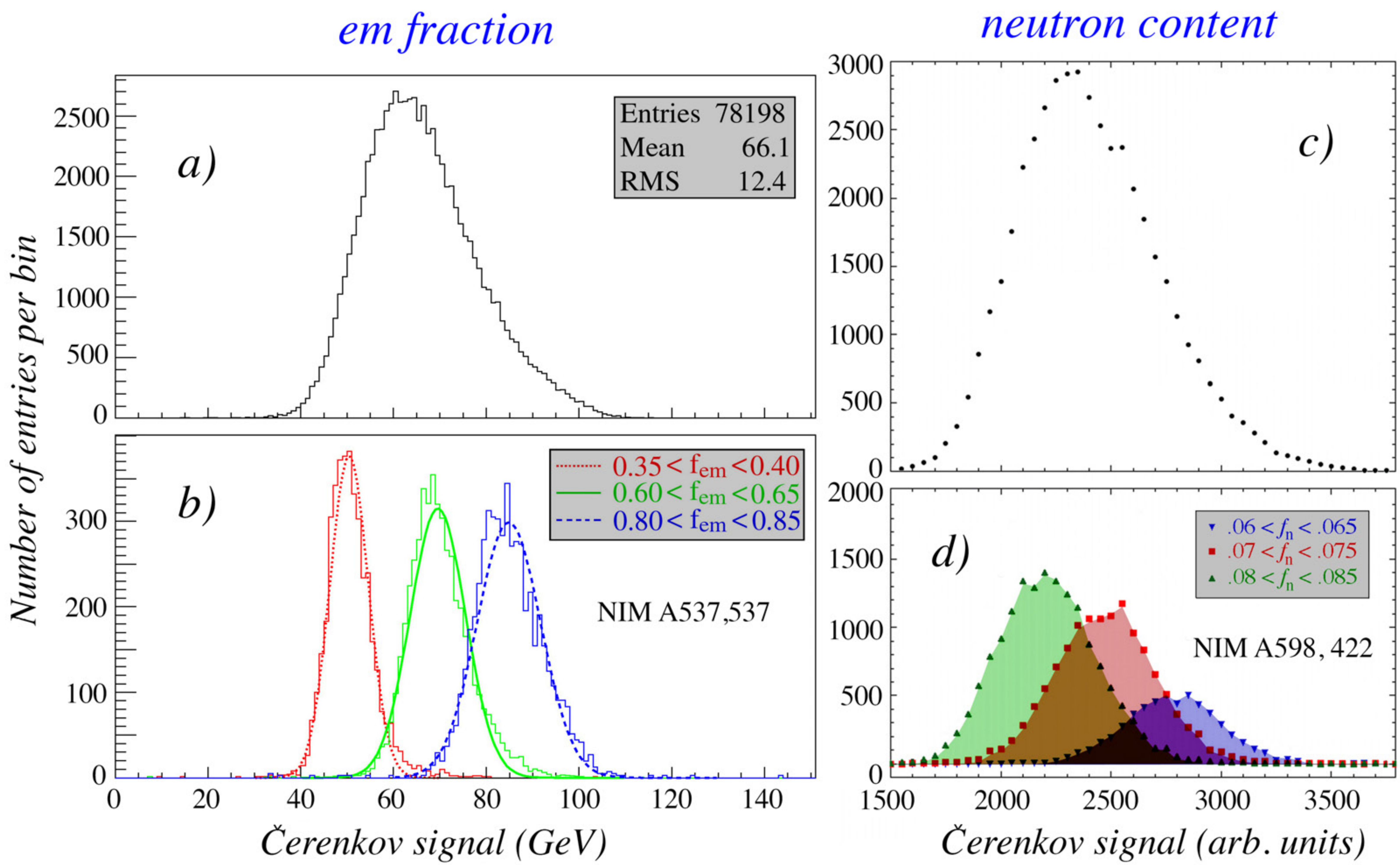
- Dual-readout is better than compensation

- The hadronic energy resolution 20%/$\sqrt{E}$ can be achieved

- Nucl. Instr. and Meth. in Phys. Res. A 882 (2018) 148

Backup

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



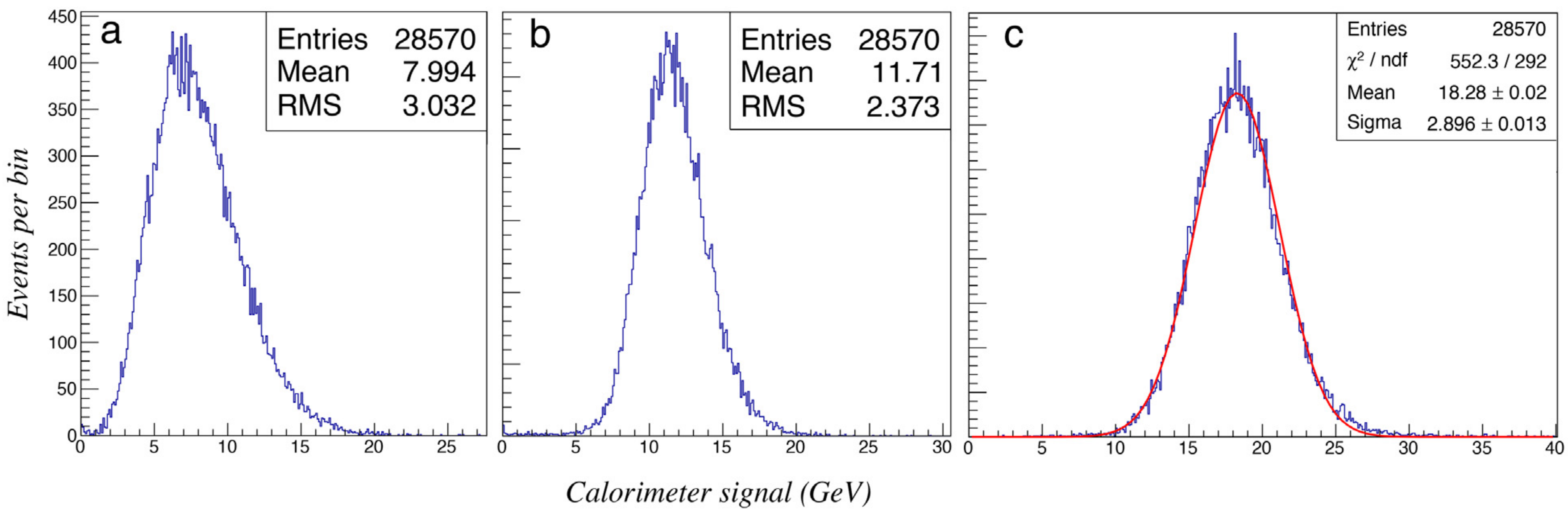


Fig. 11. Signal distributions for 20 GeV π^- particles. Shown are the measured Čerenkov (a) and scintillation (b) signal distributions as well as the signal distribution obtained by combining the two signals according to Eq. (2), using $\chi = 0.45$ (c).