On the limits of the hadronic energy resolution of calorimeters

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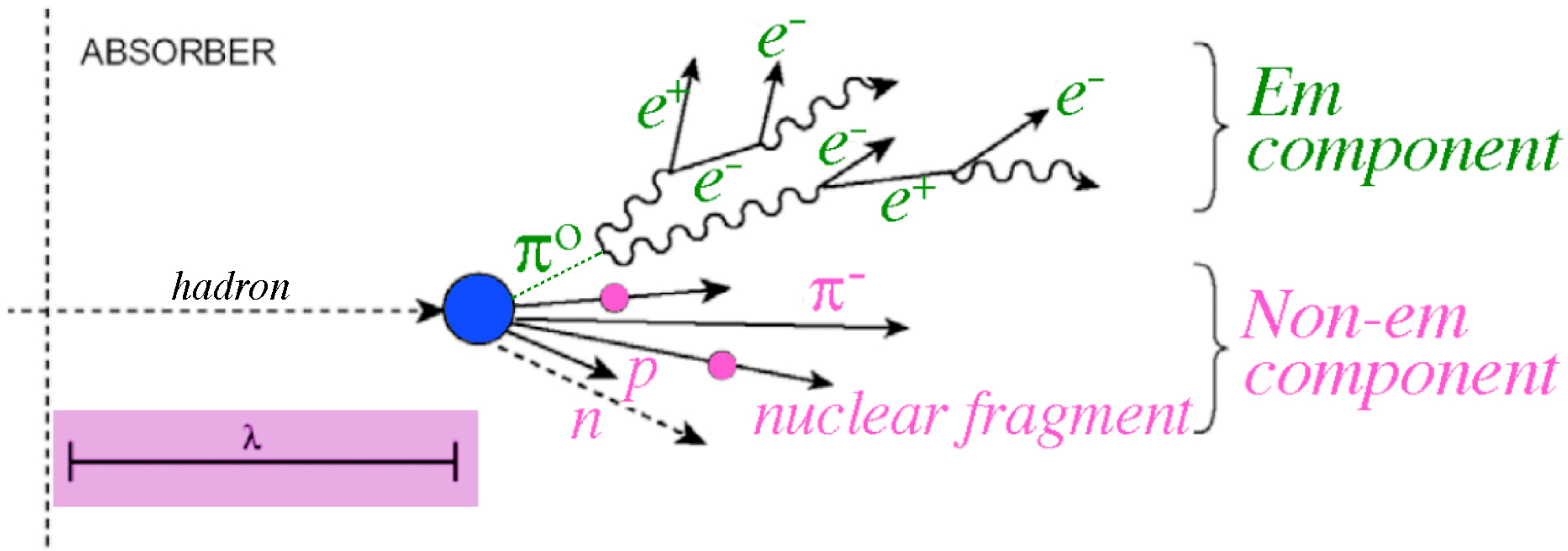
The Physics of Hadron Shower Development



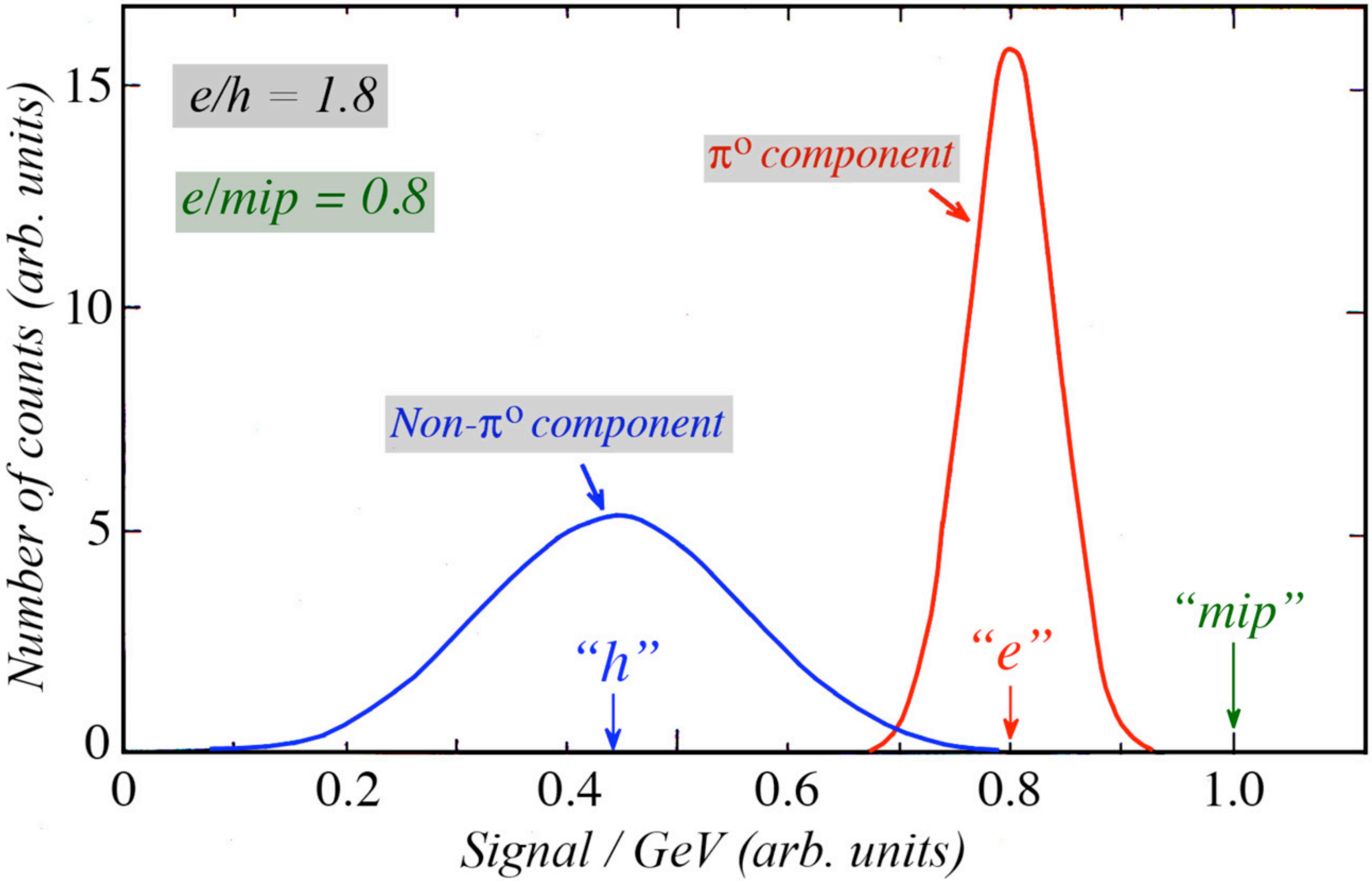
- *Electromagnetic component*
  - electrons, photons
  - neutral pions → 2 γ

- *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***

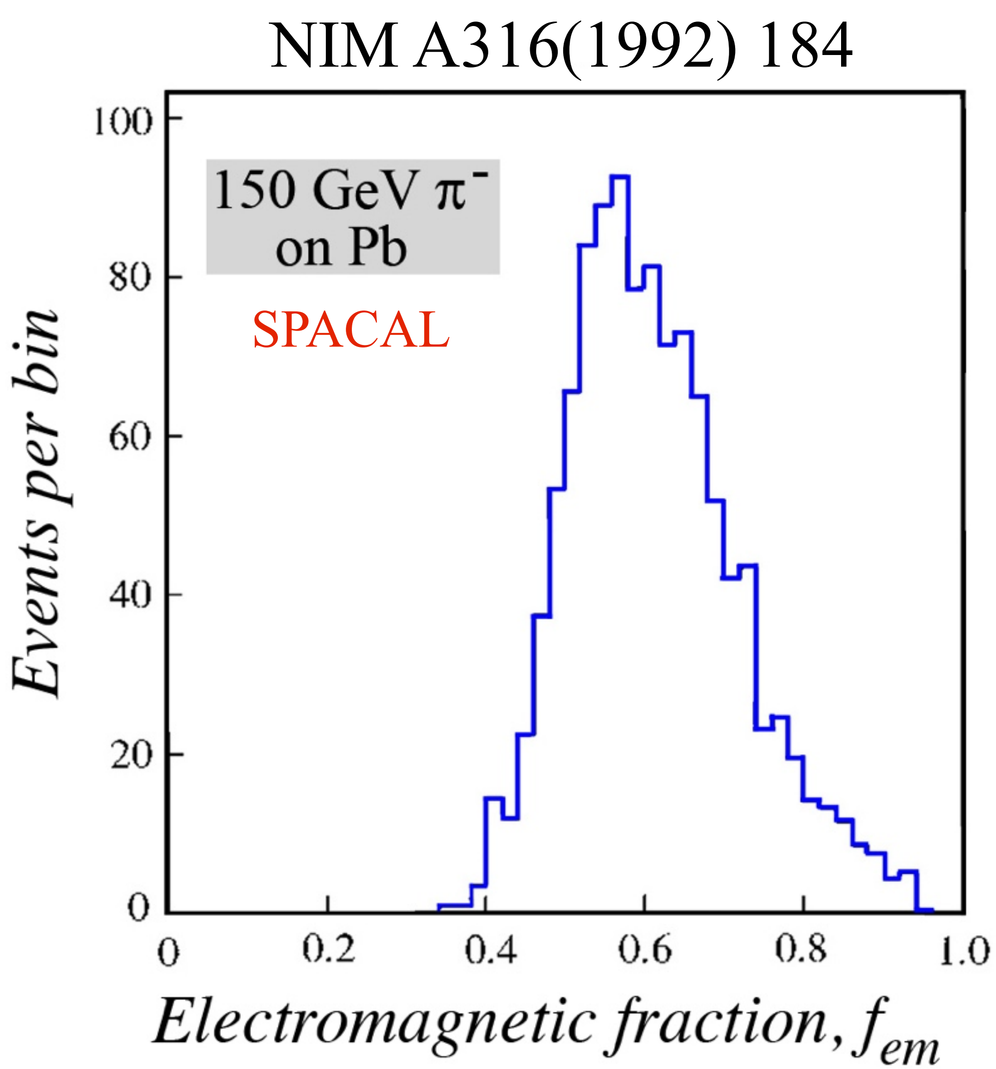
- ***Responsible for the Fluctuations of Hadron Showers***

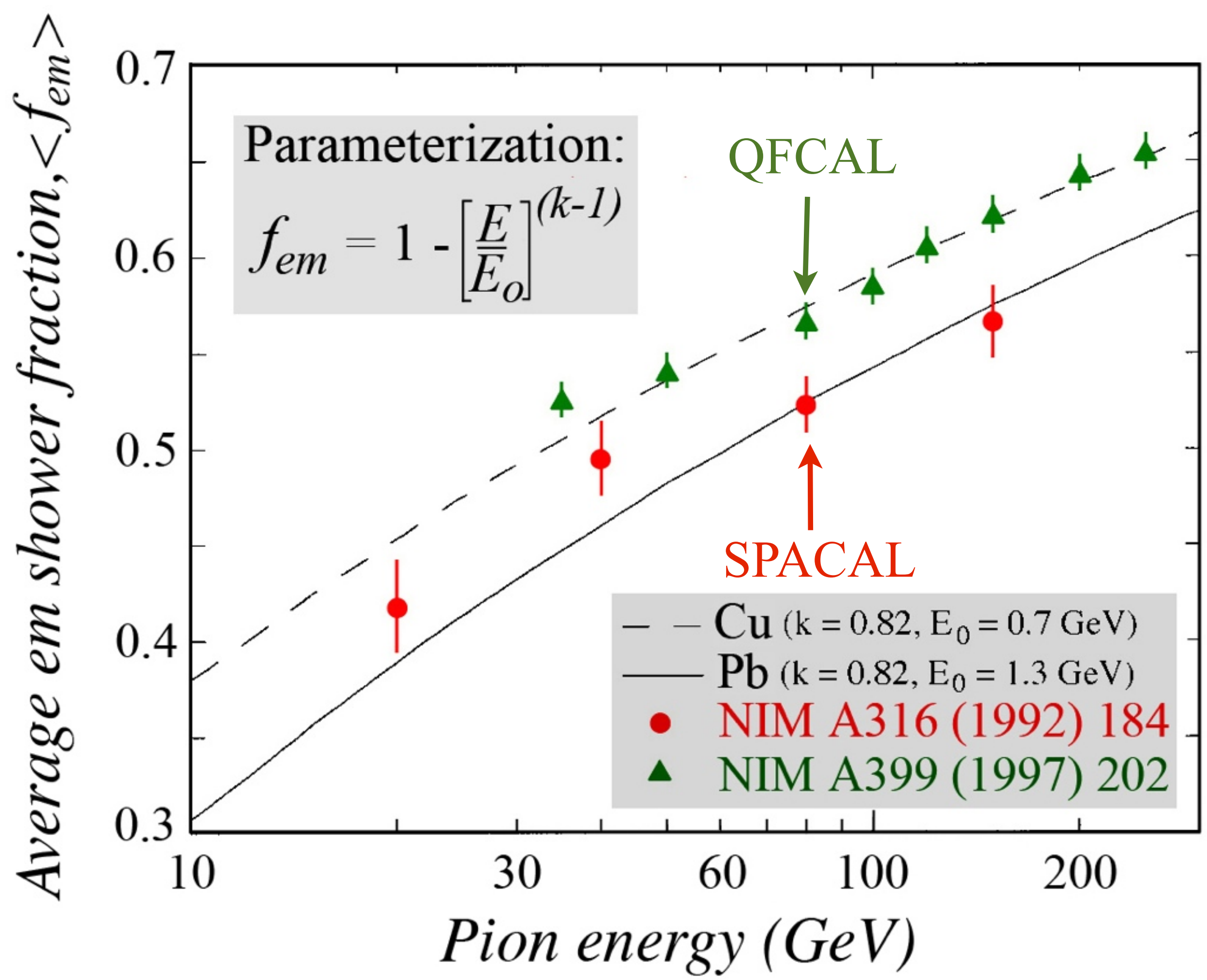
The Calorimeter Response



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

Fluctuations of electromagnetic shower fraction

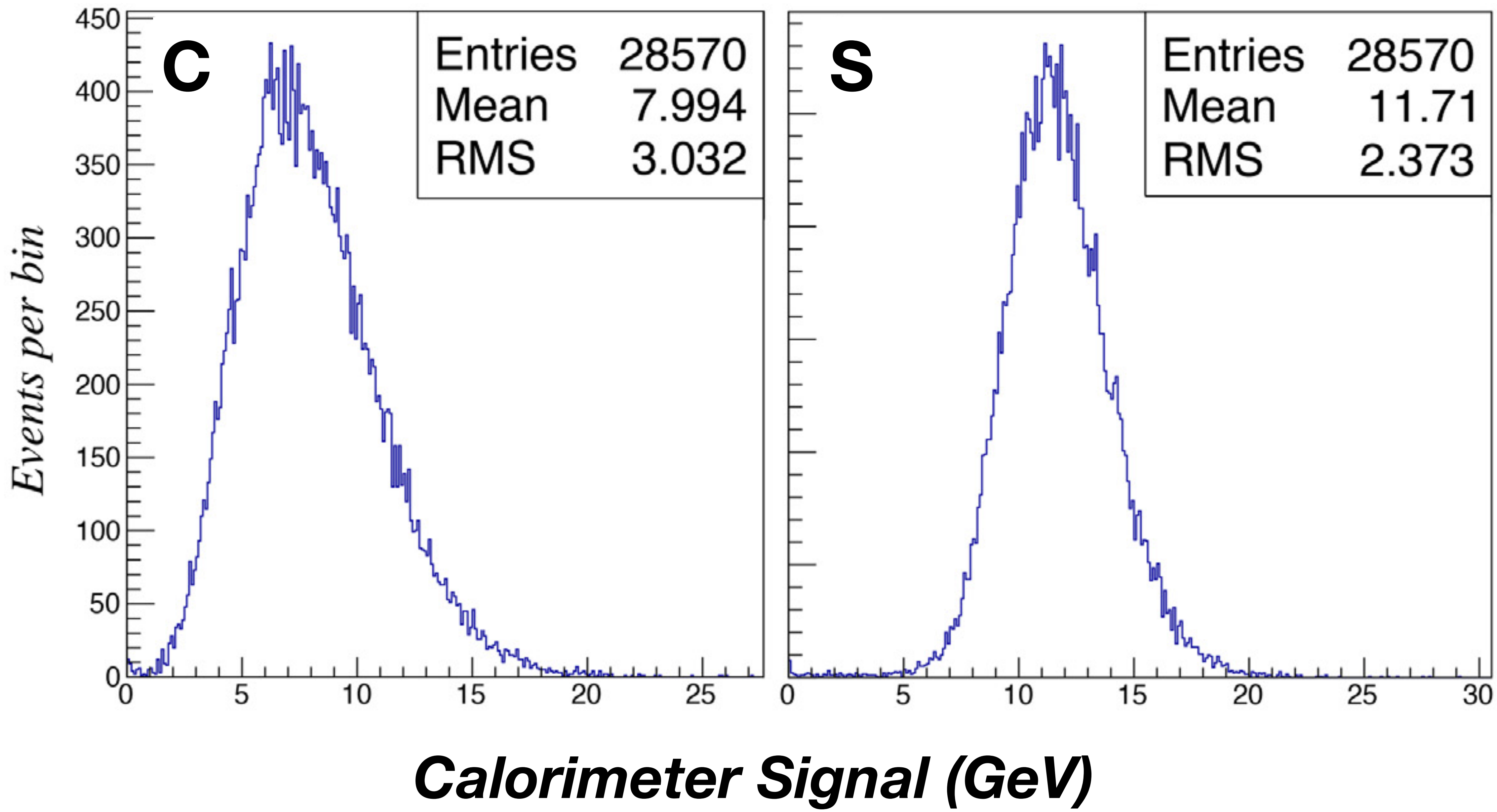




Large, non-Gaussian fluctuations in f_{em}

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

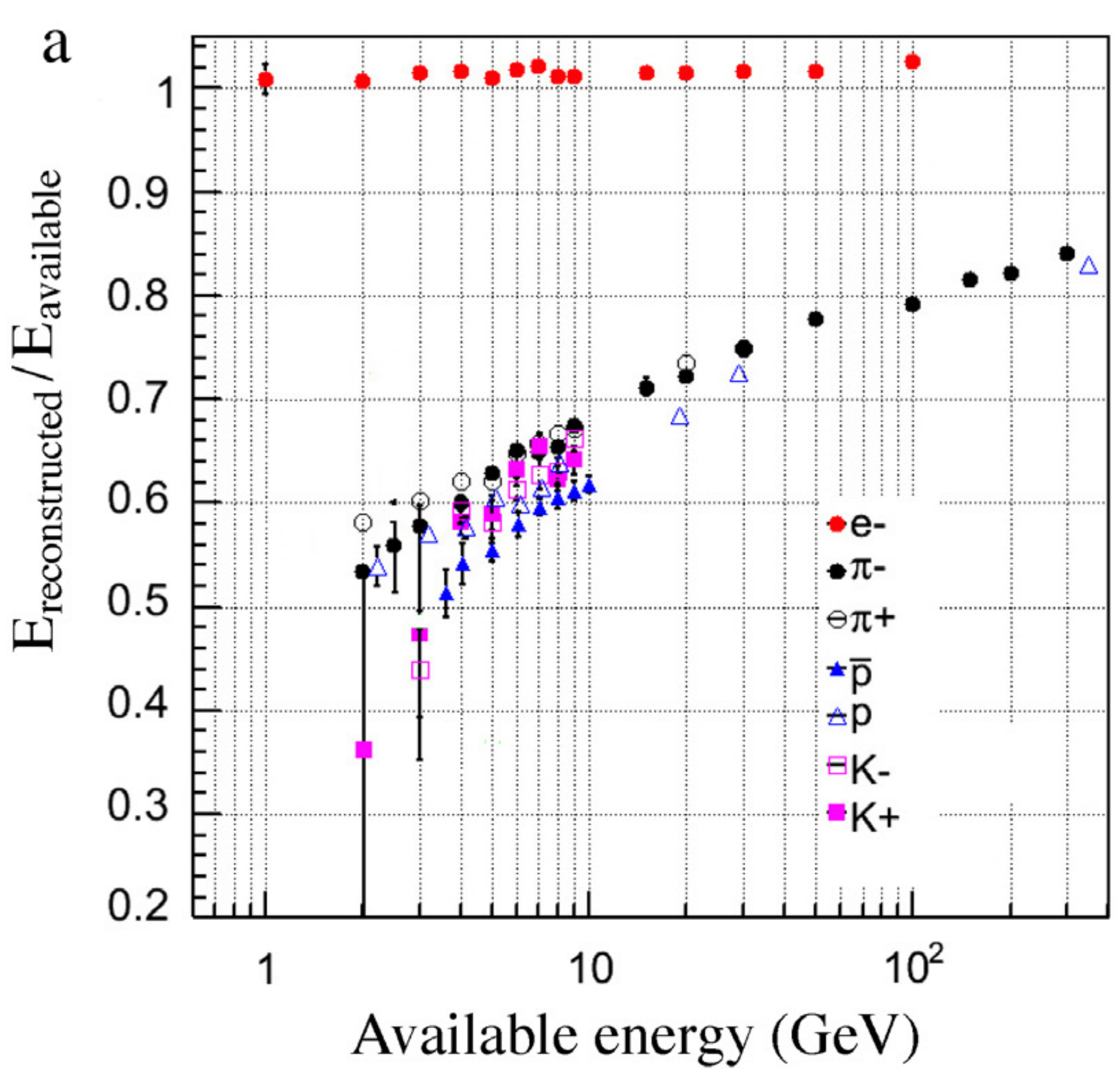
20 GeV π^-
(Pb-fiber RD52 calorimeter)



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

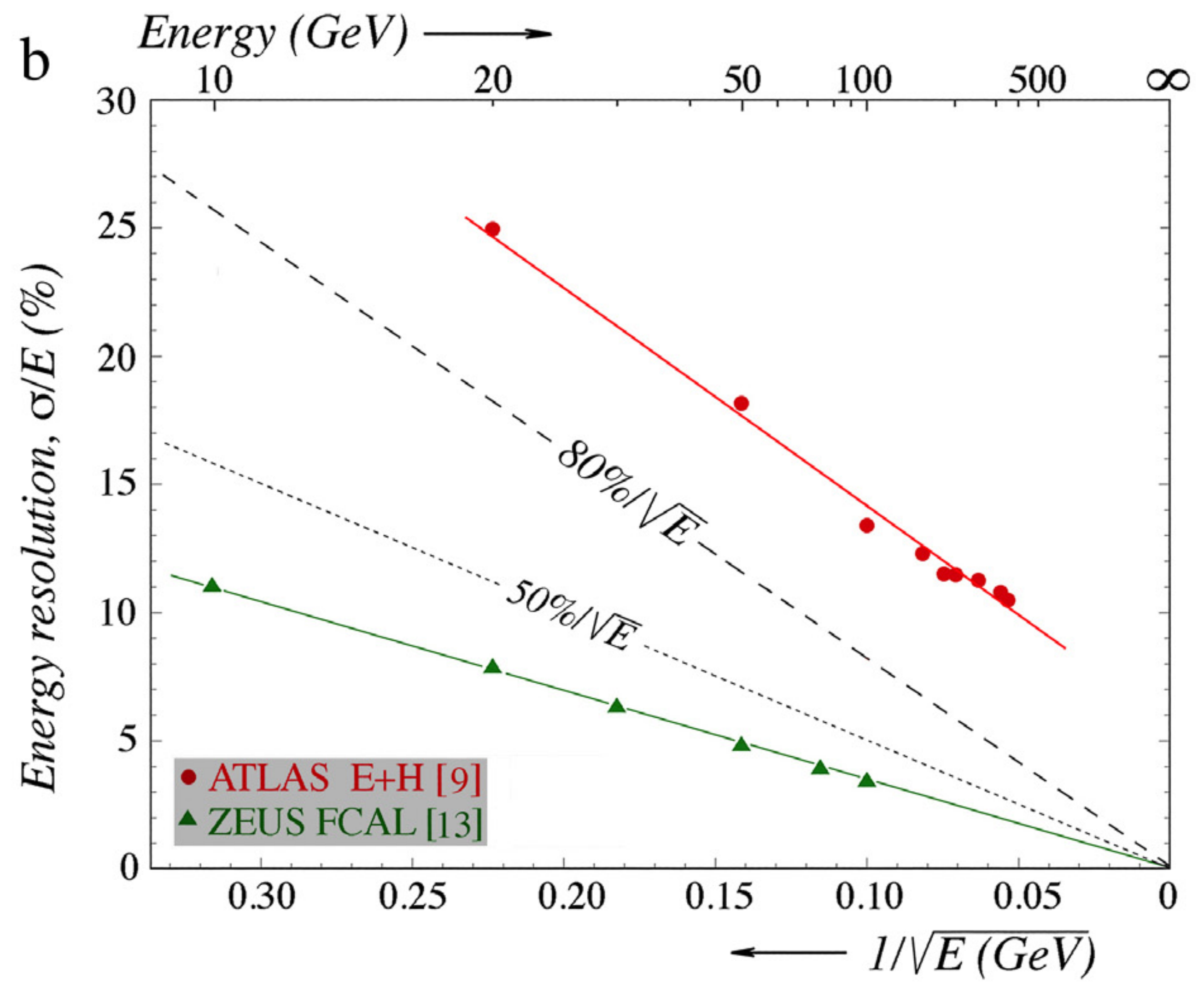
Non-linear response to hadrons

CMS Calorimeter



Deviation from 1/√E scaling in hadronic energy resolution

ATLAS Calorimeter



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

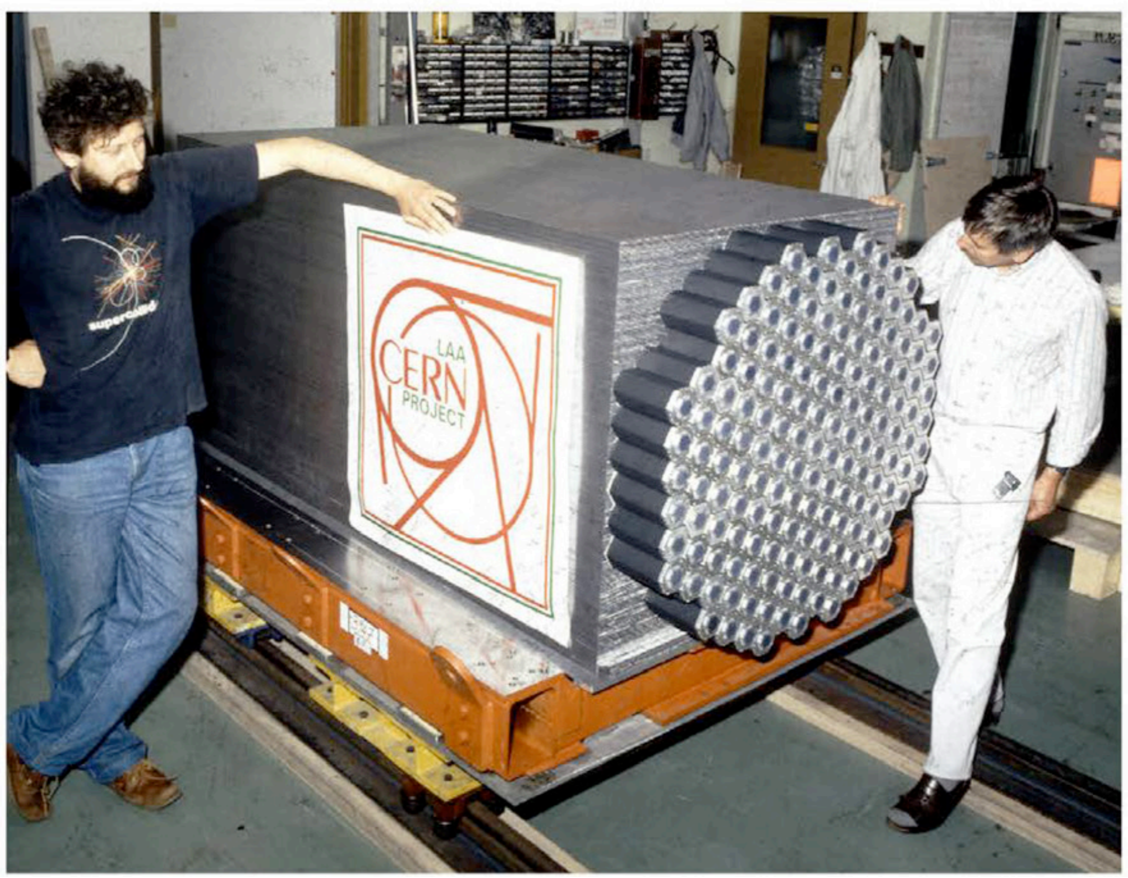
- *the electromagnetic shower fraction*

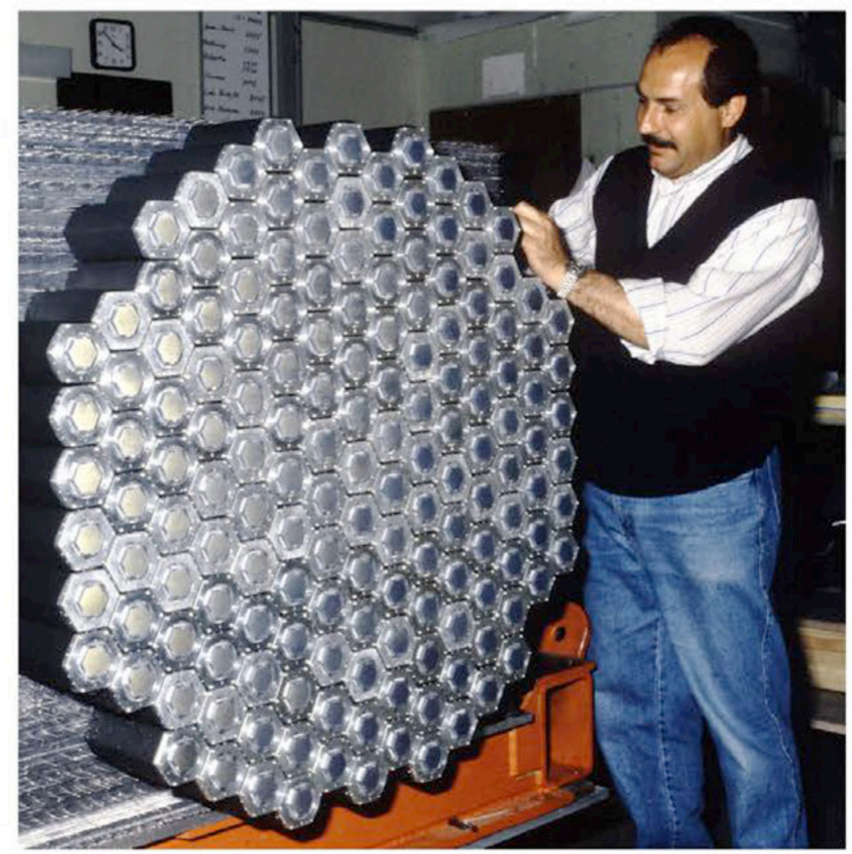
These are measurable quantities that are correlated to the binding energy losses

Compensation

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

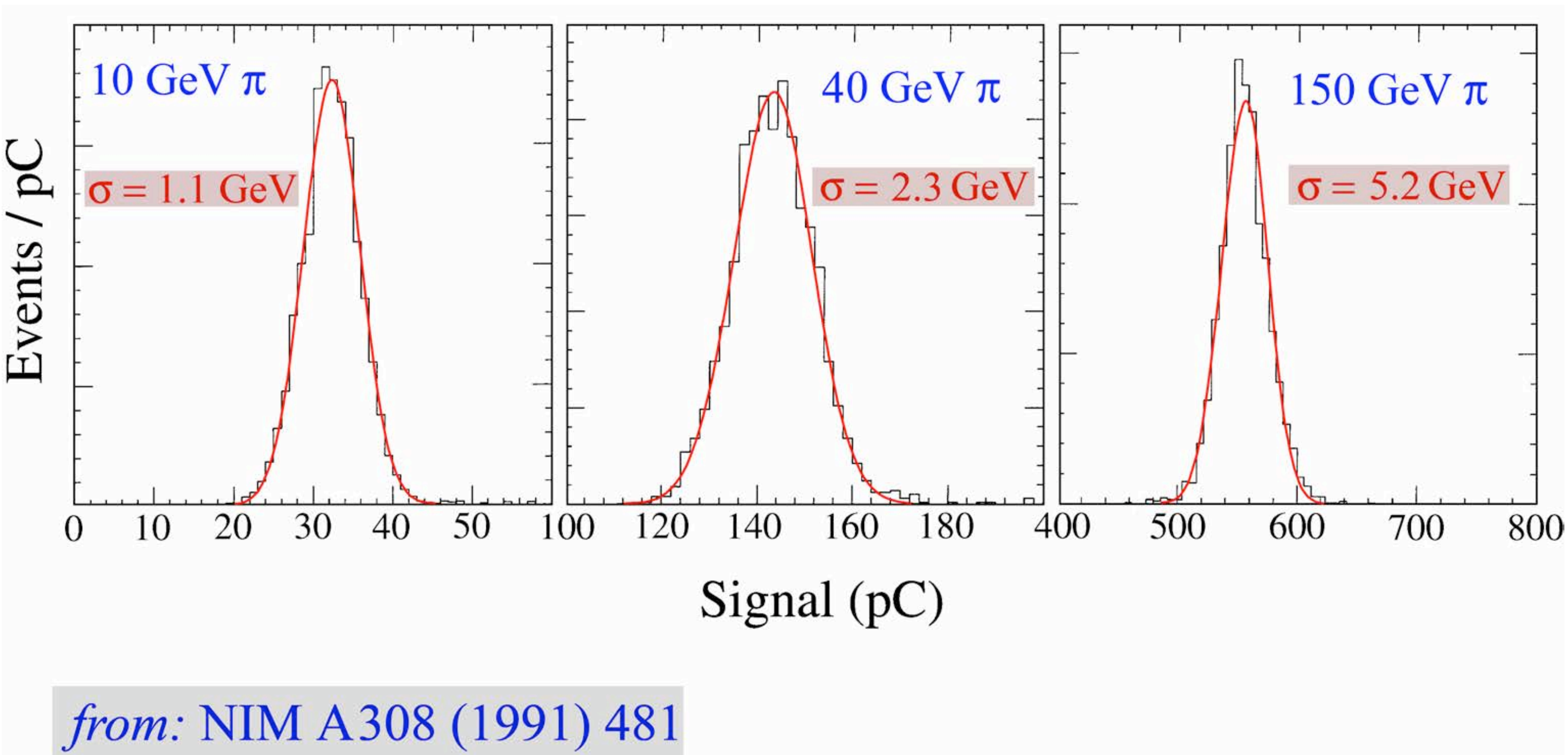
SPACAL 1989





Pb - plastic fibers
(4:1 volume ratio)

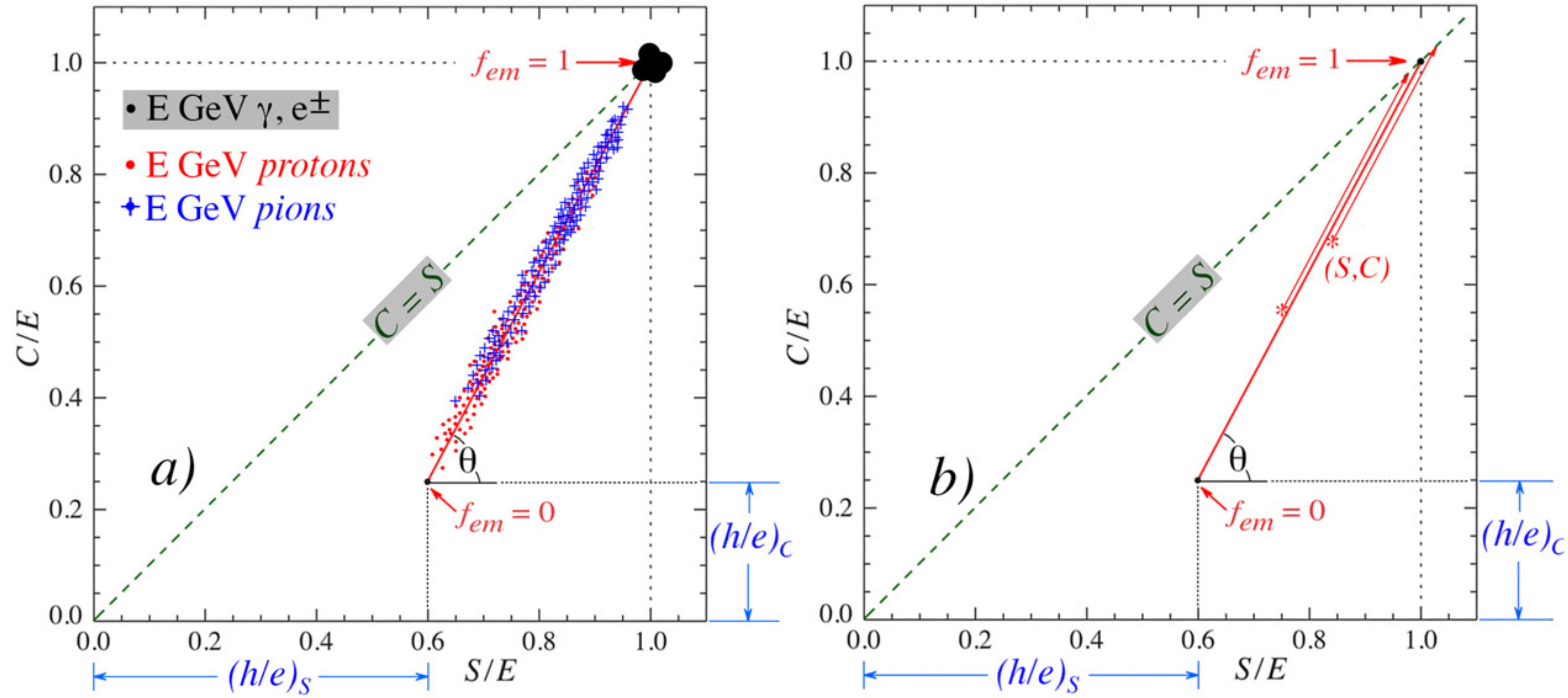
Hadronic signal distributions measured with SPACAL (Pb-Scintillation fiber) (Compensating Calorimeter)



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

Dual-Readout Method



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

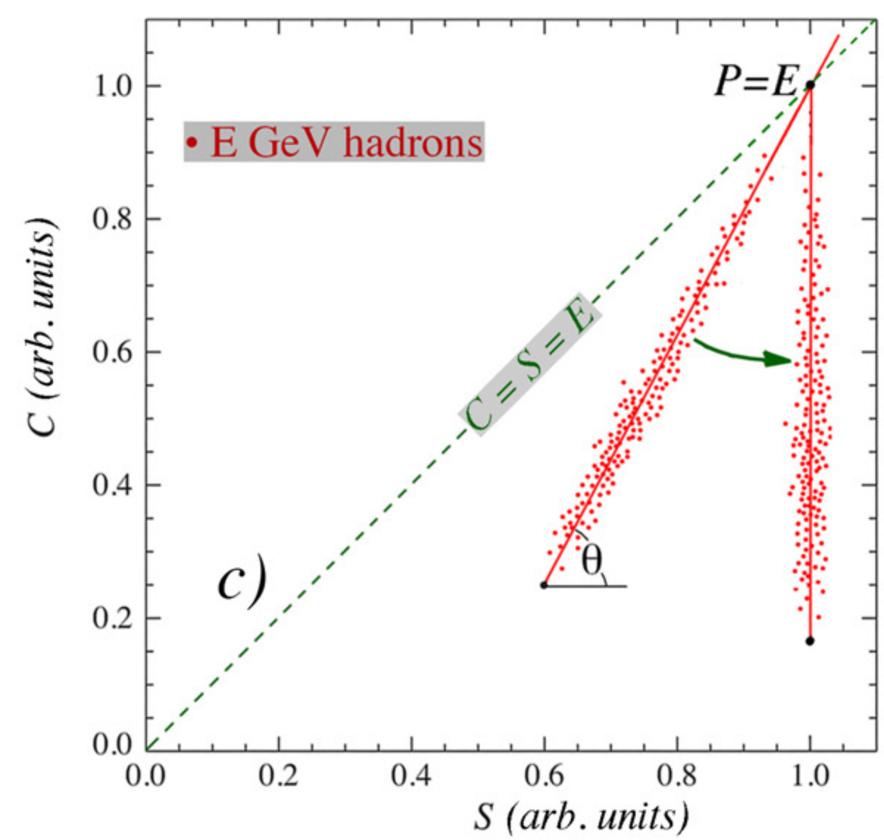
$$C = E\left[f_{\rm em} + \frac{1}{(e/h)_C}(1 - f_{\rm em})\right]$$

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

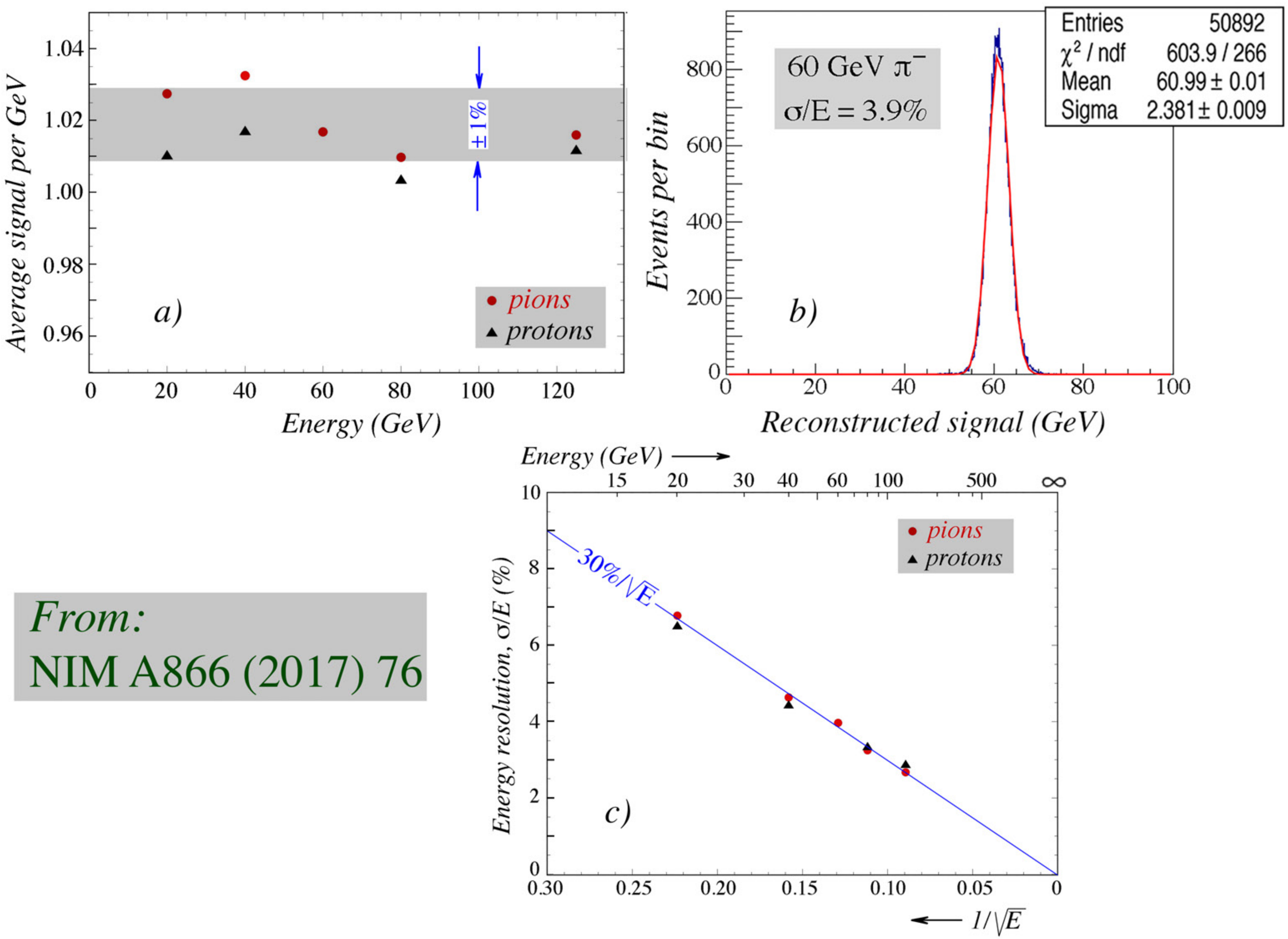
$$E = \frac{S - \chi C}{1 - \chi}$$

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

From: NIM A866 (2017) 76

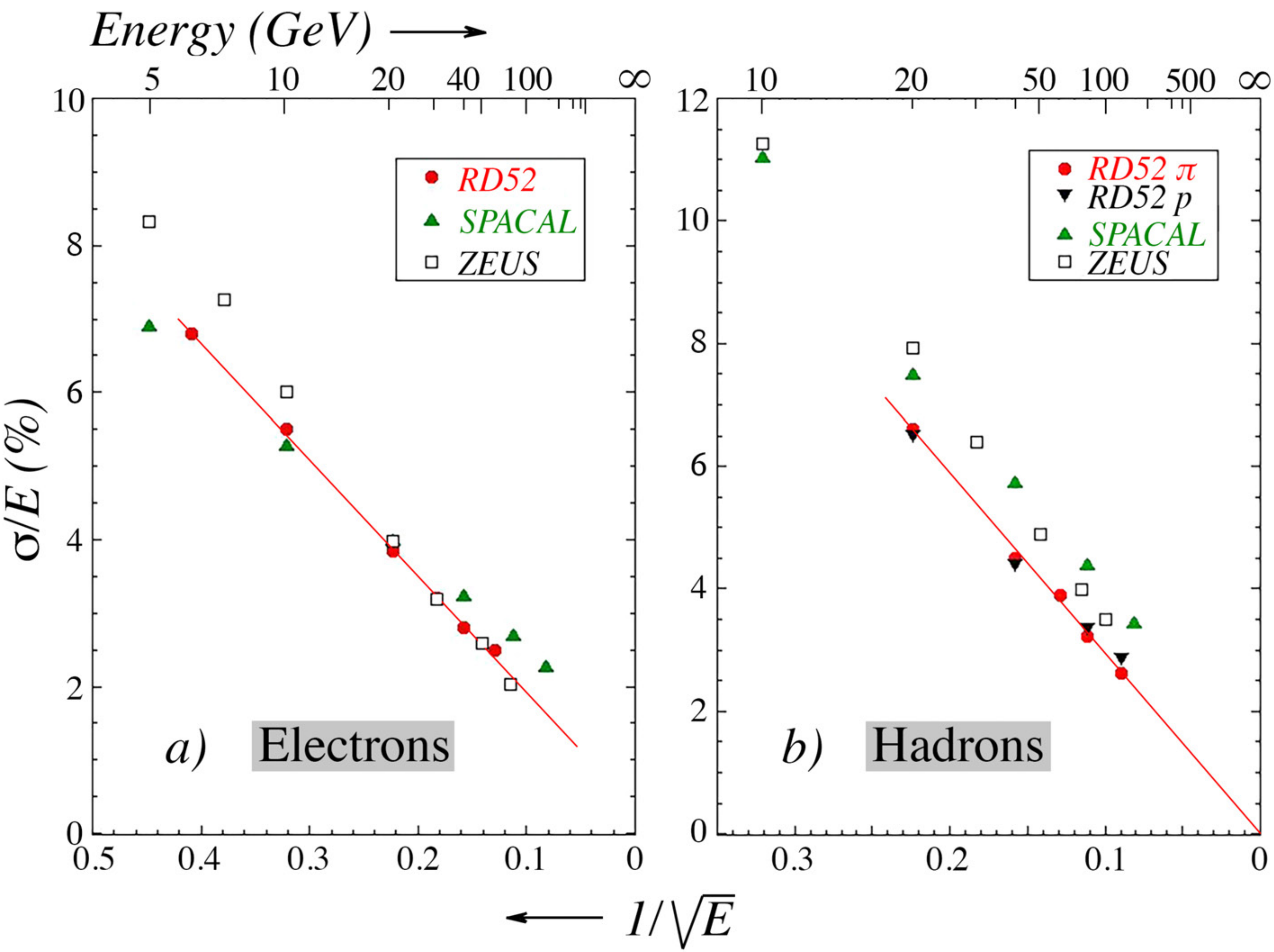


Hadronic Performance of a Dual-Readout Fiber Calorimeter



From:
NIM A866 (2017) 76

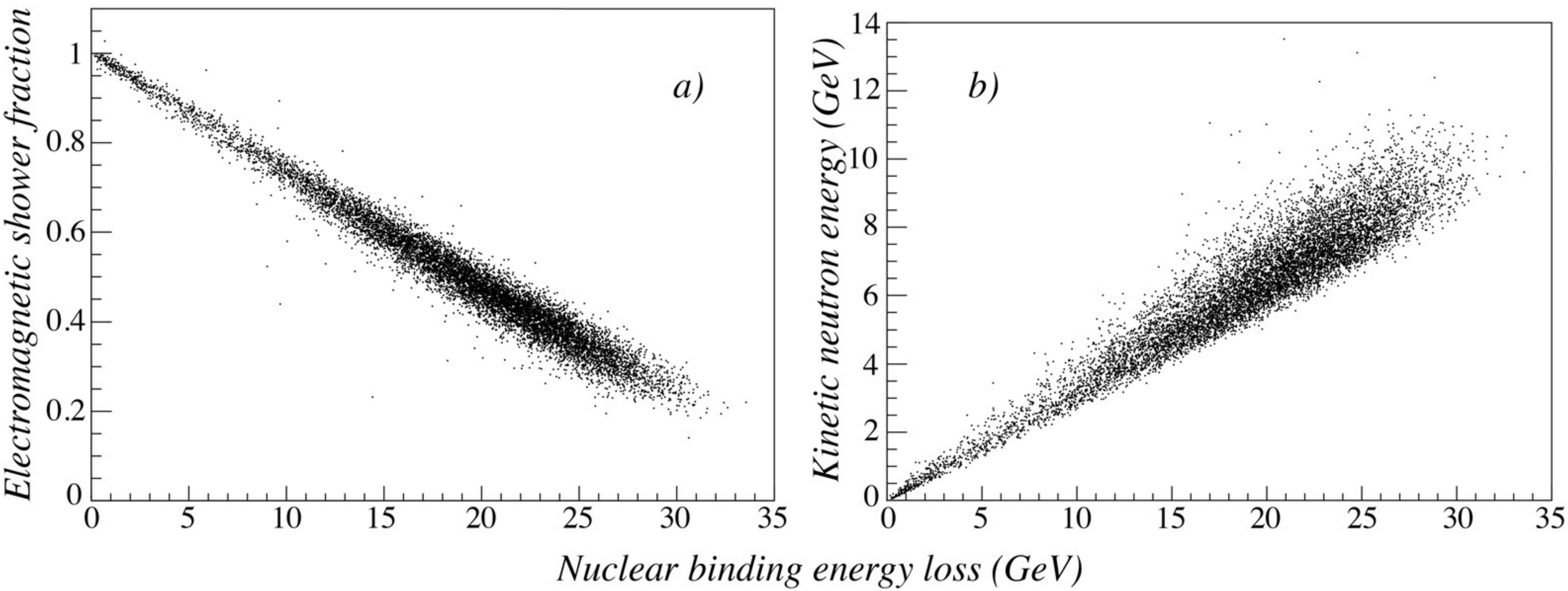
Comparison of Dual-Readout and Compensation



Prediction of the limits of the hadronic energy resolution

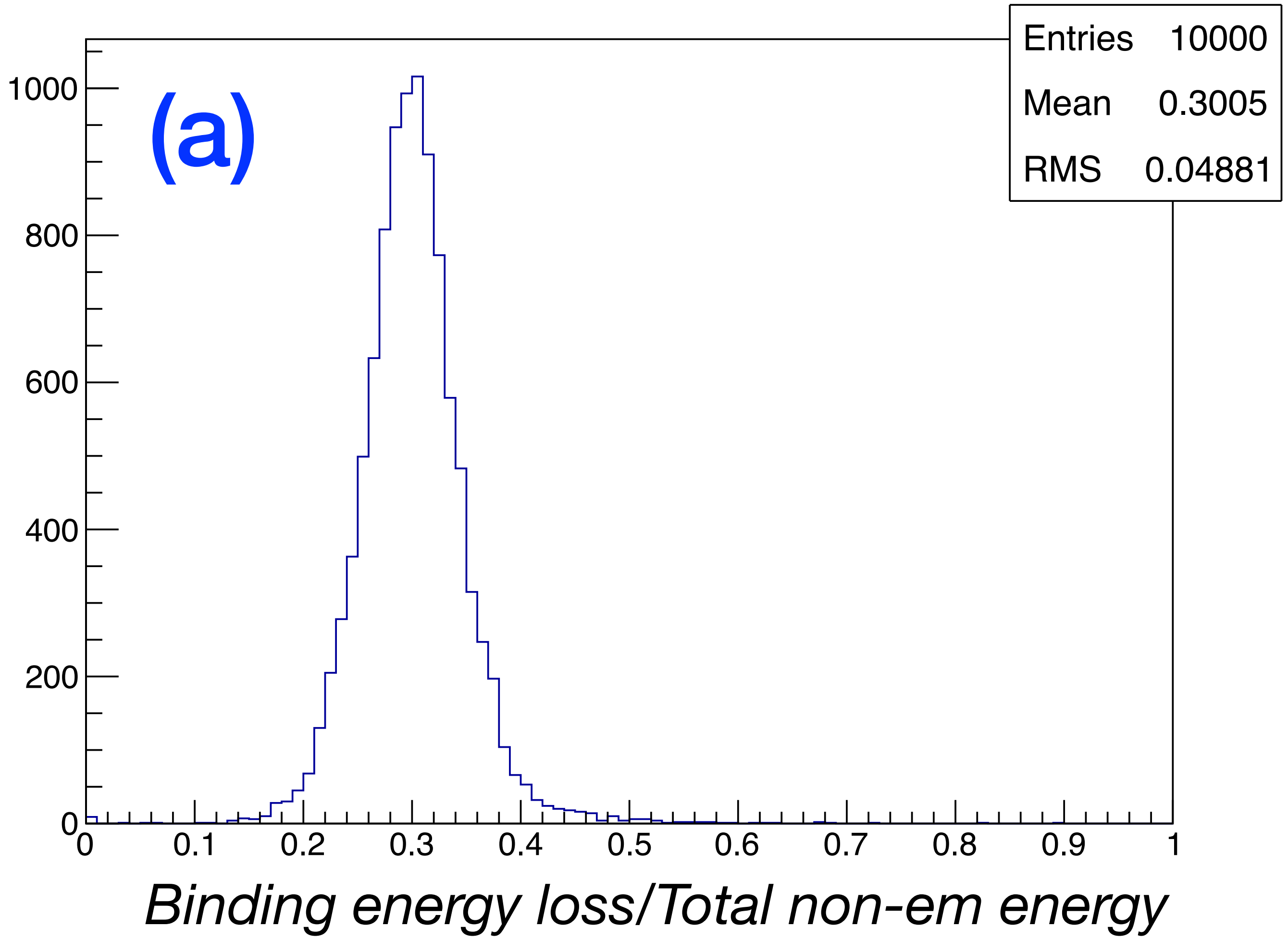
- GEANT 4.10.3-patch2
- FTFP_BERT physics list
- Very large absorber to contain the entire hadron shower
- 10, 20, 50, 100, 200, 500, 1000 GeV π^- sent to Cu and Pb (10,000 events)
- Obtained information in each event:
  - The em shower fraction
  - The total nuclear binding energy loss
  - The total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

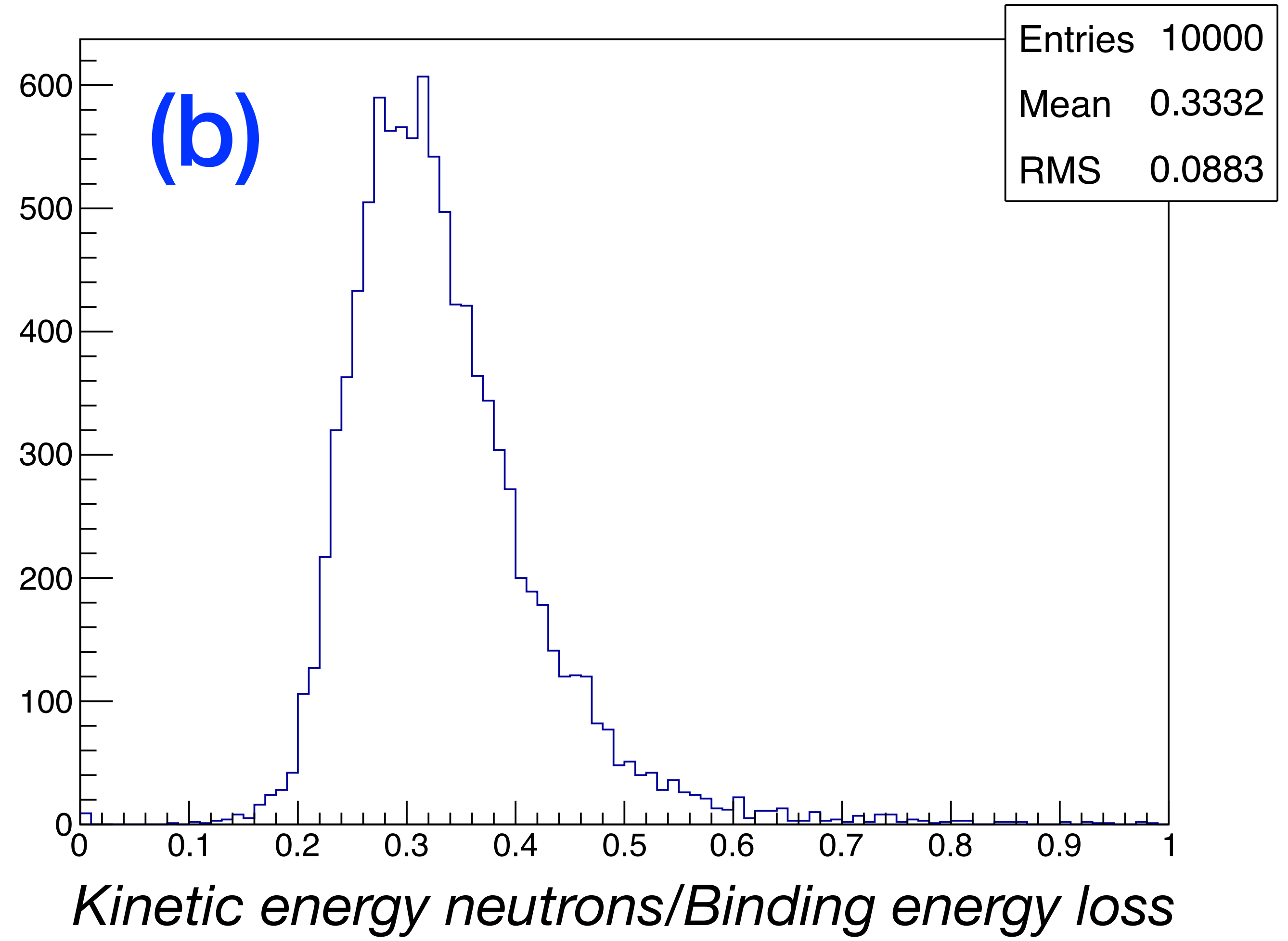
Correlation between binding energy loss and f_{em} (a) and kinetic energy of neutrons(b)



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)

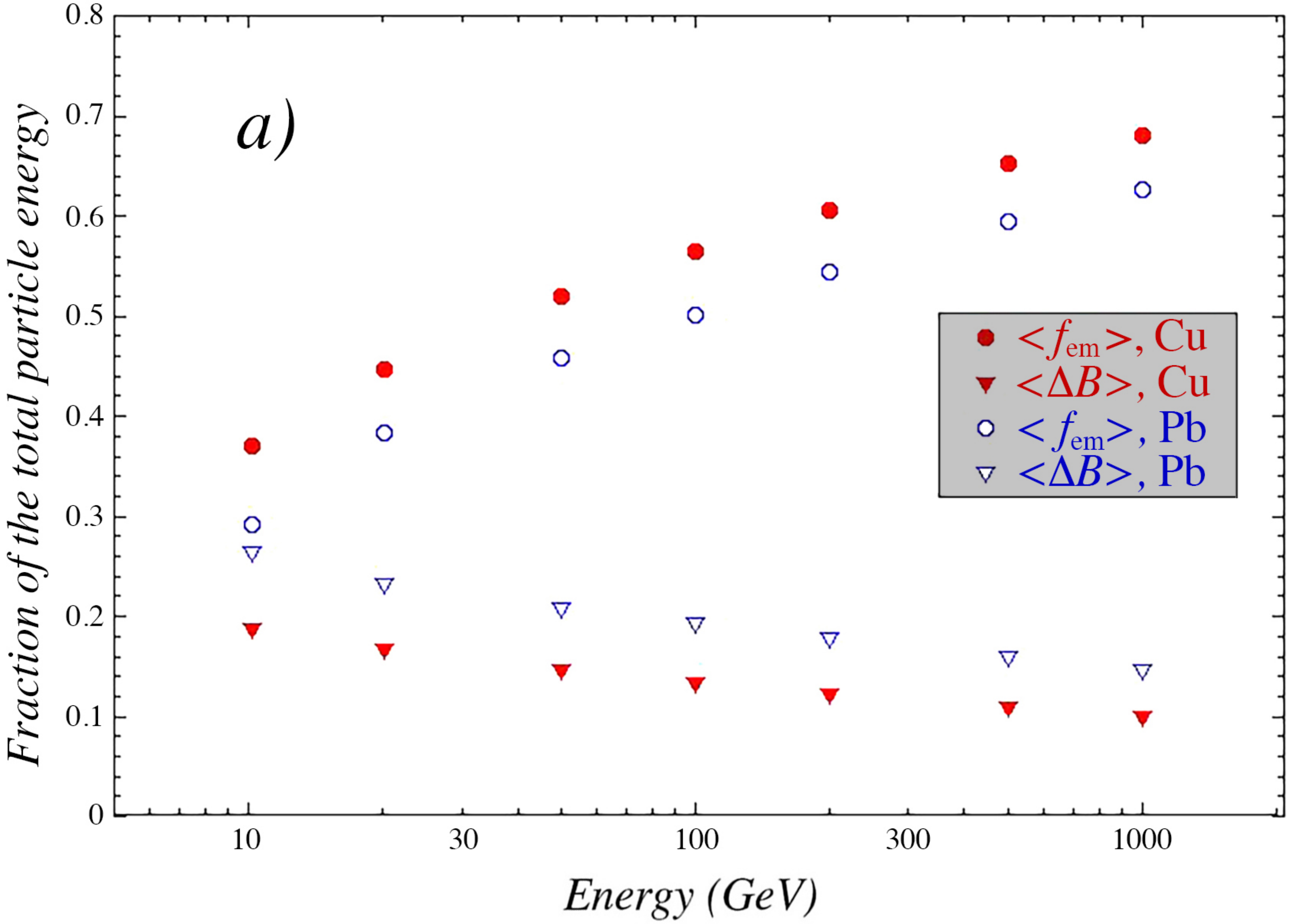


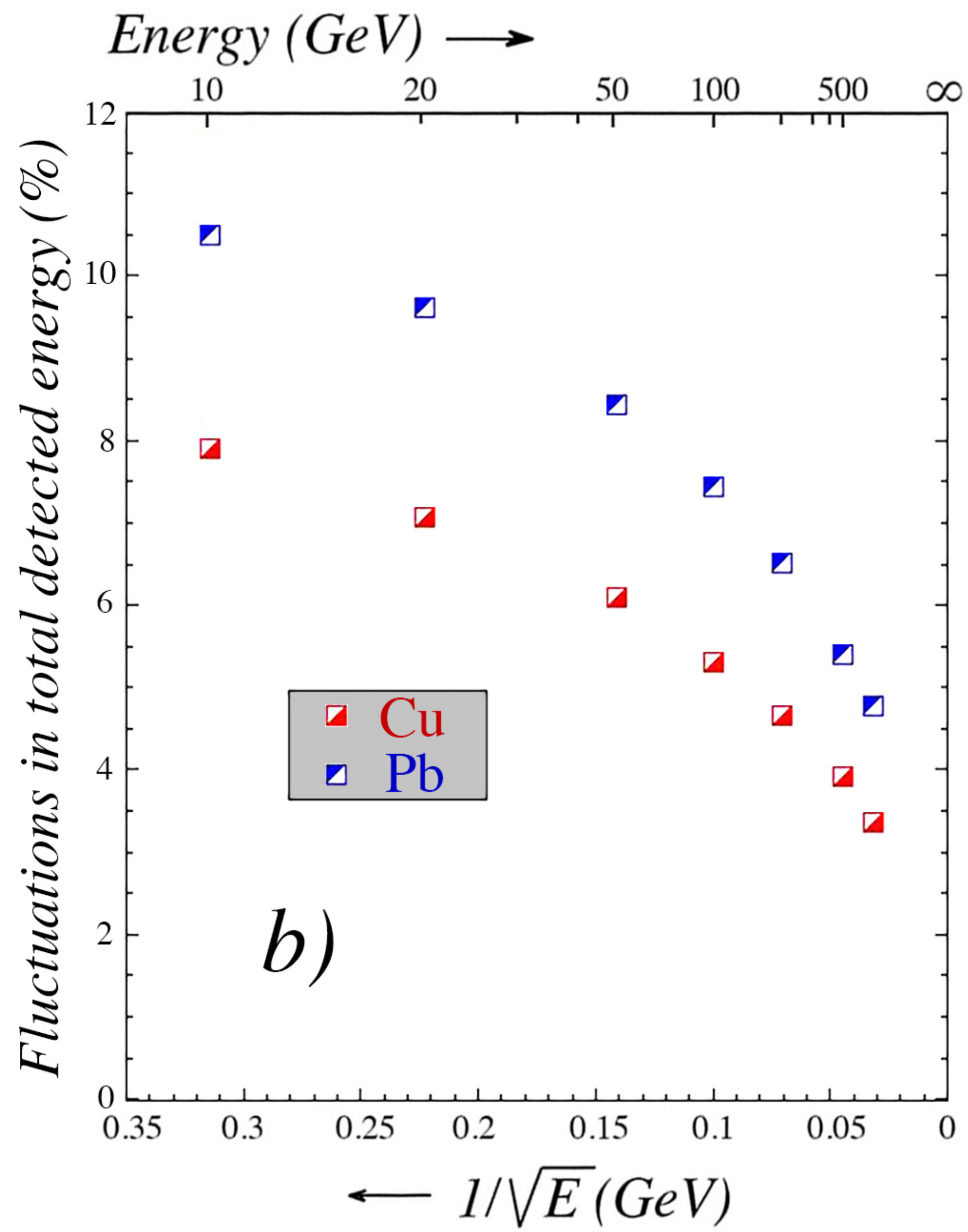


20 GeV π^- in copper

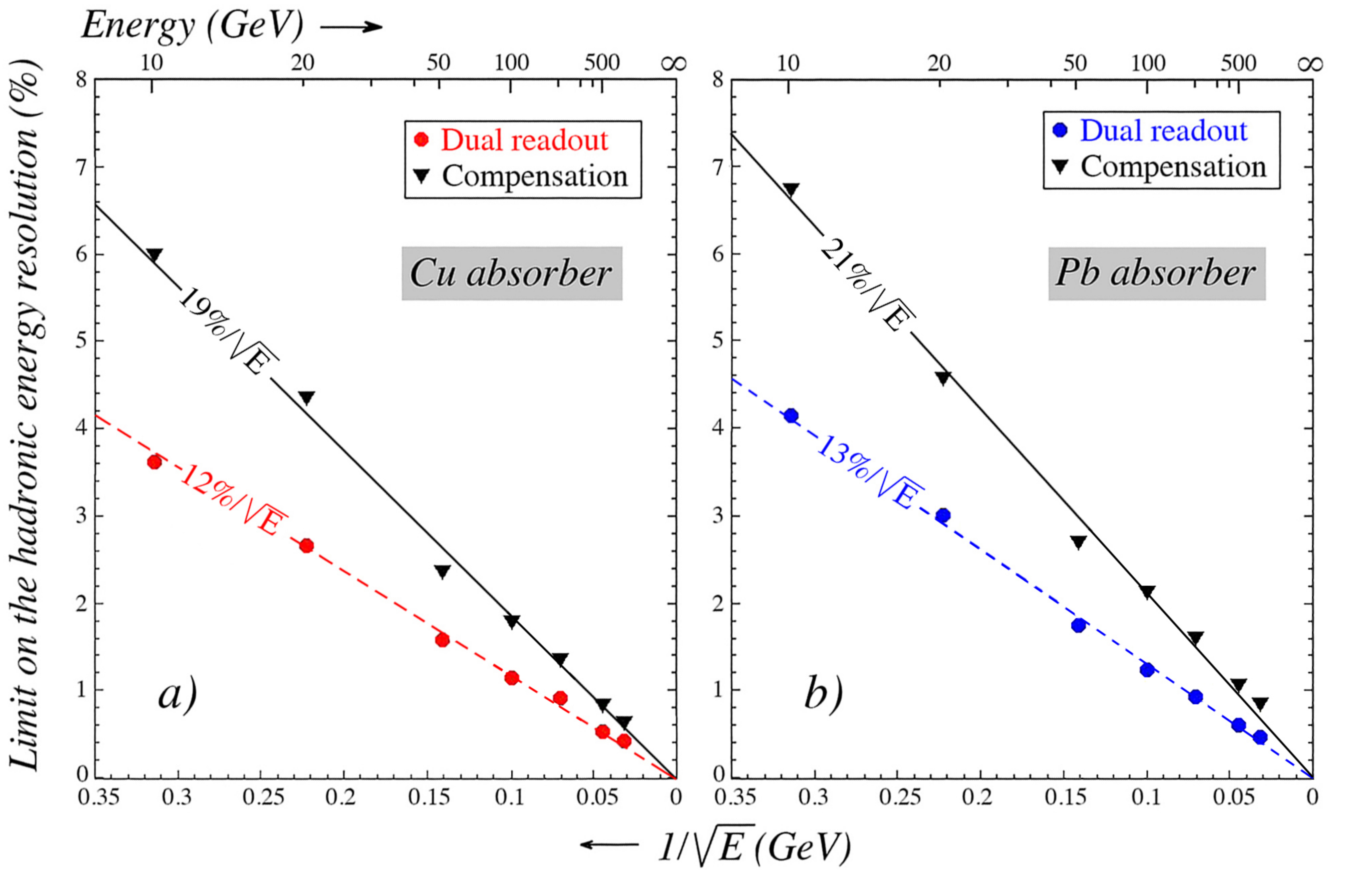
<EM Shower fraction> and <Binding Energy Loss>

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





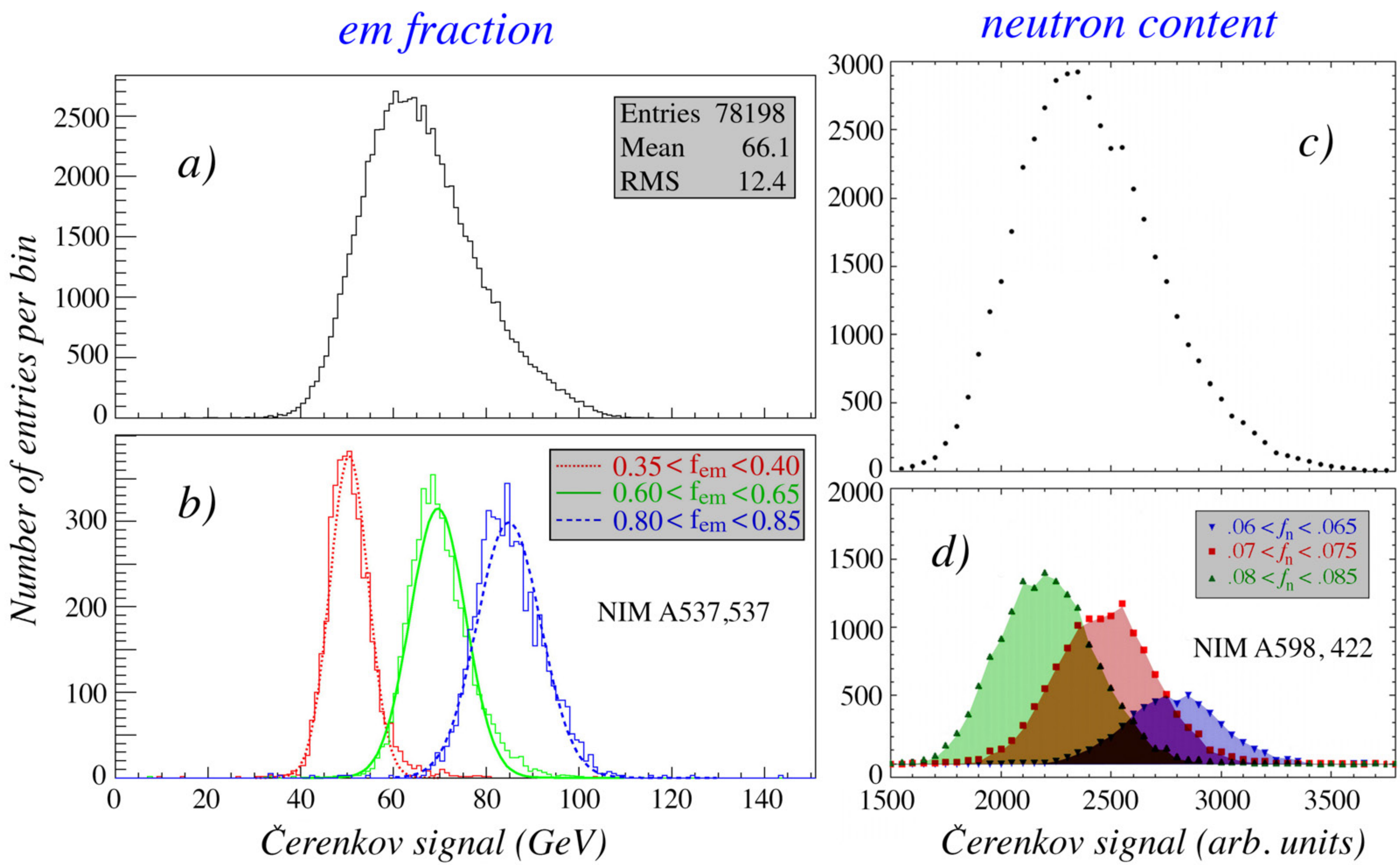
Limits on the hadronic energy resolution



Conclusion

- Dual-readout and compensation approaches remedy the poor hadronic performance caused by fluctuations of the invisible energy losses
- Theoretical limits of the hadronic energy resolution were investigated
- Dual-readout has better hadronic energy resolution than compensation
- 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

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

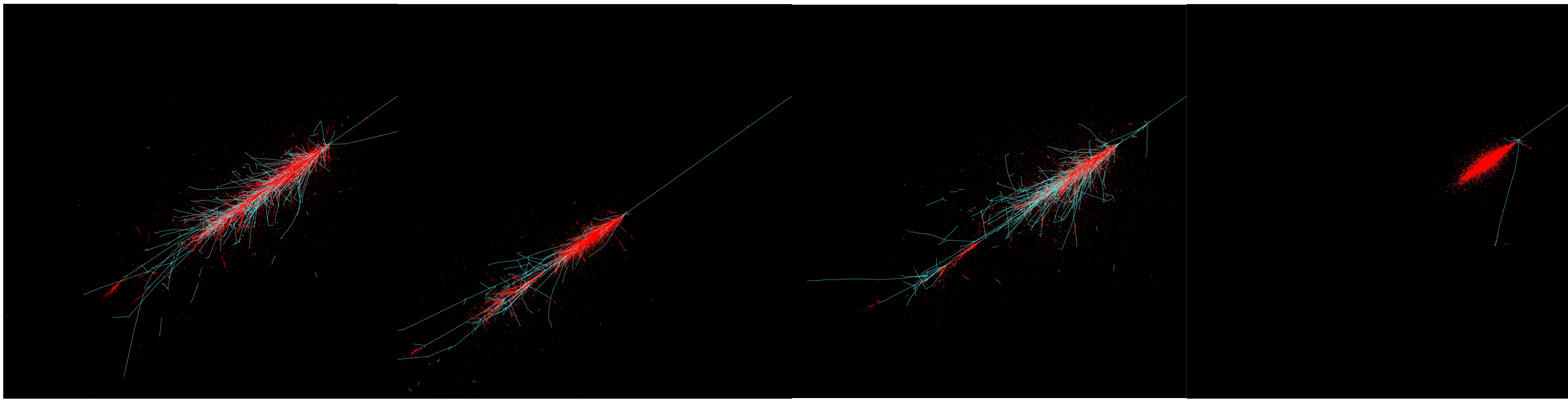


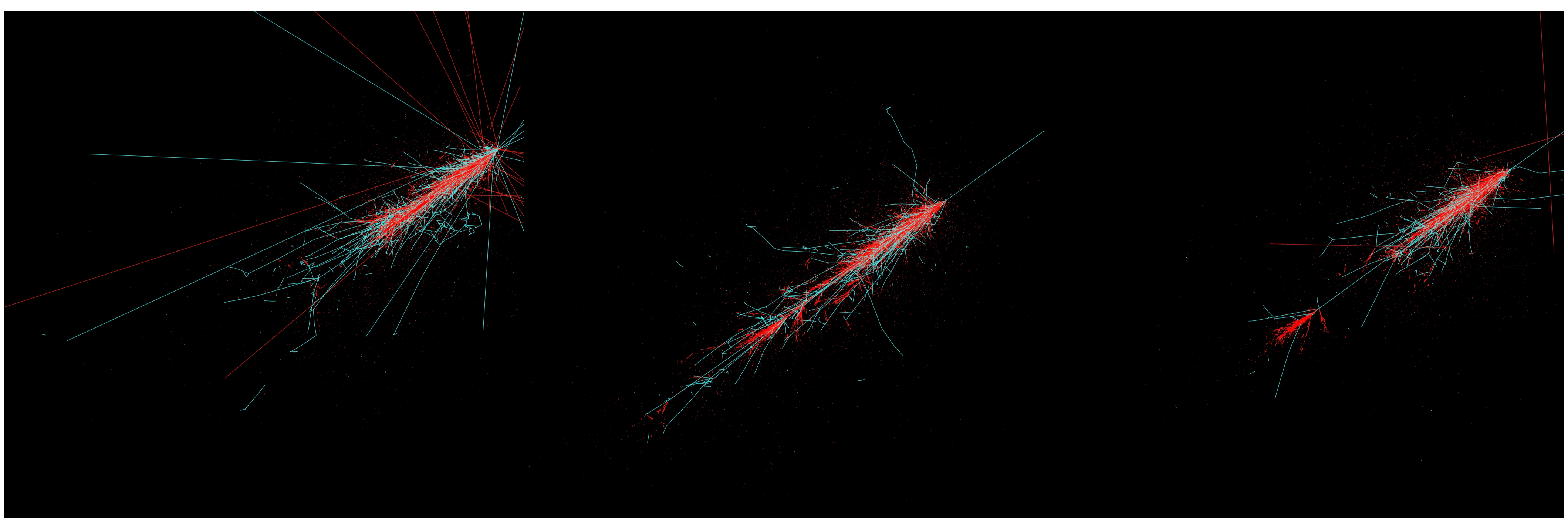
Backup

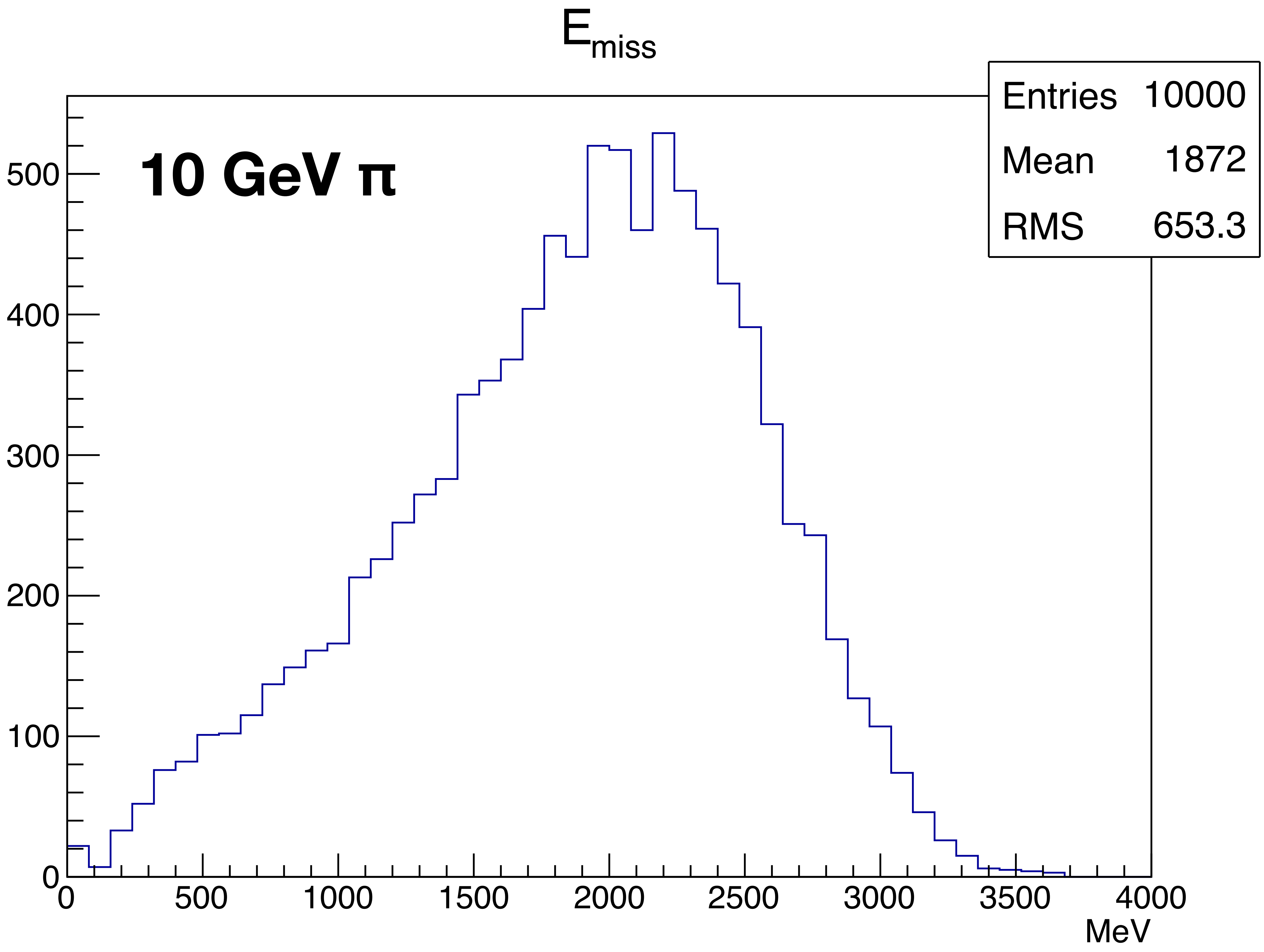
Fluctuations of Hadron Showers

500 GeV Pions, Cu absorber

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






E$_{miss}$
10 GeV π
Entries 10000
Mean 1872
RMS 653.3
0
100
200
300
400
500
0
500
1000
1500
2000
2500
3000
3500
4000
MeV