# *On the limits of the hadronic energy resolution of calorimeters*

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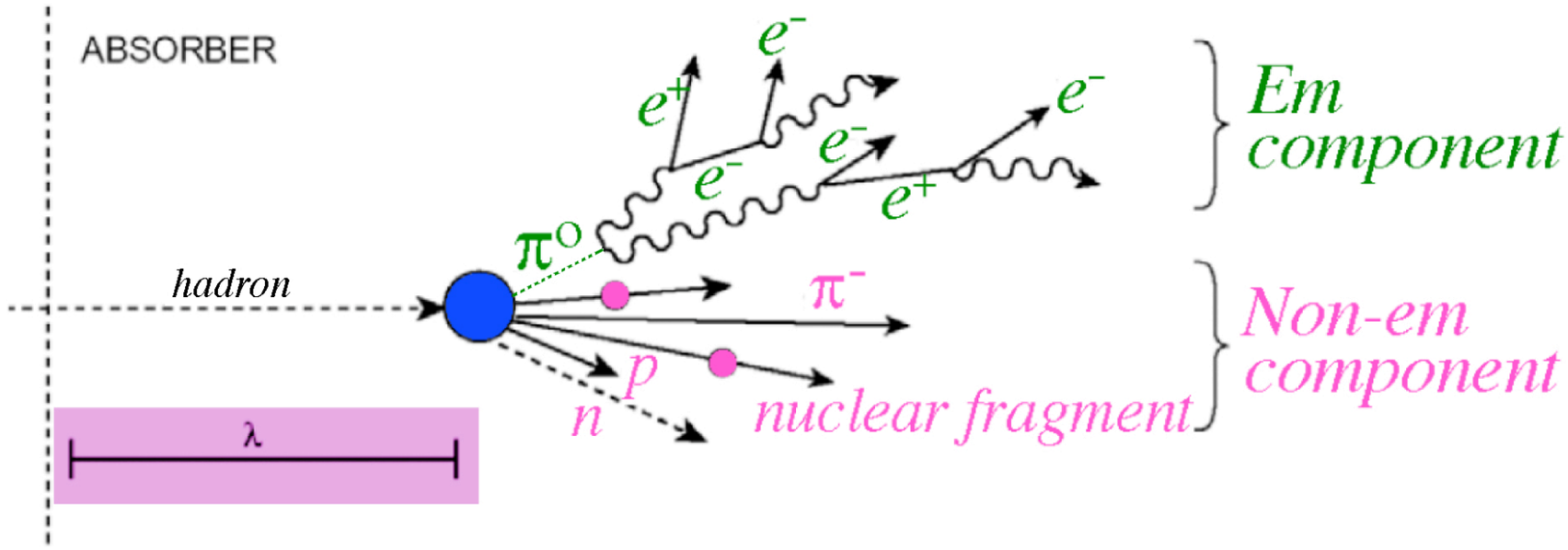
# The Physics of Hadron Shower Development



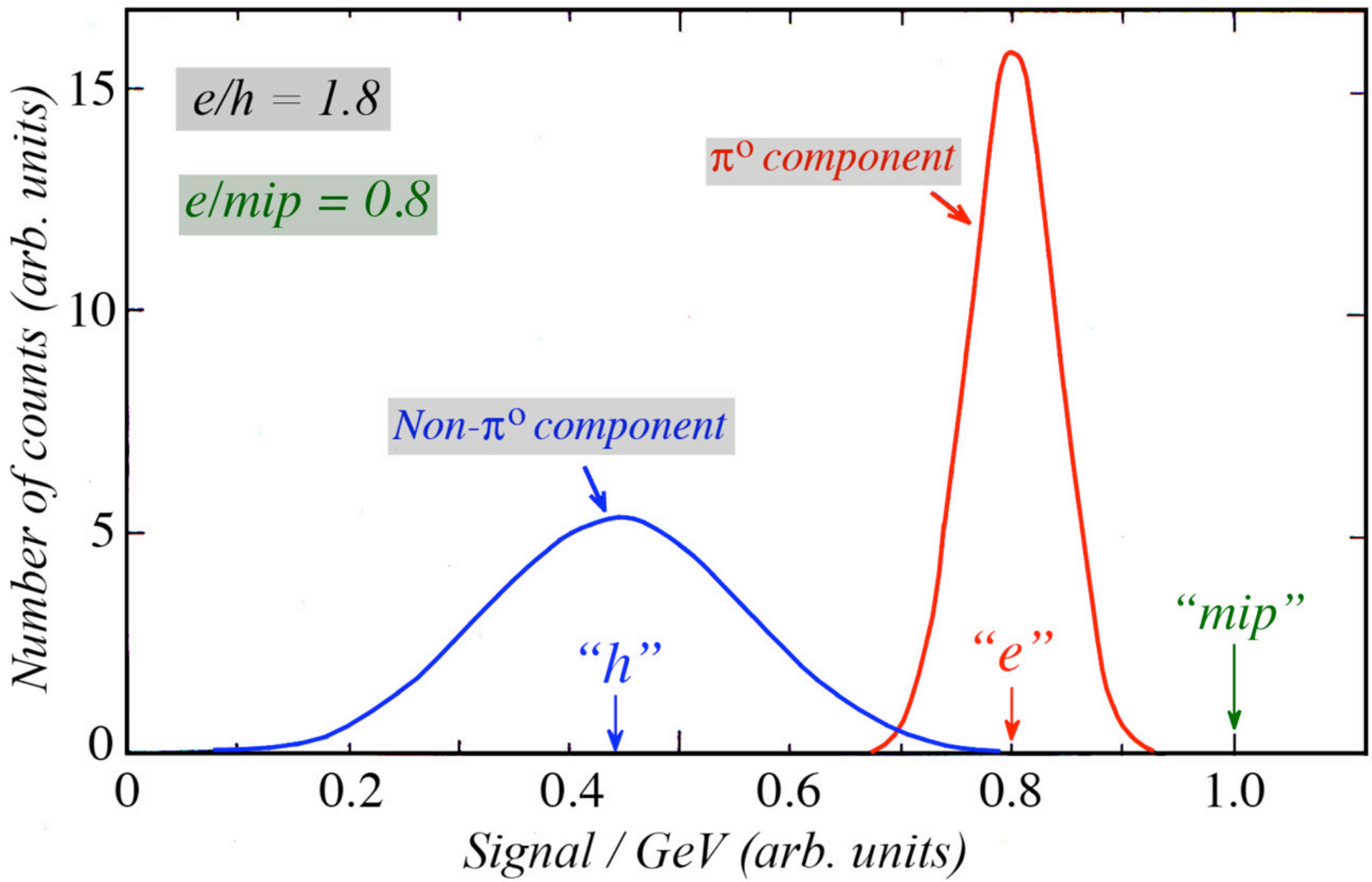

- *Electromagnetic component*
  - electrons, photons
  - neutral pions $\rightarrow 2\,\gamma$

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

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

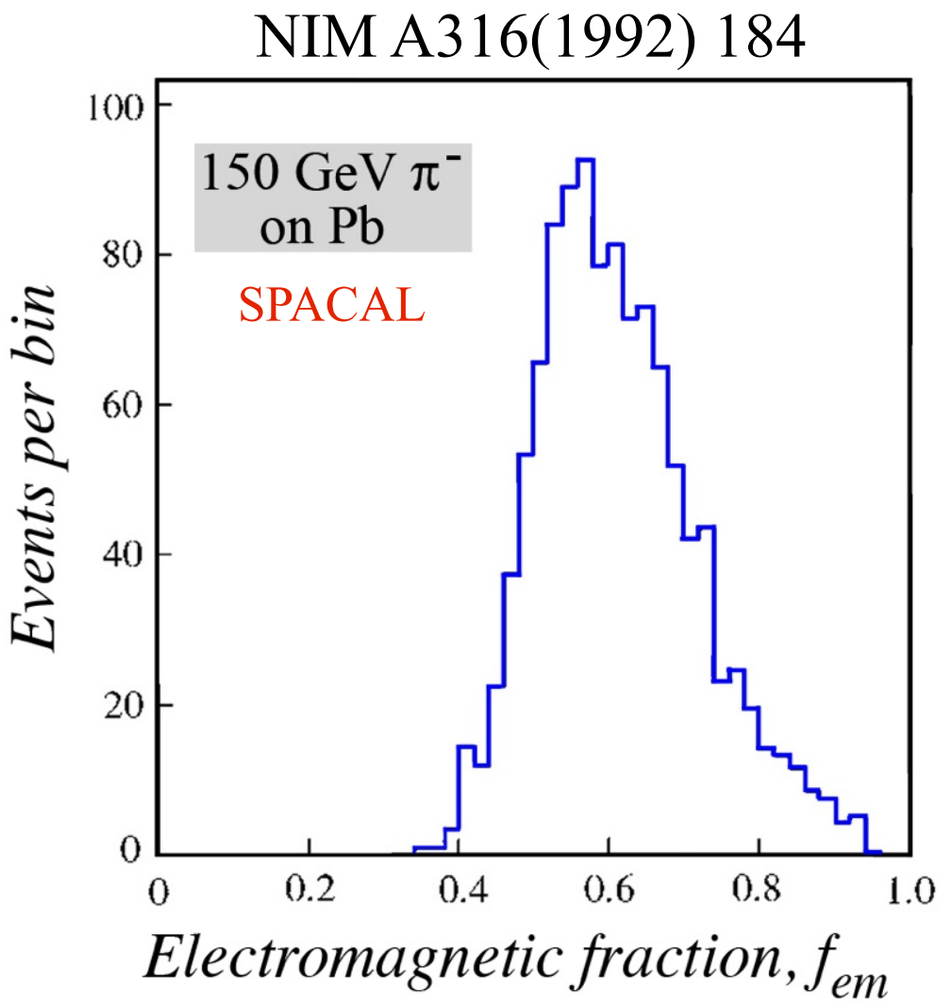
- ***Responsible for the Fluctuations of Hadron Showers***

# The Calorimeter Response

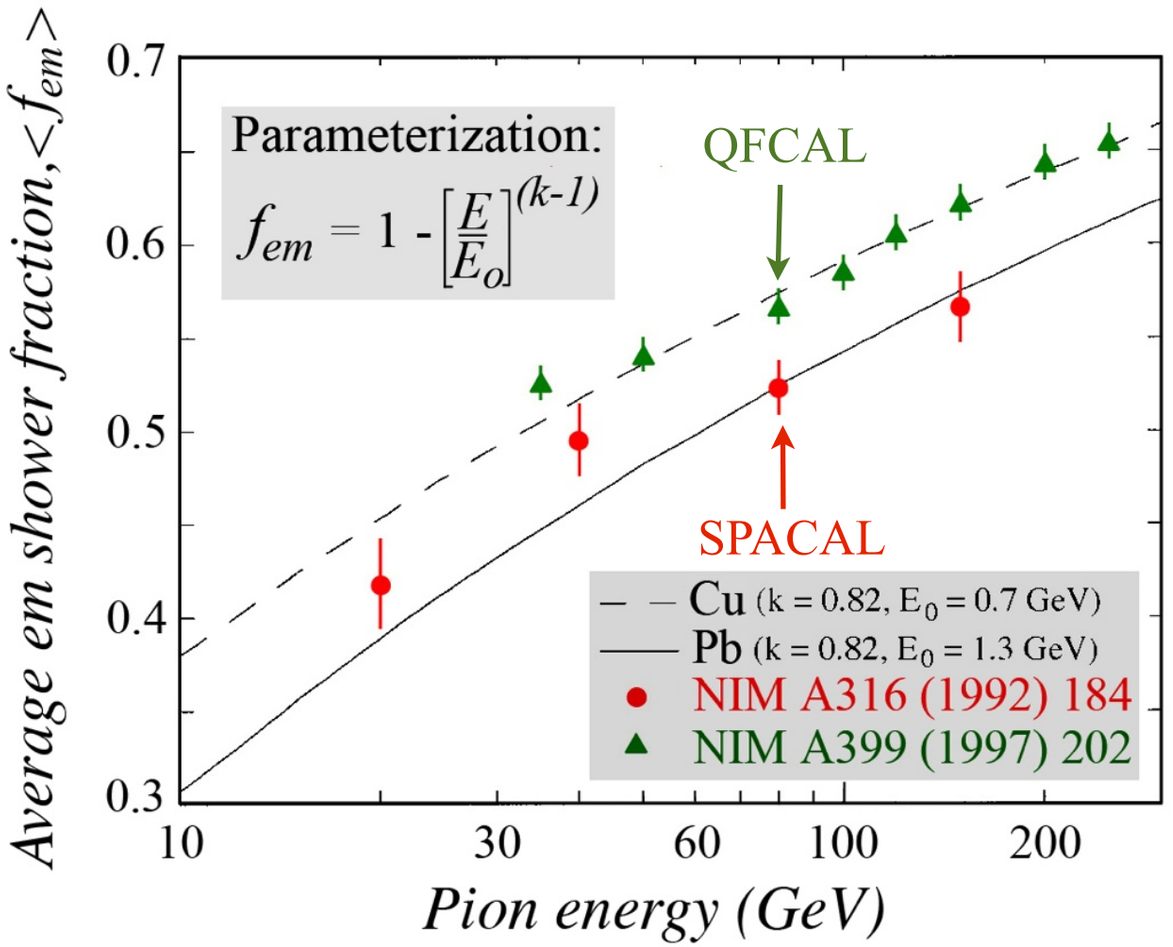



The calorimeter responses to the em and non-em components of hadron showers

# Fluctuations of electromagnetic shower fraction

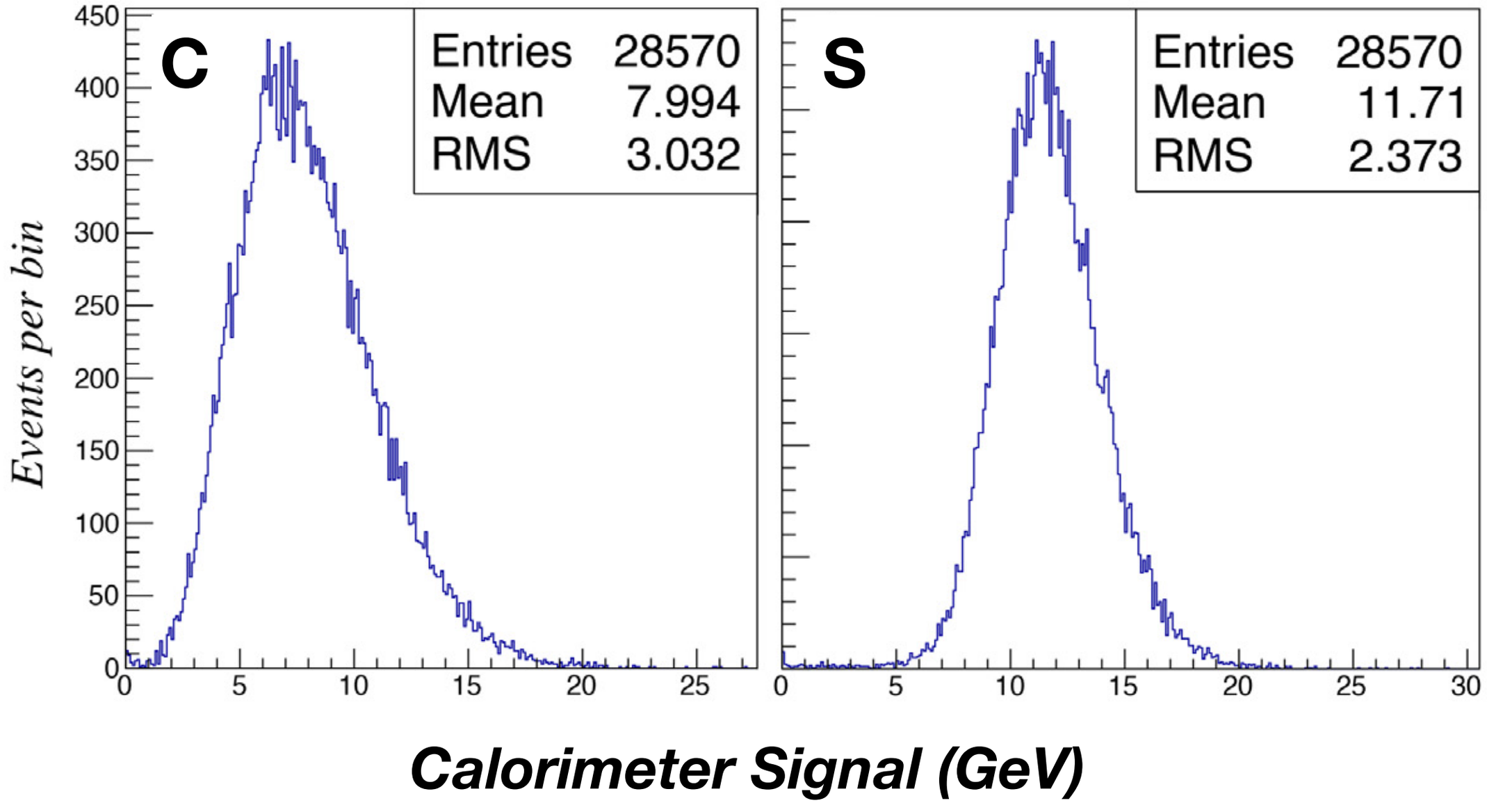



Large, non-Gaussian fluctuations in $f_{em}$




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

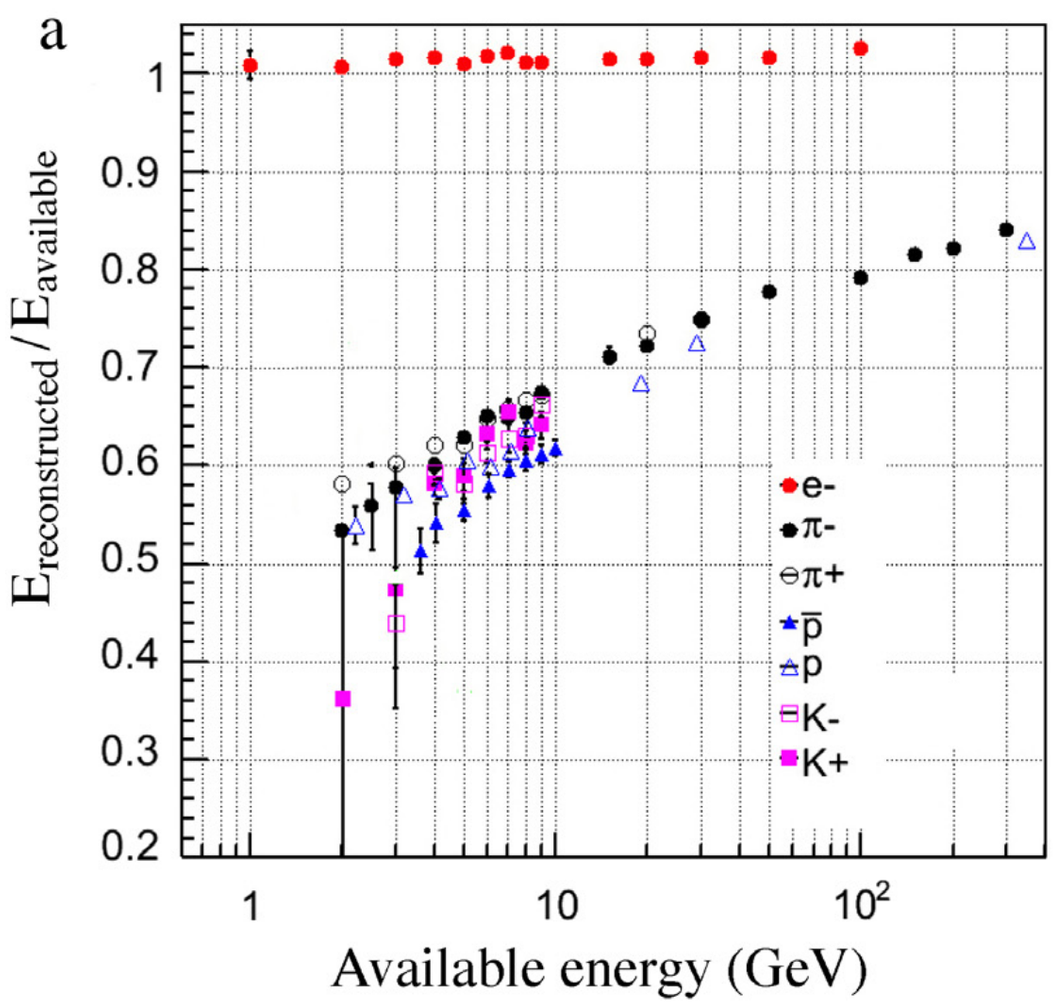
# 20 GeV $\pi^-$
# (Pb-fiber RD52 calorimeter)



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

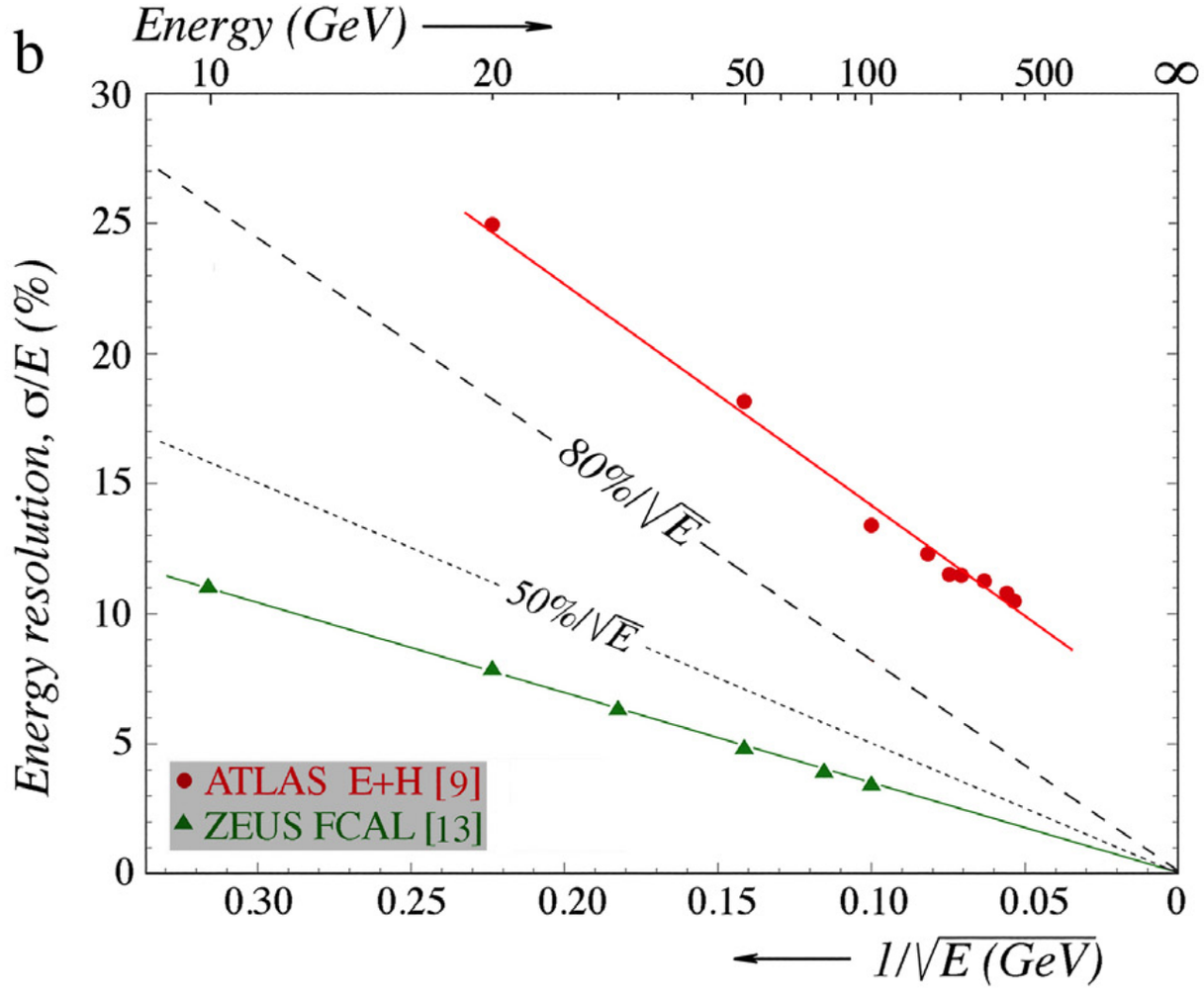
***Non-linear response to hadrons***

***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*

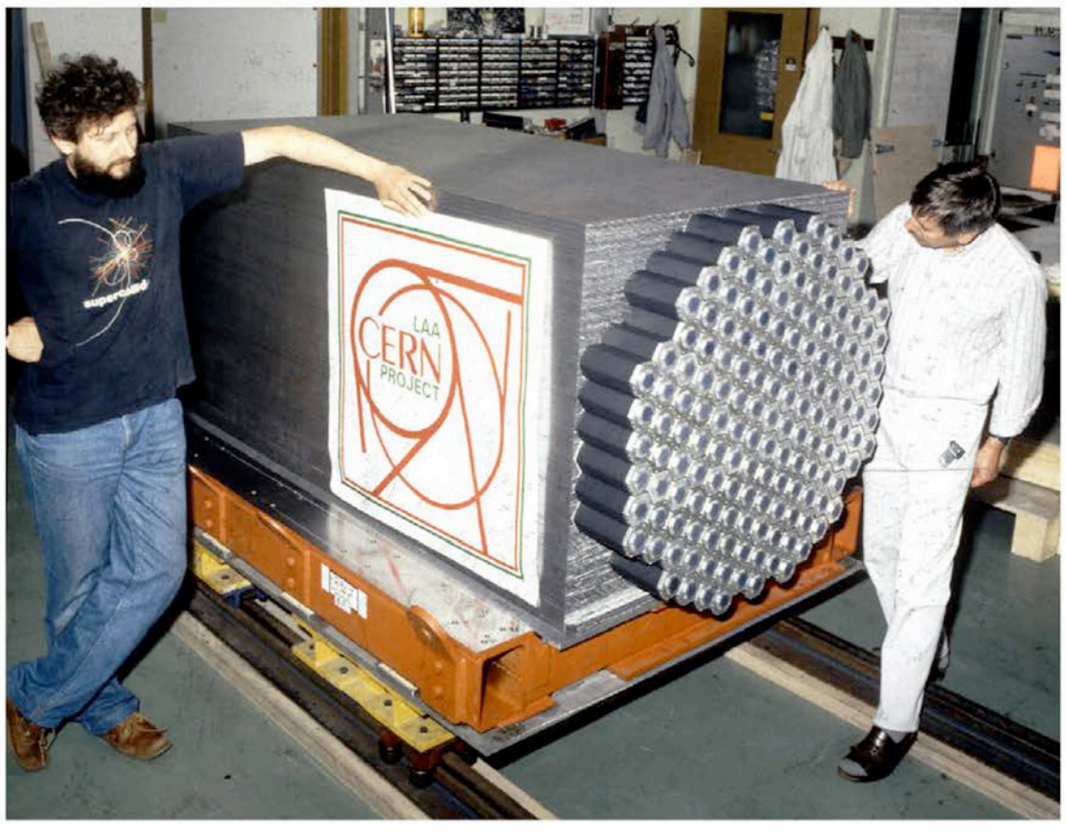
- *the electromagnetic shower fraction*

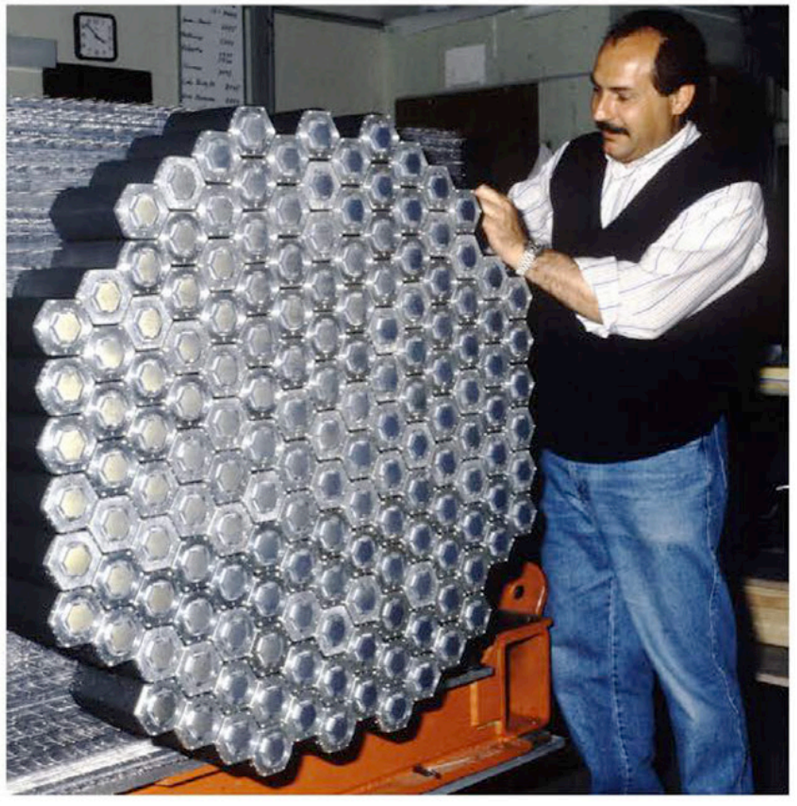
**These are measurable quantities that are correlated to the binding energy losses**

# *Compensation*

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

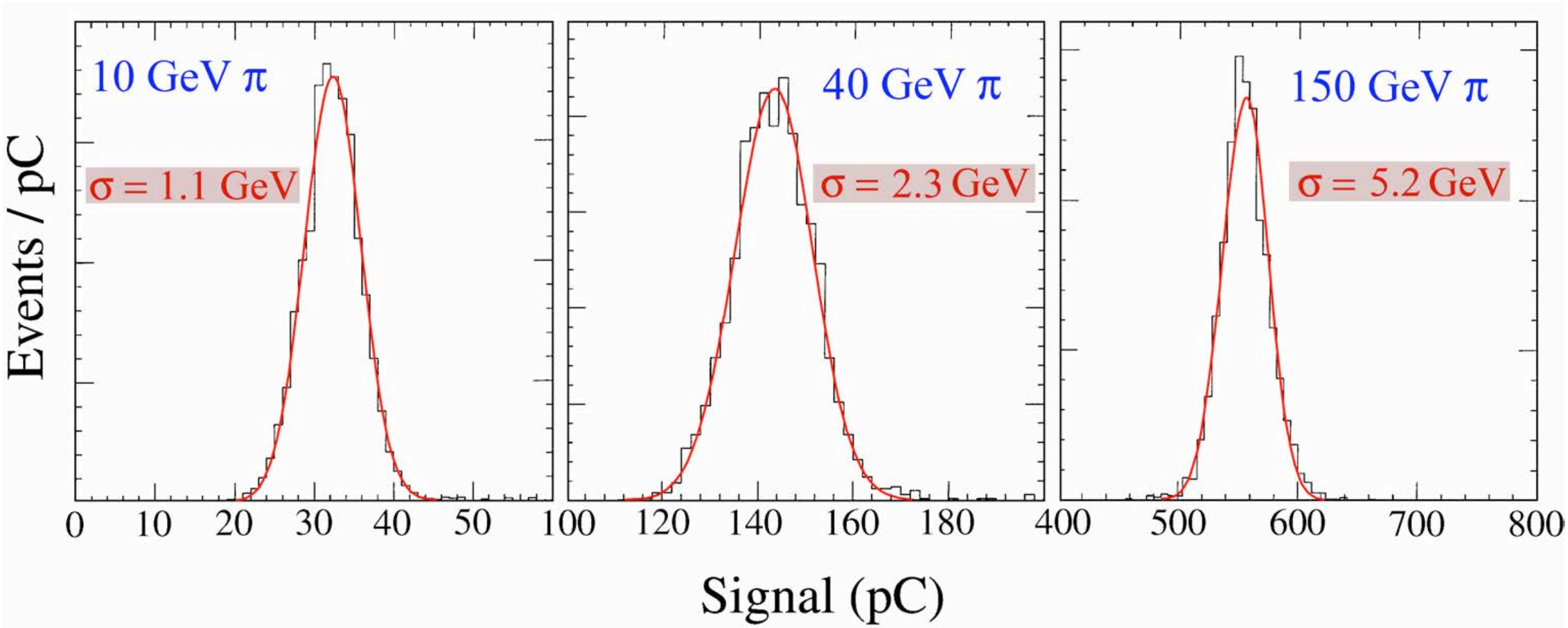
*SPACAL 1989*



*Pb - plastic fibers*
*(4:1 volume ratio)*

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



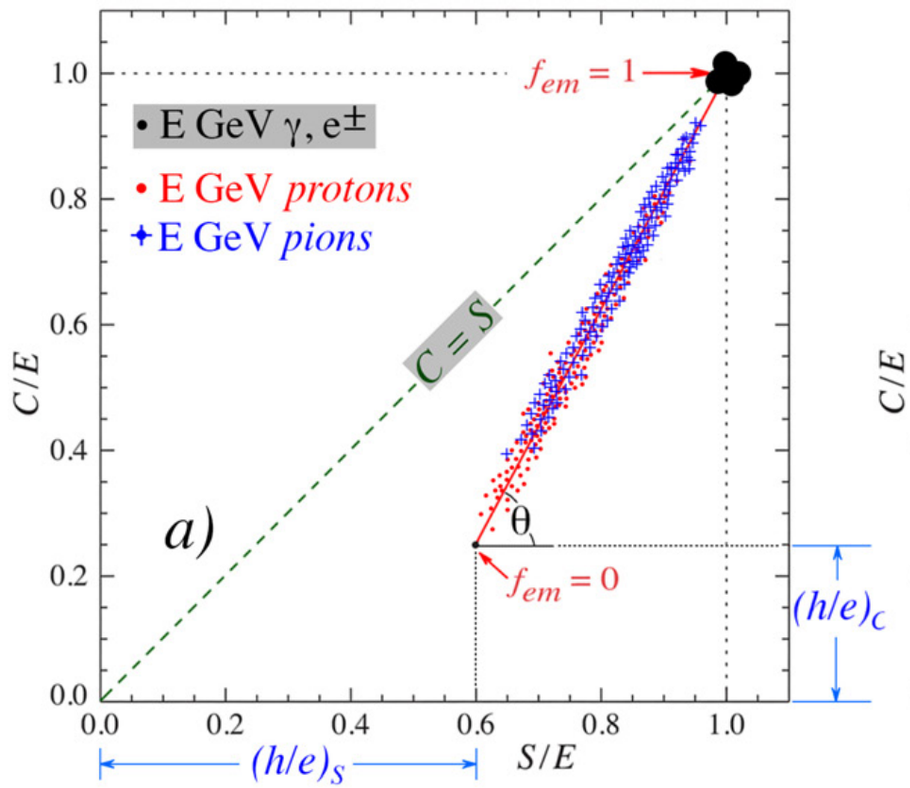

*from:* NIM A308 (1991) 481

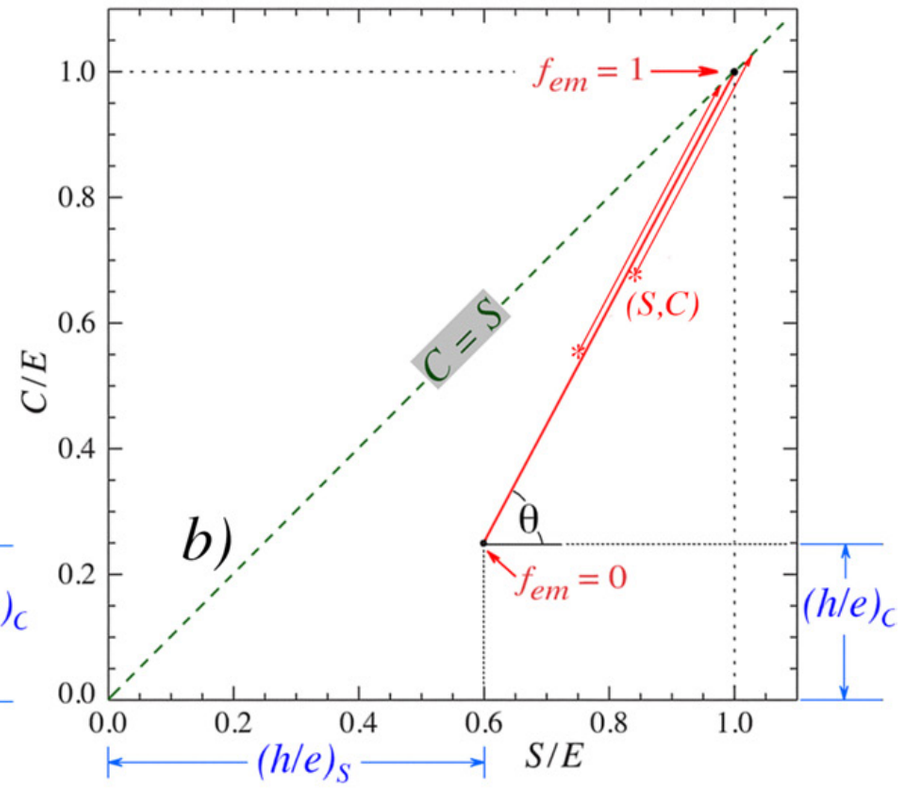
# *Dual-Readout Calorimetry*

- 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
  - the small sampling fraction
  - a large detector volume
  - a long signal integration time

# Dual-Readout Method



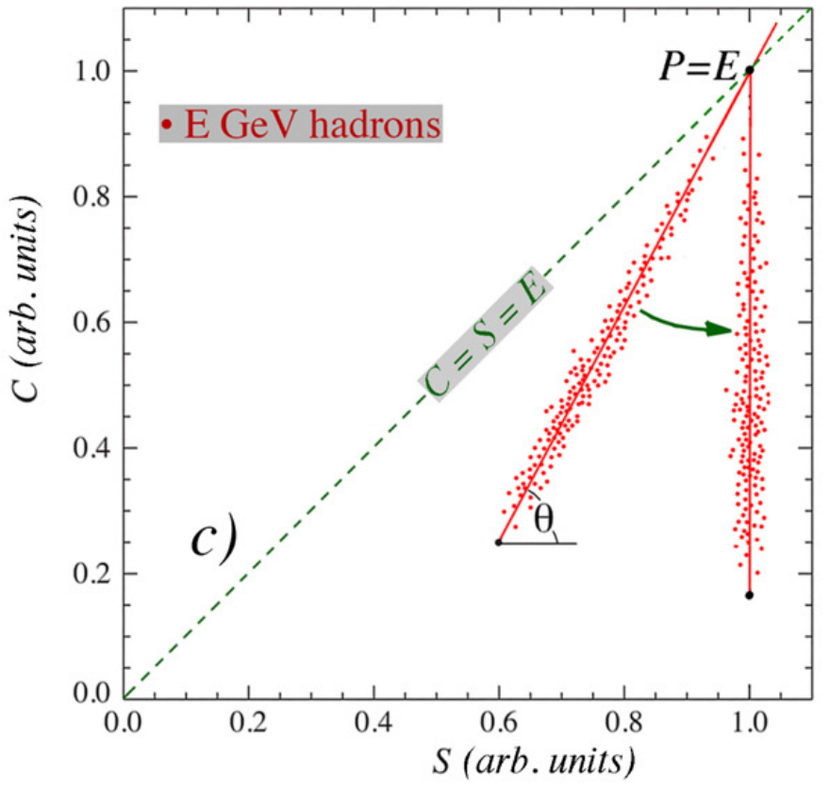

$$S = E\left[f_{\rm em} + \frac{1}{(e/h)_S}(1 - f_{\rm em})\right]$$

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

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

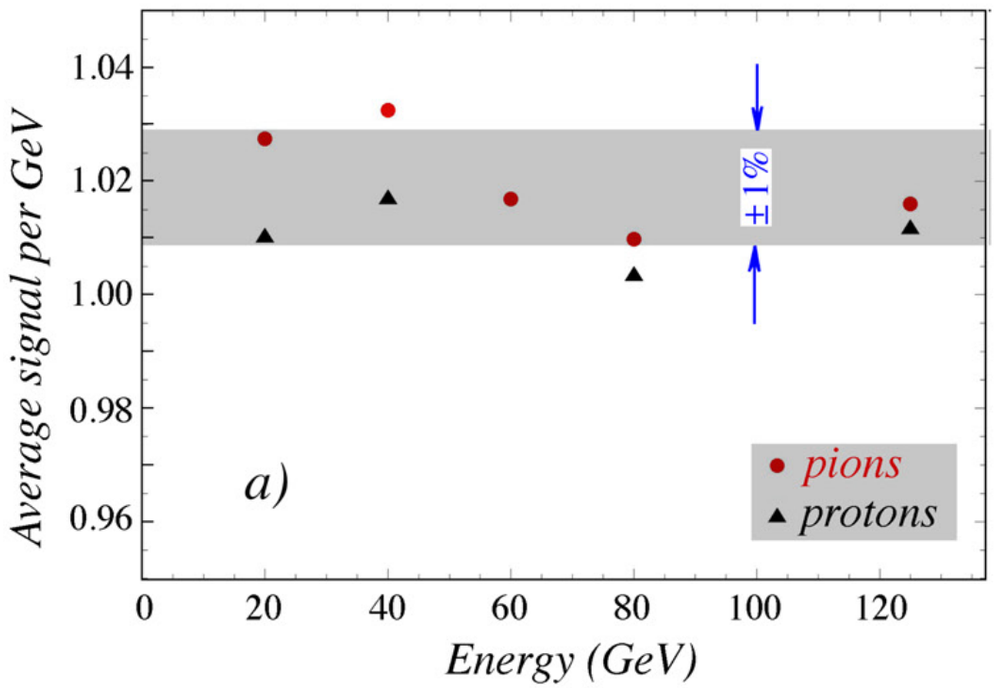
$$f_{\rm em} = \frac{(C/S)(h/e)_S - (h/e)_C}{[1-(h/e)_C] - (C/S)[1-(h/e)_S]}$$

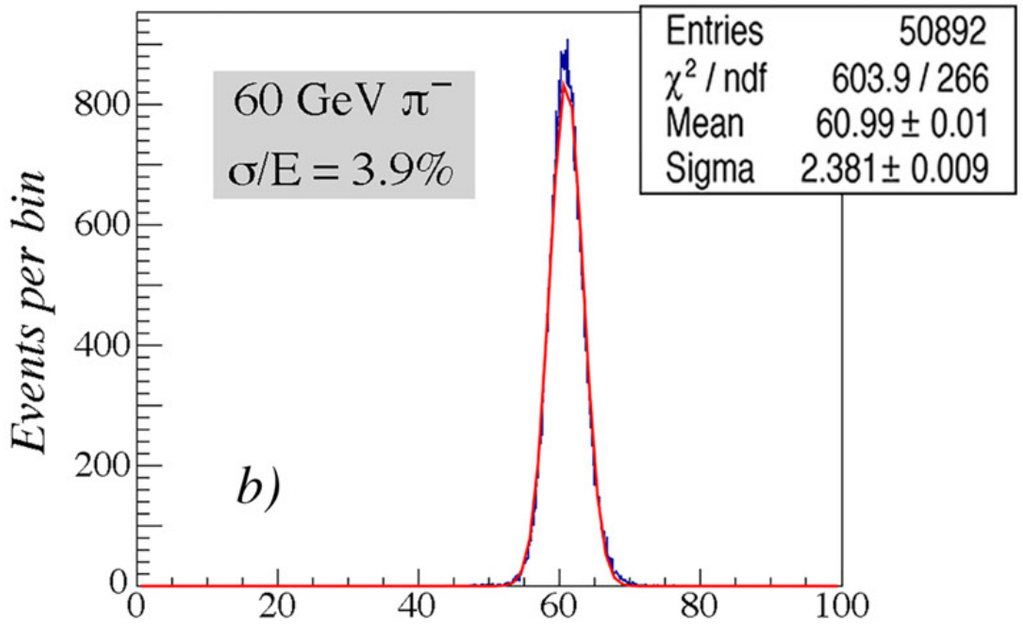
$$E = \frac{S - \chi C}{1 - \chi}$$



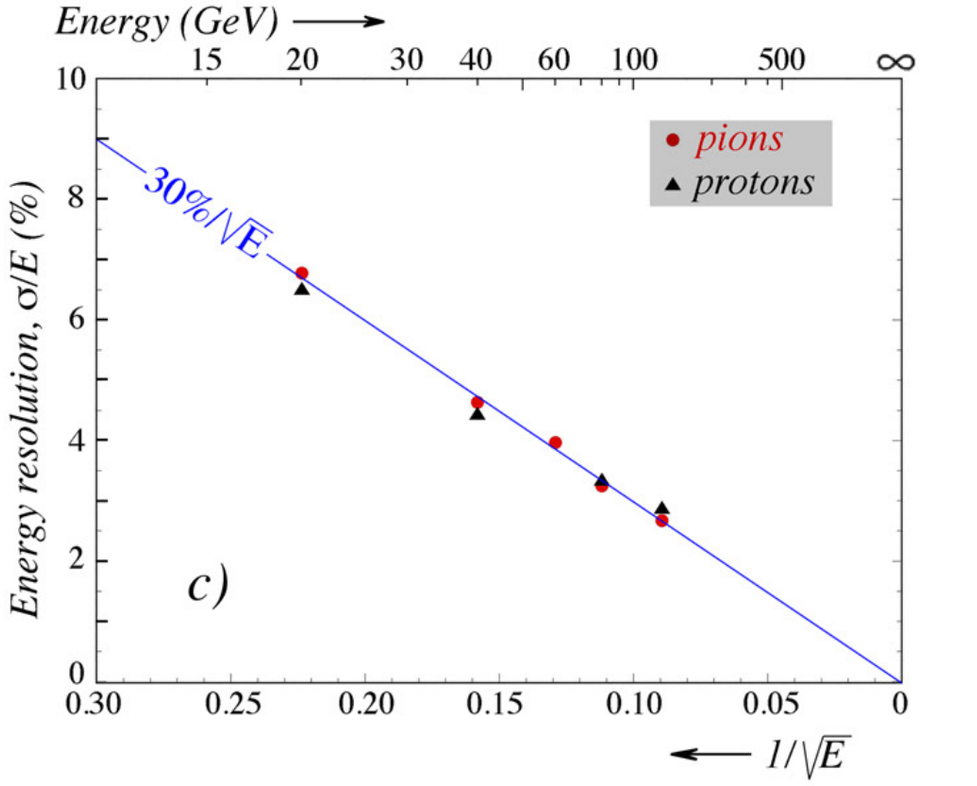

*From:* NIM A866 (2017) 76

# Hadronic Performance of a Dual-Readout Fiber Calorimeter

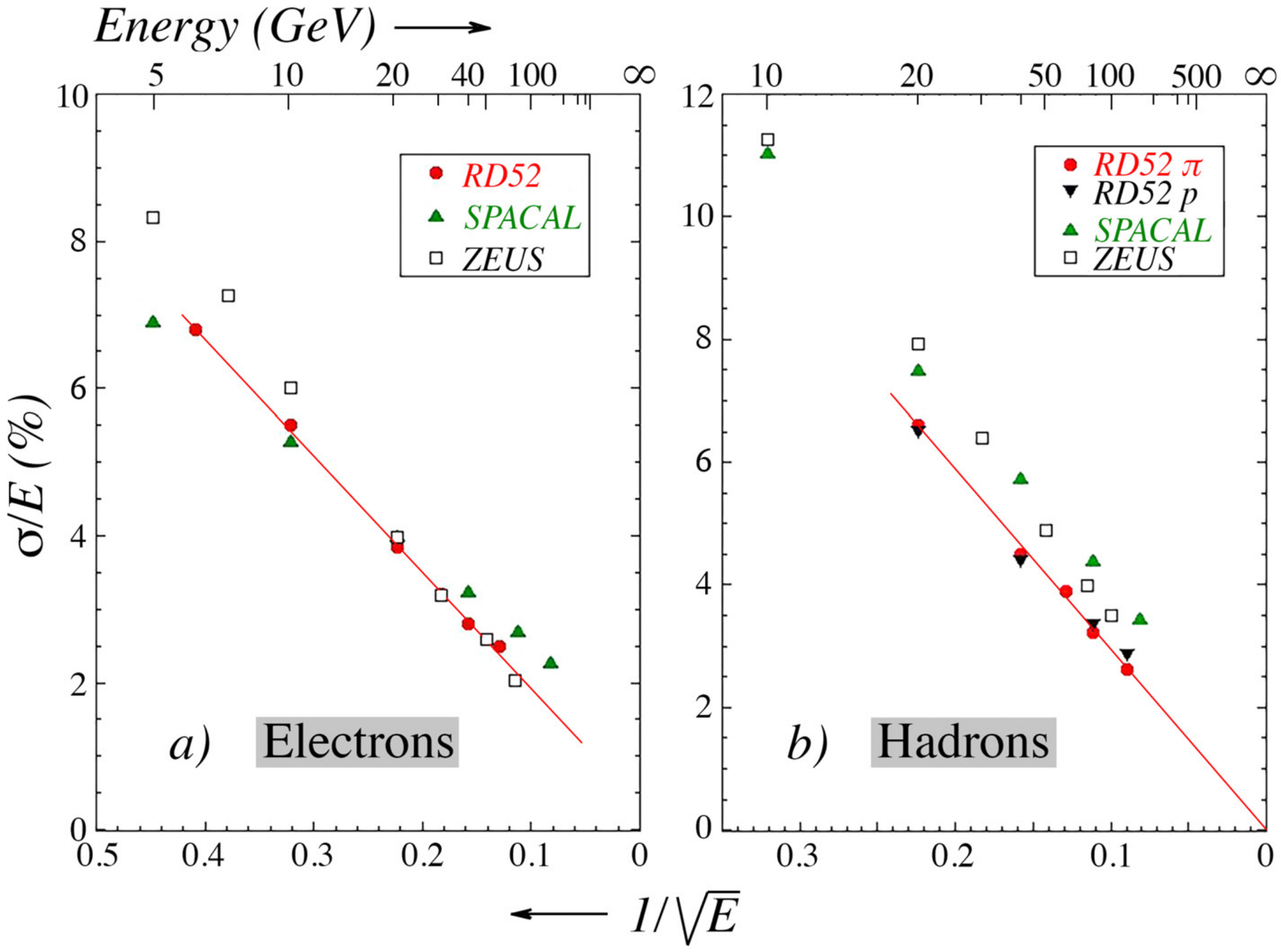



*From:*
NIM A866 (2017) 76



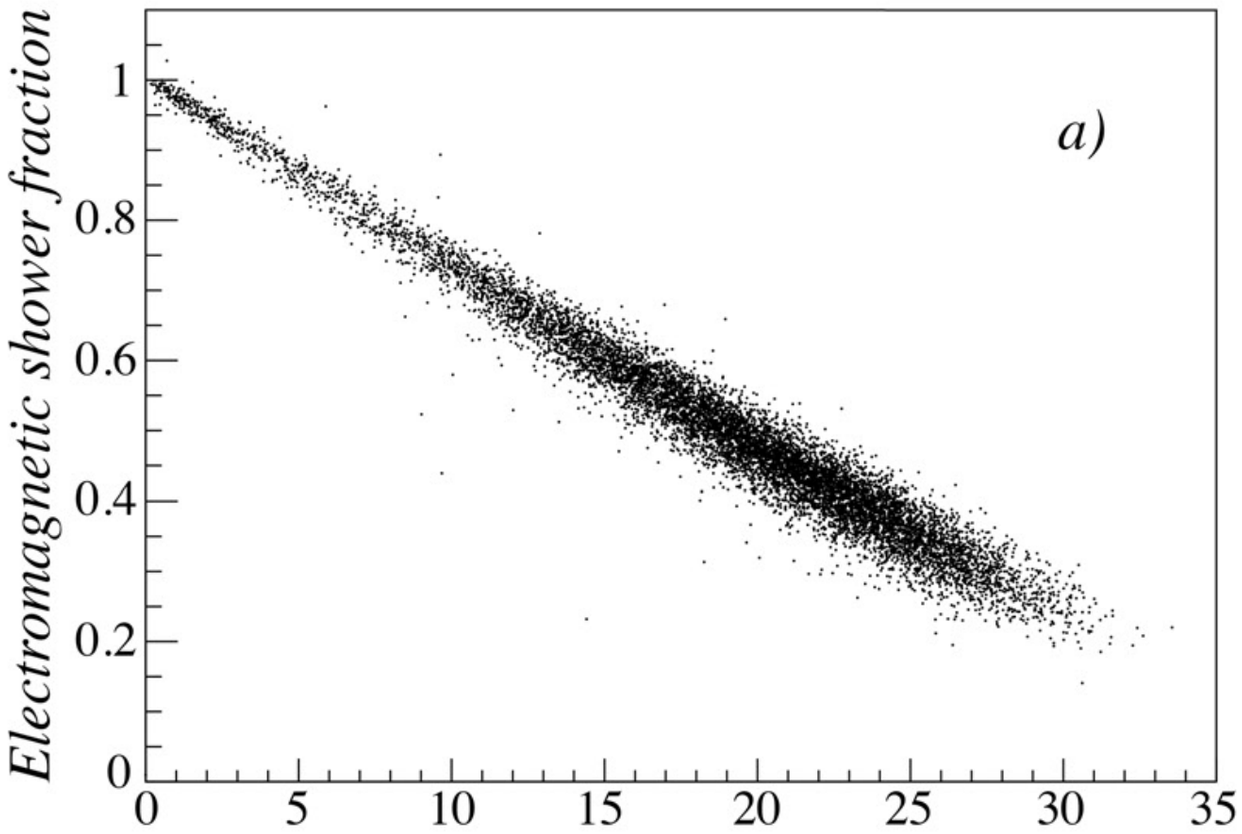
# Comparison of Dual-Readout and Compensation

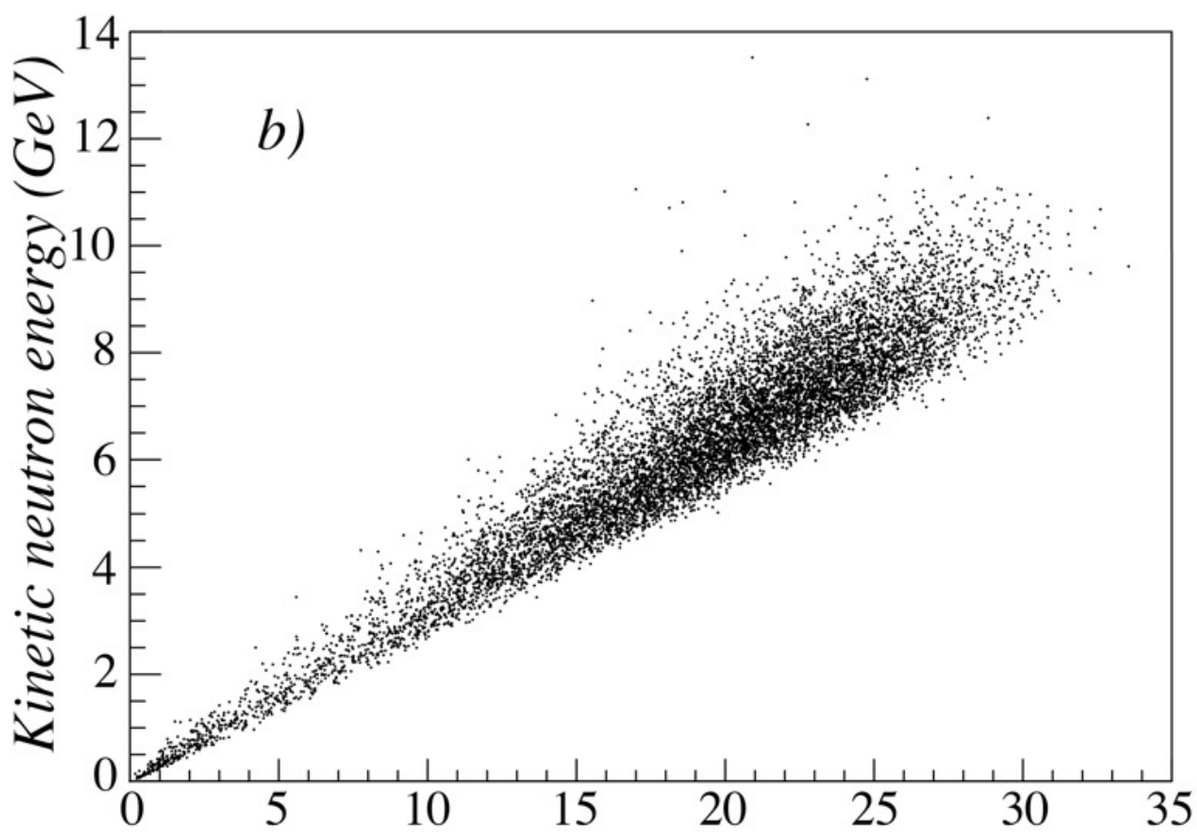


# *Prediction of the limits of the hadronic energy resolution*

- 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 $\pi^-$ 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)

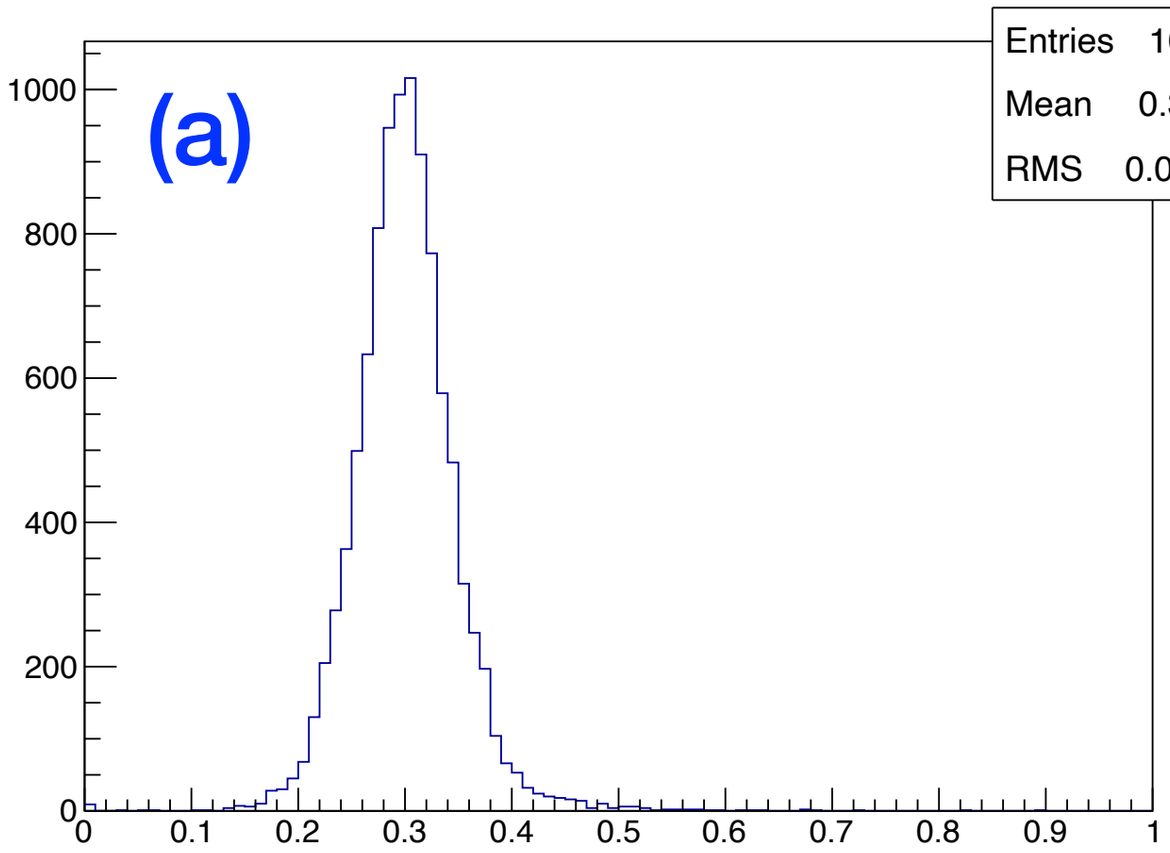


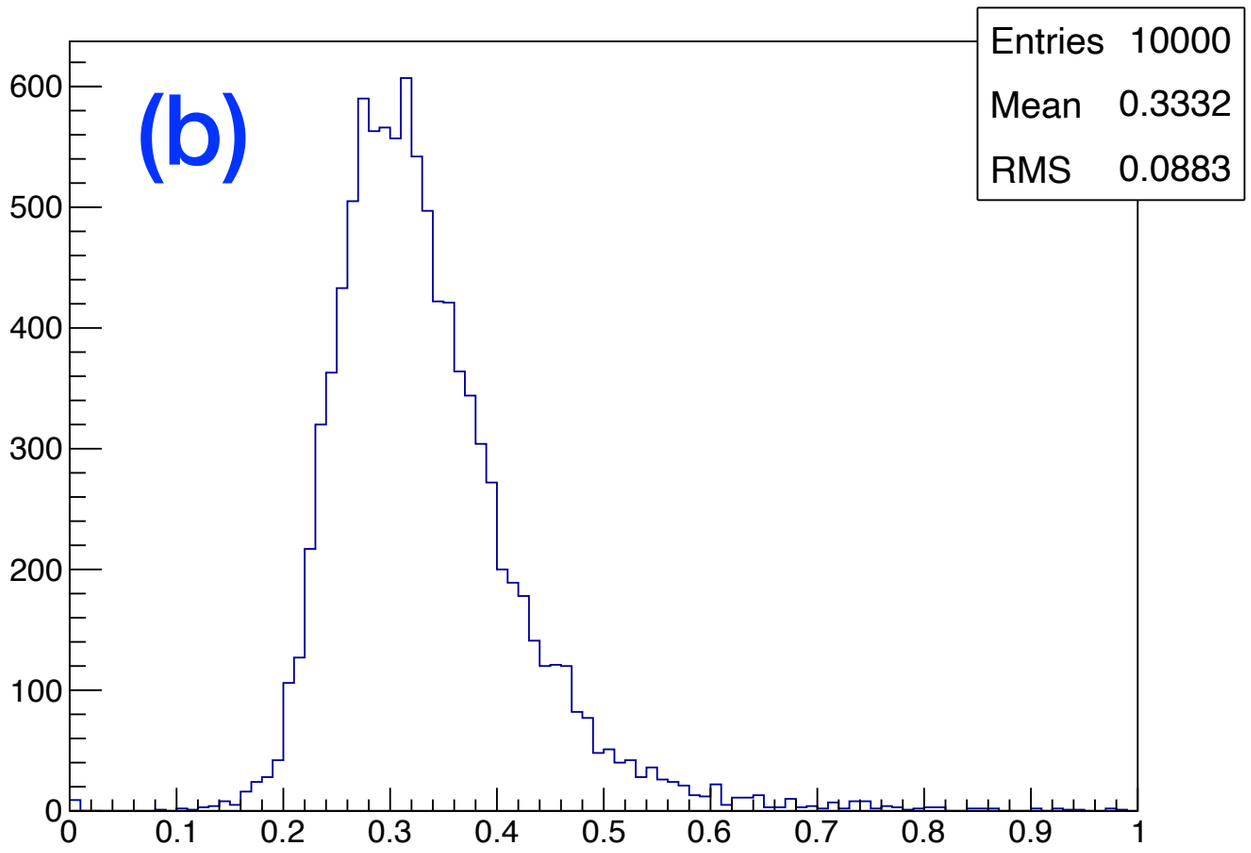

Nuclear binding energy loss (GeV)

*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)



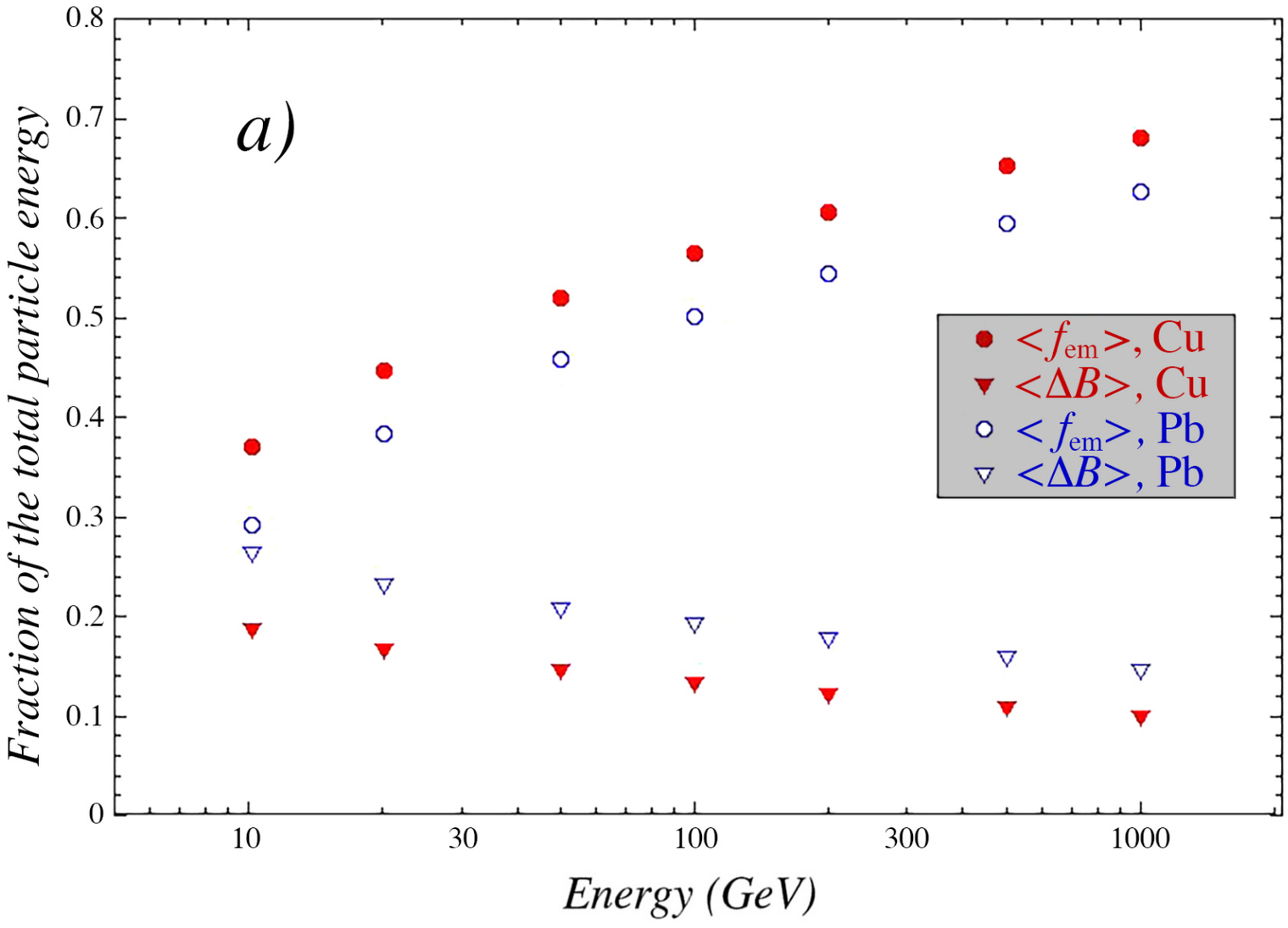

*Binding energy loss/Total non-em energy*



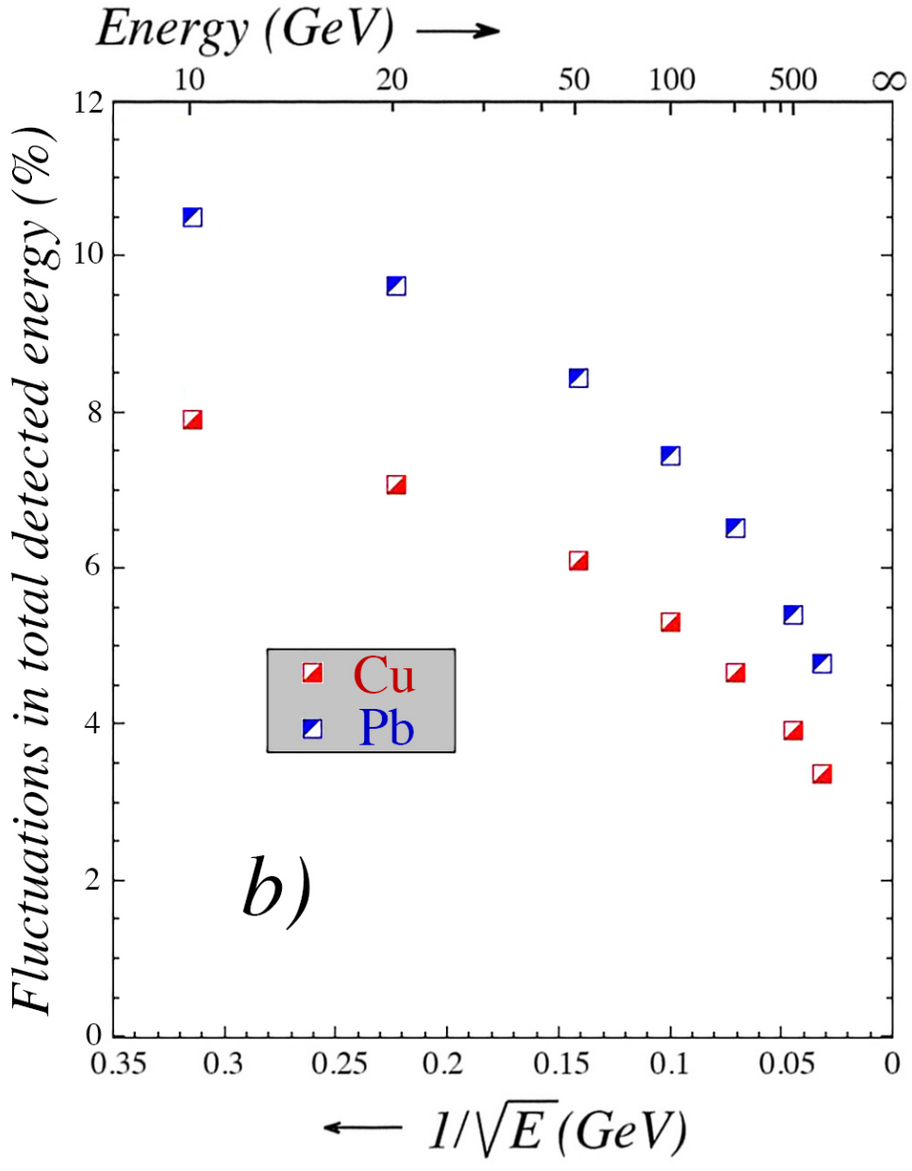

*Kinetic energy neutrons/Binding energy loss*

*20 GeV $\pi^-$ in copper*

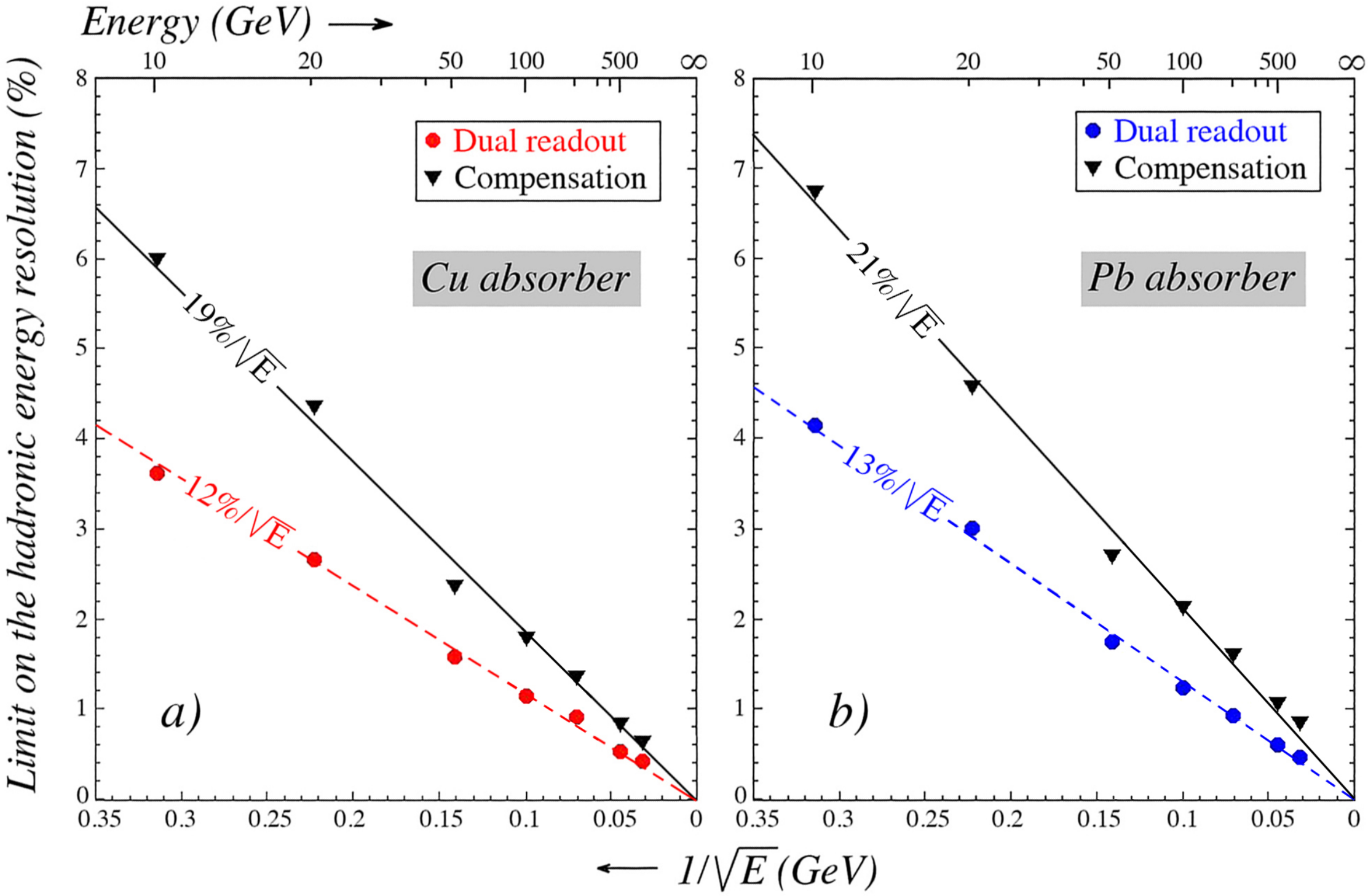
## <EM Shower fraction> and <Binding Energy Loss>




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



# Limits on the hadronic energy resolution



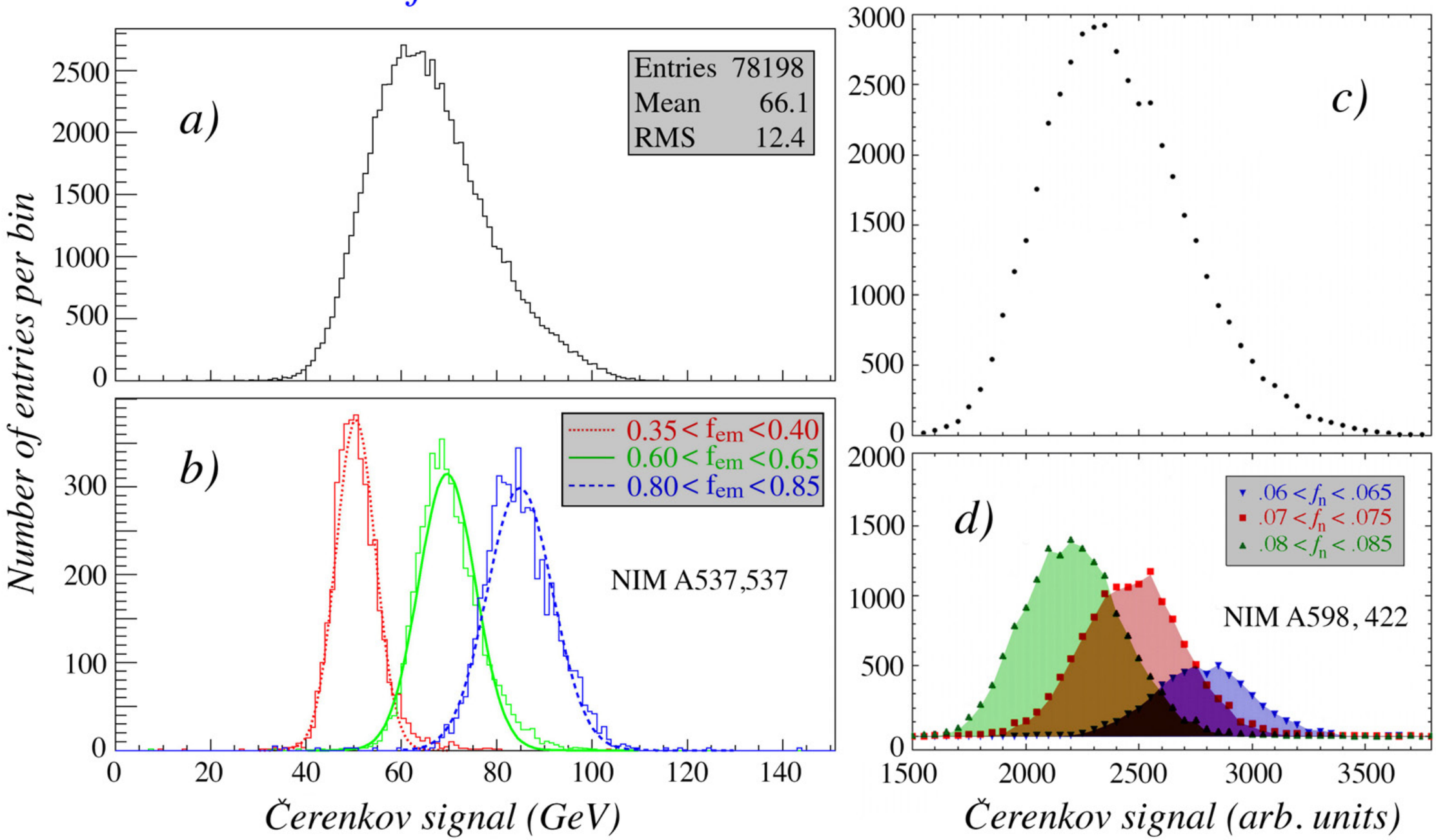
# *Conclusion*

- 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*

*em fraction*

*neutron content*

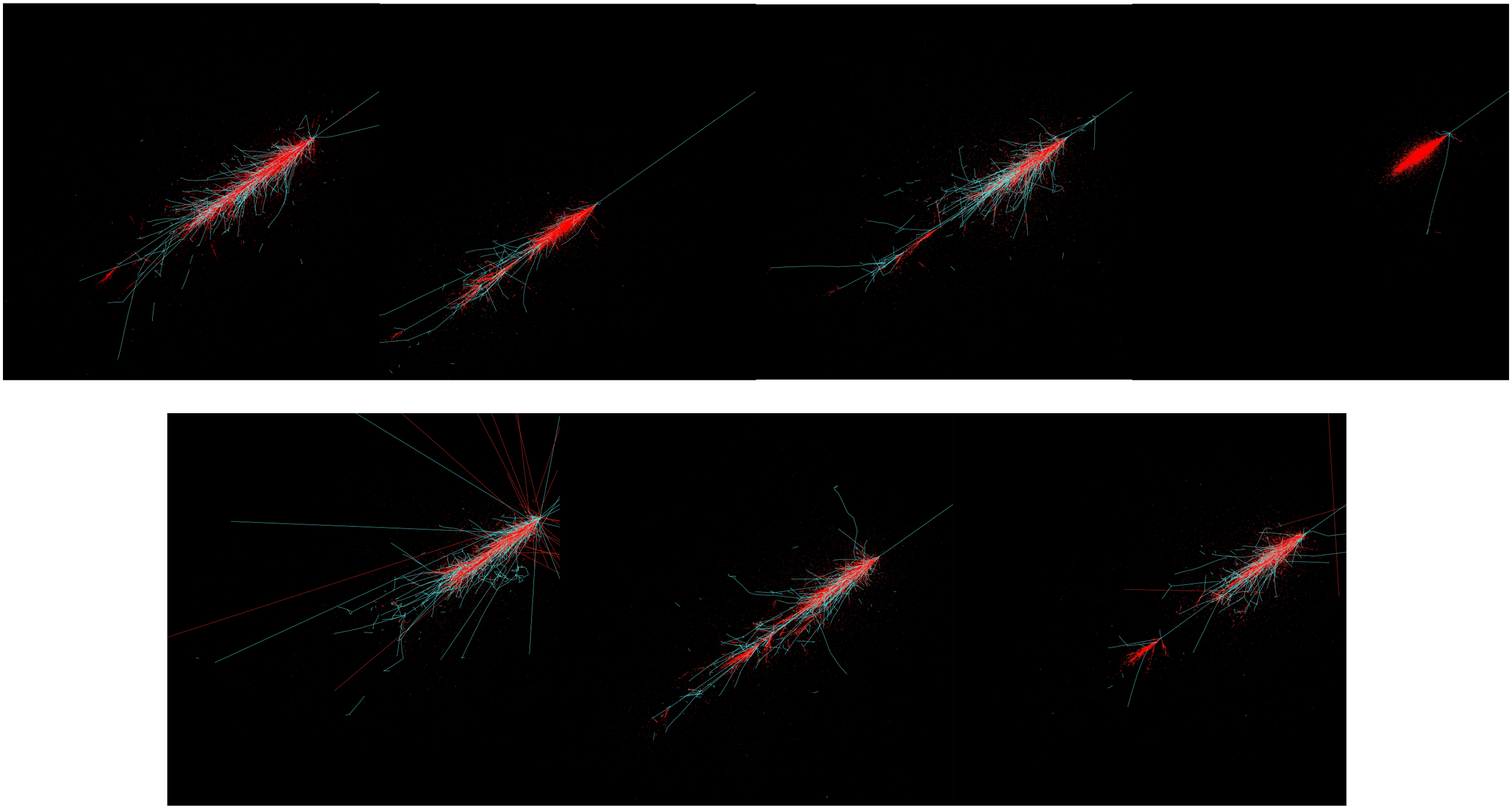


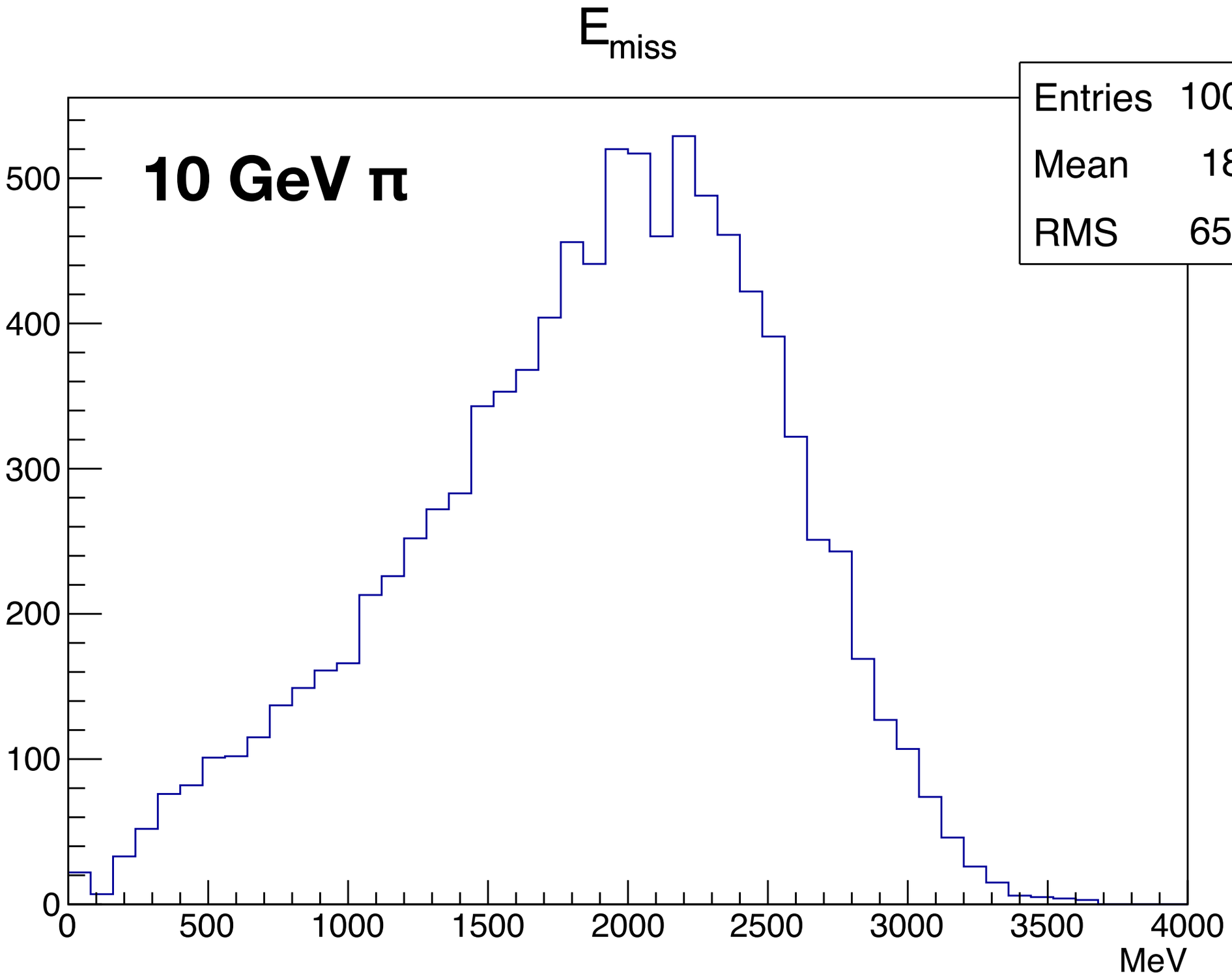
# Backup

# 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
500
400
300
200
100
0
0
500
1000
1500
2000
2500
3000
3500
4000
MeV