Invisible Energy in Cosmic Ray Showers

RESEARCH PROJECT

Author: Bc. Šimon Novák

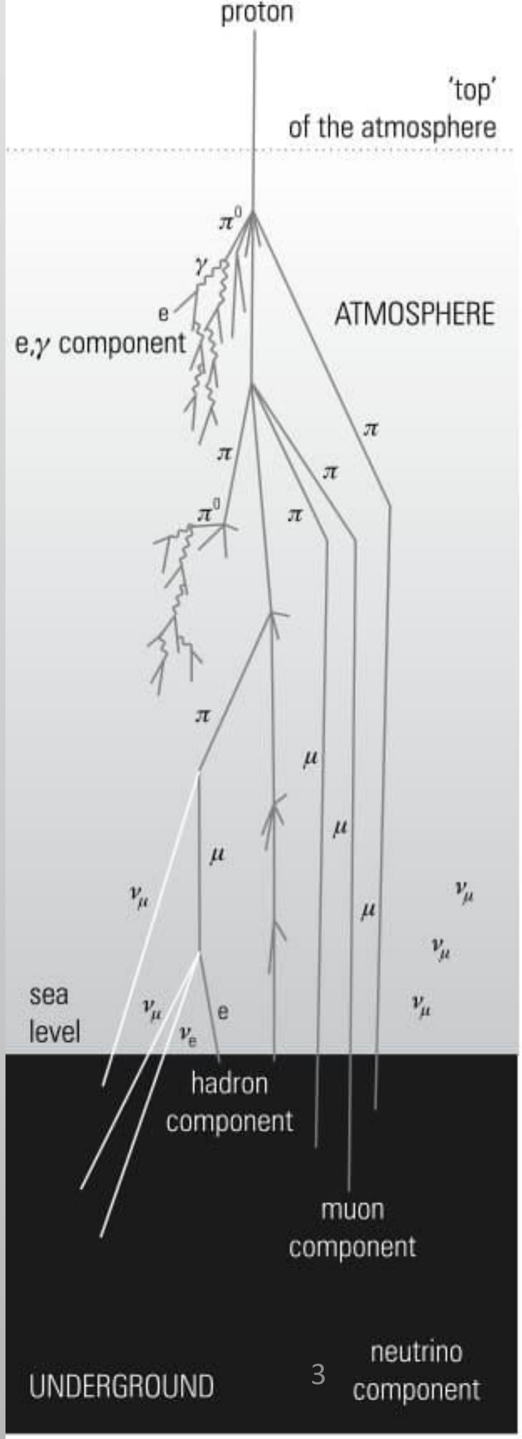
Supervisor: RNDr. Petr Trávníček, Ph.D.

Outline

1) Cosmic ray shower
2) Fluorescence detector of the Pierre Auger Observatory
3) Shower missing energy
4) C_{miss} and muon number reconstruction method
5) Summary

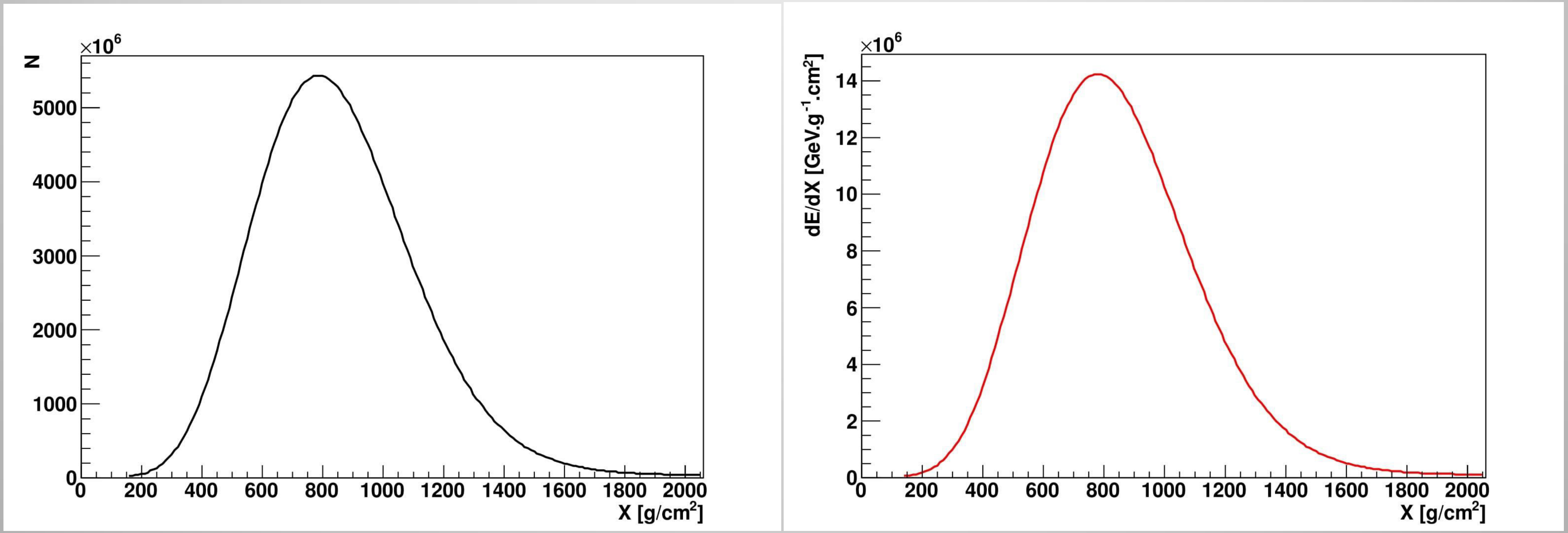
Cosmic ray shower

- secondary cosmic ray particles = result of primary particle interaction with atmosphere molecules
- hadronic component: n, p, nucleus fragments, pions, kaons
- electromagnetic component: $\pi^0 \rightarrow \gamma + \gamma$
  $\gamma \rightarrow e^- + e^+$
  -> electromagnetic cascades
- muon component: $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
- neutrino component: $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
  $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$



Right: A scheme of cosmic ray shower components [1]

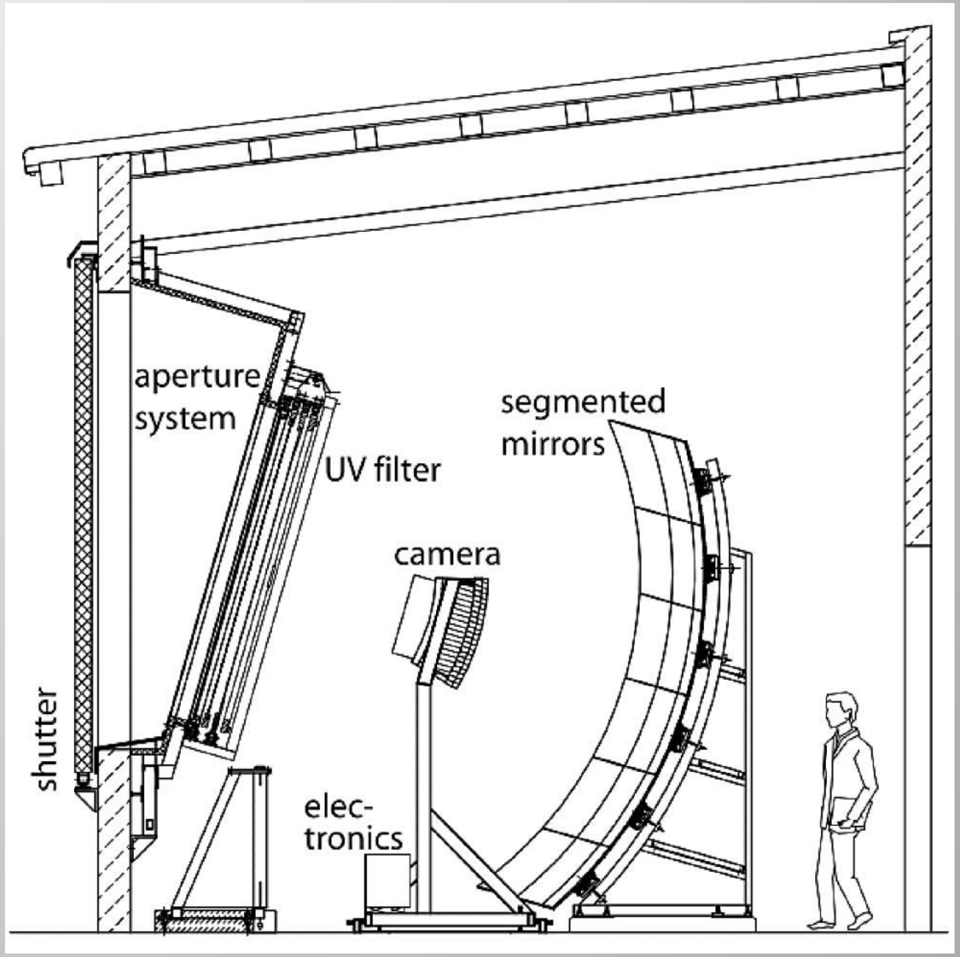
- particles multiplicate exponentially through hadronic and EM cascades
- up to 10^{10} new particles at the depth of shower maximum X_{max}
- shower energy deposition by excitation of atmospheric molecules



Number of shower particles (left) and shower energy deposition (right) as functions of atmospheric depth X. Simulated proton induced shower of energy $E = 10^{19}$ eV.

Fluorescence telescope at the PAO

- measures UV light from atmospheric molecules deexcitacion
- light is concentrated by mirrors onto 440 pixel camera of PMTs
- reconstruction of shower axis
- measurement of calorimetric energy E_{cal}
- 24 telescopes in total overwatch the site in 4 stations



A scheme of a fluorescence telescope at the PAO [2].

Shower missing energy

- a part of total shower energy not measured by fluorescence telescopes
- almost all energy deposited in the atmosphere is from EM component
- some shower energy is carried away mainly by muon and neutrino component
- missing part must be estimated from shower MC simulations
- 5600 showers were simulated by program CONEX using interaction models EPOS LHC and QGSJET-II-04
  - primary particle proton or iron nucleus
  - primary particle energies [log(E_0/eV)] - 17, 17.5, 18, 18.5, 19, 19.5, 20

E_{miss} calculation

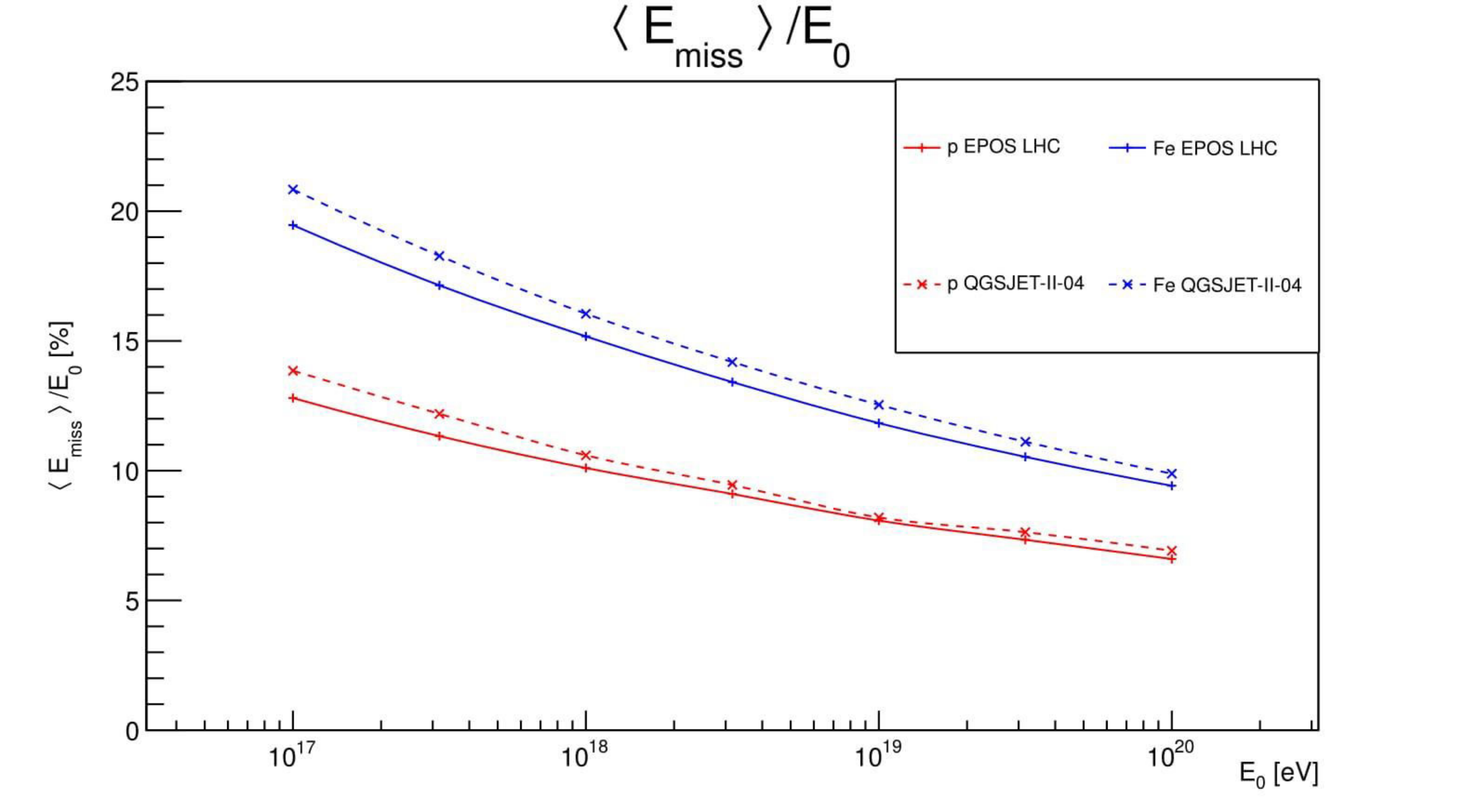
- shower energetic profile fitted by integrated Gaisser-Hillas function (4)

$$f_{GH}(X) = \left(\frac{\mathrm{d}E}{\mathrm{d}X}\right)_{max} \left(\frac{X - X_0}{X_{max} - X_0}\right)^{\frac{X_{max}-X_0}{\lambda}} e^{\frac{X_{max}-X}{\lambda}}. \qquad (1)$$

$$E_{cal} = \int_0^\infty f_{GH}(X)\mathrm{d}X \qquad (2)$$

$$E_{cal} = \lambda \left(\frac{\mathrm{d}E}{\mathrm{d}X}\right)_{max} \left(\frac{e\lambda}{X_{max} - X_0}\right)^{\frac{X_{max}-X_0}{\lambda}} \Gamma\left(\frac{X_{max} - X_0}{\lambda} + 1\right) \qquad (3)$$

$$f_{GH}(X) = \frac{E_{cal}}{\lambda} \left(\frac{X - X_0}{\lambda}\right)^{\frac{X_{max}-X_0}{\lambda}} e^{\frac{X_0-X}{\lambda}} \left[\Gamma\left(\frac{X_{max} - X_0}{\lambda} + 1\right)\right]^{-1} \qquad (4)$$



Behavior of missing energy fraction as a function of shower total energy.

C_{miss} reconstruction method

- parametrization $C_{miss}(E_{cal})$ estimated from simulated data

$$\langle C_{miss} \rangle = \frac{\langle E_{cal} \rangle}{E_0} = a - b \left(\frac{\langle E_{cal} \rangle}{1\,\mathrm{EeV}} \right)^c \tag{5}$$

- shower total energy can be reconstructed as

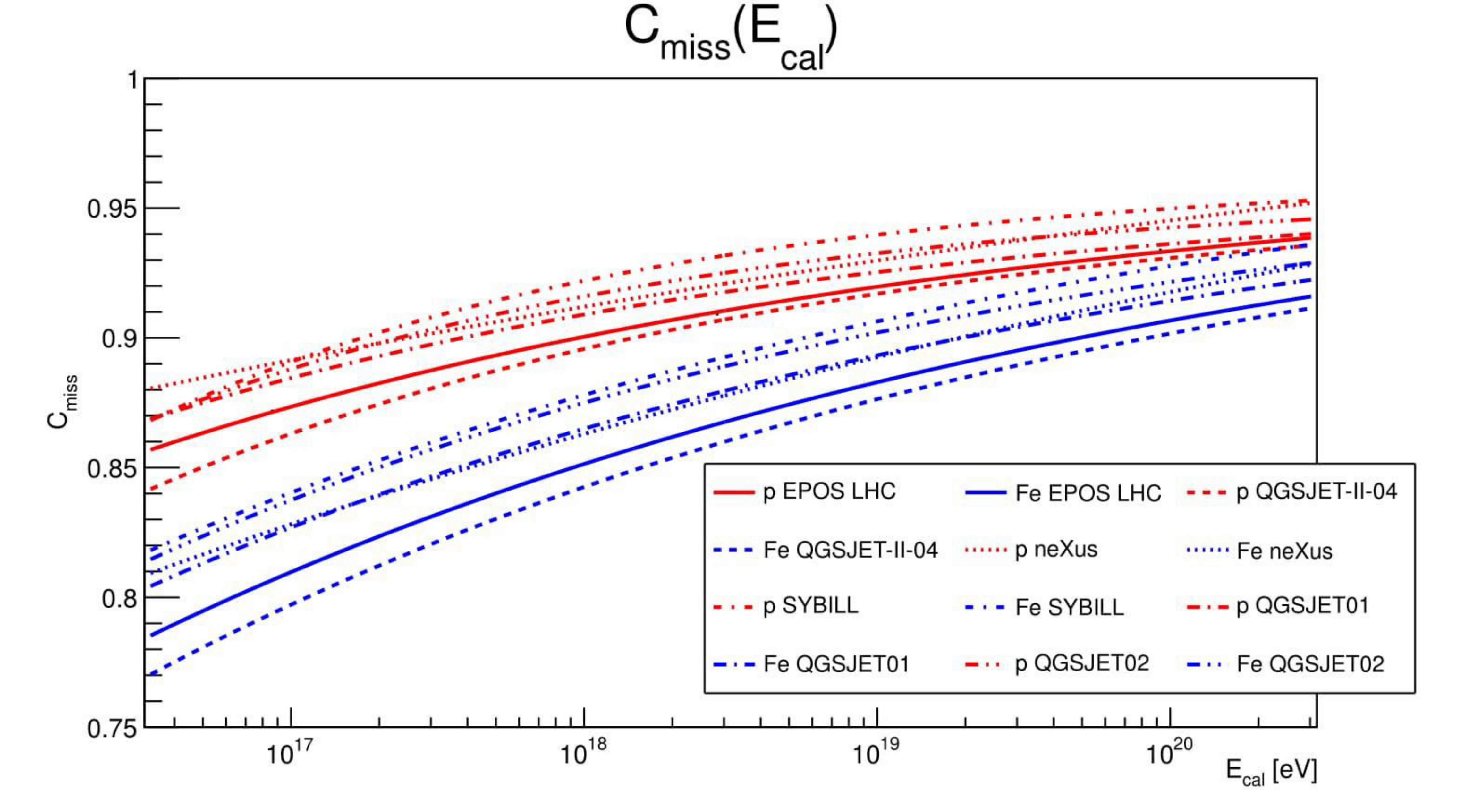
$$E_0 = \frac{E_{cal}}{C_{miss}(E_{cal})} \tag{6}$$

Tables of calculated parameters a, b and c from eq. (5) are listed below. First two tables are calculated only for protons or iron nuclei induced showers. Third table shows calculated parameters as even mixtures of proton and iron showers and both interaction models. Results of this work are in bold, others are taken from [3,4] for comparison.

	protons		
	a	b	c
EPOS LHC	$\mathbf{0.968 \pm 0.005}$	$\mathbf{0.067 \pm 0.005}$	$\mathbf{-0.147 \pm 0.011}$
QGSJET-II-04	$\mathbf{0.956 \pm 0.004}$	$\mathbf{0.060 \pm 0.004}$	$\mathbf{-0.187 \pm 0.012}$
neXus	1.046	0.134	-0.062
SYBILL	0.963	0.041	-0.246
QGSJET01	0.958	0.049	-0.176
QGSJET02	0.957	0.041	-0.226

	iron nuclei		
	a	b	c
EPOS LHC	$\mathbf{0.980 \pm 0.003}$	$\mathbf{0.129 \pm 0.003}$	$\mathbf{-0.121 \pm 0.003}$
QGSJET-II-04	$\mathbf{0.976 \pm 0.002}$	$\mathbf{0.133 \pm 0.002}$	$\mathbf{-0.127 \pm 0.002}$
neXus	1.059	0.196	-0.071
SYBILL	0.993	0.115	-0.123
QGSJET01	0.975	0.110	-0.129
QGSJET02	0.972	0.097	-0.142

a	b	c
$\mathbf{0.970 \pm 0.004}$	$\mathbf{0.097 \pm 0.004}$	$\mathbf{-0.146 \pm 0.007}$
0.978	0.085	-0.135
0.967	0.078	-0.140



Parametrization function $C_{miss}(E_{cal})$ for different parameters a, b, c listed in previous tables.

Muon number reconstruction method

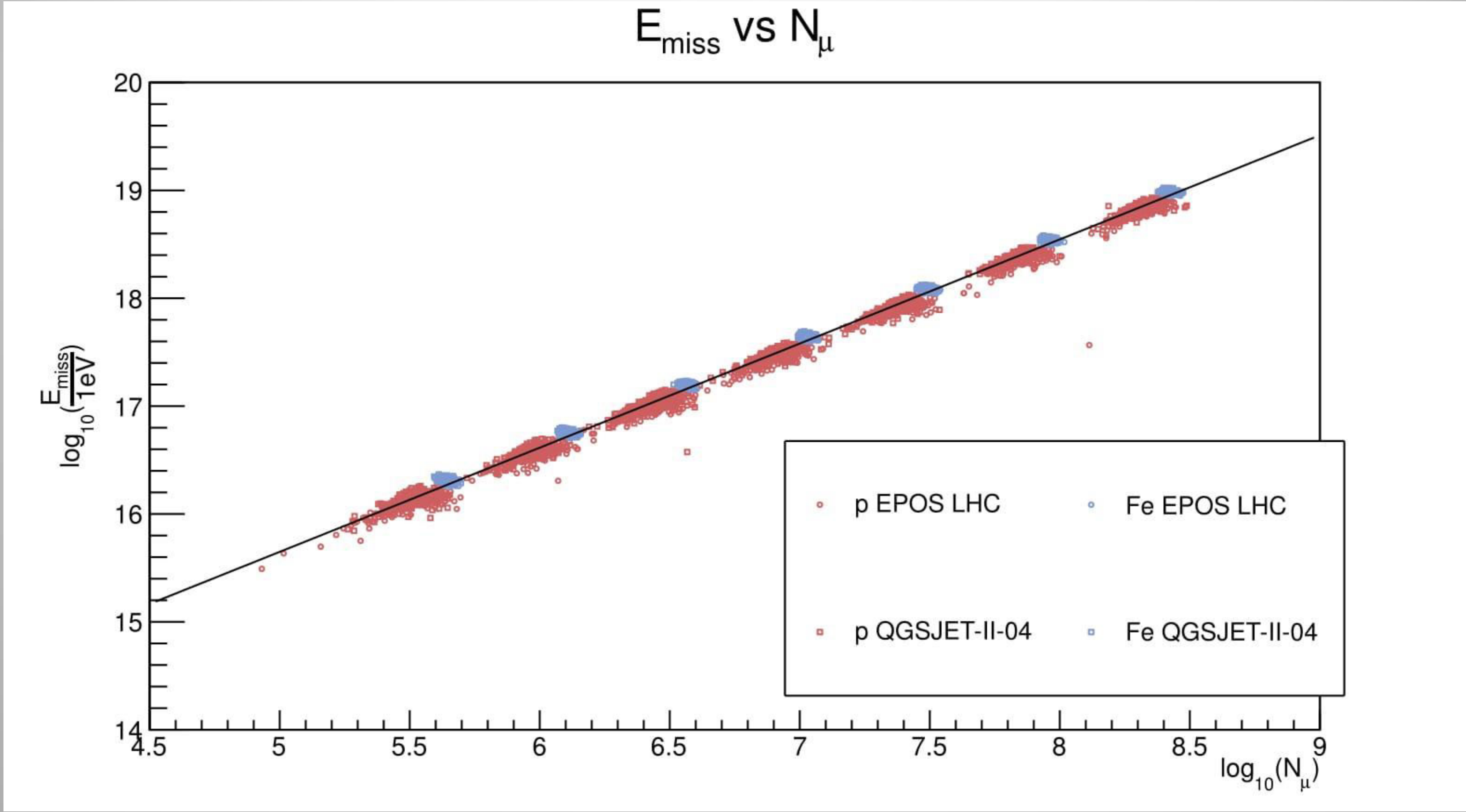
- direct link between the shower missing energy and the number of shower muons reaching ground is expressed by equation

$$\log_{10}(\frac{E_{miss}}{1\text{ eV}}) = a.\log_{10}(N_\mu) + b \qquad (7)$$

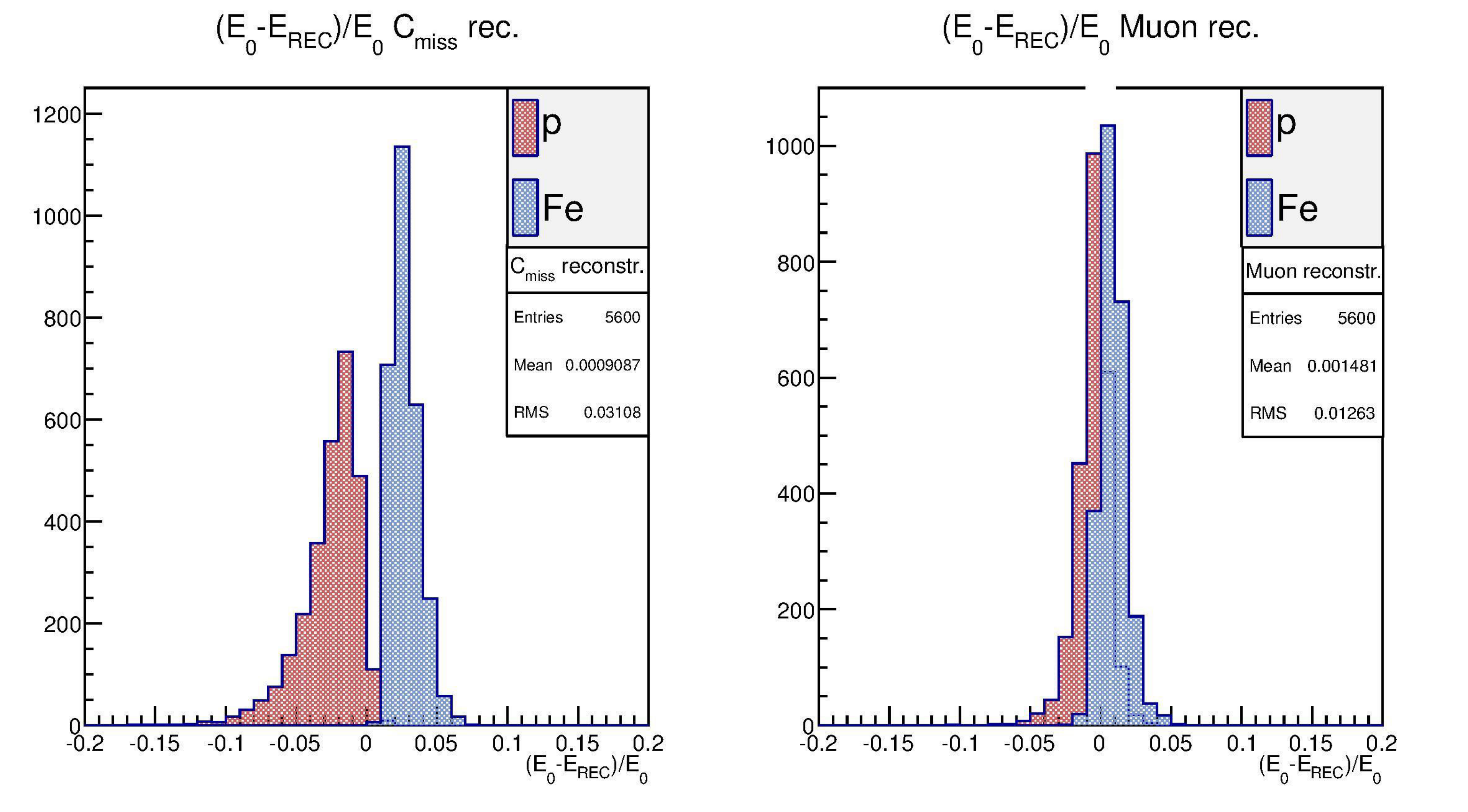
$$a = 0.9656 \pm 0.0007$$

$$b = 10.822 \pm 0.005.$$

- parameters a and b are calculated by fitting the plot of calculated E_{miss} for every simulated shower versus its respective number of muons N_μ



A linear fit of the plot of E_{miss} as a function of N_{μ} for all 5600 simulated showers.



Comparison of both reconstruction methods using histograms of errors in reconstructed primary energy for all simulated showers.

Summary

- The C_{miss} reconstruction method parameters a,b,c were calculated using newer hadronic interaction models EPOS LHC and QGSJET-II-04
- The muon reconstruction method was established using simulated data and compared to the C_{miss} method
- Muon reconstruction method was showed more precise, however accurate muon measurement is currently not possible at the PAO
- AugerPrime upgrade -> muon singal distinguishion from EM signal in the surface detectors by adding scintillators at the top of each SD station
- Muon reconstruction method can decrease the systematic error of the shower energy reconstruction at the PAO

References

[1] C. Grupen, *Astroparticle physics,* Springer Science & Business Media, 2005, ISBN 978-3-540-25312-9

[2] J. Abraham et al., The Fluorescence Detector of the Pierre Auger Observatory, *Nucl.Instrum. Meth*., A620:227-251, 2010

[3] Henrique M. J. Barbosa, F. Catalani, J. A. Chinellato, and Carola Dobrigkeit. Determination of the calorimetric energy in extensive air showers. *Astropart. Phys*., 22:159-166, 2004

[4] M. Nyklíček, J. Řídký, and P. Trávníček, Influence of hadronic interaction models on determination of chemical composition and size of the missing energy, *GAP notes*, 2008