The muon deficit problem: a new method to calculate the muon rescaling factors and the Heitler-Matthew's β-exponent

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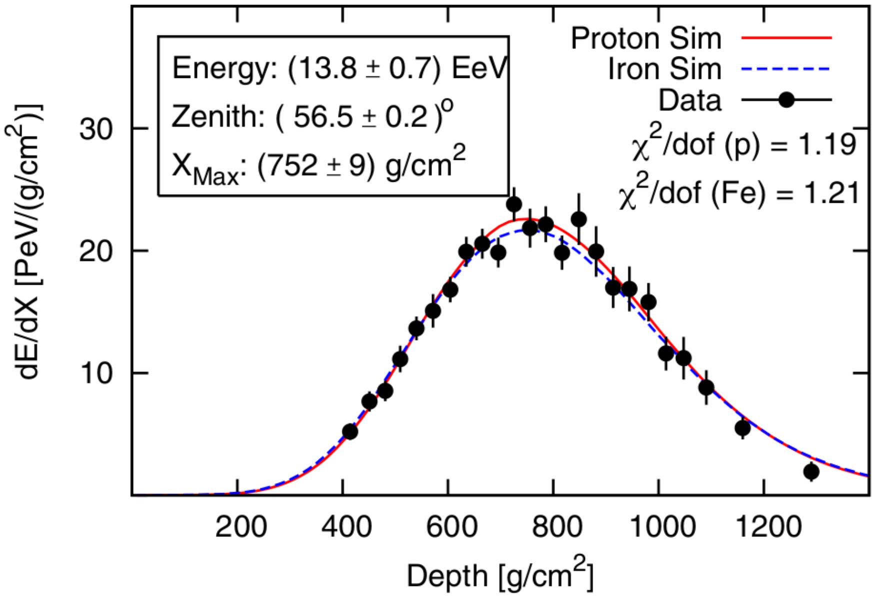
Introduction

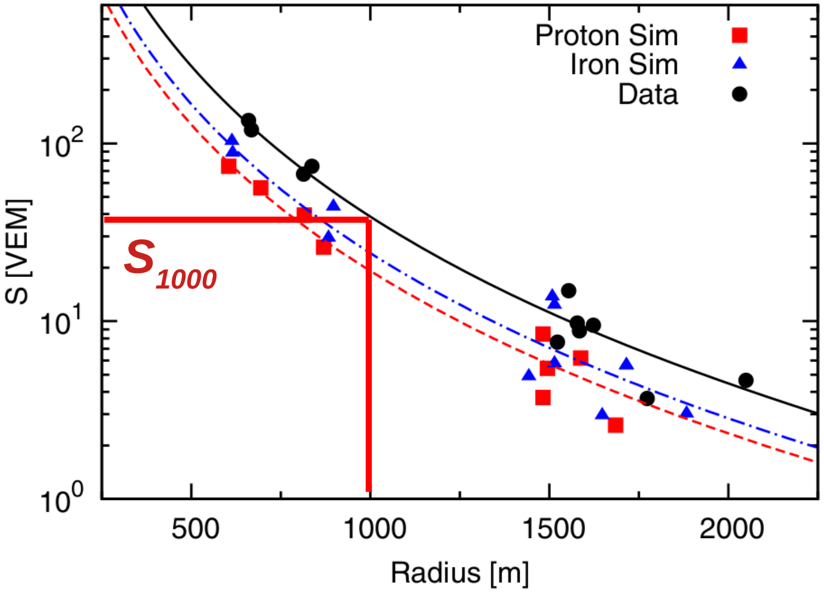
Muon numbers predicted by simulations of extensive air showers using current hadronic interaction models are too small:
- simulations with the LHC-tuned models (EPOS-LHC, QGSJetII-04) have 30% to 60% lower muon numbers than what is observed at the shower energy of 10^{19} eV
(*PRL 117(2016)192001*)

Top-down method:
- use longitudinal profile observed in fluorescence detector (FD) to construct air shower simulations matching the observed ones,
- compare reconstructions of showers simulated and observed with surface detectors (SD)

FD: longitudinal profile



SD: lateral distribution

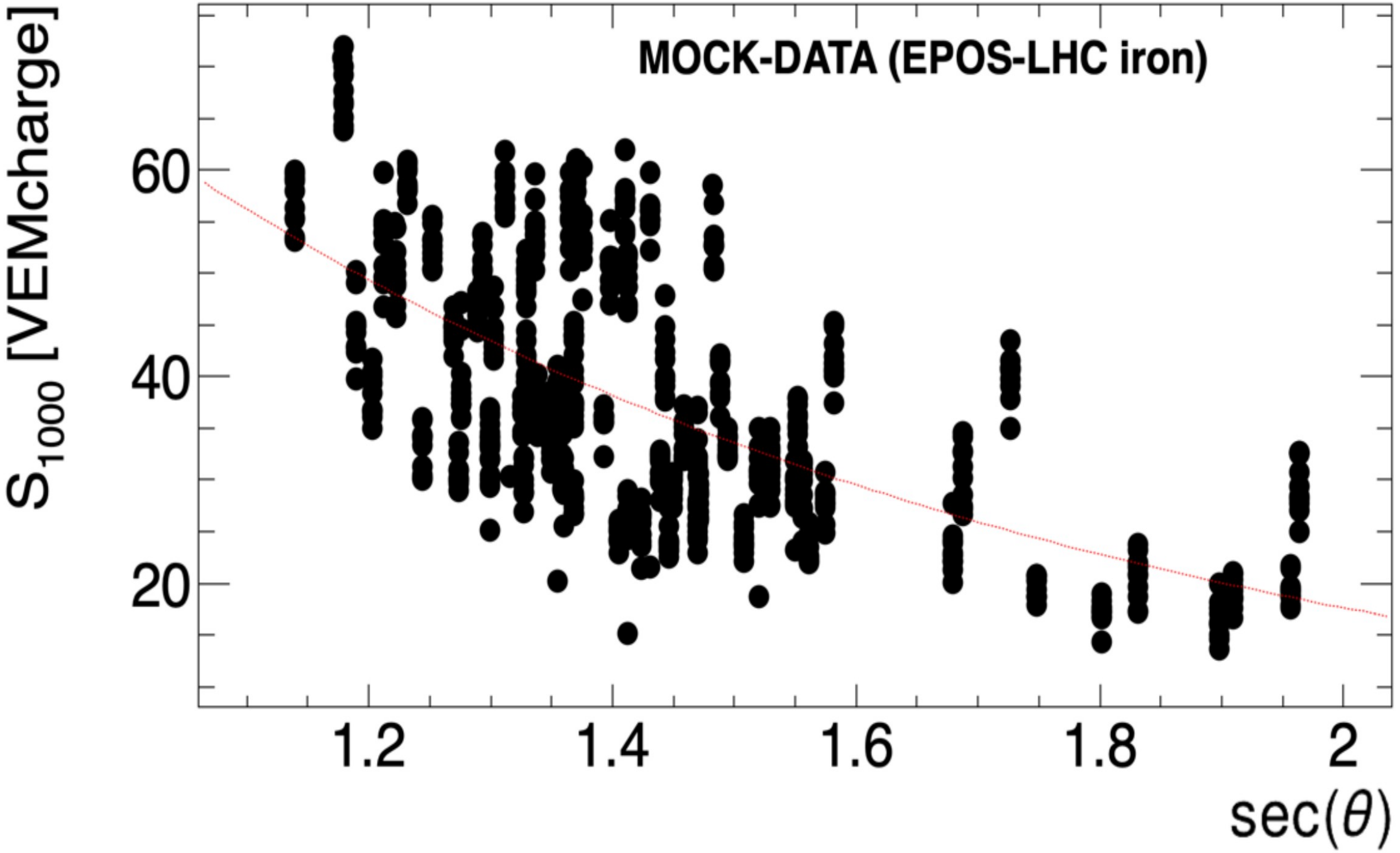


Software used: CORSIKA-75600, Auger Offline
Nuclear interaction models: EPOS-LHC, QGSJetII-04.
Primaries: proton, helium, nitrogen, iron

Method

- using simulations with EPOS-LHC at 10^{19} eV as a MOCK-DATA set

- and simulations with QGSJETII-04 as Monte Carlo signal to reproduce muon signal in the MOCK-DATA



Method to calculate muon scaling factors *R*

Signal can be divided into two main parts: **electromagnetic** and **muonic** components

$$S^{\mathrm{MOCK-DATA}}(R_E, R_\mu)_j \equiv S^{\mathrm{MOCK-DATA}}_{EM,j} + S^{\mathrm{MOCK-DATA}}_{\mu,j}$$
$$= R_E S^{\mathrm{MC}}_{EM,i,j} + R_\mu R_E^\alpha S^{\mathrm{MC}}_{\mu,i,j}$$

Instead of S_{1000} the **difference between signals** is used as the main observable:

$$z_j \equiv S^{\mathrm{MOCK-DATA}}_{1000,j} - S^{\mathrm{MC}}_{1000,j}$$

Electromagnetic component of air shower is well reproduced in simulations (*PRL 117(2016)192001*) $\longrightarrow$ rescaling factor for electromagnetic part equals 1:

$$S^{\mathrm{MC}}_{\mu,i} = \frac{z_i}{R_{\mu,i} - 1}$$

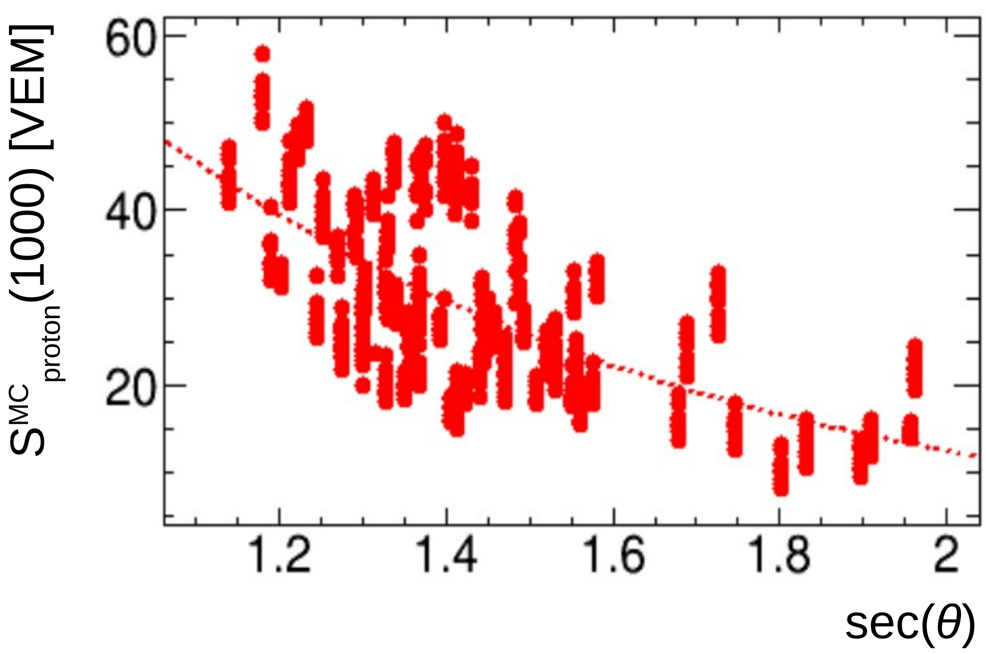
Distribution of z = $S^{MOCK\text{-}DATA} - S^{MC}$ (QGSJETII-04)

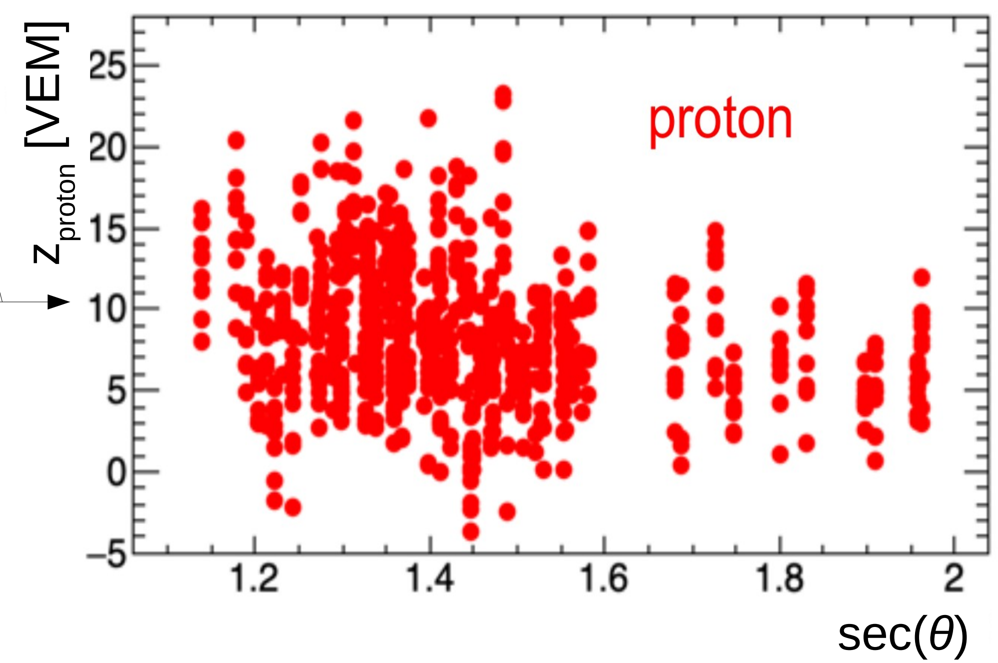
different muon scaling factors for different primaries are introduced (p, He, N, Fe)

- average z connected to average muon Monte Carlo signal at 1000 m

- z depends on primary particle type

- z should only slightly depend on the zenith angle





Estimated muon signal in MC simulations

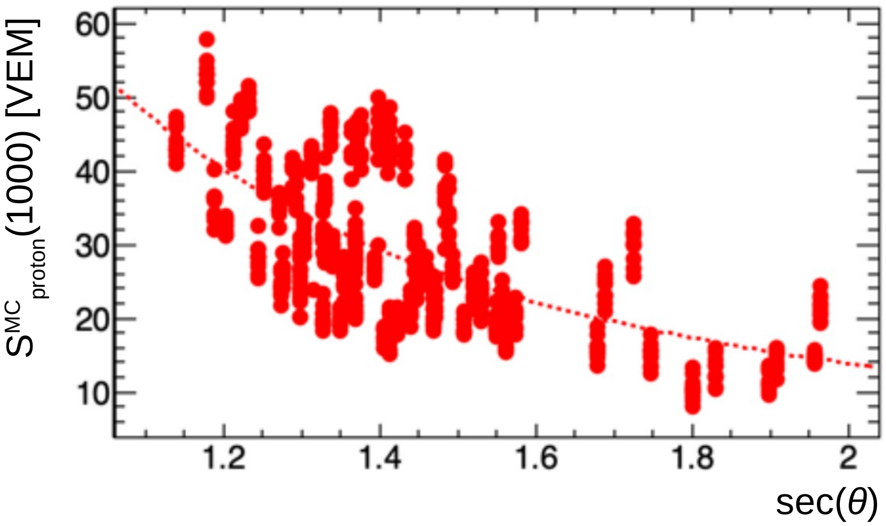
Estimated muon signal at 1000 m:

$$S^{\mathrm{MC}}_{\mu,i,j}(\theta) = g_{\mu,i}(\theta) \times S^{\mathrm{MC}}_{1000,i,j}(\theta)$$

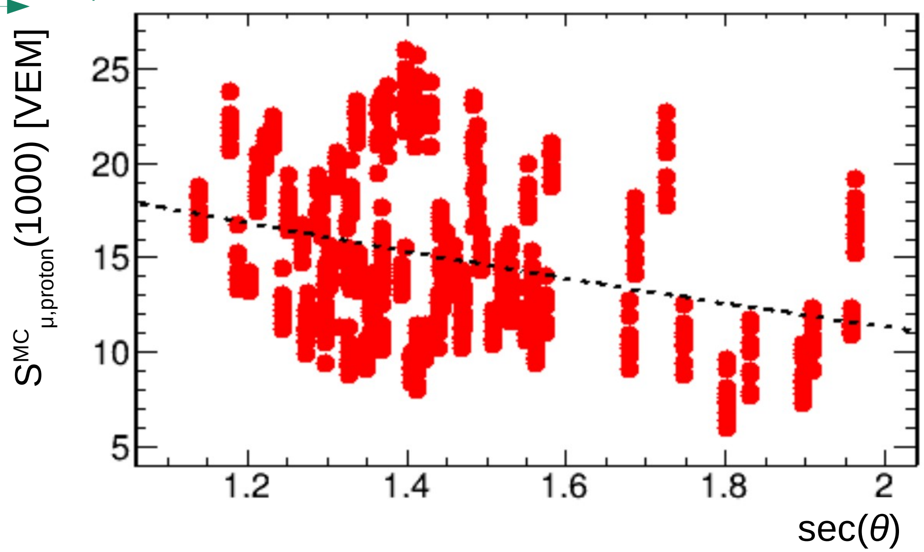
muon fraction in the total signal, from MC simulations *(ICRC-2013, astro-ph 1307.5059)*

S^{MC}_{1000} from MC simulations with QGSJETII-04

i – primary type, *j* - event



calculated using $g_{\mu}(\theta)$



Scaling factors $R_{\mu,i,j}$ from event-by-event calculations

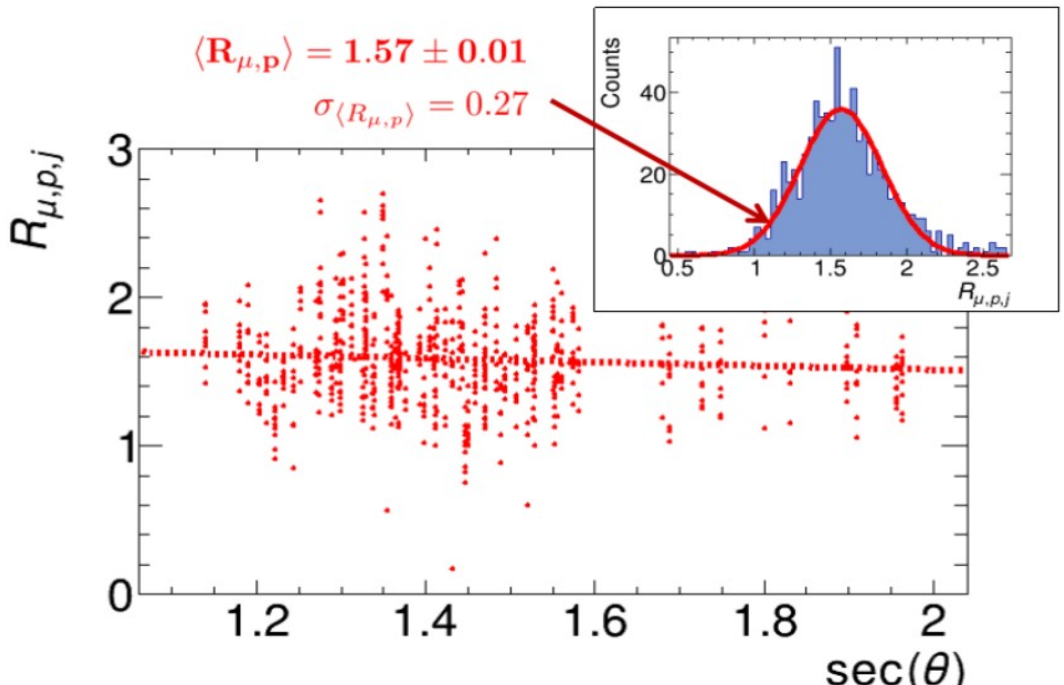
Having: 1) individual values of z_i from MC simulations, 2) corresponding SD signal at 1000 m, 3) parametrization of the muon fraction

⟶ the **muon scaling factor** for an individual hybrid event *j*, for any primary *i*, can be calculated:

$$R_{\mu,i,j}(\theta) = 1 + \frac{z_{i,j}(\theta)}{g_{\mu,i}(\theta) \times S^{\mathrm{MC}}_{1000,i,j}(\theta)}$$

QGSJETII-04 muon signal needs to be rescaled by a factor ~1.6 (proton) / 1.1(iron) to get the muon signal for iron in EPOS-LHC

The method reproduces an average muon signal calculated for iron with EPOS-LHC within 2 – 4%



$S_{\mu,Fe}^{MOCK\text{-}DATA}$ = 23.09 VEM *$R_{\mu,p}^{MC}$ = 1.57* *$S_{\mu,p}^{MC}$ = 15.05 VEM* *$R_{\mu,p}^{MC} \times S_{\mu,p}^{MC}$ = 23.63 VEM*

$R_{\mu,Fe}^{MC}$ = 1.14 *$S_{\mu,Fe}^{MC}$ = 21.08 VEM* *$R_{\mu,Fe}^{MC} \times S_{\mu,Fe}^{MC}$ = 24.03 VEM*

The β index

From Heitler-Matthews model (*Astropart. Phys. 22(2005)387*):

$$N_\mu \simeq A(\frac{E/A}{\epsilon_c^\pi})^\beta = N_\mu^p A^{1-\beta}$$

Detailed MC simulations show β depending on hadronic interaction properties, like the multiplicity, the charge ratio and the baryon anti-baryon pair production (*PRD 83(2011)054026*)

Model values: $\boldsymbol{\beta \approx 0.927}$ (EPOS-LHC) and $\boldsymbol{\beta \approx 0.925}$ (QGSJet II-04)

Assuming that $\langle N_\mu \rangle \propto \langle S_\mu \rangle$; $\quad S_{\mu,i}^{\mathrm{MOCK-DATA}} \equiv \langle R_{\mu,i} \rangle \times \langle S_{\mu,i}^{\mathrm{MC}} \rangle$

$$\beta_{m,n} = 1 - \frac{\log\langle S_{\mu,m}^{\mathrm{MOCK-DATA}} \rangle - \log\langle S_{\mu,n}^{\mathrm{MOCK-DATA}} \rangle}{\log A_m - \log A_n} = 1 - \frac{\log(\langle R_{\mu,m}\rangle \langle S_{\mu,m}^{\mathrm{MC}} \rangle) - \log(\langle R_{\mu,n}\rangle \langle S_{\mu,n}^{\mathrm{MC}} \rangle)}{\log A_m - \log A_n}$$

m,n - primaries

Method to calculate the β exponent

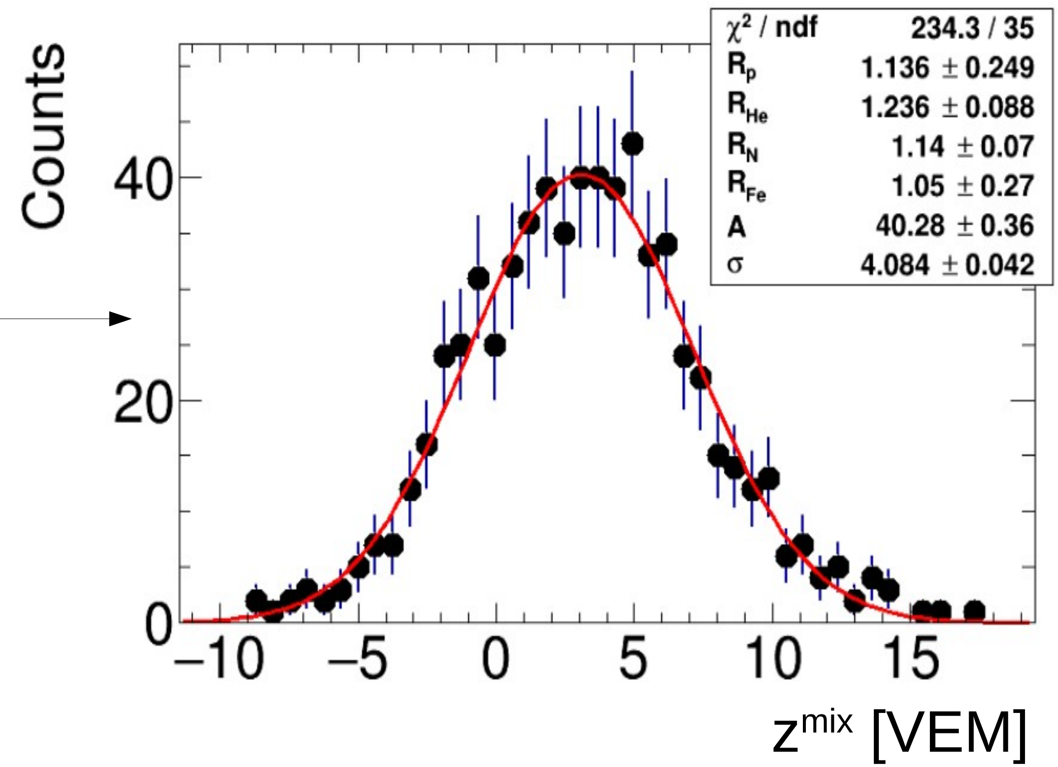
1) Generation of a new MOCK-DATA set, in such a way that considered fractions of events follow Auger predictions for EPOS-LHC (*PoS(ICRC2017)506*)

$$\mathbf{f_p \simeq 15\%, f_{He} \simeq 38\%, f_N \simeq 46\%, f_{Fe} \simeq 1\%}$$

2) z-variable for mixed composition

$$z_j^{\mathrm{mix}} \equiv S_{1000,j}^{\mathrm{MOCK-DATA}} - \sum_i f_i S_{\mu,i,j}^{\mathrm{MC}}$$

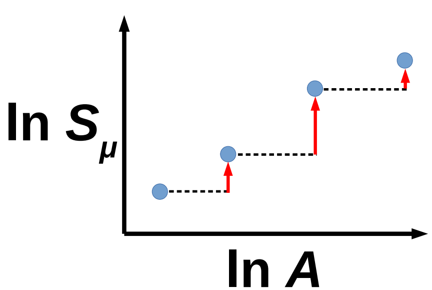
3) The Gaussian fit to z^{mix}-histogram



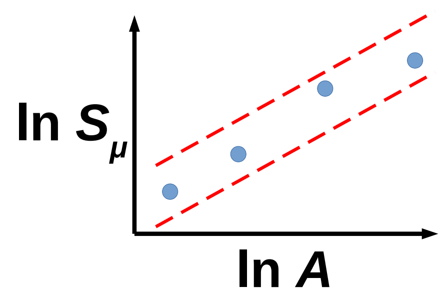
$$P(A, \sigma, \mathbf{R}_\mu^{\mathrm{fit}}) = A \exp(-(z^{\mathrm{mix}} - \langle z^{\mathrm{mix}} \rangle)^2 / 2\sigma^2)$$
$$\text{where } \langle z^{\mathrm{mix}} \rangle = \sum f_i \times \langle S_{\mu,i}^{\mathrm{MC}} \rangle (R_{\mu,i}^{\mathrm{fit}} - 1)$$

4) The solution should fulfill cuts:

- *the average muon number growing with primary mass:*



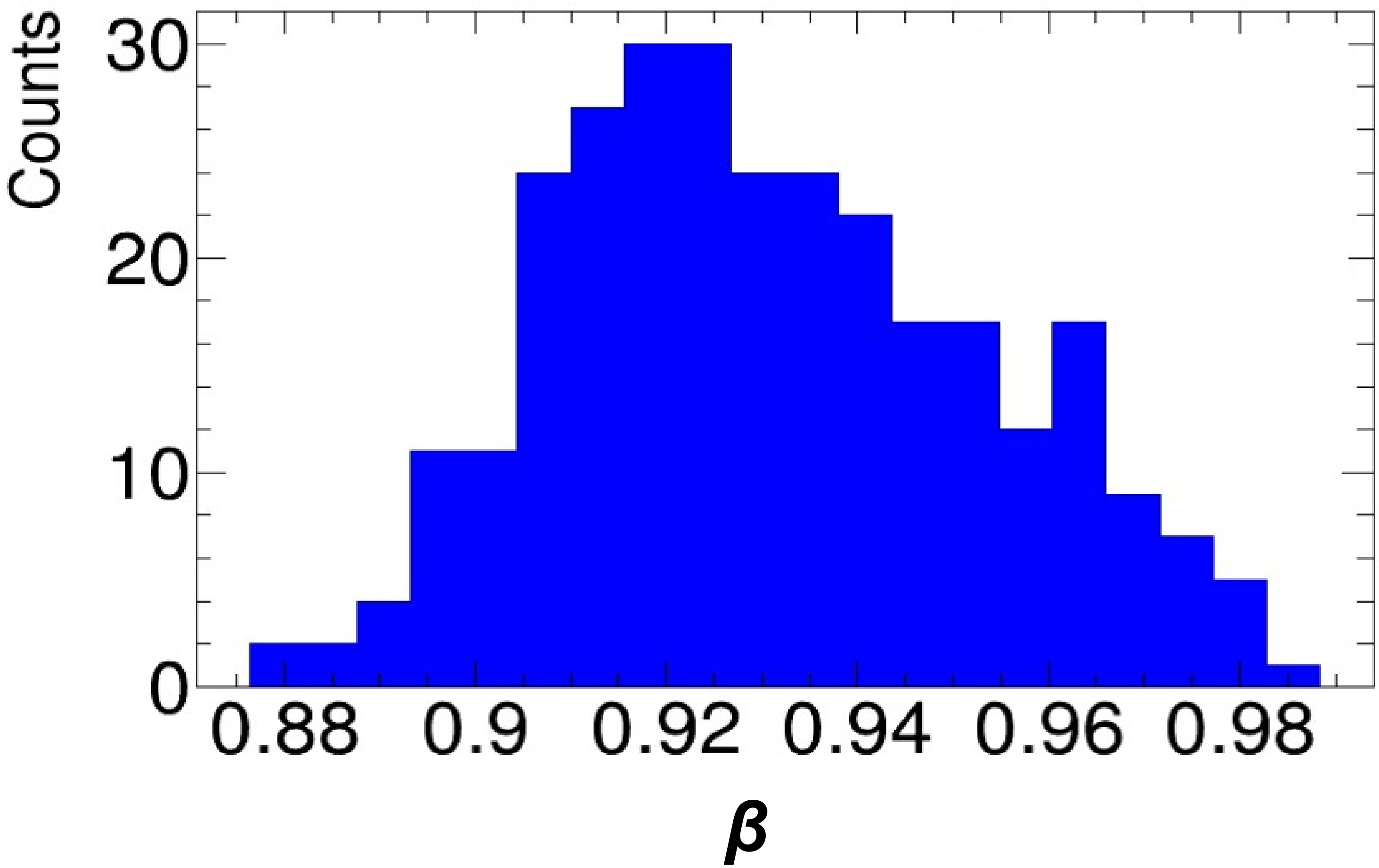
- *linearity:*



β exponent – results

- **the ratio in the muon signal between EPOS-LHC and QGSJetII-0.4 is recovered**, on average within **5%**

- **the parameter β = 0.92 for the studied system**, which is a consequence of the good recovery (less than 6% on average) of the muon signal for each primary



Summary

We present a new method to derive muon rescaling factors by analyzing reconstructions of simulated showers.

The variable z is connected to the muon signal, and is roughly independent of the zenith angle, but depends on the mass of primary cosmic ray.

We calculate the multiplicative ***rescaling parameters of the muon signals*** *in the ground detector even for an individual event, and study its dependence as a function of zenith angle and the mass of primary cosmic ray.*

This gives a possibility to test/calibrate the hadronic interaction models, and also to derive the β exponent, describing increase of the number of muons as a function of primary energy and mass.