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# Analysis of the muon component of extensive air showers in the SUGAR data.

**ISCRA-2019**

# Introduction and motimation

1 Discrepancies between theoretical models and real EAS data: muon excess , see e.g. [arXiv:1609.05764]

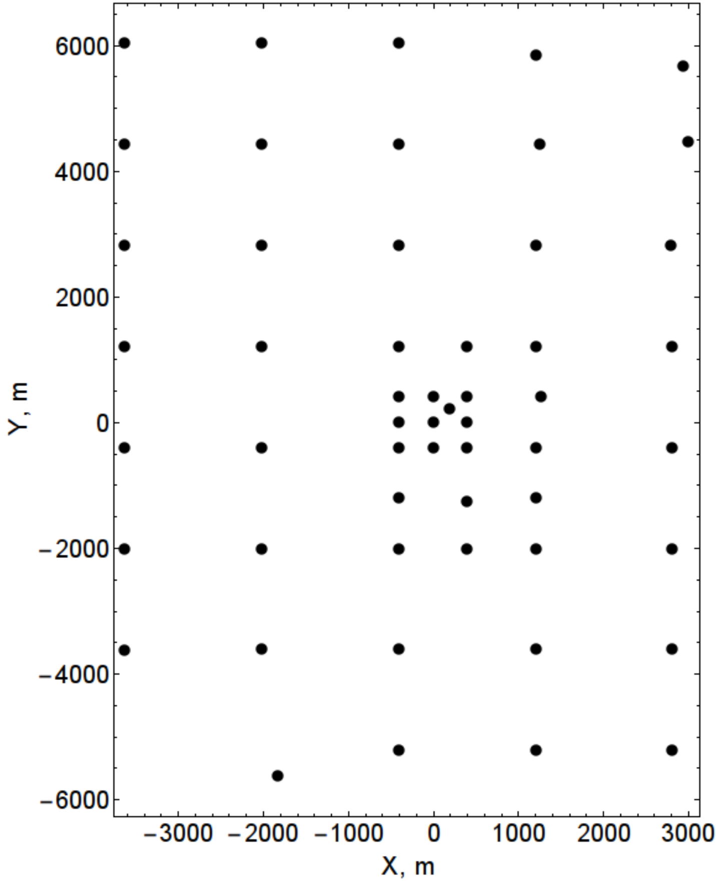
2 How does an muons excess depend on EAS parameters?

- **primary energy**
- **primary composition**
- **distance to the shower core (the LDF shape)**
- **zenith angle**
- **muon energy threshold**

**To study the dependence of the muon excess on the EAS parameters, an installation with a muon detector is required**

# SUGAR array

- operated between 1968 and 1979
- located near the town of Narrabri in New South Wales, Australia, and altitude~250 m above sea level
- area of about 70 km^2 and consisted of 54 underground detector stations
- each detector station had two liquid-scintillator tanks 50 m apart in the North-South direction, buried at the depth varying within 1.5±0.3 m
- The effective area of each scintillator tank was 6.0 m^2
- threshold energy for detected muons was (0.75±0.15) sec(θμ) GeV



# SUGAR muon LDF and vertical muon number

- muon lateral distribution function (LDF)

$$\rho_\mu = N_\mu k(\theta)\left(\frac{r}{r_0}\right)^{-a}\left(1+\frac{r}{r_0}\right)^{-b}$$

where $r_0$=320m, a=0.75, b =1.5+1.86*cos(θ),
k(θ) =Γ(b)/(2*Pi*$r_0^2$Γ(2-a)Γ(a+b-2)), **$N_\mu$ - muon number**

- In SUGAR data **$N_\mu$** was determined by fitting individual detector readings

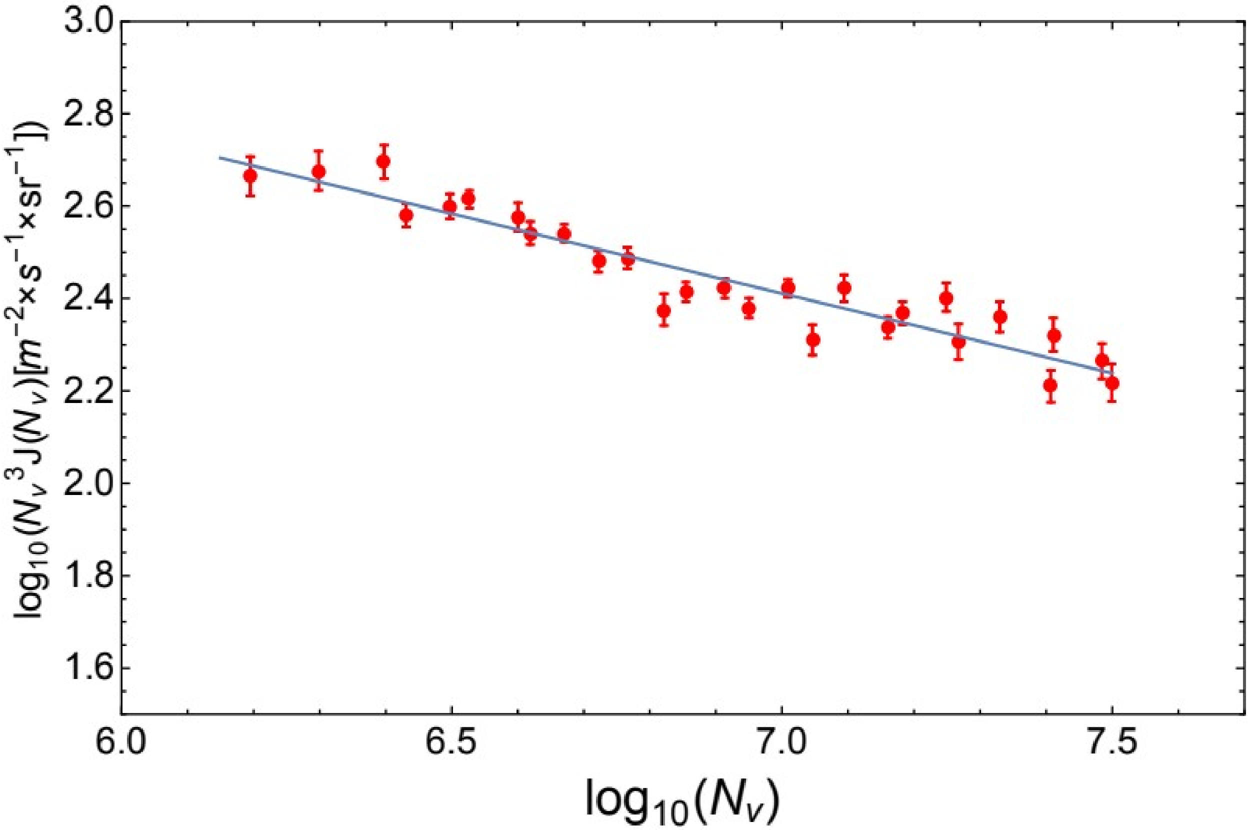
- for each observed EAS with a reconstructed **$N_\mu$** and **θ**, the number of vertical muons **$N_\nu$** was determined by the expression

$$\log\left(\frac{N_\nu}{N_r}\right)=\frac{(1-\gamma_\nu-A(\cos(\theta)-1))\log\left(\frac{N_\mu}{N_r}\right)+B(\cos(\theta)-1)+\log\dfrac{1-\gamma_\nu}{1-\gamma_\nu-A(\cos(\theta)-1)}}{1-\gamma_\nu}$$

where the coefficients are A= 0.47, B= 2.33, γv= 3.35, $N_r=10^7$

# SUGAR differential vertical muon number spectrum

We use the spectrum presented in J. Phys. G12(1986) 653.



Primary energy E is related to $\mathbf{N_v}$ by the following expression

$$E(N_\nu)=E_r\left(\frac{N_\nu}{N_r}\right)^{\alpha}$$

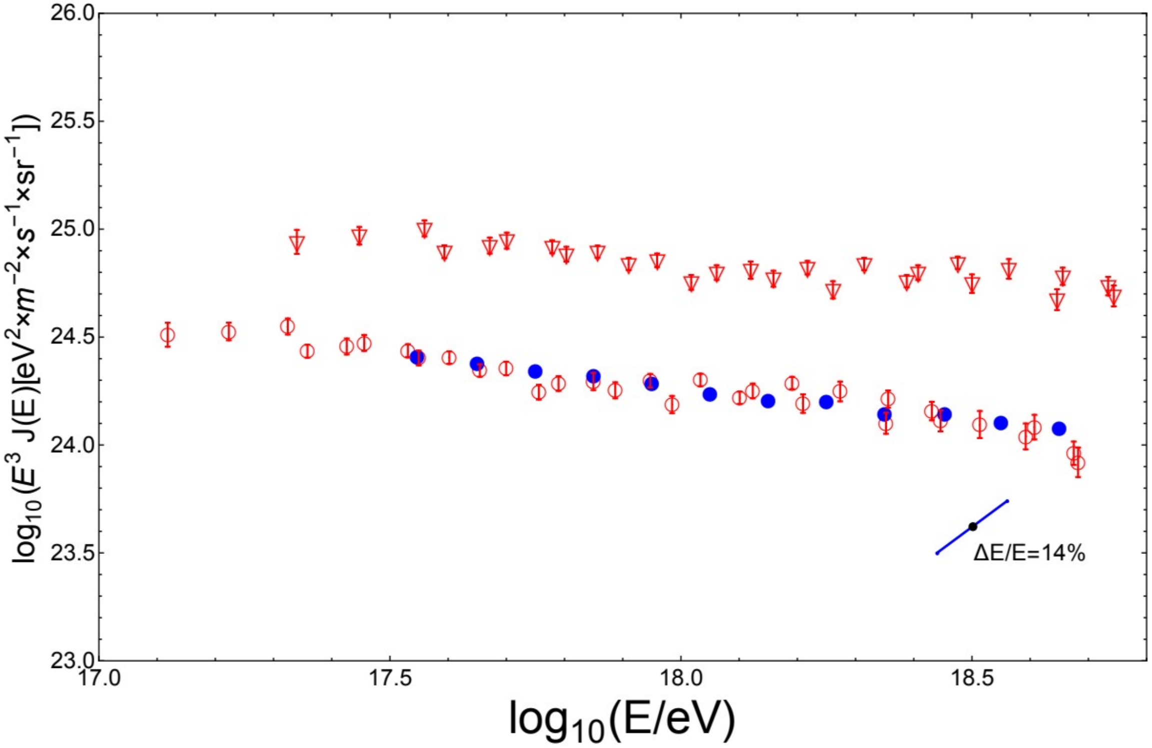
$E_r$=1.64×$10^{18}$ eV,

α= 1.075.

$N_r$=$10^7$

(Hillas model)

# Comparison of energy spectra SUGAR and Auger



Blue circles - the Auger differential combined energy spectrum arXiv:1708.06592

Red triangles — SUGAR old differential energy spectrum estimated using the Hillas model

**Red circles this work - SUGAR differential energy spectrum estimated using the empirical E(Nv) relation**

$$E_r = (8.67 \pm 0.21_{\mathrm{stat}} \pm 0.26_{\mathrm{syst\ SUGAR}} \pm 1.21_{\mathrm{syst\ Auger}}) \times 10^{17}\ \mathrm{eV},$$

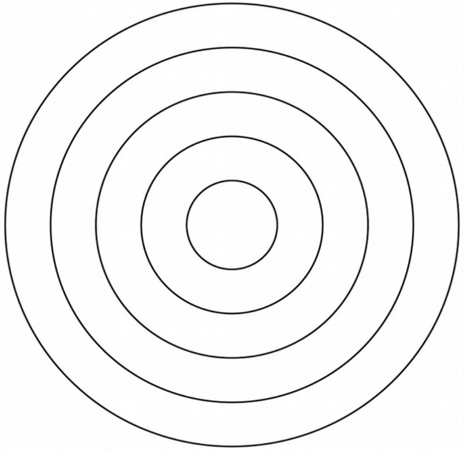
$$\alpha = 1.018 \pm 0.0042_{\mathrm{stat}} \pm 0.0043_{\mathrm{syst\ SUGAR}} \pm 0.0028_{\mathrm{syst\ Auger}},$$

# Monte Carlo simulation

- CORSIKA7.4001
- QGSJET-II-04, EPOS-LHC and SYBYLL-2.3c as high-energy hadronic interaction models
- FLUKA2011.2c[27] as the low-energy hadronic interaction models
- primary energies following an E^ −3.19 differential spectrum
- energy range 9×10^16 eV< E <4×10^18 eV.
- θ in the range between 0 and 75 degrees
- thinning parameter ε = 10^−5
- particles within 100 m from the core were discarded
- For each hadronic interaction models, we simulated 10000 showers for primary protons and the same number of showers for primary iron.

# Monte Carlo simulation

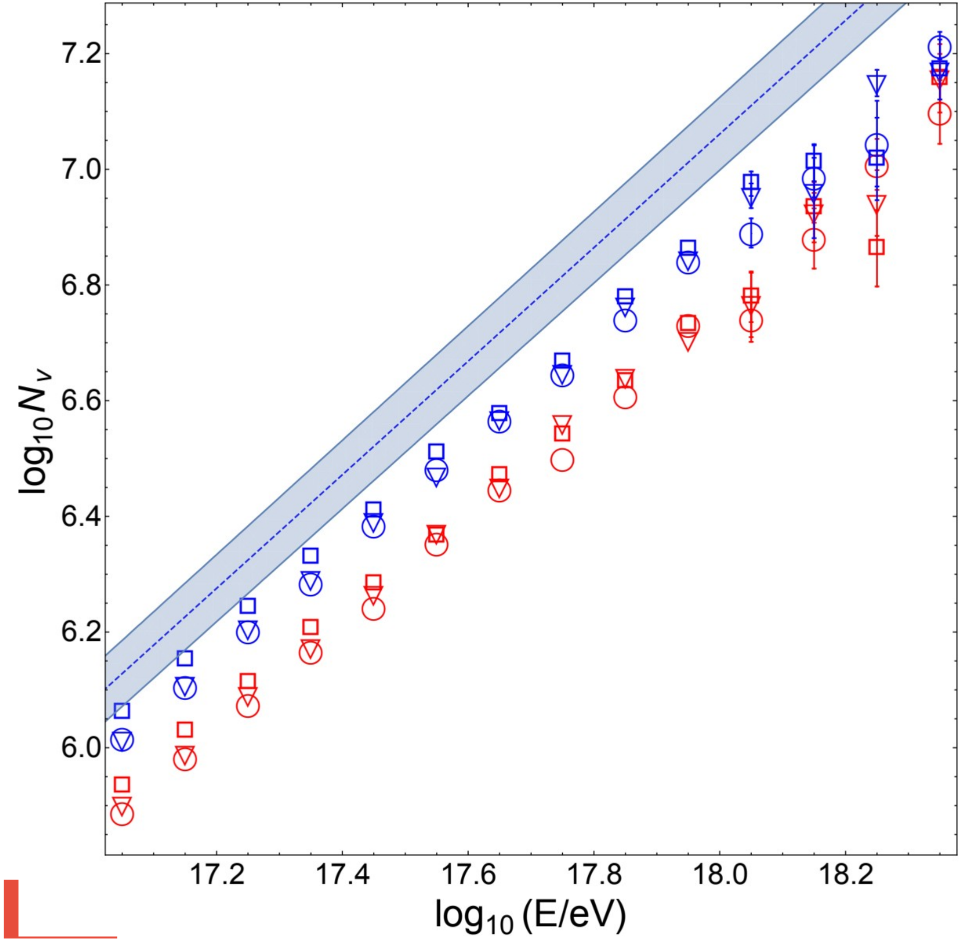
- calculate the muon density in concentric rings around the shower axis
- we use the experimental muon LDF and fit the muon density distribution in MC for obtaining **Nμ**
- for each artificial shower with the **Nμ** and the θ, we obtain the number of vertical muons **$N_v$**



- experimental reconstruction errors in determining the shower axis and **50 m** and **2.6 degrees**
- use this errors and our toy MC we we estimated the error in determining **Nμ - 19%**

# Comparison of number muons in observe data to simulation

Mean effective number of vertical muons Nv as a function of the primary energy.



The dashed blue line corresponds to our empirical model.
The shaded blue area indicates the total uncertainly.

QGSJET-II-04
(protons - red open circles,
iron - blue open circles),

EPOS-LHC
(protons - red open triangles,
iron - blue open triangles,)

SIBYLL-2.3c
(protons - red open quares,
iron - blue open quares)

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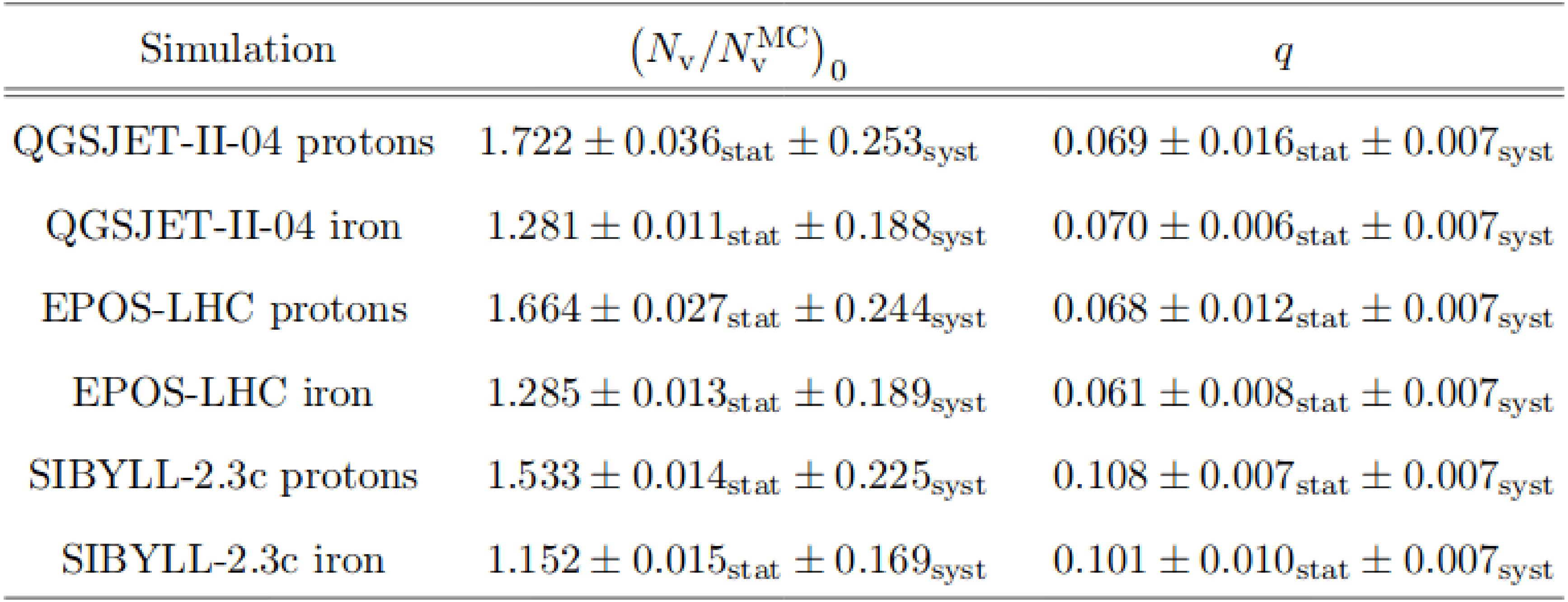
# Muon excess vs primary energy E

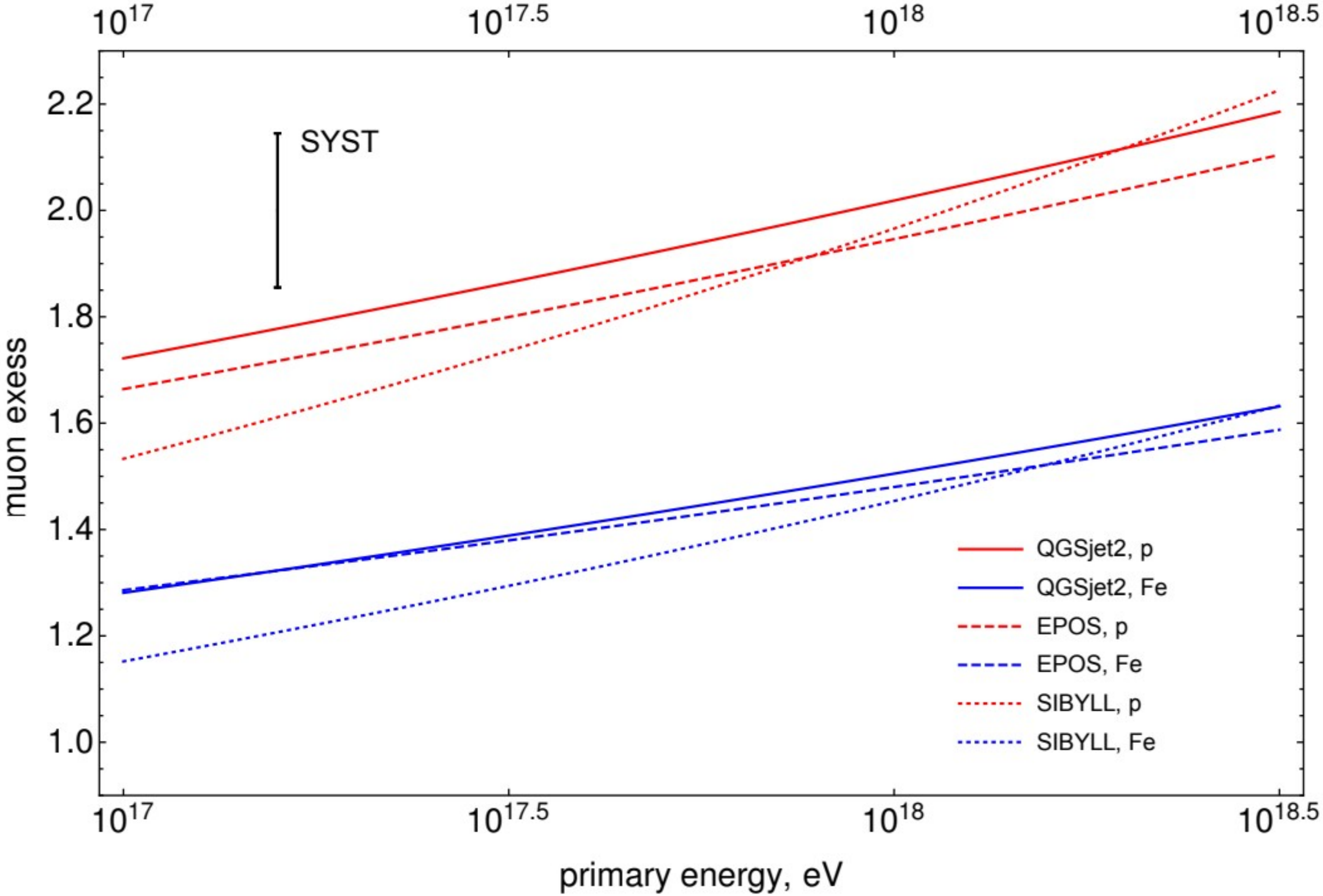
$$\frac{N_\nu}{N_\nu^{MC}} = \left(\frac{N_\nu}{N_\nu^{MC}}\right)_0 \left(\frac{E}{E_0}\right)^q$$

$E_0 = 10^{17}$eV

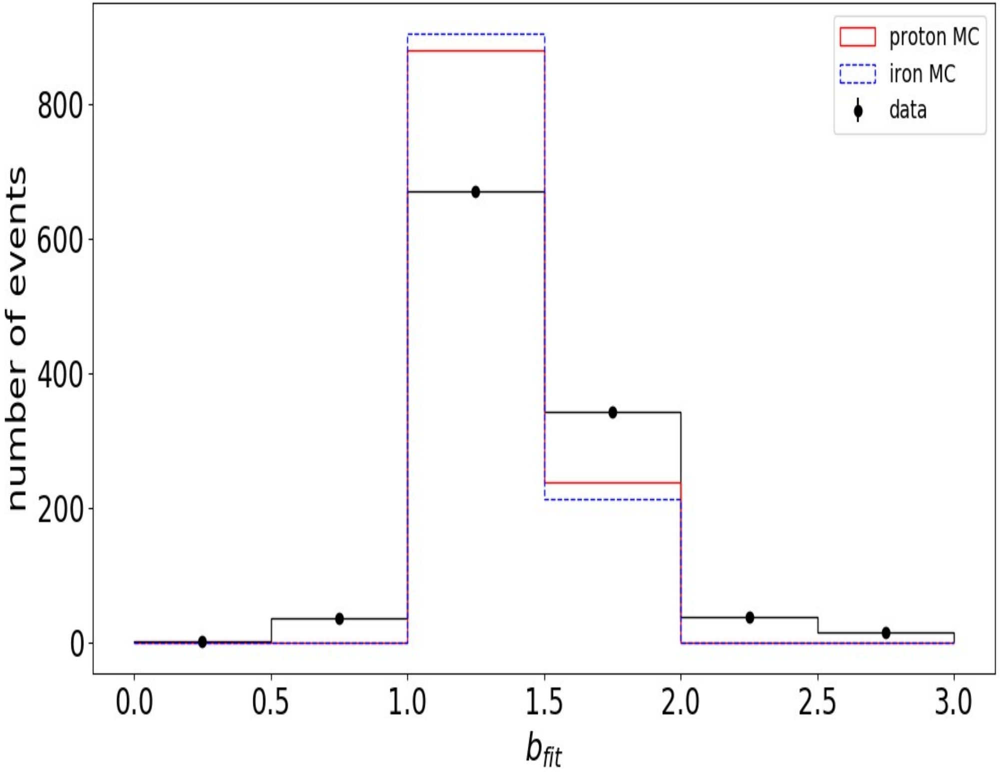


| Simulation | $(N_\nu/N_\nu^{\mathrm{MC}})_0$ | $q$ |
|---|---|---|
| QGSJET-II-04 protons | $1.722 \pm 0.036_{\mathrm{stat}} \pm 0.253_{\mathrm{syst}}$ | $0.069 \pm 0.016_{\mathrm{stat}} \pm 0.007_{\mathrm{syst}}$ |
| QGSJET-II-04 iron | $1.281 \pm 0.011_{\mathrm{stat}} \pm 0.188_{\mathrm{syst}}$ | $0.070 \pm 0.006_{\mathrm{stat}} \pm 0.007_{\mathrm{syst}}$ |
| EPOS-LHC protons | $1.664 \pm 0.027_{\mathrm{stat}} \pm 0.244_{\mathrm{syst}}$ | $0.068 \pm 0.012_{\mathrm{stat}} \pm 0.007_{\mathrm{syst}}$ |
| EPOS-LHC iron | $1.285 \pm 0.013_{\mathrm{stat}} \pm 0.189_{\mathrm{syst}}$ | $0.061 \pm 0.008_{\mathrm{stat}} \pm 0.007_{\mathrm{syst}}$ |
| SIBYLL-2.3c protons | $1.533 \pm 0.014_{\mathrm{stat}} \pm 0.225_{\mathrm{syst}}$ | $0.108 \pm 0.007_{\mathrm{stat}} \pm 0.007_{\mathrm{syst}}$ |
| SIBYLL-2.3c iron | $1.152 \pm 0.015_{\mathrm{stat}} \pm 0.169_{\mathrm{syst}}$ | $0.101 \pm 0.010_{\mathrm{stat}} \pm 0.007_{\mathrm{syst}}$ |

# Muon excess vs primary energy E



# Comparison of slope LDF in observe data and simulation



$$\rho_\mu = N_\mu k(\theta)\left(\frac{r}{r_0}\right)^{-a}\left(1+\frac{r}{r_0}\right)^{-b}$$

where

$r_0$=320m,

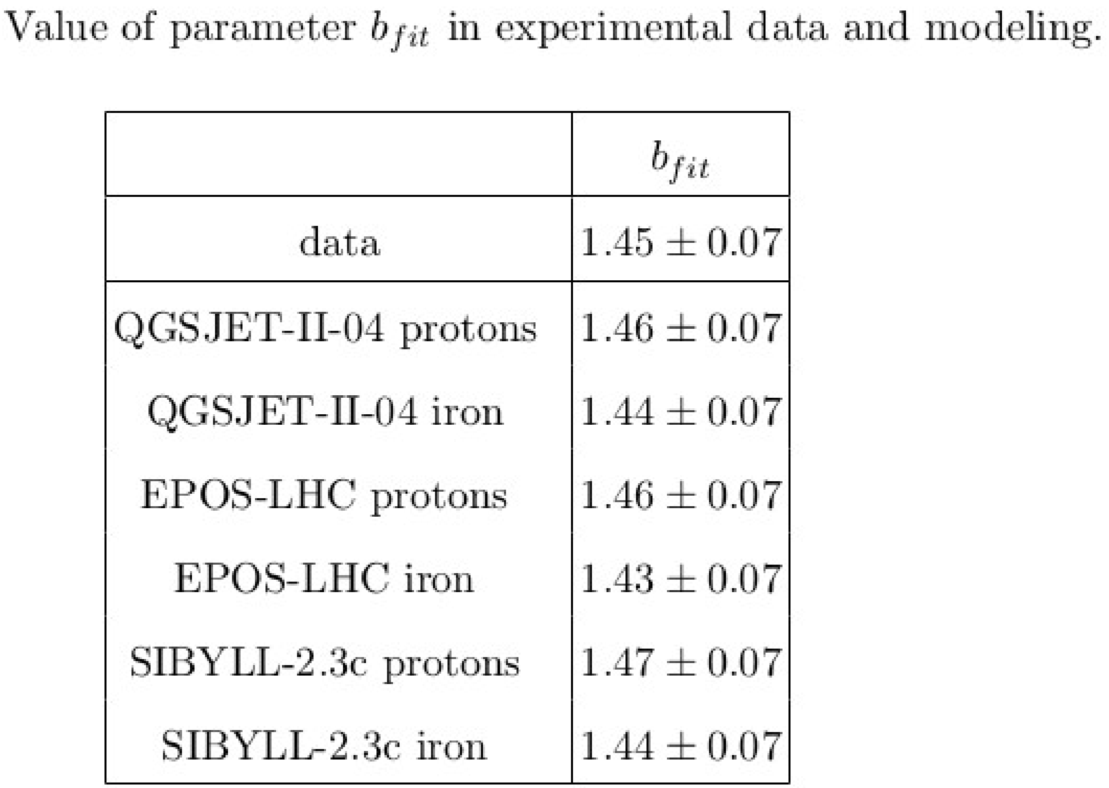
a=0.75,

**b =$b_{fit}$+1.86*cos(θ)**

The experimental **$b_{fit}$** is determined by fitting the observed response of the detectors of events in which 5 or more stations triggered.

Out of **13716** events we use **3653** events for analysis

# Comparison of slope LDF in observe data and simulation



Value of parameter $b_{fit}$ in experimental data and modeling.

| | $b_{fit}$ |
|---|---|
| data | $1.45 \pm 0.07$ |
| QGSJET-II-04 protons | $1.46 \pm 0.07$ |
| QGSJET-II-04 iron | $1.44 \pm 0.07$ |
| EPOS-LHC protons | $1.46 \pm 0.07$ |
| EPOS-LHC iron | $1.43 \pm 0.07$ |
| SIBYLL-2.3c protons | $1.47 \pm 0.07$ |
| SIBYLL-2.3c iron | $1.44 \pm 0.07$ |

# Conclusions and perspectives

- we obtained an empirical relation between the number of muons in anextensive air shower and the primary energy **N_mu(E_primary)**, for energies **10^17 - 10^18.5 eV**
- we found the excess of muons in real air showers with respect to simulation
- we found the dependence of muon excess on the primary energy
- In addition, we estimated the slope of the LDF for the experimental data and in the simulation, the difference turned out to be insignificant.

# Thank you for your attention

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