No muon excess in EAS at 100 PeV: results of EAS-MSU experiment

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Outline

- Motivation: study of muons in extensive air showers (EAS)
- The EAS-MSU experiment
- The method of muon excess description
- Results & Conclusions

Motivation: study of muons in EAS

- Muon content of EAS as a tool for study the hadronic interactions at high energies.
- At highest energies ($E_{CR} > 10^{19}$ eV) the presence of "muon excess" is well established.
- The cosmic-ray energy $\sim 10^{19}$ eV correspond to $\sim$ 100 TeV LHC energy.

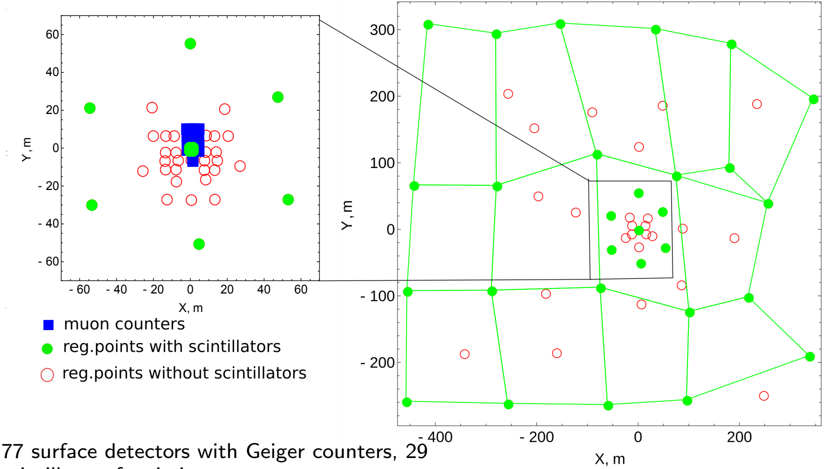
The "muon excess" is the overabundance of muons in a real EAS comparing to high-energy hadronic models predictions.

Published results for EAS muon content in various parameter regions

Experiment	X, g/cm^2	E, eV	E_μ, GeV	r/r_0	θ	μ excess
HiRes-MIA	860	$10^{17} - 10^{18}$	$\gtrsim 0.85$	$\gtrsim 10$	N/A	yes
PAO	880	$\gtrsim 10^{19}$	$\gtrsim 1$	$\gtrsim 10$	70°	yes
Yakutsk	1020	$\gtrsim 10^{19}$	$\gtrsim 1$	$\gtrsim 10$	45°	yes
IceTop	680	$10^{15} - 10^{17}$	$\gtrsim 0.2$	$\gtrsim 3$	13° mean	no

For TA muon results see R. Takeishi poster on 18.07

EAS-MSU experiment



- 77 surface detectors with Geiger counters, 29 scintillators for timing
- $\sim$ 0.5 km^2 area
- Underground muon detector ($E_\mu \geq 10$ GeV)
- $\sim$ 1500 days of operation (1982-1990)
- Total $\sim 10^6$ EASes detected

Effective for EAS with

$$10^{15.5} \lesssim E_{primary} \lesssim 10^{17.75} eV$$

Full Monte-Carlo simulation

Yu. Fomin et al., JINST 11, T08005 (2016)

CORSIKA (p + Fe primaries) + EGS4 + Fluka + QGSJetII

$$10^{15.5} \leq E_{primary} \leq 10^{17.75} eV \ , \quad \frac{dN}{dE} \sim E^{-3.1}$$

avg. of PDG 2014 spectra

$\Downarrow$

C^{++} code simulating the facility

$\Downarrow$

Reconstruction with the same code as for data

Monte-Carlo & reconstruction I

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Reconstruction with the same code as for data

SD reconstruction parameters

- N_e — number of charged particles
- S — shower age parameter
- θ, ϕ — shower zenith and azimuthal angle
- R — shower core distance from the array center

$\Rightarrow$

All particle lateral distribution function (LDF)

$$\rho(S,r) \sim N_e \cdot \left(\frac{r}{r_0}\right)^{(S+\alpha(r/r_0)-2)} \times \left(\frac{r}{r_0}+1\right)^{(S+\alpha(r/r_0)-4.5)}$$

$r_0 \simeq 80m$ — is the Moliere radius

Monte-Carlo & reconstruction II

Selection cuts

- $N_e > 2 \cdot 10^7$ ($E_{MC} \gtrsim 10^{16.5}$ eV for p-primaries)
- $R < 240\mathrm{m}$
- $\theta < 30^\circ$
- $0.3 < S < 1.8$

1σ accuracy of the reconstruction for p/Fe mix

- $\Delta\psi < 1.1^\circ$ — arrival direction
- $\Delta R < 5.7$ m — axis position
- $\Delta N_e/N_e < 0.17$ — number of charged particles
- The efficiency is $\gtrsim 95\%$

Total exposure is 7.7×10^6 km s sr, **809 events selected**

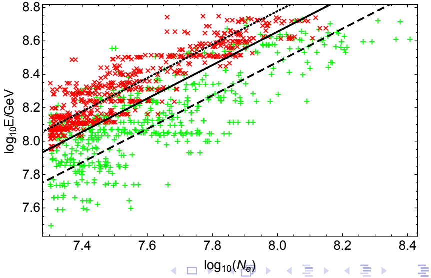
Primary energy reconstruction

For best fit p/Fe mix:

$$\log(E/GeV) = 0.65 + \log_{10} N_e$$

$$\Downarrow$$

$$\Delta E/E < 0.41 \quad (1\sigma)$$

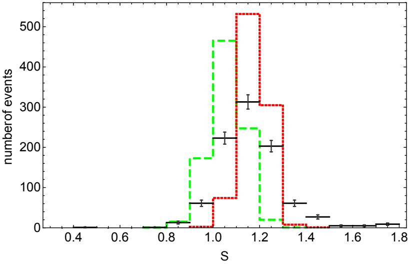


Monte–Carlo: SD chemical composition

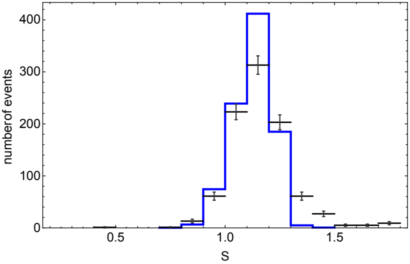
Chemical composition from the fit of SD data over LDF S-parameter.

$$\rho(S, r) \sim N_e \cdot \left(\frac{r}{r_0}\right)^{(S+\alpha(r/r_0)-2)} \times \left(\frac{r}{r_0}+1\right)^{(S+\alpha(r/r_0)-4.5)}$$

Data vs. MC p and MC Fe



Data fitted with MC p/Fe mix

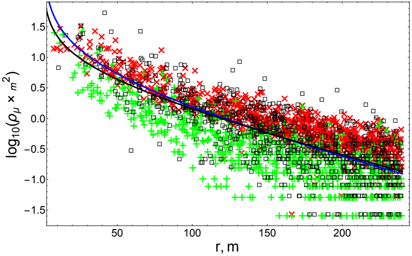


$$\frac{N_p}{N_p+N_{Fe}} = 43\%, \qquad \frac{N_{Fe}}{N_p+N_{Fe}} = 57\%$$

Cf. the results of other experiments. KASCADE-Grande: 41% p , 59% Fe .
Tunka-133: 49% p , 51% Fe .

Muon measurement & MC

- Muon detector locates in the center of array at 40 m w.e. depth
- The muon energy threshold is $E_\mu \geq 10$ GeV
- Consists of Geiger counters, total area is $\sim 36\mathrm{m}^2$

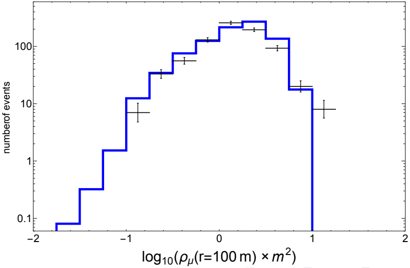


Results for ρ_μ at 100 m from shower core

Use μLDF to calculate $\rho_\mu(R = 100\mathrm{m})$:

$$\rho_\mu(r) = N_\mu \left(\frac{r}{r_0}\right)^{-a_\mu} \exp\left(-r/r_0\right) \ , \ a_\mu = 0.7$$

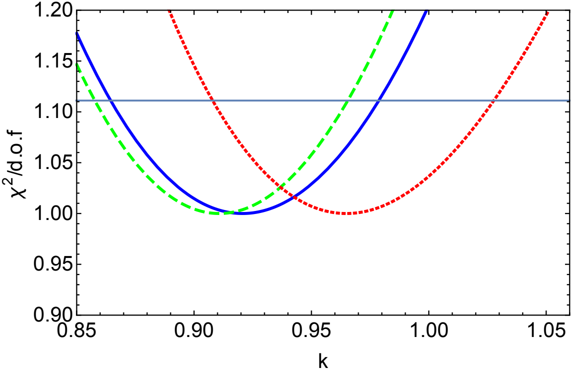
Data agree well with Monte-Carlo



Test for muon excess

Make MC sets of EASes with artificially multiplied or reduced number of muons: $\widetilde{N_\mu} = k \cdot N_\mu$

Results of $\rho_\mu(100\mathrm{m})$ fit for various chemical composition



EAS-MSU SD: $k = 0.92 \pm 0.06$, $k > 1$ excluded at 92 % C.L.

KASCADE-Grande: $k = 0.91 \pm 0.05$, $k > 1$ excluded at 95 % C.L.

Tunka-133: $k = 0.96 \pm 0.06$, $k > 1$ excluded at 67 % C.L.

No muon excess

Comparison with results of other experiments

Experiment	X, g/cm^2	E, eV	E_μ, GeV	r/R_0	θ	μ excess
HiRes-MIA	860	$10^{17}-10^{18}$	$\gtrsim 0.85$	$\gtrsim 10$	N/A	yes
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IceTop	680	$10^{15}-10^{17}$	$\gtrsim 0.2$	$\gtrsim 3$	13° mean	no
EAS-MSU	990	$10^{17}-10^{18}$	$\gtrsim 10$	$\lesssim 3$	30°	no

The results are not contradictory but complementary.

Test μ-excess for other interaction models (simplified Monte-Carlo)

Model	mean Fe fraction from S, %	k
QGSJET-II-04	57	0.92±0.06
EPOS-LHC	42	0.96±0.06
SIBYLL 2.1	76	1.00±0.07
QGSJET-01	58	0.95±0.06

Conclusions

- EAS-MSU archival data was studied with full Monte-Carlo.
- There is no "muon excess" at $10^{17} \lesssim E_{CR} \lesssim 10^{18}$ eV, $E_\mu \geq 10$ GeV and in the central part of the shower.

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- EAS-MSU archival data was studied with full Monte-Carlo.
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Addition

The search for ~ 100 PeV photons was also performed with EAS-MSU data, the stringent flux upper-limits was set.

See my poster on 18.07

Thank you!

Simplified Monte-Carlo for EPOS, QGSJet-01 and Sibyll

- Simulation of 800 p and 800 Fe CORSIKA events with $E = 10^{17}$ and $E = 4 \cdot 10^{17}$ eV with $\varepsilon = 10^{-5}$ thinning.
- For thinning the maximal e/m and hadronic weights are equal to 4000 and 40 respectively.
- The equivalence between thinned and non-thinned showers was justified.
- The age parameter S was calculated by averaging the particle density over concentric rings around the shower axis.
- The muon number N_μ was calculated by counting CORSIKA muons.

The EAS-MSU statics is not enough to study:

- Dependence of μLDF upon variation of zenith angle
- Dependence of the result upon spectral features (like "second knee").
- Chemical composition beyond p/Fe mix approximation