Estimations of the muon content of cosmic ray air showers between 10 PeV and 1 EeV from KASCADE-Grande data

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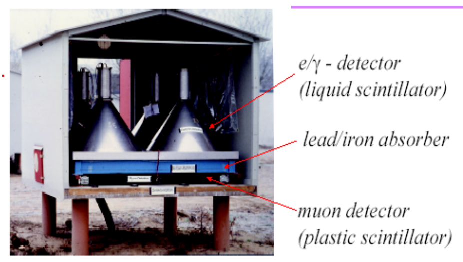
KASCADE-Grande experiment/Measured data

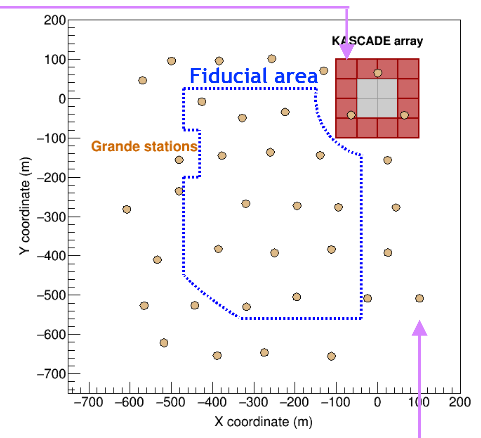
Detector characteristics:

- Cosmic ray studies E = 1 PeV - 1 EeV.
- Extensive air shower (EAS) array.
- 110 m a.s.l. (KIT, Karlsruhe, Germany).
- Total size of 0.5 km².
- Main detector clusters: KASCADE and Grande.
- Measurements of N_e, N_μ, N_{ch}, etc.



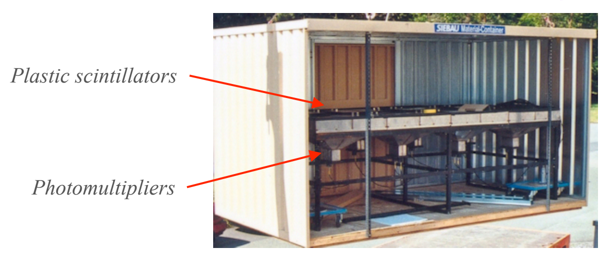
KASCADE array:

- 200 x 200 m².
- 252 e/γ scintillator detectors.
- 192 μ detectors (E_μ > 230 MeV).



Analyzed data:

- Collected from December 2003 to November 2012.
- 1.276 x 10⁷ selected events.
- θ < 40°.
- Maximum efficiency thresholds: E > 12 PeV, N_μ > 1.4 x 10⁵.
- EAS cores at center of Grande array.
- From stable runs with no hardware problems.
- N_e > 1 x 10⁴.
- Shower age = [-0.39, 1.49].
- More than 11 Grande stations activated.



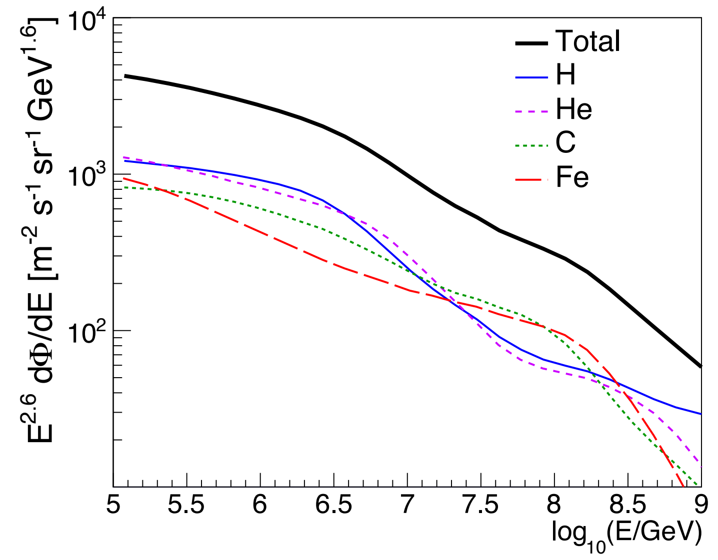
Grande array:

- 700 x 700 m².
- 37 scintillator detectors.
- Detection of charged particles.

Monte Carlo (MC) simulations

MC data:

- Corsika v7.5.
- Hadronic interaction models:
  - Low energy (Eh ≤ 200 GeV): FLUKA.
  - High energy: QGSJET-II-04, EPOS-LHC, SIBYLL 2.3, SIBYLL 2.3c
- Primaries: H, He, C, Si, Fe
- E^{-2} spectrum.



The reference cosmic ray composition model used in MC simulations for the present study.

Reference cosmic ray composition model:

- Obtained by re-weighting MC simulations.
- All-particle spectrum from:
  - Pierre Auger data (E ≥ 3 x 10⁷, PAO Collab., PoS(ICRC2019) 450),
  - GSF model (E < 3 x 10⁷, H. Dembinski et al., PoS (ICRC2017) 533).
- Primary mass groups: H, He, C and Fe.
- Relative cosmic ray abundances from GSF model.

Analysis

Description of the study:

- Due to the lack of a model independent energy estimator in KASCADE-Grande, we used a method proposed by NEVOD-DECOR (Phys. Atom. Nuc. 73 (2010) 1852) and SUGAR (PRD 98 (2018) 023014) to obtain $N_\mu(E)$.
- First, we correct N_μ for systematic errors (App 95 (2017) 25) by means of a correction function based on QGSJET-II-04.
- Then, we compare the experimental N_μ histogram against predictions with our reference cosmic ray model using:

$$X^2 = \sum_{i=1}^{m}\left(\frac{n_{exp,i} - n_{MC,i}}{\sigma_{i,MC}}\right)^2$$

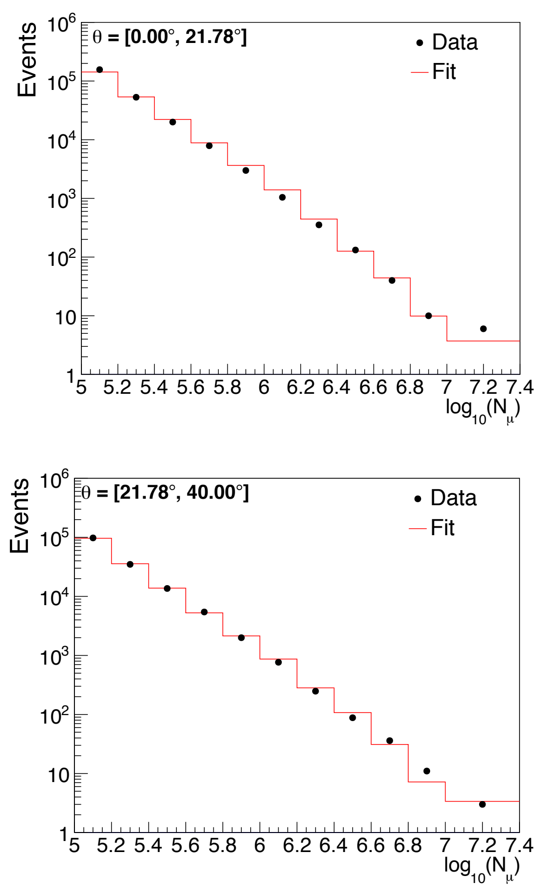
- By minimizing the X^2, we estimate the shift between MC and measured data

$$\delta_\mu = \Delta\log_{10}(N_\mu) = a_0 + a_1\cdot\log_{10}(E/\mathrm{GeV}) + a_2\cdot\log^2_{10}(E/\mathrm{GeV})$$

  that allows to describe the experimental N_μ distribution.
- Finally, the shift is applied to MC simulations to estimate the actual muon content:

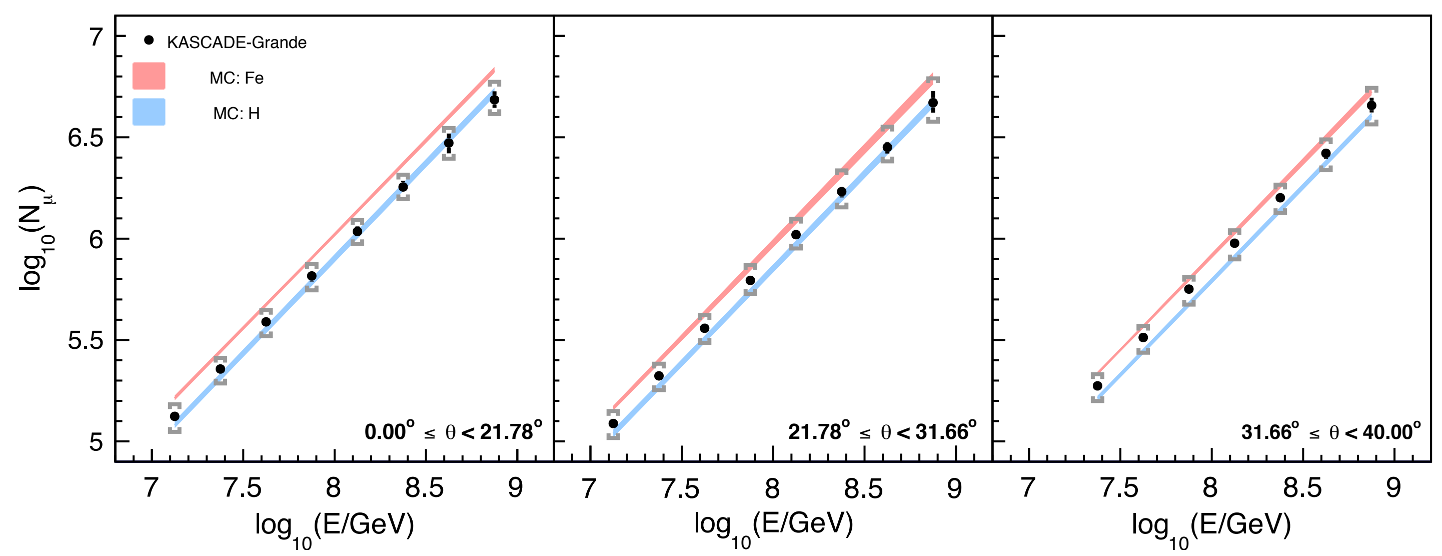
$$\log_{10}[N_\mu(E)] = \log_{10}[N_{\mu,MC}(E)] + \delta_\mu$$

- We divided the data into three zenith angle intervals: [0°, 21.78°], [21.78°, 31.66°], [31.66°, 40°] .
- The procedure is repeated for each hadronic interaction model.



Results of the fits to the measured N_μ histograms for two zenith angle ranges to find δ_μ with QGSJET-II-04.

Results

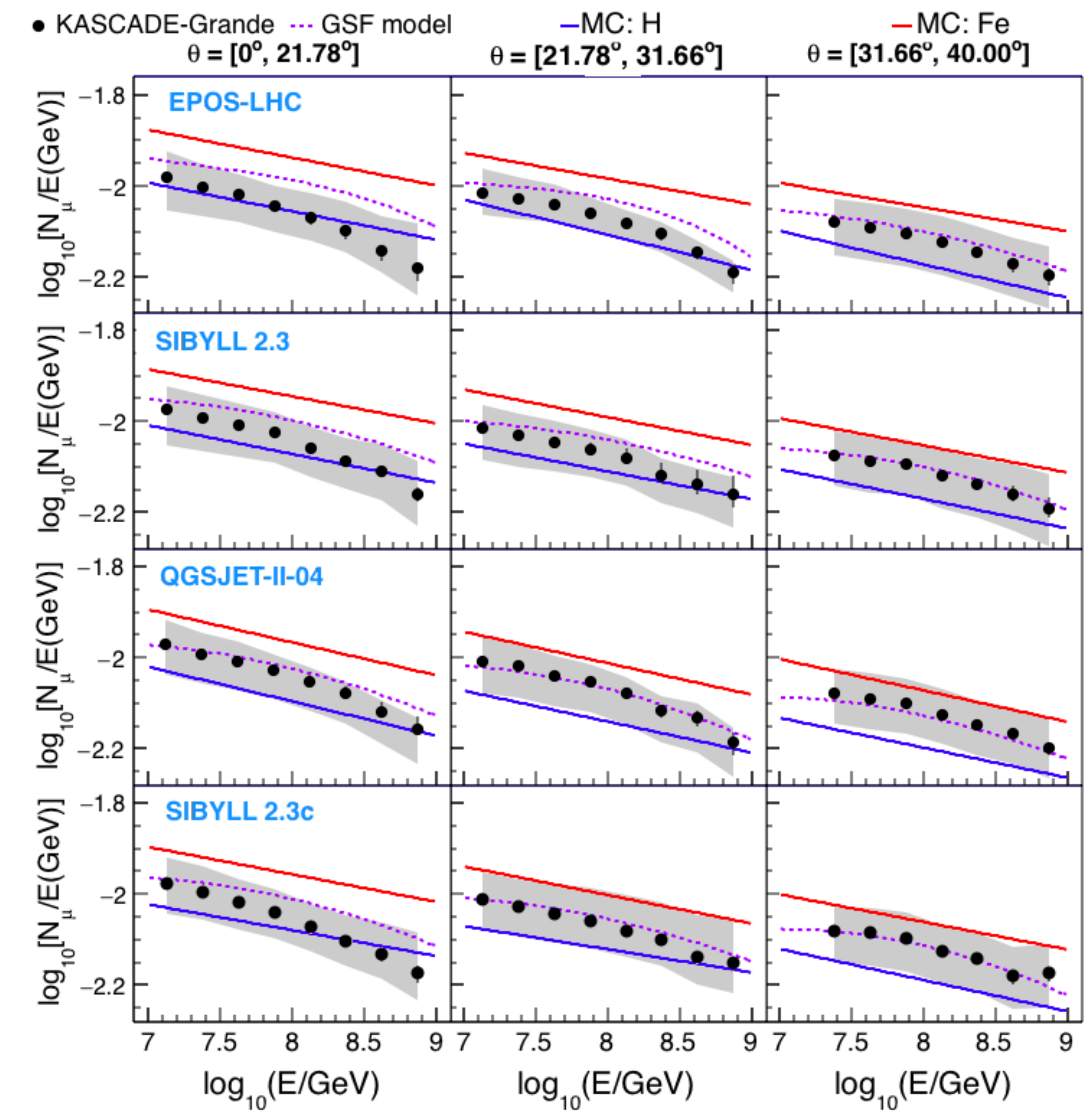


The mean shower muon size vs the primary energy for different zenith angle intervals. Data points represent the average on the mean experimental values obtained in the present analysis with QGSJET-II-04, EPOS-LHC, SIBYLL 2.3 and SIBYLL 2.3c. Statistical errors are shown with vertical error bars, while systematic errors, with squared brackets. The red and blue lines show the predictions for Fe and H primaries, respectively, from the four post-LHC models used in this work.

Statistical and systematic errors:

- Statistical errors include uncertainties due to the limited sizes of measured and MC data samples.
- Systematic errors take into account uncertainties in the shape of the spectrum, in composition, lateral distribution of muons, fitted parameters of the δ_μ function and energy scale (using estimated uncertainty ±14% from PAO Collab., PoS(ICRC2019) 450).

Results



Experimental (data points) and expected (lines mean values) of $\log_{10}[N_\mu/E]$ vs primary energy as obtained fro this analysis using the hadronic interaction models (from top to bottom): EPOS-LHC, SIBYLL 2.3, QGSJET-II-04 and SIBYLL 2.3c. Each column corresponds to a different zenith angle bin. In each panel, the red lines represent the expectations for Fe, the segmented violet lines, for the GSF model, and the blue lines, for H. The vertical error bars on the experimental plot represent statistical errors, while the gray band, the total systematic error.

Conclusions

- None of the high-energy hadronic interaction models studied here is able to describe consistently the total muon number of EAS measured in KASCADE-Grande at different zenith angles and energies.
- Predictions of EPOS-LHC, SIBYLL 2.3 and SIBYLL 2.3c on N_μ for primary energies between 100 PeV and 1 EeV are above the KASCADE-Grande data for vertical EAS.
- Attenuation of N_μ with zenith angle is smaller in data than in MC simulations, which is in agreement with previous results on the muon attenuation length (App 95 (2017) 25).
- Measurements and expectations seem to be in better agreement for θ = [31.66°, 40°]. For vertical EAS, hadronic interaction models seem to produce more muons.
- For large zenith angles, we are sampling the muon energy spectrum at production site for higher muon energies. Therefore, these anomalies could imply that the energy spectrum of muons from real EAS at a given primary energy is harder than the predicted ones from QGSJET-II-04, EPOS-LHC, SIBYLL 2.3 and SIBYLL 2.3c.