Muon measurements of cosmic-ray induced air showers with KASCADE-Grande

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Overview:

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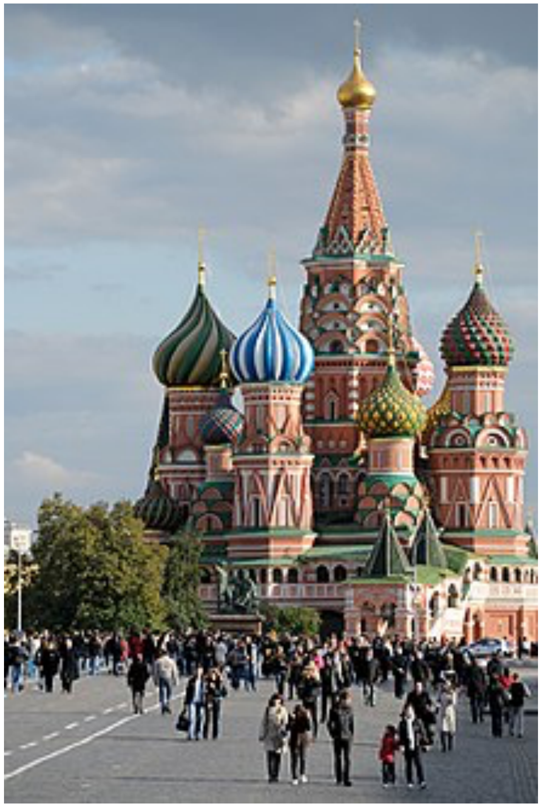
5. Summary



The KASCADE-Grande experiment

1. Location:
   KIT, Campus North, Karlsruhe, Germany.

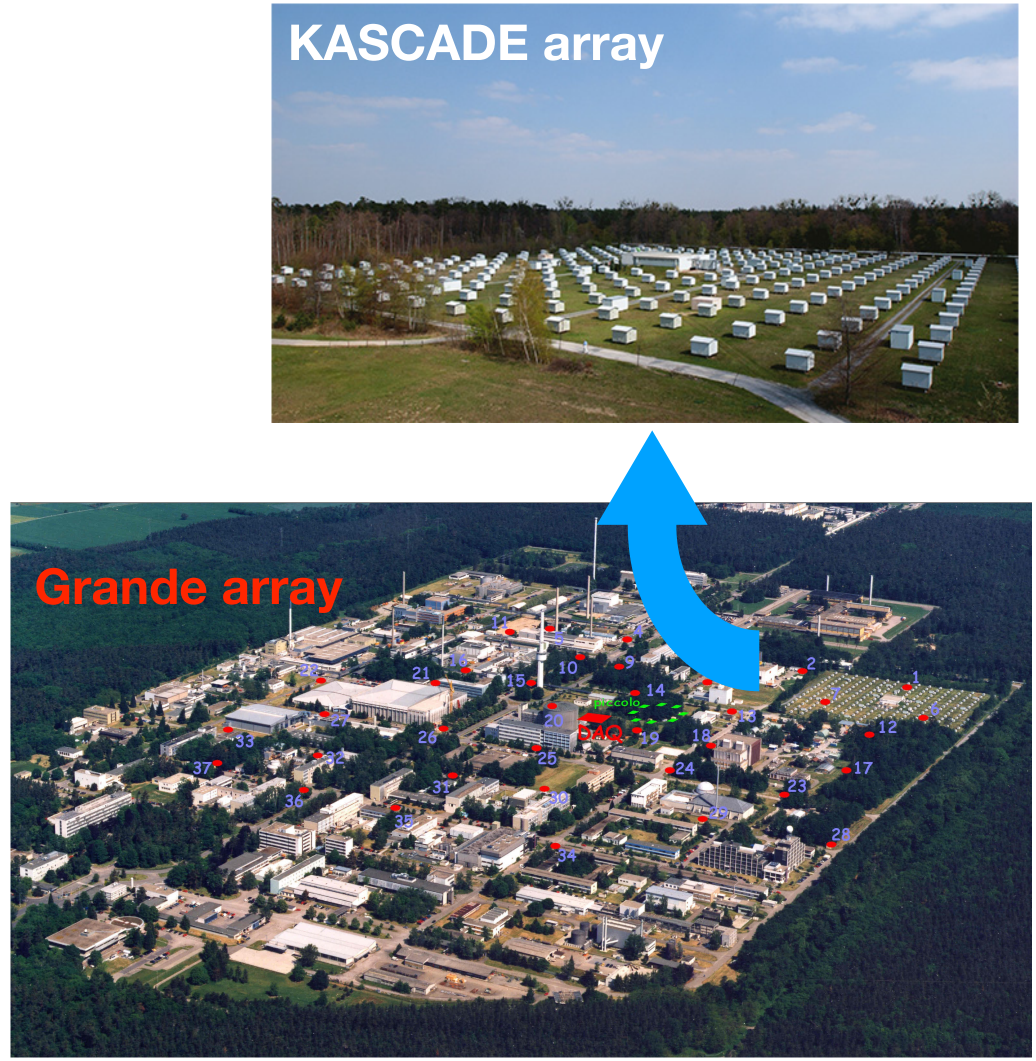
2. Cosmic ray detection: E = 1 PeV - 1 EeV

4. Multi-detector system:
   KASCADE array (200×200 m^2)
   - 252 e/γ and μ scintillator detectors
   - Muon tracking detector
   - Central detector

   Grande array (0.5 km^2)
   - 37 plastic scintillator detectors

5. EAS measurements at ground level
   (110 m a.s.l.):
   N_{ch}, N_e, N_μ

6. Research
   - Cosmic ray energy, composition, and arrival direction.
   - Origin of the knee, search of iron knee, look for galactic-extragalactic transition.
   - Tests of hadronic interaction models.

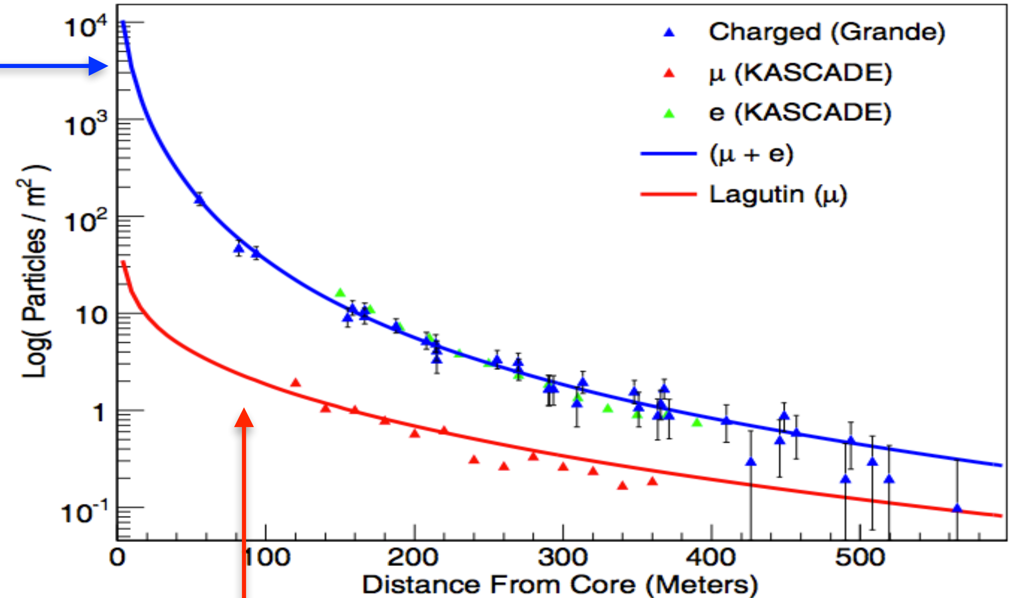


December 2003 - November 2012

The KASCADE-Grande experiment

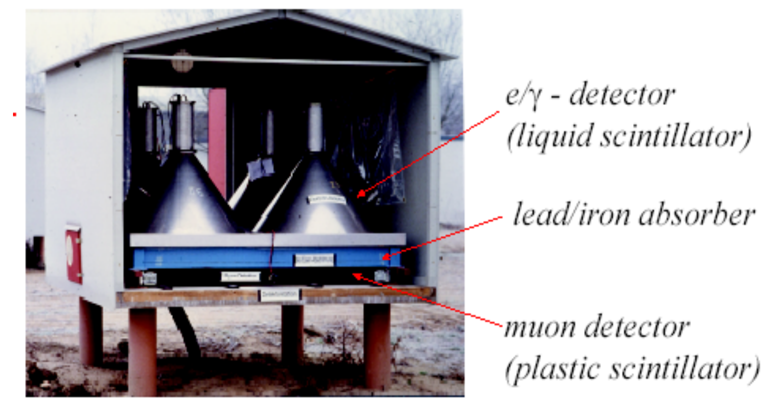
$$\rho_{ch}(r) = N_{ch} \cdot f_{ch}(r) = N_{ch} \cdot C(s) \left(\frac{r}{r_0}\right)^{s-\alpha} \left(1 + \frac{r}{r_0}\right)^{s-\beta}$$

Grande station



$$\rho_\mu(r) = N_\mu \cdot \frac{0.28}{r_0^2} \left(\frac{r}{r_0}\right)^{p_1} \left(1 + \frac{r}{r_0}\right)^{p_2} \left(1 + \left(\frac{r}{10 \cdot r_0}\right)^2\right)^{p_3}$$

Detector	Particle	Threshold
Grande	charged	3 MeV
KASCADE	e/γ	5 MeV
KASCADE	μ	230 MeV

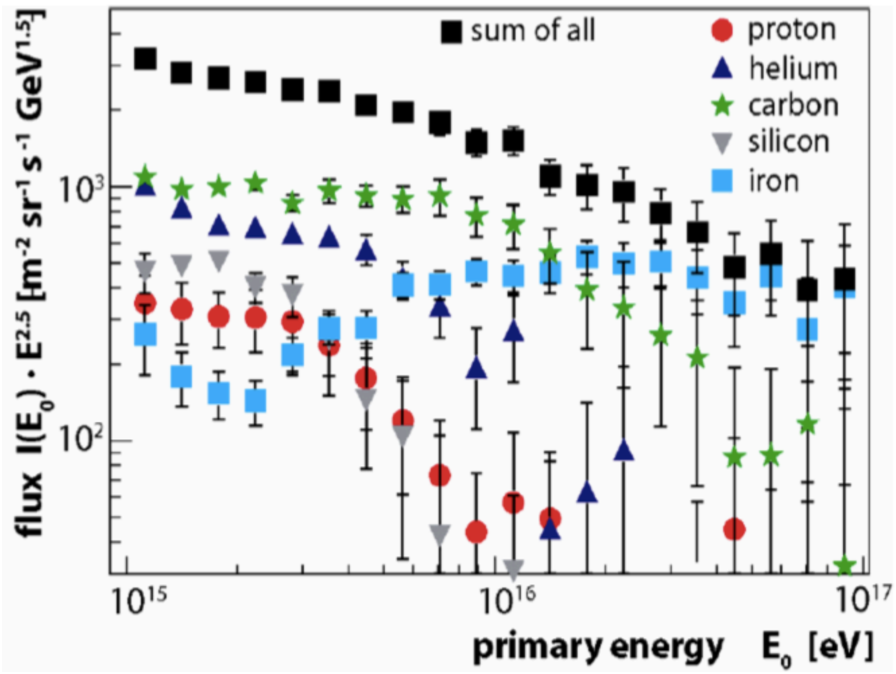


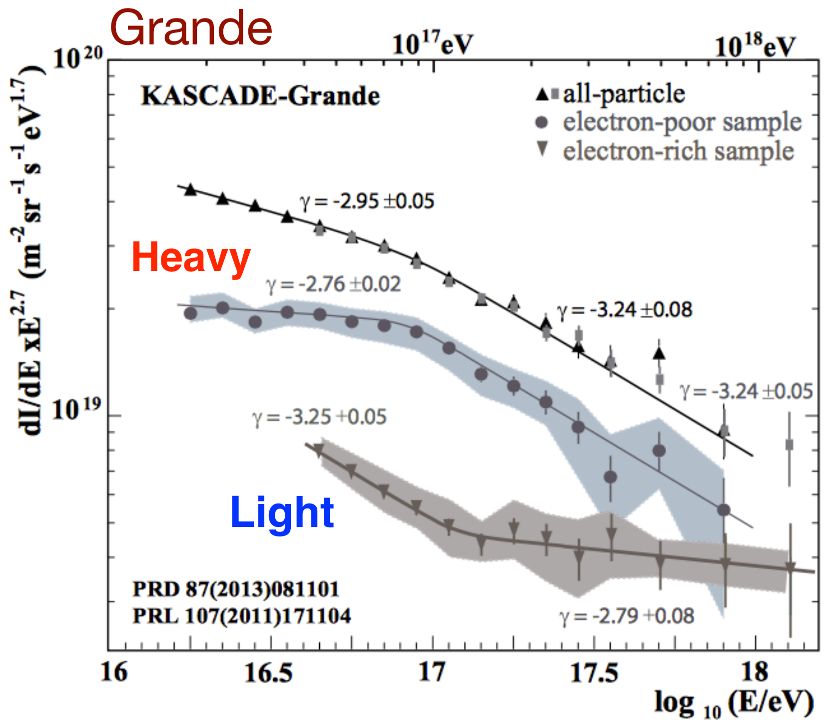
[NIMA 620 (2010) 202]

KASCADE station

The KASCADE-Grande experiment

Exploit $N_{ch}(N_e)$-N_μ correlation





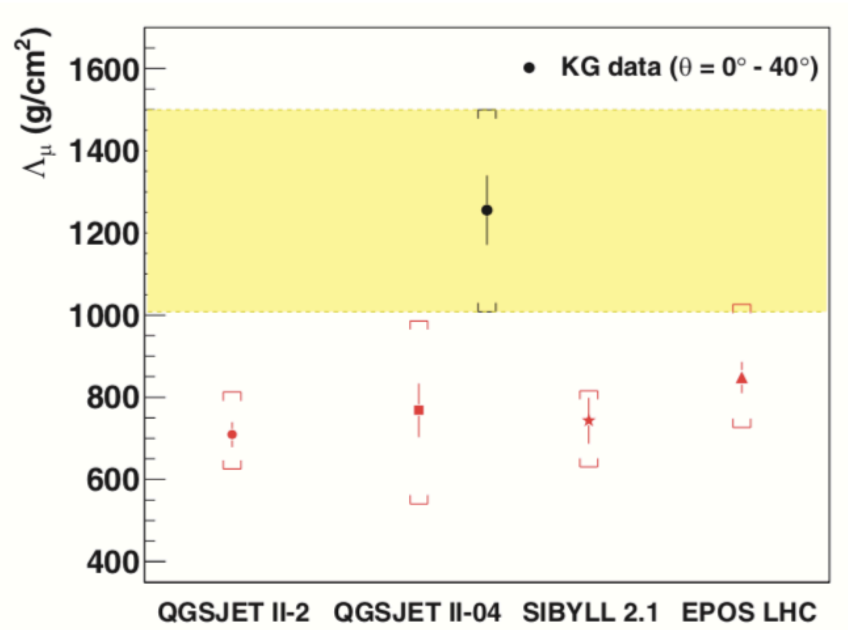
- Knee of light primaries at around 3 x 10^{15} eV.
- Hardening of all-particle spectrum at 10^{16} eV is due to knee of medium component.

- Knee in the heavy component at 8 x 10^{16} eV.
- Hardening of light spectrum at approximately 10^{17} eV.

[PRL 107 (2011) 171104, Astrop. Phys. 36 (2012) 183, PRD 85 (2013) 071101]

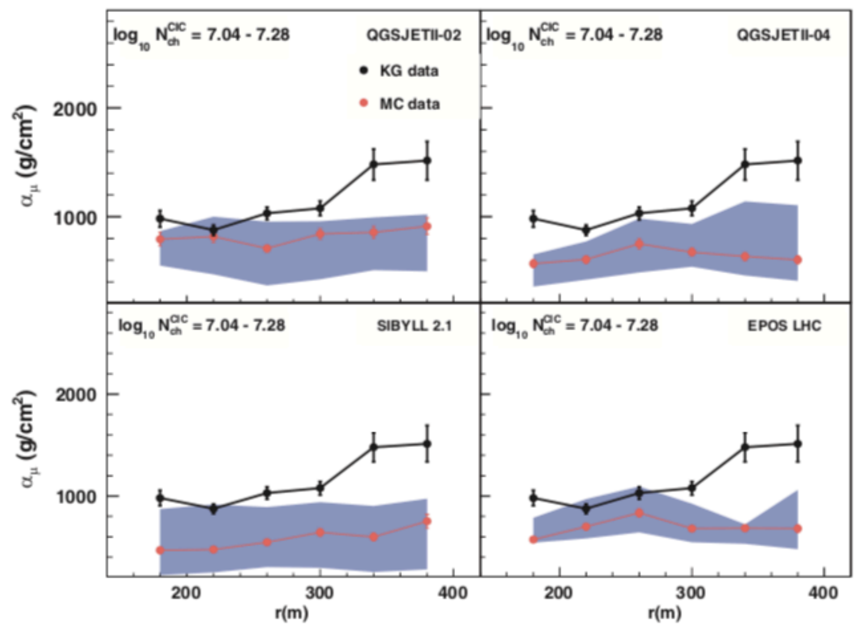
Motivation of the muon study

QGSJET II-02, SIBYLL 2.1, EPOS-LHC and QGSJET II-04 do not reproduce the zenith angle evolution of the KASCADE-Grande muon data



$$N_\mu(\theta) = N_\mu^o \, e^{-(X_o \sec\theta/\Lambda_\mu)}$$

- The **muon attenuation length** as measured with the Constant Intensity Cut (CIC) method is **larger than model predictions.**

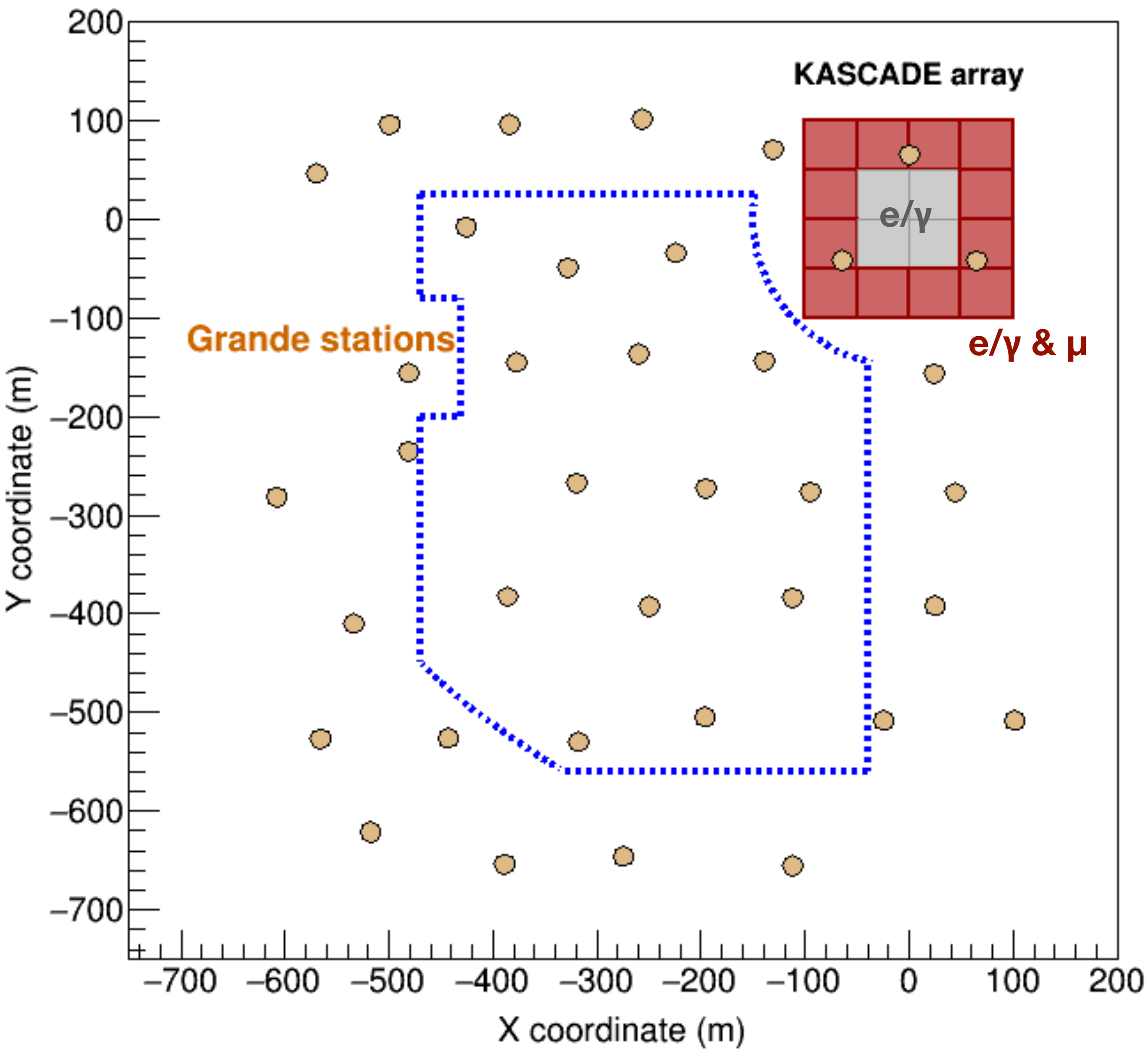


$$\rho_\mu(r,\theta) = \rho_\mu^o(r) \, e^{-(X_o \sec\theta/\alpha_\mu)}$$

- In atmosphere, experimental muon data is less attenuated than expected.

[Astrop. Phys. 95 (2017) 25]

Analysis: Selection cuts



- No hardware problems.
- Zenith angle smaller than 35°.
- EAS core inside central area.
- Successfully reconstructed.
- More than 11 stations activated.
- N_{ch} (N_e) > 1.1 x 10^4.
- N_μ > 3 x 10^4.

Data from December 2003 to November 2012:
+ T_{eff} = 1.58 x 10^8 s
+ 1.1 x 10^6 selected events

Analysis: Simulations

MC sample with CORSIKA:

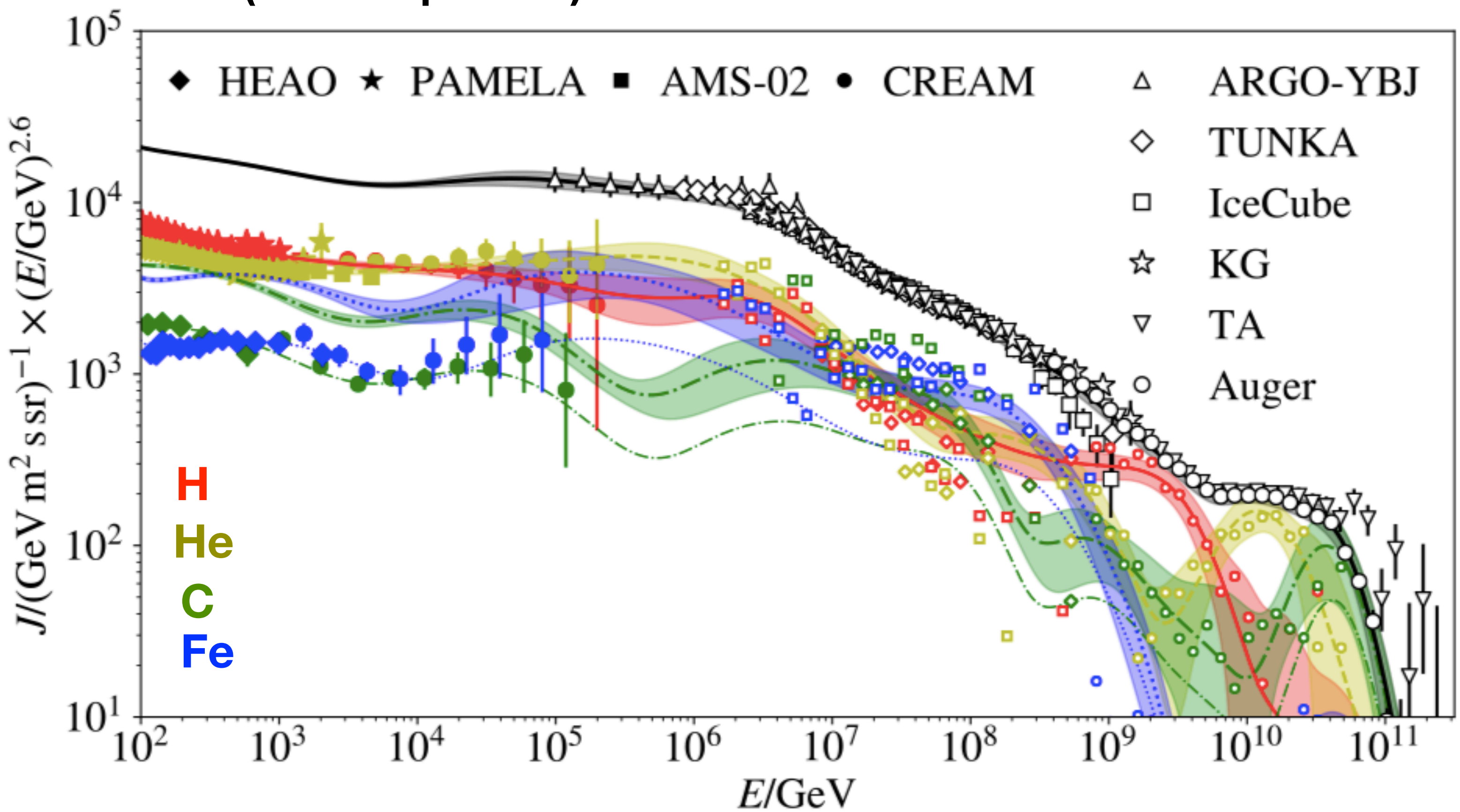
❖ QGSJET-II-04
❖ EPOS-LHC
❖ SIBYLL 2.3
❖ SIBYLL 2.3c

No thinning

Simulated spectra:

❖ Composition: H, He, C, Si, Fe, Mixed & GSF model
❖ $\log_{10}(E/eV)$ = [14, 18.5]
❖ E^{γ}, γ= -2.8, -3, -3.2 (for single elemental nuclei)

GSF (Global spline fit) model [H. Dembinski et al, arXiv 1711.11432 (astro-ph.HE)]



Analysis: Simulations

Mean accuracy (in region of full efficiency):

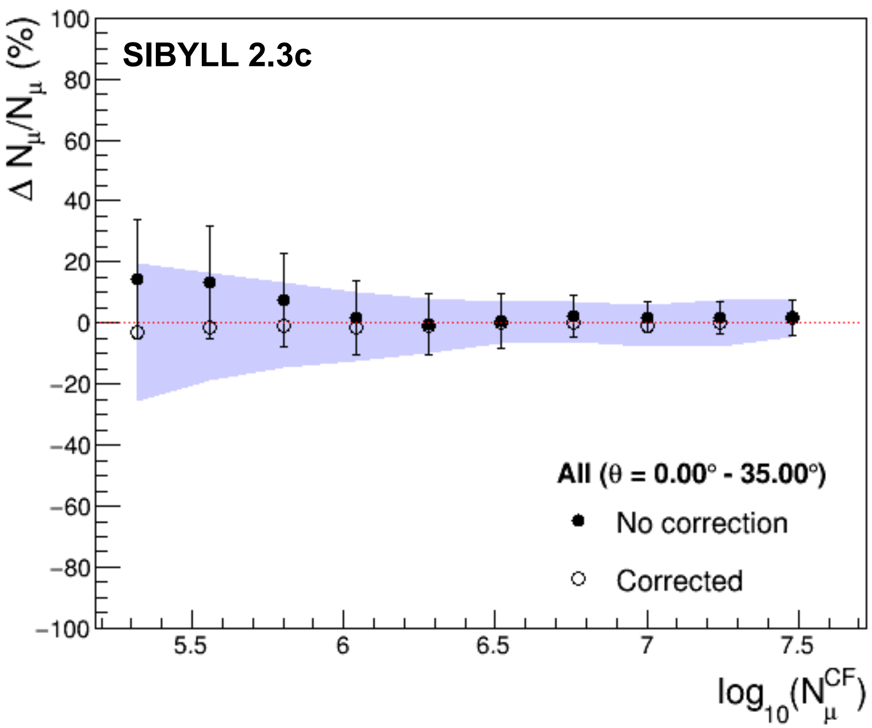
- ❖ ΔN_μ < 20%
- ❖ ΔN_{ch} < 15%
- ❖ $\Delta \theta$ < 0.6°
- ❖ σ_{Core} < 10 m

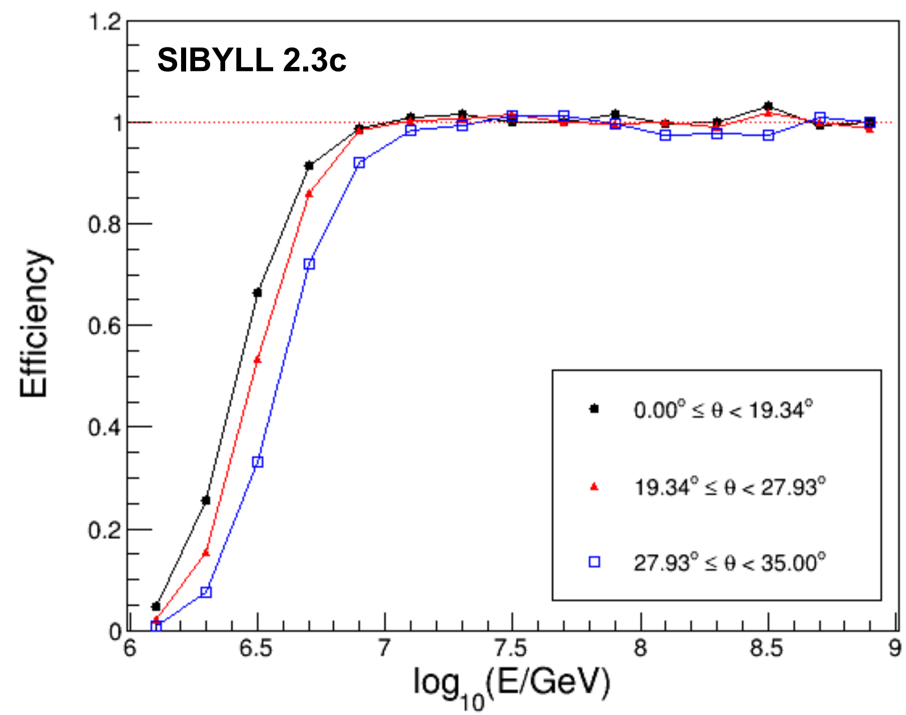
Maximum efficiency:

- ❖ $\log_{10} N_\mu$ > 5.15 ± 0.15
- ❖ $\log_{10}$ (E/GeV) > 7.1 ± 0.2

N_μ corrected for systematic effects:

Use correction function from MC





Analysis: Energy calibration

- Data divided into three zenith angle intervals:
  [0°, 19.34°)
  [19.34°, 27.93°)
  [27.93°, 35°]

- $\mathbf{N_{ch}}$ and $\mathbf{N_{\mu}}$ with MC simulations are used for event-by-event energy calibration

$$\log_{10} E = [a_H + (a_{Fe} - a_H) \cdot k] \cdot \log_{10} N_{ch} + [b_H + (b_{Fe} - b_H) \cdot k]$$

where:

$$k(N_{ch}, N_{\mu}) = \frac{\log_{10}(N_{ch}/N_{\mu}) - \log_{10}(N_{ch}/N_{\mu})_H}{\log_{10}(N_{ch}/N_{\mu})_{Fe} - \log_{10}(N_{ch}/N_{\mu})_H}$$

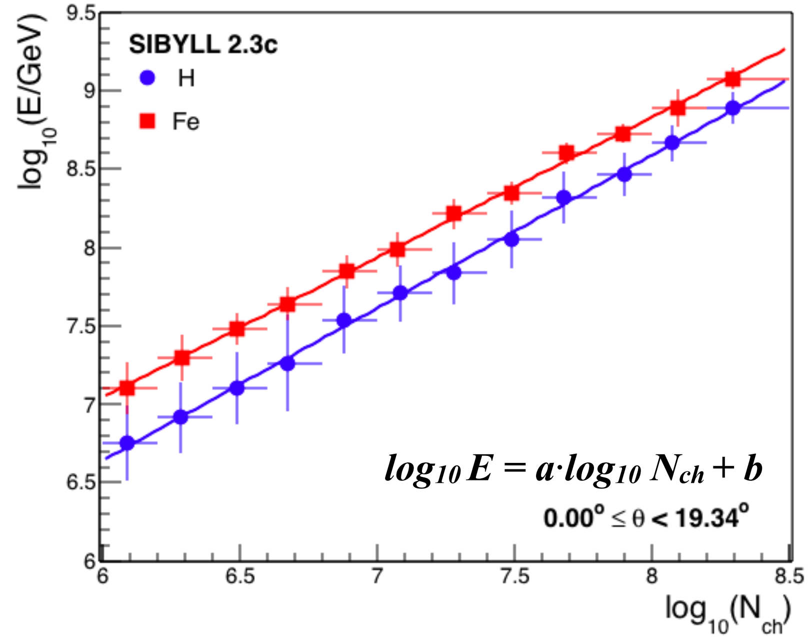
with:

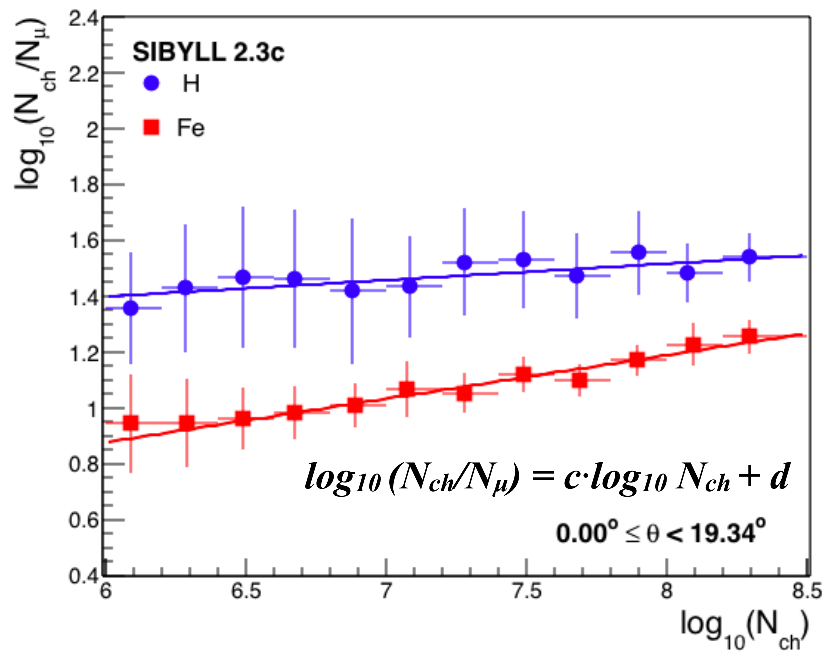
$k = 0$ (H)

$k = 1$ (Fe)

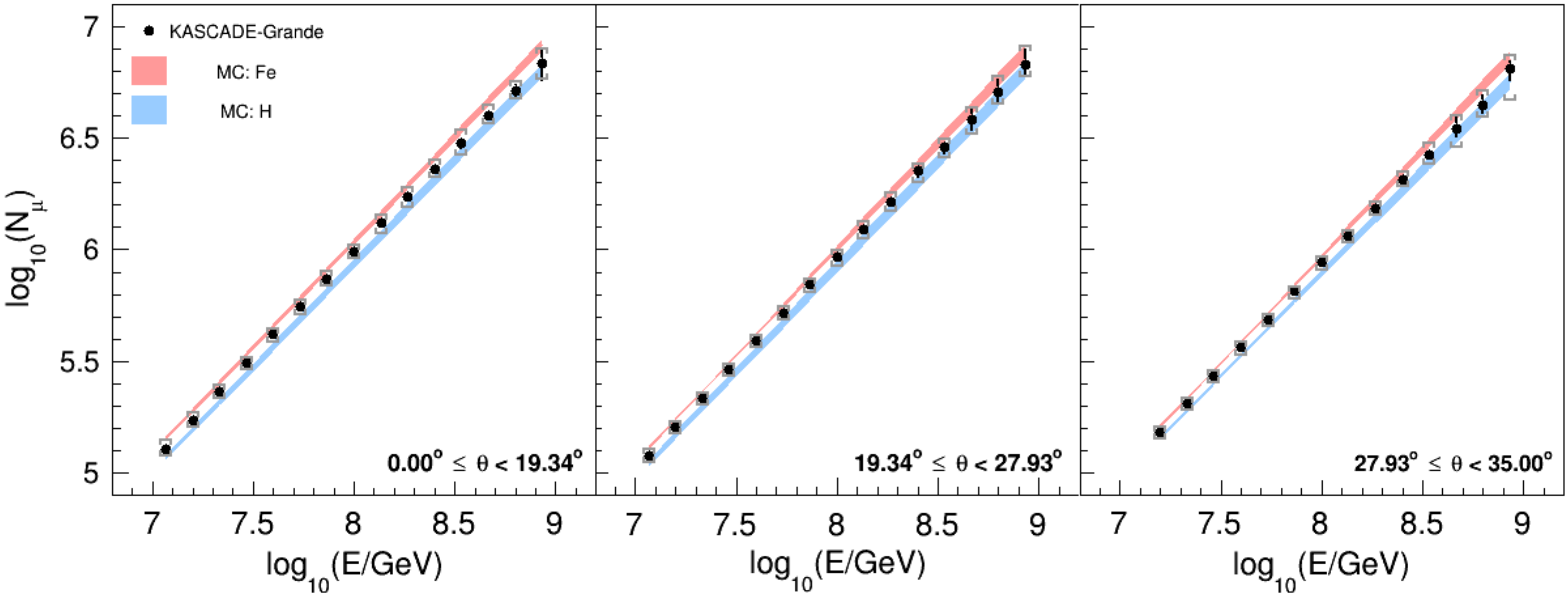
[Astrop. Phys. 36 (2012) 183]

- Energy calibration and muon correction function are derived with the same hadronic interaction model.





Results

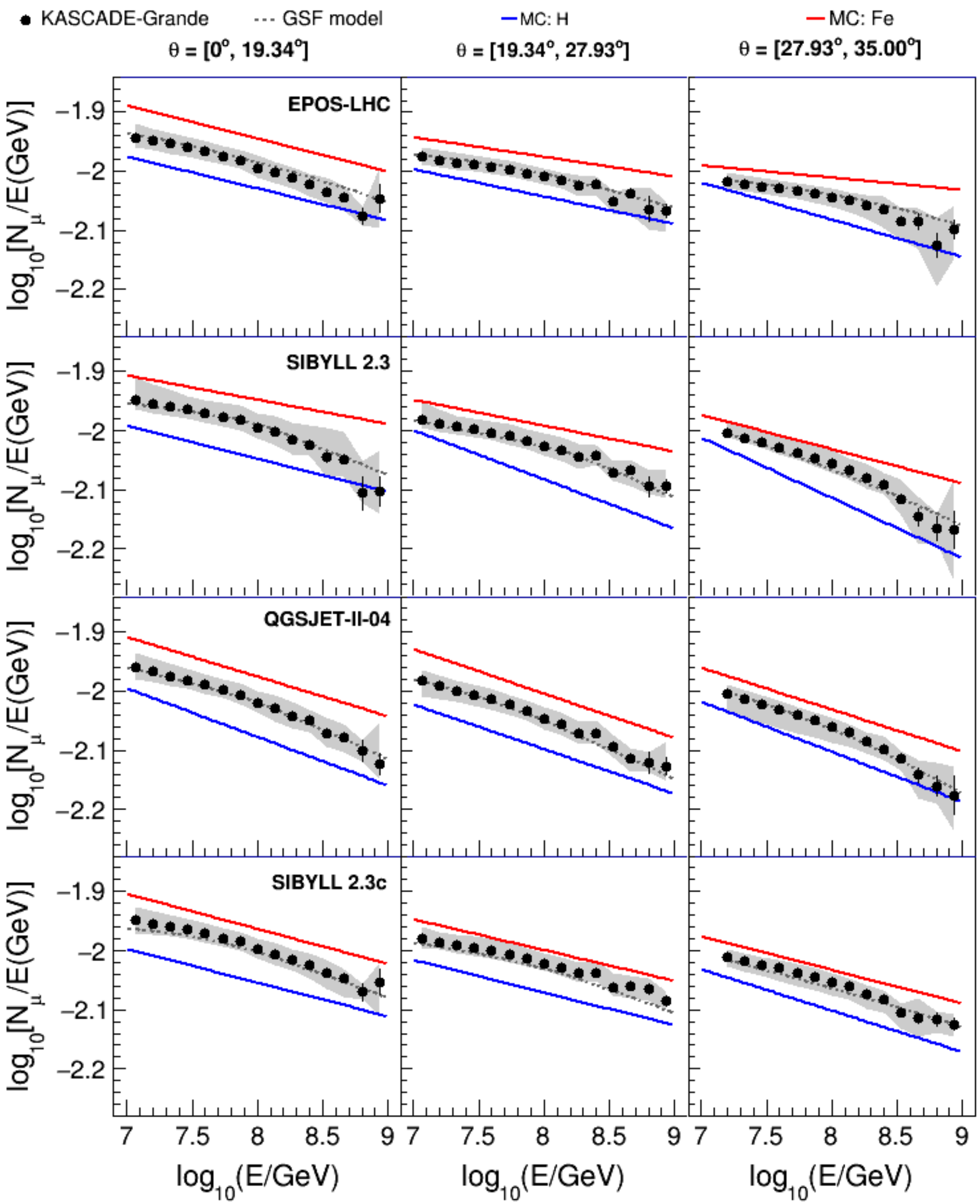


Muon data above 230 MeV at sea level (X_0 = 1023 g/cm²) from KASCADE-Grande in the primary energy range **from 10 PeV to 1 EeV lies between the model predictions** for protons and iron nuclei**.**

Systematic uncertainties (Gray brackets):

- **N_μ correction function**
- **N_μ uncertainty**
- **Estimated E**
- **Post-LHC hadronic model**
- **Muon LDF**
- **Nch uncertainty**
- **Spectral index of primary spectrum**

Results



- Energy dependence of measured muon number is not described by a simple power-law.

  → **Change in composition**

- Differences from model to model in composition

  → **N_μ is distinct for each model**

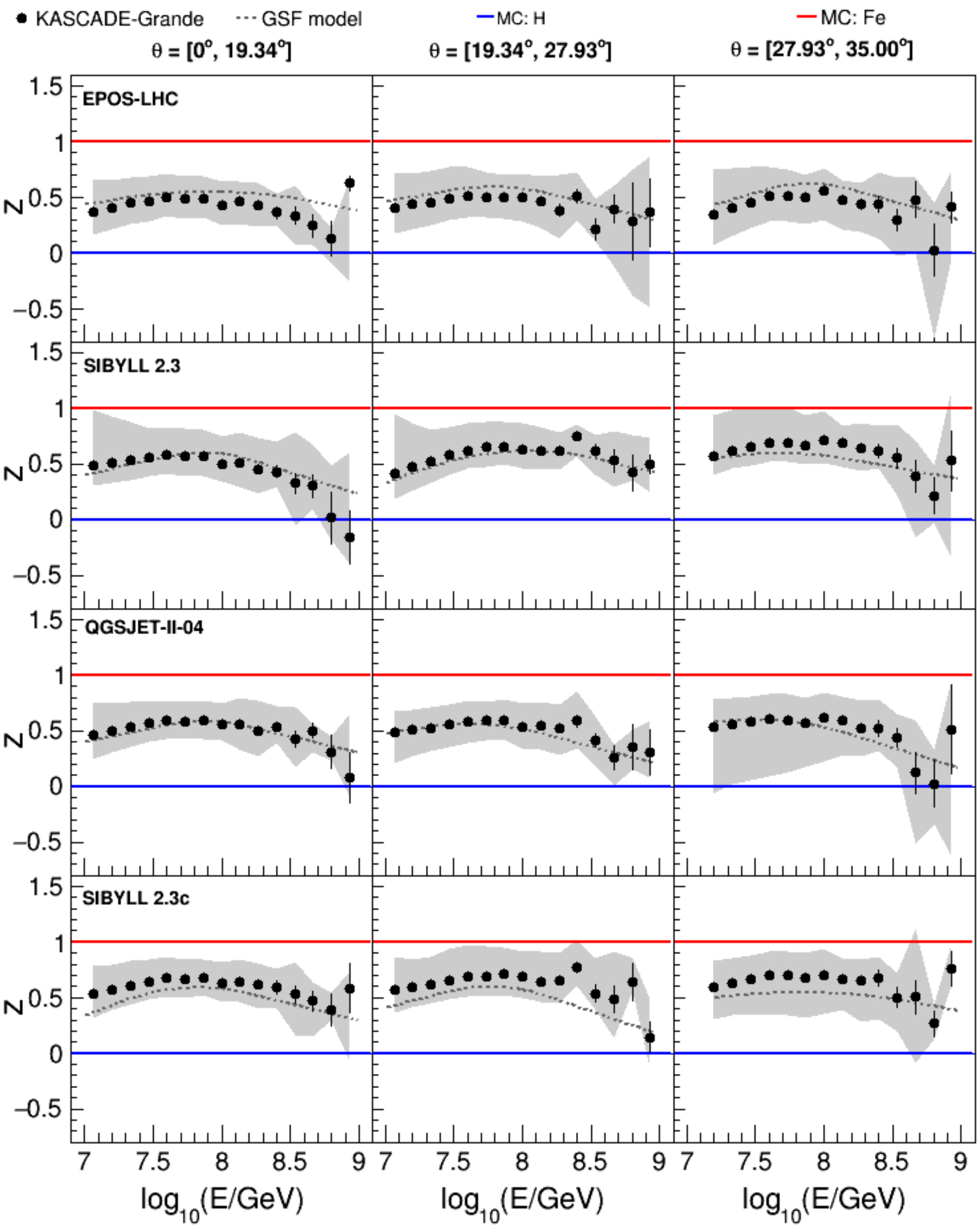
  Lighter for EPOS-LHC

  Heavier for SIBYLL 2.3c

- Within each model differences in composition at distinct zenith angles

  → **θ dependent mismatch**

Results



$$Z = \frac{\ln(N_\mu^{exp}) - \log_{10}(N_\mu^{H})}{\ln(N_\mu^{Fe}) - \log_{10}(N_\mu^{H})}$$

- Same structure in evolution of composition is observed

→ **Heavier around 10^{17} eV**

Agreement with light/heavy composition studies of KG

- Cosmic ray composition tends to be slightly heavier at high zenith angles

→ **More muons for inclined data**

Agreement with mismatch in muon attenuation length observed with KG

Summary

- **KASCADE-Grande muon data above 230 MeV at sea level** in the primary energy range from **10 PeV to 1 EeV** were **compared with predictions of QGSJET-II-04, EPOS-LHC, SIBYLL 2.3 and SIBYLL 2.3c**.

- The measured **muon number lies between** model predictions for **hydrogen and iron** nuclei.

- Cosmic ray **composition from muon data** shows a **dependence with the model and θ** (slightly heavier for inclined EAS).

- The results **support** previous findings of KASCADE-Grande about a **problem in the predicted Λ_μ** and seem to **point out to a problem with the expected N_μ between 10 PeV and 1 EeV** as observed in Auger at higher energies but weaker.