A measurement of the muon number of extensive air showers from cosmic ray collisions using the data from KASCADE-Grande

J. C. Arteaga-Velázquez for the KASCADE-Grande collaboration

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- Data and selection cuts.
- Analysis method.
- Results.
- Conclusions.

Objective

- To estimate $N_{\mu}(E)$ from 10 PeV to 1 EeV using KASCADE-Grande EAS data for zenith angles $\theta < 40^{o}$.

- To compare measurements with the predictions of QGSJET-II-04, EPOS-LHC and SIBYLL 2.3d.

KASCADE-Grande experiment

The KASCADE-Grande Collaboration

Germany

Karlsruhe Institute of Technology
University of Hamburg
Siegen University
Universität Wuppertal

The Netherlands

Radboud University Nijmegen

Poland

National Centre for Nuclear Research

Italy

Università degli Studi di Torino

Romania

University of Bucharest
Horia Hulubei National Institute of Physics and Nuclear Engineering

Brasil

Universidade São Paulo

Mexico

Universidad Michoacana

Spokesperson:
Dr. Andreas Haungs

KASCADE-Grande webpage: https://cr.iap.kit.edu/kascade

KASCADE-Grande experiment

Detector characteristics

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

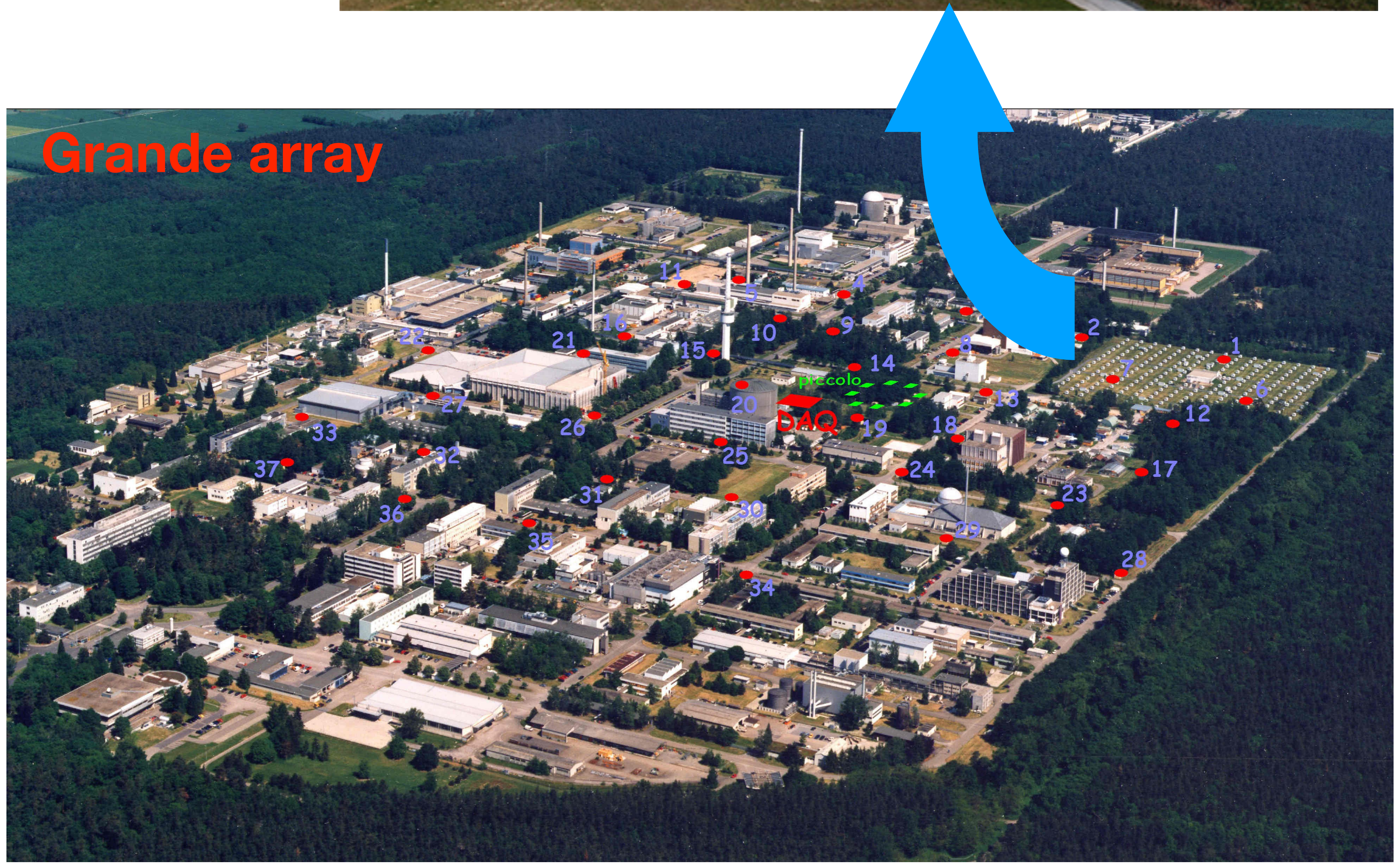
2. Cosmic ray detection: E = 1 PeV - 1 EeV

4. Multi-detector system:
   KASCADE array (200 x 200 m^2)
   - 252 e/γ and 192 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, arrival direction, core position

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

KASCADE-Grande experiment

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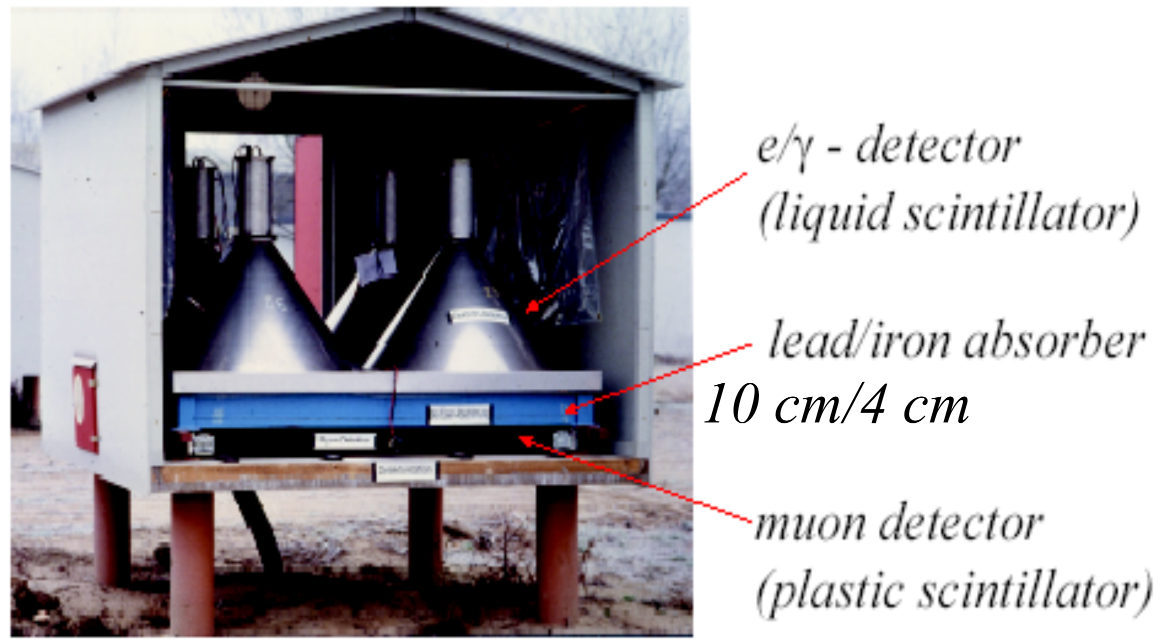
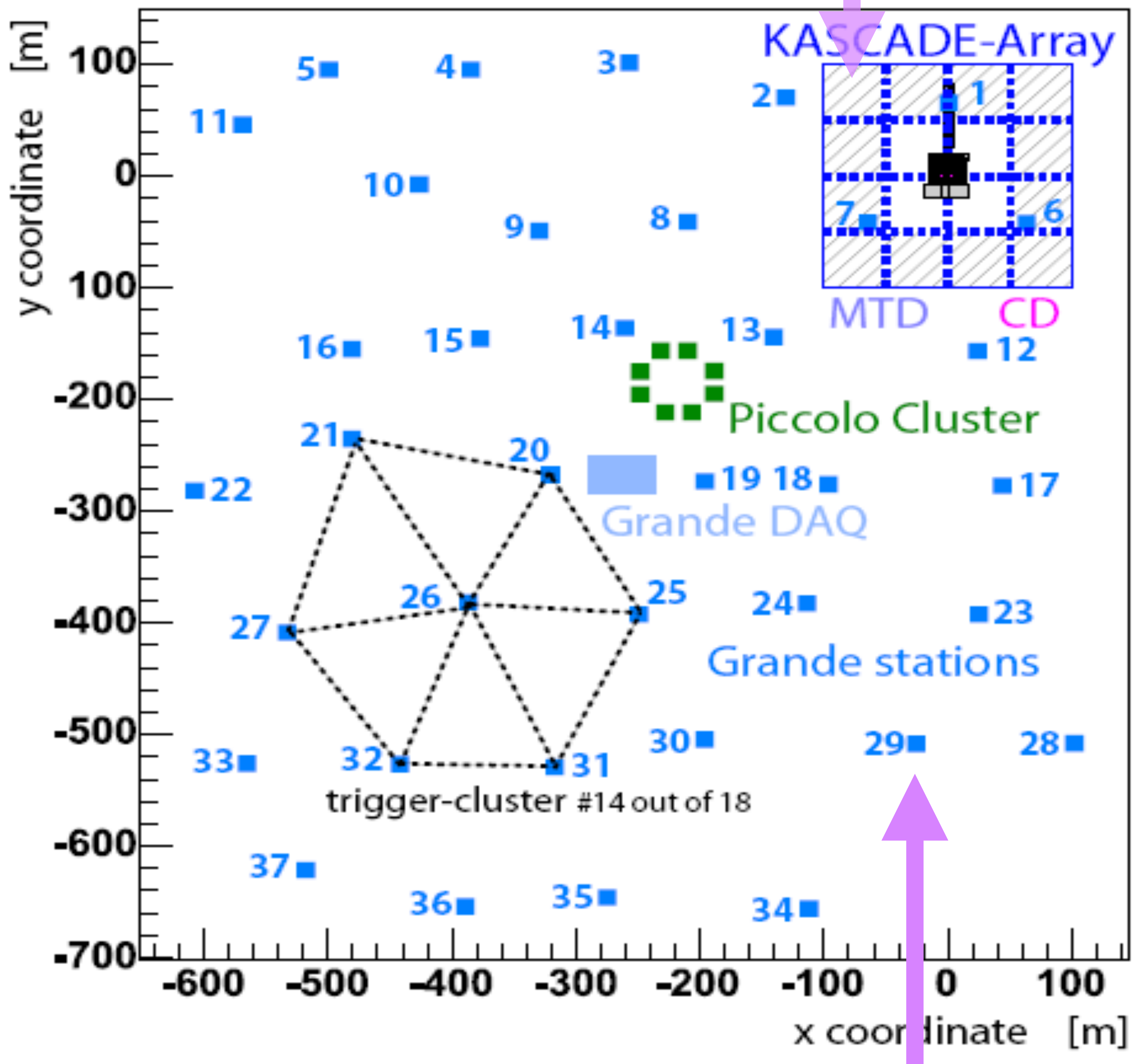
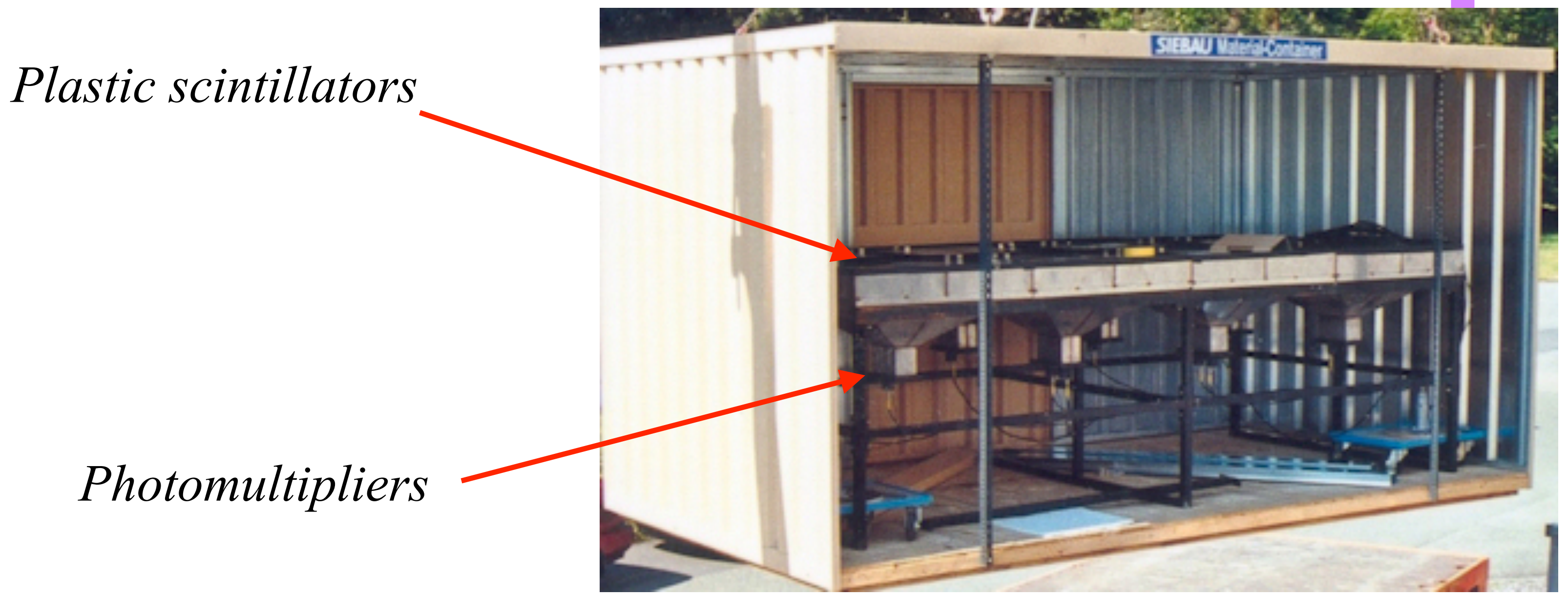


KASCADE station

Particle	Threshold
e/γ	5 MeV
μ	230 MeV





Grande array

Particle	Threshold
e + μ	5 MeV

Muon size determination

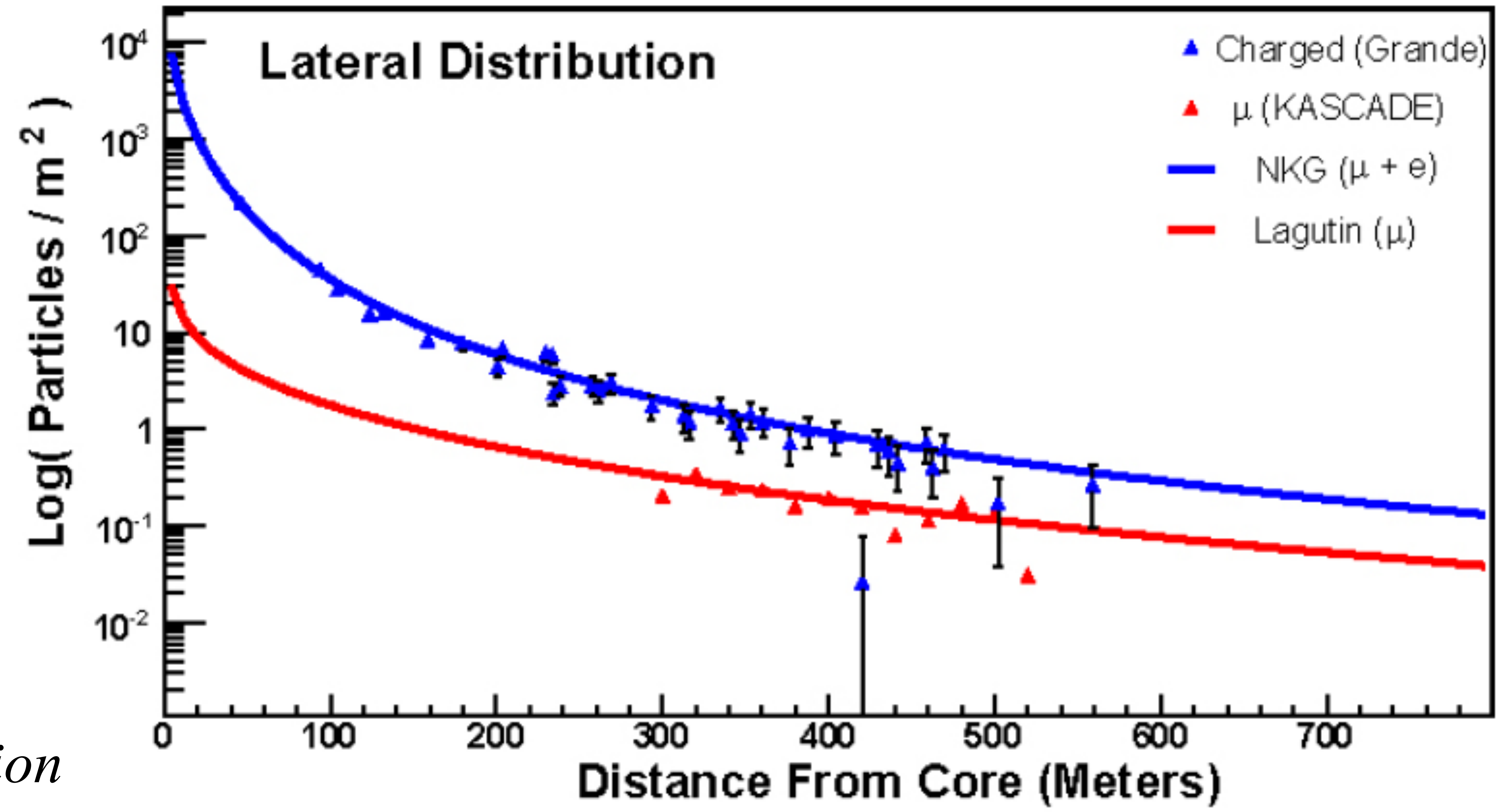
- Data from KASCADE shielded detectors.
- $E_\mu > 230$ MeV
- N_μ from a ML estimator and $\rho_\mu(r)$ data.

$$N_\mu^{rec} = \sum_{i=1}^{k} n_i / \sum_{i=1}^{k} (f(r_i) A_i \cdot \cos(\theta))$$

n_i: number of muons in station i

A_i: Area of station i

f(r): Lagutin-Raikin lateral distribution function (fixed shape)



[KG Coll., NIMA 620 (2010) 202]

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

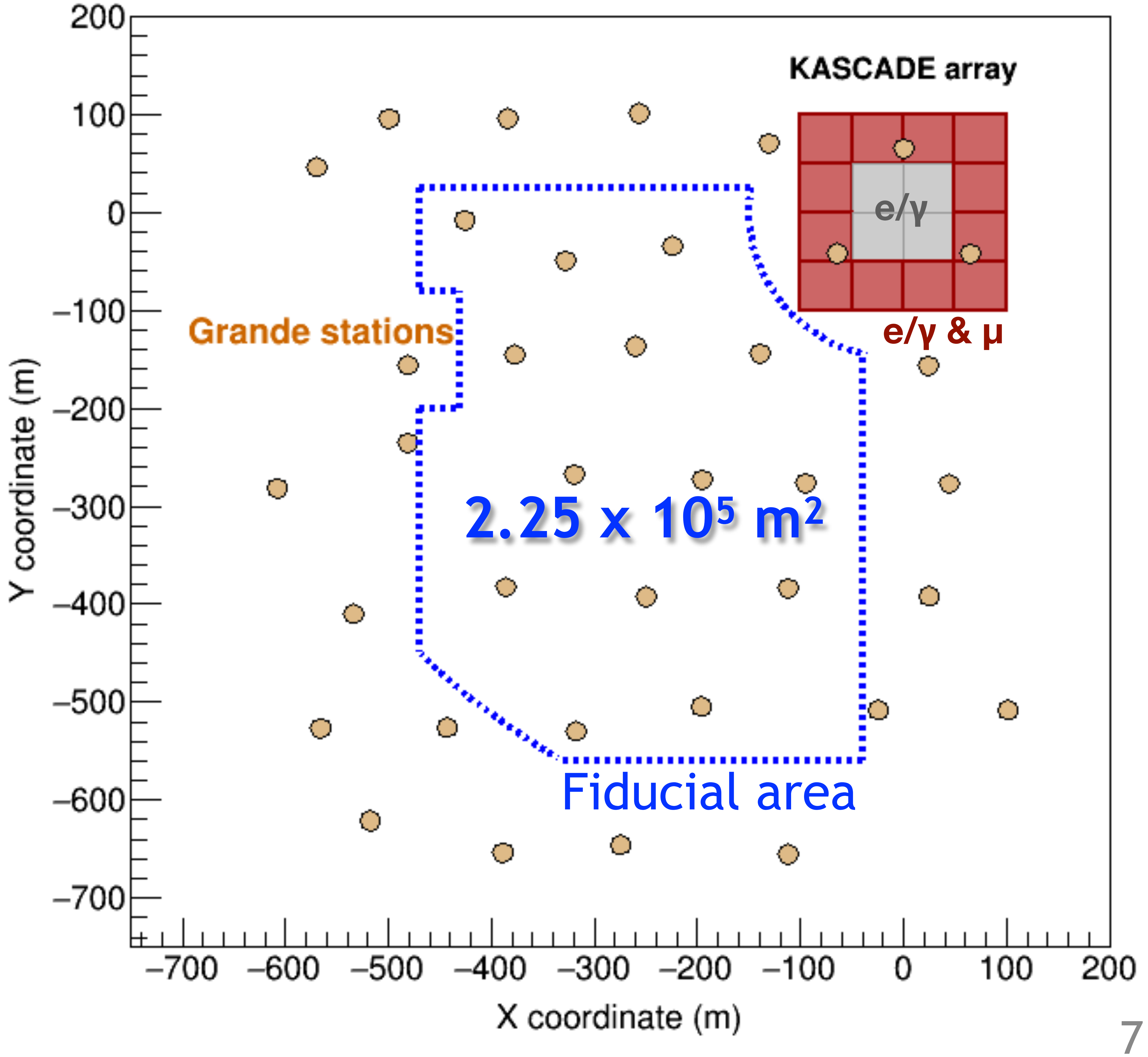
Data and selection cuts

Data sample

- Period: December 2003 - November 2012.
- Effective time: 1825 days, number of selected events: 1.276×10^7.

Selection cuts

- Successfully reconstructed
- $\theta < 40^o$.
- EAS cores at center of Grande array.
- From stable runs with no hardware problems.
- $N_e > 1.1 \times 10^4$.
- Shower age = [-0.39, 1.49].
- More than 11 Grande stations activated.
- $N_\mu > 3 \times 10^4$.



MC simulations

Thresholds for maximum detection and trigger efficiency

- CORSIKA
- Primaries: H, He, C Si, Fe.
- E^{-2} spectrum.
- LE hadronic model: Fluka ($E_h \leq 200$ GeV):
- HE hadronic interaction models ($E_h > 200$ GeV):
  - QGSJET-II-04 → Used to build a muon correction function following [Astrop. Phys. 36 (2012) 183].
  - EPOSLHC
  - SIBYLL 2.3d

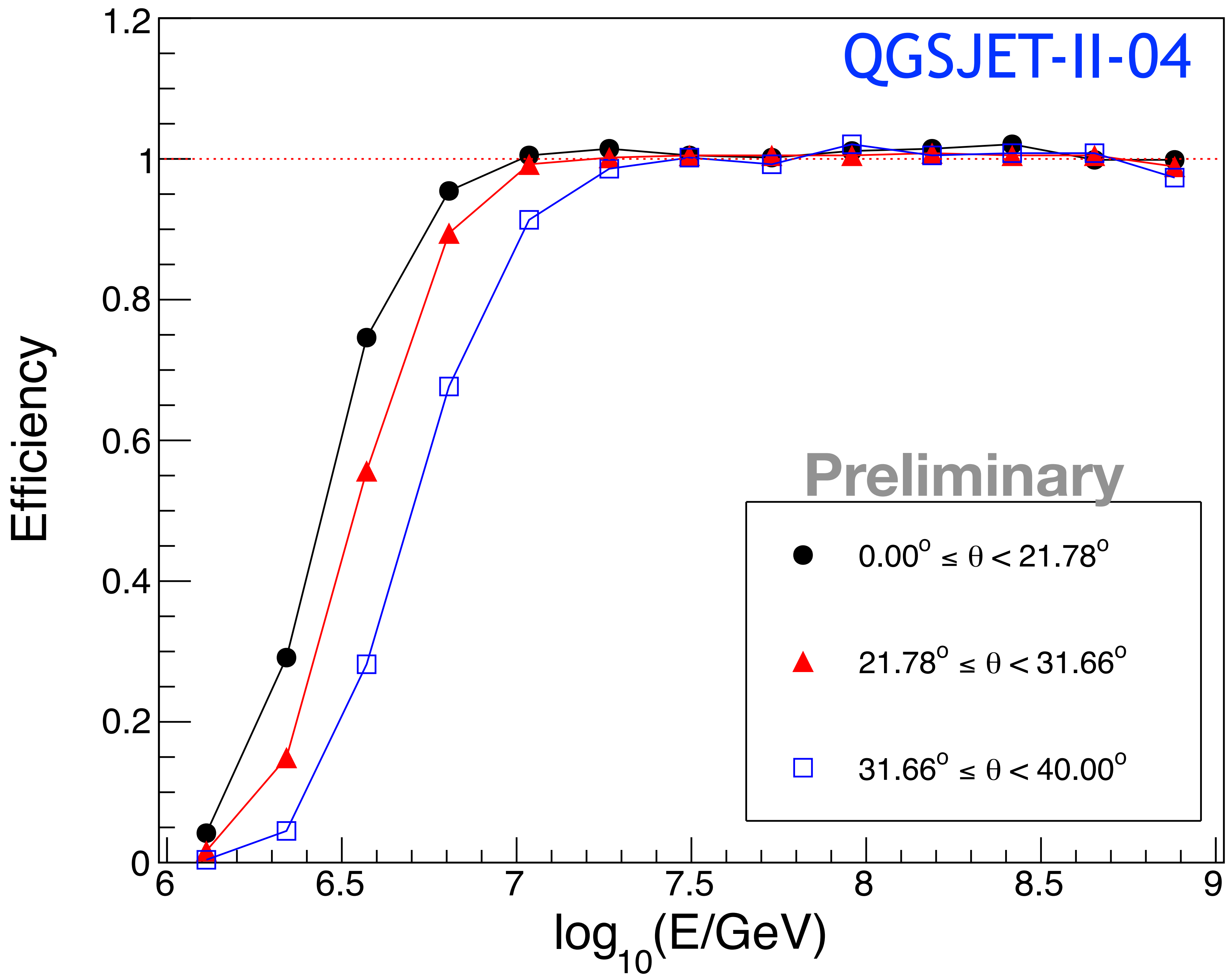
Data and selection cuts

Thresholds for maximum efficiency

$\log_{10}(E/\text{GeV}) = 7.1 \pm 0.2$

$\log_{10}(N_\mu) = 5.15 \pm 0.15$

$\log_{10}(N_{ch}) = 6.1 \pm 0.3$



Brief description of the analysis

- No model independent energy estimator in KASCADE-Grande —> Use **NEVOD-DECOR** [Phys.Atom.Nucl.73,1852(2010), Astropart.Phys.98,13(2018)] and **SUGAR's** [PRD 98,023014(2018)] strategy.

- Compare measured muon number flux against the prediction of a reference cosmic ray energy spectrum

  $\mathbf{\Phi_{exp}(N_{\mu,\, exp})}$ **vs** $\mathbf{\Phi_{MC}(N_{\mu,\, MC})}$

  and, from the observed difference, to estimate the data/MC muon ratio ($\mathbf{R = N_{\mu,\, exp}/N_{\mu,\, MC}}$) that best describe the measurements.

- The ratio is then applied to the MC simulations

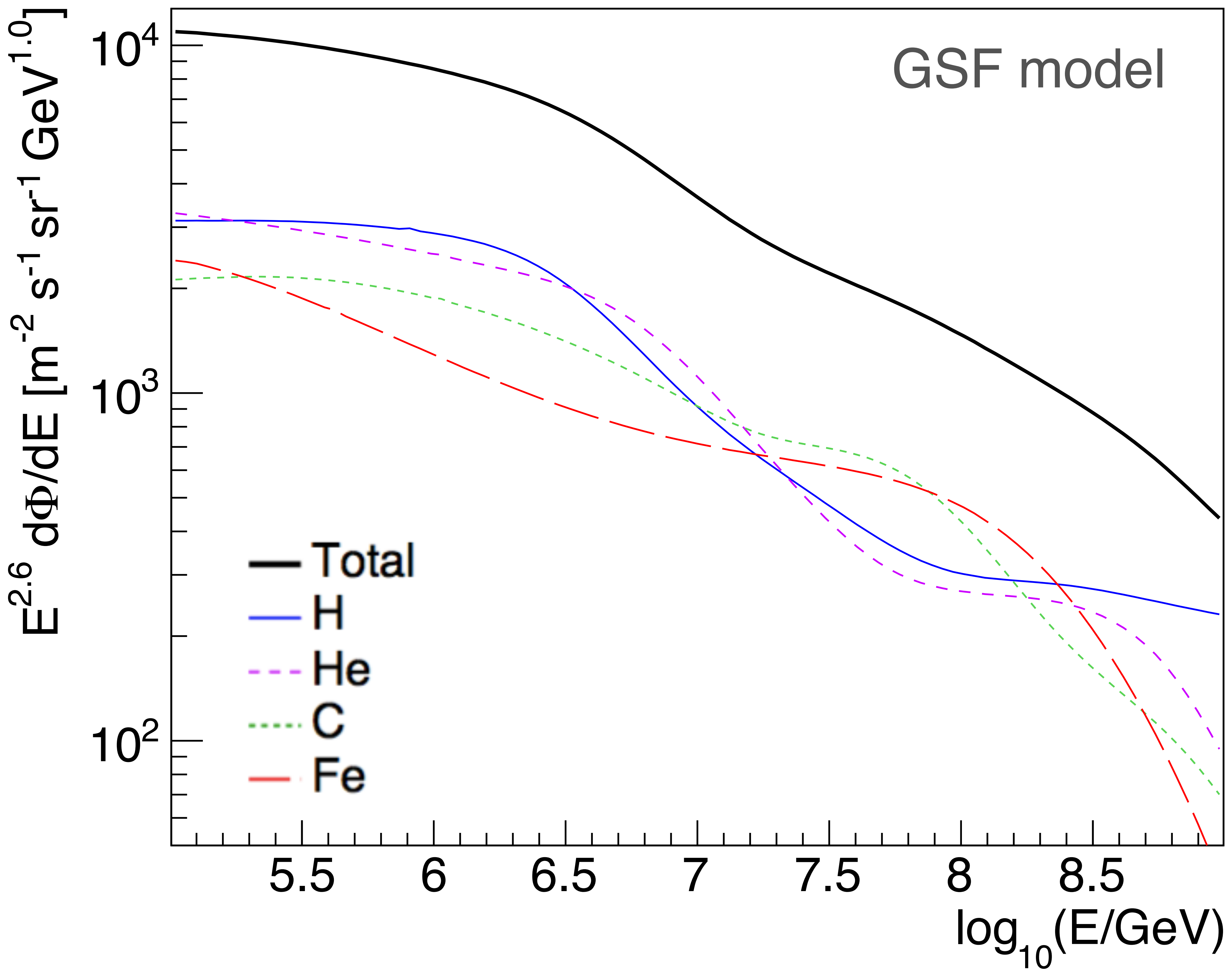
  $\mathbf{N_{\mu,\, estimated} = R \times N_{\mu,\, MC}}$

  and from here, we estimate N_μ vs E.

Reference cosmic ray composition model:

- Obtained by re-weighting all MC simulations.
- All-particle energy spectrum and relative cosmic-ray abundances from the GSF model [H. Dembinski et al., PoS (ICRC2017) 533].
- Primary mass groups: H, He, C and Fe.
- Energy scale from Pierre Auger Observatory [PAO Collab., PoS(ICRC2019) 450].

$$E^{Auger}/E^{GSF} = 0.87$$



Analysis method

- Correct muon data (MC and measurements) for systematic bias using muon correction function.

- Divide data into three zenith-angle intervals [0°, 21.78°], [21.78°, 31.66°] and [31.66°, 40°].

- Compare experimental N_μ histogram vs prediction of one hadronic interaction model for our reference composition model.

- By a minimun Chi² procedure

$$\chi^2 = \sum_{i=1}^{m} \frac{\left[n_{exp,i}^{(k)} - n_{MC,i}^{(k)}(\delta_{\mu,k})\right]^2}{(\sigma_{i,exp}^{(k)})^2 + (\sigma_{i,MC}^{(k)})^2},$$

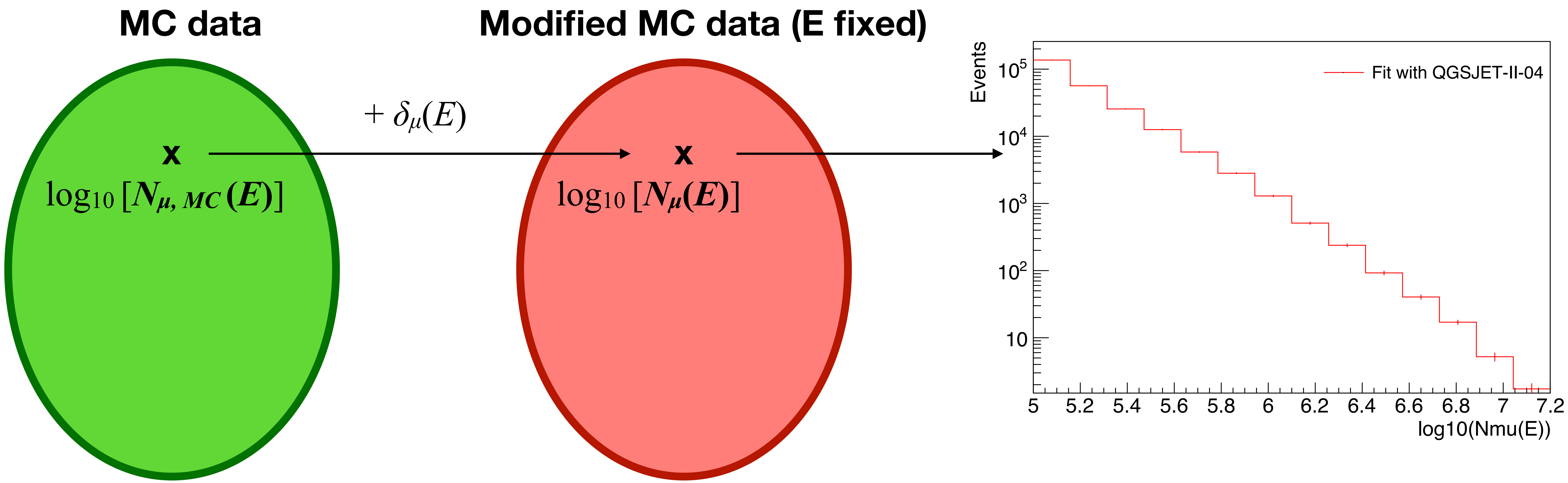
find the shift δ_μ

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

between MC and measured data that allows to describe the experimental N_μ distribution.

- Apply the shift to the MC model to estimate the actual muon content.

Analysis method

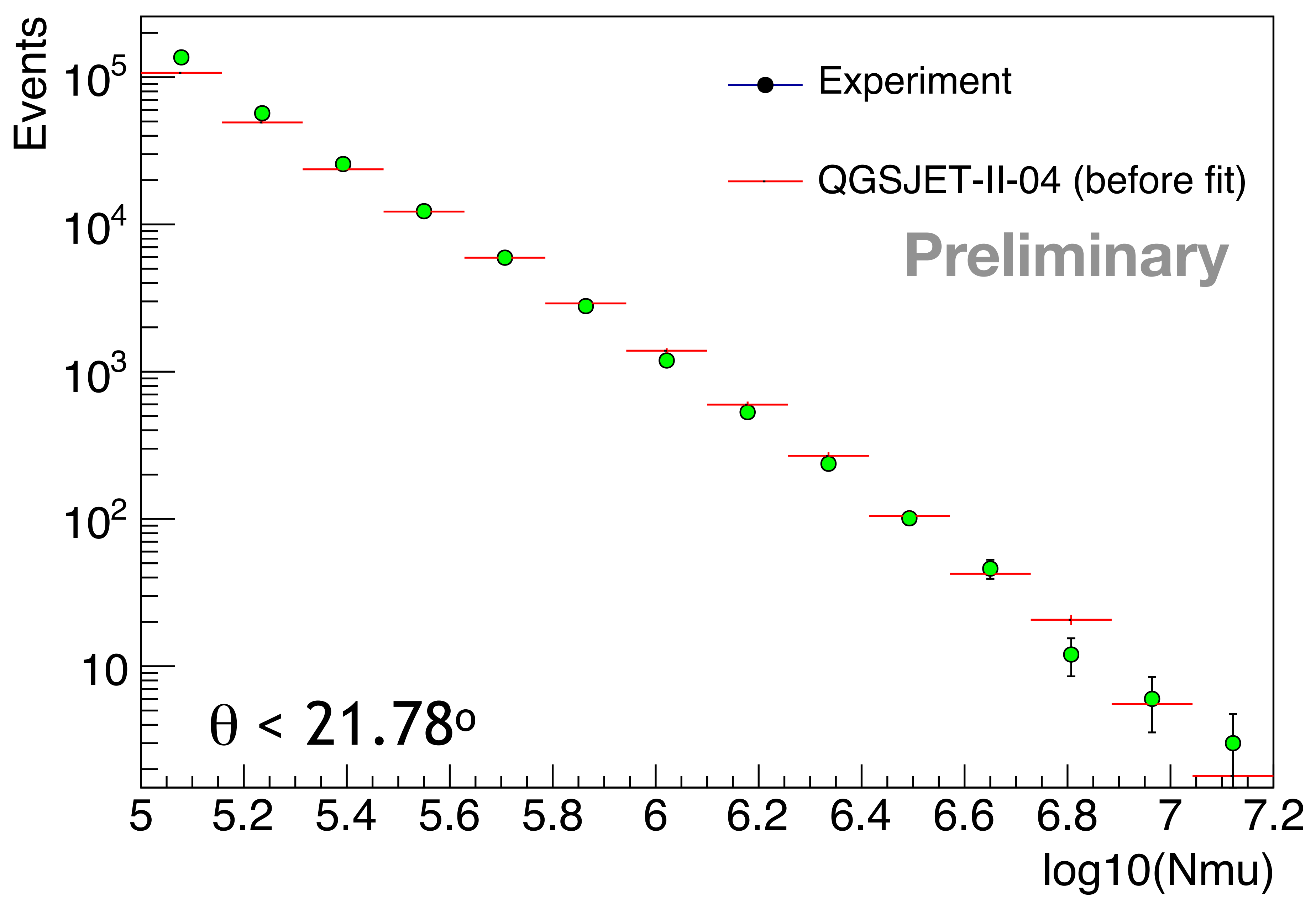


Where:

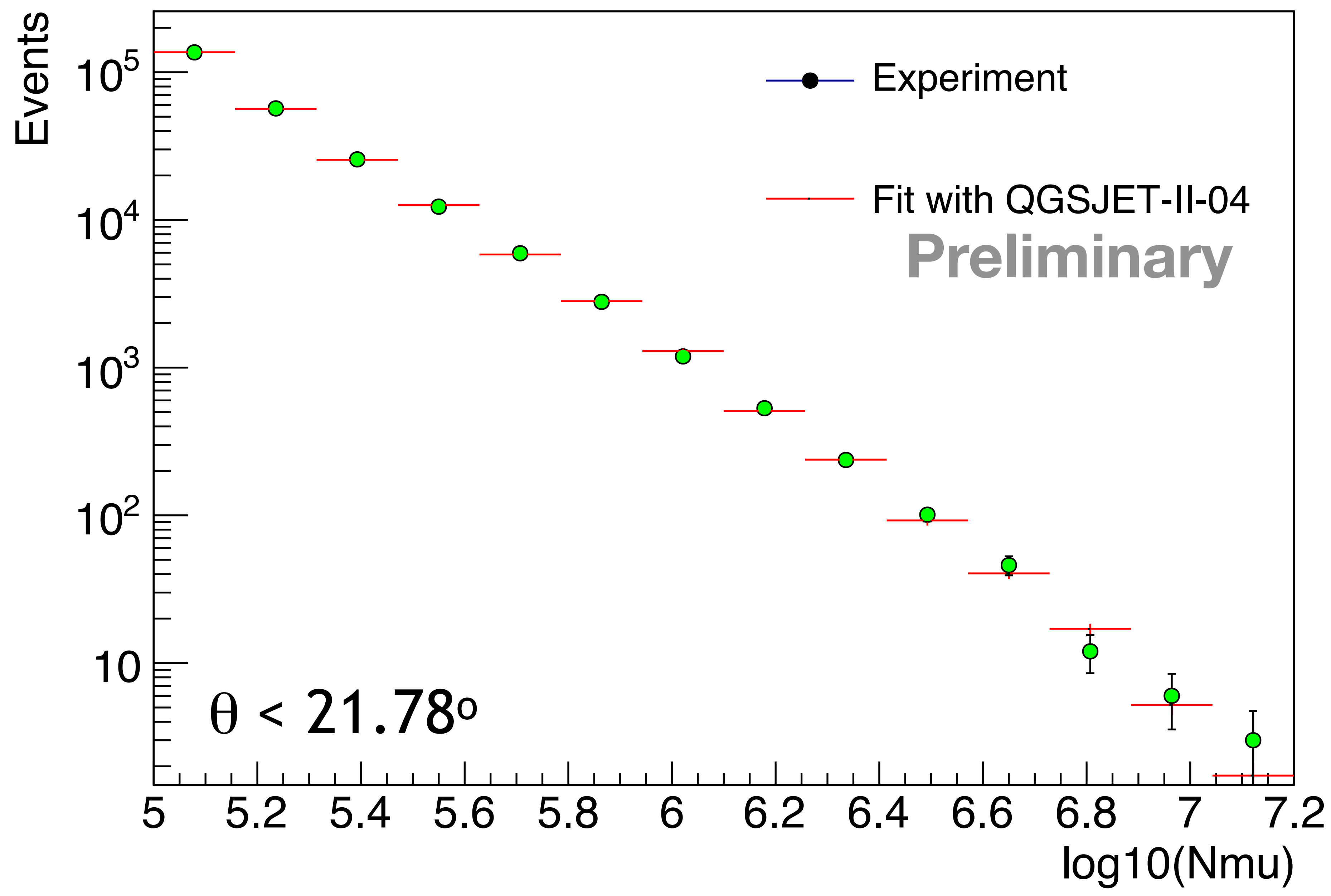
$$\log_{10}[N_\mu(E)] = \log_{10}[N_{\mu, MC}(E)] + \delta_\mu(E)$$

Analysis method

Before the fit



After the fit



2nd order pol. fit:

$\delta\mu(E) = p_0 + p_1\,[\log_{10}(E/GeV) - 8] + p_2\,[\log_{10}(E/GeV) - 8]^2$

$X^2/ndf = 8.271/9$

$p_0 = -0.020 \pm 0.010$

$p_1 = -0.019 \pm 0.019$

$p_2 = 0.025 \pm 0.011$

Statistical and systematic errors:

- Statistical errors include uncertainties due to

  - fitted parameters of the δ_{μ} function and

- Systematic errors take into account uncertainties in

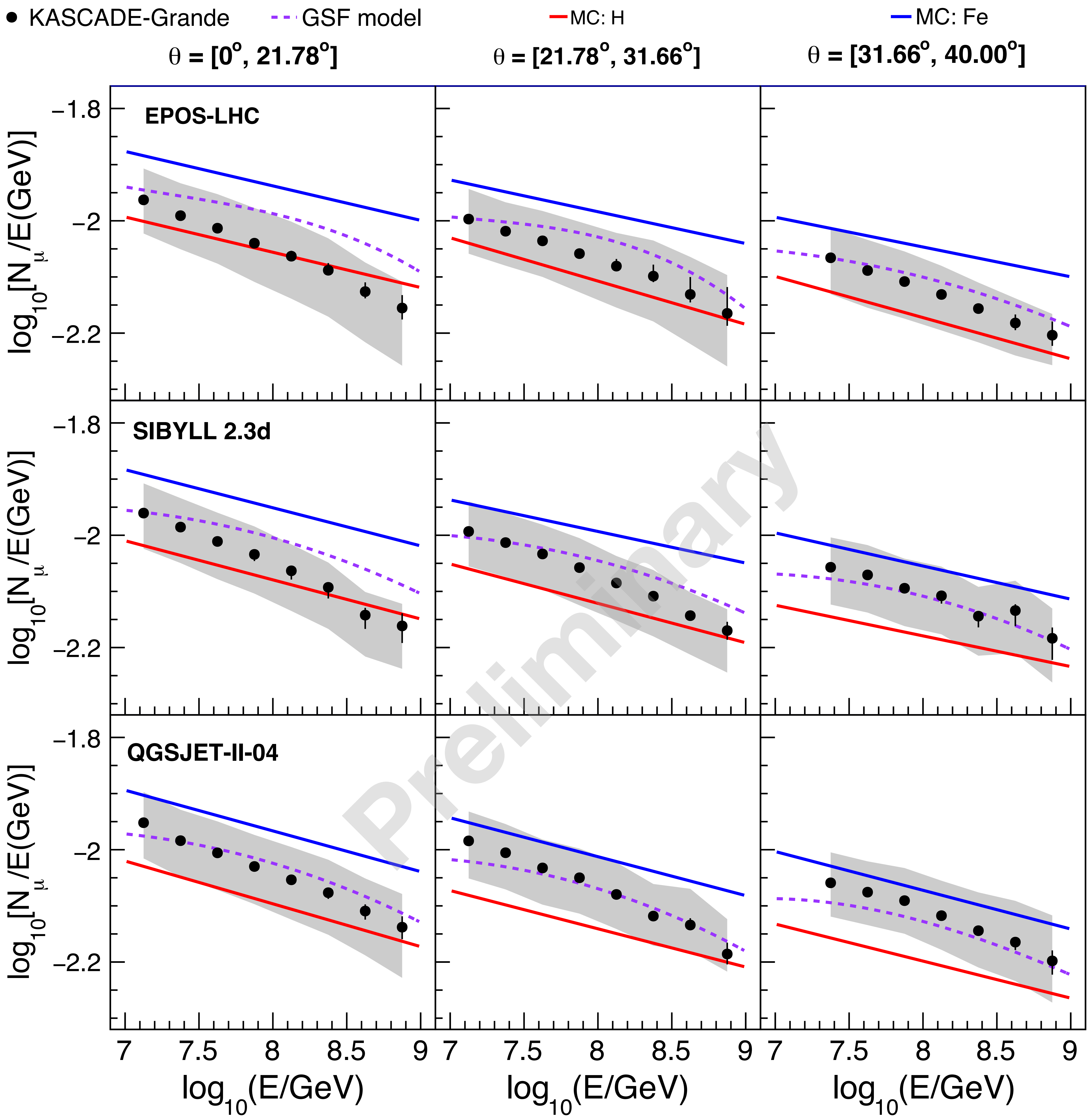
  - in composition (change light/heavy ration using max/min values observed in past KG analysis with QGSJET-II-04, EPOS-LHC, SIBYLL 2.3 and SIBYLL 2.3c),

  - lateral distribution of muons (divide fiducial area in two regions separated by a cut at r = 410 m),

  - energy scale (using estimated uncertainty ±14% from PAO Collab., PoS(ICRC2019) 450).

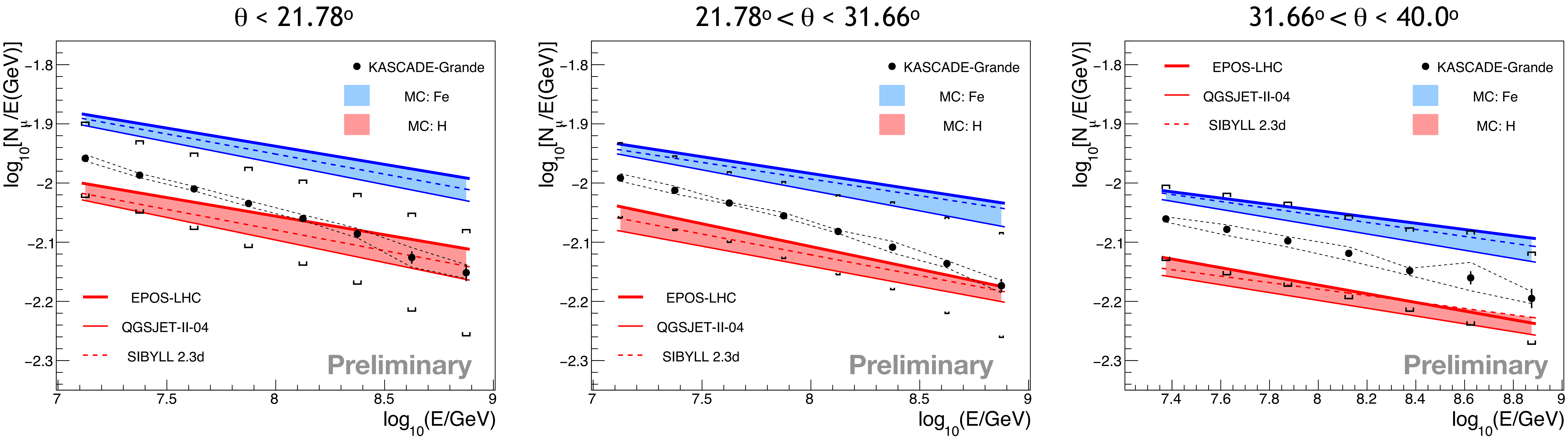
  - Muon correction function(using alternative function derived with EPOS-LHC).

Results



- No excess of EAS muon data with respect to the models.
- A deficit is observed in data for vertical EAS close to 1 EeV.
- Reasonable agreement between experiment and data for inclined events.
- Smaller atmospheric attenuation of actual EAS muon data.

Results



Hadronic interaction models

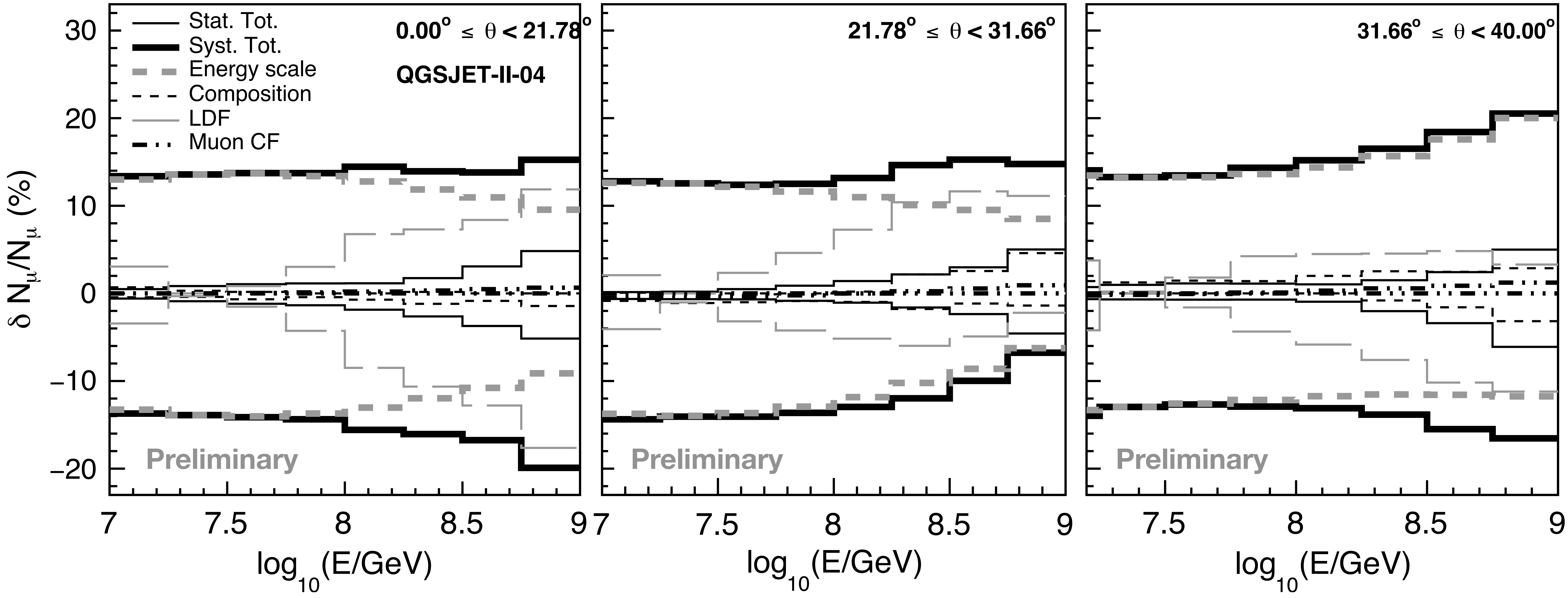
Data points : Mean value (average of the results for the three hadronic interaction models)

Vertical error bars: Statistical errors

Brackets : Systematic errors

Results

Statistical and systematic errors:



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 and SIBYLL 2.3d 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 $\theta = [31.66^o, 40^o]$. For vertical EAS, hadronic interaction models seem to produce more muons.

- Work in progress: Study $\rho_\mu(r)$ vs E and θ at r = 600 m and distances close to shower core.

KASCADE-Grande webpage: https://cr.iap.kit.edu/kascade
KCDC data base: https://kcdc.iap.kit.edu/