Tests of HE hadronic interaction models with the muon attenuation length in KASCADE-Grande

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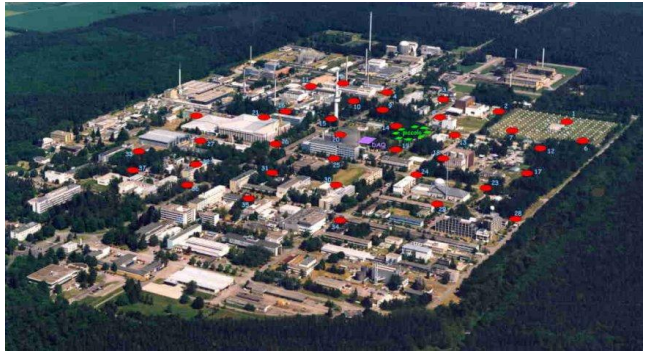


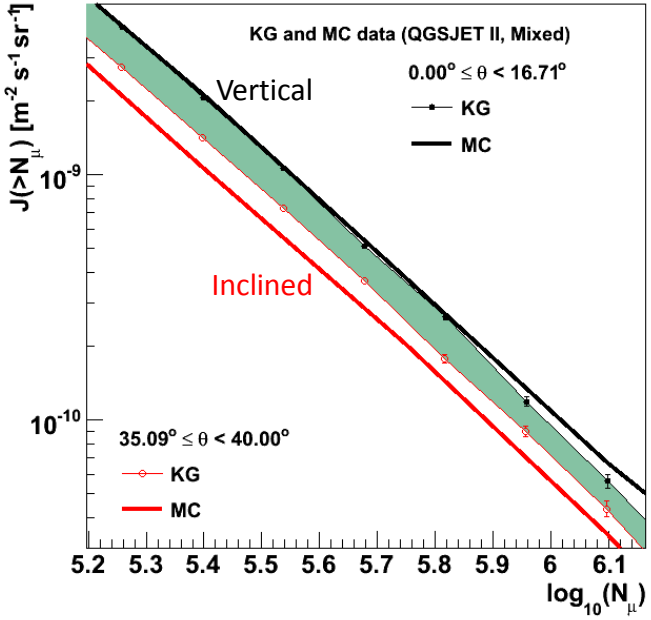
1) The Problem

- Preliminary studies show that zenith angle dependence of the muon content of EAS is not described by hadronic interaction models.

- Attenuation length of muons in the atmosphere seems to be higher than that predicted by simulations.

$$\Lambda_\mu^{exp} > \Lambda_\mu^{MC}$$

- How statistically significant are the results? Need a complete study of statistical and systematic errors.



2) The objective

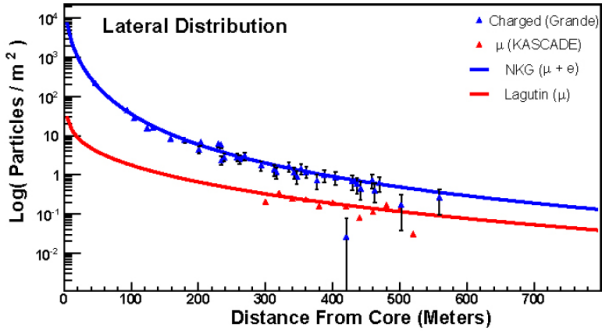
- Look for statistical/systematic errors that may be responsible for the origin of the discrepancy.

- If no error can explain the difference, how significant is the result?

3) Experiment and data

KASCADE-Grande:

- KASCADE (200 x 200 m^2) + Grande (0.5 km^2)
- EAS detector: E = 10^{15}-10^{18} eV.
- Total N_μ (E_μ>230 MeV): $\rho_\mu(r)$ data from 192 KASCADE μ detectors



4) Data and systematics

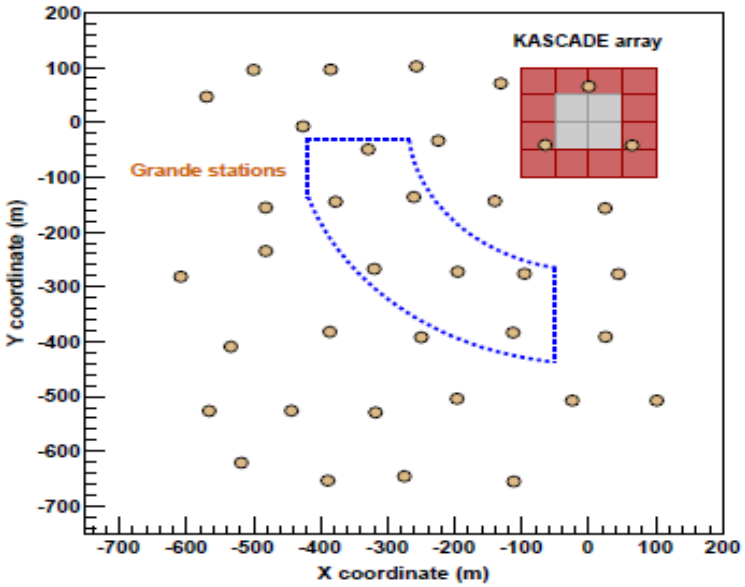
Data sample:

- Effective observation time: 1434 days
- Total exposure: 1.3×10^3 m^2 s sr

Selection cuts:

- Central area: 370 x 520 m^2.
- $\theta < 40^o$ ($N_\mu \geq 3.98 \times 10^4$).
- Reconstruction & experimental cuts.

2 744 850 selected events



Advantages:

- Reduction of muon uncertainties, avoid punch-through bias and edge effects,
- Remove events with under- and over-estimated muon numbers, poor muon reconstruction, etc.

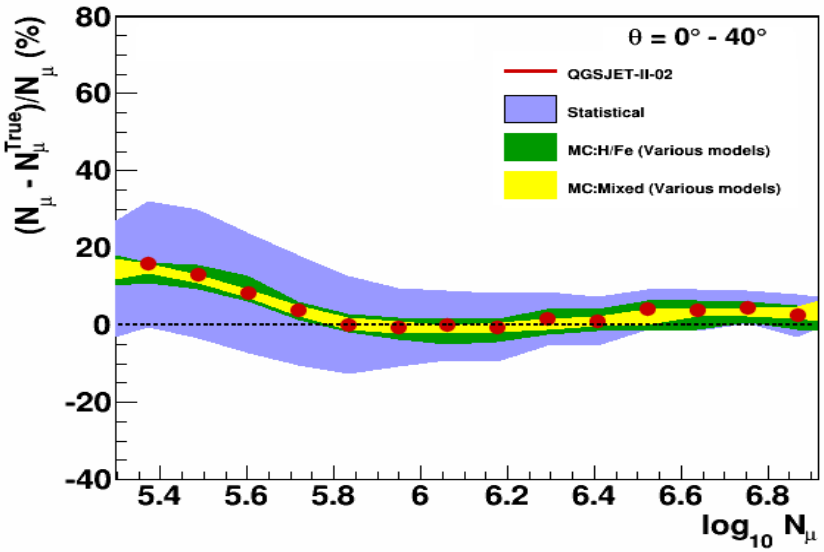
4) Data and systematics

MC sample:

- QGSJET-II-02
- EPOS 1.99
- SIBYLL 2.1
- QGSJET-II-04
- EPOS LHC

Simulated spectra:

- Composition: H, He, C, Si, Fe & Mixed
- E^{γ}, γ= -2.8, -3, -3.2

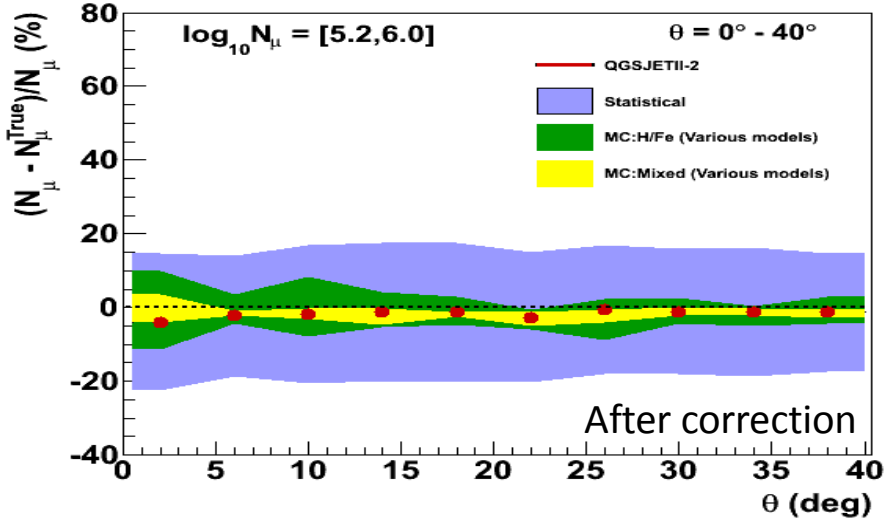


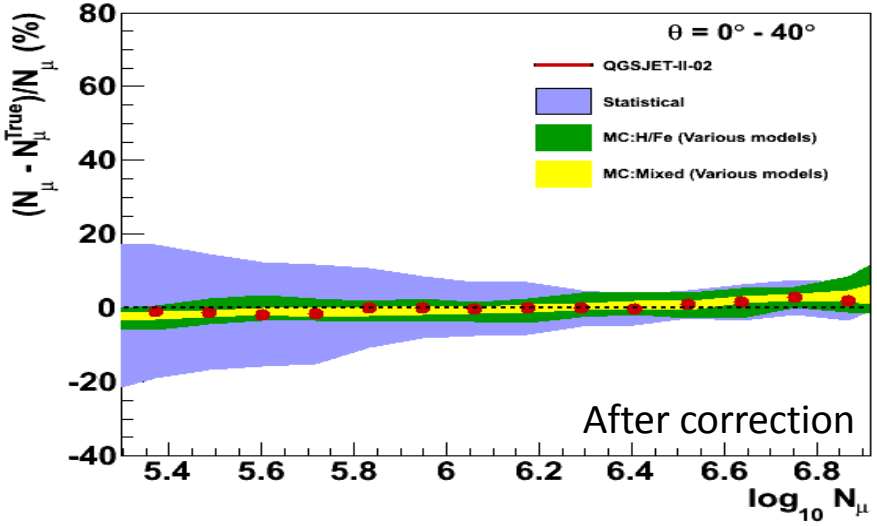
Mean accuracy (in region of full efficiency):

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

4) Data and systematics

- All muon data is corrected for systematic errors (using a correction function derived from QGSJET-II-02)

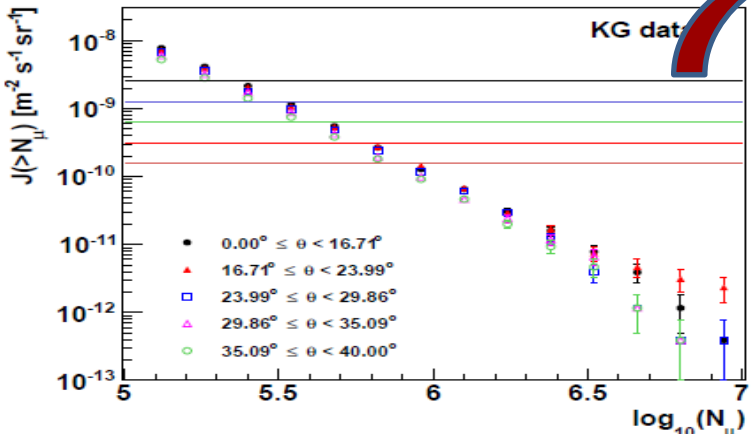


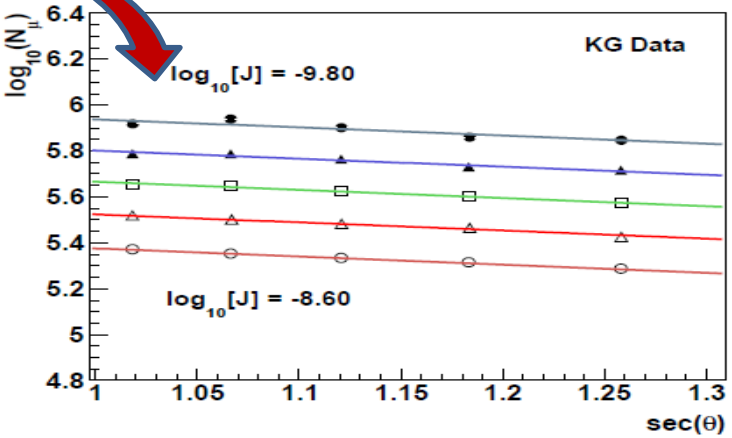


No dependence with core position, zenith angle and muon shower size

5) The method

- Constant Intensity method: Quantify zenith angle evolution of data.
- Method is independent of MC model.





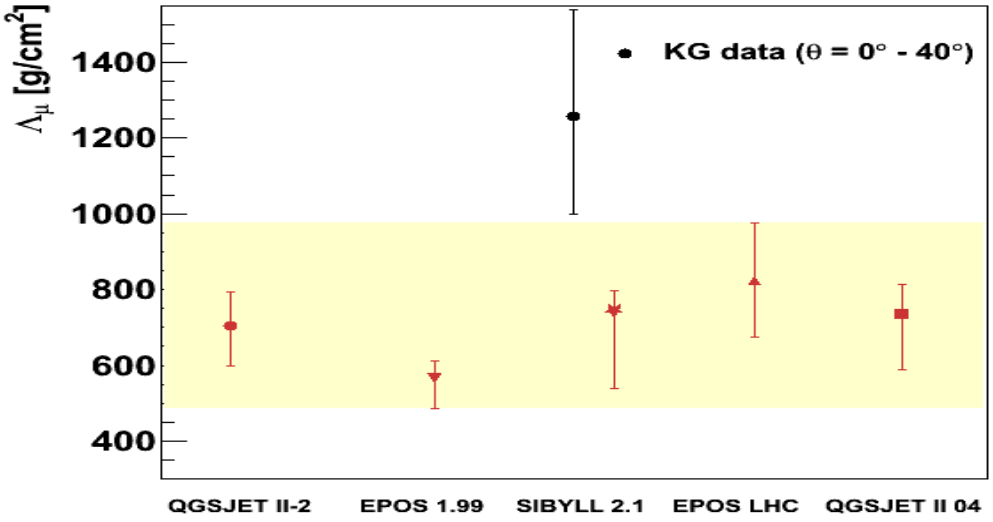
$$J(>N_\mu) = \int_{N_\mu}^{\infty} \Phi_\mu(N_\mu)\, dN_\mu$$

$$N_\mu = N_\mu^0 \exp[-X_0 \sec(\theta)/\Lambda_\mu]$$

1 • Apply cuts at fixed frequencies.

2 • Attenuation curves -> Global Fit -> Λ_μ.

6) The results



Error bars: Syst.& Stat. errors.

MC (CORSIKA/FLUKA):
Include errors from:
γ = -2.8, -3.0, -3.2
H, Fe and mixed composition

	QGSJET-II-02	EPOS 1.99	SIBYLL 2.1	EPOS LHC	QGSJET-II-04	KG data
Λ_μ (g/cm2)	706^{+87}_{-108}	564^{+49}_{-79}	743^{+54}_{-205}	823^{+153}_{-148}	735^{+78}_{-145}	1256^{+283}_{-258}

6) The results

Deviations and C.L. for agreement between model predictions and experimental data

	QGSJET-II-02	EPOS 1.99	SIBYLL 2.1	EPOS LHC	QGSJET-II-04	KG data
Λ_μ (g/cm2)	706^{+87}_{-108}	564^{+49}_{-79}	743^{+54}_{-205}	823^{+153}_{-148}	735^{+78}_{-145}	1256^{+283}_{-258}
Deviation(σ)	+2.02	+2.63	+1.94	+1.44	+1.93	
C.L .(%)	2.17	0.43	2.62	7.49	2.68	

- Probability of agreement between experiment and MC is low.
- Measurements and predictions are not consistent.

6) The results

Systematic/Statistical uncertainties of the measured Λ_μ			
Reconstruction/Analisys method	+9%/-2%	Muon systematics	+13%/-10%
Correction function	+6%/-9%	Statistical fluctuations	+9%/-9%
EAS core position	+12%/-11%		

- Aging of detectors is not the origin of the discrepancy

	Period	Effective time (s)	Λ_μ(g/cm2)
Sample 1	20/12/2003 – 07/11/2006	3.3×10^7	1233 ± 89
Sample 2	07/11/2006 – 11/04/2009	5.2×10^7	1295 ± 85
Sample 3	11/04/2009 – 31/10/2011	3.9×10^7	1219 ± 89

6) The results

- Studying systematics with MC

Source	Error
Fluctuations on $\rho_\mu(r)$	+15%
core position, arrival angle and $\rho_\mu(r)$ reconstruction	±3%
Shape of lateral distribution function	+5%/ -4%

- Other discarted sources:

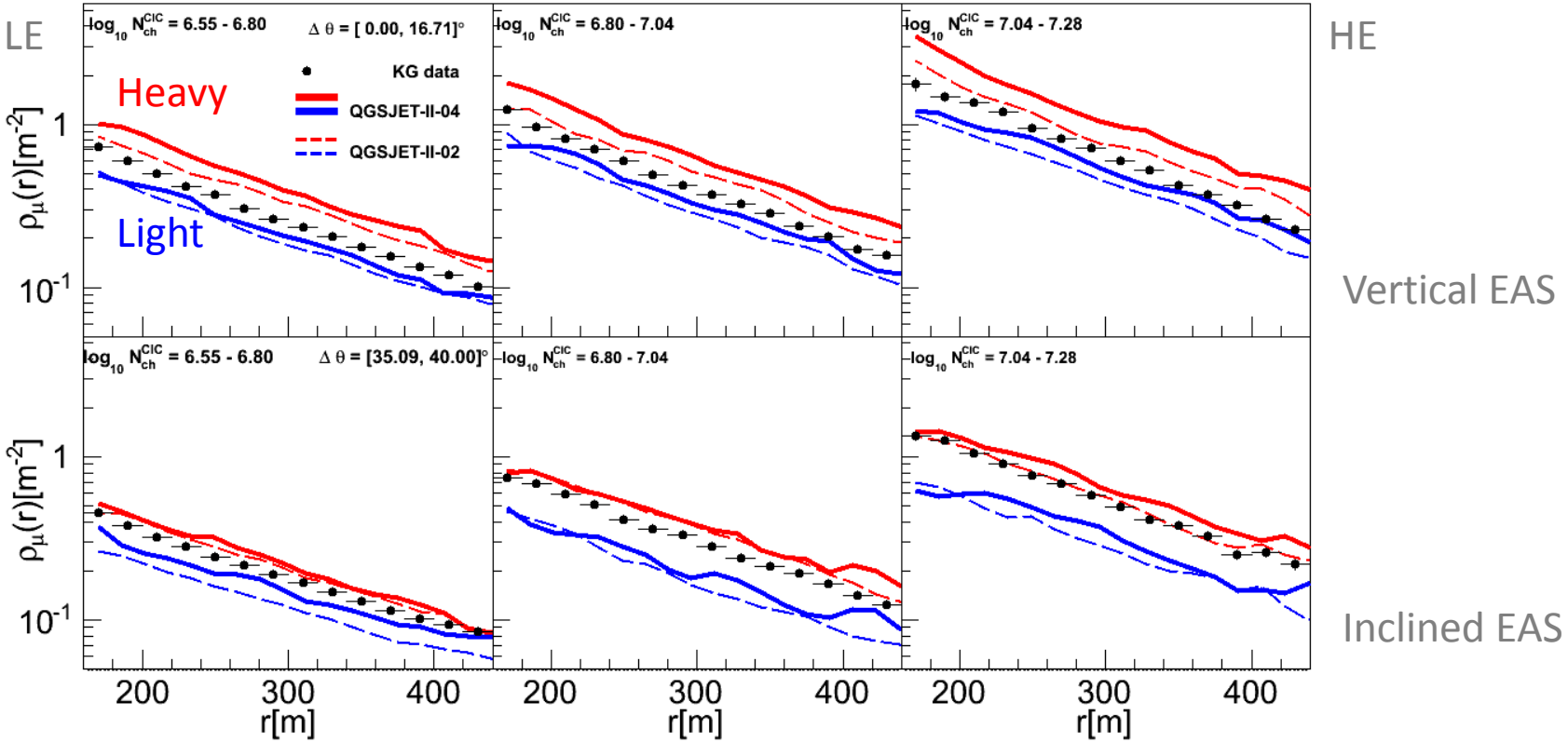
- Flat atmosphere in MC

- Atmosphere model

- Local variations of air pressure and temperature.

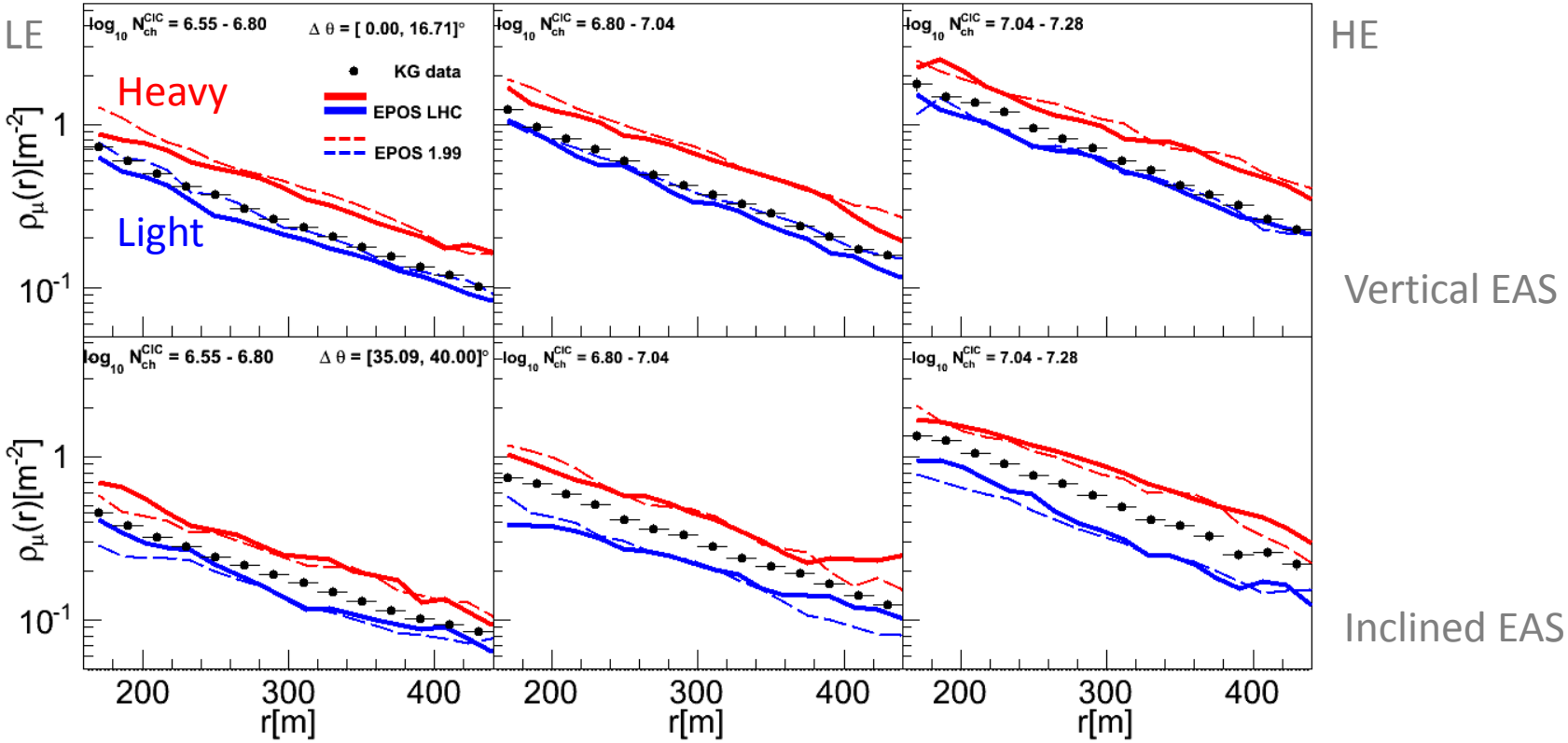
6) The results

Differences can be tracked down to the evolution of lateral muon densities in atmosphere



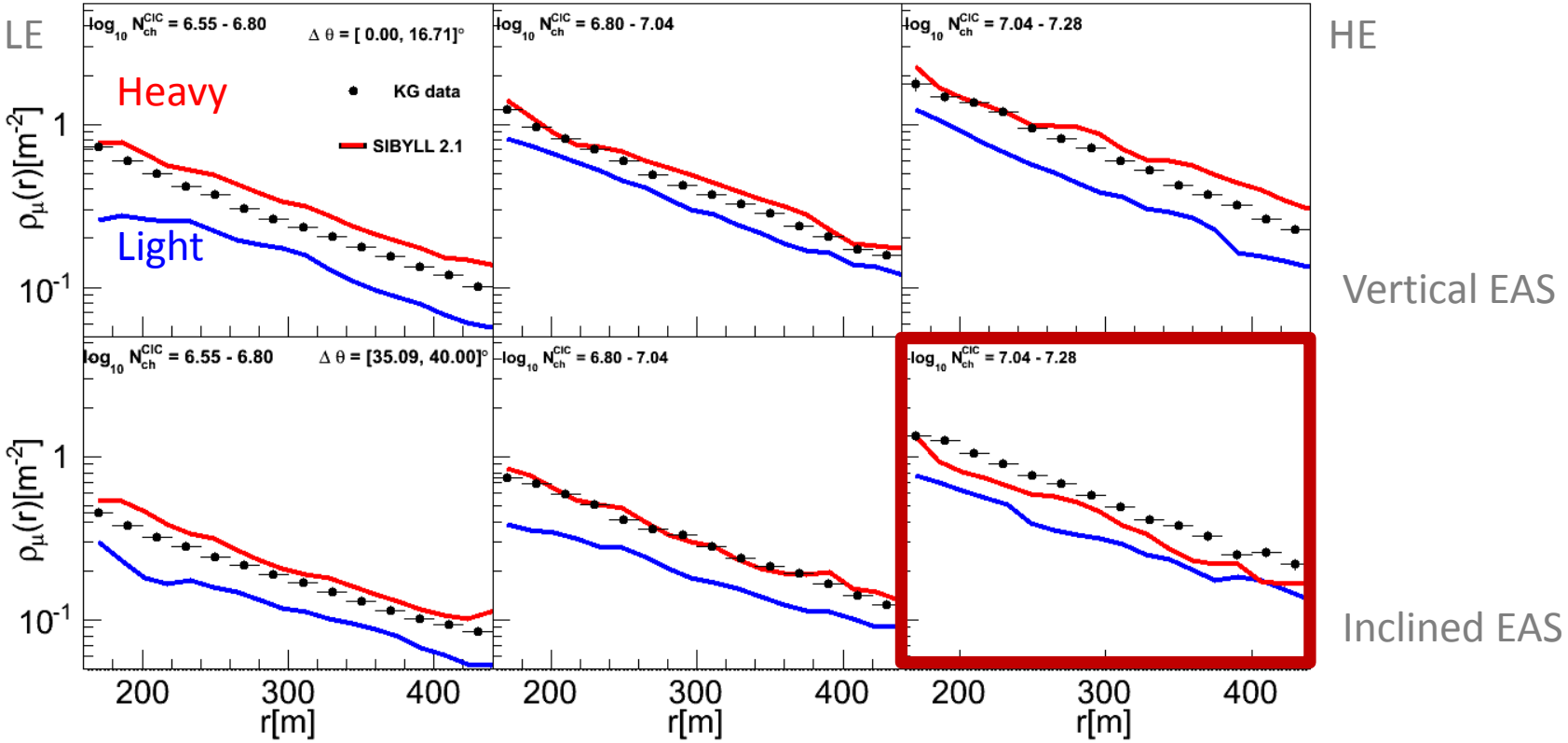
QGSJET-II-02 and QGSJET-II-04 predictions for Fe+Si/H+He bracket the measurements

6) The results



EPOS 1.99 and EPOS LHC predictions for Fe+Si/H+He also bracket KASCADE-Grande measurements

6) The results



SIBYLL 2.1 predictions for Fe+Si/H+He are **smaller than the measured data** at HE for inclined EAS

7) Conclusions

- The observed zenith angle evolution of the muon content in the atmosphere is not consistent with predictions from the models: QGSJETII-02, QGSJET-II-04, EPOS 1.99, EPOS LHC and SIBYLL 2.1.

- Statistical/Systematics errors do not explain the observed deviation.

- Deviations are tracked down to the different evolution of the muon density distributions of real data with the atmospheric depth.

- Measured EAS have more muons than the predictions of SIBYLL 2.1 for heavy/light nuclei at high energies and zenith angles.