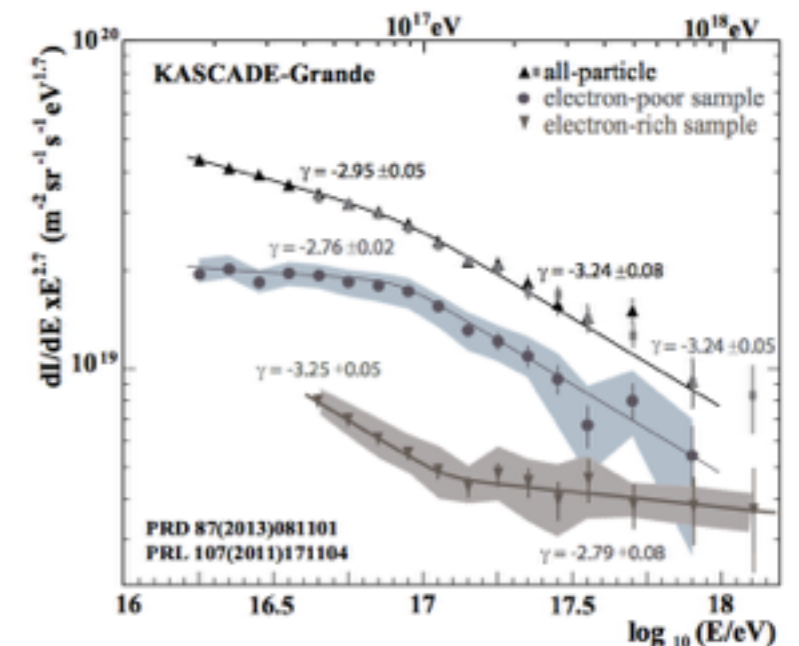# Muon density measurements for the light and heavy mass groups of cosmic rays at the KASCADE-Grande observatory

Juan Carlos Arteaga-Velázquez* for the KASCADE-Grande Collaboration

*Universidad Michoacana, México
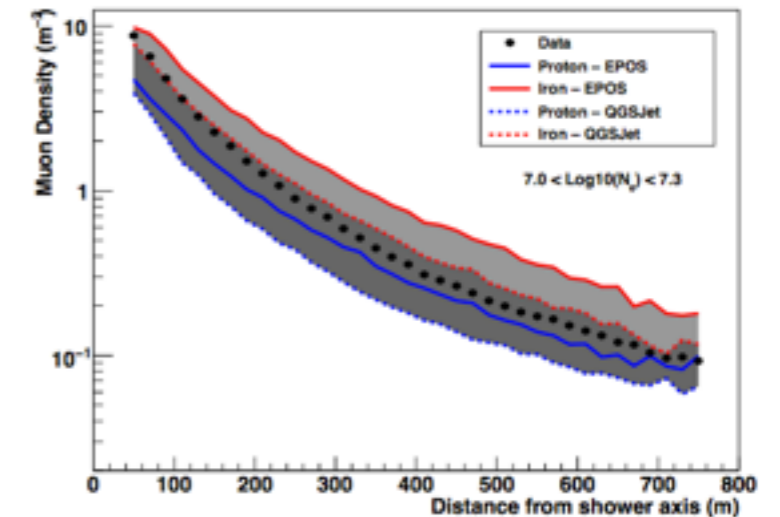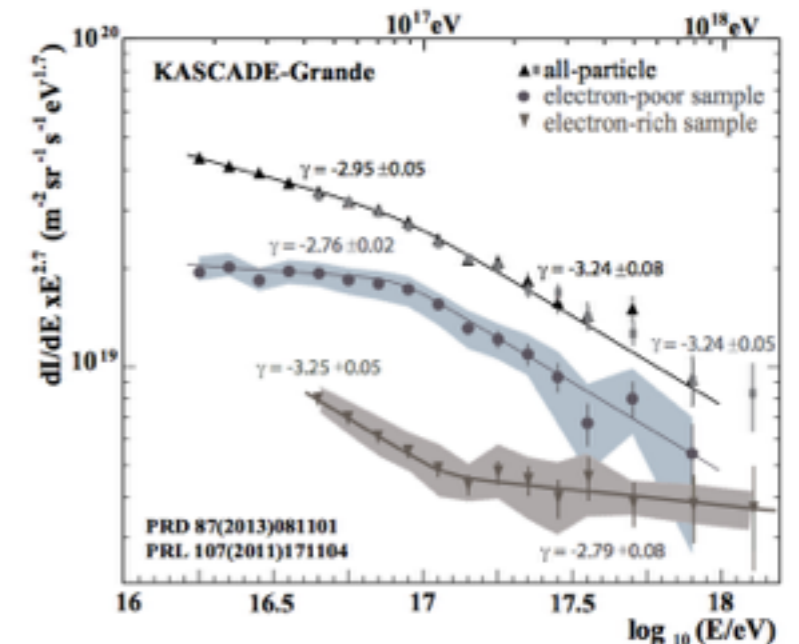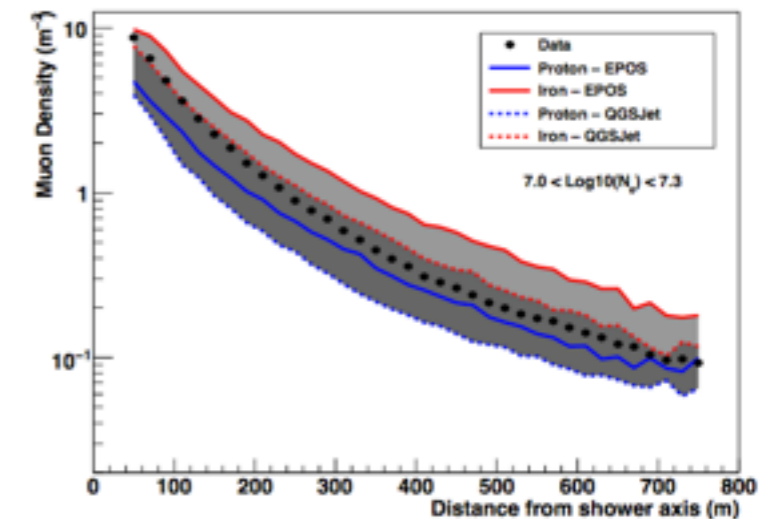
Muon density measurements for the light and heavy mass groups of cosmic rays at the KASCADE-Grande observatory

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Outline

1. Motivation

2. Objective

3. The KASCADE-Grande detector

4. Data & Simulations
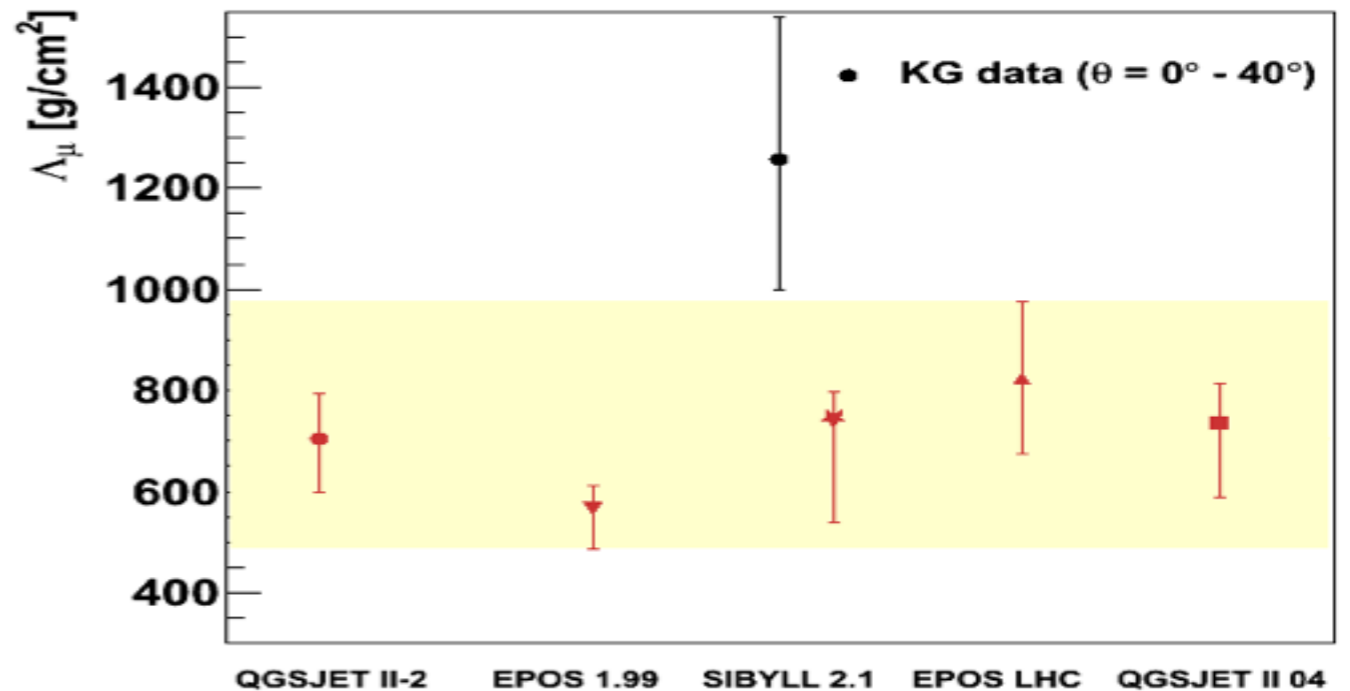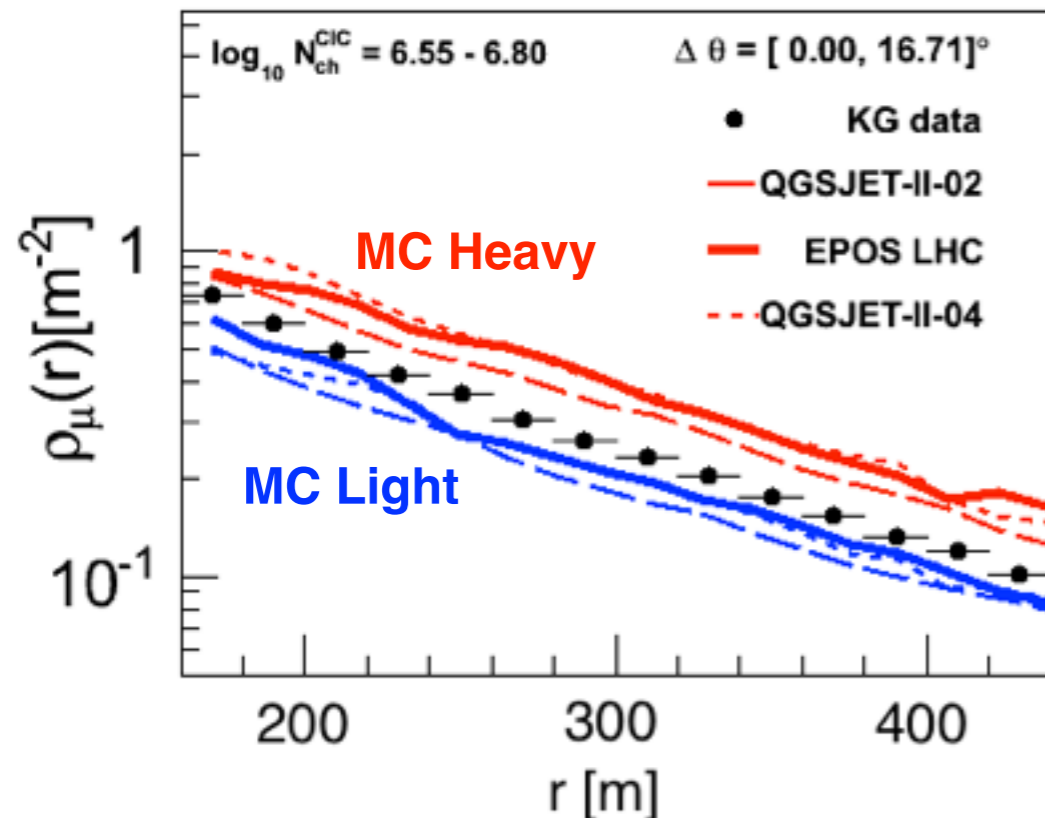
5. Analysis

6. Results

7. Summary

Motivation

KASCADE-Grande EAS muon data

The measured muon attenuation length ($E \sim 10^{16}$ - 10^{17} eV) deviates from MC predictions.

$$N_\mu = N_\mu{}^o \, e^{-(Xo \, Sec\theta / \Lambda\mu)}$$

(J.C. Arteaga, KASCADE-Grande Coll., ICRC2015)

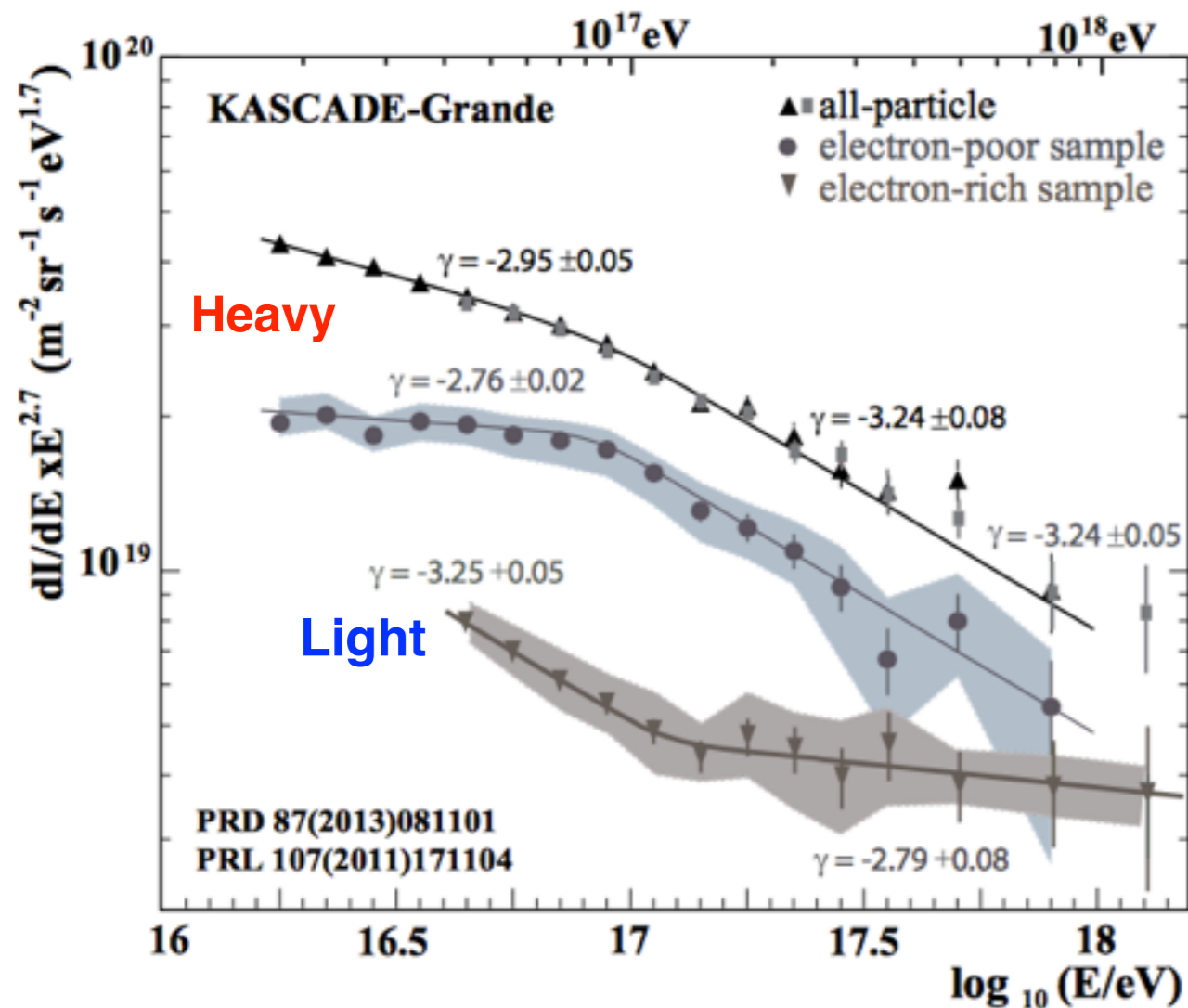Evolution of local muon densities in atmosphere is bracketed by model predictions (but by SIBYLL 2.1)

Muon E_{th} > 230 MeV x Secθ

Motivation

New questions arise

In KASCADE-Grande is possible to **separate EAS data** into a light/heavy mass group

Exploit N_{ch}-N_μ correlation

KASCADE-Grande

▲■ all-particle
● electron-poor sample
▼ electron-rich sample

Heavy

$\gamma = -2.95 \pm 0.05$

$\gamma = -2.76 \pm 0.02$

$\gamma = -3.24 \pm 0.08$

$\gamma = -3.24 \pm 0.05$

$\gamma = -3.25 + 0.05$

Light

PRD 87(2013)081101
PRL 107(2011)171104

$\gamma = -2.79 + 0.08$

1. Is the Λ_μ deviation also observed for the light and heavy mass groups?

2. Is the evolution of the mean muon densities in the atmosphere for both mass groups still contained by MC predictions?

3. For which mass group are the MC predictions in better agreement with the data?

Objectives

1. **Test post-LHC hadronic interaction models**

   -> Use zenith-angle evolution of the **local muon densities** of EAS for **light/heavy mass groups**.

2. To **provide new EAS results**, complementary to that from accelerators

   -> They **might help to improve** high-energy hadronic interaction **models**.
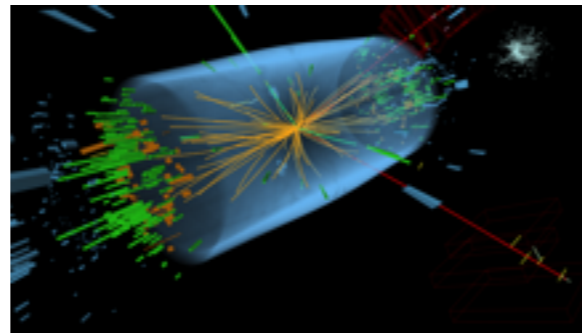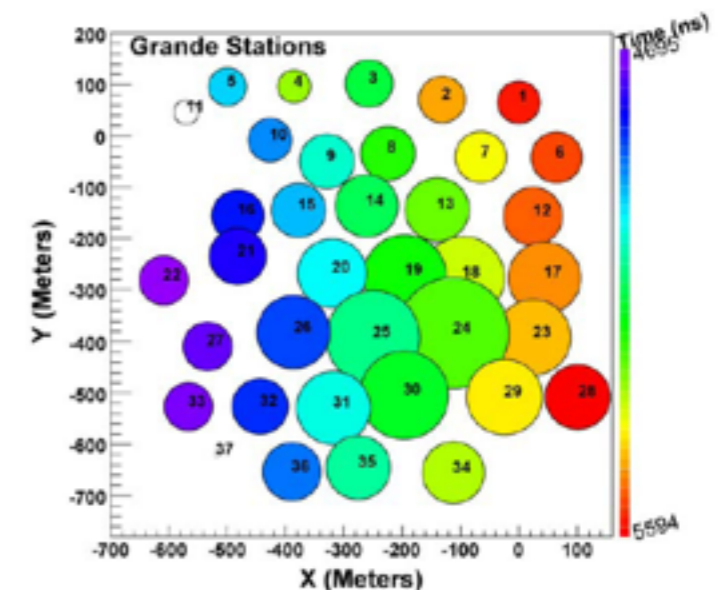

(CMS event, May 27, 2012, CMS Coll.)

(Grande event, July 8, 2005, KASCADE-Grande Coll.)

Muons: penetrating particles, direct data from hadronic interactions.

Proton @ 10^{15} eV, Corsika simulation, F. Schmidt & J. Knapp

The KASCADE-Grande detector
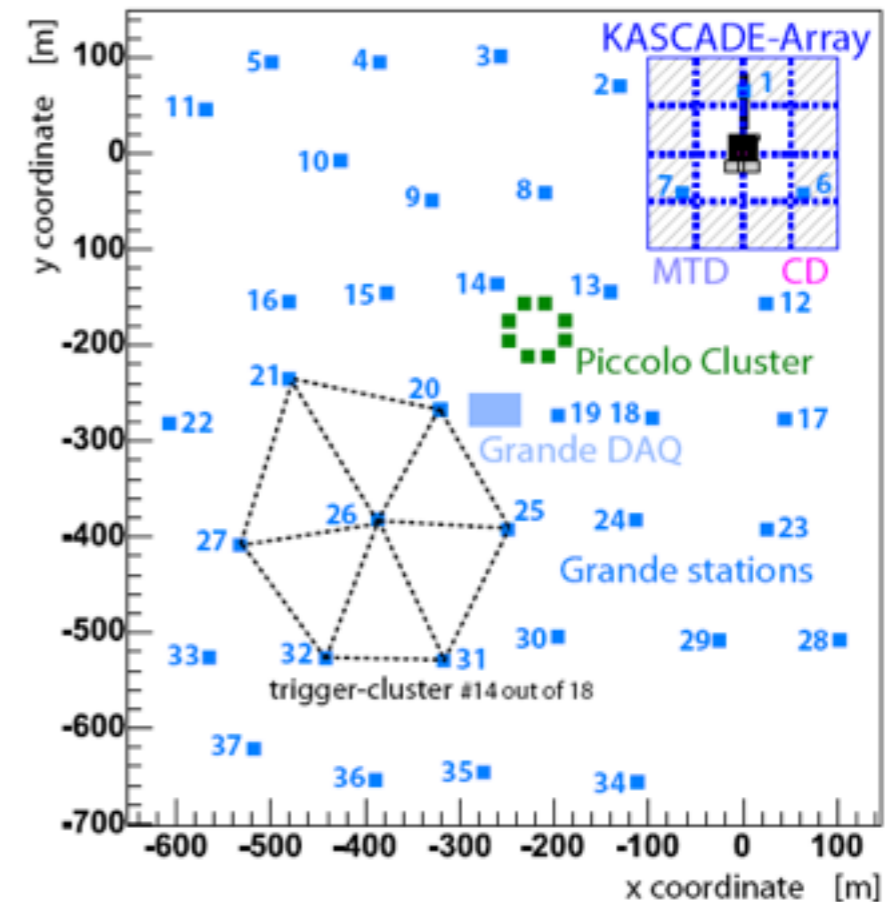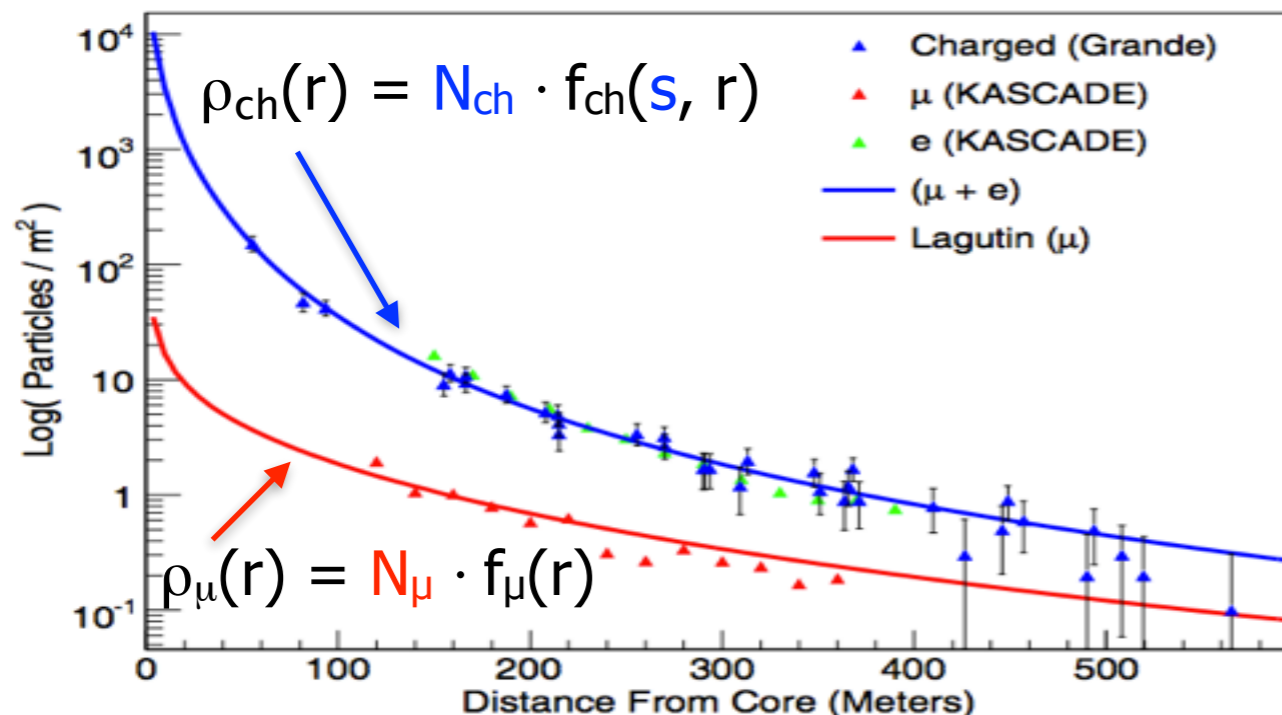
December 2003 - November 2012 $\qquad$ $E = 10^{15} - 10^{18}$ eV

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

2. KASCADE (200×200 m^2) + Grande (0.5 km^2)

3. They provide:

   N_{ch}: Number of charged particles
   N_e : Number of electrons
   N_μ : Number of muons

$$\rho_{ch}(r) = N_{ch} \cdot f_{ch}(s, r)$$

$$\rho_\mu(r) = N_\mu \cdot f_\mu(r)$$

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

The KASCADE experiment

The KASCADE experiment

Karlsruhe **S**hower **C**ore and **A**rray **De**tector

- Components:

    - Ground array with 252 e/γ and μ
      scintillator detectors
    - Central detector (Calorimeter, μ detectors)
    - Muon tracking detector
- Energy range:
    100 Tev - 1 PeV

Scintillator detectors

e.m.detector

- Electrons (> 5 MeV) and
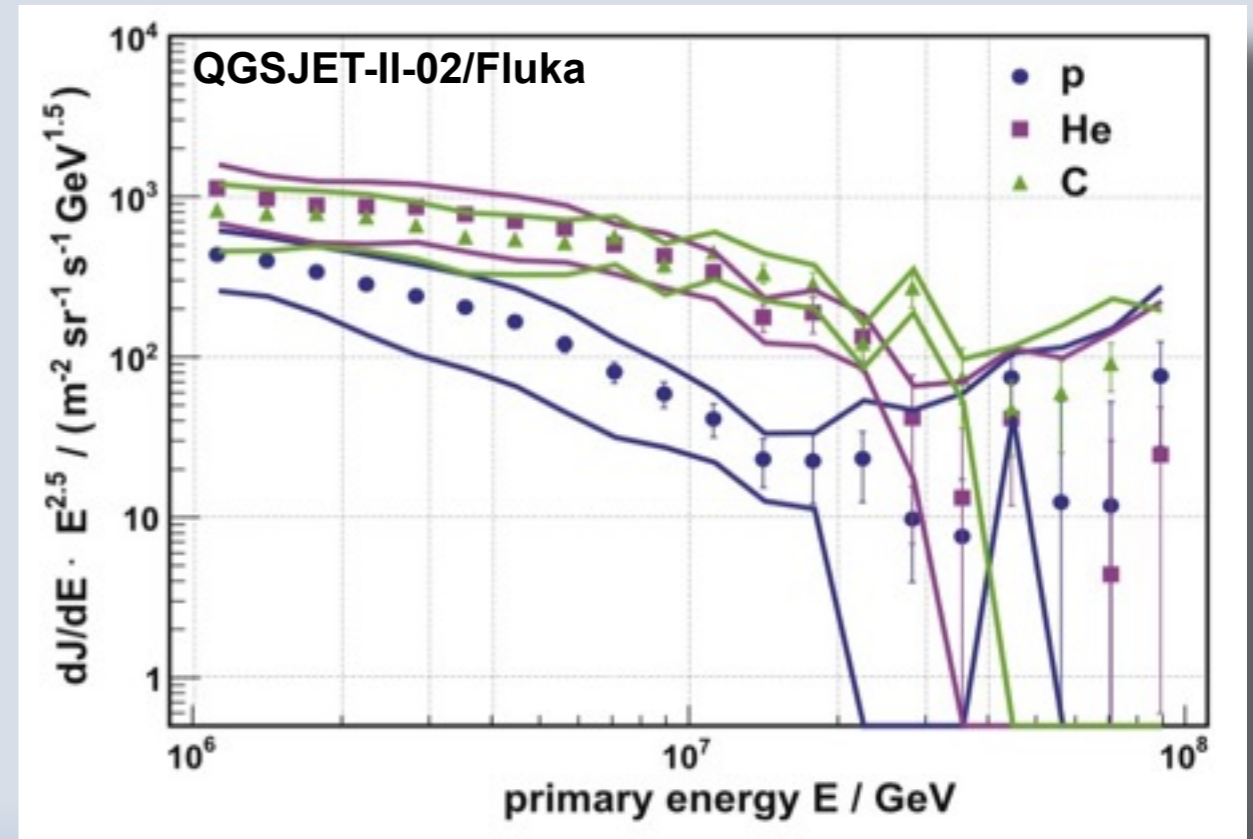 muons (> 230 MeV)

Pb/Fe shielding

μ detector

T. Antoni, et al., NIMA 513
(2003) 490

The KASCADE experiment

Unfolding of spectra of elemental mass groups

Knee at 1 PeV in the all-particle cosmic ray spectrum is caused by a break in the flux of the light components

QGSJET-II-02/Fluka

KG Collab., Astrop. Phys. 47 (2013)
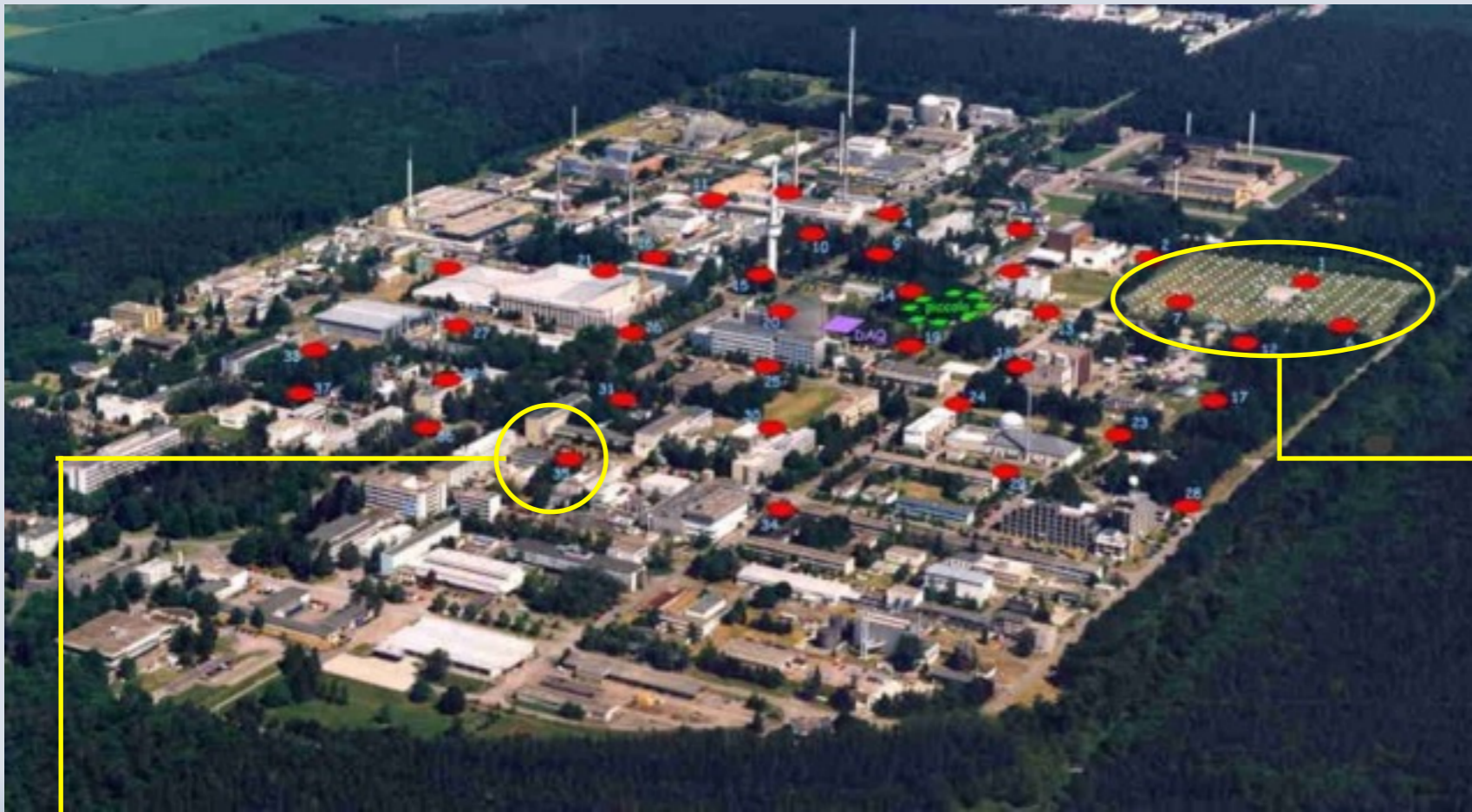
The KASCADE-Grande detector

Grande array

KASCADE array
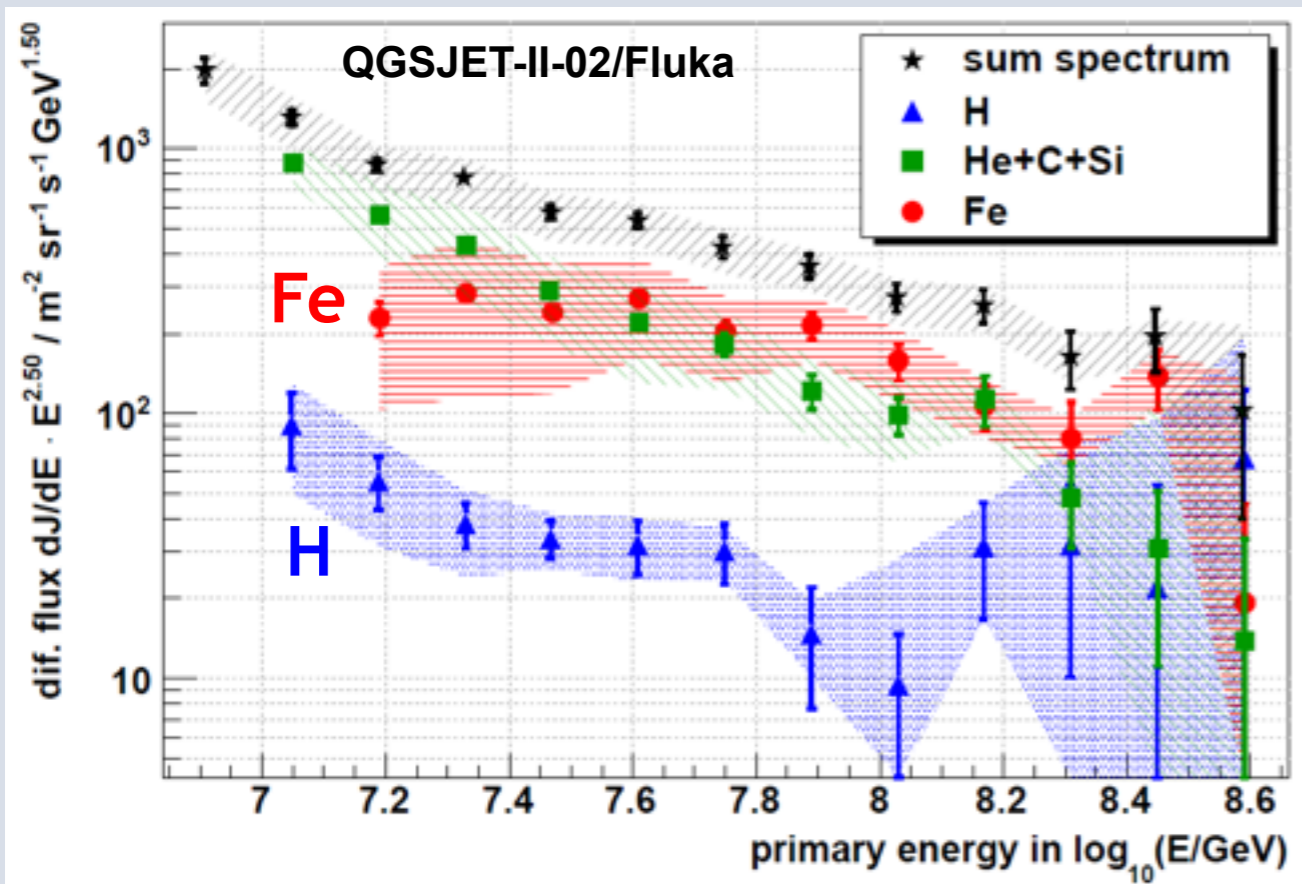
The KASCADE-Grande detector

Grande array

Grande

- Components:
  - Ground array with 37 scintillator detectors
  - Piccolo array
  - KASCADE & LOPES arrays
- Energy range:
  1 Pev - 1 EeV

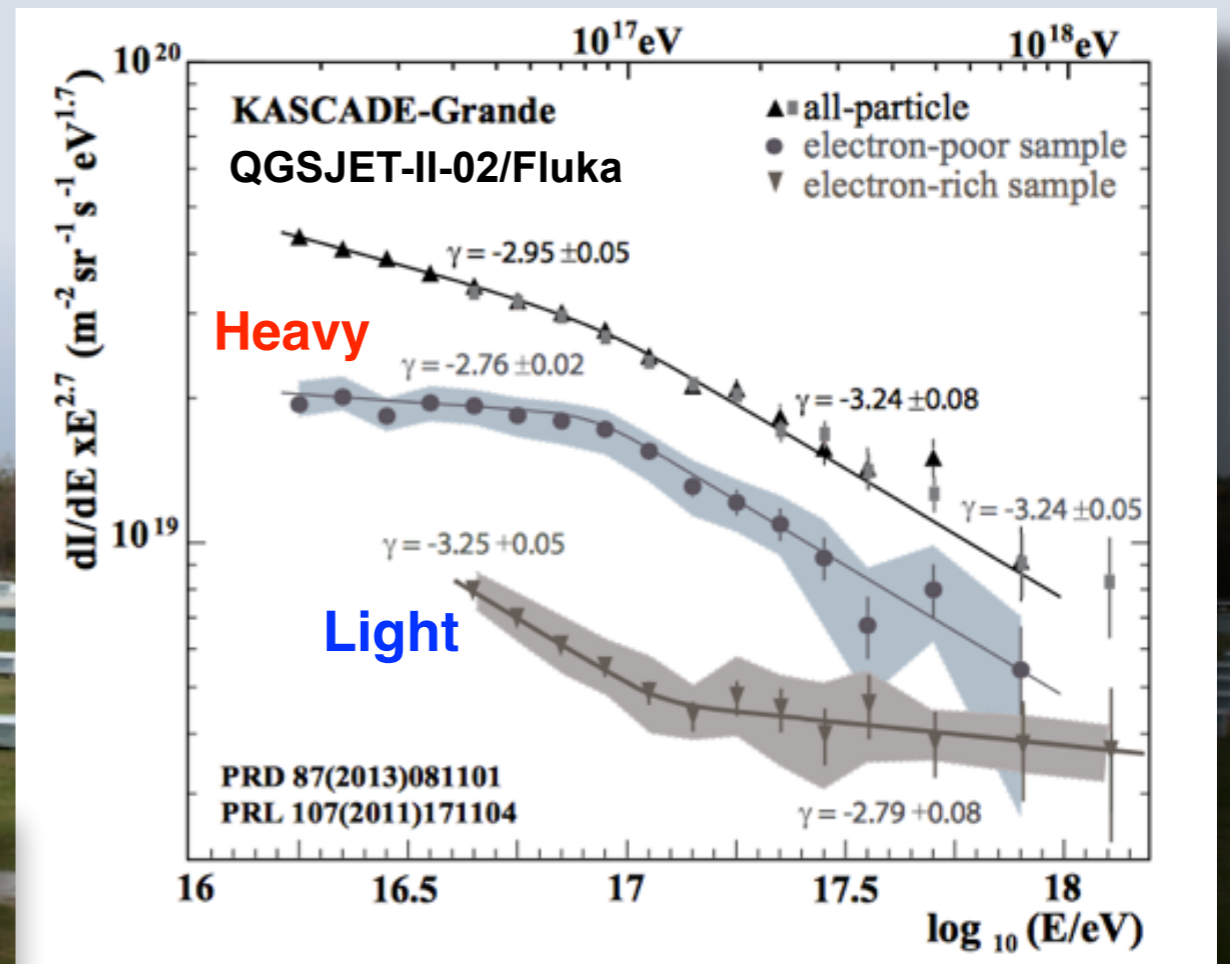Scintillator detectors

KASCADE array

W.D. Apel et al., NIMA 620 (2010) 490

- Charged particles (> 3 MeV)

The KASCADE-Grande detector

QGSJET-II-02/Fluka

Legend:
- ★ sum spectrum
- ▲ H
- ■ He+C+Si
- ● Fe

Fe

H

KG Collab., Astrop. Phys. 47 (2013)

Iron knee at 80 PeV

KASCADE-Grande
QGSJET-II-02/Fluka

- ▲■ all-particle
- ● electron-poor sample
- ▼ electron-rich sample

Heavy

$\gamma = -2.95 \pm 0.05$

$\gamma = -2.76 \pm 0.02$

$\gamma = -3.24 \pm 0.08$

$\gamma = -3.24 \pm 0.05$

$\gamma = -3.25 + 0.05$

Light

PRD 87(2013)081101
PRL 107(2011)171104

$\gamma = -2.79 + 0.08$

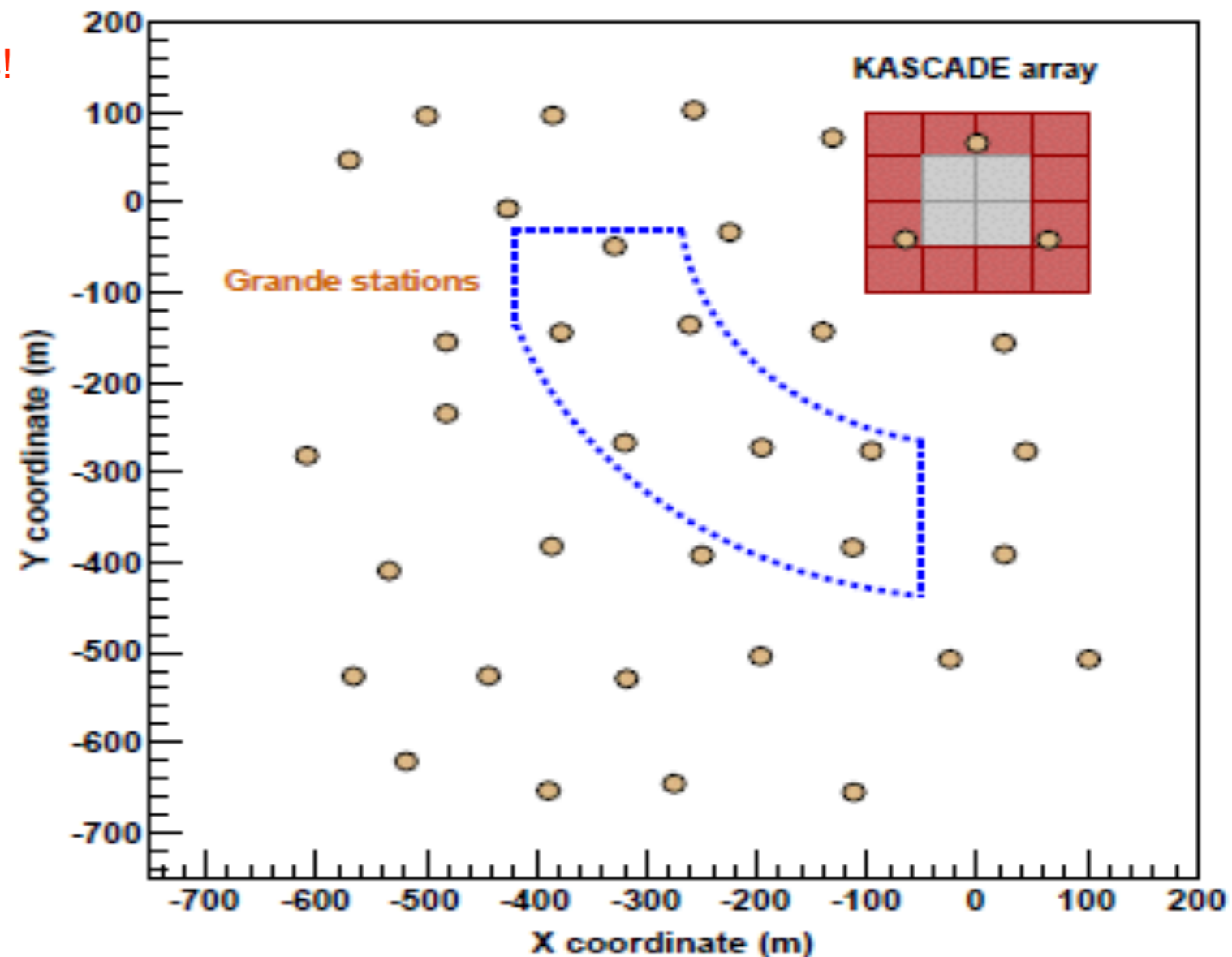Ankle-like feature at 120 PeV
in the light component

Data & simulations

Experimental data

1. Effective time: 1821 days   Full statistics!
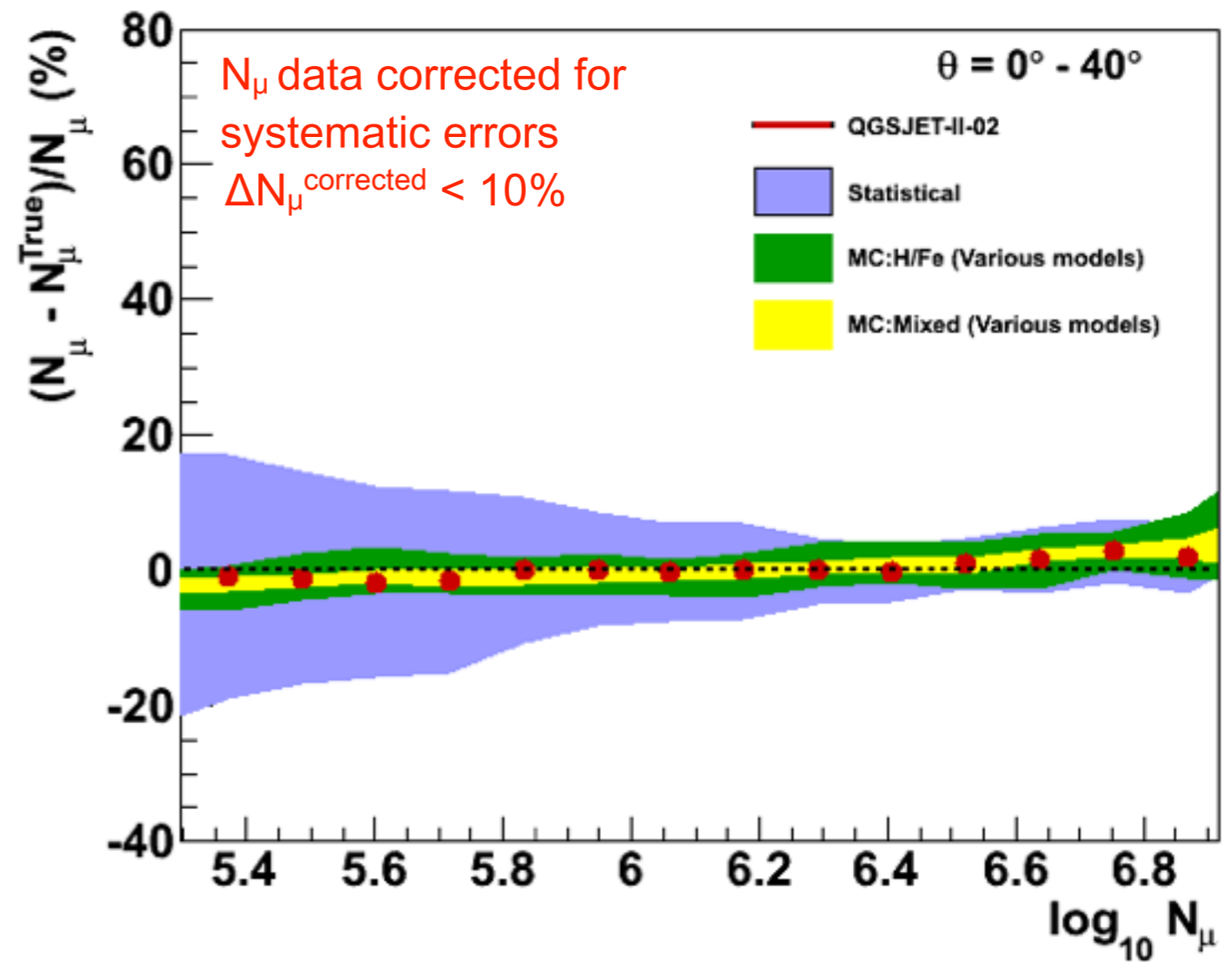
2. Exposure: 3.3×10^{12} m^2 s sr

3. Cuts:
   - Central area
   - $\theta < 40º$
   - Instrumental & reconstruction cuts
   - Optimized for **E = [10^{16}, 10^{17}] eV**
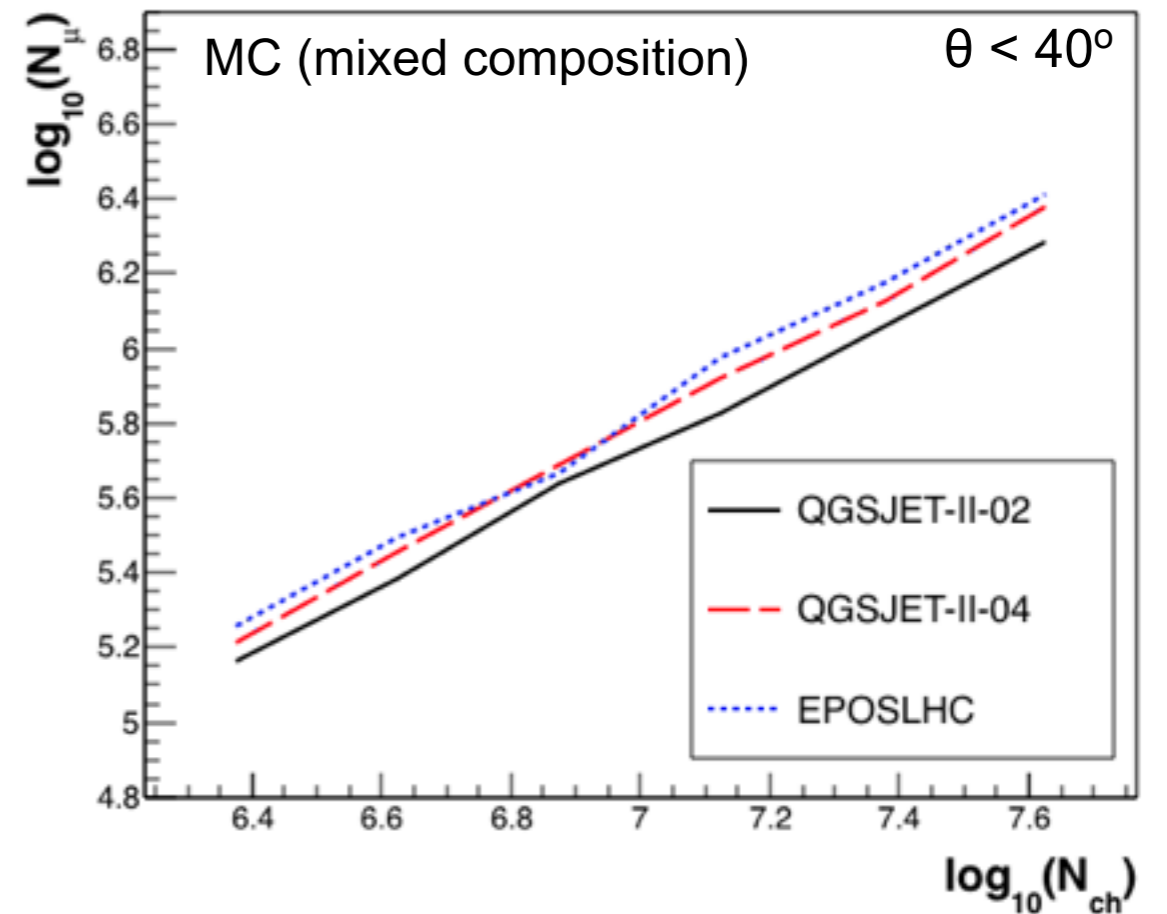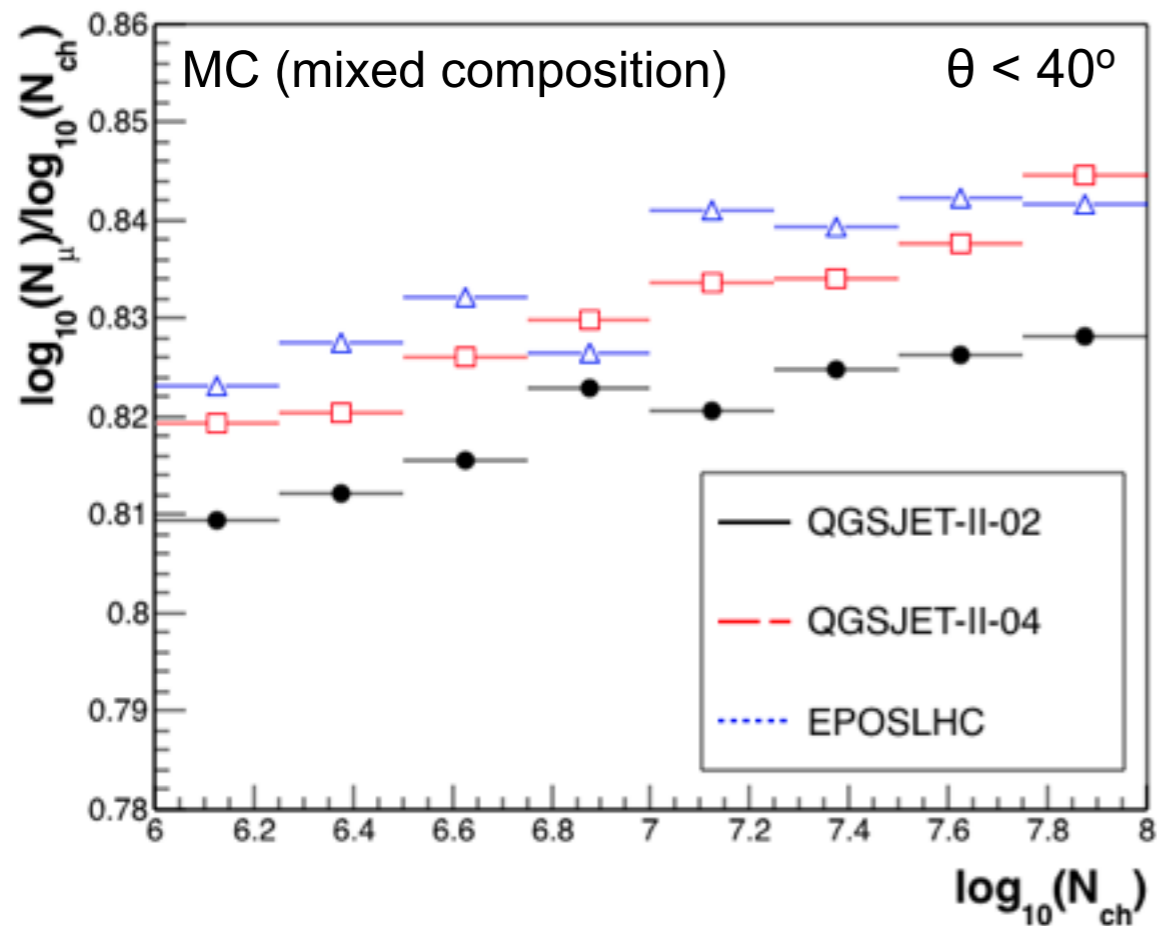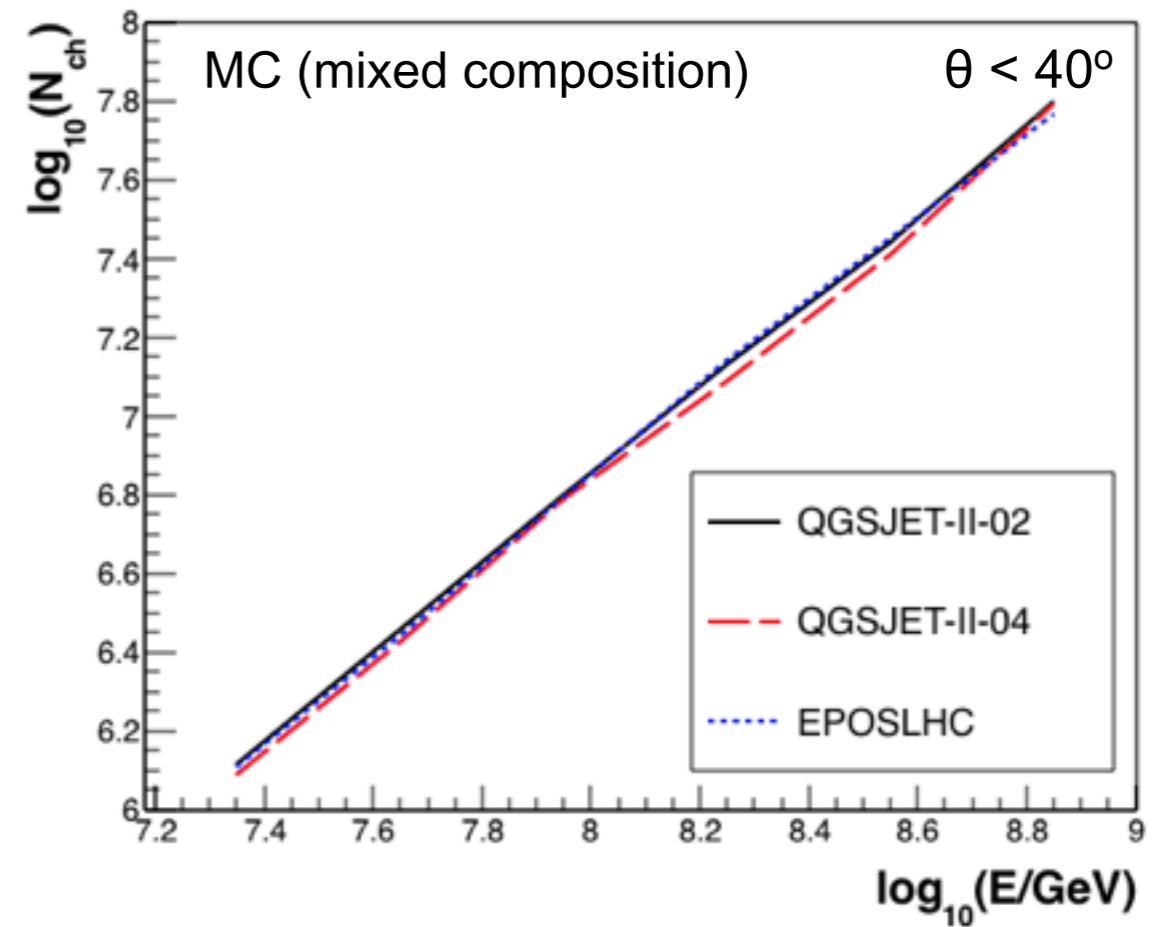
Data & simulations

MC data (CORSIKA/Fluka)

1. HE Models: QGSJET-II-02
   QGSJET-II-04
   EPOS-LHC

2. Simulation: H, He, C, Si, Fe, mixed;
   $\gamma = -3$

3. Systematics:
   - $\Delta N_{ch} < 12\%$ $\Delta N_\mu < 20\%$
   - $\Delta\theta < 0.6°$
   - $\sigma_{core} < 10$ m

Data & simulations

MC data (CORSIKA/Fluka)

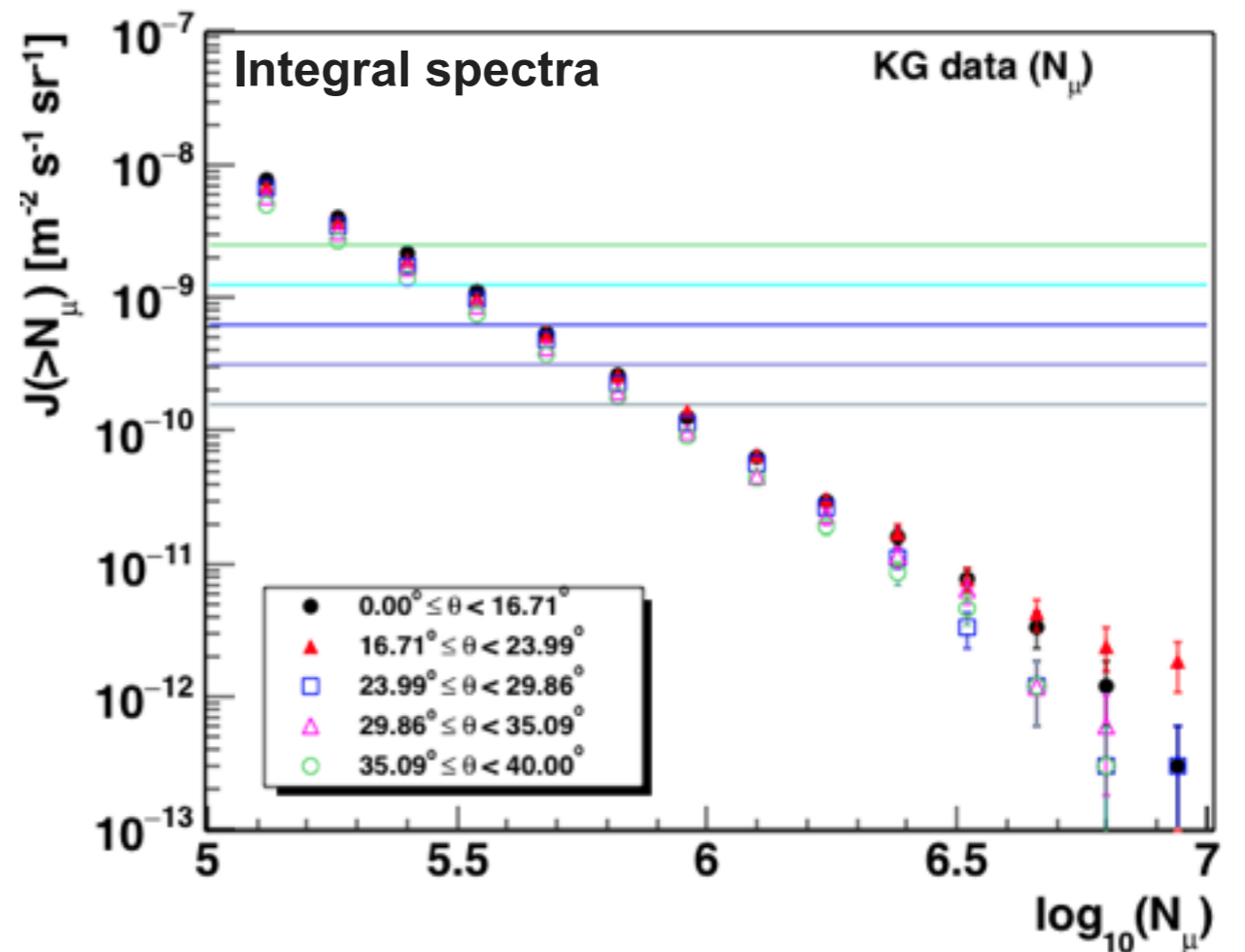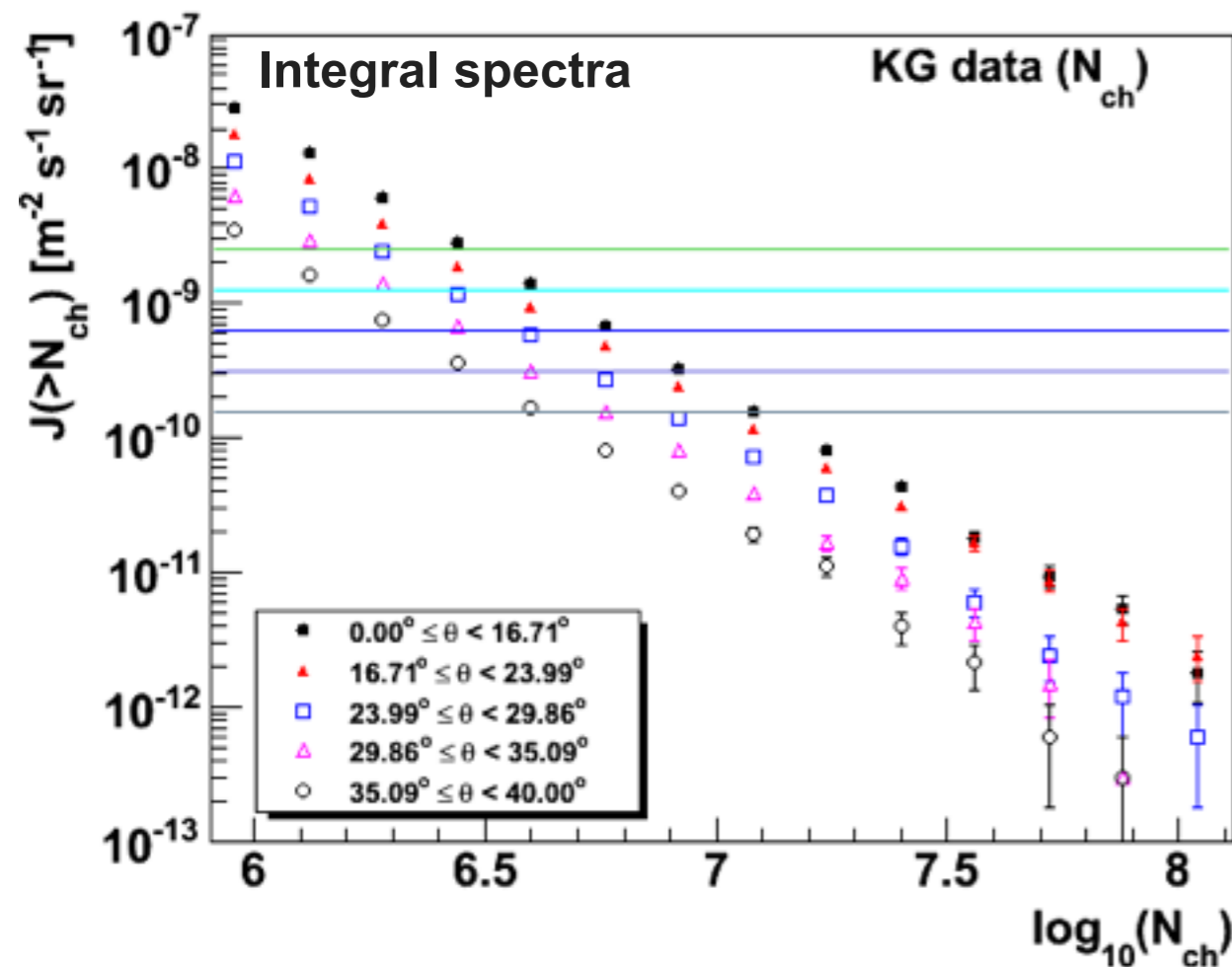1. HE Models: QGSJET-II-02
   QGSJET-II-04
   EPOS-LHC

The Analysis

1. EAS observables: θ, N_{ch}, N_μ, ρ_μ

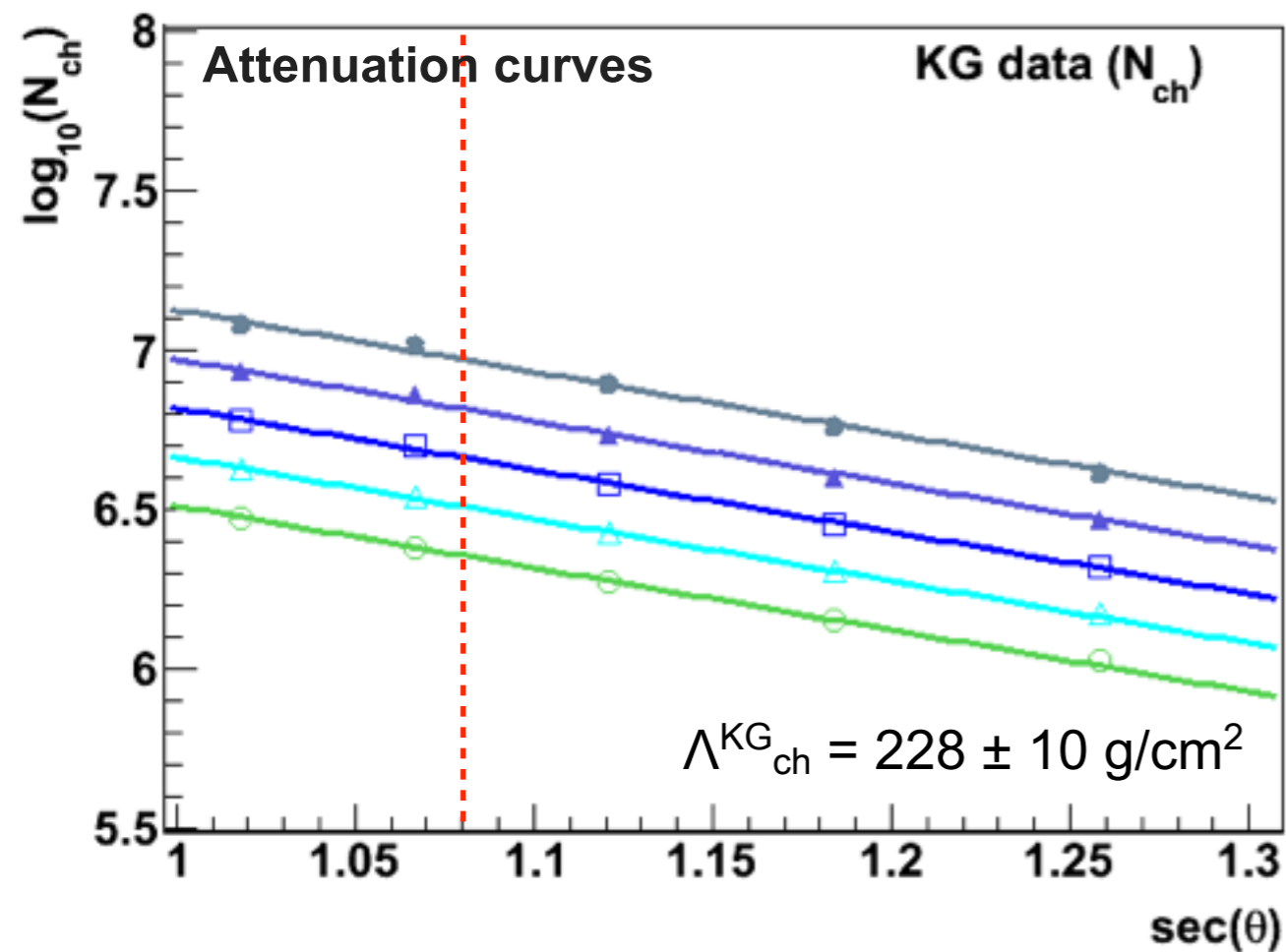**2. Correct N_{ch} and N_μ for atmospheric attenuation:** Use Constant Intensity Cut method for each data sample
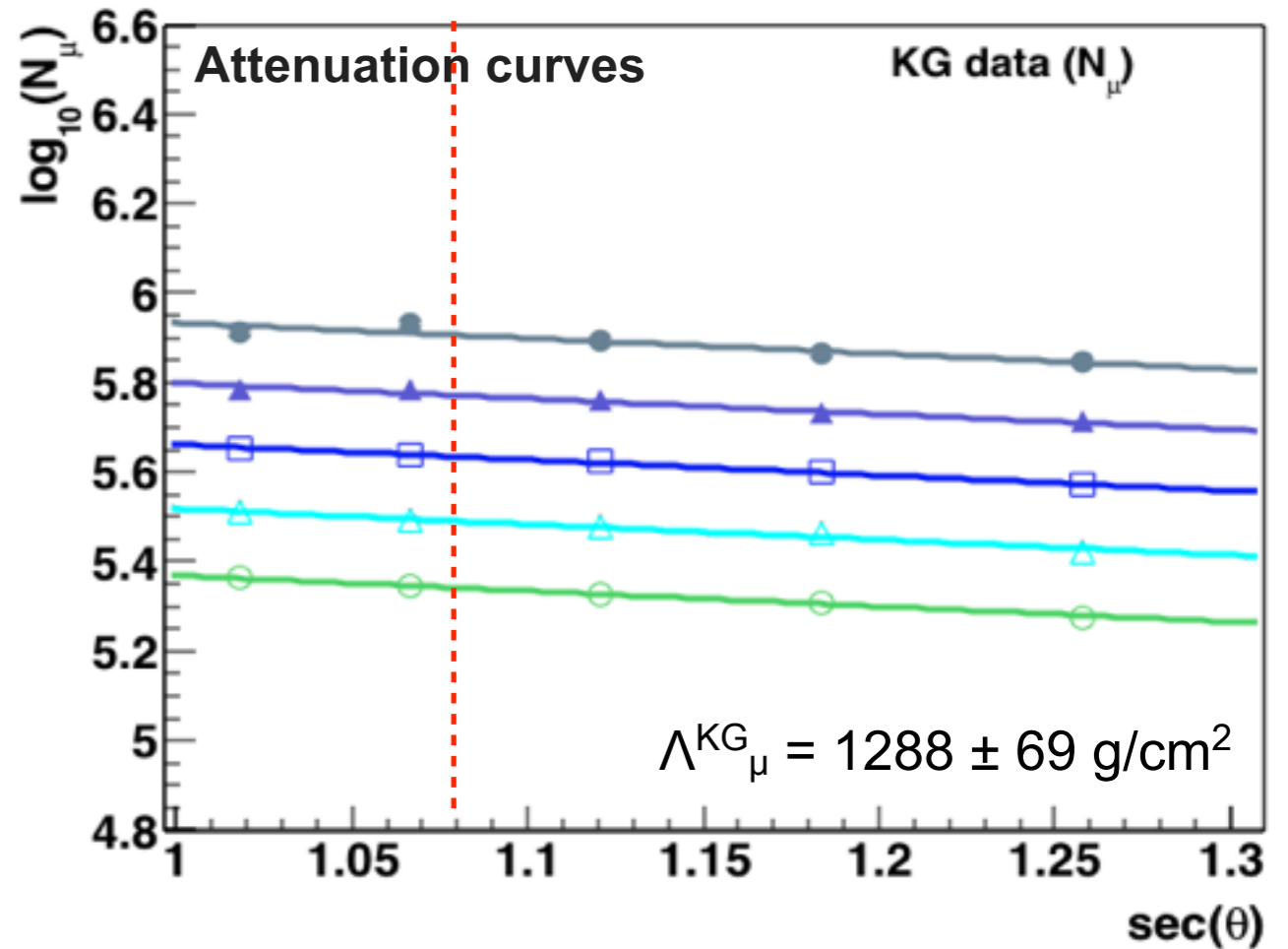

Five θ intervals with equal exposure.

The Analysis

Correct for attenuation effects in atmosphere

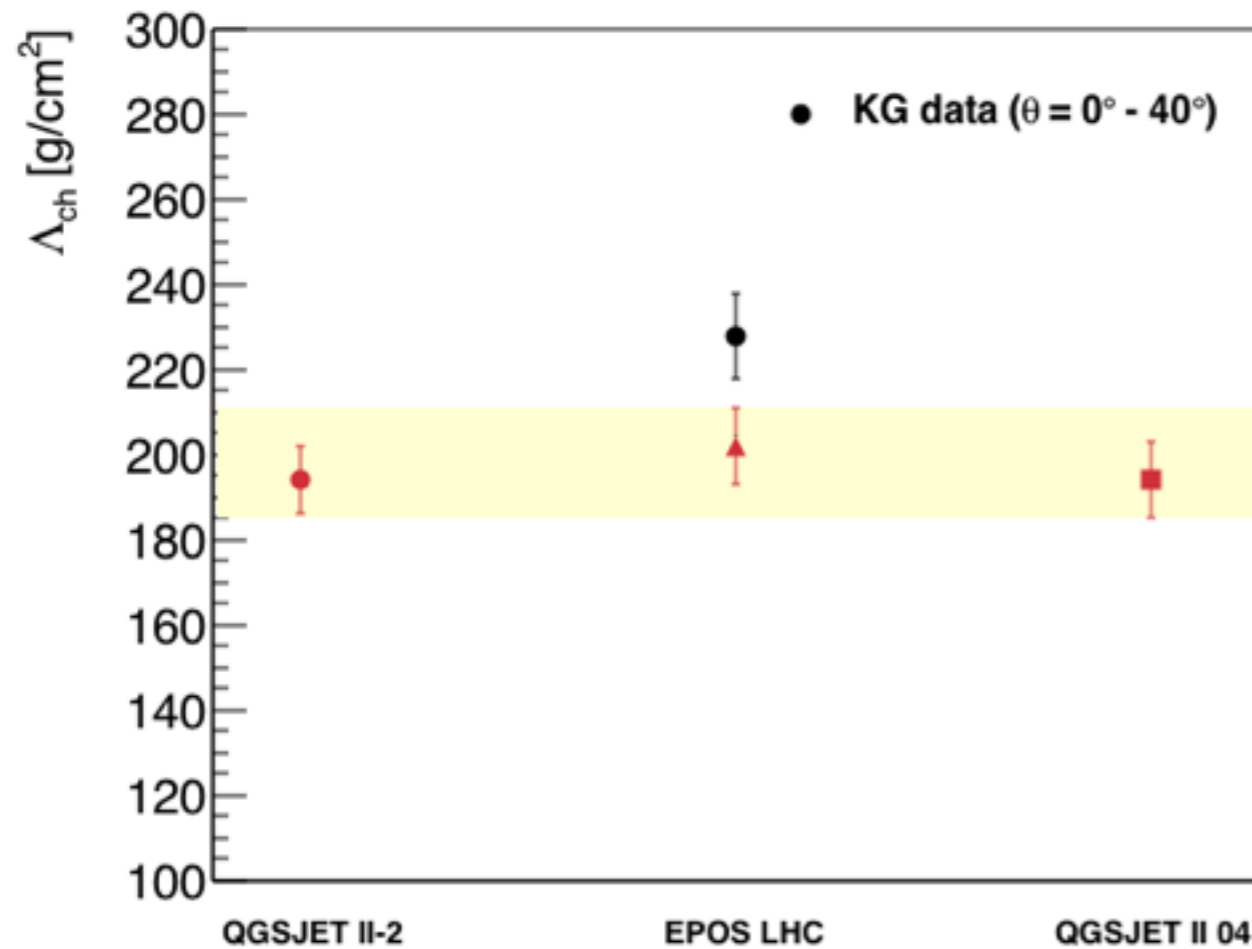$$N_{ch} = N_{ch}^{o} \, e^{-(X_o \, Sec\theta / \Lambda_{ch})}$$

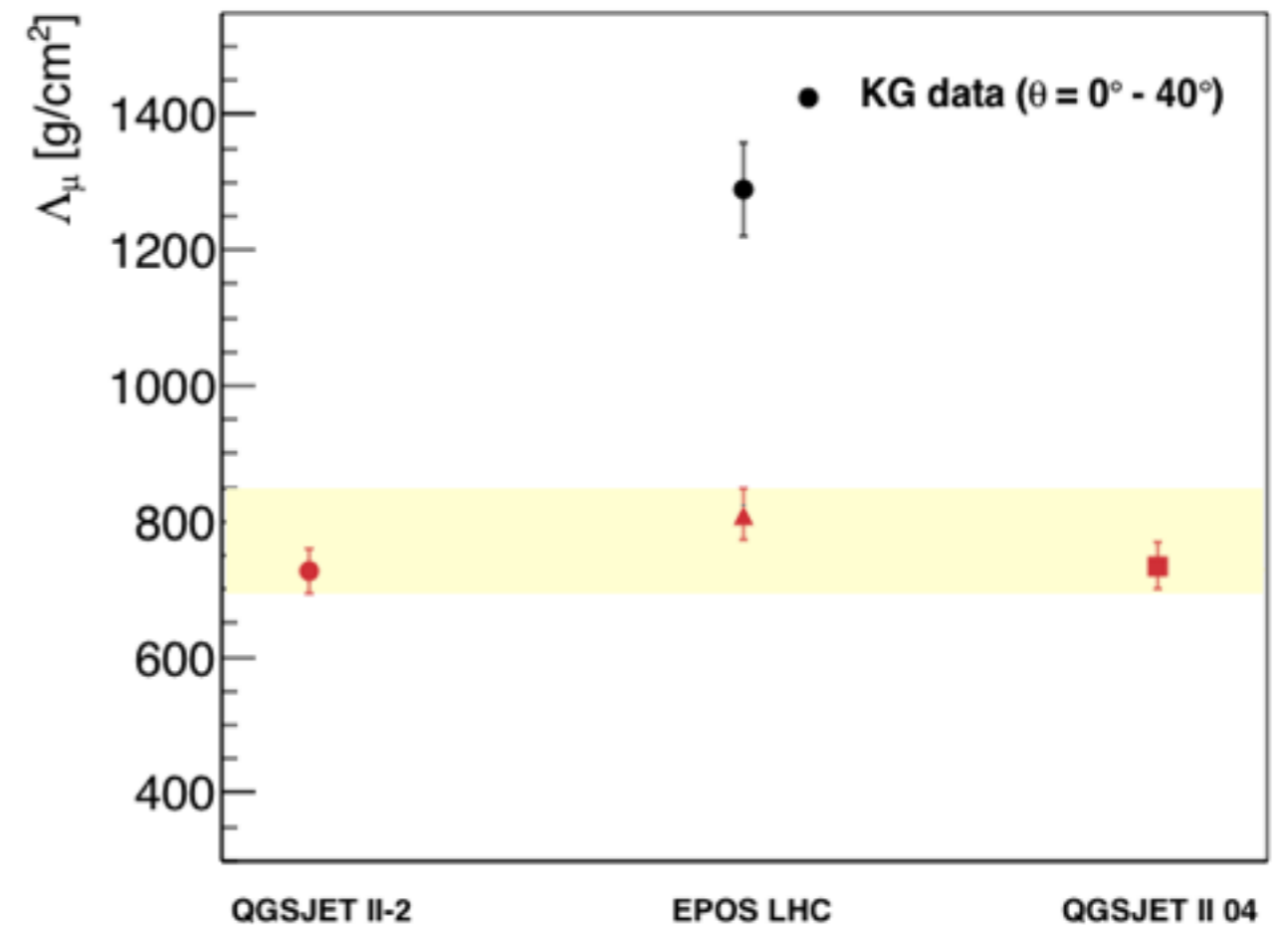$$N_{\mu} = N_{\mu}^{o} \, e^{-(X_o \, Sec\theta / \Lambda_{\mu})}$$

Shower sizes corrected event-by-event -> find values @ $\theta^{CIC}_{ref} = 22^o$

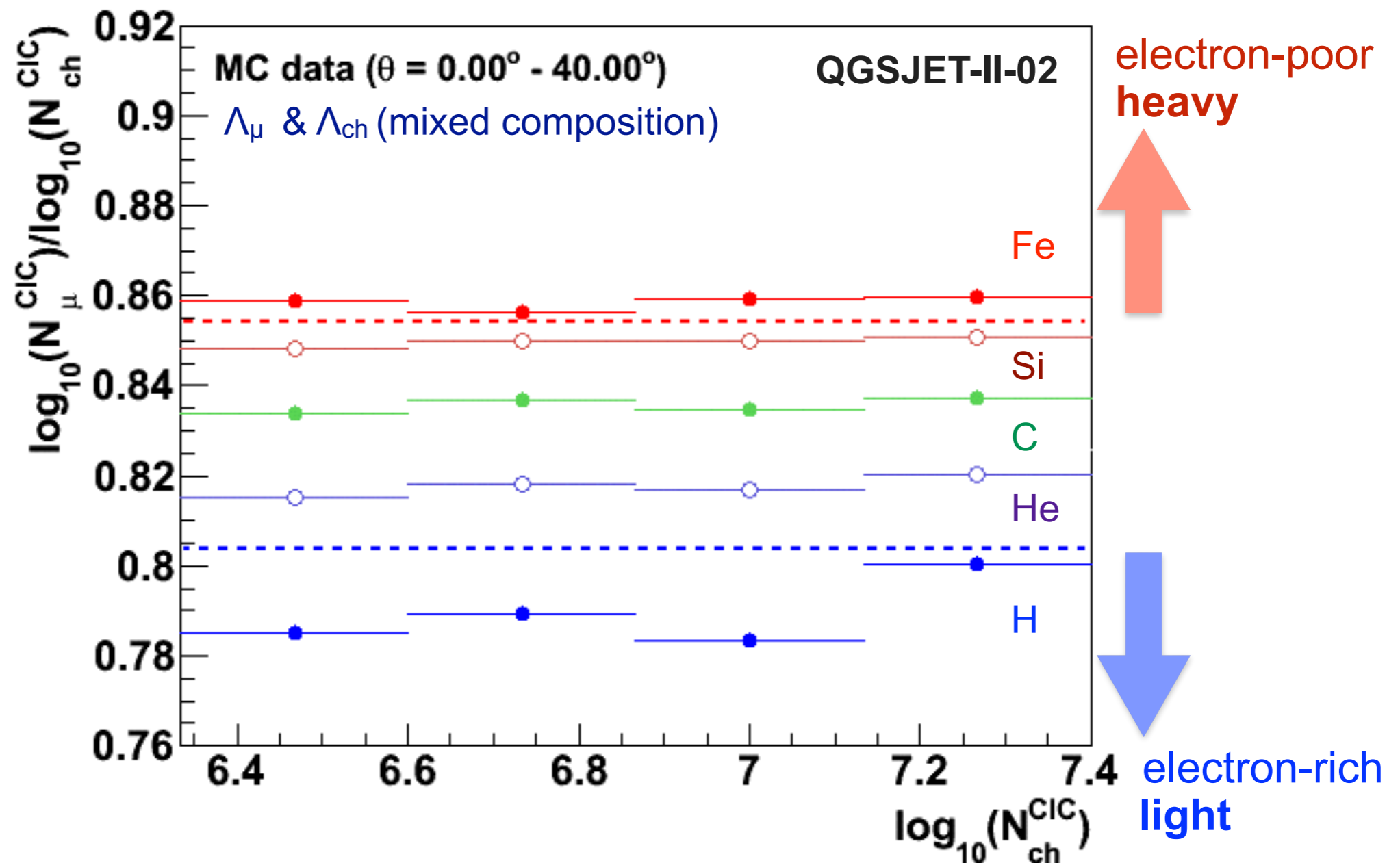# The Analysis

Attenuation lengths

MC (mixed composition)

MC (mixed composition)

* Only statistical errors are considered

The Analysis
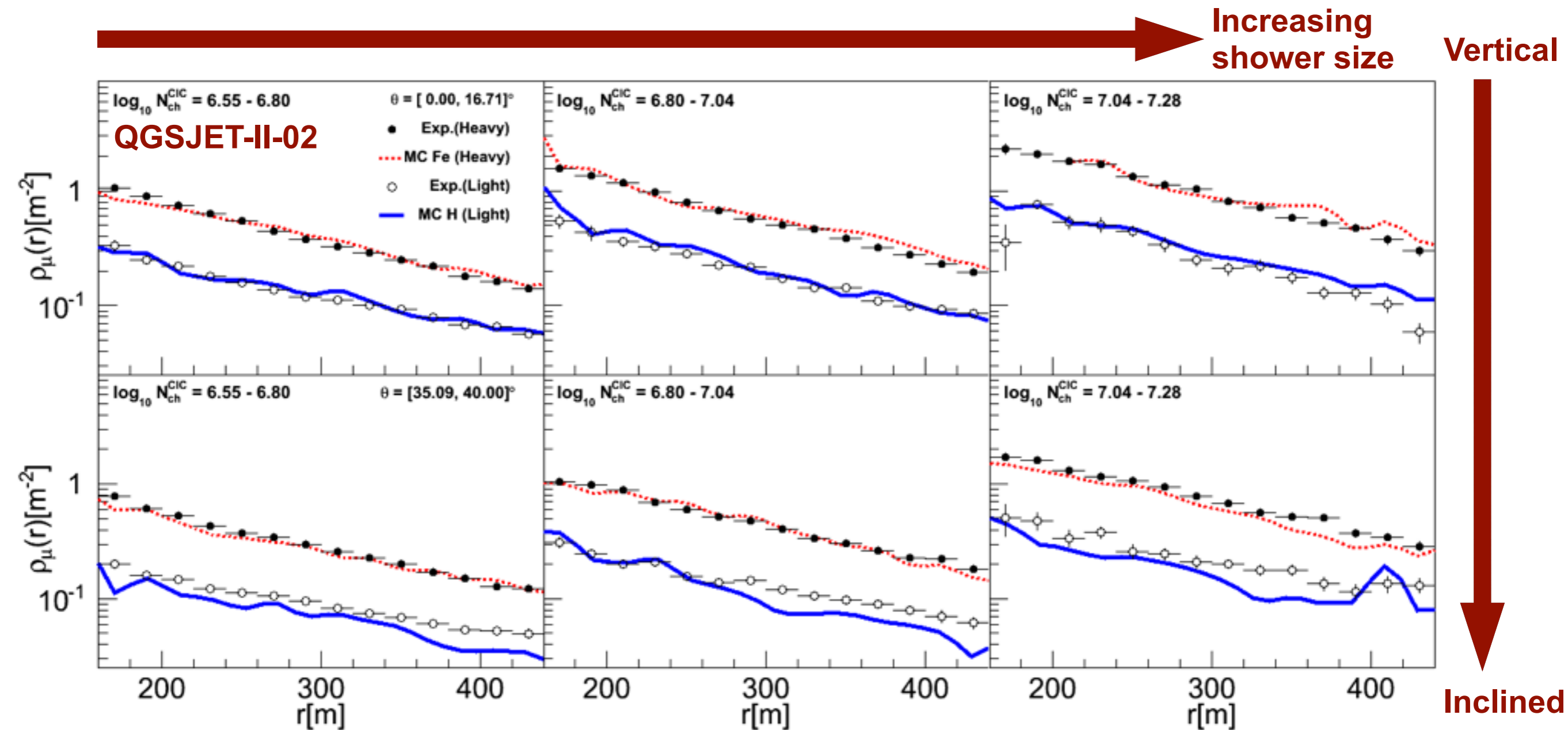
3. Separation of data in electron-poor and electron-rich samples: Exploit N_{ch}-N_μ correlation.

Cuts are derived for
each model separately

Results

4. Compare $\rho_\mu(r)$ **data for each mass group with MC:** Different zenith and N_{ch} intervals
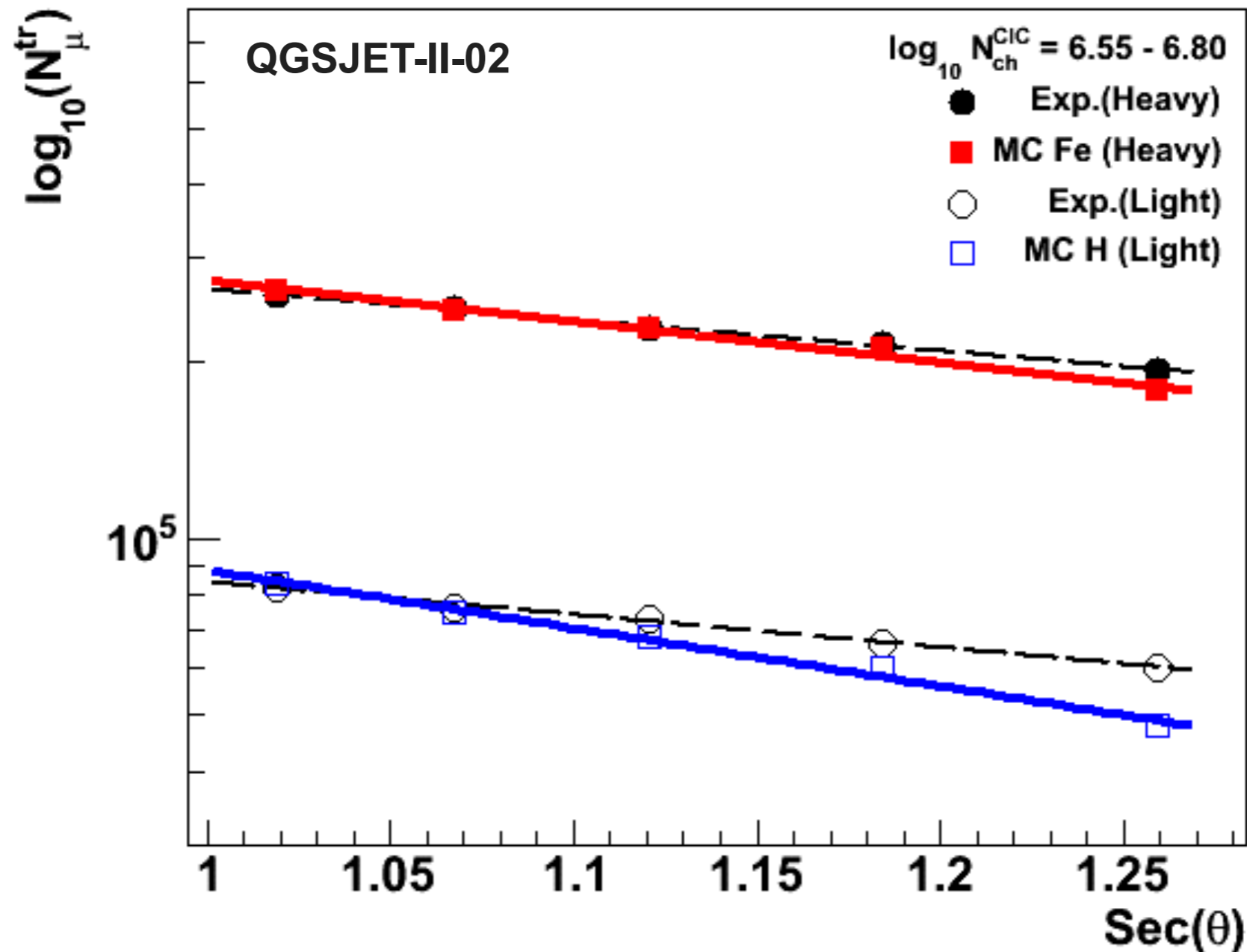
Increasing shower size

Vertical

QGSJET-II-02

QGSJET-II-02 do not bracket all the measured local muon densities for the heavy and light mass groups along CIC curves

Inclined

5. Calculate mean truncated N_μ (r = 200 - 400 m) from LDF **& study attenuation**

$N^{tr}_\mu = N_\mu^{tr,o}\, e^{-(Xo\, Sec\theta/\Lambda\mu)}$
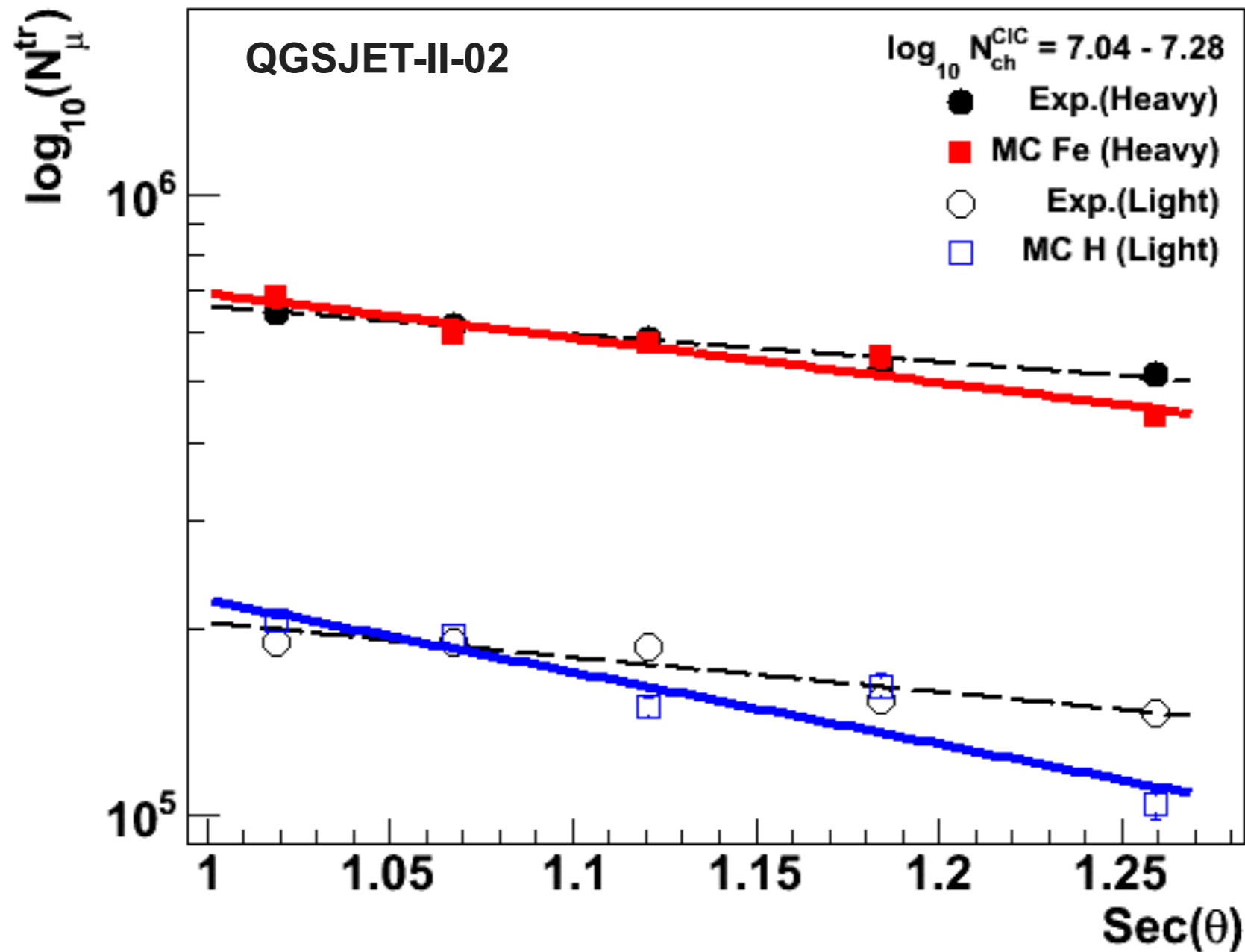
- Dependence with zenith angle
- For the same N_{ch}^{CIC} interval

Results

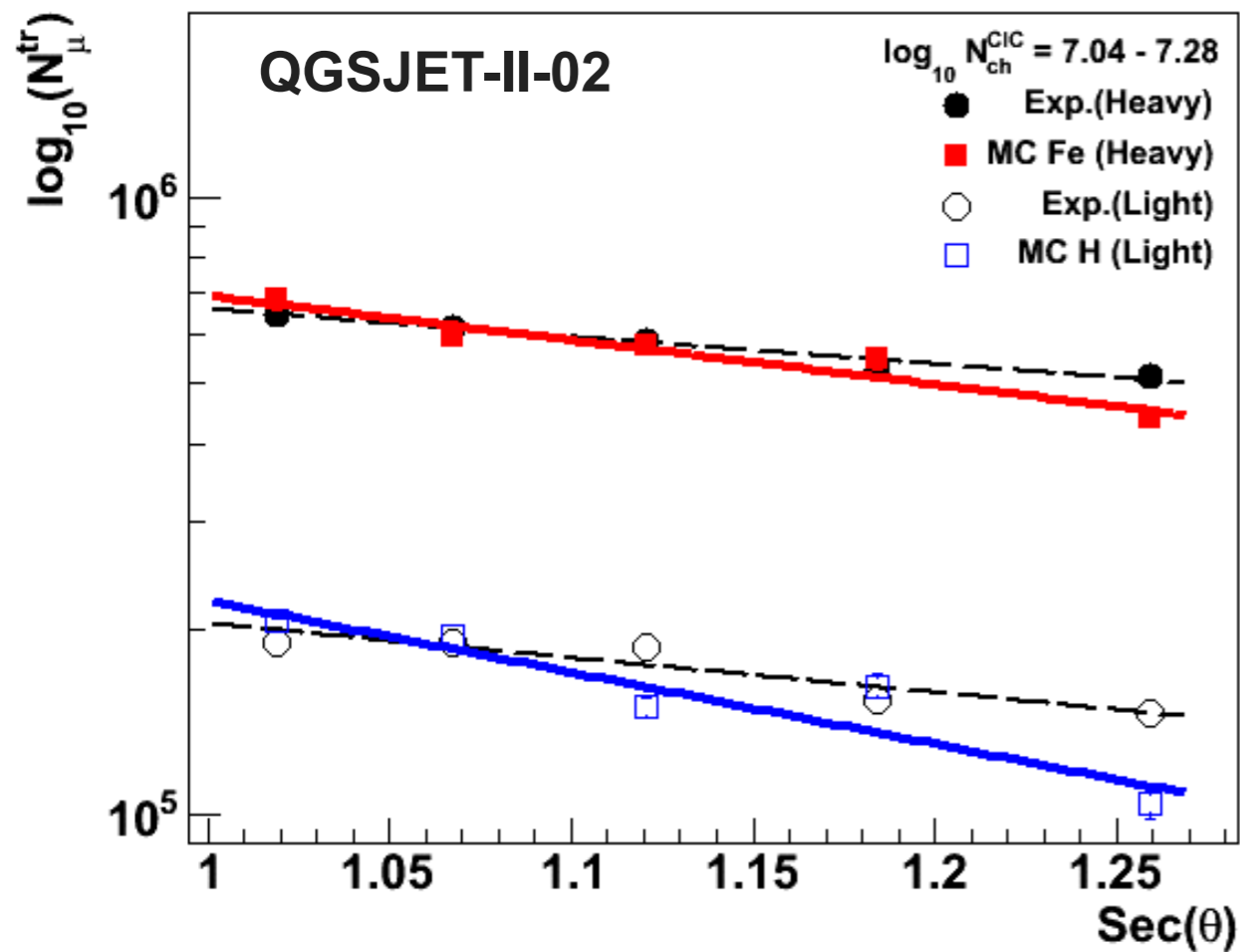Discrepancy between MC and experiment is observed for both mass groups

$$N^{tr}_{\mu} = N^{tr,o}_{\mu} \, e^{-(Xo \, Sec\theta/\Lambda\mu)}$$

Results

Is Λ_μ the same for each mass group?

$$N^{tr}_\mu = N^{tr,o}_\mu \, e^{-(X_o \, Sec\theta/\Lambda_\mu)}$$

QGSJET-II-02

$\log_{10} N^{CIC}_{ch} = 7.04 - 7.28$

● Exp.(Heavy)
■ MC Fe (Heavy)
○ Exp.(Light)
□ MC H (Light)

Data for $\log_{10} N_{ch}$ = [7.04, 7.28]

	KG Data	**MC**
Heavy	$\Lambda_\mu = 997 \pm 73$ g/cm^2	$\Lambda_\mu = 618 \pm 62$ g/cm^2
Light	$\Lambda_\mu = 794 \pm 129$ g/cm^2	$\Lambda_\mu = 383 \pm 30$ g/cm^2

$\Lambda_\mu^{Heavy} > \Lambda_\mu^{Light}$

Results

Is there a dependence of Λ_μ in the local muon data with the EAS size?

$$N^{tr}_\mu = N_\mu^{tr,o} \, e^{-(X_o \, Sec\theta / \Lambda\mu)}$$

KG Data

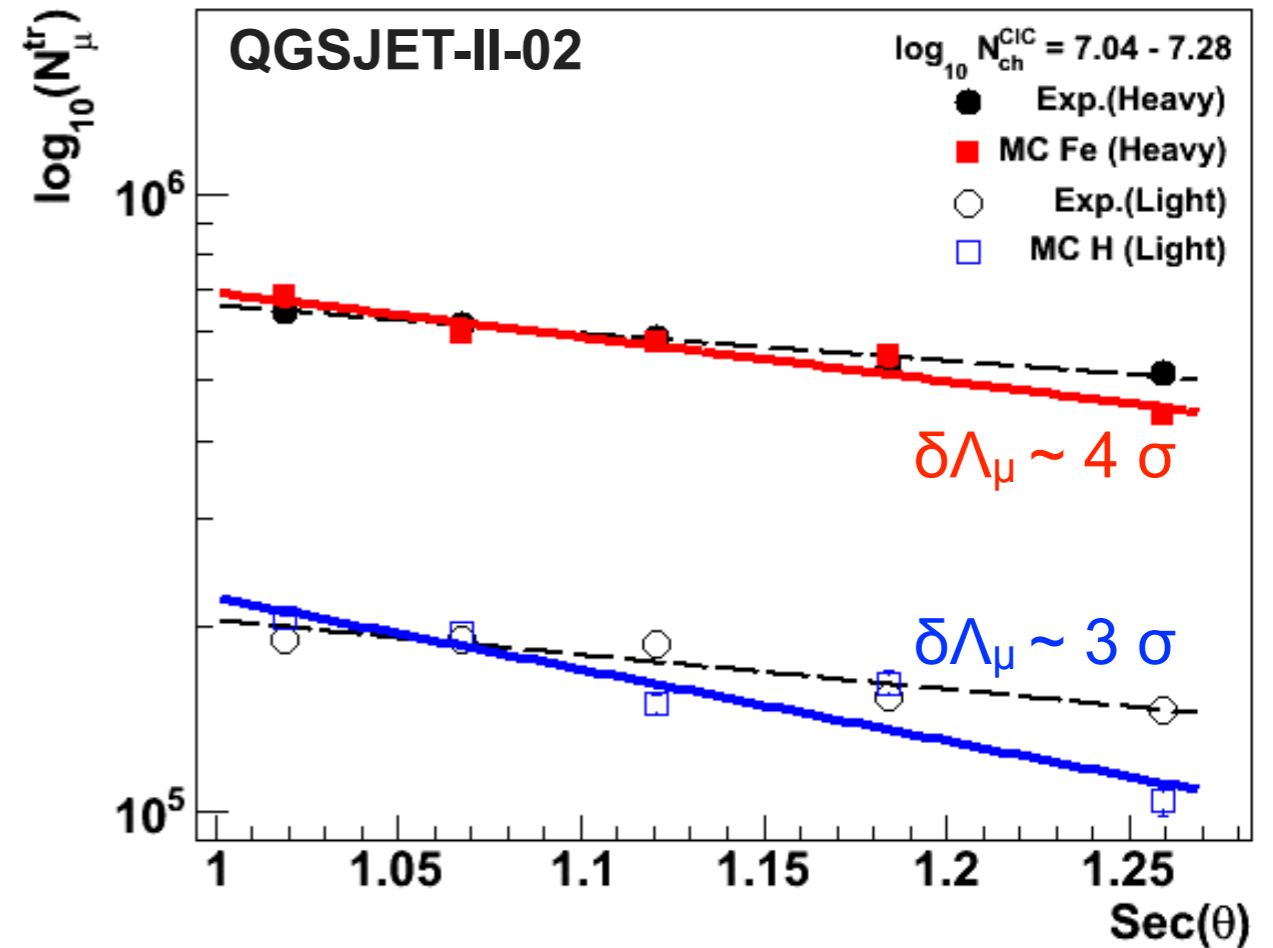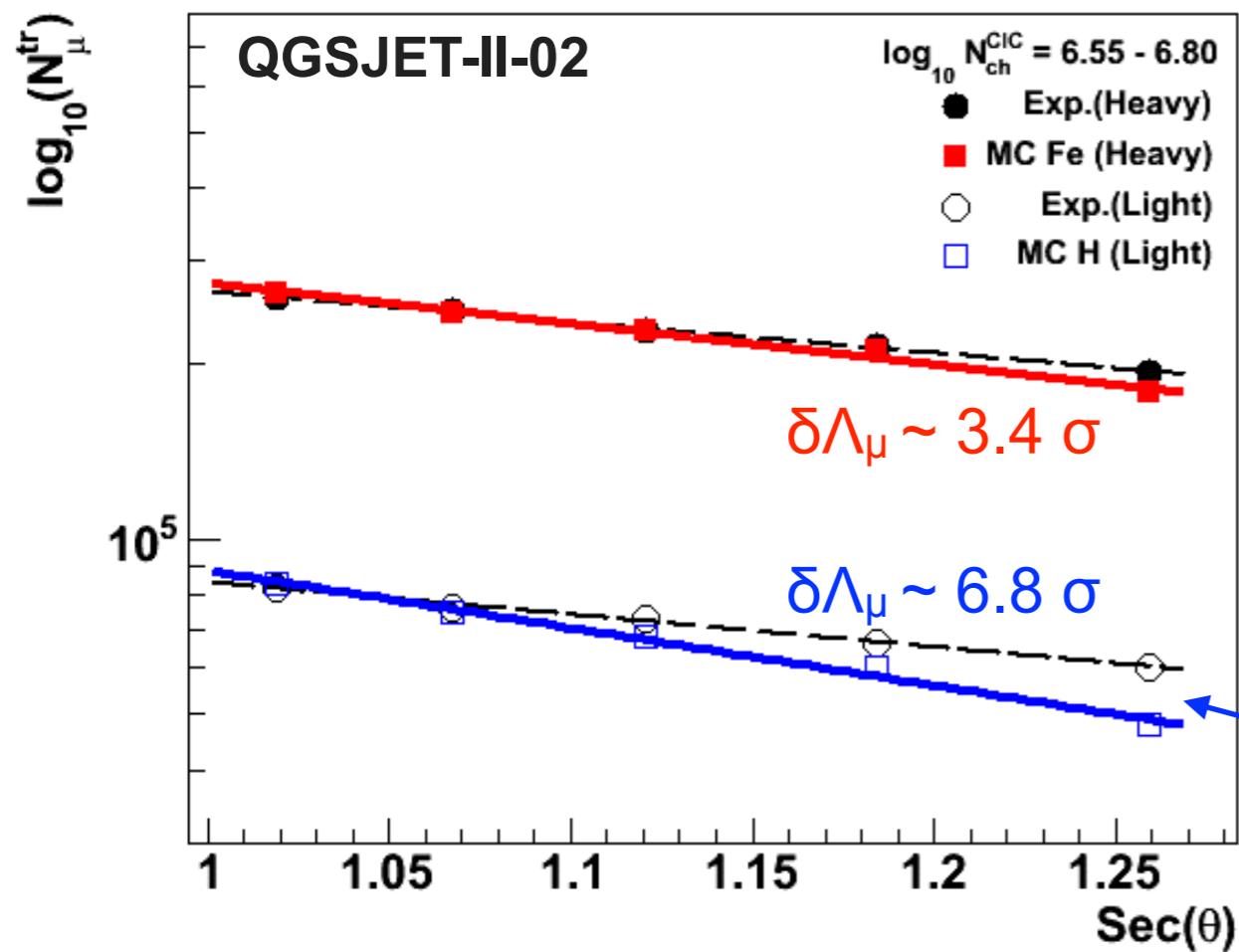| $\log_{10} N_{ch}$	Heavy*
[6.55, 6.80]	$\Lambda_\mu = 841 \pm 27 \, g/cm^2$
[6.80, 7.04]	$\Lambda_\mu = 890 \pm 42 \, g/cm^2$
[7.04, 7.28]	$\Lambda_\mu = 997 \pm 73 \, g/cm^2$

Possible increase of attenuation length of the heavy component with the EAS size

*Separation based on QGSJET-II-02

Results

Is the deviation different for each mass group?

Deviations are not the same for each mass group

QGSJET-II-02

$\log_{10} N_{ch}^{CIC} = 6.55 - 6.80$
- ● Exp.(Heavy)
- ■ MC Fe (Heavy)
- ○ Exp.(Light)
- □ MC H (Light)

$\delta\Lambda_\mu \sim 3.4\ \sigma$

$\delta\Lambda_\mu \sim 6.8\ \sigma$

QGSJET-II-02

$\log_{10} N_{ch}^{CIC} = 7.04 - 7.28$
- ● Exp.(Heavy)
- ■ MC Fe (Heavy)
- ○ Exp.(Light)
- □ MC H (Light)

$\delta\Lambda_\mu \sim 4\ \sigma$

$\delta\Lambda_\mu \sim 3\ \sigma$

Larger deviation is observed for the light component

Results

What about the post-LHC models?

QGSJET-II-04

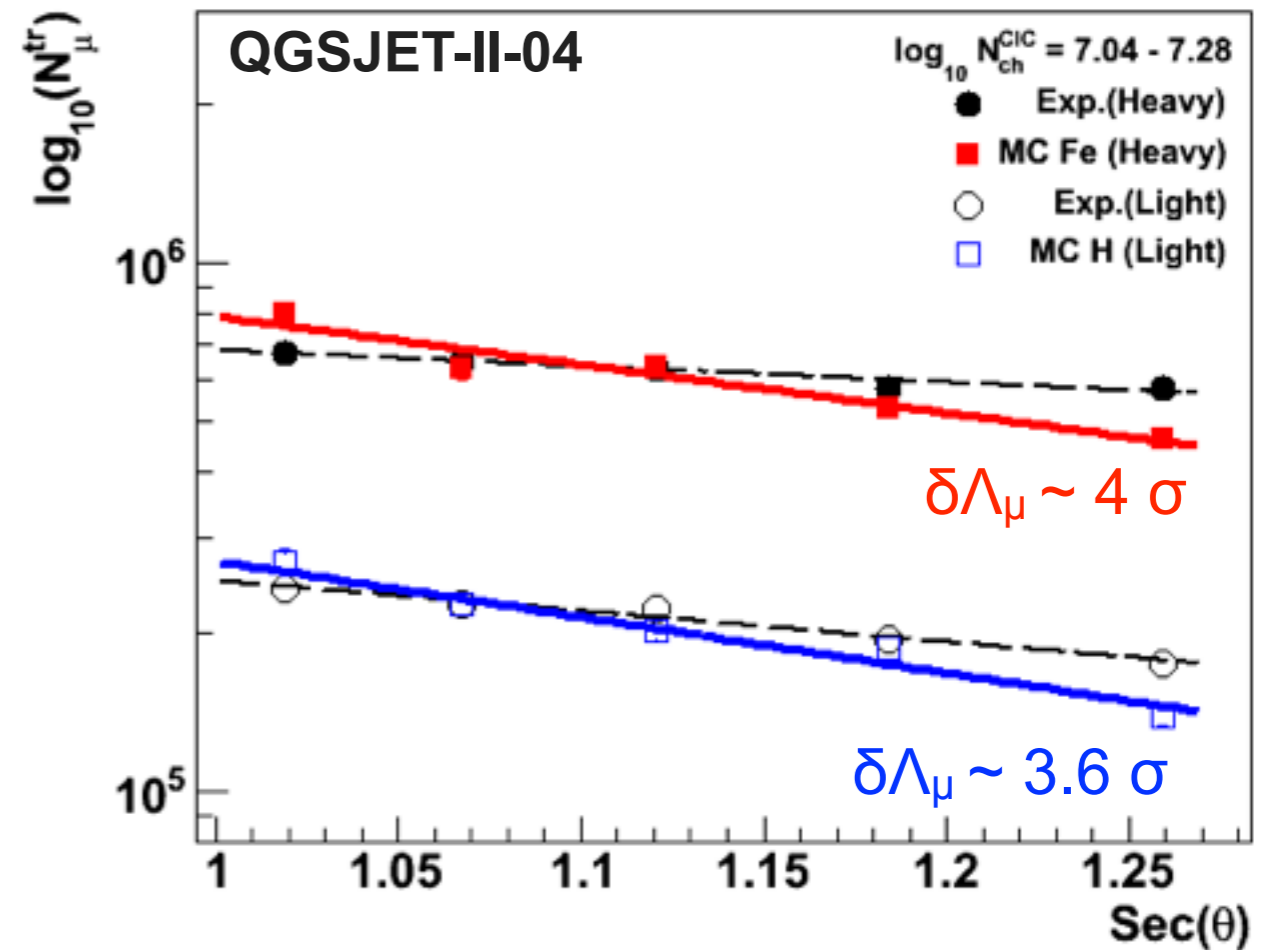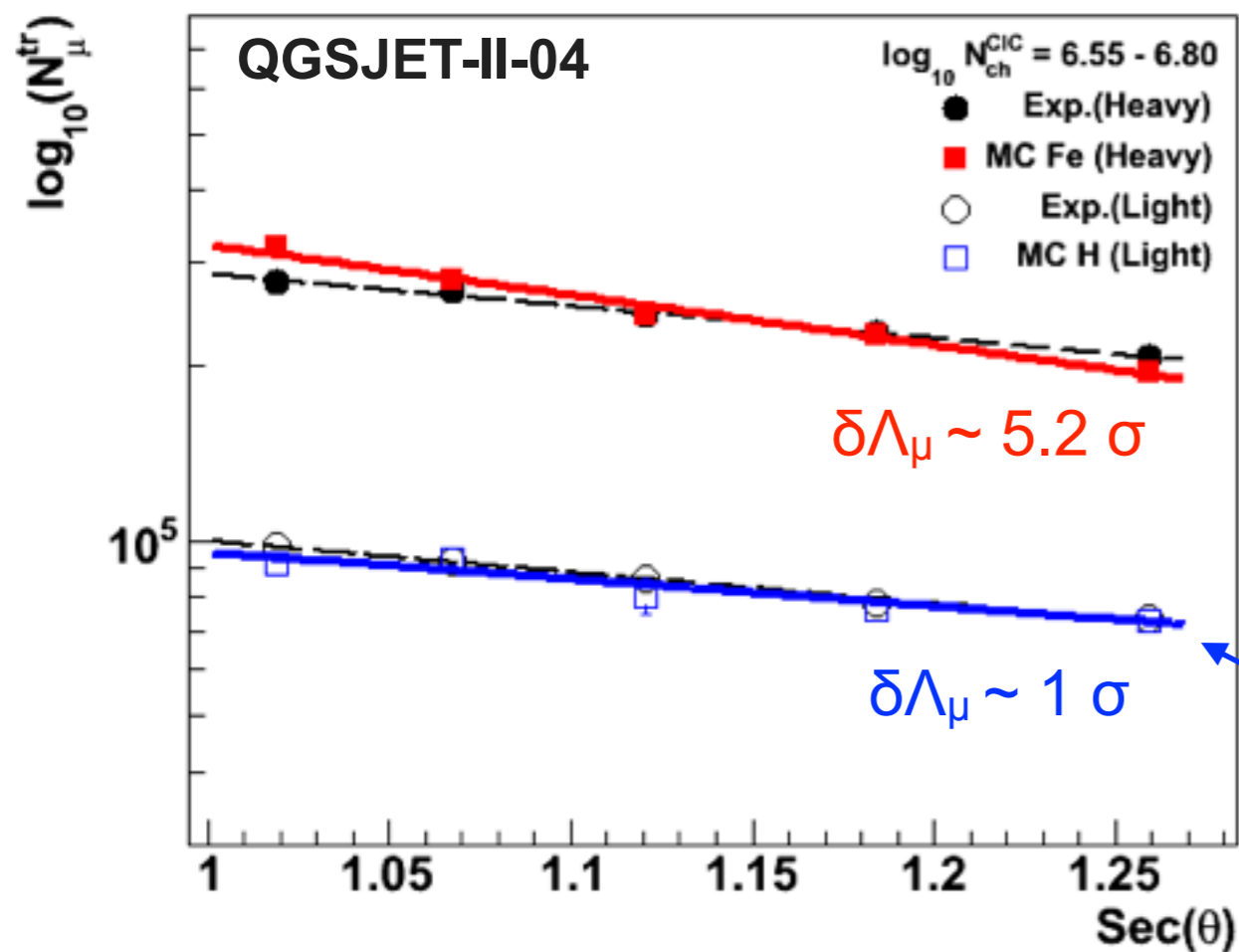**Model does not bracket all the local muon data**

Results

What about the post-LHC models?

QGSJET-II-04

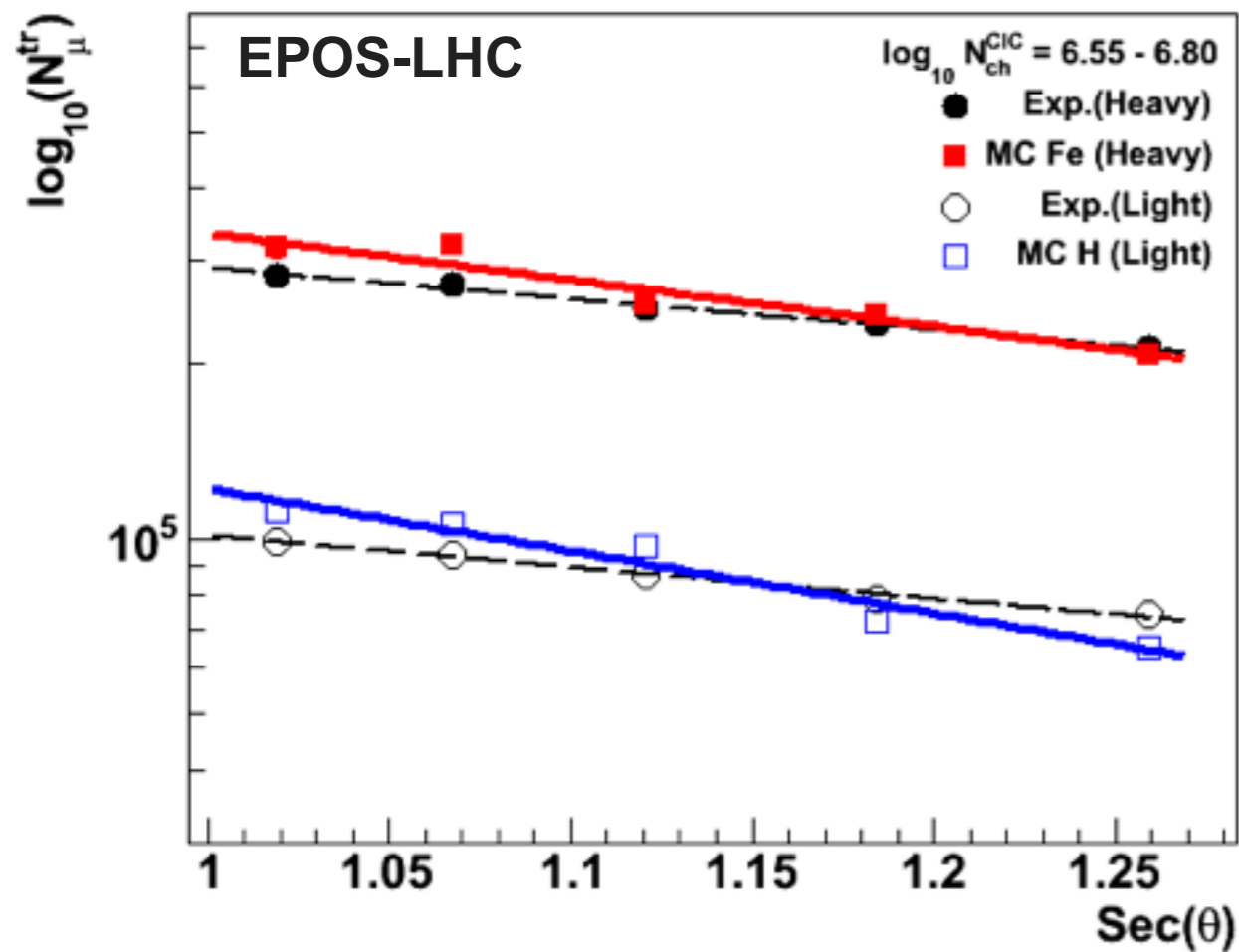Model does not bracket all the local muon data

δΛ$_μ$ ~ 5.2 σ

δΛ$_μ$ ~ 1 σ

δΛ$_μ$ ~ 4 σ

δΛ$_μ$ ~ 3.6 σ
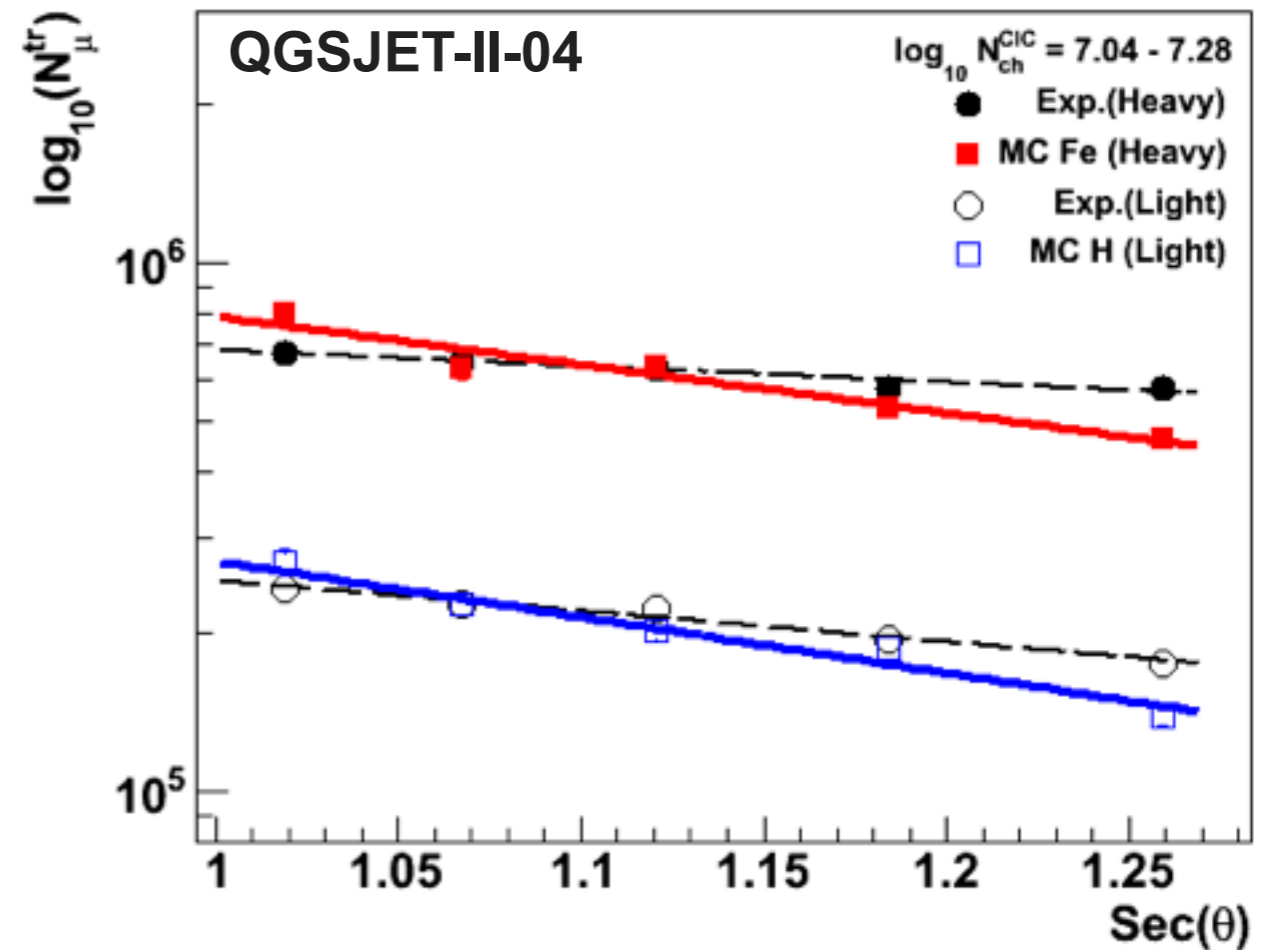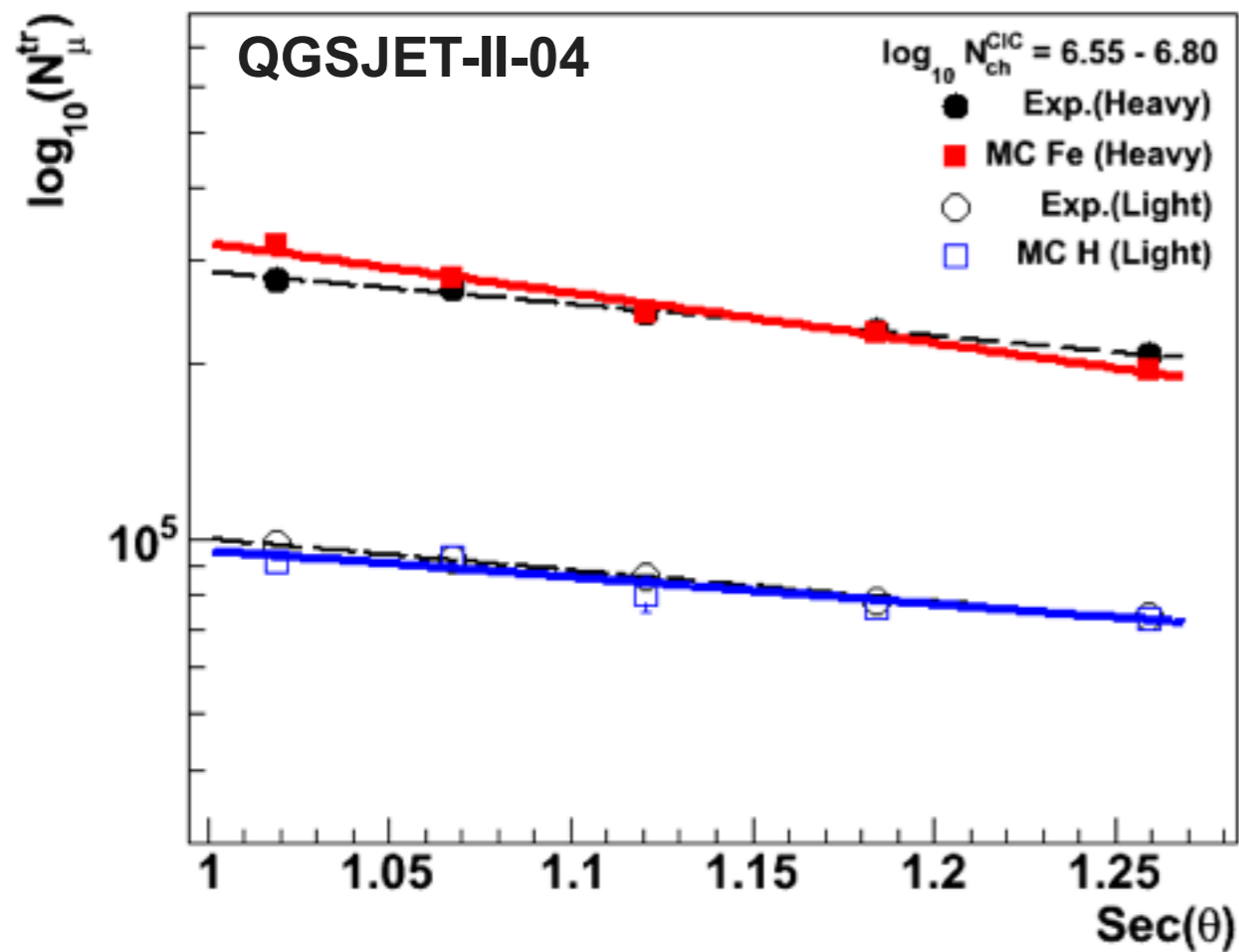
Smaller deviation appears for the light component

Results

What about the post-LHC models?

EPOS-LHC

Model brackets data at E ~ 10^{17} eV

Model does not bracket all local muon data at E ~ 10^{16} eV

Results

What about the post-LHC models?

EPOS-LHC

Model brackets data at E ~ 10^{17} eV

Model does not bracket all local muon data at E ~ 10^{16} eV

$\delta\Lambda_\mu \sim 3.9\ \sigma$

$\delta\Lambda_\mu \sim 9.3\ \sigma$

$\delta\Lambda_\mu \sim 2.2\ \sigma$

$\delta\Lambda_\mu \sim 3.5\ \sigma$
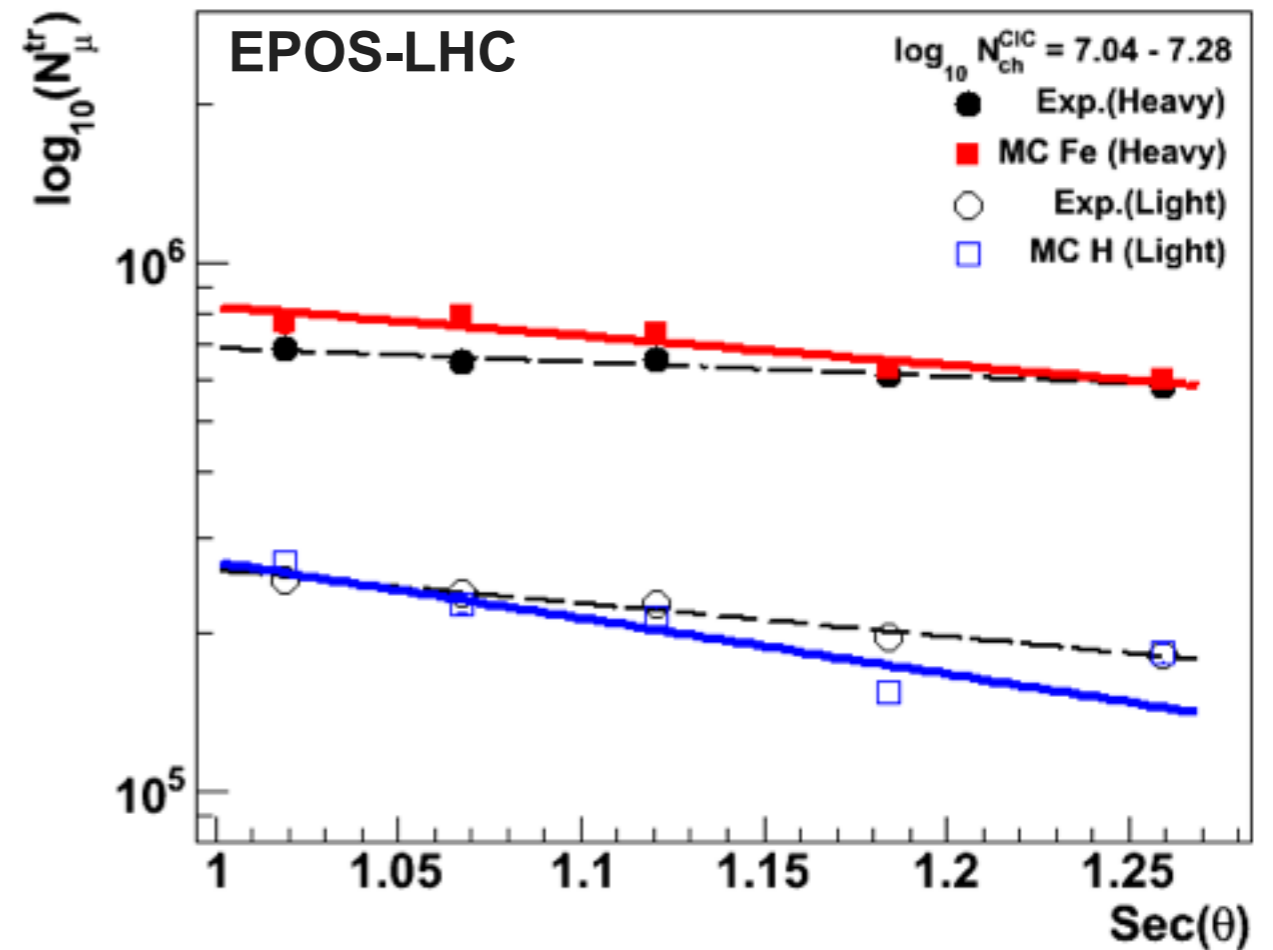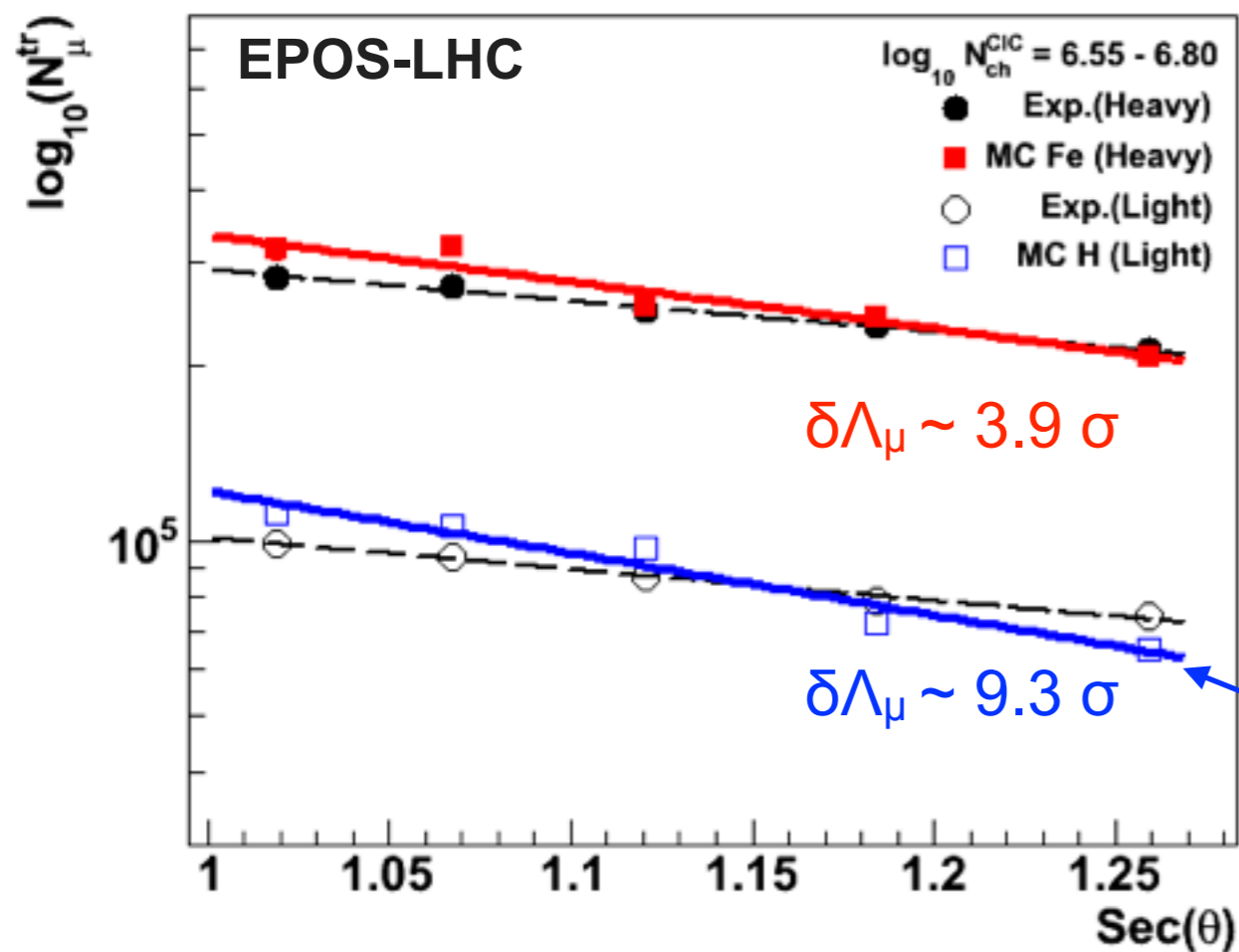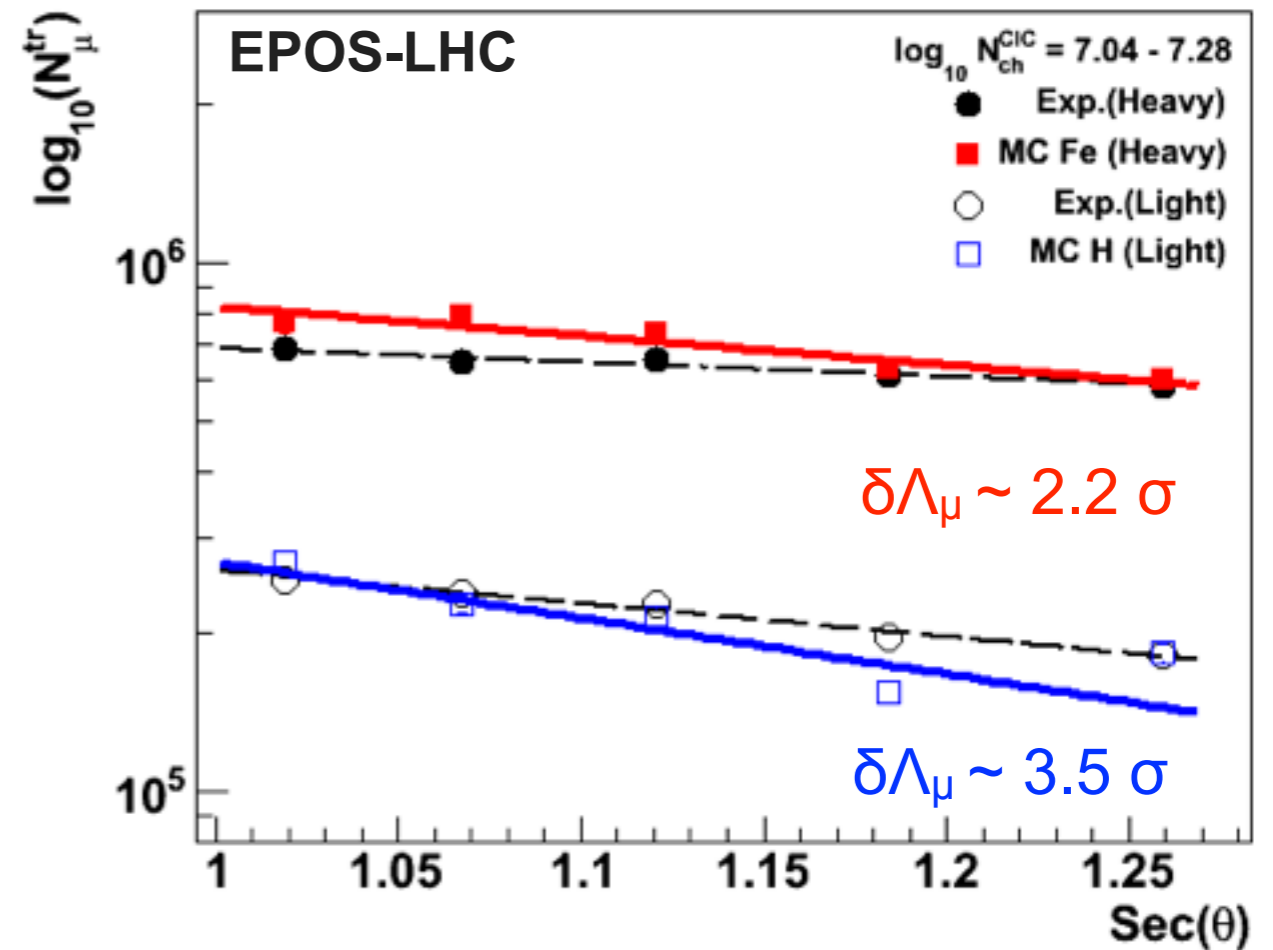
Here, larger deviation belongs to light component

Summary

1. **The attenuation lengths** of the heavy and light mass groups for the local muon **data** are **larger than** the corresponding **predictions** of QGSJET-II-02, QGSJET-II-04 and EPOS-LHC.

2. The local $\rho_\mu(r)$ **distributions** for the light and heavy mass groups that are measured **along CIC curves** are **not completely contained by model** expectations.

3. In general, Λ_μ for the **heavy component is larger** than that for the light mass group at the same EAS size.

4. **Deviations** between data and MC at the same shower number are **different for each mass group**.

Thank you!

KASCADE-Grande Collaboration

**Institut für Kernphysik & Institut für Experimentelle Kernphysik
KIT - Karlsruhe Institute of Technology**

W.D.Apel, K.Bekk, J.Blümer, H.Bozdog, F.Cossavella, K.Daumiller, P.Doll, R.Engel, J.Engler, M.Finger, B.Fuchs, H.J.Gils, A.Haungs, D.Heck, D.Huber, T.Huege, D.Kang, H.O.Klages, K.Link, M.Ludwig, H.-J.Mathes, H.J.Mayer, M.Melissas, J.Milke, J.Oehlschläger, N.Palmieri, T.Pierog, H.Rebel, M.Roth, H.Schieler, S.Schoo, F.G.Schröder, H.Ulrich, A.Weindl, J.Wochele, M.Wommer

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