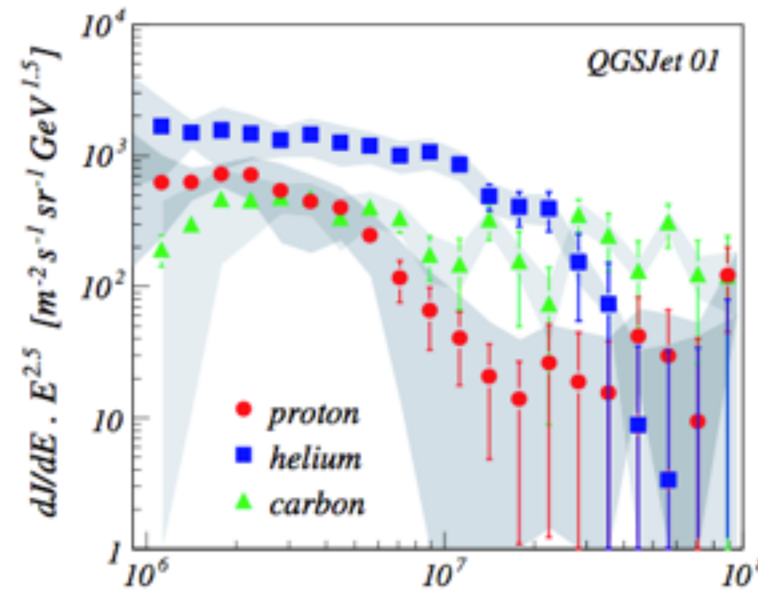
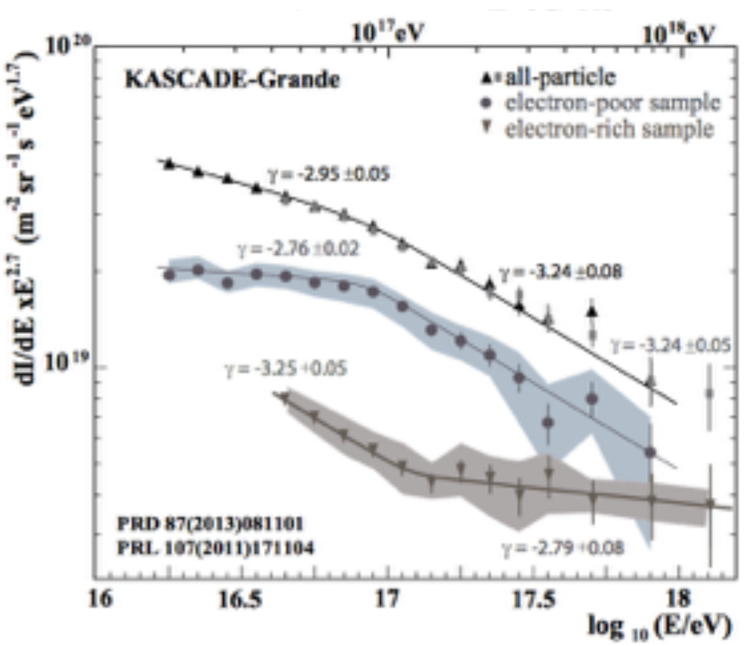
Test of the SIBYLL 2.3 high-energy hadronic interaction model using the KASCADE-Grande muon data

Juan Carlos Arteaga-Velázquez*, D. Rivera for the KASCADE-Grande Collaboration

Instituto de Física y Matemáticas, Universidad Michoacana, México





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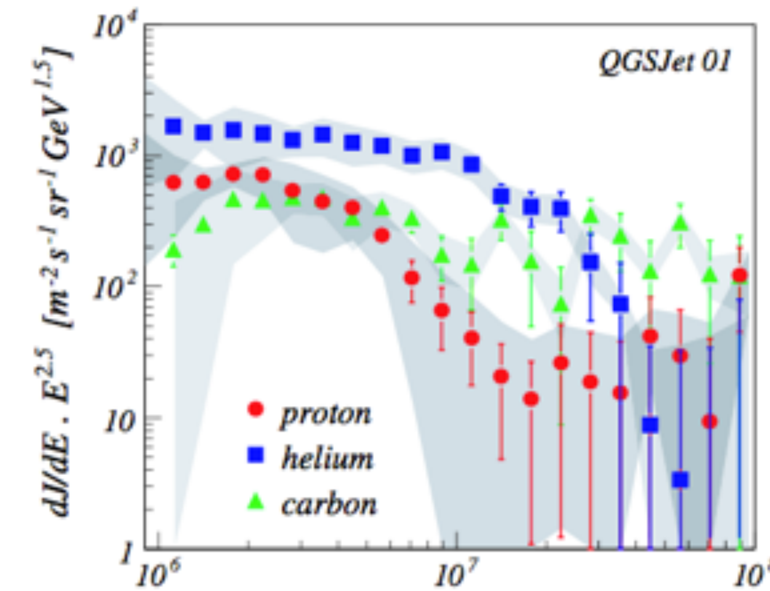
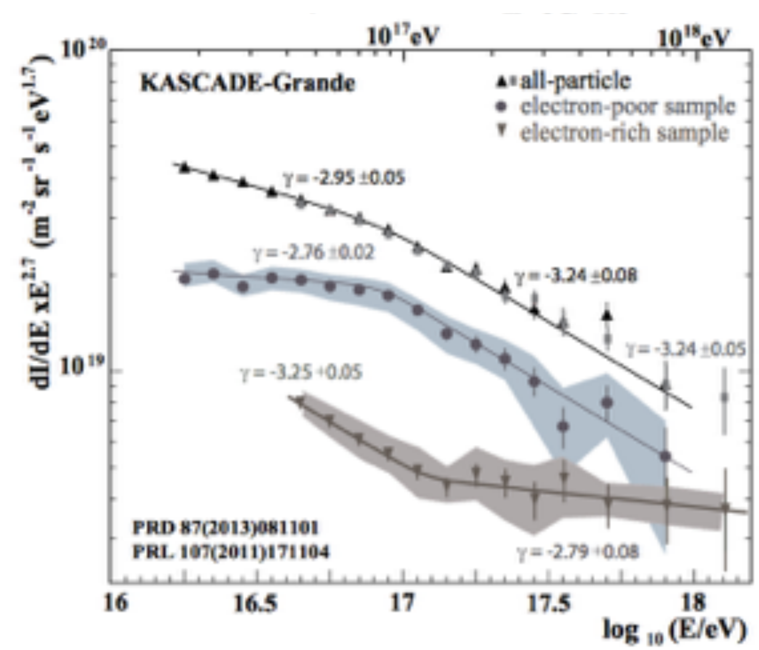
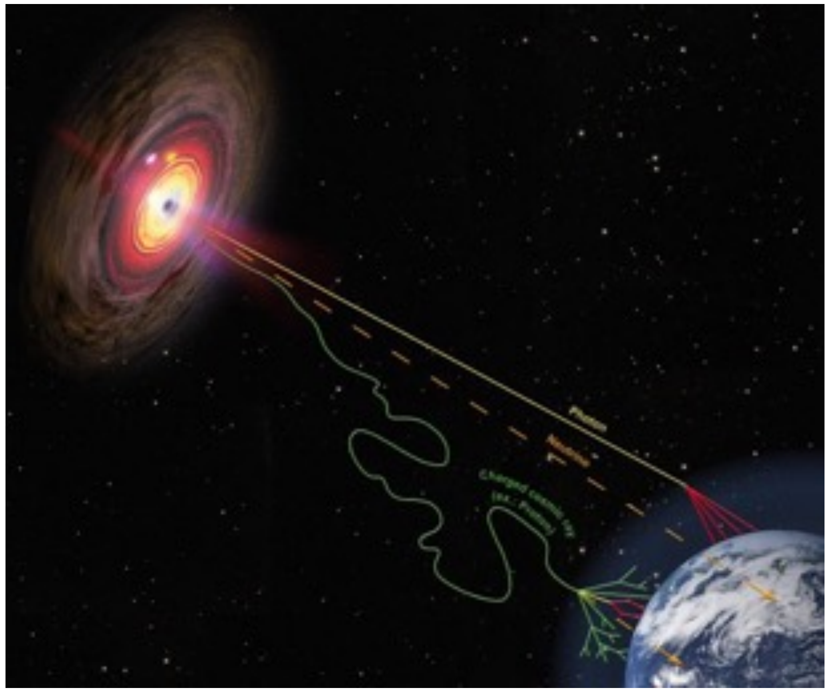
Outline

1. Introduction
2. Motivation
3. The KASCADE-Grande detector
4. Data & Simulations
5. Analysis
6. Results
7. Summary



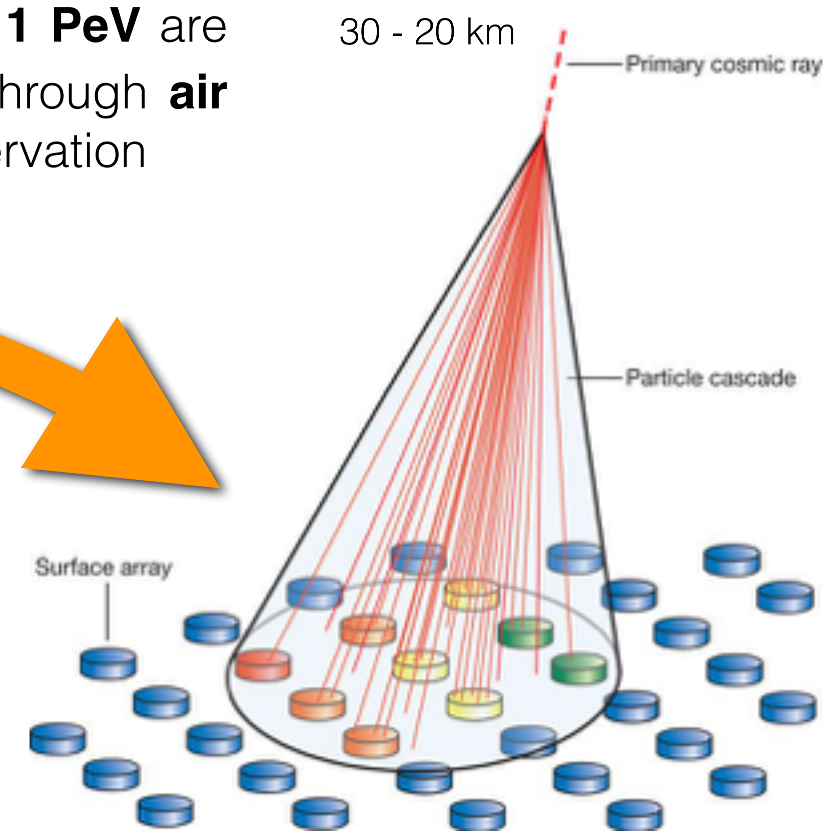


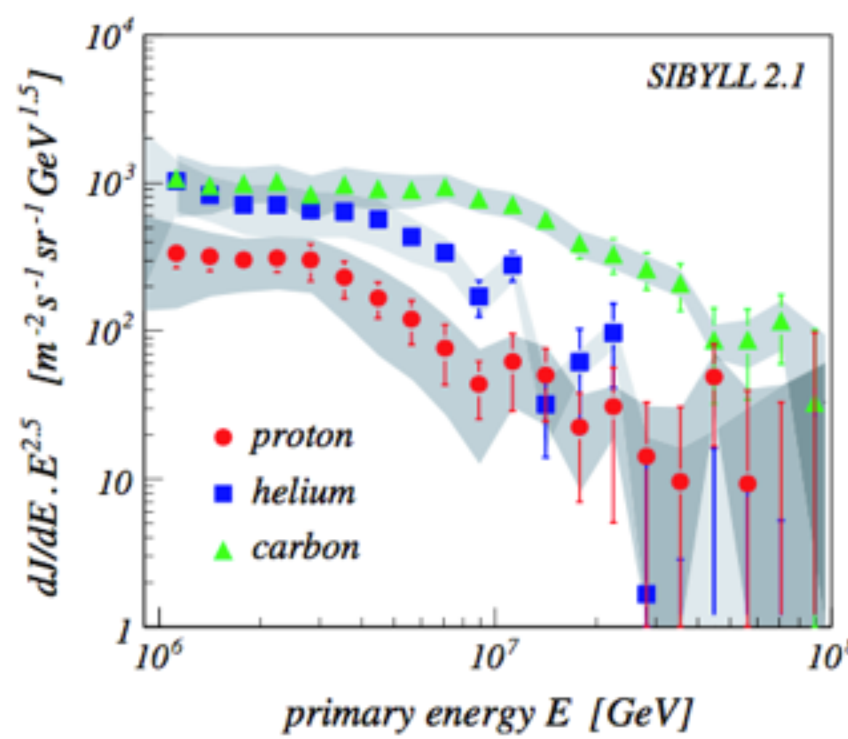
Introduction



Cosmic rays are produced in HE astrophysical sources (**SNR's, AGN's, etc?**).

Primaries with **E > 1 PeV** are **detected** at Earth through **air shower (EAS)** observation





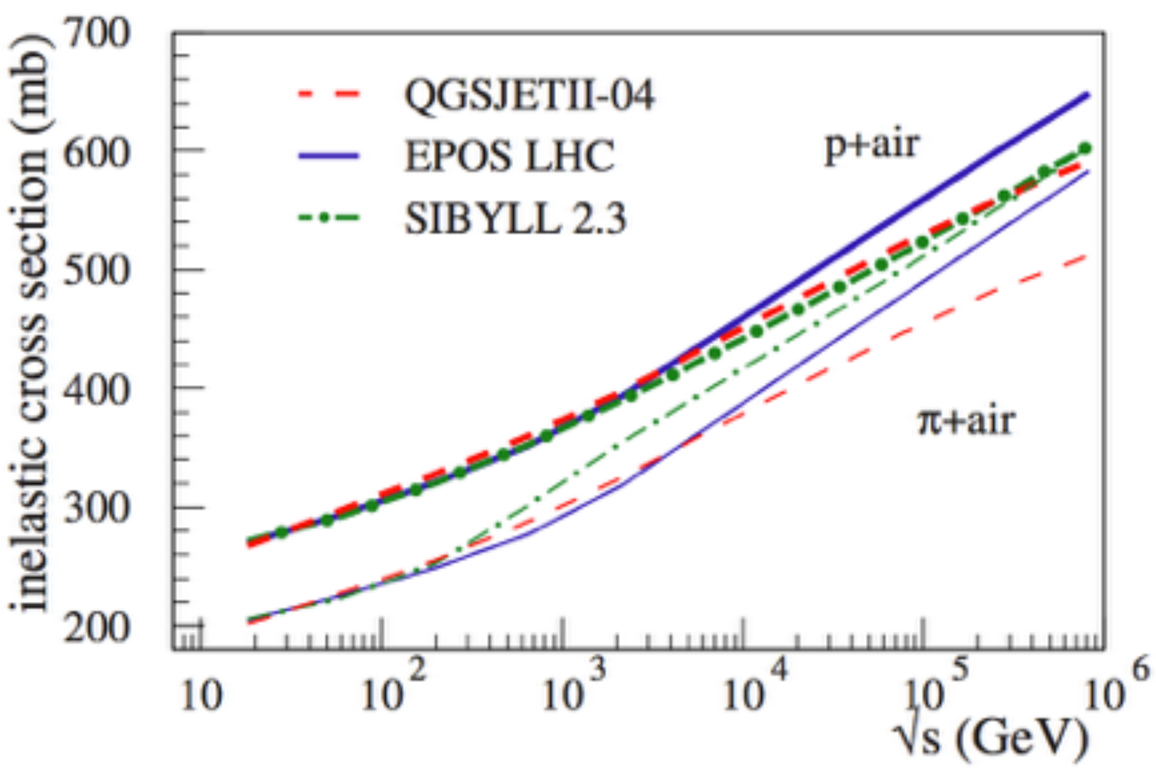
EAS **data** is **interpreted with hadronic models** to study energy and composition

Introduction

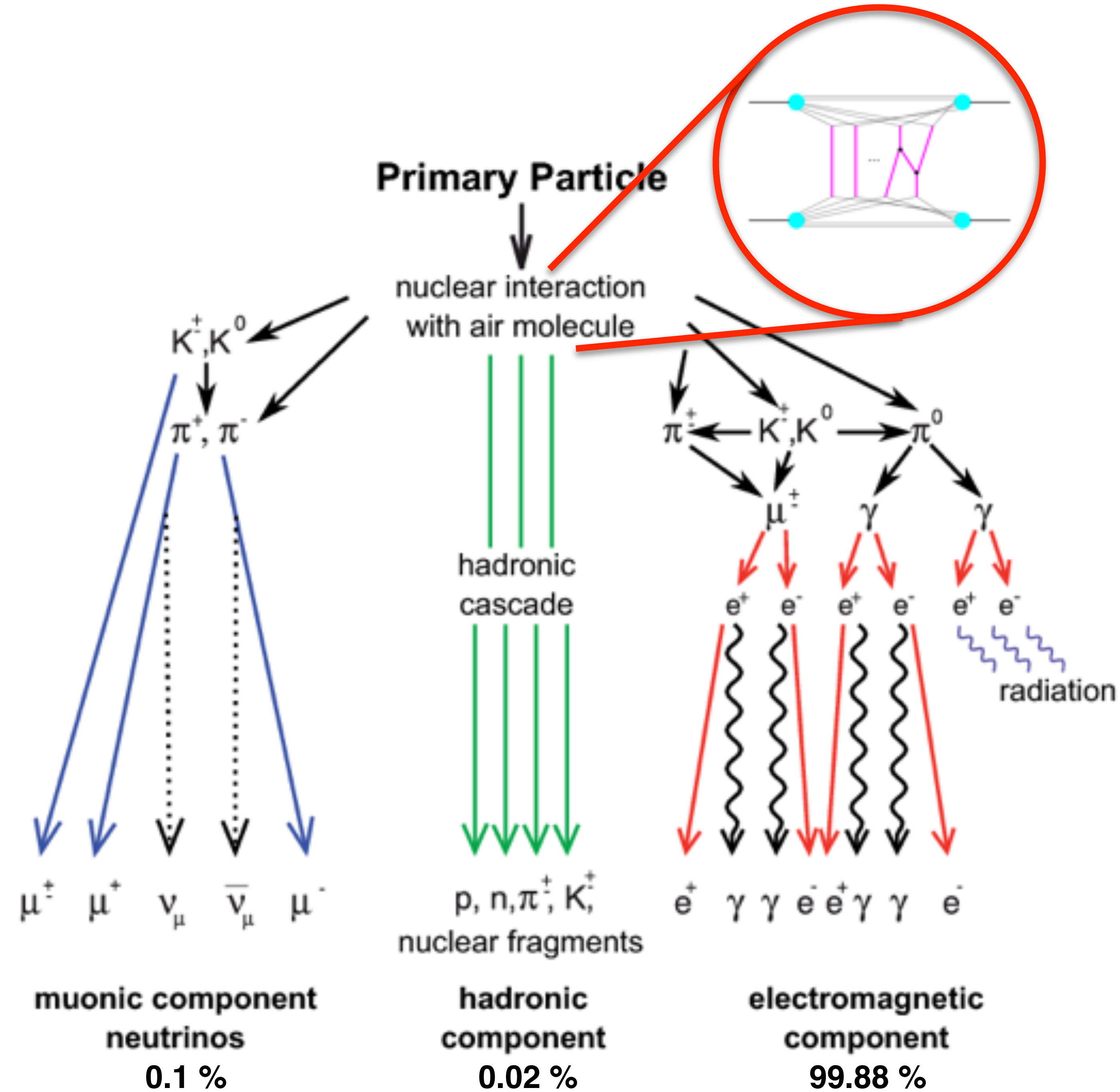
Hadronic interaction models:

1. Phenomenological models inspired in QCD.
3. Calibrated with accelerator data.
4. **Extrapolated** to **high energies** (HE's) and **forward region** ($p_T \sim 0$).

Soft physics (low Q^2) is relevant for CR interactions



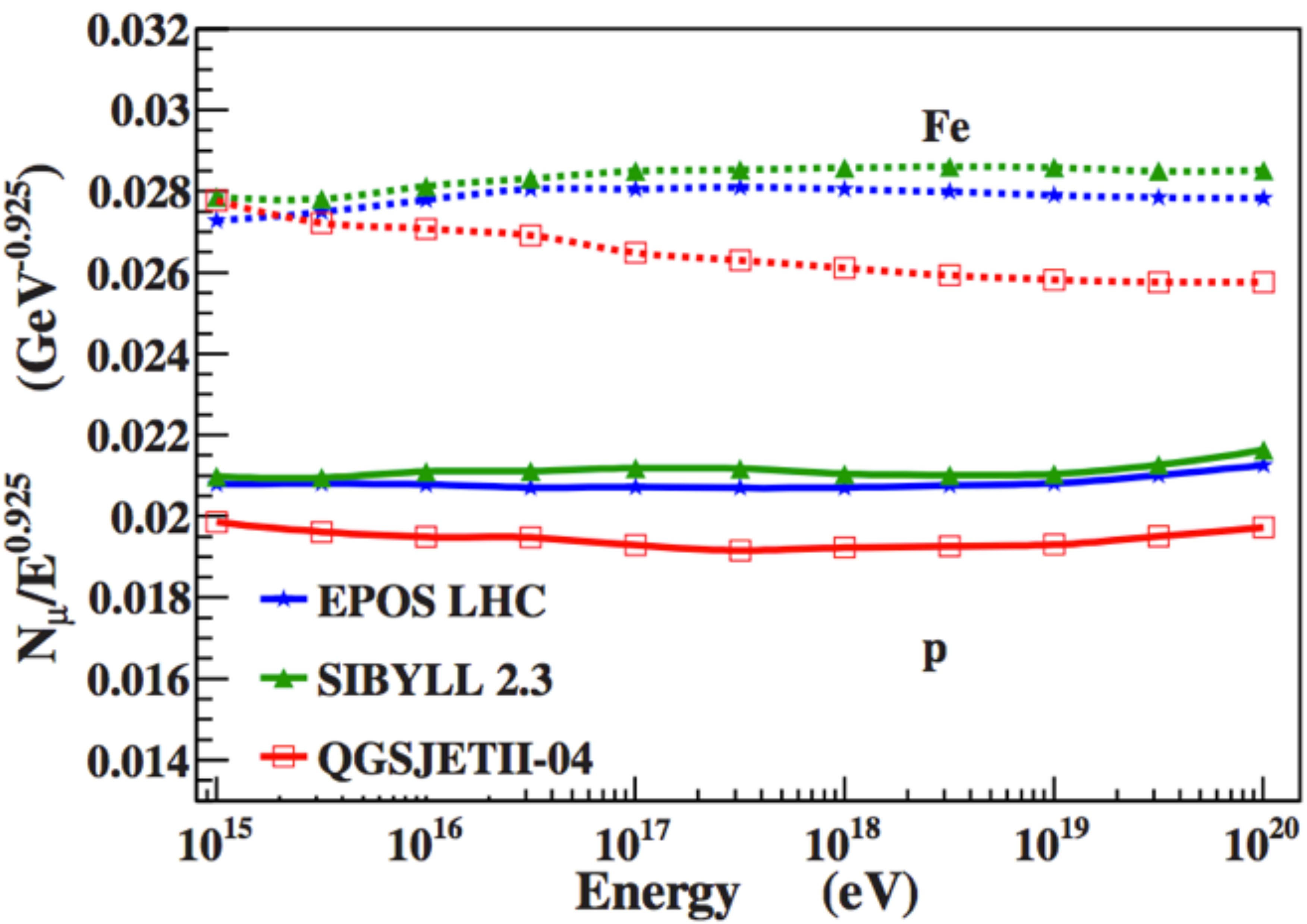
T. Pierog,EPJ web of conferences 145, 18002 (2017)



Model uncertainties produce uncertainties in predictions of EAS parameters

Introduction

Differences in EAS observables due to uncertainties in the models

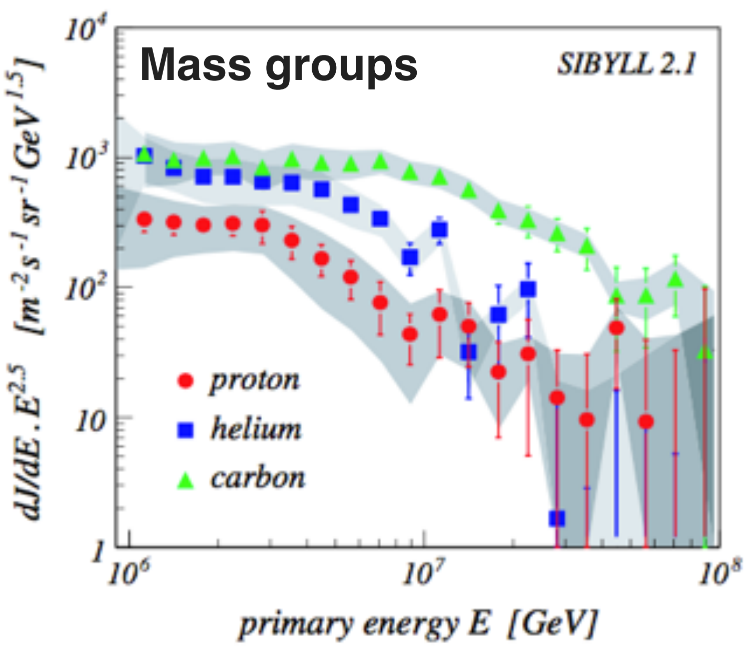


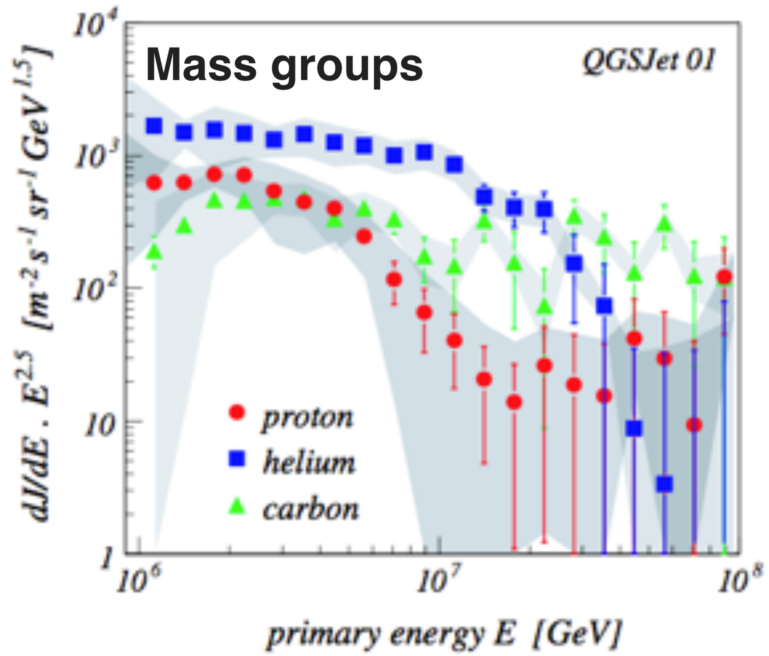
T. Pierog,EPJ web of conferences 145, 18002 (2017)

Introduction

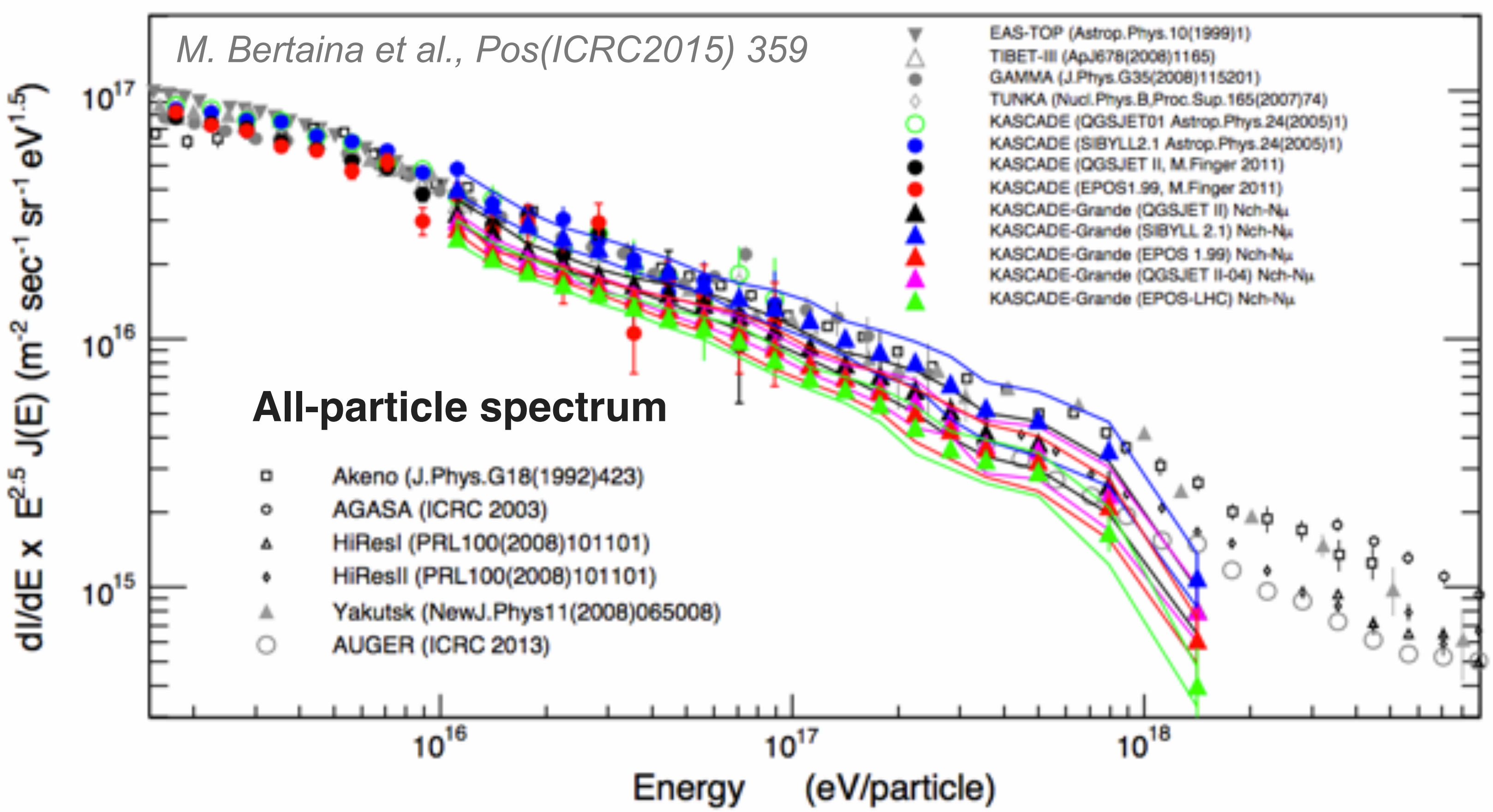
Dependence of relative abundances and spectrum of CR's with hadronic interaction models:

KASCADE Coll., Astrop. Phys. 24 (2005) 1.





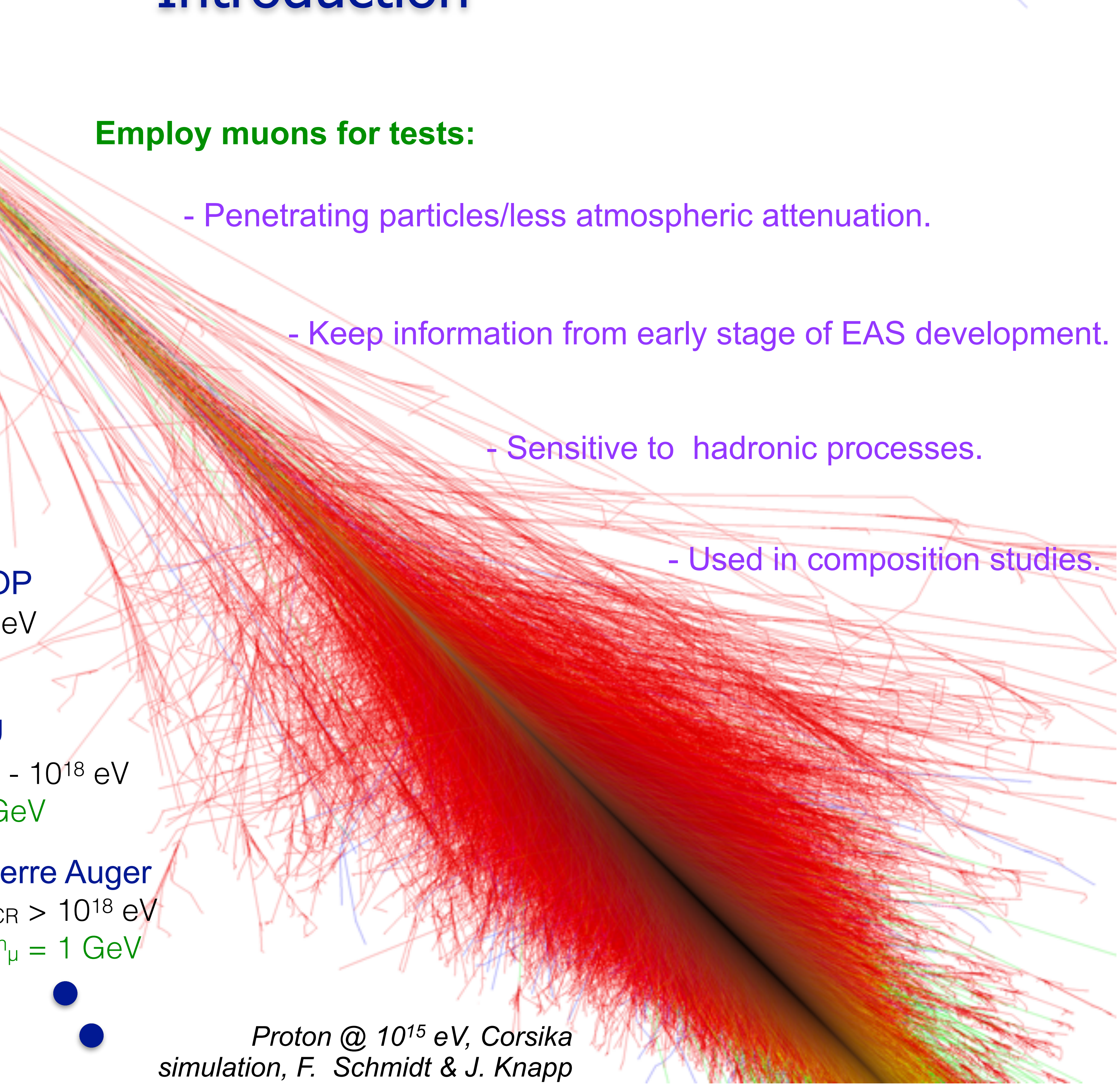
KASCADE-Grande experiment



Composition and **energy scale** are **affected by model uncertainties**

Imperative to check validity of hadronic models

Introduction

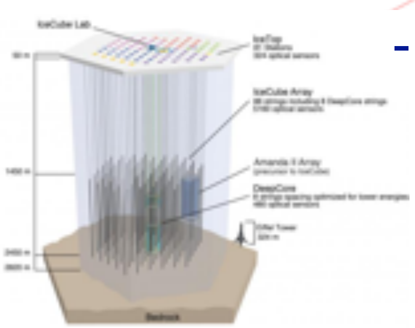


Employ muons for tests:

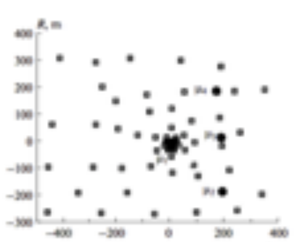
- Penetrating particles/less atmospheric attenuation.
- Keep information from early stage of EAS development.
- Sensitive to hadronic processes.
- Used in composition studies.

Use CR observatories to constrain/test models:

- KASCADE-Grande
  $E_{CR} = 10^{15} - 10^{18}$ eV
  $E^{th}_{\mu} = 230$ MeV, 490 MeV, 800 MeV, 2.4 GeV



- ICECUBE/ICETOP
  $E_{CR} = 10^{15} - 10^{17}$ eV
  $E^{th}_{\mu} = 0.2$ GeV

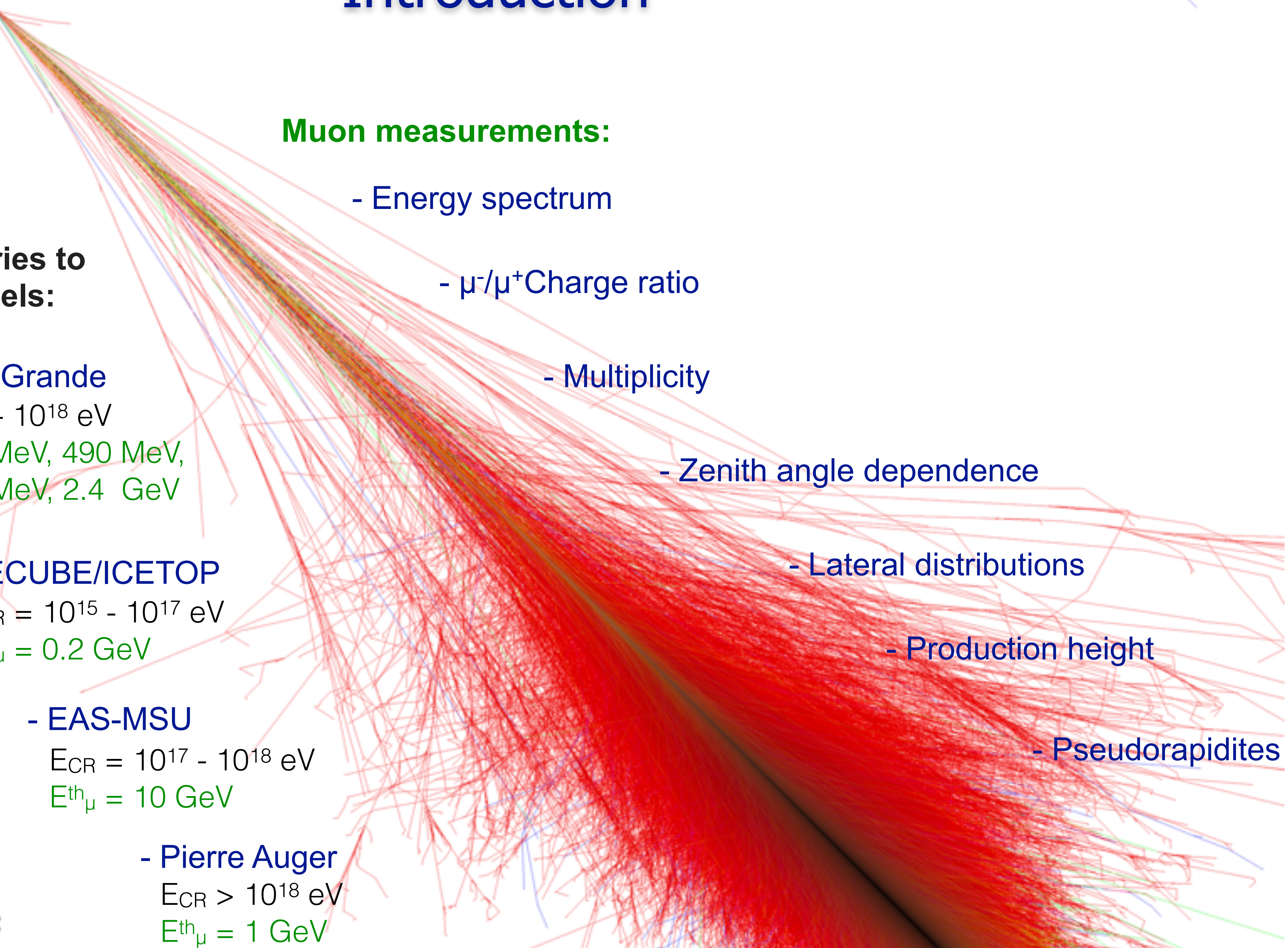


- EAS-MSU
  $E_{CR} = 10^{17} - 10^{18}$ eV
  $E^{th}_{\mu} = 10$ GeV

- Pierre Auger
  $E_{CR} > 10^{18}$ eV
  $E^{th}_{\mu} = 1$ GeV

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

Introduction



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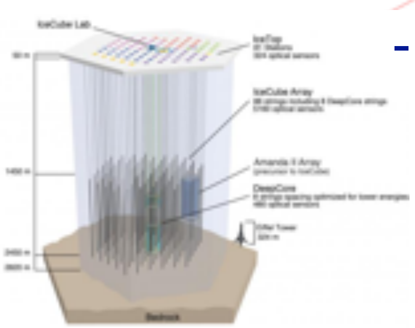

E_{CR} = 10^{15} - 10^{17} eV
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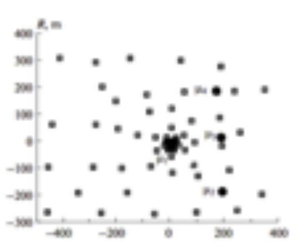


E_{CR} = 10^{17} - 10^{18} eV
E^{th}_{μ} = 10 GeV

- Pierre Auger

E_{CR} > 10^{18} eV
E^{th}_{μ} = 1 GeV

Muon measurements:

- Energy spectrum
- μ^-/μ^+Charge ratio
- Multiplicity
- Zenith angle dependence
- Lateral distributions
- Production height
- Pseudorapidites

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

Motivation

KASCADE-Grande EAS muon data

Muon attenuation length (Λ_μ):

1. Parameterizes dependence of **number of μ's** in EAS with the atmospheric depth:

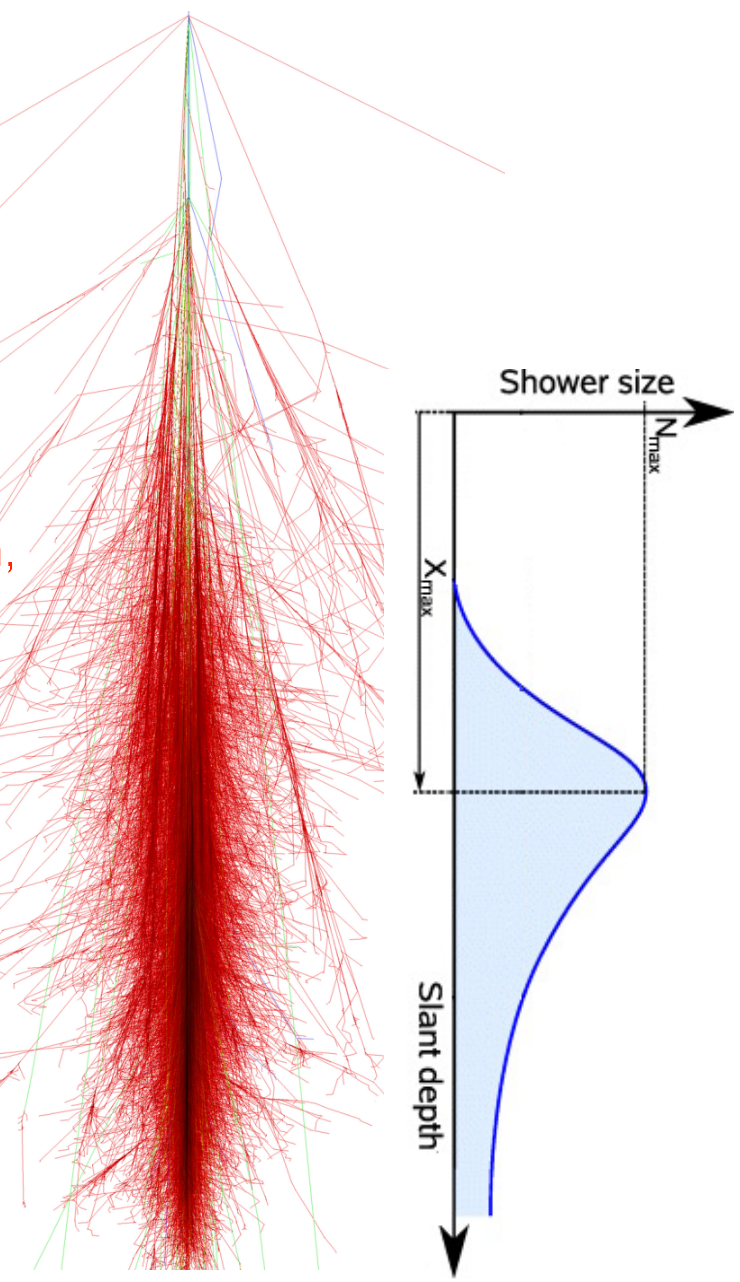
$$N_\mu = N_\mu^o \, e^{-(X/\Lambda\mu)}$$

2. **Correct data** for attenuation in the atmosphere.

3. **Affected by details of shower production:**

- π energy spectrum, cross section, p_T distribution,
- $\pi^\pm/\pi^0$ ratios,
- Baryon/resonance production,
- Multiplicity <N>
- Inelasticity (y), etc.

Muon E_{th} > 230 MeV x Secθ



Motivation

KASCADE-Grande EAS muon data

Muon attenuation length (Λ_μ):

Measured muon attenuation length (E_{CR} ~ 10^{16} - 10^{17} eV) **is above** MC predictions from:

Pre-LHC models (~ 2 σ):

- SIBYLL 2.1
- QGSJET-II-02

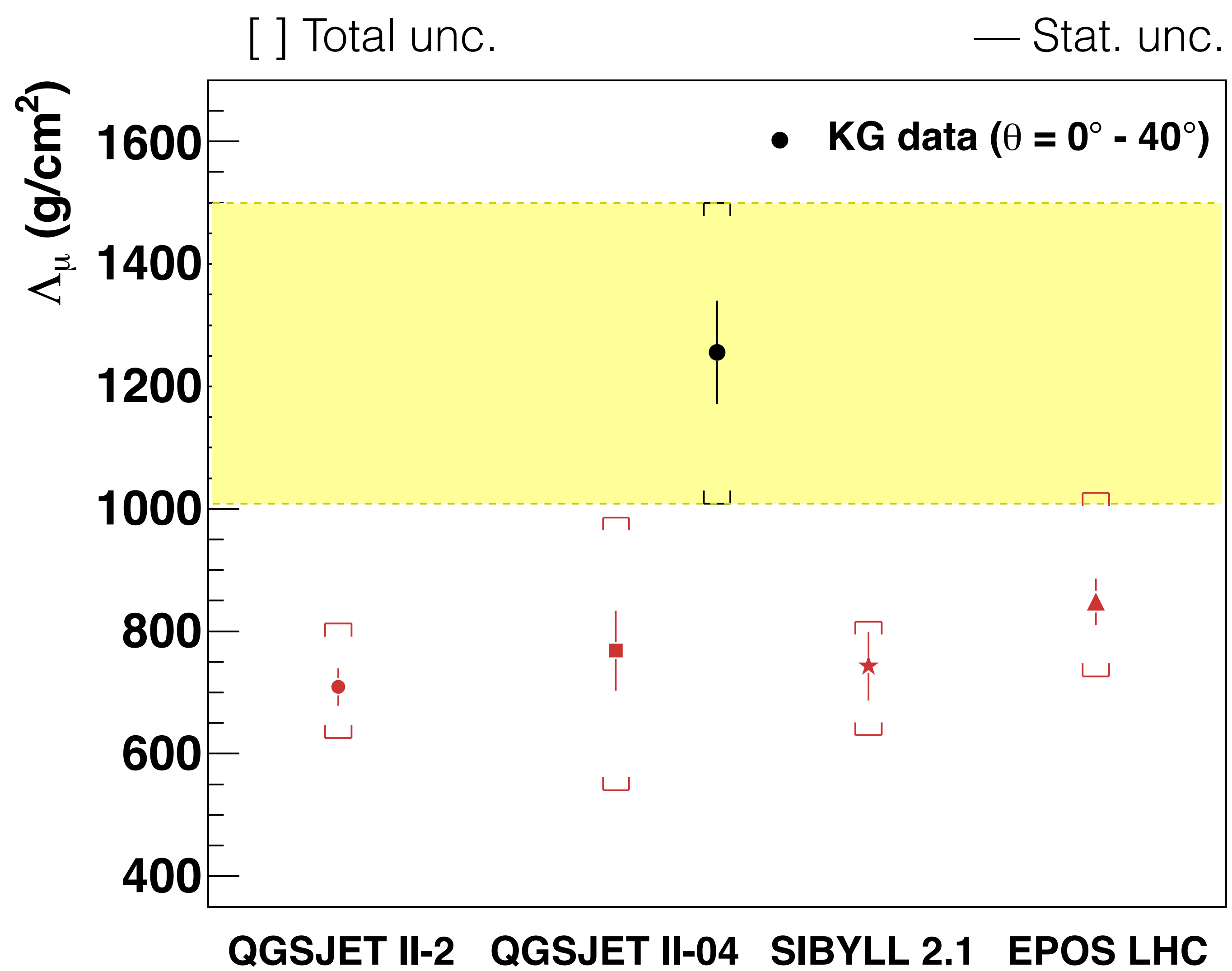
Post-LHC models (~ 1.34 σ to 1.48 σ):

- EPOS-LHC
- QGSJET-II-04

Better agreement with post-LHC models.

Does SIBYLL 2.3* perform better?

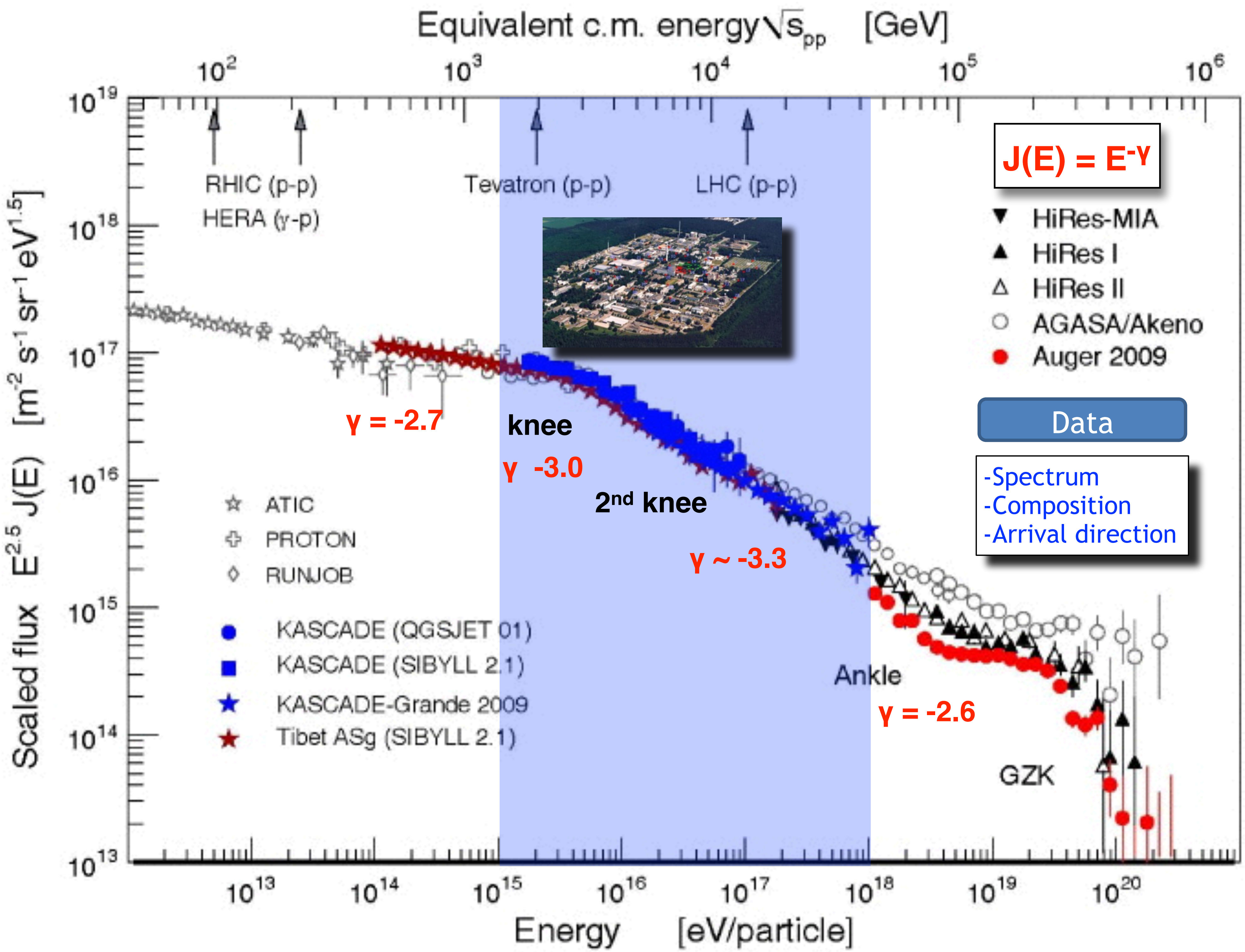
F. Riehn et al., PoS(ICRC2015) 558



J.C. Arteaga et al., Astropar. Phys. 95 (2017) 25

Less effective attenuation in exp. data

The KASCADE-Grande detector



The KASCADE-Grande detector

1. What is the origin of the features in the spectrum?

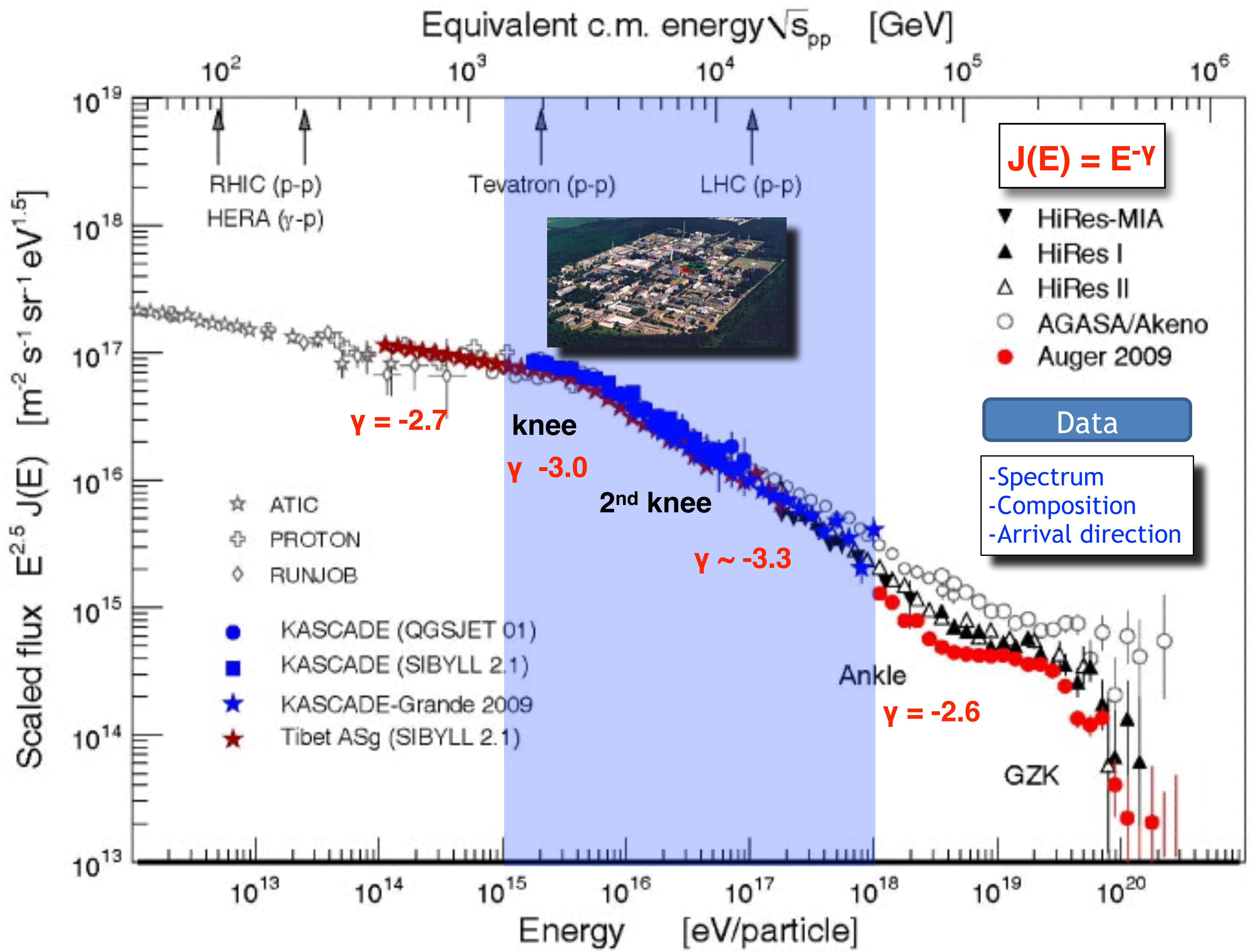
2. Where do they come from?

3. What is their nature?

4. How do they get accelerated?

5. Are there nearby sources?

6. Where is the galactic to extragalactic transition?



The KASCADE-Grande detector

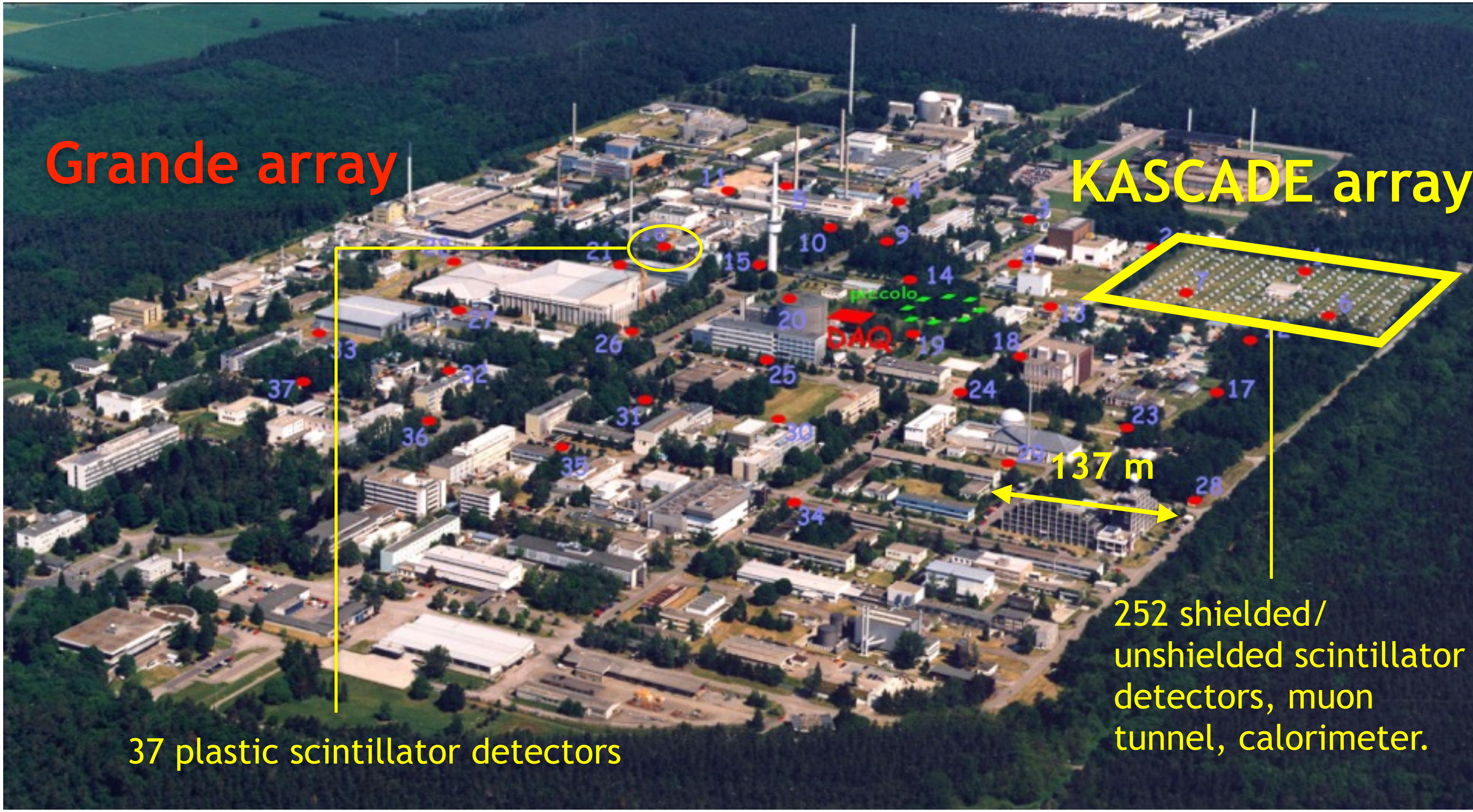
December 2003 - November 2012

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

The KASCADE-Grande detector

KASCADE (200 x 200 m^2) + Grande (0.5 km^2)

E= 1 PeV - 10^{18} eV



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

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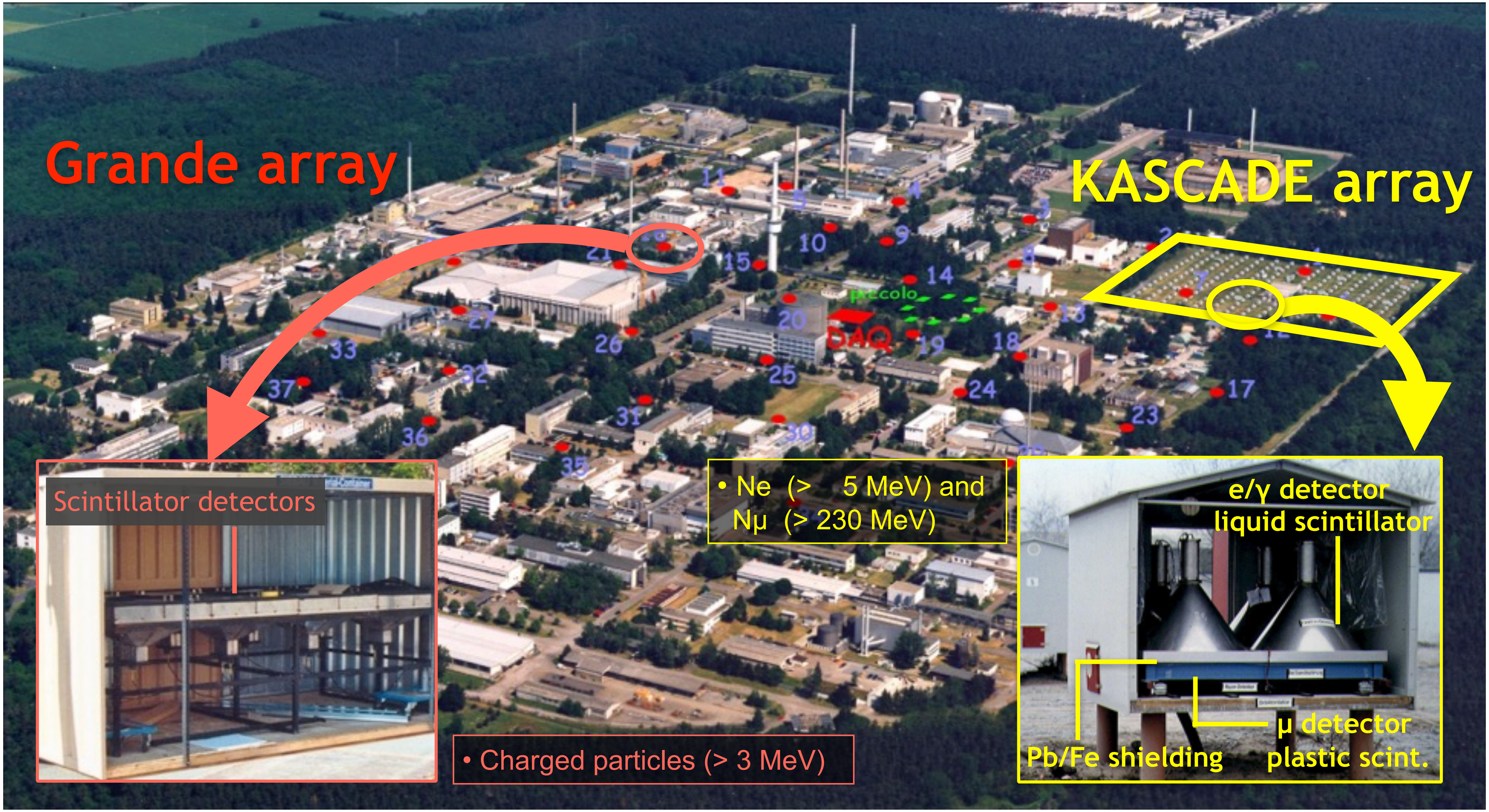
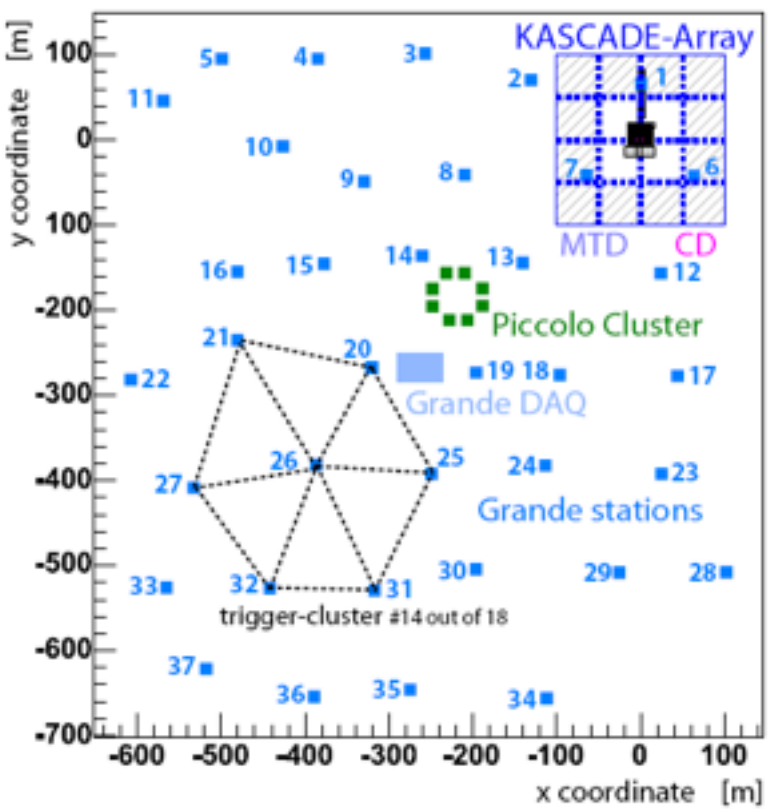


H. Falcke et al., Nature 435 (2005) 313

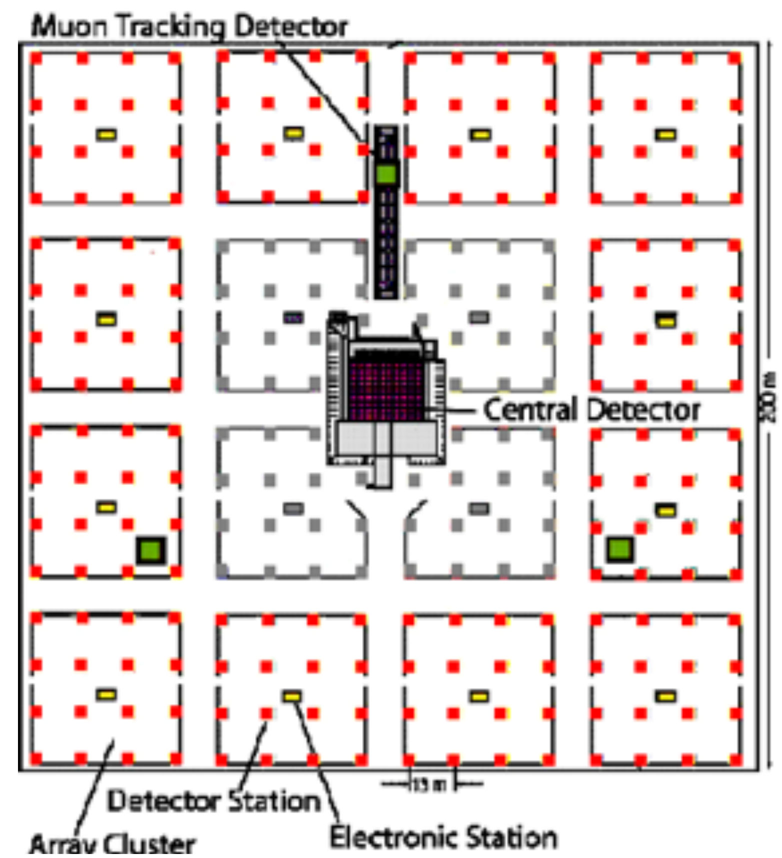
W.D. Apel et al., NIMA 620 (2010) 490

The KASCADE-Grande detector

1. Grande provides
   N_{ch}: Number of charged particles

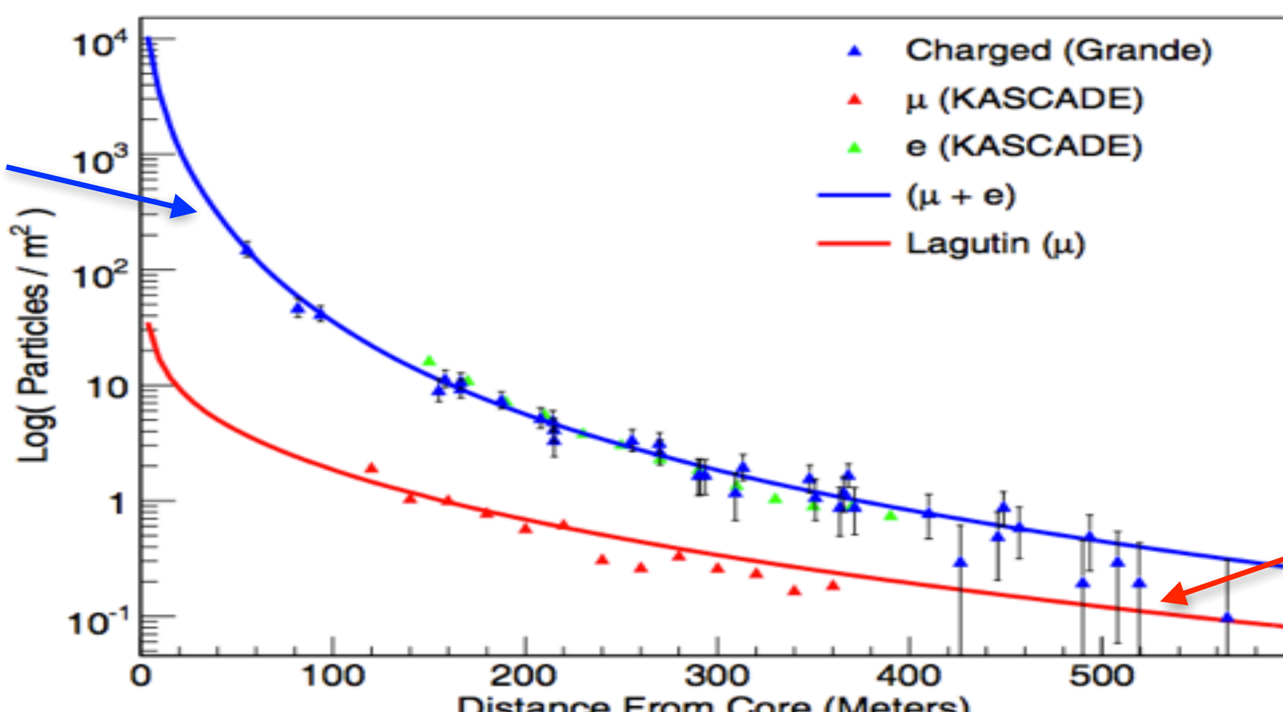


2. KASCADE provides
   N_{μ} : Number of muons



Fit to data:

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



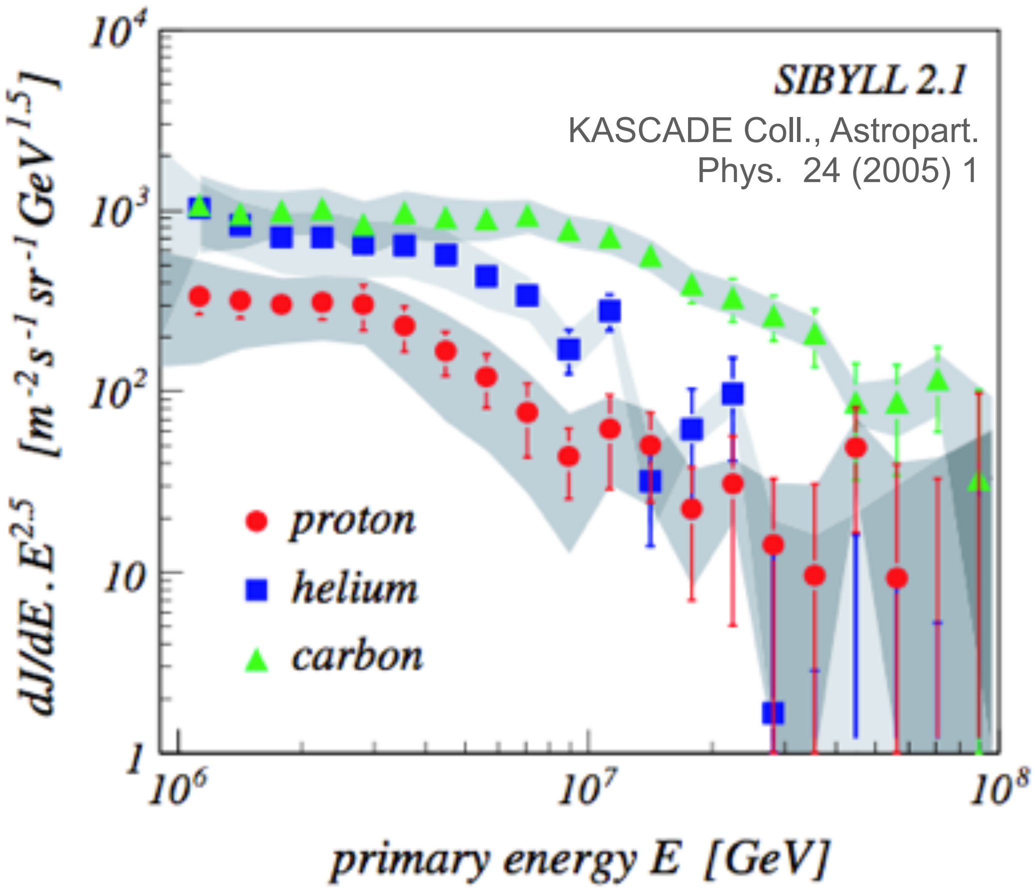
Fit to data:

$\rho_{\mu}(r) = N_{\mu} \cdot f_{\mu}^{Lagutin}(r)$

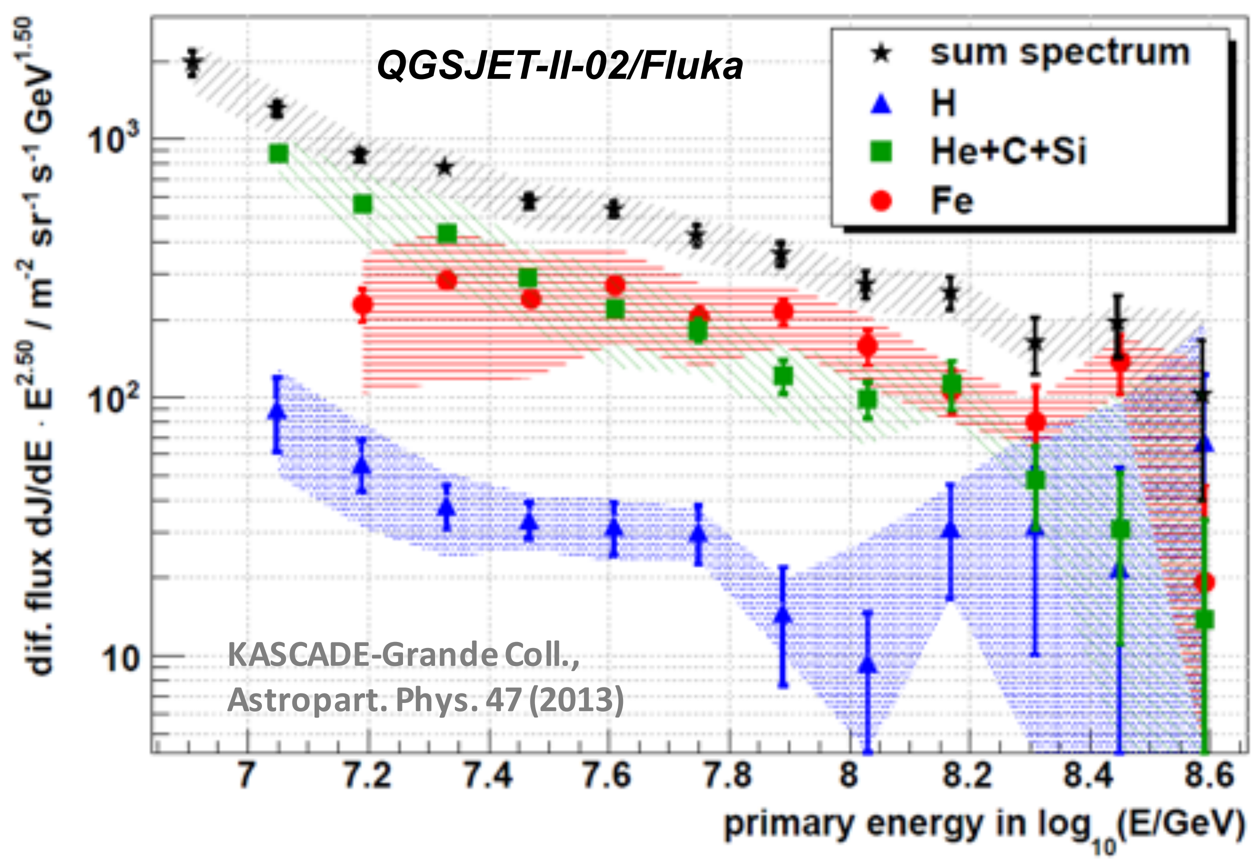
The KASCADE-Grande detector

Unfolding methods capable of reconstructing spectra of elemental groups:

Exploit N_e-N_μ correlation



Exploit N_{ch}-N_μ correlation



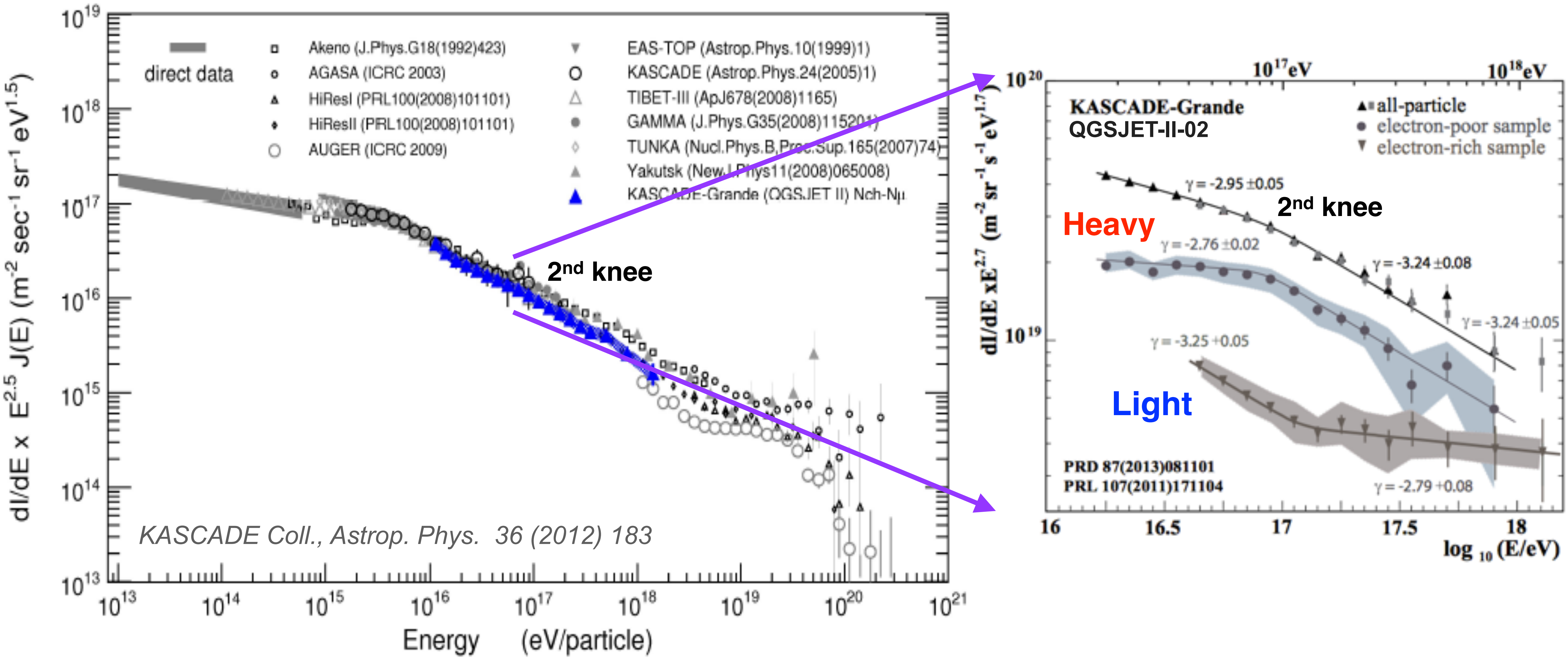
- Knee at E~10^{15} eV due to a break in the spectrum of light components
- Spectral features independent of the hadronic interaction models

- Iron knee around 80 PeV

Knee positions ∝ Z

The KASCADE-Grande detector

– Knee structure around 80 PeV in the heavy component



– Ankle-like feature at 120 PeV in the light component

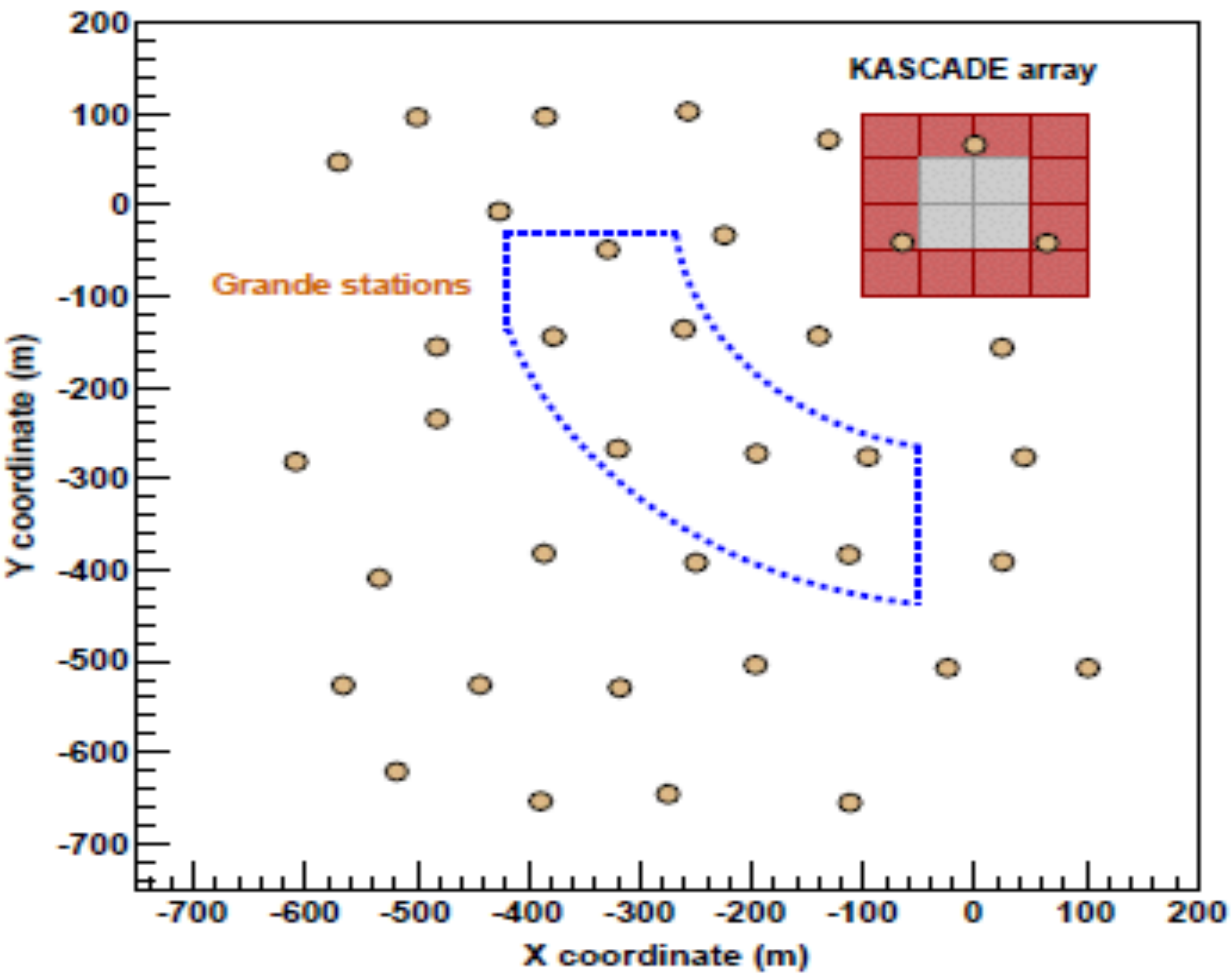
Galactic-extragalactic transition?

Data & simulations

Experimental data

2 744 950 selected events

1. Effective time: 1434 days
2. Área: 8×10^4 m^2
3. Exposure: 2.6×10^{12} m^2 s sr
4. Cuts (reduction of EAS uncertainties):
   - Central area
   - $\theta < 40^o$
   - Instrumental & reconstruction cuts
   - Optimized for **E = [10^{16}, 10^{17}] eV**



Efficiency: $\log_{10}(E/GeV) = 7 \pm 0.20$

$\log_{10}(N_\mu) = 5 \pm 0.20$

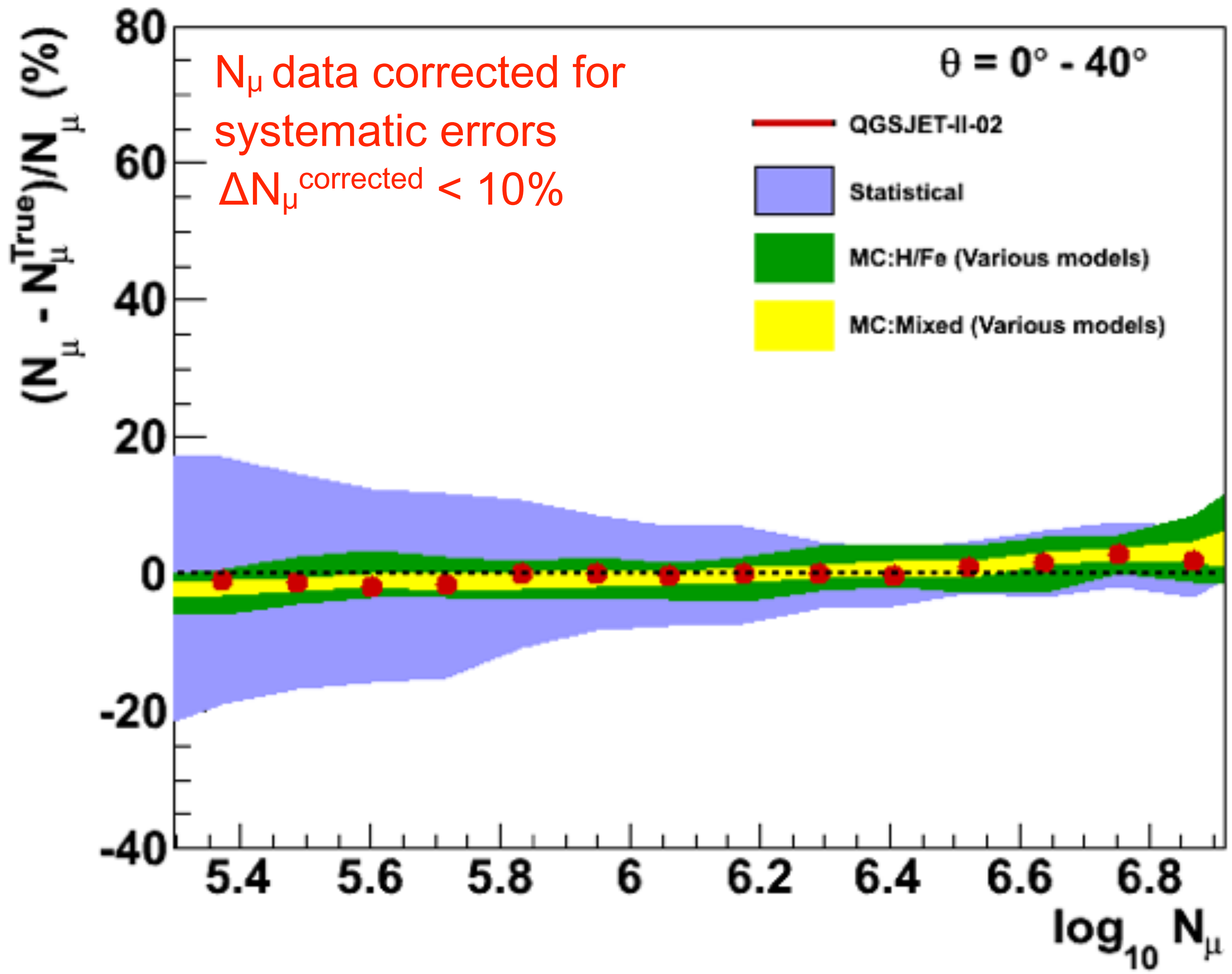
Data & simulations

MC data (CORSIKA/Fluka)

1. HE hadronic interaction
   Model: SIBYLL 2.3

2. Simulation: H, He, C, Si, Fe, mixed;
   $\gamma = -3, -3.2, -2.8$
   $\theta < 42^o$
   $E = 10^{14} - 3 \times 10^{18}$ eV

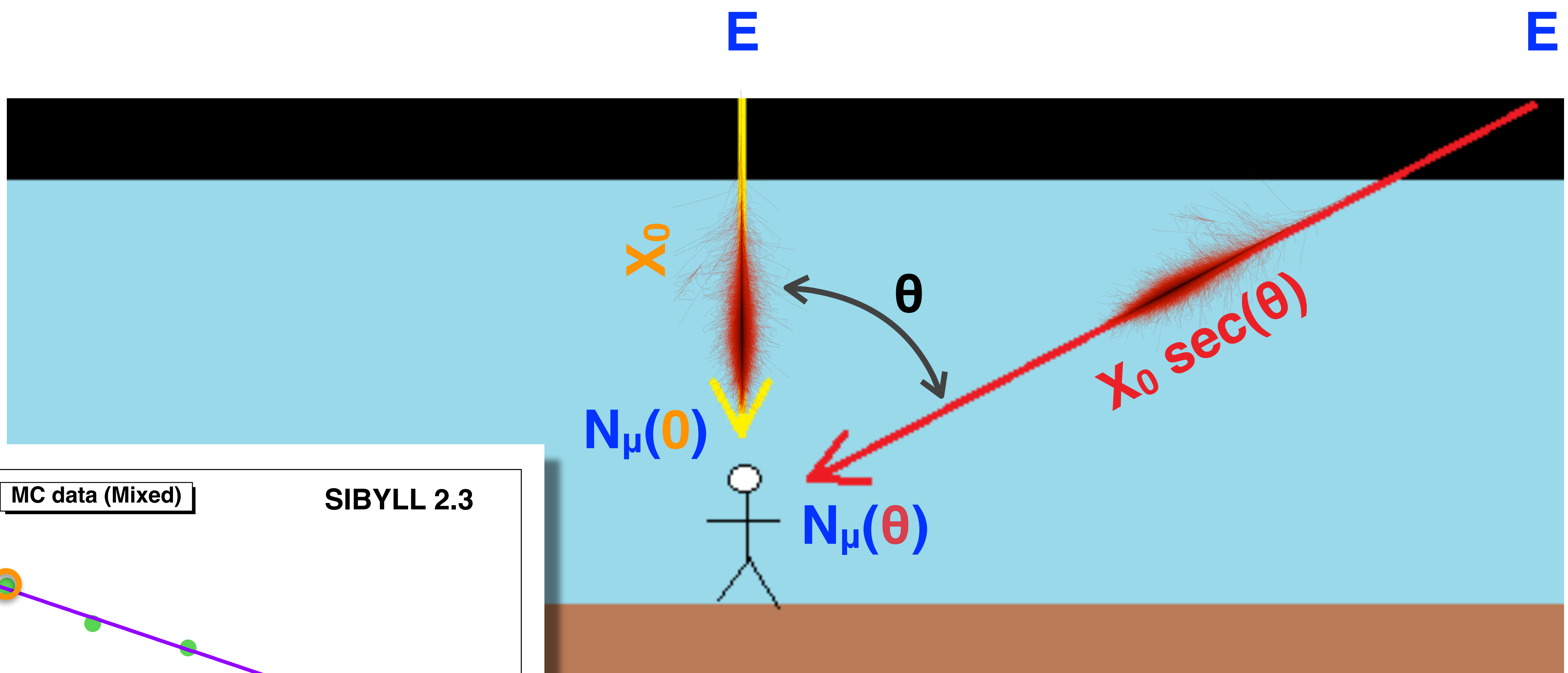
3. Systematics:
   - $\Delta N_{ch} < 12\%$ $\Delta N_\mu < 20\%$
   - $\Delta\theta < 0.6^o$
   - $\sigma_{core} < 10$ m

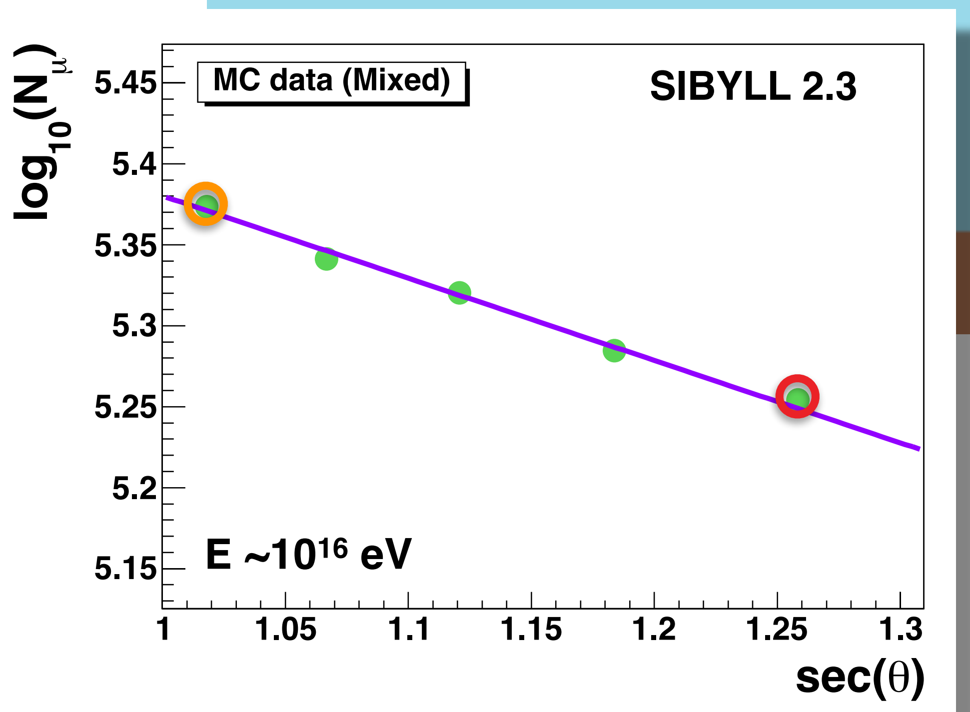


Analysis

Shower content at same Energy (E) is attenuated with atmospheric depth (X):

Large X —> High zenith angles (θ)

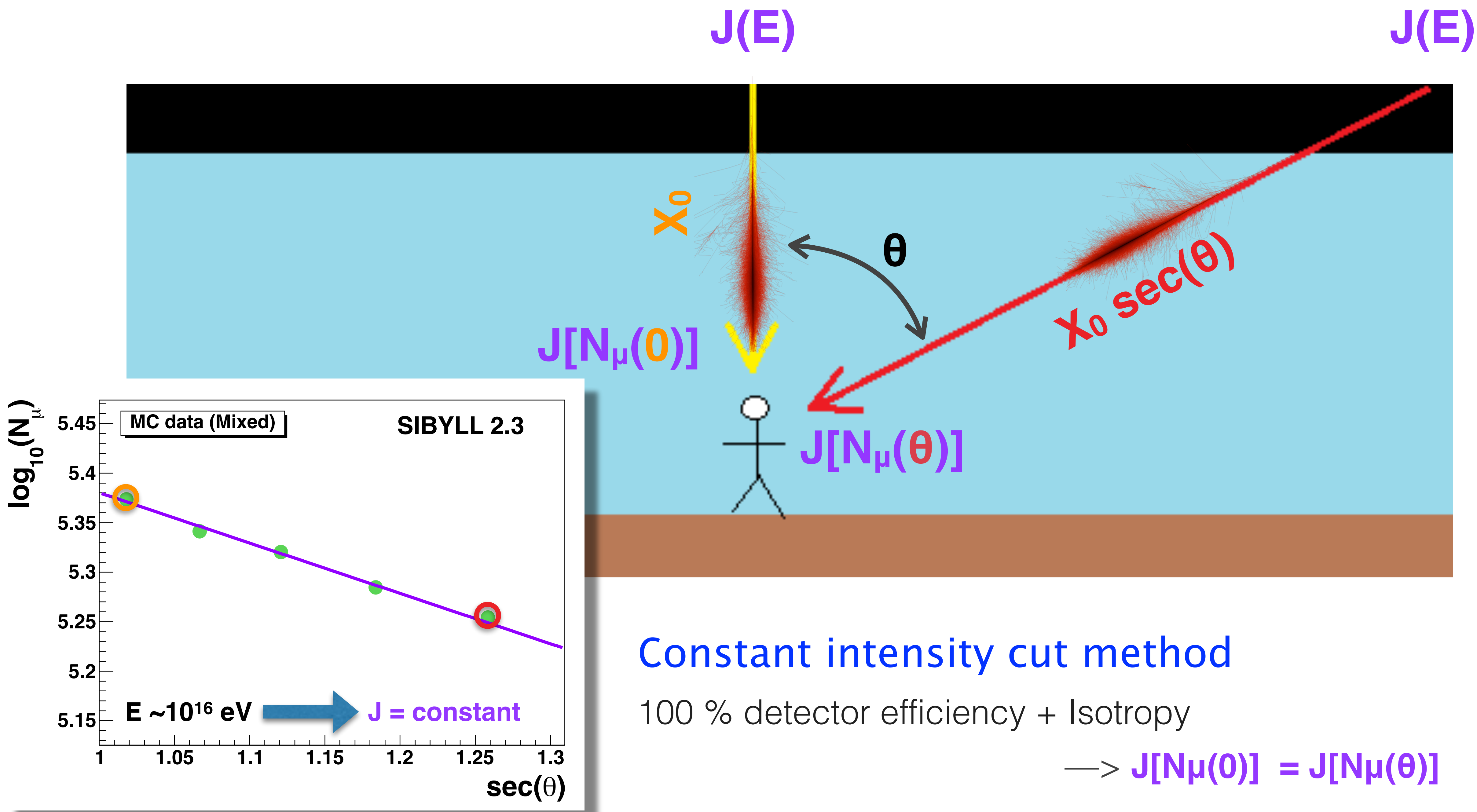




$$N_\mu = N_\mu^0 \exp[-X_0 \sec(\theta)/\Lambda_\mu]$$

Analysis

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



Constant intensity cut method

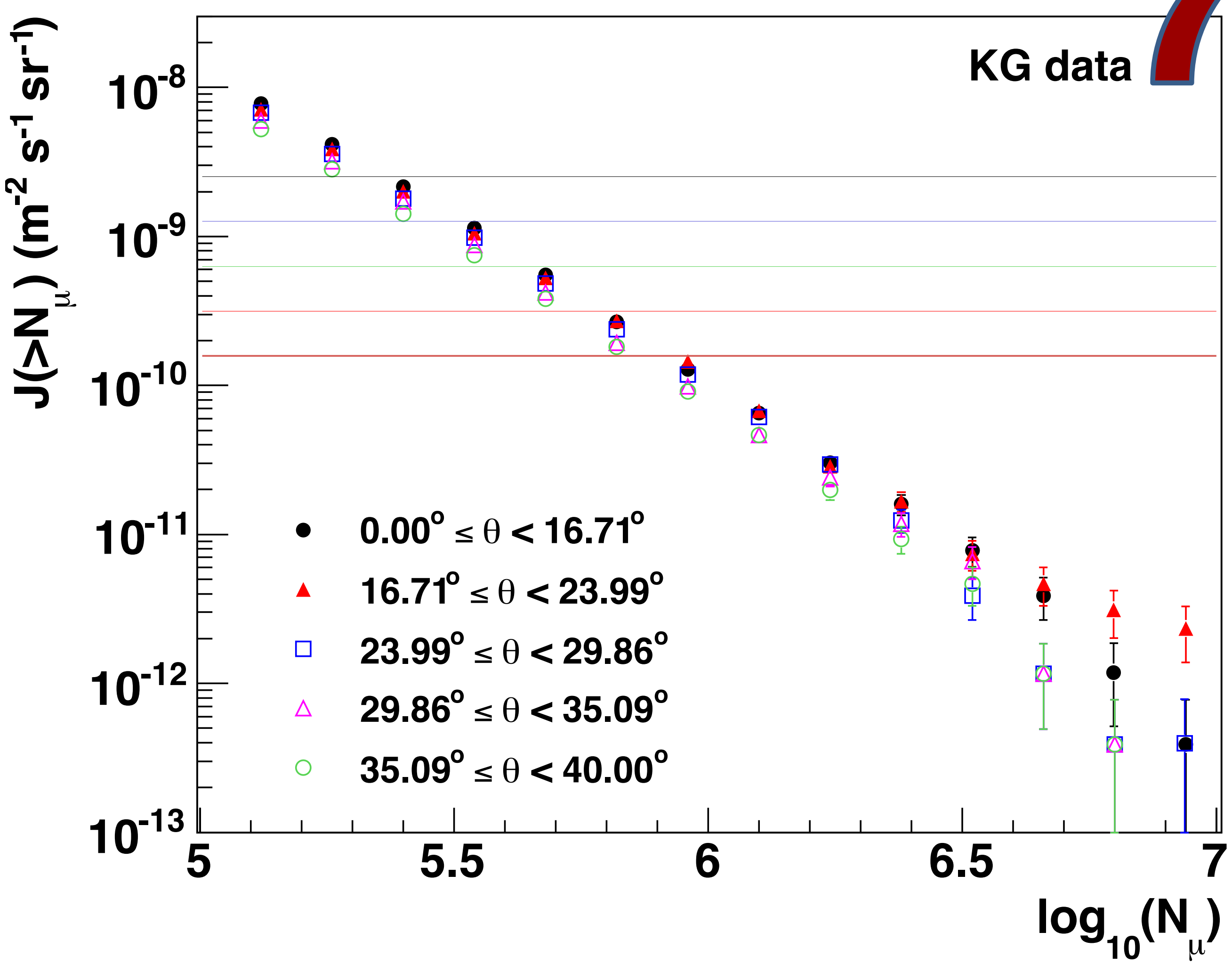
100 % detector efficiency + Isotropy

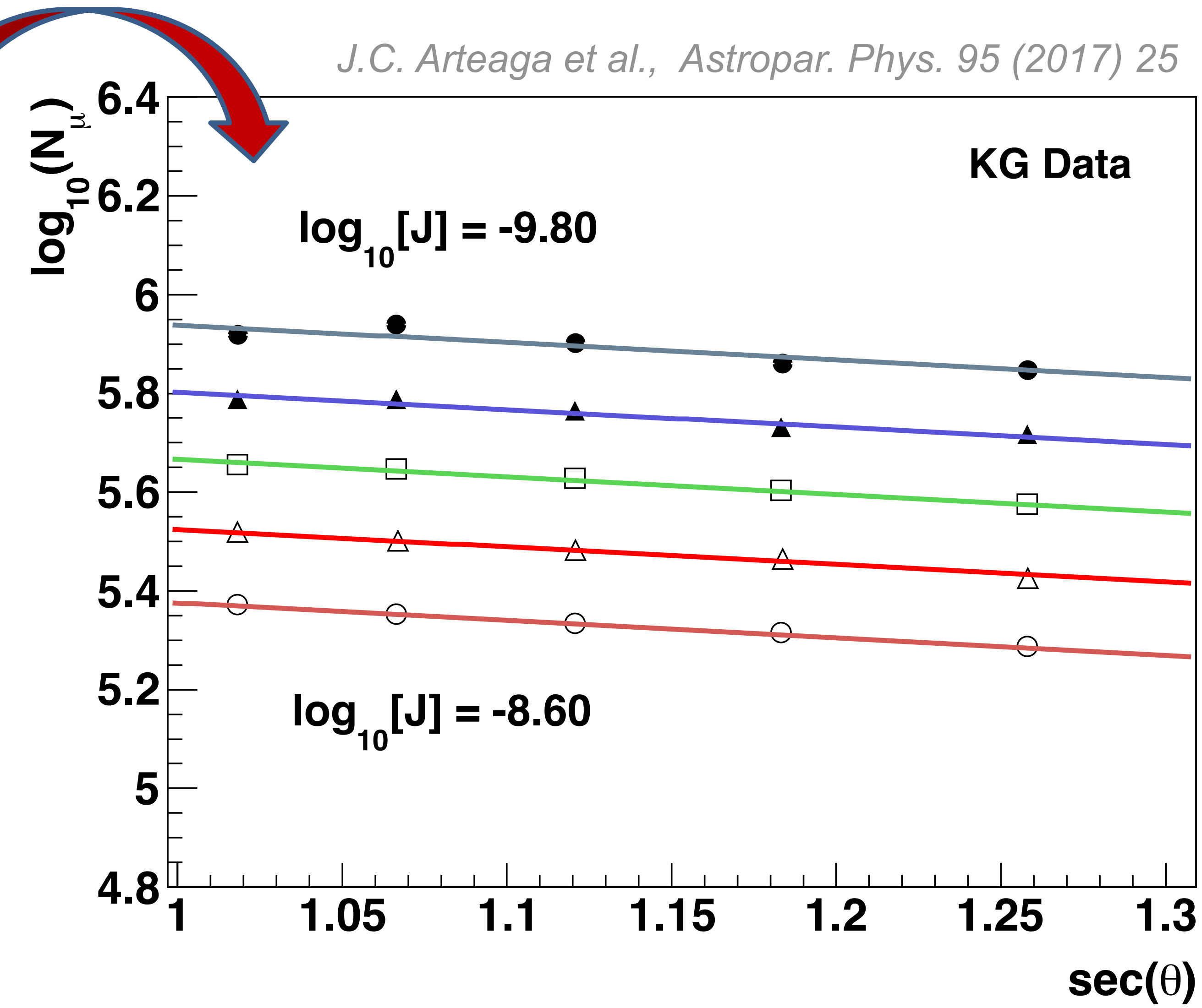
—> J[Nμ(0)] = J[Nμ(θ)]

Analysis

Data divided in five θ intervals with equal exposure.

J.C. Arteaga et al., Astropar. Phys. 95 (2017) 25





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

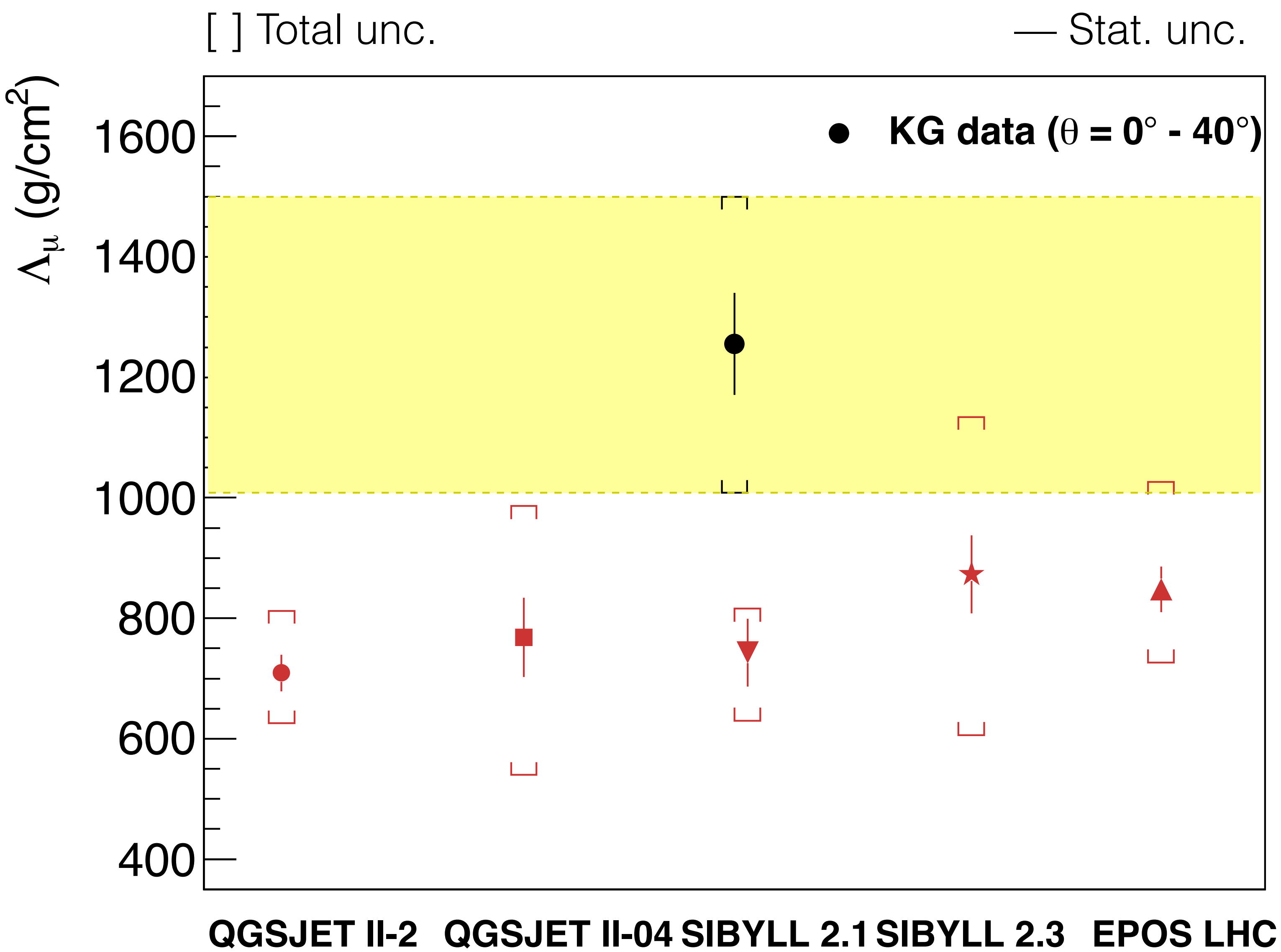
$$N_\mu = N_\mu^0 \exp[-X_0 \sec(\theta)/\Lambda_\mu]$$

1. **Apply** cuts at **fixed frequencies**

2. Get attenuation curves

3. Apply a **fit** to get Λ_μ

Results



MC data also include:
- Errors from composition
- Unc. from spectral index of CR intensity

MC data points:
Mixed composition

ΔΛμ	QGSJET-II-2	QGSJET-II-4	SIBYLL 2.1	SIBYLL 2.3	EPOS-LHC
σ	+2.04	+1.48	+1.99	+1.06	+1.34

Discrepancy between SIBYLL 2.3 and measurement is small, but large uncertainty from composition

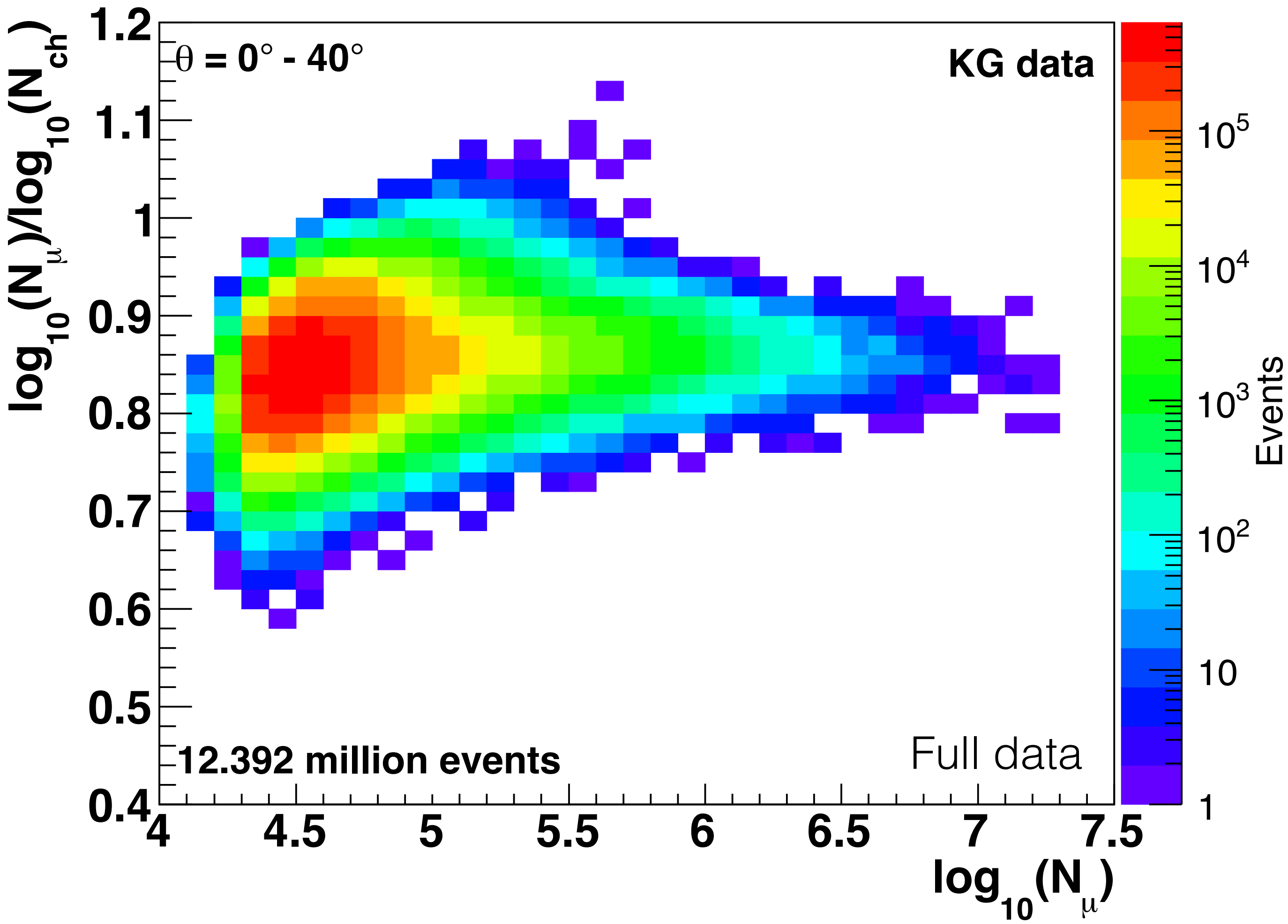
*Errors on SIBYLL 2.3 are preliminary

Results

Reduce error due to composition uncertainties:

- X^2 **fit to measured data** with 4 mass groups: H, He, C, Si+Fe (50 % mixture).
- Use **double power-law** for energy spectrum of each mass group.
- Employ **templates** from SIBYLL 2.3 for each mass group.

J.C. Arteaga et al., (KG Collab.) PoS (ICRC2017) 316

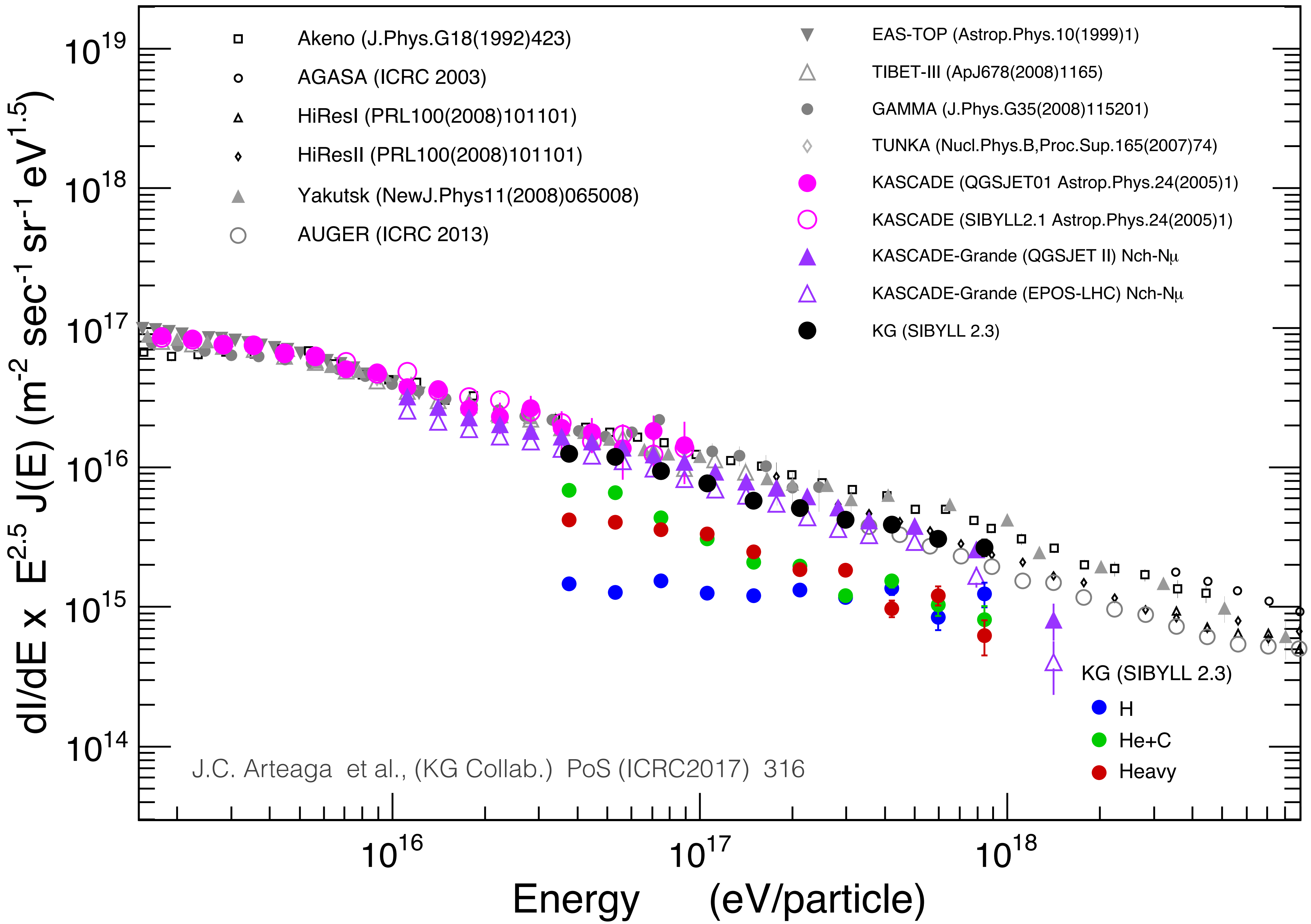


$$\chi^2 = \sum_{i,j} \frac{[n_{ij}^{exp} - \sum_A n_{ijA}^{MC}(\mathbf{p}_A)]^2}{(\sigma_{ij}^{MC})^2}$$

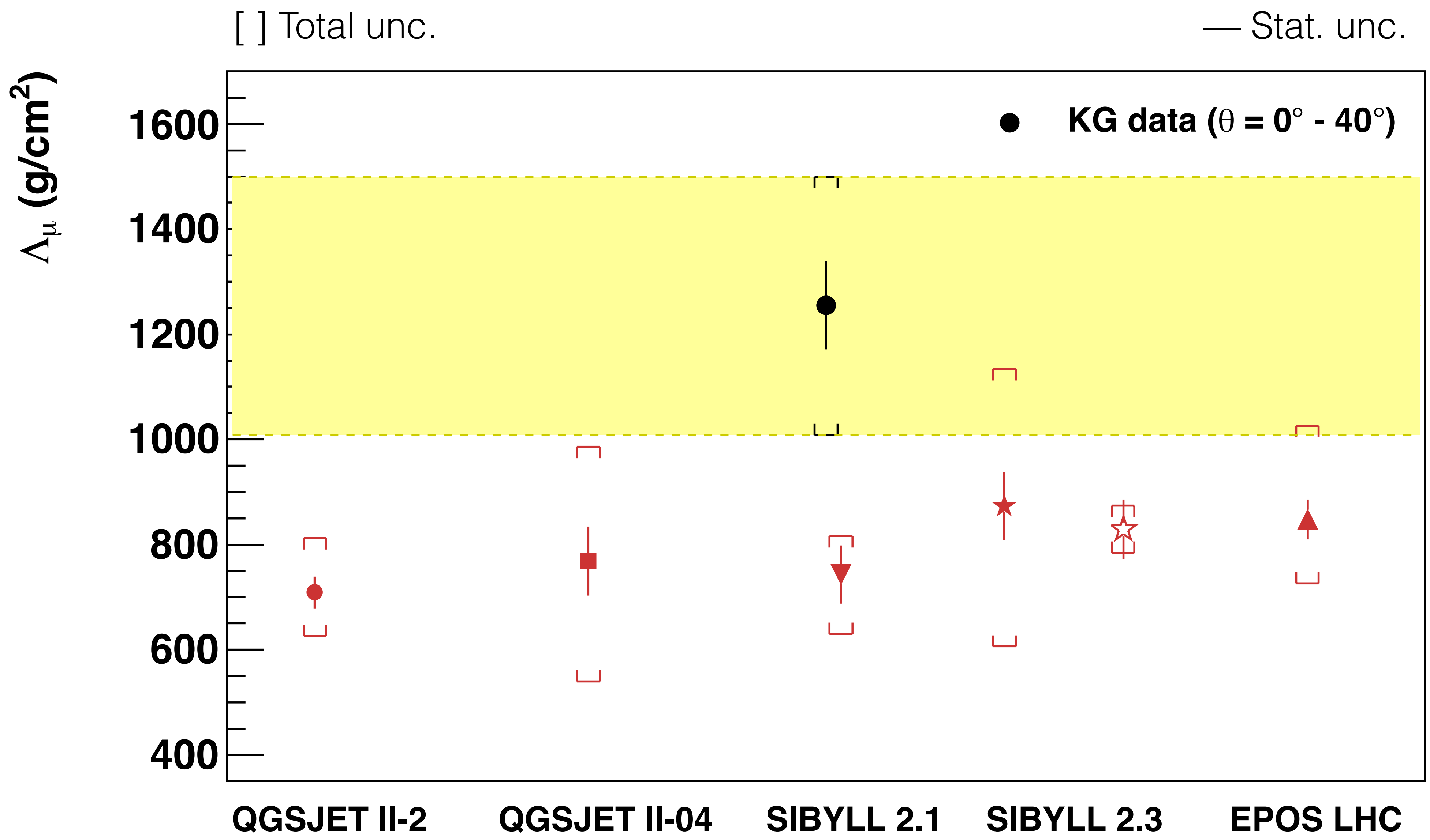
A: atomic mass

Results

Composition model obtained from measured data using SIBYLL 2.3



Results



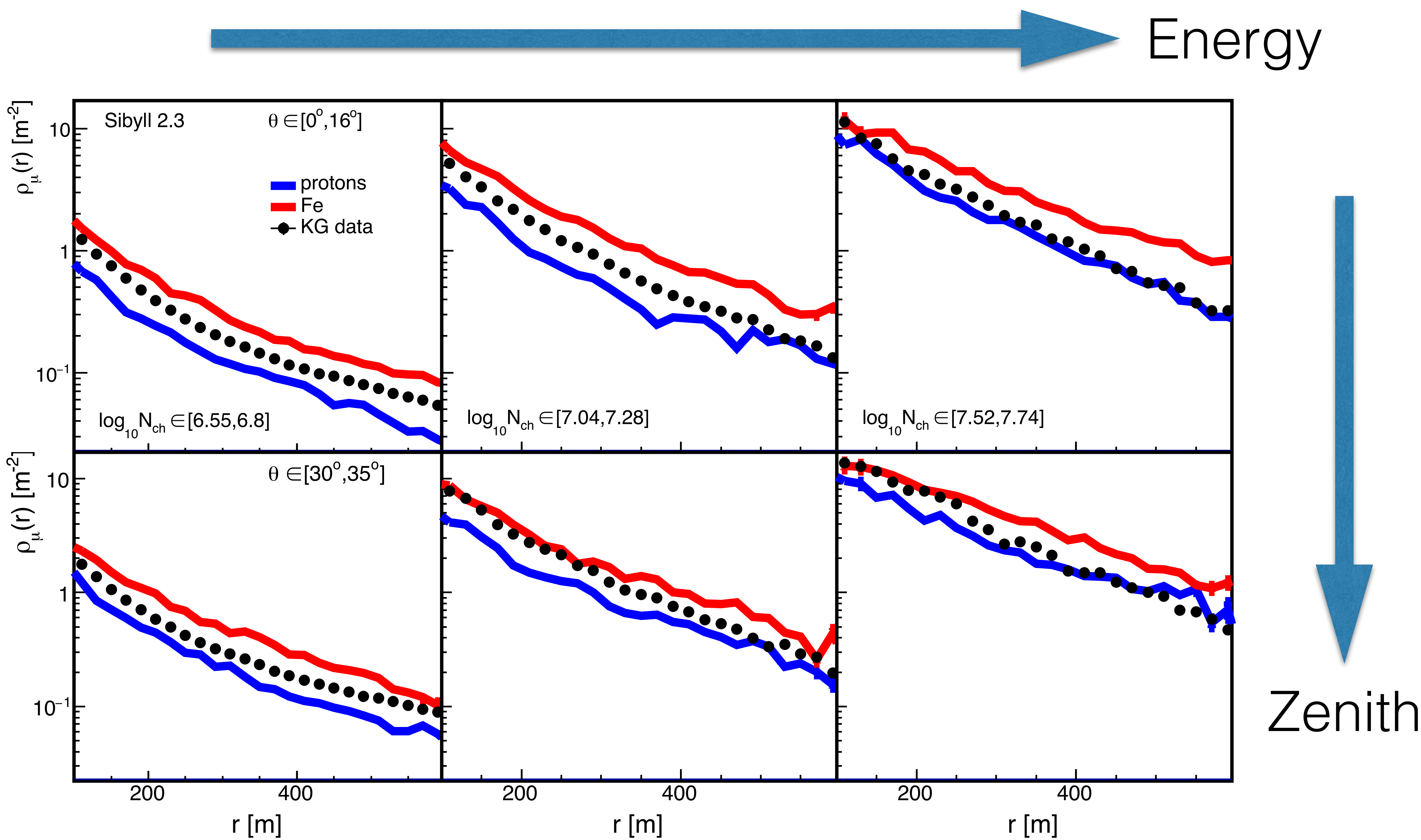
$\Delta\Lambda\mu$	QGSJET-II-2	QGSJET-II-4	SIBYLL 2.1	SIBYLL 2.3	SIBYLL 2.3	EPOS-LHC
					Composition model	
σ	+2.04	+1.48	+1.99	+ 1.06	+ 1.52	+1.34

*Errors on SIBYLL 2.3 are preliminary

SIBYLL 2.3 has also problems to describe the data

Results

Muon lateral densities



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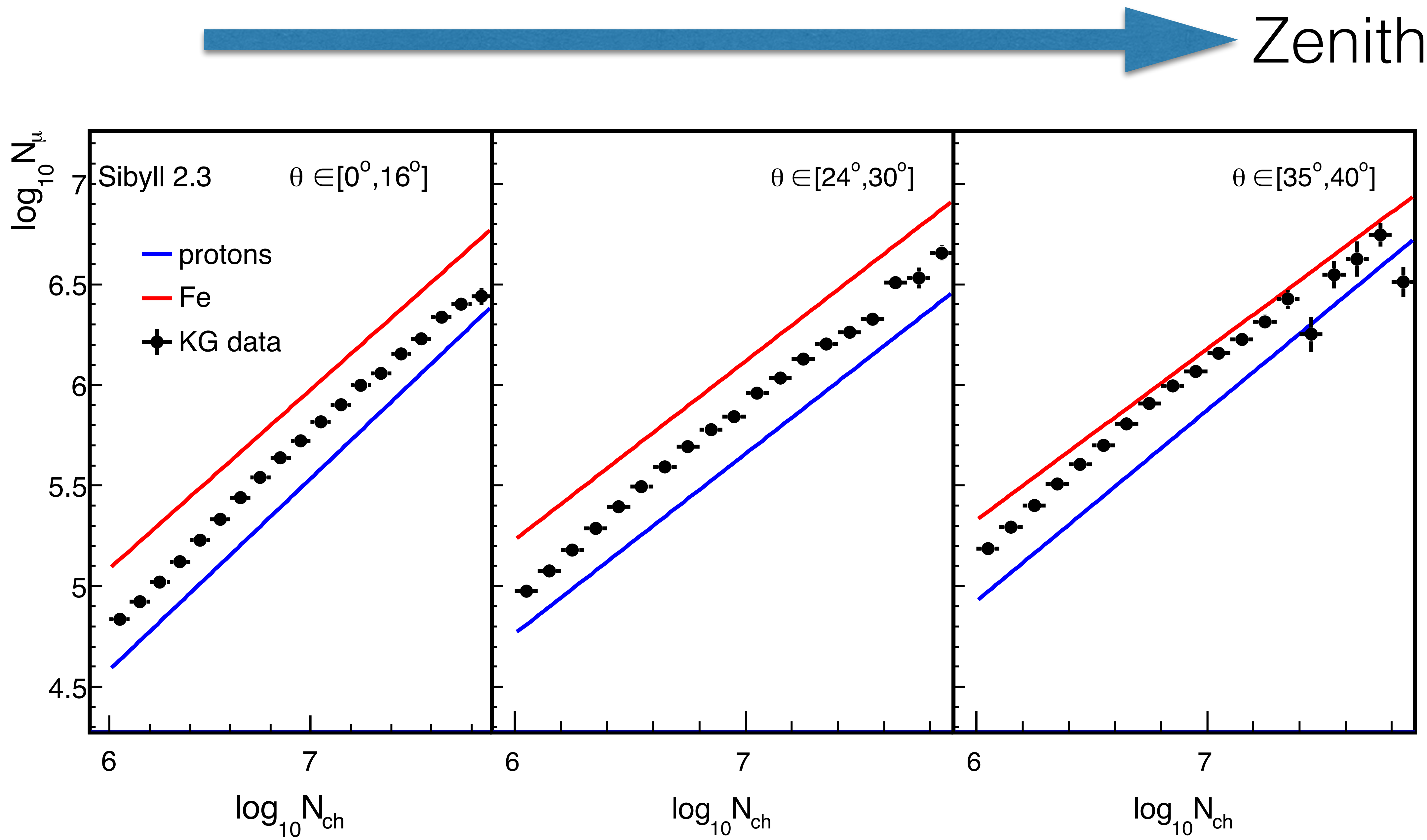
Results

N_μ - N_{ch} correlation



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Summary

1. The measured Λ_μ at KASCADE-Grande is above predictions of HE hadronic interaction models: QGSJET-II-02, QGSJET-II-04, EPOS-LHC and SIBYLL 2.3.

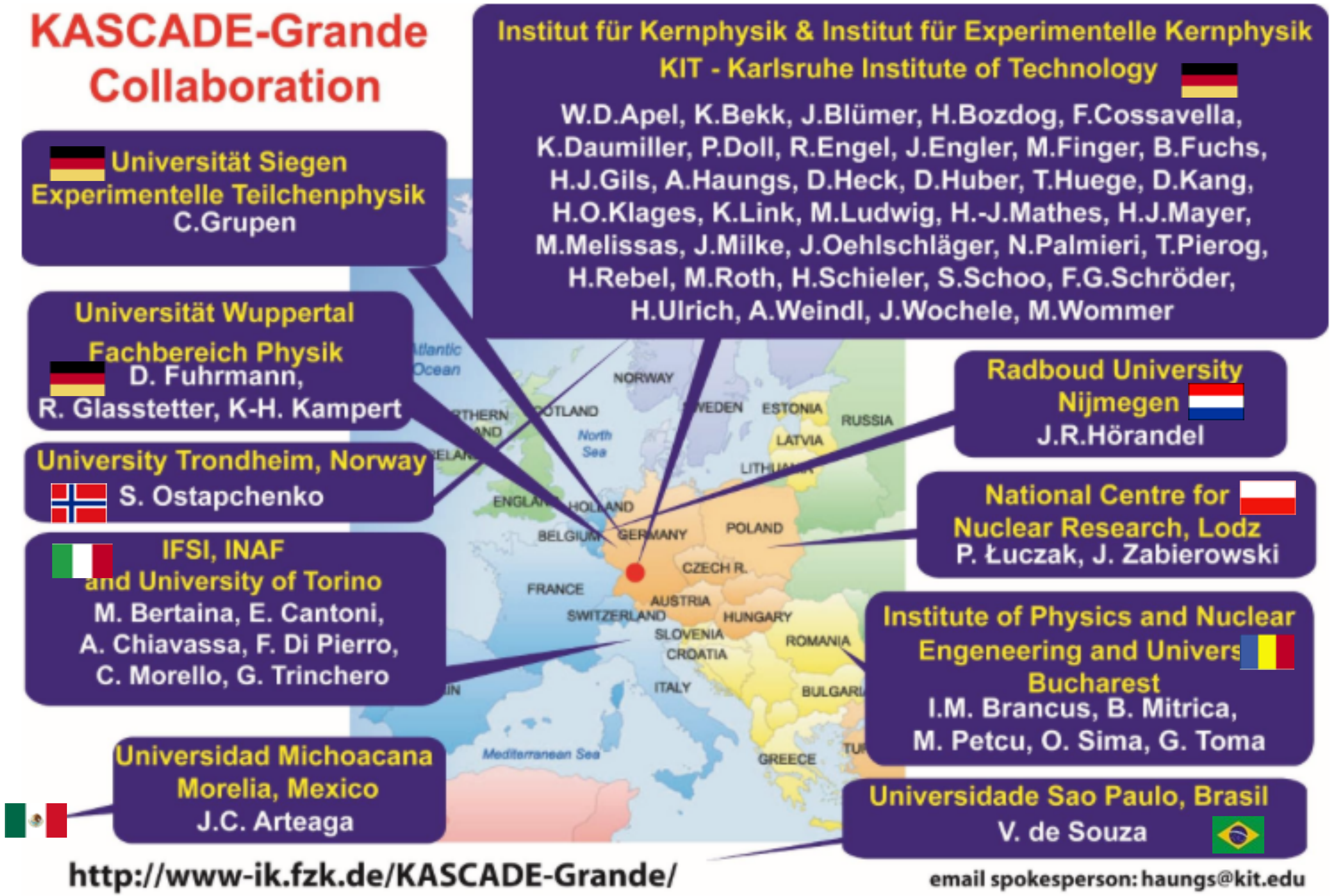
2. Post-LHC models predict a Λ_μ value higher than that predicted by Pre-LHC models.

3. The models might need:

   - a harder μ energy spectrum,
   - a decrease of elasticity in pion interactions,
   - a reduction of forward production of baryon/antibaryon pairs, etc.,

   to agree with the data.

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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Experimentelle Teilchenphysik
C.Grupen
Universität Wuppertal
Fachbereich Physik
D. Fuhrmann, R. Glasstetter, K-H. Kampert
University Trondheim, Norway
S. Ostapchenko
IFSI, INAF and University of Torino
M. Bertaina, E. Cantoni, A. Chiavassa, F. Di Pierro, C. Morello, G. Trinchero
Universidad Michoacana
Morelia, Mexico
J.C. Arteaga
Radboud University Nijmegen
J.R.Hörandel
National Centre for Nuclear Research, Lodz
P. Łuczak, J. Zabierowski
Institute of Physics and Nuclear Engeneering and Univers Bucharest
I.M. Brancus, B. Mitrica, M. Petcu, O. Sima, G. Toma
Universidade Sao Paulo, Brasil
V. de Souza
NORWAY
ESTONIA
RUSSIA
LATVIA
North Sea
HOLLAND
BELGIUM
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CZECH R.
FRANCE
AUSTRIA
SWITZERLAND
HUNGARY
SLOVENIA
CROATIA
ROMANIA
ITALY
GREECE
Mediterranean Sea
http://www-ik.fzk.de/KASCADE-Grande/
email spokesperson: haungs@kit.edu