Confronting EPOS-LHC predictions on the charged particle and muon attenuation lengths of EAS with KASCADE-Grande data

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

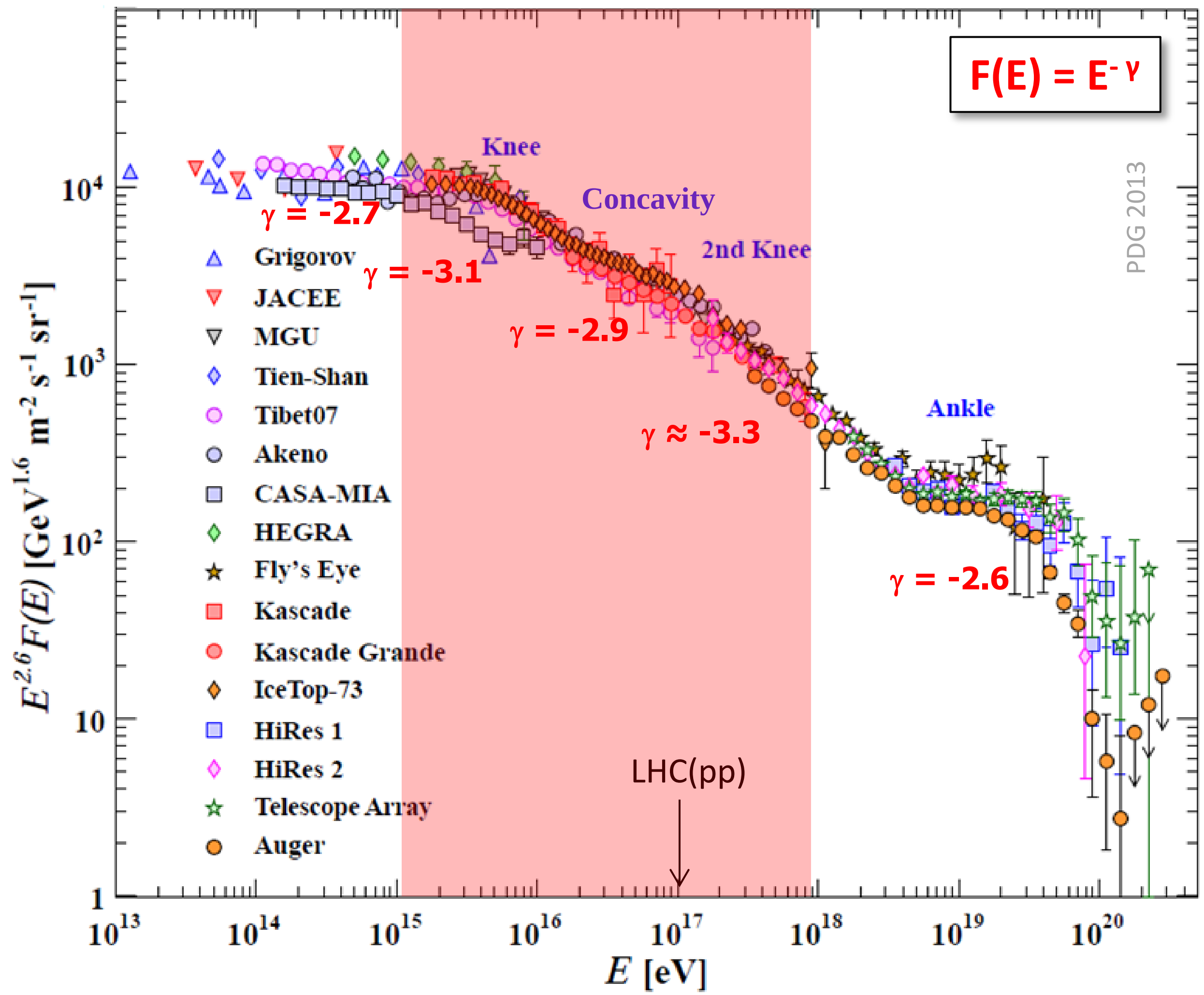
Institute of Physics and Mathematics, Universidad Michoacana
Morelia, Michoacan, Mexico

Structure of the talk:

1) Introduction
2) KASCADE experiment
3) KASCADE-Grande experiment
4) Analyses
5) Results
6) Summary

1) Introduction

1. What is the origin of features in 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?



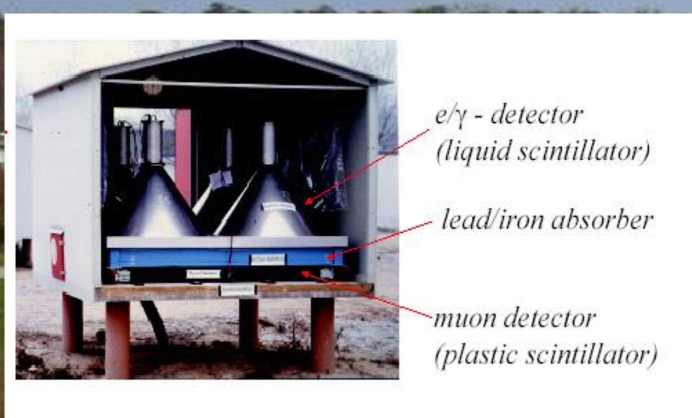
Karlsruhe Shower Core and Array Detector

Study:

- Origin of the knee
  - Composition
  - Energy spectrum
  - Arrival direction

Karlsruhe Shower Core and Array Detector

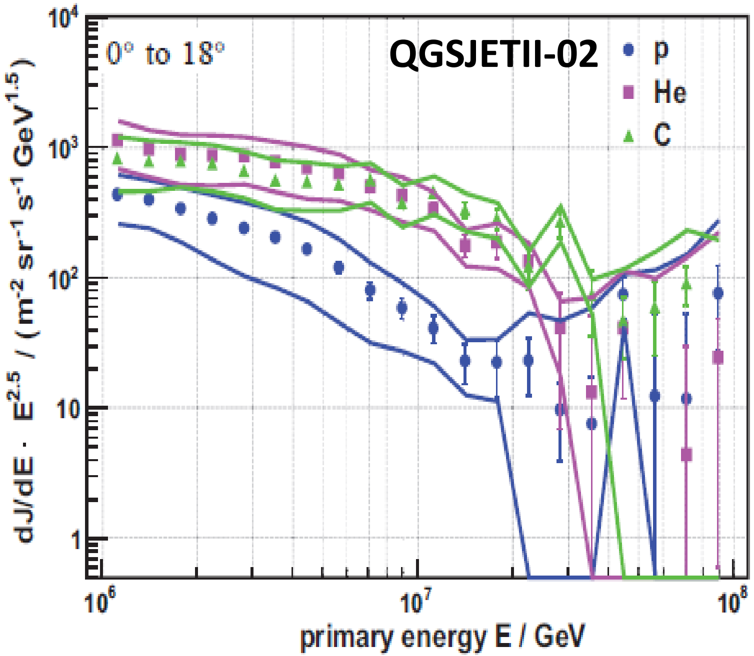
- Components:
  - Ground array (200 x 200 m^2)
    - + 252 e/γ scintillator detectors
    - + 192 μ detectors
  - Central detector
    - + Calorimeter
    - + μ detectors
  - Muon tracking detector
- Observables:
  - N_e, N_μ, N_{hadron}
- $E = 10^{14} – 10^{17}$ eV

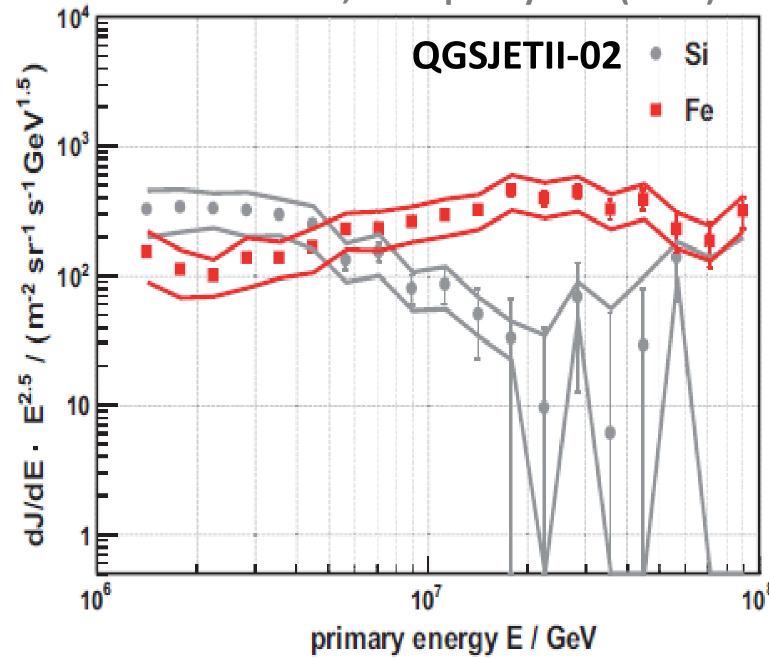


2) KASCADE experiment

Unfolding of energy spectra from KASCADE data

Kascade Coll, Astrop. Phys. 47 (2013) 54





- PeV Knee in all-particle spectrum due to knees of light components:
  - -H knee: E = 4 …
  - -He kn… 10^{15} eV
  - -C kn… E = 20 $\cdot 10^{15}$ eV
- He & C almost equally abundant.

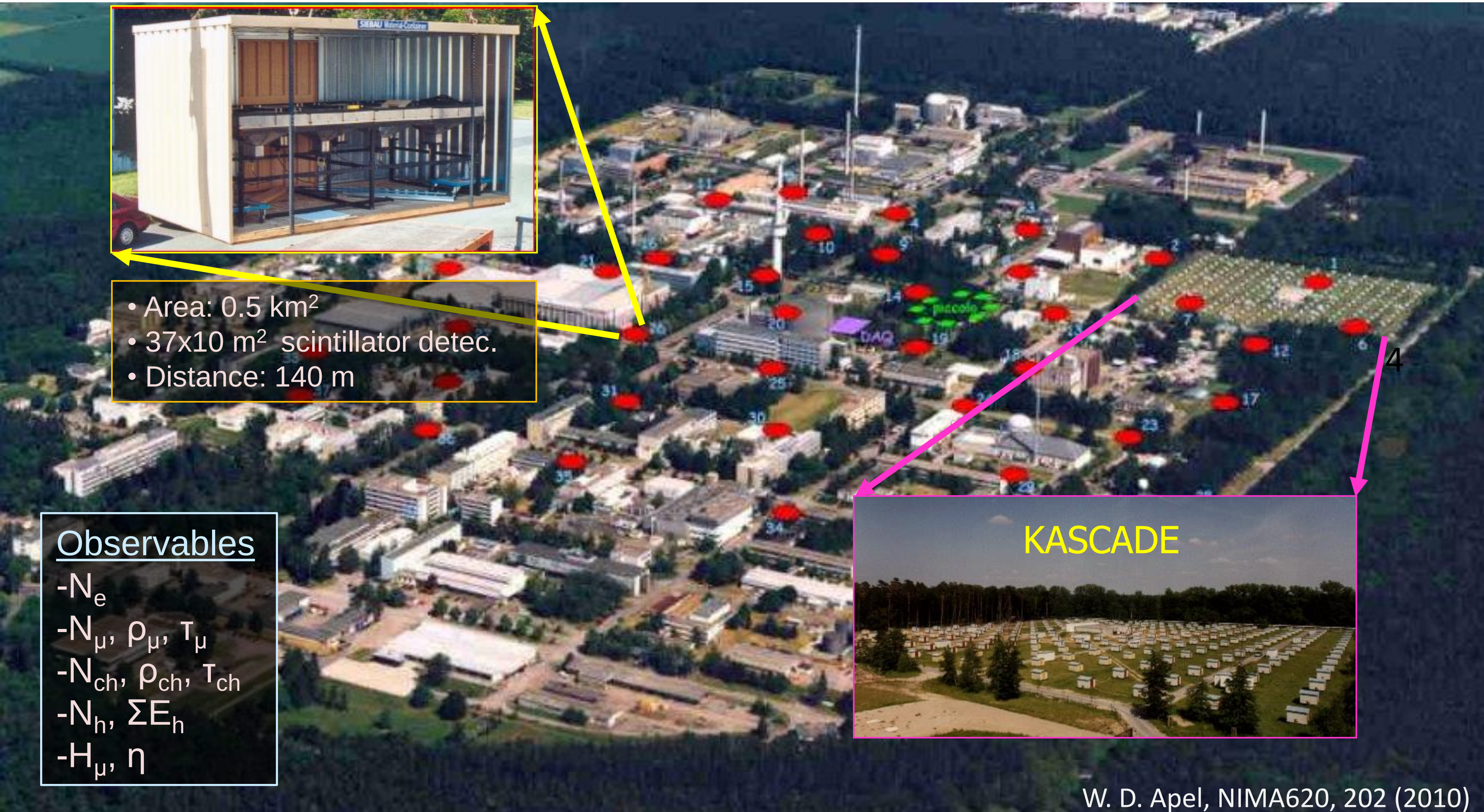
Knee position $\propto$ Z?

- KASCADE measurements of Fe nuclei only up to $< 10^{17}$ eV.
- Where is the Fe knee?

3) KASCADE-Grande experiment

KASCADE-Grande detector (December 2003 – November 2012)

$E = 10^{16} - 10^{18}$ eV



- Area: 0.5 km^2
- 37x10 m^2 scintillator detec.
- Distance: 140 m

Observables

- N_e
- N_μ, ρ_μ, τ_μ
- N_{ch}, ρ_{ch}, τ_{ch}
- N_h, ΣE_h
- H_μ, η

3) KASCADE-Grande experiment

KASCADE-Grande detector (December 2003 – November 2012)

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3) KASCADE-Grande experiment

KASCADE-Grande detector (December 2003 – November 2012)

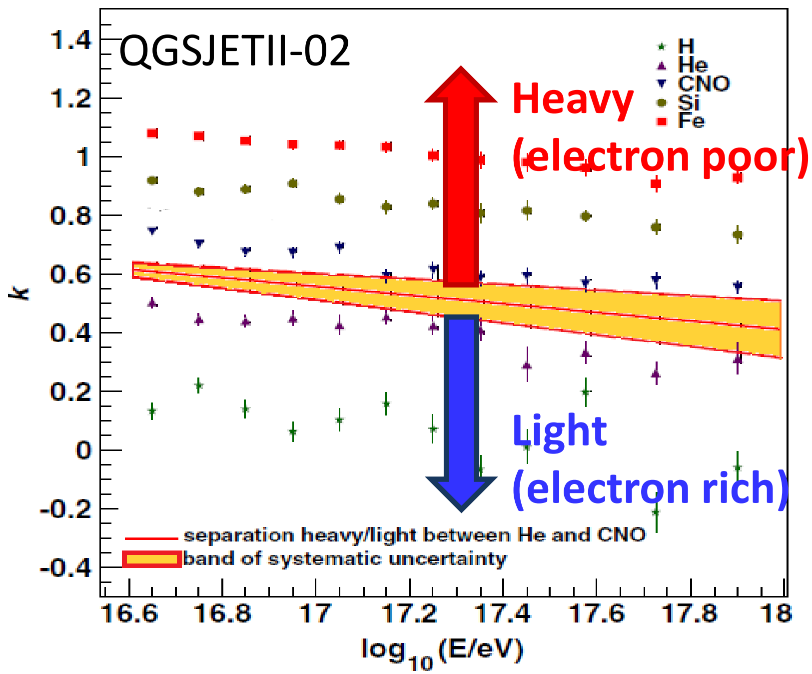
$E = 10^{16} - 10^{18}$ eV

3) KASCADE-Grande experiment

Energy spectrum: K-method

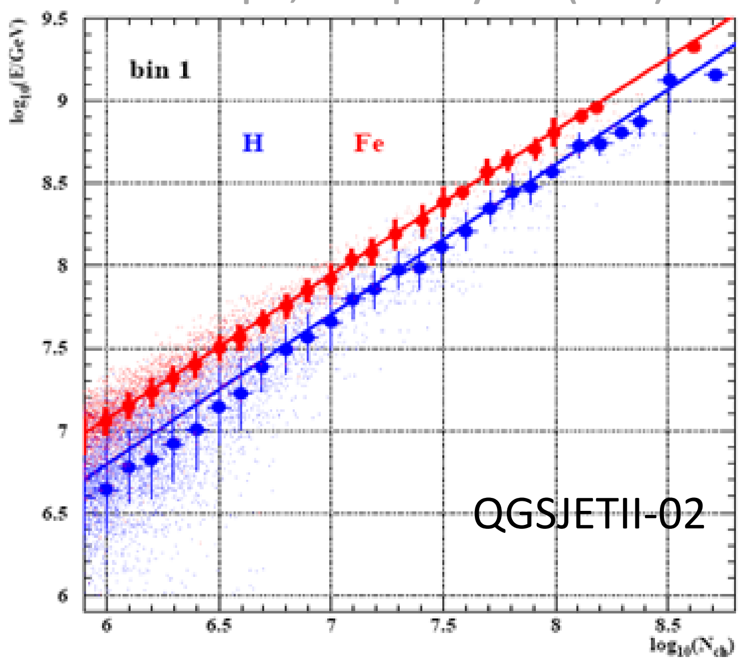
- **Composition independent**
- **Performed for different zenith angle bins independently of each other**

KASCADE-Grande Coll., PRD87 (2013)



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

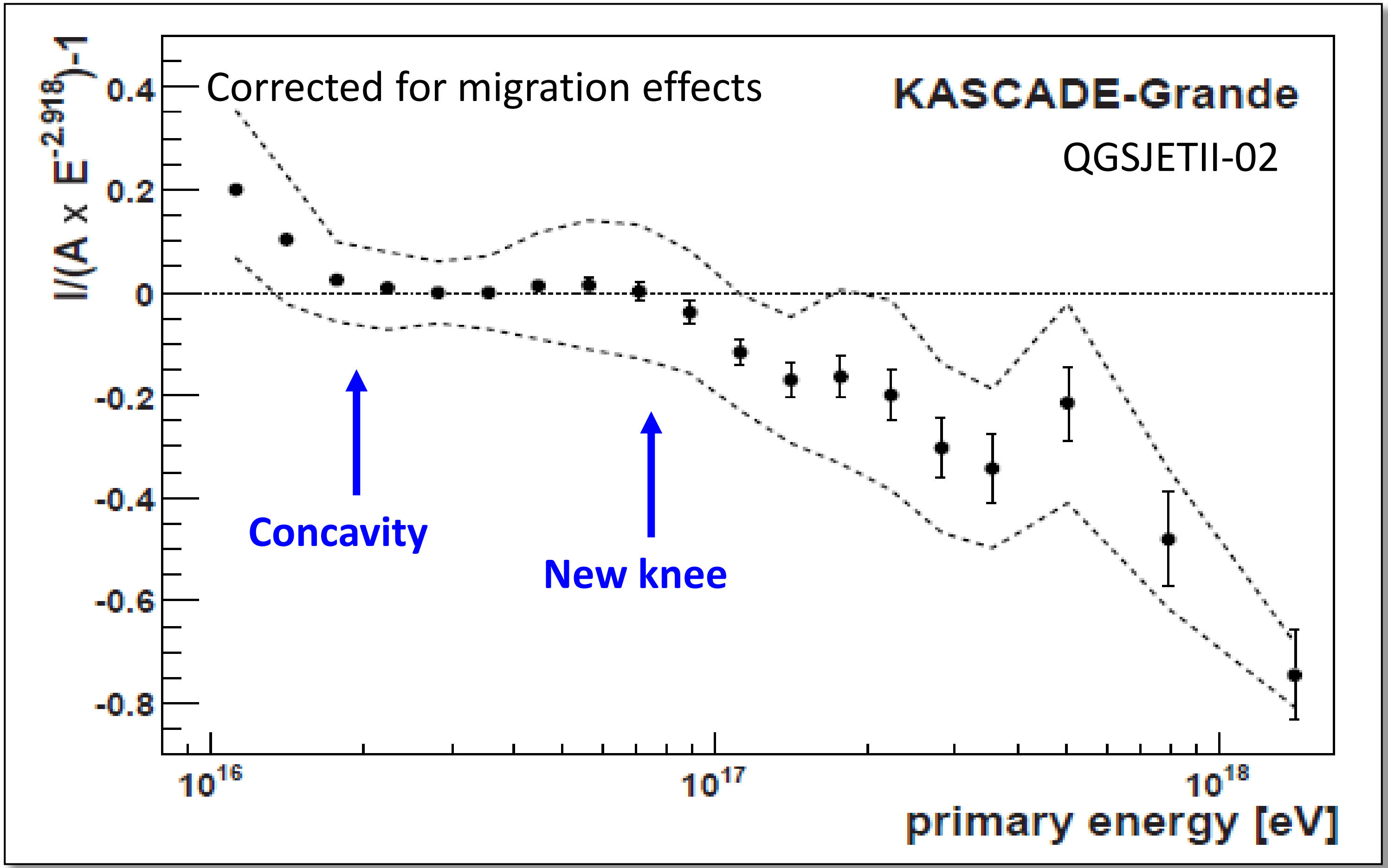
W.D.Apel, Astrop. Phys. 36 (2012) 183



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

Energy spectrum: K-method

W.D.Apel, Astrop. Phys. 36 (2012) 183

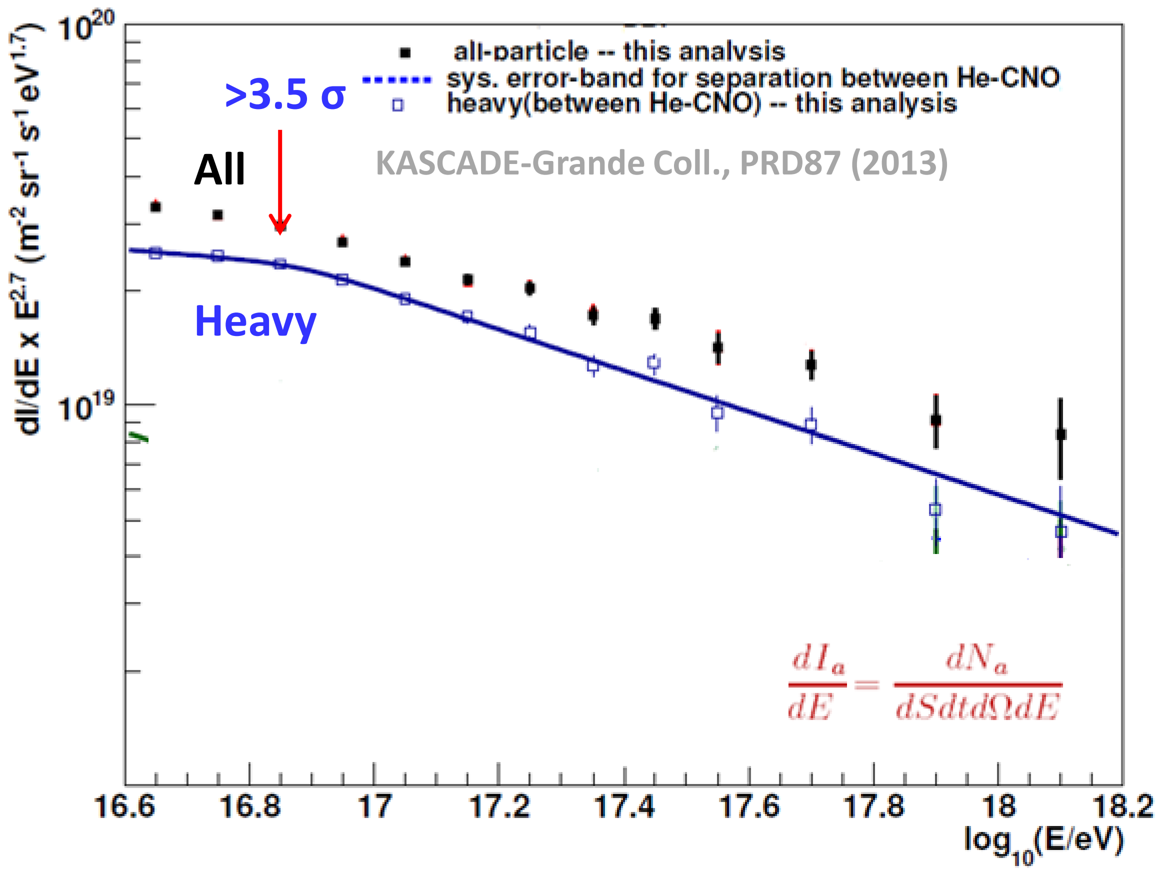


3) KASCADE-Grande experiment

Heavy component

- Dominant, it shows a knee at
  $\log_{10}(E_{break,\ heavy}/eV) = 16.88 \pm 0.03$
- Responsible for new knee in all particle energy spectrum
- Change in spectral index:
  $\gamma_1 = -2.83 \pm 0.01,\ \gamma_2 = 3{,}24 \pm 0.03,$

QGSJETII-02



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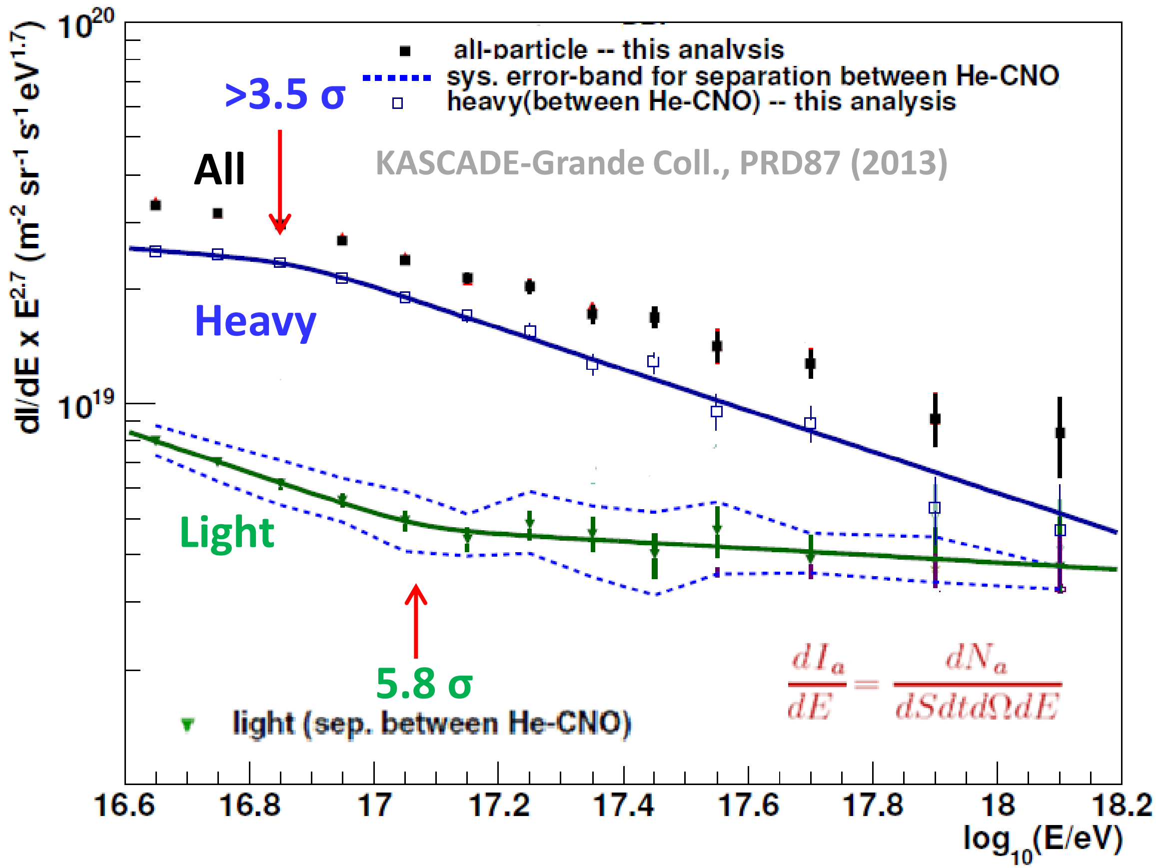
Light component

- Shows an **ankle** → **Recovery**
  $\log_{10}(E_{break,\ light}/eV) = 17.08 \pm 0.08$
- Responsible for galactic to extragalactic transition?
- Change in spectral index:
  $\gamma_1 = -3.25 \pm 0.05, \gamma_2 = -2.79 \pm 0.08$

QGSJETII-02



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Light component

- Shows an ankle at

  $\log_{10}(E_{break,\ light}/eV) = 17.08 \pm 0.08$

- Responsible for galactic to extragalactic transition?

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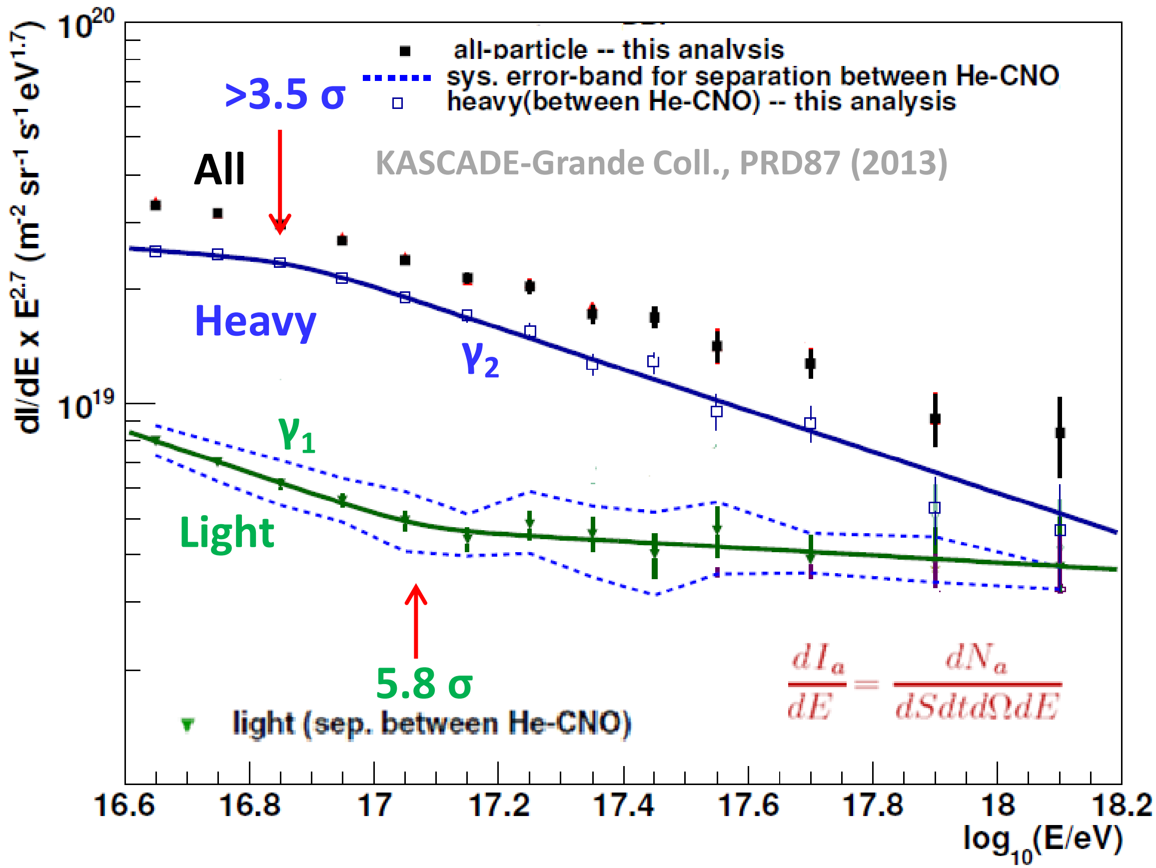
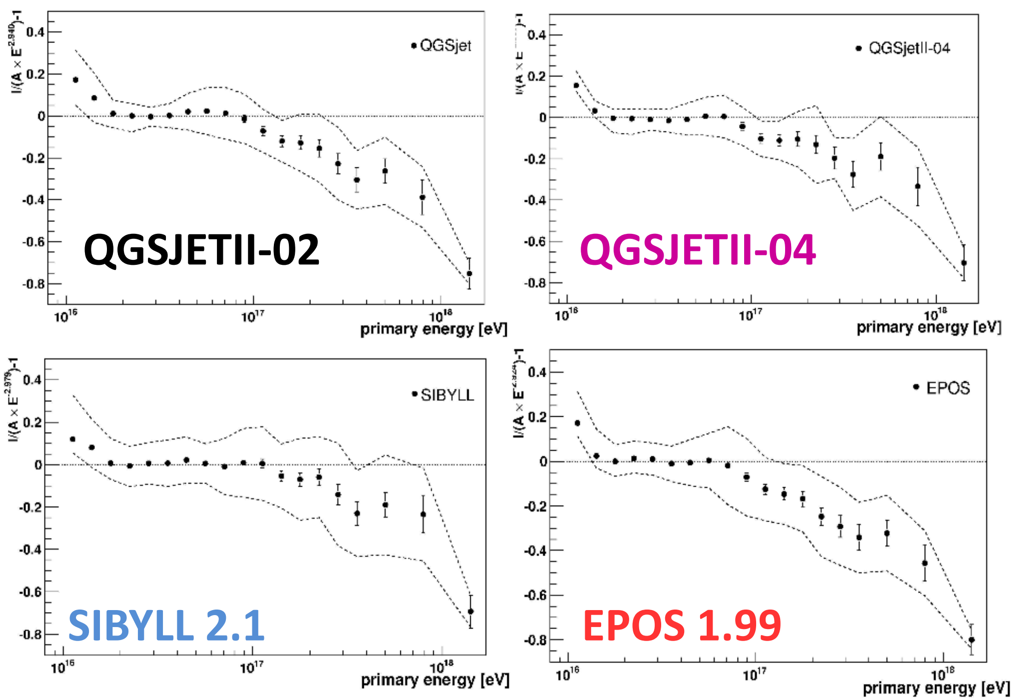
QGSJETII-02



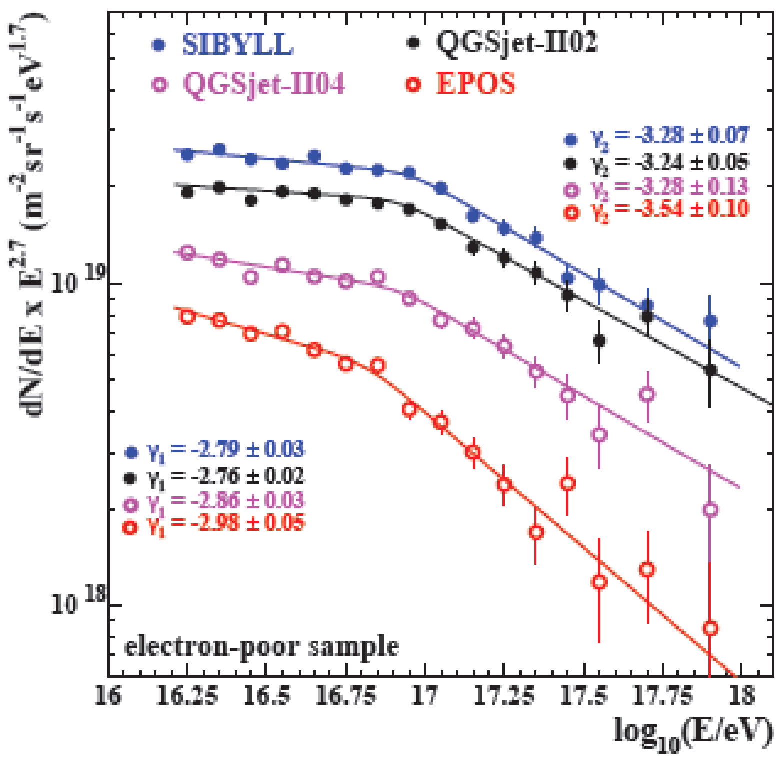
* **The γ_2 of heavy group ≈ γ_1 of light group do they have the same origin?**

All-particle energy spectrum



KASCADE Grande Coll., Nucl. Phys. B (Proc. Suppl.), to be published

Heavy mass group spectrum

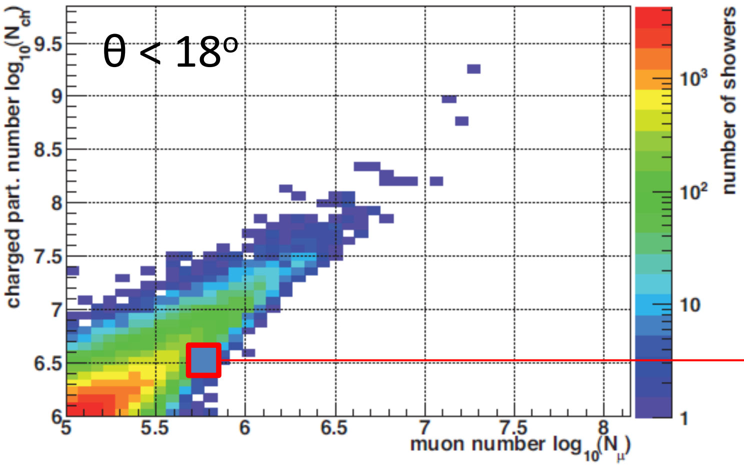


KASCADE Grande Coll., Adv. in Space R. (2013)

Main results are independent of both the method and the model:

-) Shape of individual spectra is retained

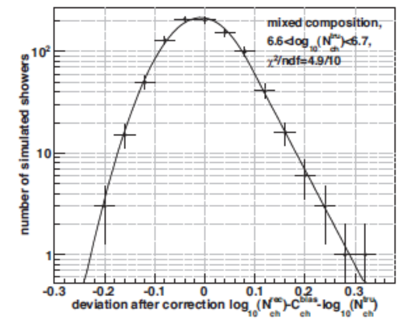
Energy spectrum: Deconvolution



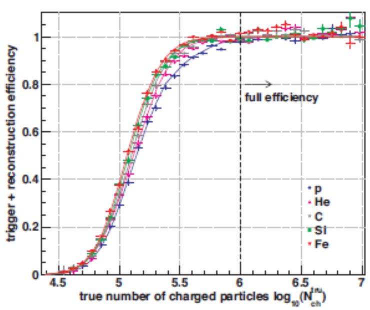
Problem: Find E and A of primary CRs from N_{ch} and N_μ.

$$n_A(\lg N_{ch}, \lg N_\mu) = \int_0^\infty p_A(\lg N_{ch}, \lg N_\mu \,|\, E)\, f_A(E)\, dE$$

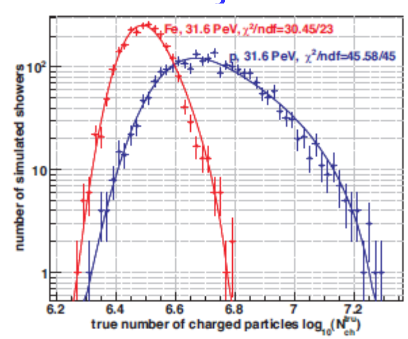
Reconstruction Precision



Efficiency



Air shower fluctuations

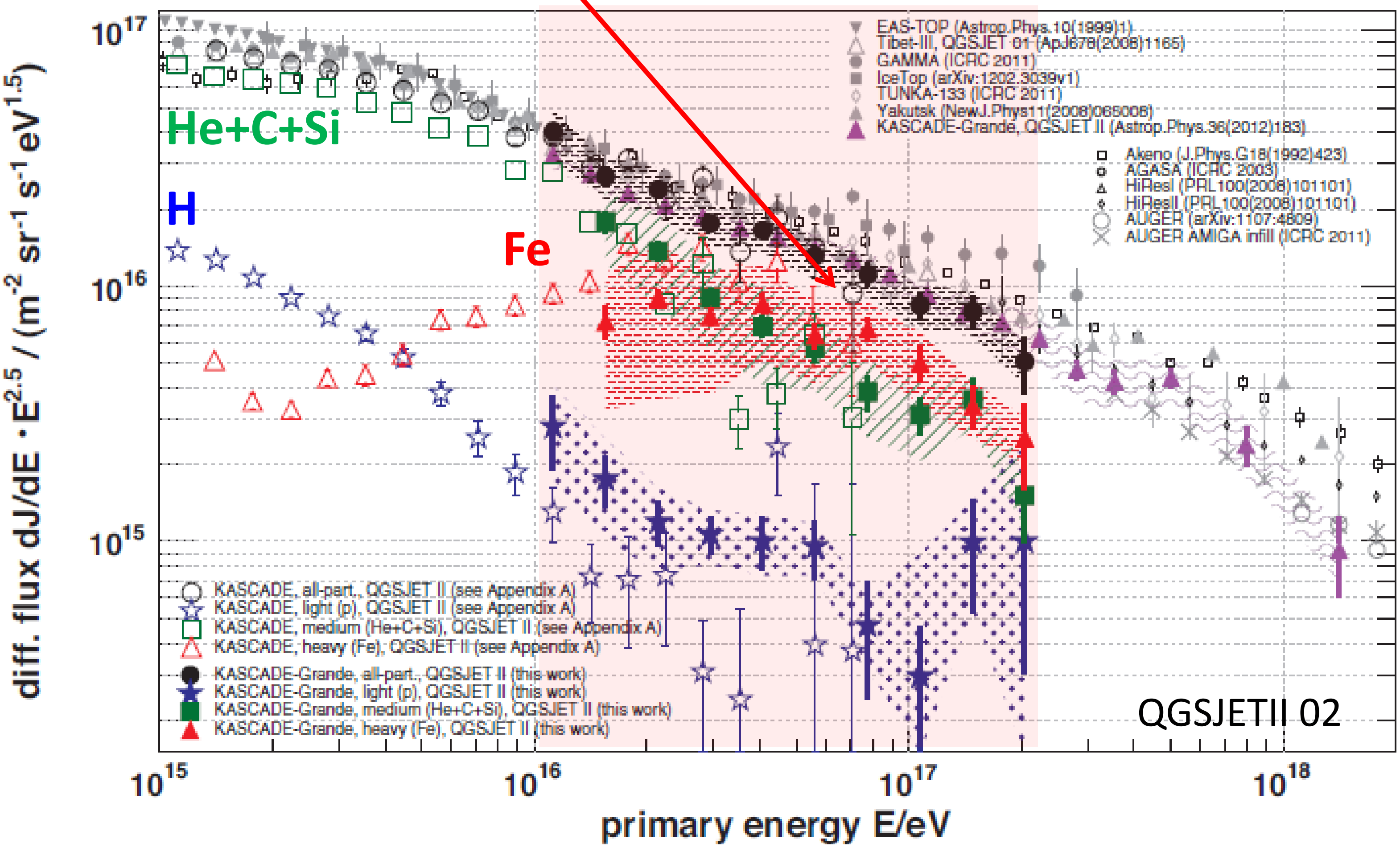


KASCADE-Grande Coll., Astropart. Phys. 47 (2013)

3) KASCADE-Grande experiment

Iron knee (E ≈ 80 PeV)

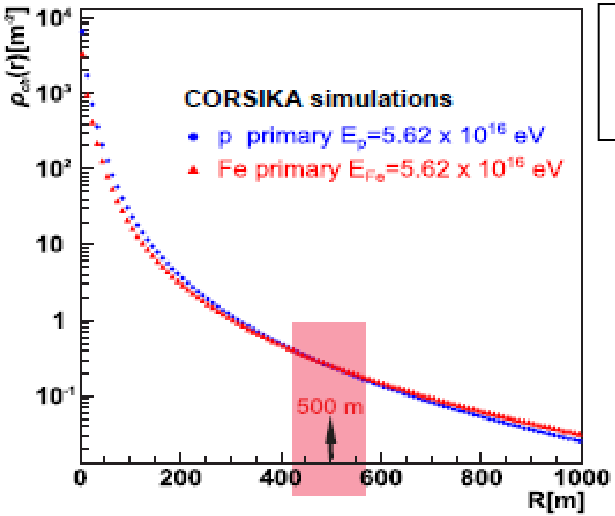
Consistent with position of break-off in heavy knee from K-method



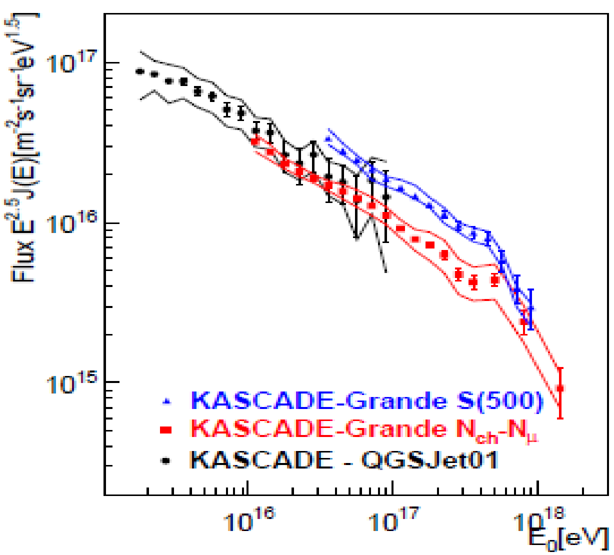
KASCADE-Grande Coll., Astropart. Phys. 47 (2013)

3) KASCADE-Grande experiment

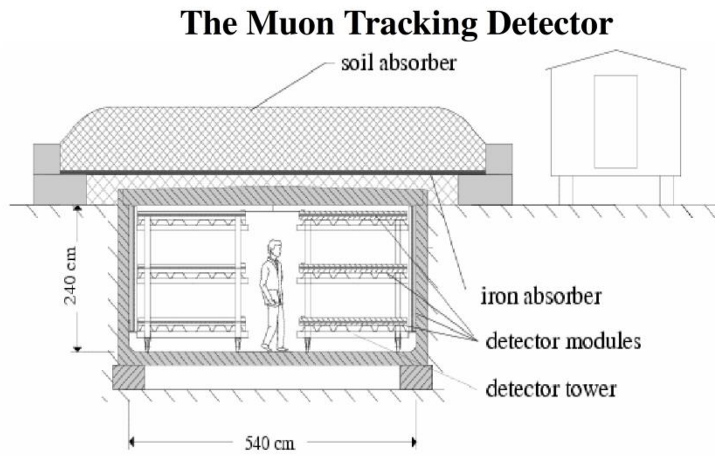
Energy spectrum from S(500)

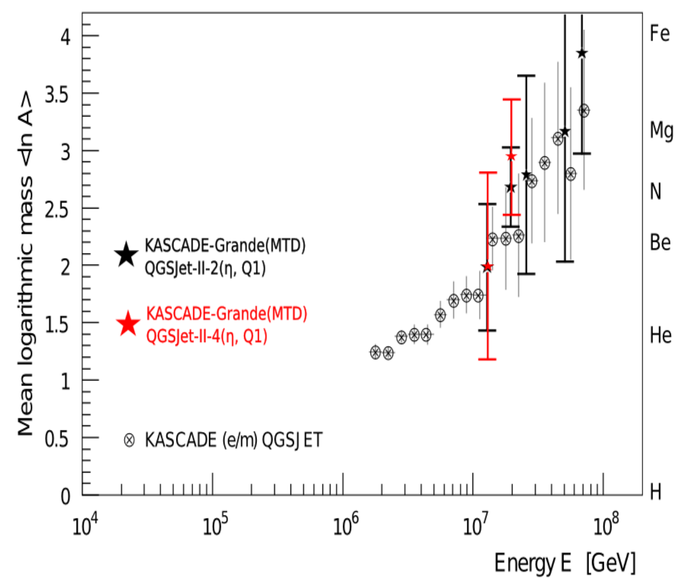


See G. Toma's Poster



Mean lnA from μ pseudorapidities



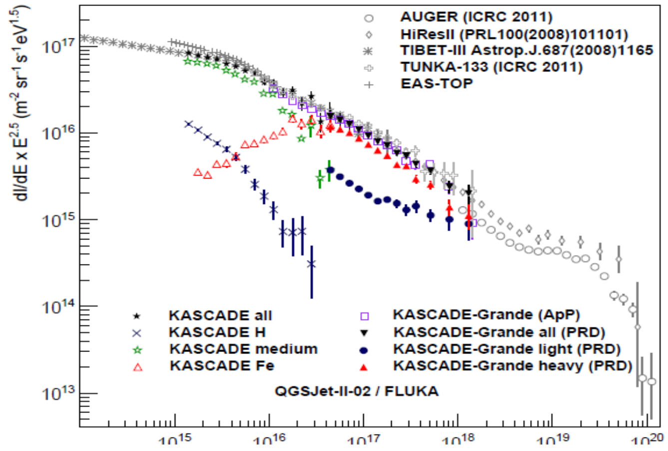


See P. Luczak's Talk

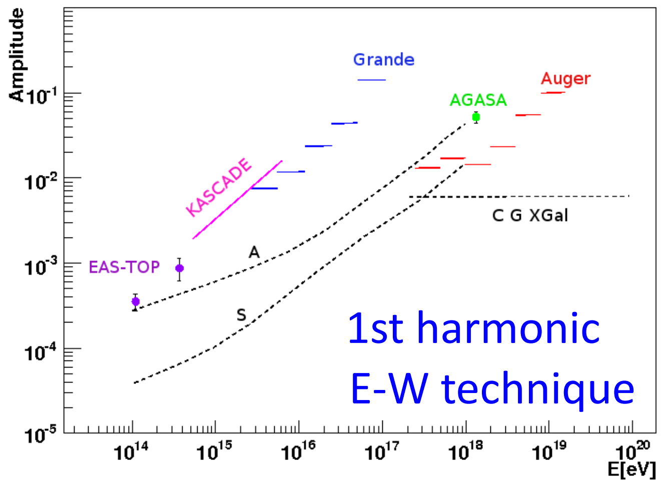
3) KASCADE-Grande experiment

Work in progress

1. Combined KASCADE/KASCADE-Grande energy spectrum E = 10^{14}-10^{18} eV.
2. Test of hadronic interaction models.
3. Anisotropy studies.
4. Limits of gamma-ray flux.
5. Radio analysis with LOPES & CROME.
6. KASCADE Cosmic Ray Data Center.



A. Haungs, ICRC 2013



A. Chiavassa, ICRC 2013

4) Attenuation lengths

Goal:

❖ To test hadronic interaction models: QGSJETII-02/04, EPOS 1.99/LHC, SIBYLL 2.1 at very high energies with KASCADE-Grande.

→ Employ EAS data on muons & charged particles

Strategy:

❖ Analyze zenith angle dependence of N_{μ} and N_{ch} in the atmosphere.

→ Attenuation lengths

❖ Compare predictions of hadronic interaction models against experimental estimations.

→ Use MC predictions for Protons and Iron nuclei

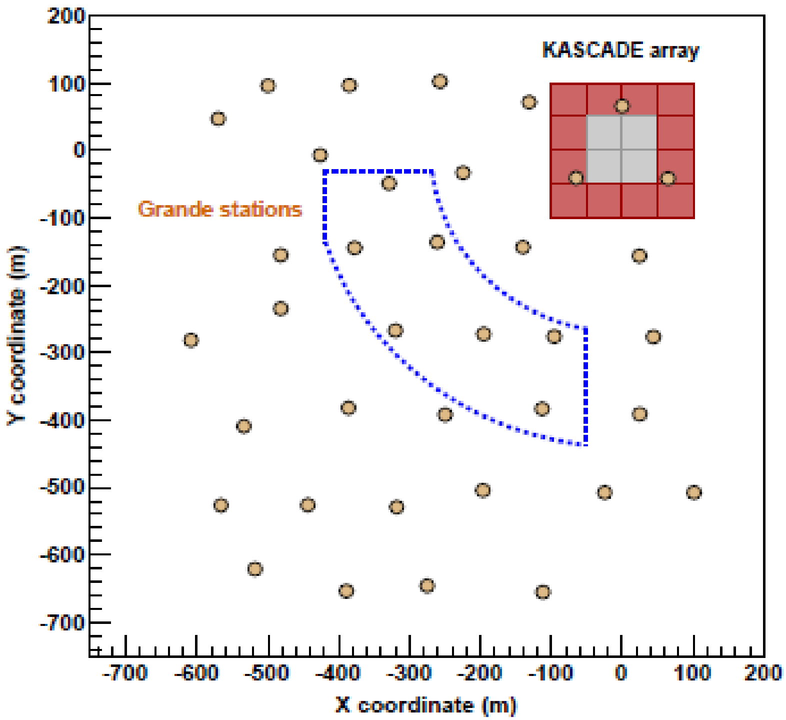
4) Analyses

Data sample:

- December 2003 – November 2012
- Effective observation time: 1434 days

Selection cuts:

- Central area: 370 x 520 m^2.
- $\theta < 40^o$ ($N_\mu \geq 3.98 \times 10^4$).
- No experimental problems.
- Stable DAQ.
- All muon clusters working.



Exposure: $1.3 \times 10^{13}\,\mathrm{m^2 \cdot s \cdot sr}$

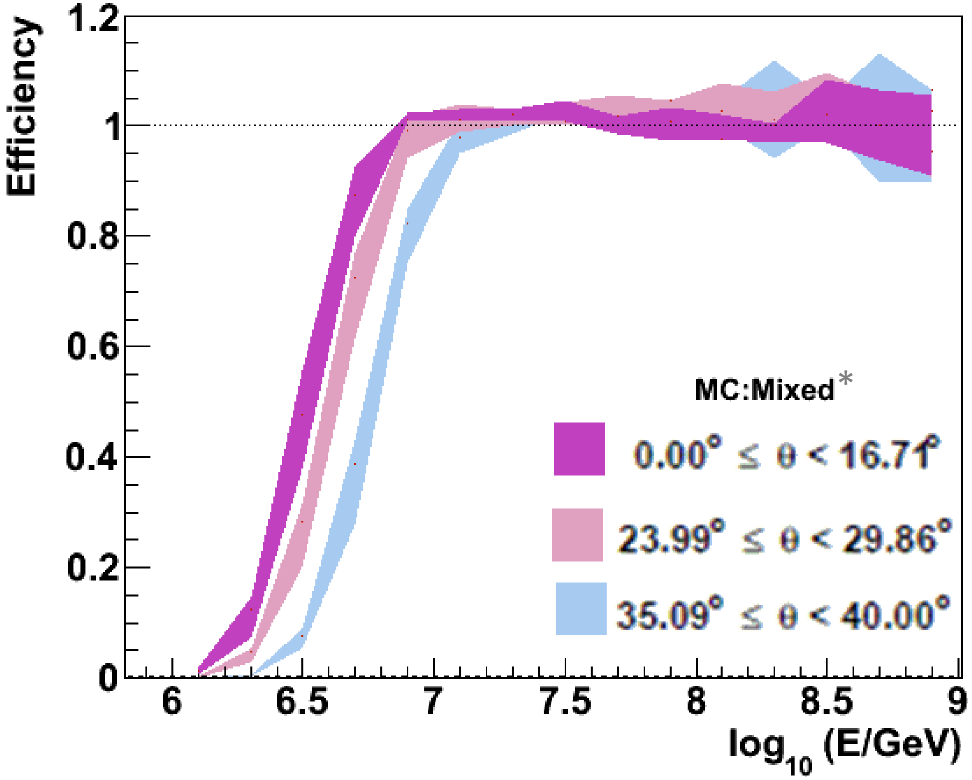
4) Analyses

MC sample:

- QGSJETII-02/04
- EPOS 1.99/LHC
- SIBYLL 2.1

Simulated spectra:

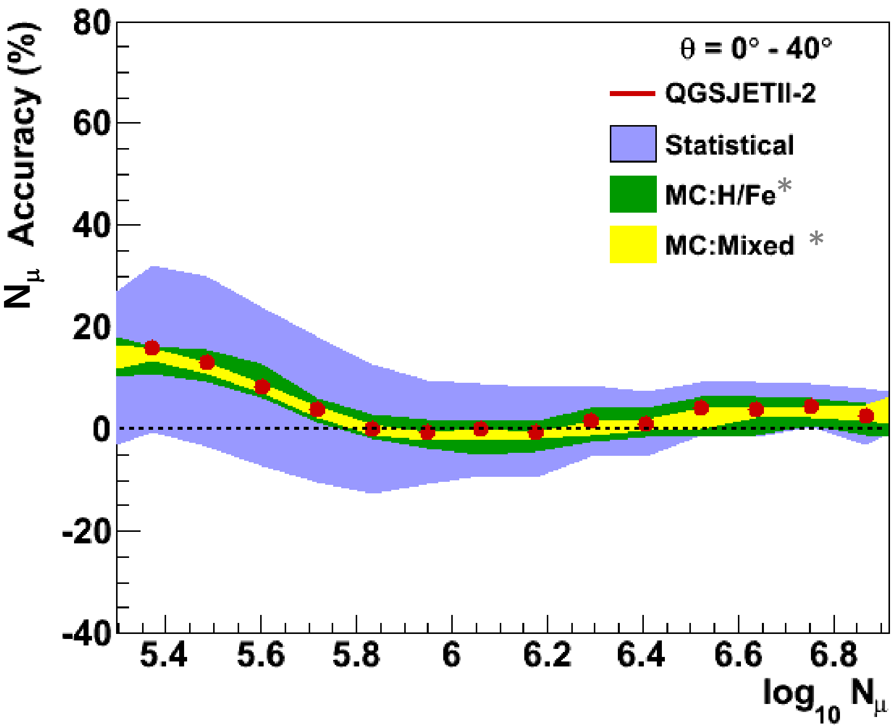
- Pure composition:
  H, He, C, Si, Fe
- Mixed composition
  (primary elements on equal abundances)
- E^{γ}, γ= -2
  reweighted to have
  γ = -2.8, -3, -3.2

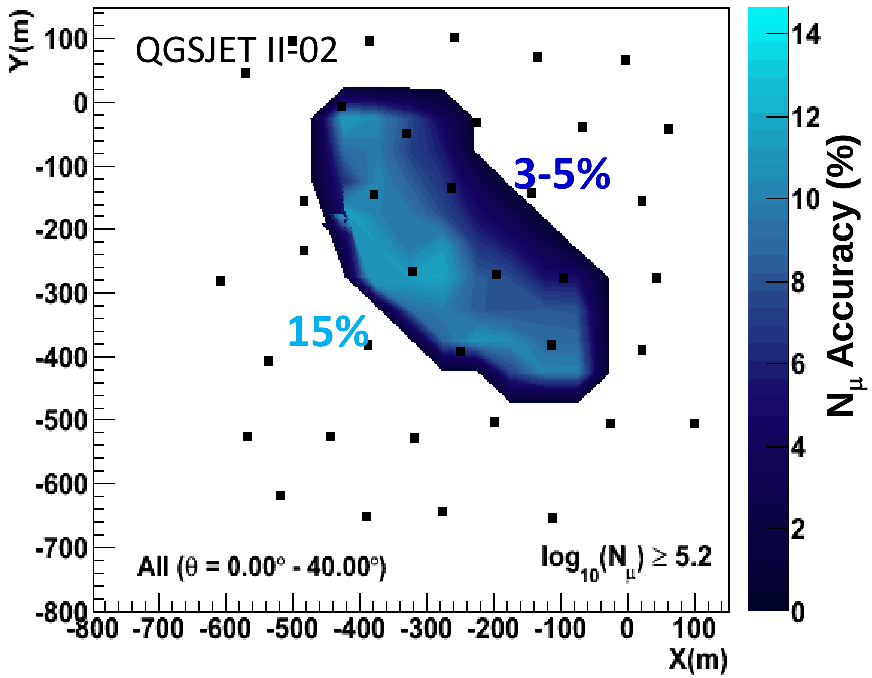


Fulll efficiency:	$\log_{10}$(E/GeV) ~ 6.8 - 7.2
Threshold:	$\log_{10}(N_\mu)$ ~ 4.8 - 5.2

*Bands take into account variation among different models

4) Analyses



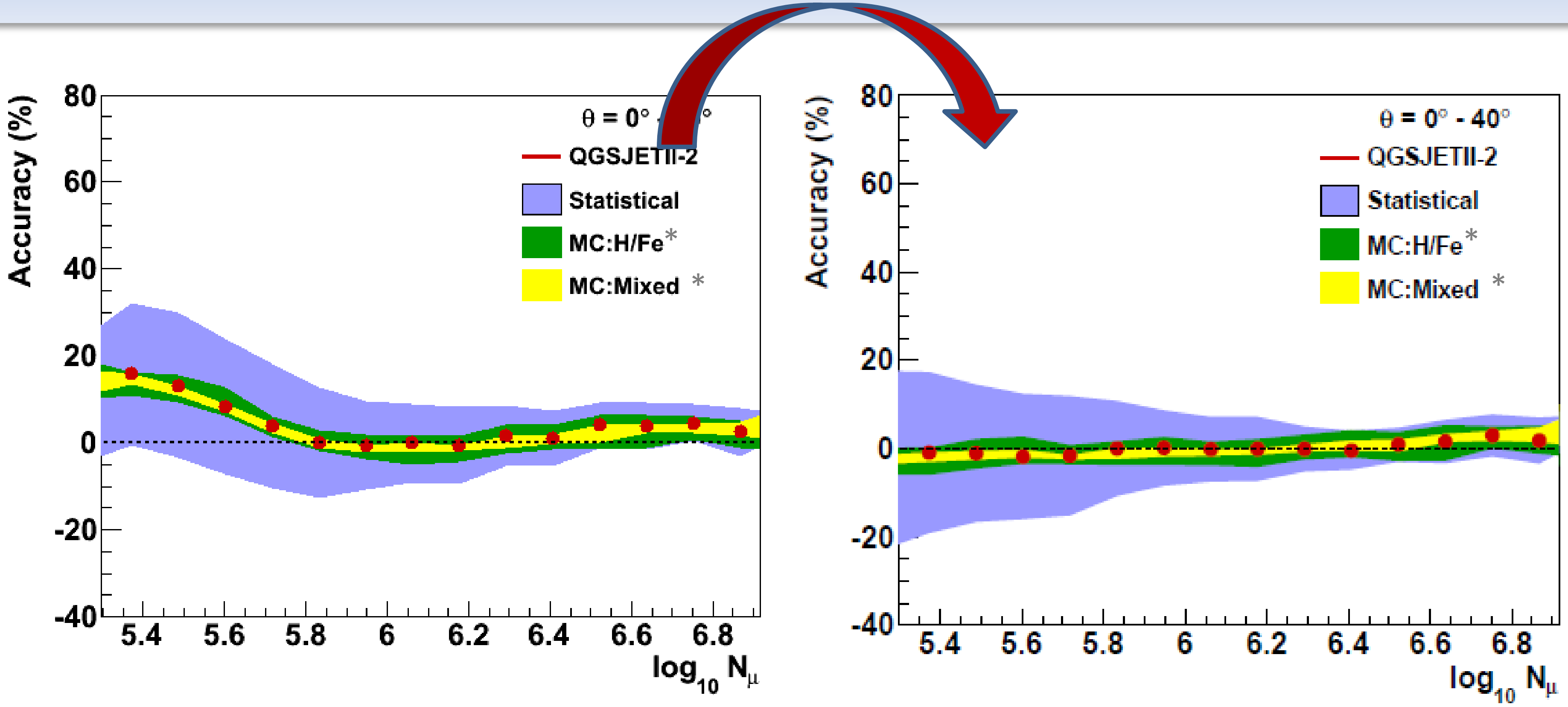


Mean accuracy (in region of full efficiency)

- δN_μ < 20%
- δN_{ch} < 20%
- $\delta\theta$ ~ 0.4°

*Bands take into account variation among different models

4) Analyses

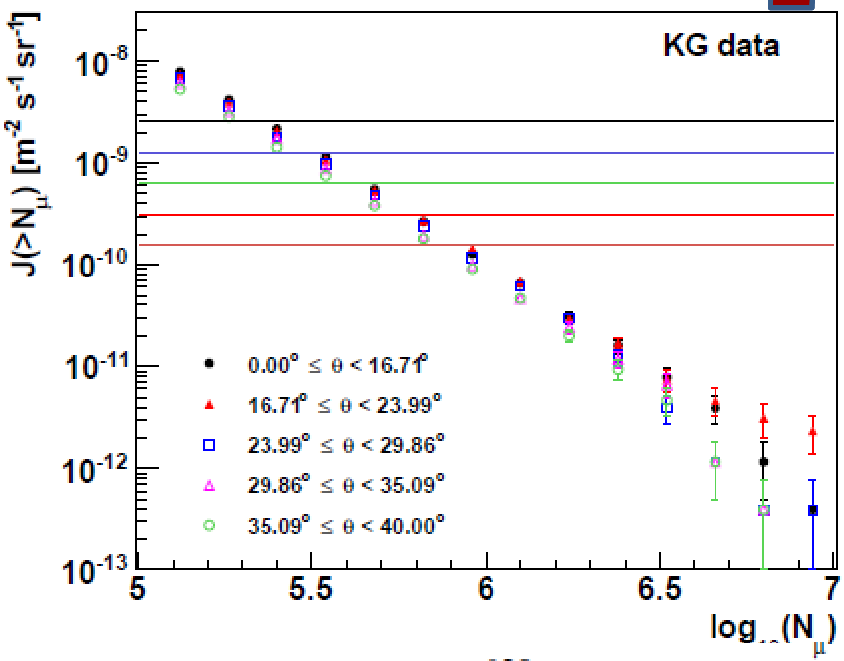


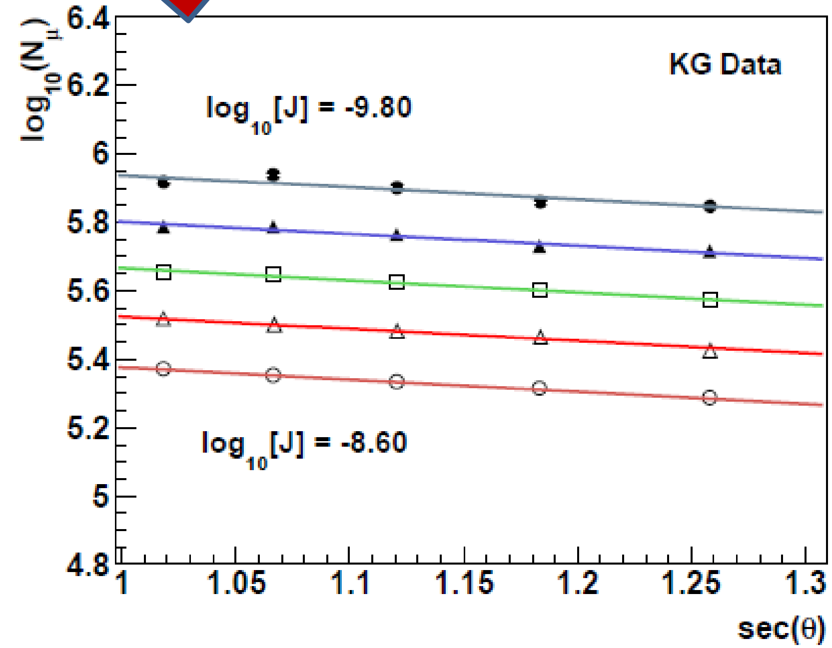
All muon data is corrected for systematic errors (using a correction function derived from QGSJETII-02)

*Bands take into account variation among different models

4) Analyses

Constant Intensity Cut Method





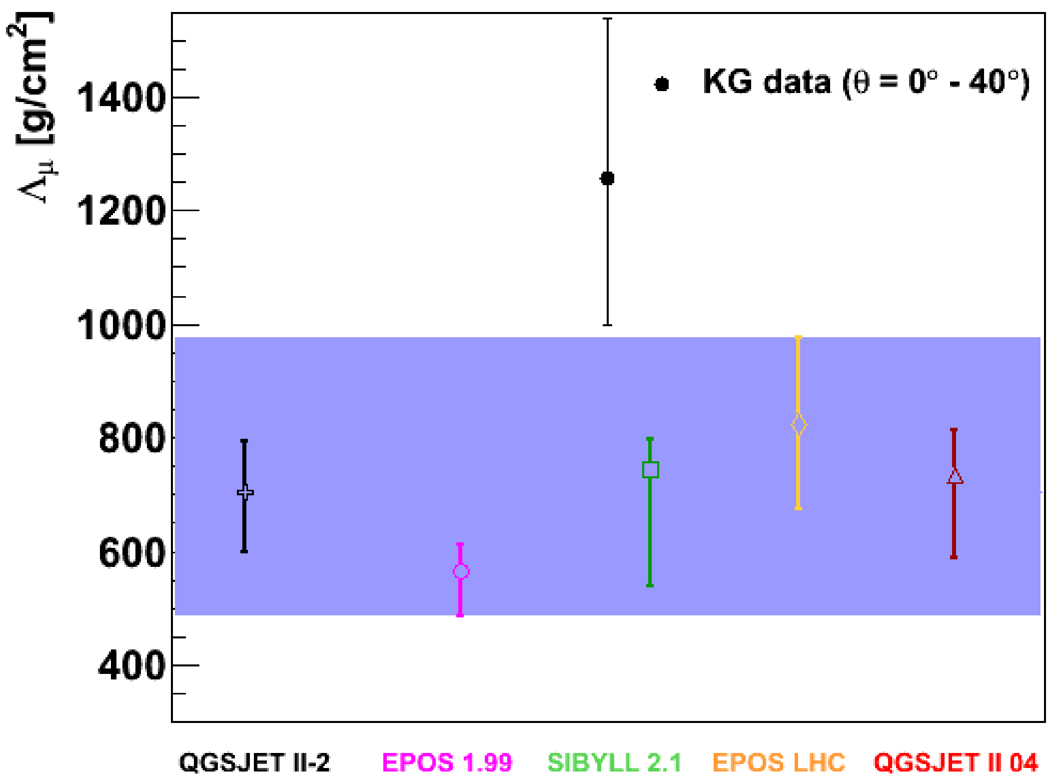
$$J(>N_\mu) = \int_{N_\mu}^{\infty} \Phi_\mu(N_\mu)\,dN_\mu$$

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

1. • Apply cuts at fixed frequencies.

2. • Get attenuation curves.
   • Apply a global fit to get Λ_μ.

5) Results



KASCADE-Grande data
Syst.& Stat. errors included

MC (CORSIKA/FLUKA):
γ = -2.8, -3.0, -3.2
H, Fe and mixed composition
Syst.& Stat. errors included *

$\delta\Lambda_\mu$	QGSJETII-2	EPOS 1.99	SIBYLL 2.1	EPOS LHC	QGSJETII-4
σ	+2.02	+2.63	+1.94	+1.44	+1.93
CL(%)	2.17	0.43	2.62	7.49	2.68

Discrepancies between MC and experimental data

*For EPOS-LHC results are preliminary

5) Results

What we know up to now: Statistical and systematic uncertainties do not explain the difference

Main contributions to systematic error of measured value:

Reconstruction method:	**+9%/-2%**
Correction function:	**+6%/-9%**
EAS core position:	**+12%/-11%**
Muon Systematics:	**+13%/-10%**

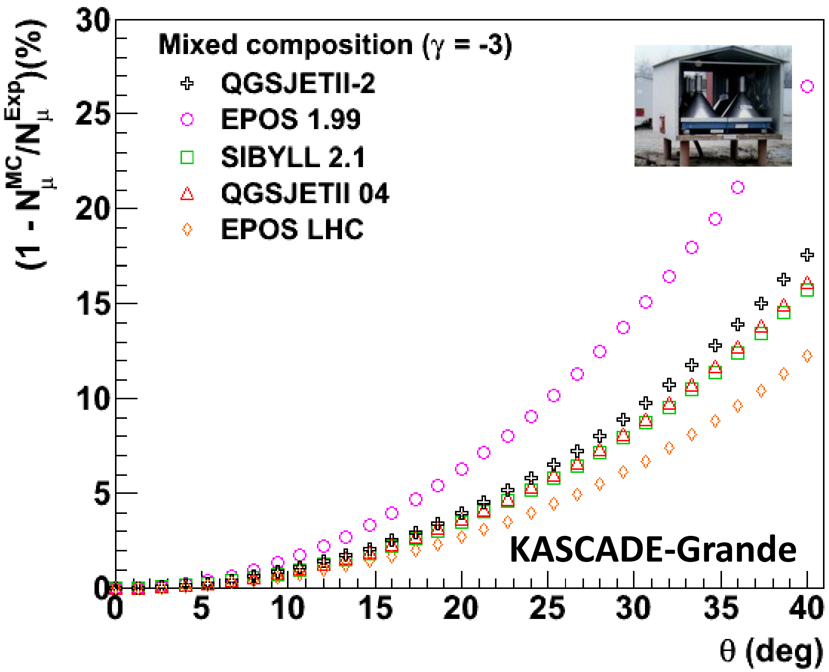
5) Results

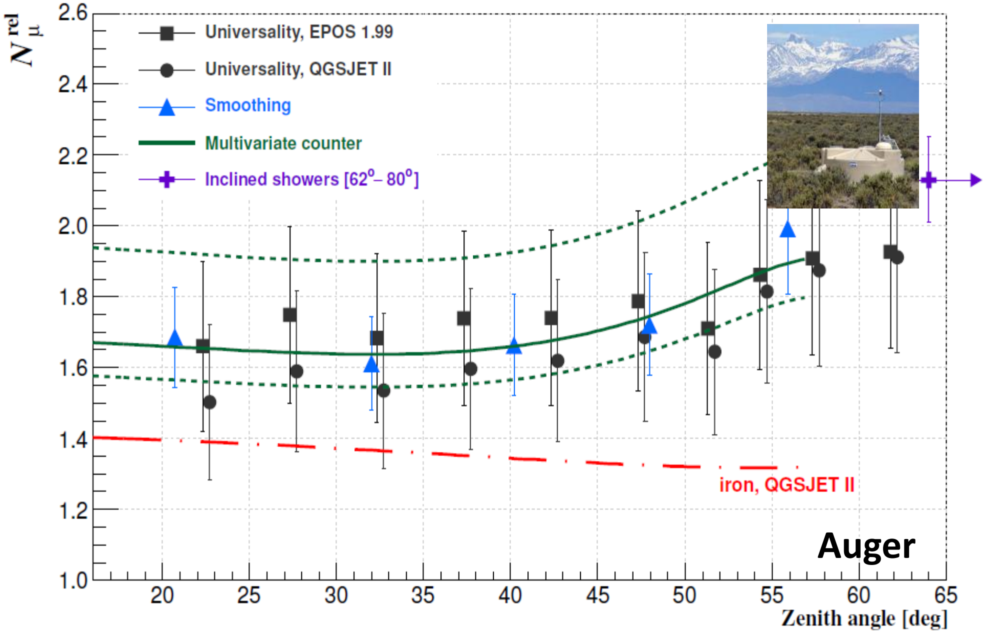
What we know up to now: Statistical and systematic uncertainties do not explain the difference

Other systematic errors derived from MC studies

Fluctuations at the shower front:	**< 15 %**
Lateral distribution function of muons:	**+5%/-4%**
Misreconstructed core, arrival direction and number of muons per detector:	**< 3%**
Systematics in core and arrival direction according to differences between KASCADE and KASCADE-Grande:	**< 7%**

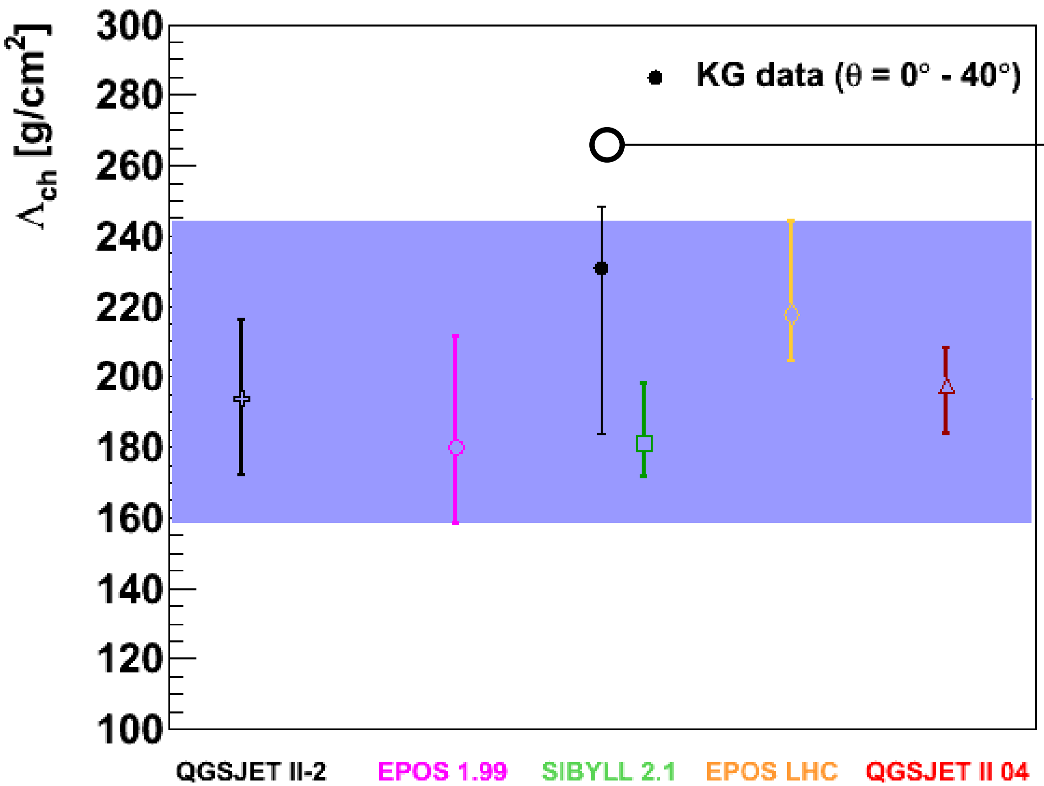
A. Yushkov j.EPJ W. of Conf. 53, PAO 2013





- ❖ **Observed differences between observed and predicted Λ_μ** may imply more muons in experimental data at high zenith angles than in simulations**.**
- ❖ **That** may be correlated with Auger´s muon deficit **problem at higher energies.**

5) Results



KASCADE-Grande data:
Systematics on Nch (calculated from MC data) increase lower error limit.

$\delta\Lambda_{ch}$	QGSJETII-2	EPOS 1.99	SIBYLL 2.1	EPOS LHC	QGSJETII-4
σ	+0.71	+0.90	+0.99	+0.25	+0.69
CL(%)	23.88	18.41	16.11	40.13	24.51

Better agreement between MC and experimental data

*For EPOS-LHC results are preliminary

6) Summary

KASCADE-Grande results on N_μ and N_{ch} attenuation lengths:

- At $E=10^{16}$-10^{18} eV, none of the hadronic interaction models (QGSJET II, EPOS 1.99, SIBYLL 2.1, QGSJETII-04, EPOS-LHC) is able to describe the $N_\mu(\theta)$ data of KASCADE-Grande consistently.

- The measured Λ_μ is bigger than the MC values.

- At high zenith angles more muons are observed in the experiment than in MC simulations.

- The measured Λ_{ch} is in better agremeent with MC predictions.

- Results from EPOS-LHC for Λ_μ and Λ_{ch} are closer to the experimental observations than the ones from other hadronic interaction models.

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, B.Fuchs, H.J.Gils, A.Haungs, D.Heck, D.Huber, T.Huege, D.Kang, H.O.Klages, K.Link, H.-J.Mathes, H.J.Mayer, 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

Universität Siegen
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

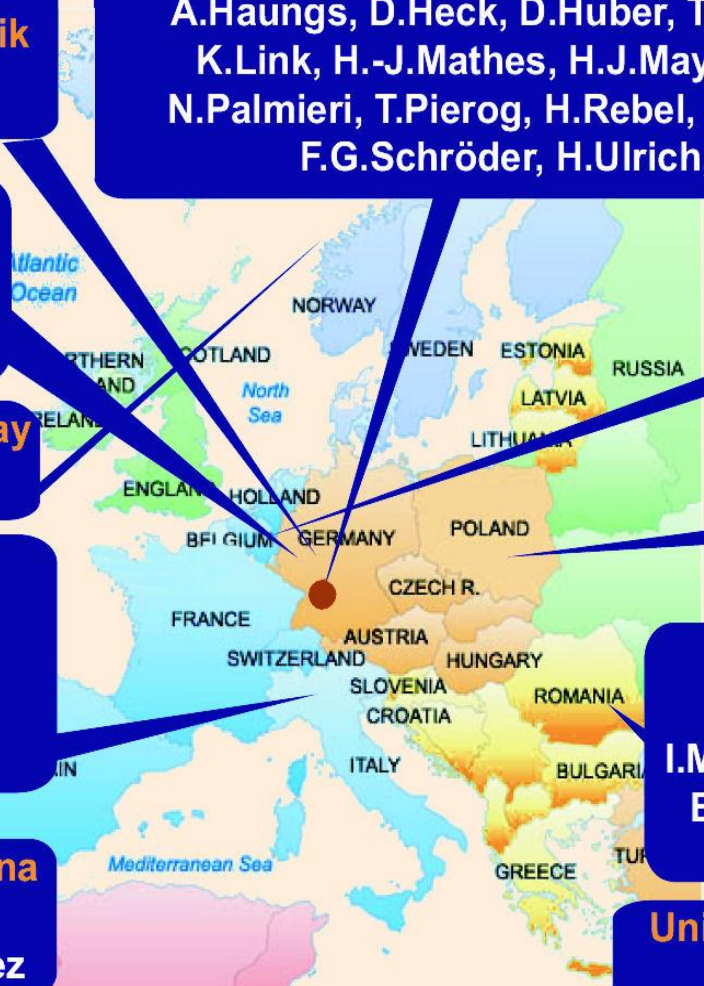
Universidad Michoacana
Morelia, Mexico
J.C. Arteaga-Velázquez

Radboud University Nijmegen
J.R.Hörandel

National Centre for Nuclear Research, Lodz
P. Łuczak, J. Zabierowski

IFIN Horia Hulubei and University Bucharest
I.M. Brancus, A.Gherghel-Lascu, B. Mitrica, M. Petcu, O. Sima, G. Toma

Universidade Sao Paulo, Brasil
V. de Souza



https://web.ikp.kit.edu/KASCADE/

July 2014