Summary of the KASCADE-Grande experiment results

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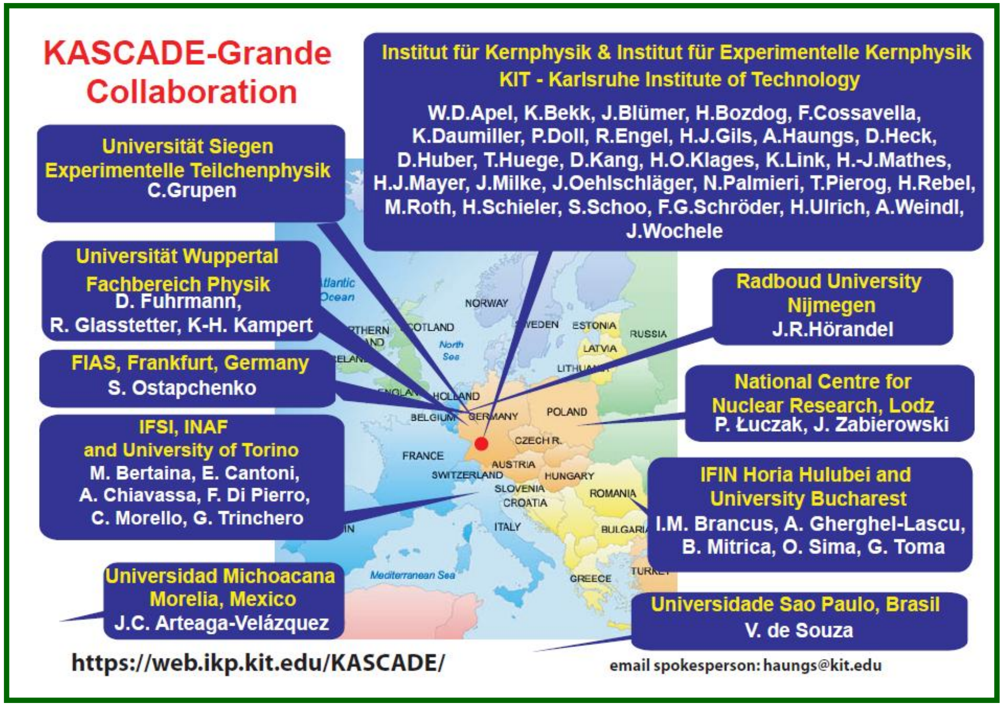
➢ Main goal of the KASCADE-Grande experiment was a detailed study of the 10^{16}-10^{18} eV energy range with a **Large Surface and High Resolution array**, with the primary goal was the detection of the knee of the heavy component of cosmic rays

➢ Ten years of data taking showed that:

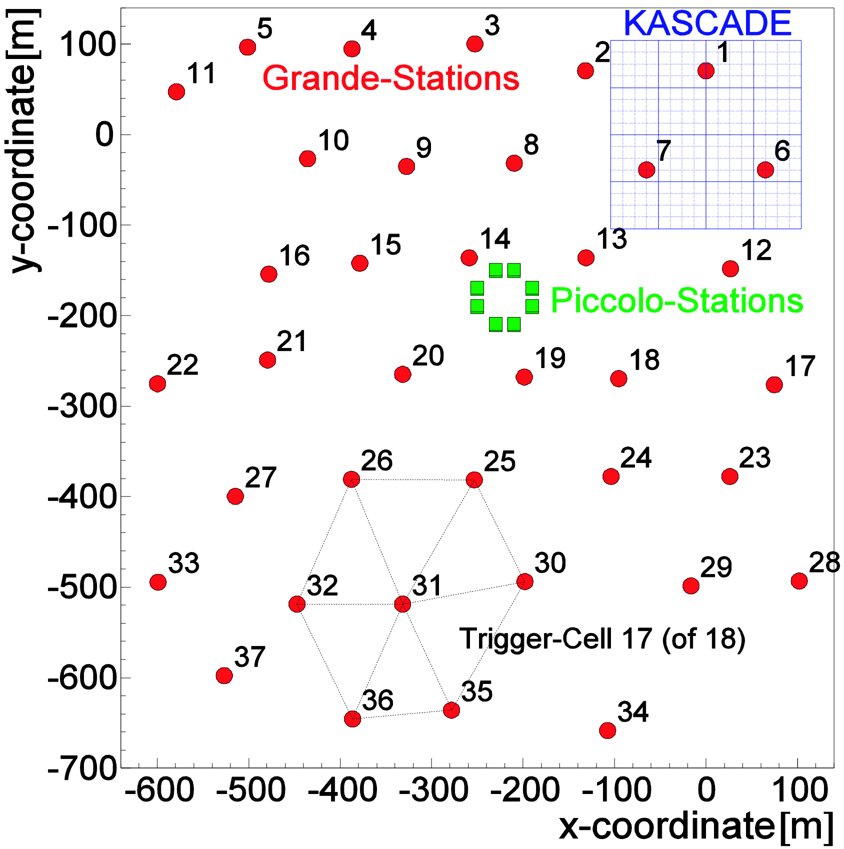
✓ We measured the charged particle and μ EAS components with high resolution.

✓ We separate two mass groups samples (light and heavy)

✓ Surface was not large enough for anisotropy studies



KASCADE-Grande detectors & observables



Grande array → cover an area of 0.5 km², detecting EAS with high resolution

Detector	Detected EAS compone nt	Detection Technique	Detect or area (m²)
Grande	Charged particles	Plastic Scintillators	37x10
KASCADE array e/γ	Electrons, γ	Liquid Scintillators	490
KASCADE array μ	Muons (E_μ^{th}=230 MeV)	Plastic Scintillators	622
MTD	Muons (Tracking) (E_μ^{th}=800 MeV)	Streamer Tubes	4x128

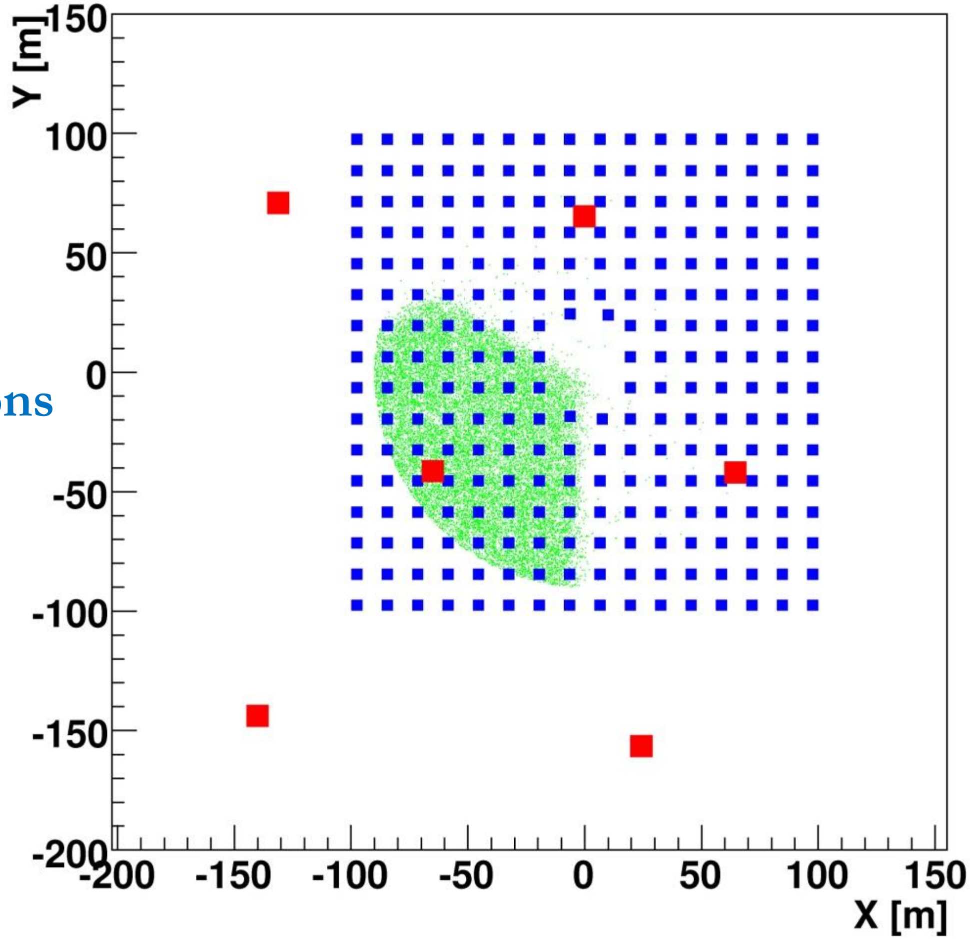
- Shower core and arrival direction
  - Grande array
- Shower Size (N_{ch} number of charged particles)
  - Grande array
    - Fit NKG like ldf

- μ Size (E_μ>230 MeV)
  - KASCADE array μ detectors
    - Fit Lagutin Function
- μ density & direction (E_μ>800 MeV)
  - Streamer Tubes

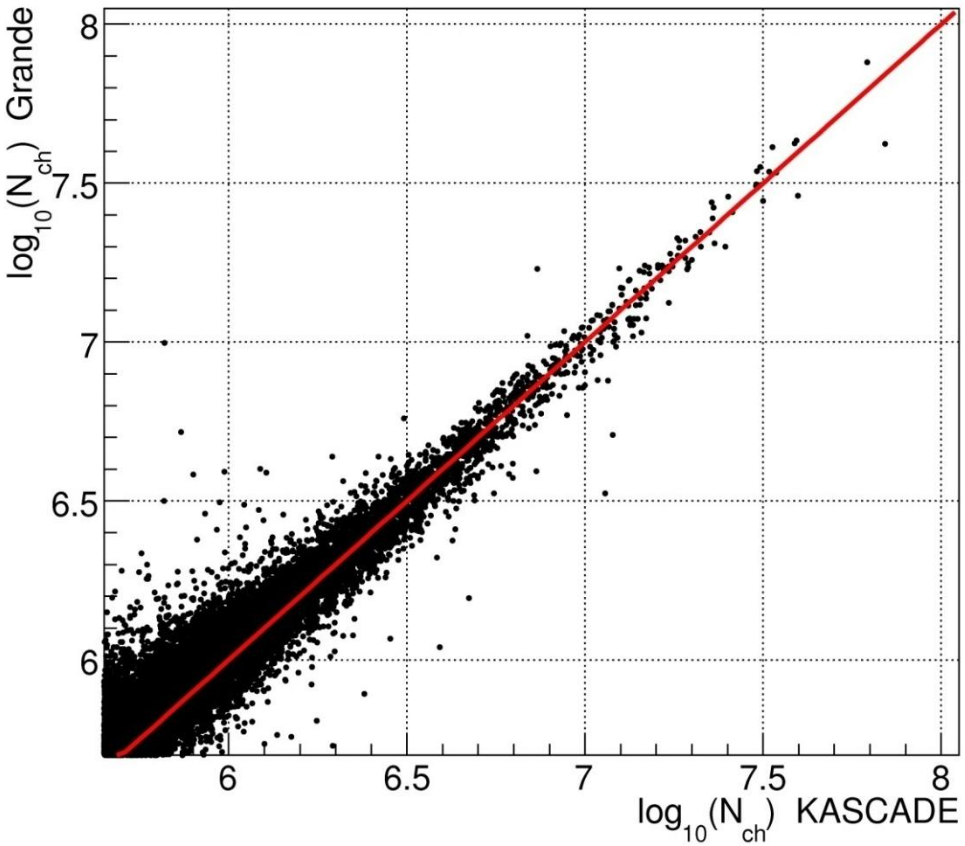
KASCADE-Grande accuracies with a subsample of common events KASCADE + Grande

■ KASCADE stations

■ Grande stations

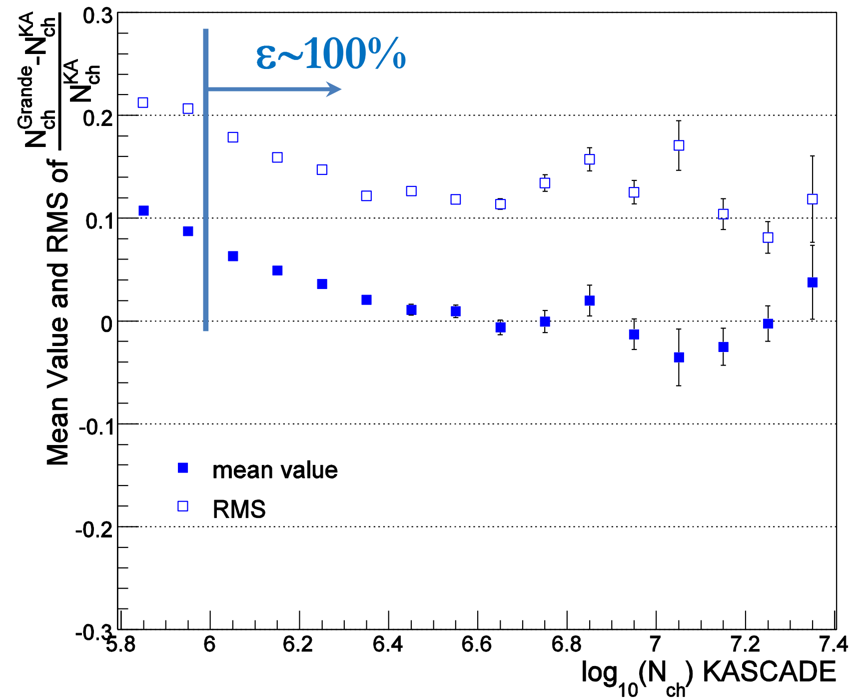


Apel et al. NIMA 620 (2010) 202-216



In each Shower Size bin we obtain the distribution of the difference between the Shower Size determined by the KASCADE and the Grande arrays

$$\frac{N_{ch,G} - N_{ch,K}}{N_{ch,K}}$$



Systematic differences → < 5-8%

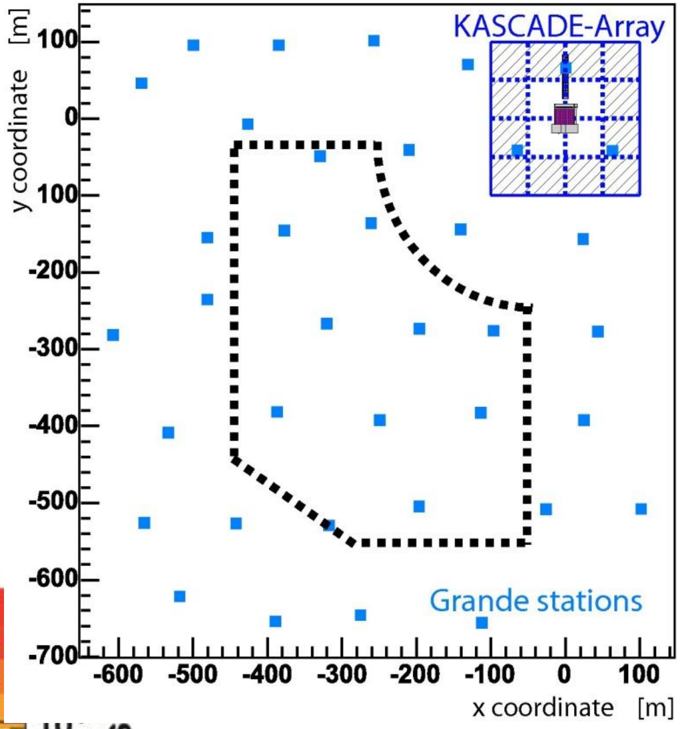
Grande resolution → < 15%

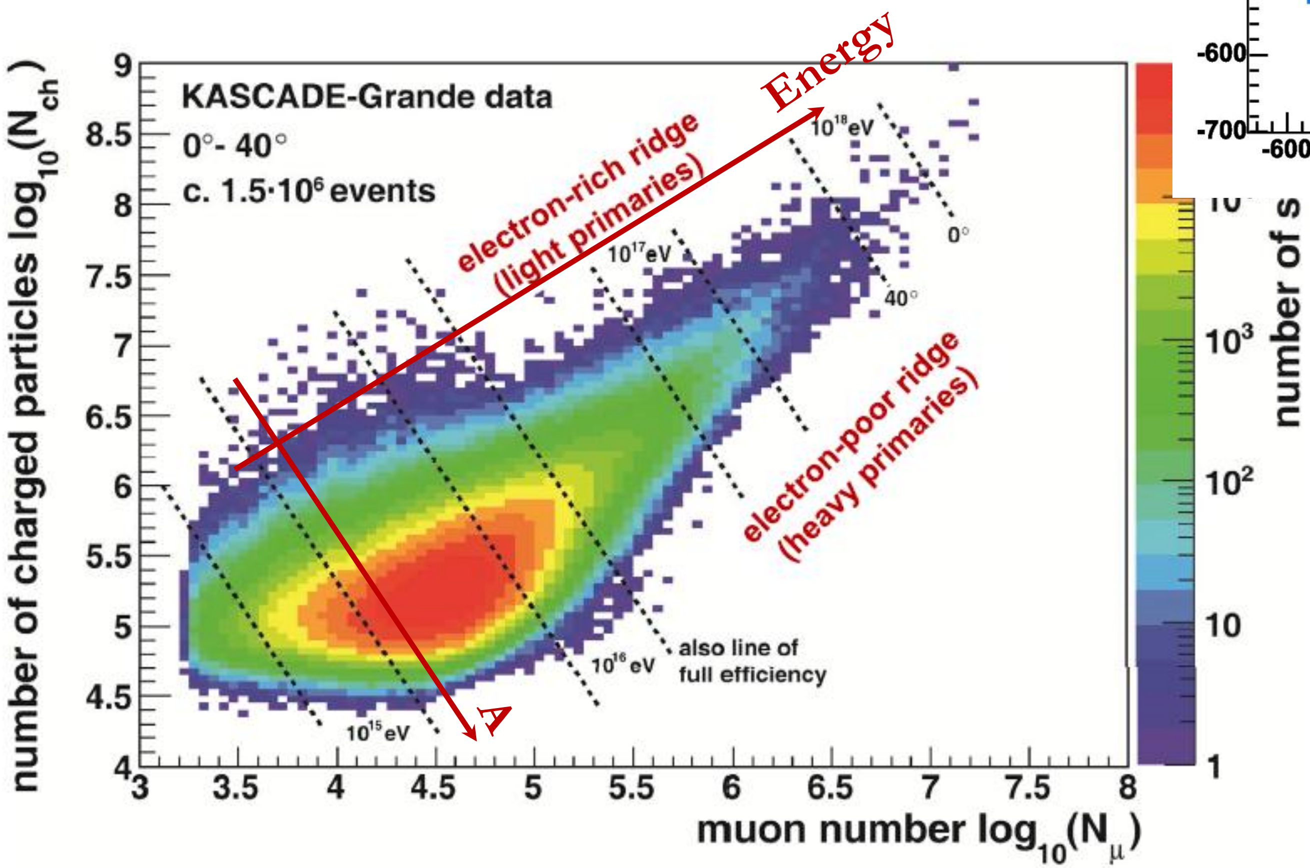
Apel et al. NIMA 620 (2010) 202-216

Main KASCADE-Grande physics results

1. All particle energy spectrum
2. Elemental groups spectra by:
   a) Unfolding
   b) Event by event classification
3. Large Scale Anisotropy
4. μ attenuation length in atmosphere

- ~ 1250 days of effective DAQ time
- Performance of reconstruction and detector is stable
- $\theta < 40°$
- $250\ m < r_{KAS} < 600\ m$





All particle energy spectrum

- Combination of N_{ch} and N_{μ}
- Five different angular bins (to take into account EAS attenuation)

$$\log_{10}(N_{ch}/N_{\mu})_{H,Fe} = c_{H,Fe} \cdot \log_{10} N_{ch} + d_{H,Fe}$$

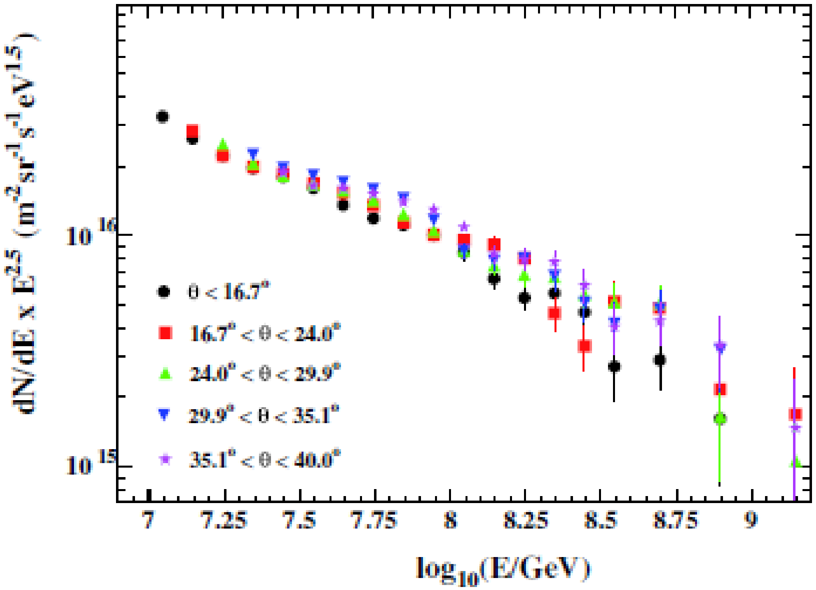
$$k = \frac{\log_{10}(N_{ch}/N_{\mu}) - \log_{10}(N_{ch}/N_{\mu})_H}{\log_{10}(N_{ch}/N_{\mu})_{Fe} - \log_{10}(N_{ch}/N_{\mu})_H}$$

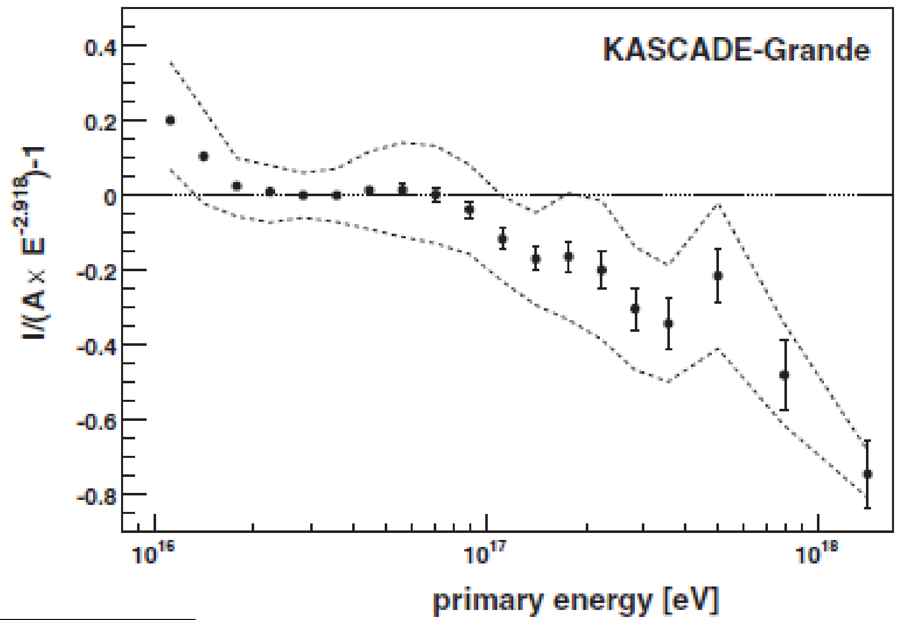
- κ parameter evaluates chemical composition

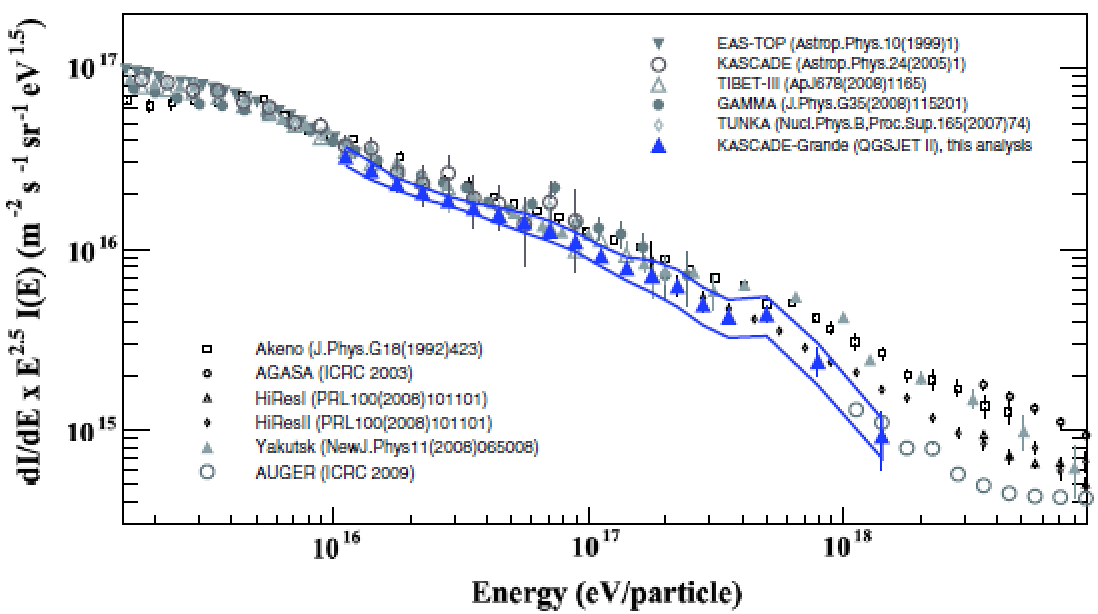
$$\log_{10} E = [a_H + (a_{Fe} - a_H) \cdot k] \cdot \log_{10} N_{ch} + b_H + (b_{Fe} - b_H) \cdot k$$

- Based on QGSJet II-02

Astroparticle Physics **36**, (2012) 183







•Spectrum cannot be described by a single power law

•Hardening above 10^{16} eV

•Steepening close to 10^{17} eV significance 2.1σ

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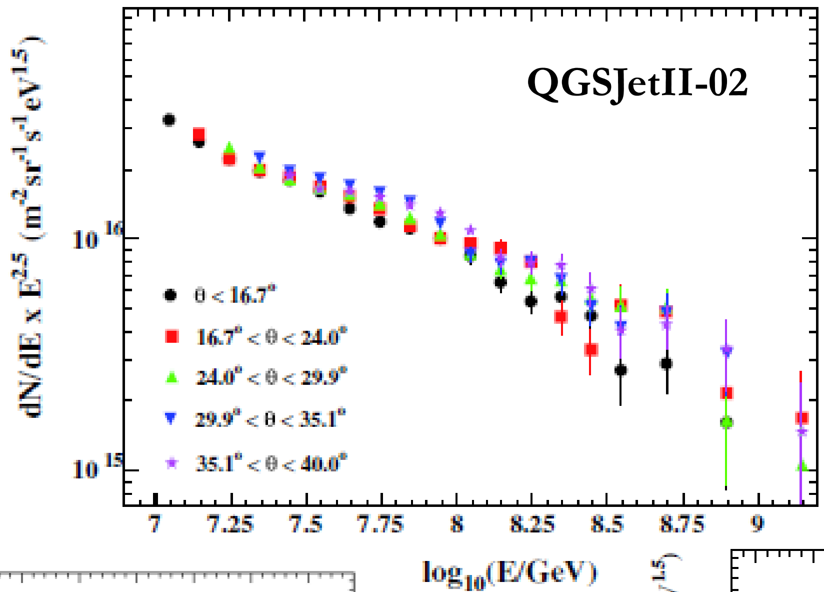
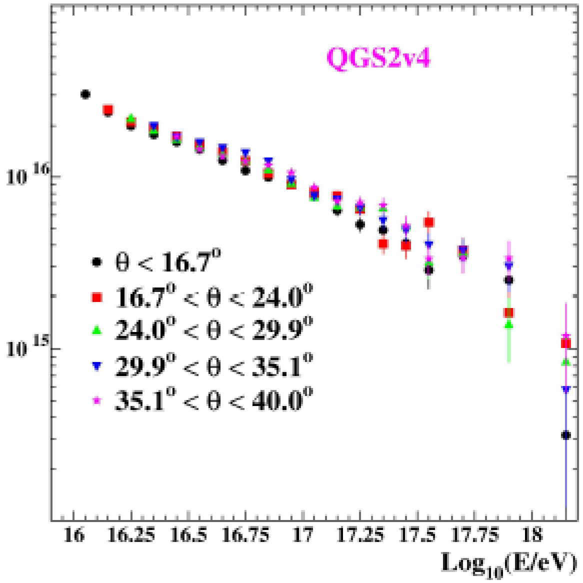
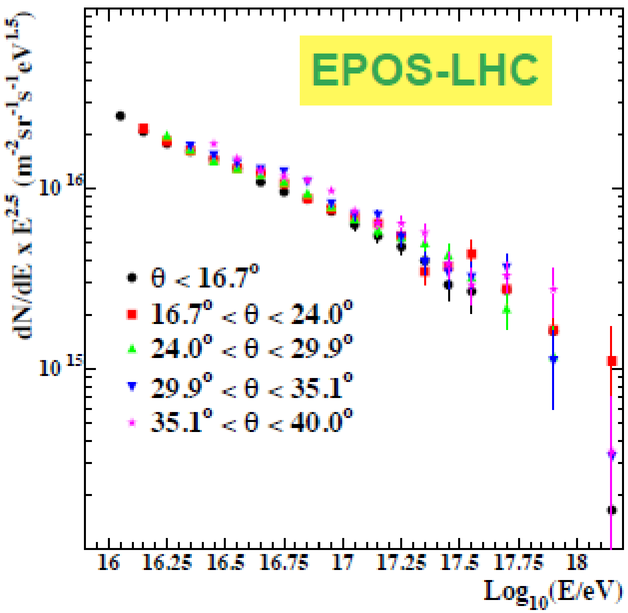
Hadronic interaction models tuned by LHC data give a better description of EAS evolution in atmosphere

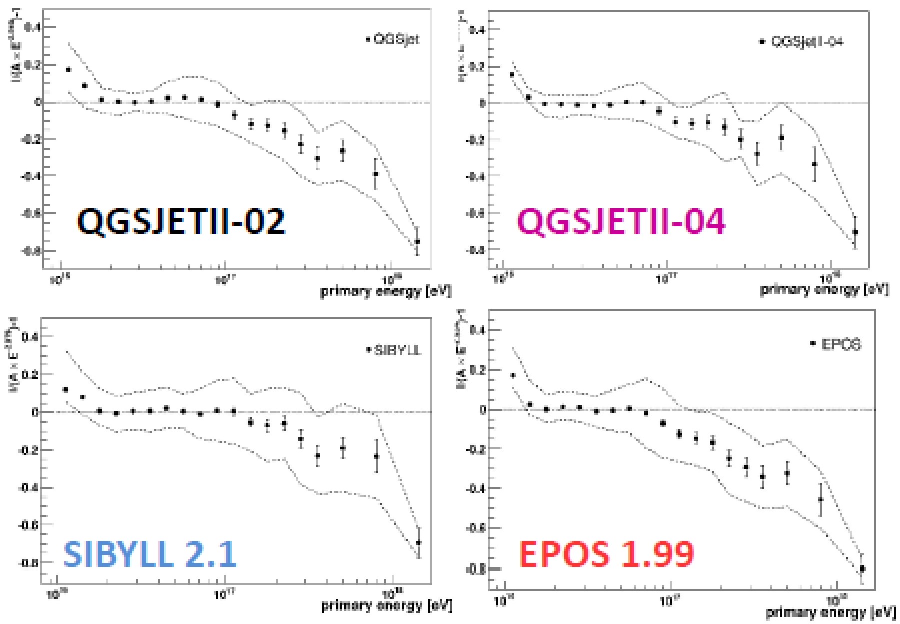


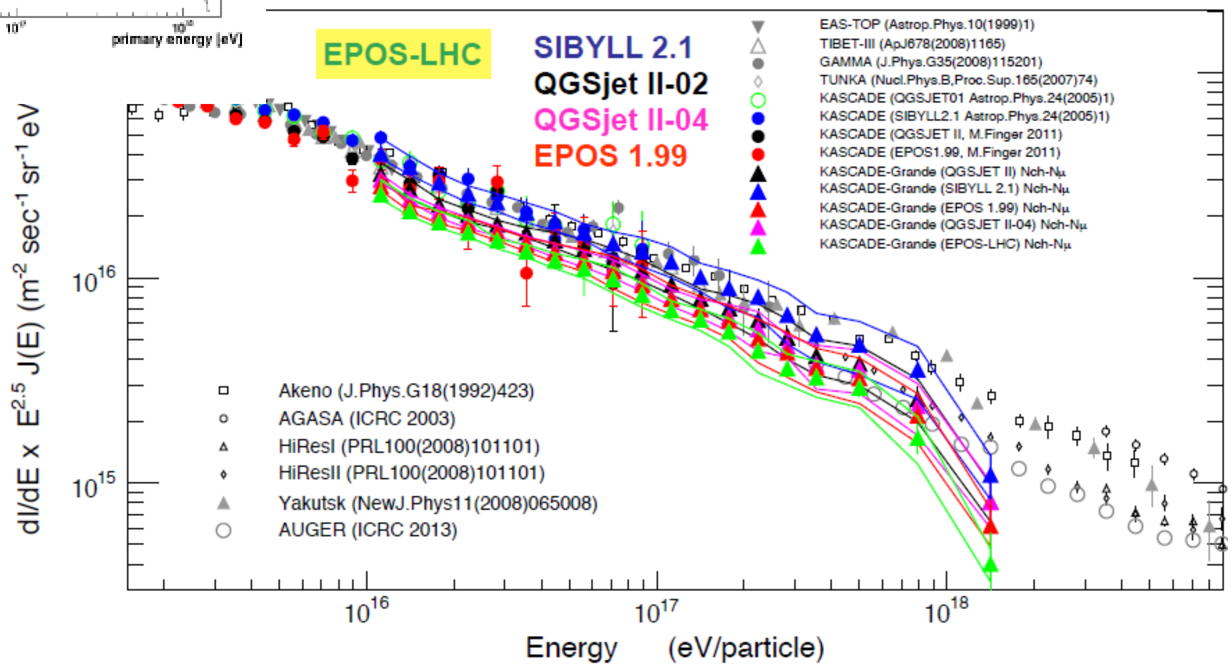




All-particle energy spectrum

Spectral features are visible in the spectra obtained with all interaction models





Advances in Space Research **53**, (2014) 1456-1469

Mass Groups Energy Spectra by Unfolding the N_{ch} vs N_{μ} spectra

Analysis objective is to compute the spectra of N_{Nucl} mass groups:
N_i number of events expected in the bin $(\log N_{ch}^{rec}, \log N_{\mu}^{rec})$ **:**

$$N_i = 2\pi AT \sum_{n=i}^{N_{Nucl}} \int_0^{18} \int_{-\infty}^{\infty} \frac{dJ_n}{dLog_{10}E} p_n \sin\vartheta \cos\vartheta \, dLog_{10}E \, d\vartheta$$

p_n is obtained from full EAS (based on QGSJet II-02) and detector simulation

$$p_n((Log_{10}N_{ch}^{rec}, Log_{10}N_{\mu}^{rec}), | Log_{10}E) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} s_n \varepsilon_n r_n \, dLog_{10}N_{ch}^{true} \, dLog_{10}N_{\mu}^{true}$$

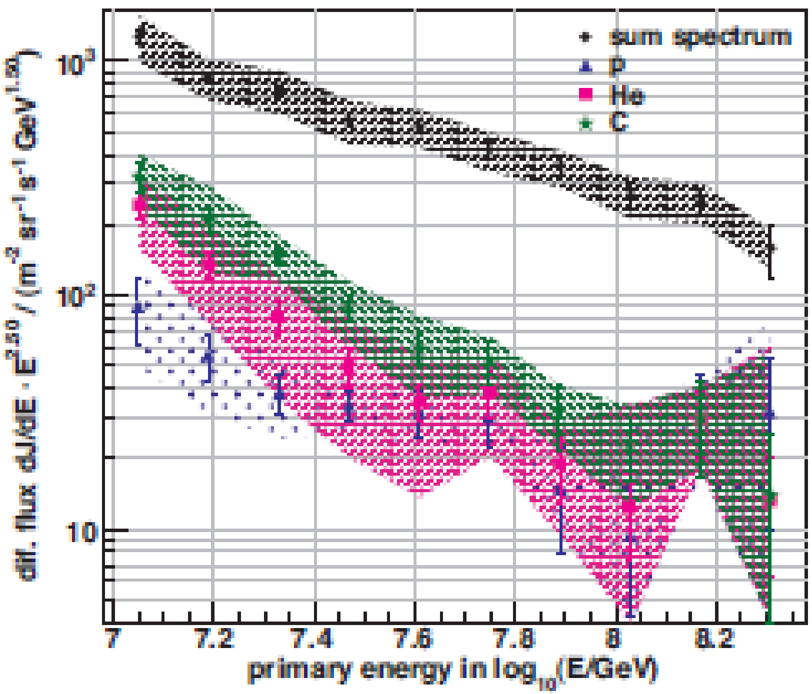
s_n EAS development fluctuations

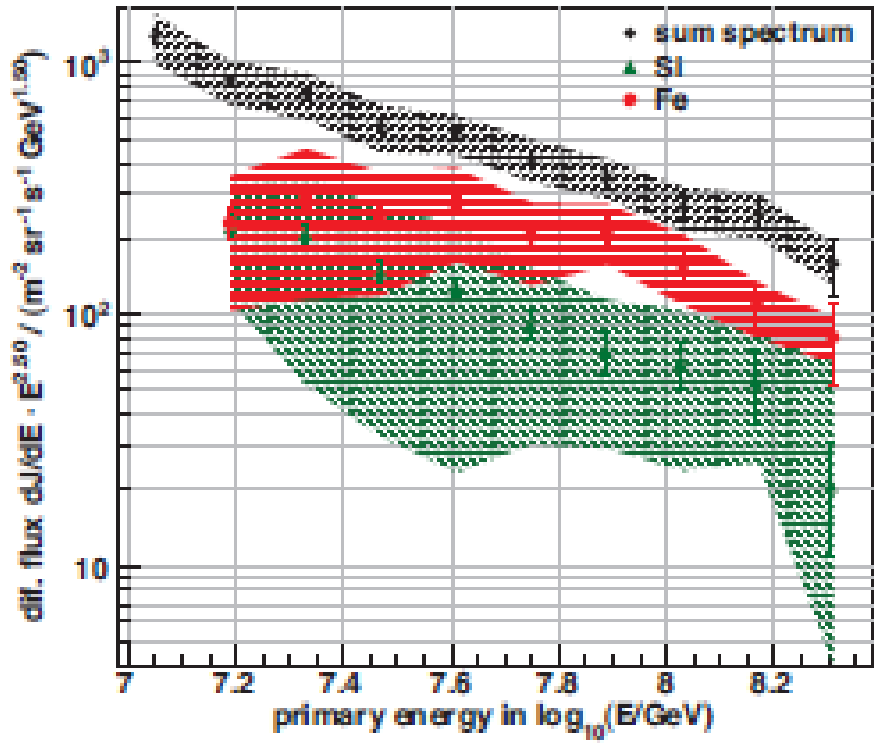
ε_n, trigger efficiency

r_n, reconstruction resolution, including systematic reconstruction effects

Apel et al., Astroparticle Physics **47**, (2013), 54-66

QGSJet II-02

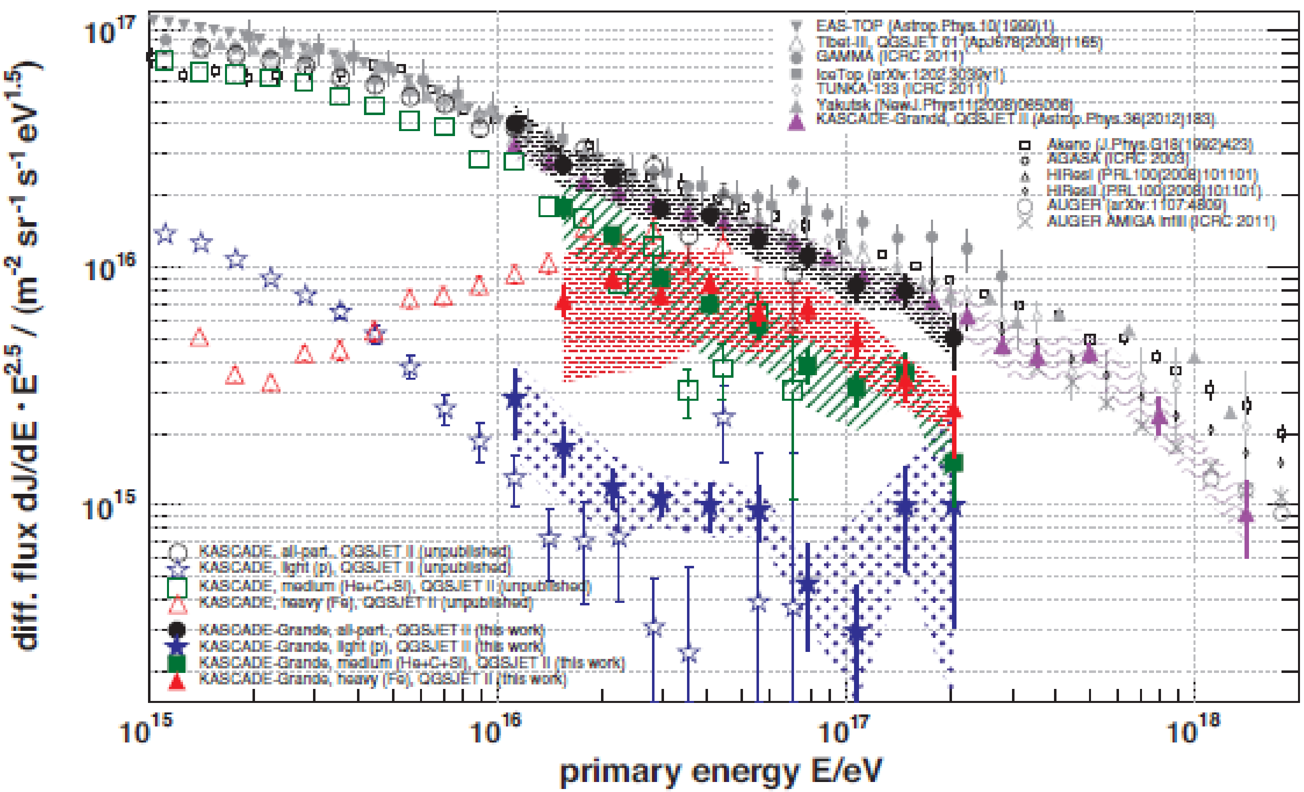




Spectra of five mass groups obtained applying the unfolding technique to the KASCADE-Grande data. Only the heavier mass group spectrum (Fe) shows a significant steepening

Apel et al., Astroparticle Physics **47**, (2013), 54-66

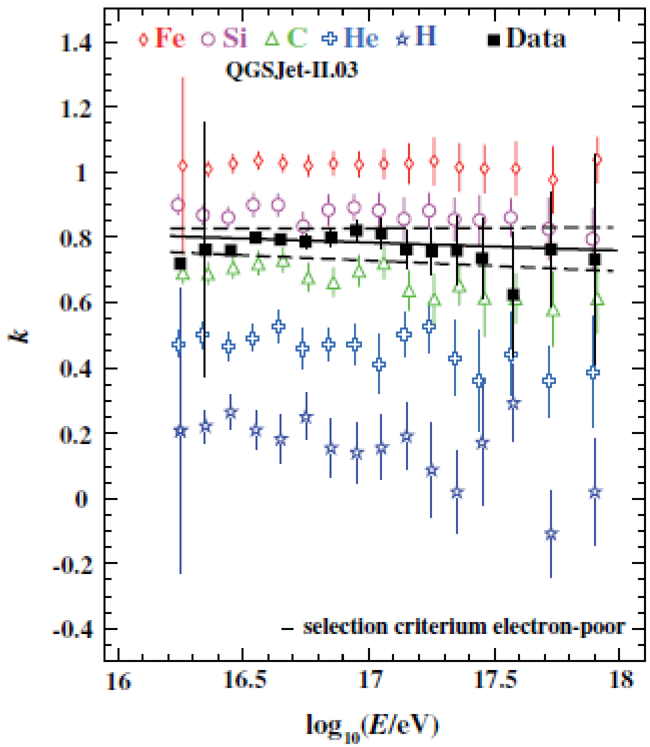
- Spectra agree with those obtained applying the unfolding technique to KASCADE data.
- Both data sets are analyzed with the QGSJetII-02 hadronic interaction model

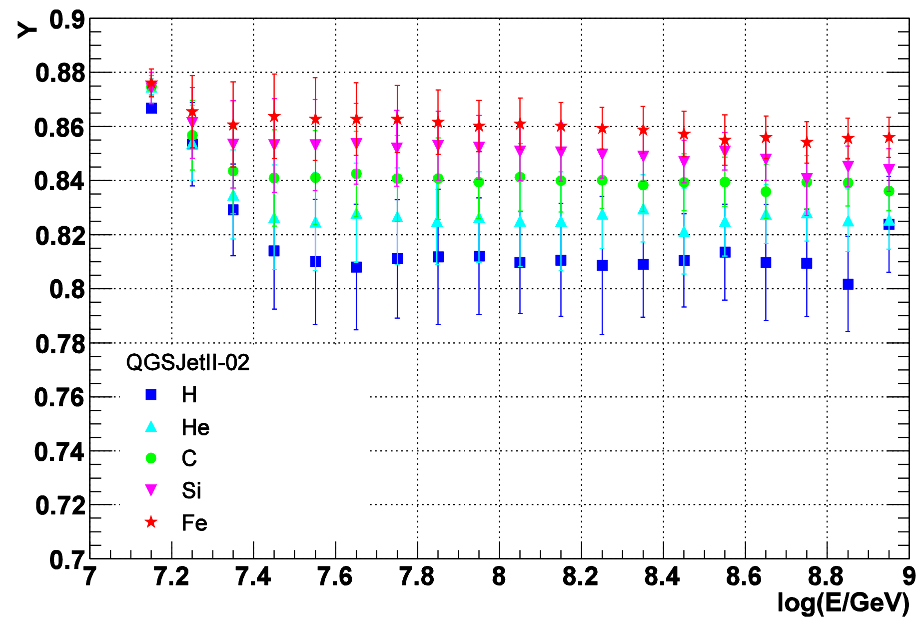


Apel et al., Astroparticle Physics **47**, (2013), 54-66

Event by event separation in two mass groups by the N_{ch}/N_{μ} ratio

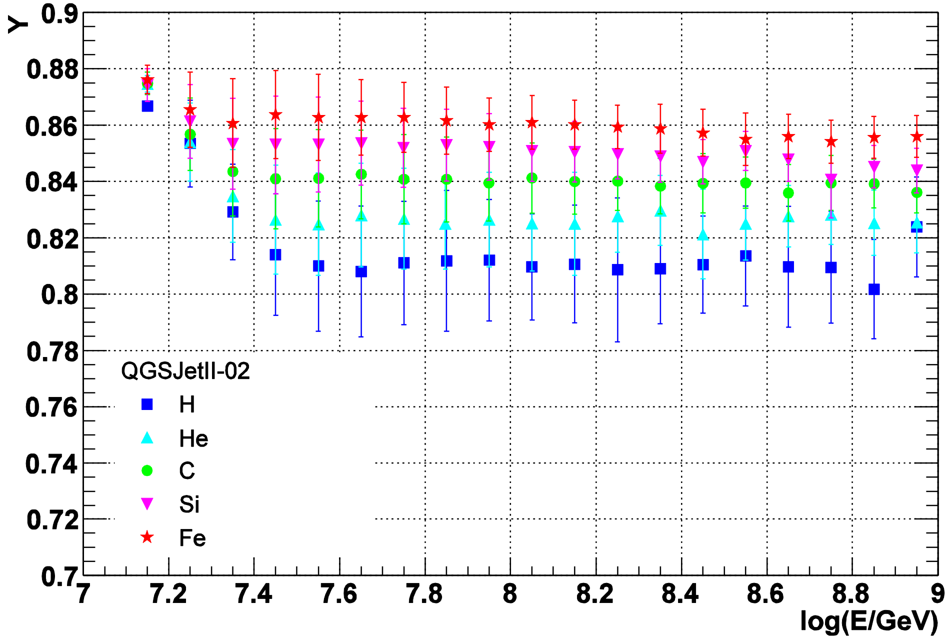
Two different ways of taking into account the EAS attenuation in atmosphere





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

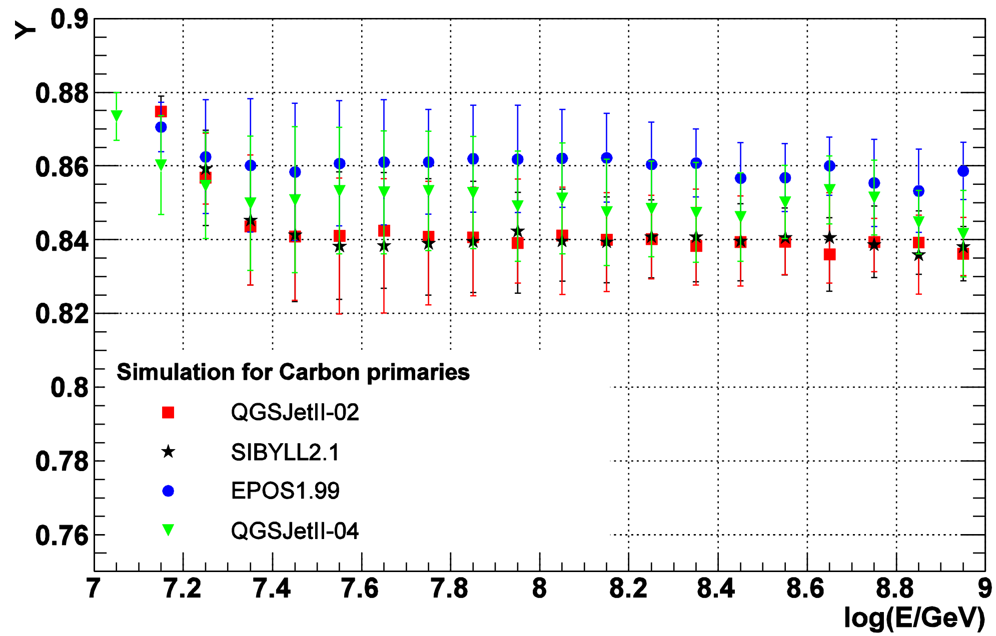
$$Y_{CIC} = \frac{\ln N_{\mu}(\vartheta_{ref})}{\ln N_{ch}(\vartheta_{ref})}$$



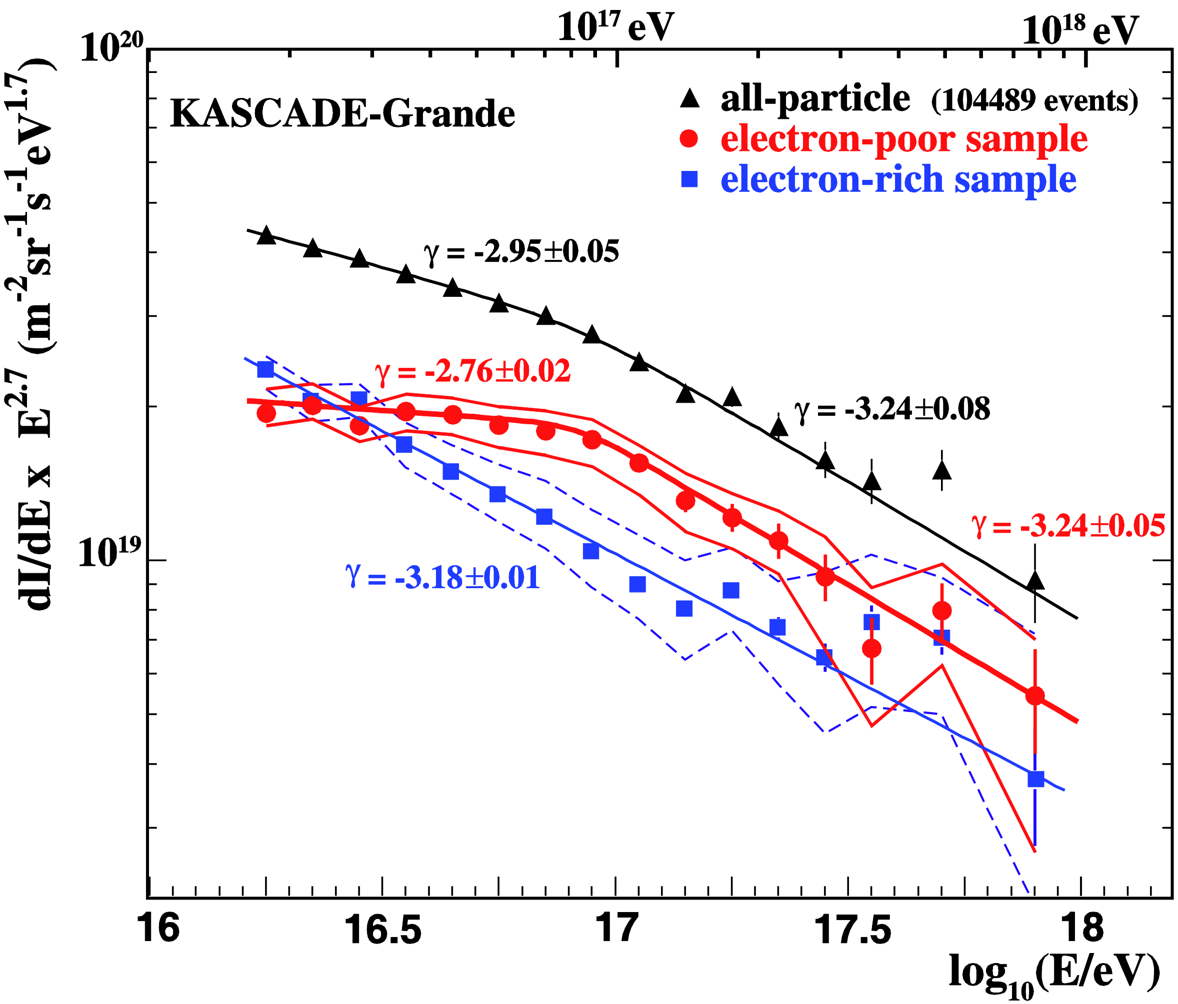
Y_{CIC} is constant with E
(E > full efficiency)

For a specific hadronic interaction model Y_{CIC} increases with primary Mass.
Cutting on Y_{CIC} → cutting on the primary mass

For the same primary element Y_{CIC} increases when it is calculated by a model generating EAS with higher N_{μ} → for the same primary mass the choice of Y_{CIC} is shifted



Heavy primaries mass group spectrum: cut between C and Si (QGSJetII-02)



- **Energy spectra of the samples obtained by an event selection based on the k parameter**
- **Spectrum of the electron poor sample: $k>(k_C+k_{Si})/2$ → steepening observed with increased significance → 3.5σ**
- **Spectrum of electron rich events → can be described by a single power law → hints of a hardening above 10^{17} eV**

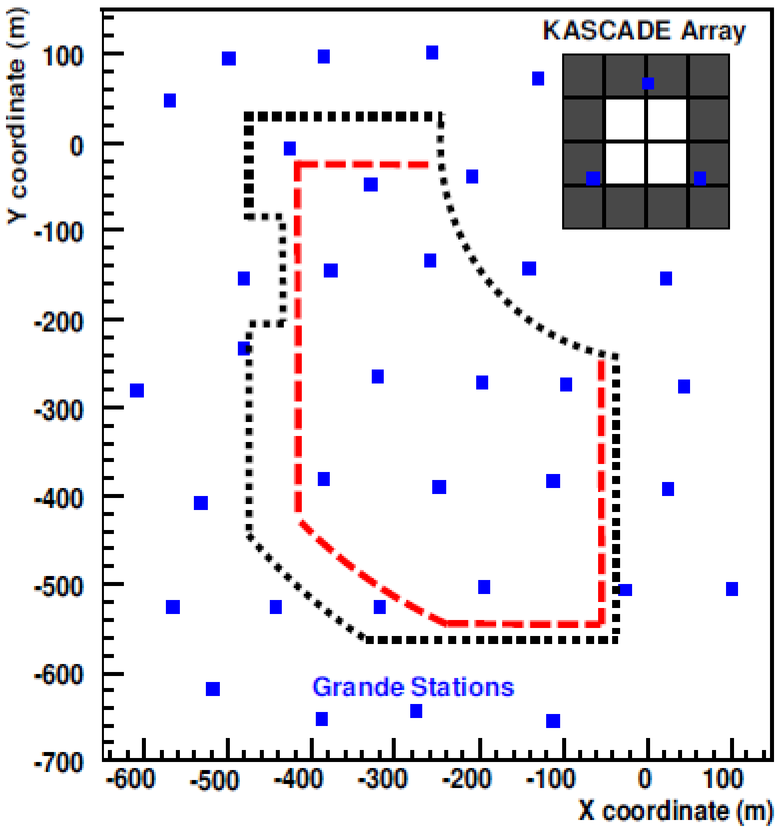
$$\gamma_1 = -2.76 \pm 0.02 \qquad E_b = 10^{16.92 \pm 0.04}\ \mathrm{eV}$$
$$\gamma_2 = -3.24 \pm 0.05$$

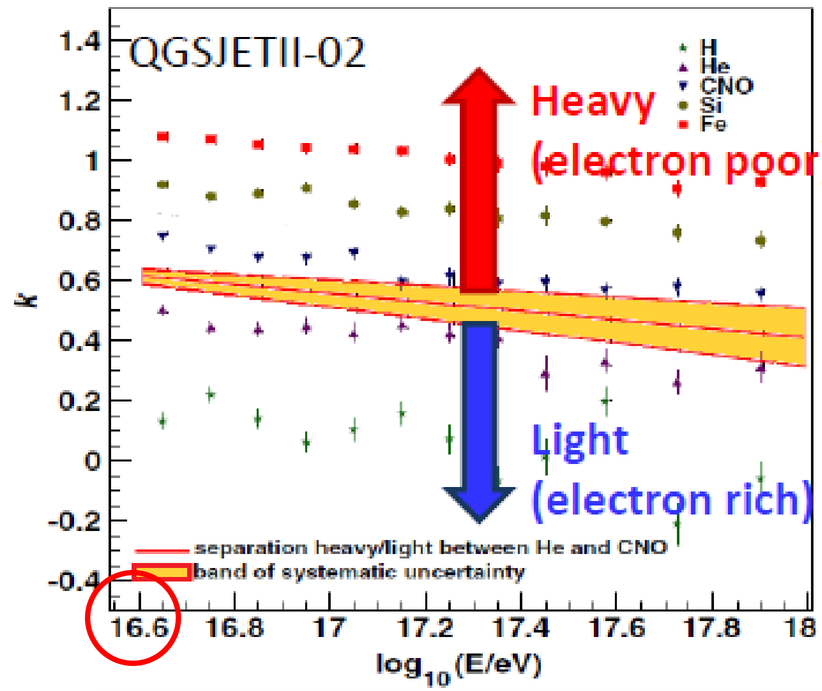
Phys. Rev. Lett. **107** (2011) 171104

Investigations of the electron rich sample

KASCADE-Grande Coll., PRD87 (2013)

Statistics increased by 36% adding new data sets and increasing the effective area





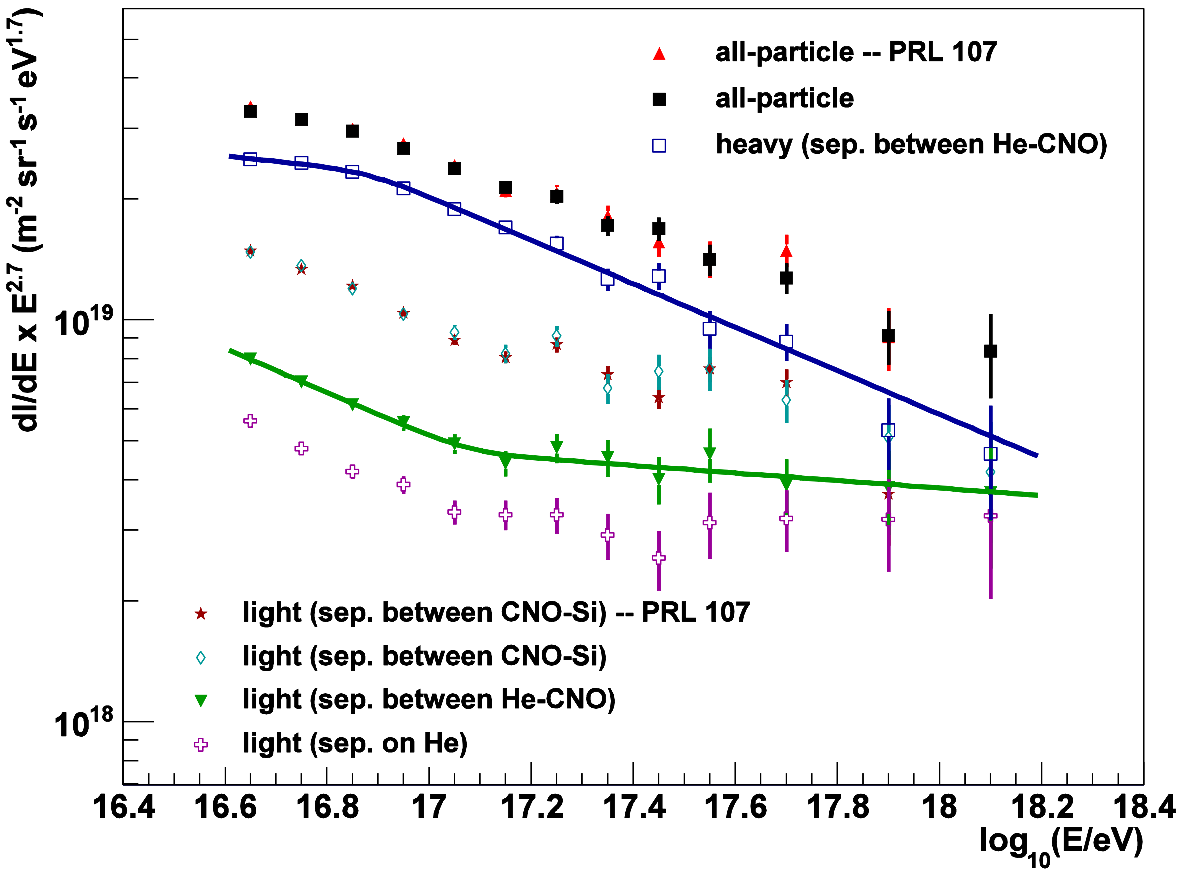
$$k = \frac{log_{10}(N_{ch}/N_{\mu}) - log_{10}(N_{ch}/N_{\mu})_p}{log_{10}(N_{ch}/N_{\mu})_{Fe} - log_{10}(N_{ch}/N_{\mu})_p}$$

To enhance possible structures of the electron rich sample →

$k < (k_C + k_{He})/2$

Phys. Rev. D **87**, 081101(R) (2013)

- **Spectra obtained enhancing the electron-rich event selection show a hardening above 10^{17} eV**



$\gamma_1 = -3.25 \pm 0.05$
$\gamma_2 = -2.79 \pm 0.08$

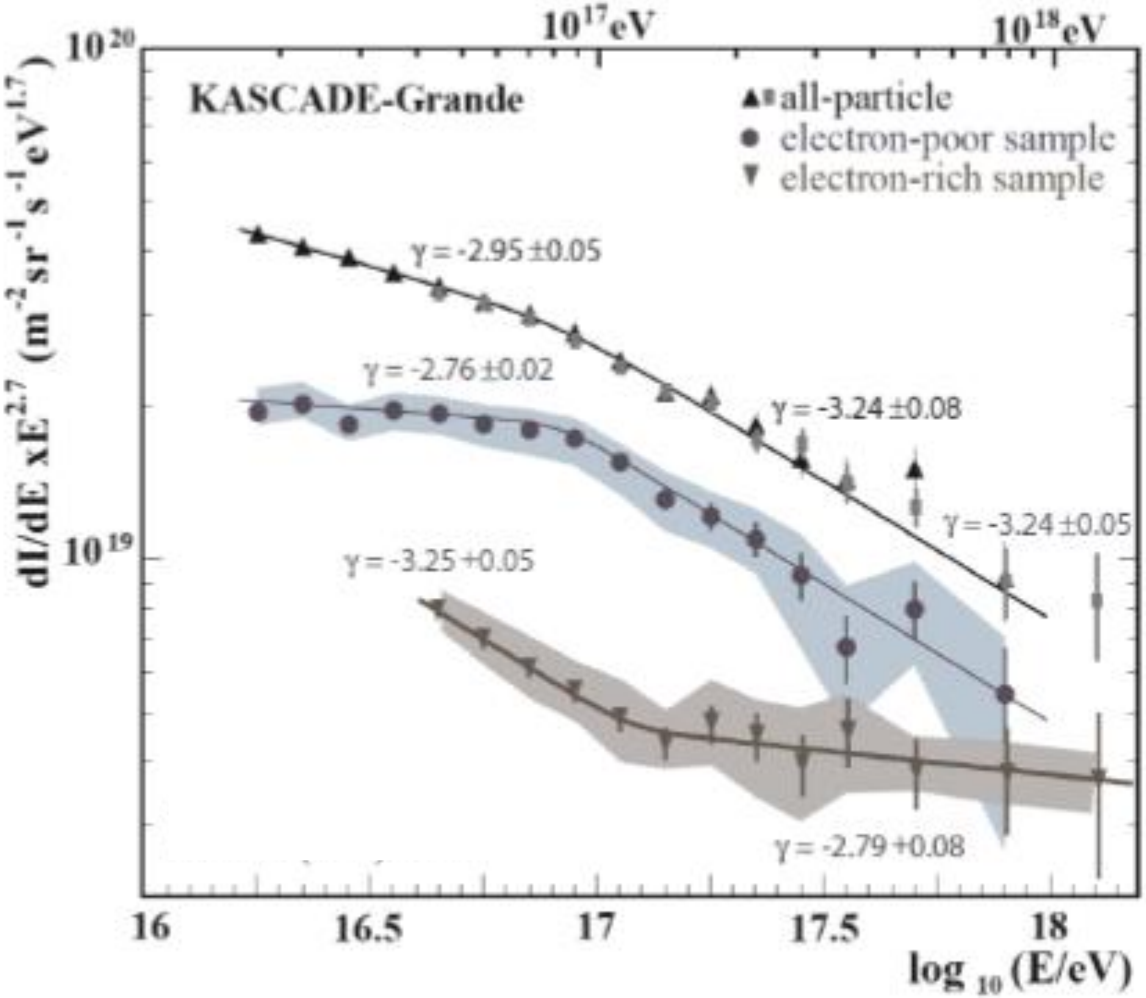
$E_b = 10^{17.08 \pm 0.08}$ eV

$N_{meas} = 579$
$N_{exp} = 467$

$P(N>N_{meas}) \approx 7.23 \times 10^{-09}$

5.8σ significance

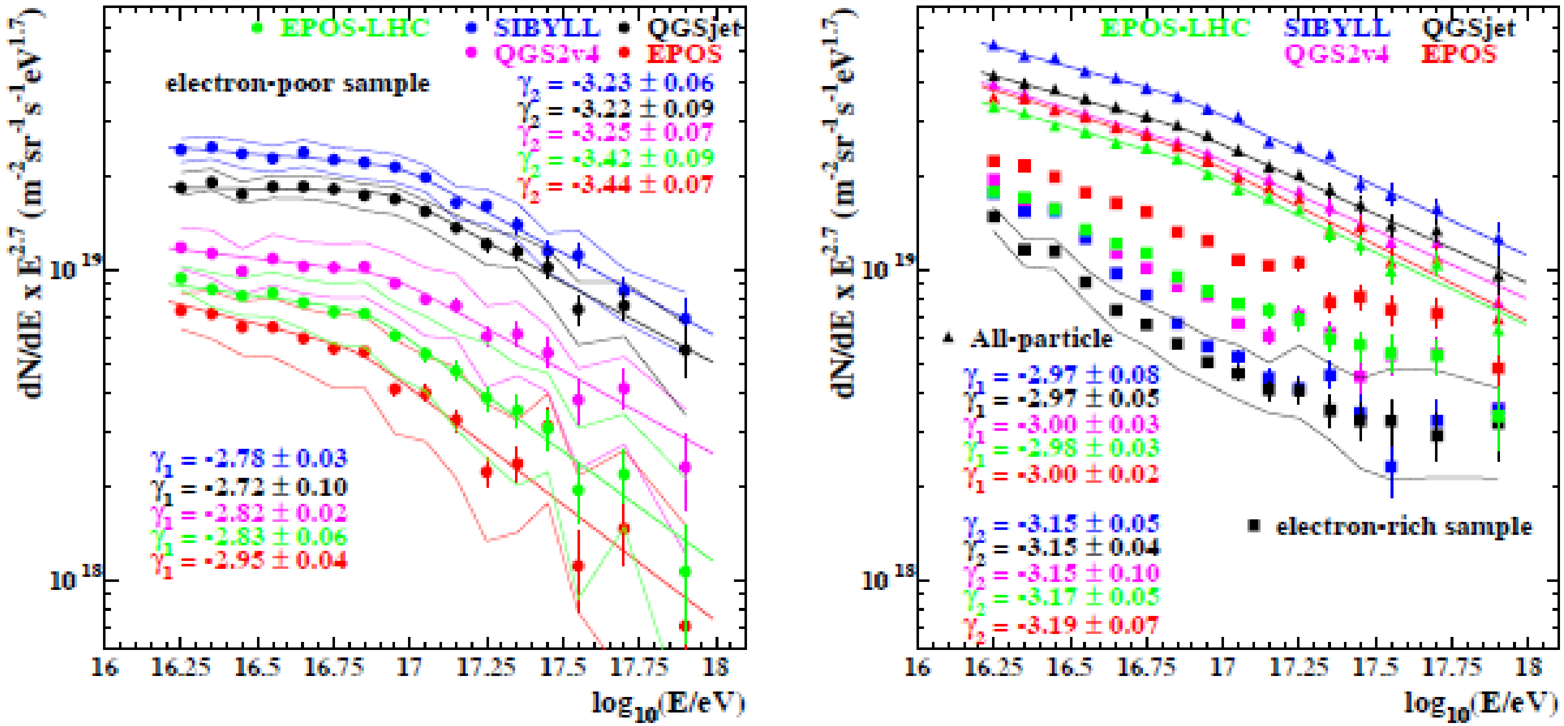
Phys. Rev. D **87**, 081101(R) (2013)



Astroparticle Physics **36**, (2012) 183

Phys. Rev. Lett. **107** (2011) 171104

Phys. Rev. D **87**, 081101(R) (2013)

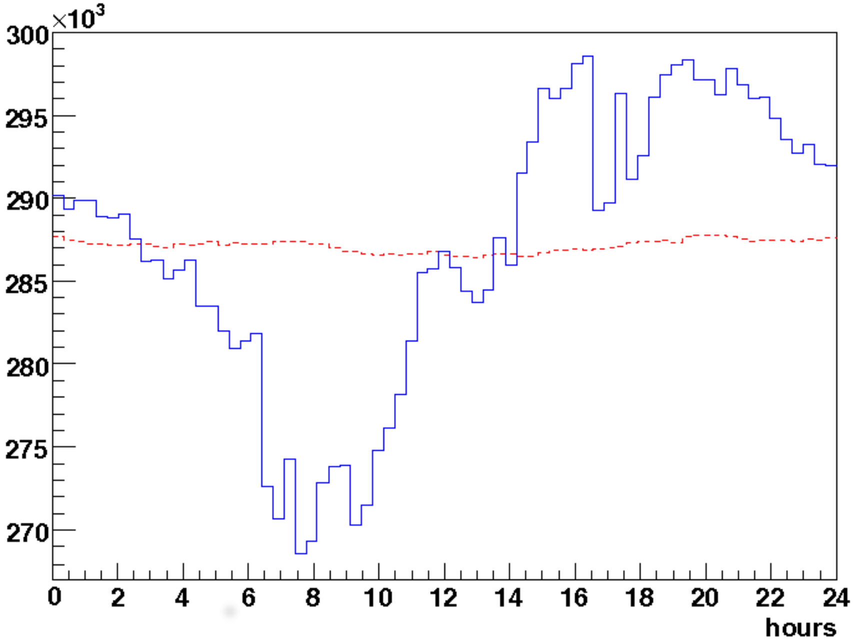


Analysis performed with different hadronic interaction models (pre and post LHC data). Both spectral features can be detected independently from the hadronic interaction models used, while the absolute flux depends on it.

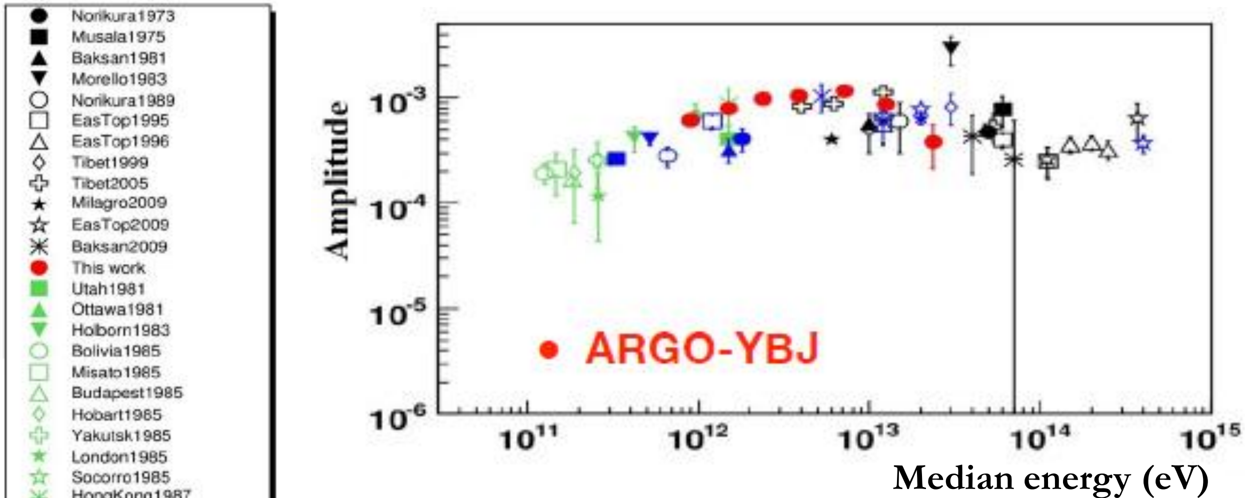
Search for Large Scale Anisotropies

- East-West method
  - Allows to remove counting rate variations due to atmospheric and instrumental effects
- Data set from December 2003 to October 2011 (10^7 events)
  - $\theta<40°$
  - Log $N_{ch} > 5.2$

Counting rate distribution in Solar Time
- Blue line → no corrections
- Red line → E-W method



A. Chiavassa et al. 2014, J. Phys.: Conf. Ser. **531** 012001

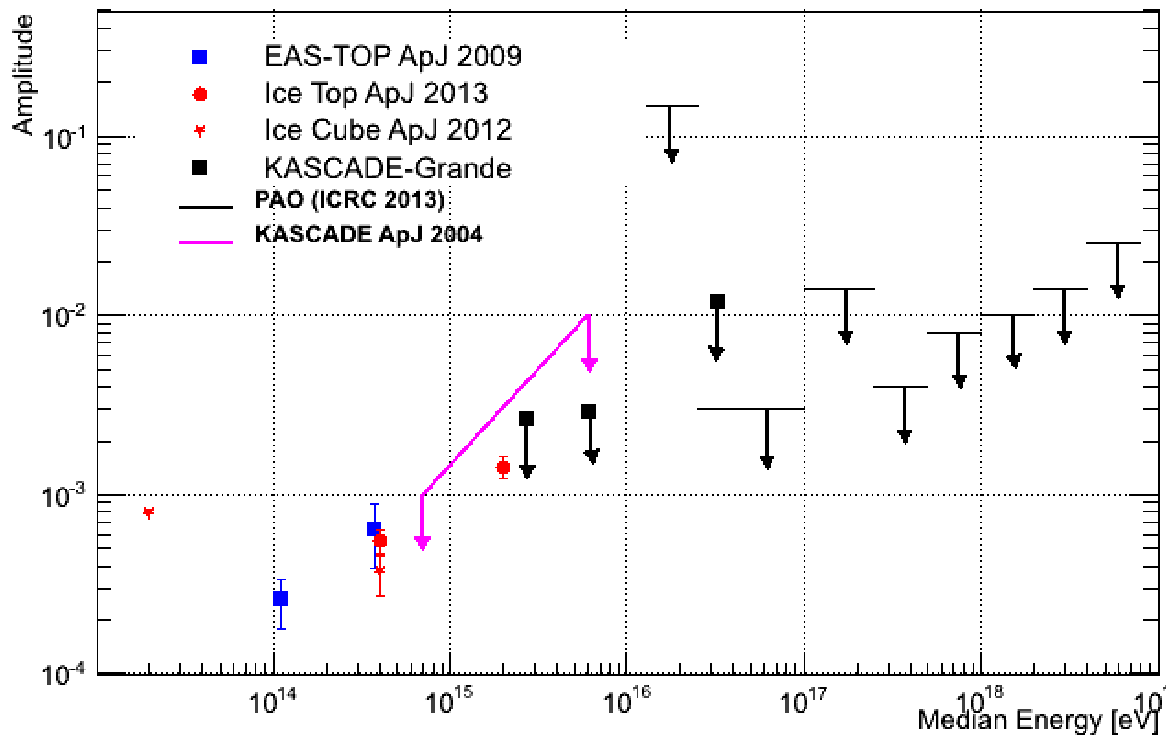


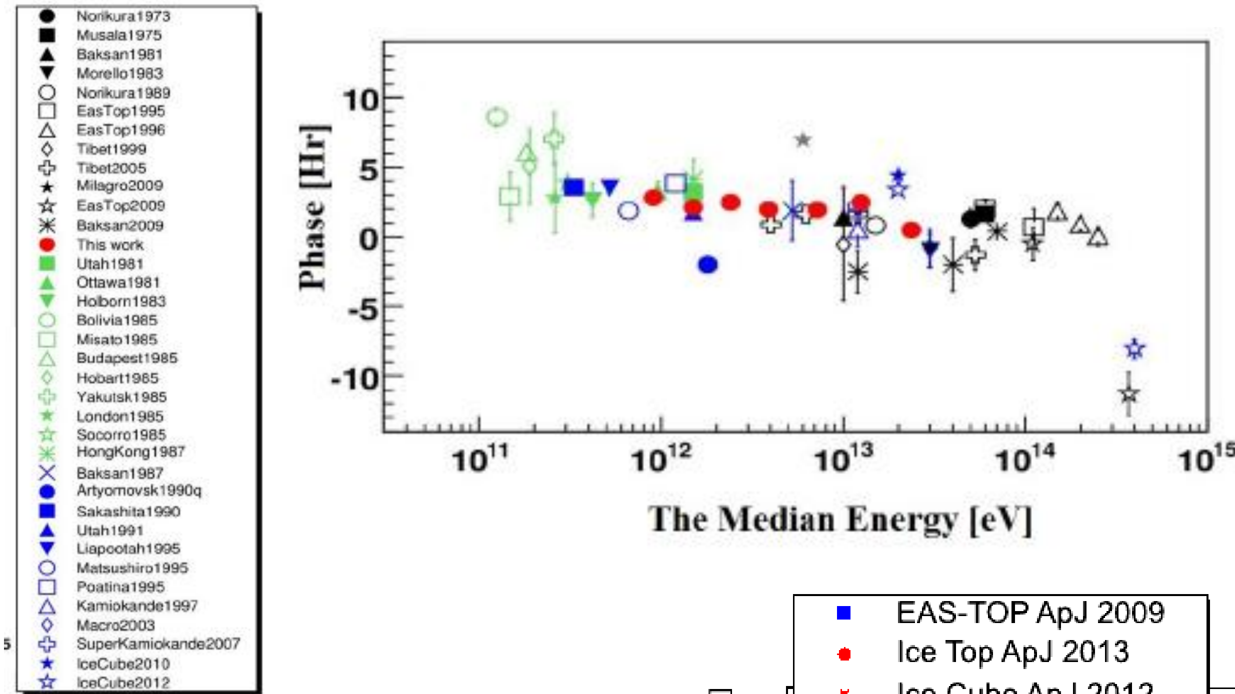
1st Harmonic Amplitudes measured at different energies

$E < 10^{15}$ eV
(thanks to G. DiSciascio)

Hint of an increasing amplitude crossing knee energies

$E > 5 \times 10^{15}$ eV → only upper limits



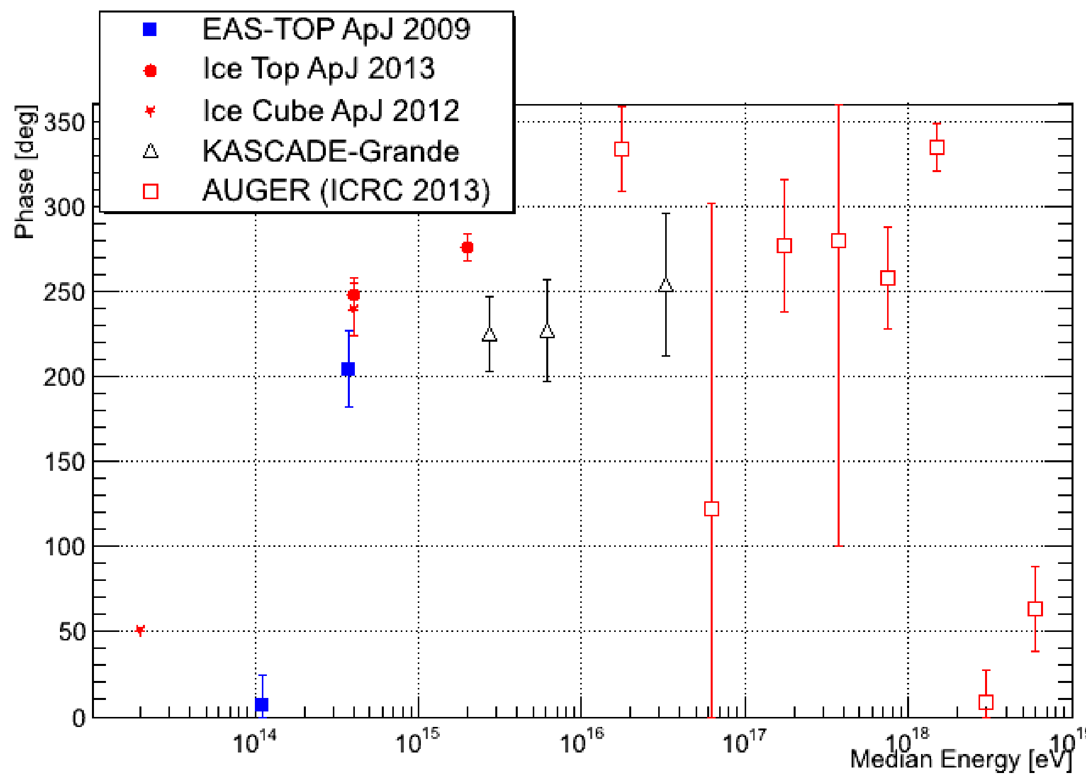


1^{st} Harmonic Phases Measured at different energies

E < 10^{15} eV
(thanks to G. DiSciascio)

Hint of a change of the phase for E>10^{14} eV

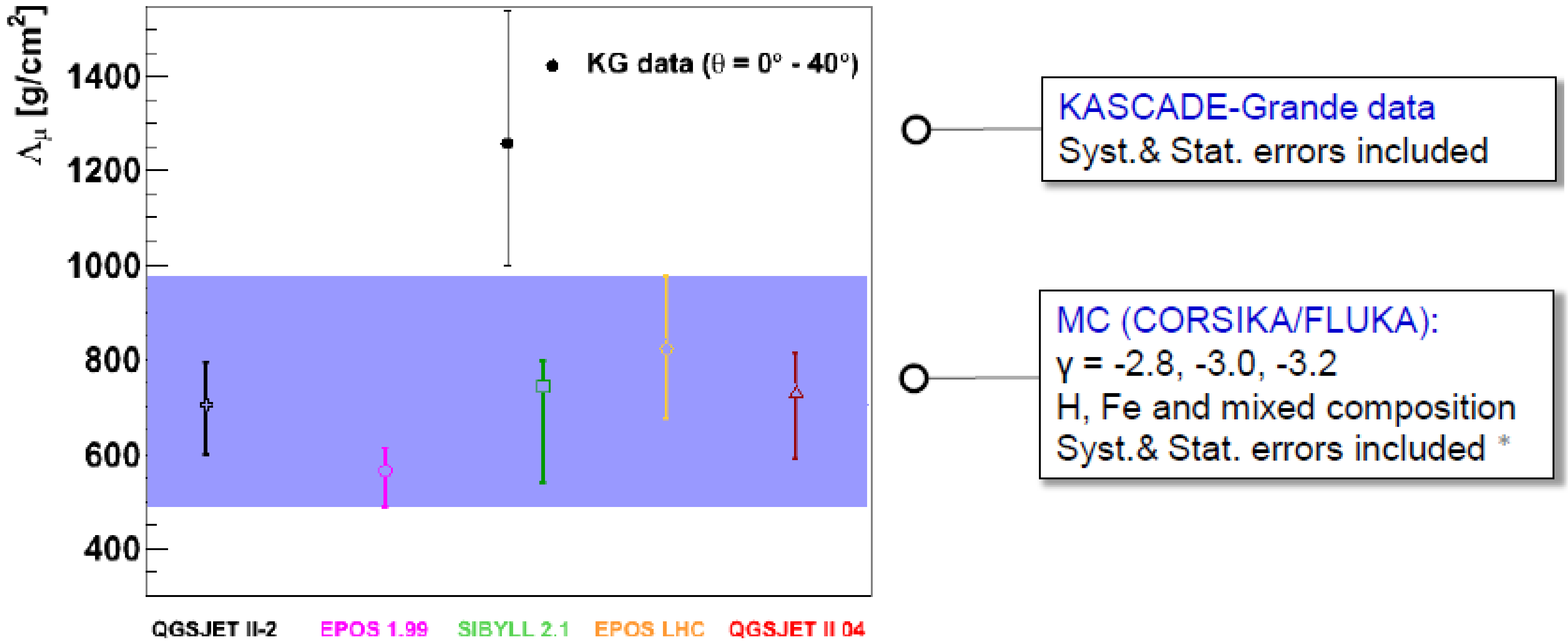
Indication that the phases measured above 5x10^{14} eV are consistent



N_μ attenuation in atmosphere

- Compare the zenith angle dependence of the μ EAS content measured with experimental data (applying Constant Intensity Cut) and predicted by the MC simulations
  - *QGSJetII-02*
  - *QGSJetII-04*
  - *EPOS1.99*
  - *EPOS-LHC*
  - *SIBYLL2.1*

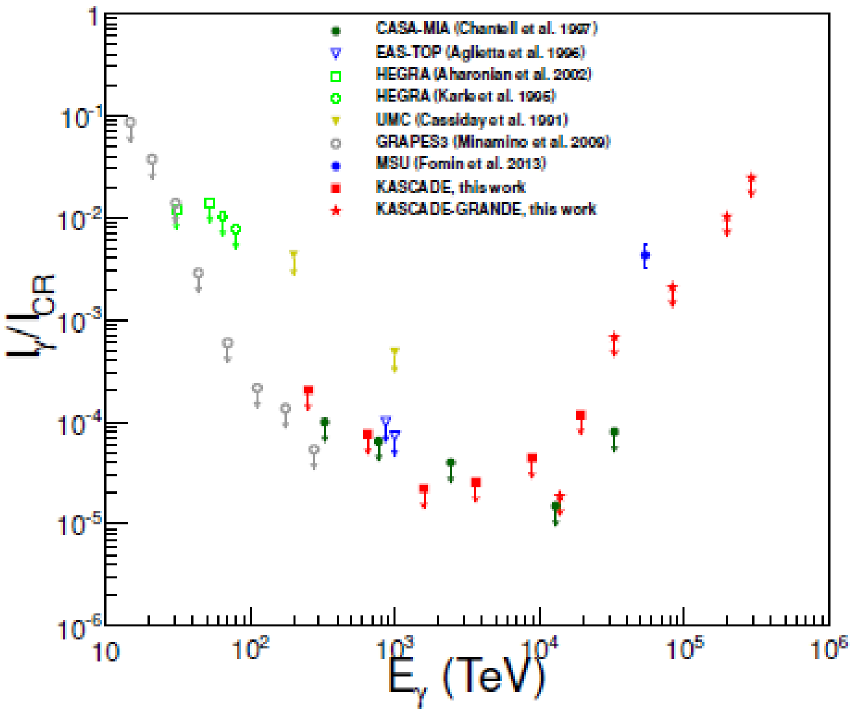
- ***Results show that Λ_μ measured is bigger than the one predicted by MC simulations***

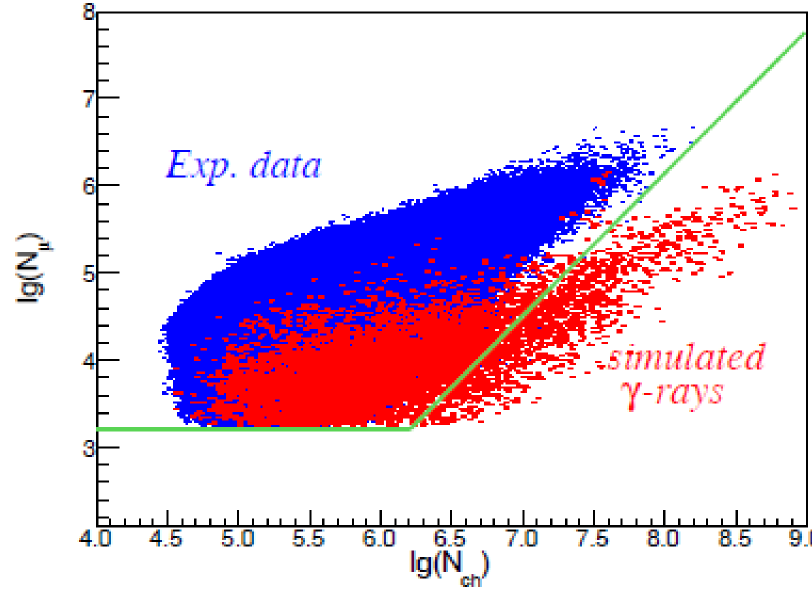


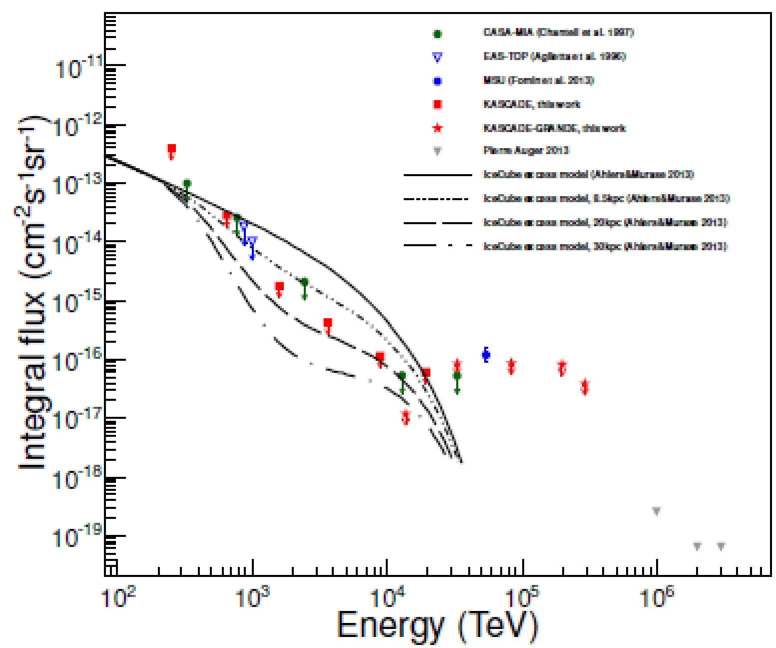
$\delta\Lambda_\mu$	QGSJetII-02	EPOS1.99	SIBYLL2.1	EPOS-LHC	QGSJetII-04
σ	+2.02	+2.63	+1.94	+1.44	+1.93
C.L. (%)	2.17	0.43	2.62	7.49	2.68

Statistical and systematic uncertainties do not explain the difference

γ rays events



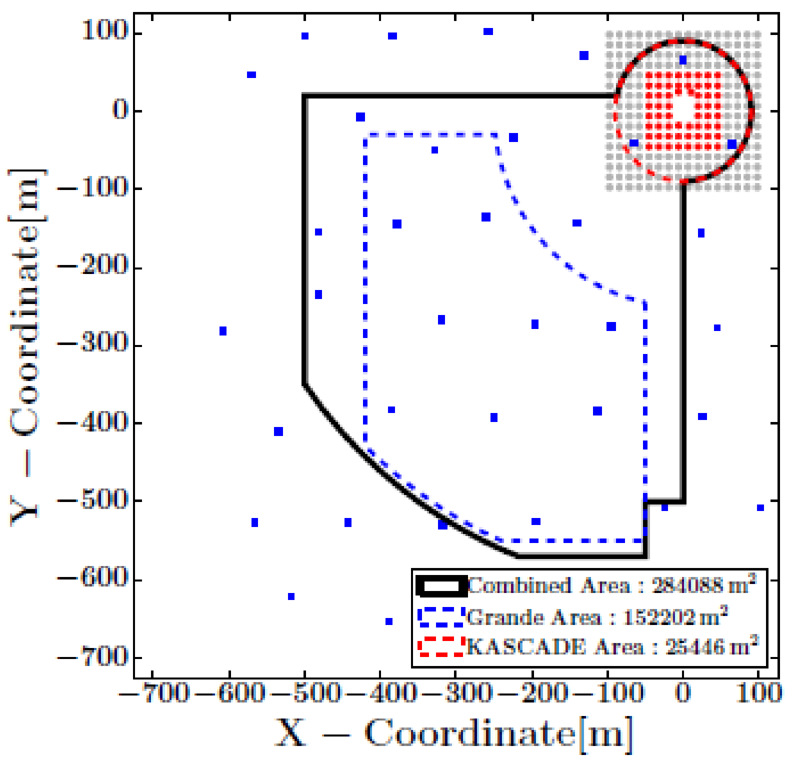


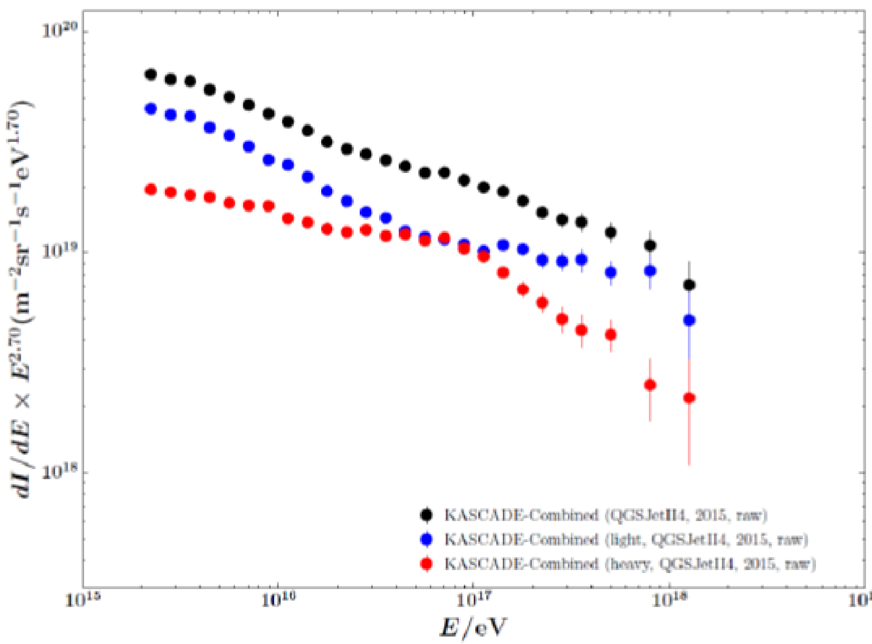


Limits on the diffuse γ-ray flux already constrain the origin of IceCube neutrinos, rejecting the model of IceCube excess coming from <20Kpc in the galaxy

Work in Progress

- Events are analyzed with a combined event reconstruction using both KASCADE and Grande detectors.
- Same event reconstruction to study the 10^{14}-10^{18} eV energy range





KASCADE - timeline

- **53 collaborative papers in reviewed journals** (8 still in queue, short author list papers not included)
- **55 PhD thesis**
- **86 diploma/master thesis**

Xmax by radio

light ankle

EAS GHz emission

iron knee

muon production height

proof-of-principle radio detection

(an)isotropy

γ limit

light knee

model tests

1992 – 1996 – 2000 – 2004 – 2008 – 2012 – 2016

KCDC

CROME

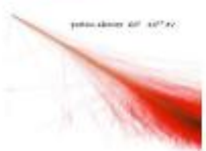
Karlsruhe Air Shower Test Facility

Cosmic Revelation

LOPES

KASCADE-Grande

KASCADE



Proposal

CORSIKA