# Results of the KASCADE-Grande experiment

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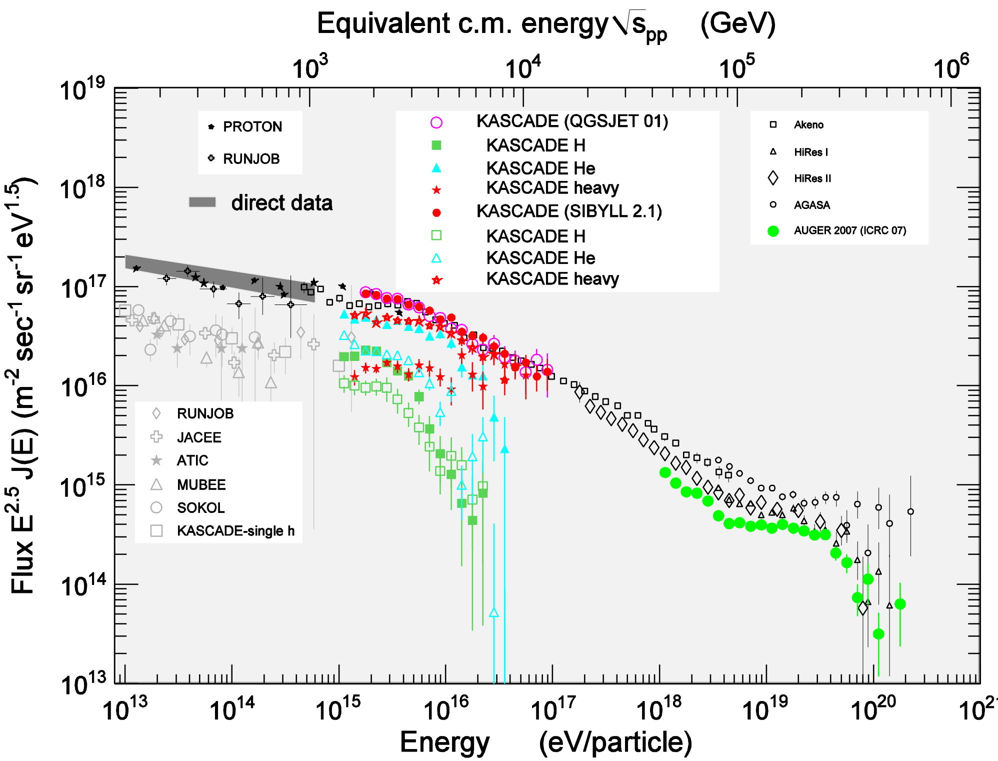
**ICPPA 2015 – Moskow 6-10 October 2015**

- Knee observed in the spectra of all EAS components
- Primary chemical composition gets heavier crossing knee energies
- Knee is due to light primaries

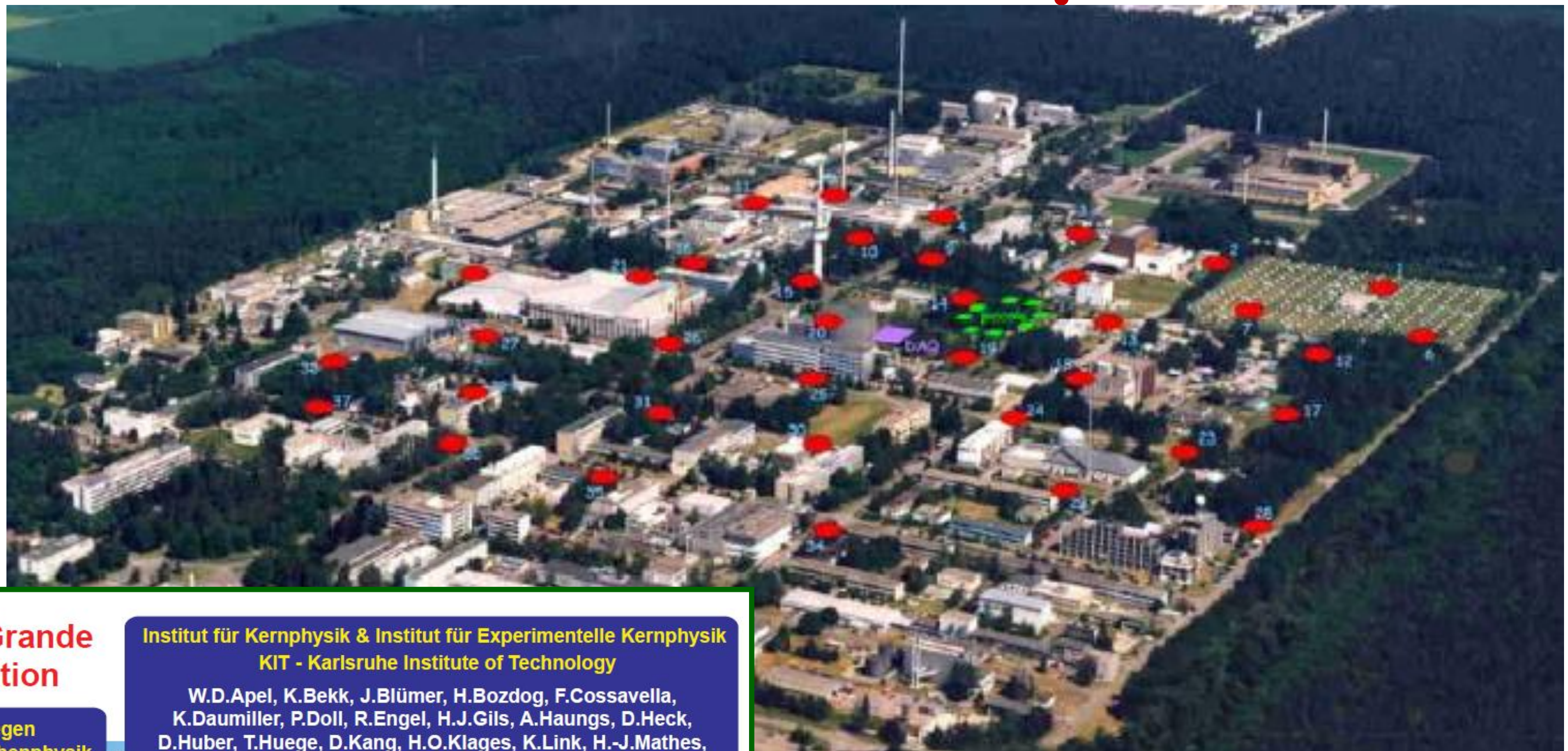


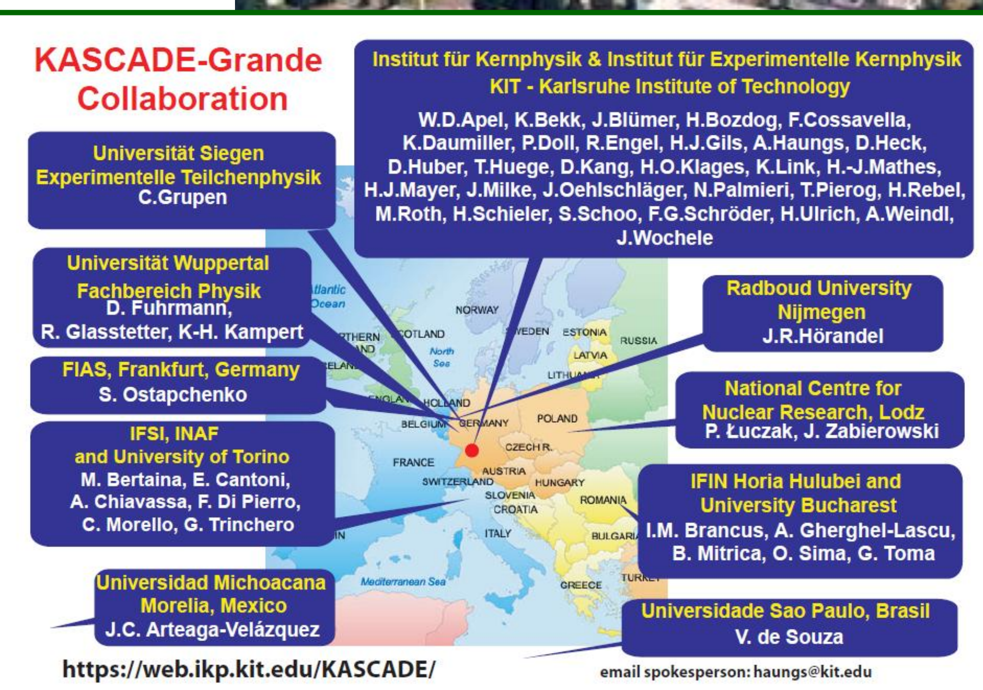

✓ Rigidity Dependent knee?

✓ Composition at the knee?

✓ Transition Galactic-Extragalactic radiation?

# KASCADE-Grande experiment

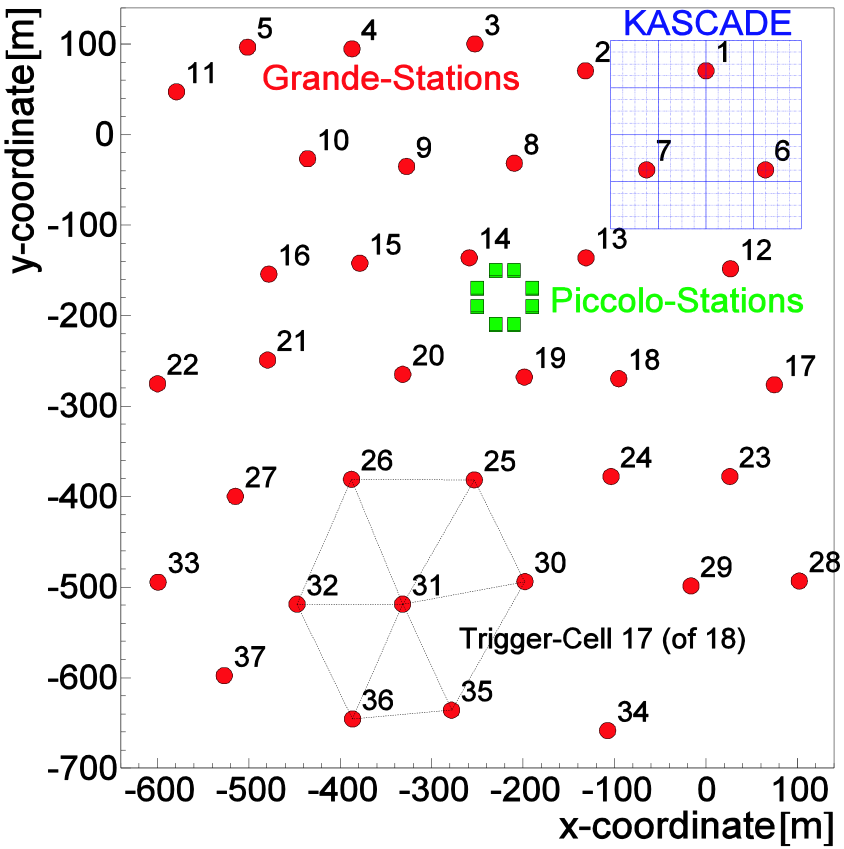





**KIT Campus North, Karlsruhe**

**Data taking:**
**November 2003 – November 2012**

# KASCADE-Grande detectors & observables




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

| Detector | Detected EAS component | 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 ($E_\mu^{th}$=230 MeV) | Plastic Scintillators | 622 |
| MTD | Muons (Tracking) ($E_\mu^{th}$=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 ($E_\mu$>230 MeV)**
  - **KASCADE array μ detectors**
    - **Fit Lagutin Function**
- **μ density & direction ($E_\mu$>800 MeV)**
  - **Streamer Tubes**

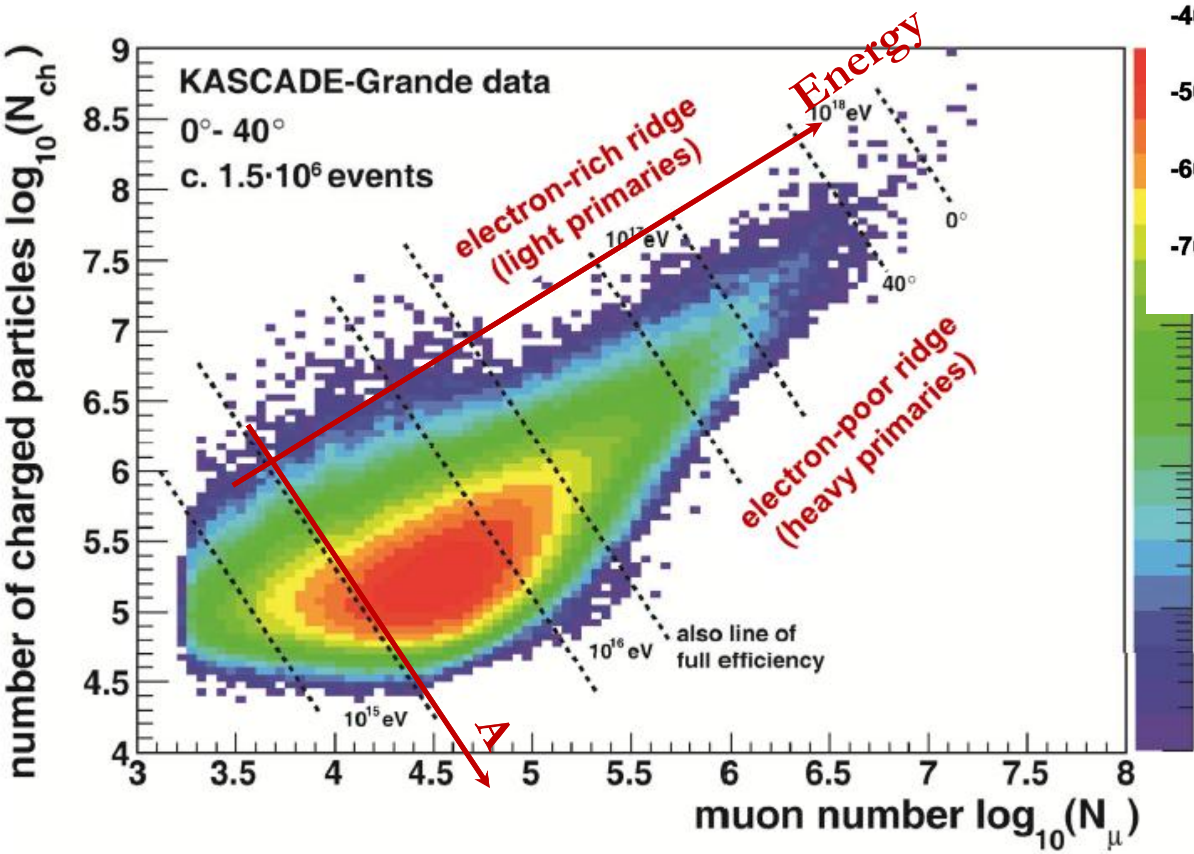
*KASCADE-Grande Data taking concluded in Autumn 2012.*

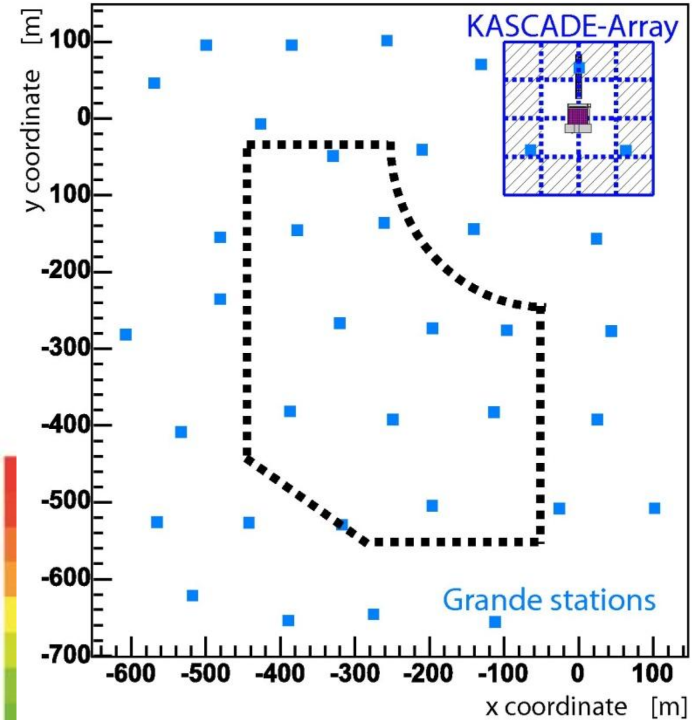
All the Grande scintillators and PMT have been transferred to the TUNKA and NEVOD/DECOR experimental sites

# Main KASCADE-Grande Results

1. All particle energy spectrum
2. Elemental mass groups spectra by:
   a) Unfolding
   b) Event by event classification
3. Large Scale Anisotropy
4. $\mu$ attenuation length in atmosphere
5. Search of $\gamma$ primaries

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




**Energy & mass calibration depends on Hadronic Interaction Model**

# All particle energy spectrum

- Primary energy estimated from a combination of $N_{ch}$ and $N_{\mu}$

- To take into account EAS attenuation in atmosphere we use five different angular bins
- For each event we define a parameter ($\kappa$) used to "evaluate" the mass of the primary particle

- **Published results calibrated by QGSJetII-02**

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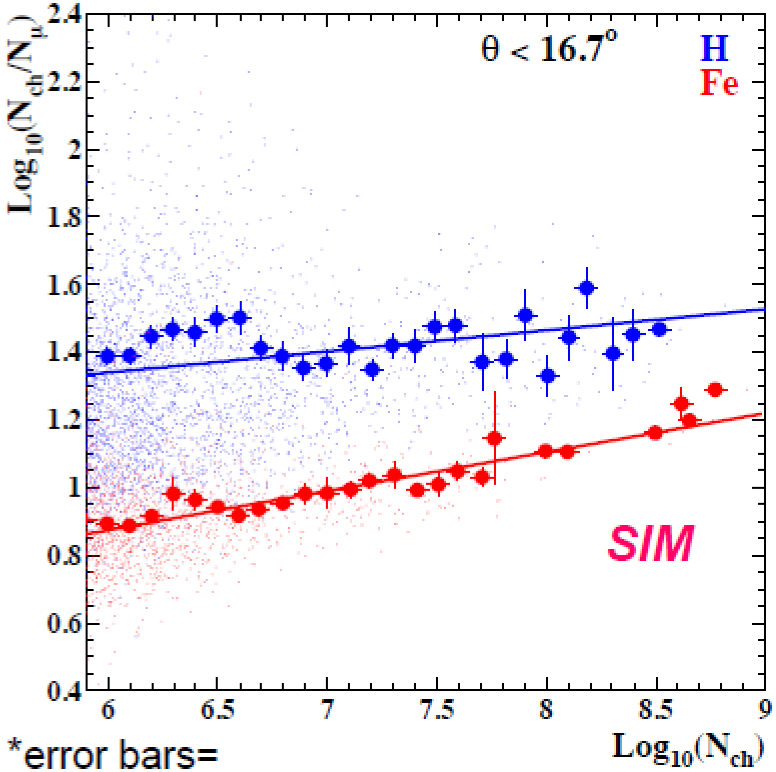
# $N_{ch} - N_{\mu}$ technique

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

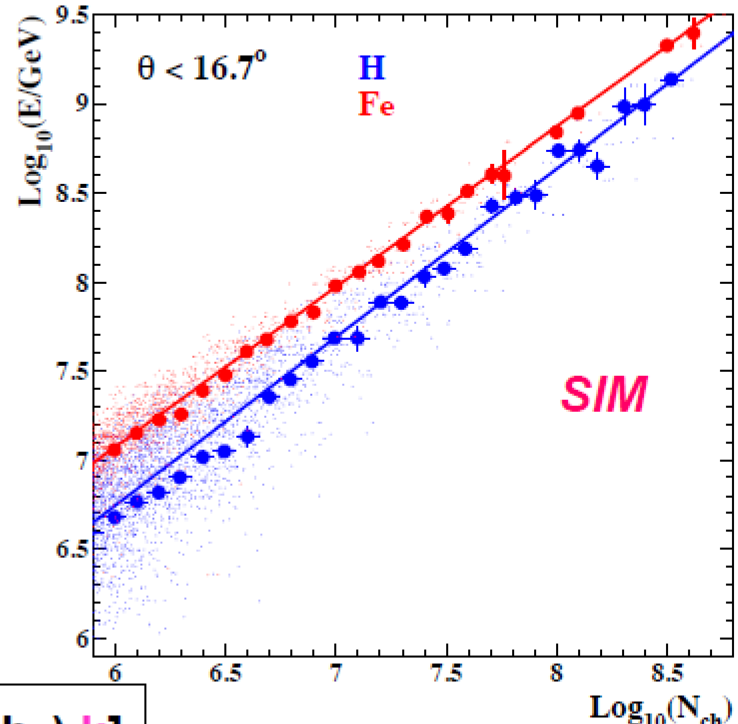



*error bars=
RMS of distributions

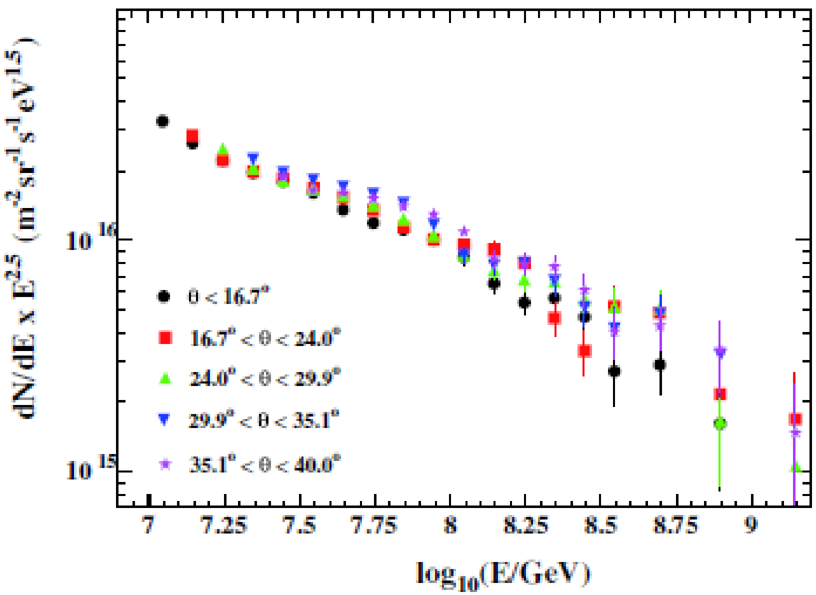
**5 angular bins (0 - 40°) treated independently**

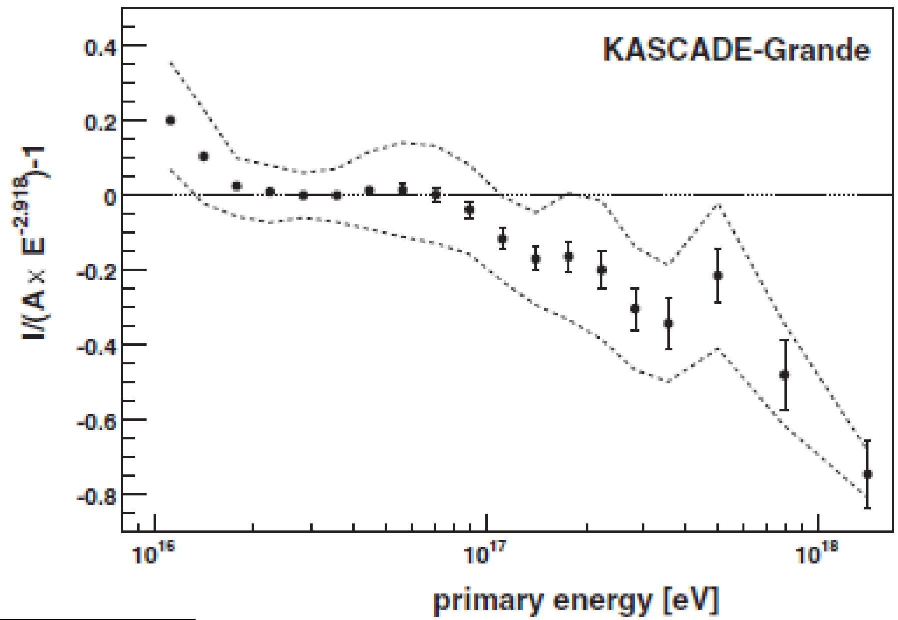
$$k = \frac{\log_{10}(N_{ch}/N_{\mu}) - \log_{10}(N_{ch}/N_{\mu})_p}{\log_{10}(N_{ch}/N_{\mu})_{Fe} - \log_{10}(N_{ch}/N_{\mu})_p}$$

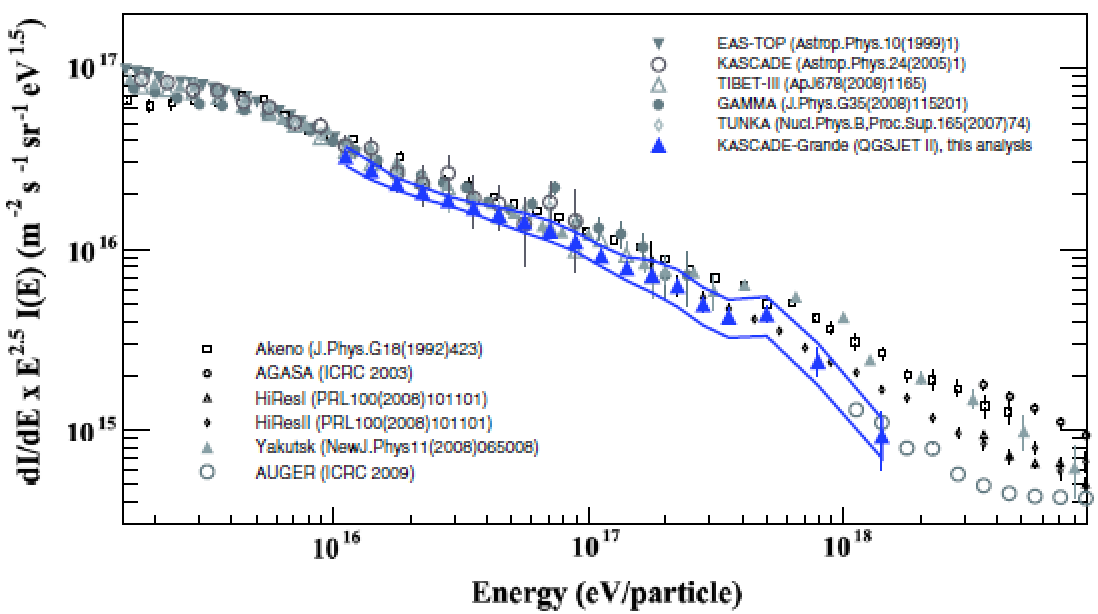
$$\log_{10}E_{p,Fe} = a_{p,Fe}\log_{10}N_{ch} + b_{p,Fe}$$




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




- **Spectrum cannot be described by a single power law**
- **Concavity above $10^{16}$ eV**
- **Steepening at ~$8x10^{16}$ eV significance 2.1σ**

**QGSJetII-02**

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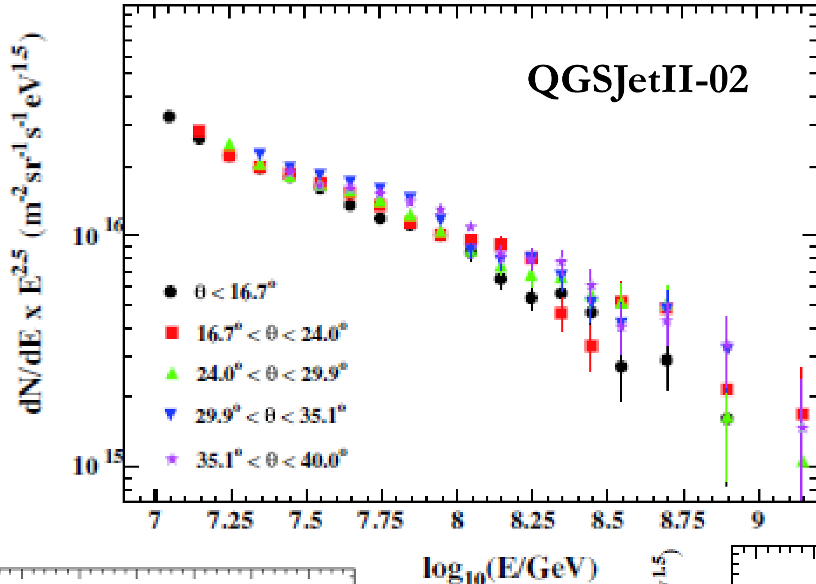
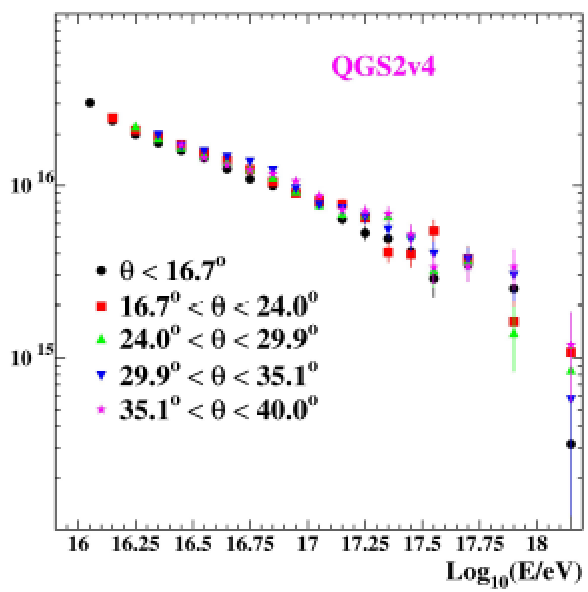
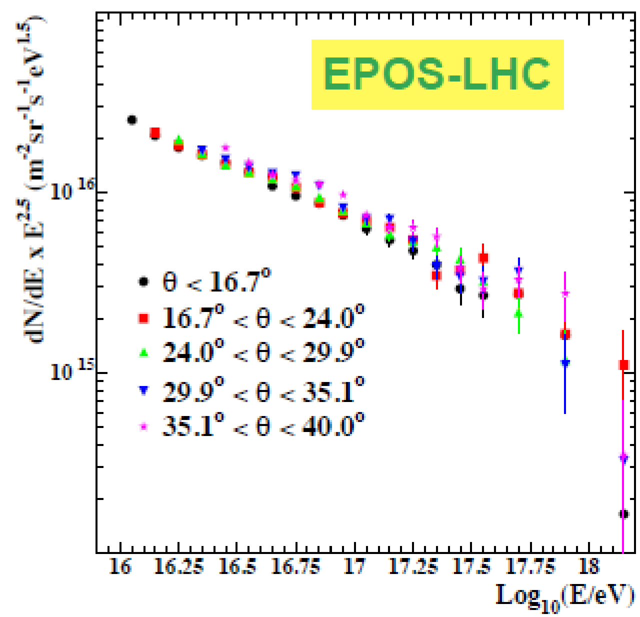
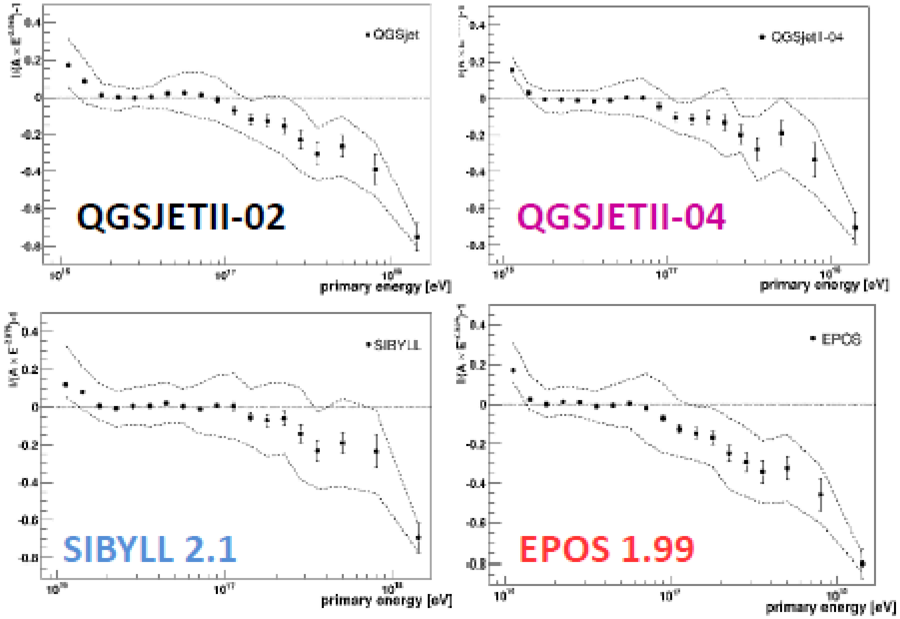
# Hadronic interaction models tuned by LHC data give a better description of EAS evolution in atmosphere



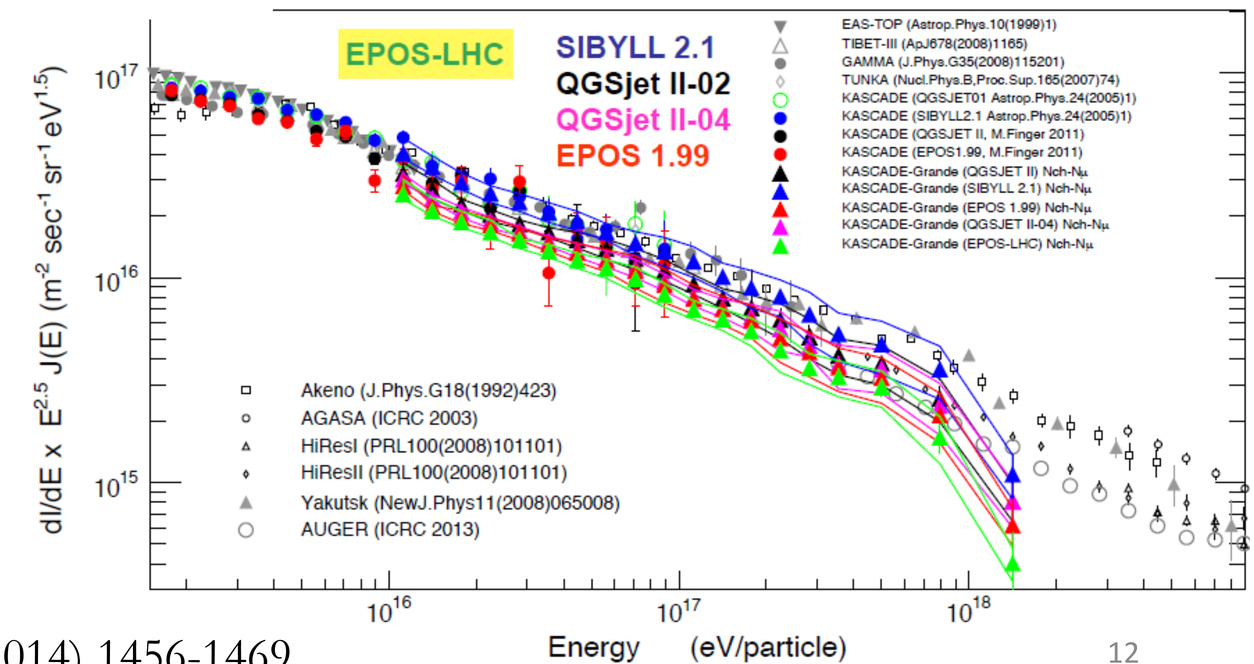



# All-particle energy spectrum



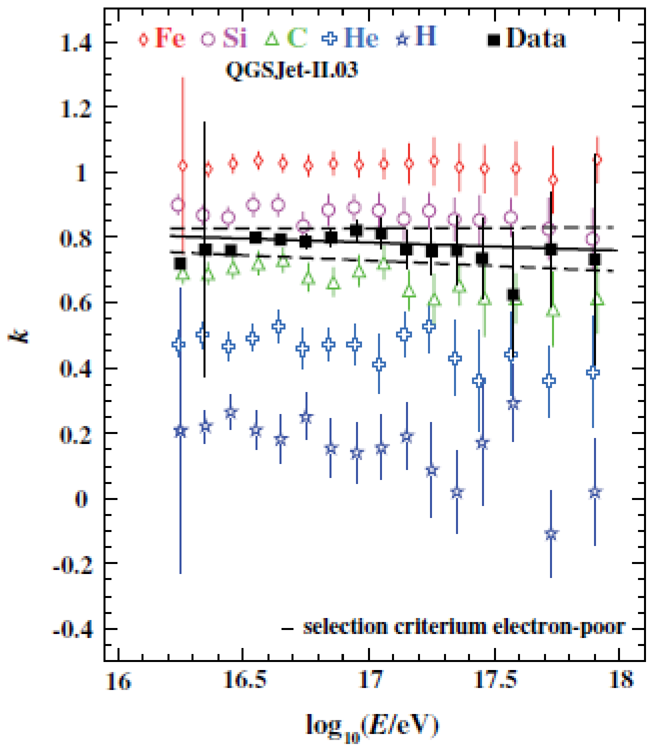

Spectral features are visible in the spectra calibrated with all interaction models

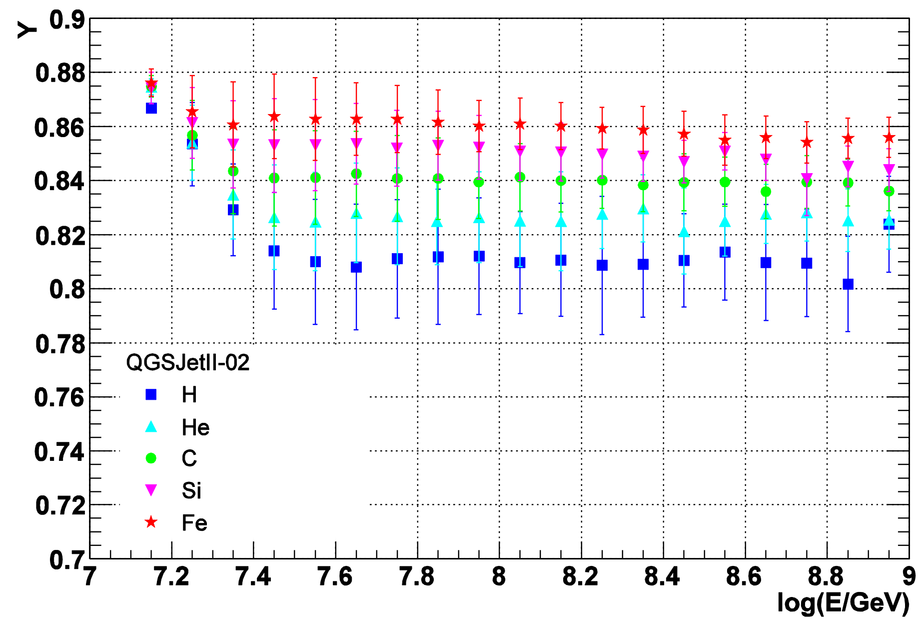



Advances in Space Research **53**, (2014) 1456-1469

# Event by event separation in two mass groups by the $N_{ch}/N_{\mu}$ ratio

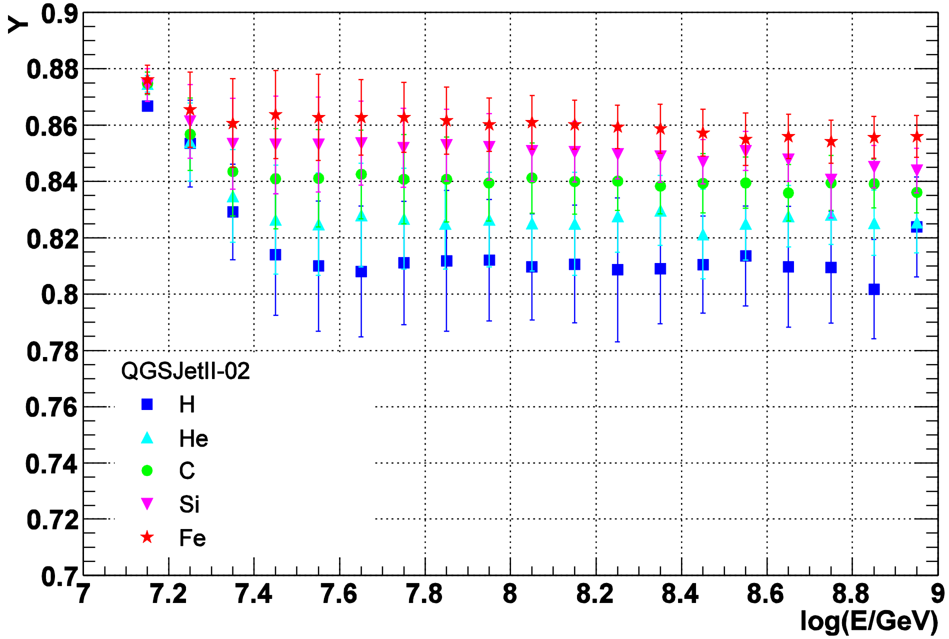
Two different ways of taking into account the EAS attenuation in atmosphere




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

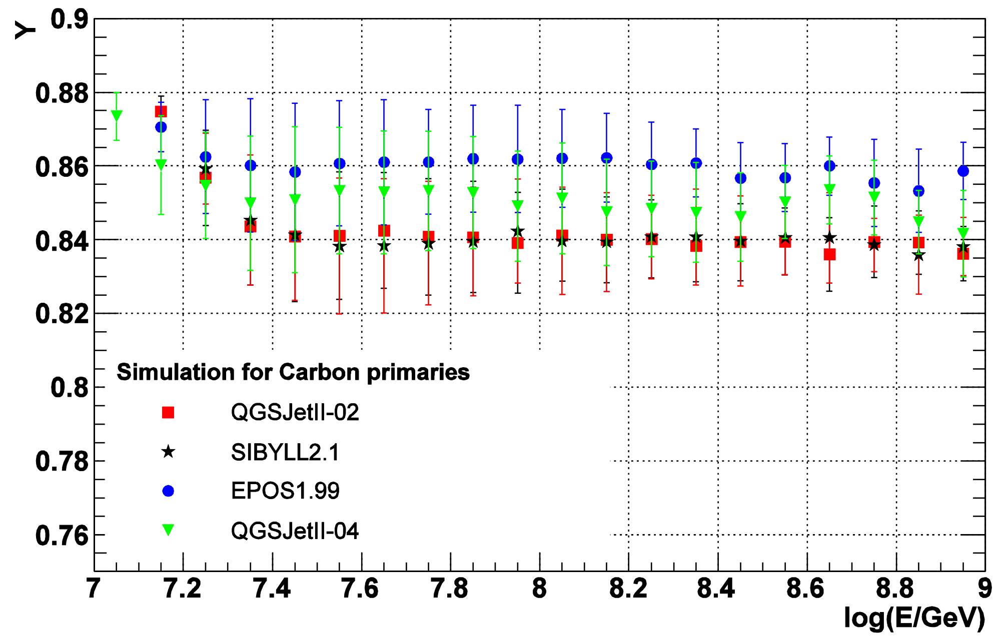
$$Y_{CIC} = \frac{\ln N_{\mu}(\vartheta_{ref})}{\ln N_{ch}(\vartheta_{ref})}$$

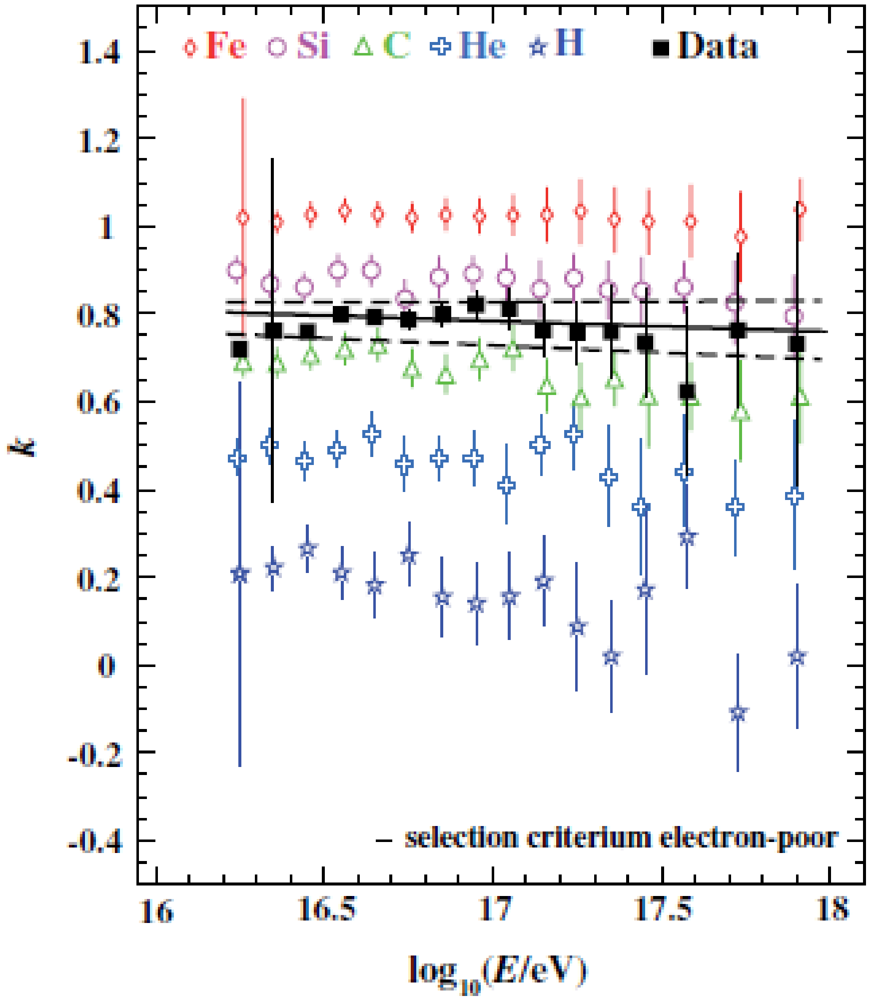



$Y_{CIC}$ is constant with E
(E > full efficiency)

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 $N_{\mu}$ → for the same primary mass the choice of $Y_{CIC}$ is shifted

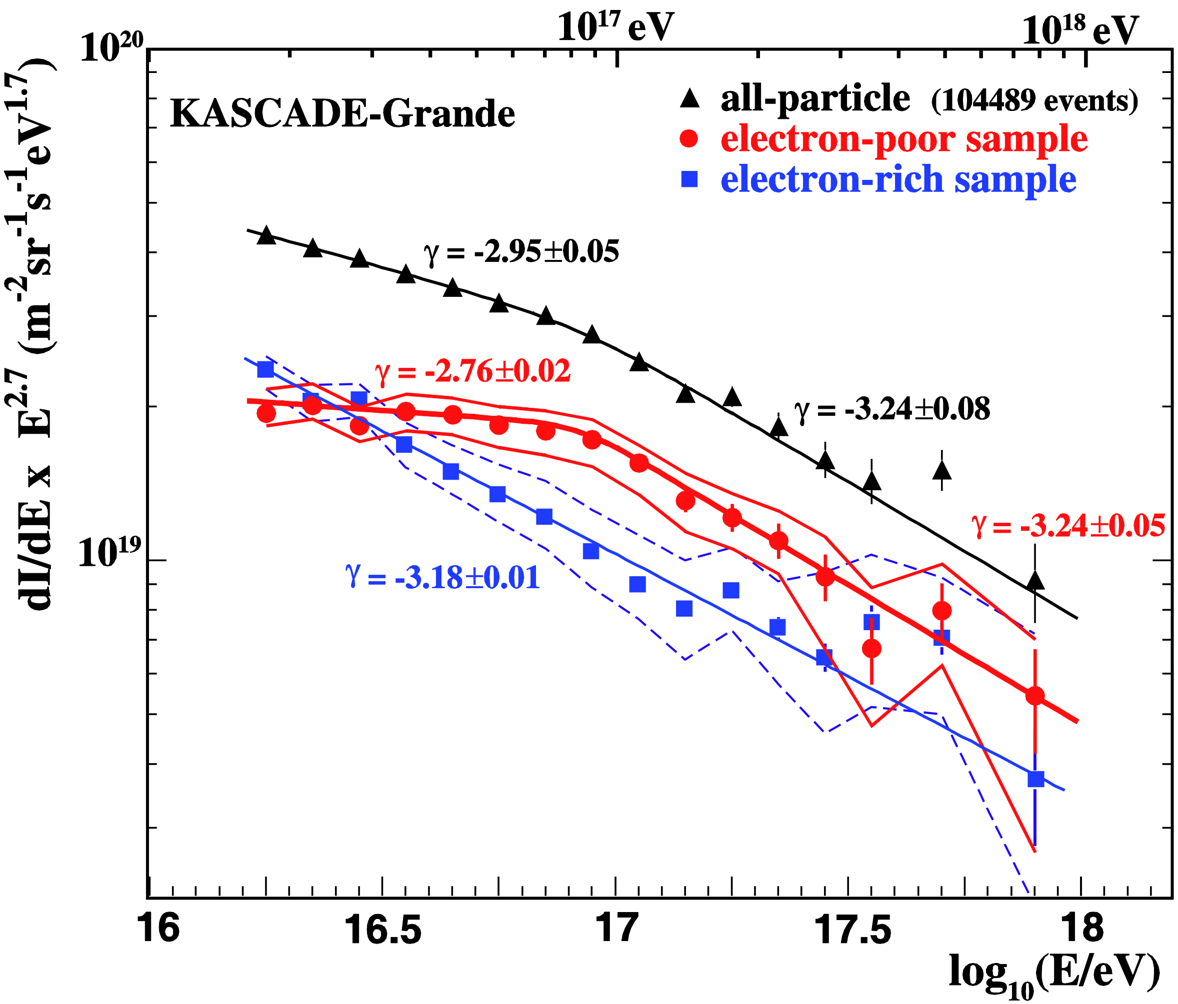





- **Electron poor events (i.e. heavy primaries) are those with κ values greater than the solid line**
- **QGSJetII-02**

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

# 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

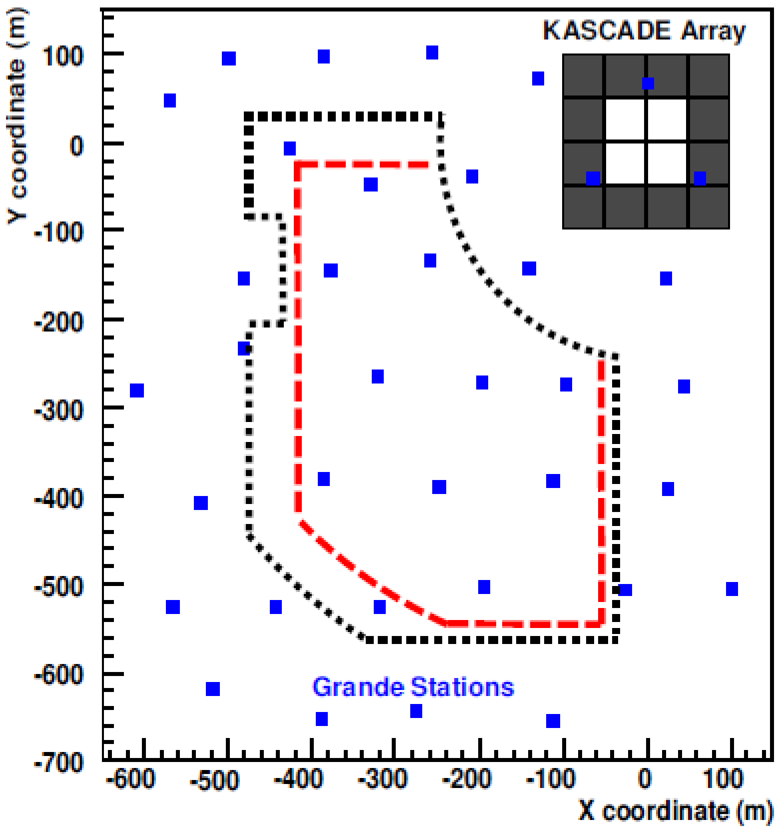
$$\gamma_1 = -2.76 \pm 0.02 \quad E_b = 10^{16.92 \pm 0.04}\ \text{eV}$$

$$\gamma_2 = -3.24 \pm 0.05$$

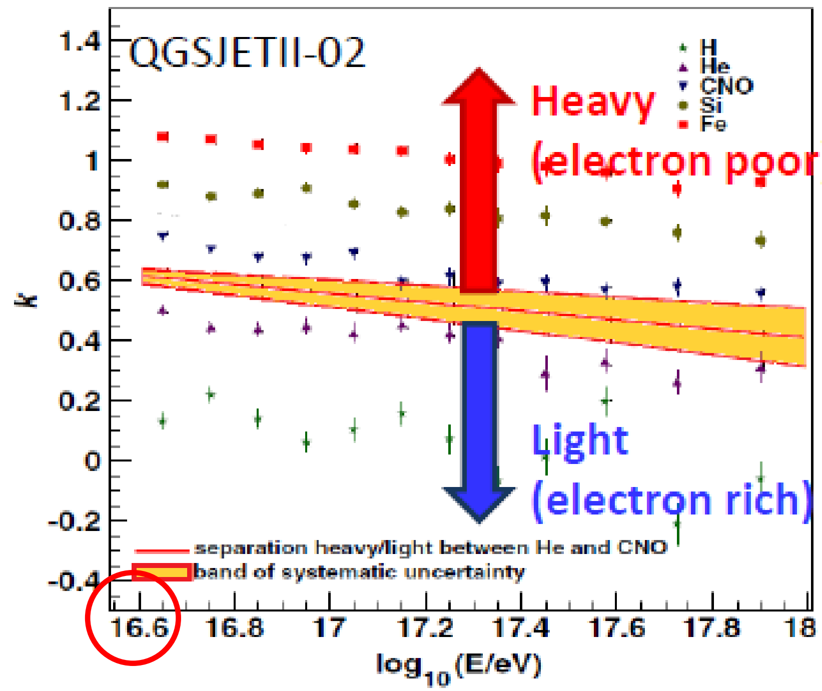
Phys. Rev. Lett. **107** (2011) 171104

# Investigations of the electron rich sample

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




KASCADE-Grande Coll., PRD87 (2013)



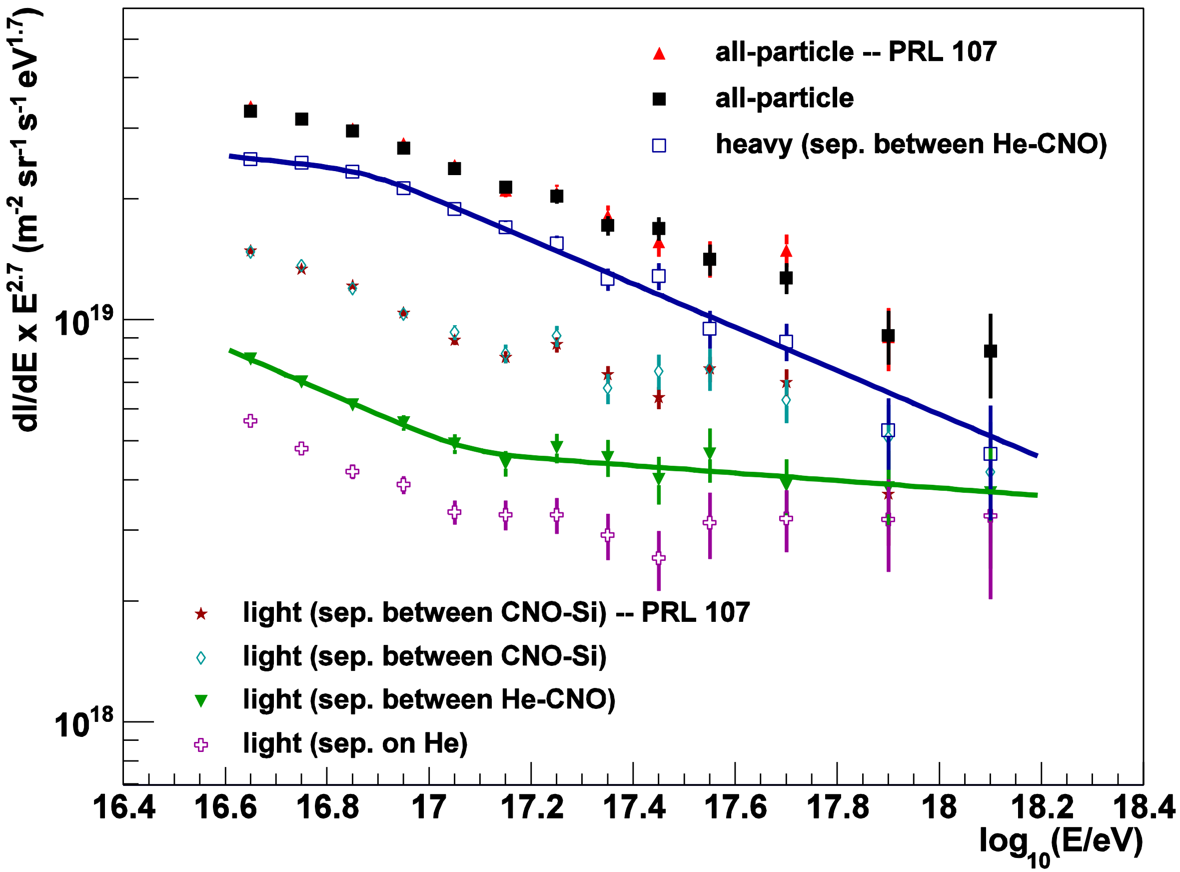

$$k = \frac{log_{10}(N_{ch}/N_{\mu}) - log_{10}(N_{ch}/N_{\mu})_p}{log_{10}(N_{ch}/N_{\mu})_{Fe} - log_{10}(N_{ch}/N_{\mu})_p}$$

**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




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

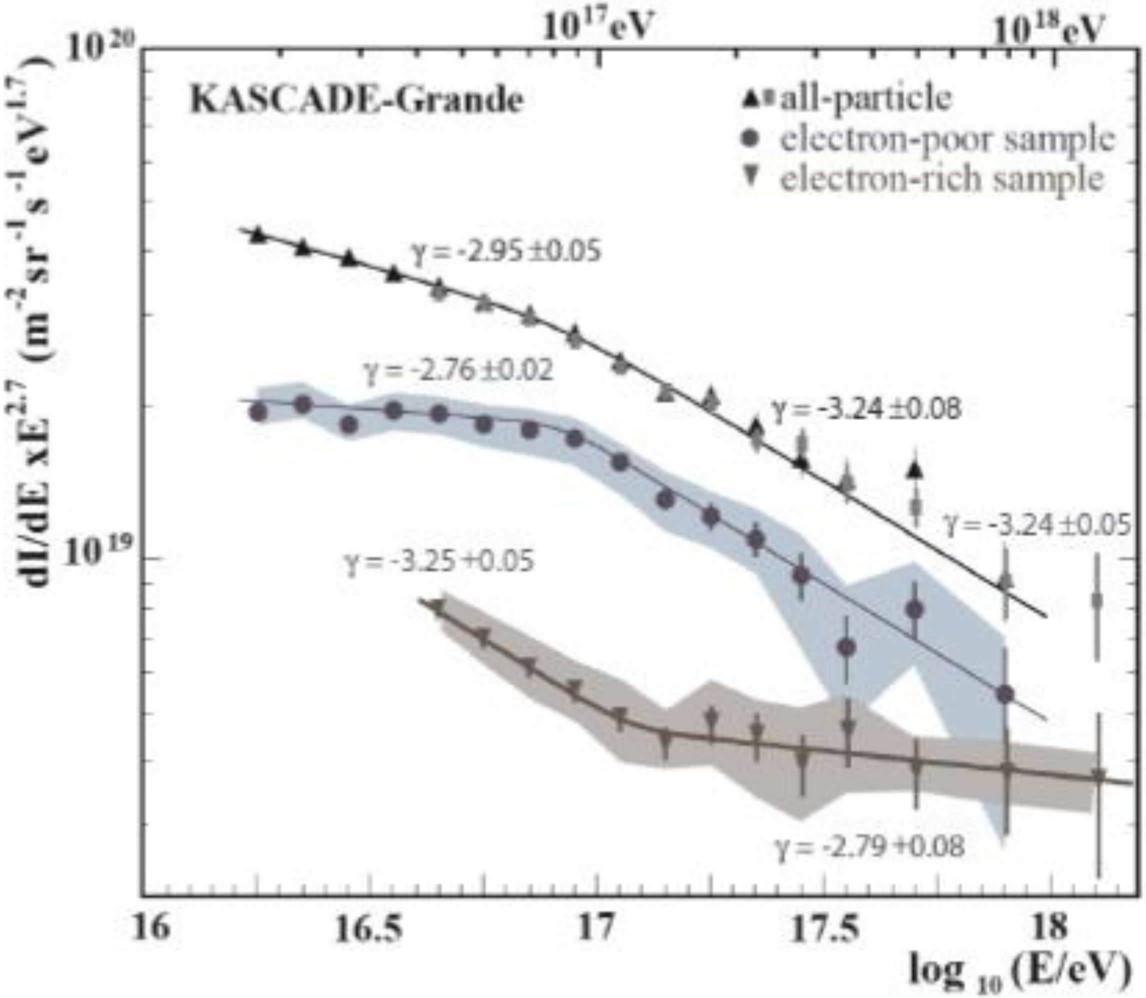
$E_b = 10^{17.08 \pm 0.08}$ eV

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

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

5.8σ significance

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

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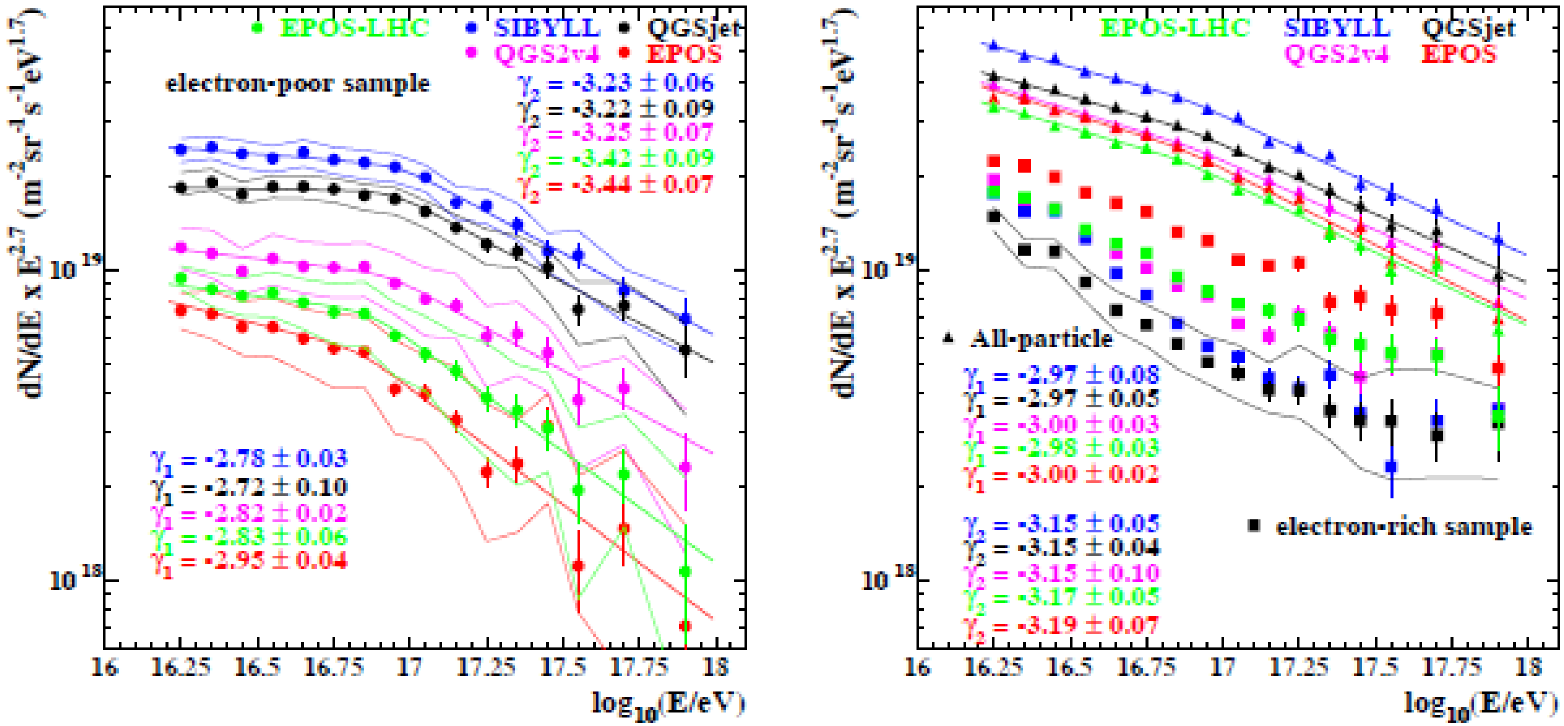
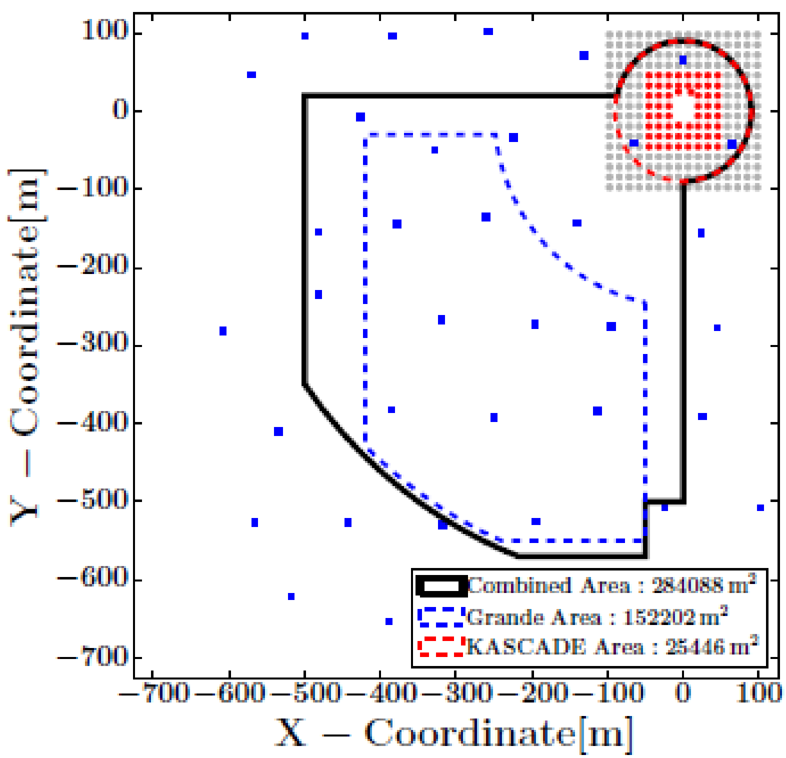
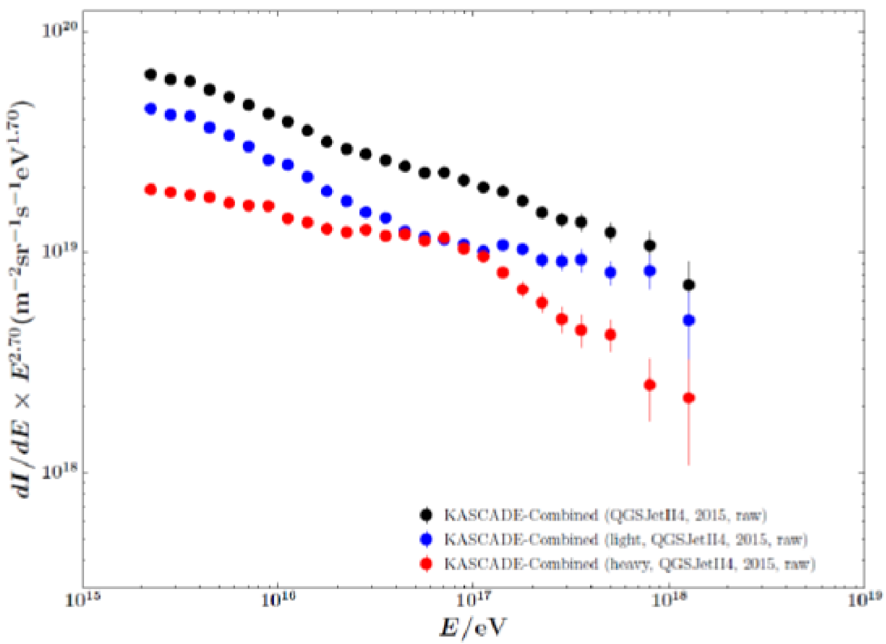



Analysis performed with different hadronic interaction models (pre and post LHC data). Both spectral features can be detected independently from the hadronic interaction models used, while the absolute flux depends on it.

# Further analysis 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



# CONCLUSIONS

- KASCADE-Grande experiment was a **Large Surface and High Resolution array**, that investigated the $10^{16}$-$10^{18}$ eV energy range

- Main results of ten years of data taking:
  - ✓ The primary spectrum cannot be described, in the $10^{16}$-$10^{18}$ eV energy range, by a single slope power law.
  - ✓ We separate two mass groups samples (light and heavy):
    - Knee of the heavy spectrum ($8 \times 10^{16}$ eV)
    - Hardening of the light spectrum ($10^{17.08}$ eV)
  - ✓ Upper limits to the amplitude of large scale anisotropy.
  - ✓ $\mu$ attenuation length in EAS is not agreement with current simulations.