Review on Galactic Cosmic Ray Detection

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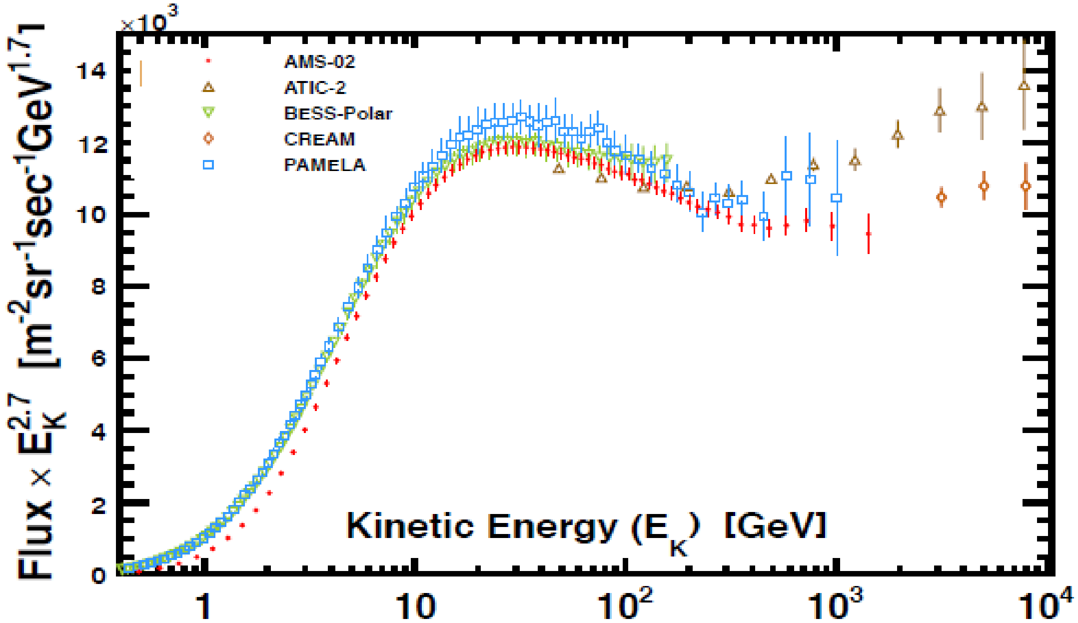
- **10^{10} eV < E < $10^{17\text{-}18}$ eV**

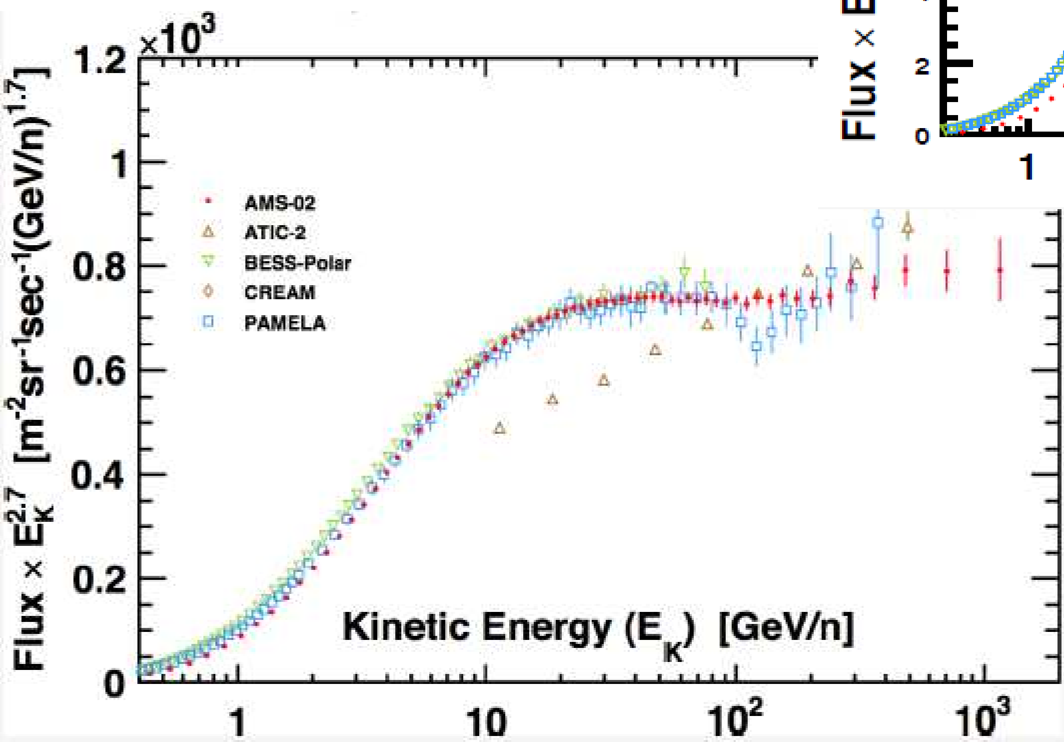
- **E < 10^{14} eV** direct experiments:
  - Primary particle identified on a event by event basis ($\sigma_Z < 1$)
  - Limited by experiments dimensions (surface & mass)
- **E > 10^{14} eV** indirect-EAS experiments
  - Huge surfaces.
  - Limited by:
    - EAS fluctuations
    - Poor resolution on Z
    - Absolute energy calibration

- E<10^{14} eV precise measurements of **single elements spectra** (see P. Picozza presentation). The main limitations are due to statistics and precision at very high energies.



Spectra cannot be described by a Single slope power law.
H spectrum steeper other elements

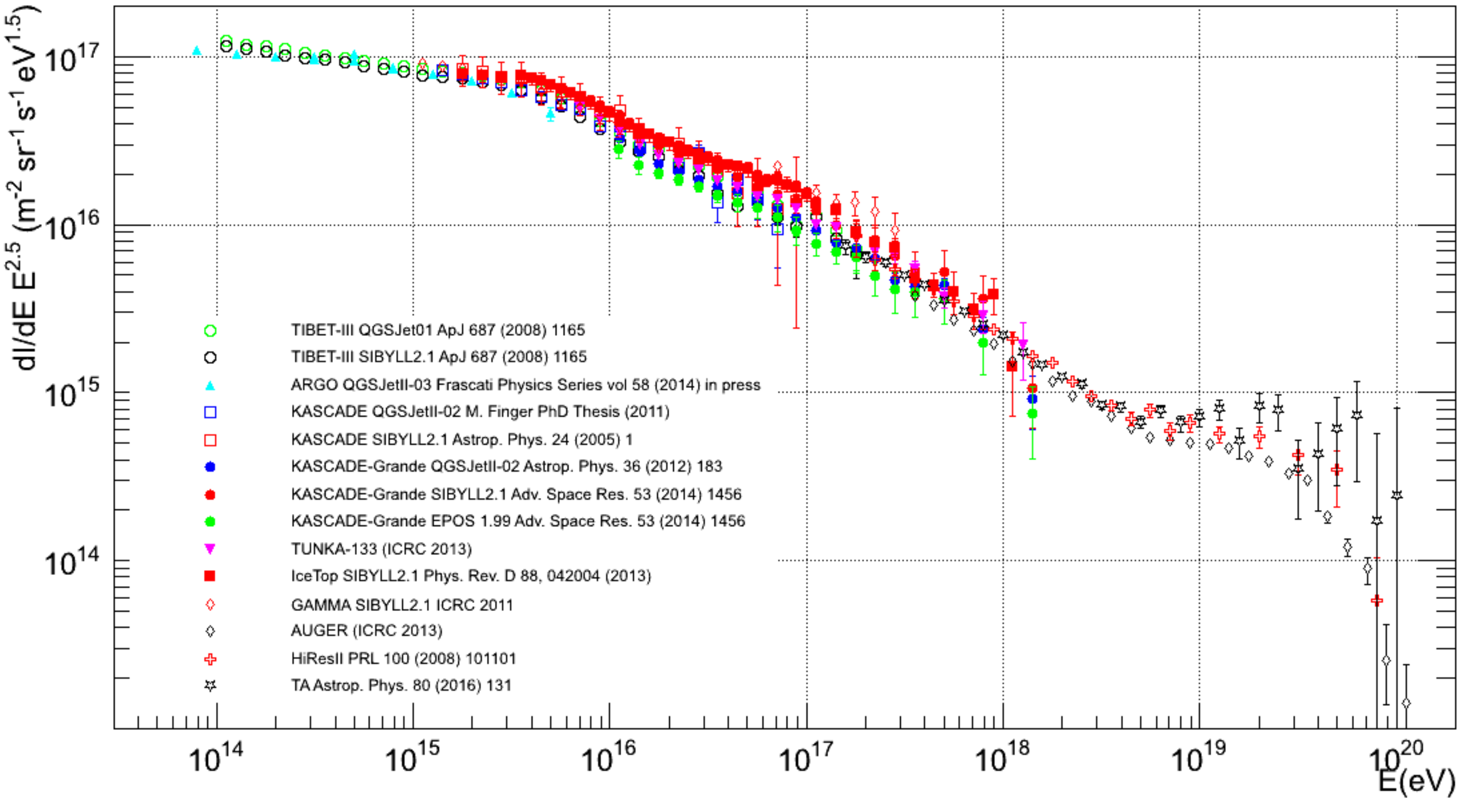
H spectrum → hardening at ~300 GeV



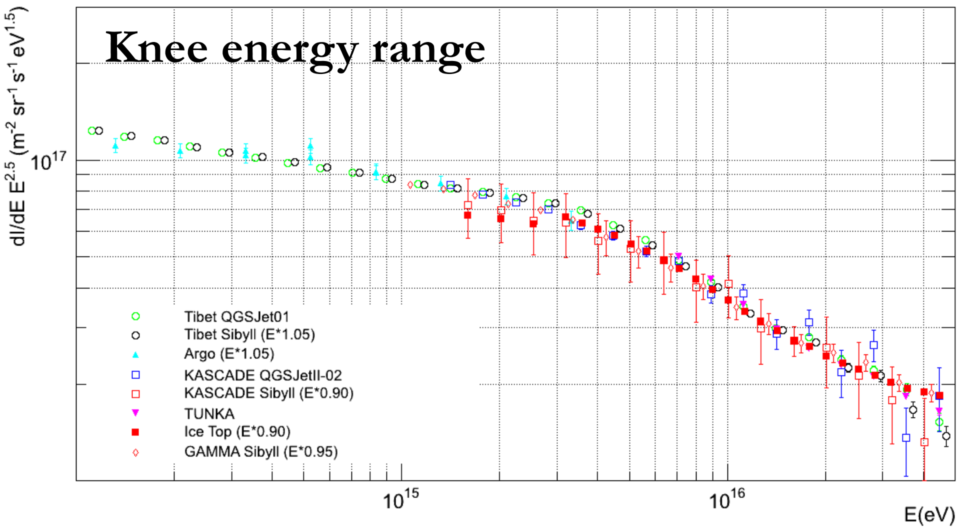
He spectrum → hardening at ~300 GeV/nucleon

Figures: L. Derome invited talk @TAUP2015

All Particle Spectrum

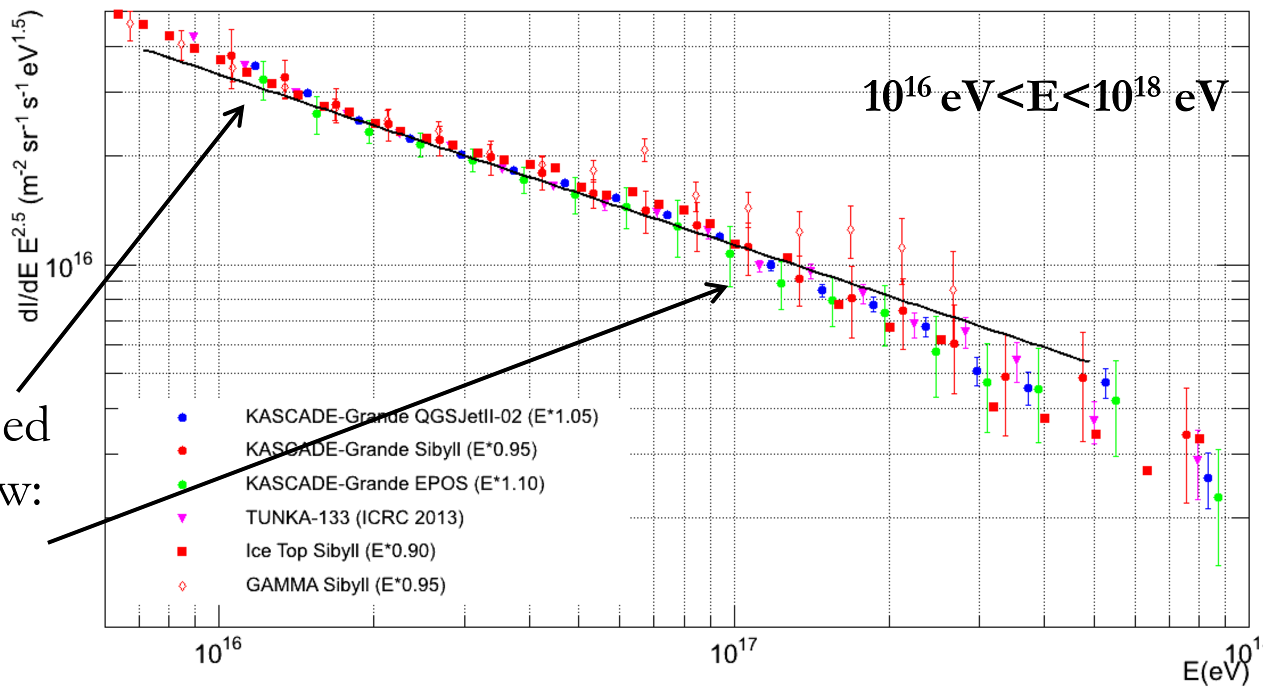


I. Spectral features are very similar.
II. Differences mainly due to the Energy calibration.
III. Most of the data are calibrated with pre-LHC models.
IV. Same experiment calibrated with different hadronic interaction models indicates the magnitude of the systematic errors.



All particle spectra obtained shifting the energies by a factor smaller than what can be estimated as systematic error: i.e. 15-20%

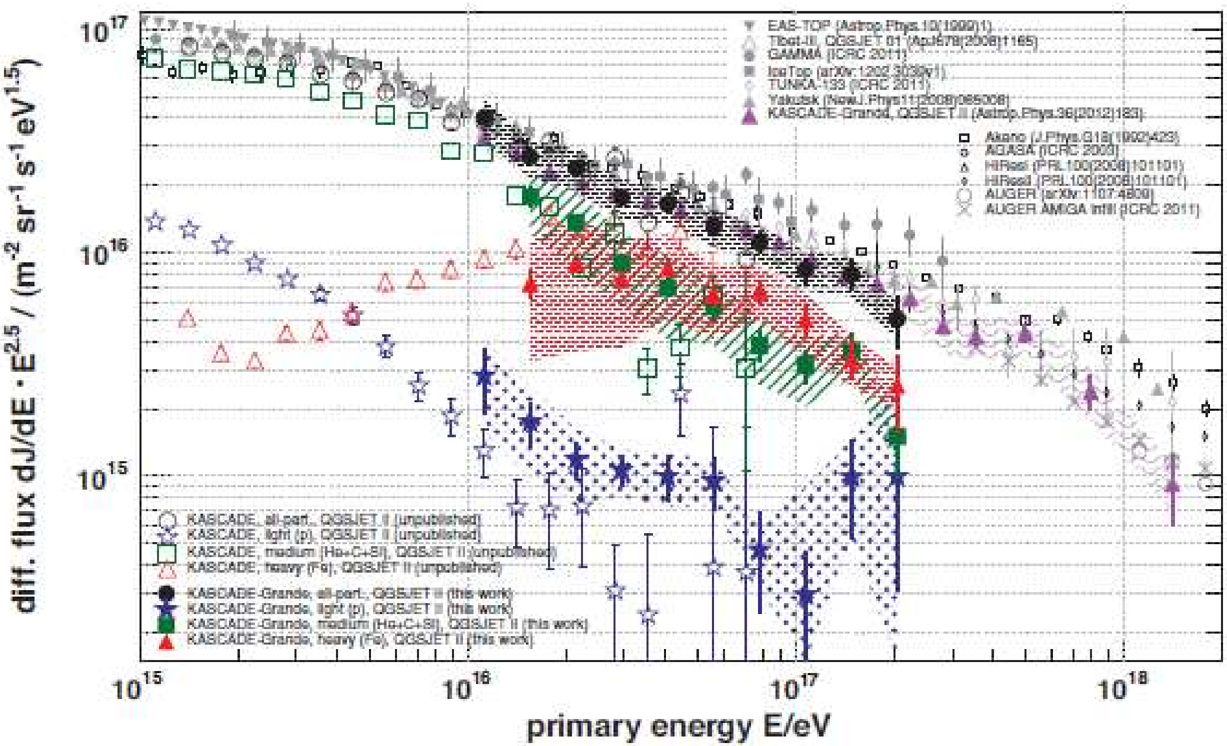
Difference between measurements can be mainly attributed to systematic effects in the energy calibration



Spectra cannot be described by a single slope power law:
hardening (~10^{16} eV)
steepening (~10^{17} eV)

Indirect experiments → statistical approaches to element spectra

- Unfolding or Neural Network analyses based on the detection of different EAS parameters.
- In principle we can separate up to 4/5 mass groups.

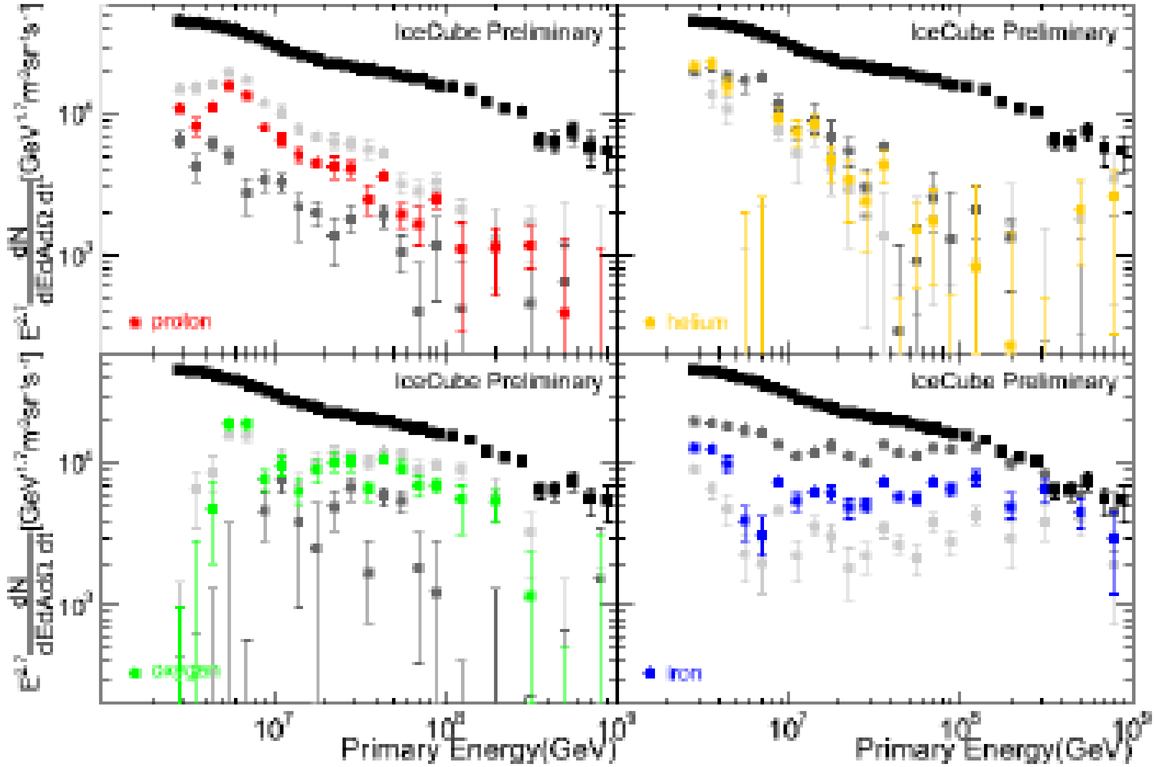


- KASCADE & KASCADE-Grande results.
- Both data sets are analyzed with the QGSJetII-02 hadronic interaction model

IceTop – IceCube

Neural Network approach based on five observables:

1) Particle density at 125m from the core
2) Zenith Angle
3) dE/dX @ 1500 m
4) N of HE stochastics 1
5) N of HE stochastics 2



EAS simulation:
SIBYLL2.1

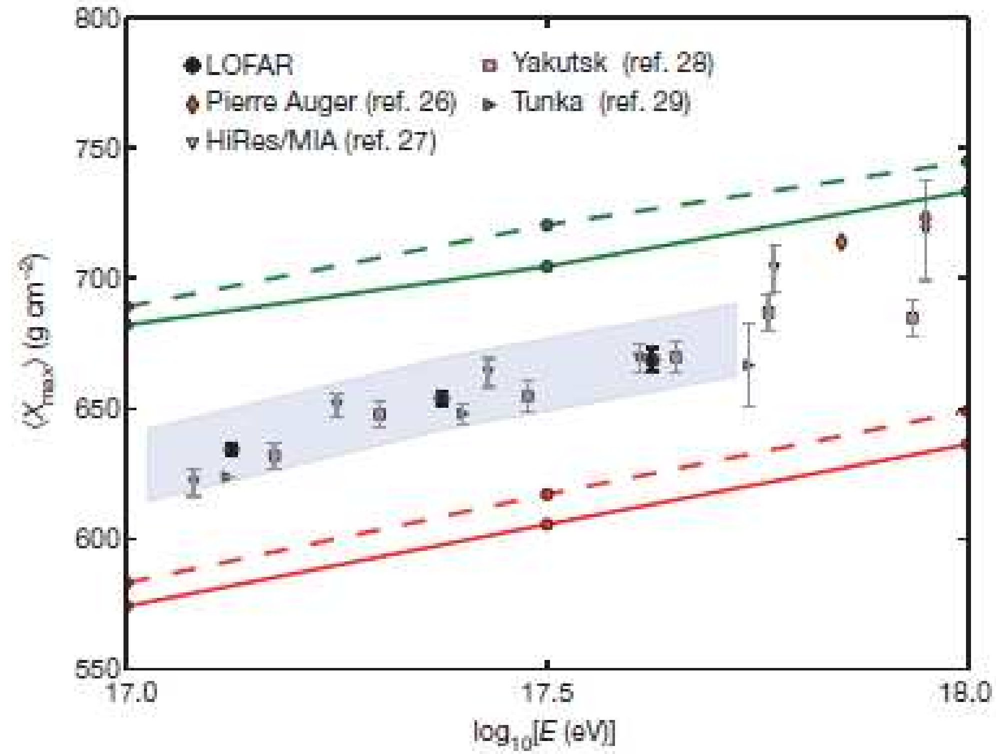
H & He steeper spectra
O & Fe harder spectra

LOFAR → EAS radio detection

- Hybrid approach: simultaneous fit of radio (X_{max}) and particle (E) data

- Applying strict cut
  → 118 events

- High resolution
  → $\sigma(X_{max}) \approx 16$ g cm^{-2}

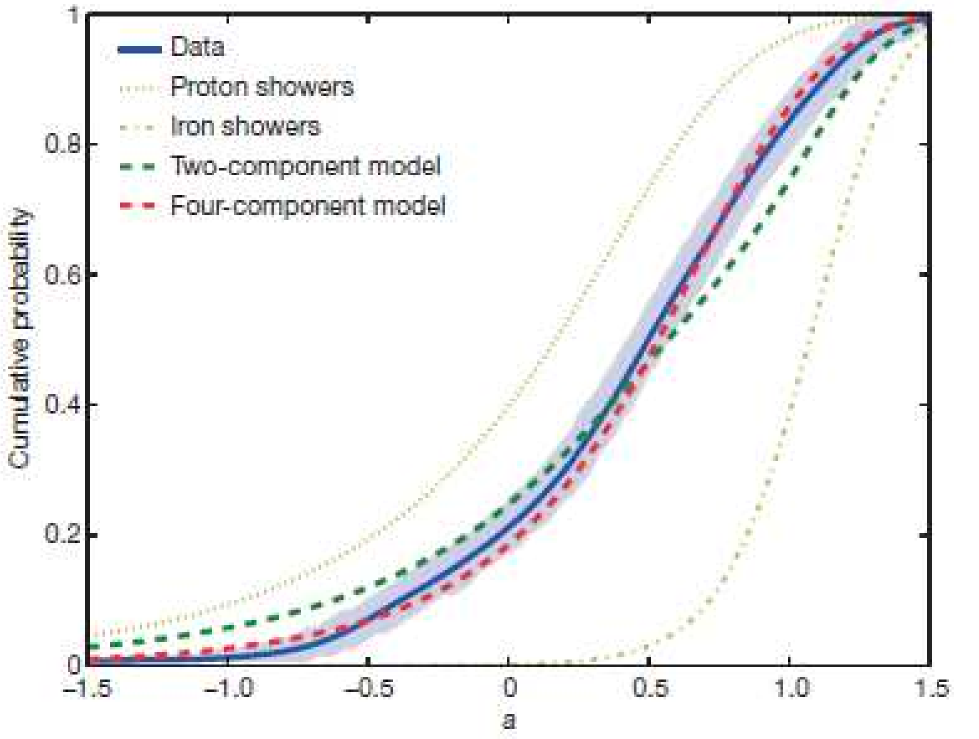


--- H EPOS-LHC __ H QGSJetII-04
--- Fe EPOS-LHC __ Fe QGSJetII-04

Nature 531, (2016) 70

$$a = \frac{\langle X_H \rangle - X_{shower}}{\langle X_H \rangle - \langle X_{Fe} \rangle}$$

$\langle X_H \rangle$ and $\langle X_{Fe} \rangle$ based on QGSJetII-04
Cumulative probability density function



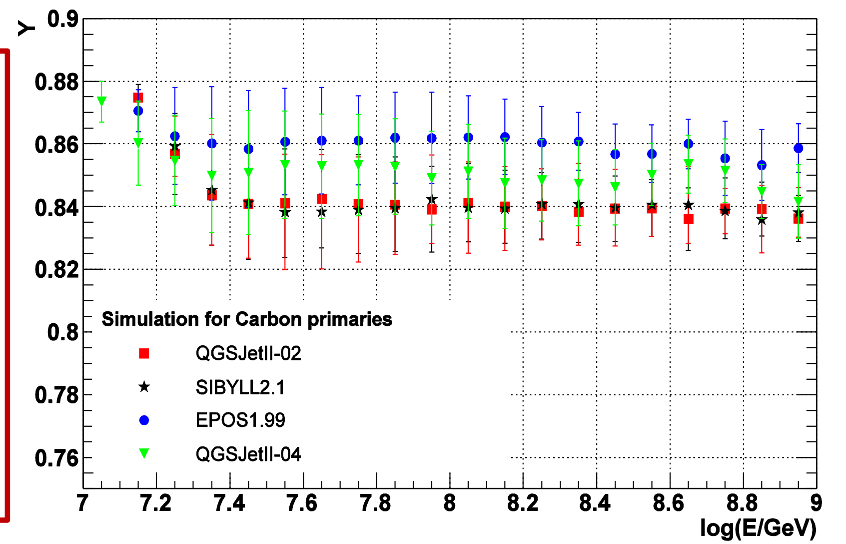
✓ Good data description achieved with a four component model (H, He, N, Fe)

✓ Light Elements (H+He) dominates → $0.38 < light_{fraction} < 0.98$

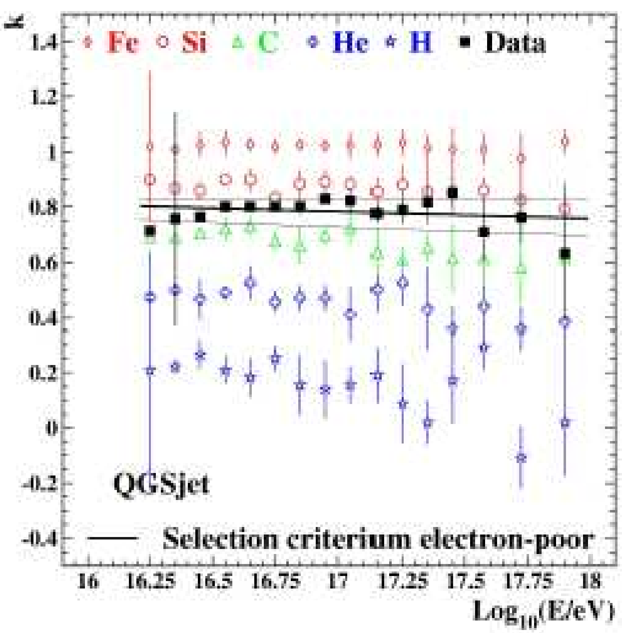
✓ Best fit value $l_f = 0.8$

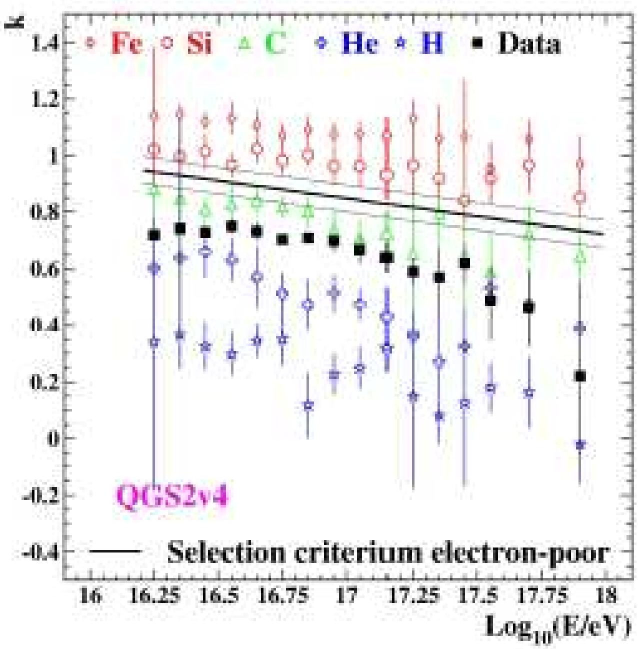
Nature 531, (2016) 70

- LHC-tuned hadronic interaction models predict showers with a higher μ content.
- Pre-LHC models lead to a larger fraction of heavy elements.



$Y = \ln N_\mu / \ln N_{ch}$



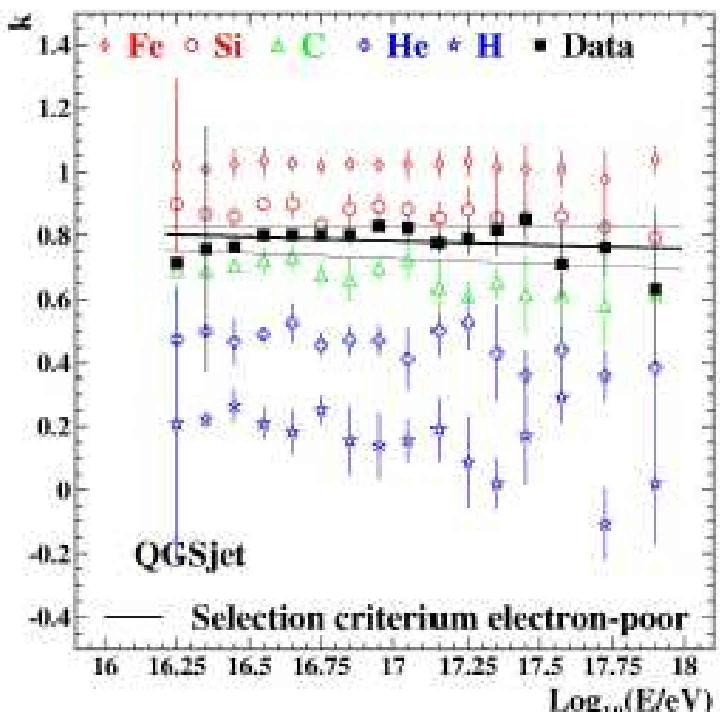


$$k = \frac{\log_{10}(N_{ch}/N_\mu) - \log_{10}(N_{ch}/N_\mu)_H}{\log_{10}(N_{ch}/N_\mu)_{Fe} - \log_{10}(N_{ch}/N_\mu)_H}$$

Indirect experiments → event by event selection → mass groups spectra

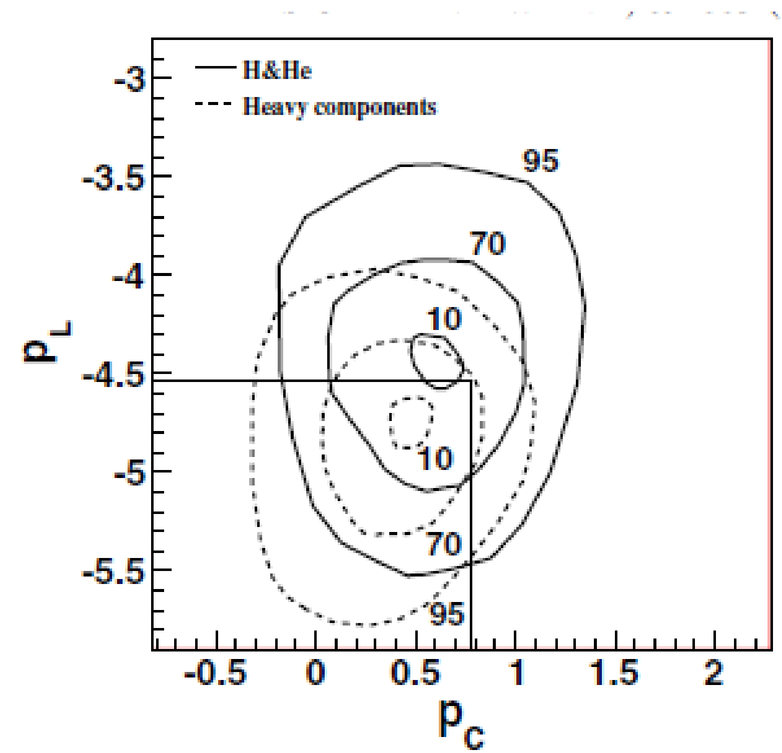
KASCADE-Grande
N_μ / N_{ch} ratio

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



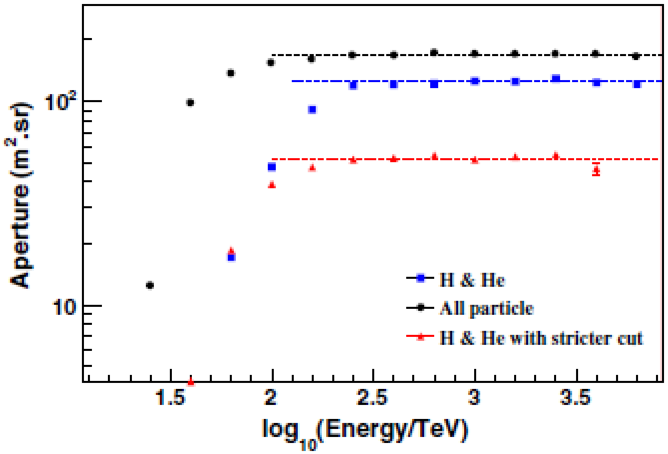
ARGO-YBJ + WFCTA
ldf + shower image

$$p_L = \log_{10} N_{max} - 1.44\, N^{pe}_0$$
$$p_C = L/W - R_p/109.9\text{m} - 0.1 \log_{10} N^{pe}_0$$

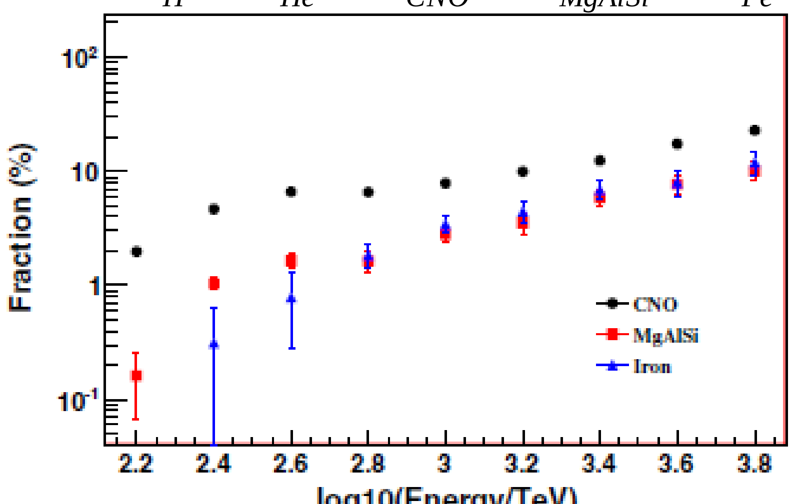


Different definition of contaminations from other mass groups

ARGO-YBJ + WFCTA
Hörandel model

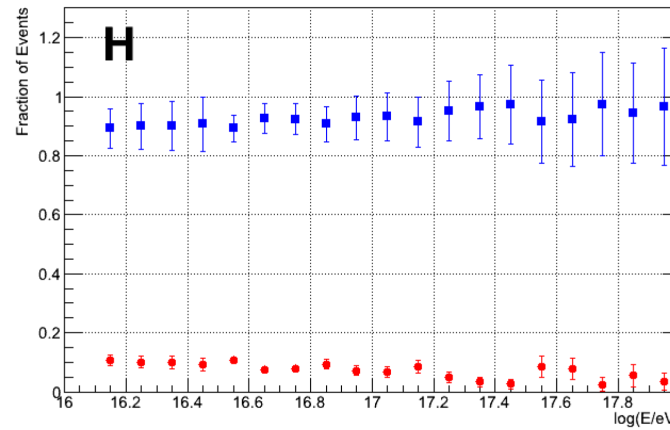


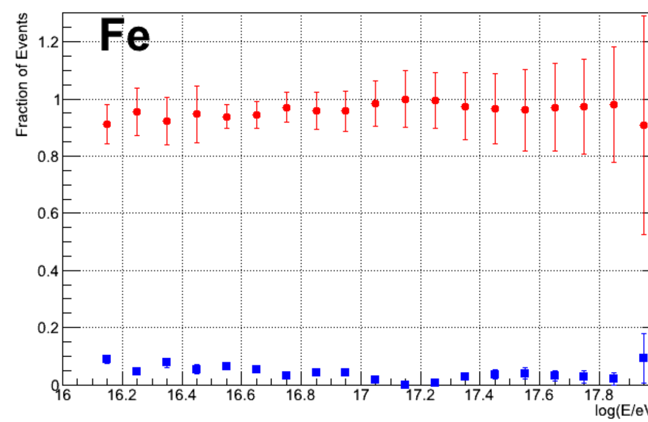
$$\frac{N_i}{N_H + N_{He} + N_{CNO} + N_{MgAlSi} + N_{Fe}}$$



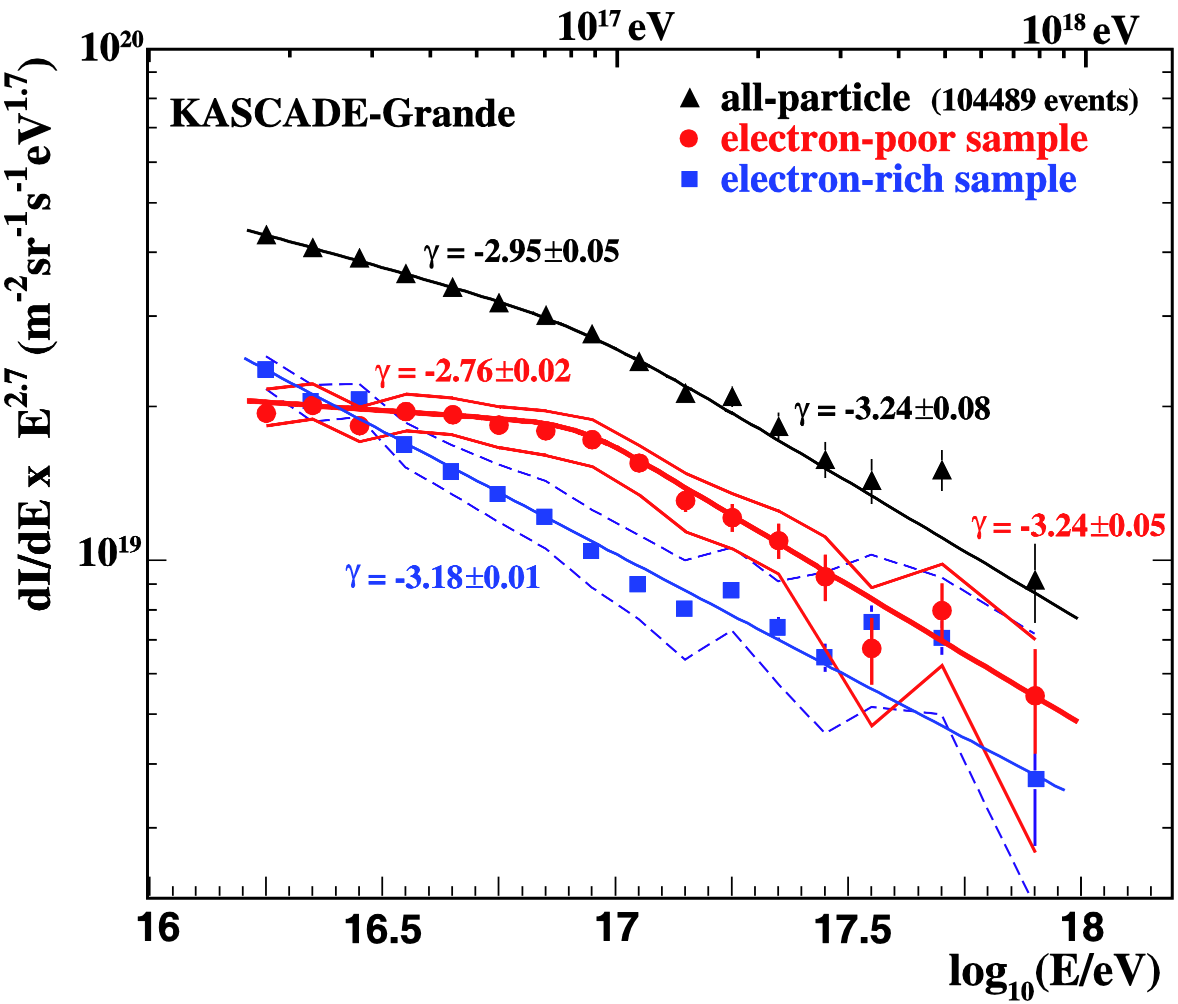
KASCADE-Grande
E^{-3} spectra for each element

Fraction of misclassified events for each element





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

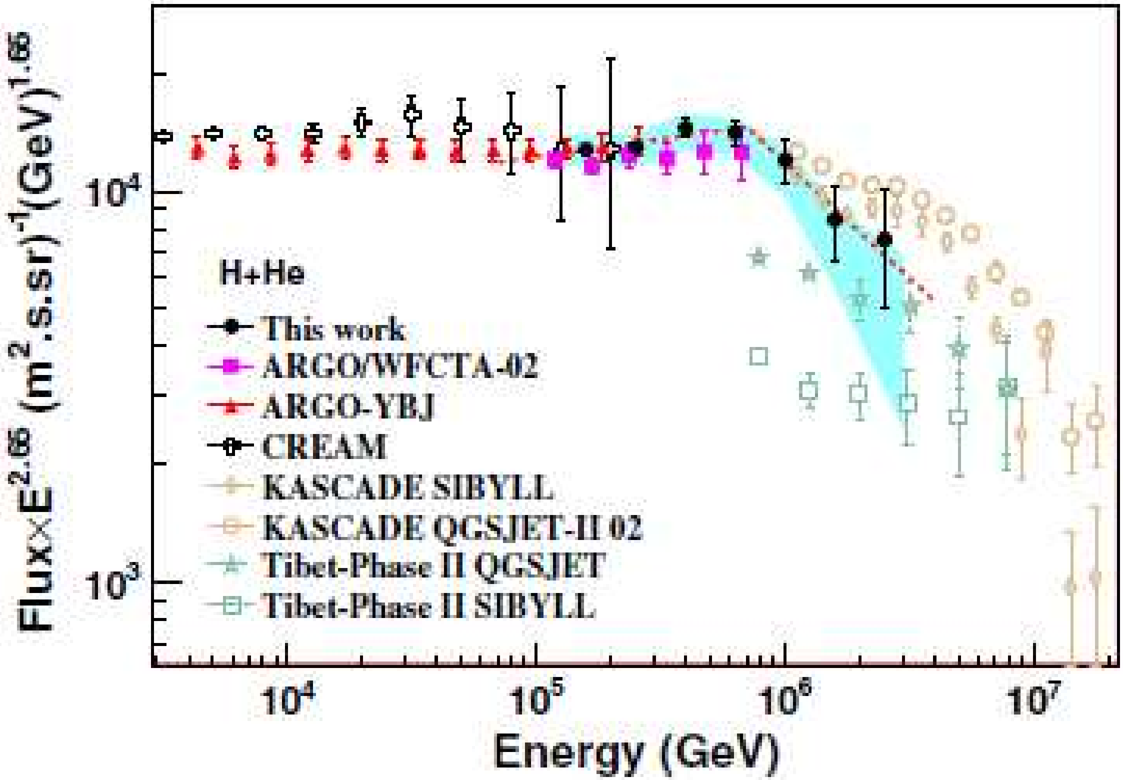


- Energy spectra of the samples obtained by an event selection based on the k parameter
- Spectrum of the electron poor sample: $k>(k_C+k_{Si})/2$ → Steepening observed with increased significance → 3.5σ
- Spectrum of electron rich events → can be described by a single power law → hints of a hardening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



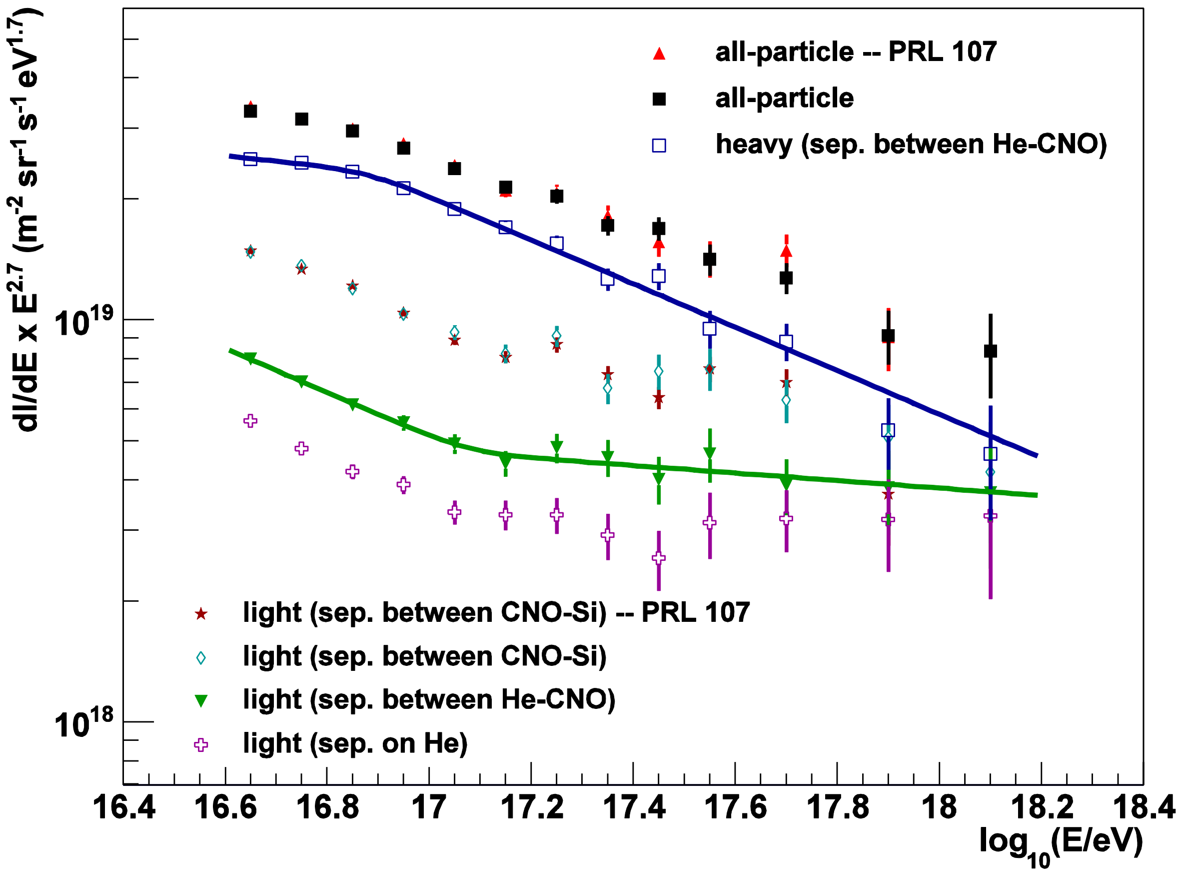
H&He spectrum measured by the ARGO-YBJ+WFCT hybrid experiment.

$$E_k = 700 \pm 230 \pm 70 \text{ TeV}$$

$$\gamma_1 = -2.56 \pm 0.05 \qquad \gamma_2 = -3.24 \pm 0.36$$

B. Bartoli et al., Phys. Rev. D **92**, 092005 (2015)

- **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

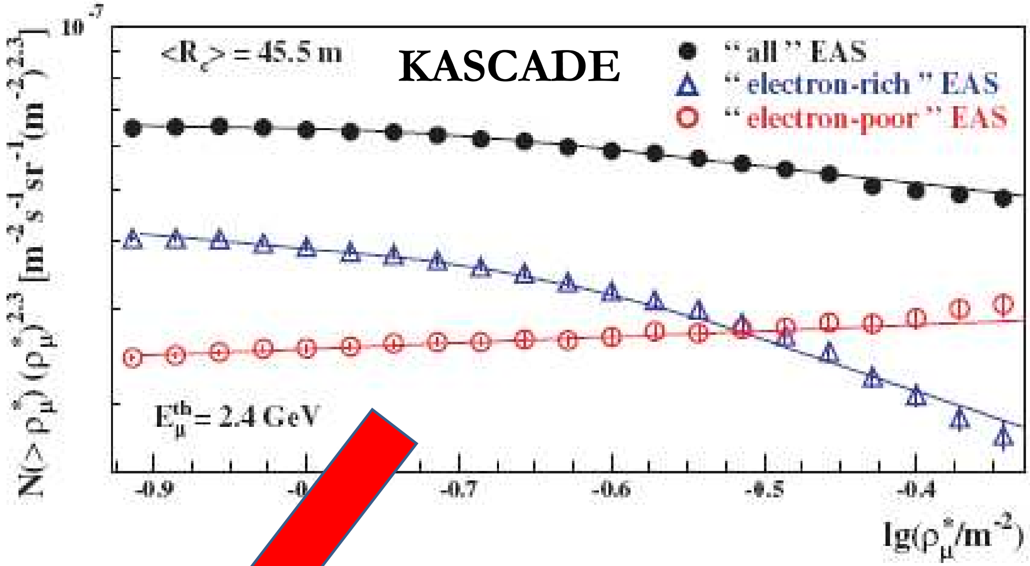
$N_{meas} = 579$
$N_{exp} = 467$

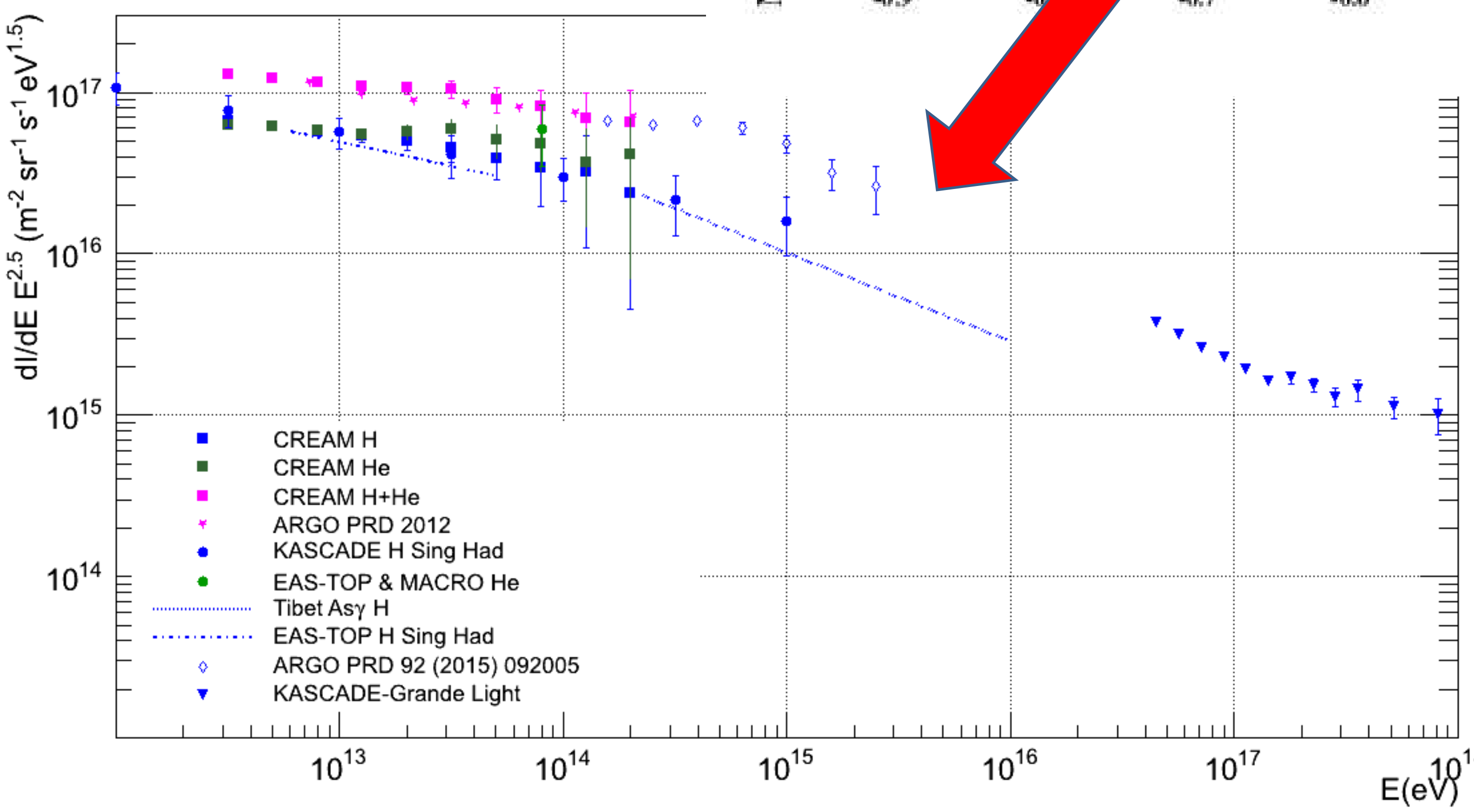
$P(N>N_{meas}) \approx 7.23 \times 10^{-09}$

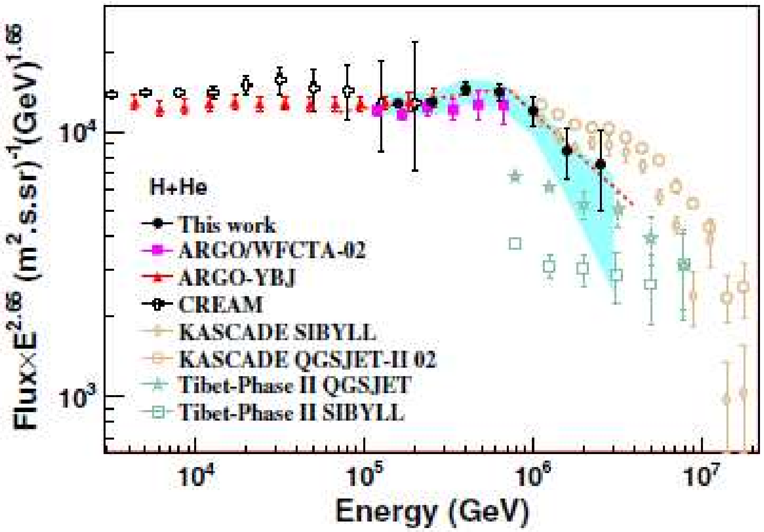
5.8σ significance

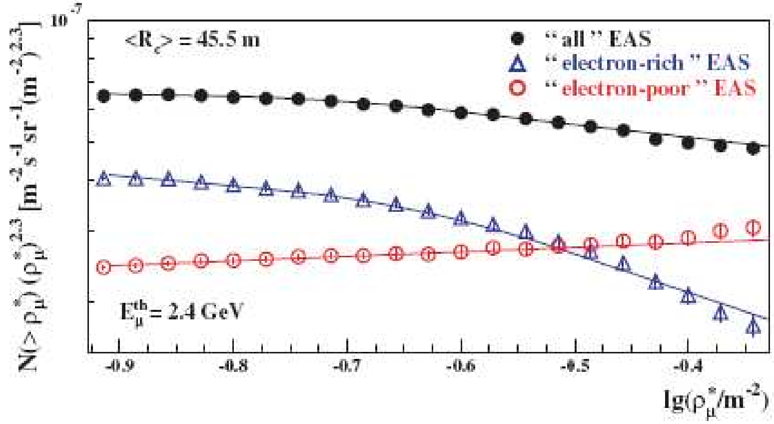
Phys. Rev. D **87**, 081101(R) (2013)

Integral flux above the change of slope → ~10^{-7} m^{-2} s^{-1} sr^{-1}
→ ~2-4x10^{15} eV

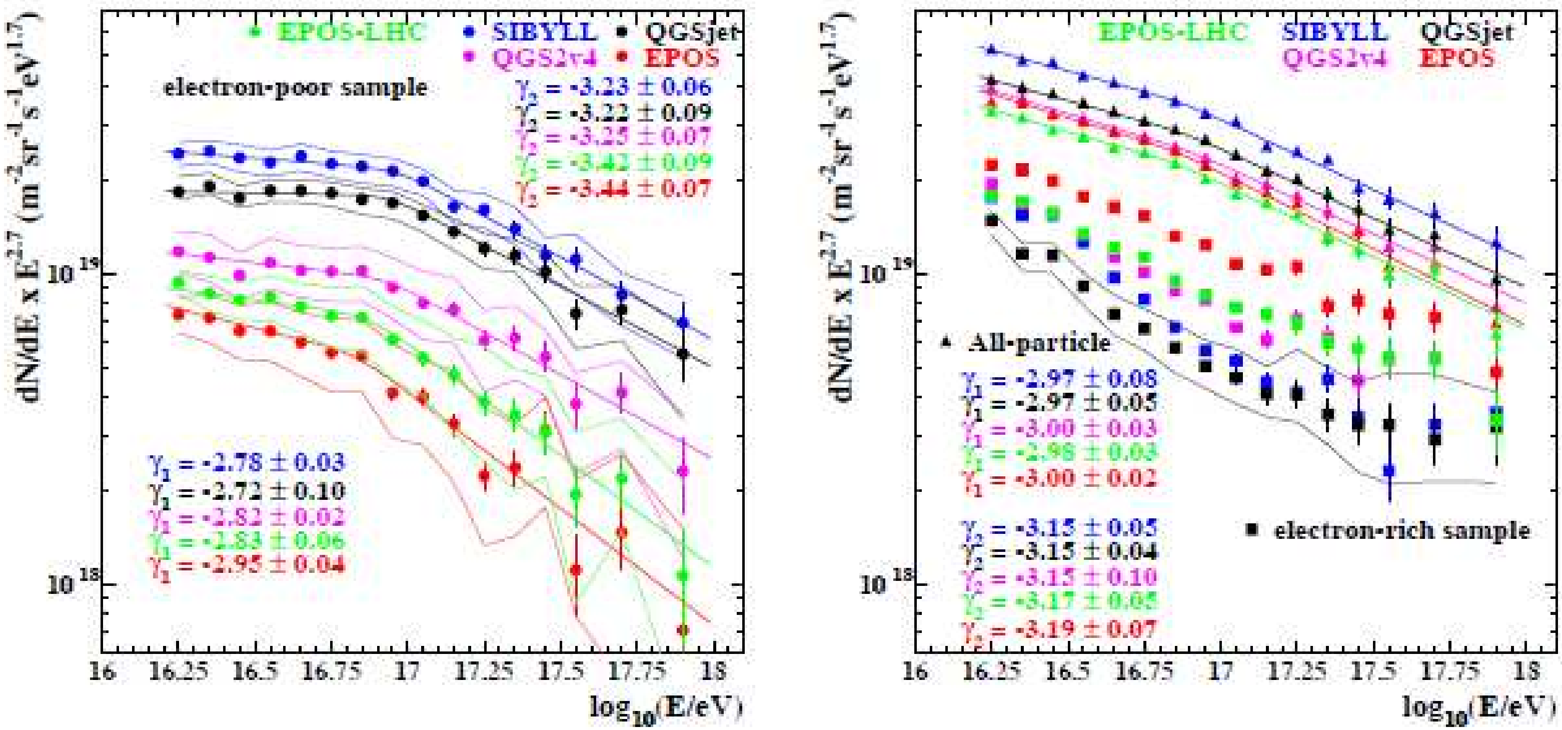






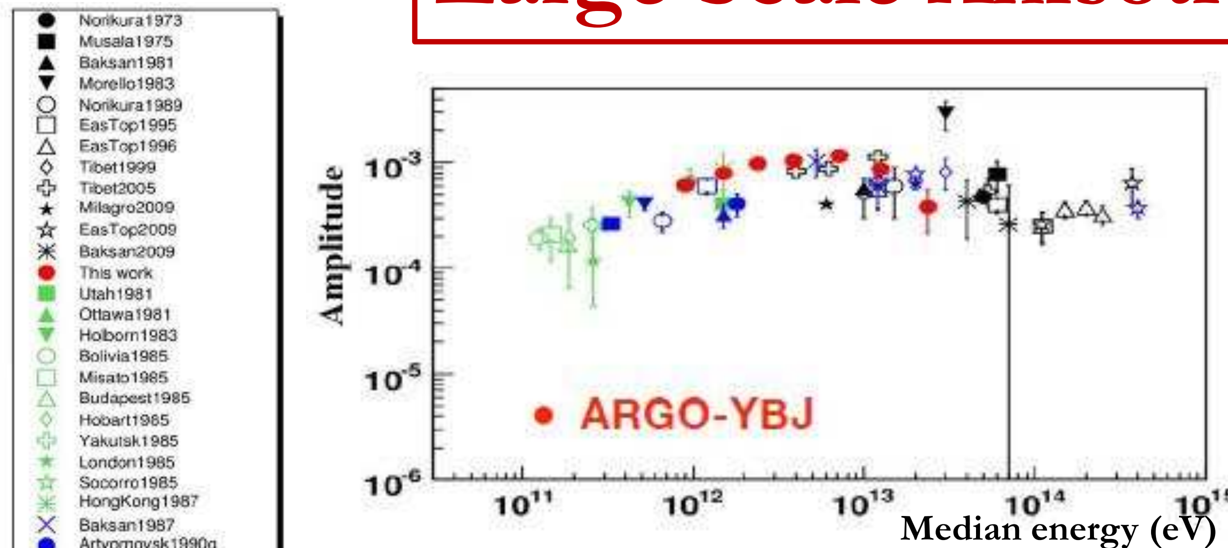


- Fitting procedures and different energy bin widths may emphasize differences.
- Results are different for high and low altitude experiments → problems in EAS evolution simulation??
- Systematic errors?



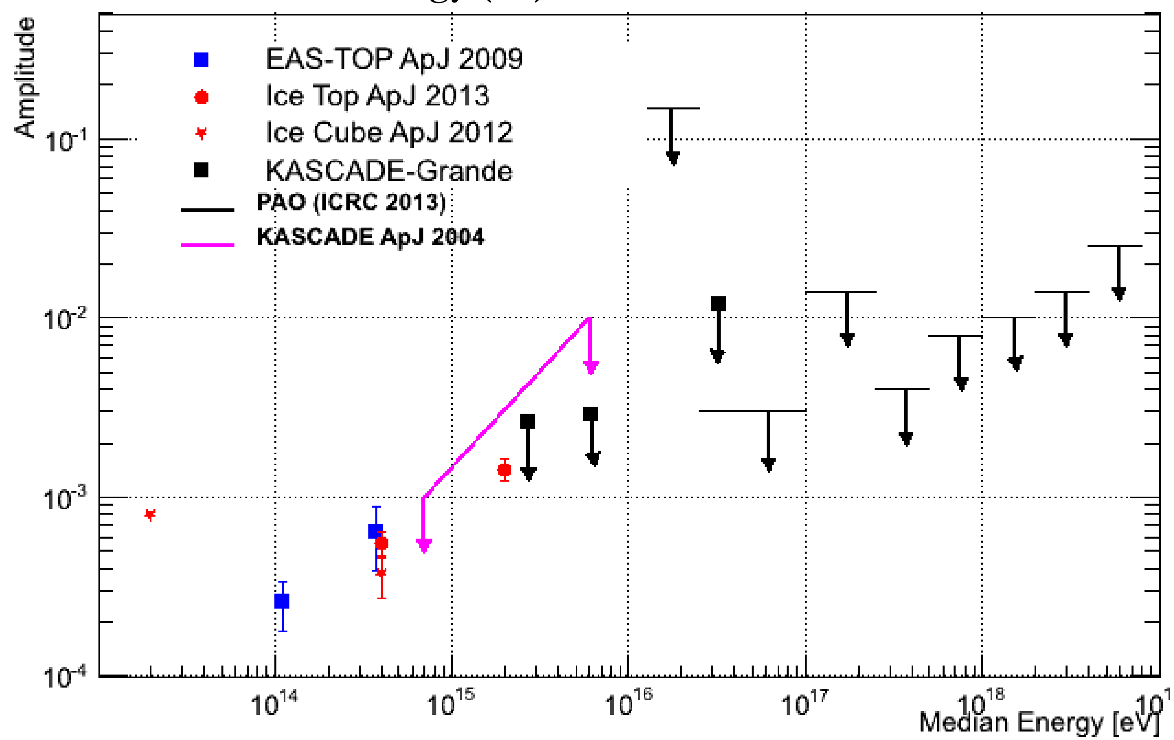
Analysis based on different hadronic interaction models (pre and post LHC data). Spectral features are detected independently from the hadronic interaction models used, while the absolute flux depends on it.

Large Scale Anisotropies



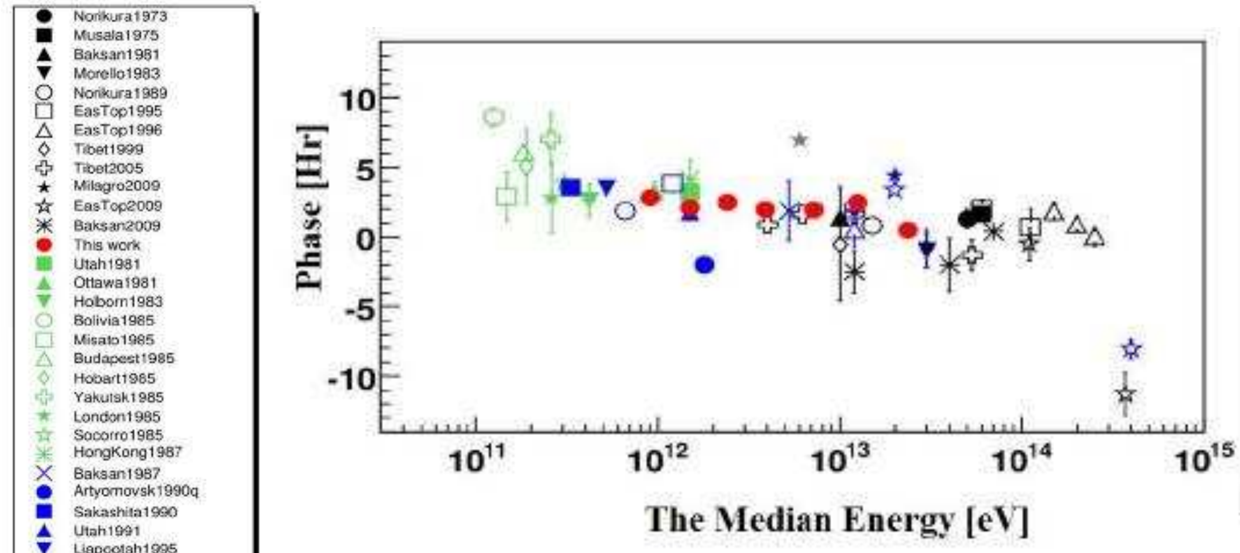
1[st] Harmonic Amplitudes measured at different energies

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



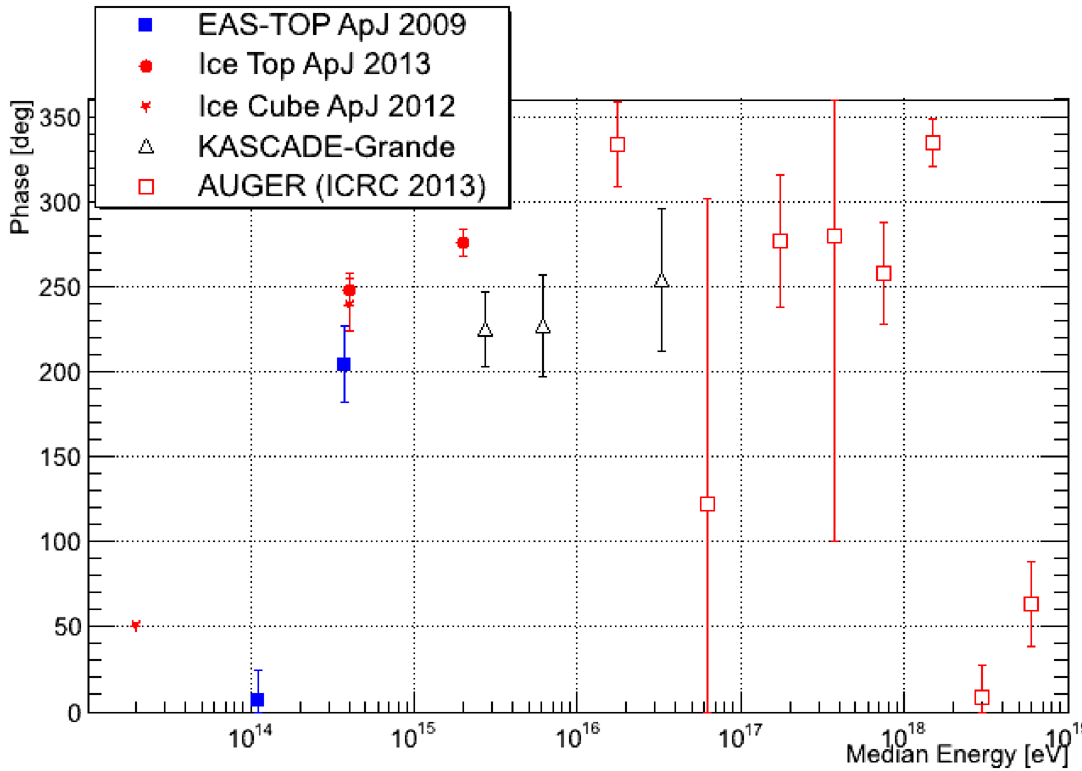
Hint of an increasing amplitude crossing knee energies

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



1st 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 5×10^{14} eV are consistent

Concluding remarks

- Galactic cosmic ray spectrum is more complicated than we thought few years ago. Improving experiments resolution more structures have been discovered.
- Elemental (or mass group) spectra
  - Light knee observed at different energies
  - Heavy elements knee at ~ $8x10^{16}$ eV
  - Light elements hardening at 10^{17} eV
- LHC-tuned hadronic interaction models lead to a lighter chemical composition.
- Extend large scale anisotropy measurements to higher energies.
- Currently missing are large scale anisotropies studies for different mass groups.
- Km^2, high resolution, multi component experiments will answer these questions.