Measurements of the cosmic ray spectrum and composition in the 10^{15}-10^{18} eV energy range

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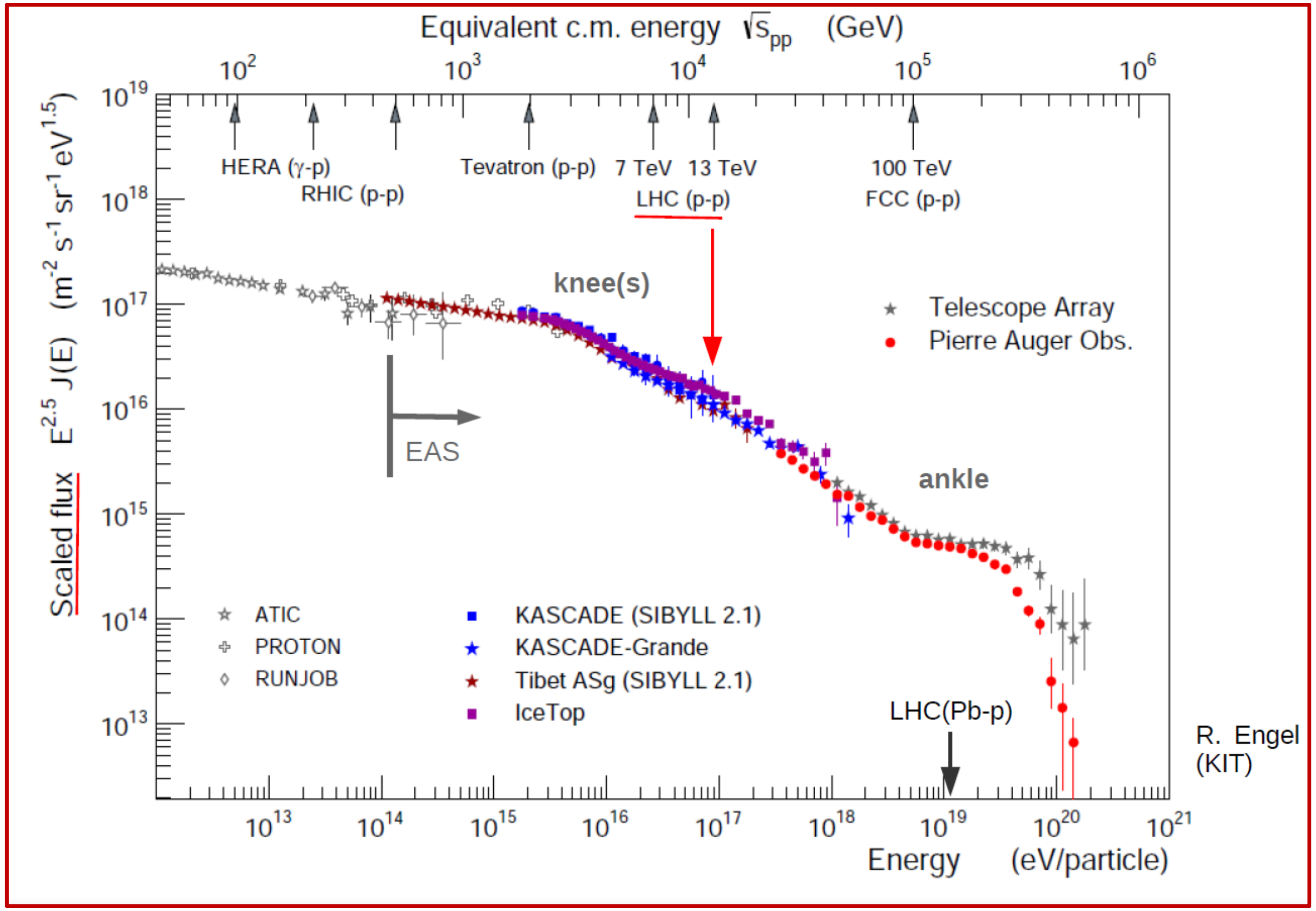
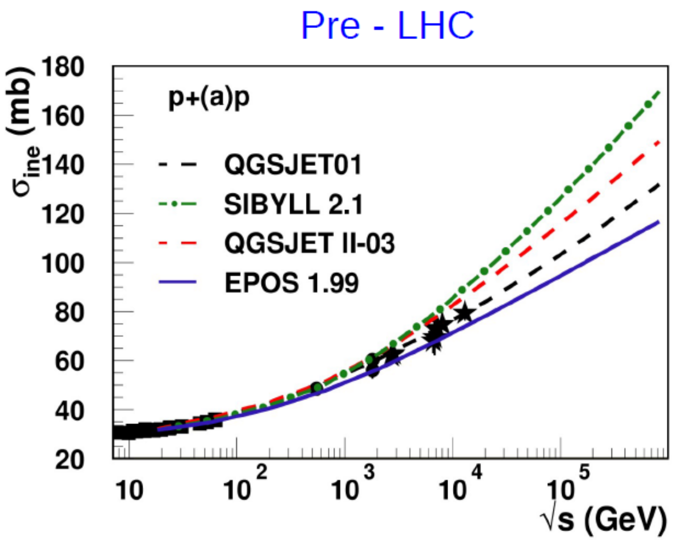


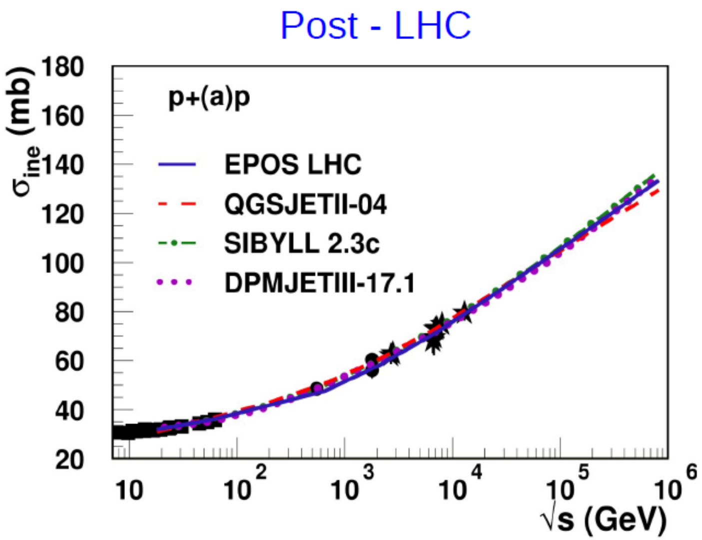
- **E<10^{14} eV - Direct measurements**
    - Surface (low fluxes)
    - Mass (Energy resolution)
- **E>10^{13} eV indirect EAS experiments.**
    - 10^{13}<E<10^{18} eV no limitations by statistics.
    - Main experimental limitation due to absolute calibration that is based on EAS simulations for:
        - Energy calibration
        - Mass calibration
        - γ/hadron separation.

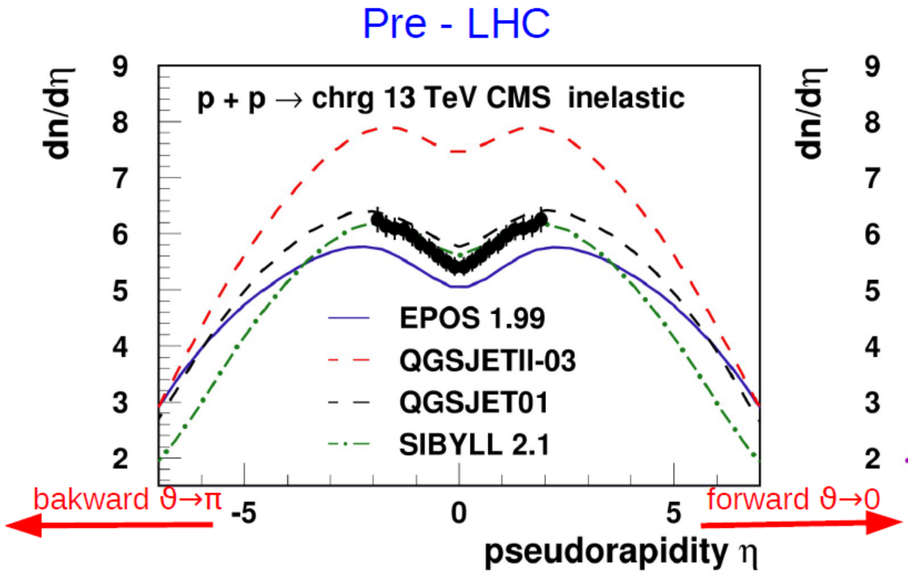
- $10^{13}<E<10^{18}$ eV
  - $E<10^{17}$ eV → surface, multicomponent arrays
    → Cherenkov Light experiments
  - $E>10^{17}$ eV → surface, multicomponent arrays
    → radio experiments
    → low energy extensions of UHE experiments
- Energy measurements
  - Number of particles at observation level (surface and Cerenkov Light detectors)
  - Measurement of the longitudinal shower profile (Fluorescence Light and Radio detectors)
  - Calibration without EAS simulation
    - $E<10^{14}$ eV → cross calibration with direct measurements
      → moon shadow
    - $E>10^{17}$ eV → hybrid experiments
  - Calibration using EAS simulations depends on:
    - Hadronic Interaction Models
    - Choice of the mass of the Primary Particle

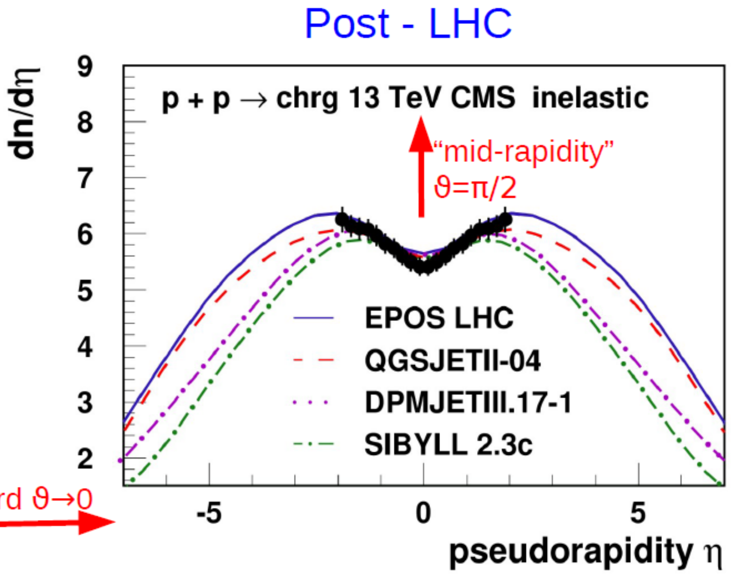
Hadronic Interaction models developments after LHC data

Total cross section



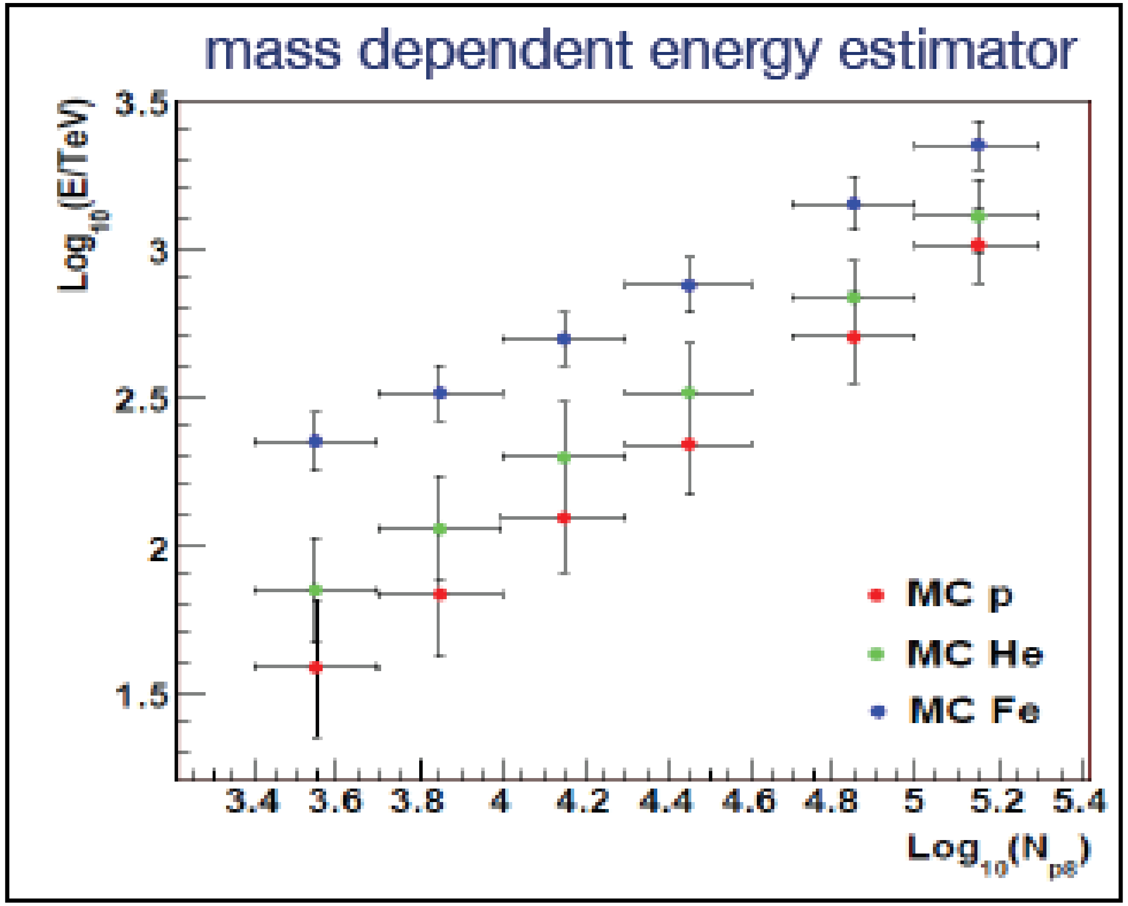






Particle number vs Pseudorapidity

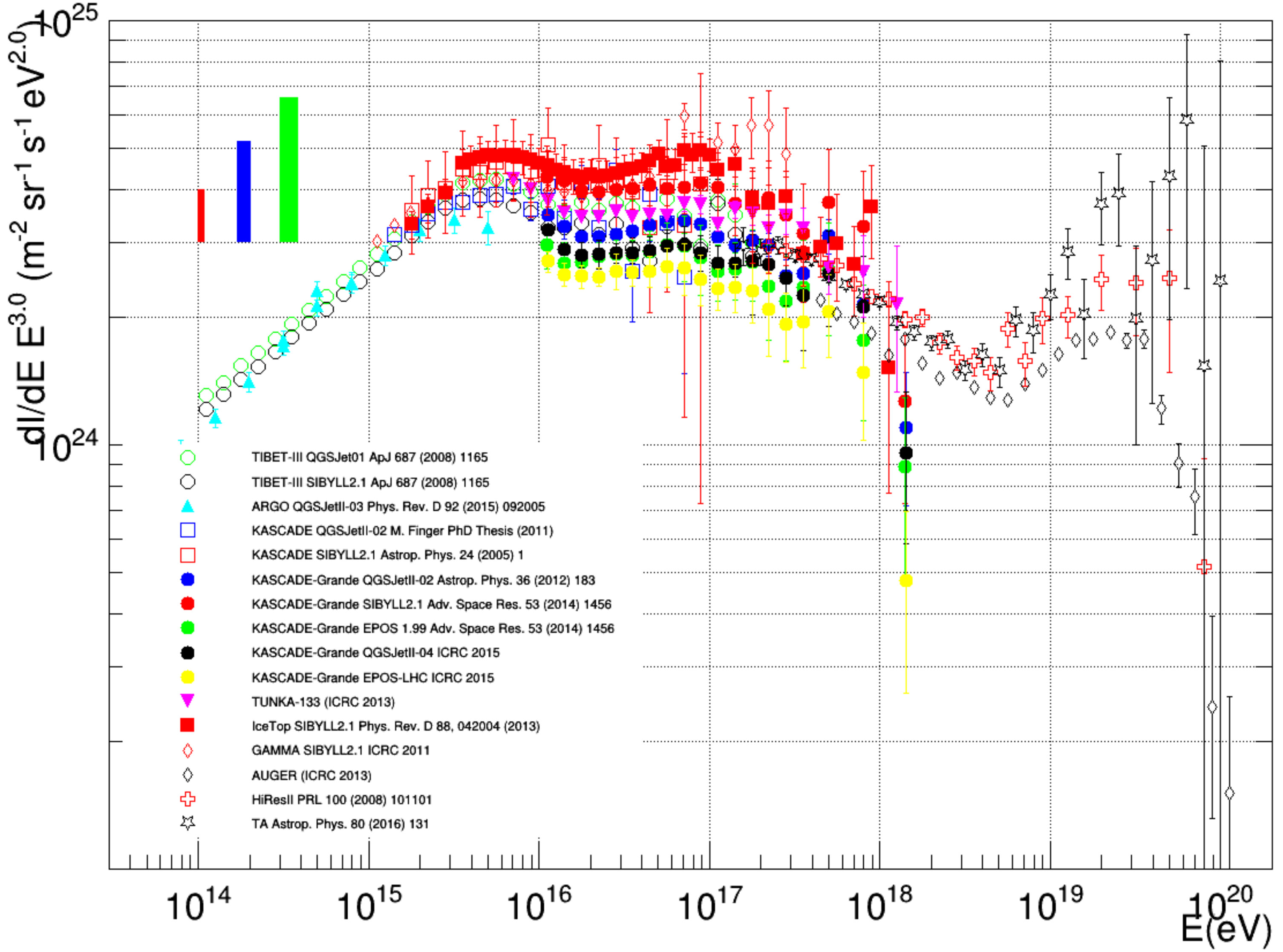
Figures from T. Pierog talk @ ICRC 2017



Example from ARGO-YBJ

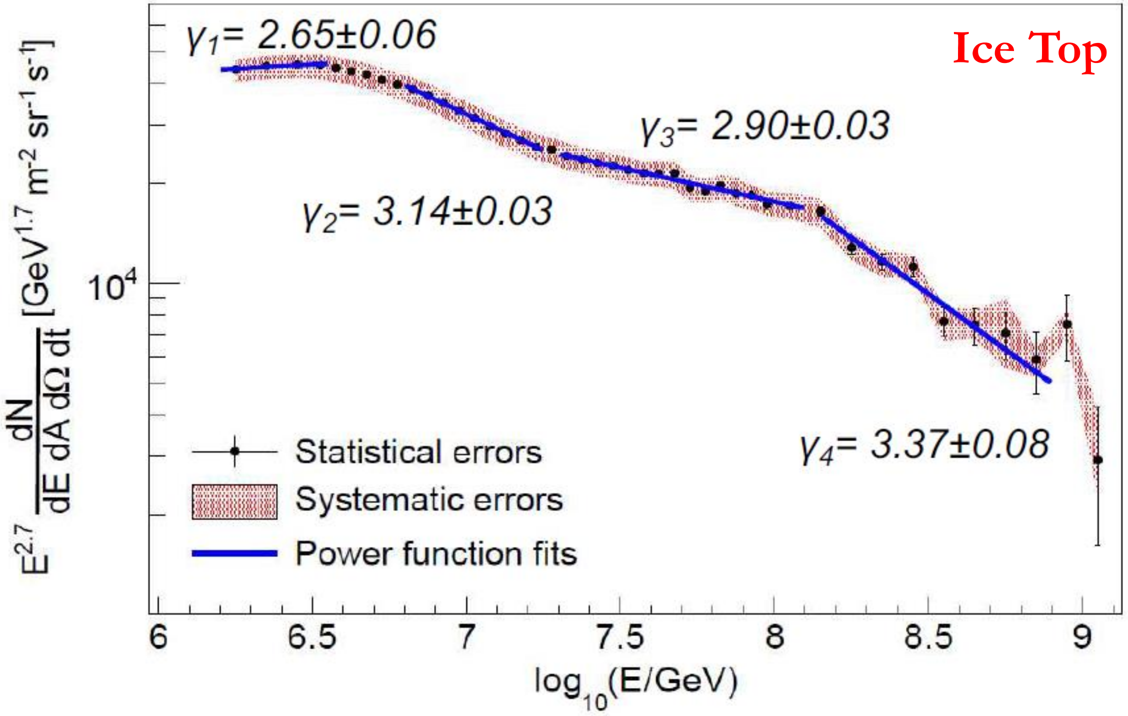
Energy Calibration differences due to the choice of the primary particle mass

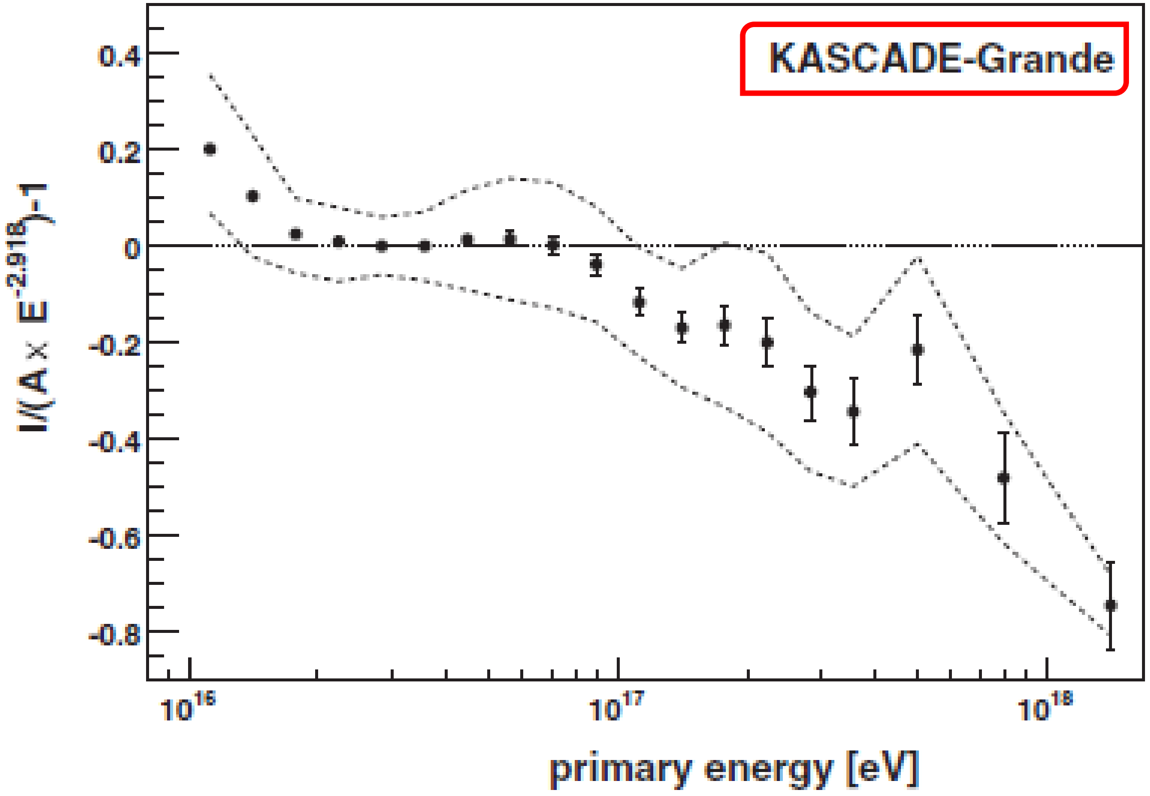
Primary Spectra Measurements



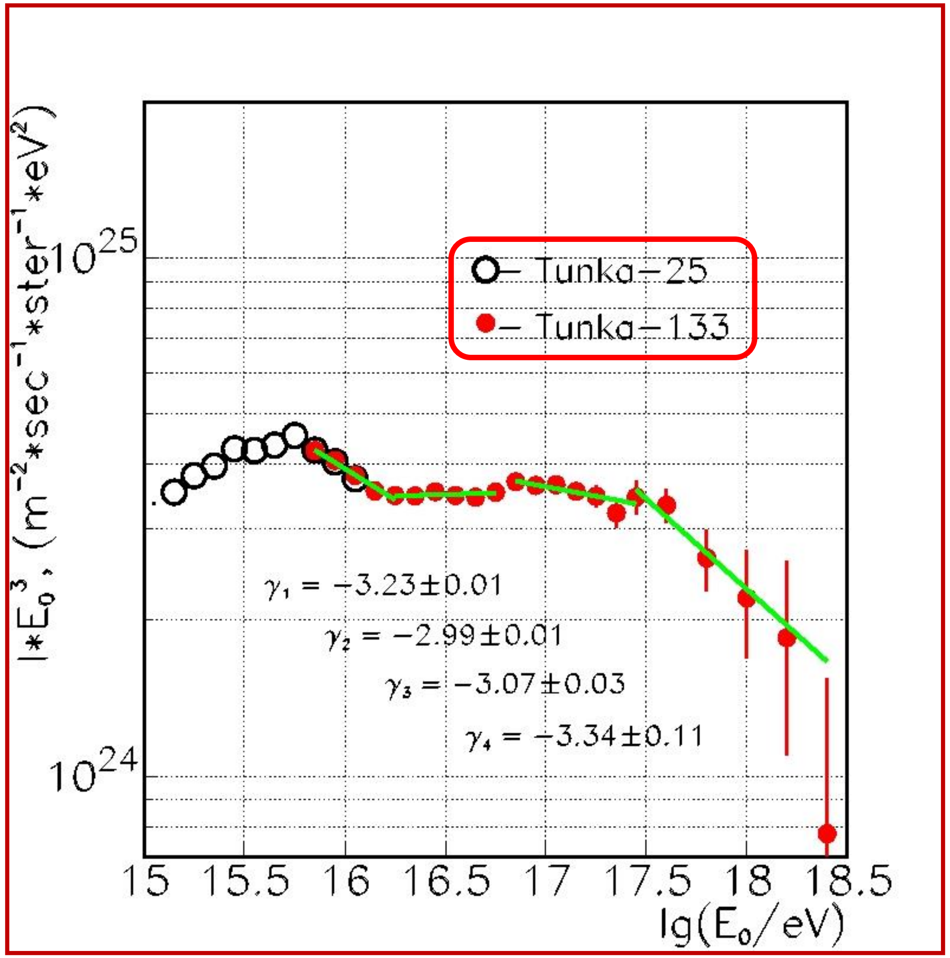
- Differences, in this plot, due to energy calibrations.
  - 10% E error
  - 20% E error
  - 30% E error
- Better agreement if we compare data calibrated with the same hadronic interaction model.
- Spectral shapes agree

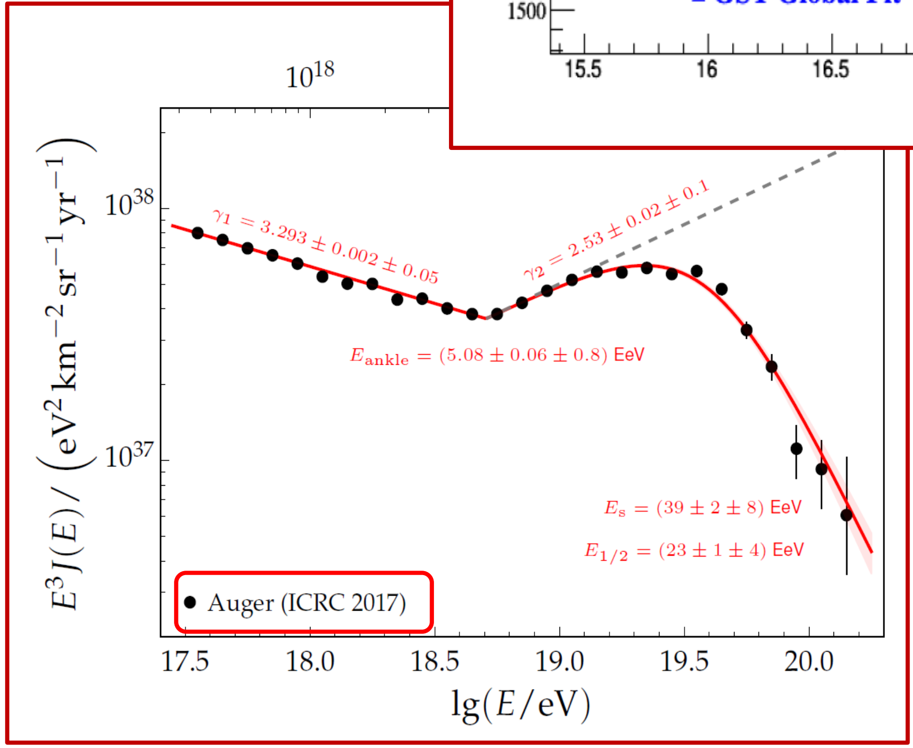
The spectrum above the knee cannot be described by a single slope power law

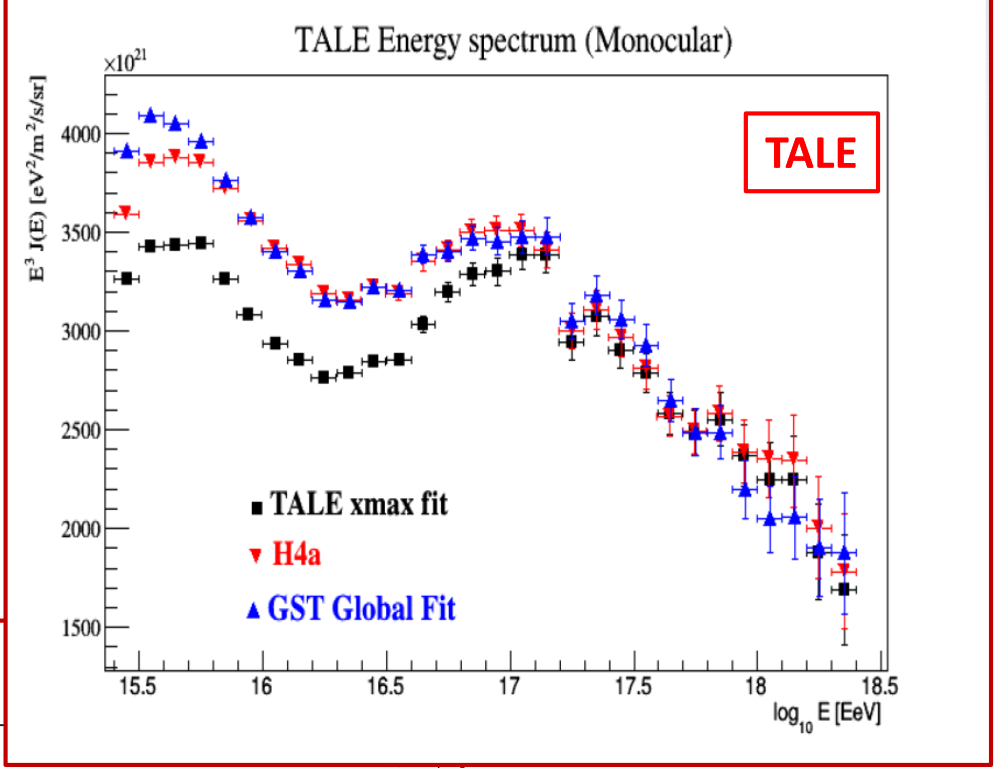




Hardening at 18±2 PeV
Steepening at 130±30 PeV


Tunka−25
Tunka−133
$\gamma_1 = -3.23 \pm 0.01$
$\gamma_2 = -2.99 \pm 0.01$
$\gamma_3 = -3.07 \pm 0.03$
$\gamma_4 = -3.34 \pm 0.11$
$I * E_0^3, (m^{-2} * sec^{-1} * ster^{-1} * eV^2)$
$lg(E_0/eV)$


$\gamma_1 = 3.293 \pm 0.002 \pm 0.05$
$\gamma_2 = 2.53 \pm 0.02 \pm 0.1$
$E_{ankle} = (5.08 \pm 0.06 \pm 0.8)$ EeV
$E_s = (39 \pm 2 \pm 8)$ EeV
$E_{1/2} = (23 \pm 1 \pm 4)$ EeV
Auger (ICRC 2017)
$E^3 J(E) / (eV^2 km^{-2} sr^{-1} yr^{-1})$
$lg(E/eV)$


TALE Energy spectrum (Monocular)
TALE
TALE xmax fit
H4a
GST Global Fit
$E^3 J(E) [eV^2/m^2/s/sr]$
$log_{10} E$ [EeV]

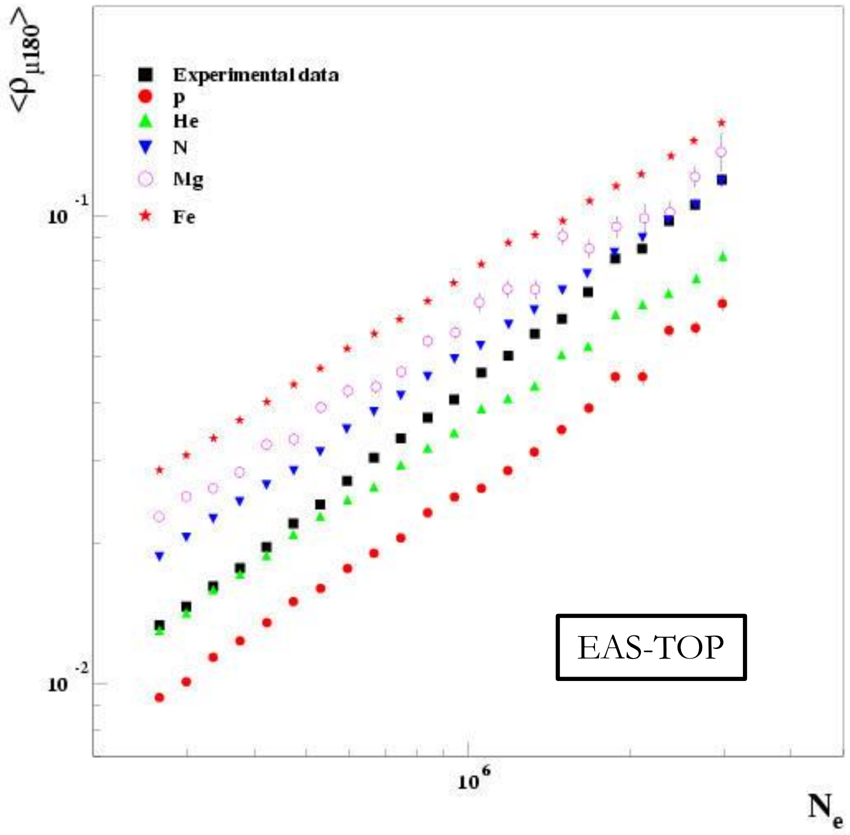
	γ_{knee}	γ_{hard}	γ_{step}	E_{hard} (PeV)	E_{step} (PeV)
Ice Top	3.14±0.03	2.90±0.03	3.37±0.08	18±2	130±30
KASCADE-Grande	-	2.95±0.05	3.24±0.08	-	83±10
TUNKA	3.28±0.01	2.98±0.01	3.4±0.11	-	-
TALE	3.21±0.015	2.87±0.01	3.19±0.018	17.8±0.8	109±8
PAO	--	-	3.29±0.05	-	-

Chemical Composition Measurements

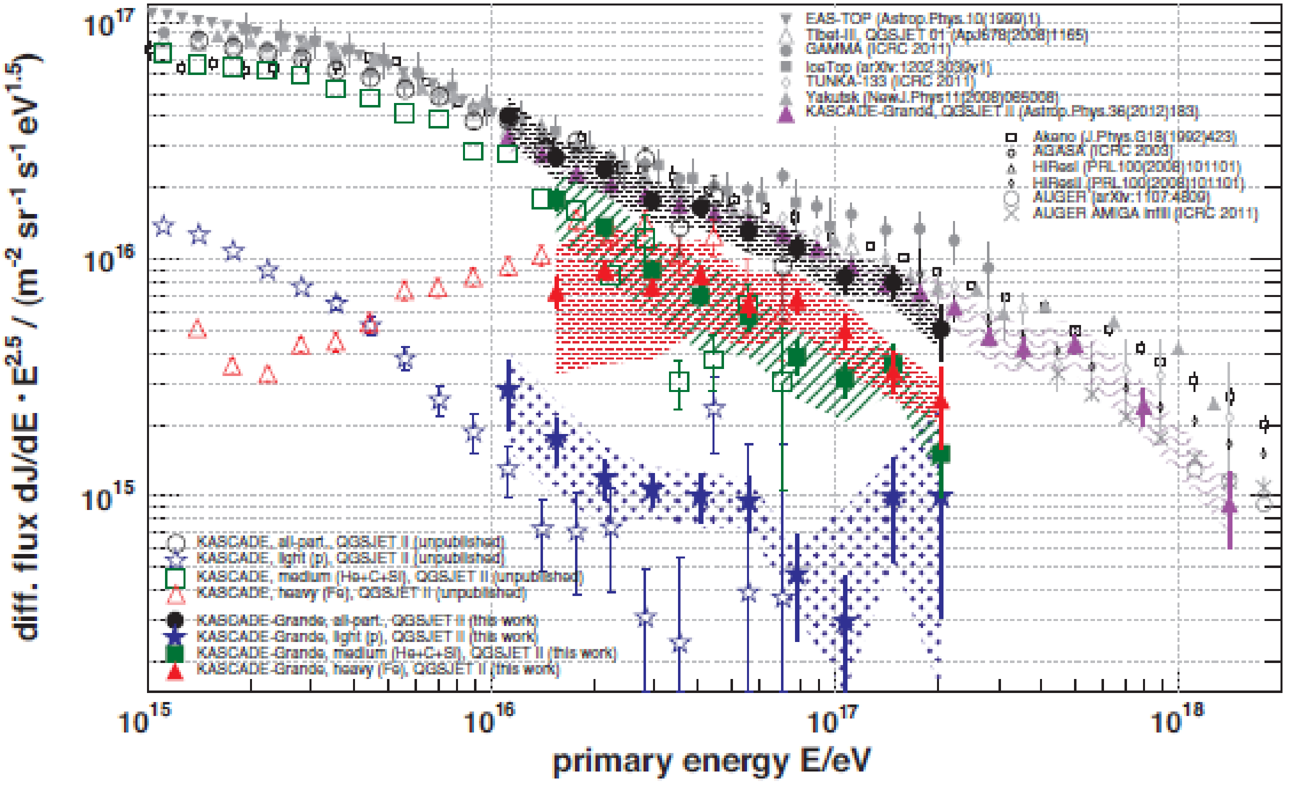
- EAS experiments can study the primary chemical composition only measuring at least two parameters of the showers both depending on E and Z
  - Ne and N_μ
    - Surface Arrays
  - E and Shower geometry
    - Slope of the lateral Distribution
    - Image of the Cherenkov Light
  - E and Xmax
    - Fluorescence Light Detectors
    - EAS radio emission
    - EAS Cherenkov Light Detectors
- All these measurements must rely on a calibration based on EAS complete simulation → High Energy Hadronic Interaction Modelis

Chemical Composition Results

- In the last years we have moved from the study of the moments of the distributions of experimental observables to the measurement of the spectra of primaries mass groups.
- Obtained either by:
  - **Statistical analysis** or **Event by event classification**



KASCADE & KASCADE-Grande



event by event selection → mass groups spectra

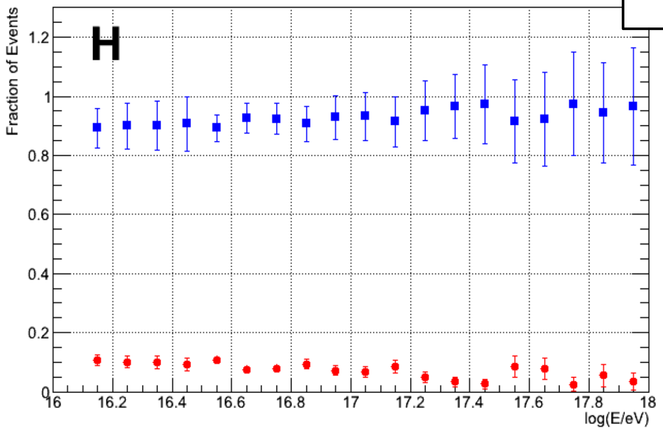
KASCADE & KASCADE-Grande – N_{μ} / N_{ch} ratio

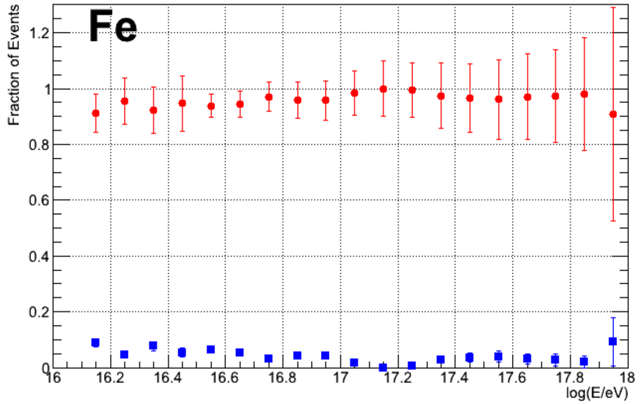
ARGO-YBJ + WFCTA- ldf + shower image

Different definition of contaminations from other mass groups

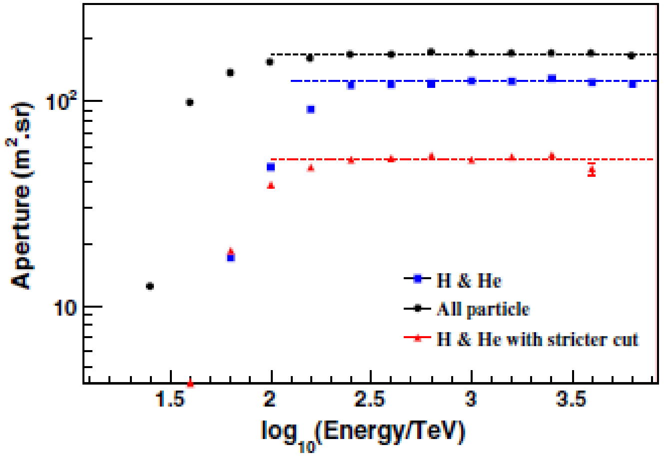
E^{-3} spectra for each element

$$\varepsilon = \frac{N_i}{N_{elem}}$$

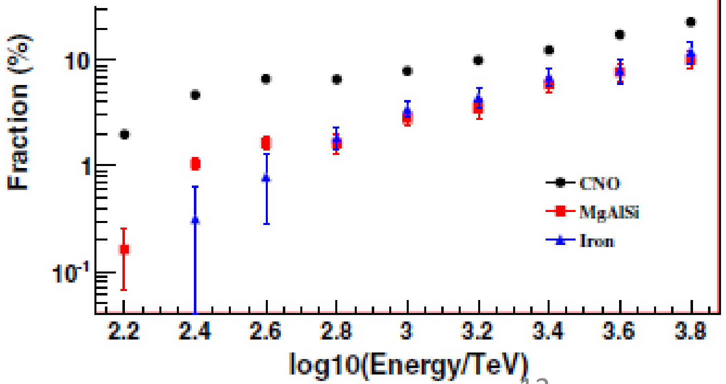


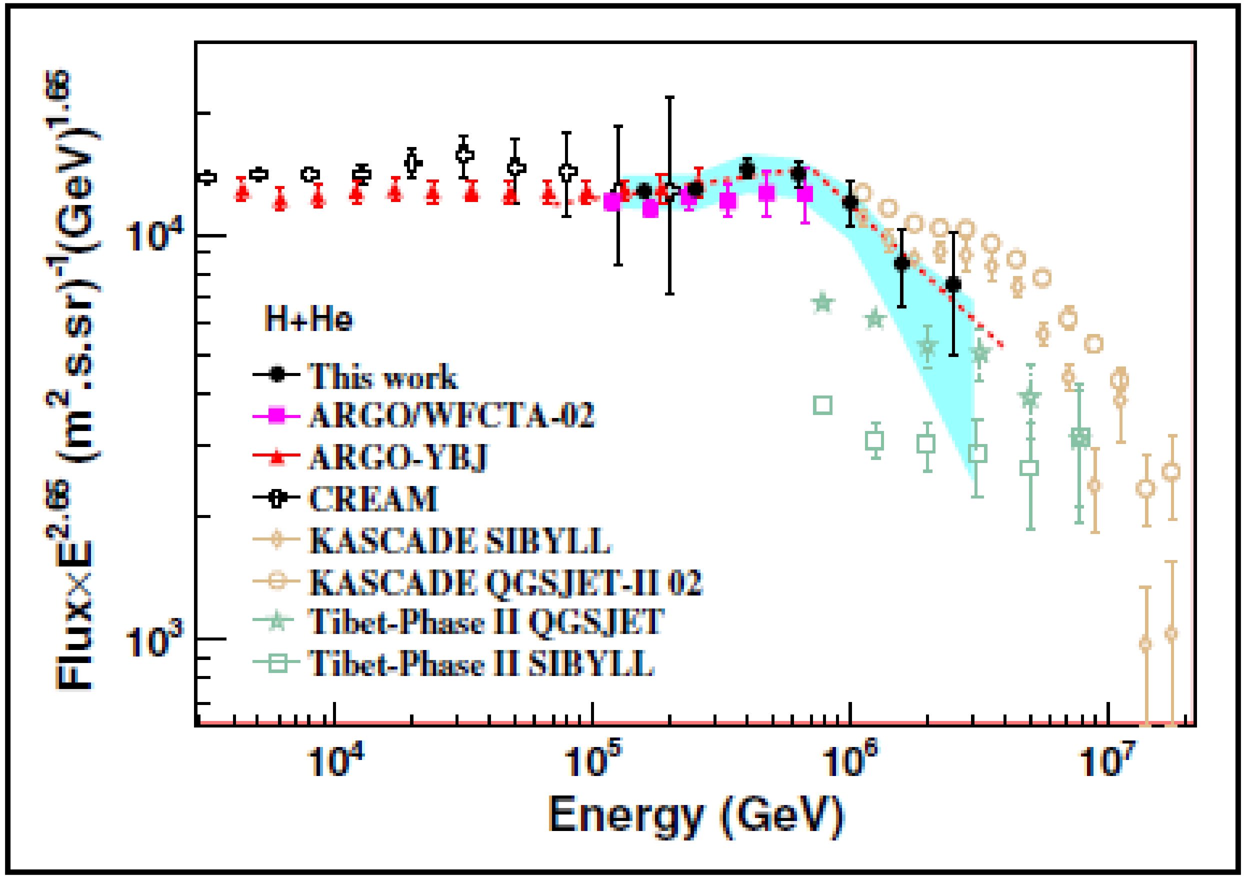


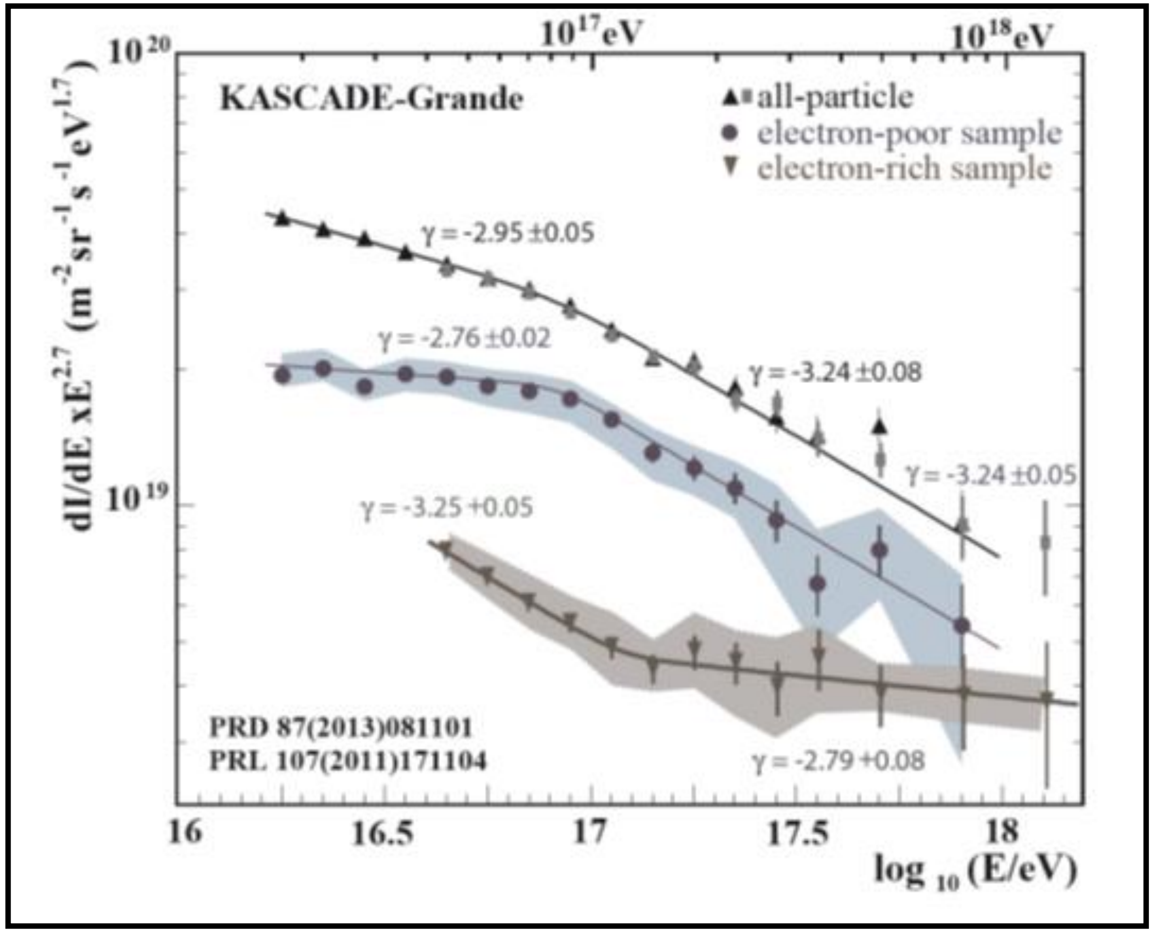
Events are sampled according to a composition model



$$fraction = \frac{N_i}{N_H + N_{He} + N_C + N_{Si} + N_{Fe}}$$







- Steepening in the all partcile spectrum (2.1σ) near to 10^{17} eV
- Feature due to heavy component (3.5σ)
- Hardening of the light component at $10^{17.08}$ eV(5.8σ)
- Slope change from γ=3.25 to γ=2.79

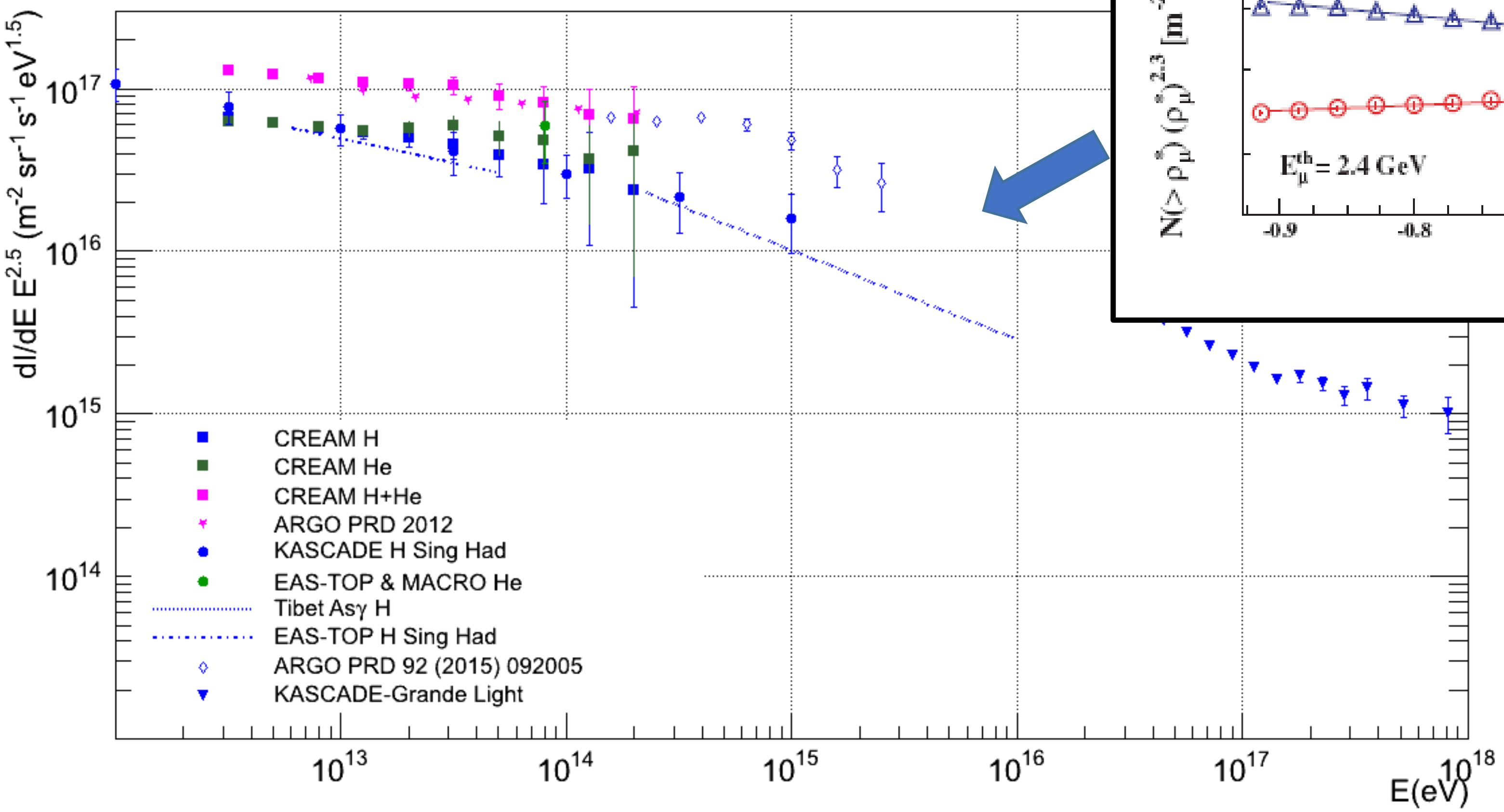
H&He spectrum measured by the ARGO-YBJ+WFCTA hybrid experiment.

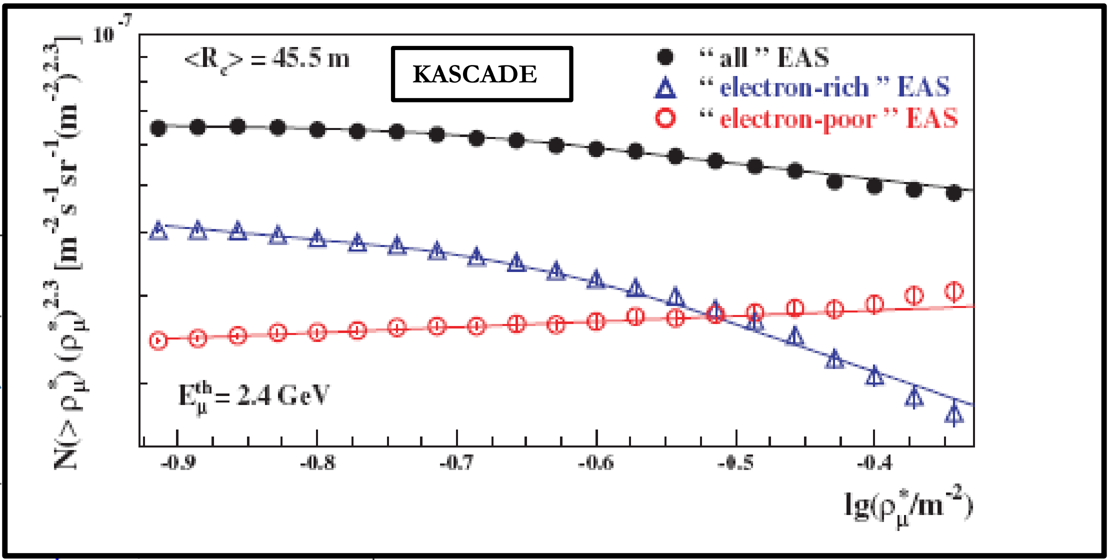
E_k=700 ± 230 ± 70 TeV

γ_1= -2.56 ± 0.05 γ_2 = -3.24 ± 0.36

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

Measurements of the light component spectrum (i.e. mainly protons)





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

→ ~2-4x10^{15} eV

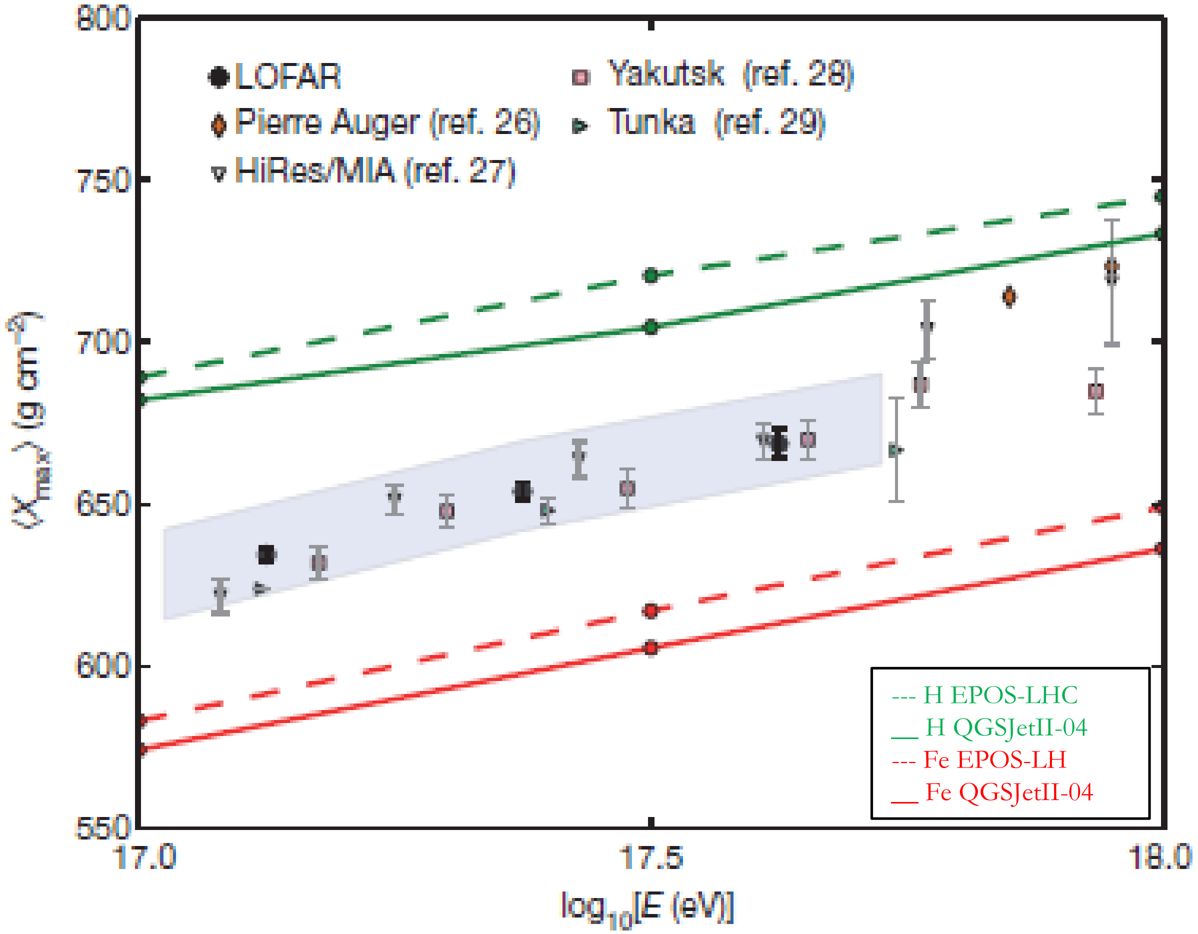
LOFAR → EAS radio detection

- 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}

Nature 531, (2016) 70



Large Scale Anisotropies

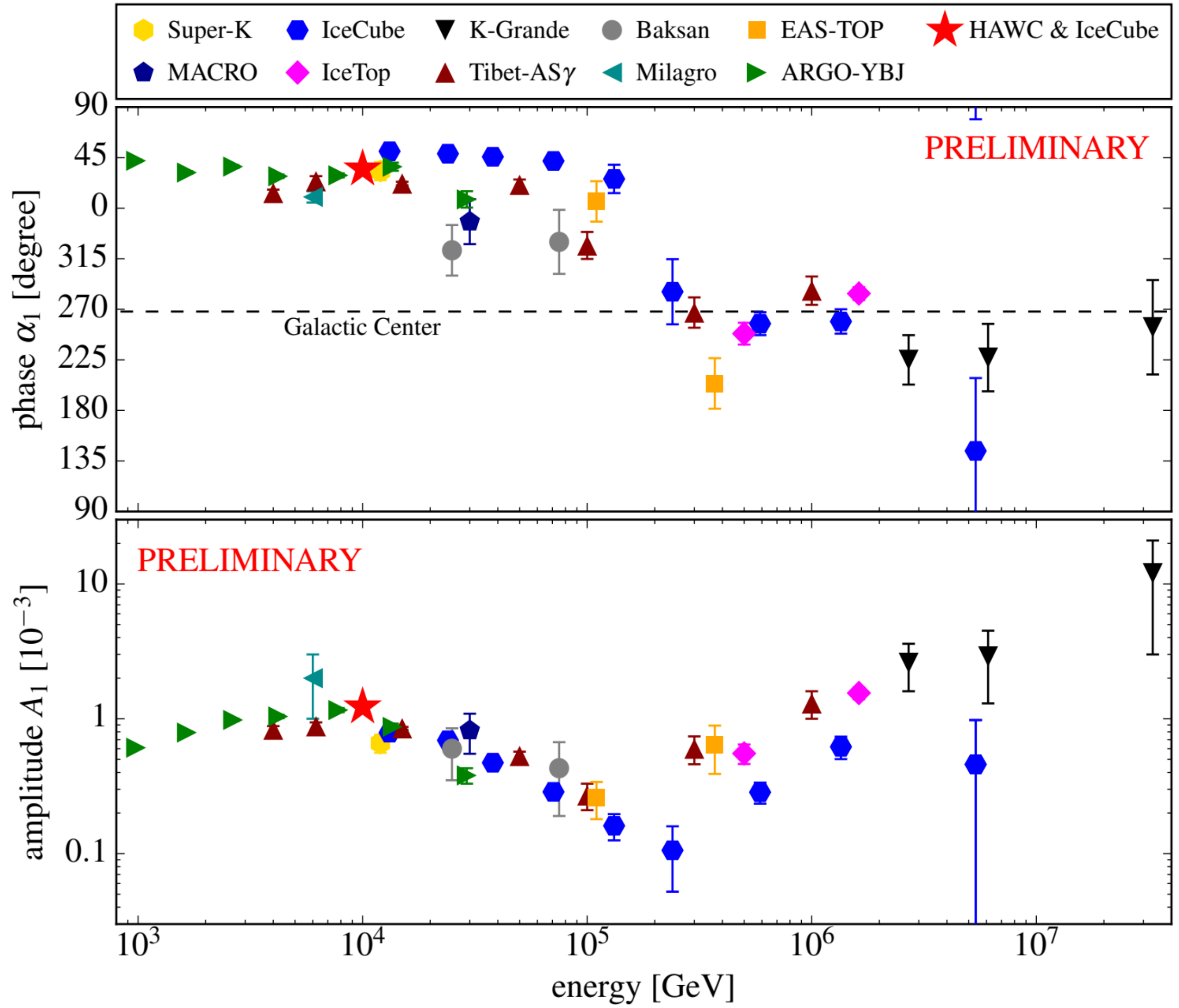
1st Harmonic Amplitudes and Phase measured at different energies

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

The phases measured above 5x10^{14} eV are consistent with those obtained by UHE experiments

Hint of an increasing amplitude crossing knee energies

E > 5x10^{15} eV → only upper limits



M. Ahelrs & P. Mertsch 1612.01873v1

What we have learned

1. Spectrum above the knee has structures
2. Knee due to light component
3. Steepening of the heavy component spectrum around 10^{17} eV
4. Hardening of the light component spectrum slightly above 10^{17} eV
5. Very small anisotropies
6. Hints of an increasing amplitude and of a change of the phase

What we still don't know

1. Conflicting results about the knee of the light component
   1. Are we observing two real features of light primaries spectrum?
   2. Are we introducing spectral shapes because of systematic effects not under control?
2. EAS development is not completely understood
   1. Absolute energy calibration?
   2. μ excess?
3. Knee Energy grows with Z or with A?
4. Anisotropy behaviour above the knee
5. Anisotropy measurements for different mass groups

Conclusions

- Knowledge of the knee energy range has improved
  - Escape from magnetic field hypothesis is favoured
  - Acceleration limits or Propagation effects?
- We must achieve better control of systematic errors
- Separate on a event by event basis more than two mass groups
  - Are we limited by EAS fluctuations?
- Precise and High statistics measurement are needed
  - LHAASO → High Altitude, High Precision, 1 km^2 array