# Summary of Cosmic Ray Spectrum and Composition below $10^{18}$ eV

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- $10^{14}<E<10^{18}$ eV
  - $E<10^{17}$ eV → surface, multicomponent arrays
    → Cherenkov experiments
  - $E>10^{17}$ eV → surface, multicomponent arrays
    → radio experiments
    → low energy extensions of UHE experiments
- Energy calibration of the Surface arrays
  - Calibration without EAS simulation
    - Low energies → cross calibration with direct measurements
      → moon shadow
    - High energies → hybrid experiments
  - Calibration using EAS simulations depends on:
    - Hadronic Interaction Models
    - Choice of the mass of the Primary Particle
- Mass measurements
  - Correlation between different EAS components/parameters
    - Calibration based on EAS simulation (Hadronic Interaction Models dependence)
  - $E>10^{17}$ eV → $X_{max}$ → Fluorescence light and Radio detectors

# Where do we were ~25 years ago

- Spectrum: one spectral feature
- Experiments: multicomponent arrays were at the beginning of the data taking.
- EAS simulation: almost every experiment had his own code.

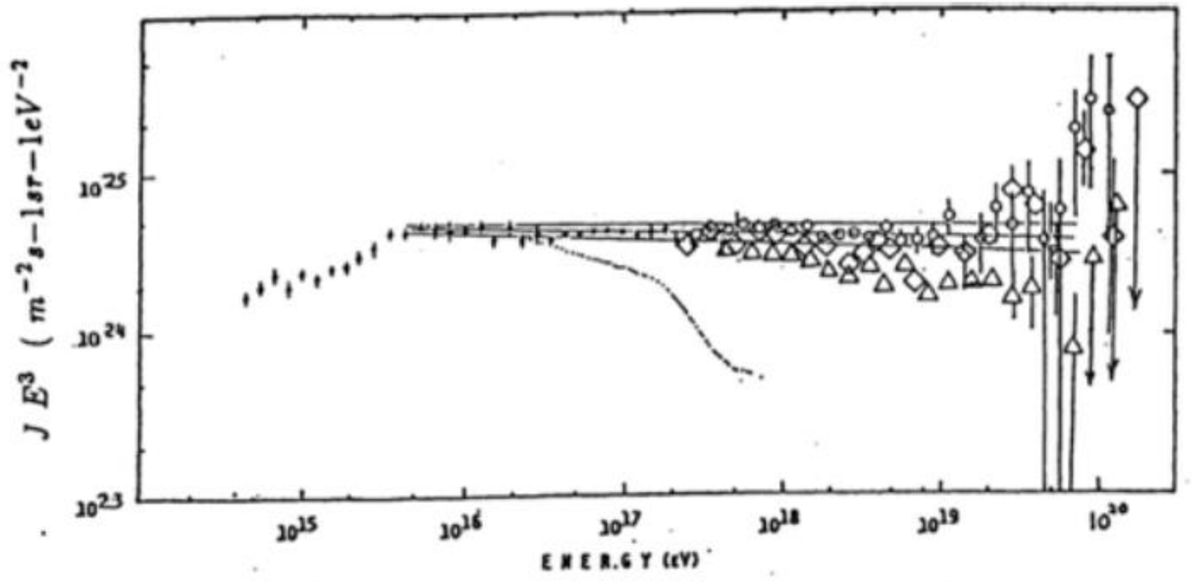
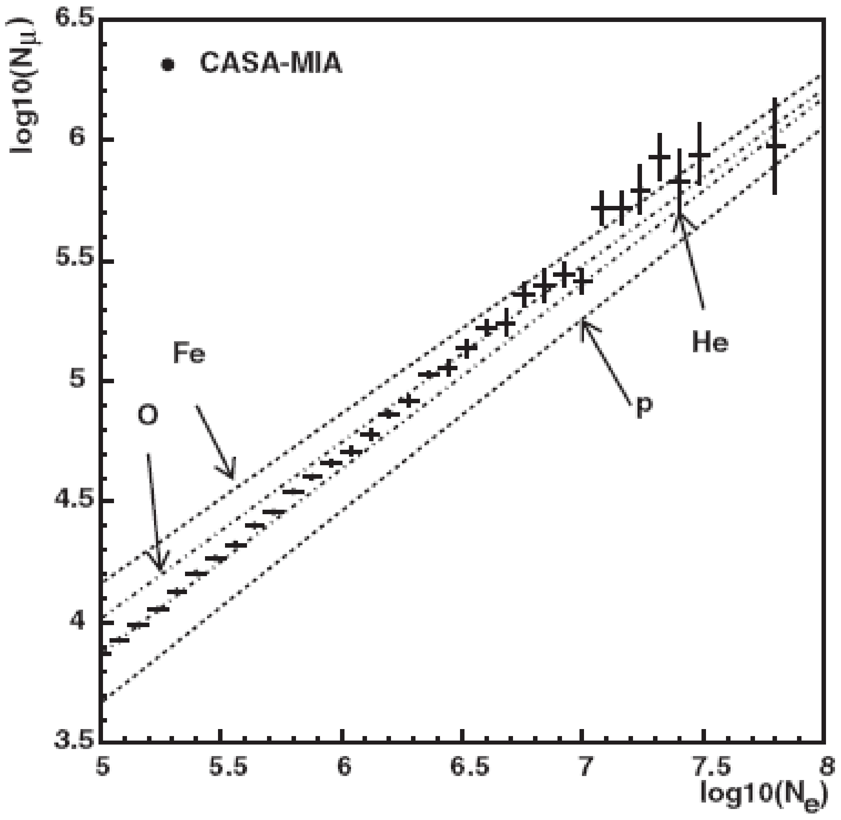


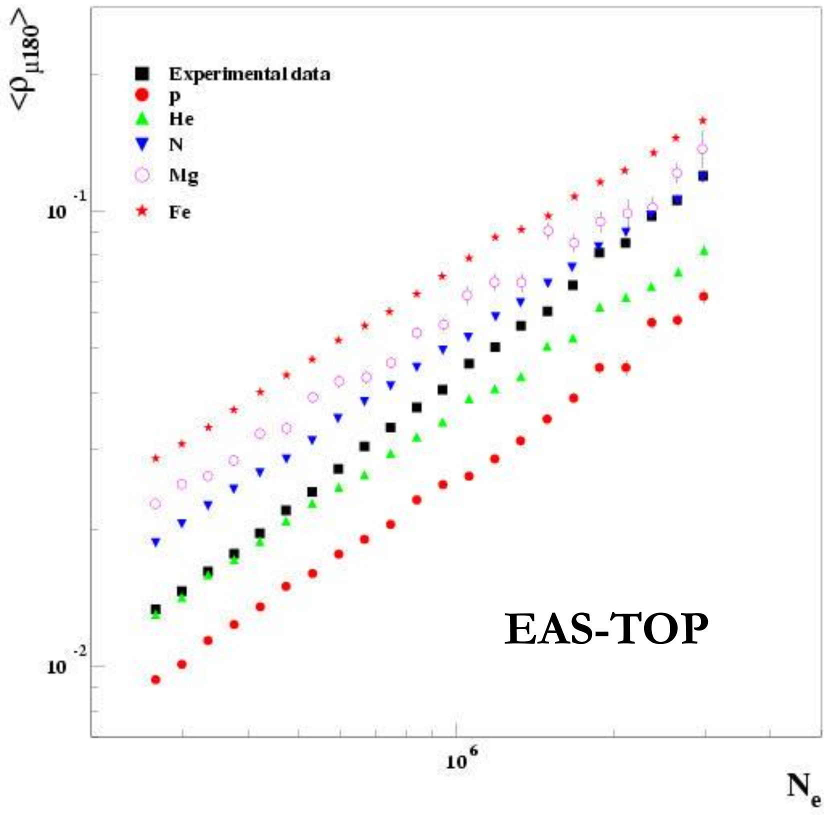

*Fig. 19. Spectrum of cosmic ray. The symbols, • and ○ are for 1 km² and 20 km² array of Akeno, and △ and ◇ are Fly's Eye and Haverah Park data, respectively. The dotted curve indicates Moscow State University data.*

From T. Kifune rapporteur talk @1990 ICRC (Adelaide)

# Roughly ten years later

- Composition: only first momentum (mean values) of the distributions were used



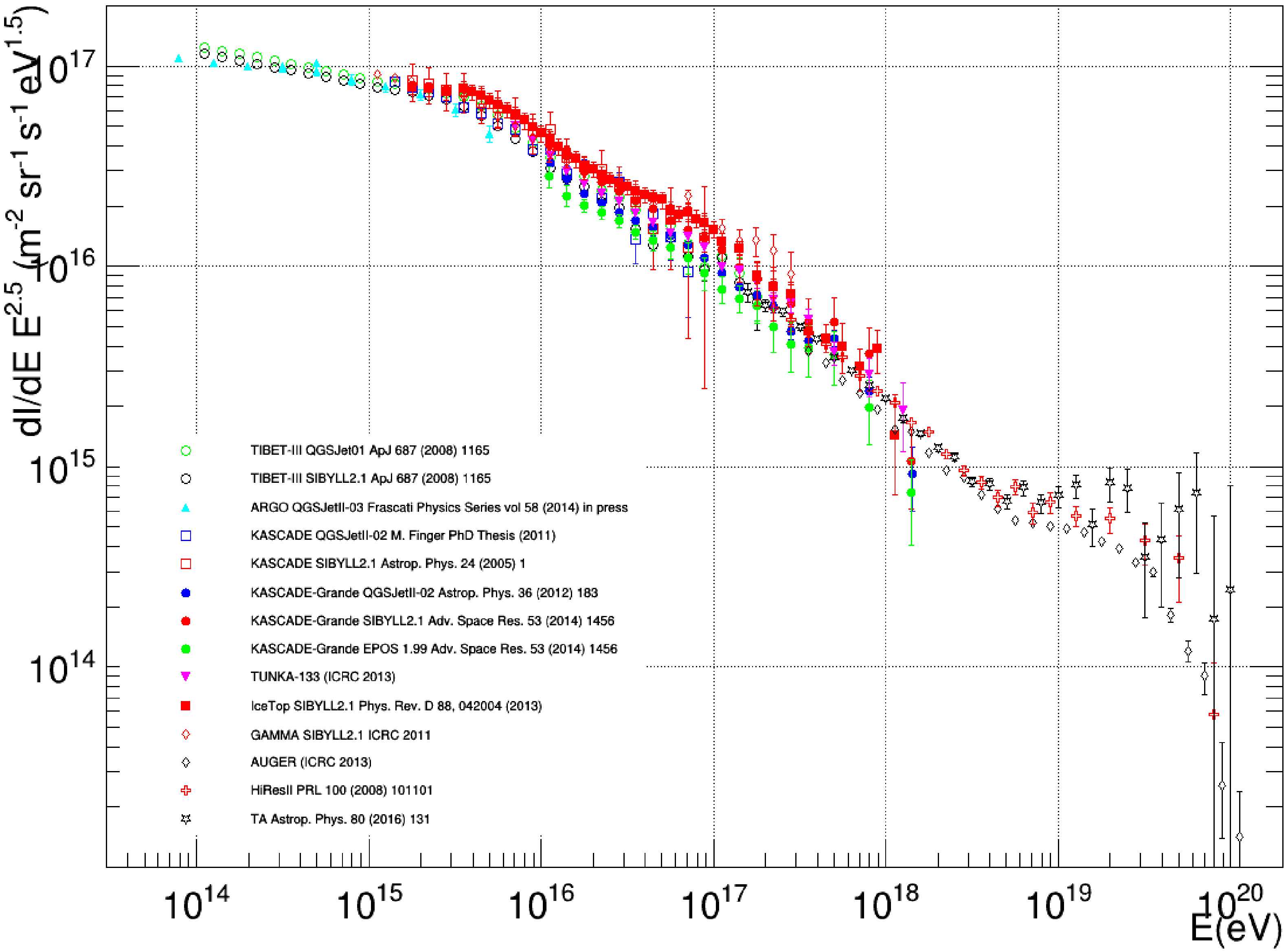



# What has changed nowadays?

- Experiments
  - High precision, multicomponent EAS arrays
  - Hybrid experiments
- EAS simulation
  - CORSIKA with different high and low energies hadronic interaction models
- Spectrum Measurements
  - Hardening ~$10^{16}$ eV; Steepening ~$10^{17}$ eV
  - Differences in the absolute fluxes measurement → attributed to energy calibration
- Composition Measurements
  - Multi parameters statiscal analysis
  - Event by event mass group separation

  } mass groups spectra

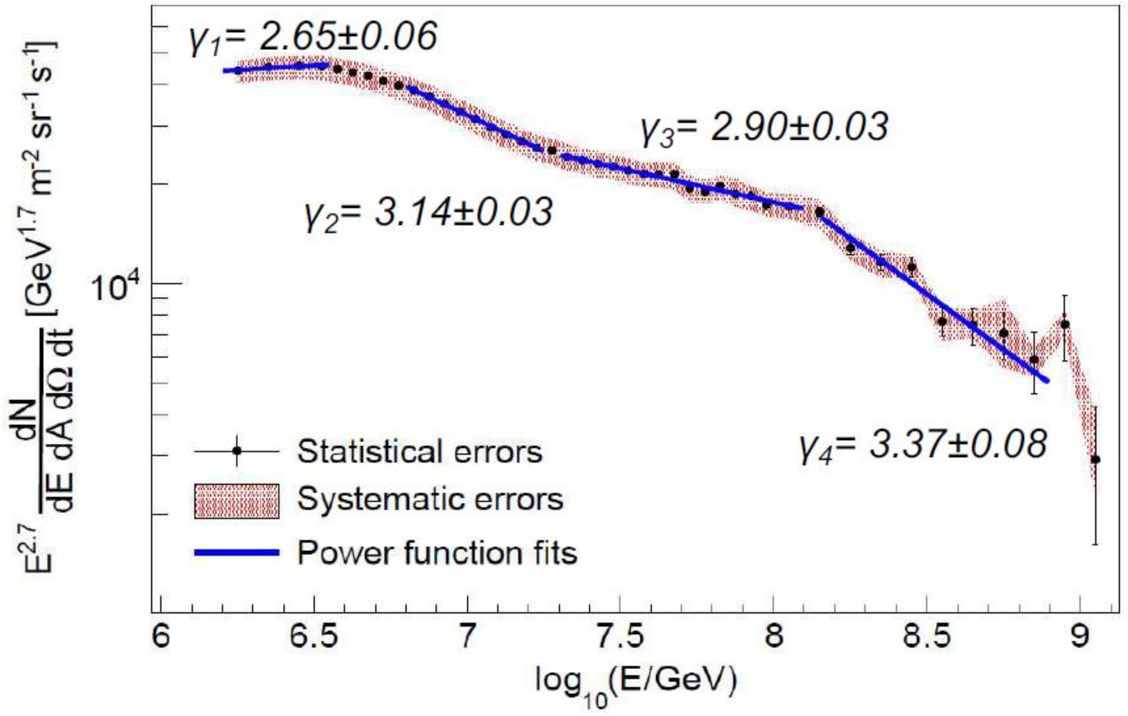
# Summary of Spectra Measurements

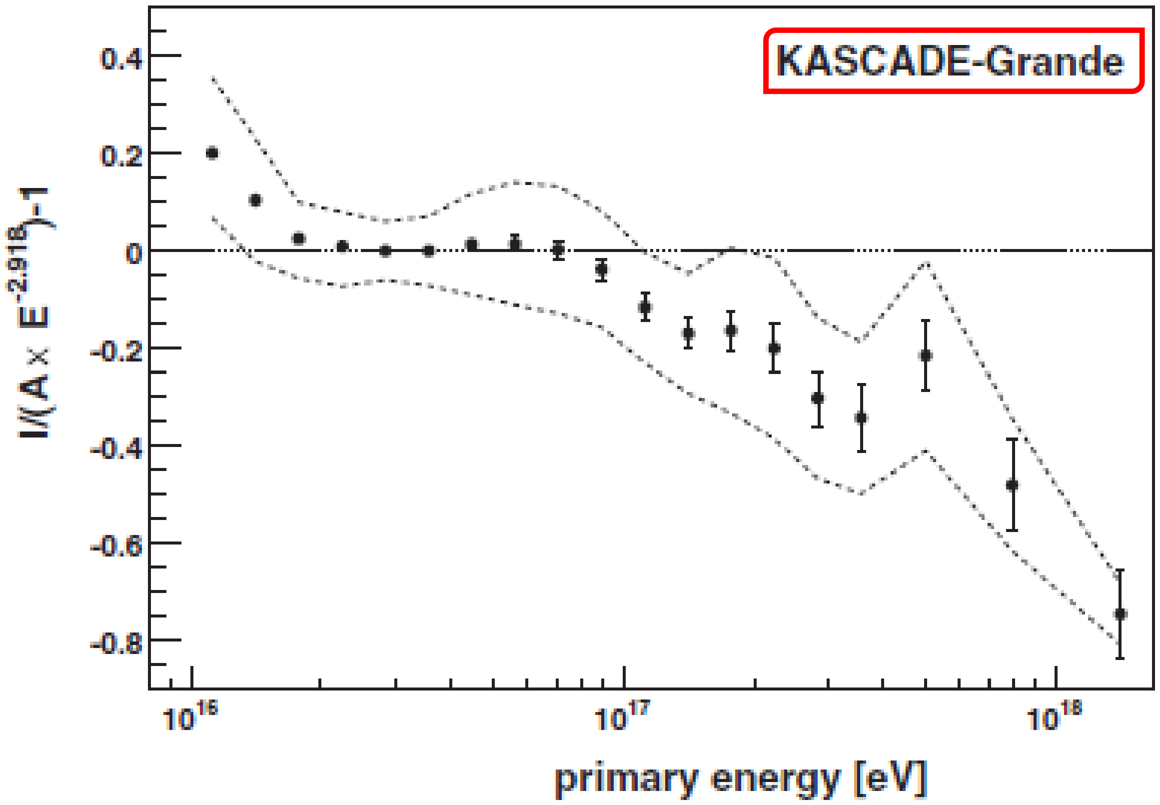



- Flux differences due to energy calibrations.
- Spectral shapes agree

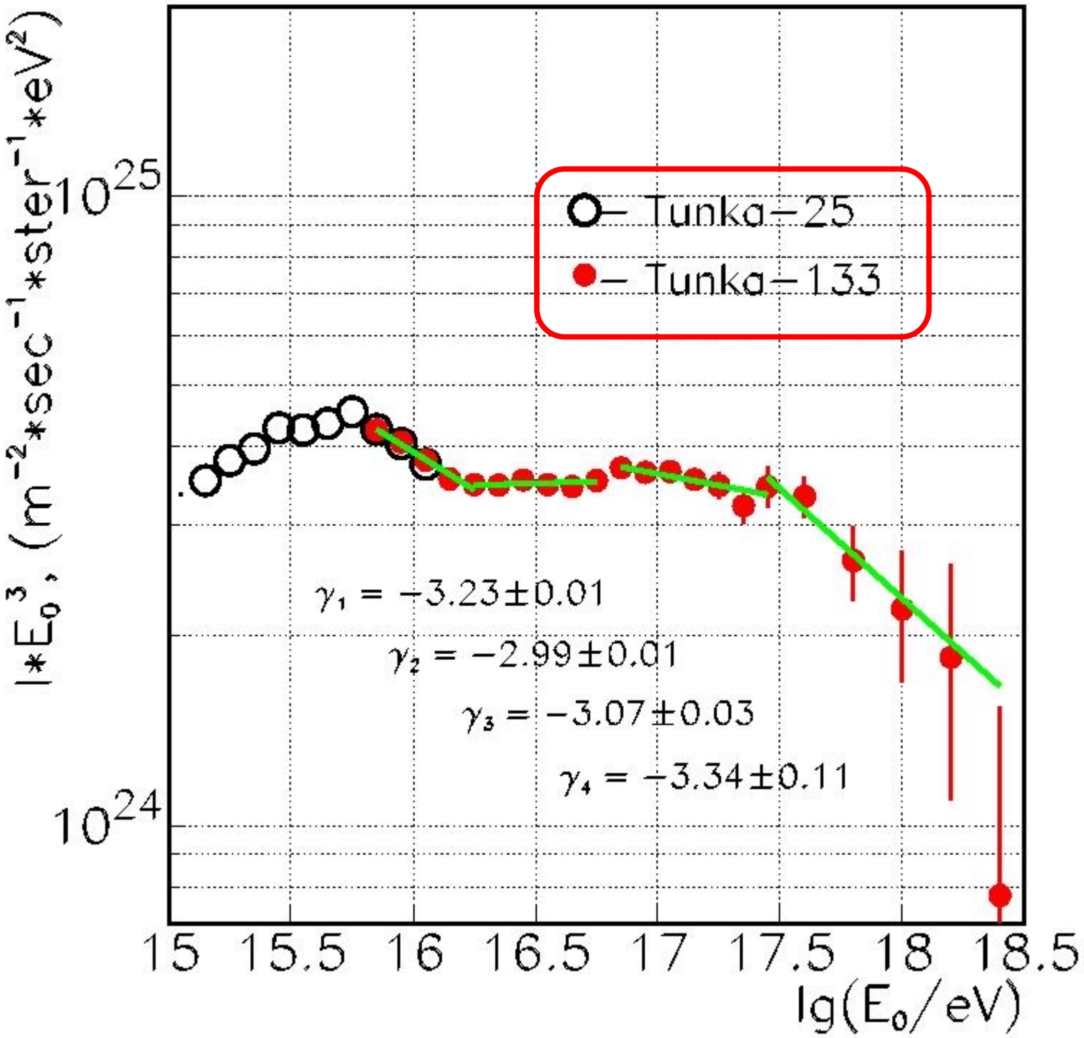
# The spectrum above the knee cannot be described by a single slope power law

**Ice Top**



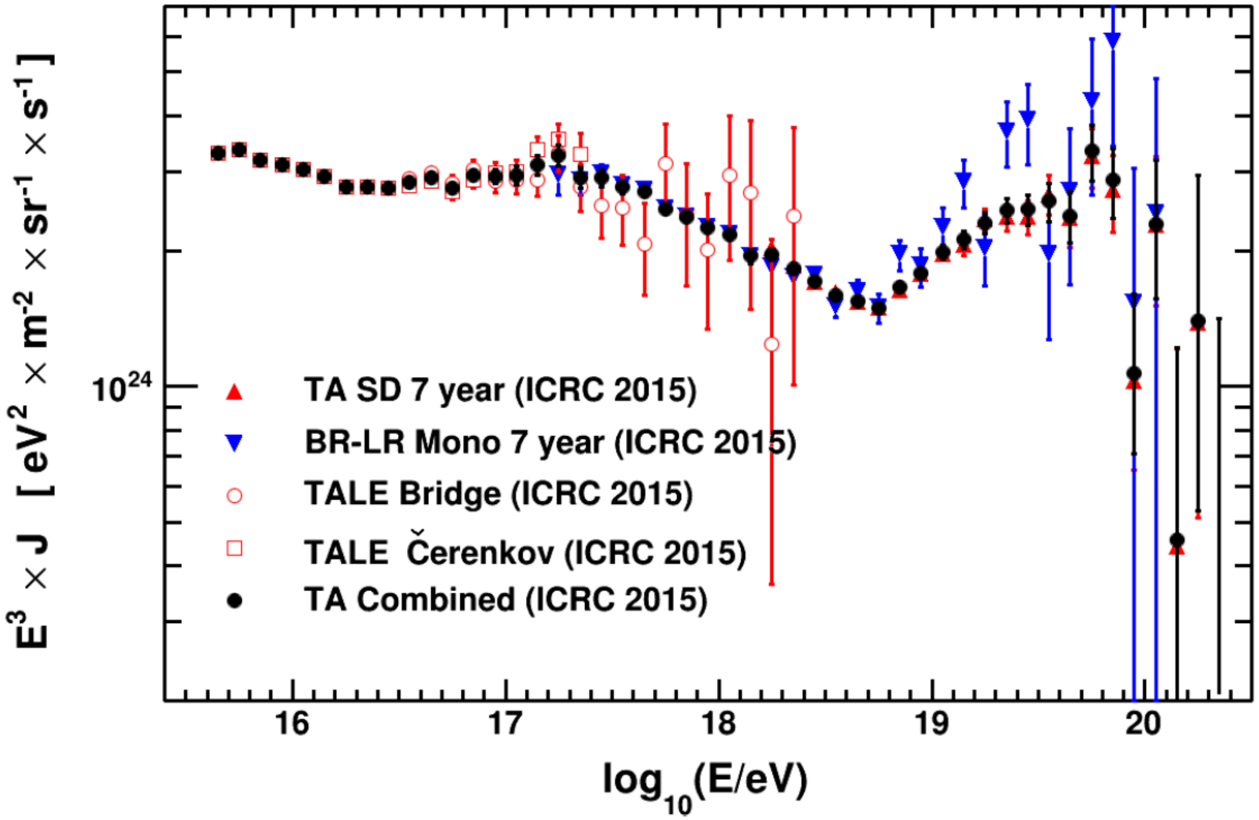




Hardening at 18±2 PeV
Steepening at 130±30 PeV



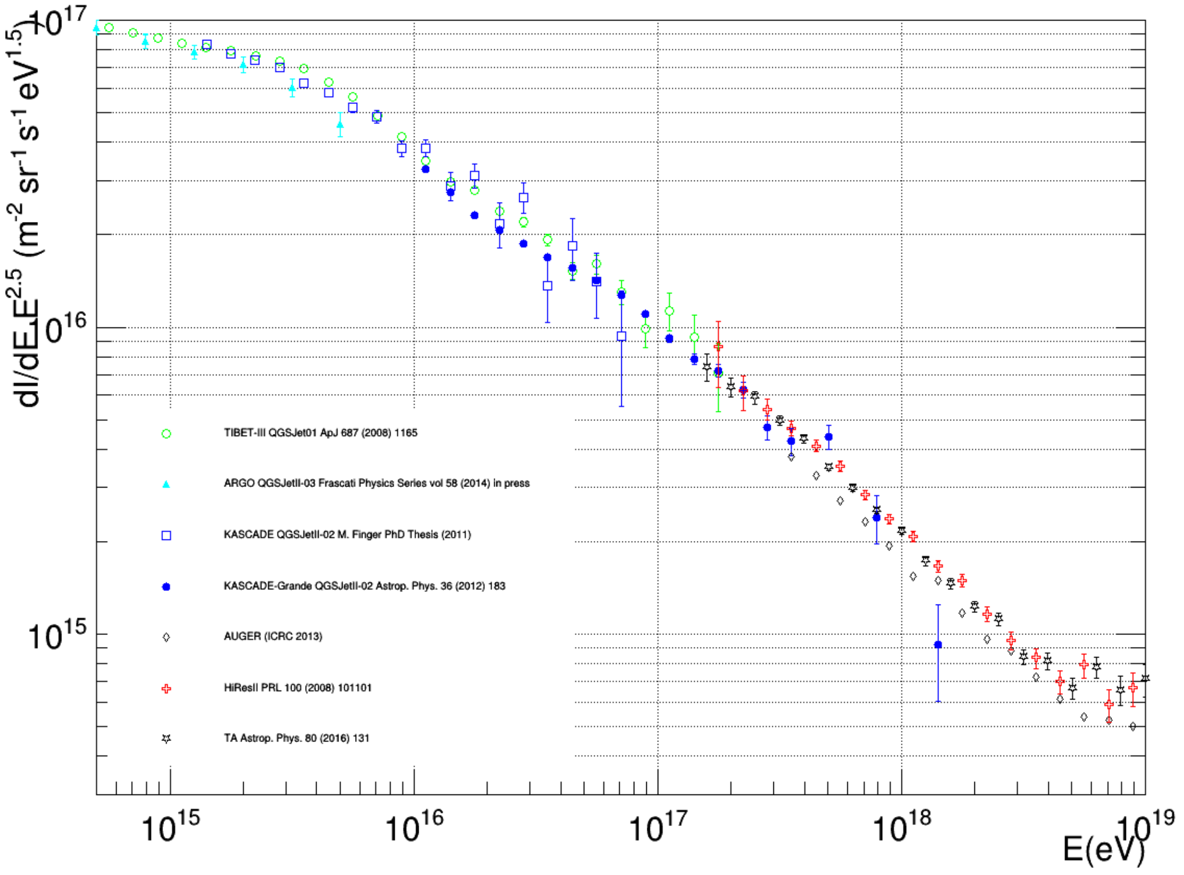
Tunka-25
Tunka-133
$\gamma_1 = -3.23 \pm 0.01$
$\gamma_2 = -2.99 \pm 0.01$
$\gamma_3 = -3.07 \pm 0.03$
$\gamma_4 = -3.34 \pm 0.11$
$I*E_0^3$, $(m^{-2}*sec^{-1}*ster^{-1}*eV^2)$
$lg(E_0/eV)$


TALE

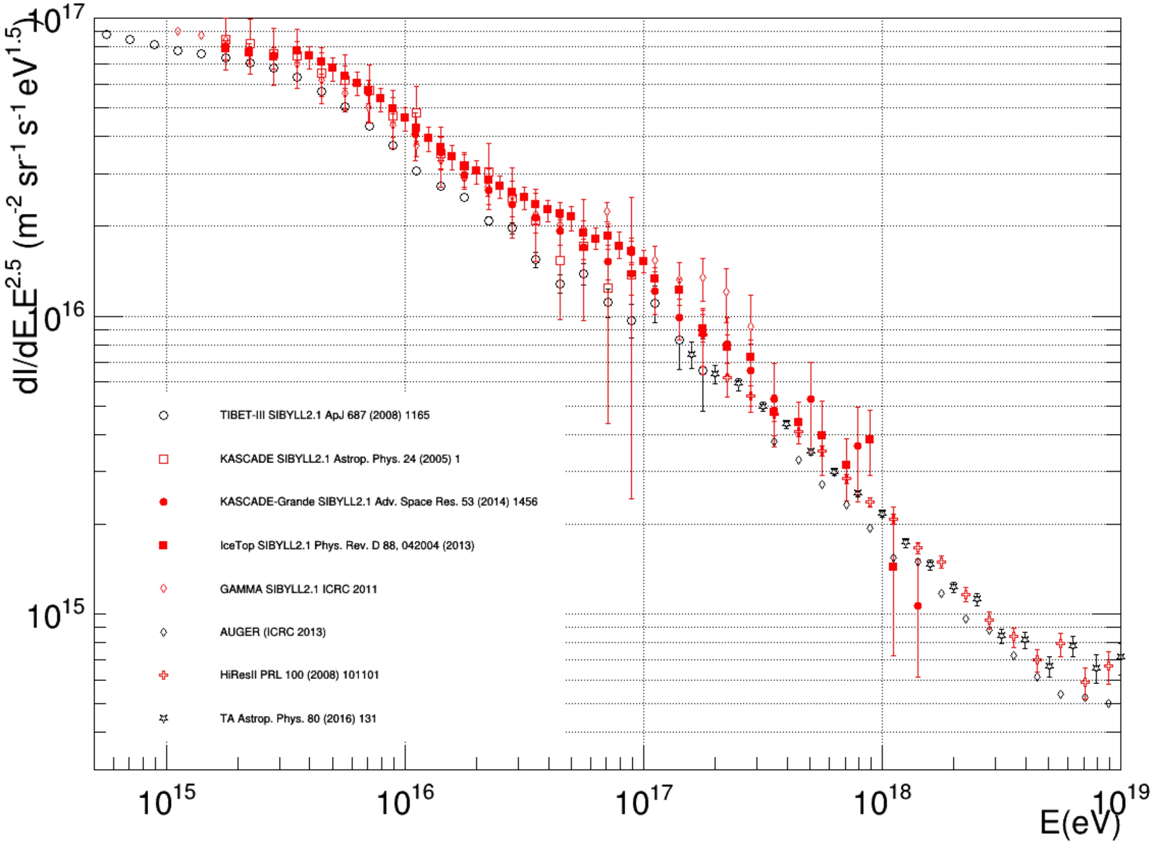


TA SD 7 year (ICRC 2015)
BR-LR Mono 7 year (ICRC 2015)
TALE Bridge (ICRC 2015)
TALE Čerenkov (ICRC 2015)
TA Combined (ICRC 2015)
$E^3 \times J$ [ $eV^2 \times m^{-2} \times sr^{-1} \times s^{-1}$ ]
$log_{10}(E/eV)$

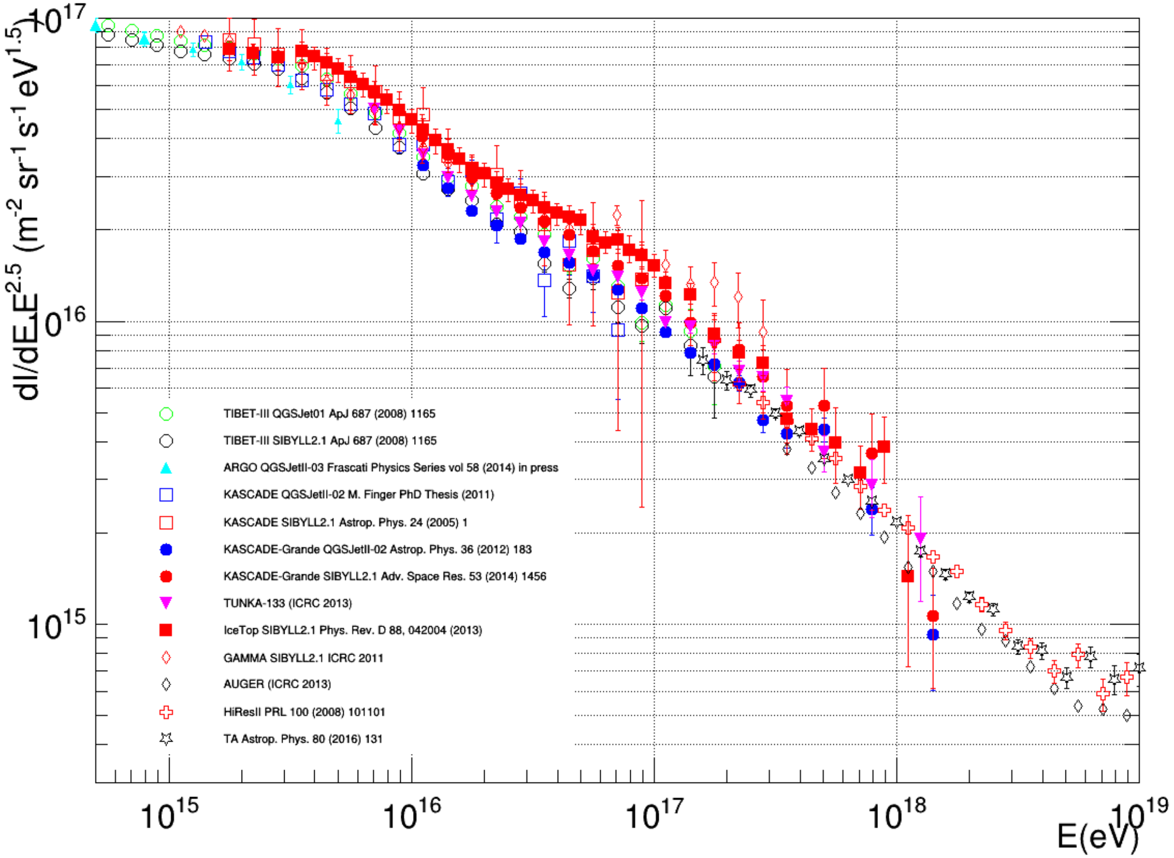
# Fluxes obtained with experiments calibrated by means of Pre-LHC hadronic interaction models



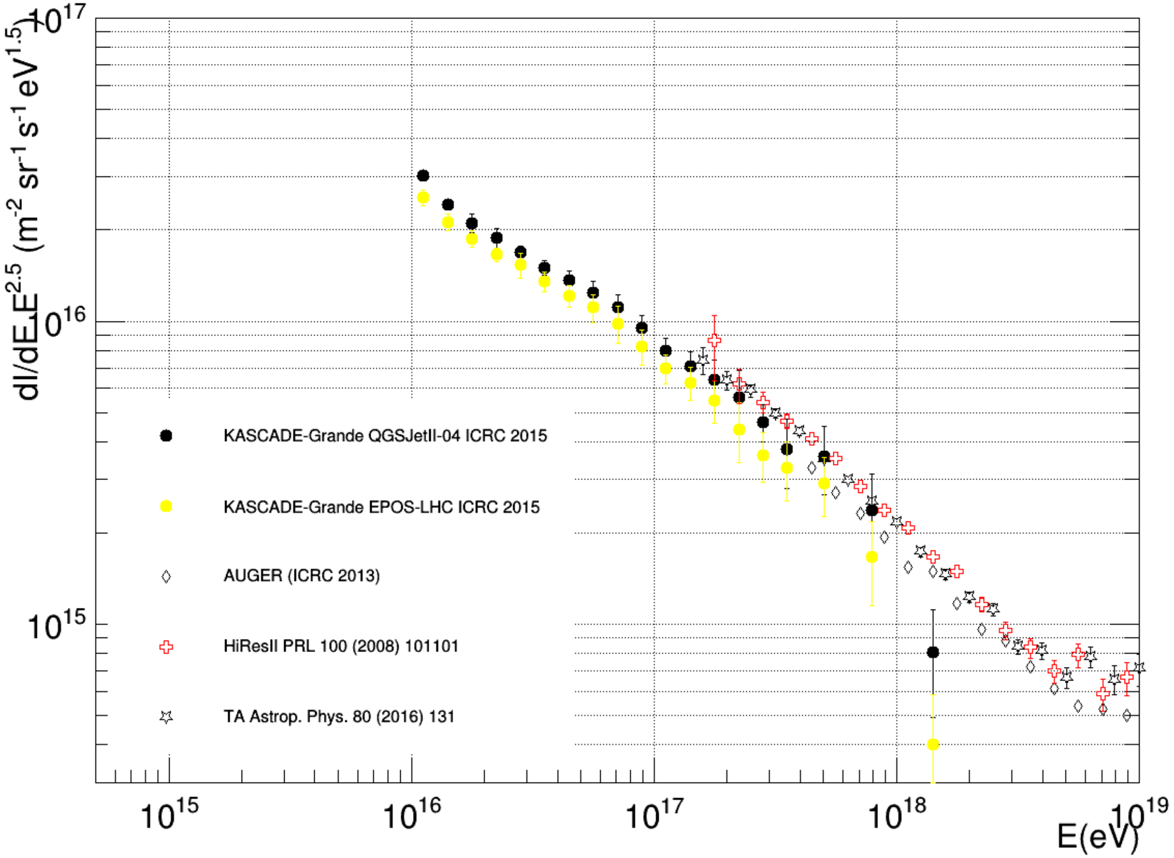

Experiments calibarted with QGSJet0%




Experiments calibarted with Sibyll2.1



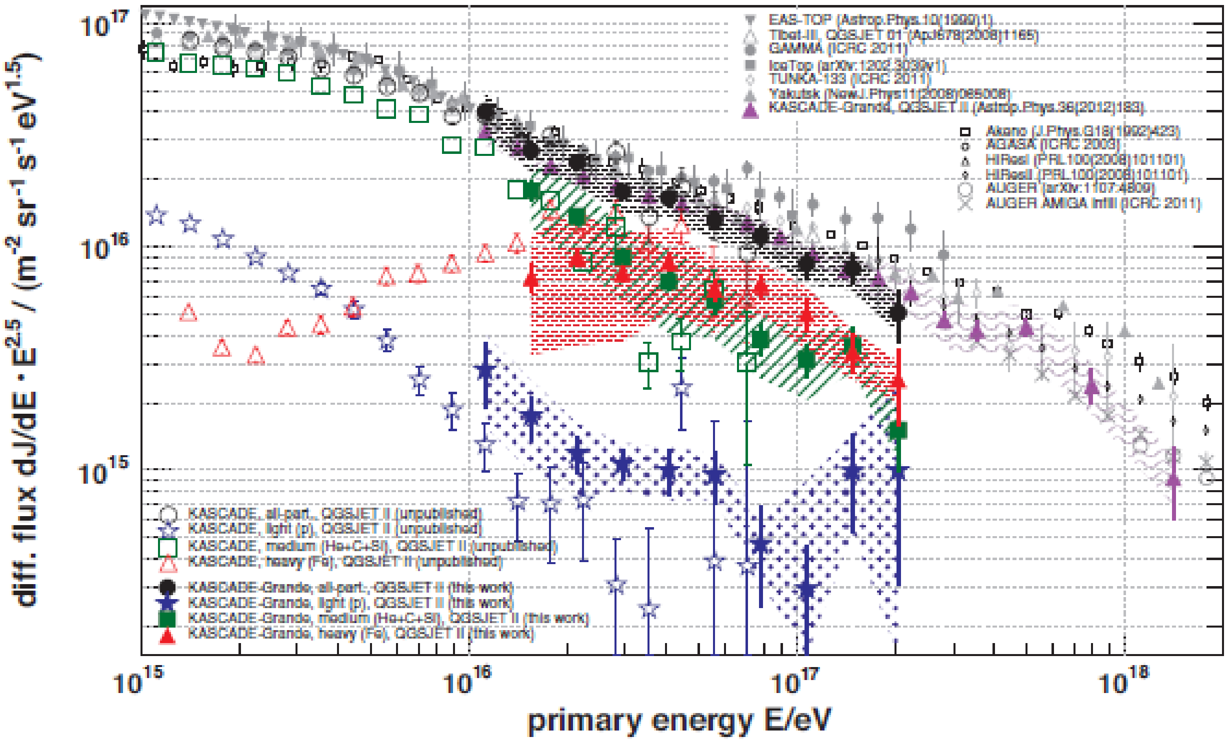

**Pre-LHC Models**




**Post-LHC Models**

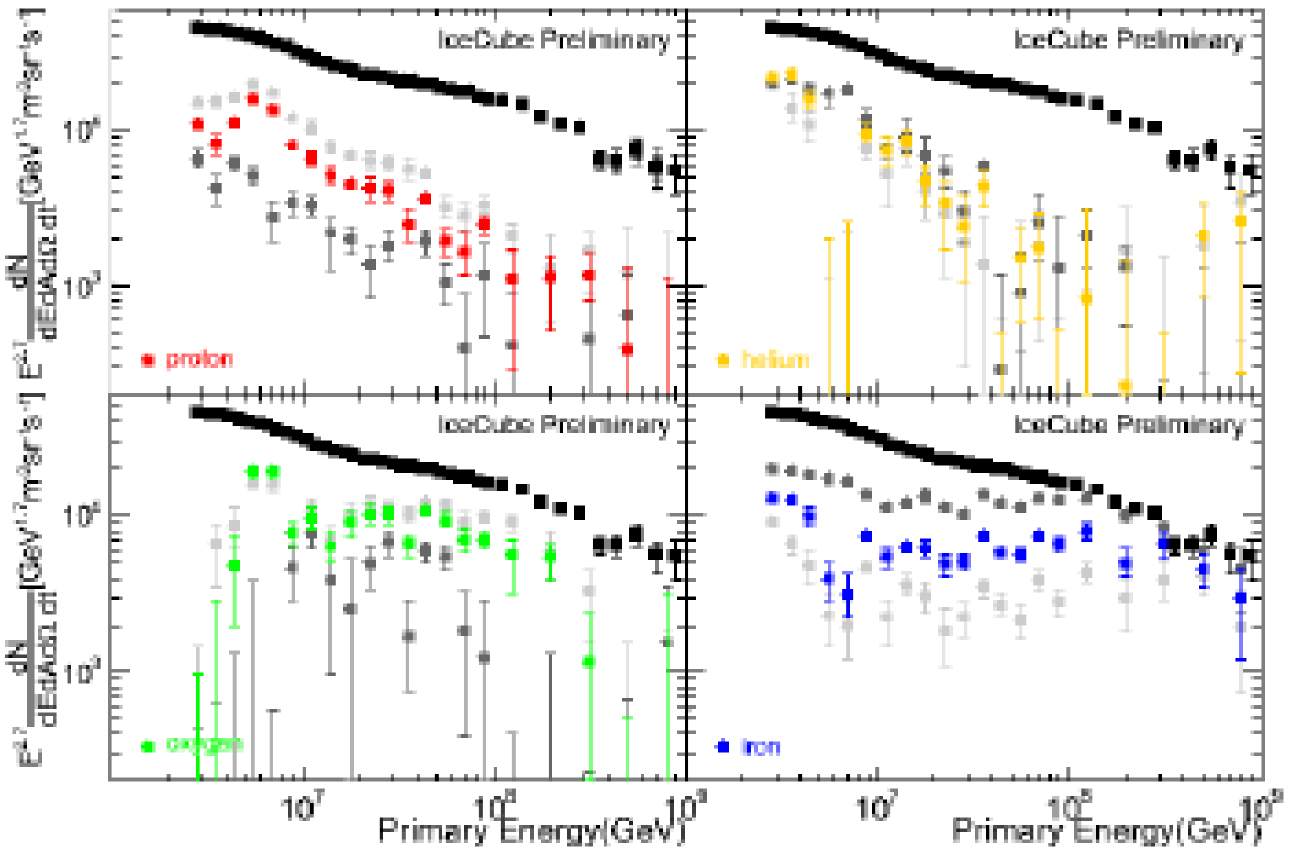
# Chemical Composition Results

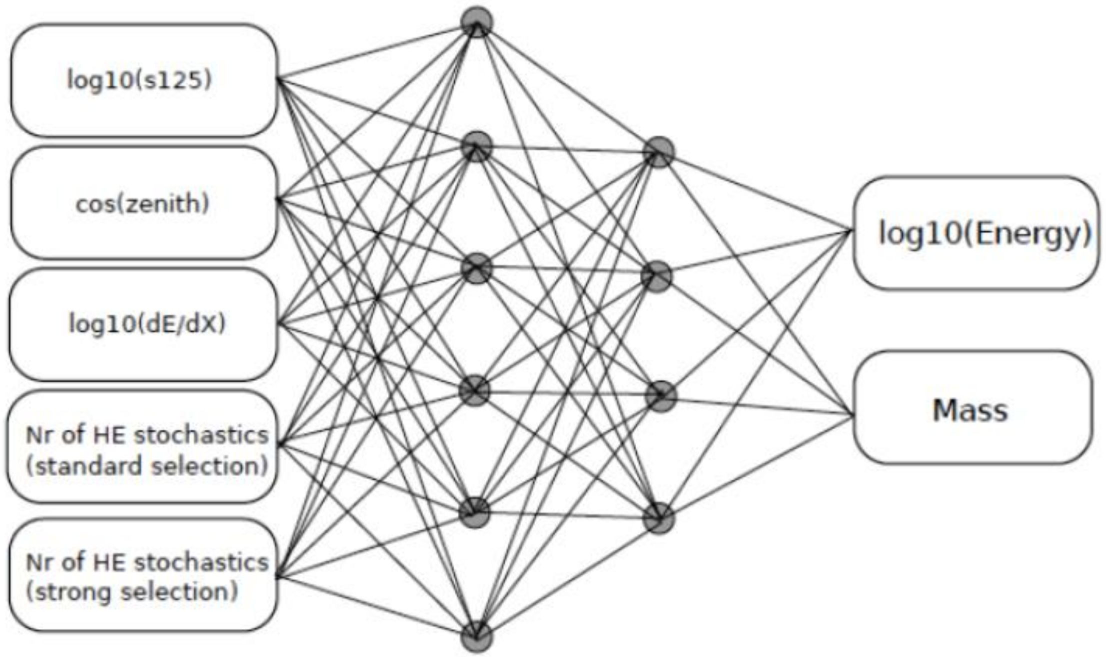
- We have moved from the study of the moments of the distribution of experimental observables to the one of the spectra of primaries mass groups. Obtained either by:
  - Statistical analysis
  - Event by event classification




- $N_e$ vs $N_\mu$ spectra unfolding
- KASCADE & KASCADE-Grande results.
- Both data sets are analyzed with the QGSJetII-02 hadronic interaction model

# IceTop – IceCube

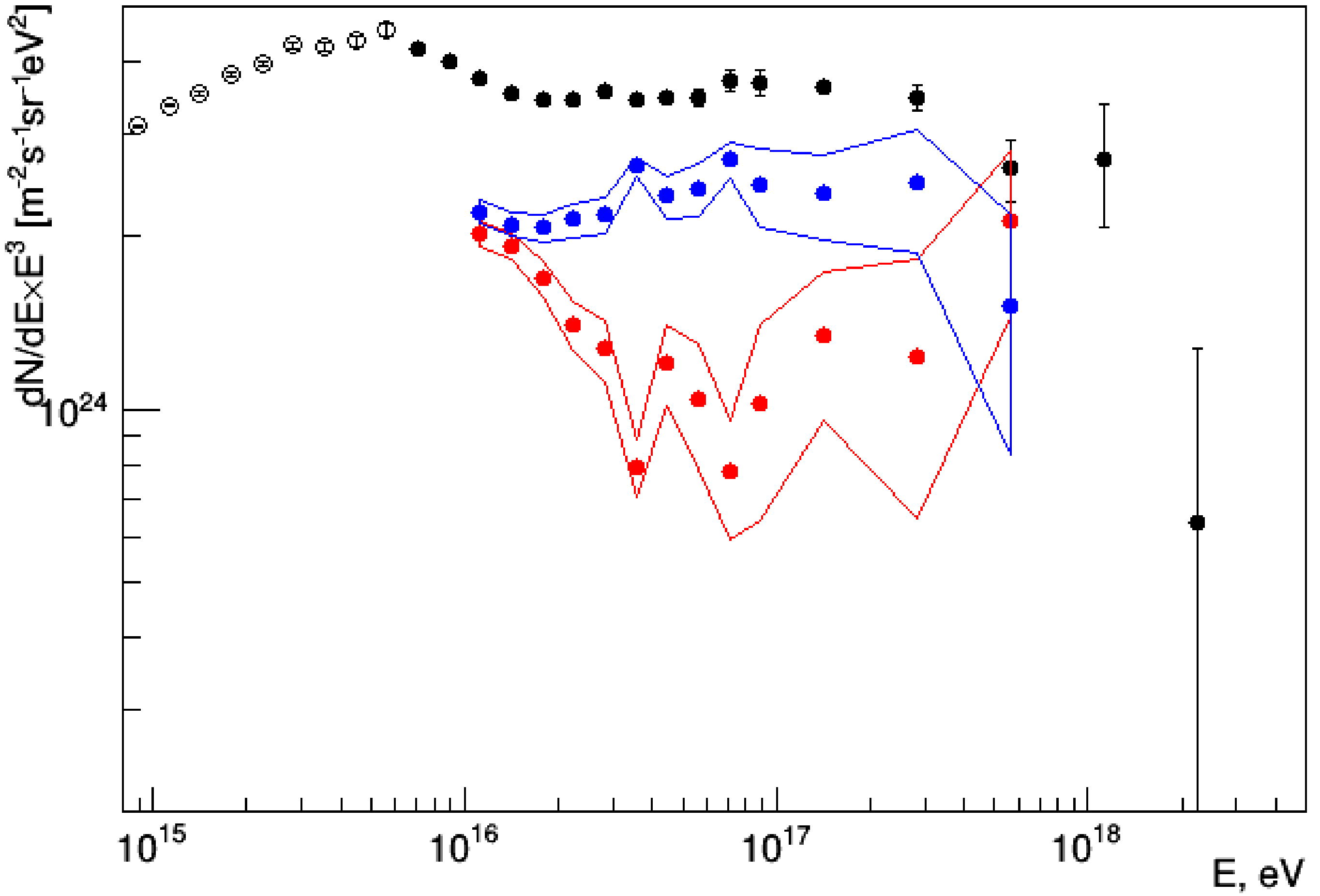



EAS simulation: SIBYLL2.1

**H & He steeper spectra**
**O & Fe harder spectra**

- Tunka-133 spectra of the light and heavy components

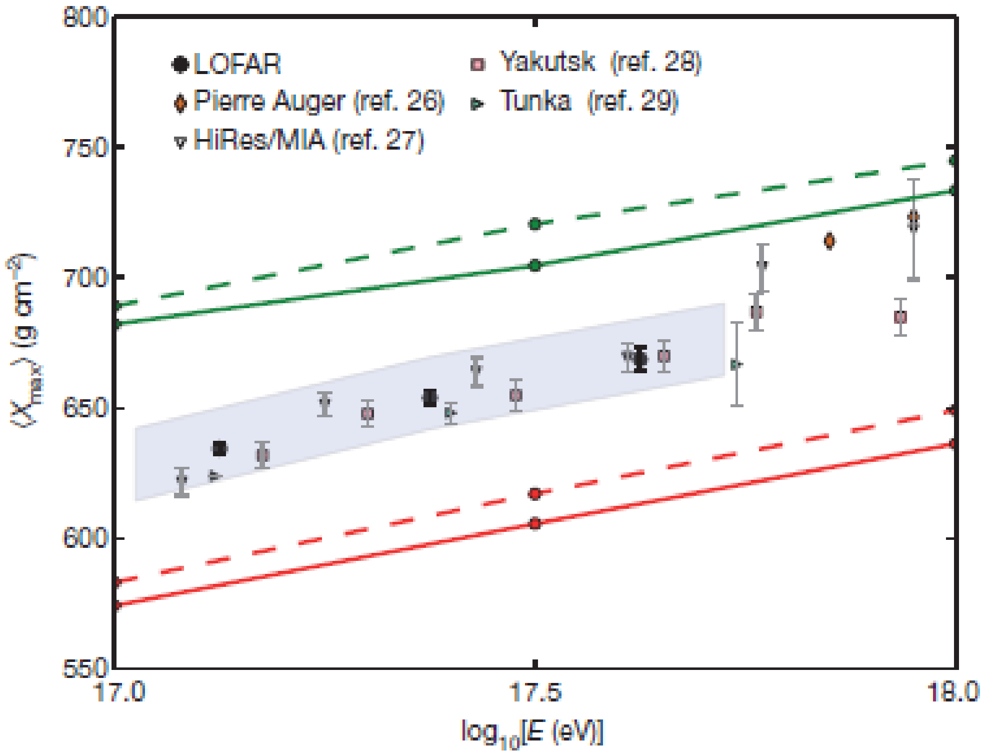


# LOFAR → EAS radio detection

- 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$^{-2}$

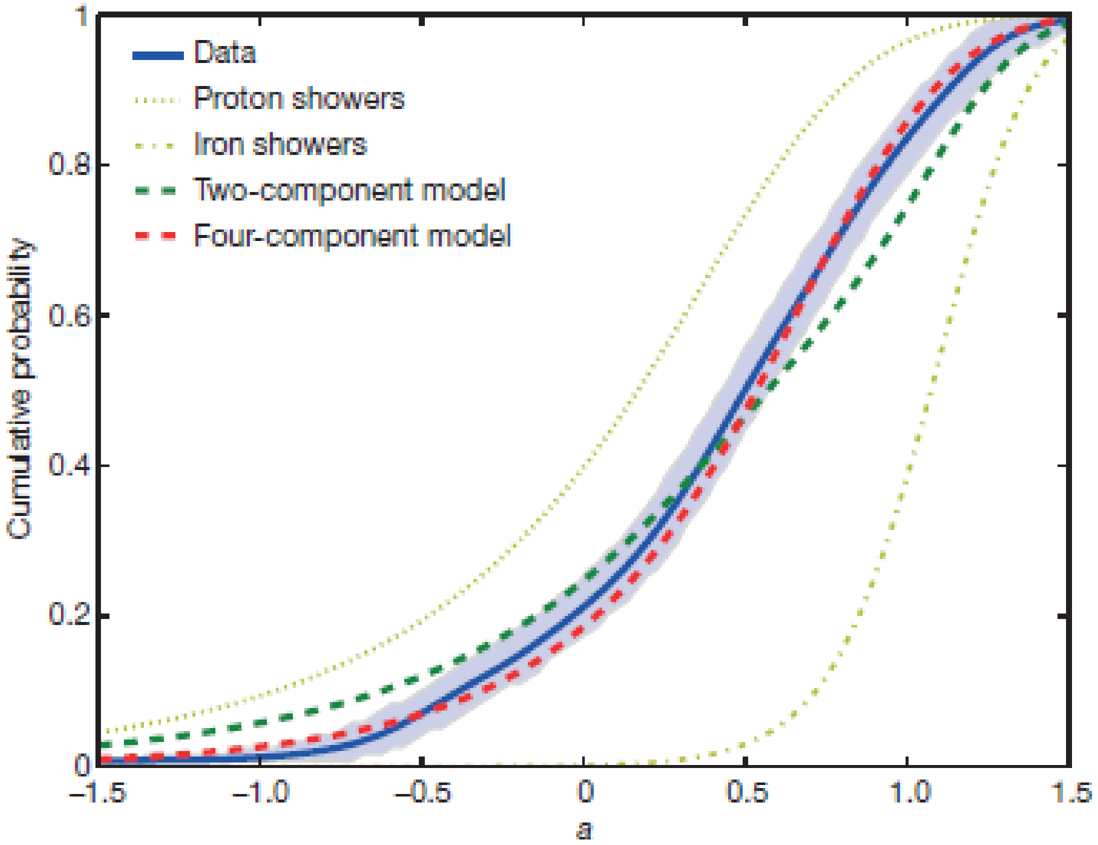



--- H EPOS-LHC __ H QGSJetII-04
--- Fe EPOS-LHC __ Fe QGSJetII-04

Nature 531, (2016) 70

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

$<X_H>$ and $<X_{Fe}>$ 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

# event by event selection → mass groups spectra

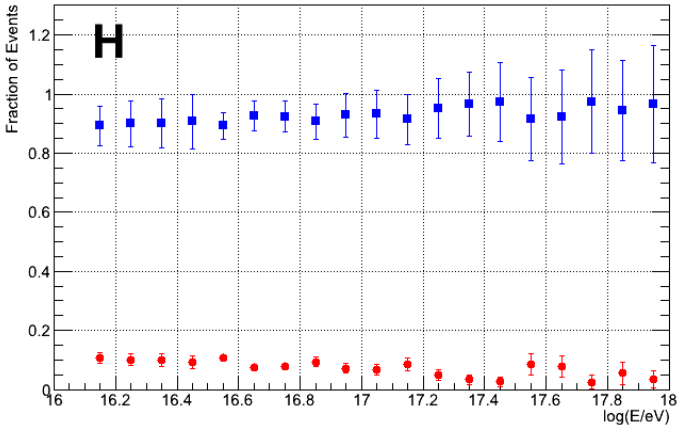
KASCADE & KASCADE-Grande - $N_\mu$ / $N_{ch}$ ratio

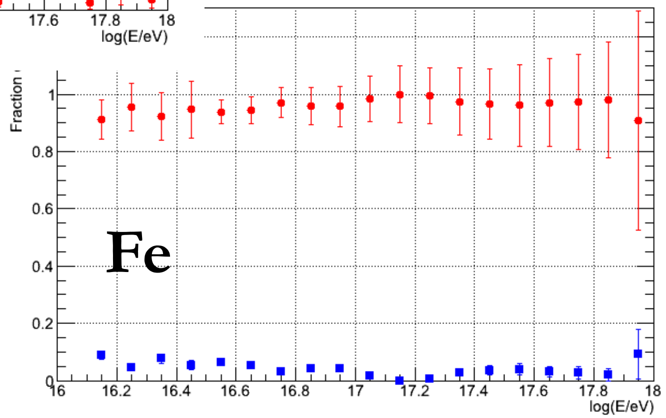
ARGO-YBJ + WFCTA- ldf + shower image

Different definition of contaminations from other mass groups

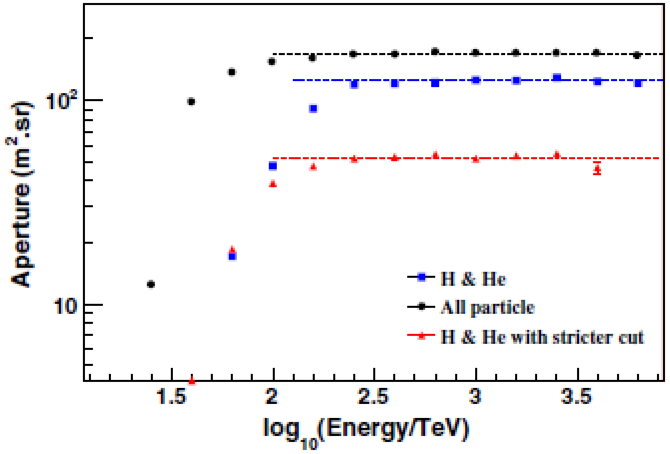
$E^{-3}$ spectra for each element

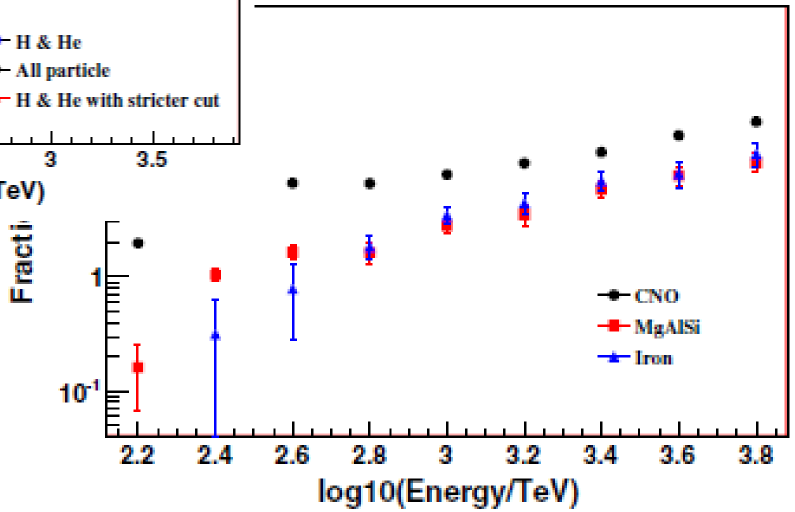
$$\varepsilon = \frac{N_i}{N_{elem}}$$



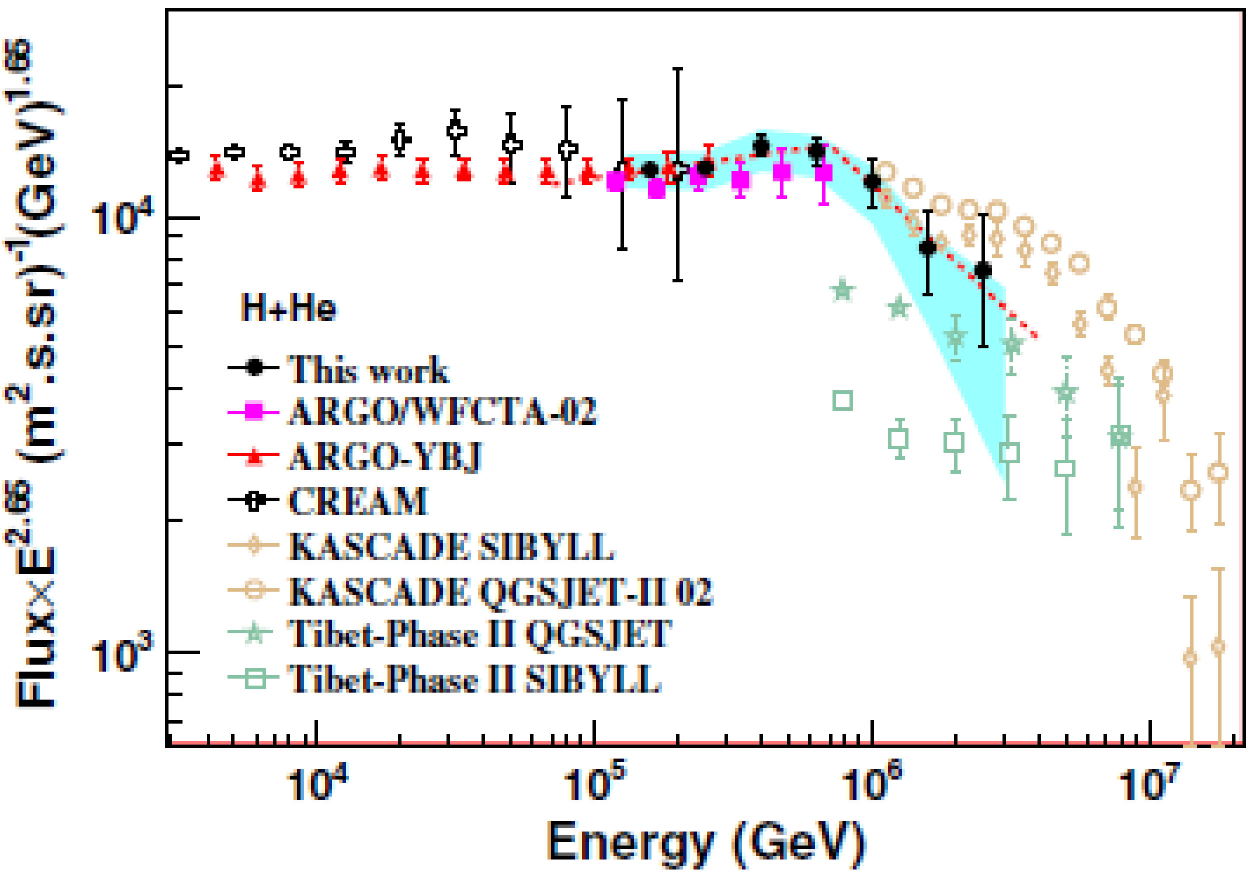




Events are sampled according to a composition model




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

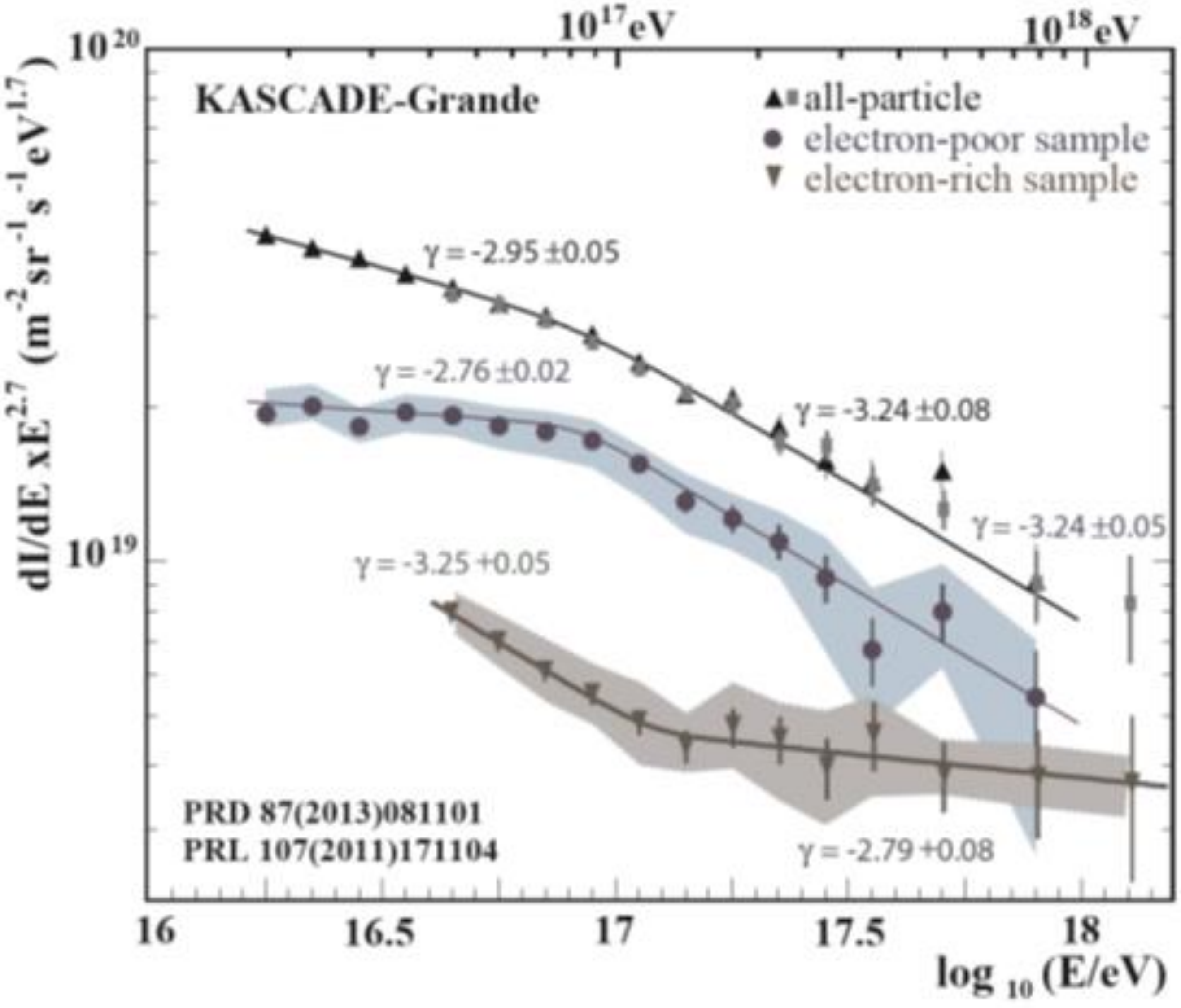



**H&He** spectrum measured by the ARGO-YBJ+WFCT hybrid experiment.

$E_k$=700 ± 230 ± 70 TeV

$\gamma_1$= -2.56 ± 0.05 $\gamma_2$ = -3.24 ± 0.36

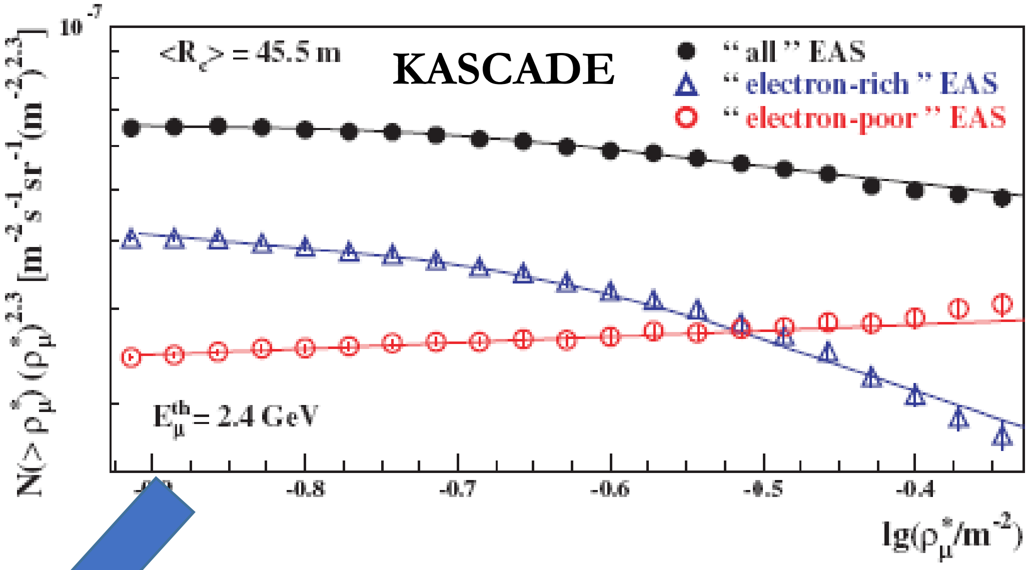
B. Bartoli et al., Phys. Rev. D **92**, 092005 (2015)

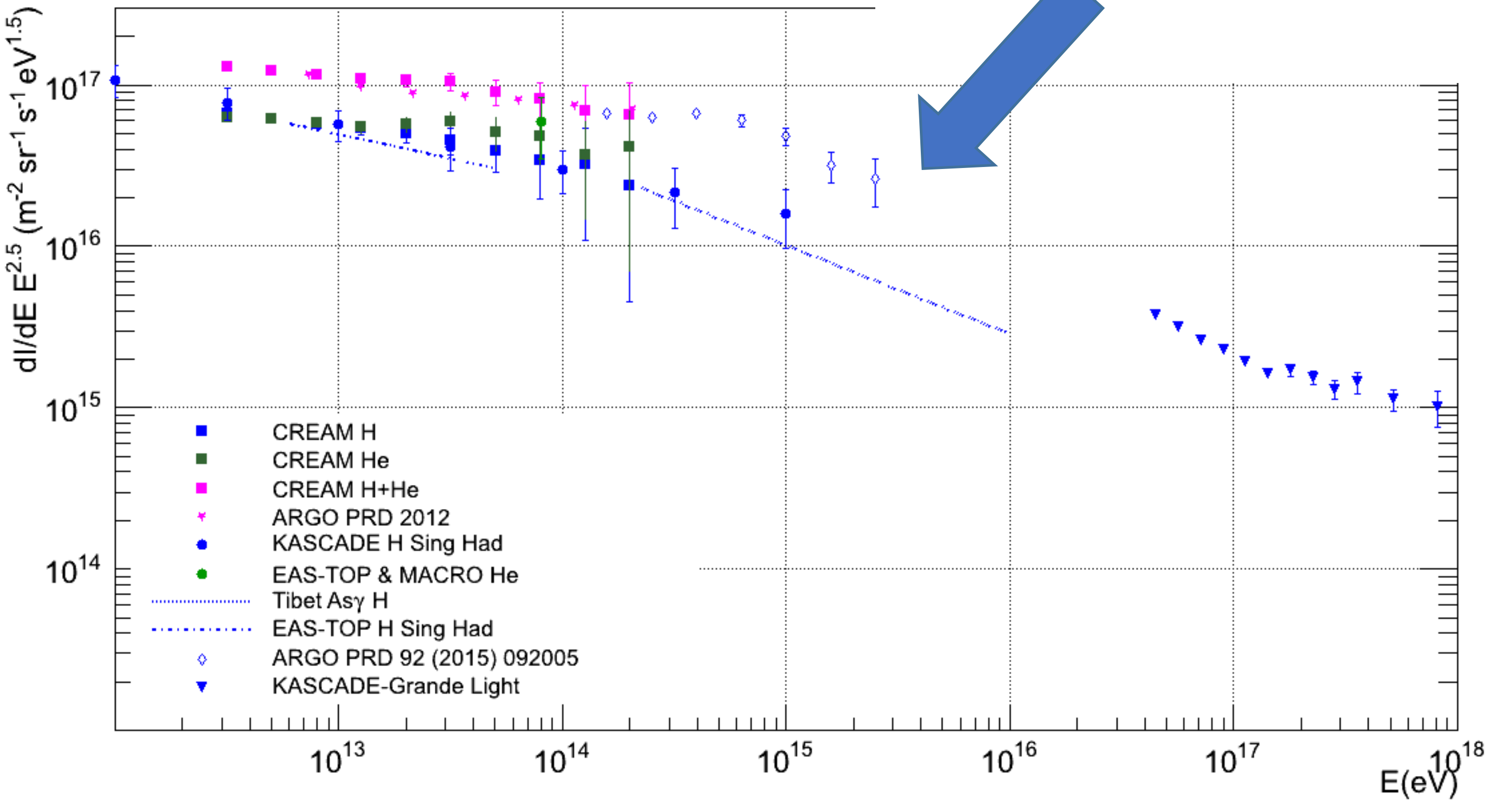



- **Steepening in the all partcile spectrum (2.1σ) near to $10^{17}$ eV**
- **Feature due to heavy component (3.5σ)**
- **Hardening of the light component at $10^{17.08}$ eV(5.8σ)**
- **Slope change from γ=3.25 to γ=2.79**

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

→ ~2-4x$10^{15}$ eV

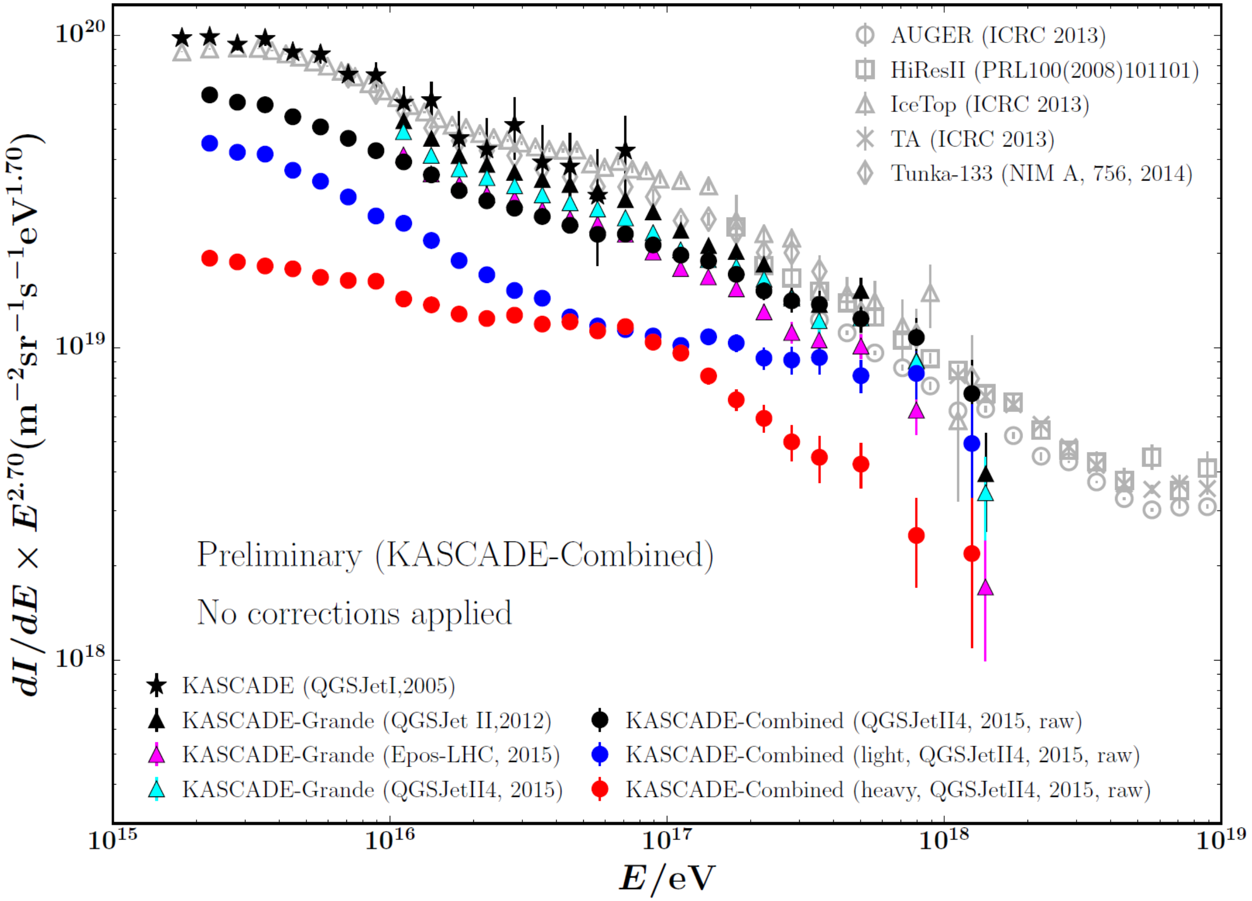


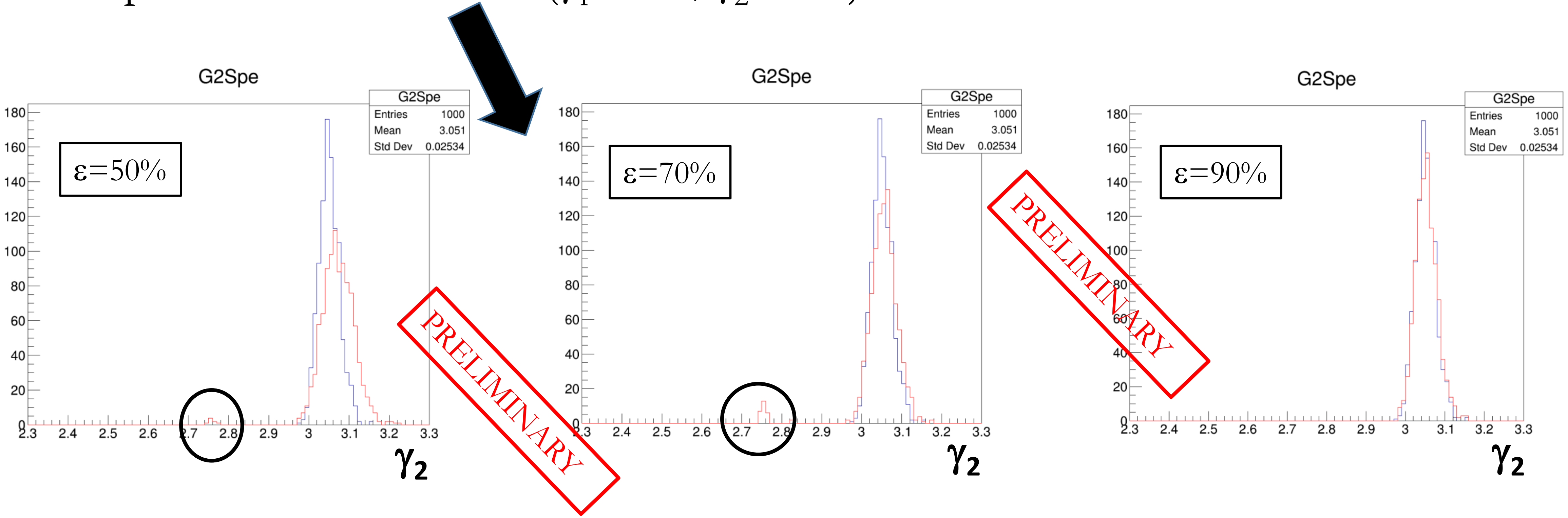
# Combined KASCADE & KASCADE-Grande analysis → one code to reconstruct events.

**All particle, light and heavy spectra measured over 3 orders of magnitude**

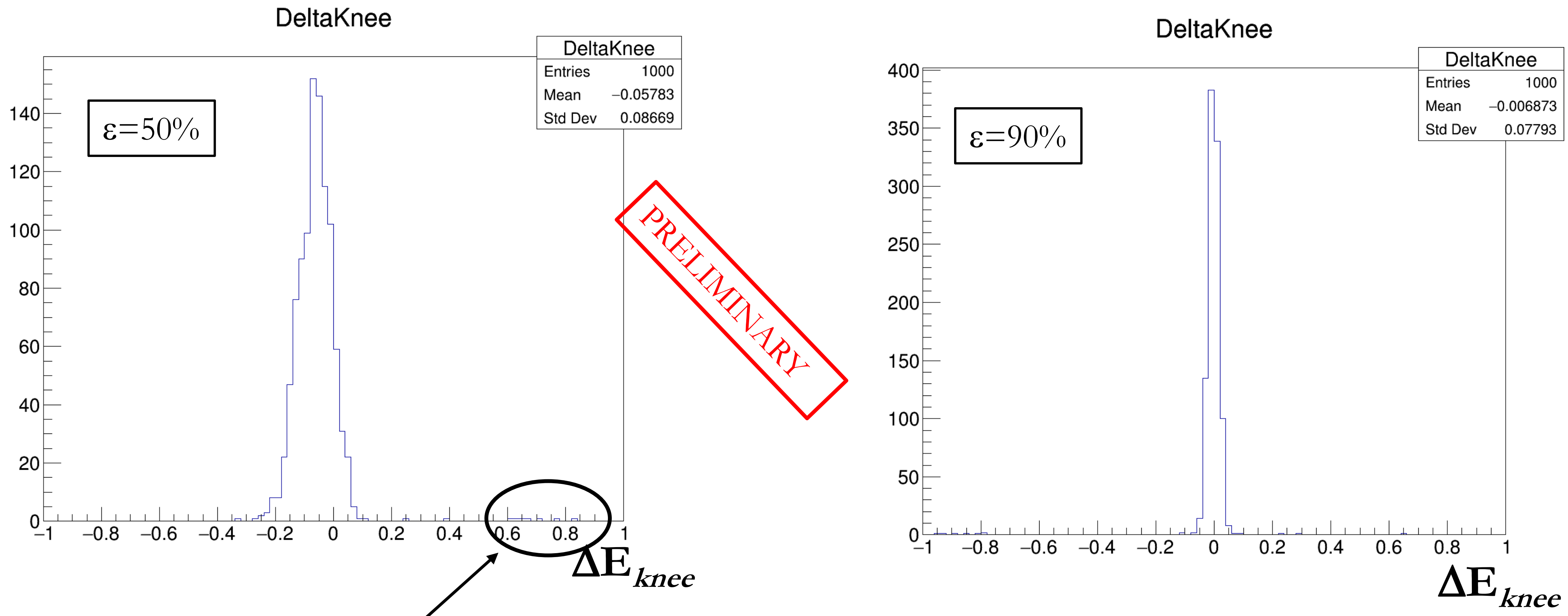
**Spectral features are confirmed**



- Toy Monte Carlo to investigate the effects of selecting a fraction of events on a power law spectra → can we artificially introduce spectral features?
- Generate events on a single slope power law or on a spectrum with a change of slope → select randomly a fraction of events → fit the output spectrum.
- Single power law → even with low efficiency (50%) → in 1000 samples ($10^6$ each, $E_{max}$ = 100 $E_{min}$) was never introduced a spectral feature
- Spectrum with a «knee» ($\gamma_1$=-2.7; $\gamma_2$=-3.0)



# Shift a of the knee position $\longrightarrow \Delta E_{knee} = \dfrac{E_{knee}^{true} - E_{knee}^{rec}}{E_{knee}^{true}}$




very rarely (~5‰) a 60-80% shift of the fitted knee energy can be introduced

# Conclusions

- Last generation experiments brought improvements to our knowledge of cosmic rays spectrum and composition below $10^{18}$ eV
  - Spectral features above the knee
  - Steepening of the light component spectrum ~4 PeV (and/or below?)
  - Steepening of the heavy component spectrum ~80 PeV
- The key points were
  - High resolution measurements of different EAS characteristics
  - Improvments in the EAS simulation
- Careful studies of the systematics are mandatory. Both the experimental ones and those due to the analysis strategies.
  - Statistical approaches
    - Give an estimation of how far from the best fit values are different scenarios?
  - Event by event classification
    - Always show the mass groups selection efficiency, and its energy dependence
- Further improvments requires:
  - Spectra of individual mass groups (elements??). Main limitation will come from EAS development fluctuations.
  - High statistics ($km^2$) + high resolution + large dynamic range experiments