Cosmic rays around the knee: status and open problems

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Energy spectrum and mass composition around and above the knee

- 4 dedicated sessions
  - 22 oral presentations
  - 28 posters
- Very rich panorama from Direct Measurements to EAS experiments.
- New results
- Open problems
- Systematics of Energy and Mass (EAS experiments) calibration

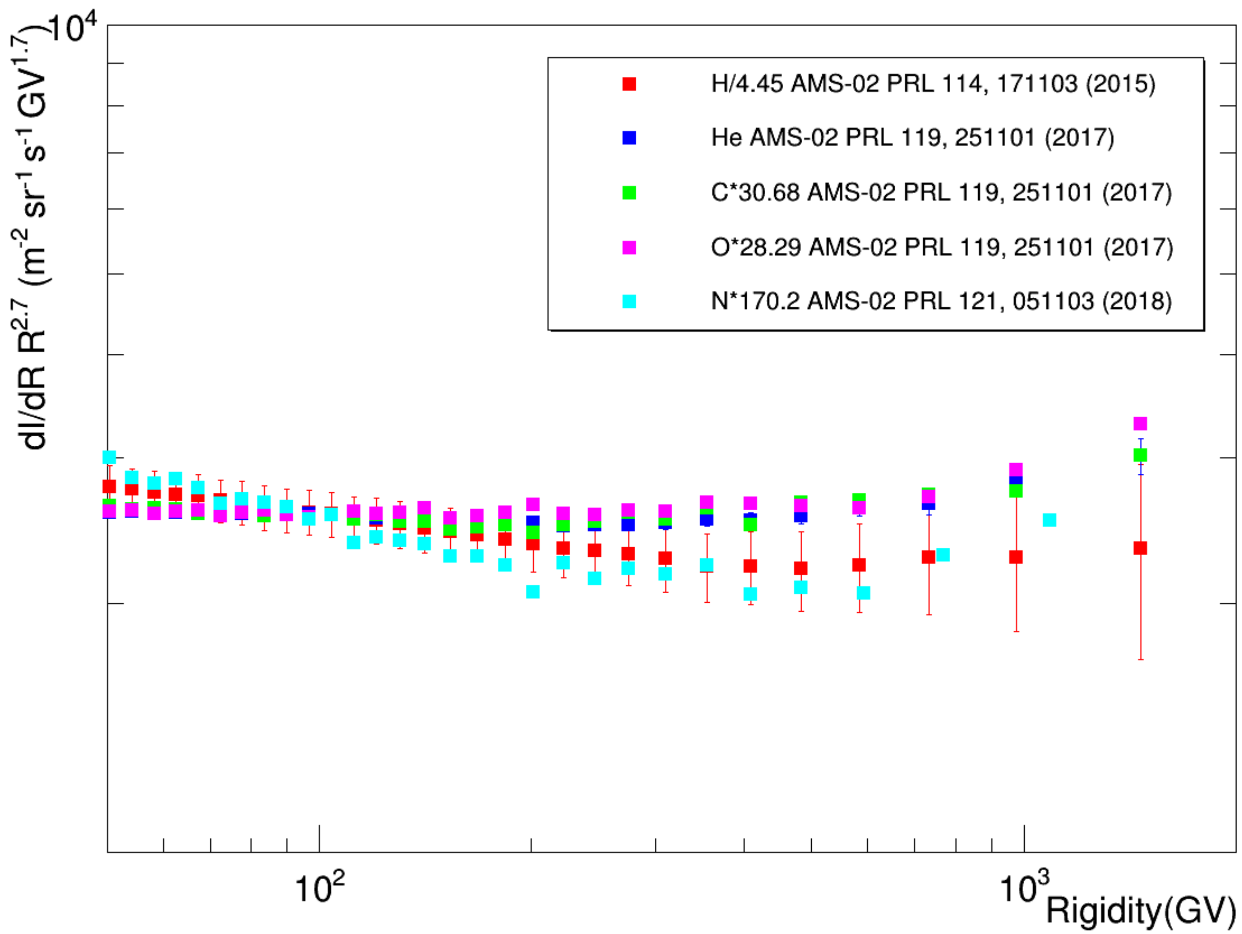
- Apologize for the results that I will not show or mention

Approaching the knee from lower energies: Direct Measurements and High Altitude EAS Experiments

- Direct measurements
  - Spectrometer (PAMELA, AMS-02)
  - Calorimeter (CALET, ATIC)
  - KLEM (NUCLEON)
- High statistics and high resolution experiments.
- Energy calibration → test beam
- $\sigma_Z < 1$
- Limited by:
  - Statistics
  - Mass of the experiment

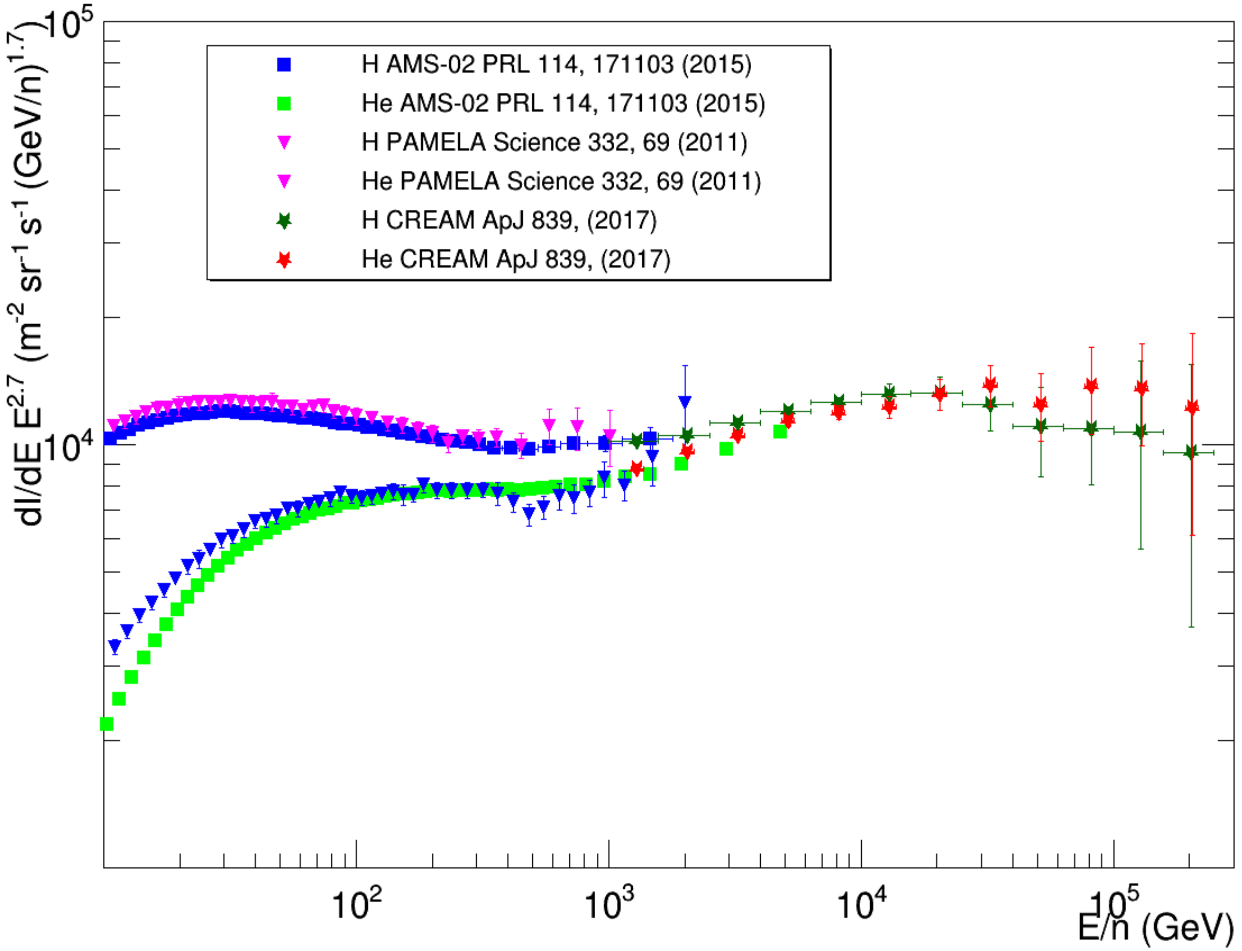
Elemental spectra

- Hardening at R≈200-300GV
- In the figure AMS-02 spectra are normalized at ≈100 GV



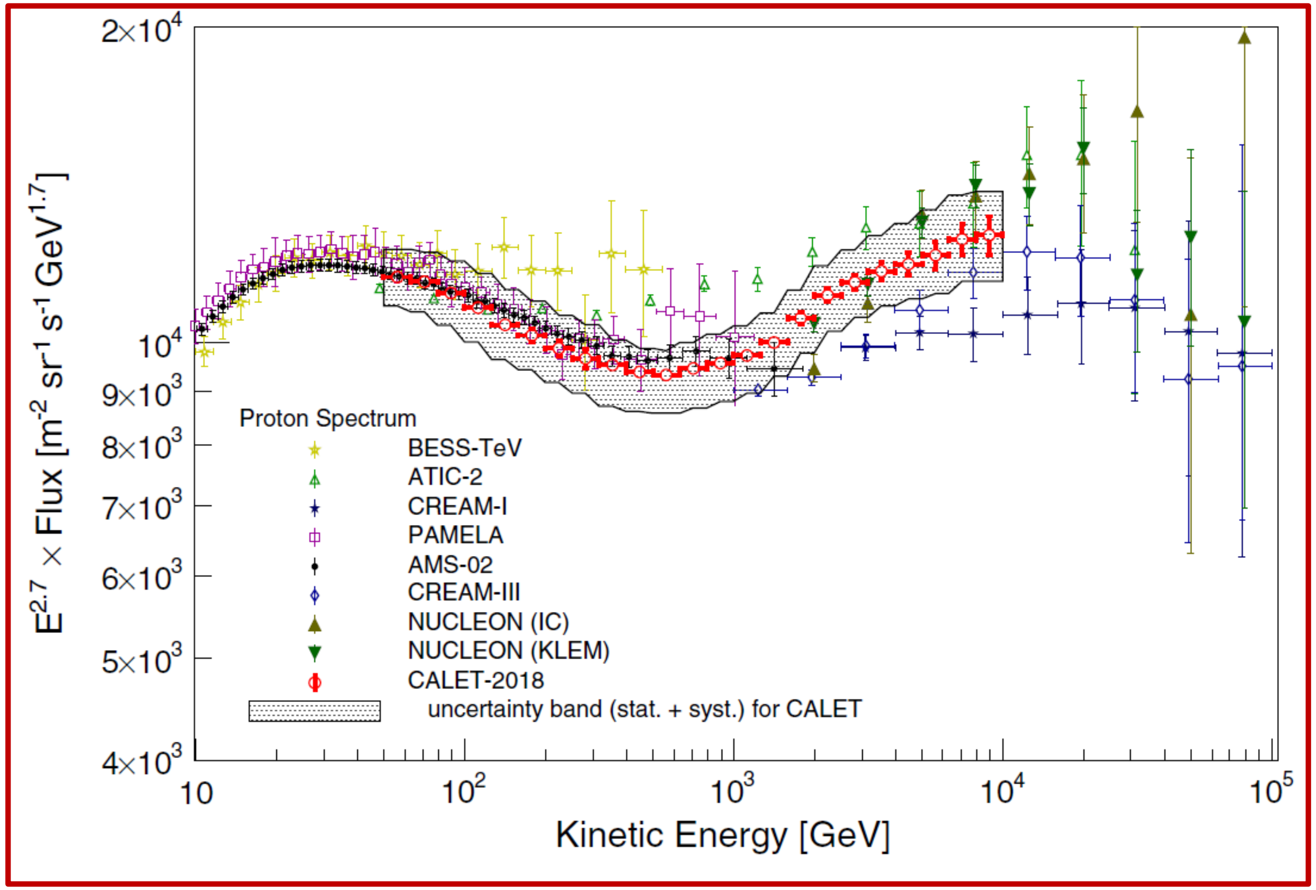
Elemental spectra

- H spectrum steeper than other elements



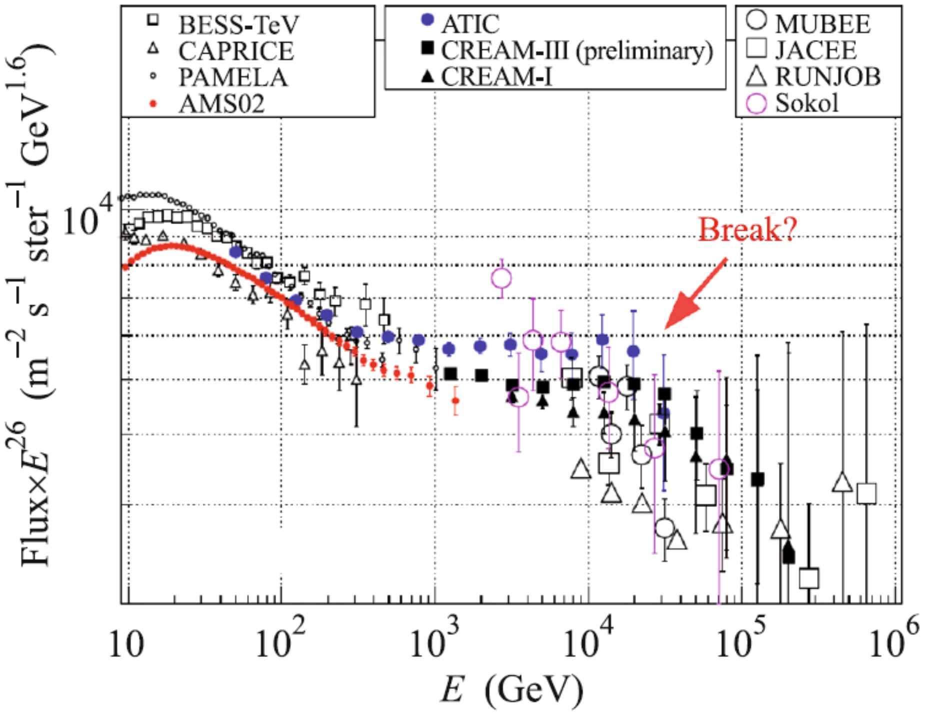
Proton spectrum

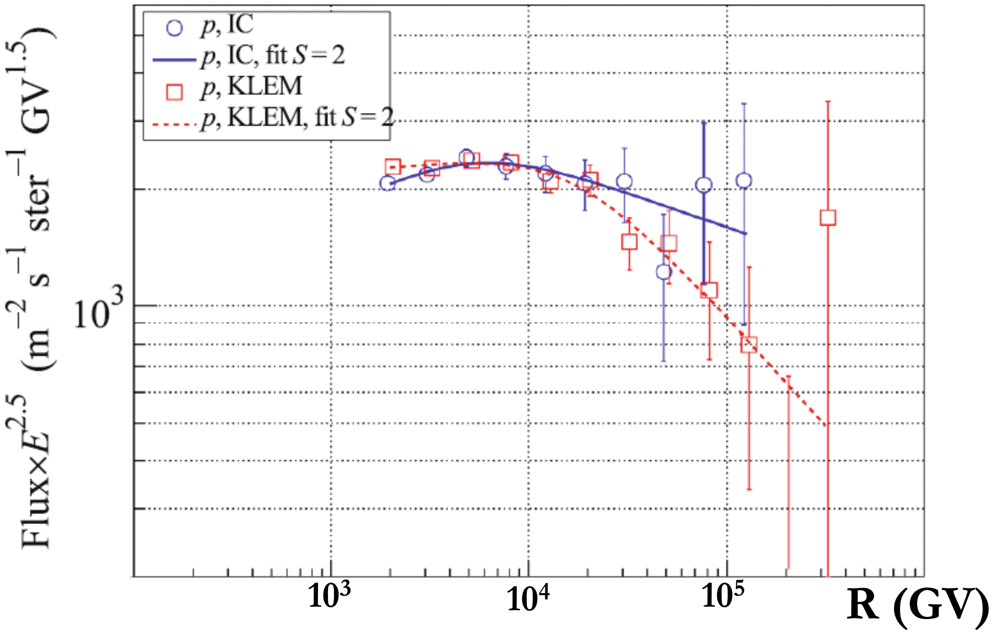
	Δγ	Hardening
AMS-02	0.133±0.032±0.046	R=336±66±68 GV
CALET	0.25±0.04	E=486±175 GeV
PAMELA	0.18±0.05	R=232+35-30 GV



PRL 122, 181102 (2019)

Proton spectrum



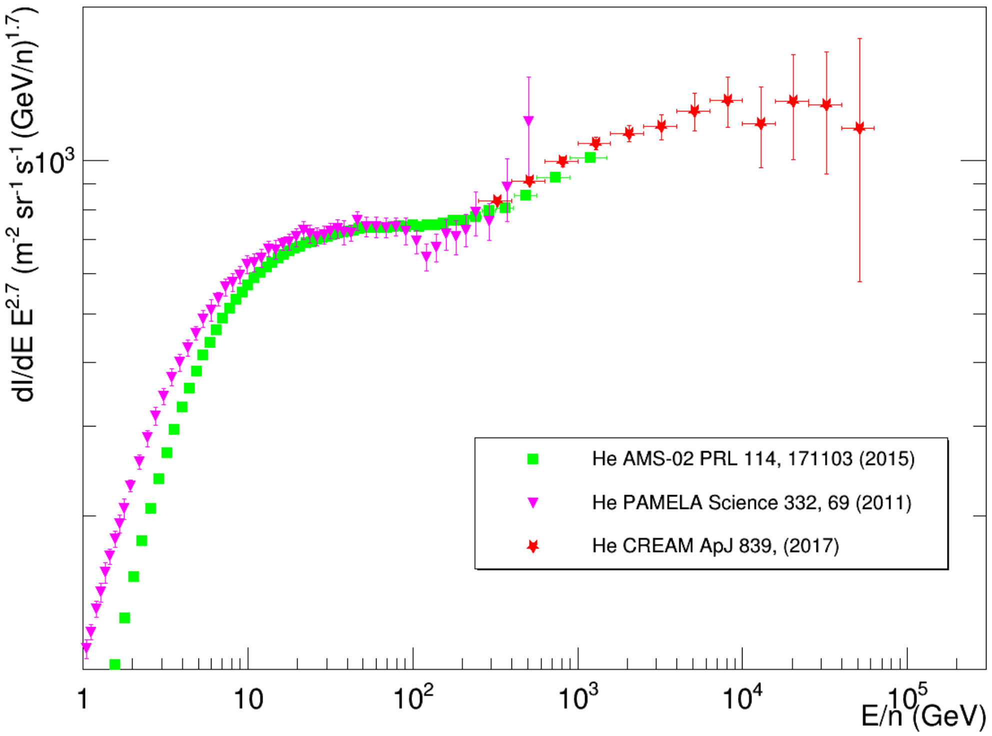


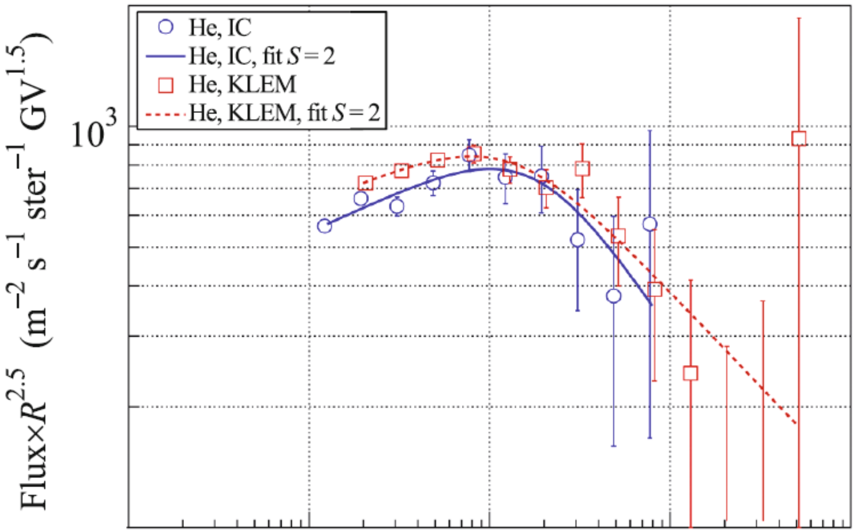
JETP Letters 108, 5 (2018)

Indication of a break in the proton spectrum above 10 TeV
NUCLEON data:
$\Delta\gamma$ = 0.44 R* (TV) = 5.45 (IC)
$\Delta\gamma$ = 0.61 R* (TV) = 17.05 (KLEM)

He spectra

	Δγ	Hardening
AMS-02	0.119±0.013±0.032	R=245±35±33 GV
PAMELA	0.19±0.06	R=243+27-31 GV





Break above 10 TeV in the NUCLEON data:

Δγ = 0.89 R* (TV) = 18.18 (IC)

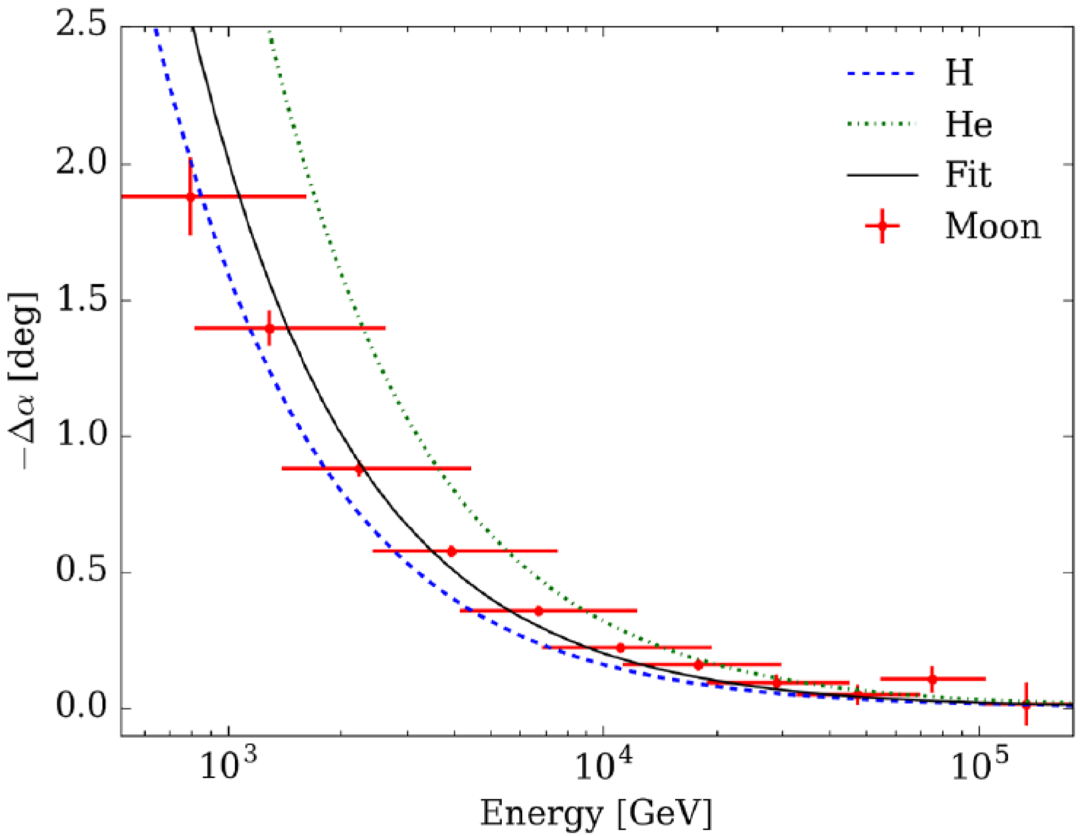
Δγ = 0.65 R* (TV) = 12.90 (KLEM)

EAS experiments

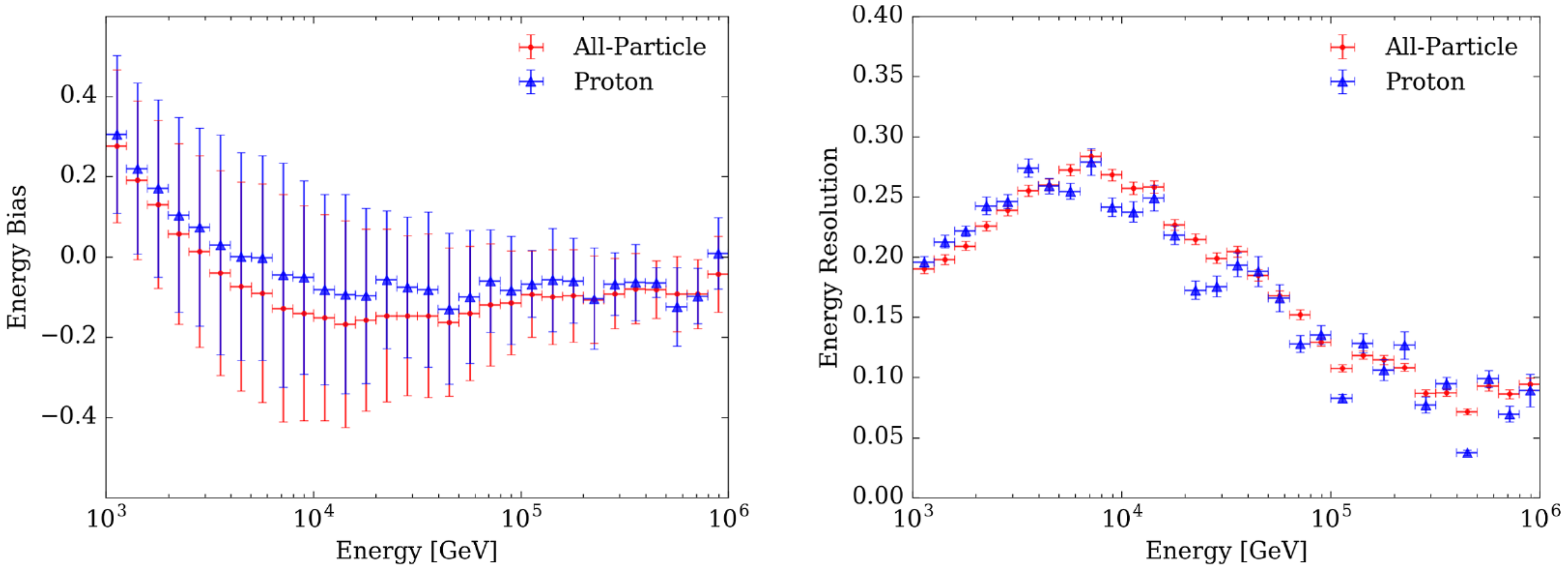
- EAS experiments (surface arrays) energy calibration requires full EAS and detector simulation
- Experimental observable: number of particle at observation level (either total or at fixed distance from the core)
- Limited resolution on the charge of the primary particle
  - $X_{max} - N_{\mu}$
  - $\sigma_Z >> 1$
- Calibration function depends on
  - Hadronic interaction model
  - Mass of the primary particle
- EAS radio emission measurements.

Overlap between direct and EAS experiments

- 1<E<100 TeV → High statistics → measure of the displacement of the moon shadow as a function of the energy
- HAWC → expected deflection:
  - $\delta\omega \approx 1.59° \, Z(\frac{E}{TeV})^{-1}$
- $<Z_{MC}>=1.23\pm0.02$
- From measured deflection:
  - $<Z>= 1.25\pm0.06$



Overlap between direct and EAS experiments



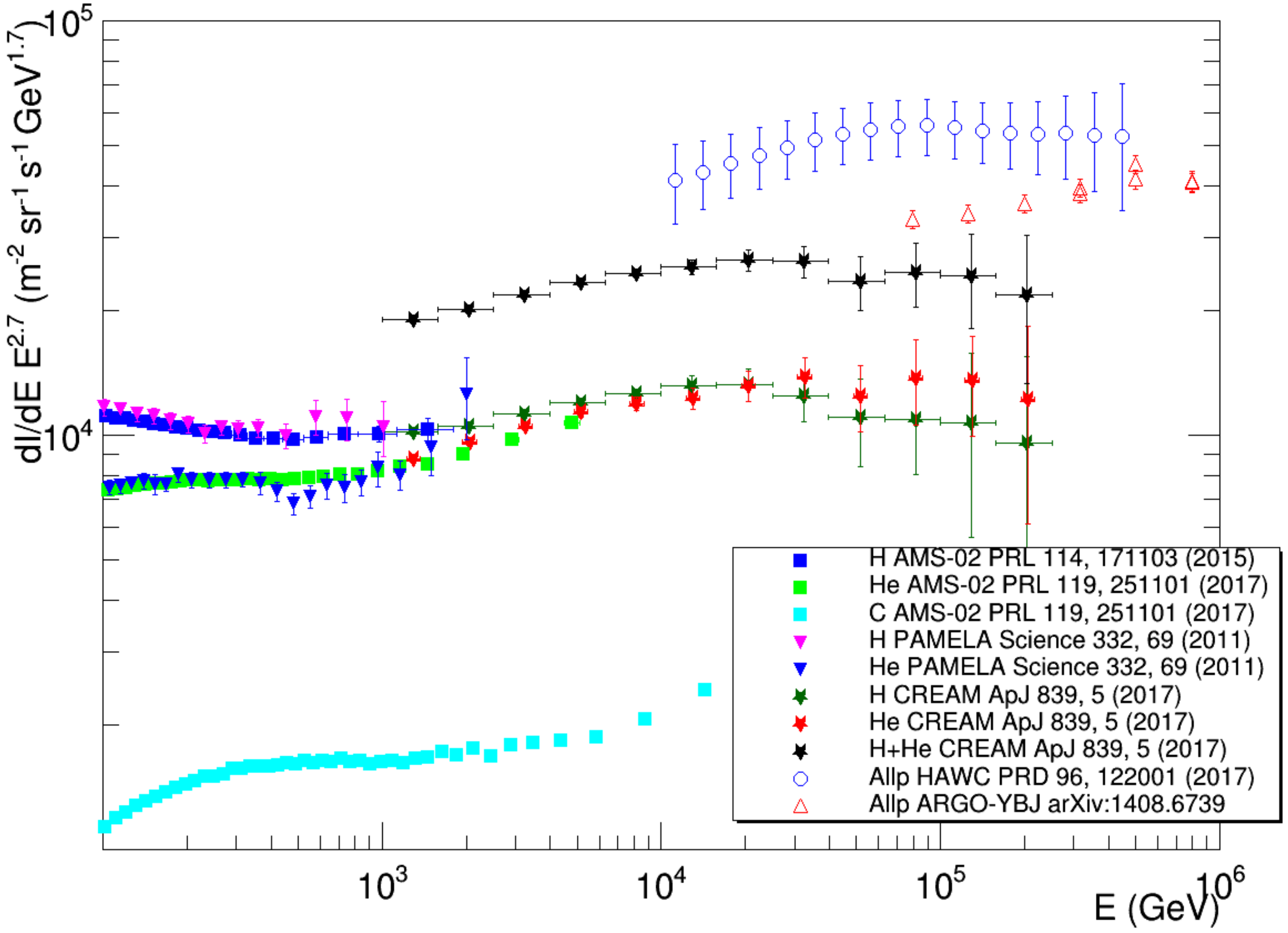
PRD **96**, 122001 (2017)

- HAWC
- Systematic errors: -20%/+12% (10 TeV); -14%/15% (100 TeV); -20%/+13% (1 PeV)

Overlap between direct and EAS experiments

ARGO-YBJ, HAWC and the sum of the H and He spectra measured by CREAM agree inside the systematic errors.

HAWC
Broken power law spectrum
γ_1=-2.49±0.01
γ_2=-2.71±0.01
E_b= 45.7±0.1 TeV

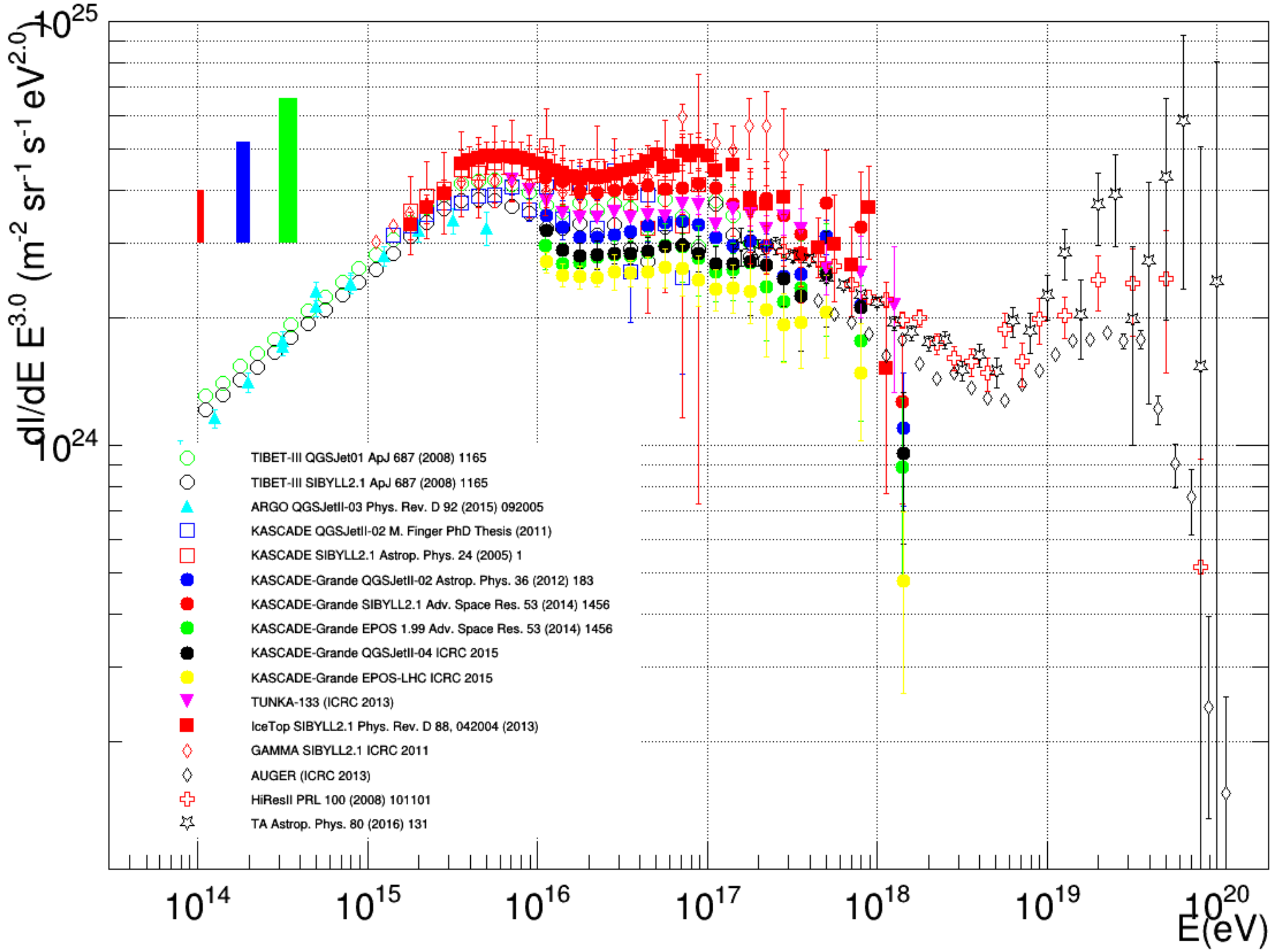


Knee energies

- At these energies no possibilities to check the absolute energy scale.
- Possibility from radio EAS detection (TUNKA-133 and KASCADE-Grande energy scale compared through the TUNKA-Rex and LOPES radio detectors) → The two energy scales show a systematic difference <10%.
- Absolute energy scale of EAS experiments can differ by a larger value.
- Above the knee the spectrum cannot be described by a single slope power law.

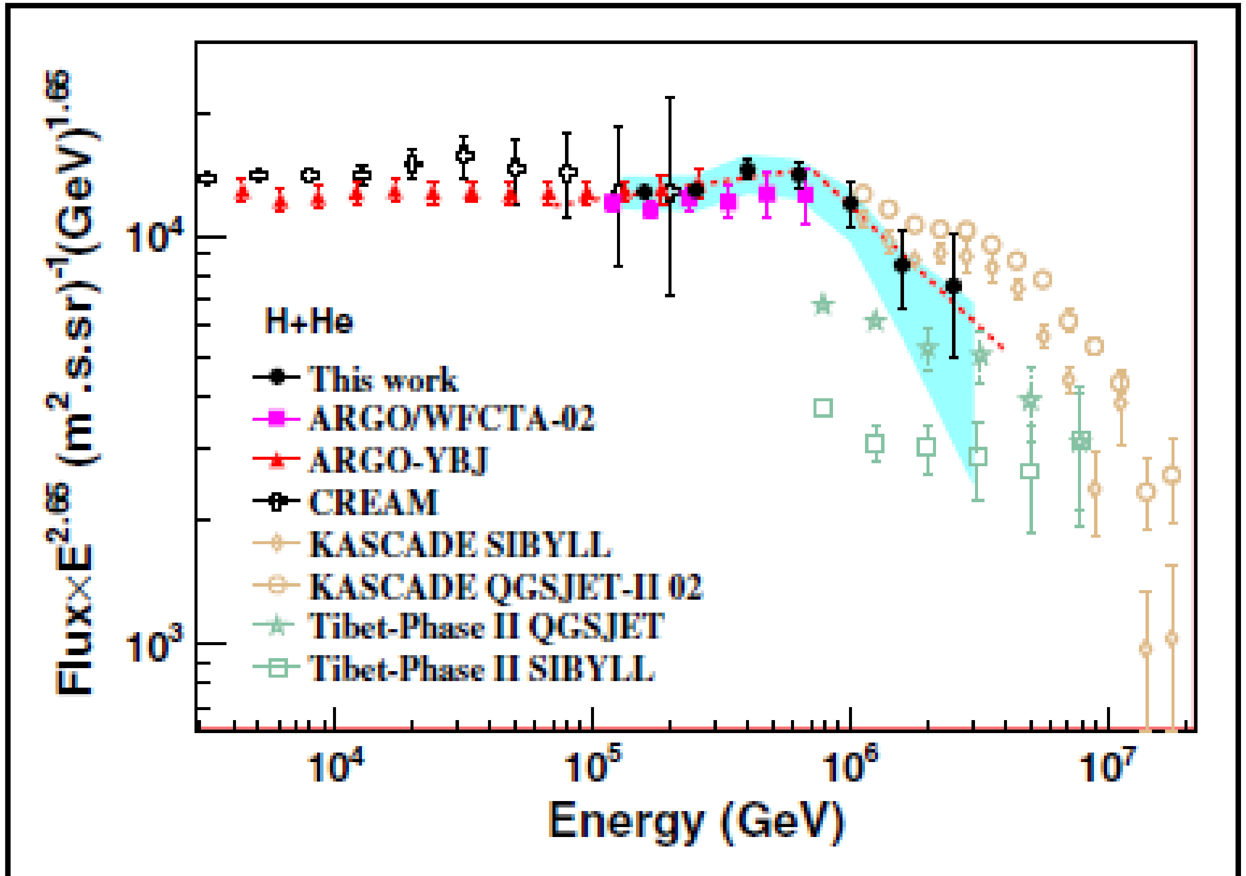
	γ_{knee}	γ_{hard}	γ_{step}	E_{hard} (PeV)	E_{step} (PeV)
Ice Top	3.14±0.03	2.90±0.03	3.37±0.08	18±2	130±30
KASCADE-Grande	-	2.95±0.05	3.24±0.08	-	83±10
TUNKA	3.28±0.01	2.99±0.01	3.22±0.08	-	-
TALE	3.12±0.007	2.92±0.008	3.19±0.017	16.6±0.1	109±8

Primary Spectra Measurements



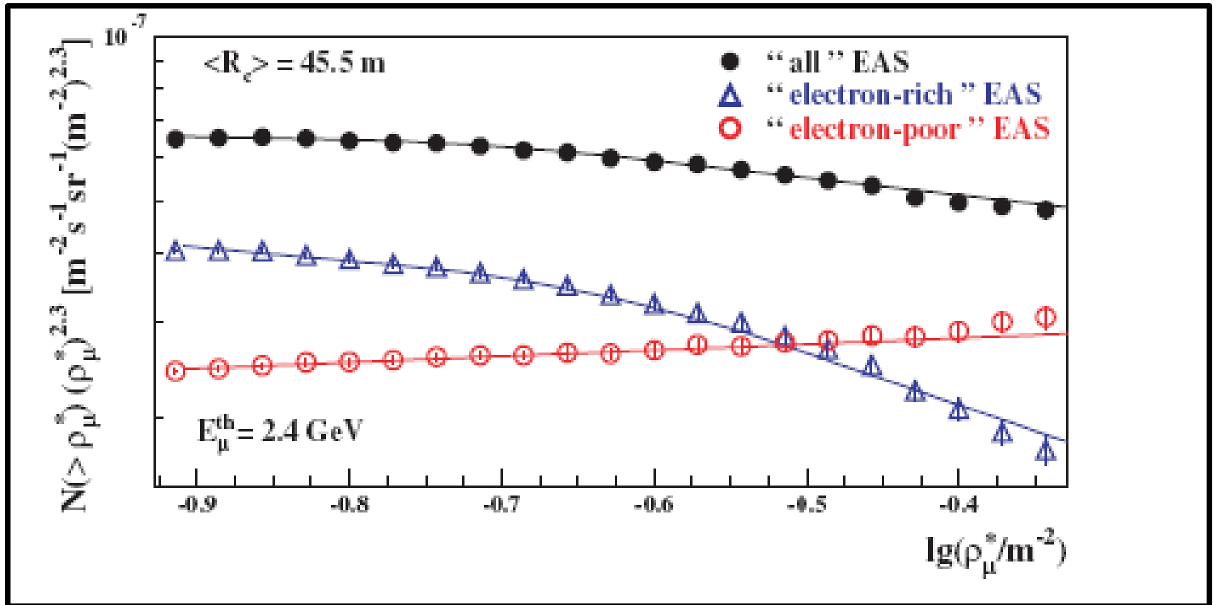
- Differences, in this plot, due to energy calibrations.
  - **10% E error**
  - **20% E error**
  - **30% E error**
- Better agreement if we compare data calibrated with the same hadronic interaction model.
- Spectral shapes agree

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



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)



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

Astroparticle Physics **16** (2002) 373

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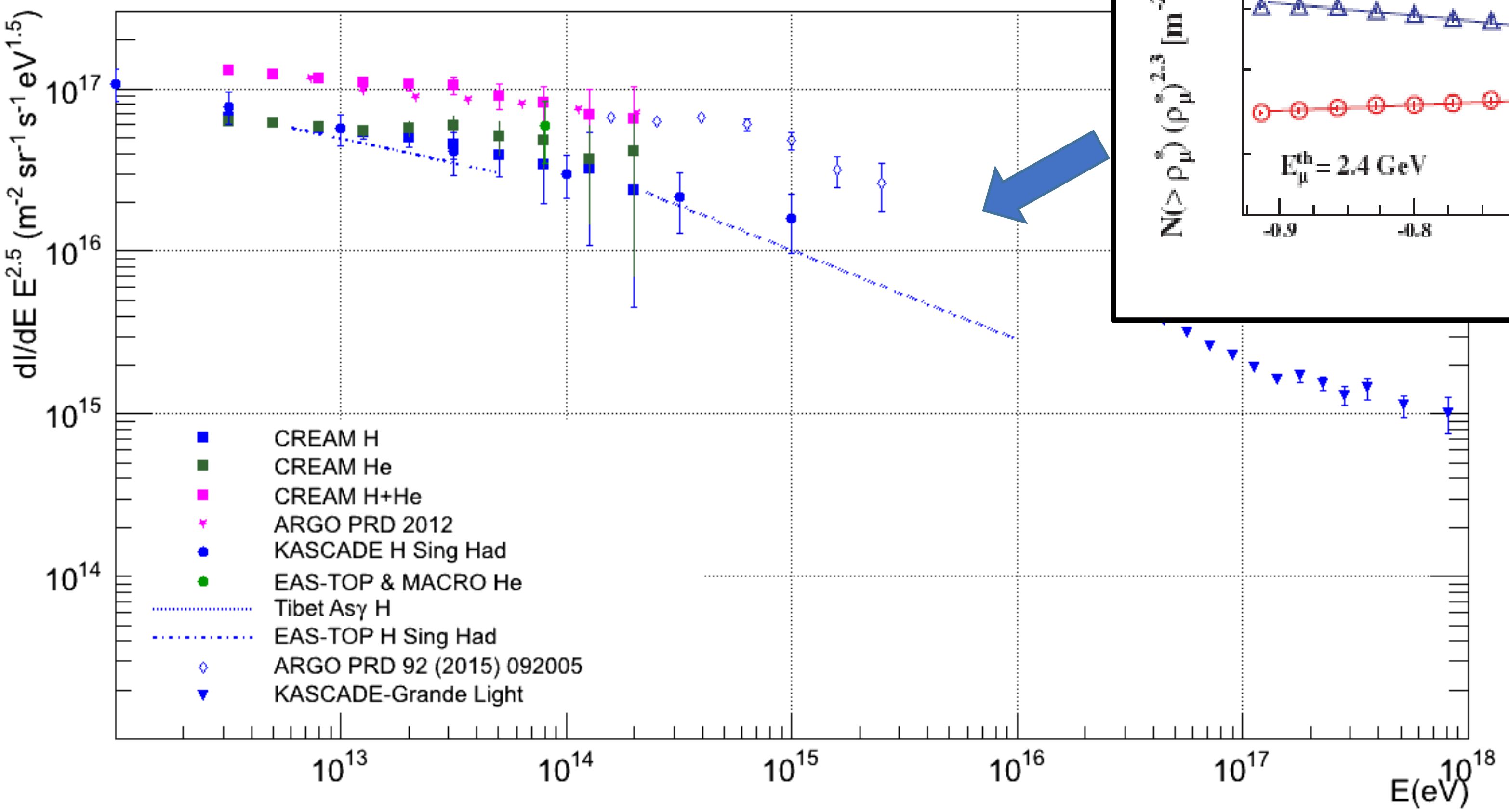

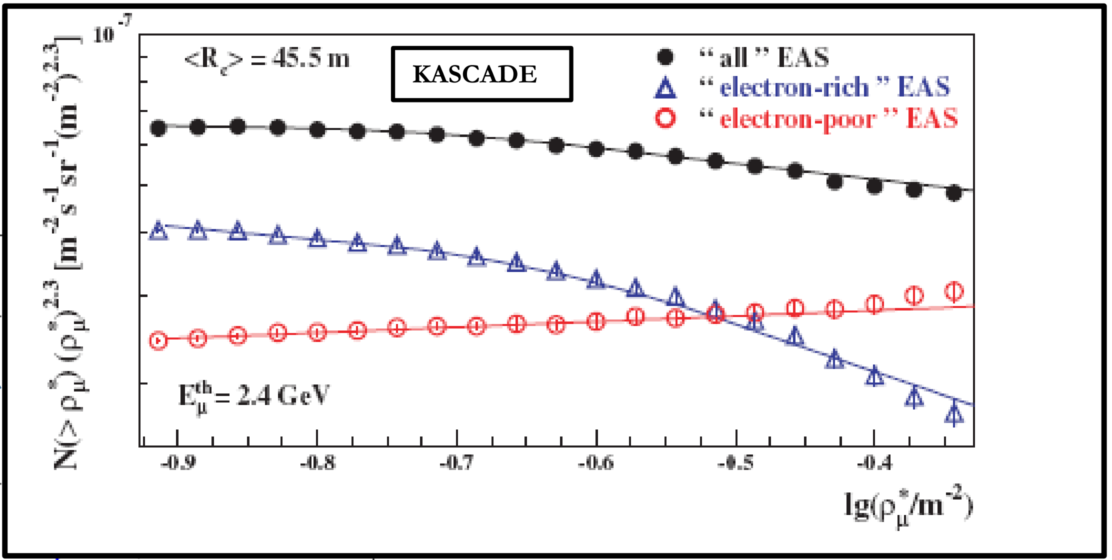

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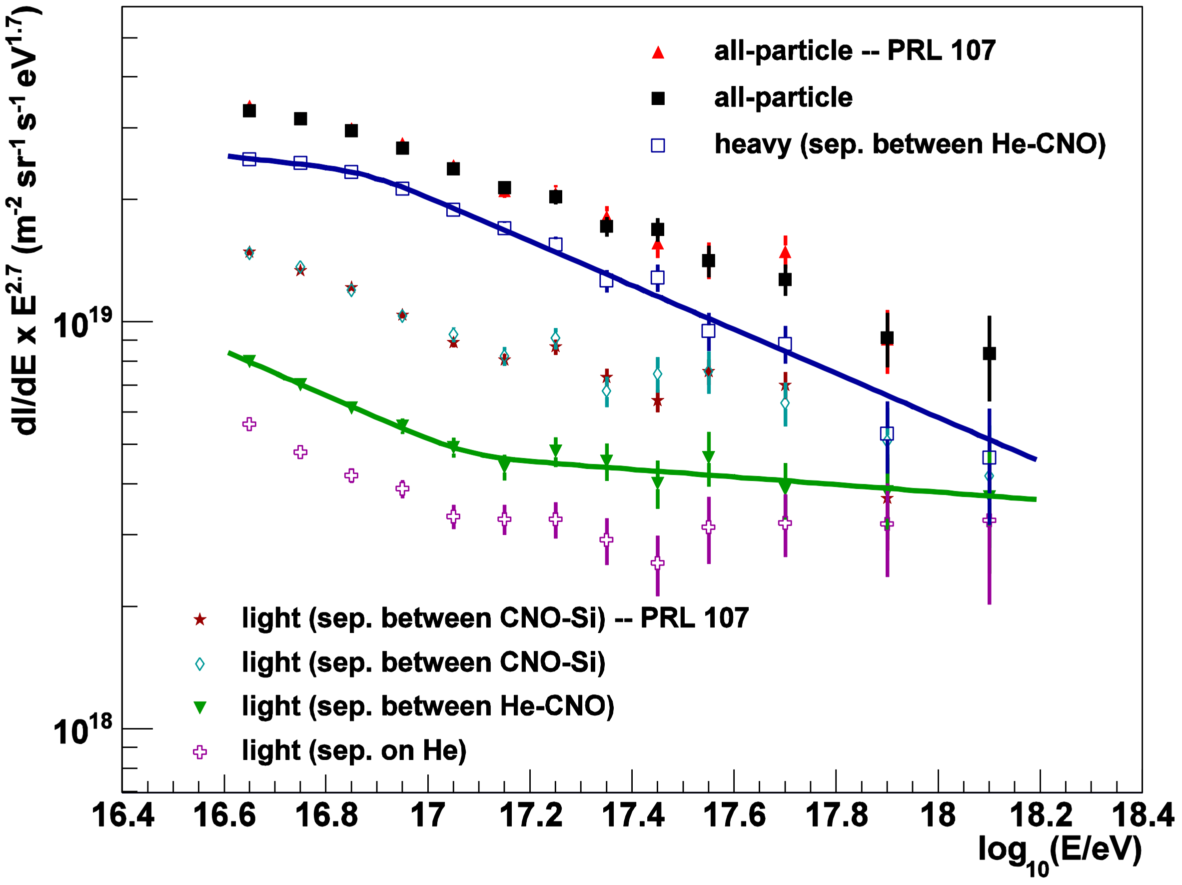


$\gamma_1 = -3.25 \pm 0.05$
$\gamma_2 = -2.79 \pm 0.08$

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

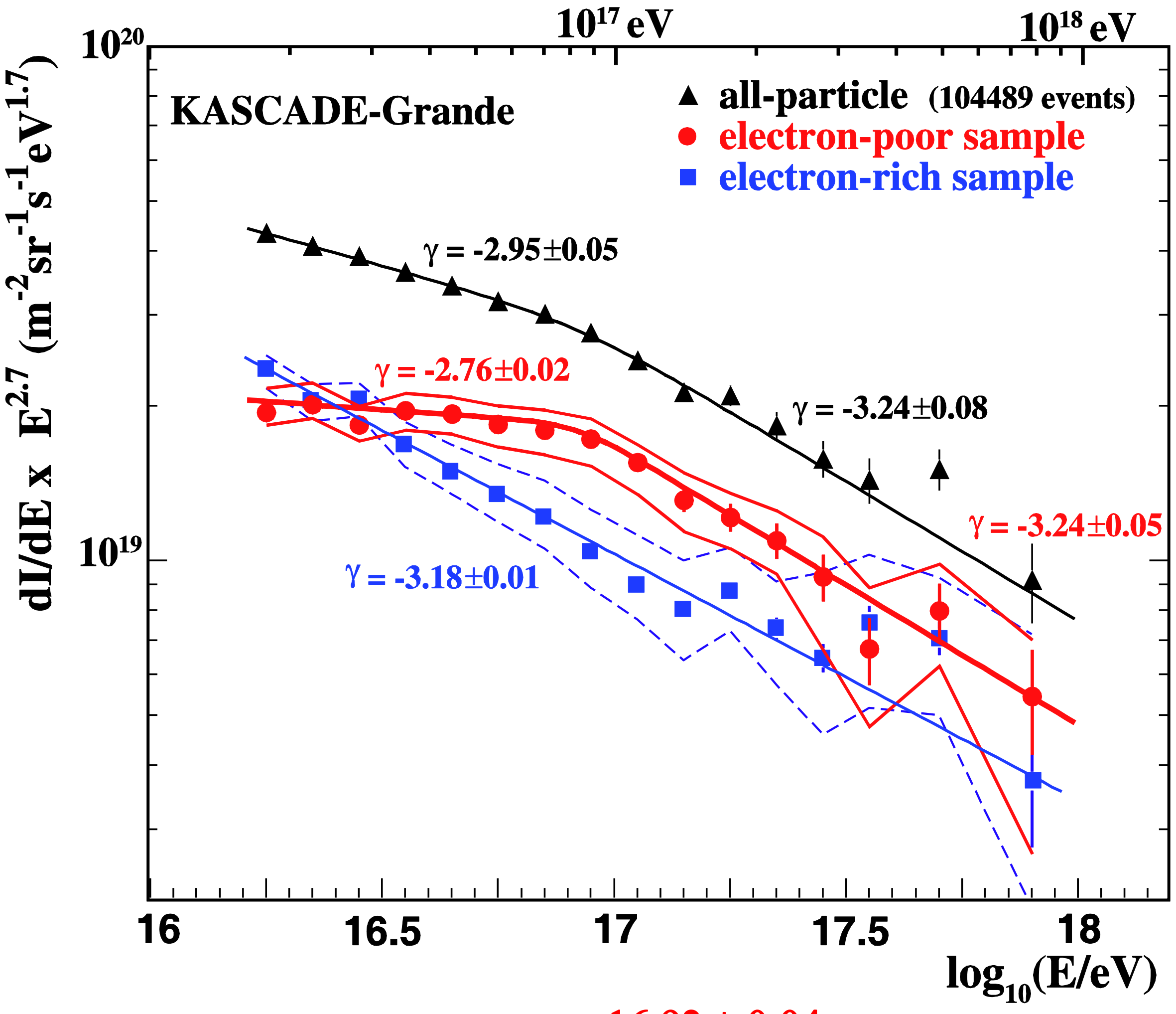
$N_{meas} = 579$
$N_{exp} = 467$

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

5.8σ significance

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

Measurements of the heavy component spectrum (i.e. mainly iron)



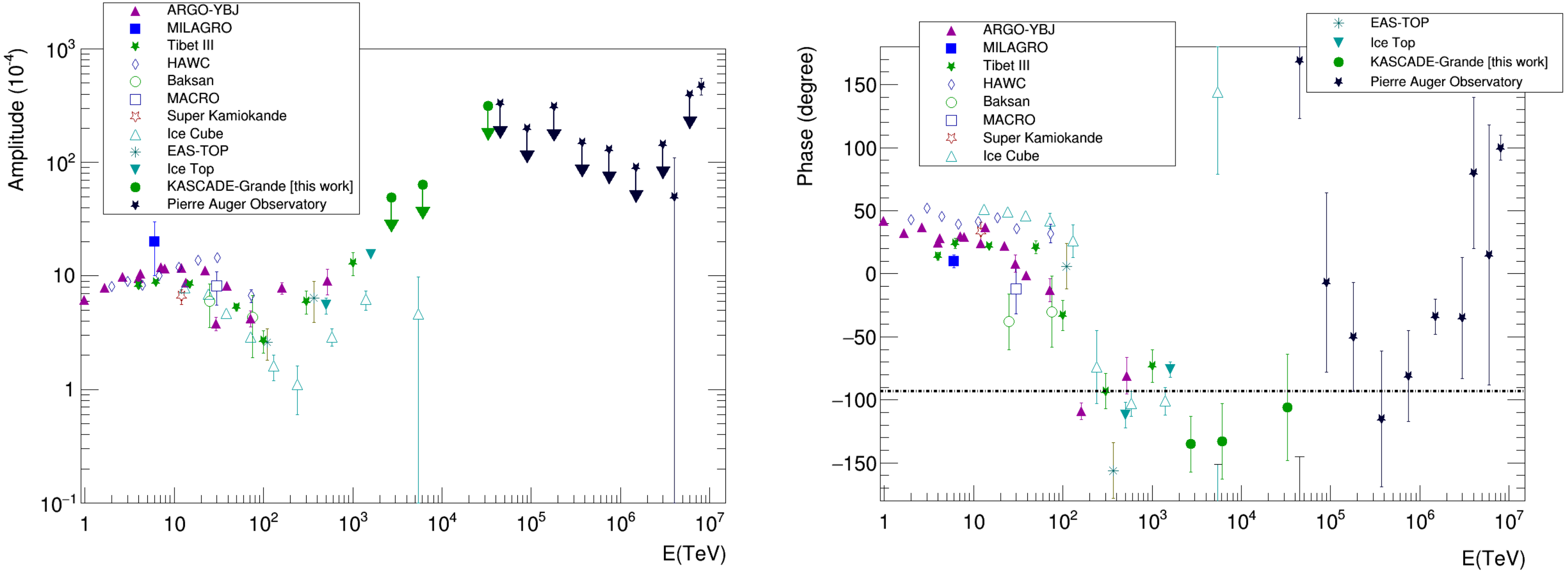
$\gamma_1 = -2.76 \pm 0.02 \quad E_b = 10^{16.92 \pm 0.04}$ eV

$\gamma_2 = -3.24 \pm 0.05$

- 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

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

Large Scale Anisotropies



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

No measurements of the LSA for different mass groups

What we have learned

1. H spectrum steeper than other elements
2. Hardening of elemental spectra at 200-300 GV
3. Knee due to light component
4. Steepening of the heavy component spectrum around 10^{17} eV
5. Hardening of the light component spectrum slightly above 10^{17} eV
6. Very small anisotropies
7. Hints of an increasing amplitude and of a change of the phase

What we still don't know

1. Extend direct measurements to higher energies
2. 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?
3. EAS development is not completely understood
    1. Absolute energy calibration?
    2. μ excess?
4. Anisotropy behaviour above the knee
5. Anisotropy measurements for different mass groups