PIERRE AUGER OBSERVATORY

Mass composition of cosmic rays with energies from $10^{17.2}$ eV to 10^{20} eV using surface and fluorescence detectors of the Pierre Auger Observatory

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Pierre Auger Observatory

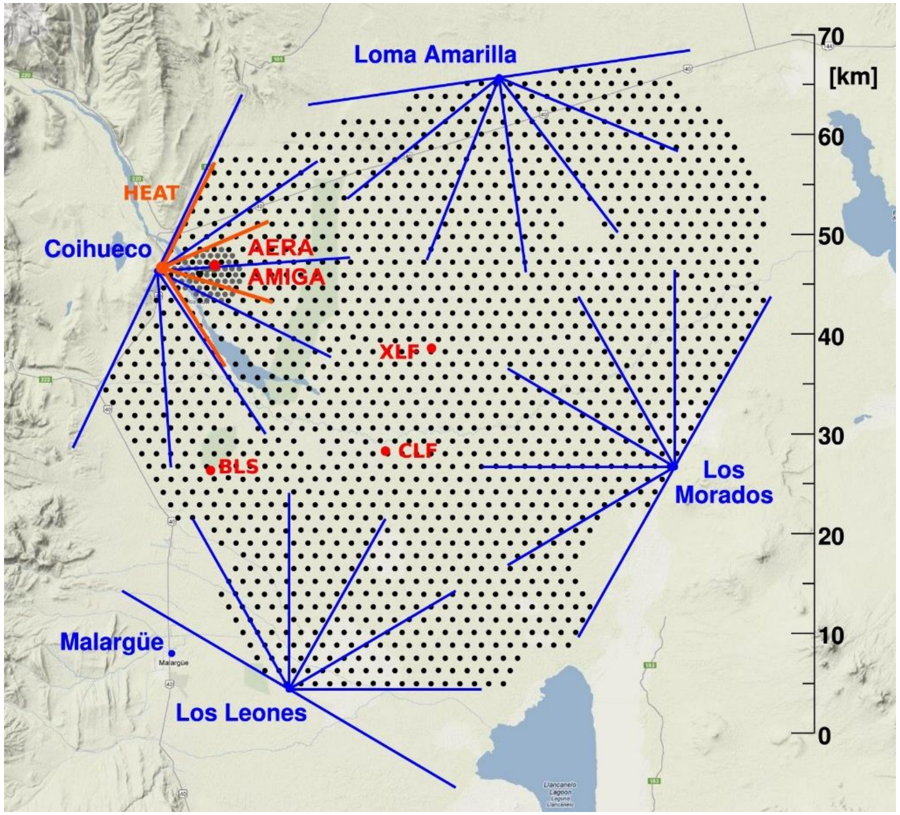
SD: 1600 water-Cherenkov stations, 1500 m separation, 3000 km^2 area

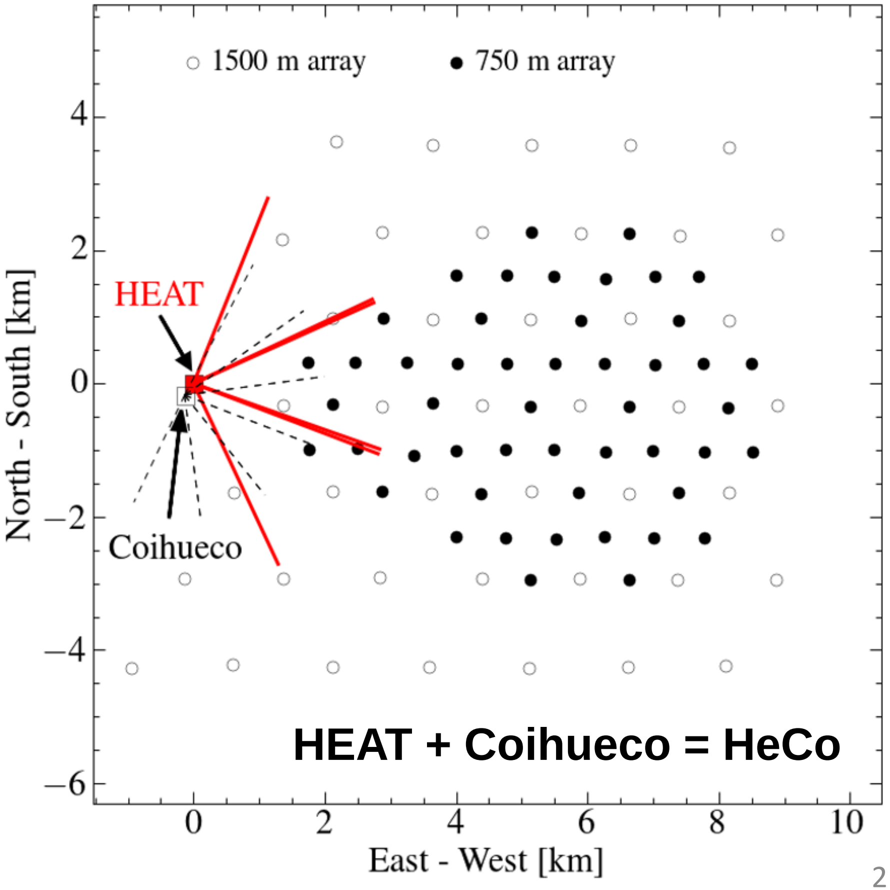
FD: 24 fluorescence telescopes at 4 locations

Low energy upgrade

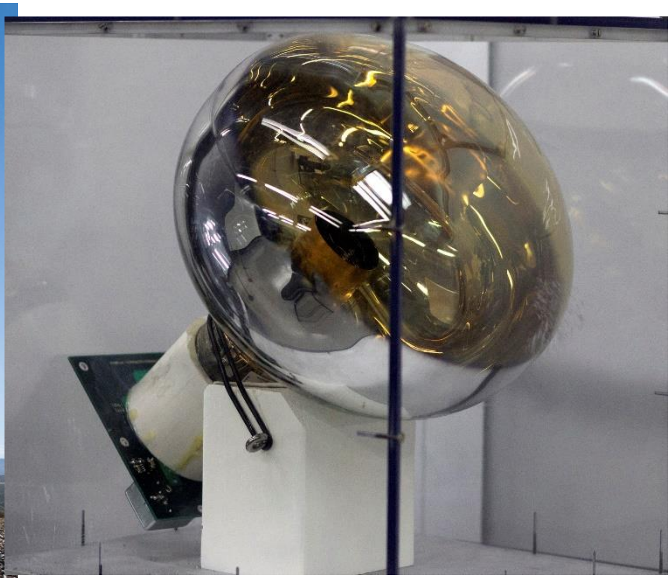
SD (750 m): 61 water-Cherenkov stations, 750 m separation, 23.5 km^2 area

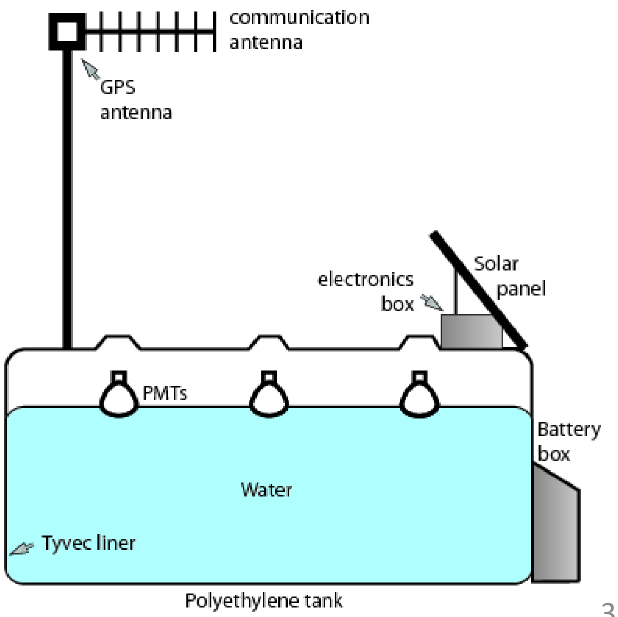
FD (HEAT): 3 fluorescence telescopes close to Coihueco FD location





SD water-Cherenkov stations





Each station filled with 12 tonnes of deionized water

Passing charged particles produce Cherenkov light, detected by 3x(9" PMTs)

Operational nearly 100% of the time

750 m array reduces lower energy limit from $10^{18.5}$ eV to $10^{17.5}$ eV

FD telescopes

Standard-FD

FOV 0° to 30° elevation
Low energy limit: $10^{17.8}$ eV

HEAT (in up position)

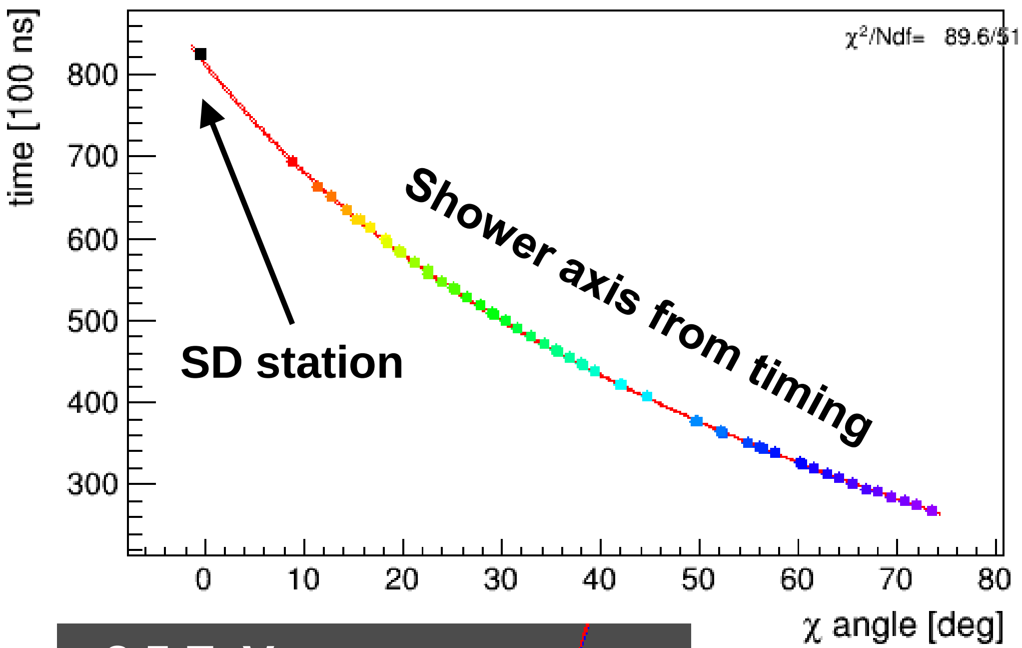
FOV 30° to 60° elevation
Energy range: $10^{17.2}$ eV – $10^{18.1}$ eV

Measurement of fluorescent light (N deexcitation, 300-450 nm)

440 PMT pixel camera (1.5° per pixel)

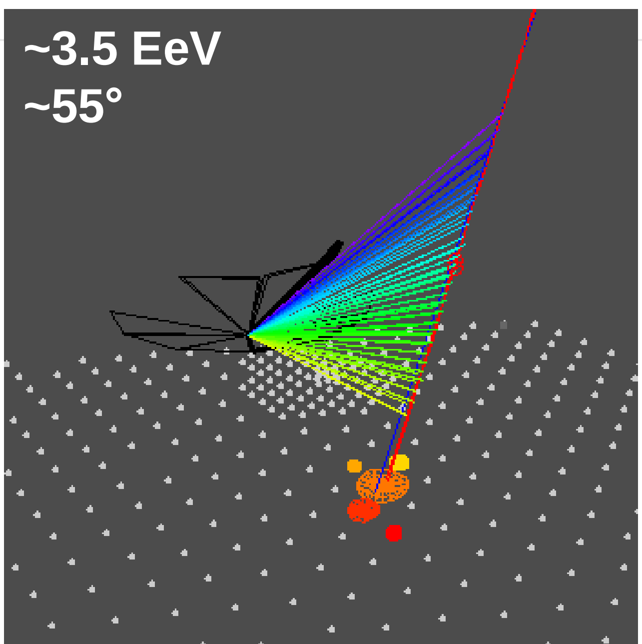
FD measurements operational ~15% of the time (clear nights, with low moon fraction)

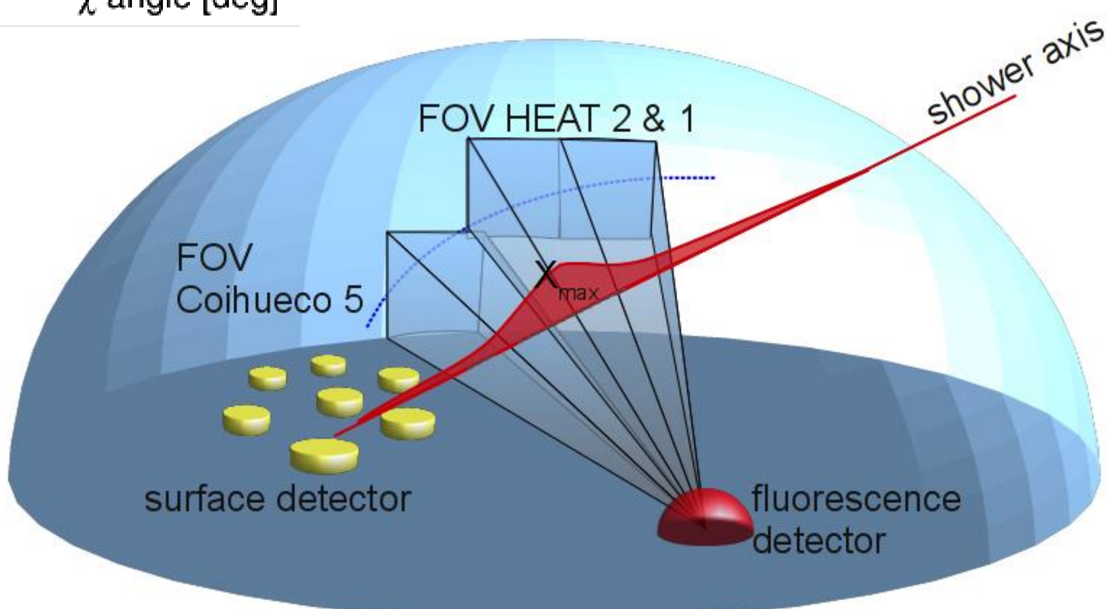
Hybrid detection



Hybrid event: Event observed with SD and FD

SD stations give a better geometry reconstruction → better energy and zenith angle reconstruction

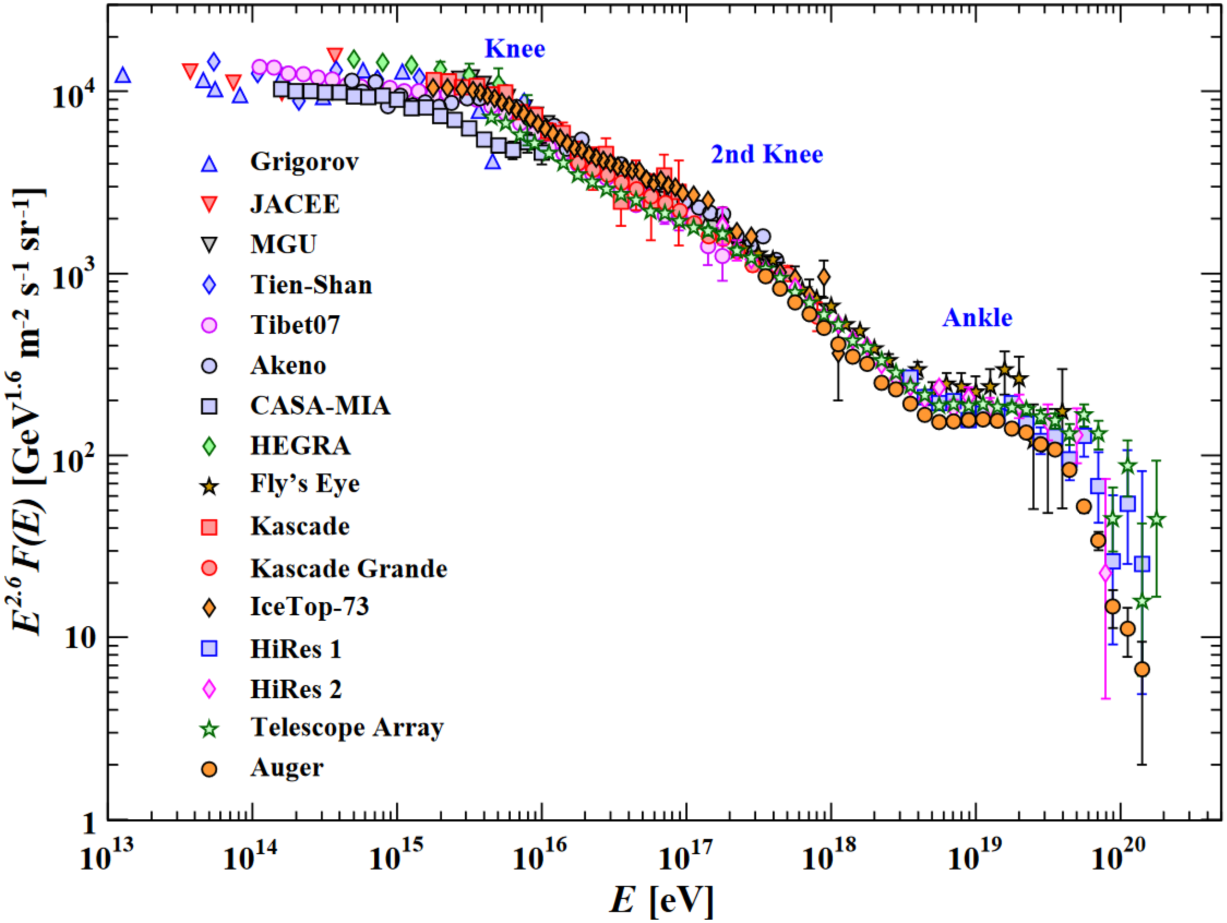




Mass composition studies

Identifying energy spectrum features: Transition from galacitc to extra-galactic sources, ankle, flux suppression (possibly GZK)

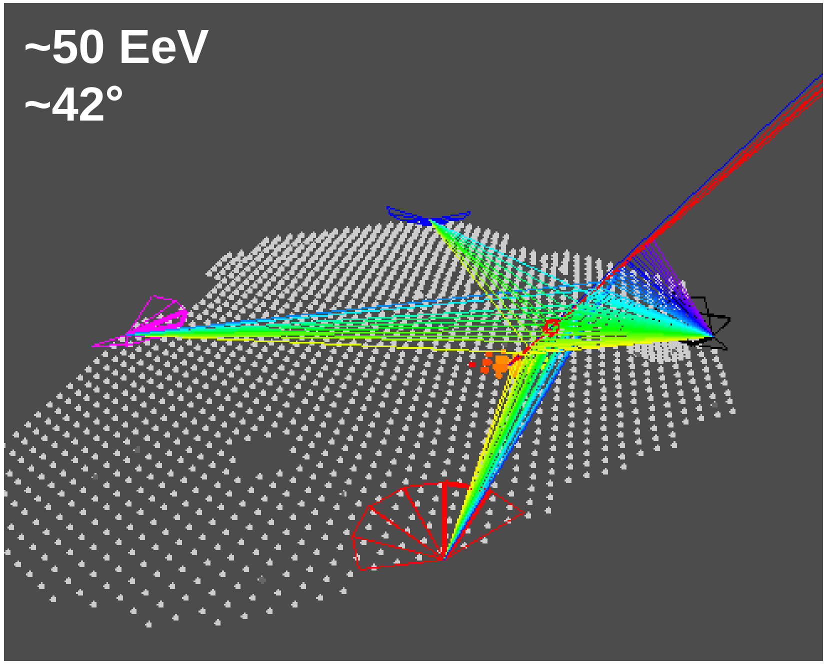
Uncovering origin of ultra-high-energy cosmic rays (UHECR): Acceleration to collision center-of-mass energies above 40 TeV (equivalent to CR with energy 10^{18} eV)



However, mass composition can only be inferred by **comparison of data to hadronic interaction models**!

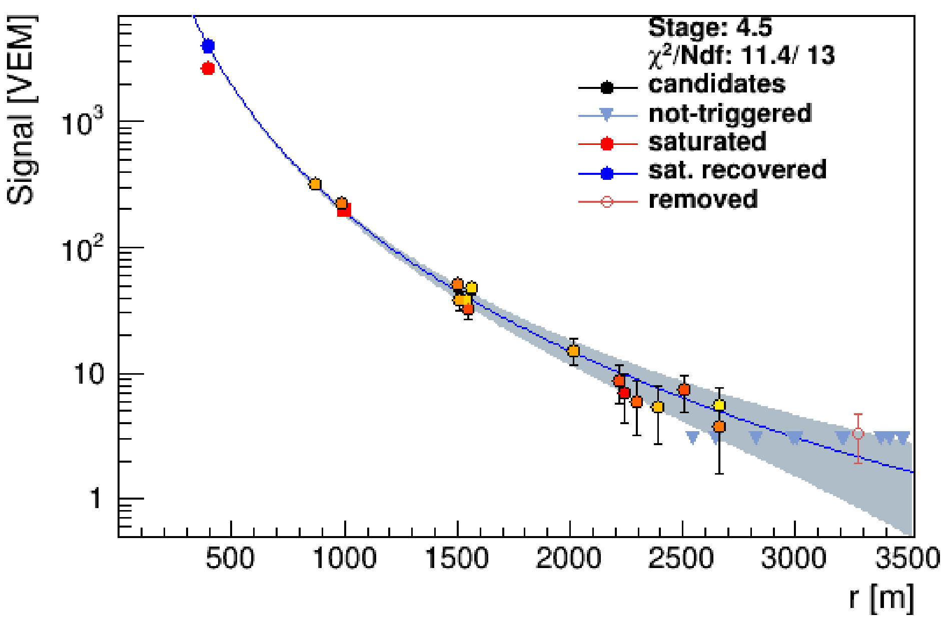
Collision cross-sections are extrapolated from collider experiments

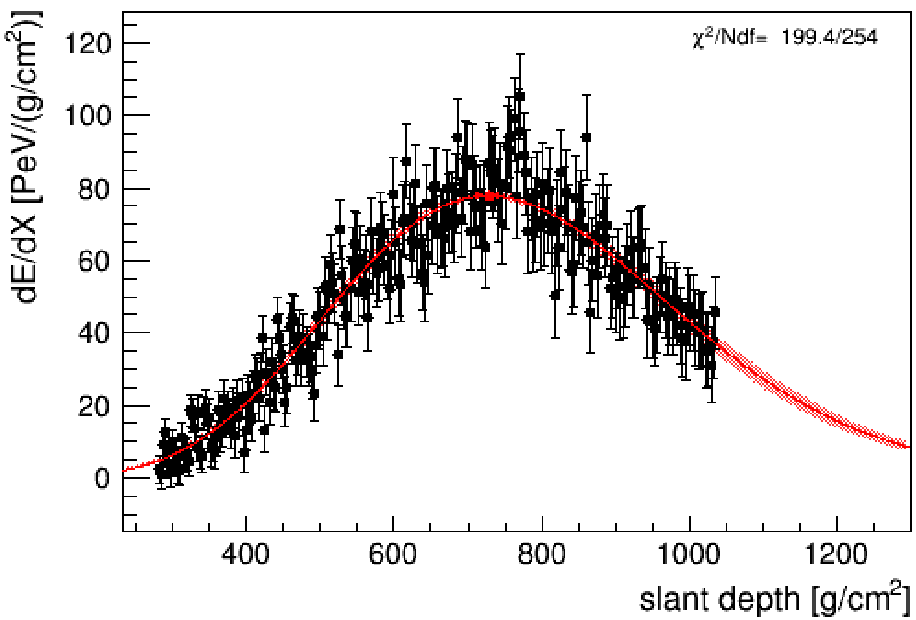
Observables



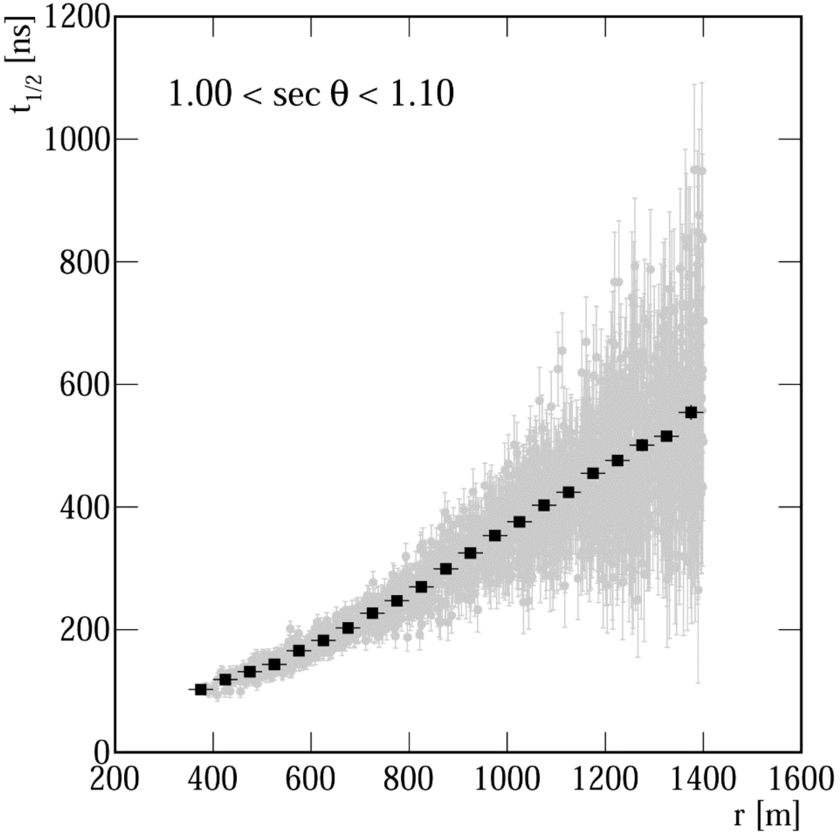
Observables:
Observed shower parameters that hold information on the shower and the primary particle

Observables sensitive to mass composition:
Depth of shower maximum (X_{max})
Surface detector lateral distribution (LDF)
Risetime ($t_{1/2}$)
Number of particles at ground
Muon production depth



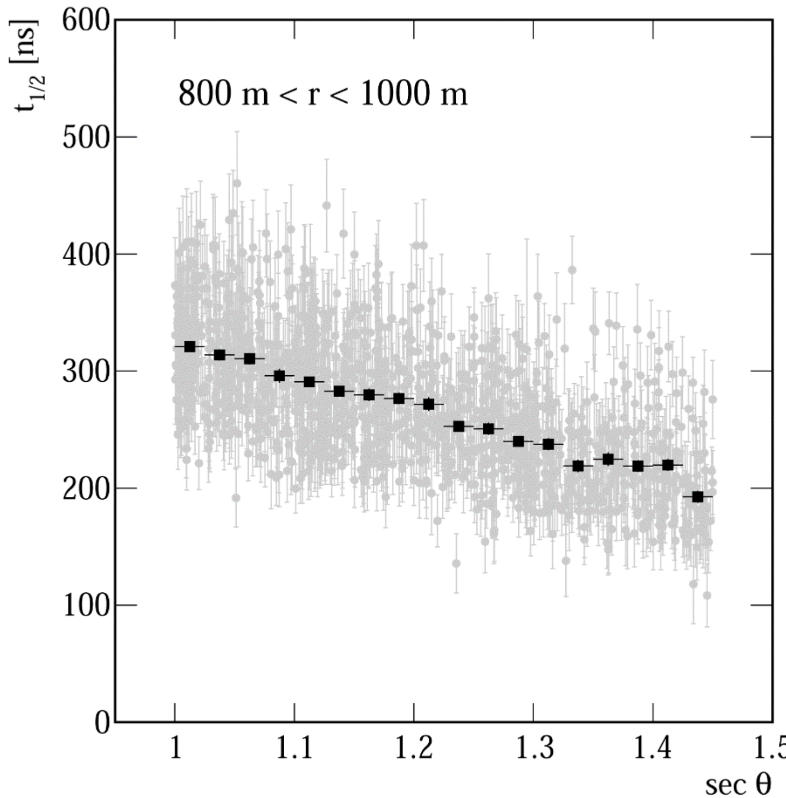


SD station risetime



Risetime: Time for the integrated signal to increase from 10% to 50% of its final magnitude

SD station signal includes both electronic and muonic parts of the shower (separation difficult)



Measured with high-gain or low-gain FADCs

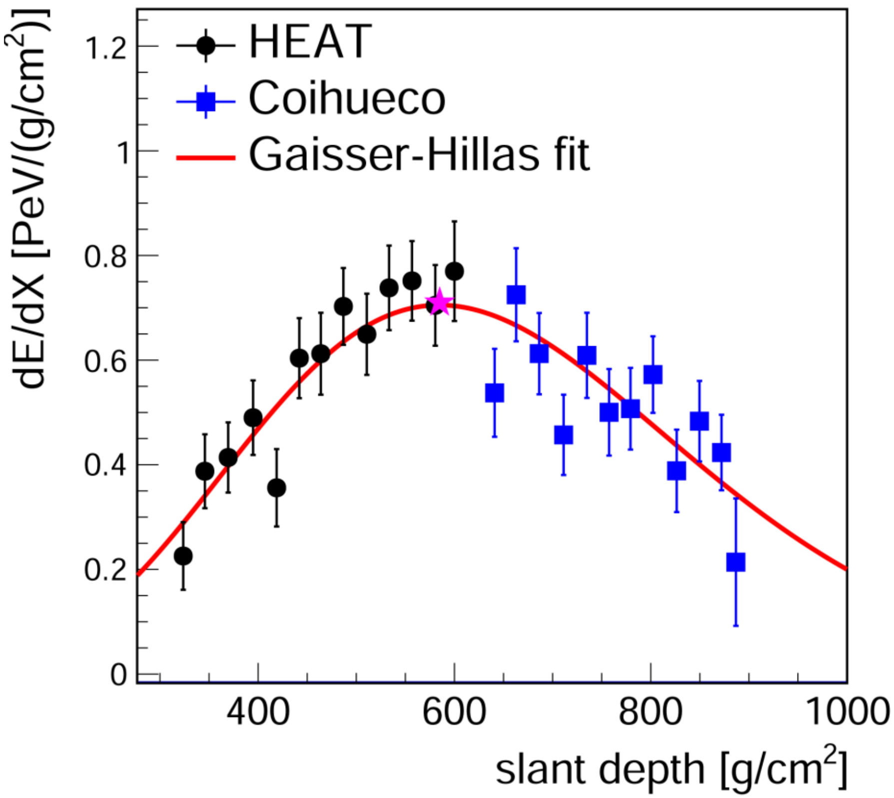
First parameter to show the shower-to-shower fluctuations (Haverah Park)

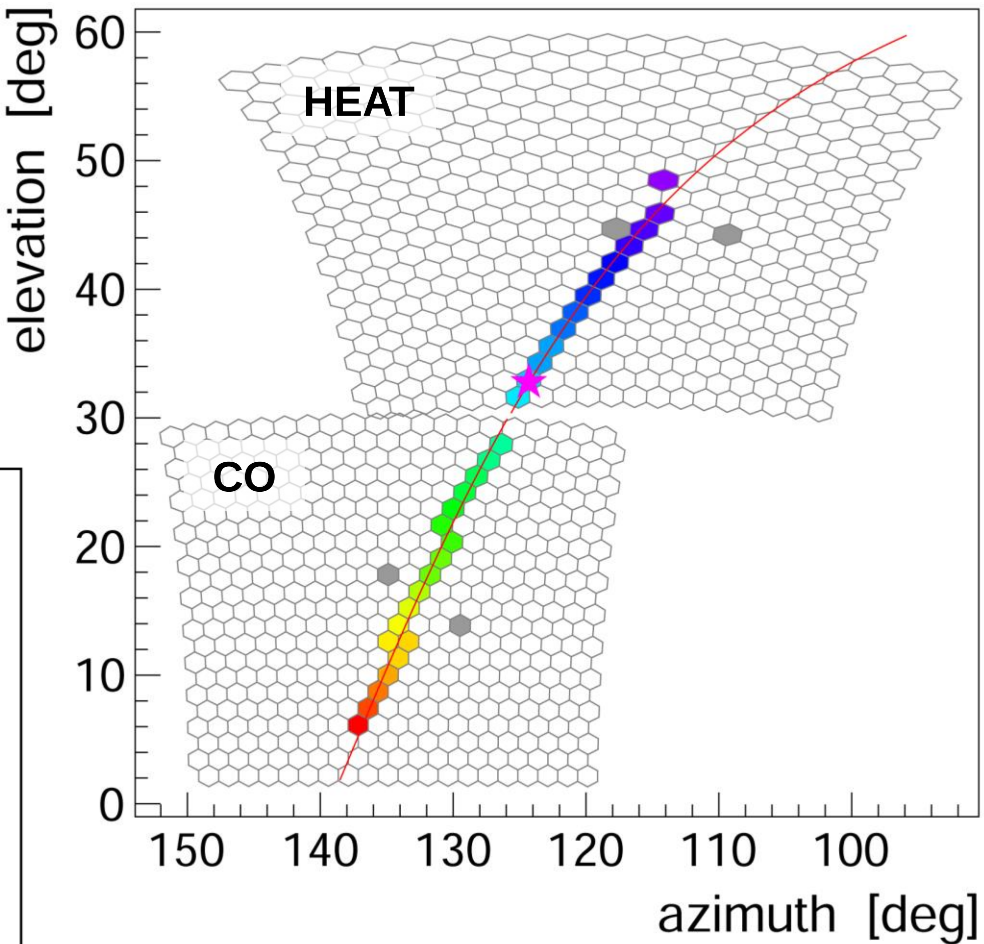
Can be used to estimate primary mass, but is a function of distance from shower axis distance, zenith angle and energy

Shower profile, X_{max}

Shower reaches X_{max} **(depth of shower maximum)** when particles reach critical energy

Showers with heavier primary particle will in general develop earlier in the atmosphere (superposition principle)





Using the HeCo dataset gives a better estimation of X_{max}

Electromagnetic components dominate for FD measurements

Composition implications from FD

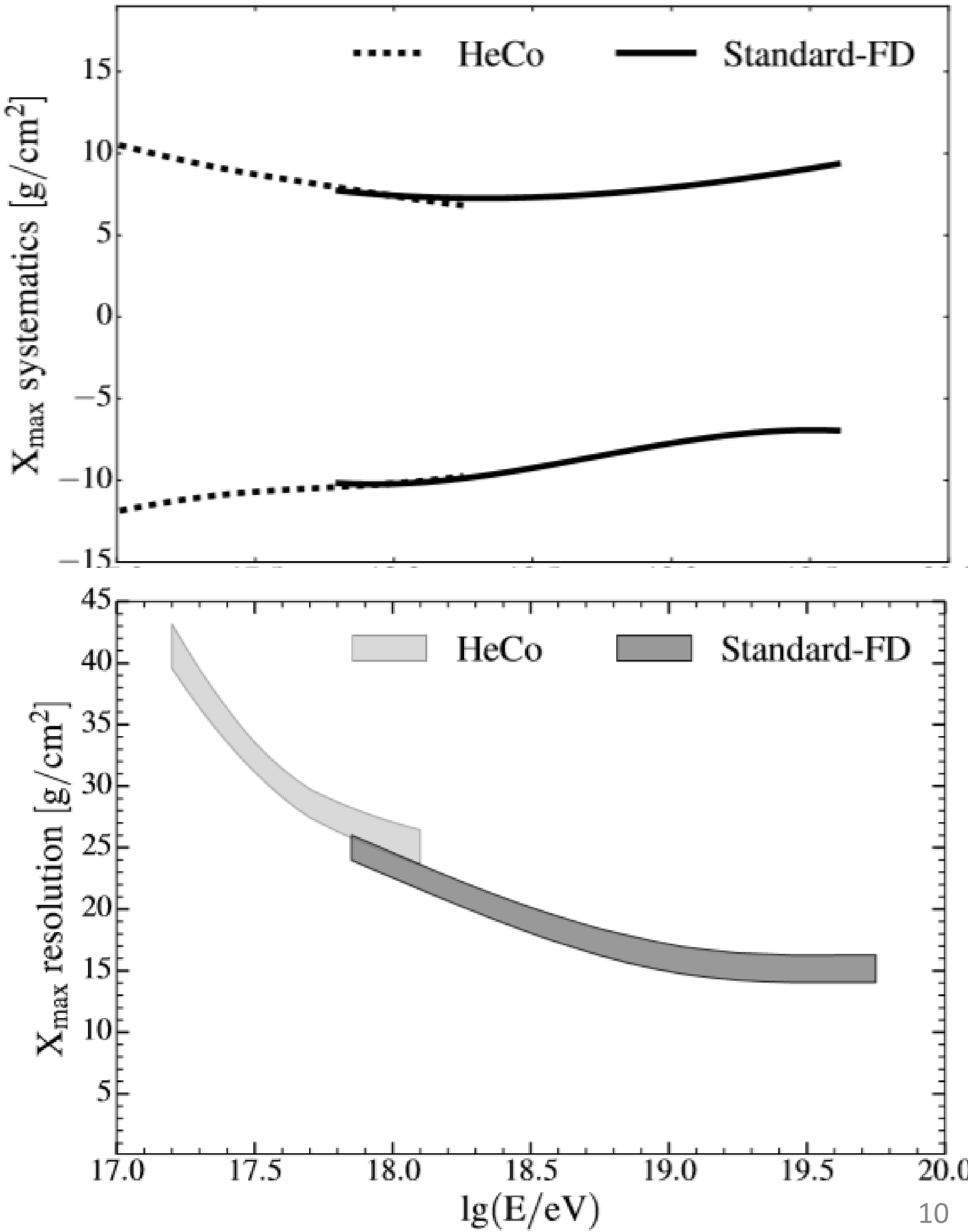
Data: Standard-FD (1. December 2004 – 31. December 2015), HeCo (1. June 2010 – 31. December 2015)

Energy range: Standard-FD (> $10^{17.8}$ eV), HeCo ($10^{17.2}$ eV – $10^{18.1}$ eV)

Quality and fiducial cuts: Stable running and atmospheric conditions, hybrid events, X_{max} inside field-of-view, X_{max} resolution below 40 g/cm^2

Number of events: Standard-FD (25688), HeCo (16778)

Systematics: Detector calibration, reconstruction, atmosphere (~10 g/cm^2)

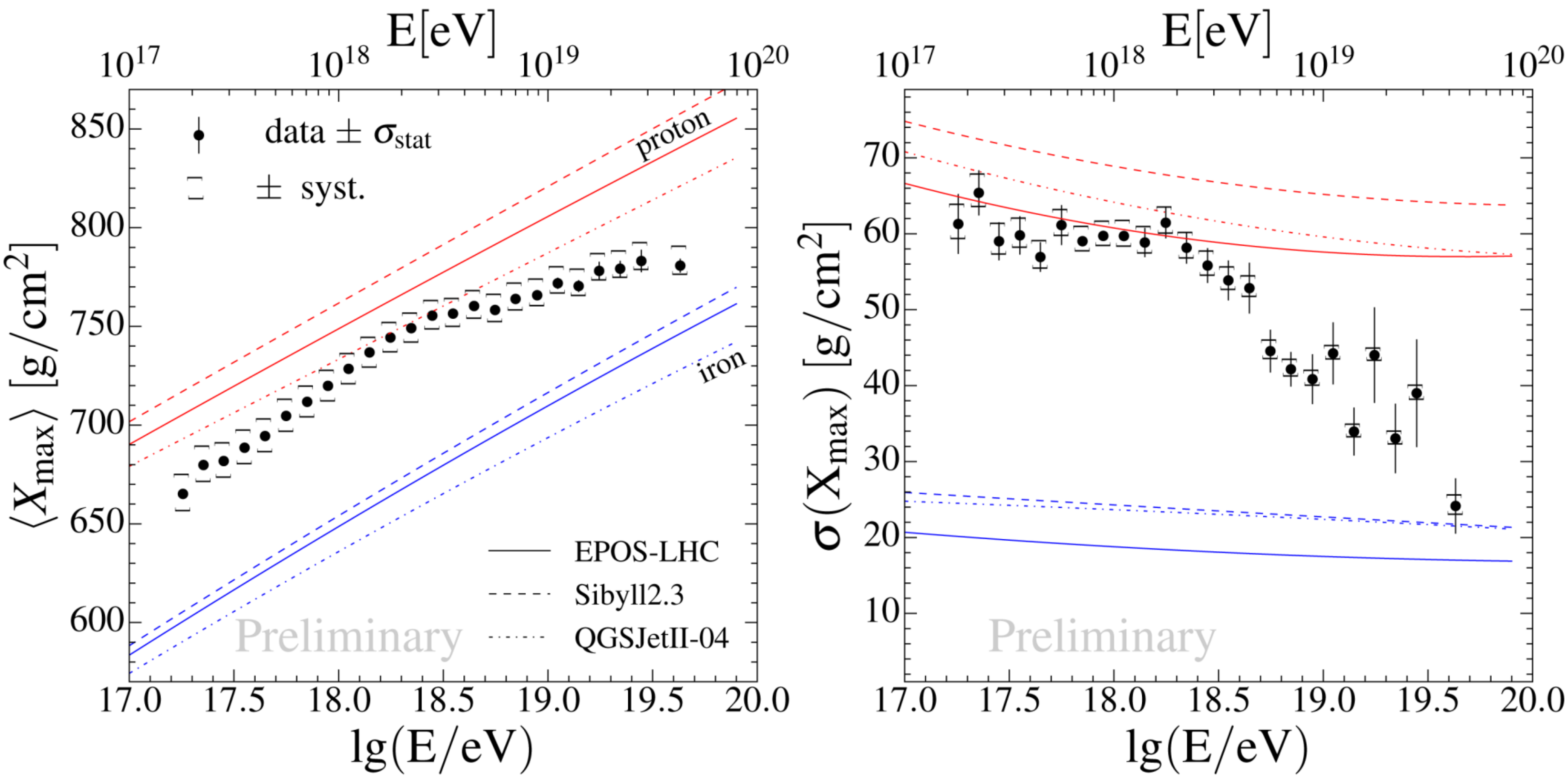


$\langle X_{max} \rangle$ moments

Constant mass: $\langle X_{max} \rangle$ = ~60 g/cm²/decade

Composition becoming **lighter** until $10^{18.33}$ eV: $\langle X_{max} \rangle$ = (79±1) g/cm²/decade

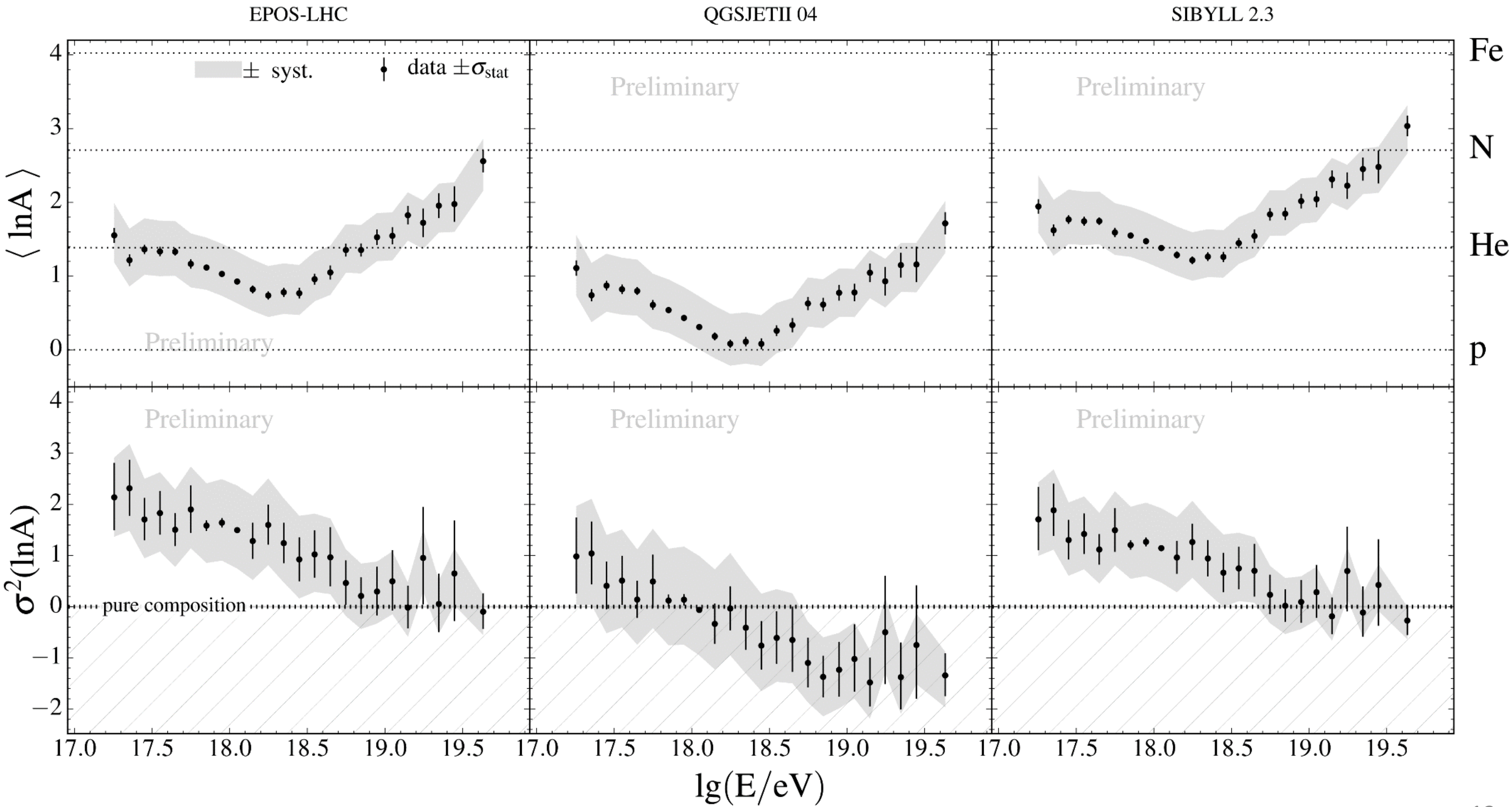
Composition becoming **heavier** after $10^{18.33}$ eV: $\langle X_{max} \rangle$ = (26±2) g/cm²/decade



$\langle \ln A \rangle$ moments

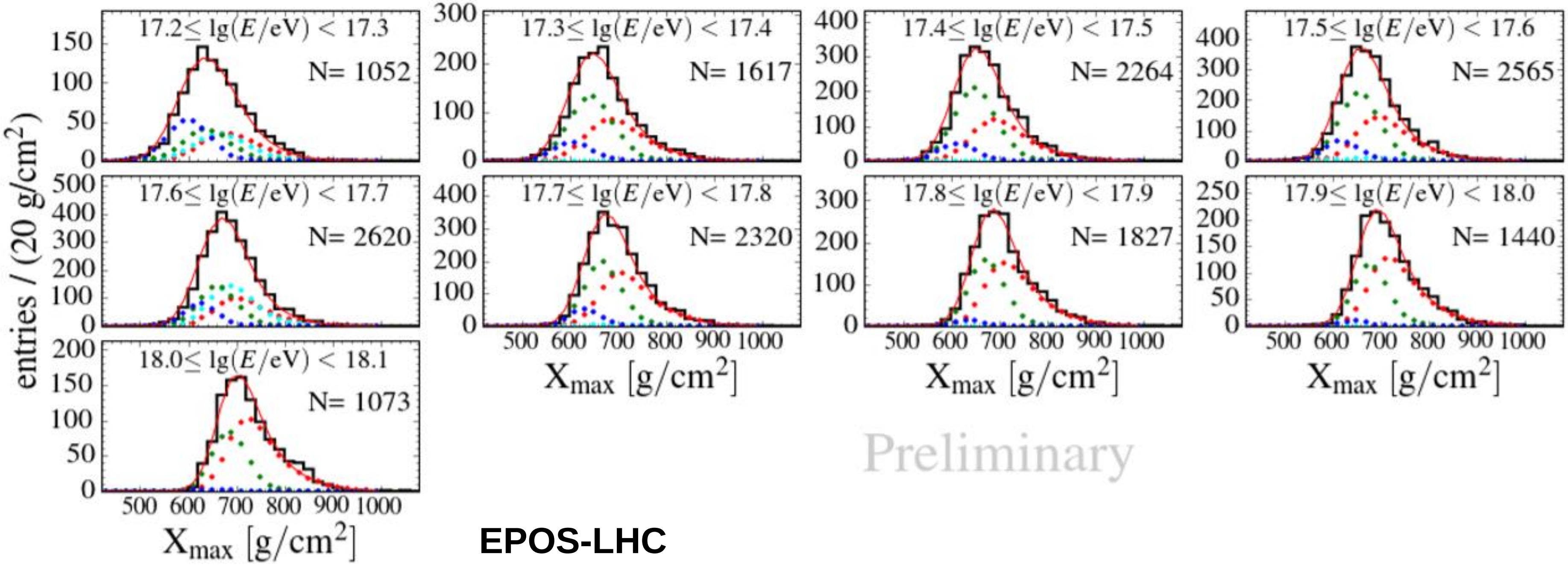
Break in the masses: At the same energy as before

Unphysical negative $\sigma^2\langle \ln A \rangle$ values: Models are predicting larger X_{max} fluctuations



HeCo X_{max} distributions

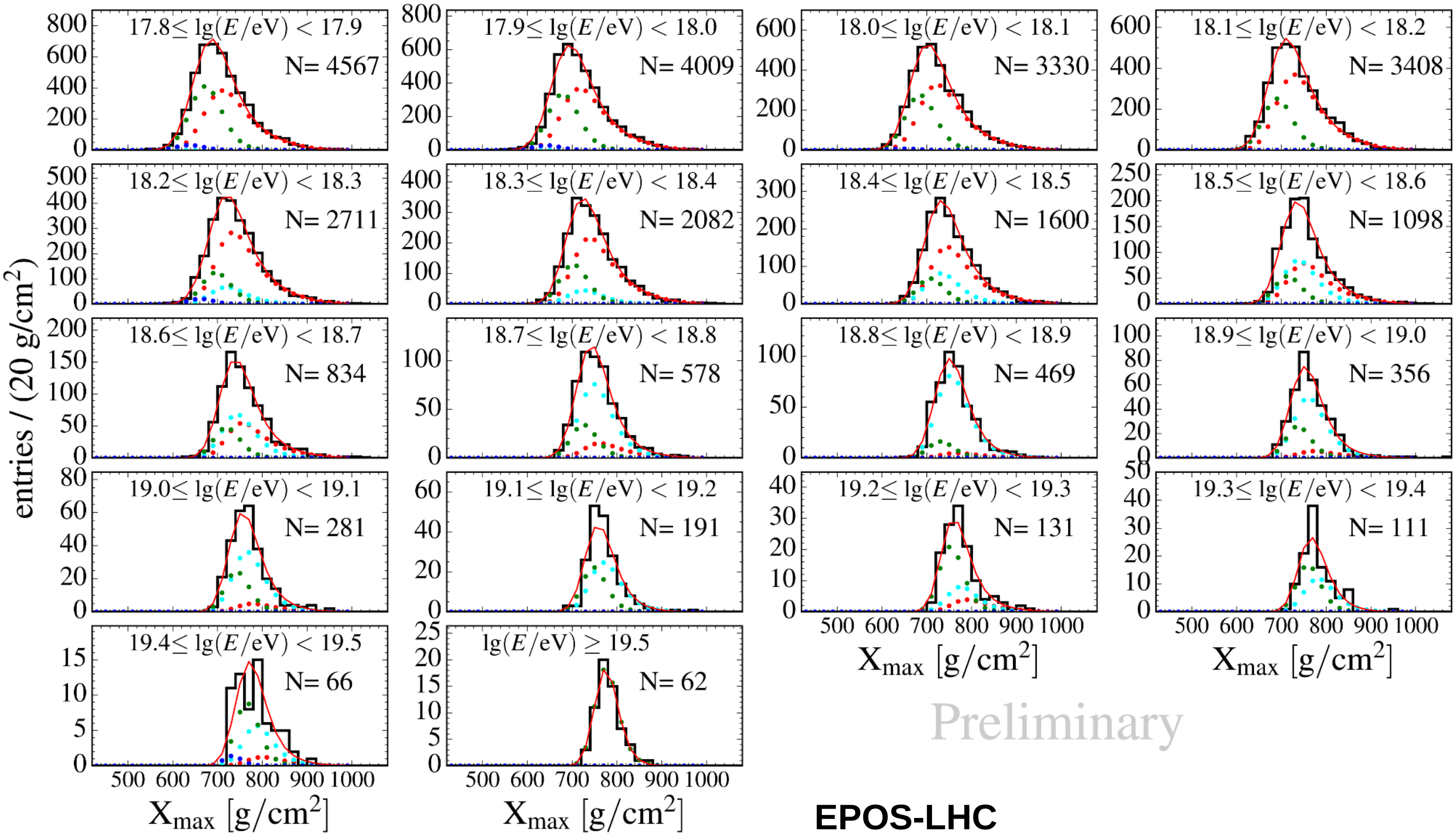
Distributions are fitted with **Gumbel functions** for protons, helium, nitrogen and iron:



EPOS-LHC

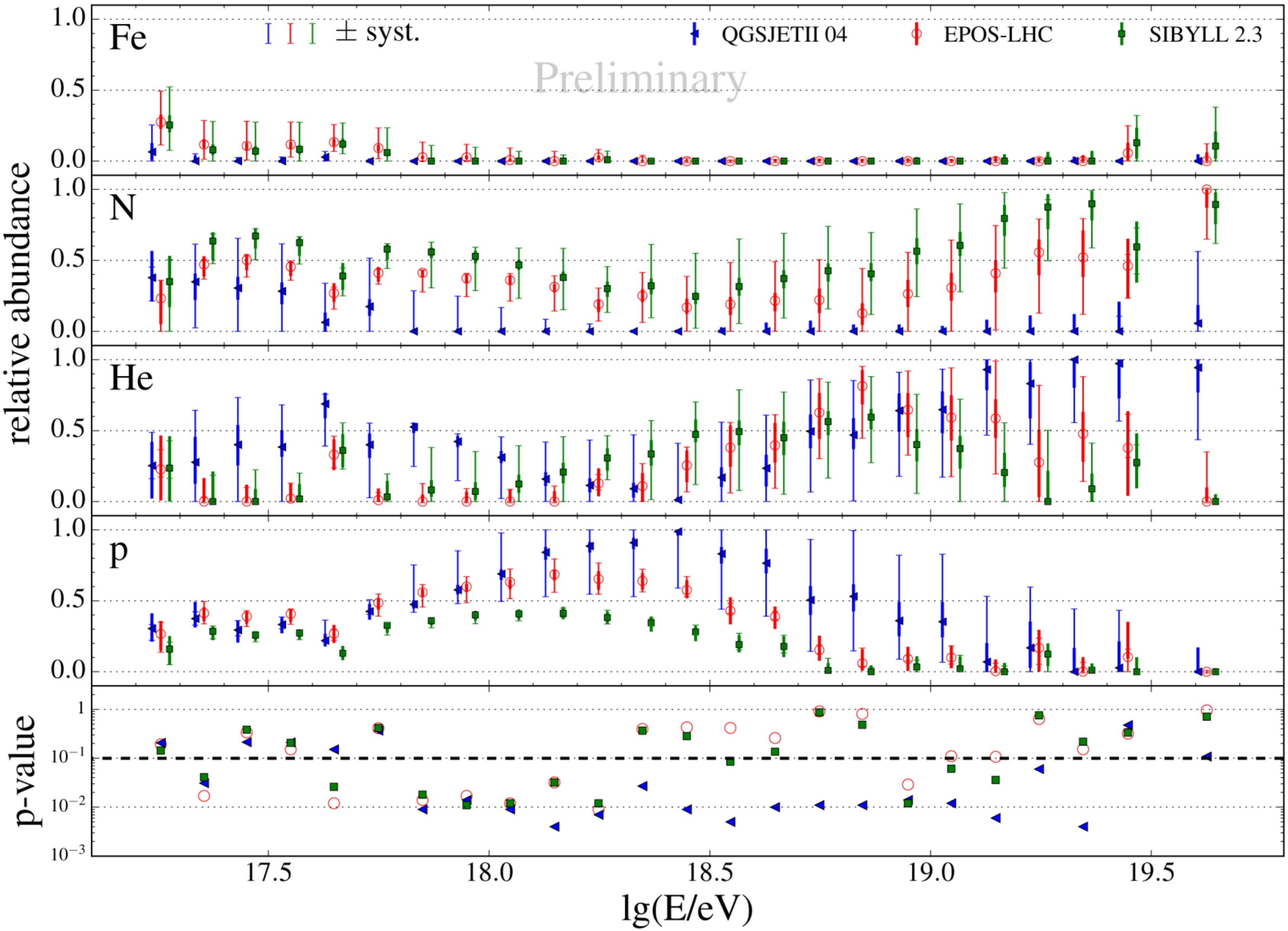
Standard-FD X_{max} distributions

Distributions are fitted with **Gumbel functions** for **protons**, **helium**, **nitrogen** and **iron**:



EPOS-LHC

Mass fractions



Composition implications from SD

Delta method: Express risetimes from all stations of an event with a single value

$$\Delta_i = \frac{t_{1/2} - t_{1/2}^{bench}}{\sigma_{1/2}}$$

$$\Delta_s = \frac{1}{N}\sum_{i=1}^{N}\Delta_i$$

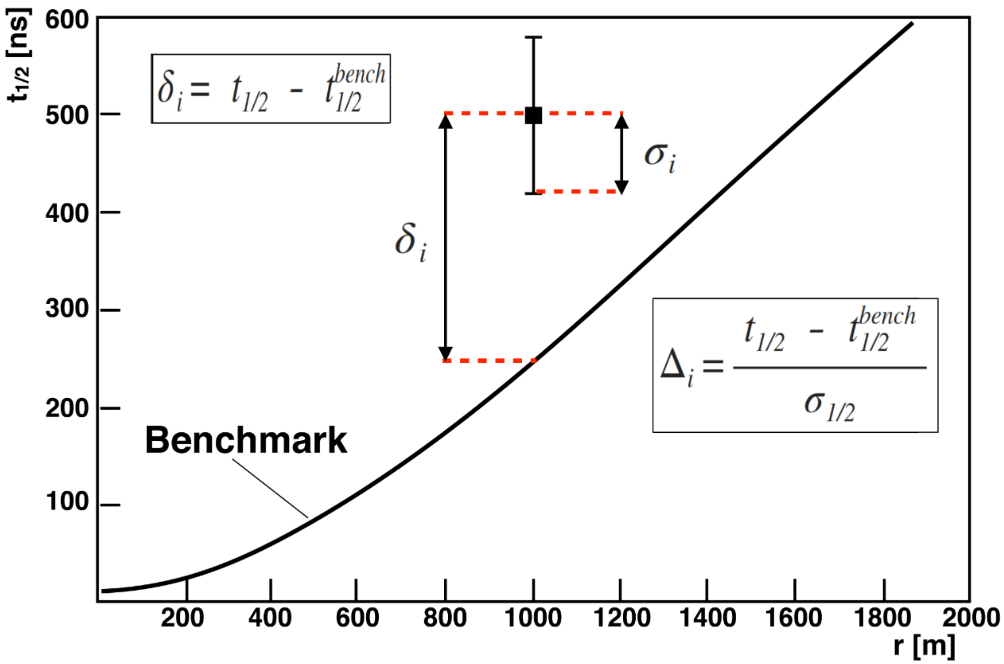
Data: 1500 m (1. January 2004 – 31. December 2014), 750 m (1. January 2008 – 31. December 2014)

Energy range: 1500 m (> $10^{18.5}$ eV), 750 m ($10^{17.5}$ eV – $10^{18.5}$ eV)

Quality cuts: Rejected bad periods, active 6T5 trigger, 3 or more stations in event, zenith angles below $\sec\theta < 1.45$ (1500 m) and $\sec\theta < 1.3$ (750 m)

Number of events: 1500 m (54022), 750 m (27553)

Systematics: Seasonal effects, day-night effects, detector aging, dependence on $\sec\theta$ (~0.11 for 1500 m, ~0.07 for 750 m)

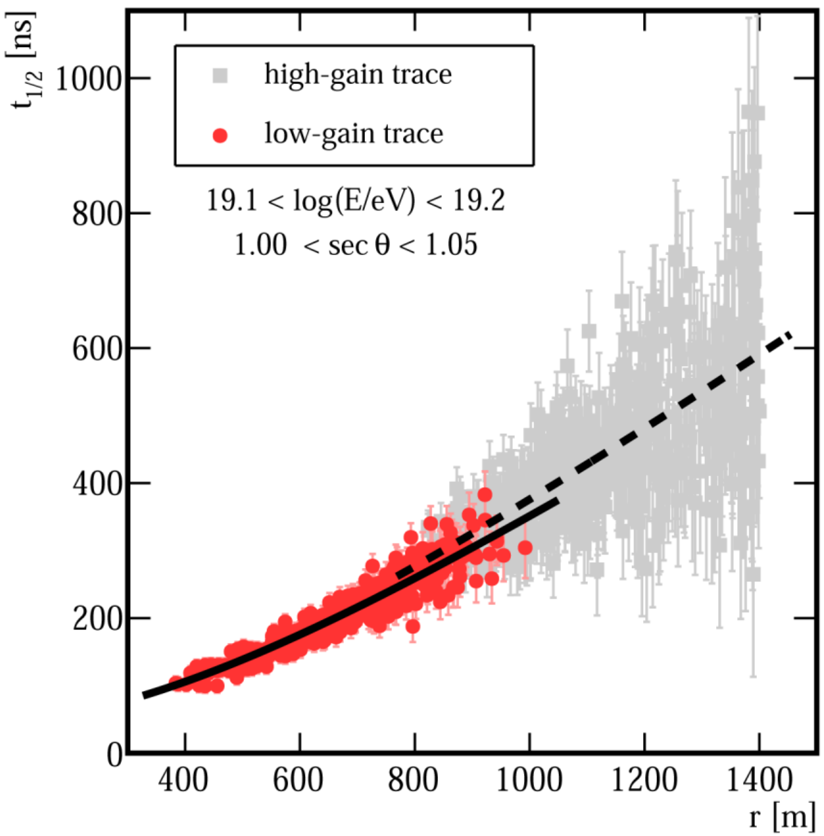


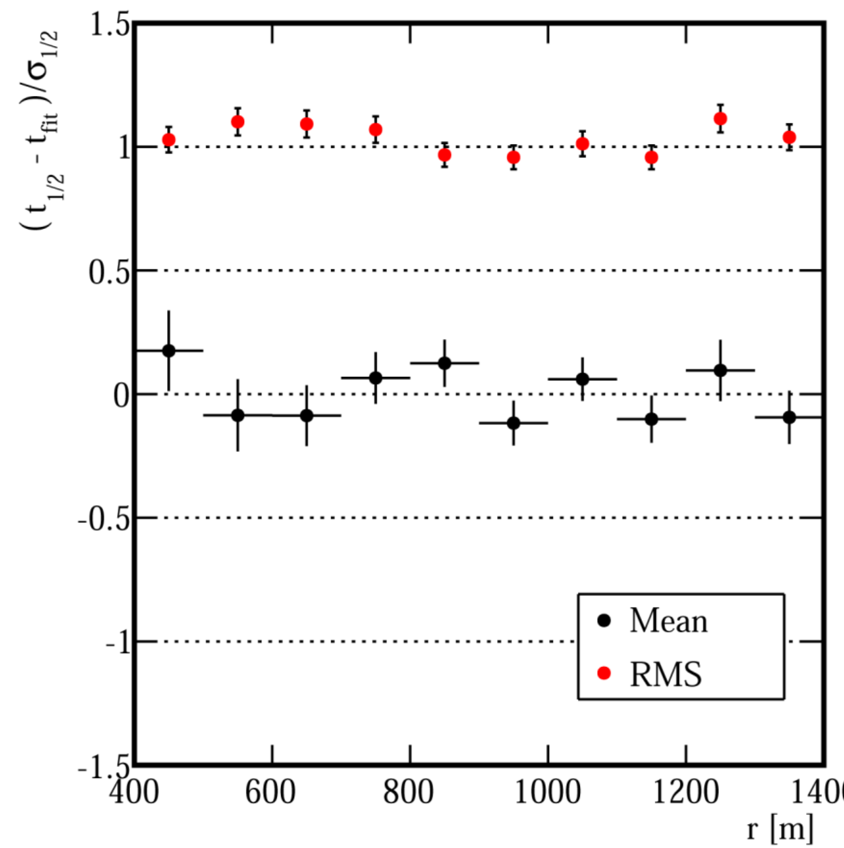
Delta method – Benchmark fit

Using a fit for high-gain and low-gain measurements of risetime

Taking 6 $\sec\theta$ bins for 750 m array and 9 $\sec\theta$ bins for 1500 m array

Benchmark fitting function and zenith angle binning removes dependence of Δ_i on distance from shower axis and zenith angle



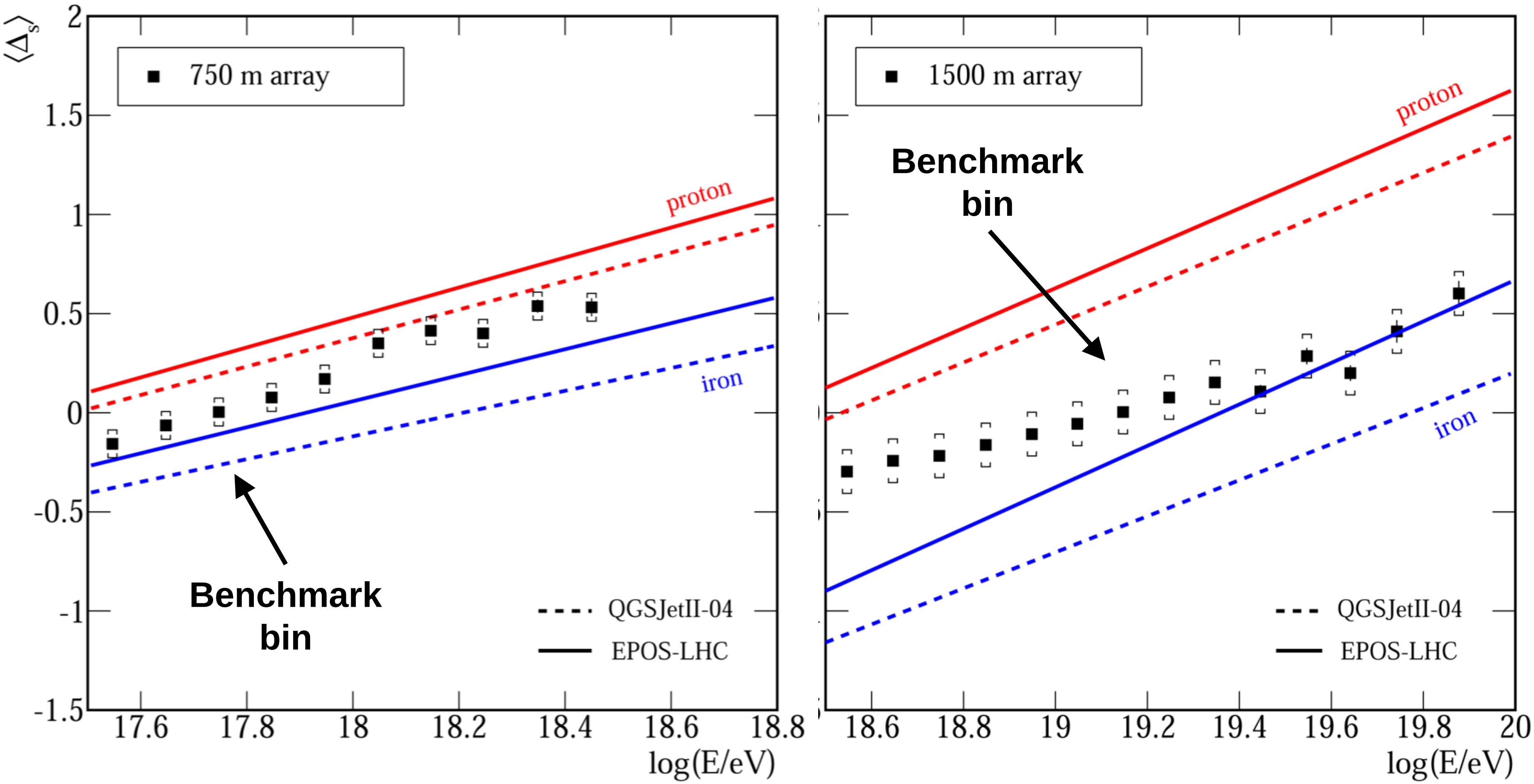


$\langle\Delta_s\rangle$ moments

Benchmark bin: Delta value is zero (as per definition)

Composition becoming **lighter** for 750 m array (lower energies)

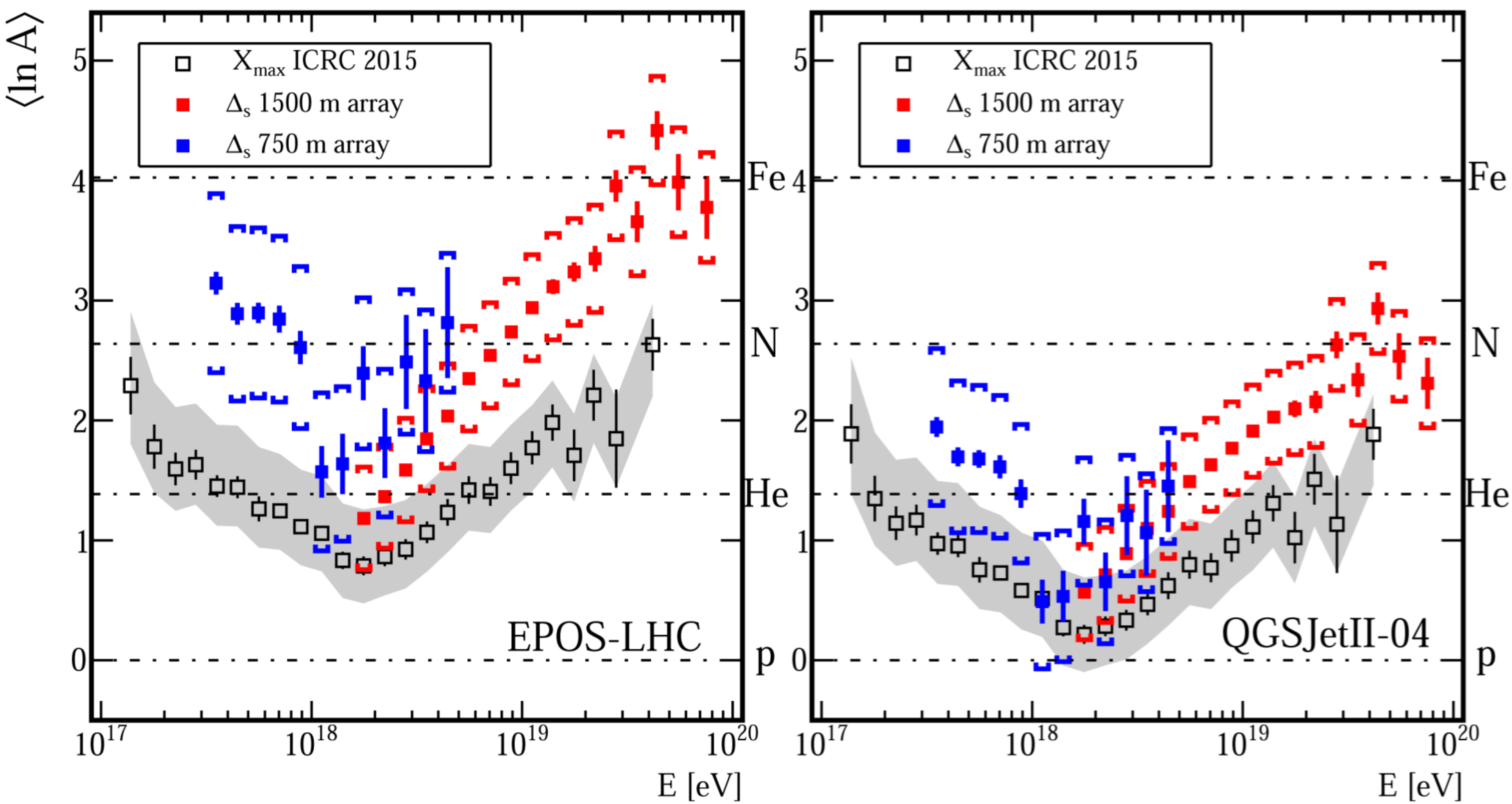
Composition becoming **heavier** for 1500 m array (higher energies)



$\langle \ln A \rangle$ moments

Trend in $\langle \ln A \rangle$ with energy similar, but with heavier composition over complete range

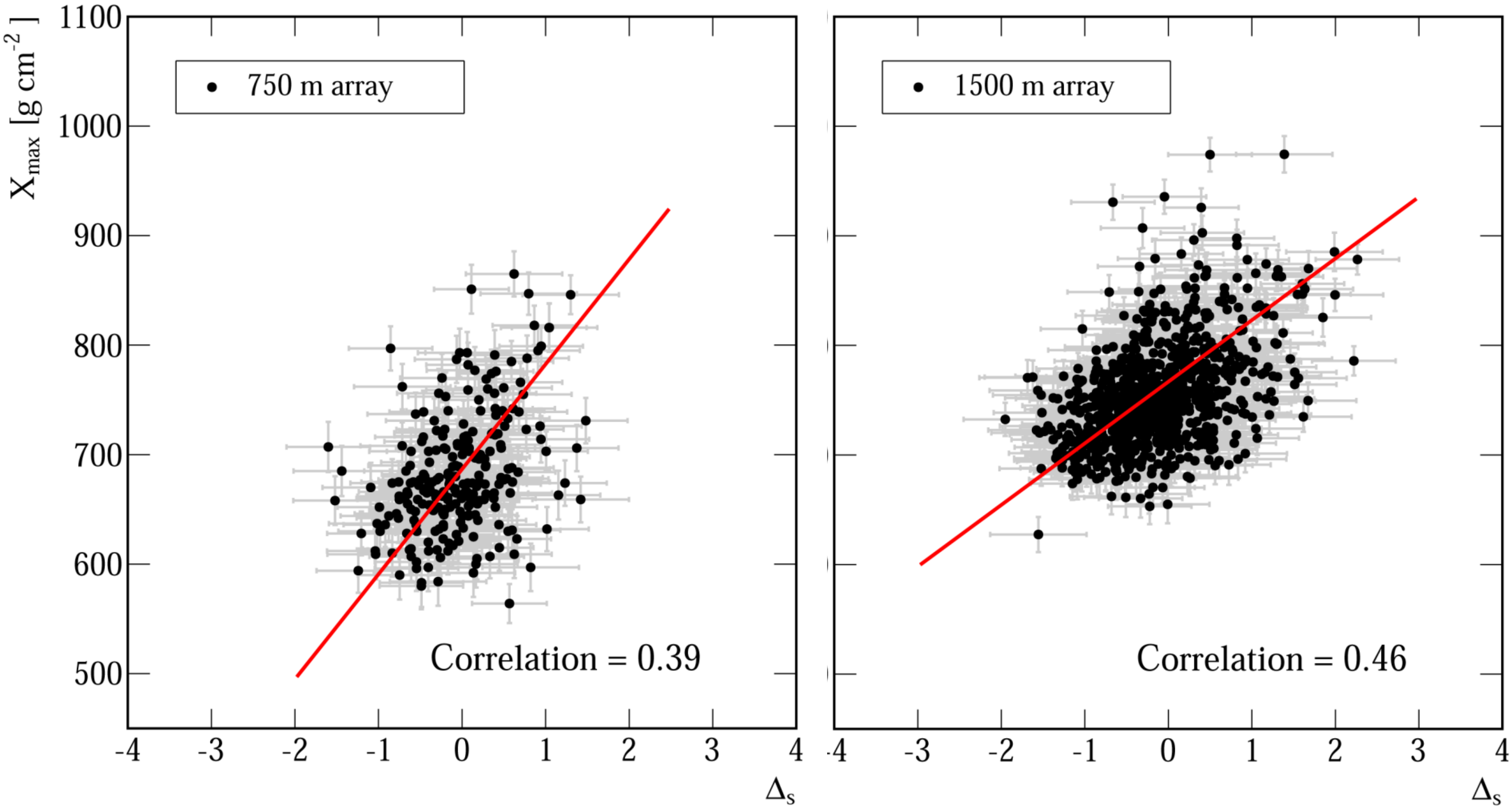
Inadequate description of muonic component by hadronic models



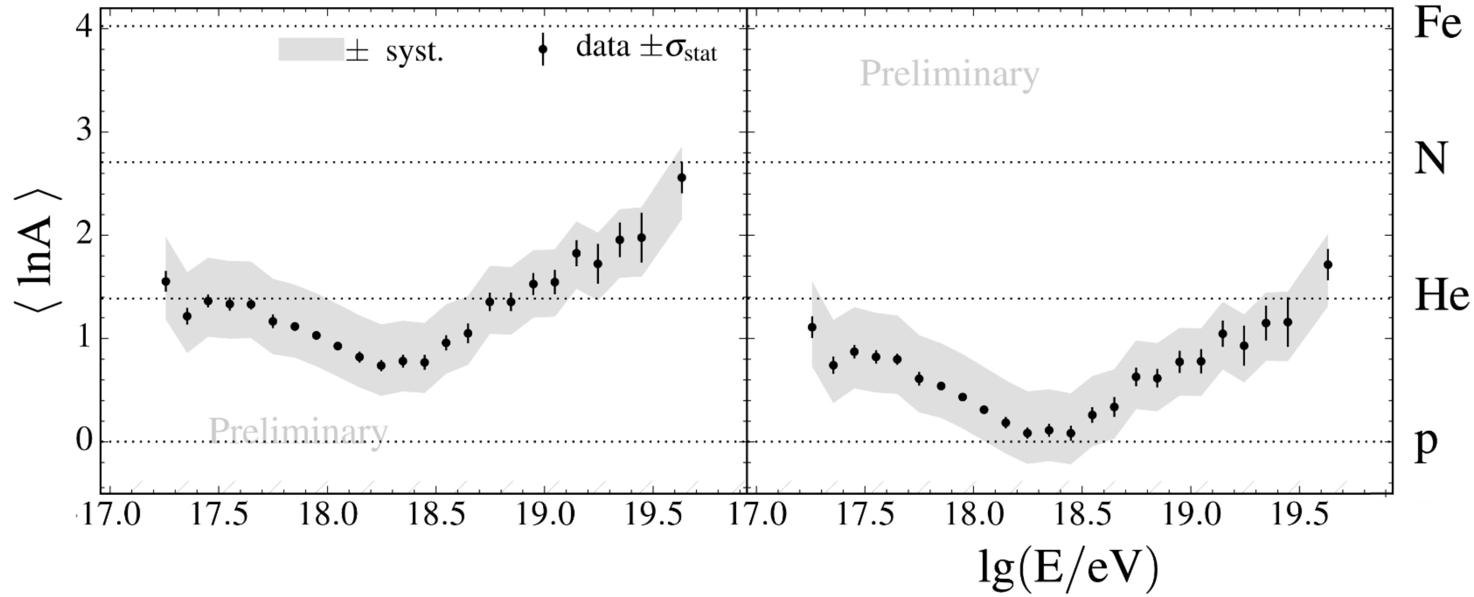
Calibration with FD X_{max}

Surviving 885 events from 1500 m array and 252 events from 750 m array fitted with:

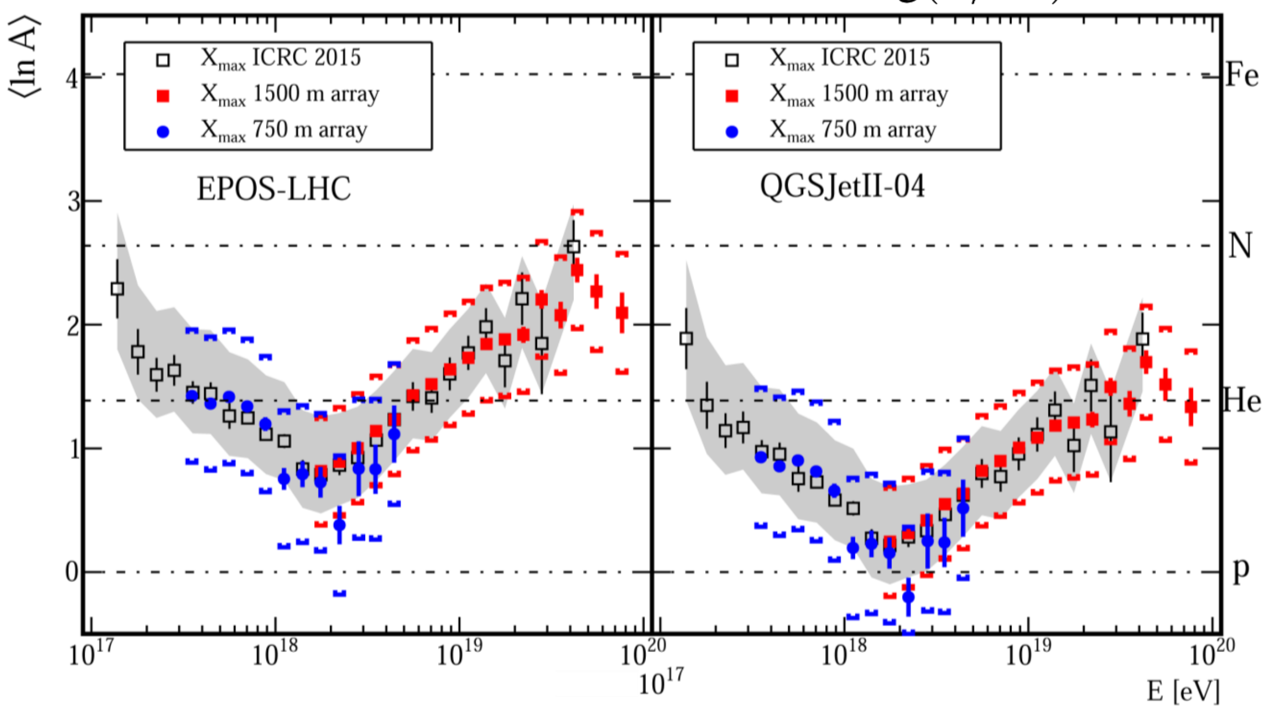
$$X_{max} = a + b\,\Delta_s + c\;\log(E/eV)$$



Composition implications



ICRC 2017 (FD)

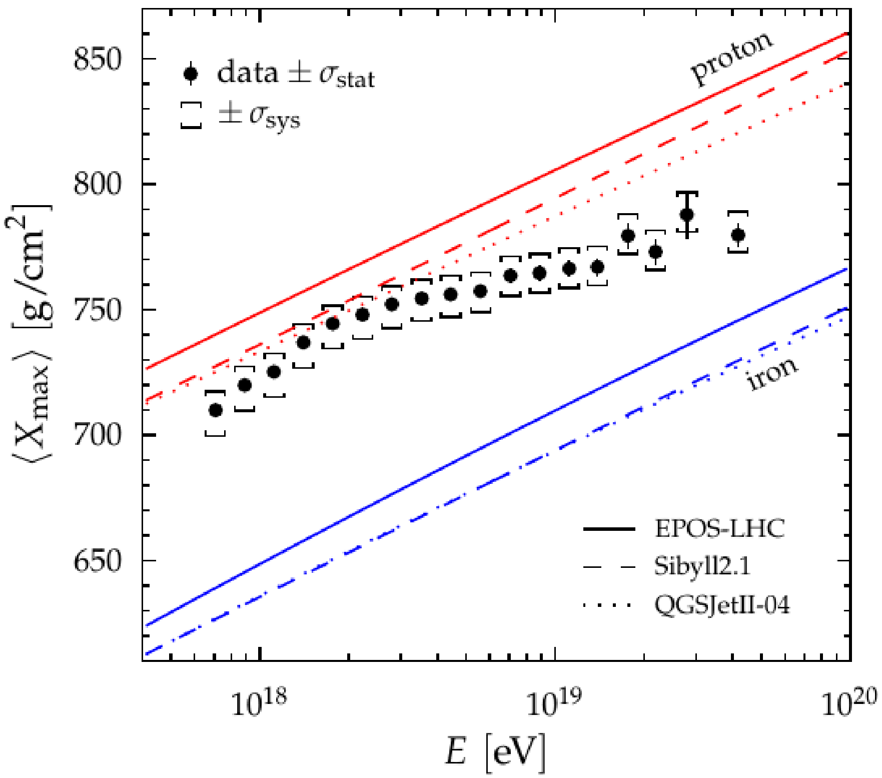


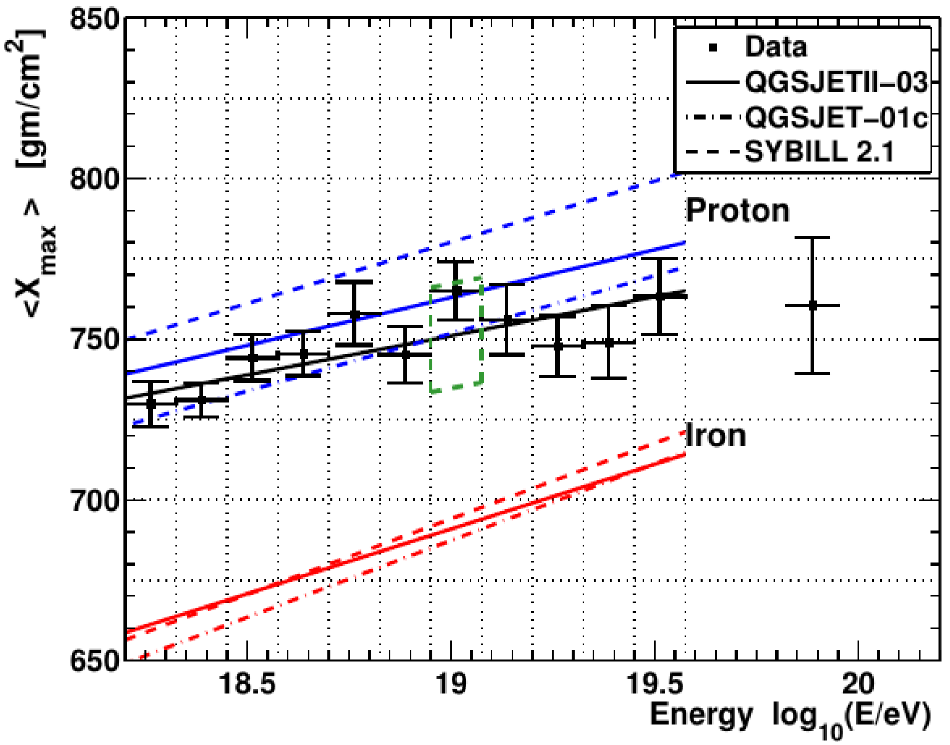
ICRC 2015 (FD) &
ICRC 2017 (SD)

Pierre Auger Observatory and Telescope Array

Pierre Auger data and Telescope Array data can not be directly compared:

- Pierre Auger Observatory additionally corrects for acceptance, reconstruction and resolution (detector effects)
- For X_{max} comparison, Pierre Auger Observatory mass composition is folded with Telescope Array detector response, reconstruction and analysis





Pierre Auger Observatory and Telescope Array

Pierre Auger Observatory

Hybrid data: 1. December 2004 – 31. December 2012)

Number of events: 7365

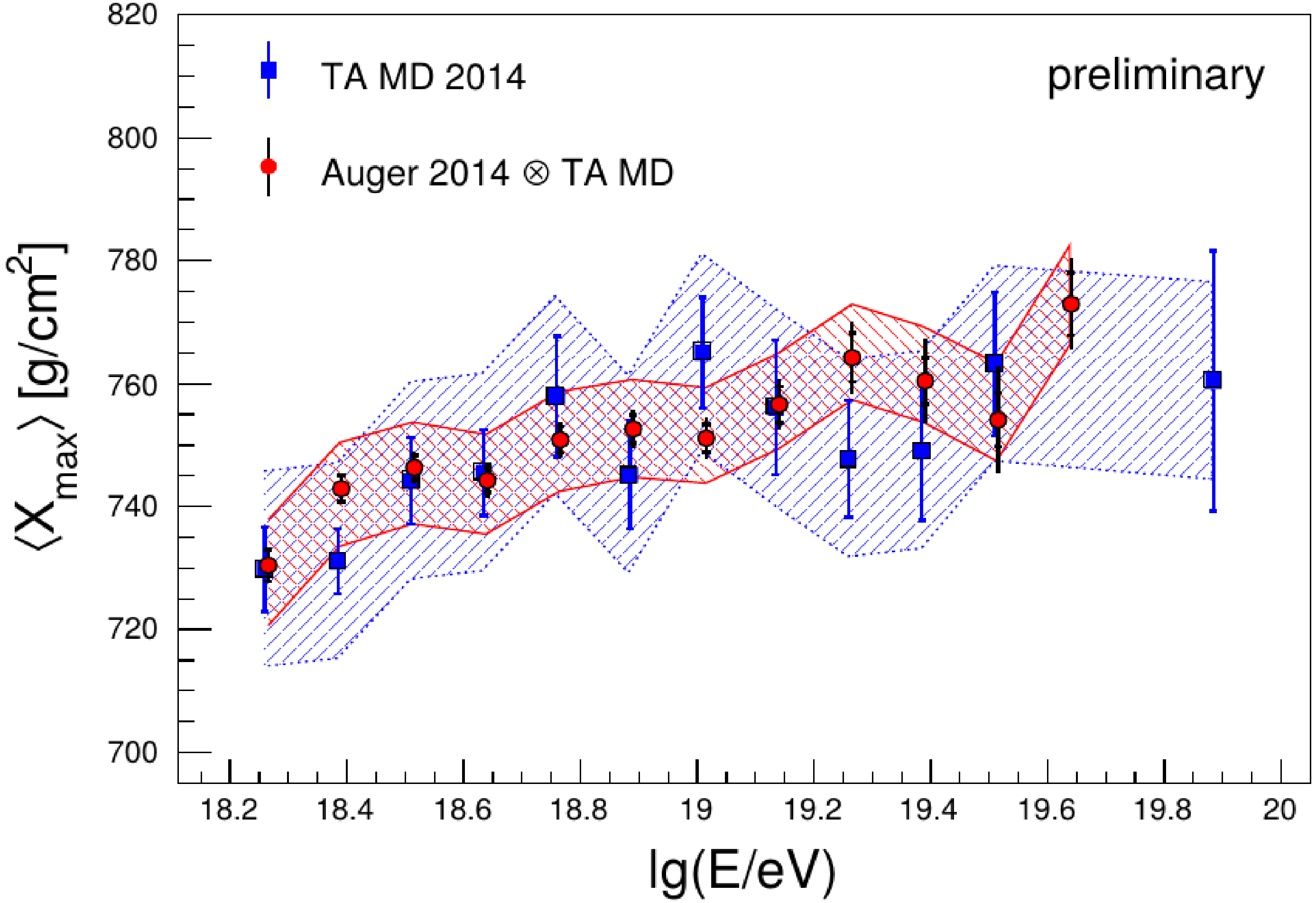
Energy range: Above $10^{17.8}$ eV

Telescope Array

Hybrid data (MD): 27. May 2008 – 2. May 2013)

Number of events: 438

Energy range: Above $10^{18.2}$ eV



Conclusions

FD mass composition implications:

- Composition becoming lighter until ~$10^{18.33}$ eV, after that again becoming heavier.

SD mass composition implications:

- Heavier composition than that determined by FD
- **Hadronic models do not describe measurements with muonic component of the shower well**
- Calibrated SD data agrees well with FD data

Pierre Auger Observatory and Telescope Array:

- After accounting for detector response, reconstruction and analysis effects, the two results are comparable

Thank you for your attention!

References

1. A. Aab *et al.*, Pierre Auger Collaboration, *Depth of maximum of air-shower profiles at the Pierre Auger Observatory. II. Composition implications*, Phys. Rev. **D** 90 (2014) 122006.
2. J. Bellido for the Pierre Auger Collaboration, *Depth of maximum air-shower profiles at the Pierre Auger Observatory: Measurements above* $10^{17.2}$ *eV and Composition Implications*, ICRC 2017, 40 – 47, arXiv:1708.06592.
3. P. Abreu *et al.*, Pierre Auger Collaboration, *Interpretation of the depths of maximum of extensive air showers measured by Pierre Auger Observatory*, JCAP **02** (2013) 026.
4. A. Aab *et al.*, *Inferences on mass composition and tests of hadronic interactions from 0.3 to 100 EeV using the water-Cherenkov detectors of the Pierre Auger Observatory*, Phys. Rev. **D** 96 (2017) 122003.
5. M. Unger for the Pierre Auger Collaboration and the Telescope Array Collaboration, *Report of the Working Group on the Composition of Ultra-High Energy Cosmic Rays*, ICRC 2015, 10 – 17, arXiv:1511.02103.

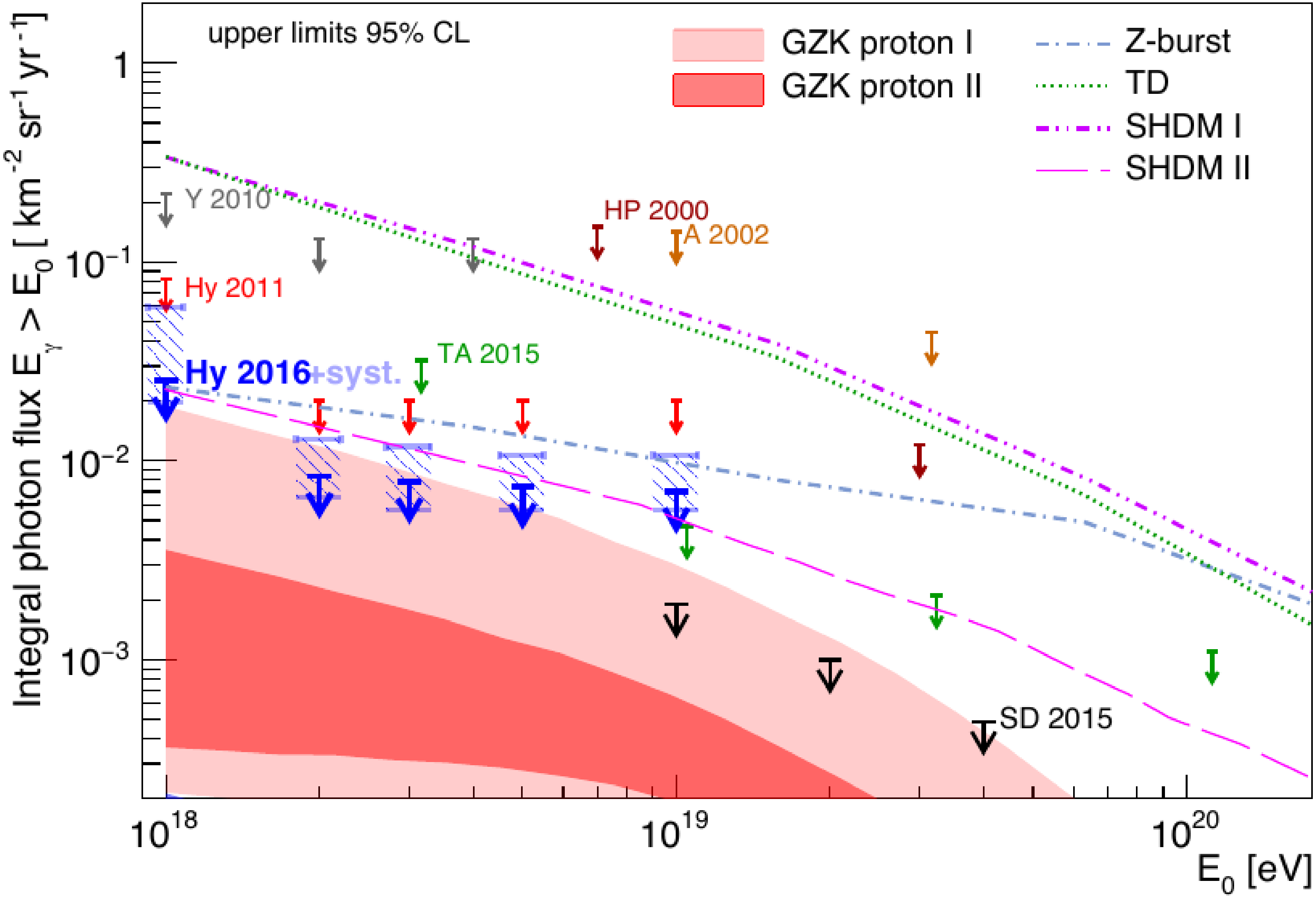
Backup slides

FD telescope

Search for diffuse high energy photons

Photons could form in GZK process:

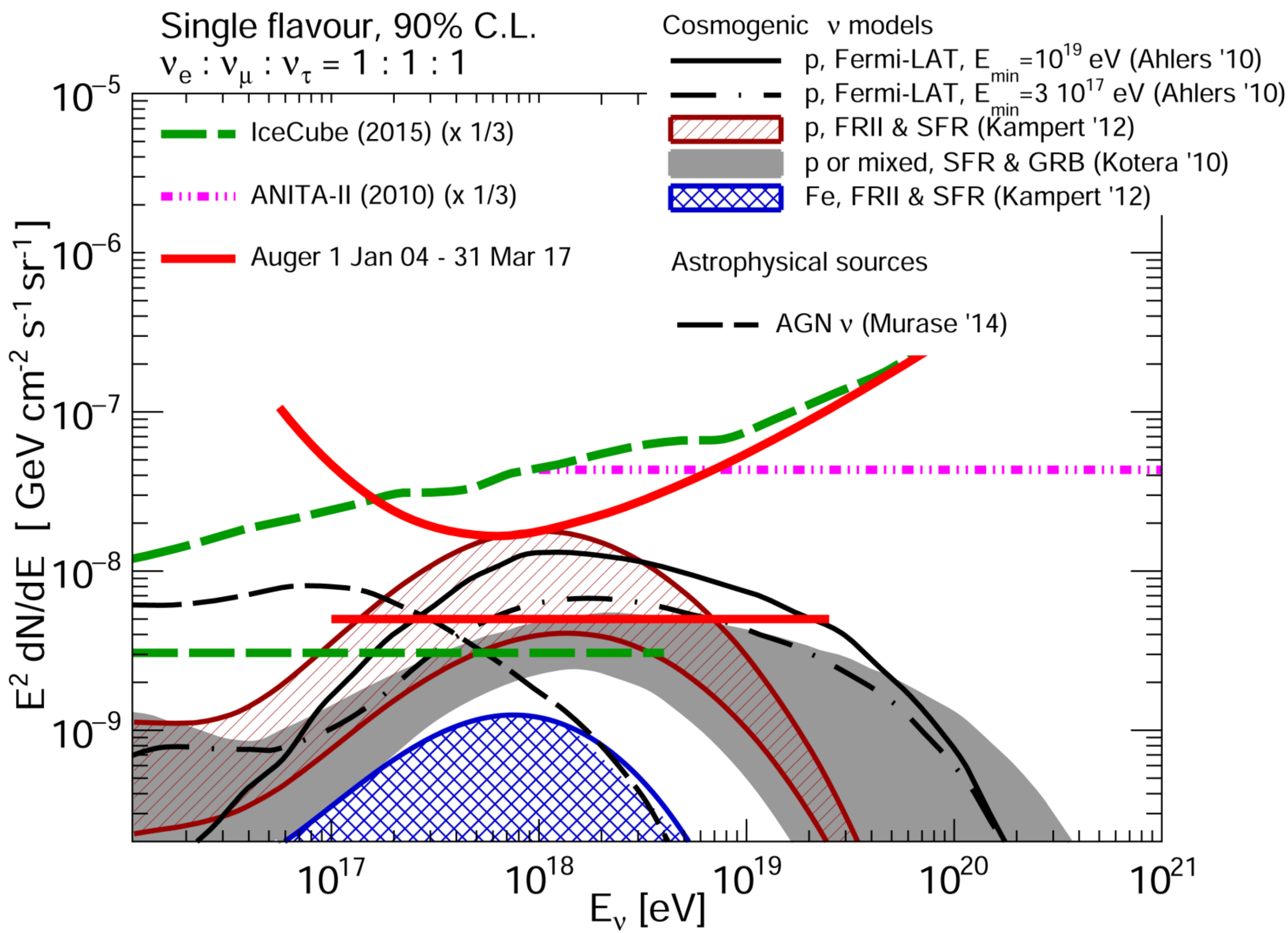
$$p + \gamma_{CMB} \longrightarrow p + \pi^0 \longrightarrow p + \gamma + \gamma$$



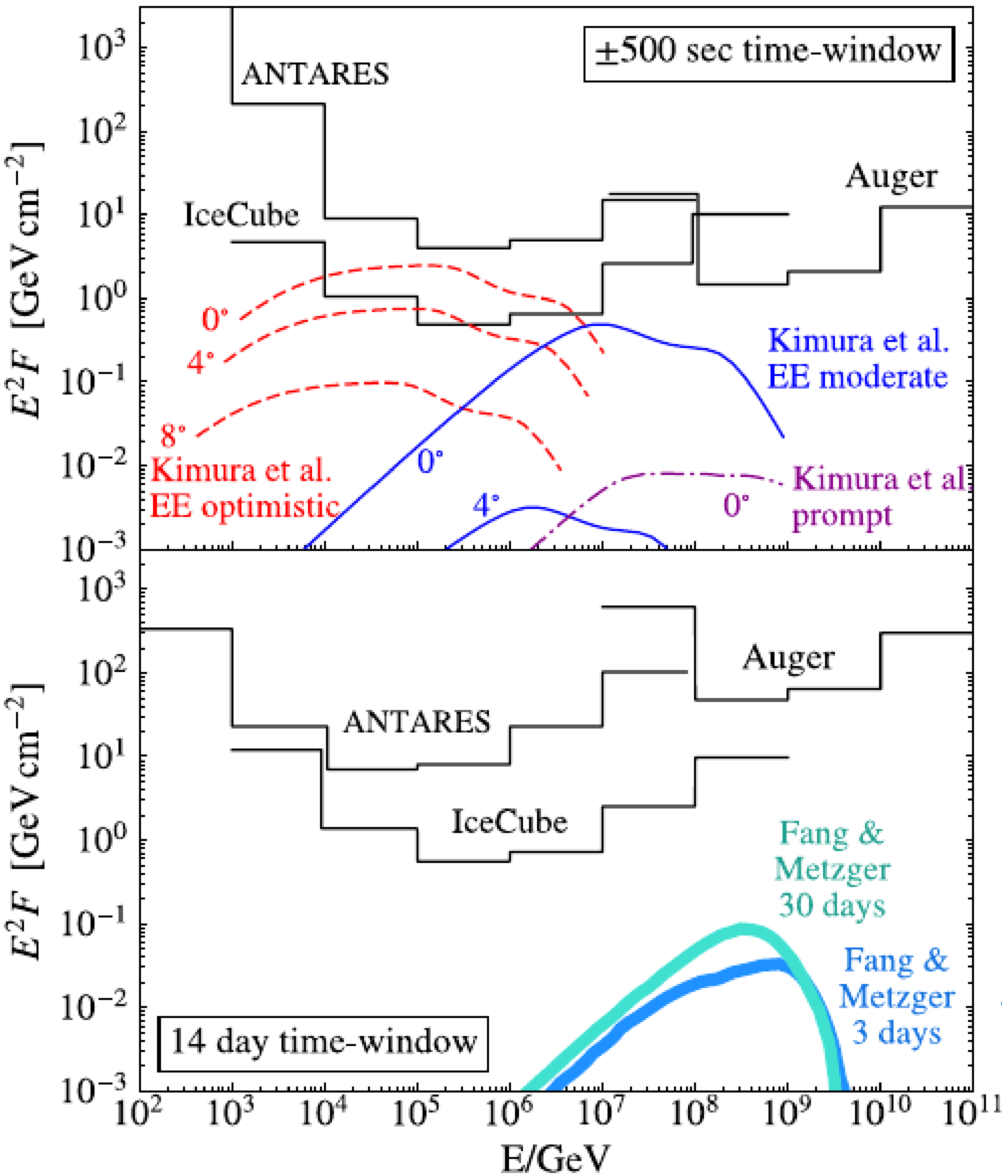
Search for diffuse high energy neutrinos

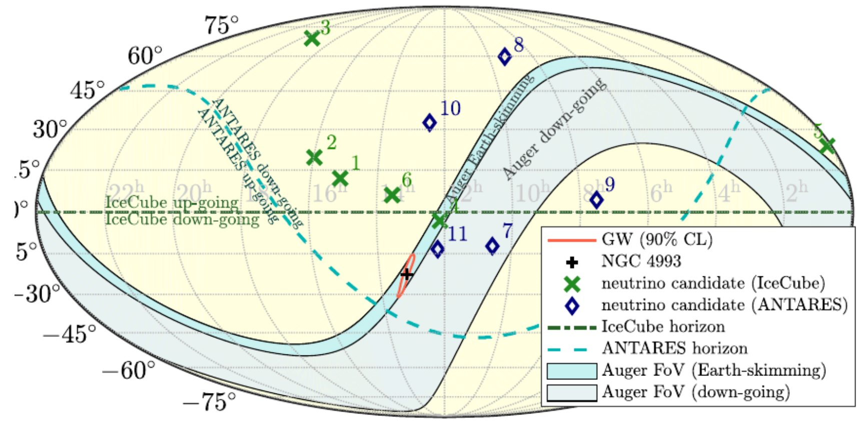
Neutrinos (cosmogenic) could form in GZK process:

$$p + \gamma_{CMB} \longrightarrow n + \pi^+ \longrightarrow n + \mu^+ + \nu_\mu \longrightarrow n + e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$



GW170817 merger





No neutrino events detected in either of the two time windows

More information at:

Search for High-energy neutrinos from binary neutron star merger GW170817 with ANTARES, IceCube, and the Pierre Auger Obervatory, http://doi.org/10.3847/2041-8213/aa9aed

Backup references

1. A. Aab *et al.*, Pierre Auger Collaboration, *Search for photons with energies above 10^{18} eV using the hybrid detector of the Pierre Auger Observatory*, JCAP **04** (2017) 009.
2. A. Aab *et al.*, *Improved limit to the diffuse flux of ultrahigh energy neutrinos from the Pierre Auger Observatory*, Phys. Rev. **D** 91 (2015) 092008.
3. *Search for High-energy neutrinos from binary neutron star merger GW170817 with ANTARES, IceCube, and the Pierre Auger Obervatory*, Astropart. J. Lett. 850:L35 (2017) 18pp, http://doi.org/10.3847/2041-8213/aa9aed.