Measurements of the mass composition of UHECRs with the Pierre Auger Observatory

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12.10.16

UHECR16 – Kyoto, Japan

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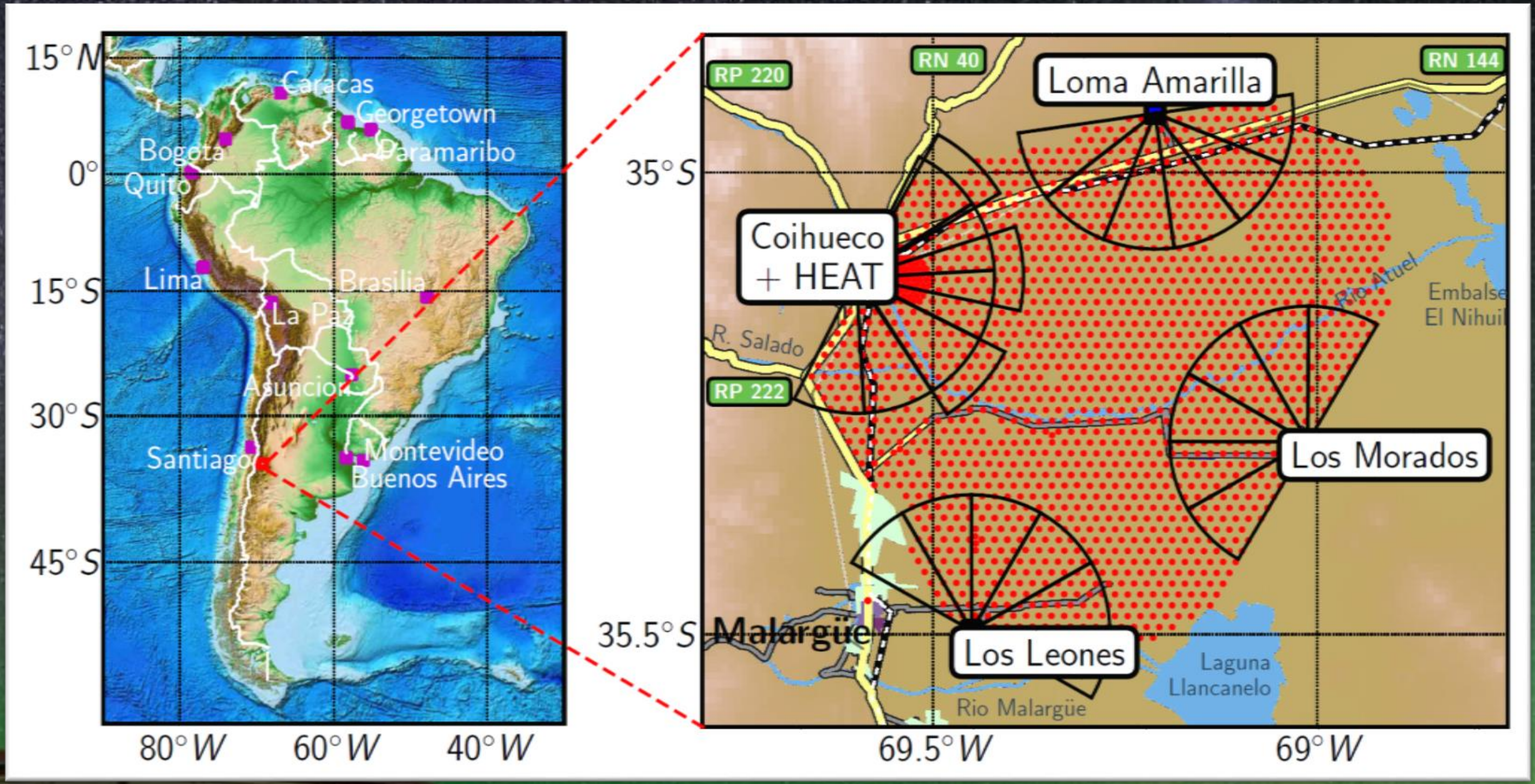
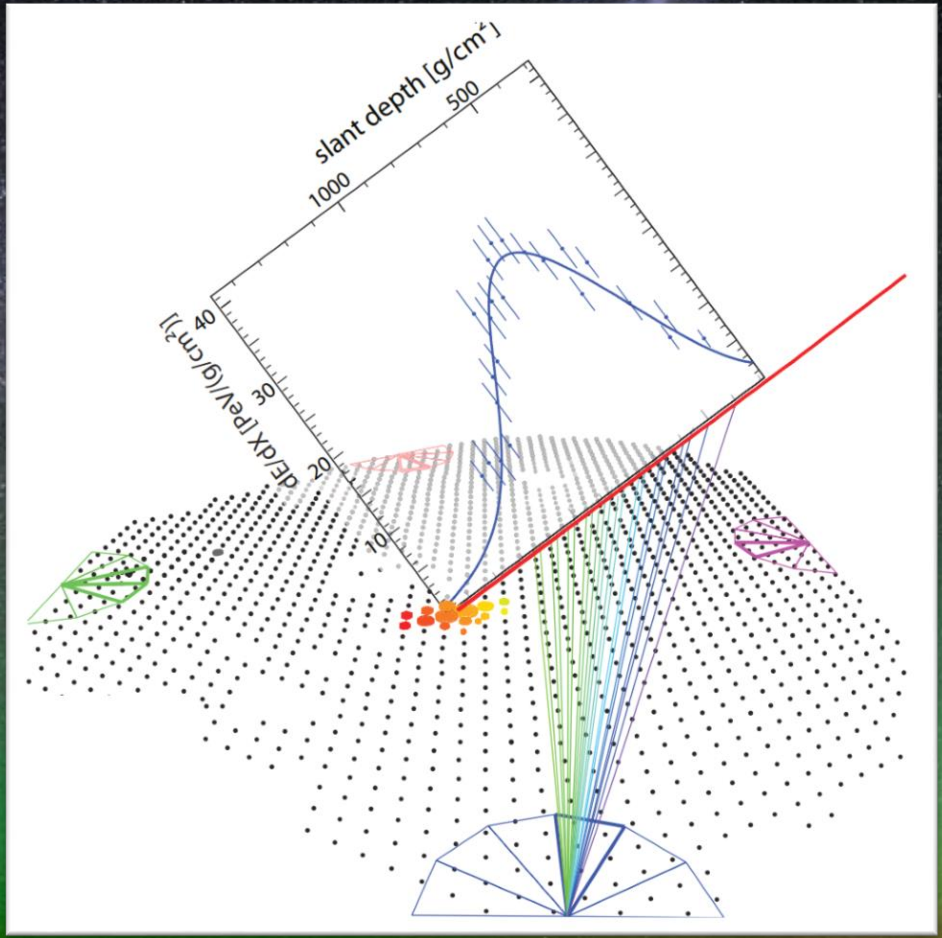
Outline

- Pierre Auger Observatory
- Composition measurements
  - X_{max} moments
  - FD and SD correlation study
- Summary and outlook



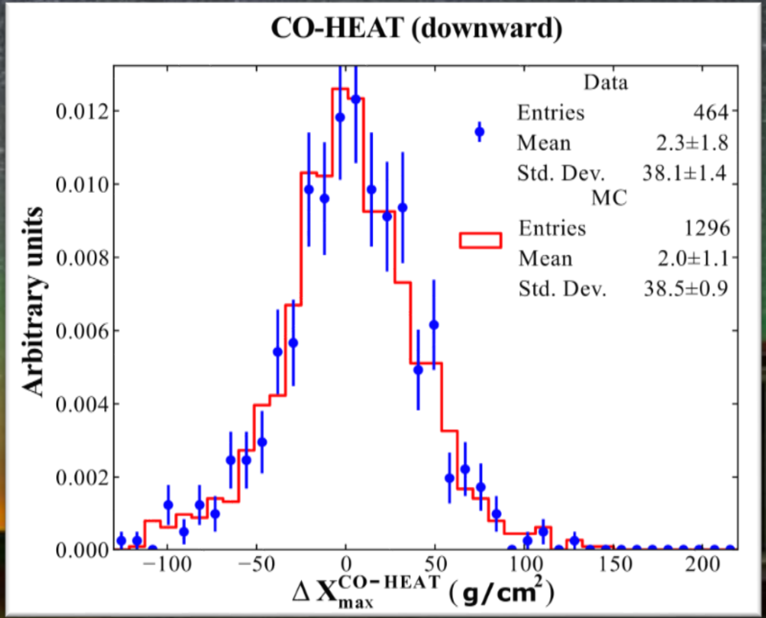
Hybrid Detector of UHECRs

- 1660 water Cherenkov stations
  - Study lateral shower signal on the ground
- 24 + 3 fluorescence telescopes
  - Study longitudinal shower profiles in the atmosphere
- Hybrid detection allows extensive studies of the arrival direction, energy and **chemical composition** of UHECRs

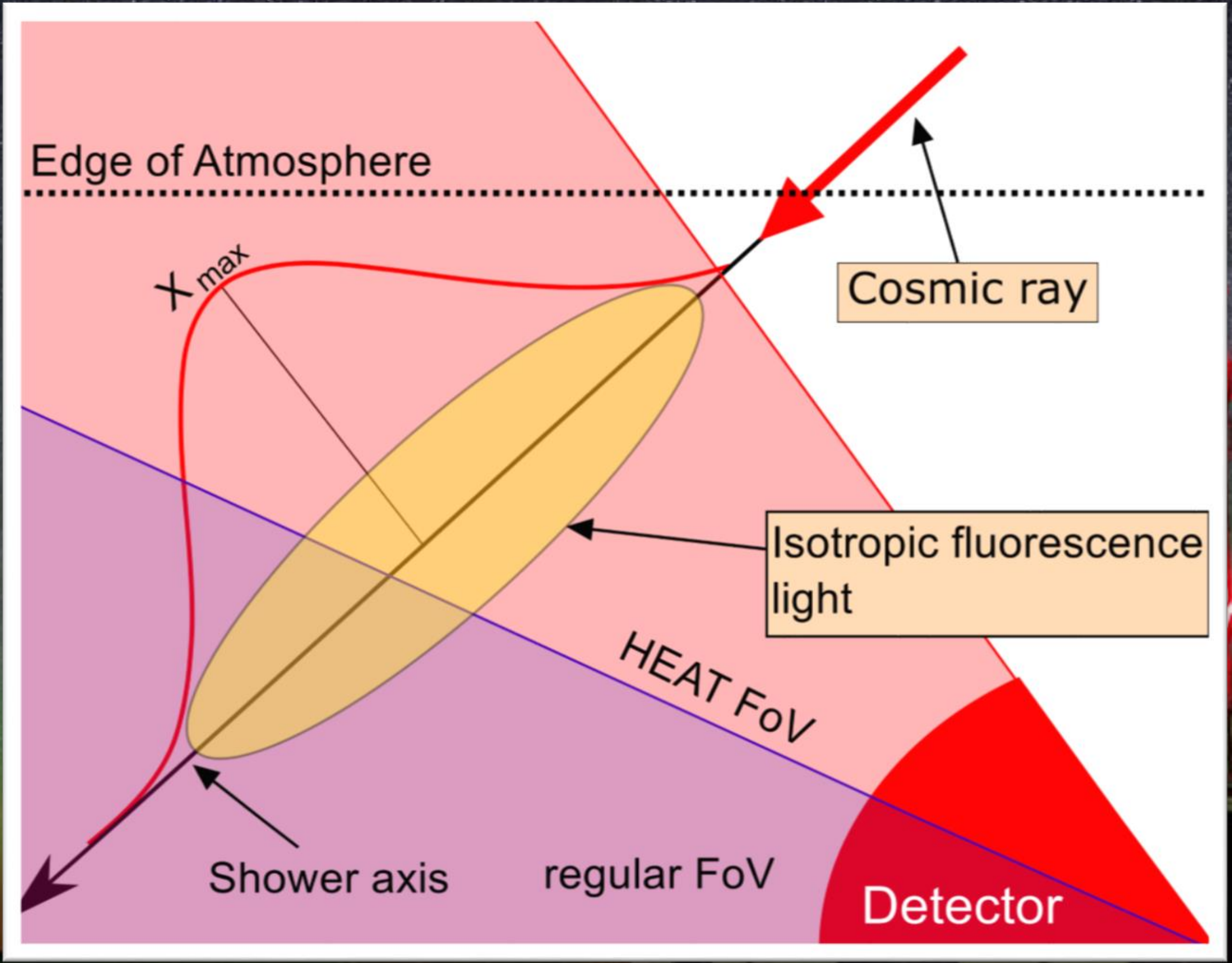


High Elevation Auger Telescopes (HEAT)

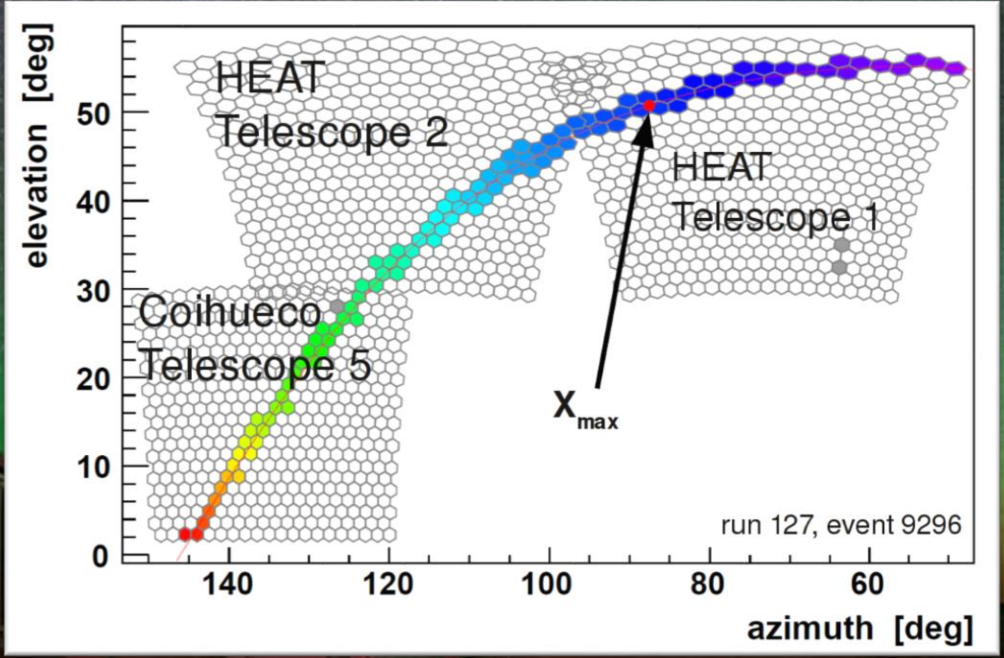
- Low energy telescope enhancement next to regular FD station ‘Coihueco’
- Lower energy threshold down to 10^{17} eV
- 30° tiltable telescopes
  - Upward mode (Normal operation)
  - Downward mode (especially systematic studies)



Virtual telescope HECO (HEAT + Coihueco)



- Low energy cosmic ray produce less fluorescence light
  - Only near air shower can be studied
- Extended field of view is needed to study X_{max}

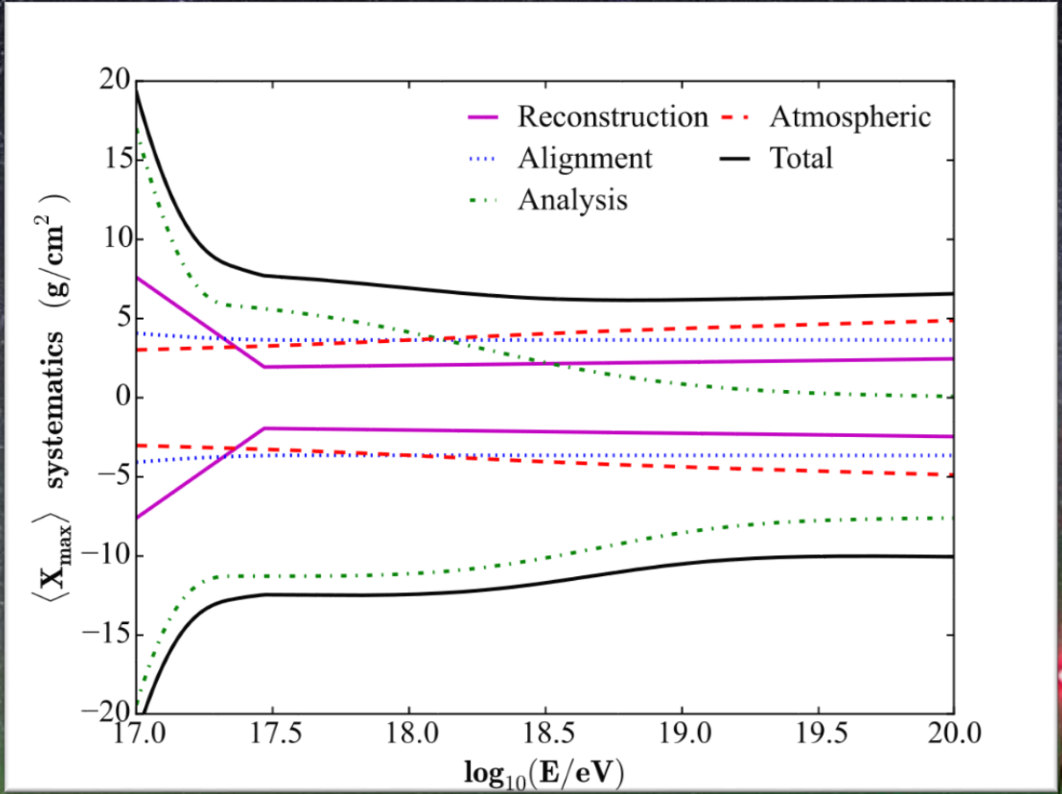


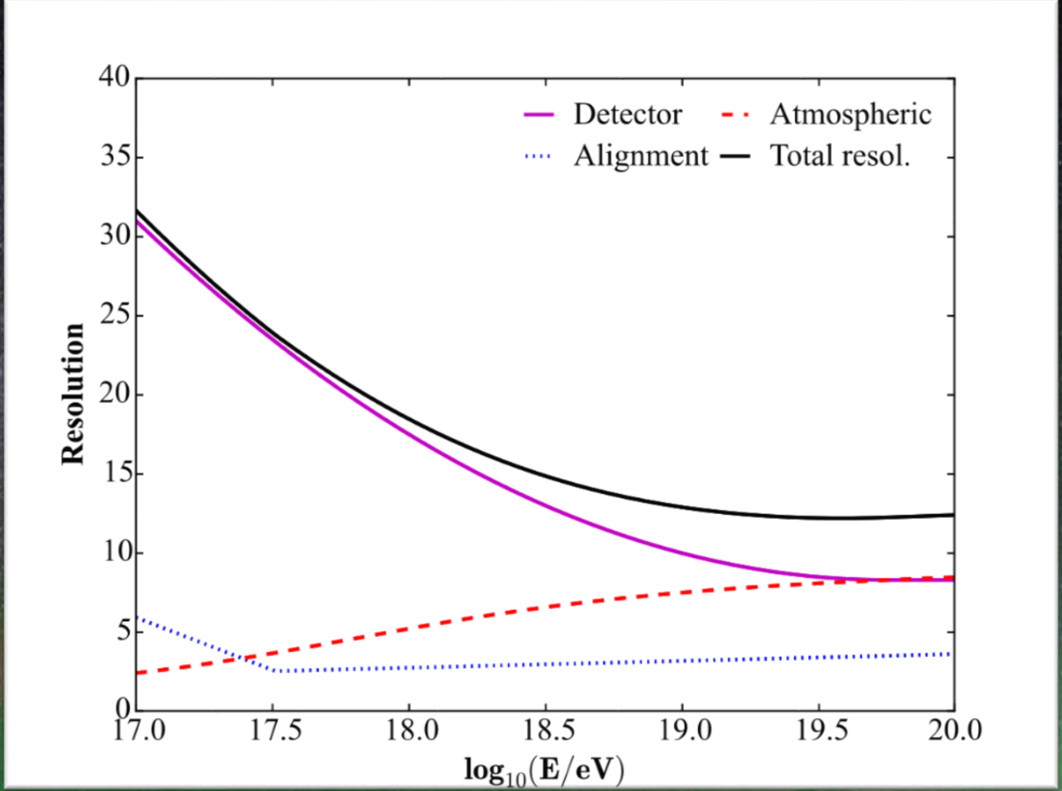
FD Data Selection for X_{max} Study

- Regular FD telescopes (LL,LM,LA,CO)
  - 01.12.2004 and 31.12.2012
  - $>10^{17.8}$ eV
- Virtual telescope HECO
  - 01.06.2010 and 15.08.2012
  - 10^{17} to $10^{18.3}$ eV

Quality Selection	
Data and detector status	• Good data periods and camera calibrations • Measured aerosol profile • Reject high aerosol periods (VAOD @ 3 km < 0.1) • Reject high cloud contamination
X_{max} and energy reconstruction	• Hybrid geometry reconstruction • Good X_{max} and energy reconstruction • Observed X_{max} with expected resolution < 40 g/cm² • Reduced χ^2 of profile fit normal distributed
Field of view	• Unbiased dataset with fiducial field of view analysis
HECO	• Considered higher trigger probability of Fe-like events in SD • SD, HEAT and CO must be able to trigger simultaneously

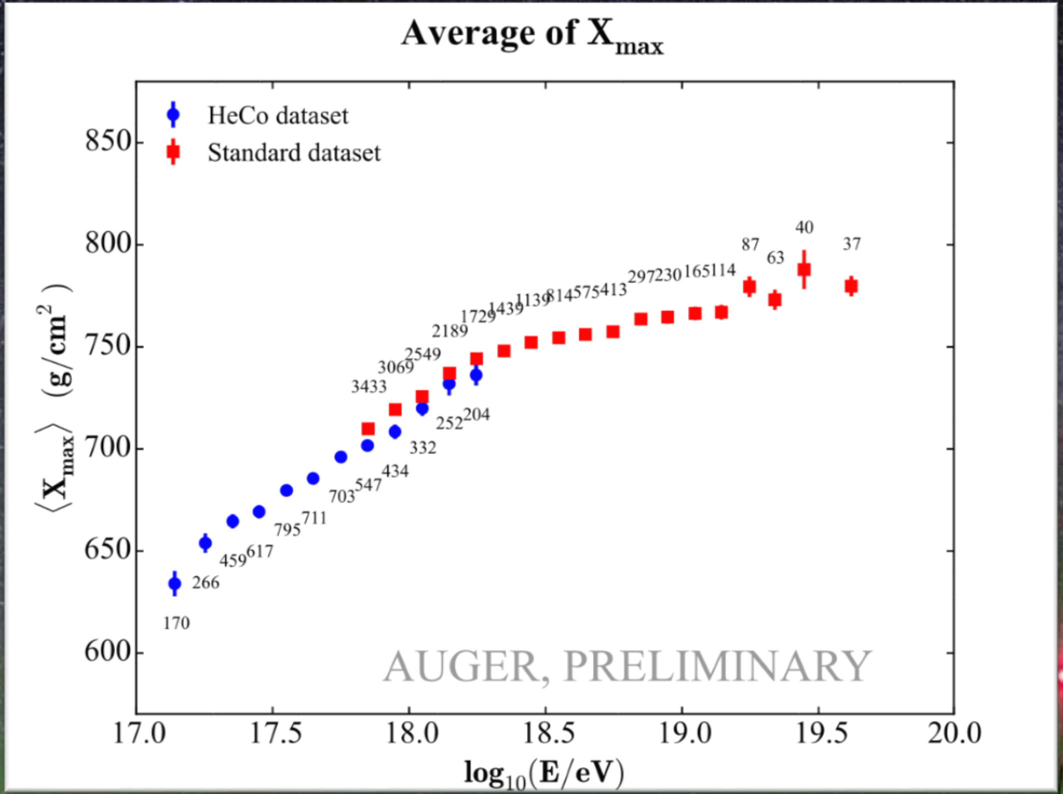
X_{max} Systematic Uncertainties & Resolution

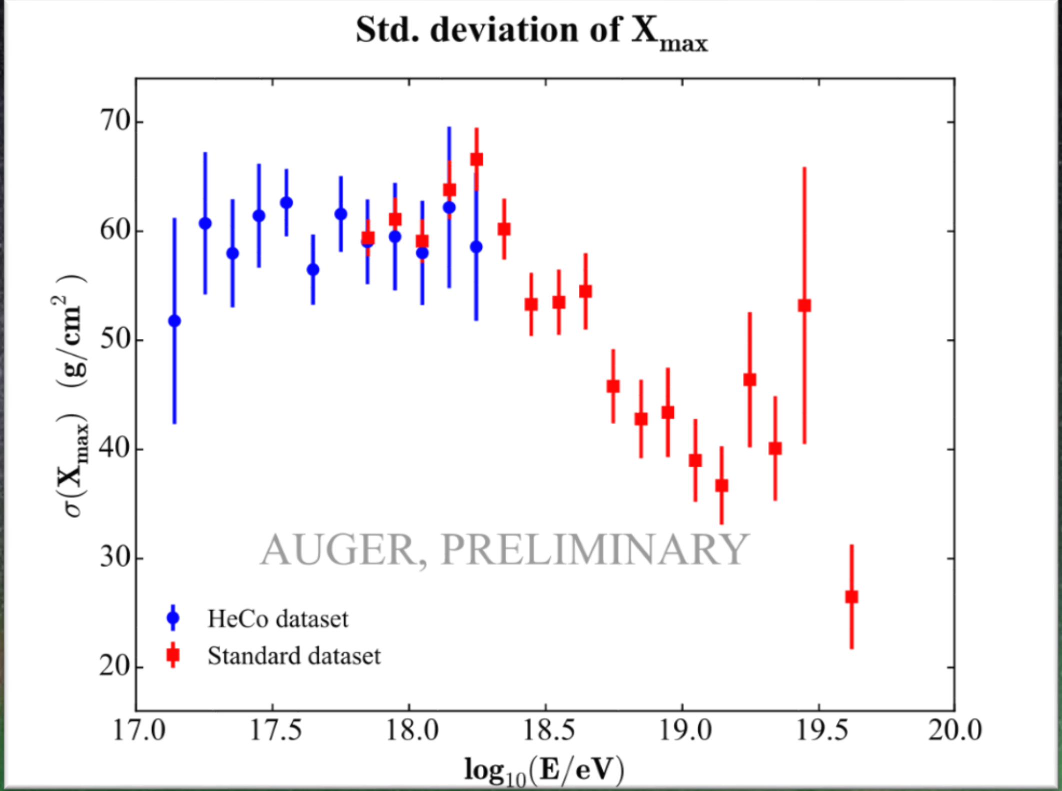




- Reconstruction bias and detector resolution
- SD-FD timing, calibration and telescope alignment
- Analysis
- Atmospheric uncertainty and fluorescence light yield

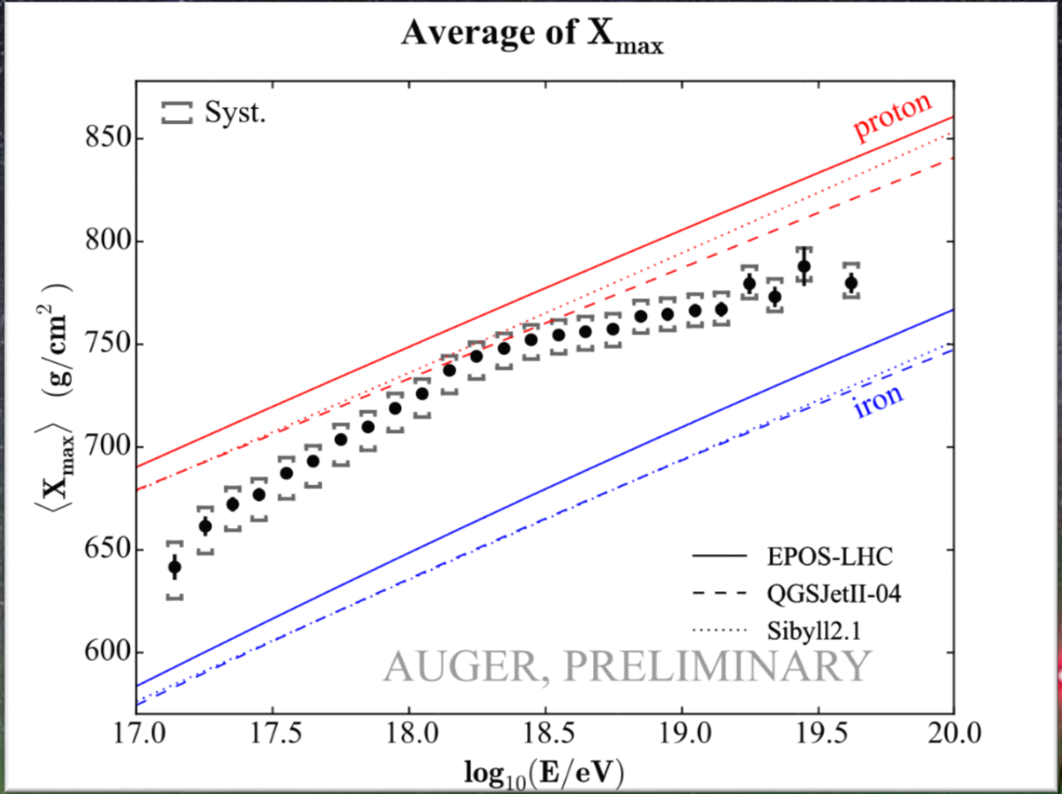
Standard vs HECO X_{max} Moments

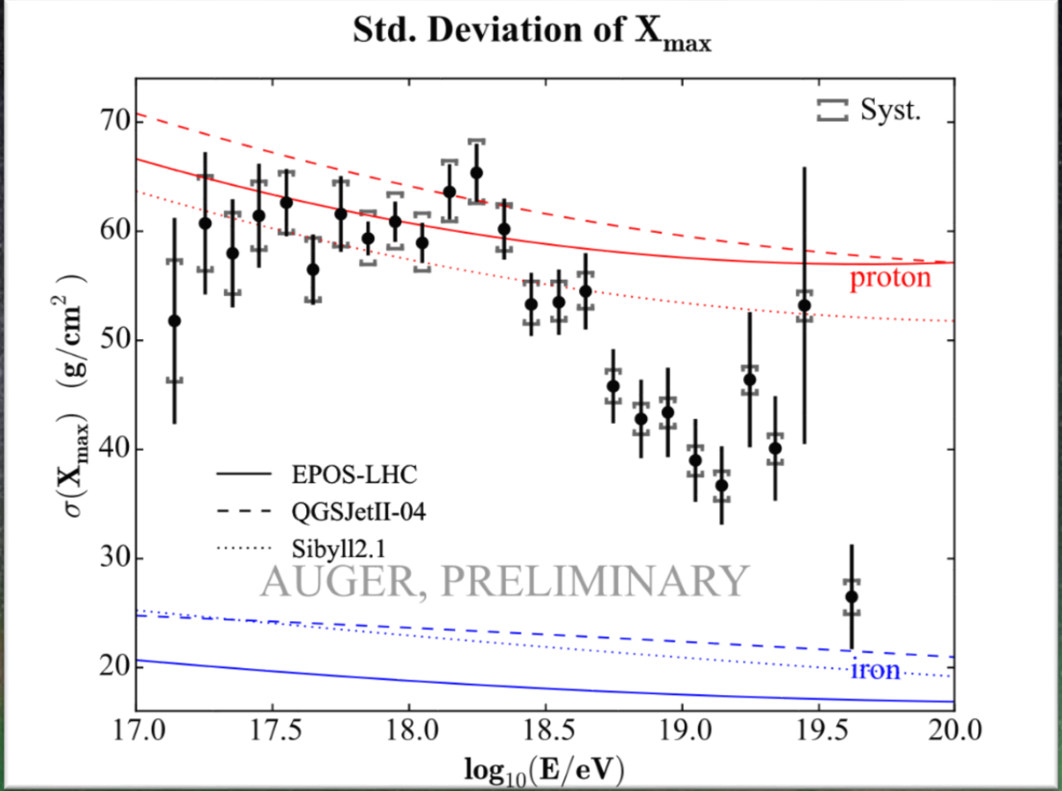




- Standard FD and HECO are statistically independent data sets
- Small systematic shift of the mean (~7 g/cm²) – Under investigation
- Overall good agreement inside the uncorrelated systematic uncertainty

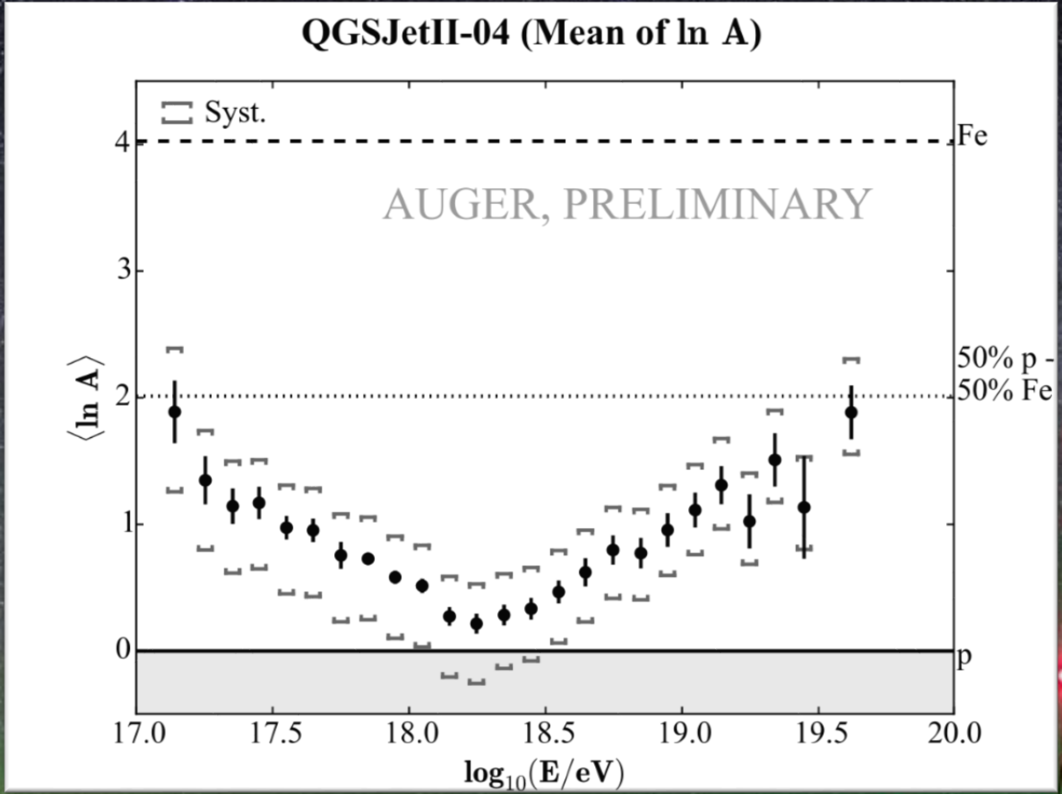
X_{max} Moments

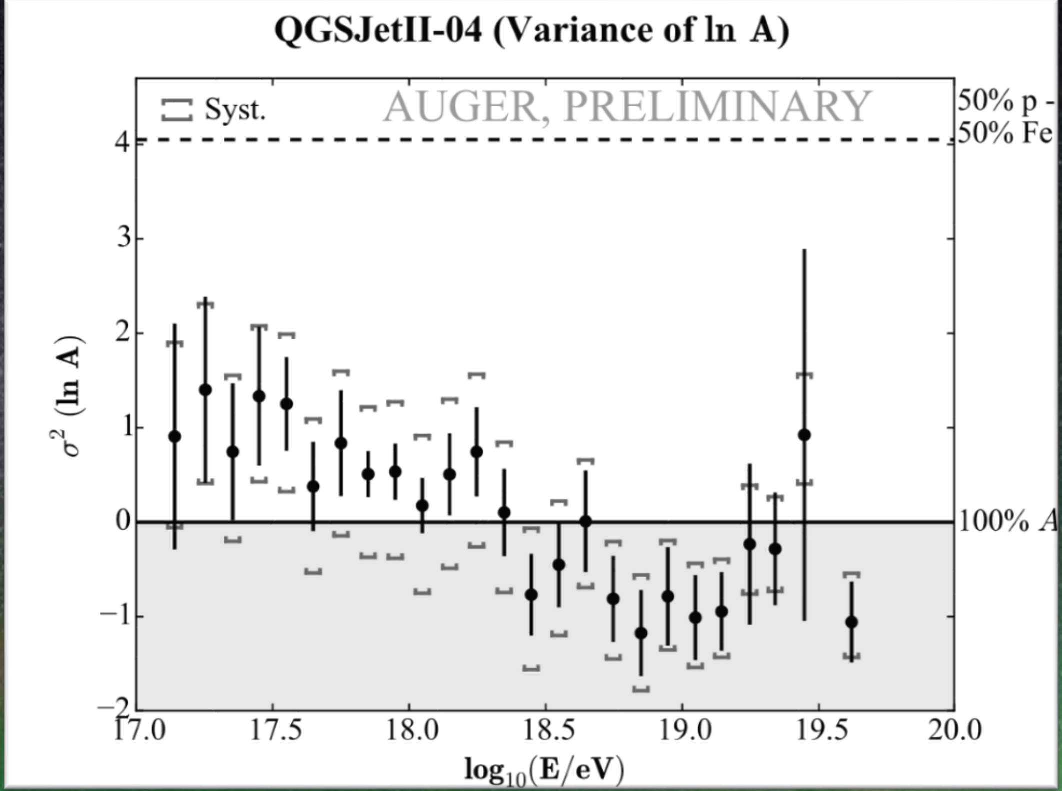




Combination of the data sets shows a change in the mass composition at ~$10^{18.3}$ eV

Ln A Moments QGSJetII-04

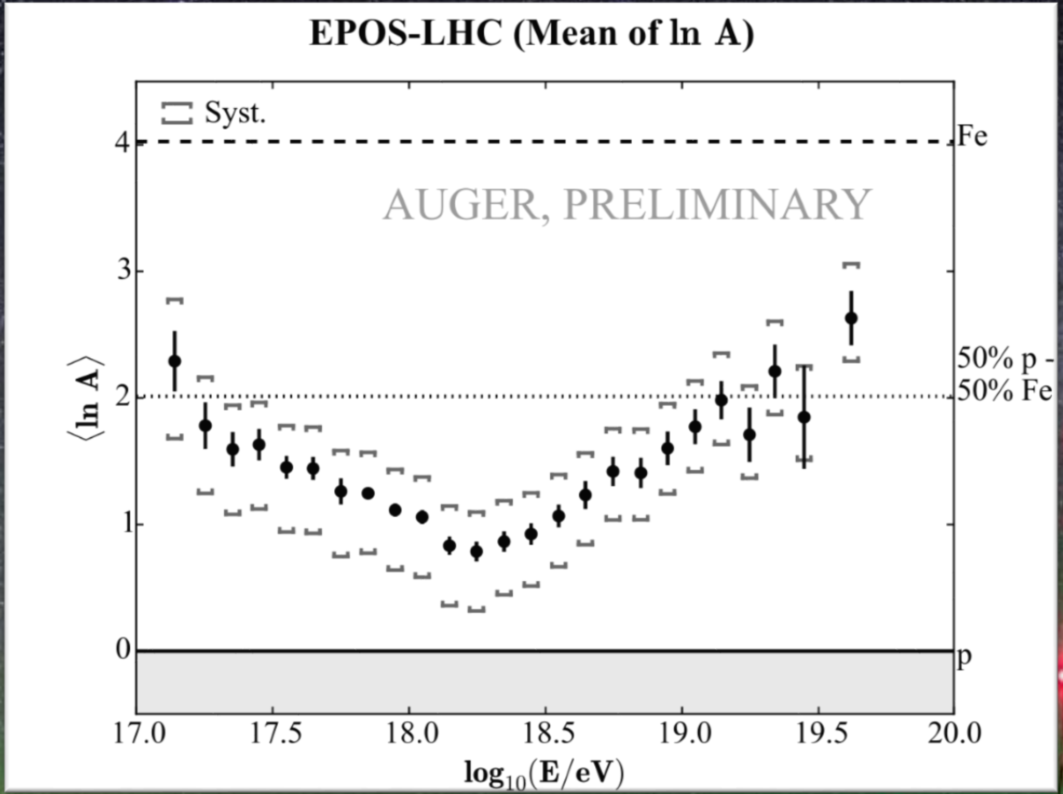


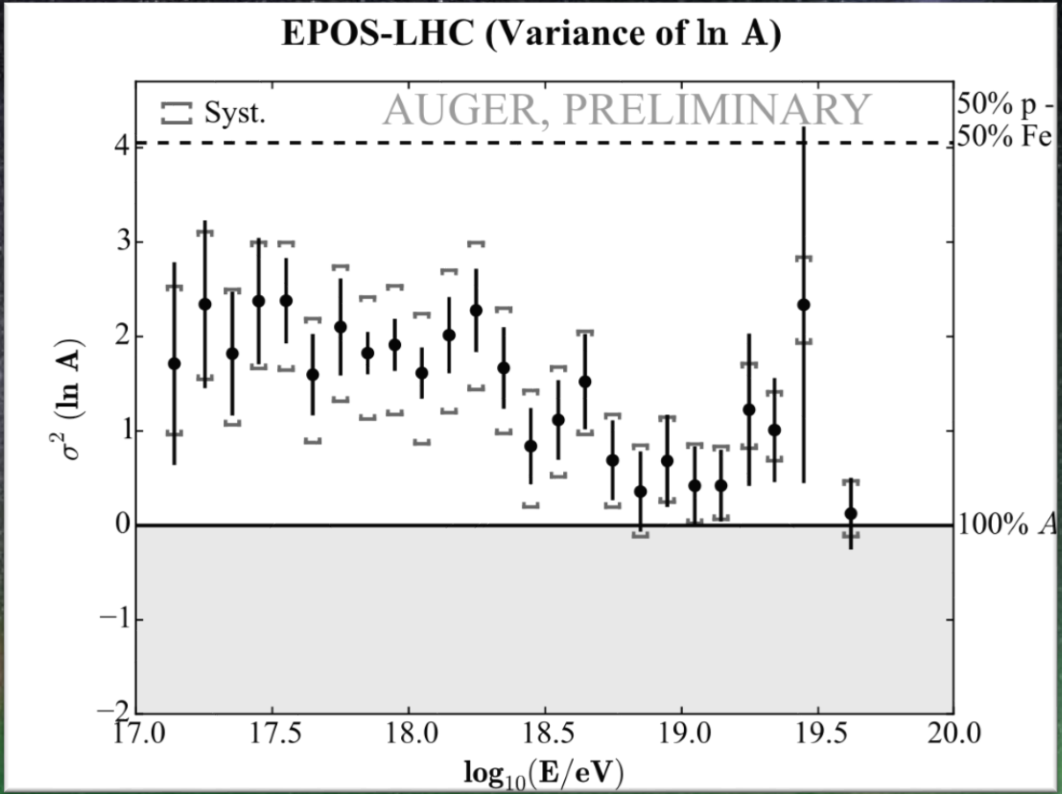


Low energy: largest mass dispersion, dominated by intermediate and heavy primaries

High energy: from the lightest at $10^{18.3}$ eV to heavier with less dispersion of masses

Ln A Moments EPOS-LHC





Low energy: largest mass dispersion, dominated by intermediate and heavy primaries

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Arxiv 1609.08567, accepted from PLB

FD & SD Correlation Analysis

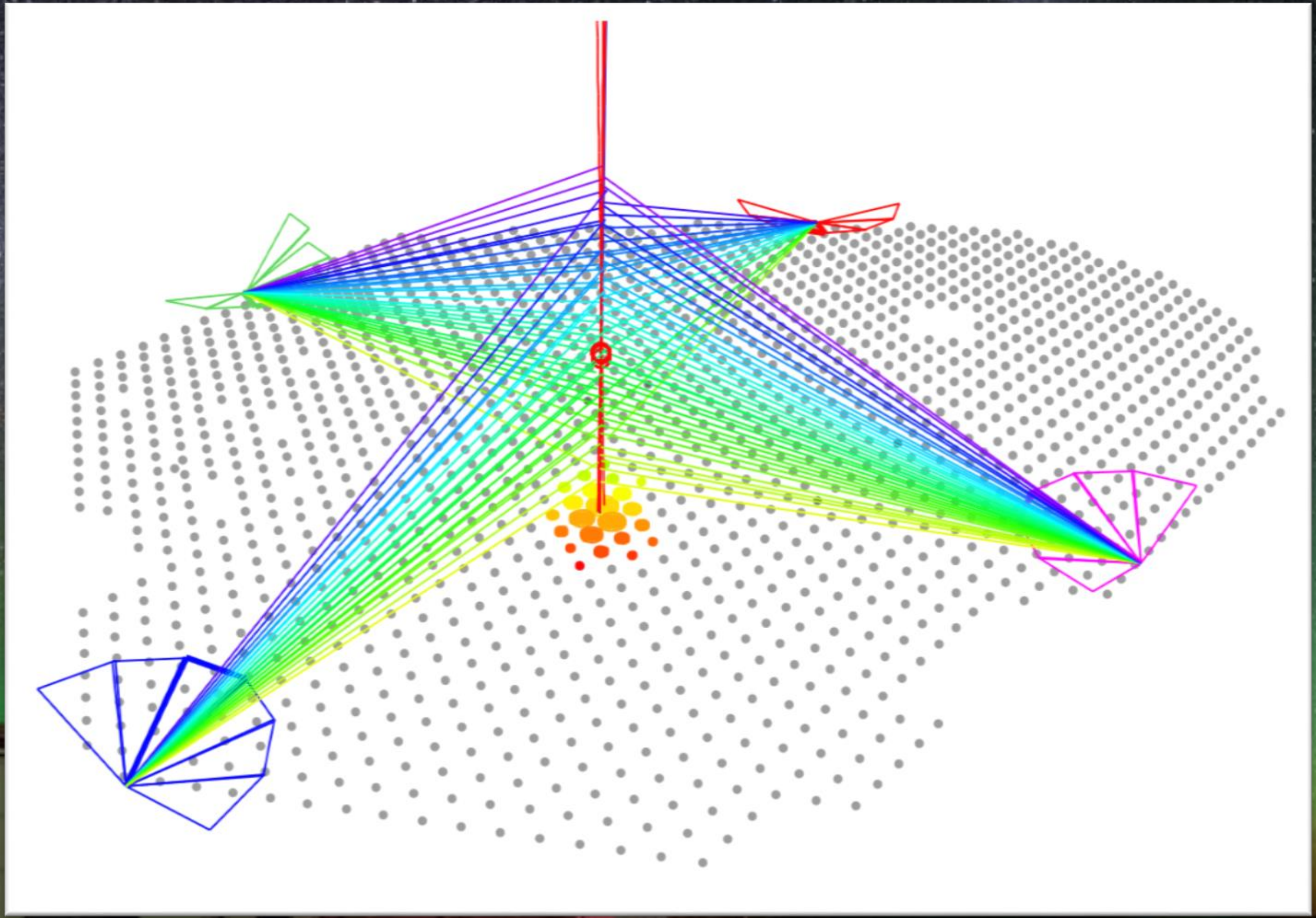
Check model independent composition observable by using the hybrid detector advantage

'Ankle' region: Log(E/eV) = 18.5 – 19.0

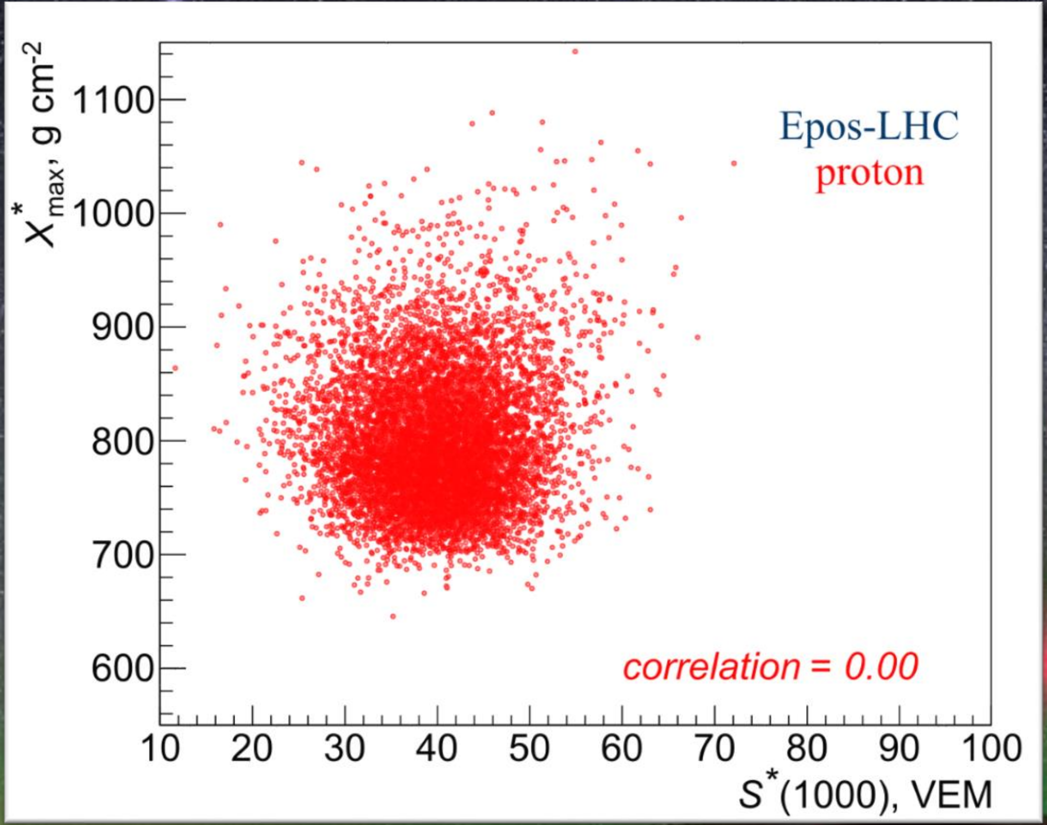
Basic observables for correlation analysis:

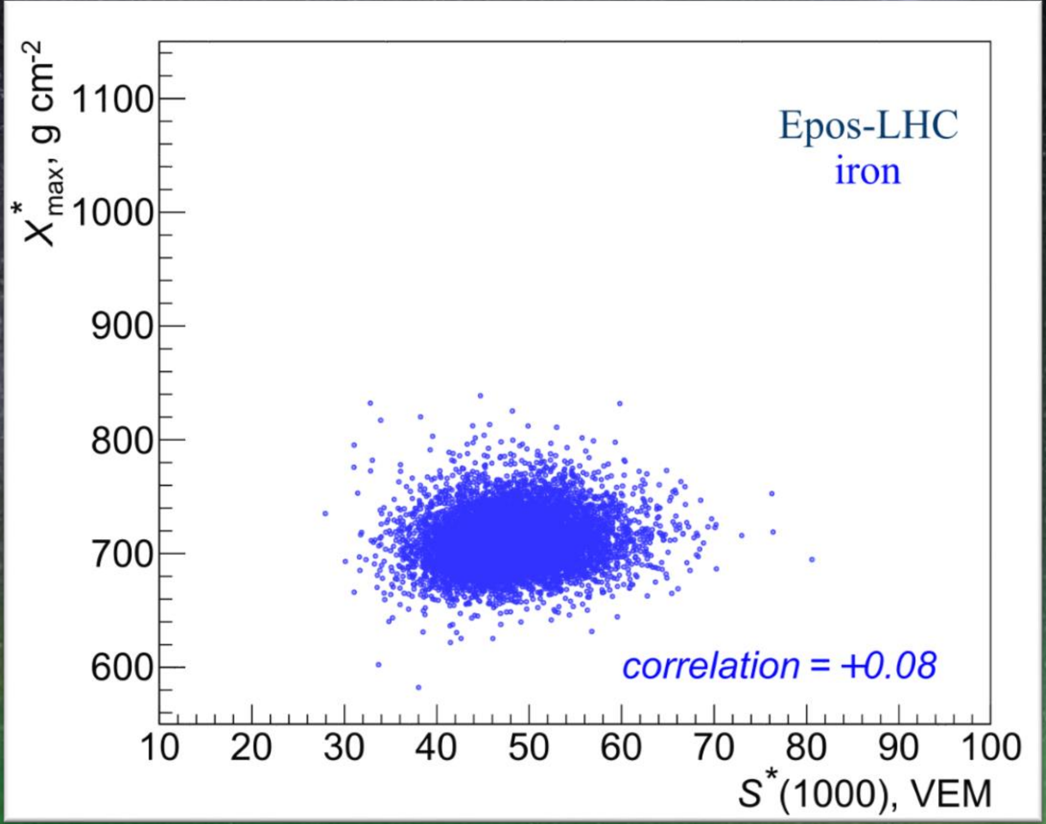
FD: X_{max} , scaled to 10 EeV called X^*_{max}

SD: signal at 1000 m from the core, S(1000), scaled to 10 EeV, 38° called S^*_{38}



Correlation $r_G(X^*_{max}; S^*(38))$ in Monte Carlo





Correlation between X^*_{max} and $S^*(38)$ depends on the purity of the primary beam

- ❖ Use ranking coefficient r_G [R. Gideon, R. Hollister, JASA 82 (1987) 656]

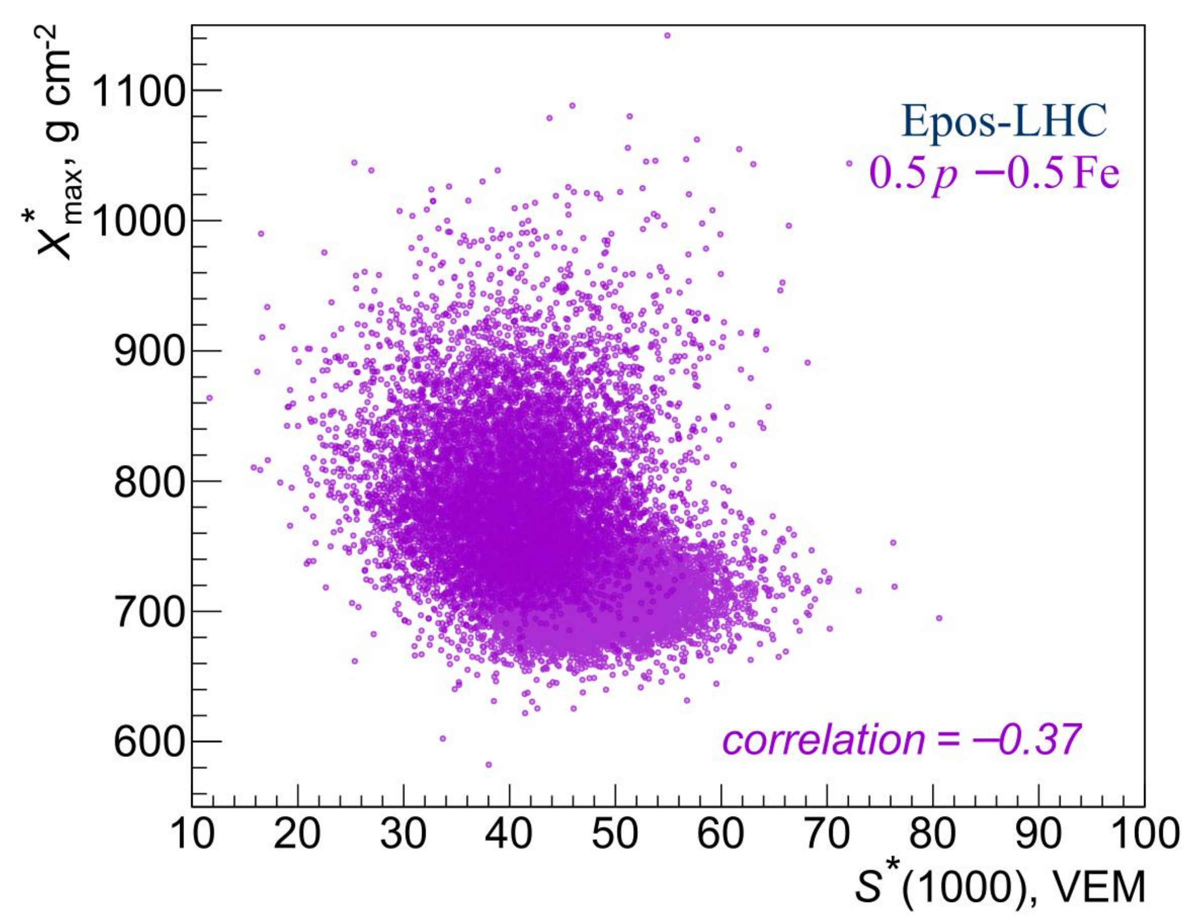
Pure compositions → correlation ≥ 0

Correlation $r_G(X^*_{max}; S^*(38))$ in Monte Carlo

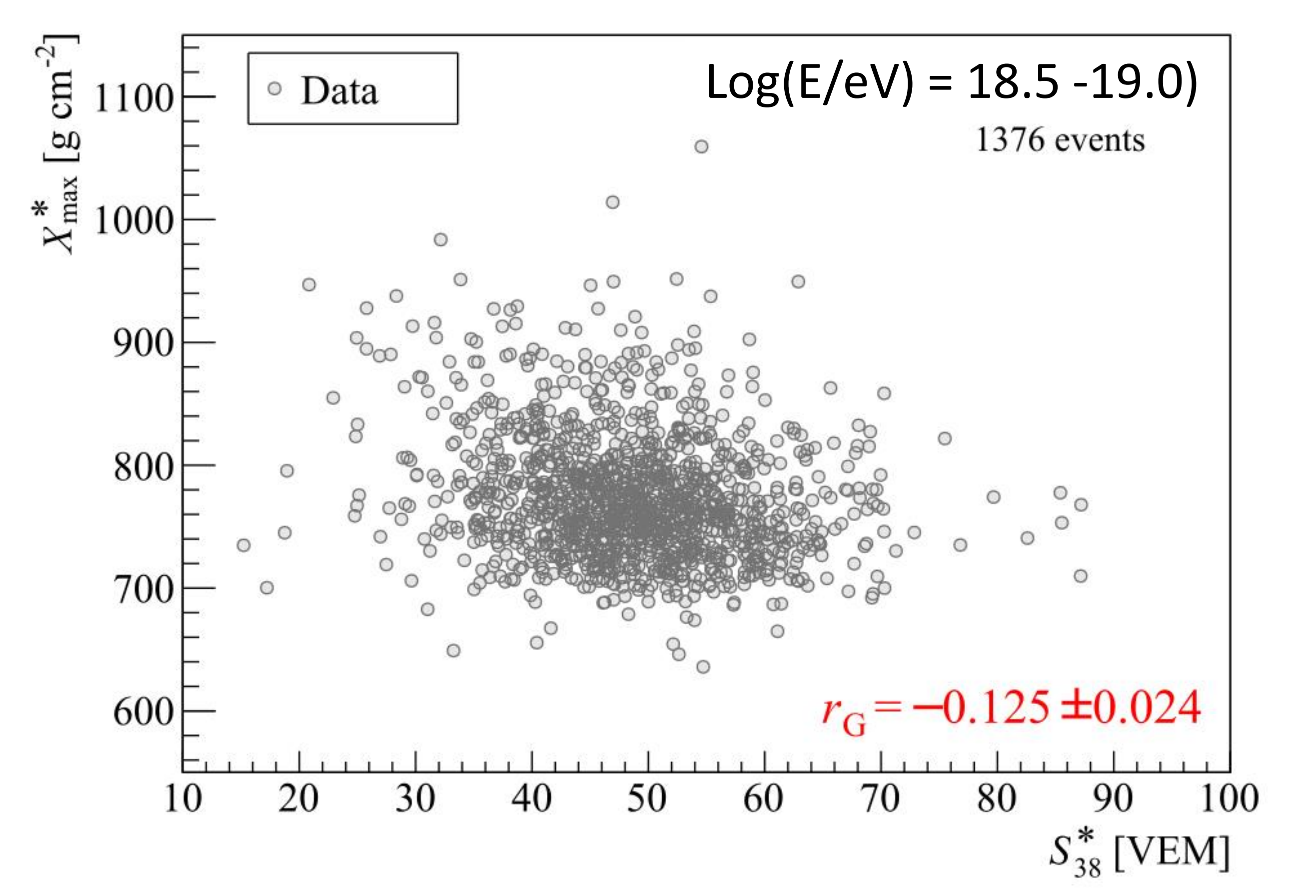
General characteristics of air showers:

- Heavier nuclei produce shallower showers with larger ground signal
- Minor model dependency

More negative correlation
→ more mixed composition



Correlation $r_G(X^*_{max}; S^*(38))$ in data



Correlation is significantly negative

$r_G(X^*_{max}; S^*(38))$ for protons:		
Epos-LHC	QGSJetII-04	Sibyll 2.1
0.00	+0.08	+0.07
Difference to data		
5 σ	8 σ	7.5 σ

Sys. uncertainty from X^*_{max} and $S^*(38)$

$\sigma_{sys}(r_G) \leq 0.01$

Composition is mixed, nuclei with A>4 are needed to explain data

$r_G(X^*_{max}; S^*(38))$ vs. σ(Ln A) from QGSJetII-04

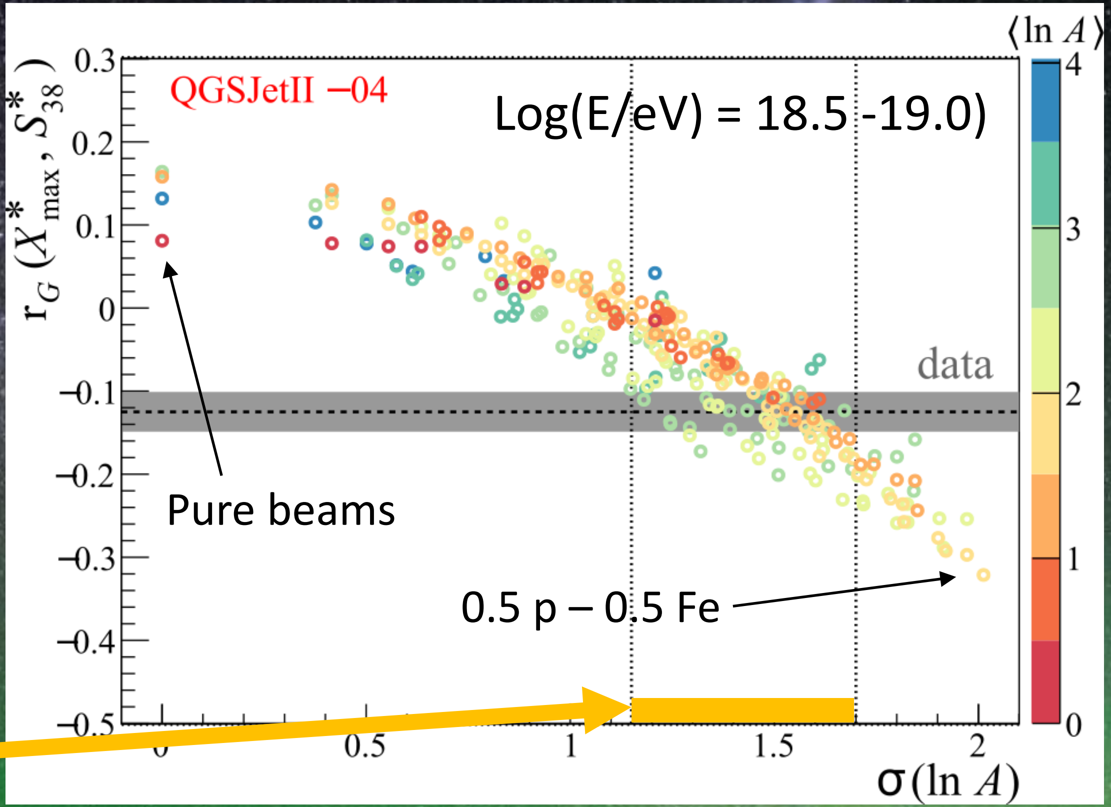
Use $r_G(X^*_{max}; S^*(38))$ to estimate the dispersion σ(Ln A) of primary masses:

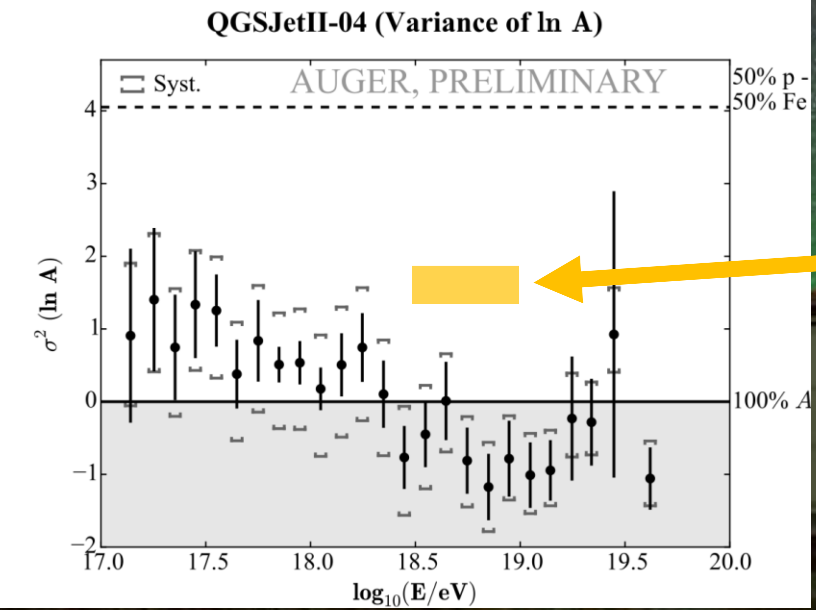
$$\sigma(\text{Ln A}) = \sqrt{\langle \text{Ln}^2 \text{ A}\rangle - \langle \text{Ln A}\rangle^2}$$

$$\langle \text{Ln A}\rangle = \textstyle\sum_i f_i \, Ln\, Ai$$

$$\langle \text{Ln}^2\text{A}\rangle = \textstyle\sum_i f_i \, Ln^2 A_i$$

f_i relative fractions of masses A_i = 1; … ;56





Data are compatible with dispersion of masses σ(Ln A) ≥ 1.1

$r_G(X^*_{max}; S^*(38))$ vs. σ(Ln A) from EPOS-LHC

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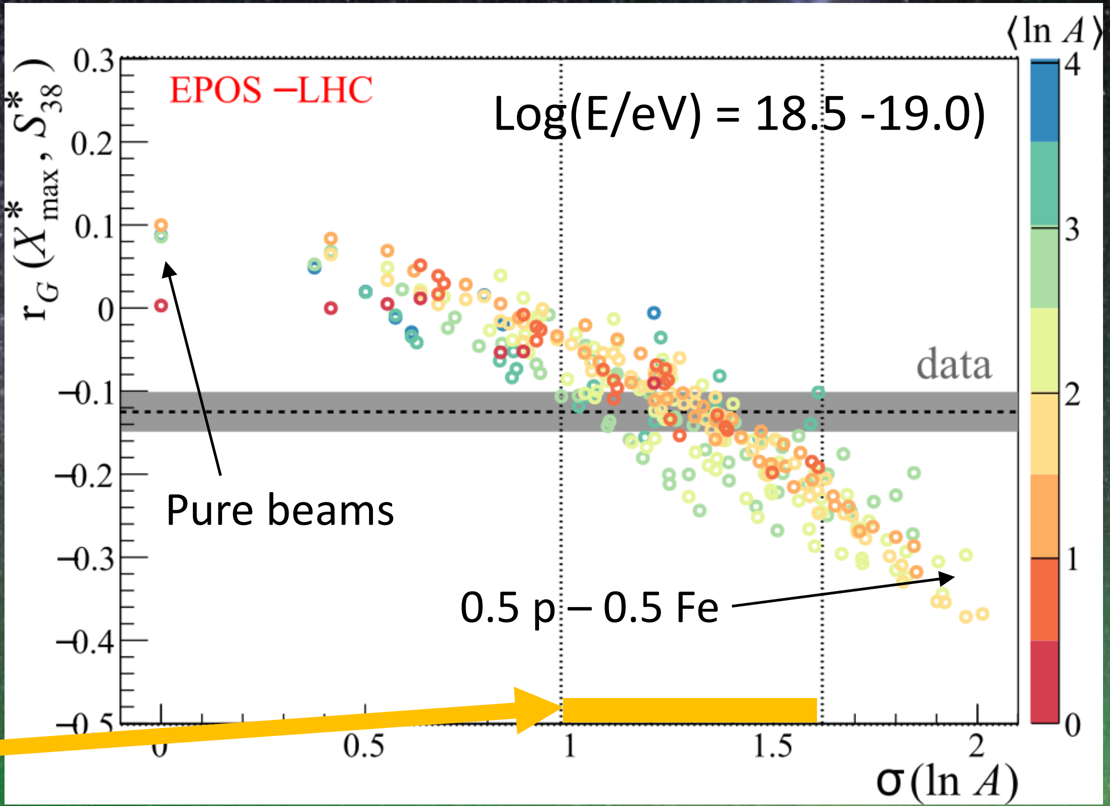
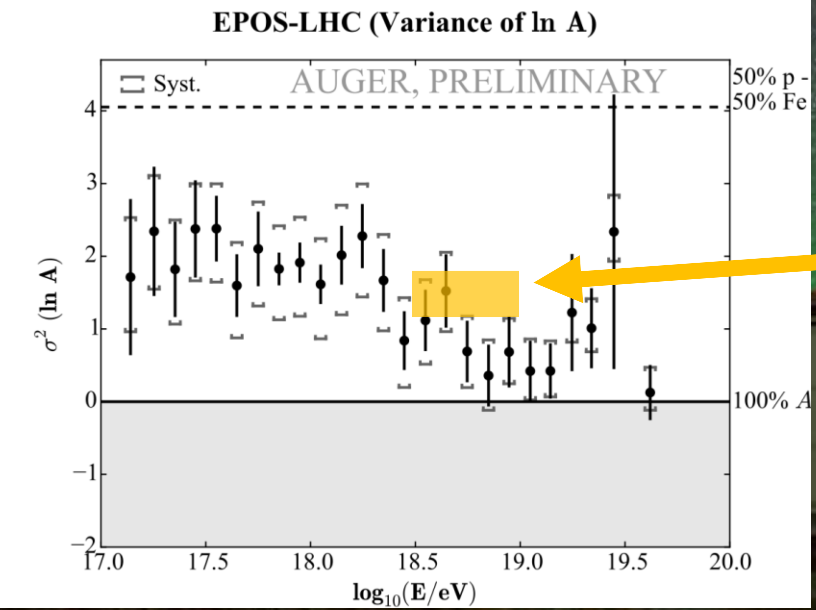




Data are compatible with dispersion of masses σ(Ln A) ≥ 1.0

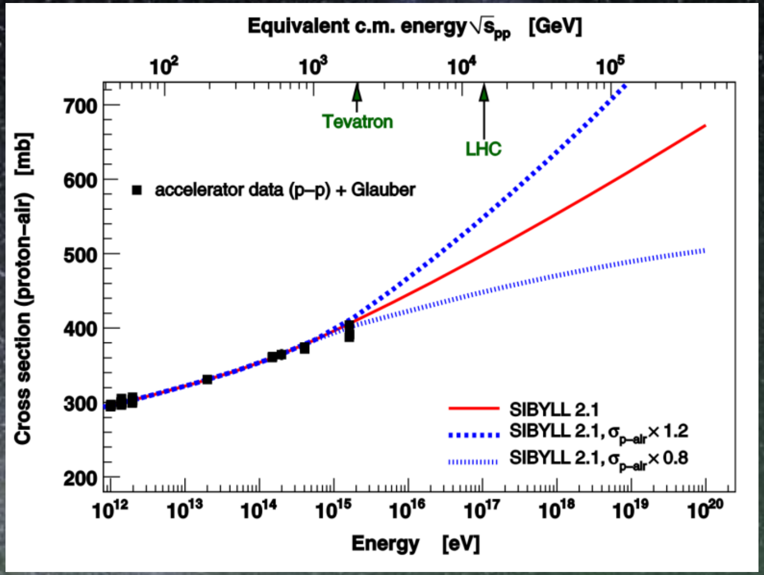
Correlation Systematic Uncertainties

Change proton-air interactions(study with CONEX 3D)

[T. Bergmann et al., ApP 26 (2007) 420, R. Ulrich et al., PRD 83 (2011) 054026]

- Modified parameters:
  - cross-section
  - elasticity
  - pion charge ratio
  - multiplicity

Only cross-section change result in r_G decrease by ≤ -0.06, but $\Delta r_G \approx 0$ (0°-45° Zenith) and $\Delta r_G \approx -0.1$ (45°-65° Zenith) - incompatible to data



Change of muon production factor by hadronic models

[G. Farrar for the Pierre Auger Collaboration (2013) arXiv:1307.5059, A. Aab et al., PRD 91 (2015) 032003]

- re-weighting of muons at ground by factor 1.3
  - ➢ r_G decrease by ≤ 0.03

Only small changes compared to difference between data and protons

Summary

- X_{max} moments are presented from 10^{17} eV to $10^{19.5}$ eV
- Ln A moments indicate a change in the composition of UHECRs:
  - From heavy to light to heavy composition

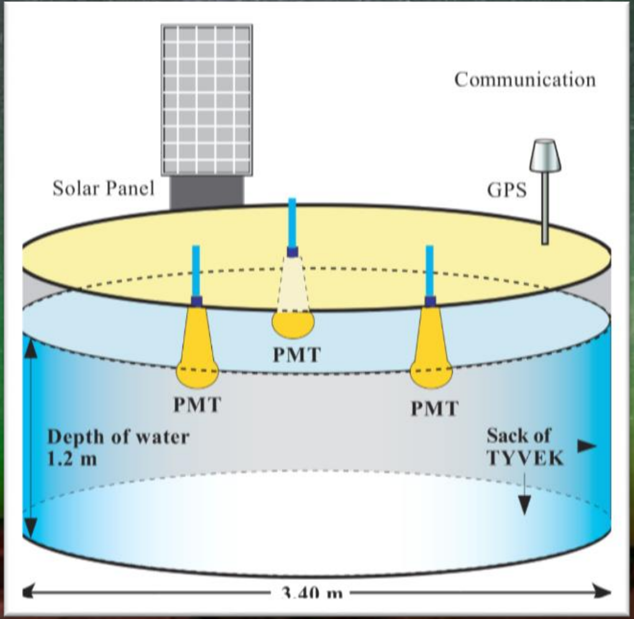
- Correlation analysis of FD and SD events are incompatible with pure composition at the ‘ankle’
- Cosmic ray composition is mixed with a **significance > 5 σ** independent of the hadronic interaction model in the energy range $10^{18.5}$ eV to $10^{19.0}$ eV
  - Nuclei A>4 are needed to describe the data

Outlook

- Publication of X_{max} moments including HECO events in preparation
- Additional data for both analysis will improve the results in the near future

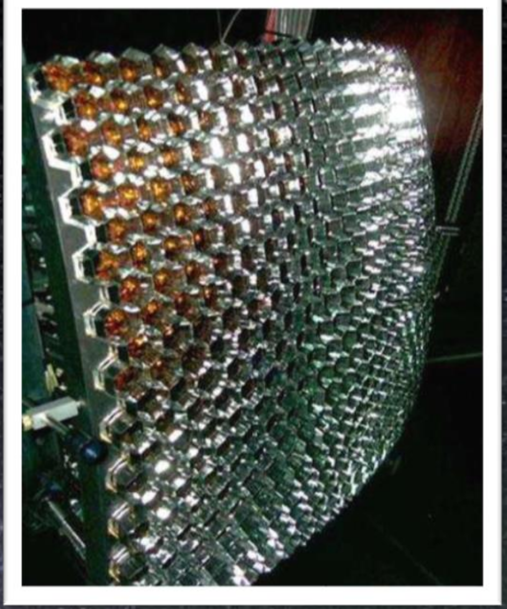
Surface Detector

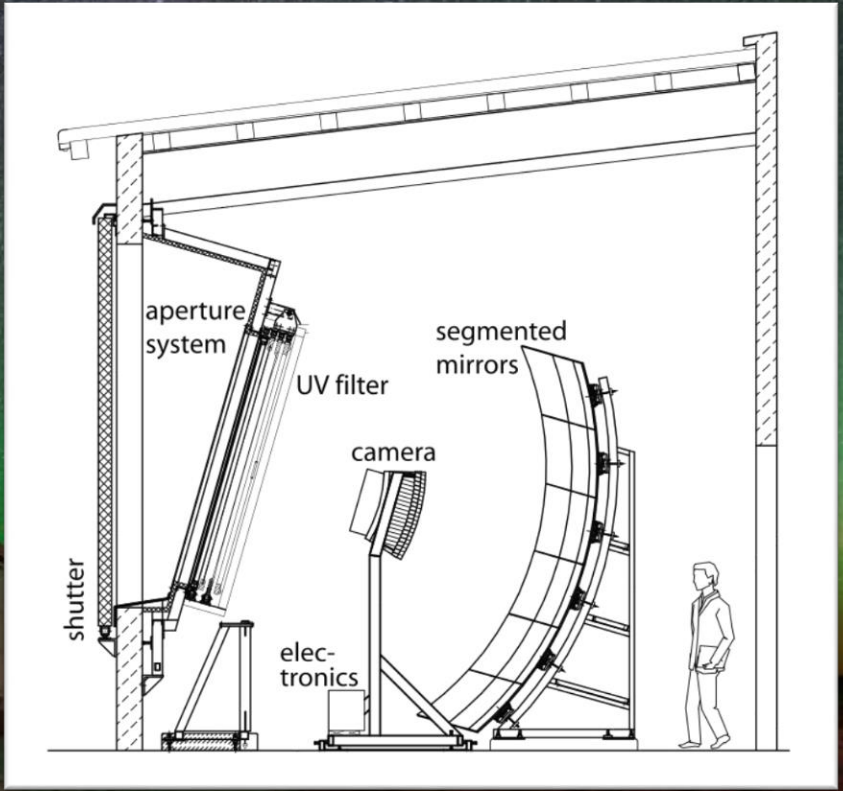
- Array of 1660 water autonomous Cherenkov detectors
- Covers 3000 km² on an 1500 m hexagonal grid
- 12 m³ pure water
- 3 PMTs per station
- Samples lateral shower profile
- Study energy and arrival direction
- Duty cycle 100%



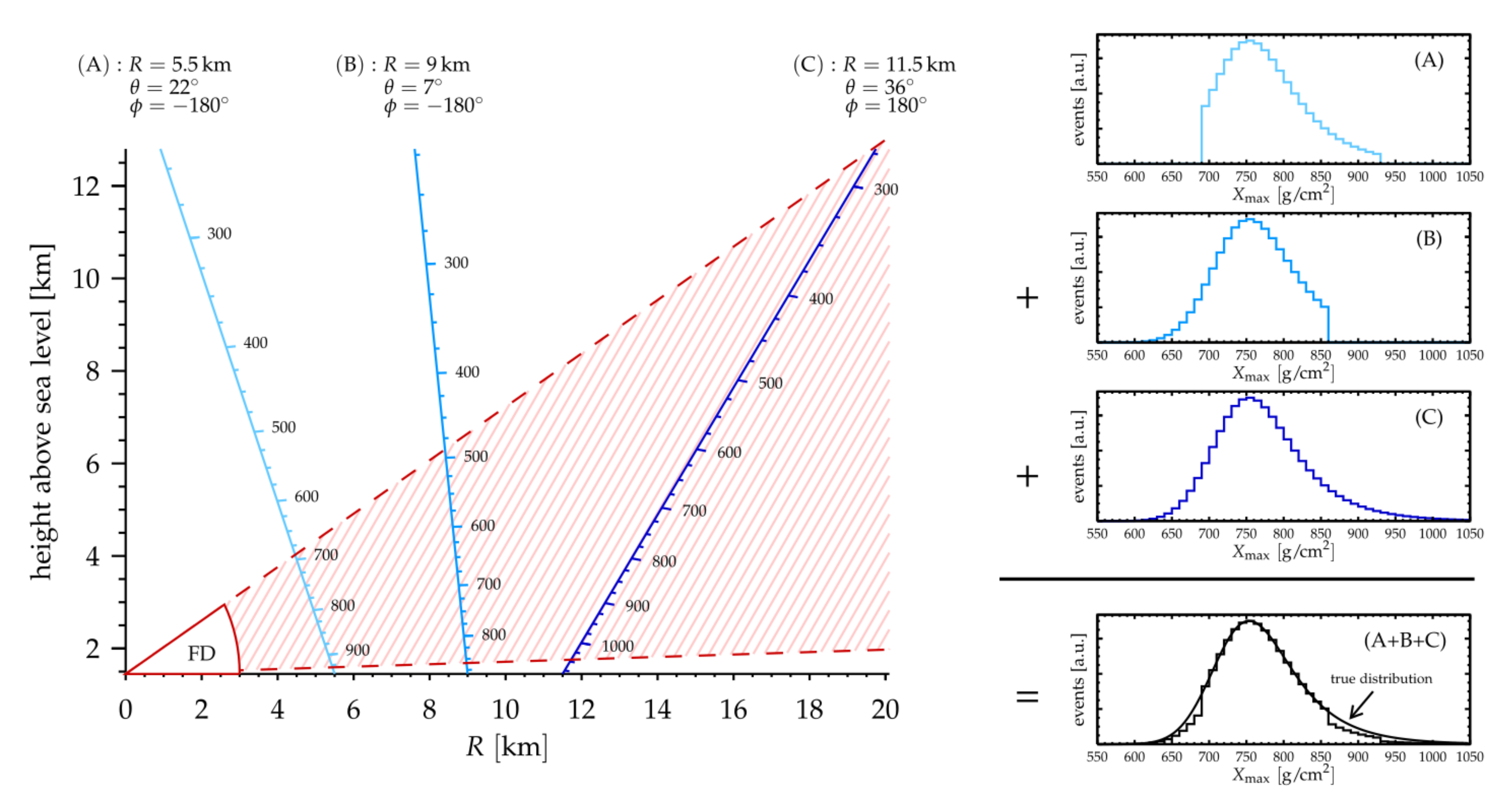
Fluorescence Detector

- 27 telescopes at the border of the SD array
- Segmented mirror with 13 m²
- 440 PMTs with each 1.5° field of view
- Each telescope 30° x 30° field of view
- Samples longitudinal shower profile
- Study energy, arrival direction and shower profile
- Duty cycle ~15% (only clear and moonless nights)

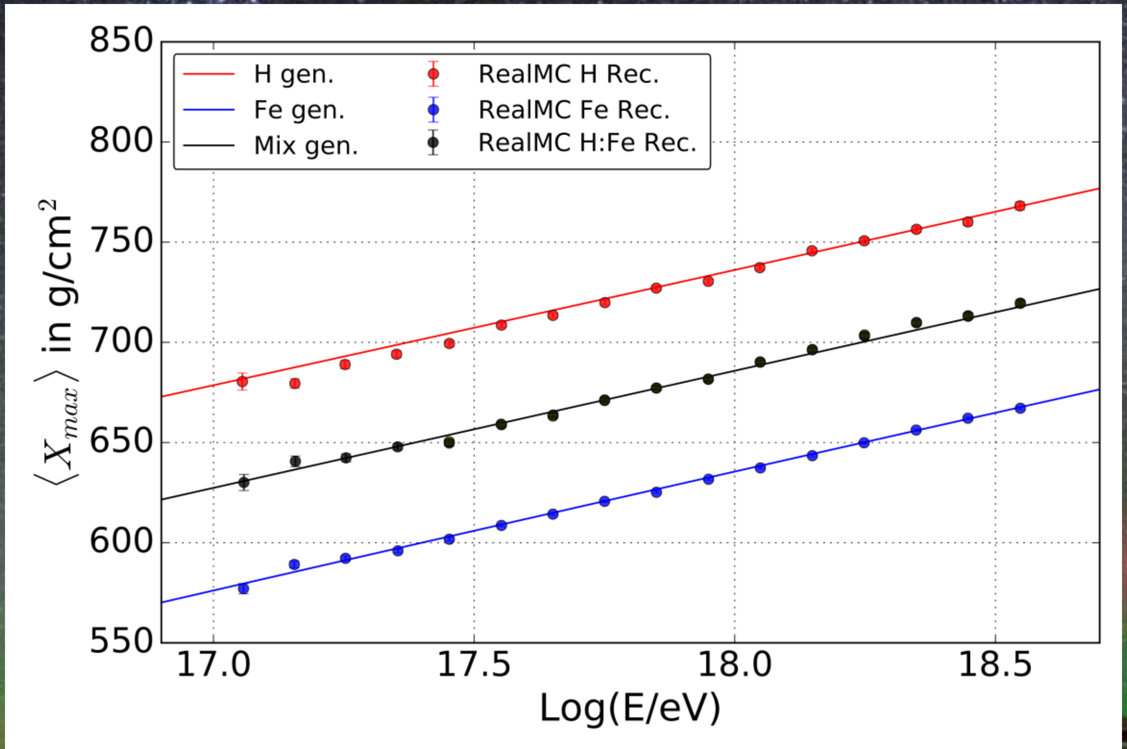


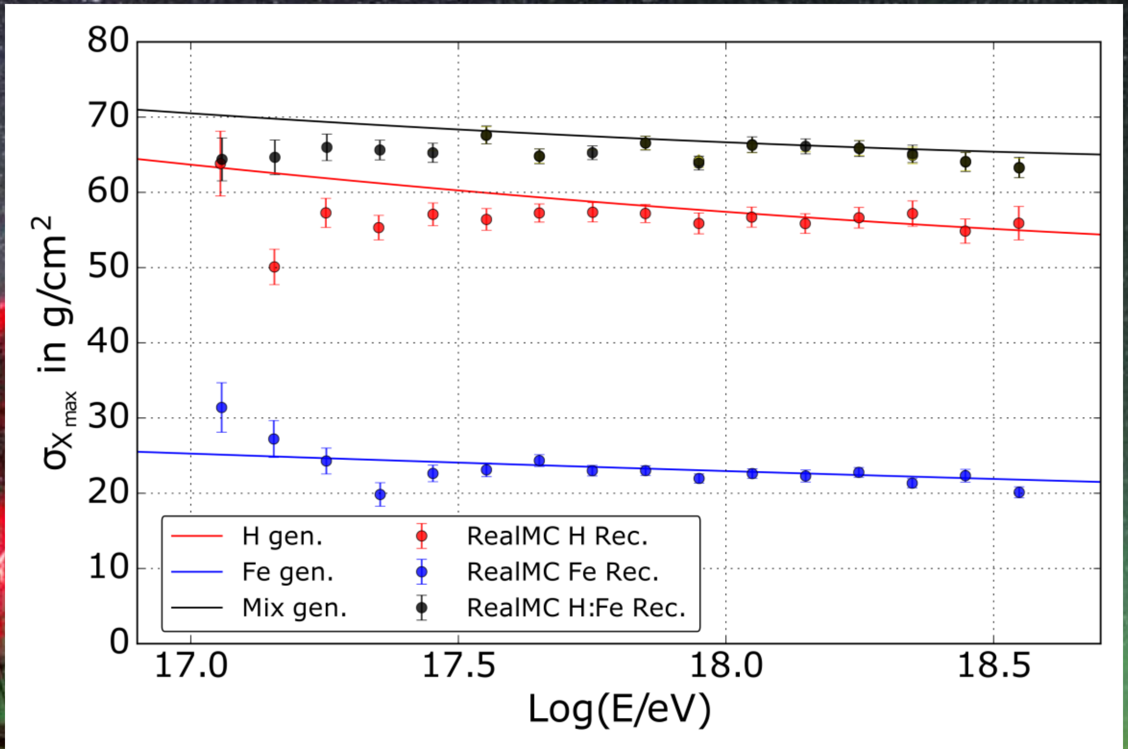


X_{max} Field of View Analysis

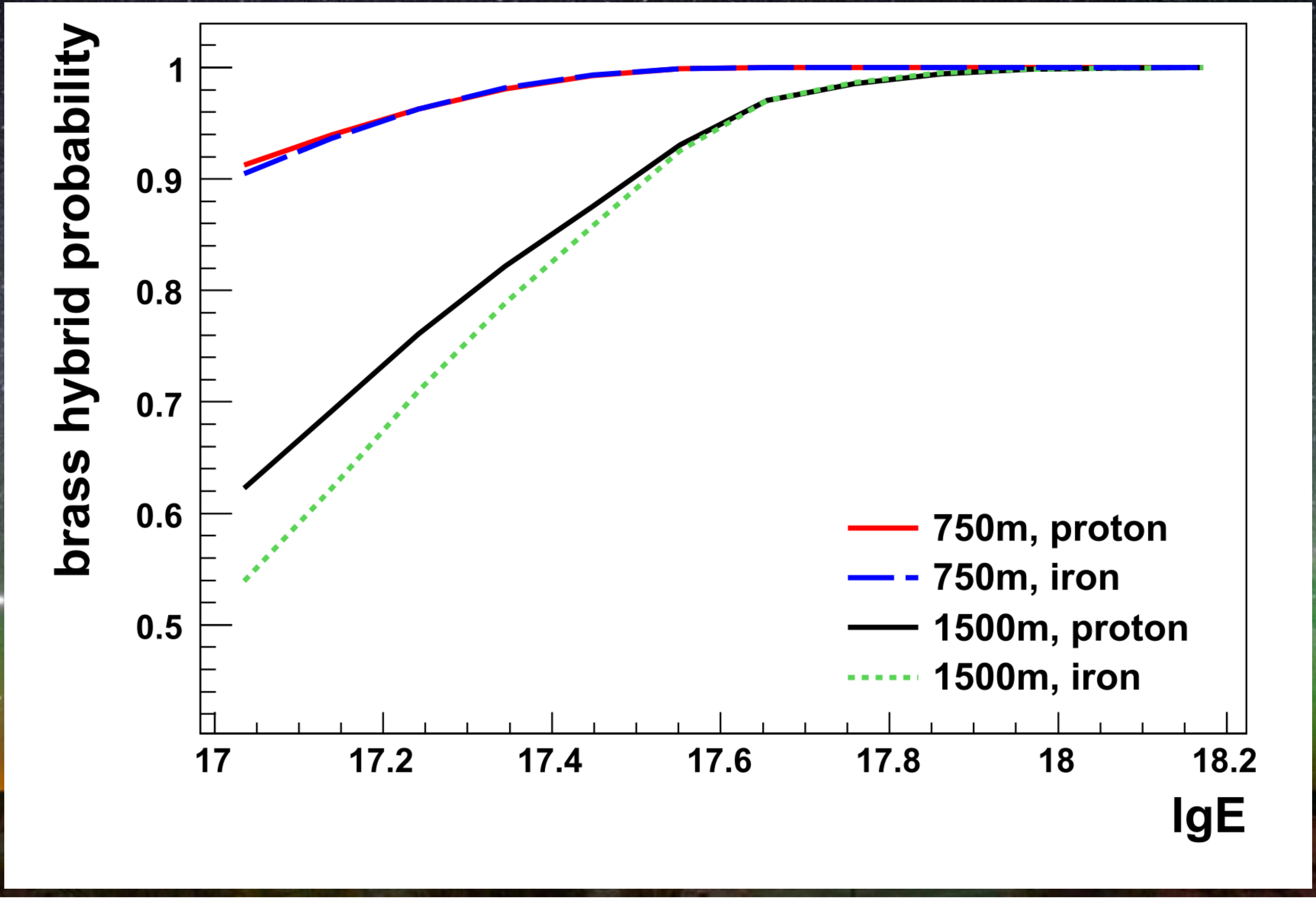


X_{max} End-to-End Study





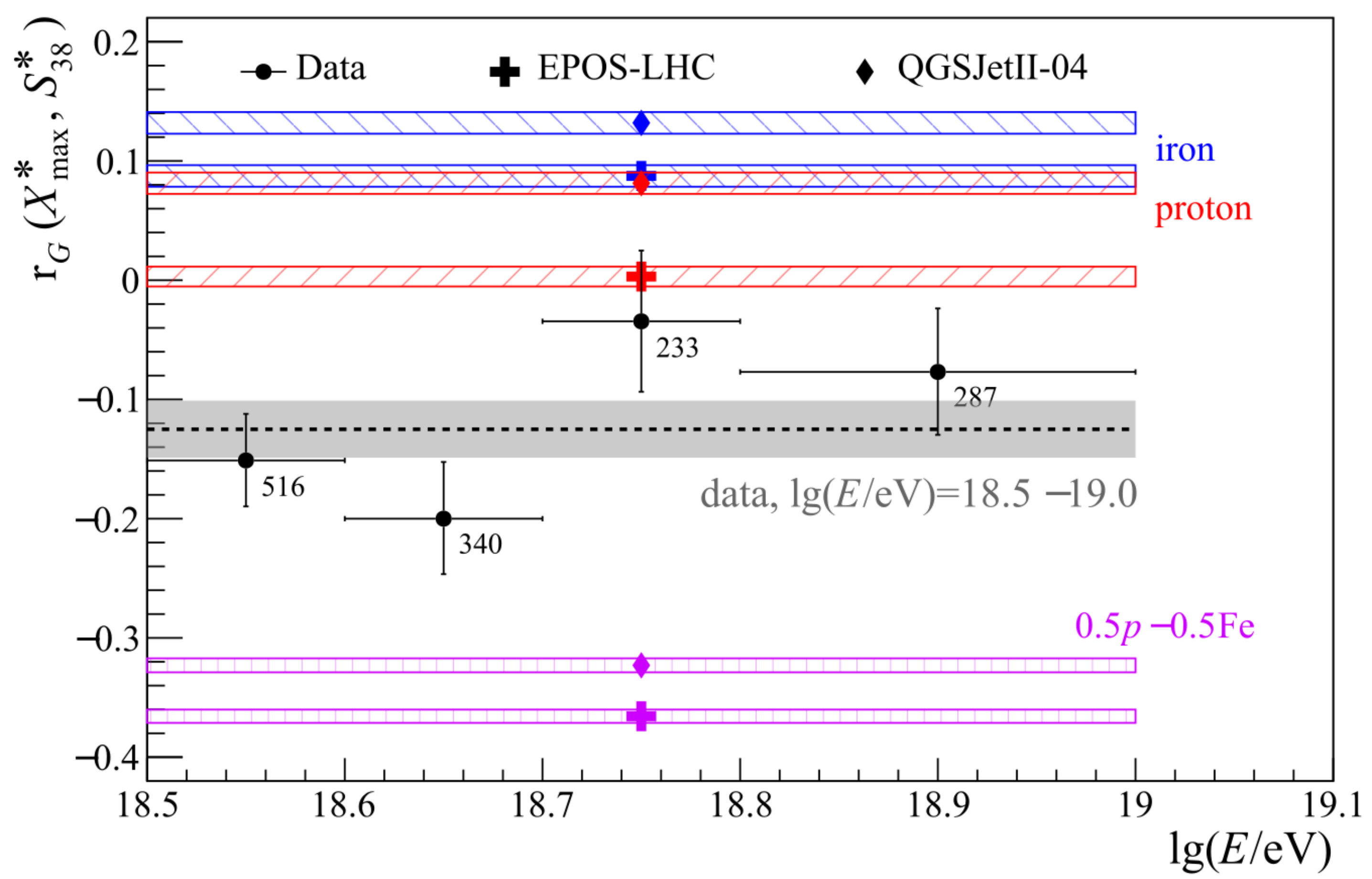
SD Trigger Probability



Correlation Study Data Selection

- SD Selection
  - at least 5 working stations around the station with the highest signal
  - exclusion of events with stations having saturated signal traces
- FD Selection
  - same as X_{max} analysis

Correlation as Function of Energy



- Only minor changes in simulated r_G with energy is expected for constant composition
- Binned data are consistent with a constant r_G with X^2/dof = 6.1/3