Karlsruhe Institute of Technology

The UHECR Mass Composition Measurements at the Pierre Auger Observatory

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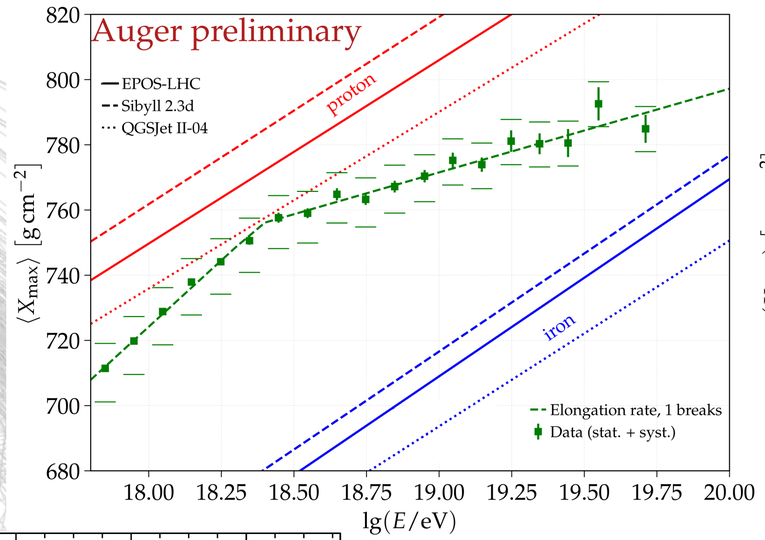
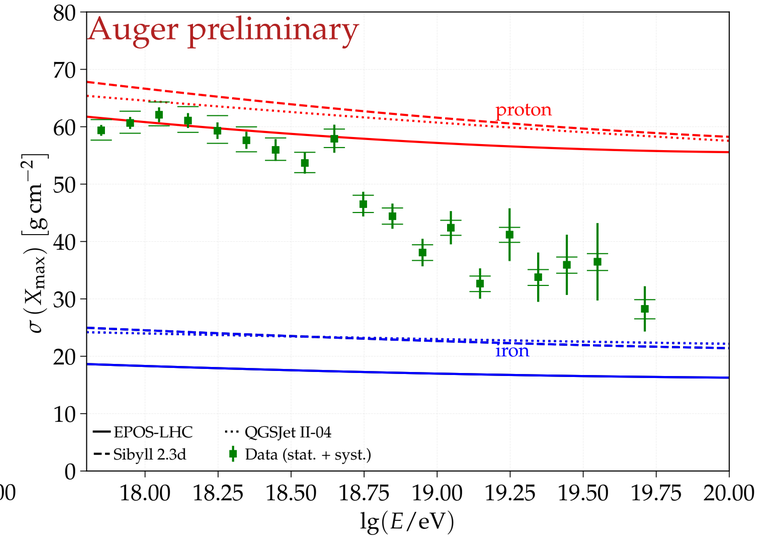
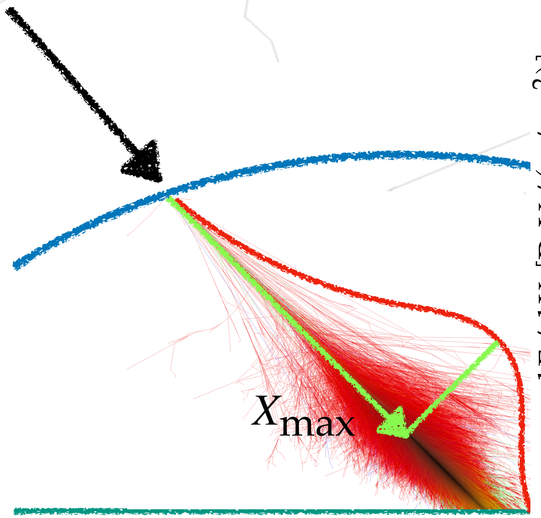
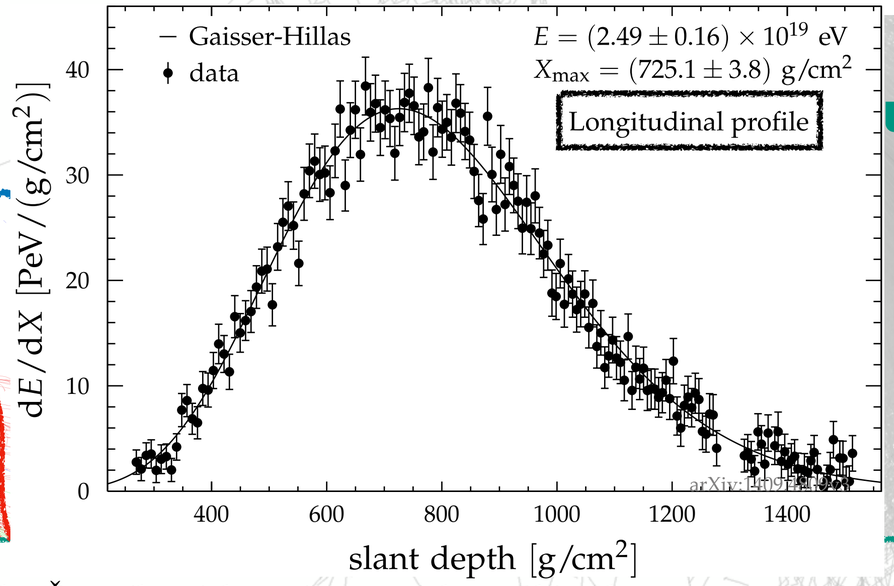
Introduction

- Ultrahigh-energy cosmic rays (UHECRs)
  - Extraterrestrial charged particles with ultra-high energies (above 10^{18} eV)
  - Acceleration mechanisms and sources are unknown









- Determination of cosmic ray (CR) mass
  - Due to scarcity only indirect detection possible
  - Estimation relies on quantities statistically encoding mass (number of muons, depth of the shower maximum X_{max})

Pierre Auger Observatory

- Malargüe, Argentina
- 3000 km^2

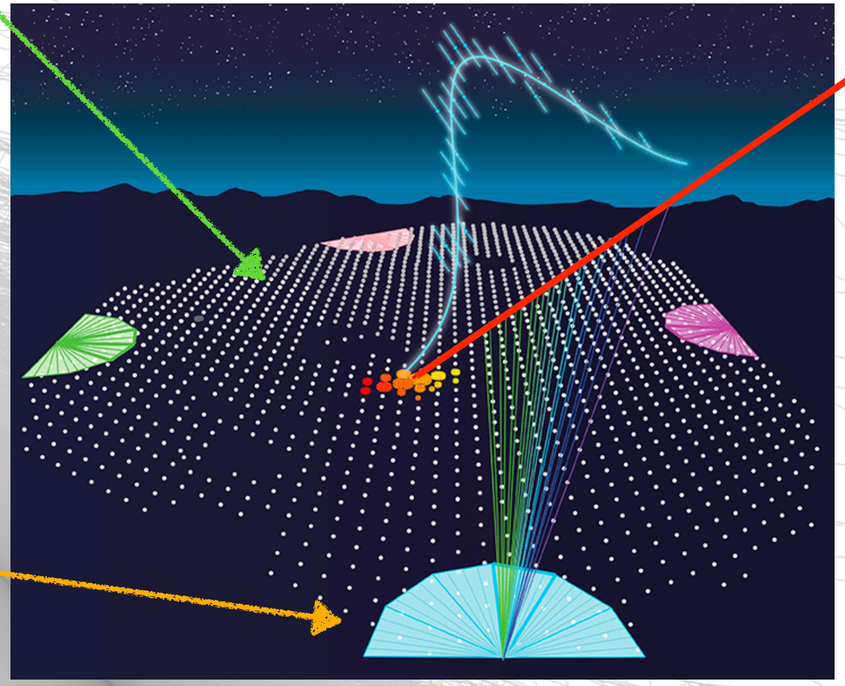
Water-Cherenkov Detector

Surface Detector:

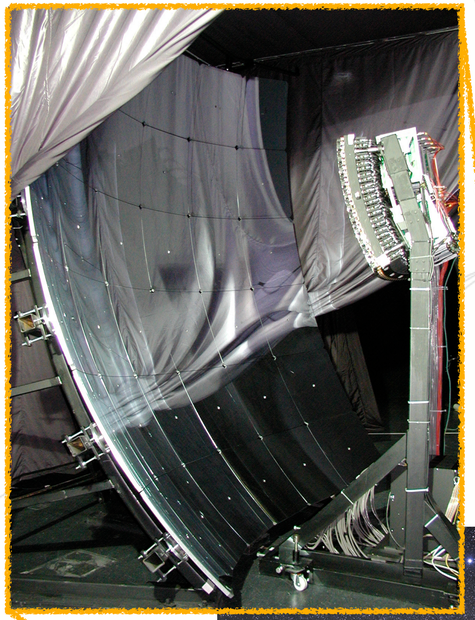
- 1600 stations with a spacing of 1.5 km
- Multiple sub-detectors
- Main detector: water-Cherenkov detectors in a triangular grid

Fluorescence Detector

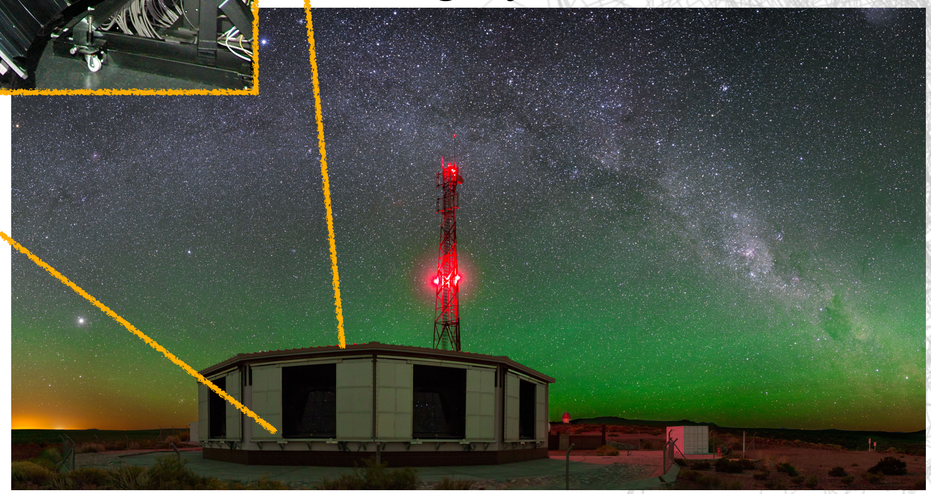
- Fluorescence Detector:
  - Overlooking the SD
  - Direct X_{max} measurement

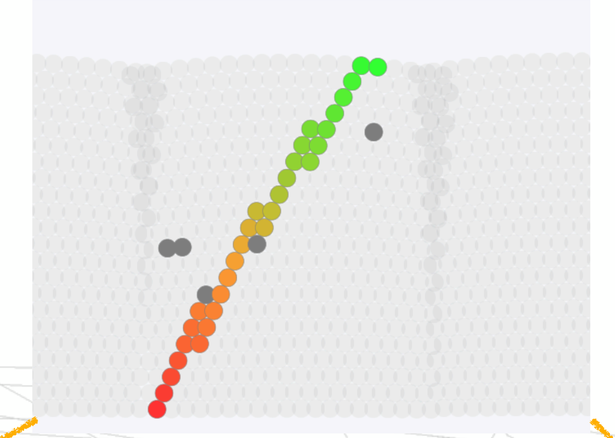


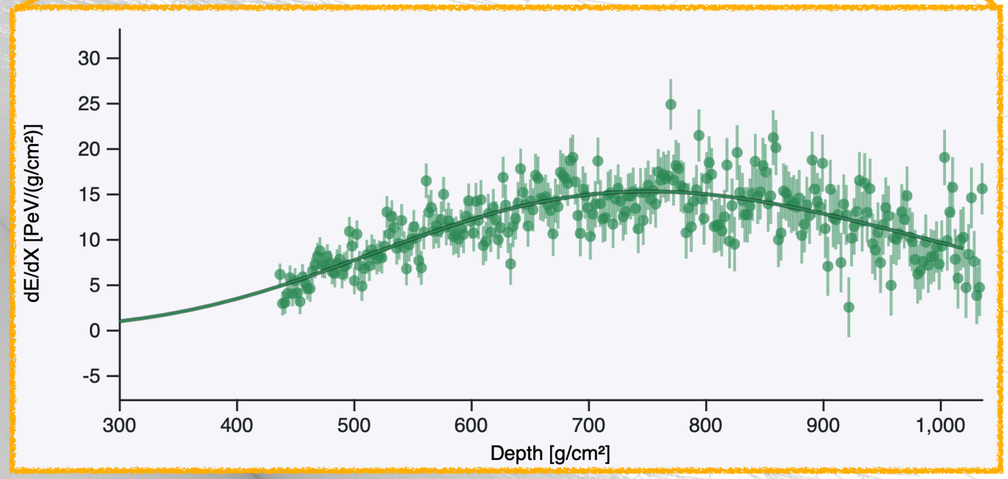
Fluorescence detector



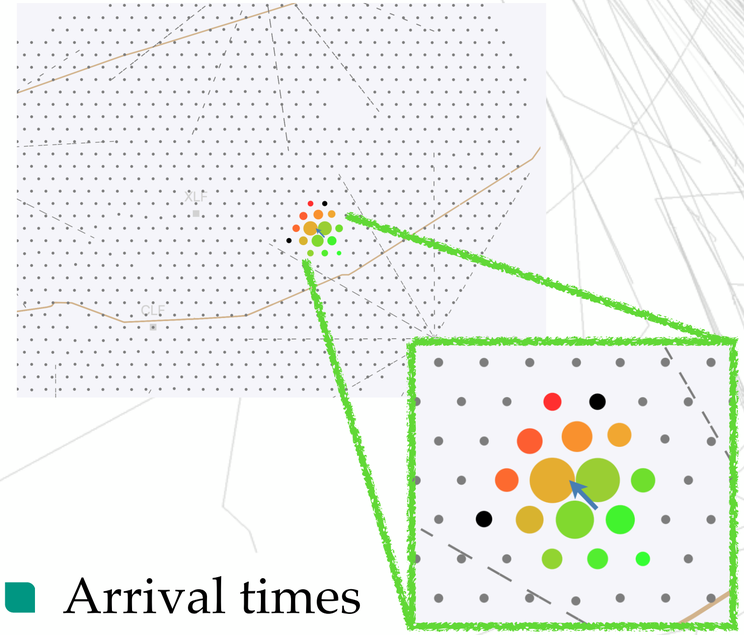
- Direct measurement of the longitudinal profile
  → shower maximum $X_{\max}$
- 27 telescopes at five sites
  - 6 telescopes at each of four sites
  - 3 telescopes at the High Elevation Auger Telescopes (HEAT) site - lower energies
- Highly sensitive cameras - 15% duty cycle



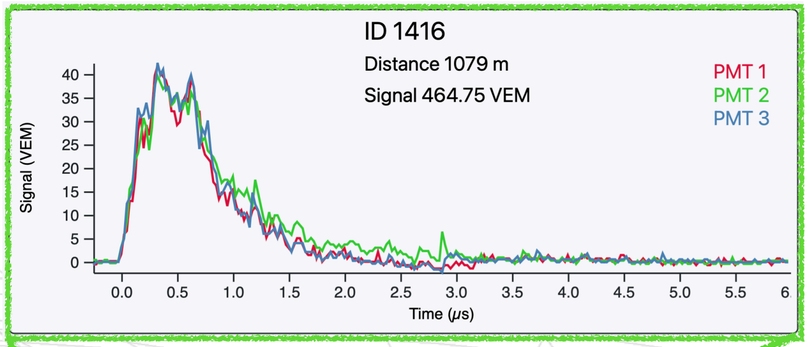




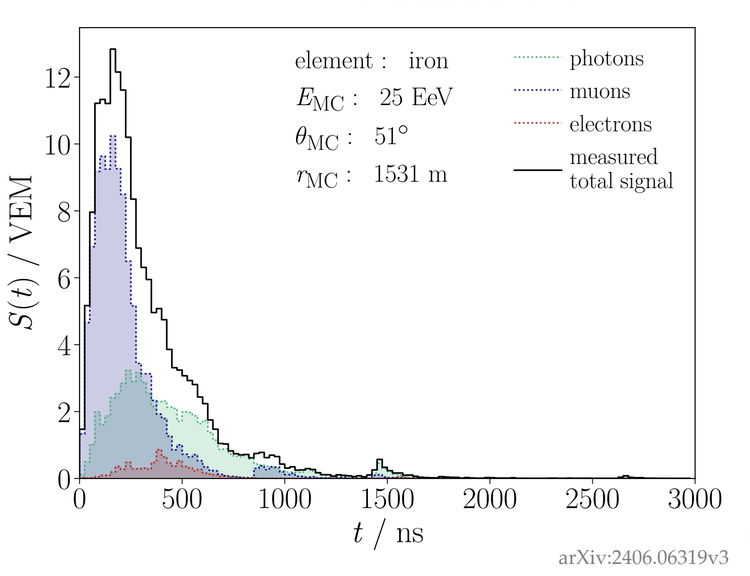
Surface detector signal



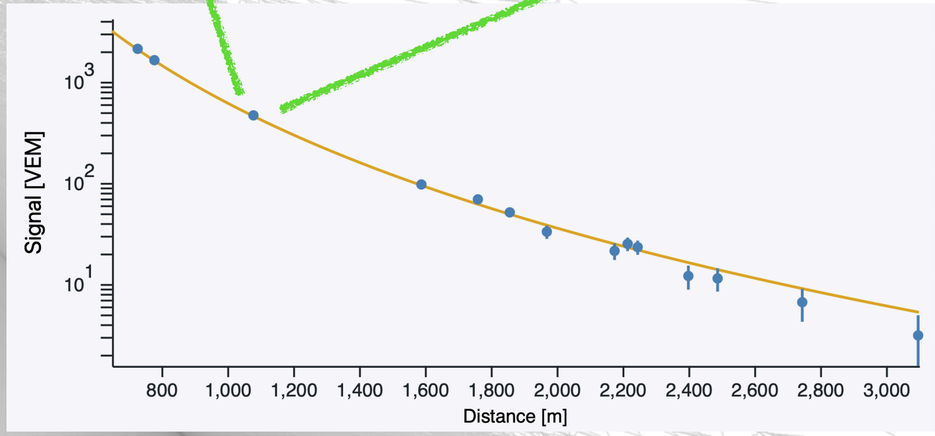
- Signal traces from 3 PMTs in each WCD
- Total recorded signal depends on the energy of the primary CR and the distance from the shower core (reconstructed shower axis)
- Shape depends on the different shower components (muonic, electromagnetic)



- Arrival times
  → shower geometry

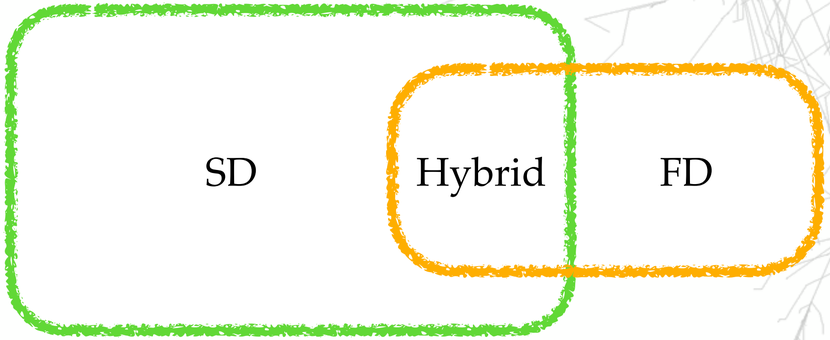


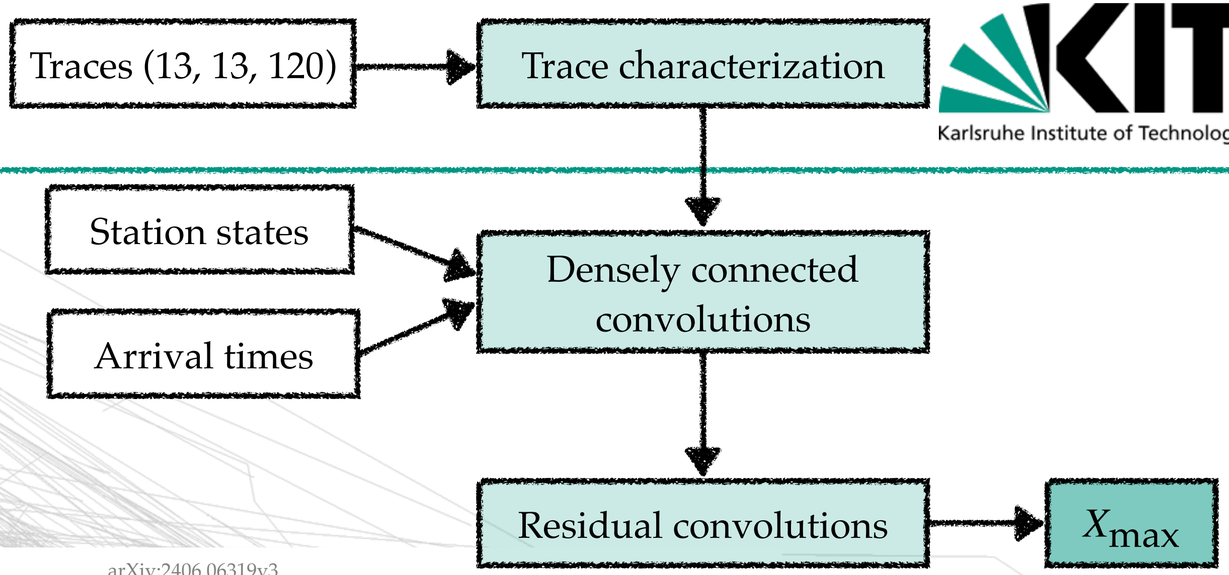
arXiv:2406.06319v3

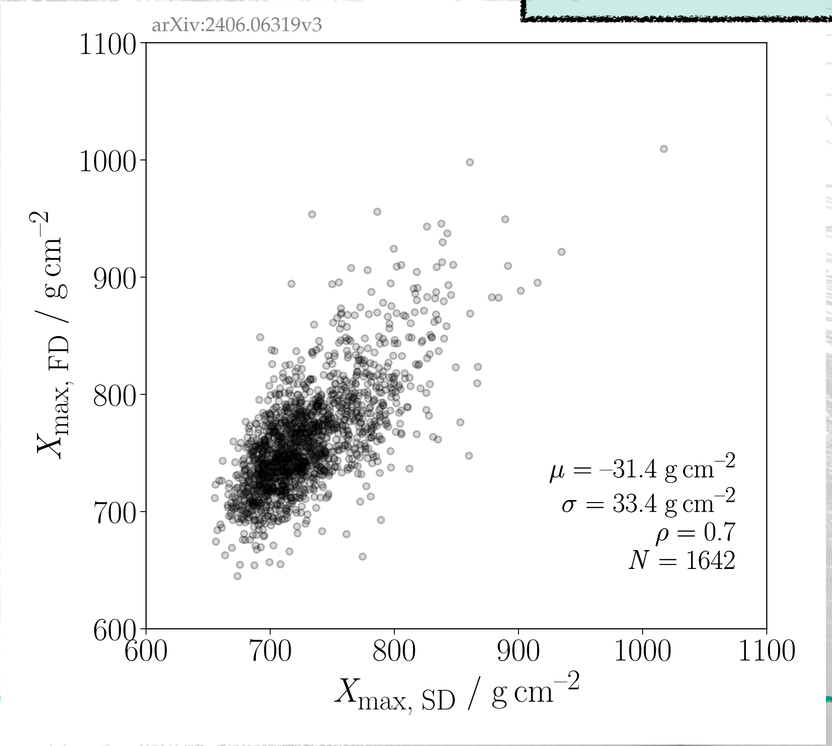


Mass estimation with DNN

- $X_{\max}$ reconstruction from a shower footprint on the SD dataset
  - Vertical events $\theta < 60°$, $\lg(E/\mathrm{eV}) > 18.5$, analysis specific selection
  - 48 824 events
- Calibration with the Hybrid dataset
  - Events measured by both SD and FD
  - 1 642 events after high-quality selection







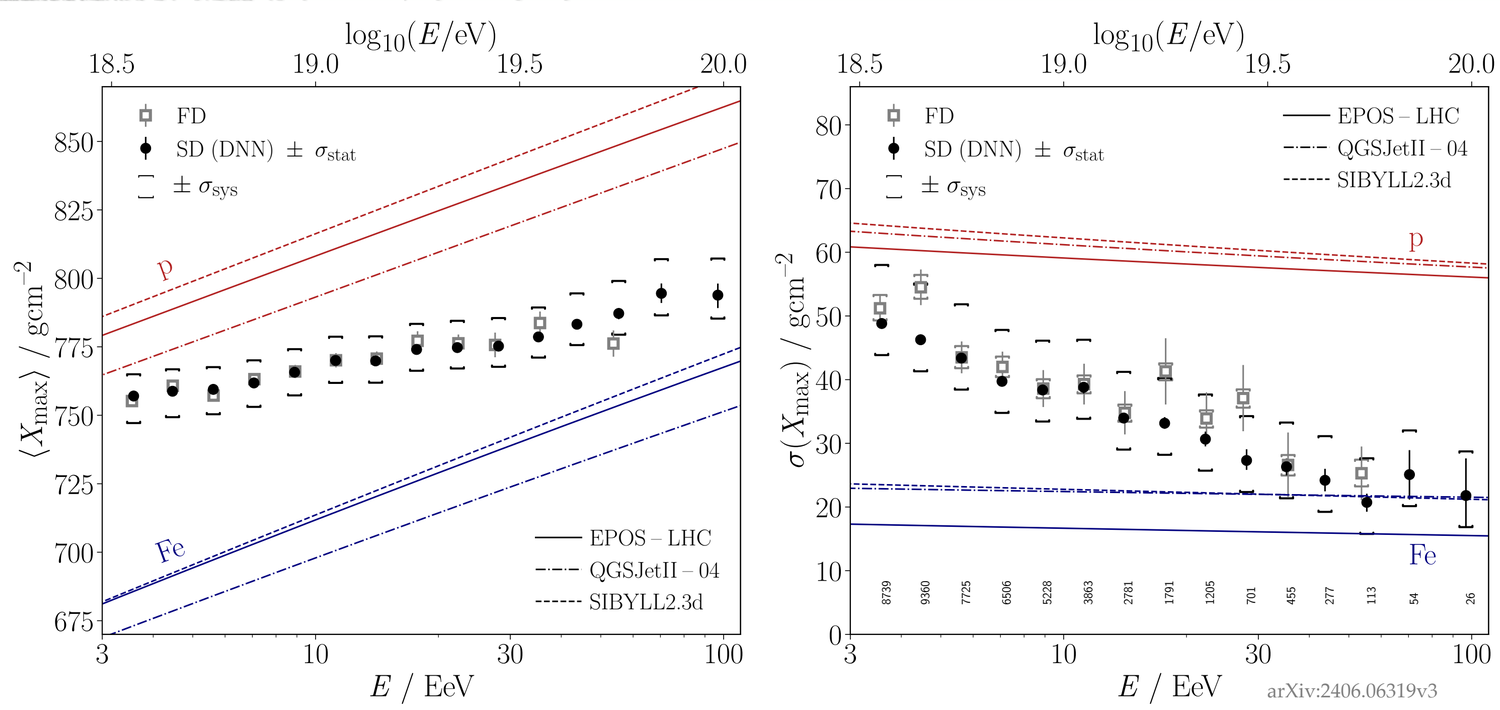
Investigating the mass composition

- Mass composition of UHECRs connected to the energy evolution of $\langle X_{\max} \rangle$ and $\sigma(X_{\max})$
- Using the SD dataset (48 824 events) compared to the full FD dataset (9 822 events)
- $\langle X_{\max} \rangle$ and $\sigma(X_{\max})$ of SD dataset predictions in agreement with the FD dataset
- Change of $\langle X_{\max} \rangle$ per decade of energy described by the *elongation rate*

$$D_{10} = \frac{\mathrm{d}\langle X_{\max} \rangle}{\mathrm{d}\lg E} = D_{10}^{\mathrm{MC}} \left(1 - \frac{\mathrm{d}\langle \ln A \rangle}{\mathrm{d}\ln E} \right)$$

$$\Rightarrow \frac{\mathrm{d}\langle \ln A \rangle}{\mathrm{d}\ln E} = 1 - \frac{D_{10}}{D_{10}^{\mathrm{MC}}}$$

- Average elongation rate of the SD data agrees with the FD measurements

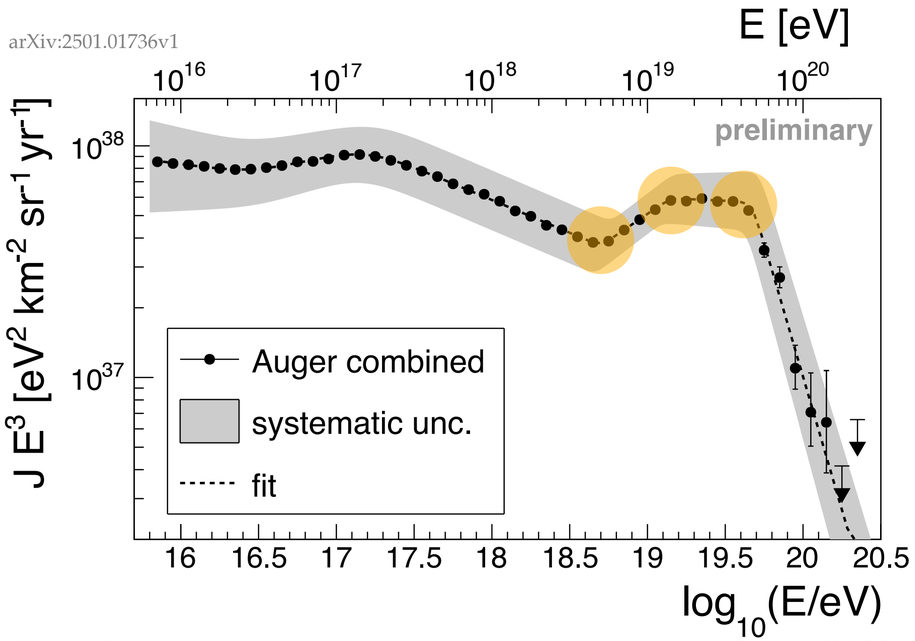


Interpretation of the results

- A simple linear model does not describe the elongation rate well
- Model with 3 breaks with 4.4σ significance
  - Non-trivial composition changes
  - Breaks close to the features in the energy spectrum

Elongation rate		Spectrum	
1st break	6.5 EeV	ankle	5.1 EeV
2nd break	11 EeV	instep	13 EeV
3rd break	30 EeV	suppression	48 EeV

arXiv:2501.01736v1



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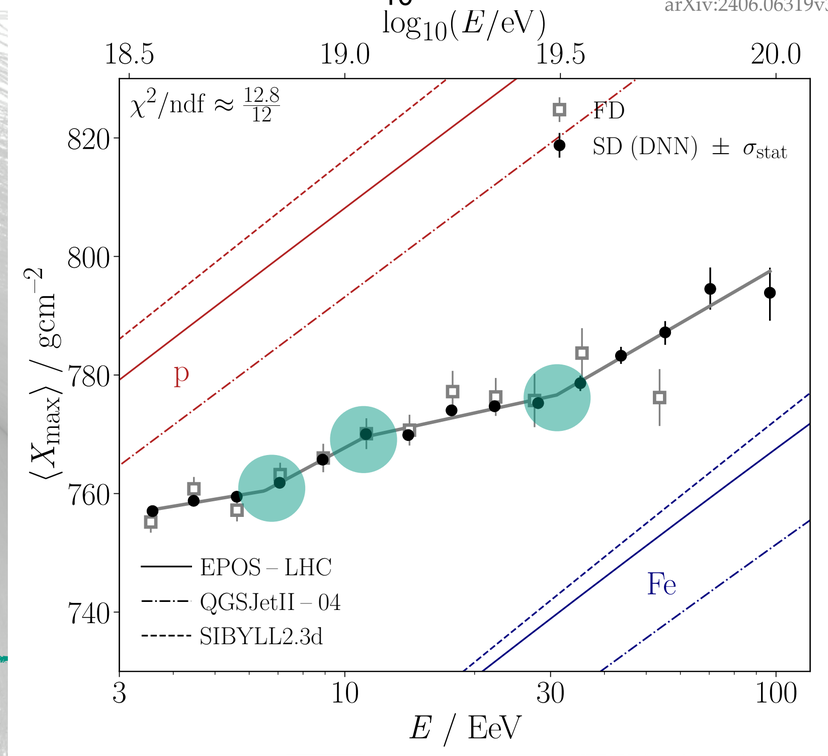


Interpretation of the results

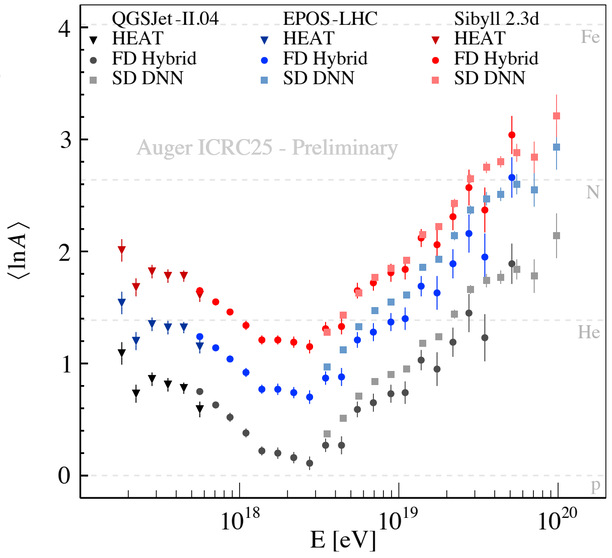
- Converting $X_{\max}$ to $\ln A$:

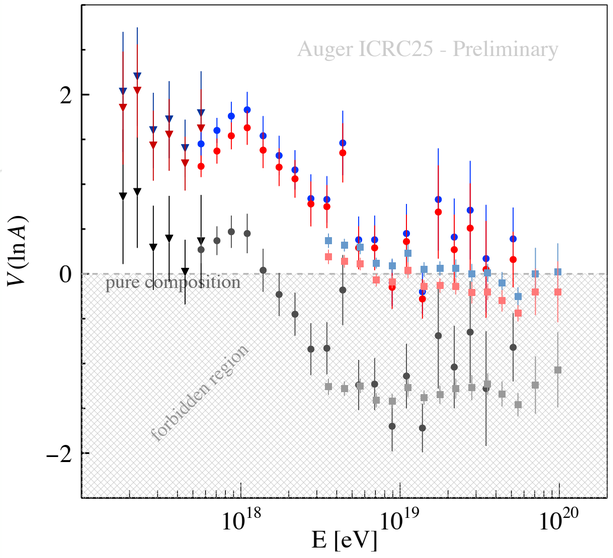
$$\langle \ln A \rangle = \frac{\langle X_{\max} \rangle - \langle X_{\max} \rangle_{\mathrm{p}}}{f_E}, \quad V[\ln A] = \frac{\sigma^2(X_{\max}) - \sigma^2_{\mathrm{sh}}(\ln A)}{b\sigma^2_{\mathrm{p}} - f_E^2},$$

$$f_E = \left(\langle X_{\max} \rangle_{\mathrm{Fe}} - \langle X_{\max} \rangle_{\mathrm{p}} \right) / \ln 56$$

- Light to heavier composition with energy

arXiv-2507.10292v1





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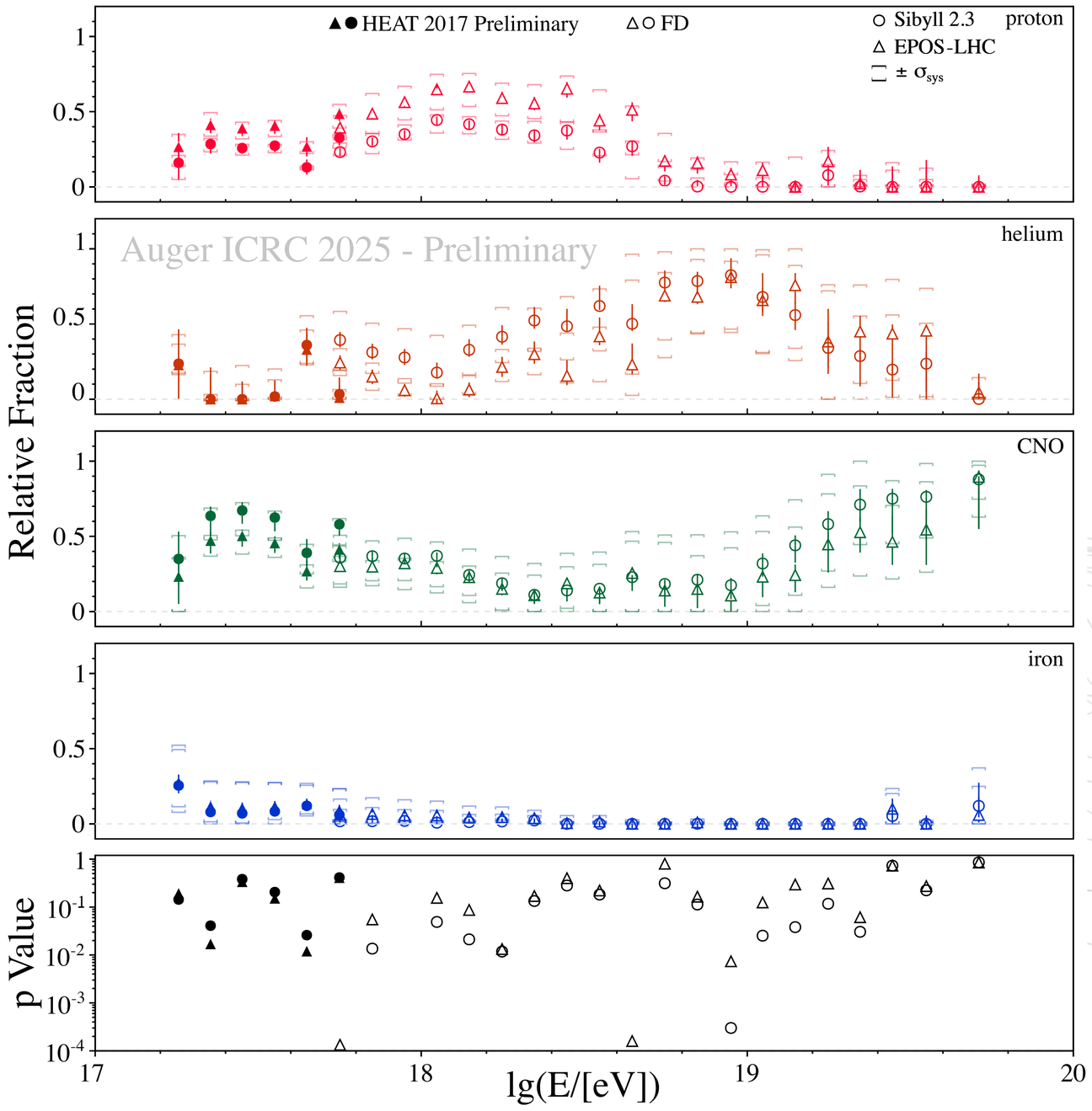
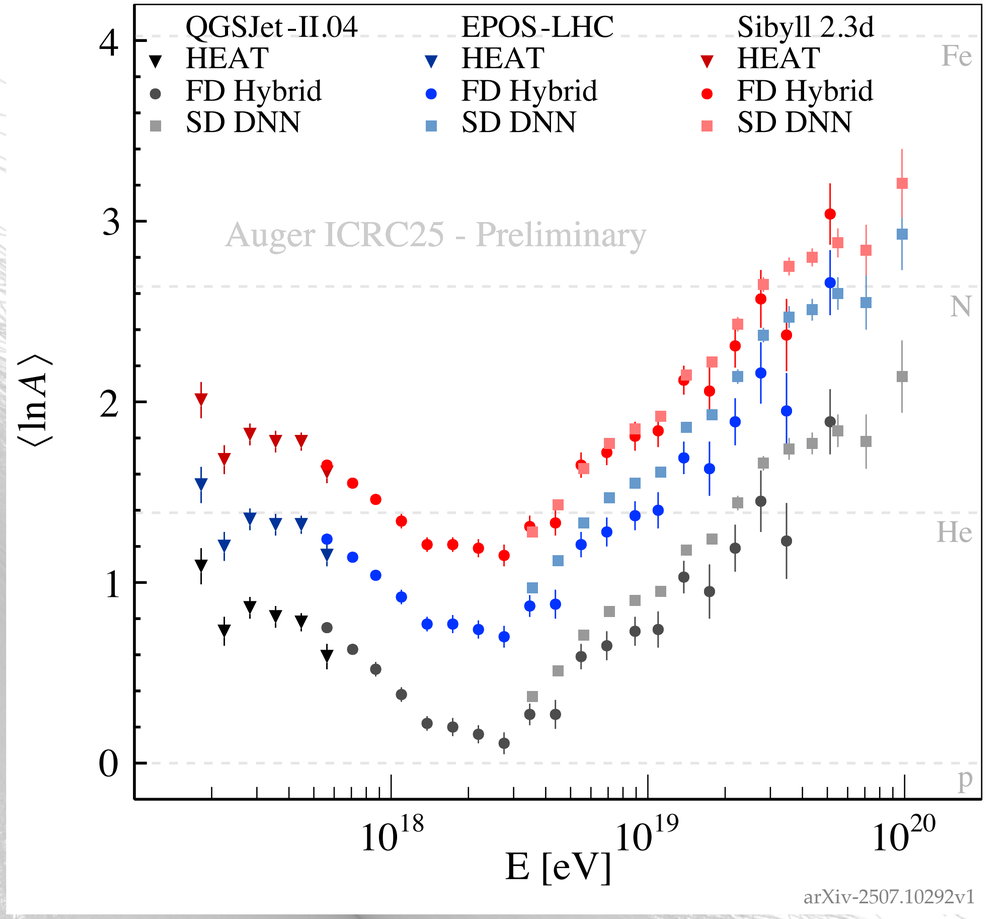


Summary

- Excellent agreement of DNN $\langle X_{\max} \rangle$ reconstruction with FD measurements
- Confirming a heavier and purer composition with increasing energy
- A 3-break model fits the elongation data better

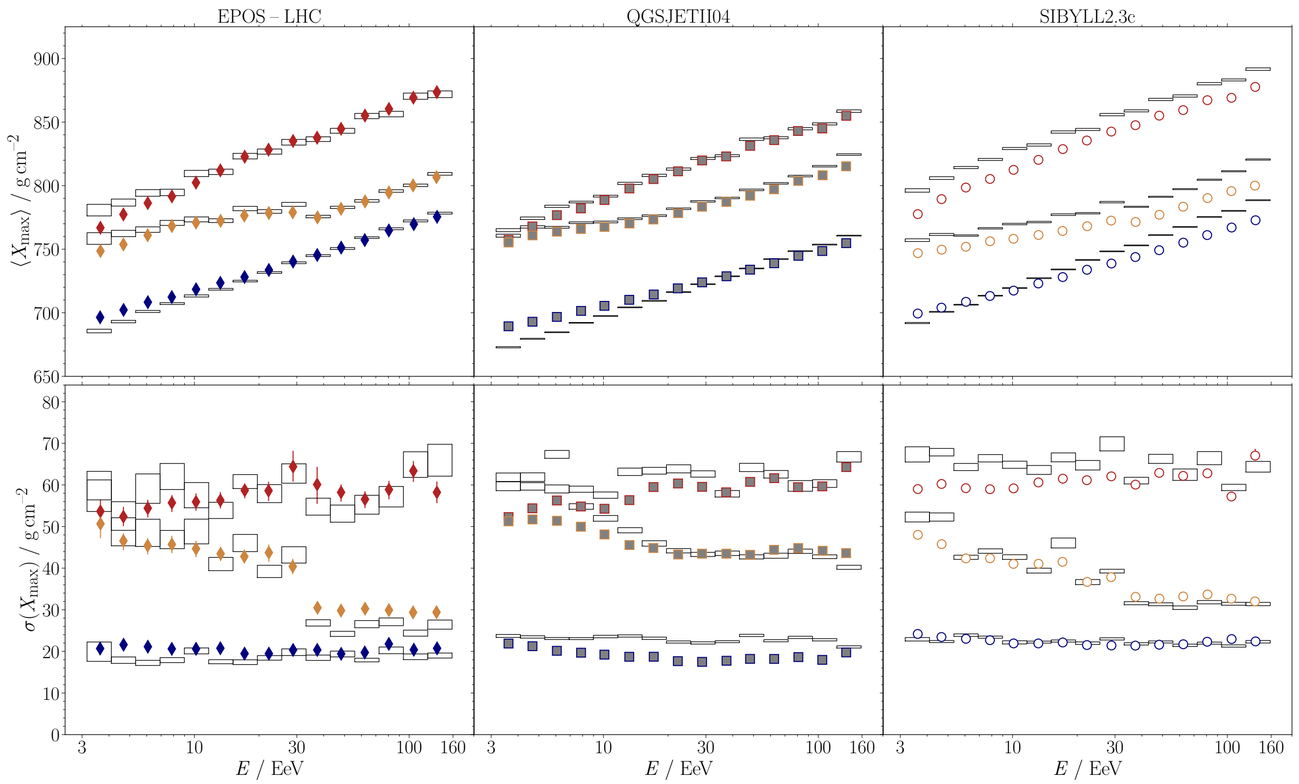


Back-up

Mass estimation with DNN

- Triangular to Cartesian grid - 13x13 stations
- Input normalization
- Training with 400 000 simulated detector responses
- CORSIKA with the EPOS-LHC hadronic interaction model (p, He, O, Fe)
- Energy between 1 and 160 EeV, spectral index $\gamma = -1$, zenith angles $\theta < 65°$
- Testing on EPOS-LHC, QGSJetII-04, Sibyll2.3c hadronic interaction models

arXiv:2406.06319v3



Data selection

TABLE I: Basic and analysis-specific selections (separated by a line) for the SD data set.

Cut	Events	ε (%)
reconstructed vertical event ($\theta < 60°$)	5,994,712	—
is 6T5	4,858,291	81.1
$\log_{10}(E/\mathrm{eV}) > 18.5$	133,167	2.7
hardware status	129,403	97.2
station start slot	128,308	99.2
$2.75 < A/P < 3.45$	126,033	98.2
$\bar{S}_{\mathrm{tot}} > 5$ VEM in surrounding hexagon	125,828	99.8
350 m < core distance < 1000 m	101,392	80.6
fiducial SD cut	48,824	48.1

arXiv:2406.06319v3

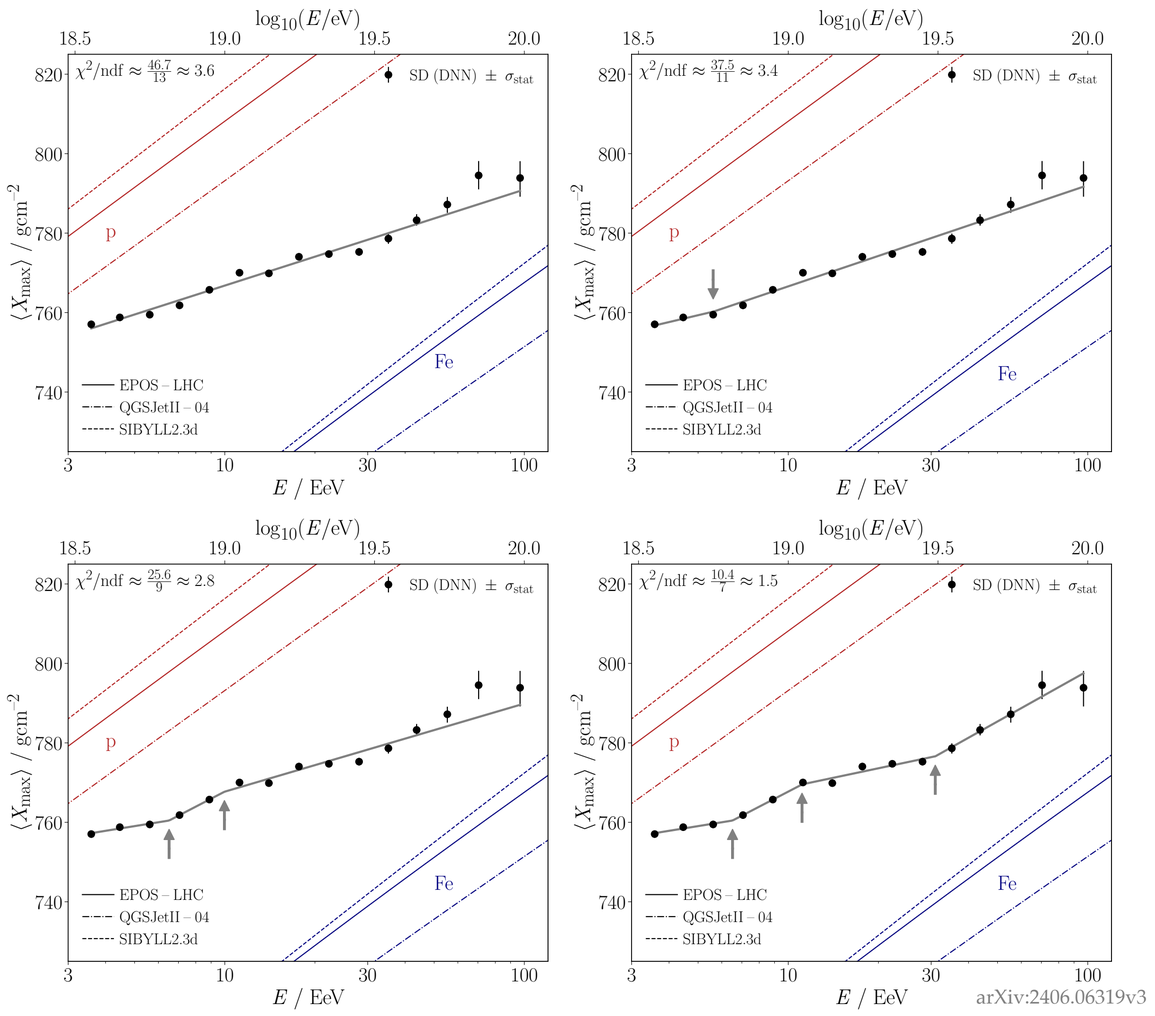
TABLE II: Selections for hybrid data.

Cut	Events	ε (%)
number of events	25,076	—
telescope cuts	19,733	78.7
hardware status	16,916	85.7
aerosols/clouds	9,822	58.1
hybrid geometry	9,157	93.2
fiducial FoV cut	3,497	38.2
profile cuts	3,331	95.3
passed SD selection	3,086	92.6
analysis-specific cuts	1,642	53.2

arXiv:2406.06319v3

Elongation rate models

Parameter	Const. elong. $\mathrm{Val} \pm \sigma_{\mathrm{stat}} \pm \sigma_{\mathrm{sys}}$	1-break model $\mathrm{Val} \pm \sigma_{\mathrm{stat}} \pm \sigma_{\mathrm{sys}}$	2-break model $\mathrm{Val} \pm \sigma_{\mathrm{stat}} \pm \sigma_{\mathrm{sys}}$	3-break model $\mathrm{Val} \pm \sigma_{\mathrm{stat}} \pm \sigma_{\mathrm{sys}}$	Energy spectrum $\mathrm{Val} \pm \sigma_{\mathrm{stat}} \pm \sigma_{\mathrm{sys}}$
b / $\mathrm{g\,cm^{-2}}$	$743 \pm 5 \pm 13$	$743 \pm 5 \pm 13$	$750.5 \pm 4 \pm 13$	$750.5 \pm 3 \pm 13$	
D_0 / $\mathrm{g\,cm^{-2}\,decade^{-1}}$	$24 \pm 1 \pm 4$	$23 \pm 2 \pm 12$	$12 \pm 6 \pm 5$	$12 \pm 5 \pm 6$	
E_1 / EeV		$35 \pm 12 \pm 16$	$6.5 \pm 0.9 \pm 1$	$6.5 \pm 0.6 \pm 1$	$4.09 \pm 0.1 \pm 0.8$
D_1 / $\mathrm{g\,cm^{-2}\,decade^{-1}}$		$39 \pm 14 \pm 12$	$39 \pm 12 \pm 10$	$39 \pm 5 \pm 14$	
E_2 / EeV			$10 \pm 2 \pm 3$	$11 \pm 2 \pm 1$	$14 \pm 1 \pm 2$
D_2 / $\mathrm{g\,cm^{-2}\,decade^{-1}}$			$22 \pm 3 \pm 8$	$16 \pm 3 \pm 6$	
E_3 / EeV				$31 \pm 5 \pm 3$	$47 \pm 3 \pm 6$
D_3 / $\mathrm{g\,cm^{-2}\,decade^{-1}}$				$42 \pm 9 \pm 12$	



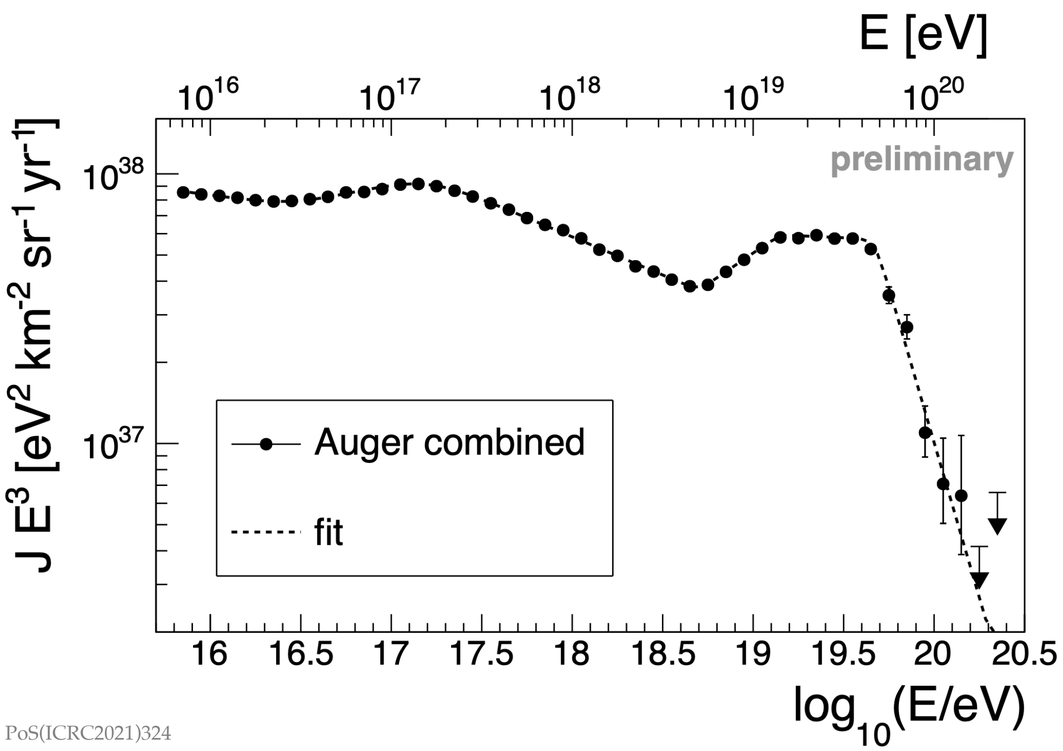
Spectrum

$$J(E) = J_0 \left(\frac{E}{10^{16}\,\mathrm{eV}}\right)^{-\gamma_0} \prod_{i=0}^{4} \left[1 + \left(\frac{E}{E_{ij}}\right)^{\frac{1}{\omega_{ij}}}\right]^{(\gamma_i - \gamma_j)\omega_{ij}}, \qquad j = i+1, \qquad (1)$$

Table 1: Parameters of the best fit of Eq. (1) to the combined spectrum. The first uncertainty is statistical and the second one systematic. The fit has been performed with a set of transition width parameters that well describe the data: $\omega_{01} = \omega_{12} = 0.25$ and $\omega_{23} = \omega_{34} = \omega_{45} = 0.05$ [5].

$J_0 = (8.34 \pm 0.04 \pm 3.40) \times 10^{-11}\ \mathrm{km^{-2}sr^{-1}yr^{-1}eV^{-1}}$

		$\gamma_0 = 3.09 \pm 0.01 \pm 0.10$
low energy ankle	$E_{01} = (2.8 \pm 0.3 \pm 0.4) \times 10^{16}$ eV	$\gamma_1 = 2.85 \pm 0.01 \pm 0.05$
2nd *knee*	$E_{12} = (1.58 \pm 0.05 \pm 0.2) \times 10^{17}$ eV	$\gamma_2 = 3.283 \pm 0.002 \pm 0.10$
ankle	$E_{23} = (5.0 \pm 0.1 \pm 0.8) \times 10^{18}$ eV	$\gamma_3 = 2.54 \pm 0.03 \pm 0.05$
instep	$E_{34} = (1.4 \pm 0.1 \pm 0.2) \times 10^{19}$ eV	$\gamma_4 = 3.03 \pm 0.05 \pm 0.10$
suppression	$E_{45} = (4.7 \pm 0.3 \pm 0.6) \times 10^{19}$ eV	$\gamma_5 = 5.3 \pm 0.3 \pm 0.1$



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