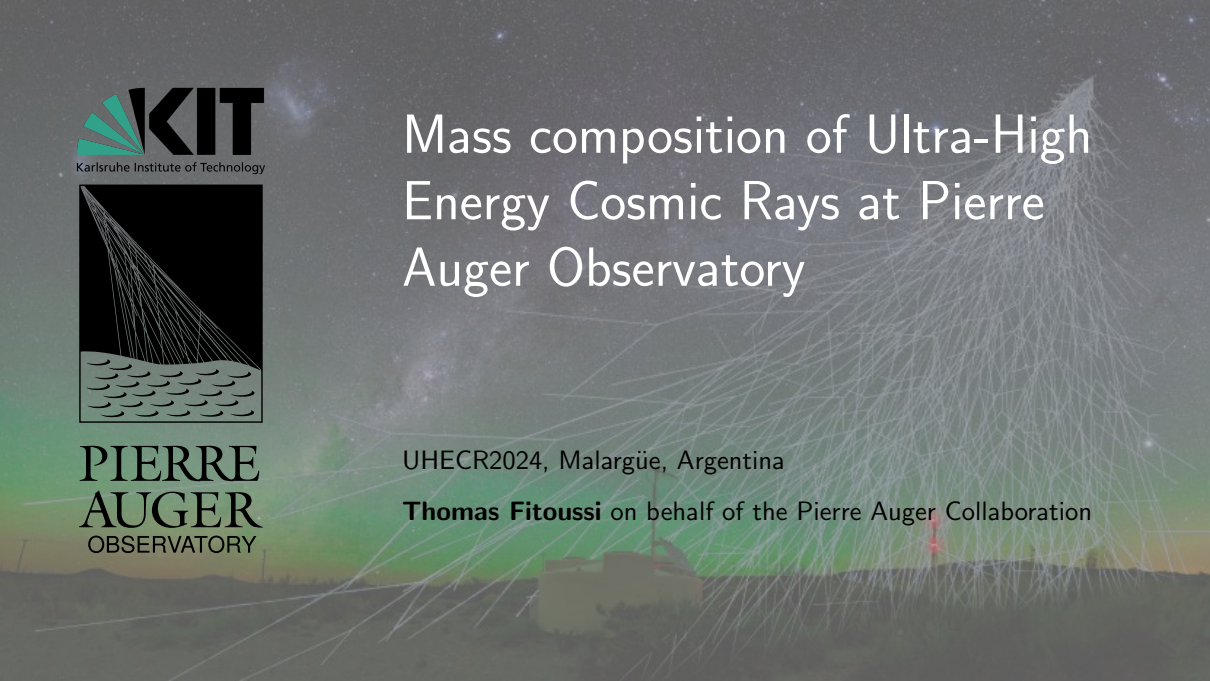


Karlsruhe Institute of Technology

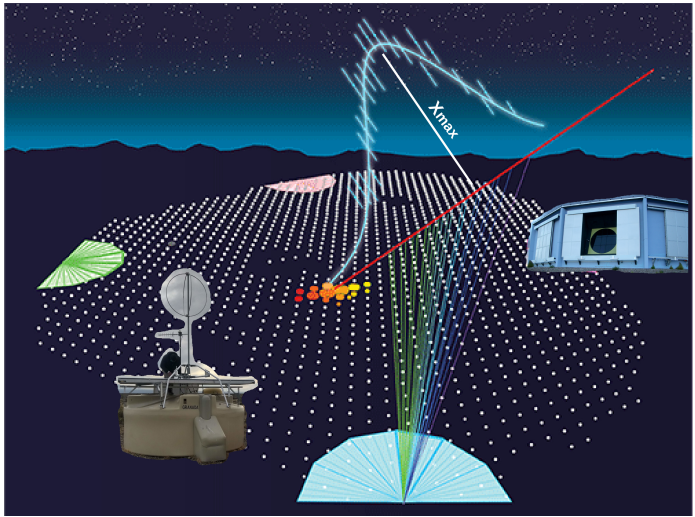
PIERRE AUGER OBSERVATORY

Mass composition of Ultra-High Energy Cosmic Rays at Pierre Auger Observatory

UHECR2024, Malargüe, Argentina

Thomas Fitoussi on behalf of the Pierre Auger Collaboration

Pierre Auger Observatory



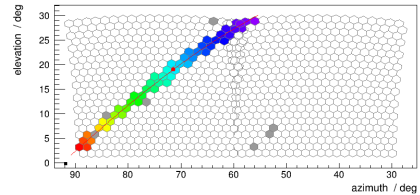
Hybrid detection

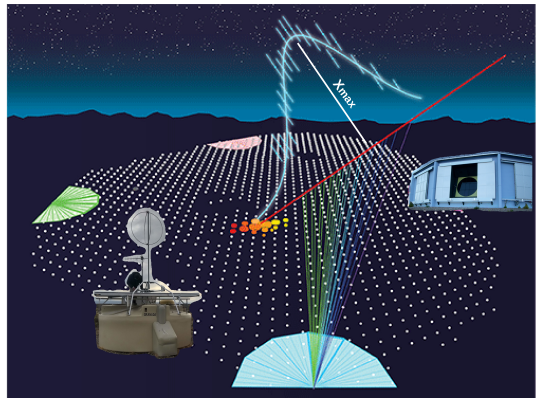
- Fluorescence Detector (FD)
  - 27 fluorescence telescopes at 4 different sites
  - 4 × 6 looking "down" → high energy
  - 3 looking "up" (HEAT) → low energy
- Surface Detector (SD)
  - 1660 water Cherenkov detectors

Reconstructing $X_{\max}$

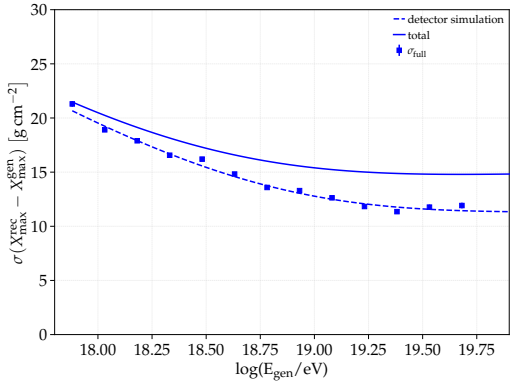
With FD

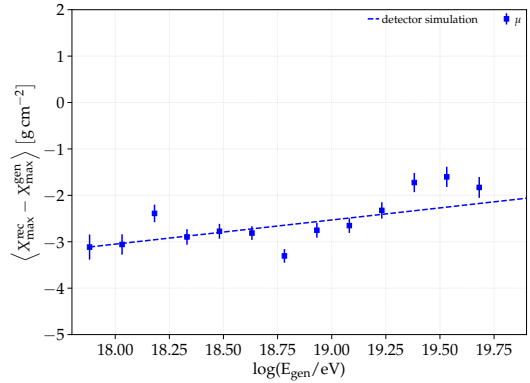
- ✔ Direct access to $X_{\max} \sim \ln A$
- ✘ Duty cycle 10-15% $\rightarrow$ limited statistic





$X_{\max}$ bias and resolution

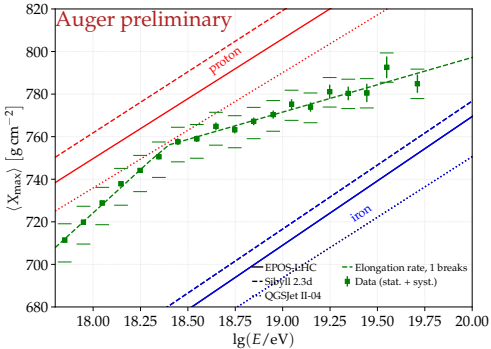


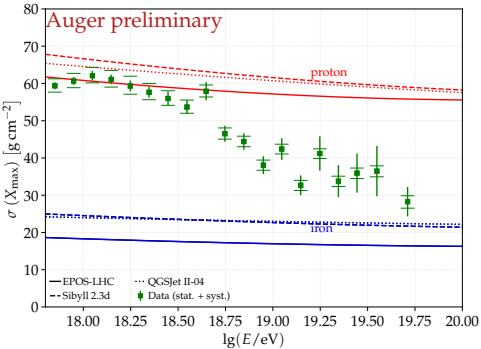


- Total resolution improves from 23 g/cm^{2}to 10 g/cm^2

- $X_{\max}$ bias $\sim -2/-3$ g/cm^2(50p/50Fe)
- Systematic uncert. $\sim \pm 10$ g/cm^2
  $\Rightarrow$ small fluctuations of $X_{\max}$ bias negligible

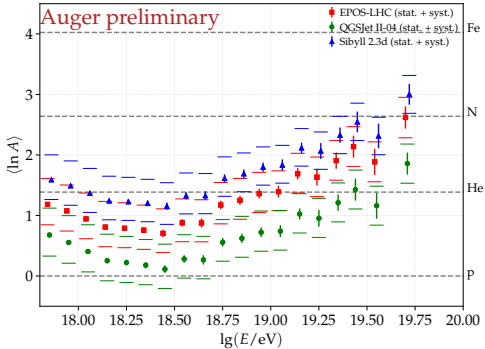
$X_{\max}$ moments from FD

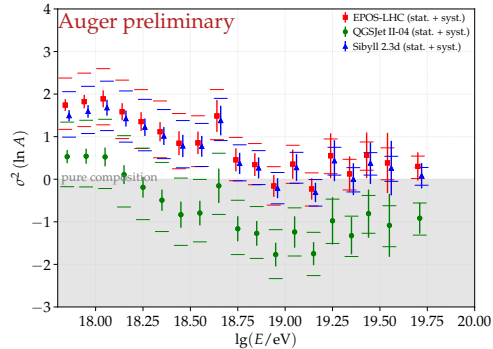




- ICRC23 results (67.986 events) between 0.5 EeV and 102.8 EeV
- Elongation rate best fitted with 1 break at $\sim 10^{18.4}$eV

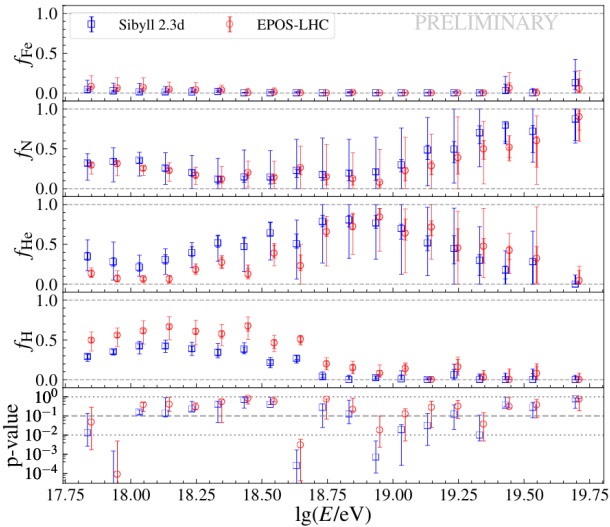
$X_{\max}$ moments from FD

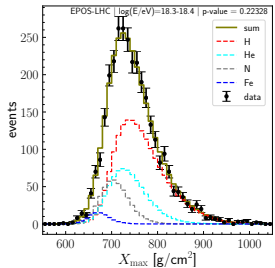




- ICRC23 results (67.986 events) between 0.5 EeV and 102.8 EeV
- Elongation rate best fitted with 1 break at $\sim 10^{18.4}$eV
- The average mass increases above the break independently on the hadronic model used
- QGSJet II-04 $\sigma\left(X_{\max}\right)$ in tension with data

Energy evolution of nuclear fractions





- Fitting the observed X_{max} distributions using simulated (p, He, N, Fe) templates
- ankle ($10^{18.7}$ eV): disappearance of protons
- highest energy dominated by medium mass nuclei

$X_{\max}$ from the Surface Detector data

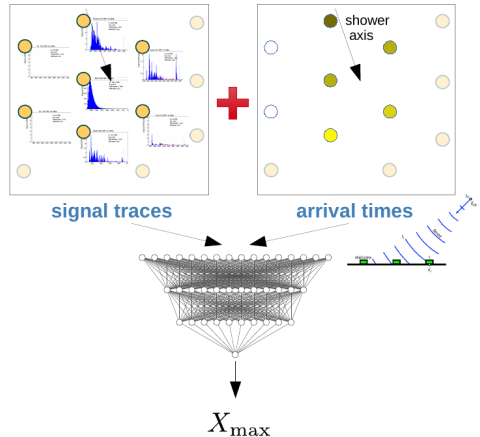
With SD

- ✘ No direct access to $X_{\max}$
- ✔ Duty cycle $\sim$100% $\rightarrow$ large statistic

- ▶ $X_{\max}$ estimation at the event level
- ▶ Cross-calibration with FD
- ▶ Training using simulations with EPOS-LHC

DNN architecture

- ▶ process time-dependent signal traces using recurrent networks (LSTMs)
- ▶ process shower footprint $\rightarrow$ exploit symmetry of the SD using hexagonal convolutions



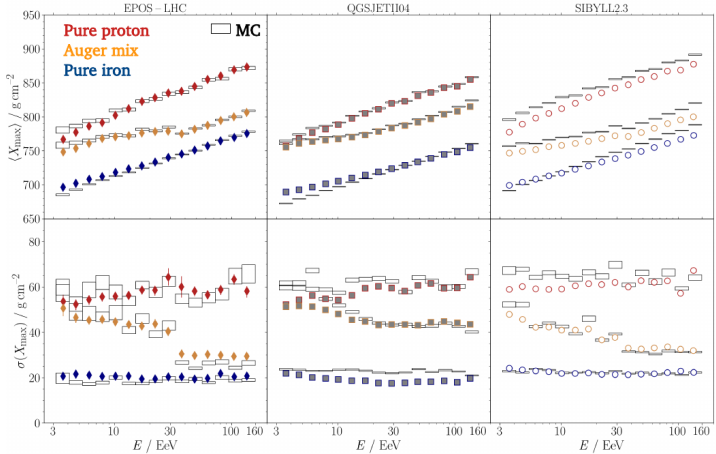
Performance on simulations

Interaction model bias

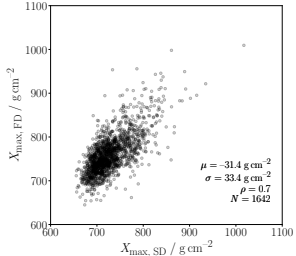
- 1^{st} moment
  - QGSJet -5 g/cm^2
  - Sybill 2.3d -12 g/cm^2
- 2^{nd} moment
  - no strong dependency

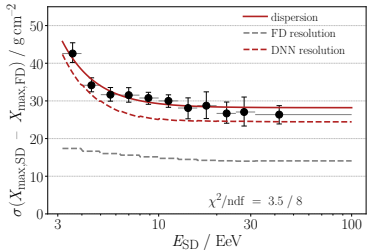
Composition bias

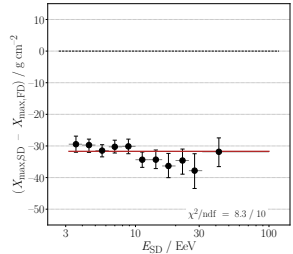
- small for Auger mix
- for proton and iron, small above 10 EeV



Calibration with hybrid data



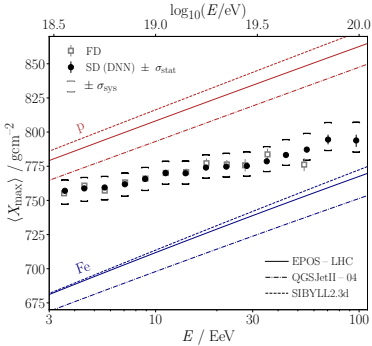


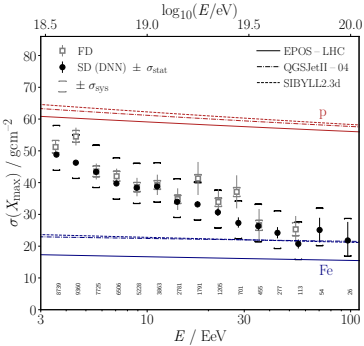


- Calibration of DNN predictions using Golden hybrid data (1642 events)
- Strong correlation ($\rho = 0.7$)
- Resolution from 40 g/cm^{2}to 25 g/cm^2

- Bias between SD and FD ~ -30 g/cm^2
  - larger than expected from simulations
  - could be due to 'muon puzzle' / detector simulations
  - perform energy-independent calibration

Application to SD-1500 data





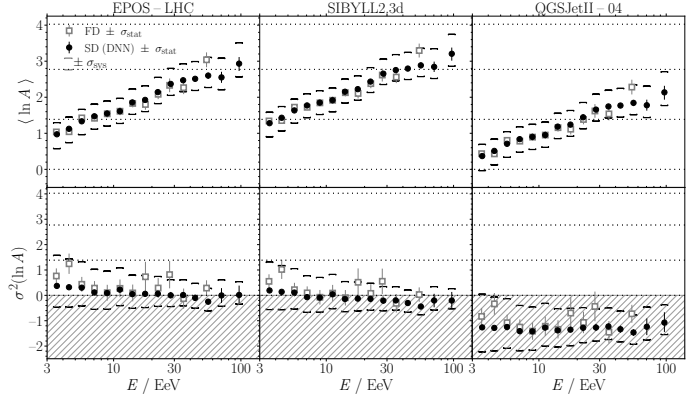
SD-1500 data

- High-quality selection
- 48824 events ($\times$10 FD in the same energy range)

Results

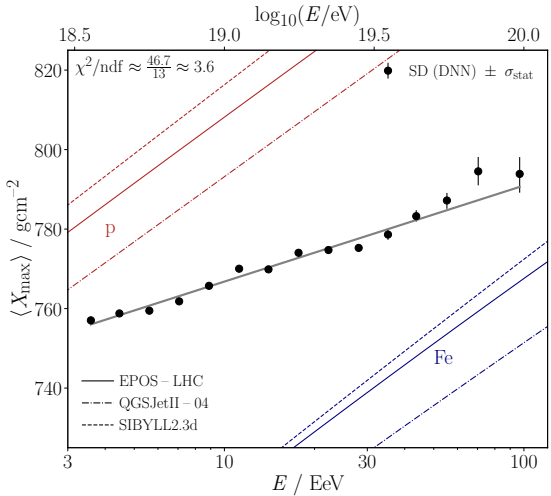
- Excellent agreement with FD (ICRC19)
- transition to heavier and purer composition

Interpretation using interaction models



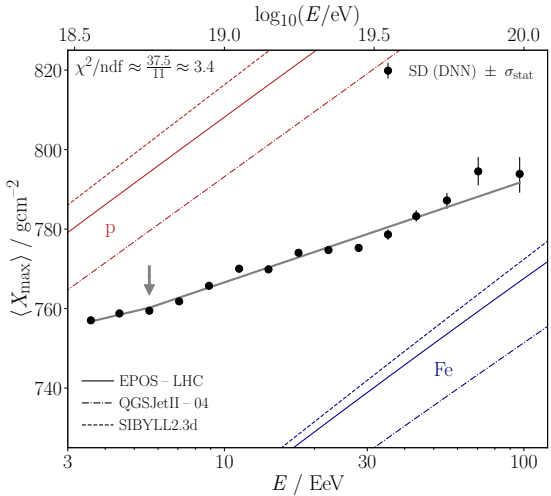
- Sybill 2.3 and EPOS-LHC
  - consistent with SD and FD
- QGSJet II-04
  - Disfavored by SD and FD

Indication for changes in the elongation rate



- Constant elongation rate compatible with FD results
  $D_{10,SD} = 24.1 \pm 1$ g/cm^2,
  $D_{10,FD} = 25.6 \pm 2$ g/cm^2

Indication for changes in the elongation rate



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  $D_{10,SD} = 24.1 \pm 1$ g/cm^2,
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- Evidence for structure beyond

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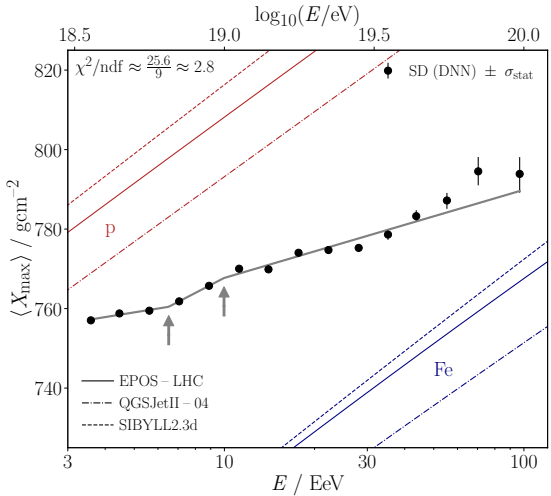

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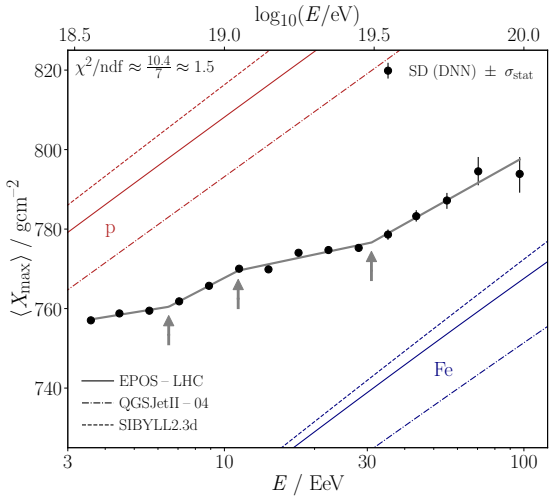

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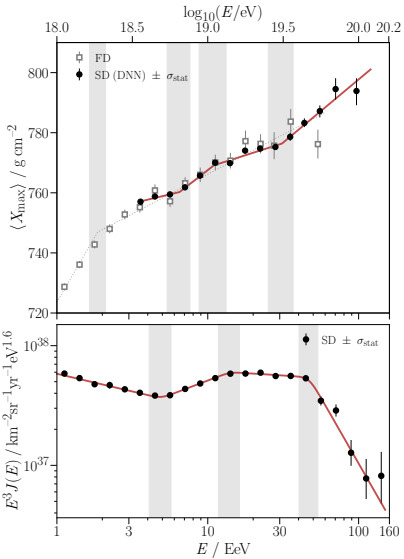
- Evidence for structure beyond
- Constant elongation rate rejected with 4.4σ
- One break rejected with 3σ
- Two breaks rejected with 2σ

Indication for changes in the elongation rate



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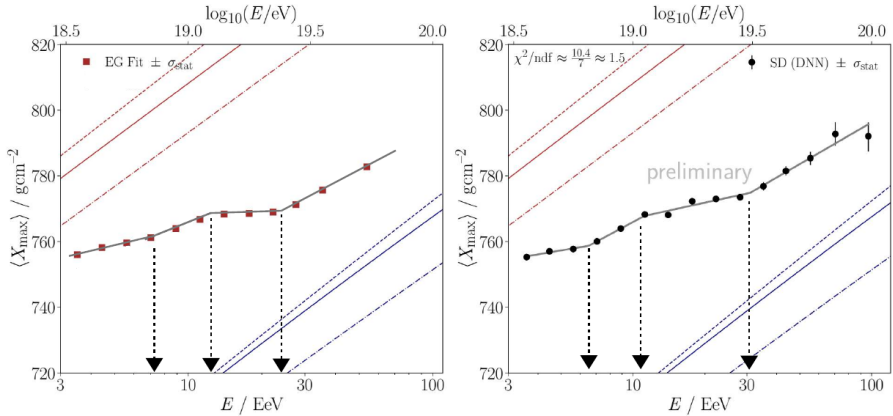
- Evidence for structure beyond
- Constant elongation rate rejected with 4.4σ
- One break rejected with 3σ
- Two breaks rejected with 2σ
- Found kinks coincide with spectrum features

Comparison to astrophysical model

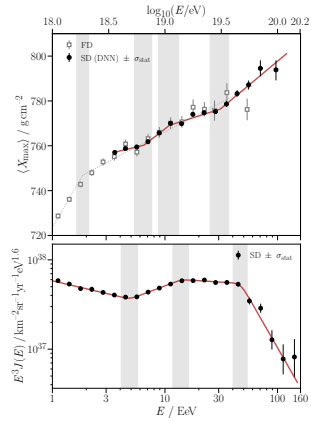


- One of the astrophysical scenarios describing the Auger data on the energy spectrum and FD $X_{\max}$ [JCAP 05 (2023) 024]
- Breaks at positions similar to the indications in SD $X_{\max}$

Summary

UHECR composition using FD and SD $X_{\max}$

- FD and SD measurement are in good agreements
- Transition to lighter composition until $\sim 10^{18.4}$eV, then transition to heavier and purer composition
- The conclusion is invariant to the hadronic interaction models
- QGSJet II.04 predictions are strongly disfavored by the SD and FD data



Xmax with DNNs and SD statistics

- compared to FD, a 10-fold larger data set above 5 EeV
- evidence for a structure beyond constant elongation rate at 4.4σ
- possible breaks in proximity to the energy spectrum features

SD $X_{\max}$: 10.48550/arXiv.2406.06319 (accepted PRD), 10.48550/arXiv.2406.06315 (accepted PRL)
FD $X_{\max}$: paper soon to be published