Mass composition of Ultra-High Energy Cosmic Rays

- latest results from Pierre Auger Observatory

ICHEP 2024 - Prague
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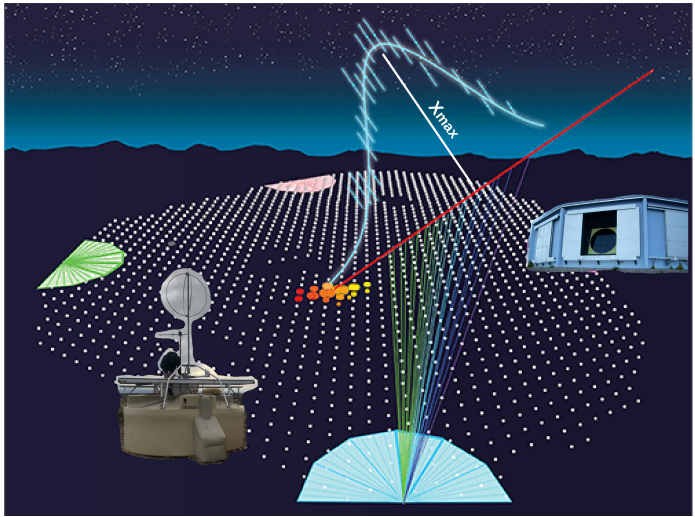
Thomas Fitoussi on behalf of the Pierre Auger Collaboration

Pierre Auger Observatory



Hybrid detection

- Fluorescence Detector (FD)
  - 27 fluorescence telescopes at 4 different places
  - 4×6 looking "down" $\rightarrow$ high energy
  - 3 looking "up" (HEAT) $\rightarrow$ high energy
- Surface Detector (SD)
  - 1660 water tanks with photo-multipliers
  - Auger Prime upgrade: scintillators + radio detectors for SD

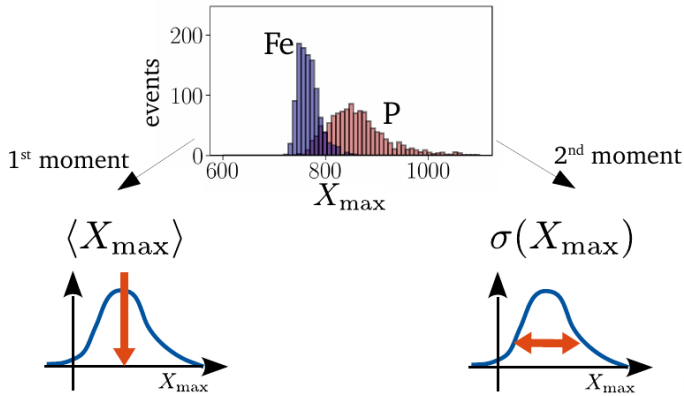
Infering mass composition

Mass composition

$X_{\max} \sim \ln A$

But ...

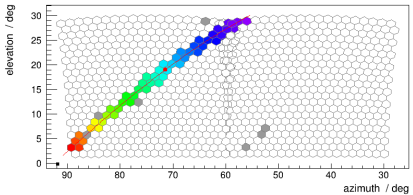
- Shower-to-shower fluctuations $\Rightarrow X_{\max}$ vary for the same particle
- can only infer $\langle X_{\max} \rangle \sim \langle \ln A \rangle$ and $\sigma^2(X_{\max}) \sim \sigma^2(\ln A)$

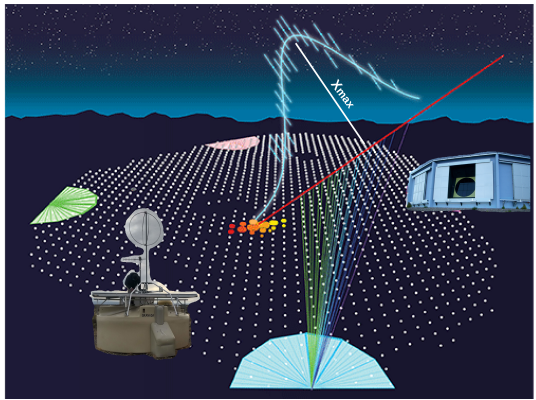


Reconstructing $X_{\max}$

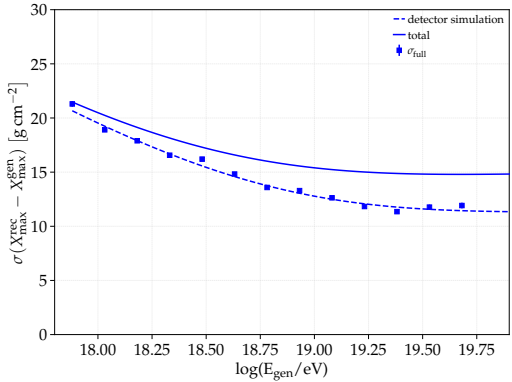
With FD

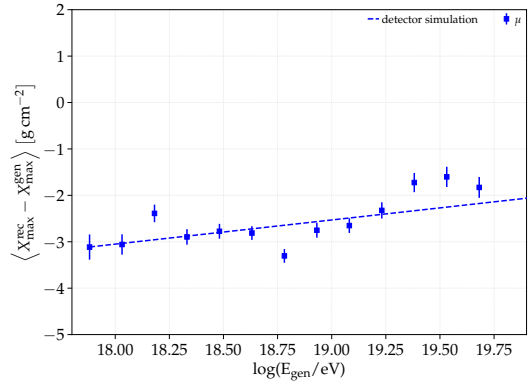
- ✔ Direct access to $X_{\max}$
- ✘ Duty cycle 10-15% $\rightarrow$ limited statistic





$X_{\max}$ bias and resolution

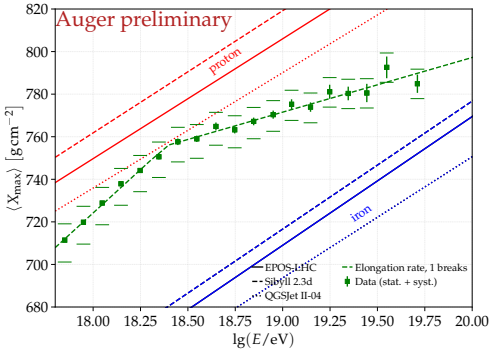


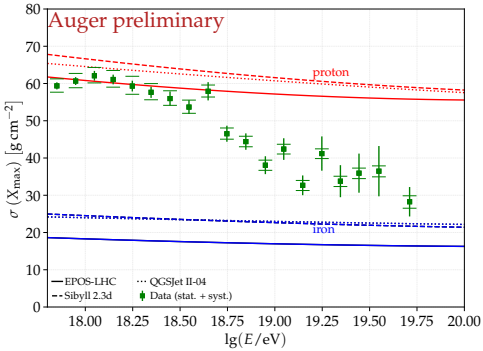


- Total resolution 10 $\rightarrow$ 23g/cm^2

- $X_{\max}$ bias $\sim -2/-3$g/cm^2
- Systematic uncert. $\sim \pm 10$g/cm^2
  $\Rightarrow$ small fluctations of $X_{\max}$ bias negligeable

Composition from FD





- ICRC23 results (75210 events)
- Elongation rate best fitted with 1 break at $\sim 10^{18.4}$eV

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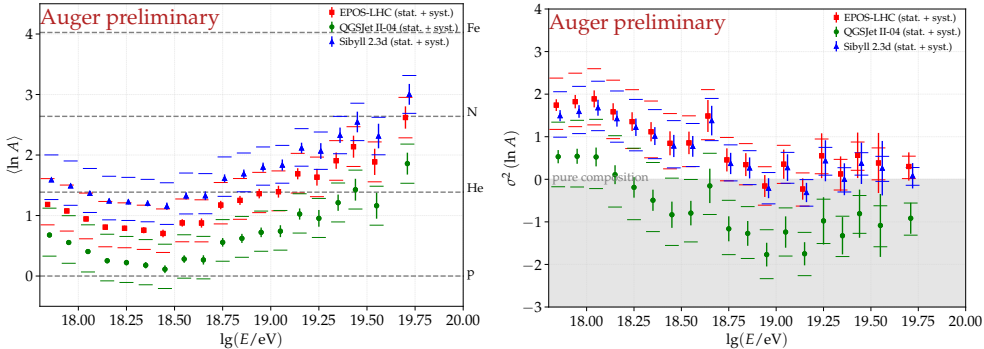


- ICRC23 results (75210 events)
- Elongation rate best fitted with 1 break at $\sim 10^{18.4}$eV
- QGSJet II-04 in tension with data

Reconstructing X_{max}

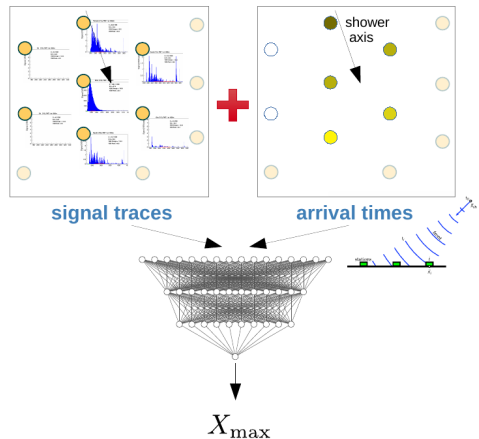
With SD

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

- Reconstruct X_{max} on event level
- Cross-calibration with FD
- Train using MC library (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



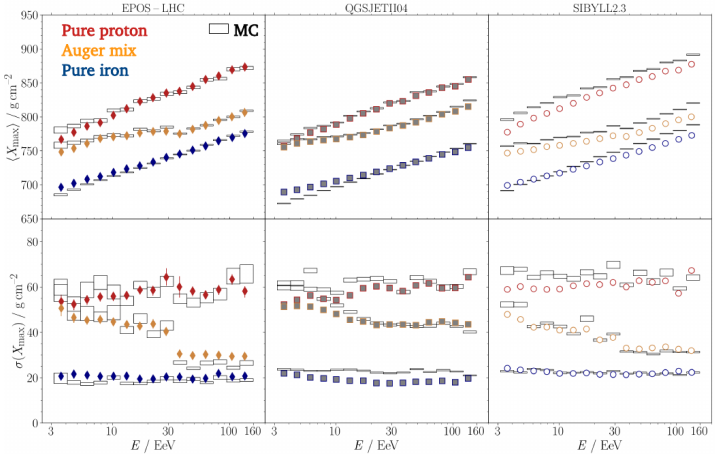
Performance on simulations

Interaction model bias

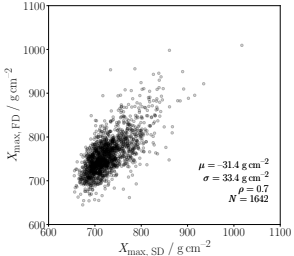
- 1^{st} moment
  - QGSJet $-5 \mathrm{g/cm^2}$
  - Sybill 2.3d $-12 \mathrm{g/cm^2}$
- 2^{nd} moment
  - no strong dependency

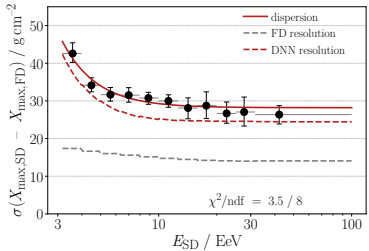
Composition bias

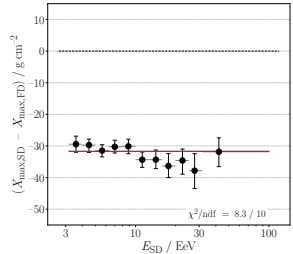
- small for Auger mix
- for proton and iron, small beyond 10EeV



Calibration to hybrid data



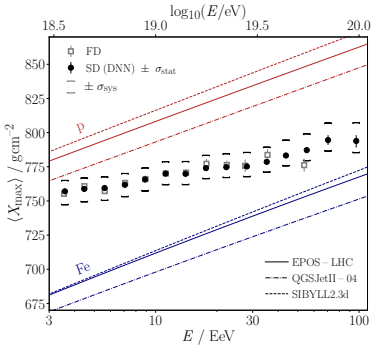


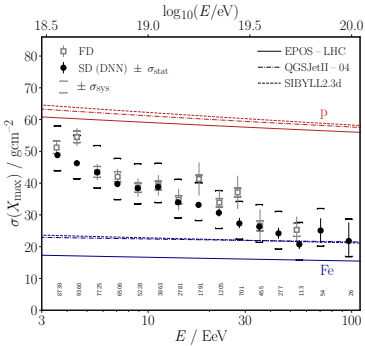


- Calibration of DNN predictions using Golden hybrid data (1642 events)
- Strong correlation ($\rho = 0.7$)
- Resolution 40 $\rightarrow$ 25g/cm^2

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

Application to SD-1500 data



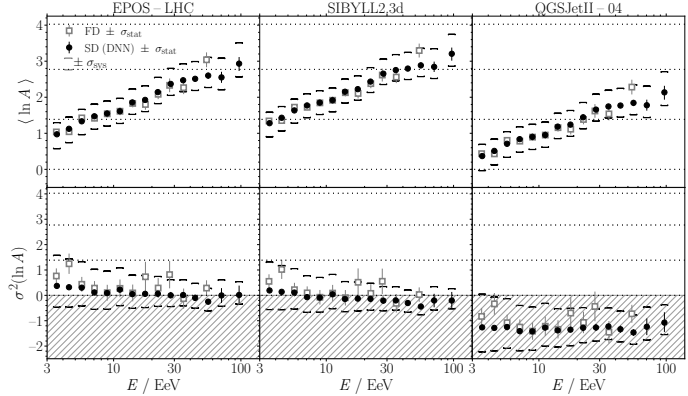


SD-1500 data

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

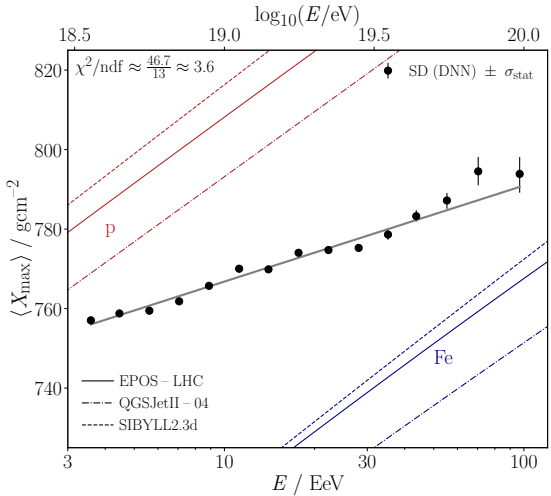
- Excellent agreement with FD
- transition fro lighter to heavier and purer composition

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
  $D_{10,SD} = 24.1 \pm 1\,\mathrm{g/cm^2}$,
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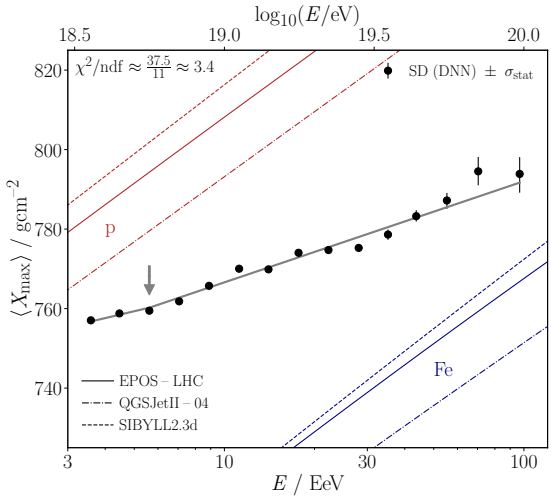

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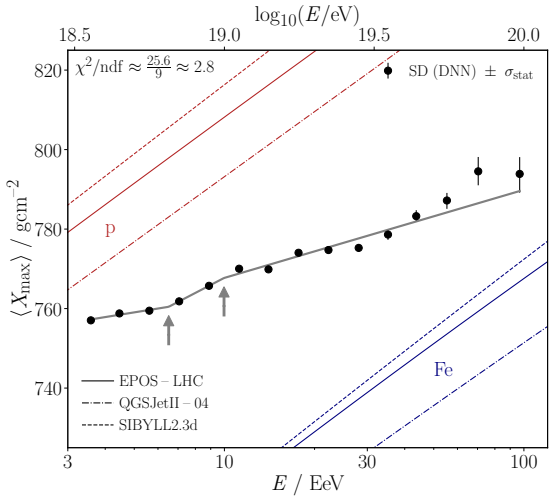

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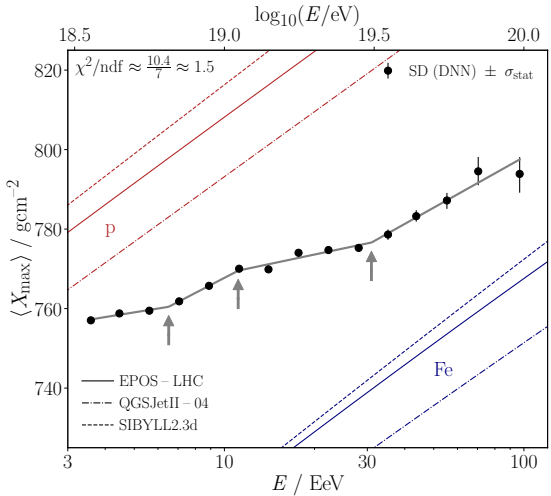

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- One break rejected with 4.4σ
- Two breaks rejected with 3.3σ

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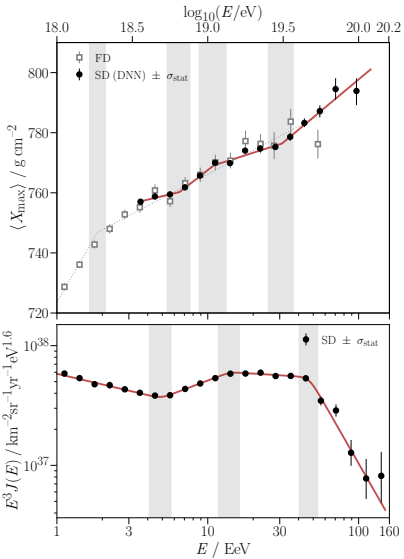

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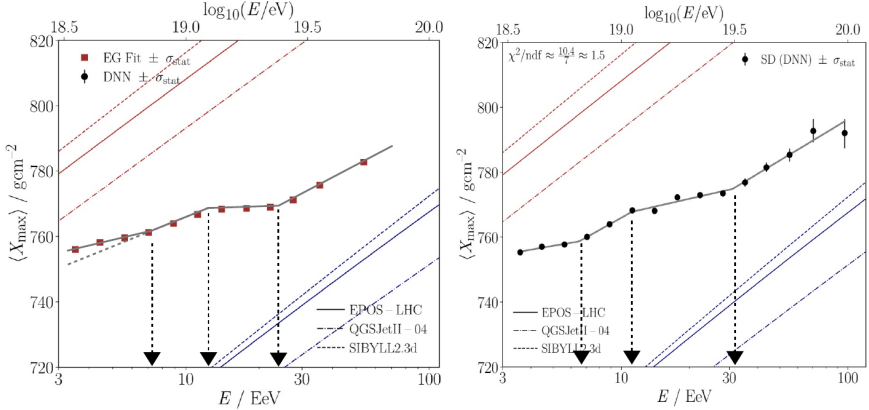
- Found kinks coincide with spectrum features

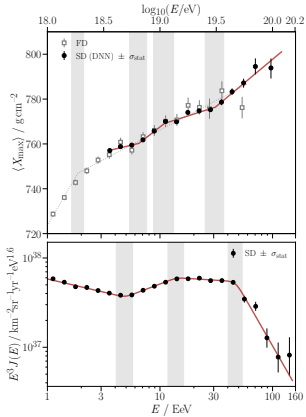
Comparison to astrophysical model



- Extragalactic fit of Auger data (JCAP05(2023)024)
- Prediction from astrophysical model derived with FD data
- Find similar breaks, position of measured features agrees with predictions

Summary

- Derive UHECR composition using FD and SD X_{max}
  - FD and SD measurement are in good agreements
  - transition form light to heavy with mixed composition ($< 10^{18.4}$eV, FD)
  - transition to heavier and purer composition ($> 10^{18.4}$eV, FD and SD)
- Measurement of Xmax with SD statistics
  - 10-fold increase in statistics beyond 5 EeV compare to FD
  - evidence: structure beyond constant elongation rate (4.6σ)
  - found kinks positioned at energy spectrum breaks



Further information

- SD X_{max}:
  10.48550/arXiv.2406.06319
  10.48550/arXiv.2406.06315
- FD X_{max} paper soon to be published