Mass composition analysis with the Pierre Auger Observatory: results and prospects

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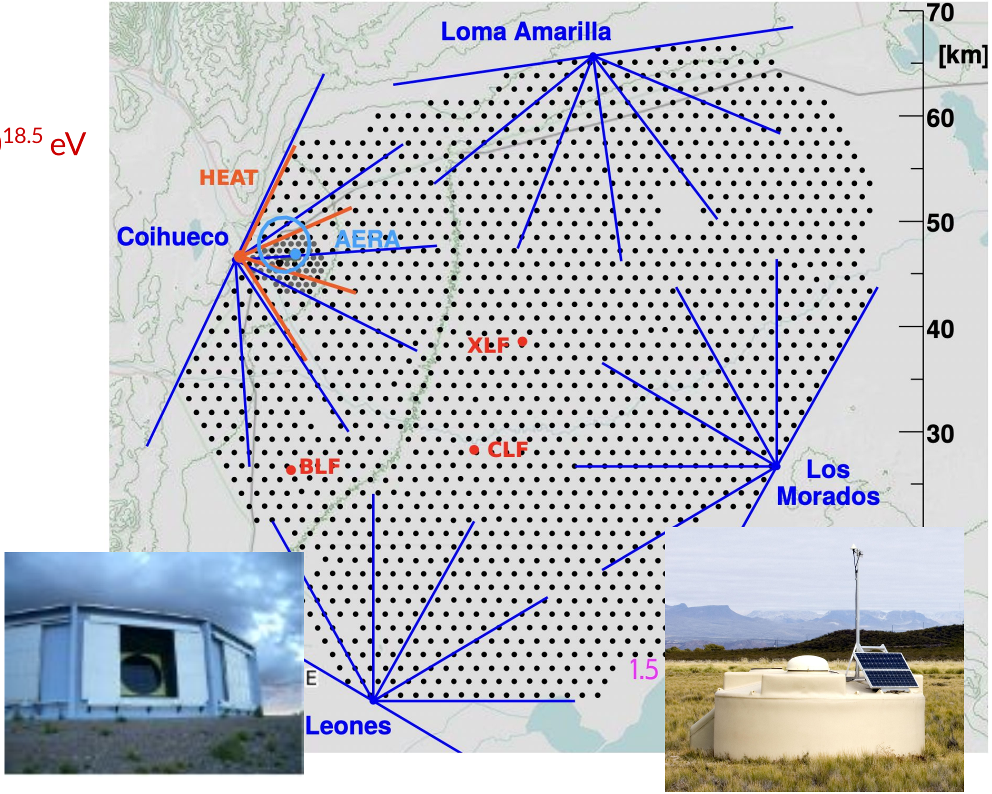
The Pierre Auger Observatory: Phase-I

- Data taking from 2004
- Since 2008
  - 1600 Water Cherenkov Detectors (SD1500) – E > $10^{18.5}$ eV
  - 4 Fluorescence detectors (FD)



Fluorescence Detector
~15% Duty Cycle

Water Cherenkov Detector
~100% Duty Cycle

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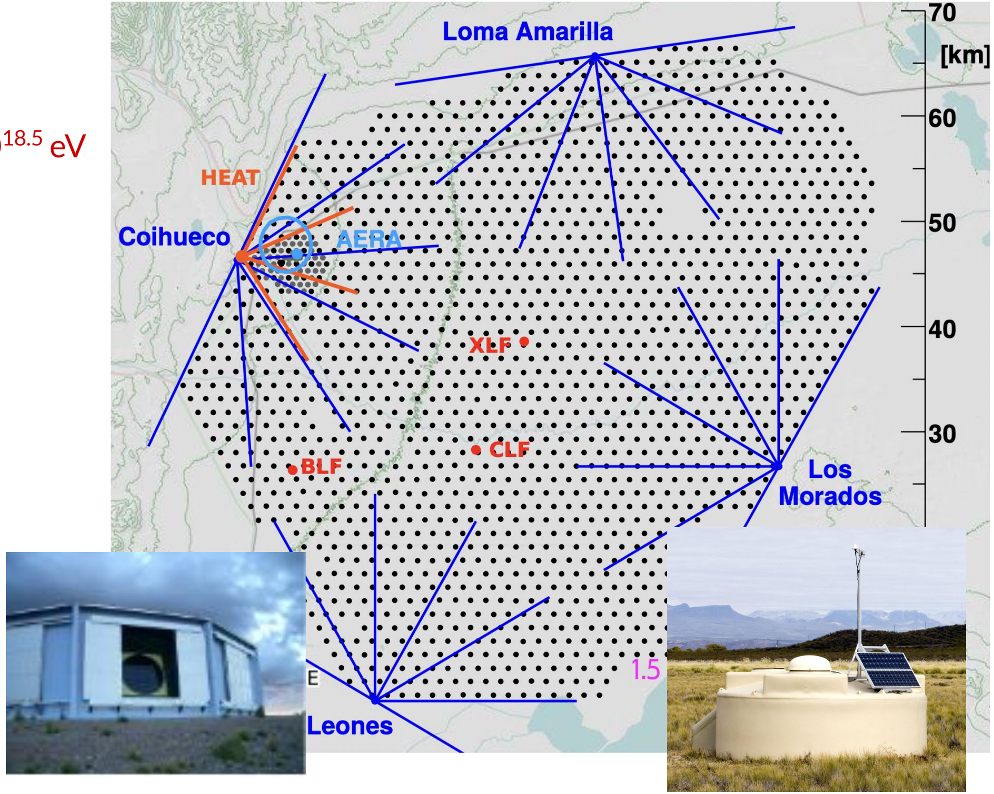
- Lower energy extension
  - 71 WCDs (SD750) – E > $10^{17.5}$ eV
  - 19 WCDs (SD433) – E > $10^{16.8}$ eV
  - High-elevation angle FD (HEAT) – E > $10^{17.0}$ eV



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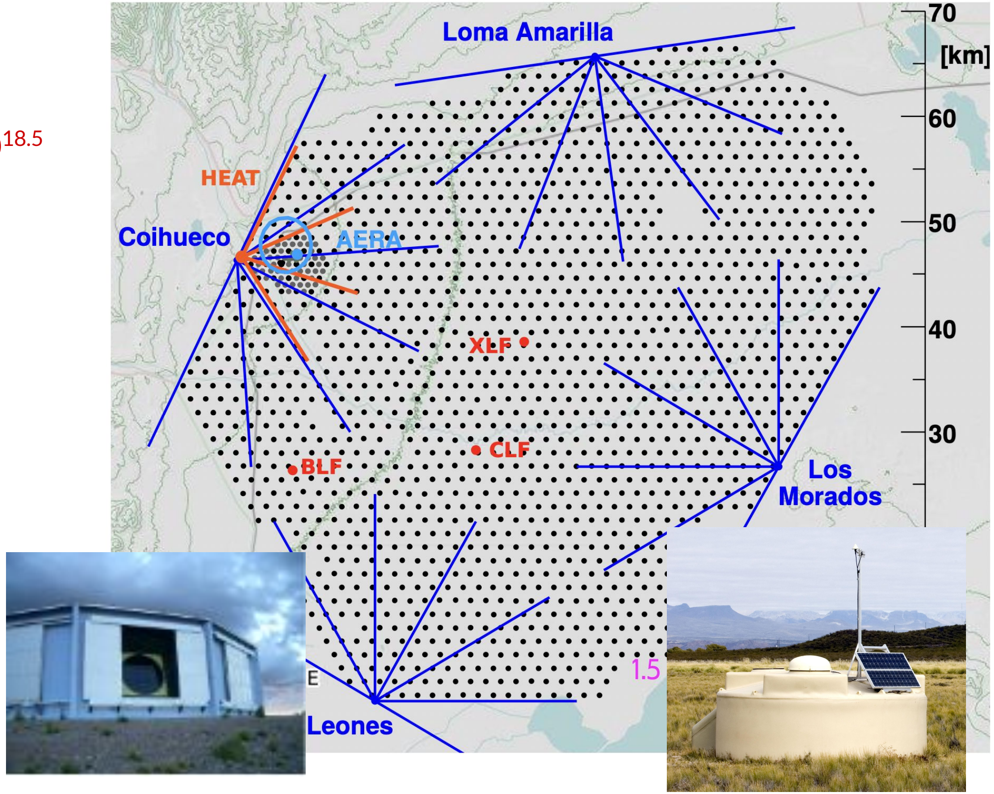
- Hybrid detection with combined SD + FD data subset

Phase-I dataset: events up to 2023

~20 years of data



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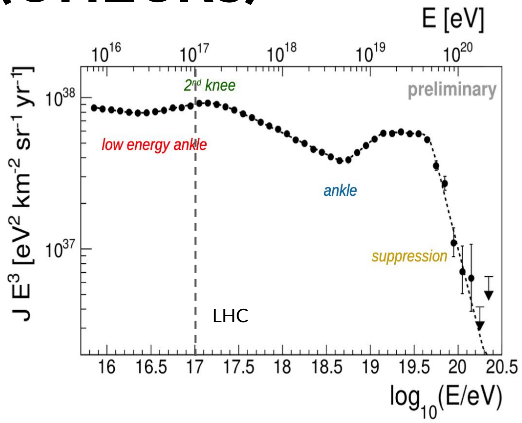
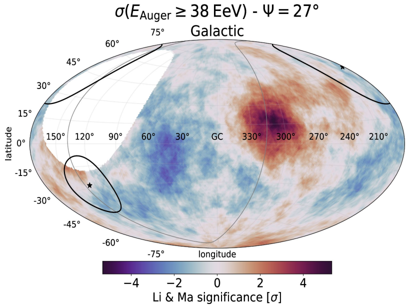
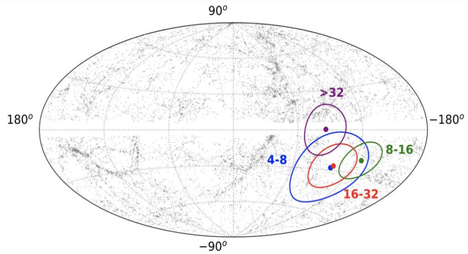
Origin of Ultra Energetic Cosmic Rays (UHECRs)

Key feats to answer the origin of UHECRs



- Energy spectrum





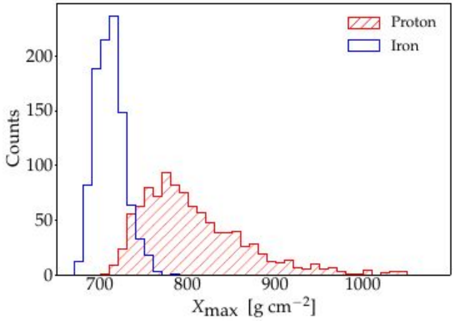
- Arrival direction distribution

- Mass composition → Rely on hadronic interaction models
    - Energies below UHERCs
    - Source of systematic uncertainties

Mass sensitive observables

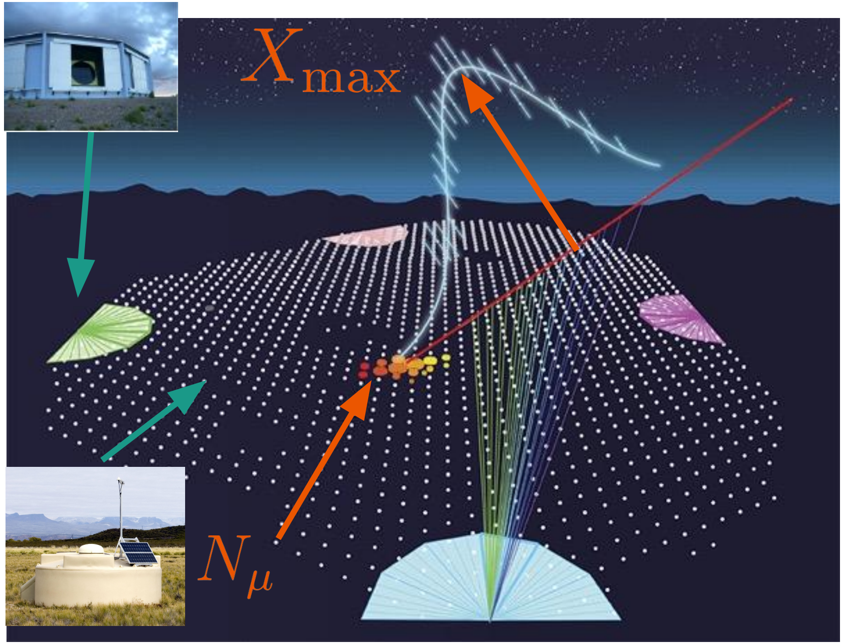
Depth of maximum development: X_{max}

$$X(l) = \int_l^\infty \rho(l')dl'$$



- Extracted from the longitudinal profile of the shower
- Currently the most precise mass estimator

Number of muons at ground: N_μ



X_{max} estimation

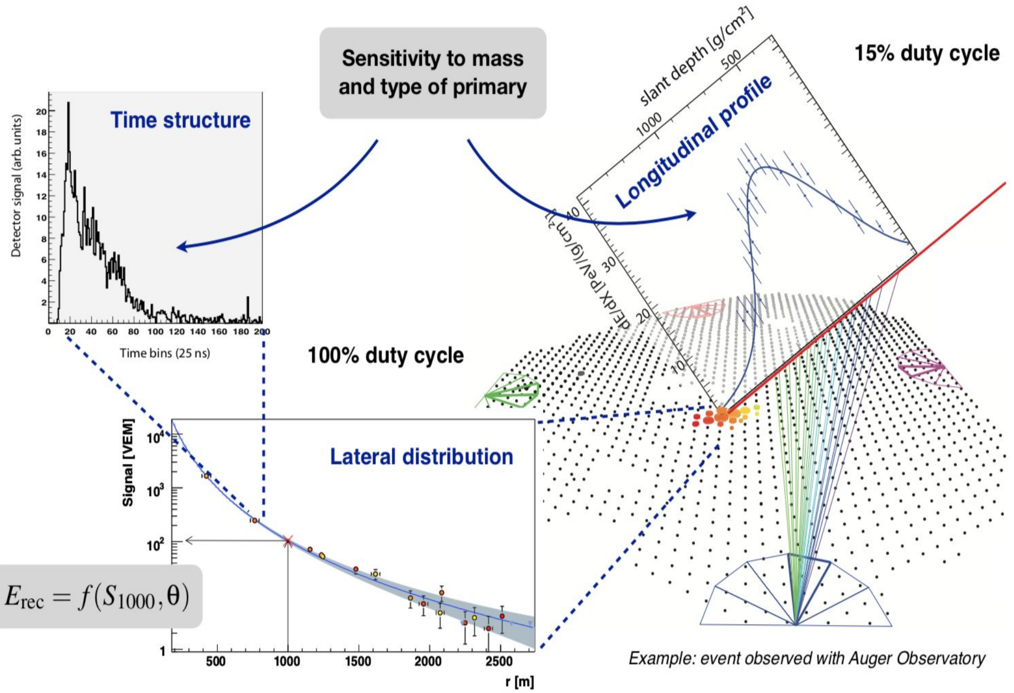
FD: energy deposition rate

- Direct measurement
- Limited by FD low uptime

SD: time structure of signals measured by the WCDs

- Mass sensitive parameter
- Substantially more events
- X_{max} calibrated with FD

$$E_{cal} = \int_0^\infty \left(\frac{dE}{dX}\right)_{obs} dX$$



Example: event observed with Auger Observatory

X_{max} estimation

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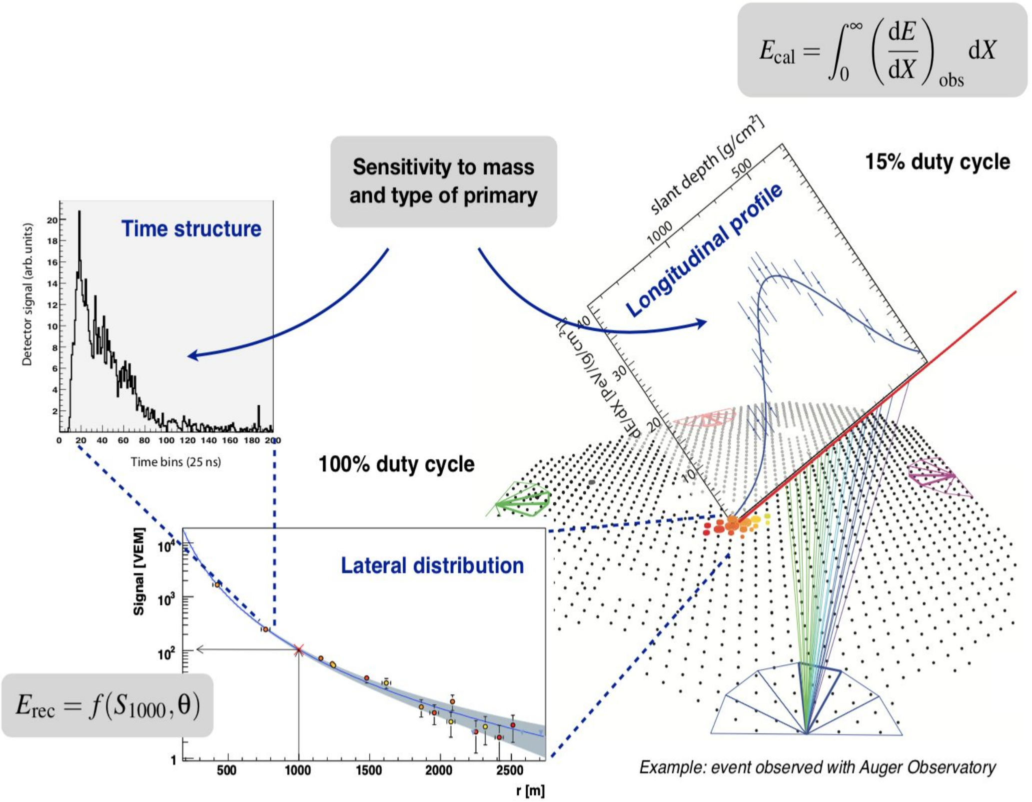
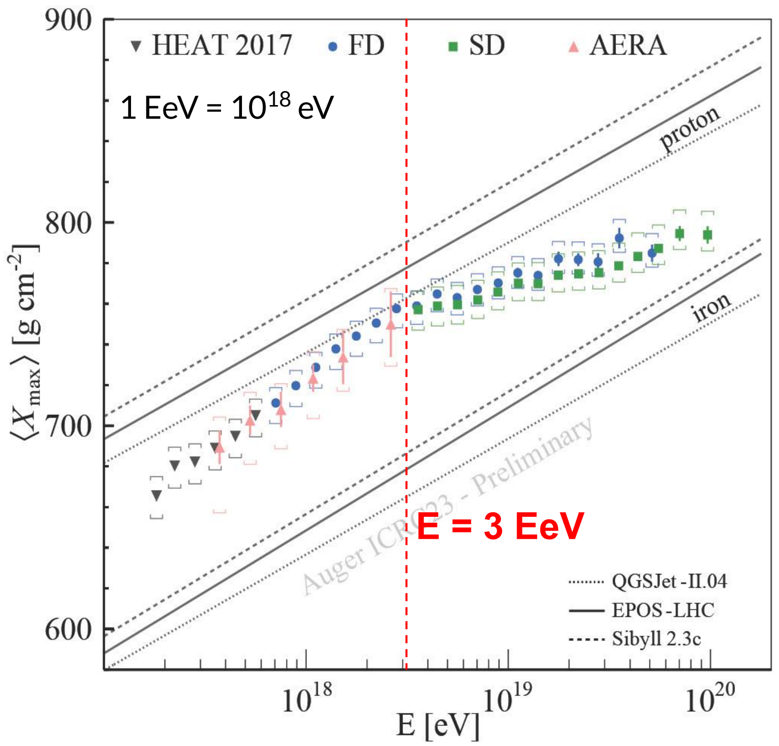
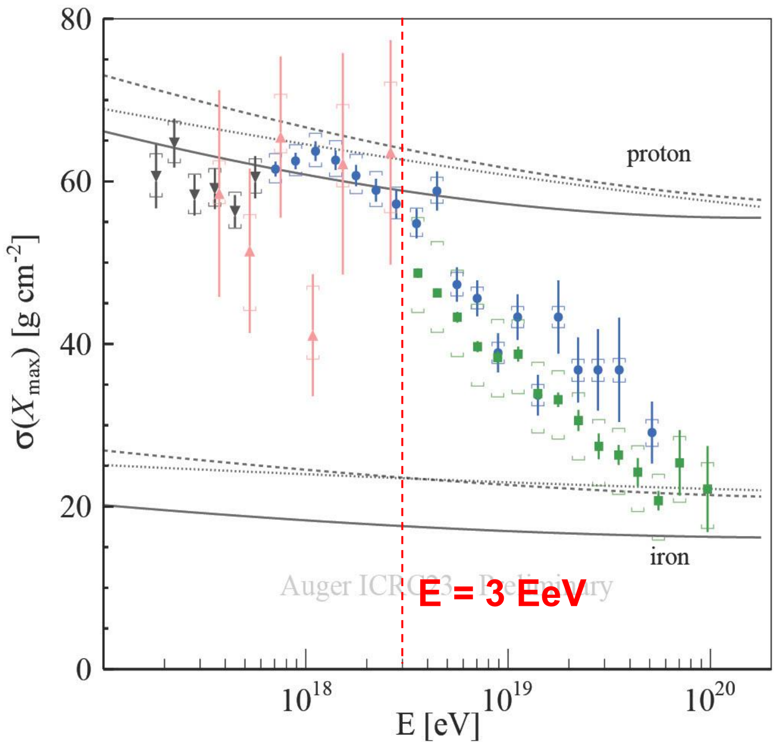
e.g. deep-learning reconstruction algorithm to estimate X_{max}[1,2]



The moments of X_{max}



Lighter to heavier composition from 3 EeV



SD[2], FD[3], HEAT[4] and AERA[5] data

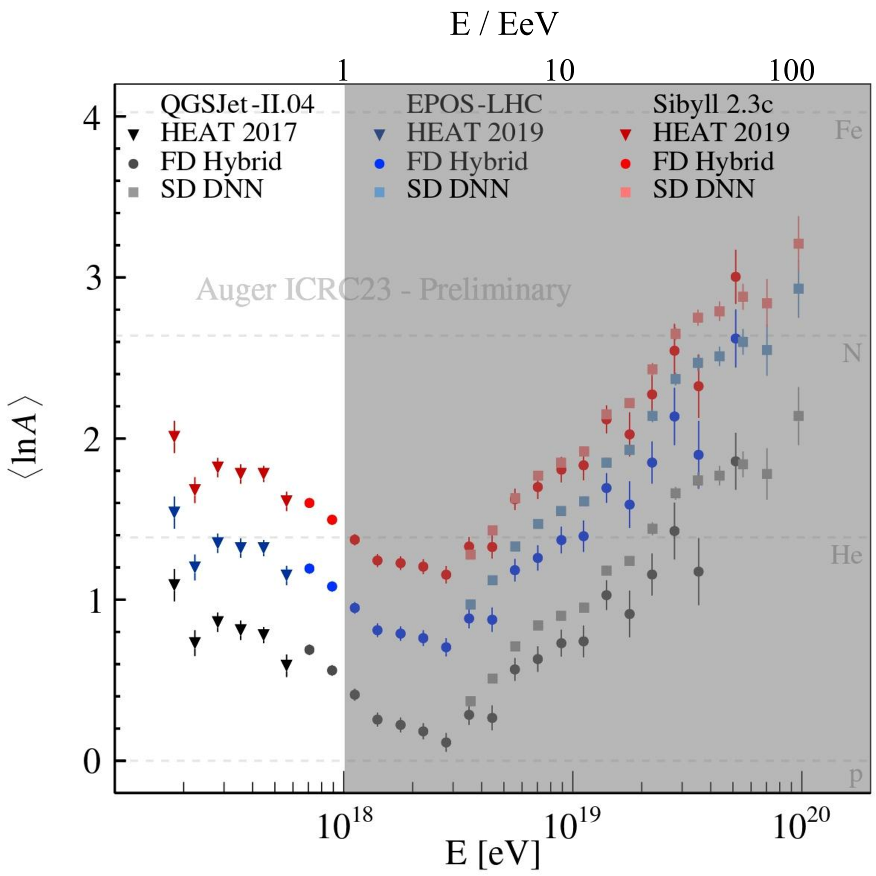
Decreasing σ compatible with increasing heavy fraction in primary beam

Mean of the mass number ln*A*

Mean of the log of the mass of the primary nuclei

$$\langle lnA \rangle = \frac{\langle X_{max} \rangle - \langle X_{max}^{p} \rangle}{\langle X_{max}^{Fe} \rangle - \langle X_{max}^{p} \rangle} ln(56)$$

E < 1 EeV Moderately heavy composition becoming lighter



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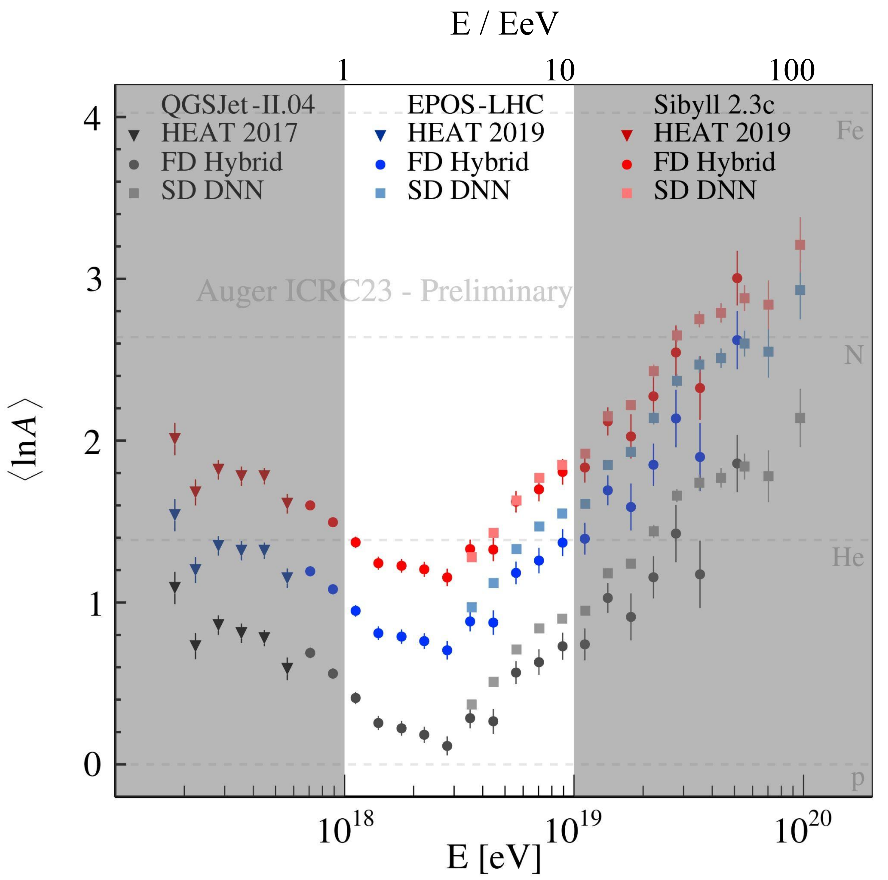
1 to 10 EeV Lightest composition at 2-3 EeV



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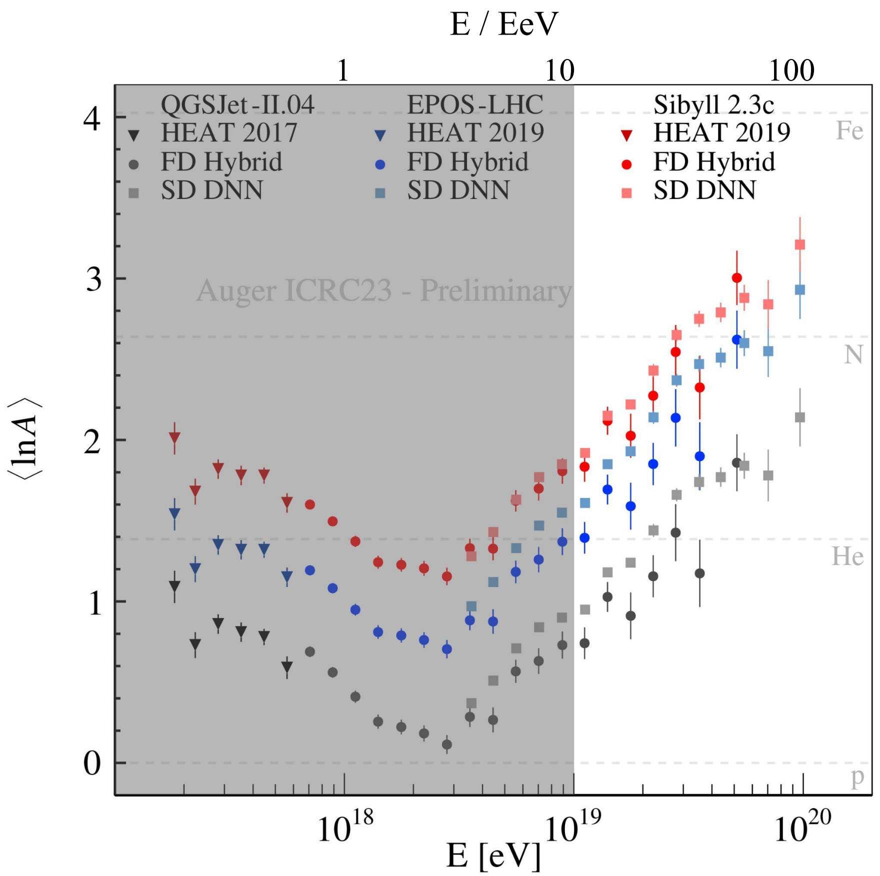
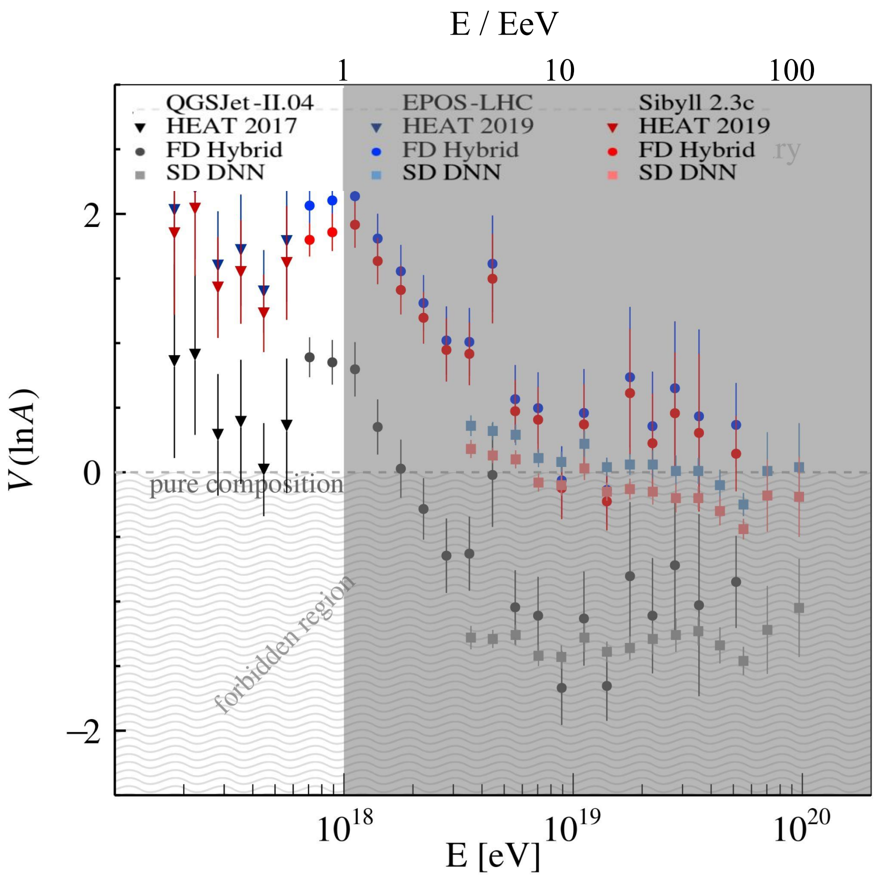
E > 10 EeV UHECR composition becomes increasingly heavy with energy



Dispersion of the mass number

Dispersion of the log of the mass of the primary nuclei

E < 1 EeV Highly mix composition



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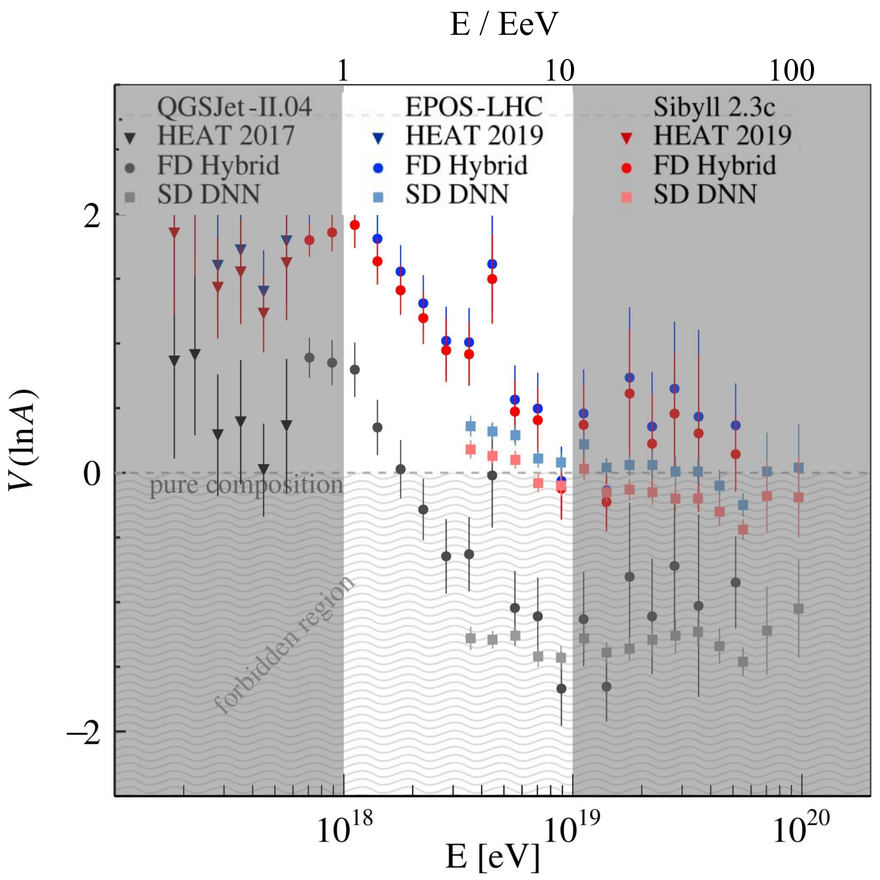
1-10 EeV Transition to relatively pure beam



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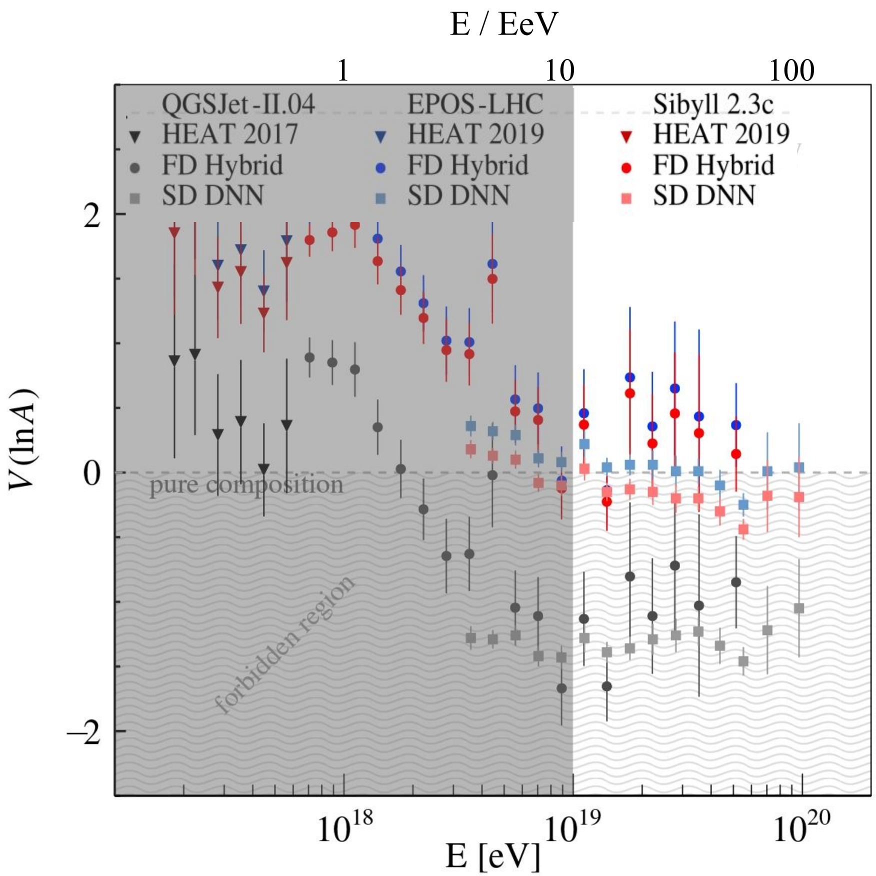
E > 10 EeV Beam has **only one or two components**



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Dispersion of the log of the mass of the primary nuclei

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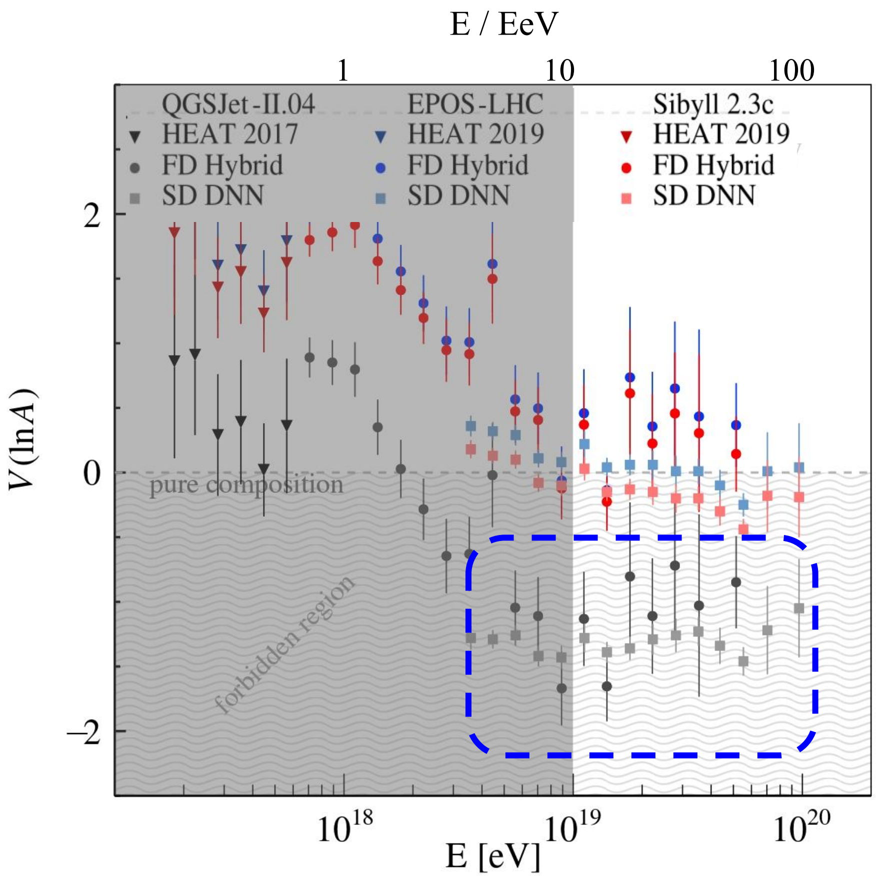
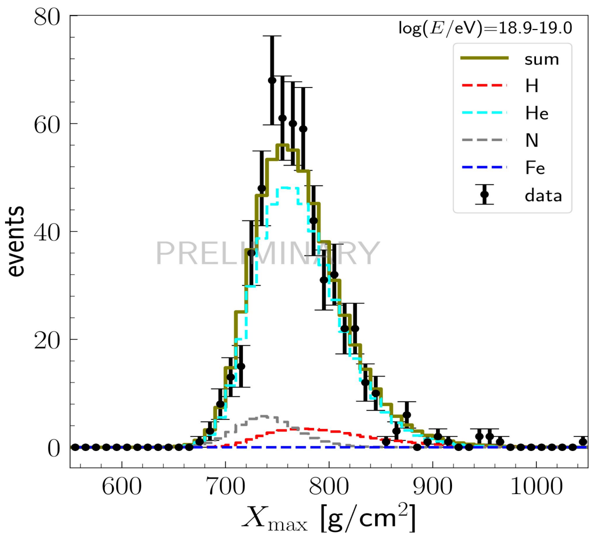
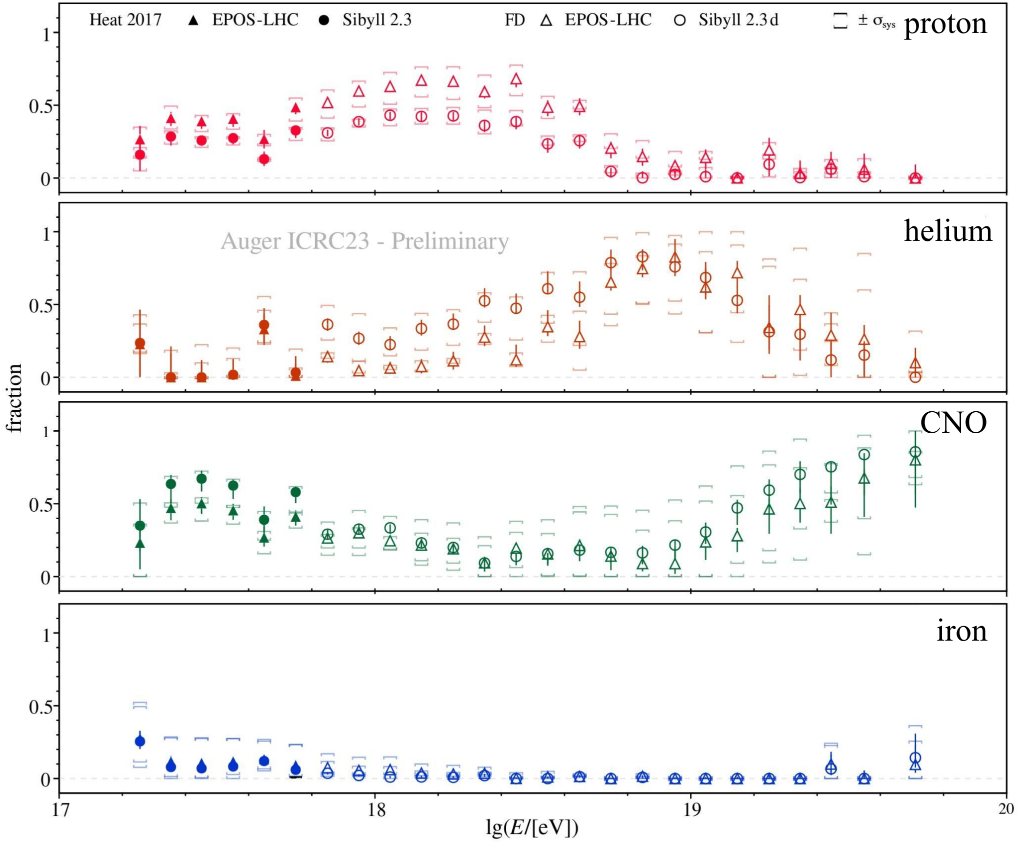
Unphysical predictions from QGSJet-II.04 from ~ 1EeV



Model dependent mass fraction

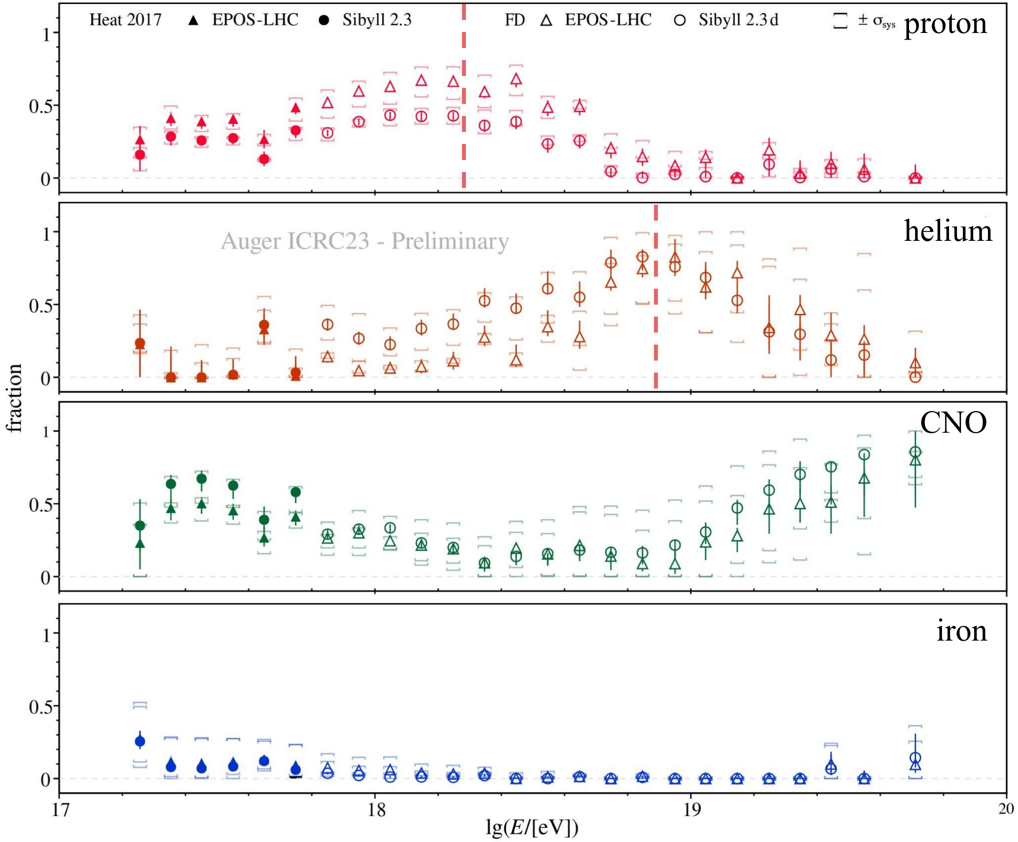
X_{max} distribution fit with different model-generated templates of mass groups to estimate their relative contribution[6]





Model dependent mass fraction

- **Protons** are important for energies up to ~2 EeV and become a minor component
- **Helium** peaks at ~8 EeV
- **CNO** is growing steadily up to the highest energies and could continue beyond
- **Iron** is almost entirely absent from the flux in this energy range



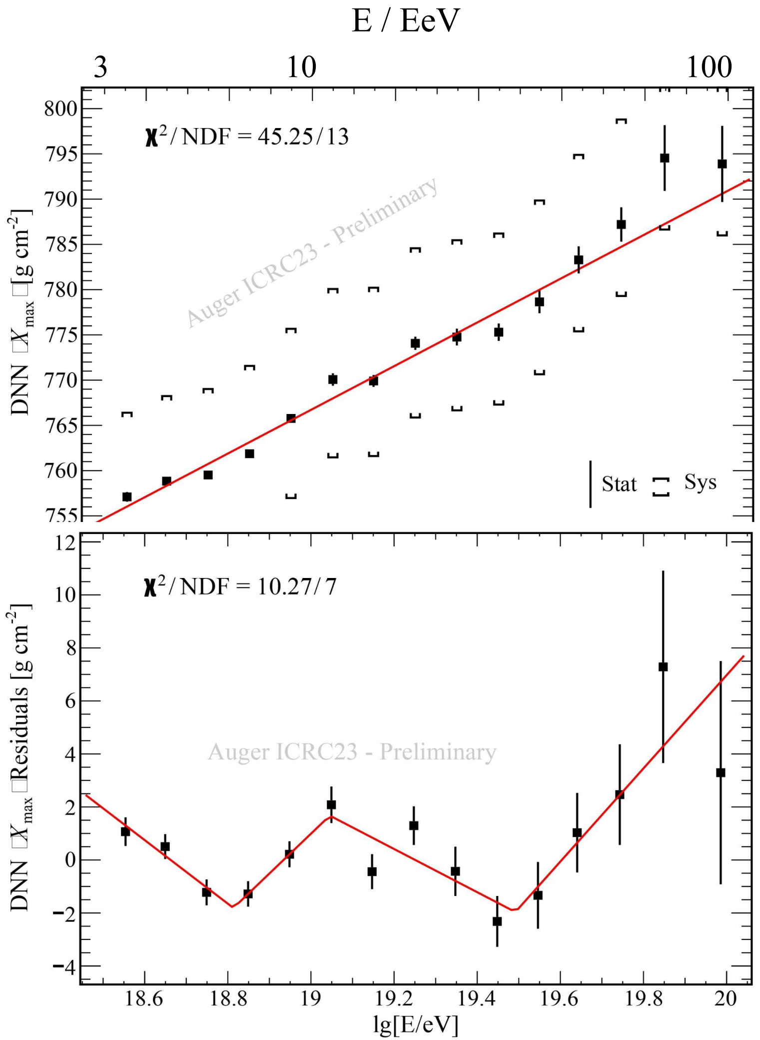
Complex evolution in SD X_{max}

Constant mass evolution can be rejected with SD X_{max} at more than 4σ for E > 3 EeV[2]

Test: linear fit followed by 3-break fit to the residuals

Linear model χ^2/NDF = 3.33

3-break model χ^2/NDF = 1.47



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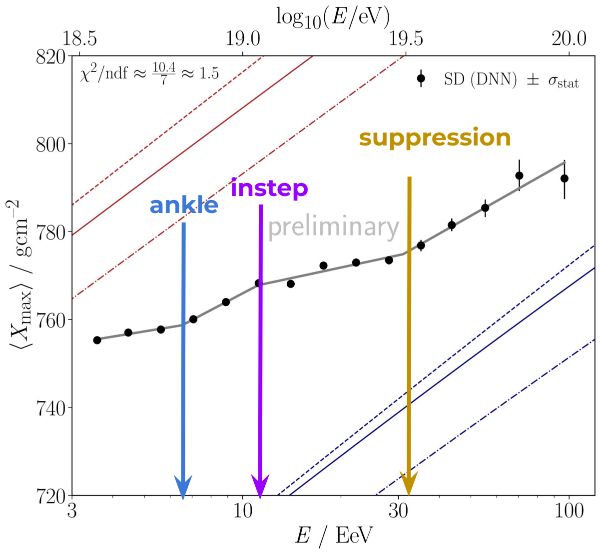
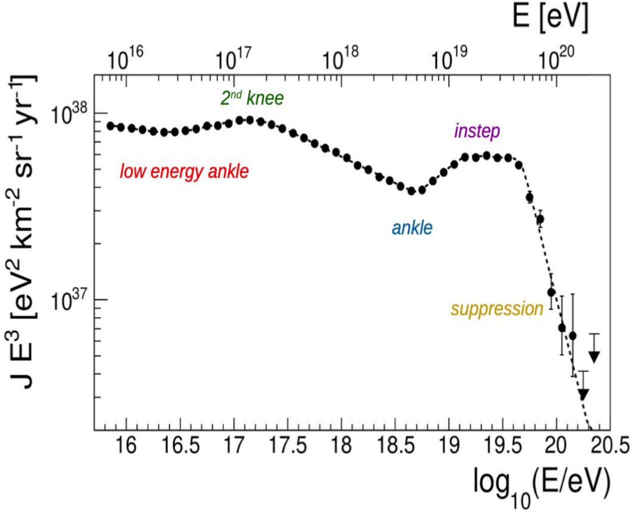
3-break fit produce lower χ^2/NDF with **signatures similar to the energy spectrum**





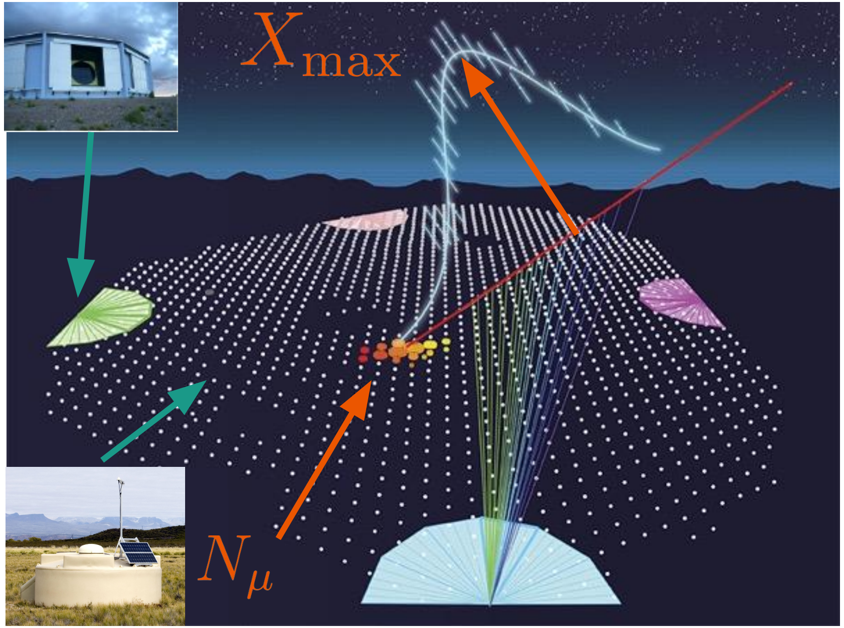
Mass sensitive observables

Depth of maximum development: X_{max}

- Extracted from the longitudinal profile of the shower
- Currently the most precise mass estimator

Number of muons at ground: N_μ

- Arrival time of secondary particles at ground
- Direct measurement of muons underground

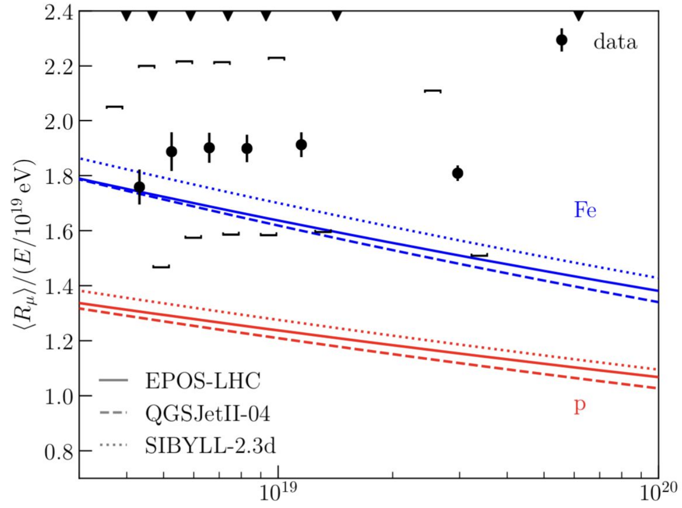


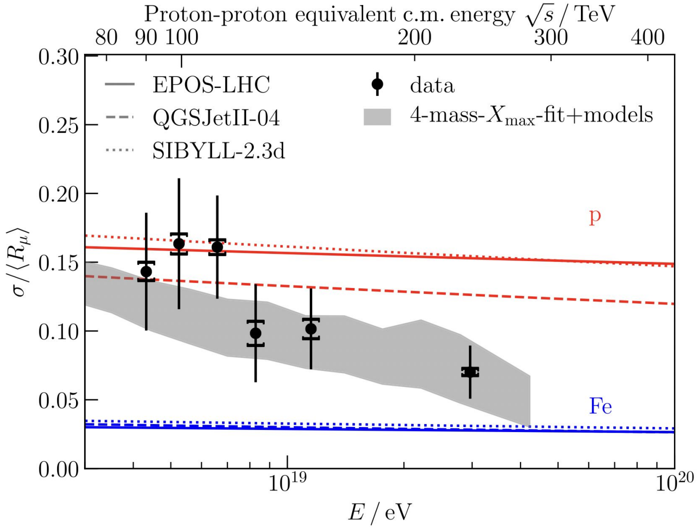
Number of muons from inclined showers

For inclined showers, the EM component is absorbed in the atmosphere and signal at ground correspond predominantly to muons.

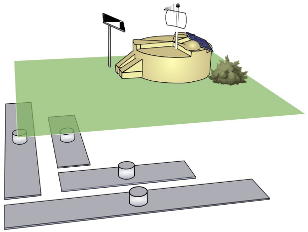
Average number of muons: the measurement **does not** fall within the expected range from the models[7].

Relative fluctuations of the number of muons: the measurements **do** fall within the expected range from the models.





Number of muons with the Underground Muon Detector



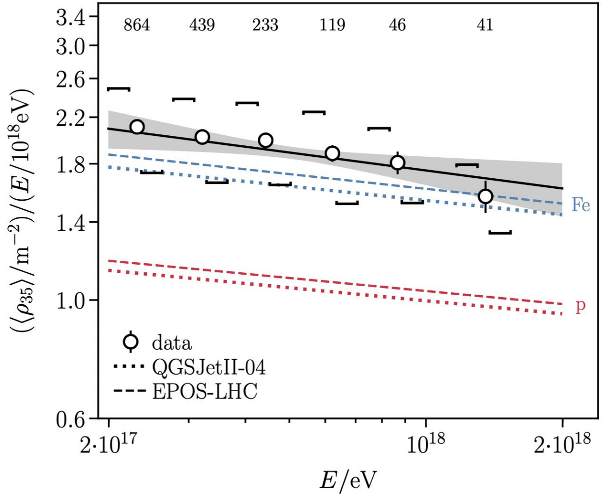
Underground Muon Detector: next to SD stations in the low energy region. **Part of Auger Prime, still in deployment.**

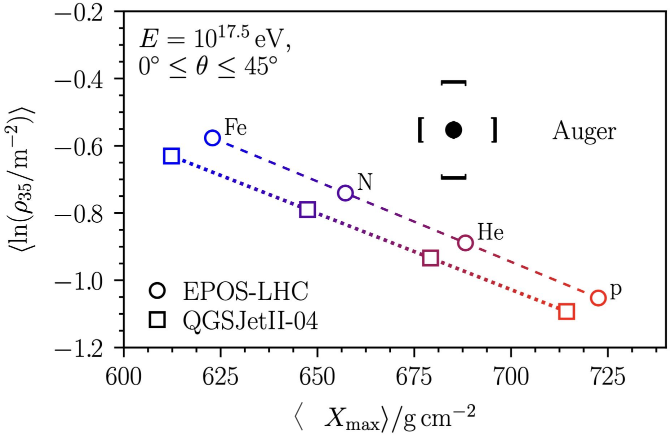
Lower energy measurements (closer to LHC data).

First direct measurement of muon content[8]

Larger muon content in data than in predictions, but compatible with iron primaries.

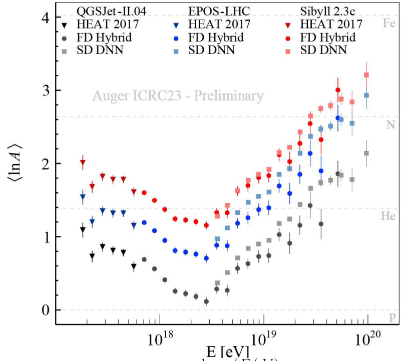
When X_{max} information is considered, data is in tension with models.

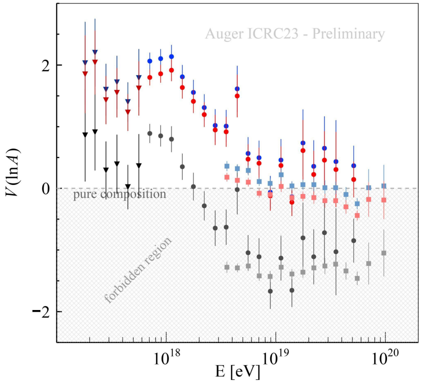


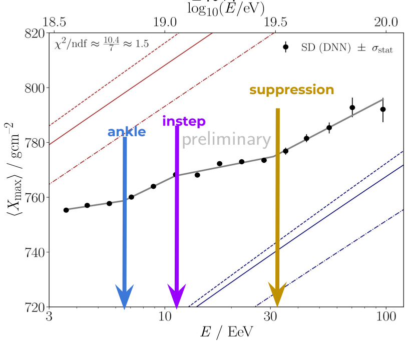


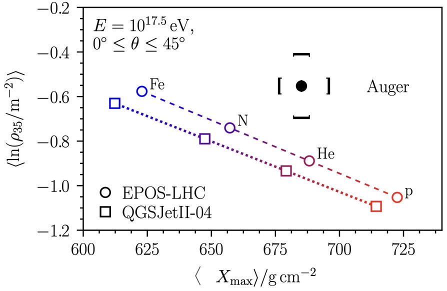
Summary

- Evidence strongly support mix composition that is **lightest around 2-3 EeV**
- Above 3 EeV, **UHECRs increase in mass** with energy
- Primary beams:
  - **Mixed** under 1 EeV
  - **Increases** in purity for energies between 1 to 10 EeV
  - **1 or 2 components** above 10 EeV
- Energy evolution of SD X_{max} suggest the existence of a **complex structure** at energies above 3 EeV
- **Tension** between predictions of muon content and experimental results









Auger Prime will provide more sensitive and precise measurements on an event-by-event basis for mass composition studies

Thanks for your attention!

References

[1] A. Aab et al., [Pierre Auger Coll.], JINST 16 (2021) P07019 [2101.02946]

[2] J. Glombitza et al., [Pierre Auger Coll.], PoS ICRC2023 (2023) 278

[3] T. Fitoussi et al., [Pierre Auger Coll.], PoS ICRC2023 (2023) 319

[4] J. Bellido, [Pierre Auger Coll.], PoS ICRC2017 (2018) 506

[5] B. Pont, [Pierre Auger Coll.], EPJ Web Conf. 283 (2023) 02010

[6] O. Tkachenko et al., [Pierre Auger Coll.], PoS ICRC2023 (2023) 438

[7] A. Aab *et al.* (Pierre Auger Collaboration), Phys. Rev. Lett. **126**, 152002

[8] Eur. Phys. J. C 80 (2020) 751

Backup slides

Auger Prime

3.8 m^2 scintillators (SSD) on each SD station

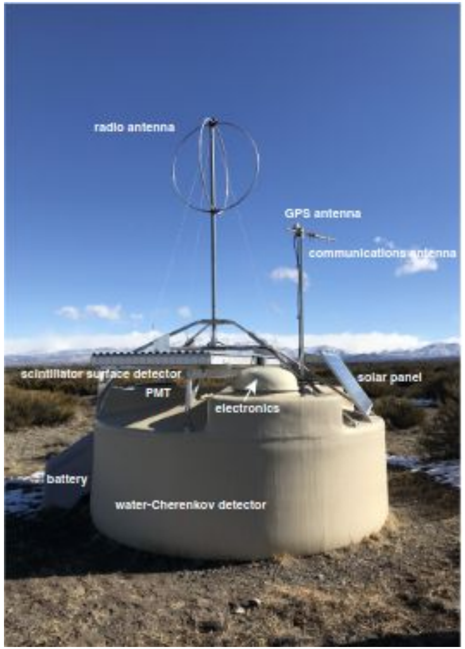
Upgrade SD electronics

Additional small PMT to increase dynamic range

Buried muon counters (UMD) in SD-750 stations

Increase FD uptime

Will increase accuracy of muon measurements also for individual events

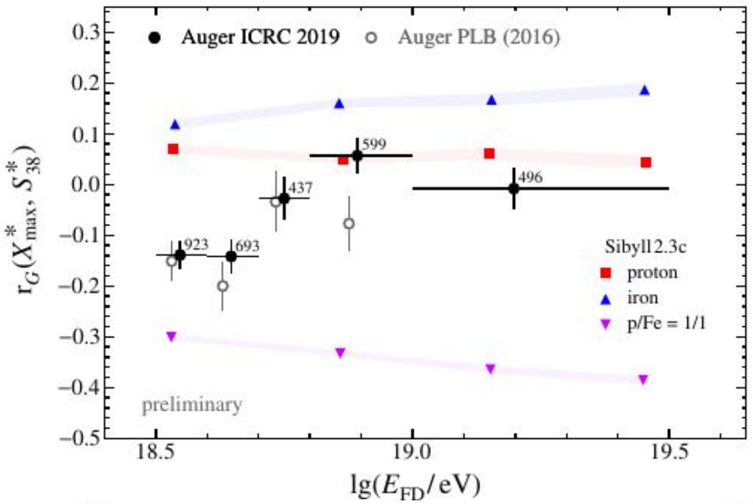


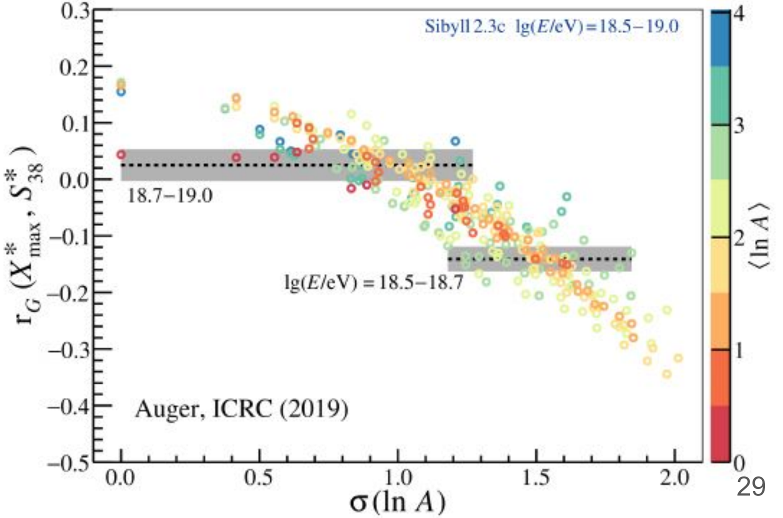
X_{max} - Signal in WCD correlation

- Parameter for UHERC composition model-independent
- Degree of correlation between X_{max} and the signal in WCD at reference distance (1000 for SD1500): r_G
    - r_G <0 for mix composition
    - r_G goes to zero as purity increases

- Correlation remains significantly negative (6.4σ from zero) below $10^{18.8}$ eV and then becomes compatible with zero.

- Negative values observed below the ankle are compatible only to mixes with σ(ln A) > 1.0





Complex evolution in SD X_{max}

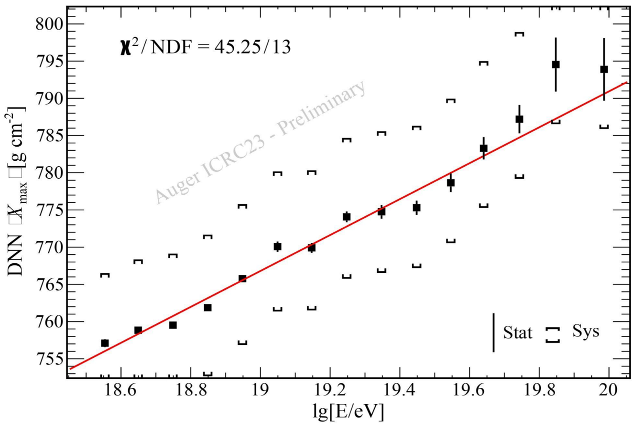
DNN SD X_{max}: Higher statistics than FD, but model dependent to train DNNs

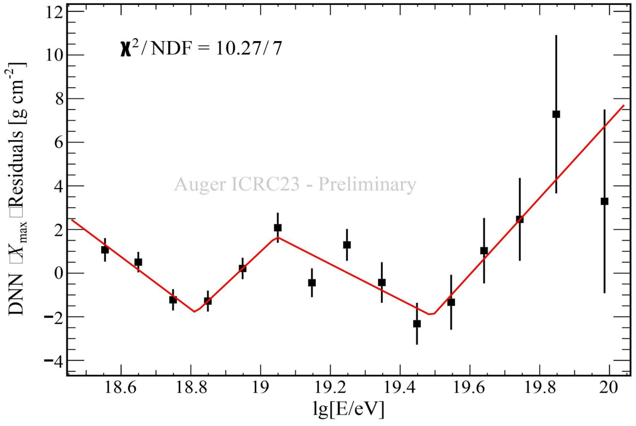
Data-driven method to compare

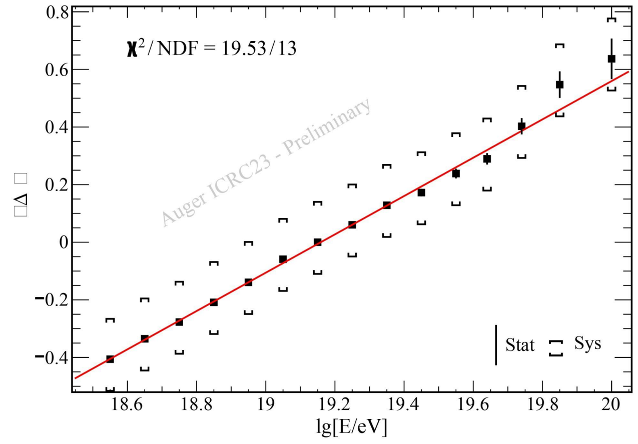
Δ method based on risetimes of SD signals

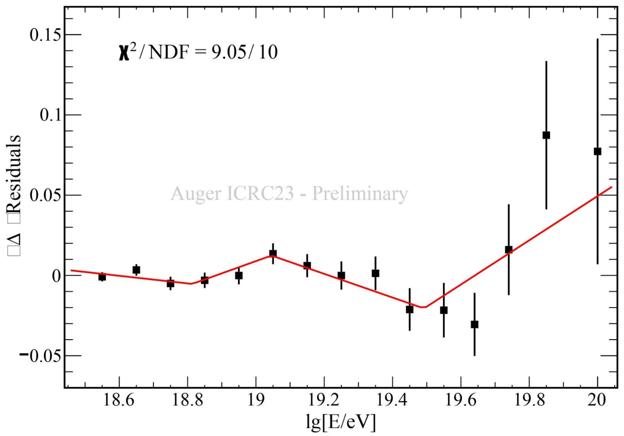
Linear model $\chi^2/NDF = 1.50$

3-break model $\chi^2/NDF = 0.91$





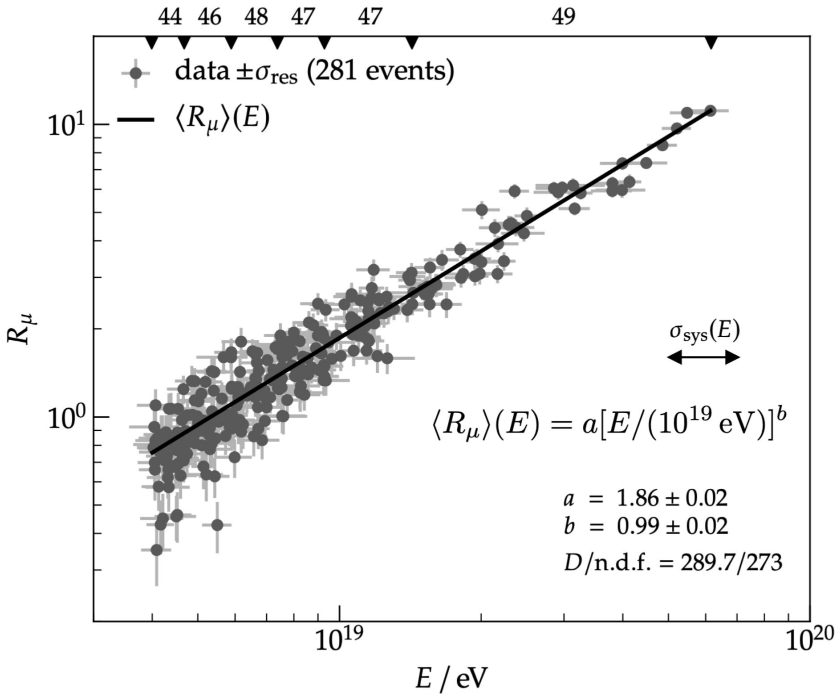




Number of muons from inclined showers

R_μ: integrated number of muons at ground divided by a reference value given by N_μ in simulated showers at 10^{19} eV

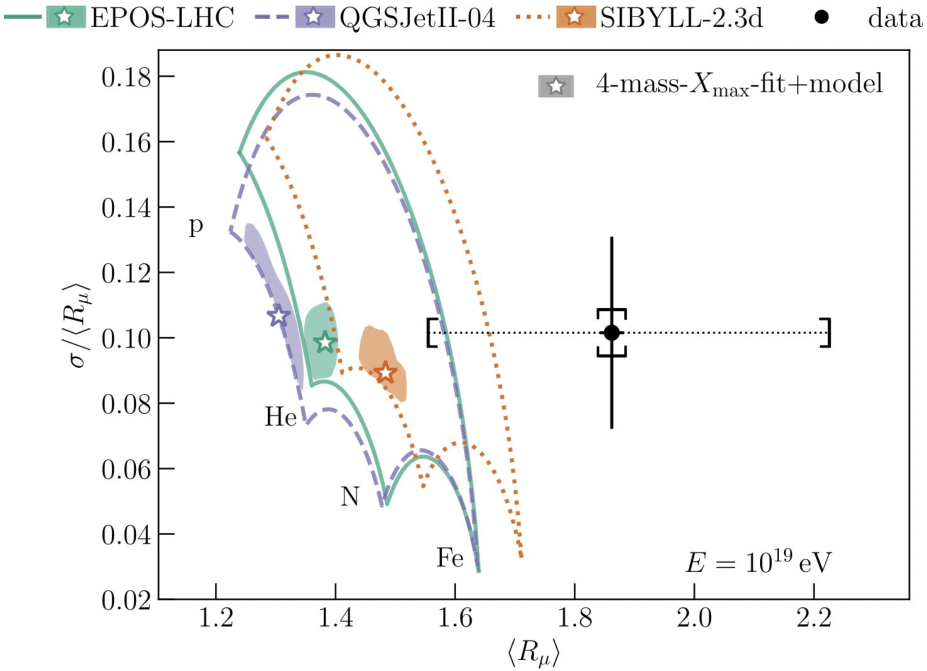
Fitted function: considering detector response, physical fluctuations (**σ**) and the probability distribution of hybrid events



Number of muons from inclined showers

Stars and shaded regions: allowed regions considering statistical and systematic uncertainties from X_{max} measurements.

Data point: at 10^{19} eV, with statistical (error bars) and systematic (square brackets) uncertainties.



None of the predictions is consistent with the measurement.