Energy evolution of cosmic-ray mass and intensity measured by the Pierre Auger Observatory

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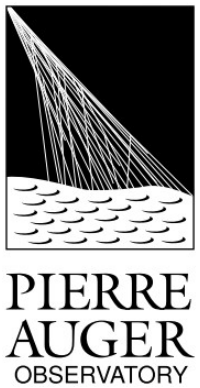
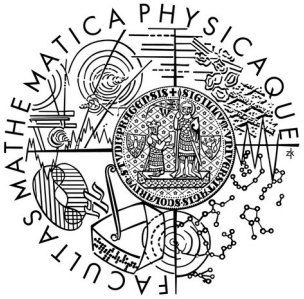




Co-funded by
the European Union

The Pierre Auger Observatory – hybrid detector

Fluorescence detector (FD)

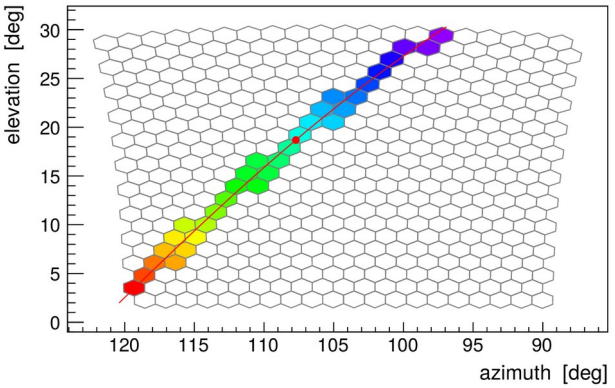
- 4 sites with 27 telescopes
  - 24 horizontally-looking
  - 3 High Elevation Auger Telescopes (HEAT)

+

Surface detector (SD)

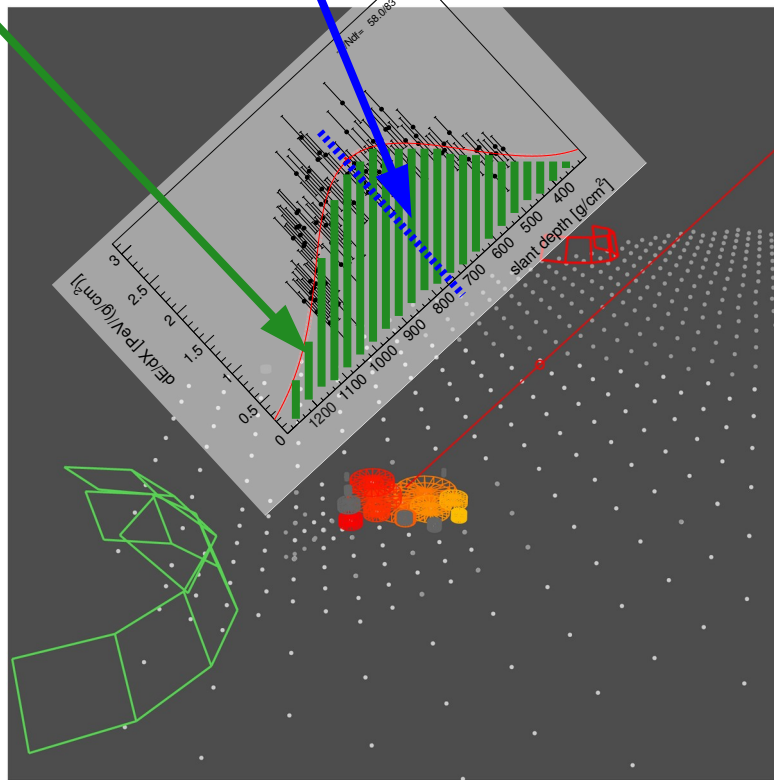
- 1600 water-Cherenkov stations
- total area 3000 km^2
- triangular grid arrays
  - spacing of 1500 m, 750 m and 433 m

FD

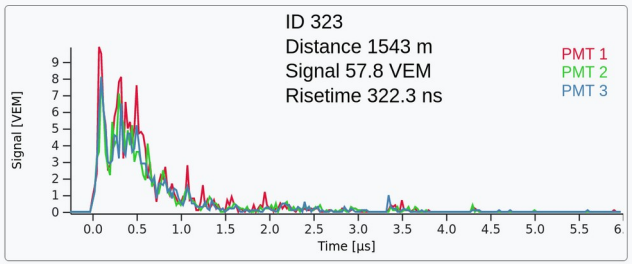


E_{FD}

X_{max}



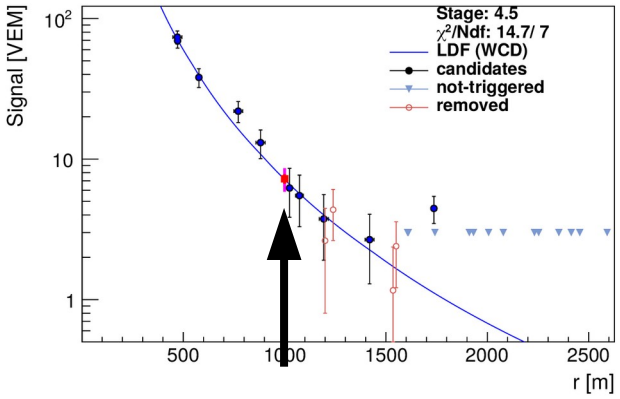
SD



Nucl. Instrum. Meth. A 798 (2015) 172-213

Energy spectrum – SD calibration

Vertical SD events - 1500 m (θ < 60°) and 750 m (θ < 40°)



S(1000)

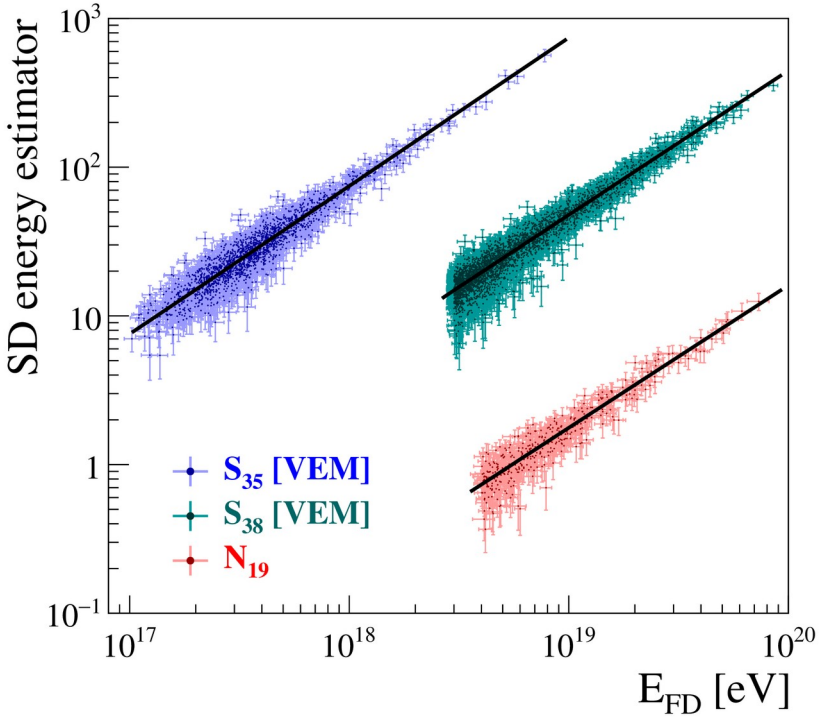
CIC (attenuation correction):
shower size → energy estimator

SD1500: **S(1000)** → S_{38}

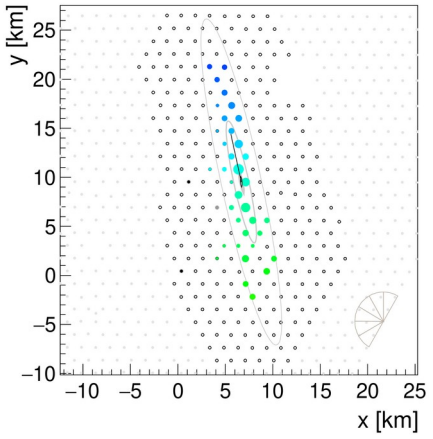
SD750: **S(450)** → S_{35}

SD calibrated to the FD scale

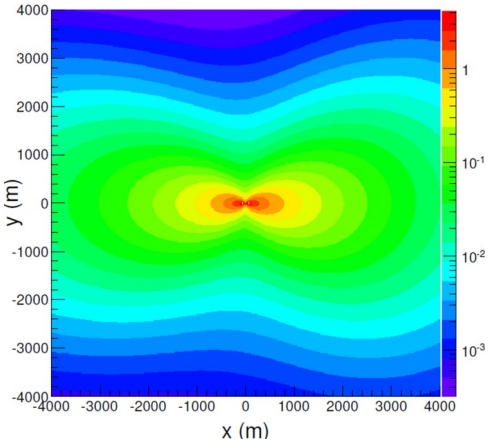
$E_{SD} = a\ \Sigma^b$, $\Sigma = S_{35}, S_{38}, N_{19}$



Inclined SD events - 1500 m (60° < θ < 80°)



muon density map



energy estimator

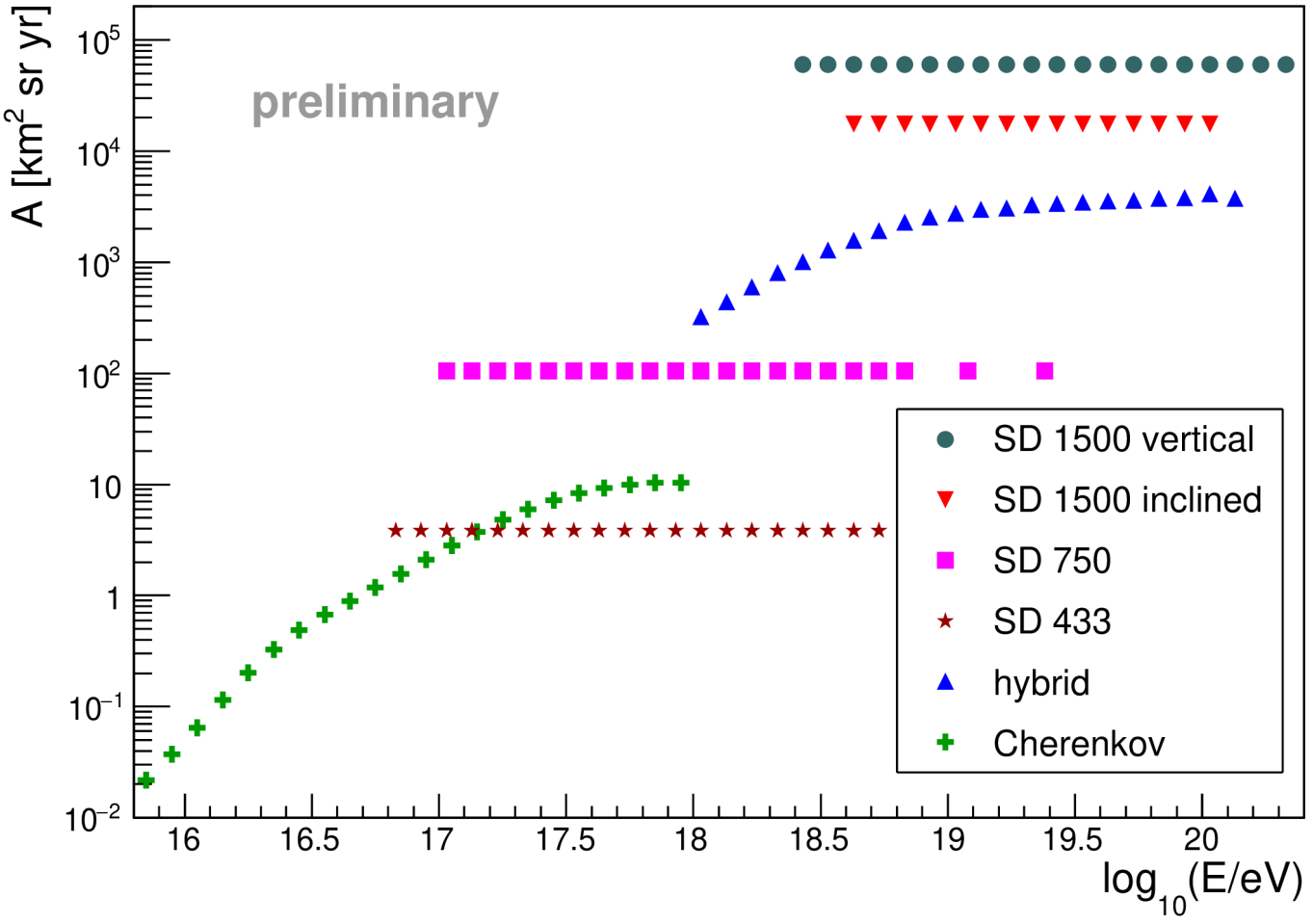
$$\rho_\mu(\vec{r}) = N_{19}\ \rho_{\mu,19}(\vec{r};\theta,\phi)$$

N_{19}

SD433 calibrated with SD750

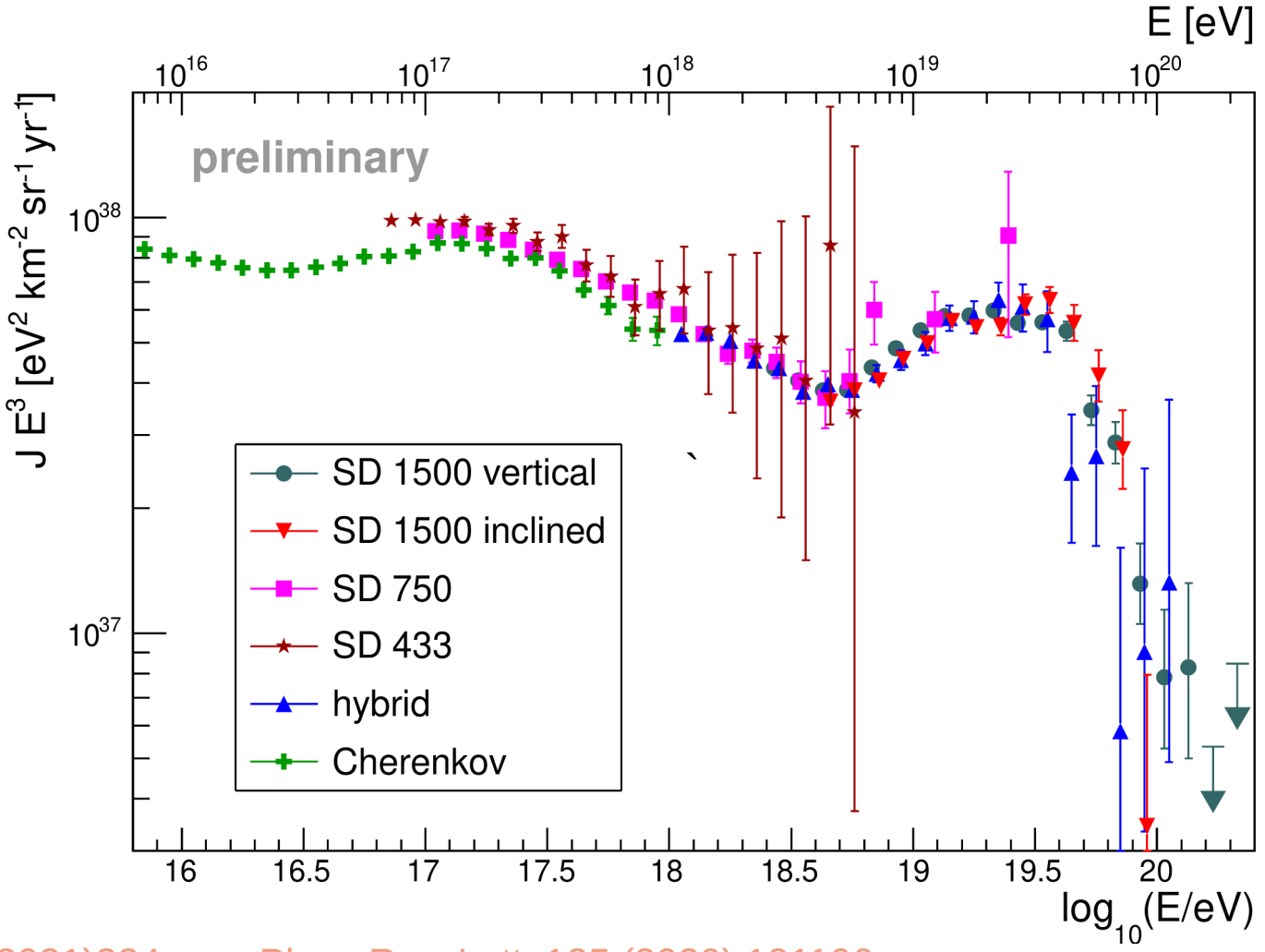
Energy spectrum – exposure

- **SD exposure is geometrical** – results above full trigger efficiency threshold
- **FD** exposure based on detailed **MC simulations** (showers and detector)
  - hybrid uses FD+1 SD station to determine shower geomtery
  - Cherenkov events reconstructed using profile-constrained geometry fit



Energy spectrum – individual methods

- **FD ontime ~14%** of total time, better energy resolution
- **SD** ontime ~100% → **larger statistics**
- spectra consistent within uncorrelated systematic uncertainties

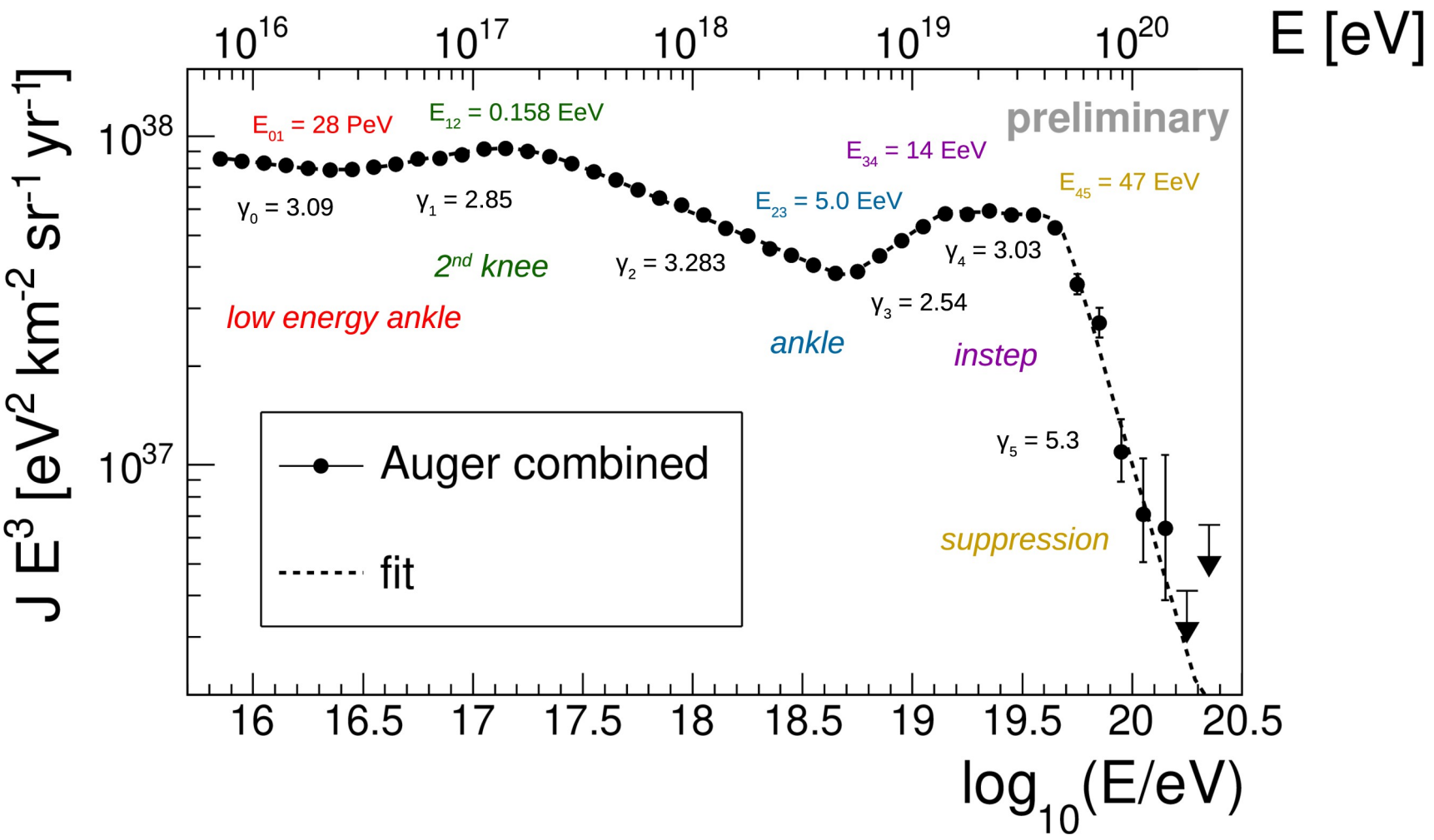


PoS(ICRC2021)324 Phys. Rev. Lett. 125 (2020) 121106

PoS(ICRC2023)398 Phys. Rev. D 102 (2020) 062005 Eur. Phys. J. C 81 (2021) 966

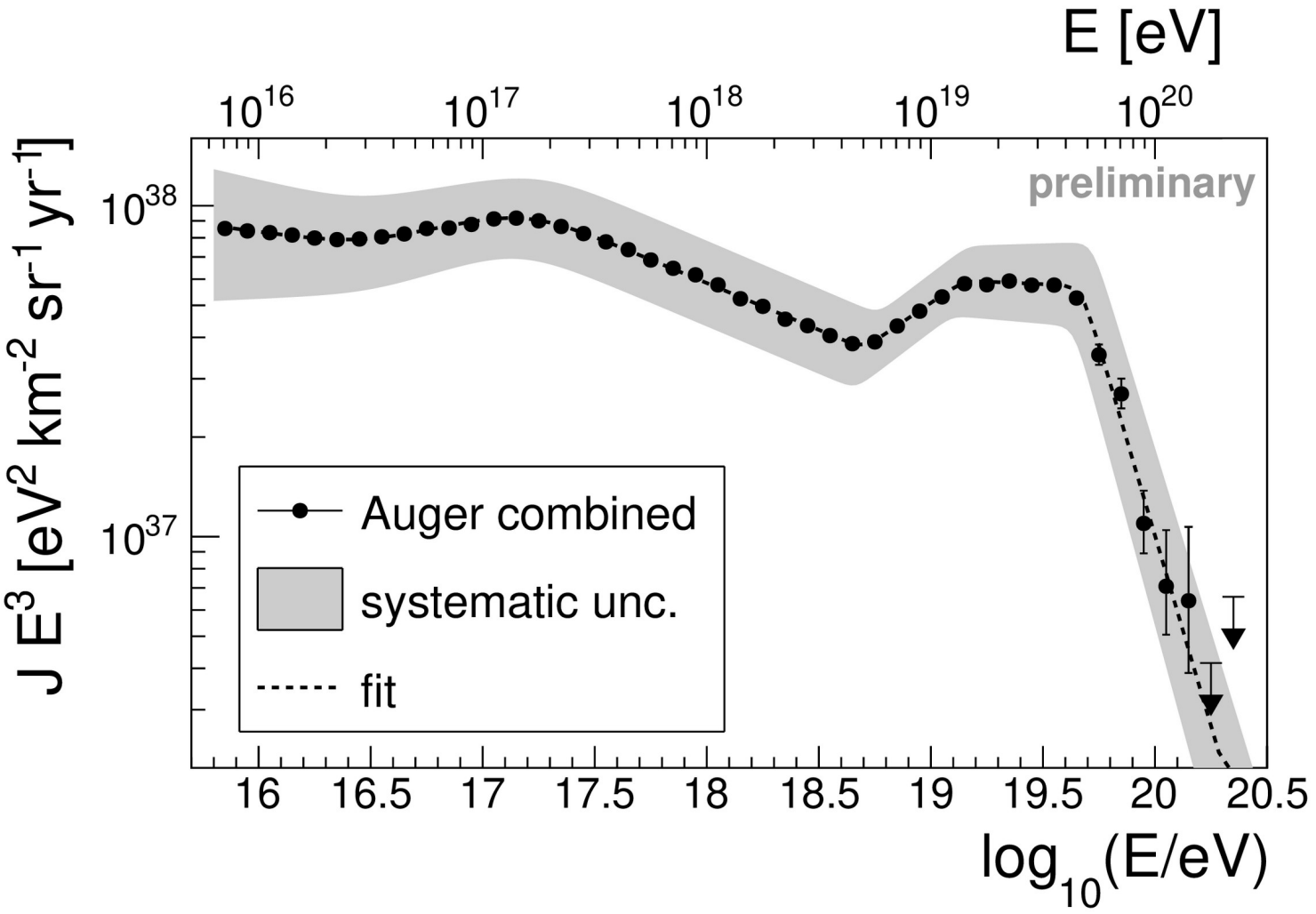
Energy spectrum – combined

- combined using **forward-folding of all data** distributions at once
  - accounts for residual systematic unc.
- complex structure - **five breaks observed**



Energy spectrum – systematic uncertainty

- syst. unc. dominated by **energy scale systematics** of 14%
  - ~30% when propagated to CR intensity



Systematic uncert. in energy scale	
Fluorescence yield	3.6%
Atmosphere	3.4% – 6.2%
FD calibration	9.9%
FD profile recon.	6.5% – 5.6%
Invisible energy	3% – 1.5%
Energy scale stability	5%
TOTAL	14%

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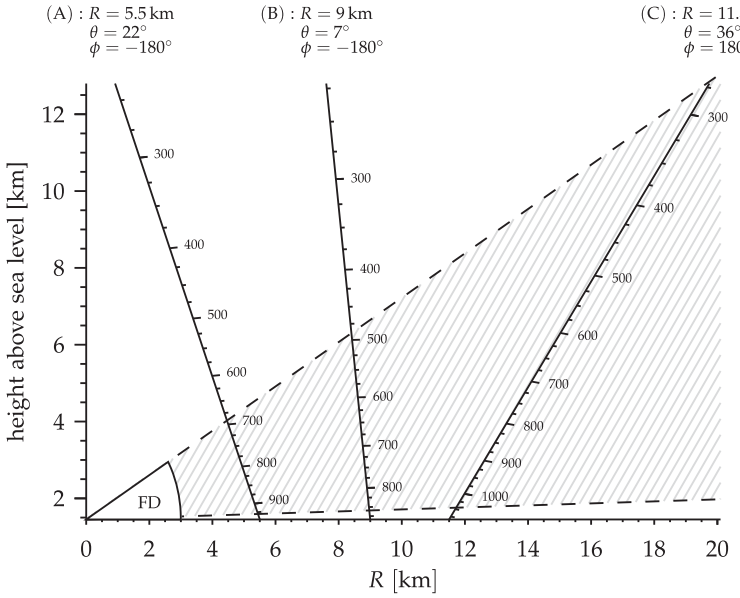
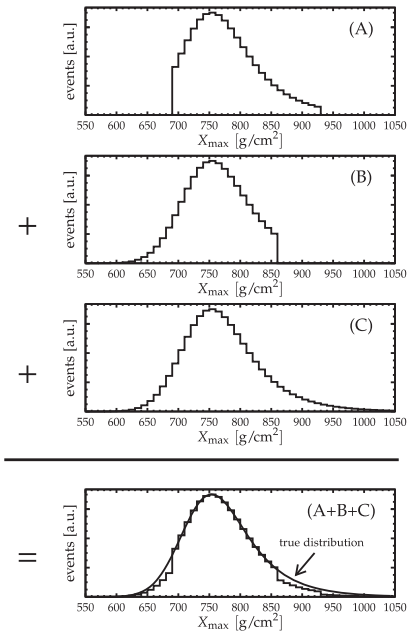
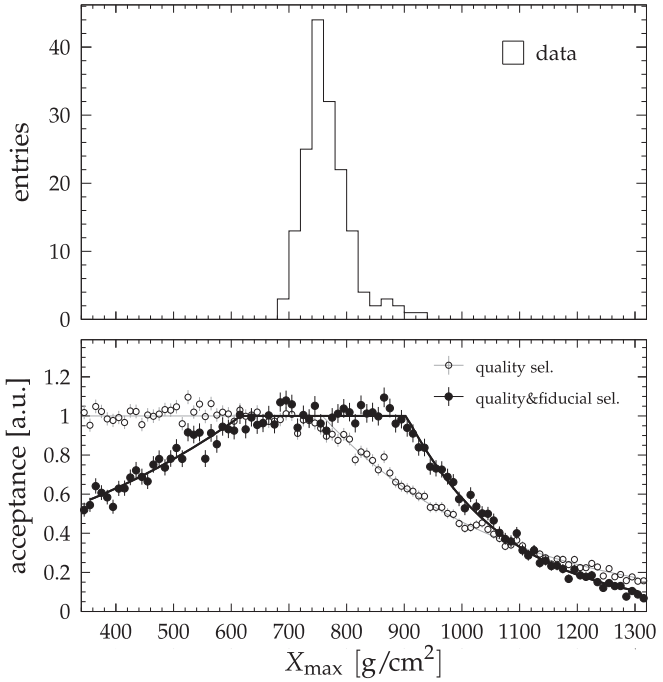
Mass composition – FD method

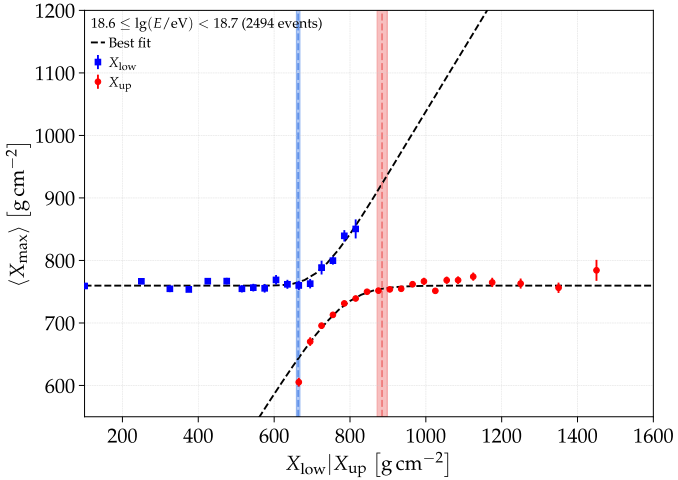
- possible selection bias – diminished by **fiducial field of view selection**
- tails corrected for residual acceptance decrease
- Auger X_{max} results are directly comparable with the output of shower simulations
- systematic uncertainty ≤ 10 g cm^{-2}, resolution 26 – 15 g cm^{-2}

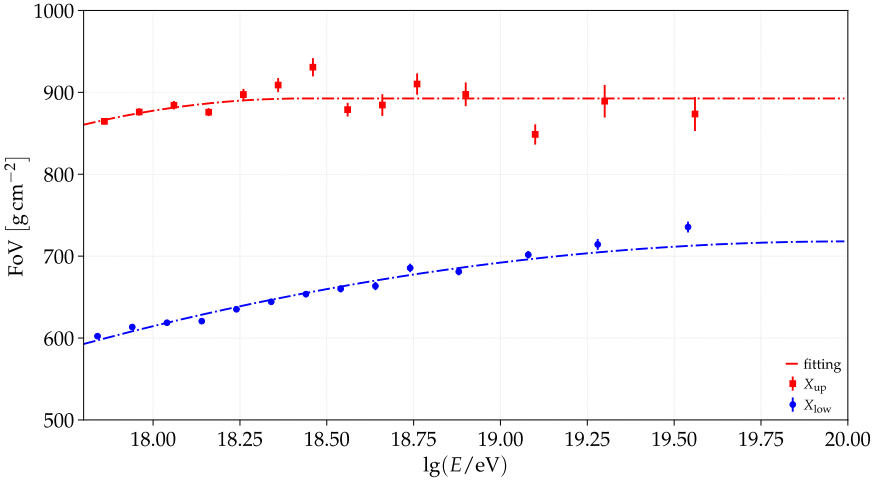
Phys. Rev. D 90 (2014) 122005





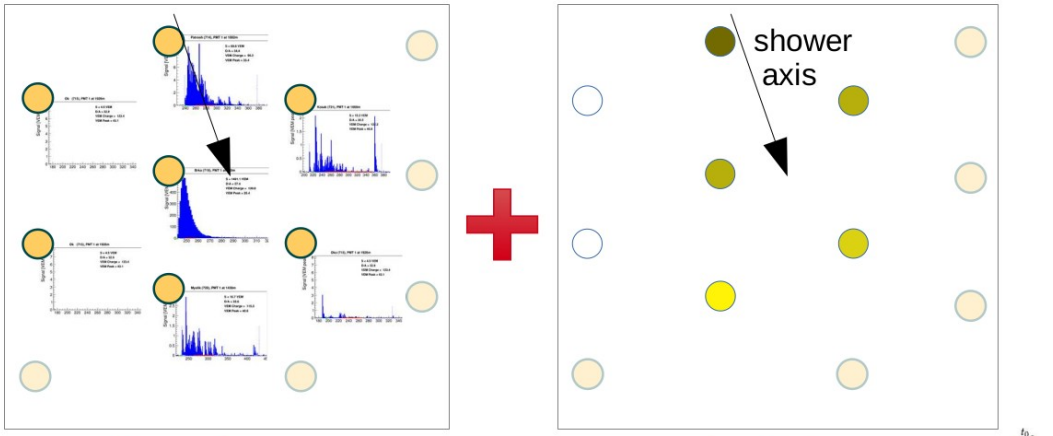


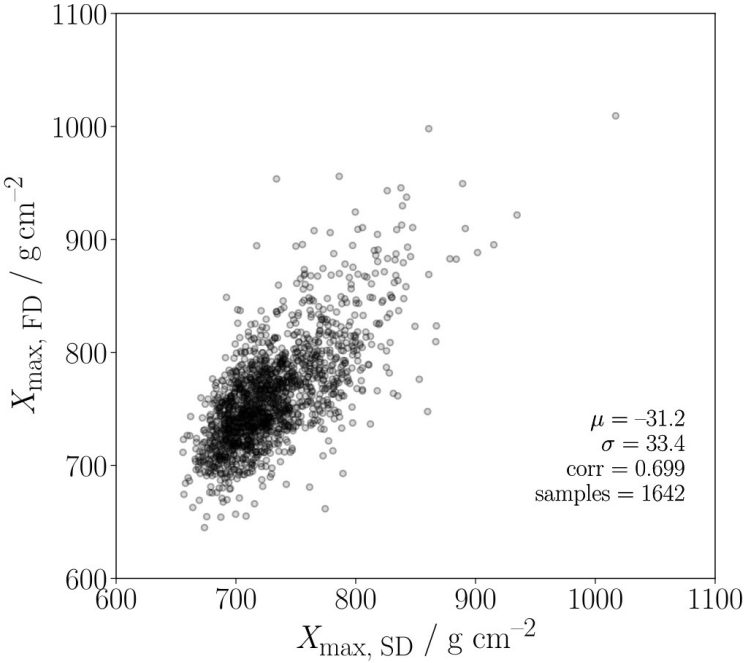


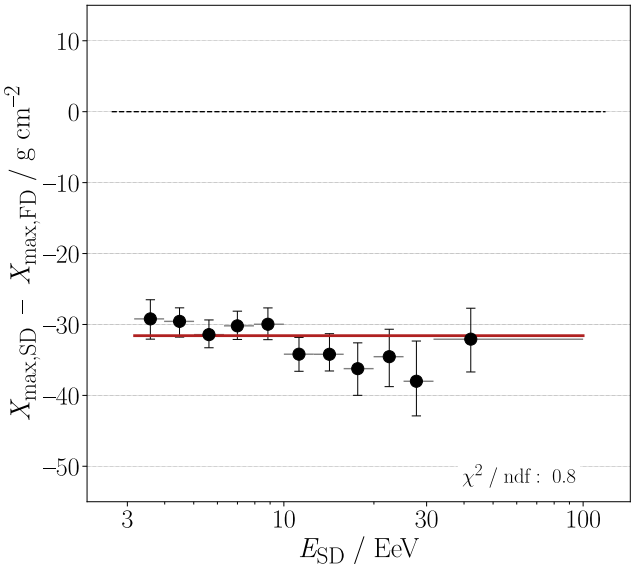


Mass composition – SD method

- reconstructed using **deep neural network** – recurrent+convol. networks (LSTMs+HexaConv)
- trained on EPOS-LHC generated MC library – full simulation of the SD response
- **calibrated to the FD** X_{max} scale on the hybrid subset
- syst. unc. 9 – 13 g cm^{-2}, resolution 40 – 20 g cm^{-2}



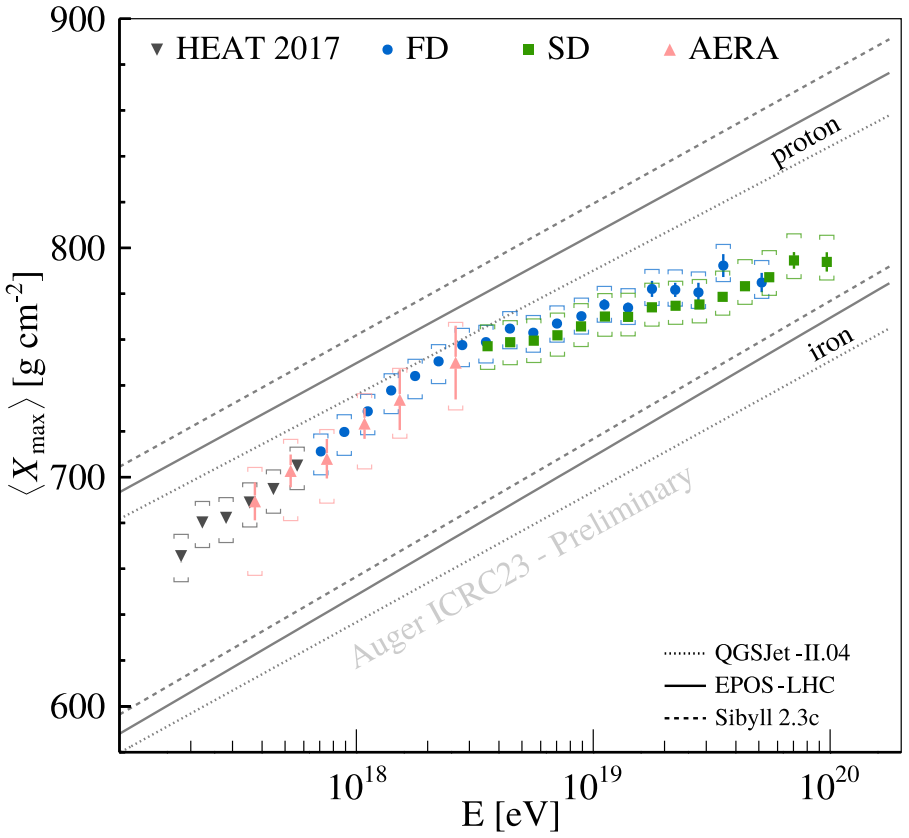


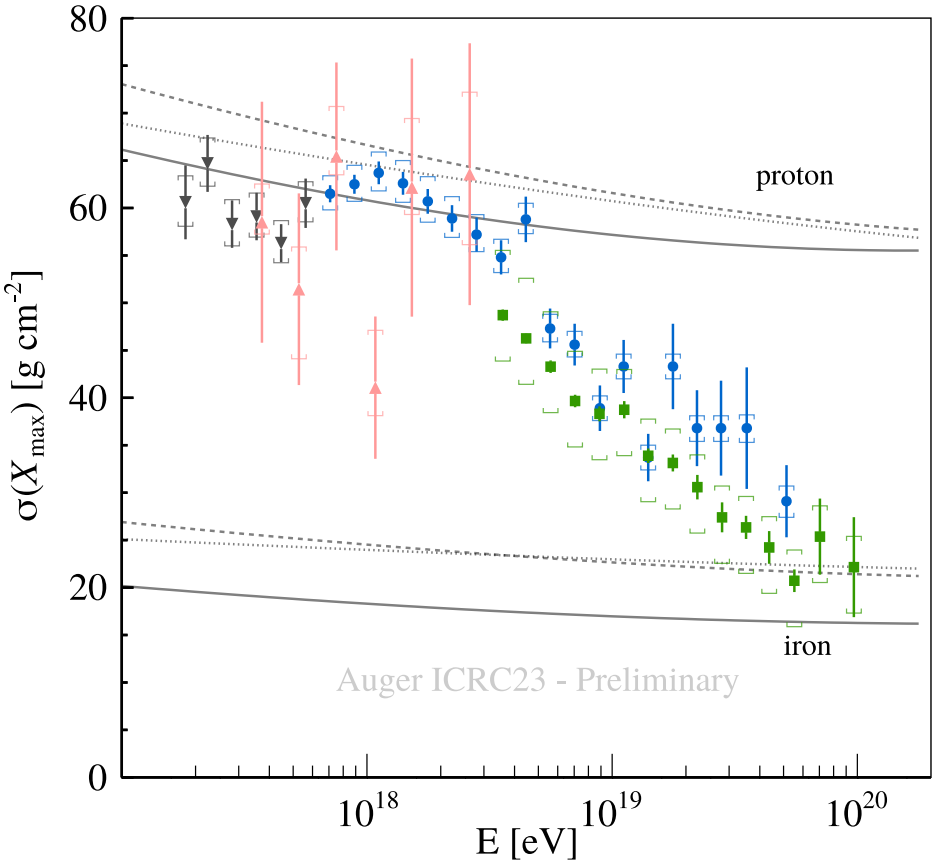


PoS(ICRC2023)278
arXiv:2406.06319 (submitted to Phys. Rev. D)

Mass composition – X_{max} results

- getting **lighter up to 3 EeV**, then getting heavier
- stdev. contain shower-to-shower fluctuations + changes in mass – more difficult to interpret
- AERA (radio) measurements also available – low statistics
    - compatible with FD results





PoS(ICRC2023)365 Phys. Rev. Lett. 132 (2024) 021001

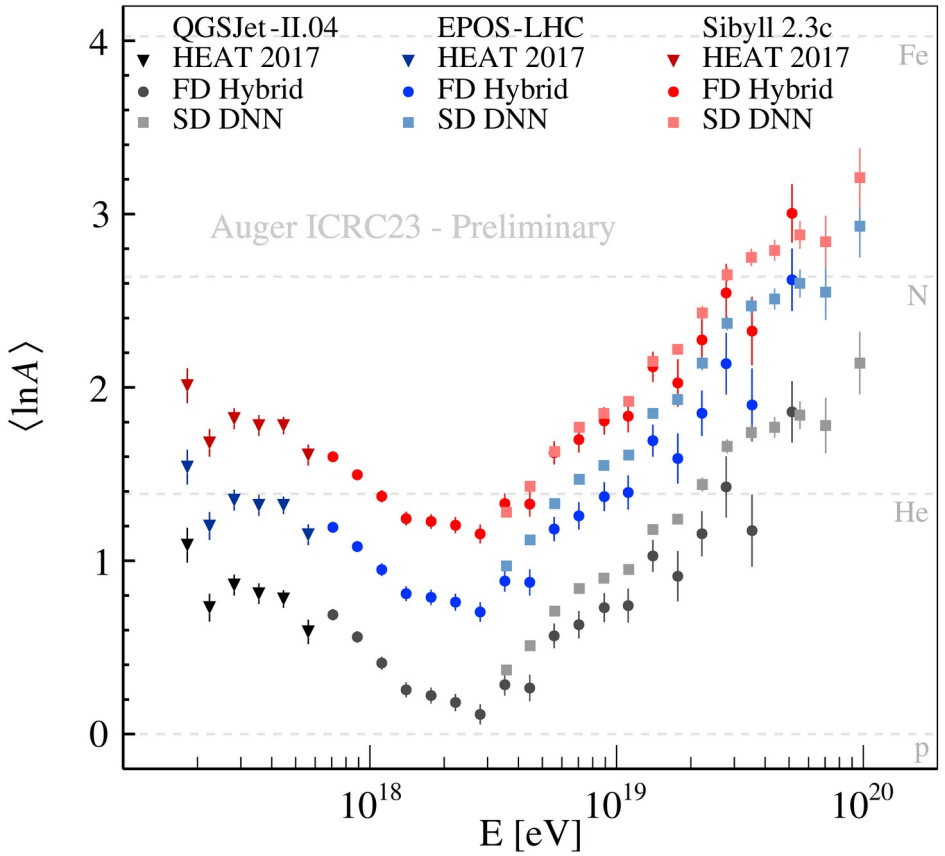
PoS(ICRC2023)319 Phys. Rev. D 109 (2024) 022002

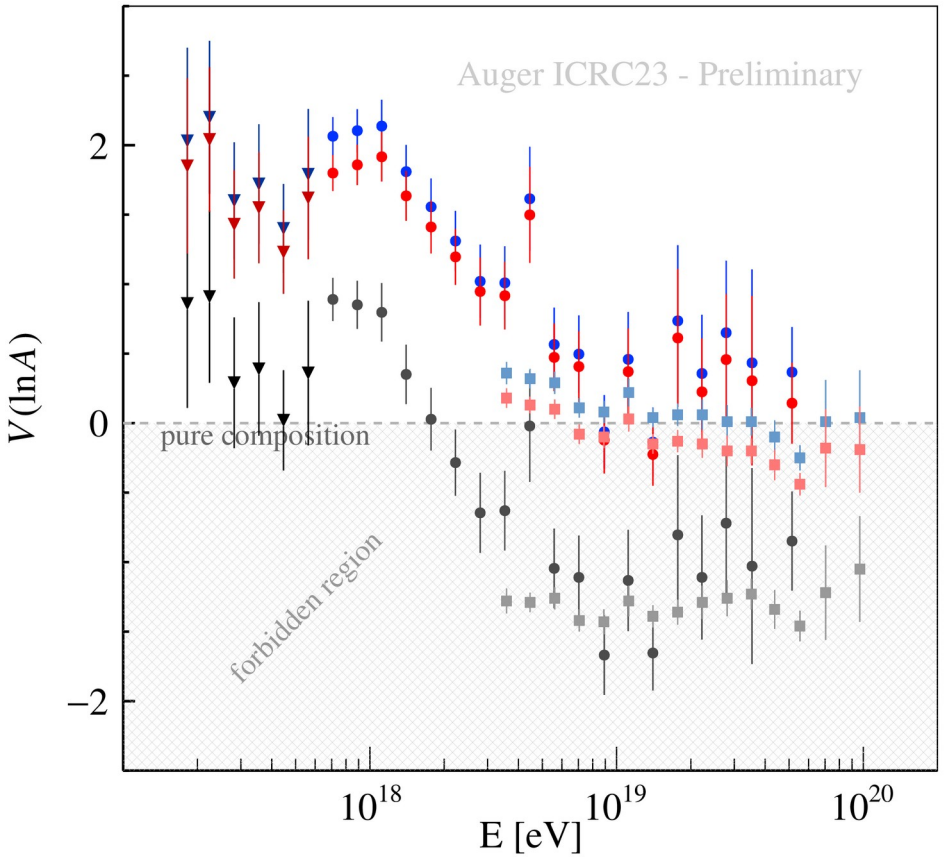
Mass composition – X_{max} interpretation

- average + variance in a simple relation:
- moments of ln *A* from inversion
  - contains **model-dependent** parameters
- QGSJet-II.04 does not describe well Auger data

$$\langle X_{\max} \rangle = \langle X_{\max} \rangle_{\mathrm{p}} + f_E \langle \ln A \rangle$$

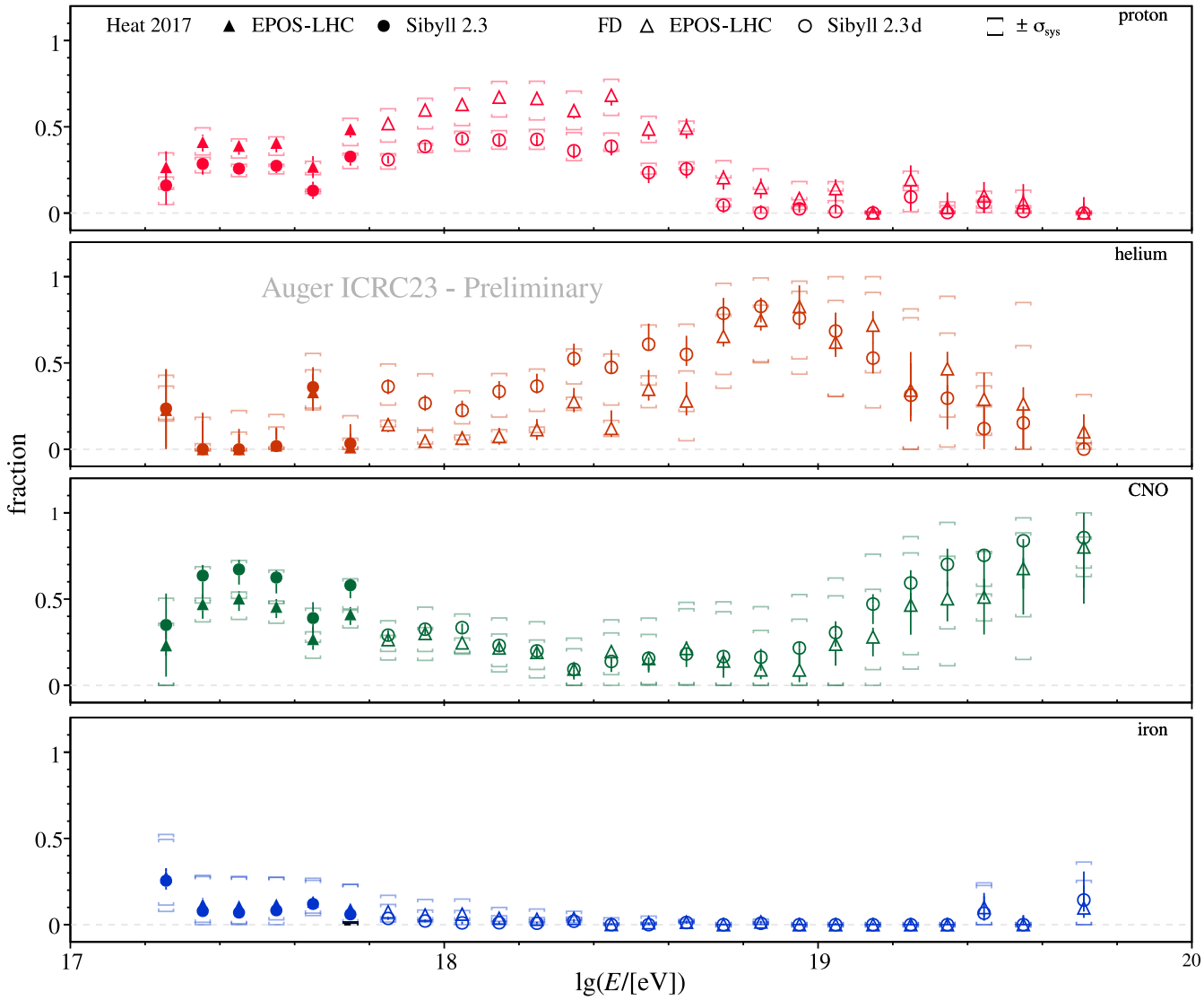
$$\sigma^2(X_{\max}) = \langle \sigma^2_{\mathrm{sh}} \rangle + f_E^2 \, \sigma^2(\ln A)$$

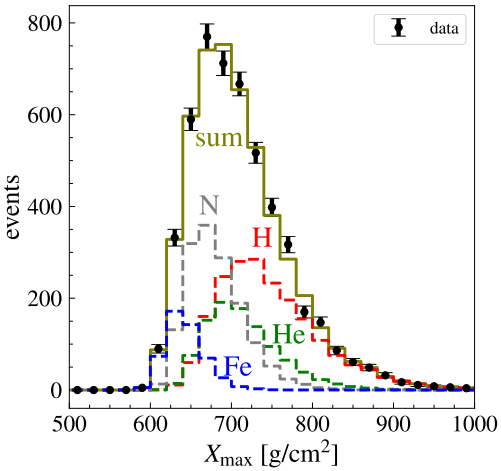




Mass composition – X_{max} interpretation

- fits of the whole **X_{max} distributions from FD** in each energy bin →

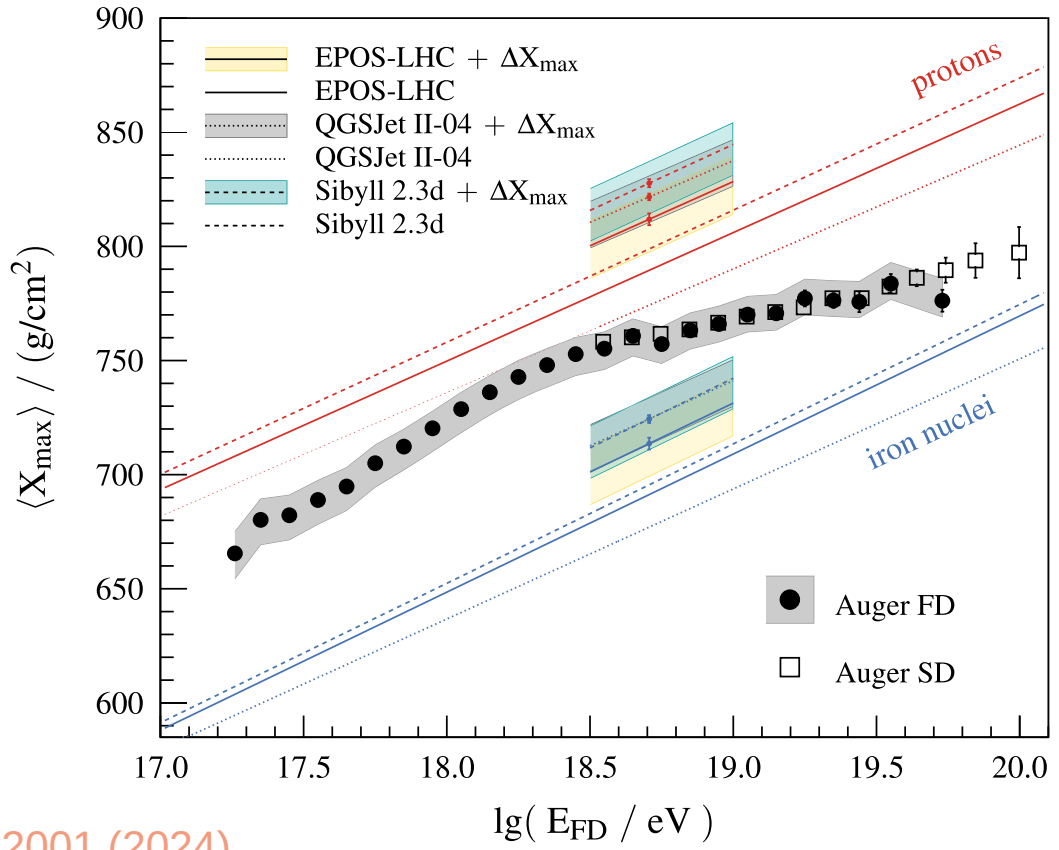




- resembles Peters cycle
- **very pure** at highest energies
- **almost no Fe**

Mass composition – X_{max} scale

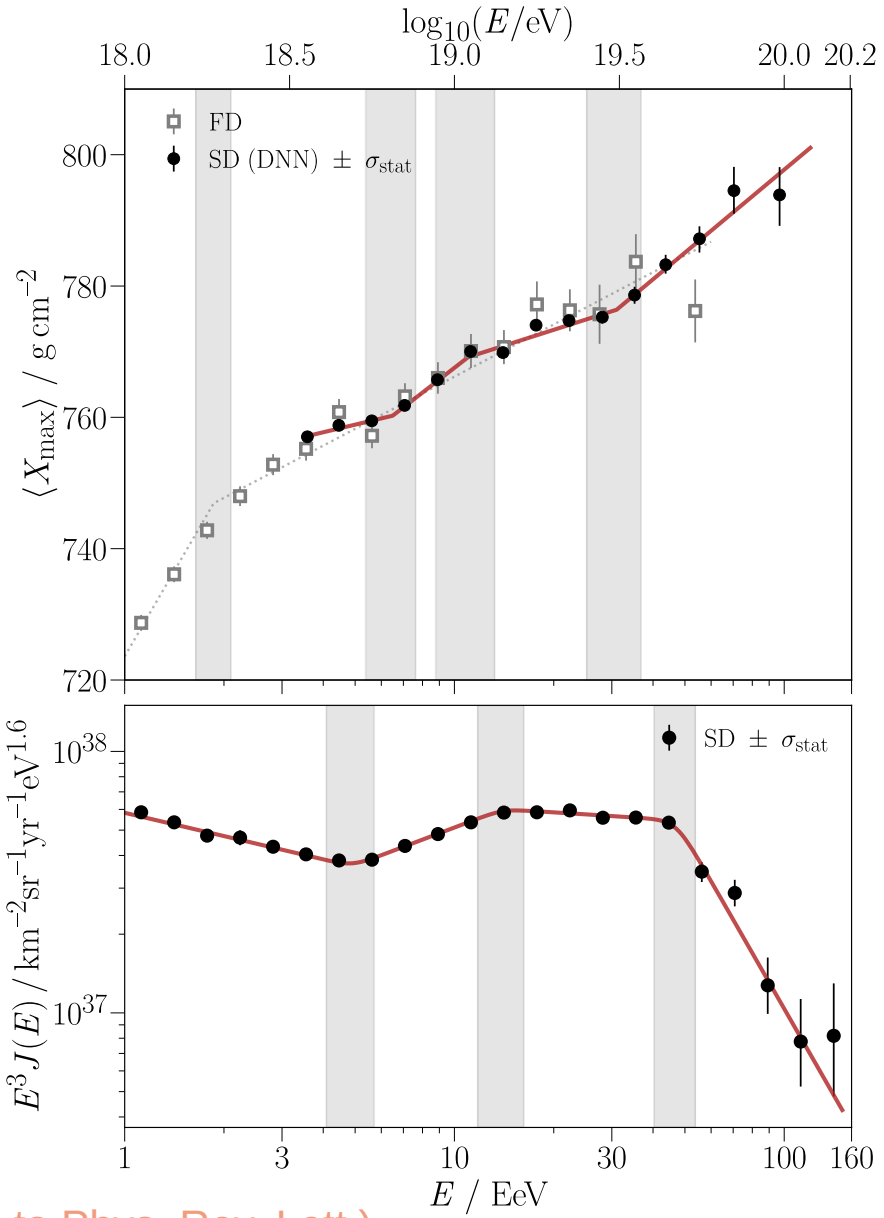
- interpretation crucially depends on models and all seem to be inappropriate
- study: **fits of both X_{max} and S(1000) distributions** in zenith angle bins, results are
  - **shift in X_{max}** necessary – **20-50 g cm^{-2}** (differs between models)
  - **shift in S(1000)** necessary → level of muon discrepancy **15-25%**
  - mass composition – heavier composition inferred
  - valid in $10^{18.5}$ – $10^{19.0}$ eV (but the elongation rate very rigid)
- interpreted this way, we have very pure Fe-like composition at the highest energies



Phys. Rev. D 109, 102001 (2024)

Breaks in intensity and X_{max}

- **substructure** in the high energy part of both measurements
- X_{max} - seen in SD DNN, FD lacks statistics to distinguish such breaks



arXiv:2406.06315 (submitted to Phys. Rev. Lett.)

Conclusions

- **Phase I of the Pierre Auger Observatory** measurements provided high quality data
- Evolution of the cosmic-ray **intensity with energy is complex** – several breaks
- **Mass composition evolves** from mixed to light and then to intermediate/heavy
- When seen with sufficient statistics (SD) the **$\langle X_{max} \rangle$ also exhibits substructure**

Astrophysical interpretation to be revealed

PIERRE AUGER OBSERVATORY

RICAP 24

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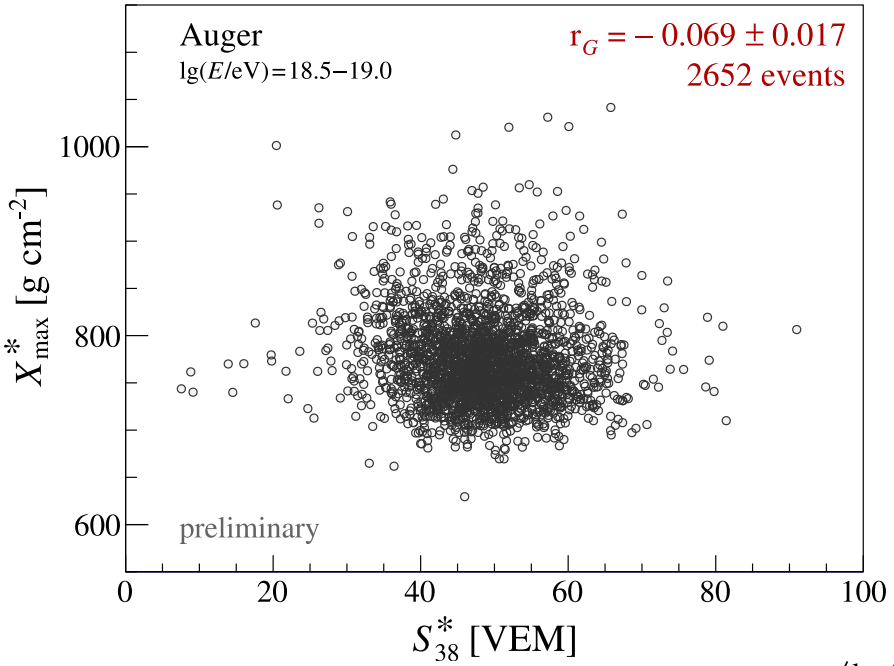
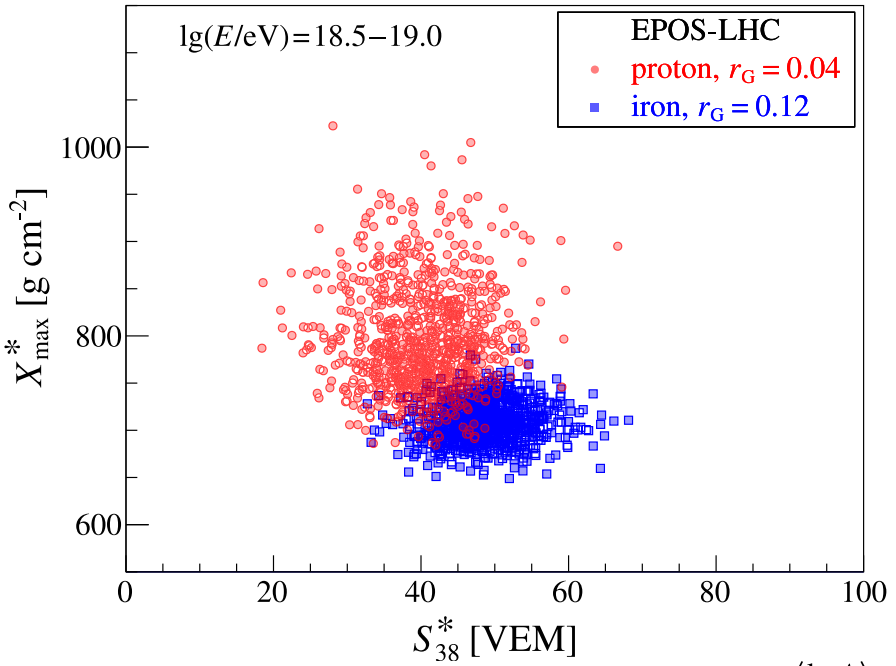
Co-funded by the European Union

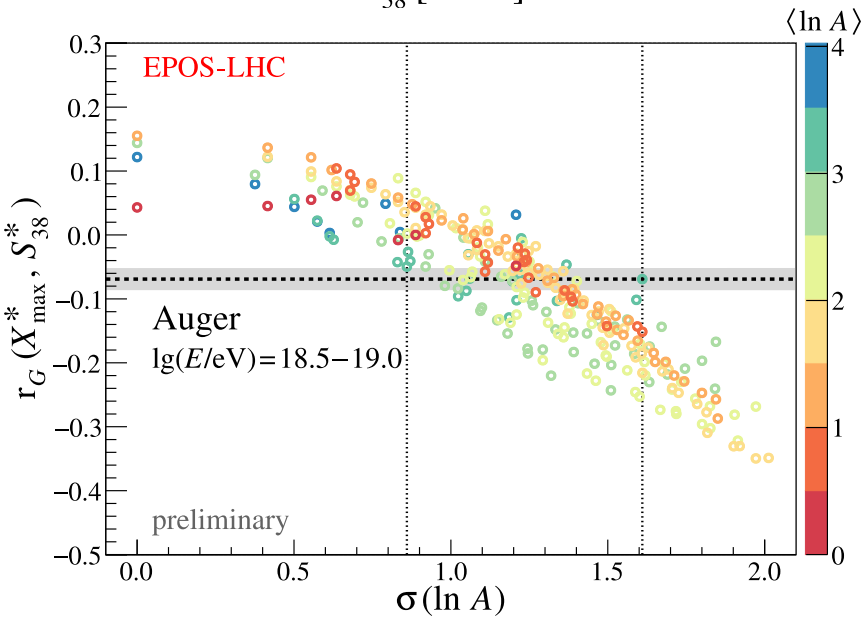
MINISTRY OF EDUCATION, YOUTH AND SPORTS

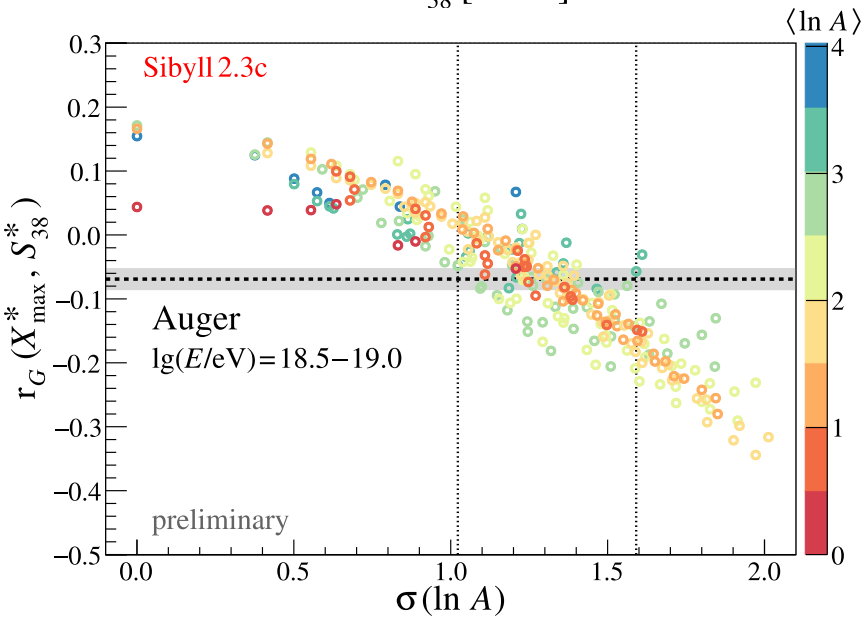
Backup – mixed composition around ankle

- largely model-independent



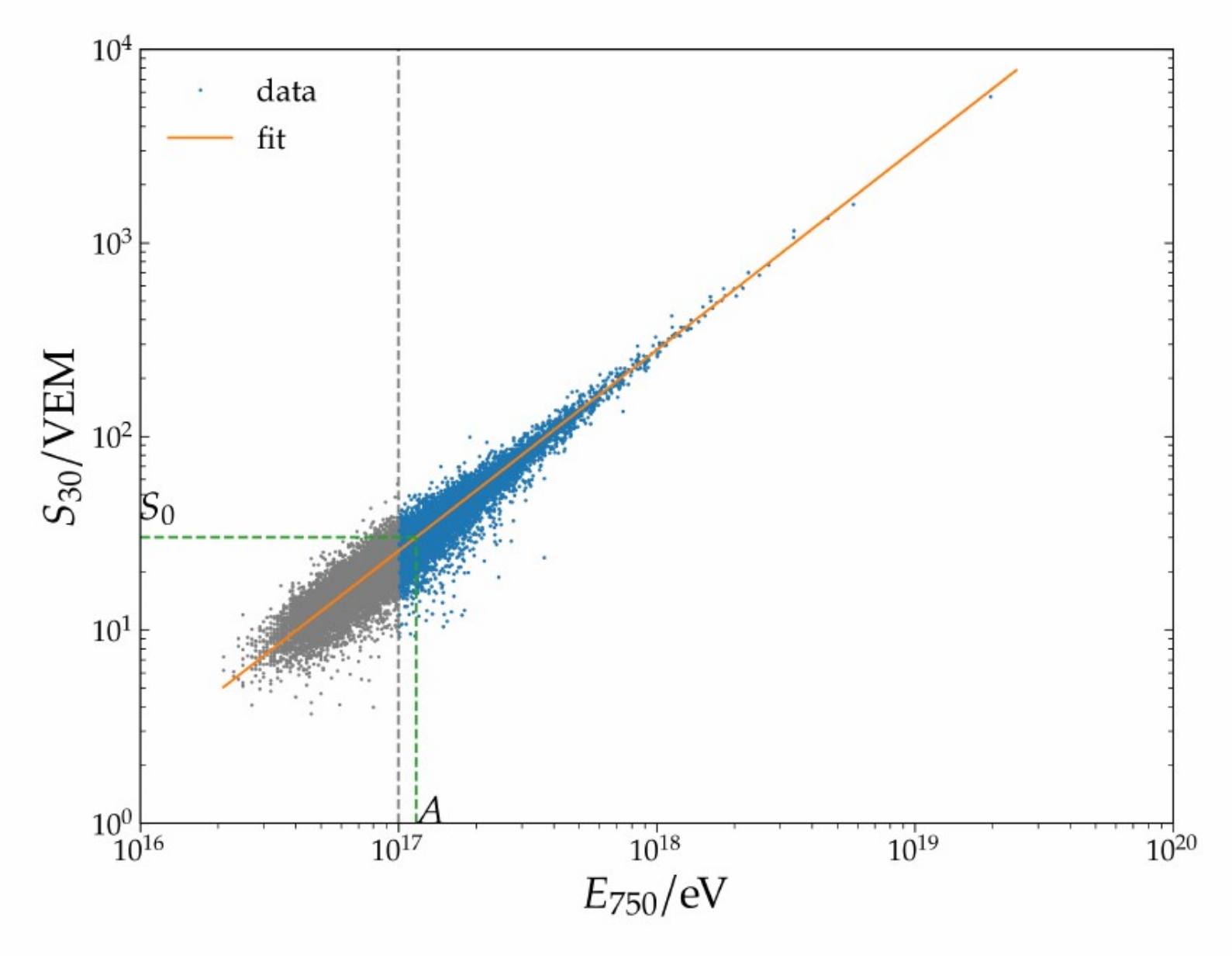




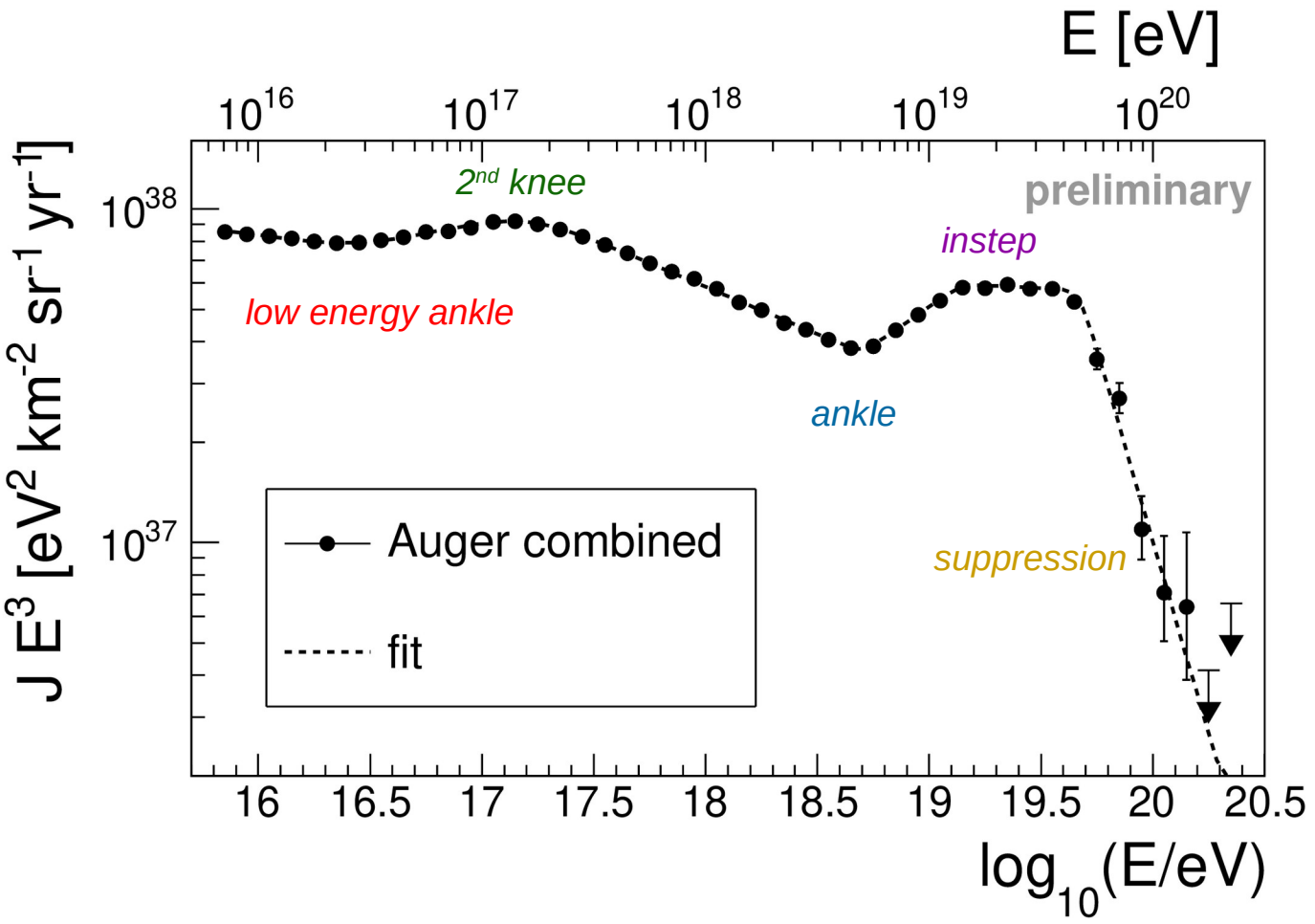


PoS(ICRC2019)482 Phys. Lett. B762 (2016) 288-295

Backup – SD433 calibration



Backup – spectral features



fit parameters (± stat. ± syst.)

$y_0 = 3.09 \pm 0.01 \pm 0.10$

$E_{01} = (2.8 \pm 0.3 \pm 0.4) \times 10^{16}$ eV

$y_1 = 2.85 \pm 0.01 \pm 0.05$

$E_{12} = (1.58 \pm 0.05 \pm 0.2) \times 10^{17}$ eV

$y_2 = 3.283 \pm 0.002 \pm 0.10$

$E_{23} = (5.0 \pm 0.1 \pm 0.8) \times 10^{18}$ eV

$y_3 = 2.54 \pm 0.03 \pm 0.05$

$E_{34} = (1.4 \pm 0.1 \pm 0.2) \times 10^{19}$ eV

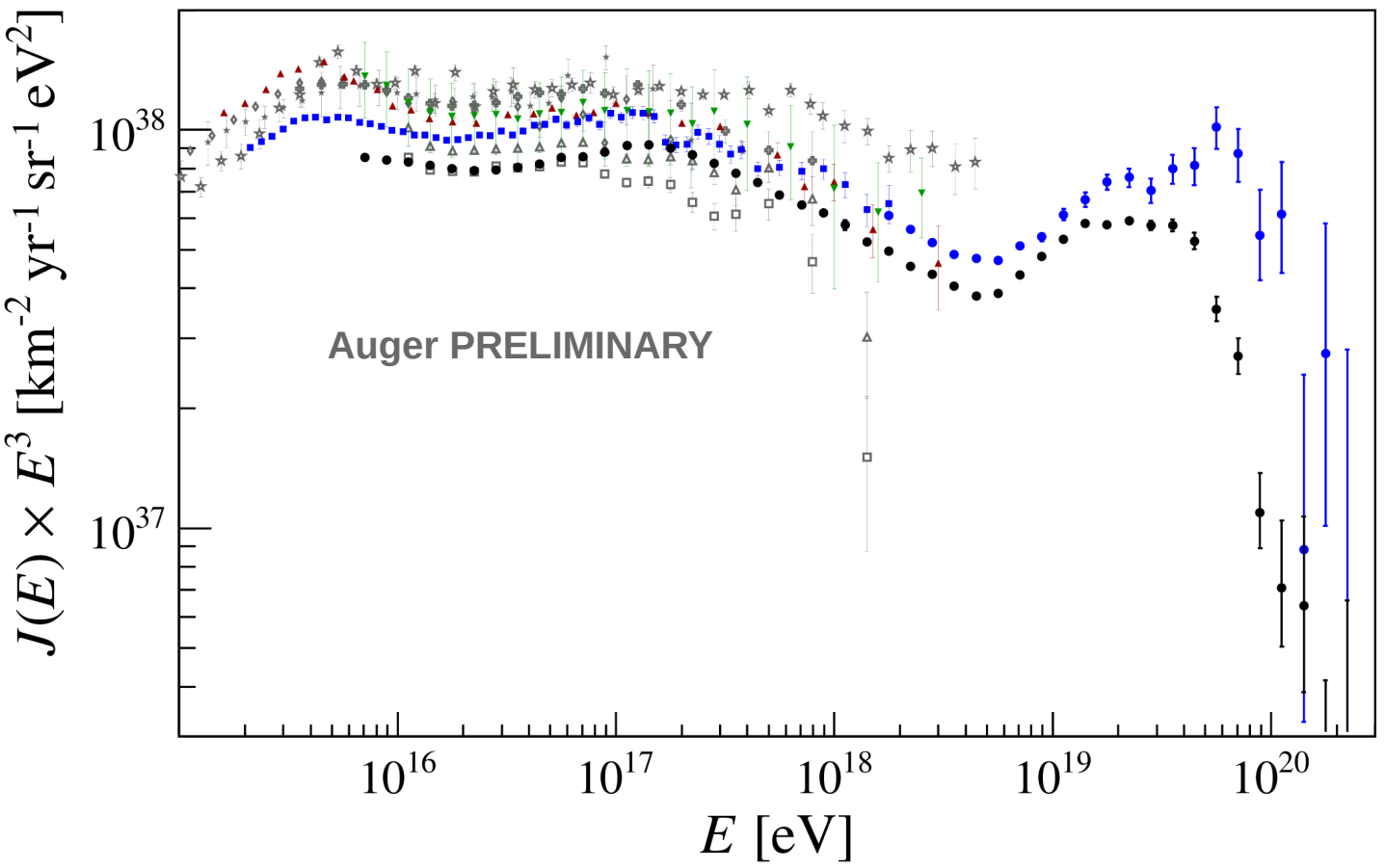
$y_4 = 3.03 \pm 0.05 \pm 0.10$

$E_{45} = (4.7 \pm 0.3 \pm 0.6) \times 10^{19}$ eV

$y_5 = 5.3 \pm 0.3 \pm 0.1$

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

Comparison with other experiments



- Auger (2021)
- TA SD (2019)
- TA TALE (2018)
- TUNKA-133 (2020)
- Yakutsk (2015)
- Ice Top (2019)
- KAS. Gr. EPOS-LHC (2015)
- KAS. Gr. QGSII-04 (2015)
- Tibet-III (2008)
- GAMMA (2014)
- AKENO (1992)

calorimetric in colour

MC based in gray

Backup – SD750 vs. Cherenkov syst. unc.