# A combined analysis from the WHISP working group on the muon data from ten extensive air shower experiments

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## Content



# 1) Introduction



- Discrepancies between muon lateral density data and predictions of high-energy hadronic interaction models between 100 PeV and 10 EeV have been observed in different experiments.

- The Working group on Hadronic Interactions and Shower Physics (WHISP):
  - EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array and Yakutsk EAS Array
  - Compilation of muon density measurements in air showers from 11 cosmic-ray experiments.
  - Combined analysis of the data.
  - Common parameter for the comparisons with the models (z-scale).
  - Correction for differences in the primary energy scale among the instruments.

[H.P. Dembinski et al., EPJ Web Conf. 210 (2019) 02004]

[D. Soldin et al., PoS (ICRC2021) 349]

# 1) Introduction

ISVHECRI 2024

- Progress report:
  - Updated results from Yakutsk and SUGAR.
  - Data from Haverah Park [L. Cazon et al., PoS(ICRC2023) 431].
  - Estimations from KASCADE-Grande data using the energy scale of the Pierre Auger Observatory [ J.C. Arteaga-Velázquez et al., PoS(ICRC2023) 376].
  - Review of the detector characteristics.
  - Summary of the properties of the collected data.

# 1) Introduction

## Muon data for WHISP analysis

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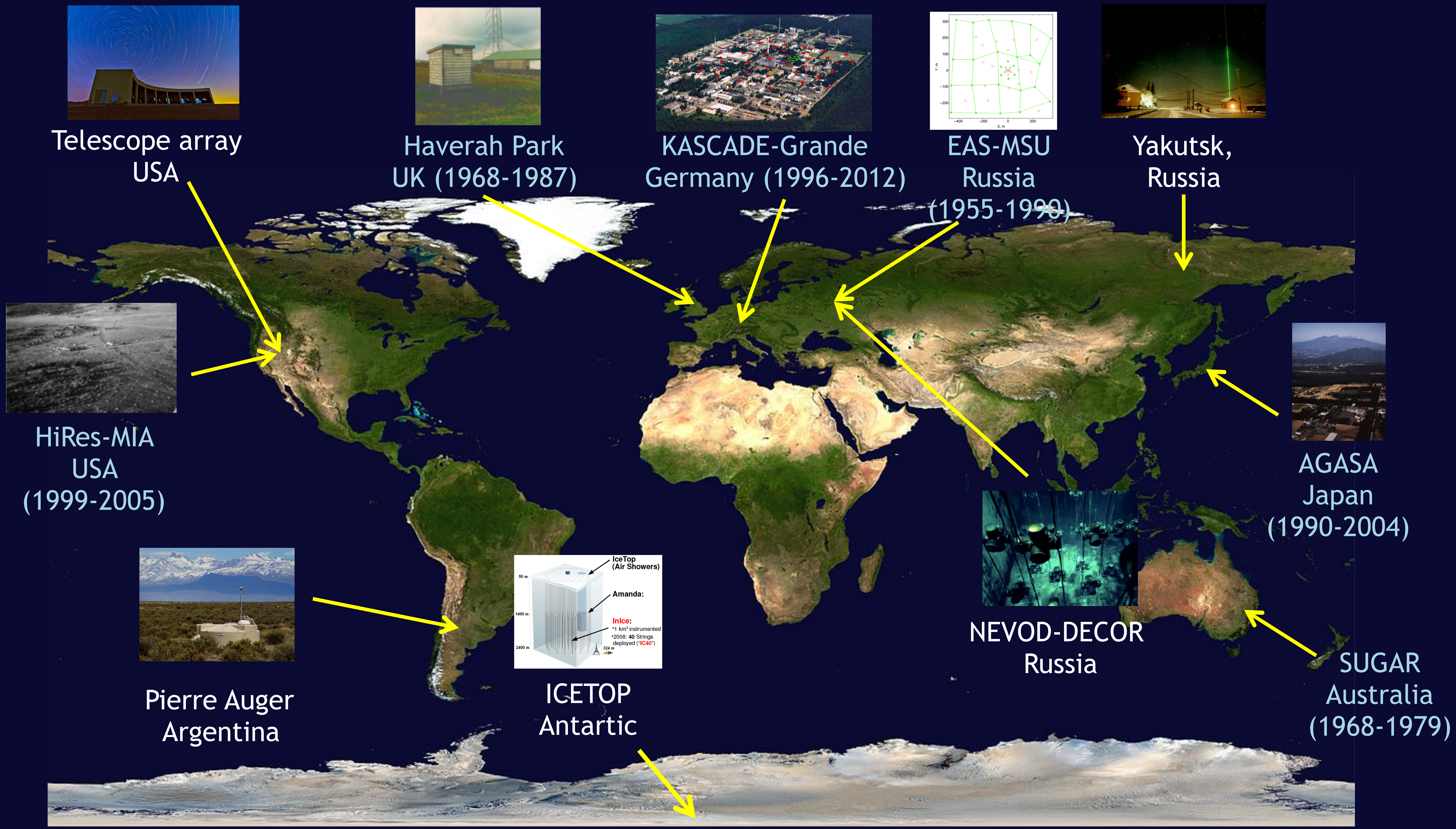


Credit images: PAO, TA, ICECUBE, Yakutsk, NEVOD-DECOR, SUGAR, KASCADE-Grande, EAS-MSU, AGASA, HiRes, Haverah Park.

Credit map: NASA.

# 2) Experimental conditions

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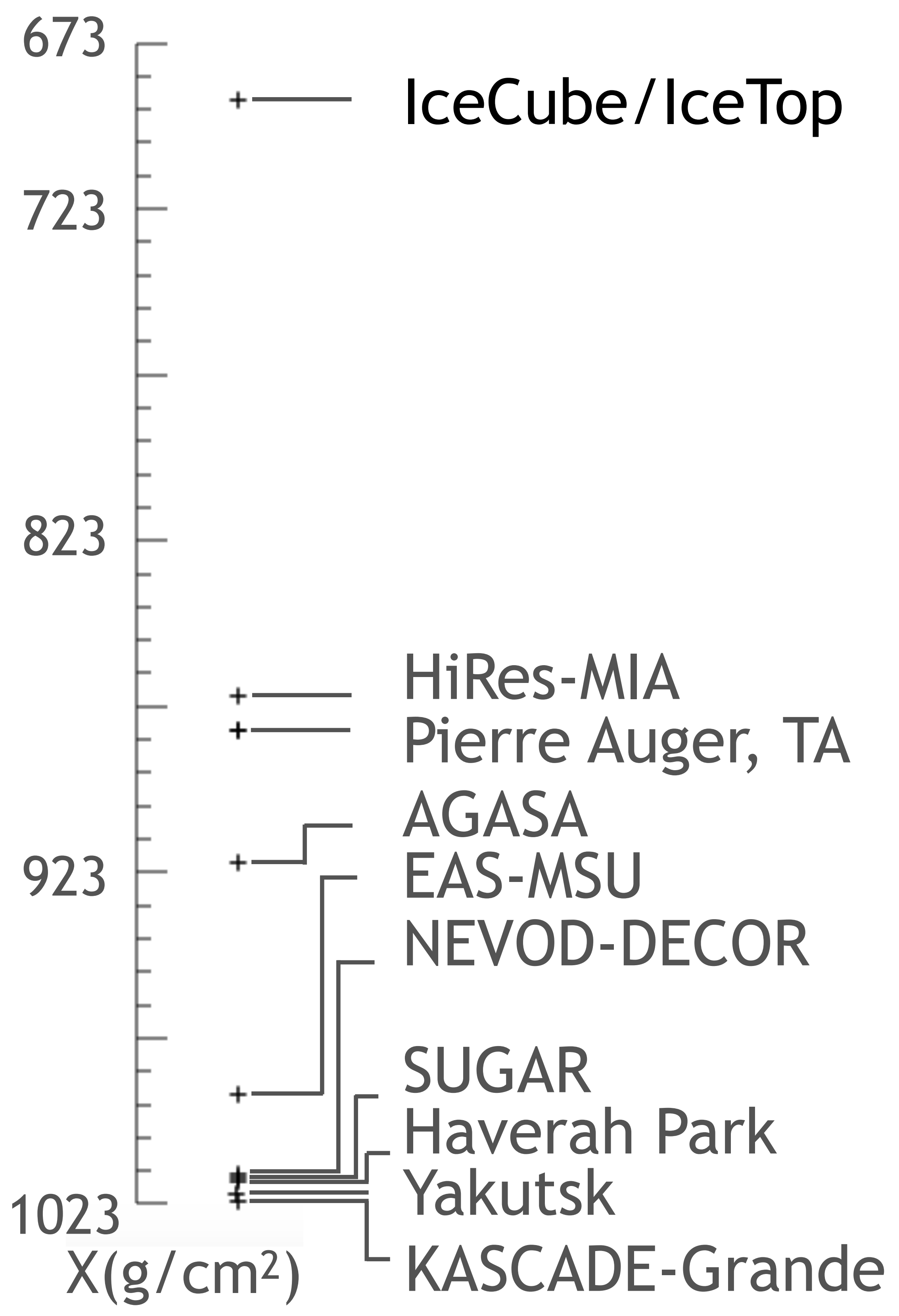
| Experiment | Muon detection |
|---|---|
| IceCube/IceTop | Ice Cherenkov stations |
| TA | Plastic scintillator array |
| Pierre Auger | Surface water Cherenkov array + Underground scintillator modules |
| HiRes-MIA | Underground scintillator counters |
| EAS-MSU | Underground Geiger-Mueller counters |
| SUGAR | Underground liquid-scintillator tanks |
| Yakutsk | Underground scintillation detectors |
| Haverah Park | Shielded liquid scintillator detectors |
| AGASA | Shielded scintillator array |
| KASCADE-Grande | Shielded scintillation detectors |
| NEVOD-DECOR | Tracking detector + Water Cherenkov Calorimeter |

## Vertical atmospheric depth



# 2) Experimental conditions



| Experiment | E estimation | Muon contribution in E estimator | Full detection simulation | Vertical atm. depth (g/cm$^2$) |
|---|---|---|---|---|
| EAS-MSU | SD | (10%, 50%) | ✓ | 990 |
| HiRes-MIA | FD | (−10%, 0%) | ✓ | 870 |
| Pierre Auger | | | | |
| FD+SD | FD | (−10%, 0%) | ✓ | 880 |
| UMD+SD | FD/SD | (−10%, 0%)/< 10% | ✓ | 880 |
| SUGAR | Flux | −− | ✗ | 1015 |
| KASCADE-Grande | Flux | −− | ✓ | 1022 |
| Telescope Array | FD | (−10%, 0%) | ✓ | 880 |
| NEVOD-DECOR | Flux | −− | ✗ | 1014 |
| Haverah Park | SD | > 50% | ✗ | 1016 |
| IceCube/IceTop | SD | < 10% | ✓ | 690 |
| Yakutsk EAS array | SD | (10%, 50%) | ✓ | 1020 |
| AGASA | SD | (10%, 50%) | ✗ | 920 |

SD: Surface detector

[J.C. Arteaga-Velázquez et al., PoS(ICRC2023) 466]

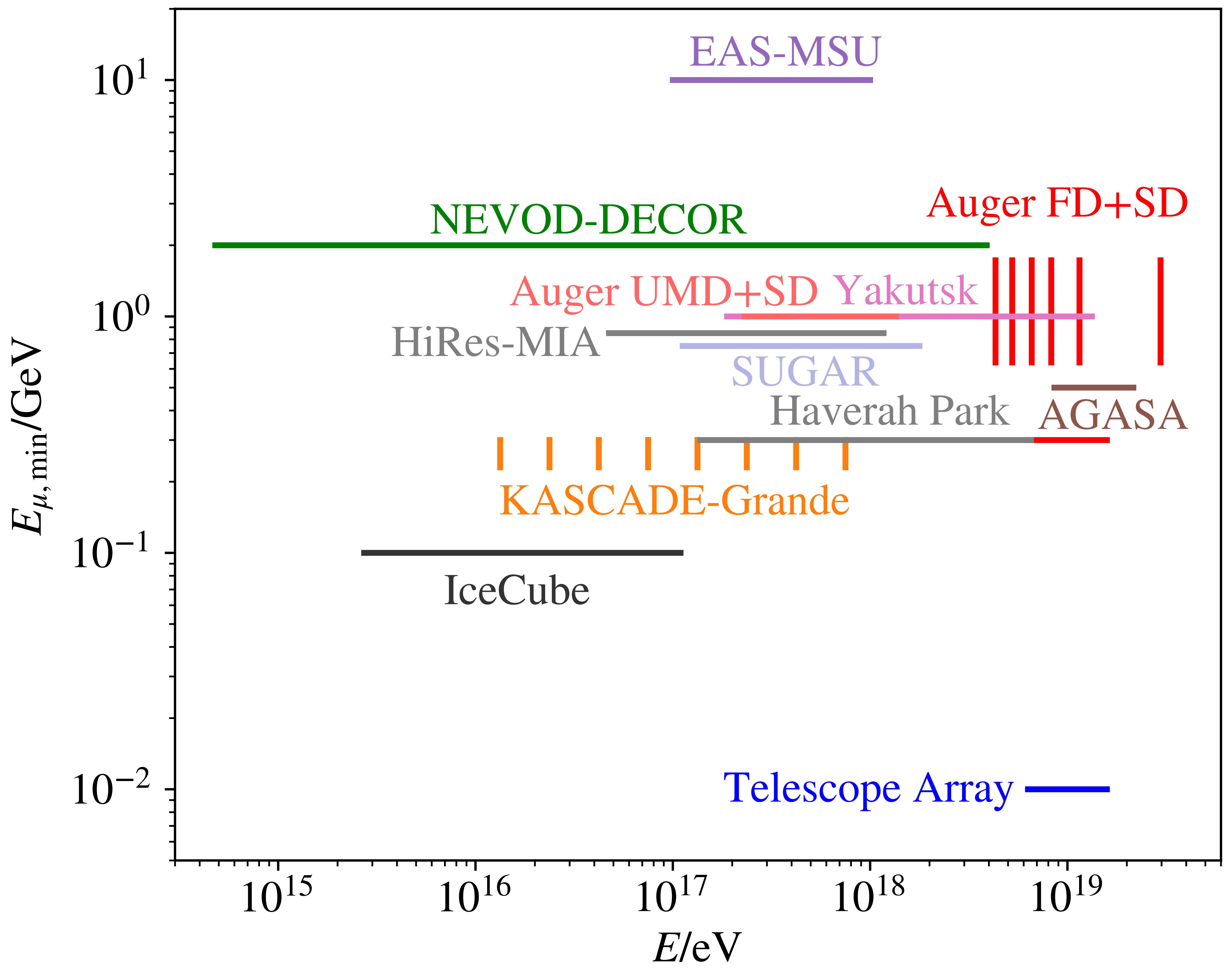
FD: Fluorescence detector

SD/FD: Internal calibration between SD and FD

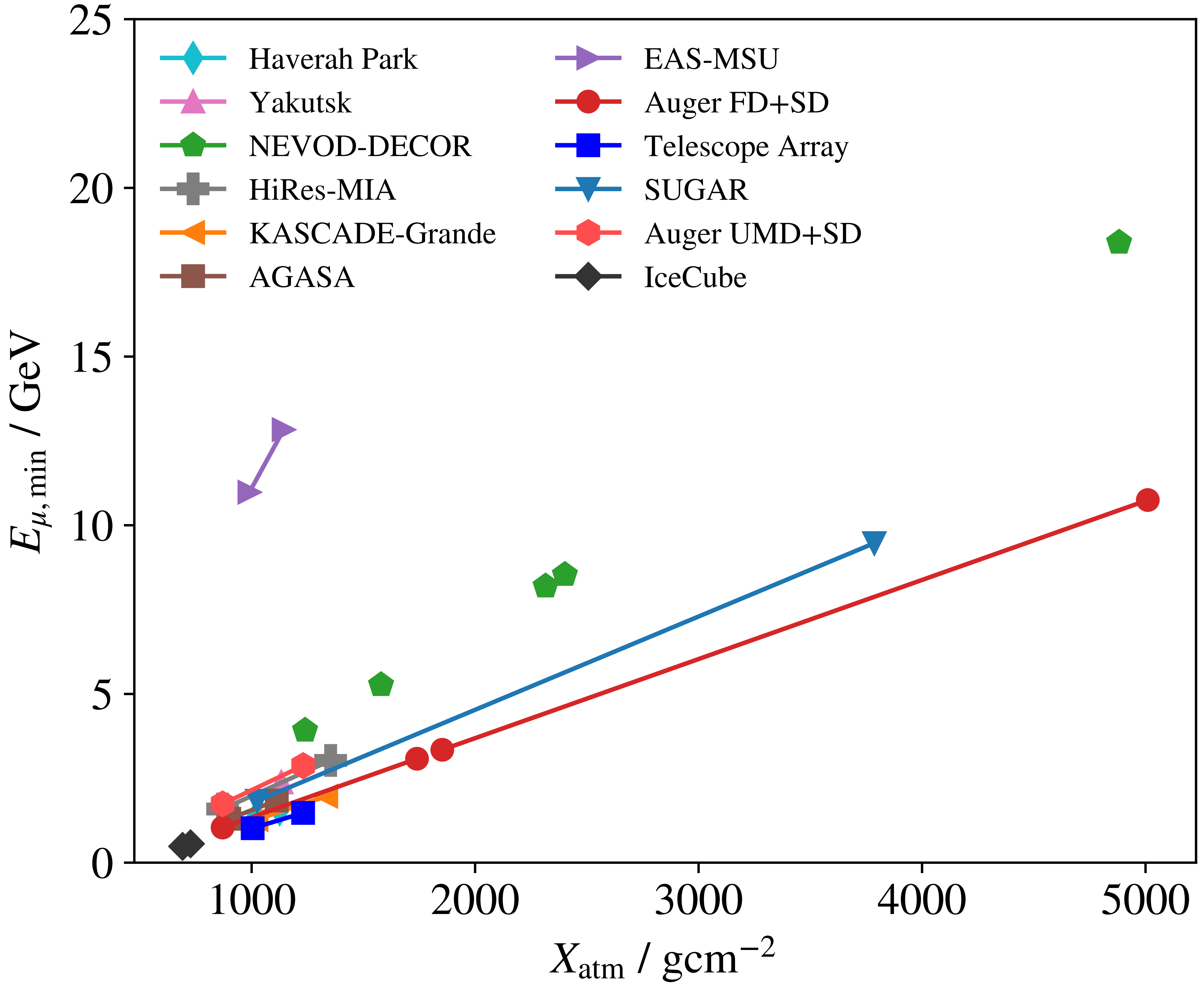
Flux: Comparison of total spectrum with a spectrum of reference

# 3) Muon phase space






Muon energy threshold at ground vs primary energy

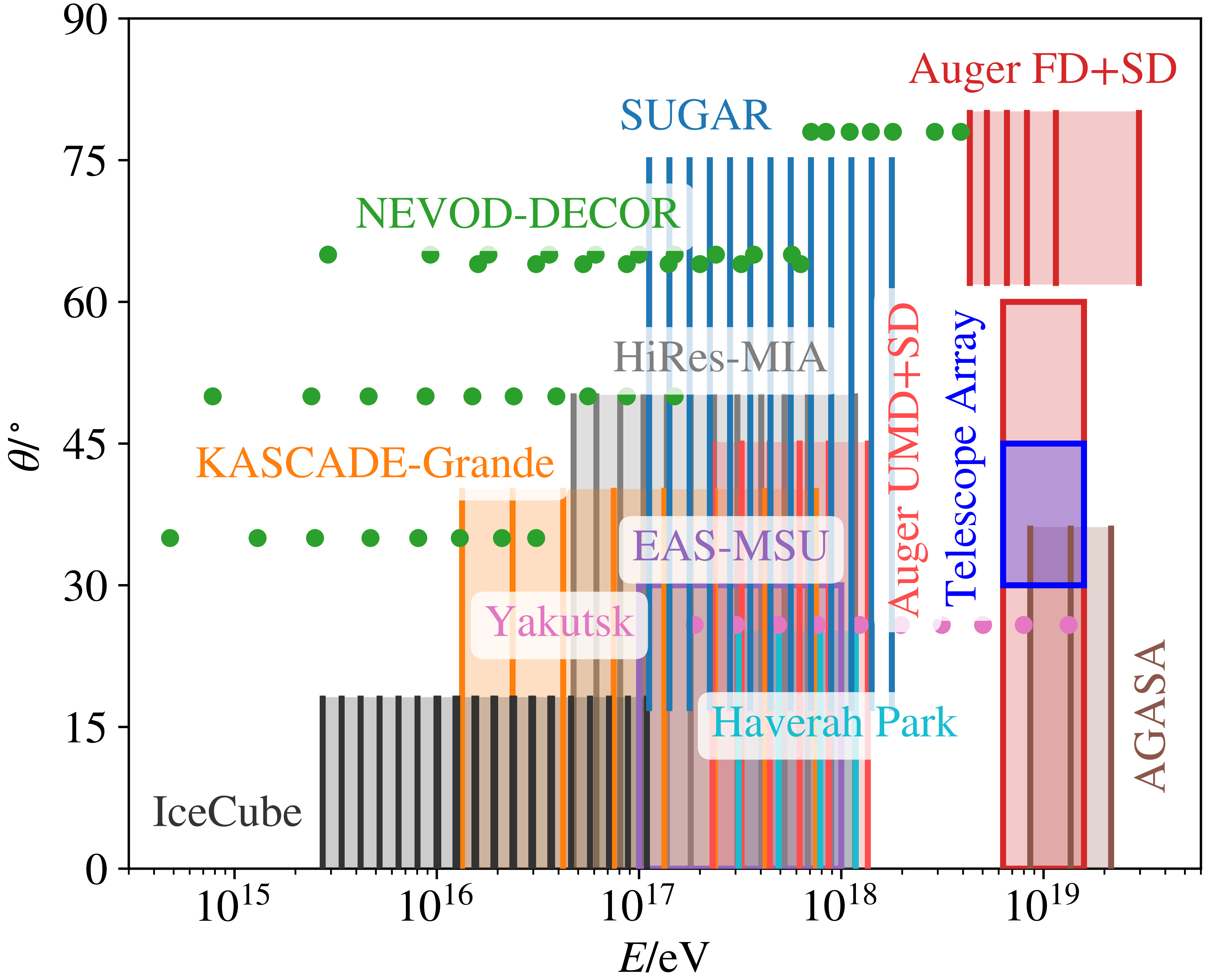



Muon energy threshold at production site vs effective atmospheric depth

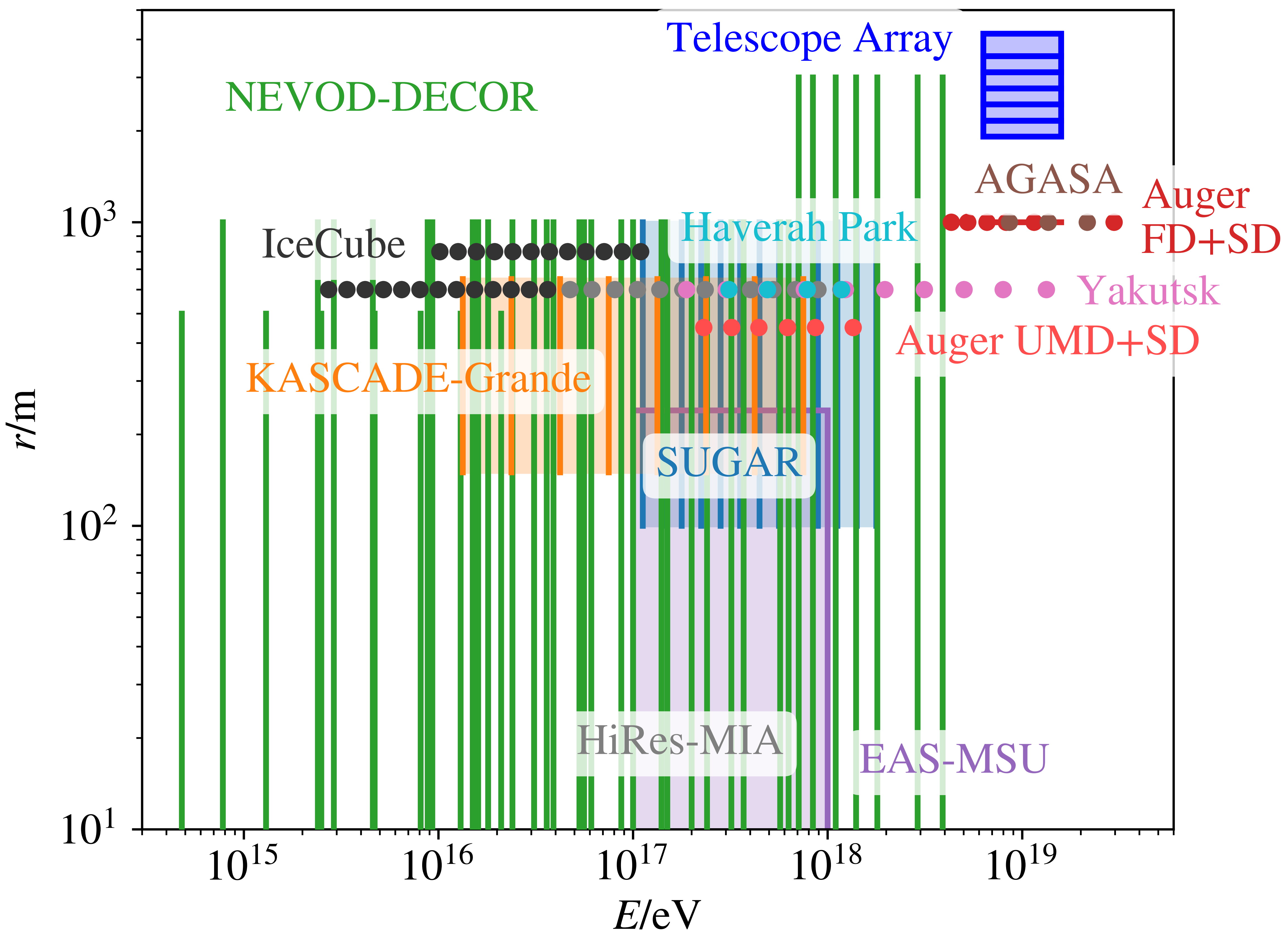
$$E_{\mu,prod} = E_{\mu,min} \sec(\theta) + dE_\mu/dX\, [X \sec(\theta) - 400 \text{ g/cm}^2]$$

# 3) Muon phase space






Zenith angle of observation vs primary energy




Lateral distance vs primary energy

# 4) Combined analysis

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- Data is compared with MC simulations (protons/iron) of air shower development, detector response and analysis chain.
- Use z-scale for comparison with models

$$z = \frac{\ln\langle N_{\mu}^{\text{det}}\rangle - \ln\langle N_{\mu,\text{p}}^{\text{det}}\rangle}{\ln\langle N_{\mu,\text{Fe}}^{\text{det}}\rangle - \ln\langle N_{\mu,\text{p}}^{\text{det}}\rangle}$$

$$z = \begin{cases} 0, & \text{proton} \\ 1, & \text{iron} \end{cases}$$

$\langle N_{\mu}^{\text{det}}\rangle$ Measured value

$\langle N_{\mu,\text{p}}^{\text{det}}\rangle$ ($\langle N_{\mu,\text{Fe}}^{\text{det}}\rangle$) MC simulations for proton (iron nuclei)

- Eliminates energy dependence of data and cancel possible linear biases.

# 4) Combined analysis

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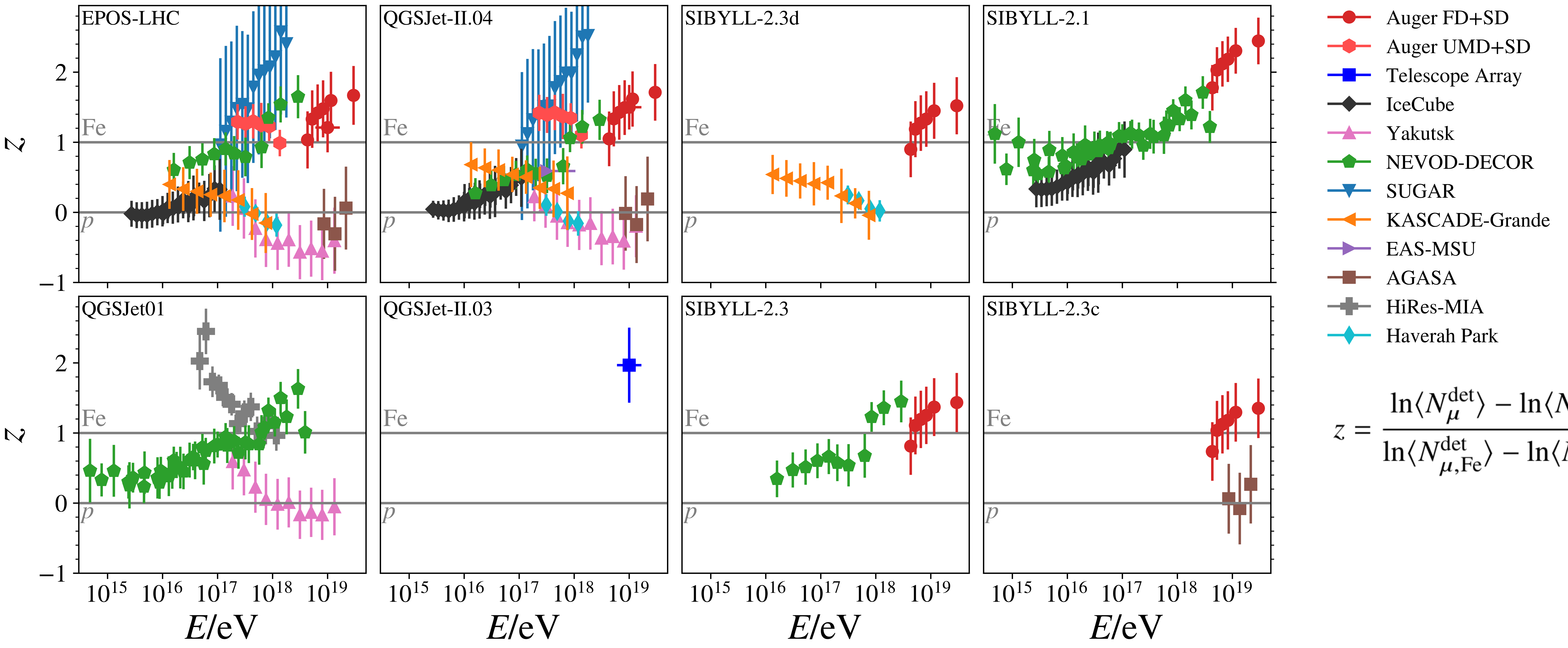
Preliminary




$$z = \frac{\ln\langle N_{\mu}^{\mathrm{det}}\rangle - \ln\langle N_{\mu,\mathrm{p}}^{\mathrm{det}}\rangle}{\ln\langle N_{\mu,\mathrm{Fe}}^{\mathrm{det}}\rangle - \ln\langle N_{\mu,\mathrm{p}}^{\mathrm{det}}\rangle}$$

# 4) Combined analysis



- Correct measurements for differences in the energy scale between data and MC simulations.
- Since

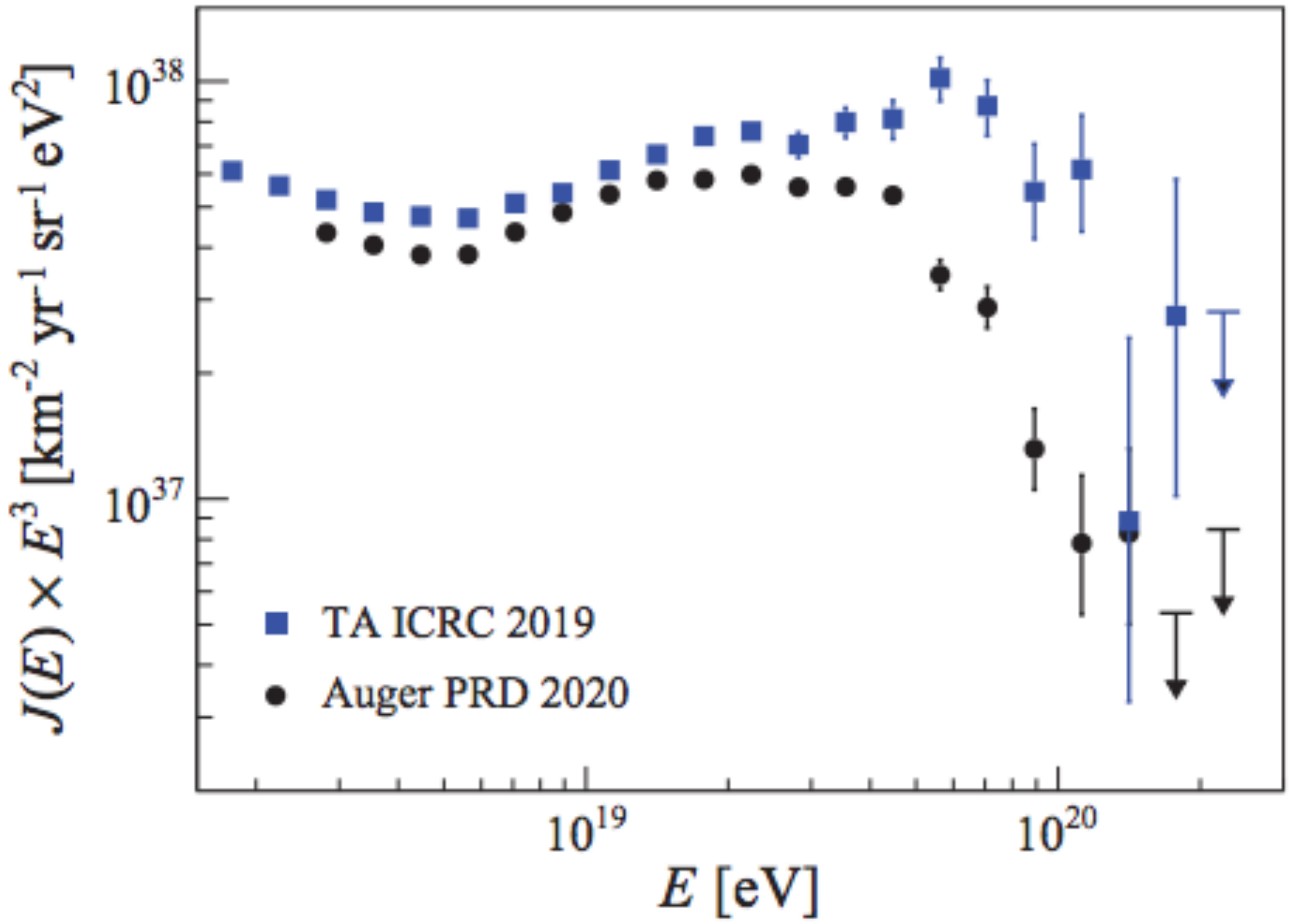
[J. Matthews, Astrop. Phys. 22, (2005) 387]

$$N_\mu = A^{1-\beta} \cdot (E/\xi_C)^\beta$$

$\beta$ = 0.9; $\xi_C$ = 100 GeV; $A$ = *Atomic Mass*

then 20% offset in energy scale ($E$) => 18% shift in muon content ($N_\mu$)

- Apply energy adjustment to match energy spectrum of reference, which is located between spectra from **Pierre Auger** and **Telescope Array**.




[D.R. Bergman, EPJ Web of Conferences 283, 02003 (2023)]

| Experiment | $E_{data}/E_{ref}$ |
|---|---|
| EAS-MSU | −− |
| HiRes-MIA | −− |
| Pierre Auger | |
| FD+SD | 0.948 |
| UMD+SD | 0.948 |
| SUGAR | 0.948 |
| KASCADE-Grande | 0.948 |
| Telescope Array | 1.052 |
| NEVOD-DECOR | 1.08 |
| Haverah Park | 1.16 |
| IceCube/IceTop | 1.19 |
| Yakutsk EAS array | 1.24 |
| AGASA | 1.47 |

# 4) Combined analysis

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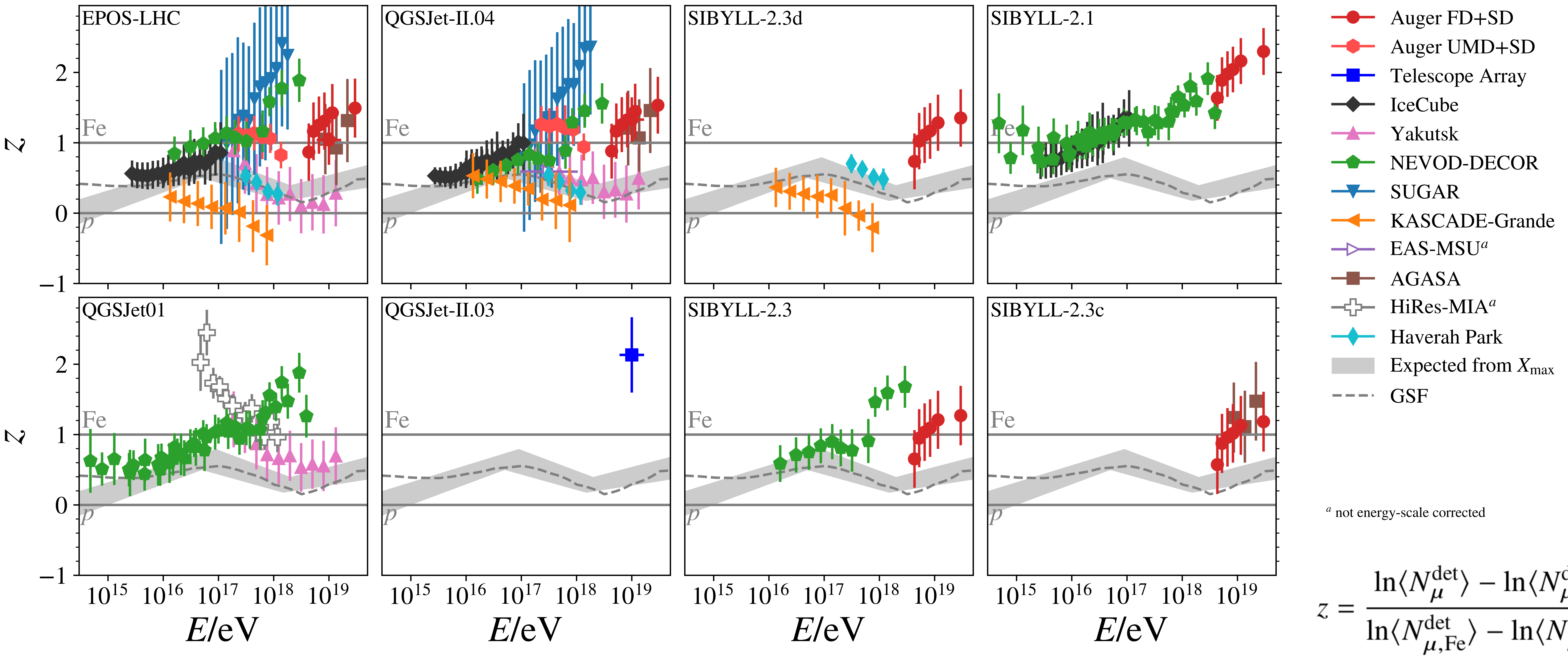
- The z-scale after applying the energy shifts for common energy calibration.

Preliminary




[a] not energy-scale corrected

$$z = \frac{\ln\langle N_\mu^{det}\rangle - \ln\langle N_{\mu,p}^{det}\rangle}{\ln\langle N_{\mu,Fe}^{det}\rangle - \ln\langle N_{\mu,p}^{det}\rangle}$$

# 4) Combined analysis

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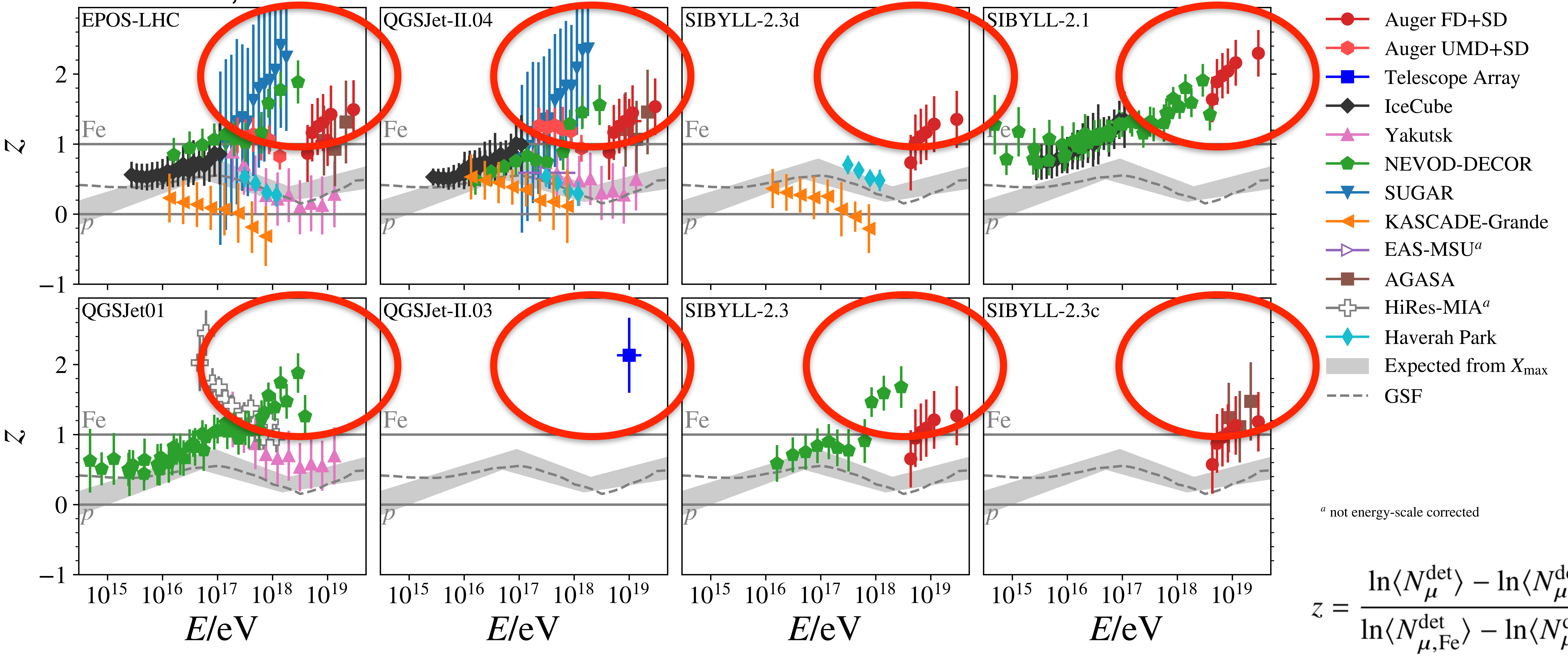
- **Muon deficit in MC** is observed for E > $10^{17}$ eV in Auger, TA, NEVOD-DECOR, SUGAR and AGASA.

Preliminary



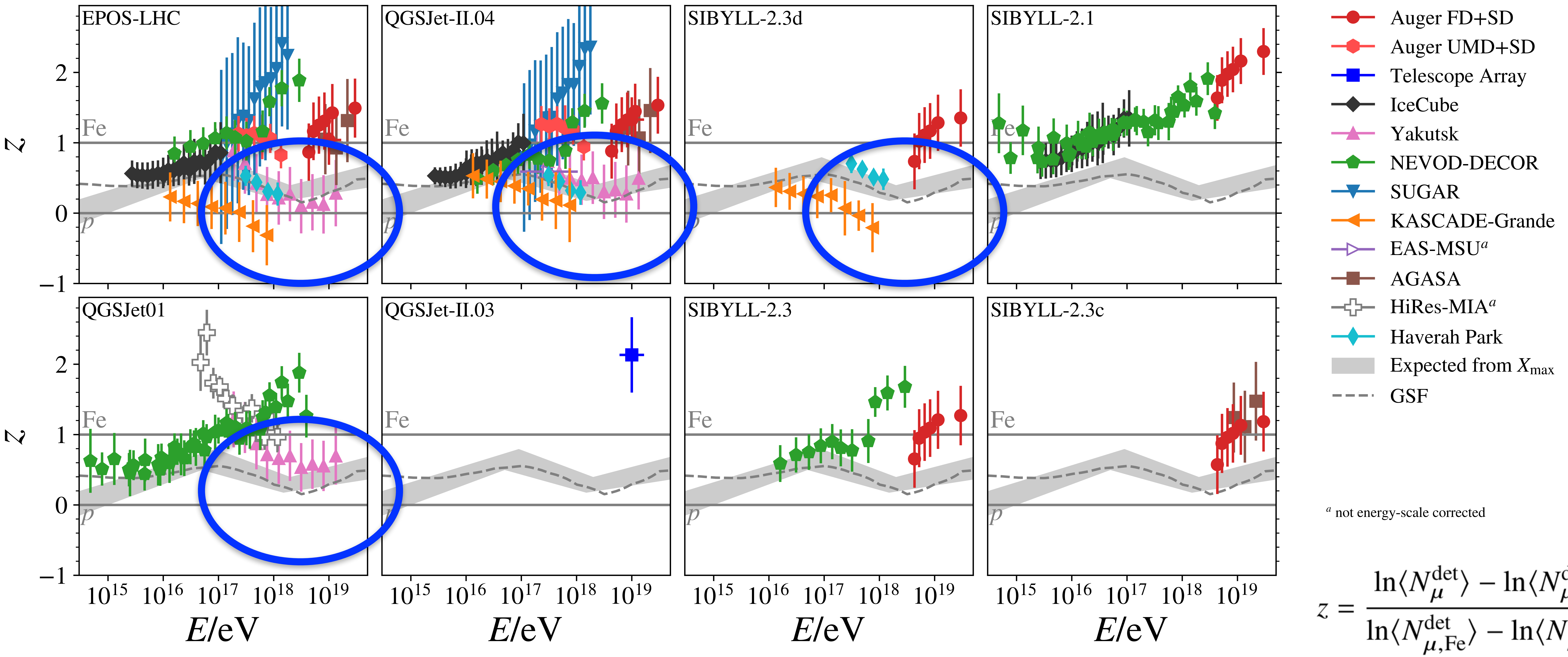

$$z = \frac{\ln\langle N_{\mu}^{det}\rangle - \ln\langle N_{\mu,p}^{det}\rangle}{\ln\langle N_{\mu,Fe}^{det}\rangle - \ln\langle N_{\mu,p}^{det}\rangle}$$

# 4) Combined analysis



- **No deficit in MC** is seen for Haverah Park, Yakutsk and KASCADE-Grande.

Preliminary



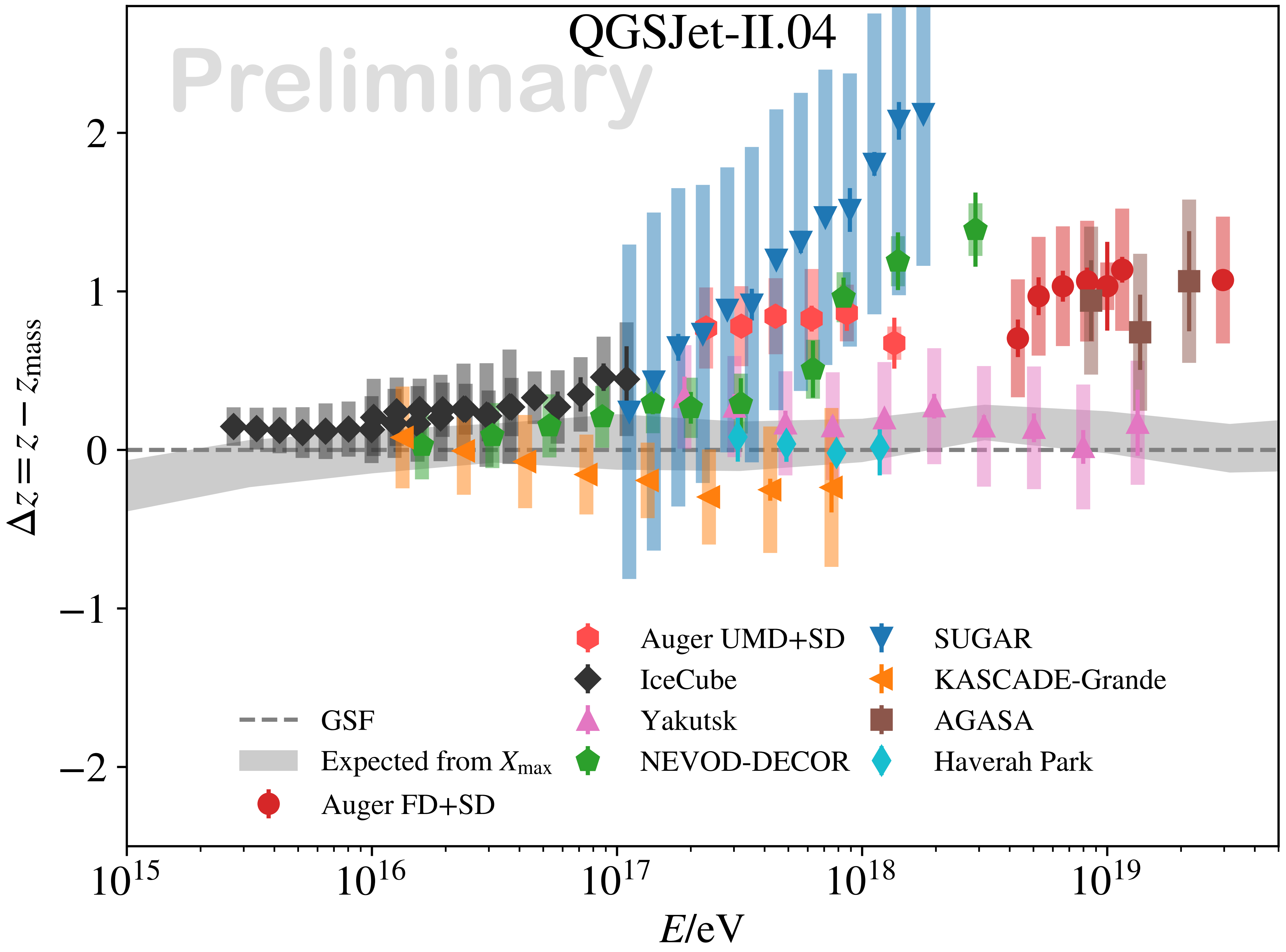

[a] not energy-scale corrected

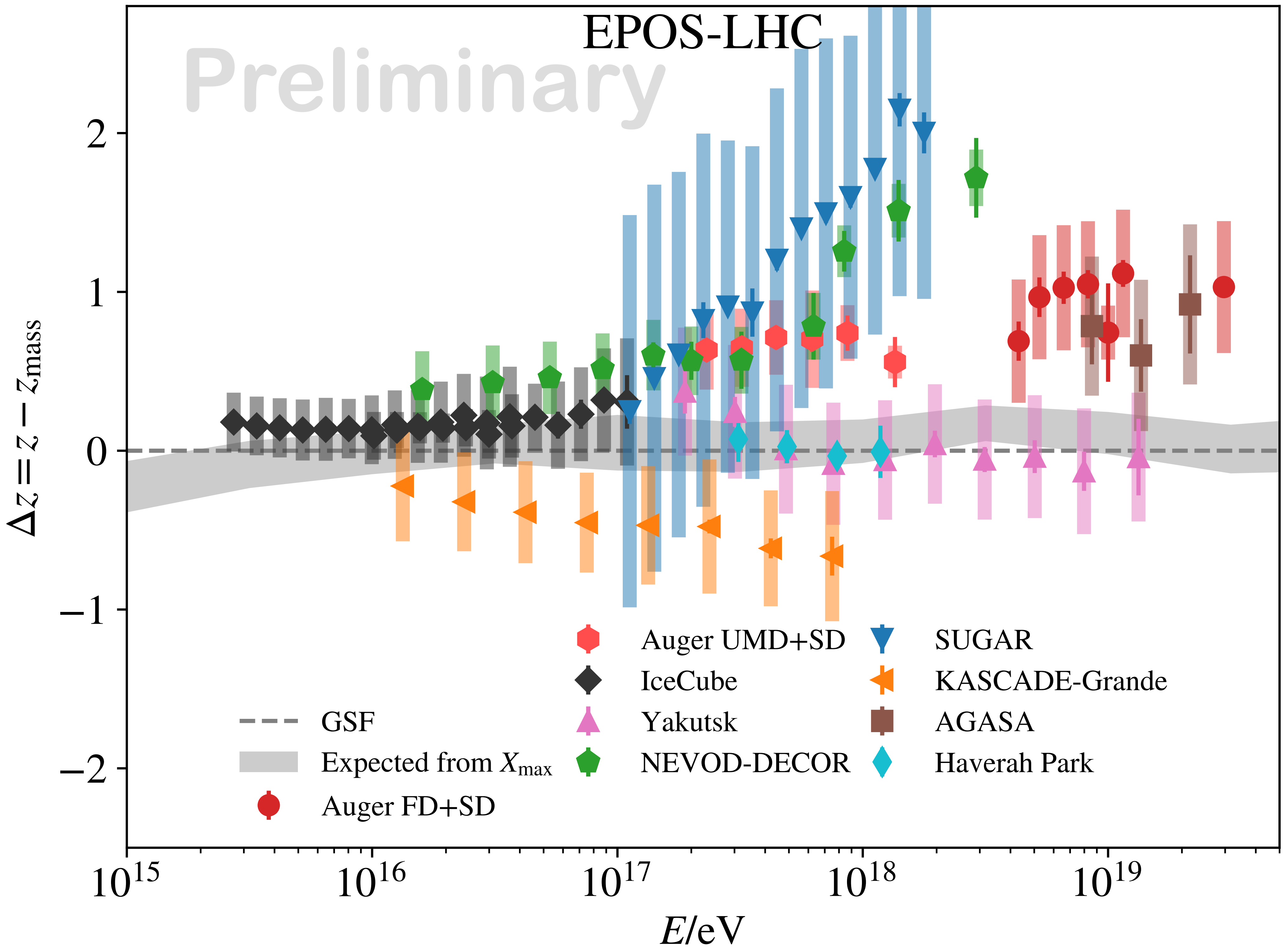
$$z = \frac{\ln\langle N_\mu^{det}\rangle - \ln\langle N_{\mu,p}^{det}\rangle}{\ln\langle N_{\mu,Fe}^{det}\rangle - \ln\langle N_{\mu,p}^{det}\rangle}$$

# 4) Combined analysis



- Remove mass dependence on z-scale: Substract $z_{mass}$, predicted by the Global-Spline-Fit (GSF) model of cosmic rays [H. Dembinski et al., arxiv: 1711.11432astro-ph.He], from the z values.



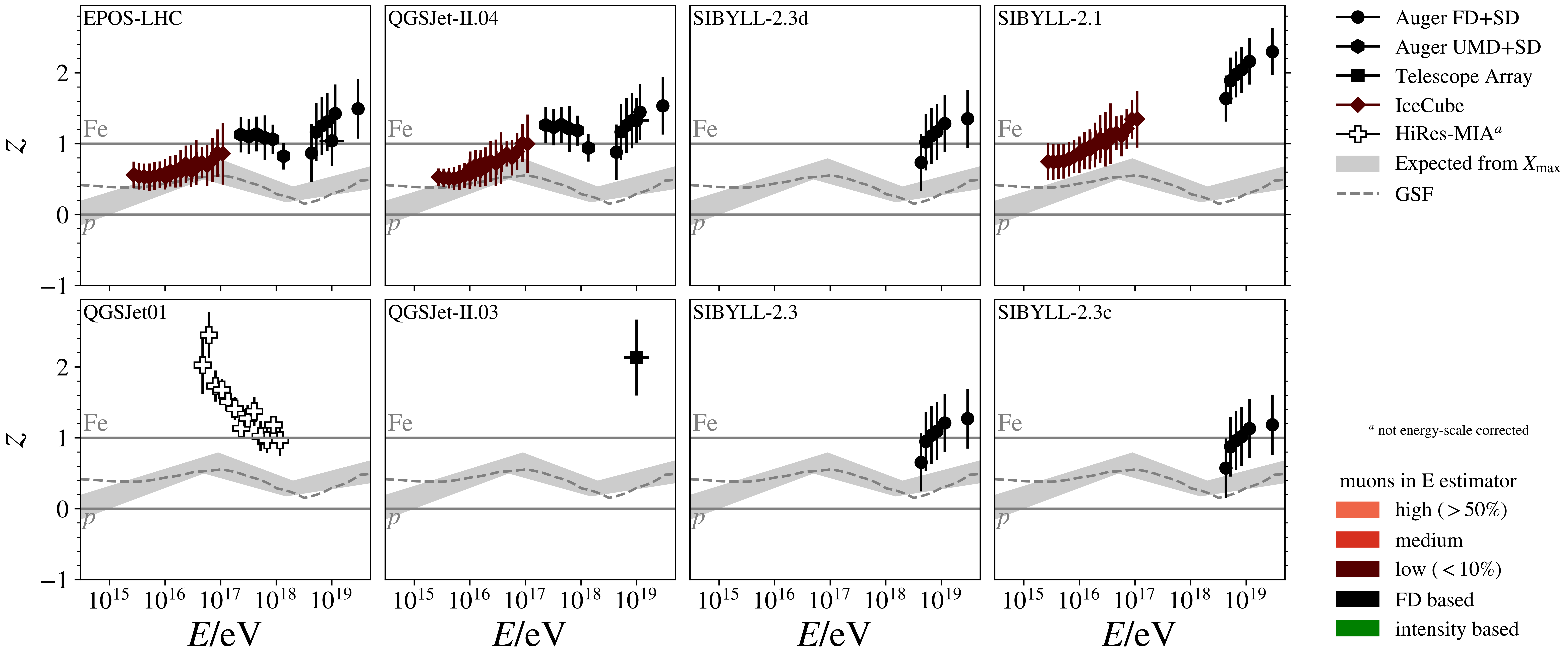




- Above $10^{17}$ eV, we observe two trends in the data: an excess in measurements over GSF expectations and a tendency to lie between the GSF predictions or below them.

# 4) Combined analysis



- Classification according to the muon contamination in the estimated primary energy.



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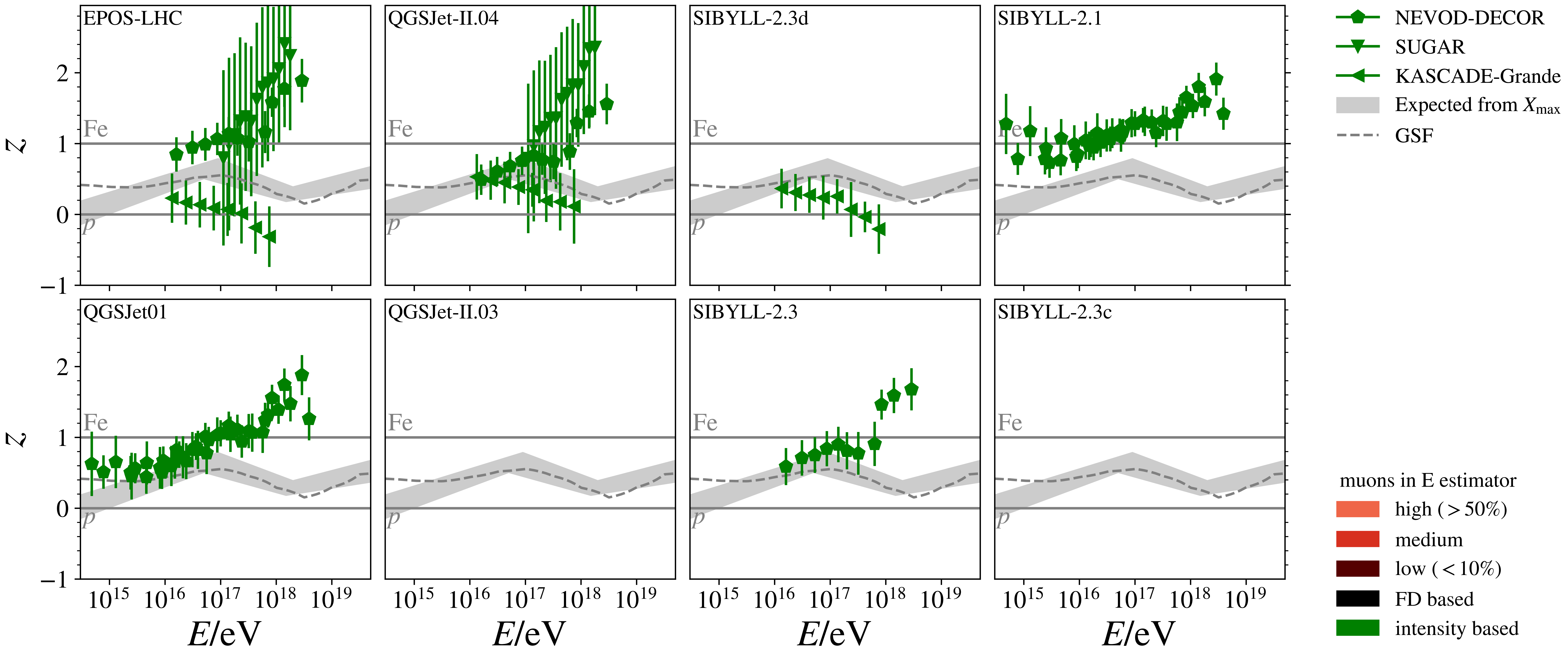

# 4) Combined analysis

ISVHECRI 2024

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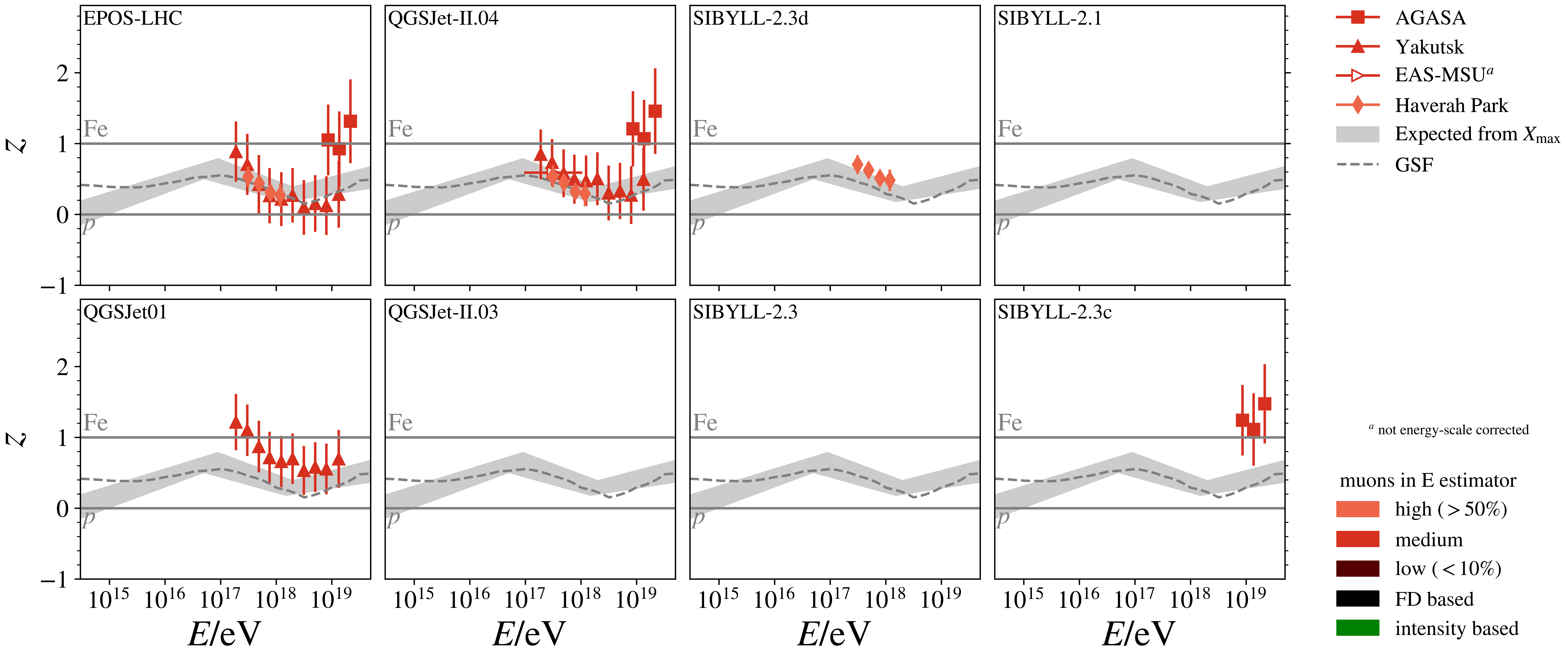

# 4) Combined analysis



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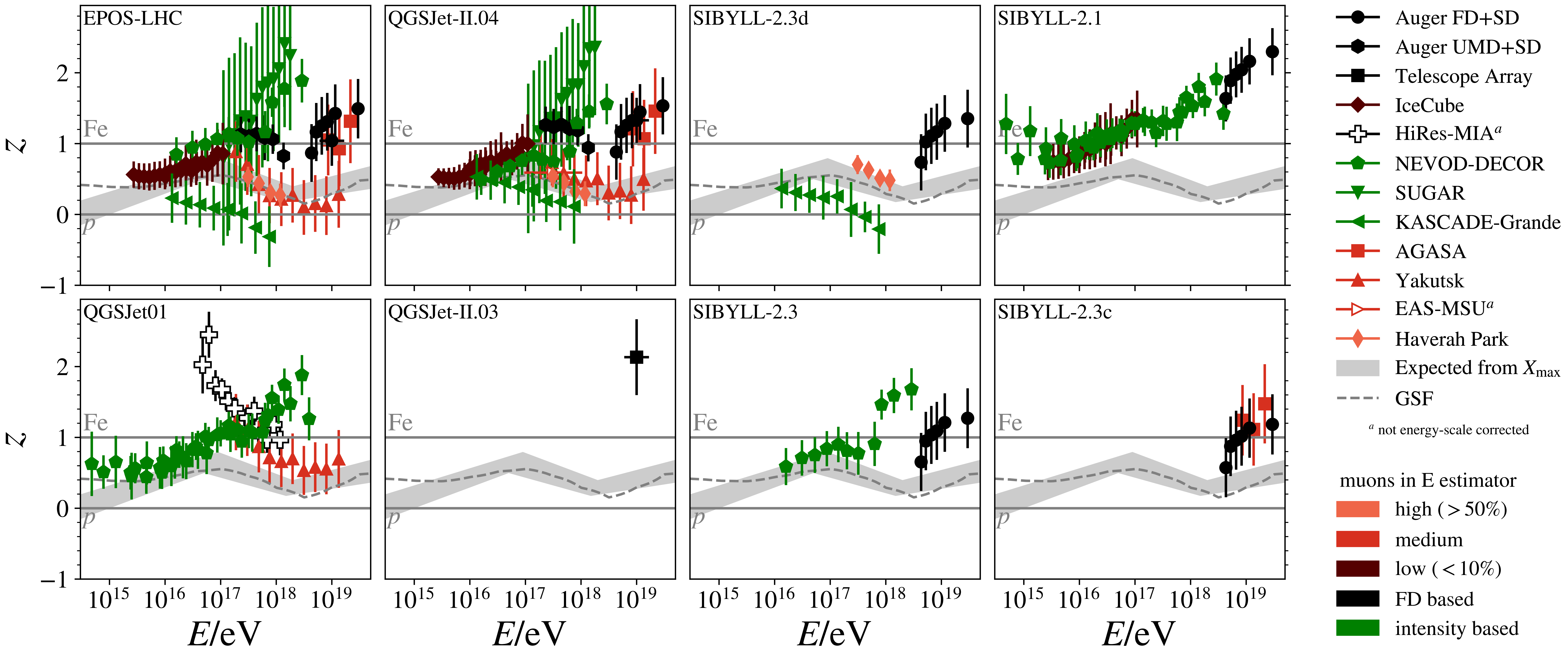

# 5) Summary



- A **progress report** on the WHISP **meta-analysis of different shower muon measurements** with several air-shower experiments was presented for energies between 1 PeV and 10 EeV.

- In the **ultra-high energy regime**, **Pierre Auger Observatory, Telescope Array, SUGAR, AGASA and NEVOD-DECOR show an excess of muons in the data with regard to MC predictions** with post-LHC hadronic interaction models for p and Fe primaries.

- The **discrepancy** is **not observed by Yakutsk, Haverah Park and KASCADE-Grande calibrated with the Auger energy scale**.

- To understand these differences the experimental conditions, simulation characteristics, detection methods, energy calibrations techniques, low-energy hadronic interaction models, etc. must be studied.

# Acknowledgements




- The WHISP working group thanks the support, comments, suggestions, data and plots provided by the EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array and Yakutsk EAS Array Collaborations and the Haverah Park Working Group for the elaboration of this work.

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# Backup

# Global-Spline-Fit (GSF) model

[H. Dembinski et al., arxiv: 1711.11432astro-ph.He ]