Report on the Combined Analysis of Muon Data Recorded by Nine Air Shower Experiments

Dennis Soldin[1,2] for the UHECR Working Group for Hadronic Interactions and Shower Physics (WHISP)

[1] Institute of Experimental Particle Physics, Karlsruhe Institute of Technology
[2] Bartol Research Institute and Dept. of Physics and Astronomy, University of Delaware

6th International Symposium on Ultra High Energy Cosmic Rays
UHECR 2022
L'Aquila, Italy October 3 - 7 2022

Karlsruhe Institute of Technology

UNIVERSITY OF DELAWARE
BARTOL RESEARCH INSTITUTE

Introduction

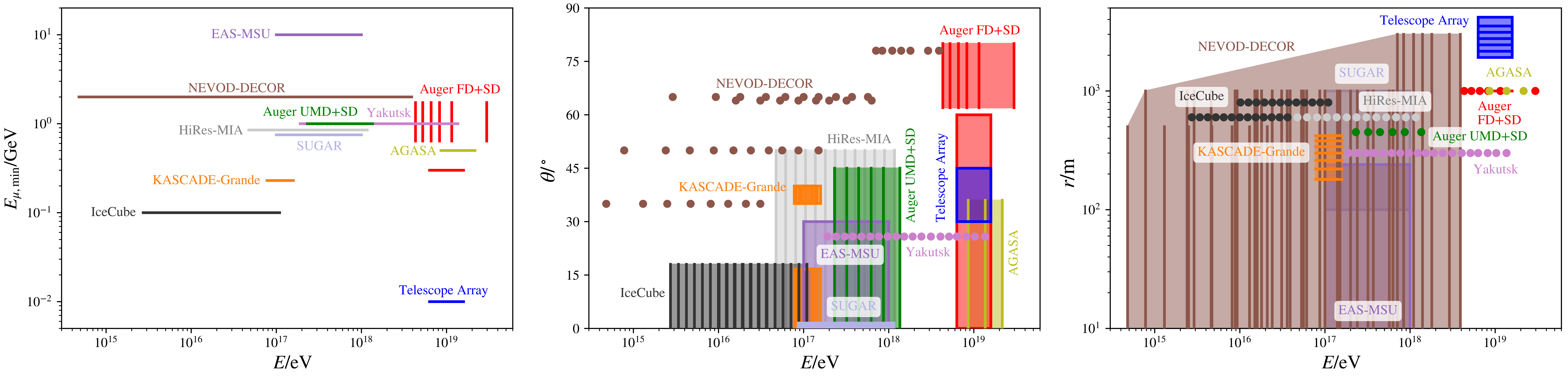
- Systematic comparison of measurements of the muon lateral density in extensive air showers (EAS) from 9 experiments
- UHECR Working Group for Hadronic Interactions and Shower Physics (WHISP)
  - First WHISP report at UHECR2018
    [H.P. Dembinski et al., EPJ Web Conf. 210 (2019)]
  - Updates at ICRC2019 and ICRC2021
    [L. Cazon et al., PoS ICRC2019 (2020) 214, D. Soldin et al., PoS ICRC2021 (2021) 349]
- This talk: Update of the WHISP meta-analysis presented at UHECR2018
  - Updated data from the Pierre Auger Observatory
  - Updated data from the IceCube Neutrino Observatory
  - (New) re-analyzed data from AGASA
  - Updated systematic statistical analysis of the combined muon measurements
  - Additional systematic checks…

WHISP Meta-Analysis

- 9 experiments: Data taken over large parameter space under very different experimental conditions!
- Muon content is expressed in terms of z-scale:

$$z = \frac{\ln(N_{\mu}^{\text{det}}) - \ln(N_{\mu,\text{p}}^{\text{det}})}{\ln(N_{\mu,\text{Fe}}^{\text{det}}) - \ln(N_{\mu,\text{p}}^{\text{det}})} \quad , \quad z = 0\text{: proton, } z = 1\text{: iron}$$

  - N_{μ}^{det}: muon content measured in the detector
  - $N_{\mu,\text{p}}^{\text{det}}$, $N_{\mu,\text{Fe}}^{\text{det}}$: muon content in simulated EAS (proton/iron) at the detector



WHISP Meta-Analysis

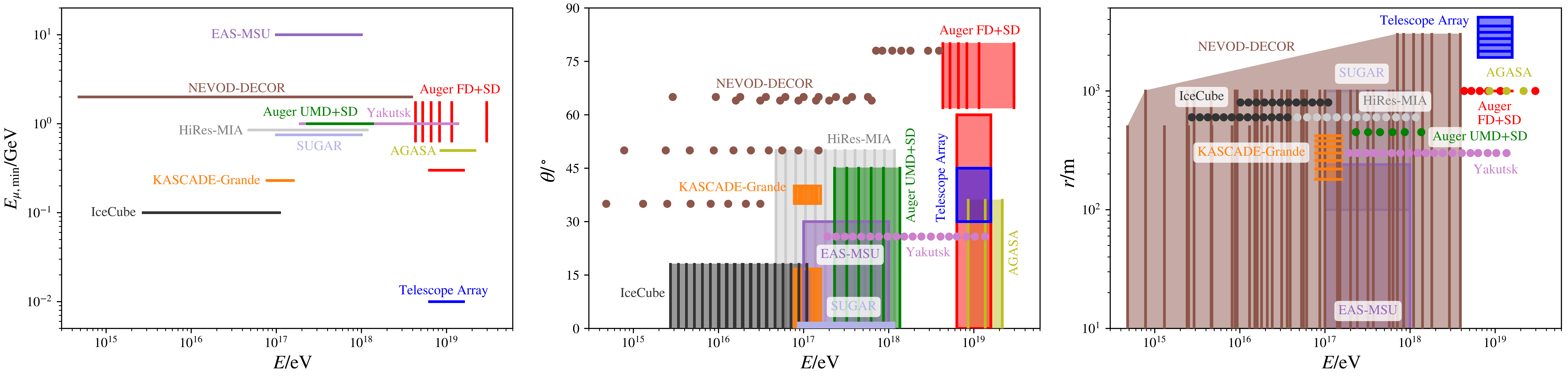
- 9 experiments: Da… n over large parameter space under very different experimental conditions!

data

- Muon content is expressed in terms of z-scale:

$$z = \frac{\ln(N_{\mu}^{\mathrm{det}}) - \ln(N_{\mu,\mathrm{p}}^{\mathrm{det}})}{\ln(N_{\mu,\mathrm{Fe}}^{\mathrm{det}}) - \ln(N_{\mu,\mathrm{p}}^{\mathrm{det}})} \quad , \quad z = 0\text{: proton, } z = 1\text{: iron}$$

  - N_{μ}^{det}: muon content measured in the detector
  - $N_{\mu,\mathrm{p}}^{\mathrm{det}}, N_{\mu,\mathrm{Fe}}^{\mathrm{det}}$: muon content in simulated EAS (proton/iron) at the detector

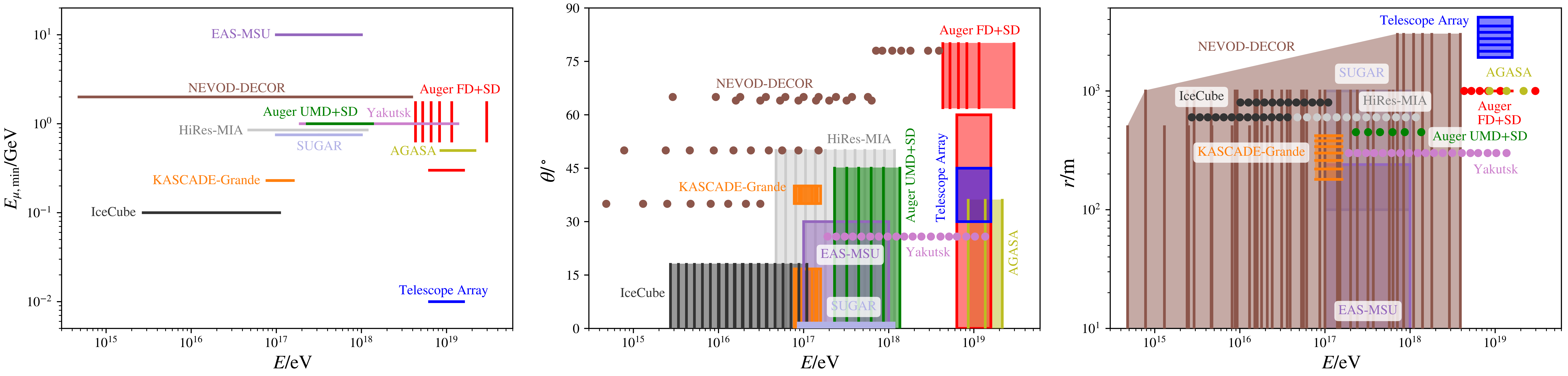


WHISP Meta-Analysis

- 9 experiments: Da[data]n over large parameter space under very different experimental conditions!
- Muon content is expressed in term[MC] scale:

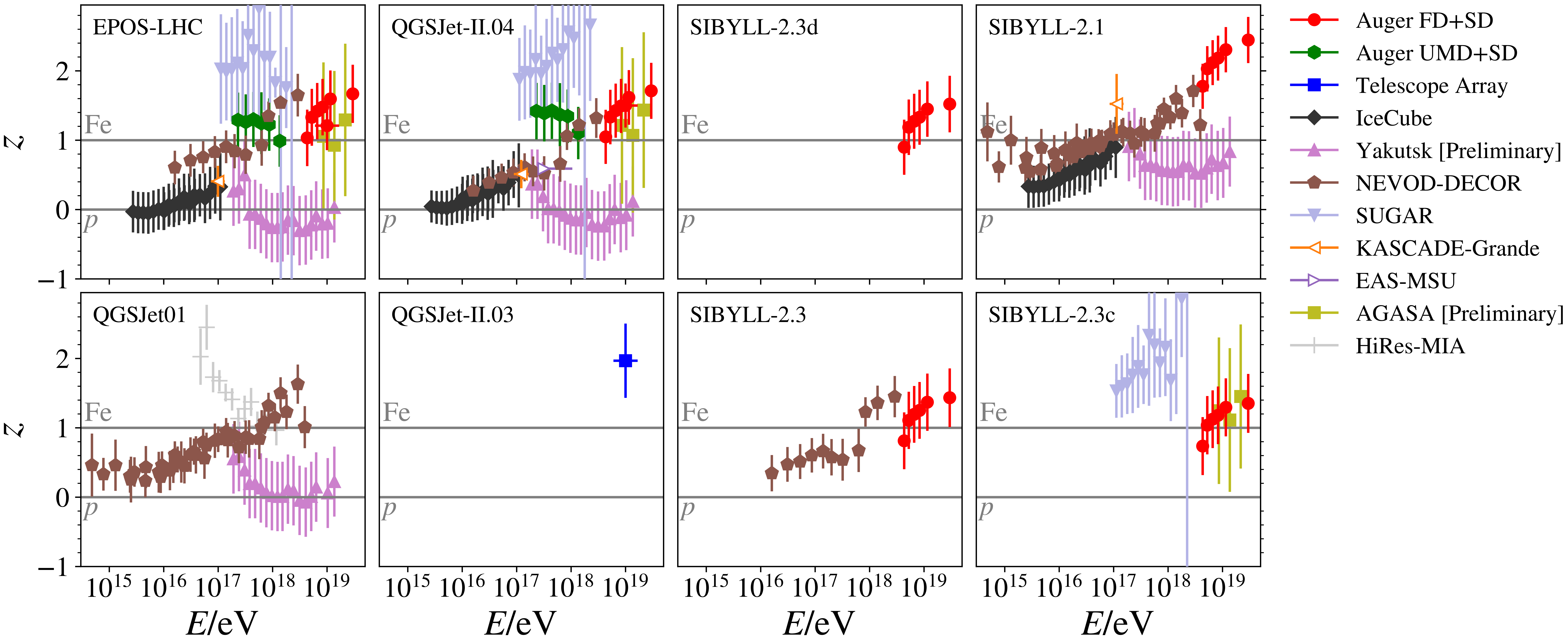
$$z = \frac{\ln(N_\mu^{\mathrm{det}}) - \ln(N_{\mu,\mathrm{p}}^{\mathrm{det}})}{\ln(N_{\mu,\mathrm{Fe}}^{\mathrm{det}}) - \ln(N_{\mu,\mathrm{p}}^{\mathrm{det}})}, \quad z = 0\text{: proton, } z = 1\text{: iron}$$

  - N_μ^{det}: muon content measured in the detector
  - $N_{\mu,\mathrm{p}}^{\mathrm{det}}$, $N_{\mu,\mathrm{Fe}}^{\mathrm{det}}$: muon content in simulated EAS (proton/iron) at the detector



Combined Muon Measurements

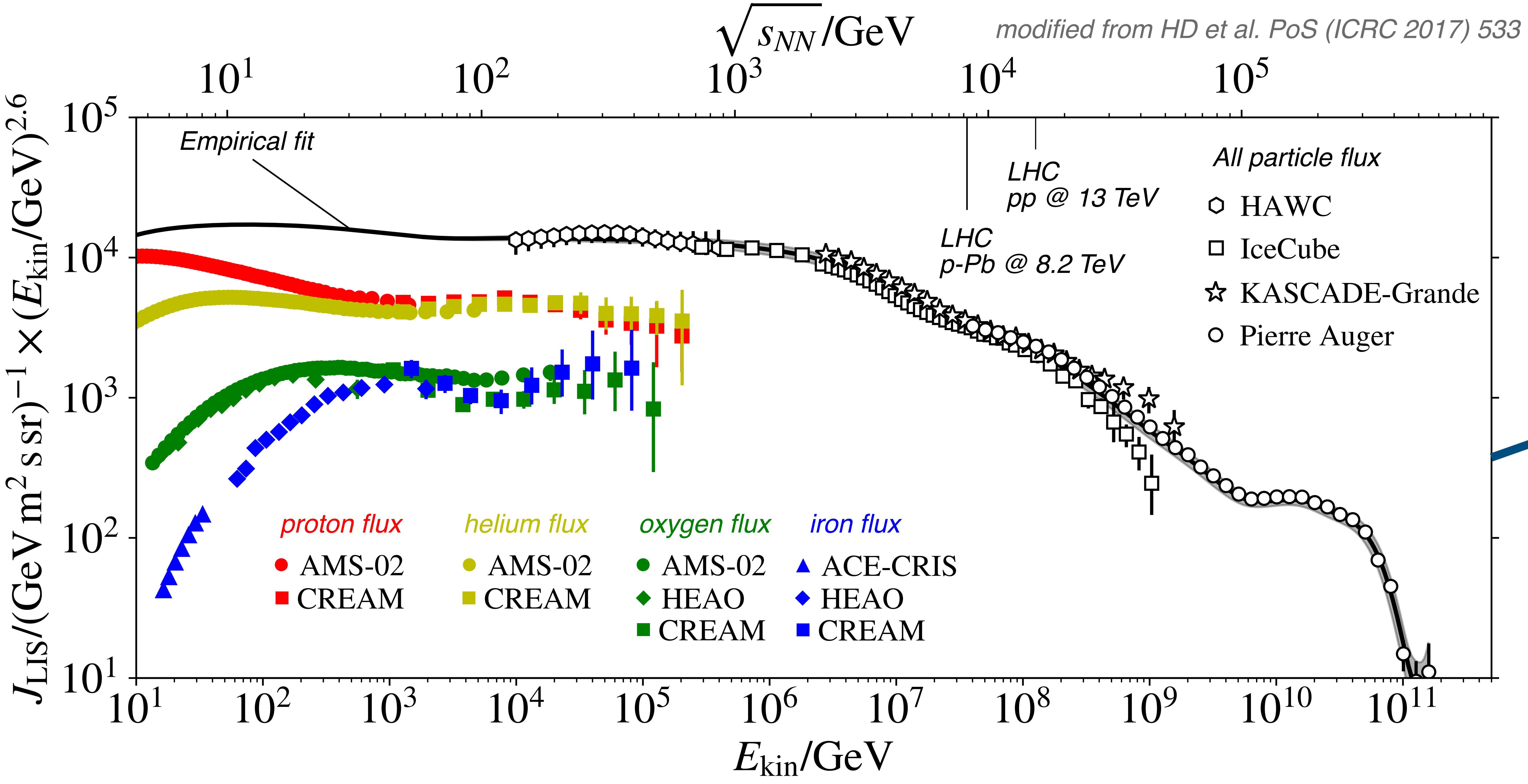
- Muon lateral density in EAS as reported by 9 (10) experiments



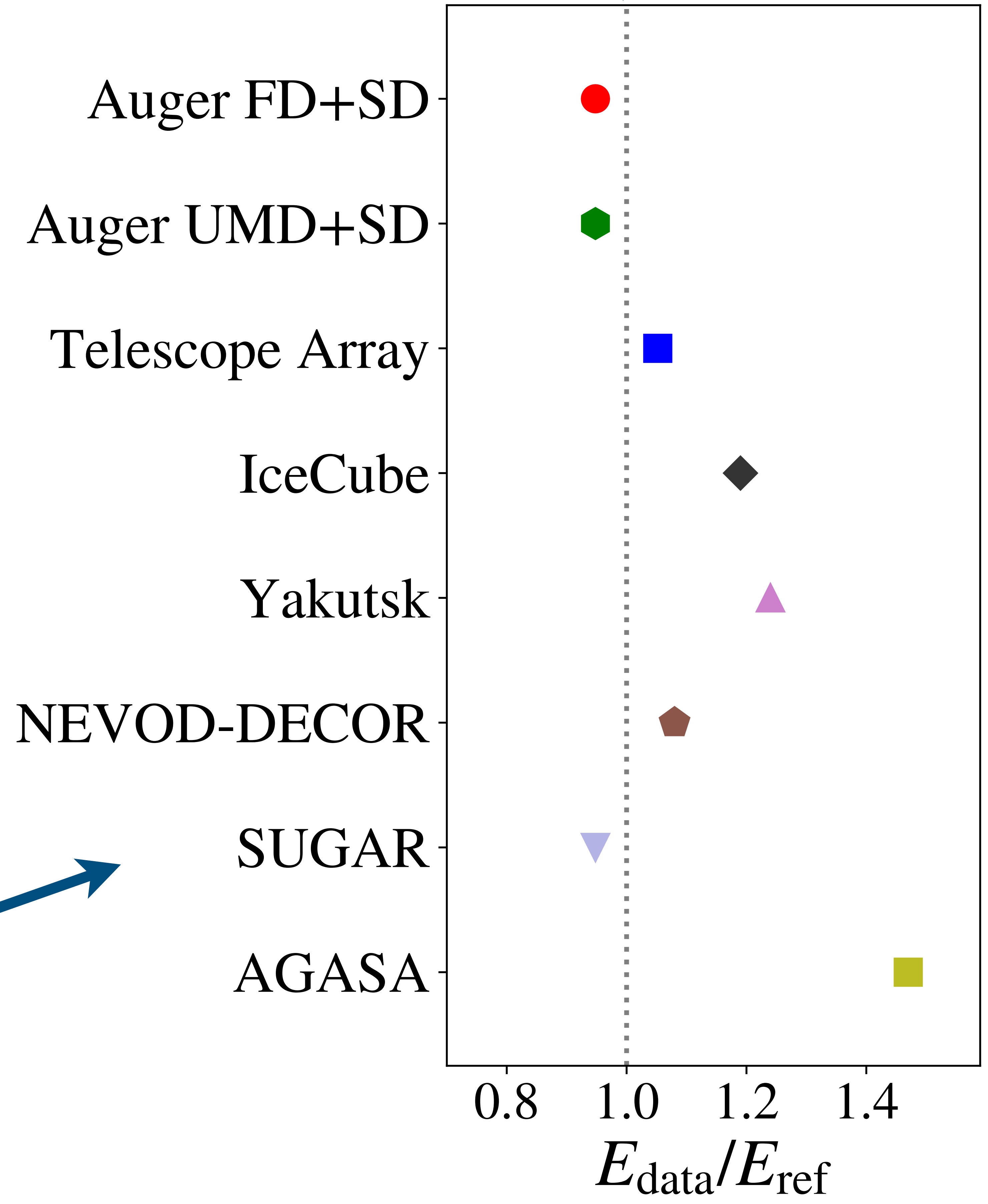
[D. Soldin et al., PoS ICRC2021 (2021) 349]

Energy-Rescaling

- Known energy-scale offsets between EAS experiments!
- 20% offset in energy causes 18% shift in muons!
  - Energy rescaling required!
- Reference model: Global-Spline Fit Model (GSF)



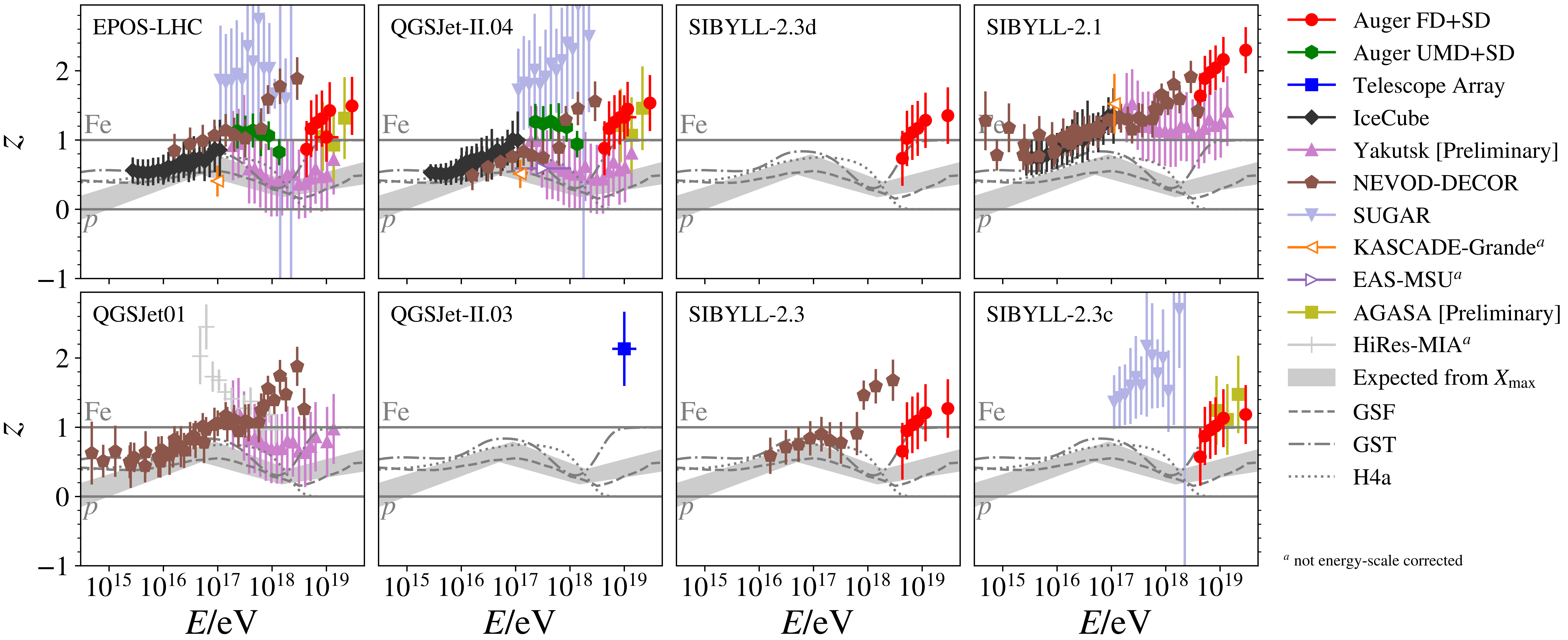
E_{ref} from Auger/TA spectrum working group
(see also talk by Valerio Verzi)



[H.P. Dembinski et al., PoS ICRC2017 (2018) 533]

Energy-Rescaled Muon Measurements

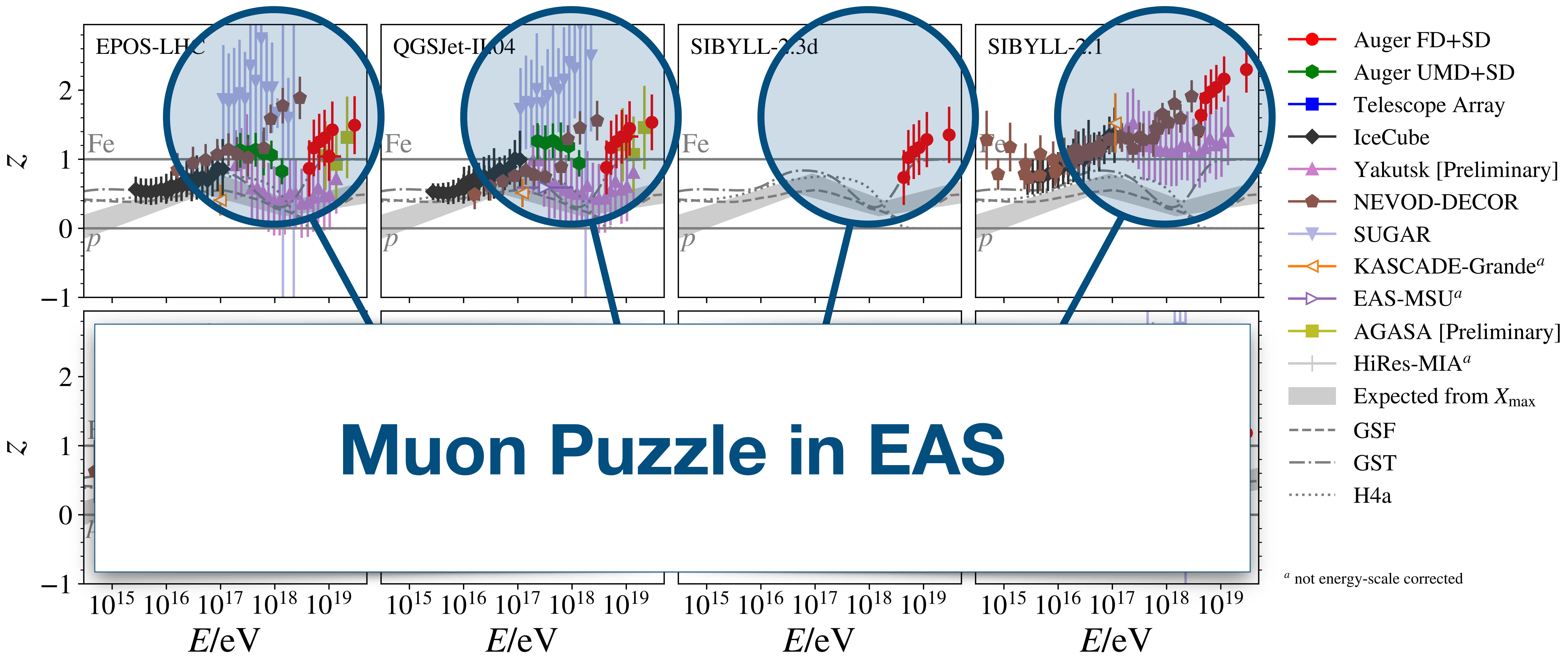
- Muon lateral density in EAS after cross-calibration of the energy-scales



[D. Soldin et al., PoS ICRC2021 (2021) 349]

Energy-Rescaled Muon Measurements

- Muon lateral density in EAS after cross-calibration of the energy-scales



Muon Puzzle in EAS

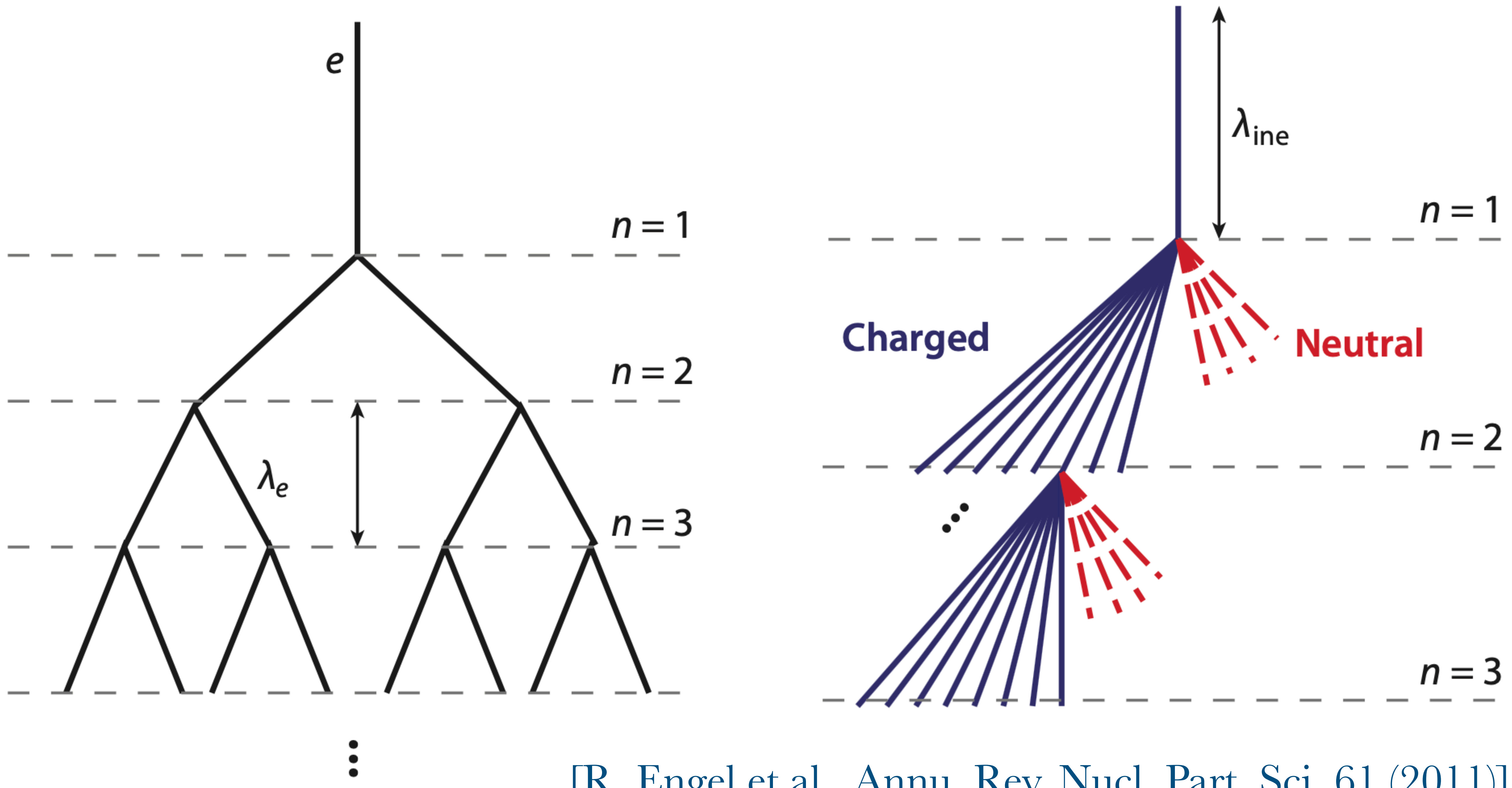
[D. Soldin et al., PoS ICRC2021 (2021) 349]

Mass Dependence

- Number of muons is described by the Heitler-Matthews model:

$$N_\mu = A^{1-\beta} \cdot \left(\frac{E}{\xi_C}\right)^\beta \quad , \quad \beta \simeq 0.9$$

  - E: primary cosmic ray energy
  - A: primary mass number
  - ξ_C: energy constant



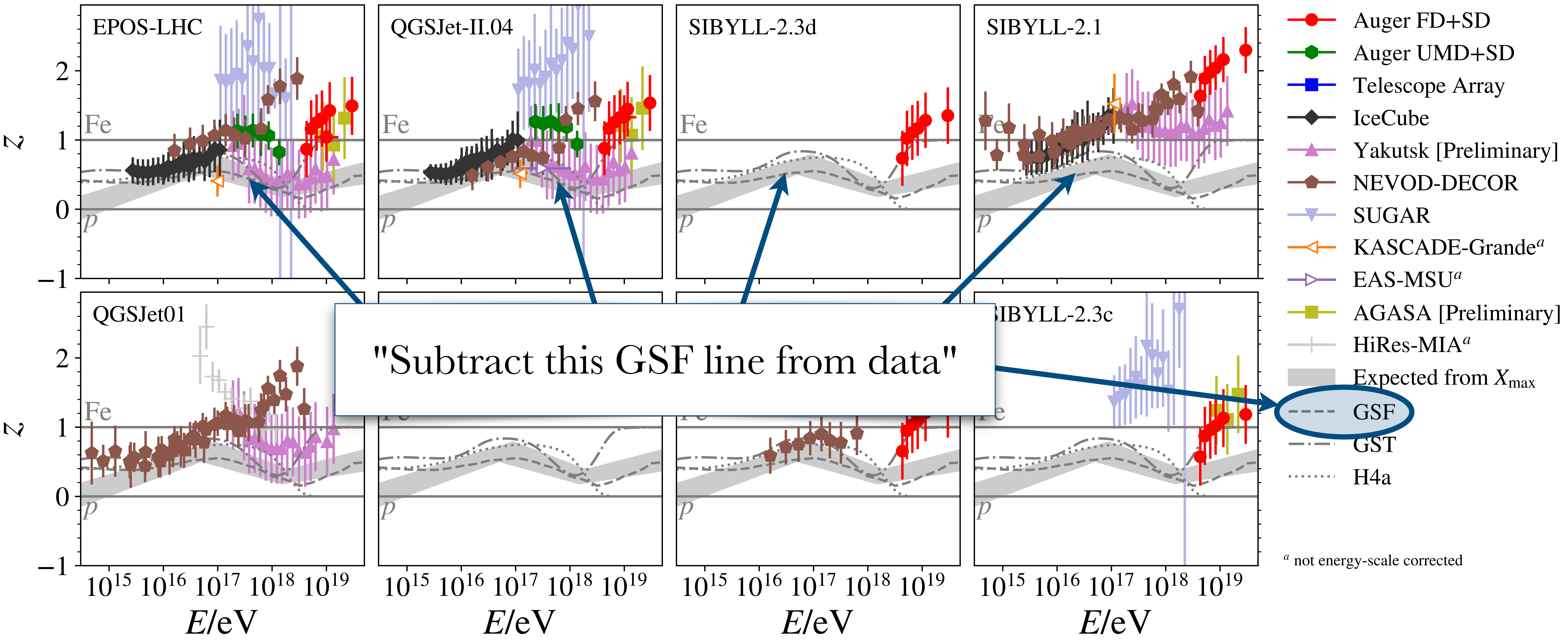
[R. Engel et al., Annu. Rev. Nucl. Part. Sci. 61 (2011)]

- When studying the energy-dependent trend in the muon measurements, the (energy-dependent) cosmic ray mass need to be taken into account!

- Mass dependence can be removed by subtracting z_{mass} based on the GSF model, i.e. in the plot on the previous slide "subtract the GSF line from the data points"

Energy-Rescaled Muon Measurements

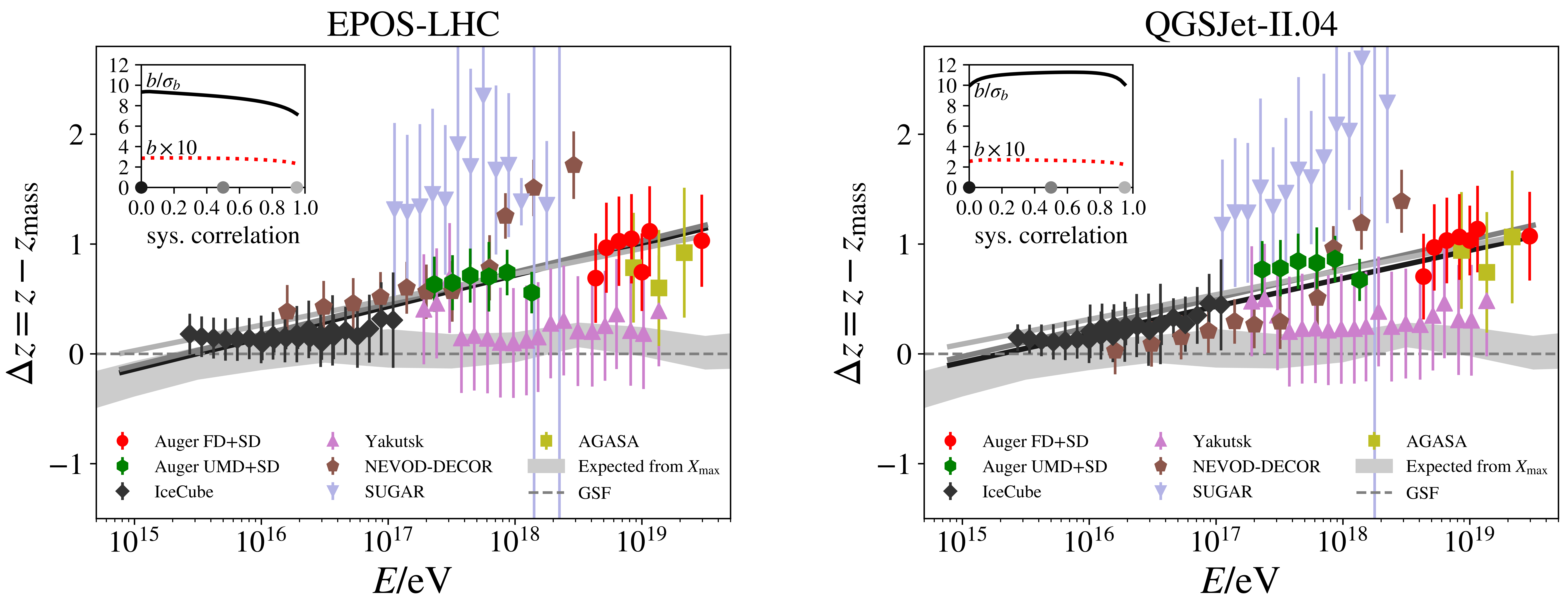
- Muon lateral density in EAS after cross-calibration of the energy-scales



[D. Soldin et al., PoS ICRC2021 (2021) 349]

Mass-Corrected z-Scale

[D. Soldin et al., PoS ICRC2021 (2021) 349]

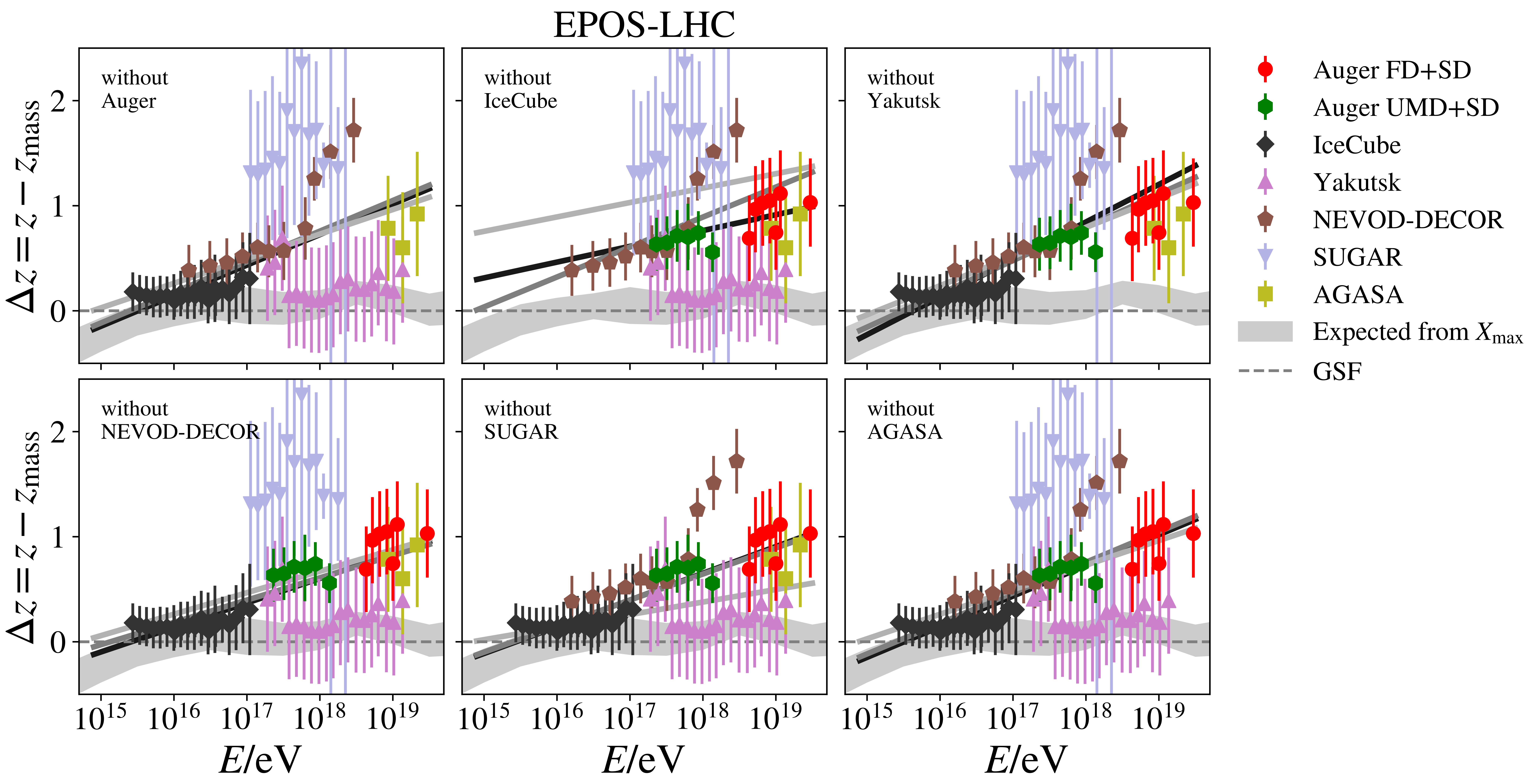


- Fit $\Delta z_{fit} = a + b \cdot \log_{10}(E/10^{16}\text{eV})$ depends on assumption of systematic correlation, α
- Slope of the fit: $b = 0.23 - 0.29$ (EPOS-LHC), $b = 0.22 - 0.25$ (QGSJet-II.04)
- Significance of the slope: $\sim 7\sigma - 9\sigma$ (EPOS-LHC), $\sim 10\sigma - 11\sigma$ (QGSJet-II.04)

N-1 Tests

[D. Soldin et al., PoS ICRC2021 (2021) 349]

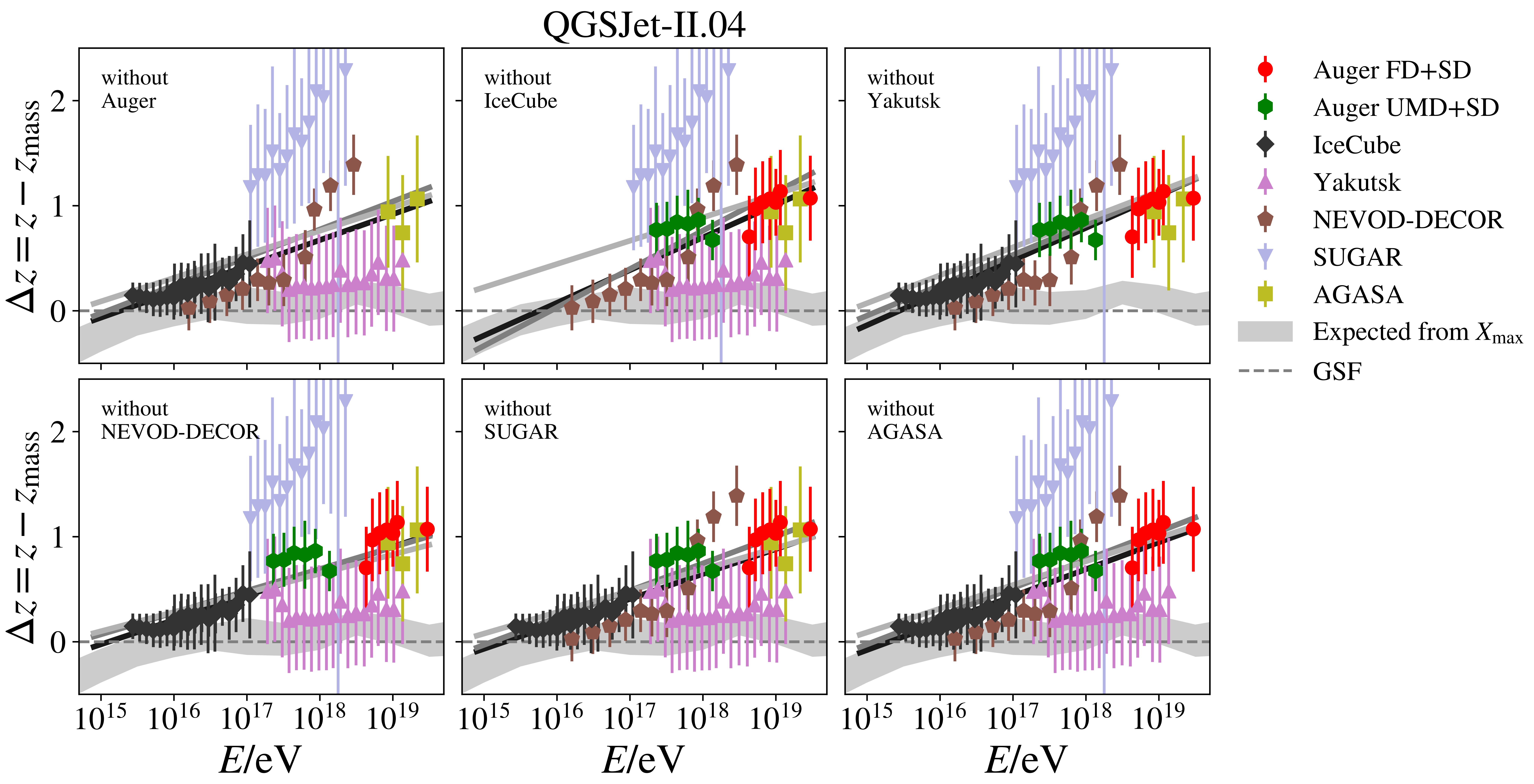
- How do the fits change when we remove one experiment at a time?



N-1 Tests

[D. Soldin et al., PoS ICRC2021 (2021) 349]

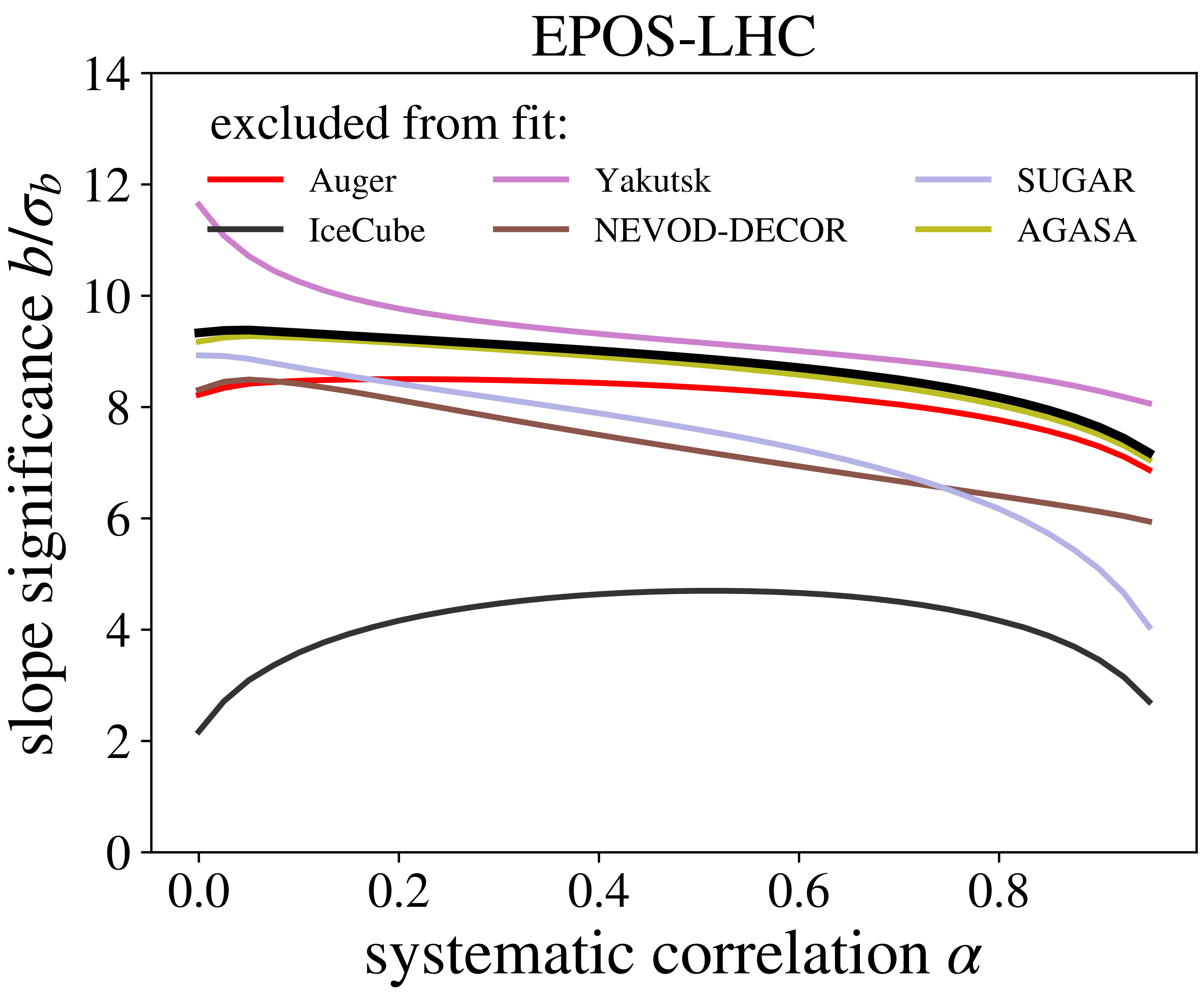
- How do the fits change when we remove one experiment at a time?

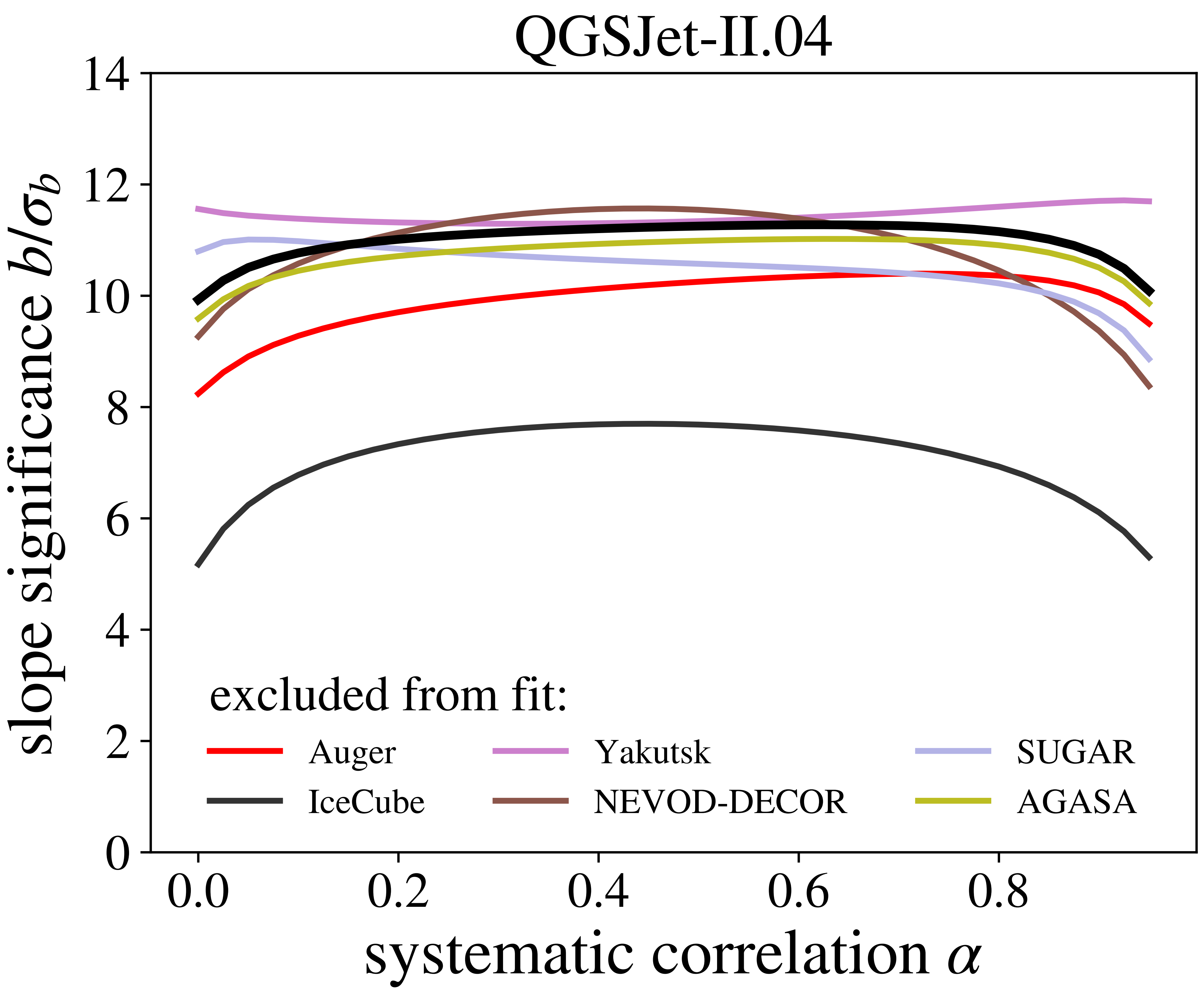


N-1 Tests

[D. Soldin et al., PoS ICRC2021 (2021) 349]

- Significance of the slope when removing one experiment

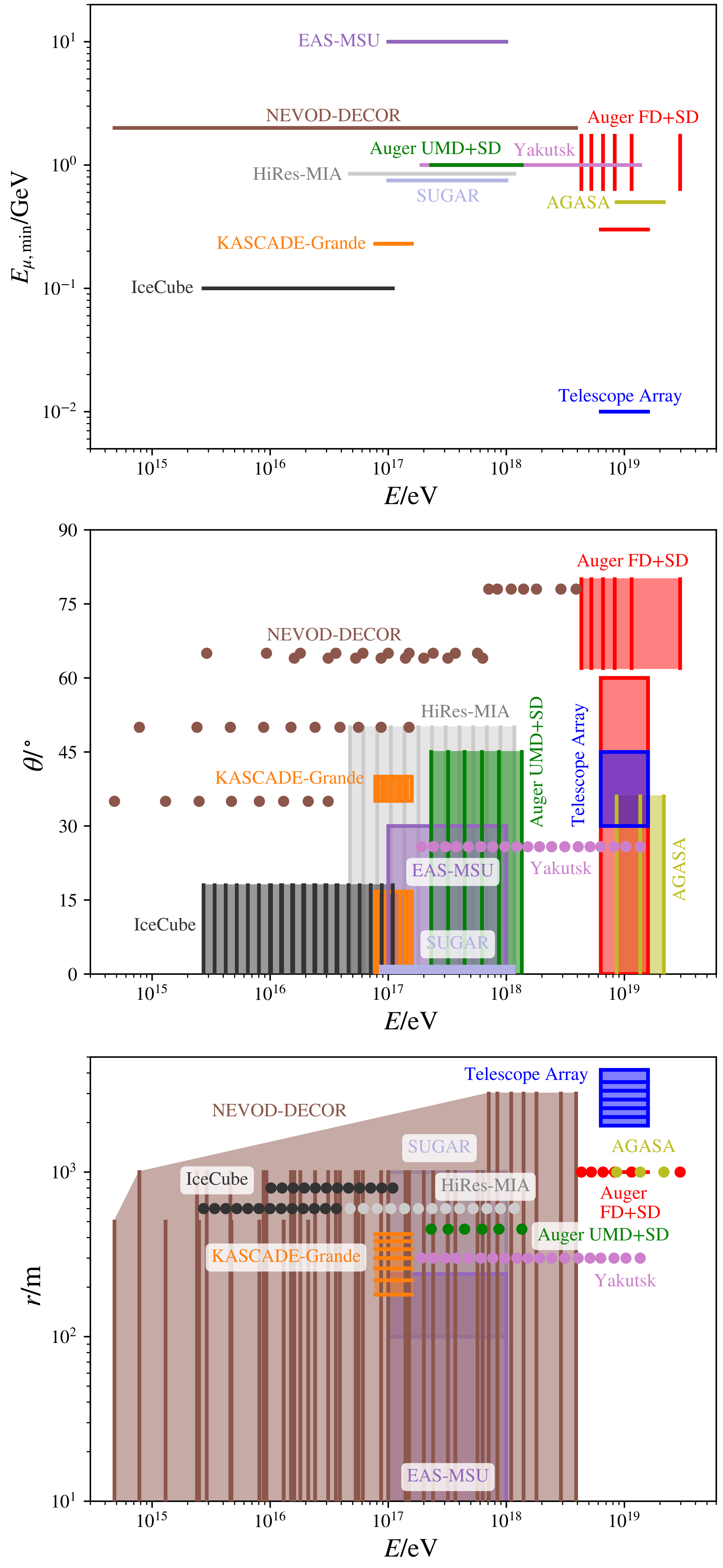




- Decrease of significance without IceCube (also NEVOD-DECOR / SUGAR)
- Yakutsk data becomes more important but is in tension with other measurements

Further Systematic Checks

- Muon energy dependence?
  [L. Cazon et al., PoS ICRC2019 (2020) 214]
  - Different energy thresholds for each experiment
  - Minimum energy required at production: $E_{\mu,\mathrm{prod}} = E_{\mu,\mathrm{min}}(\theta) + E_{\mu,\mathrm{atm}}(\theta)$
  - Fit accounting for this effect: $\Delta z_{\mathrm{fit}} = a + b \cdot \log_{10}(E/10^{16}\mathrm{eV}) + c \cdot E_{\mu,\mathrm{prod}}$
  - Inconclusive due to limited experimental data
- Zenith / atmospheric depth dependence?
  - Evidence for zenith angle discrepancies from KASCADE-Grande
    [KASCADE-Grande Collaboration, Astropart. Phys. 95 (2017)]
  - Inconclusive due to limited experimental data
- Absolute energy reference scale?
  - Constant up or down shift of experimental data in z
  - No change of slope parameter and significance in Δz_{fit}
- More high-precision EAS data and further studies required!



Summary & Conclusions

- Linear fit, Δz_{fit}, finds significant ($> 7\sigma$) non-zero slope of muon excess in data
- <u>N-1 tests:</u>
  - Fits stable when removing most experiments
  - Strong effects when removing IceCube (NEVOD-DECOR / SUGAR)
- Better understanding of systematic uncertainties of individual experiments needed
- <u>Next steps:</u>
  - Comparison to optical composition measurements (i.e. X_{max}) under investigation
  - Include updated KASCADE-Grande data
  - Paper in preparation
- <u>Ongoing/future detector upgrades:</u> (e.g. AugerPrime, IceCube-Gen2, GCOS, see talk by F. Schröder)
  - Reduced systematic uncertainties
  - More high-precision muon data, additional observables

Summary & Conclusions

- Linear fit, Δz_{fit}, finds significant ($> 7\sigma$) non-zero slope of muon excess in data
- N-1 tests:
  - Fits stable when removing most experiments
  - Strong effects when removing IceCube (NEVOD-DECOR / SUGAR)
- Better understanding of systematic uncertainties of individual experiments needed

Highly inclusive working group: Any (new or old) muon data is very welcome!
(e.g. latest addition AGASA data)

- Ongoing/future detector upgrades: (e.g. AugerPrime, IceCube-Gen2, GCOS, see talk by F. Schröder)
  - Reduced systematic uncertainties
  - More high-precision muon data, additional observables

Thank you!