International Cosmic Ray Conference 2021

Update on the Combined Analysis of Muon Measurements from Nine Air Shower Experiments

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(Working Group for Hadronic Models and Shower Physics - WHISP)

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Introduction

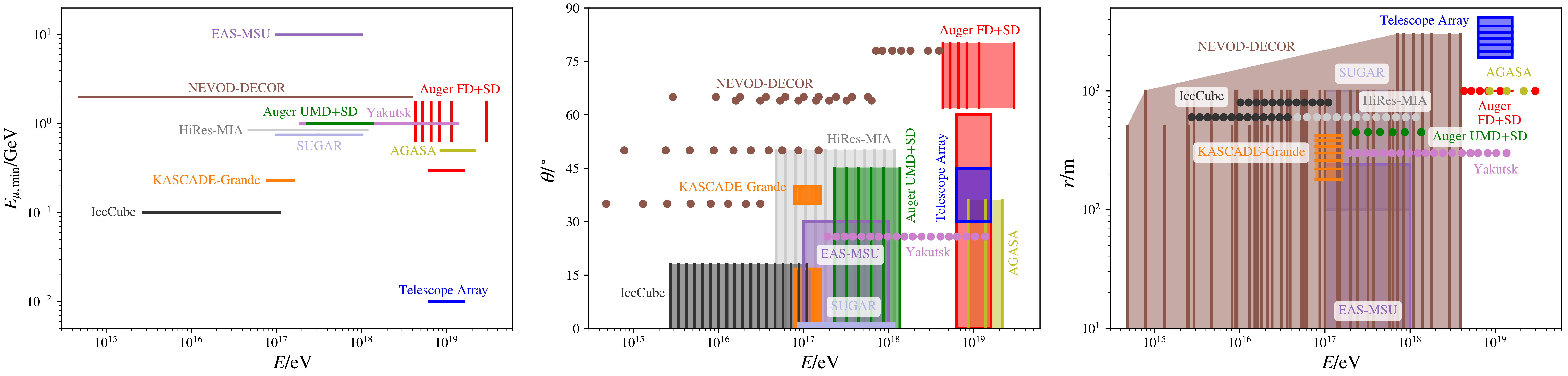
- Systematic comparison of measurements of the muon lateral density in extensive air showers (EAS) from 9 experiments
  - Working Group for Hadronic Models and Shower Physics (WHISP)
- This talk: Update of the meta-analysis previously reported by the WHISP (UHECR2018/ICRC2019) [H.P. Dembinski et al., EPJ Web Conf. 210 (2019)] [L. Cazon et al., PoS(ICRC2019)214]
  - Updated data from the Pierre Auger Observatory
  - Updated data from the IceCube Neutrino Observatory
  - Data from AGASA for the first time
- Systematic statistical analysis of the combined muon measurements
- New systematic checks…

WHISP Meta-Analysis

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

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

  - 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



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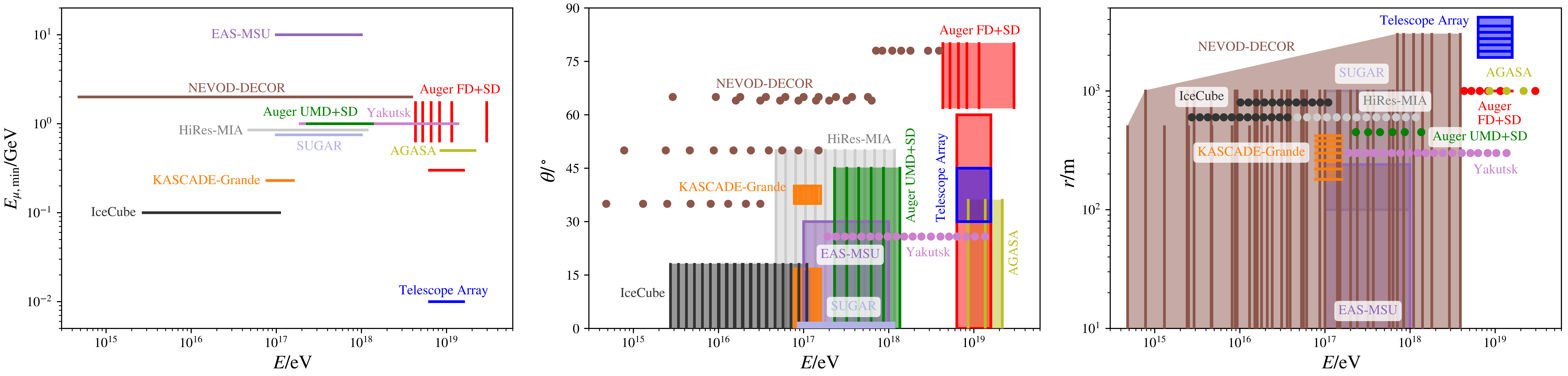
Depends on hadronic interaction models!



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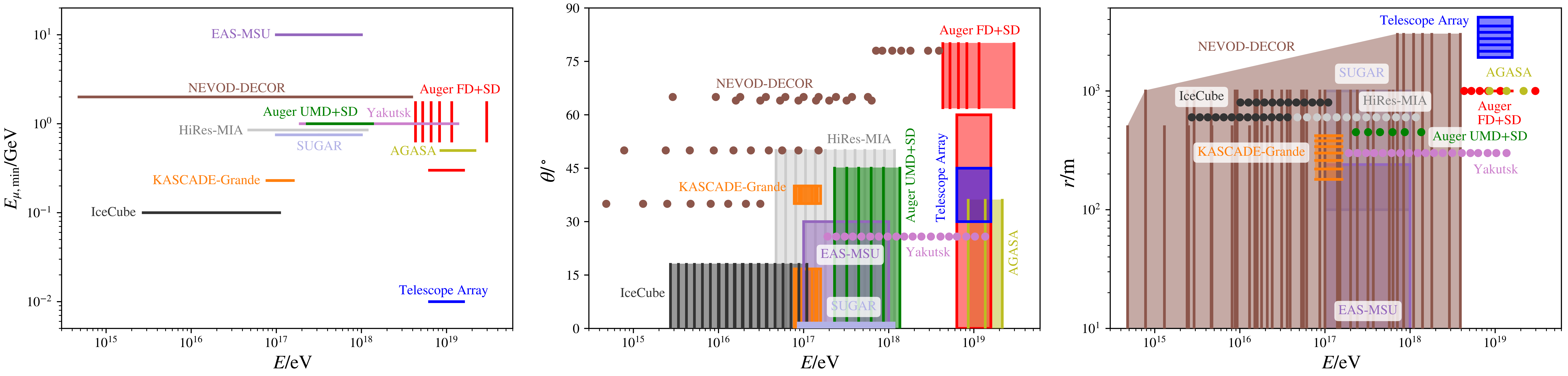
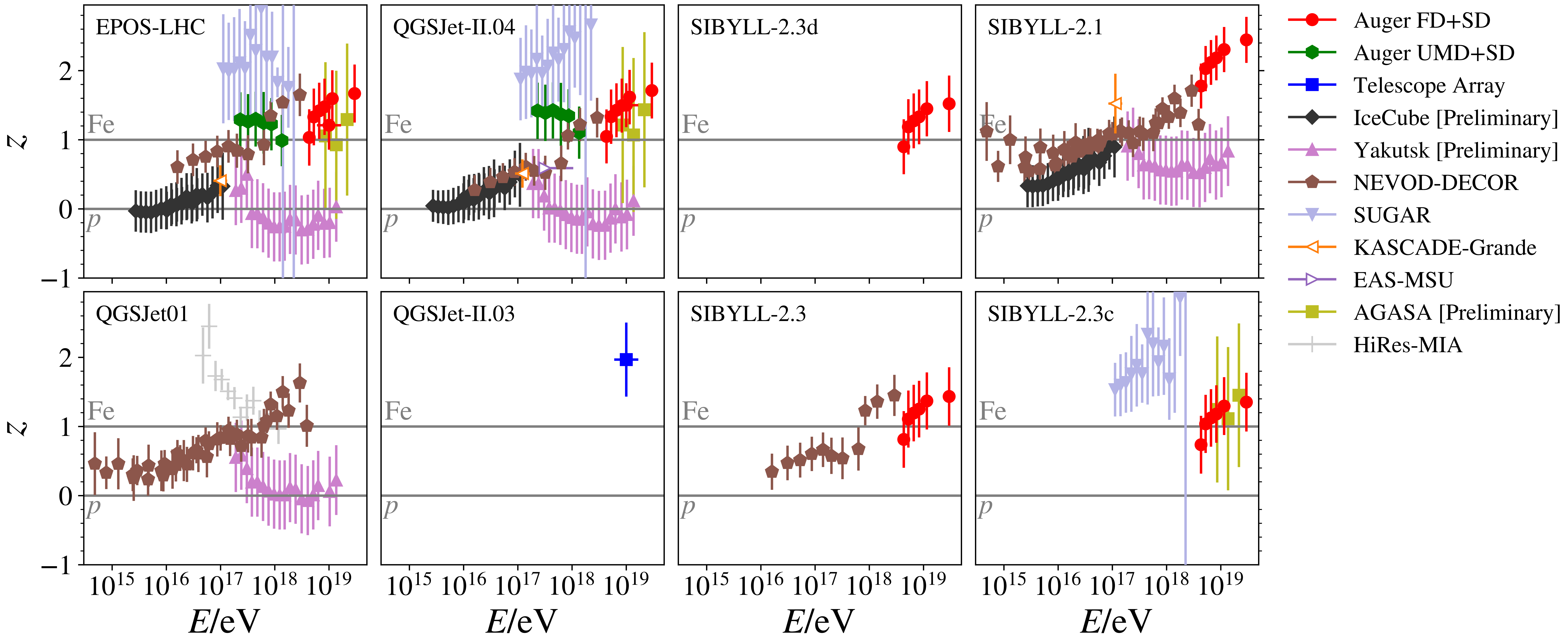


Combined Muon Measurements

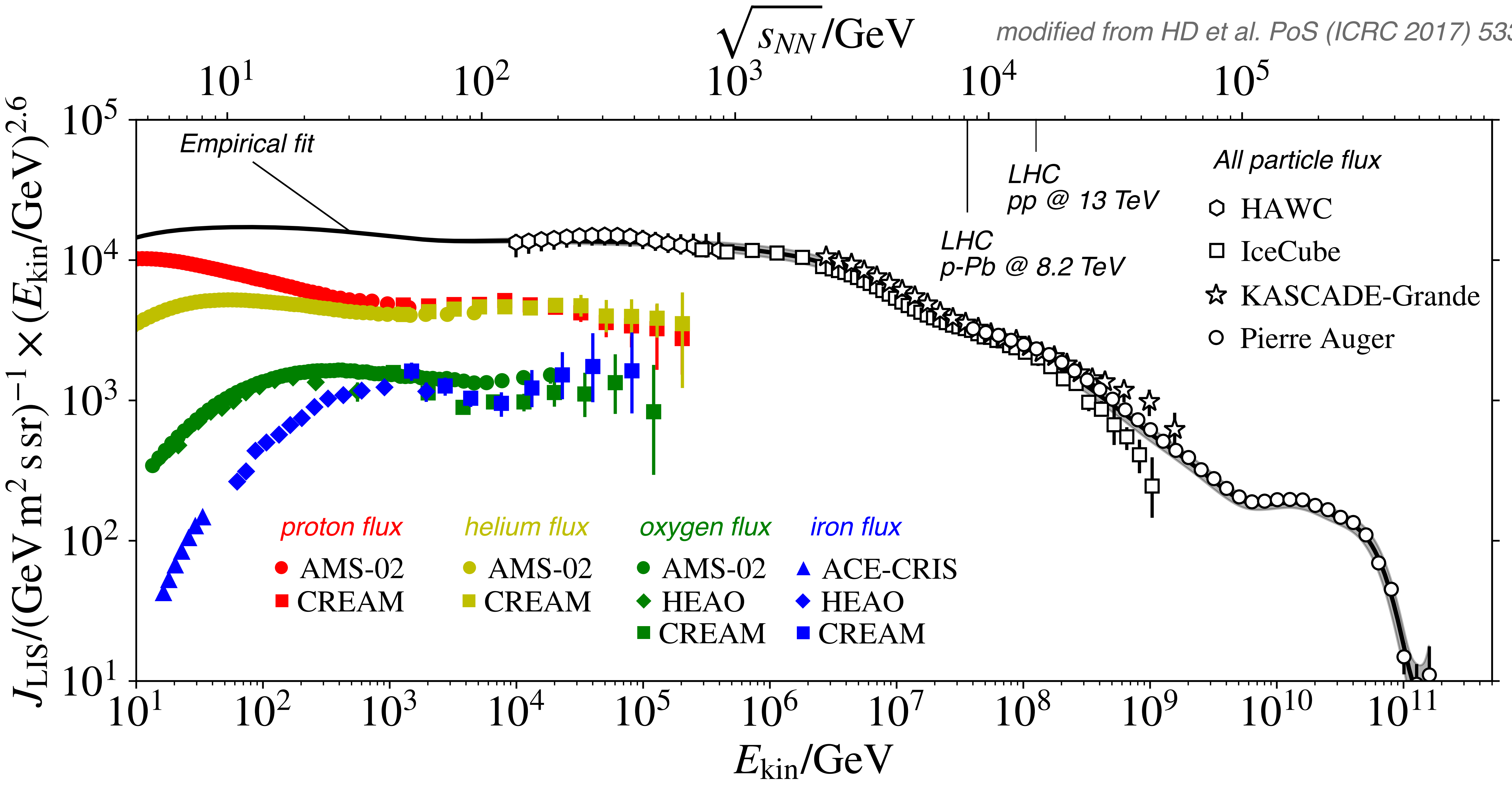
- Muon lateral density in EAS as reported by 9 experiments

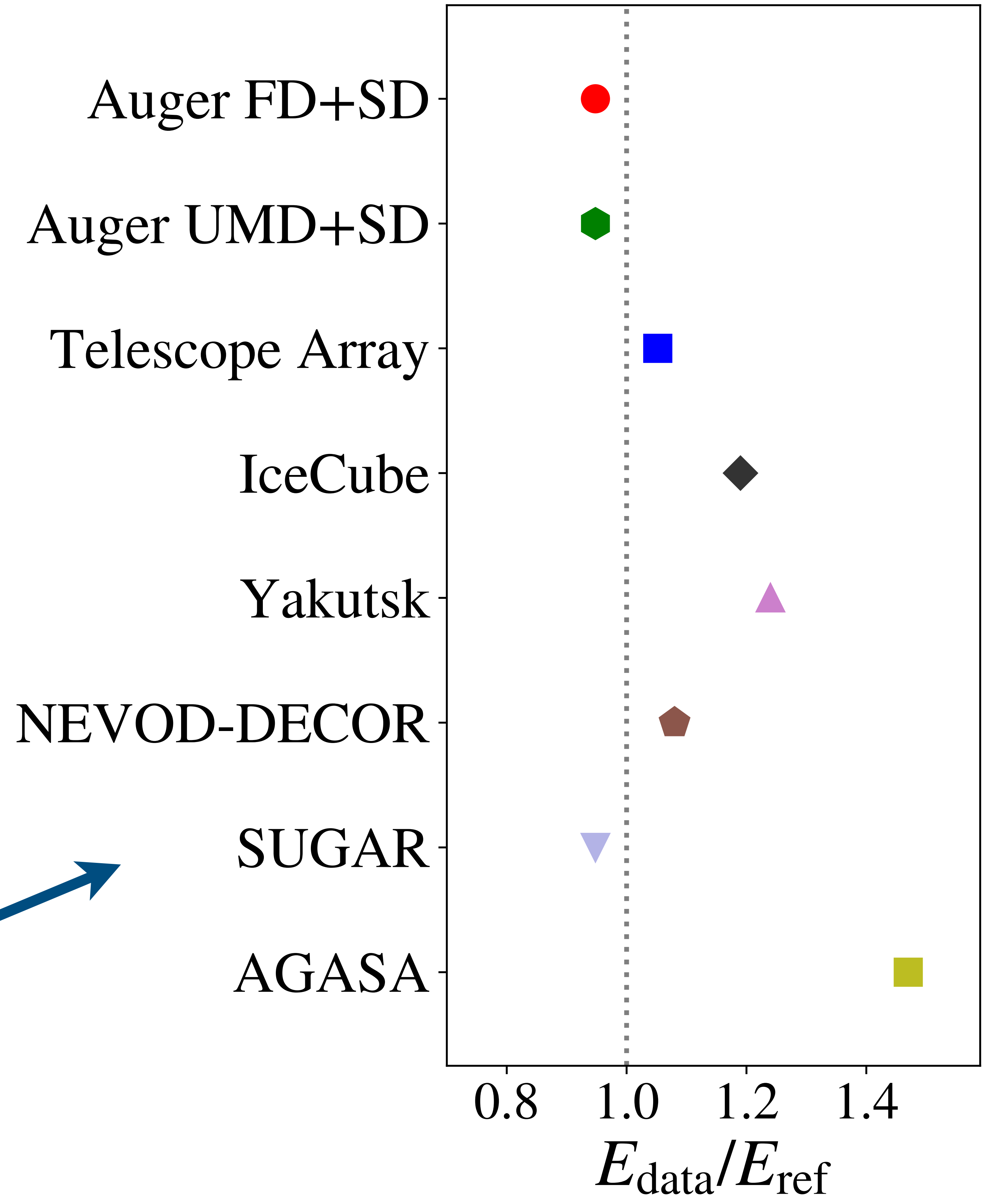


Energy-Rescaling

- 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)

modified from HD et al. PoS (ICRC 2017) 533

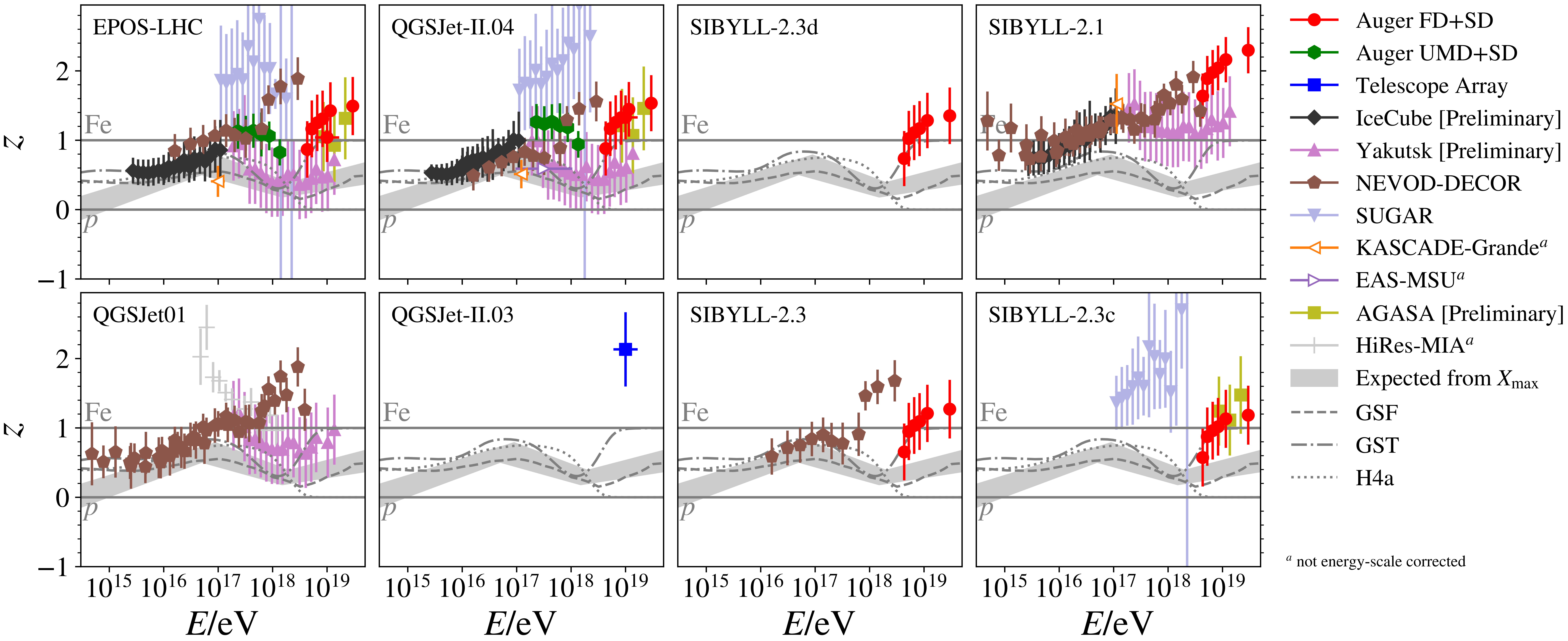




[H.P. Dembinski et al., PoS(ICRC2017)533]

Energy-Rescaled Muon Measurements

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



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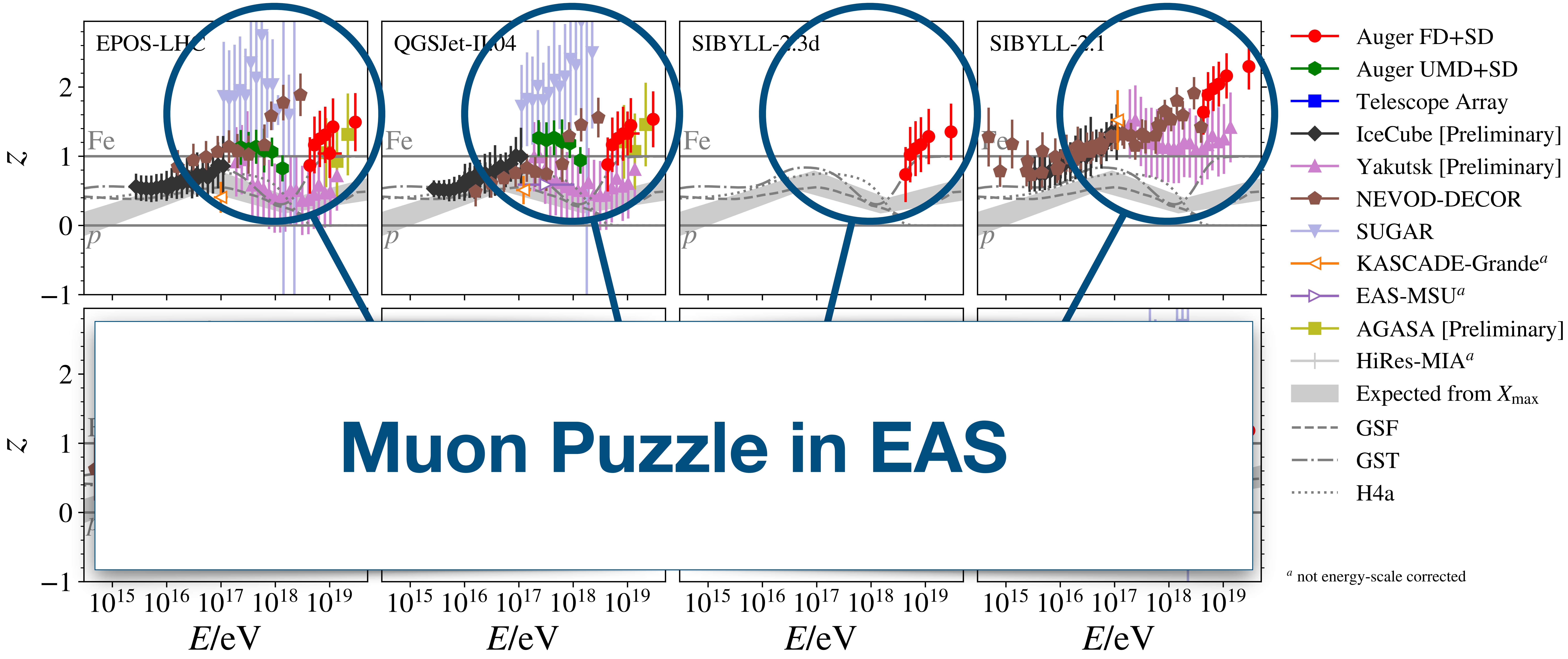
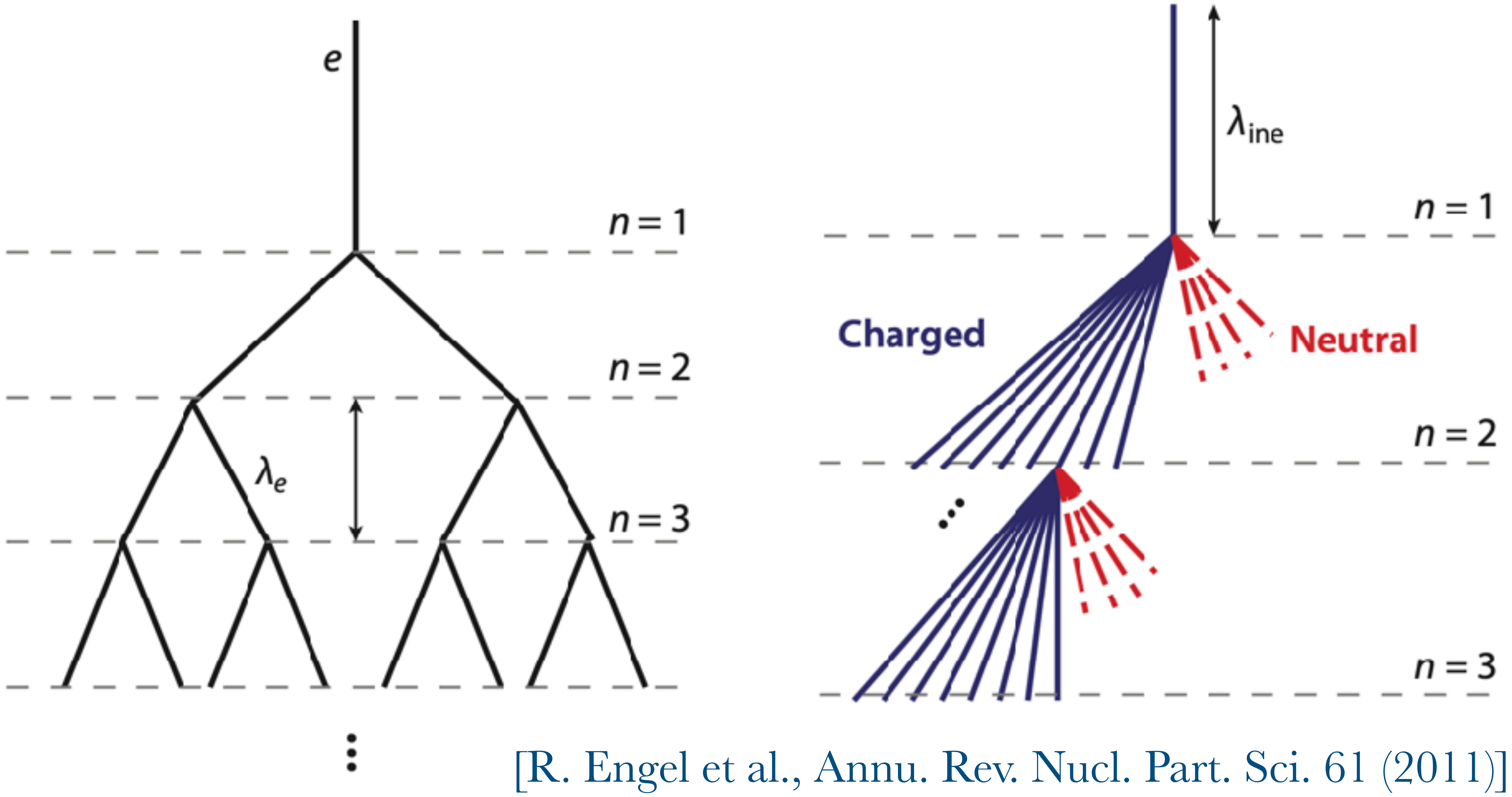


Mass Dependence

- Number of muons is described by the <u>Heitler-Matthews model:</u>

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

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

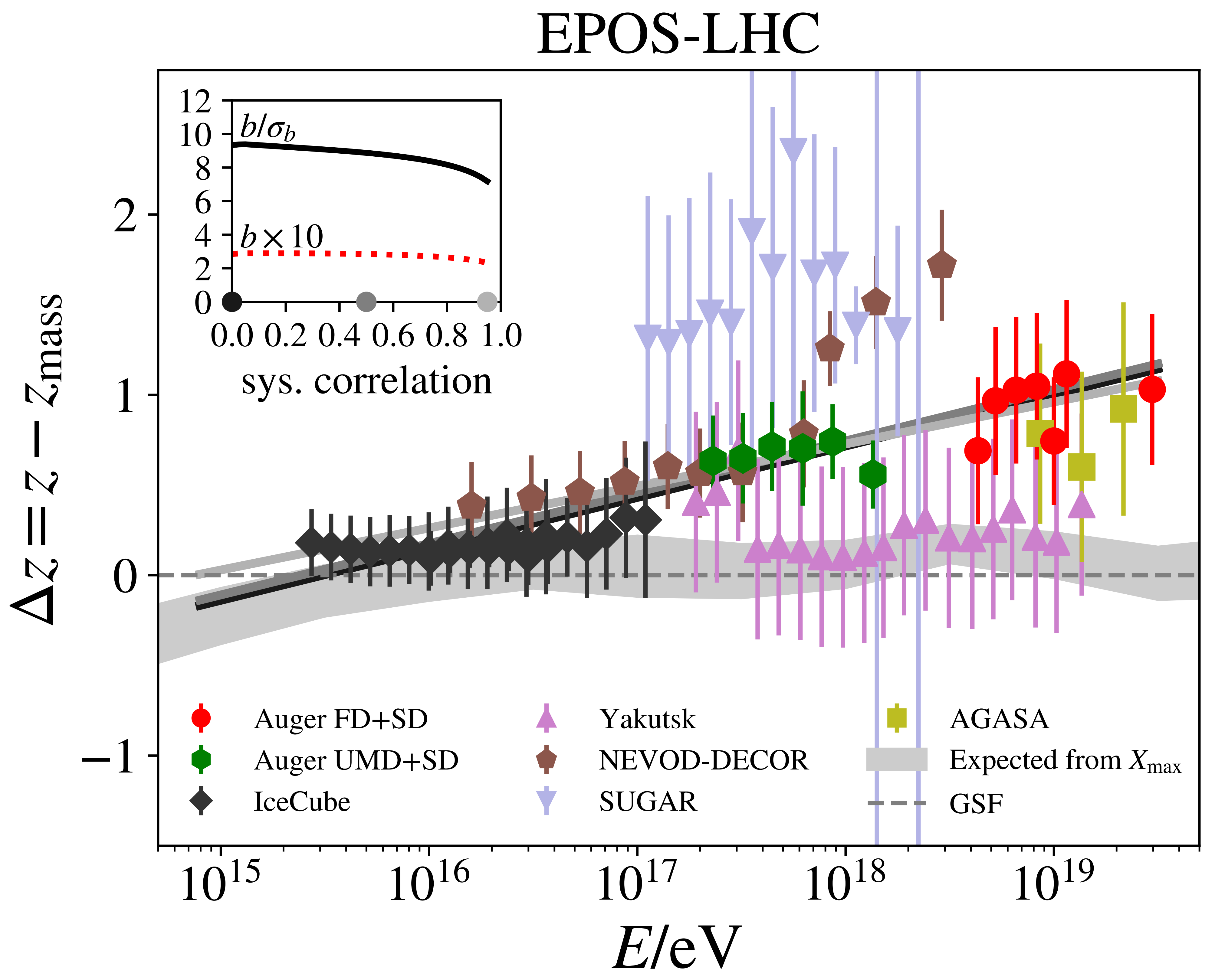


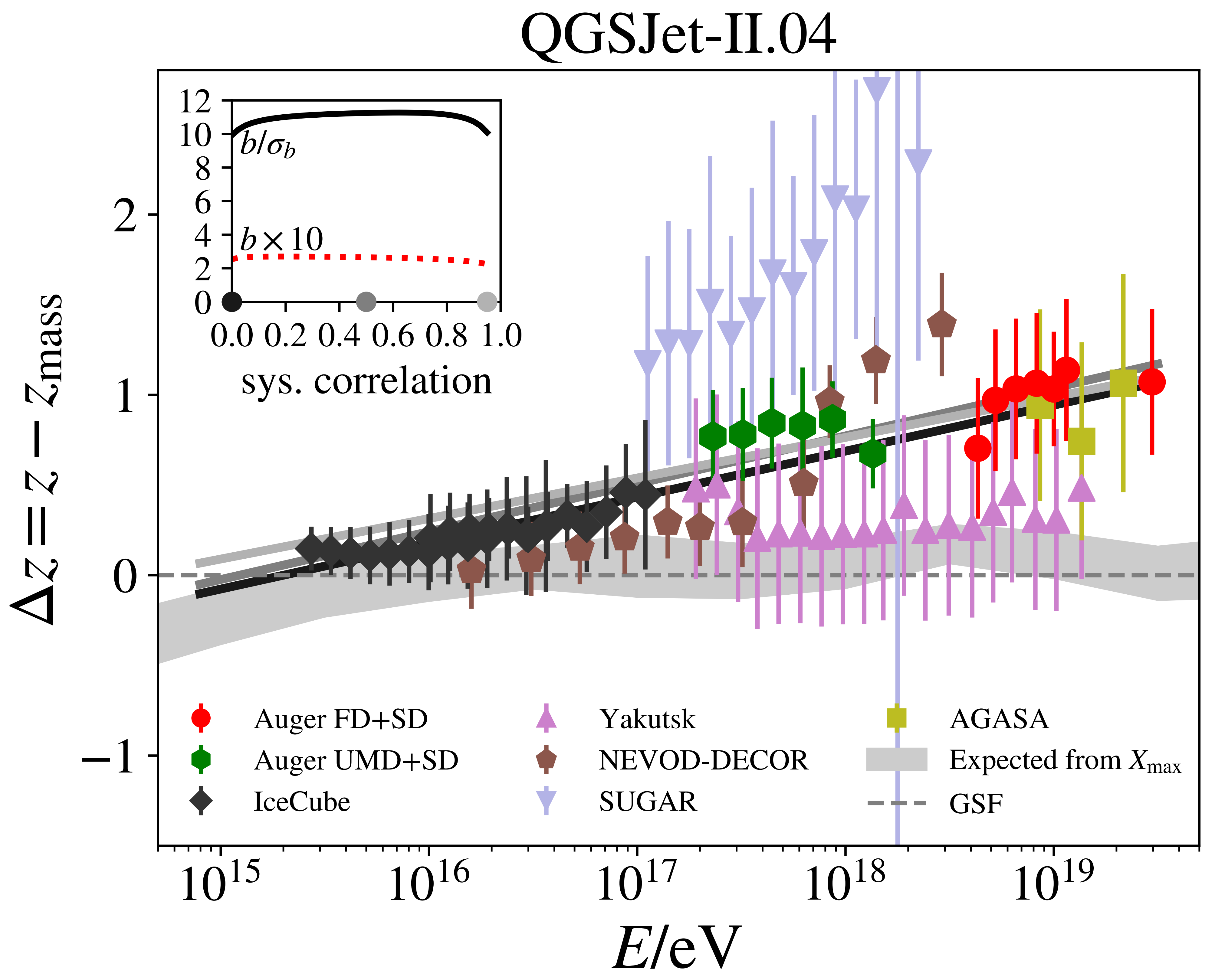
[R. Engel et al., Annu. Rev. Nucl. Part. Sci. 61 (2011)]

- When studying the energy-dependent trend in the muon measurements, the <u>cosmic ray mass need to be taken into account!</u>

- 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"

Mass-Corrected z-Scale

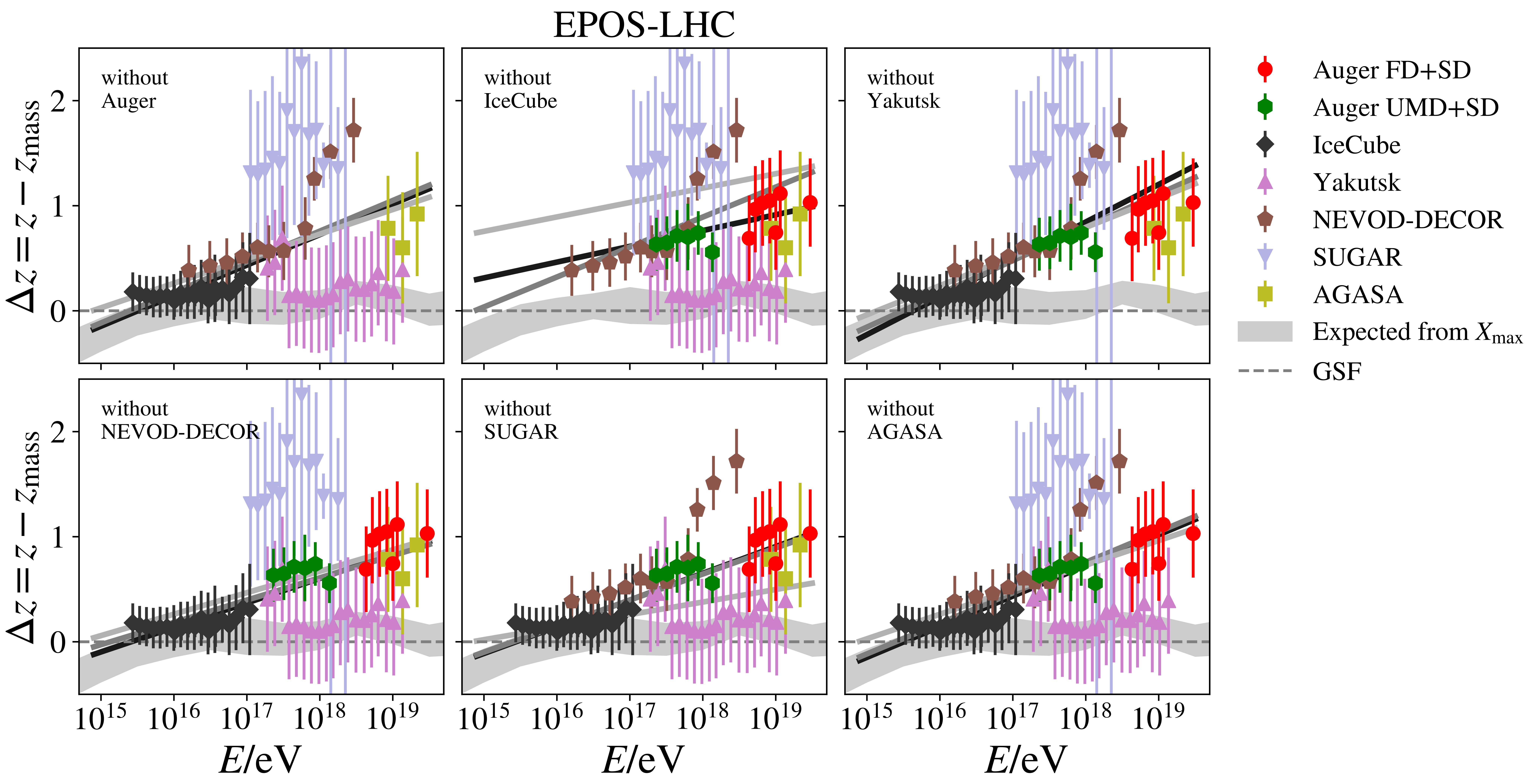




- Fit depends on assumption of correlation, α, between systematic uncertainties
- Slope of the fit: $b = 0.23 - 0.29$ (EPOS-LHC), $b = 0.22 - 0.25$ (QGSJet-II.04)
- Significance of the slope: $\sim 7\sigma - 9\sigma$ (EPOS-LHC), $\sim 10\sigma - 11\sigma$ (QGSJet-II.04)

N-1 Tests

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



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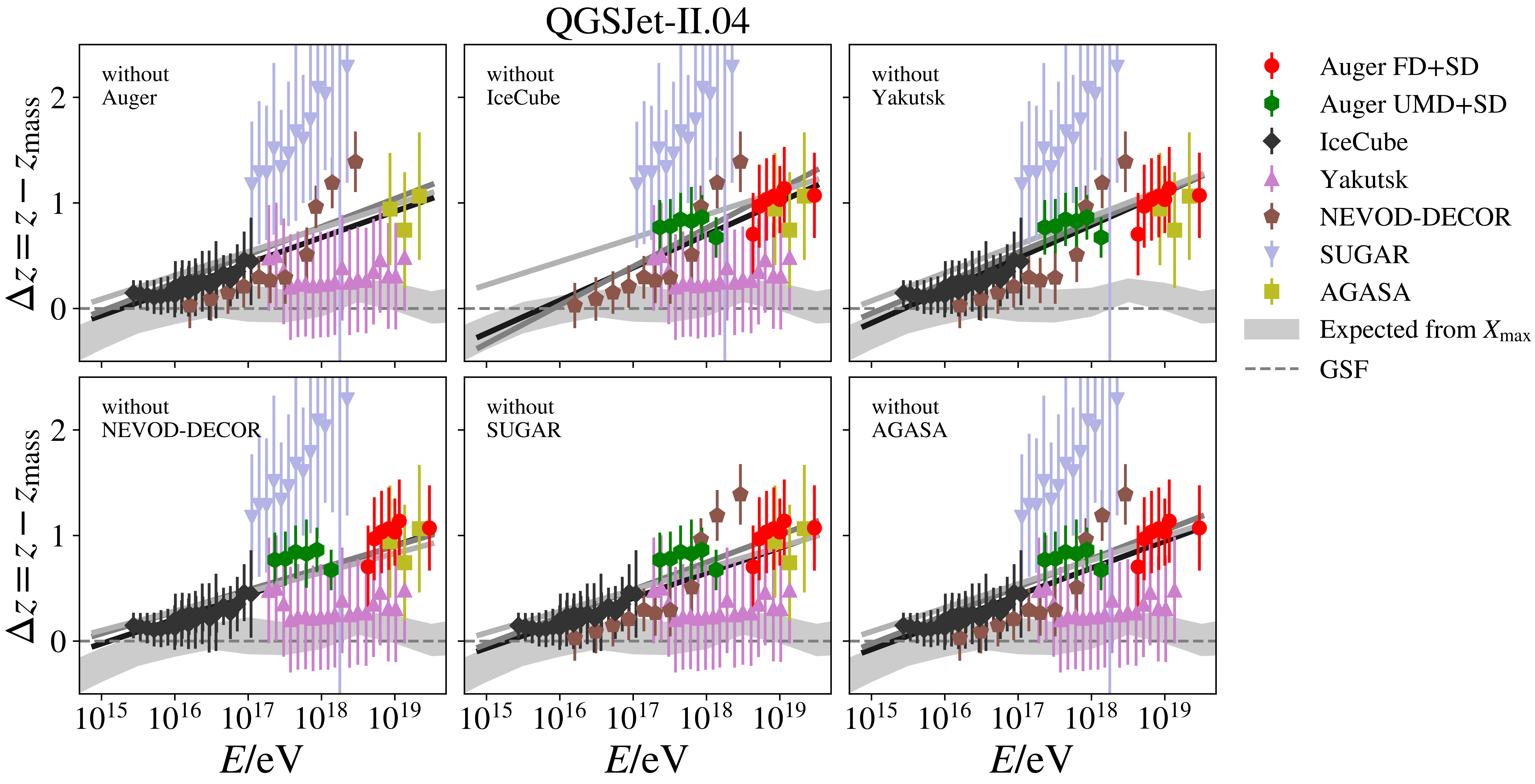
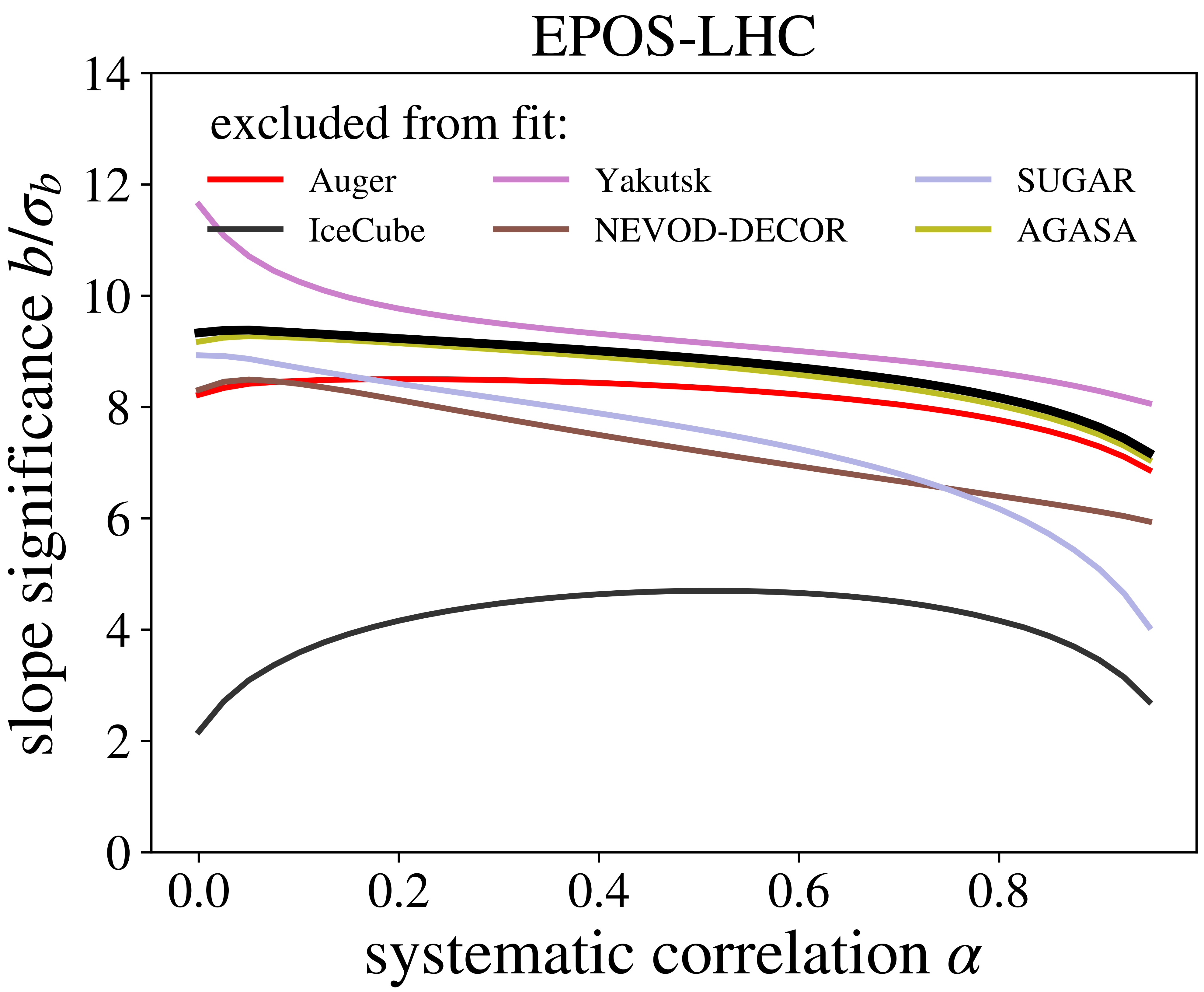
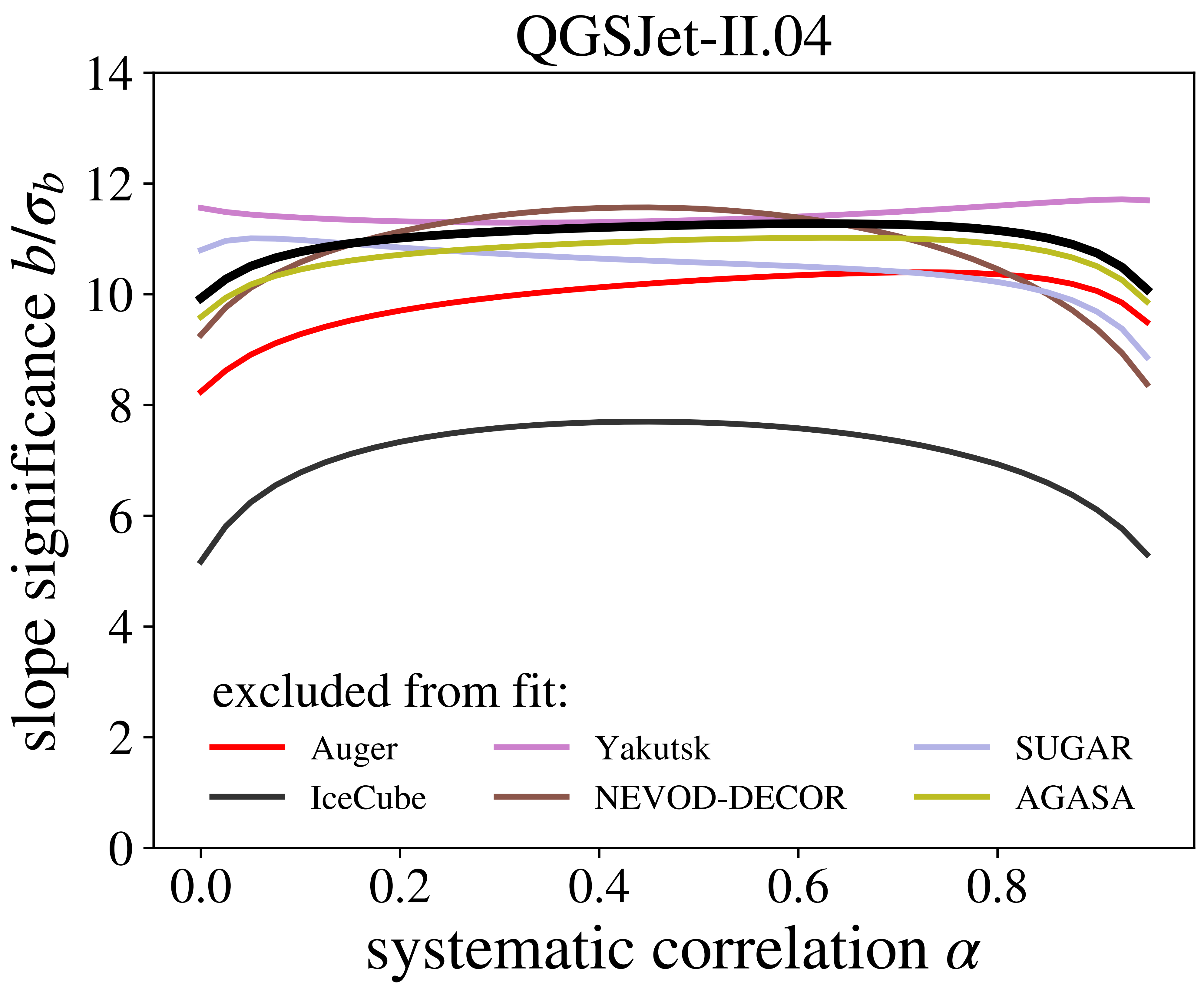


N-1 Tests

- 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

Summary & Conclusions

- Update of WHISP meta-analysis of measurements if the muon content in EAS
- Energy-rescaling and mass subtraction required for comparison
- Linear fit finds significant slope of muon excess in data at ~8/10 sigma level
- N-1 tests:
  - Fits stable when removing most experiments
  - Strong effects when removing IceCube (NEVOD-DECOR / SUGAR)
  - Yakutsk (in strong tension with other measurements) becomes important
- Better understanding of systematic uncertainties of individual experiments needed
- Ongoing detector upgrades:
  - Reduced systematic uncertainties
  - High-precision data
- Comparison to optical composition measurements (i.e. X_{max}) under investigation