Report on the UHECR2018 hadronic interaction WG results

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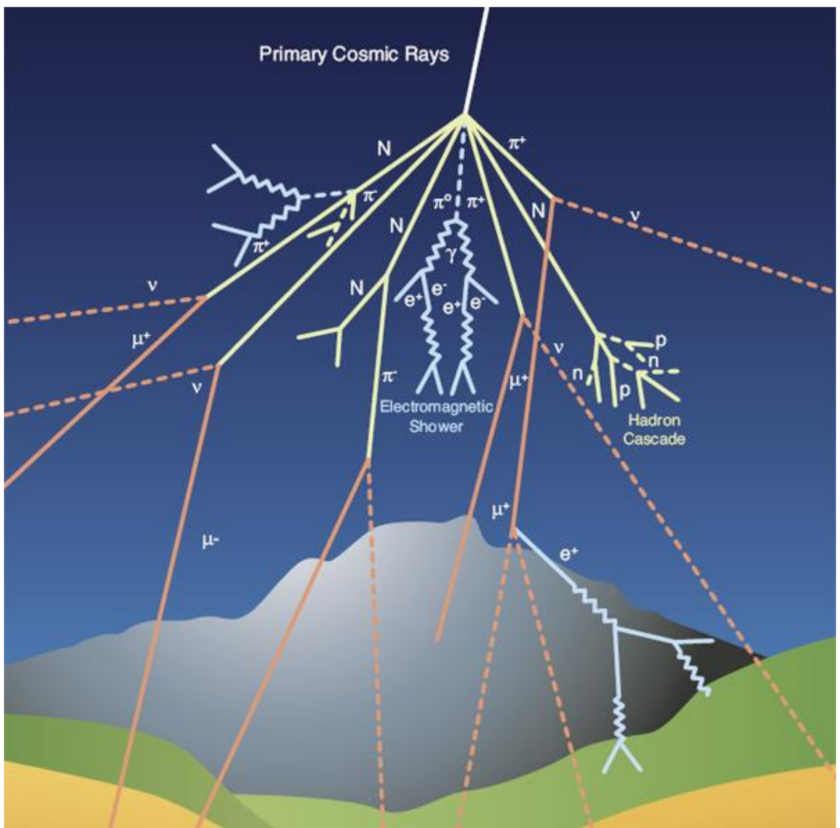
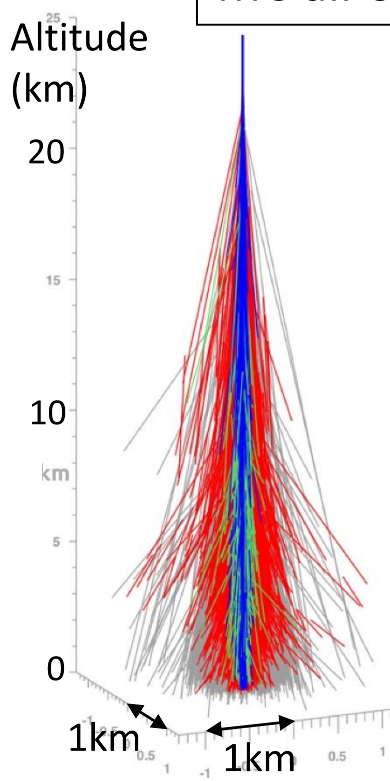
第三回 空気シャワー観測による宇宙線の起源探索勉強会, Mar. 21, 2019

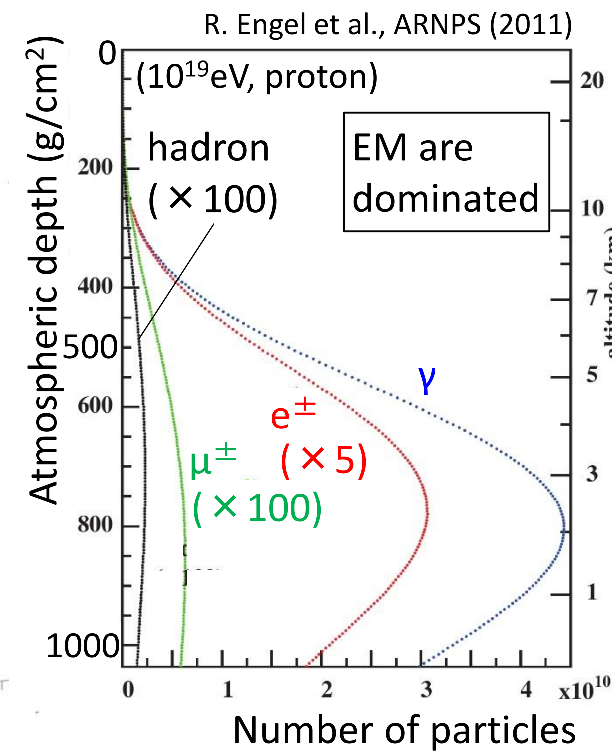
Cosmic ray air shower

- Cascade reaction of primary cosmic rays with atmospheric particles
- Larger energy showers develop deeper in the atmosphere.
- For E >~ 10^{15} eV, electromagnetic (EM) and muon components are generated from $\pi^{\pm}$ and π^{0} and reach the ground.



MC air shower propagation



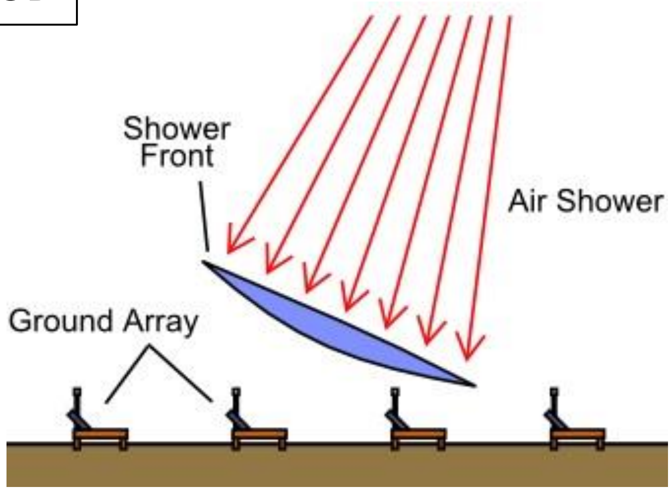


Method of air shower observation

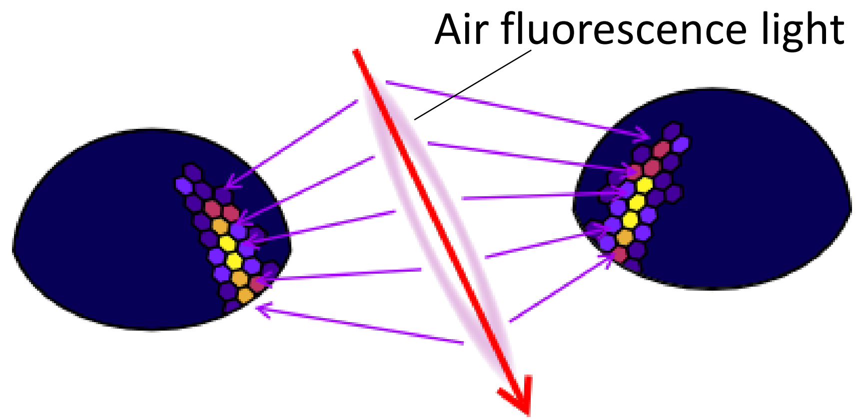
- Using air shower signals and MC, spectrum and arrival direction of primary cosmic rays are reconstructed.

Surface detector (SD) : measures EM（e・γ）and muon components on the ground
Fluorescence detector (FD) : measures fluorescence light generated by EM component in the atmosphere

SD



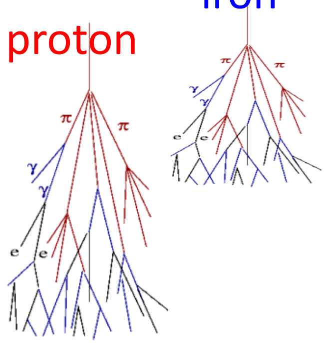
FD



Uncertainty in air shower observation

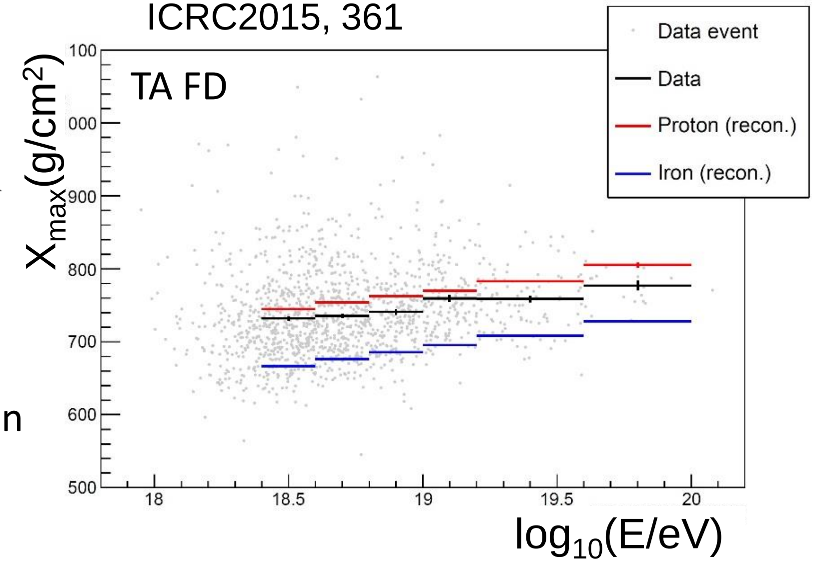
- UHECR energy (>10^{18}eV) is beyond accelerator experiments.
- Hadronic interaction models of MC utilize extrapolated values from lower energy data for cross section, multiplicity etc.
- Air showers are not fully understood and composition results has uncertainty in hadronic interaction models.

Mass composition is estimated by the depth of air shower maximum (X_{max})

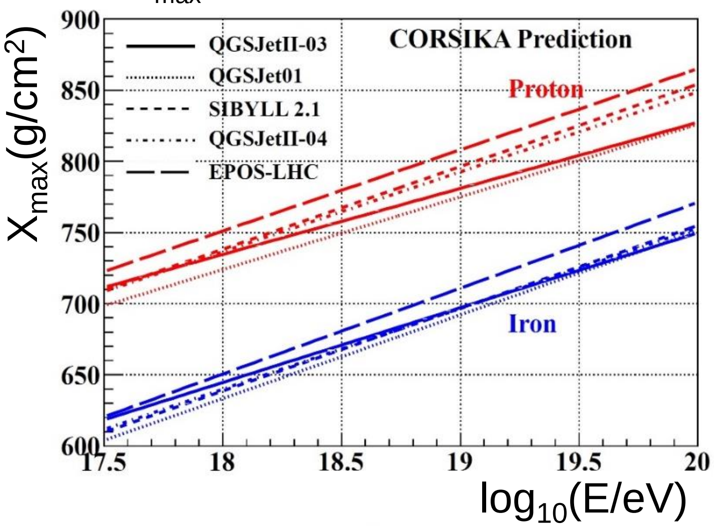


Lighter composition develops deeper at same energy

ICRC2015, 361



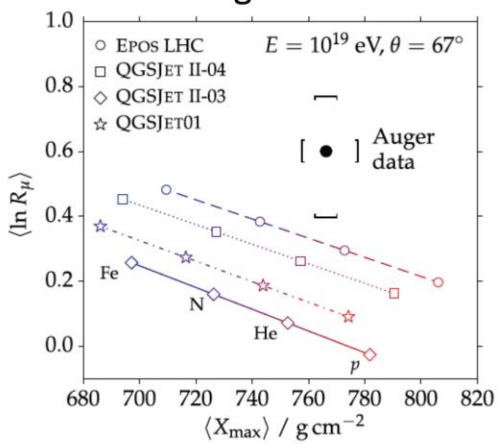
<X_{max}> in each hadronic model



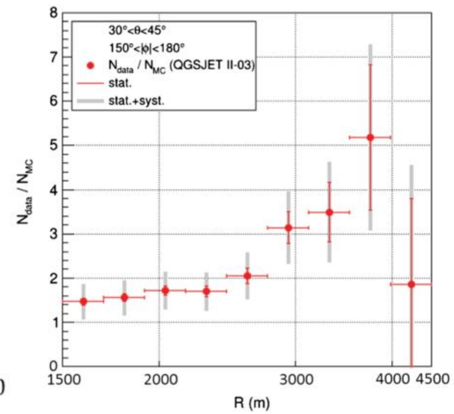
Muon excess issue

- Air shower muons are measured by different experiments.
- Several air shower experiments reported a discrepancy in muon densities between data and MC at energies PeV-EeV.

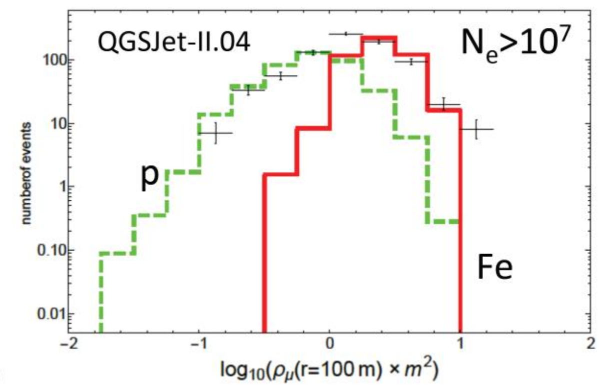
Pierre Auger



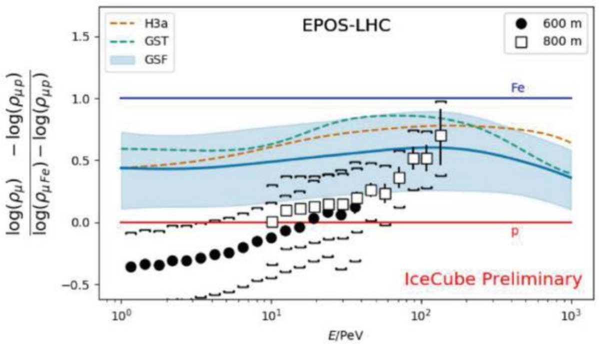
Telescope Array



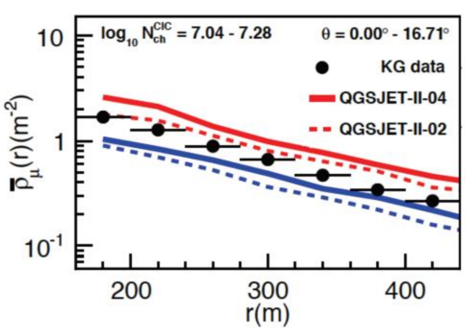
EAS-MSU



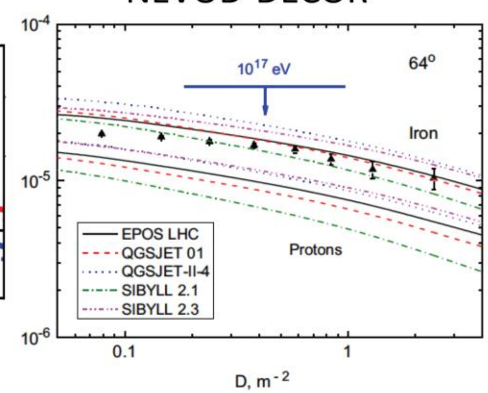
IceTop



KASCADE-Grande



NEVOD-DECOR



Study of muons from air showers

- Composition uncertainty, muon excess issue

  → Present hadronic models do not fully reproduce air showers.

- It is useful to compare the measured number of muons with the MC prediction for improving hadronic interaction models.

- Here we report combined analysis using 8 air shower experiments.

Combined analysis of muons for 8 air shower experiments

(WG report at UHECR2018 conference)

arXiv: 1902.08124

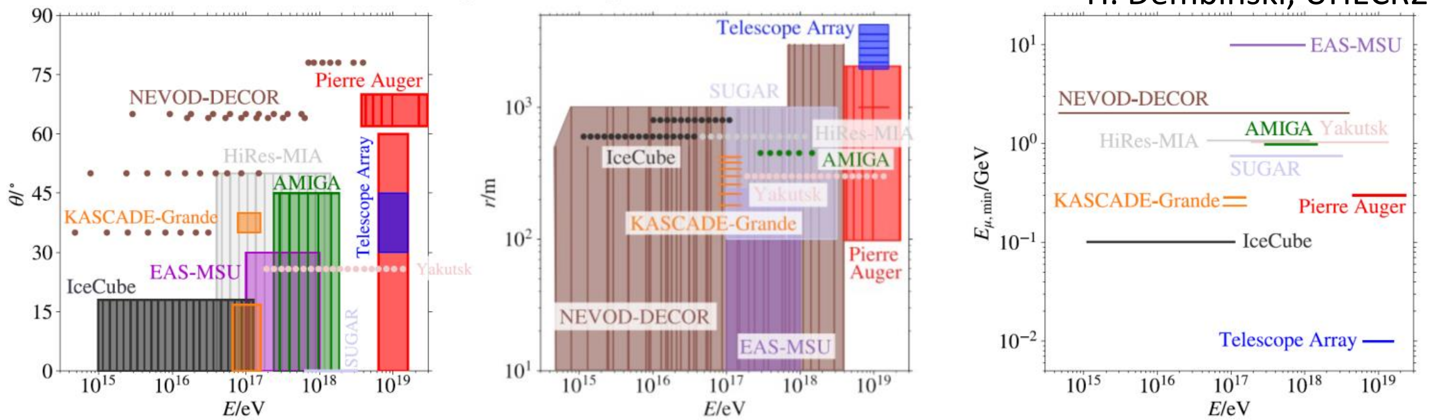
Study of muons for 8 air shower experiments

- We compared muon density data with the MC for eight leading air-shower experiments at E >~10^{15} eV.

Muon density measurement condition on various experiments

lines & boxes: result integrated over range

H. Dembinski, UHECR2018



E = 0.5 PeV ... 20 EeV **θ** = 0 ... 78 deg **r** = 0 ... 4 km $\mathbf{E_{\mu,threshold}}$ = 0.01 ... 10 GeV

Pierre Auger	AMIGA preliminary: S. Müller poster ID 204; PRL 117 (2016) 192001; PRD 91 (2015) 032003
Telescope Array	PRD 98 (2018) 022002
IceCube	ISVHECRI 2018 preliminary
KASCADE-Grande	Astropart. Phys. 95 (2017) 25
NEVOD-DECOR	Phys. Atom. Nucl. 73 (2010) 1852, Astropart. Phys. 98 (2018) 13
SUGAR	PRD 98 (2018) 023014
EAS-MSU	Astropart. Phys. 92 (2017) 1
Yakutsk	Unpublished preliminary results
HiRes-MIA	PRL 84 (2000) 4276; not part of WG, only included for comparison

Reference scale for muon densities

- Different experiments use different techniques, so we use a same reference scale named z-scale.

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

- N_{μ}^{det} : data muon density measured by the detector
- $N_{\mu,p}^{det}$: proton MC muon density estimated by the detector simulation
- $N_{\mu,Fe}^{det}$: iron MC muon density estimated by the detector simulation

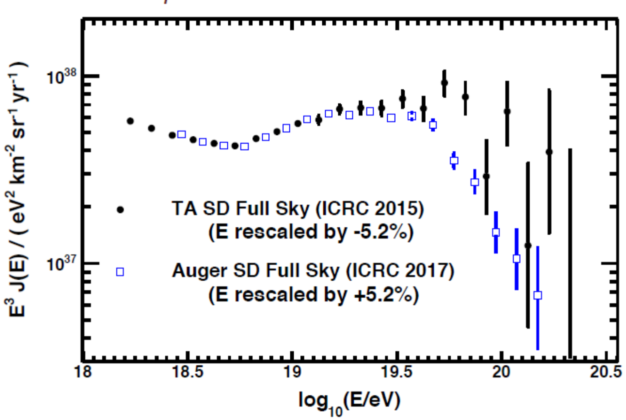
Energy scale cross-calibration

- Number of muons in air showers are larger at larger cosmic ray energy.
- We cross-calibrated energy scale of primary cosmic rays for each experiment. UHECR spectrum WG report and Global Spline Fit (GSF) model are used.

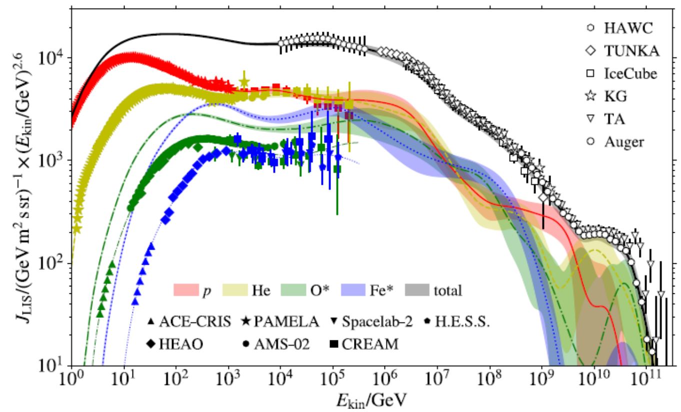
H. Dembinski, UHECR2018

Spectrum WG:	Auger **0.948**	Telescope Array **1.052**		
GSF (matched):	SUGAR **0.948**	KASCADE-Grande **0.95**	IceTop **1.19**	NEVOD-DECOR **1.08**

Spectrum WG



GSF

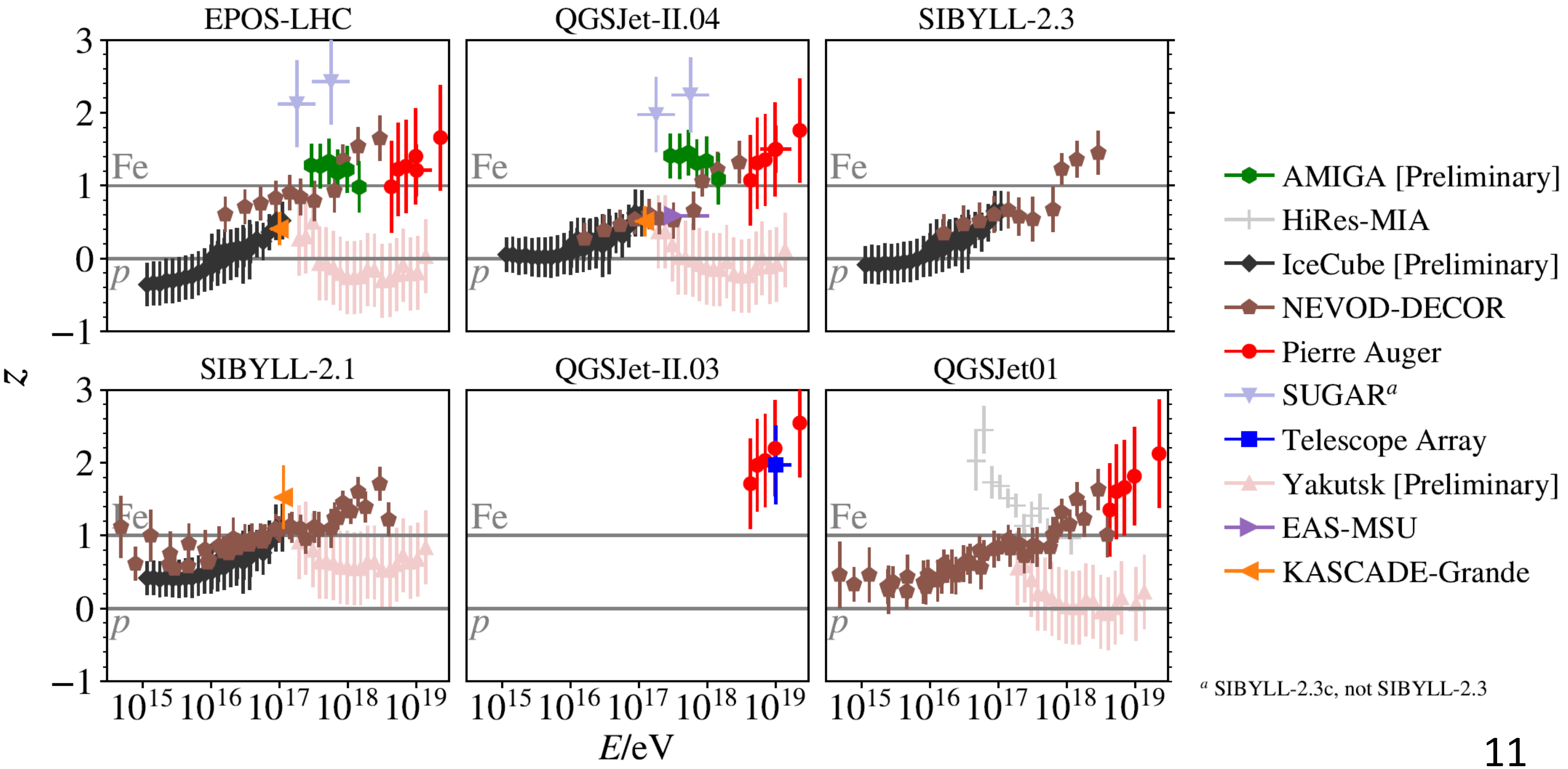


The reference scale is between TA and Auger.

GSF: H. Dembinski, R. Engel, A. Fedynitch, T. Gaisser, F. Riehn, T. Stanev, PoS(ICRC 2017)533

Combined muon measurements

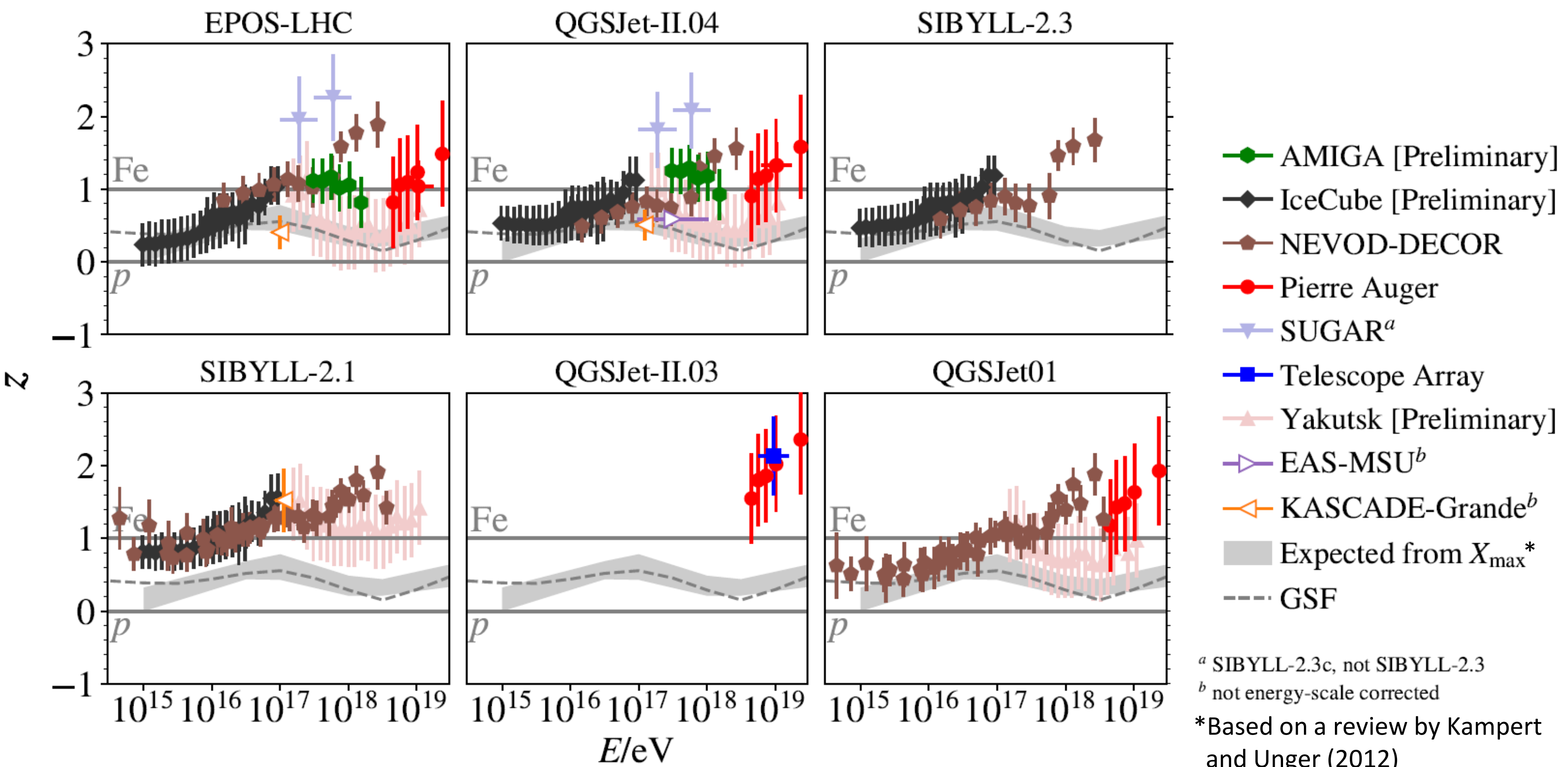
- Cosmic ray energy dependence of z-scale in each experiment
- Six hadronic models are shown (Each experiment uses different model).
- Before energy scale cross-calibration



[a] SIBYLL-2.3c, not SIBYLL-2.3

Combined muon measurements

- After energy scale cross-calibration
- Scatter of the plots is reduced.

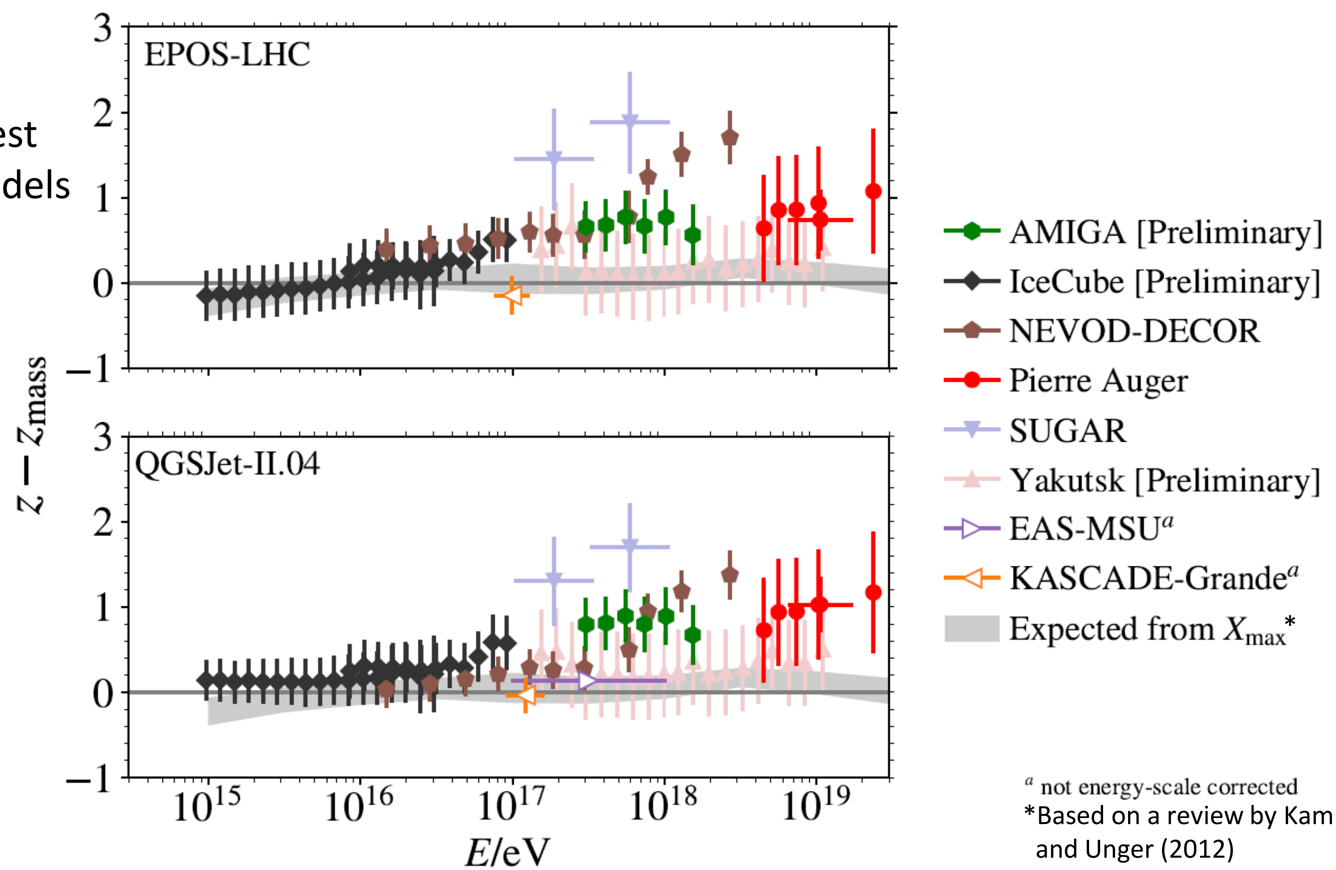


*Based on a review by Kampert and Unger (2012)

Energy-dependent trend

- We subtracted z_{mass} (GSF-model z) from z data plots to remove the effect of changing mass composition.
- Most experiments showed a muon excess in the data to the MC at energies above 10^{16} eV.

Two of the latest generation models are shown.

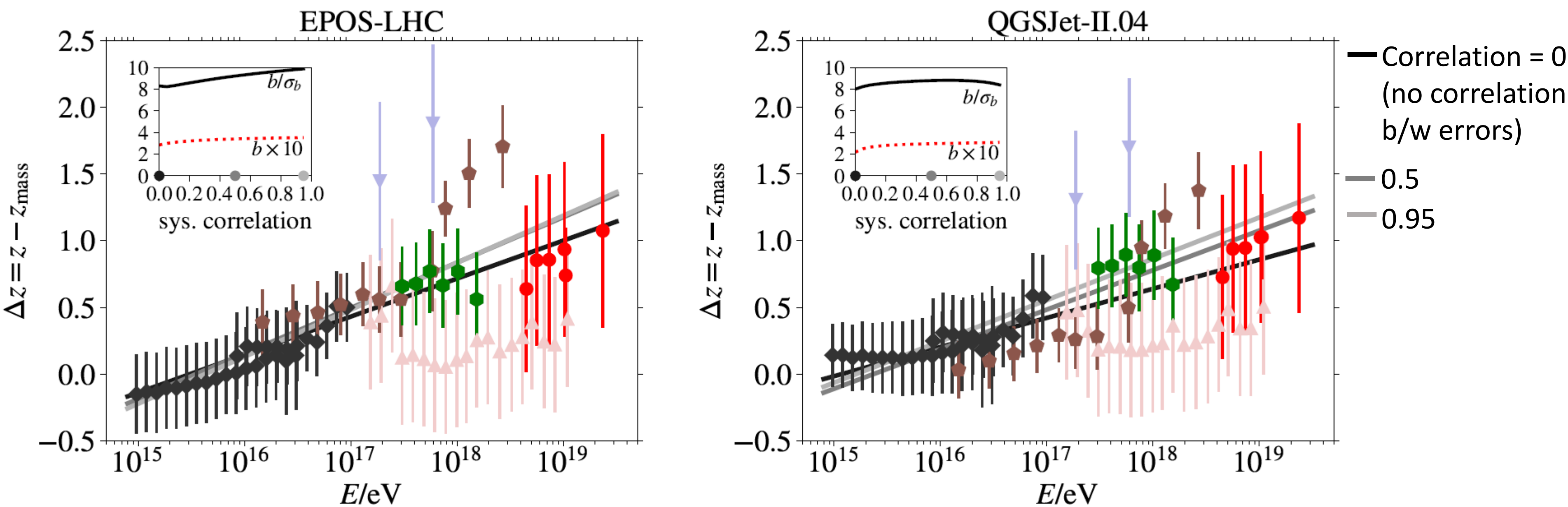


[a] not energy-scale corrected

*Based on a review by Kampert and Unger (2012)

Energy-dependent trend

- Fit the data points with a line: $\Delta z = a + b\,(\log_{10}(E/\mathrm{eV}) - 16)$
- The slope b is 0.22 to 0.35.
- The slope b deviates more than 8 standard deviations from 0.
- Larger muon discrepancy between data and MC at larger energy



Error bars are possibly correlated, so we fit assuming different correlation case.

Discussion

- After energy scale cross-calibration, most experiments seems to have consistent picture, which shows larger muon discrepancy at larger energy.
- Latest-generation hadronic interaction models, EPOS-LHC, QGSJet-II.04, SIBYLL-2.3 showed better agreement with data than others (But there still be muon excess).
- Possible dependence on shower zenith angle, core-distance, muon energy threshold needs to be checked.

Summary

- We compared muon density data with the MC using a reference scale z.
- Most experiments showed a muon excess in the data to the MC at energies above 10^{16} eV.
- The discrepancy increases with the shower energy, and the slope shows 8 sigma significance for the latest-generation models.
- obtained information to improve hadronic interaction models