Working group on Hadronic Interactions and Shower Physics

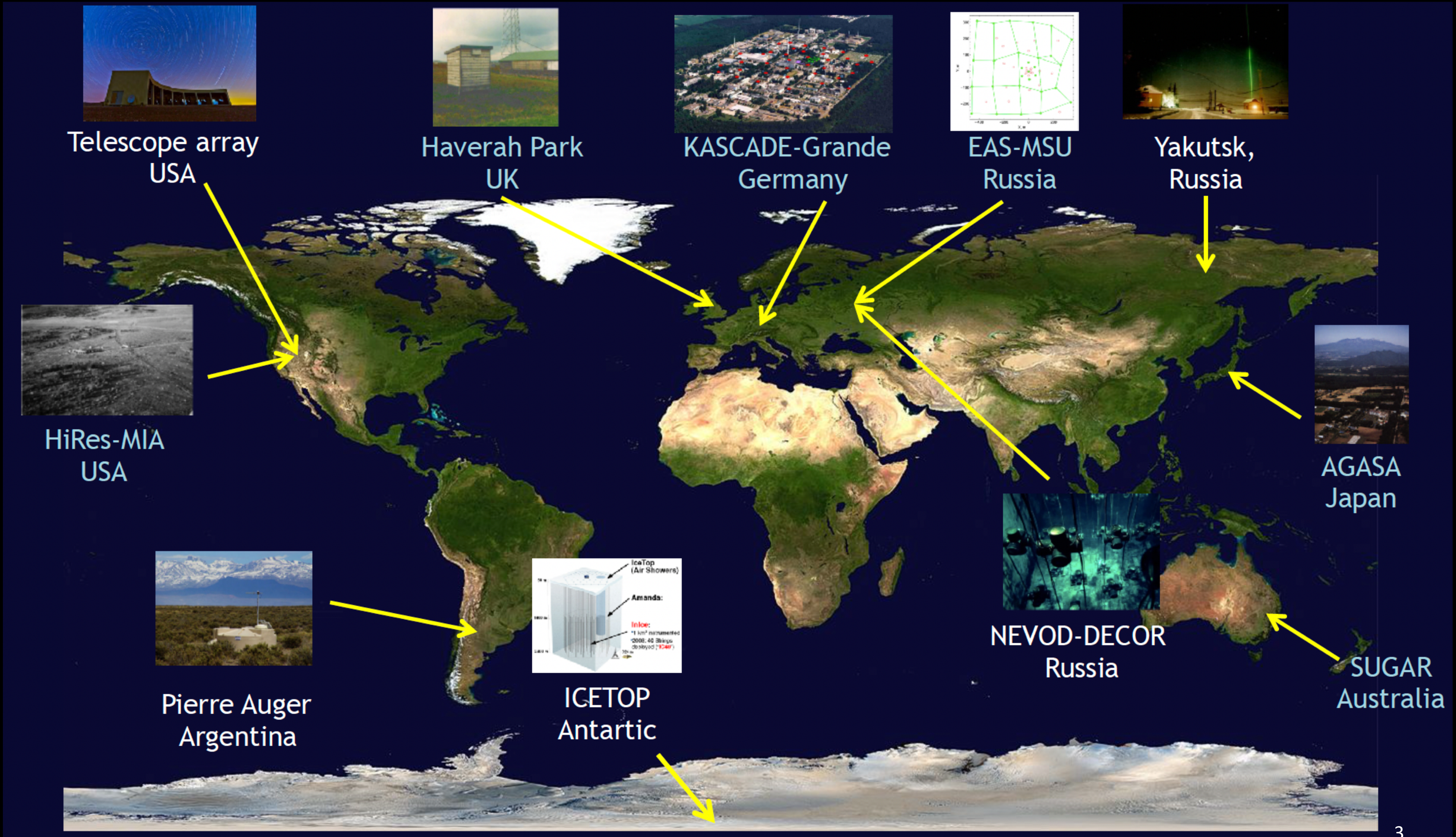
L. Cazon

Workshop on the tunning of hadronic interaction models. 22-25 January 2024, Wuppertal

- WHISP first report during UHECR18
  - Working group on EAS measurements to constraint/measure Hadronic Interactions
- It quickly became solely dedicated to the EAS **muon content/density** at ground
- It extensively compiles* measurement in EAS across experiments
  - Presents them using a universal variable z
  - Corrects for known and well stablished experimental differences (like E-scale)

(*) open debate: Should WHISP take more critical steps regarding the quality of some data sets.

1st report: H.P. Dembinski et al., EPJ Web Conf. 210 (2019) 02004
Major updates in all ICRCs ever since.
Most recent: J. C Arteaga-Velazquez *PoS* ICRC2023 (2023) 466



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

Credit map: NASA.

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

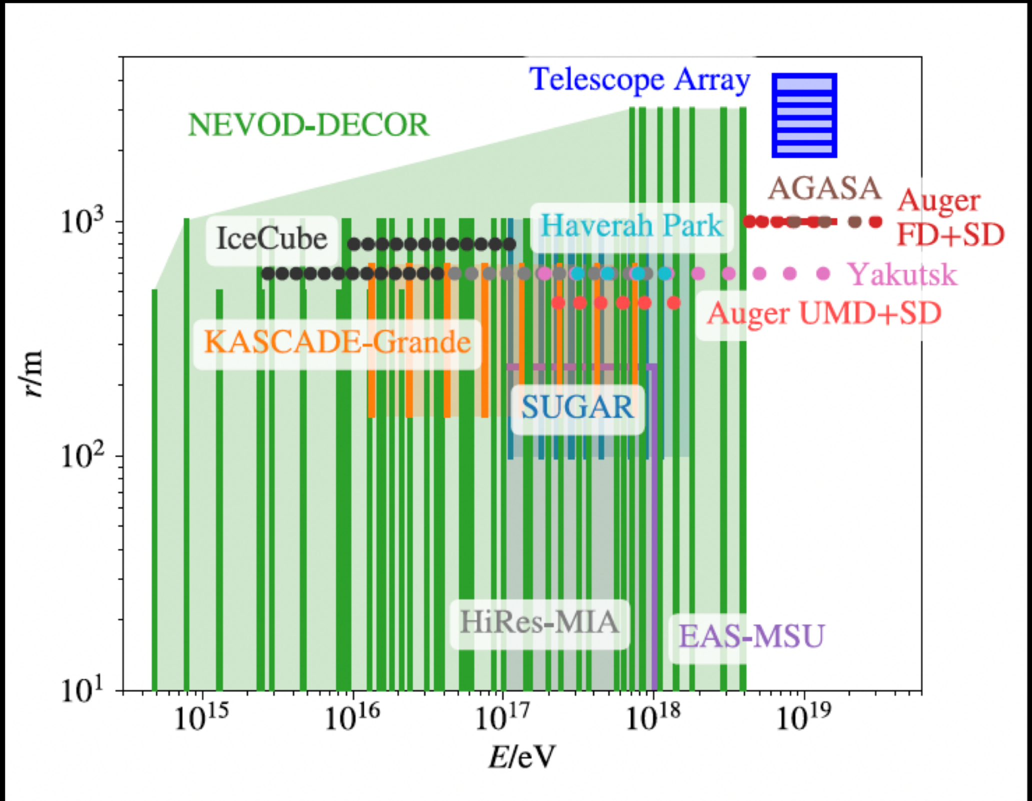
$$z = \frac{\ln\langle N_{\mu}^{\mathrm{det}}\rangle - \ln\langle N_{\mu,\mathrm{p}}^{\mathrm{det}}\rangle}{\ln\langle N_{\mu,\mathrm{Fe}}^{\mathrm{det}}\rangle - \ln\langle N_{\mu,\mathrm{p}}^{\mathrm{det}}\rangle}$$

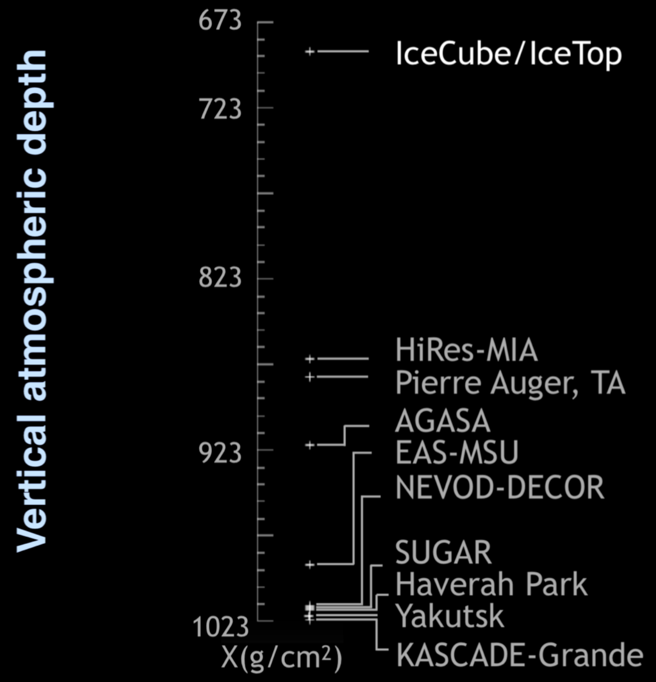
$$z = \begin{cases} 0; & \text{proton} \\ 1; & \text{iron} \end{cases}$$

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

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	

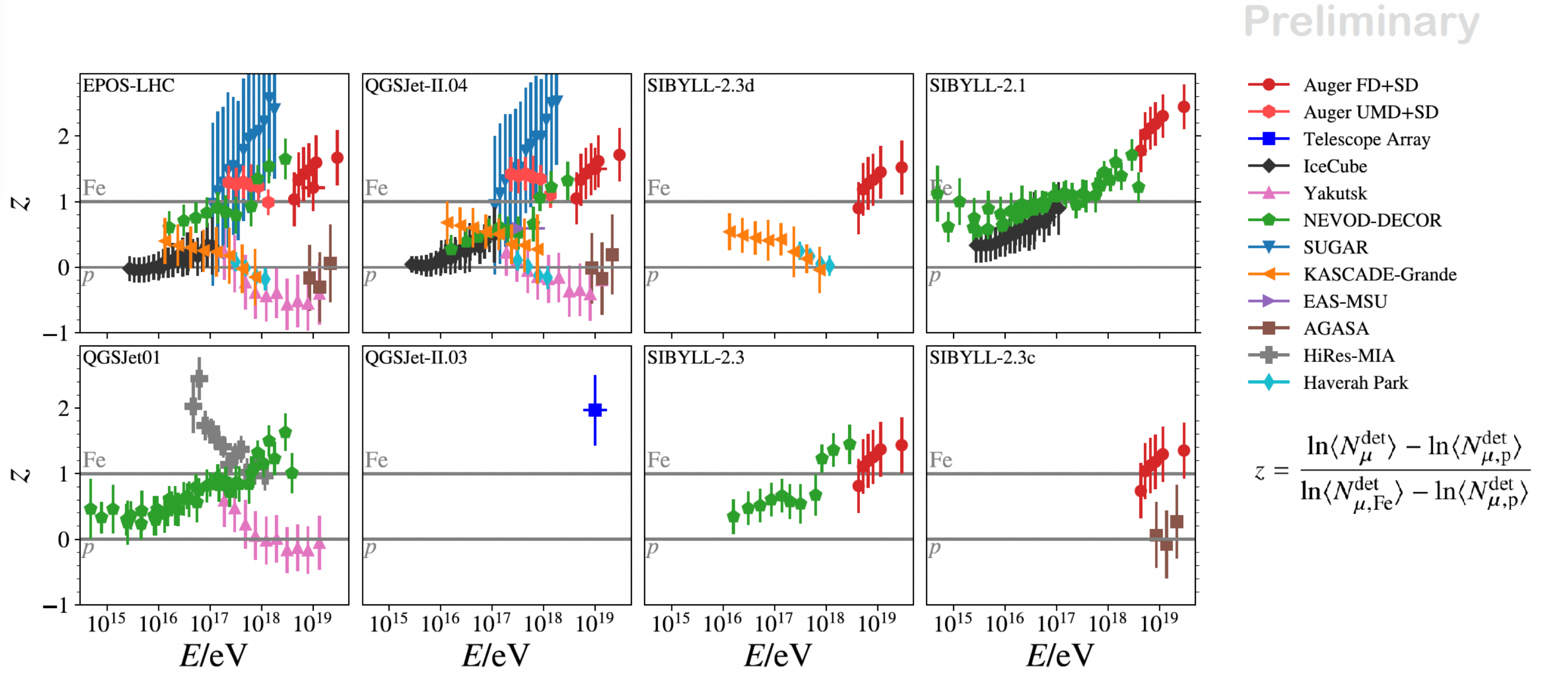
Muon Energy, zenith angle, distance to core





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

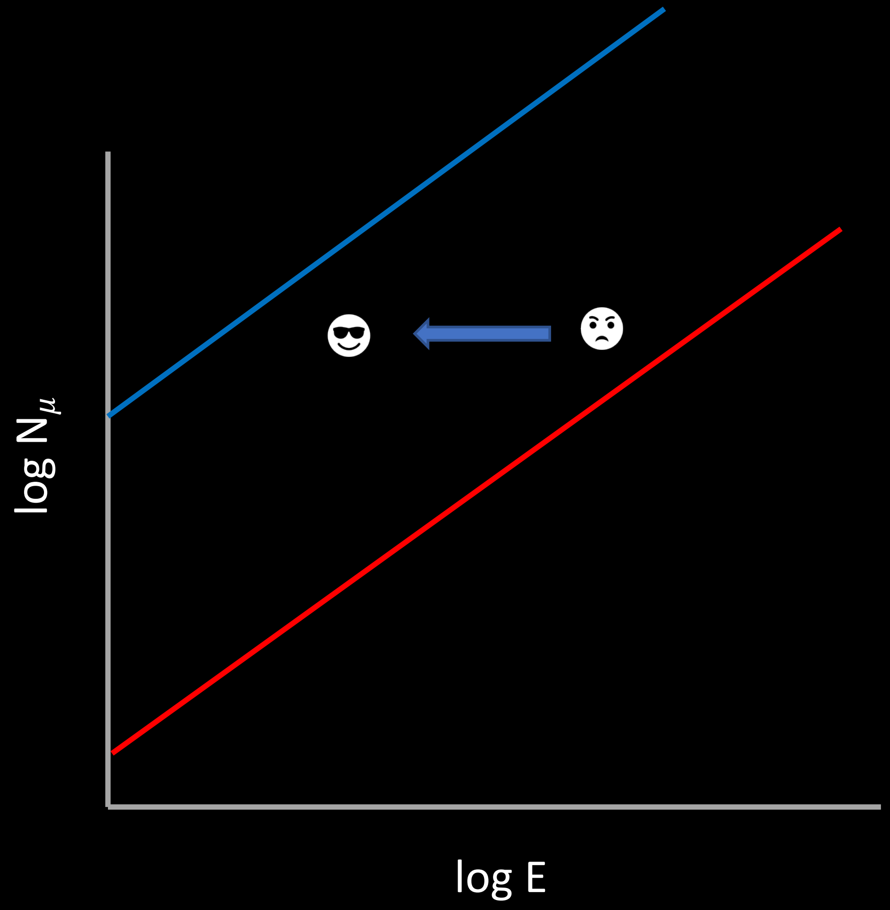
Experiment	E_{data}/E_{ref}	$\sec\theta$	$E_{\mu\,prod}$/GeV
EAS-MSU	-	1.1	11.9
IceCube Neutrino Observatory	1.19	1.0	0.7
KASCADE-Grande	-	1.0 , 1.3	1.5 , 2.1
NEVOD-DECOR	1.08	2.3 , 4.8	8.4 , 18.6
Pierre Auger Observatory	0.948	1.3 , 2.4	1.8 , 4.0
AMIGA	0.948	1.2	2.4
SUGAR	0.948	1.0	1.9
Telescope Array	1.052	1.3	1.4
Yakutsk EAS Array	1.24	1.1	2.6

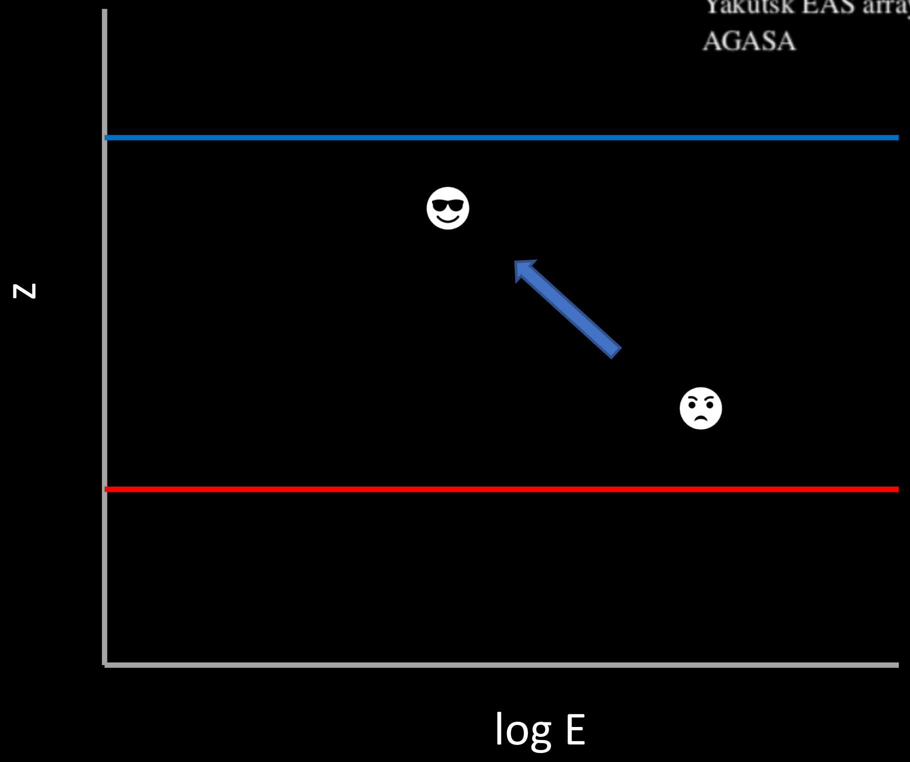

Preliminary
EPOS-LHC
QGSJet-II.04
SIBYLL-2.3d
SIBYLL-2.1
QGSJet01
QGSJet-II.03
SIBYLL-2.3
SIBYLL-2.3c
Fe
p
z
E/eV
Auger FD+SD
Auger UMD+SD
Telescope Array
IceCube
Yakutsk
NEVOD-DECOR
SUGAR
KASCADE-Grande
EAS-MSU
AGASA
HiRes-MIA
Haverah Park
$z = \frac{\ln\langle N_{\mu}^{\rm det}\rangle - \ln\langle N_{\mu,\rm p}^{\rm det}\rangle}{\ln\langle N_{\mu,\rm Fe}^{\rm det}\rangle - \ln\langle N_{\mu,\rm p}^{\rm det}\rangle}$

E-scale

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

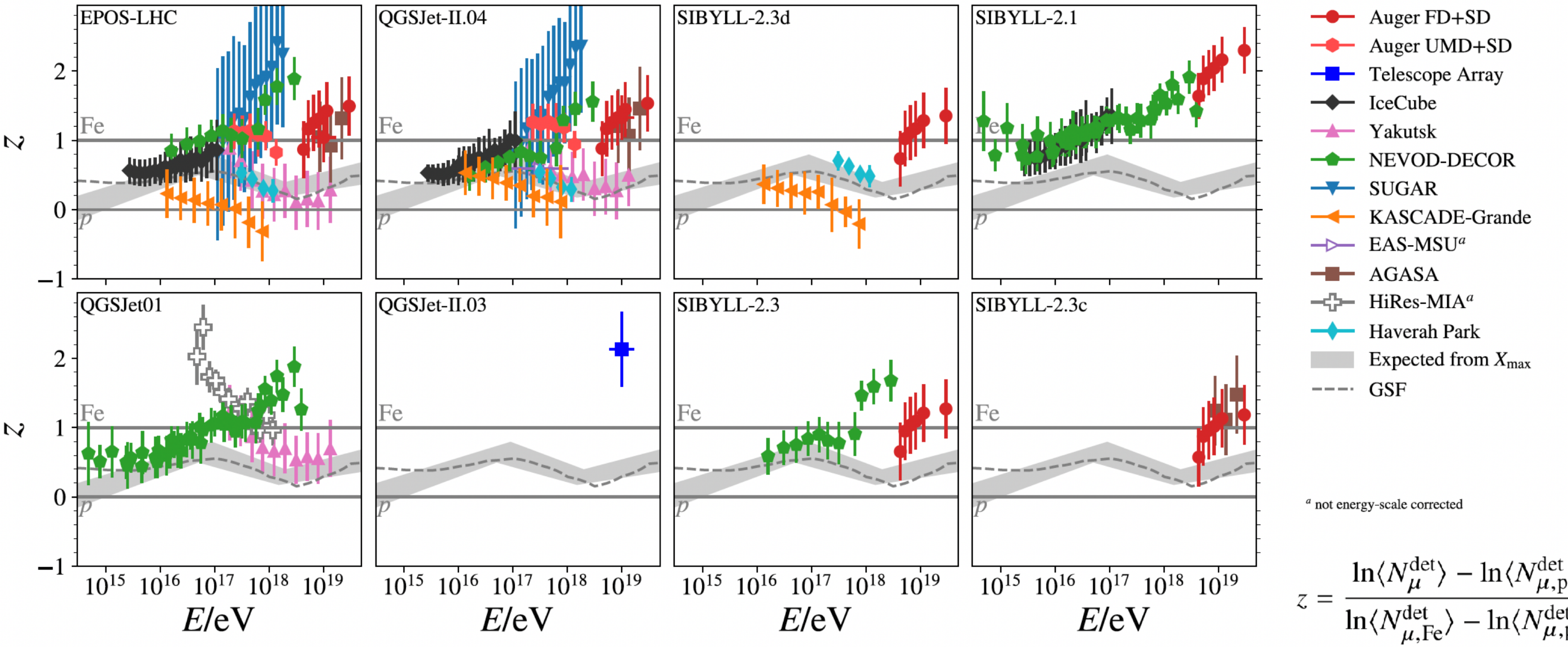
Experiment	E_{data}/E_{ref}
EAS-MSU	– –
HiRes-MIA	– –
Pierre Auger	
FD+SD	0.948
UMD+SD	0.948
SUGAR	0.948
KASCADE-Grande	0.948
Telescope Array	1.052
NEVOD-DECOR	1.08
Haverah Park	1.16
IceCube/IceTop	1.19
Yakutsk EAS array	1.24
AGASA	1.47





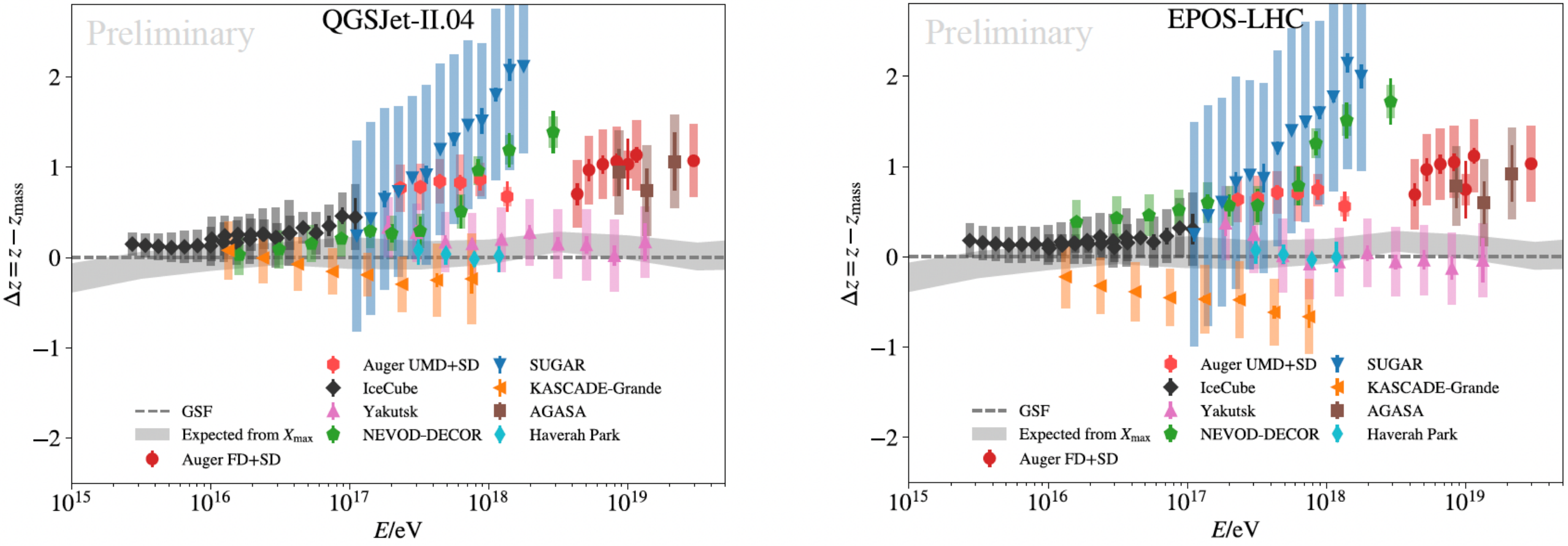
- The z-scale after applying the energy shifts for common energy calibration.

Preliminary



[a] not energy-scale corrected

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

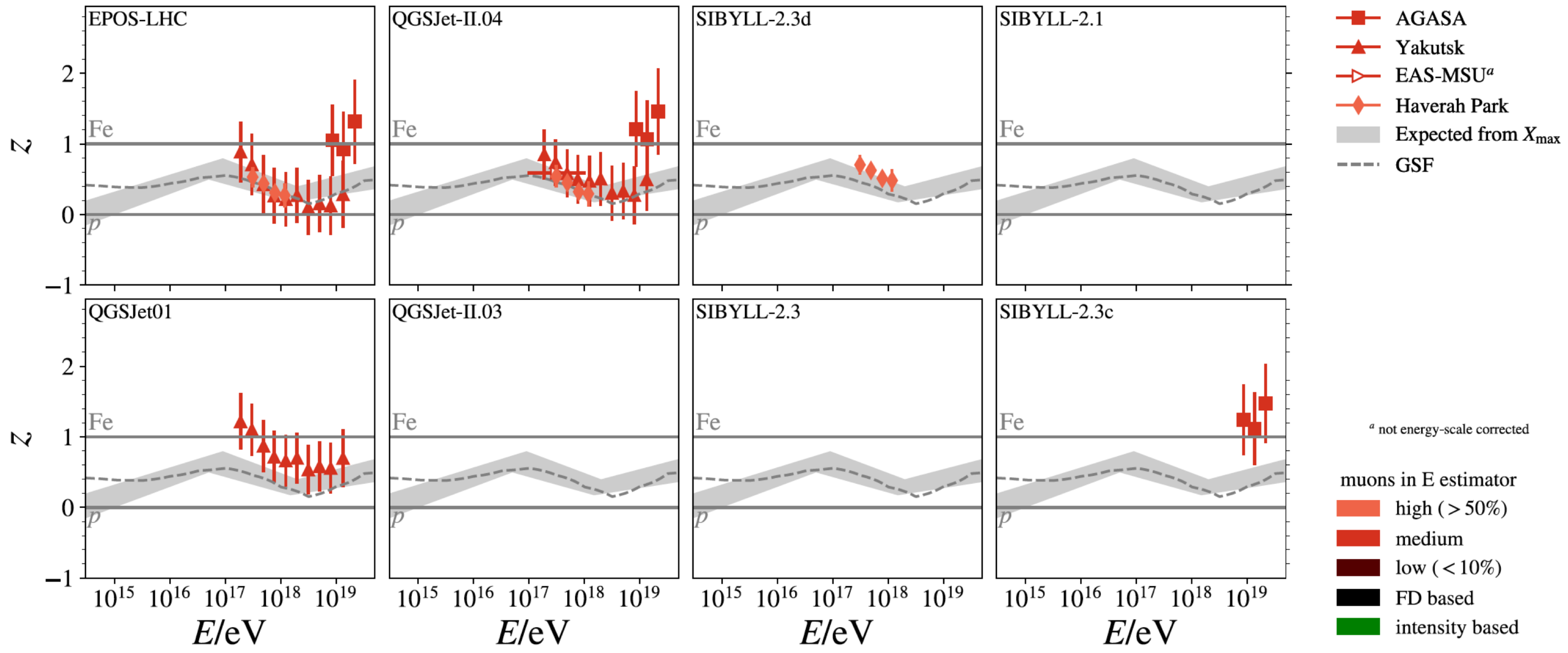


Preliminary
QGSJet-II.04
EPOS-LHC
$\Delta z = z - z_{\text{mass}}$
E/eV
GSF
Expected from X_{max}
Auger FD+SD
Auger UMD+SD
IceCube
Yakutsk
NEVOD-DECOR
SUGAR
KASCADE-Grande
AGASA
Haverah Park

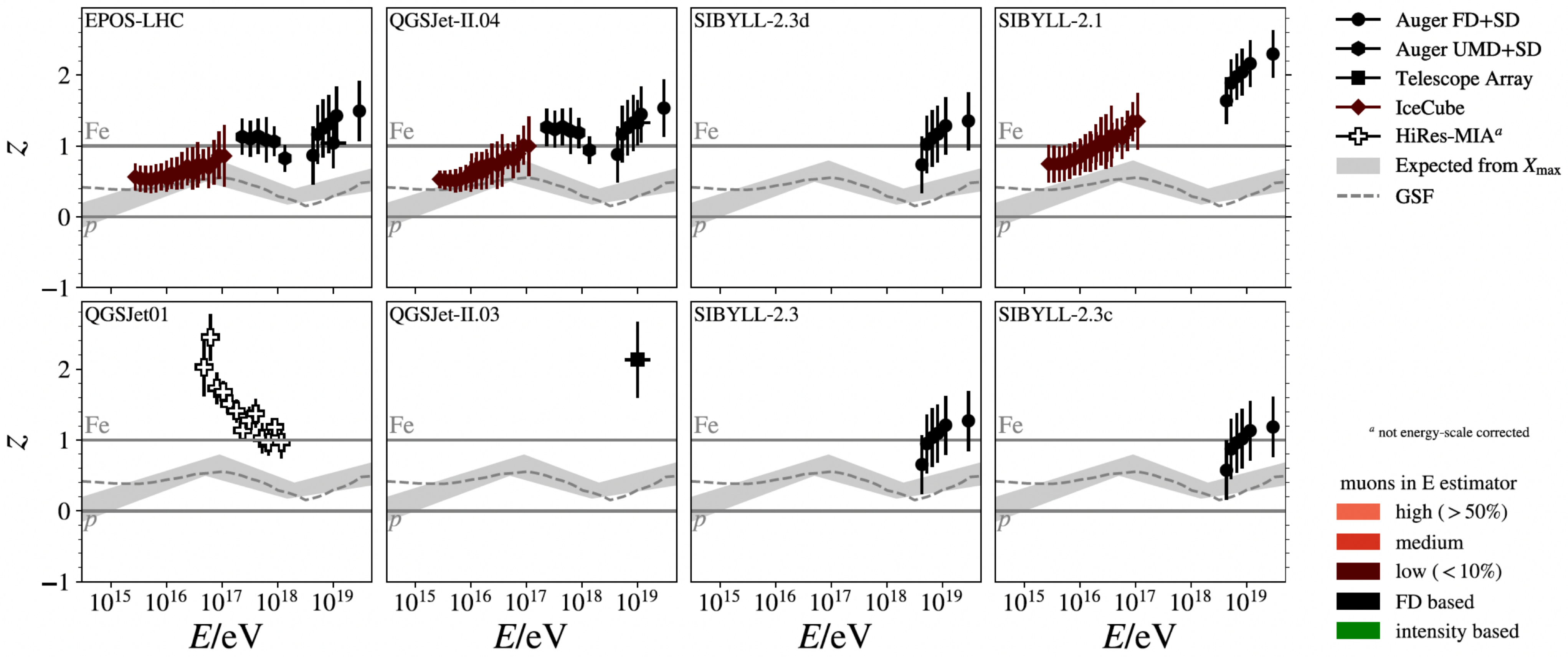
Independence of E and muon estimation

Experiment	E estimation	Muon contribution in E estimator	Full detection simulation	Vertical atm. depth (g/cm^2)	E_{data}/E_{ref}
EAS-MSU	SD	(10%, 50%)	✓	990	−−
HiRes-MIA	FD	(−10%, 0%)	✓	870	−−
Pierre Auger					
FD+SD	FD	(−10%, 0%)	✓	880	0.948
UMD+SD	FD/SD	(−10%, 0%)/$<$ 10%	✓	880	0.948
SUGAR	Flux	−−	✗	1015	0.948
KASCADE-Grande	Flux	−−	✓	1022	0.948
Telescope Array	FD	(−10%, 0%)	✓	880	1.052
NEVOD-DECOR	Flux	−−	✗	1014	1.08
Haverah Park	SD	$>$ 50%	✗	1016	1.16
IceCube/IceTop	SD	$<$ 10%	✓	690	1.19
Yakutsk EAS array	SD	(10%, 50%)	✓	1020	1.24
AGASA	SD	(10%, 50%)	✗	920	1.47

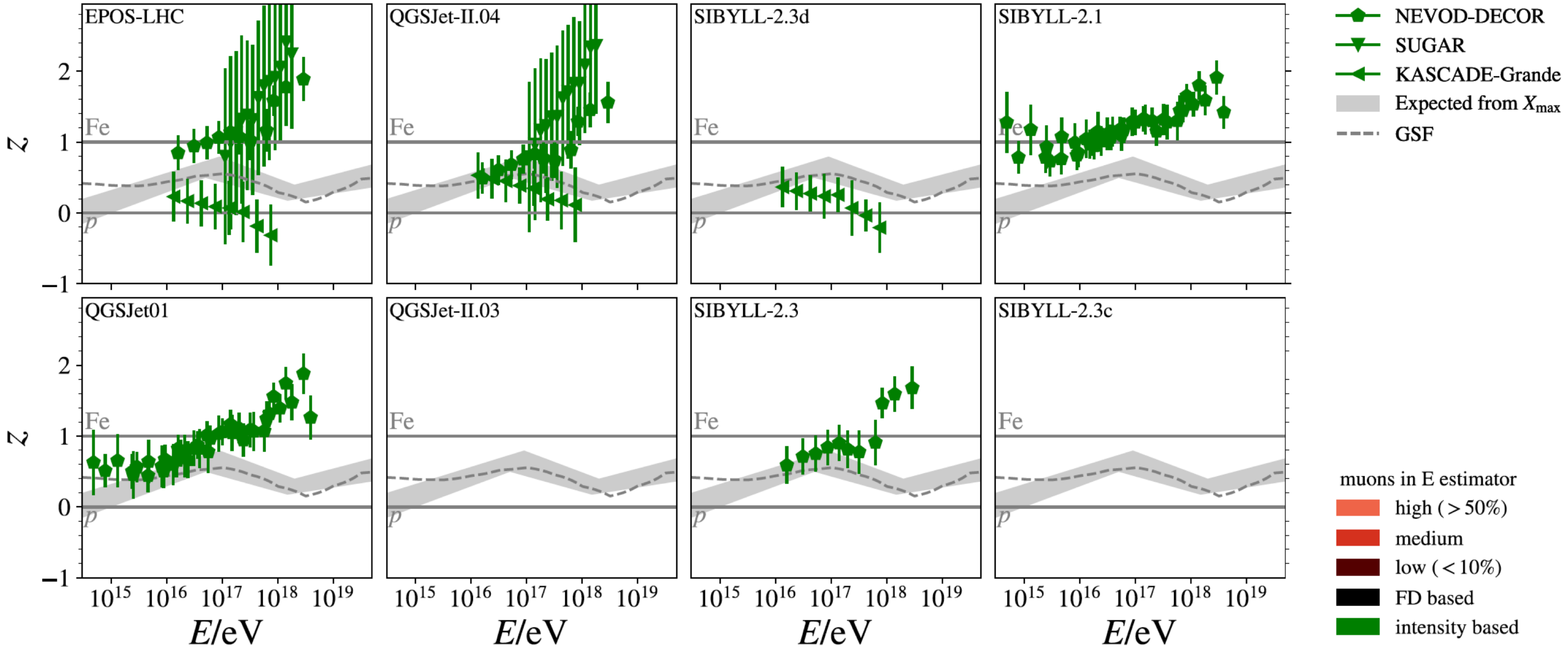
- Classification according to the muon contamination in the estimated primary energy.



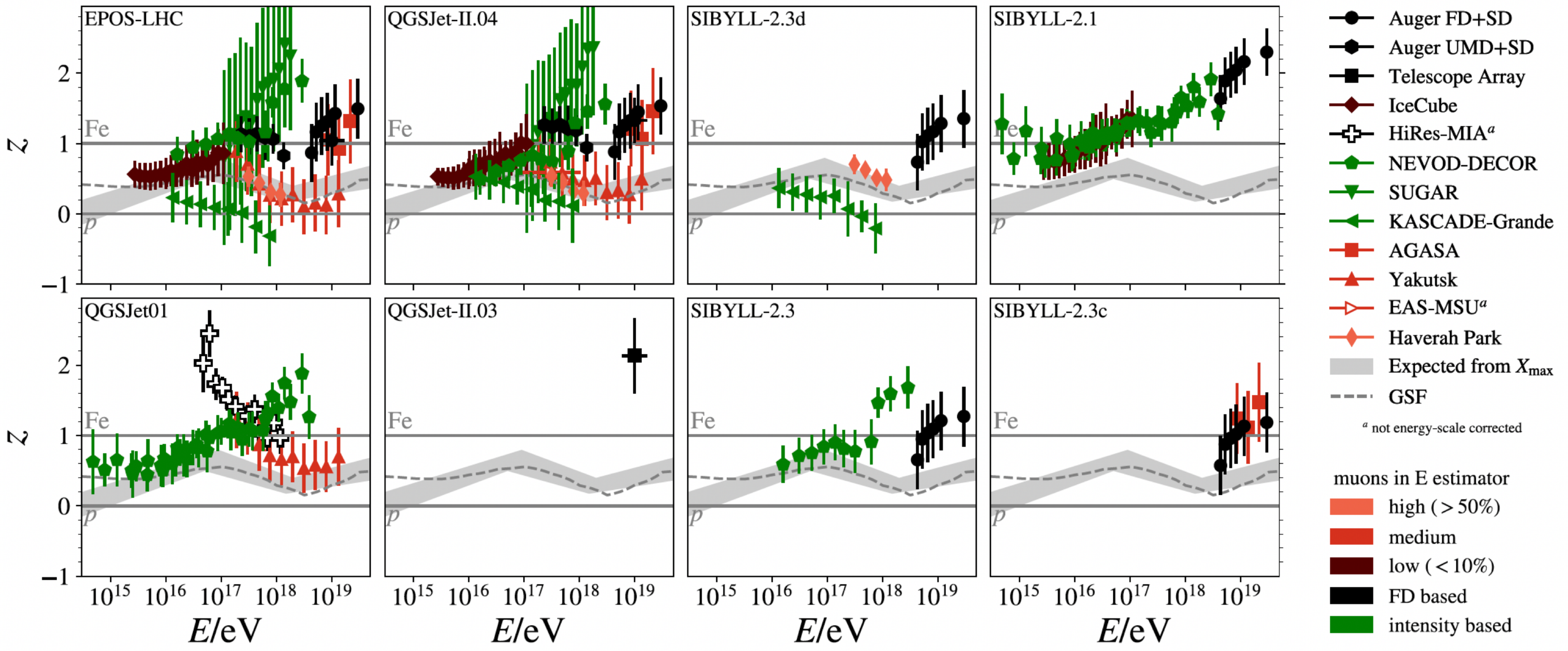
- Classification according to the muon contamination in the estimated primary energy.



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



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



Conclusions

- After the latest updates, the global compilation of results from 1 PeV to 10 EeV do not show a coherent, consistent picture on whether or not, there is a muon deficit in models wrt data.
  - Accounting for the different experimental phasespace (distance to core, zenith angle, muon energy) do not fix the problem. L. Cazon *PoS* ICRC2019 (2020) 214
- The degree of verbosity and detail of data varies.
  - It is difficult to recover relevant information in the systematics of less active/responsive collaborations
- Experiments with independent N_{μ}, and E determination show a consistent picture: muon deficit growing with Energy.
  - More work is still ongoing.