Working Group Report on the Combined Analysis of Muon Density Measurements from Eight Air Shower Experiments

PoS(ICRC2019)214

Lorenzo Cazon,

for the EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array, and Yakutsk EAS Array collaborations

Working group on **H**adronic **I**nteractions and **S**hower **P**hysics (**WHISP**) was created in 2018, 1st report in the UHECR Conference in Paris

H. Dembinski et al. EPJ Web Conf 210 (2019) 02004

Shower energy and muon density

- AUGER
  - AMIGA
- TA
- Yakutsk

Electron density and muon density

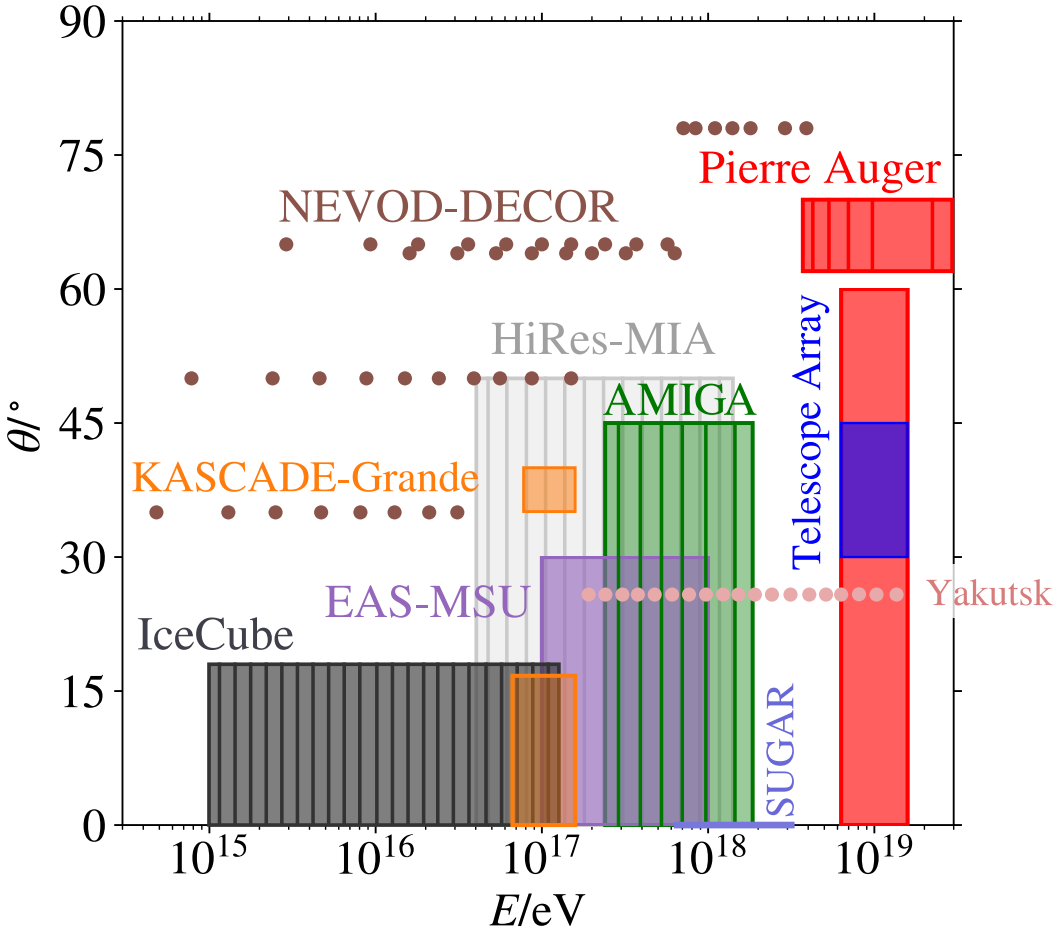
- Kascade-Grande
- EAS-MSU

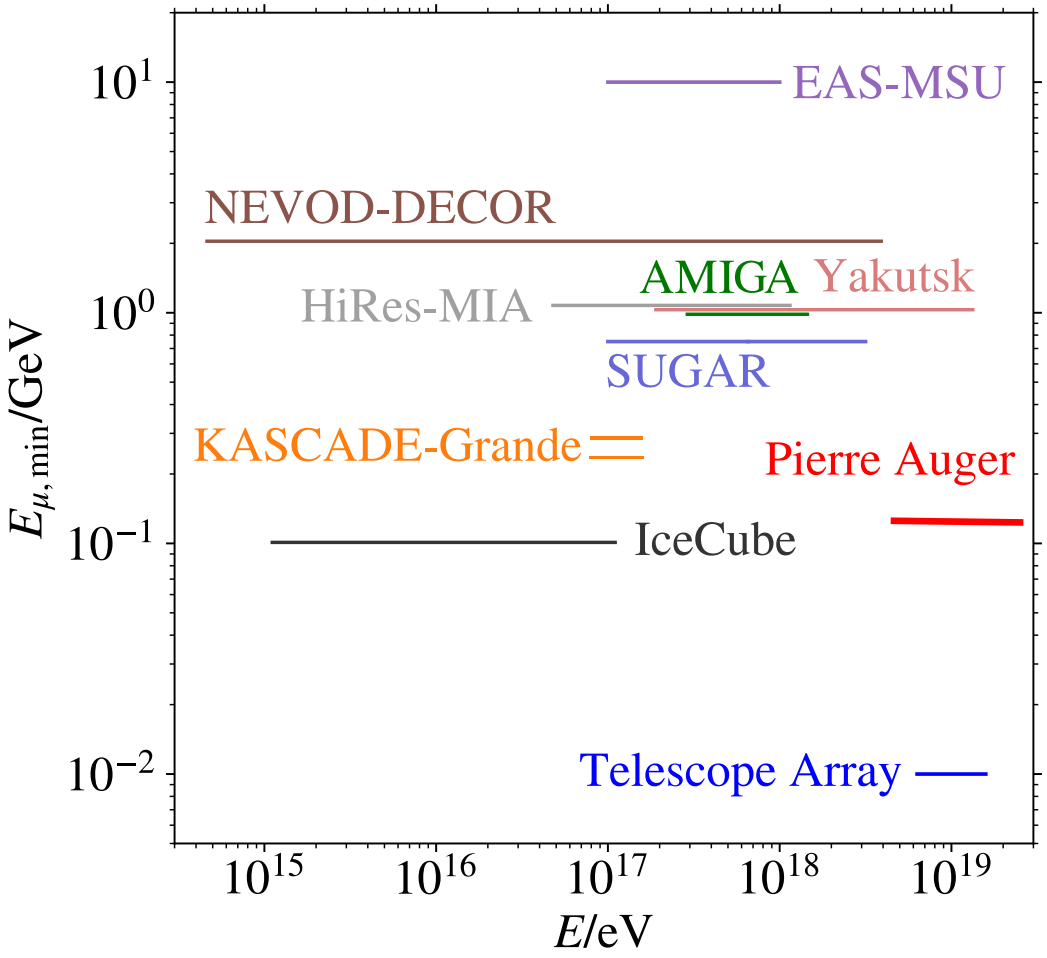
Muon density

- NEVOD-DECOR
- SUGAR

- IceCube (IceTop)

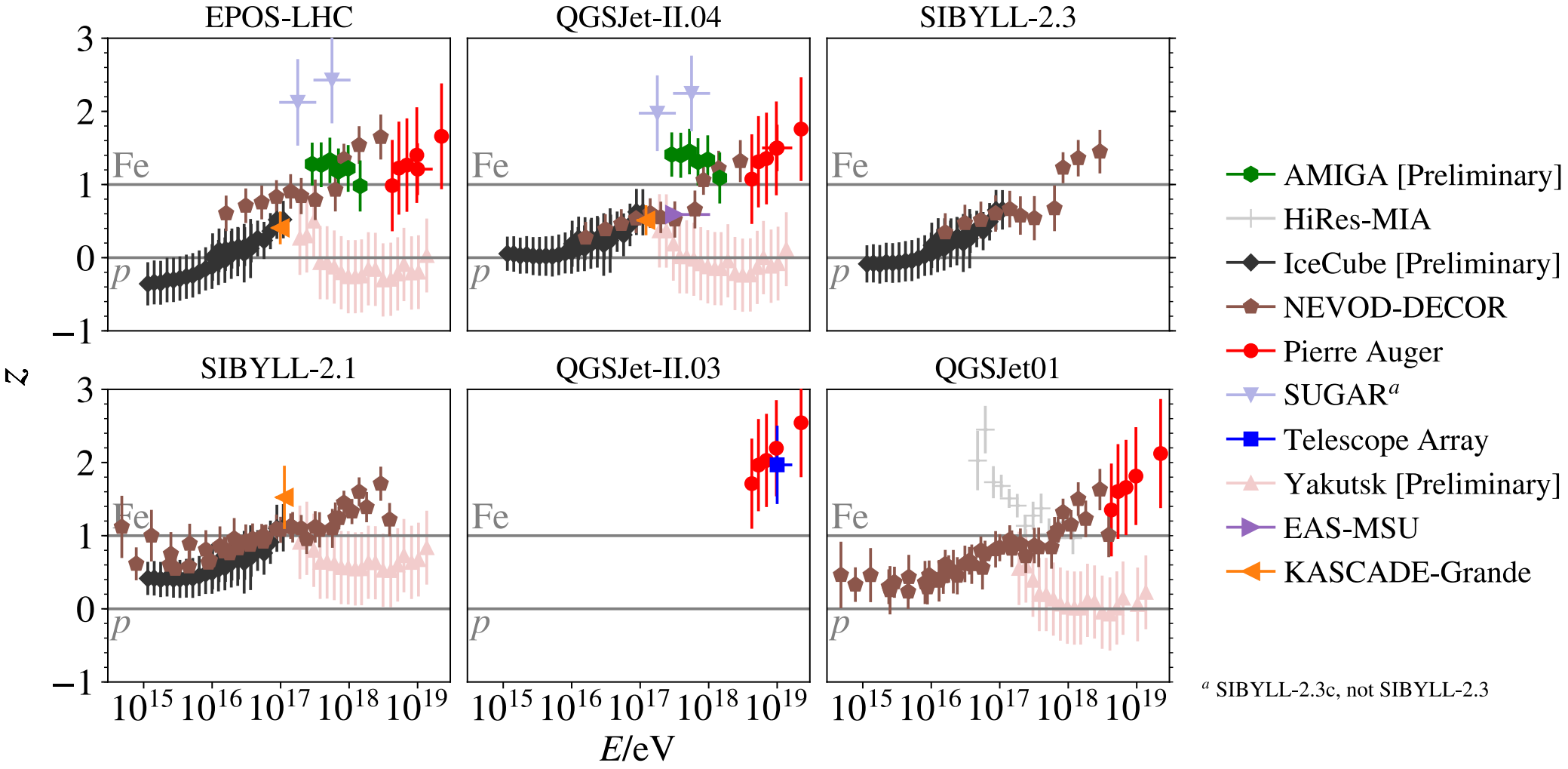
Observation parameters: zenith angle range and muon energy threshold





Universal reference

$$z = \frac{\ln N_\mu - \ln N_\mu^p}{\ln N_\mu^{Fe} - \ln N_\mu^p} \simeq 3 \ln \frac{N_\mu}{N_\mu^p}$$



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

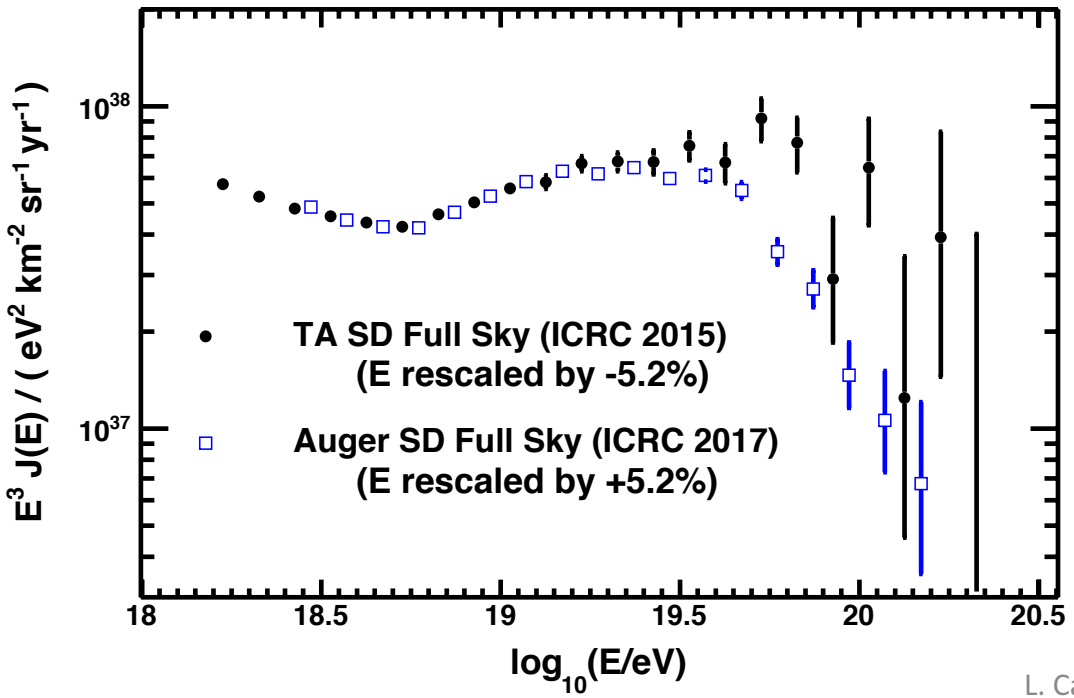
Energy rescaling

Cross-calibrate energy scales by matching all-particle fluxes

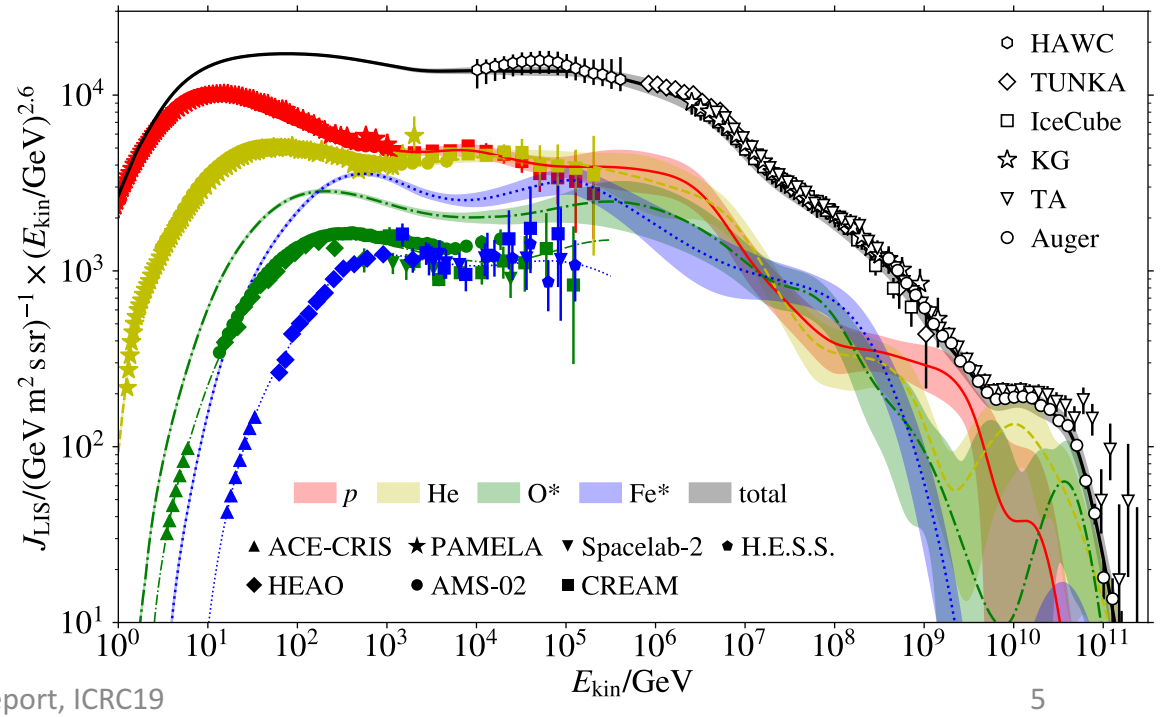
Spectrum WG: Auger **0.948** Telescope Array **1.052**

GSF (matched): SUGAR **0.948** KASCADE-Grande **0.95** IceTop **1.19** NEVOD-DECOR **1.08**

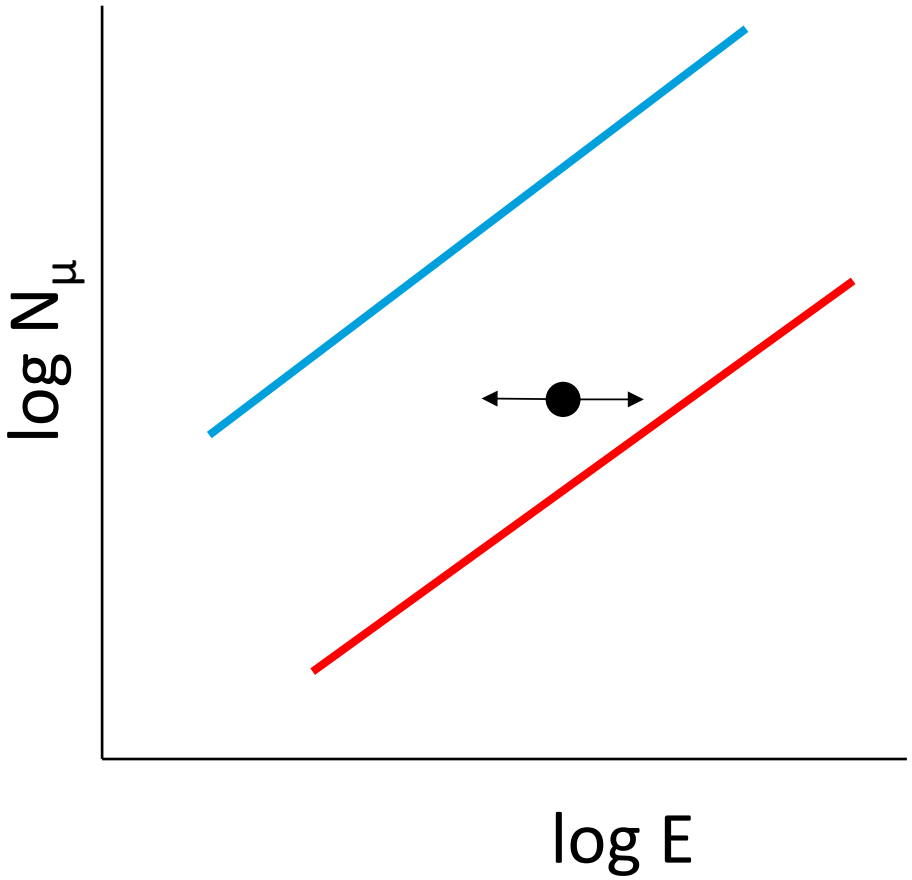
Spectrum WG

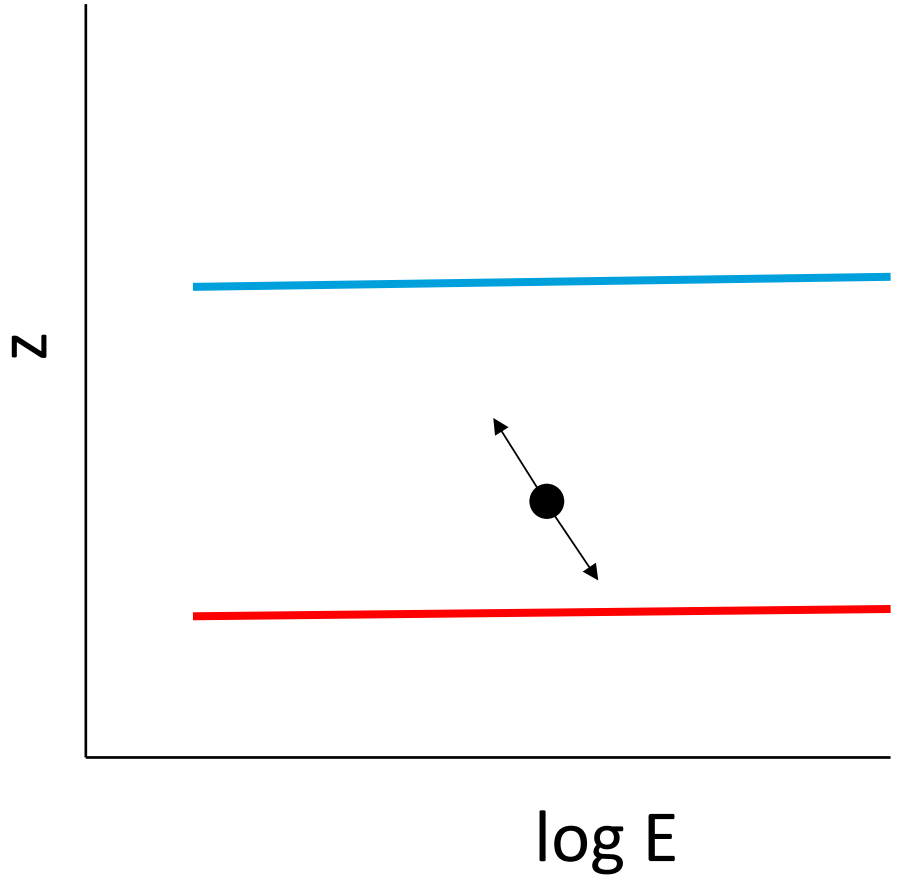


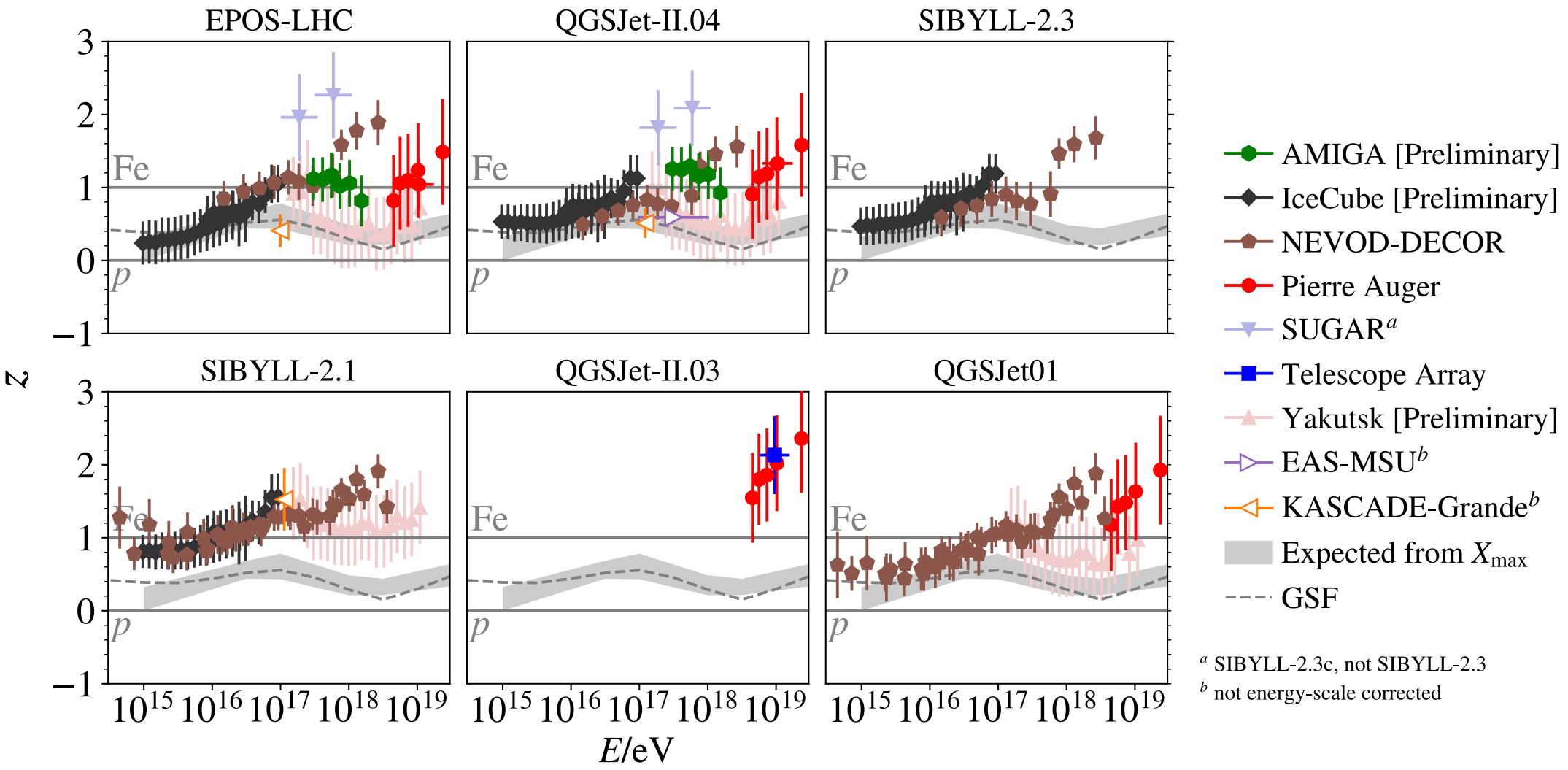
GSF



Effects on the z-scale



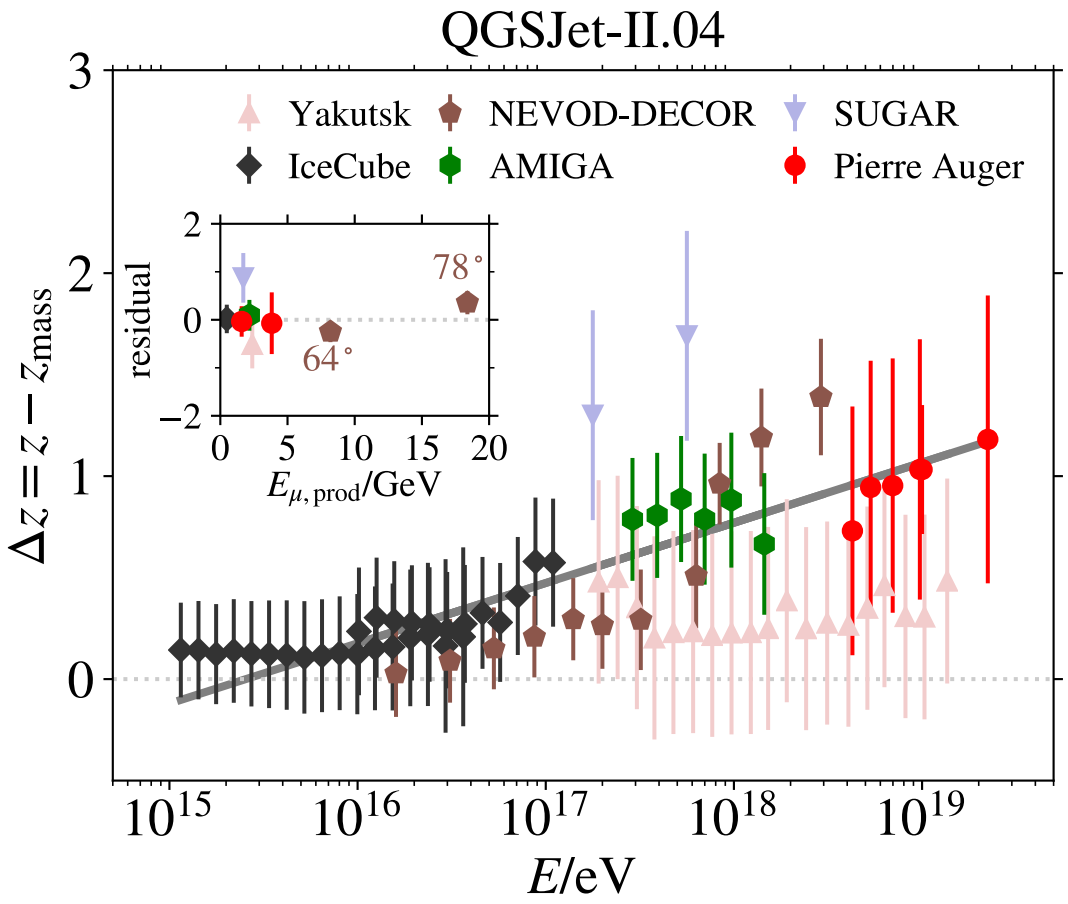


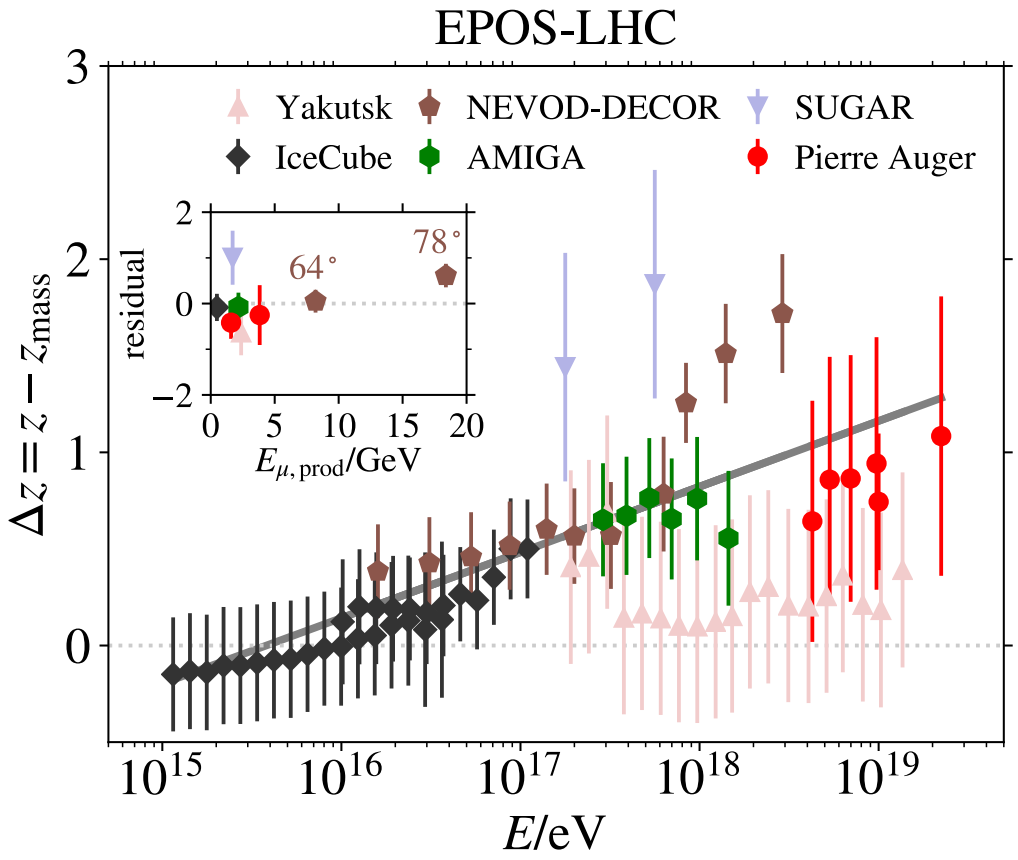

EPOS-LHC
QGSJet-II.04
SIBYLL-2.3
SIBYLL-2.1
QGSJet-II.03
QGSJet01
Fe
p
Z
E/eV
AMIGA [Preliminary]
IceCube [Preliminary]
NEVOD-DECOR
Pierre Auger
SUGAR[a]
Telescope Array
Yakutsk [Preliminary]
EAS-MSU[b]
KASCADE-Grande[b]
Expected from X_{max}
GSF
[a] SIBYLL-2.3c, not SIBYLL-2.3
[b] not energy-scale corrected

Fit

$$\Delta z = a + b \log_{10}(E/10^{16}\mathrm{eV})$$

$$\Delta z = z - z_{\mathrm{mass}} \simeq 3 \ln \frac{N_\mu}{N_\mu^{\mathrm{mass}}}$$





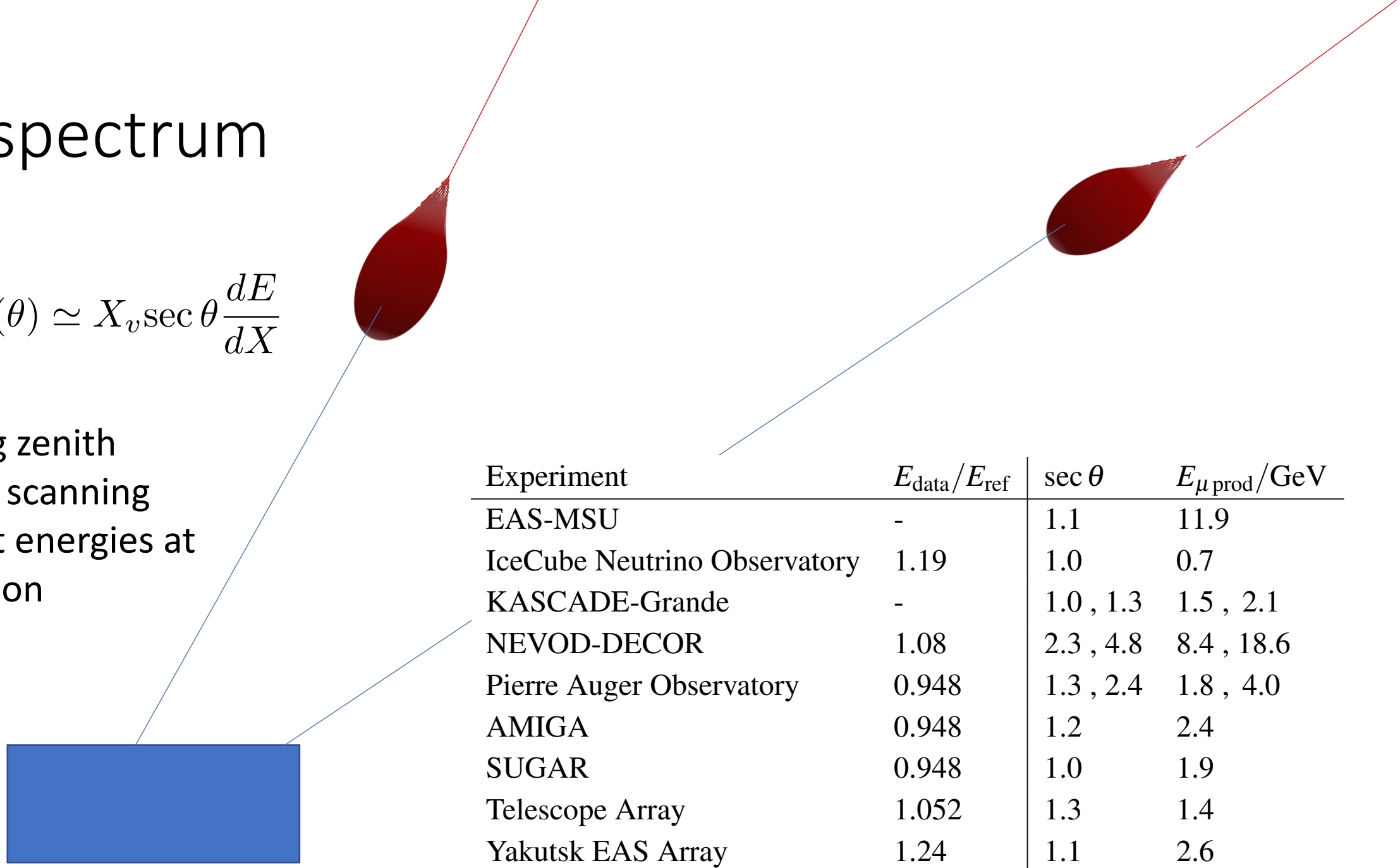
$$b = 0.30 \pm 0.03$$

$$b = 0.34 \pm 0.04$$

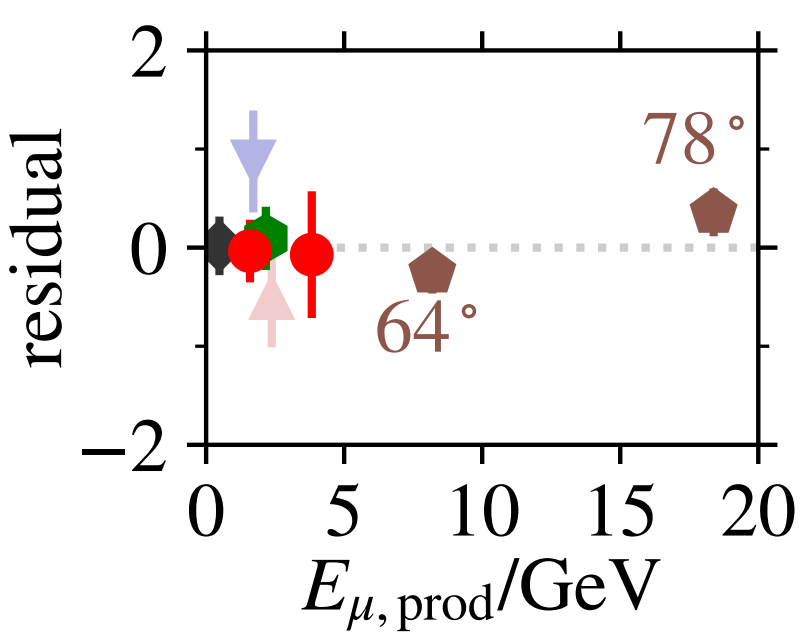
E-spectrum

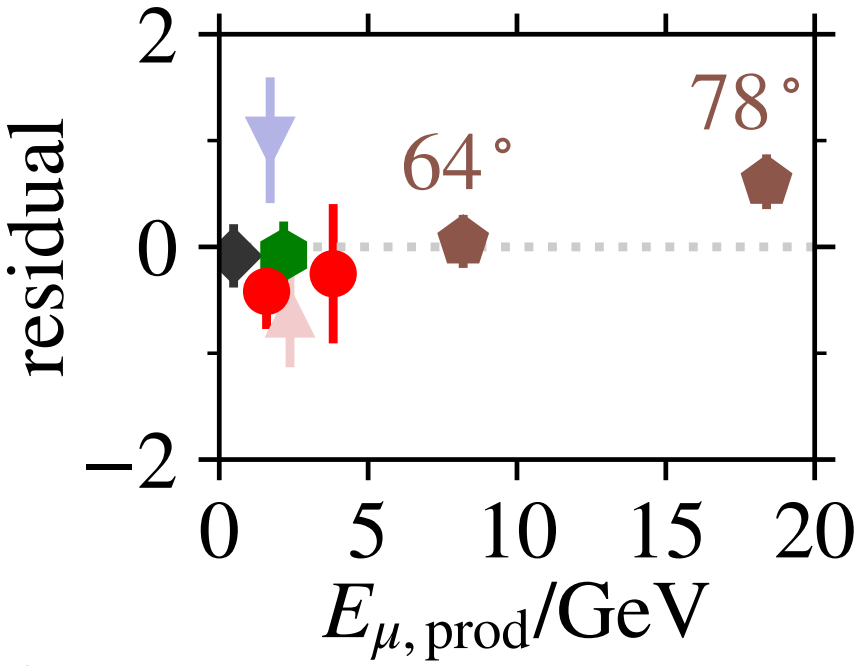
$$E_{\mu\,\mathrm{prod}}(\theta) \simeq X_v \sec\theta \frac{dE}{dX}$$

scanning zenith angles = scanning different energies at production



Experiment	$E_{\mathrm{data}}/E_{\mathrm{ref}}$	$\sec\theta$	$E_{\mu\,\mathrm{prod}}/\mathrm{GeV}$
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





$$\Delta z = a + b\log_{10}(E/10^{16}\mathrm{eV}) + cE_{\mu\mathrm{prod}}$$

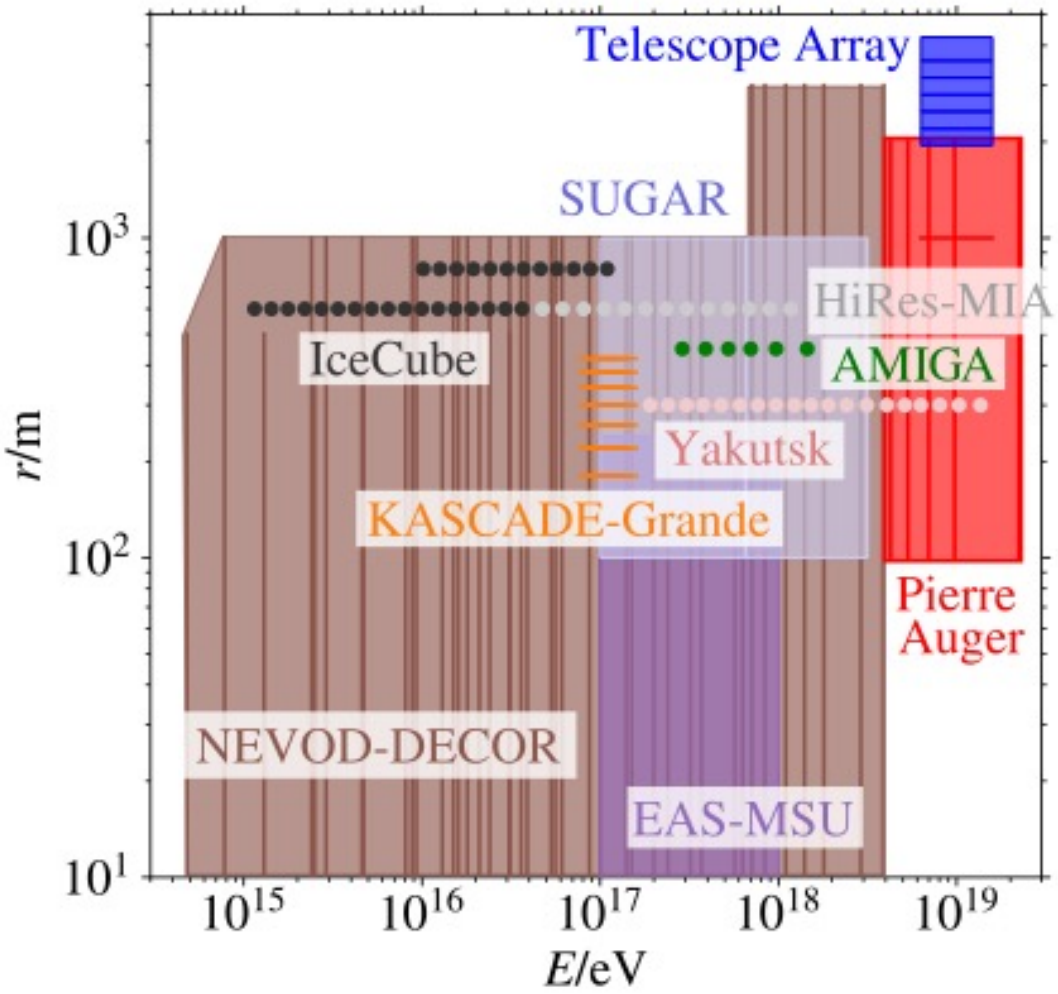
- The extra dependency allows to scan the **muon energy spectrum at production**.
  - A value of *c* larger (smaller) than 0 would indicate a harder (softer) muon E-spectrum

- **Inconclusive results**:

c totally changes when excluding NEVOD-DECOR at 78 deg.

Conclusions

- **Consistent picture** after converting and cross-calibrating data
  - Post-LHC models describe muons better than pre-LHC models
- Smooth increase of $N_\mu^{data} / N_\mu^{MC}$ with energy (8 $\boldsymbol{\sigma}$ significance)
- No deviations in the muon E-spectrum *wrt* models.
  - Inhomogeneity observation conditions in experiments
  - More work needed
  - Studies of dependence with zenith angle highly valuable.


Telescope Array
SUGAR
HiRes-MIA
IceCube
AMIGA
Yakutsk
KASCADE-Grande
Pierre Auger
NEVOD-DECOR
EAS-MSU
10^3
10^2
10^1
r/m
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
E/eV