Is there room for new physics to explain the muon anomaly in ultrahigh-energy cosmic rays showers?

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Heavy Ion and New Physics, ECT*, Zoom

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Outline

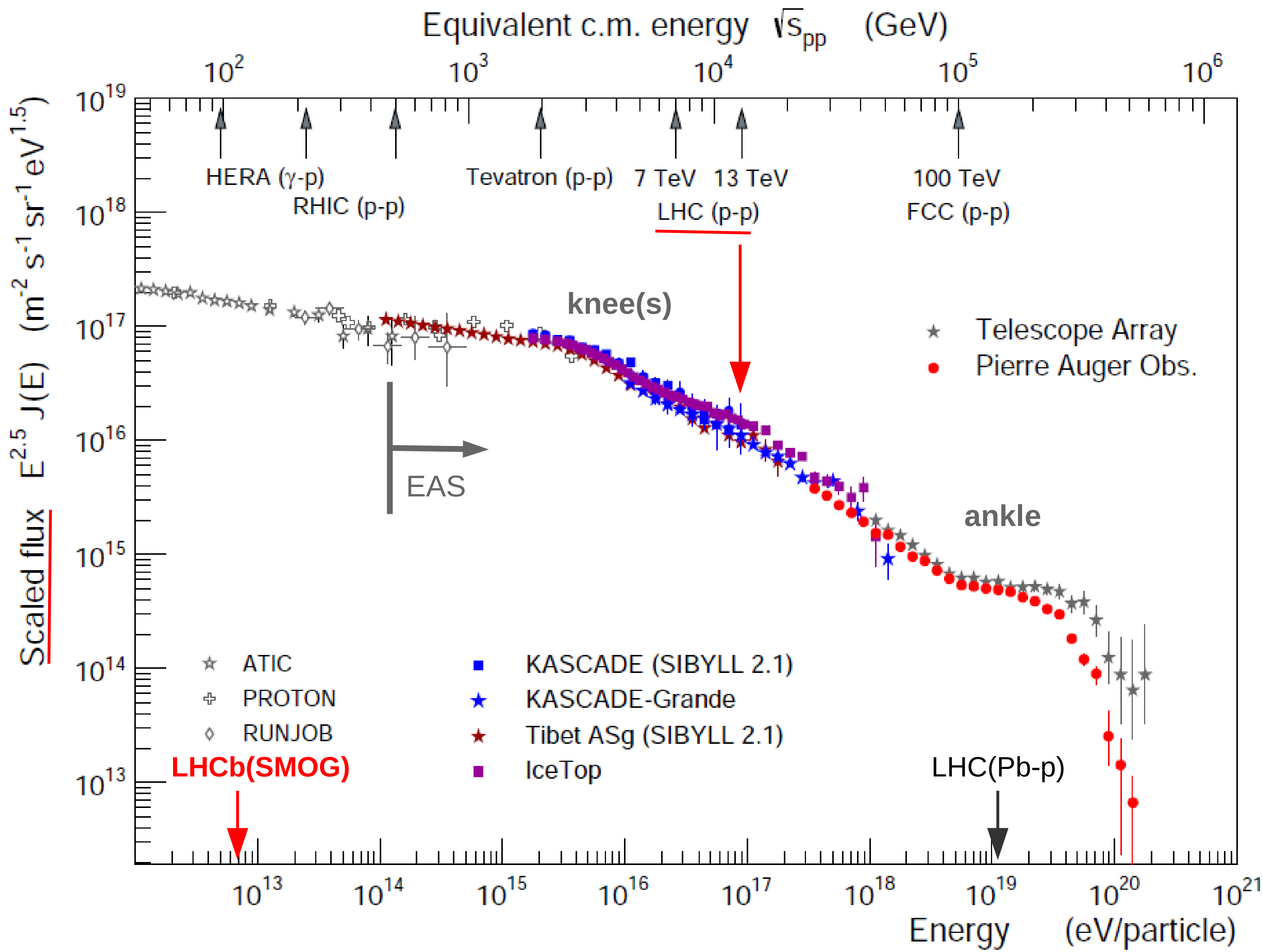
- **Introduction**
- **Muon Anomaly**
  - ➔ Possible explanations
- **Hadronization**
  - ➔ Link to LHC

hadronization in extreme conditions

- **Other Tests**

Once the latest results from LHC will be taken into account, and according to latest muon measurements, there is little room left for new physics to explain the muon anomaly.

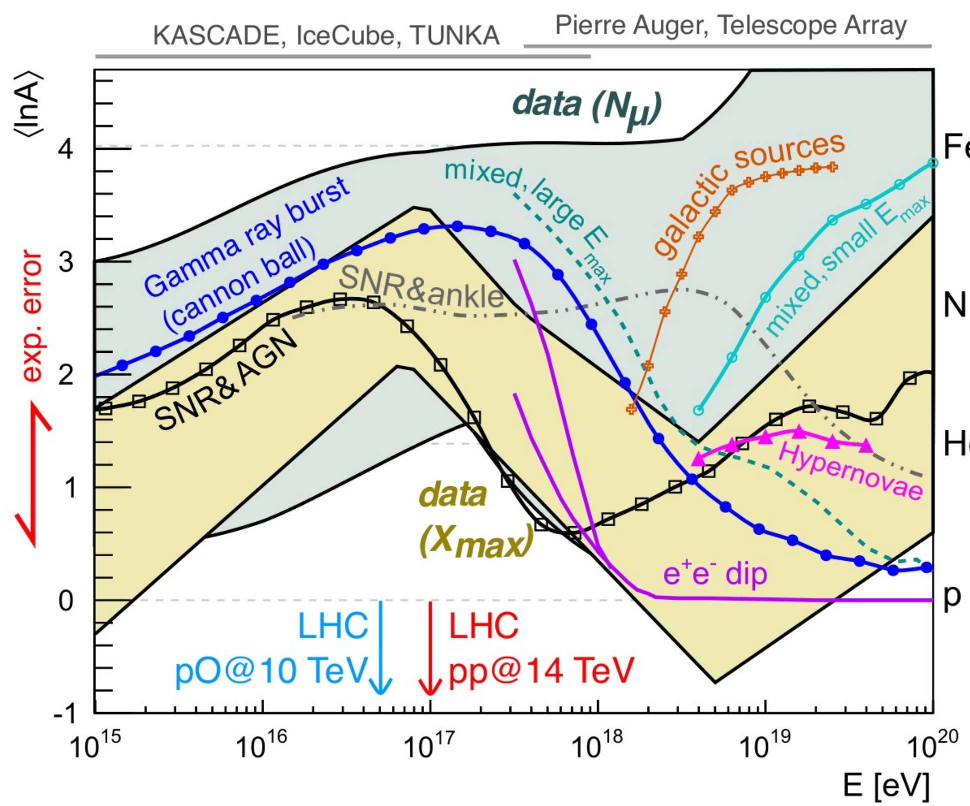
Cosmic Ray Energy Spectrum



R. Engel (KIT)

Primary Cosmic Ray Composition from Air Showers

- **Goal of Astroparticle Physics**
  - Study of astrophysical object via received cosmic ray (CR) at Earth
- **High energy cosmic rays detected via extended air showers (EAS)**
  - Degeneracy between mass and hadronic interactions (change the same basic properties like cross-section...)
  - Hadronic interactions are the key for proper EAS simulations and CR analysis



Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

- **Inconsistent mass composition point to weakness of hadronic interaction description in models : Possible new physics involve ?**

Cosmic Ray Analysis from Air Showers

- **EAS simulations necessary to study high energy cosmic rays**
  - complex problem: identification of the primary particle from the secondaries

- **Hadronic models are the key ingredient !**
  - follow the standard model (QCD)
    - but mostly non-perturbative regime (phenomenology needed)
  - main source of uncertainties

- **Which model for CR ? (alphabetical order)**
  - **DPMJETIII.(17-1/19-1)** by S. Roesler, A. Fedynitch, R. Engel and J. Ranft
  - **EPOS (1.99/LHC/3/4)** (from VENUS/NEXUS before) by H.J. Drescher, B. Guiot, Iu.A. Karpenko, F. Liu, T. Pierog, G. Sophys, M. Stefaniak, and K.Werner.
  - **QGSJET** (01/II-03/II-04/III) by S. Ostapchenko (starting with N. Kalmykov)
  - **Sibyll (2.1/2.3c/2.3d)** by E-J Ahn, R. Engel, A. Fedynitch, R.S. Fletcher, T.K. Gaisser, P. Lipari, F. Riehn, T. Stanev

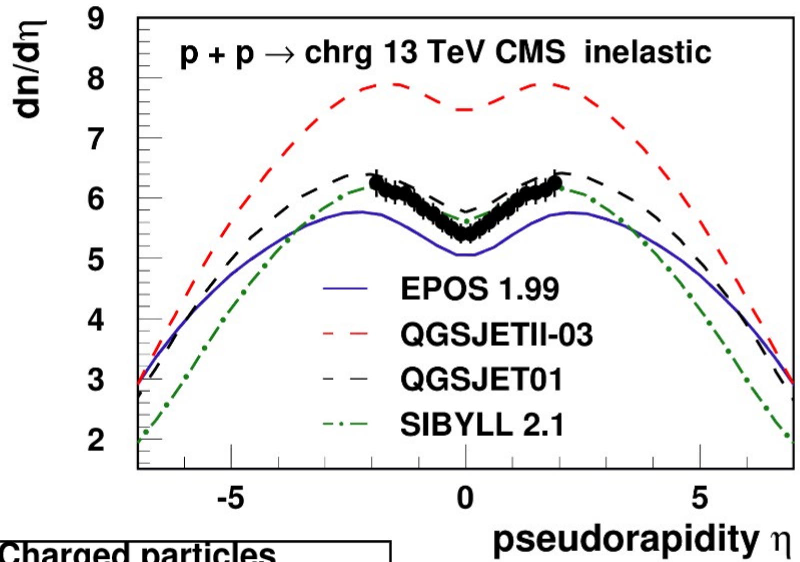
Cosmic Ray Hadronic Interaction Models

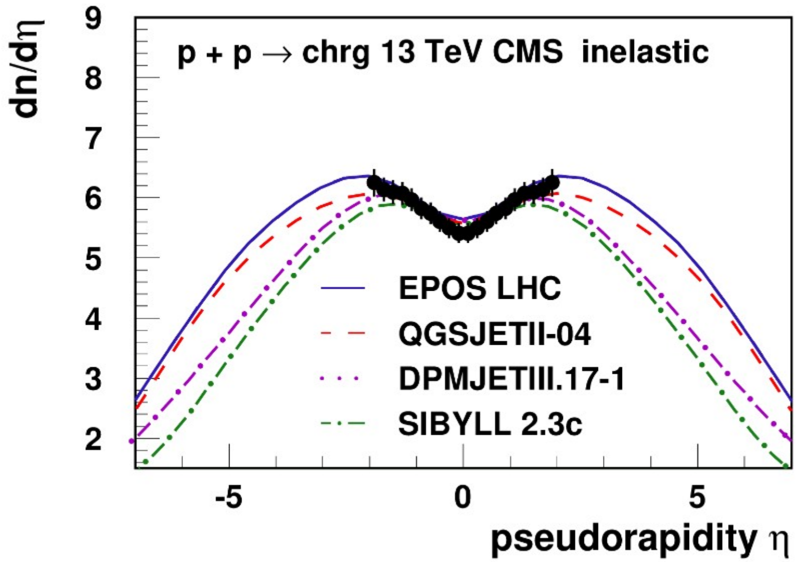
- **Theoretical basis :**
  - pQCD (large p_t) → Not fully implemented
  - Gribov-Regge Theory (cross section with multiple scattering) → inelastic/total cross section → light ions
  - energy conservation
- **Phenomenology (models) :**
  - hadronization
    - string fragmentation → Not the same level of details in all models
    - high density effects (ions) → Not treated or not enough (EPOS) → light ions
  - diffraction (Good-Walker, ...) → Not as good as expected at LHC → light ions
  - higher order effects (multi-Pomeron interactions) → light ions
  - remnants → Different approaches → Fixed target (low and high E)
- **Comparison with data to fix parameters**
  - one set of parameter for all systems/energies
  - limited use of High Energy Physics models (Pythia, Herwig) not designed to be used with nuclei and limited predictive power for high energy extrapolation (Angantyr could make the link).

Light Ion Data Needed

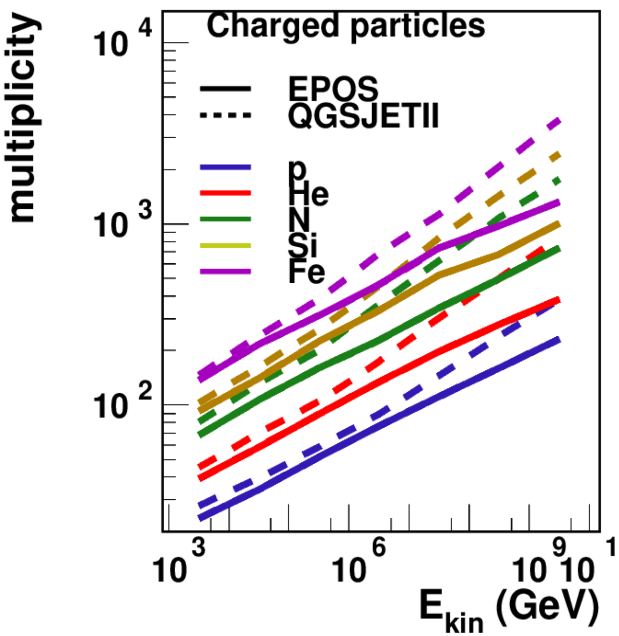
Significant improvement require new data (light ion and higher energy)

Pre - LHC





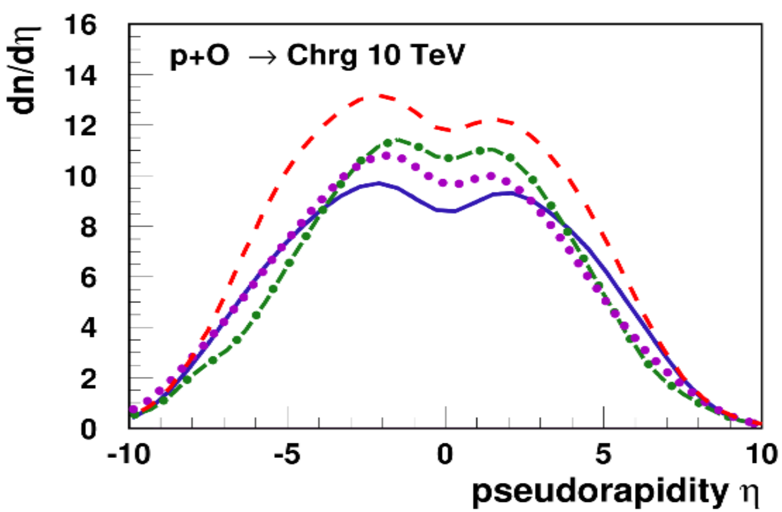
Post - LHC



After LHC, most of the model difference appear in nuclear collisions : ideal tests using p-O and O-O collisions

2024 ?

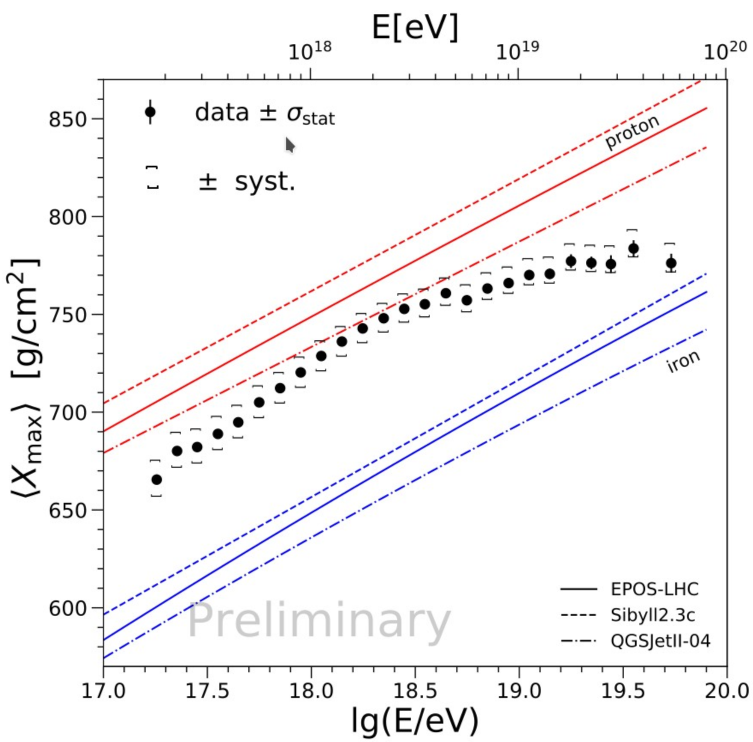
Post - LHC

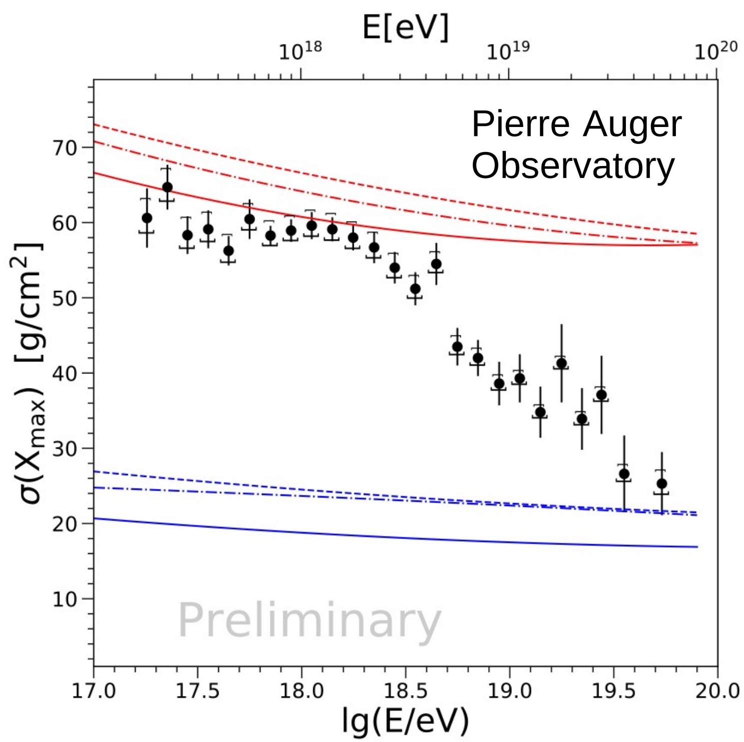


X_{max}

+/- 20g/cm² is a realistic uncertainty from models after LHC:

- Larger than modern experimental uncertainties (~15g/cm²)
- Anything below lower model or above higher model won't be compatible with LHC data
- Any new physics model would have to be compatible with both mean and fluctuation while current evolution compatible with evolving mixed composition
- Analysis of both X_{max} and signal at ground for $E \sim 10^{18.5}$eV show both deep and shalow component at the same time (light and heavy or new and standard physics)



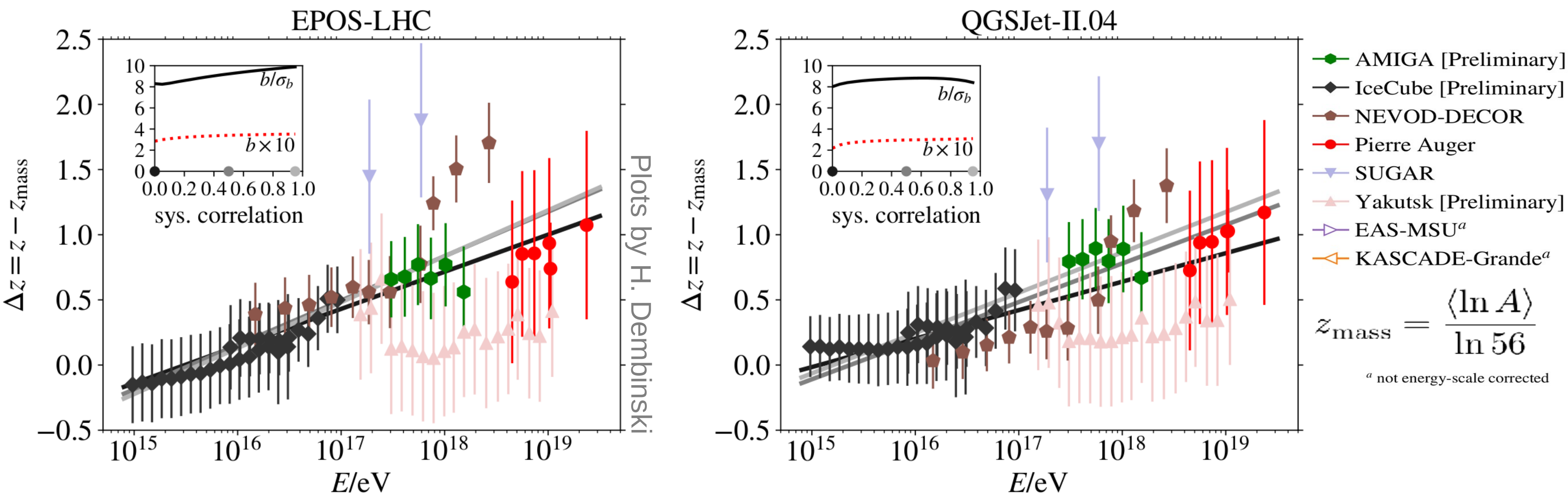


Reference measurement to test hadronic interactions : muon independent mass composition.

WHISP Meta-Analysis

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

- **Global analysis of muon measurements in EAS :**
  - Clear muon excess in data compared to simulation
  - Different energy evolution between data and simulations
    - Significant non-zero slope (>8σ)



- **Different energy or mass scale cannot change the slope**
  - Different property of hadronic interactions at least above 10^{16} eV

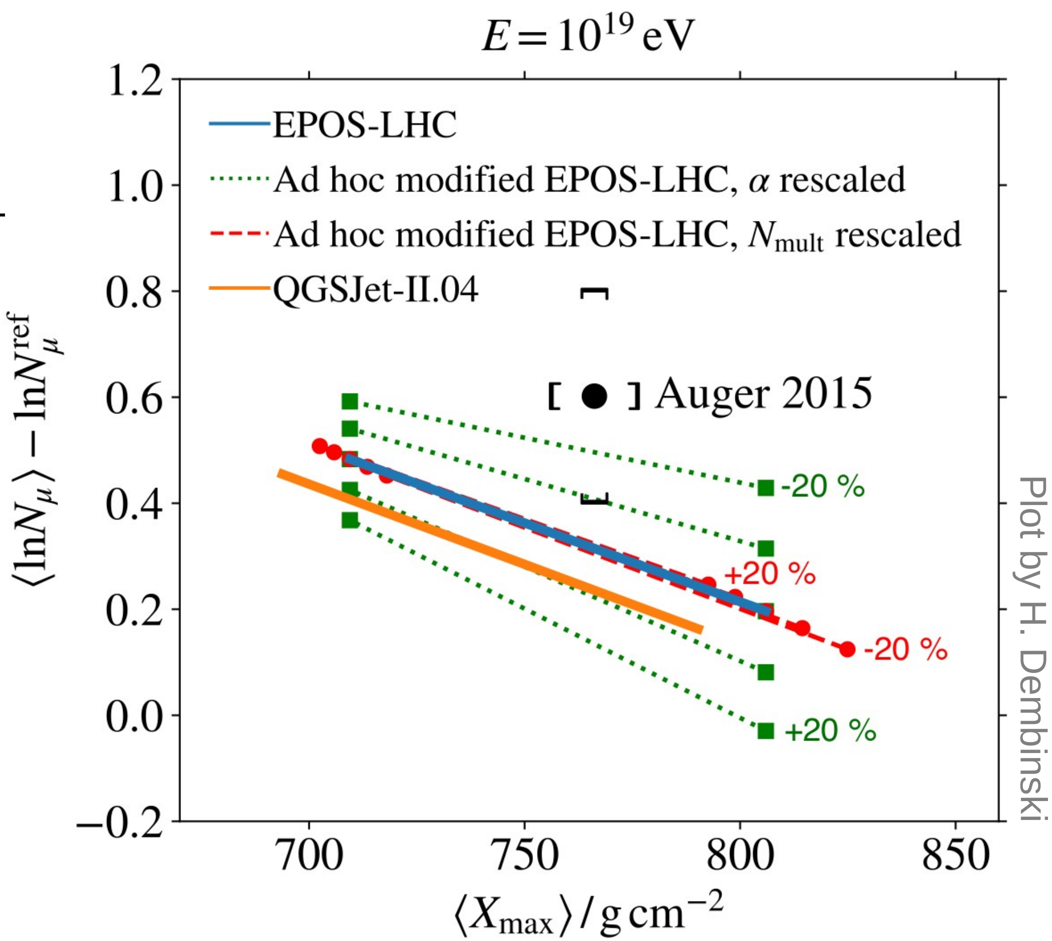
Constraints from Correlated Change

- **One needs to change energy dependence of muon production by ~+4%**

$$N_\mu = A\left(\frac{E}{AE_0}\right)^\beta = A^{1-\beta}\left(\frac{E}{E_0}\right)^\beta$$

- $$\beta = \frac{\ln(N_{mult} - N_{\pi^0})}{\ln(N_{mult})} = 1 + \frac{\ln(1-\alpha)}{\ln(N_{mult})}$$
  - +4% for β ➤ -30% for $\alpha = \frac{N_{\pi^0}}{N_{mult}}$

Depend on hadronization

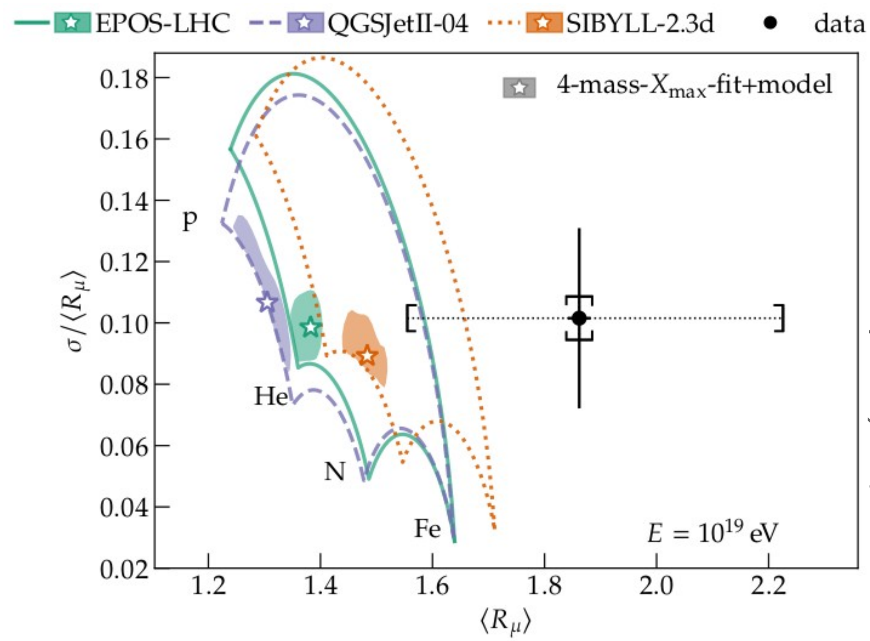


- **To reduce muon discrepancy β has to be change**
  - N_{mult} not good : X_{max} changed
  - α changes β (muon energy evolution) but not X_{max}

Possible (New) Physics Explanation

To change this slope the charge ratio $\alpha = \frac{N_{\pi^0}}{N_{mult}}$ for secondary particle production should be changed

- Reduction of about -30% !
- New Physics ?
  - Chiral symmetry restoration (Farrar et al.) ?
  - Strange fireball (Anchordoqui et al.) ?
  - Lorentz Invariance Violation (Klinkhamer et al.) ?
- No observation at LHC + fluctuation OK !



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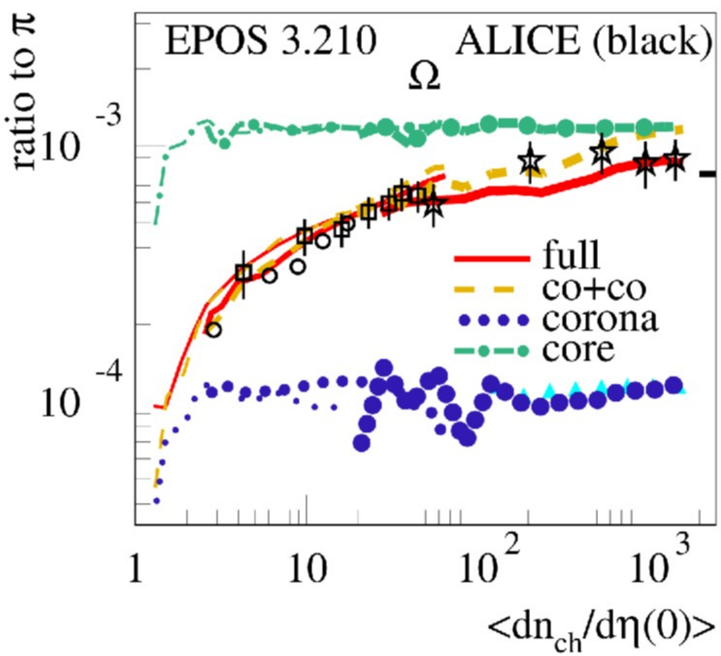
→ Solution cannot be a strong modification at high energy only !

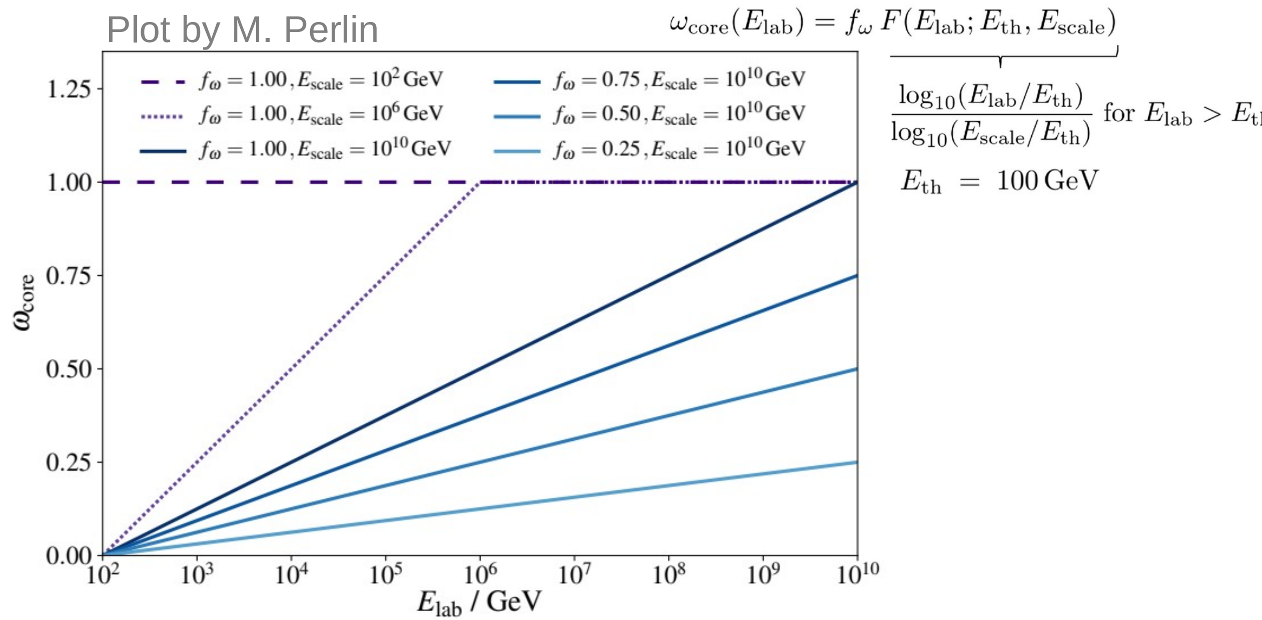
- Unexpected collective effects (QGP ???) in light systems observed at the LHC (at least modified hadronization)
  - Reduced α is a sign of QGP formation (Baur et al.) !
  - Not properly done in current MC (QGP only in extreme conditions)

→ α changed at most by 20-25% … good enough ?

Air Shower with Modified Hadronization

- **Collective effects observed at LHC in light system as a possible hint for different hadronization**
  - ➜ Reduced charged ratio $\alpha = \frac{N_{\pi^0}}{N_{mult}}$ in QGP leads to more muons
  - ➜ Test of simplified core(QGP)-corona(string) using modified CONEX



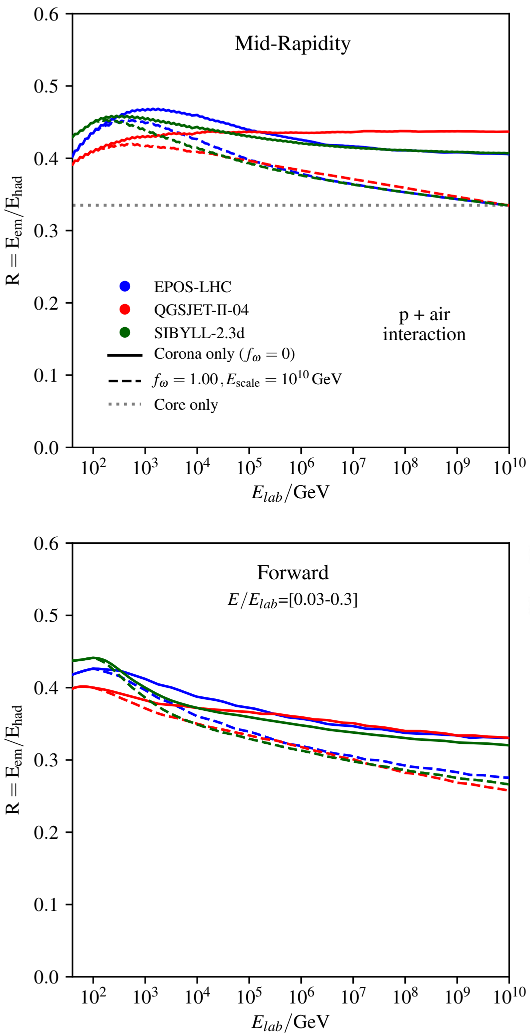


- **Increase of collective hadronization as a possible solution**
  - ➜ Qualitatively in agreement with data, but real MC needed for confirmation !

Core-Corona effect in Air Showers

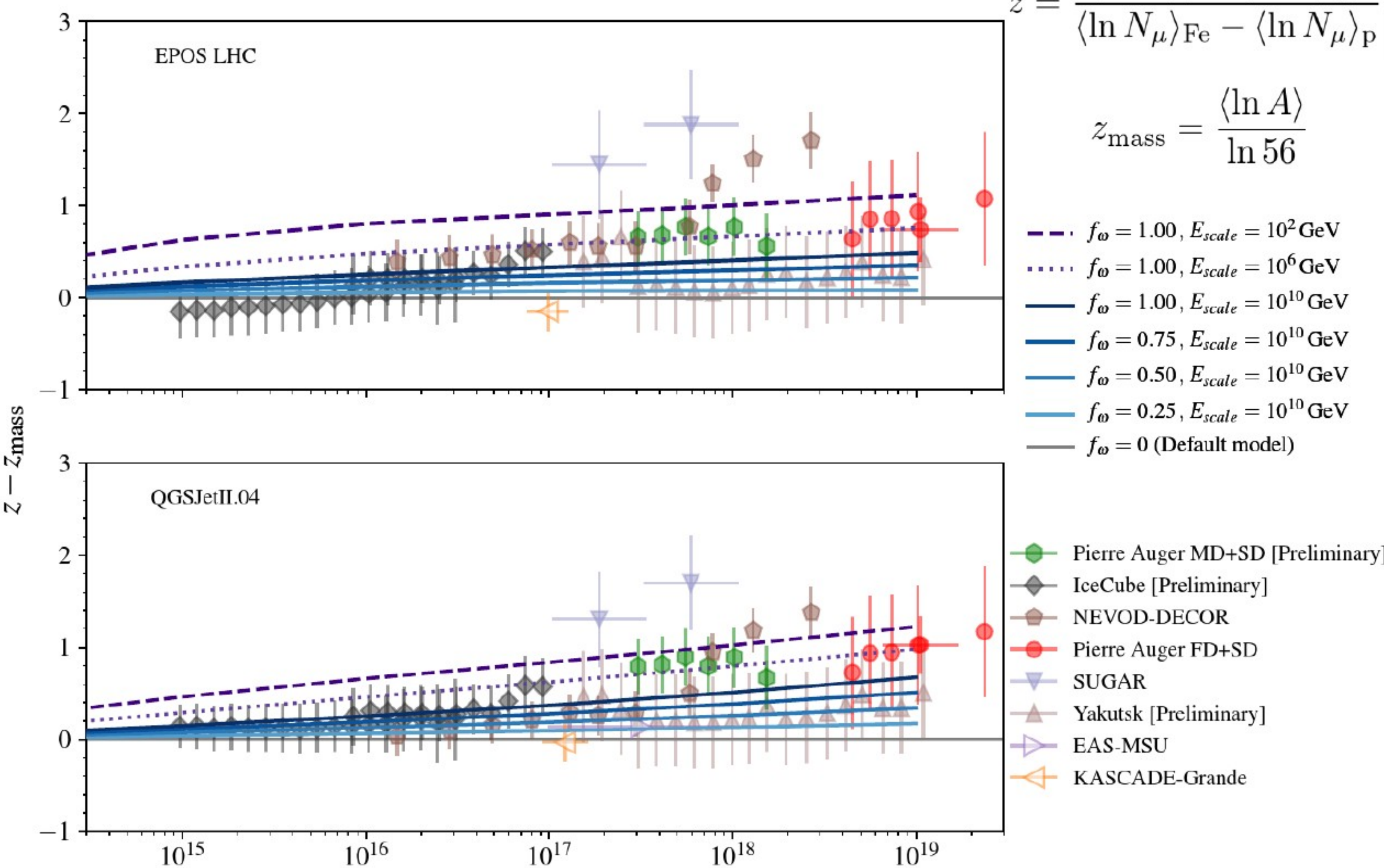
Qualitatively going in the right direction and within data uncertainty

➡ Full MC + more precise data (energy scale) to extract a small BSM signal if any !



$$z = \frac{\langle \ln N_\mu \rangle - \langle \ln N_\mu \rangle_p}{\langle \ln N_\mu \rangle_{Fe} - \langle \ln N_\mu \rangle_p}$$

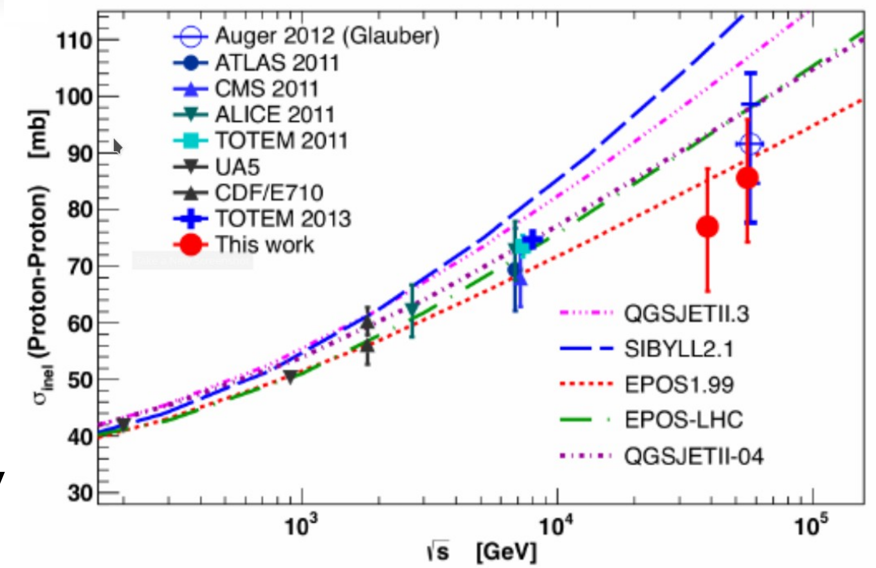
$$z_{mass} = \frac{\langle \ln A \rangle}{\ln 56}$$

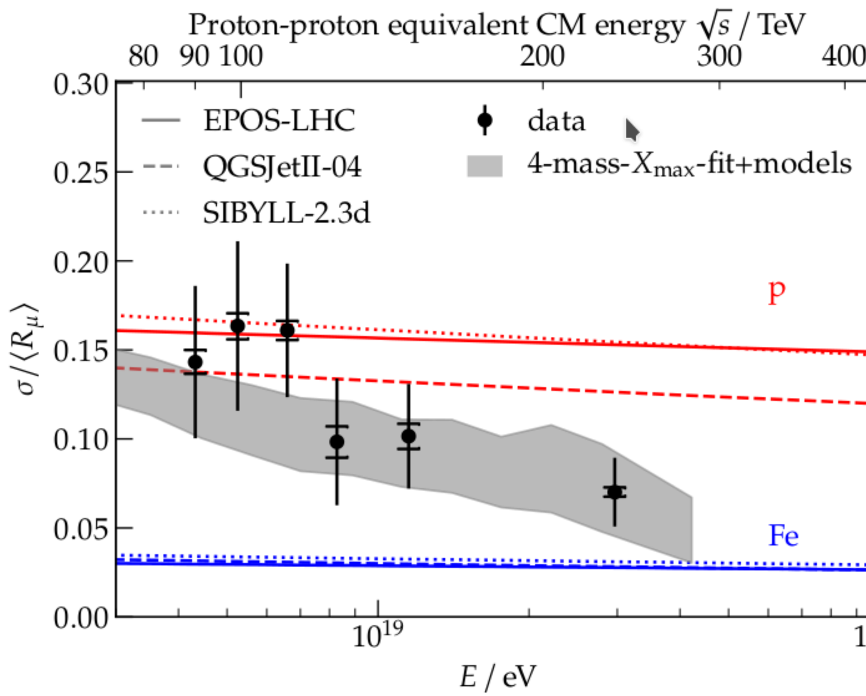


Baur et al. : 1902.09265 [hep-ph]

Air Shower Measurements

- **Inelastic cross-section :**
  - Most direct particle physic measurement
  - No sign of strange behavior
- **Muon fluctuations (1st interaction) :**
  - Same evolution than X_{max} above $E=10^{18.5}$eV
  - Mean start to diverge for $E=10^{16}$eV
  - Difficult to be associated to some BSM effect below LHC energy
- **Already excluded**
  - Strong LIV (best limit from CR)
  - Dramatic phase transition
  - Topological defects (photon limit)





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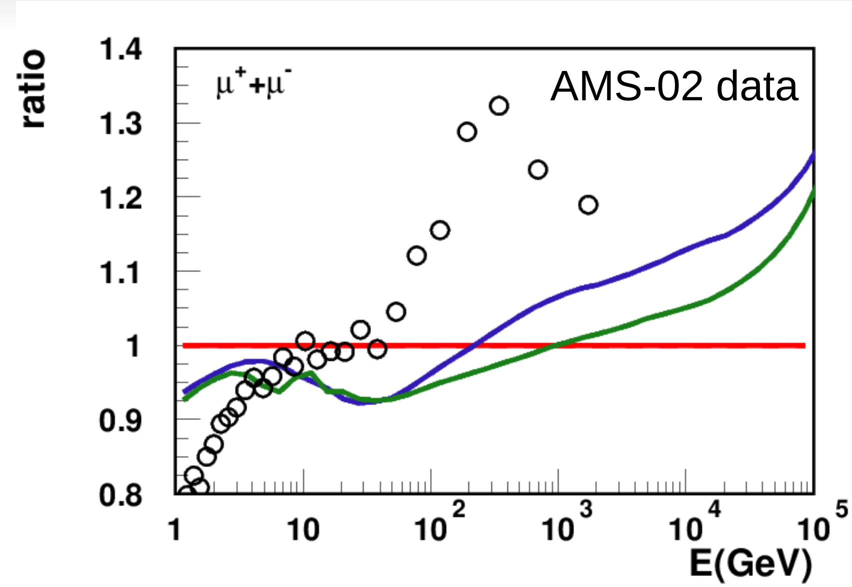
Inclusive fluxes

- **Muon “anomaly” also in low energy inclusive fluxes (20-30%)**
  - ➡ Probably solved by having more strangeness in air showers
  - ➡ In-line with core-corona approach
- **High energy muons (TeV in IceCube)**
  - ➡ Large uncertainty on prompt component (heavy flavors and unflavored mesons)
  - ➡ No real room for BSM
- **New developments to look for DM particles produced by mesons decay or photonuclear interactions**
  - ➡ Competitive limit on millicharged particles
  - ➡ ...



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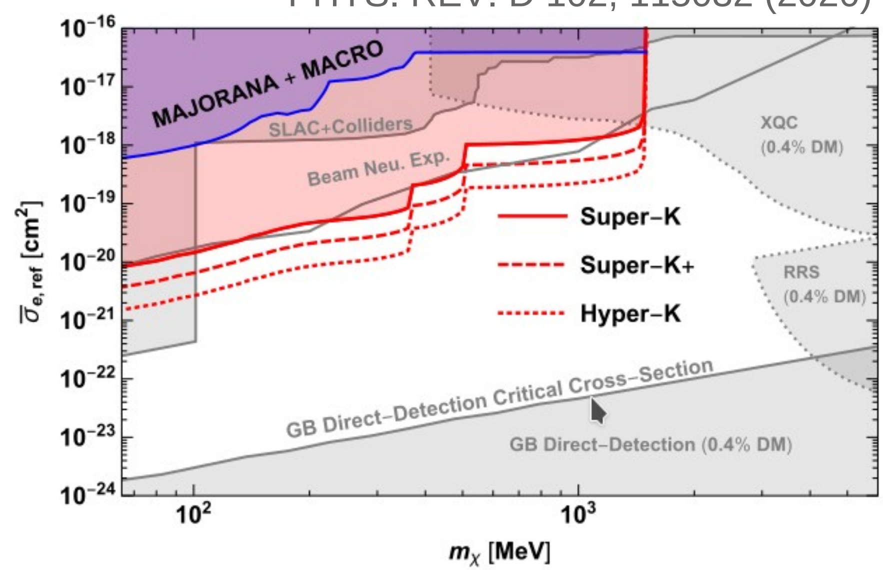


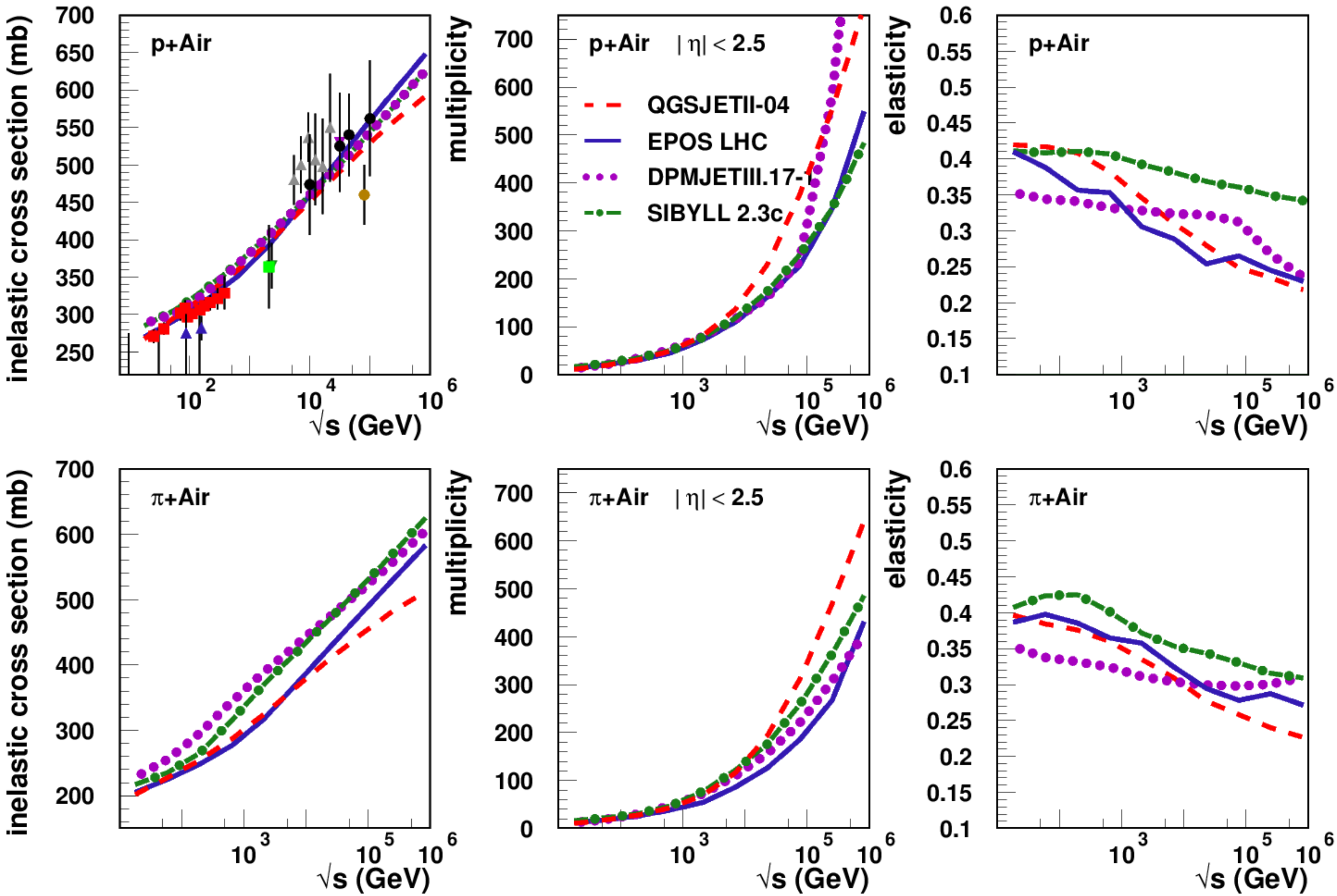
Summary

- **Bad description of muon production in air showers since decades**
  - Deficit of muons in simulations (factor of 2 in old models, now around 40%)
- **X_{max} uncertainties mostly due to nuclear collision extrapolations**
  - Precise measurements (inelastic cross-section, multiplicity, diffraction) needed in **pA and AA with A<20**
    - Light ions at (LHC) and at higher energies (FCC)
  - Benchmark measurement to constrain muon based measurements
- **Strong constraints from fluctuations which show no inconsistency with mass from X_{max}**
- **Models including latest LHC data behavior** (core-corona or string shoving) **probably within one-sigma from current CR data.**

Once the latest results from LHC will be taken into account, and according to latest muon measurements, there is little room left for new physics to explain the muon anomaly.

Backup

Model Prediction Uncertainties



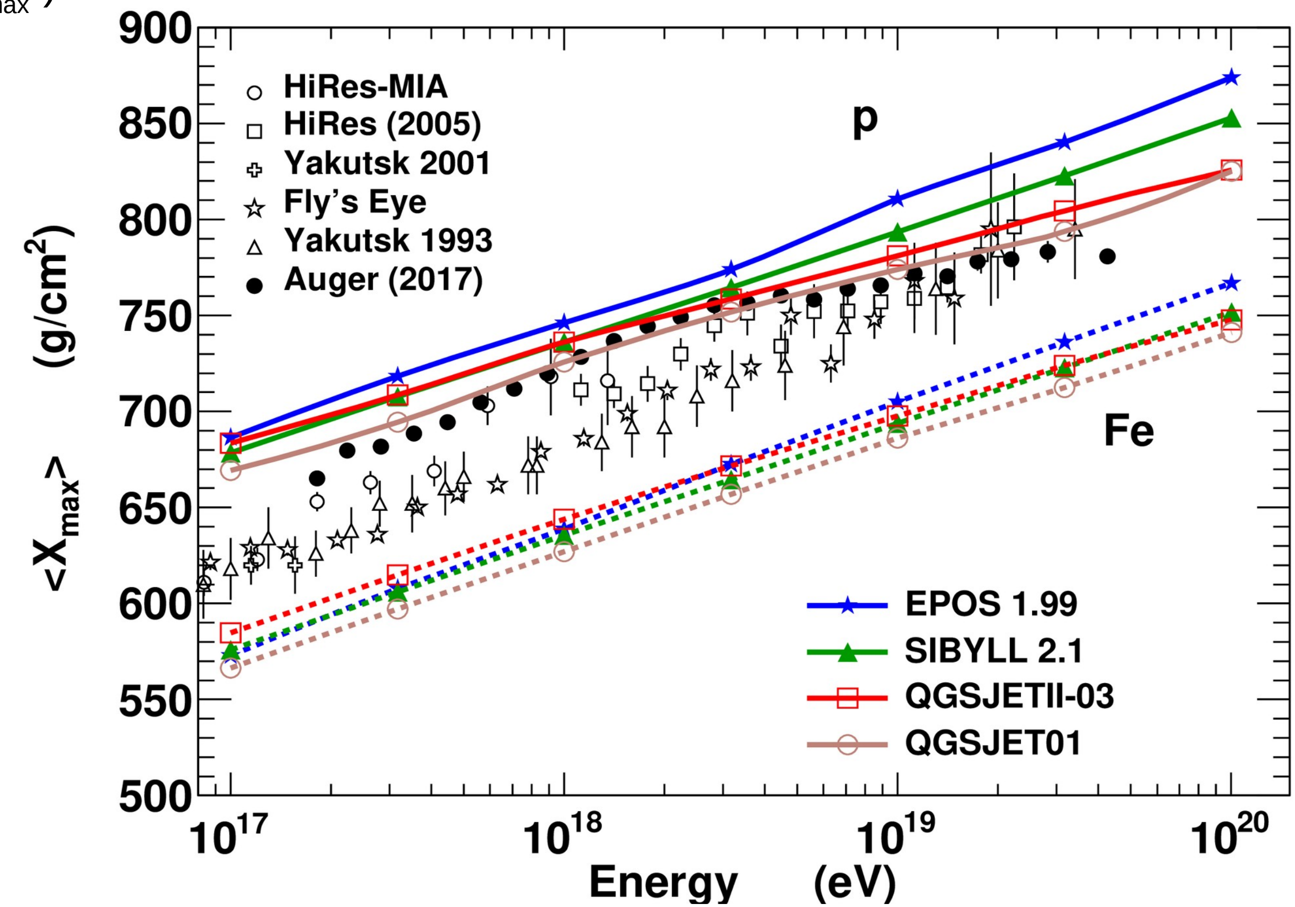
X_{max}

+/- 20 to 40 g/cm² uncertainty from models before LHC

- Larger than modern experimental uncertainties (~15g/cm²)
- Different slope for $<X_{max}>$ for different models : different data interpretation

$$LnA \sim 4 \frac{(X_{max} - X_{max}^{p})}{(X_{max}^{Fe} - X_{max}^{p})}$$

- Different astrophysical interpretation (Auger/TA composition)



Before LHC

WHISP Working Group

- **Much more measurement available**
  - Auger, EAS-MSU, KASCADE-Grande, IceCube/IceTop, HiRes-MIA, NEMOD/DECOR, SUGAR, TA, Yukutsk
- **Working group (WHISP) created to compile all results together. Analysis led and presented on behalf of all collaborations by H. Dembinski at UHECR 2018 :**

H. Dembinski (LHCb, Germany),

L. Cazon (Auger, Portugal), **R. Conceicao** (AUGER, Portugal), **F. Riehn** (Auger, Portugal), **T. Pierog** (Auger, Germany),

Y. Zhezher (TA, Russia), **G. Thomson** (TA, USA) , **S. Troitsky** (TA, Russia), **R. Takeishi** (TA, USA),

T. Sako (LHCf & TA, Japan), **Y. Itow** (LHCf, Japan),

J. Gonzales (IceTop, USA), **D. Soldin** (IceCube, USA),

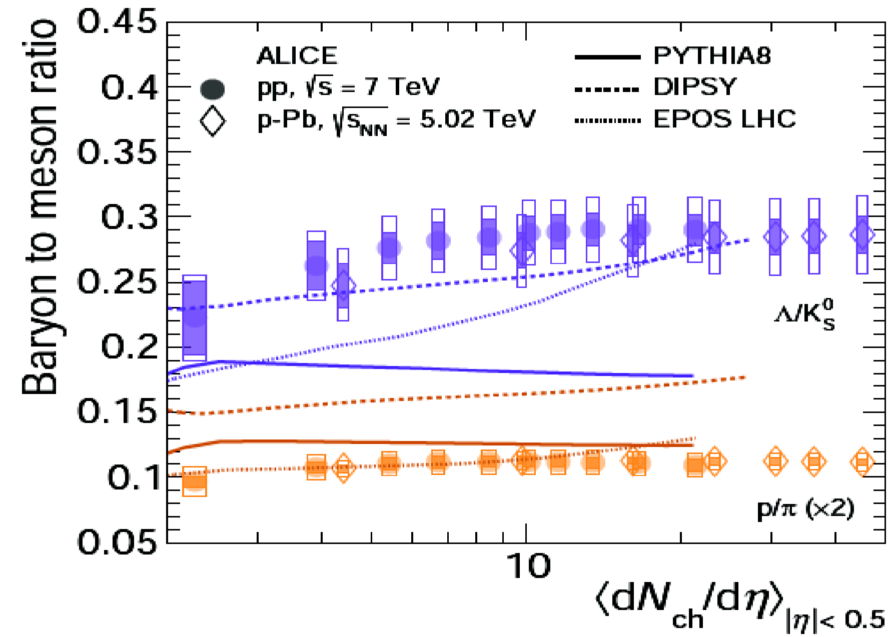
J.C. Arteaga (KASCADE-Grande, Mexico),

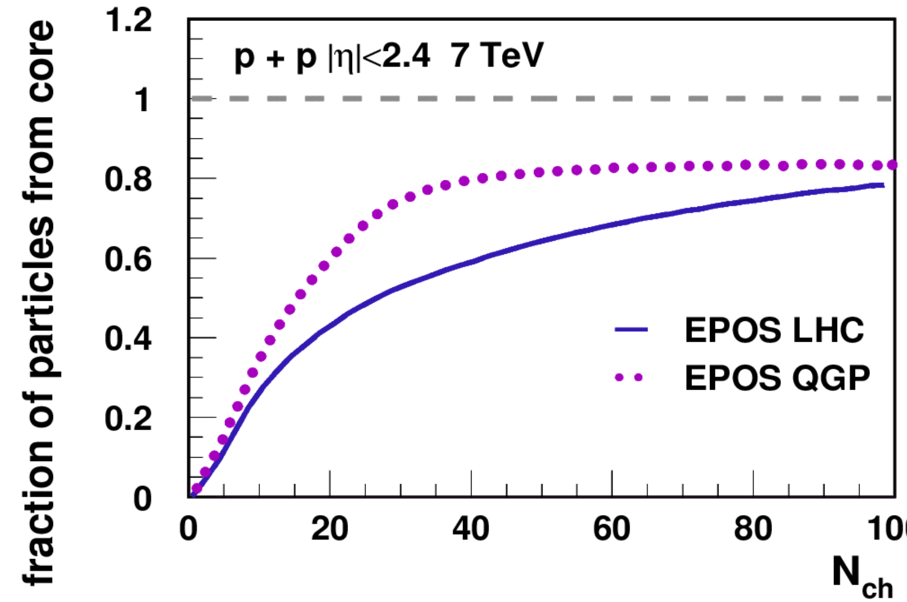
I. Yashin (NEMOD/DECOR, Russia). **E. Zadeba** (NEMOD/DECOR, Russia)

N. Kalmykov (EAS-MSU, Russia) and **I.S. Karpikov** (EAS-MSU, Russia)

Modified EPOS with Extended Core

- **Core in EPOS LHC appear too late**
  - Recent publication show the evolution of chemical composition as a function of multiplicity
  - Large amount of (multi)strange baryons produced at lower multiplicity than predicted by EPOS LHC
- **Create a new version EPOS QGP with more collective hadronization**
  - Core created at lower energy density
  - More remnant hadronized with collective hadronization
  - Collective hadronization using grand canonical ensemble instead of microcanonical (closer to statistical decay)

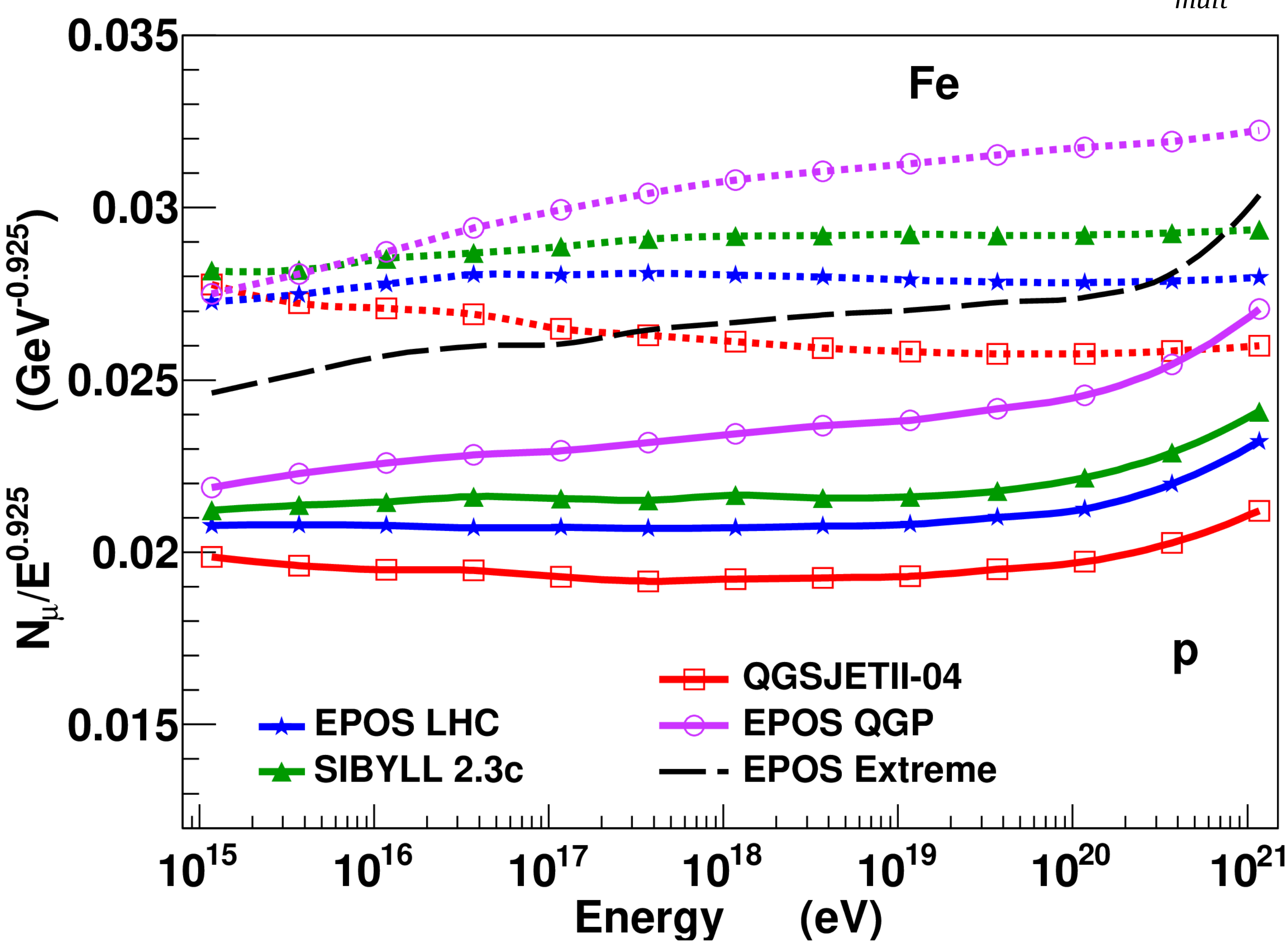


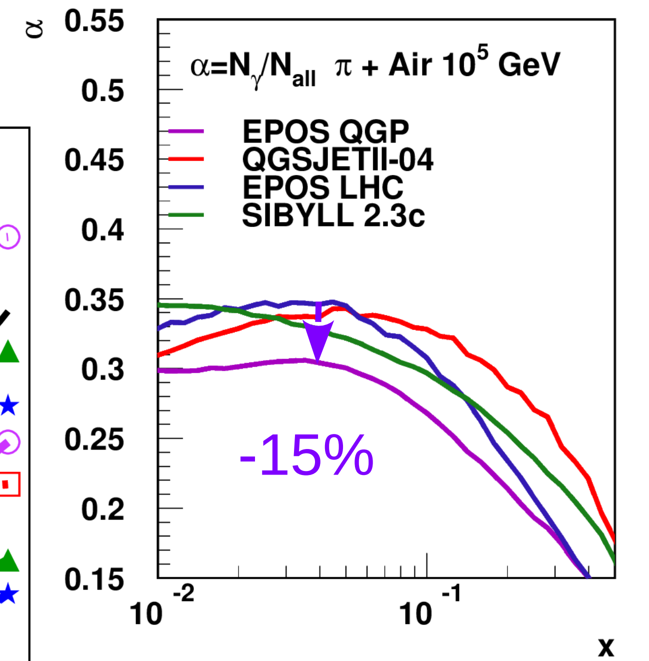


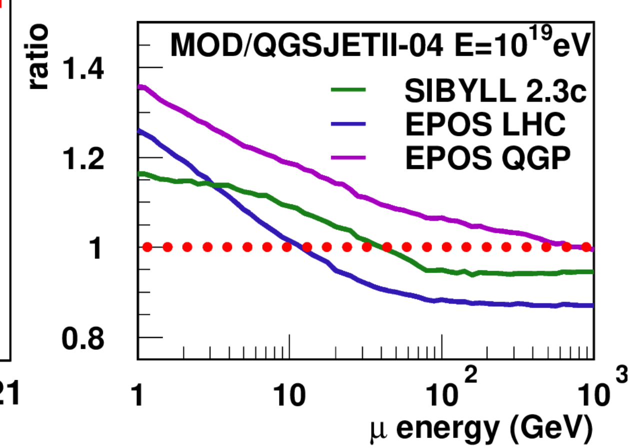
Results for Air Showers

Large change of the number of muons at ground

➜ Different slope as expected from the change in $\alpha = \frac{N_{\pi^0}}{N_{mult}}$

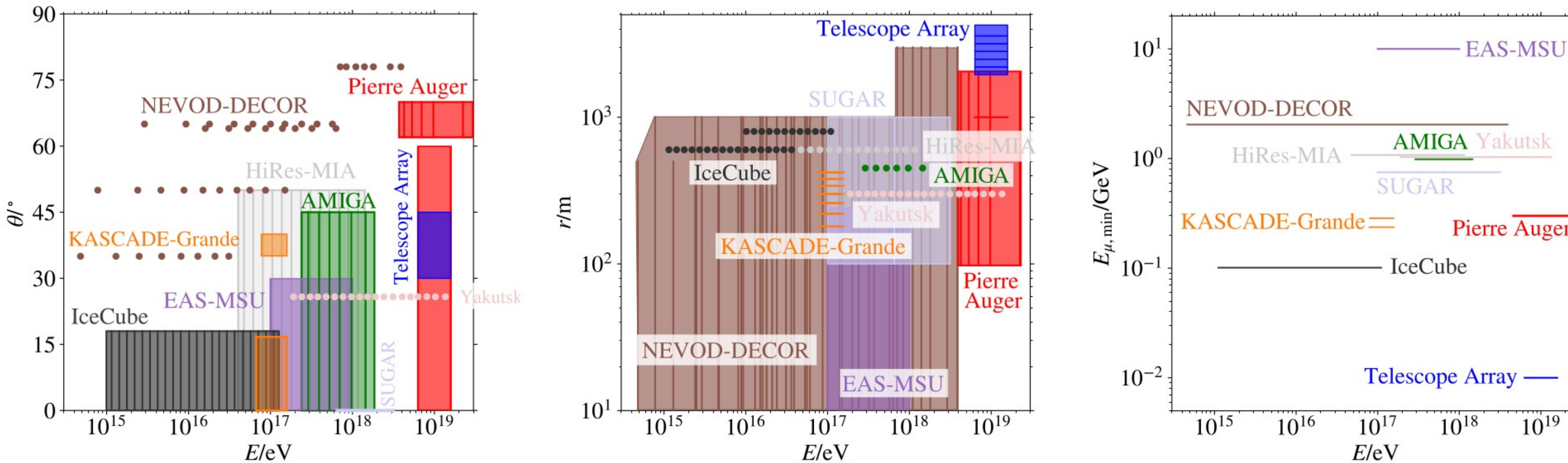






Common Representation

- **Experiments cover different phase space**
  - ➔ Distance to core, zenith angle, energy …

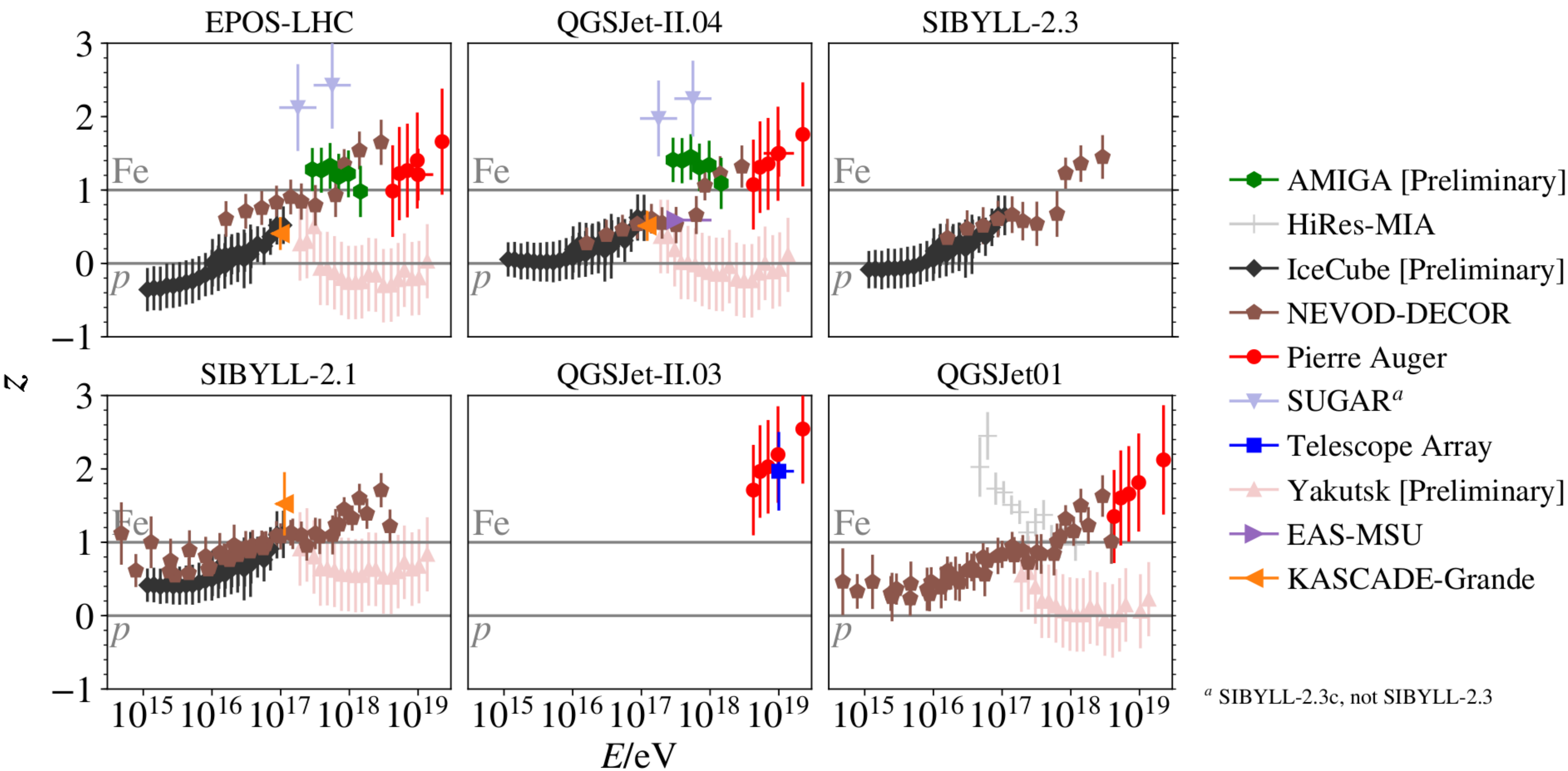


Plots by H. Dembinski

- **Define a unified scale (z) to minimize differences :**

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

Raw Data



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

Renormalization

- **Define a unified scale (z) to minimize differences :**

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

- **From a simple (Heitler) model, the energy and mass dependence of the muon number is given by :**

$$N_\mu = A \left(\frac{E}{AE_0}\right)^\beta = A^{1-\beta} \left(\frac{E}{E_0}\right)^\beta$$

➜ Where β~0.9 is link to hadronic interaction properties

- **To extract proper relative behavior between data and model :**

➜ unique energy scale

➜ estimation of mass evolution

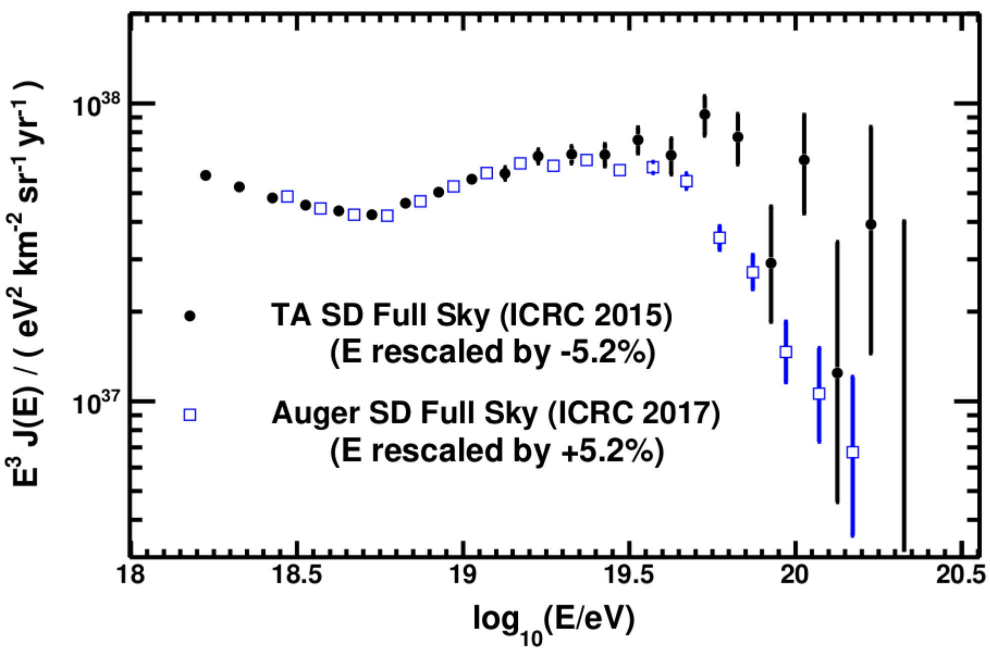
Using an external data based model !

Energy Scale

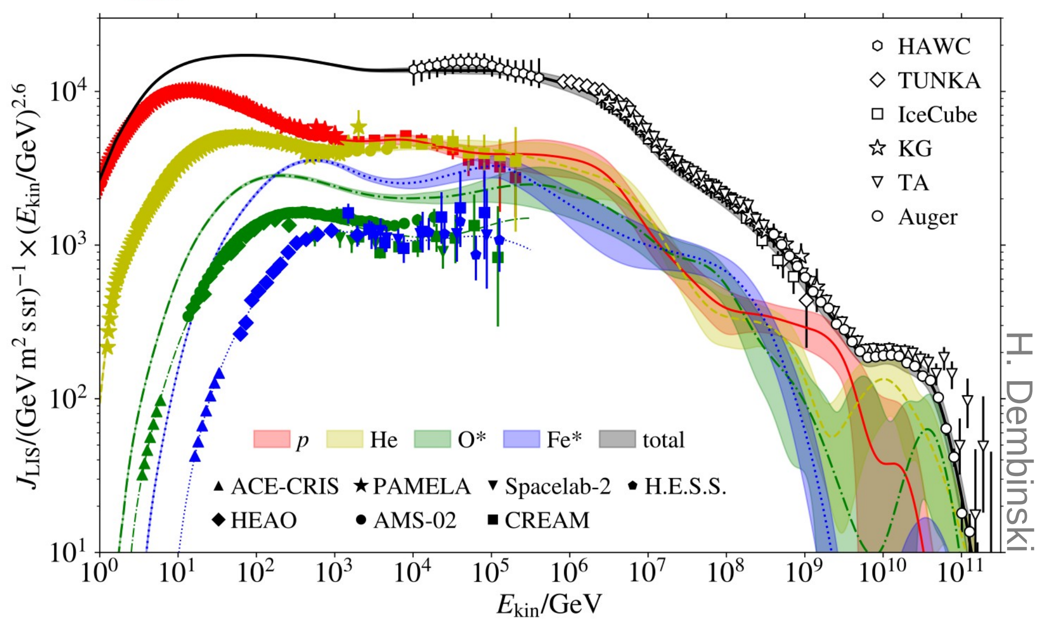
Unique energy scale obtained mixing

- Combine Auger/TA spectrum
- Relative factors between other experiment using the Global Spline Fit (GSF) from H. Dembinski (PoS(ICRC 2017)533)

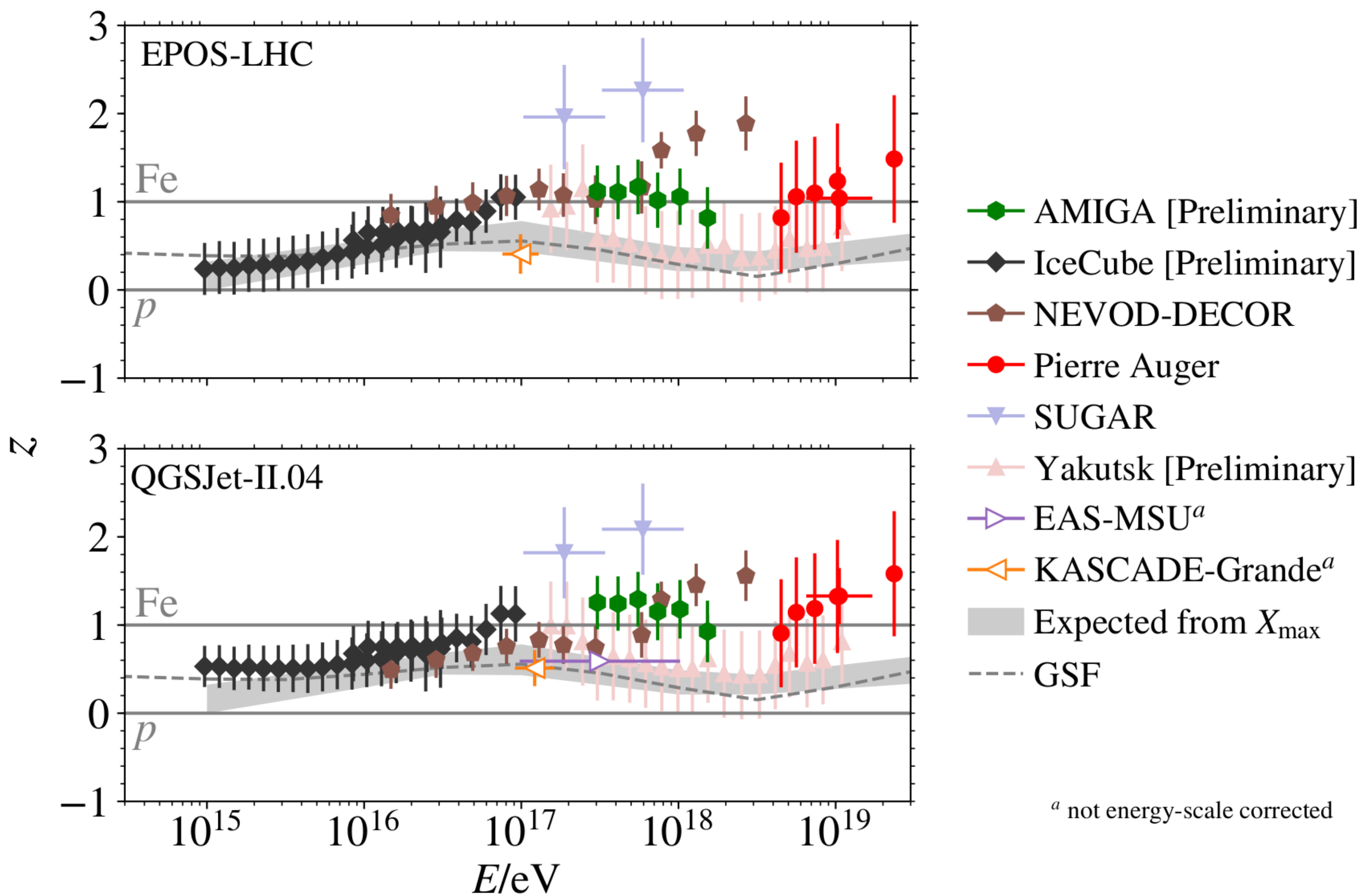
Experiment	E_{data}/E_{ref}
EAS-MSU	unknown
IceCube Neutrino Observatory	1.19
KASCADE-Grande	unknown
NEVOD-DECOR	1.08
Pierre Auger Observatory & AMIGA	0.948
SUGAR	0.948
Telescope Array	1.052
Yakutsk EAS Array	1.24



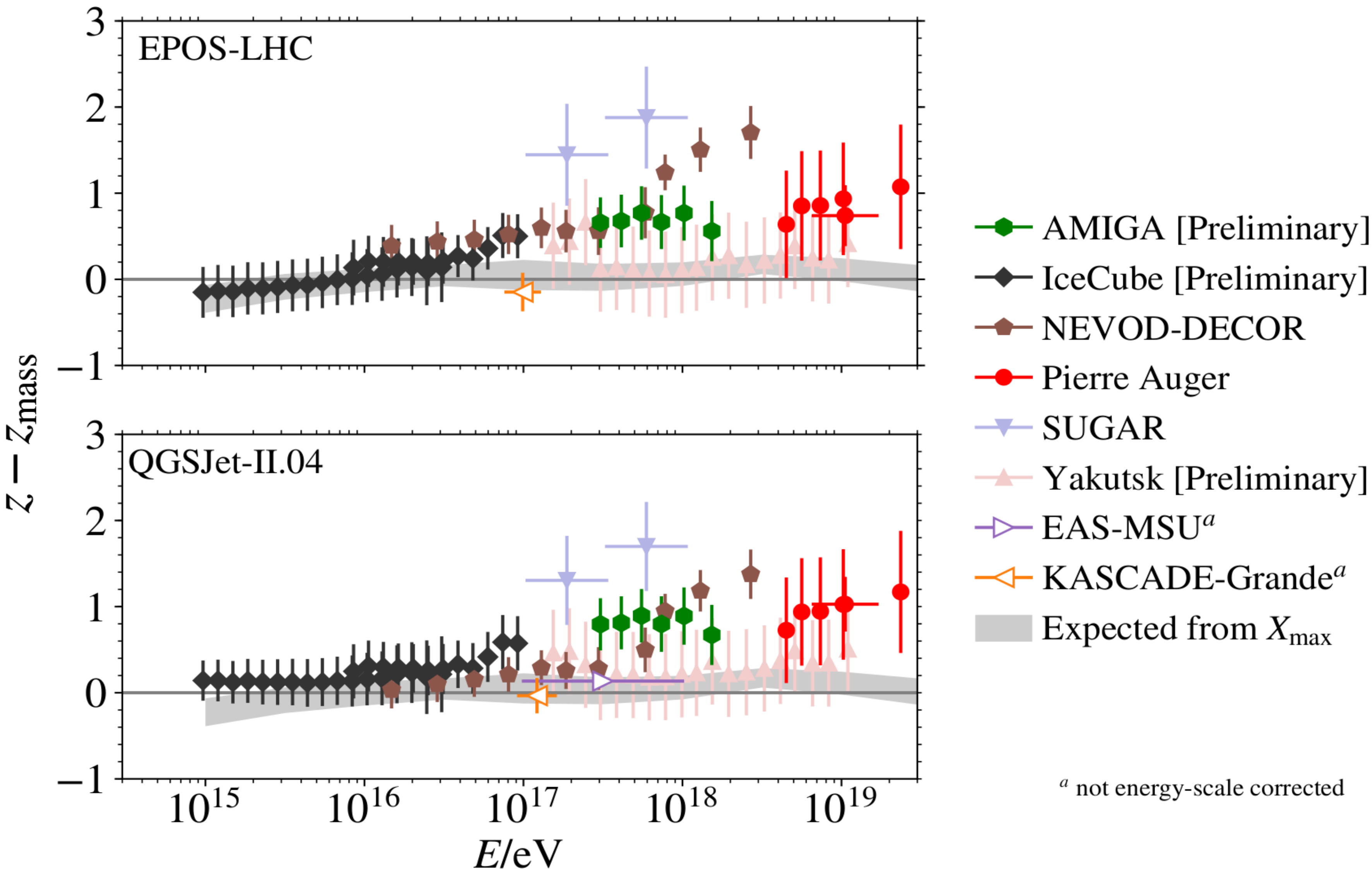
GSF



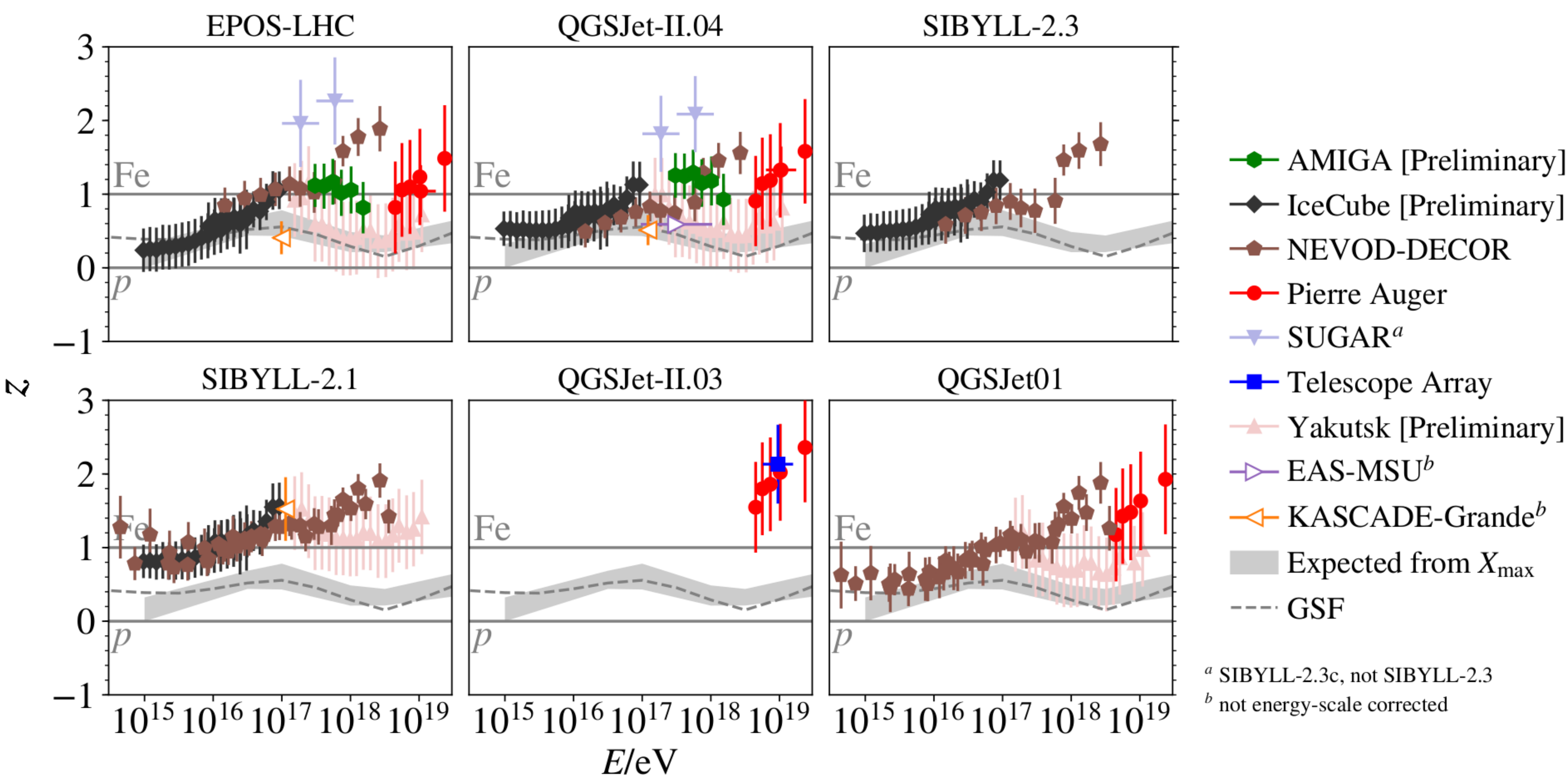
Rescaled Data



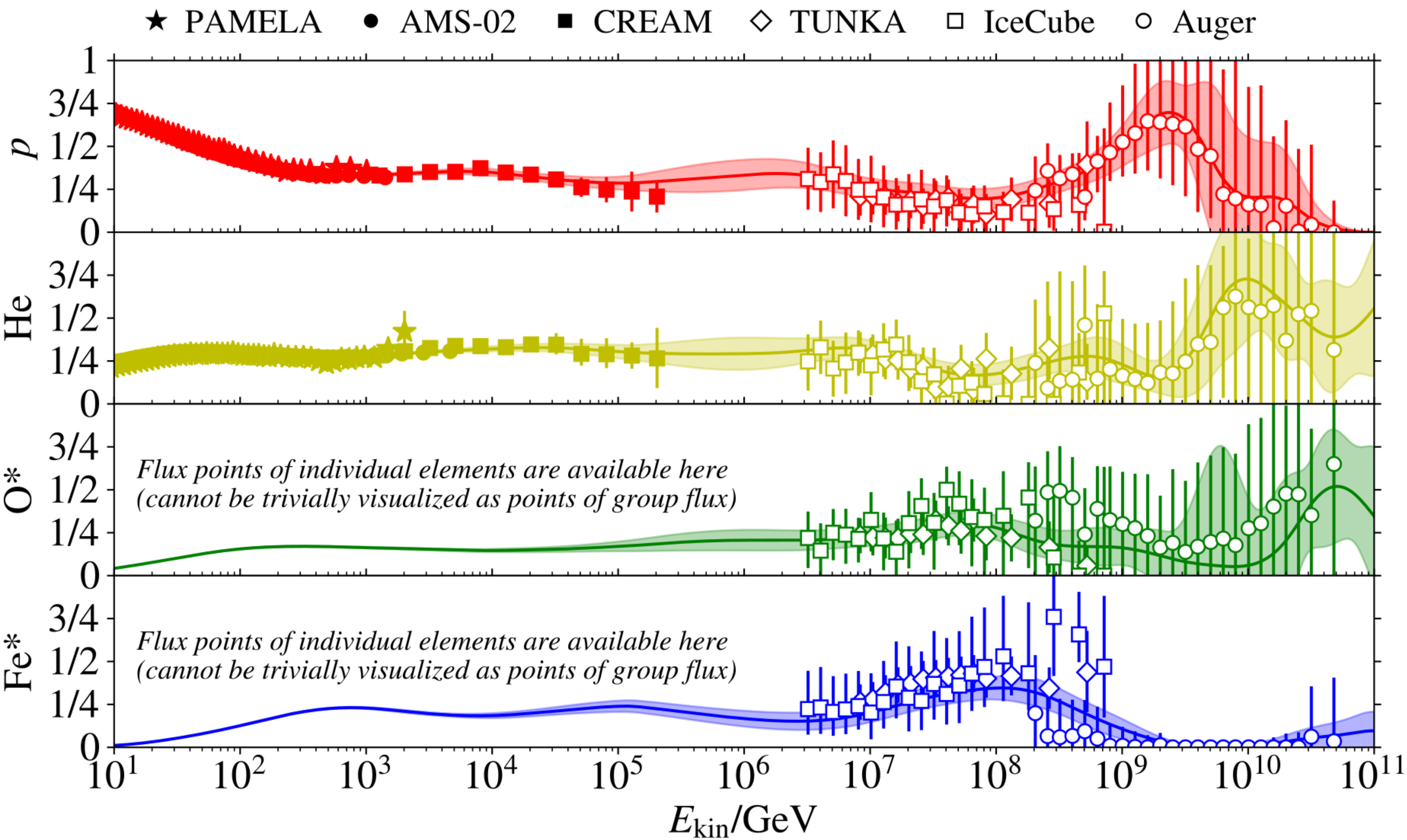
Rescaled Data with Mass Correction



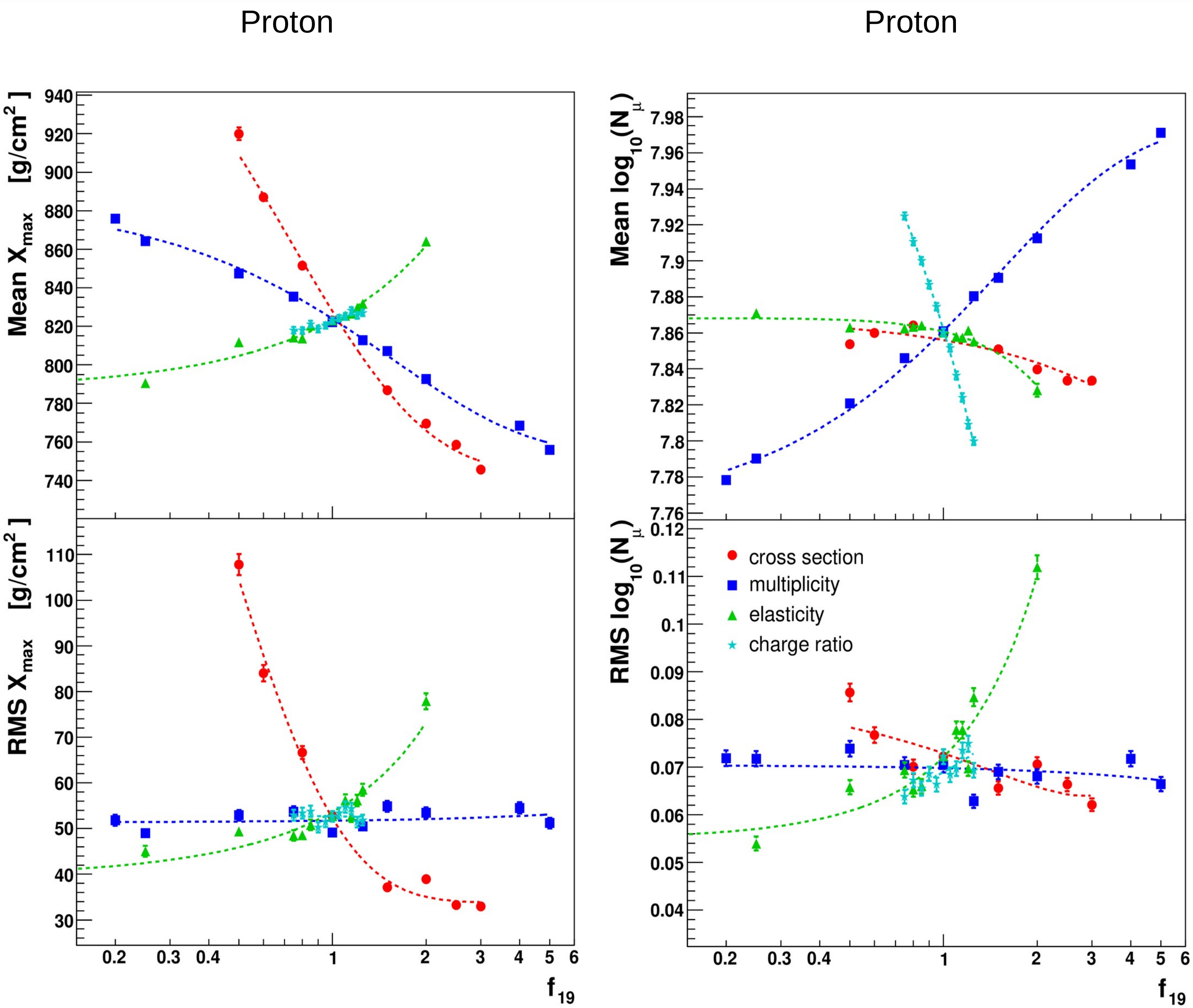
Data Rescaled



GSF Composition Details



Real Observable Dependence



Plots by R. Ulrich (KIT)

Variation of basic parameters

- SIBYLL 2.1
- Original parameters for $E<10^{15}$ eV
- Logarithmic change up to $E=10^{19}$ eV
- Correlation between parameters not taken into account
- Baryon not taken into account in charge ratio (effect can be much larger)

Large sensitivity on pion charge ratio and multiplicity