Hadronic interactions at Highest Energies, and Synergies with LHC p-O

Tanguy Pierog

Karlsruhe Institute of Technology, Institute for Astroparticle Physics, Karlsruhe, Germany

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Outline

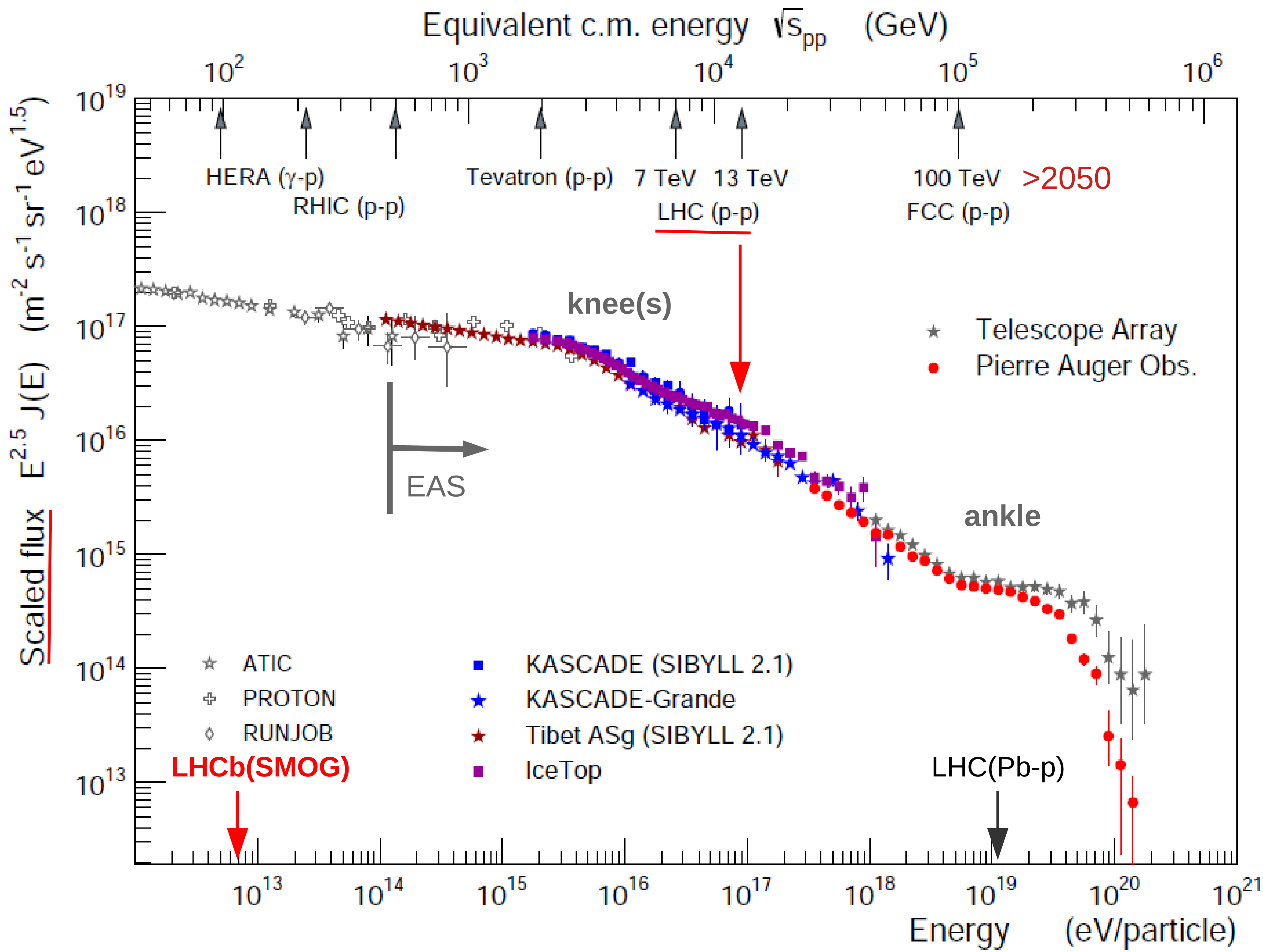
- **Introduction**
- **Particle physics Measurement**
  - ➡ Direct vs Indirect

    importance of mass composition
- **Air shower development**
  - ➡ Link to LHC

    basic observables in p-O
  - ➡ Link to nuclear physics

    hadronization in extreme conditions

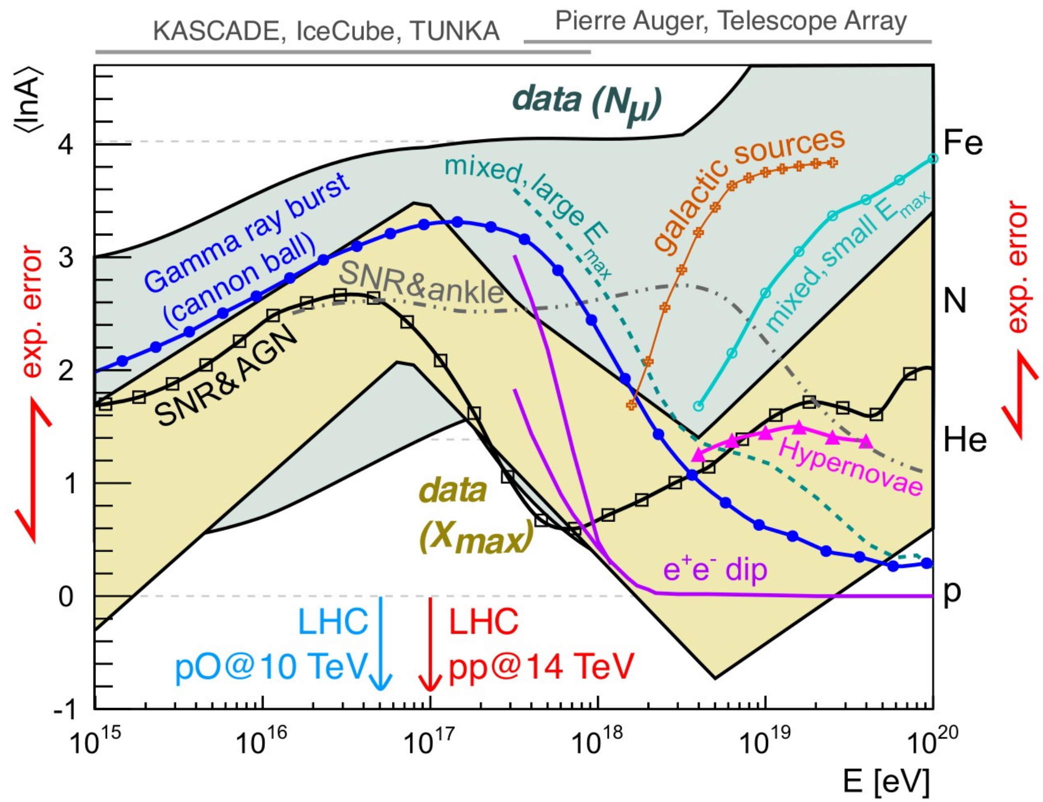
Cosmic Ray Energy Spectrum



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 : hybrid measurement is a must**

Cosmic Ray Hadronic Interaction Models

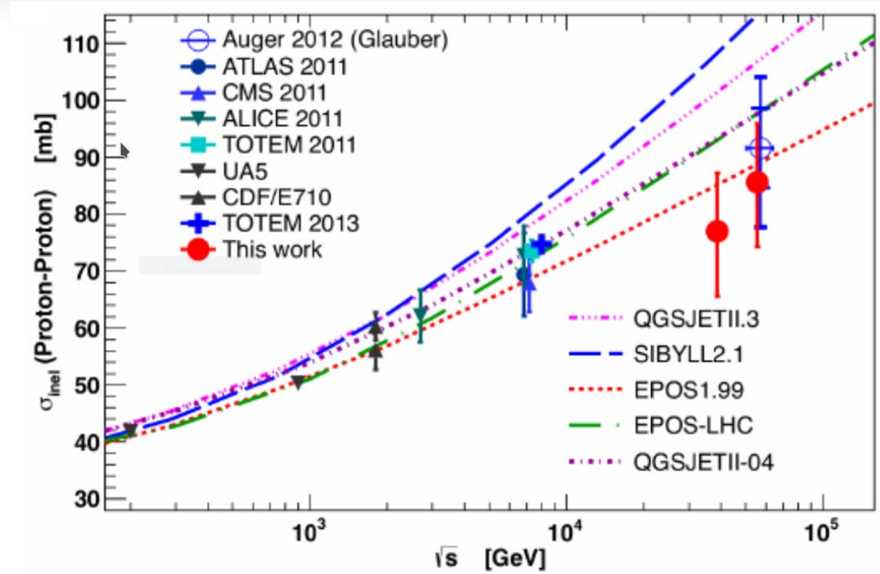
- **Theoretical basis :**
  - pQCD (large p_t)
  - Gribov-Regge Theory (cross section with multiple scattering)
  - energy conservation
- **Phenomenology (models) :**
  - hadronization
    - string fragmentation
    - high density effects (ions)
  - diffraction (Good-Walker, ...)
  - higher order effects (multi-Pomeron interactions)
  - remnants
- **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

Cosmic Ray Hadronic Interaction Models

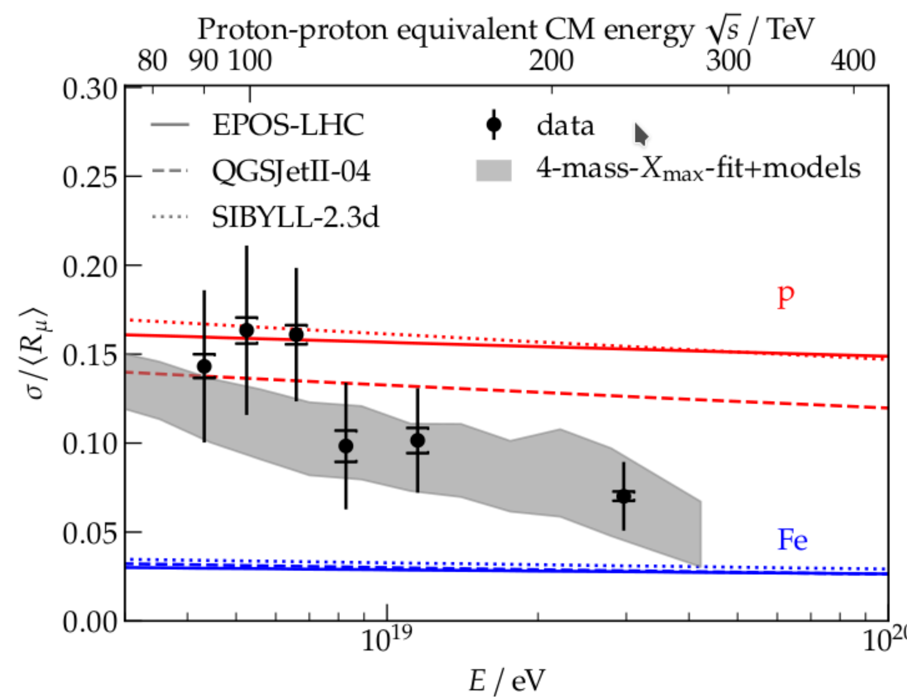
- **Theoretical basis :**
  - pQCD (large p_t) → pdf, jets, heavy flavors → LHC-HL, FCC-pp ep/eA
  - Gribov-Regge Theory (cross section with multiple scattering) → inelastic/total cross section → light ions
  - energy conservation
- **Phenomenology (models) :**
  - hadronization
    - string fragmentation → Fragmentation functions → FCC-ee
    - high density effects (ions) → QGP ? Statistical hadronization → light ions
  - diffraction (Good-Walker, ...) → small "x" physics
  - higher order effects (multi-Pomeron interactions) → light ions
  - remnants → large "x" physics → 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

"Direct" measurements

- **Inelastic cross-section :**
  - Most direct particle physic measurement
  - Require proton component in primary cosmic ray flux !
  - Good mass identification to reduce uncertainties (He contamination) …



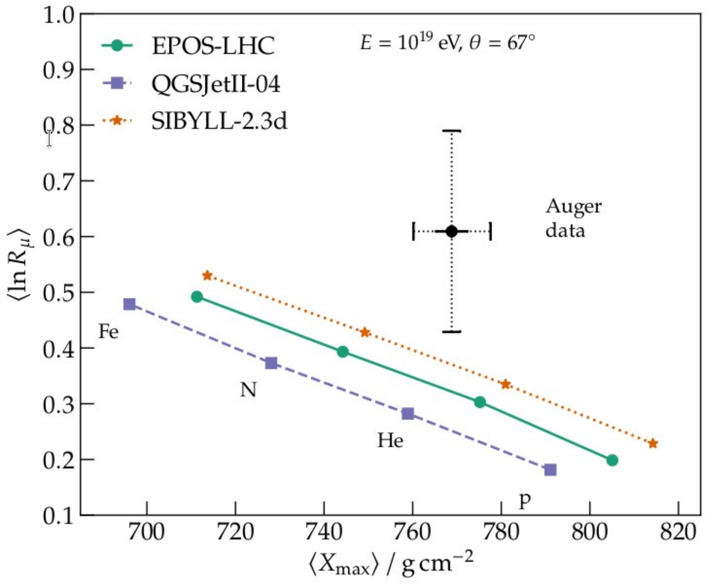
- **Pion spectra :**
  - Based on muon fluctuations (Cazon et al.)
  - Tail sensitive to first interaction
  - Require very high statistic on muon content



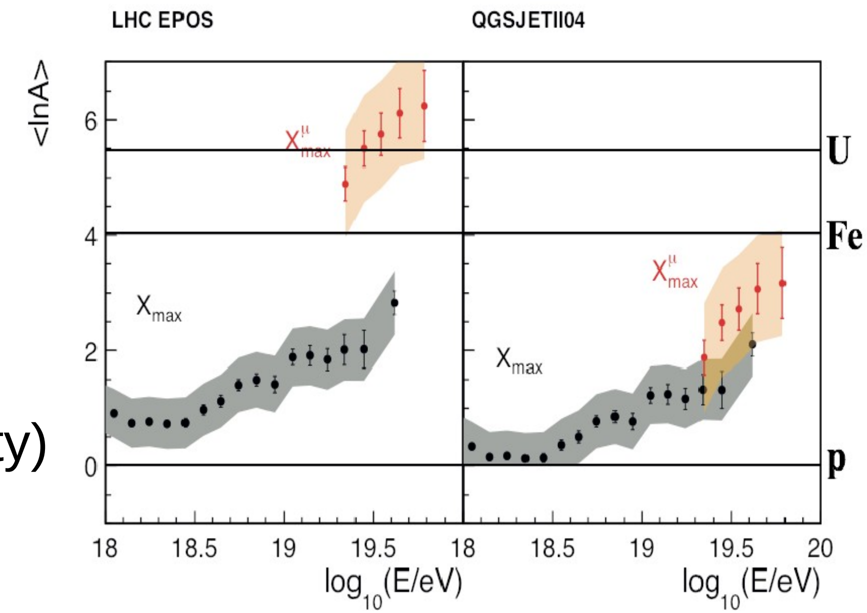
- **Unexpected behavior**
  - New physics ?

“Indirect” measurements

- **Degeneracy between mass composition and hadronic interactions**
  - With unknown mass composition, hybrid type of measurements are a must to test hadronic interactions in EAS
  - Independent measurements of EM and muon component
  - Various types of measurements (number of muons, MPD, X_{max}, rise time, …) and their correlations



- **Different observable = different type of hadronic interactions**
  - X_{max} = first interaction
  - MPD = pion interactions (diffraction, elasticity)
  - Muons = hadronization at all energies
  - ...

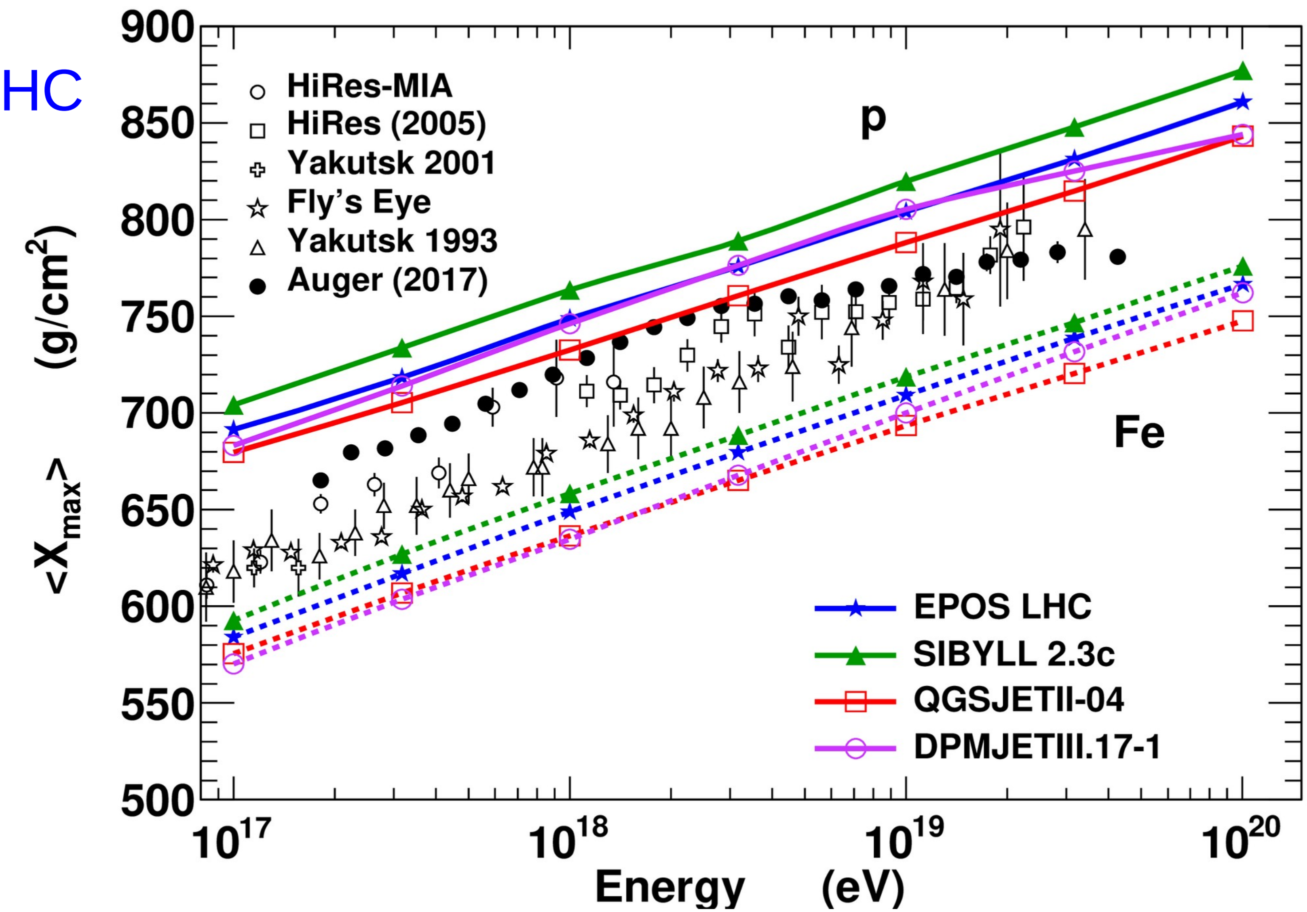


X_{max}

+/- 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
- Significant improvement of the slope : uncertainty on the mean but not on the evolution

After LHC

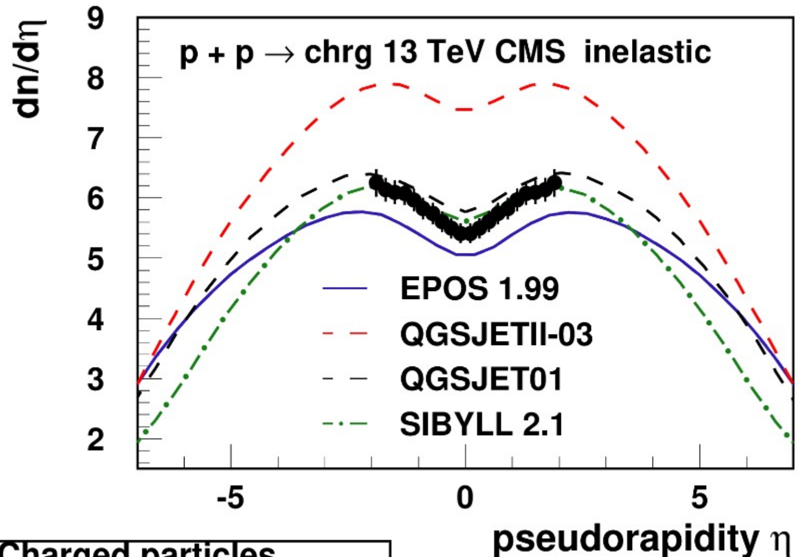


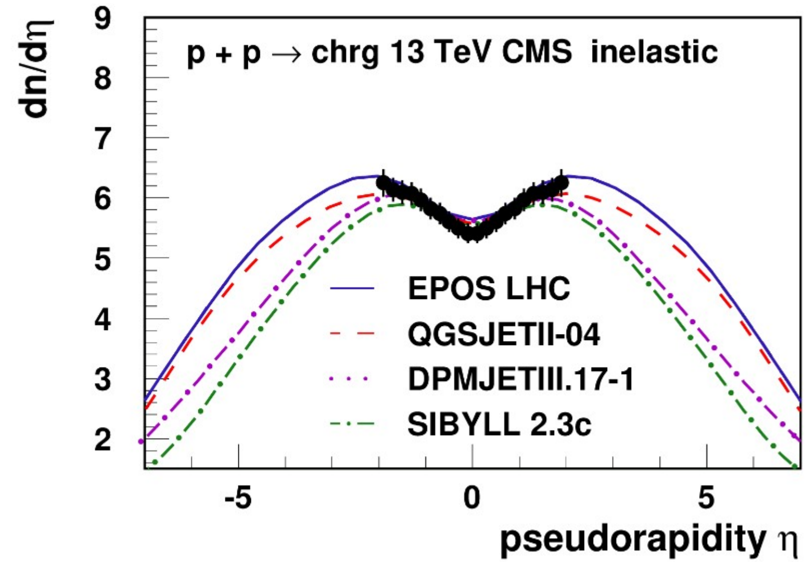
Reference measurement to test hadronic interactions : **muon independent mass composition.** High precision = high sensitivity

Light Ion Data Needed

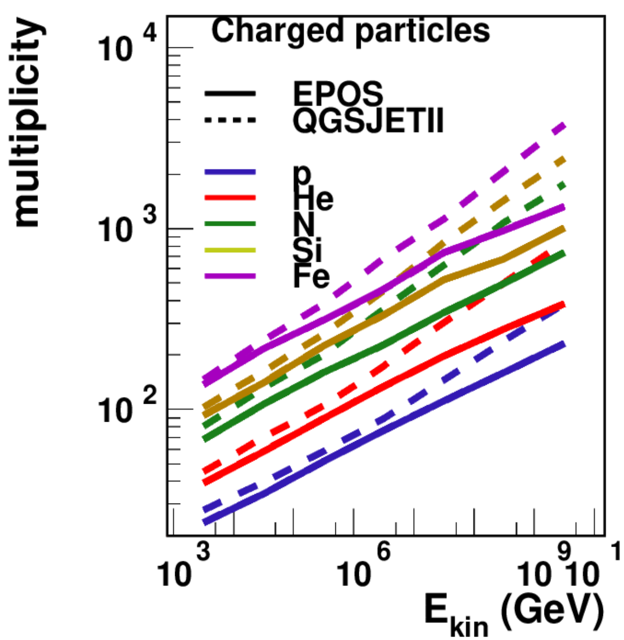
Significant improvement require new data (light ion and higher energy)

Pre - LHC





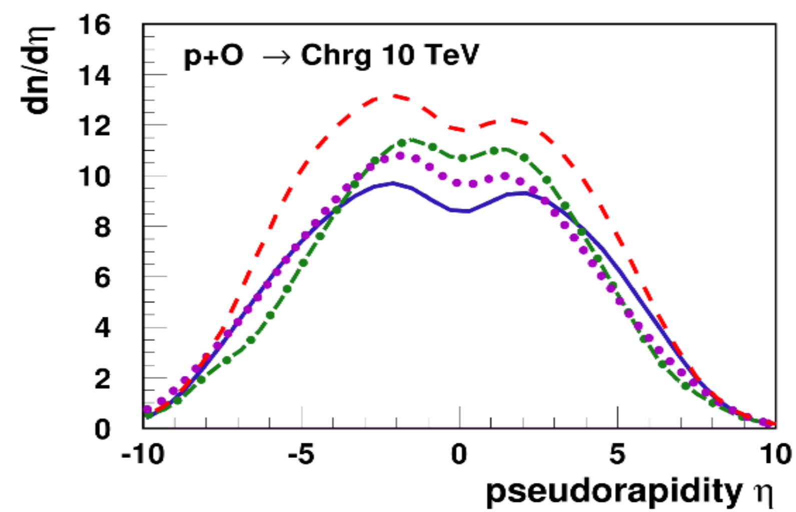
Post - LHC



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

2024 ?

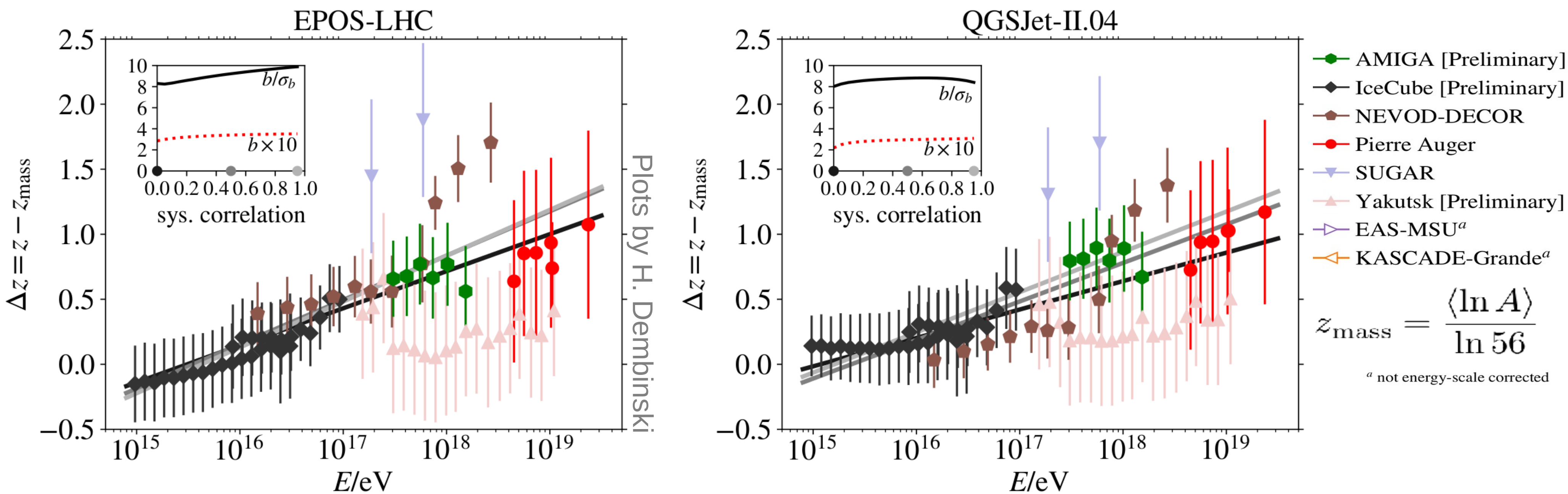
Post - LHC



WHISP Meta-Analysis

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

- **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)



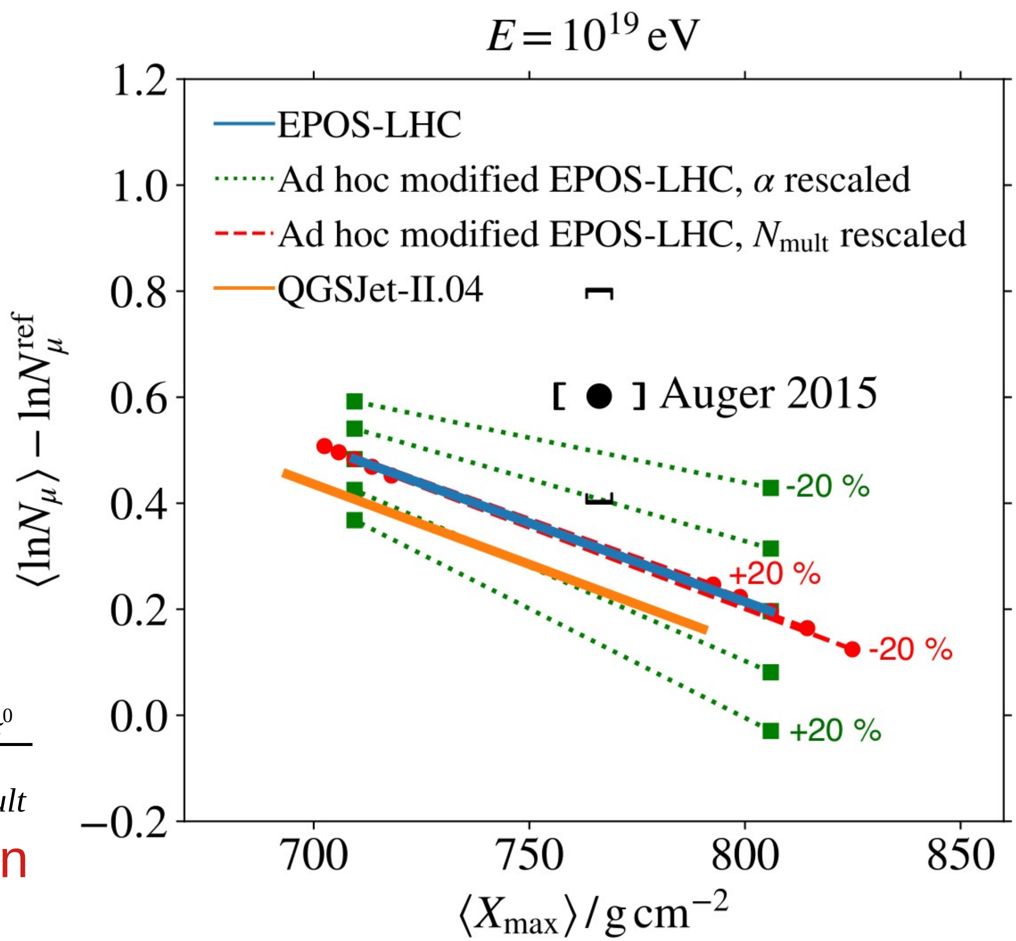
- **Different energy or mass scale cannot change the slope**
  - Different property of hadronic interactions at least above 10^{16} eV

Constraints from Correlated Change

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

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

- **To reduce muon discrepancy β has to be change**
  - X_{max} alone (composition) will not change the energy evolution
  - β changes the muon energy evolution but not X_{max}



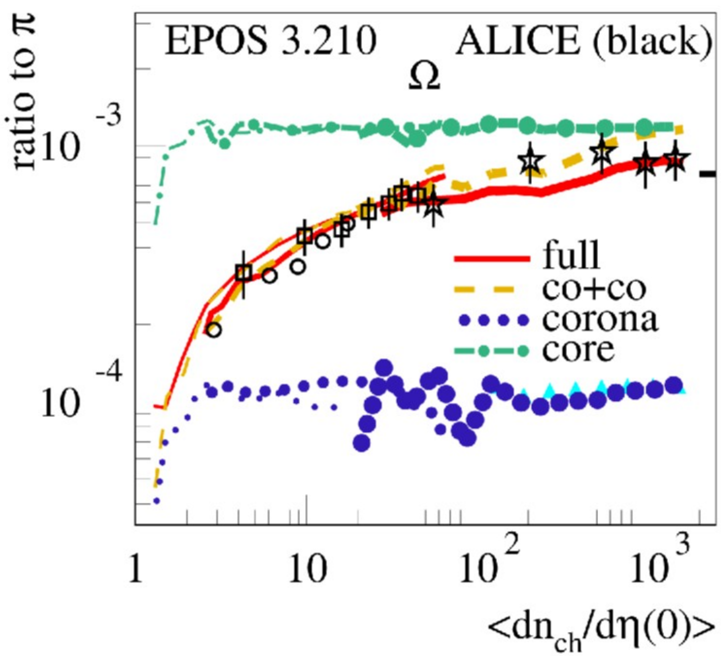
Plot by H. Dembinski

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

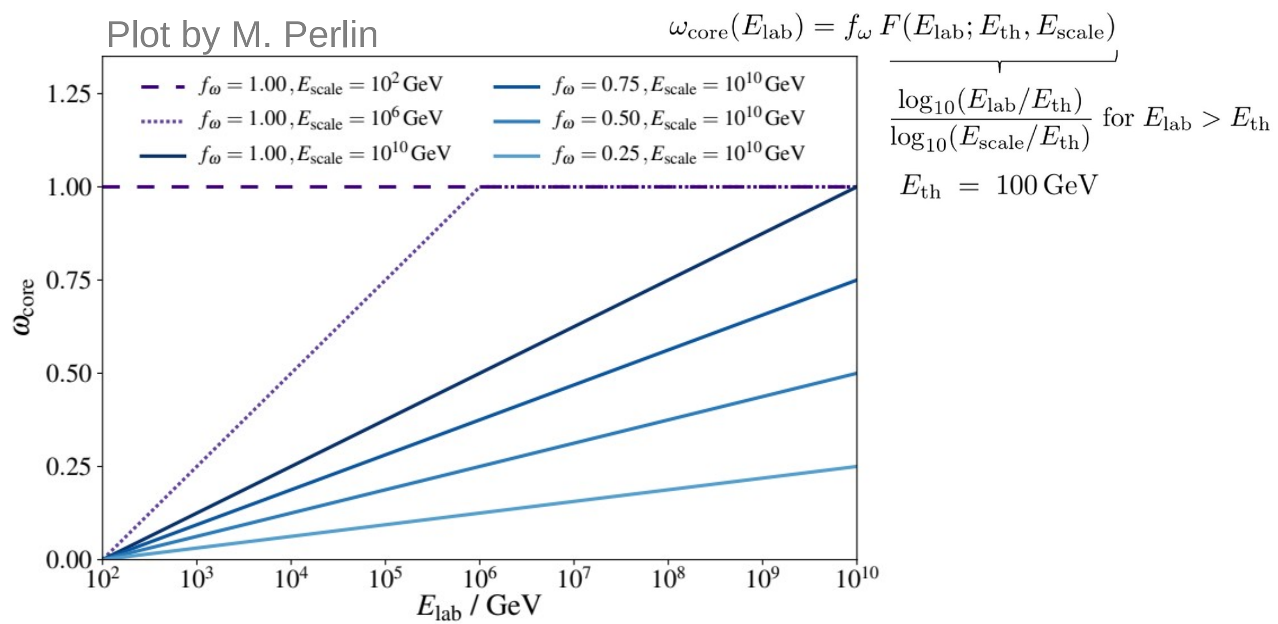
Depend on hadronization

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



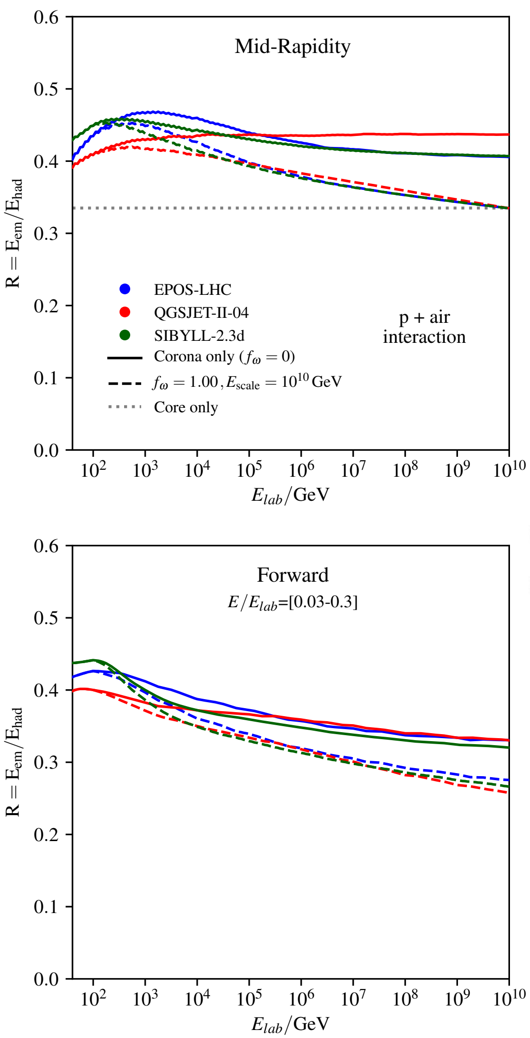
Plot by M. Perlin



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

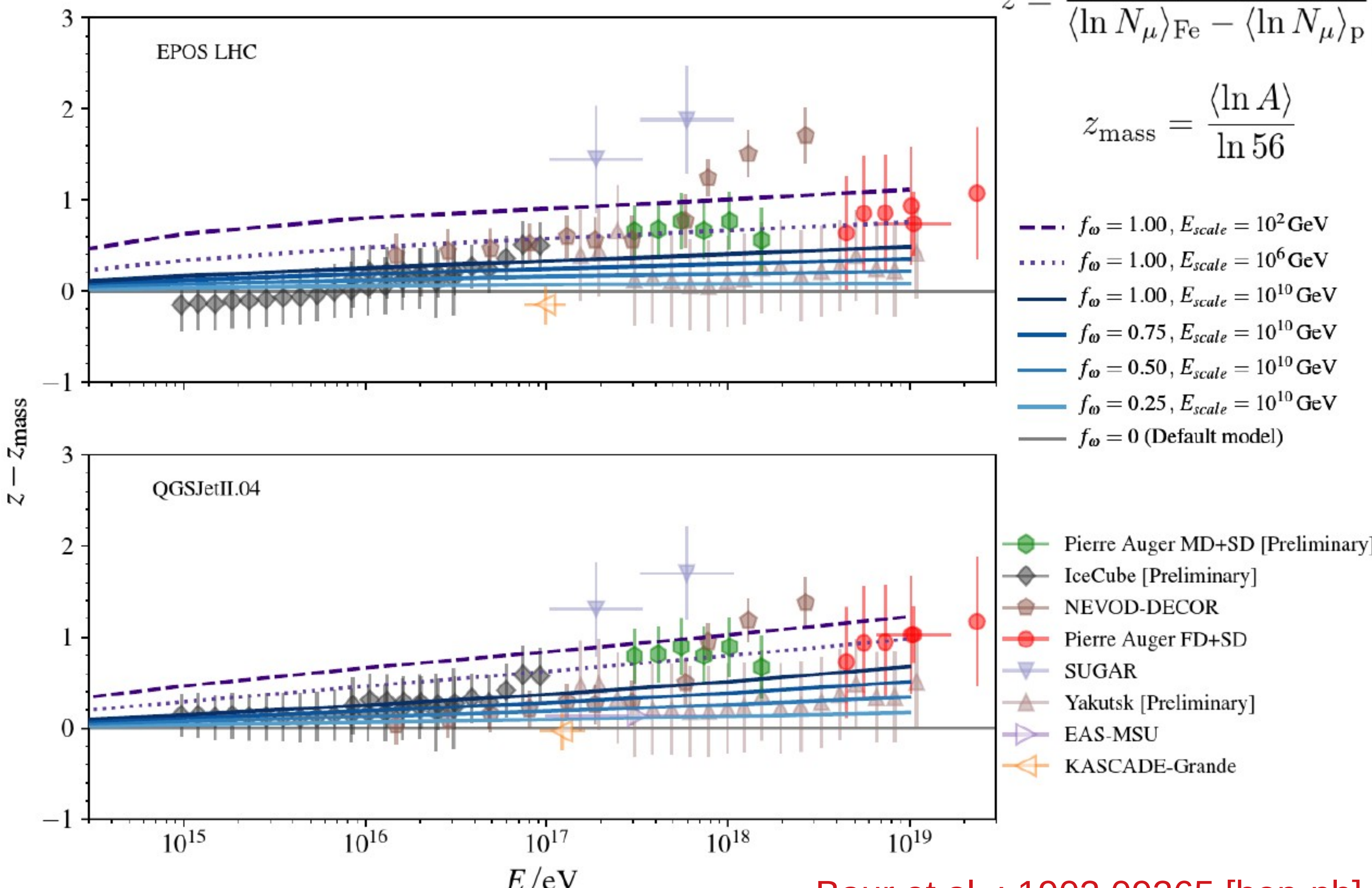
Core-Corona effect in Air Showers

- Artificially change hadronization from corona (string) to core (statistical model) at ALL rapidities (including forward) and increasing core fraction with energy



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

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



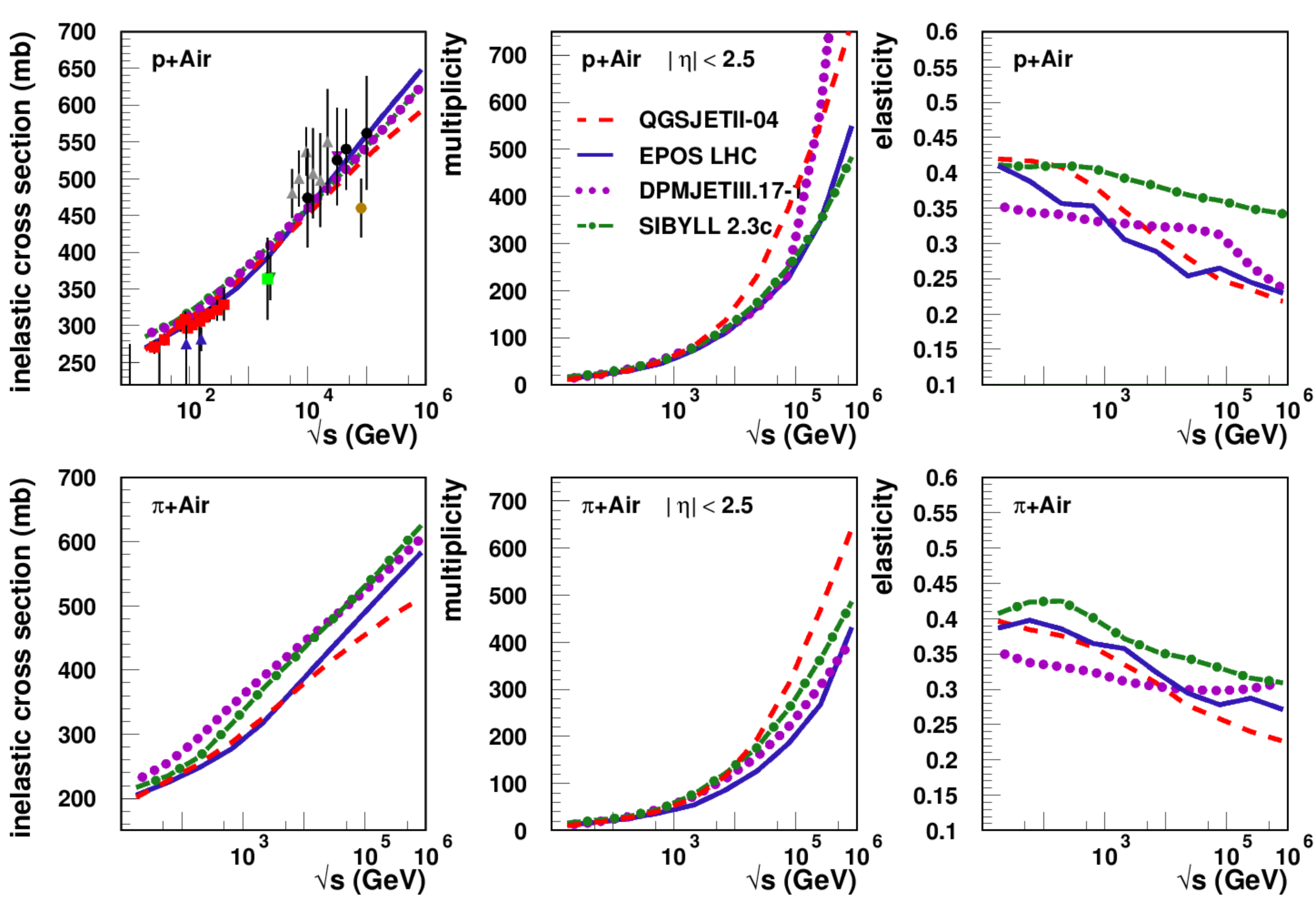
Baur et al. : 1902.09265 [hep-ph]

Summary

- **To test hadronic interactions at the highest energy with GCOS, necessary to have both EM and muons component (and timing)**
  - ➡ More type of measurements = more hadronic components tested
- **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
- **"Muon puzzle" linked to QGP ? … more measurements needed in "light" system and forward rapidities relevant for air showers**
  - ➡ Future generation of model (EPOS 4) will include both hadronization to reproduce LHC data
  - ➡ Remaining discrepancy possibly explain by extreme boost in CR (Anchordoqui et al.)
- **Consistent description of data = more precise mass composition**

Backup

Model Prediction Uncertainties



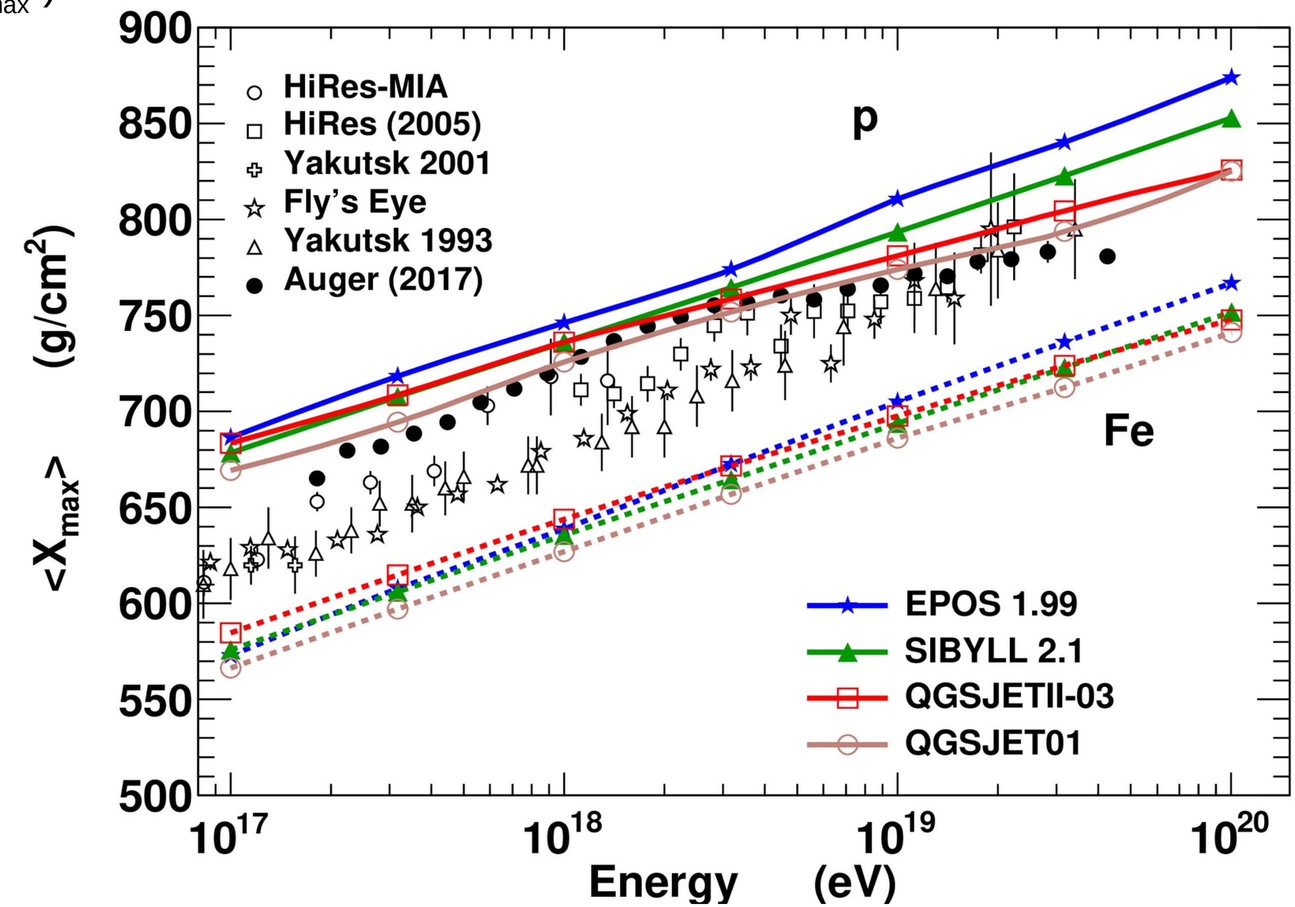
X_{max}

+/- 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

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

- 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)

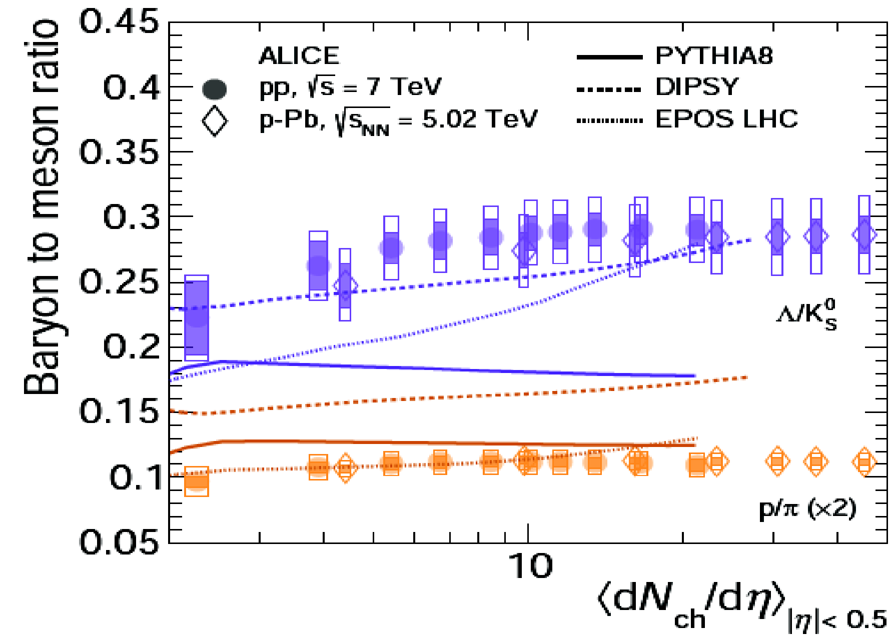
Possible Nuclear Physics Explanation

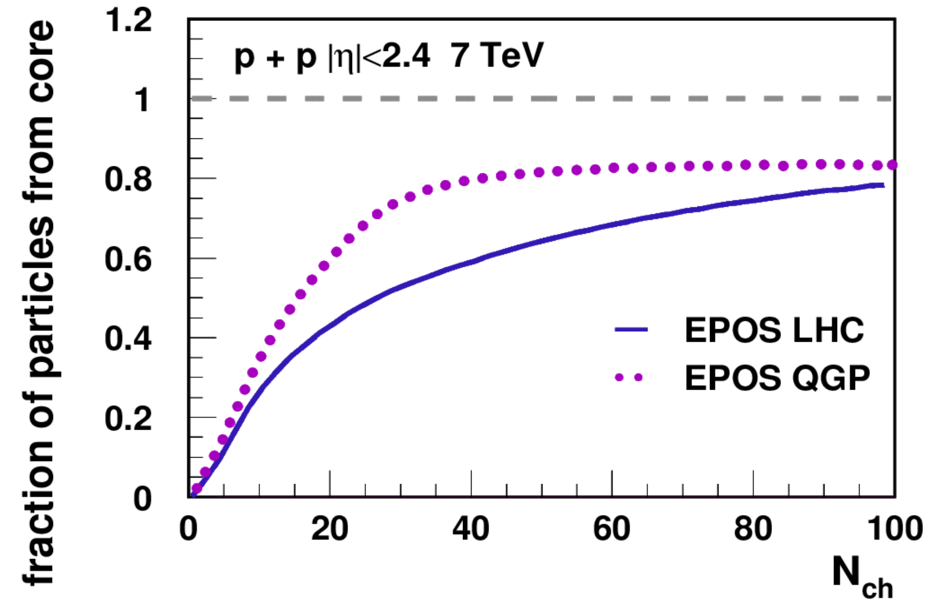
To change this slope the charge ratio $\alpha = \frac{N_{\pi^0}}{N_{mult}}$ for secondary particle production should be changed

- Reduction of about -30% !
- New Physics ?
  - Chiral symmetry restoration (Farrar et al.) ?
  - Strange fireball (Anchordoqui et al.) ?
    - Effect observed at LHC (~10^{17} eV) ?
- 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)
    - Problem : α changed at most by 20-25%

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)

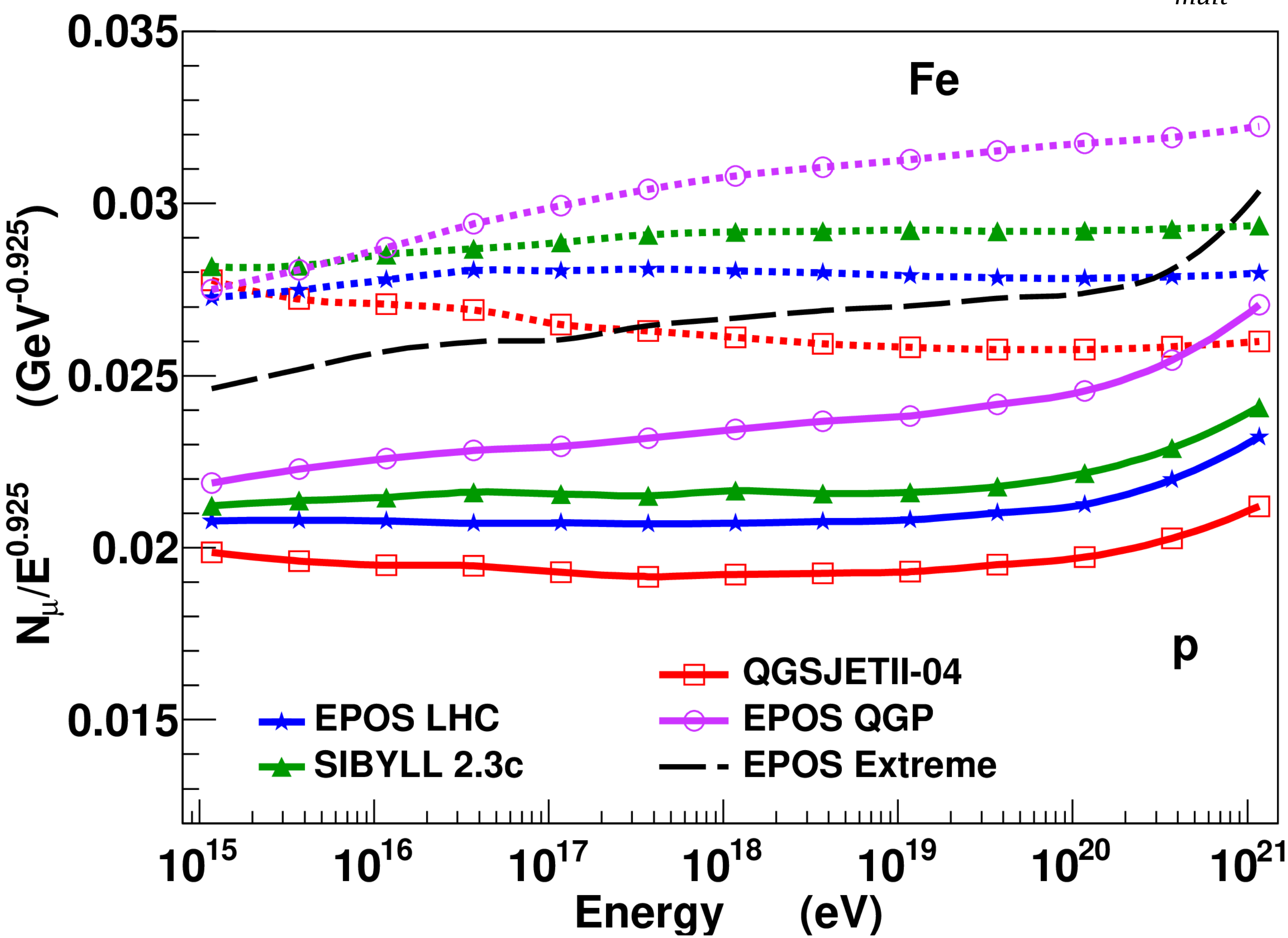


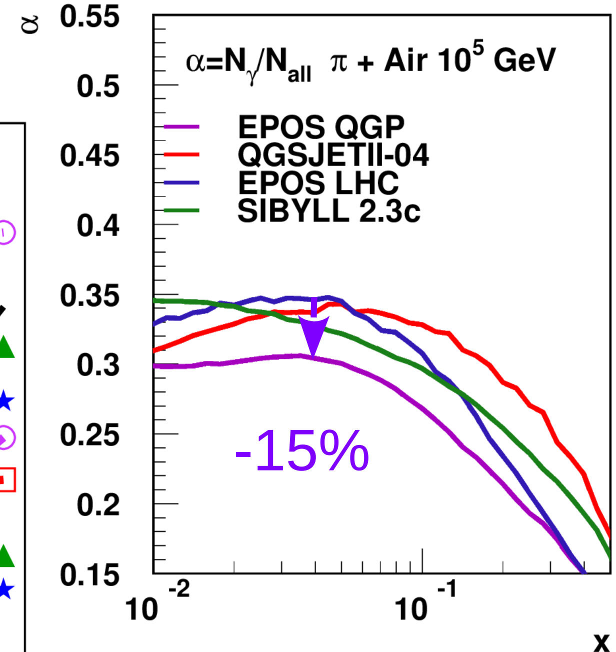


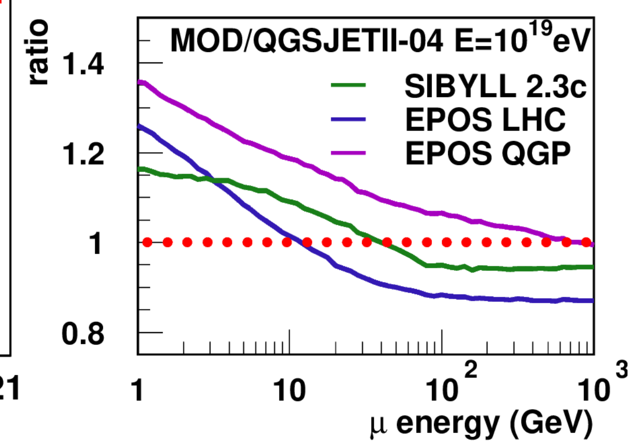
Results for Air Showers

Large change of the number of muons at ground

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

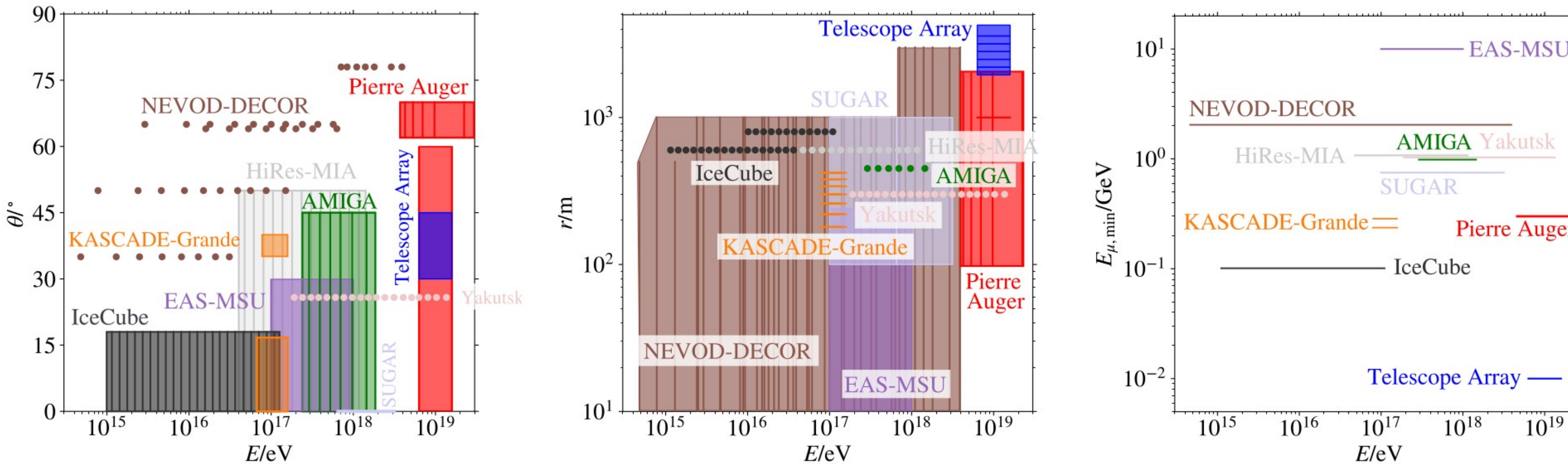






Common Representation

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

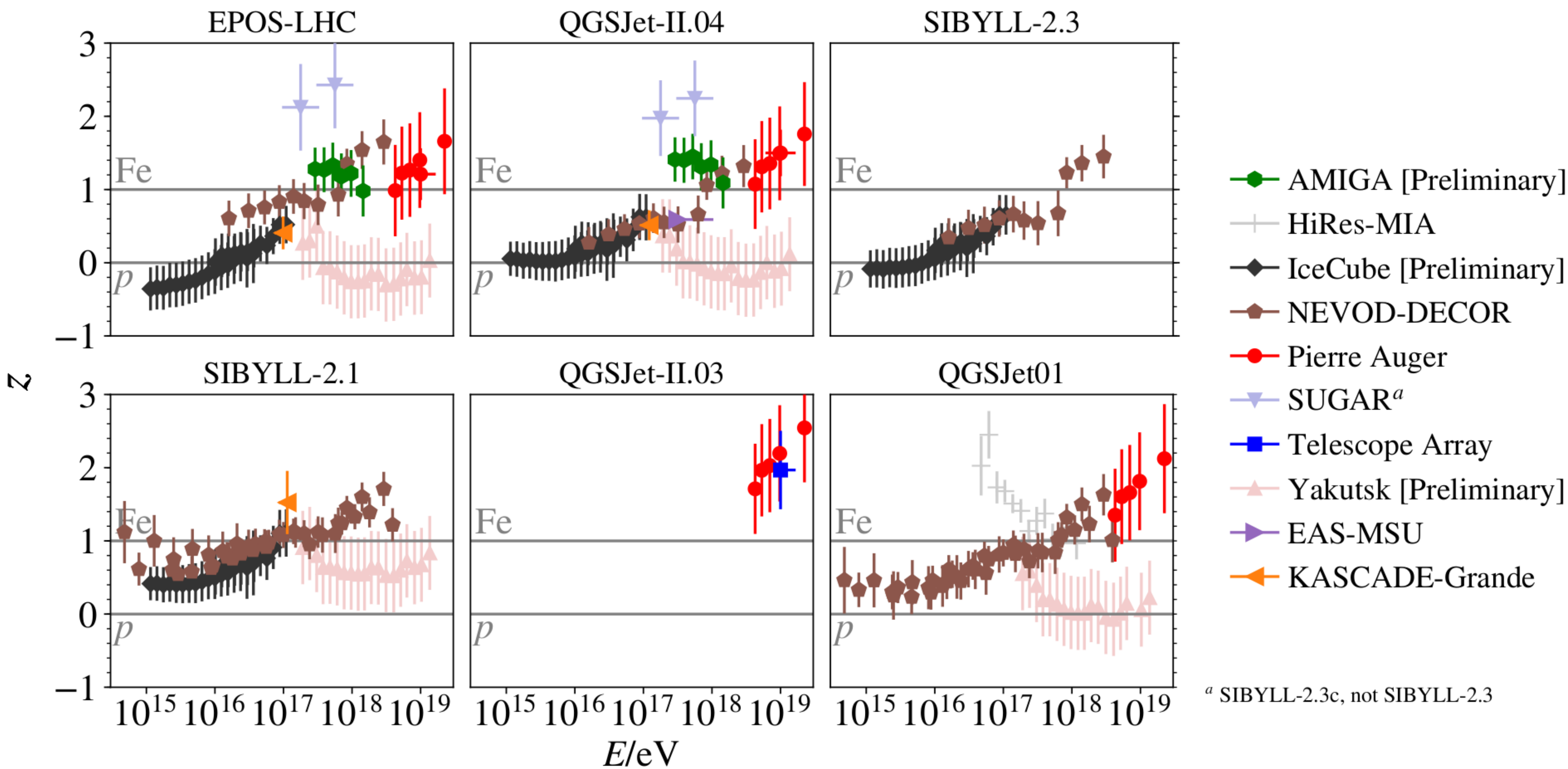


Plots by H. Dembinski

- **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


EPOS-LHC
QGSJet-II.04
SIBYLL-2.3
SIBYLL-2.1
QGSJet-II.03
QGSJet01
Fe
p
z
E/eV
AMIGA [Preliminary]
HiRes-MIA
IceCube [Preliminary]
NEVOD-DECOR
Pierre Auger
SUGAR[a]
Telescope Array
Yakutsk [Preliminary]
EAS-MSU
KASCADE-Grande
[a] SIBYLL-2.3c, not SIBYLL-2.3

Renormalization

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

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

- **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

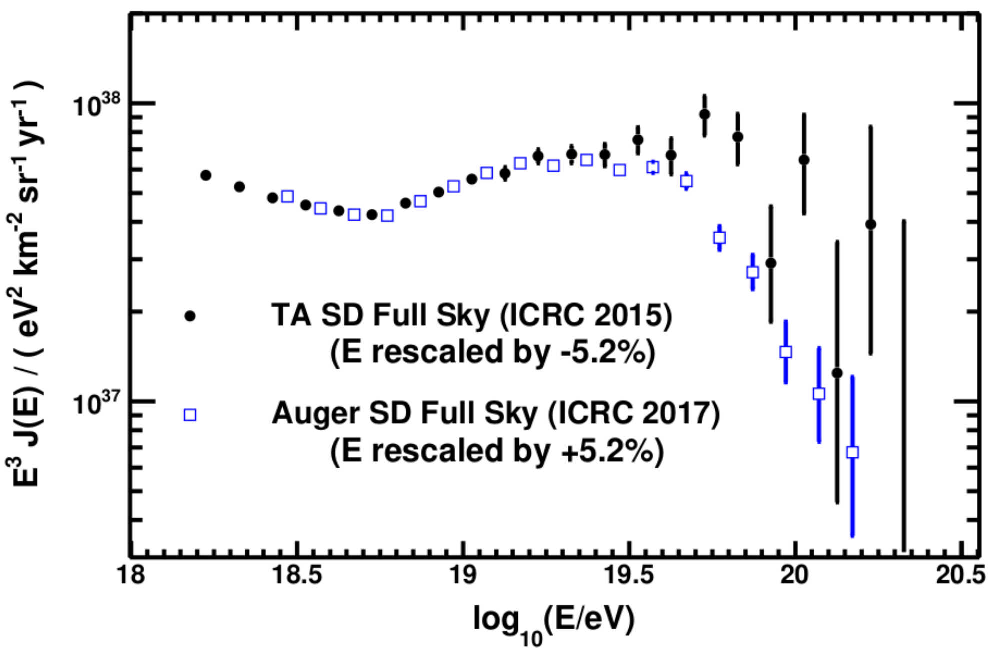
Using an external data based model !

Energy Scale

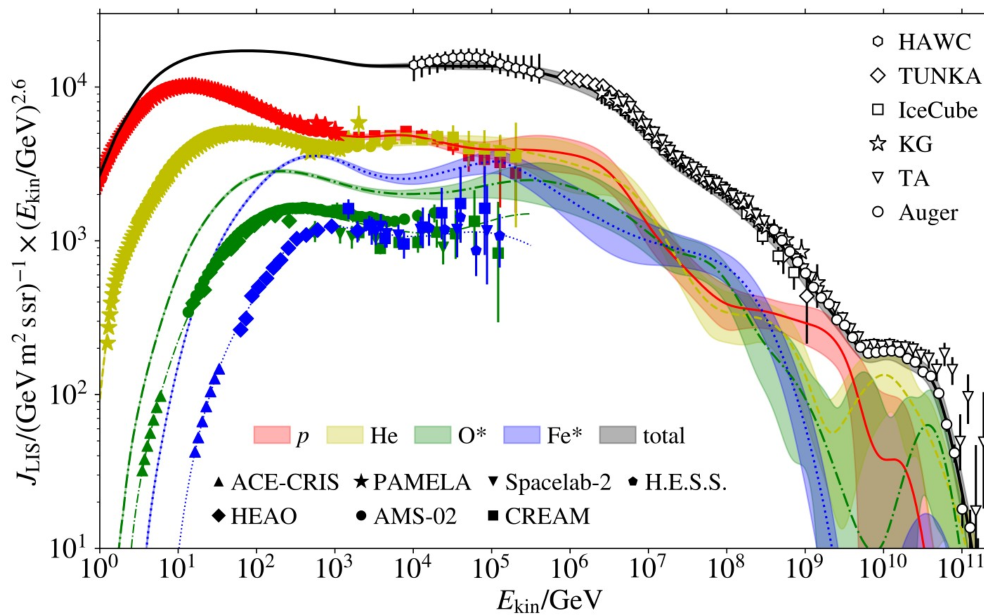
Unique energy scale obtained mixing

- 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

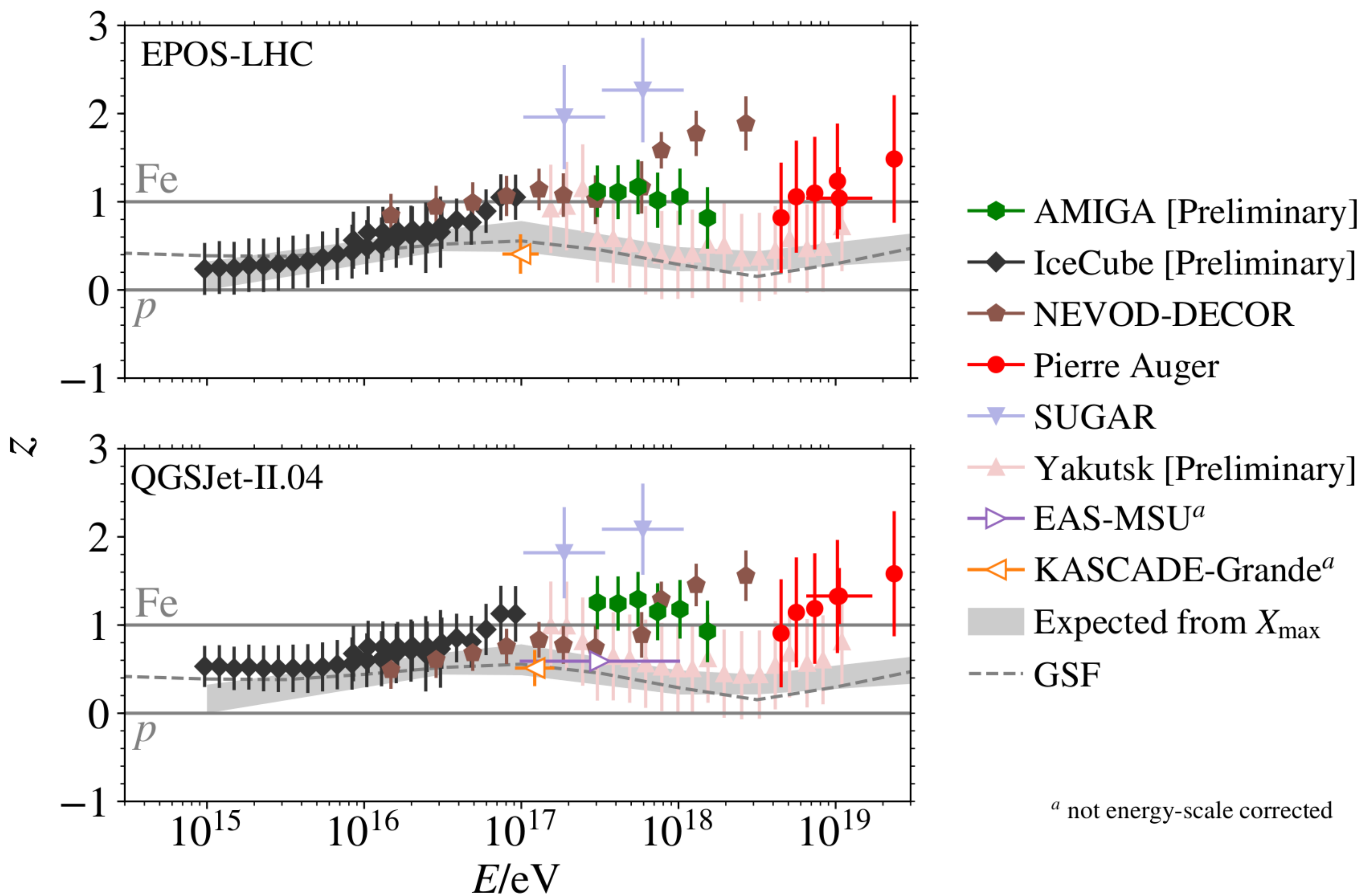


GSF

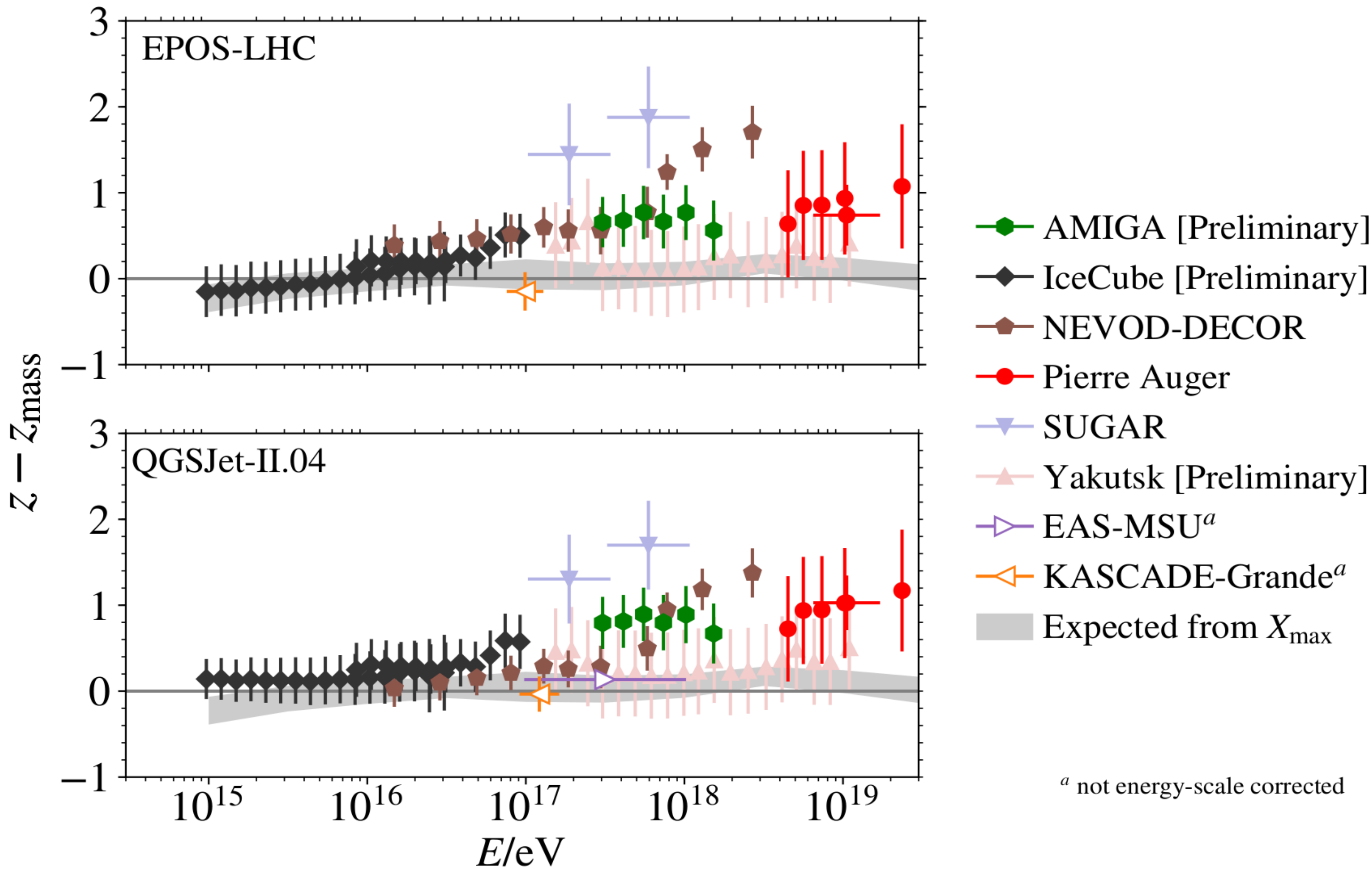


H. Dembinski

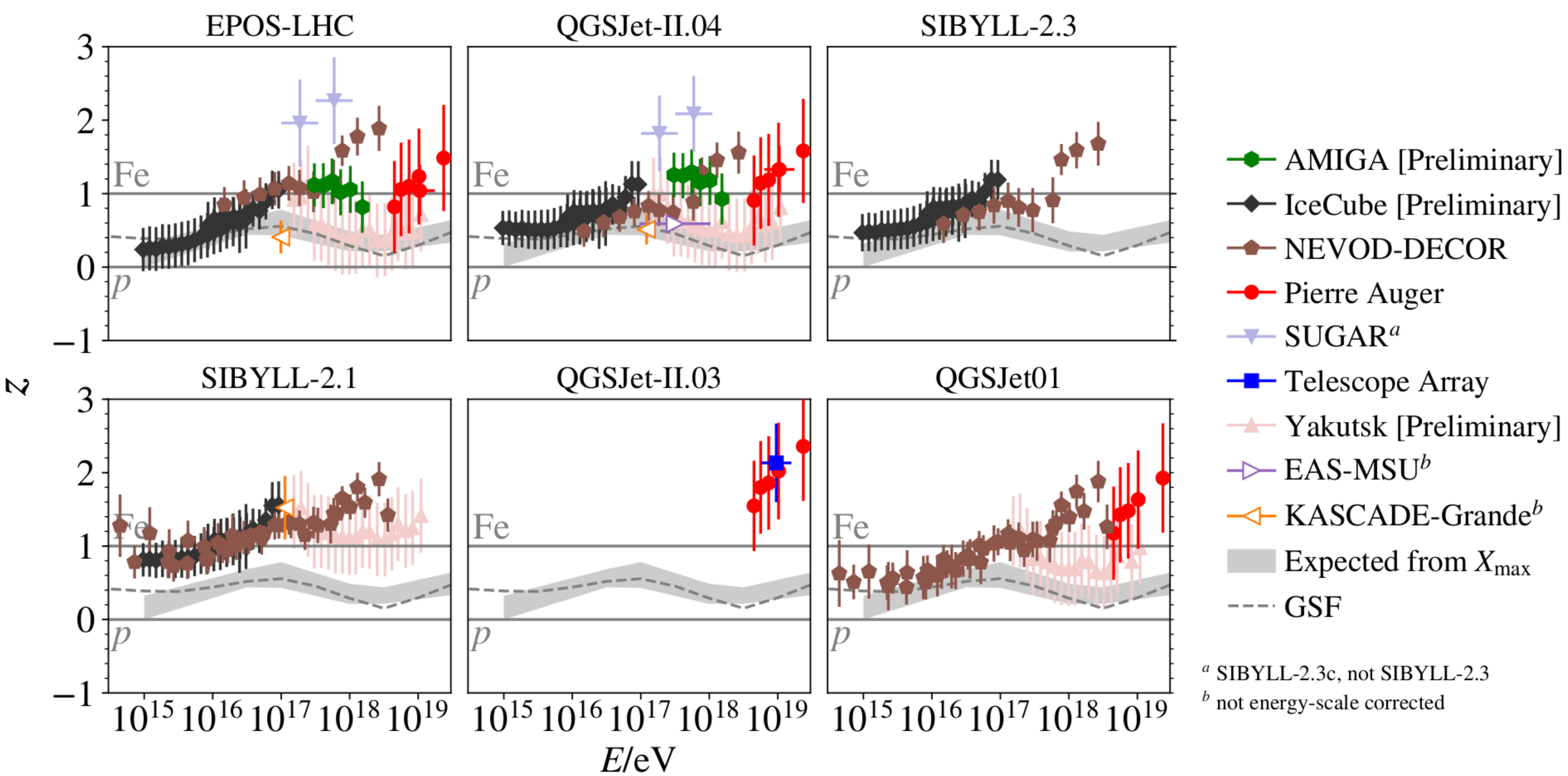
Rescaled Data



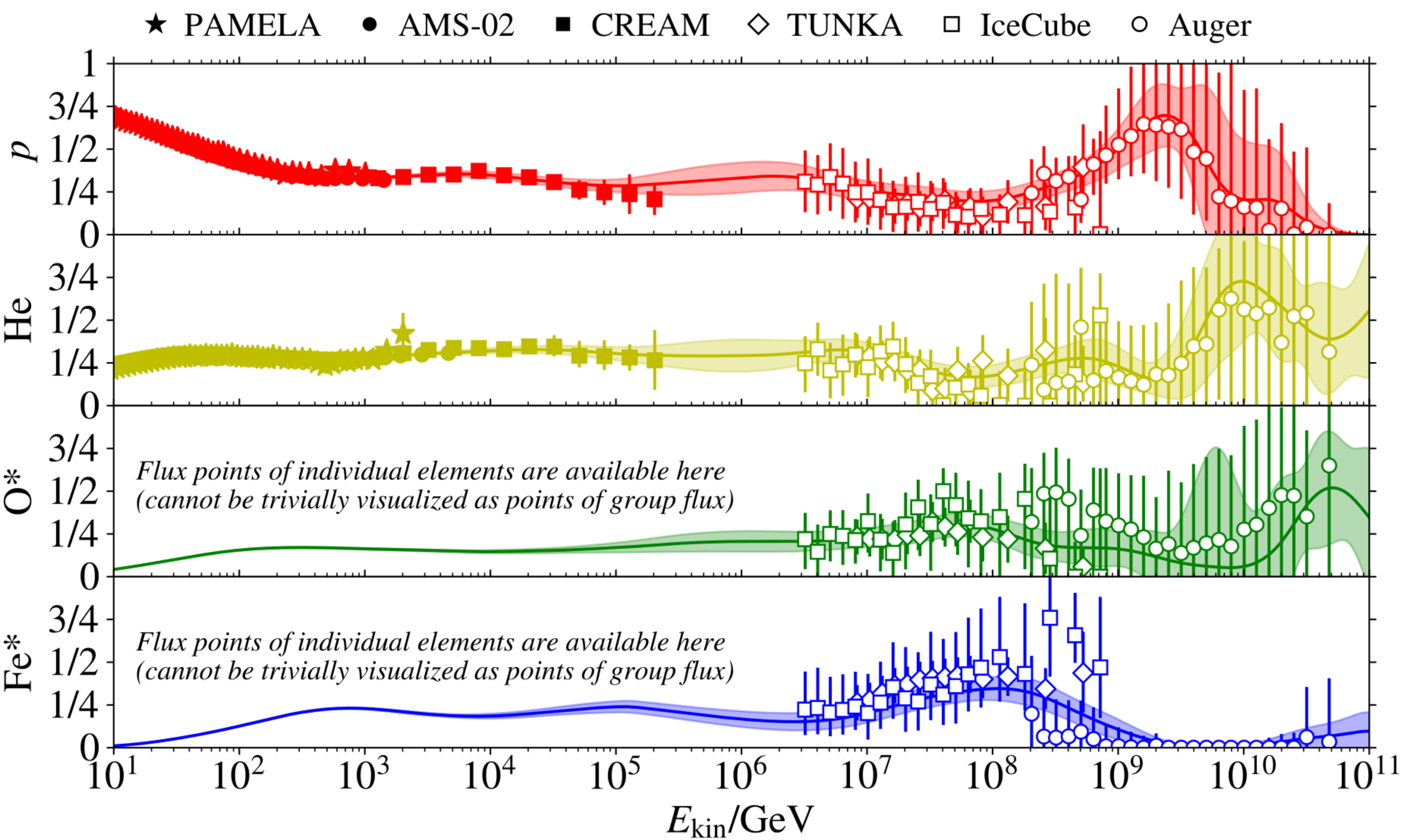
Rescaled Data with Mass Correction



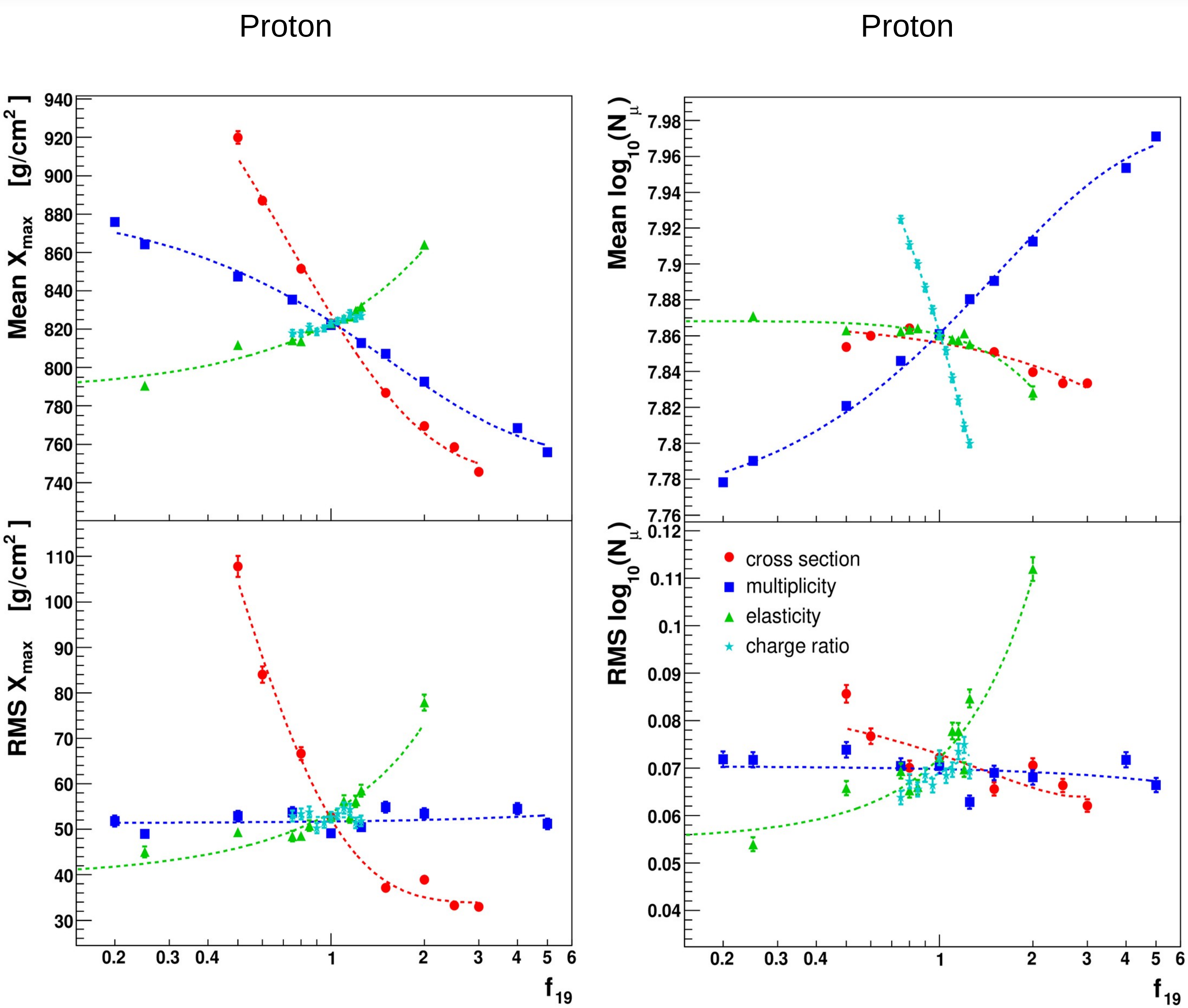
Data Rescaled



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