Synergies with Astroparticles, Nuclear and Neutrino Physics

Tanguy Pierog

Karlsruhe Institute of Technology, Institut für Kernphysik, Karlsruhe, Germany

Karlsruhe Institute of Technology

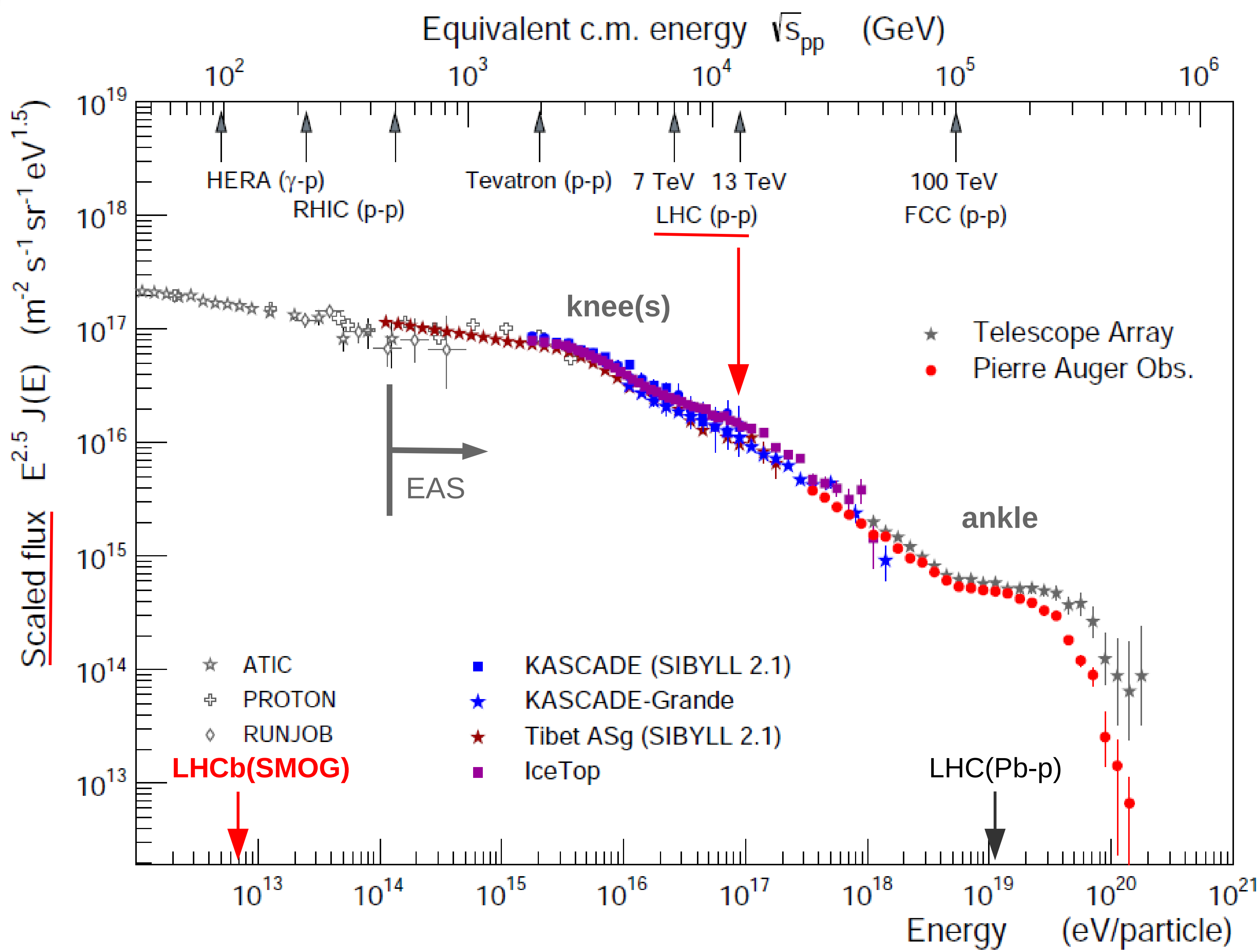
PPG – Strong Interactions, Vidyo

May the 7th 2019

Outline

- **Astroparticle Physics**
  - ➜ Link to nuclear physics
- **Neutrino Physics**
  - ➜ Link to hadronic physics

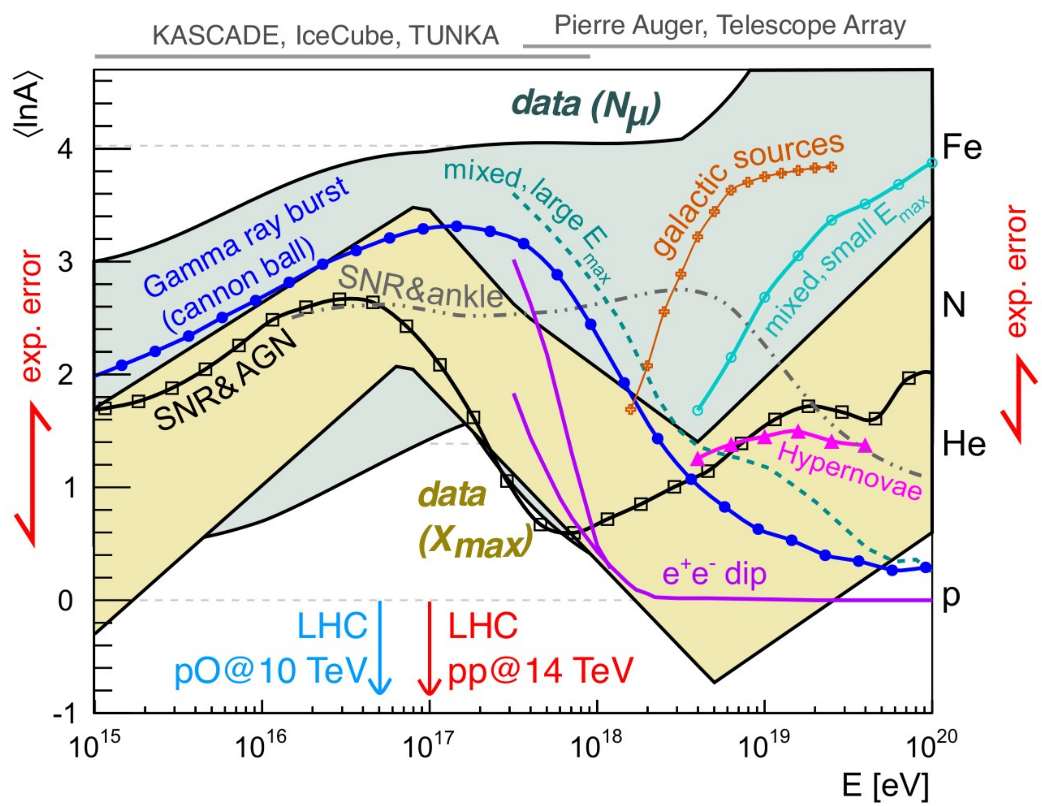
Cosmic Ray Energy Spectrum



R. Engel (KIT)

Primary Cosmic Ray Composition

- **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)**
  - ➜ Energy and composition using different observables (fluorescence light, particles at ground, radio emission, …)
  - ➜ Hadronic interactions are the key for proper EAS simulations and CR analysis



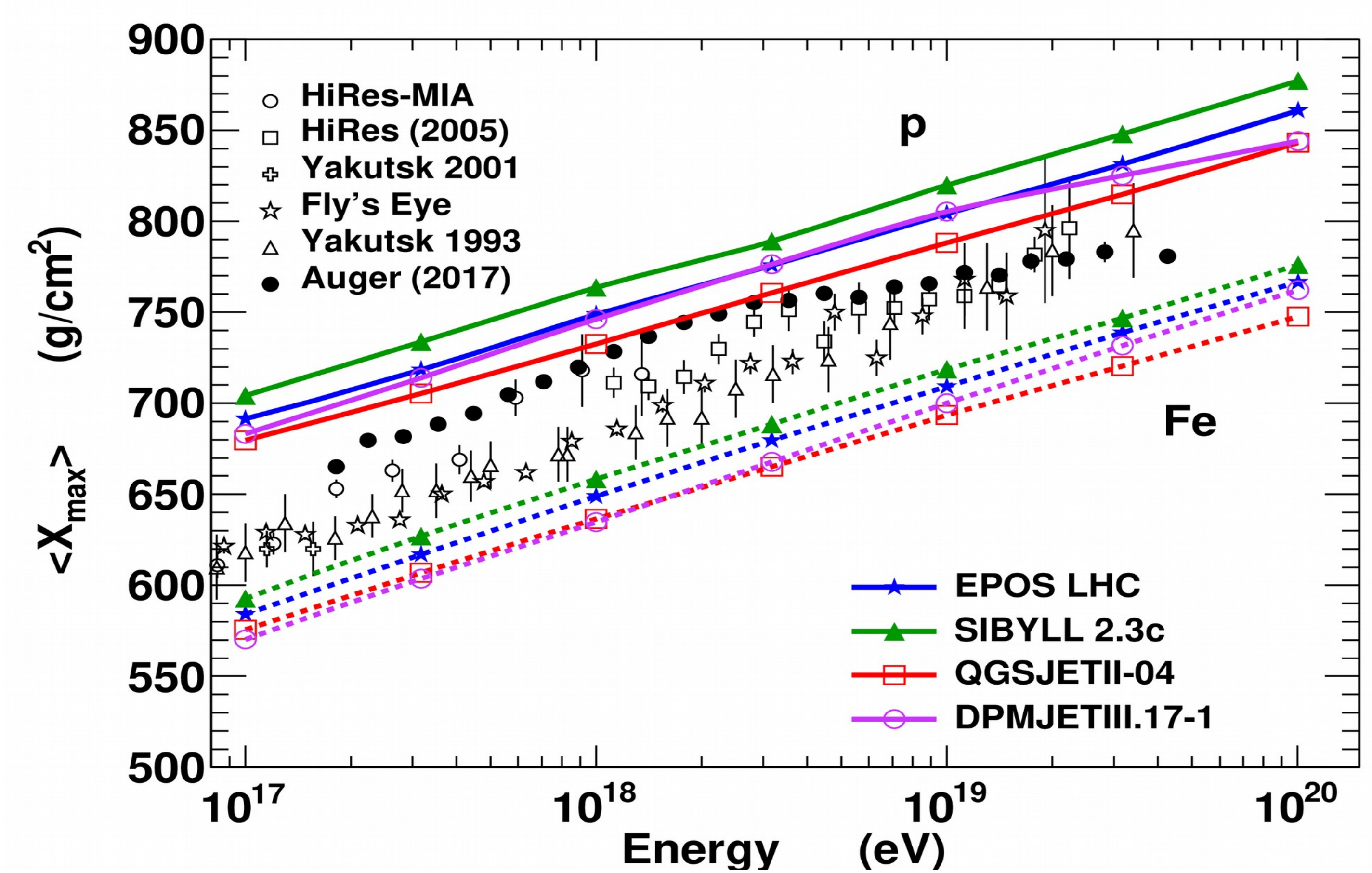
Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

- **Inconsistent mass composition point to weakness of hadronic interaction description in models**

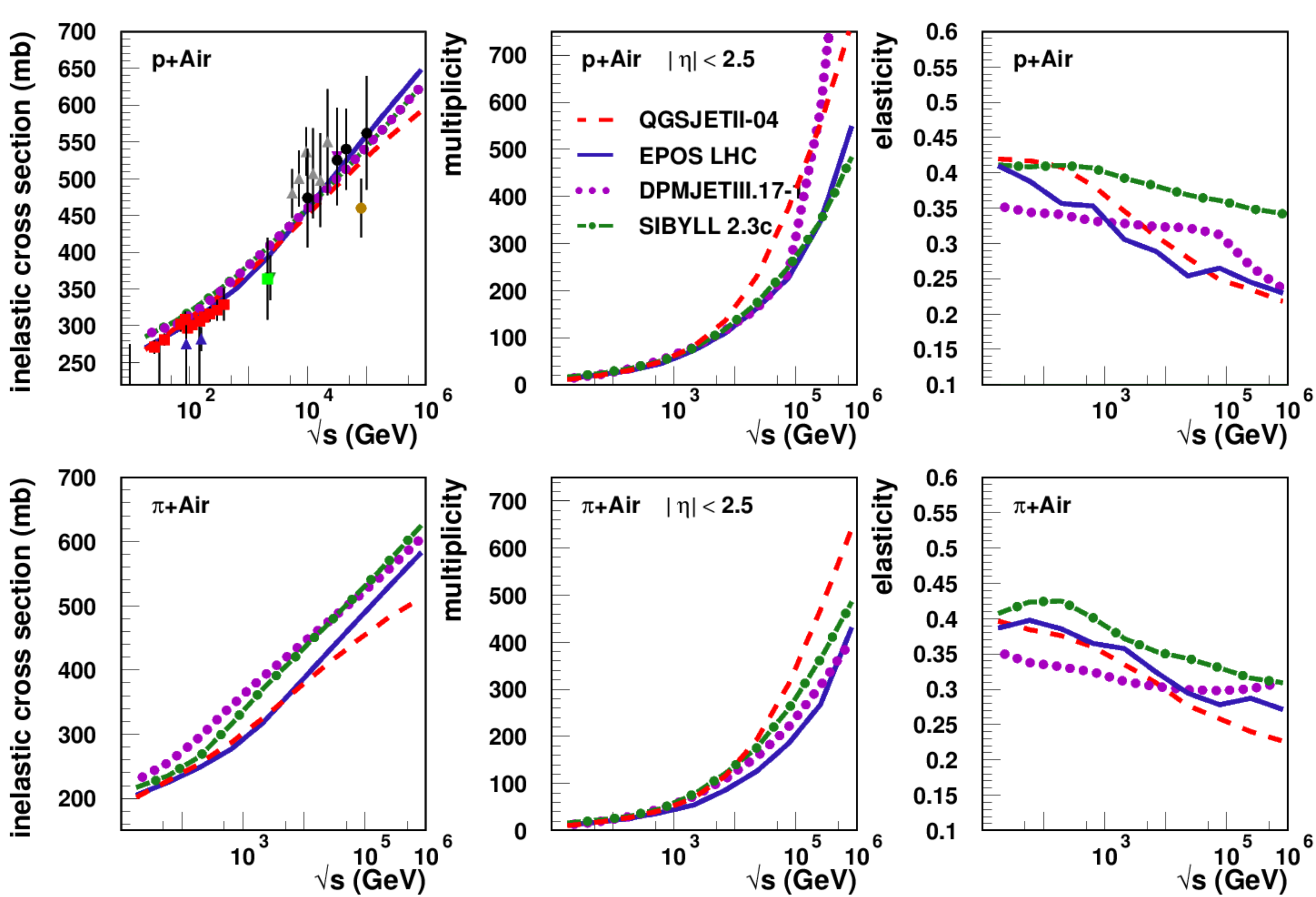
X_{max}

+/- 20g/cm² is a realistic uncertainty band but :

- minimum given by QGSJETII-04 (high multiplicity, low elasticity)
- maximum given by Sibyll 2.3c (low multiplicity, high elasticity)
- anything below or above won't be compatible with LHC data

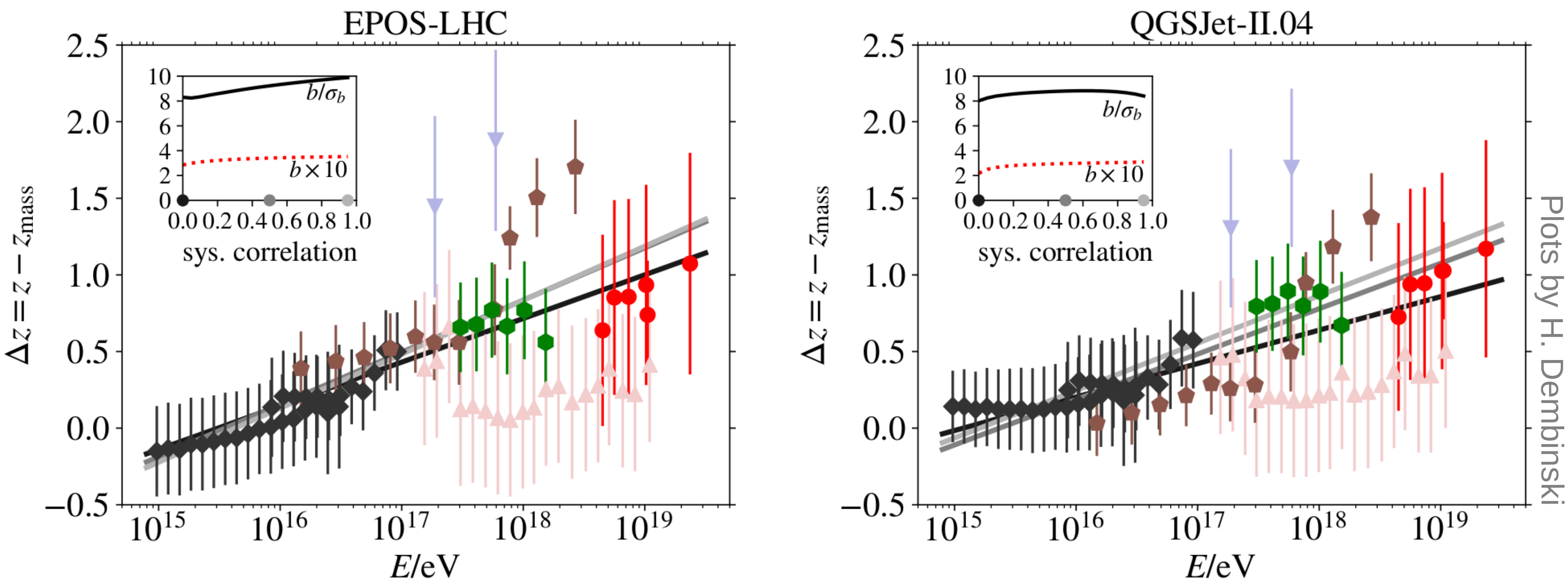


Model Prediction Uncertainties



Global Behavior

- **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

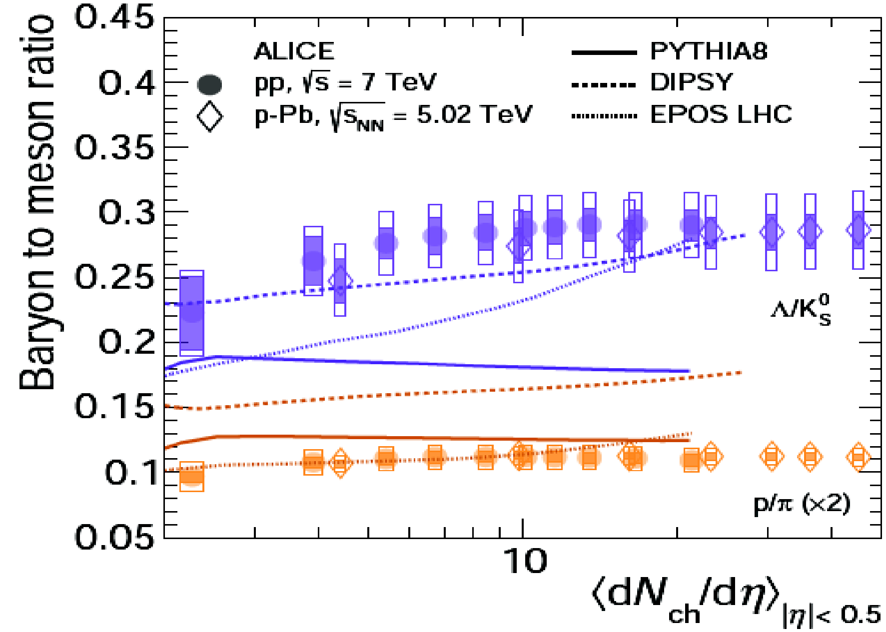
Possible Particle Physics Explanation

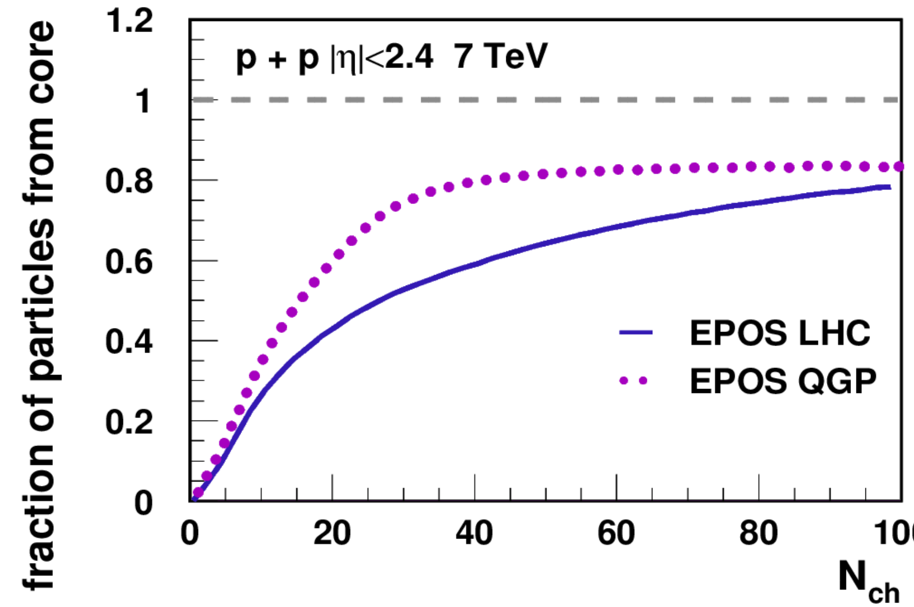
To change this slope the charge ratio $\alpha = \frac{N_{\pi^0}}{N_{mult}}$ for secondary particle production should be changed

- 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 production of Quark Gluon Plasma (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)

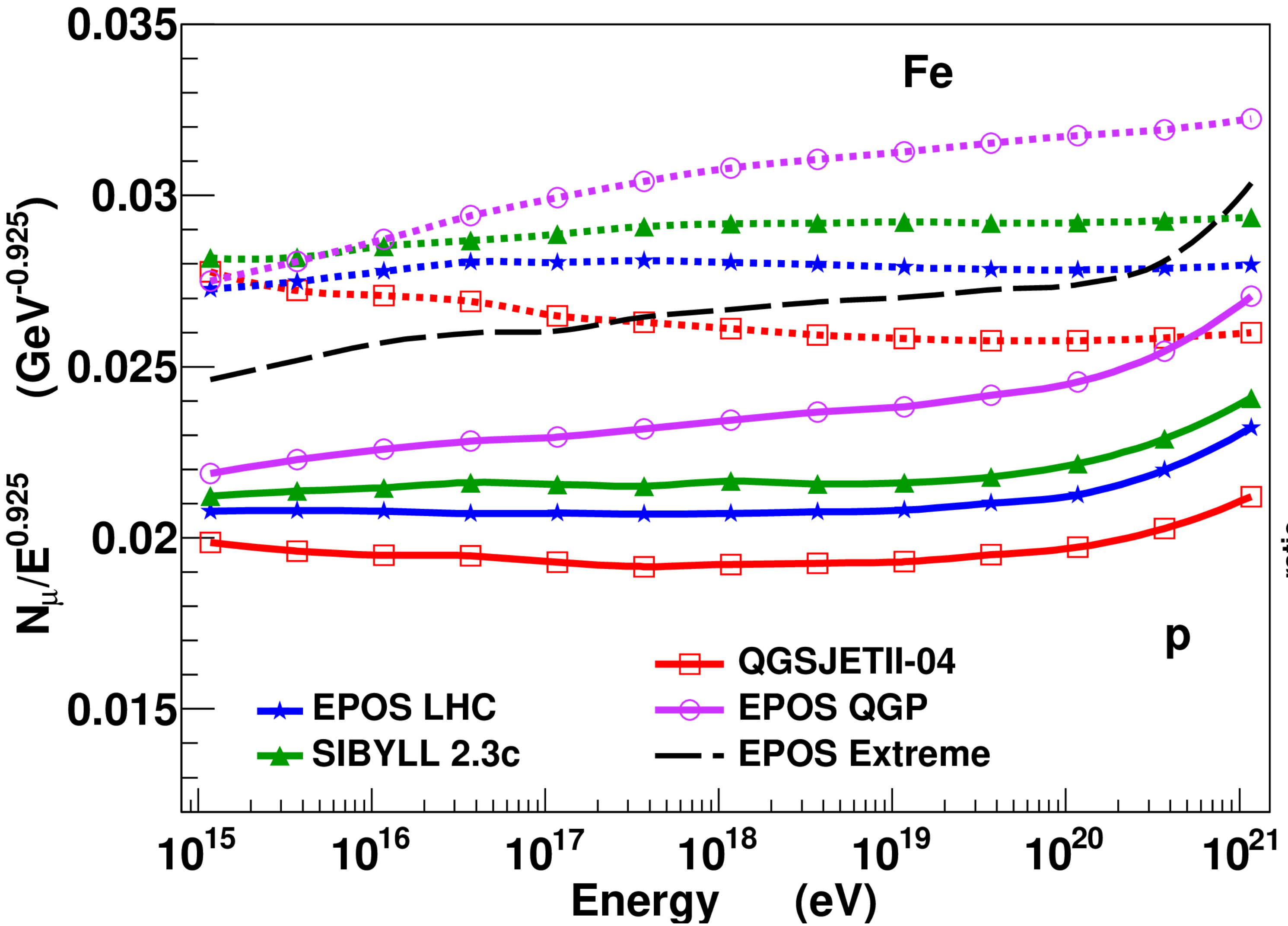


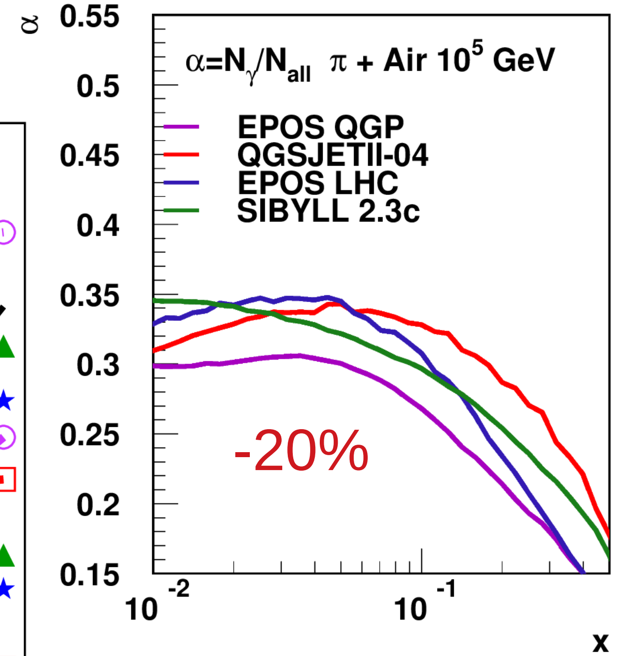


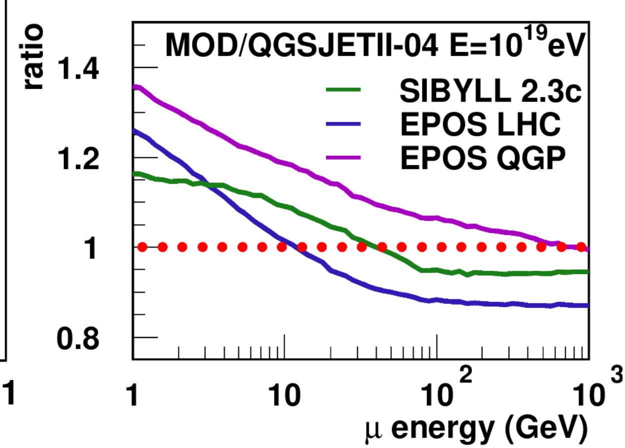
Results for Air Showers

Large change of the number of muons at ground

➡ Different slope as expected from the change in α



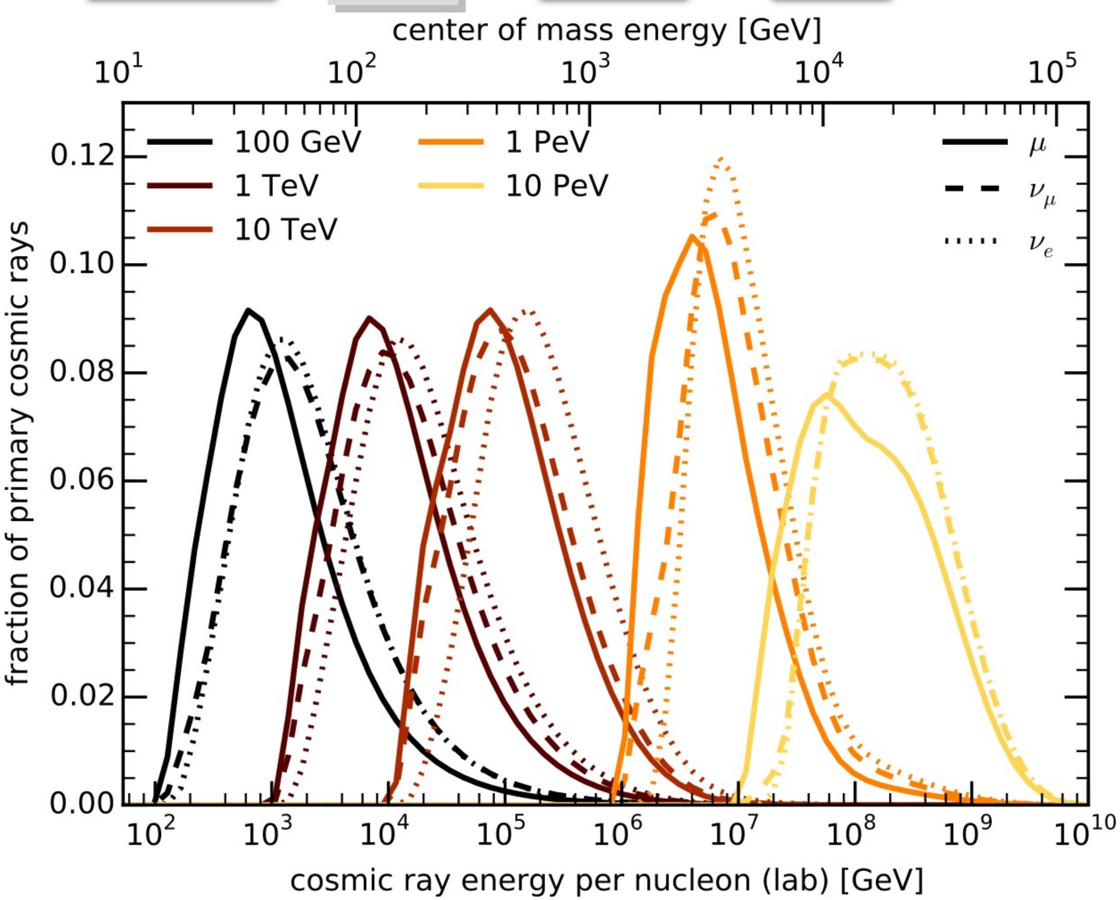


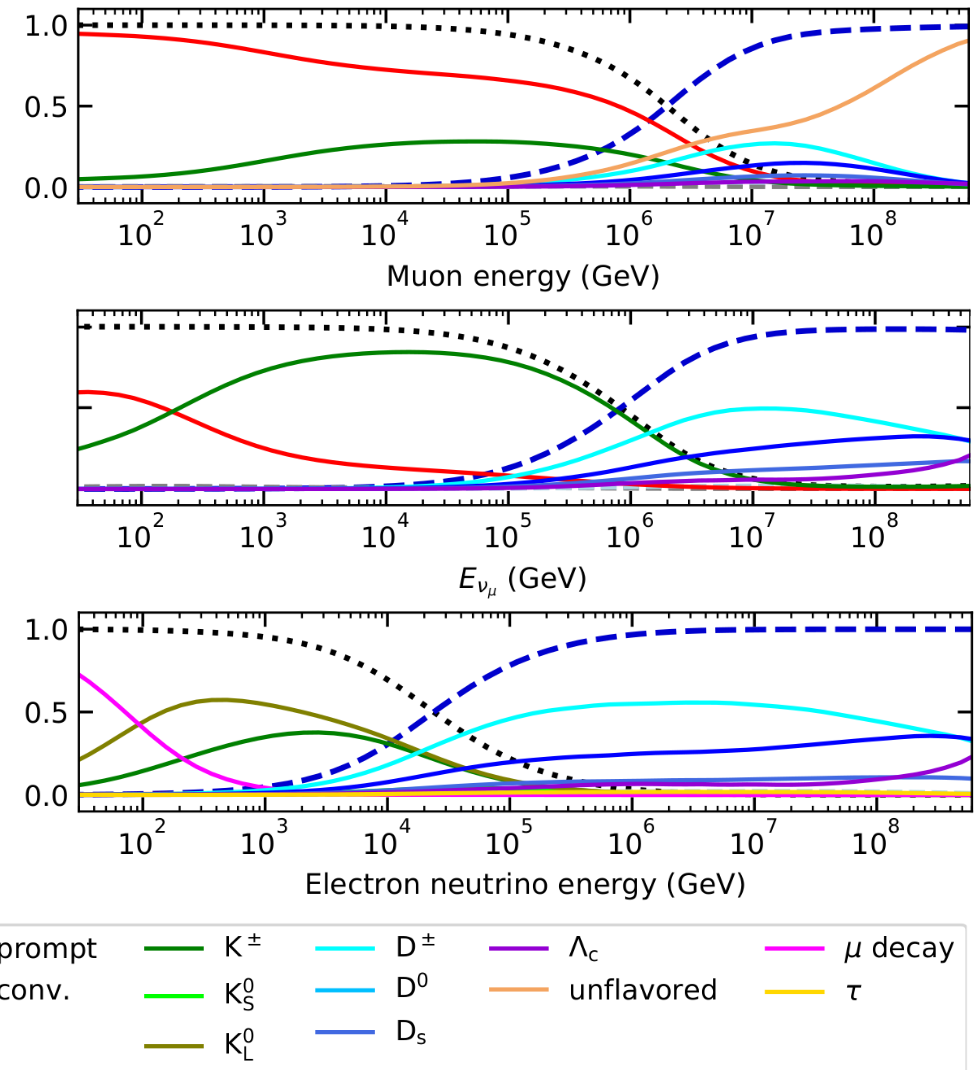


Inclusive CR Spectra and Hadronic Interaction

For inclusive spectra, particles from first interaction dominate

Fixed-target RHIC Tevatron LHC

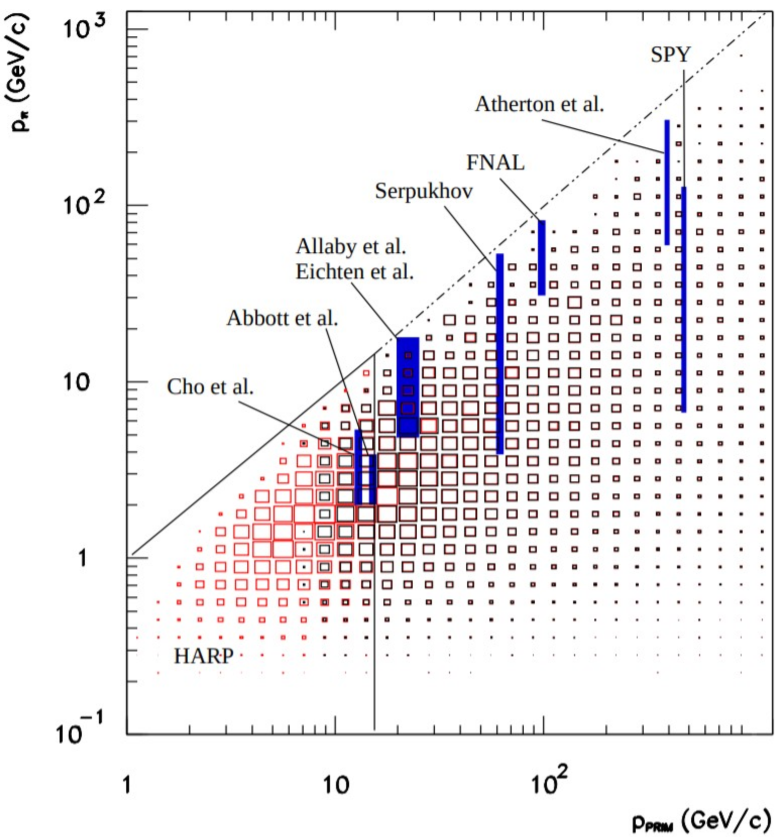


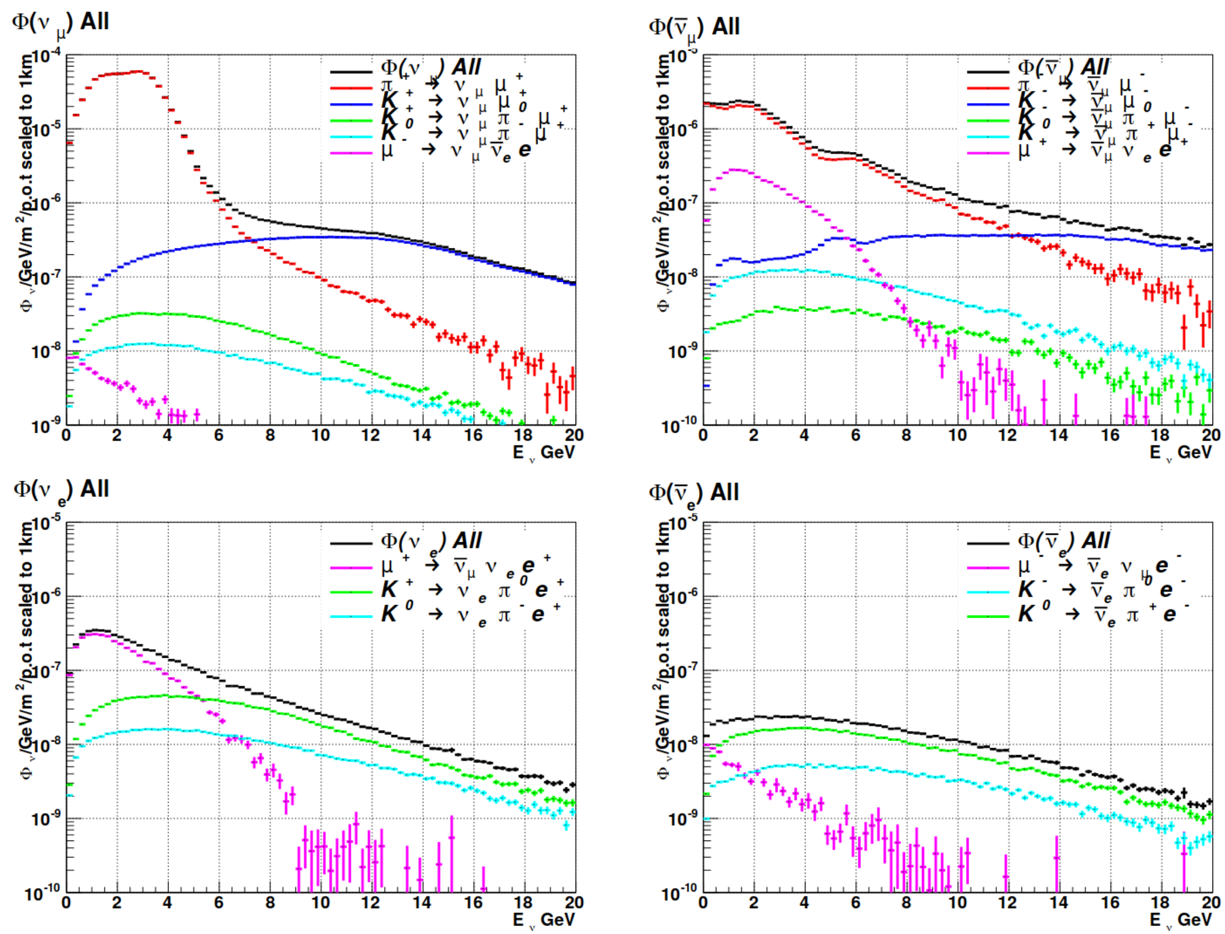


Plots from A. Fedinytch

Neutrinos Underground Experiments

- **Low energy (SPS) pA measurements to get precise accelerator/ atmospheric neutrino fluxes (Dune, Super/HyperK, IceCube...)**
  - ➡ Neutrino flux from hadronic interactions

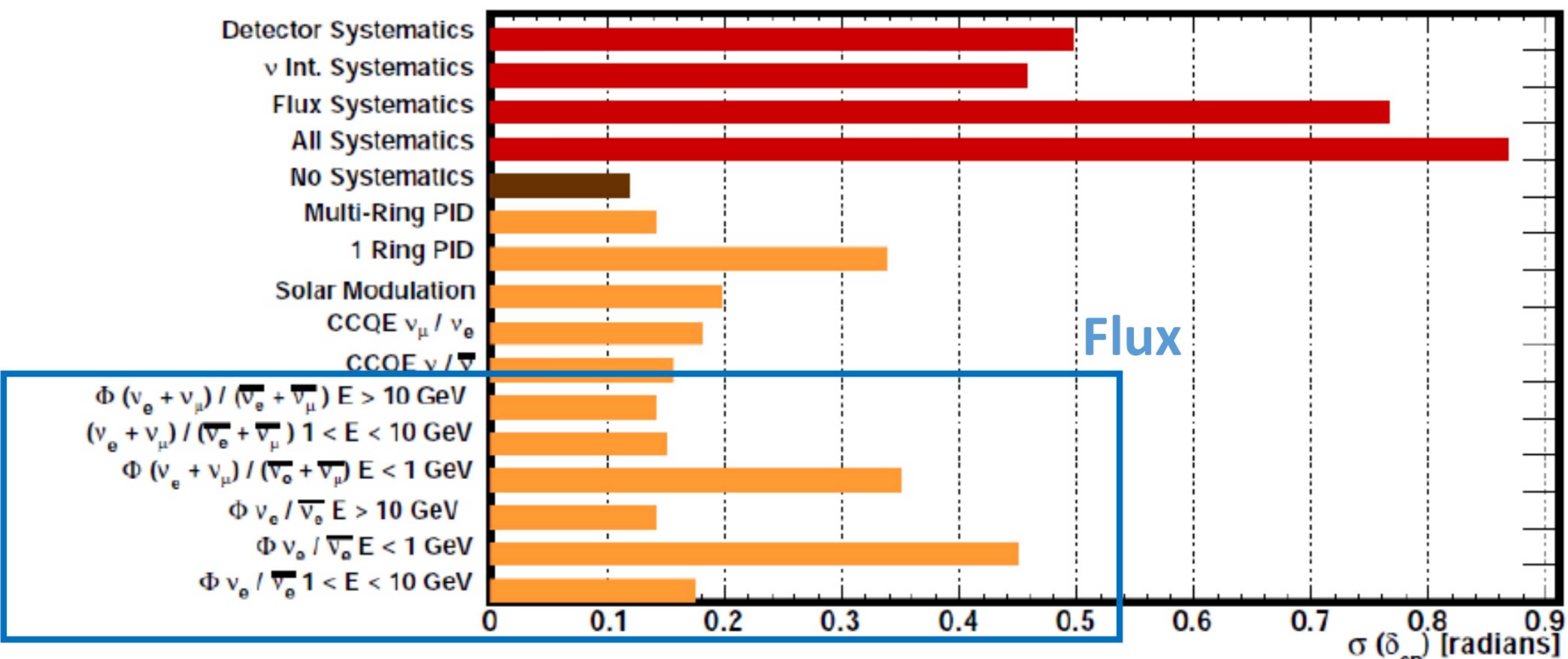




Neutrinos

- **Low energy (SPS) pA measurements to get precise accelerator/ atmospheric neutrino fluxes (Dune, Super/HyperK, IceCube...)**
  - ➔ CP violation

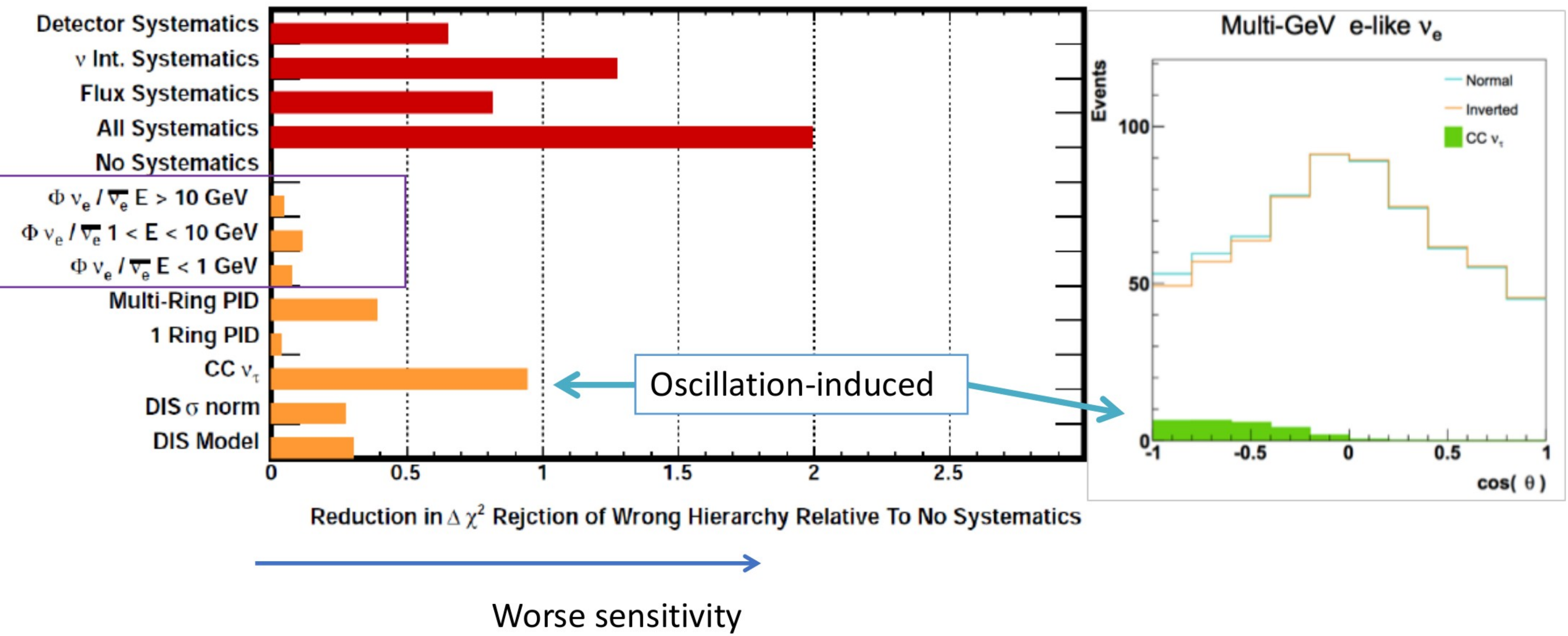
Systematics on δ_{CP} Sensitivity



Neutrinos

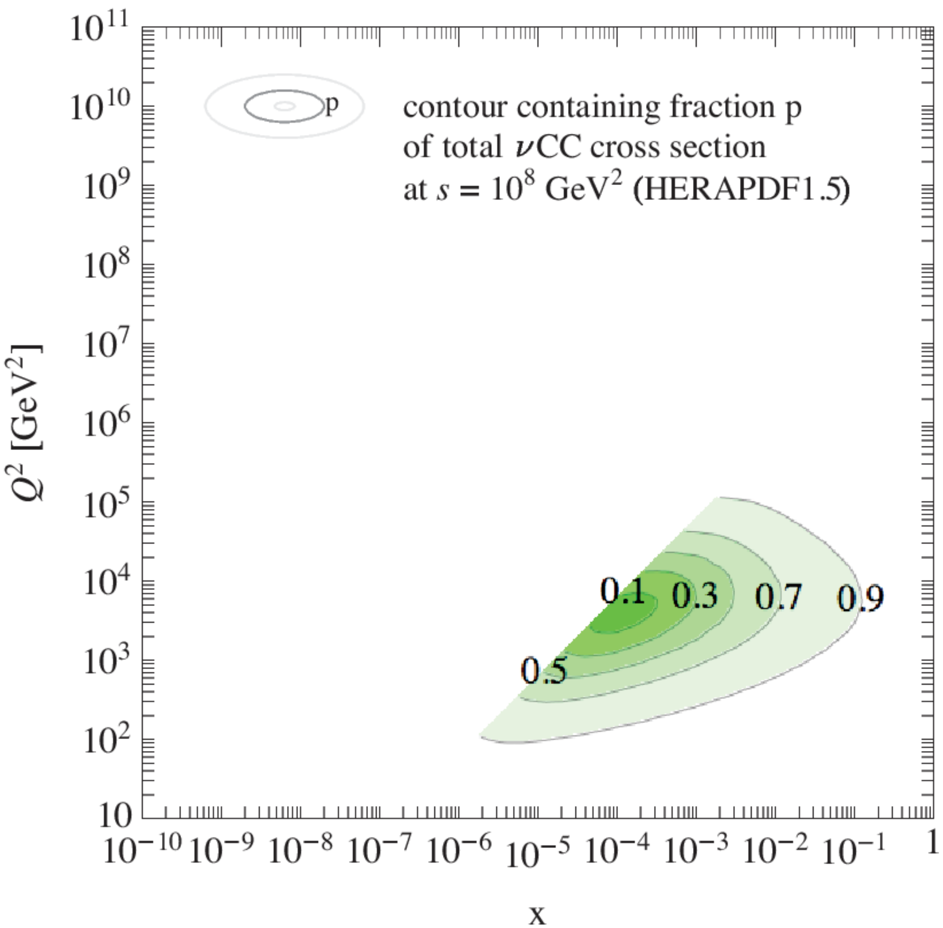
- **Low energy (SPS) pA measurements to get precise accelerator/atmospheric neutrino fluxes (Dune, Super/HyperK, IceCube...)**
  - ➡ Mass hierarchy

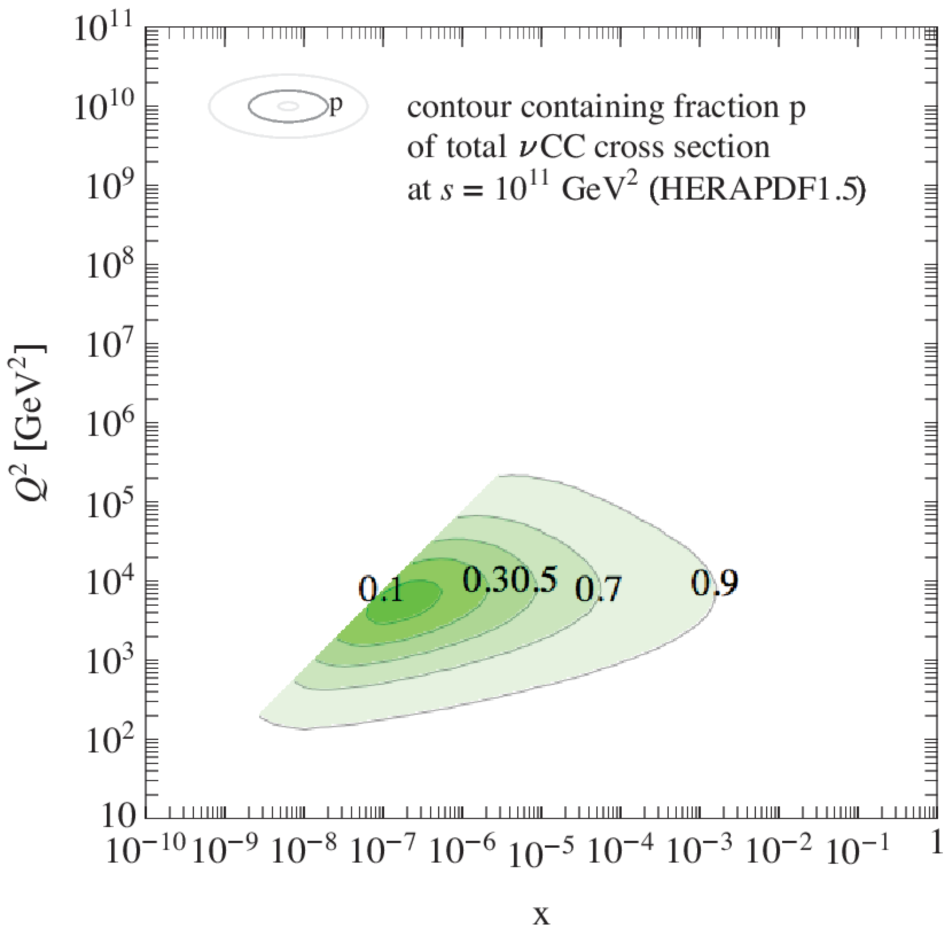
Super-K : Mass Hierarchy Systematics



Neutrinos

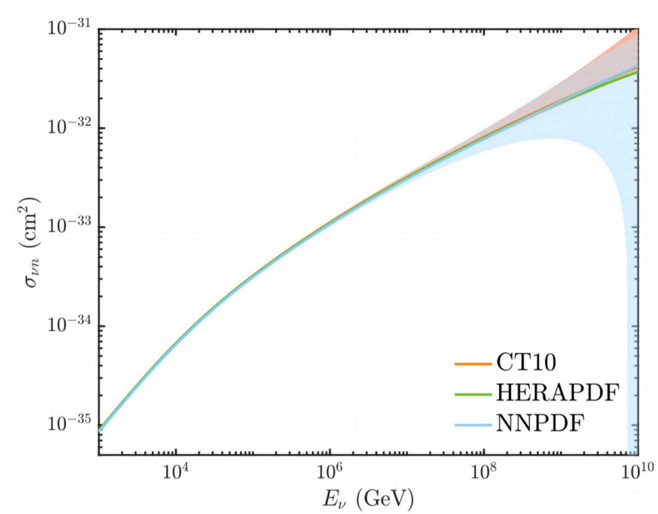
- **Neutrino cross-section depends on precise parton distribution function**
  - ➡ small x for neutrino production/interaction at high energy

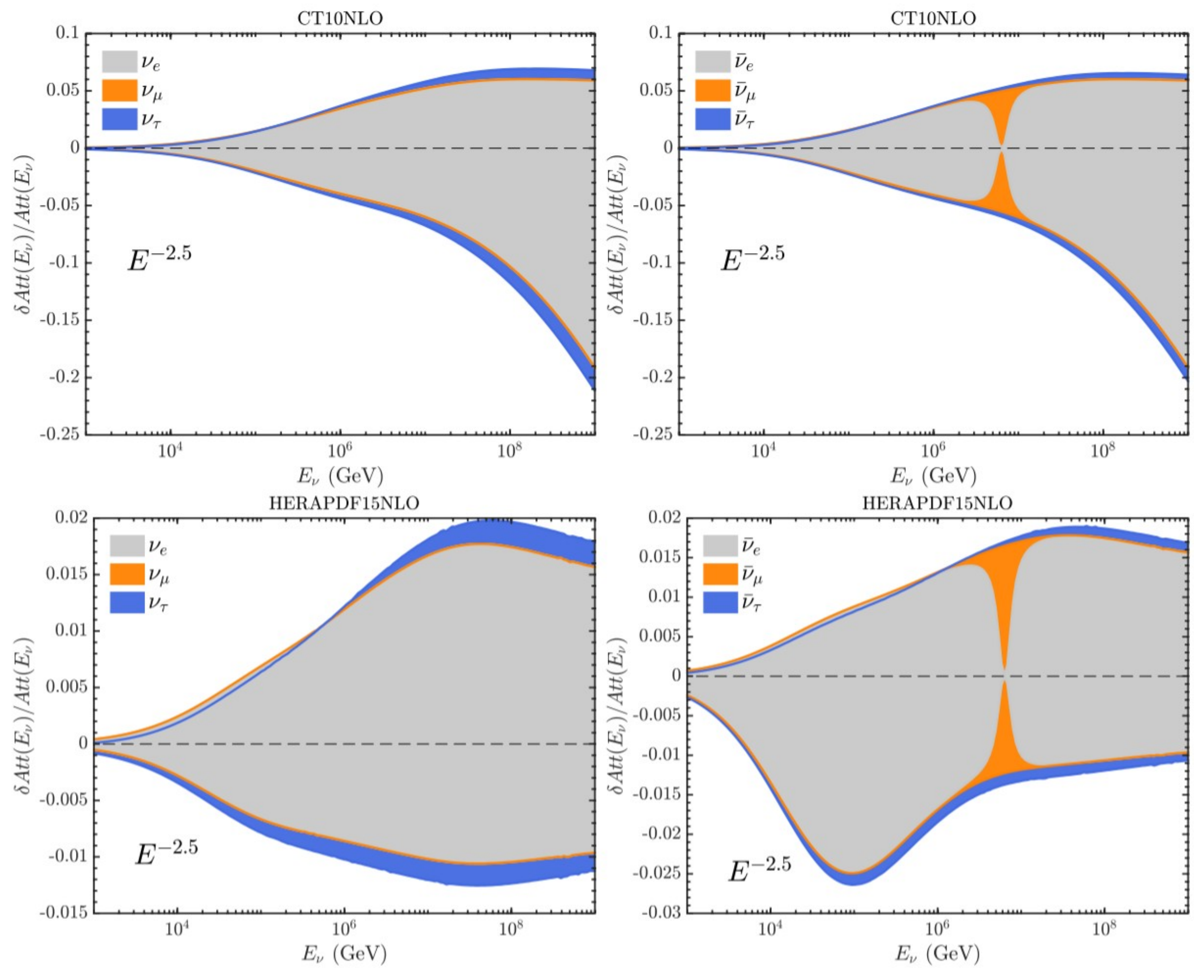




Neutrinos

- **Neutrino cross-section depends on precise parton distribution function**
  - ➜ small x for neutrino production/interaction at high energy





Synergies

- **X_{max} uncertainties mostly due to nuclear collision extrapolations**
  - ➡ Precise measurements (inelastic cross-section, multiplicity, diffraction) needed in pA and AA with A<20 !
- **"Muon puzzle" linked to QGP ? … more measurements needed in "light" system and forward rapidities relevant for air showers**
  - ➡ Possibility to study high temperature AND high chemical potential QGP in air showers ???
- **Low energy (SPS) pA measurements to constraint muon production as well and precise atmospheric neutrino fluxes (Dune, Super/HyperK, IceCube...)**
  - ➡ Indirect application for cosmic anti-matter detection (AMS02)
- **Heavy flavors important for astrophysical neutrino detection**
  - ➡ Atmospheric prompt muons and neutrino as background
  - ➡ nPDF, small x for neutrino production/interaction

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),

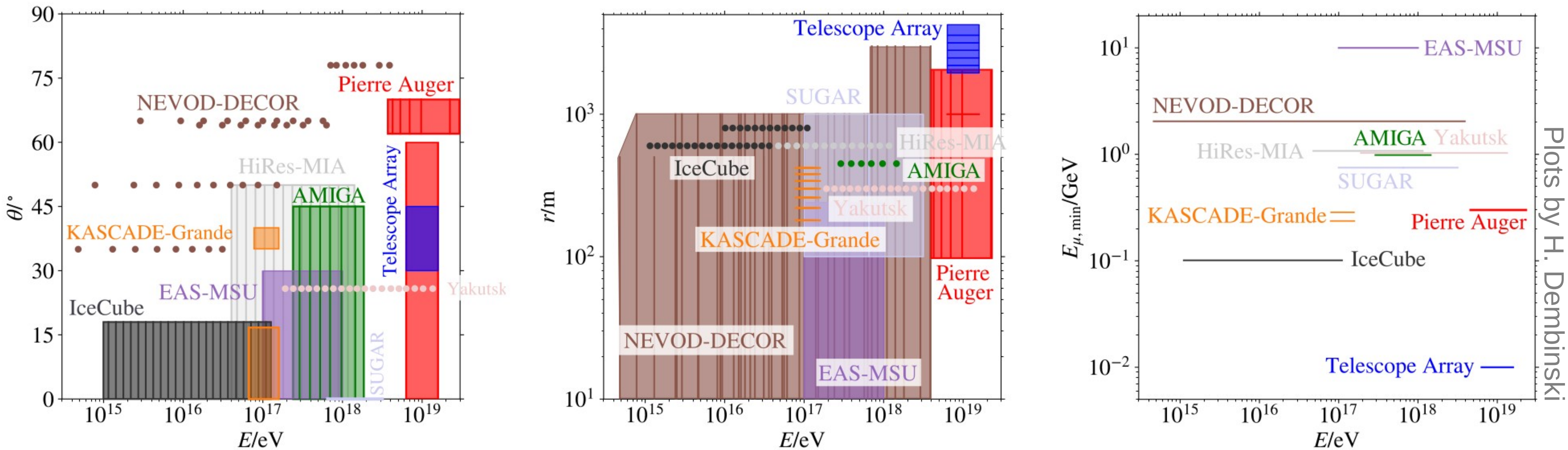
  J.C. Arteaga (KASCADE-Grande, Mexico),

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

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

Common Representation

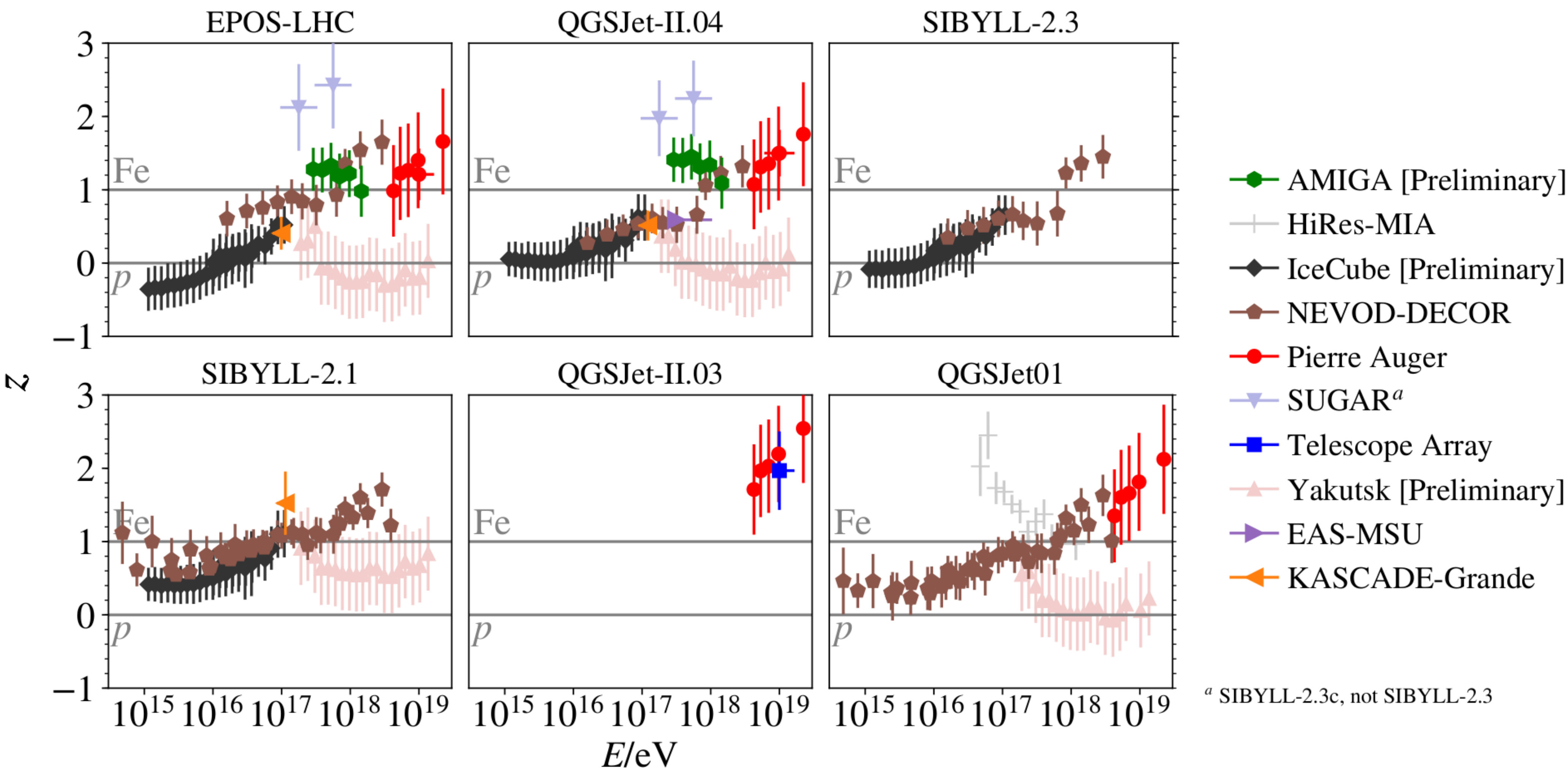
- **Experiments cover different phase space**
  - ➜ Distance to core, zenith angle, energy …



- **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
3
2
1
0
−1
10^15 10^16 10^17 10^18 10^19
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

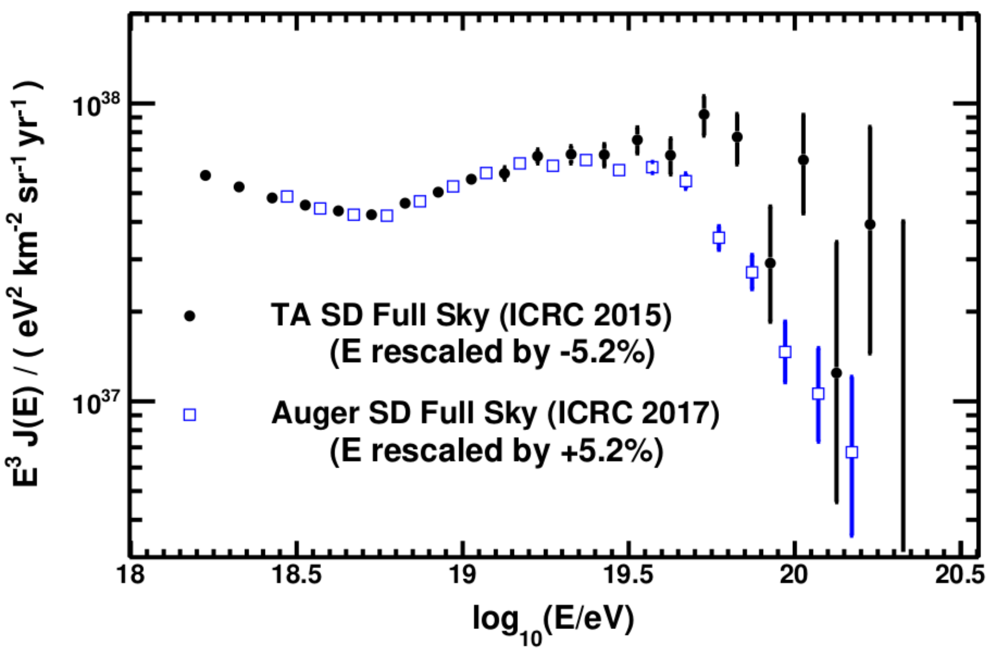
Using an external data based model !

Energy Scale

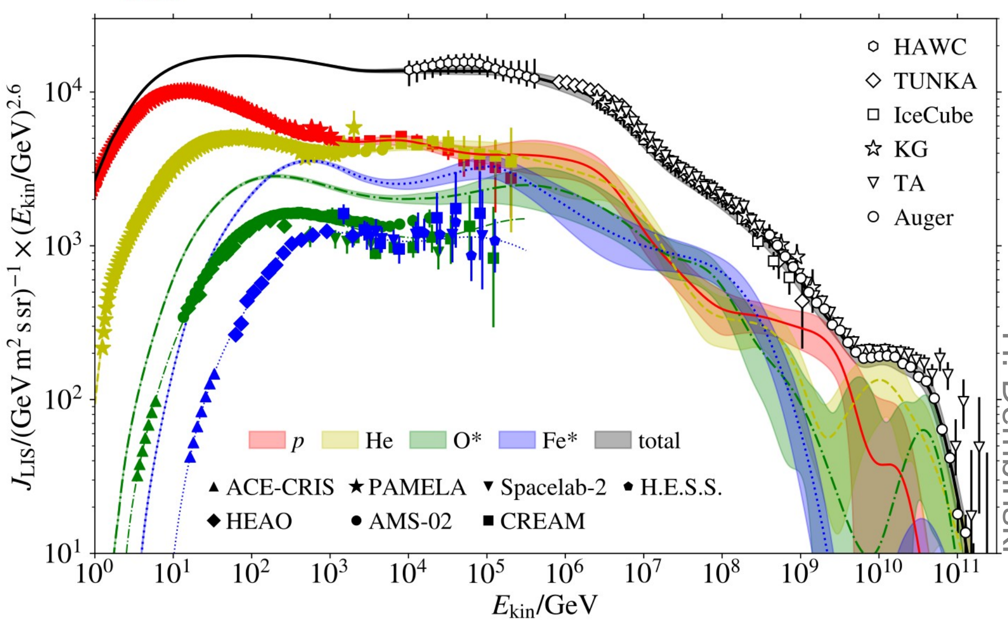
Unique energy scale obtained mixing

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

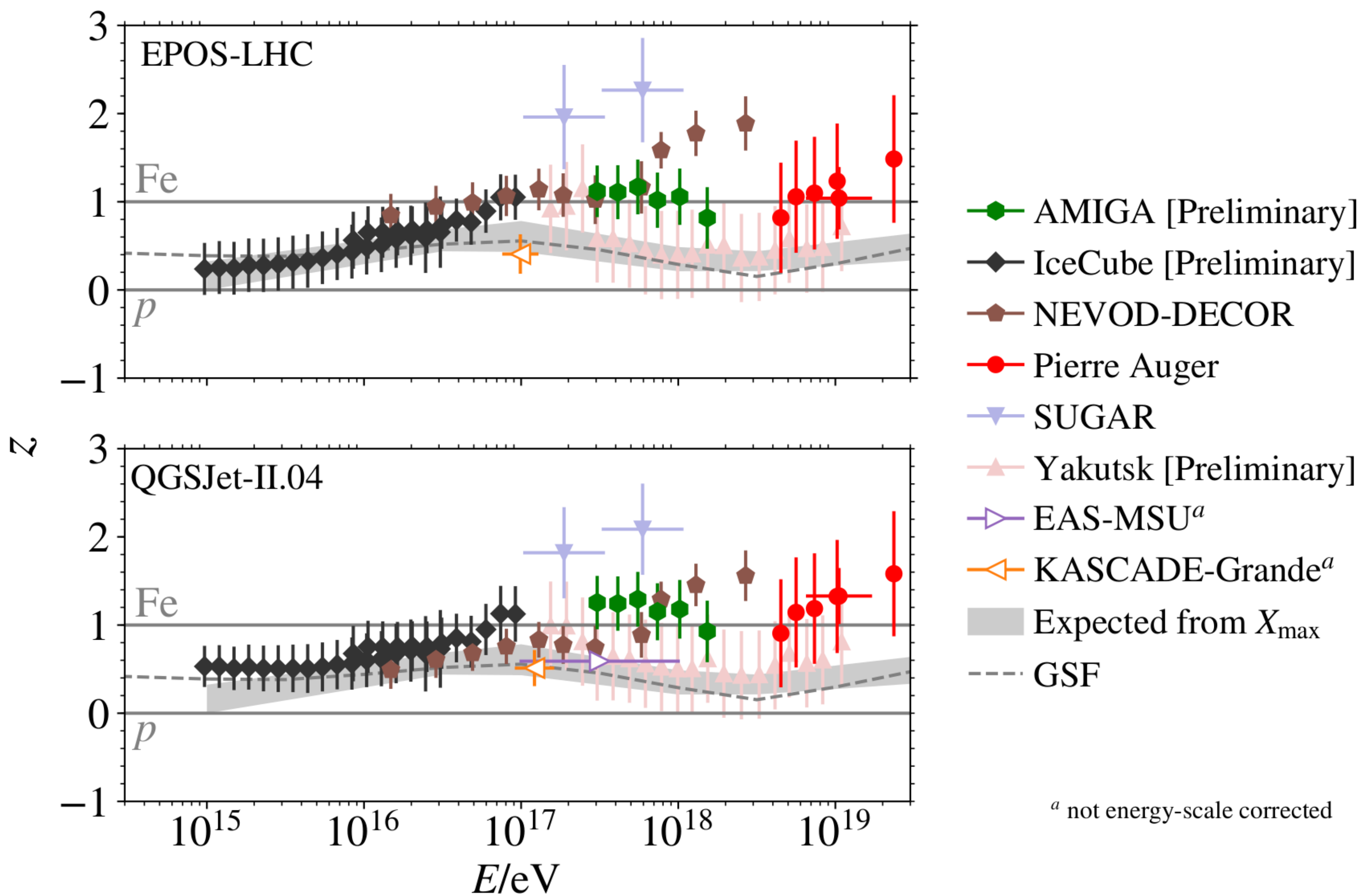
Experiment	E_{data}/E_{ref}
EAS-MSU	unknown
IceCube Neutrino Observatory	1.19
KASCADE-Grande	unknown
NEVOD-DECOR	1.08
Pierre Auger Observatory & AMIGA	0.948
SUGAR	0.948
Telescope Array	1.052
Yakutsk EAS Array	1.24



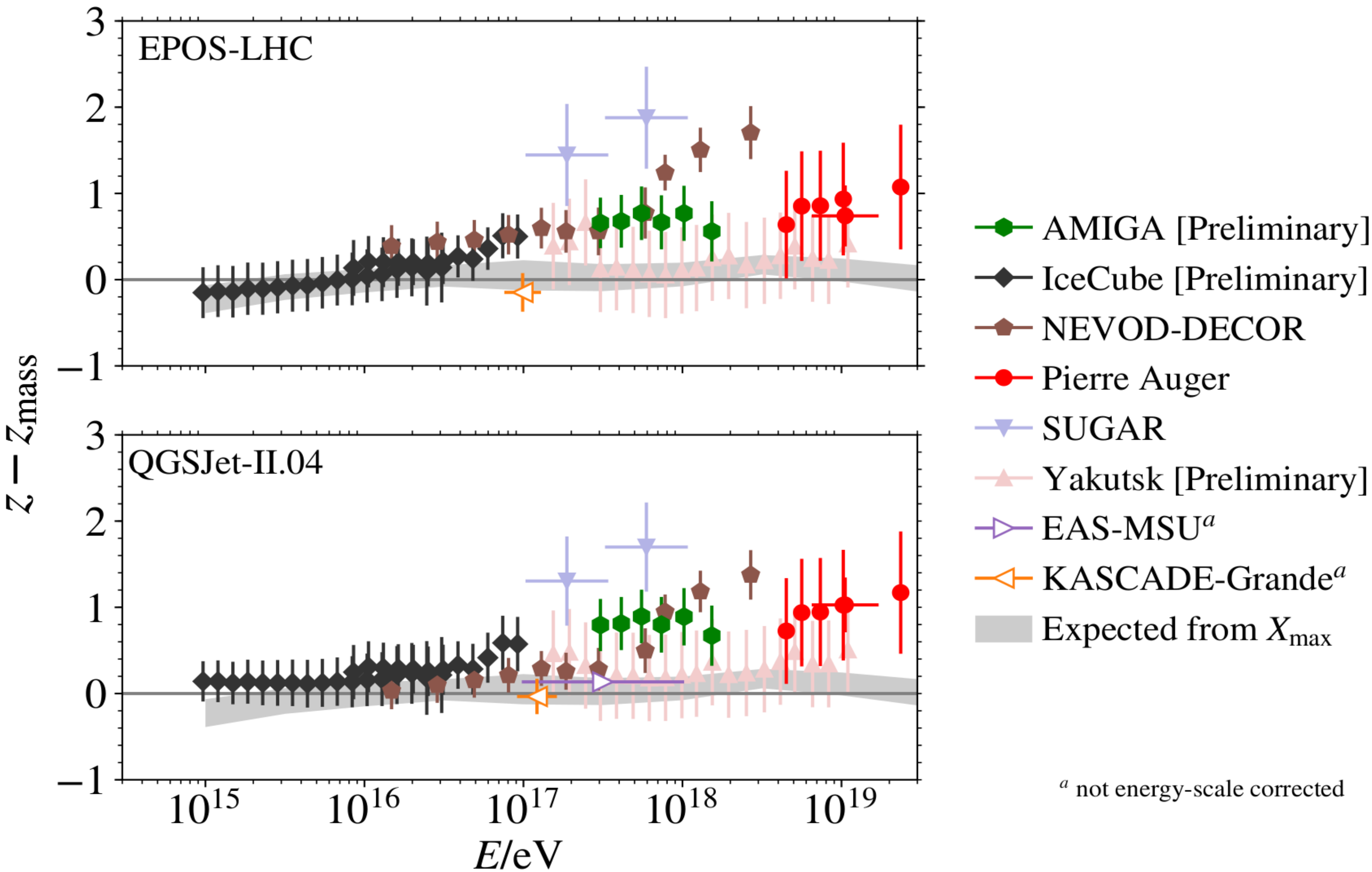
GSF



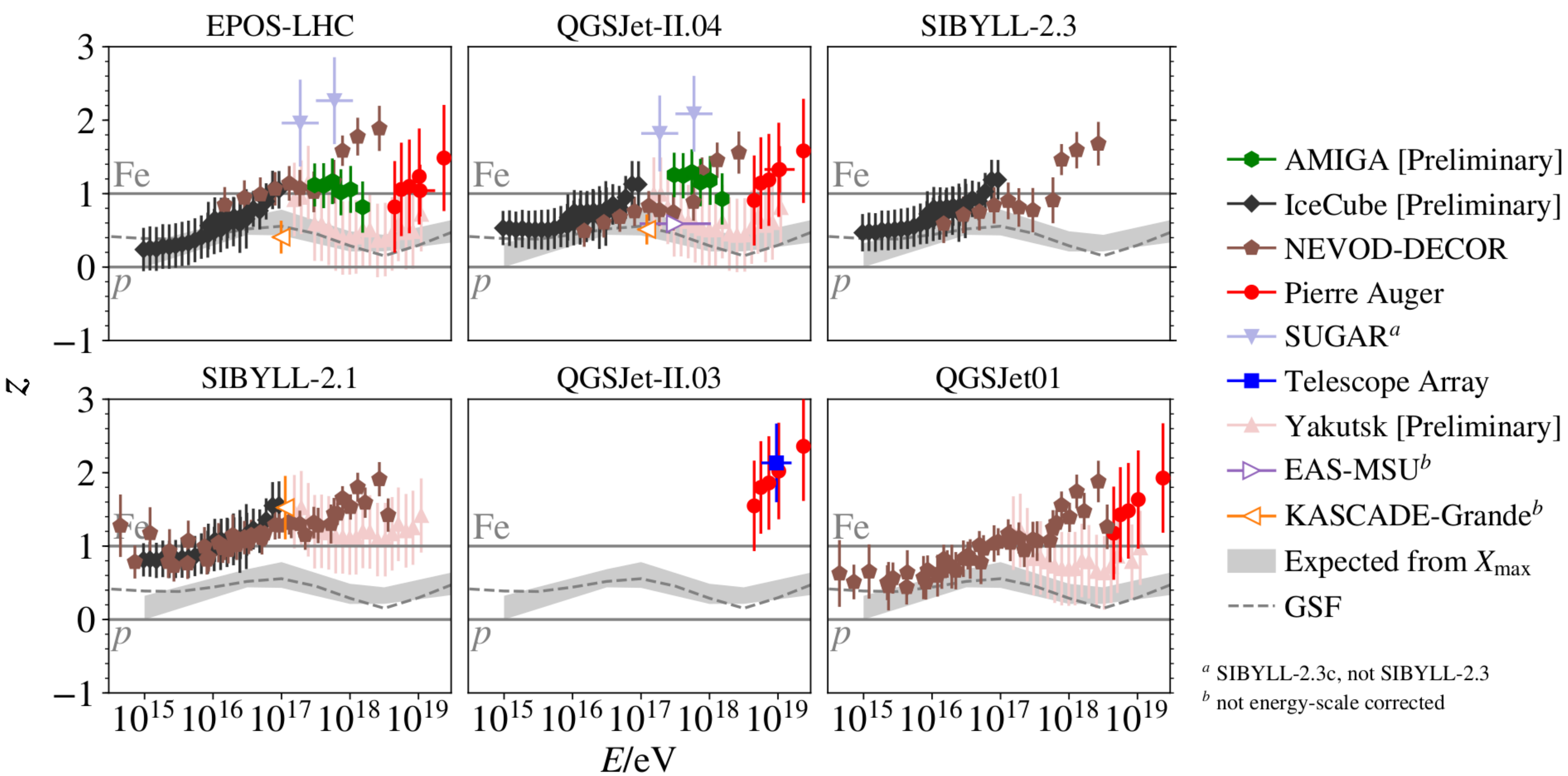
Rescaled Data



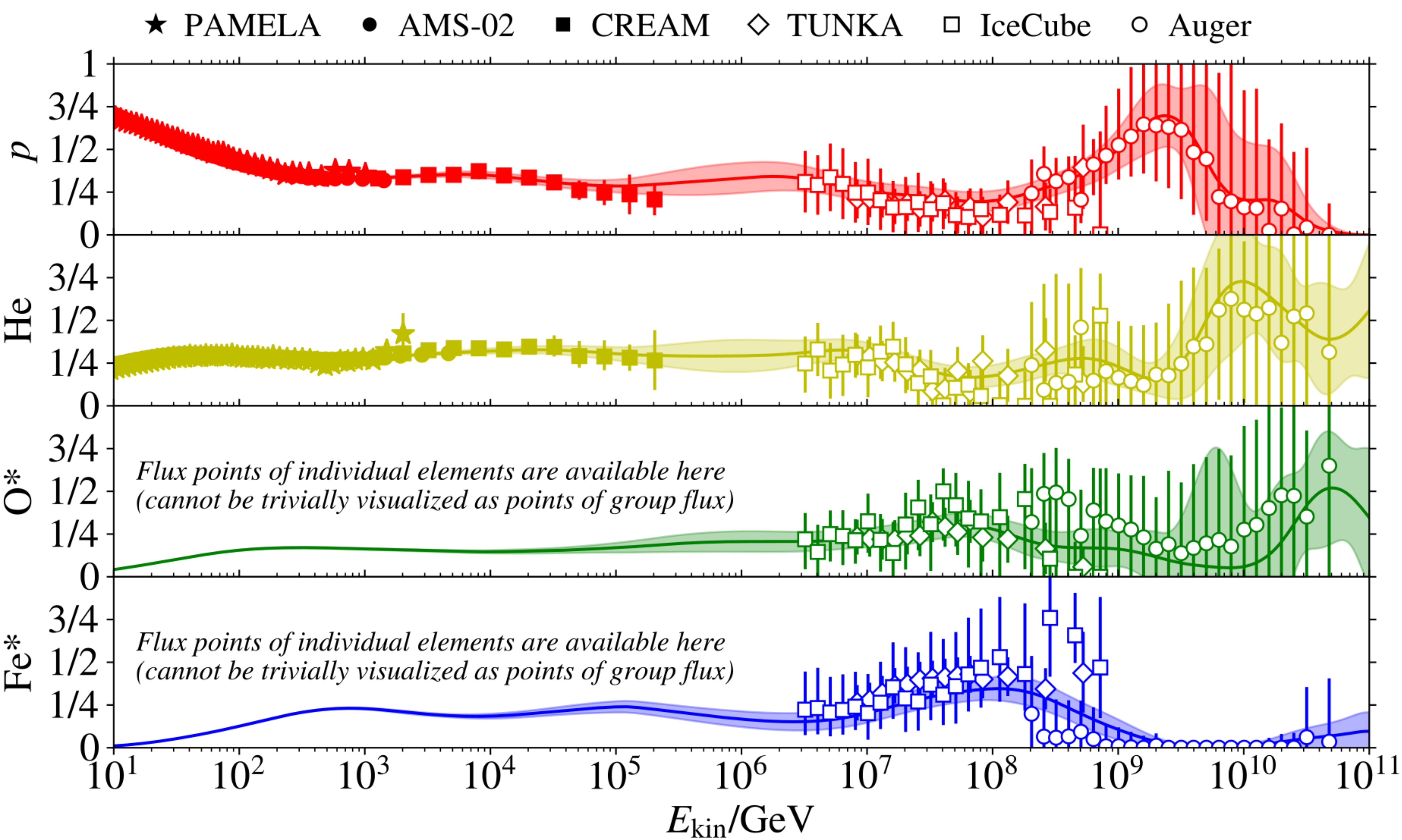
Rescaled Data with Mass Correction



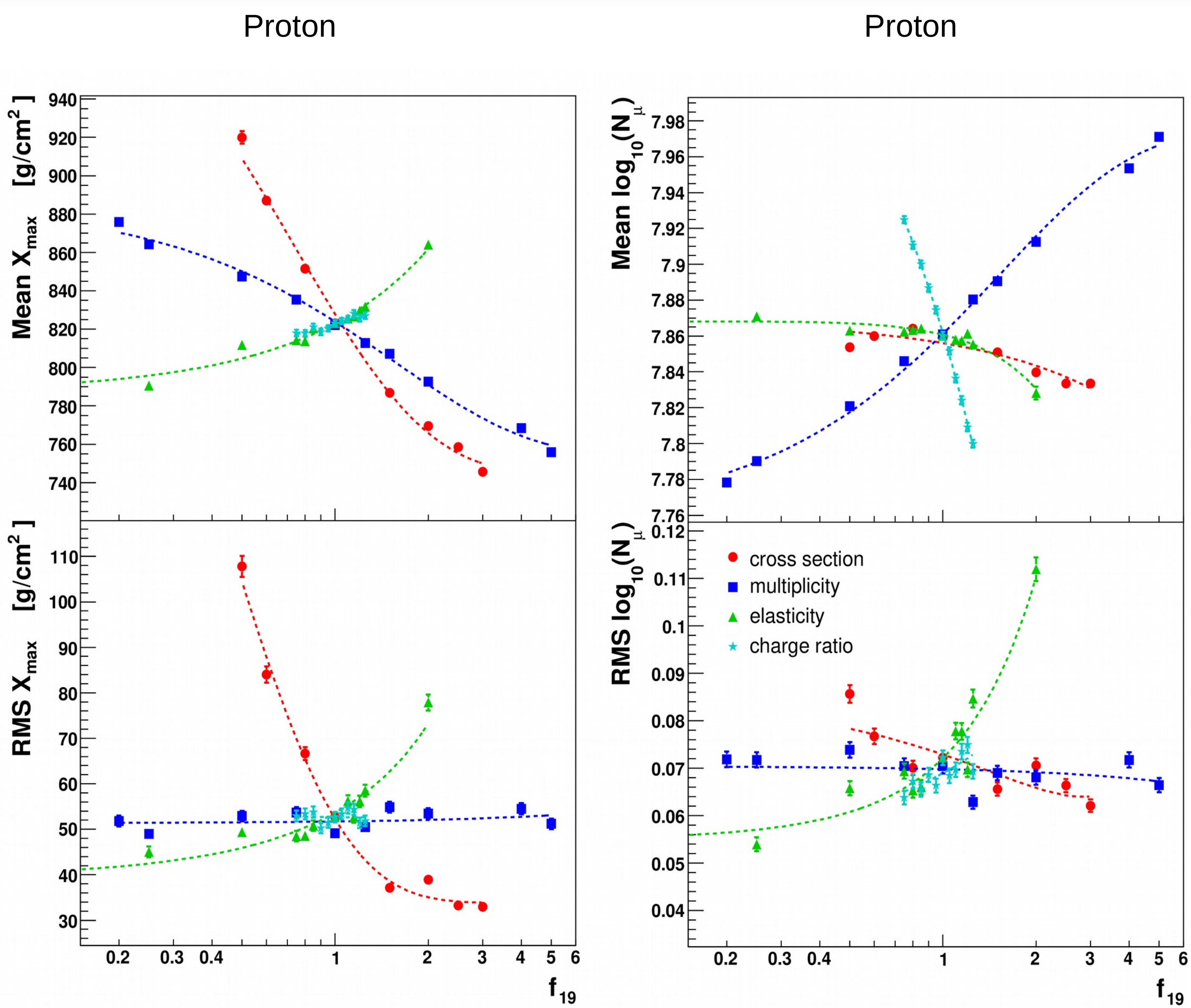
Data Rescaled



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)

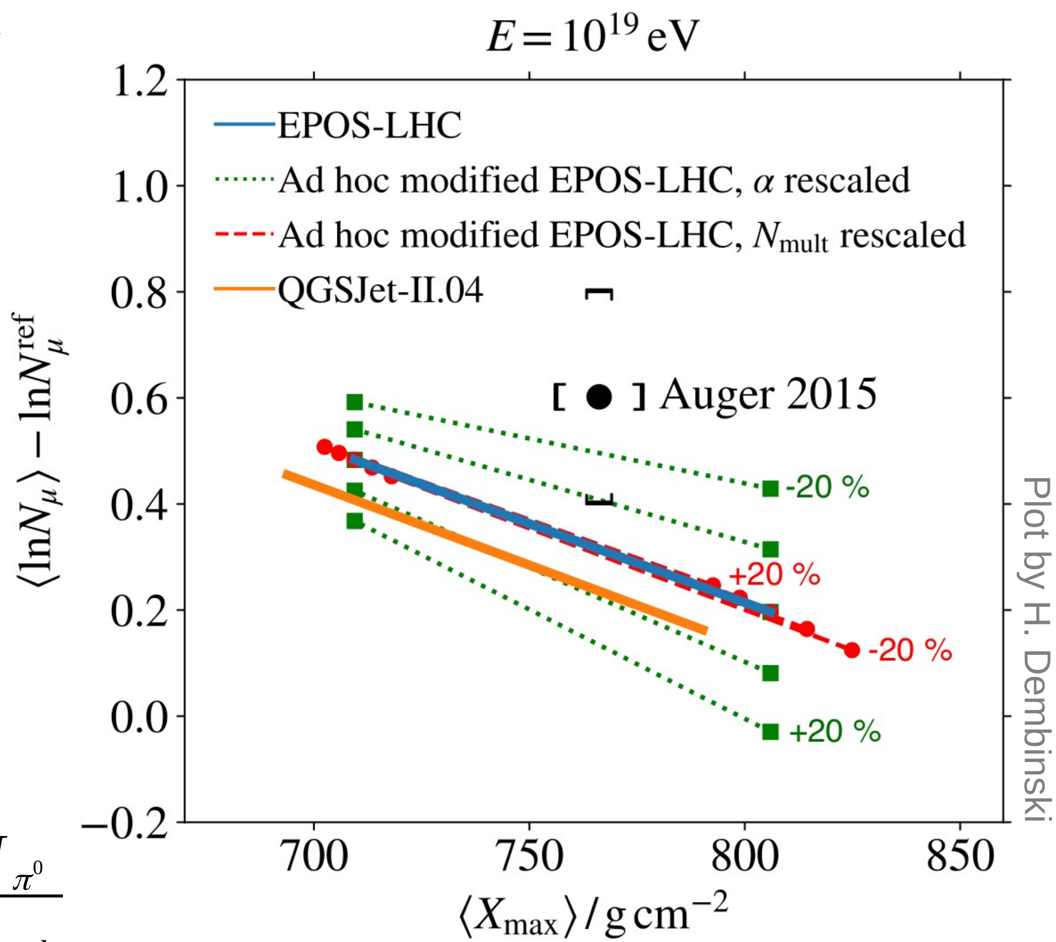
Large sensitivity on pion charge ratio and multiplicity

Constraints from Correlated Change

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

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

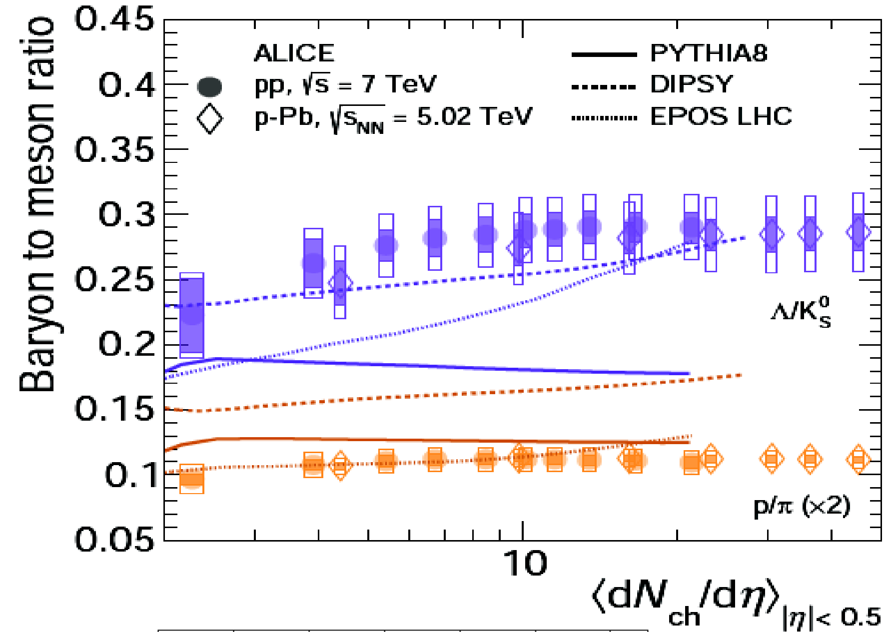
- **To reduce muon discrepancy β has to be change**
  - X_{max} alone (composition) will not change the energy evolution
  - β changes the muon energy evolution but not X_{max}

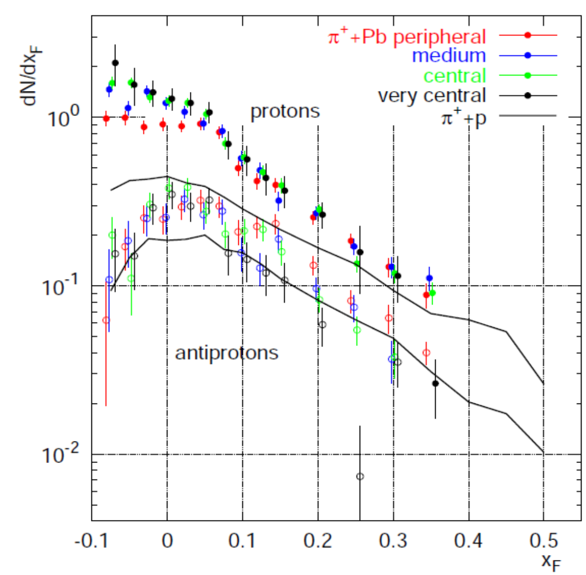


- $$\beta = \frac{\ln(N_{mult} - N_{\pi^0})}{\ln(N_{mult})} = 1 + \frac{\ln(1-\alpha)}{\ln(N_{mult})}$$
  - +4% for β ➛ -30% for $\alpha = \frac{N_{\pi^0}}{N_{mult}}$

More Accelerator Data to Take into Account

- **Future p-Oxygen collisions at LHC**
  - Model independent measurement of E_{em}/E_{had}
  - Precise measurement of particle multiplicity and cross-section
- **Use complete LHC data set**
  - Proper hadron chemistery
  - Very forward measurements (LHCf)
    - Pion exchange ?
- **NA61 data set**
  - Resonance and baryon production
- **NA49 data set**
  - Nuclear effects
  - Baryon stopping





N49
G.Veres
PhD