Connection between neutrino flux, muon excess and LHC data

Tanguy Pierog

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

Karlsruhe Institute of Technology

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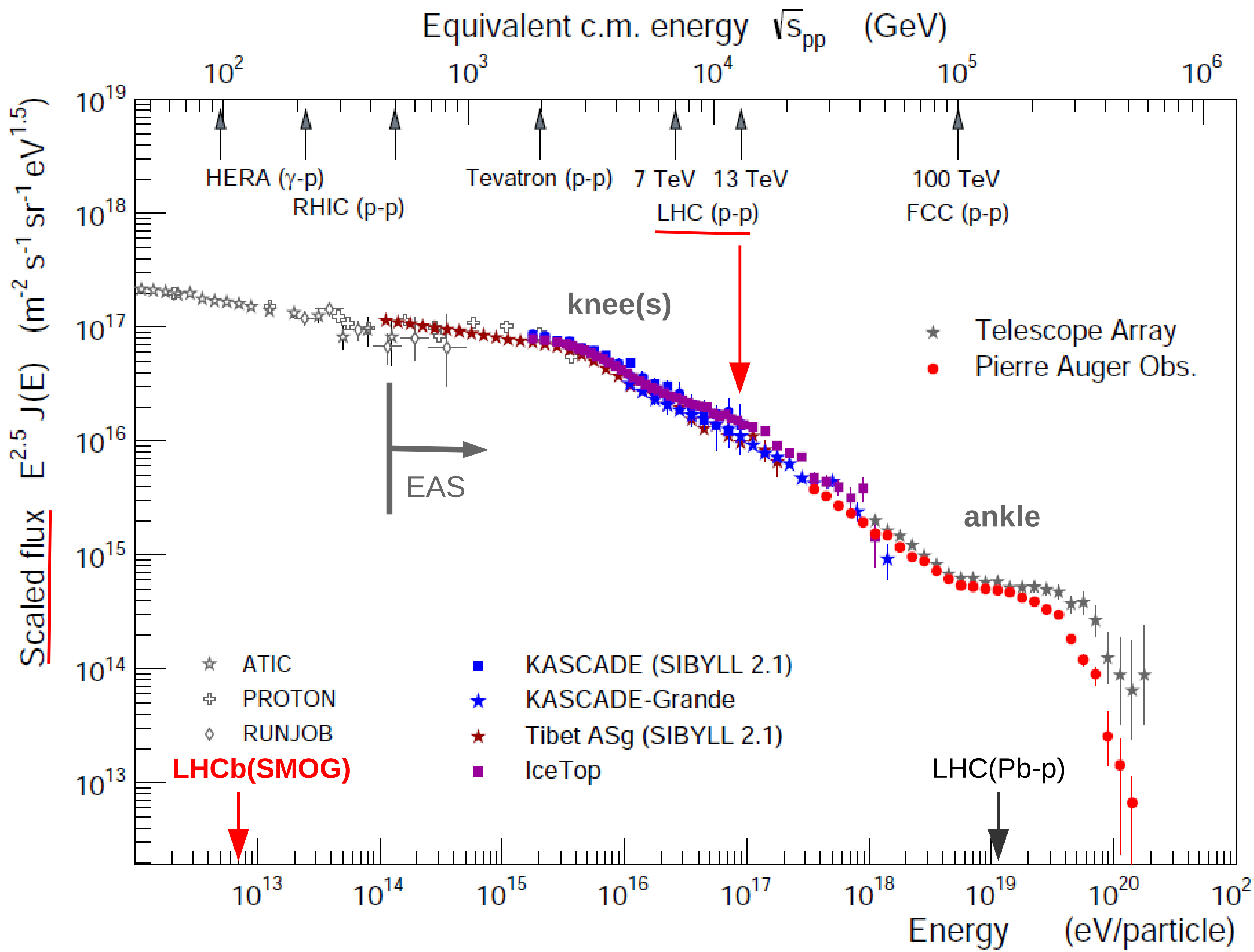
Outline

- **Hadronic interactions (Monte-carlo (MC)) and extended air showers (EAS)**
- **Muon signal in EAS and simulations**
- **New input from LHC**
- **Consequence on inclusive muon and neutrino flux from cosmic rays**

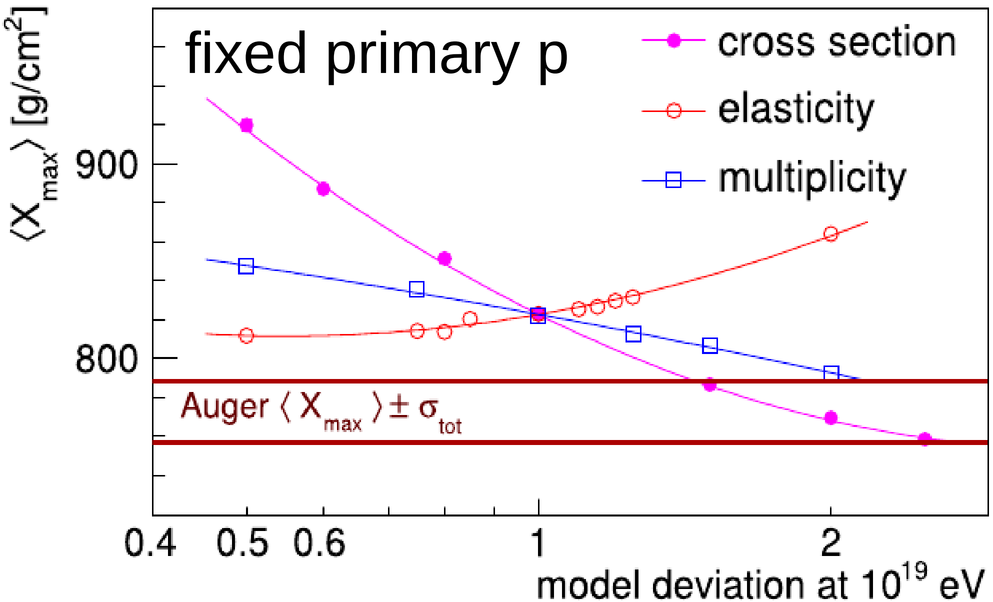
New input from LHC which could help to reproduce EAS data consistently but solution still under study. Possible consequences on TeV to PeV muons and neutrinos.

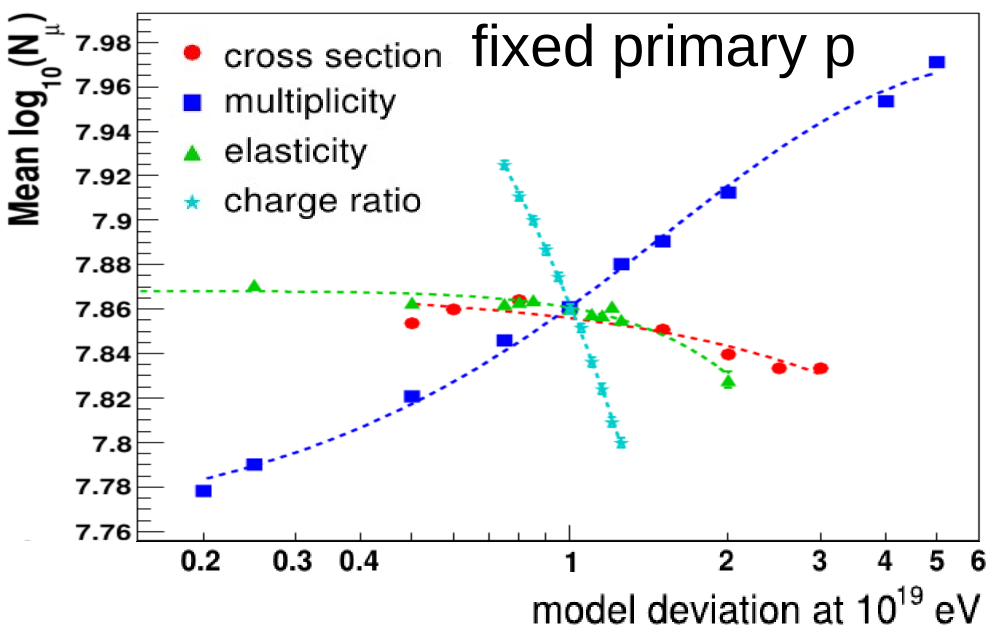
Energy Spectrum



R. Engel (KIT)

Sensitivity to Hadronic Interactions





From R. Ulrich (KIT)

- **Air shower development dominated by few parameters**
  - ➡ mass and energy of primary CR
  - ➡ cross-sections (p-Air and (π-K)-Air)
  - ➡ (in)elasticity
  - ➡ multiplicity
  - ➡ charge ratio and baryon/resonance production
- **Change of primary = change of hadronic interaction parameters**
  - ➡ cross-section, elasticity, mult. ...

With unknown mass composition hadronic interactions can only be tested using various observables which should give consistent mass results

Cosmic Ray Analysis from Air Showers

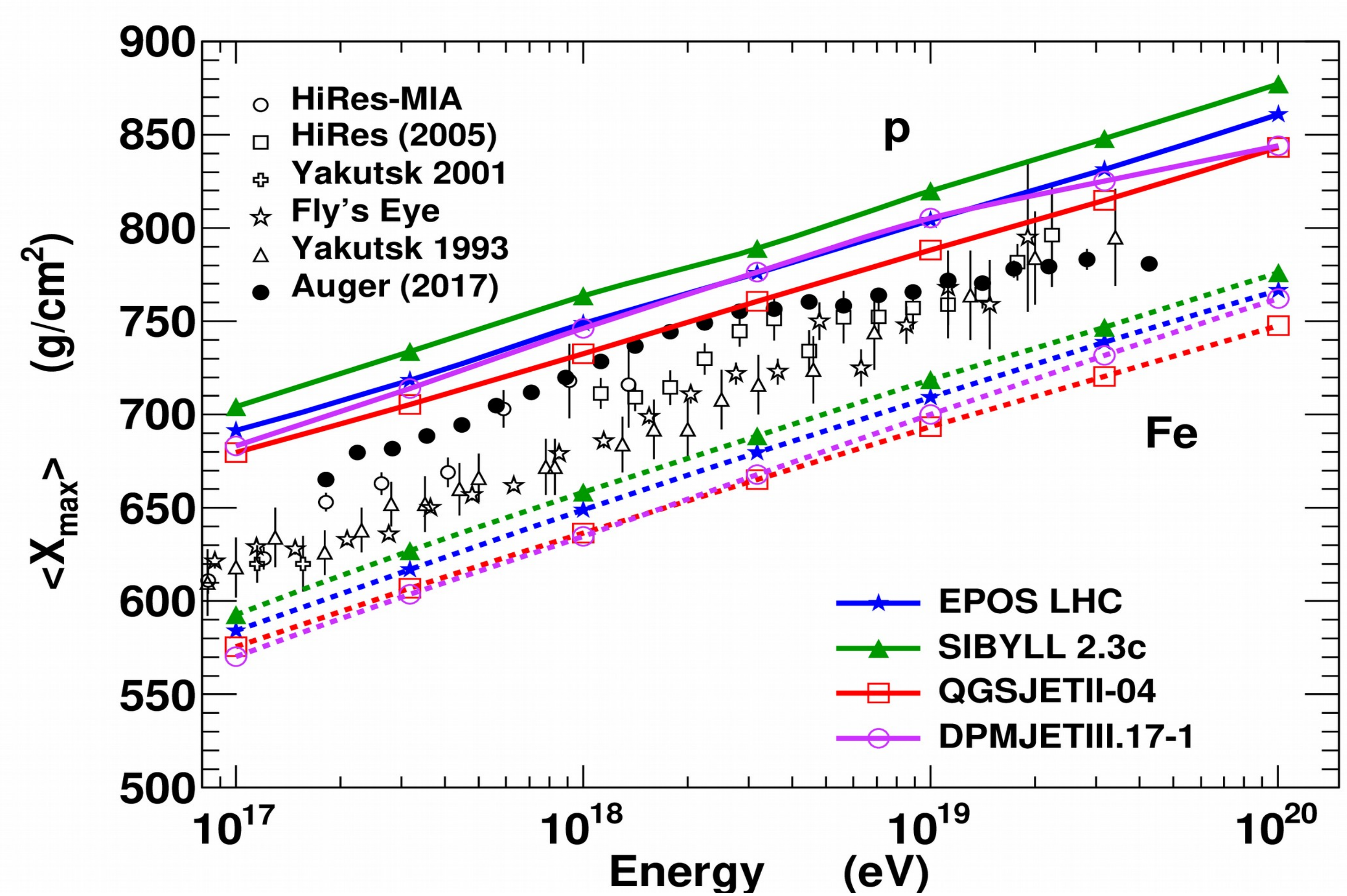
- **EAS simulations necessary to study high energy cosmic rays**
  - complex problem: identification of the primary particle from the secondaries

- **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** by S. Roesler, A. Fedynitch, R. Engel and J. Ranft
  - **EPOS (1.99/LHC/3)** (from VENUS/NEXUS before) by H.J. Drescher, F. Liu, T. Pierog and K.Werner.
  - **QGSJET** (01/II-03/II-04/III) by S. Ostapchenko (starting with N. Kalmykov)
  - **Sibyll (2.1/2.3c)** by E-J Ahn, R. Engel, R.S. Fletcher, T.K. Gaisser, P. Lipari, F. Riehn, T. Stanev

$<X_{max}>$

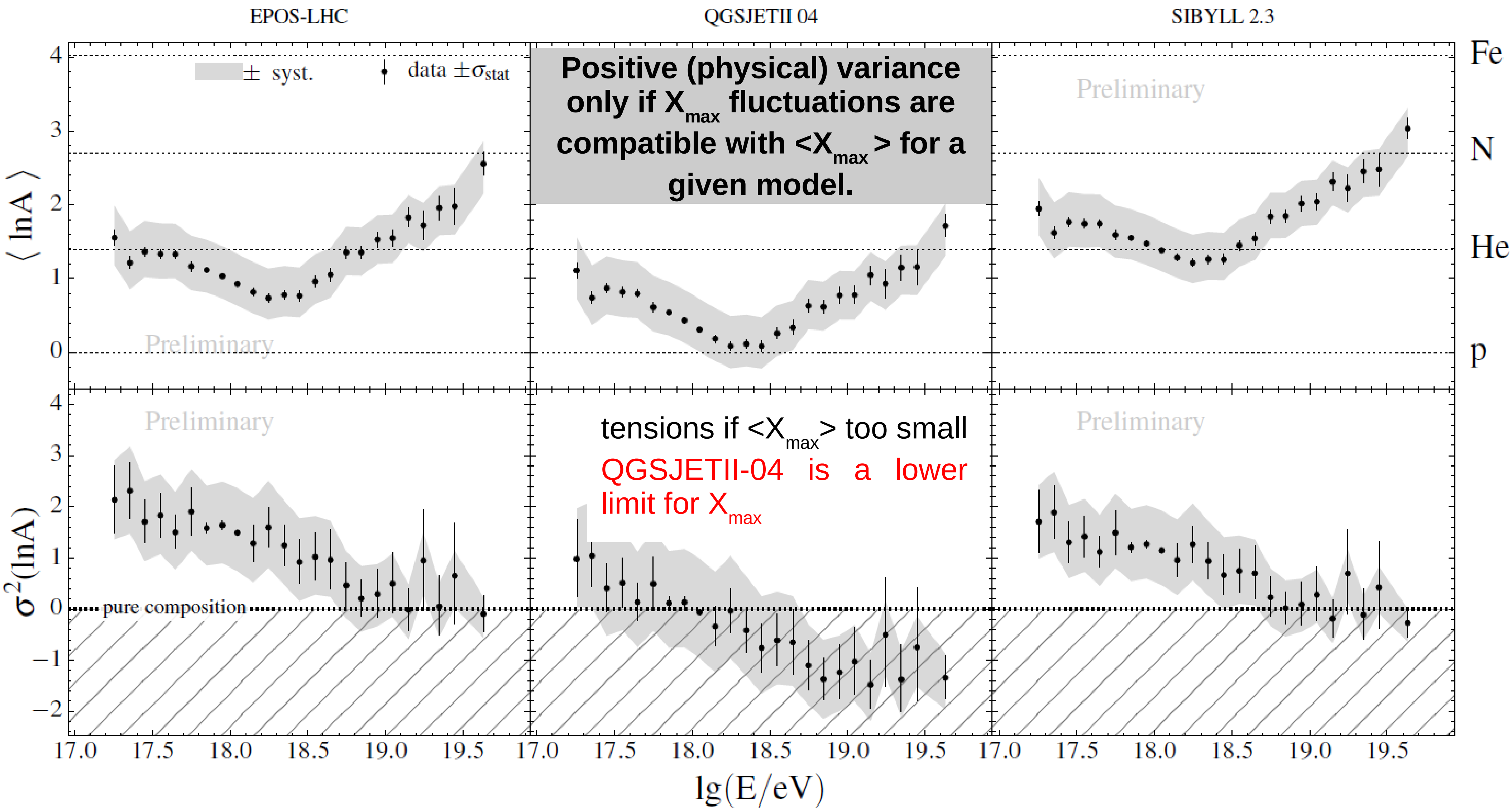
- **very similar elongation rate (slope) for all models**
- **same mass composition evolution**
- **still differences in absolute values**
  - ➡ +/- 20g/cm² is a realistic uncertainty band



Model Consistency using Electromagnetic Component

Study by Pierre Auger Collaboration

➡ std deviation of lnA allows to test model consistency.



Positive (physical) variance only if X_{max} fluctuations are compatible with $<X_{max}>$ for a given model.

tensions if $<X_{max}>$ too small

QGSJETII-04 is a lower limit for X_{max}

Cross-Section

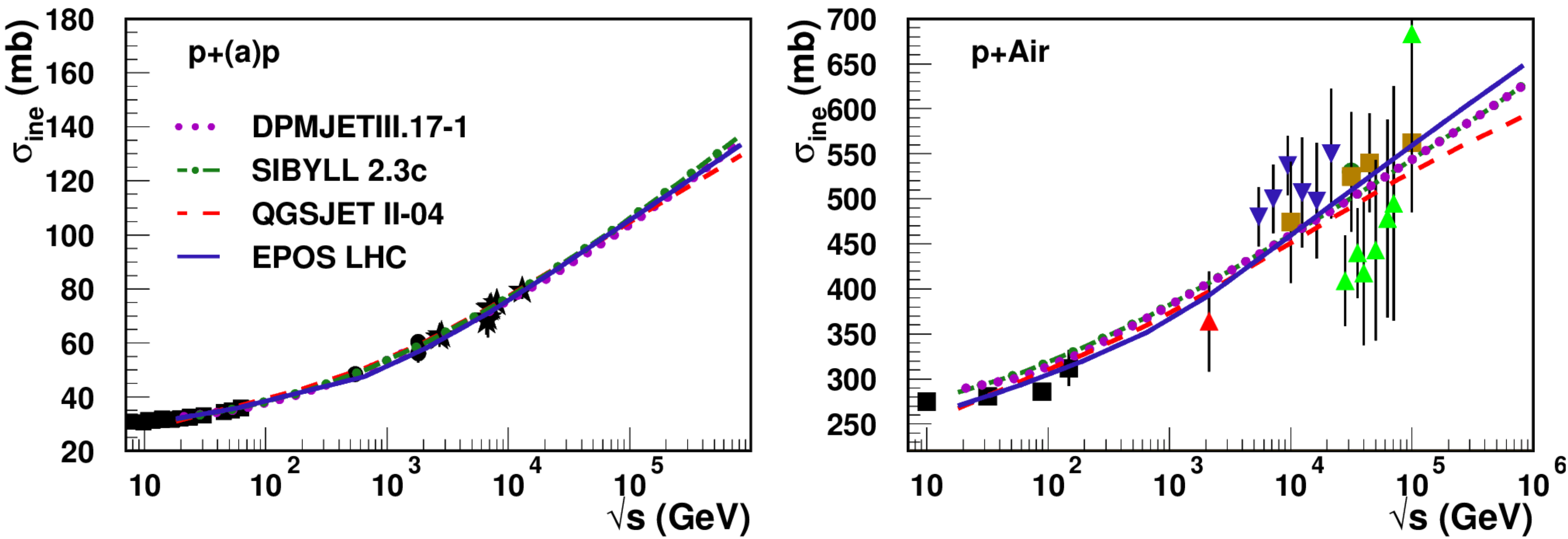
For all models cross-section calculation based on optical theorem

- total cross-section given by elastic amplitude

$$\sigma_{\text{tot}} = \frac{1}{s}\Im m(A(s,t\to 0))$$

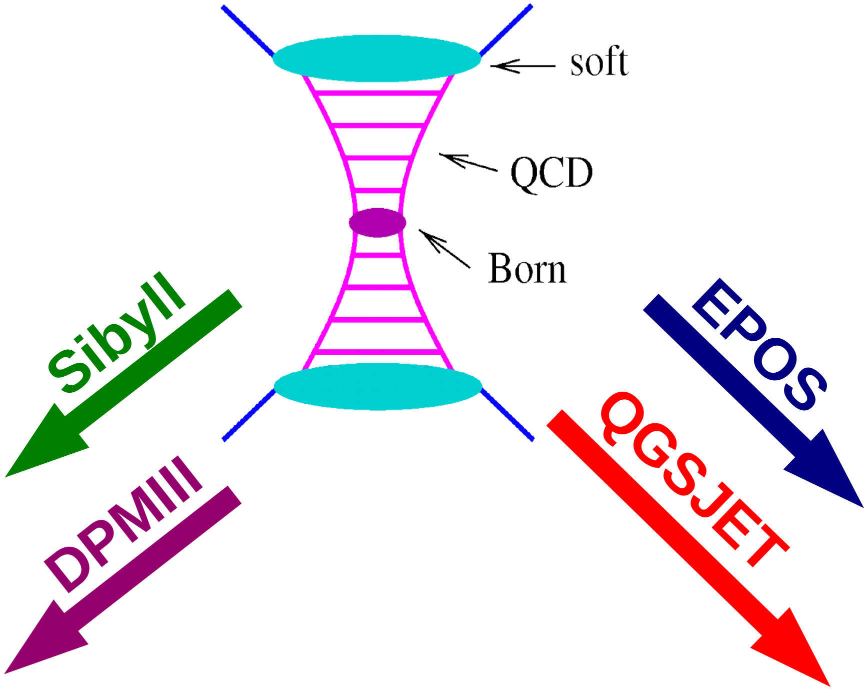
- different amplitudes in the models but free parameters set to reproduce all p-p cross-sections
- basic principles + high quality LHC data = same extrapolation

pp p-Air



Pseudorapidity

- **Field theory : scattering via the exchange of an excited field**
  - parton, hadron, quasi-particle = Reggeon or Pomeron (vacuum excitation)
- **QCD based theory so at high energy, perturbative QCD can be used to build the field amplitude (amplitude used for the cross-section)**
  - all minijet based (parton cascade and pQCD born process hadronized using string fragmentation) but different definitions



- soft+hard in different components
- external parton distribution functions (**GRV98**,**cteq14**)
- connection to projectile/target with small “x”

- soft+hard in the same amplitude
- own parton distribution function compatible with HERA data (<u>not for QGSJET01: pre-HERA time</u>)
- connection to projectile/target with large “x”

Ostapchenko et al. Phys.Rev. D94 (2016) no.11, 114026

Pseudorapidity

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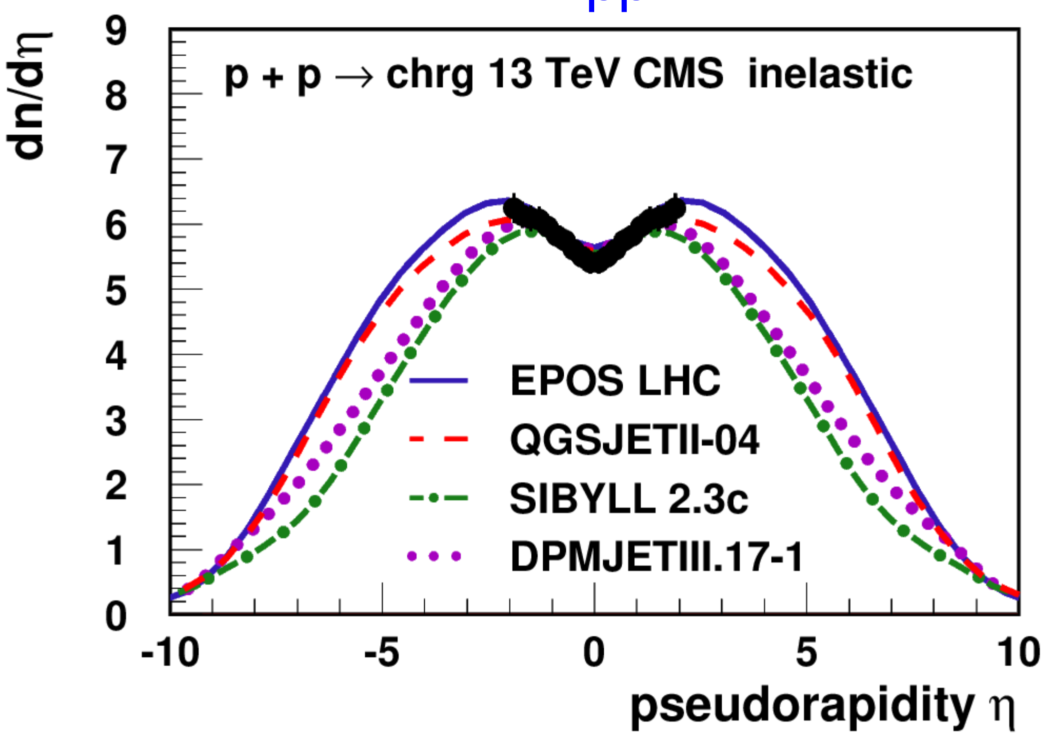
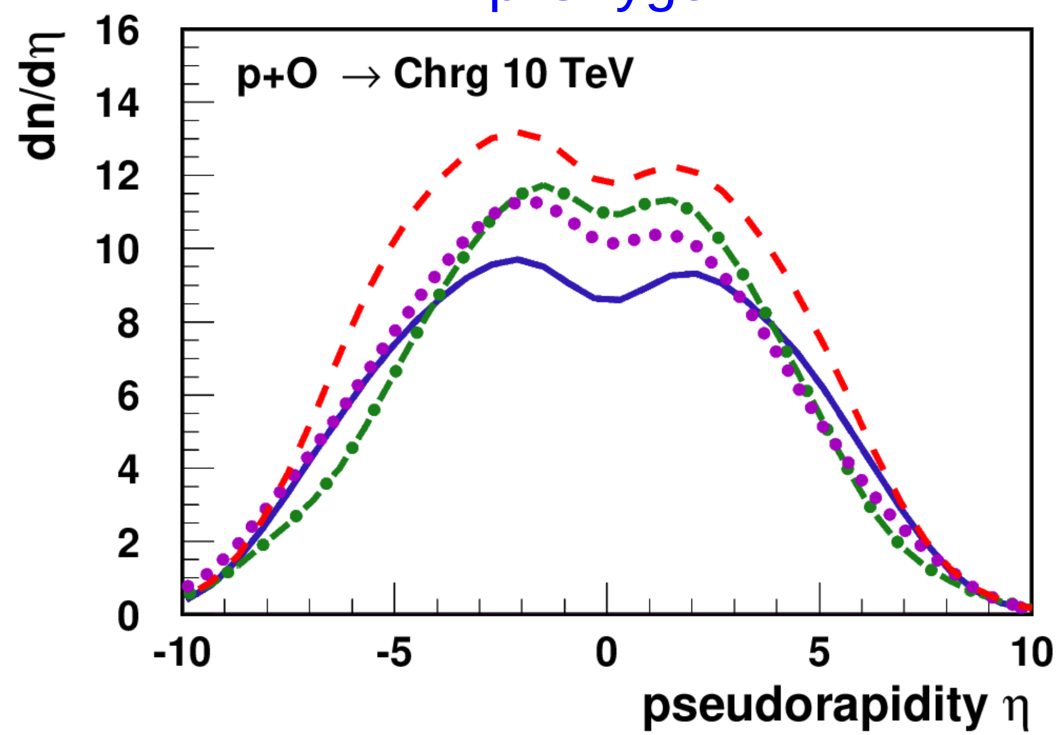
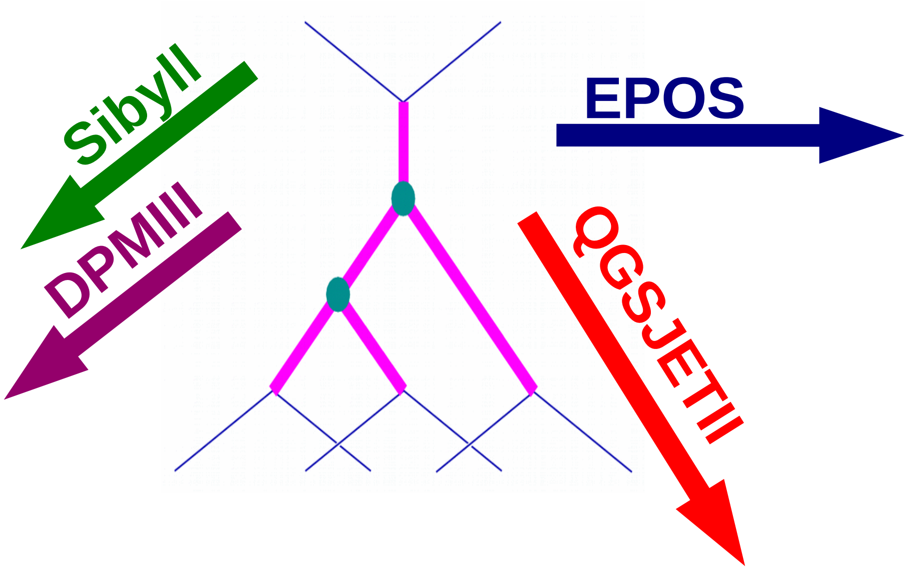


p-Oxygen



Energy Evolution

- **Multiple scattering not enough to reconcile pQCD minijet cross-section and total cross-section**
  - non-linear effect should be taken into account (interaction between scatterings)
- **Solution depends on amplitude definition**



- hard amplitude depend on minimum p_t
- parametrize minimum p_t as a function of energy (and impact parameter for DPMJETIII)
- fit to data (multiplicity and cross-section)

- fixed minimum p_t in hard part
- theory based “fan diagrams” re-summed to infinity without energy sharing

- fixed minimum p_t in hard part
- enhanced diagrams not compatible with energy sharing
- modification of vertex function to take into account non linear effects (data driven phenomenological approach)

Energy Evolution

- **Multiple scattering not enough to reconcile pQCD minijet cross-section and total cross-section**
  - ➡ non-linear effect should be taken into account (interaction between scatterings)
- **Solution depends on amplitude definition**
  - ➡ still large uncertainties at high energy (but reduced after LHC)

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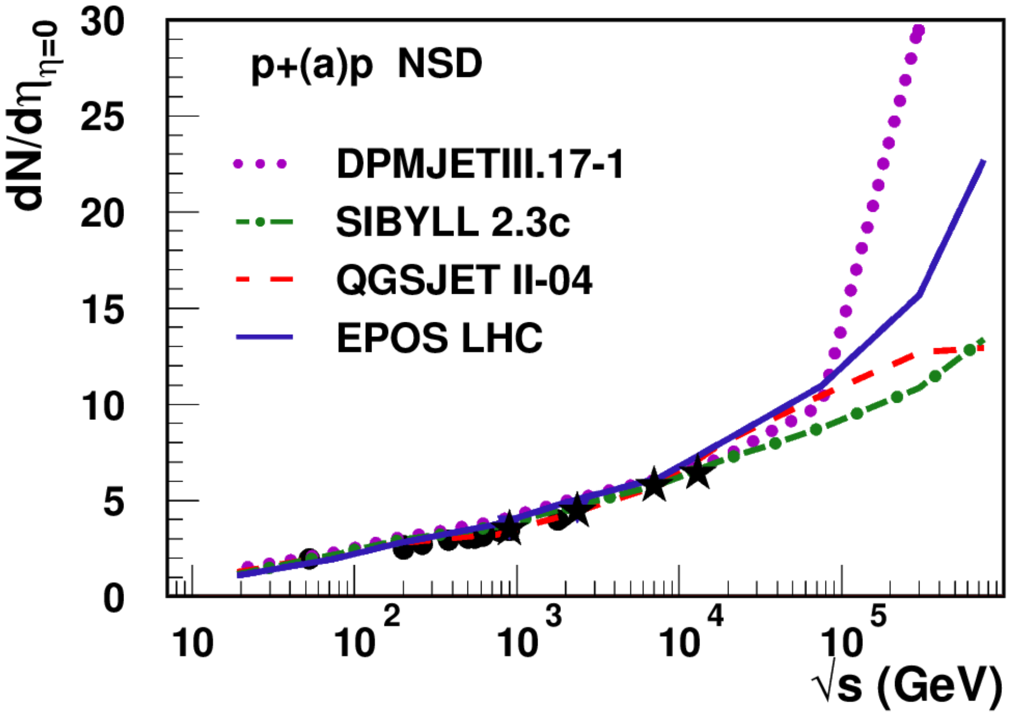
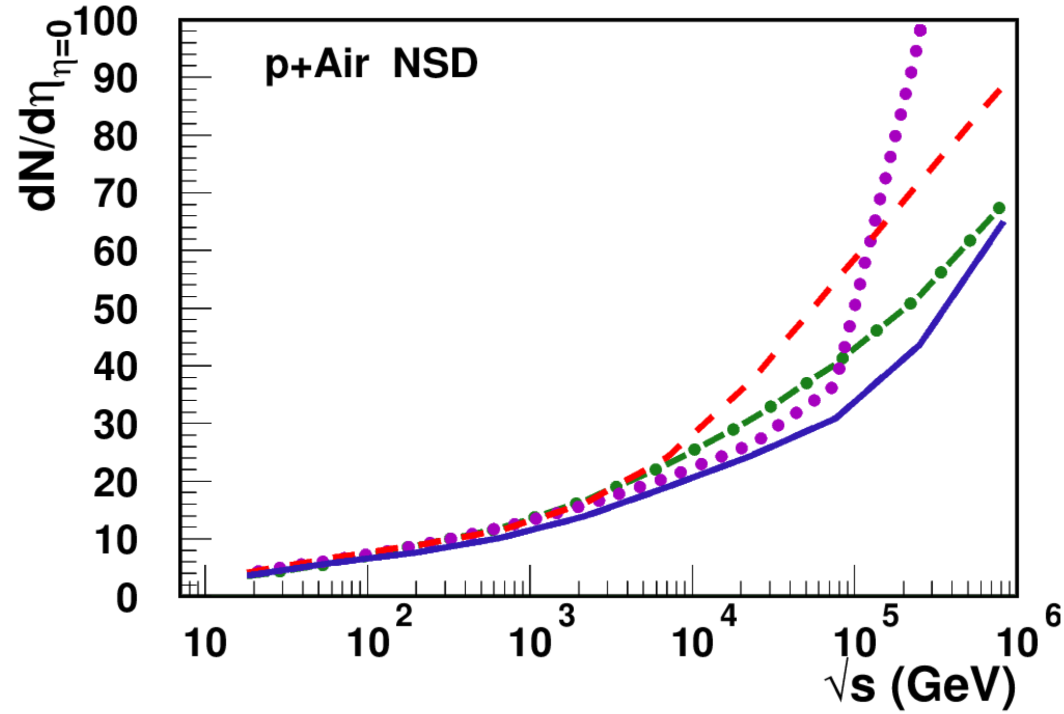


p-Air



Inelasticity

- **In most of the cases, the projectile is destroyed by the collision**
  - ➡ non-diffractive scattering : high energy loss for leading particle, high multiplicity
- **In 10-20% of the time, the projectile have a small energy loss (high elasticity) and is unchanged**
  - ➡ diffractive scattering : low energy loss, low multiplicity on target side
- **Model difference mostly at technical level (and choice of data)**

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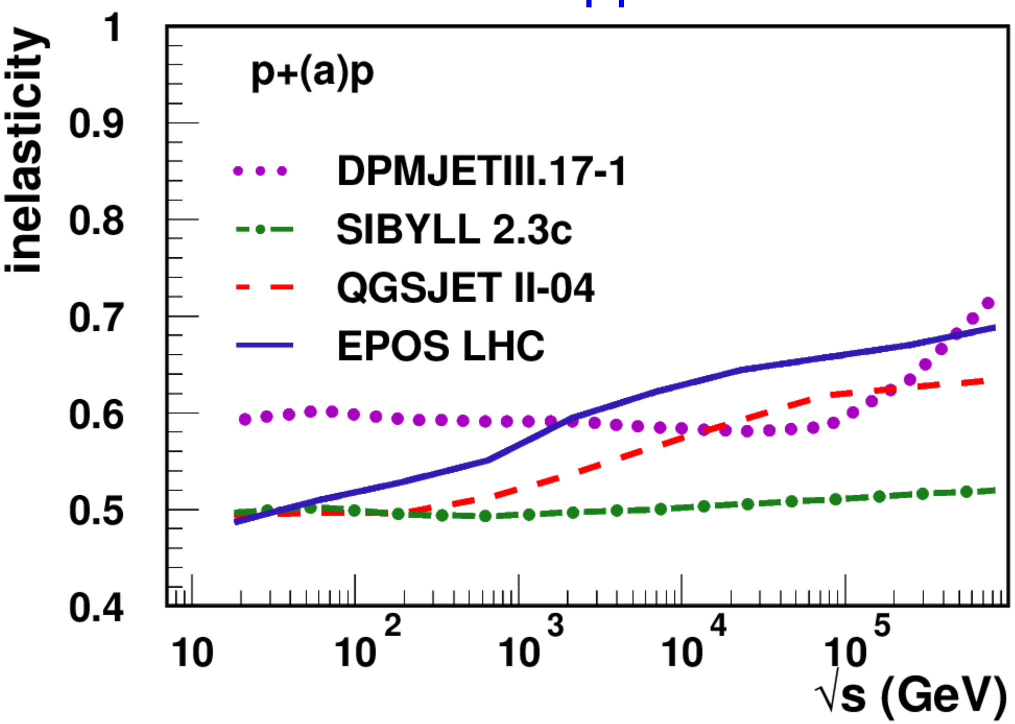
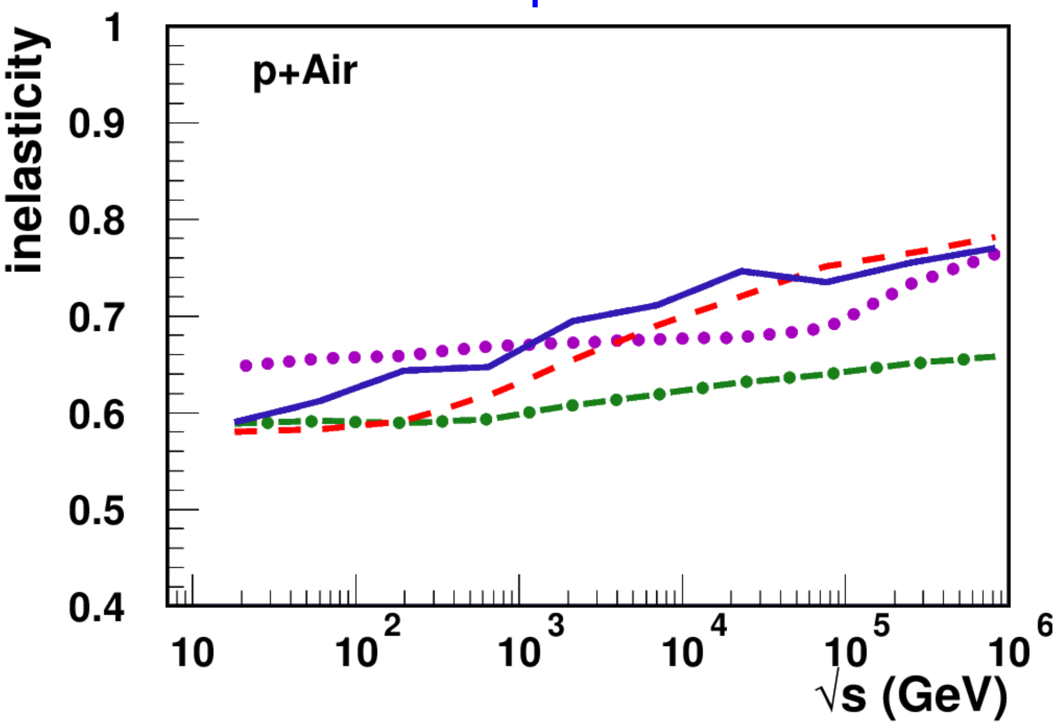


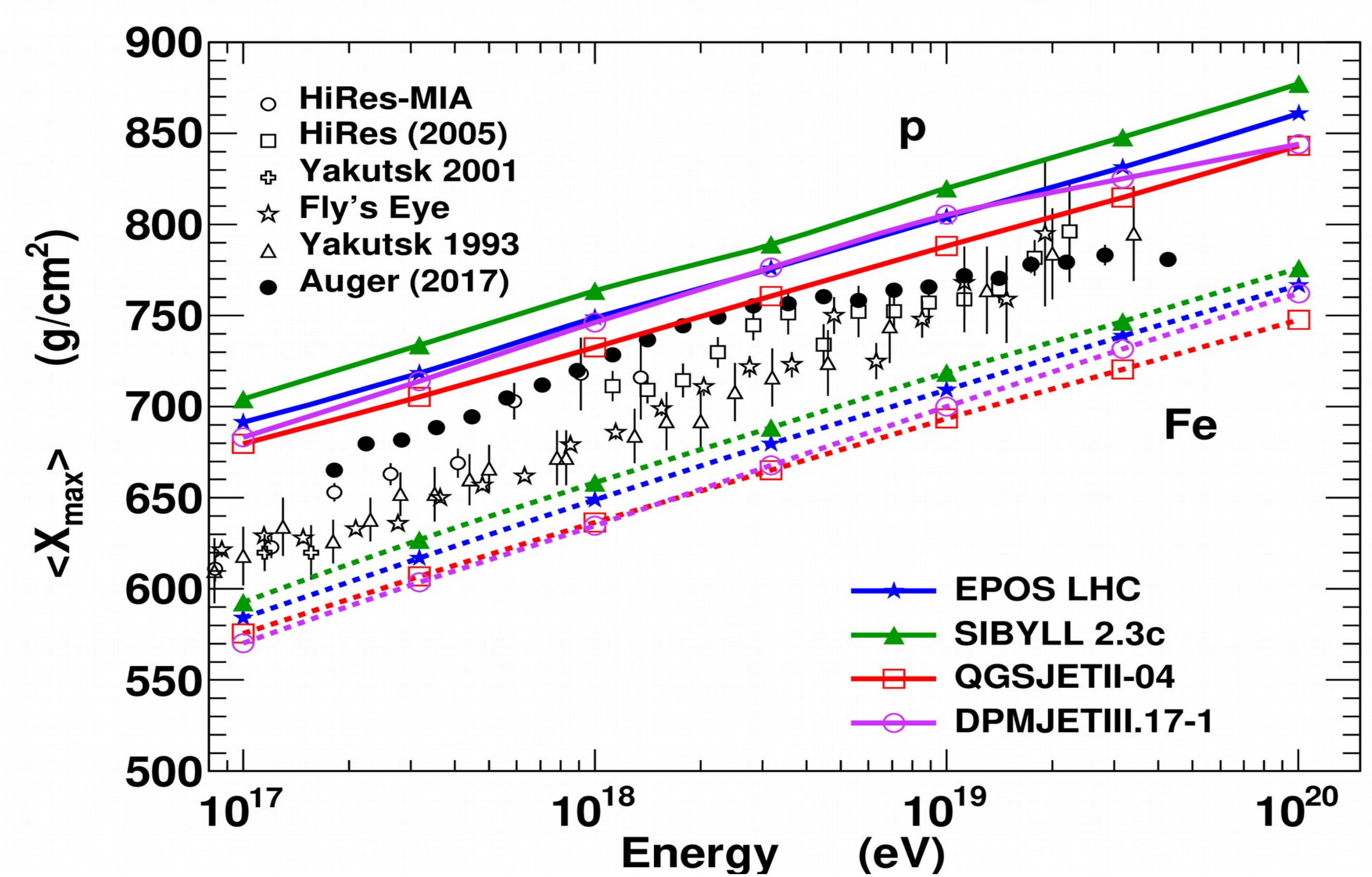
p-Air



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



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),

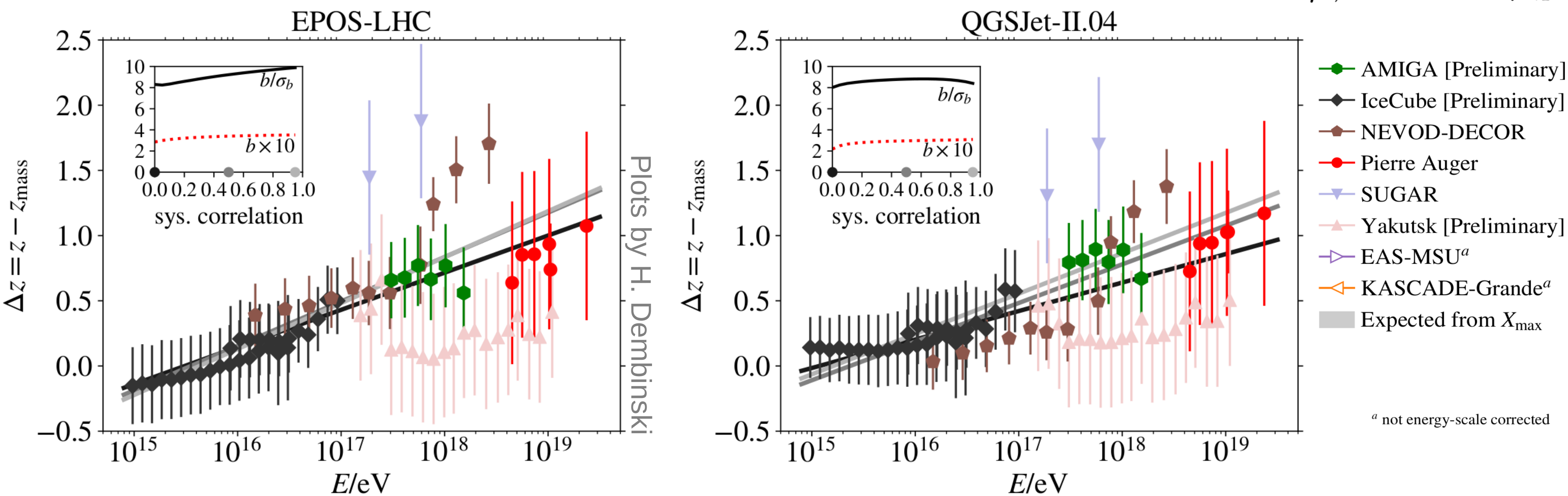
I. Yashin (NEMOD/DECOR, Russia). **E. Zadeba** (NEMOD/DECOR, Russia)

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

Global Behavior

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

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

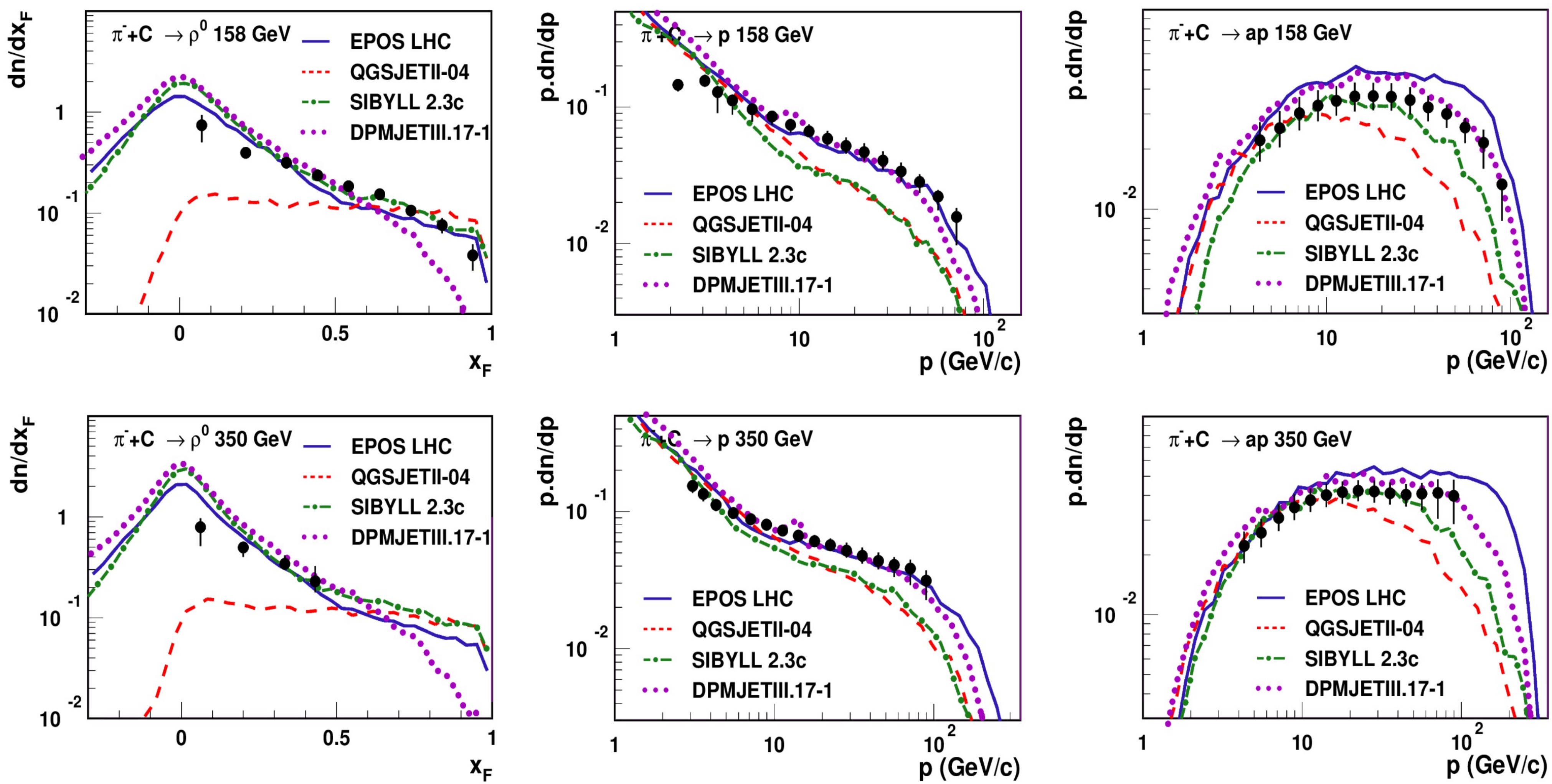


- **Different energy or mass scale cannot change the slope**
  - Different property of hadronic interactions at least above 10^{16} eV

NA61 Pion-Carbon Data

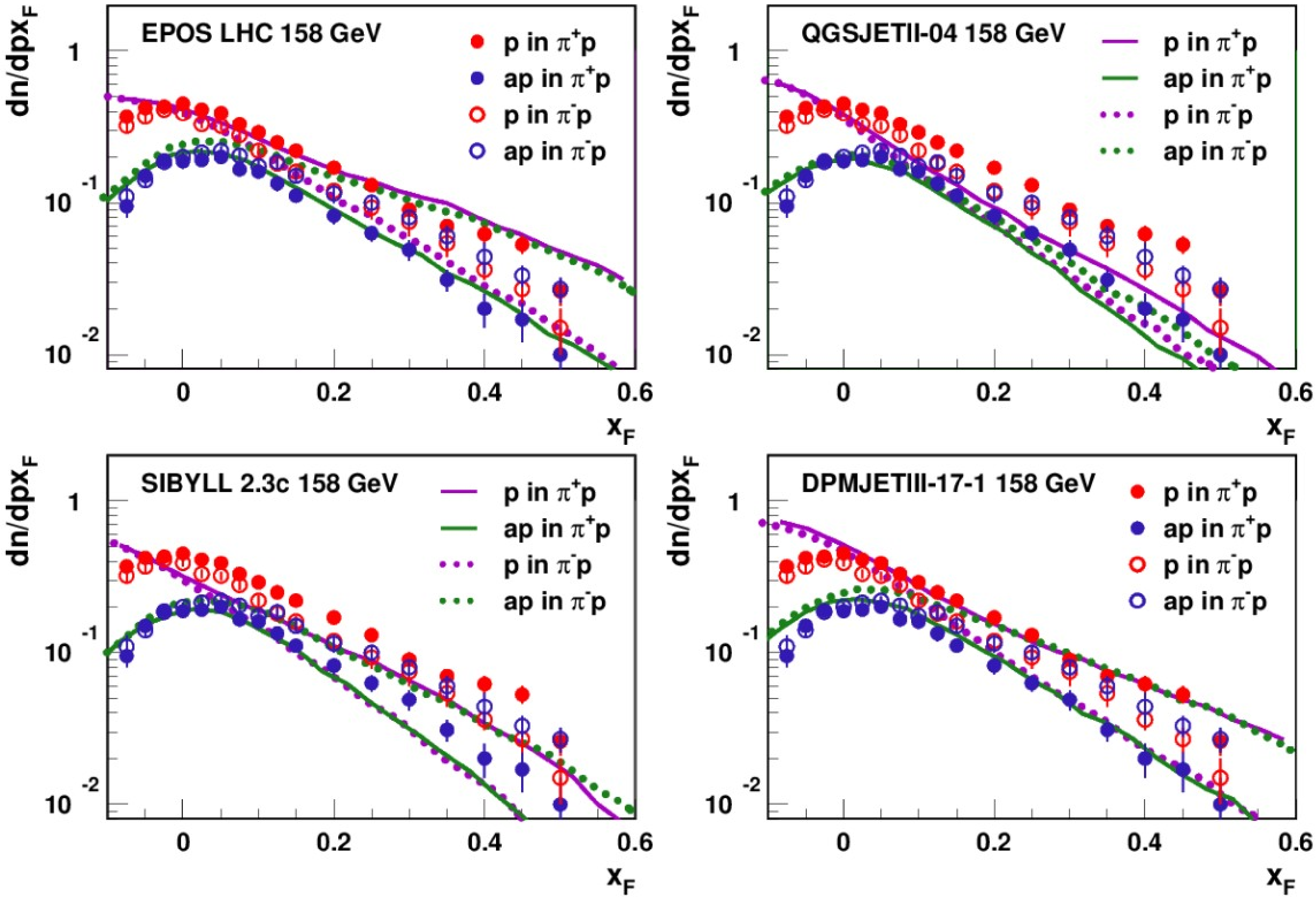
New data from NA61 : wrong old data interpretation

- over production of anti-baryons in EPOS LHC : problem in air showers
- confirmation that QGSJETII-04 underestimate forward baryon production



Baryons in Pion Interactions

Data from NA49 (Gabor Veres PhD) : full picture

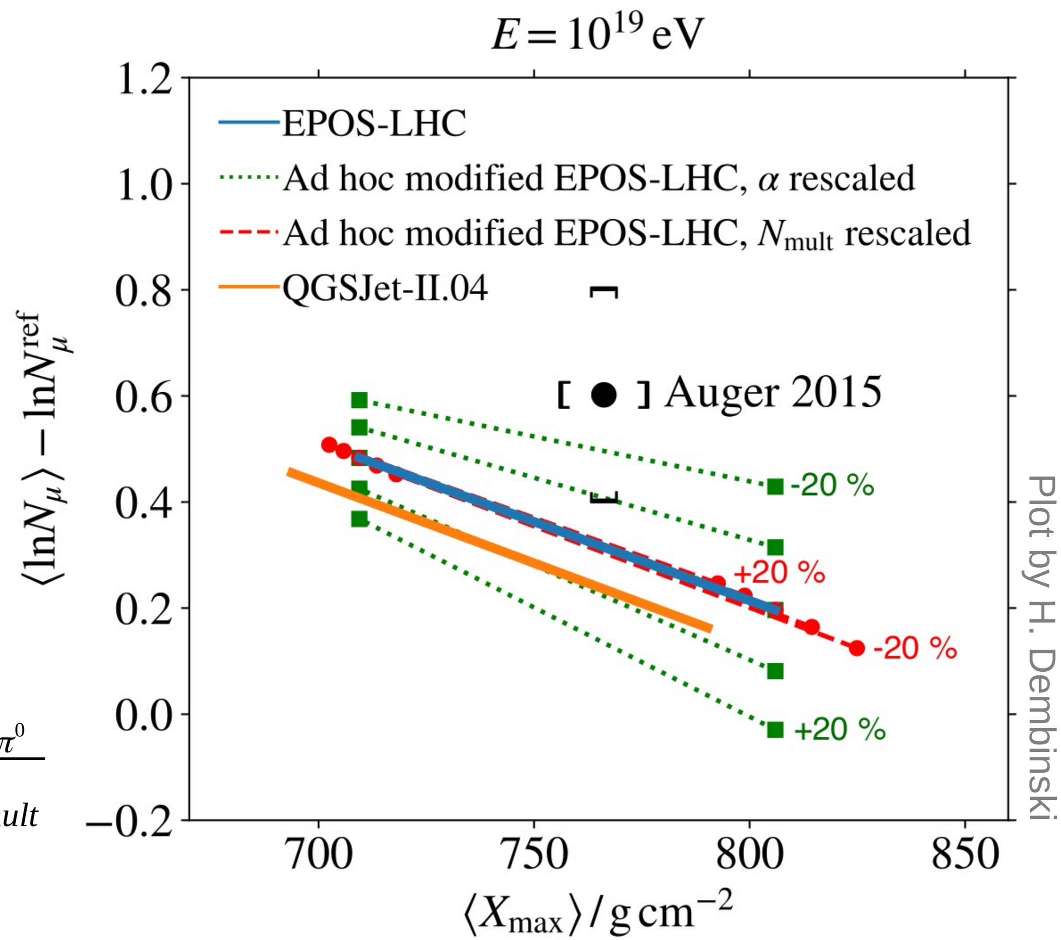


Constraints from Correlated Change

- **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 $\alpha = \frac{N_{\pi^0}}{N_{mult}}$

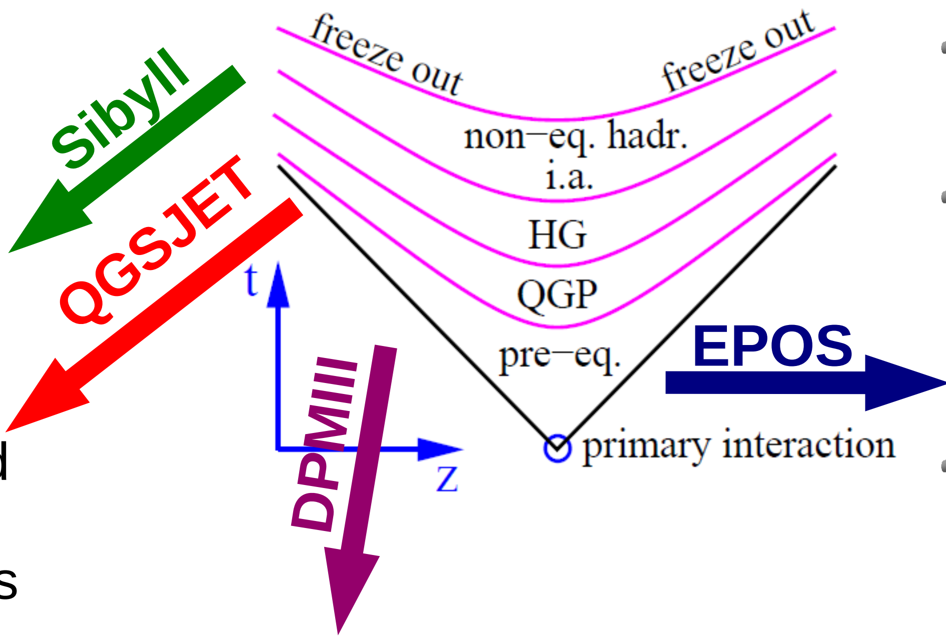
Possible Particle Physics Explanations

A 30% change in particle charge ratio ($\alpha = \frac{N_{\pi^0}}{N_{mult}}$) is huge !

- Possibility to increase N_{mult} limited by X_{max}
- New Physics ?
  - Chiral symmetry restoration (Farrar et al.) ?
  - Strange fireball (Anchordoqui et al.) ?
  - String Fusion (Alvarez-Muniz et al.) ?
    - Problem : no strong 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 EPOS LHC (QGP only in extreme conditions)
    - Problem : α changed at most by 20-25%

Should Everything Be Taken into Account in CR Models ?

- **Models have different philosophies !**
  - number of parameters increase with data set to reproduce
  - predictive power may decrease with number of parameters
  - predictive power increase if we are sure not to neglect something



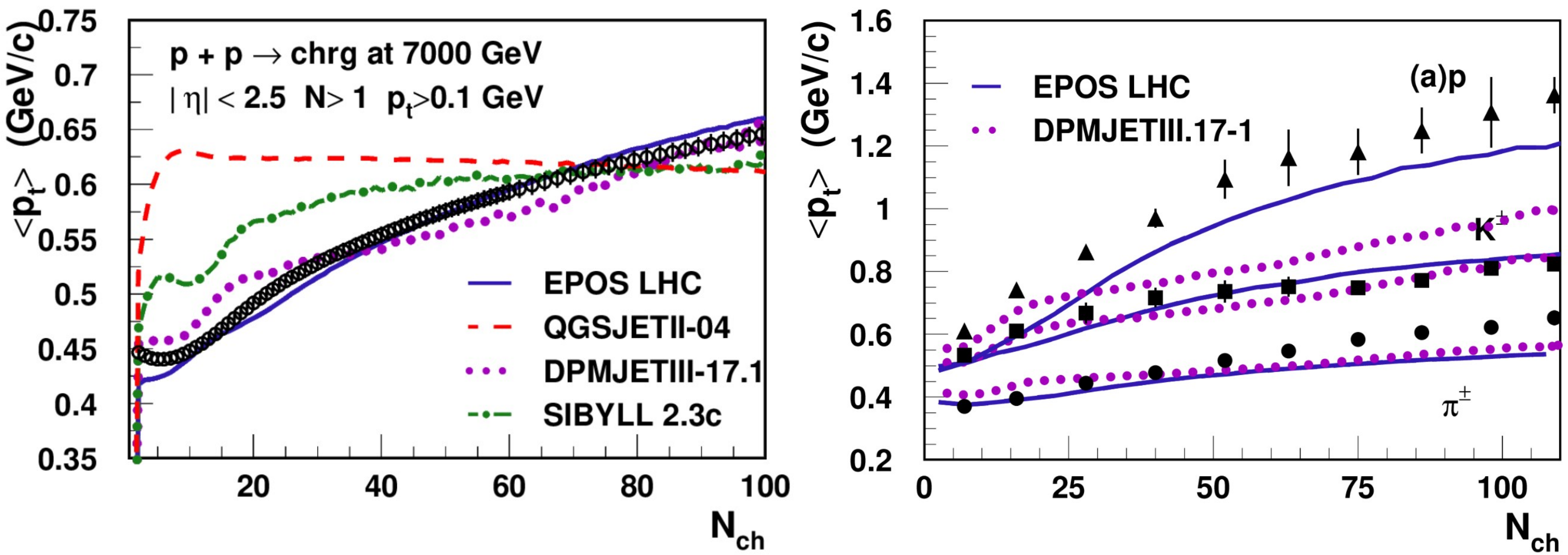
Sibyll / QGSJET:
- models for CR only
- fast and not suppose to describe everything
- no detailed hard scattering or collective effects

DPMJET III:
- heavy ion model intended to be used for high energy physics
- limited development for collective effects but correct hard scattering

EPOS:
- developed first for heavy ion interactions
- detailed description of every possible “soft” observable (not good for hard scattering yet)
- sophisticated collective effect treatment (real hydro for EPOS 2 and 3)
- very large complete data set (LEP, HERA, SPS, RHIC, LHC)

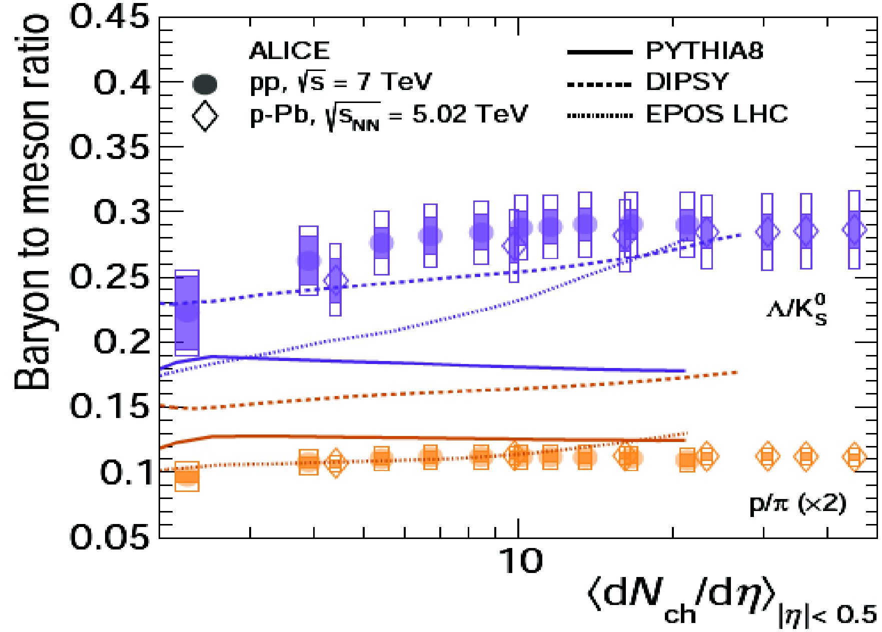
Should Everything Be Taken into Account in CR Models ?

- **Models have different philosophies !**
  - number of parameters increase with data set to reproduce
  - predictive power may decrease with number of parameters
  - predictive power increase if we are sure not to neglect something
- **No direct influence on air showers but different parameters and extrapolations ?**

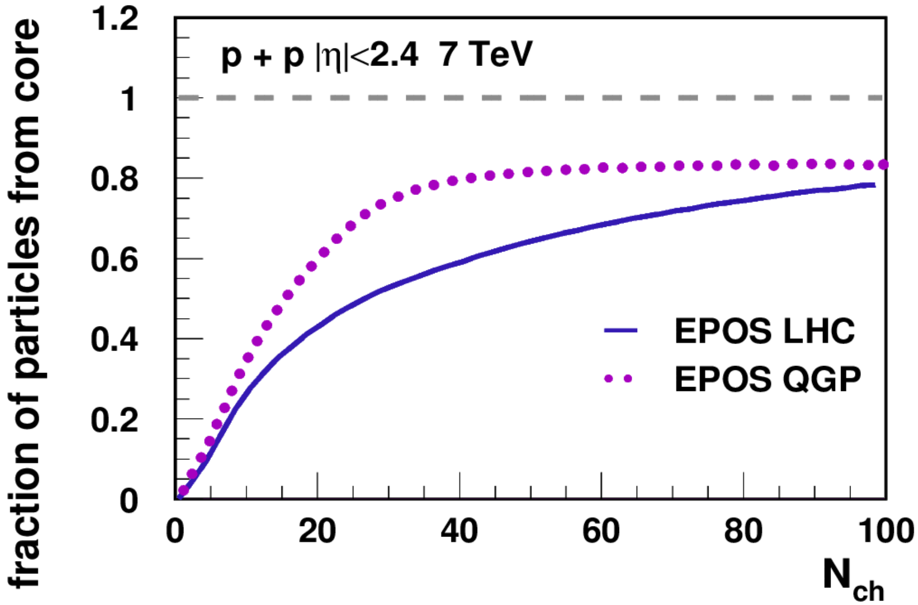


Modified EPOS with Extended Core

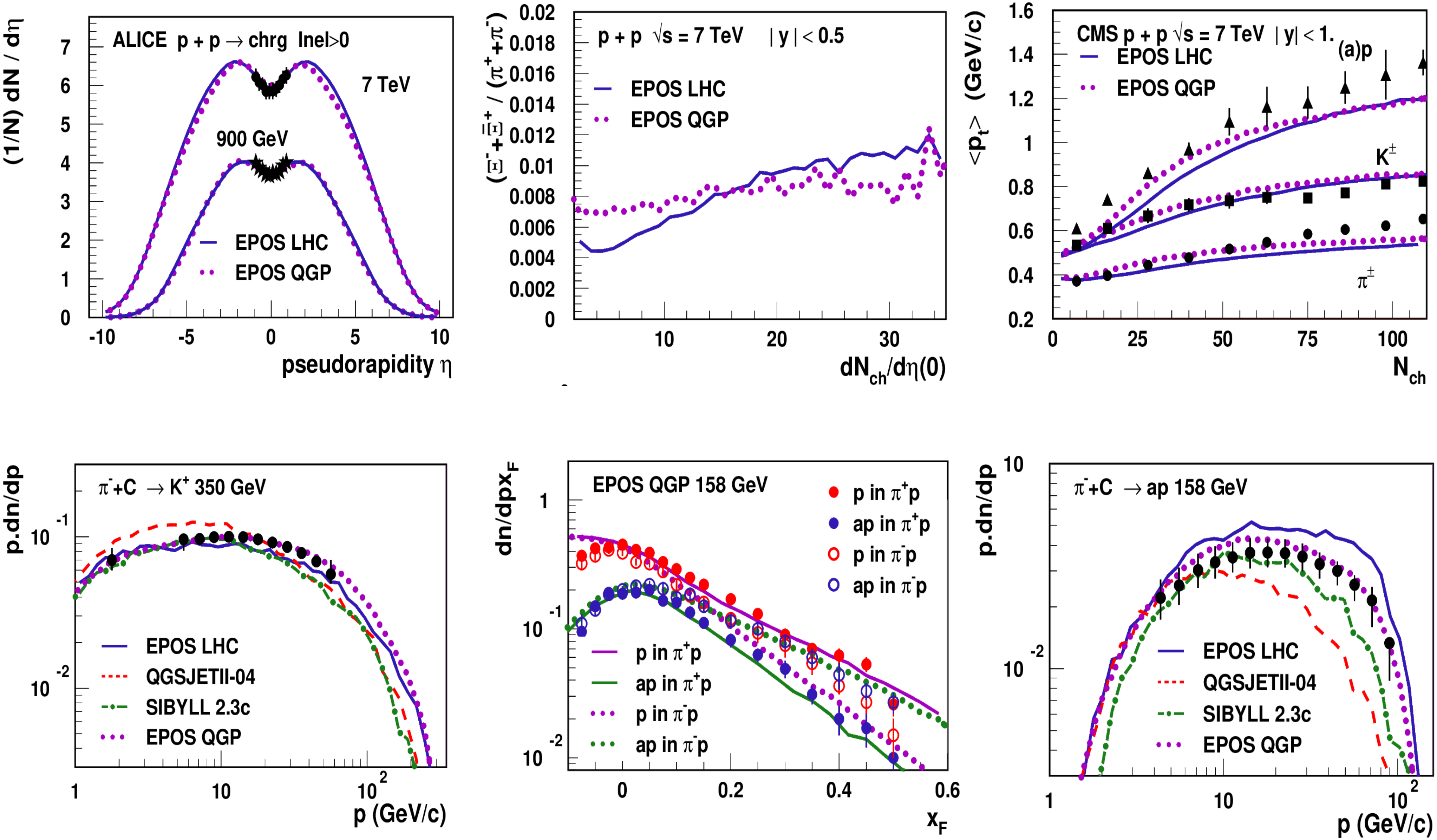
- **Core in EPOS LHC appear too late**
  - Recent publication show the evolution of chemical composition as a function of multiplicity
  - Large amount of (multi)strange baryons produced at lower multiplicity than predicted by EPOS LHC



- **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)

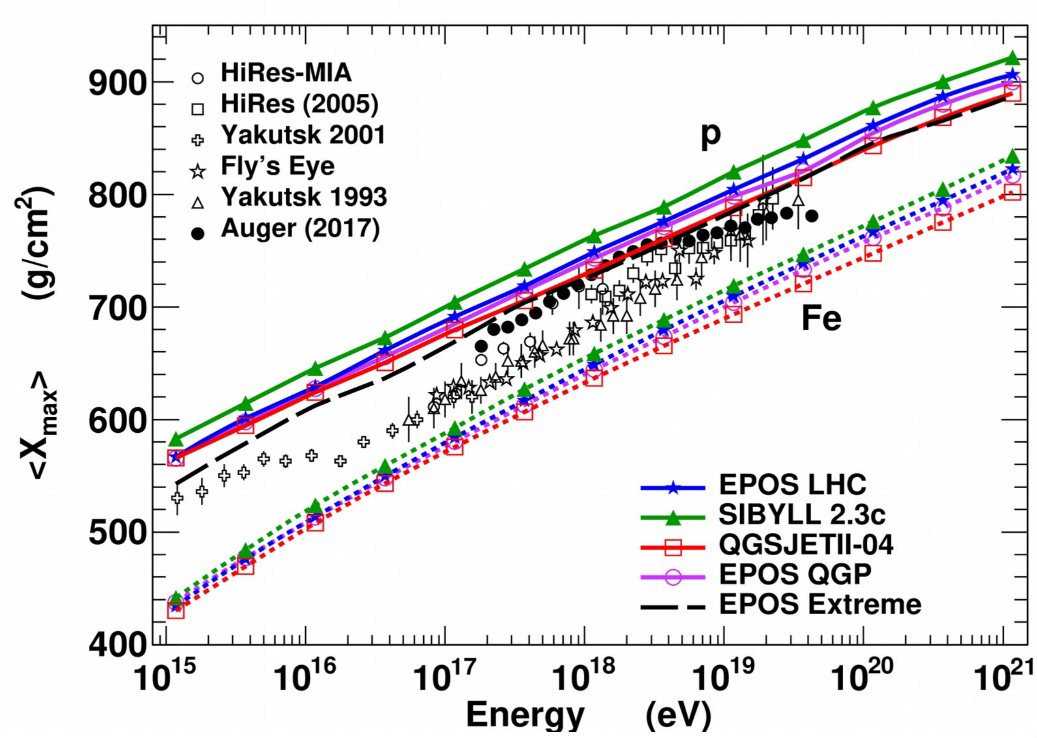


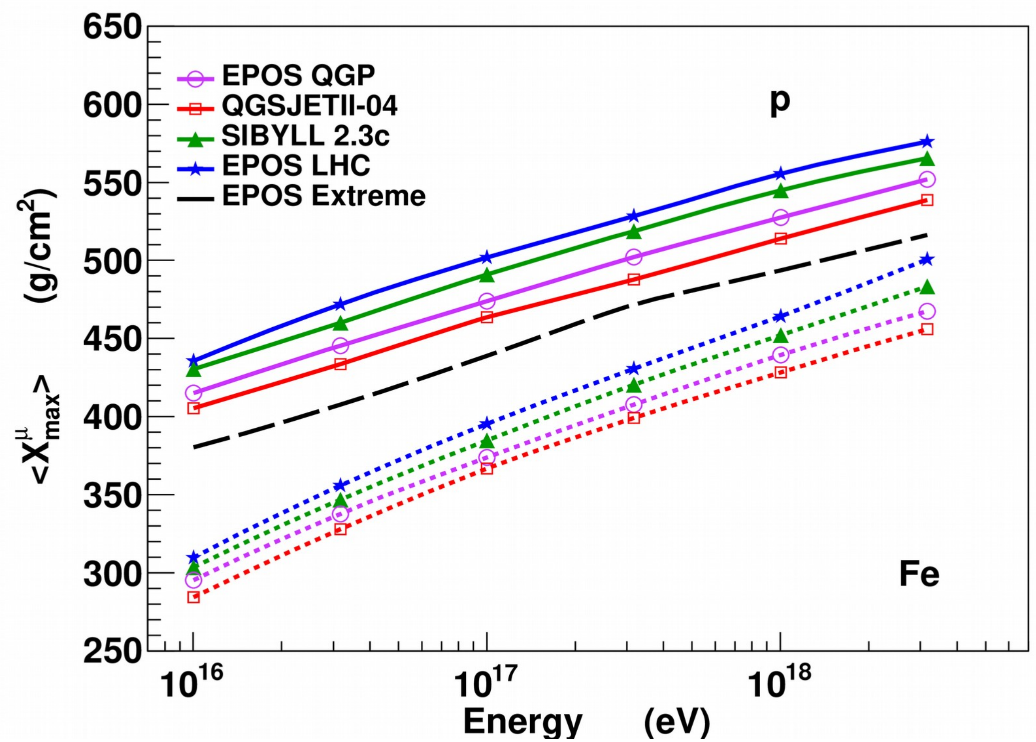
Preliminary Version with Minimum Constraints



Results for Air Showers (1)

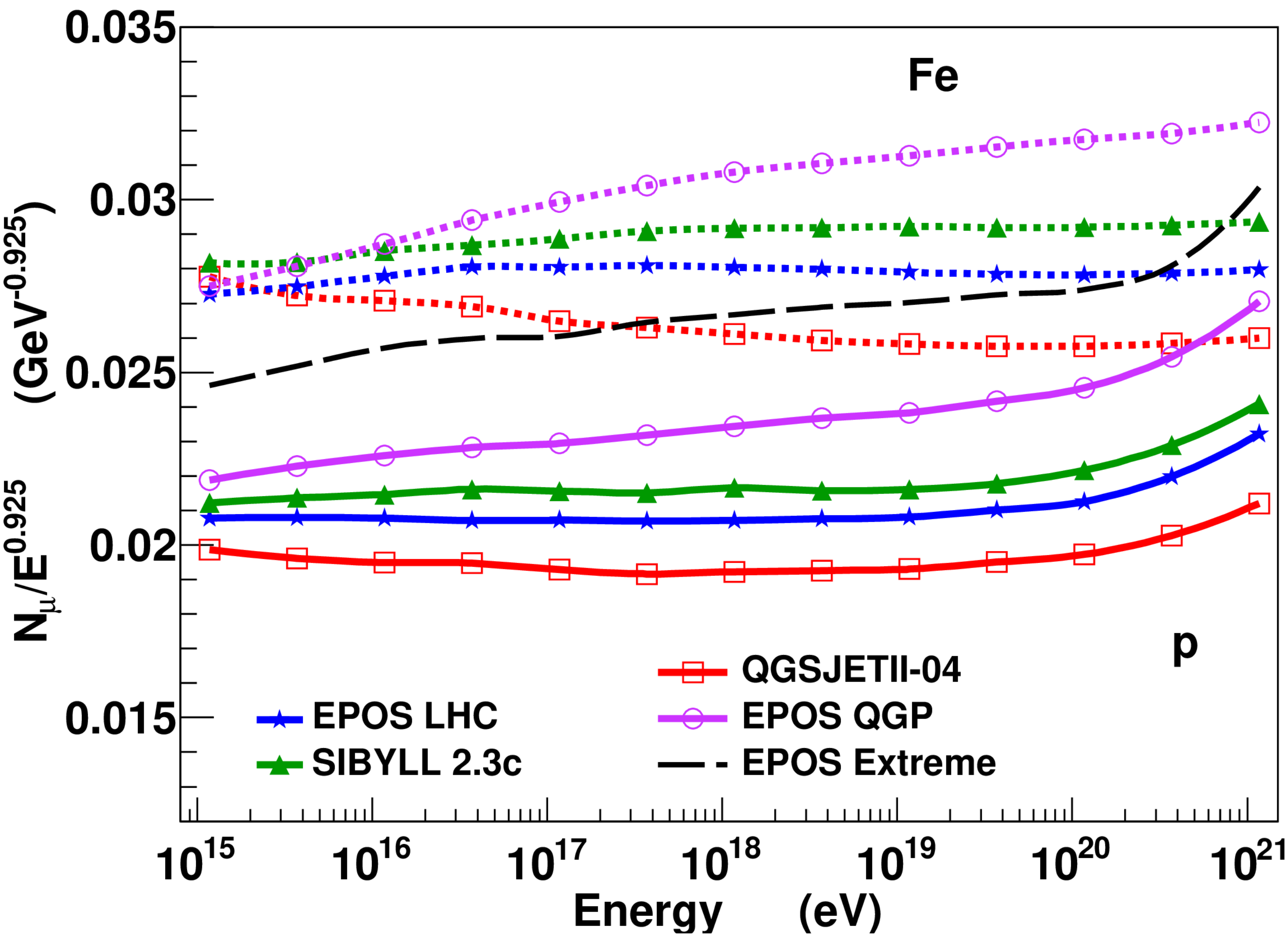
- Small change for $<X_{max}>$ as expected
- Significant change of $<X^{\mu}_{max}>$
- Comparison with extreme case (almost only grand canonical hadron.)
  - ➡ maximum effect using this approach
  - ➡ not compatible with accelerator data

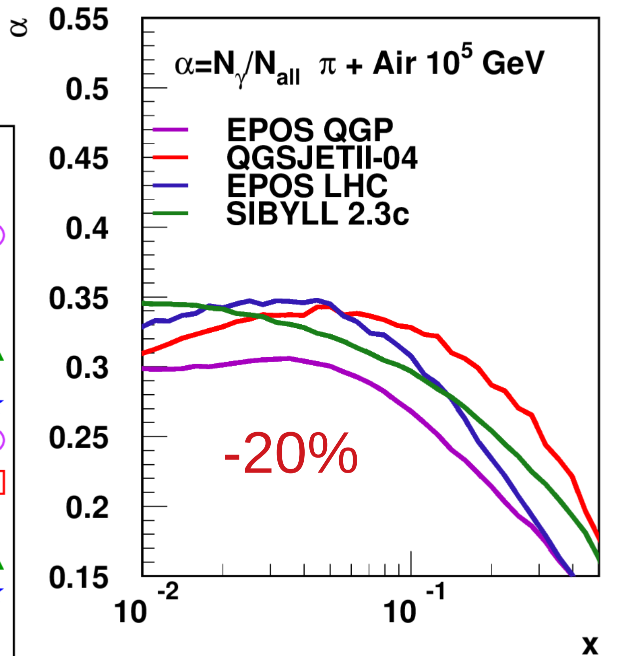


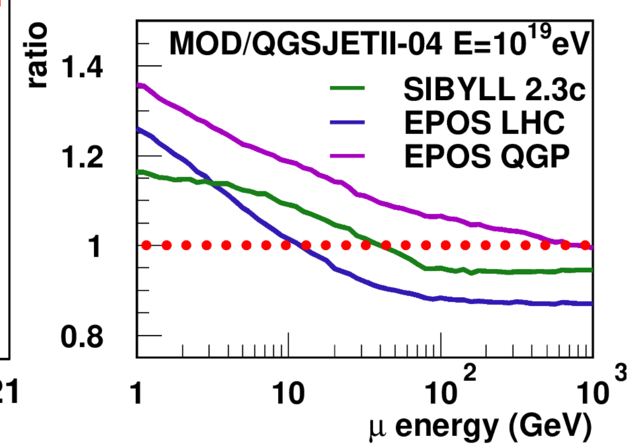


Results for Air Showers (2)

- **Large change of the number of muons at ground**
  - ➡ Different slope as expected from the change in α



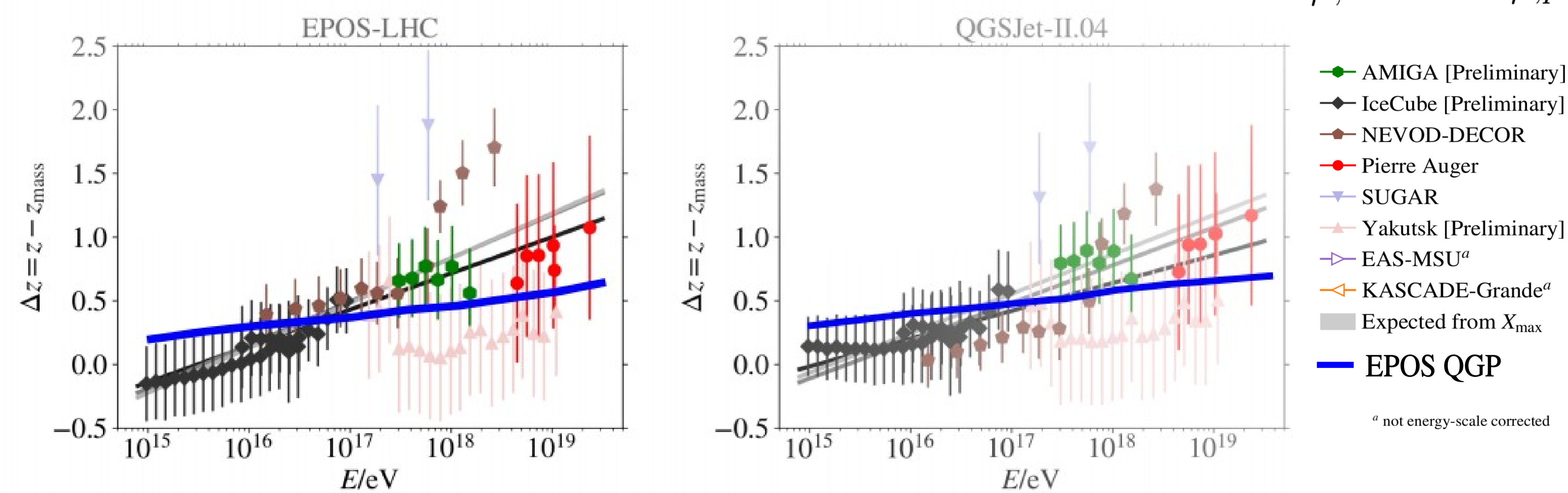




Comparison with Data

- **Collective hadronization gives a result compatible with data**
  - Still different energy evolution between data and simulatic
    - Significance to be tested

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

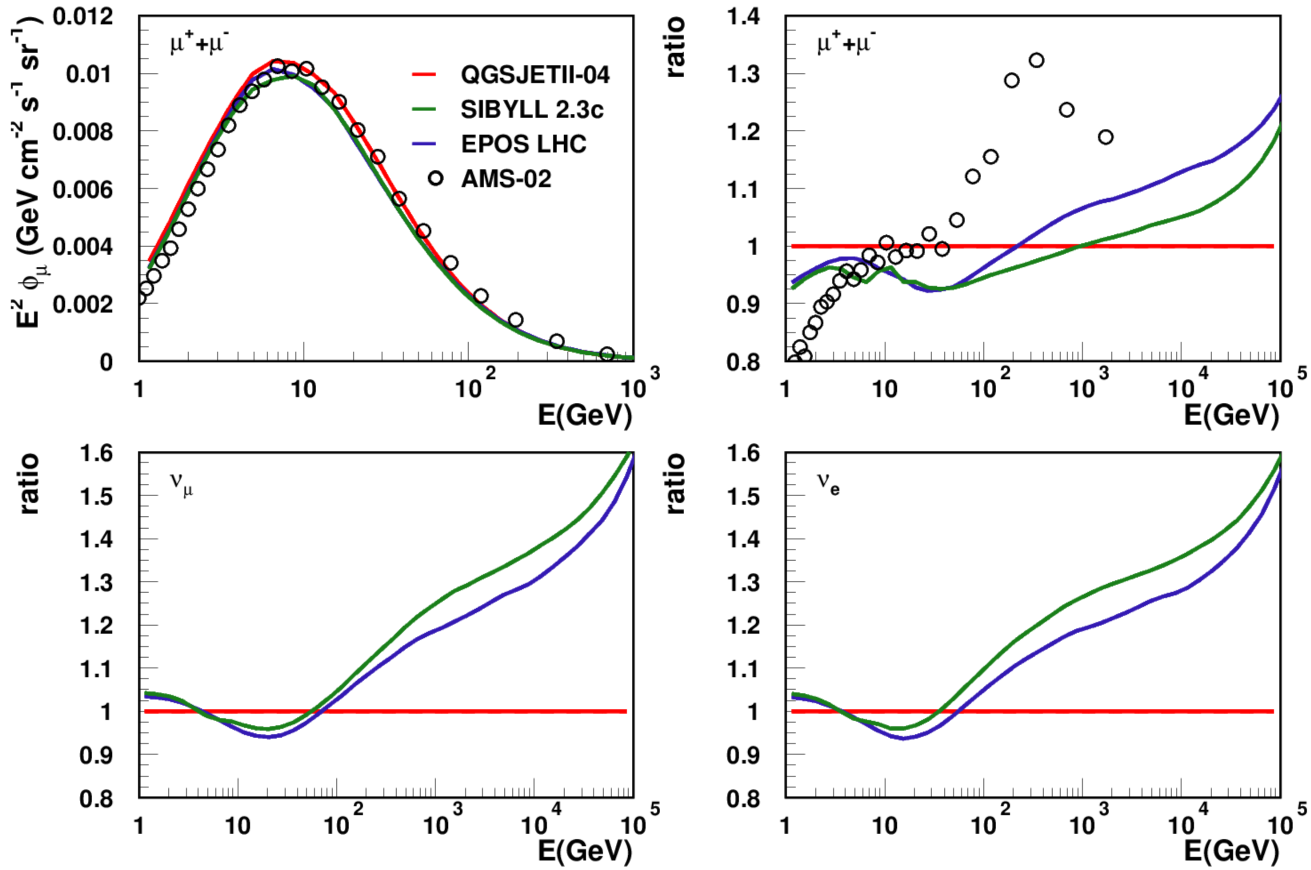


- **Probably tension at low energy (too many muons)**
  - Ideally a larger slope would be needed … what kind of hadronization possible ?

Muon and Neutrino Fluxes

Low energy inclusive muon flux compared to predictions from different models (MCEq)

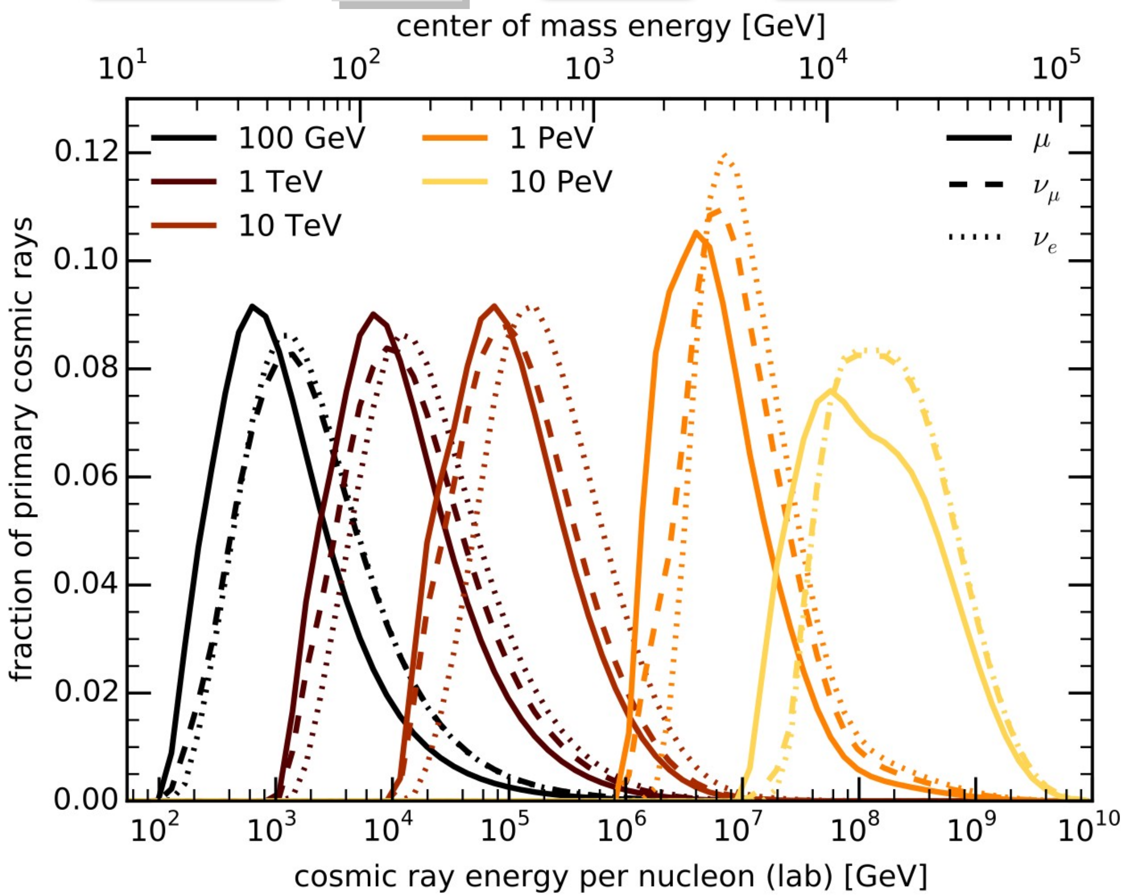
- ➡ Reasonable agreement below 100 GeV.
- ➡ Uncertainties due to primary CR flux/mass choice (H3a)

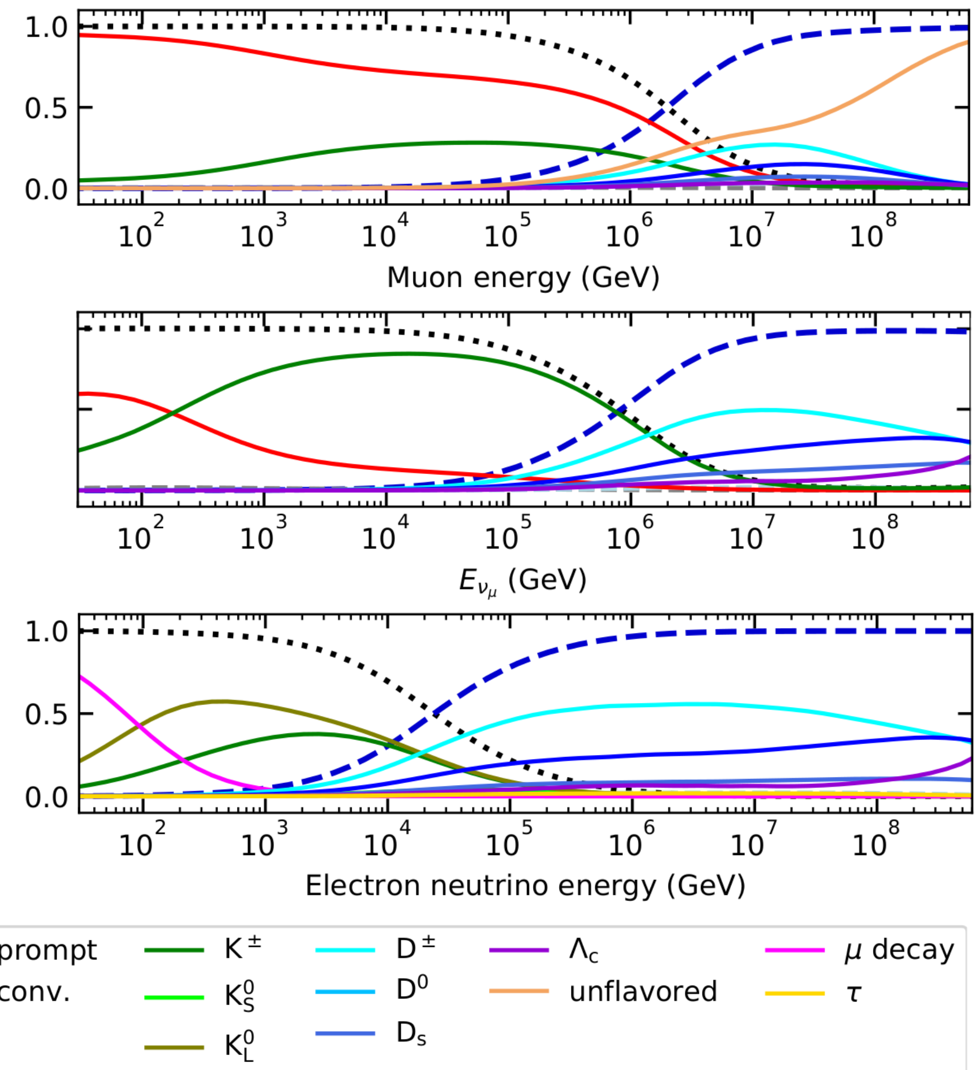


Inclusive Spectra and First Interaction

For inclusive spectra, particles from first interaction dominate

Fixed-target RHIC Tevatron LHC



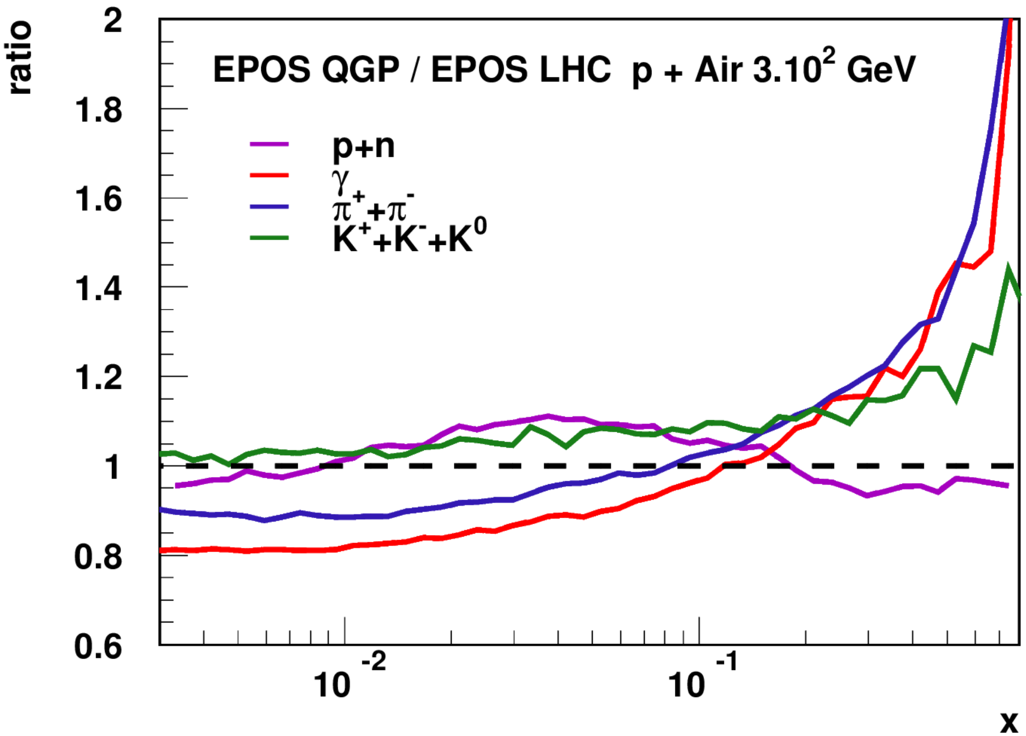


Plots from A. Fedinytch

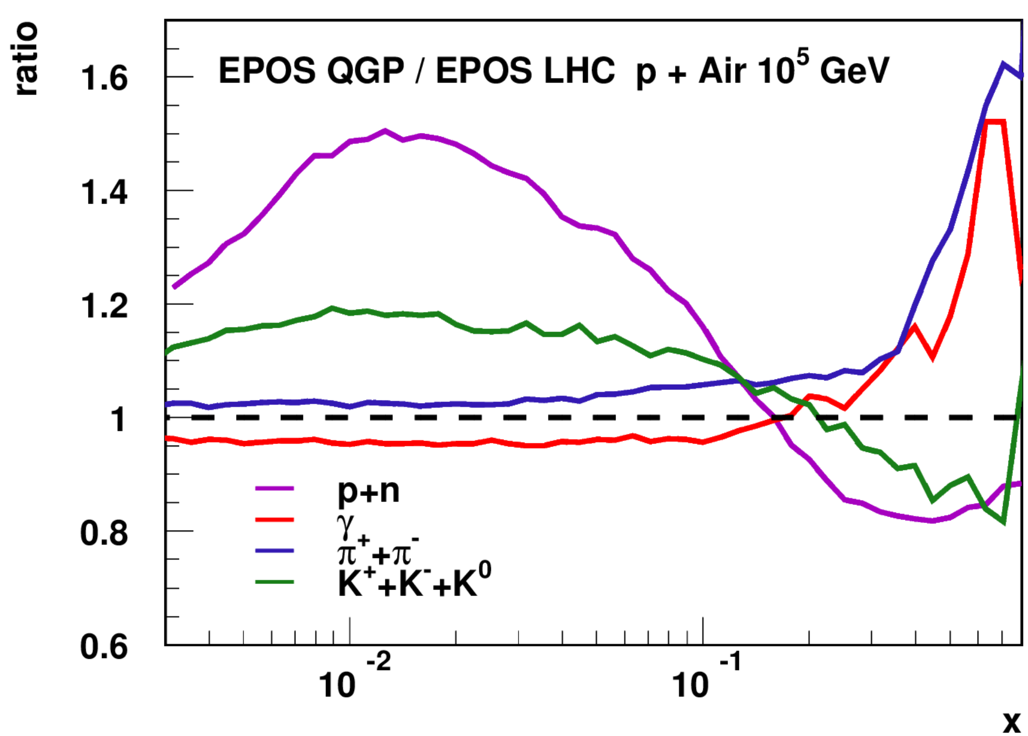
Modified Spectra with EPOS QGP

- **Muons above 100 GeV and neutrinos very sensitive to kaon production**
  - ➜ Kaon production increased by up to 20% in EPOS QGP
- **Collective hadronization will change inclusive fluxes**
  - ➜ Additional constrain to take into account !

Source of TeV leptons



Source of PeV leptons

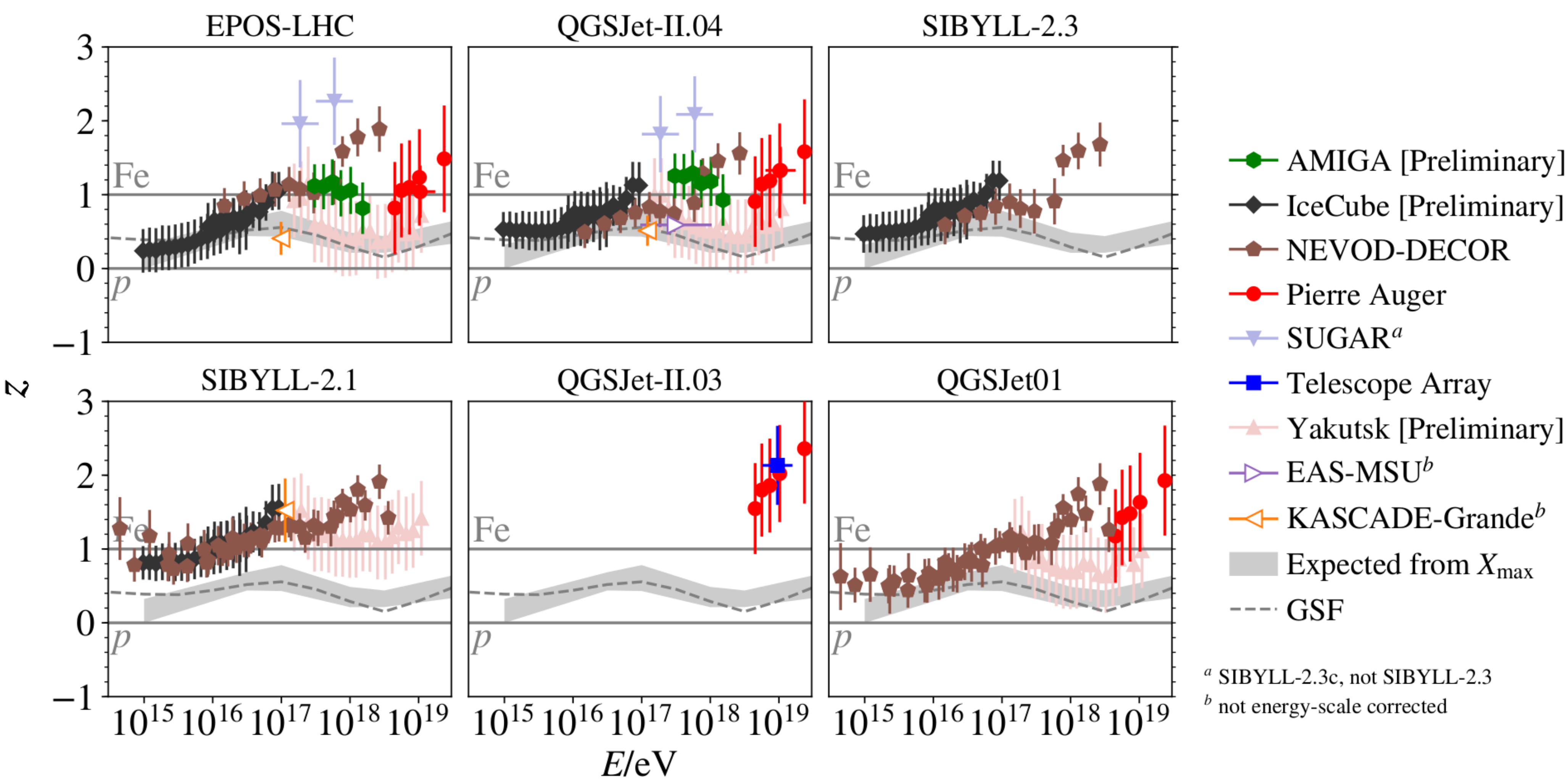


Summary

New input from LHC which could help to reproduce EAS data consistently but solution still under study. Possible consequences on TeV to PeV muons and neutrinos.

- **WHISP working group clearly established a muon production deficit in air shower simulations.**
  - ➡ Exact scale not known (dependent on energy and mass)
- **Most "natural" explanation given by a change in pion charge ratio.**
  - ➡ Other possibilities limited by X_{max} (multiplicity, inelasticity)
- **Large change needed for a well constrained observable.**
  - ➡ Different type of hadronization (extended range for QGP)
  - ➡ Possible to approach data but energy slope at the lower limit (preliminary)
- **Same effect will increase the inclusive lepton flux above 100 GeV.**
  - ➡ Inclusive flux will constrain solution for "muon puzzle" of EAS
- **Not all relevant CERN data taken into account in model yet.**
  - ➡ NA61, LHCf (+RHICf) ...

Data Rescaled



Pion Interactions

MPD measurement helped to understand the importance of pion interactions (lack of accelerator data until NA61) and baryon effect on propagation

- low pion elasticity in DPMJETIII
- high pion elasticity (diffraction) in EPOS and Sibyll driven by LHC data (and high baryon number (Ostapchenko et al. Phys.Rev. D93 (2016) no.5, 051501))
- diffraction with pion projectile or proton projectile are different