# LHC and Cosmic Rays : the Chicken or the Egg ?

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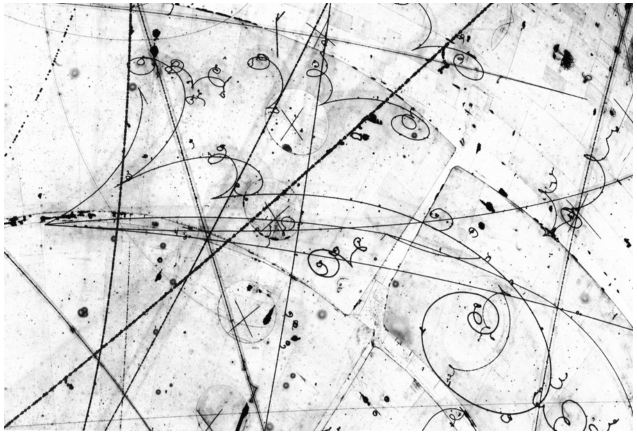
# Outline

- **Introduction**
- **Monte-carlo for Cosmic Ray analysis**
  - MC comparison to accelerator data
- **$X_{max}$**
  - Mass composition of primary cosmic rays after LHC
- **Muons**
  - New input from LHC
  - Test phase diagram outside the reach of LHC ?

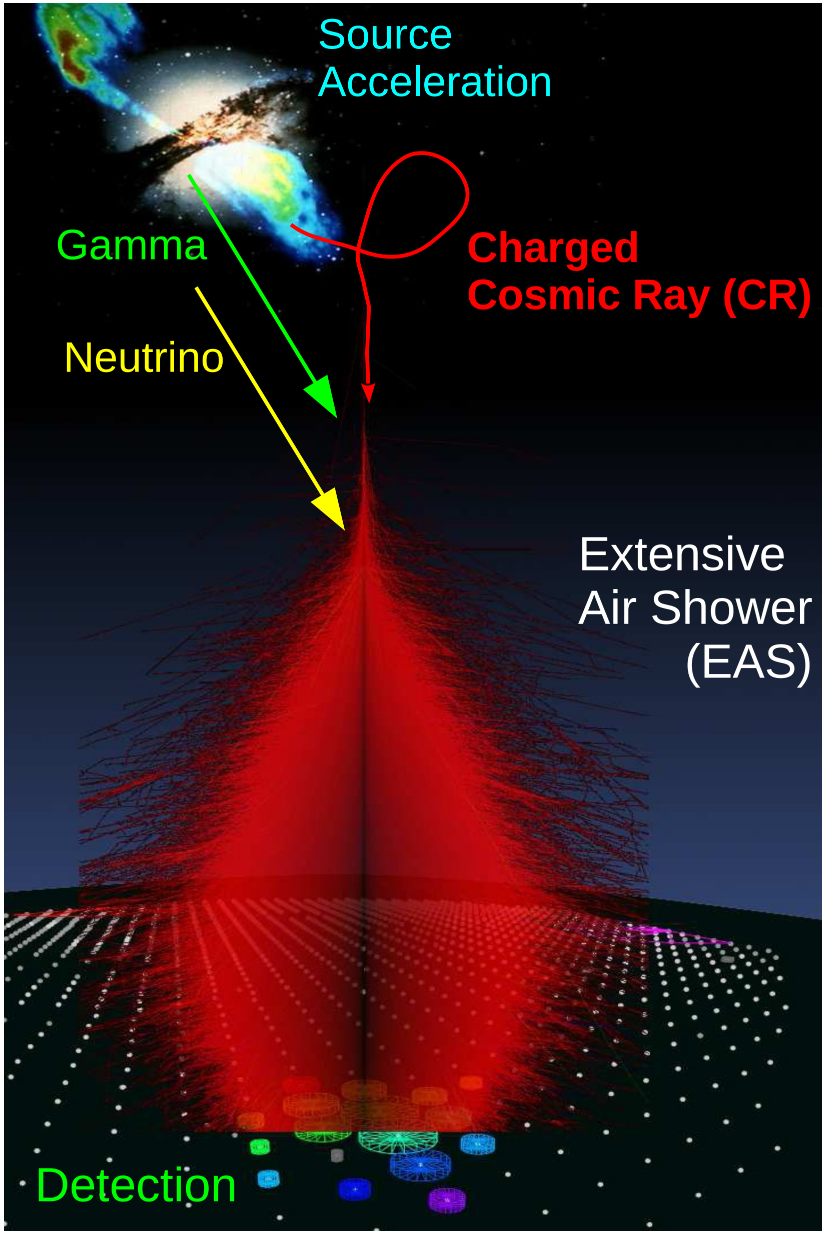
**LHC data reduced the model uncertainties for mass composition and might open a change for muon production. Good description of air showers improve model predictive power for the description of min. bias LHC data and test new phase space.**

# History

- **Victor Hess discovered in 1912 that natural radioactivity was increasing with height**
  - ➜ radiation from space
- **Pierre Auger discovered air showers in 1937**
  - ➜ secondary particles produced by primary cosmic rays
- **until ~1950 particle physics was studied thanks to cosmic rays**
  - ➜ all first unstable particles discovered in cosmic rays
    - muon, pion, strangeness …
  - ➜ cosmic rays could not be used for astrophysics
- **after first start of accelerators, things changed ... until now !**



# Astroparticles

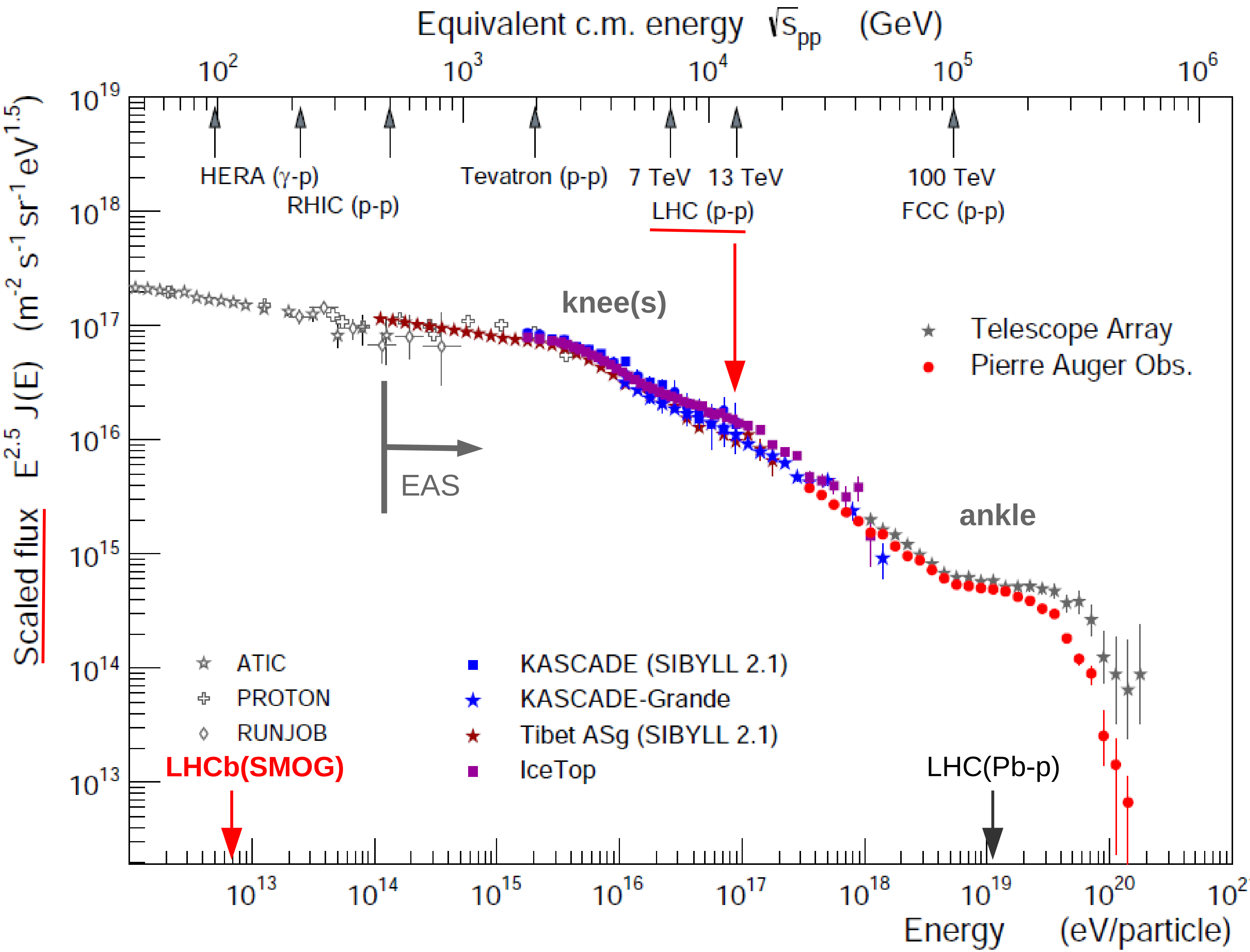



From R. Ulrich (KIT)

- **Astronomy with high energy particles**
  - gamma (straight but limited energy due to absorption during propagation)
  - neutrino (straight but difficult to detect)
  - charged ions (effect of magnetic field)
- **Measurements of charged ions**
  - source position (only for light and high E)
  - energy spectrum (source mechanism)
  - mass composition (source type)
    - light = hydrogen (proton)
    - heavy = iron (A=56)
  - test of hadronic interactions in EAS via correlations between observables.

**mass measurements should be consistent and lying between proton and iron simulated showers if physics is correct**

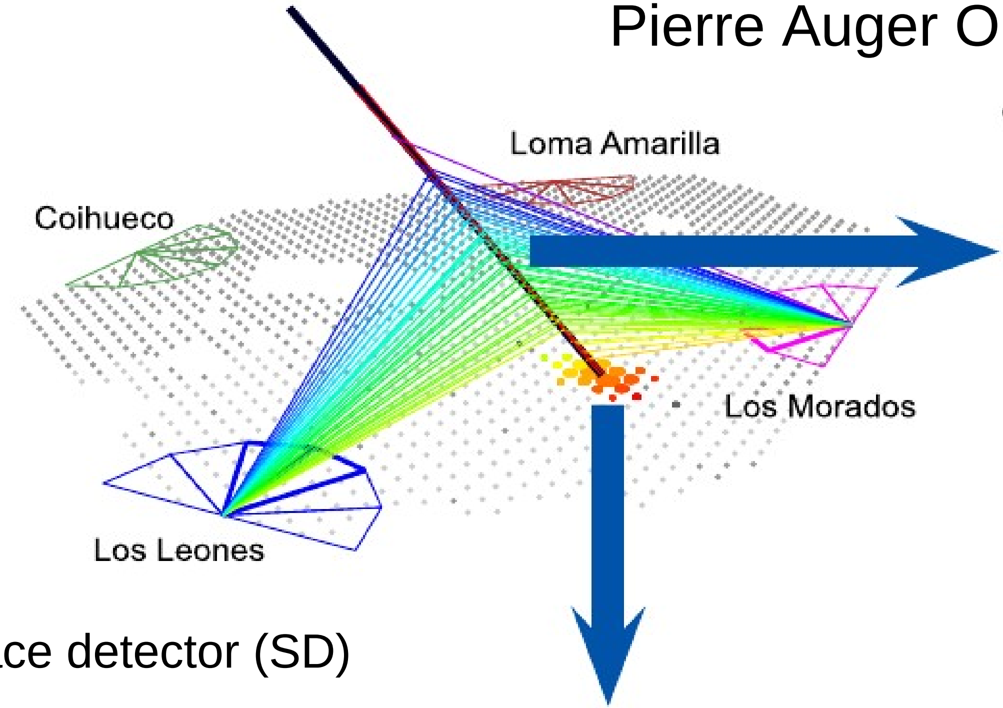
# Energy Spectrum




R. Engel (KIT)

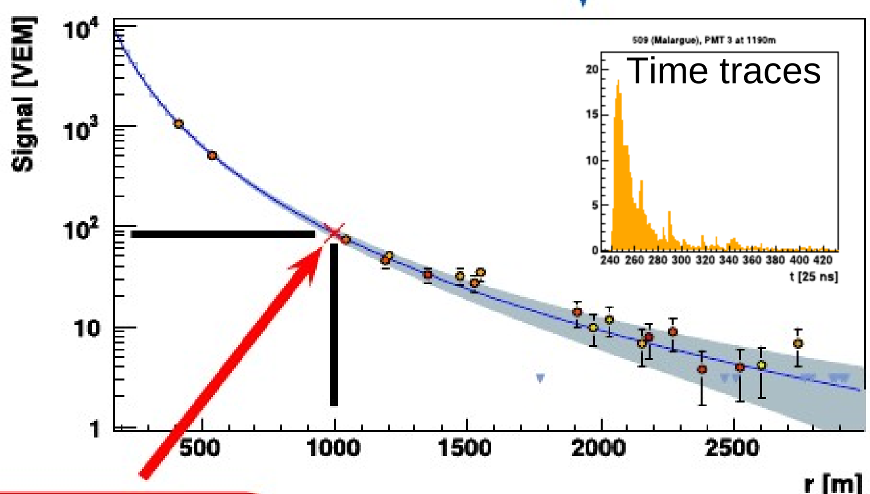
# Hybrid Detection

Pierre Auger Observatory / Telescope Array



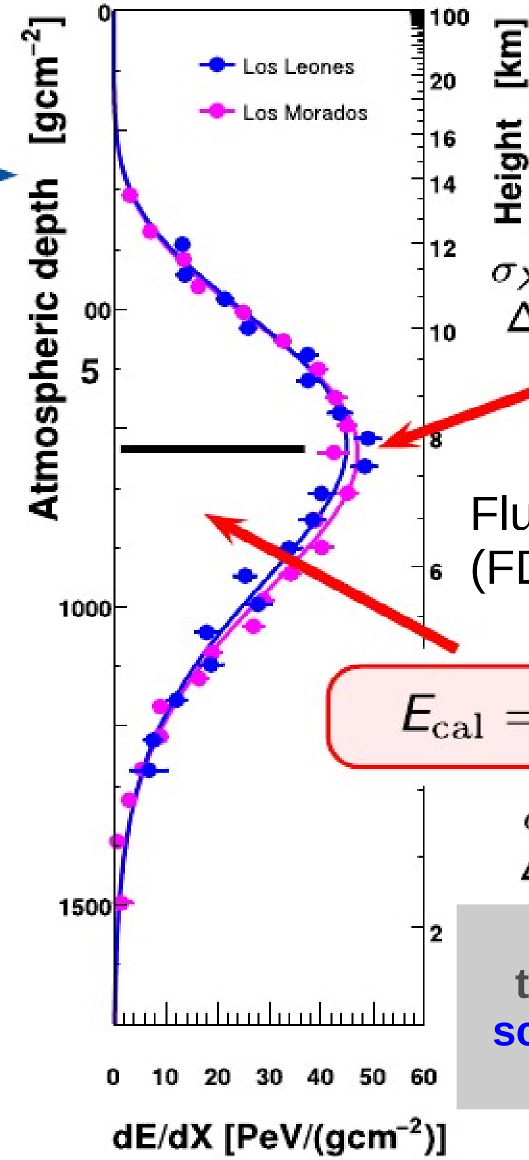

Surface detector (SD)

From R. Ulrich (KIT)




$S_{1000}$

$E_{\rm surface} = f(S_{1000},\ \theta)$




$\sigma X_{\rm max} < 20\,{\rm g/cm^2}$
$\Delta_{\rm sys} \approx 15\,{\rm g/cm^2}$

$X_{\rm max}$

Fluorescence detector (FD)

$E_{\rm cal} = \int {\rm d}X\ \frac{{\rm d}E}{{\rm d}X}$

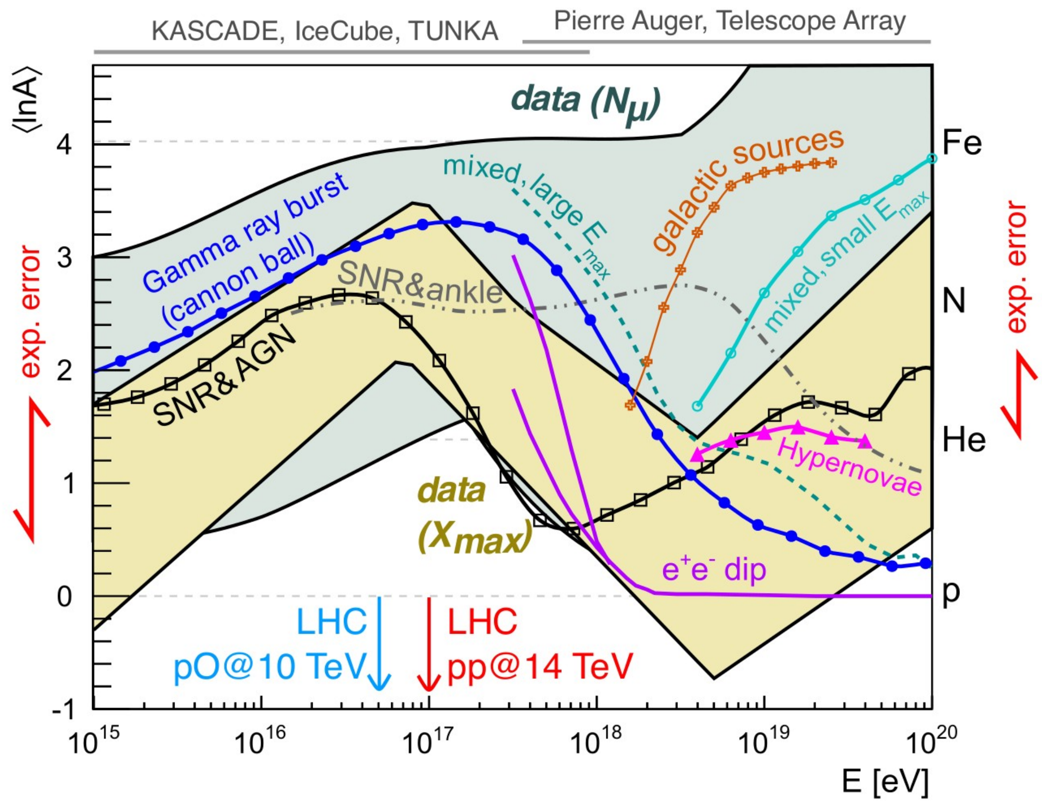
$\sigma_E/E \sim 8\,\%$
$\Delta_{\rm sys} \approx 14\,\%$

**Various detection technique = energy scale independent of EAS simulations**

# UHECR Composition

## With muons current CR data are impossible to interpret

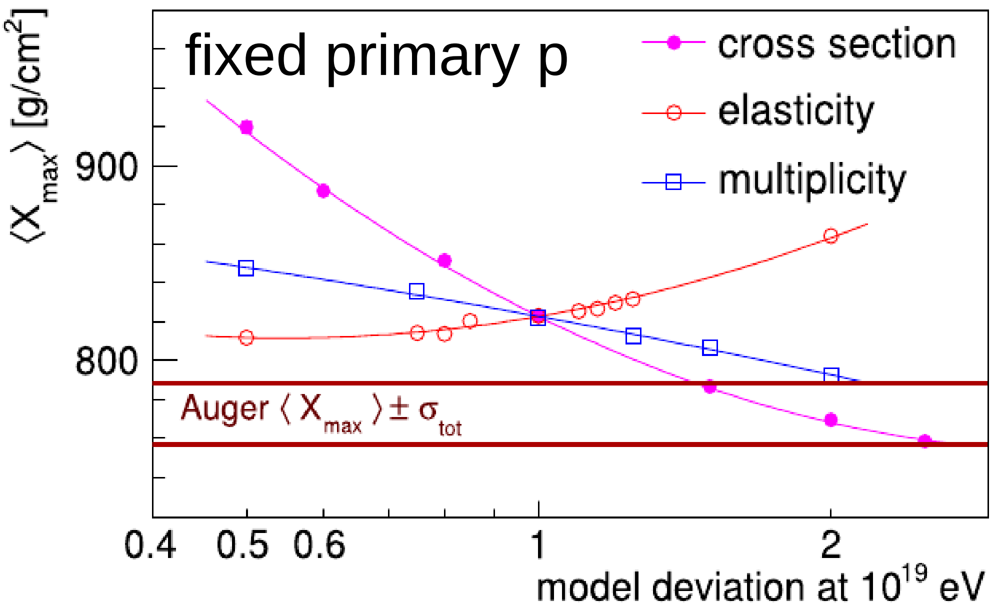
- Very large uncertainties in model predictions
- Mass from muon data incompatible with mass fro $X_{max}$

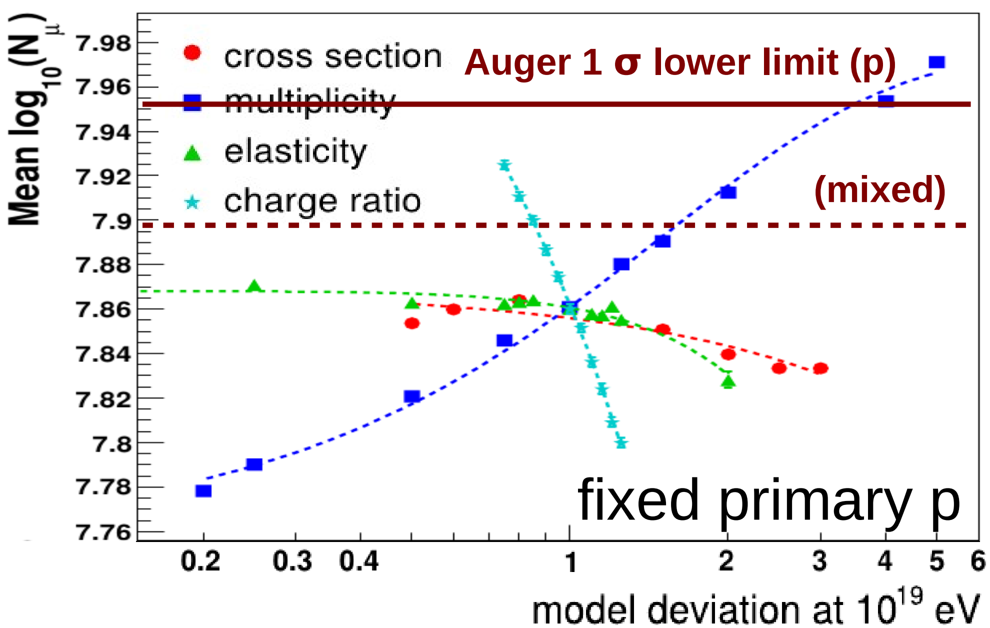



Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

H. Dembinski UHECR 2018 (WHISP working group)

# Sensitivity to Hadronic Interactions



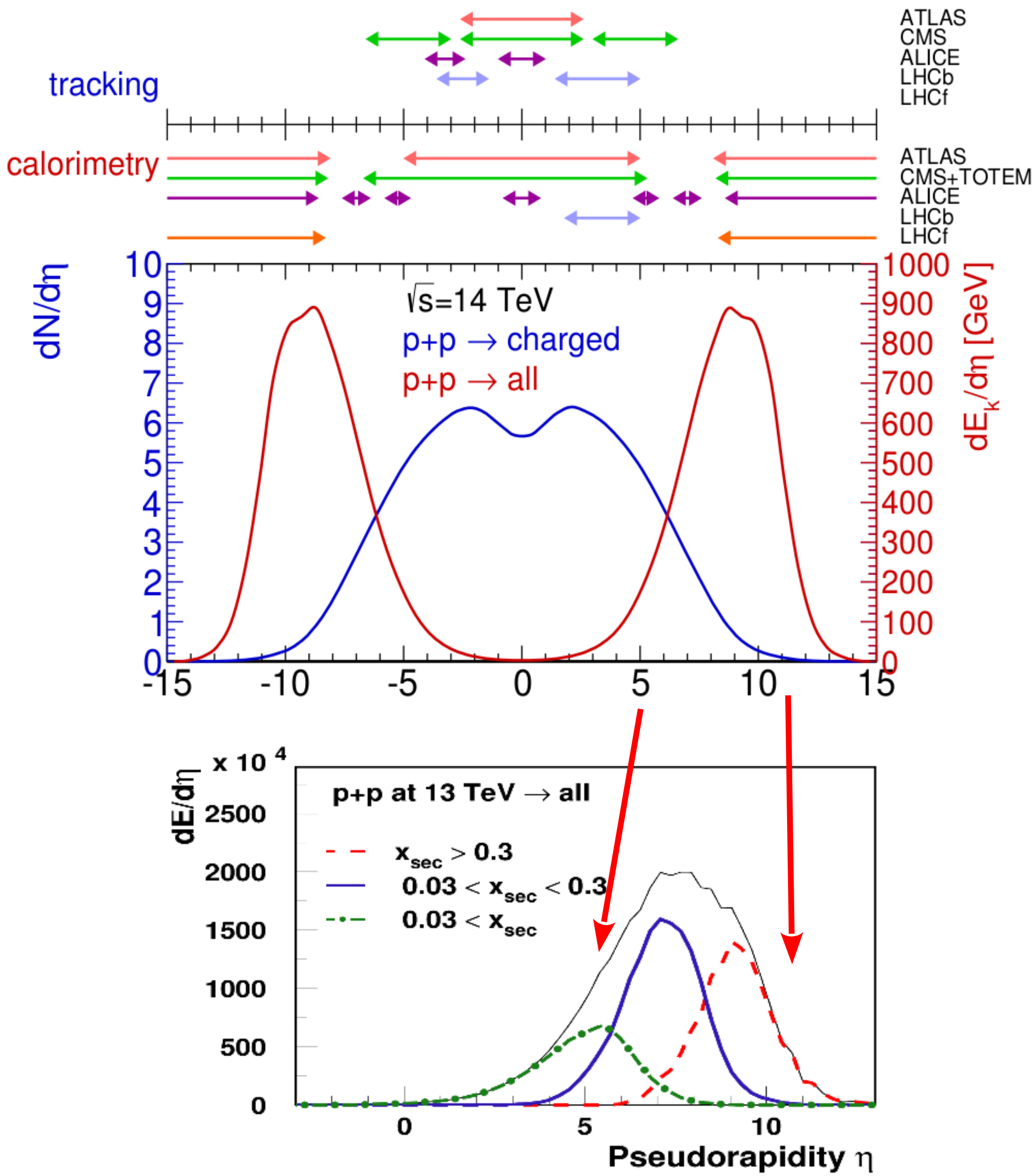




From R. Ulrich (KIT)

- **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 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**

# LHC acceptance and Phase Space




- **p-p data mainly from "central" detectors**
  - pseudorapidity $\eta=-\ln(\tan(\theta/2))$
  - $\theta=0$ is midrapidity
  - $\theta>>1$ is forward
  - $\theta<<1$ is backward
- **Different phase space for LHC and air showers**
  - most of the particles produced at midrapidity
    - important for models
  - most of the energy carried by forward (backward) particles
    - important for air showers

# 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

# When does a projectile interact ?

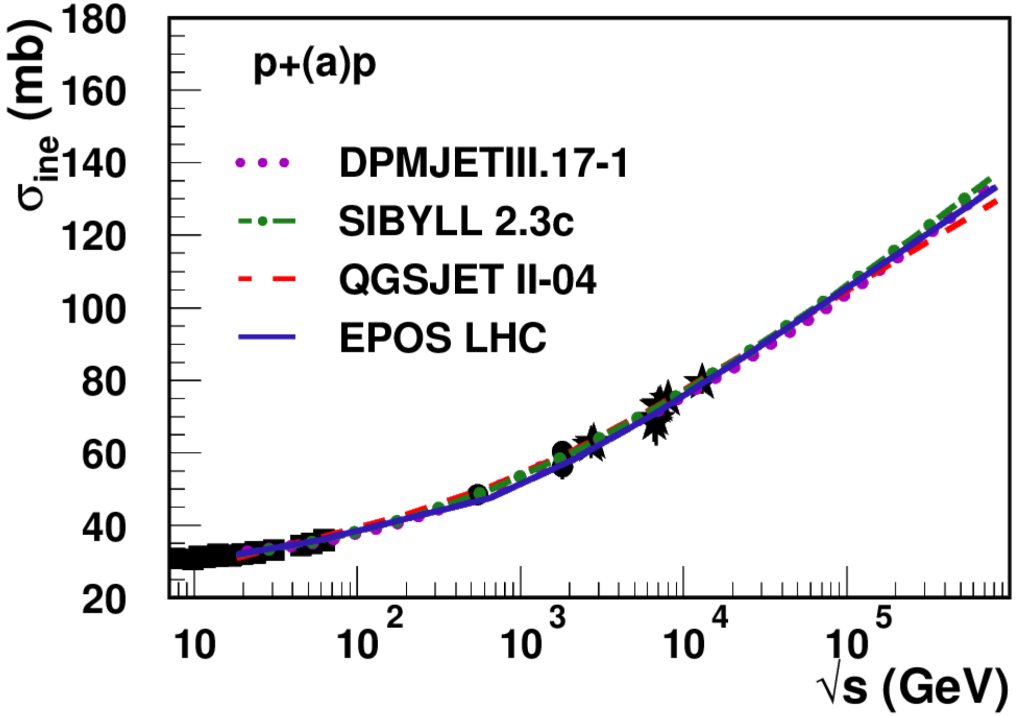
## For all models cross-section calculation based on optical theorem

- total cross-section given by elastic amplitude

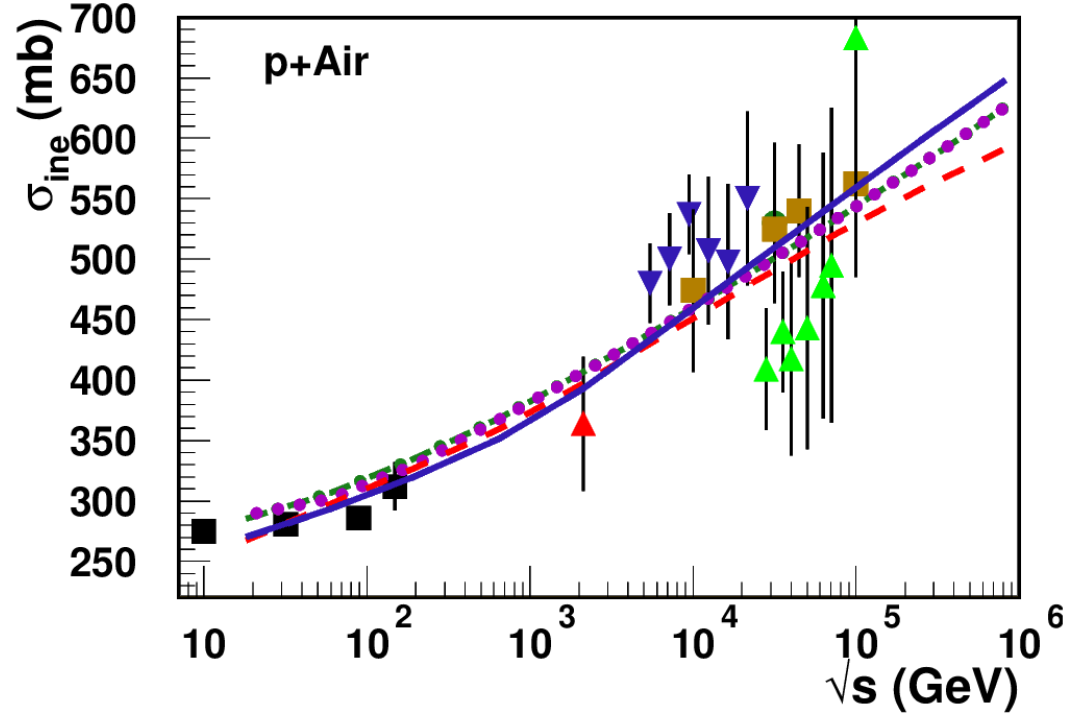
$$\sigma_{tot} = \frac{1}{s}\Im m(A(s,t \to 0))$$

- 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



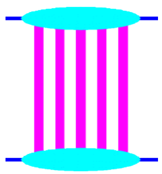

p-Air

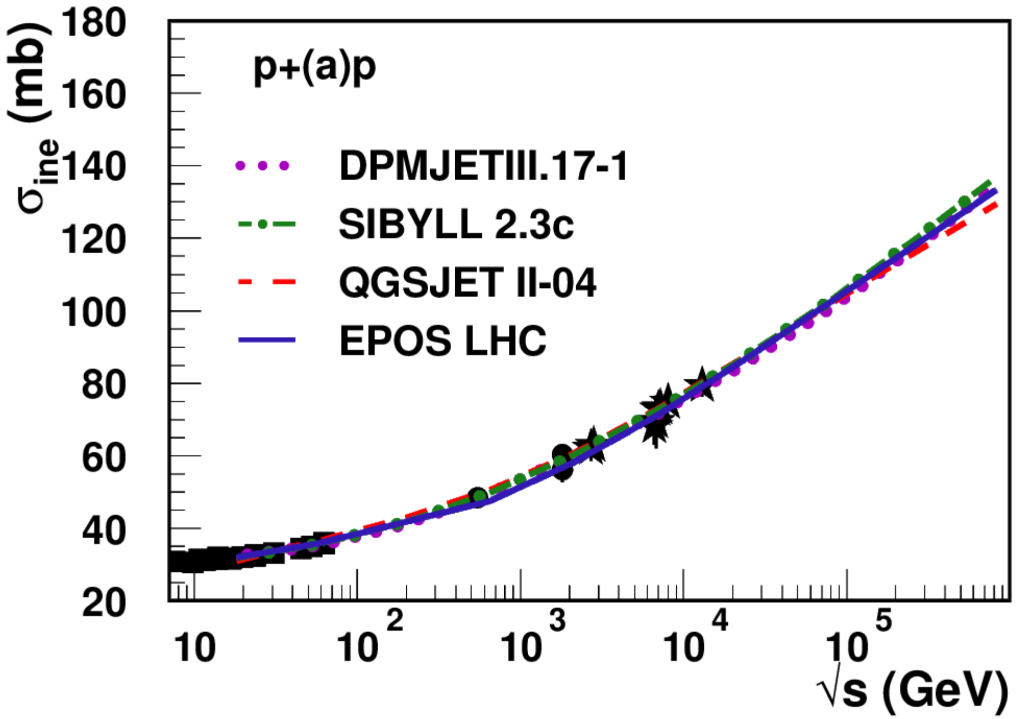


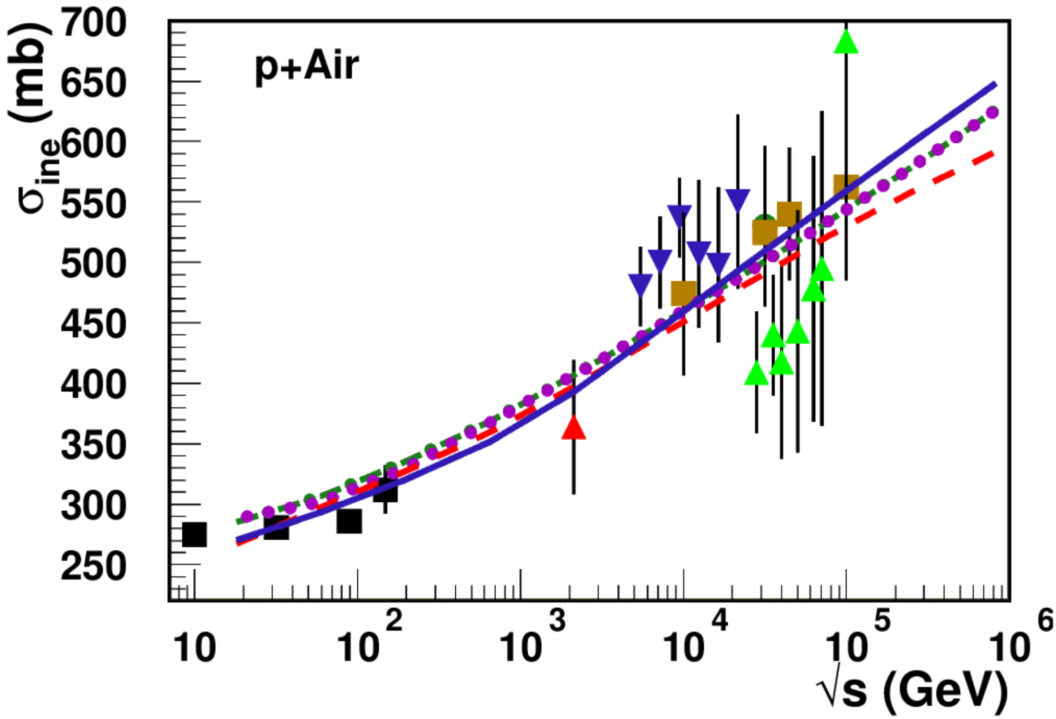
# Model Differences

**Cross-section :** Optical theorem

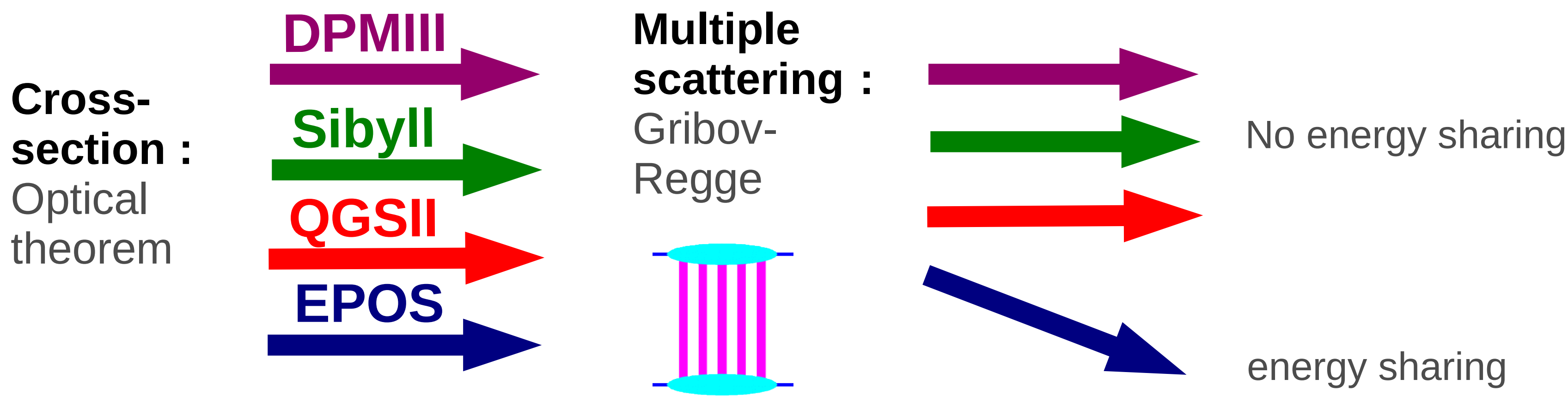

**Multiple scattering :** Gribov-Regge



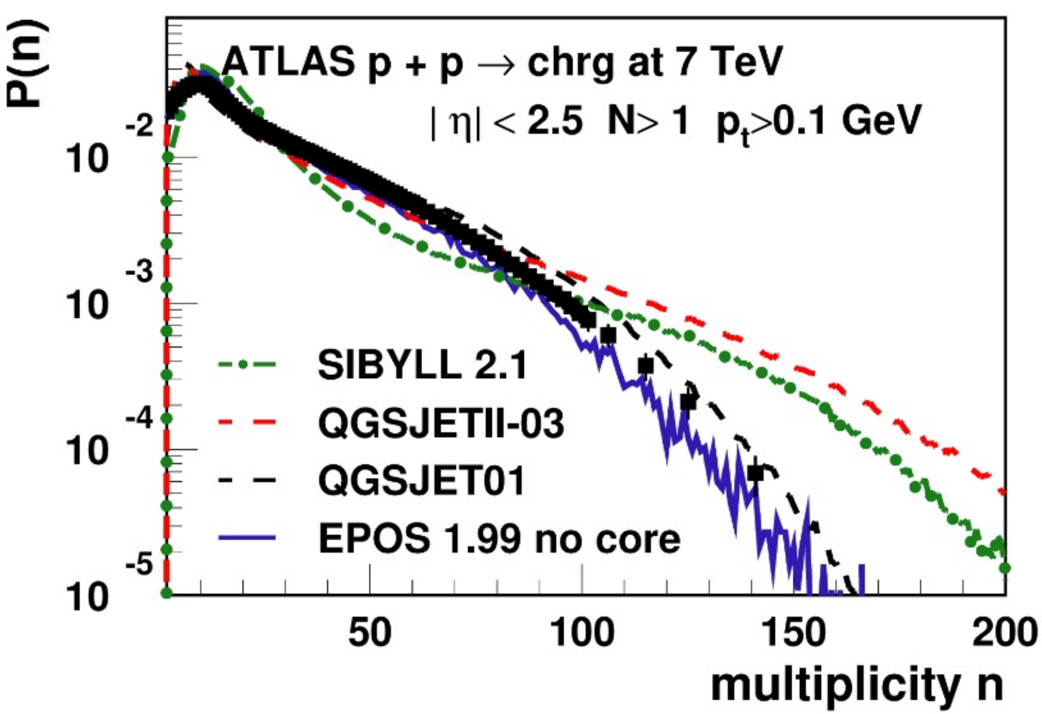


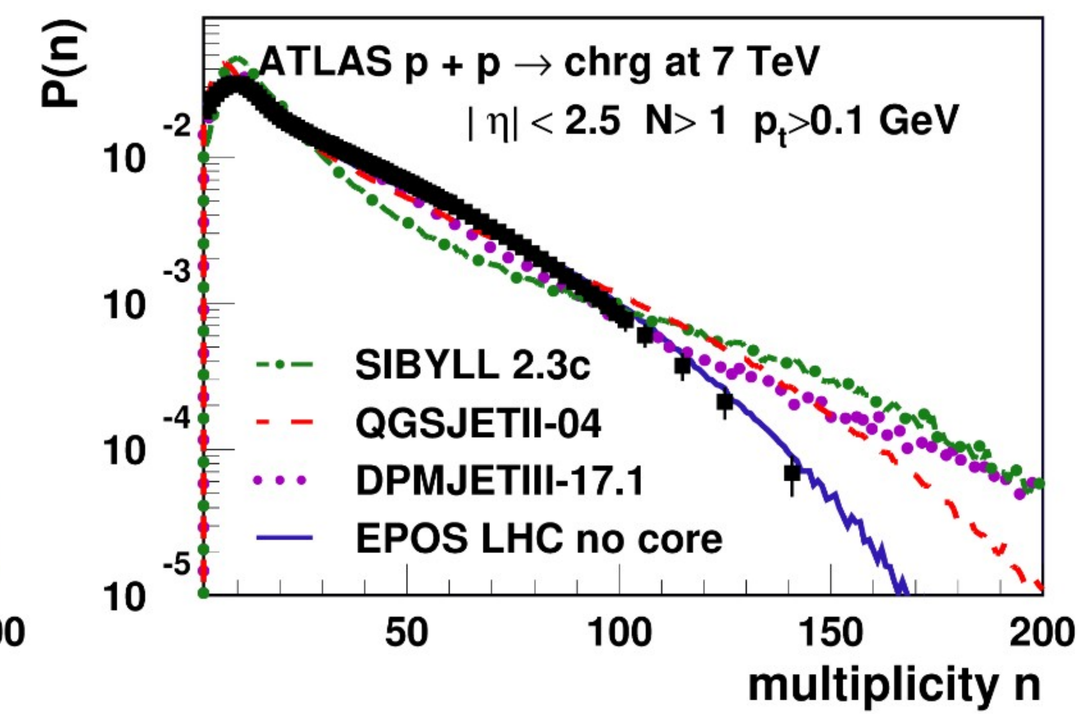
# Model Differences



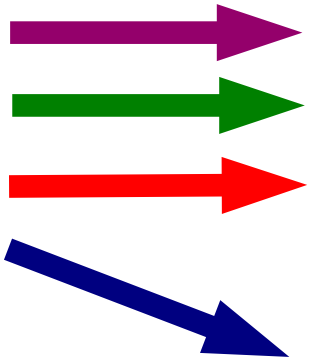

## Pre - LHC



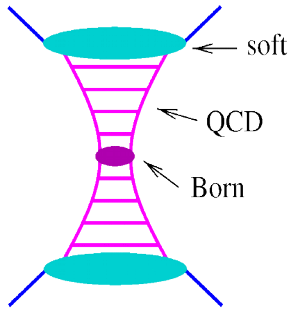

## Post - LHC

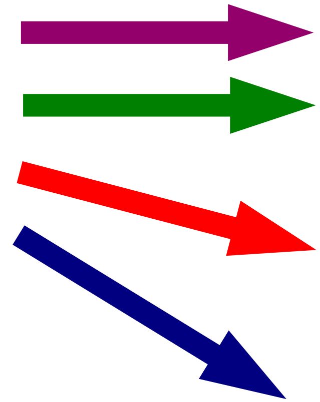


# Model Differences



**Amplitude :**
soft (Regge)
+ pQCD

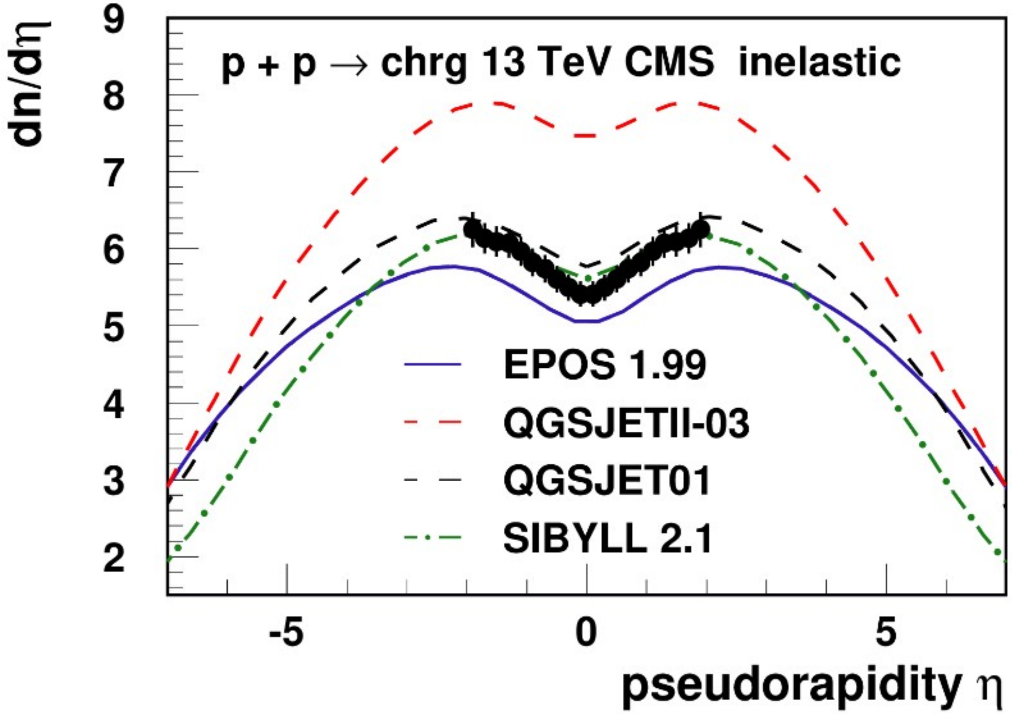


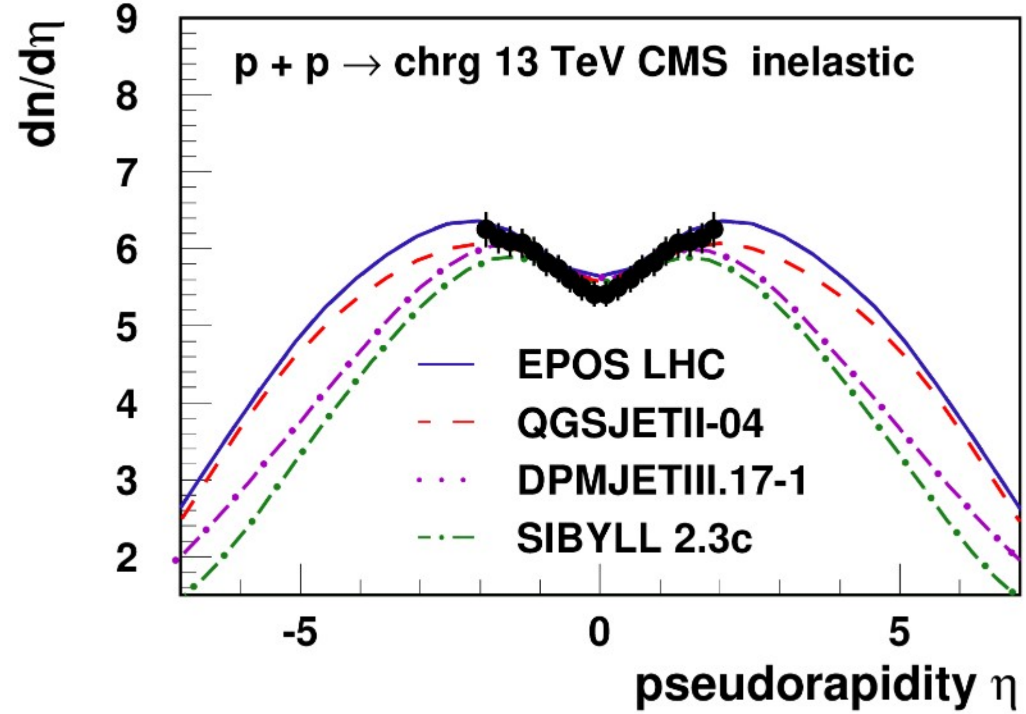
hard small "x"
connection

small large "x"
connection

## Pre - LHC

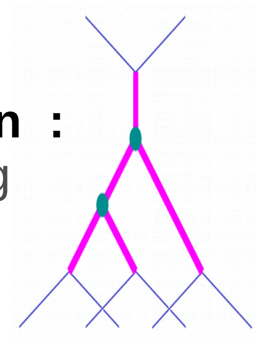



## Post - LHC



# Model Differences

**Evolution :**
screening effects

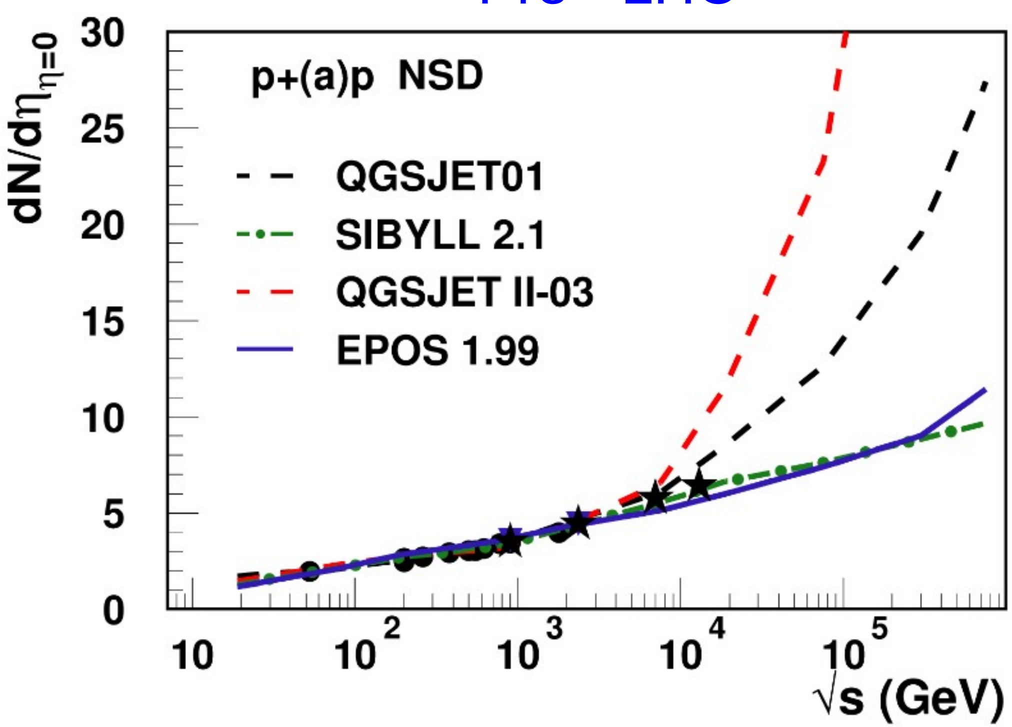


Minijet pt cutoff evolution

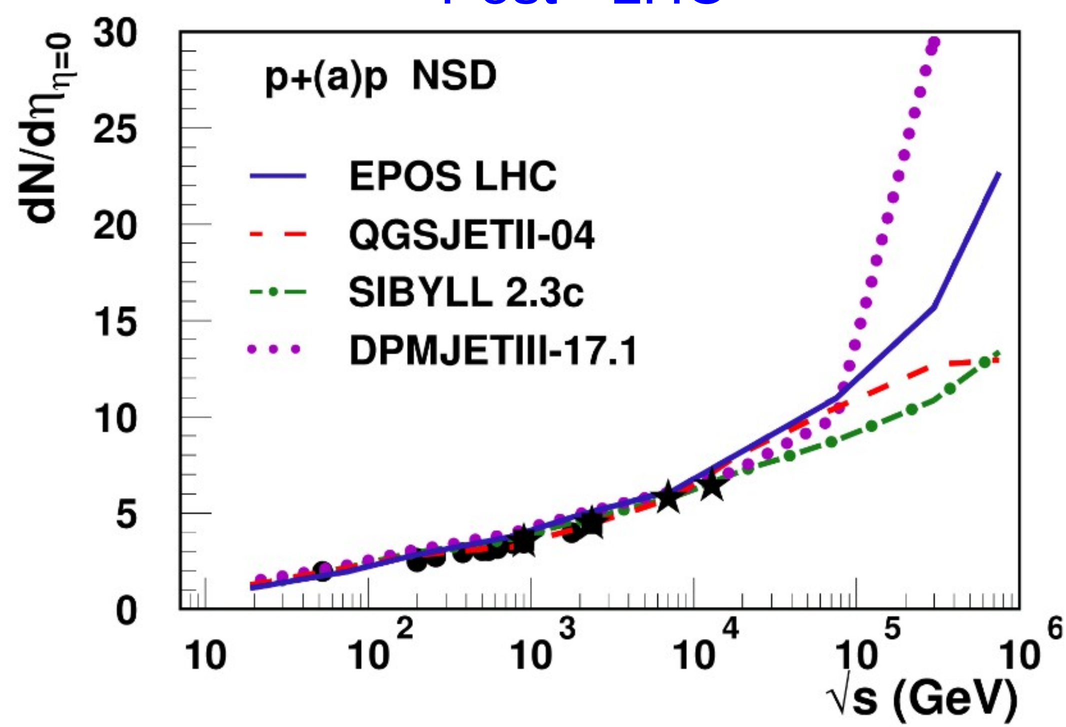
Resummation of fan diagrams

Phenomenological amplitude correction

## Pre - LHC

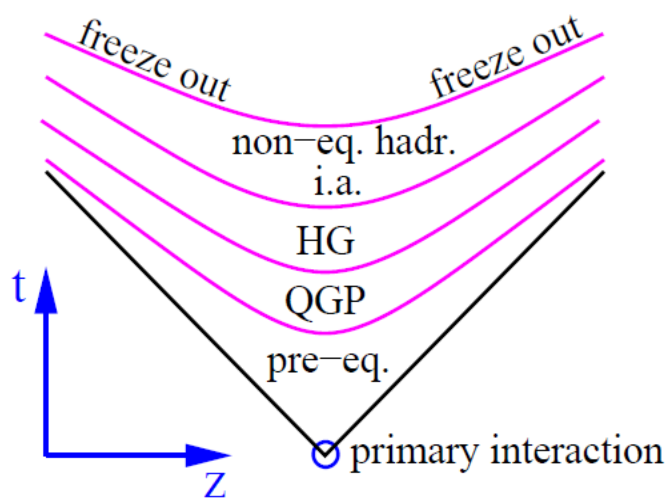



## Post - LHC

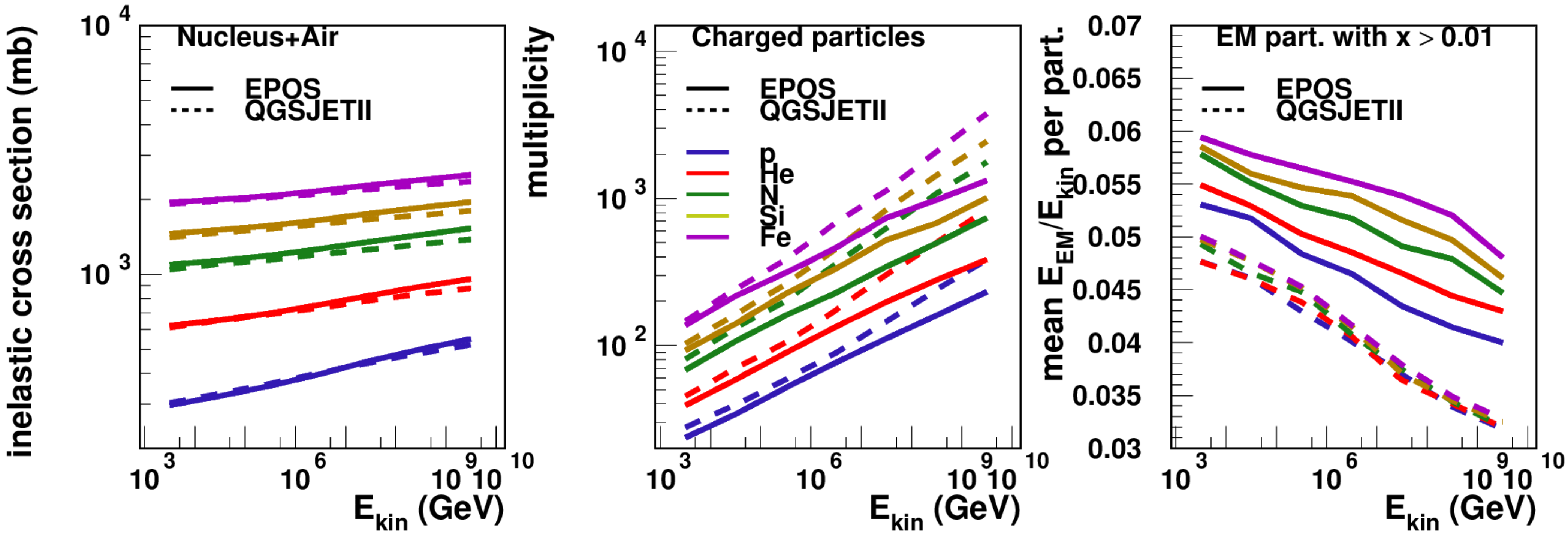


# Model Differences

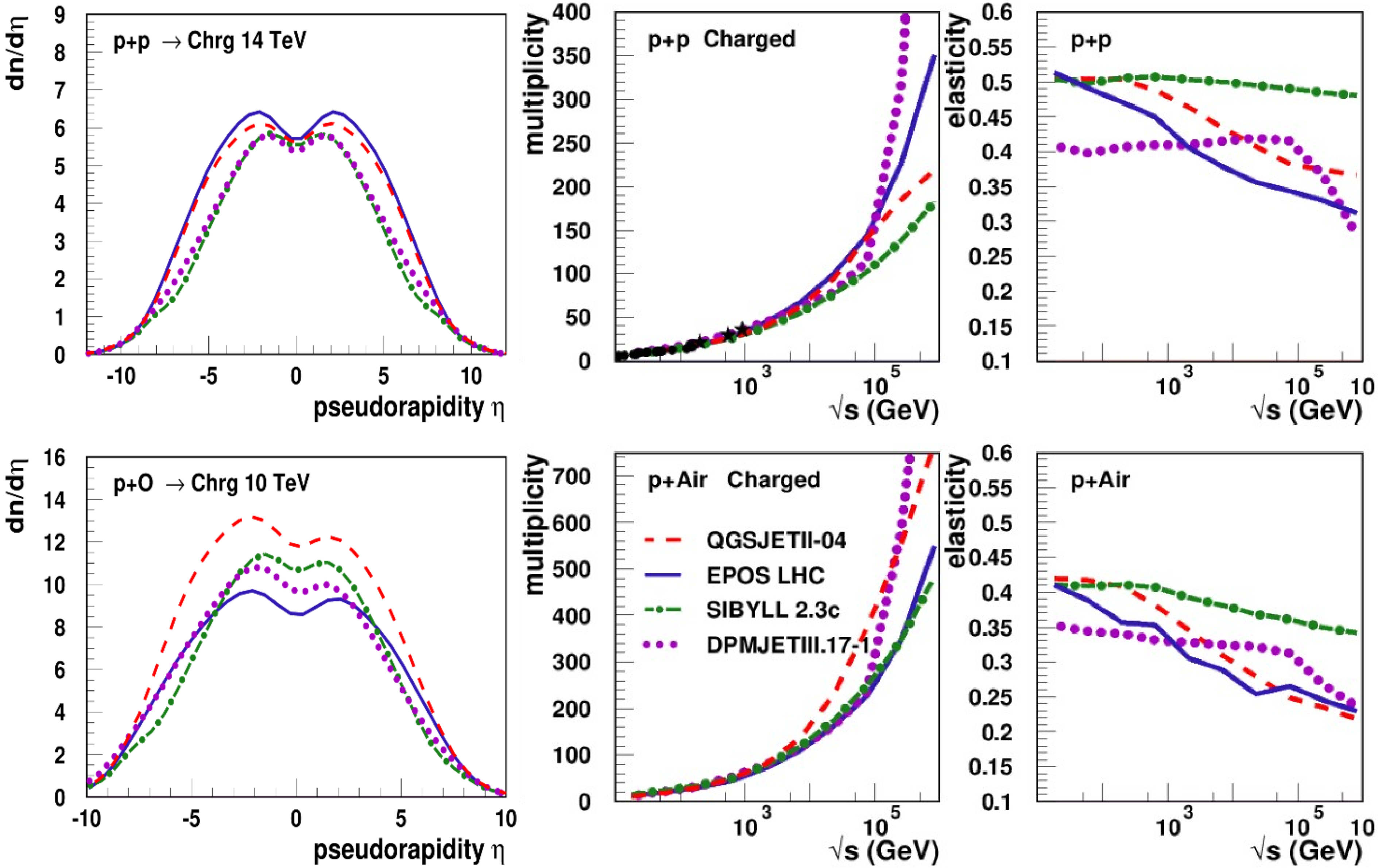
**Nuclear effects :** amplitude correction and collective effects




- Glauber
- Superposition model
- Nuclear amplitude
- Nuclear amplitude + collective effects



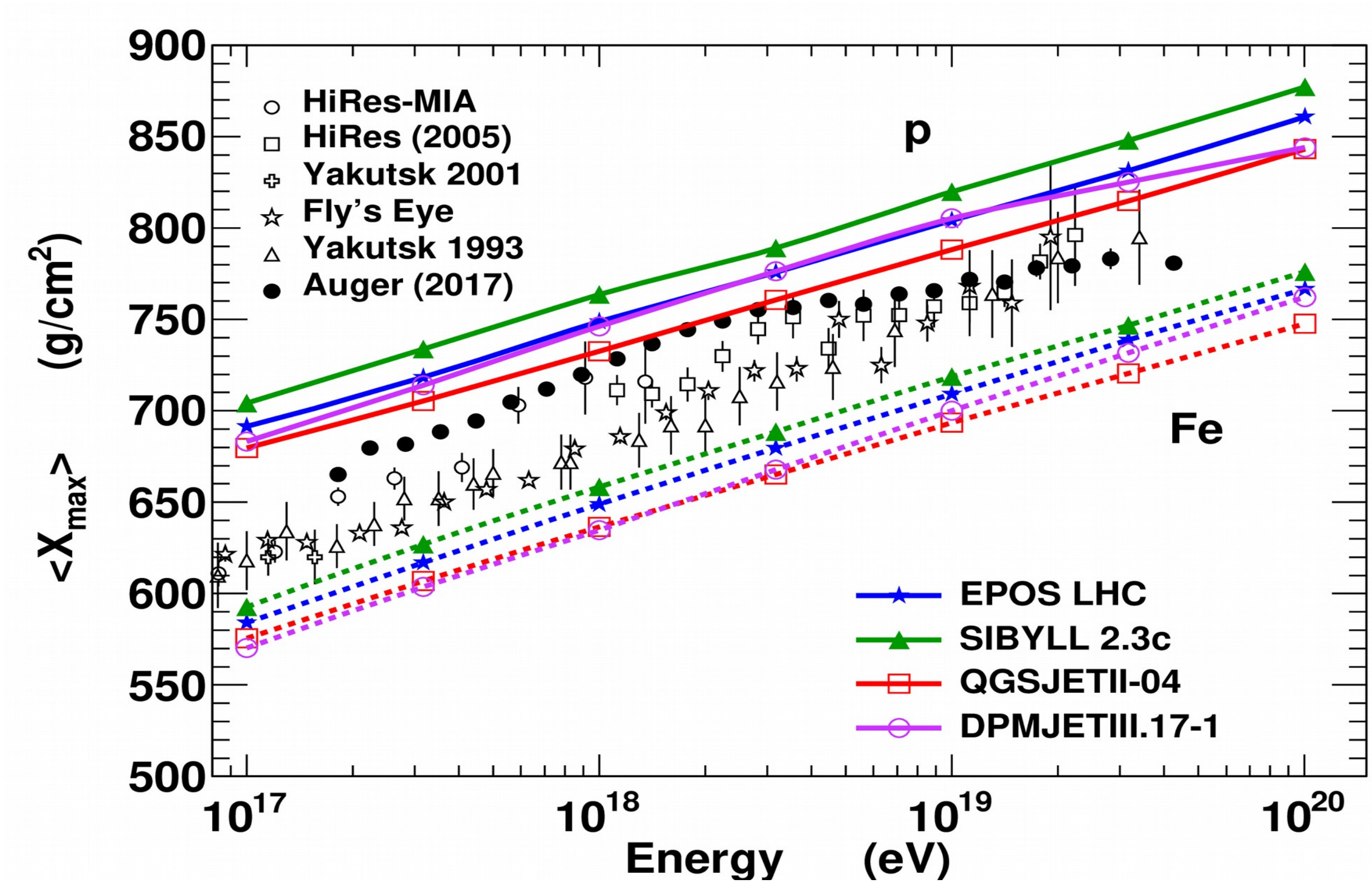
# Ultra-High Energy Hadronic Model Predictions p-Air



# $X_{max}$

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

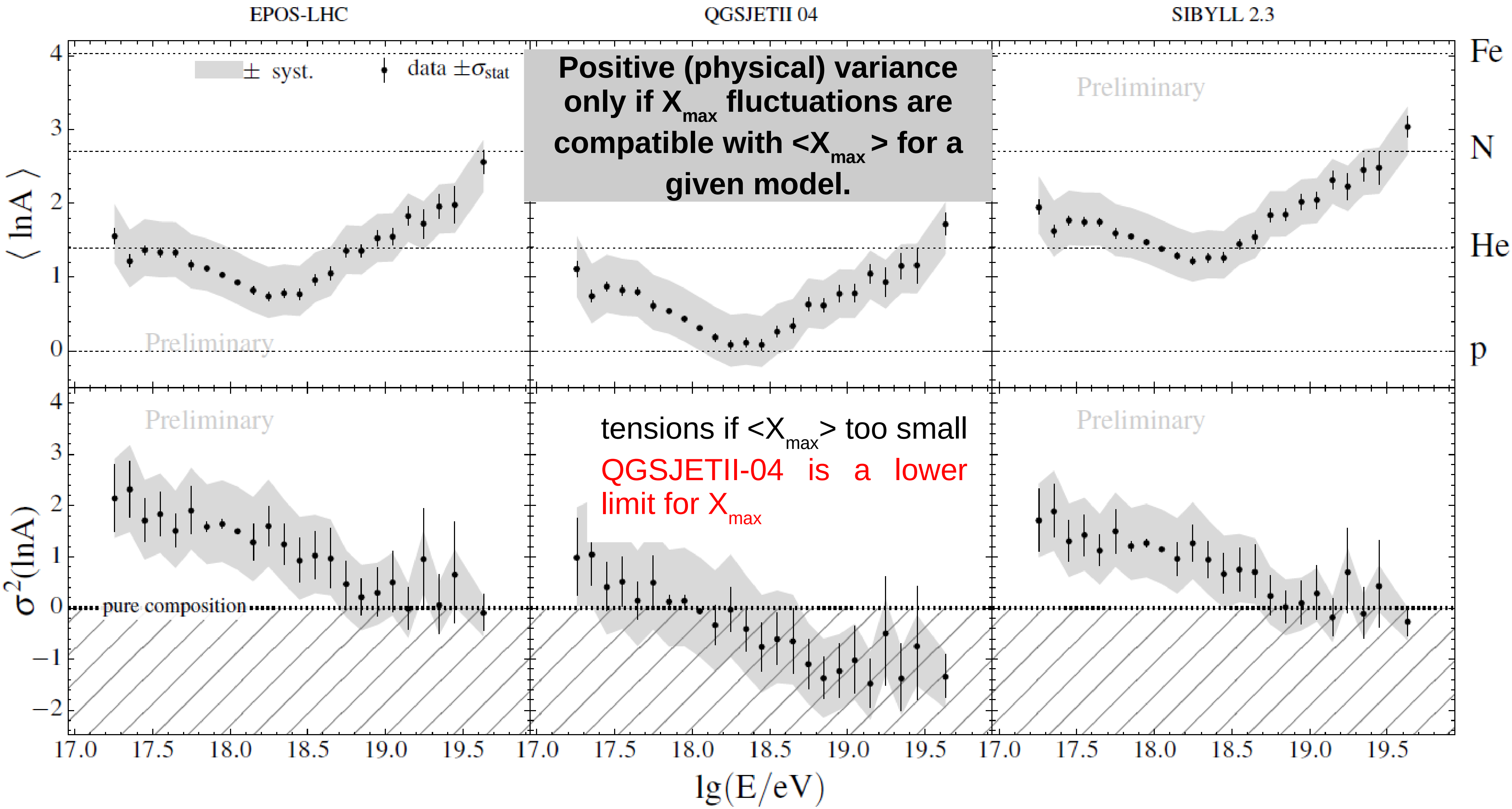
- ➡ minimum given by QGSJETII-04 (high multiplicity, low elasticity)
- ➡ maximum given by Sibyll 2.3c (low multiplicity, high elasticity)
- ➡ anything below or above won't be compatible with LHC data



# Model Consistency using Electromagnetic Component

## Study by Pierre Auger Collaboration (ICRC 2017)

- std deviation of lnA allows to test model consistency.



# WHISP Working Group

- **Lot of measurements available**
  - Auger, EAS-MSU, KASCADE-Grande, IceCube/IceTop, HiRes-MIA, NEMOD/DECOR, SUGAR, TA, Yakutsk
- **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),**

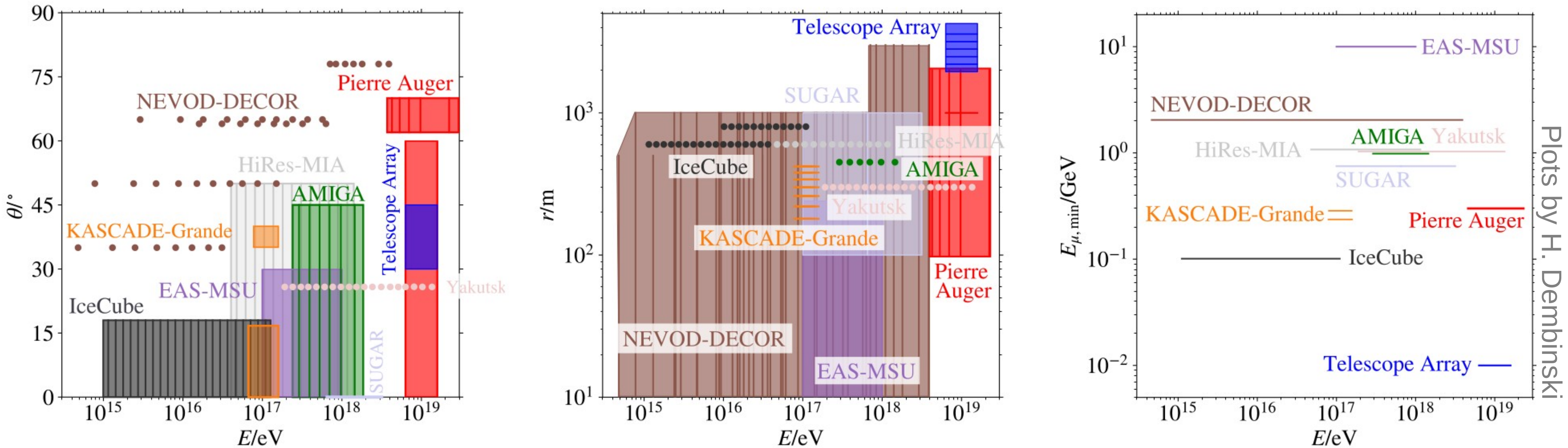
**J.C. Arteaga (KASCADE-Grande, Mexico),**

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

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

# Common Representation

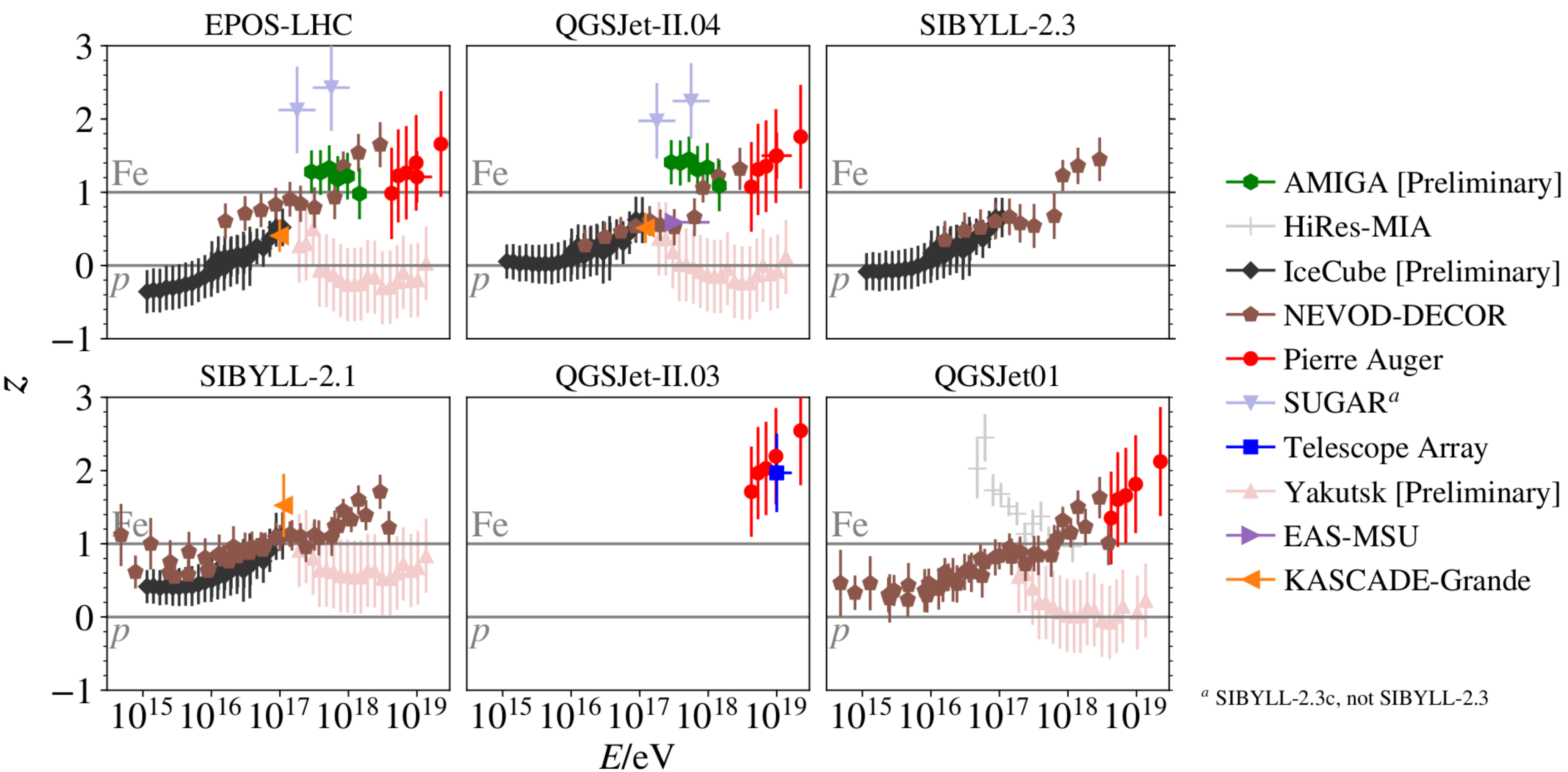
- **Experiments cover different phase space**
  - ➜ Distance to core, zenith angle, energy …




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

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

# 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

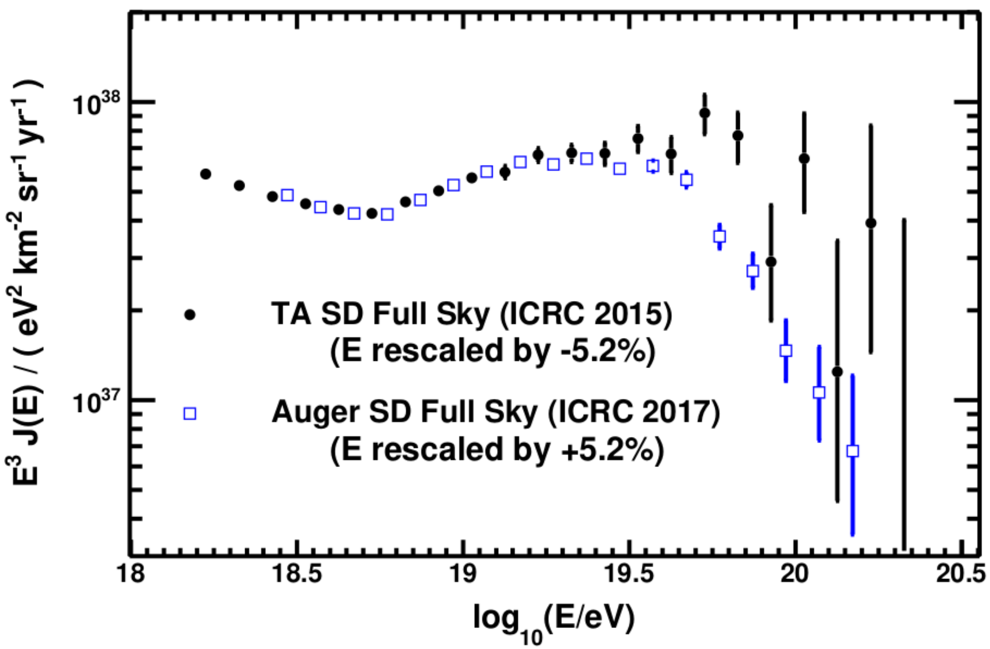
**Using an external data based model !**

# Energy Scale

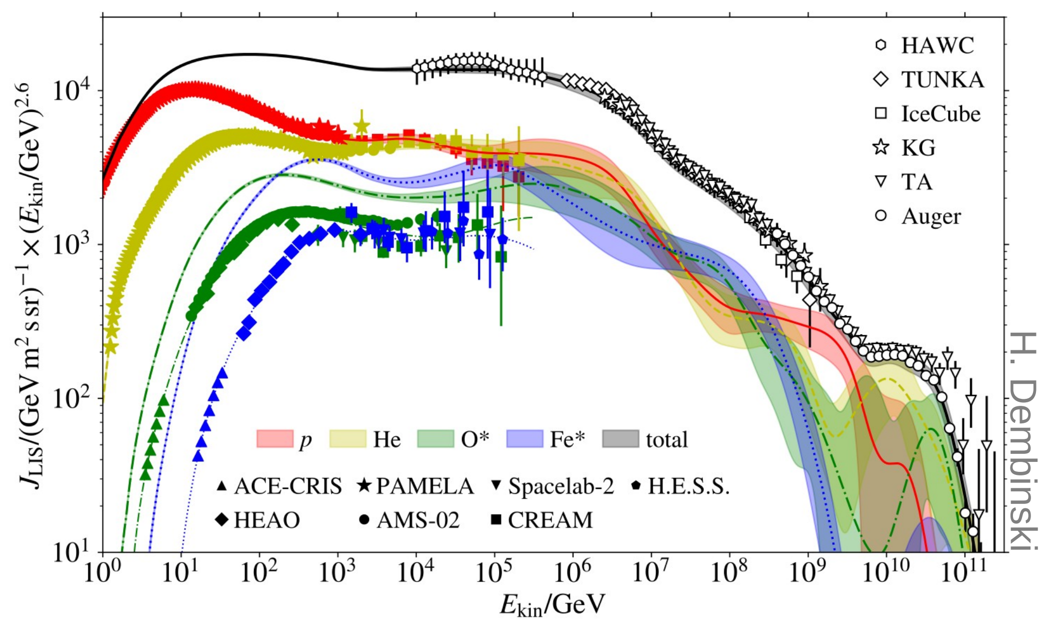
## Unique energy scale obtained mixing

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

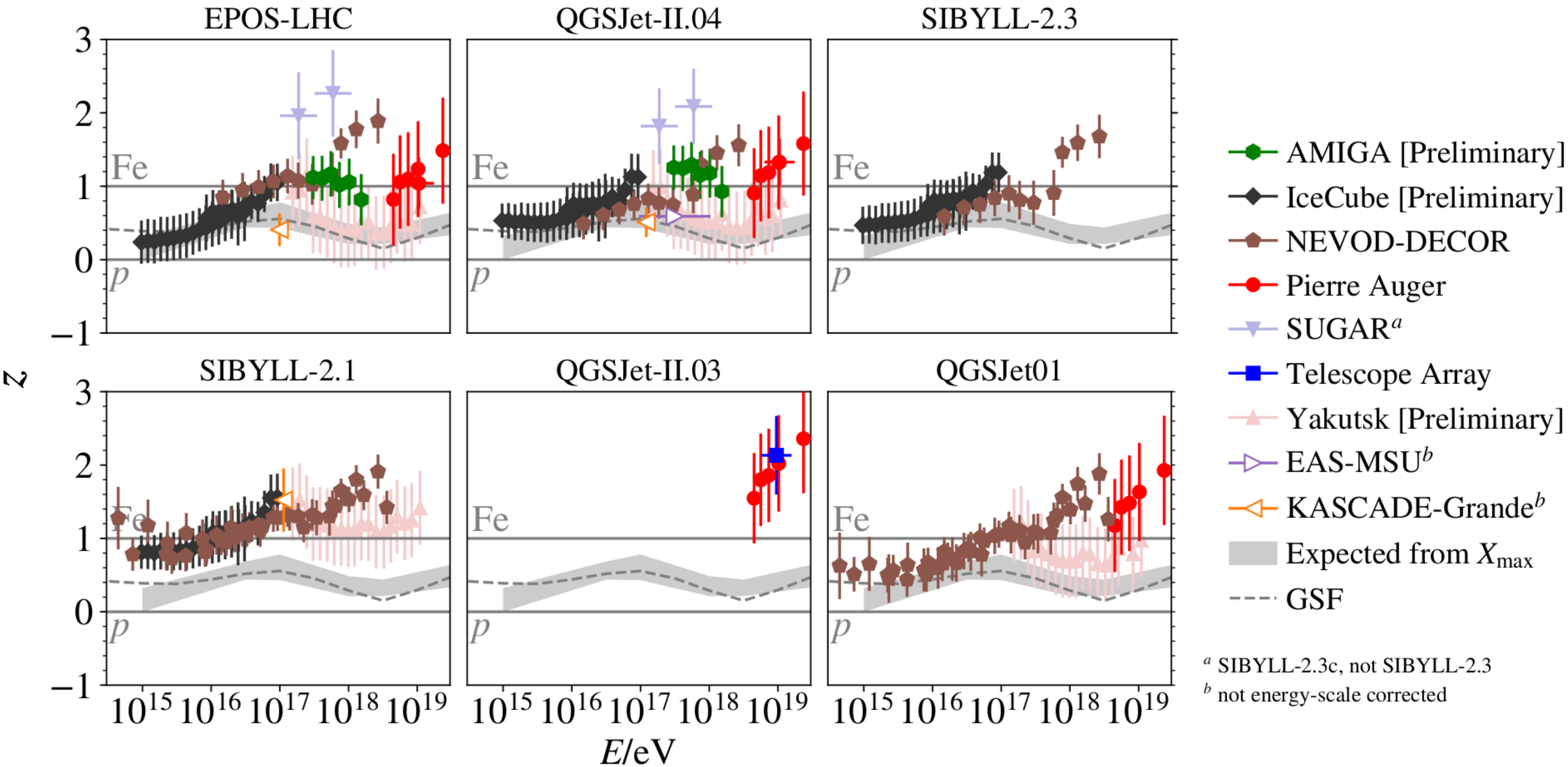
| Experiment | $E_{data}/E_{ref}$ |
|---|---|
| EAS-MSU | unknown |
| IceCube Neutrino Observatory | 1.19 |
| KASCADE-Grande | unknown |
| NEVOD-DECOR | 1.08 |
| Pierre Auger Observatory & AMIGA | 0.948 |
| SUGAR | 0.948 |
| Telescope Array | 1.052 |
| Yakutsk EAS Array | 1.24 |



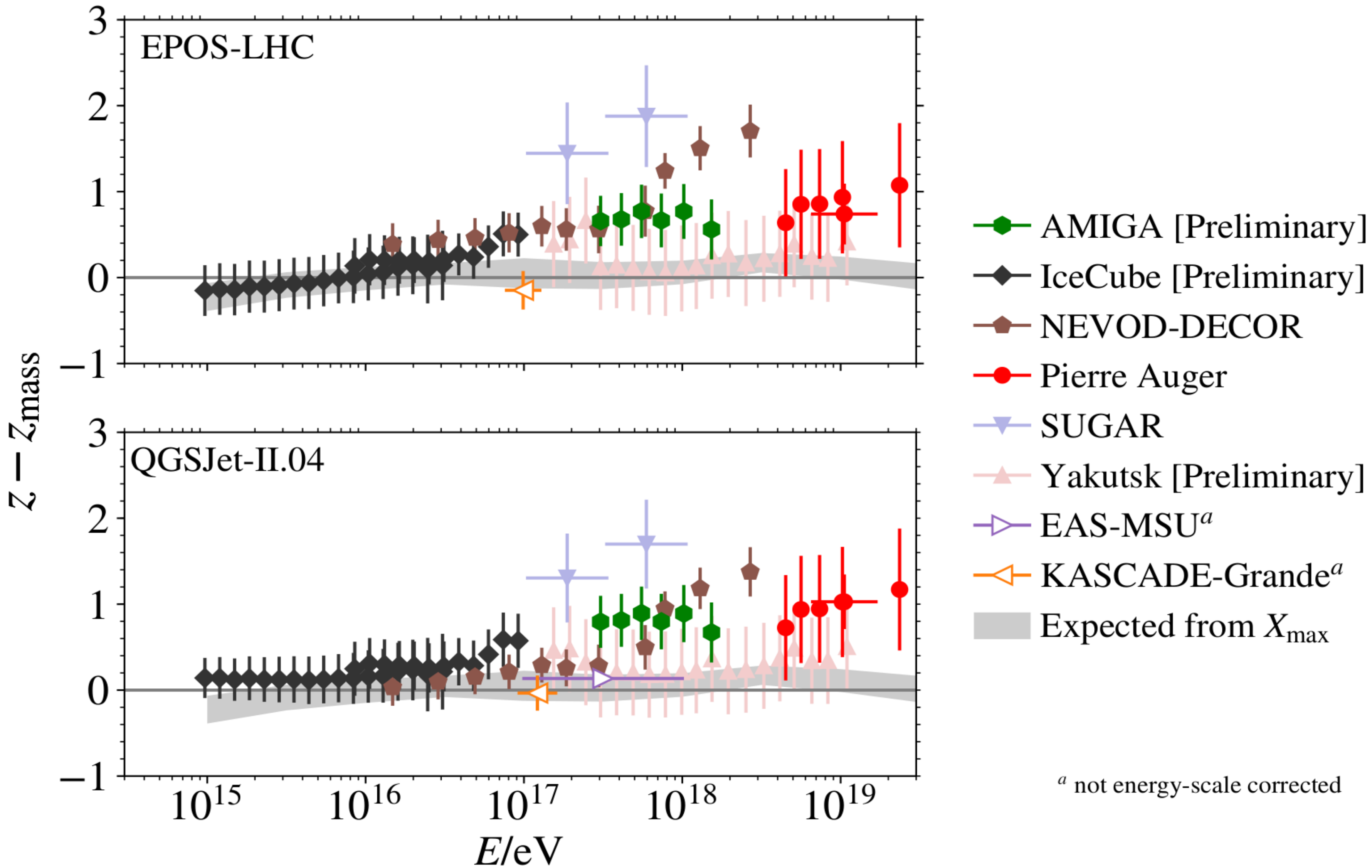

GSF



# Data Rescaled



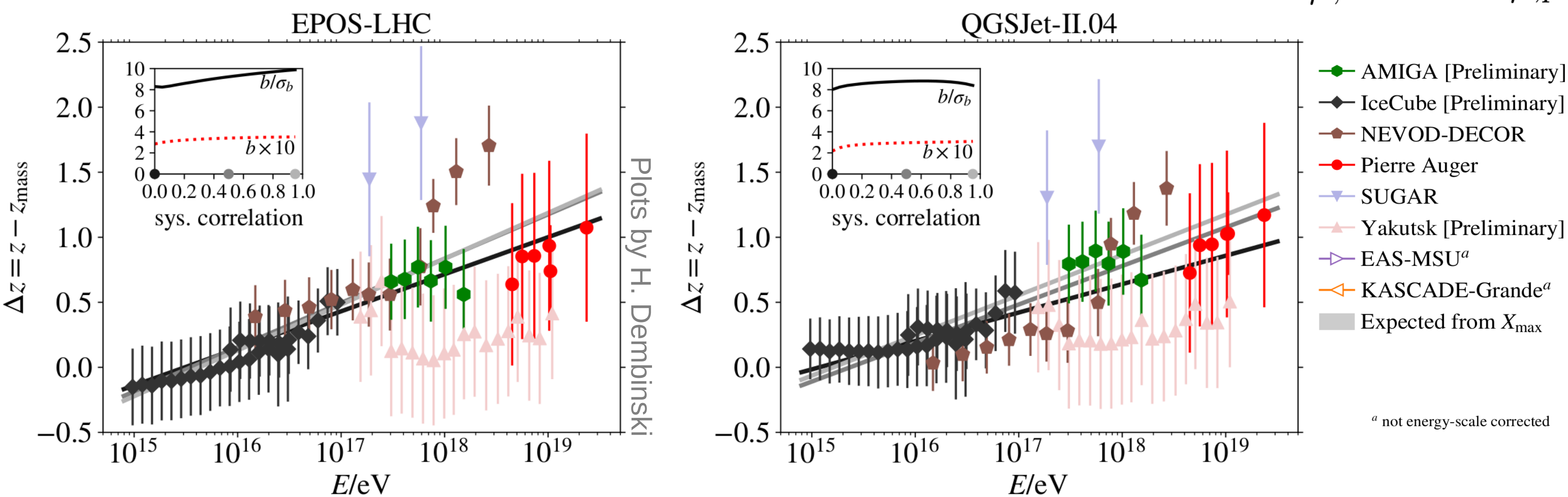
# Rescaled Data with Mass Correction



# Global Behavior after Corrections

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

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



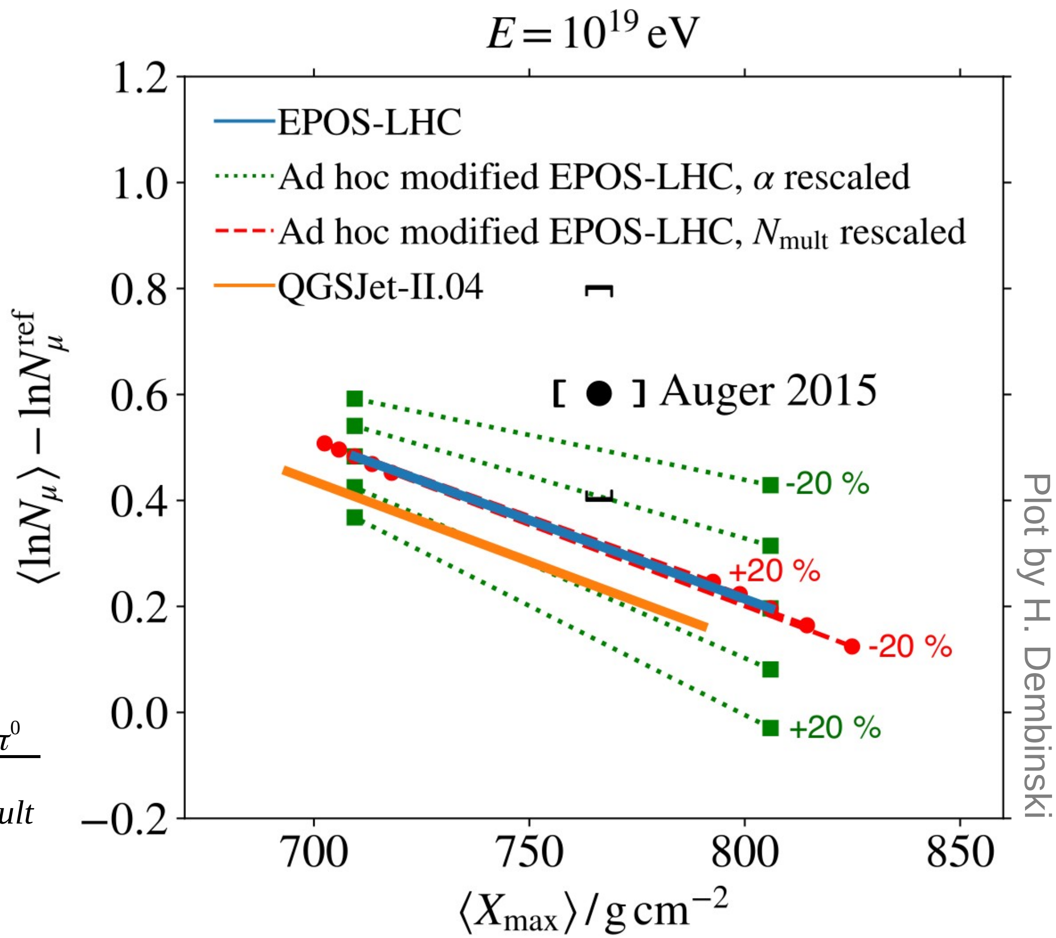

- **Different energy or mass scale cannot change the slope**
  - ➡ Different property of hadronic interactions at least above $10^{16}$ eV

# Constraints from Correlated Change

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

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

- **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 $X_{max}$



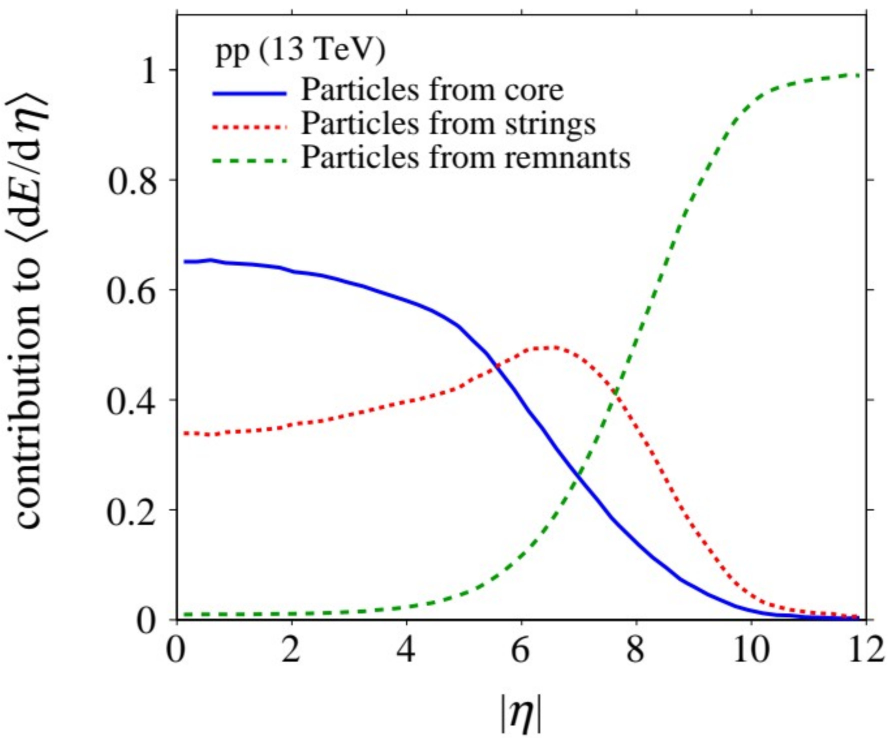

- $$\beta = \frac{\ln(N_{mult} - N_{\pi^0})}{\ln(N_{mult})} = 1 + \frac{\ln(1-\alpha)}{\ln(N_{mult})}$$
  - +4% for β ➤ -30% for $\alpha = \frac{N_{\pi^0}}{N_{mult}}$

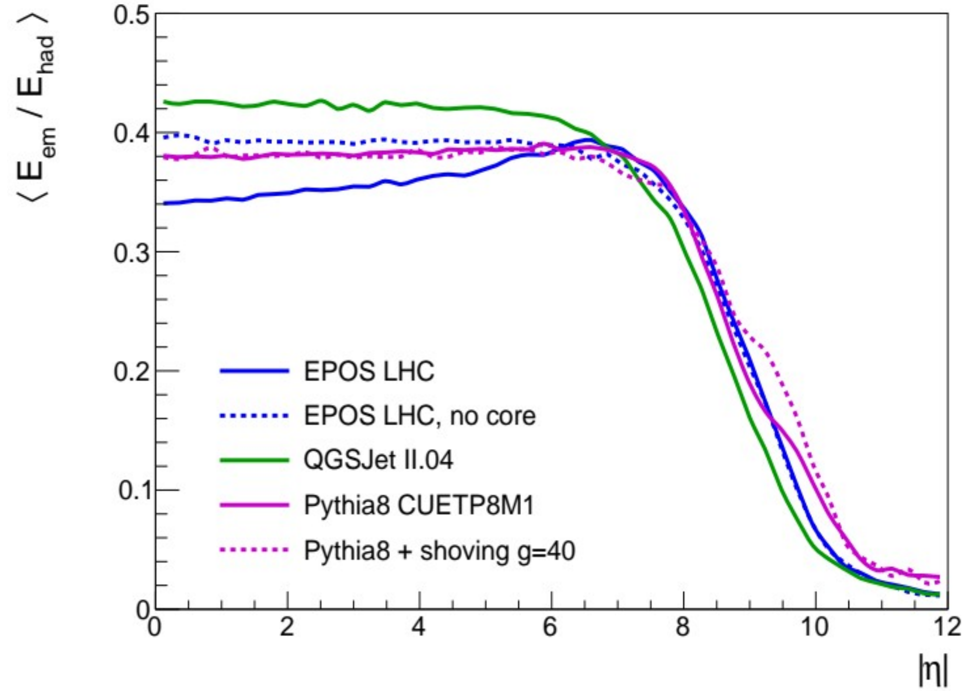
# Possible Particle Physics Explanations

**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.) !

# Effect of Collective Hadronization



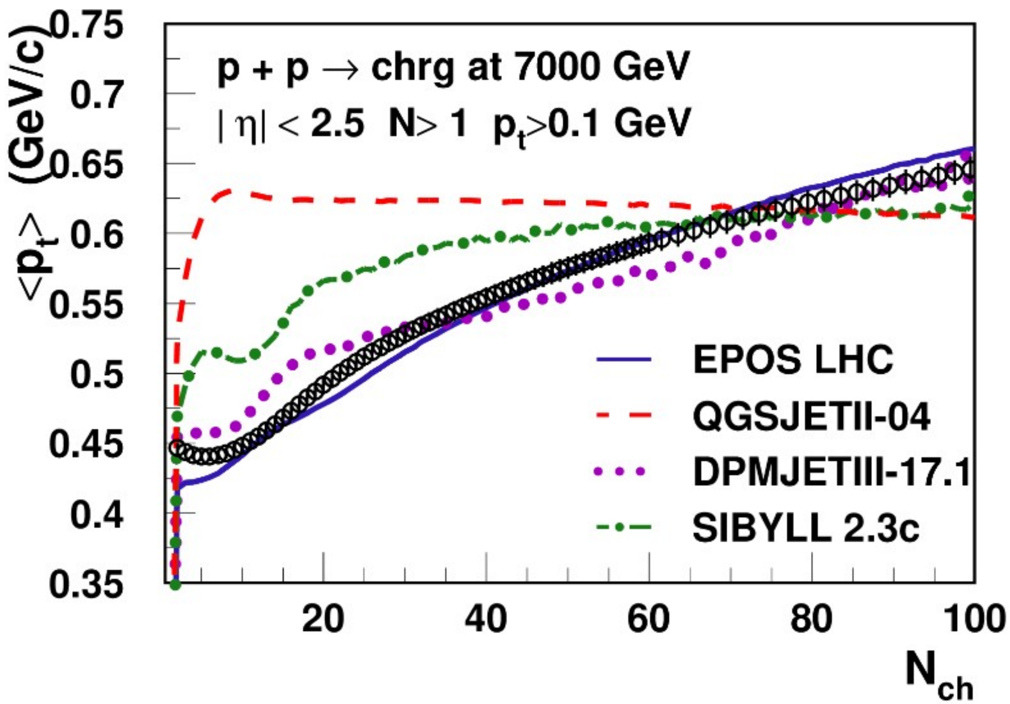



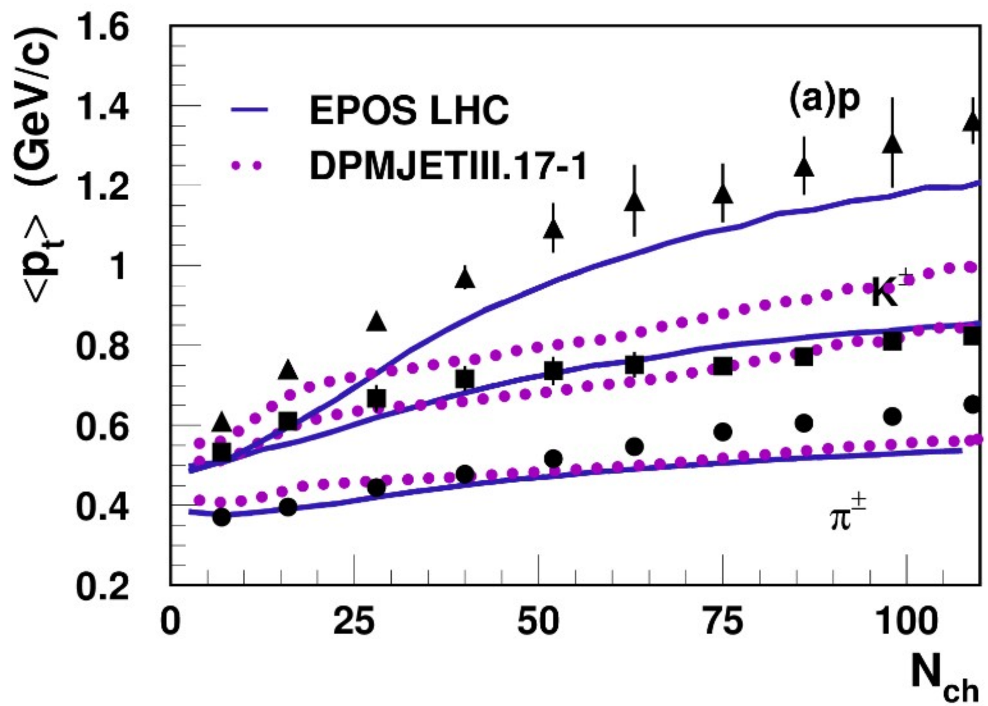

- Unexpected production of Quark Gluon Plasma (QGP) in light systems observed at the LHC (at least modified hadronization)
  - Reduced α is a sign of QGP formation (Baur et al.) !
  - Not properly done in EPOS LHC (QGP only in extreme conditions)

→ Problem : α changed at most by 20%

# Can All Models Account for It ?

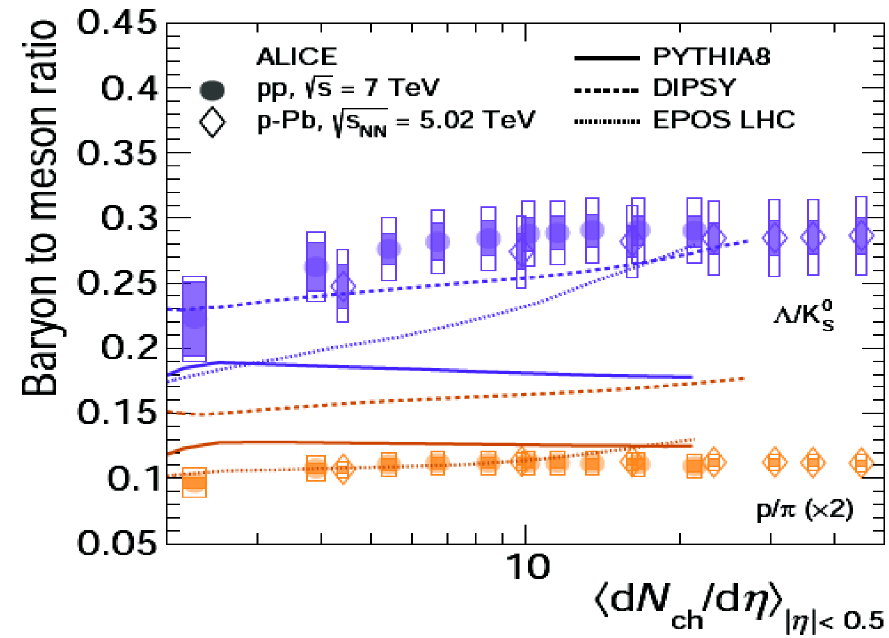
- **Models have different philosophies !**
  - ➜ number of parameters increase with data set to reproduce
  - ➜ predictive power may decrease with number of parameters
  - ➜ predictive power increase if we are sure not to neglect something
- **Different parameters and extrapolations but may be direct influence on air showers ?**
  - ➜ Different hadronization only in EPOS



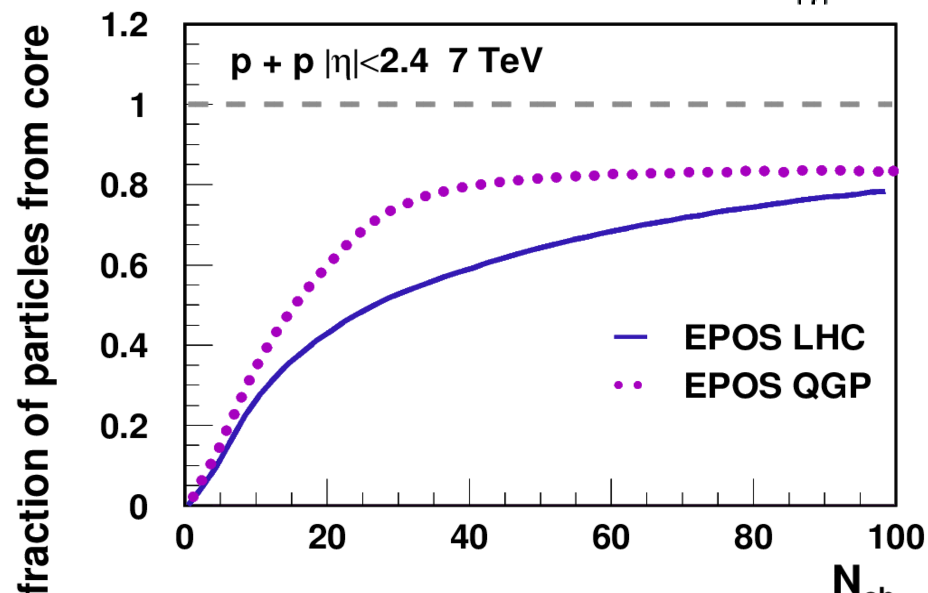



# Modified EPOS with Extended Core

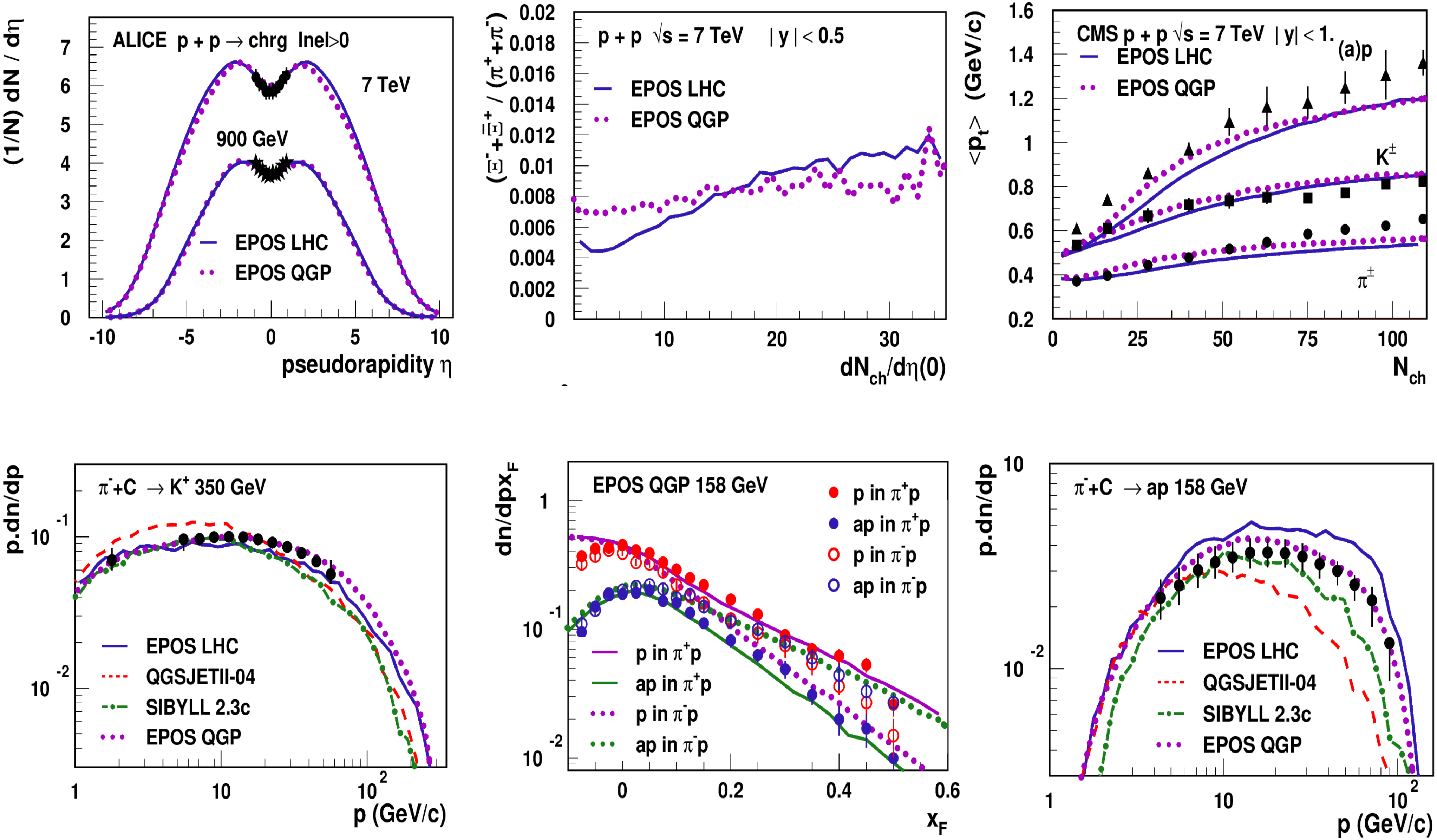
- **Core in EPOS LHC appear too late**
  - Recent publication show the evolution of chemical composition as a function of multiplicity
  - Large amount of (multi)strange baryons produced at lower multiplicity than predicted by EPOS LHC




- **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)

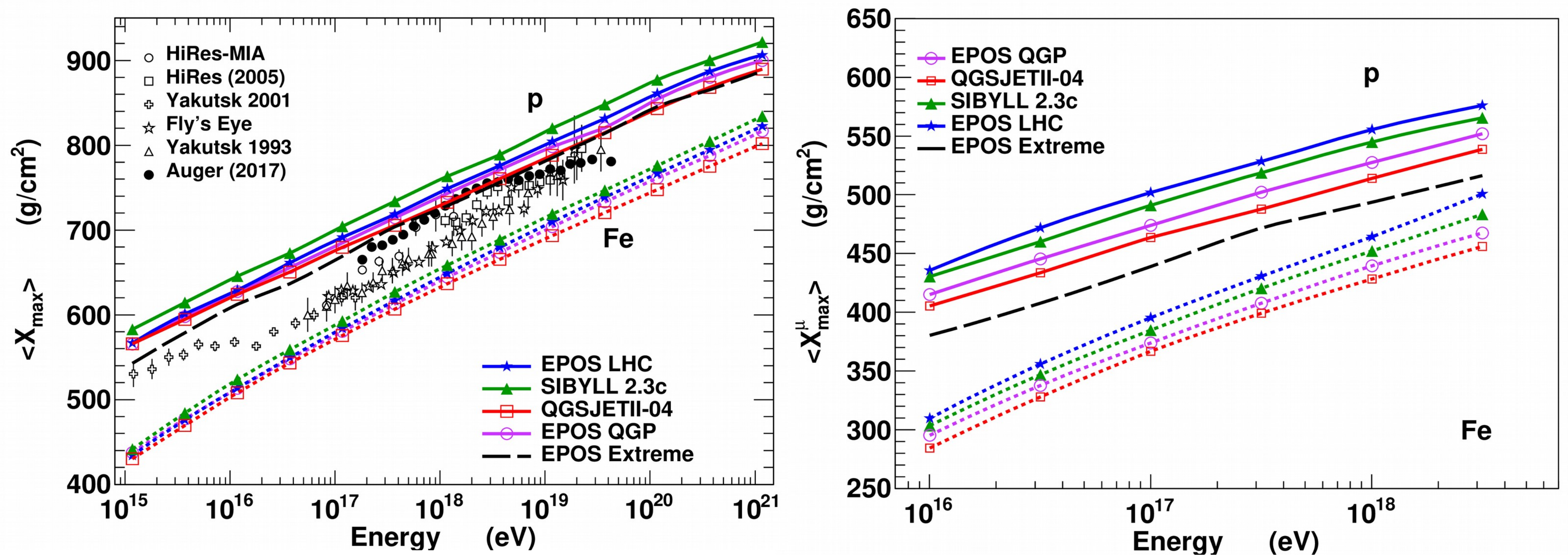


# Preliminary Version with Minimum Constraints



# Results for Air Showers

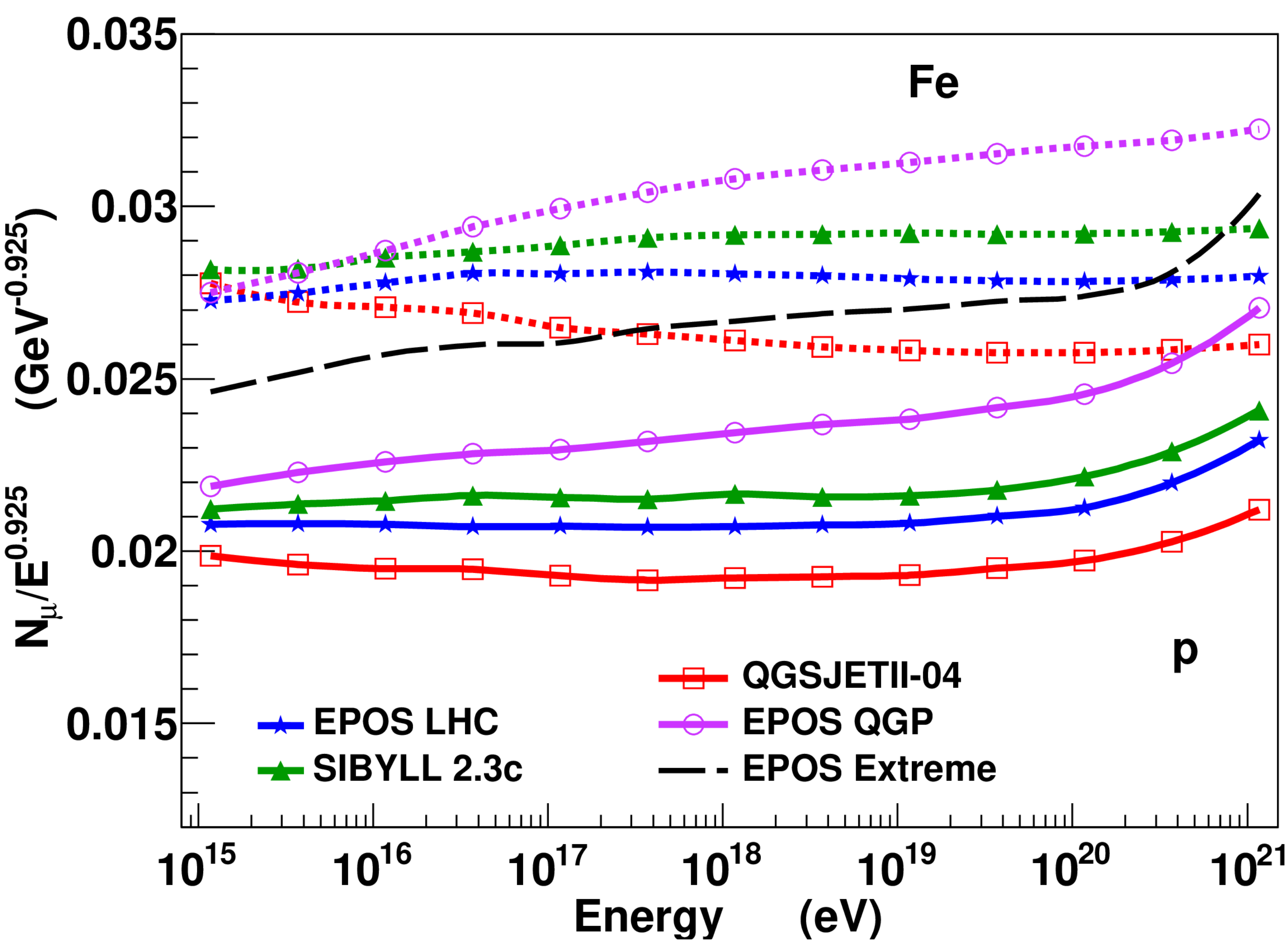
- Small change for $<X_{max}>$ as expected
- Significant change of $<X^{\mu}_{max}>$
- Comparison with extreme case (almost only grand canonical hadron.)
  - ➡ maximum effect using this approach
  - ➡ not compatible with accelerator data

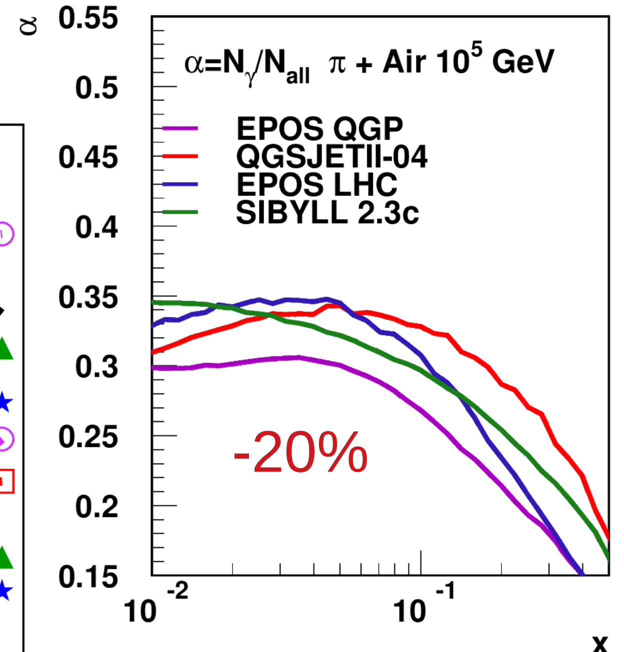


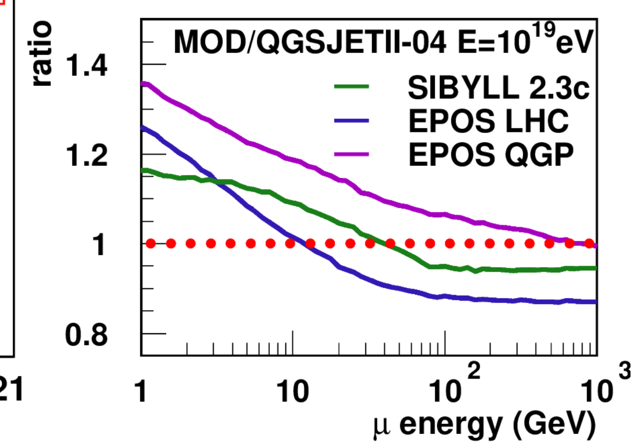
# Results for Air Showers

## Large change of the number of muons at ground

➡ Different slope as expected from the change in α



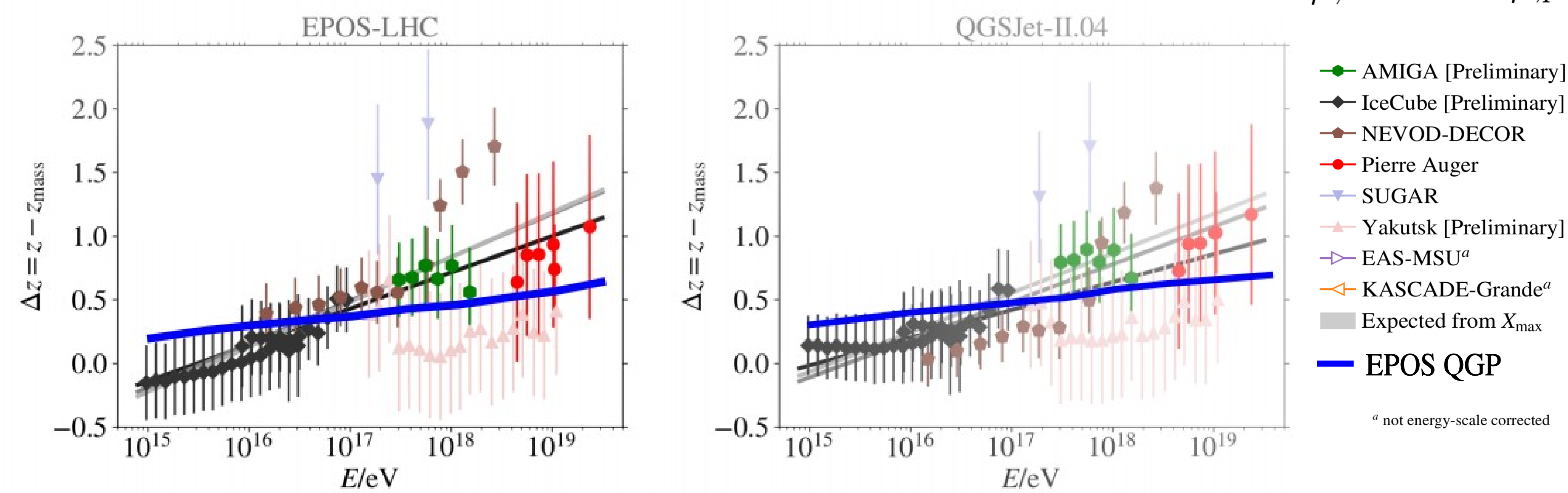



# Comparison with Data

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

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

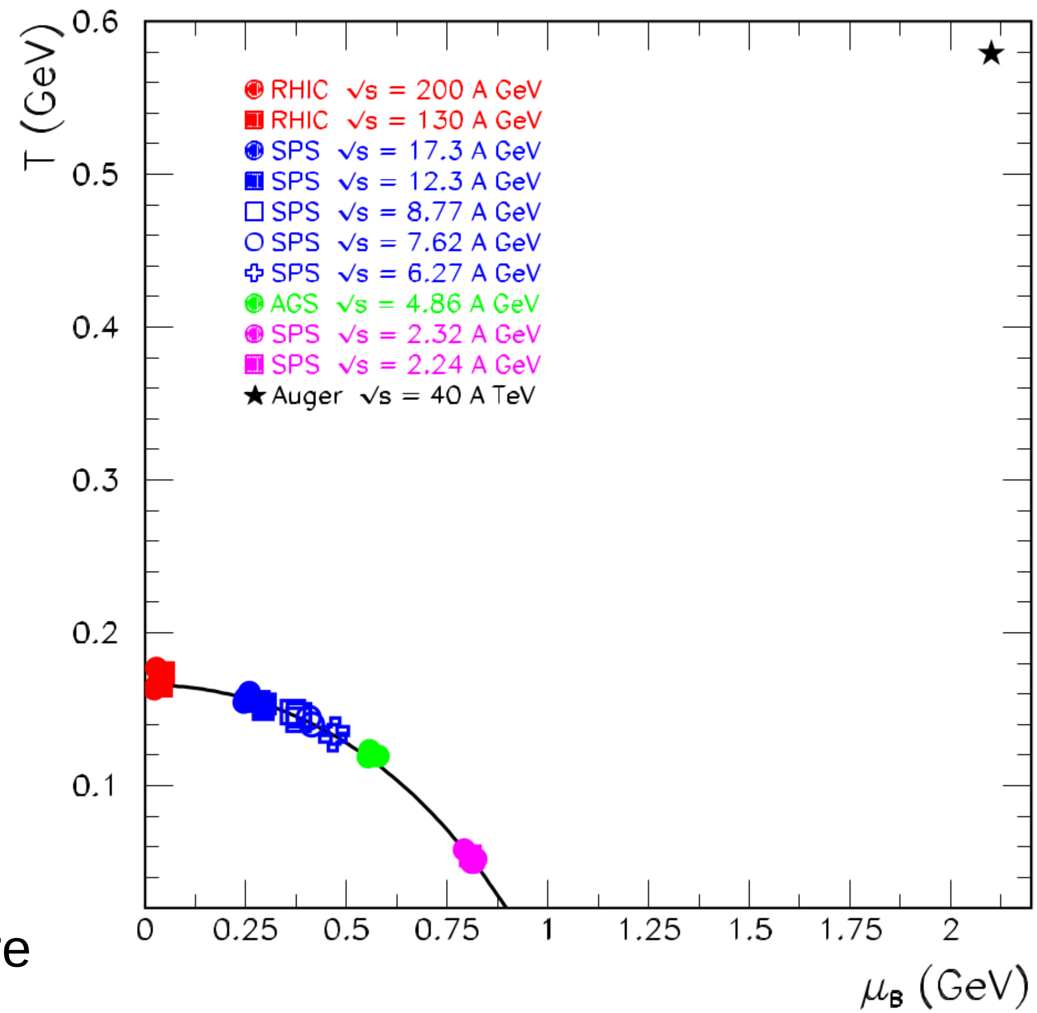



- **Probably tension at low energy (too many muons)**
  - ➜ Ideally a larger slope would be needed … what kind of hadronization possible ?
  - ➜ QGP with large chemical potential (Anchordoqui et al.) ?

# Probe Quark Matter Phase Diagram ?

- **In air showers**
  - Forward particle production in (nuclear) projectile medium
  - Higher baryonic density
  - Increased strangeness production
  - α decreased by more than 20%
  - Possibility to reproduce EAS data

- **Probe phase diagram ?**
  - Air showers data to test phase diagram in regions not accessible with accelerators (high temperature and high chemical potential) !




Anchordoqui et al. arXiv:1612.07328

# The chicken ...

- **Hadronic interaction models very important to interpret cosmic ray data**
  - mass composition
  - LHC data used to tune and complete the models
- **Central particle production at LHC reduced model uncertainties in slope of $X_{max}$**
  - same energy evolution in models important for mass of primary cosmic rays
  - all pre-LHC models in contradiction with LHC data (central and forward prod.)
  - using latest model version reduce uncertainties and avoid unphysical behavior
- **Remaining 20 $gr/cm^2$ difference for $X_{max}$ predictions**
  - linked to forward physics (photon spectra and diffraction measured at LHC) not yet taken into account in models used for EAS simulation (coming...)
  - effect of extrapolation to p-Air interaction
    - p-O beam necessary to check that p-p properly extrapolated
    - p-Pb measurements can be used but need change in most models (only EPOS reproduces p-Pb data for the moment)

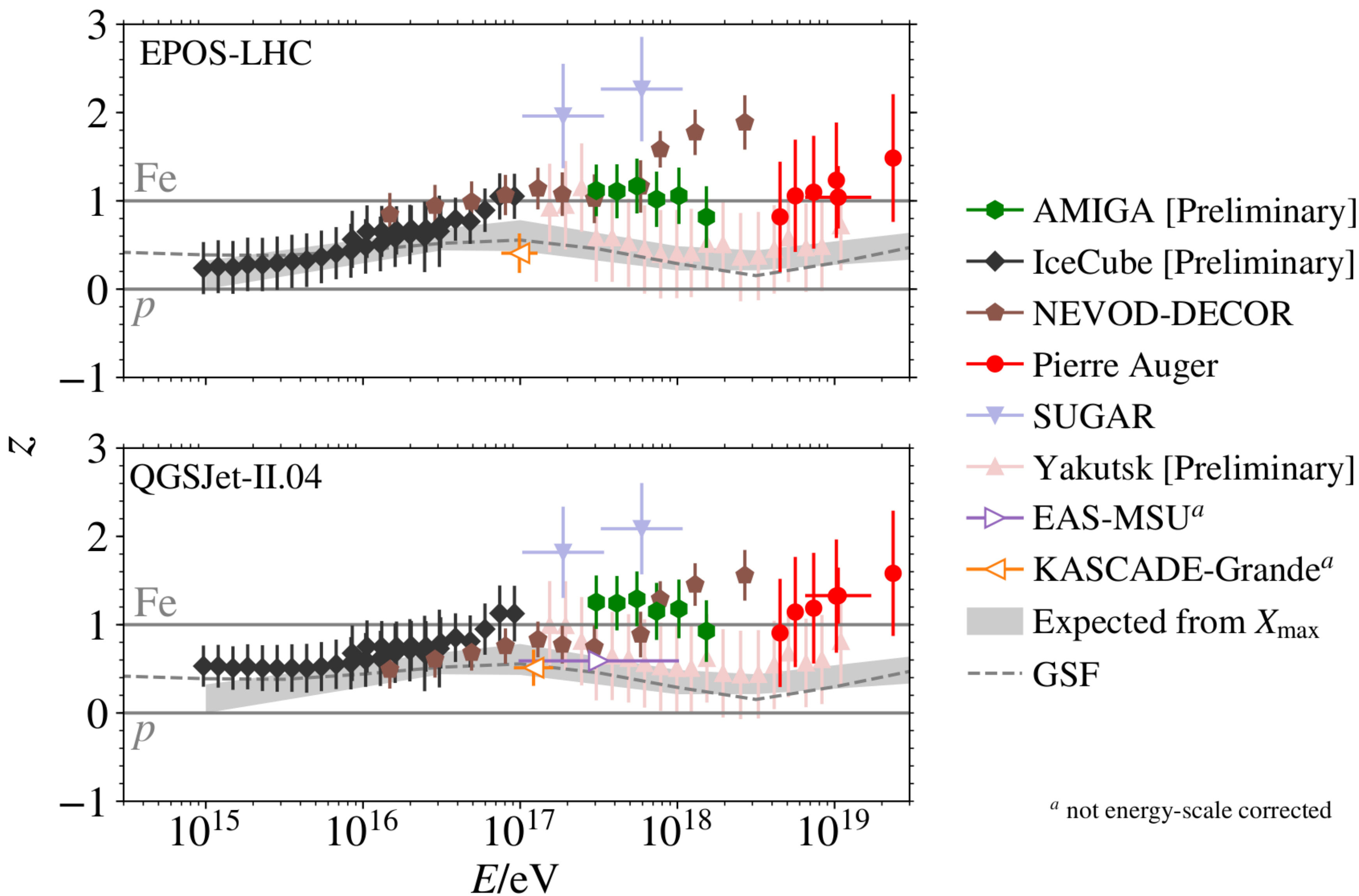
# … or the egg

- **Auger data (and other low energy cosmic ray experiments) not consistently described by hadronic interaction models (even post LHC)**
  - $<X_{max}>$ and fluctuations, number of muons and muon production depth …
  - ➡ but it has never been so good ! only 1 to 2 sigma difference in most of the cases
- **Compilation of all muon measurements clearly indicate a different slope for muon production as a function of shower energy**
  - ➡ Different hadronization required (less neutral pions / other particles)
  - ➡ Collective hadronization in small system / forward in line with LHC results ?
  - ➡ Probe new area in quark matter phase diagram ?
- **Hadronic models used for cosmic ray analysis very important for LHC**
  - ➡ constraints from CR on hadronic models improve their predictive power (better energy dependence than HEP models)
  - ➡ CR models compared to minimum bias data (best description from EPOS LHC)
  - ➡ EPOS used in detector simulations (correction, reconstruction …)
  - ➡ more reliable predictions for the Future Circular Collider (100 TeV)

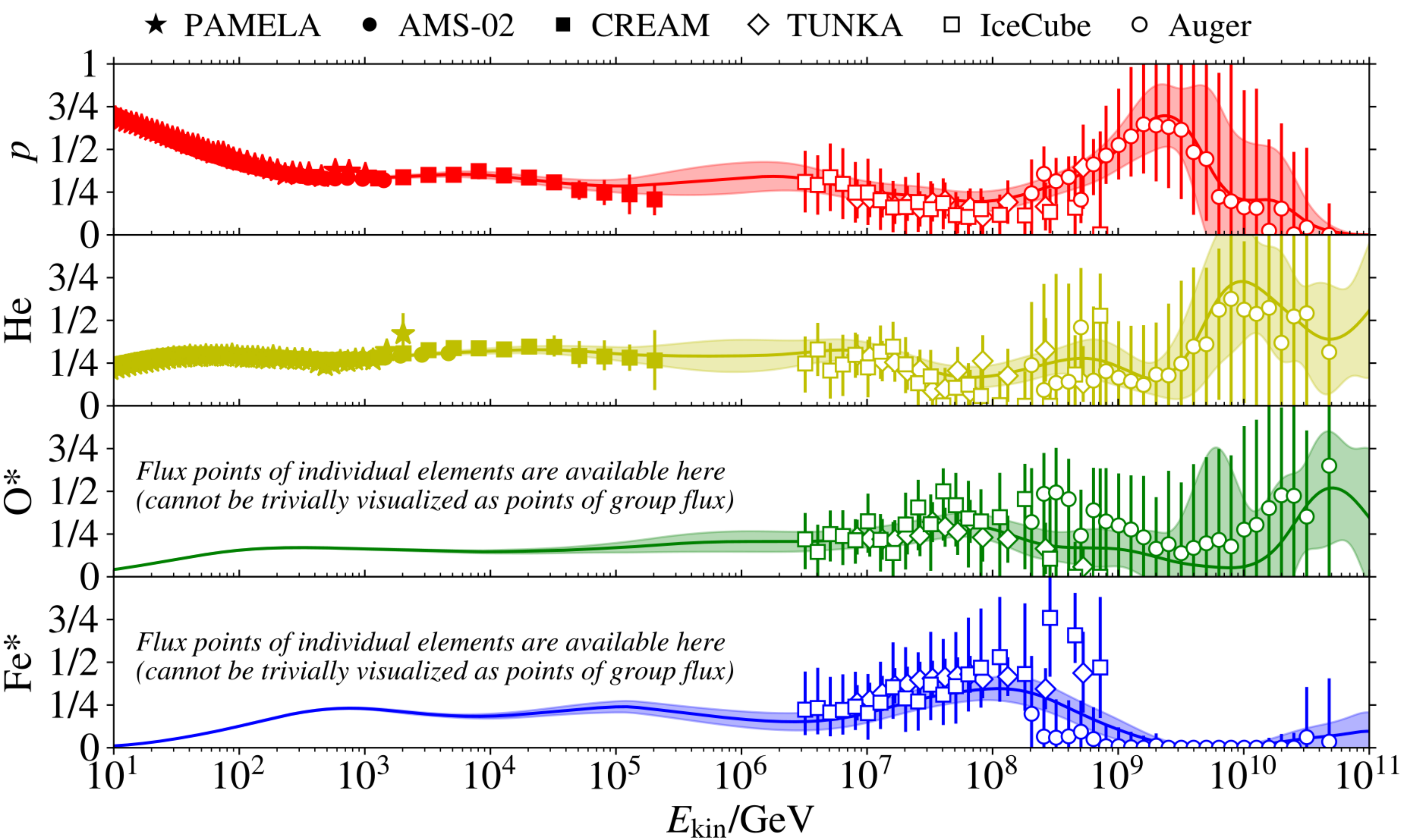
**LHC data reduced the model uncertainties for mass composition and might open a change for muon production. Good description of air showers improve model predictive power for the description of min. bias LHC data and test new phase space.**

Thank you !

# Rescaled Data

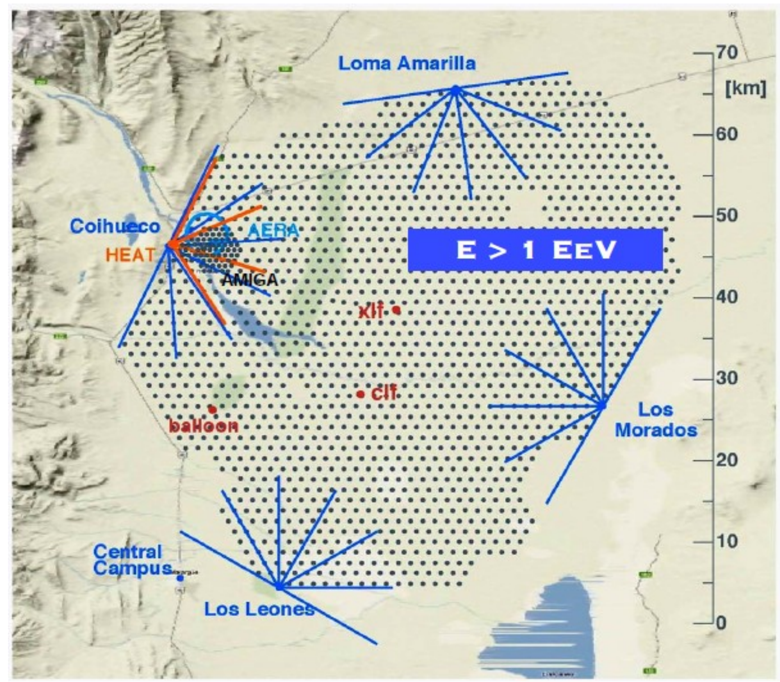


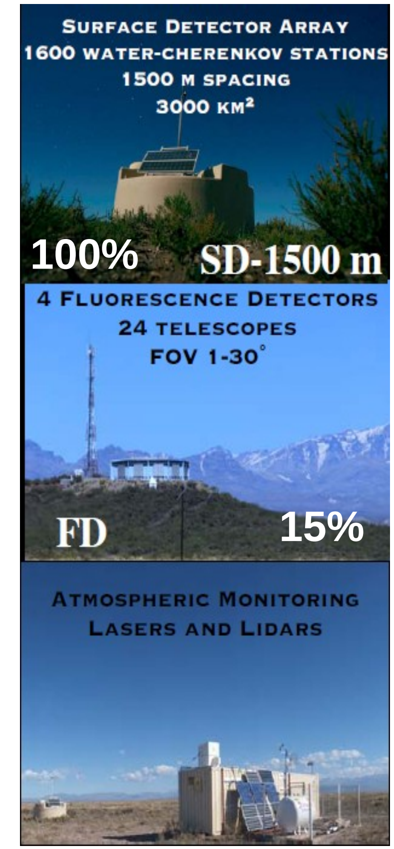
# GSF Composition Details



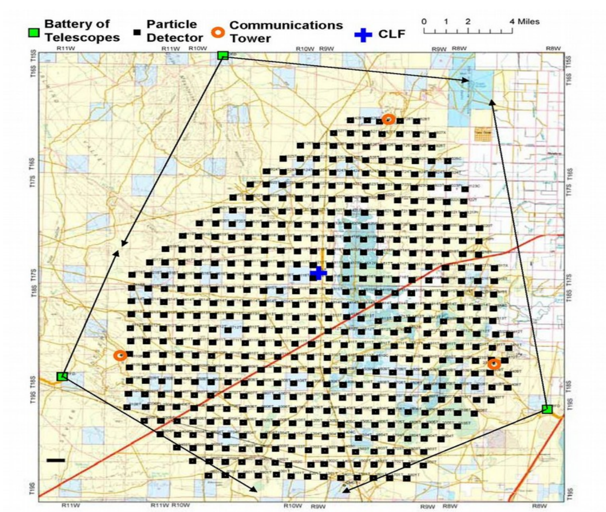
# PAO/TA

- **Pierre Auger Observatory (PAO)**
  - Mendoza, Argentina
  - Southern Hemisphere
  - 3000 km$^2$: 32000 km$^2$/sr/yr

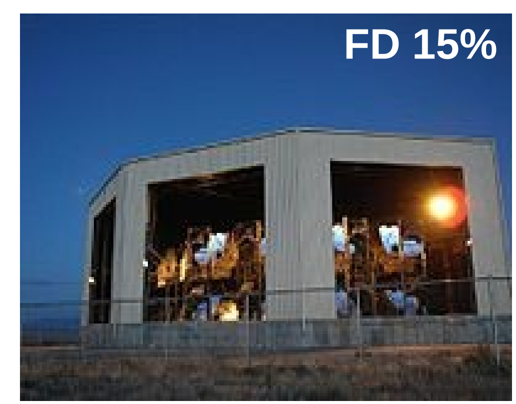


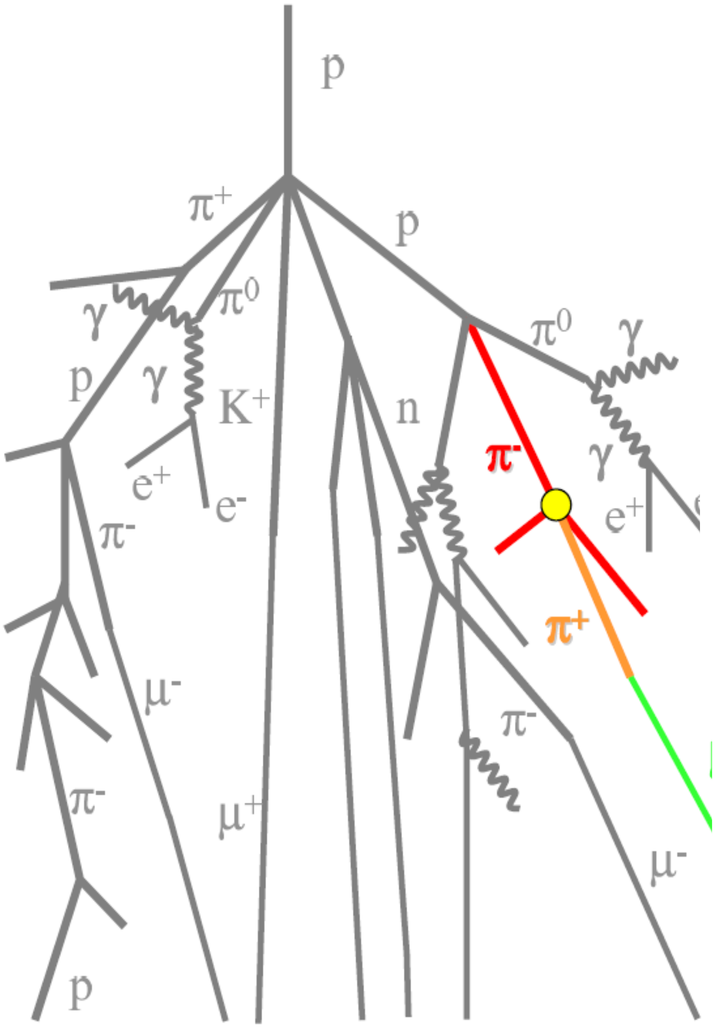

- **Telescope Array (TA)**
  - Utah, USA
  - Northern Hemisphere
  - 680 km$^2$: 3700 km$^2$/sr/yr



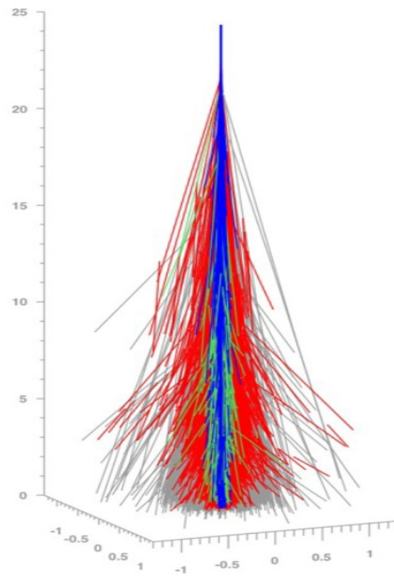




# Extensive Air Shower




From R. Ulrich (KIT)



$A + air \rightarrow \text{hadrons}$

$p + air \rightarrow \text{hadrons}$ hadronic physics

$\pi + air \rightarrow \text{hadrons}$

initial $\gamma$ from $\pi^0$ decay

$e^{\pm} \rightarrow e^{\pm} + \gamma$

$\gamma \rightarrow e^{+} + e^{-}$ well known QED

$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}/\bar{\nu_{\mu}}$

## Cascade of particle in Earth's atmosphere

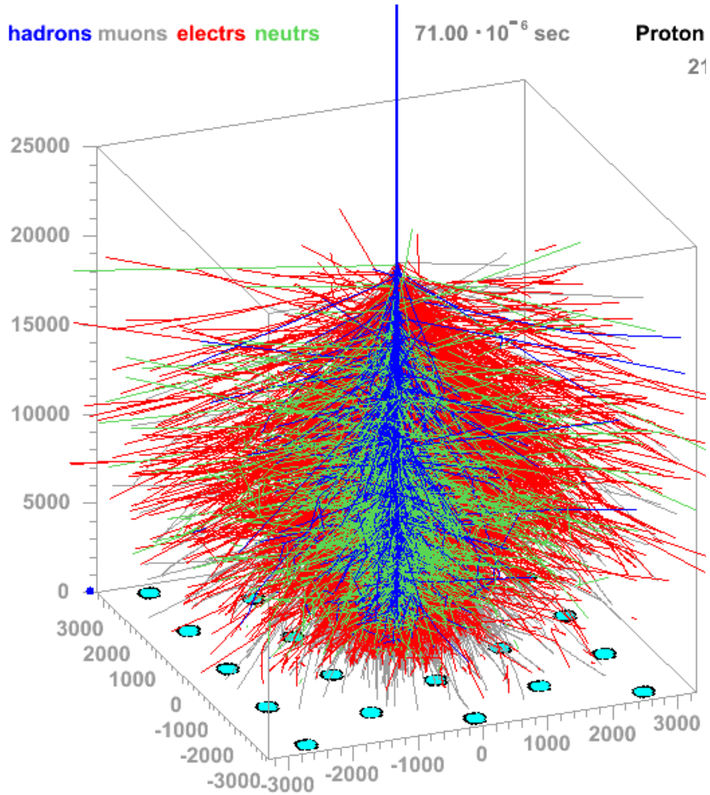
Number of particles at maximum

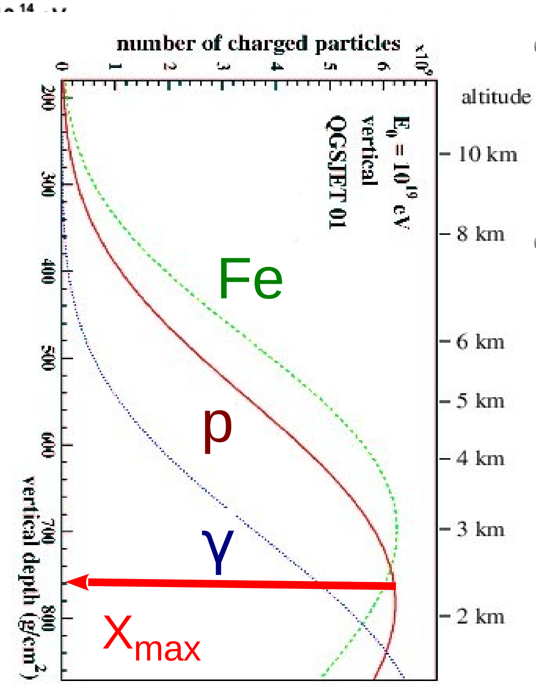
- 99,88% of electromagnetic (EM) particles
- 0.1% of muons
- 0.02% hadrons

Energy

- from 100% hadronic to 90% in EM + 10% in muons at ground (vertical)

# Extensive Air Shower Observables

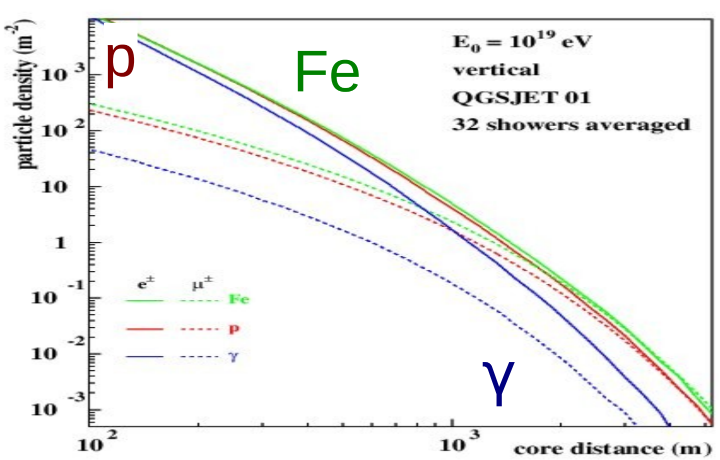



- **Longitudinal Development**
  - ➡ number of particles vs depth

    $$X = \int_h^\infty dz\, \rho(z)$$

  - ➡ Larger number of particles at $X_{max}$
    For many showers
    - mean : $\langle X_{max} \rangle$
    - fluctuations : RMS $X_{max}$
    - depends on primary mass
    - depends on Hadr. Inter.

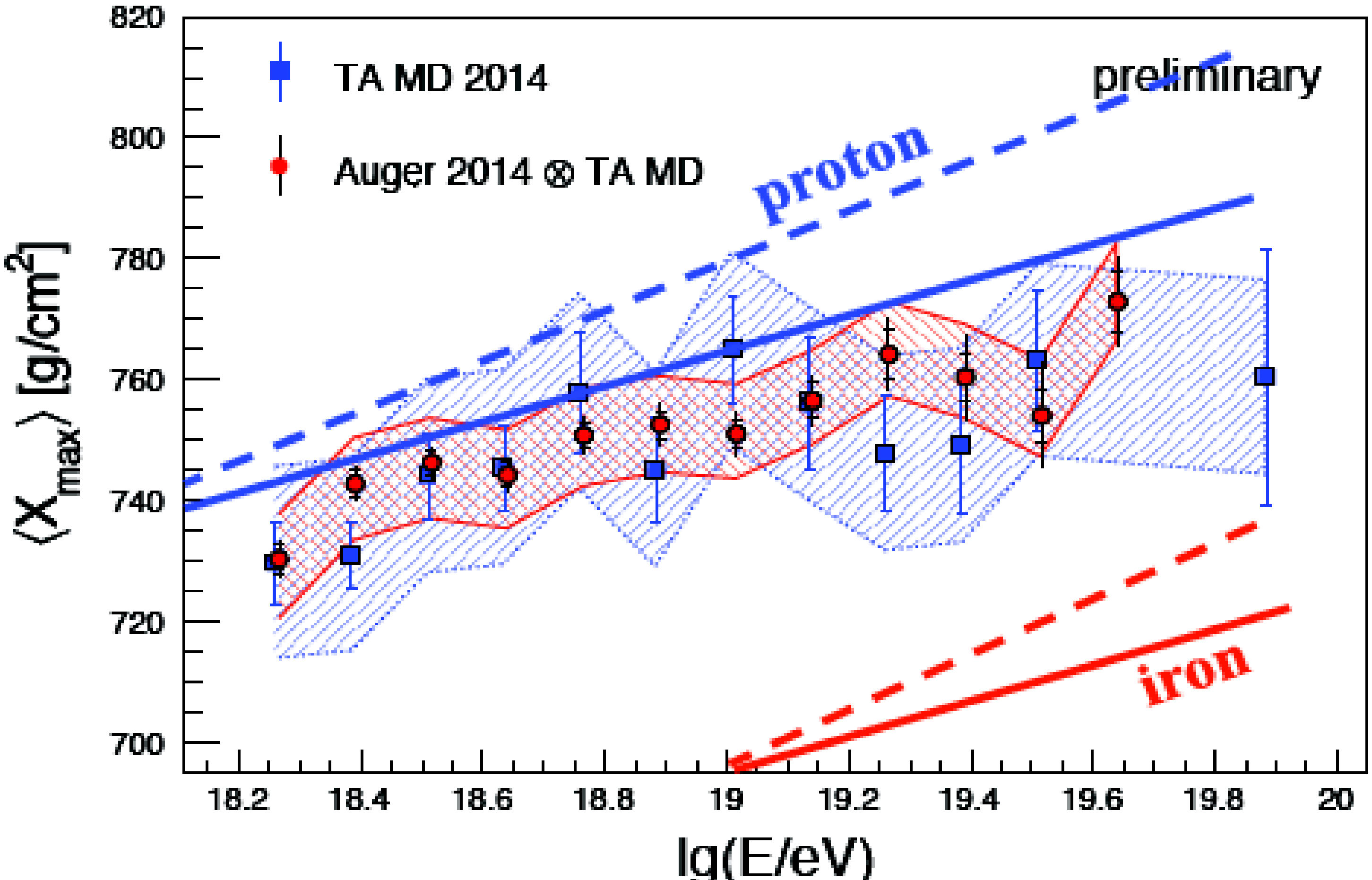



- **Lateral distribution function (LDF)**
  - ➡ particle density at ground vs distance to the impact point (core)
  - ➡ can be muons or electrons/gammas or a mixture of all.
- **Others: Cherenkov emissions, Radio signal**

# Pre-LHC UHECR Composition

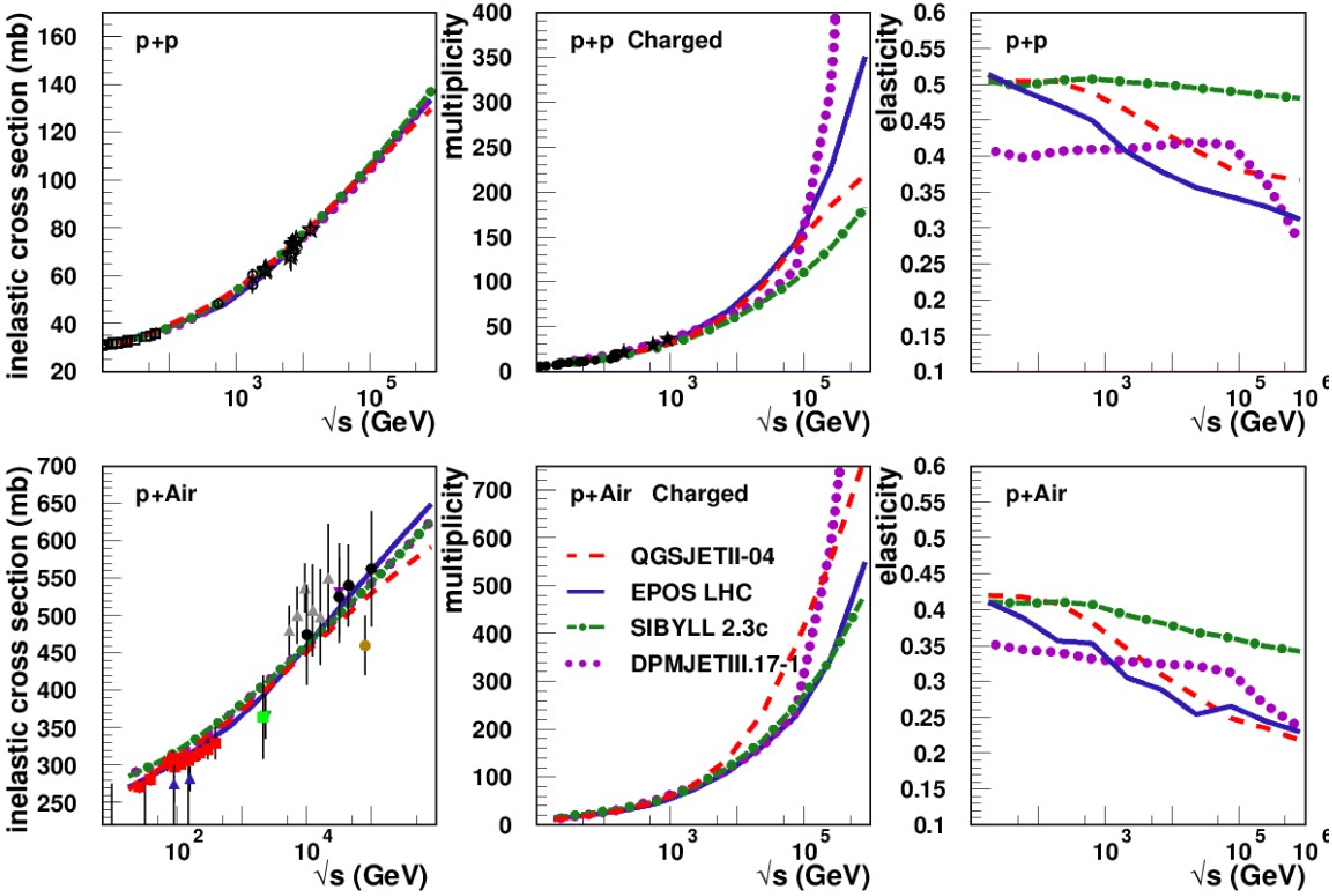
**With pre-LHC models current CR data would be difficult to interpret**

- Full (QGSJET) : proton ("easy" and "old" astrophysical interpretation)
- Dashed (EPOS/SIBYLL) : mixed composition

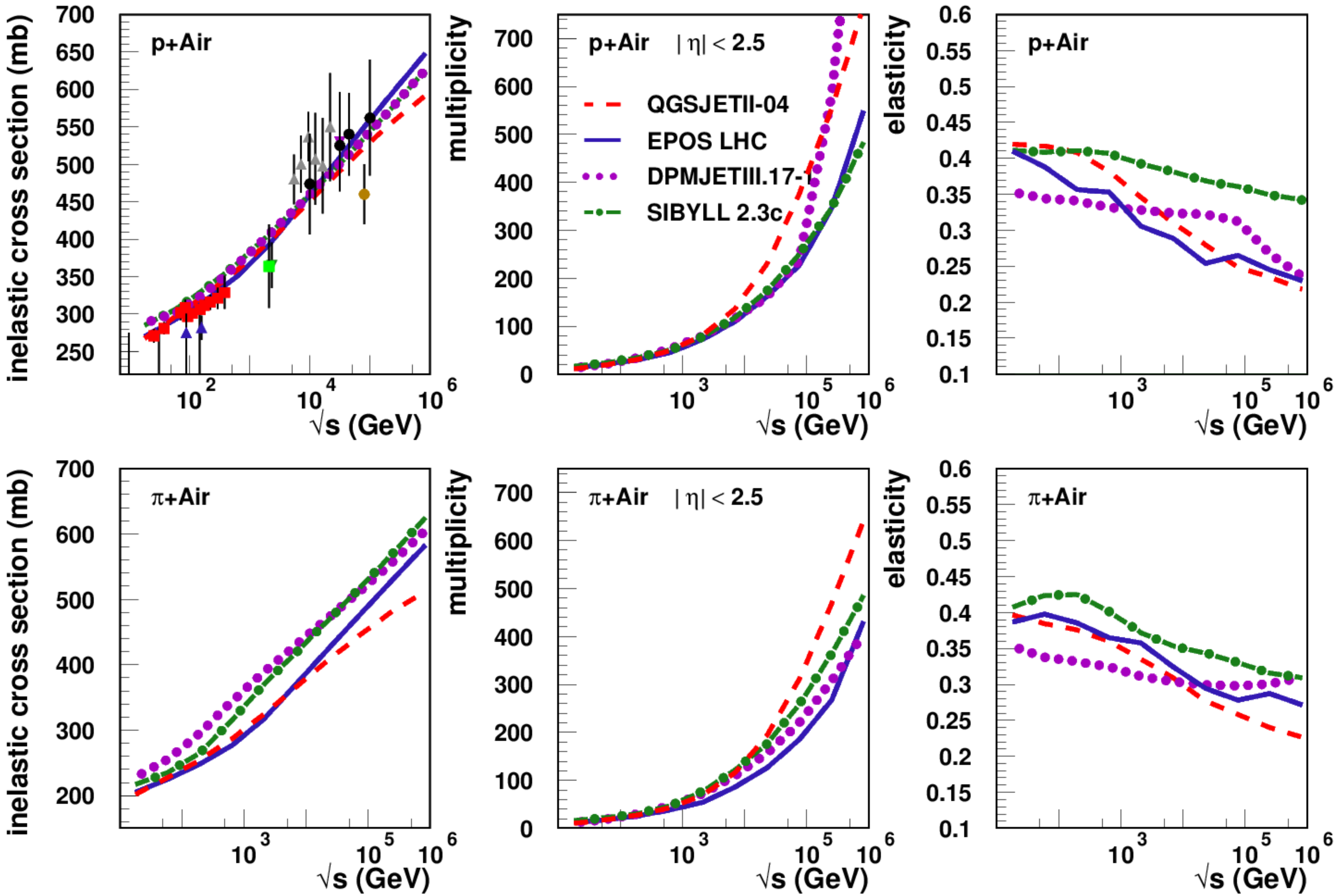



Roberto Aloiso UHECR (2015 PAO/TA working group)

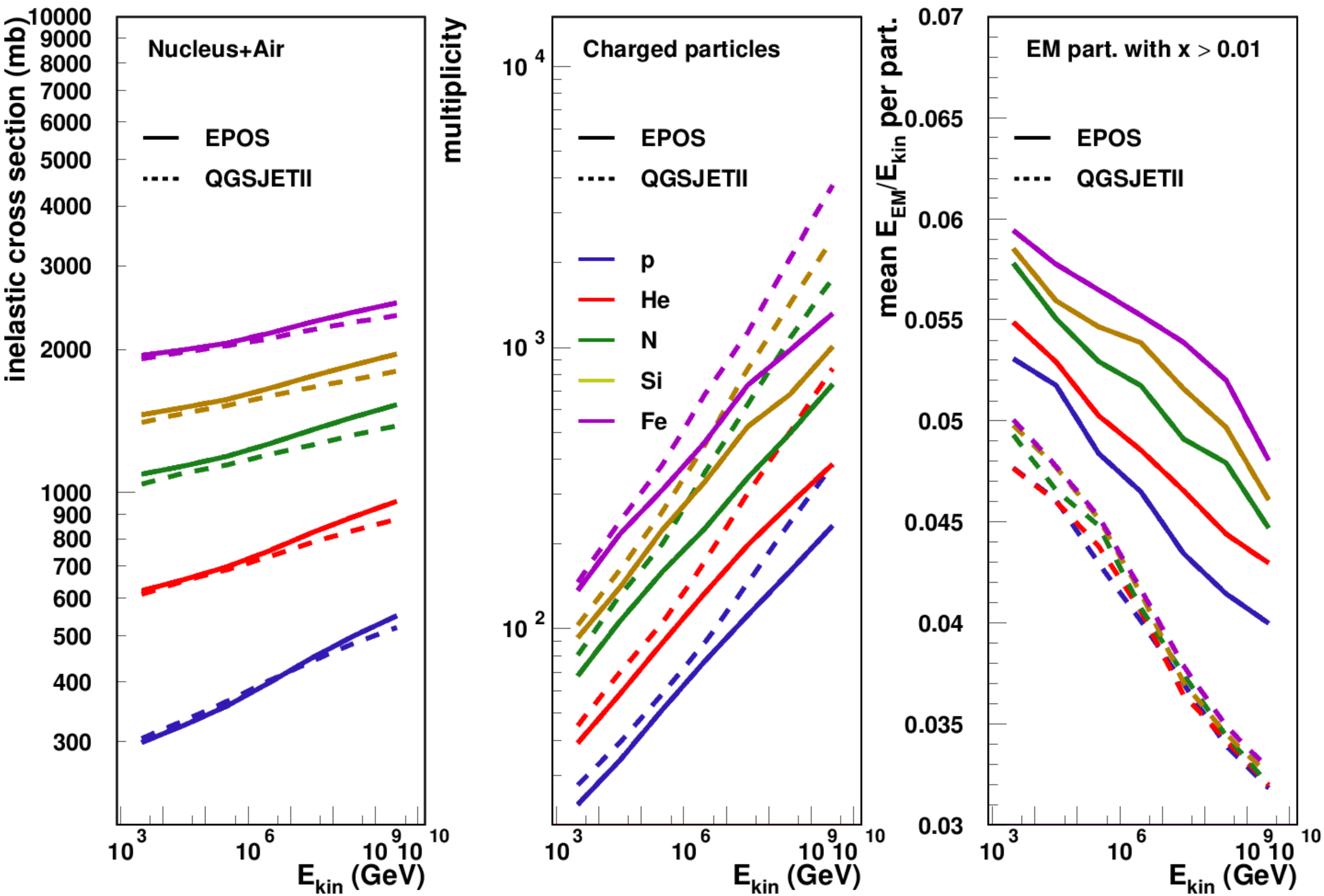
# Ultra-High Energy Hadronic Model Predictions p-Air



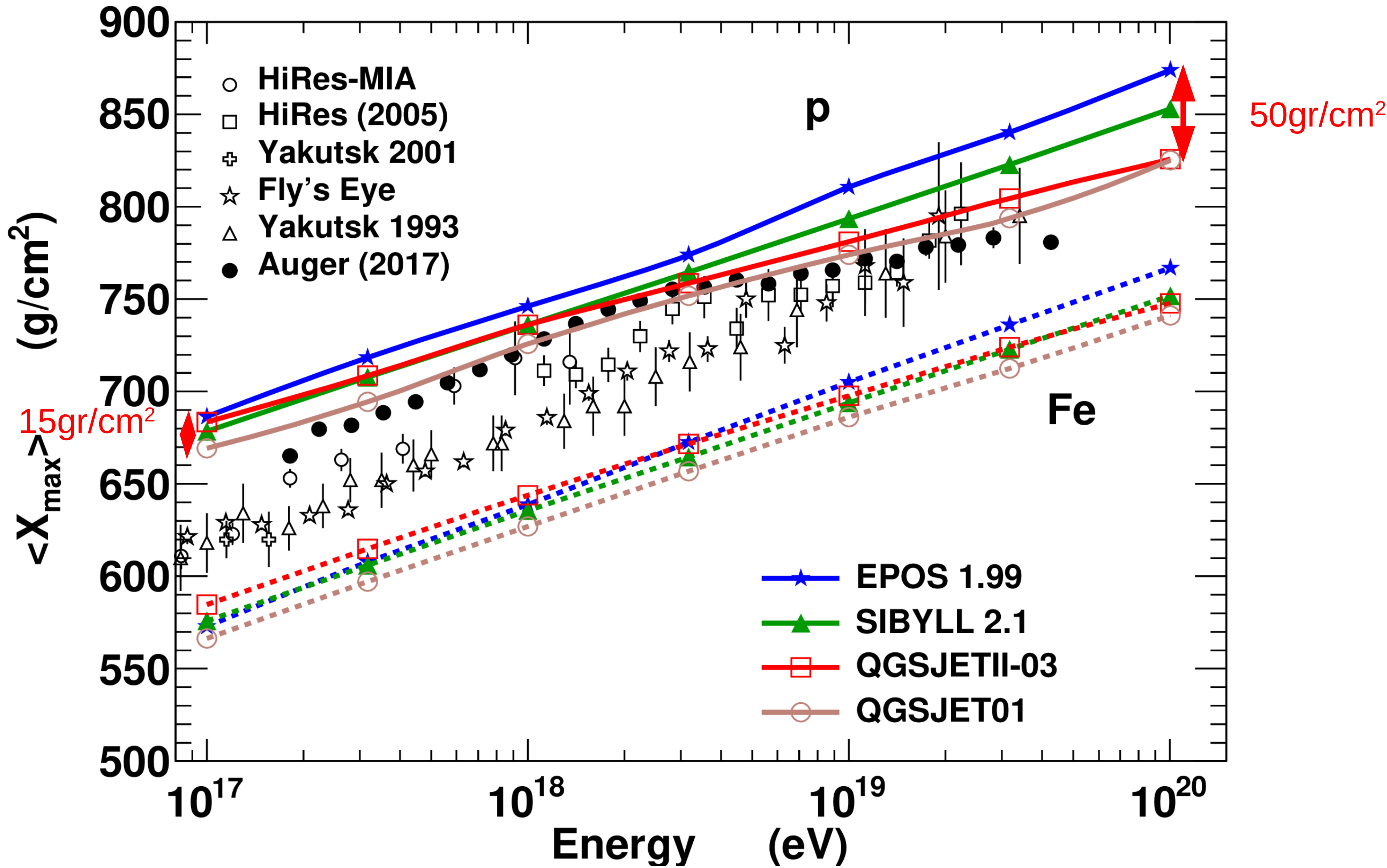
# Ultra-High Energy Hadronic Model Predictions π-Air



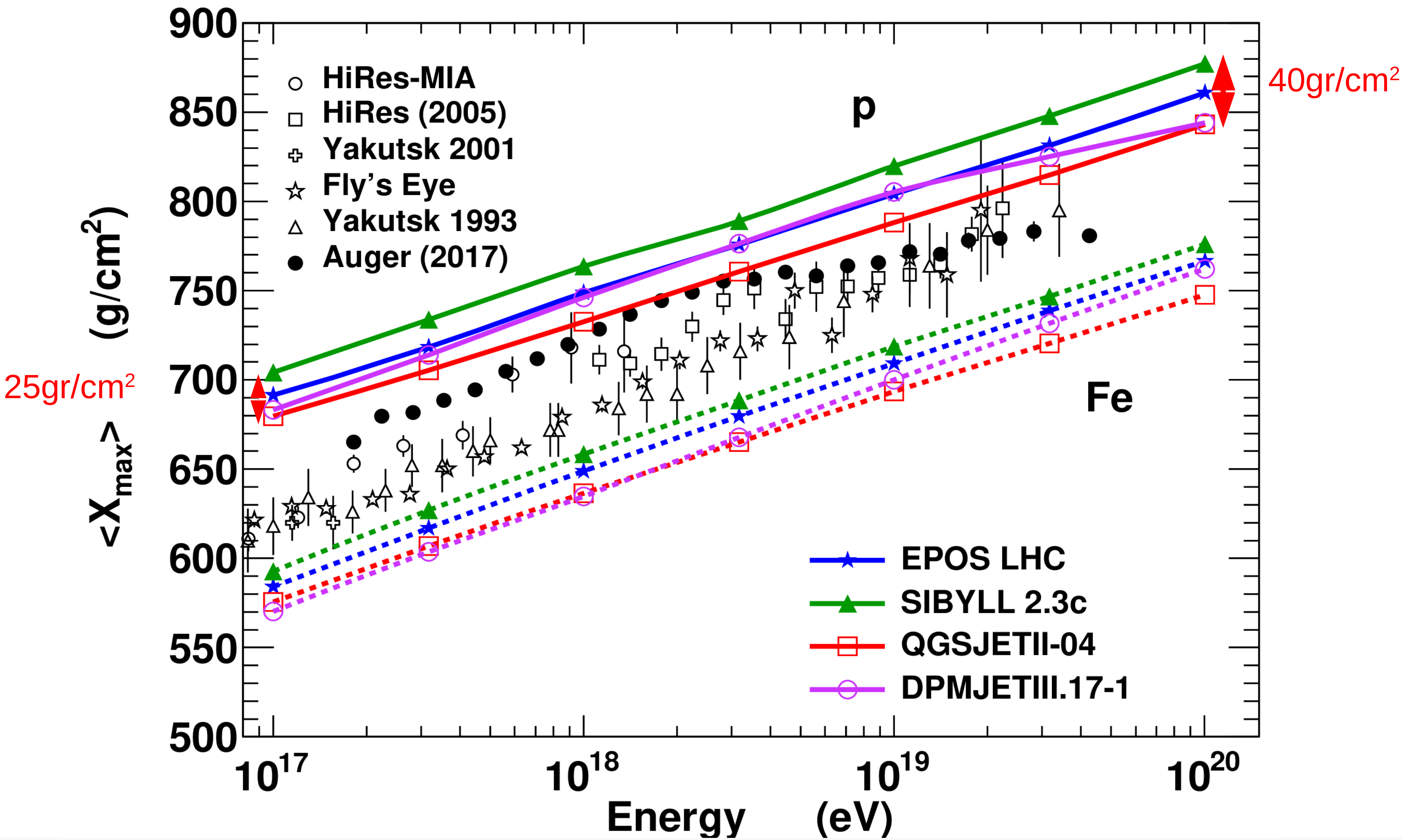
# Ultra-High Energy Hadronic Model Predictions A-Air



# EAS with Old CR Models : $X_{max}$

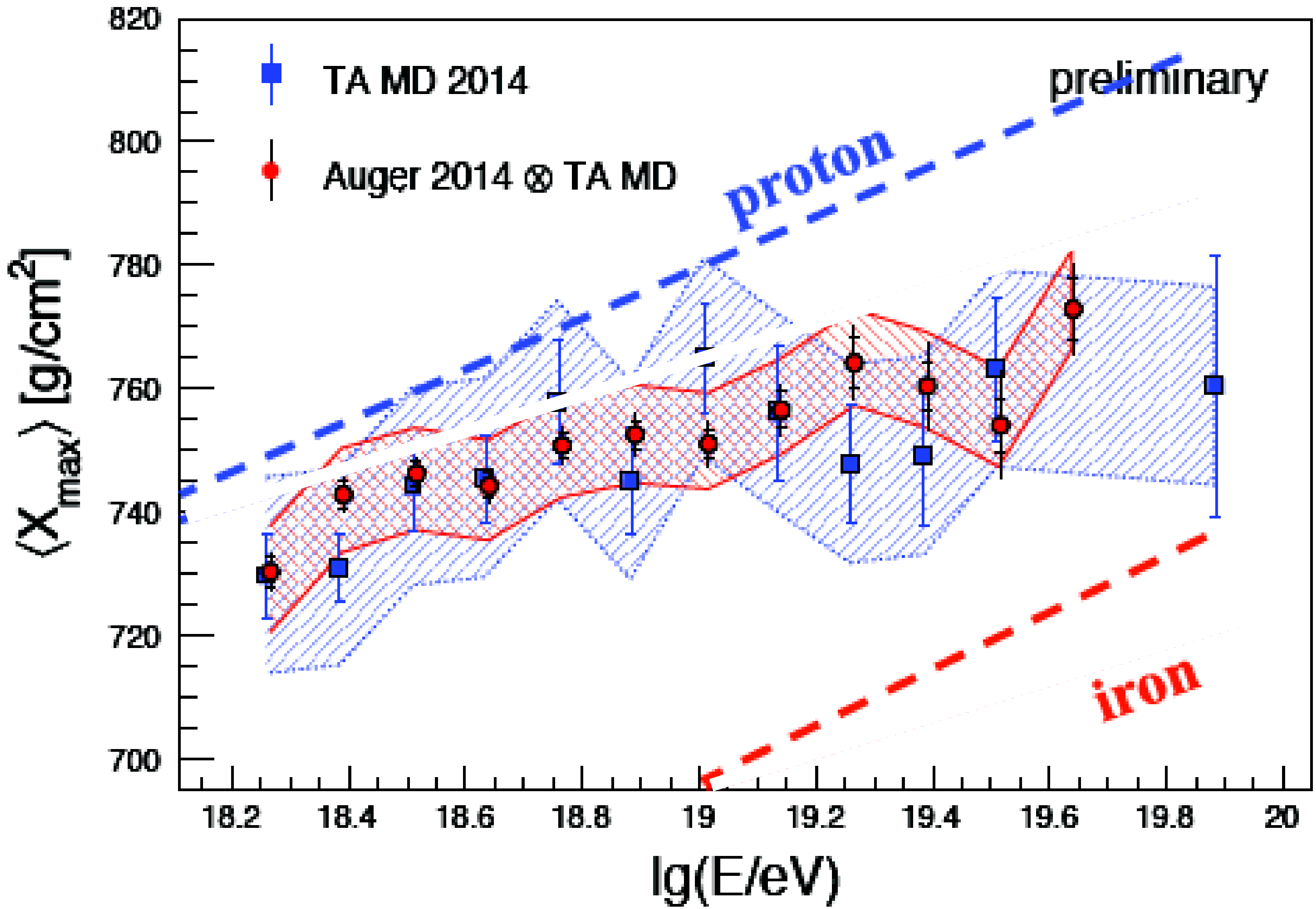


# EAS with Re-tuned CR Models : $X_{max}$

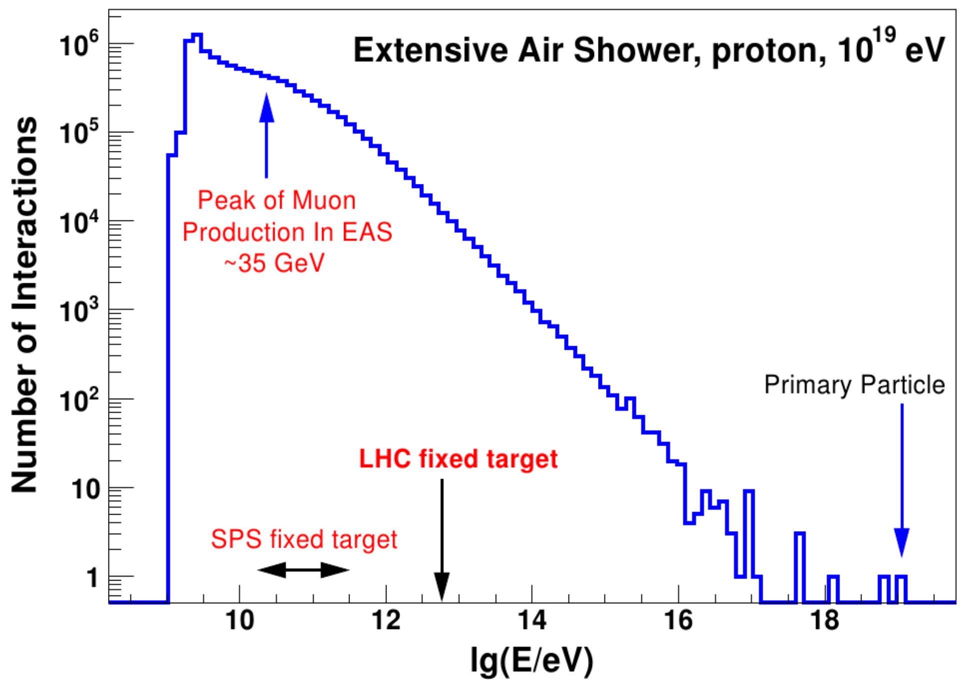


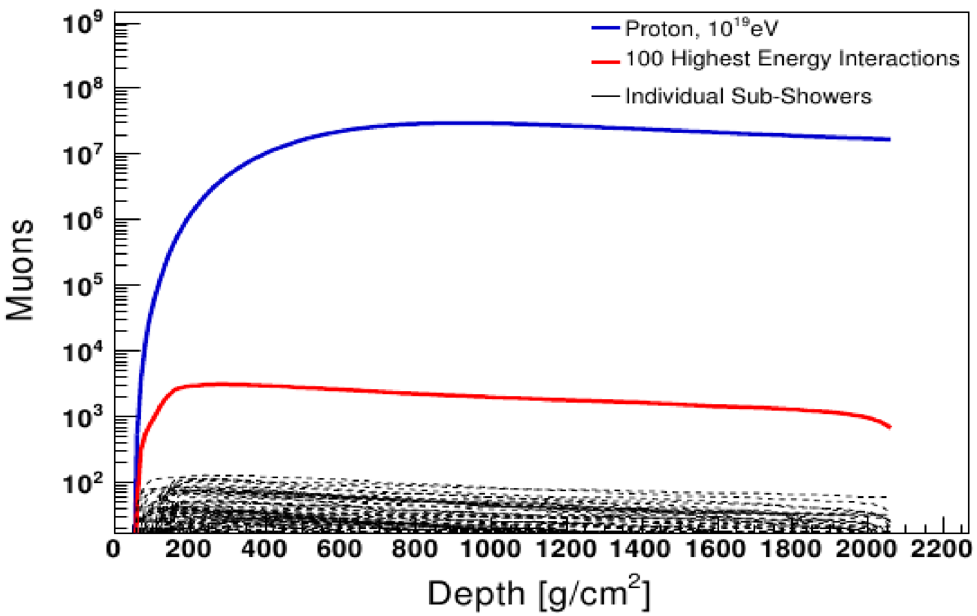
# Post-LHC Composition

**With post-LHC models there is no doubt about mixed composition**



# Surface Detectors (SD)

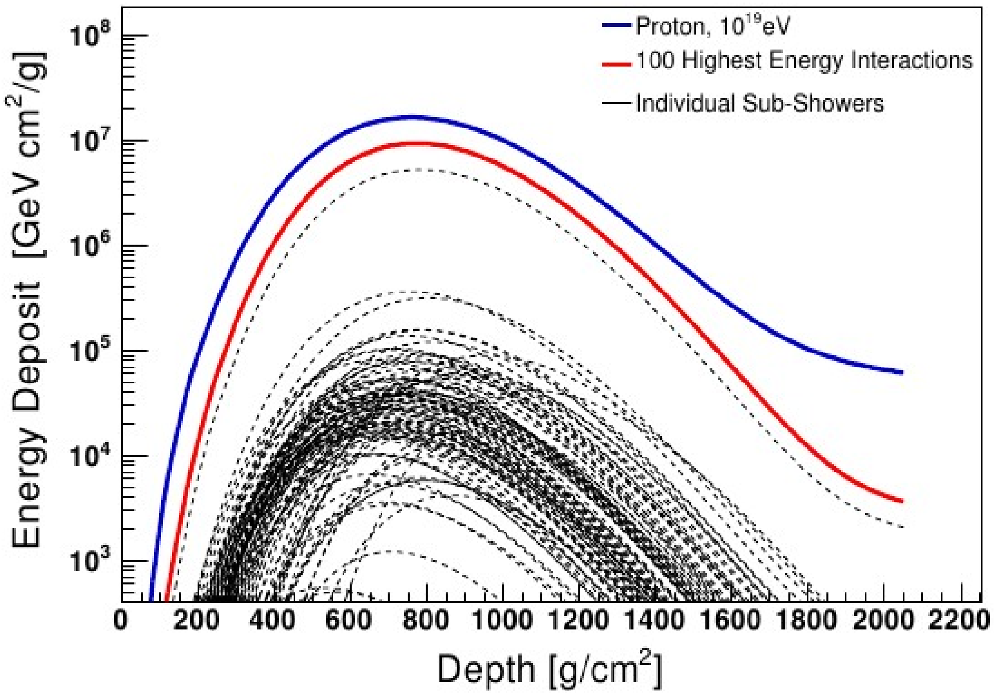


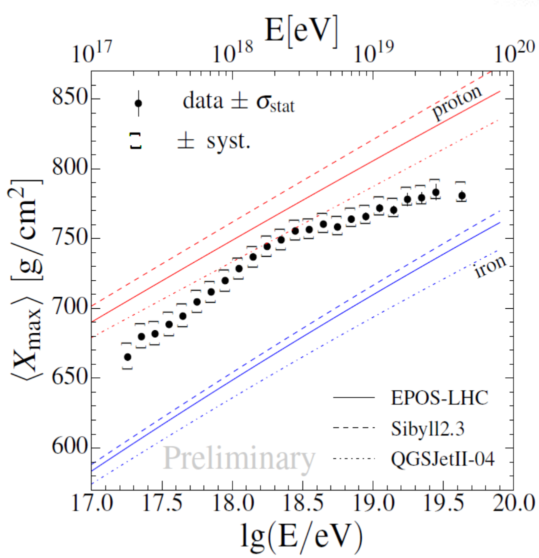



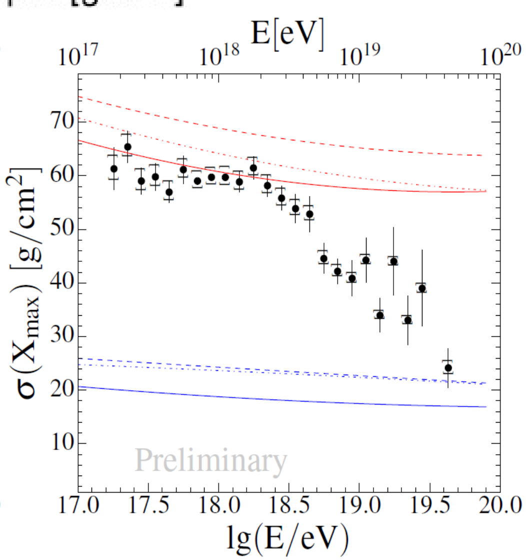

- **SD detector sensitive to**
  - electromagnetic particles (EM)
  - muons
- **Particles at ground produced after many generations of hadronic interactions**
  - most of EM particles from pure EM (universal) shower (depend on high (first) energy hadronic interactions)
  - muons produced at the end of hadronic cascade (depend on low energy hadronic interactions)
  - small fraction of EM (at large r) produced by last hadronic generation
- **EM and muons give different signal in Cherenkov detector.**
  - property of time traces

# Fluorescence Detector (FD)

From R. Ulrich (KIT)




- **Most direct measurement**
  - dominated by first interaction
- **Reference mass for other analysis**
  - <lnA> from <$X_{max}$> and RMS
- **Possibility to use the tail of $X_{max}$ distribution to measure p-Air inelastic cross-section.**
  - require no contamination from photon induced showers (independent check)
  - correction to “invisible” cross-section using hadronic models
  - conversion to p-p cross-section using Glauber model.