When Heavy Ions Meet Cosmic Rays: How the QGP Could Solve the Muon Puzzle ?

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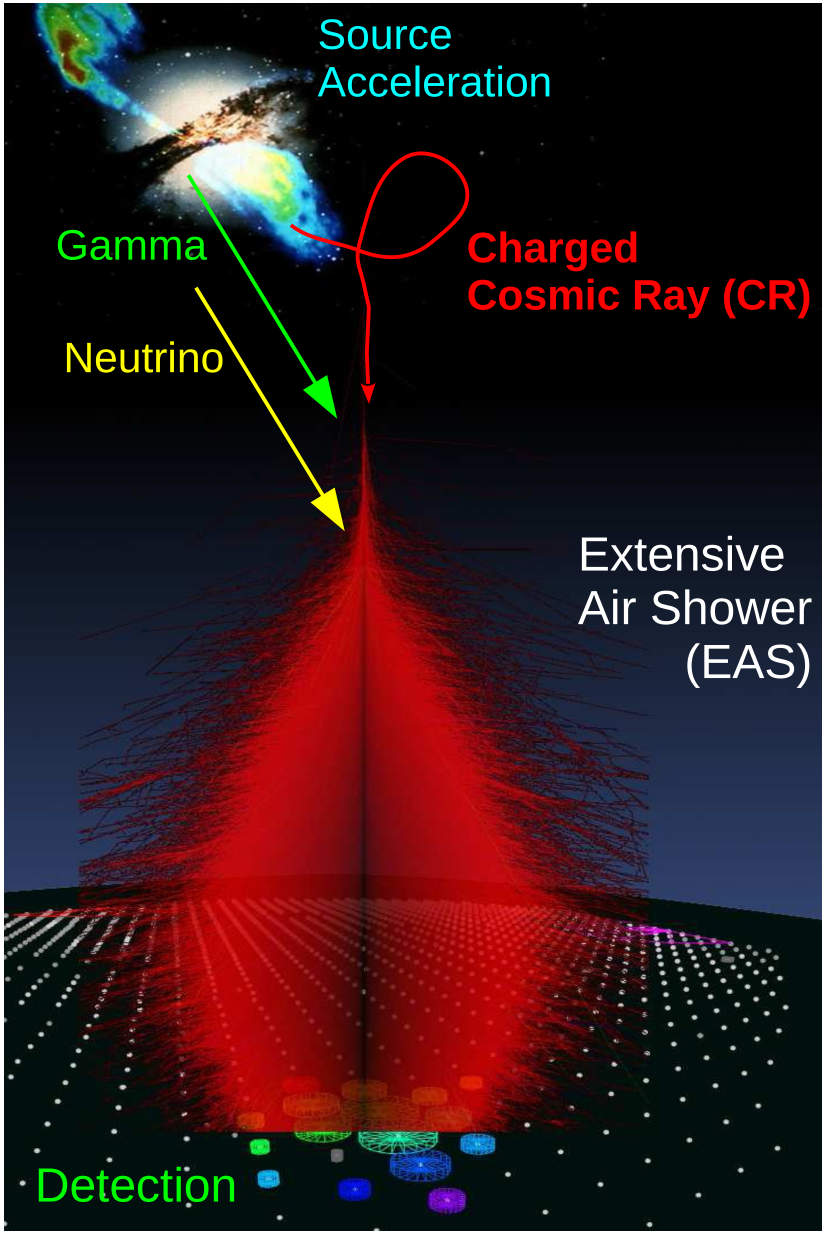
Outline

- **Introduction**
- **Extensive Air Showers (EAS)**
  - ➜ Muon deficit in simulations
- **Hadronizations**
  - ➜ Simple vs complex environment
- **Quark Gluon Plasma (QGP) and EAS**
  - ➜ Qualitative tests
  - ➜ First tests in real MC

Recent LHC data combined with the result of air shower experiment meta-analysis provide a possible explanation of the muon deficit in air shower simulations : QGP-like hadronization could be more common than thought until now.

Astroparticles

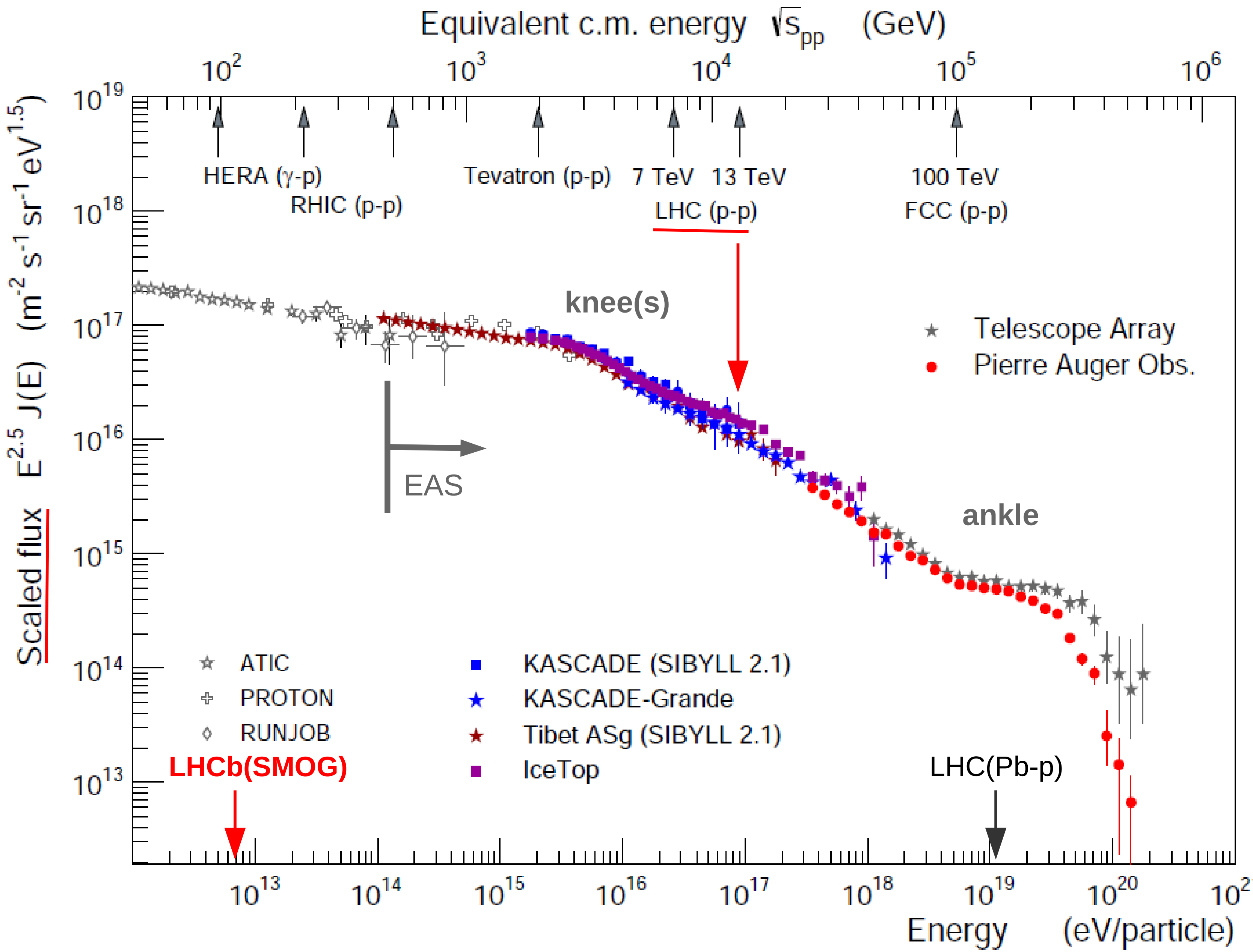


From R. Ulrich (KIT)

- **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.

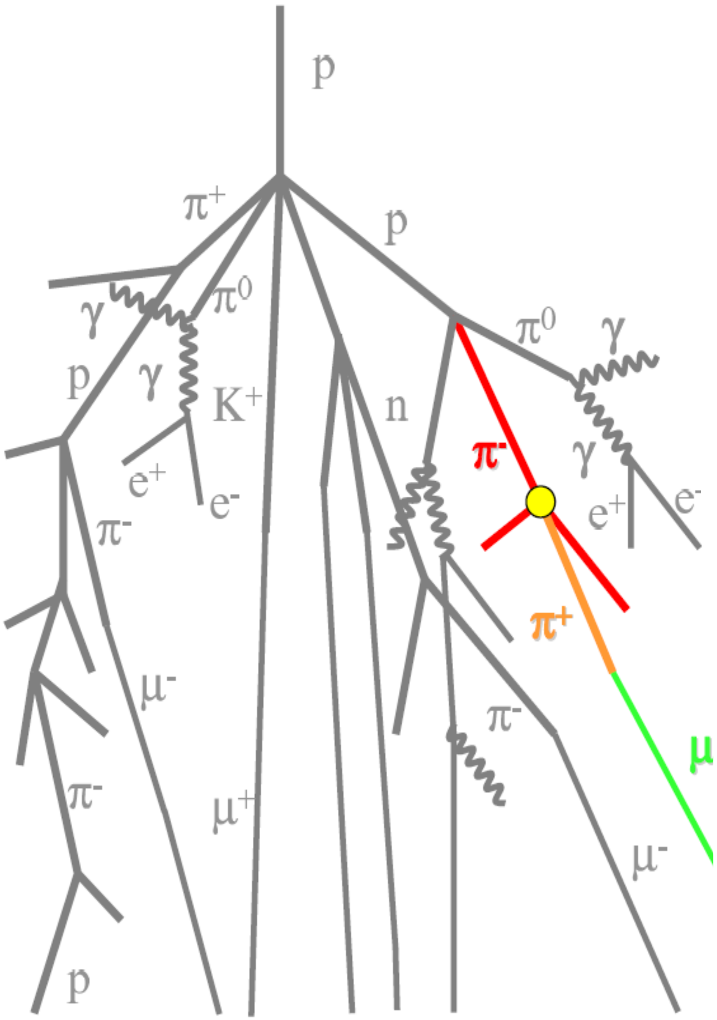
mass measurements should be consistent and lying between proton and iron simulated showers if physics is correct

Energy Spectrum

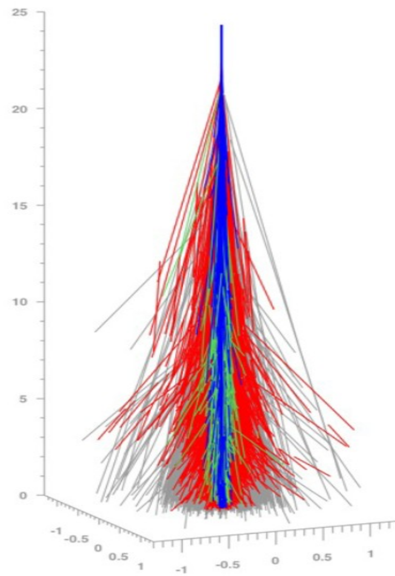


R. Engel (KIT)

Extensive Air Shower



From R. Ulrich (KIT)



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

hadronic physics

initial γ from π^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

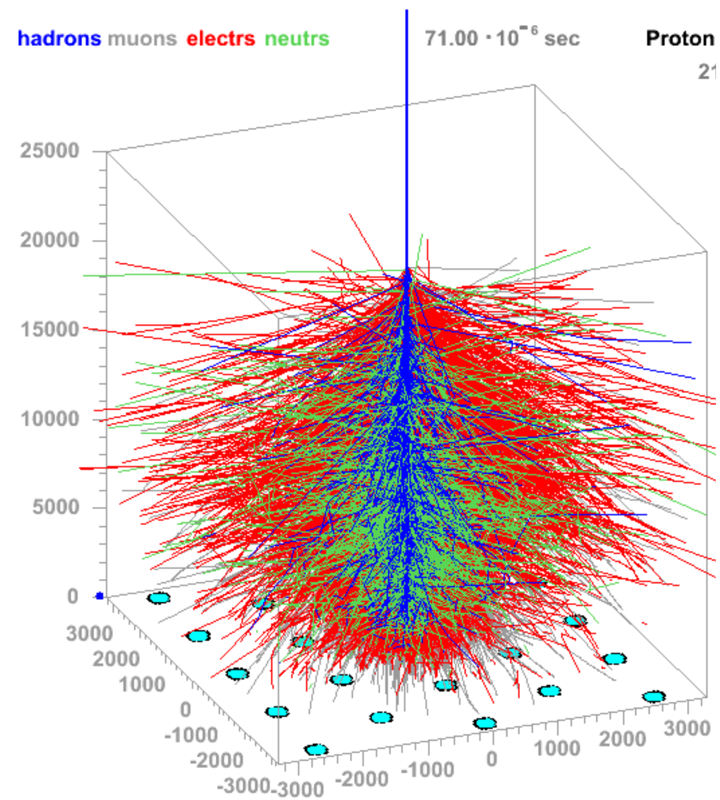
Number of particles at maximum

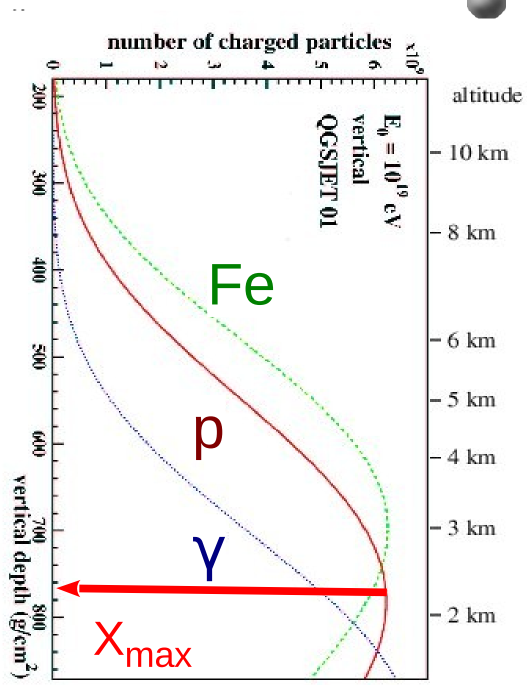
- 99,88% of electromagnetic (EM) particles
- 0.1% of muons
- 0.02% hadrons

Energy

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

Extensive Air Shower Observables



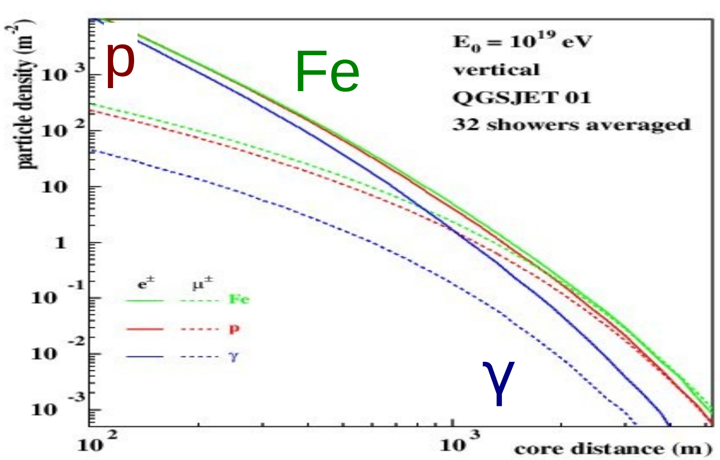


- **Longitudinal Development**
  - number of particles vs depth

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

  - Larger number of particles at X_{max}

    For many showers
    - mean : $<X_{max}>$
    - 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**

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

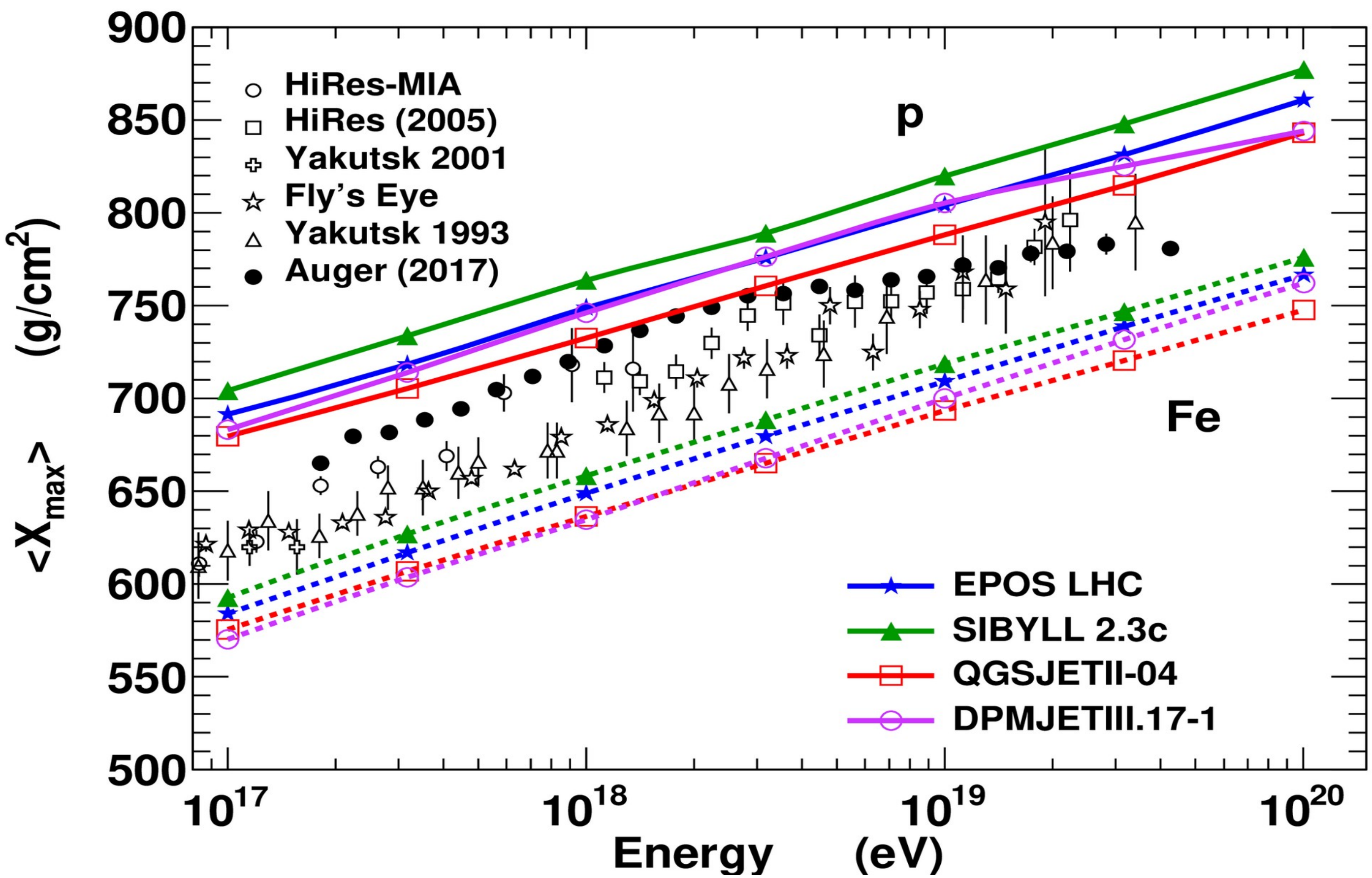
- **Hadronic models are the key ingredient !**
  - follow the standard model (QCD)
    - but mostly non-perturbative regime (phenomenology needed)
  - main source of uncertainties

- **Which model for CR ?** **(alphabetical order)**
  - **DPMJETIII.17-1** by S. Roesler, A. Fedynitch, R. Engel and J. Ranft
  - **EPOS (1.99/LHC/3/4)** (from VENUS/NEXUS before) by T. Pierog 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, R.S. Fletcher, T.K. Gaisser, P. Lipari, F. Riehn, T. Stanev

X_{max}

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

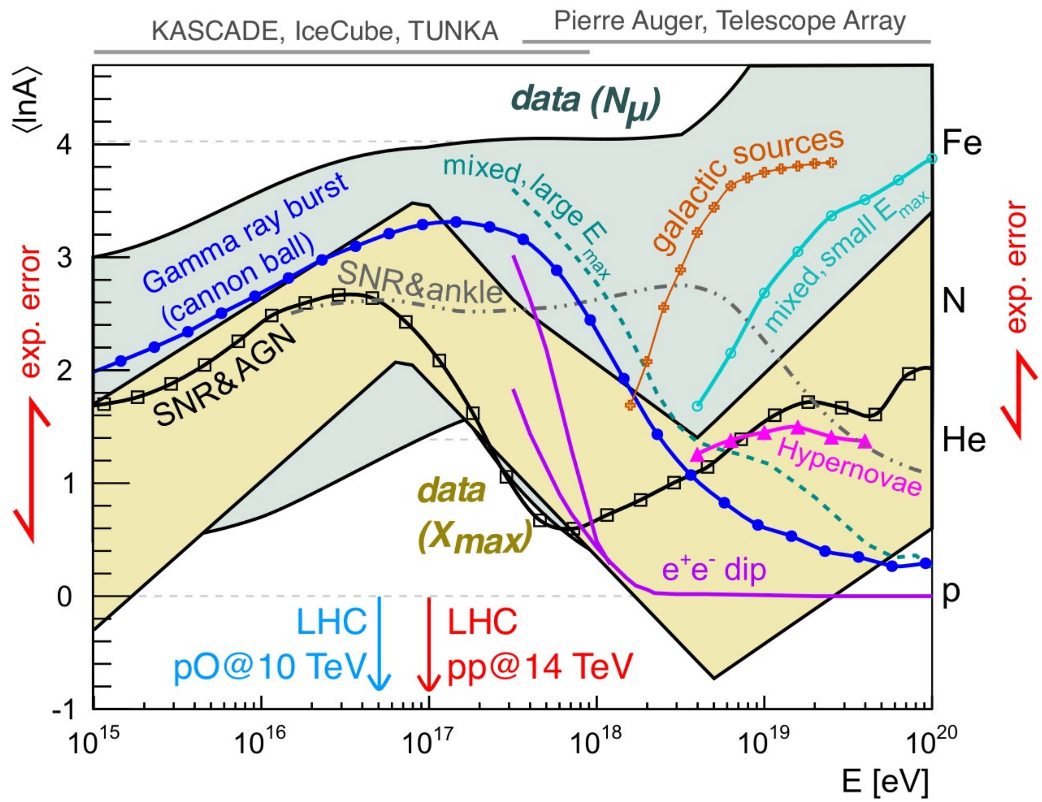
- minimum given by QGSJETII-04 (high multiplicity, low elasticity)
- maximum given by Sibyll 2.3c (low multiplicity, high elasticity)
- anything below or above won't be compatible with LHC data



UHECR Composition

With muons current CR data are impossible to interpret

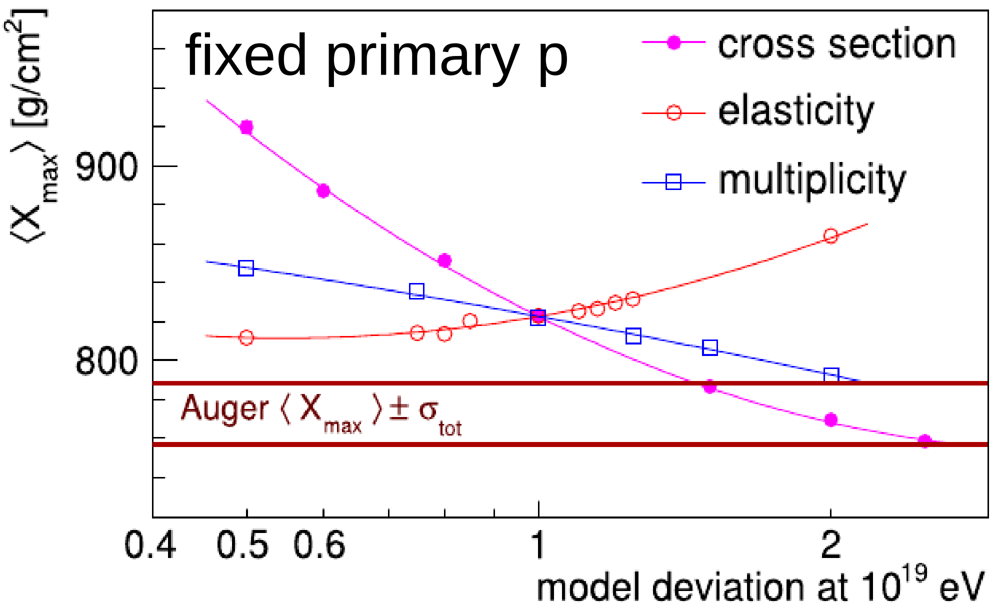
- ➡ Very large uncertainties in model predictions
- ➡ Mass from muon data incompatible with mass from X_{max}

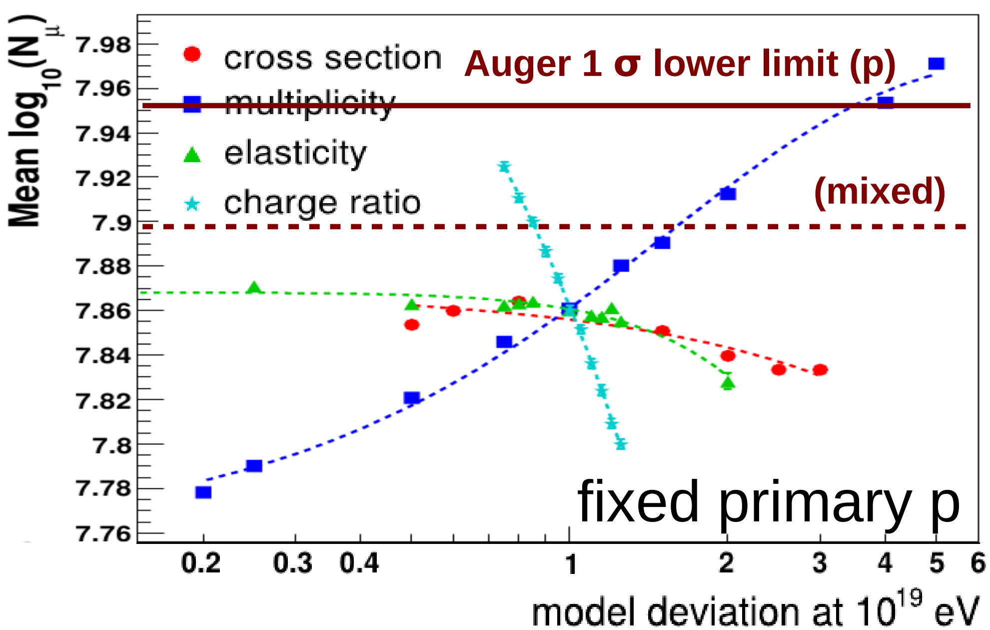


Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

H. Dembinski UHECR 2018 (WHISP working group)

Sensitivity to Hadronic Interactions





From R. Ulrich (KIT)

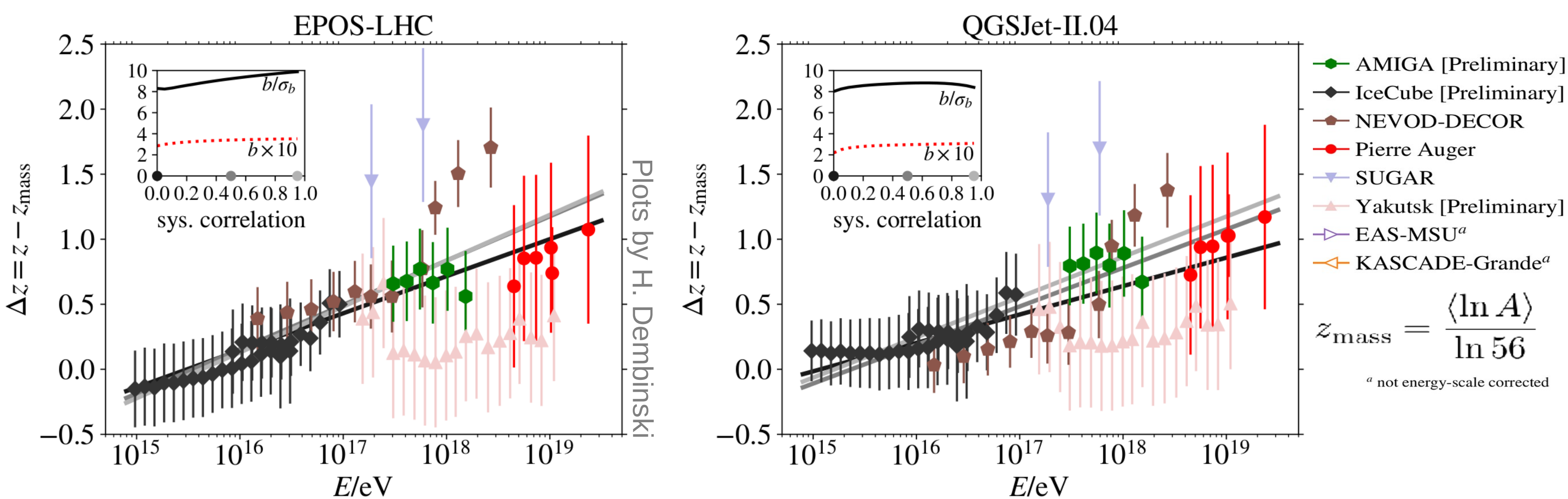
- **Air shower development dominated by few parameters**
  - mass and energy of primary CR
  - cross-sections (p-Air and (π-K)-Air)
  - (in)elasticity
  - multiplicity
  - charge ratio and baryon production
- **Change of primary = change of hadronic interaction parameters**
  - cross-section, elasticity,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

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

WHISP Meta-Analysis

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

- **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)



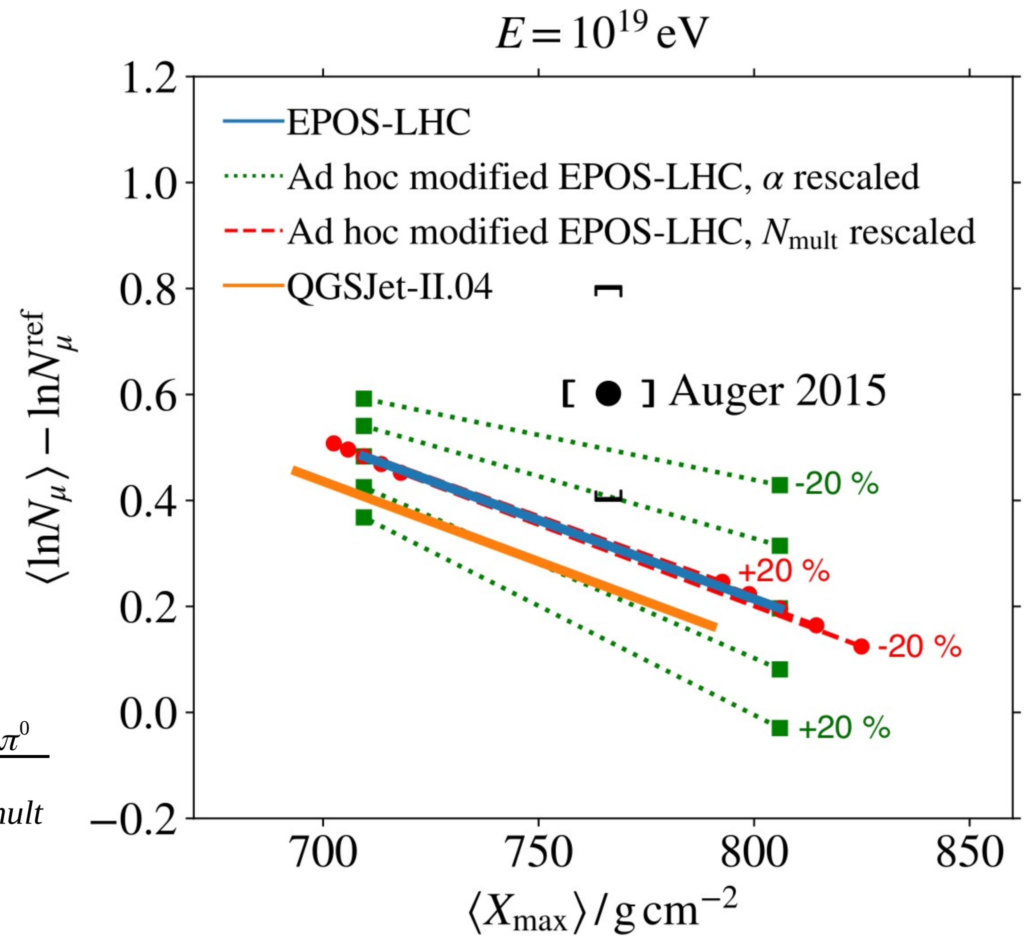
- **Different energy or mass scale cannot change the slope**
  - Different property of hadronic interactions at least above 10^{16} eV

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

Possible Particle Physics Explanations

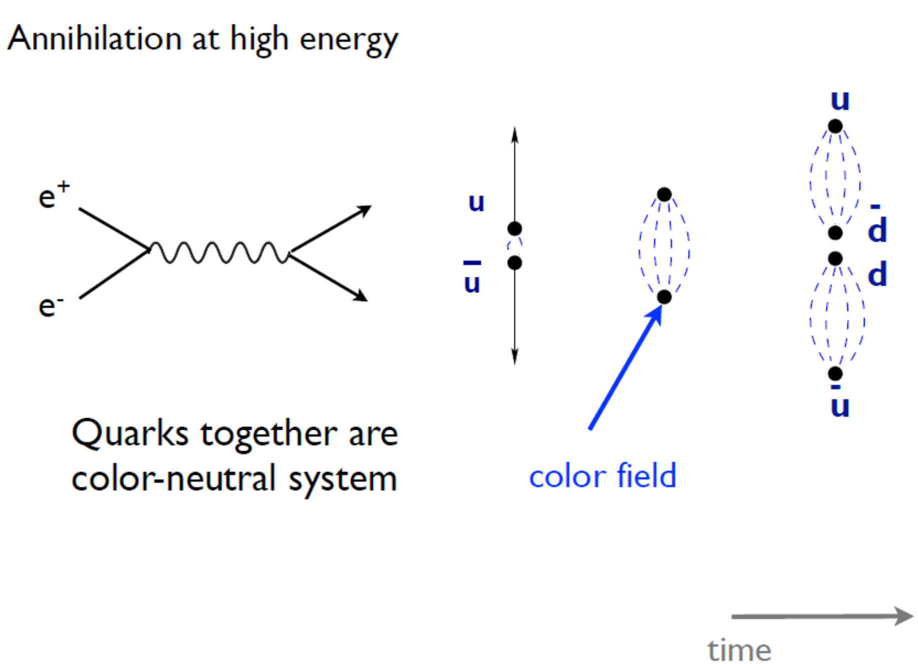
A 30% change in particle charge ratio ($\alpha = \frac{N_{\pi^0}}{N_{mult}}$) is huge !

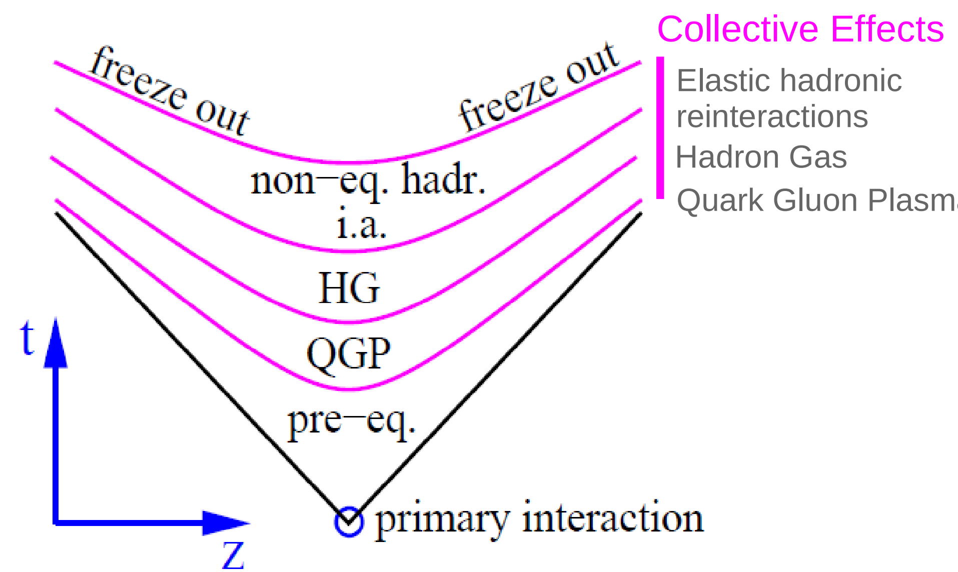
- Possibility to increase N_{mult} limited by X_{max}
- New Physics ?
  - Chiral symmetry restoration (Farrar et al.) ?
  - Strange fireball (Anchordoqui et al., Julien Manshanden) ?
  - String Fusion (Alvarez-Muniz et al.) ?
    - Problem : no strong effect observed at LHC (~10^{17} eV)
- Unexpected 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 (enhanced strangeness and baryon production reduces relative π^0 fraction. Baur et al., arXiv:1902.09265) !
  - α depends on the hadronization scheme
    - How is it done in hadronic interaction models ?

Hadronization Models

2 models well established for 2 extreme cases

➡ String Fragmentation vs Collective hadronization (statistical models)





In dilute systems...

In dense systems...

➡ What to do in between ? For proton-proton, hadron-Air, ...

Hadronization in Simulations

- **Historically (theoretical/practical reasons) string fragmentation used in high energy models (Pythia, Sibyll, QGSJET, …) for proton-proton.**

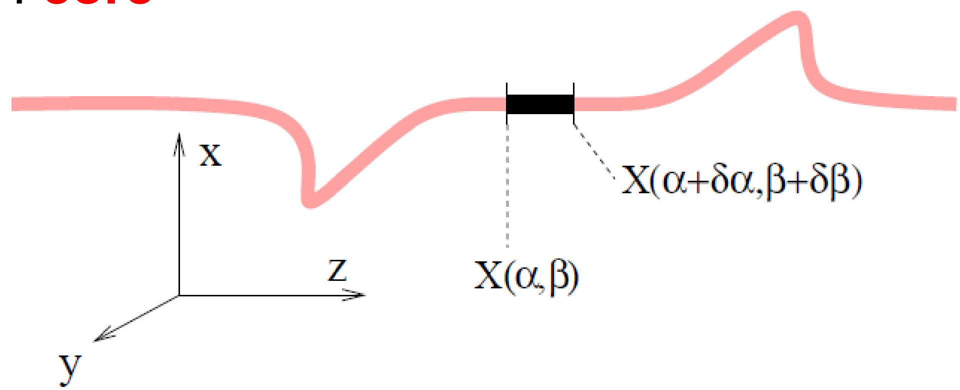
  - ➔ Light system are not “dense”
  - ➔ Works relatively well at SPS (low energy)
  - ➔ But problems already at RHIC, clearly at Fermilab, and serious at LHC :
    - Modification of string fragmentation needed to account for data
    - Various phenomenological approaches :
      - ➔ Color reconnection
      - ➔ String junction
      - ➔ String percolation, …
    - Number of parameters increased with the quality of data …

- **Statistical model only used for heavy ion (HI) in combination with hydrodynamical evolution of the dense system : QGP hadronization**
  - ➔ Account for flow effects, strangeness enhancement, particle correlations...

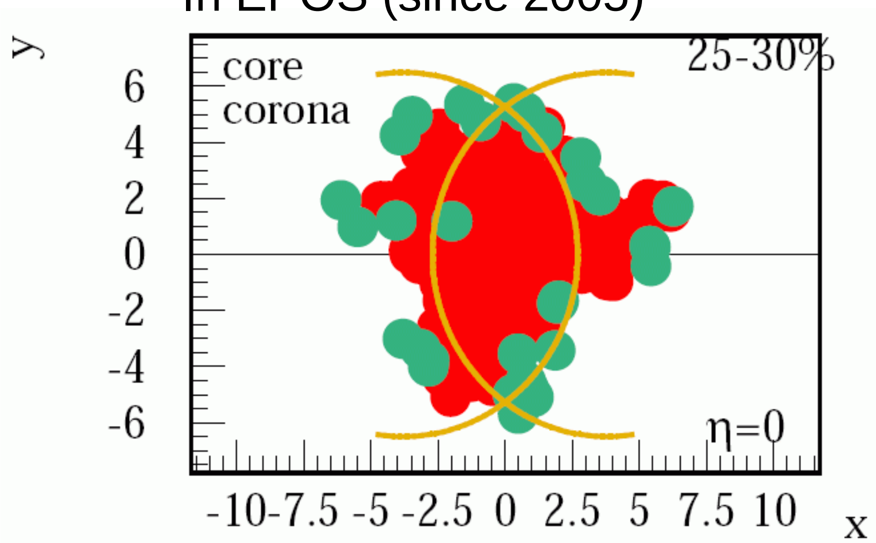
A 3rd way : the core-corona approach

Consider the local density to hadronize with strings OR with QGP:

- First use string fragmentation but modify the usual procedure, since the density of strings will be so high that they cannot possibly decay independently : **core**



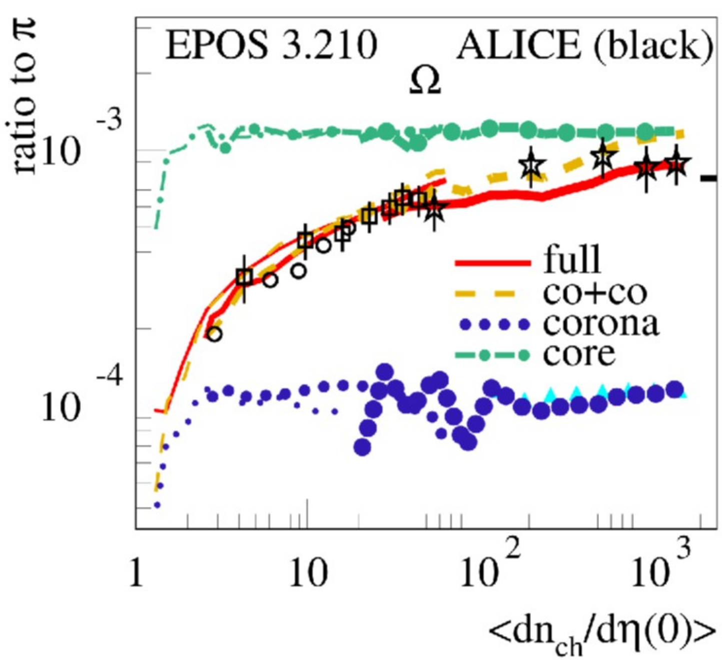
In EPOS (since 2005)

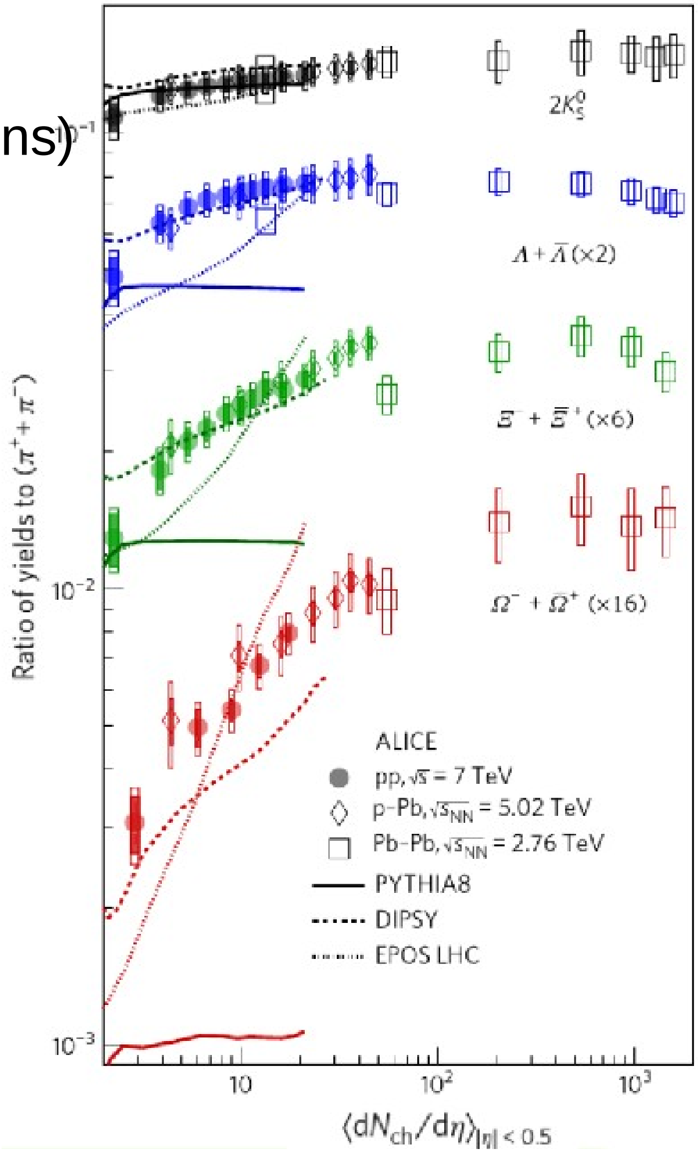


- Each string cut into a sequence of string segments, corresponding to widths δα and δβ in the string parameter space
- If energy density from segments high enough
  - segments fused into core
    - flow from hydro-evolution
    - statistical hadronization
- If low density (corona)
  - segments remain hadrons

Core in p-p (late LHC data)

- **Mixing of core and corona hadronization needed to achieve detailed description of p-p data**
  - Evolution of particle ratios from pp to PbPb
  - Particle correlations (ridge, Bose Einstein correlations)
  - Pt evolution, …
- **Both hadronizations are universal but the fraction of each change with particle density**





Core-Corona appoach and CR

To test if a QGP like hadronization can account for the missing muon production in EAS simulations a core-corona approach can be artificially apply to any model

- Particle ratios from statistical model are known (tuned to PbPb) and fixed : core
- Initial particle ratios given by individual hadronic interaction models : corona
- Using CONEX, EAS can be simulated mixing corona hadronization with an arbitrary fraction ω_{core} of core hadronization: $N_i = \omega_{\rm core}\, N_i^{\rm core} + (1-\omega_{\rm core})\, N_i^{\rm corona}$

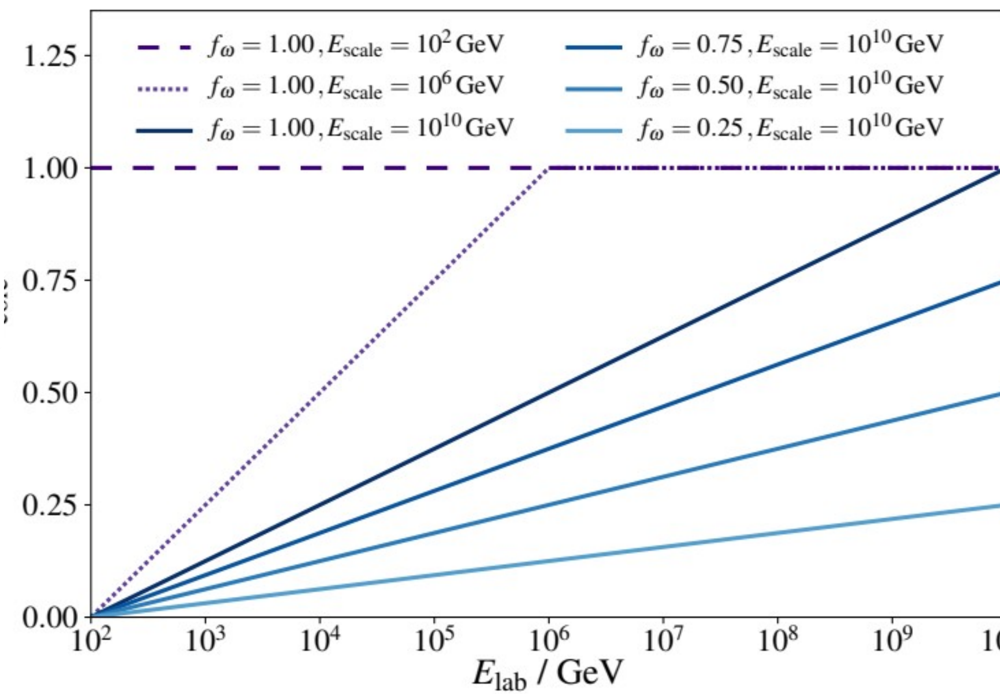
$$\omega_{\rm core}(E_{\rm lab}) = f_\omega\, \underbrace{F(E_{\rm lab}; E_{\rm th}, E_{\rm scale})}$$

$$\frac{\log_{10}(E_{\rm lab}/E_{\rm th})}{\log_{10}(E_{\rm scale}/E_{\rm th})} \text{ for } E_{\rm lab} > E_{\rm th}$$

$$E_{\rm th} = 100\,{\rm GeV}$$

Different scenarii can be studied playing with f_ω and E_{scale}.

Note : the leading particle is NOT modified (projectile remnant)



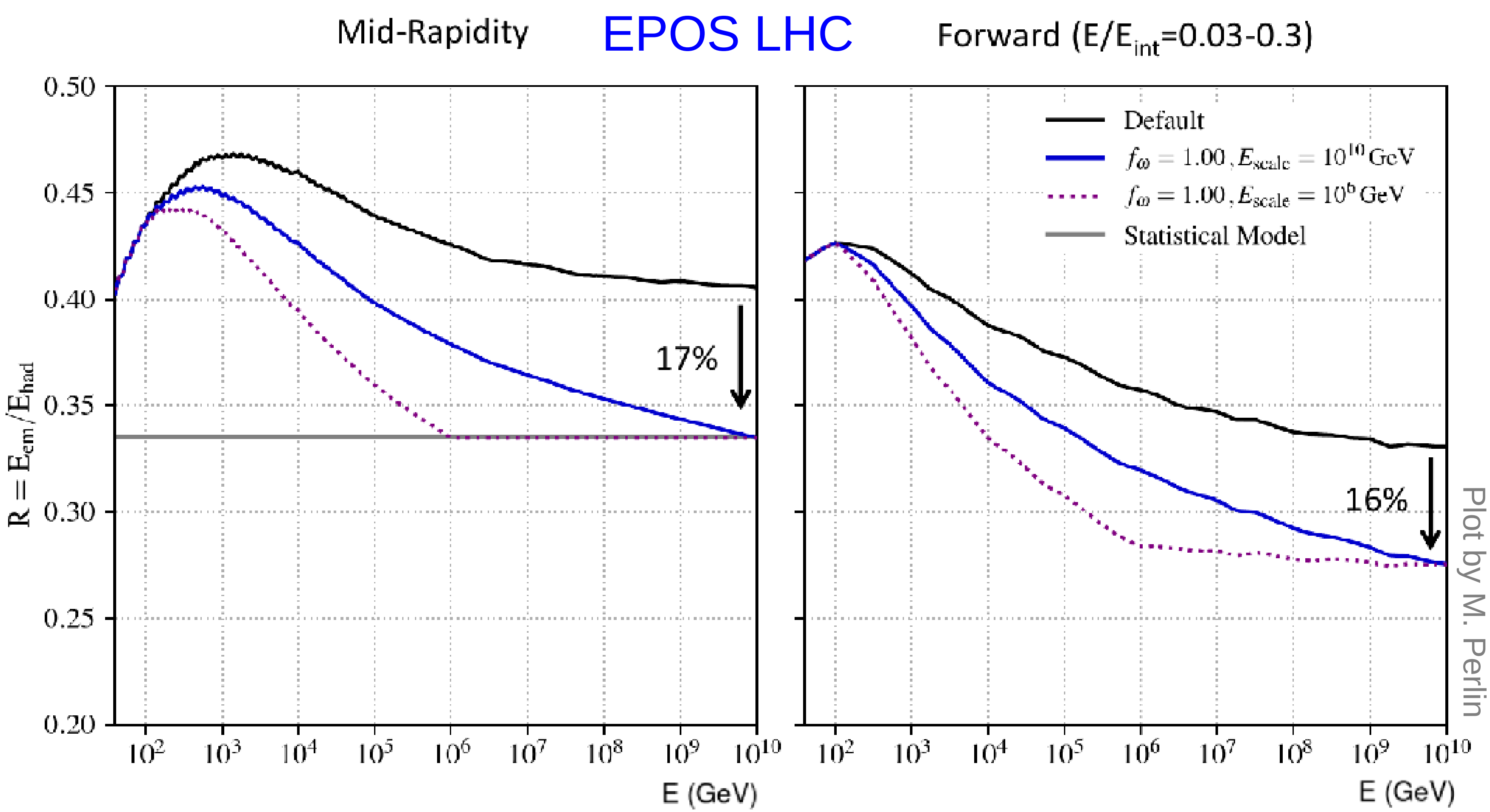
Plot by M. Perlin

Evolution of hadronization from core to corona

The relative fraction of π^0 depends on the hadronization scheme

- Change of ω_{core} with energy change $\alpha = \frac{N_{\pi^0}}{N_{mult}}$ or $R(\eta) = \frac{\langle dE_{em}/d\eta \rangle}{\langle dE_{had}/d\eta \rangle}$

  which define the muon production in air showers.



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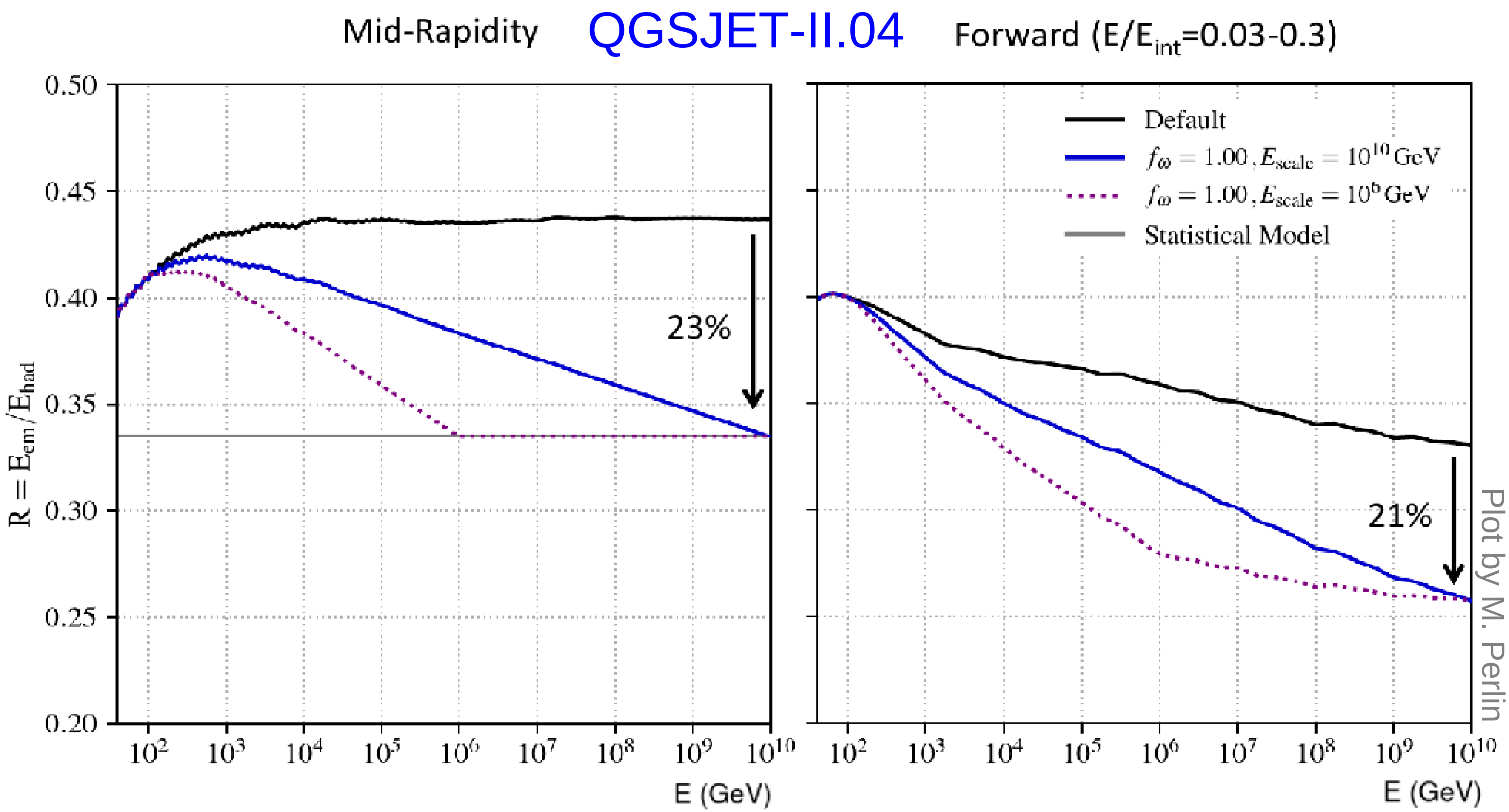

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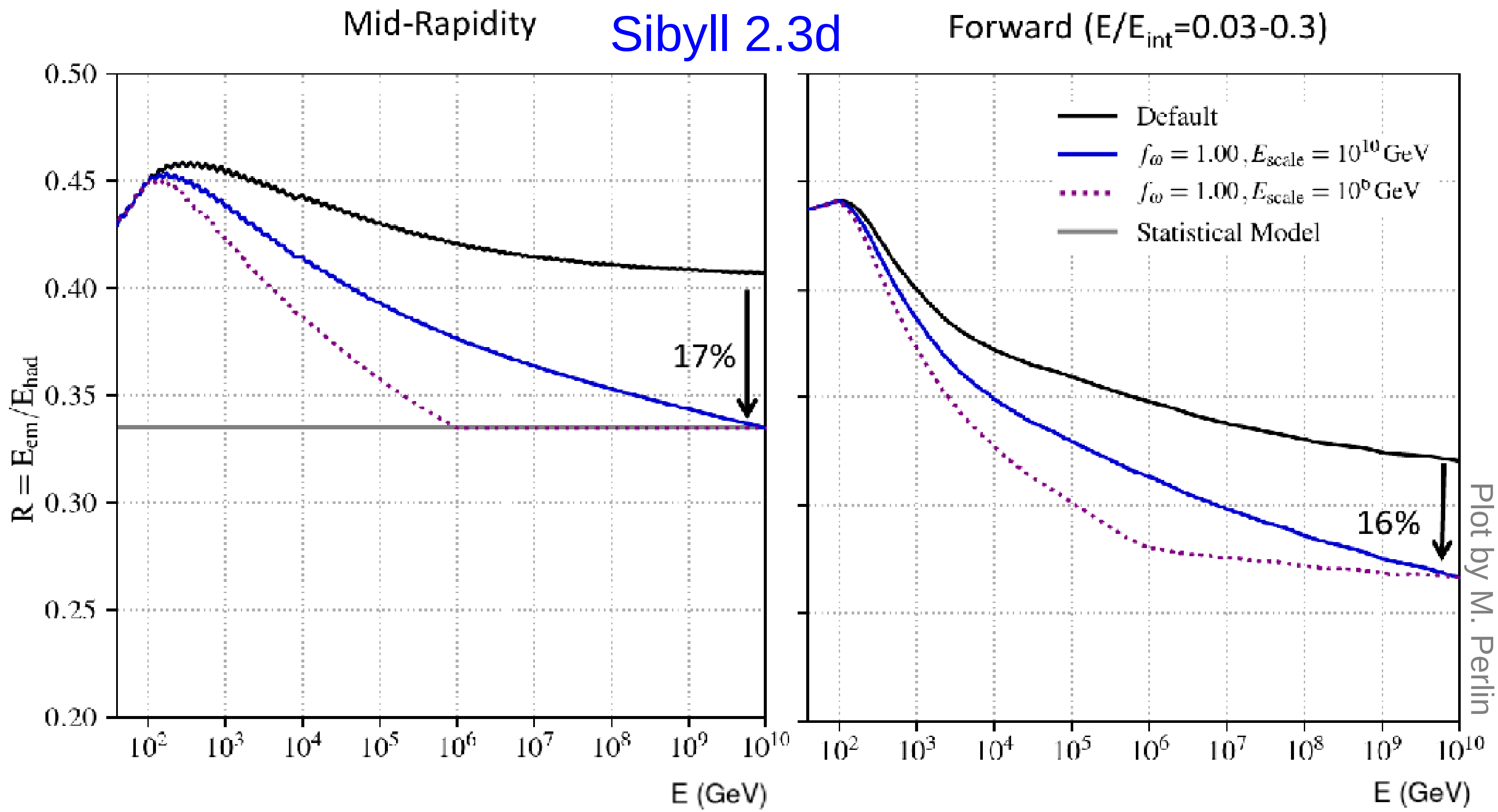
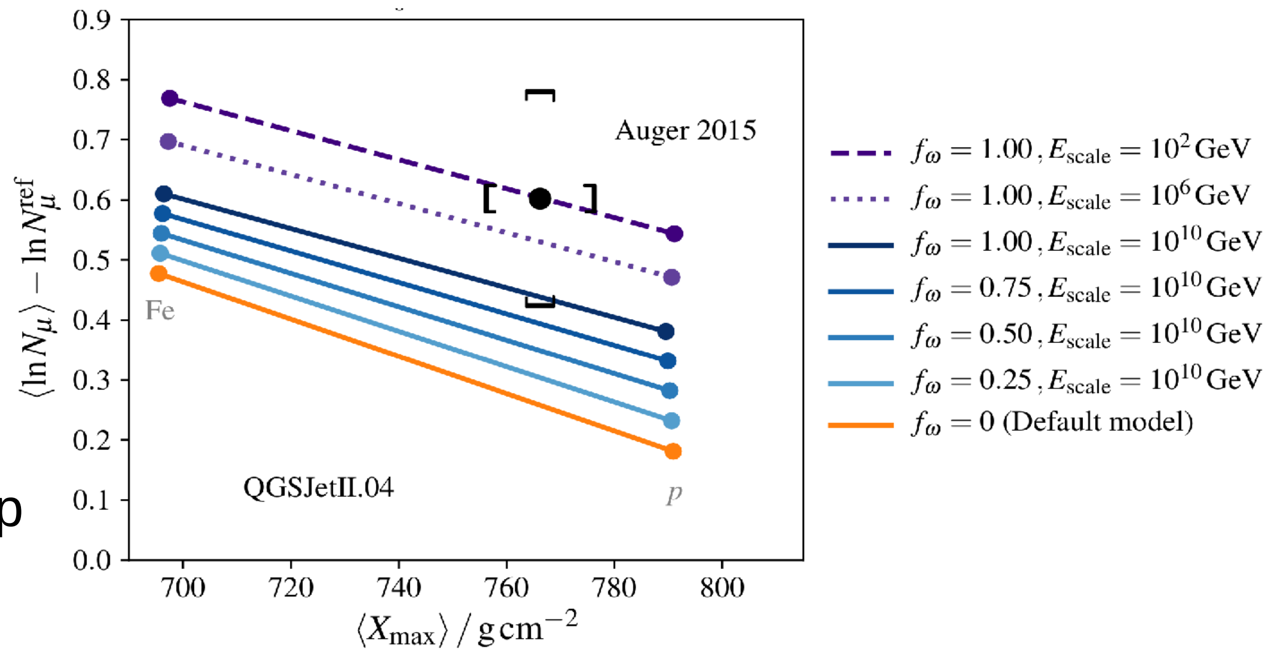
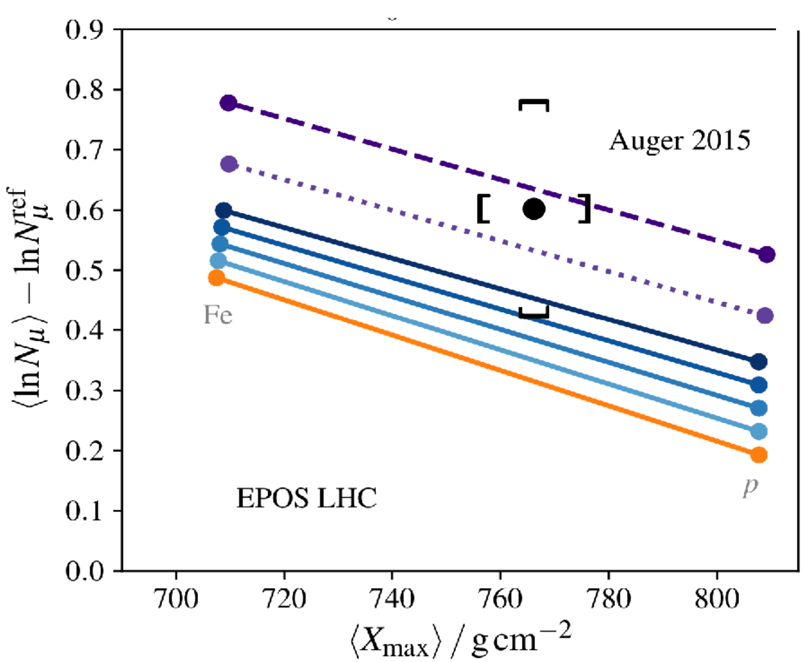


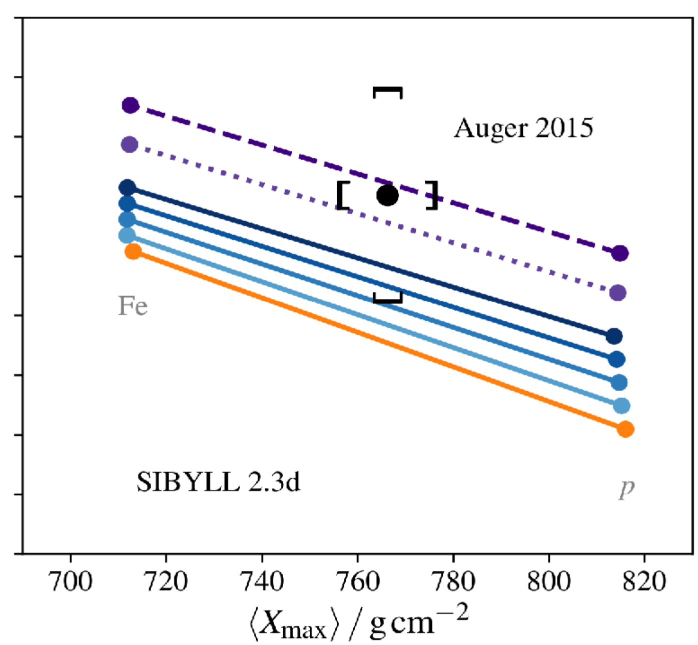
Results for X_{max}-N_{mu} correlation

Significant effect observed

- No change in X_{max}
- Needs a large part of core hadronization at maximum energy to reach Auger point
- Sibyll with higher mass (deep X_{max}) need less

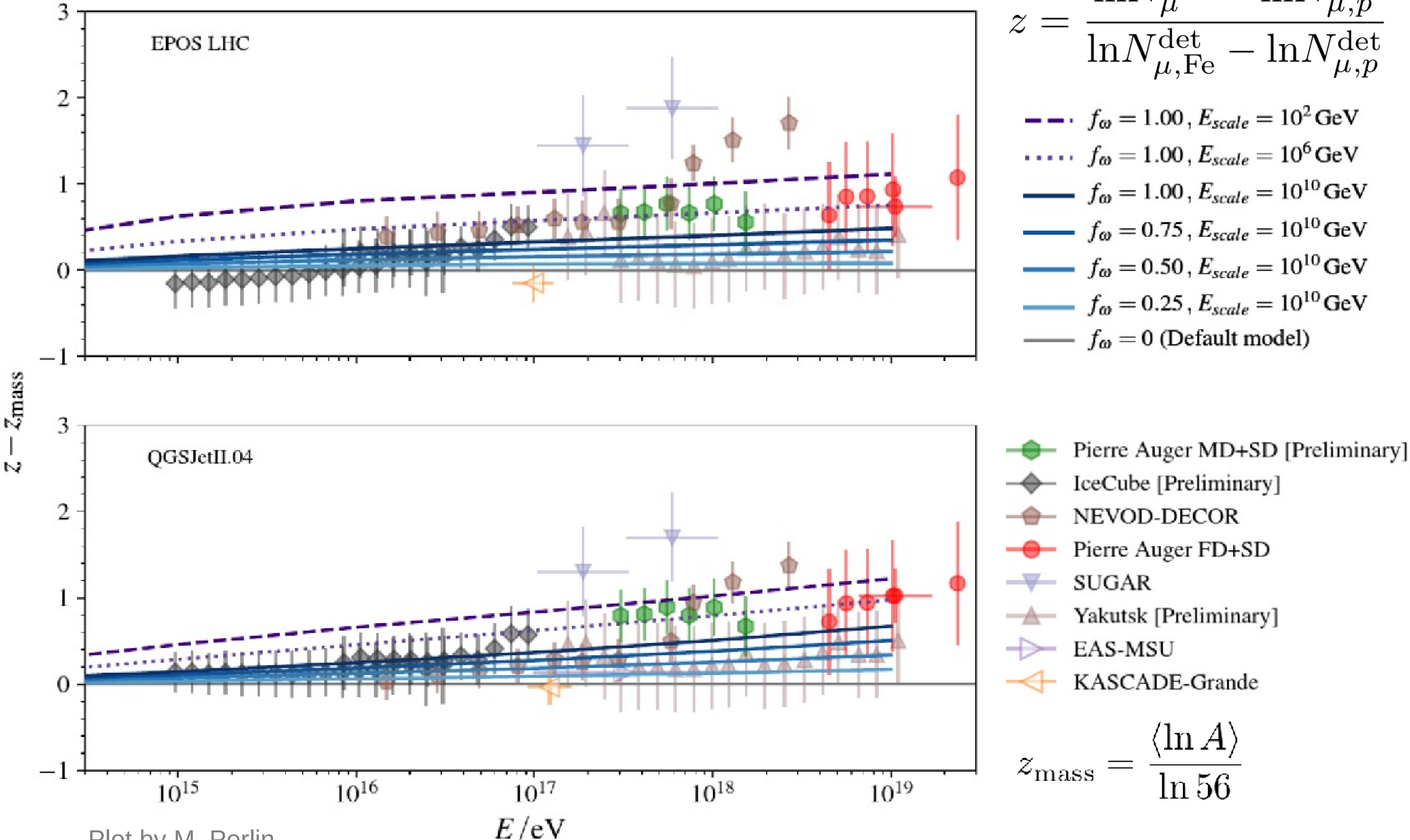






Plot by M. Perlin

Results for z-scale



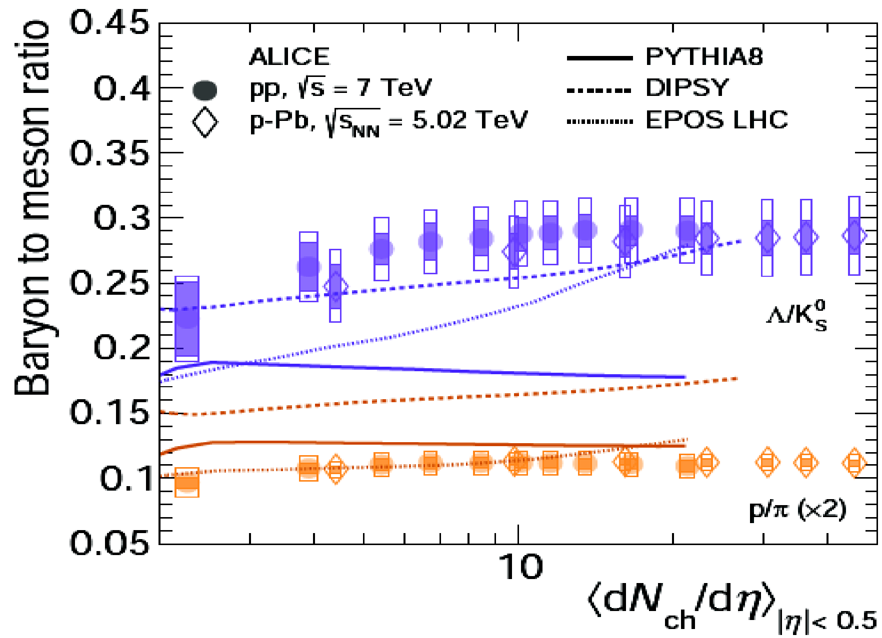
$$z = \frac{\ln N_\mu^{\rm det} - \ln N_{\mu,p}^{\rm det}}{\ln N_{\mu,\rm Fe}^{\rm det} - \ln N_{\mu,p}^{\rm det}}$$

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

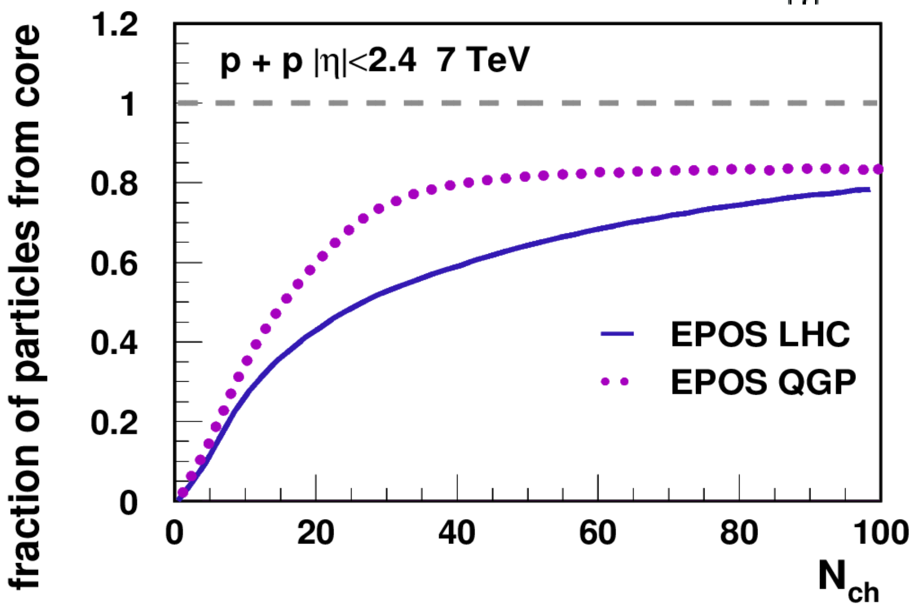
Plot by M. Perlin

Modified EPOS with Extended Core

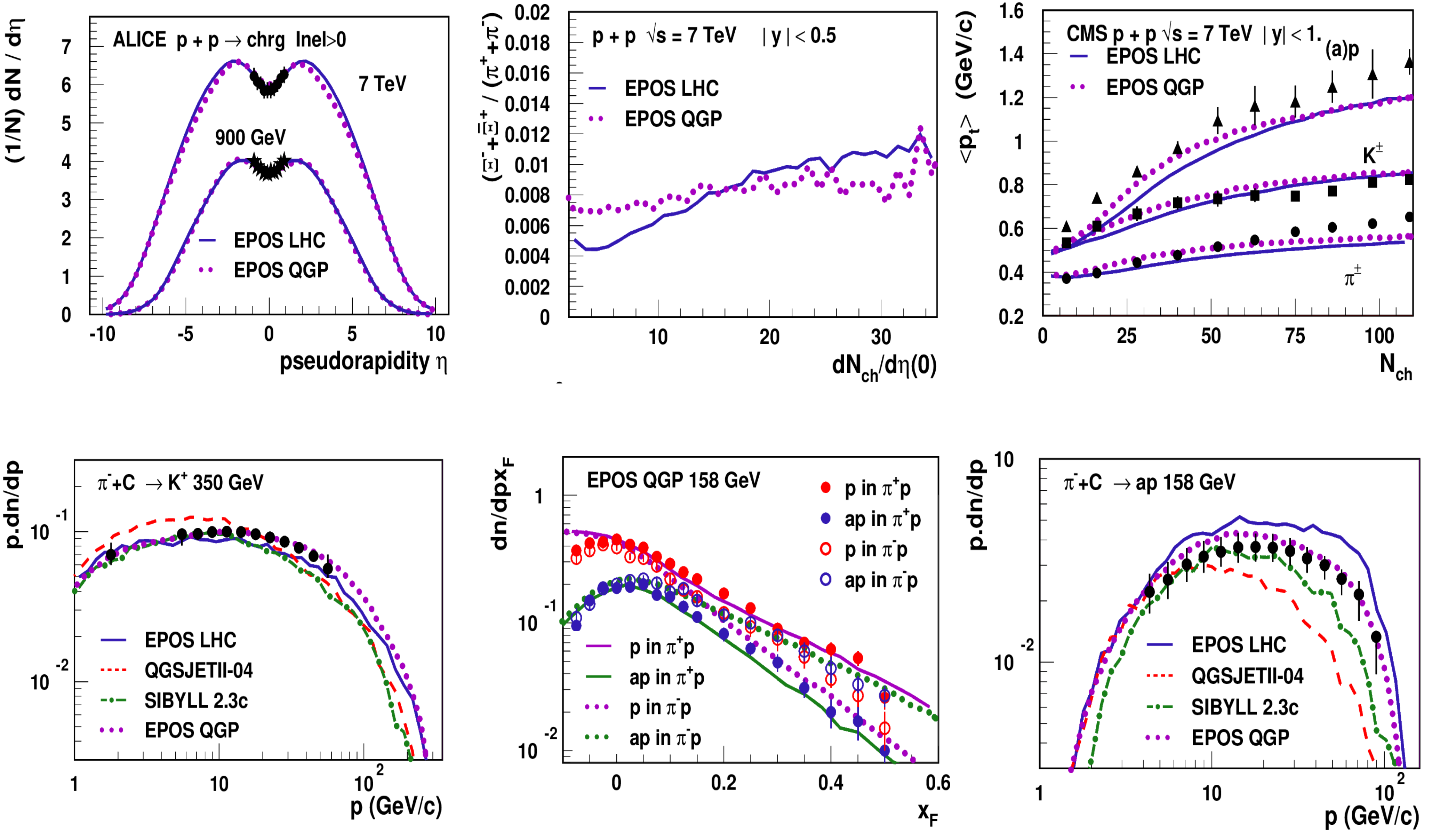
- **Core in EPOS LHC appear too late**
  - Recent publication show the evolution of chemical composition as a function of multiplicity
  - Large amount of (multi)strange baryons produced at lower multiplicity than predicted by EPOS LHC



- **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)



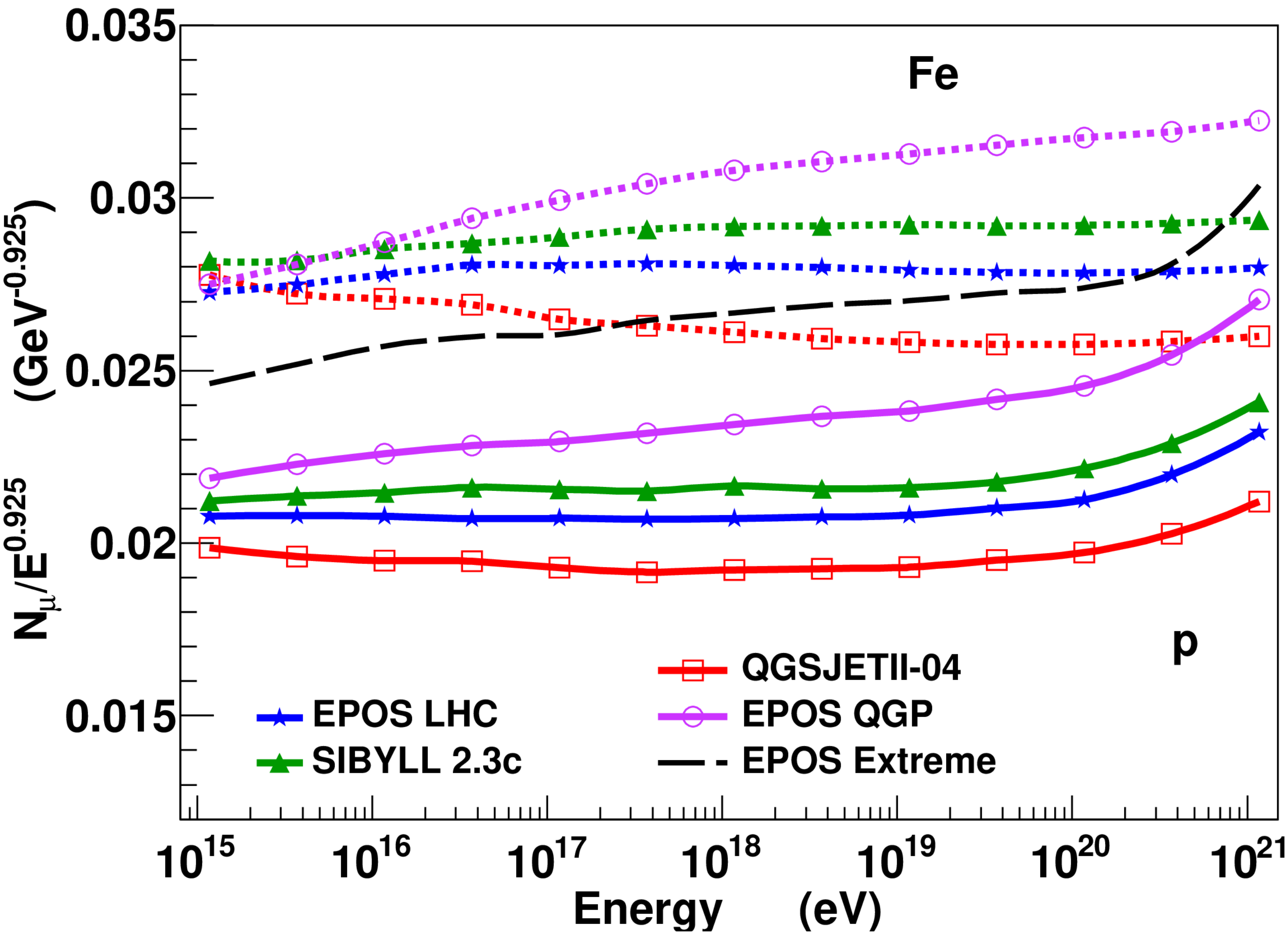
Preliminary Version with Minimum Constraints

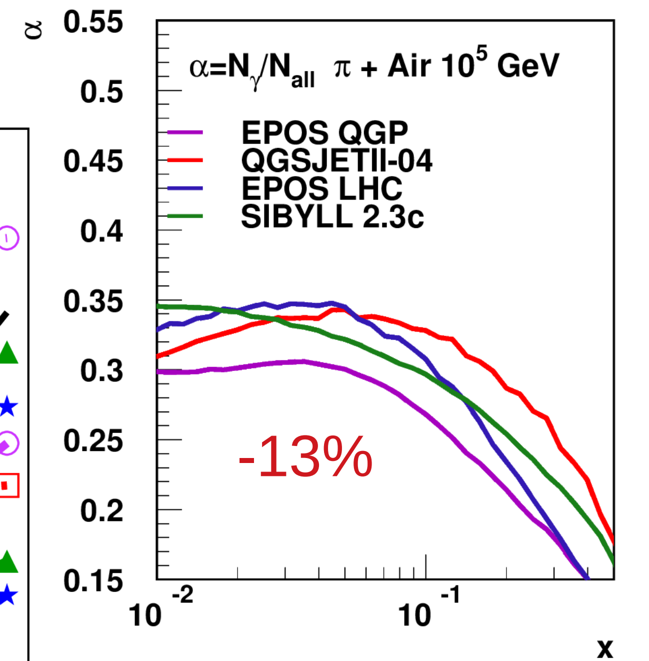


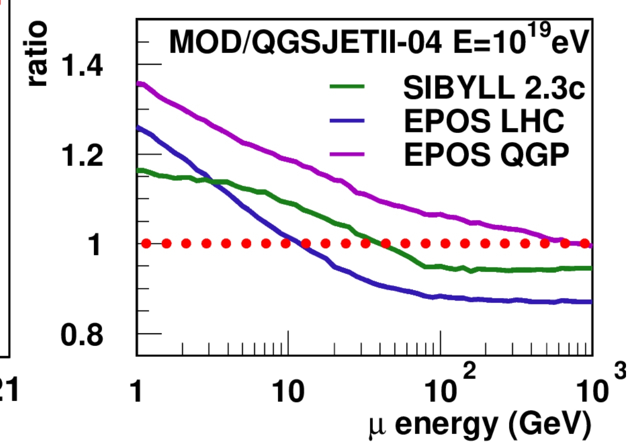
Results for Air Showers

Large change of the number of muons at ground

➡ Different slope as expected from the change in α



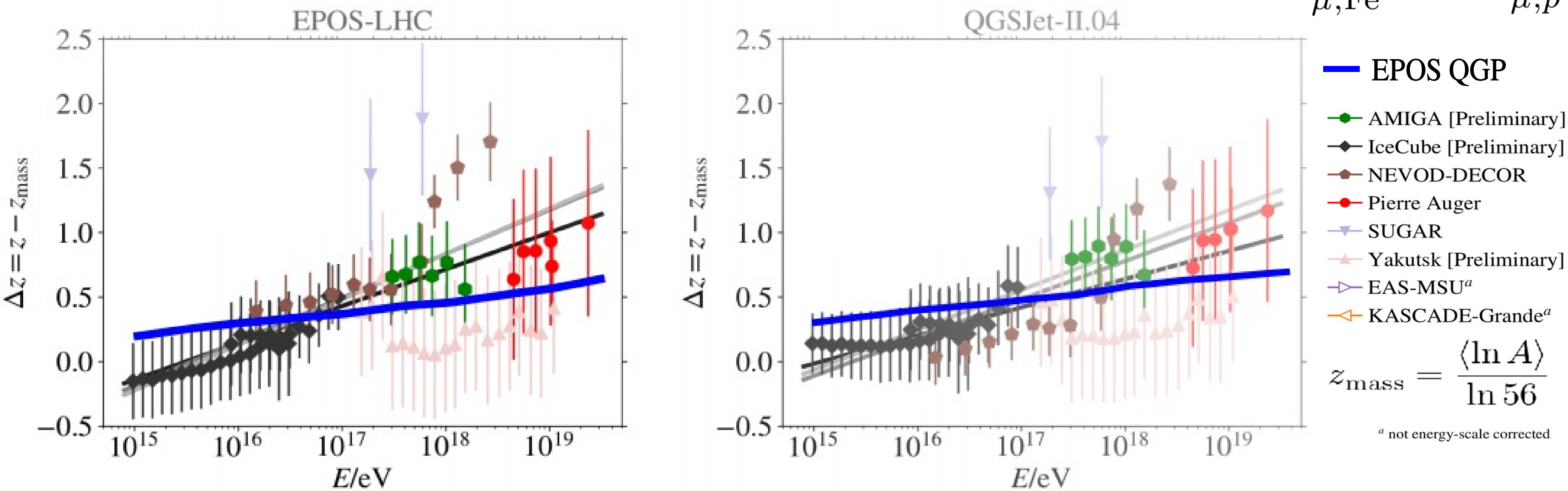




Comparison with Data

- **Collective hadronization gives a result compatible with data**
  - ➡ Still different energy evolution between data and simulations
    - ➡ Very similar to CONEX study

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



- **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.) ?

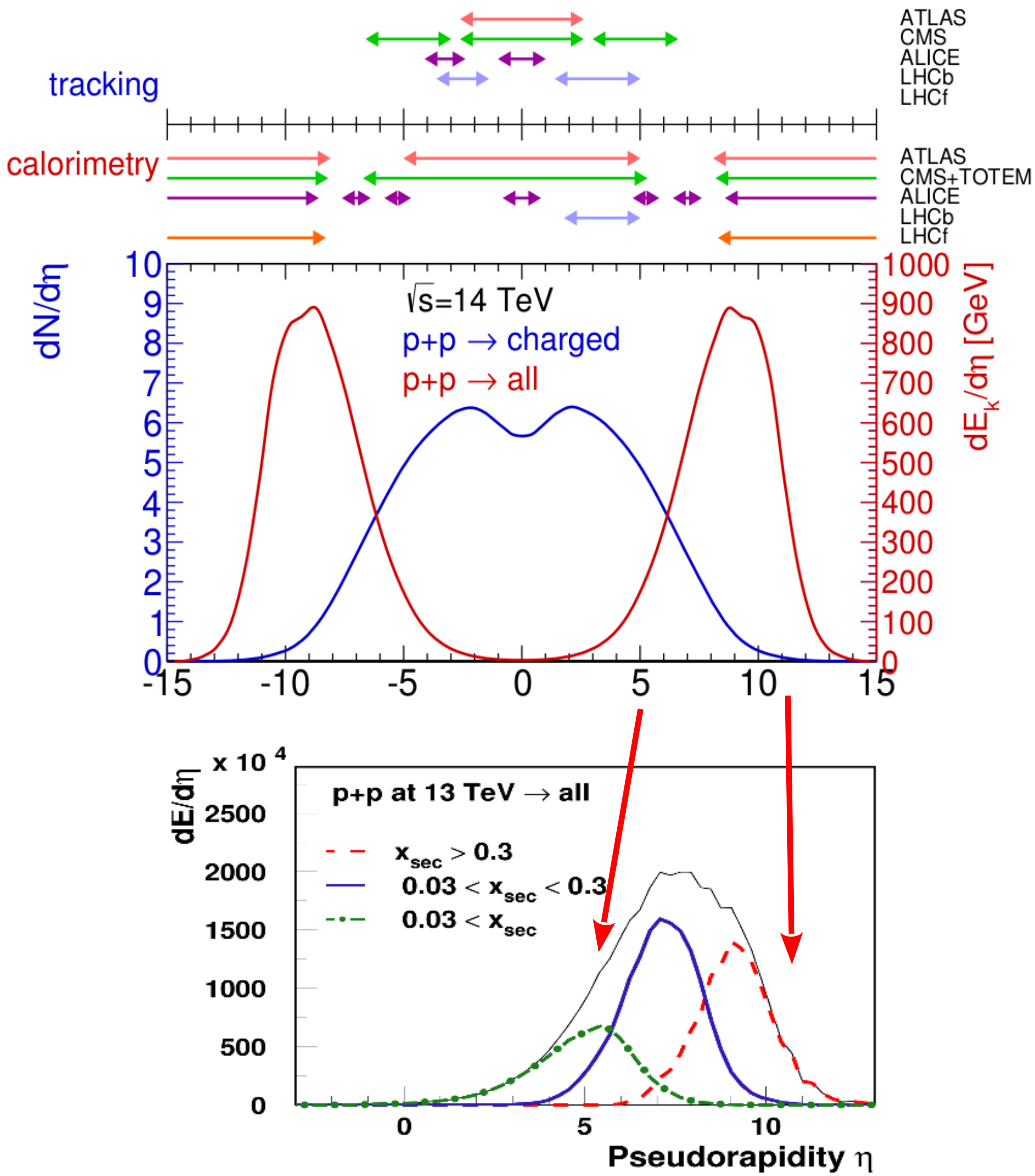
Summary

- **WHISP working group clearly established a muon production deficit in air shower simulations.**
  - ➡ Exact scale not known (dependent on energy and mass)
  - ➡ Continuous increase of difference above 10^{16} eV
    - ➡ No sudden increase
  - ➡ Zenith angle, muon energy, radial distance effect still to be studied
- **Most "natural" explanation given by a change in electromagnetic to hadronic energy 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-like hadronization could be sufficient with current uncertainties
  - ➡ New physics still needed ?
- **Not all relevant CERN data taken into account in model yet.**

Recent LHC data combined with the result of air shower experiment meta-analysis provide a possible explanation of the muon deficit in air shower simulations : QGP-like hadronization could be more common than thought until now.

Thank you !

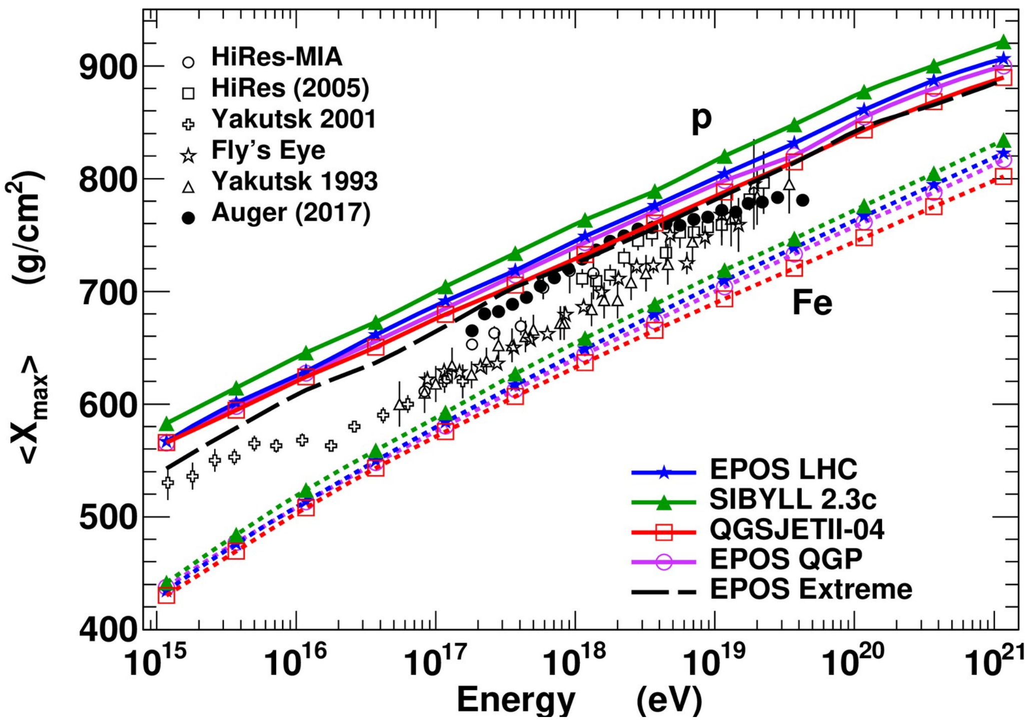
LHC acceptance and Phase Space

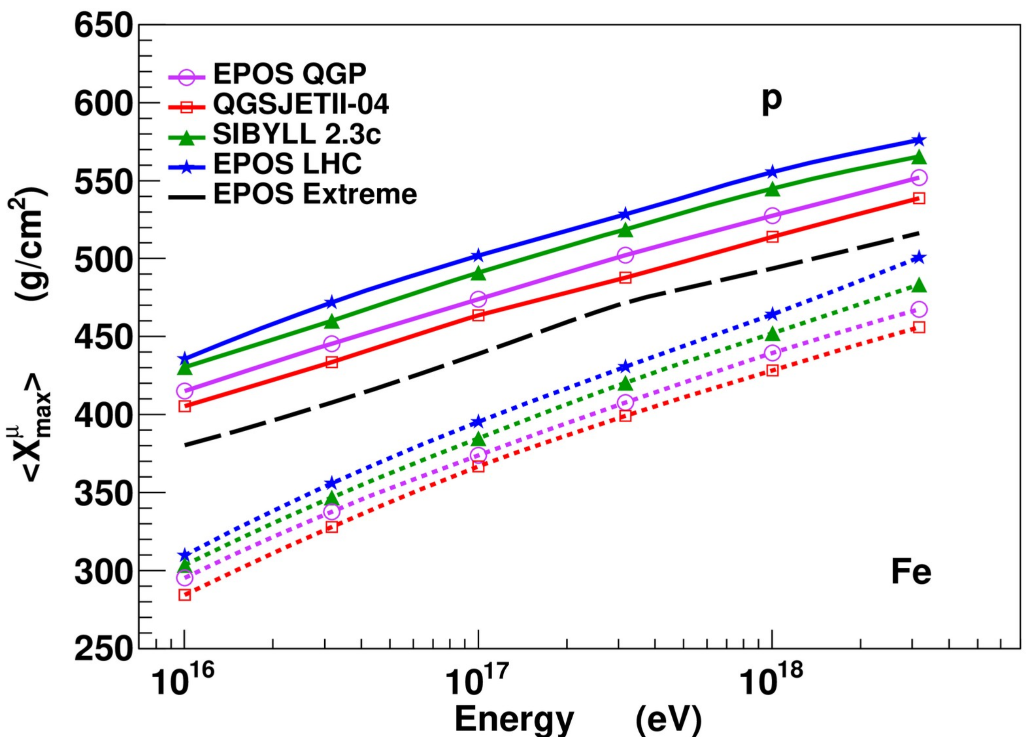


- **p-p data mainly from "central" detectors**
  - pseudorapidity $\eta=-\ln(\tan(\theta/2))$
  - $\theta=0$ is midrapidity
  - $\theta>>1$ is forward
  - $\theta<<1$ is backward
- **Different phase space for LHC and air showers**
  - most of the particles produced at midrapidity
    - important for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

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





WHISP Working Group

- **Lots of muon measurements 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),

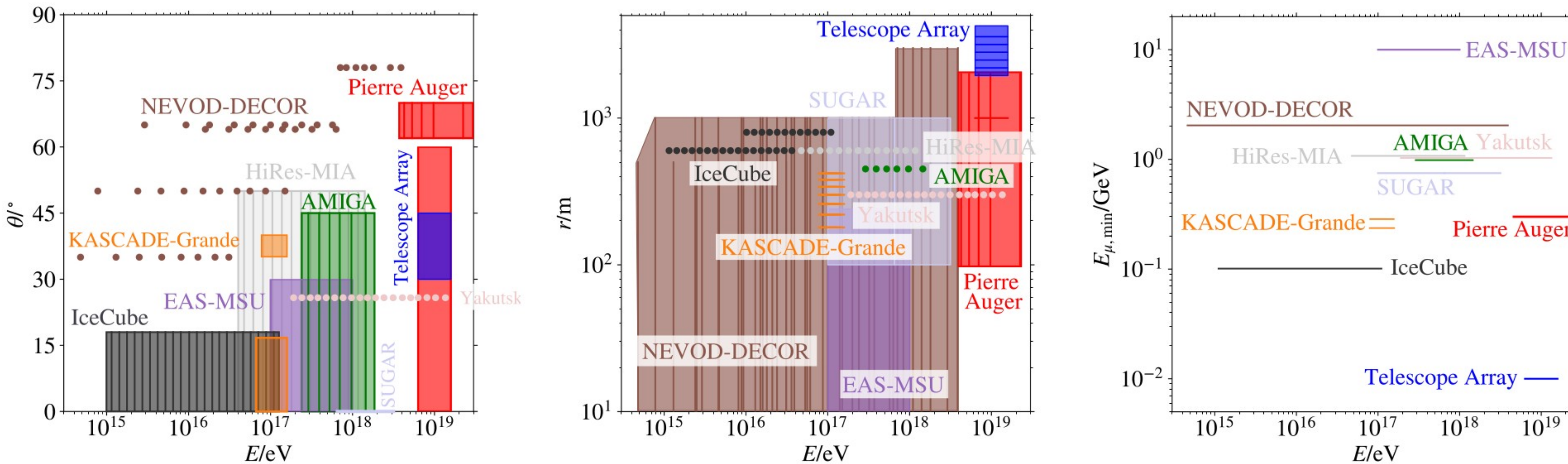
J.C. Arteaga (KASCADE-Grande, Mexico),

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 …

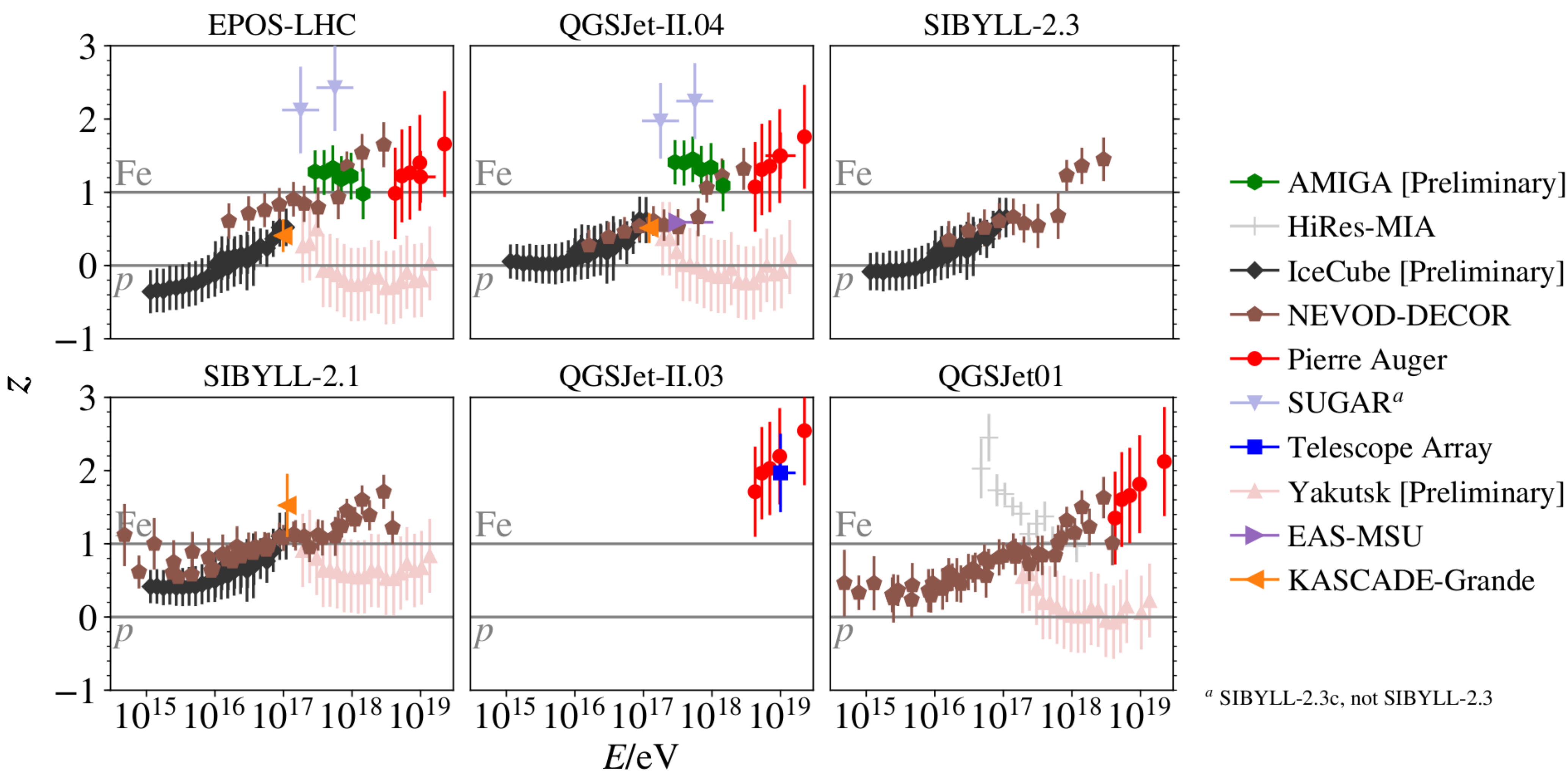


Plots by H. Dembinski

- **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 :**

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

- **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

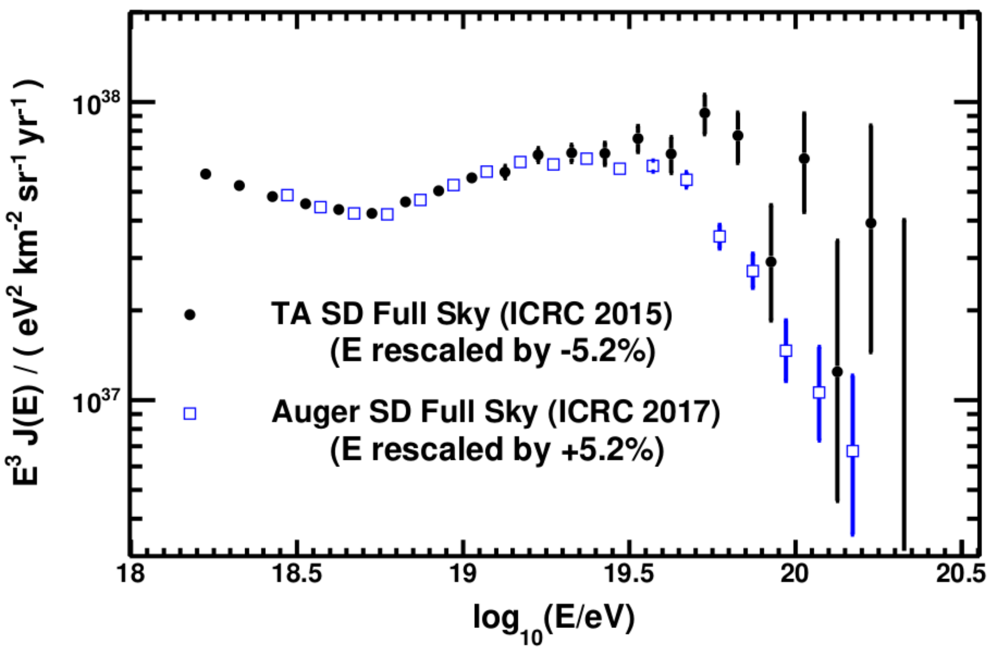
Using an external data based model !

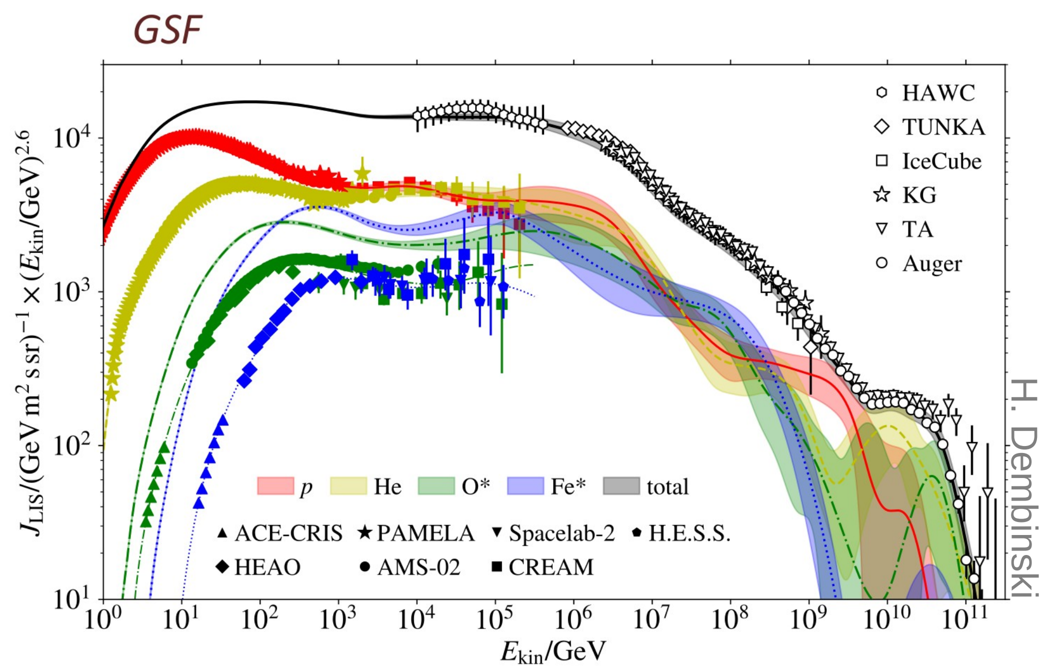
Energy Scale

Unique energy scale obtained mixing

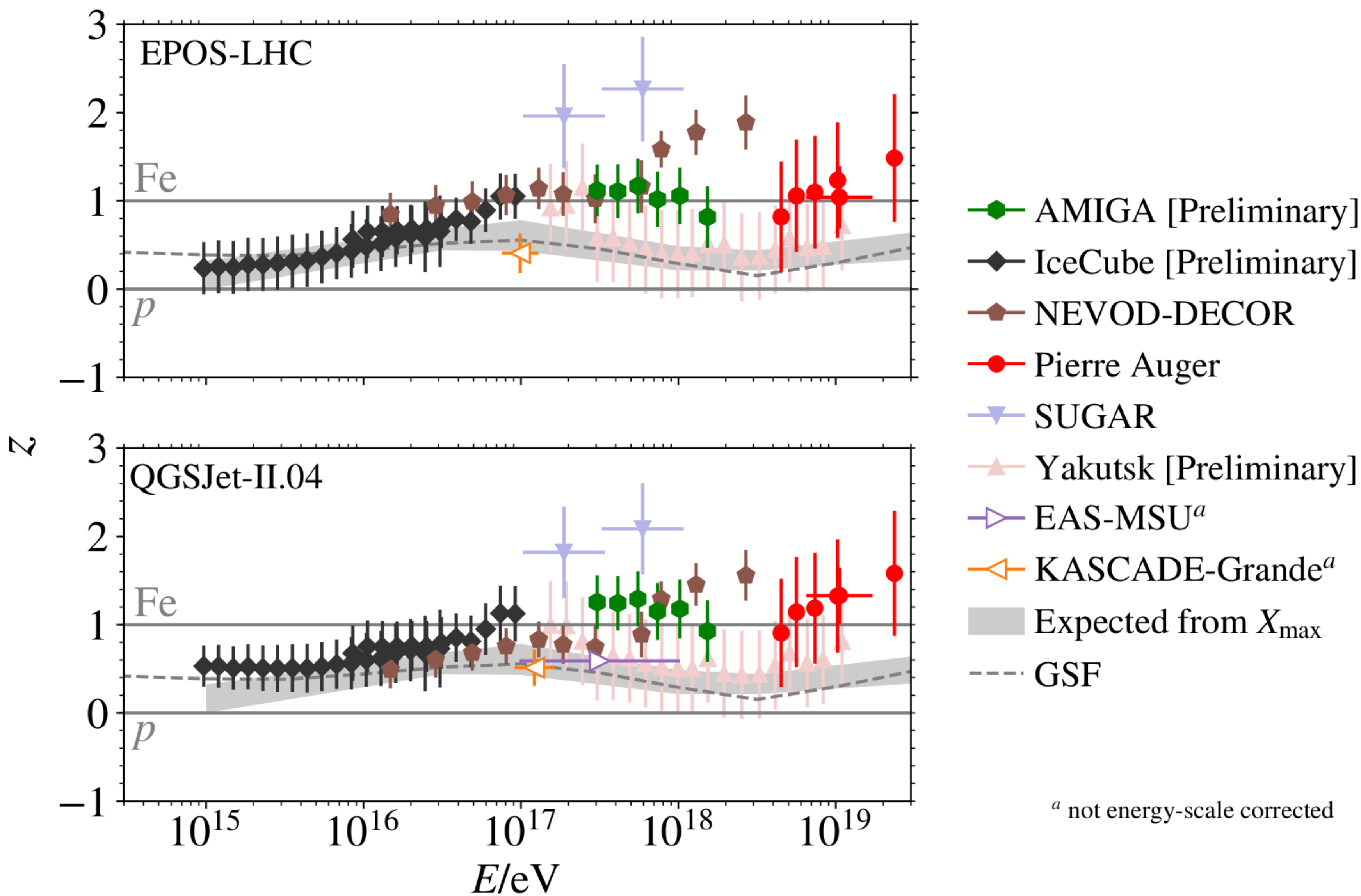
- Combine Auger/TA spectrum
- Relative factors between other experiment using the Global Spline Fit (GSF) from H. Dembinski (PoS(ICRC 2017)533)

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

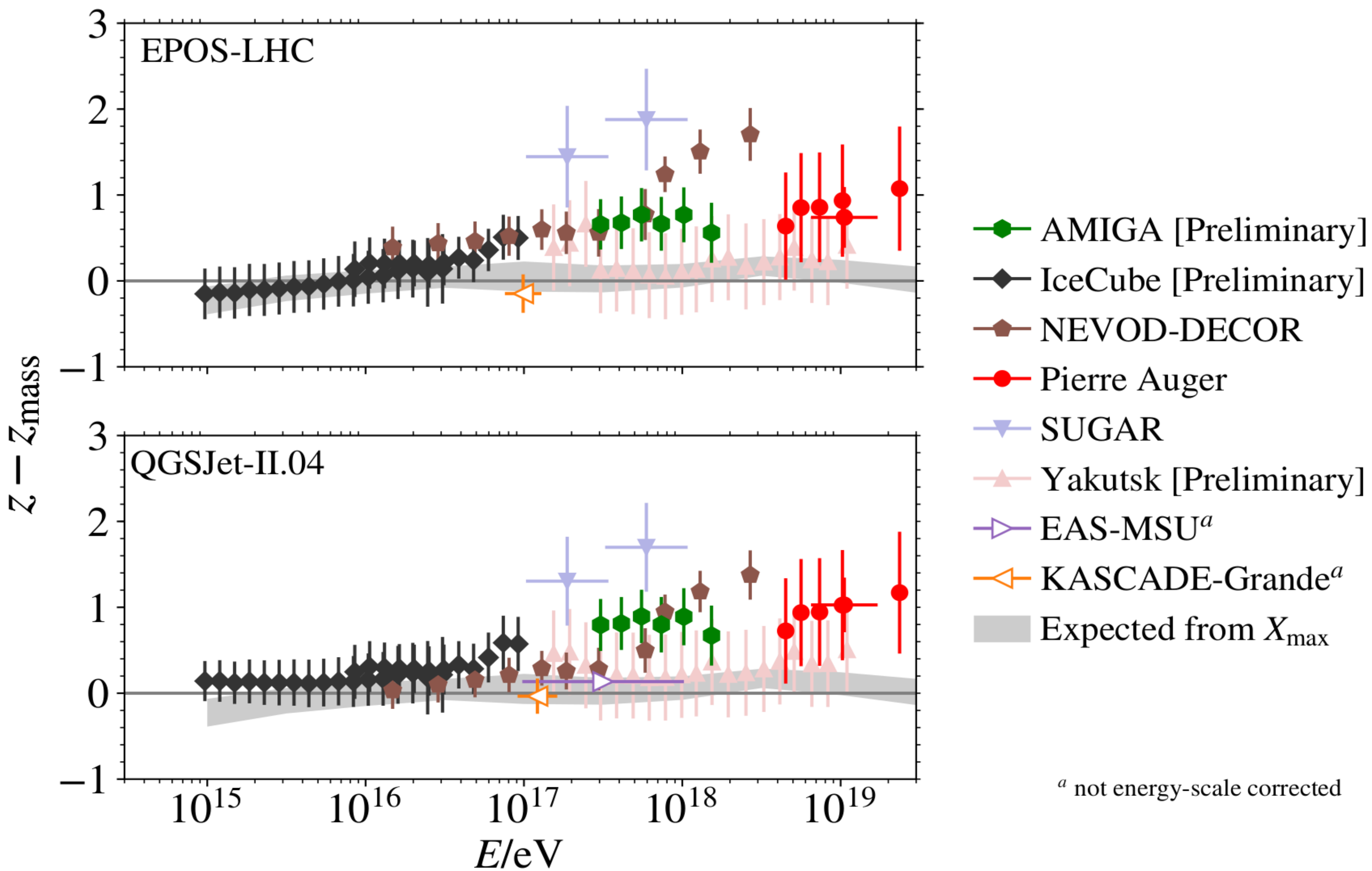




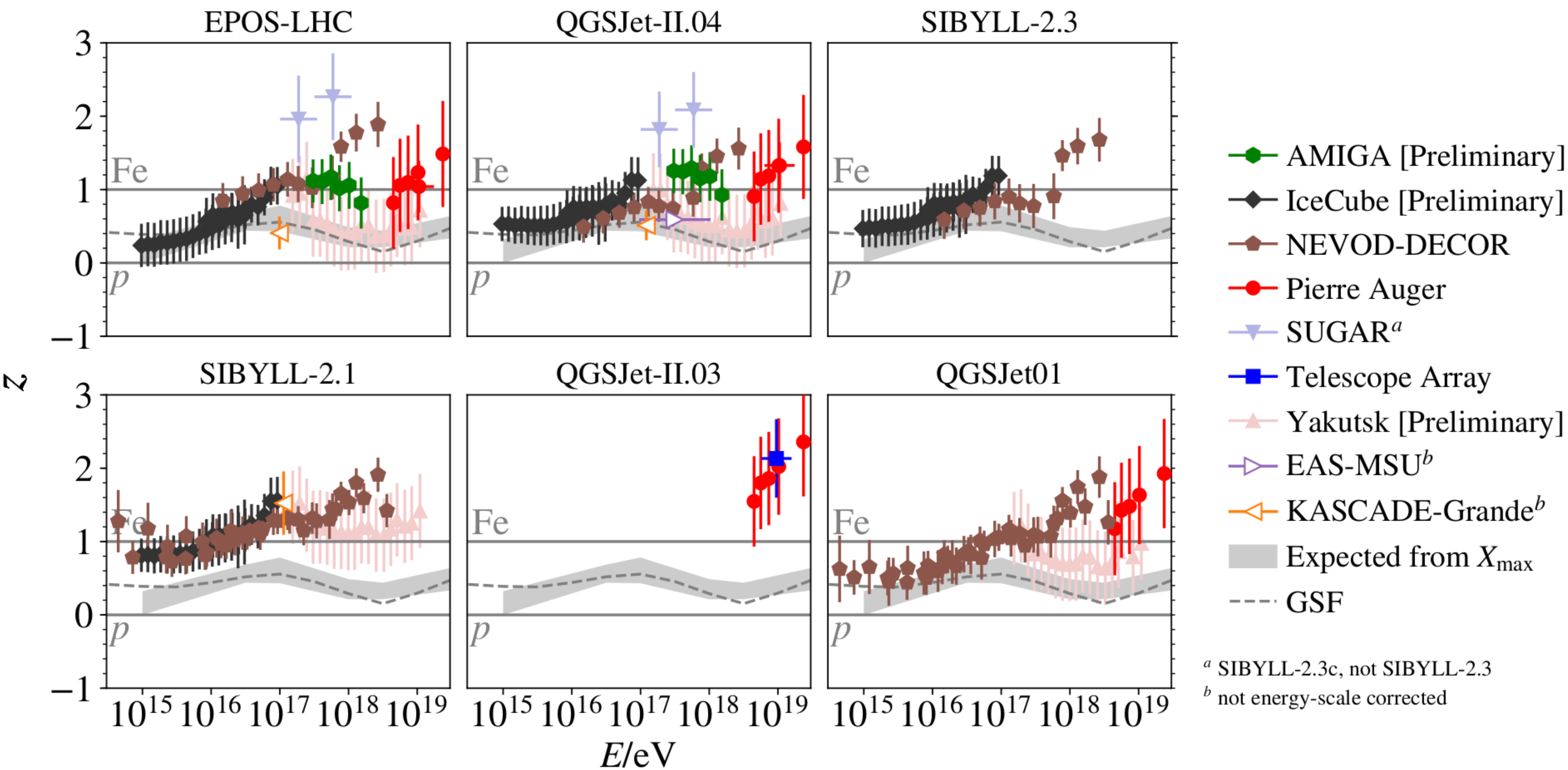
Rescaled Data



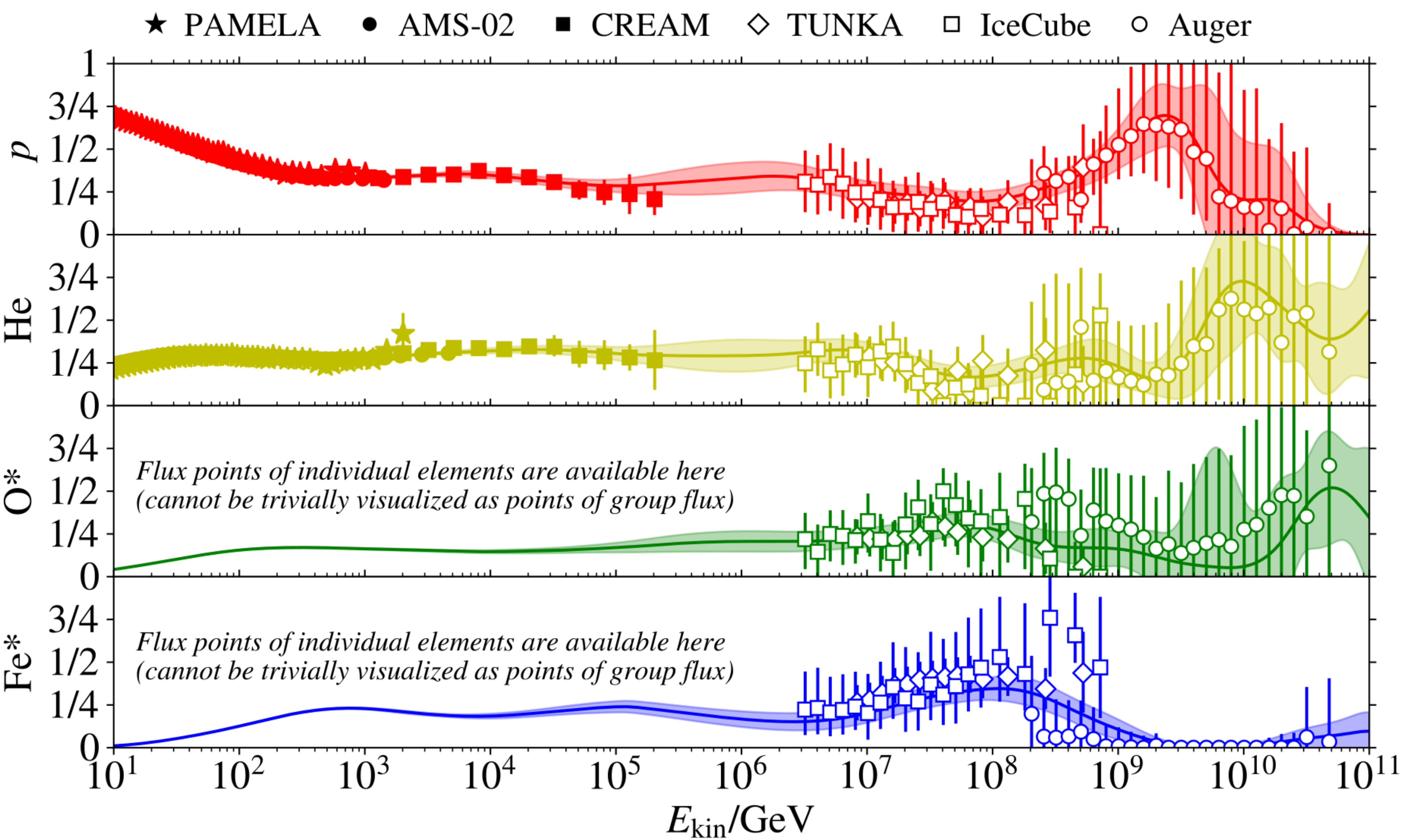
Rescaled Data with Mass Correction



Data Rescaled

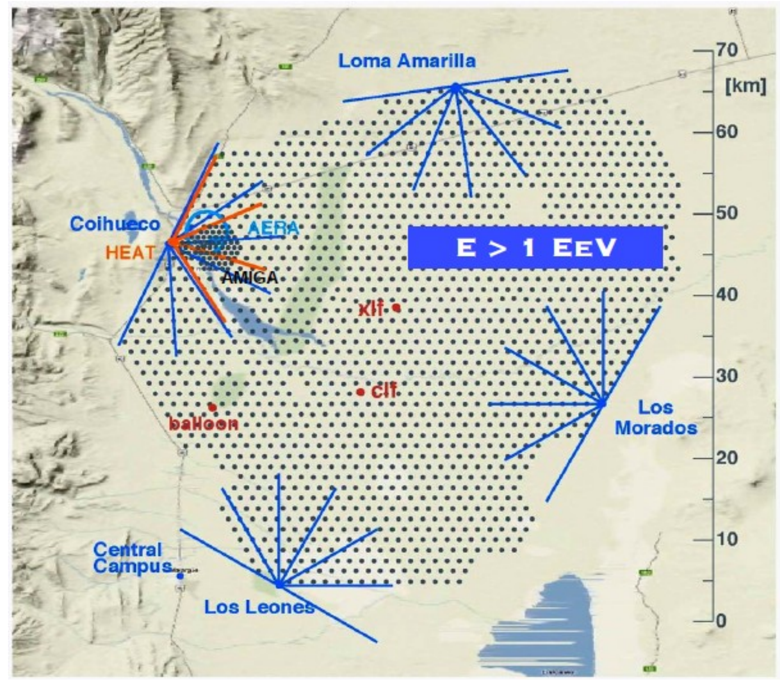


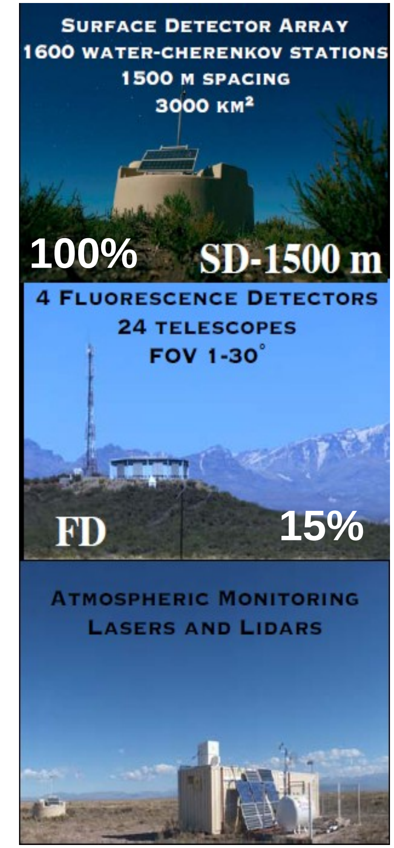
GSF Composition Details



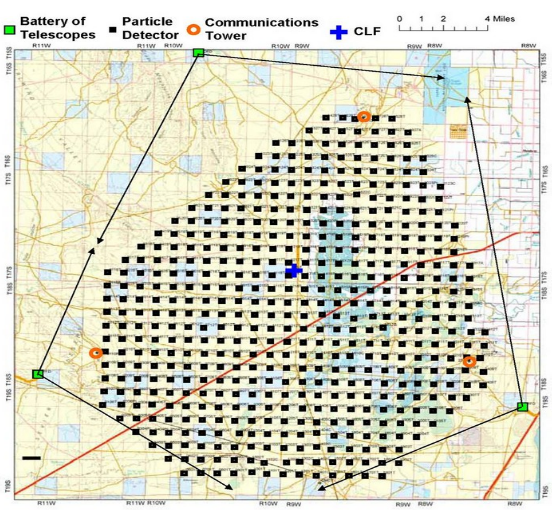
PAO/TA

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



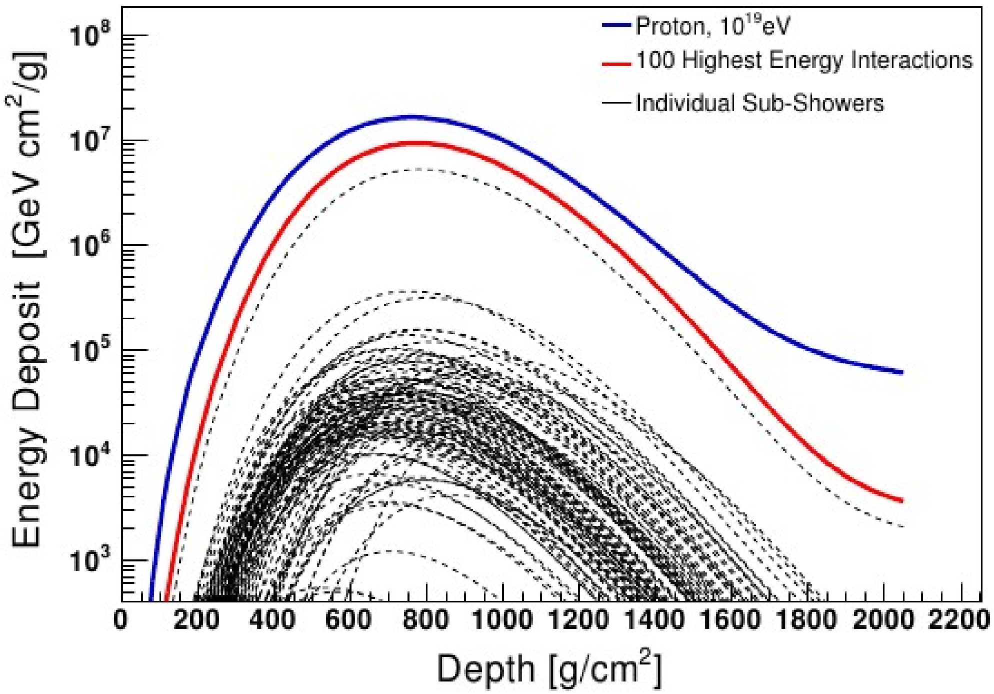


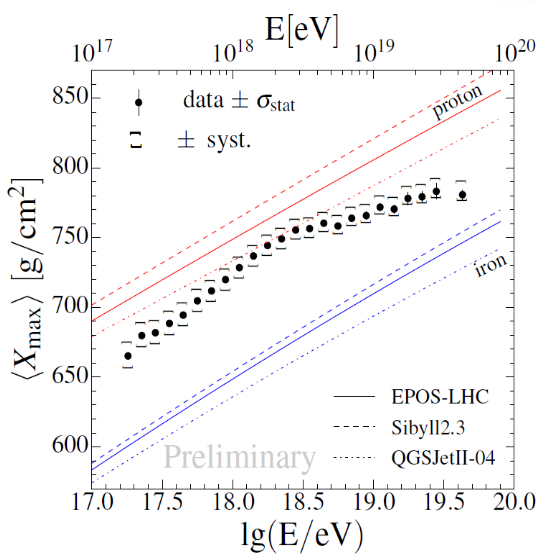
- **Telescope Array (TA)**
  - Utah, USA
  - Northern Hemisphere
  - 680 km^2: 3700 km^2/sr/yr

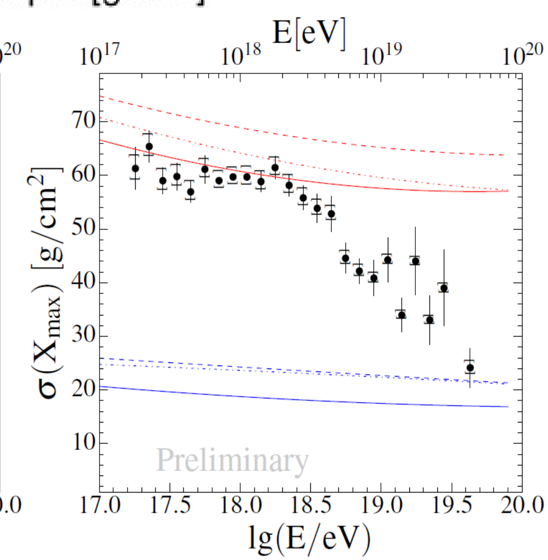


Fluorescence Detector (FD)

From R. Ulrich (KIT)

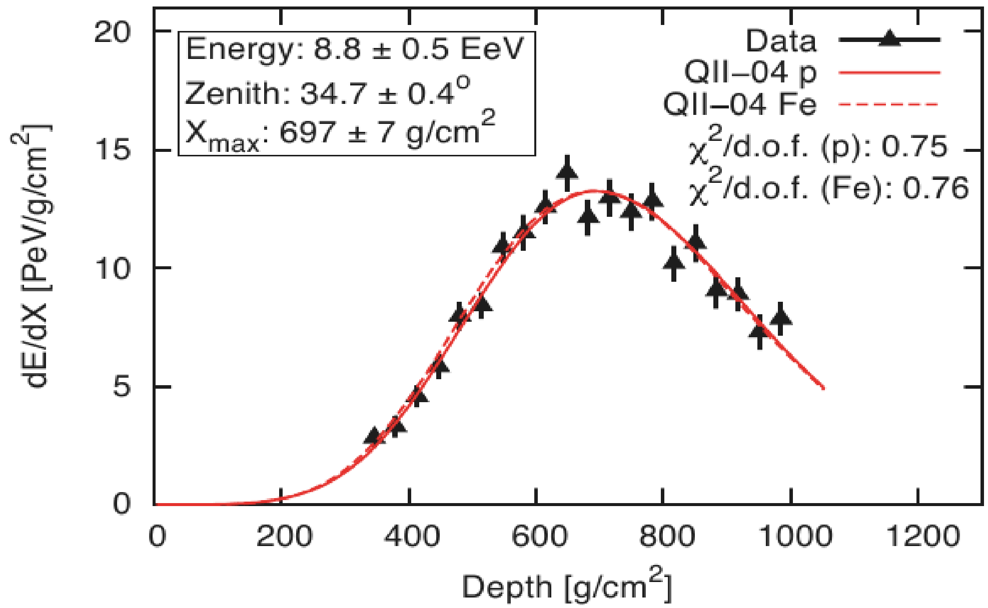


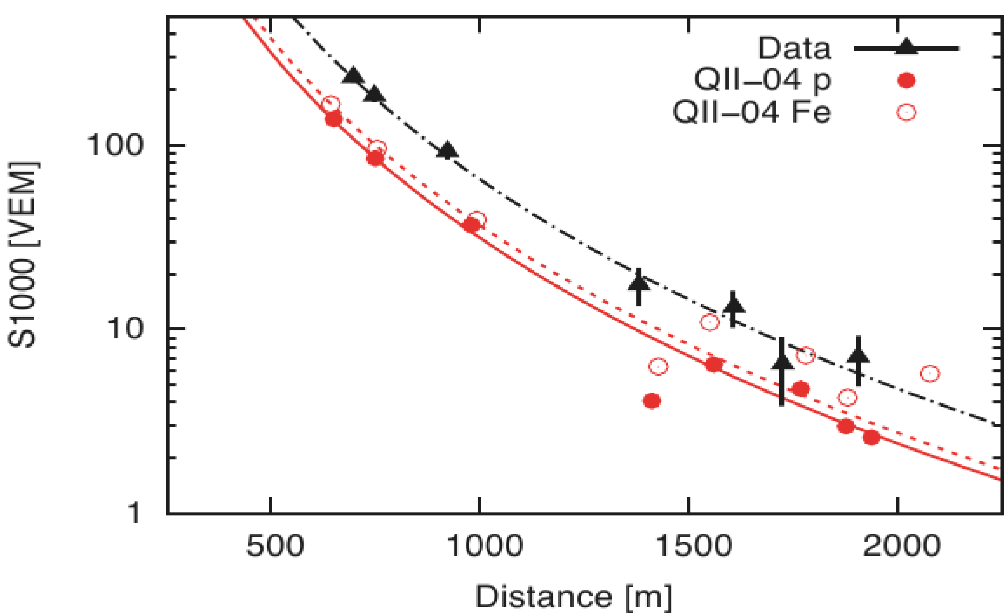




- **Most direct measurement**
  - dominated by first interaction
- **Reference mass for other analysis**
  - <lnA> from <X_{max}> and RMS
- **Possibility to use the tail of X_{max} distribution to measure p-Air inelastic cross-section.**
  - require no contamination from photon induced showers (independent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

Hybrid Analysis





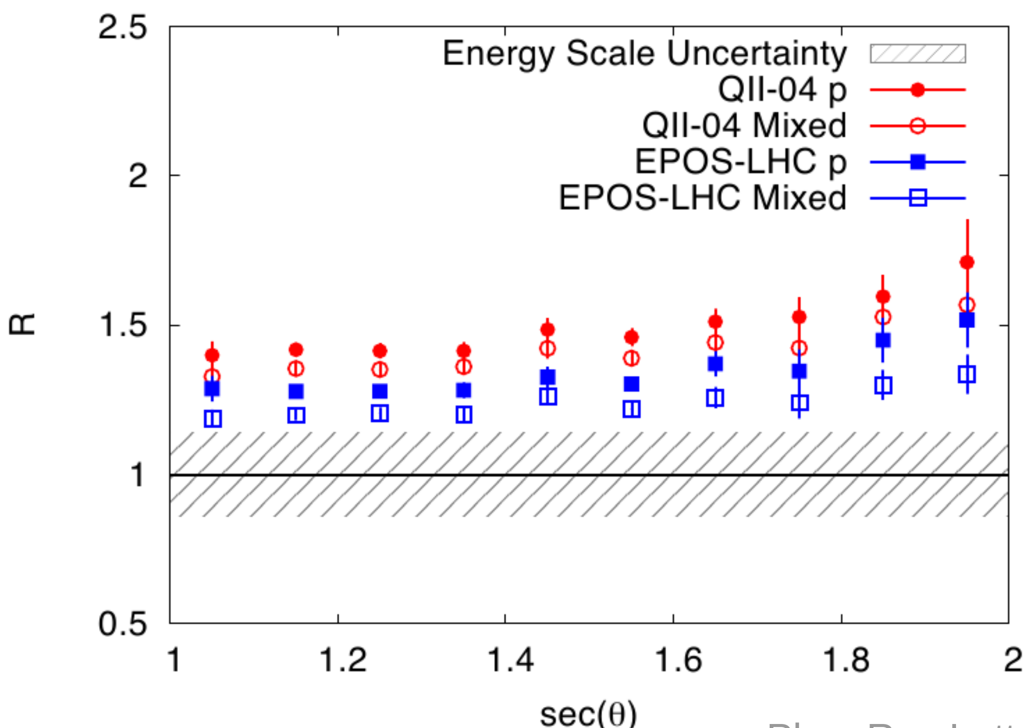
- **Analysis based on 411 Golden Hybrid Events**
  - find simulated showers reproducing each FD profile for all possible models and primary masses (p, He, N, Fe),
  - decompose ground signal into pure electromagnetic (S_{EM}) and muon dependent signal (S_μ),
  - rescale both component separately (R_E and R_μ to reproduce SD signal for each showers,

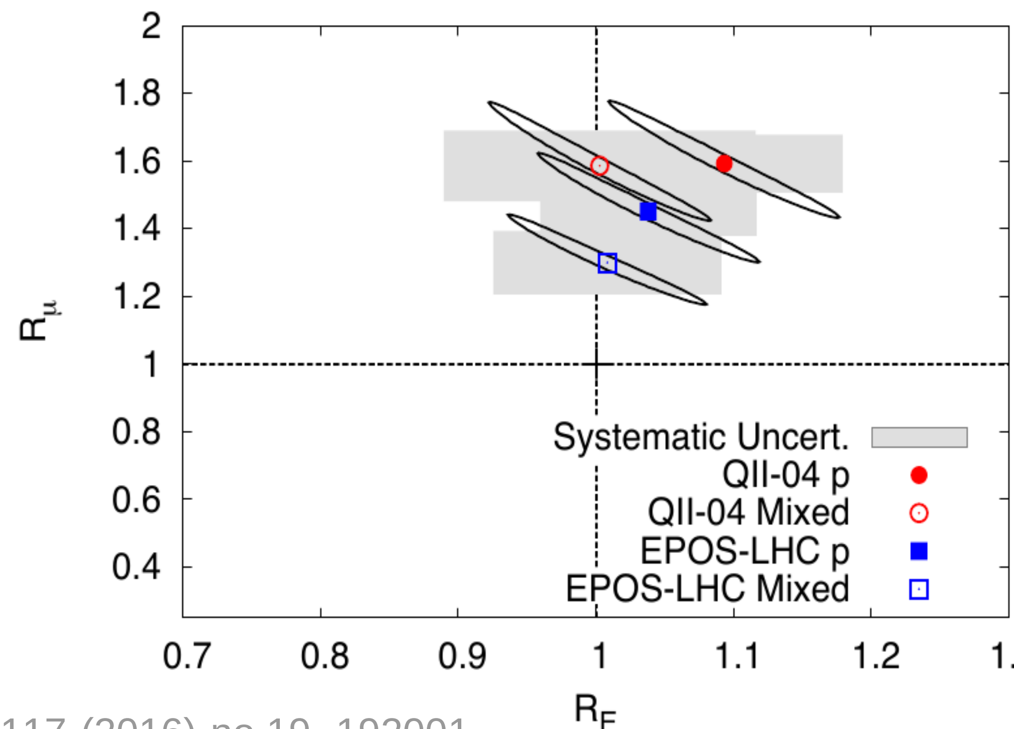
$$S_{\rm resc}(R_E, R_\mu)_{i,j} \equiv R_E\, S_{EM,i,j} + R_E^\alpha R_\mu\, S_{\mu,i,j}$$

  - for mixed composition, give weight according to X_{max} distribution.

Muon Rescaling

- **Simulations don't reproduce FD and SD signal consistently**
  - $R=S_{1000}^{observed}/S_{1000}^{predicted}$ increase with zenith angle
  - EPOS-LHC Iron could be (almost) compatible with data, but X_{max} data are NOT pure Iron (but mixed).
- **To reproduce data simulations have to be rescaled**
  - for mixed composition, only muon component has to be changed
  - correct energy scale
  - 30% muon deficit for EPOS-LHC and 59% for QGSJETII-04.

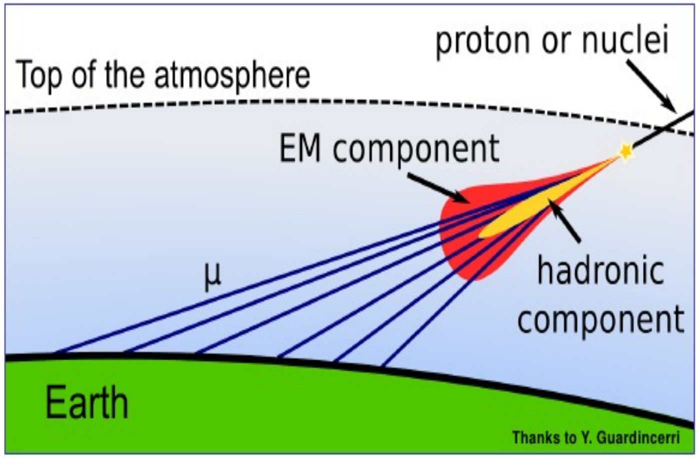


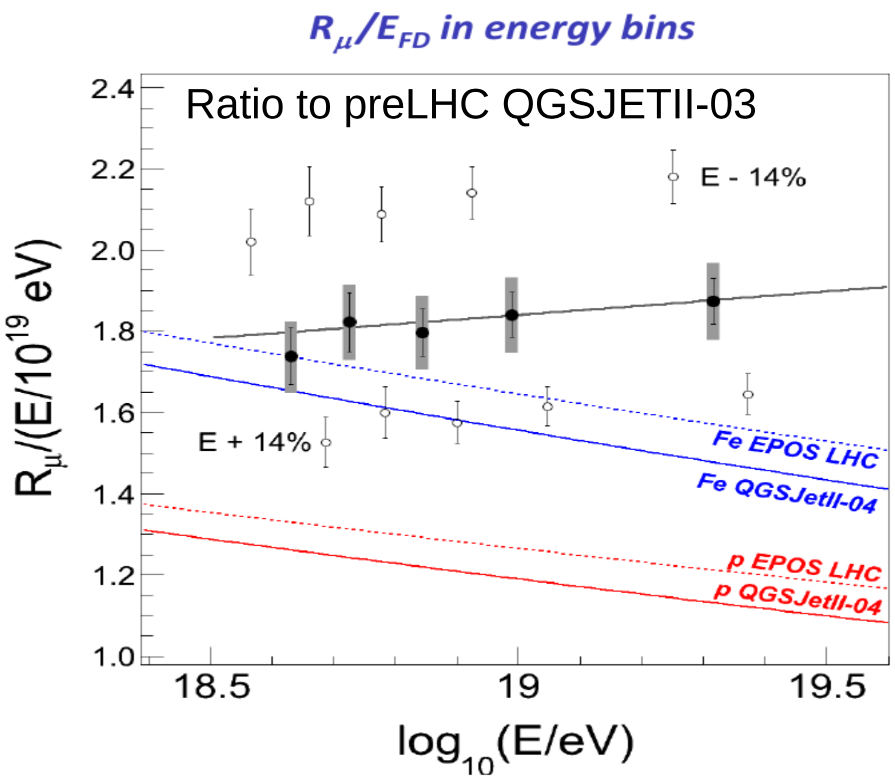


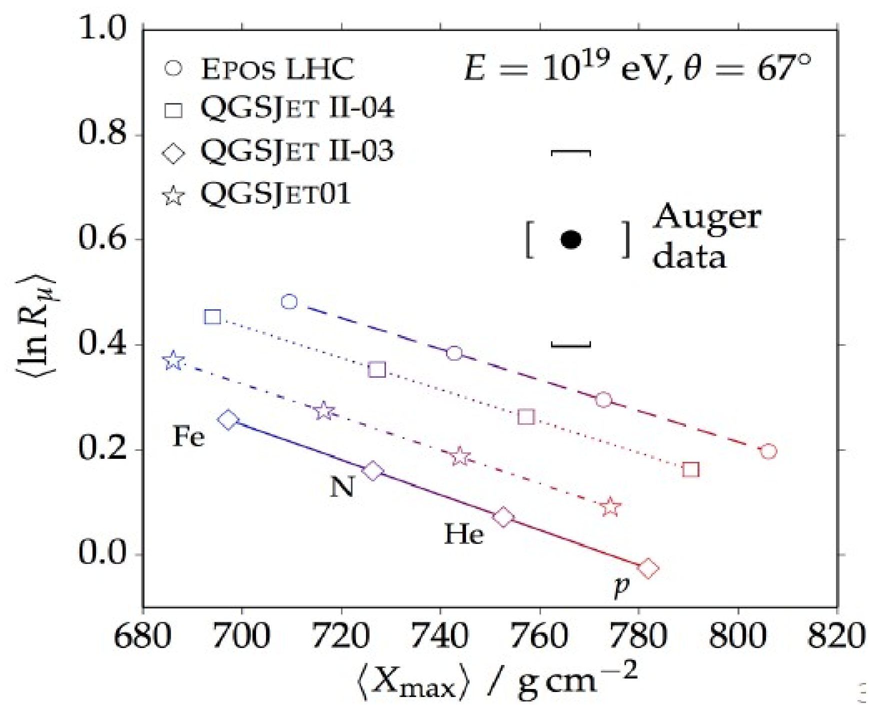
Phys.Rev.Lett. 117 (2016) no.19, 192001

Direct Muon Measurement

- **Old showers contain only muon component**
  - direct muon counting with very inclined showers (>60°) by comparing to simulated muon maps (geometry and geomagnetic field effects)
  - EM halo accounted for
  - correction between true muon number and reconstructed one from map by MC (<5%)







Muon Production Depth

- **Independent SD mass composition measurement**
  - geometric delay of arriving muons

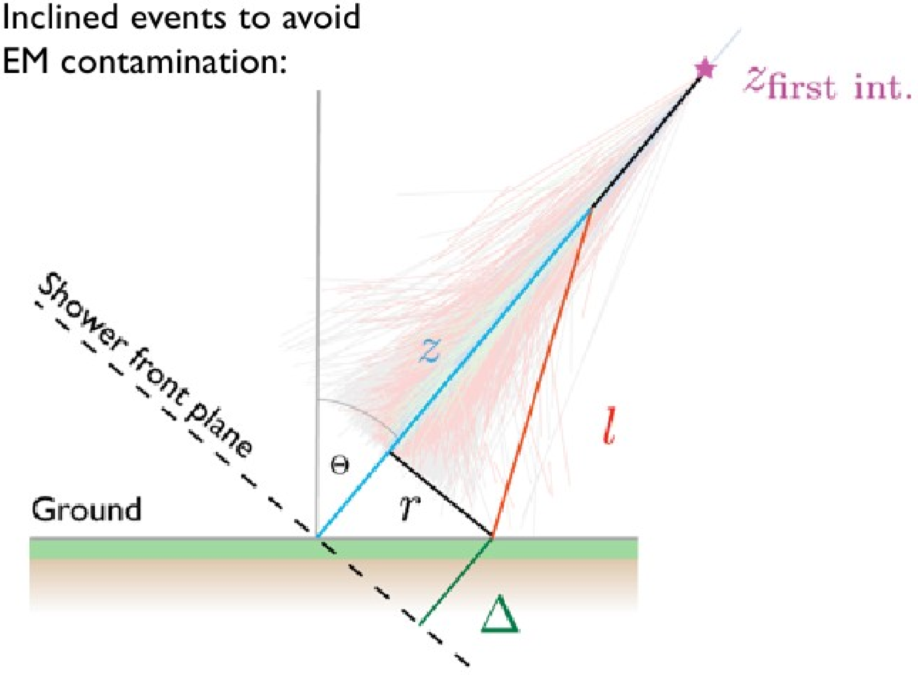
$$c \cdot t_g = l - (z - \Delta) = \sqrt{r^2 + (z-\Delta)^2} - (z - \Delta)$$

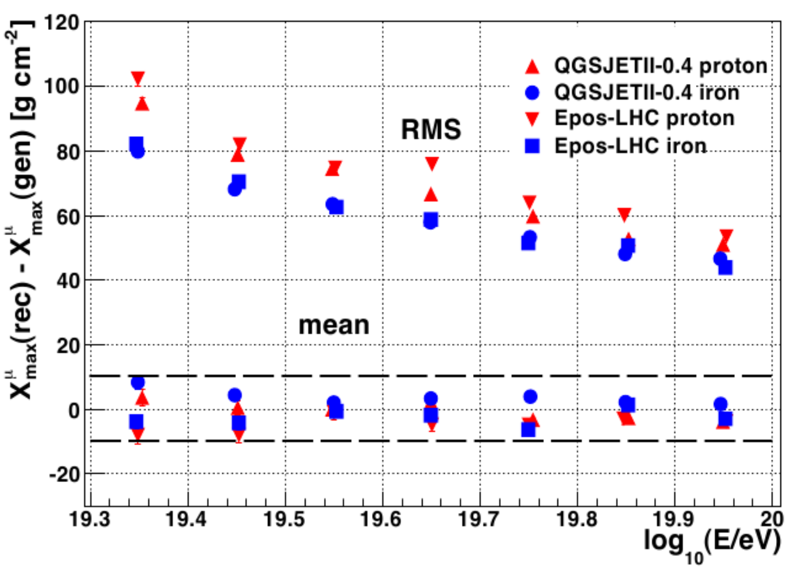
  - mapped to muon production distance

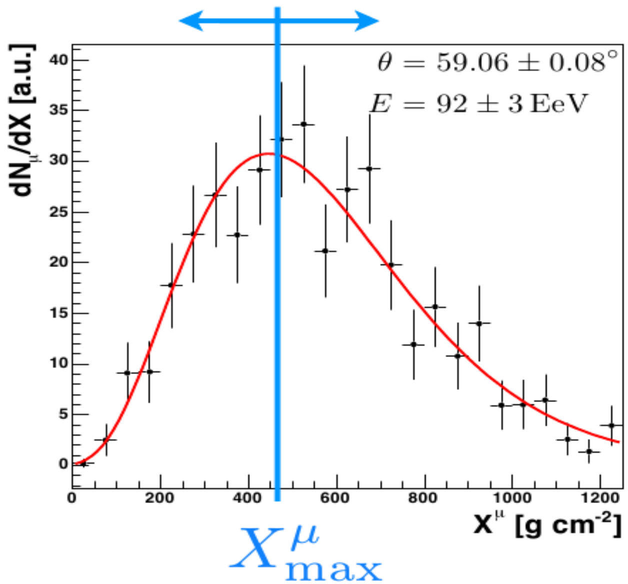
$$z = \frac{1}{2}\left(\frac{r^2}{ct_g} - ct_g\right) + \Delta$$

  - decent resolution and no bias

Inclined events to avoid EM contamination:

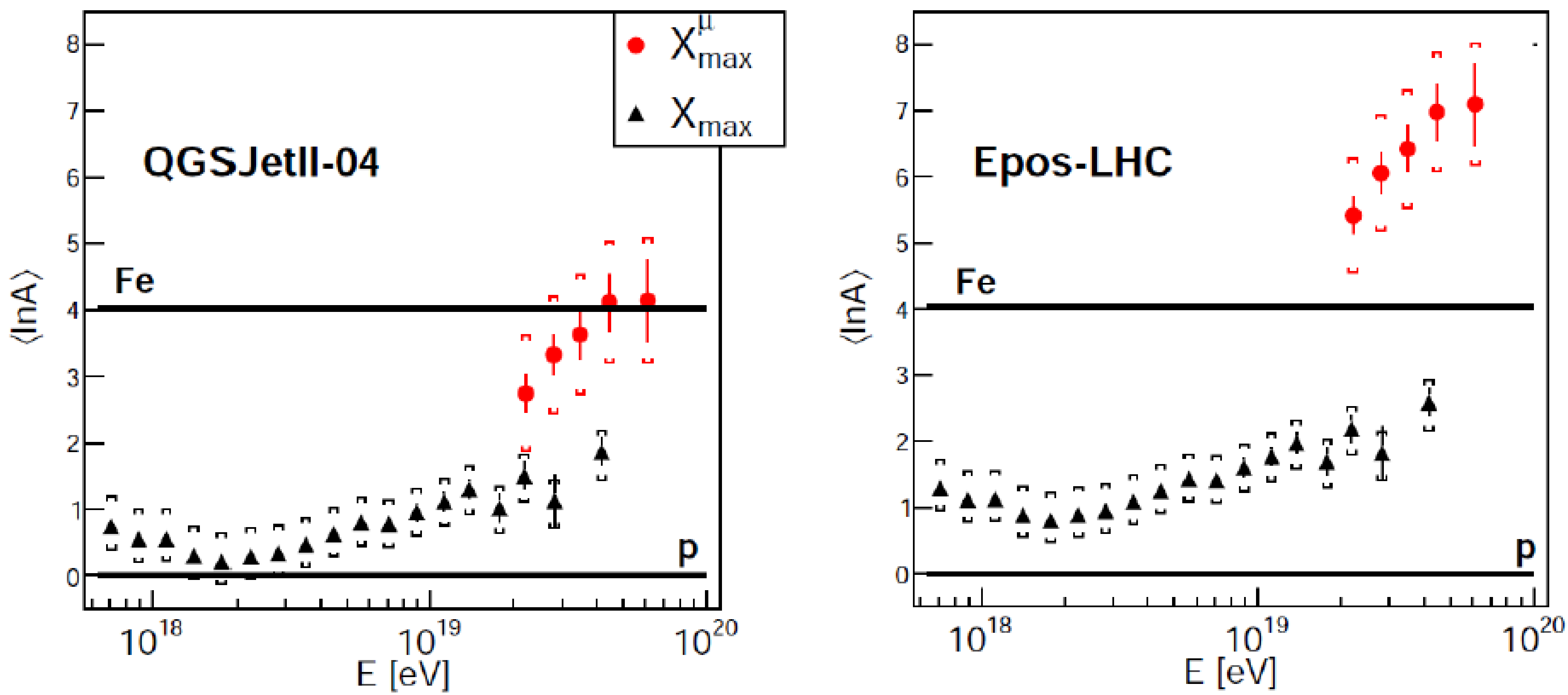






MPD and Models

- **2 independent mass composition measurements**
  - ➜ both results should be between p and Fe
  - ➜ both results should give the same mean logarithmic mass for the same model
  - ➜ problem with EPOS appears after corrections motivated by LHC data (low mass diffraction) and model consistency (forward baryon production at high energy): direct constraint on hadronic interactions.

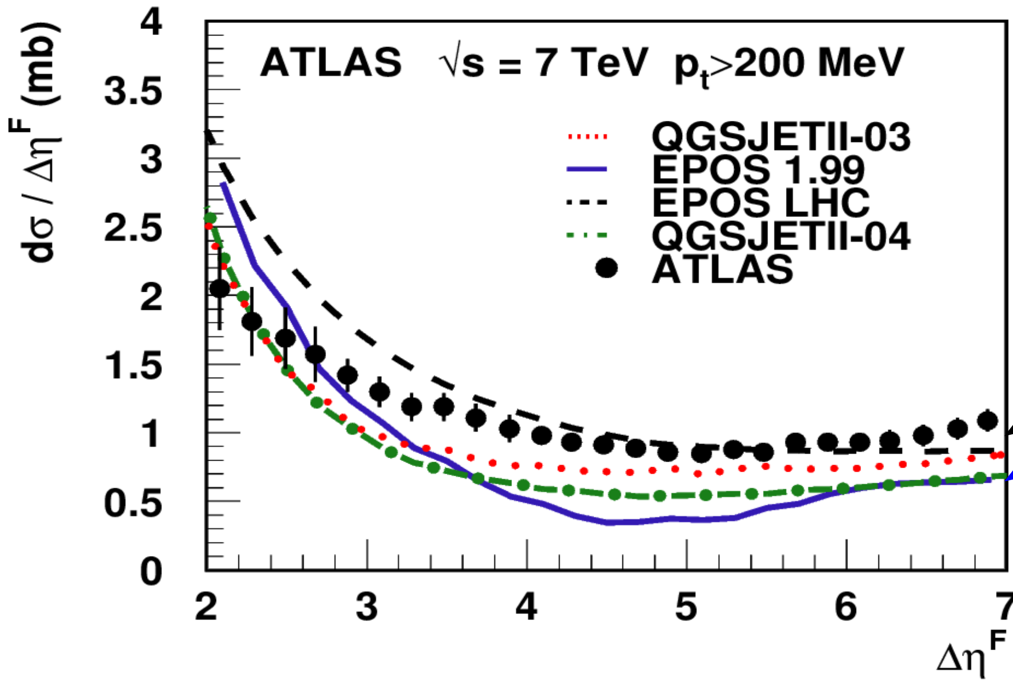


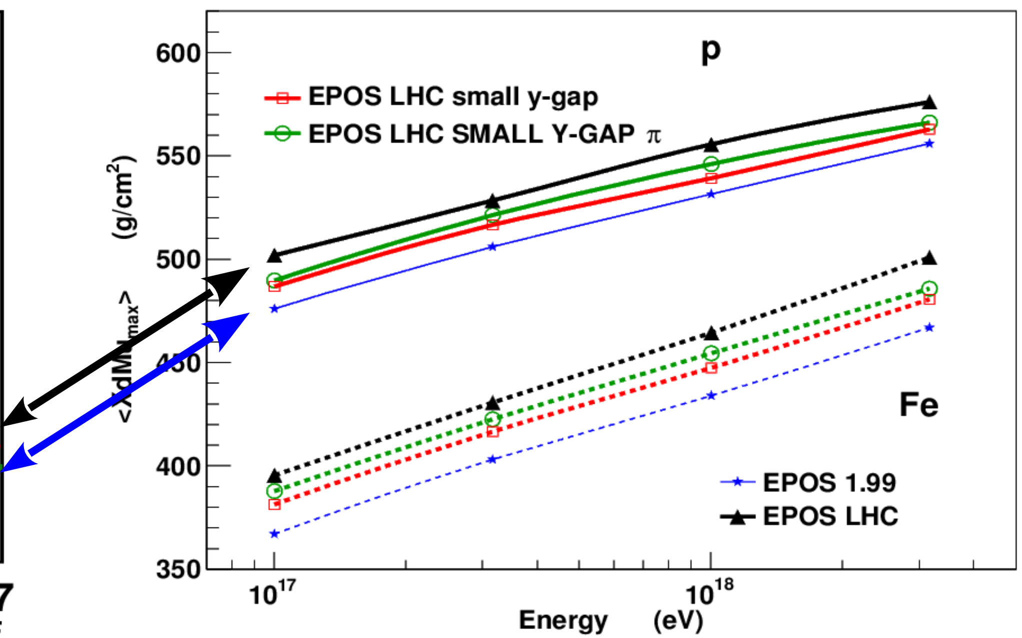
MPD and Diffraction

Inelasticity linked to diffraction (cross-section and mass distribution)

- weak influence on EM X_{max} since only 1st interaction really matters
- cumulative effect for X^{μ}_{max} since muons produced at the end of hadr. subcasc.
- rapidity-gap in p-p @ LHC not compatible with measured MPD
- harder mass spectrum for pions reduce X^{μ}_{max} and increase muon number !

different diffractive mass distribution for mesons and baryons !

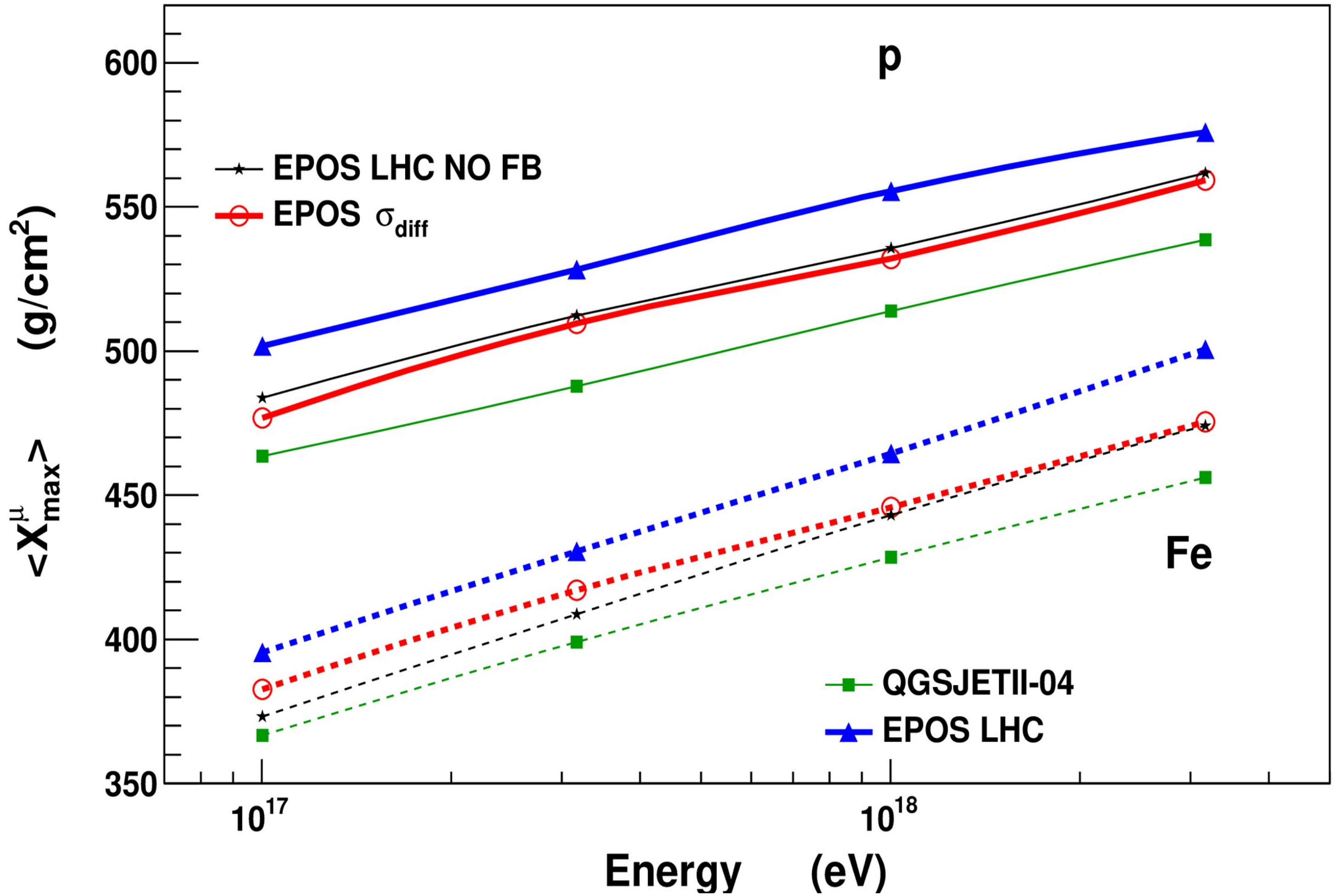




$<X^{\mu}_{max}>$ with modified EPOS LHC

Same than in mixed models

- softer meson spectra (lower elasticity) : lower X^{μ}_{max}
- less forward baryons (FB) : lower X^{μ}_{max}



-25 g/cm² for diff

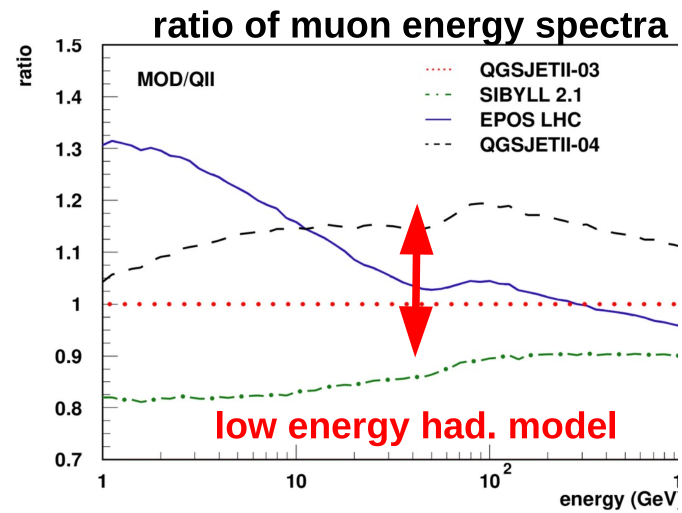
-20 g/cm² for baryons

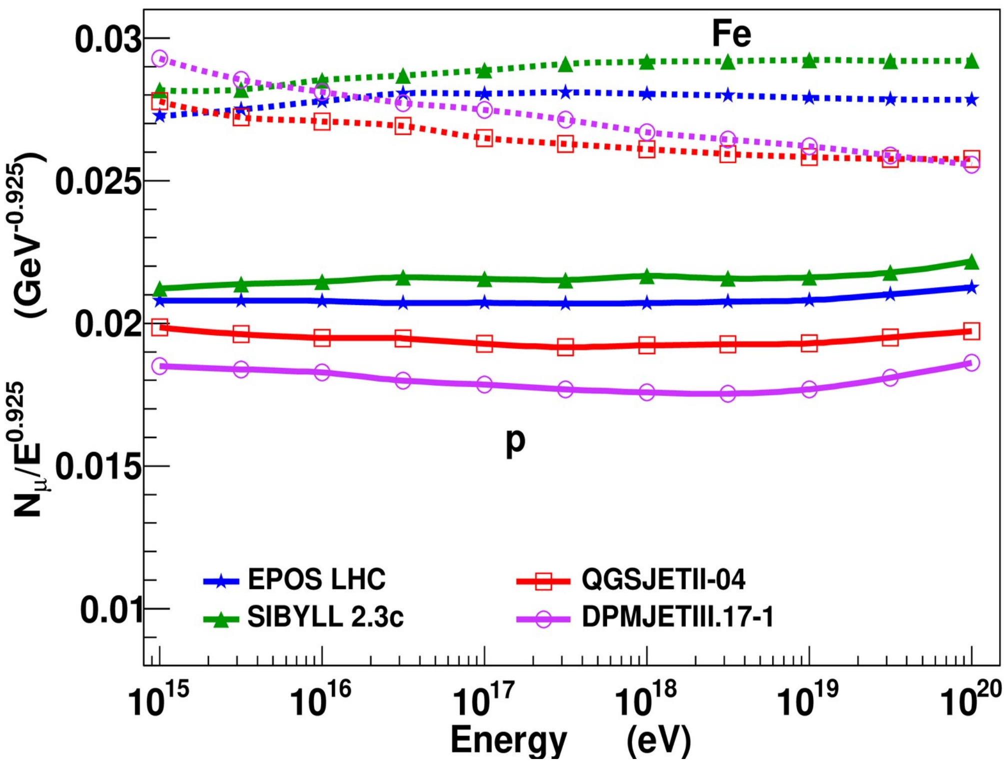
MPDs sensitive to baryon (less generation) and meson spectra in pion interactions

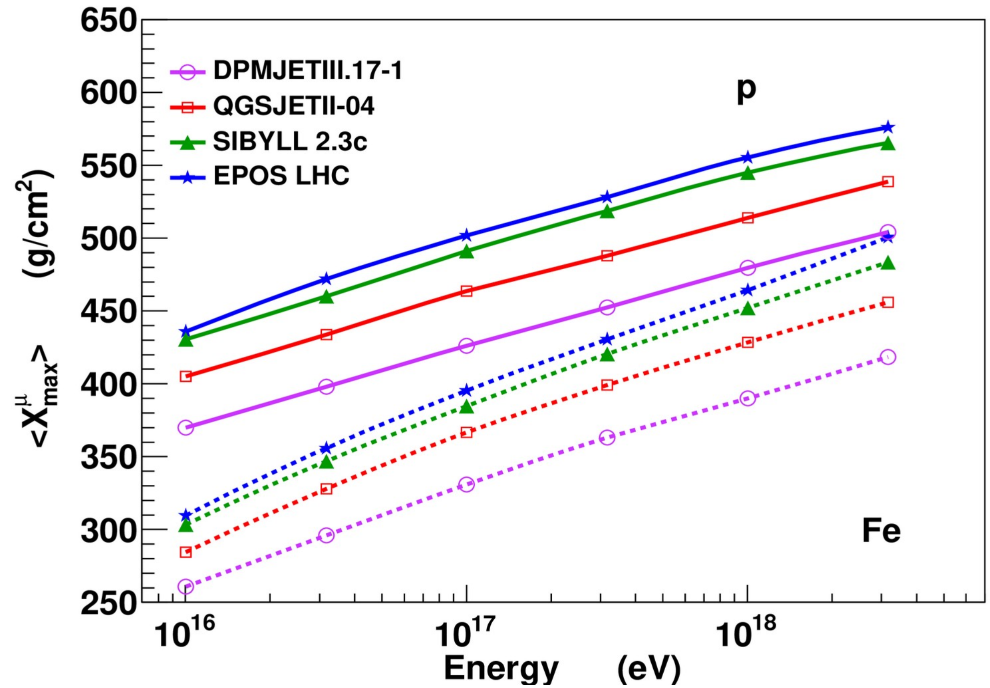
Ostapchenko et al. Phys.Rev. D93 (2016) no.5, 051501

Muons at Ground

- Muon production depends on all int. energies
- Muon production dominated by pion interactions (LHC indirectly important)
- Resonance and baryon production important
- Post-LHC Models ~ agrees on numbers but with different production height and spectra



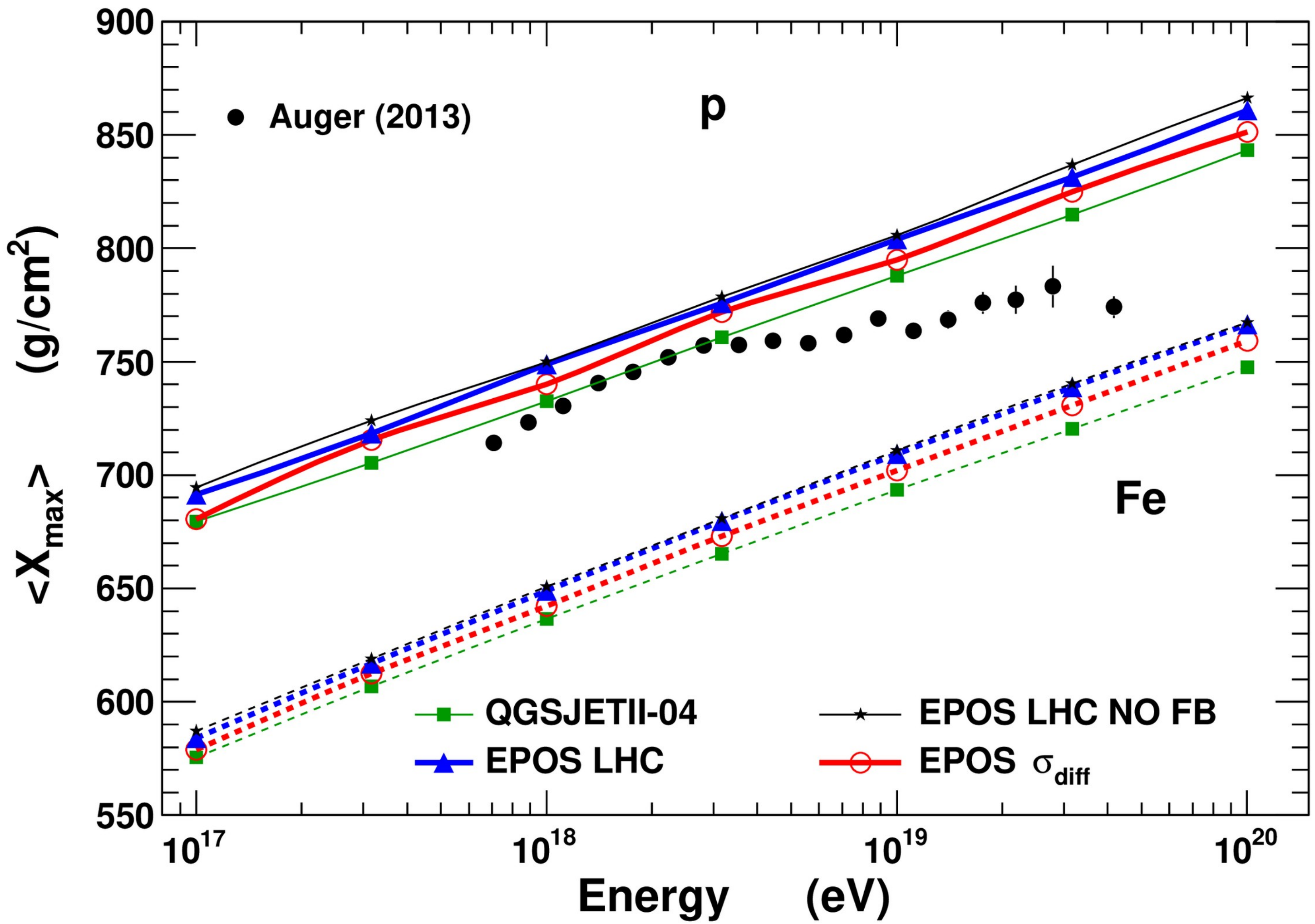




<X_{max}> with Modified EPOS

Same than in mixed models

- softer meson spectra: lower X_{max}
- forward baryons: small effect



-10 g/cm² for diff

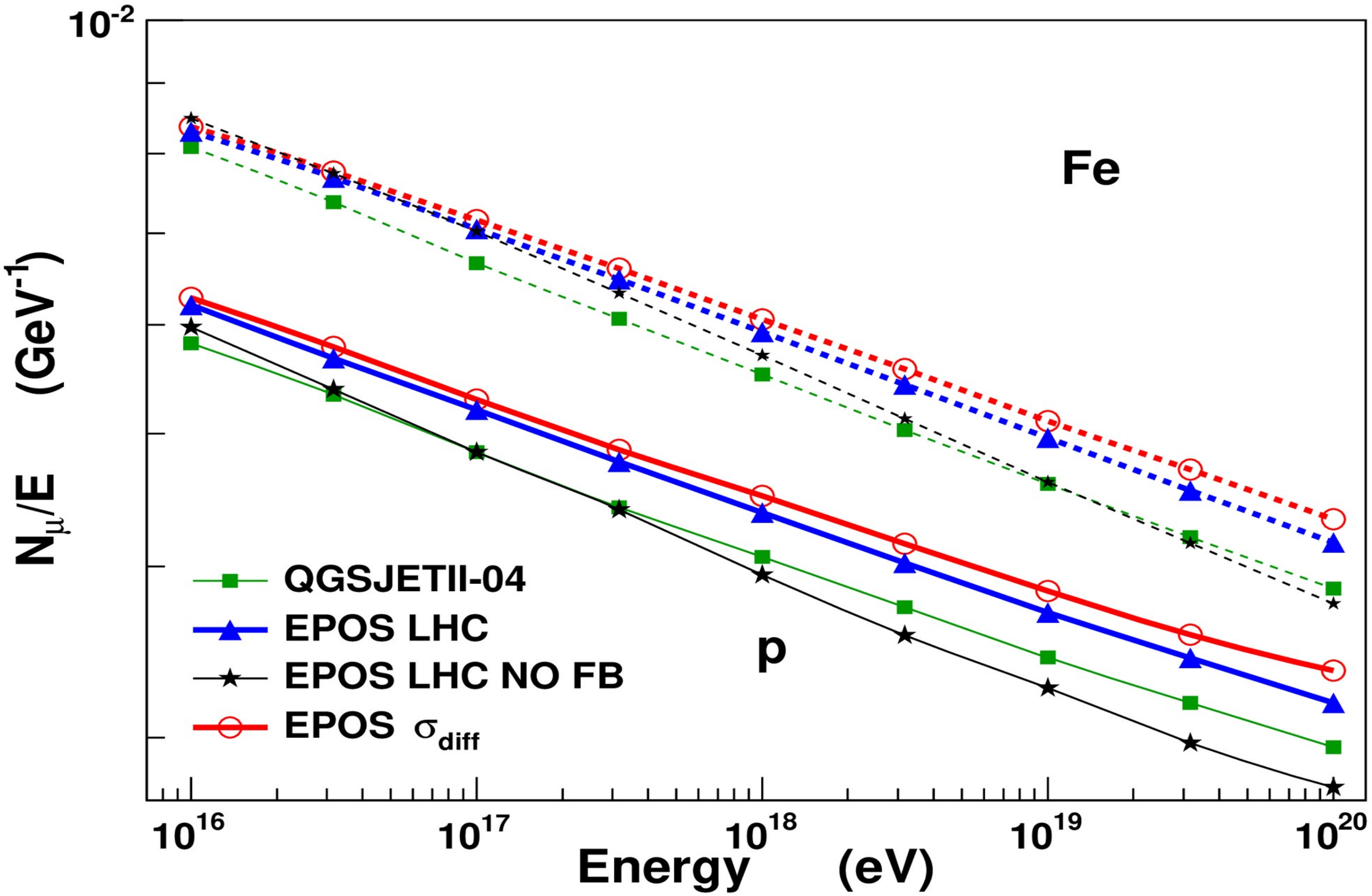
~0 g/cm² for baryons

X_{max} less sensitive to baryon spectra than to pion spectra in pion interactions

N_μ with Modified EPOS

Number of muons depends on the same parameters

- softer meson spectra: larger N_μ
- forward baryons: lower N_μ but could be compensated by ρ^0 (keep energy to produce muons but doesn't change the number of generations: lower MPD)



N_μ sensitive to baryon (less generation) and meson spectra in pion interactions

+5% for diff

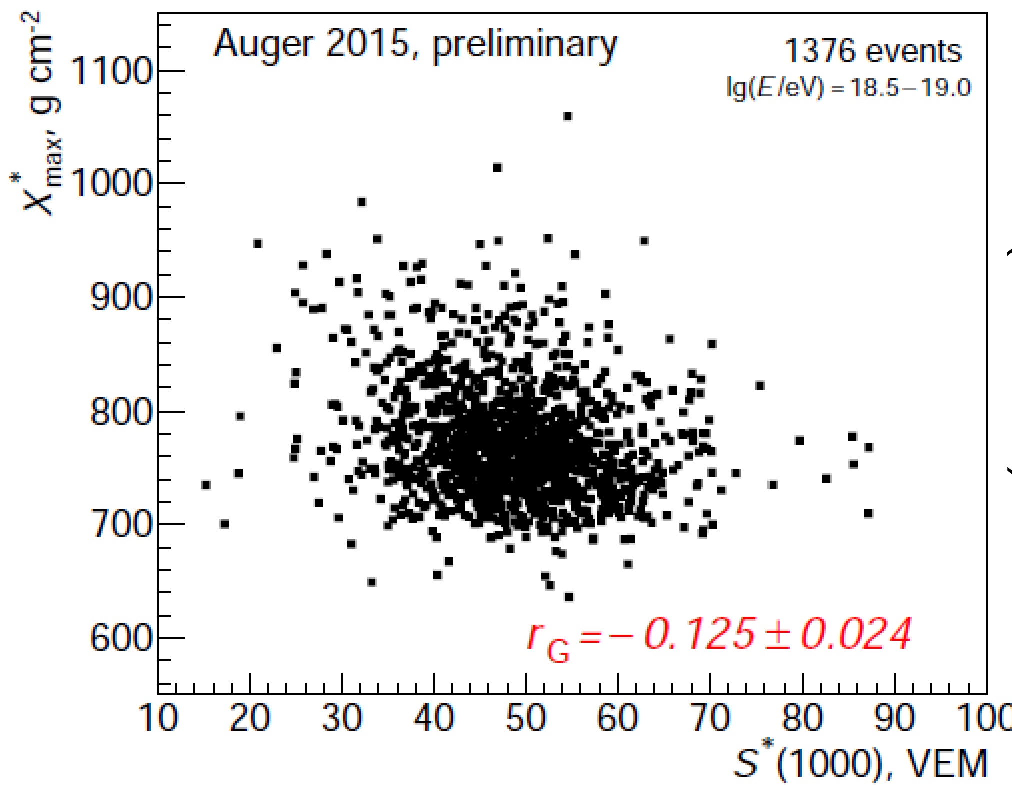
-15% without forward baryons

Correlation between X^*_{max} and $S^*(1000)$

- **in data correlation is significantly negative**
  - ➔ r_G = -0.125±0.024
- **$r_G(X^*_{max}, S^*(1000))$ for p**
  - ➔ EPOS-LHC : 0.00 (5σ to data)
  - ➔ QGSJetII-04 : +0.08 (8σ to data)
  - ➔ Sibyll 2.1 : +0.07 (7.5σ to data)
- **difference is larger for other pure beams**

primary composition near the `ankle' is mixed

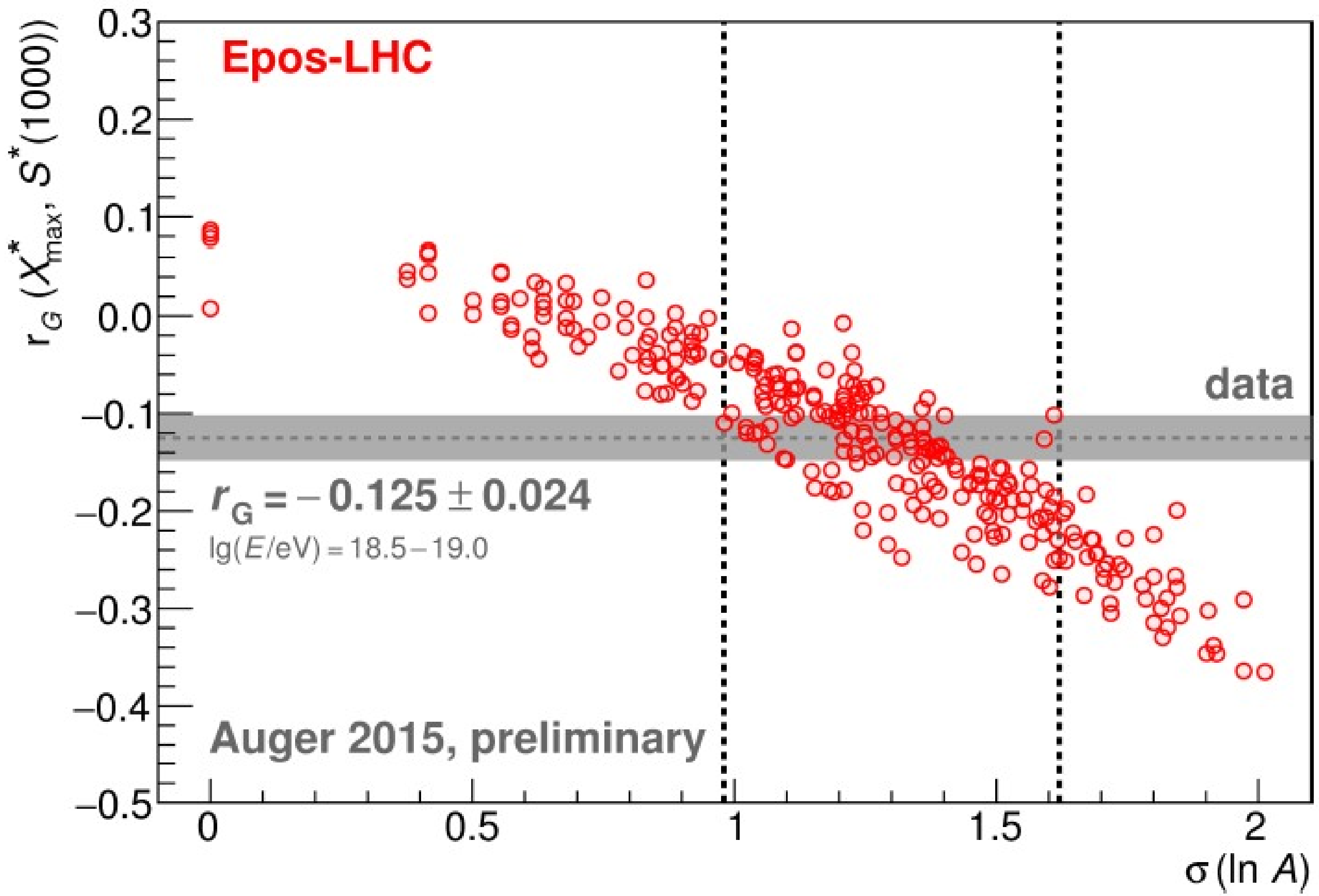
- **test of “exotic” models fails**



A. Yushkov (ICRC 2015)

r_G - rank correlation coefficient introduced in R. Gideon, R. Hollister, JASA 82 (1987) 656

Dispersion of Masses in Data



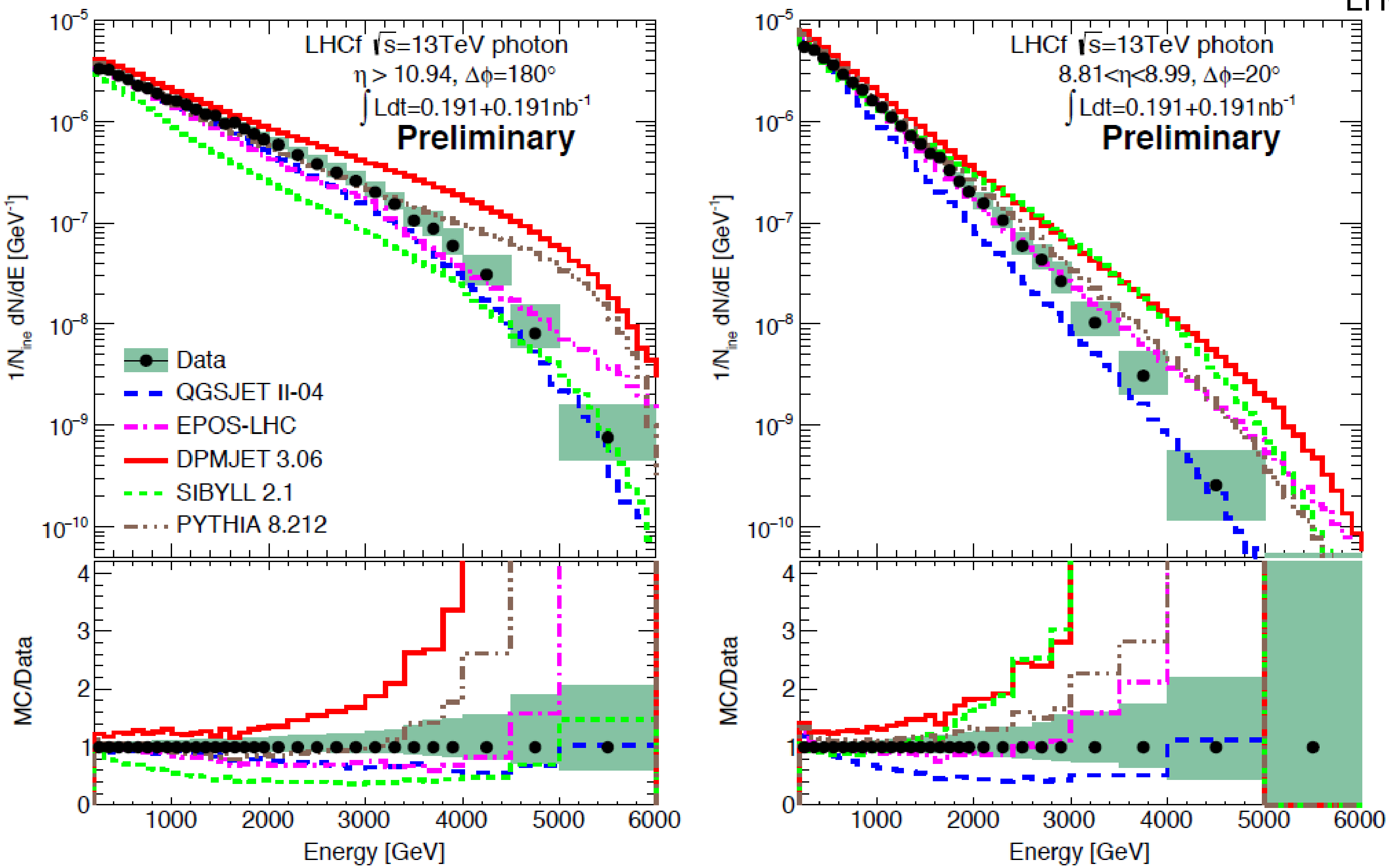
A. Yushkov (ICRC 2015)

data are compatible with 1.0 ≲ σ(ln A) ≲ 1.7

Comparison with LHCf

- LHCf favor not too soft photon spectra (EPOS LHC, SIBYLL 2.3) : deep X_{max}
- No model compatible with all LHCf measurements : room for improvments !
- Can p-Pb data be used to mimic light ion (Air) interactions ?

T.Sako for the LHCf collaboration



Baryons in Pion-Carbon

- **Very few data for baryon production from meson projectile, but for all :**
  - ➡ strong baryon acceleration (probability ~20% per string end)
  - ➡ proton/antiproton asymmetry (valence quark effect)
  - ➡ target mass dependence

- **New data set from NA49 (G. Veres' PhD)**
  - ➡ test π^+ and π^- interactions and productions at 158 GeV with C and Pb target
  - ➡ confirm large forward proton production in π^+ and π^- interactions but not for anti-protons
    - ◆ forward protons in pion interactions are due to strong baryon stopping (nucleons from the target are accelerated in projectile direction)
    - ◆ strong effect only at low energy

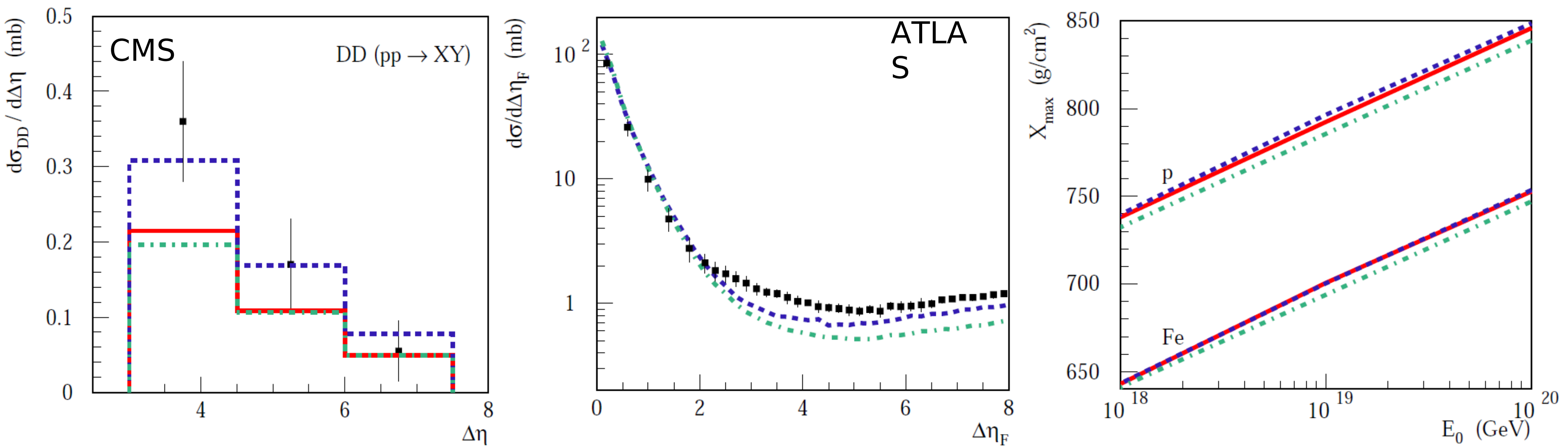
➡ EPOS overestimate forward baryon production at high energy

Diffraction measurements

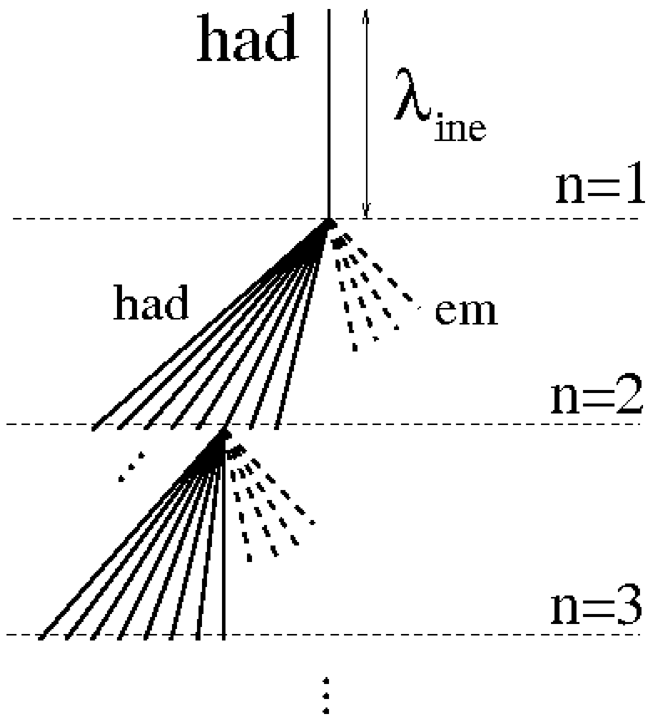
- **TOTEM and CMS diffraction measurement not fully consistent**
- **Tests by S. Ostapchenko using QGSJETII-04** **(PRD89 (2014) no.7, 074009)**
  - ➡ SD+ option compatible with CMS
  - ➡ SD- option compatible with TOTEM

M_X range	< 3.4 GeV	$3.4 - 1100$ GeV	$3.4 - 7$ GeV	$7 - 350$ GeV	$350 - 1100$ GeV
TOTEM [13, 24]	2.62 ± 2.17	6.5 ± 1.3	$\simeq 1.8$	$\simeq 3.3$	$\simeq 1.4$
QGSJET-II-04	3.9	7.2	1.9	3.9	1.5
option SD+	3.2	8.2	1.8	4.7	1.7
option SD-	2.6	7.2	1.6	3.9	1.7

- ➡ difference of ~10 gr/cm^2 between the 2 options



Simplified Shower Development



$$N_{tot} = N_{had} + N_{em}$$

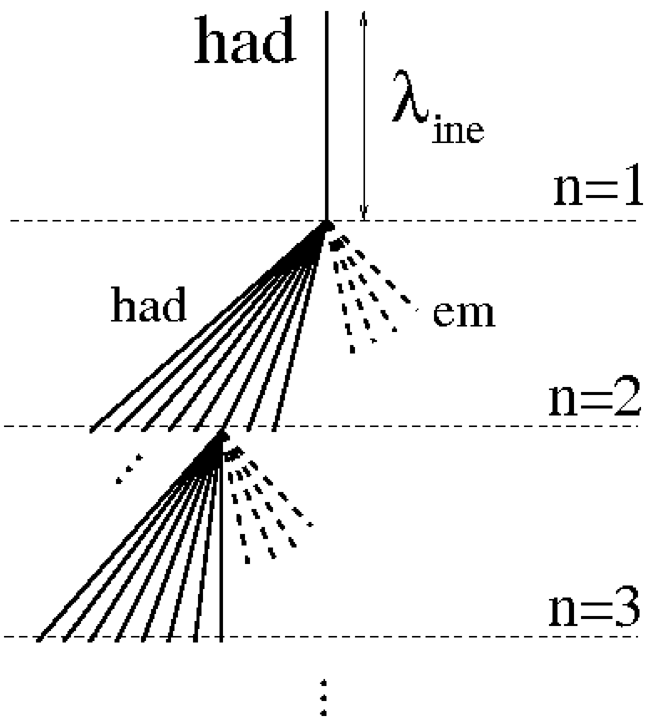
J. Matthews, Astropart.Phys. 22 (2005) 387-397

Using generalized Heitler model and superposition model :

$$X_{max} \sim \lambda_e \ln\left((1-k) . E_0 / (2.N_{tot} . A)\right) + \lambda_{ine}$$

- Model independent parameters :
  - E_0 = primary energy
  - A = primary mass
  - λ_e = electromagnetic mean free path
- Model dependent parameters :
  - k = elasticity
  - N_{tot} = total multiplicity
  - λ_{ine} = hadronic mean free path (cross section)

Toy Model for Hadronic Cascade



$$N_{tot} = N_{had} + N_{em}$$

Primary particle : hadron

Muons produced after many had. generations

N_{had}^{n} particles can produce muons after *n* interactions

$$N(n) = N_{had}^{n}$$

N_{tot}^{n} particles share E_0 after *n* interactions

$$E(n) = E_0 / N_{tot}^{n}$$

Assumption: particle decay to muon when $E = E_{dec}$ (critical energy) after n_{max} generations

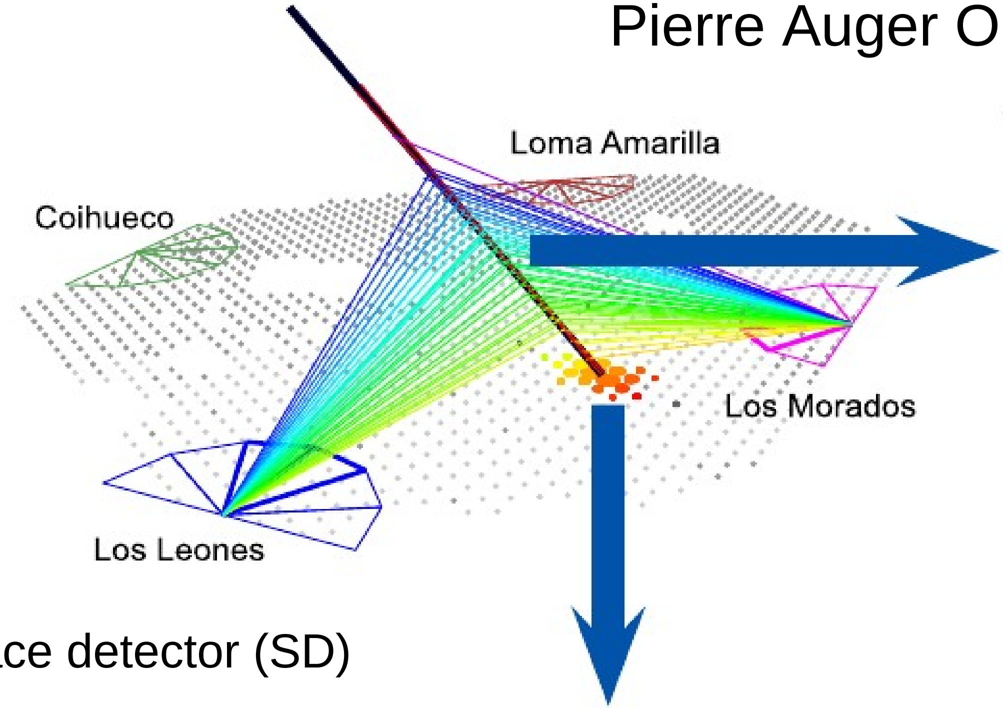
$$E_{dec} = E_0 / N_{tot}^{n_{max}}$$

$$n_{max} = \frac{\ln(E_0/E_{dec})}{\ln(N_{tot})}$$

$$\ln(N_{\mu}) = \ln(N(n_{max})) = n_{max} \ln(N_{had})$$

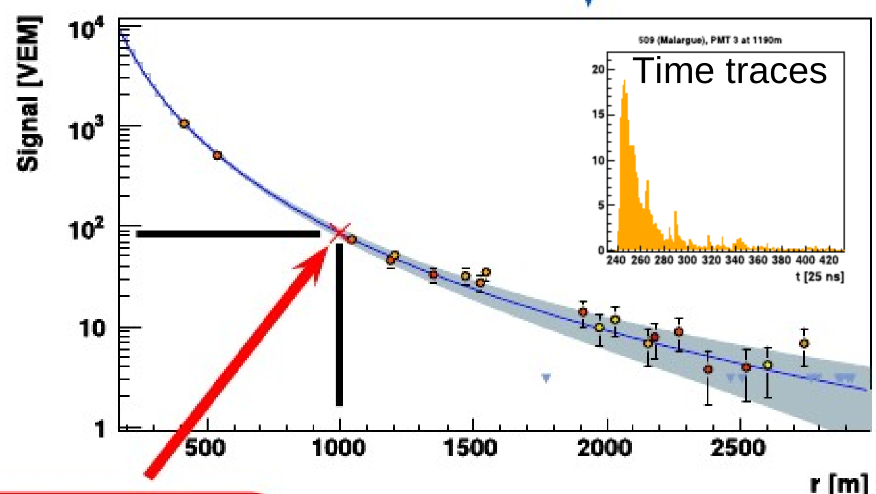
Hybrid Detection

Pierre Auger Observatory / Telescope Array



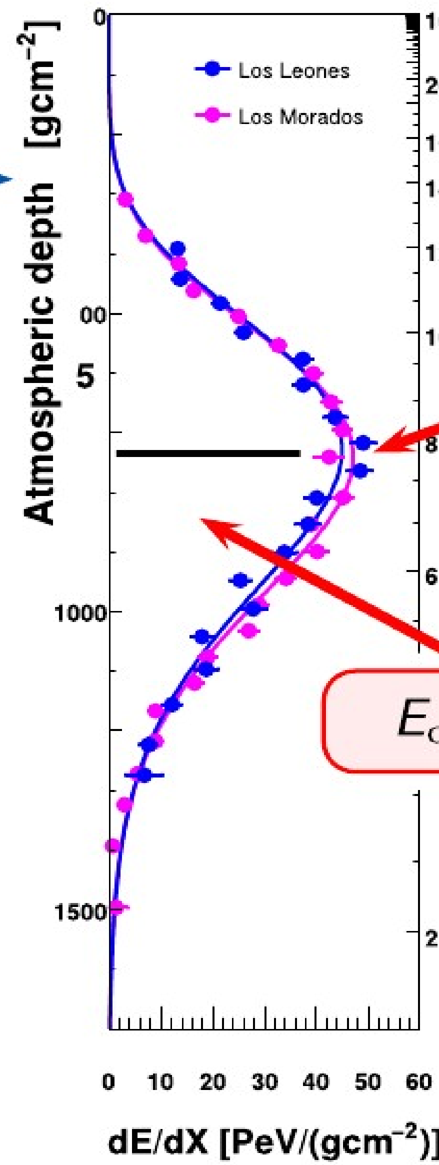
Surface detector (SD)

From R. Ulrich (KIT)



S_{1000}

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



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

X_{max}

Fluorescence detector (FD)

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

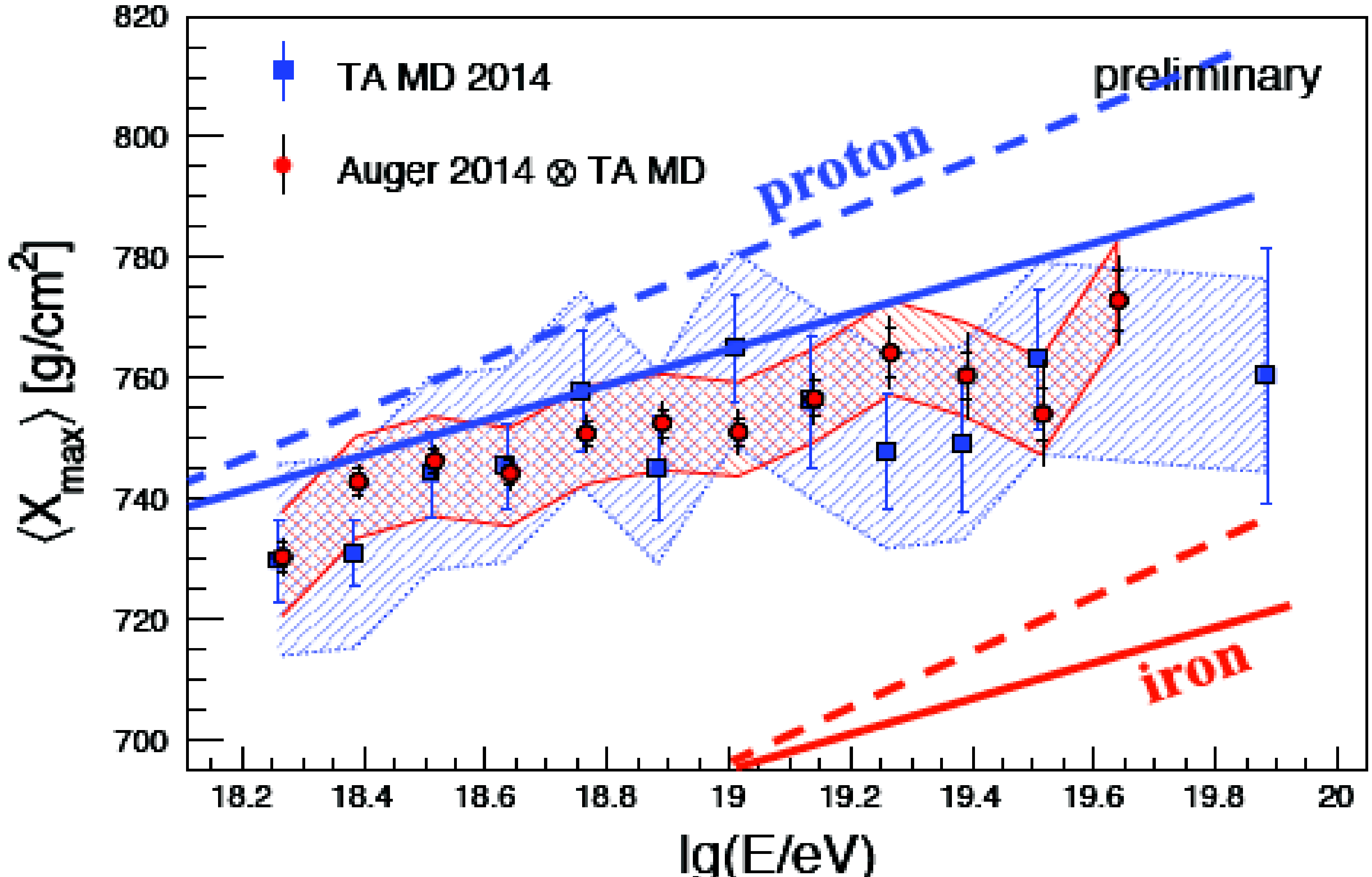
$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 14\,\%$

Various detection technique = energy scale independent of EAS simulations

Pre-LHC UHECR Composition

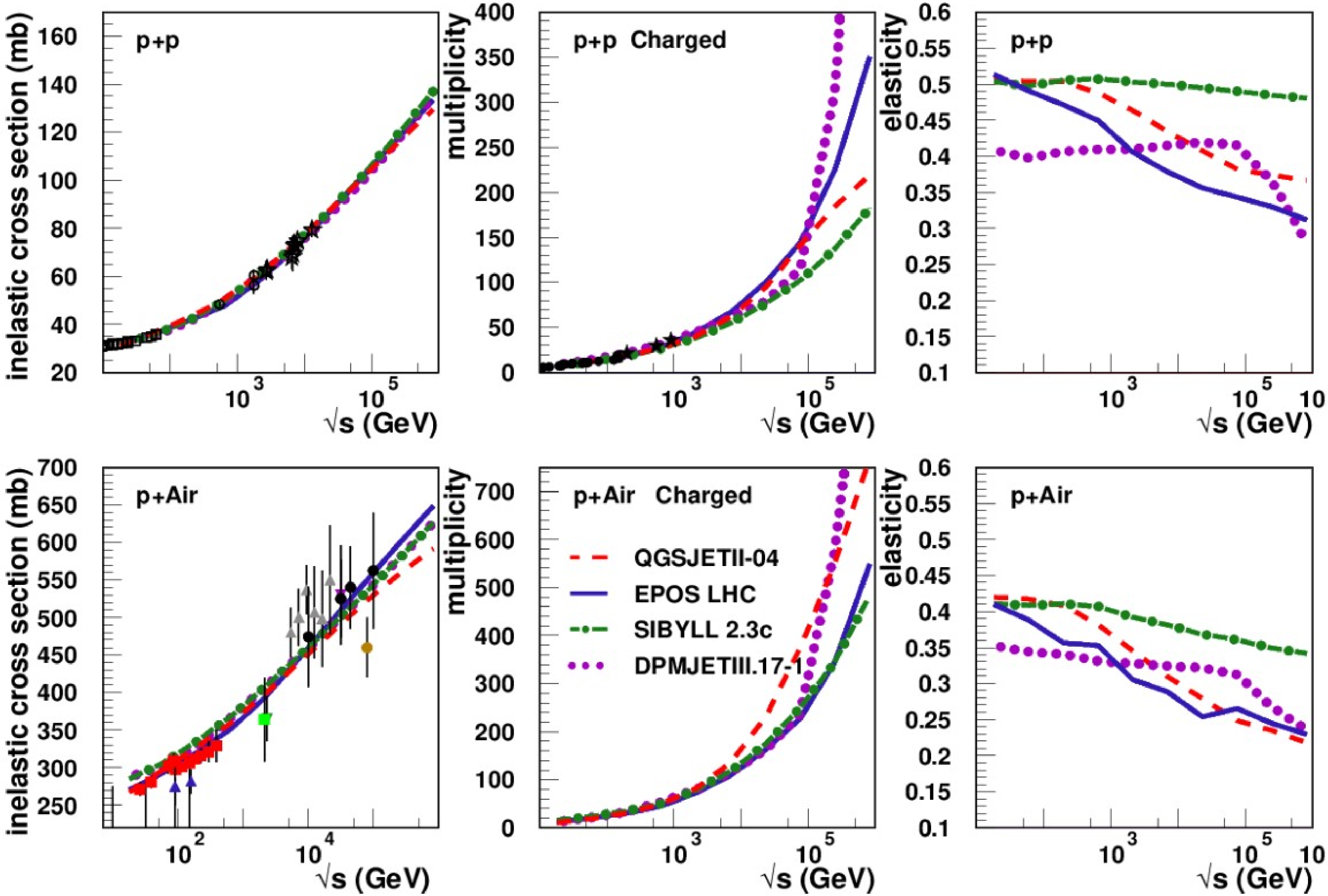
With pre-LHC models current CR data would be difficult to interpret

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

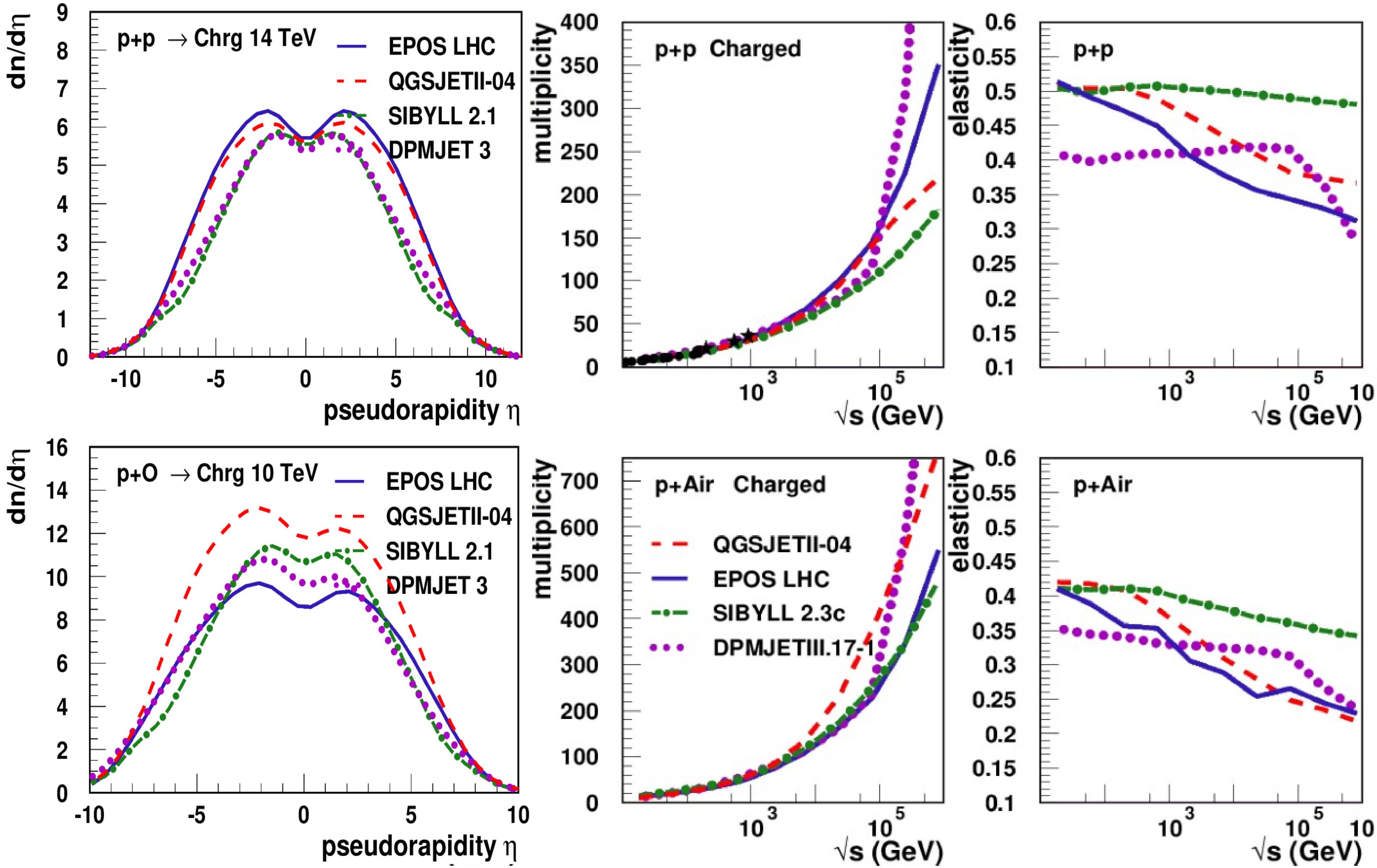


Roberto Aloiso UHECR (2015 PAO/TA working group)

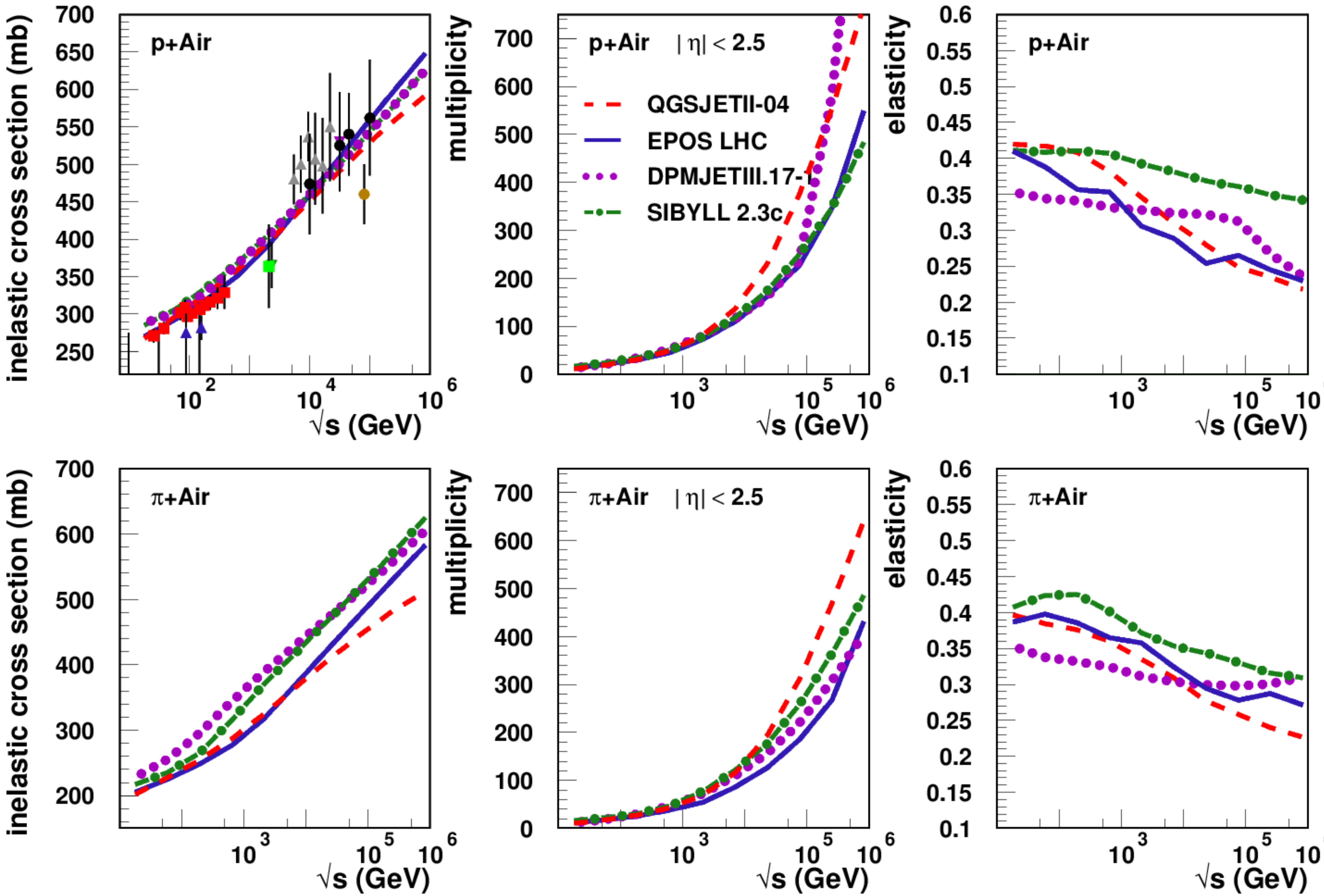
Ultra-High Energy Hadronic Model Predictions p-Air



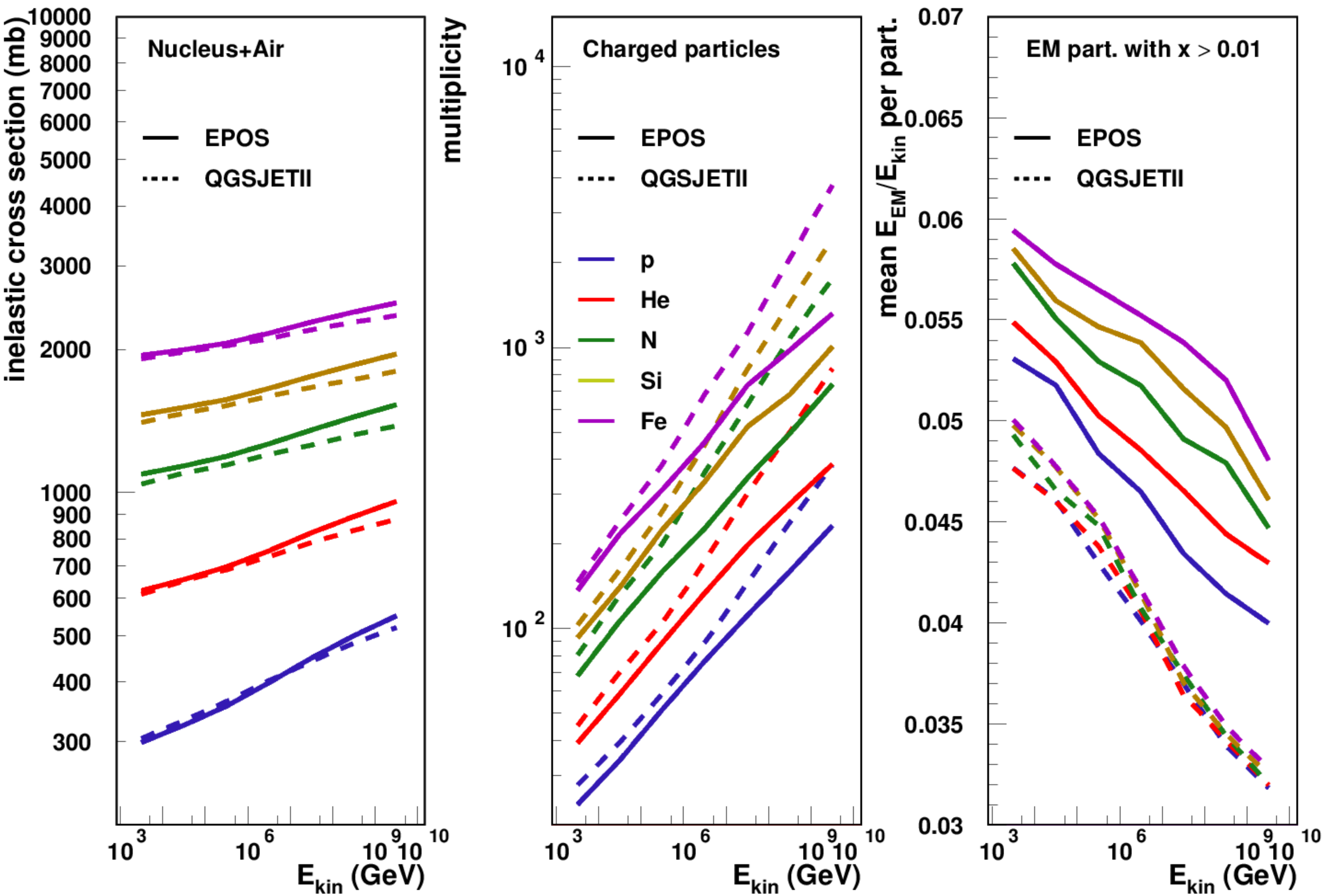
Ultra-High Energy Hadronic Model Predictions p-Air



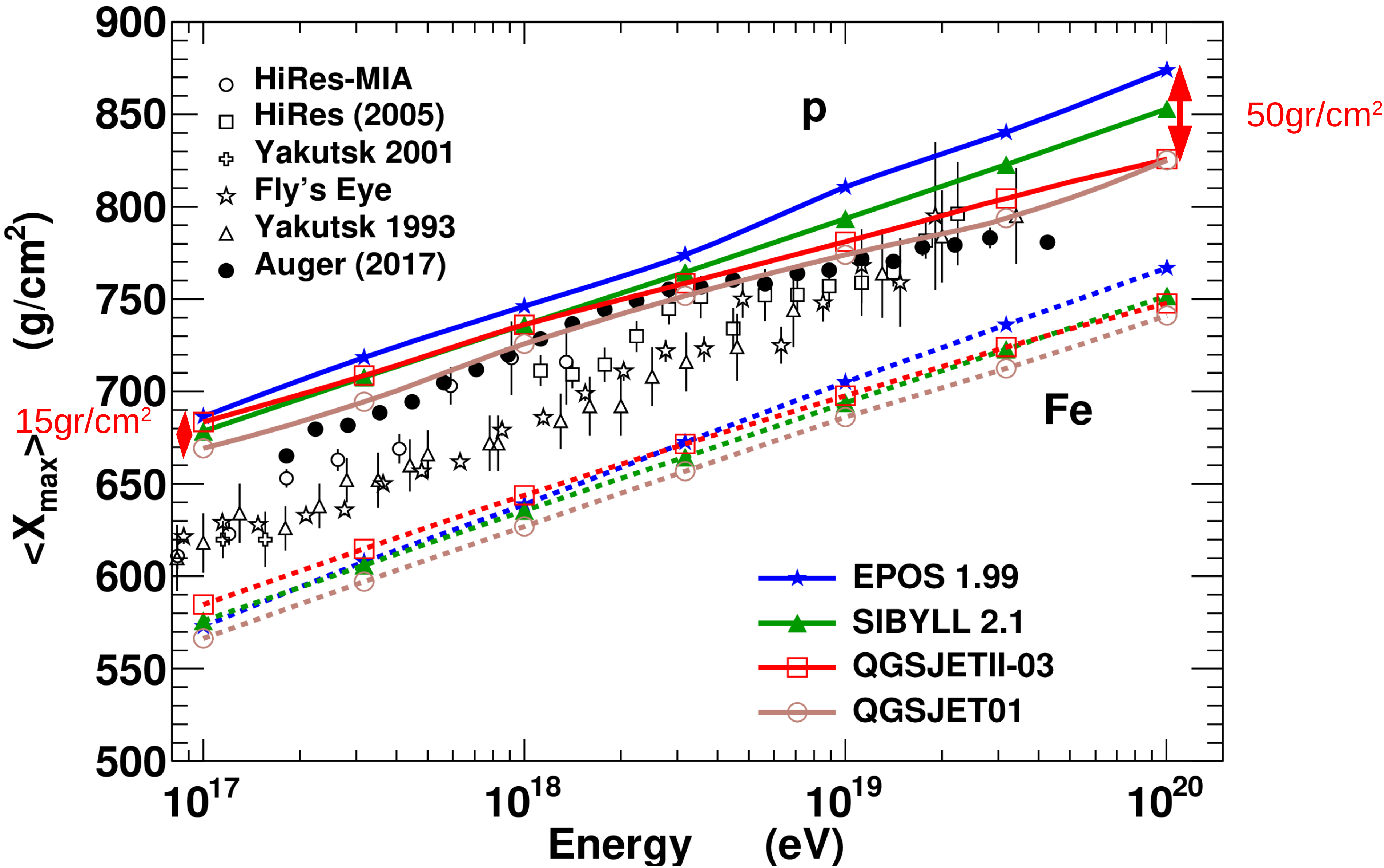
Ultra-High Energy Hadronic Model Predictions π-Air



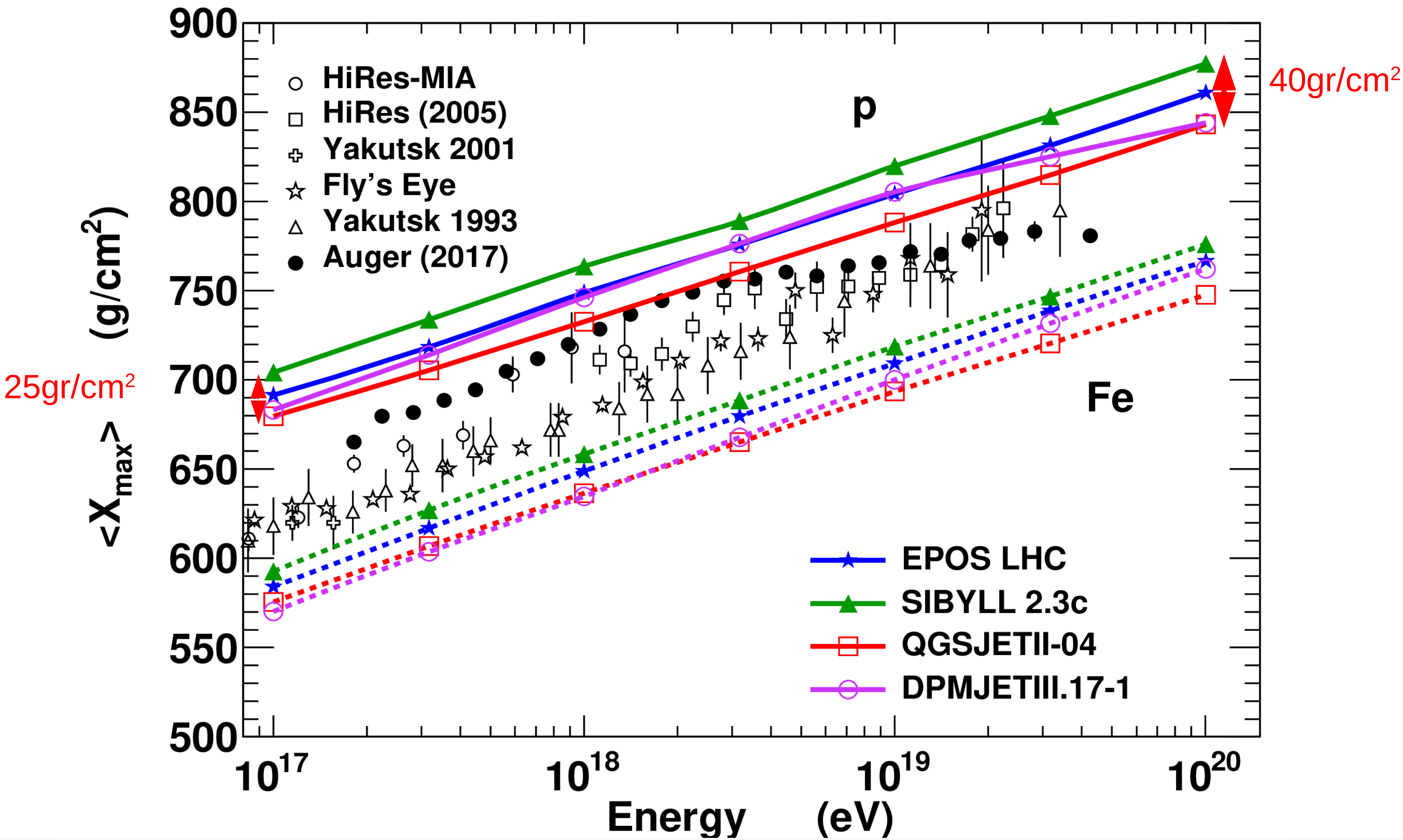
Ultra-High Energy Hadronic Model Predictions A-Air



EAS with Old CR Models : X_{max}

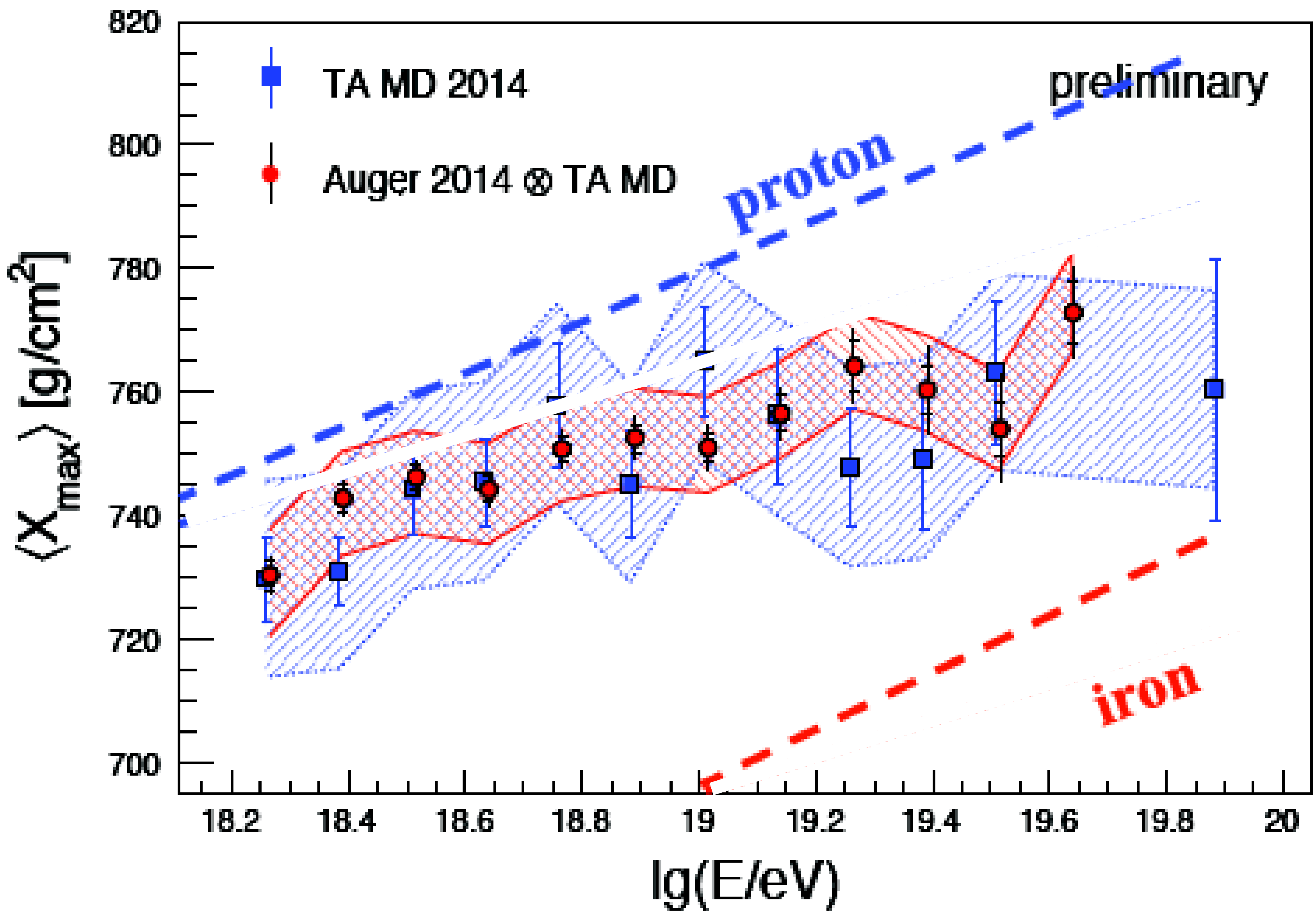


EAS with Re-tuned CR Models : X_{max}



Post-LHC Composition

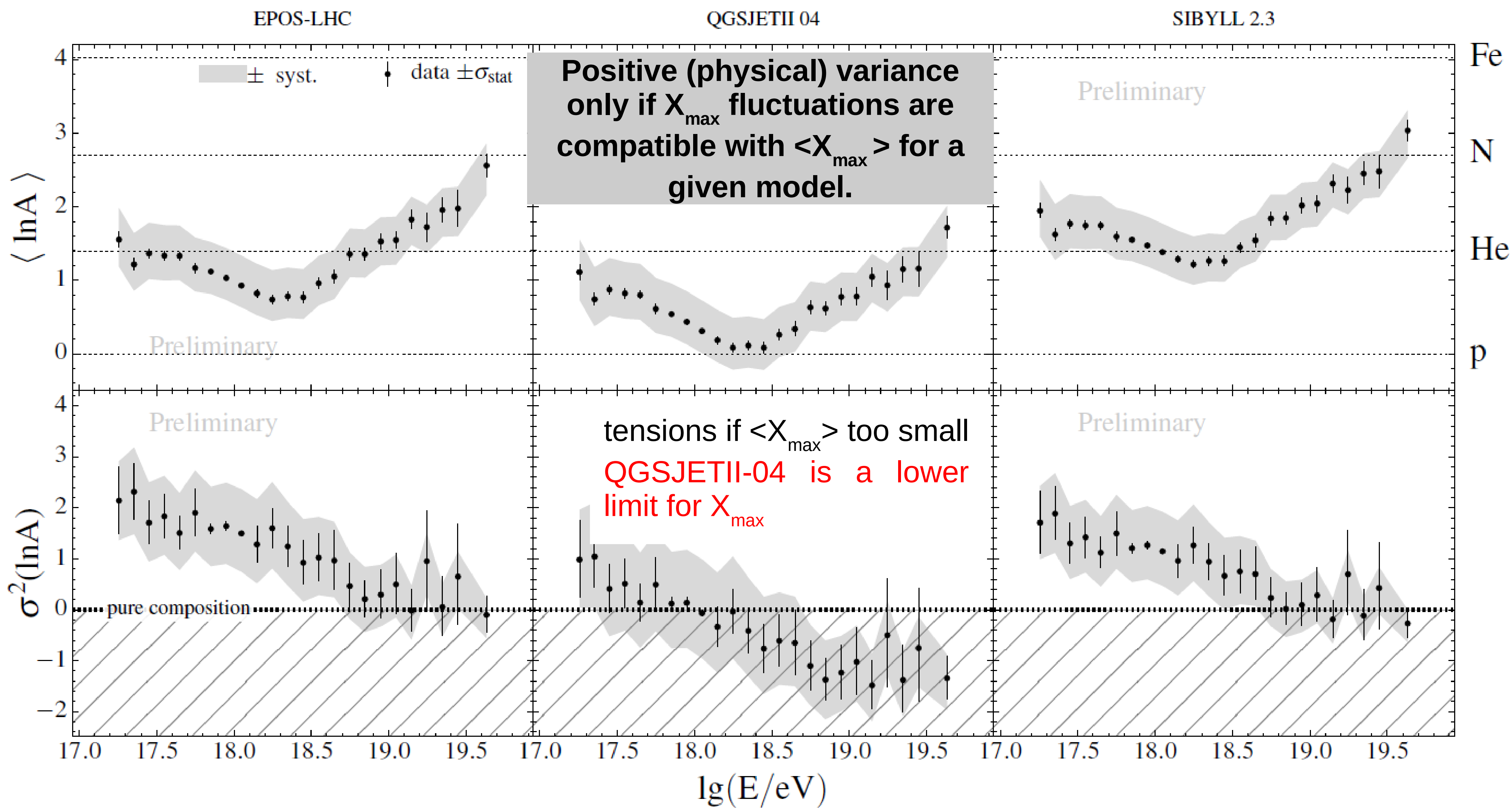
With post-LHC models there is no doubt about mixed composition



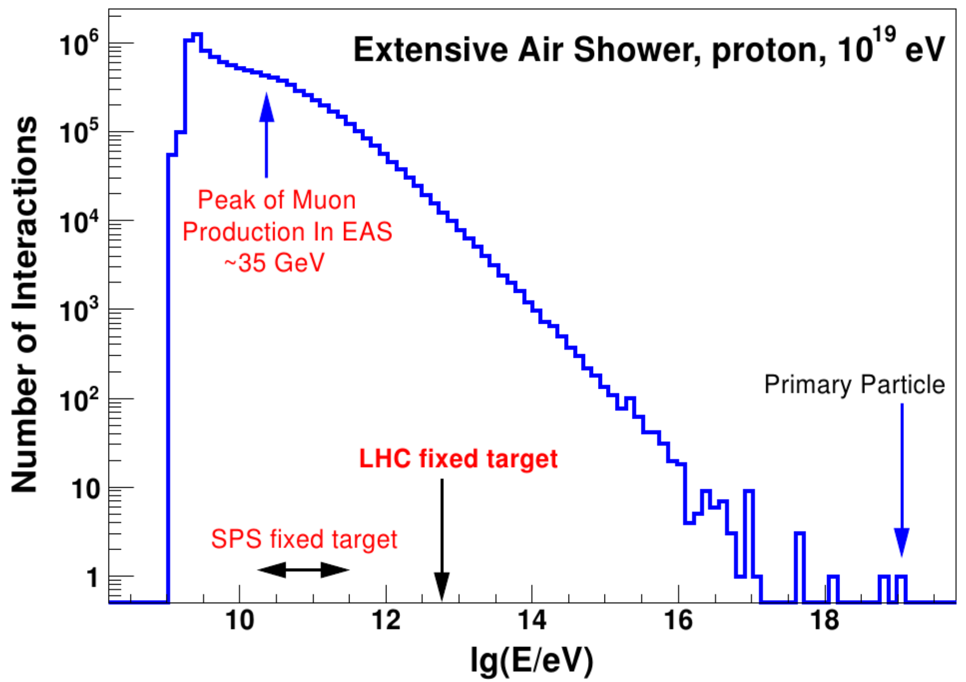
Model Consistency using Electromagnetic Component

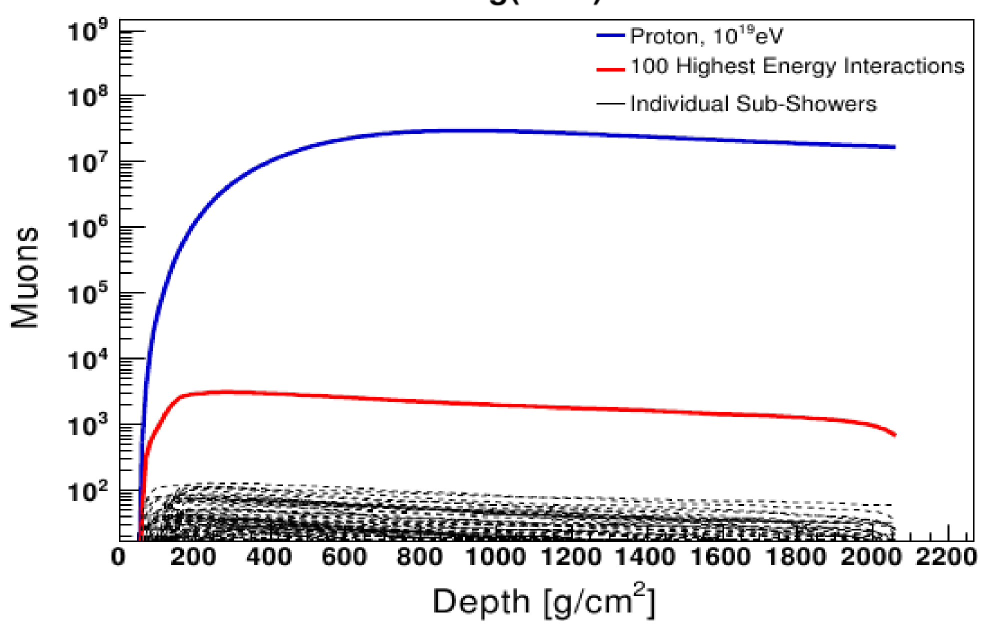
Study by Pierre Auger Collaboration (ICRC 2017)

➡ std deviation of lnA allows to test model consistency.



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

Core in p-p (early LHC data)

Detailed description can be achieved with core in pp

- identified spectra: different strangeness between string (low) and stat. decay (high)
- p_t behavior driven by collective effects (statistical hadronization + flow)
  - larger effect for multi-strange baryons (yield AND <p_t>)