Hadronic interactions and air showers : the need of Oxygen beam with LHCf

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OppOrtunities of OO and pO collisions at the LHC, CERN (remote)

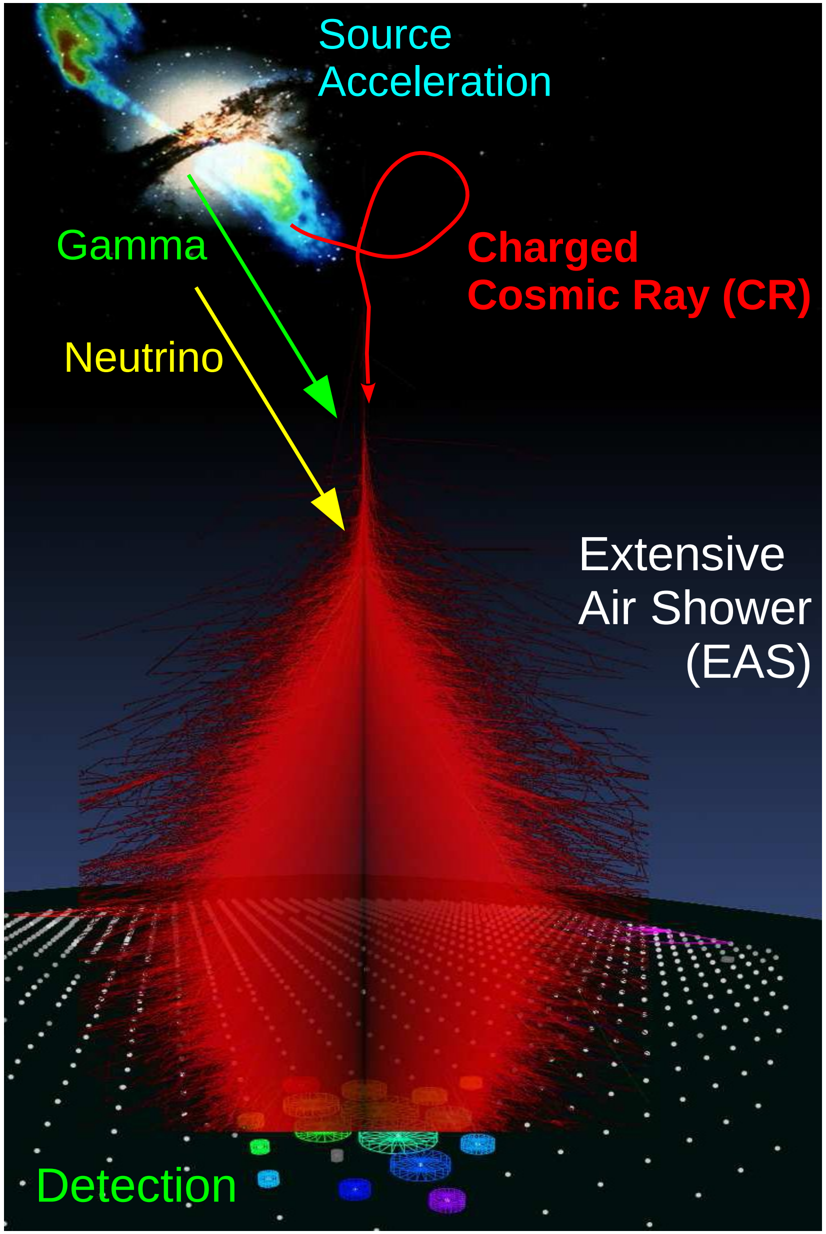
February the 10th 2021

Outline

- **Introduction on astroparticle physics and Extended air showers (EAS)**
- **Hadronic interactions for cosmic rays (Monte-carlo (MC))**
- **Constraints from LHCf**
- **More input from pO collisions**

New input from LHC in RUN3 crucial to reproduce EAS data consistently: too large uncertainties in model for forward spectra and light ion interactions.

Astroparticles

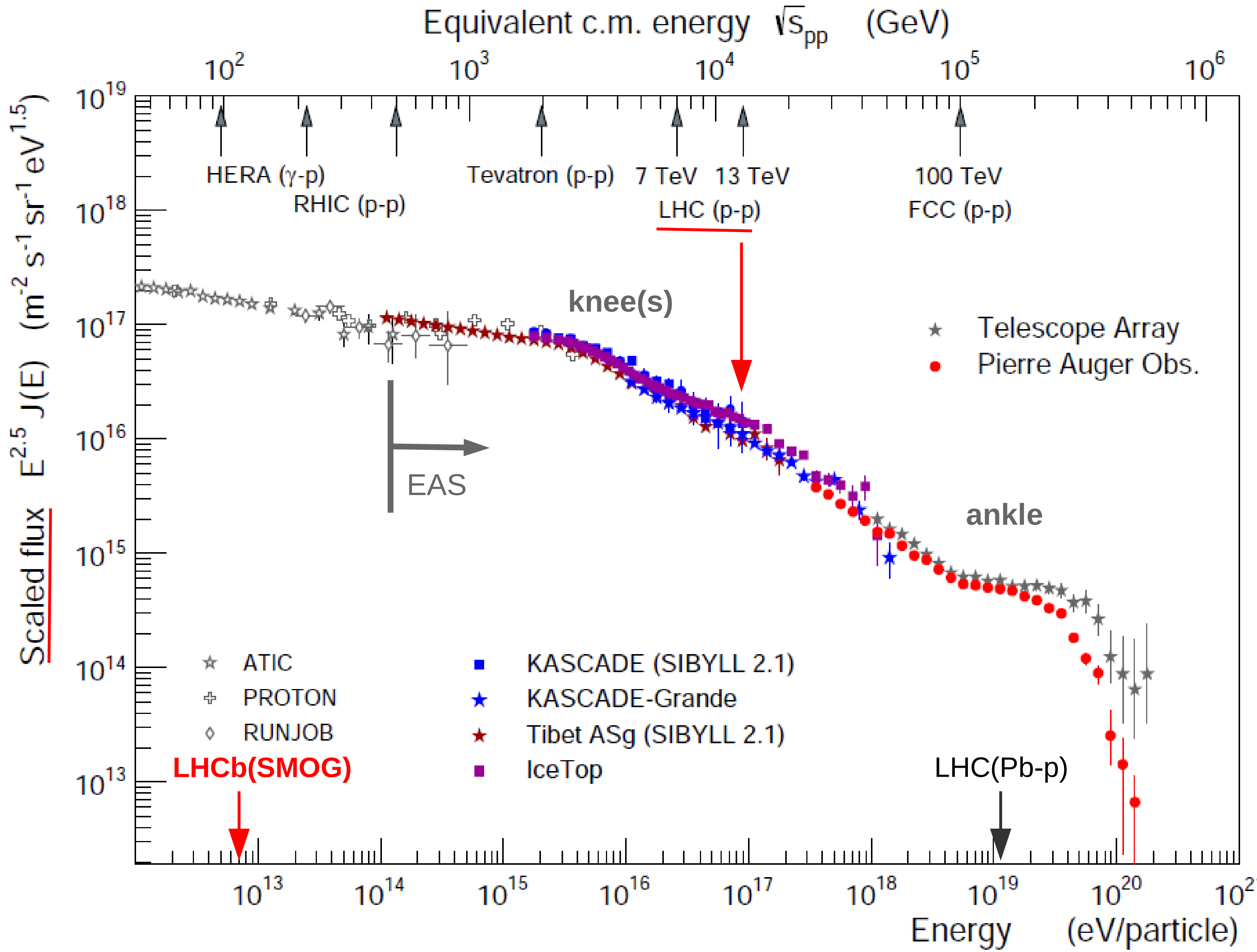


From R. Ulrich (KIT)

- **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

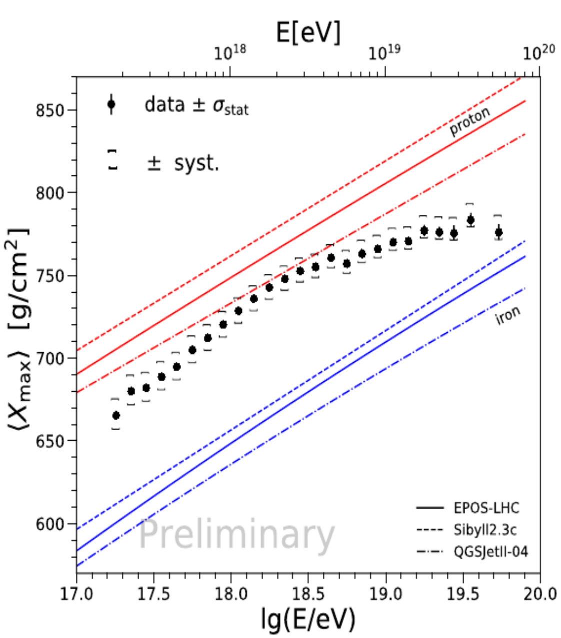
Energy Spectrum

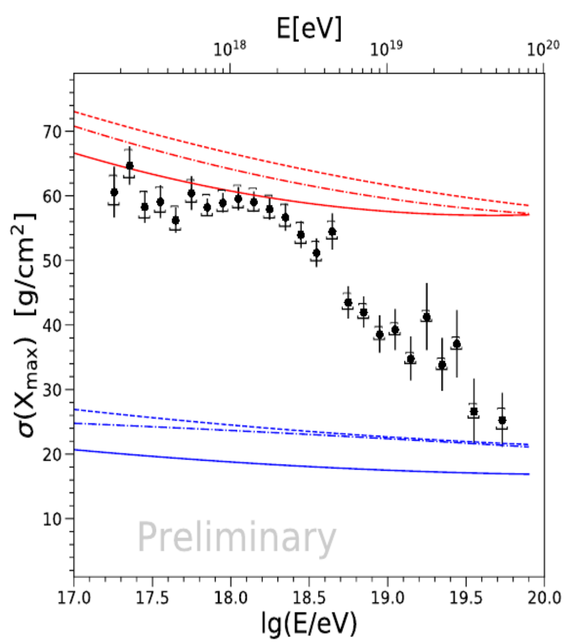


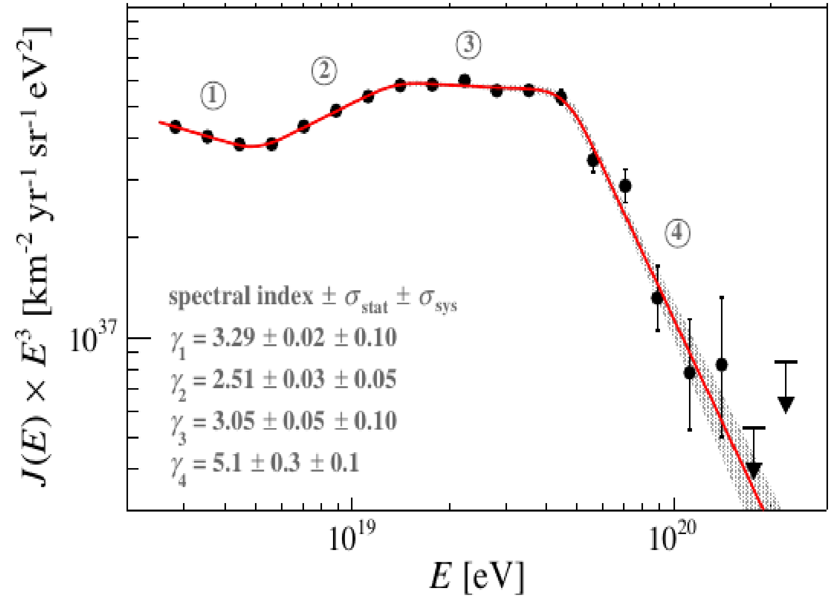
R. Engel (KIT)

Mixed Composition at High Energy

- **A precise measurement of the cosmic ray (CR) mass composition is one of the primary goal of Auger Prime (until 2030).**
  - ➜ Experimental systematic errors < Theory one
  - ➜ Differences between high energy hadronic interactions is the main source of uncertainties
- **Necessary to constrain astrophysical models**
  - ➜ Source type … but also propagation of CR in interstellar medium







Pierre Auger Collaboration

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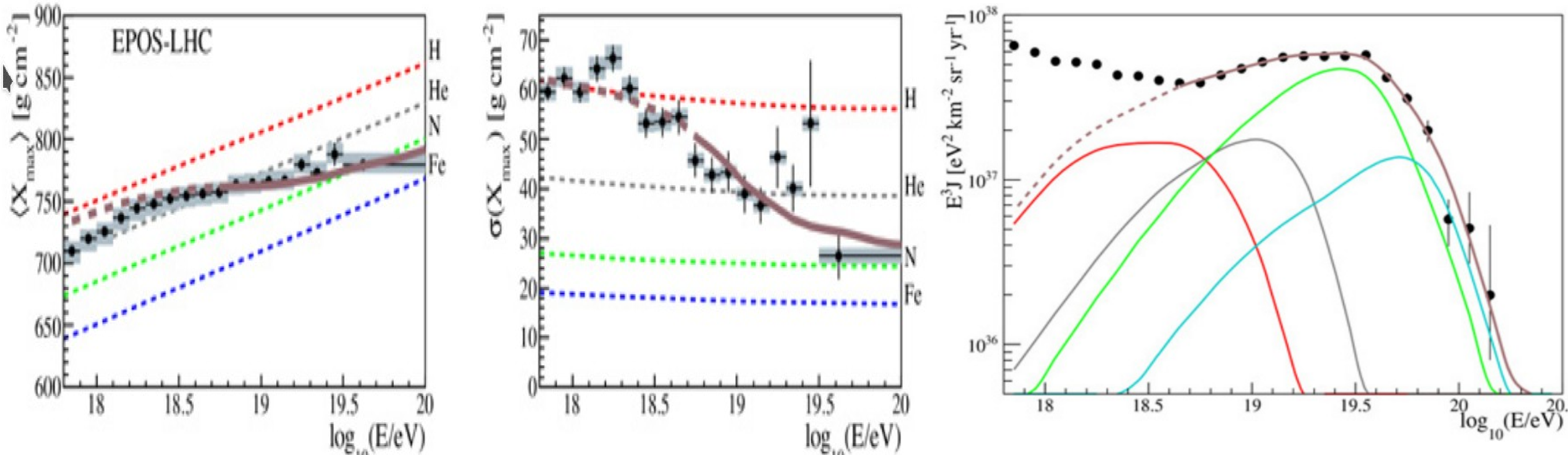
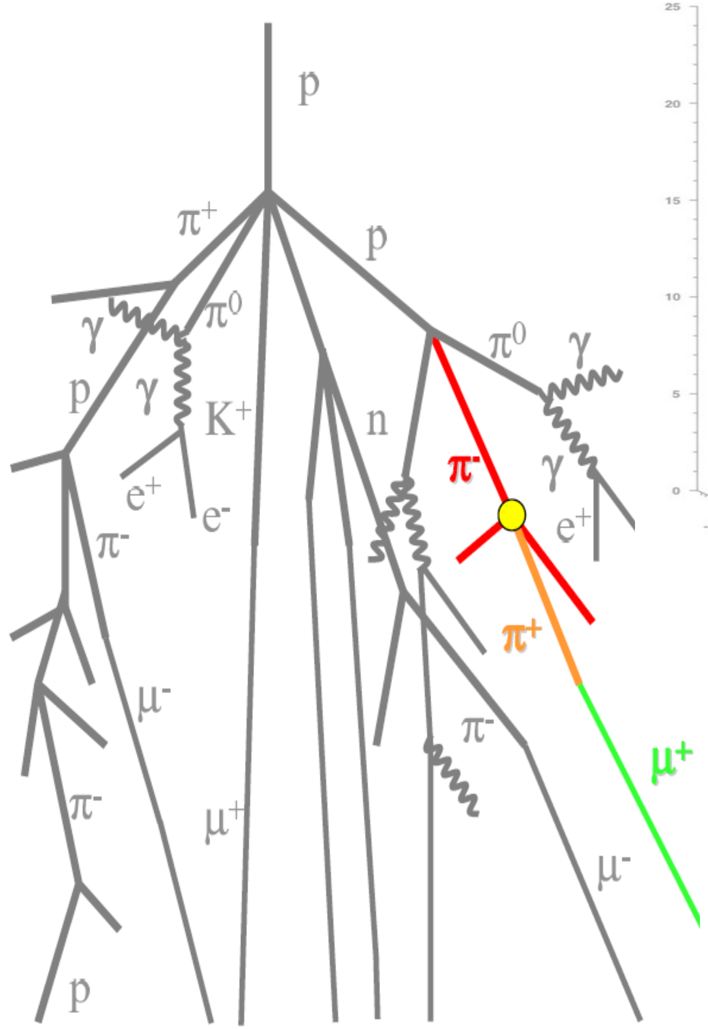
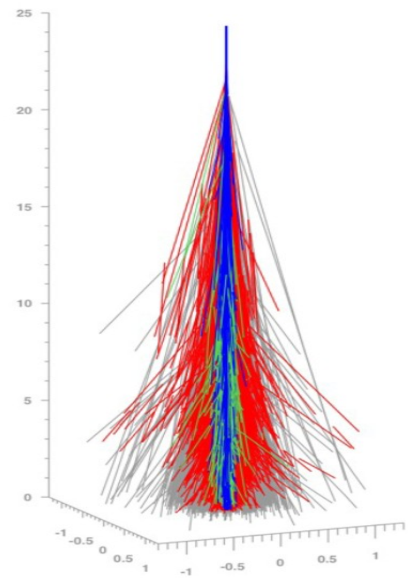


Pierre Auger Collaboration

Extensive Air Shower



From R. Ulrich (KIT)



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

hadronic physics

Air~O

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

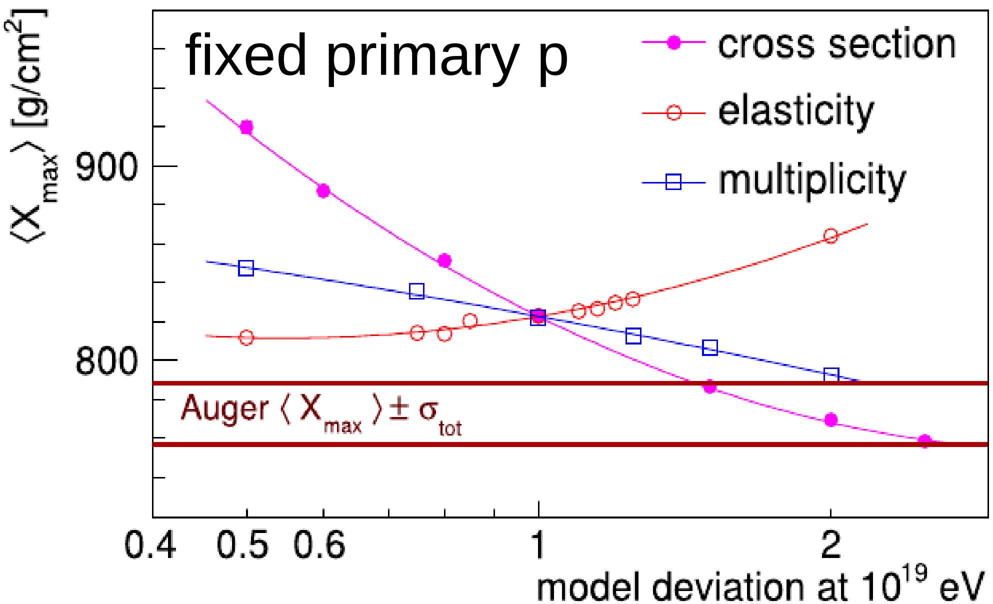
Number of particles at maximum

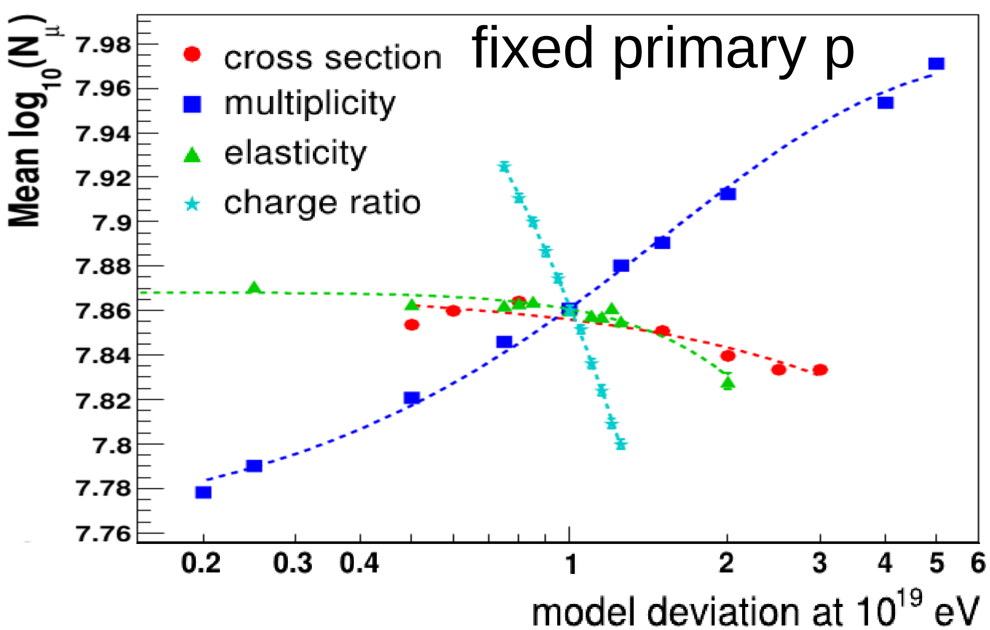
- 99,88% of electromagnetic (EM) particles
- 0.1% of muons
- 0.02% hadrons

Energy

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

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 some unknown in hadronic interactions, mass composition can not be determined precisely !

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.(17-1/19-1)** by S. Roesler, A. Fedynitch, R. Engel and J. Ranft
  - **EPOS (1.99/LHC/3/4)** (from VENUS/NEXUS before) by H.J. Drescher, B. Guiot, Iu.A. Karpenko, F. Liu, T. Pierog, G. Sophys, M. Stefaniak, 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, A. Fedynitch, R.S. Fletcher, T.K. Gaisser, P. Lipari, F. Riehn, T. Stanev

Cross-Section

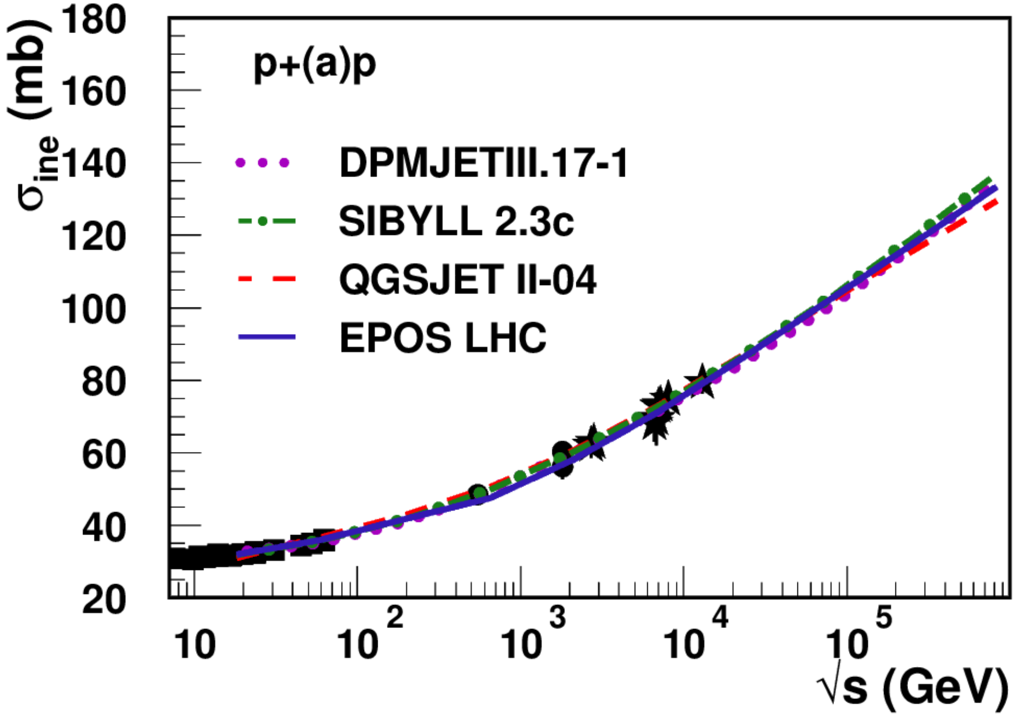
For all models cross-section calculation based on optical theorem

- total cross-section given by elastic amplitude

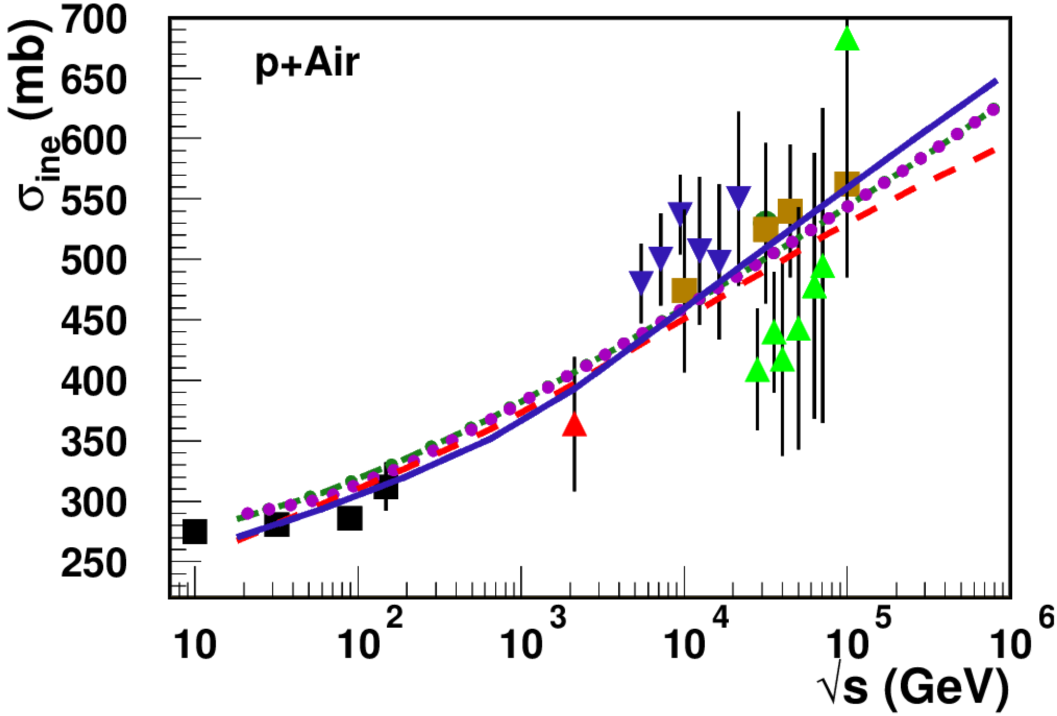
$$\sigma_{tot} = \frac{1}{s}\Im m(A(s,t \rightarrow 0))$$

- 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

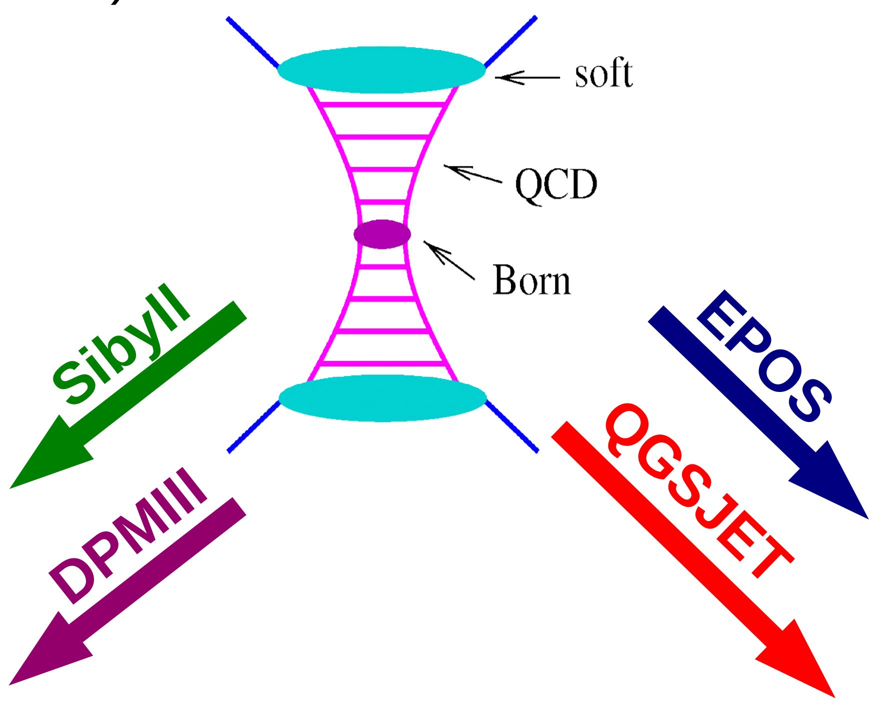


p-Air



Particle Production

- **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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  - parton, hadron, quasi-particle = Reggeon or Pomeron (vacuum excitation)
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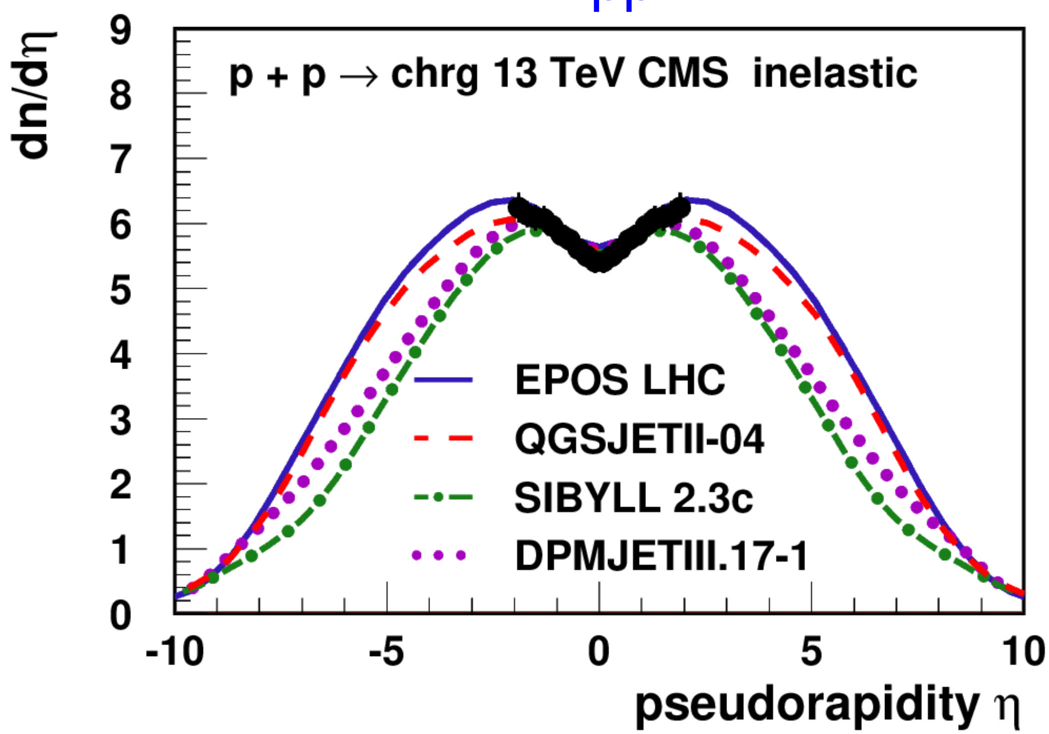
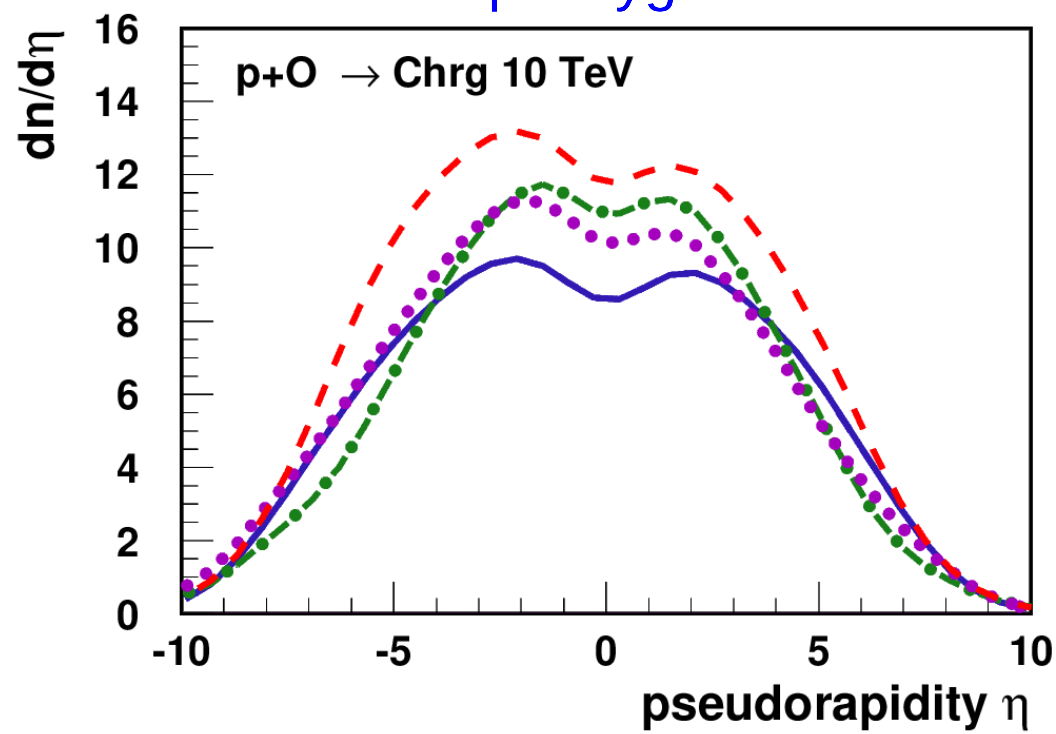


p-Oxygen



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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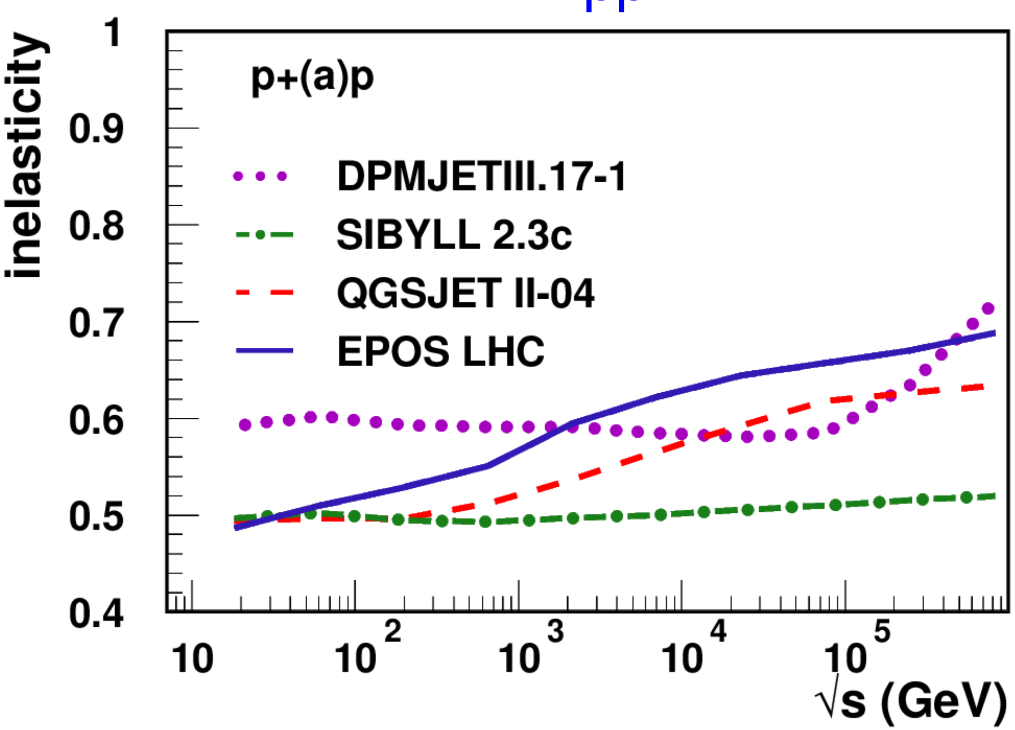
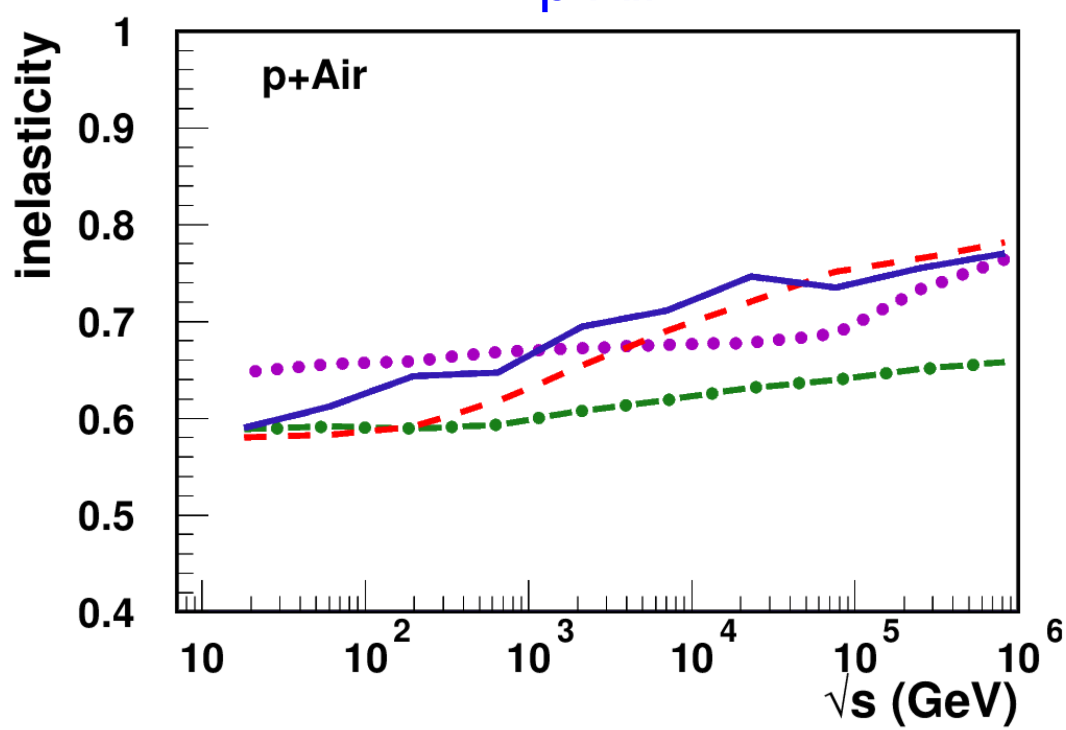


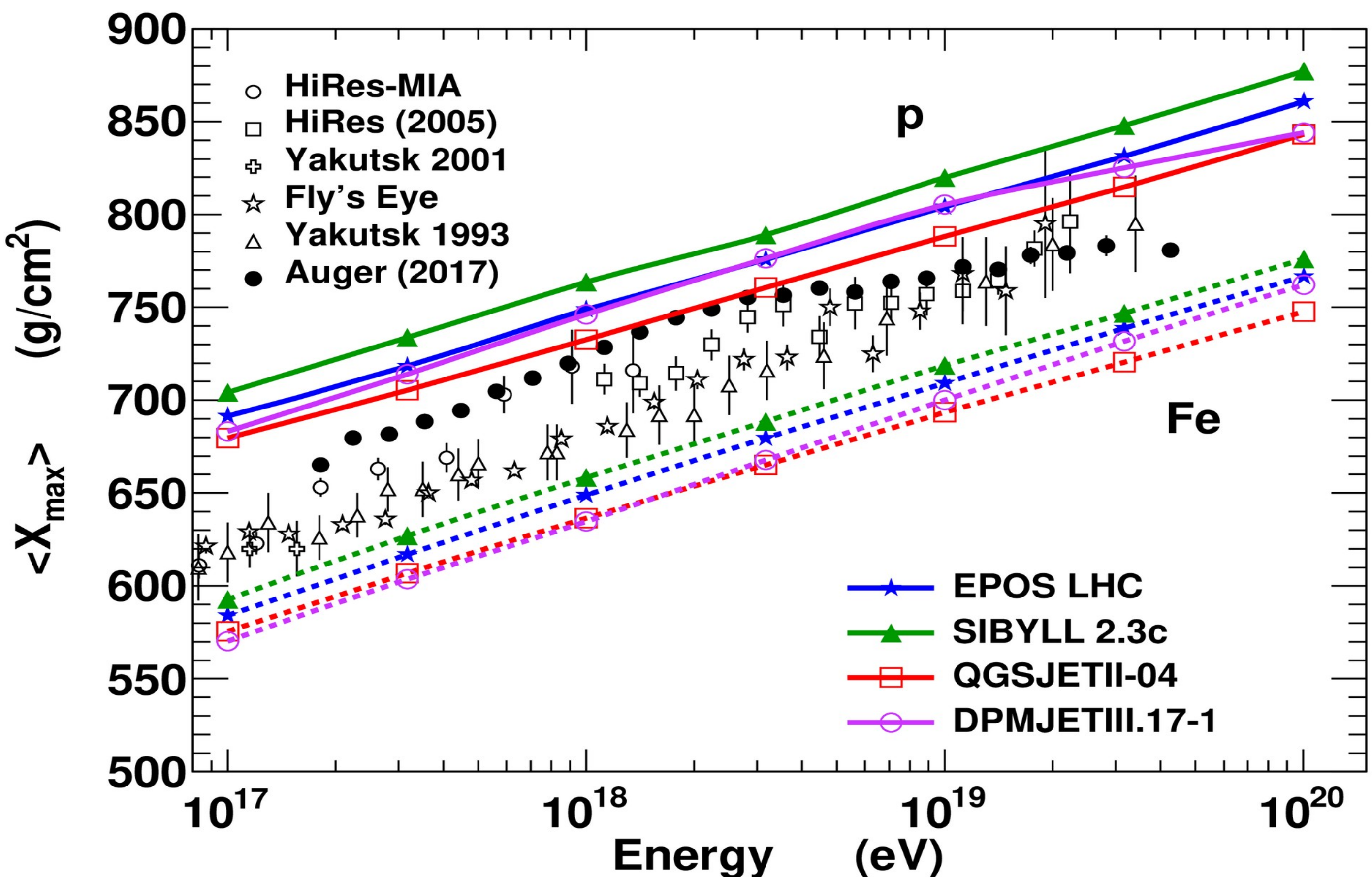
p-Air



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/d (low multiplicity, high elasticity)
- anything below or above won't be compatible with LHC data



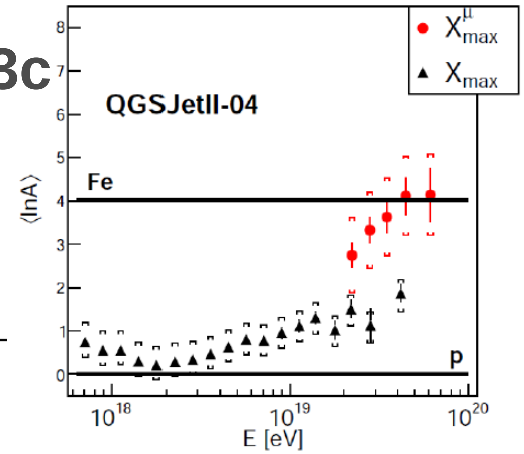
To reduce theoretical uncertainties below experimental one, basic hadronic properties should be known better than 5% !

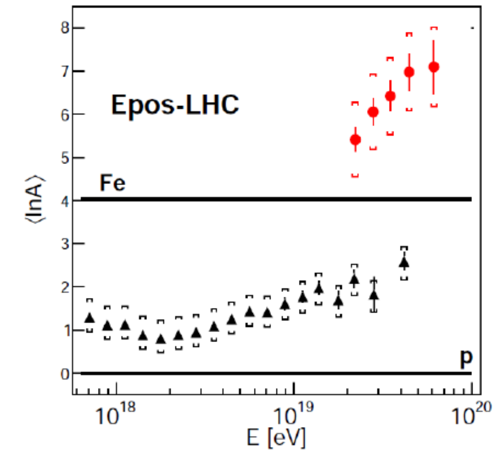
→ pO !

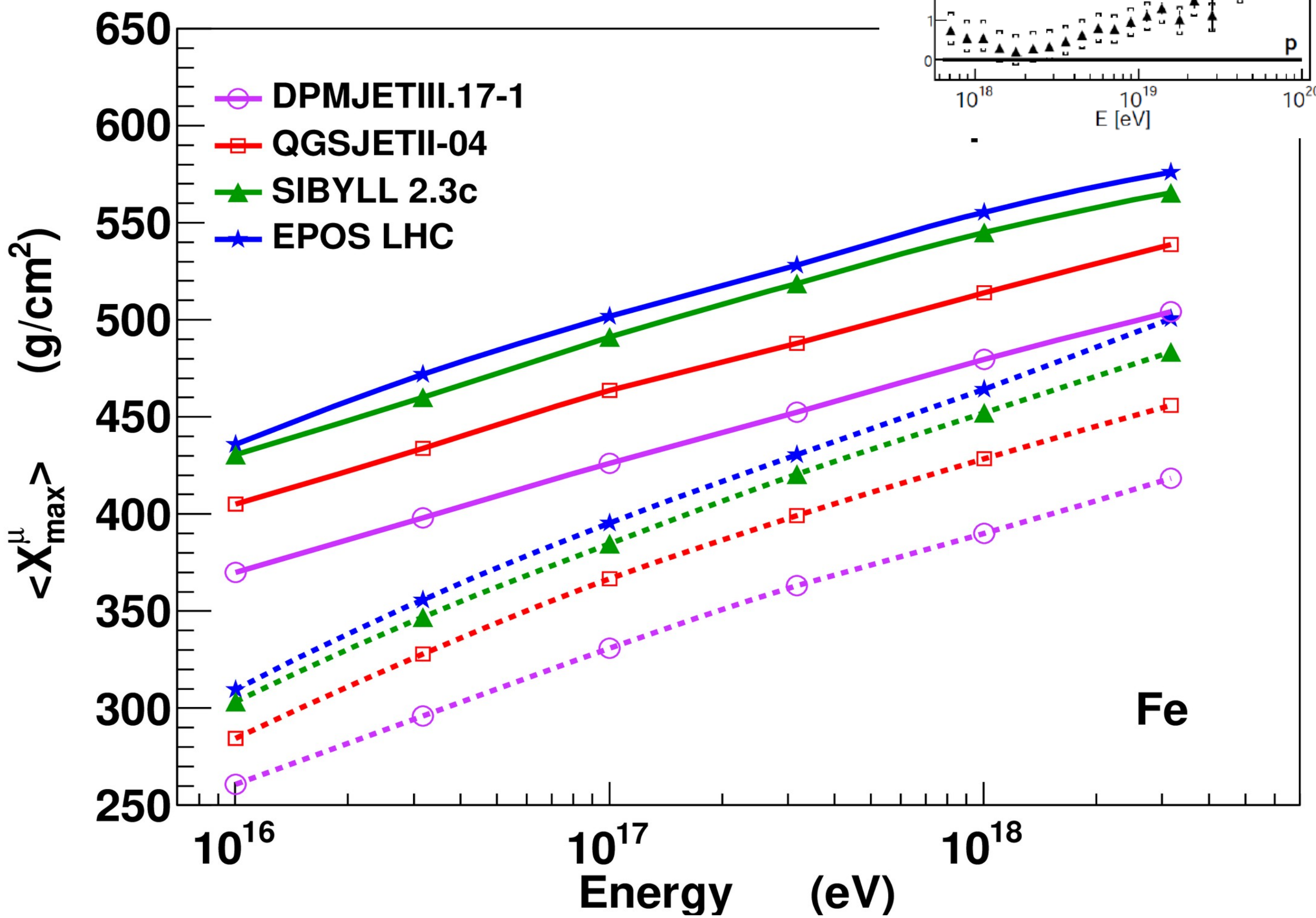
arXiv:1812.06772

Muon Production Depth

- **Same for EPOS LHC and SIBYLL 2.3c**
- **Very shallow for DPMJETIII**
  - but same X_{max} than EPOS LHC



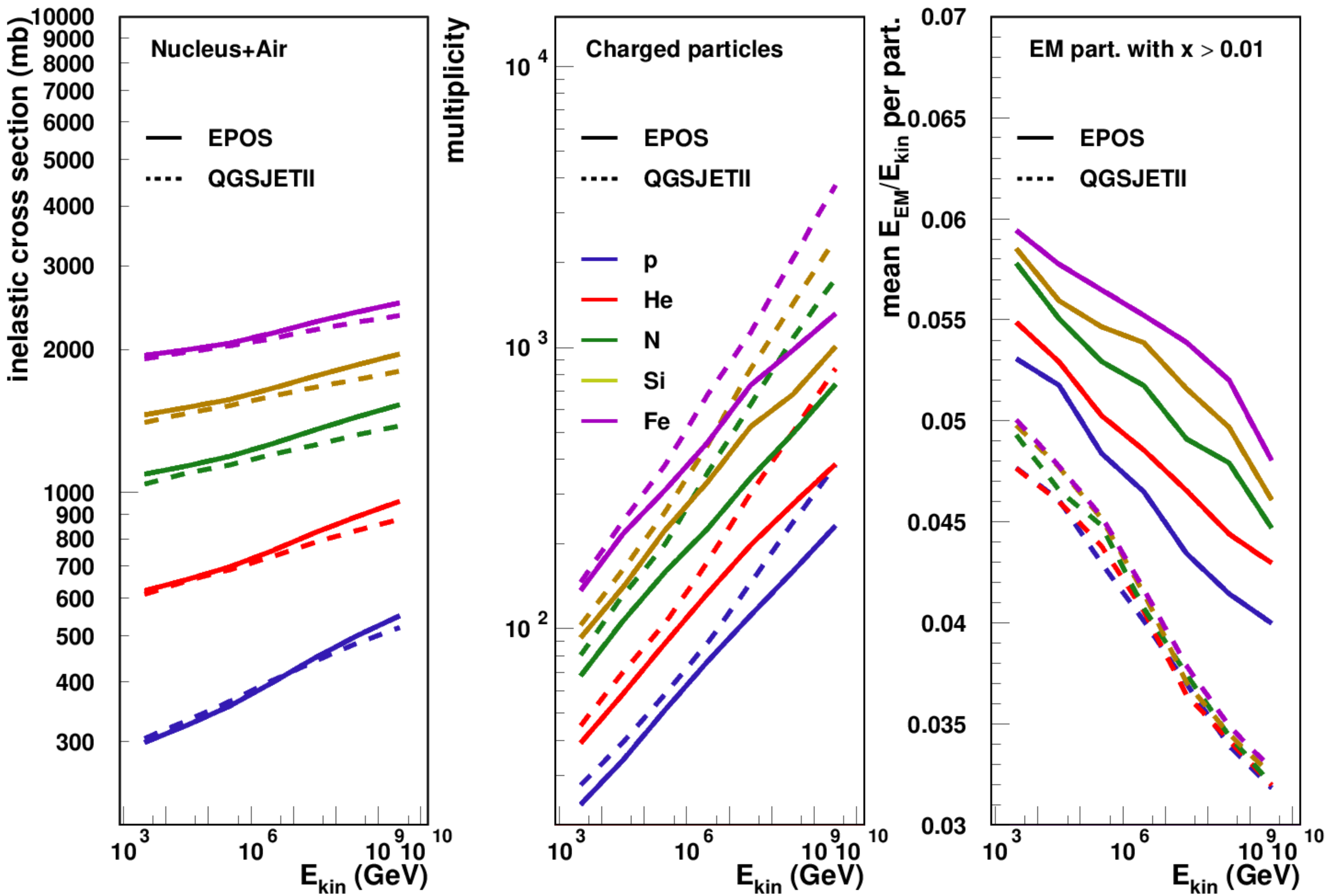




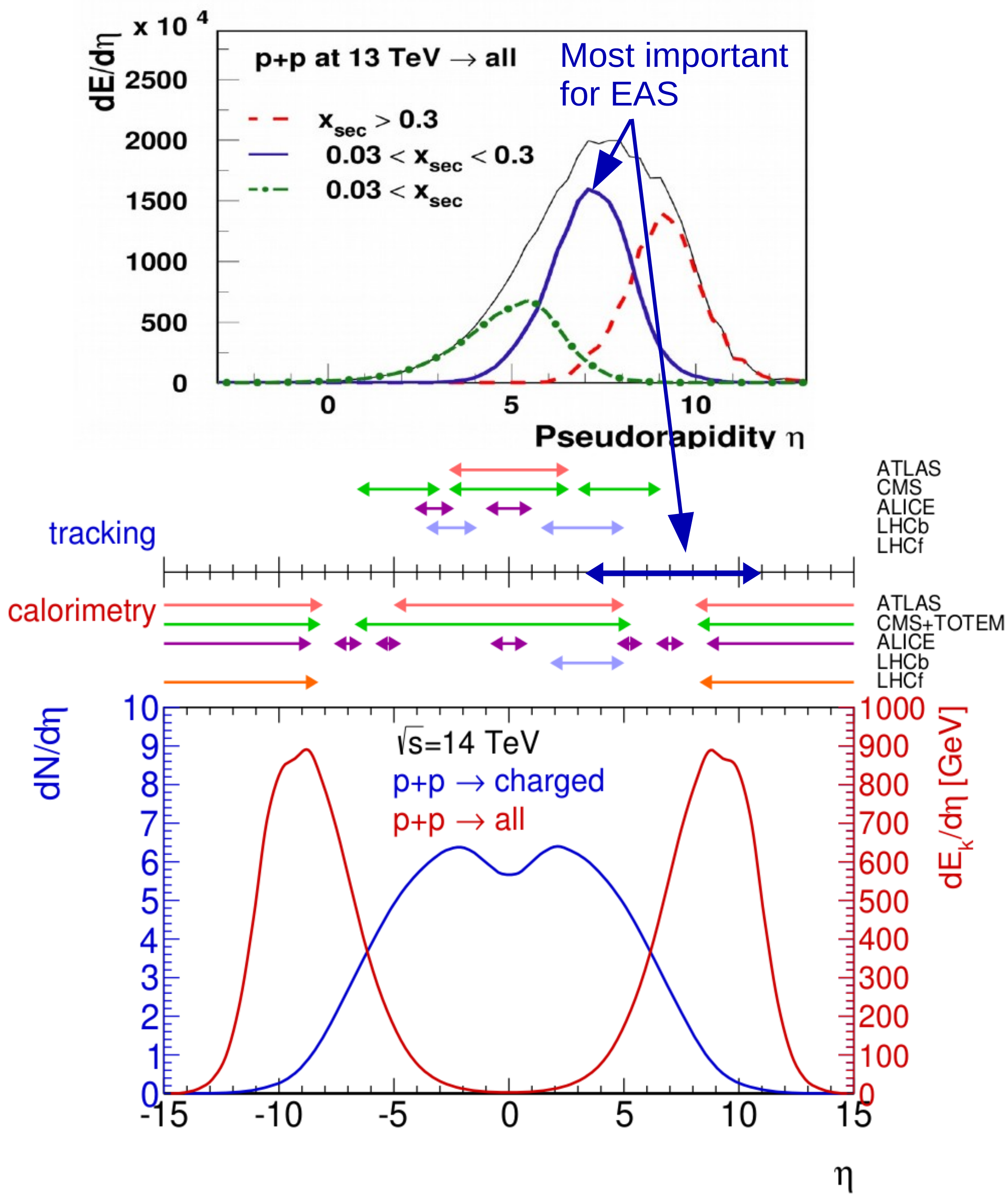
MPDs sensitive to baryon (less generation) and meson spectra in pion interactions: small effect on X_{max}

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

Ultra-High Energy Hadronic Model Predictions A-Air

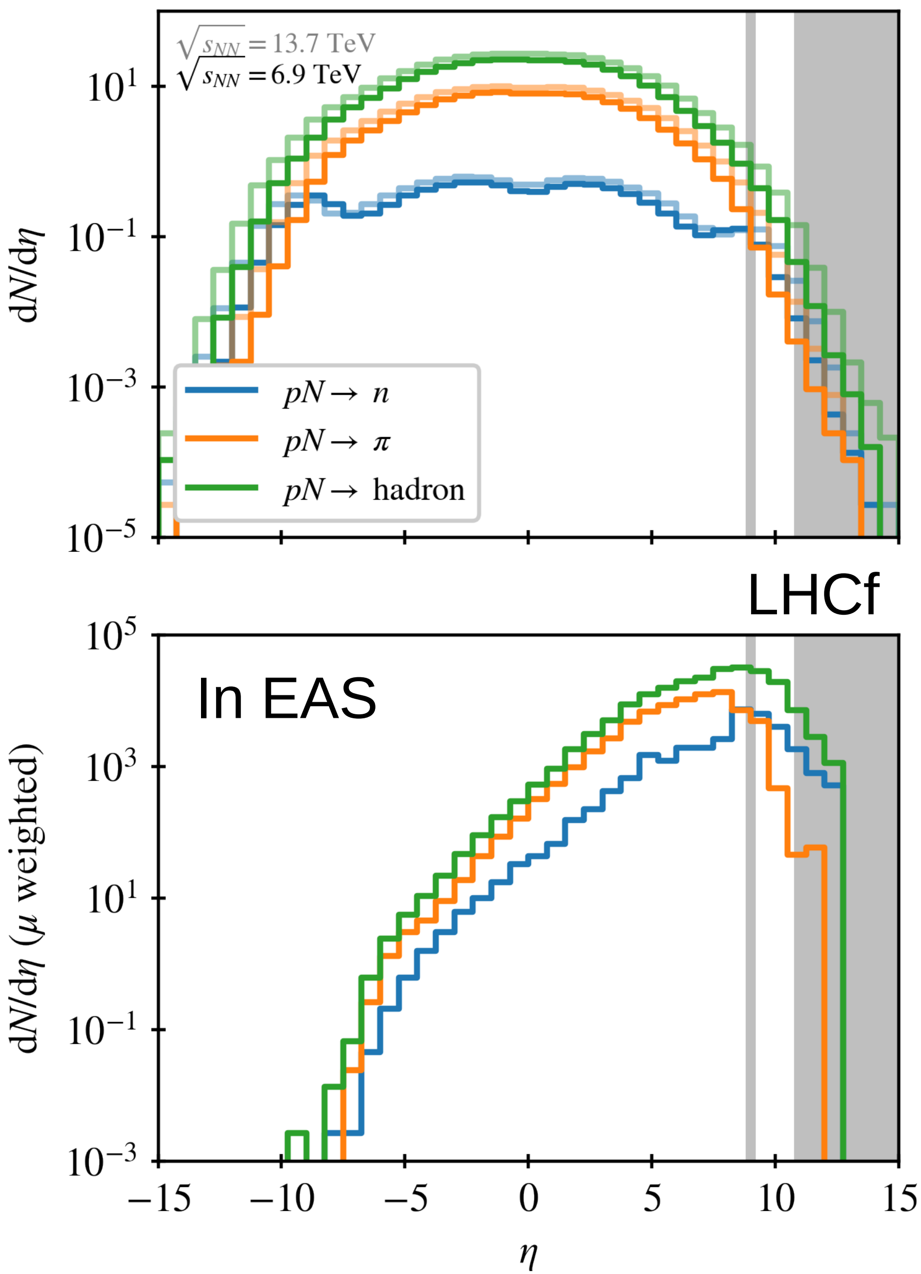


LHC acceptance



- **p-p data of central detectors used to reduce uncertainty by factor ~2. How to do more ?**
  - p-Pb difficult to compare to CR models (only EPOS)
  - special centrality selection
  - p-O (O-O) !
- **Maximum energy flow relevant for EAS**
  - x>0.01 (η~8)
- **Limited forward measurements**
  - Only calorimetric
    - LHCf
  - With particle identification
    - LHCb

LHCf acceptance in EAS

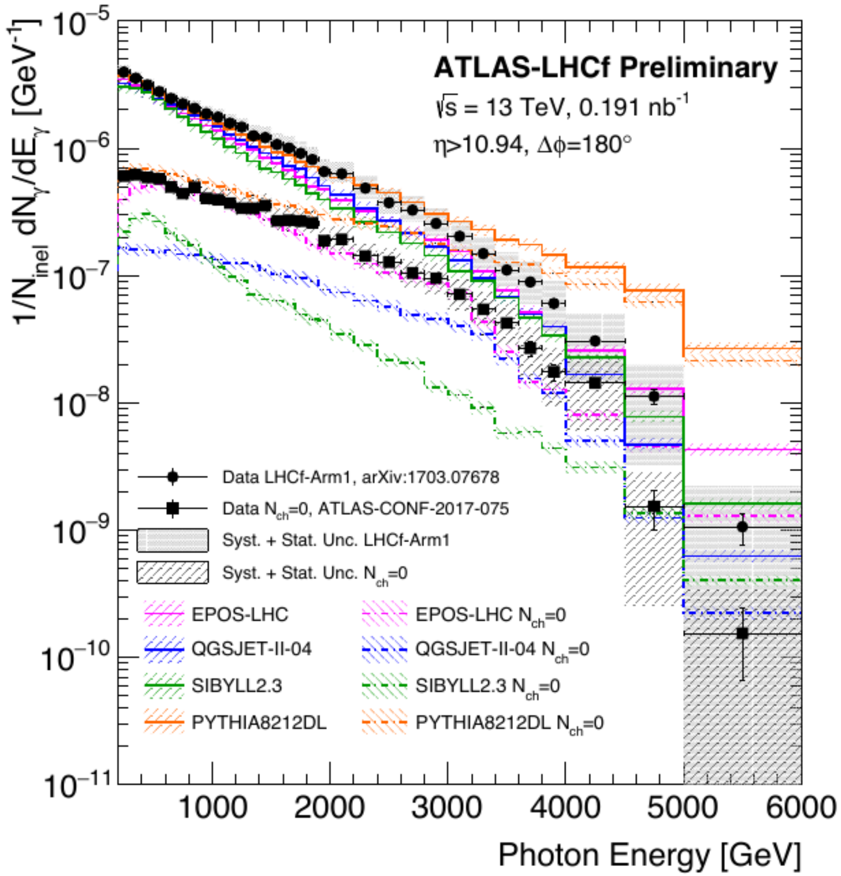


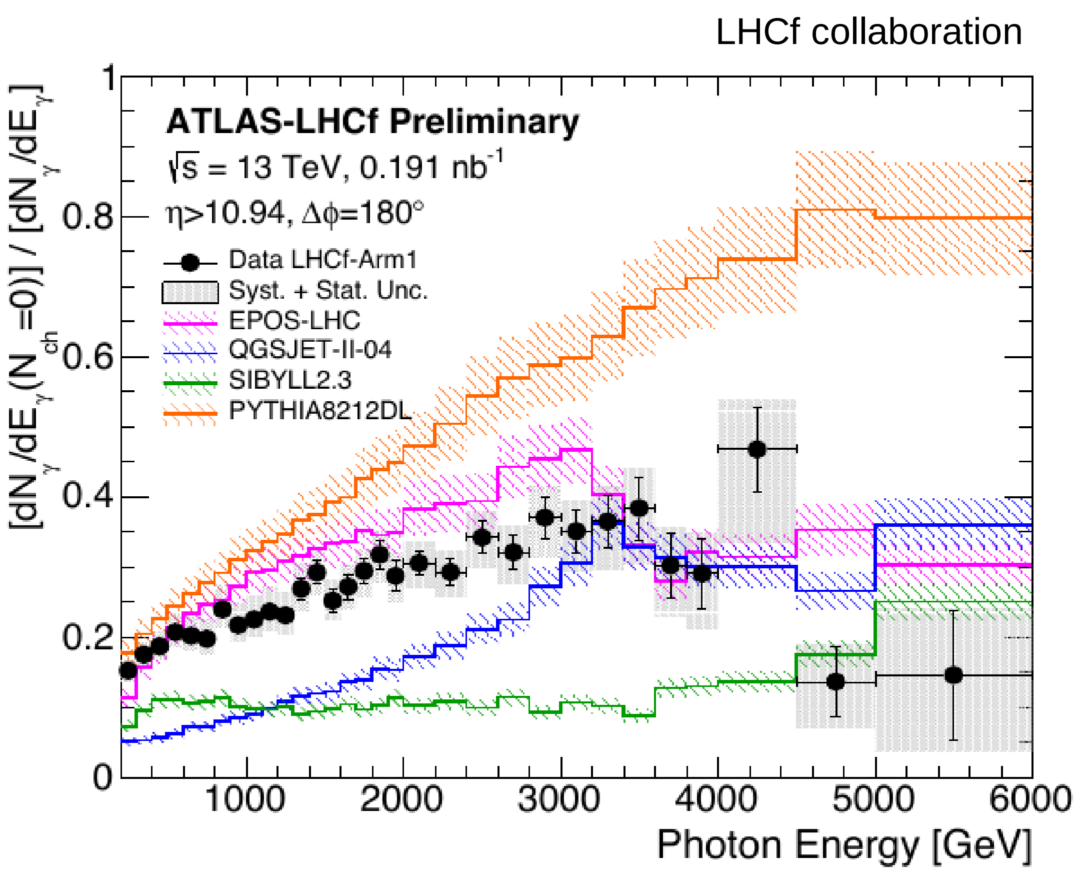
- **LHCf phase space very small in term of particle number**
- **In real EAS simulations (CORSIKA8), we can follow muon history :**
  - Distribution of ancestors of muons reaching ground for a proton induced shower at 10^{18} eV.
  - Focus on ancestors having an interaction around 10 TeV cms energy

LHCf right in the most important phase space relevant for air shower development

Comparison with LHCf

- LHCf favor not too soft photon spectra (EPOS LHC, SIBYLL 2.3) : deep X_{max}
- No model fully compatible with all LHCf measurements : room for improvements !
- p-O would reduce uncertainty to the minimum : test nuclear effect !
- In combination with ATLAS : strong constraints on the real physics

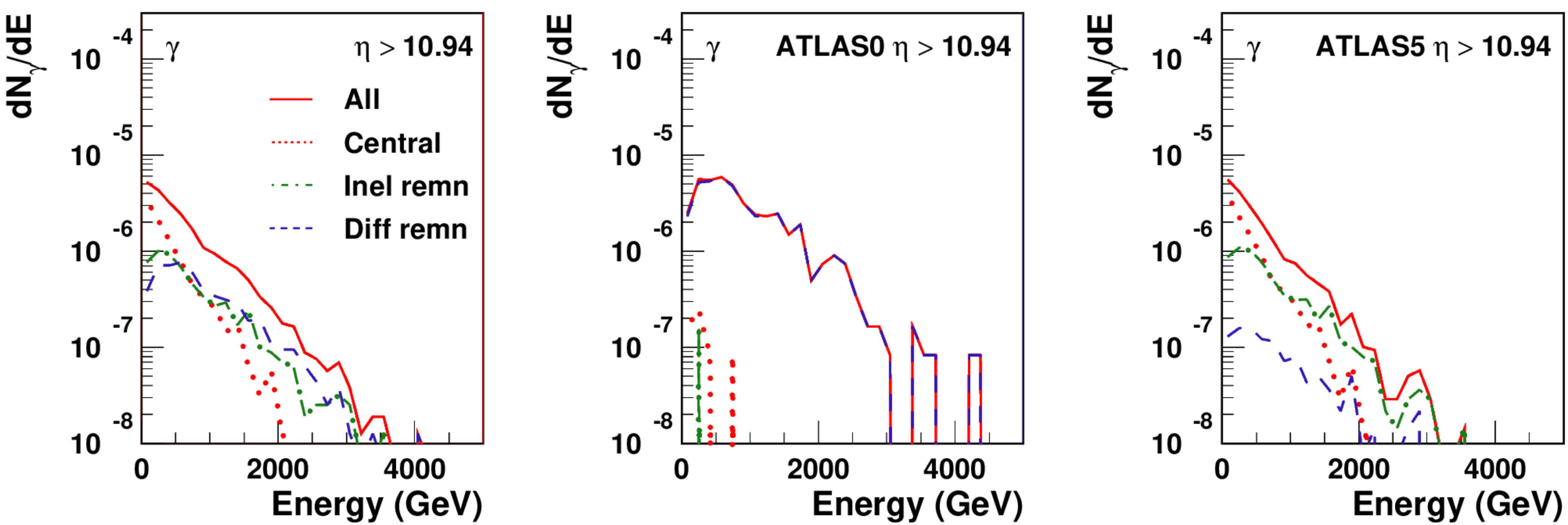




LHCf with ATLAS trigger

- **ATLAS selection**
  - ATLAS0 = 0 charged particles particle with $|\eta|<2.5$ and $p_t>0.1$ GeV/c
  - ATLAS5 = at least 5 charged particles particle with $|\eta|<2.5$ and pt>0.1 GeV/c
- **Test different component of the models**
  - ATLAS0 : select diffractive events
  - ATLAS5 : suppress diffractive contribution

p-O 10 TeV, p-side

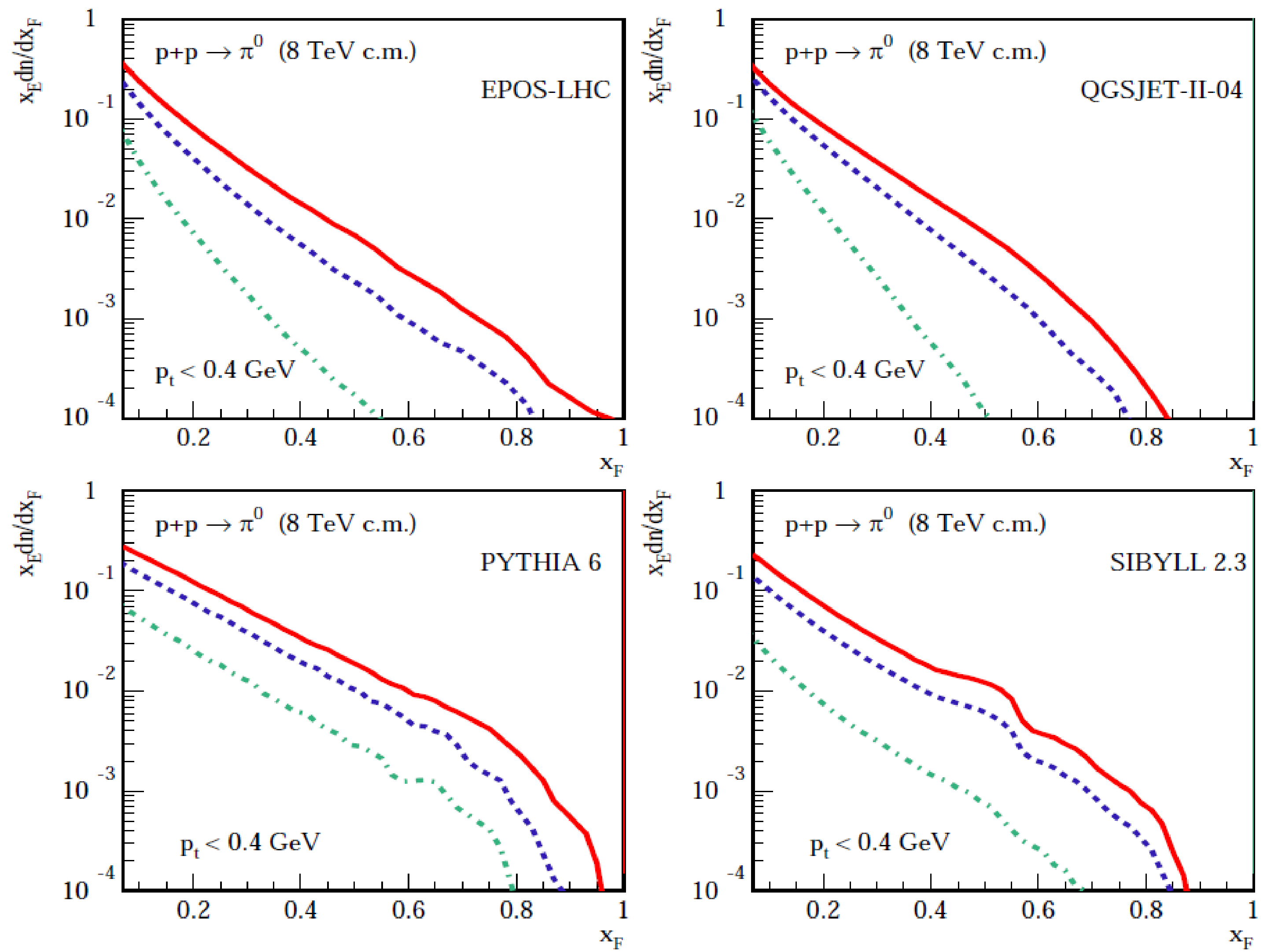


Evolution with Multiplicity

ATLAS selection

- at least 1 (red) ,6 (blue) or 20 (green) charged particles particle with |η|<2.5 and p_t>0.5 GeV/c

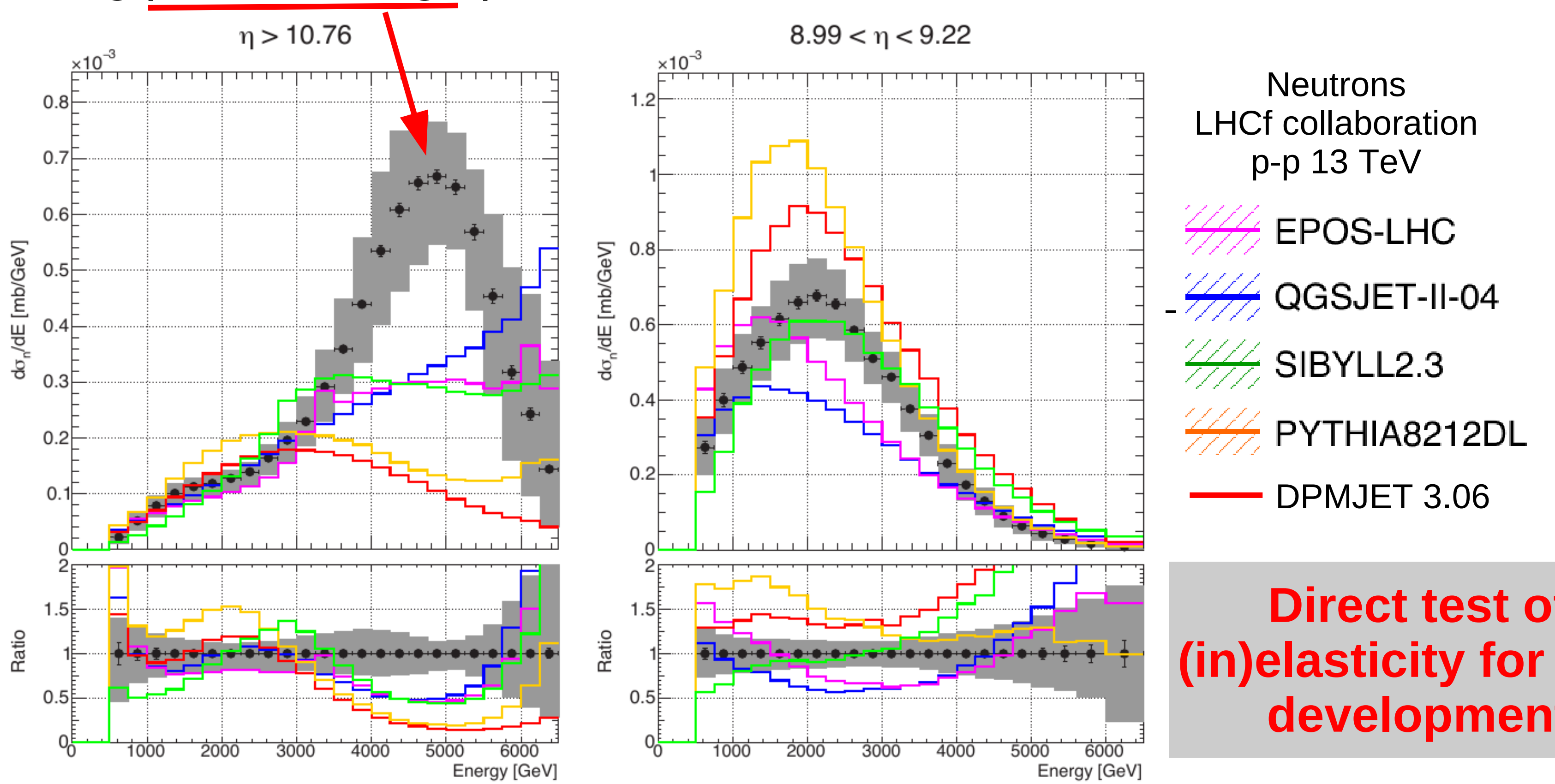
From S. Ostapchenko, arXiv 1608.07791



Best if done with Oxygen target : nuclear effects difficult to predict. **Strong impact on EAS development**

LHCf vs CR Models 13 TeV - Neutrons

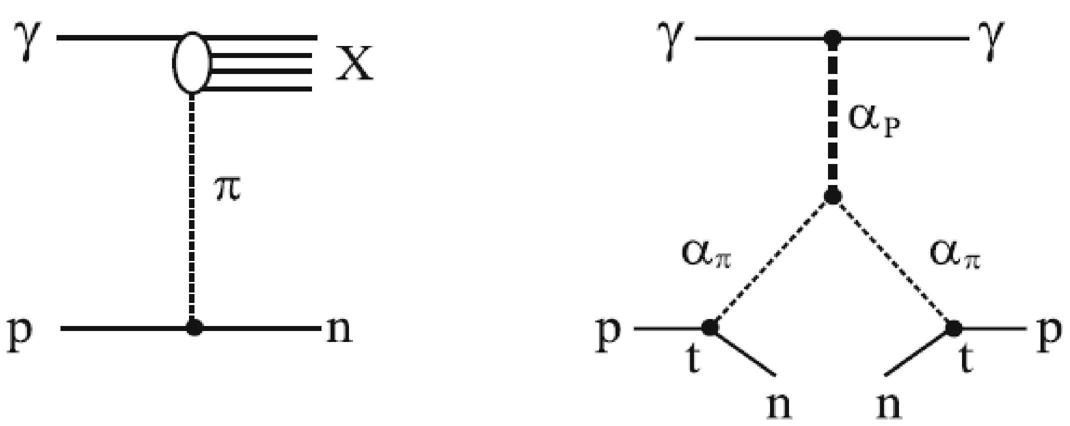
- **Reasonable results but significance differences**
  - +/- 50% data vs models
  - large differences between models
  - Missing pion exchange process in all models



Direct test of (in)elasticity for EAS development

π Exchange to Test π Interactions

Physics discussed in detail for HERA (H1 and ZEUS) measurements
(see, for example, Khoze et al. Eur. Phys. J. C48 (2006), 797 and Refs. therein)



Use neutron tag in LHCf to measure π+O in ATLAS

Unique opportunity to test most important interaction type in EAS

$$\frac{\mathrm{d}\sigma(\gamma p \to Xn)}{\mathrm{d}x_L\,\mathrm{d}t} = S^2 \frac{G^2_{\pi^+ pn}}{16\pi^2} \frac{(-t)}{(t-m_\pi^2)^2} F^2(t) \times (1-x_L)^{1-2\alpha_\pi(t)} \sigma^{tot}_{\gamma\pi}(M^2)$$

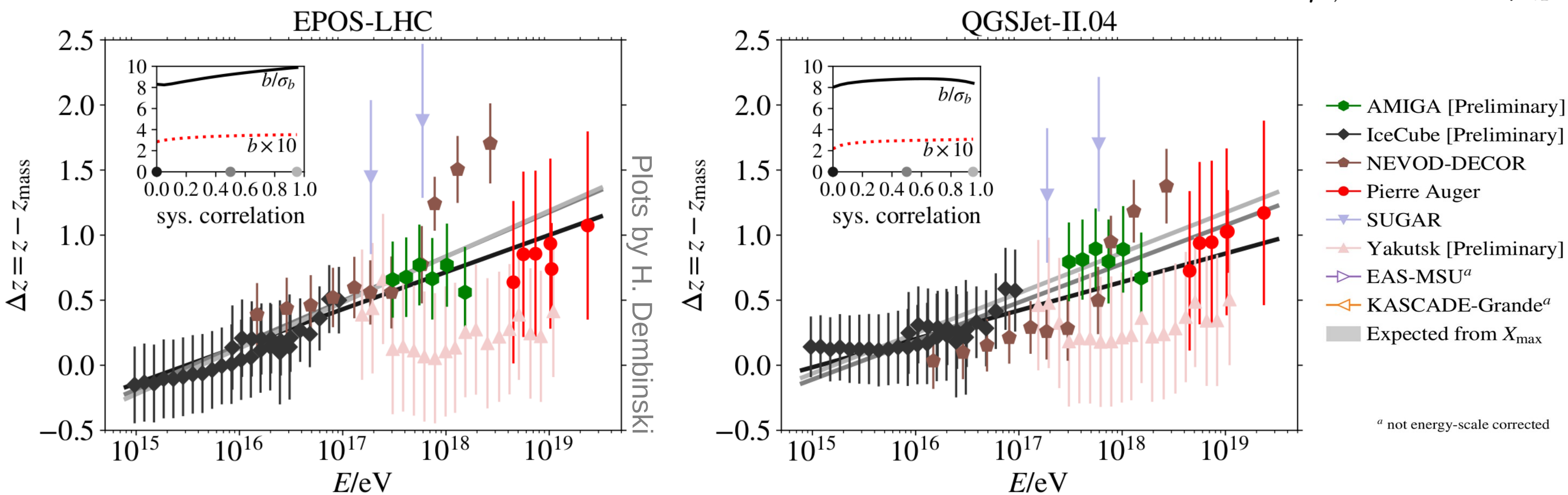
Use same expression and replace γ by p, but different absorptive corrections
(smaller rate expected, should be still possible in low-luminosity runs)

R. Engel

Muons at ground : Global Behavior

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

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



Hans Dembinski et al. for the EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array and Yakutsk EAS Array collaborations, EPJ Web of Conferences 210, 02004 (2019)

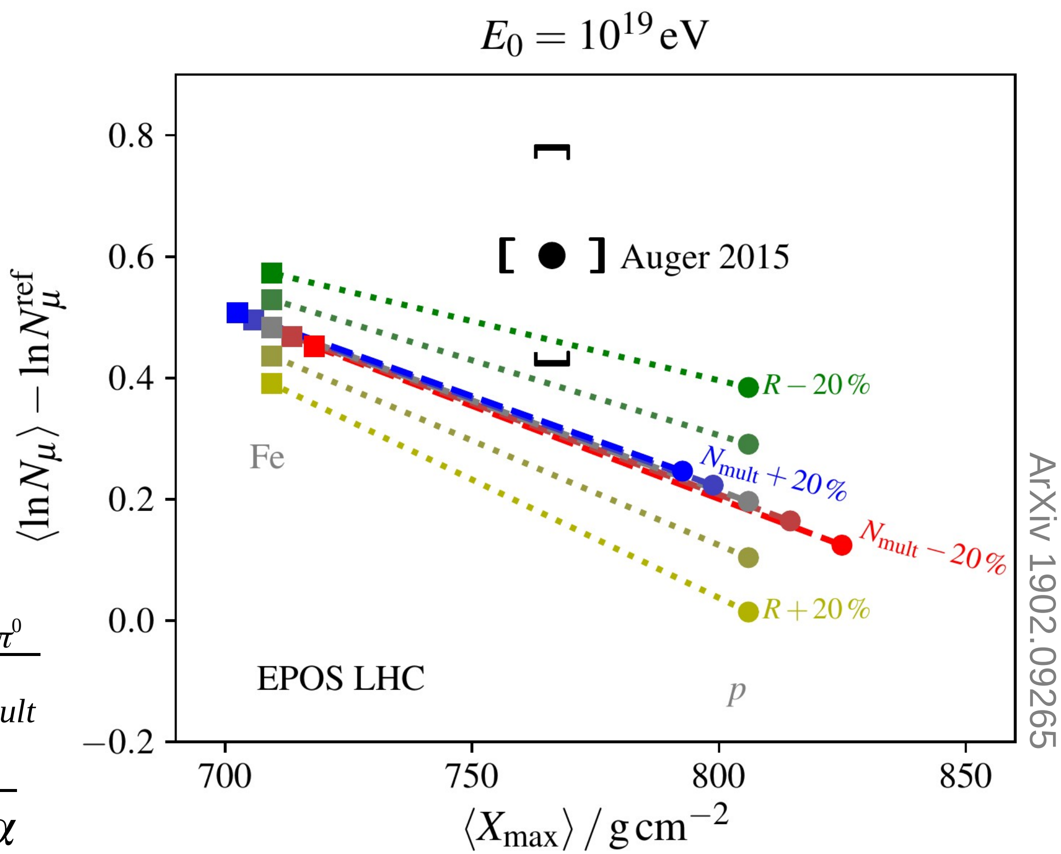
- **Different energy or mass scale cannot change the slope**
  - ➔ Different property of hadronic interactions at least above 10^{16} eV

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 $\alpha = \frac{N_{\pi^0}}{N_{mult}}$
  - Measure@LHC : $R = \frac{E_{e/m}}{E_{had}} \approx \frac{\alpha}{1-\alpha}$

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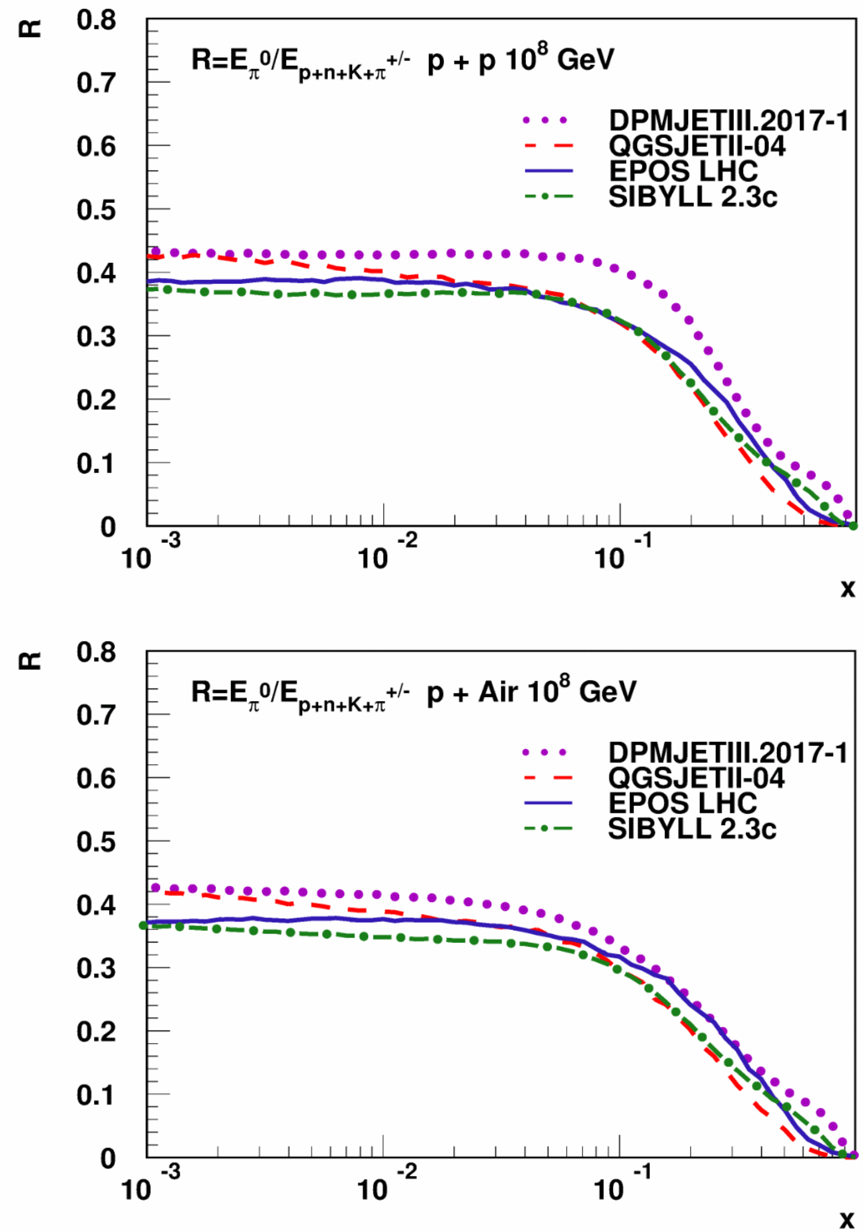


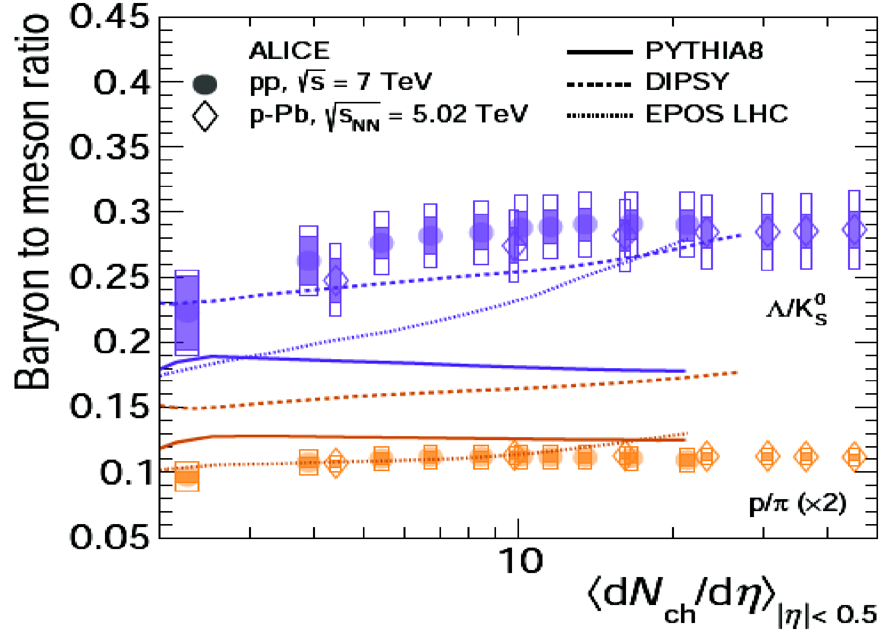
Possible Particle Physics Explanations

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

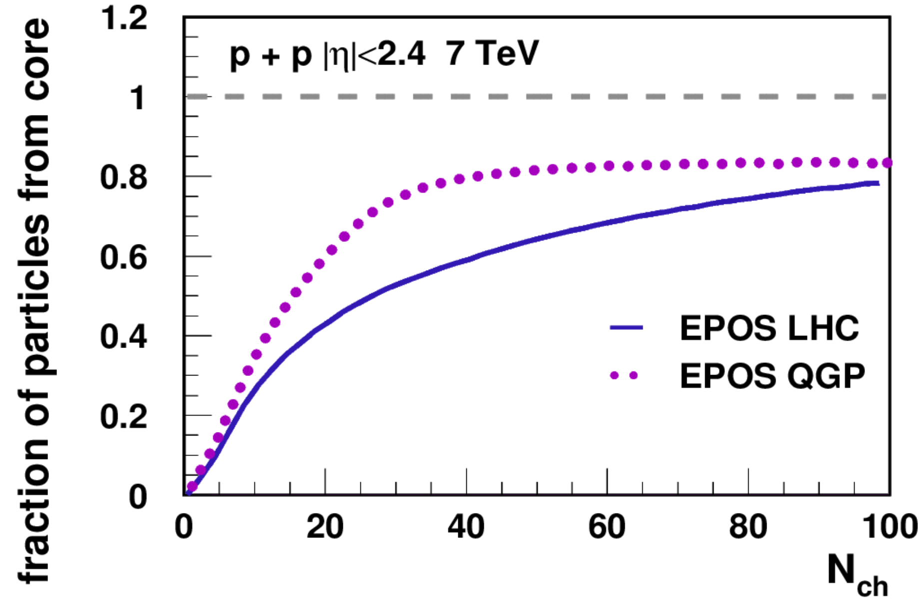
- Possibility to increase N_{mult} limited by X_{max}
- New Physics ?
  - Chiral symmetry restoration (Farrar et al.) ?
  - Strange fireball (Anchordoqui et al.) ?
  - String Fusion (Alvarez-Muniz et al.) ?
    - Problem : no strong effect observed at LHC (~10^{17} eV)
  - Different hadronization for saturated gluon field (M. Strikman) ?
- Unexpected collective hadronization (QGP ?) in light systems observed at the LHC
  - Reduced α (R) is a sign of QGP formation (Baur et al. 1902.09265 [hep-ph]) !
  - Not properly done in EPOS LHC (QGP only in extreme conditions)
    - limit : α changed at most by 20-25% but effect can be applied to lower energies (cumulative effect)

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 (core-corona effect)
  - ➡ 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
    - Effect at lower energies AND larger rapidities
  - ➡ More remnant hadronized with collective hadronization
  - ➡ Collective hadronization using grand canonical ensemble instead of microcanonical (closer to statistical decay)



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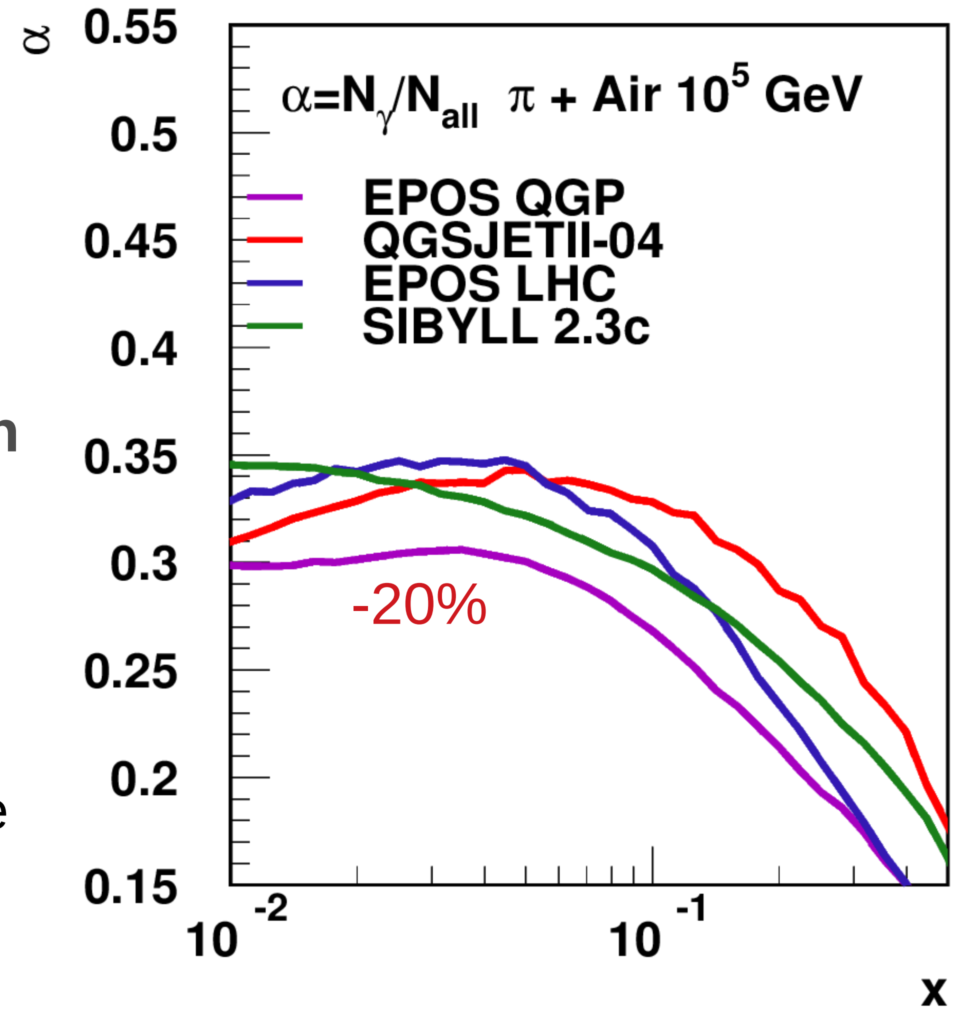
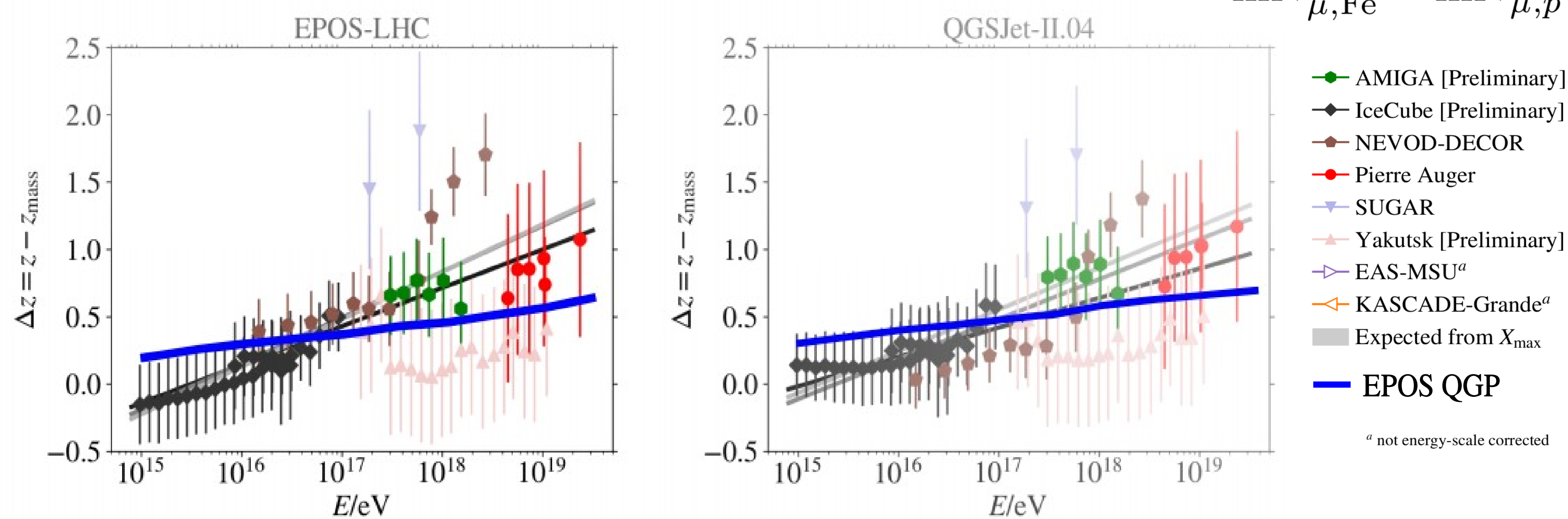


Comparison with Data

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

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



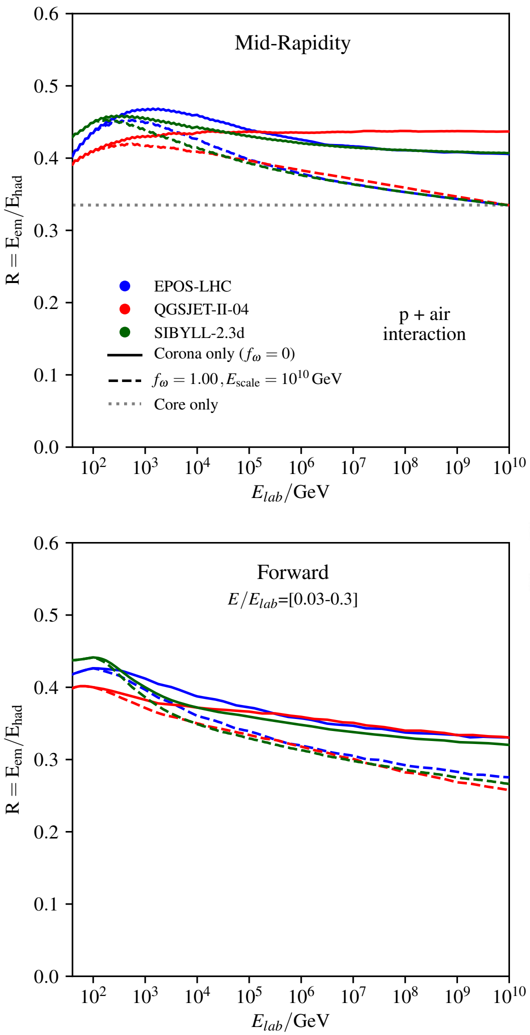
- **Core-corona approach might be a key point to solve muon puzzle**
  - ➡ Systematic study in Baur et al. : 1902.09265 [hep-ph]
- **Experimental studies with p-O and O-O very important to study core formation ! Can be done by all experiments to cover maximum η range**

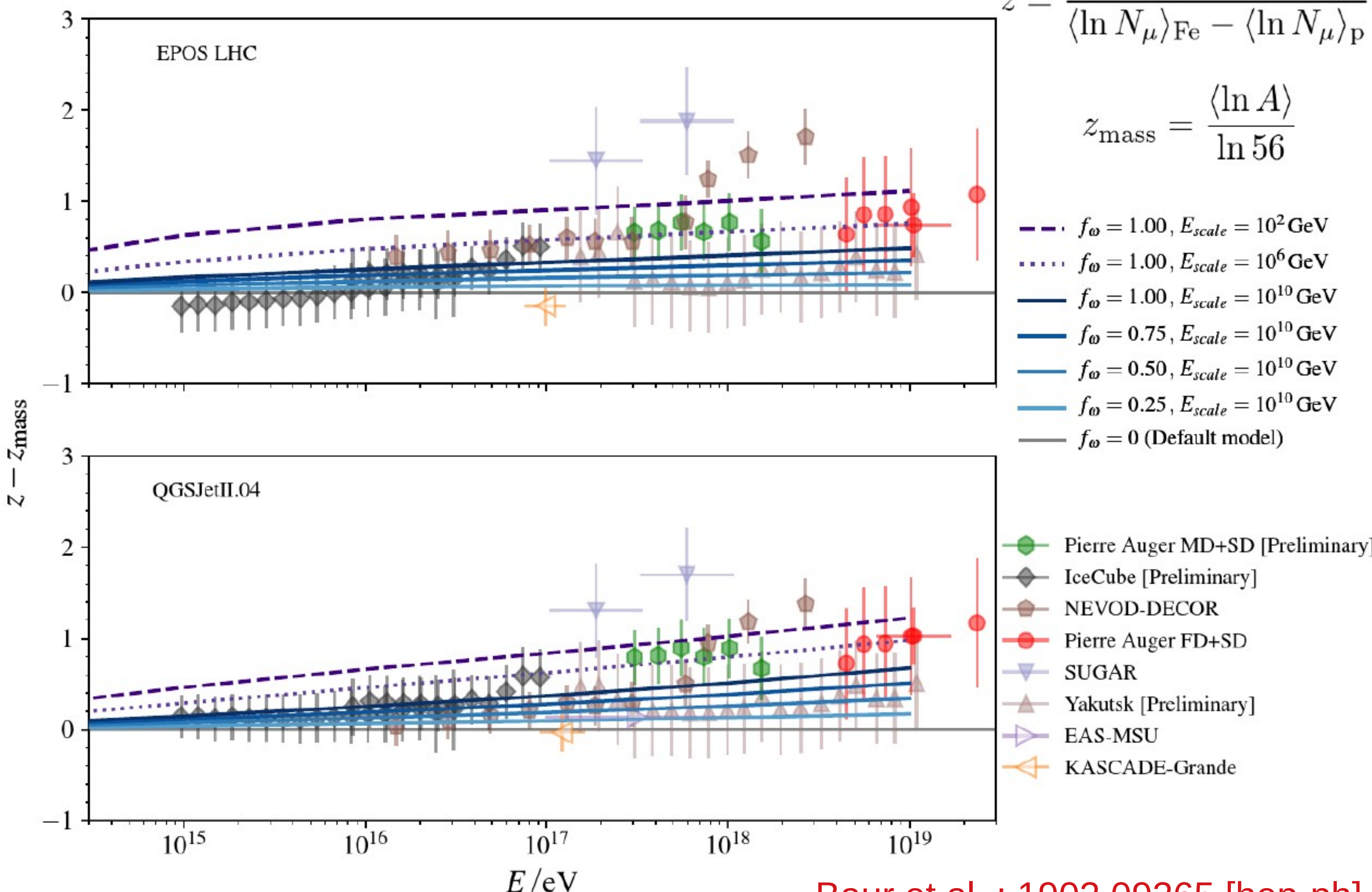
Core-Corona effect in Air Showers

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

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

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



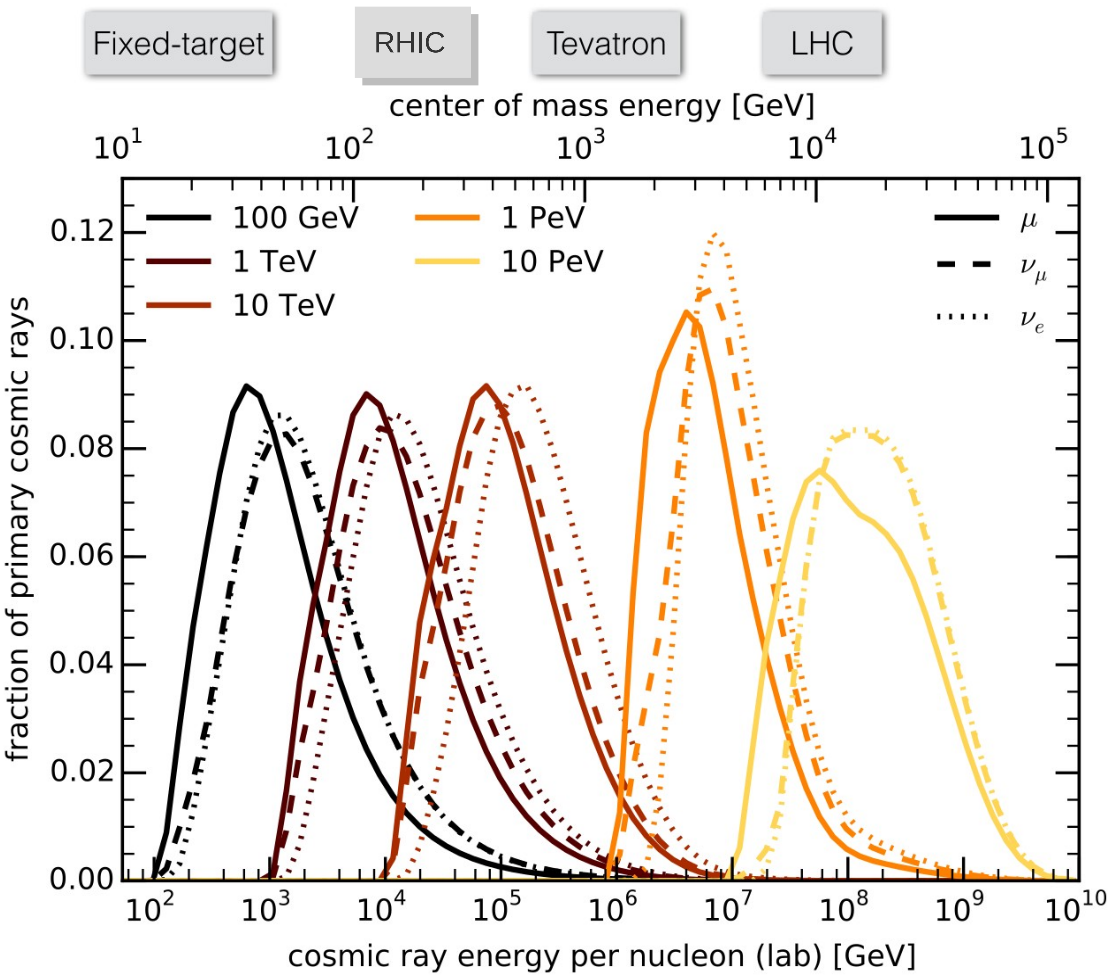


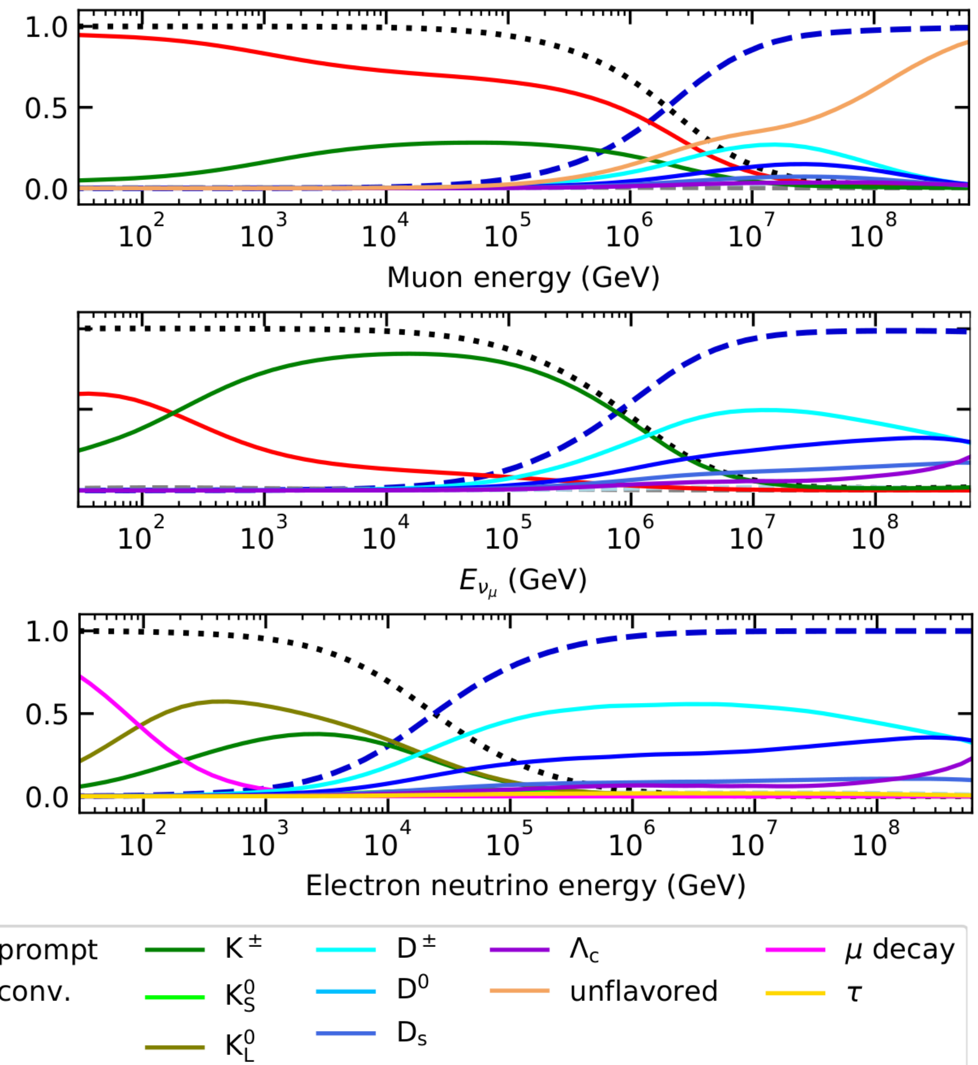
Baur et al. : 1902.09265 [hep-ph]

Inclusive Spectra and First Interaction

For inclusive spectra (IceCube), particles from first interaction dominate

➡ heavy flavor at LHCb with light nuclei





Plots from A. Fedinytch

Summary

New input from LHC RUN3 crucial to reproduce EAS data consistently: too large uncertainties in model for forward spectra and light ion interactions.

- **WHISP working group clearly established a muon production deficit in air shower simulations and X_{max} uncertainties still too large**
  - ➔ Difficult to extract real mass of primary cosmic rays
- **Large differences observed in hadronic interaction models.**
  - ➔ Different type of hadronization (string like or satistical decay)
  - ➔ Different energy spectra
  - ➔ Remaining uncertainties mostly coming from nuclear effects
- **More data are necessary to constrain the model in relevant kinematic space.**
  - ➔ Forward measurement with LHCf important to constrain (in)elasticity and low mass diffraction and calorimetric EM/had to test hadronization (core?)
  - ➔ RUN3 crucial to have LHCf AND have results from other exp. before the end of the Pierre Auger Observatory (~2030). **RUN4 would be too late for CR !**

Core-Corona effect in Air Showers

At mid-rapidity the particles come from the core or the corona

$$N_i = \omega_{\rm core}\, N_i^{\rm core} + (1-\omega_{\rm core})\, N_i^{\rm corona}$$

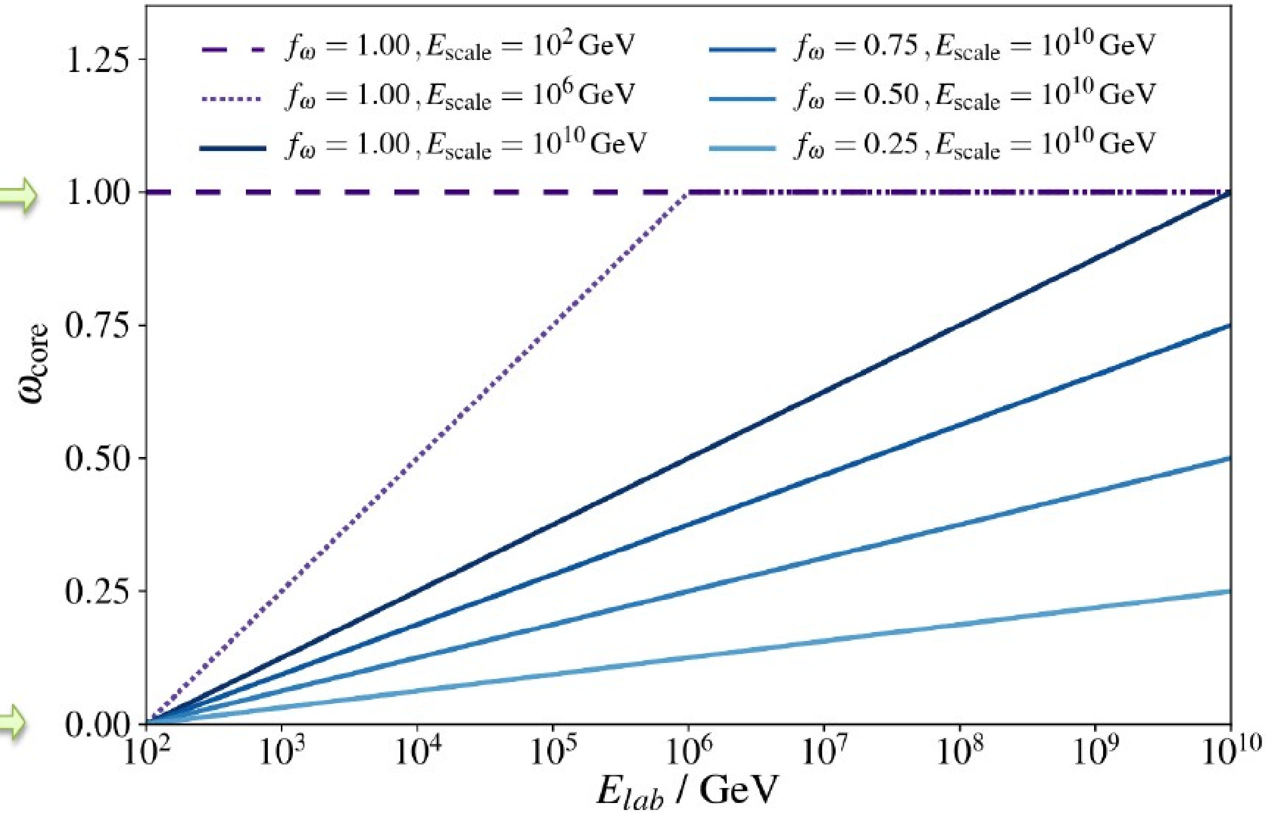
$$\omega_{\rm core}(E_{\rm lab}) = f_\omega\, \underbrace{F(E_{\rm lab}; E_{\rm th}, E_{\rm scale})}_{\frac{\log_{10}(E_{\rm lab}/E_{\rm th})}{\log_{10}(E_{\rm scale}/E_{\rm th})} \text{ for } E_{\rm lab} > E_{\rm th}}$$

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

The particle ratios are modified from the corona to the core taking different values of f_ω and $E_{\rm scale}$

Core ratio

Corona ratio



Baur et al. : 1902.09265 [hep-ph]

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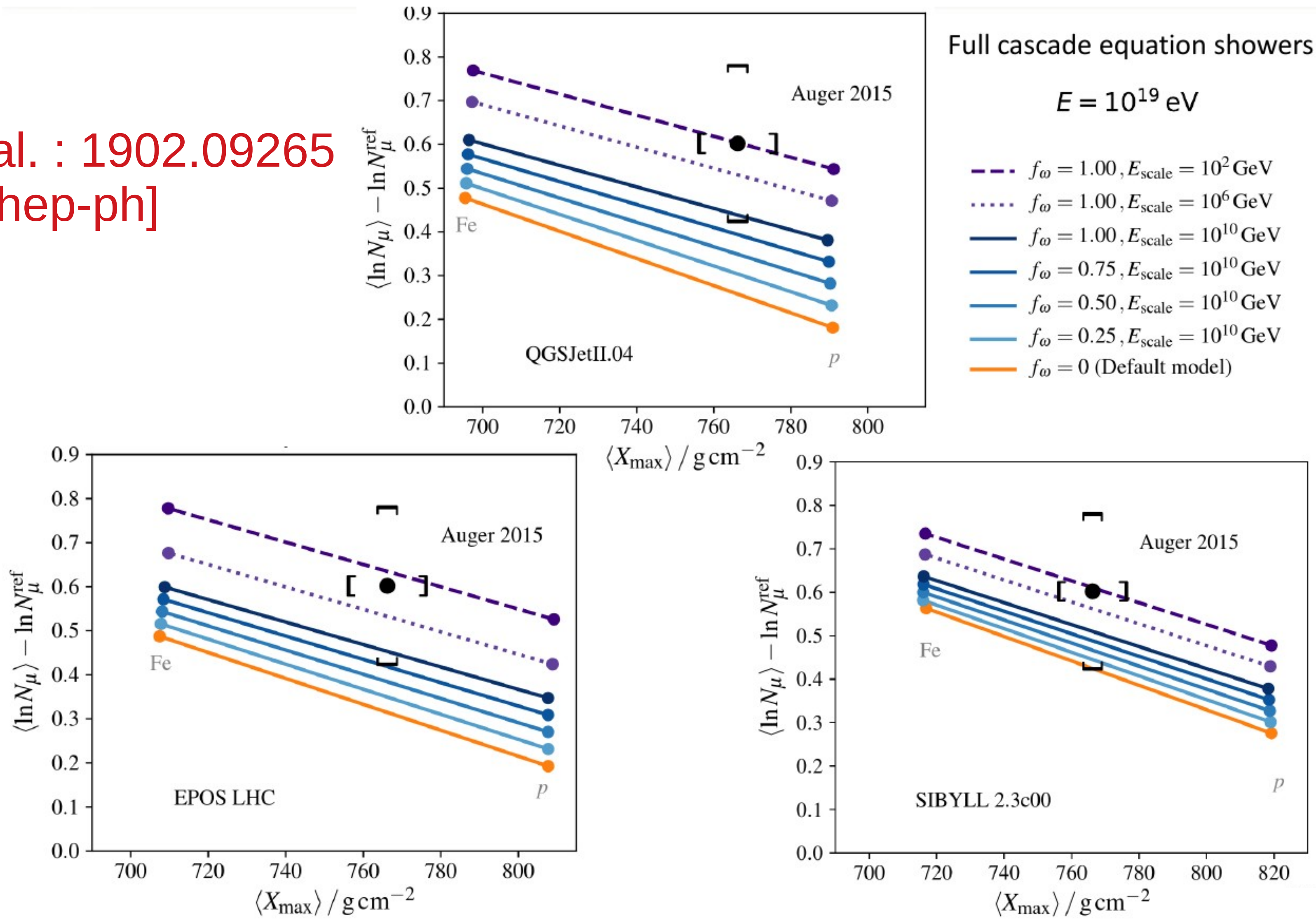
Core-Corona effect in Air Showers

Baur et al. : 1902.09265 [hep-ph]

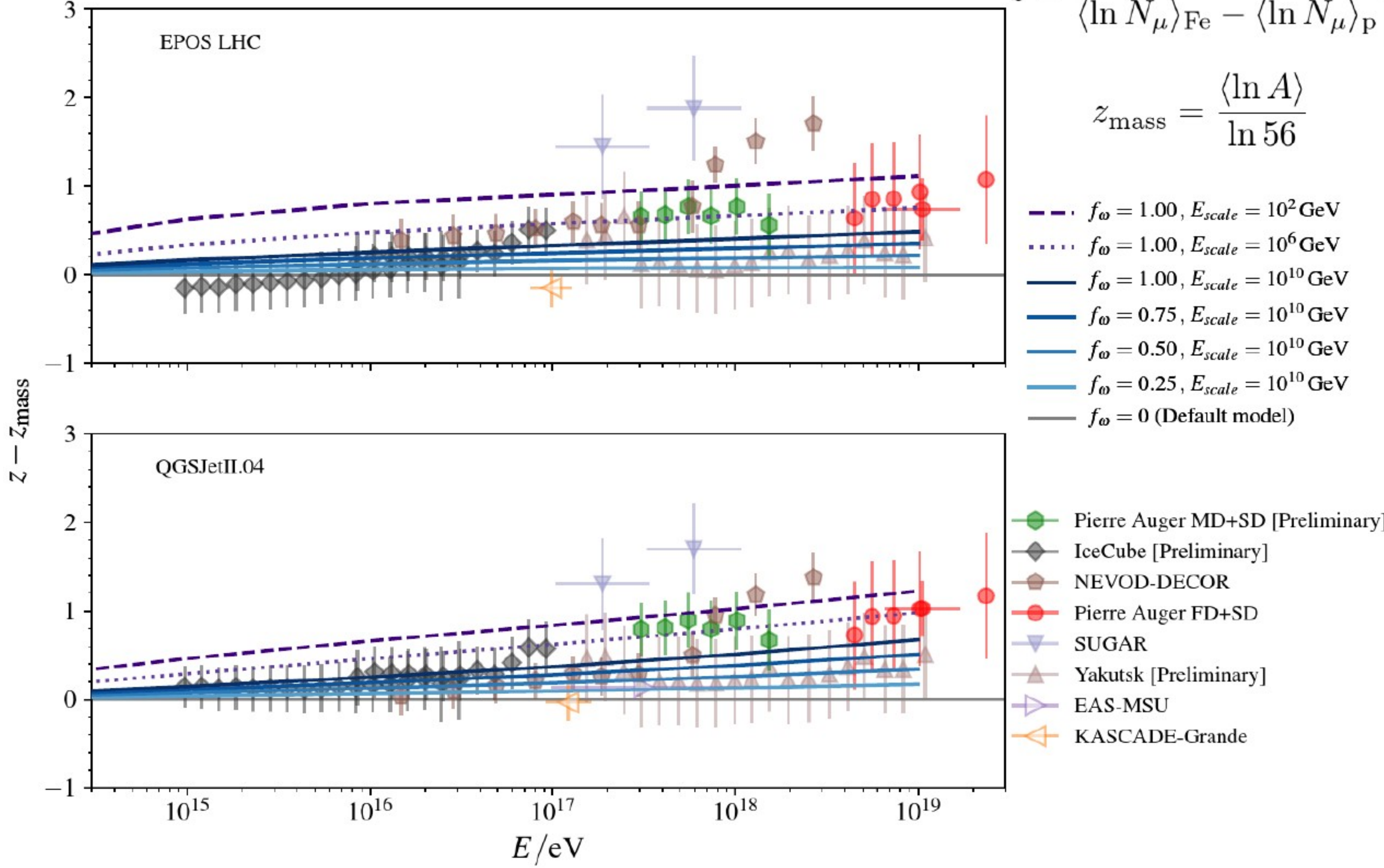


Core-Corona effect in Air Showers

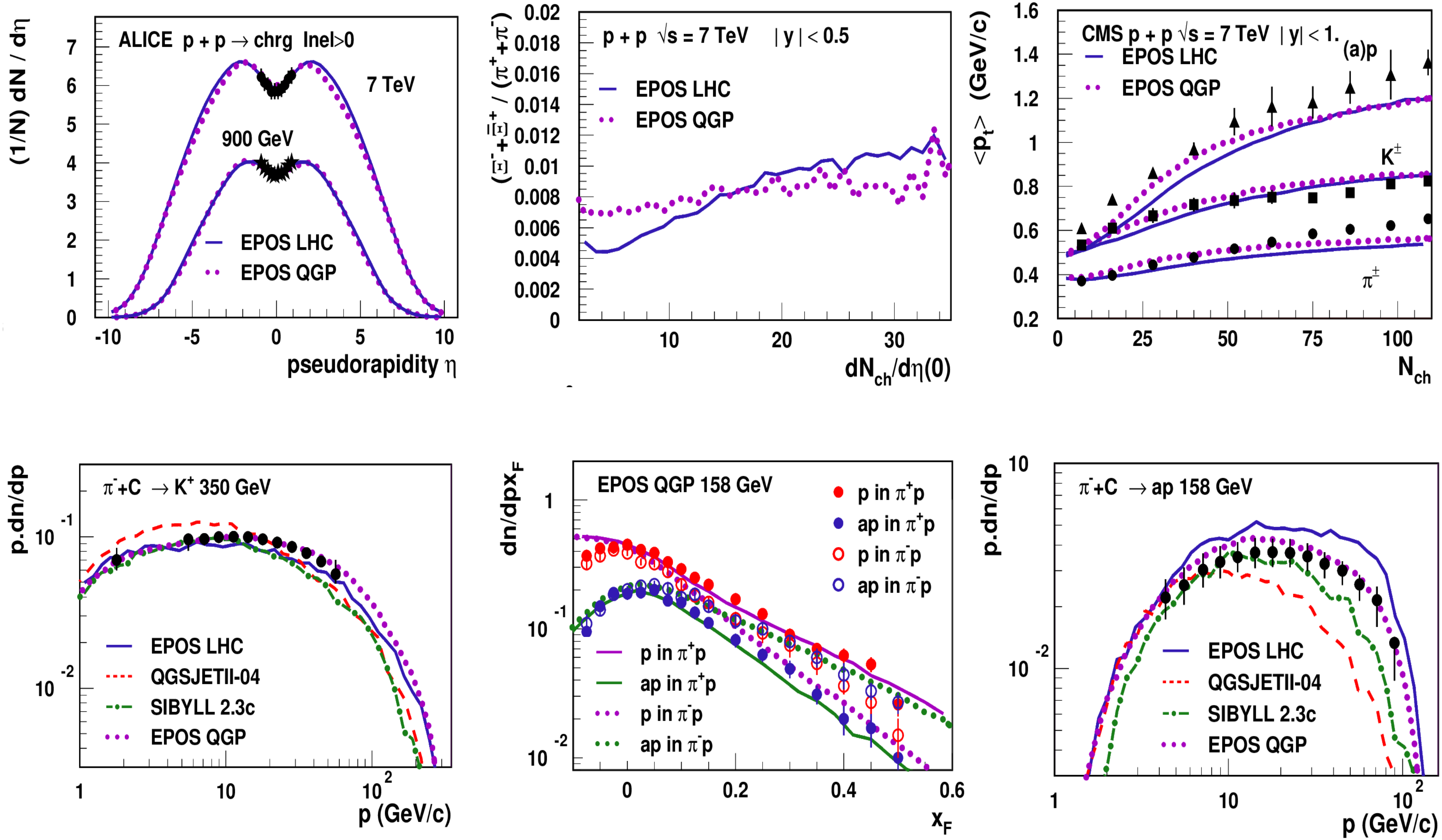
Baur et al. : 1902.09265 [hep-ph]

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

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

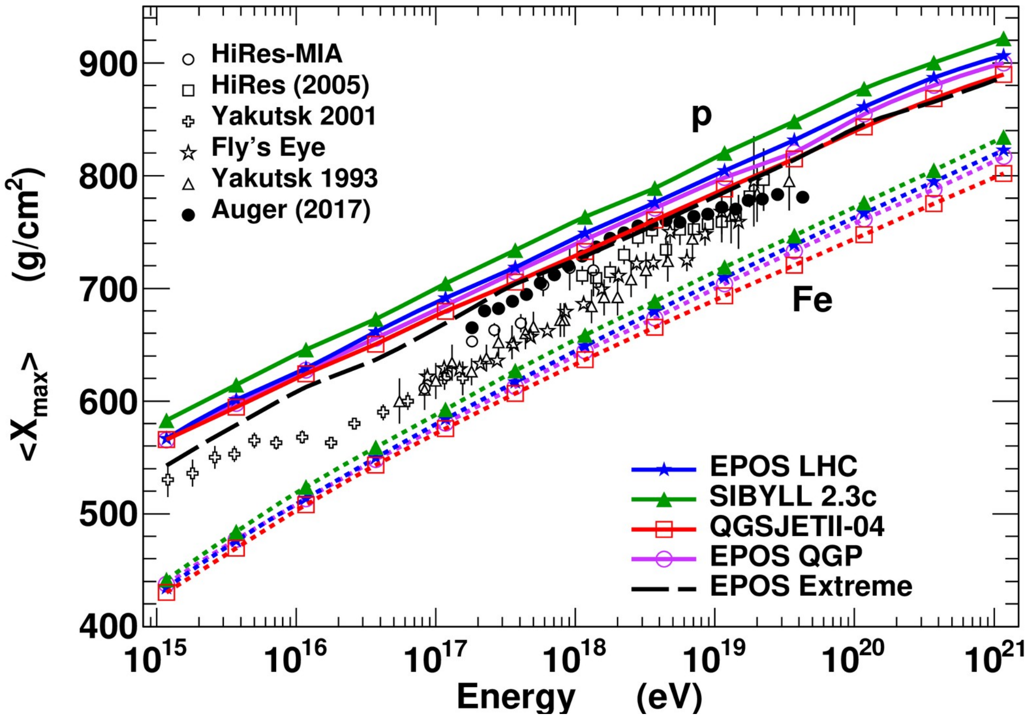


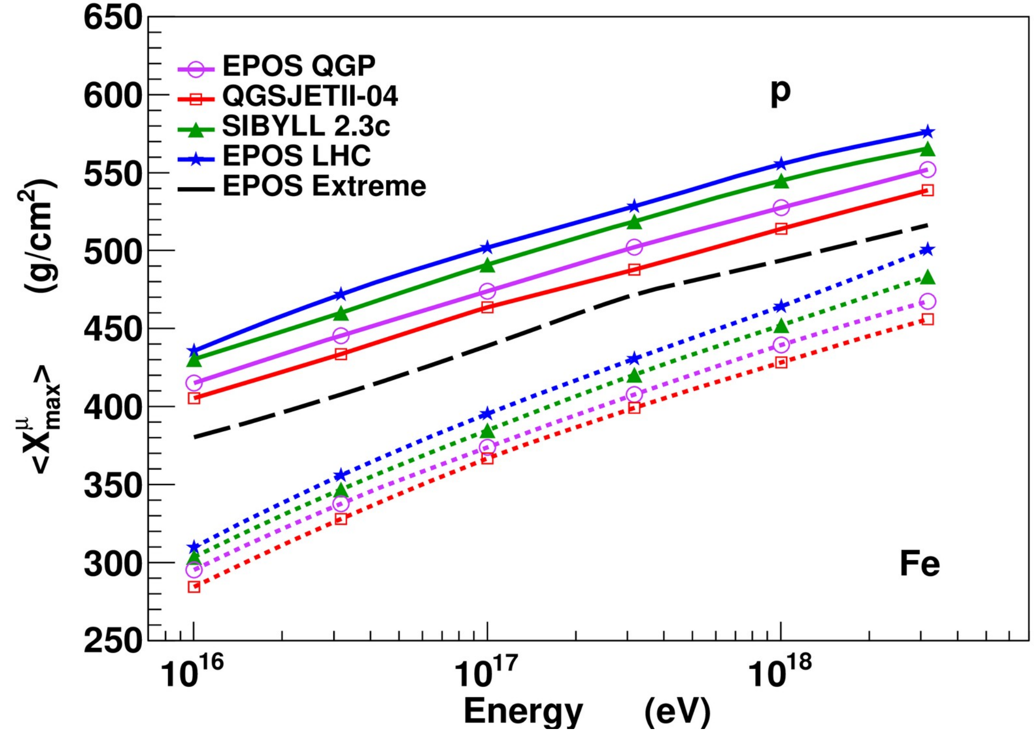
Preliminary Version with Minimum Constraints



Results for Air Showers (1)

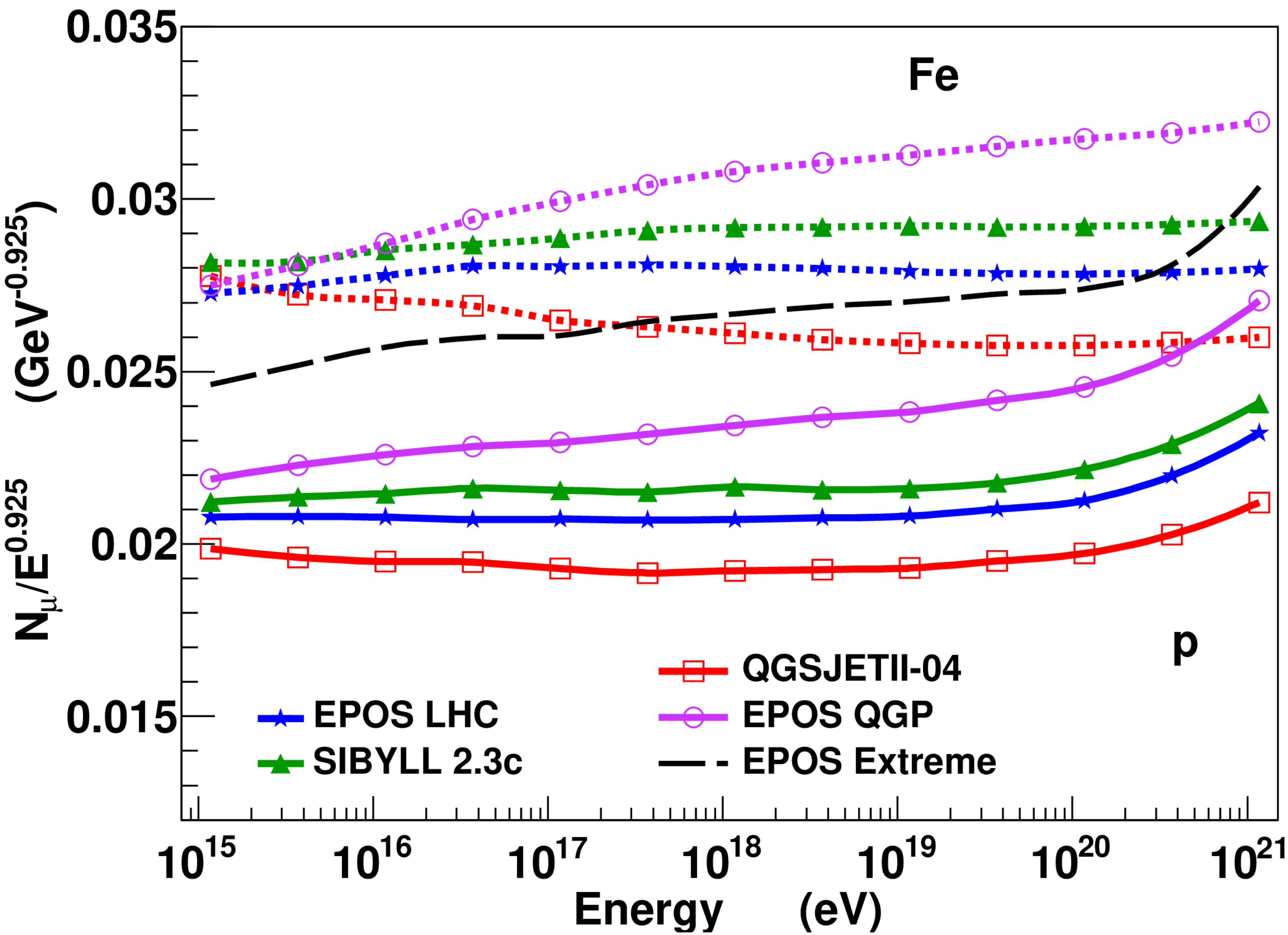
- Small change for <X_{max}> as expected
- Significant change of <X^{μ}_{max}>
- Comparison with extreme case (almost only grand canonical hadron.)
  - ➡ maximum effect using this approach
  - ➡ not compatible with accelerator data

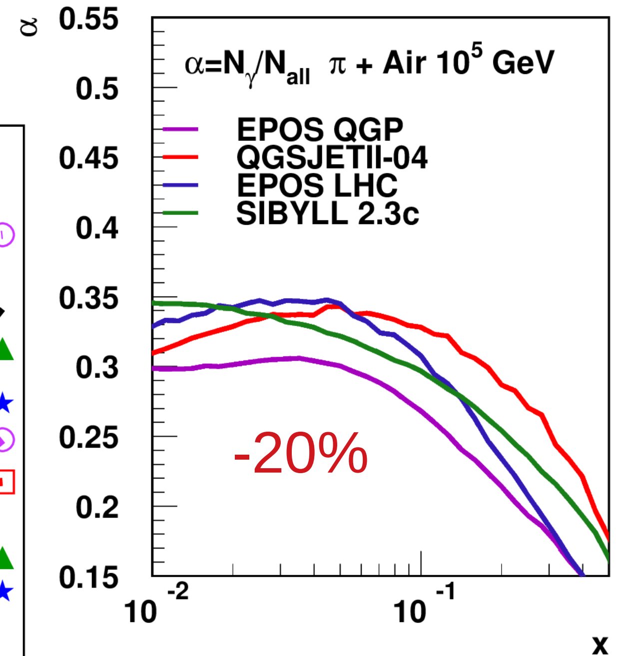


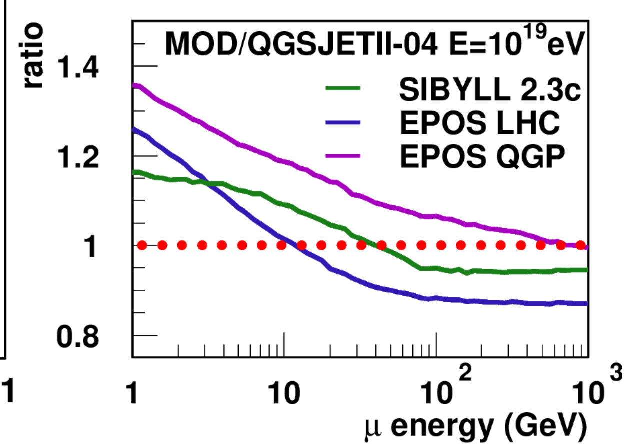


Results for Air Showers (2)

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

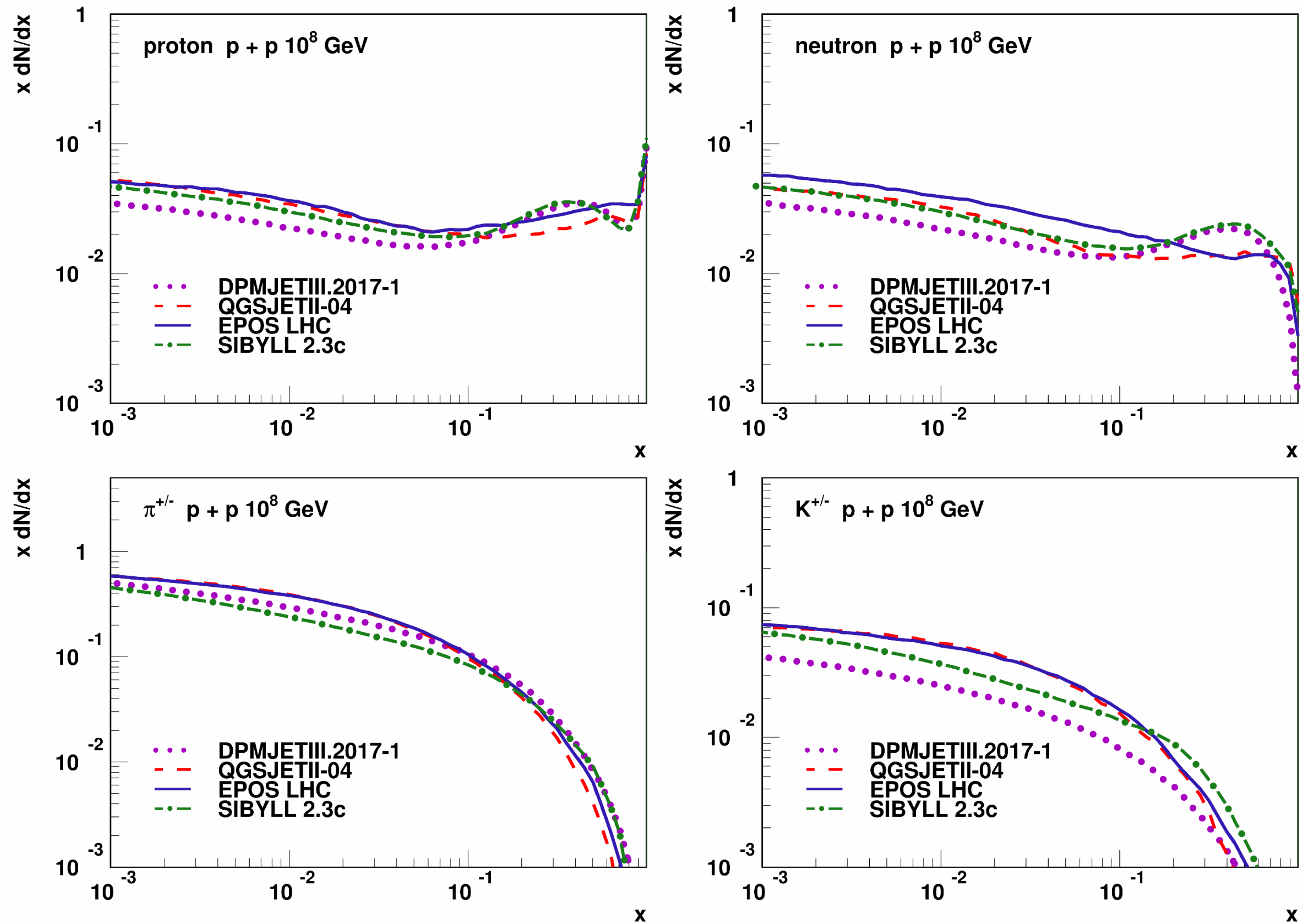






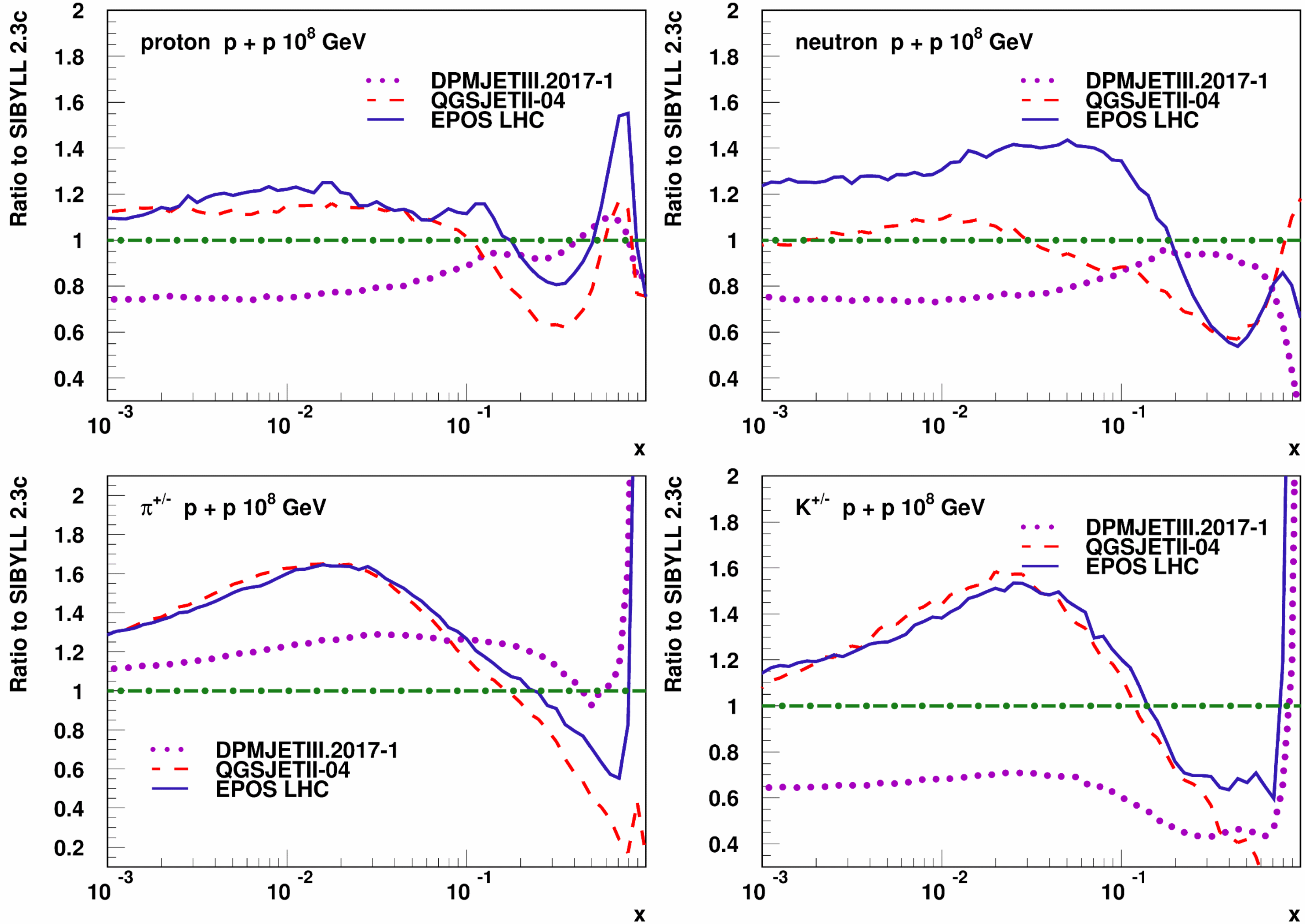
Forward Production in p-p

Simulations at 10^{17}eV lab energy ~ LHC cms energy



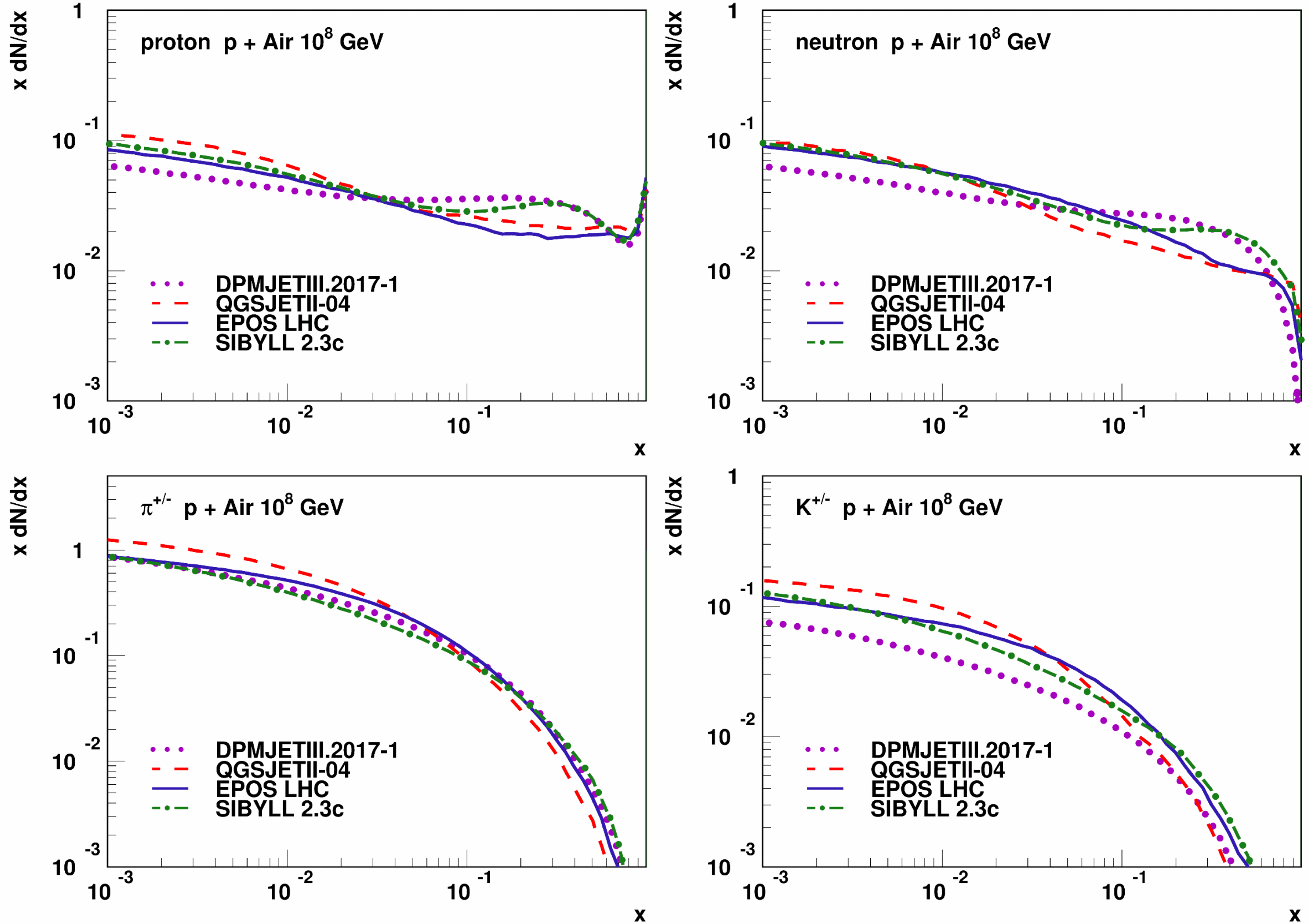
Forward Production in p-p

Simulations at 10^{17}eV lab energy ~ LHC cms energy



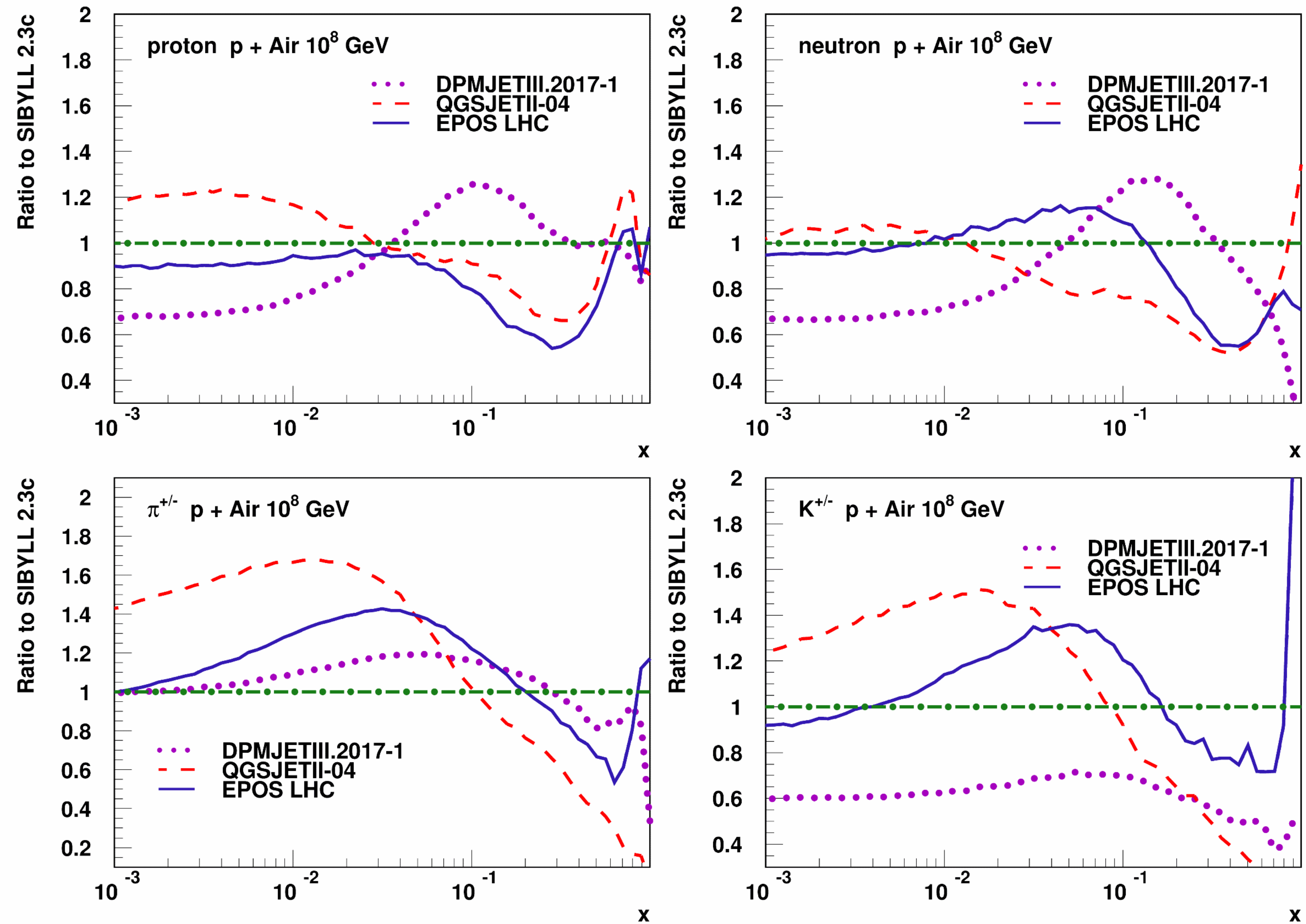
Forward Production in p-Air

Simulations at 10^{17}eV lab energy ~ LHC cms energy



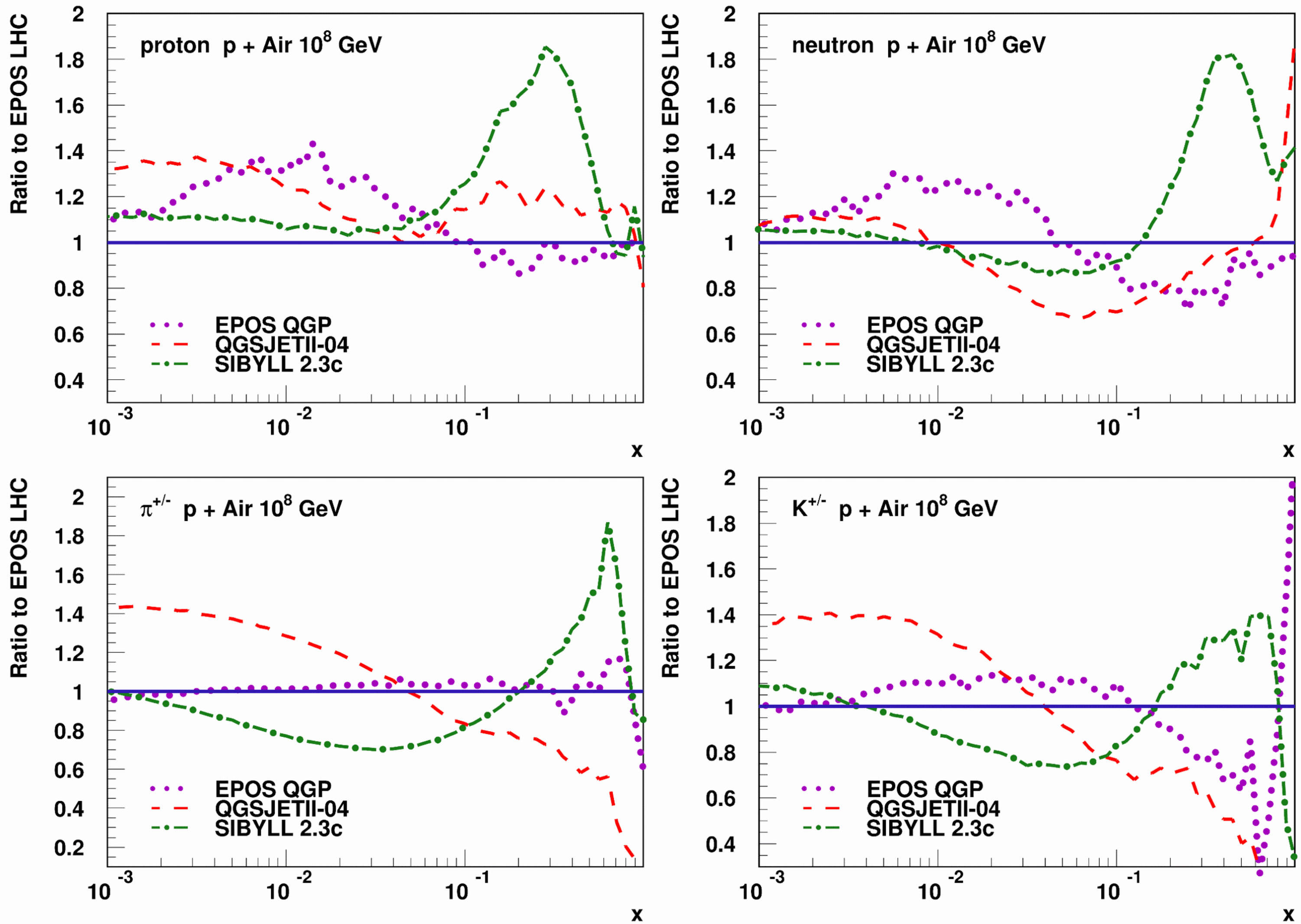
Forward Production in p-Air

Simulations at 10^{17}eV lab energy ~ LHC cms energy



Forward Production in p-Air

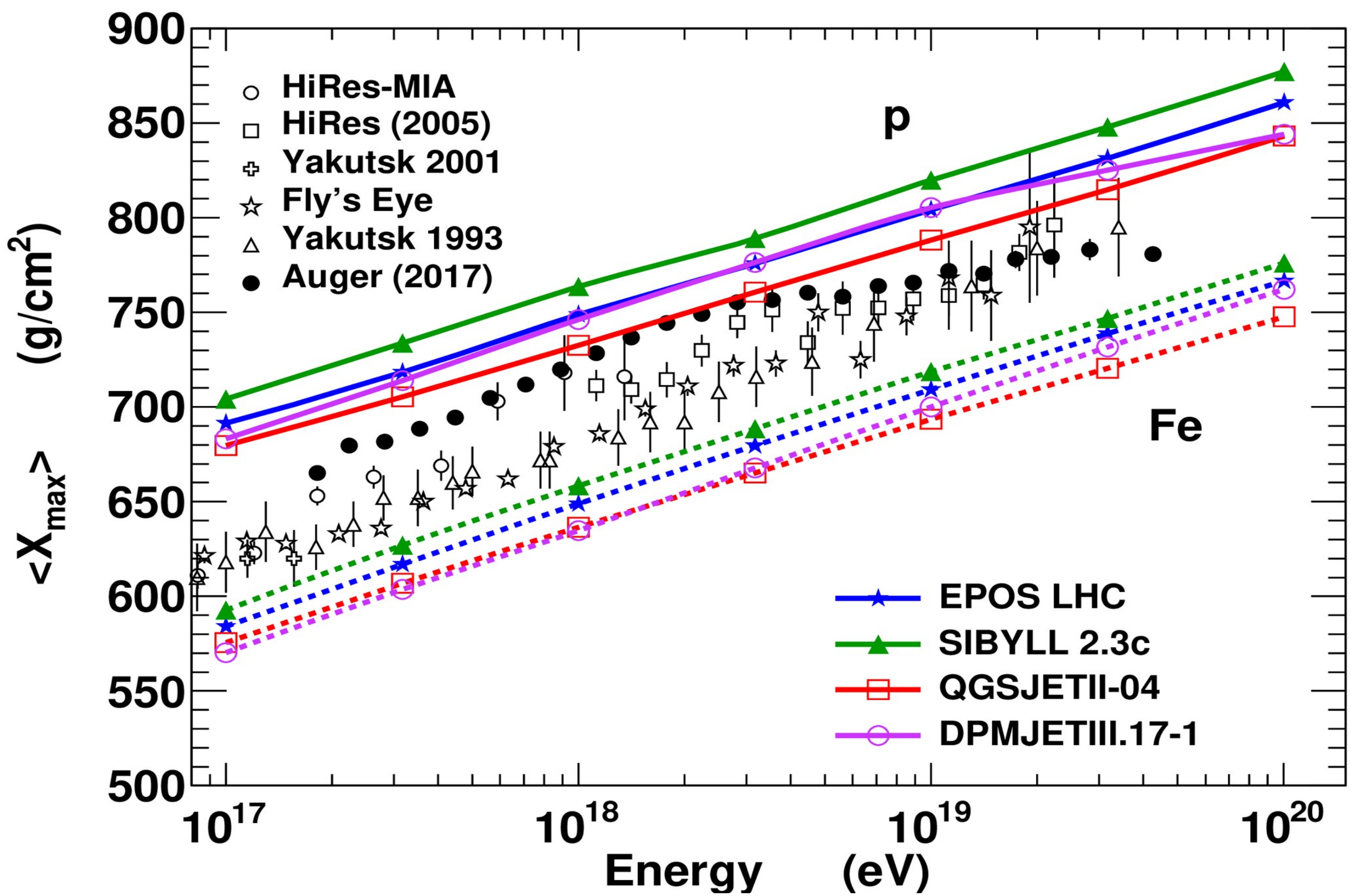
- Simulations at 10^{17}eV lab energy ~ LHC cms energy



➡ Around 10% precision needed in relevant x range (0.01 to 0.3)

$<X_{max}>$

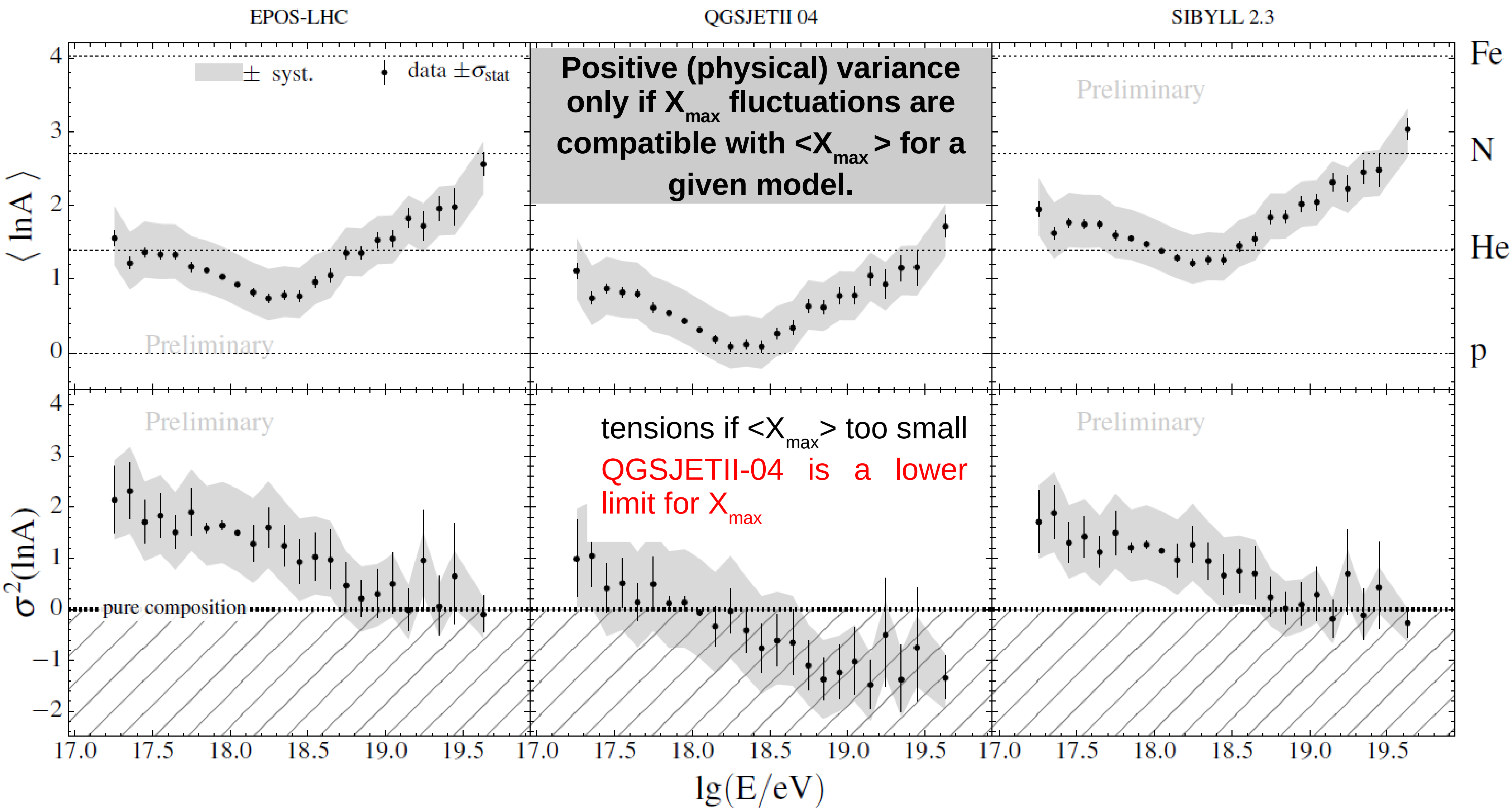
- **very similar elongation rate (slope) for all models**
- **same mass composition evolution**
- **still differences in absolute values**
  - ➡ +/- 20g/cm² is a realistic uncertainty band



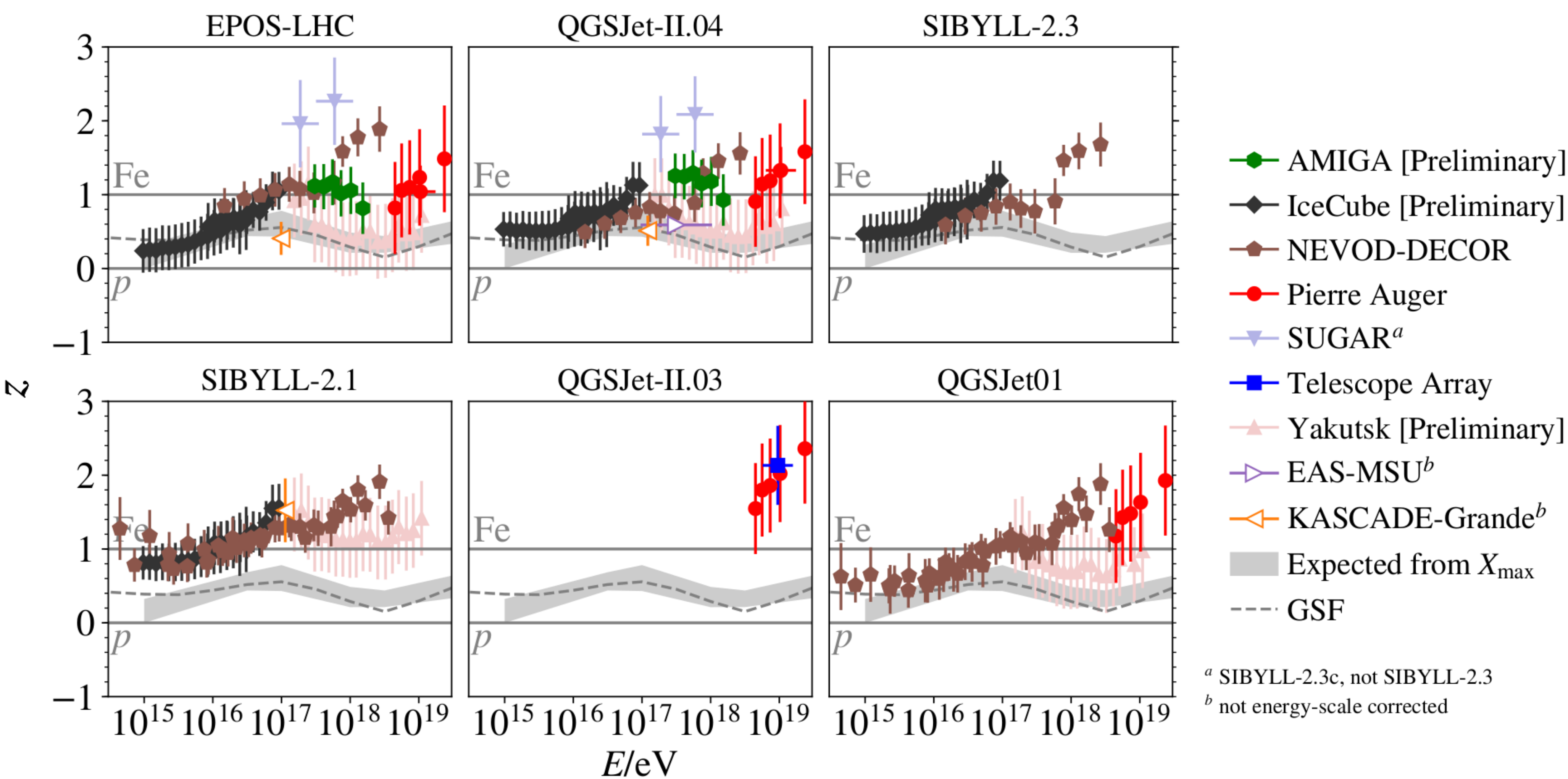
Model Consistency using Electromagnetic Component

Study by Pierre Auger Collaboration

- std deviation of lnA allows to test model consistency.



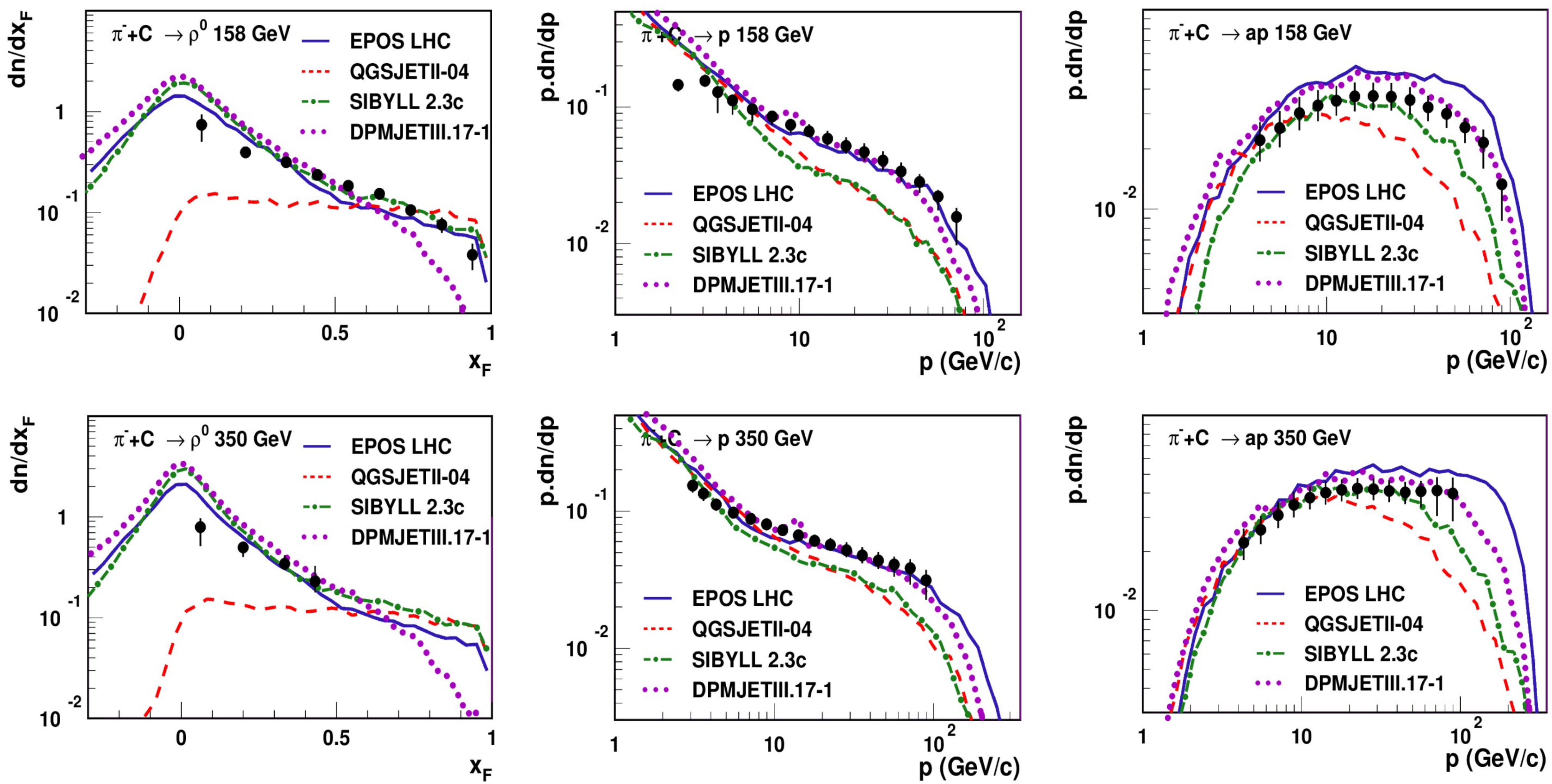
Data Rescaled



NA61 Pion-Carbon Data

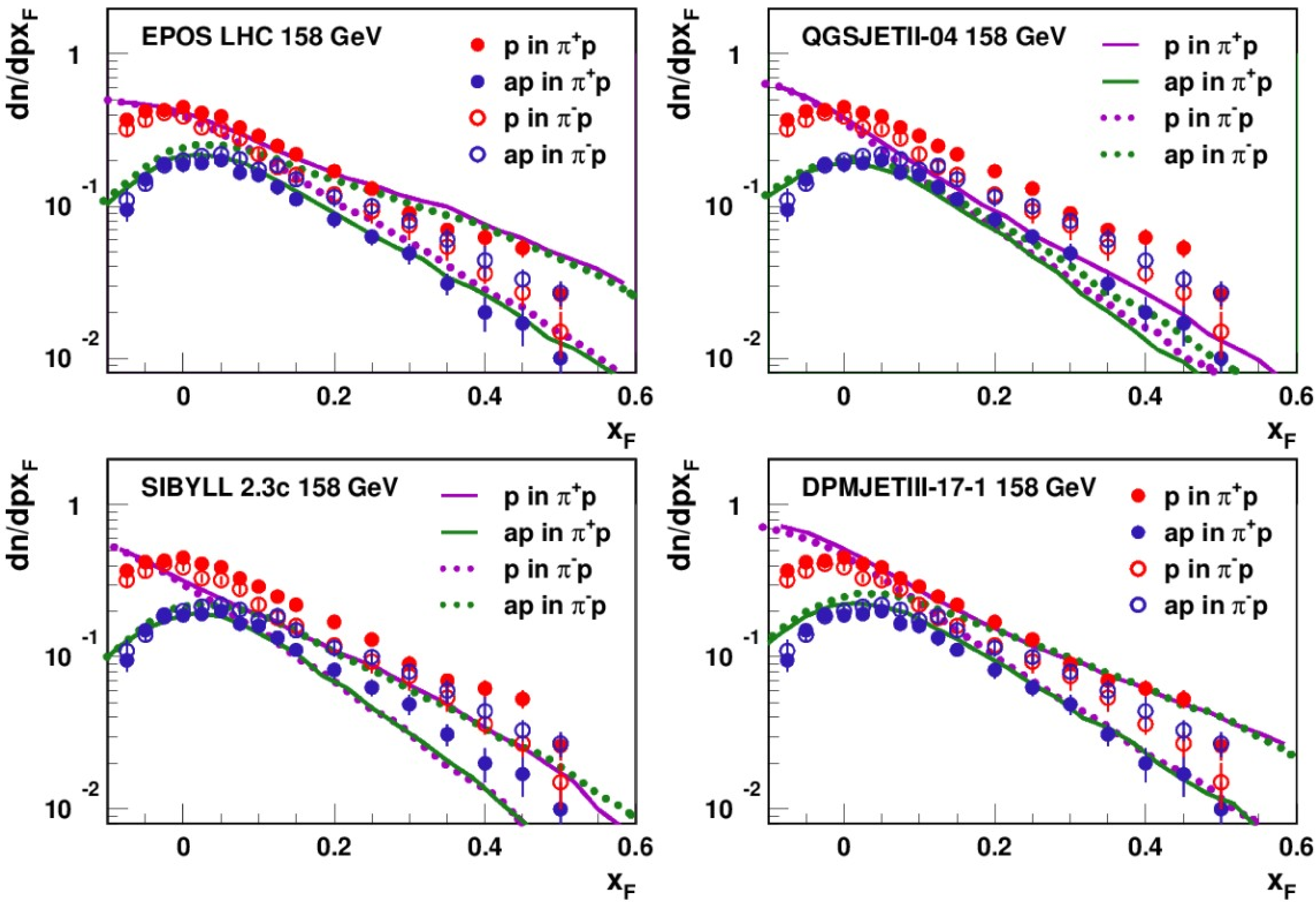
New data from NA61 : wrong old data interpretation

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



Baryons in Pion Interactions

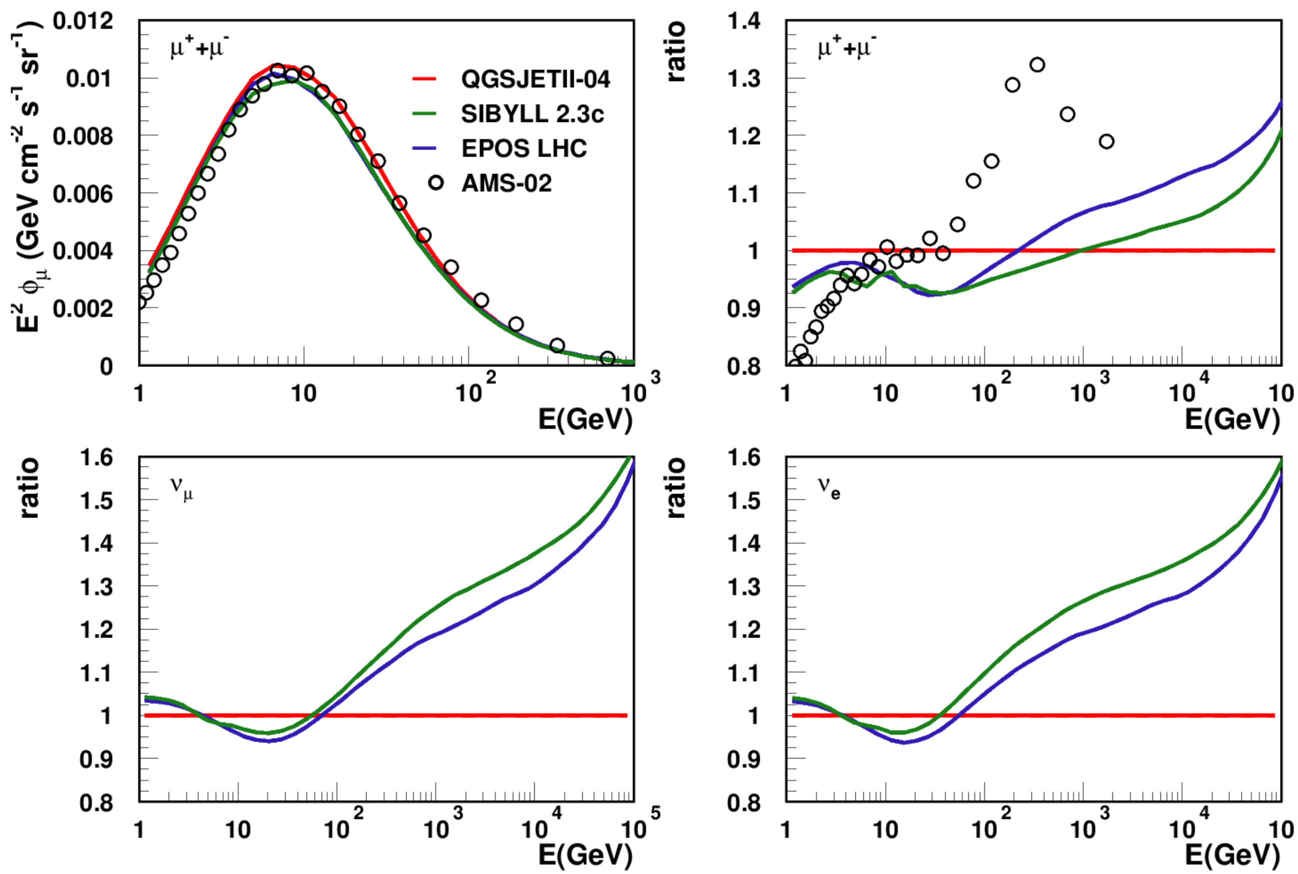
Data from NA49 (Gabor Veres PhD) : full picture



Muon and Neutrino Fluxes

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

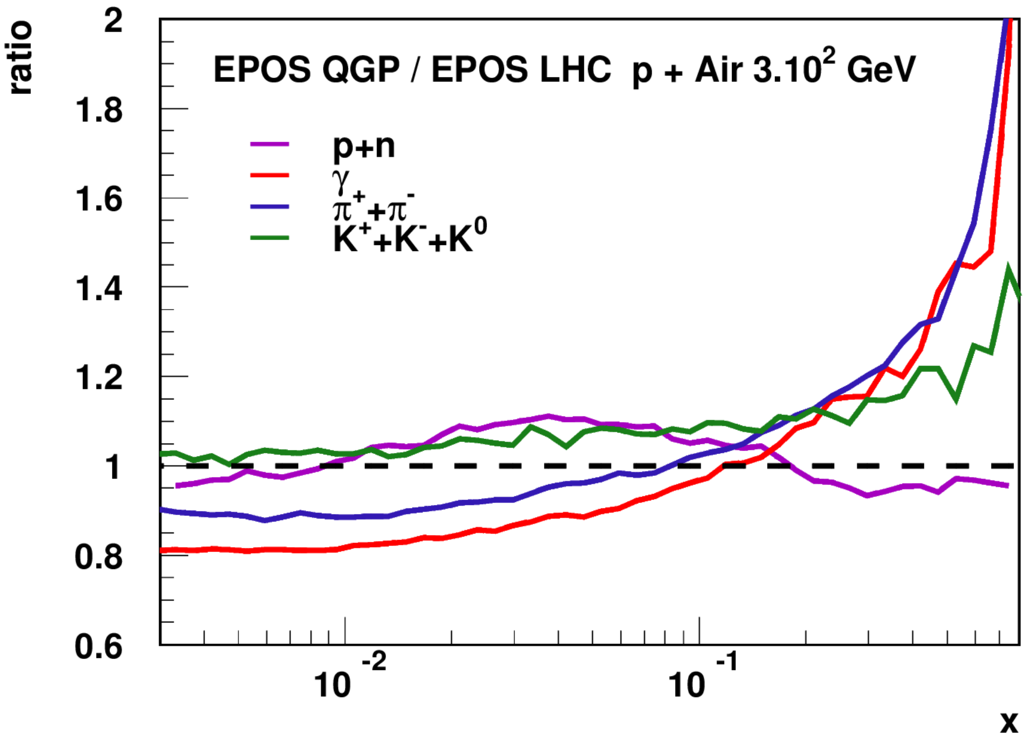
- ➡ Reasonable agreement below 100 GeV.
- ➡ Uncertainties due to primary CR flux/mass choice (H3a)



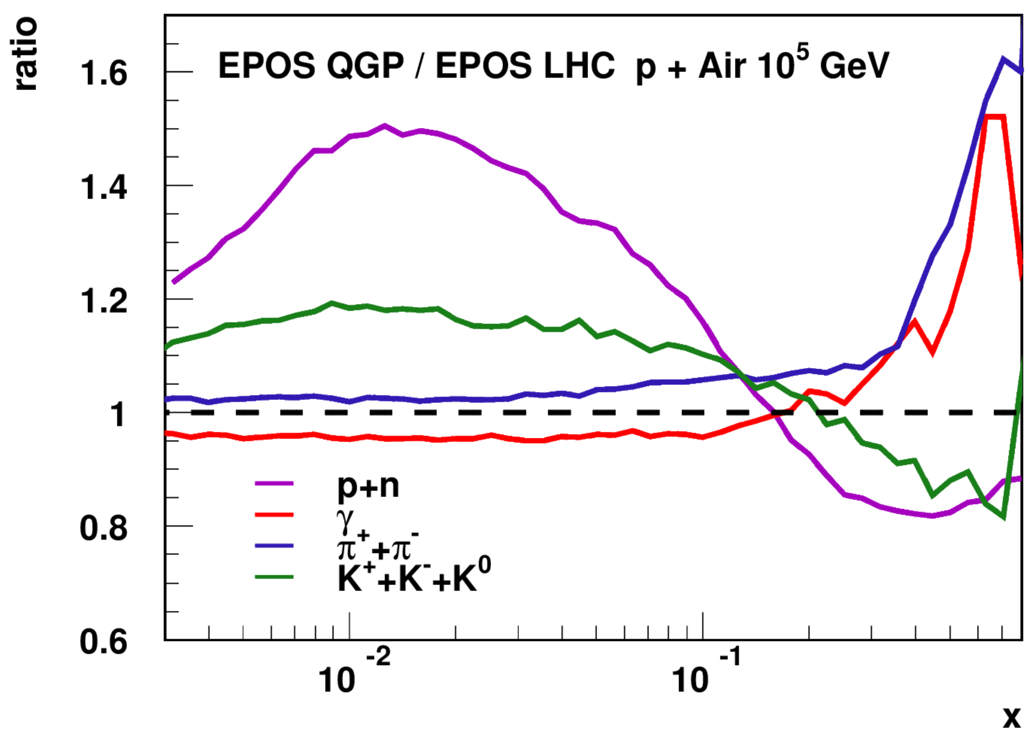
Modified Spectra with EPOS QGP

- **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



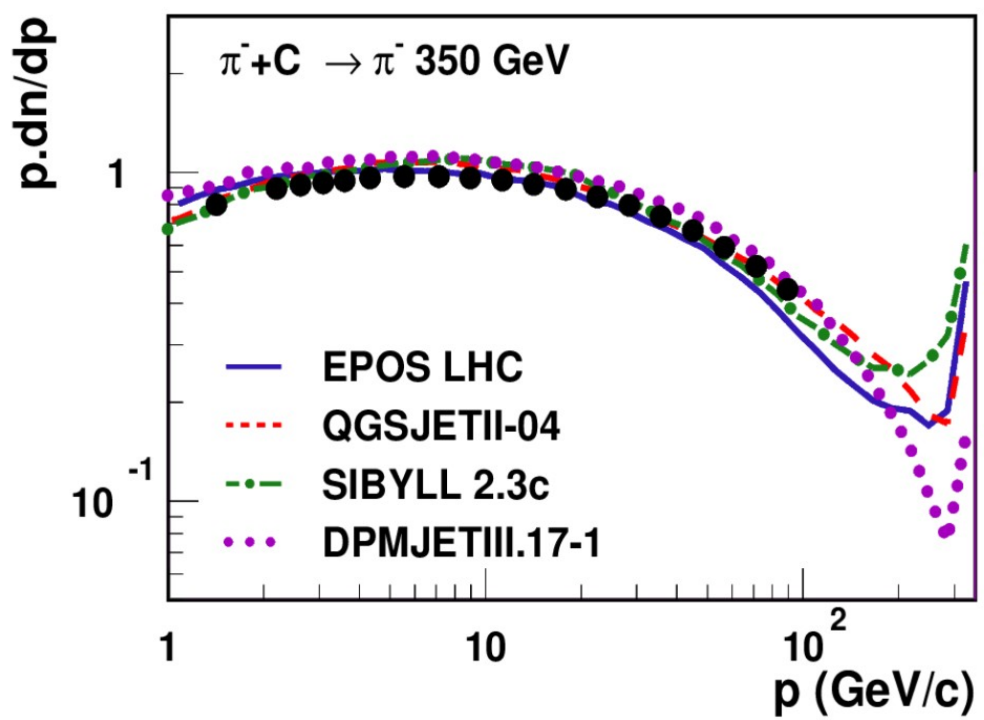
Source of PeV leptons

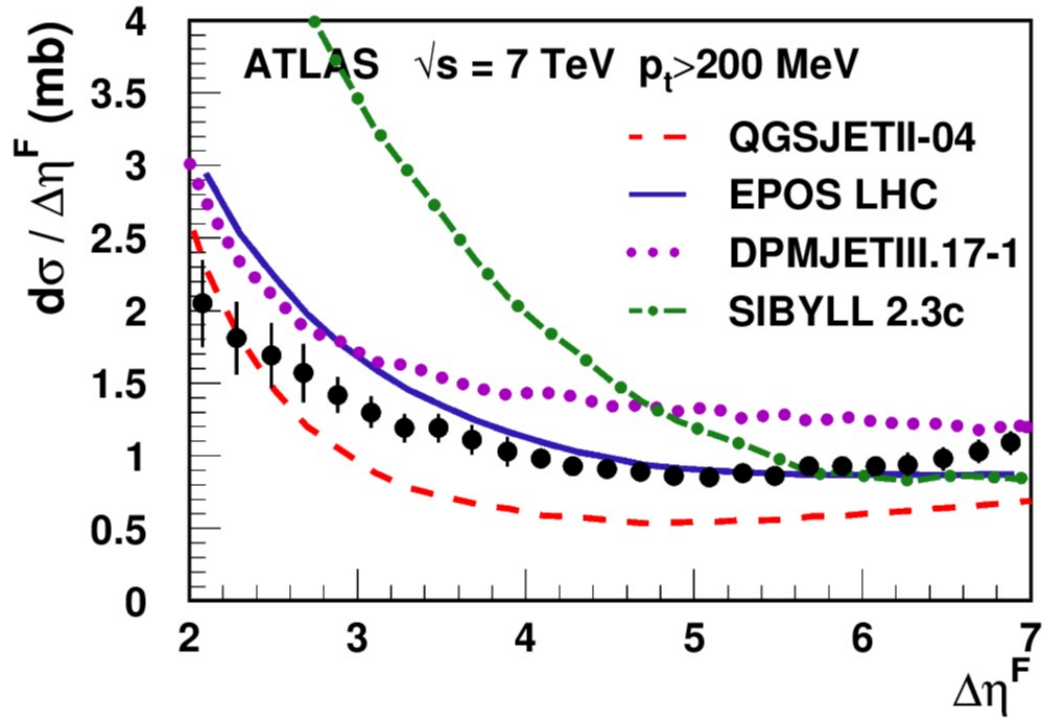


Pion Interactions

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

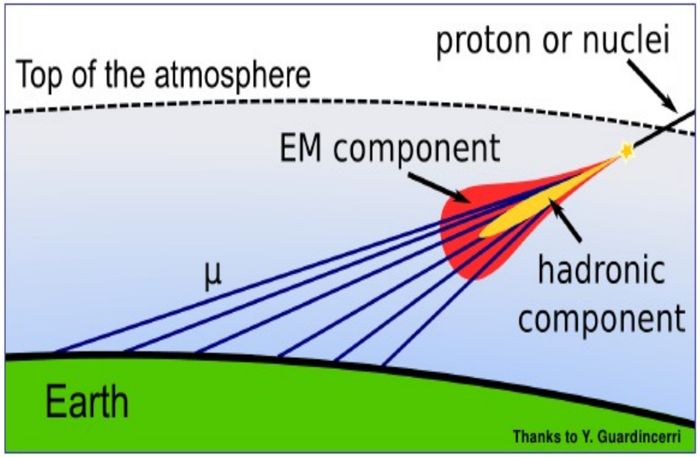


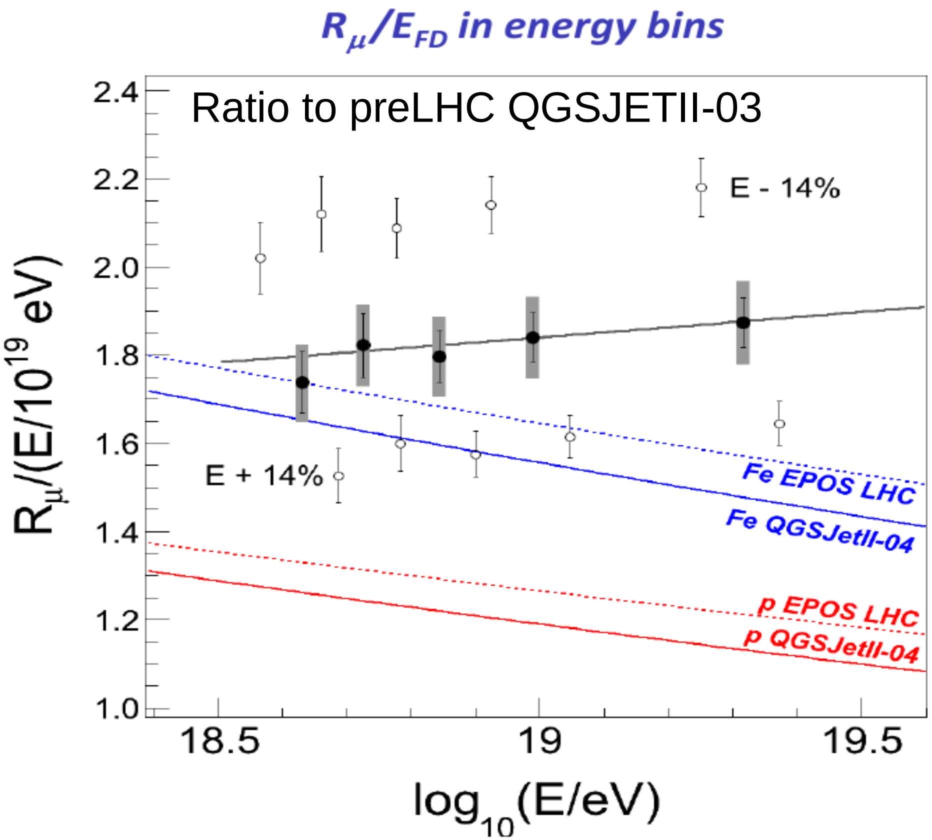


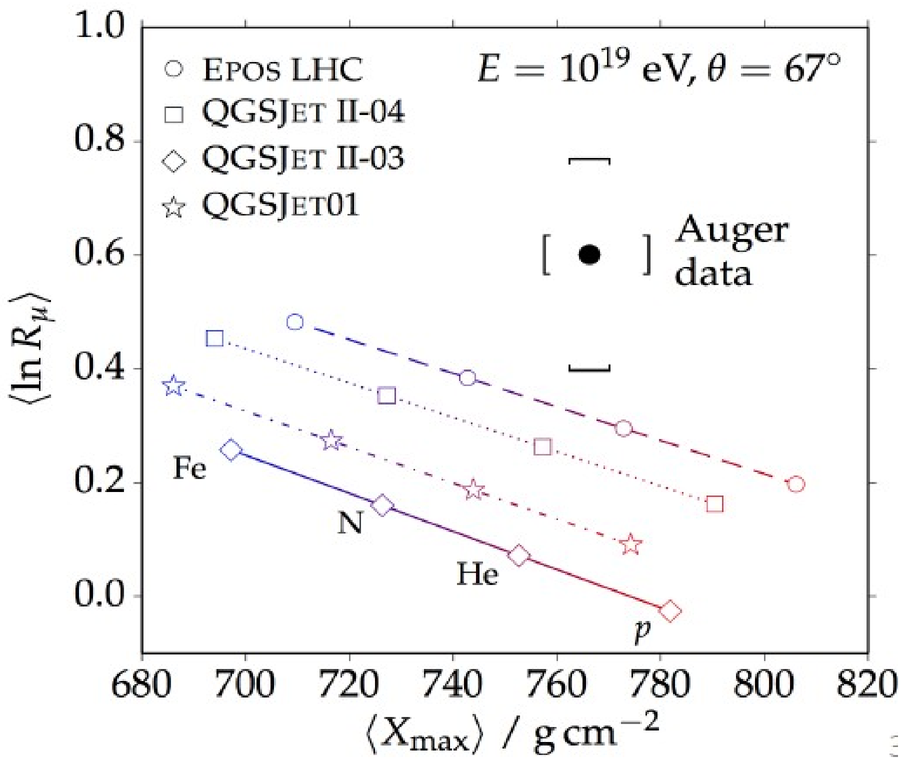
Ultra High Energy Showers

Pierre Auger Observatory direct measurements

- direct muon counting for very inclined showers (>60°) by comparing to simulated muon maps (geometry and geomagnetic field effects) at high energy
- indirect using hybrid measurement
- direct using burred detectors (AMIGA) at low energy

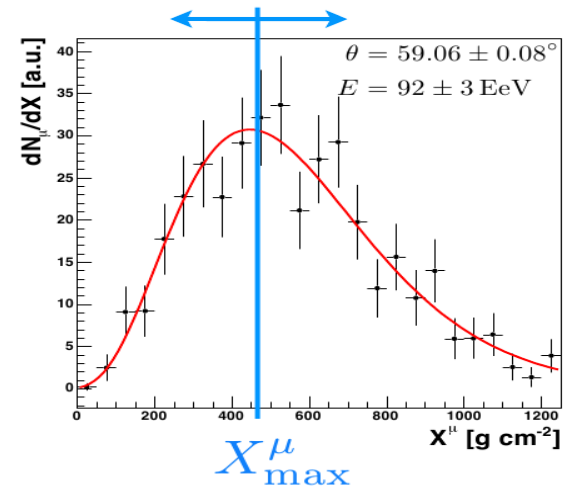


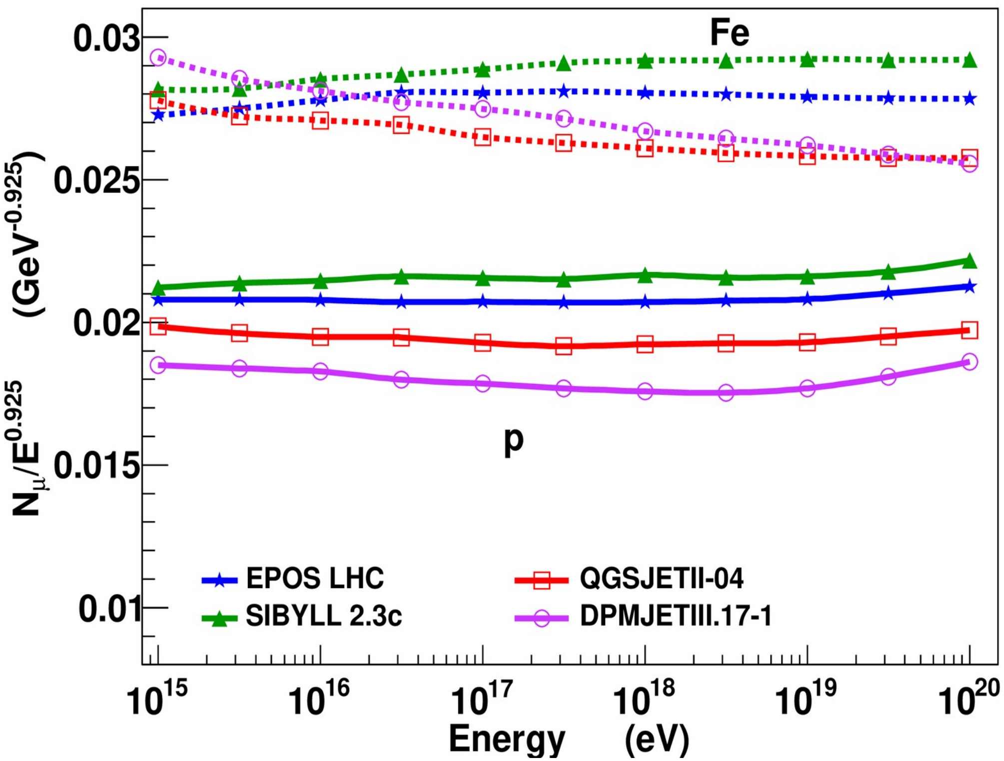


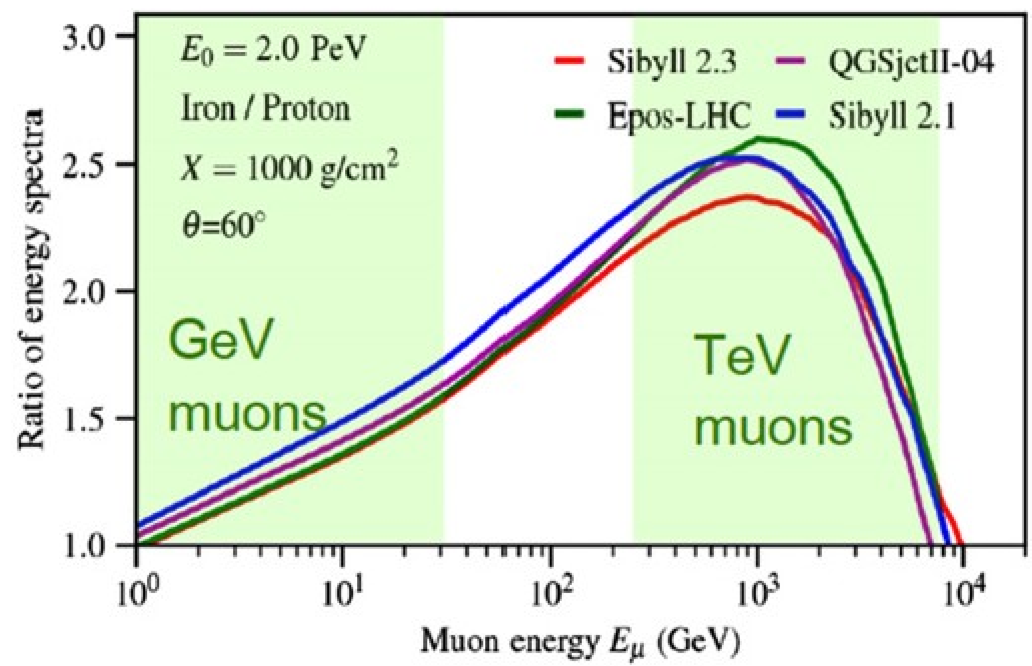


Muons at Ground

- 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 (MPD) and spectra





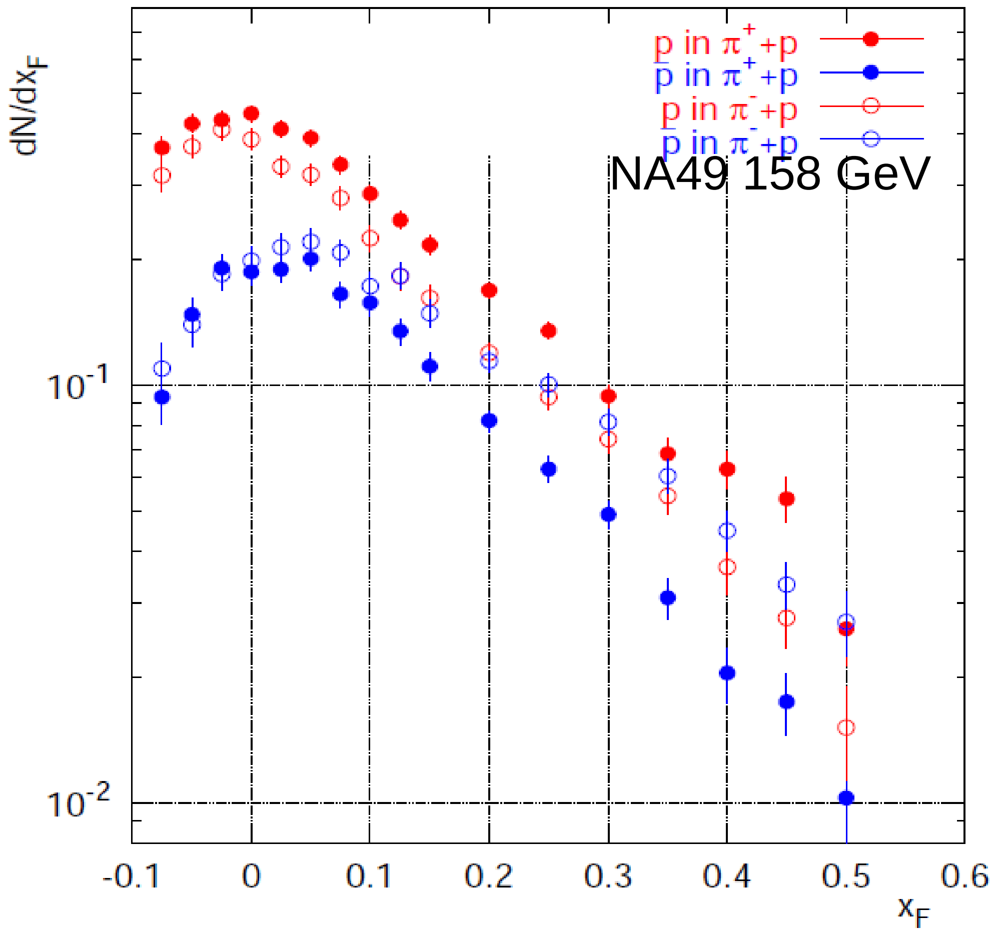


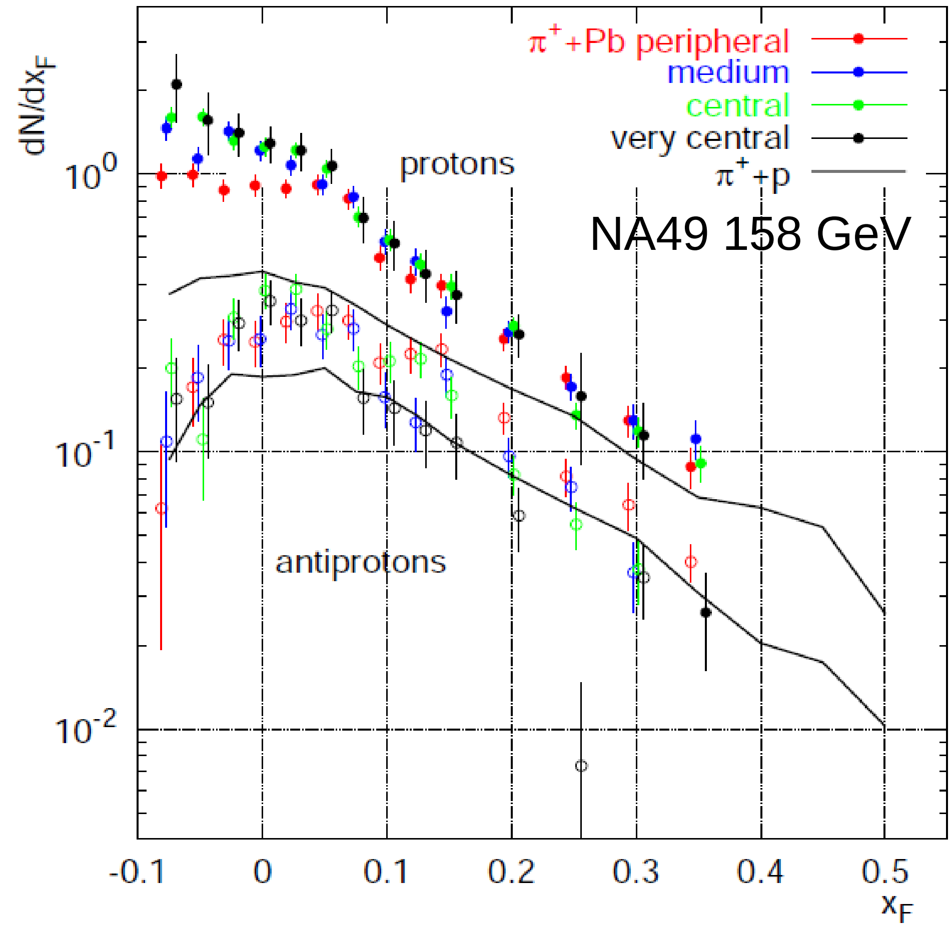
F. Riehn for IceCube

Baryons in Pion Interactions

Data from NA49 (Gabor Veres PhD) : full picture

- valence quark effect visible
- large part (half ?) of forward baryon production coming from the target !
  - possible new source of low energy muons with small effect on MPD



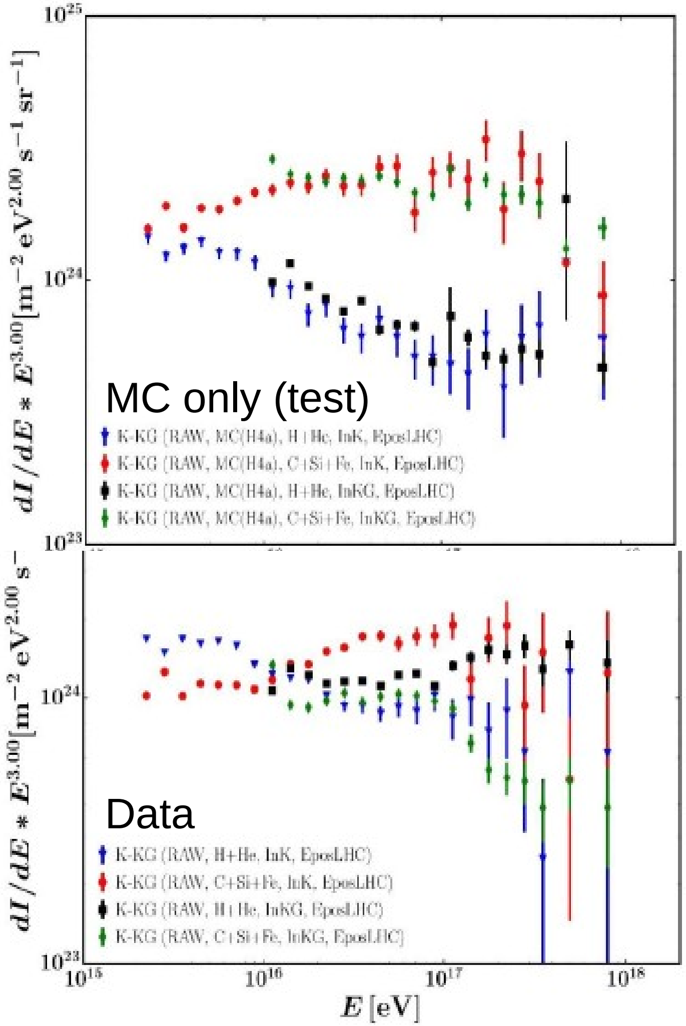


Mass Dependent Inconsistencies

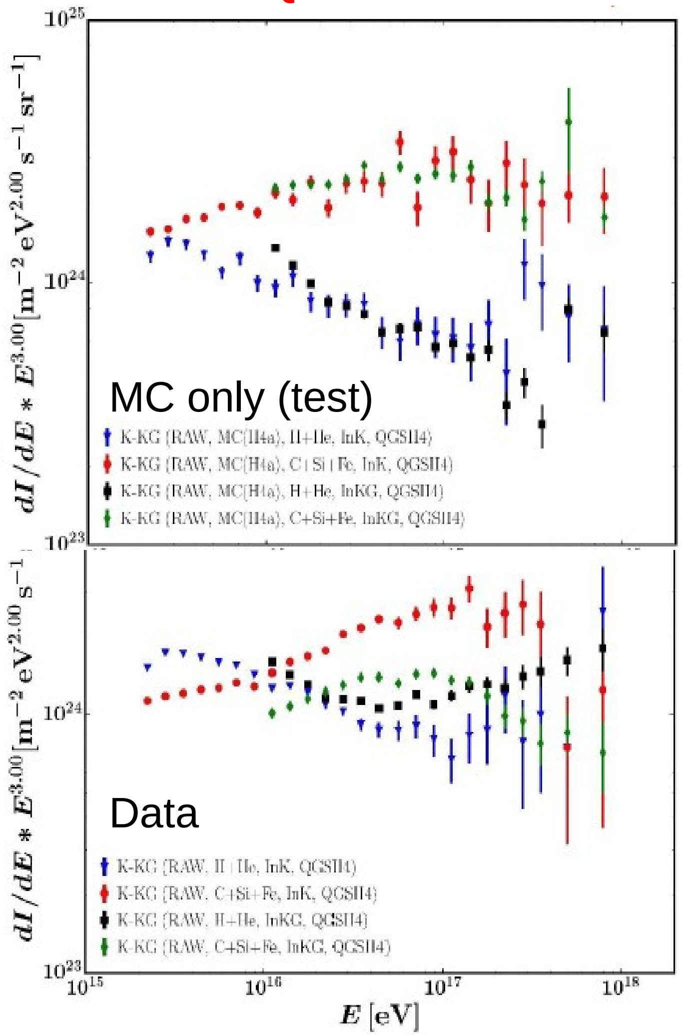
Test using KASCADE and KASCADE-Grande

➡ inconsistency must larger for heavy component !

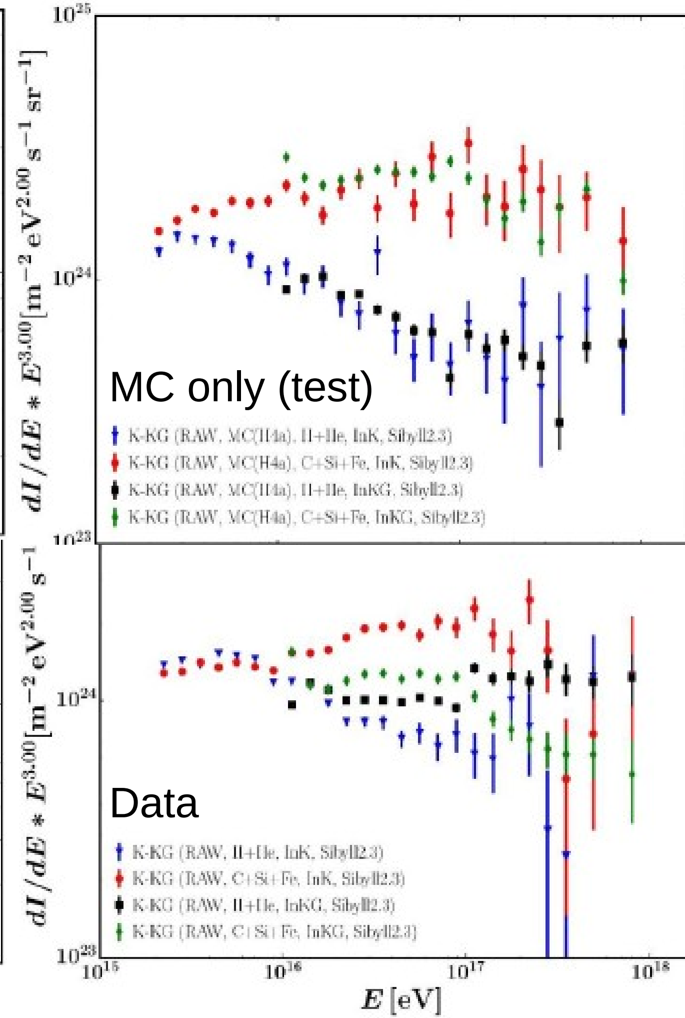
EPOS LHC



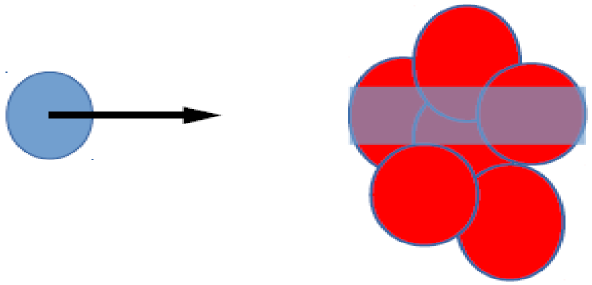
QGSJETII-04



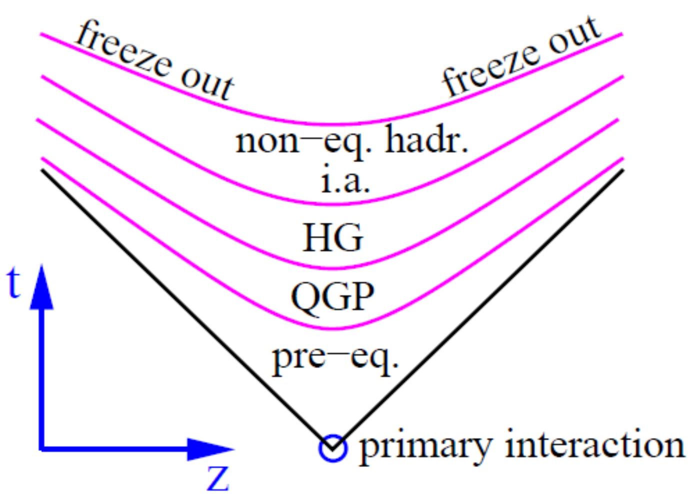
SIBYLL 2.3



Nuclear Interactions



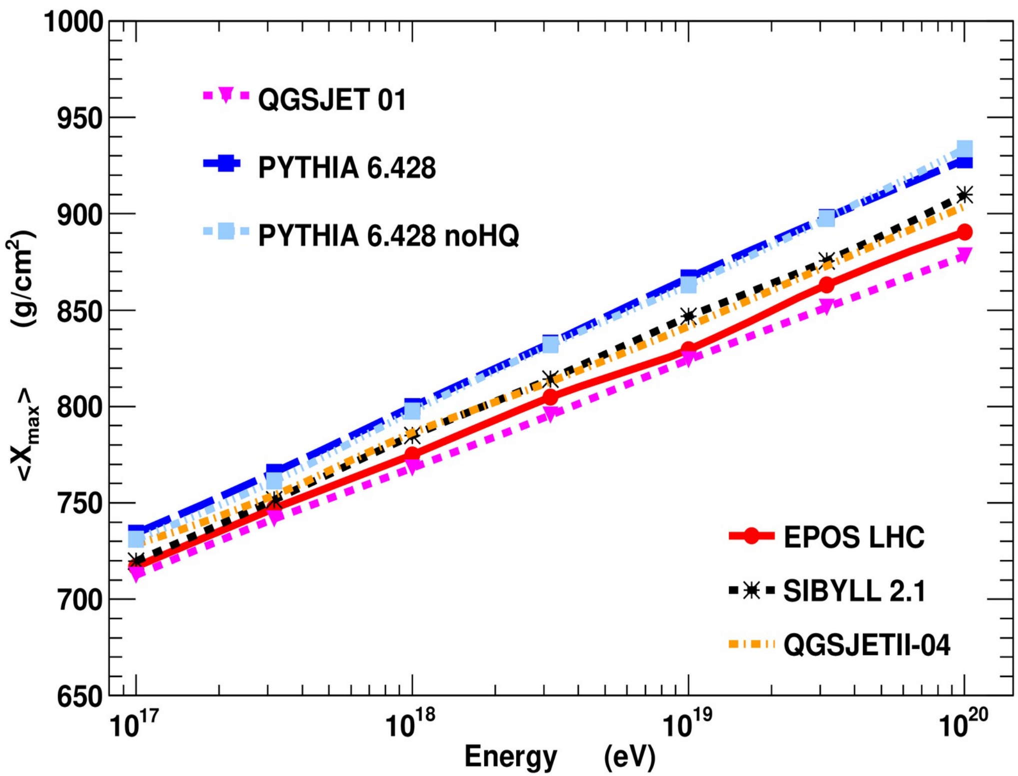
Main source of uncertainty in extrapolation :
- **very different approaches**
- **limited available data set**
- **limited models capabilities**

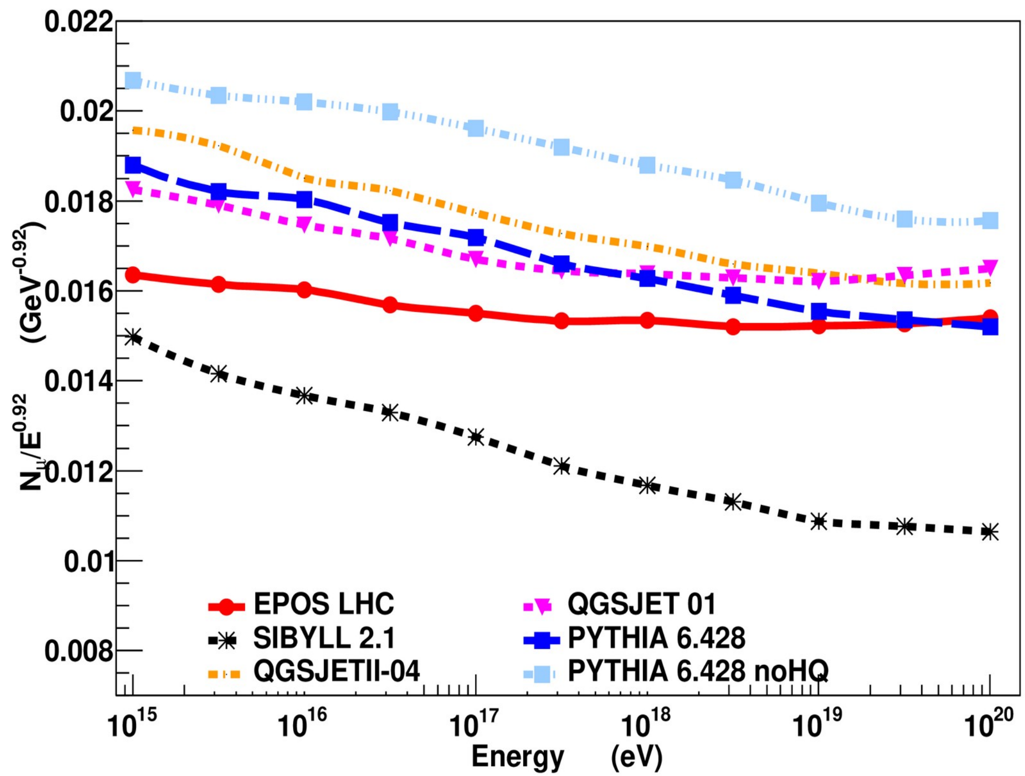


- **Sibyll** (light ion only)
  - corrected Glauber for pA
  - superposition model for AA (A x pA)
- **QGSJETII** (all masses but not all data)
  - Scattering configuration based on A projectiles and A targets
  - Nuclear effect due to multi-leg Pomerons
- **DPMJETIII (all masses)**
  - Glauber
  - limited collective effects treatment
- **EPOS** (all masses)
  - Scattering configuration based on A projectiles and A targets
  - screening corrections depend on nuclei
  - final state interactions (core-corona approach and collective hadronization with flow for core)

Tests using Hydrogen Atmosphere

- **Modified air shower simulations with air target replaced by hydrogen**
  - for interactions only (no change in density)
  - no nuclear effect
- **Relative predictions for <X_{max}> and number of muons are very different**
  - smaller difference but QGSJETII-04 larger than EPOS LHC !

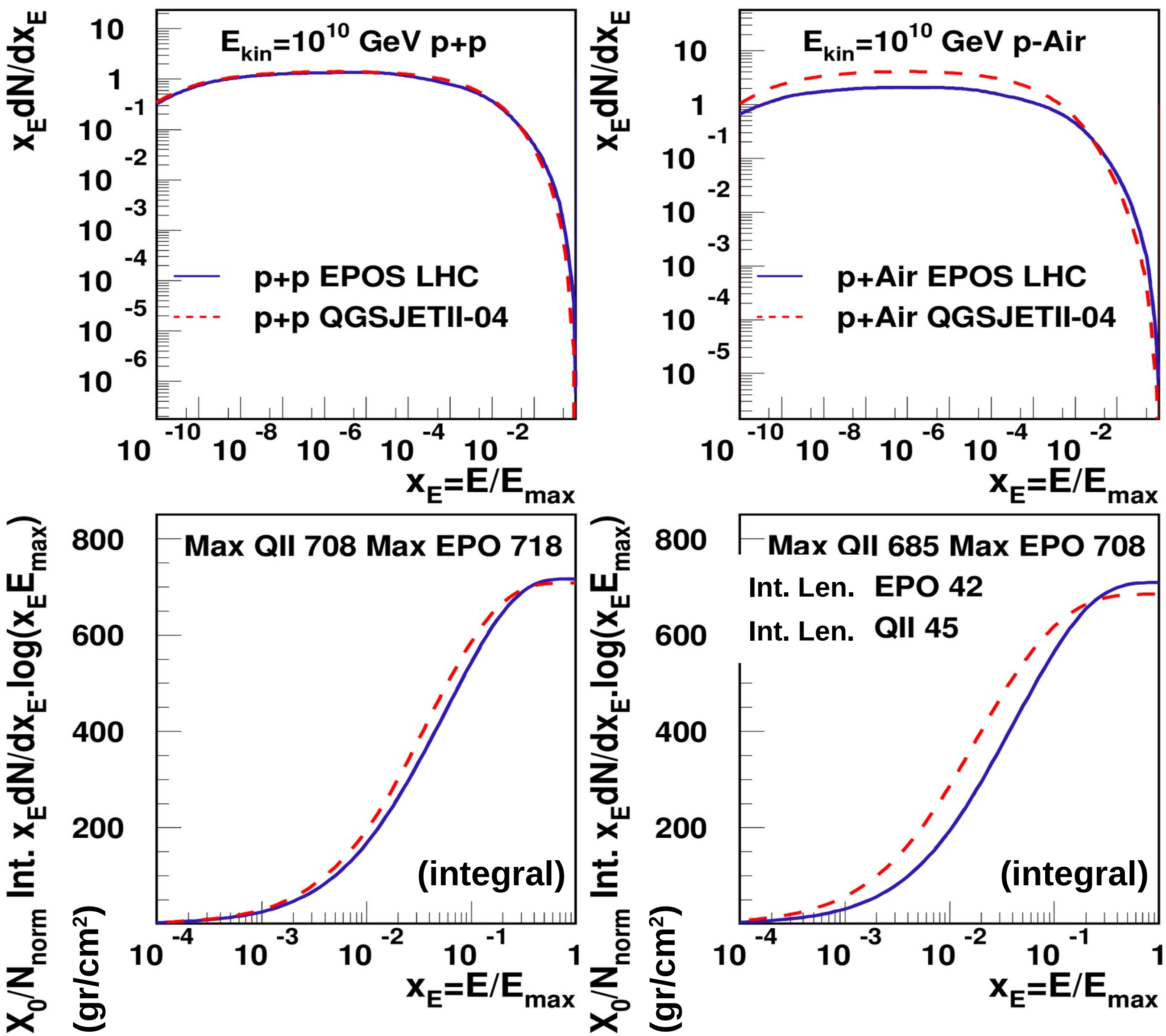




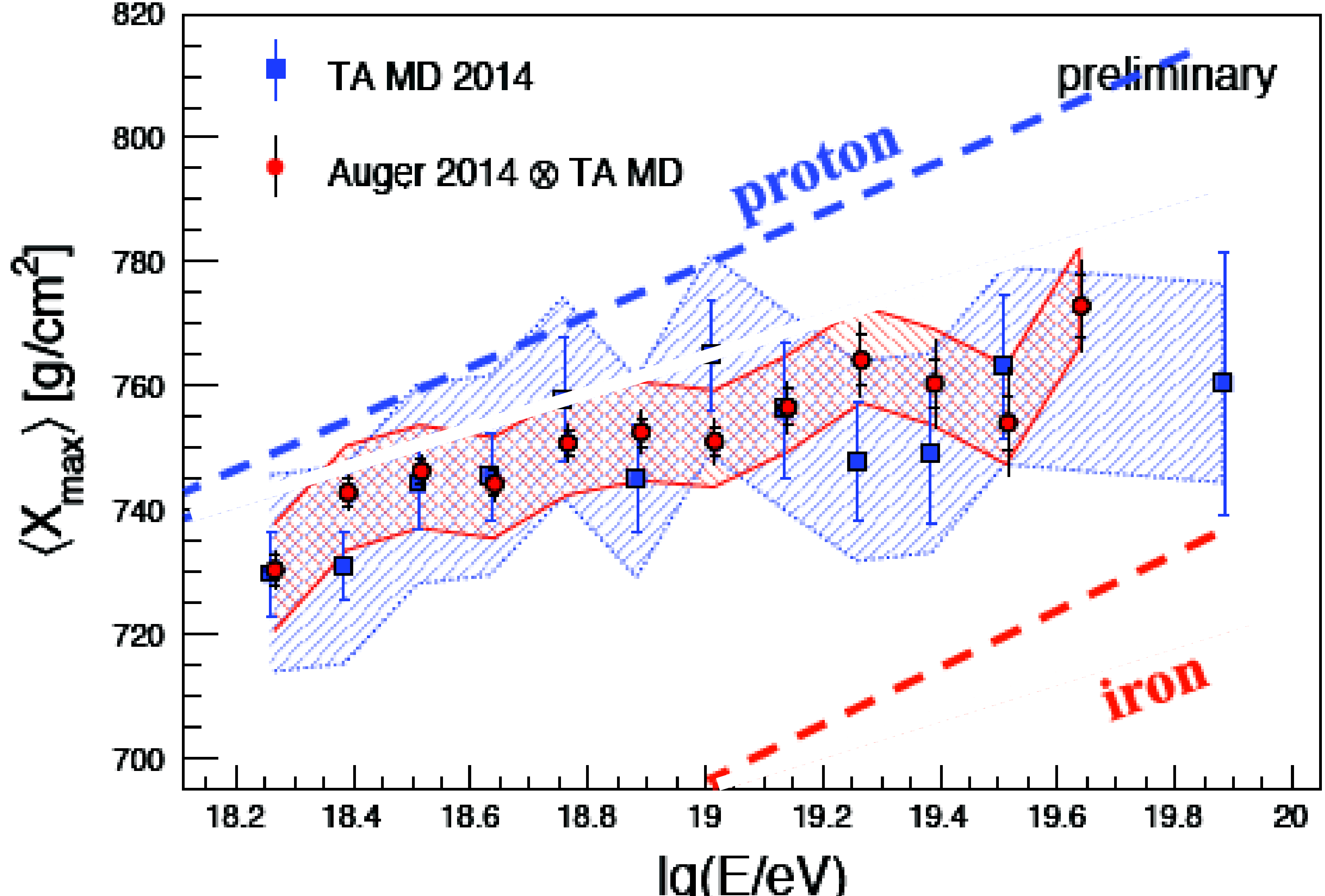
David D'Enterria (CERN), Sun Guanhao and TP

Photon Energy Spectra

- **Uncertainties in X_{max}**
  - photon energy spectra
  - elasticity (for 2[d] interaction)
  - extrapolation to nuclear interactions
- **Use directly energy spectra from first interaction**
  - which energy is important ?



PAO vs TA



From Roberto Aloiso UHECR talk (2015 working group)

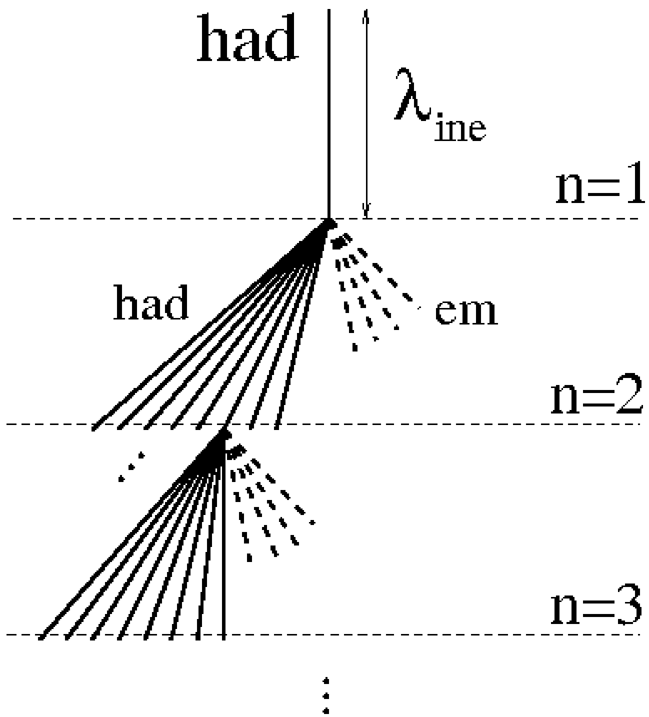
Baryons in Pion-Carbon

- **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

Simplified Shower Development



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

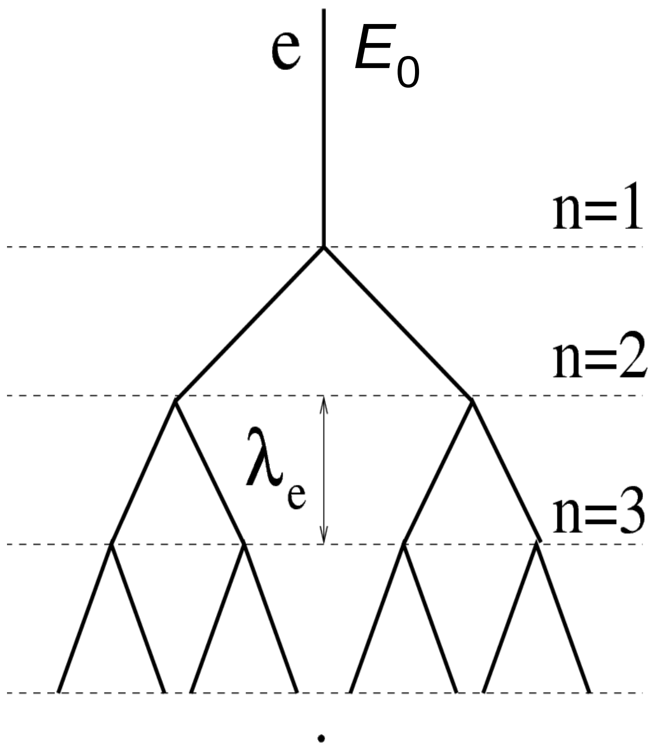
J. Matthews, Astropart.Phys. 22 (2005) 387-397

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 Electromagnetic Cascade



Primary particle : photon/electron

Heitler toy model :

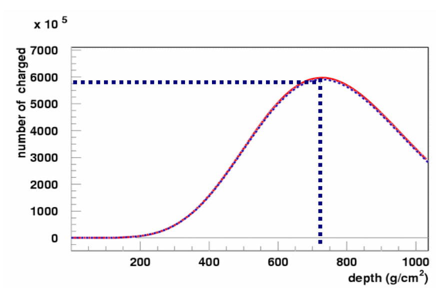
- 2 particles produced with equal energy

2^n particles after n interactions

$$n = X/\lambda_e$$

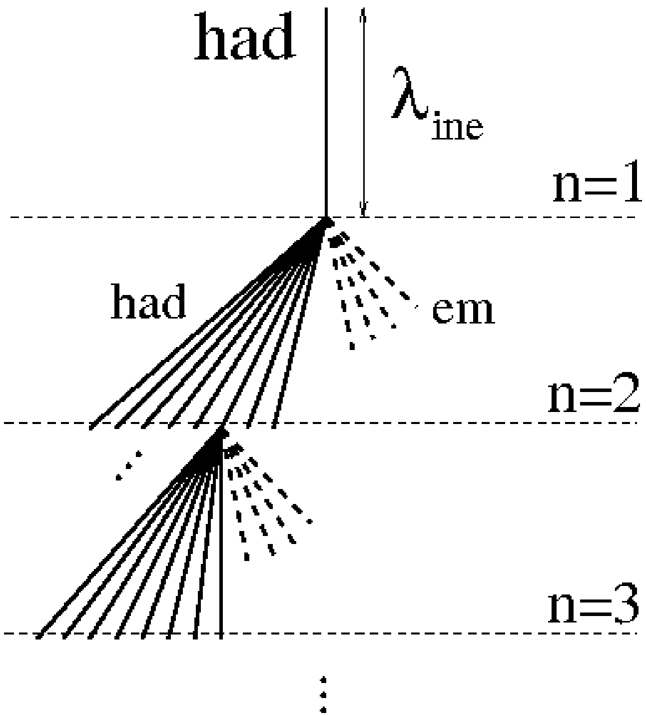
$$N(X) = 2^n = 2^{X/\lambda_e} \qquad E(X) = E_0/2^{X/\lambda_e}$$

Assumption: shower maximum reached if $E(X) = E_c$ (critical energy)



$$N_{max} = E_0/E_c \qquad X_{max} \sim \lambda_e \ln(E_0/E_c)$$

Toy Model for Hadronic Cascade



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

Primary particle : hadron

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

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

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

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

Hadronic Interaction Models in CORSIKA

(HDPM)

Old generation : (SIBYLL 2.1 QGSJET01 DPMJET 2.55 VENUS) (<2001)

All Glauber based

But differences in hard, remnants, diffraction …

Engel et al.

semi-hard

soft

NEXUS 3.97

Attempt to get everything described in a consistent way (energy sharing)

New (!) generation : (QGSJET II-03) (EPOS 1.99) (2005-2012)

LHC tuned : QGSJET II-04 EPOS LHC (2013-)

Ostapchenko

Pierog & Werner

Riehn & Engel

Fedinitch & Engel

LHC inspired : SIBYLL 2.3 QGSJET III (?) DPMJET III EPOS 4

Motivation :

- update with latest LHC results in simple model

Motivation :

- Hard Pomeron-Pomeron connexion

Motivation :

- update with LHC results
-fix high energy

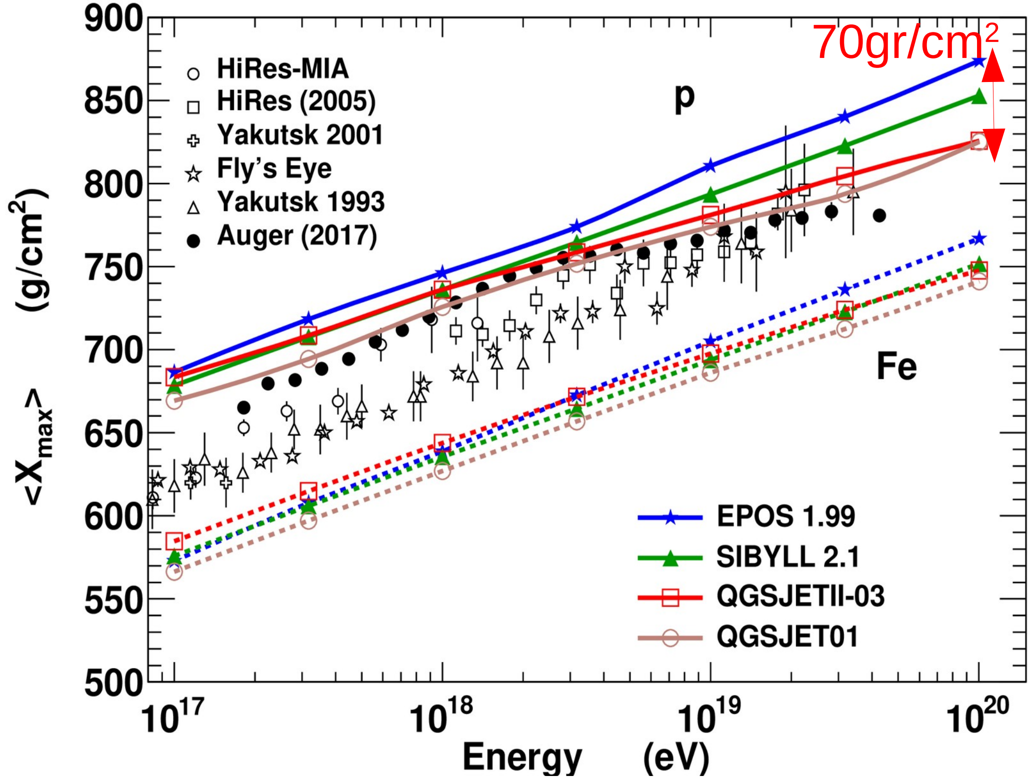
Motivation :

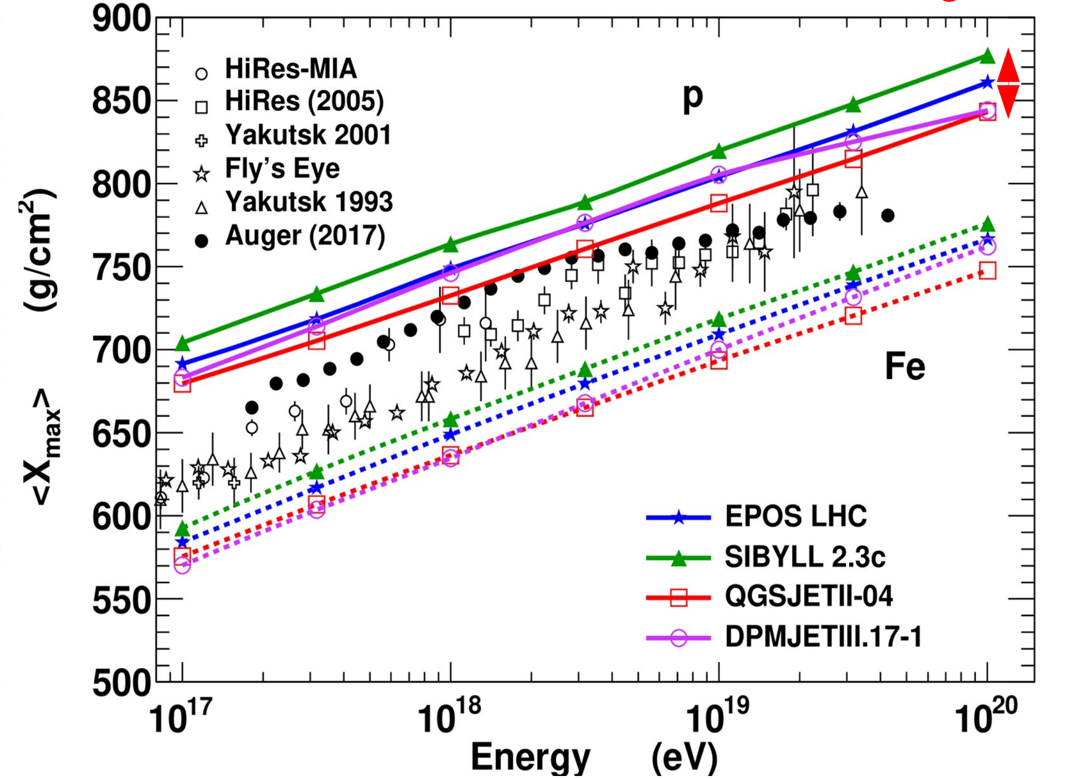
- binary scaling in hard probes

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

After LHC :

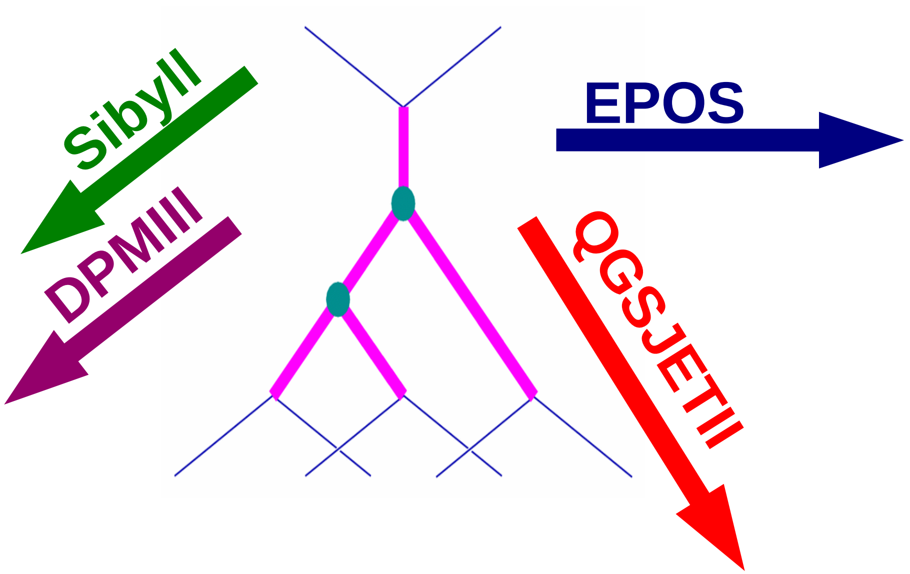
- Sibyll shifted by ~+20 g/cm^2
- for other models about the same $<X_{max}>$ value at 10^{18} eV but
  - slope increased for QGSJETII
  - slope decreased for EPOS
- very similar elongation rate (slope) for all models





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)

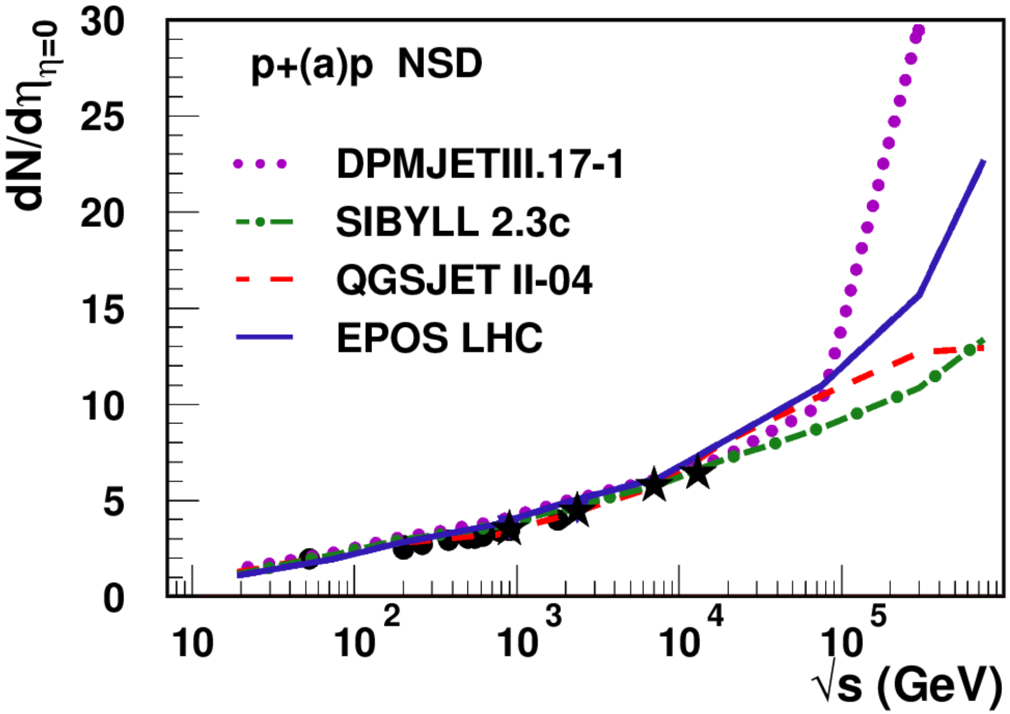
- fixed minimum p_t in hard part
- theory based “fan diagrams” re-summed to infinity without energy sharing

- 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)

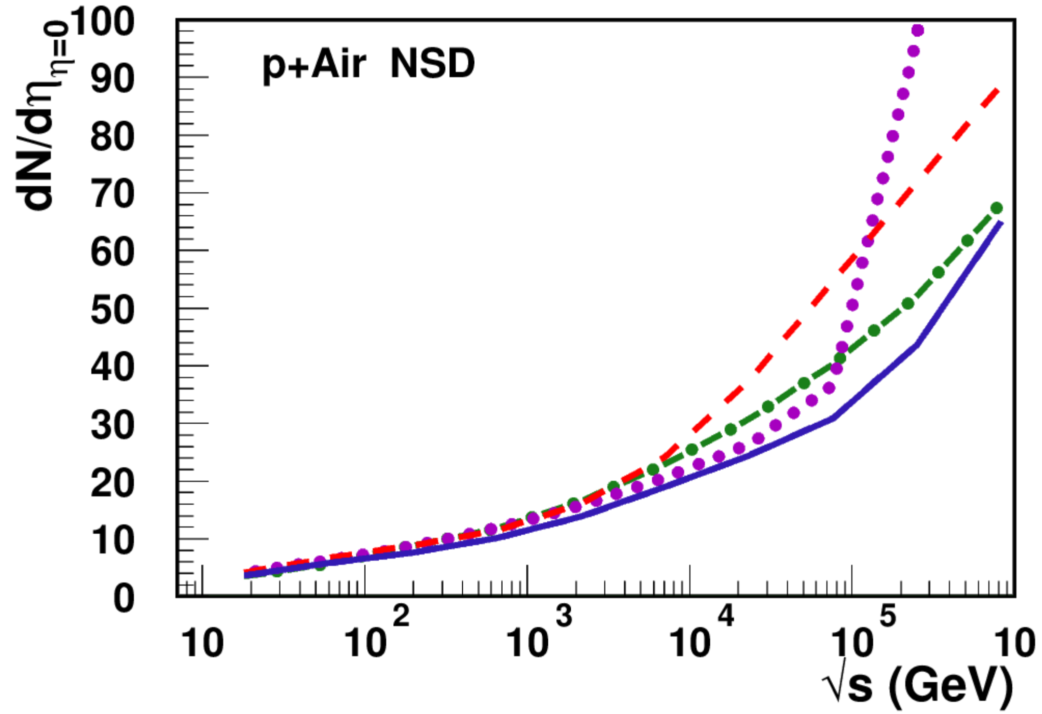
Energy Evolution

- **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)

pp

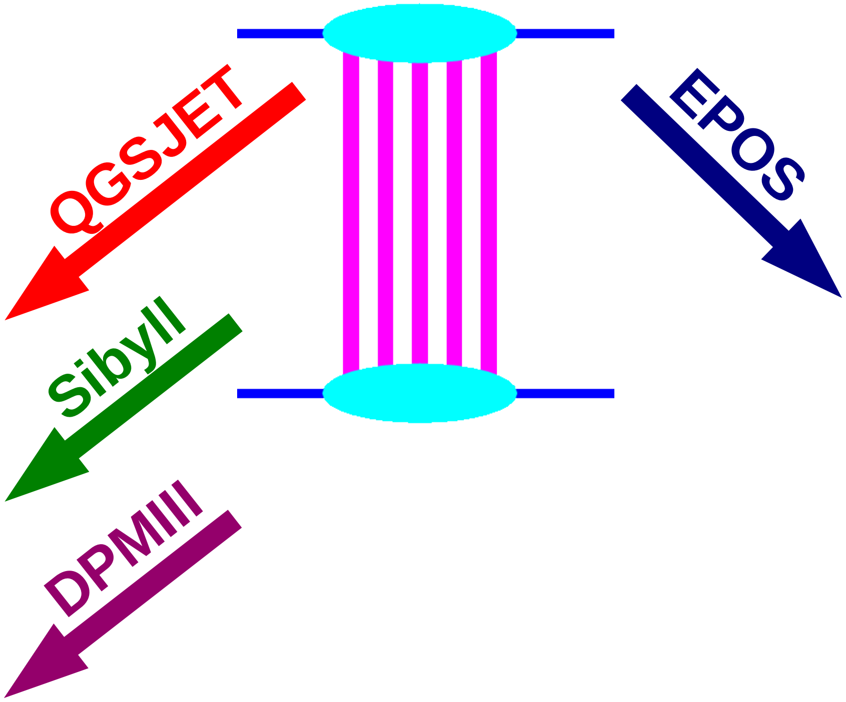


p-Air



Multiplicity

- **Field theory : scattering via the exchange of an excited field**
  - parton, hadron, quasi-particle = Reggeon or Pomeron (vacuum excitation)
- **Gribov-Regge Theory and cutting rules : multiple scattering associated to cross-section via sum of inelastic states**
  - different ways of dealing with energy conservation



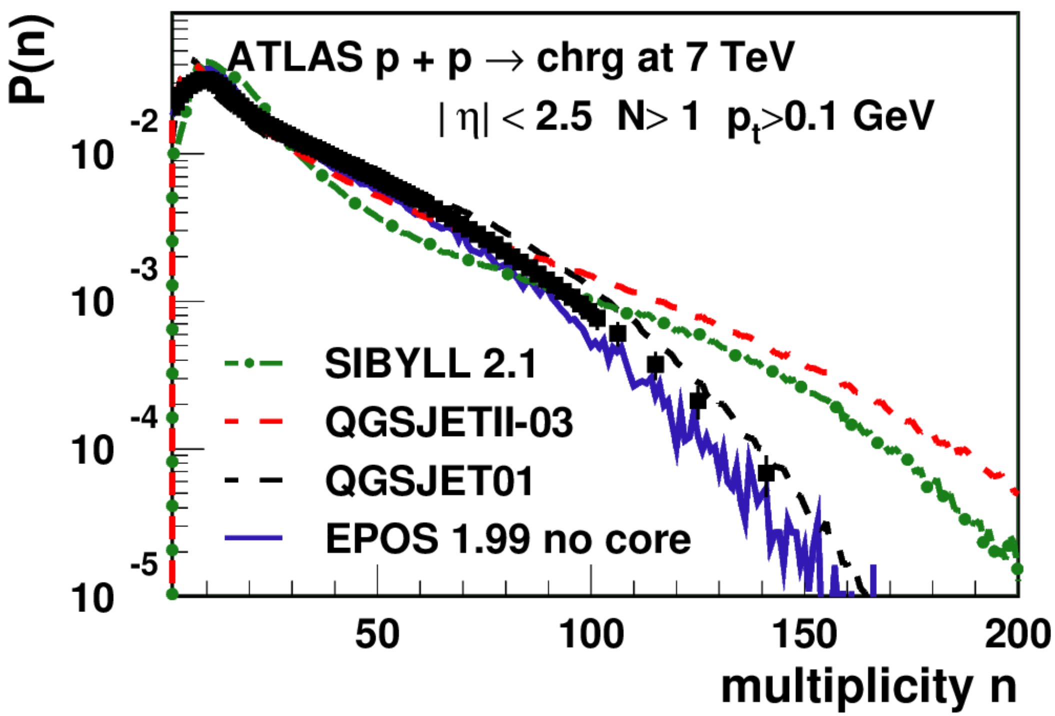
- sum all scatterings with full energy to get cross-section
- get number of elementary scattering without energy sharing (Poissonian distribution)
- share energy between scattering afterwards

- cross-section calculated with energy sharing
- get the number of scattering taking into account energy conservation
- consistent approach

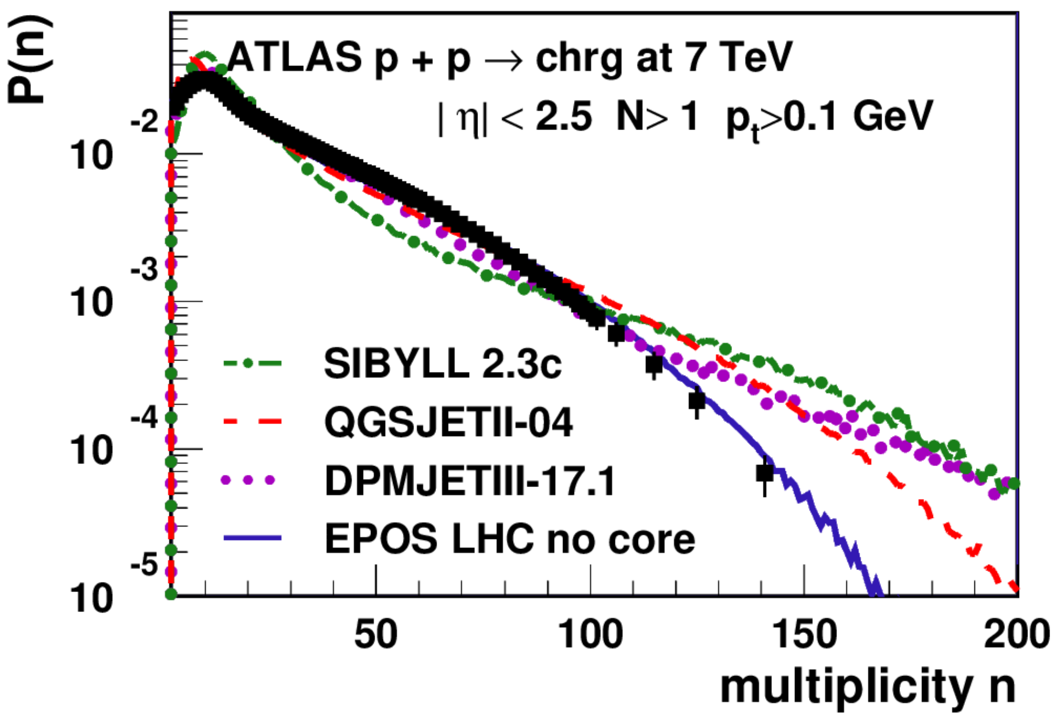
Does energy sharing order matter ?

- **Field theory : scattering via the exchange of an excited field**
  - ➡ parton, hadron, quasi-particle = Reggeon or Pomeron (vacuum excitation)
- **Gribov-Regge Theory and cutting rules : multiple scattering associated to cross-section via sum of inelastic states**
  - ➡ different ways of dealing with energy conservation

Pre - LHC



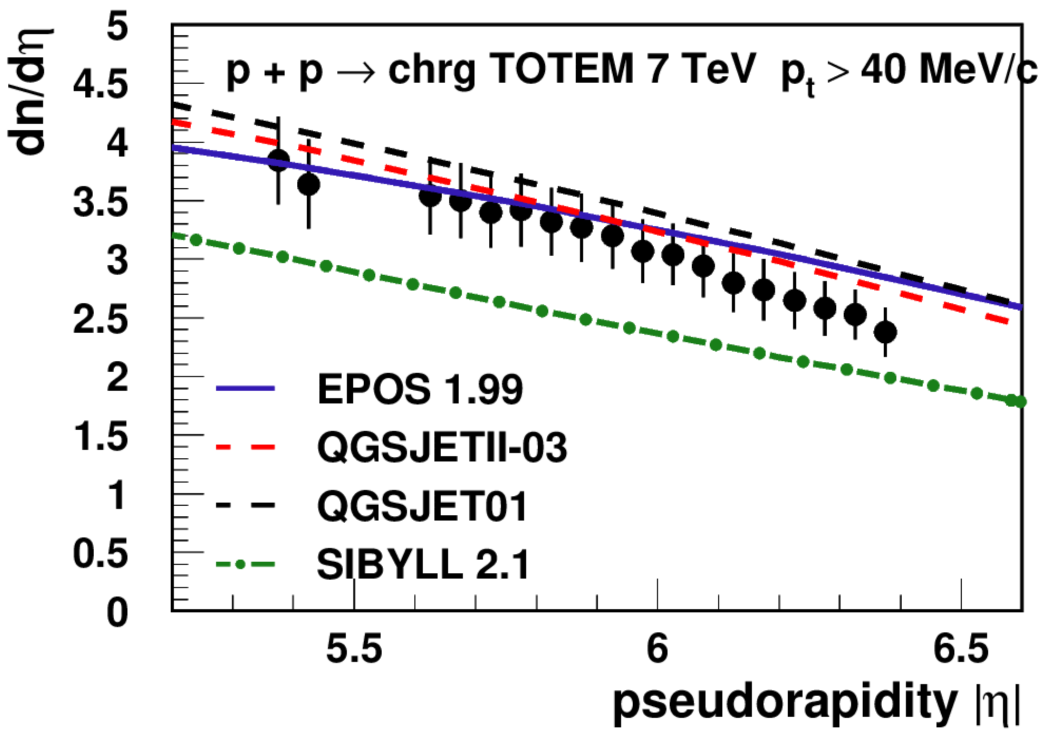
Post - LHC



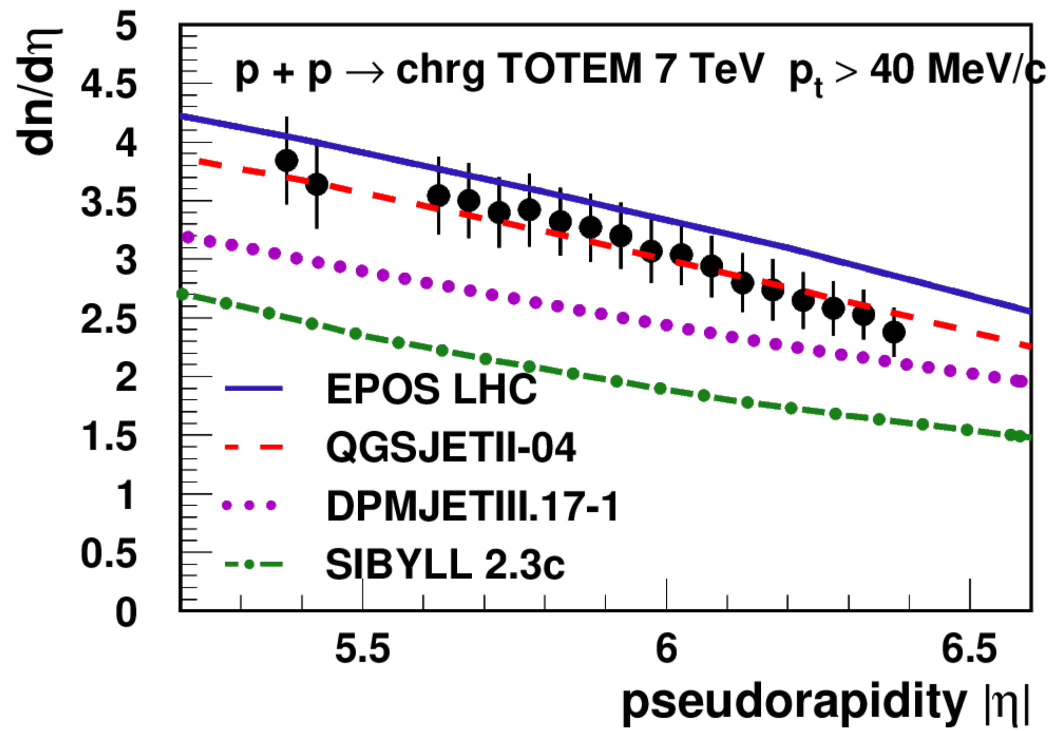
Does the minijet definition matter ?

- **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

Pre - LHC



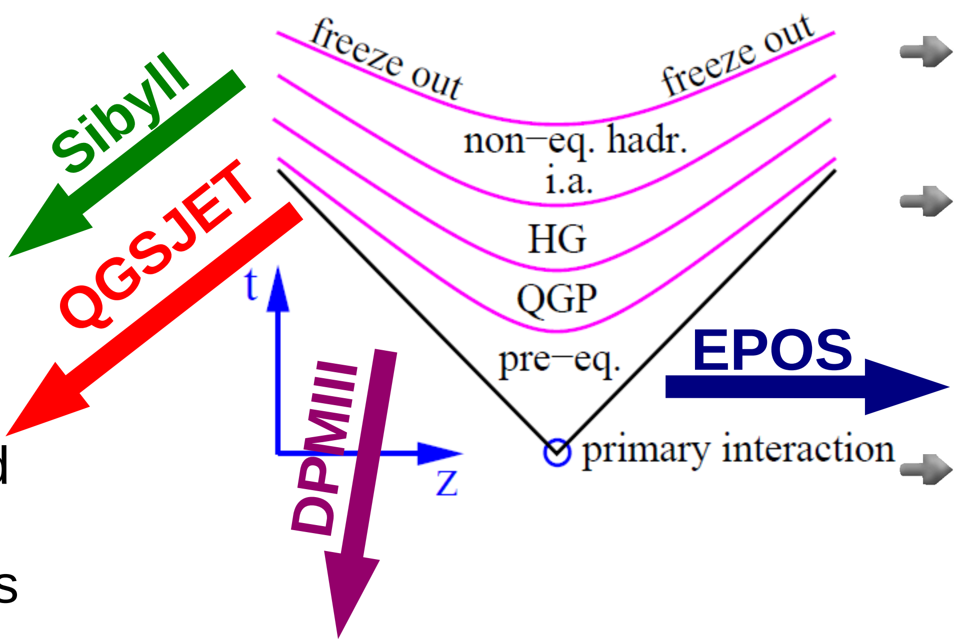
Post - LHC



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

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

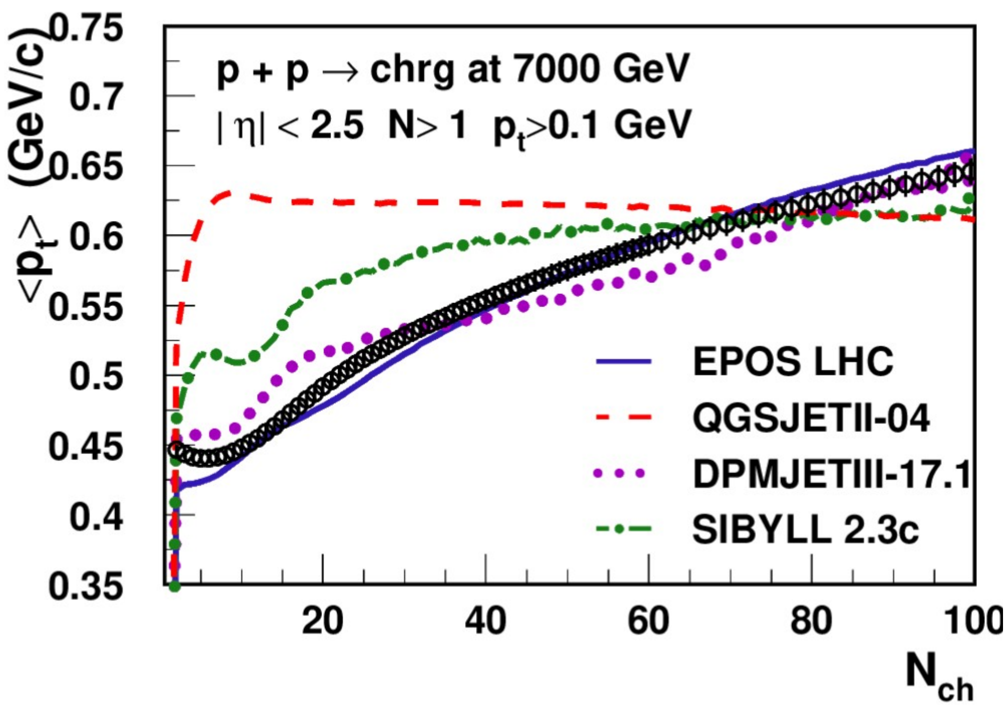


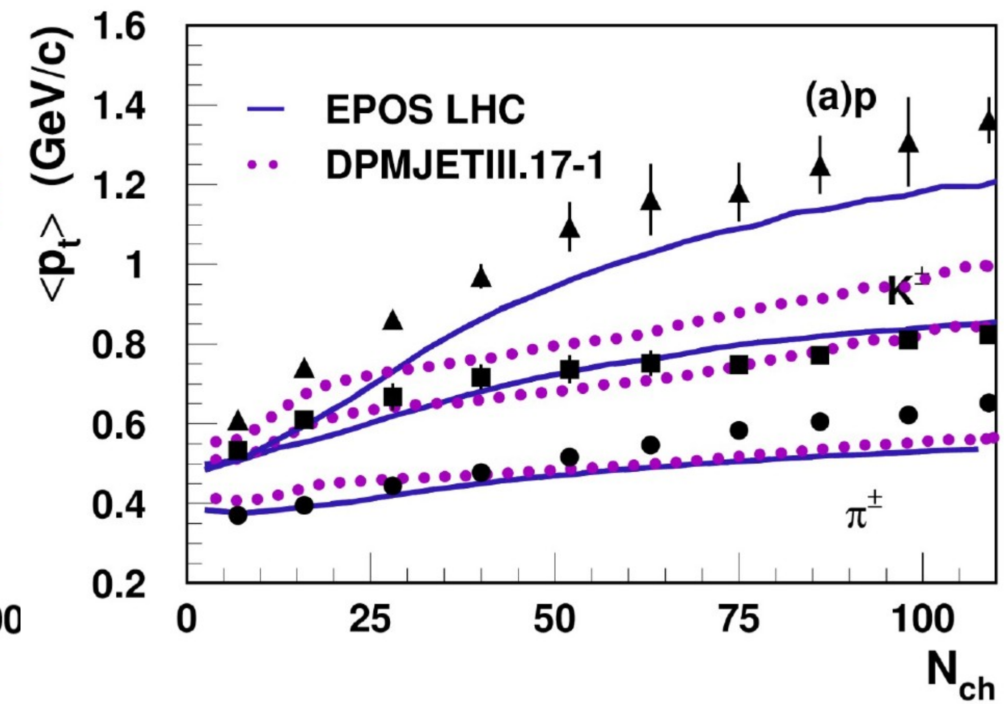
- developed first for heavy ion interactions
- detailed description of every possible “soft” observable (not good for hard scattering yet)
- sophisticated collective effect treatment (real hydro for EPOS 2,3 and 4)
- very large complete data set (LEP, HERA, SPS, RHIC, LHC)

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

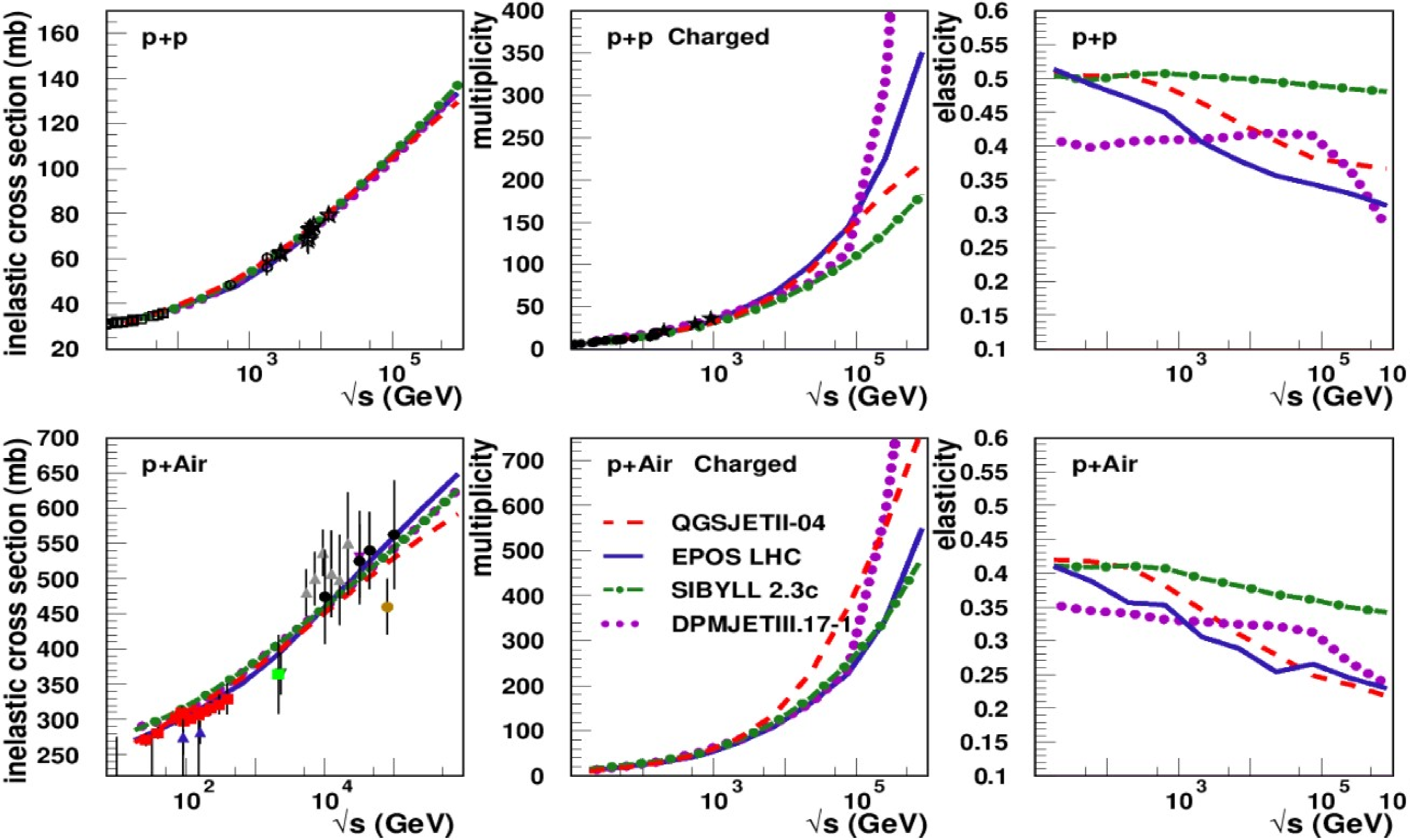
Should Everything Be Taken into Account in CR Models ?

- **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
- **Is there a direct influence on air showers ?**
  - ➜ Core-corona effect in EPOS only (core = high density = collective hadronization)

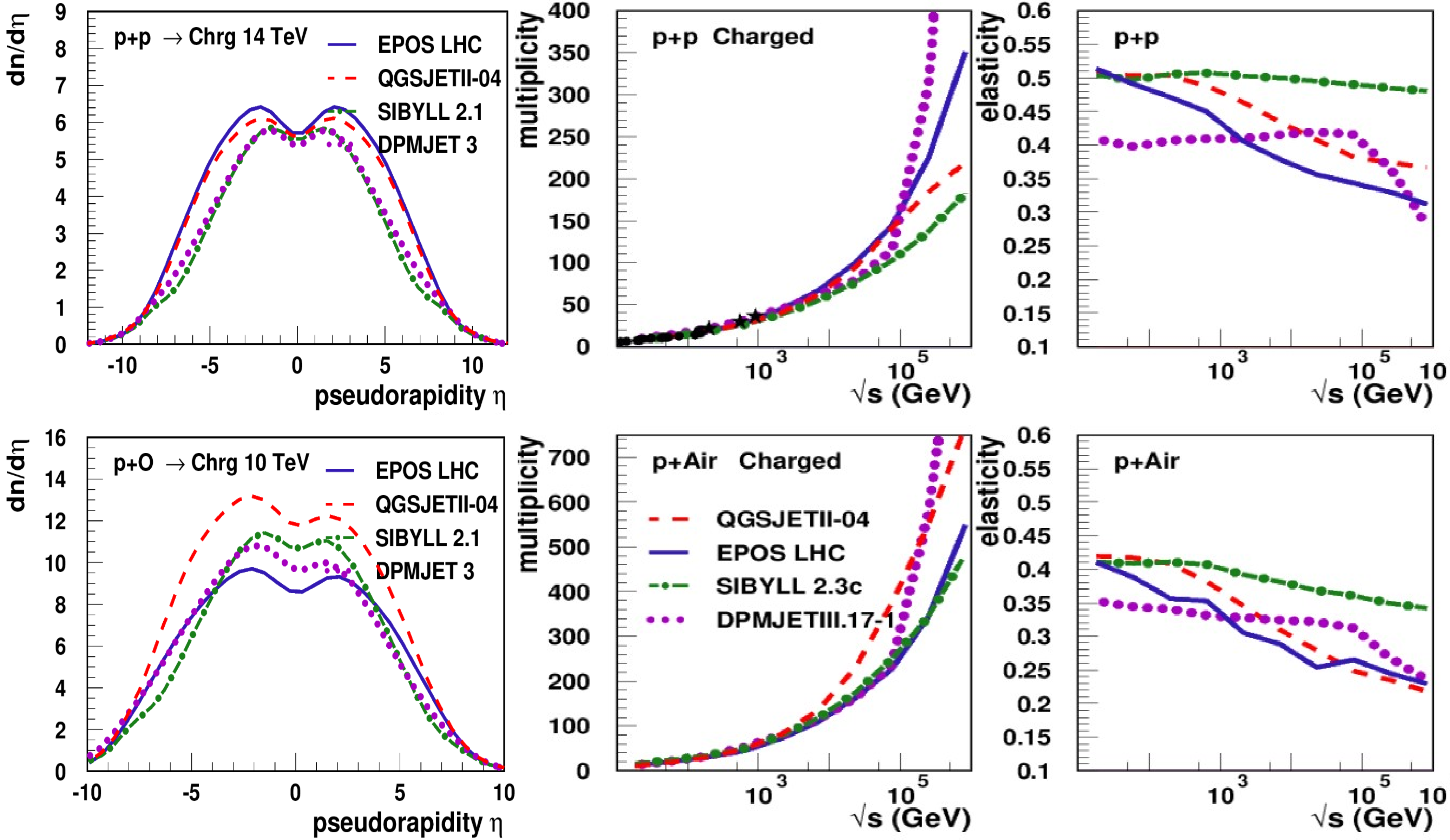




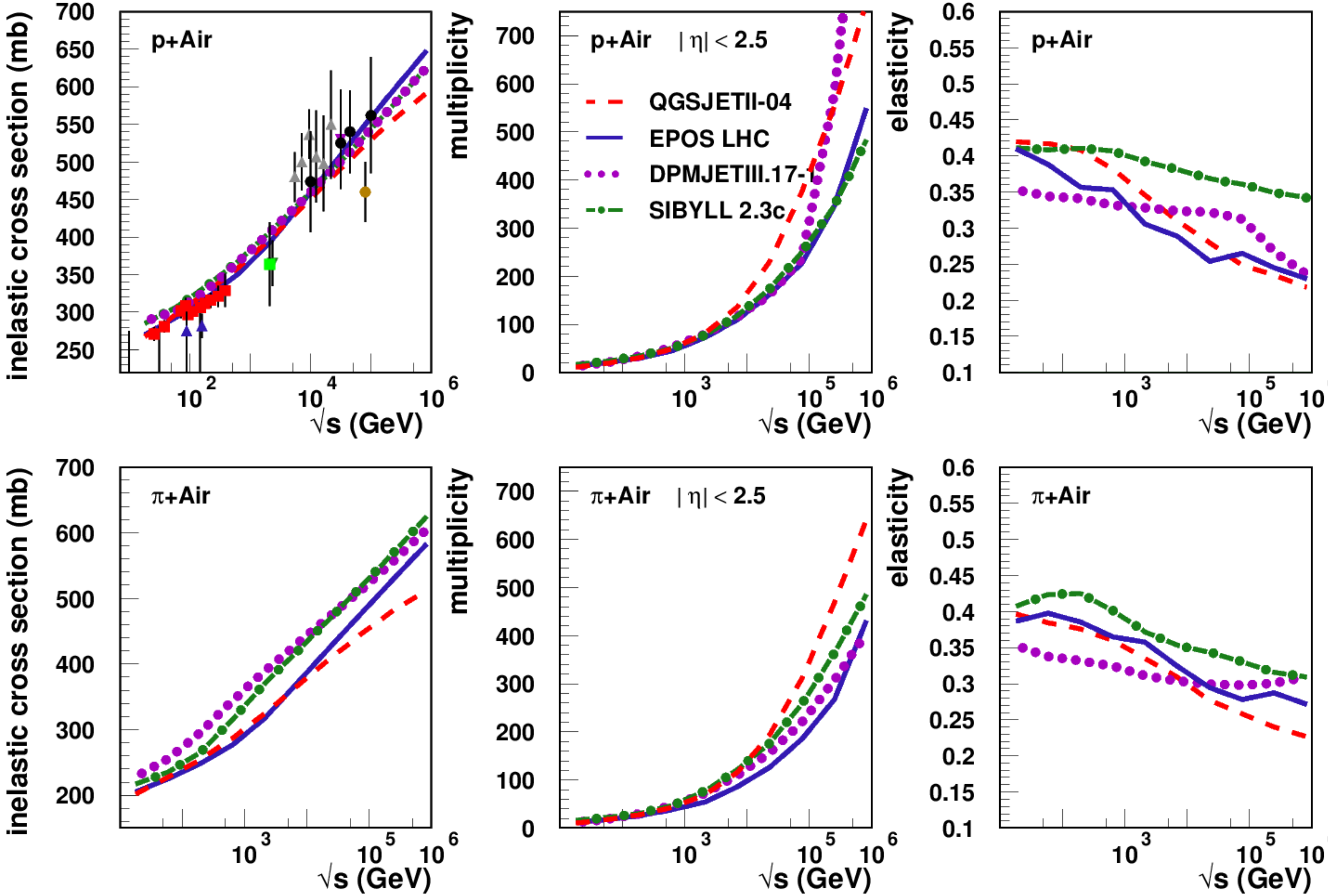
Ultra-High Energy Hadronic Model Predictions p-Air



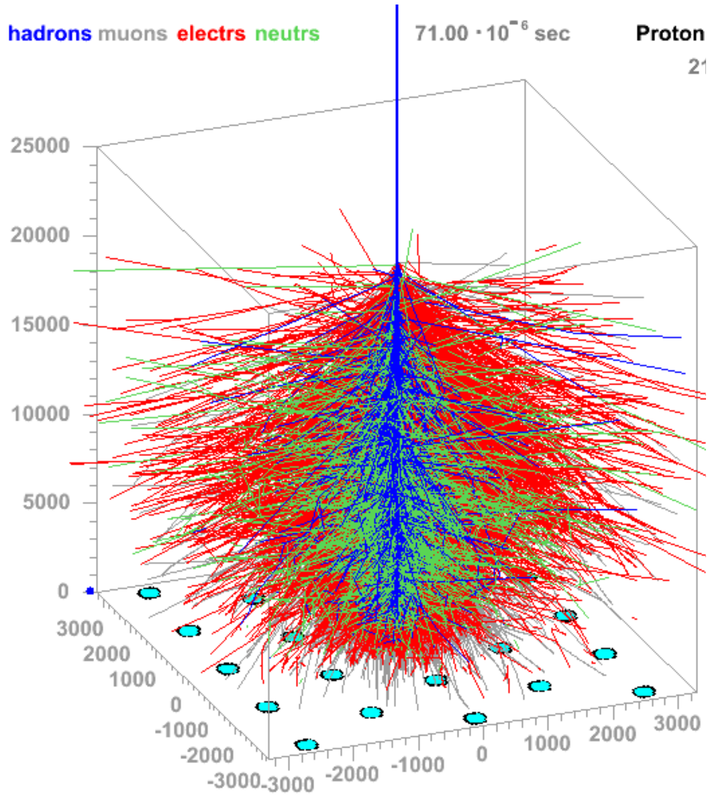
Ultra-High Energy Hadronic Model Predictions p-Air

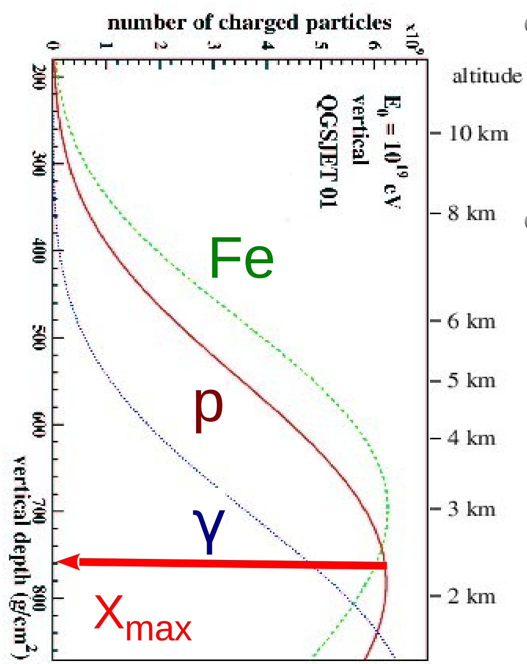


Ultra-High Energy Hadronic Model Predictions π-Air



Extensive Air Shower Observables

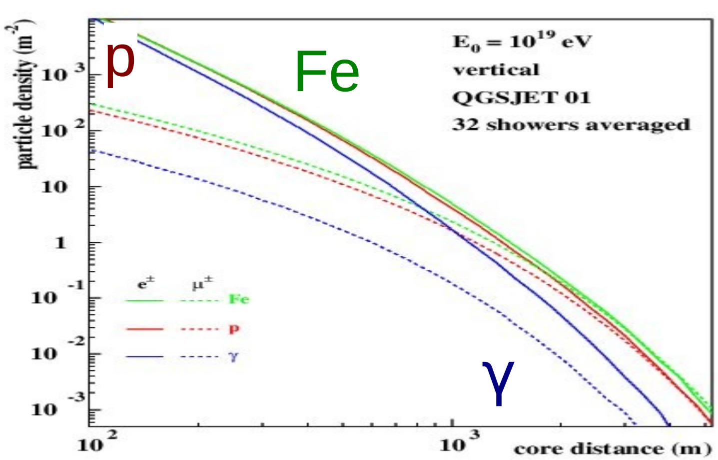




- **Longitudinal Development**
  - number of particles vs depth

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

  - 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.

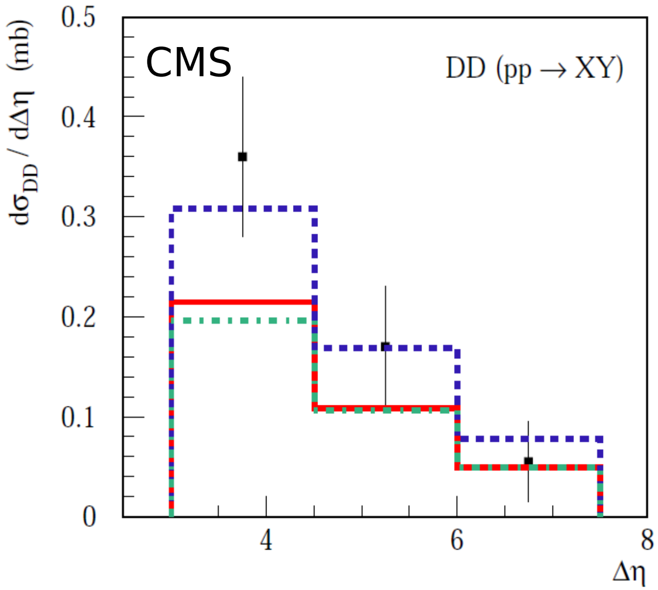
- **Others: Cherenkov emissions, Radio signal**

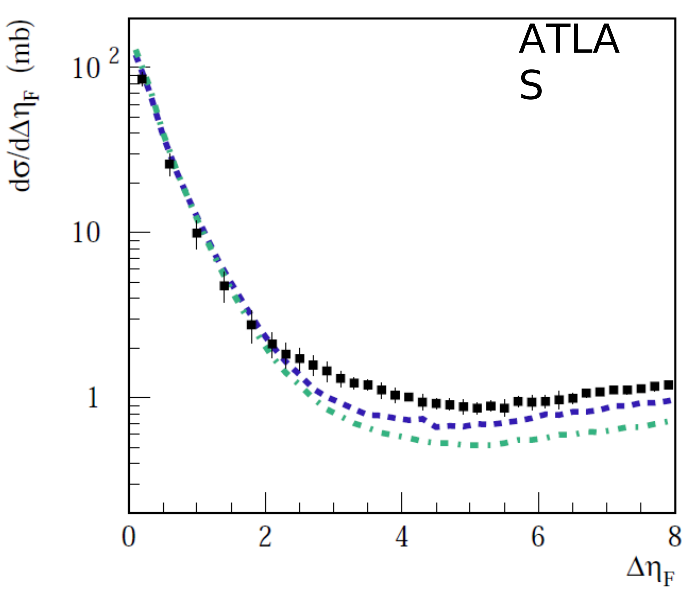
Diffraction measurements

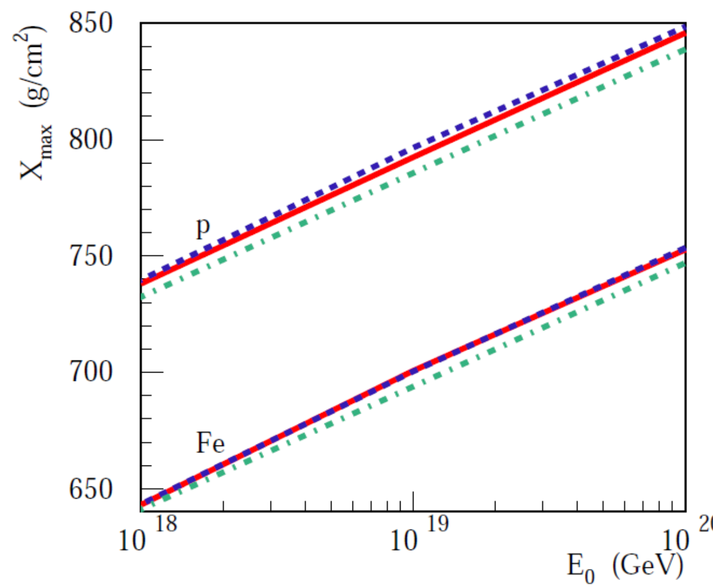
- **TOTEM and CMS diffraction measurement not fully consistent**
- **Tests by S. Ostapchenko using QGSJETII-04** **(PRD89 (2014) no.7, 074009)**
  - ➡ SD+ option compatible with CMS
  - ➡ SD- option compatible with TOTEM

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 g/cm² between the 2 options







WHISP Working Group

- **Many muon 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),

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J. Gonzales (IceTop, USA), **D. Soldin** (IceCube, USA),

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

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