Forward hadronization and the muon puzzle in air showers

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Low-x 2021, La Biodola, Italy

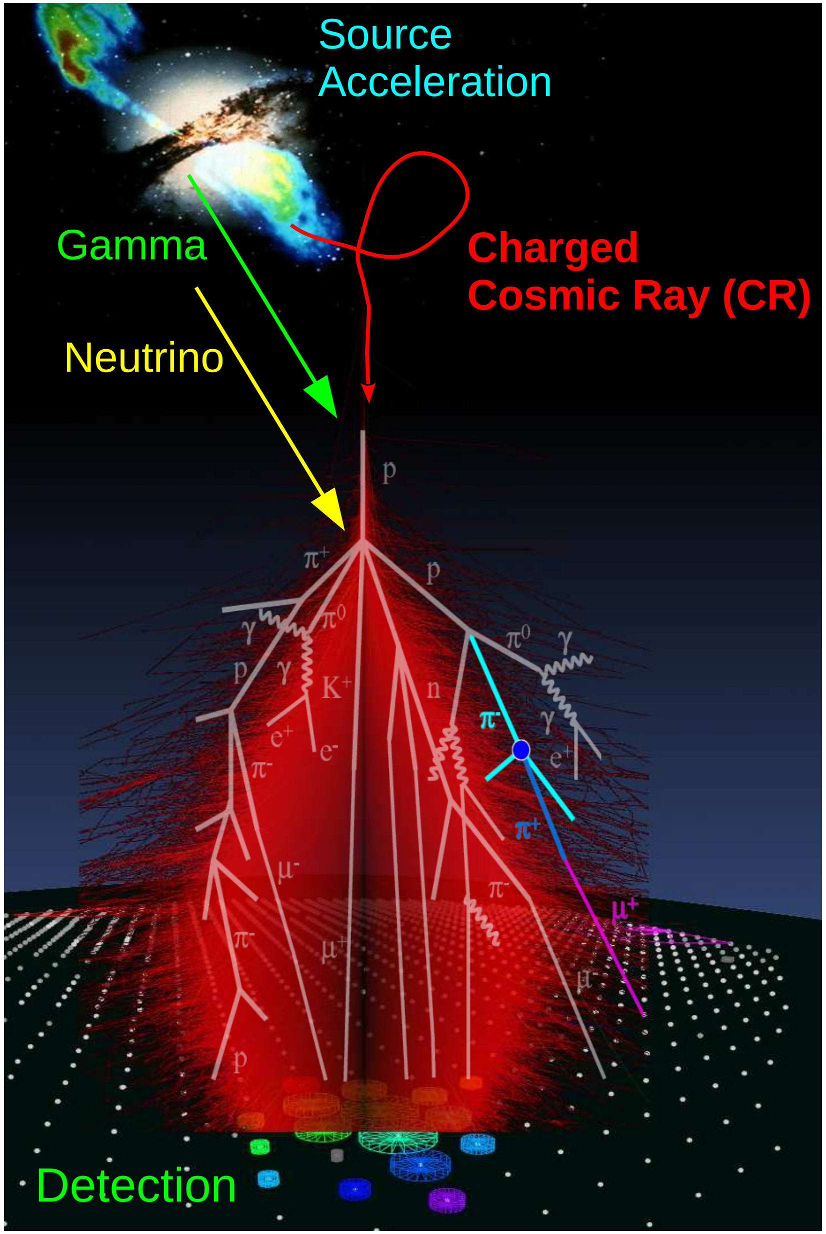
September the 28th 2021

Outline

- **Introduction**
- **Hadronization and Extended Air Showers (EAS)**
- **Uncertainties in forward spectra**

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

Astroparticles



From R. Ulrich (KIT)

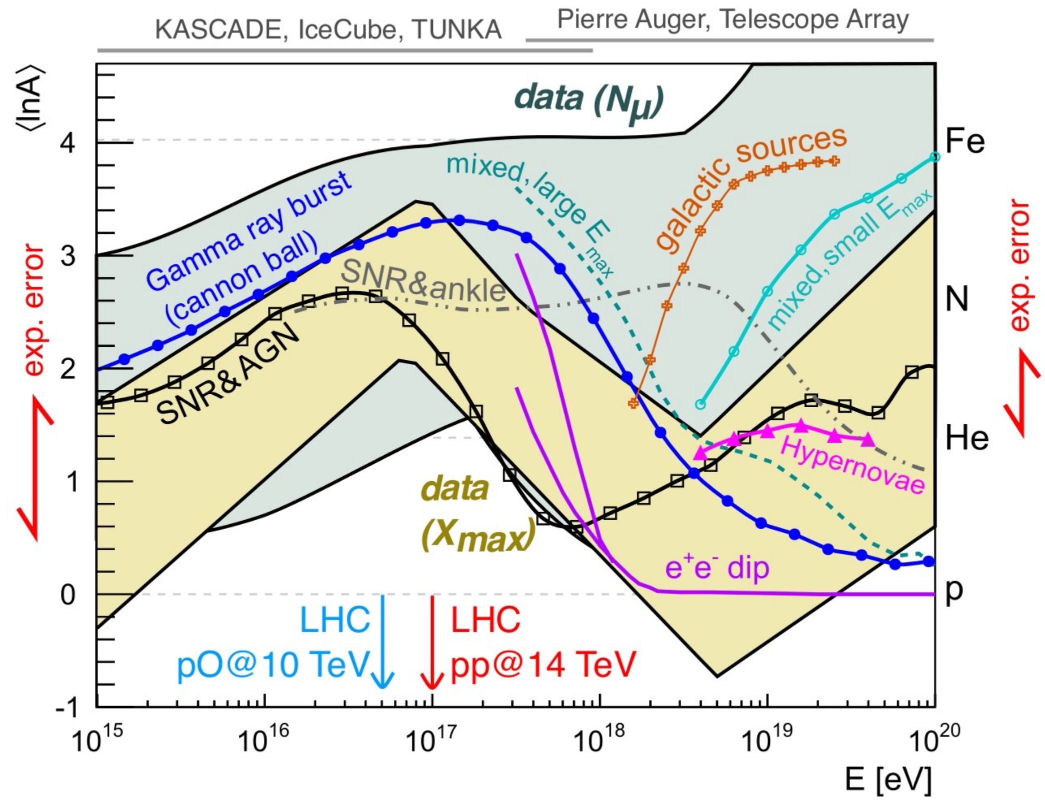
- **Astronomy with high energy particles**
  - gamma (straight but limited energy due to absorption during propagation)
  - neutrino (straight but difficult to detect)
  - charged ions (effect of magnetic field)
- **Measurements of charged ions**
  - source position (only for light and high E)
  - energy 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

UHECR Composition

With muons current CR data are impossible to interpret

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

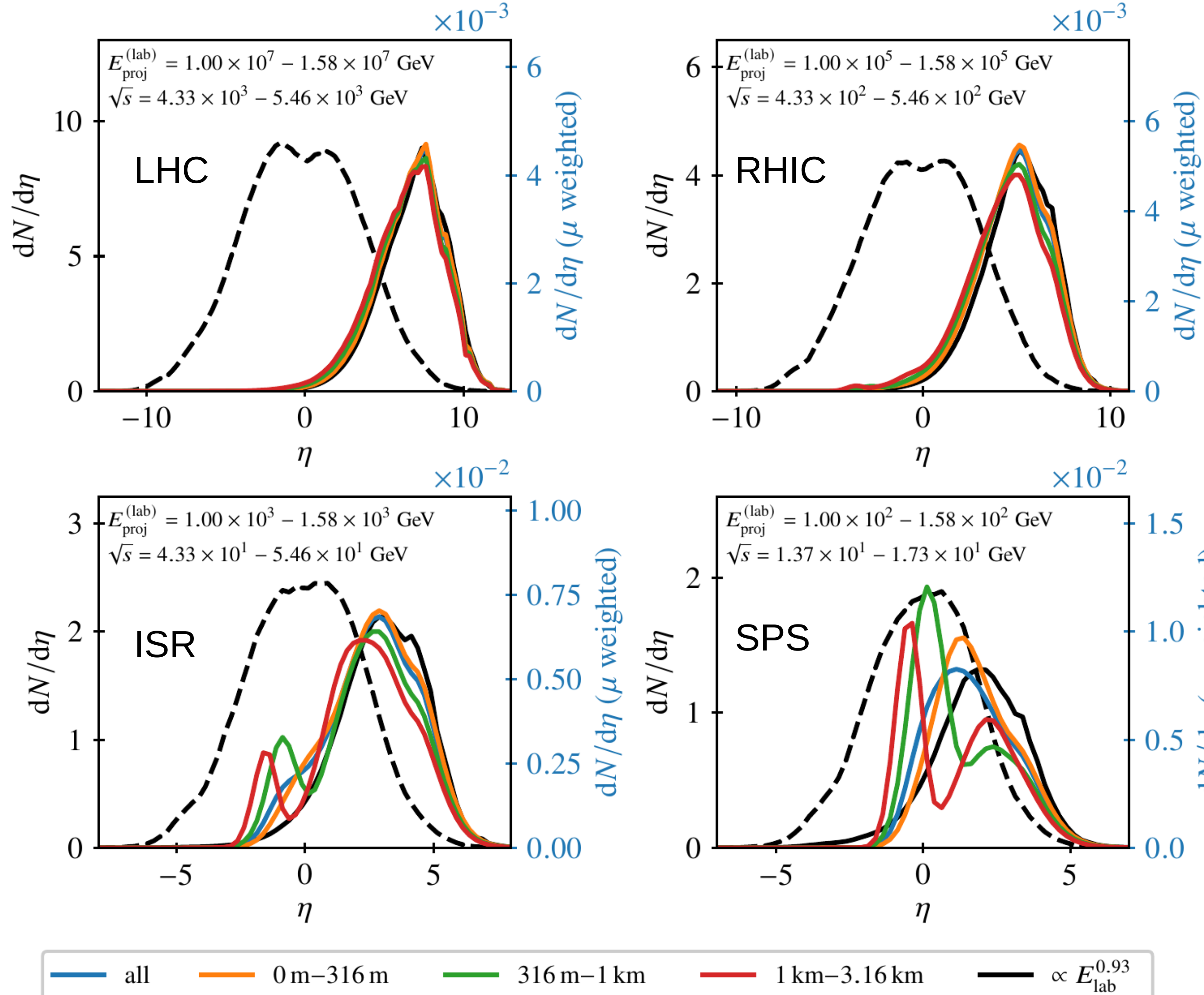


Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

H. Dembinski UHECR 2018 (WHISP working group)

Relevant Phase Space in Air Showers

- **Muon production in a showers dominated by forward produced particles**
  - ➔ True at high energy
- **Midrapidity productio important in the last generations and for muon at large distances from the shower core**
  - ➔ Low energy data as important than high energy data



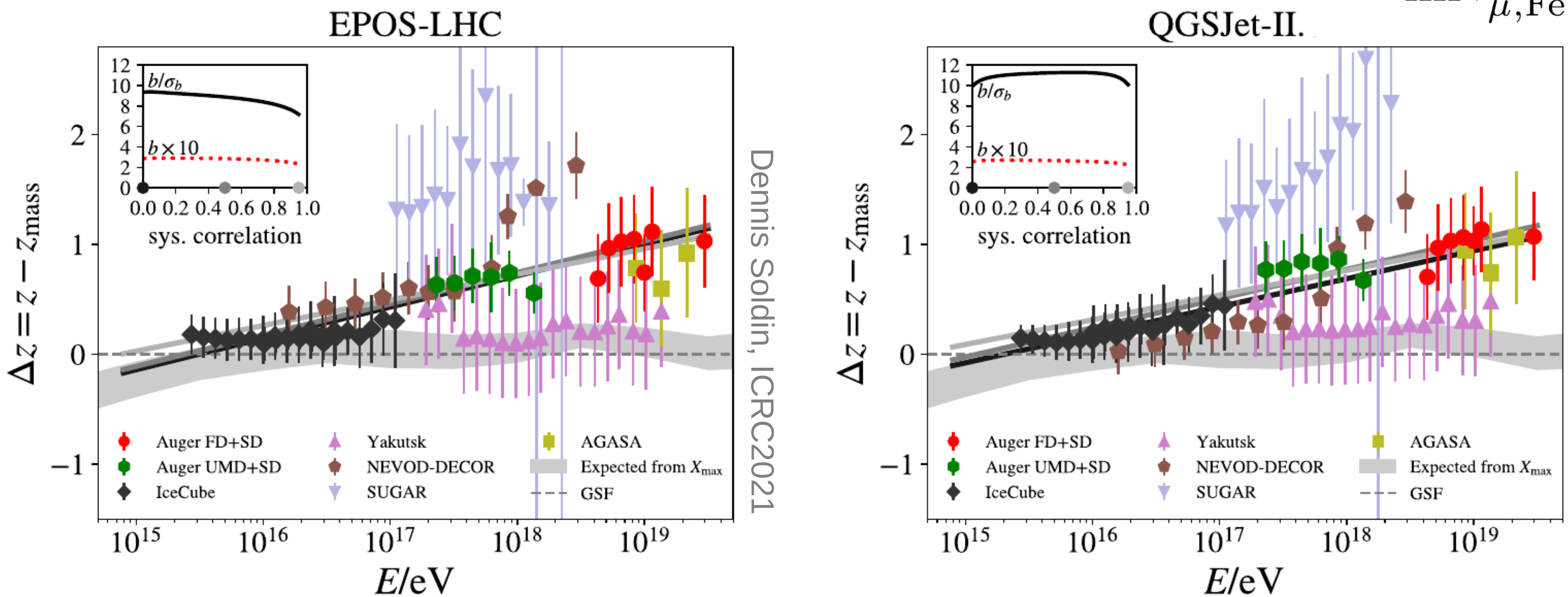
Maximilian Reininghaus, ICRC2021

Global Behavior

- **Clear muon excess in data compared to simulation**
  - ➜ Different energy evolution between data and simulations

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

➜ Significant non-zero slope (>7σ)



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

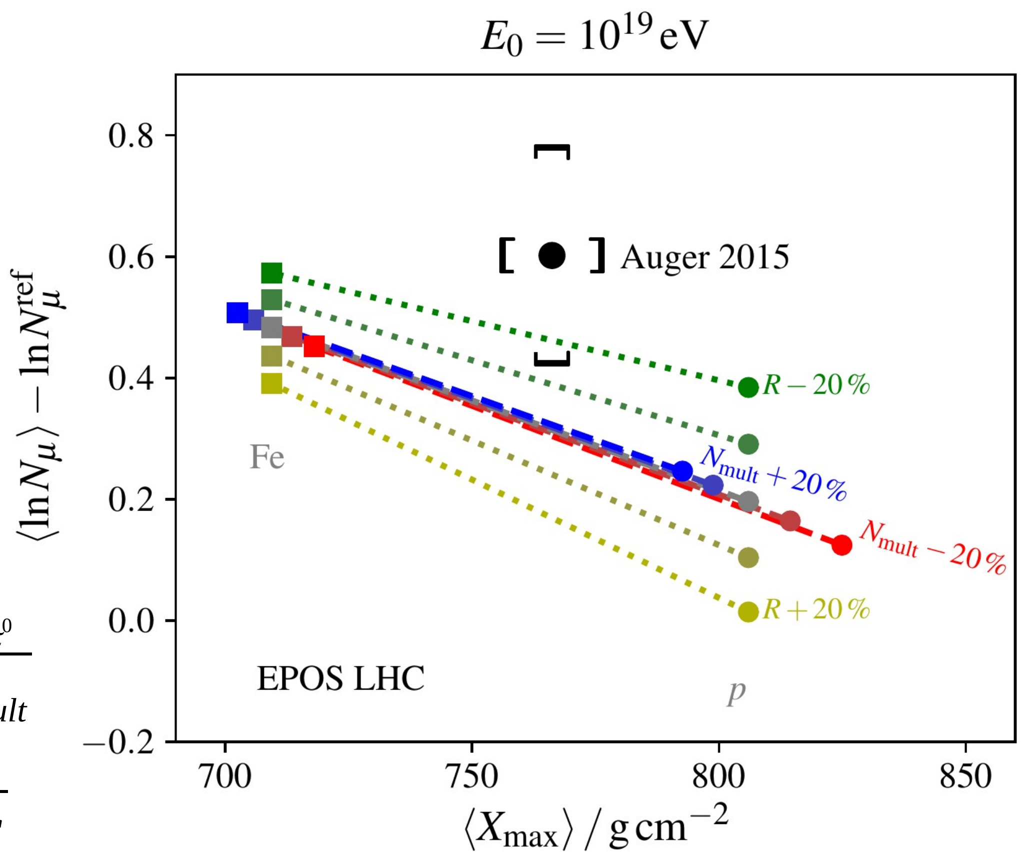
- **Different energy or mass scale cannot change the slope**
  - ➜ Different property of hadronic interactions at least above 10^{16} eV

Constraints from Correlated Change

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

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

- **One needs to change energy dependence of muon production by ~+4%**
- **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}
- $$\beta = \frac{\ln(N_{mult} - N_{\pi^0})}{\ln(N_{mult})} = 1 + \frac{\ln(1-c)}{\ln(N_{mult})}$$
  - +4% for β ➤ -30% for $c = \frac{N_{\pi^0}}{N_{mult}}$
  - Measure@LHC : $R = \frac{E_{e/m}}{E_{had}} \approx \frac{c}{1-c}$

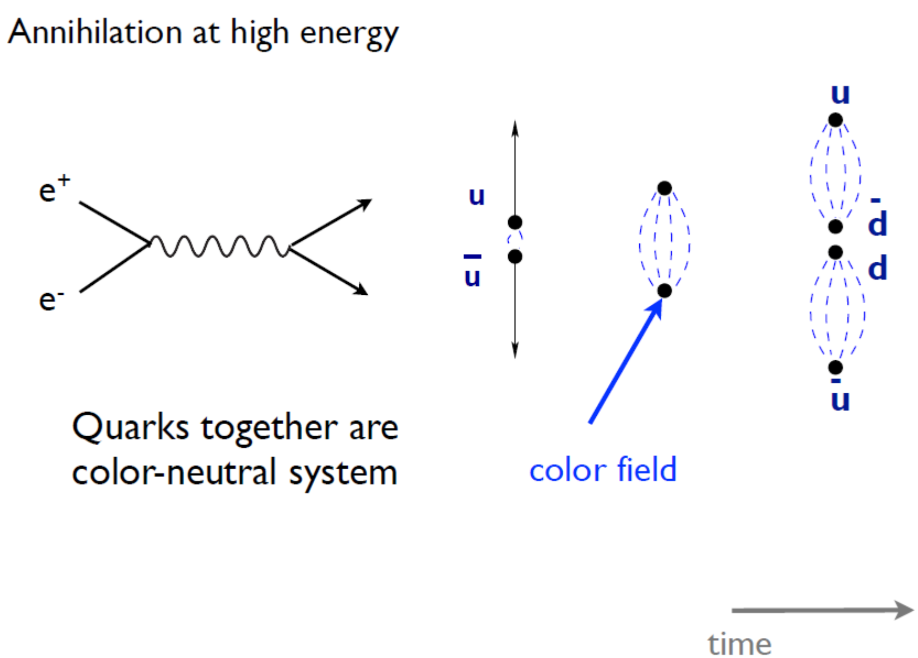


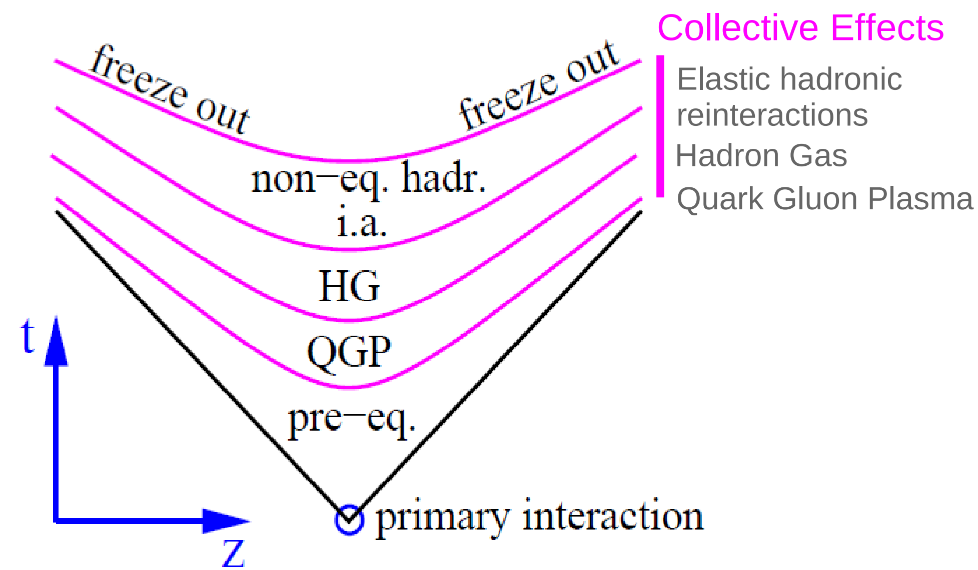
ArXiv 1902.09265

Hadronization Models

2 models well established for 2 extreme cases

➡ String Fragmentation vs Collective hadronization (statistical models)





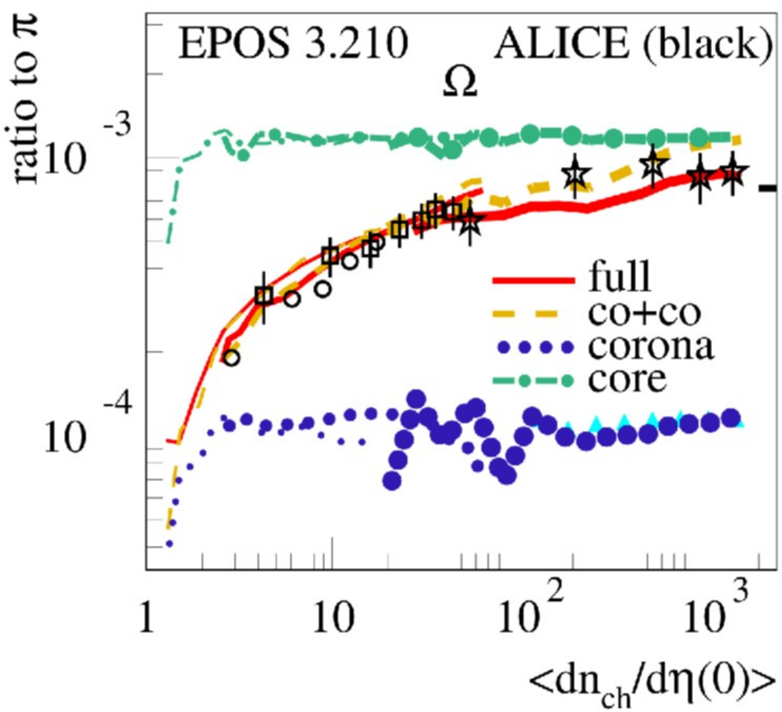
In dilute systems… CORONA
→ “high” π^0 fraction

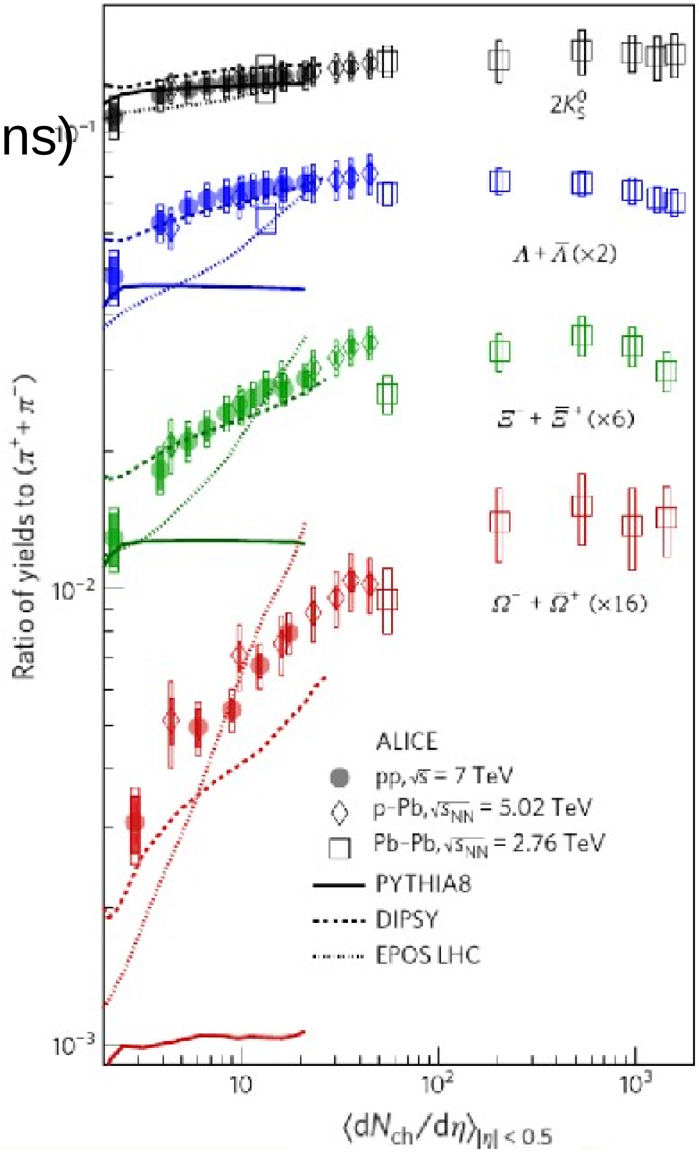
In dense systems… CORE
→ “low” π^0 fraction

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

Core-Corona @ LHC

- **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**

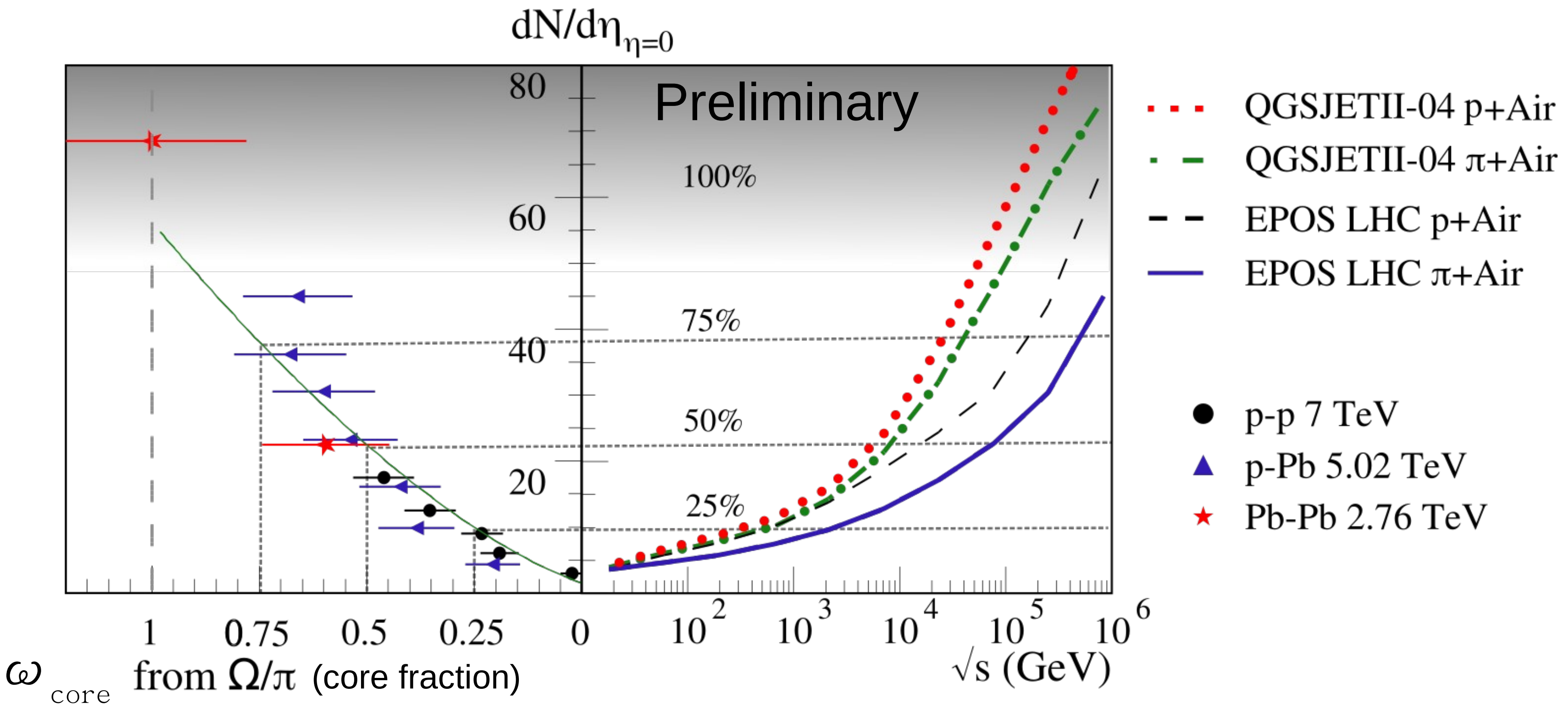




Particle Densities in Air Showers

Is particle density in air shower high enough to expect core formation ?

- Core formation start quite early according to ALICE data
- Cosmic ray primary interaction likely to have 100% core at mid-rapidity !



Core-Corona appoach and EAS

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

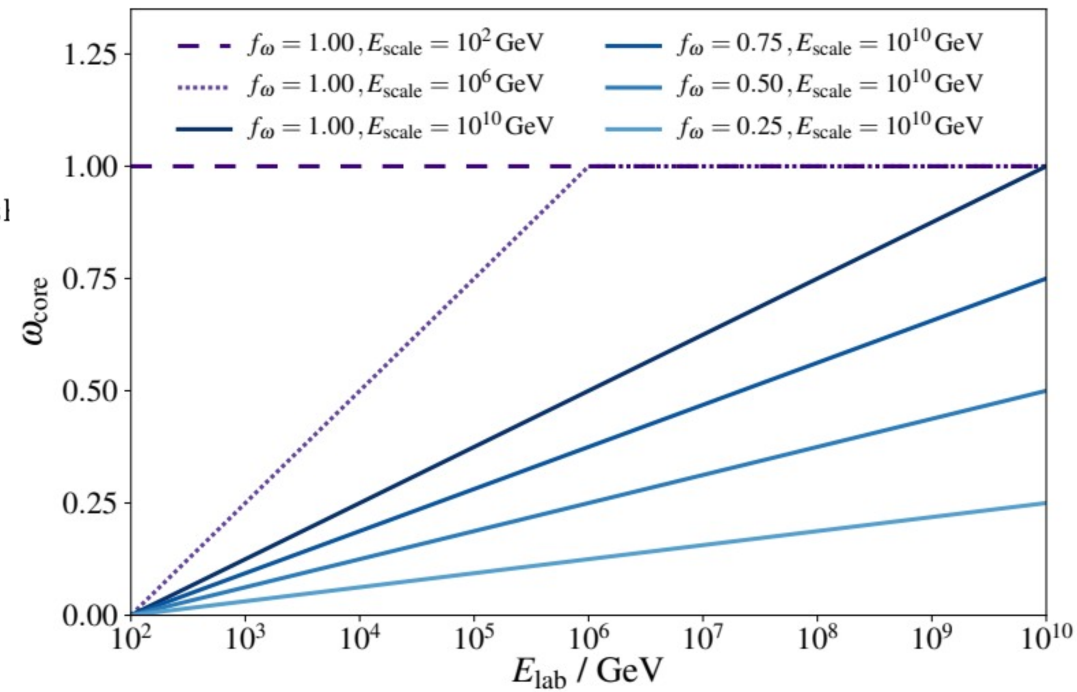
- Particle ratios from statistical model are known (tuned to PbPb) and fixed : core
- Initial particle ratios given by individual hadronic interaction models : corona
- Using CONEX, EAS can be simulated mixing corona hadronization with an arbitrary fraction ω_{core} of core hadronization: $N_i = \omega_{\text{core}}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

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

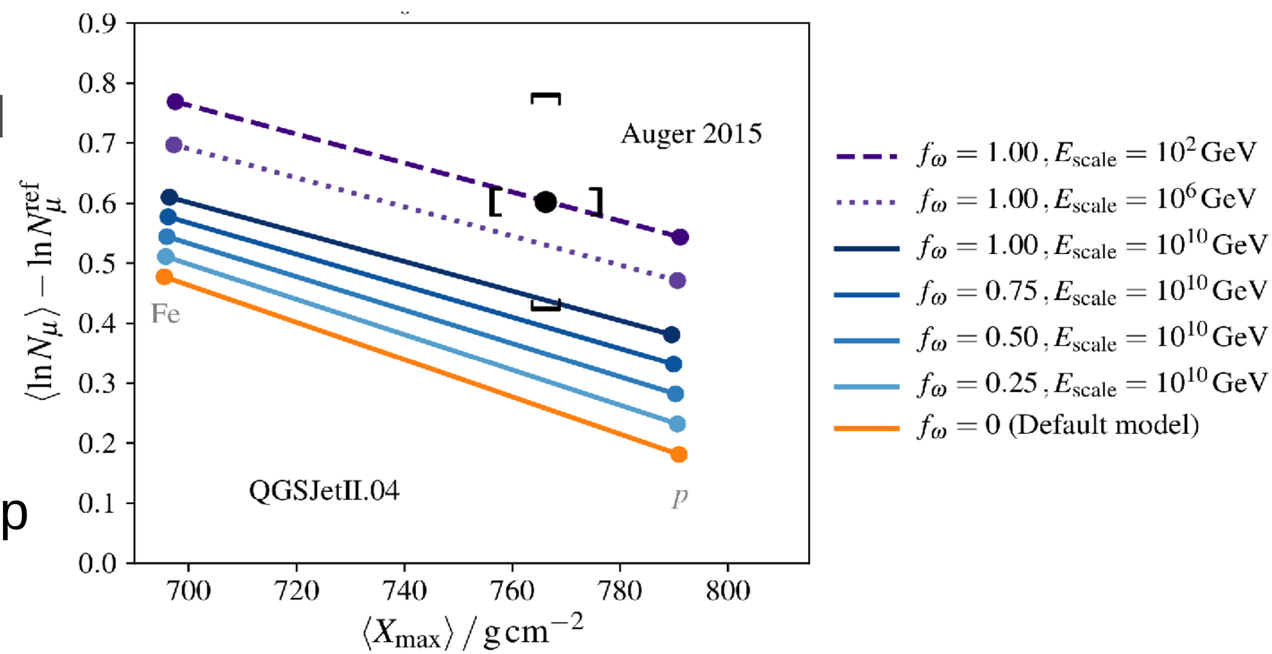
$$E_{\text{th}} = 100\,\text{GeV}$$

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

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

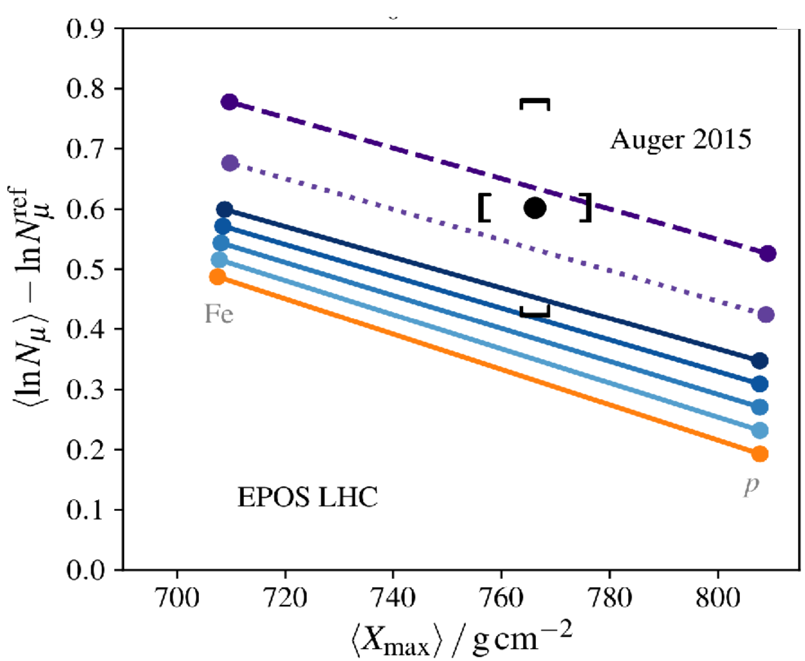


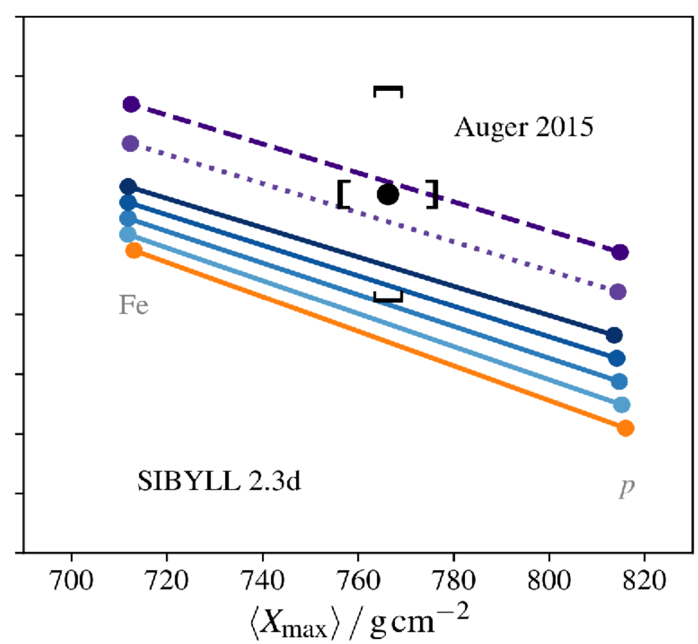
Results for X_{max}-N_{mu} correlation



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

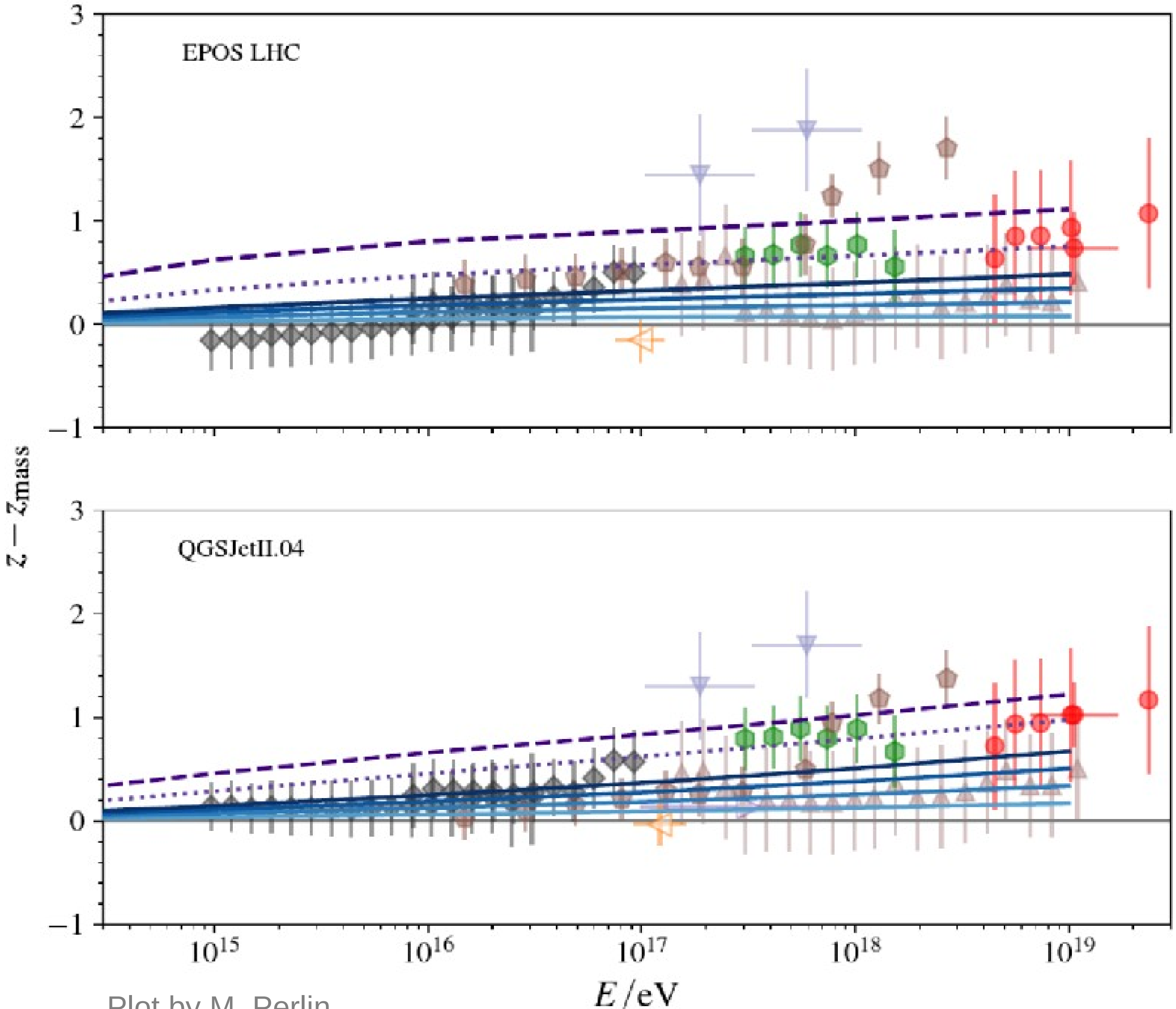




Plot by M. Perlin

Results for z-scale

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



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

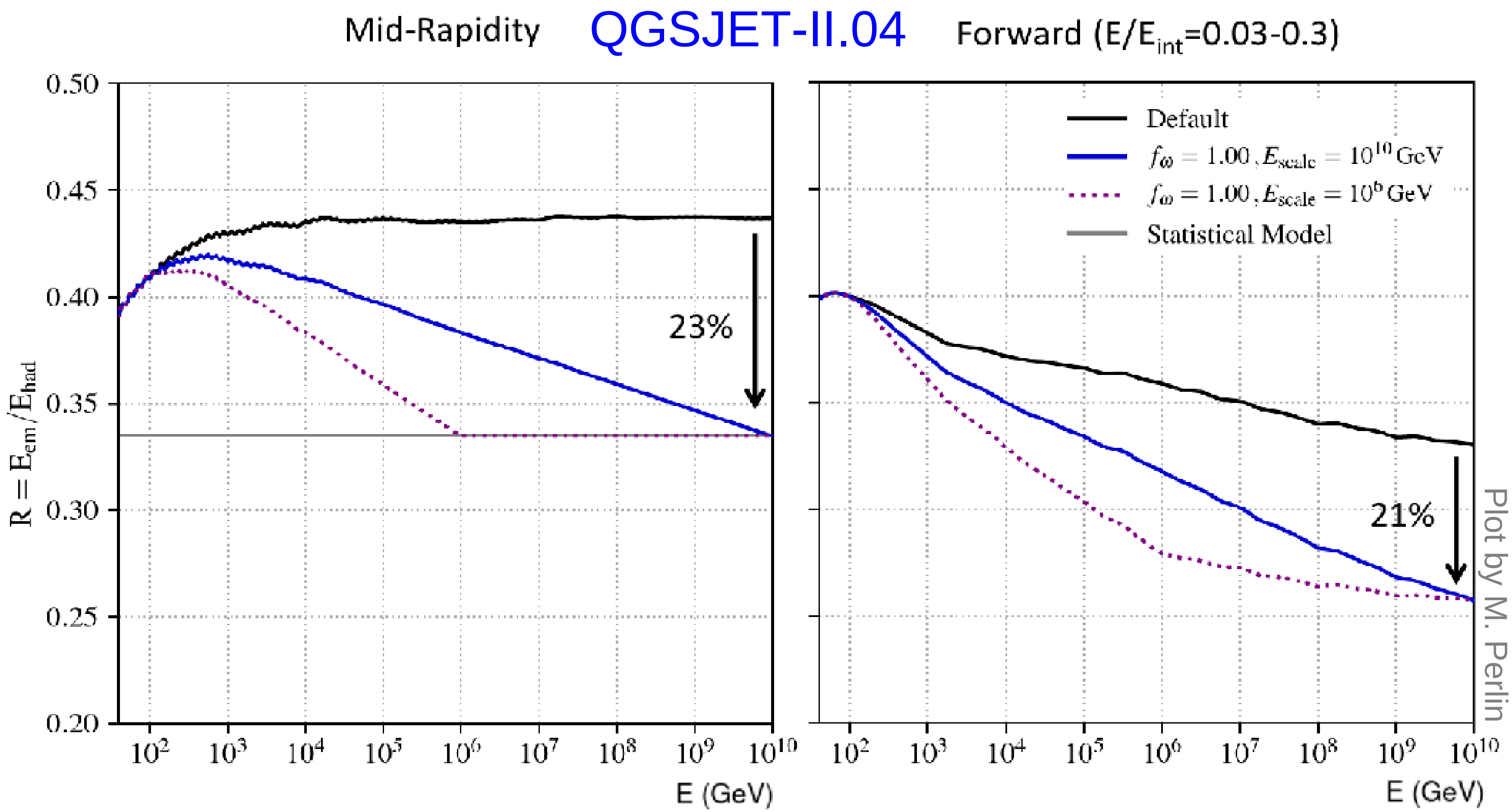
Plot by M. Perlin

Evolution of hadronization from core to corona

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

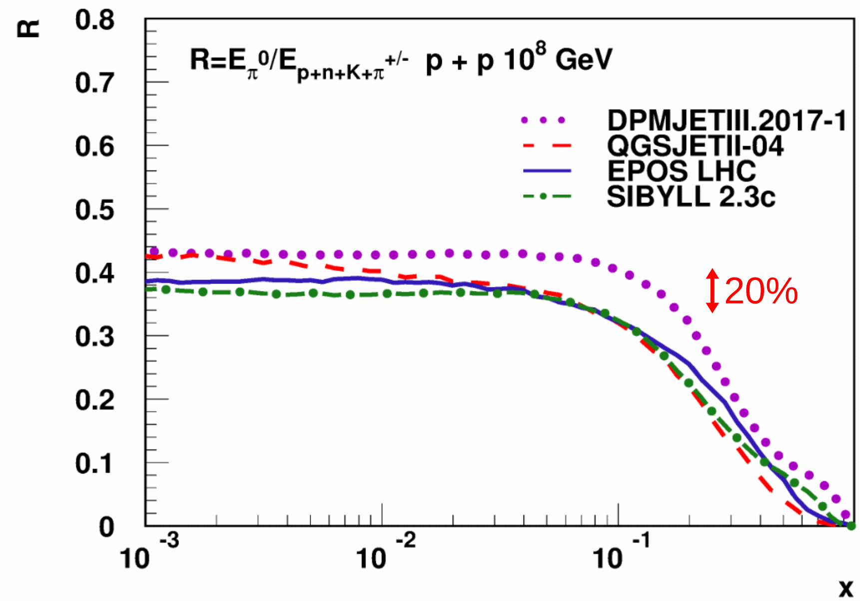
- Change of ω_{core} with energy change $c = \frac{N_{\pi^0}}{N_{mult}}$ or $R(\eta) = \frac{\langle dE_{em}/d\eta \rangle}{\langle dE_{had}/d\eta \rangle}$

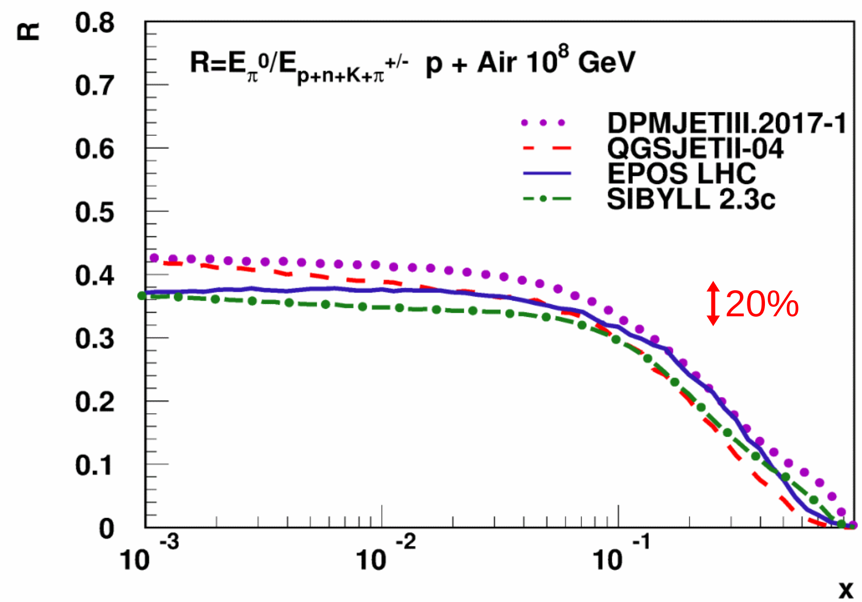
  which define the muon production in air showers.



Current Model Uncertainties

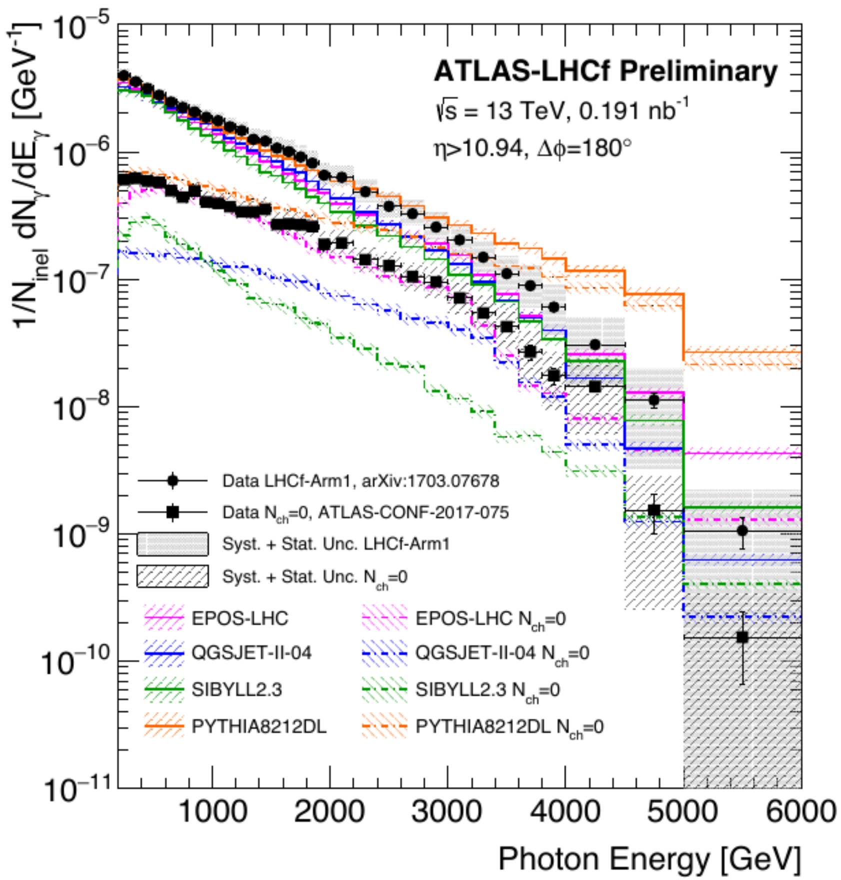
- **To reduce muon discrepancy** $R(\eta) = \frac{\langle \mathrm{d}E_{\mathrm{em}}/\mathrm{d}\eta \rangle}{\langle \mathrm{d}E_{\mathrm{had}}/\mathrm{d}\eta \rangle}$ **has to be measured**
- **One needs precise measurement of hadronization type to fix R**
  - ➡ less than 20% effect in R enough to solve the muon problem
- **Current uncertainties already at 20% level**
  - ➡ Not even including possible new effect !
- **Possibilities to study core fraction using other proxy**
  - ➡ Strangeness fraction

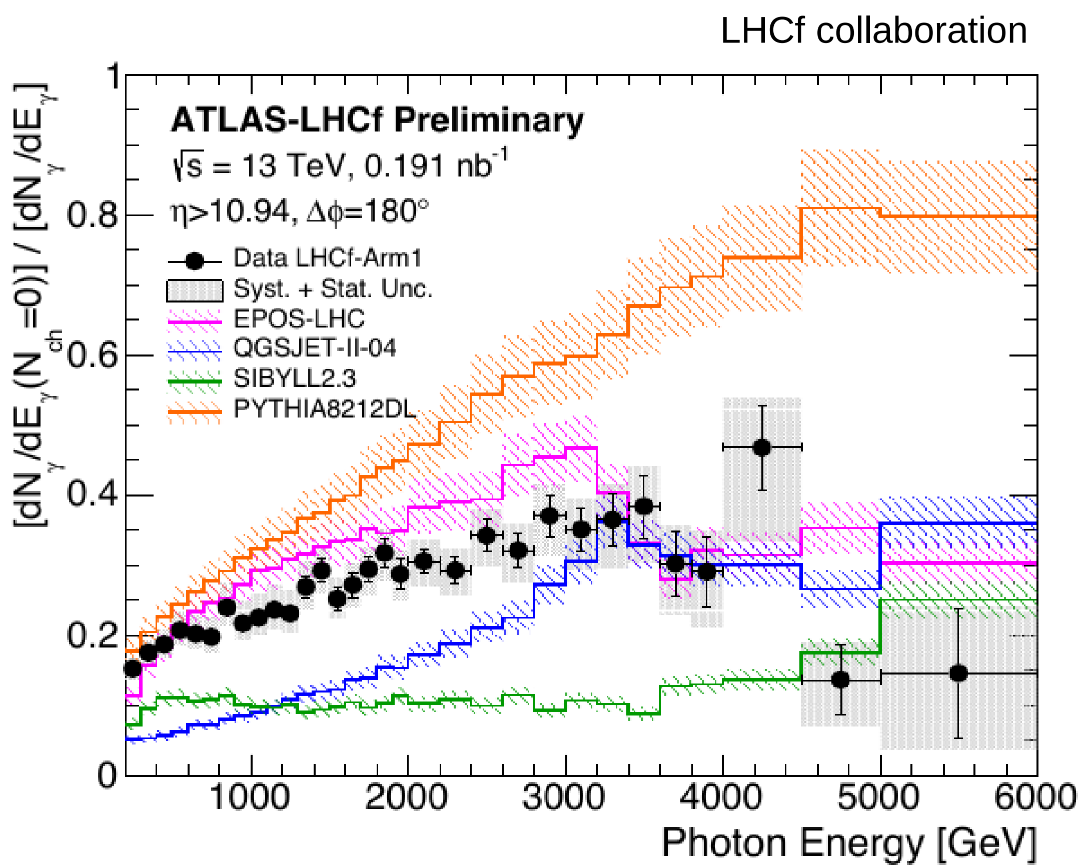




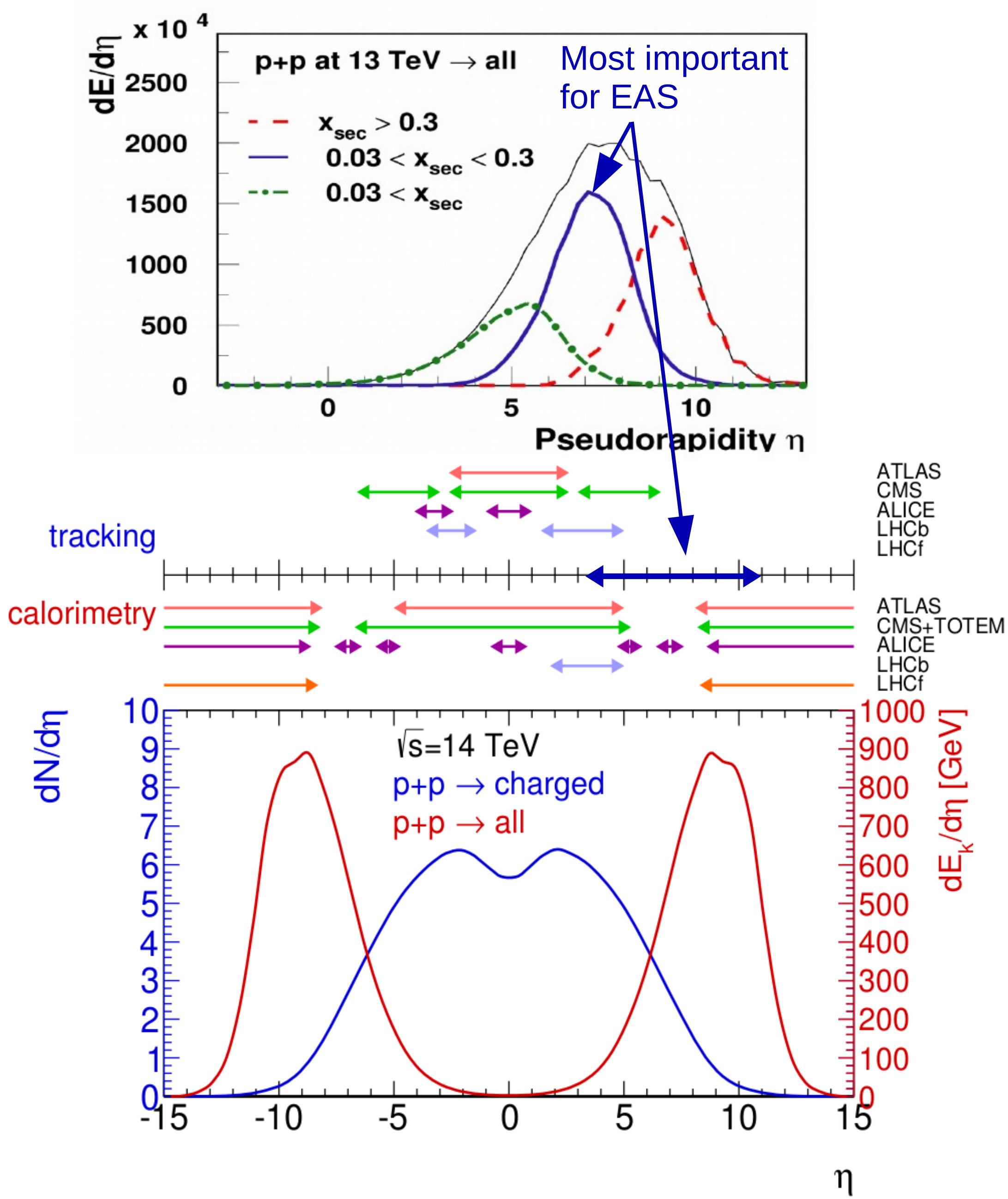
Comparison with LHCf

- Measurement of EM component but no hadronic counterpart (only neutrals)
- 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





LHC acceptance



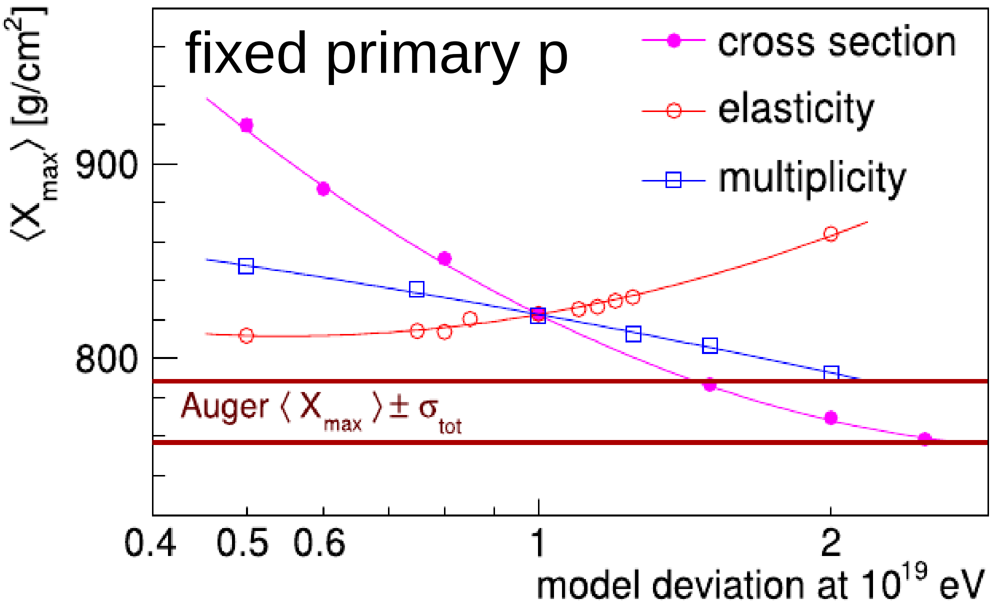
- **p-p data of central detectors used to reduce uncertainty by factor ~2. How to do more ?**
  - p-Pb difficult to compare to CR models (only EPOS)
  - special centrality selection
  - p-O (O-O) !
- **Maximum energy flow relevant for EAS**
  - x>0.01 (η~8)
- **Limited forward measurements**
  - Only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

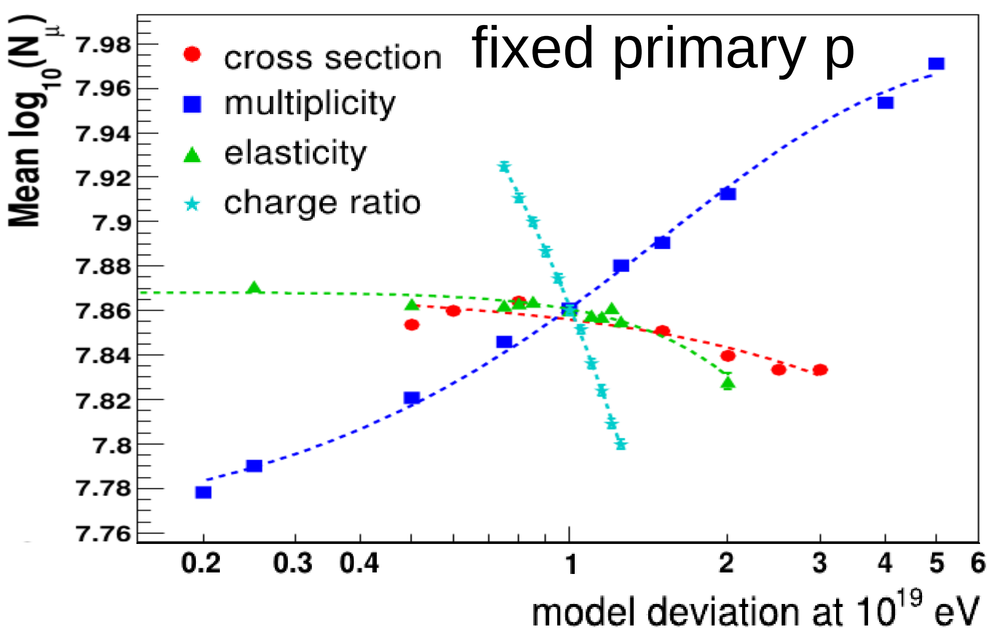
Summary

New input from LHC 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.**
  - Exact scale not known (dependent on energy and mass)
- **Most “natural” explanation given by a change in π^0 ratio.**
  - Other possibilities limited by X_{max} (multiplicity, inelasticity)
  - Supported by recent LHC data on strangeness/baryon production
- **Large differences observed in hadronic interaction models.**
  - Different type of hadronization (string like or satistical decay)
- **More data are necessary to constrain the model in relevant kinematic space.**
  - Forward measurement
  - Light ion beam (p-O, O-O)

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. ...

Precise mass composition highly depend on quality of hadronic interactions used for simulations.

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

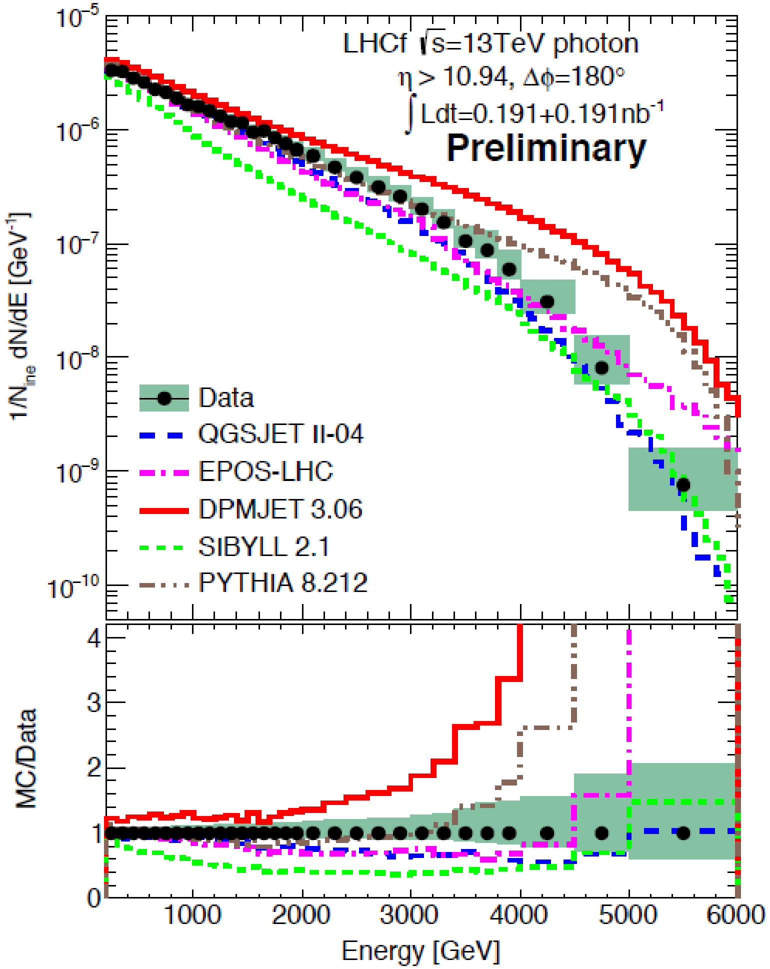
- **Hadronic models are the key ingredient !**
  - ➡ follow the standard model (QCD)
    - ➡ but mostly non-perturbative regime (phenomenology needed)
  - ➡ main source of uncertainties

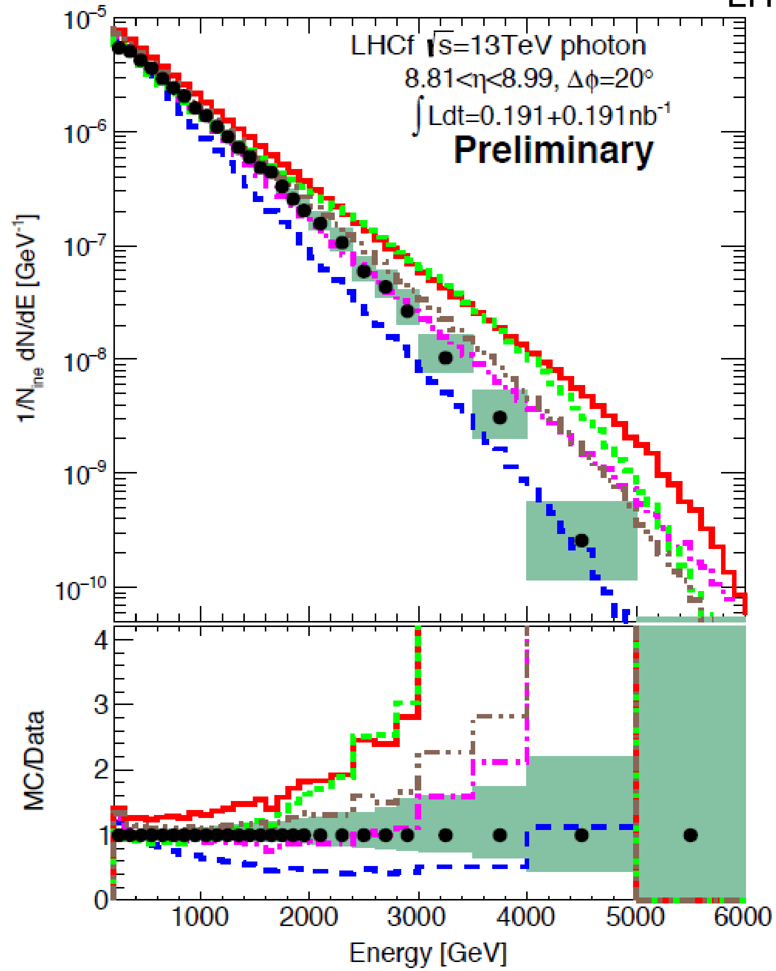
- **Which model for CR ? (alphabetical order)**
  - ➡ **DPMJETIII.17-1** by S. Roesler, A. Fedynitch, R. Engel and J. Ranft
  - ➡ **EPOS (1.99/LHC/3/4)** (from VENUS/NEXUS before) by H.J. Drescher, F. Liu, T. Pierog and K.Werner.
  - ➡ **QGSJET** (01/II-03/II-04/III) by S. Ostapchenko (starting with N. Kalmykov)
  - ➡ **Sibyll (2.1/2.3c/2.3d)** by E-J Ahn, R. Engel, R.S. Fletcher, T.K. Gaisser, P. Lipari, F. Riehn, T. Stanev

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 improvements !
- Can p-Pb data be used to mimic light ion (Air) interactions ?

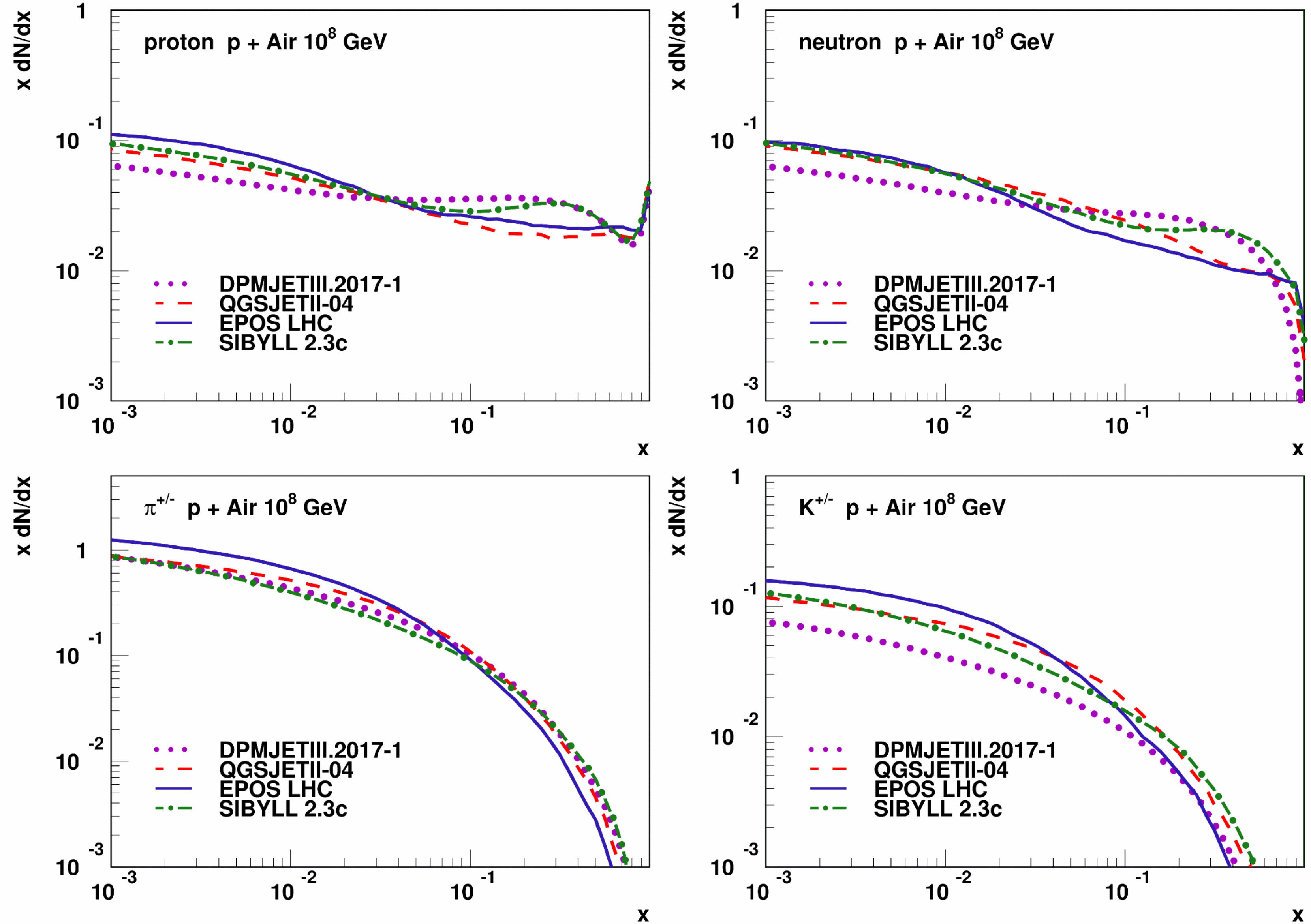
T.Sako for the LHCf collaboration





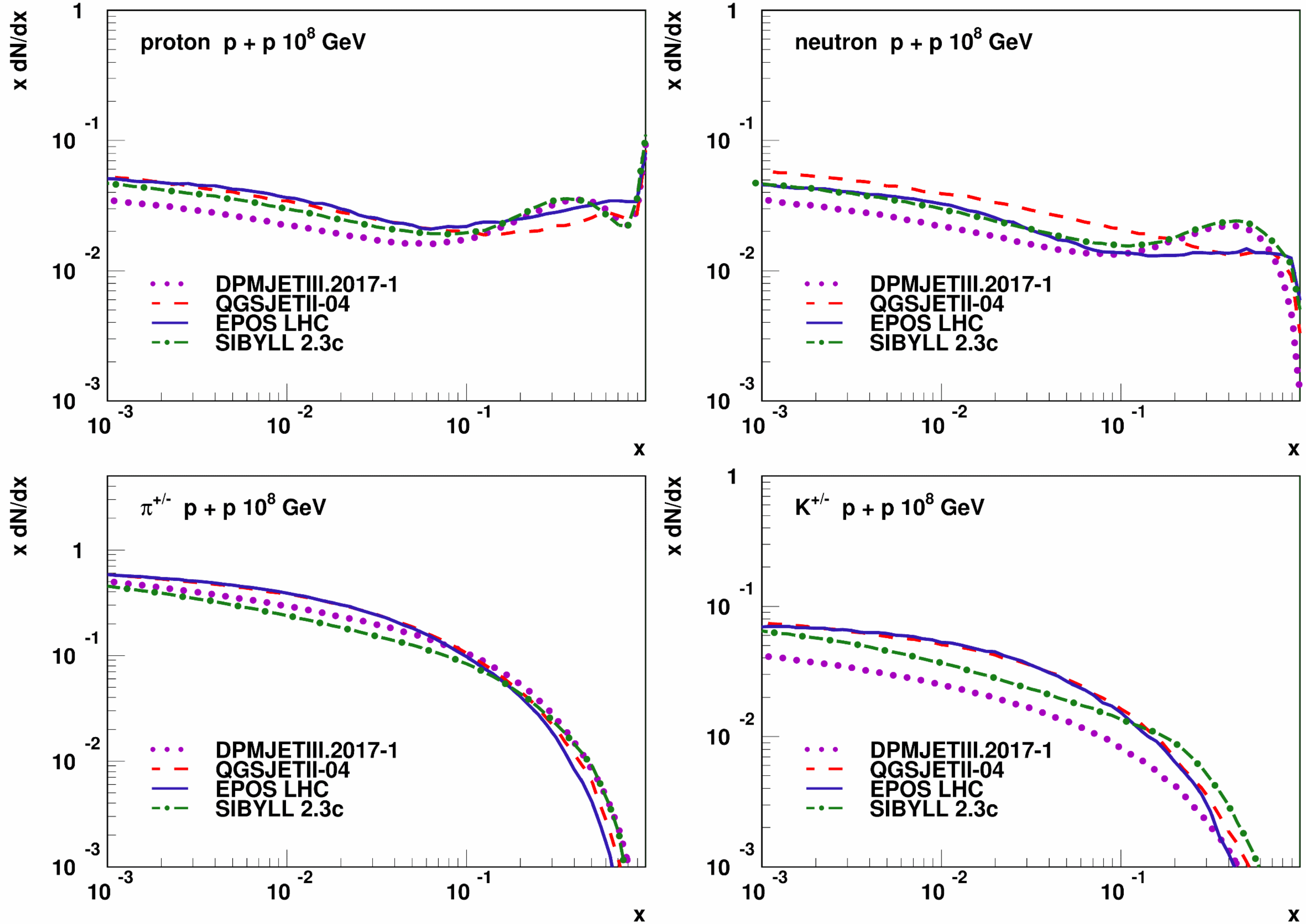
Forward Production in p-Air

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-p

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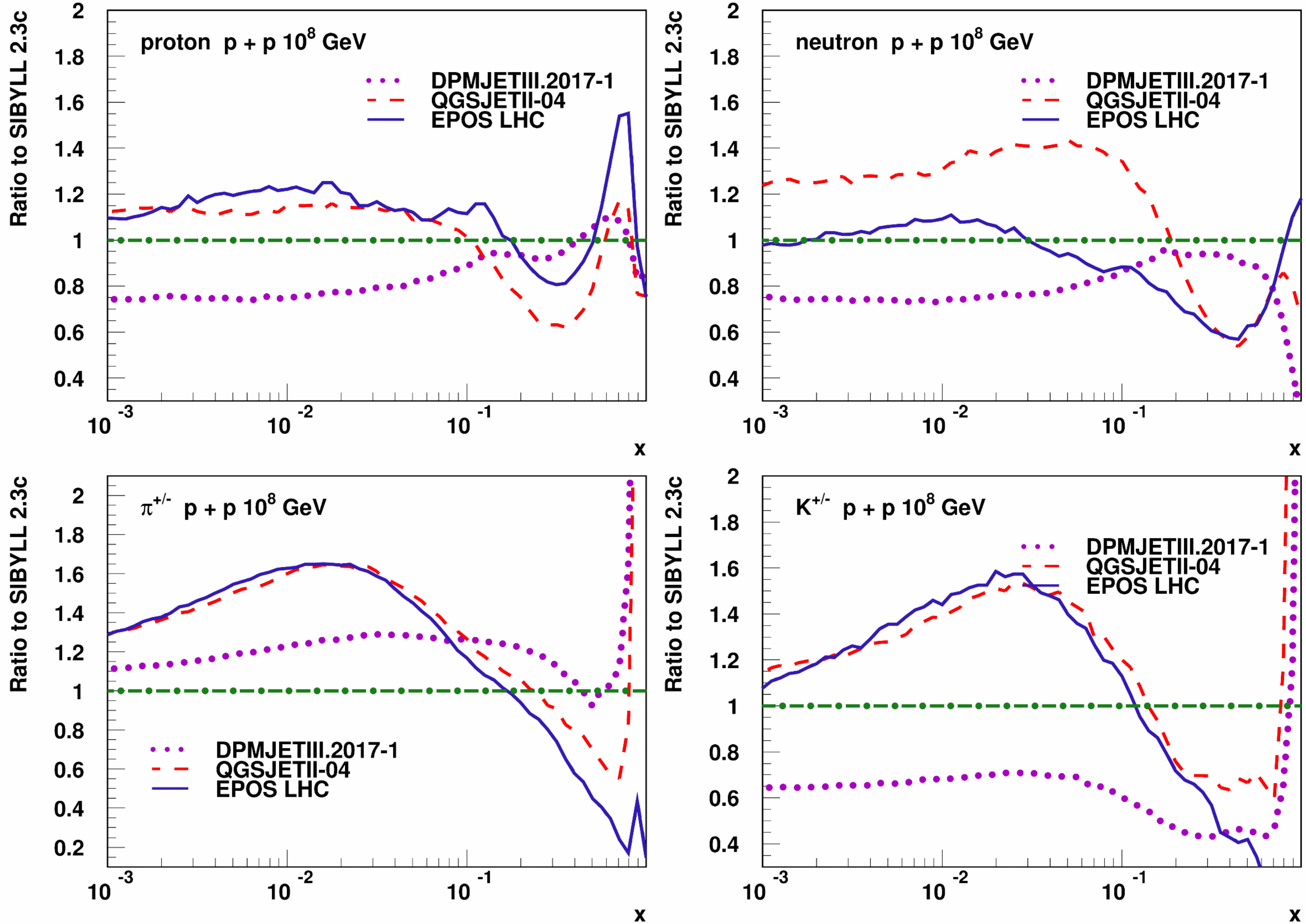

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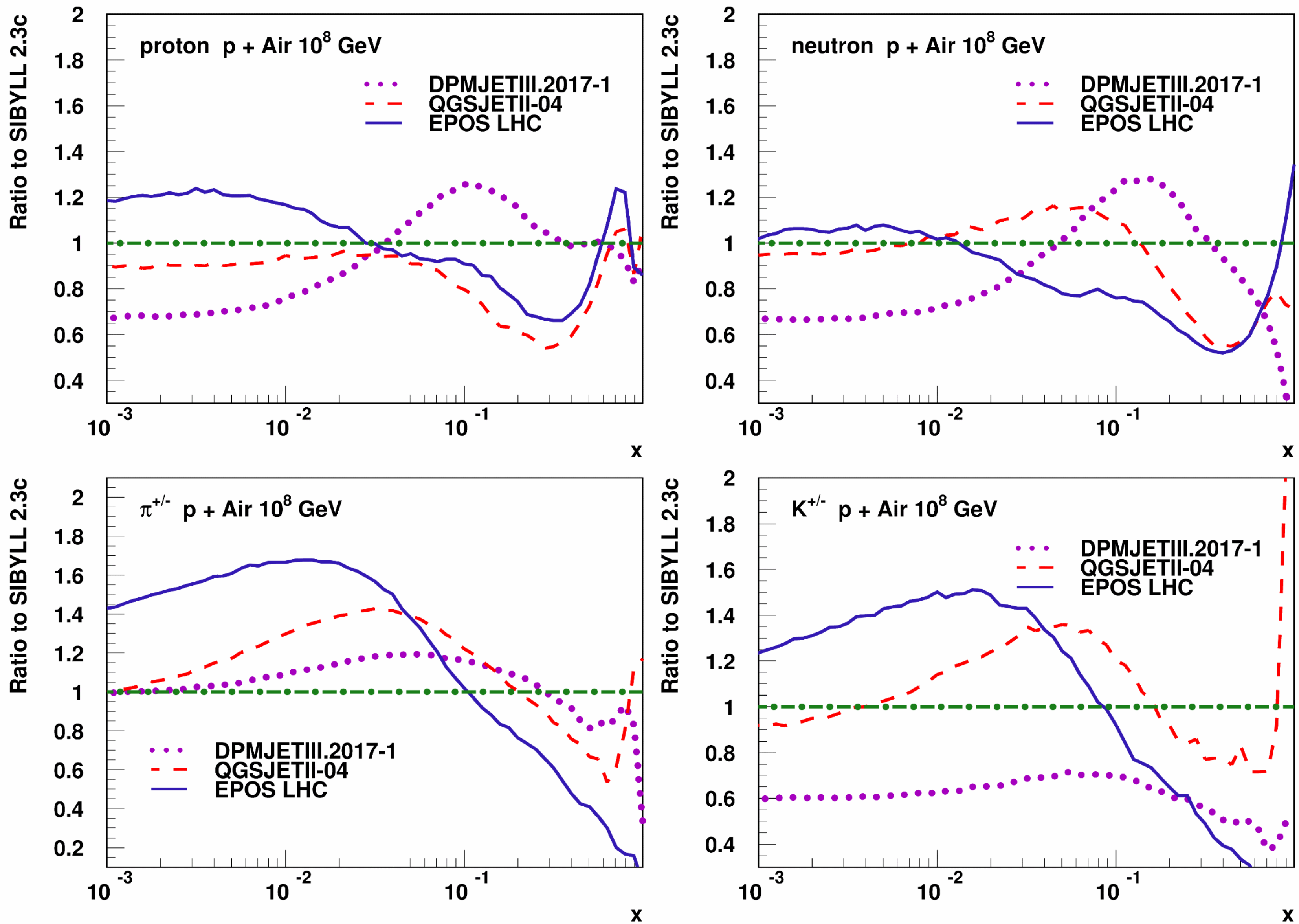
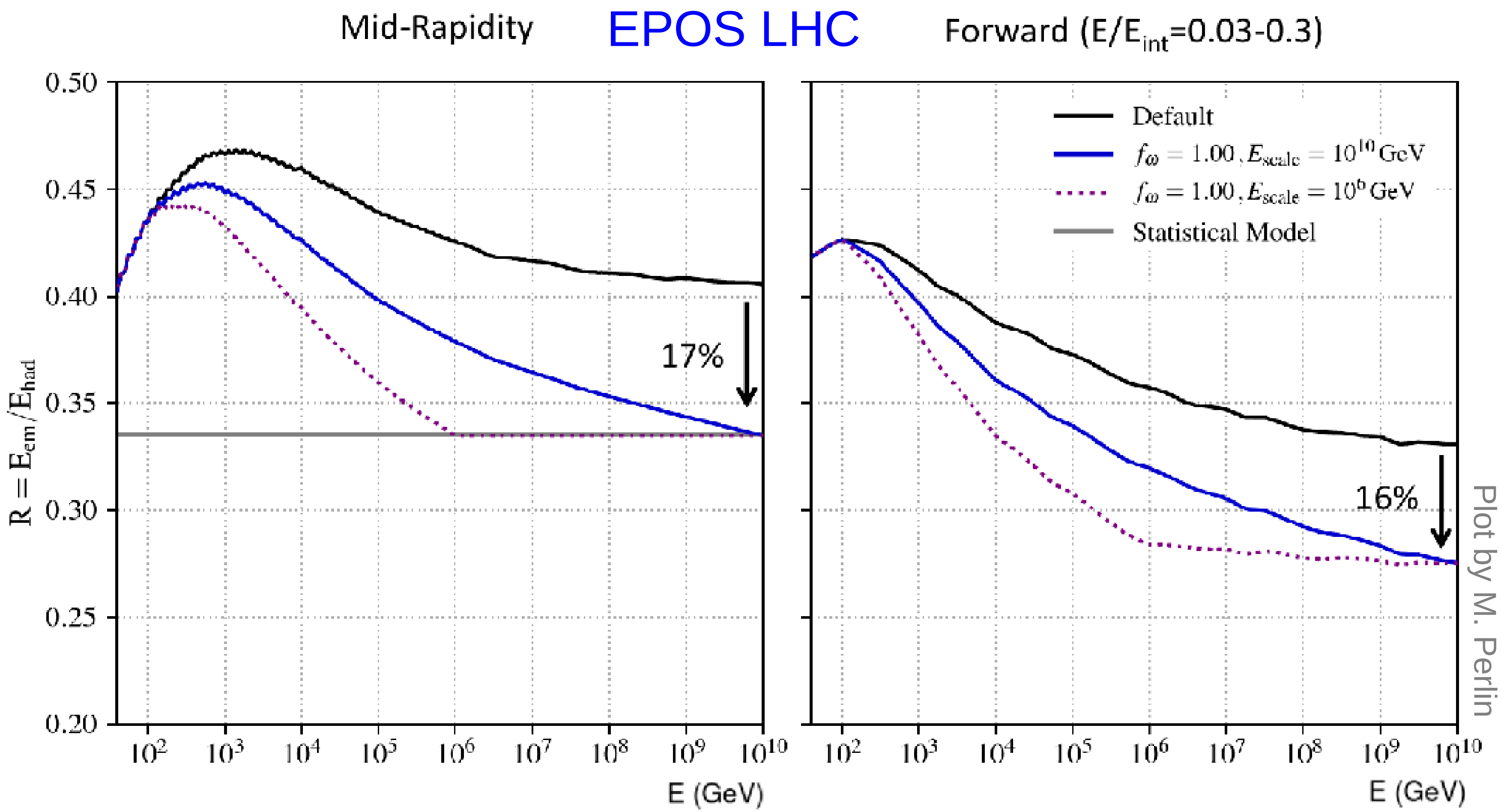


Evolution of hadronization from core to corona

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

➡ Change of ω_{core} with energy change $c = \frac{N_{\pi^0}}{N_{mult}}$ 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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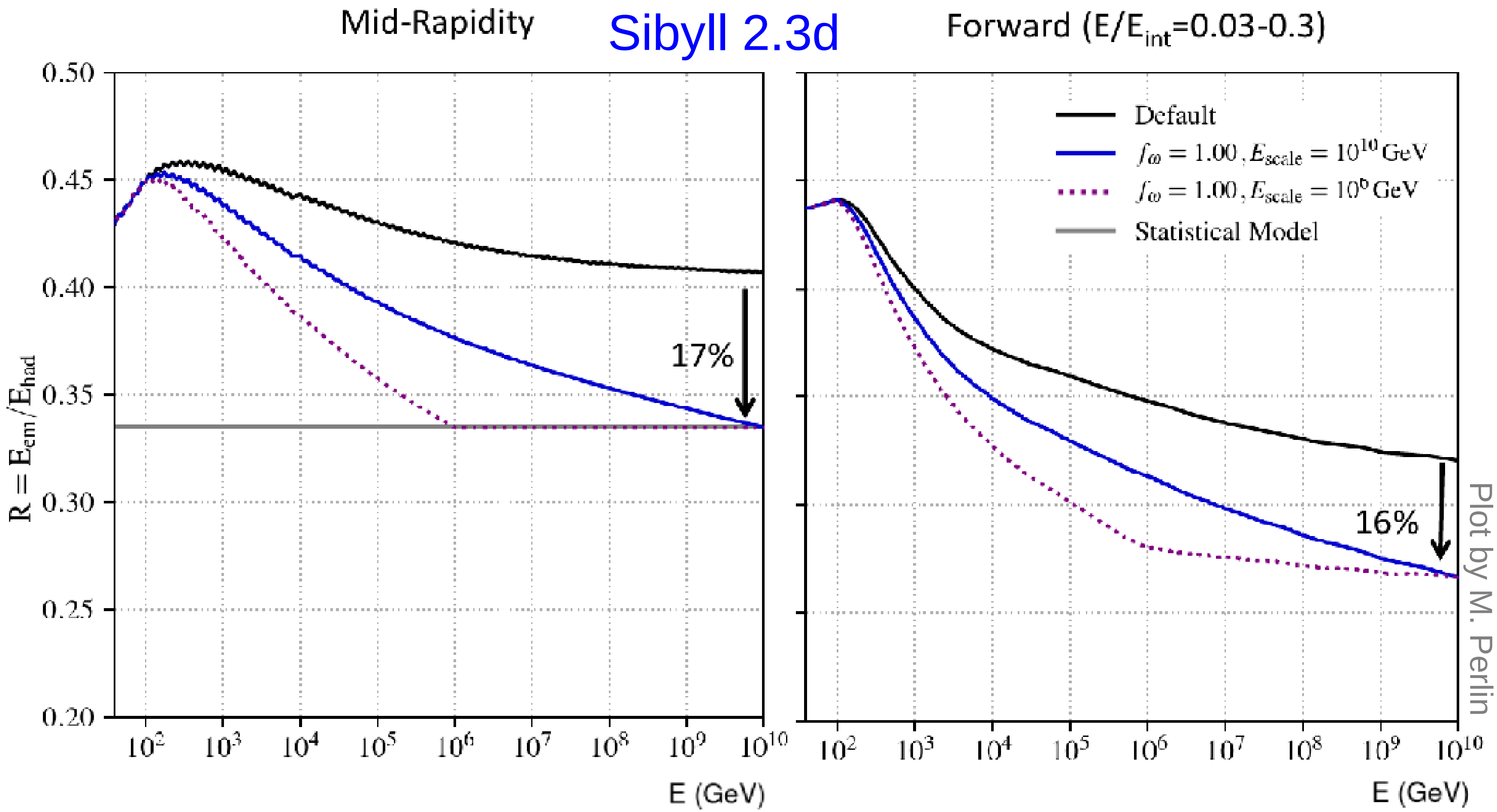
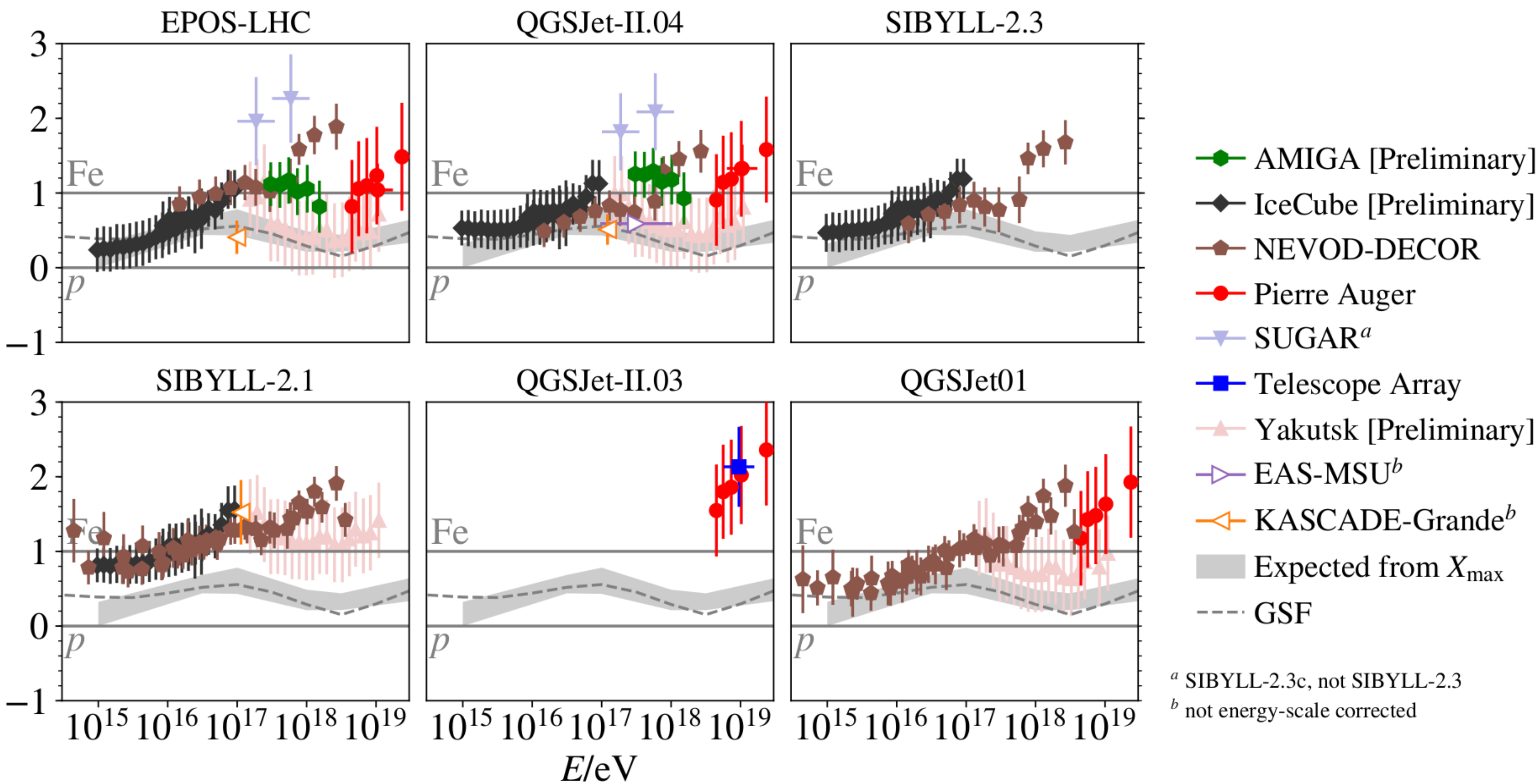


Data Rescaled



Possible Particle Physics Explanations

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

- Possibility to increase N_{mult} limited by X_{max}
- New Physics ?
  - Chiral symmetry restoration (Farrar et al.) ?
  - Strange fireball (Anchordoqui et al.) ?
  - String Fusion (Alvarez-Muniz et al.) ?
    - Problem : no strong effect observed at LHC (~10^{17} eV)
- Unexpected production of Quark Gluon Plasma (QGP) in light systems observed at the LHC (at least modified hadronization)
  - Reduced α is a sign of QGP formation (Baur et al.) !
  - Not properly done in EPOS LHC (QGP only in extreme conditions)
    - Problem : α changed at most by 20-25%

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),**

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),

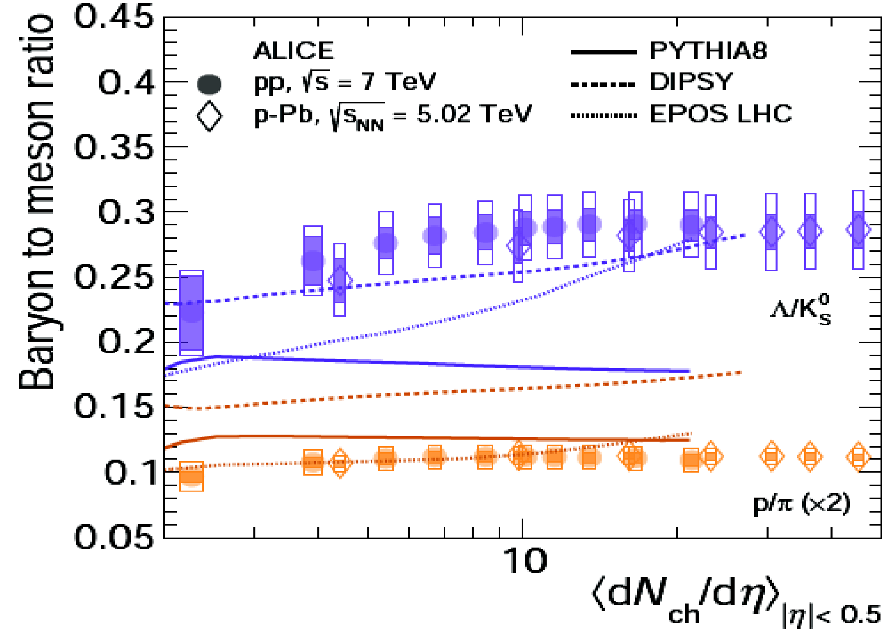
J.C. Arteaga (KASCADE-Grande, Mexico),

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

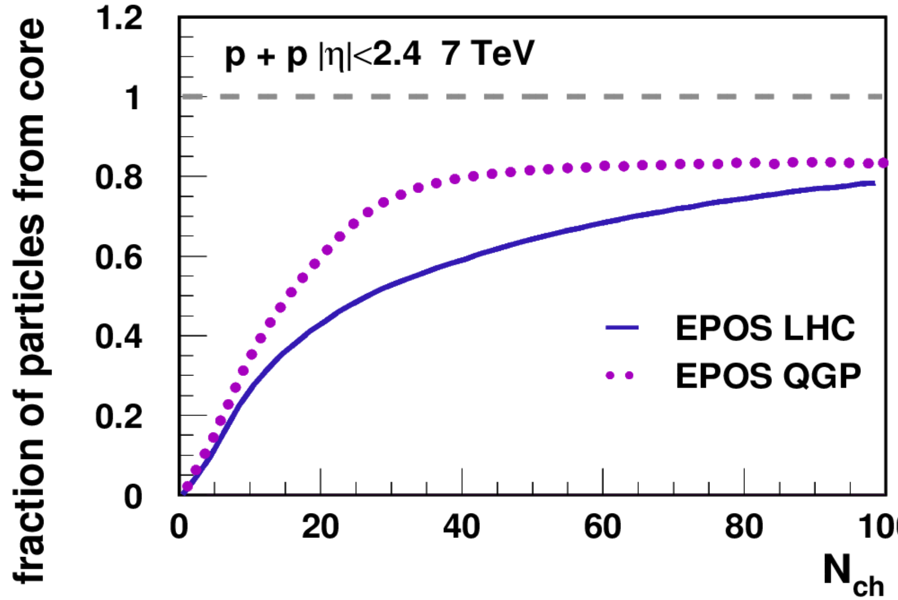
N. Kalmykov (EAS-MSU, Russia) and I.S. Karpikov (EAS-MSU, Russia)

Modified EPOS with Extended Core

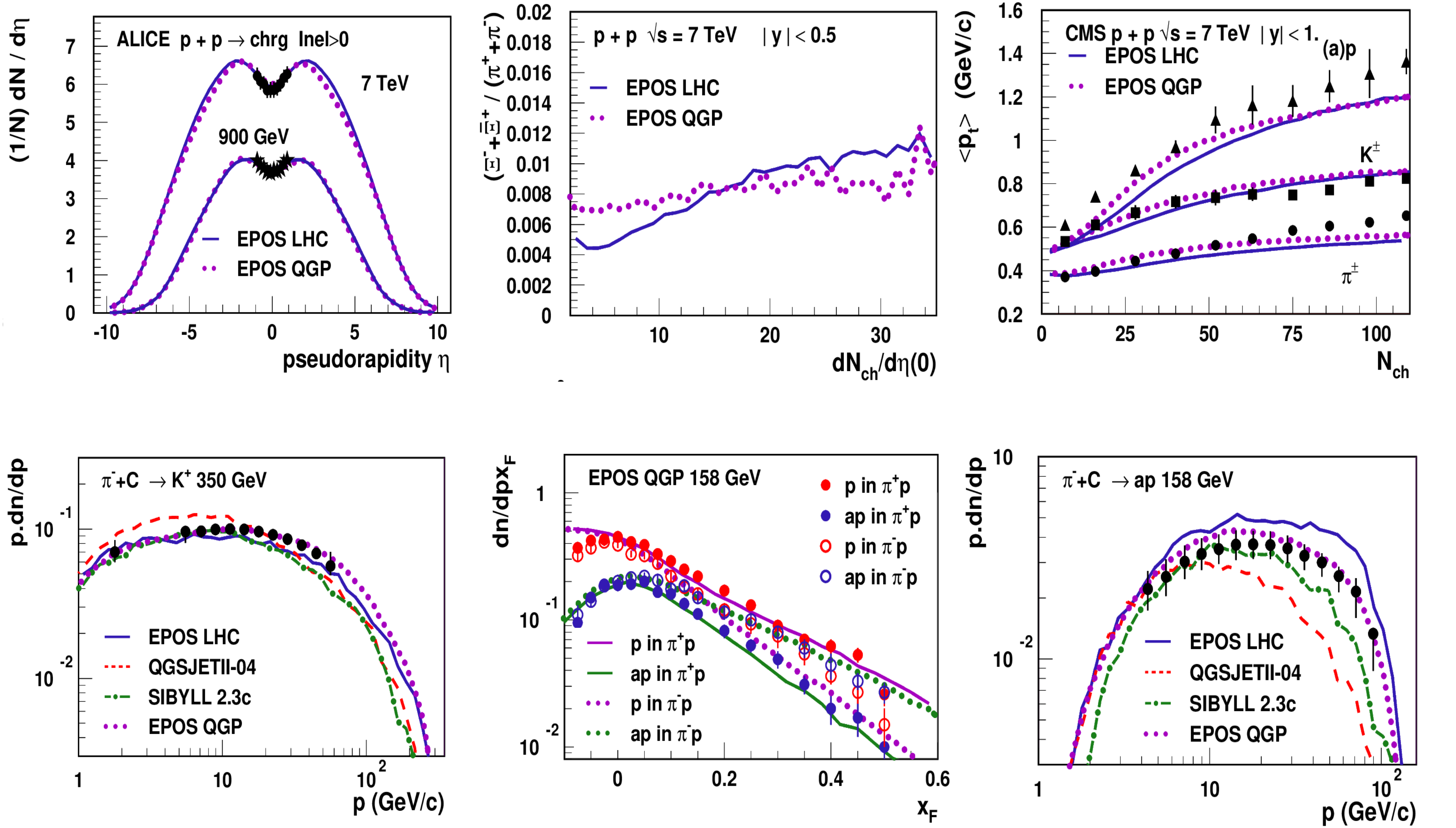
- **Core in EPOS LHC appear too late**
  - Recent publication show the evolution of chemical composition as a function of multiplicity
  - Large amount of (multi)strange baryons produced at lower multiplicity than predicted by EPOS LHC



- **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)

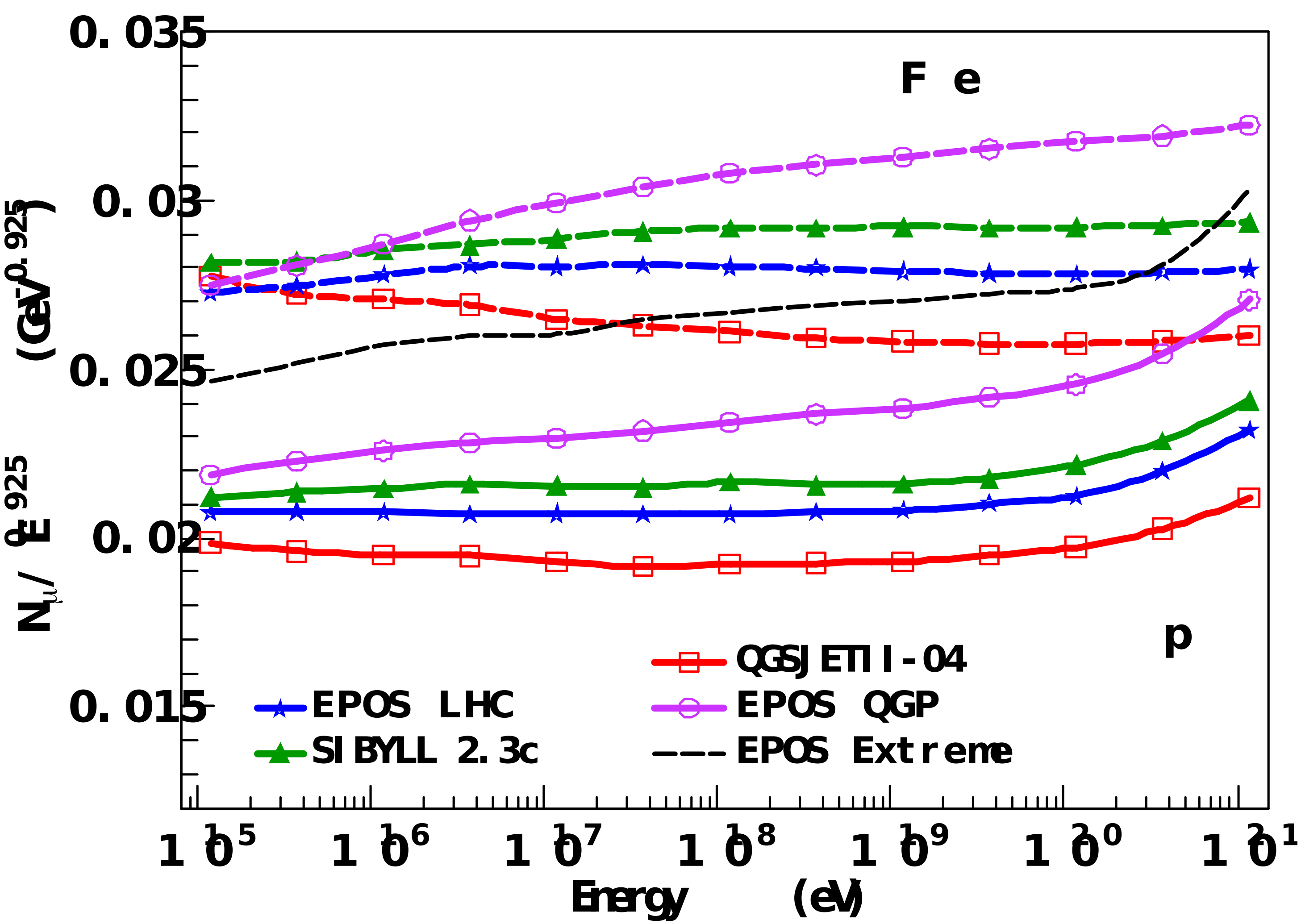


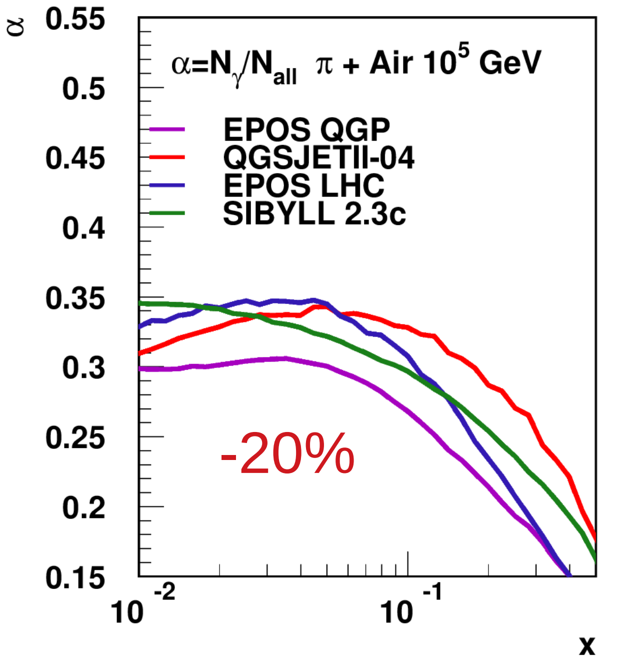
Preliminary Version with Minimum Constraints

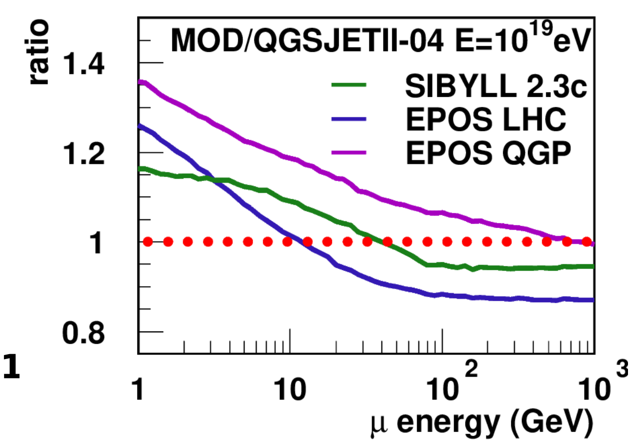


Results for Air Showers (2)

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

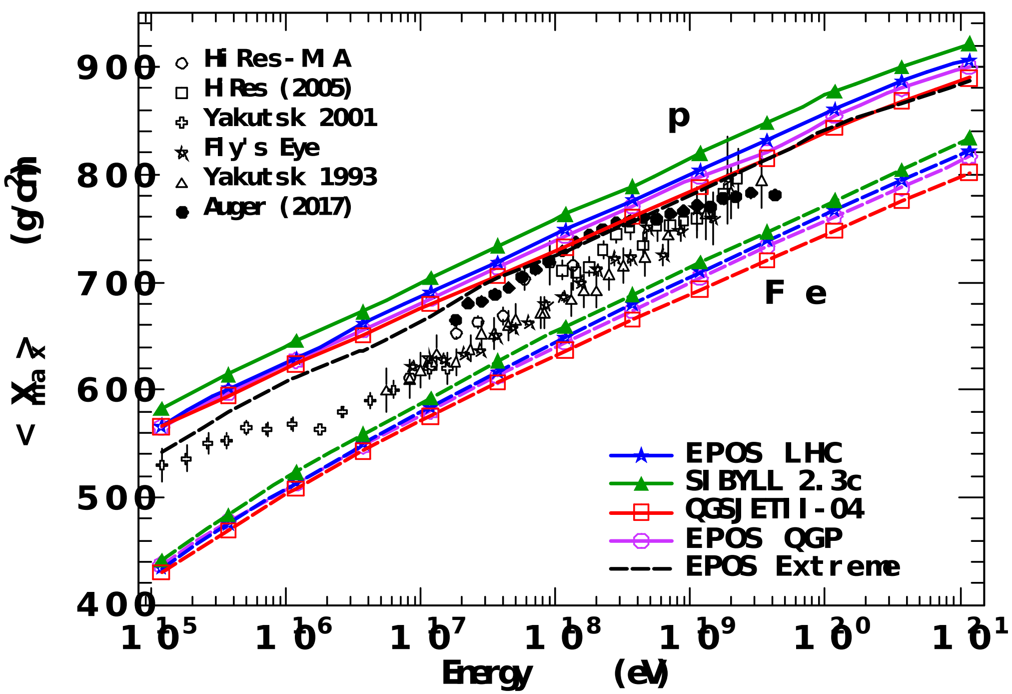


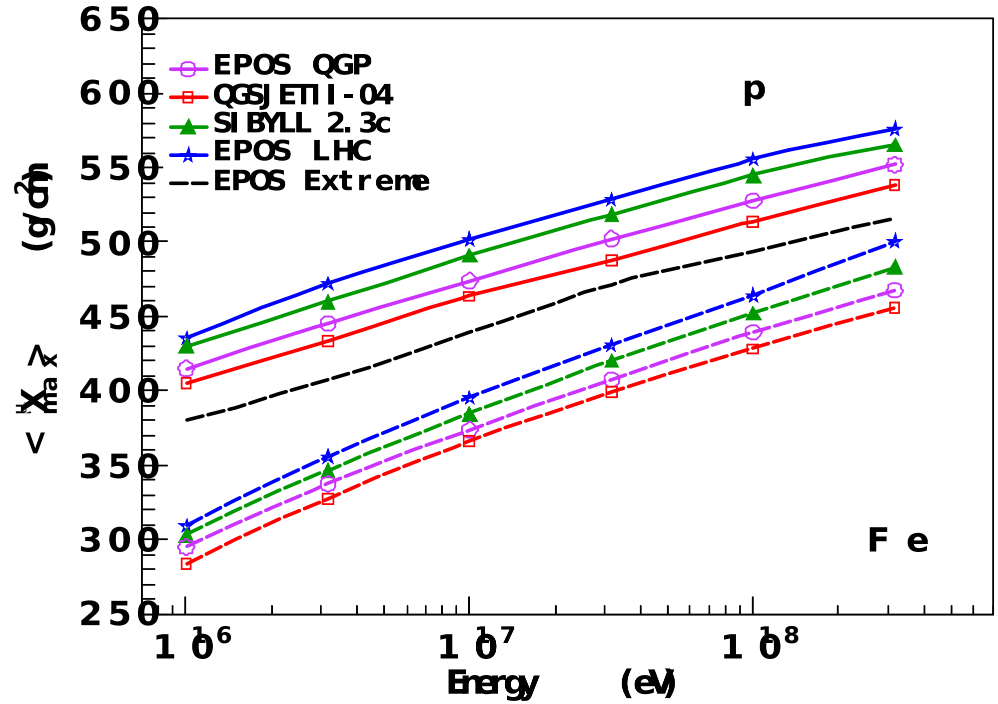




Results for Air Showers (1)

- 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



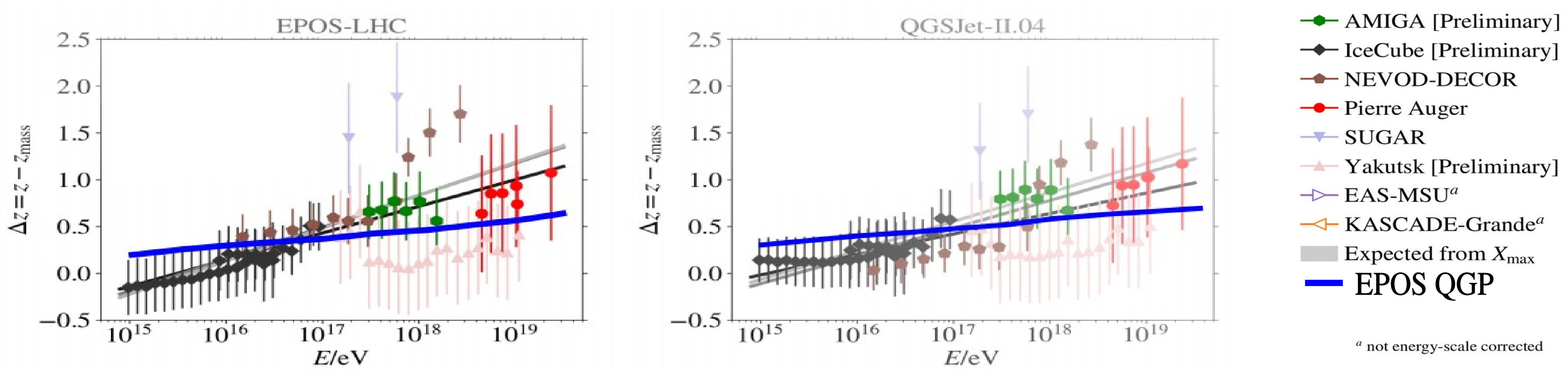


Comparison with Data

- **Collective hadronization gives a result compatible with data**
  - ➡ Still different energy evolution between data and simulatic

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

  - ➡ Significance to be tested

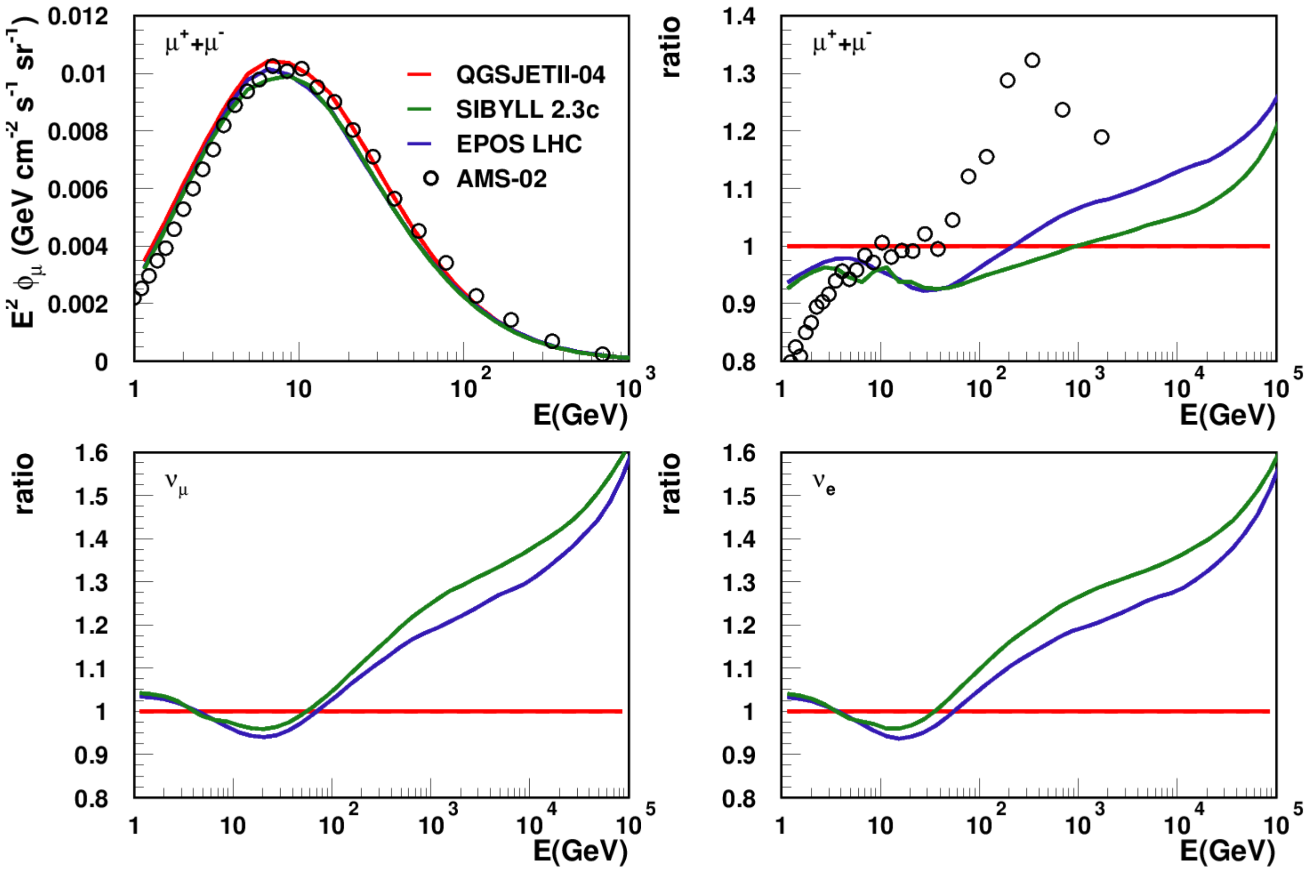


- **Probably tension at low energy (too many muons)**
  - ➡ Ideally a larger slope would be needed … what kind of hadronization possible ?

Muon and Neutrino Fluxes

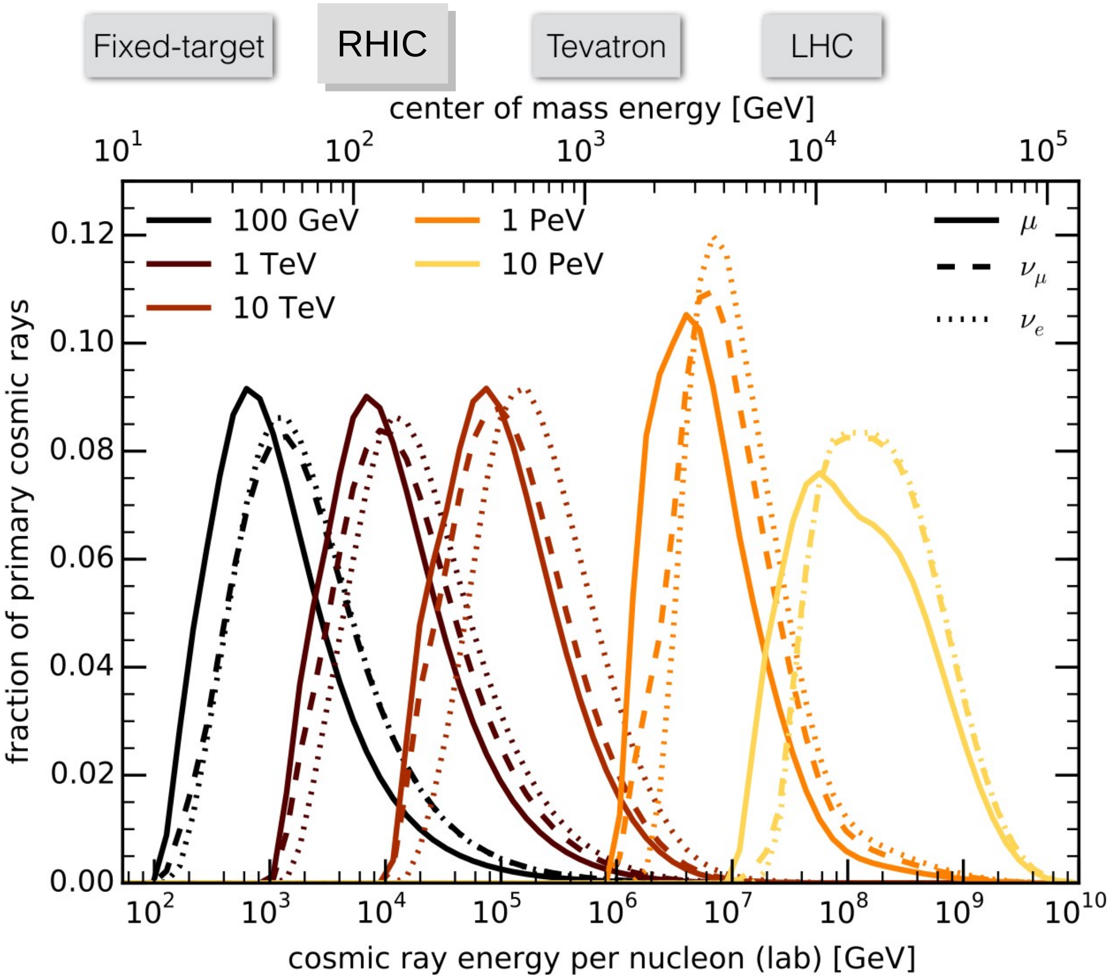
Low energy inclusive muon flux compared to predictions from different models (MCEq)

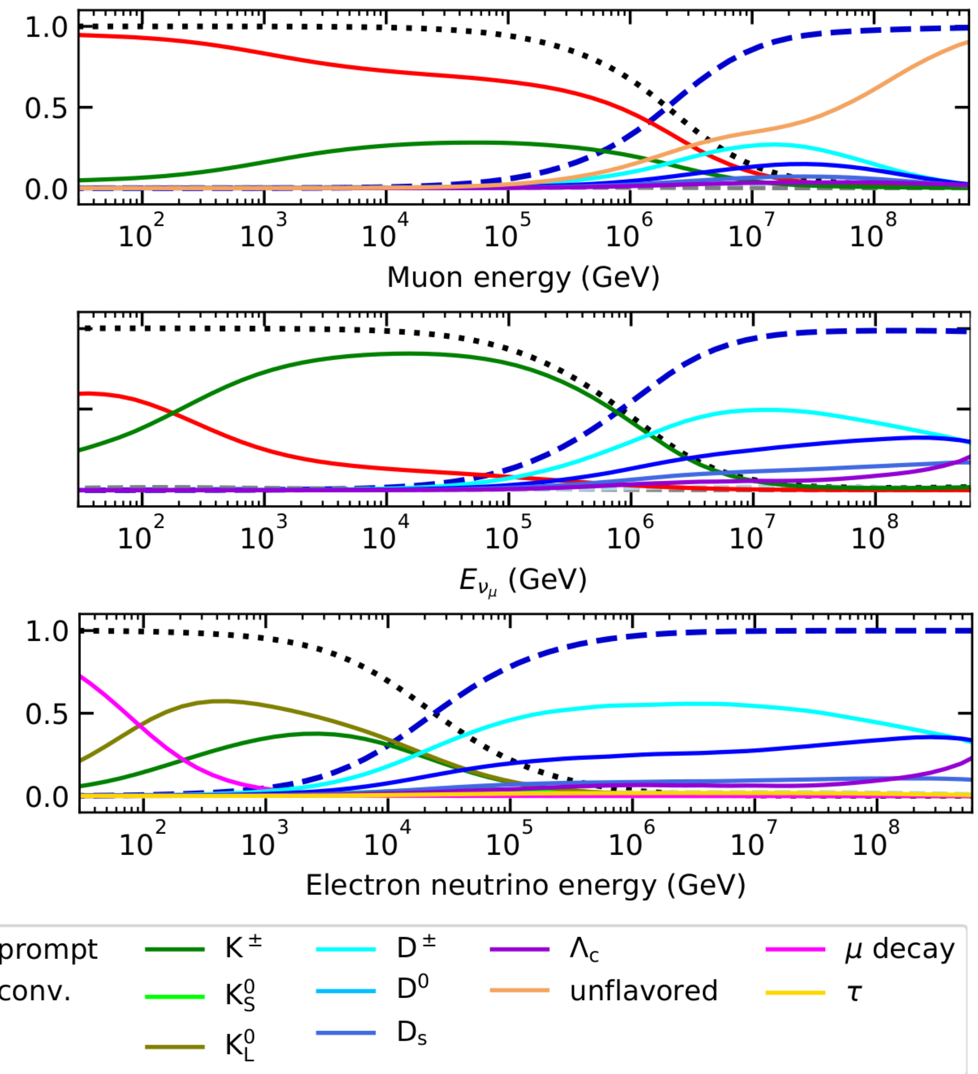
- Reasonable agreement below 100 GeV.
- Uncertainties due to primary CR flux/mass choice (H3a)



Inclusive Spectra and First Interaction

For inclusive spectra, particles from first interaction dominate



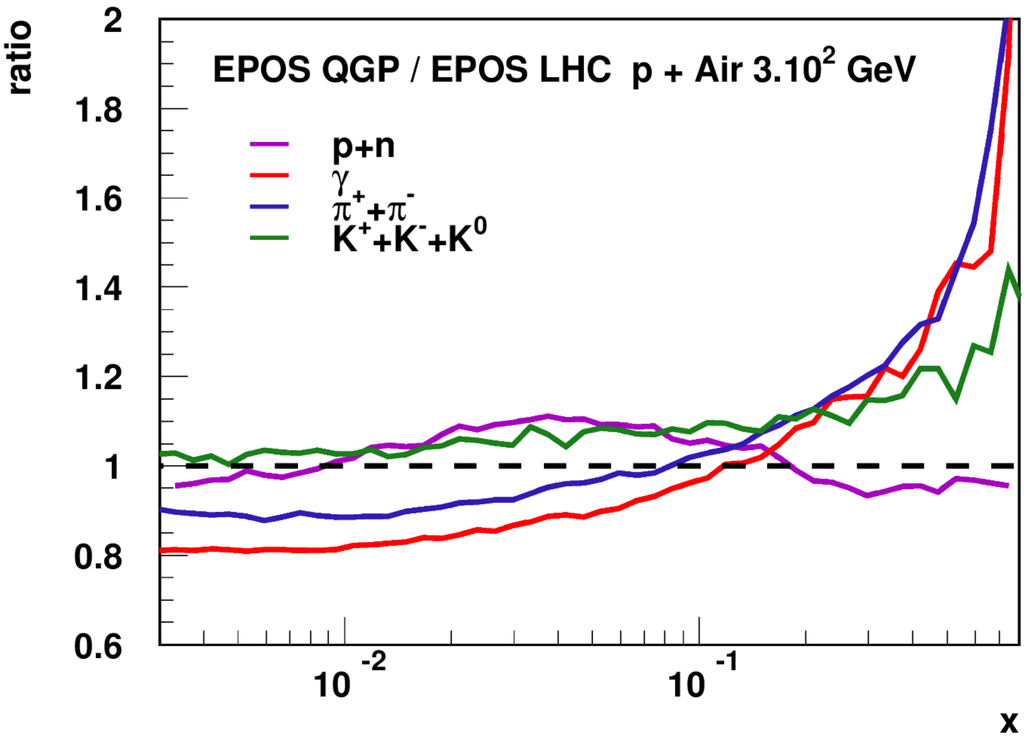


Plots from A. Fedinytch

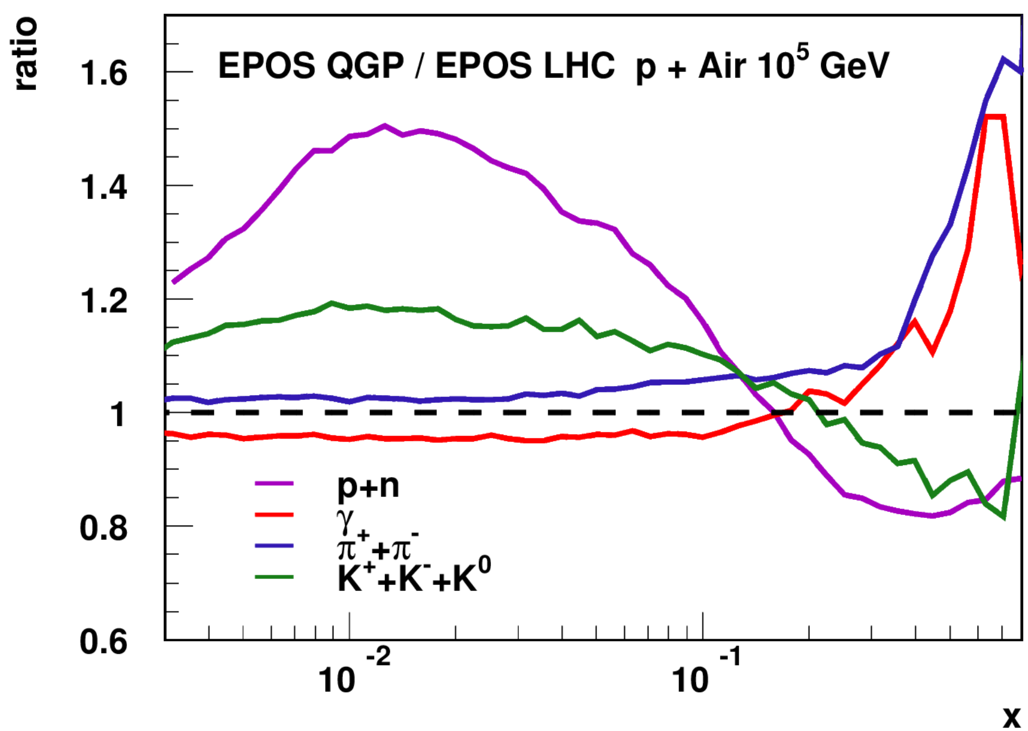
Modified Spectra with EPOS QGP

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

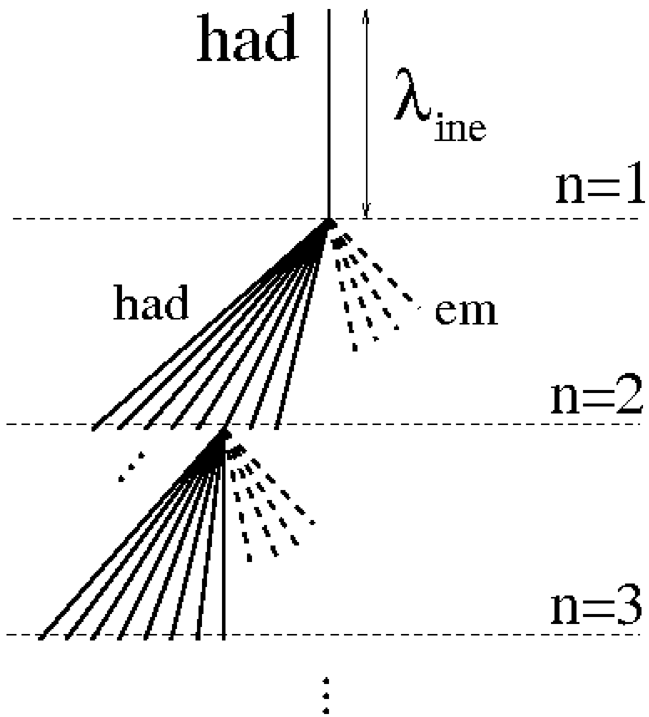
Source of TeV leptons



Source of PeV leptons



Simplified Shower Development



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

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

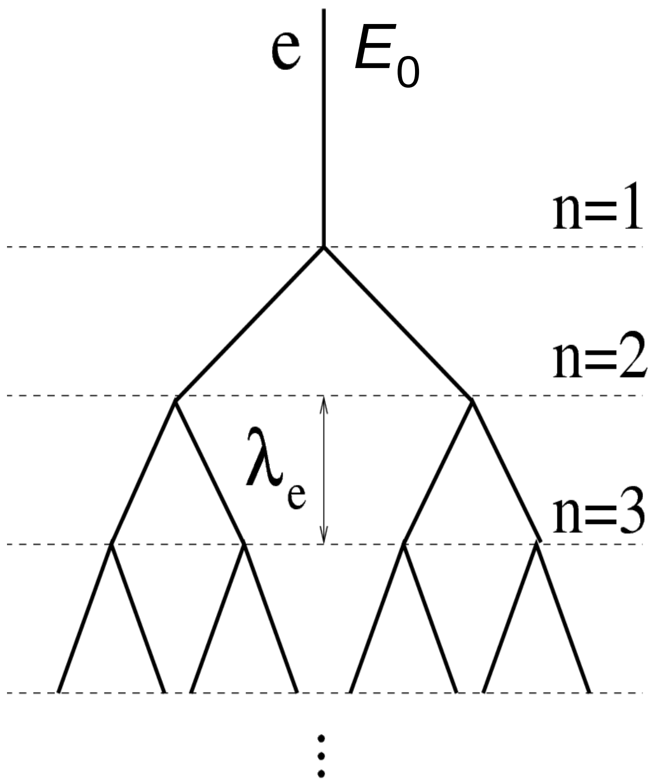
Using generalized Heitler model and superposition model :

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

- 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 :

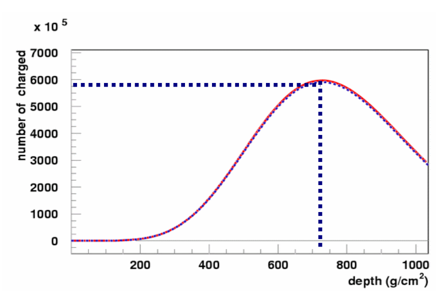
- 2 particles produced with equal energy

2^n particles after n interactions

$$n = X/\lambda_e$$

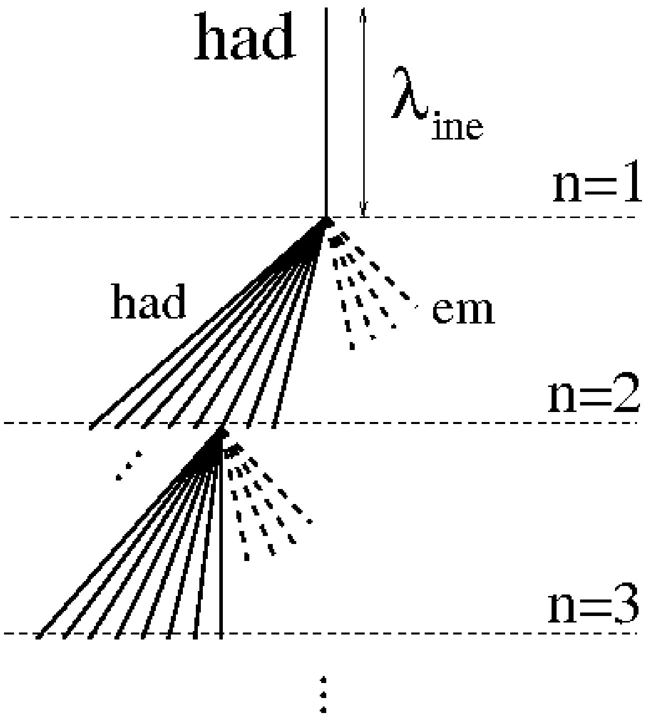
$$N(X) = 2^n = 2^{X/\lambda_e} \qquad E(X) = E_0/2^{X/\lambda_e}$$

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 3 (2016-)

Motivation :

- update with latest LHC results in simple model

Motivation :

- Hard Pomeron-Pomeron connexion

Motivation :

- update with LHC results
-fix high energy

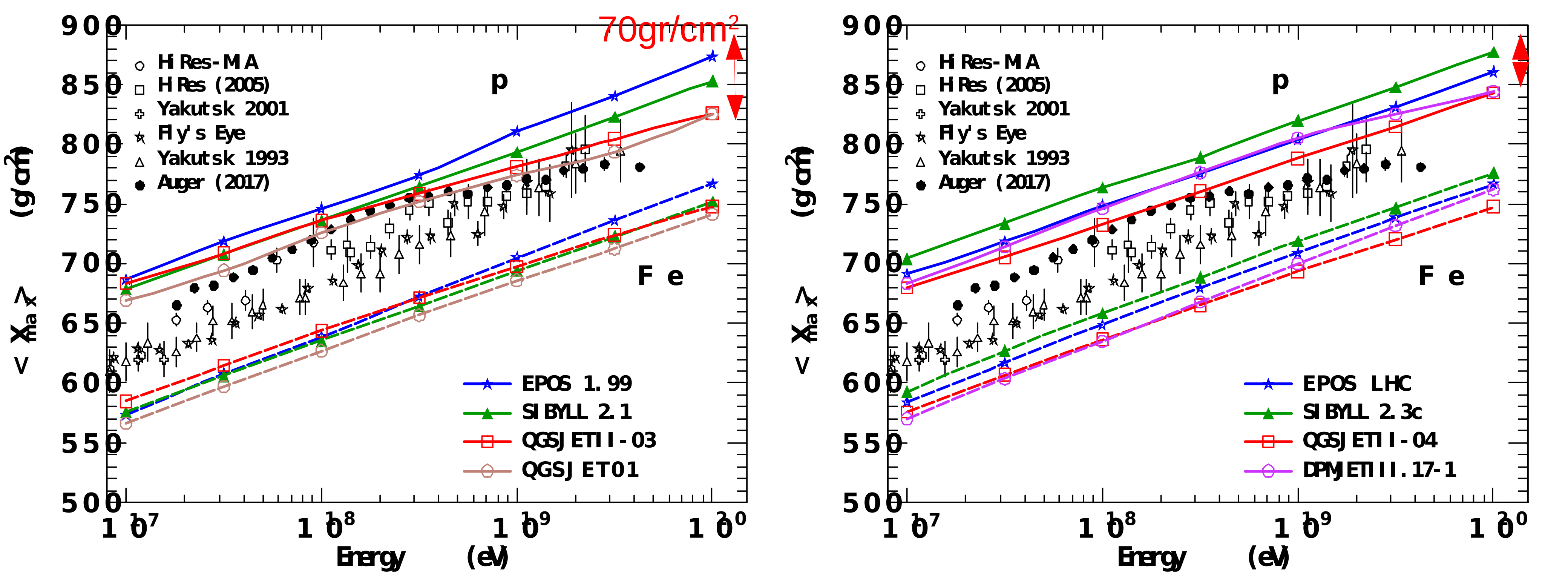
Motivation :

- binary scaling in hard probes

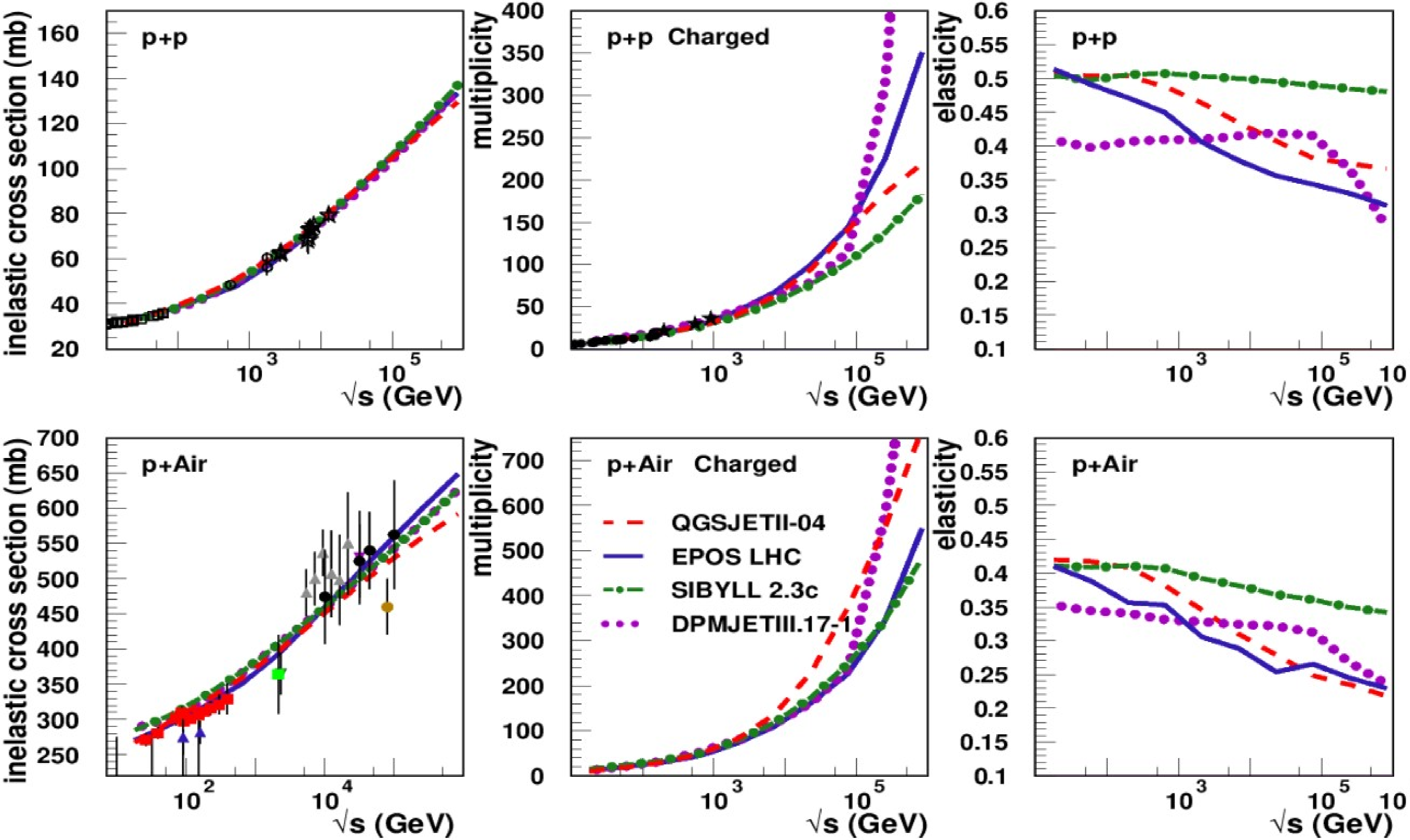
EAS with Re-tuned CR Models : X_{max}

After LHC :

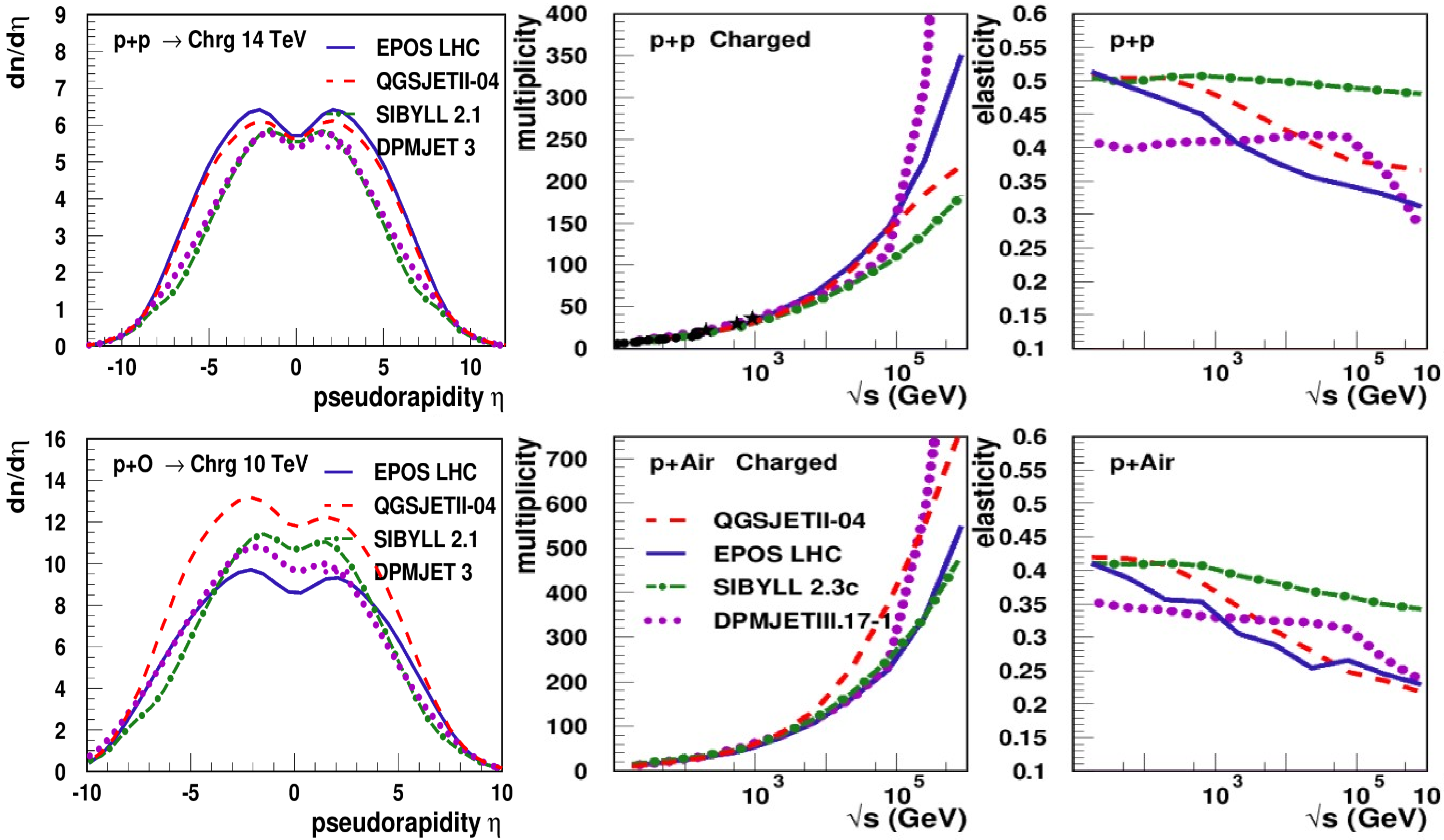
- Sibyll shifted by ~+20 g/cm²
- for other models about the same $<X_{max}>$ value at 10^{18} eV but
  - slope increased for QGSJETII
  - slope decreased for EPOS
- very similar elongation rate (slope) for all models



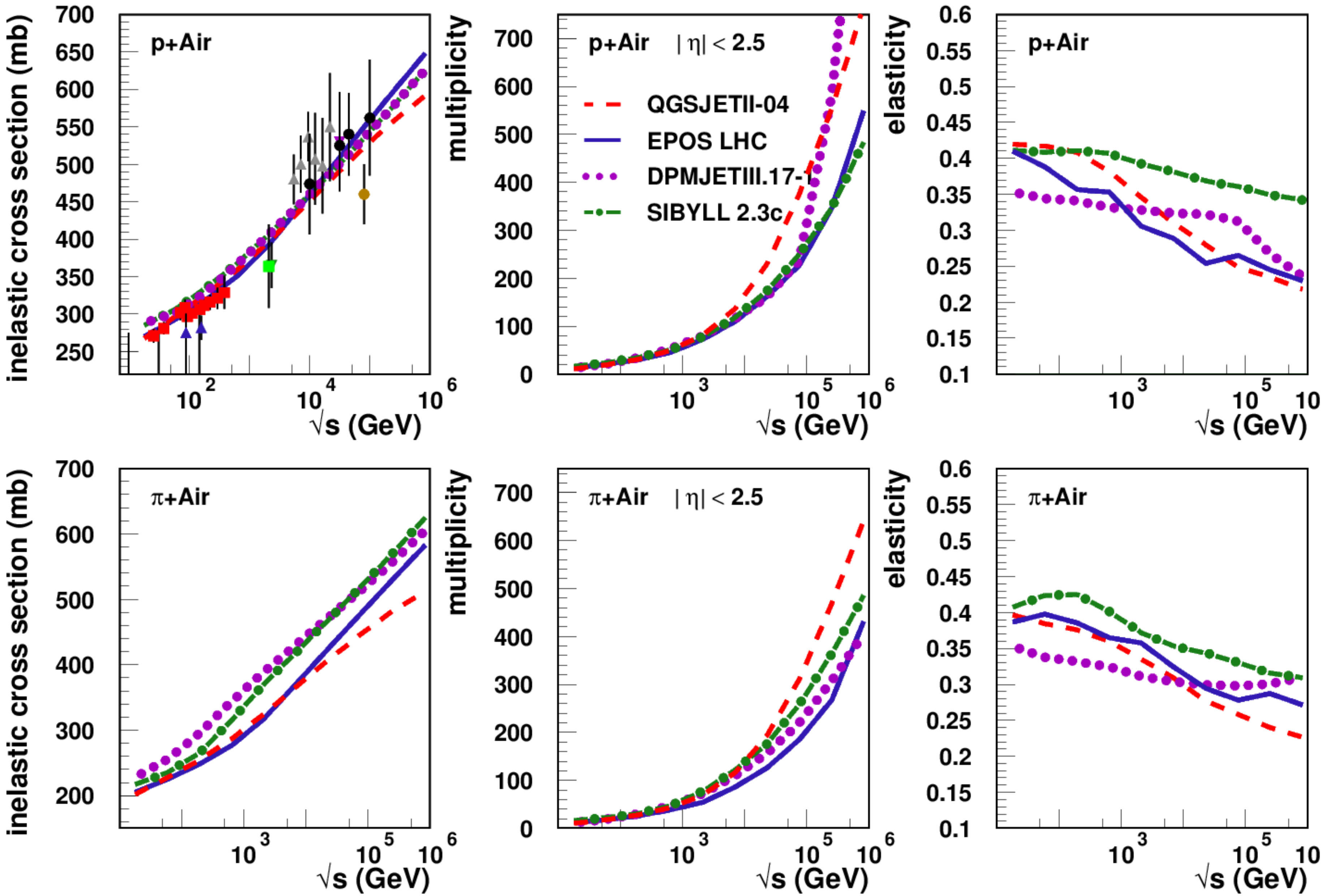
Ultra-High Energy Hadronic Model Predictions p-Air



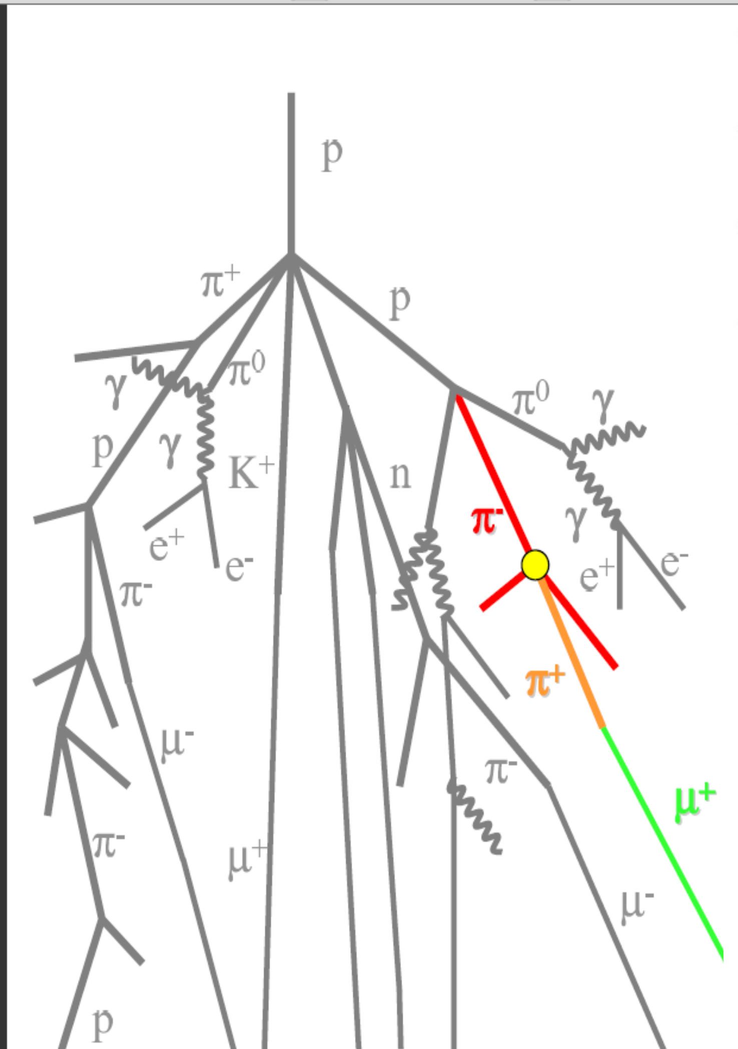
Ultra-High Energy Hadronic Model Predictions p-Air



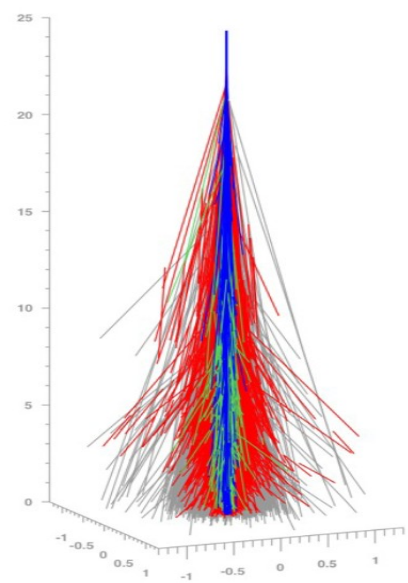
Ultra-High Energy Hadronic Model Predictions π-Air



Extensive Air Shower



From R. Ulrich (KIT)



$+ \, air \to$ hadrons
$+ \, air \to$ hadrons
$+ \, air \to$ hadrons

hadronic physics

initial γ from π^0 decay

$e^\pm \to e^\pm + \gamma$
$\gamma \to e^+ + e^-$

well known QED

$^\pm \to \mu^\pm + \nu_\mu/\bar{\nu}_\mu$

Cascade of particle in Earth's atmosphere

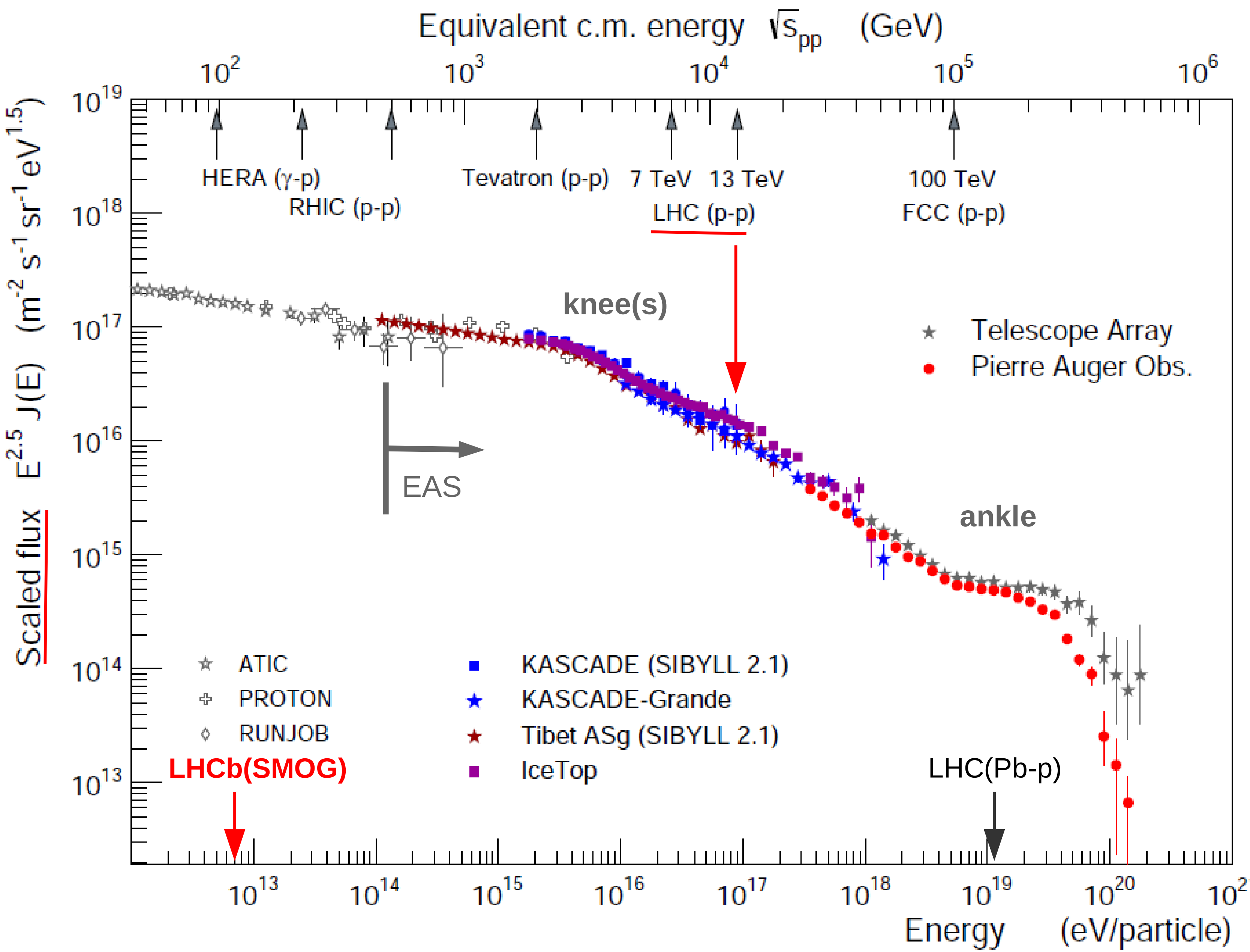
Number of particles at maximum

- 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)

Energy Spectrum



R. Engel (KIT)