Opportunities with Calorimeters at LHC : How to solve the muon puzzle ?

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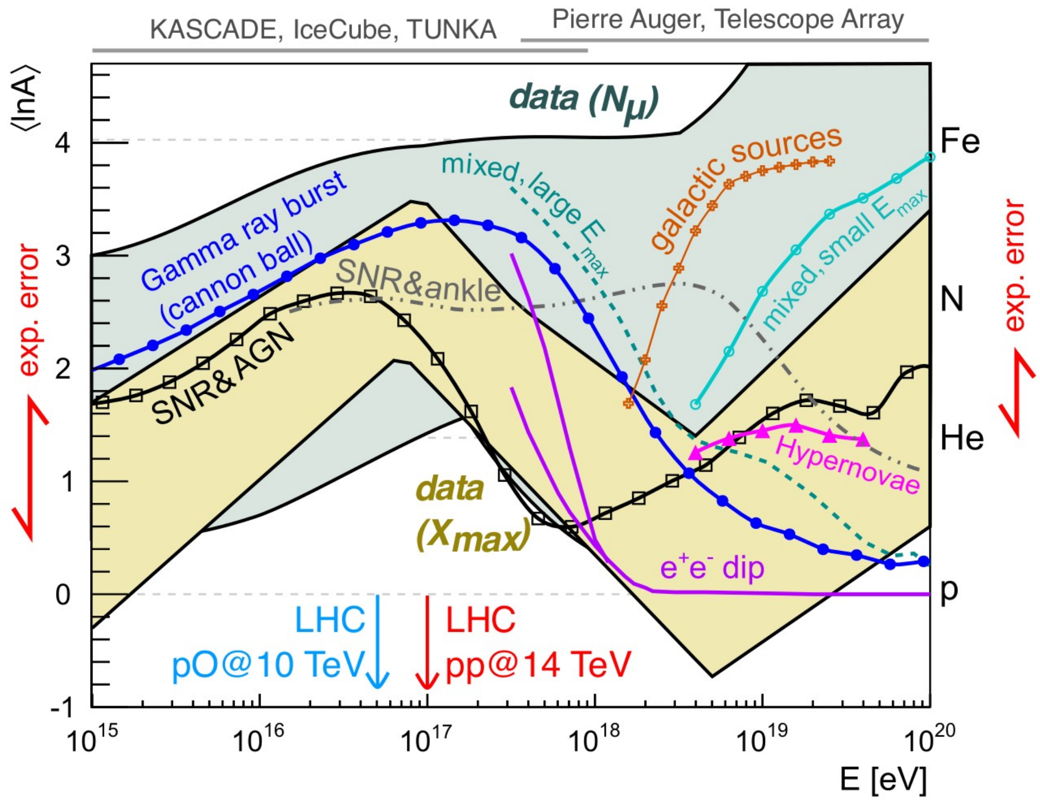
Outline

- **Muons in Extensive Air Showers (EAS)**
- **0 degree calorimeters**
  - ➜ Pion exchange
- **Muon puzzle**
  - ➜ Quark Gluon Plasma (QGP) as possible explanation
- **Forward calorimeters**
  - ➜ Test of hadronization scheme
- **Summary**

UHECR Composition

With muons current CR data are impossible to interpret

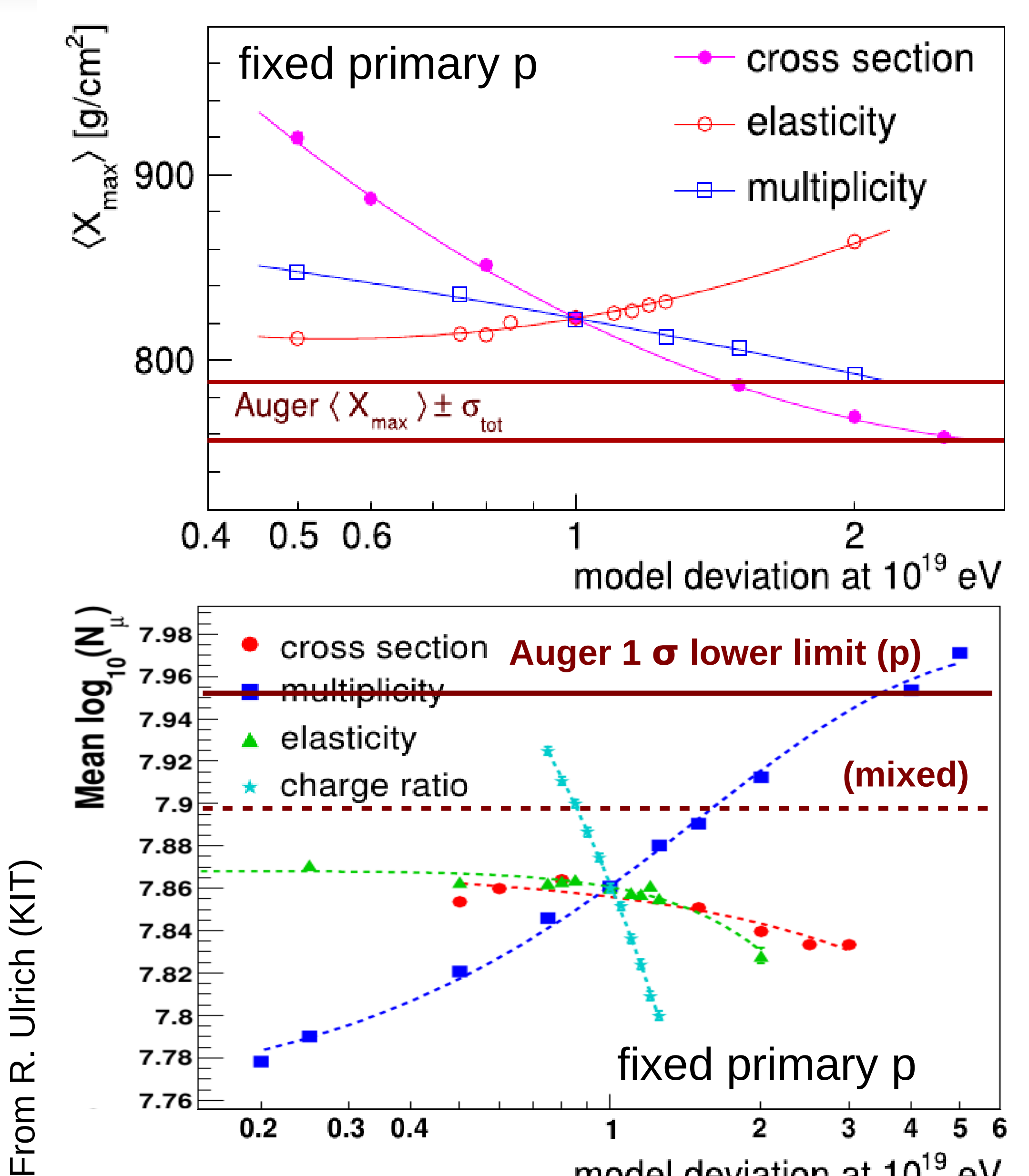
- Very large uncertainties in model predictions
- Mass from muon data incompatible with mass fro X_{max}



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

H. Dembinski UHECR 2018 (WHISP working group)

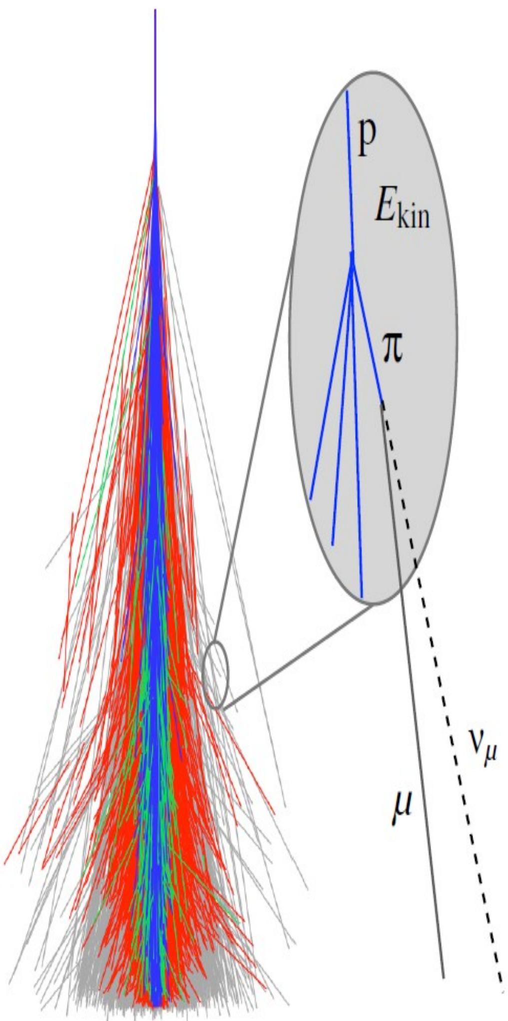
Sensitivity to Hadronic Interactions

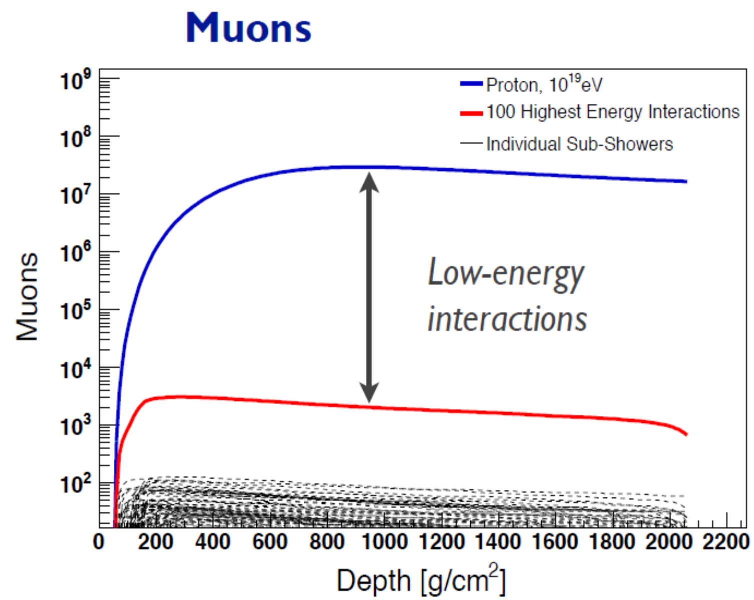


- **Air shower development dominated by few parameters**
  - ➡ mass and energy of primary CR
  - ➡ cross-sections (p-Air and (π-K)-Air)
  - ➡ (in)elasticity
  - ➡ multiplicity
  - ➡ charge ratio and baryon production
- **Change of primary = change of hadronic interaction parameters**
  - ➡ cross-section,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

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

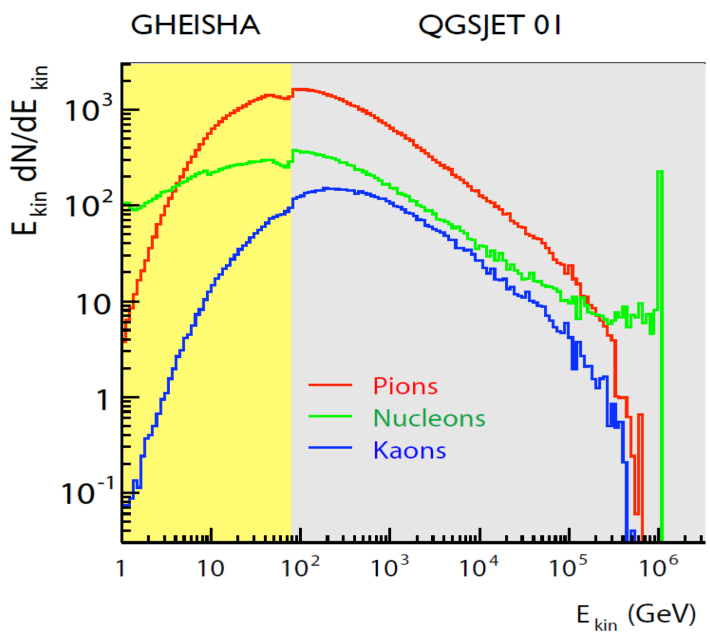
Muon production by low energy interactions

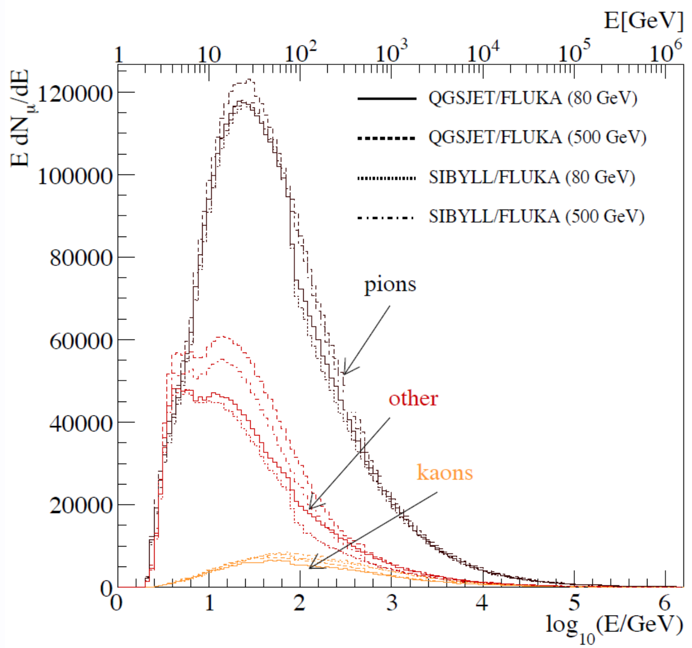




~ 100 GeV for KASCADE
~ 30 GeV for Auger

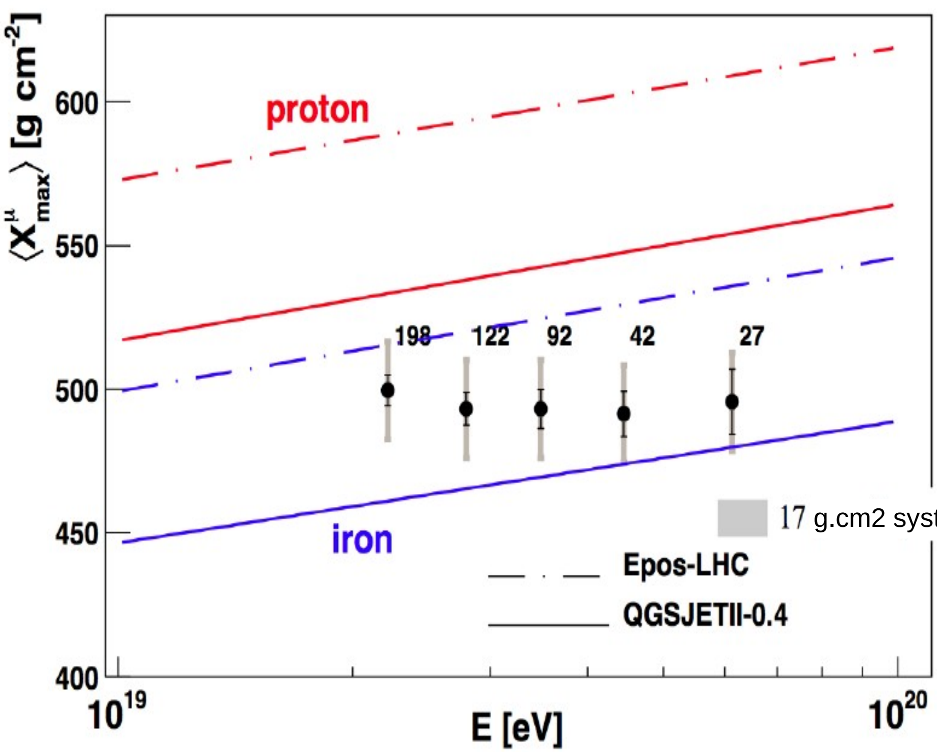
Muons/hadrons:
low-energy interactions

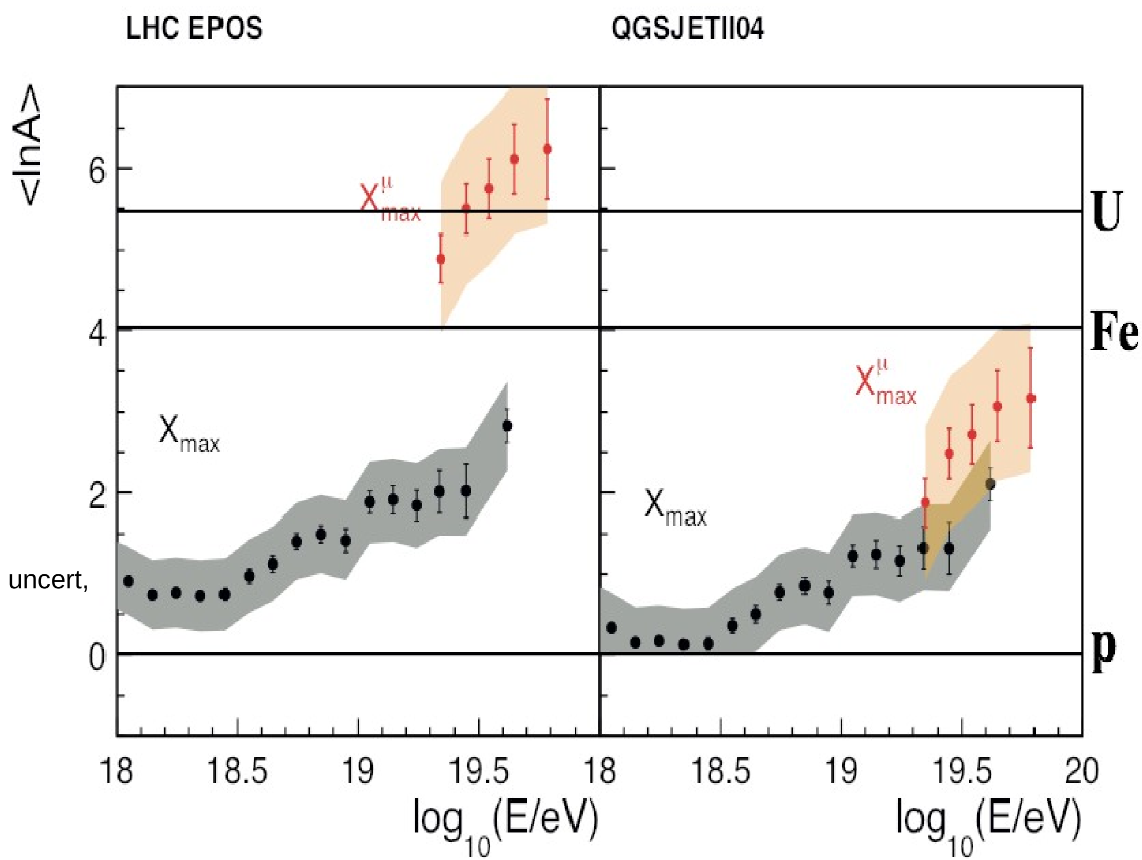




Muon Production Depth X^{μ}_{max} and X_{max}

- **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 (diffraction and forward baryon production) ➔ related to pion interaction (from low to high energy)





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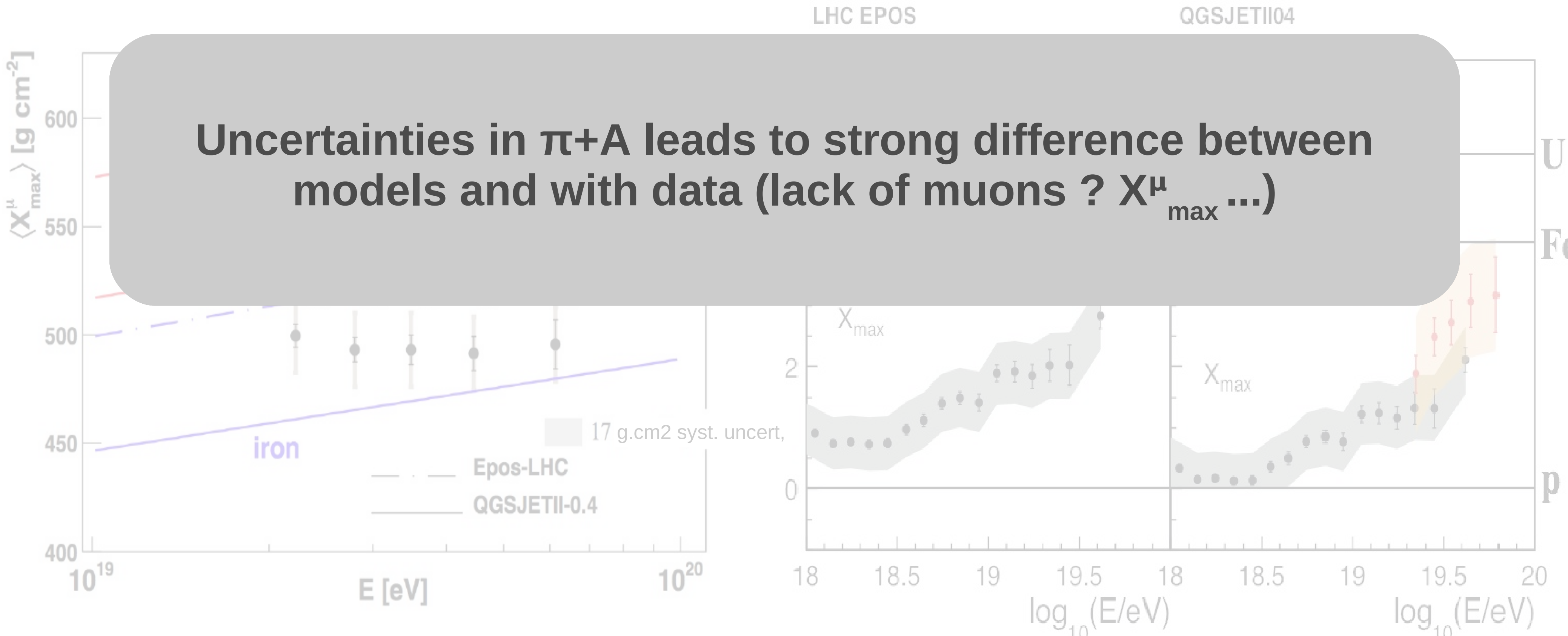
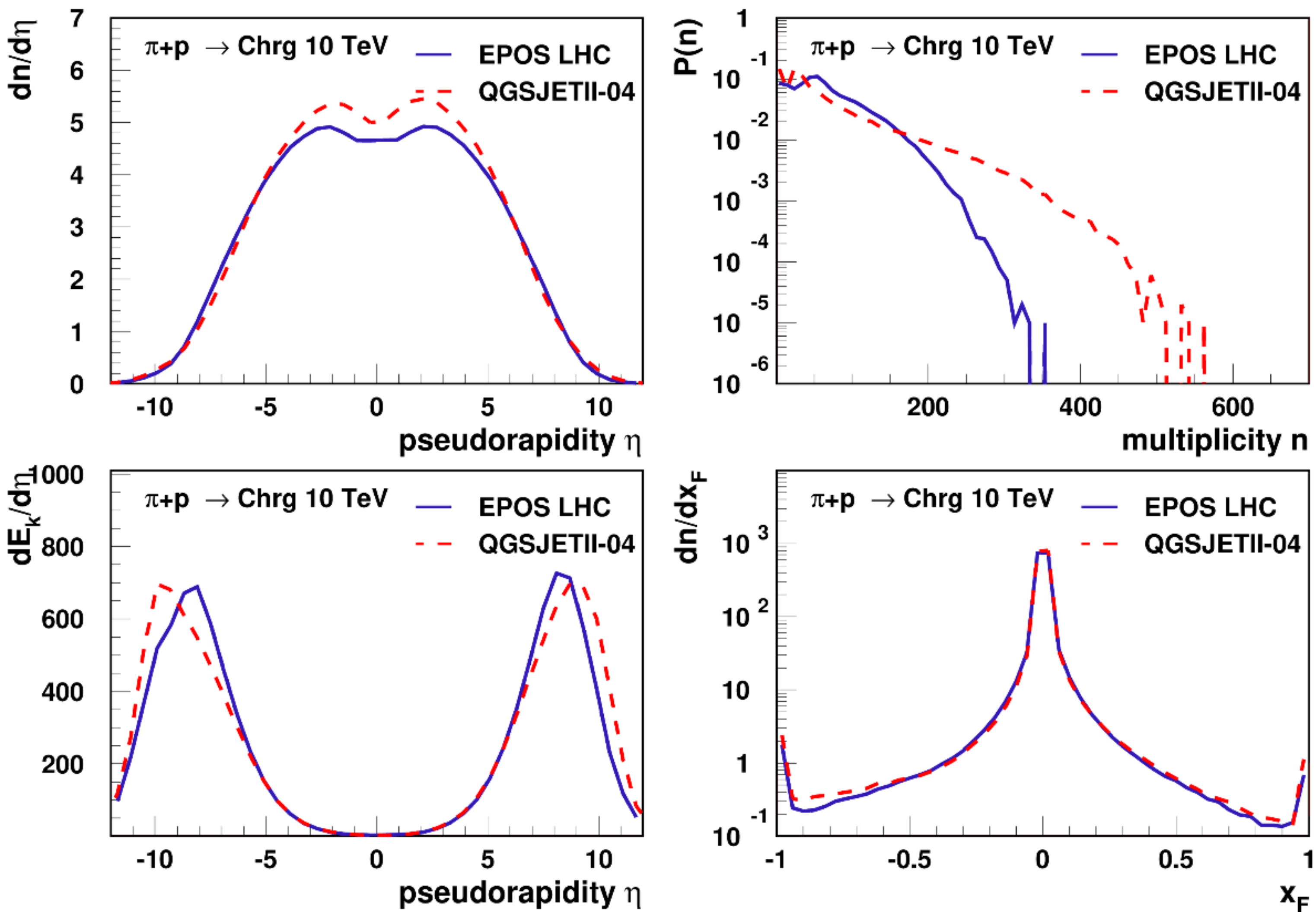


Uncertainties in π+A leads to strong difference between models and with data (lack of muons ? X^{μ}_{max} ...)

Model Predictions π+p @ LHC

Models well constraint by LHC run I for pp

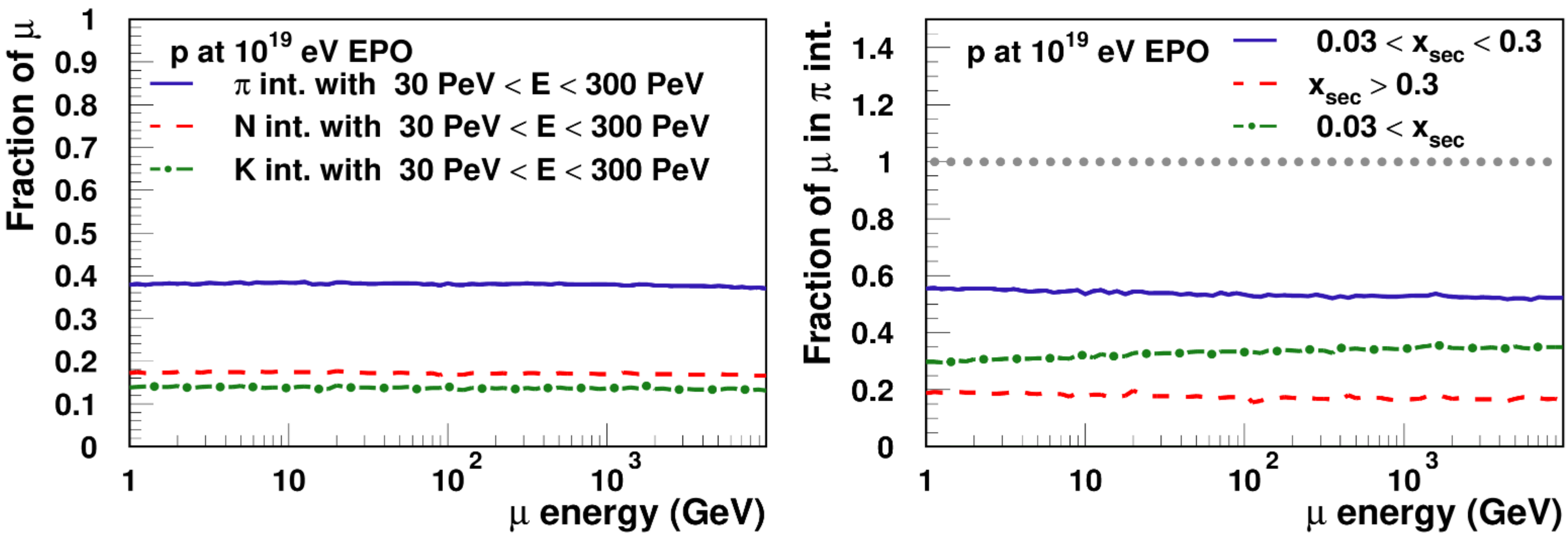
- only small differences in pp model predictions
- main difference in high multiplicity tail
- different behavior for π and p interactions
- larger differences than in pp



LHC and Muon Production

Which phase space is important at LHC for muon production ?

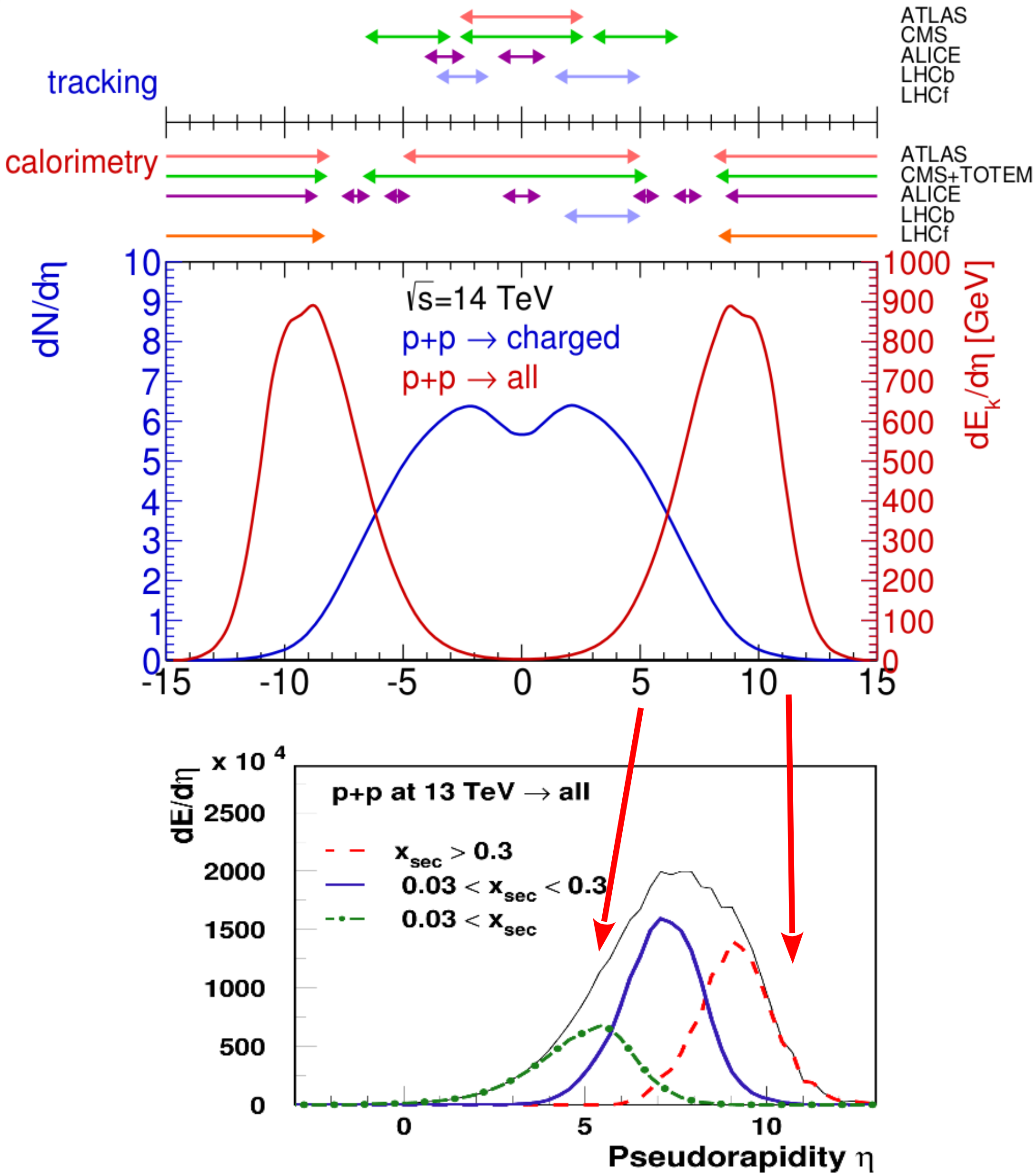
- modify CONEX (EAS simulation) to extract muons produced by subshowers with interaction energy between 30 and 300 PeV (lab ~ LHC cms)



- Muon production dominated by pion interactions

- Muon production depends on secondaries with 0.03 < x < 0.3 from primaries in LHC energy range

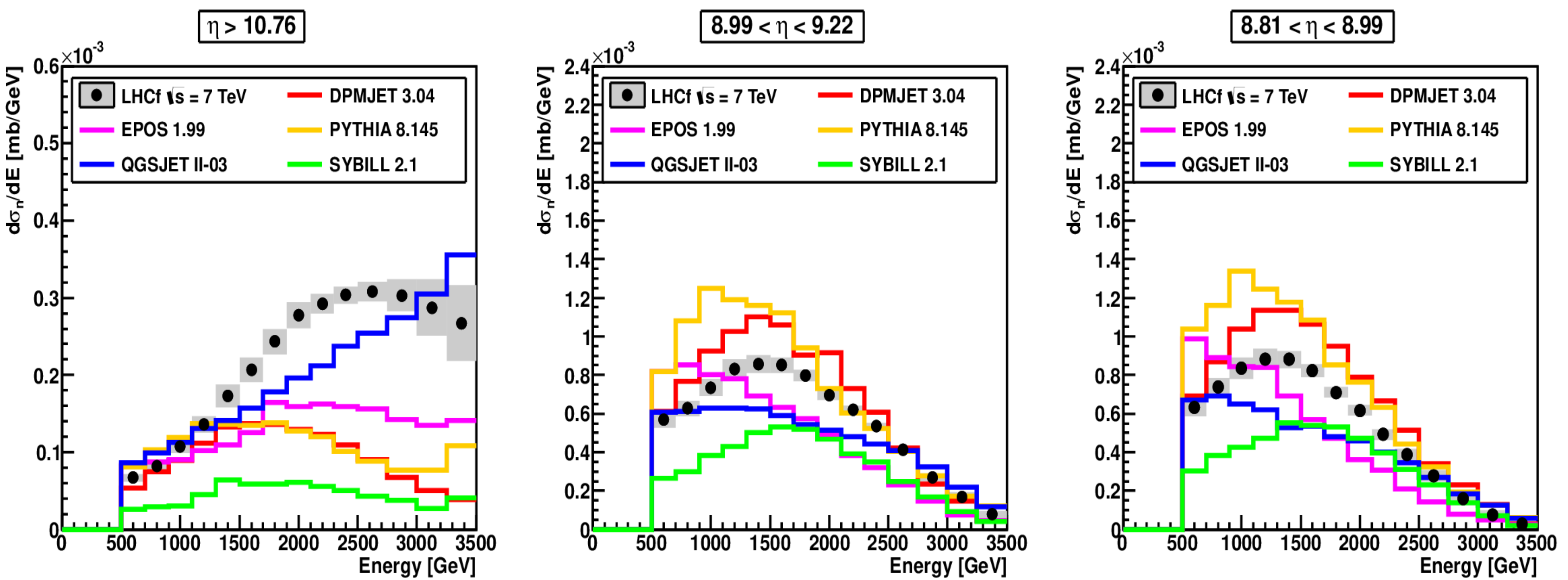
LHC acceptance and Phase Space



- **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

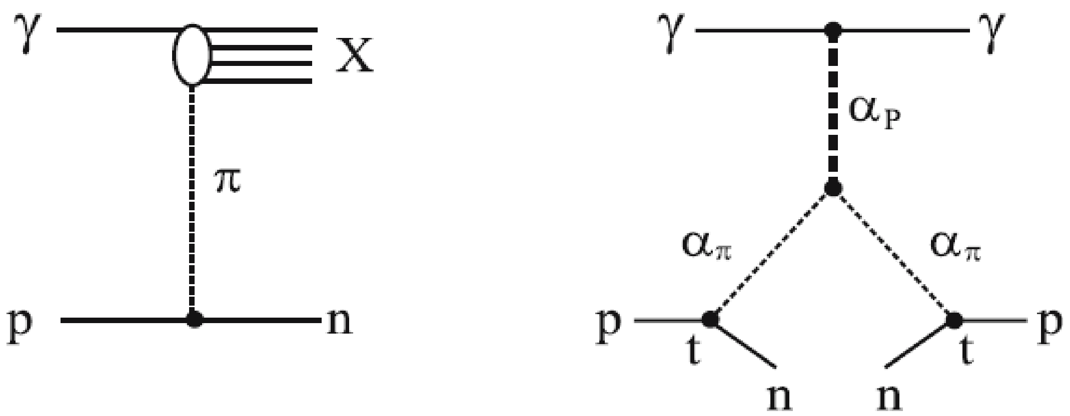
LHCf vs CR Models 7 TeV

- **Reasonable results for γ and π0**
  - 20% to 30% “excess” in models at low energy for gammas
  - large difference between models
- **Stronger deviation for neutrons**
  - Clear “pion exchange” peak (not “really” in the models)



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 with 0 degree calorimeters to measure π+p in central detectors

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

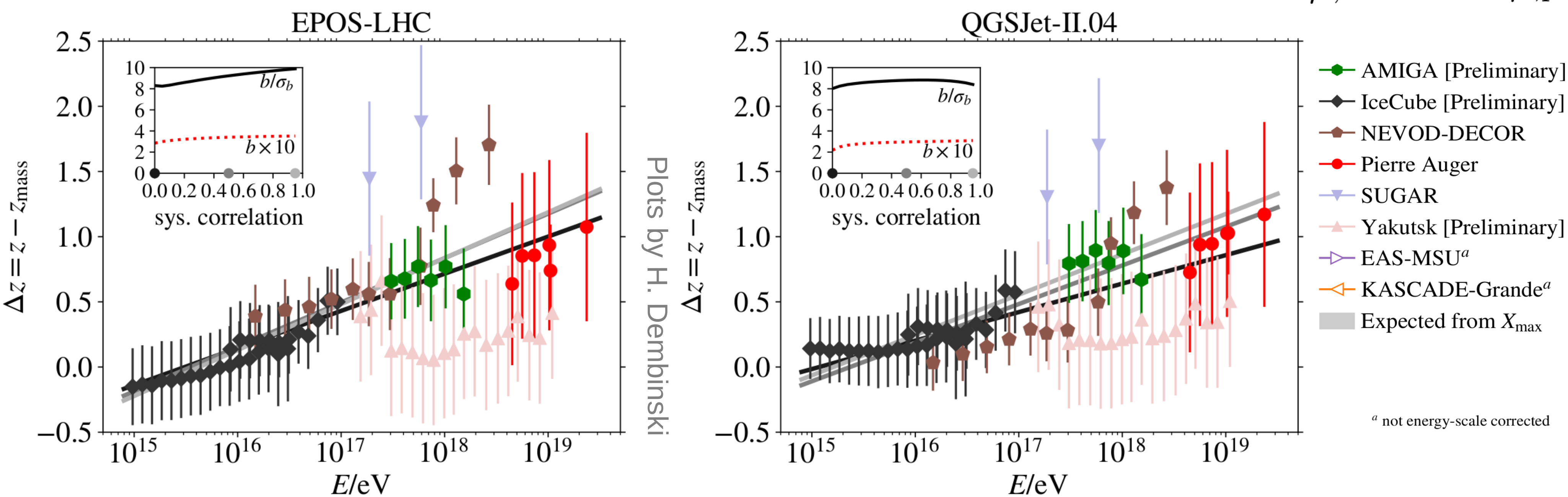
Use same expression and replace γ by p, but different absorptive corrections (smaller rate expected, should be still possible in low-luminosity runs)

R. Engel

Global Picture of Muons from EAS

- **Clear muon excess in data compared to simulation : WHISP 2018**
  - Different energy evolution between data and simulations
    - Significant non-zero slope (>8σ)

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



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

Ref: EPJ Web Conf. 210 (2019) 02004 - arXiv:1902.08124

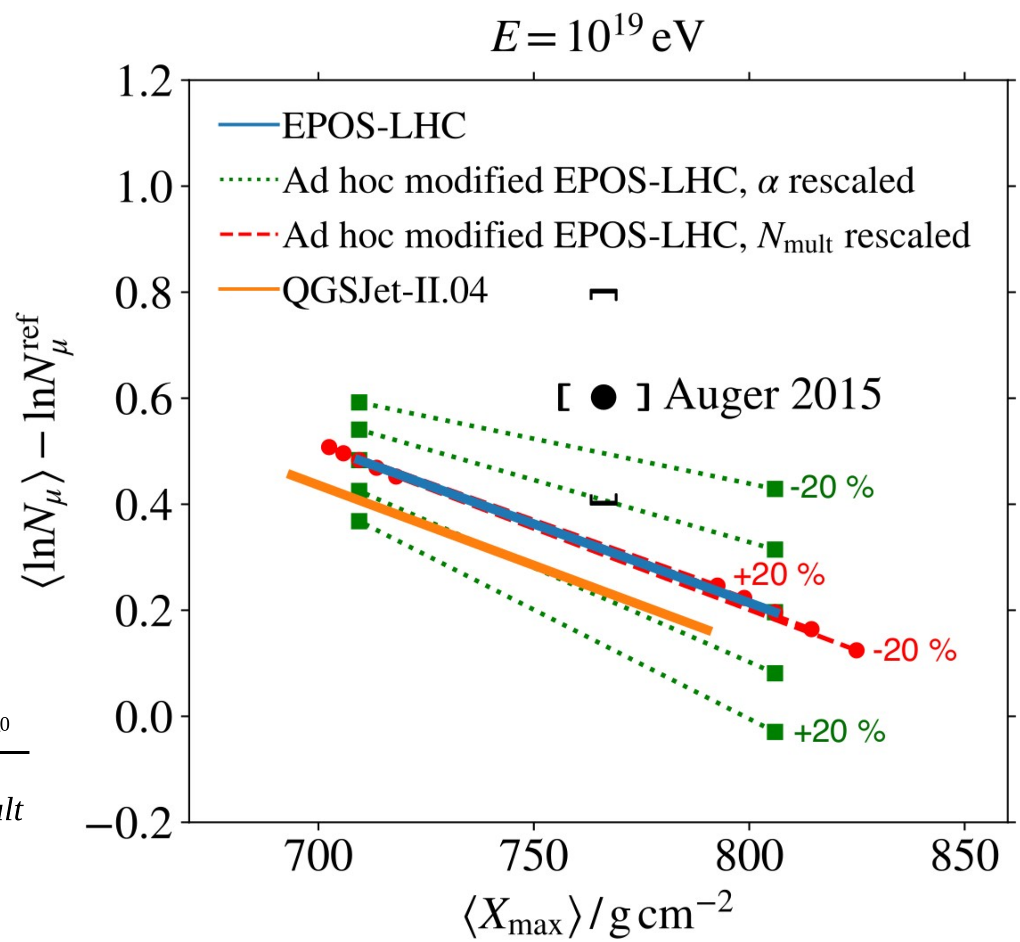
Constraints from Correlated Change

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



Plot by H. Dembinski

Possible Particle Physics Explanations

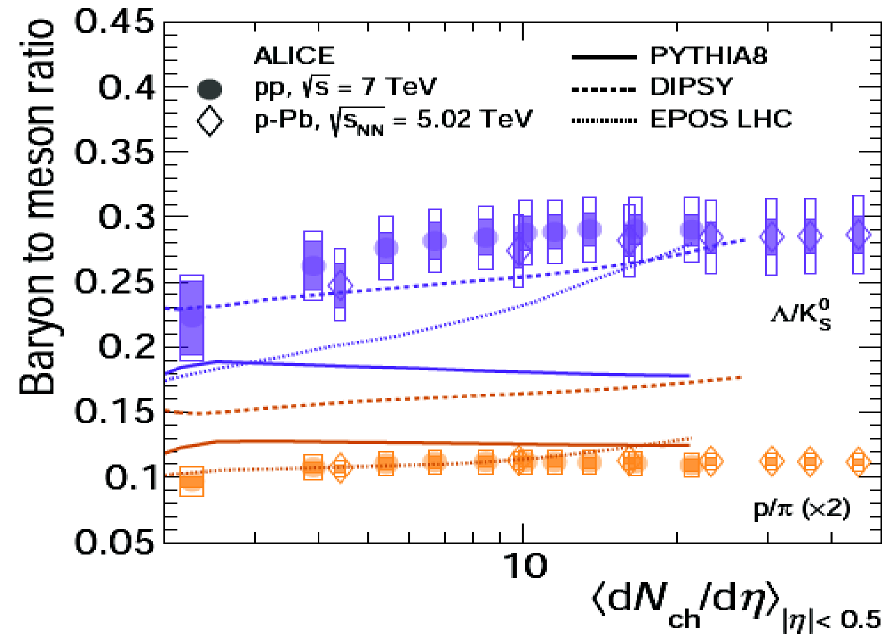
A 30% change in particle charge ratio ($\alpha = \frac{N_{\pi^0}}{N_{mult}}$) is huge !

- 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)

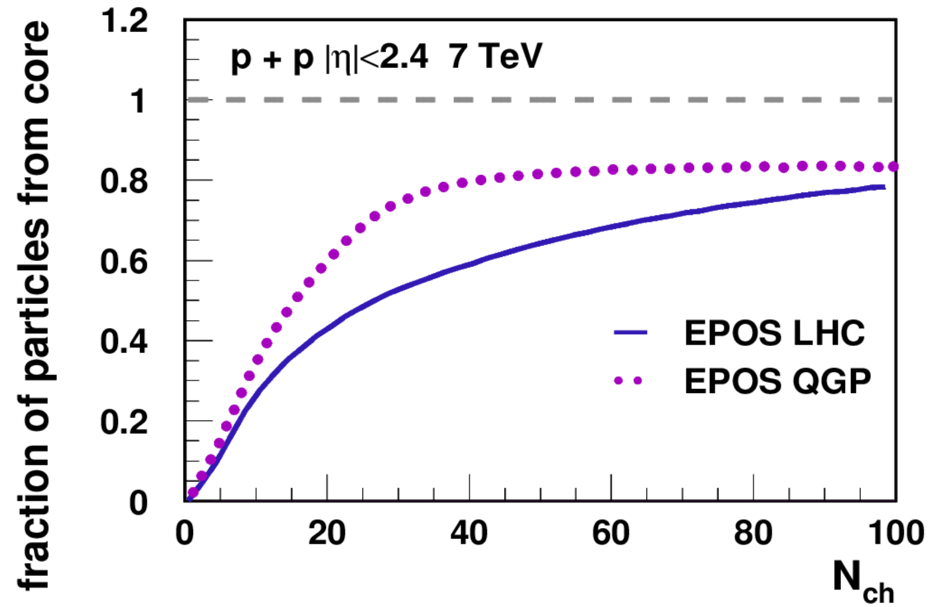
→ Try a modified version of EPOS

Modified EPOS with Extended Core

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



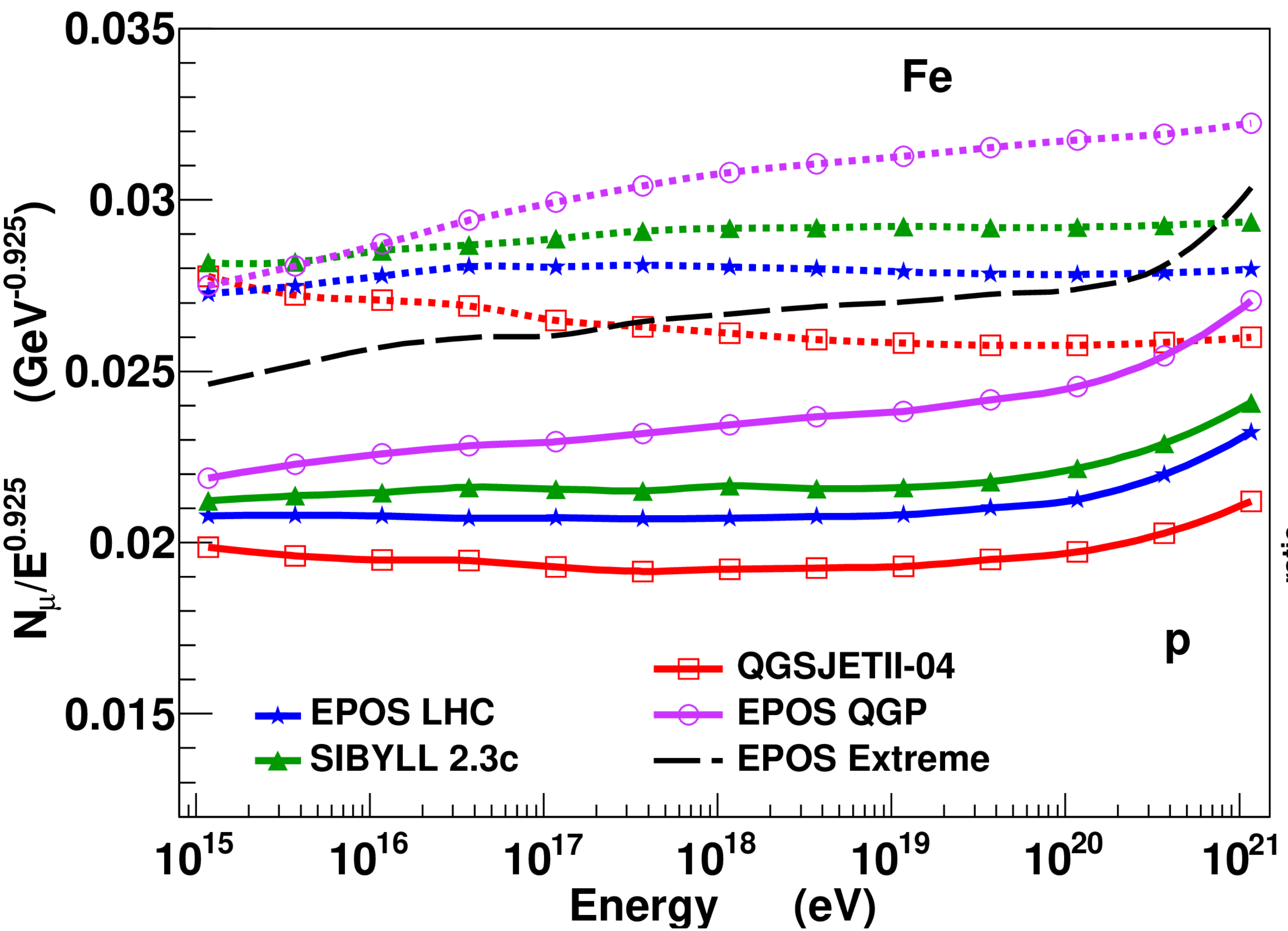
- **Create a new version EPOS QGP with more collective hadronization**
  - Core created at lower energy density
  - More remnant hadronized with collective hadronization
  - Collective hadronization using grand canonical ensemble instead of microcanonical (closer to statistical decay)

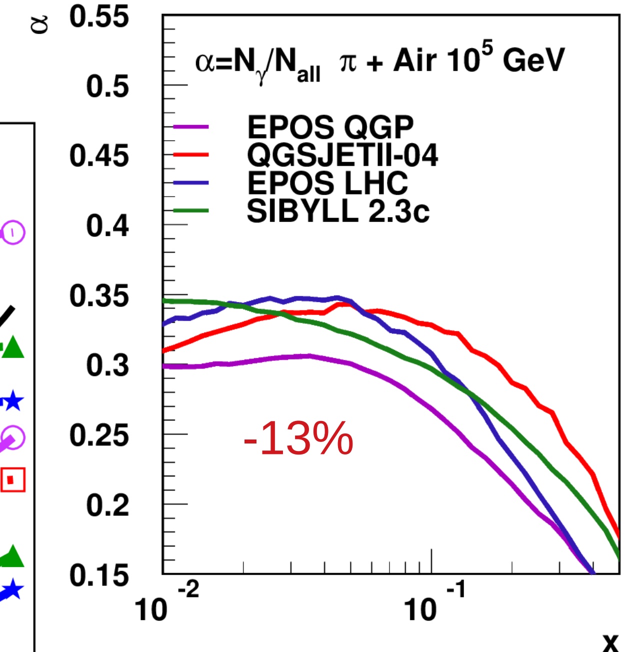


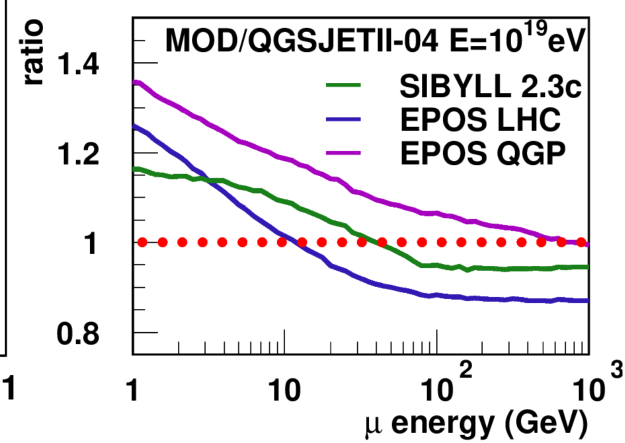
Results for Air Showers

Large change of the number of muons at ground

- Different slope as expected from the change in α



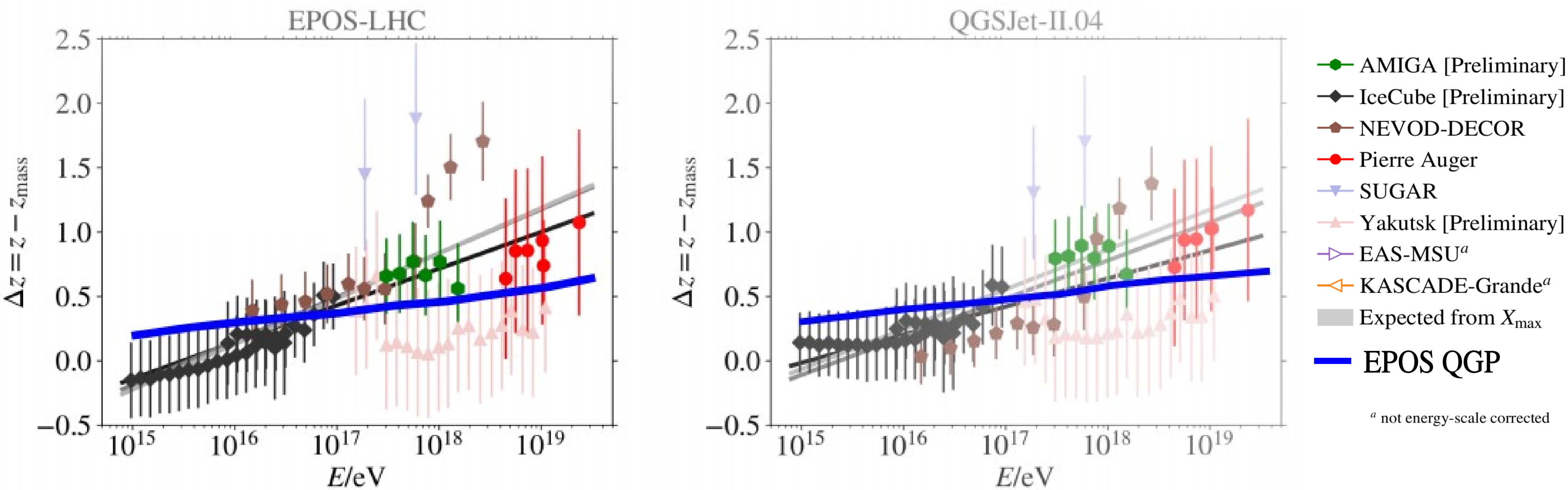




Comparison with Data

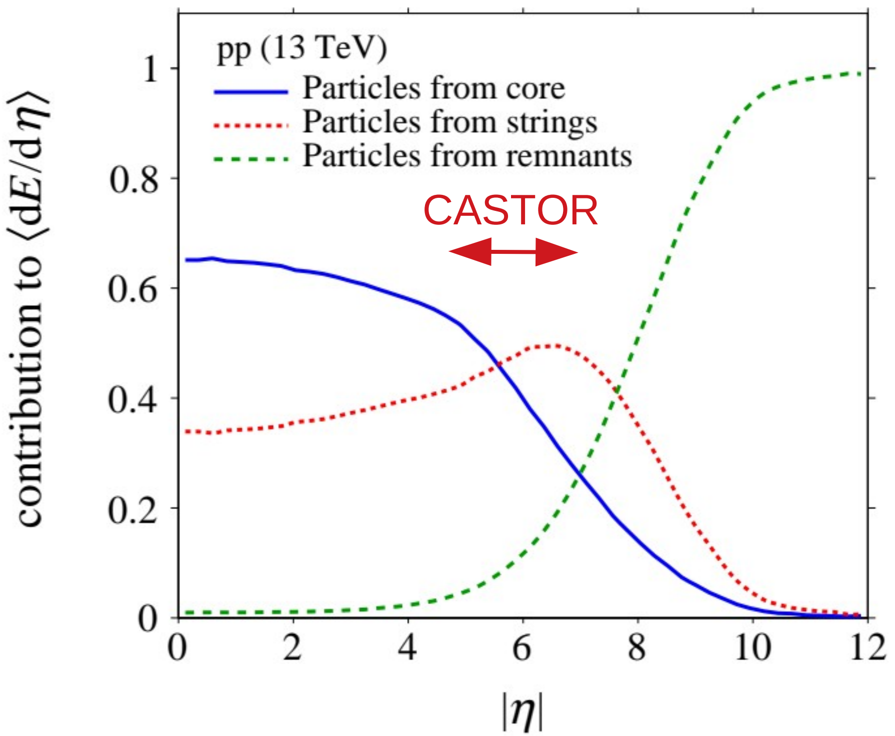
- **Collective hadronization gives a result compatible with data**
  - Still different energy evolution between data and simulations
    - Significance to be tested

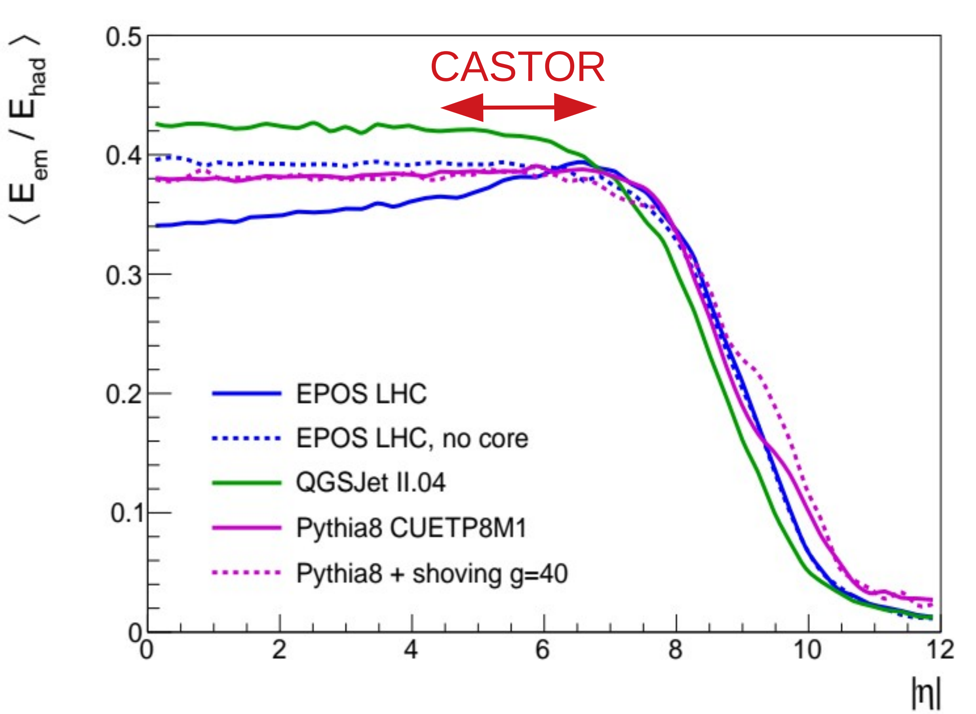
$$z = \frac{\ln N_{\mu}^{\text{det}} - \ln N_{\mu,p}^{\text{det}}}{\ln N_{\mu,\text{Fe}}^{\text{det}} - \ln N_{\mu,p}^{\text{det}}}$$



- **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.) ?

Test Effect of Collective Hadronization





- Reduced α is a sign of QGP formation (Baur et al. ArXiv:1902.09265) !
  - Problem : α changed at most by 20% for μ_B=0
  - Behavior α at different μ_B?
- Possible test using forward (and central) calorimeters at LHC
  - forward/backward asymmetry and centrality evolution

Summary

Cosmic Ray data analysis rely on air shower simulations

- hadronic models main source of uncertainty
- forward physics lead air shower development
- pion interaction very important for muon production

Zero degree calorimeter based analysis

- possibility to select pion exchange type of interactions: test pion interaction at very high energy for the first time !

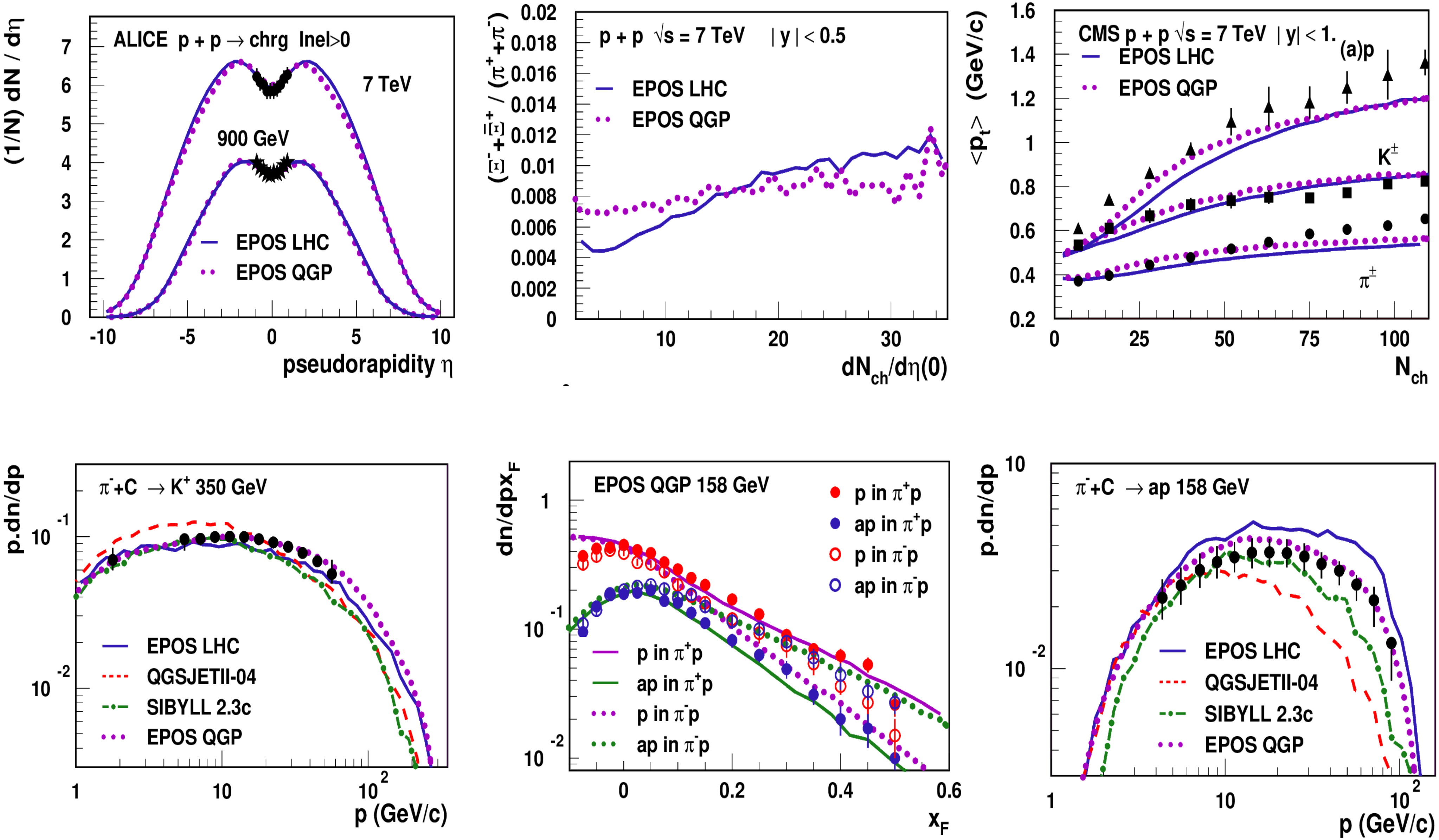
Compilation of all muon measurements clearly indicate a different slope for muon production as a function of shower energy

- Different hadronization required (less neutral pions / other particles)
- Collective hadronization in small system / forward in line with LHC results ?
- Probe new area in quark matter phase diagram ?

Combination of forward and central calorimetric measurements to probe hadronization

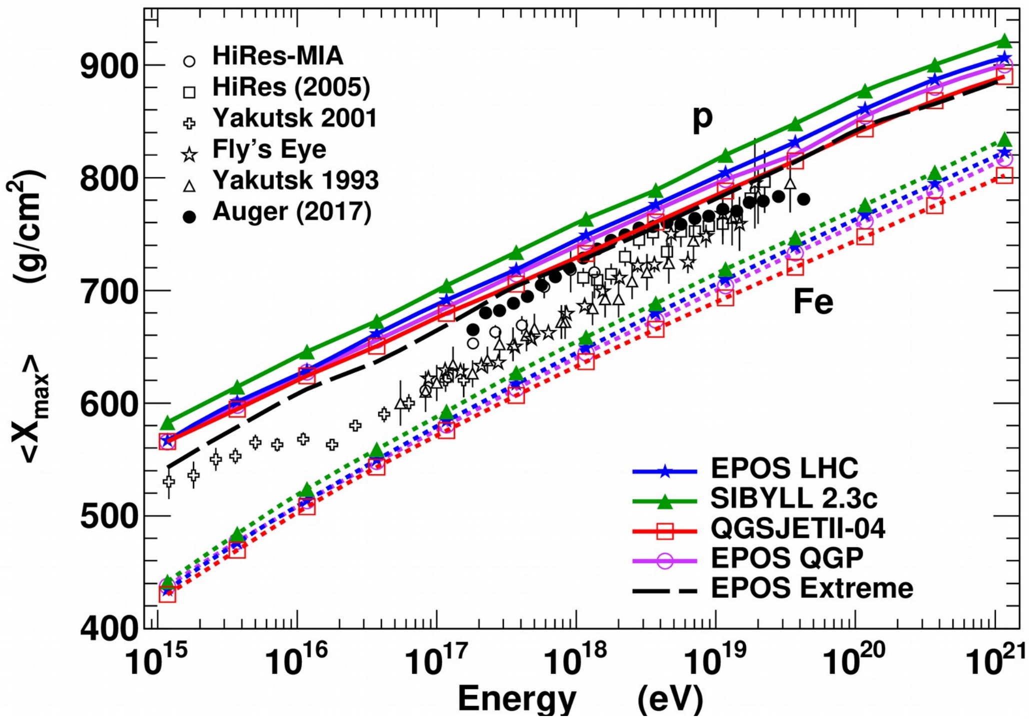
- Test forward extension of collective hadronization !

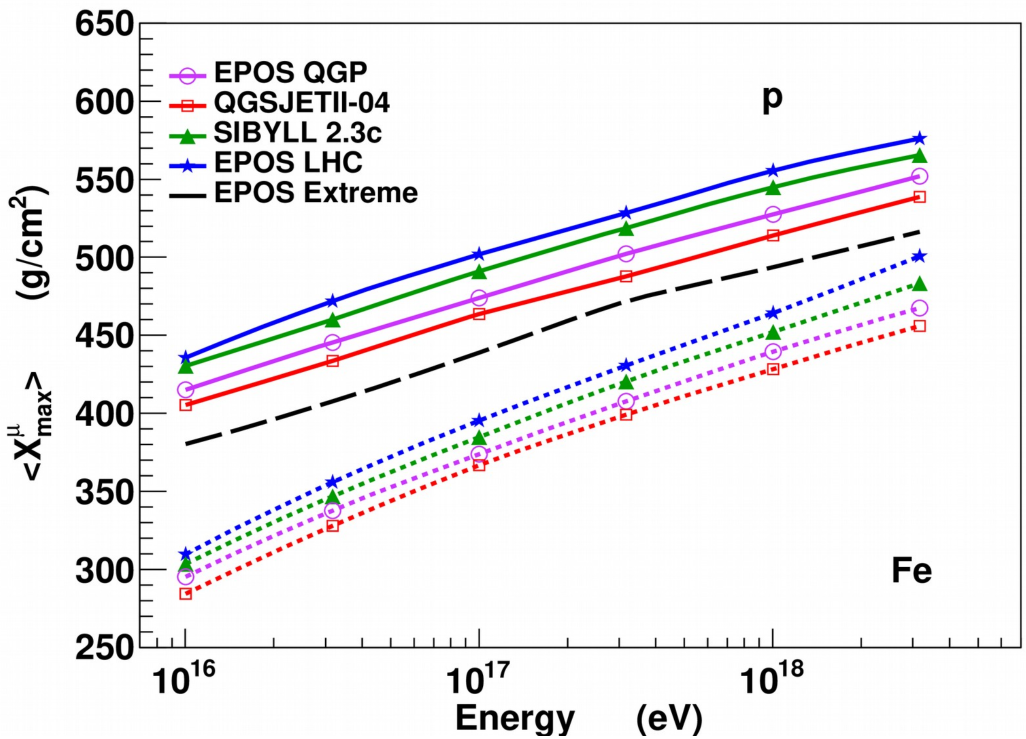
Preliminary Version with Minimum Constraints



Results for Air Showers

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





Model predictions for p+p

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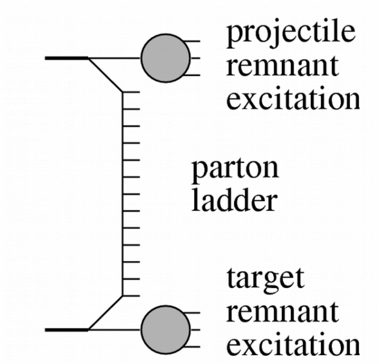
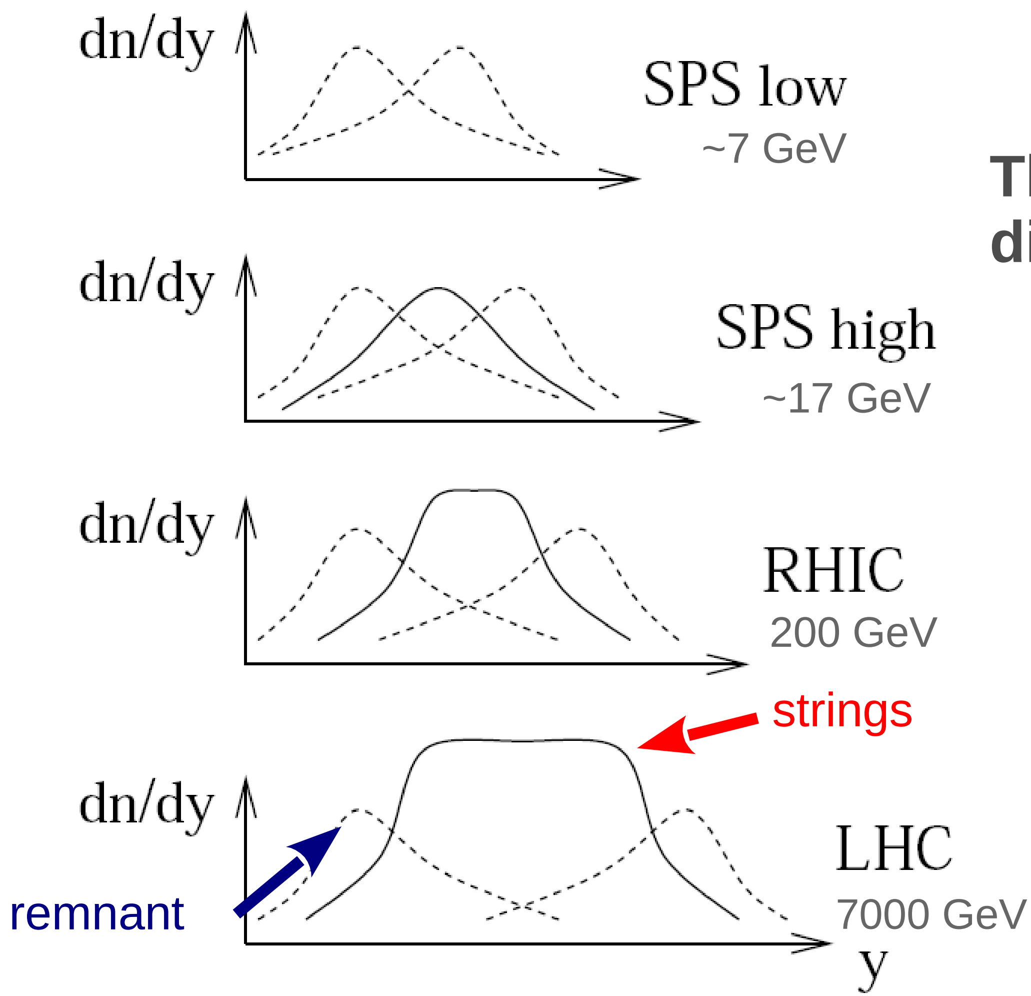
Remnants

Forward particles mainly from projectile remnant





The (in)elasticity is closely related to diffraction and forward spectra

- At very low energy only particles from remnants
- At low energy (fixed target experiments) (SPS) strong mixing
- At intermediate energy (RHIC) mainly string contribution at mid-rapidity with tail of remnants.
- At high energy (LHC) only strings at mid-rapidity (baryon free)

Source Contributions in LHCf (Neutron)