Collective hadronization and air showers: can LHC data solve the muon puzzle ?

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Outline

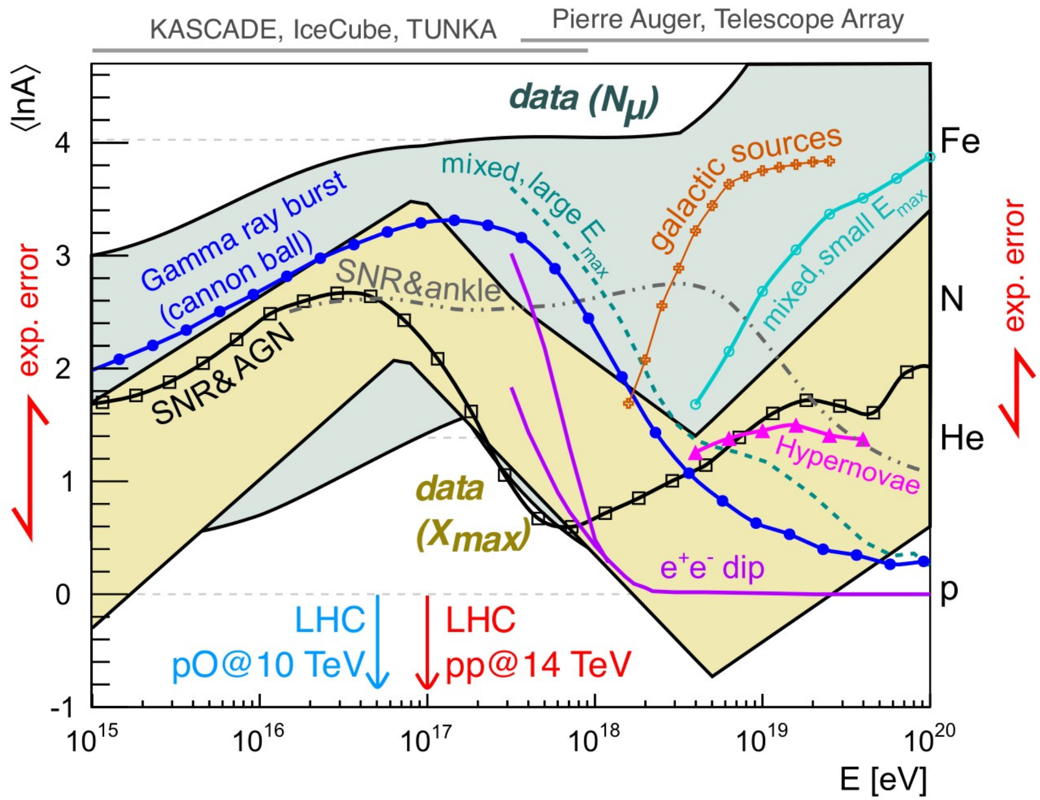
- Muons in Extensive Air Showers (EAS)
- Muon puzzle
- Quark Gluon Plasma (QGP) and EAS
- Summary

The energy evolution of muon production require a different hadronization than the one observed in vacuum. Latest LHC results indicate that a collective hadronization, with property closer to what is needed for EAS, is more frequent than traditionally thought.

UHECR Composition

With muons, current CR data are impossible to interpret

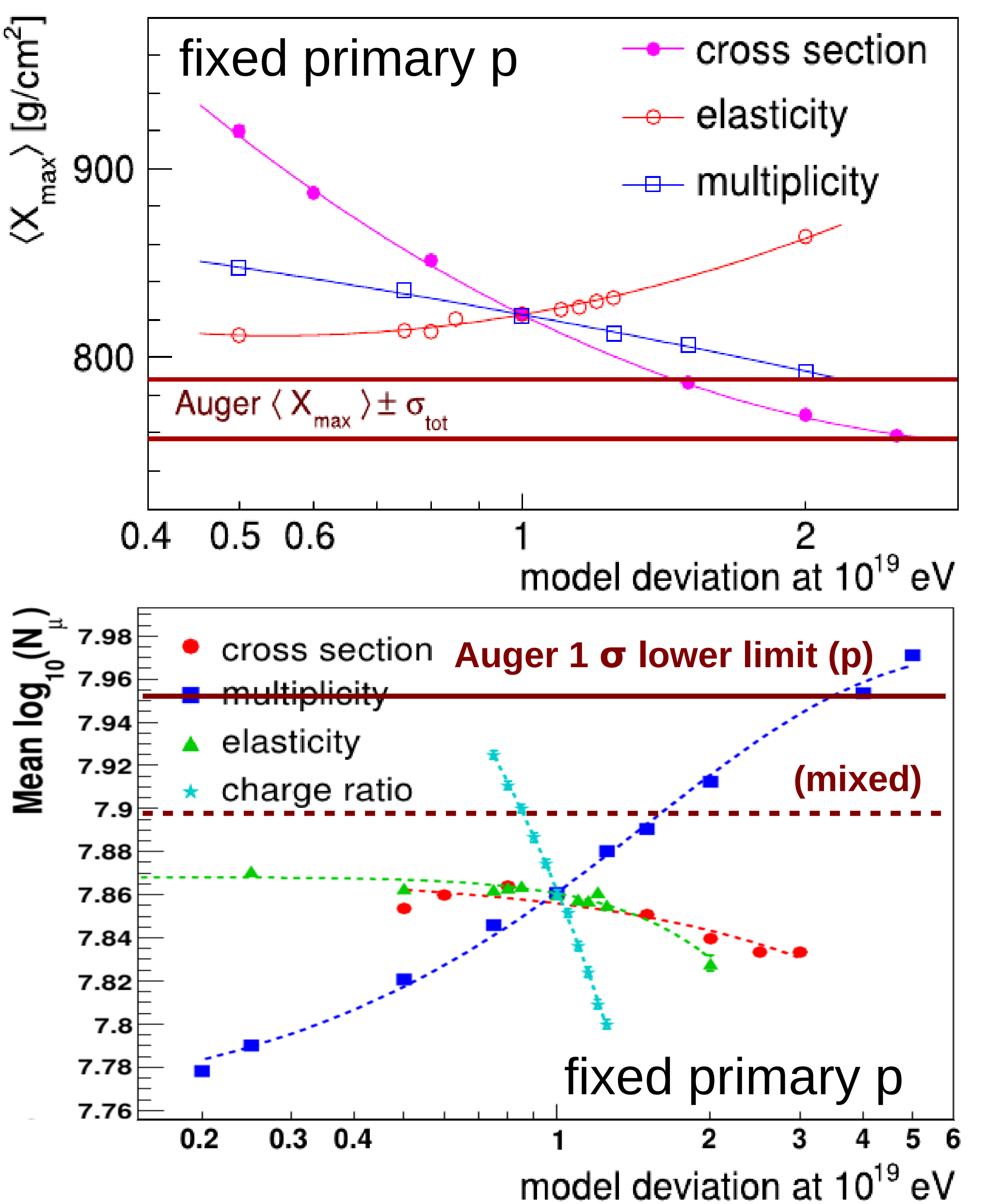
- ➡ Very large uncertainties in model predictions
- ➡ Mass from muon data incompatible with mass from X_{max}



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

H. Dembinski UHECR 2018 (WHISP working group)

Sensitivity to Hadronic Interactions



From R. Ulrich (KIT)

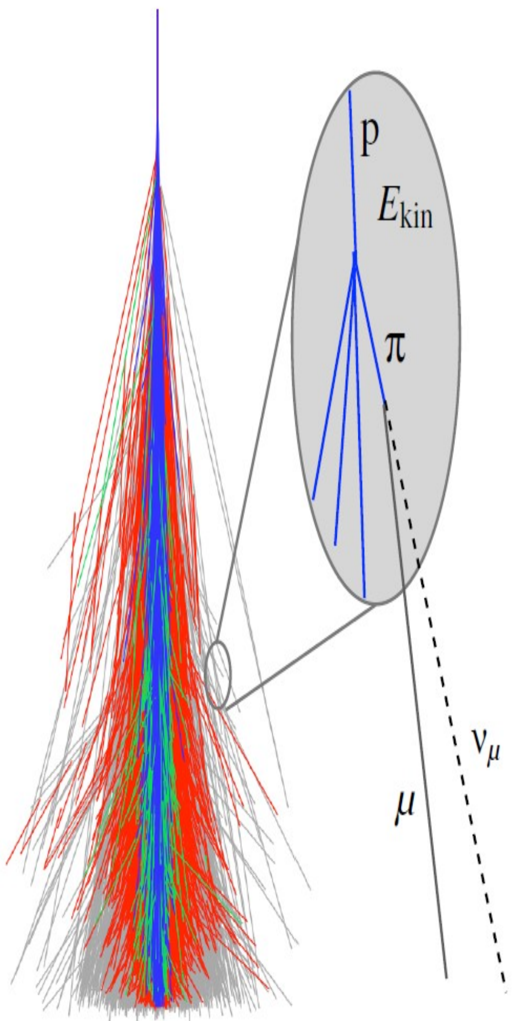
- **Air shower development dominated by few parameters**
  - ➜ mass and energy of primary CR
  - ➜ cross-sections (p-Air and (π-K)-Air)
  - ➜ (in)elasticity
  - ➜ multiplicity
  - ➜ charge ratio and baryon production
- **Change of primary = change of hadronic interaction parameters**
  - ➜ cross-section,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

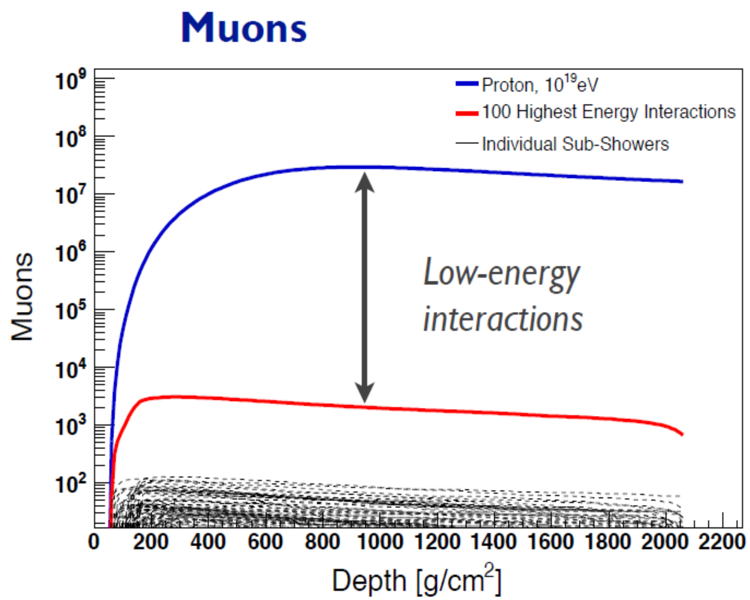
Precise prediction of air shower simulations require precise measurement of hadronic interactions properties :

Need for p(π)-O measurements

See H. Dembinski (CRI6b, Sat)

Muon production by low energy interactions

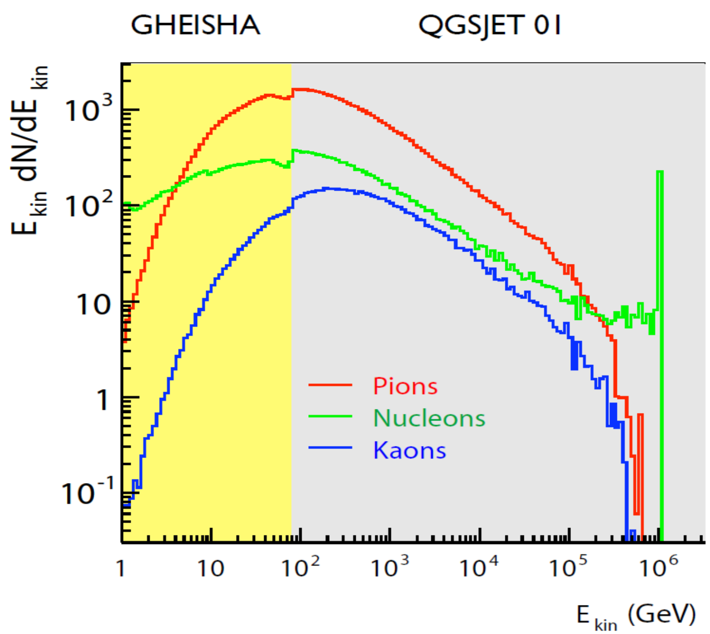


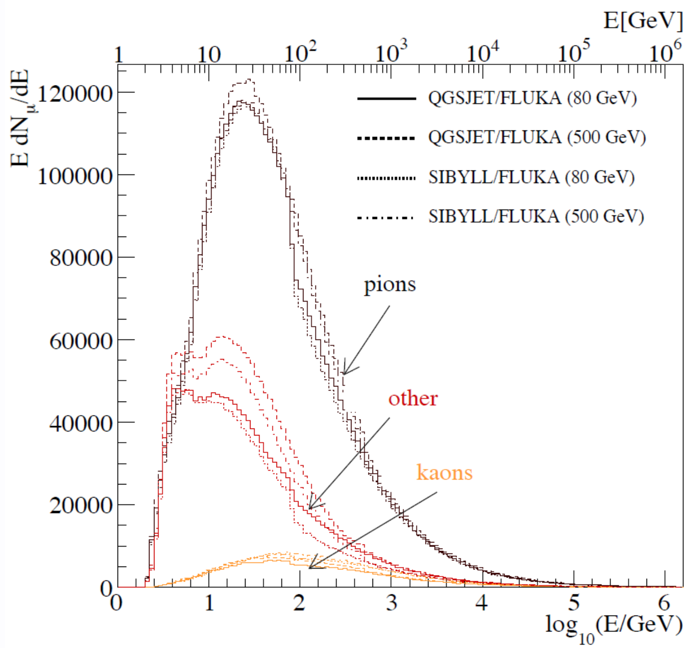


~ 100 GeV for KASCADE
~ 30 GeV for Auger

After a long chain of interactions

Muons/hadrons:
low-energy interactions

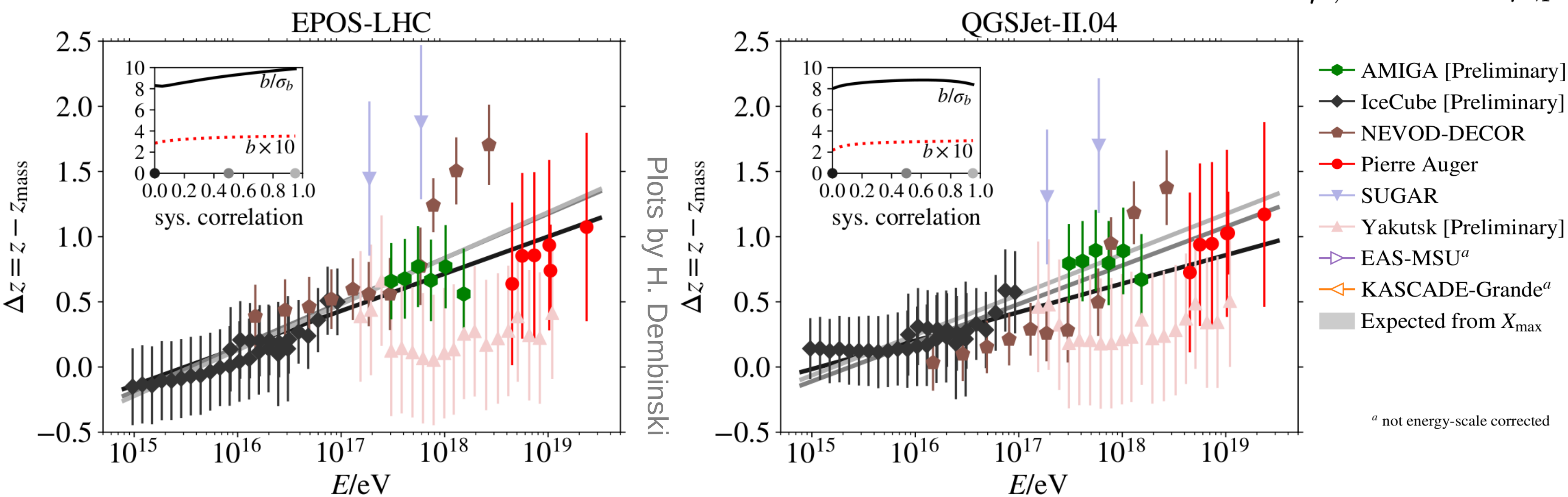




Global Picture of Muons from EAS

- **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

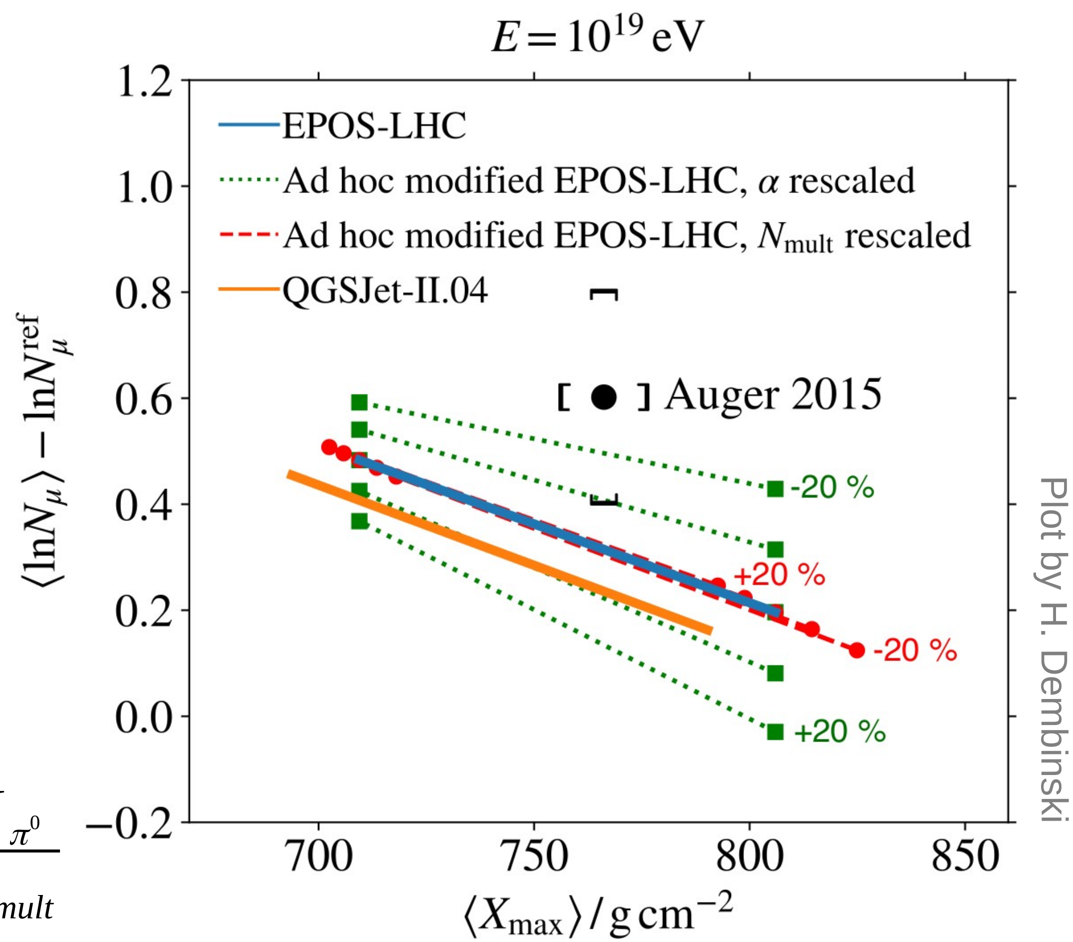
Ref: EPJ Web Conf. 210 (2019) 02004 - arXiv:1902.08124 – see Lorenzo Cazon (CRI15e, Wed) for details

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}



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

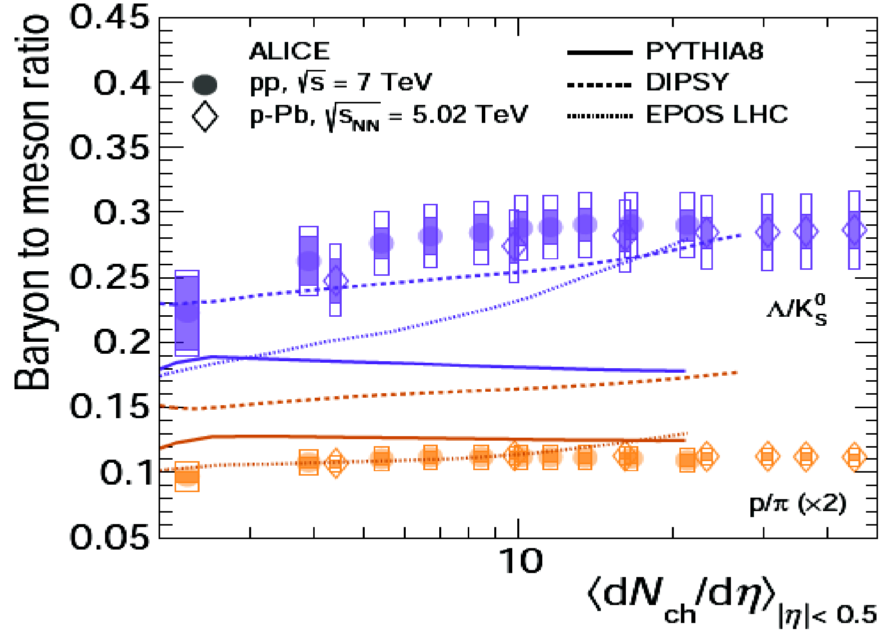
Possible Particle Physics Explanations

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

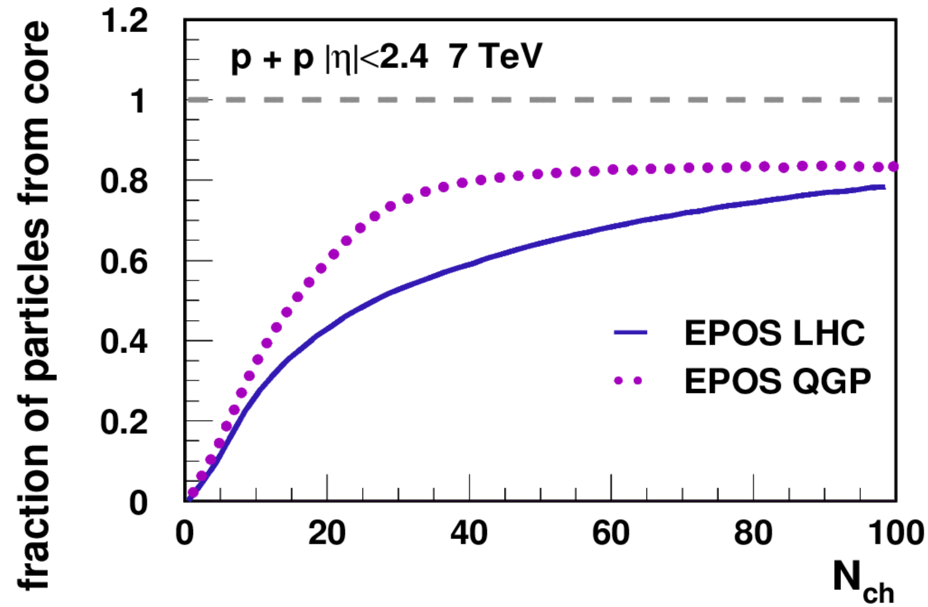
- Possibility to increase N_{mult} limited by X_{max}
- New Physics ?
  - Chiral symmetry restoration (Farrar et al.) ?
  - Strange fireball (Anchordoqui et al.) ?
  - String Fusion (Alvarez-Muniz et al.) ?
    - Problem : no strong effect observed at LHC (~10^{17} eV)
- Unexpected production of Quark Gluon Plasma (QGP) in light systems observed at the LHC ? (at least modified hadronization)
  - Reduced α is a sign of QGP formation (Baur et al., arXiv:1902.09265 and CRI6d) !
    - More strangeness and more baryons so less pions = smaller α
  - Not properly done in EPOS LHC (QGP only in extreme conditions)
    - Try a modified (test) 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

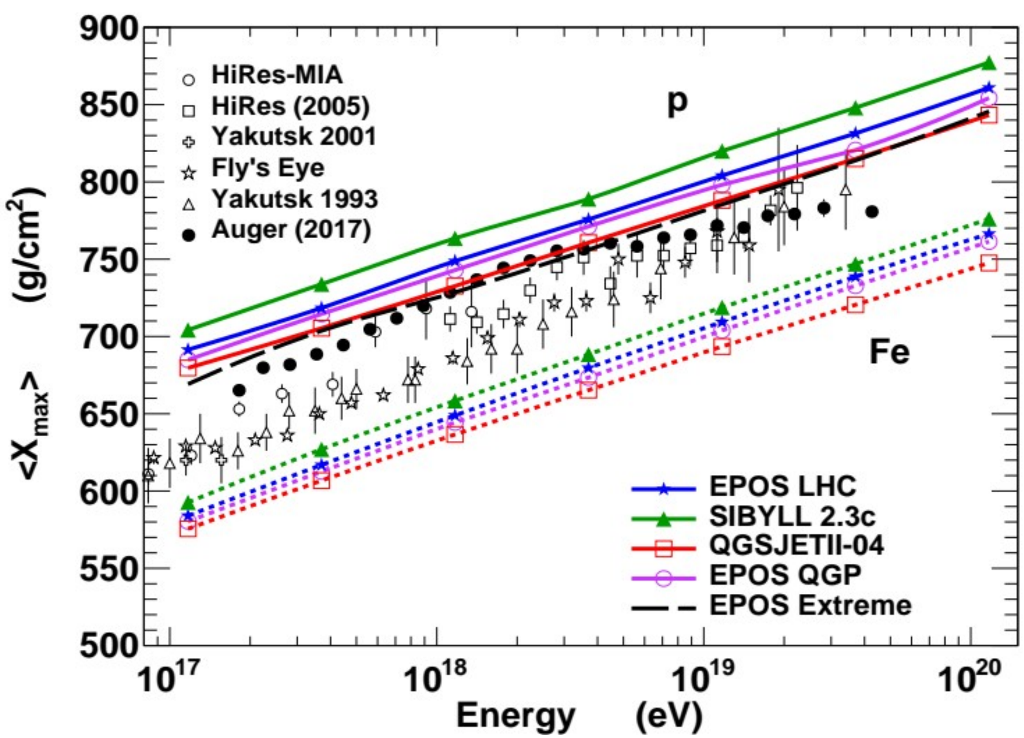


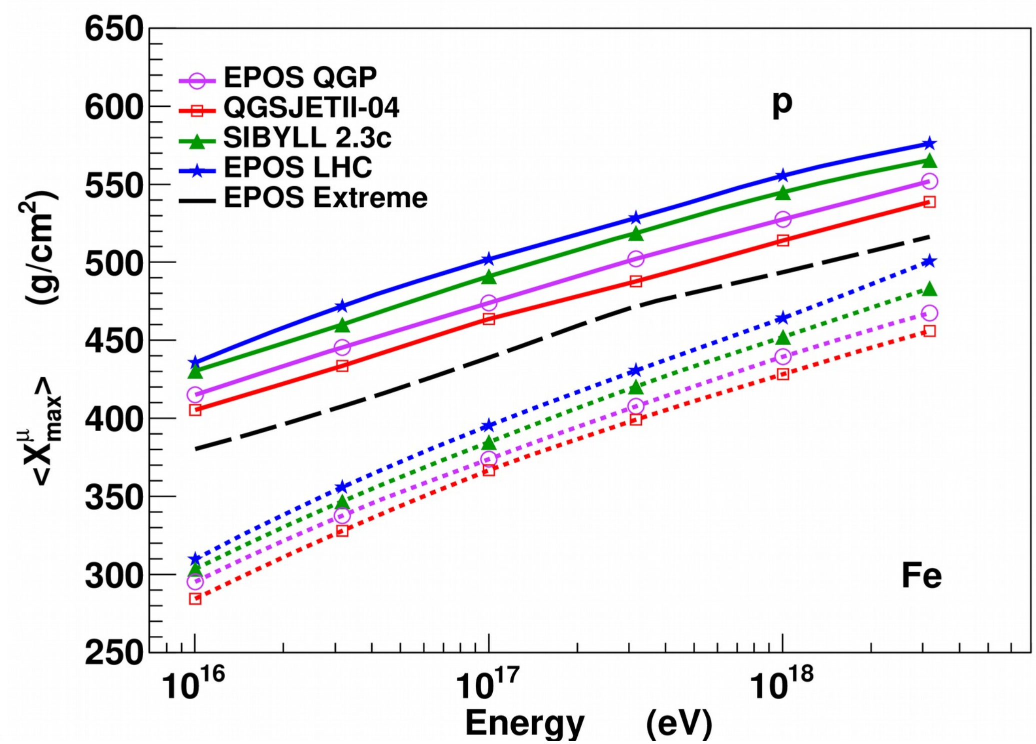
- **Create a new version EPOS QGP with more collective hadronization**
  - ➜ Core created at lower energy density
  - ➜ More remnant hadronized with collective hadronization
  - ➜ Collective hadronization using grand canonical ensemble instead of microcanonical (closer to statistical decay)



Results for Air Showers

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

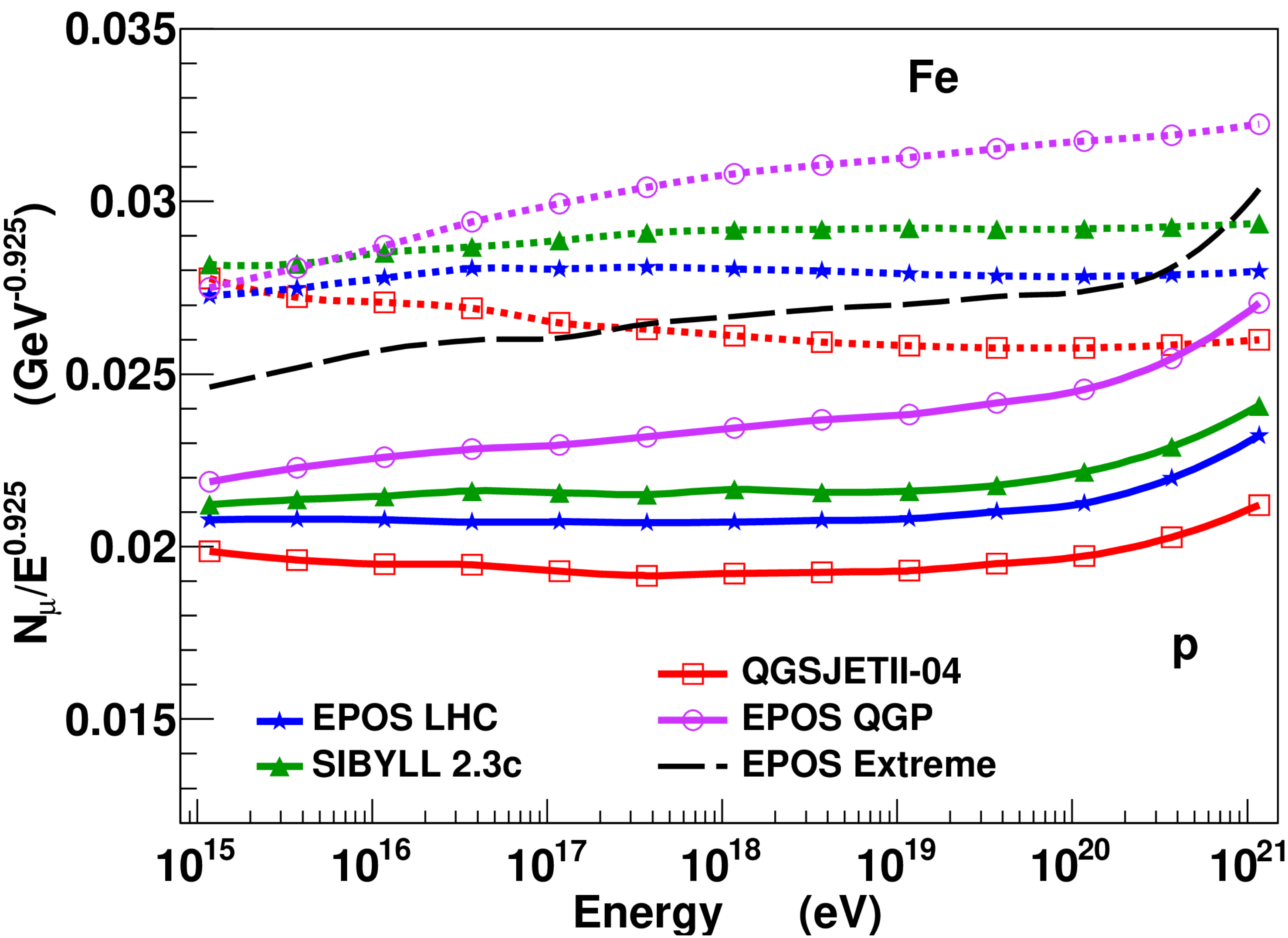


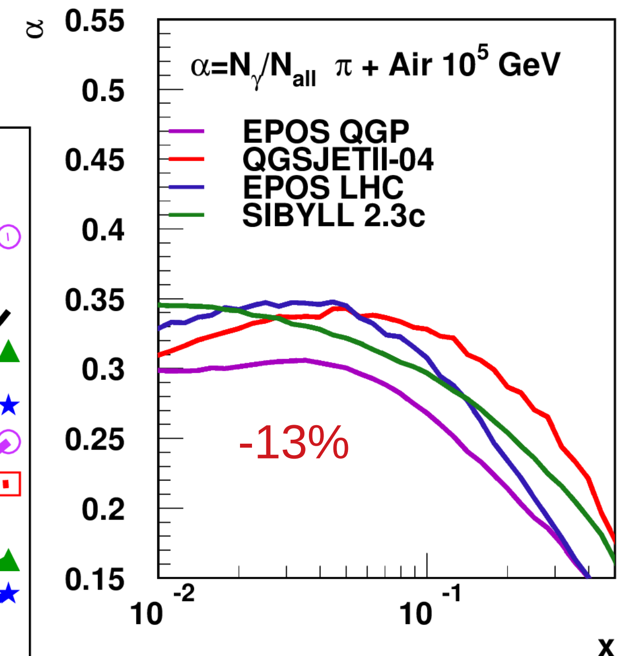


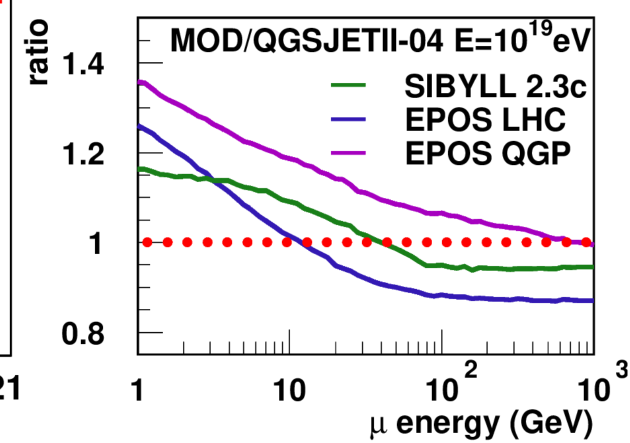
Results for Air Showers

Large change of the number of muons at ground

➡ Different slope as expected from the change in α







Comparison with Data

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

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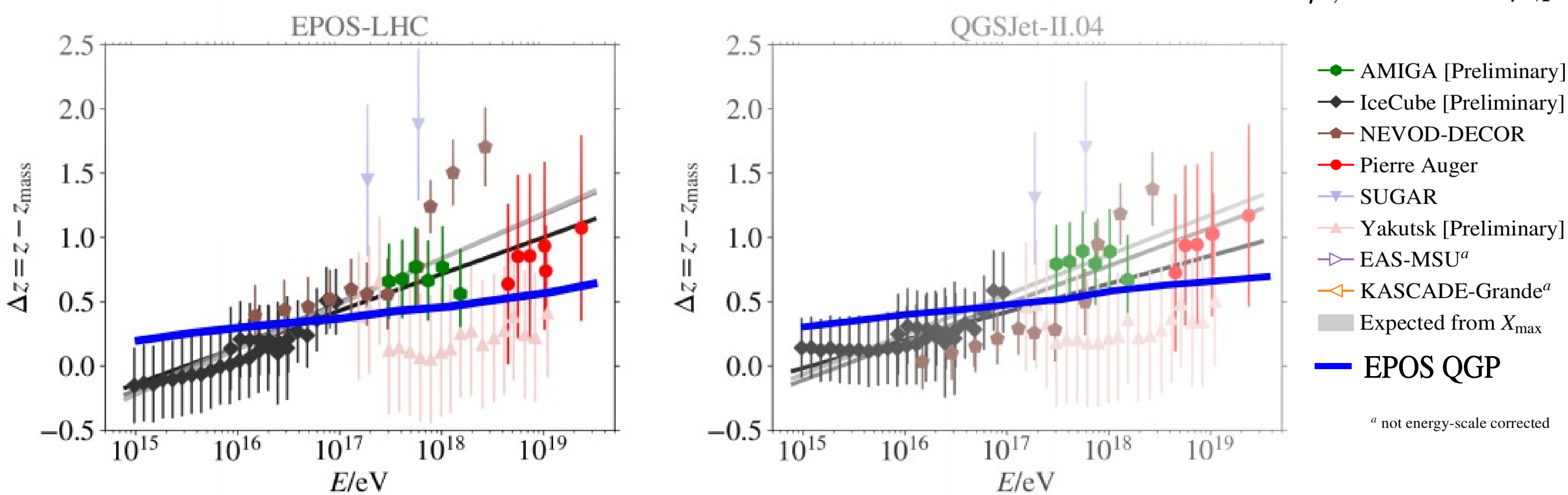


- **Probably tension at low energy (too many muons)**
  - ➡ Ideally a larger slope would be needed … what kind of hadronization possible ?
  - ➡ QGP with large chemical potential for nuclear CR (Anchordoqui et al.) ?

Summary

Cosmic Ray data analysis rely on air shower simulations

- ➡ hadronic models main source of uncertainty
- ➡ forward physics lead air shower development

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

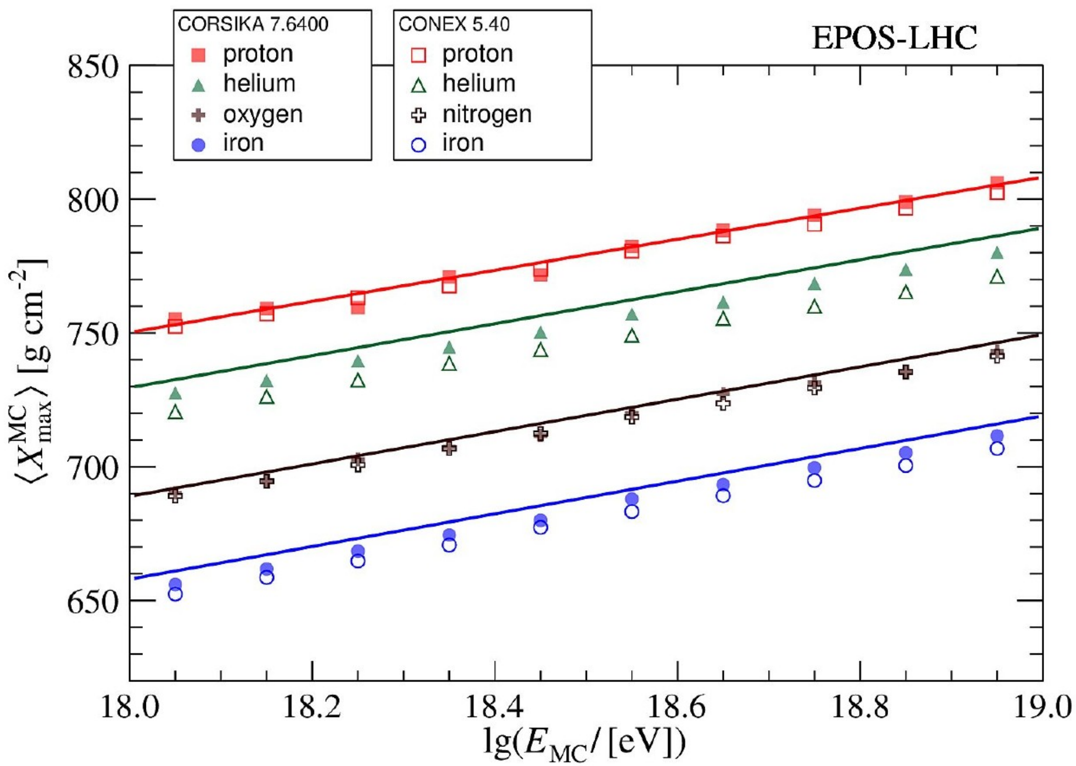
- ➡ Different hadronization required (less neutral pions / other particles)
- ➡ Collective hadronization in small system / forward in line with LHC results ?
- ➡ Probe new area in quark matter phase diagram ?
- ➡ Combination of forward and central calorimetric measurements to probe hadronization

➡ Test forward extension of collective hadronization !

The energy evolution of muon production require a different hadronization than the one observed in vacuum. Latest LHC results indicate that a collective hadronization, with property closer to what is needed for EAS, is more frequent than traditionally thought.

Comment on “problem” with EPOS LHC in CORSIKA

Discrepency observed in CONEX/CORSIKA X_{max} simulation with EPOS LHC in particular for Helium projectile :

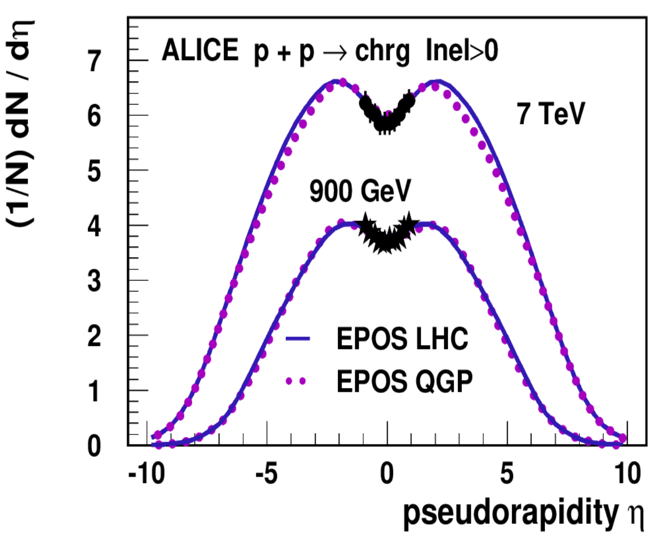


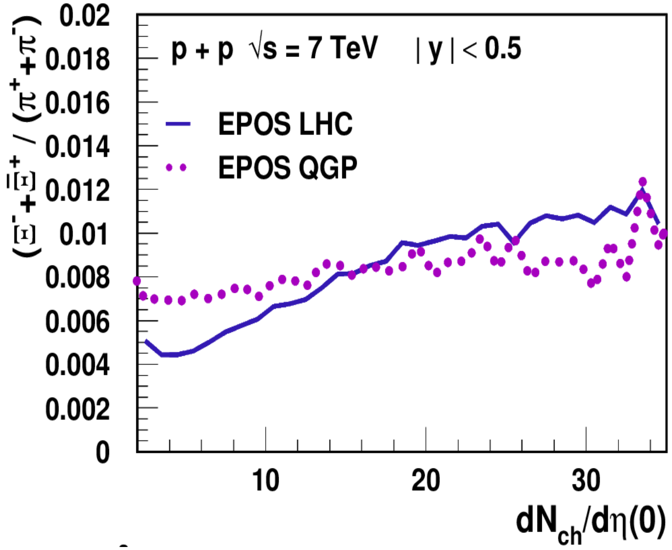
Plot from TA collaboration (William Hanlon)

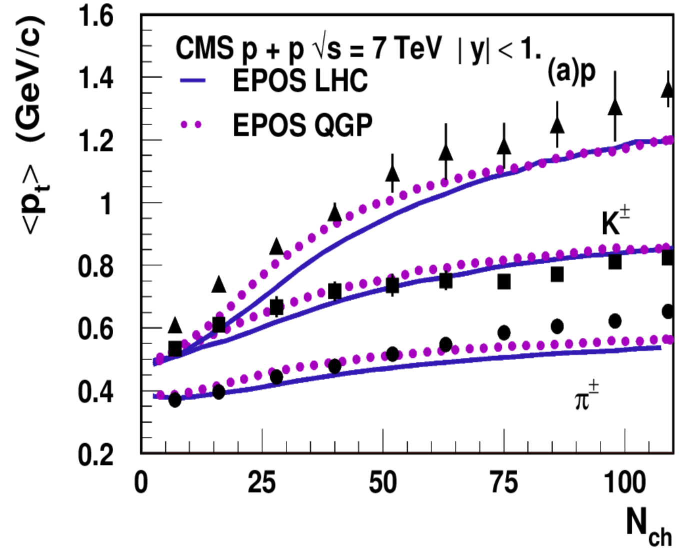
Lines from TA with CORSIKA

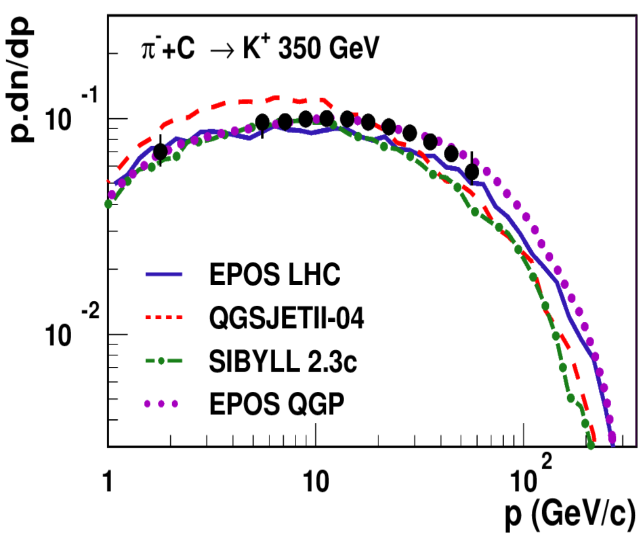
- CONEX uses the true cross-section from the model, while CORSIKA use a Glauber based calculation for the nuclear cross-section (for all models)
- Effect visible mostly in He for EPOS LHC (non Glauber like cross-section)
- Source of additional difference for TA simulations (line) unknown

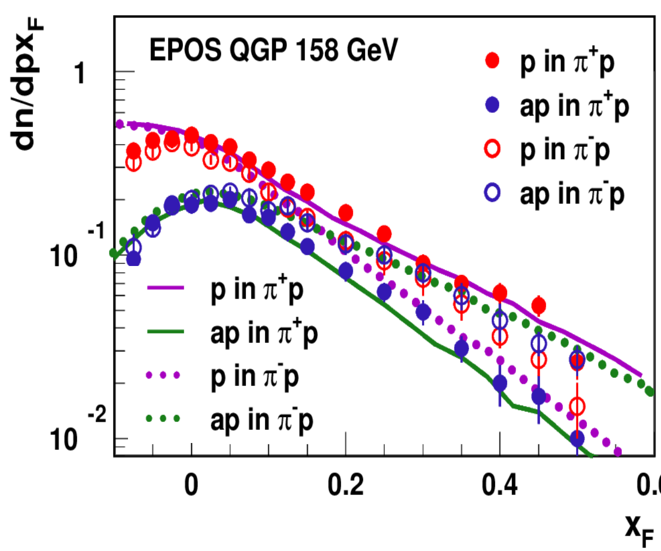
Preliminary Version with Minimum Constraints

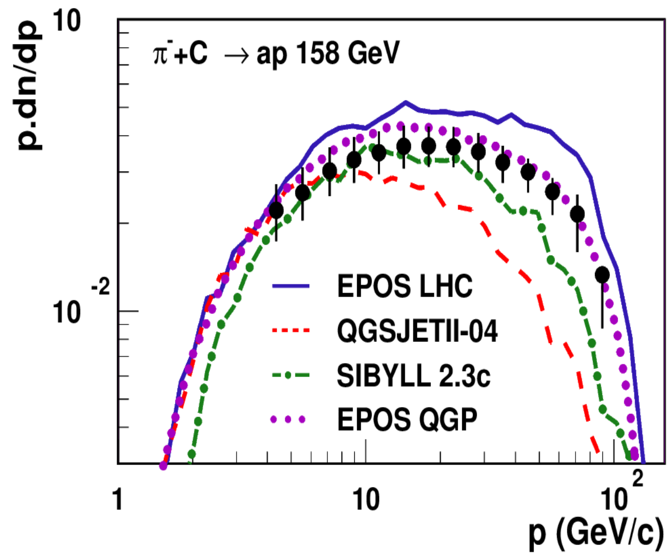




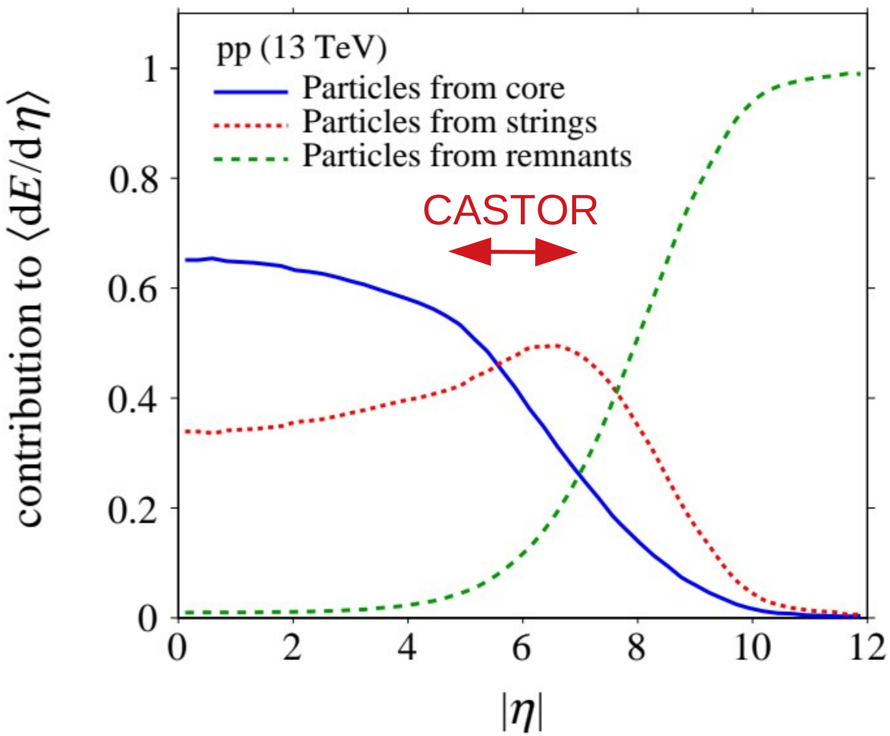


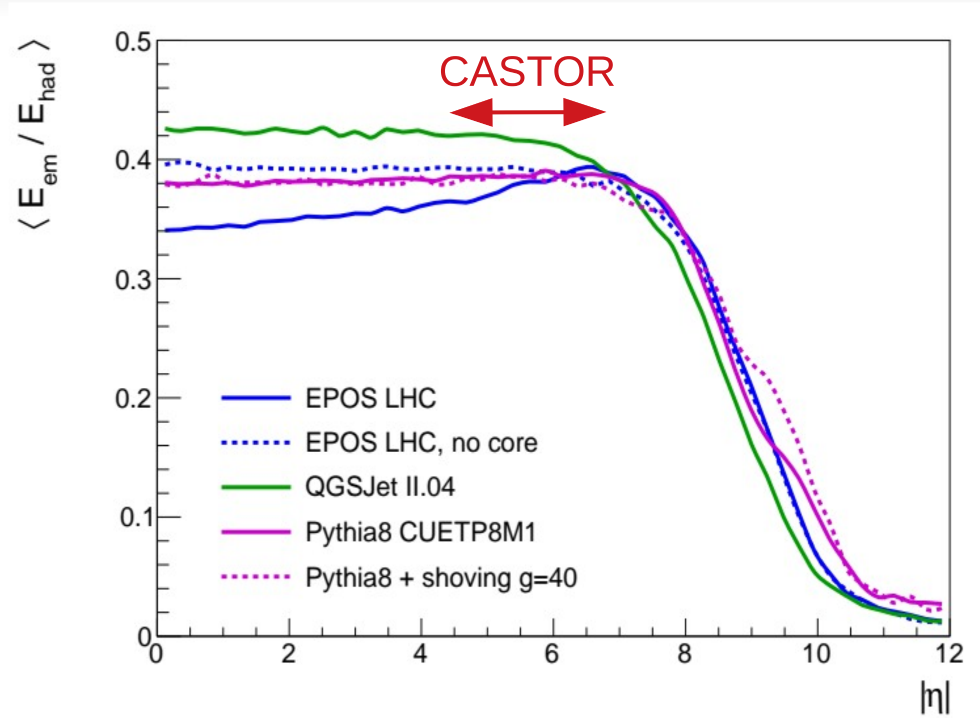






Test Effect of Collective Hadronization





- 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