When heavy ions meet cosmic rays : potential impact of QGP formation on the muon puzzle

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Outline

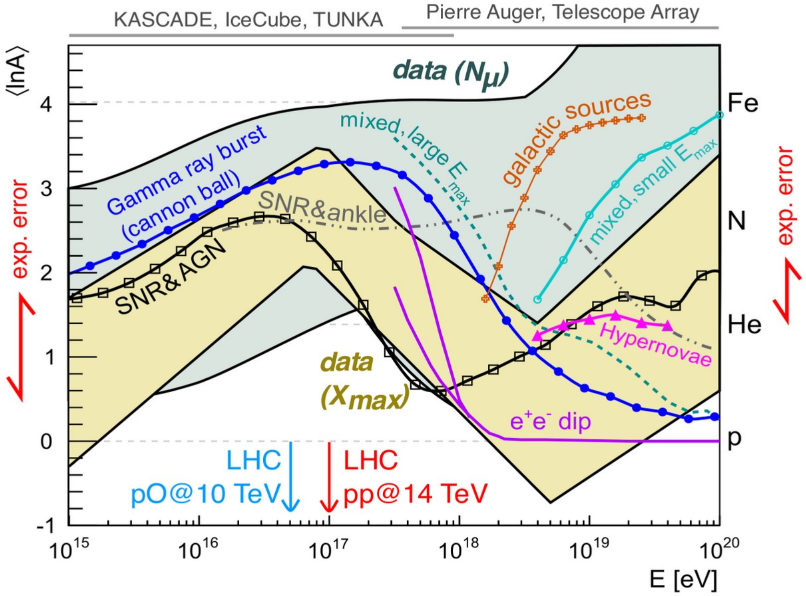
- **Introduction**
- **Hadronization and Extended Air Showers (EAS)**
- **Core-Corona model**

New input from LHC crucial to reproduce EAS data consistently: collective effects in light system may bring a solution for the muon puzzle.

Ultra High Energy Cosmic Ray 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)

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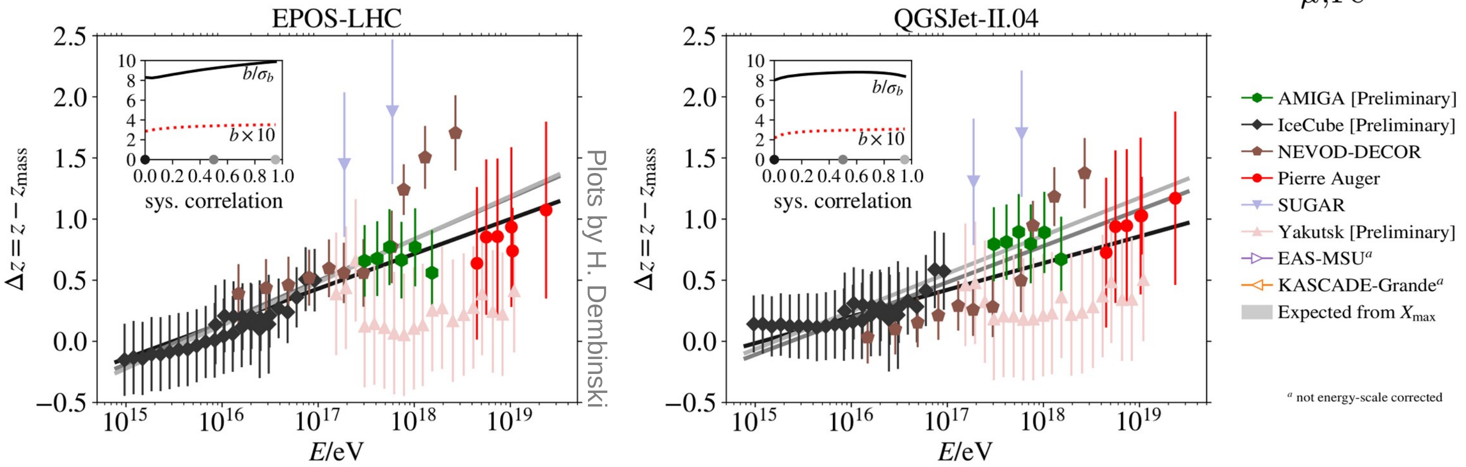
Global Behavior

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

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



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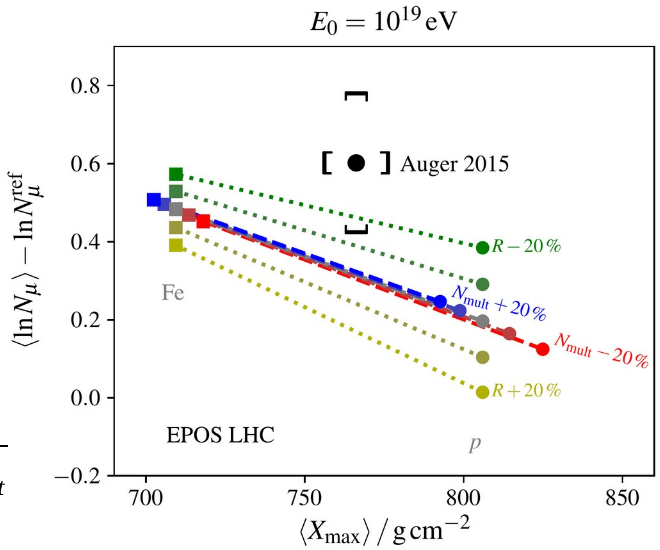
- **Different energy or mass scale cannot change the slope**
  - Different property of hadronic interactions at least above 10^{16} eV

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}

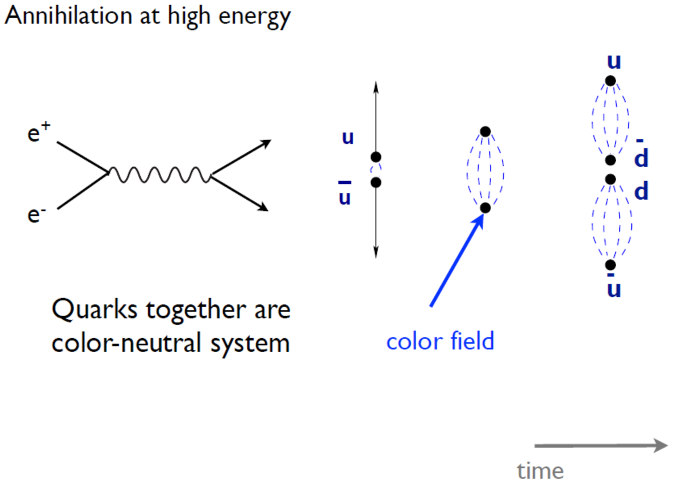


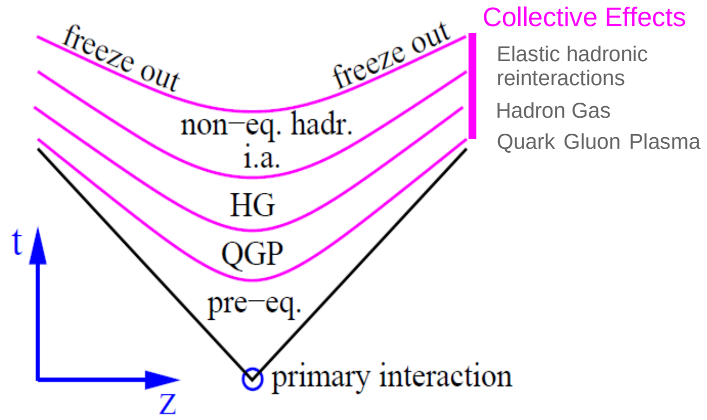
- $$\beta = \frac{\ln(N_{mult} - N_{\pi^0})}{\ln(N_{mult})} = 1 + \frac{\ln(1-c)}{\ln(N_{mult})}$$
  - ➡ +4% for β ➡ -30% for $c = \frac{N_{\pi^0}}{N_{mult}}$
  - ➡ Measure@LHC : $R = \frac{E_{e/m}}{E_{had}} \approx \frac{c}{1-c}$

Hadronization Models

2 models well established for 2 extreme cases

➡ String Fragmentation vs Collective hadronization (statistical models)





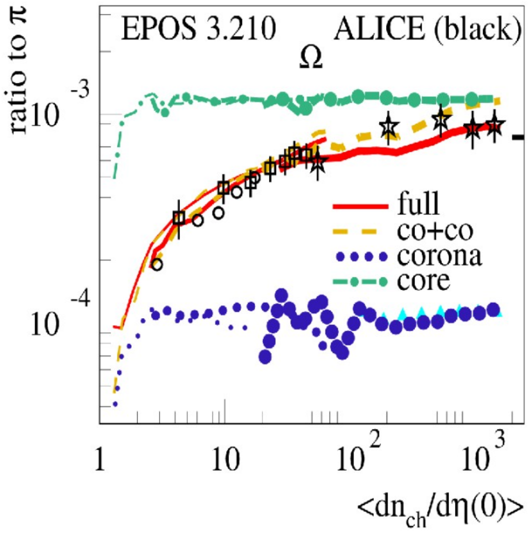
In dilute systems… CORONA
→ "high" π^0 fraction

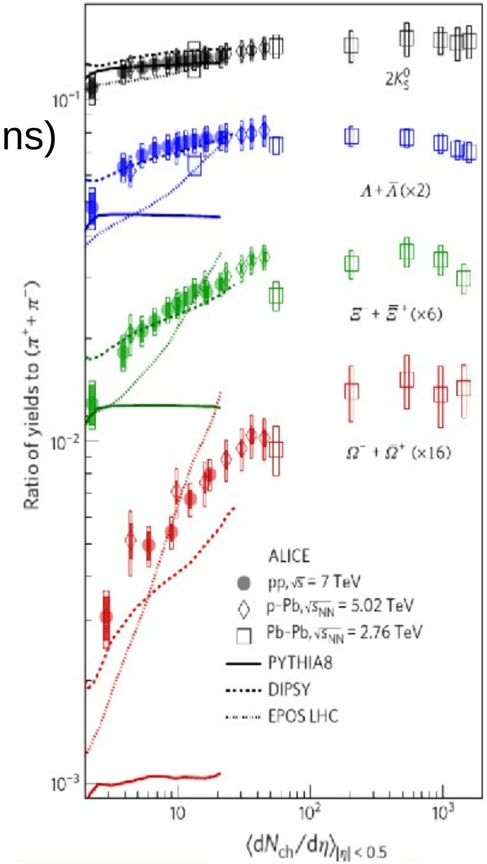
In dense systems… CORE
→ "low" π^0 fraction

➡ 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**





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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

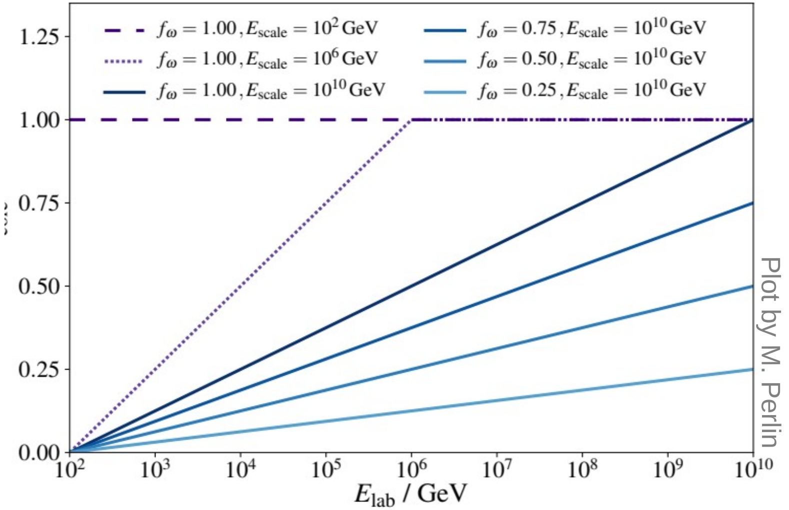
- Particle ratios from statistical model are known (tuned to PbPb) and fixed : core
- Initial particle ratios given by individual hadronic interaction models : corona
- Using CONEX, EAS can be simulated mixing corona hadronization with an arbitrary fraction ω_{core} of core hadronization: $N_i = \omega_{\mathrm{core}}\,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

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

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

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

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



Ref: <https://arxiv.org/abs/1902.09265>

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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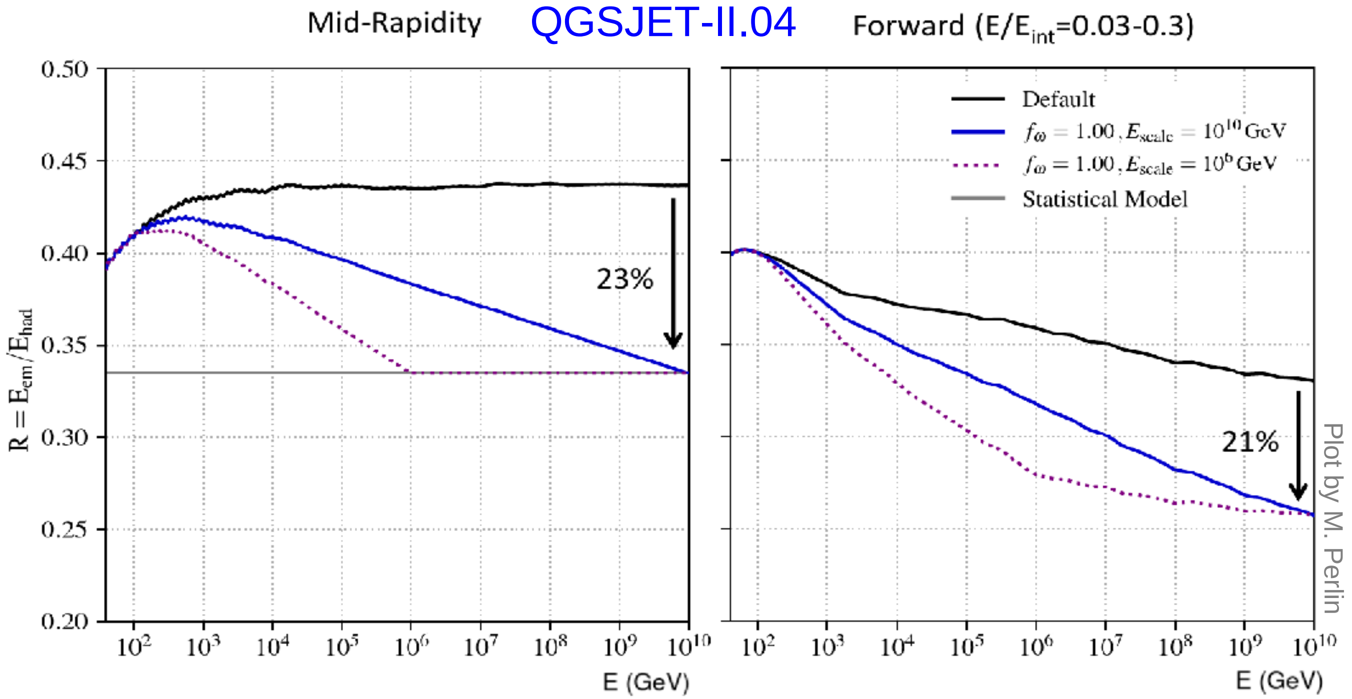

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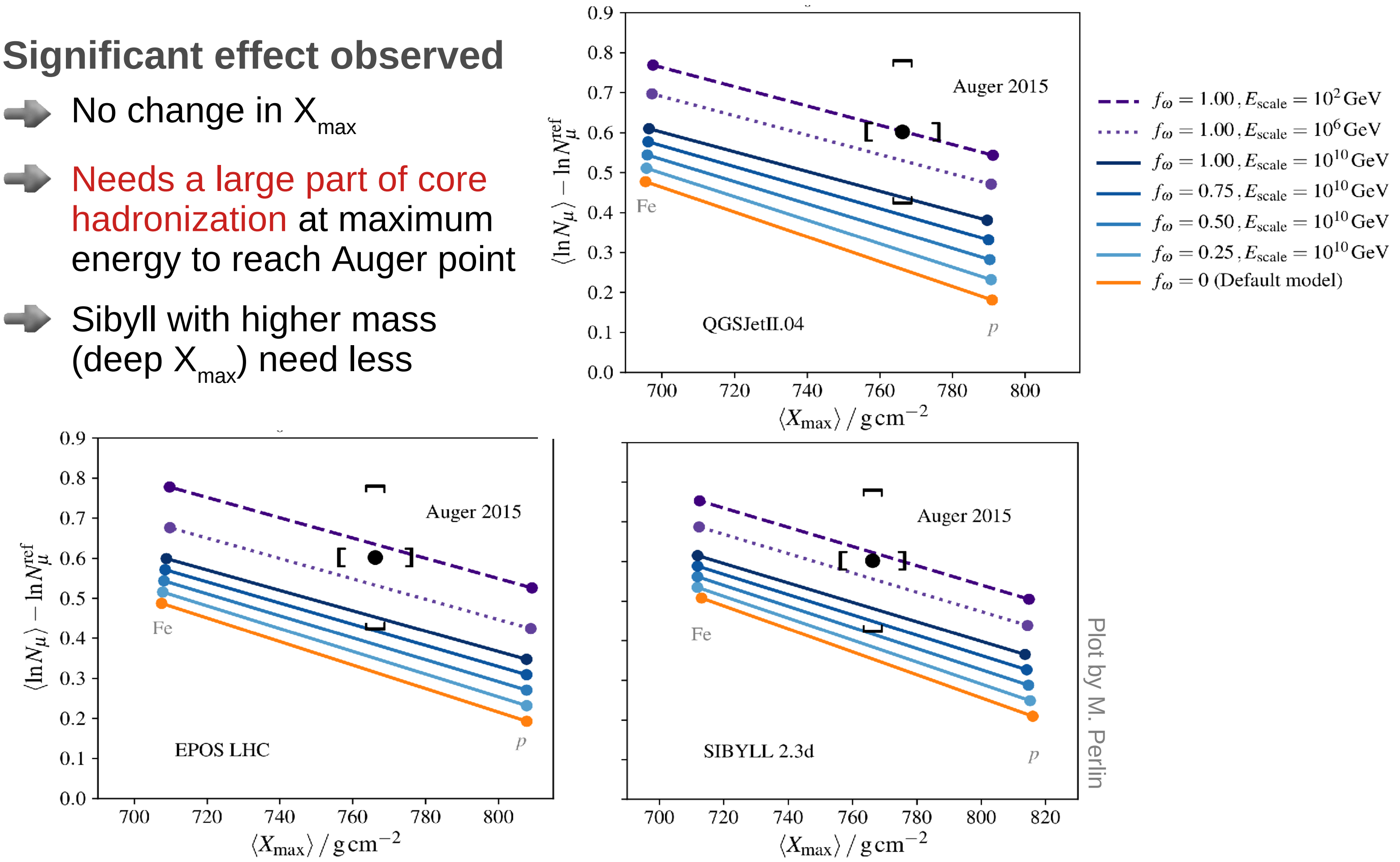
Results for X_{max}-N_{mu} correlation

Significant effect observed

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



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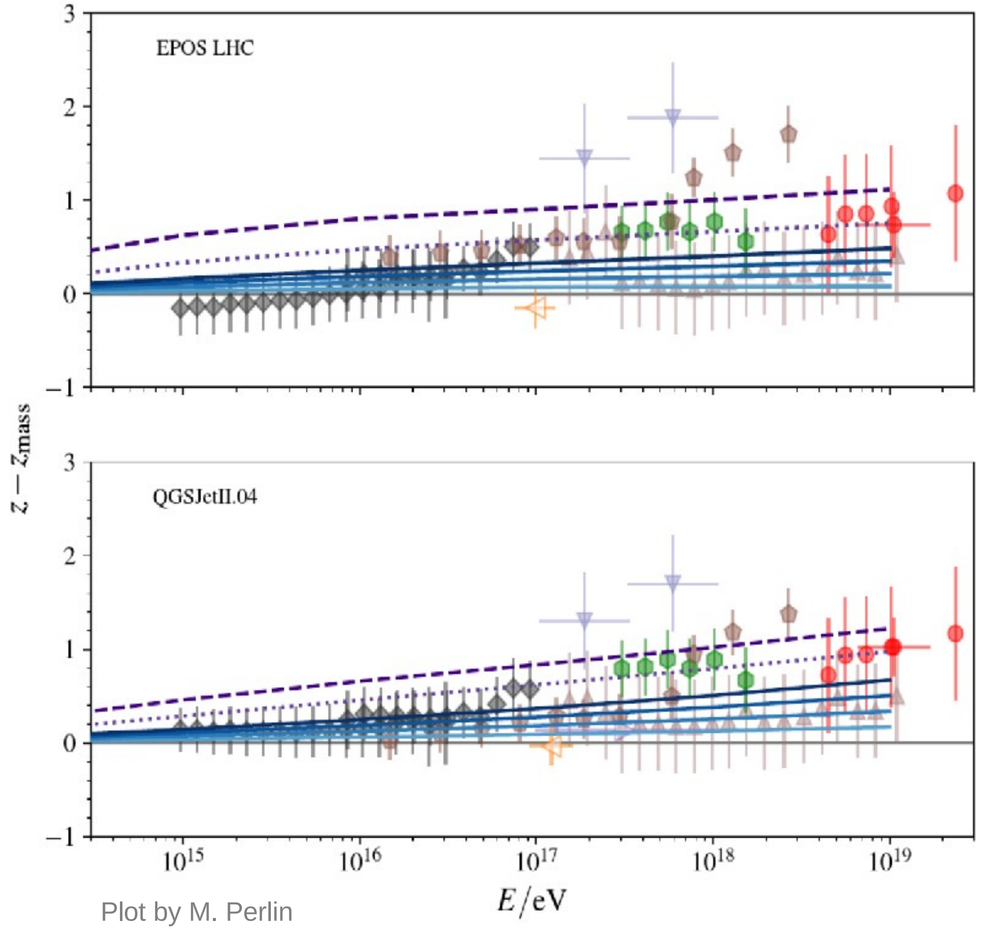
Results for z-scale



Plot by M. Perlin

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

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

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Summary

New input from LHC crucial to reproduce EAS data consistently: collective effects in light system may bring a solution for the muon puzzle.

- **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 pion charge ratio.**
  - ➡ Other possibilities limited by X_{max} (multiplicity, inelasticity)
- **LHC results show a possible mechanism to change π^0 fraction.**
  - ➡ Different type of hadronization (string like or satistical decay)
  - ➡ Core-corona model
- **More data are necessary to constrain the model in relevant kinematic space.**
  - ➡ Forward measurement (LHCb or more forward)
  - ➡ Light ion beam (p-O, O-O)

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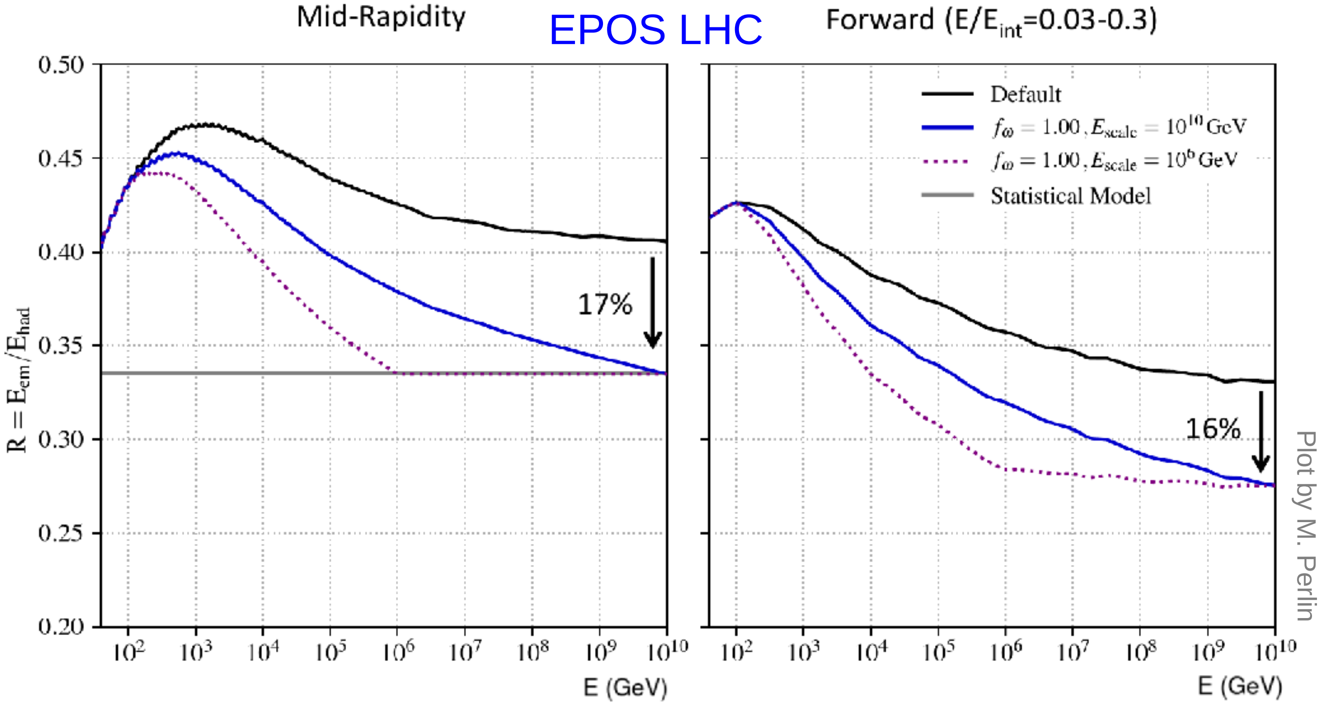

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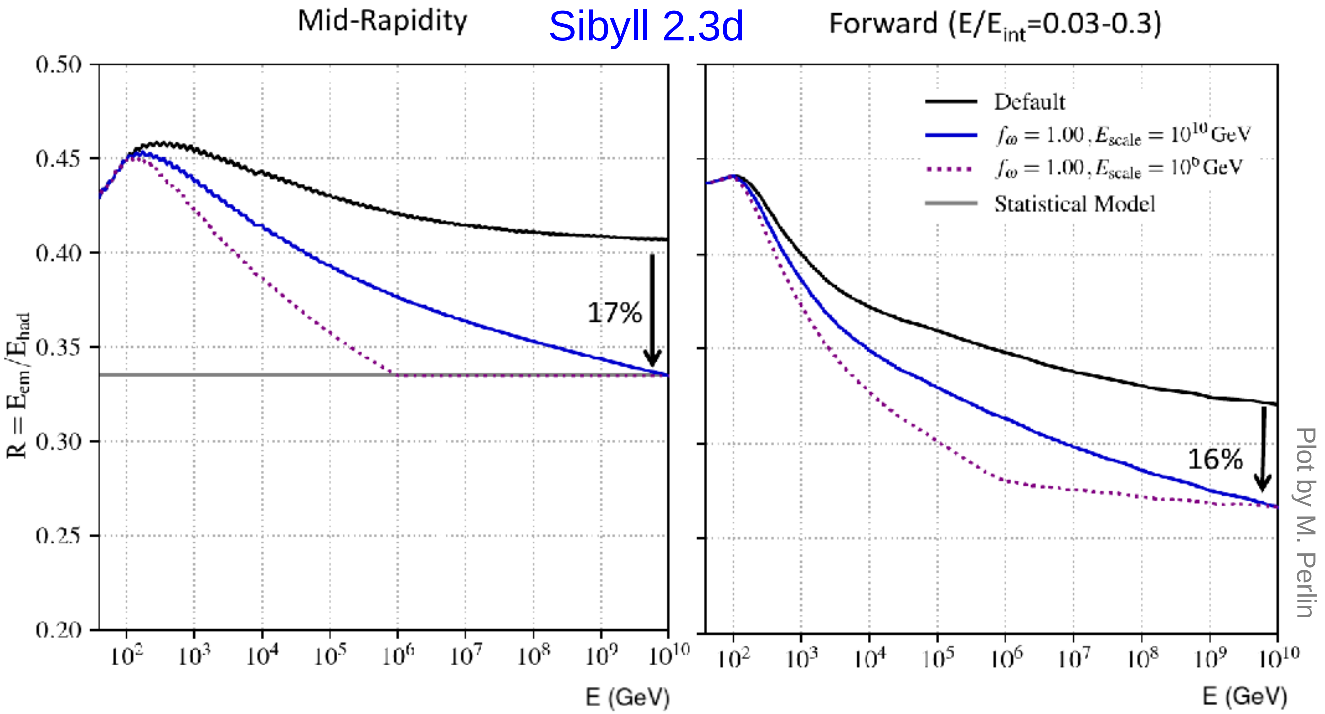

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