EPOS LHC-R
Up-to-date Hadronic Model for EAS Simulations

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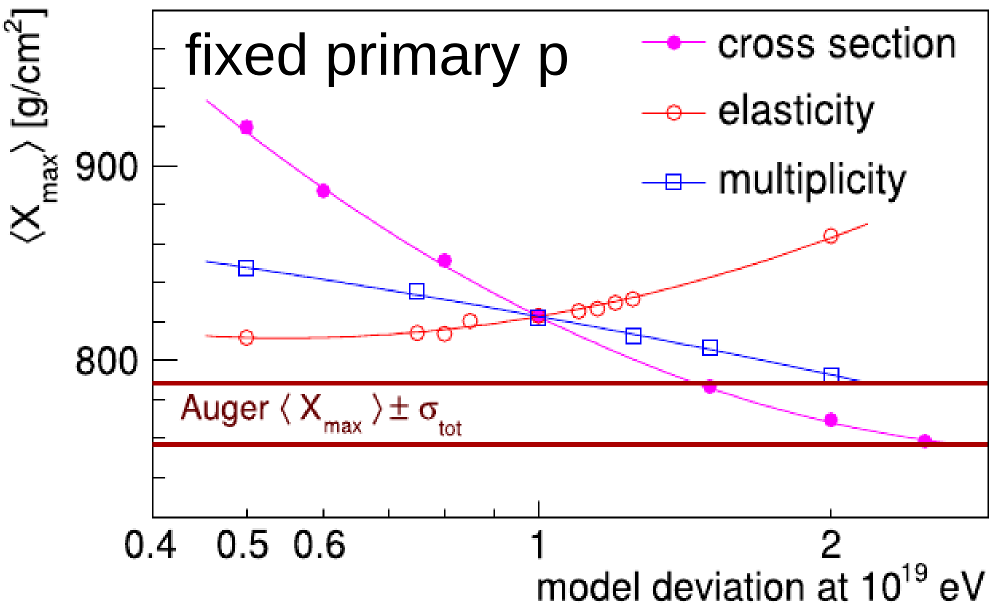
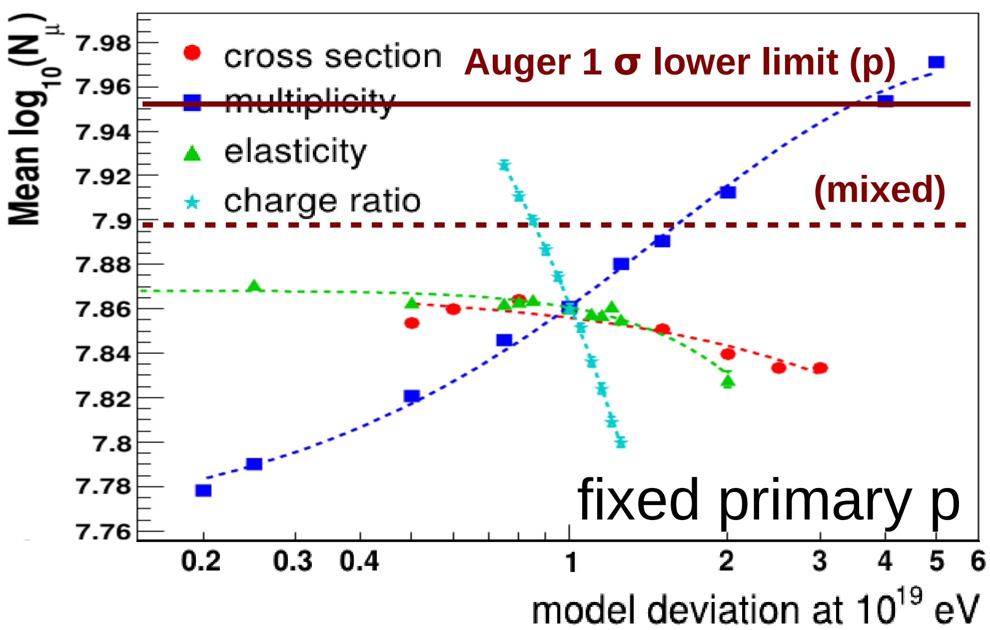
Outline

- **Introduction**
- **Updates $\rightarrow$ EPOS LHC-R**
  - Cross-section, Multiplicity, Fragmentation and Diffraction
- **Impact on X_{max}**
- **core-corona and μ**
  - Real impact of collective effect on muon production

Recent LHC data provide new constraints on models changing X_{max} and fine details on hadronization could be more important than thought until now, impacting the muon production.

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. ...

Theory AND data are important to constrain the hadronic model parameters. None of the two should be over-interpreted !

Model Improvements

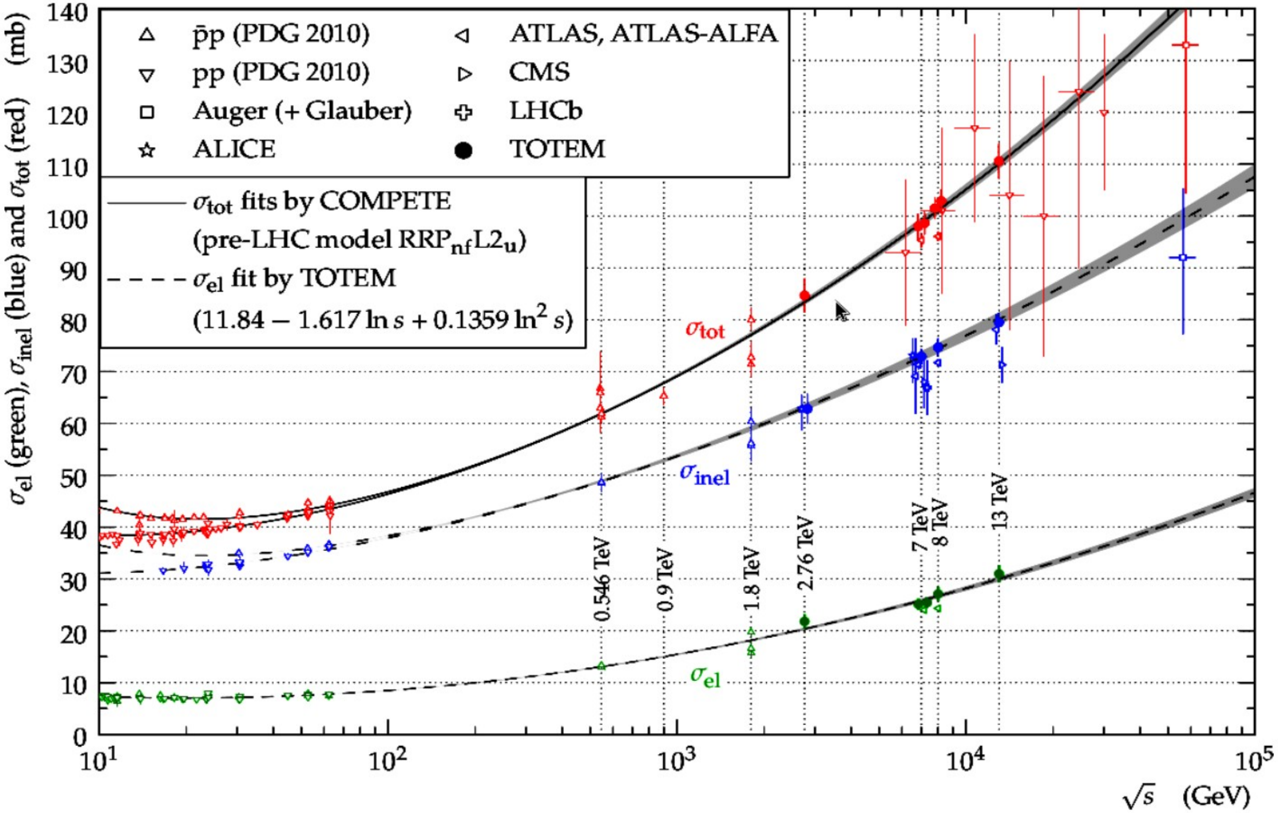
- **First LHC data lead to reduced differences between models**
- **But a number of new data since model release could be use to further improve the models :**
  - ➔ Update of the p-p cross sections (ALFA)
  - ➔ Data at 13 TeV (CMS, ATLAS, LHCf)
  - ➔ More detailed p-Pb measurements (fluctuations) CMS

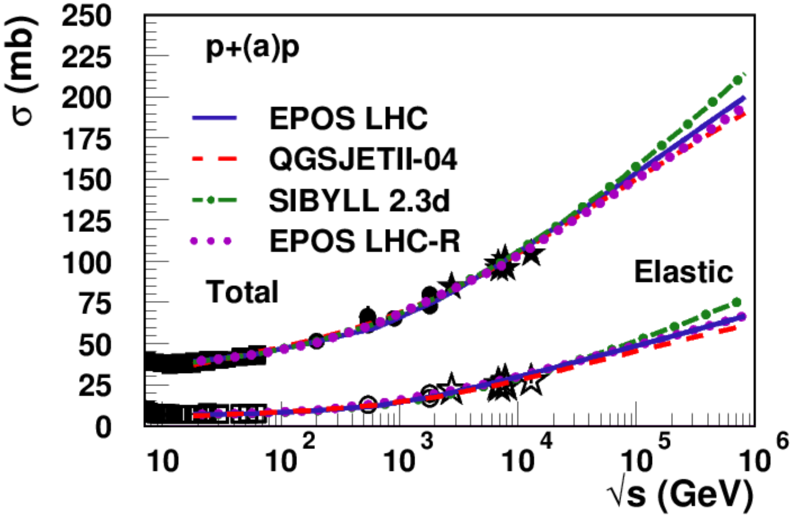
    X_{max}
  - ➔ Particle yields as a function of multiplicity (ALICE, LHCb)
    - Very important to understand the mechanism behind particle production

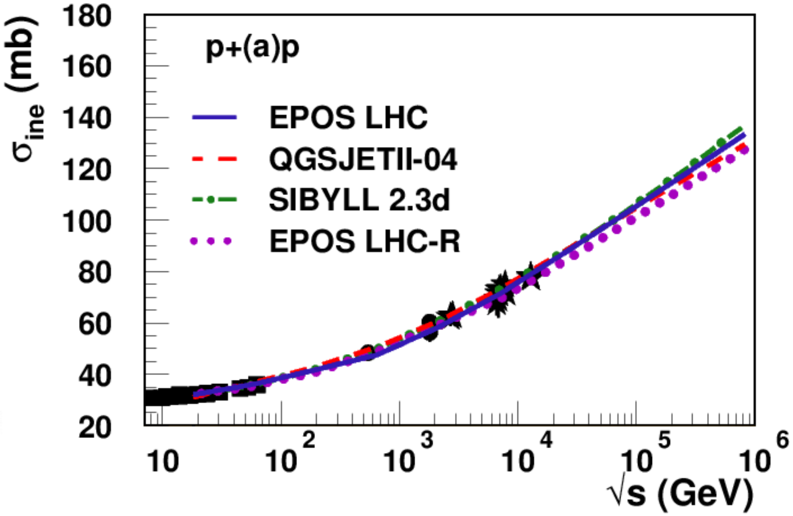
    N_{μ}
- **Update of EPOS LHC → EPOS LHC-R**
  - ➔ New EPOS 4 available for heavy ion physics but not usable for air showers (yet)
  - ➔ Modify EPOS LHC to take into account new data and new knowledge accumulated with (and code from) EPOS 4
  - ➔ Still preliminary results but with “core-corona” now !

Inelastic Cross-Section

- **Probability for the particle to interact : directly related to X_{max}**
- **After TOTEM (CMS), new measurements by ALFA (ATLAS) with higher precision**
  - ➡ p-p cross-section too high in all models



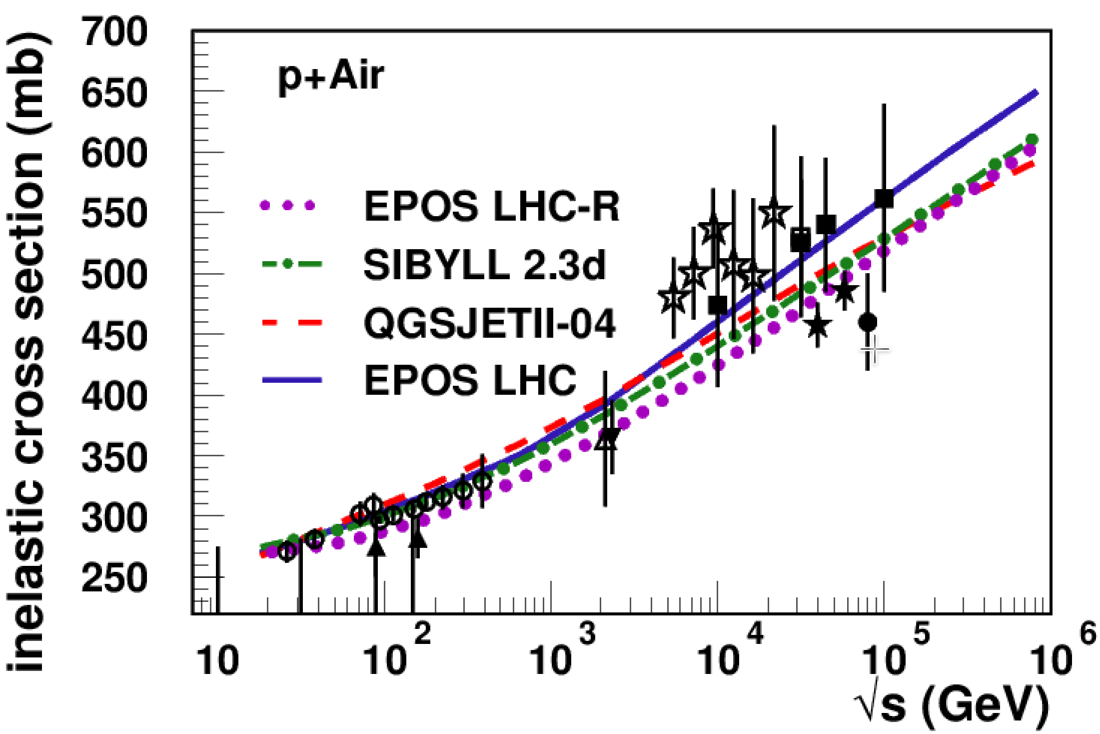


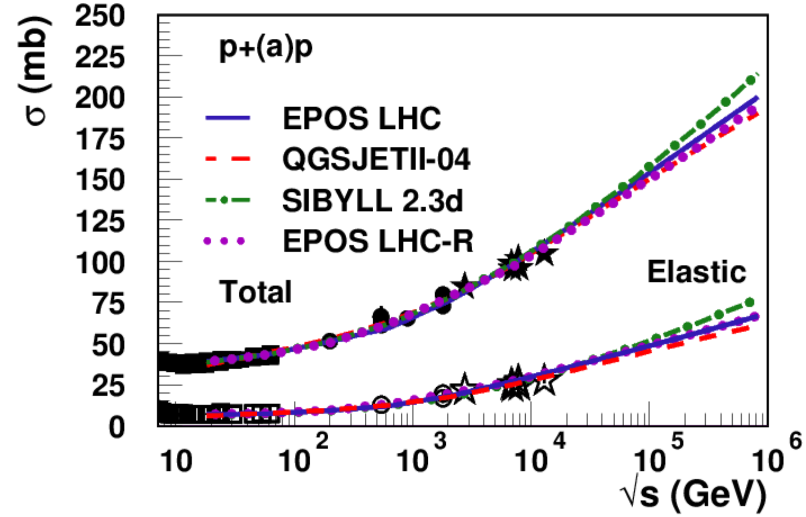


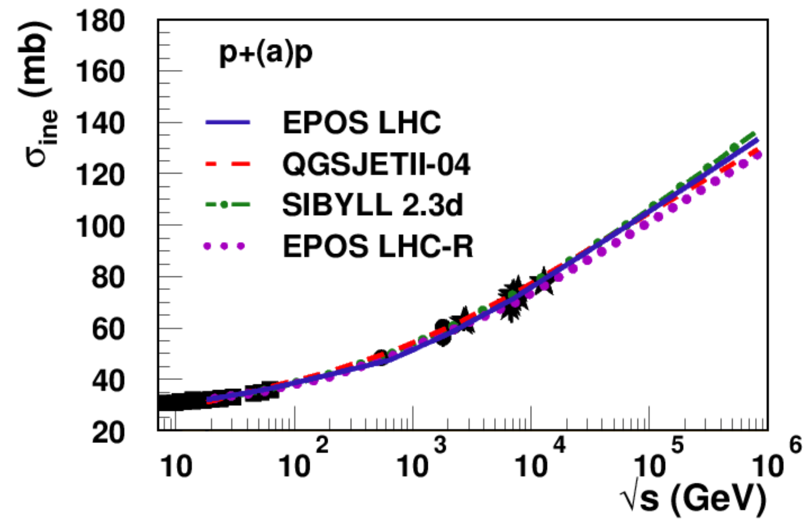
Cross-Section Reduced

- **Probability for the particle to interact : directly related to X_{max}**
- **After TOTEM (CMS), new measurements by ALFA (ATLAS) with higher precision**
  - p-p cross-section slightly too high in all models
  - Change by up to -10% at the highest energy

    using most recent CR based measurements

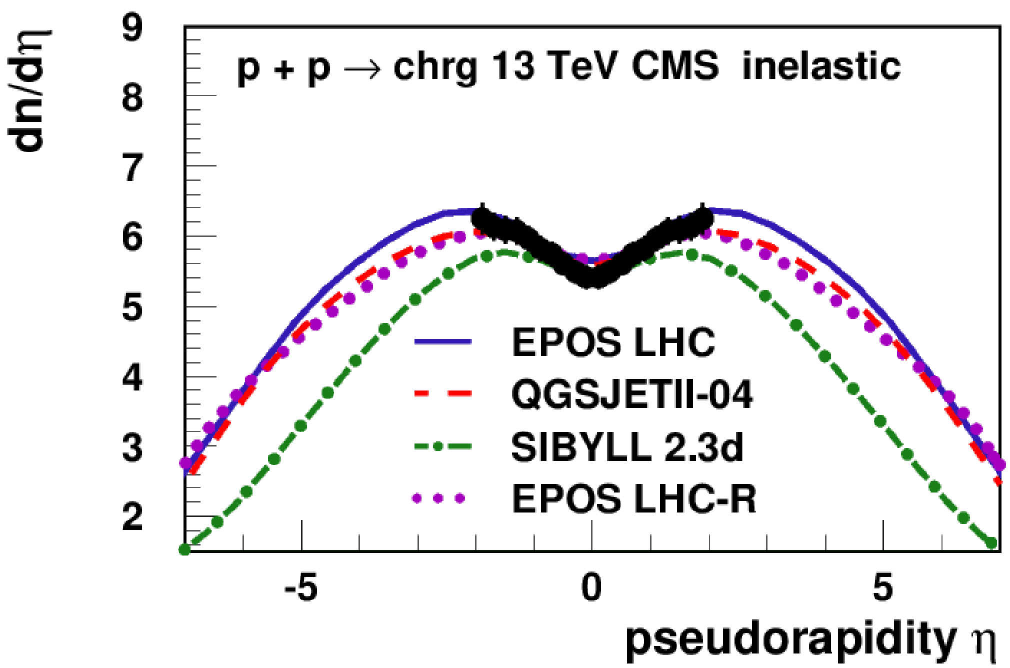


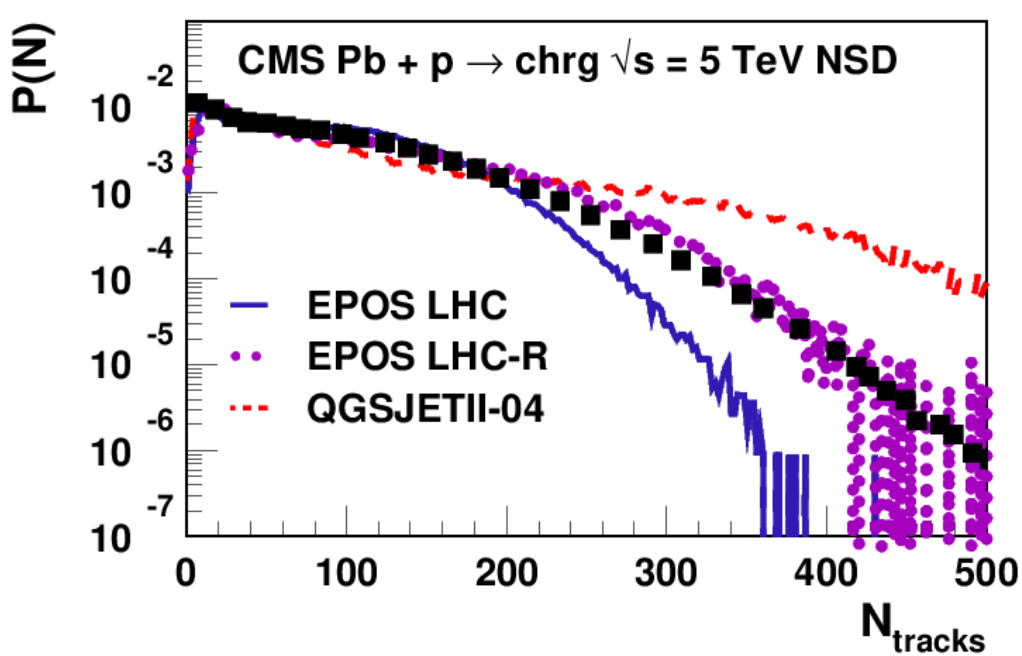




Pseudorapidity

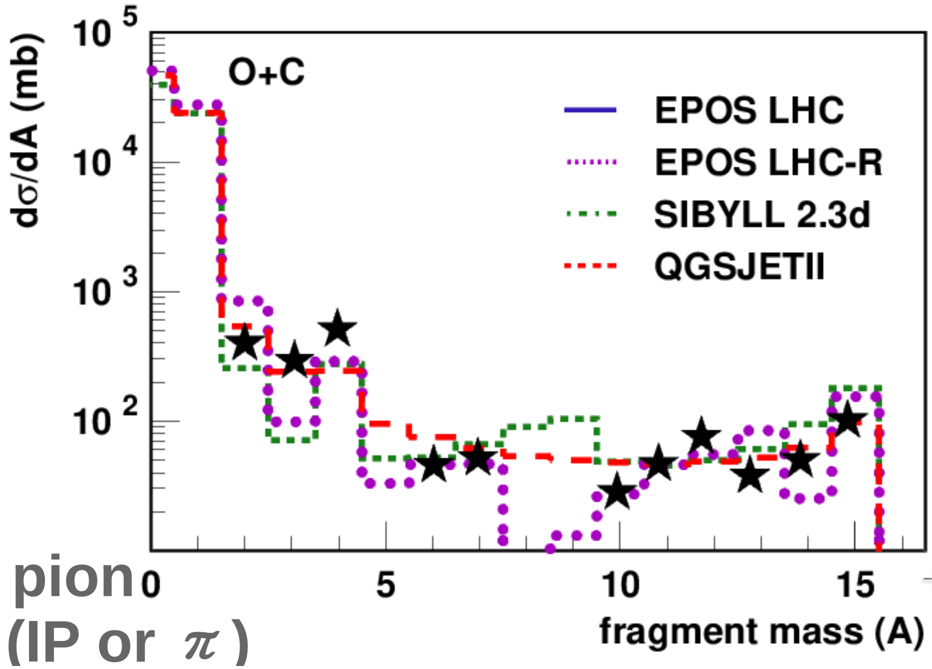
- **Angular distribution of newly produced particles**
- **New data at 13 TeV in p-p**
  - ➡ Test extrapolation with different triggers
  - ➡ Sibyll has a clear difference with other models (and data) : too narrow !
- **Detailed data at 5 TeV for p-Pb**
  - ➡ Wrong multiplicity distributions in all models (before retune)



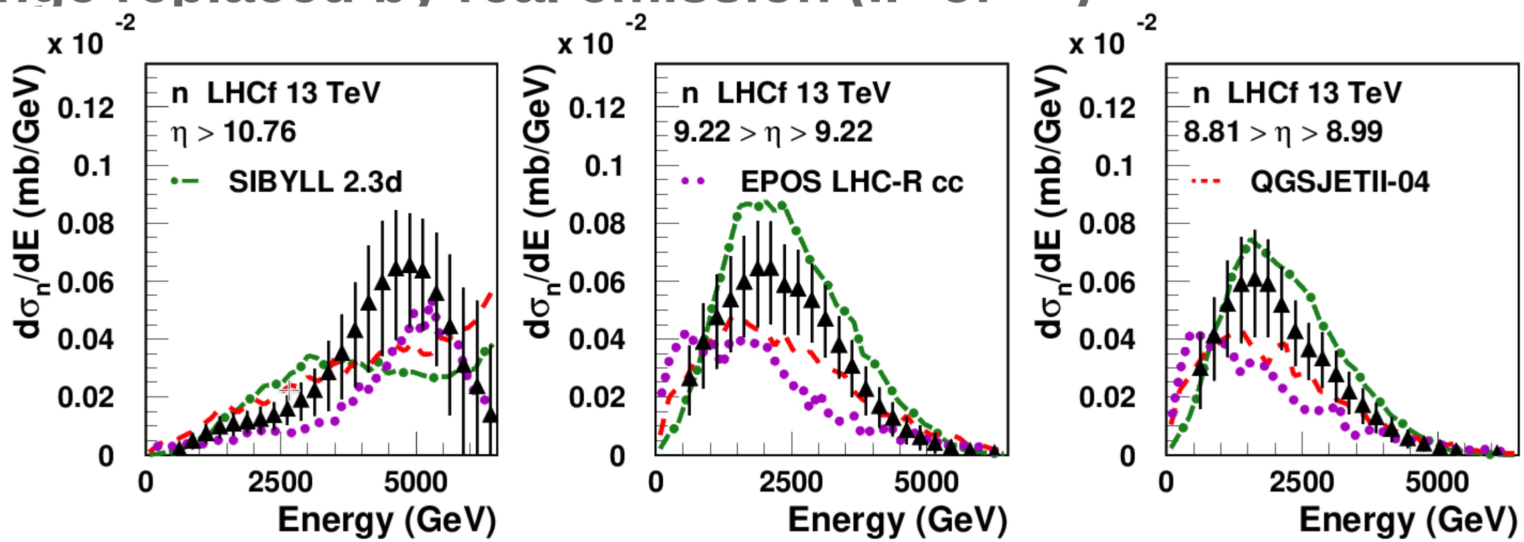


Improvements in EPOS LHC-R

- **Number of limitations identified in EPOS LHC**
- **Problem with nuclear fragments**
  - Double counting for single nucleons
  - Missing multifragment production
    - Now similar to other models
    - Significant impact on X_{max} fluctuations for nuclei

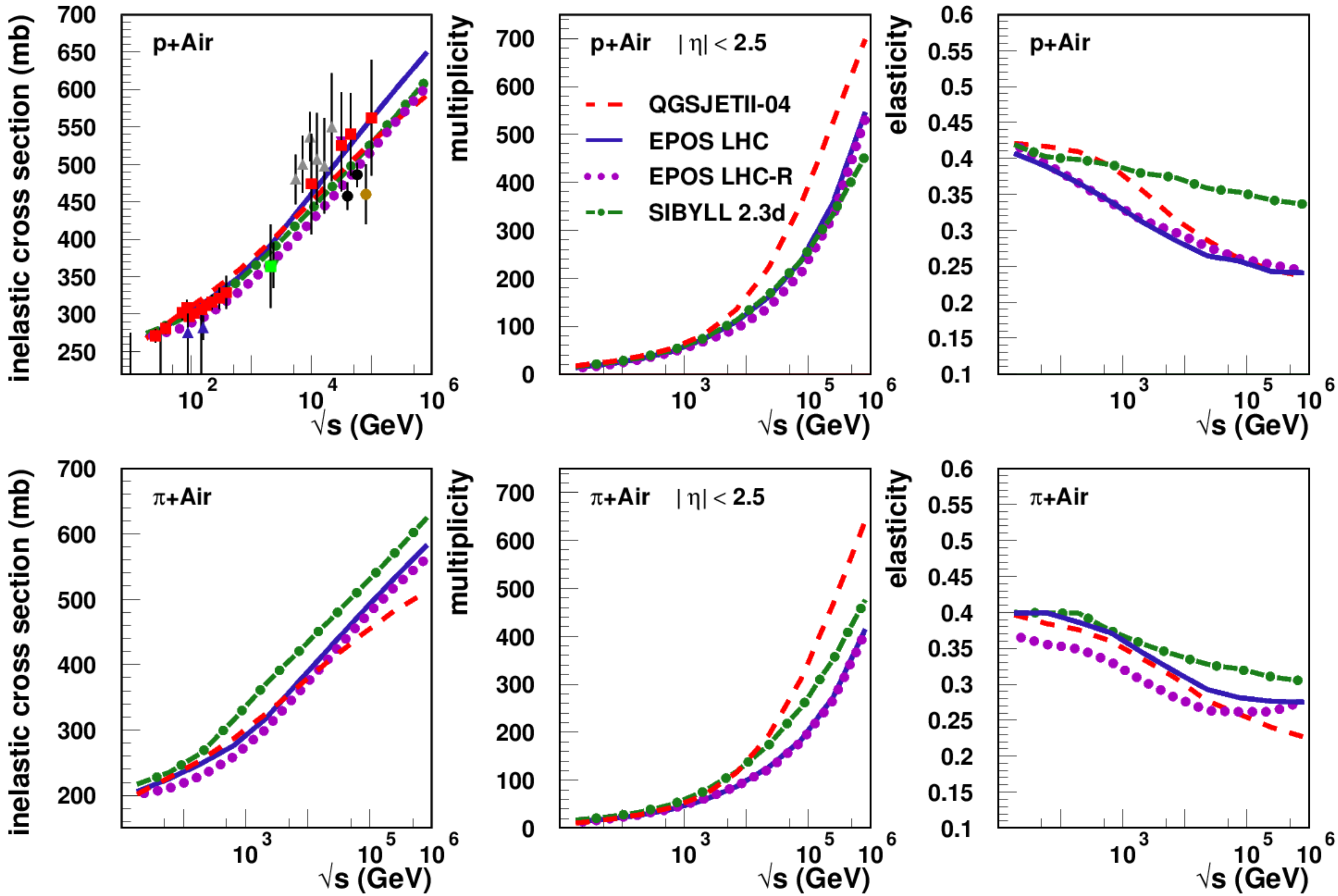


- **Simplified high mass diffraction and pion exchange replaced by real emission (IP or π)**



EPOS LHC-R interaction with Air

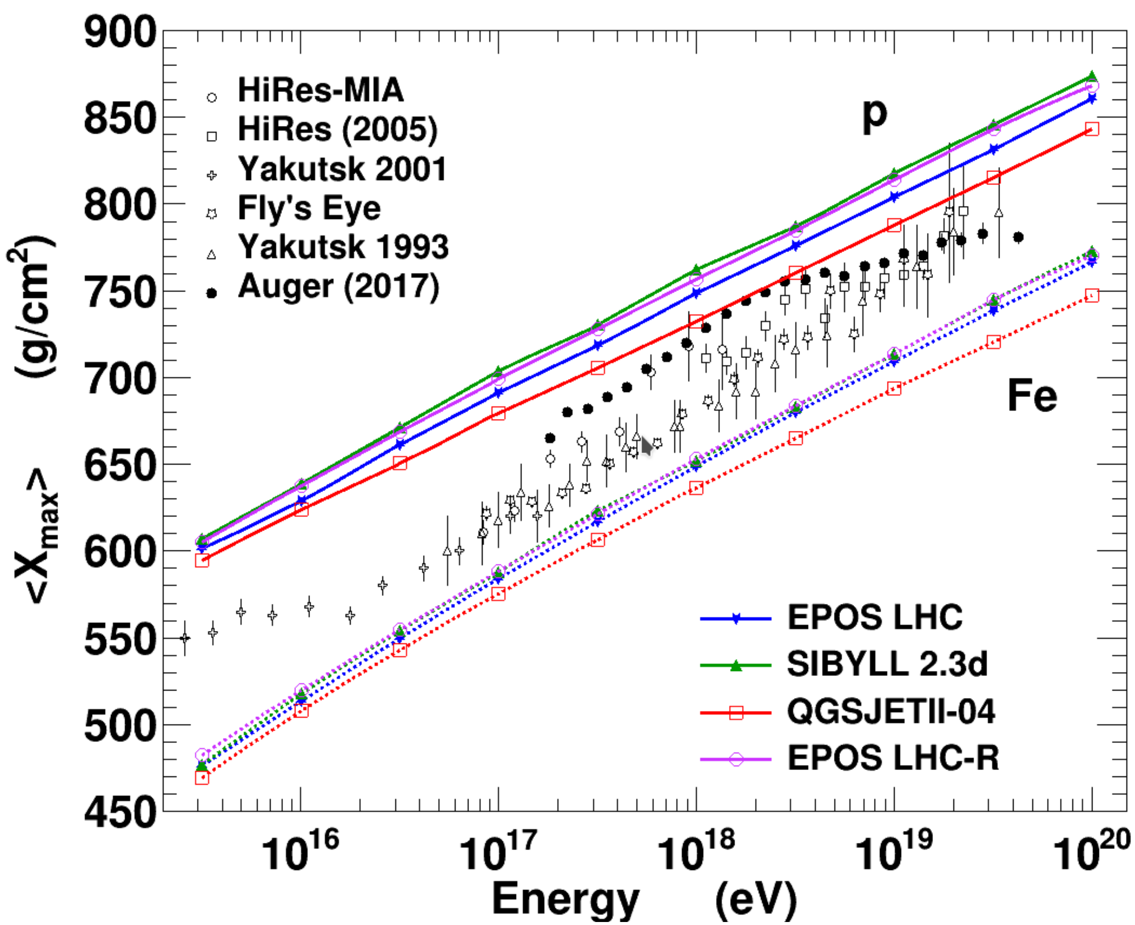
(preliminary)



X_{max}

+/- 20g/cm² is a realistic uncertainty band where is the center ?

- minimum given by QGSJETII-04 ((too) high multiplicity, low elasticity) ?
- maximum given by Sibyll 2.3d (low multiplicity, high elasticity) ?
- Taking into account new data, now EPOS shifted by +10g/cm² (~Sibyll)

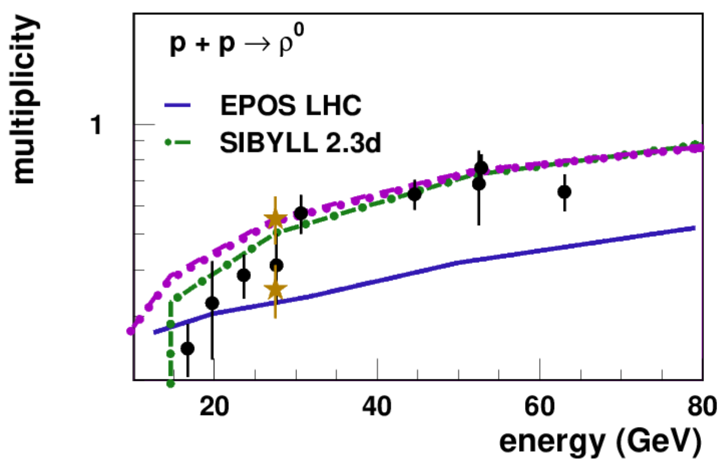


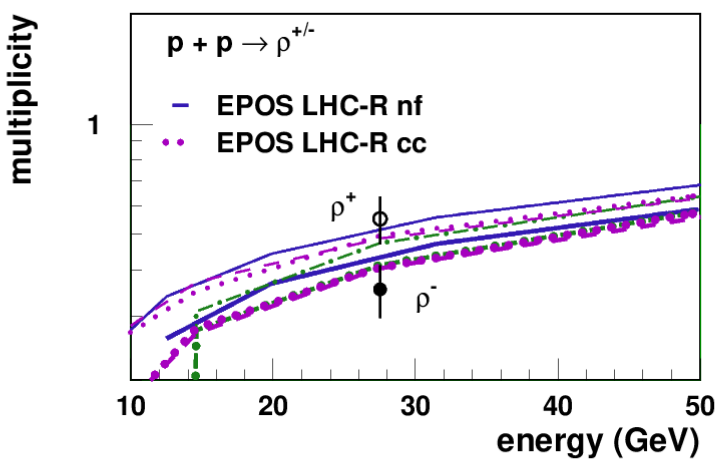
Higher <lnA> !

Correction of nuclear fragmentation in EPOS :
X_{max} RMS Fe
LHC=20g/cm2
LHC-R=24g/cm2
SIB=25g/cm2
QII=25g/cm2

Isospin Symmetry and Resonances

- **Isospin symmetry used as an argument in models to justify 1:1:1 ratios in π or ρ mesons** (or equal neutron/proton production)
  - ➡ But true only if u and d quarks have the same mass !
- **Pions can be produced directly or via ρ resonance decay**
  - ➡ Ratio $\pi^0/\pi^{+/-}$ very important for muon production
    - ➡ More π^0 means <u>less</u> μ production
  - ➡ But ρ^0 decay in $\pi^{+/-}$
    - ➡ More ρ^0 means <u>more</u> μ production
- **Mass asymmetry could lead to more ρ^0 than $\rho^{+/-}$**
    - ➡ Data not very constraining → use 20% asymmetry (high)



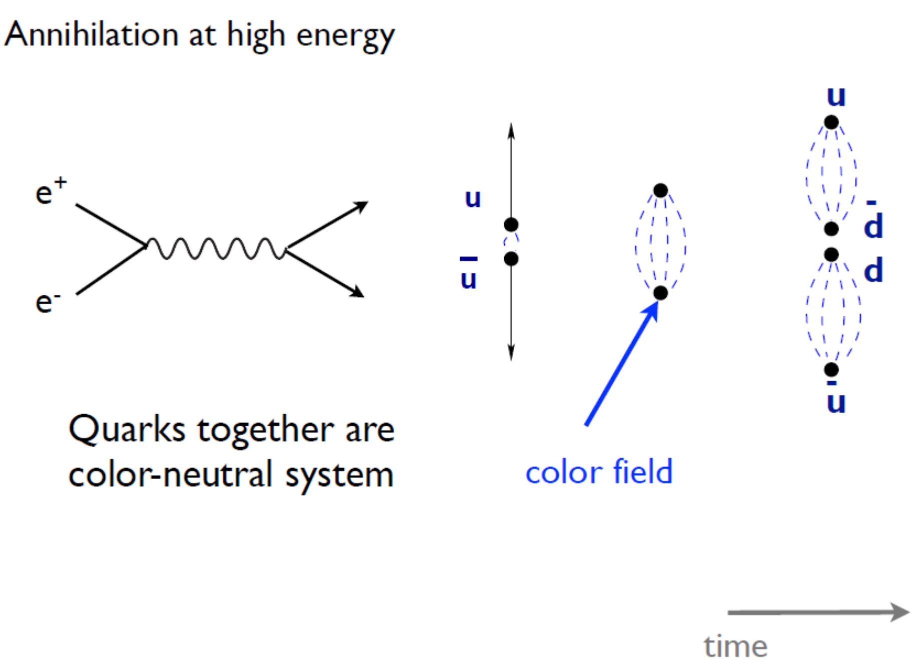


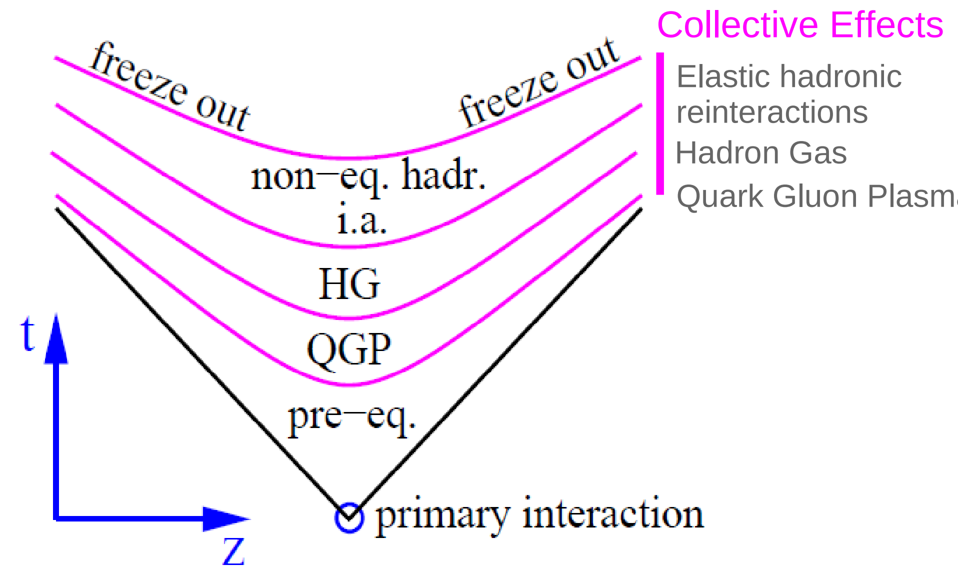
See TP ICRC 2023 contribution

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

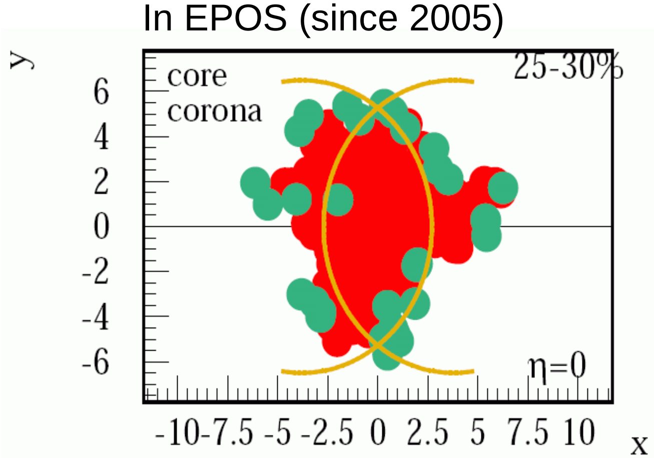
In dense systems… CORE
→ “low” π^0 fraction

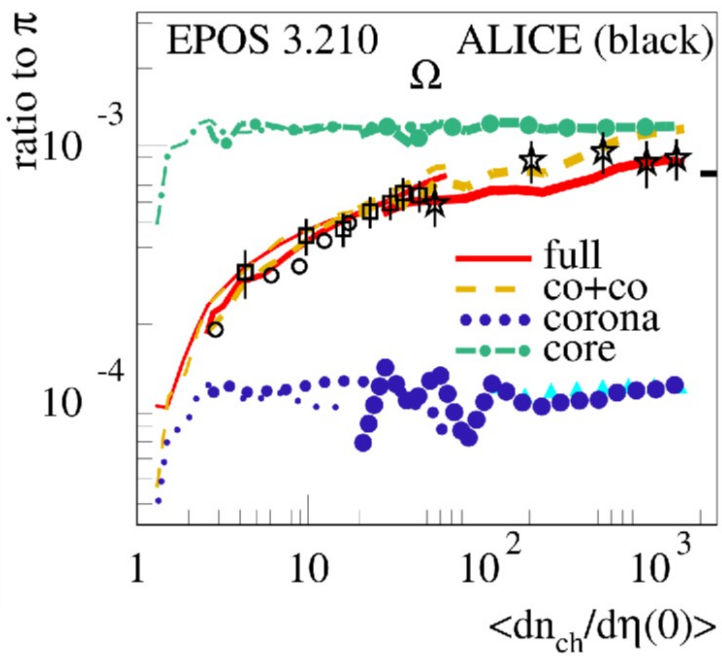
➡ What to do in between ? For proton-proton, hadron-Air, ...

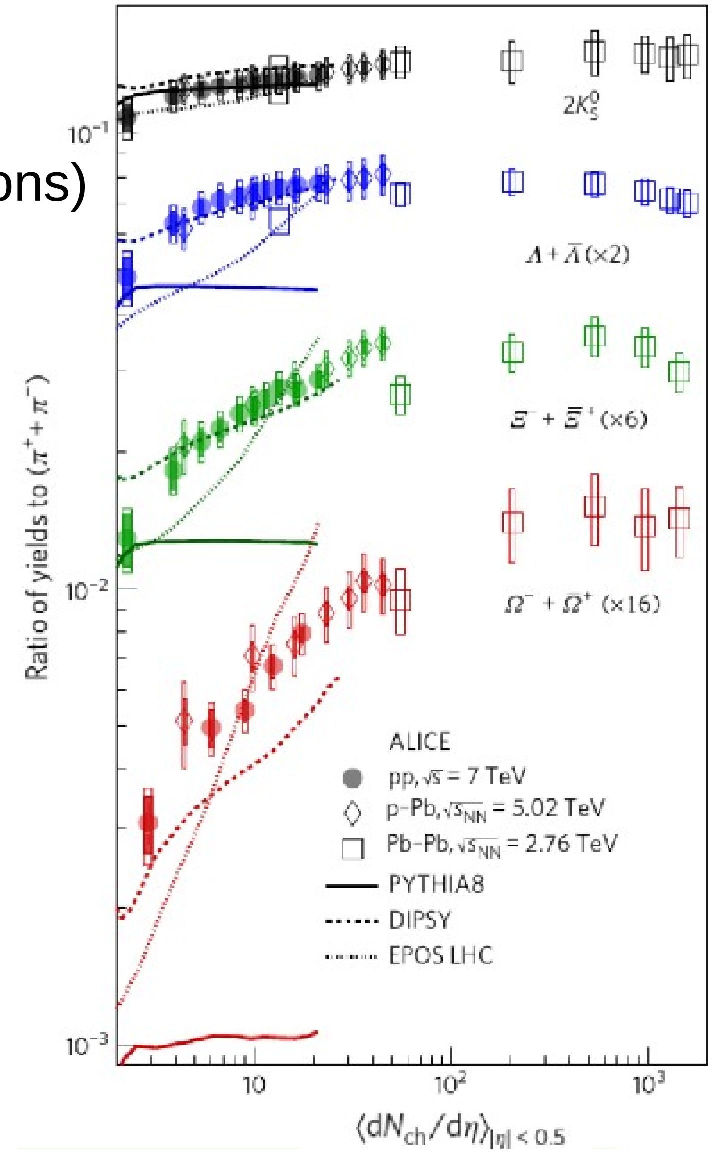
Core-Corona (CC) Approach

- **Mixing of core and corona hadronization needed to achieve detailed description of p-p data (ref K.Werner)**
  - 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**
- **2 simultaneous source of particles**

In EPOS (since 2005)



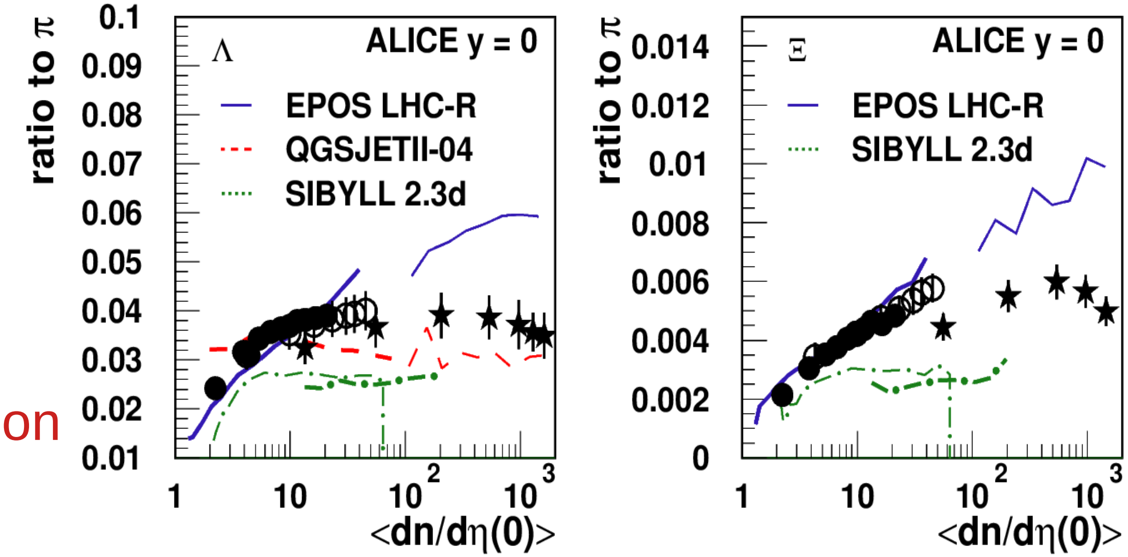


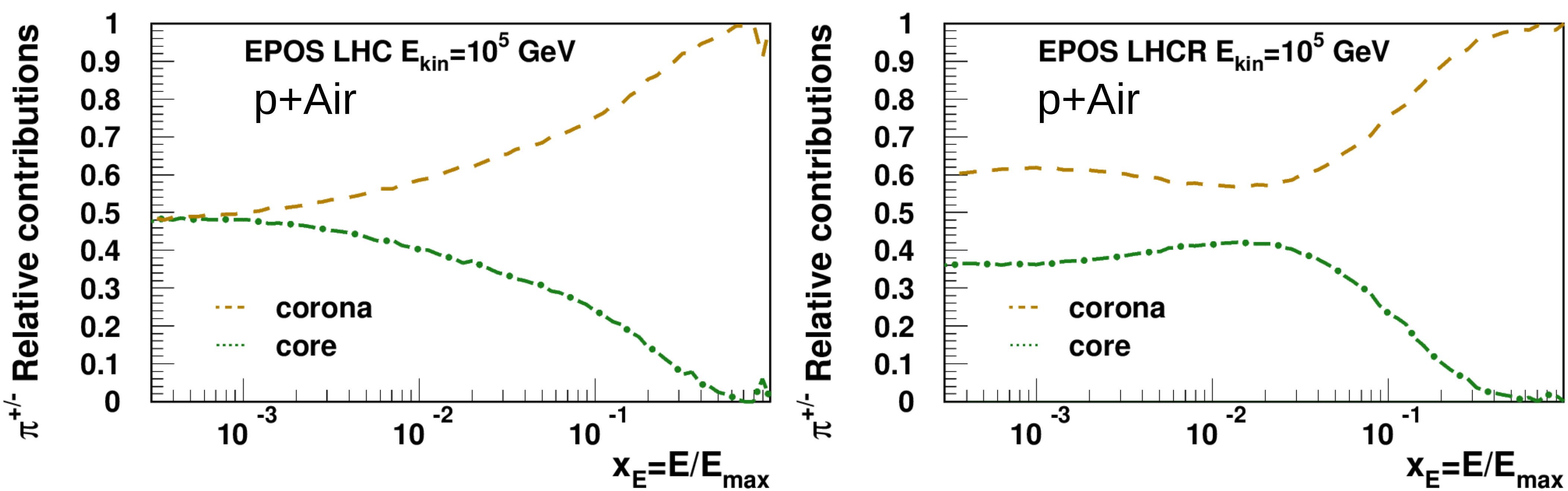


Interactions in Air Showers

Update of EPOS to reproduce ALICE data

- Lower condition (particle density) to form core
- More core forward
- What's the impact on muon production in air showers (lower π^0 fraction) ?

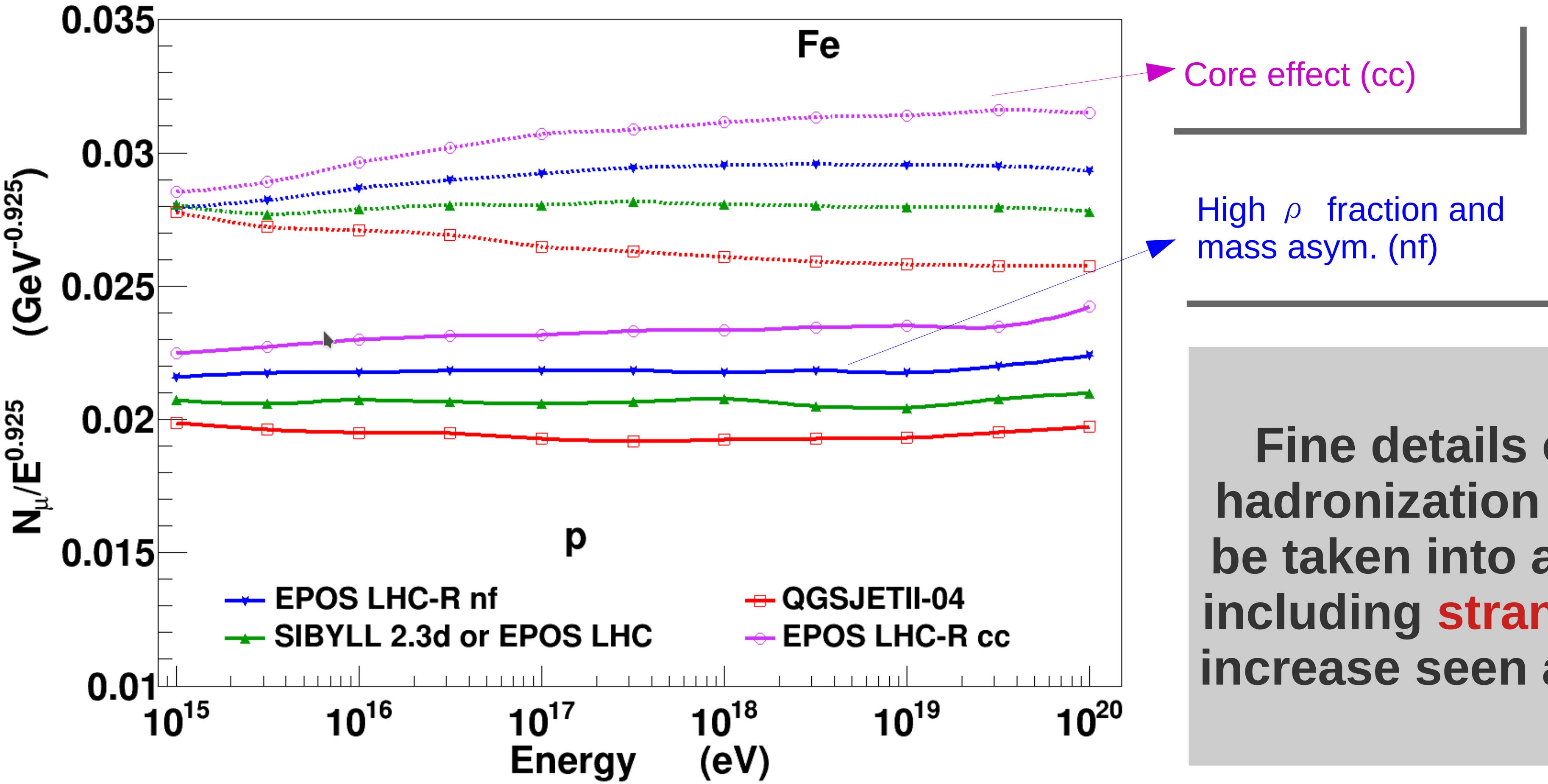




N_μ

First simulations with up-to-date core-corona implementation:

- Simulations without core-corona but ρ asymmetry already have more muons
- Additional energy and mass dependent effect due to core-corona !
- First effect could be “tuned”, less freedom for core-corona (from LHC)

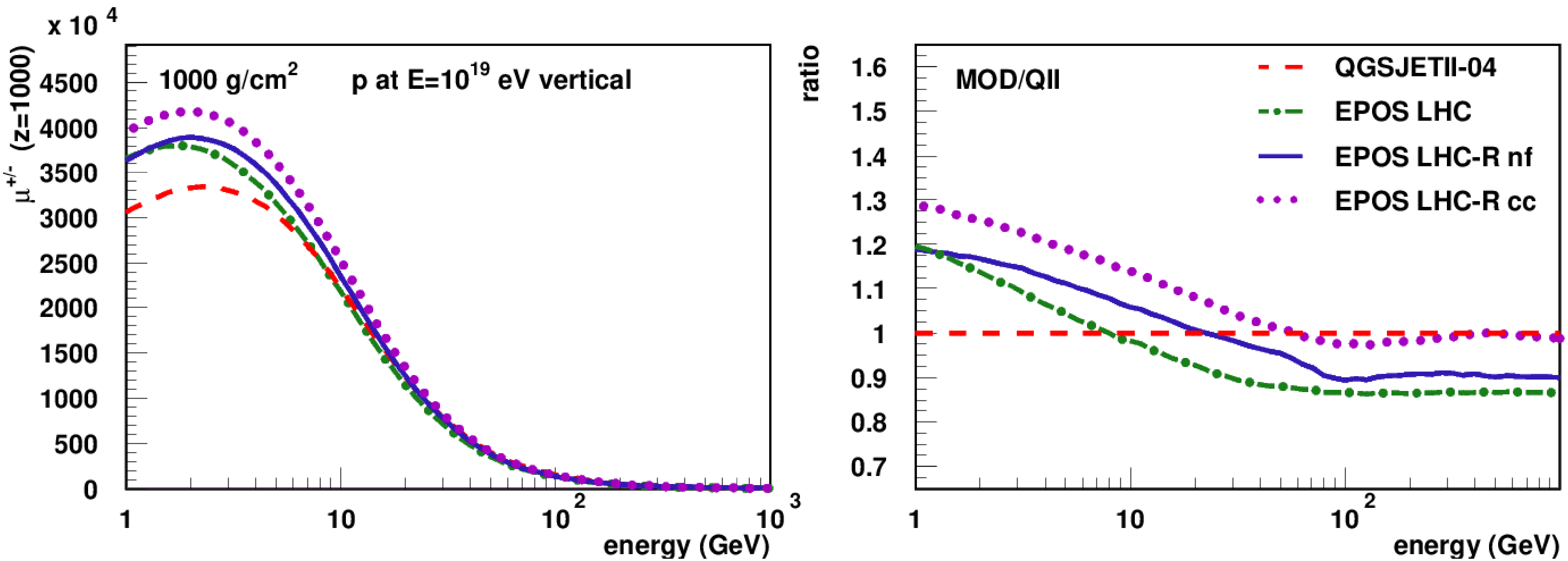


Fine details of the hadronization should be taken into account including strangeness increase seen at LHC !

E_μ

First simulations with up-to-date core-corona implementation:

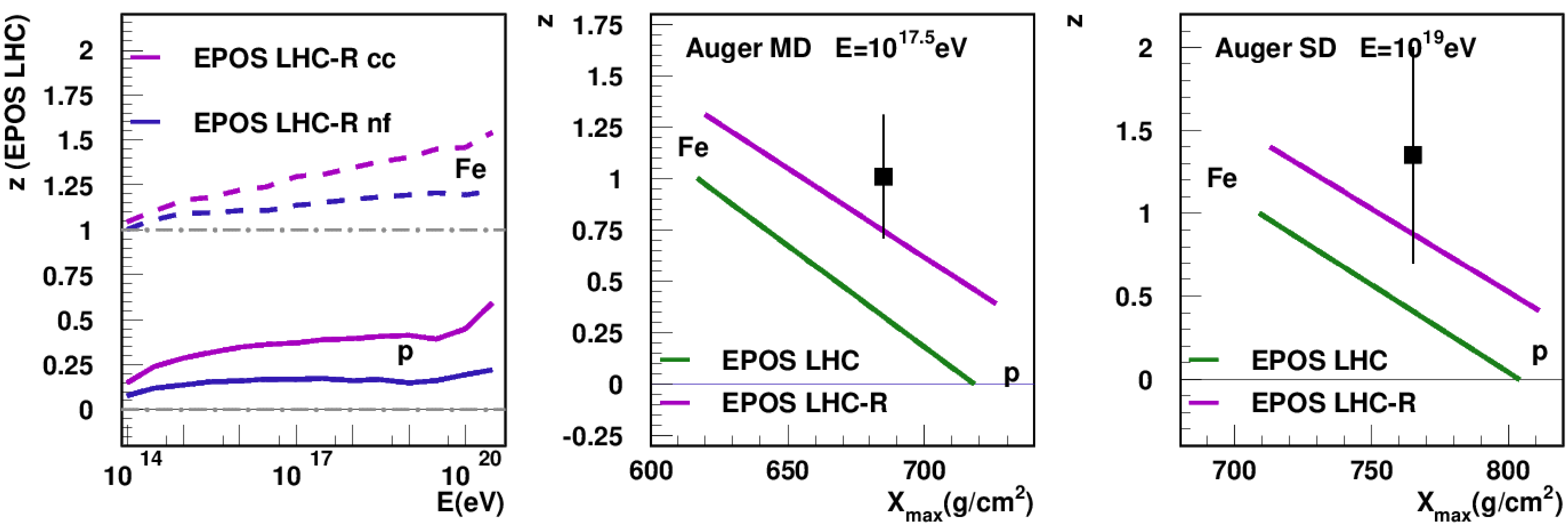
- Simulations without core-corona but ρ asymmetry already have more muons
  - Increase ~10 GeV muons
- Additional energy and mass dependent effect due to core-corona !
  - Parallel shift changing all muon energies
- First effect could be “tuned”, less freedom for core-corona (from LHC)



Muon Puzzle Solved ?

EPOS LHC-R, first model producing a deeper X_{max} and more muons and being compatible with measured accelerator data (better at LHC) :

- Deeper X_{max} give larger <lnA> reducing the gap with measured muon content
- Energy and mass dependent increase of muons due to core-corona further decrease the gap to reach Auger systematics
- What about low energy ? Less ρ^0 may be better not to have “too many” muons



Summary

- **Not all relevant CERN data taken into account in model yet**
  - 10 more years of LHC data including LHCf dedicated measurements
  - New results from SPS (NA61 - 2209.10561 [nucl-ex])
- **Updated results of cross-sections and diffraction**
  - Significant impact on X_{max}
  - Larger <lnA> (heavier primary mass → reduce "muon puzzle")
- **Details of hadronization matters**
  - Important role of resonance with sparse data = large uncertainty
    - ρ^0 increase in corona (string) compatible with data = more muons
  - Evolution of strangeness with multiplicity
    - Different type of hadronization in core = more muons
  - **Combination of the 3 effects may solve the muon puzzle (to be confirmed) !**

Updated EPOS LHC-R released in 2024 and then adapting EPOS 4 for CR

Recent LHC data provide new constraints on models changing X_{max} and fine details on hadronization could be more important than thought until now, impacting the muon production

Providing solutions to the “muon puzzle” !

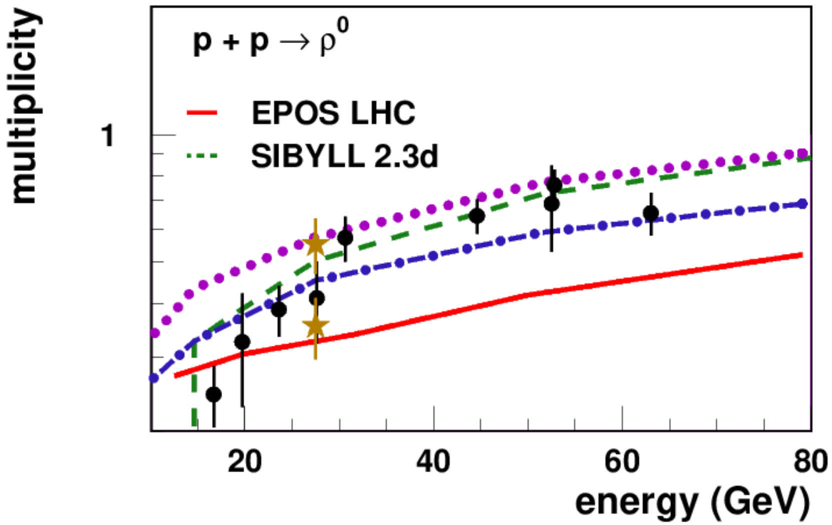
Thank you !

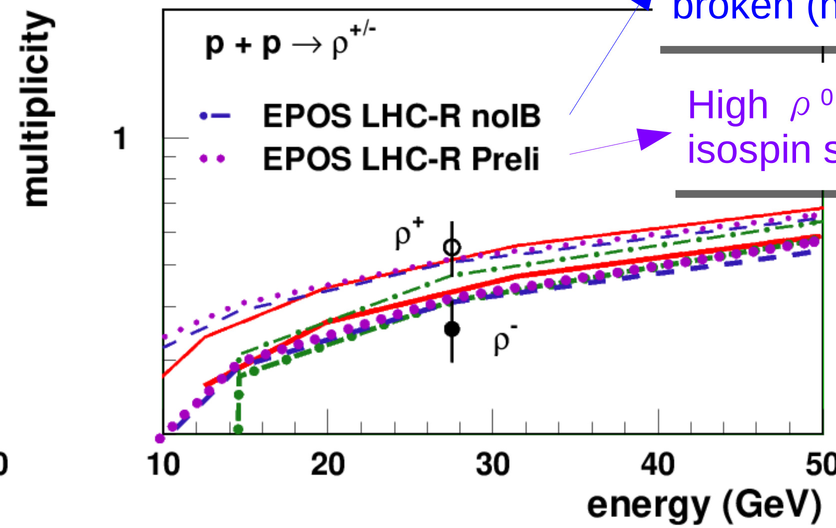
Resonance Production

Low ρ fraction and isospin sym. NOT broken (noIB)

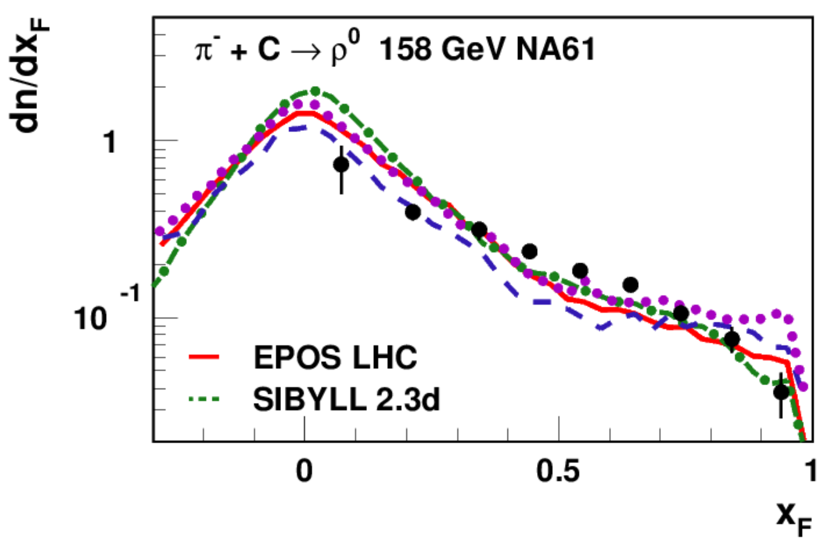
High ρ^0 fraction and isospin sym. broken

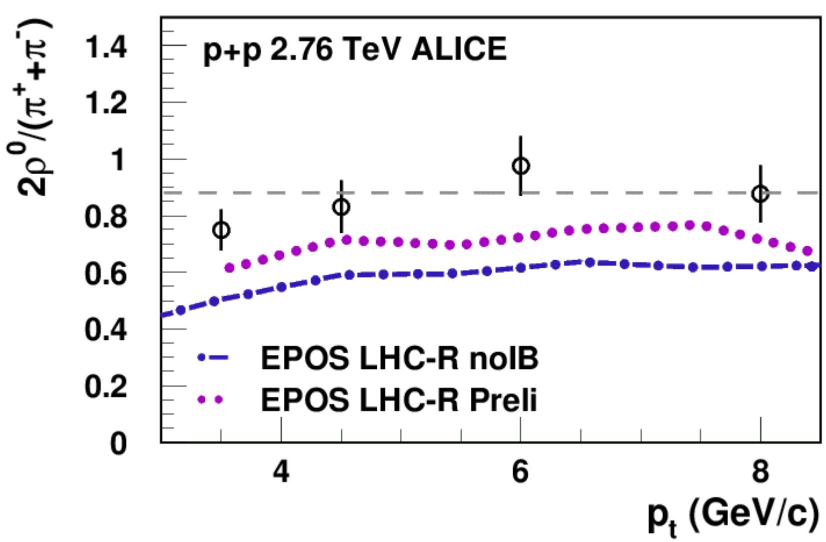
- In proton-proton interactions, ratio 1:1:1 is not observed !





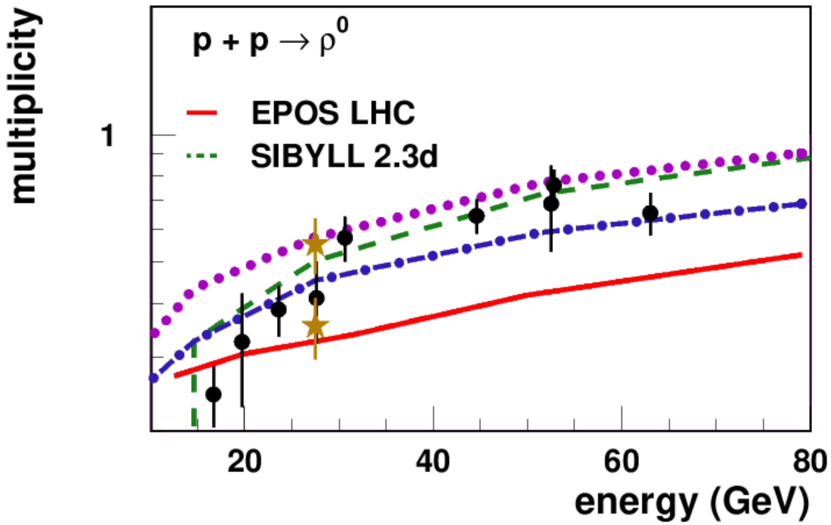
- AND high resonance fraction is favored !

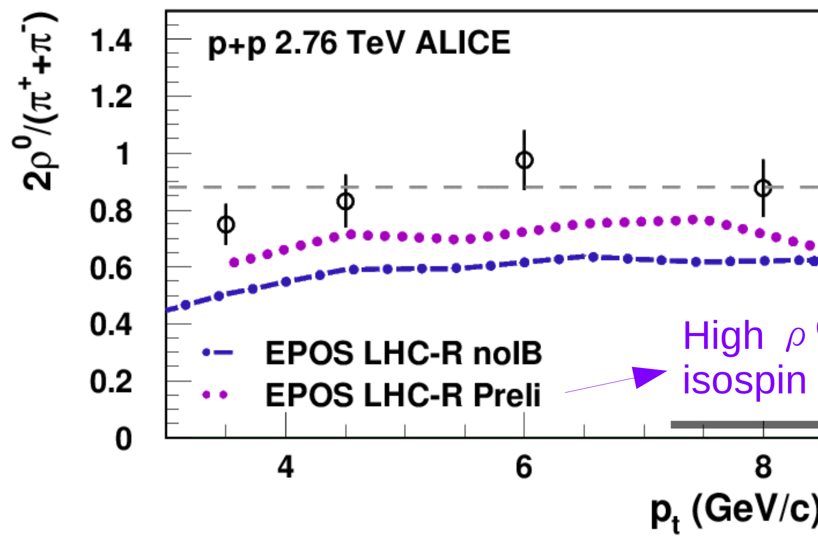




Resonance Production

➡ In proton-proton interactions, ratio 1:1:1 is not observed and high ρ ...

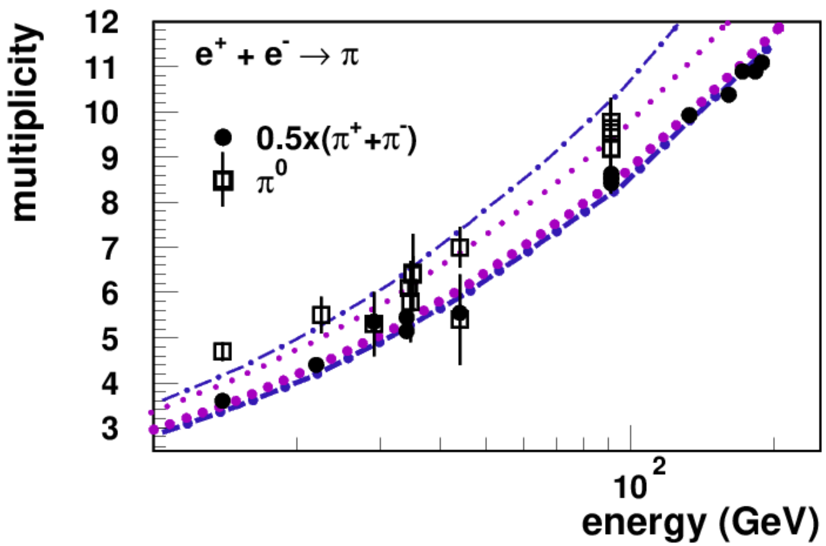


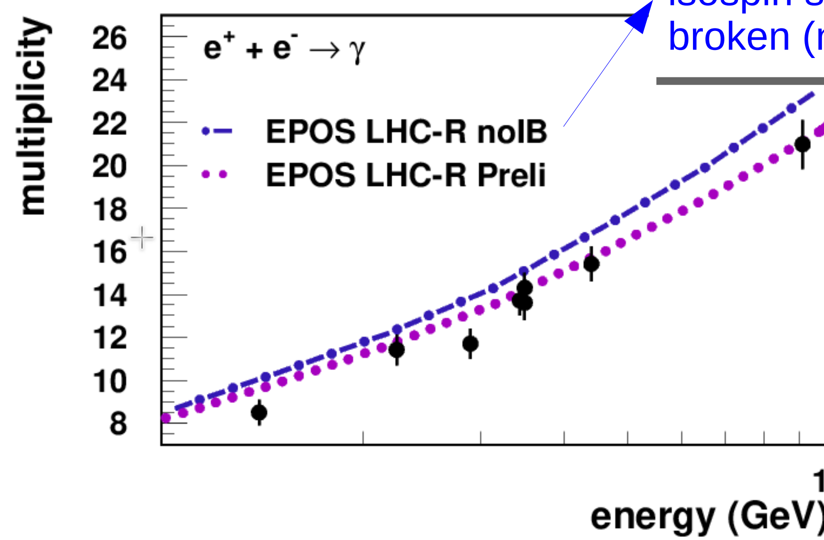


High ρ^0 fraction and isospin sym. broken

➡ Both favored in electron-positron data !

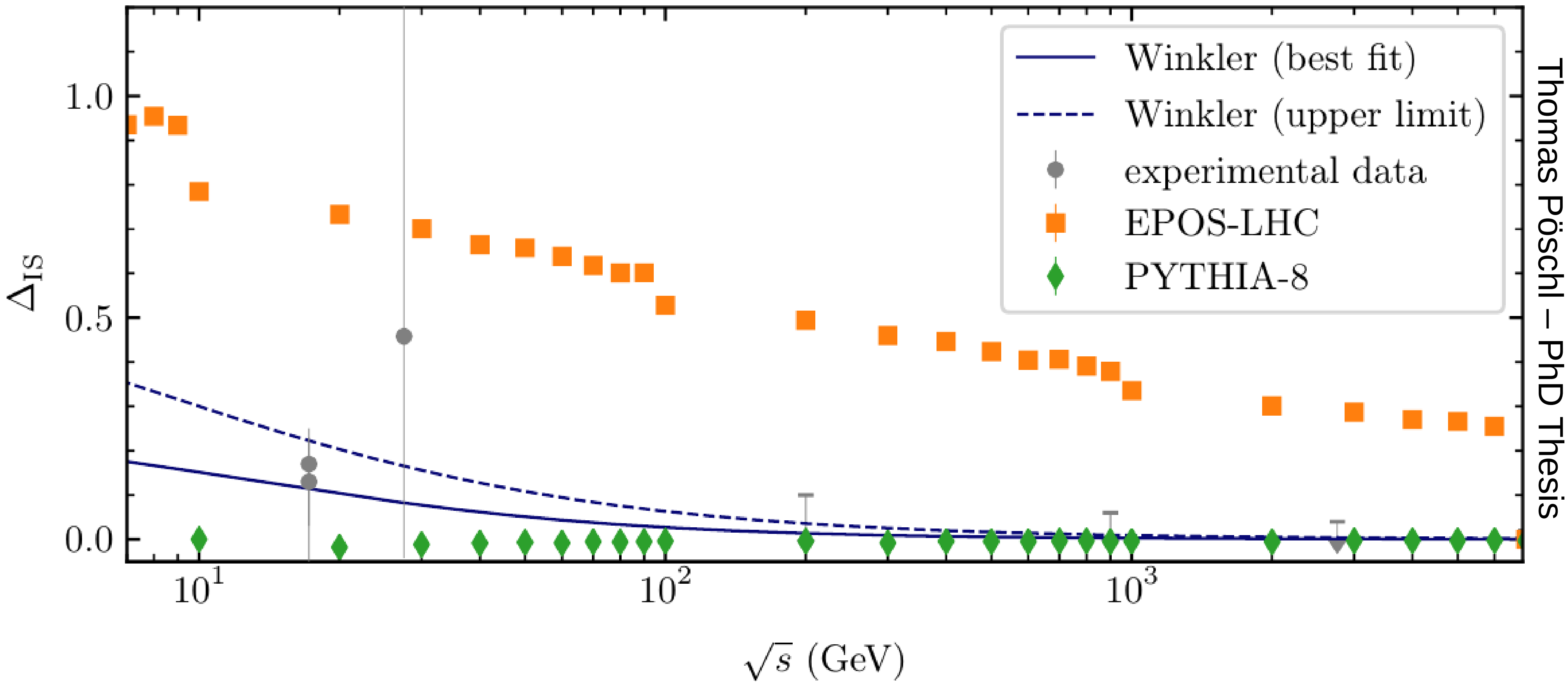
Low ρ fraction and isospin sym. NOT broken (noIB)



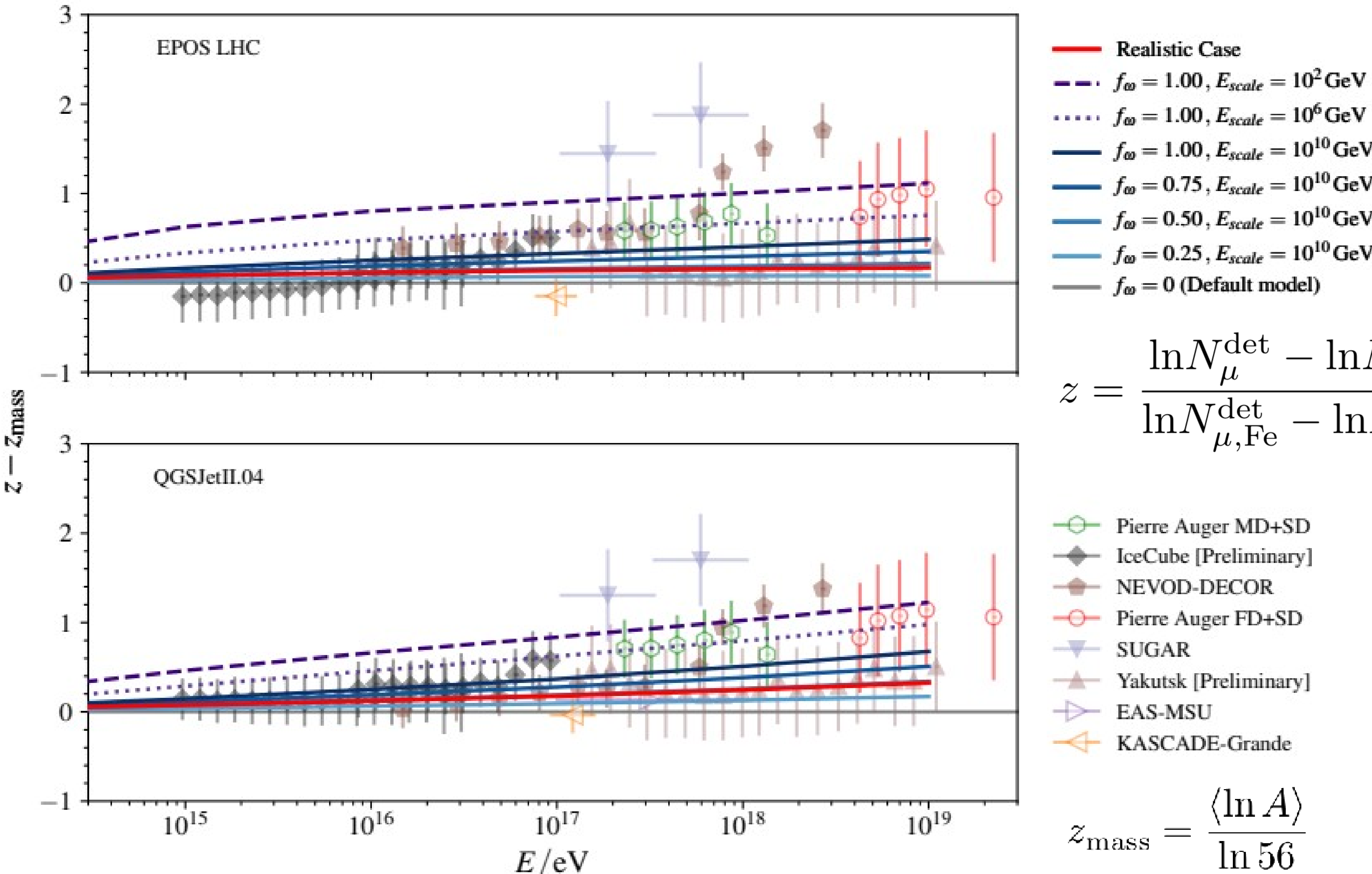


Isospin Breaking for Baryons

- NA49 data better reproduce with more neutrons than protons, but large uncertainties
- Large isospin breaking in EPOS LHC lead to additional baryons
  - But TOO large → EPOS LHC-R corrected (5% assymmetry) !



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

Hadronization in Simulations

- **Historically (theoretical/practical reasons) string fragmentation used in high energy models (Pythia, Sibyll, QGSJET, ...) for proton-proton.**
  - ➡ Light system are not “dense”
  - ➡ Works relatively well at SPS (low energy)
  - ➡ But problems already at RHIC, clearly at Fermilab, and serious at LHC :
    - Modification of string fragmentation needed to account for data
    - Various phenomenological approaches :
      - ➡ Color reconnection
      - ➡ String junction
      - ➡ String percolation, …
    - Number of parameters increased with the quality of data …
- **Statistical model only used for heavy ion (HI) in combination with hydrodynamical evolution of the dense system : QGP hadronization**
  - ➡ Account for flow effects, strangeness enhancement, particle correlations...

Core-Corona appoach and CR

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

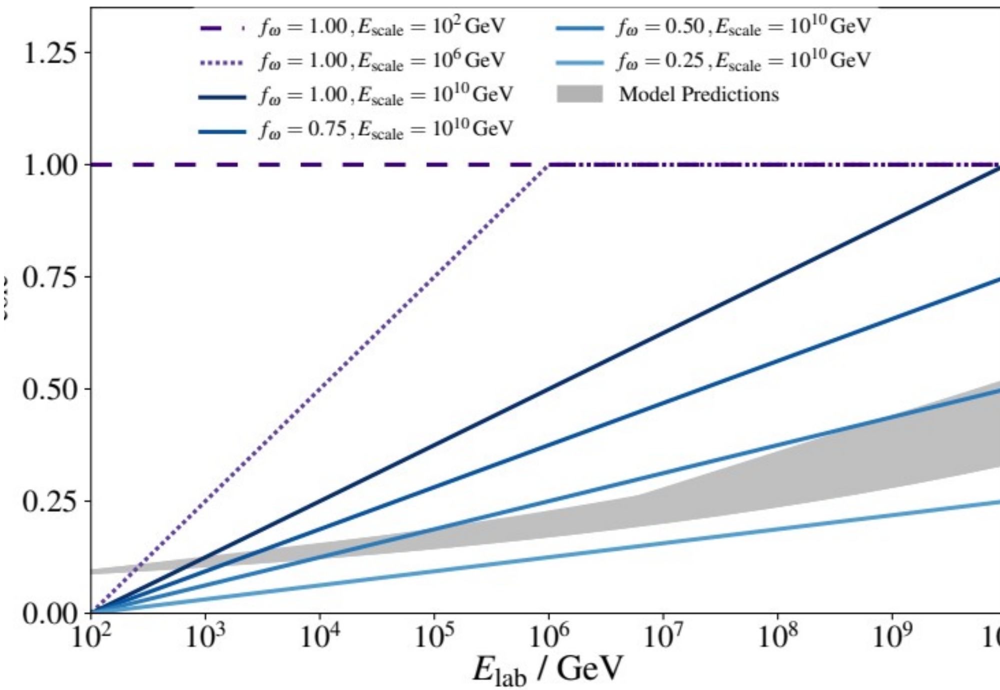
- Particle ratios from statistical model are known (tuned to PbPb) and fixed : core
- Initial particle ratios given by individual hadronic interaction models : corona
- Using CONEX, EAS can be simulated mixing corona hadronization with an arbitrary fraction ω_{core} of core hadronization: $N_i = \omega_{\text{core}}\,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

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

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

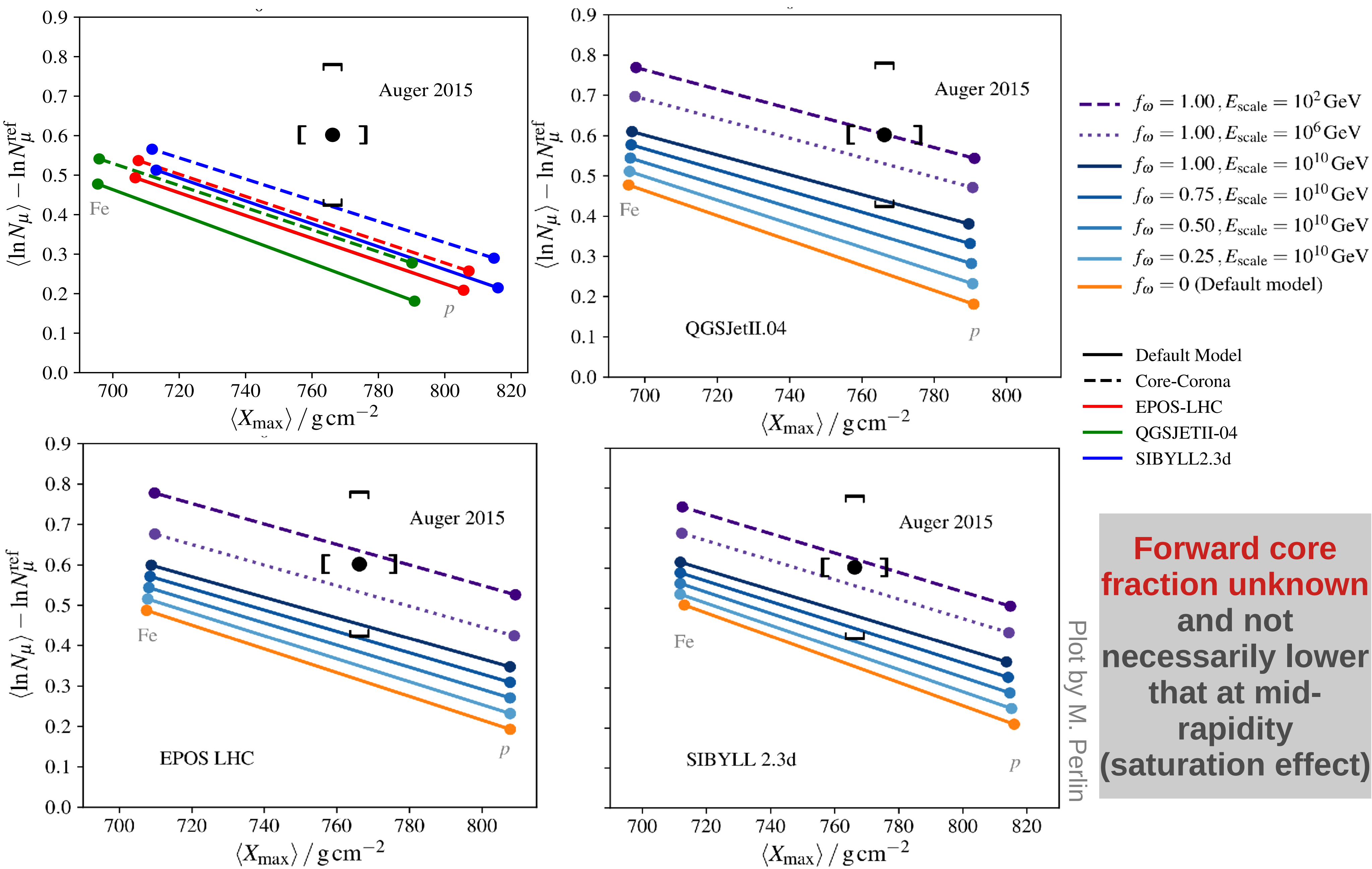
Different scenarii can be studied playing with f_ω and E_{scale}.

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



Plot by M. Perlin

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



Forward core fraction unknown and not necessarily lower that at mid-rapidity (saturation effect)

Phys.Rev.D 107 (2023) 9, 094031 1902.09265 [hep-ph]

Constraints from Correlated Change

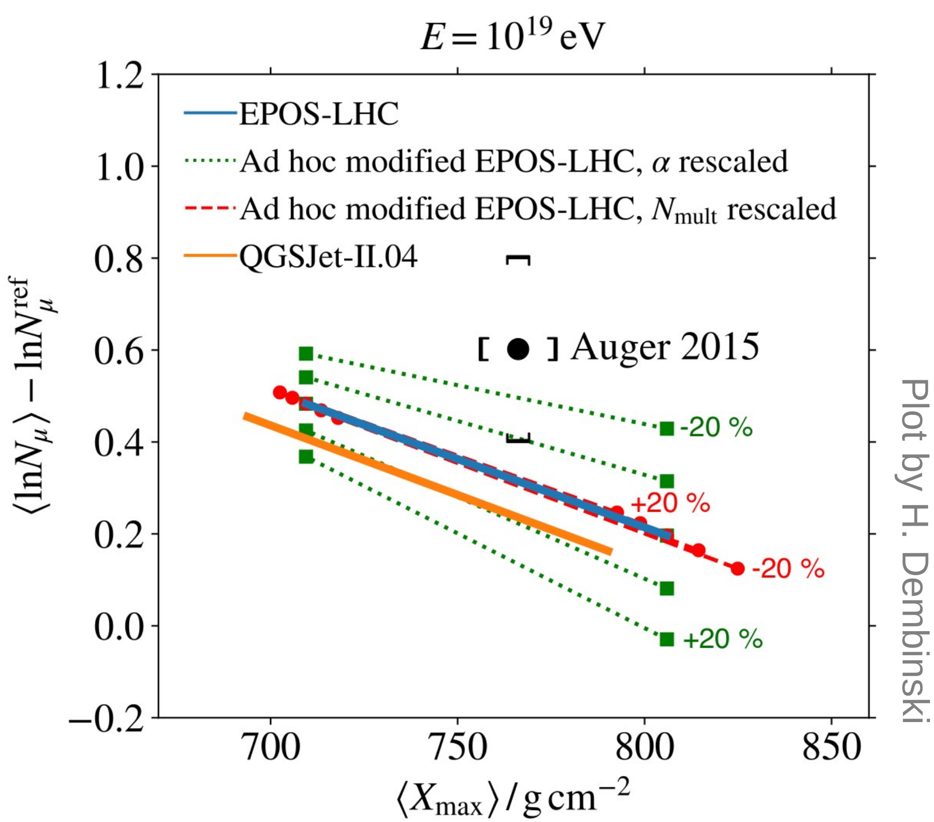
- **One needs to change energy dependence of muon production by ~+4%**

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

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

- **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}

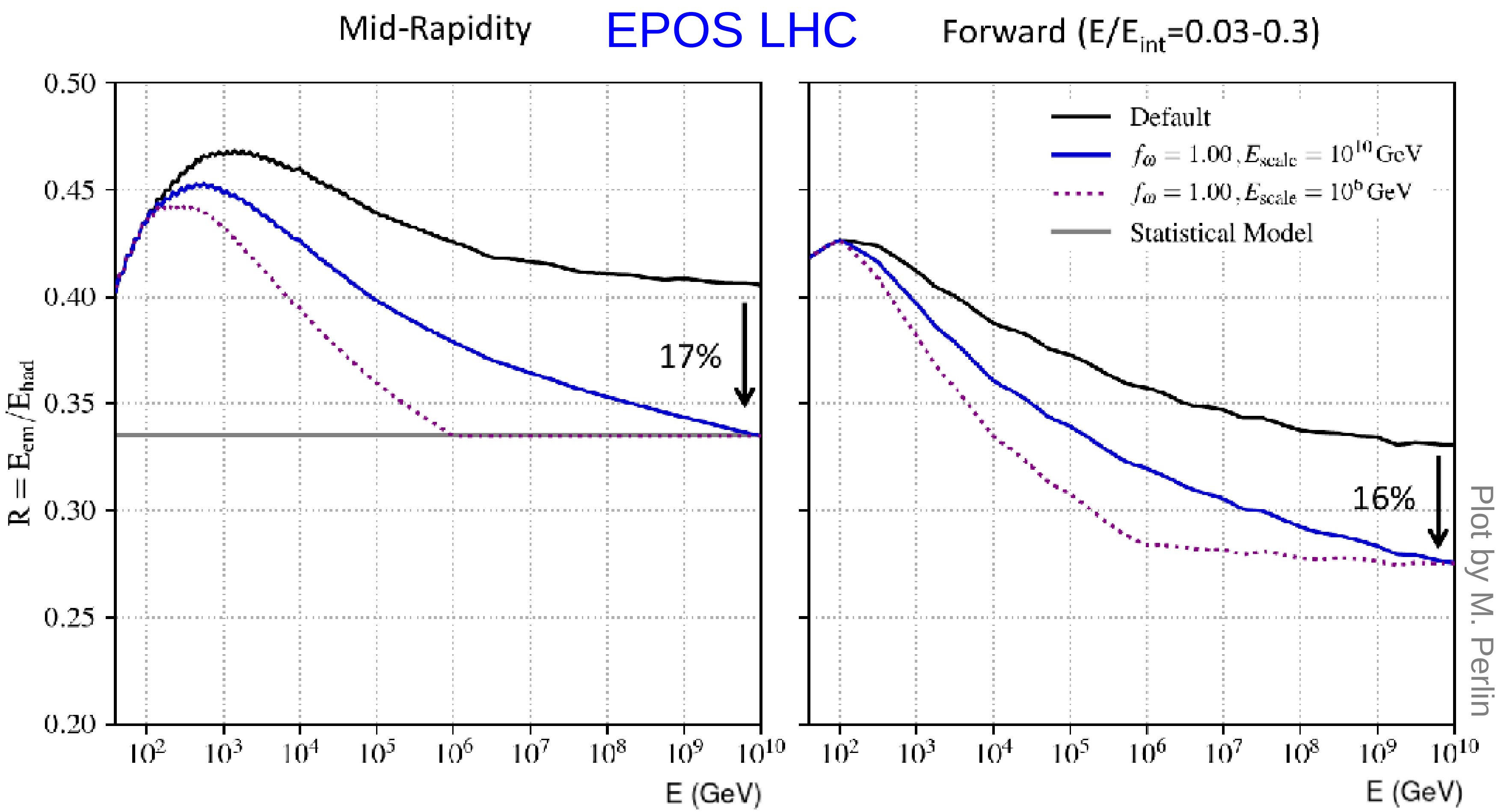
- $$\beta = \frac{\ln\left(N_{mult} - N_{\pi^0}\right)}{\ln\left(N_{mult}\right)} = 1 + \frac{\ln\left(1-\alpha\right)}{\ln\left(N_{mult}\right)}$$
  - ➔ +4% for β ➤ -30% for $\alpha = \frac{N_{\pi^0}}{N_{mult}}$



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 $\alpha = \frac{N_{\pi^0}}{N_{mult}}$ or $R(\eta) = \frac{\langle \mathrm{d}E_{\mathrm{em}}/\mathrm{d}\eta \rangle}{\langle \mathrm{d}E_{\mathrm{had}}/\mathrm{d}\eta \rangle}$ which define the muon production in air showers.



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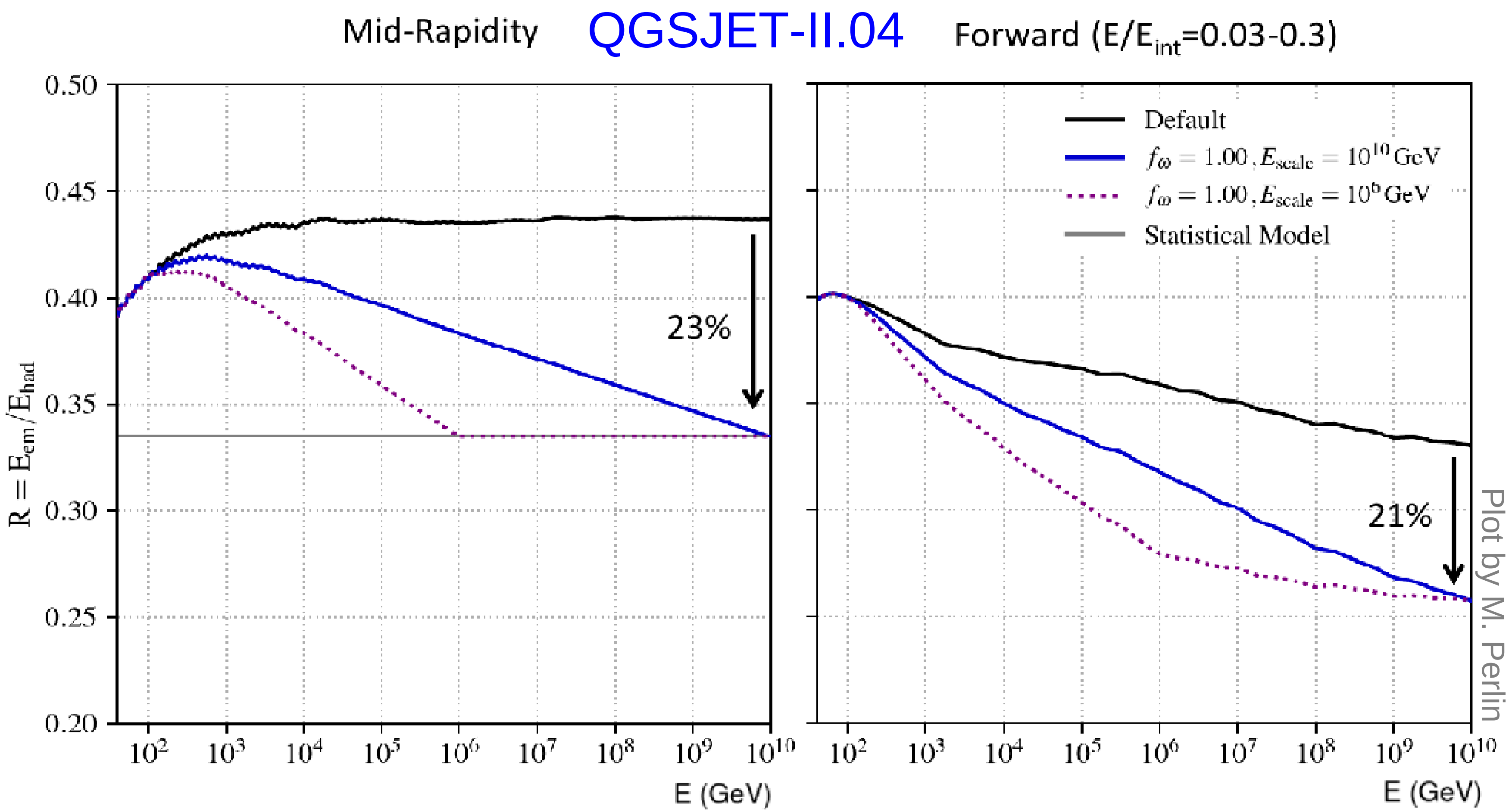
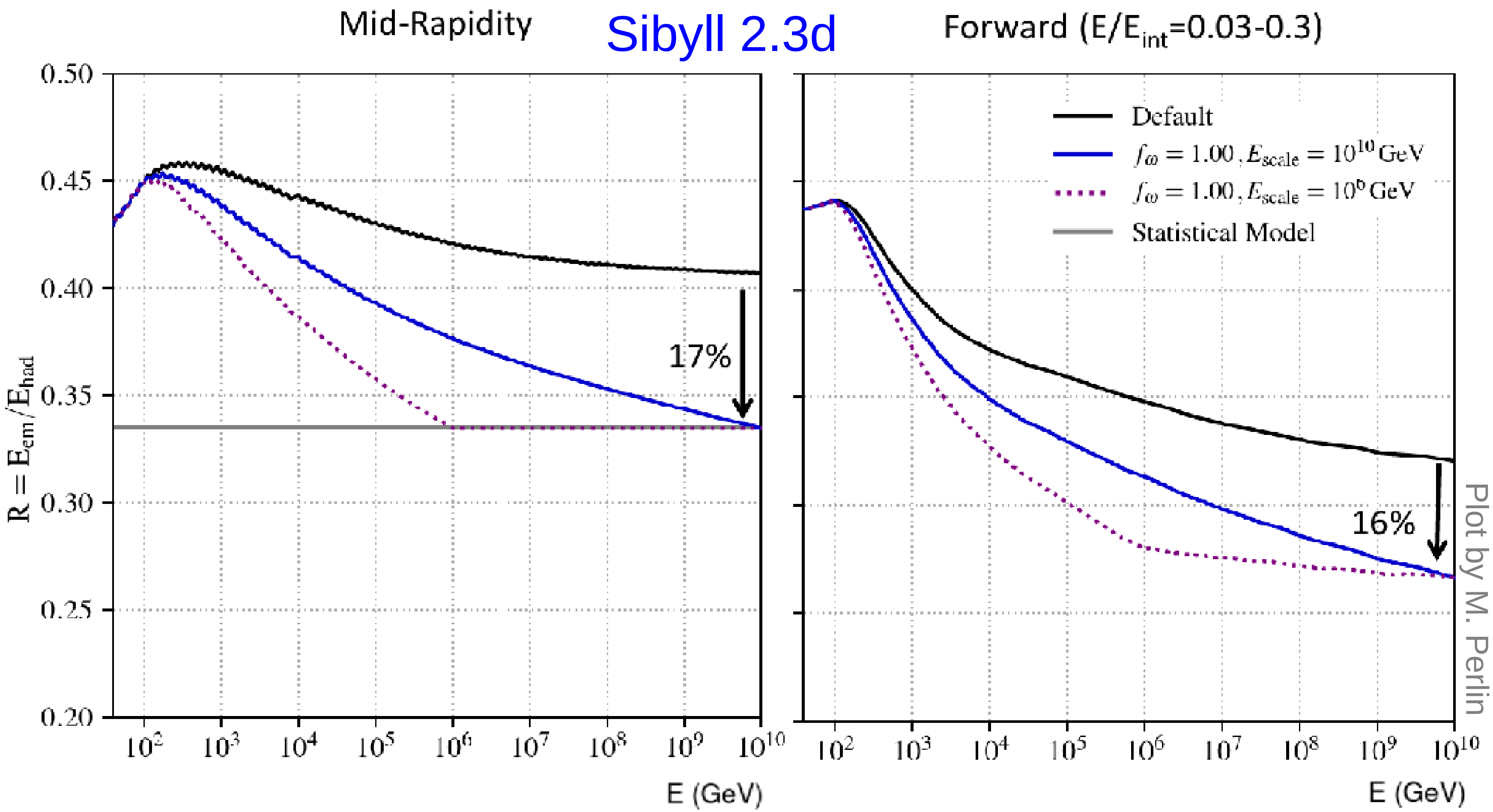


Evolution of hadronization from core to corona

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

➡ Change of ω_{core} with energy change $\alpha = \frac{N_{\pi^0}}{N_{mult}}$ or $R(\eta) = \frac{\langle \mathrm{d}E_{\mathrm{em}}/\mathrm{d}\eta \rangle}{\langle \mathrm{d}E_{\mathrm{had}}/\mathrm{d}\eta \rangle}$ which define the muon production in air showers.

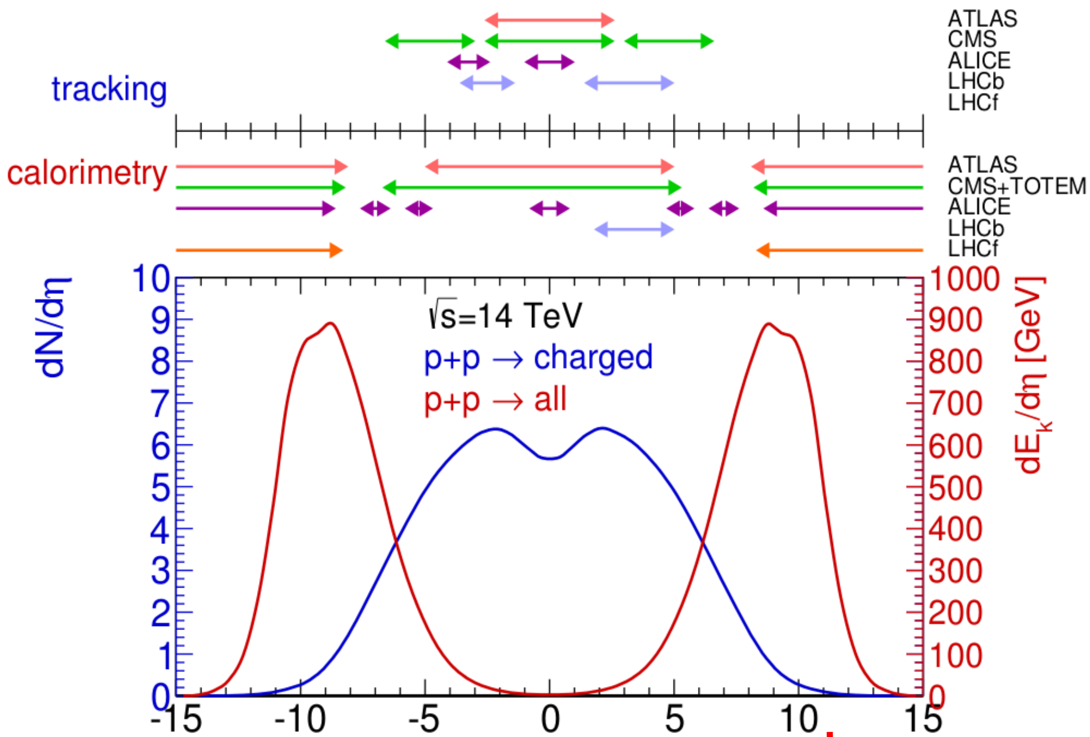


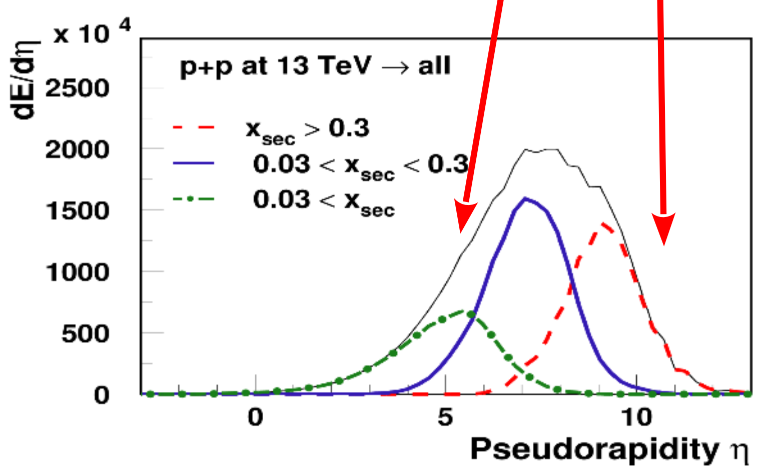
Possible Particle Physics Explanations

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., Julien Manshanden) ?
  - 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 (enhanced strangeness and baryon production reduces relative π^0 fraction. Baur et al., arXiv:1902.09265) !
  - α depends on the hadronization scheme
    - How is it done in hadronic interaction models ?

LHC acceptance and Phase Space



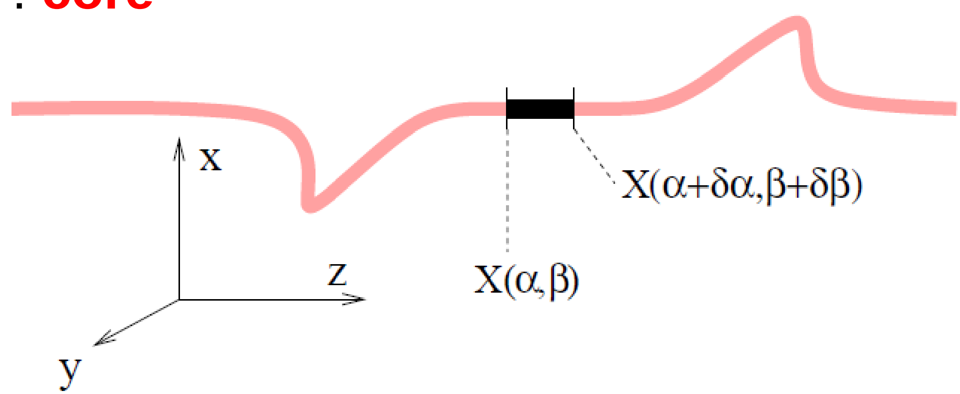


- **p-p data mainly from "central" detectors**
  - pseudorapidity η=-ln(tan(θ/2))
  - θ=0 is midrapidity
  - θ>>1 is forward
  - θ<<1 is backward
- **Different phase space for LHC and air showers**
  - most of the particles produced at midrapidity
    - important for models
  - most of the energy carried by forward (backward) particles
    - important for air showers

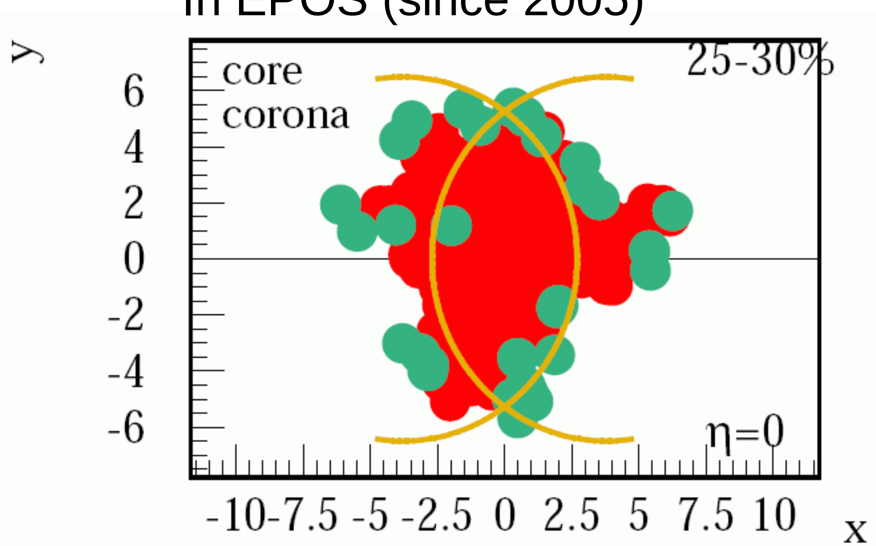
A 3rd way : the core-corona approach

Consider the local density to hadronize with strings OR with QGP:

- First use string fragmentation but modify the usual procedure, since the density of strings will be so high that they cannot possibly decay independently : **core**



In EPOS (since 2005)



- Each string cut into a sequence of string segments, corresponding to widths δα and δβ in the string parameter space
- If energy density from segments high enough
  - segments fused into core
    - flow from hydro-evolution
    - statistical hadronization
- If low density (corona)
  - segments remain hadrons