Cross-Sections in EPOS

Tanguy Pierog

Karlsruhe Institute of Technology, Institute for Astroparticle Physics, Karlsruhe, Germany

With K.Werner, SUBATECH, Nantes, France

XSCRC2024, CERN, Swisserland

October the 17th 2024

Outline

- **Introduction**
- **Updates $\rightarrow$ EPOS LHC-R**
  - ➡ Cross-section, Multiplicity, Fragmentation and Diffraction
- **Core-corona**
- **Production Cross-sections**
  - ➡ impact of collective effect on particle production

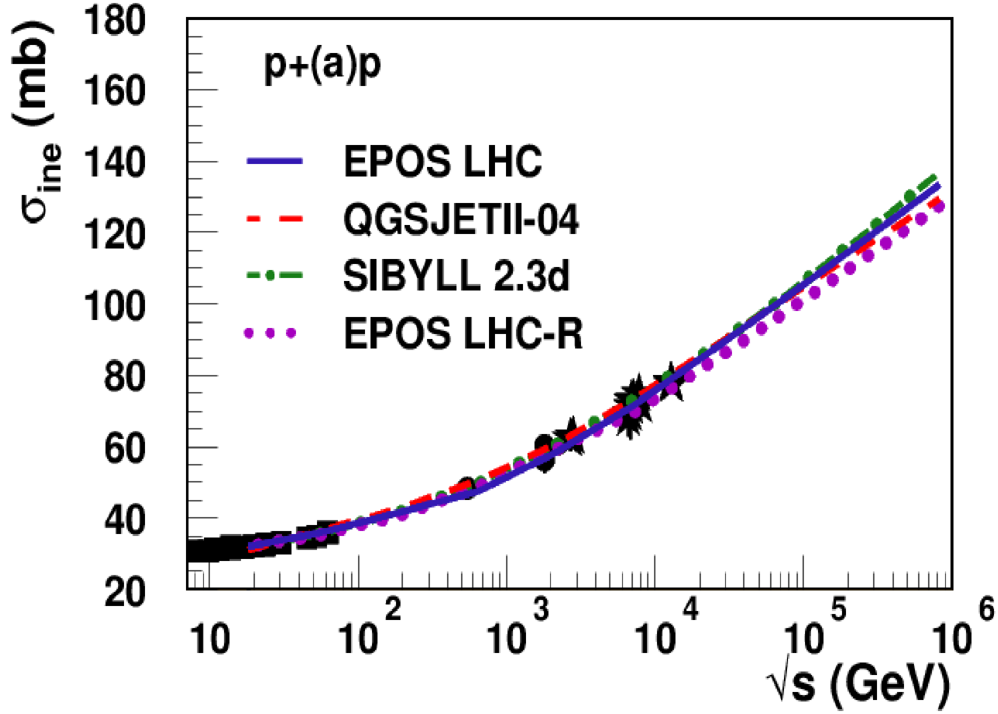
Recent LHC data provide new constraints on models changing fine details on hadronization could be more important than thought until now, impacting the particle production cross-sections.

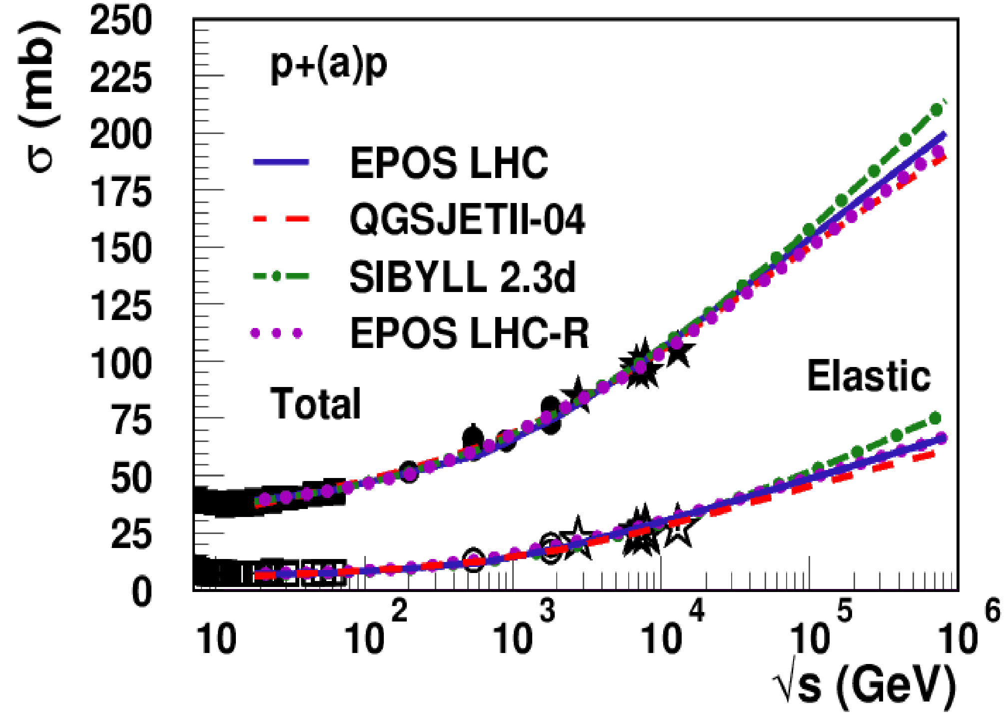
Model Improvements

- **Update of EPOS LHC → EPOS LHC-R**
  - New EPOS 4 available for heavy ion physics but not usable at variable energies
  - 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 !
- **Update to latest NA61 and LHC data :**
  - Update of the p-p cross sections (ALFA)
  - Data at 13 TeV (CMS, ATLAS, LHCf)
  - More detailed p-Pb measurements (fluctuations) ALICE
  - Particle yields as a function of multiplicity (ALICE, LHCb)
    - Very important to understand the mechanism behind particle production
  - Charm production

Inelastic Cross-Section

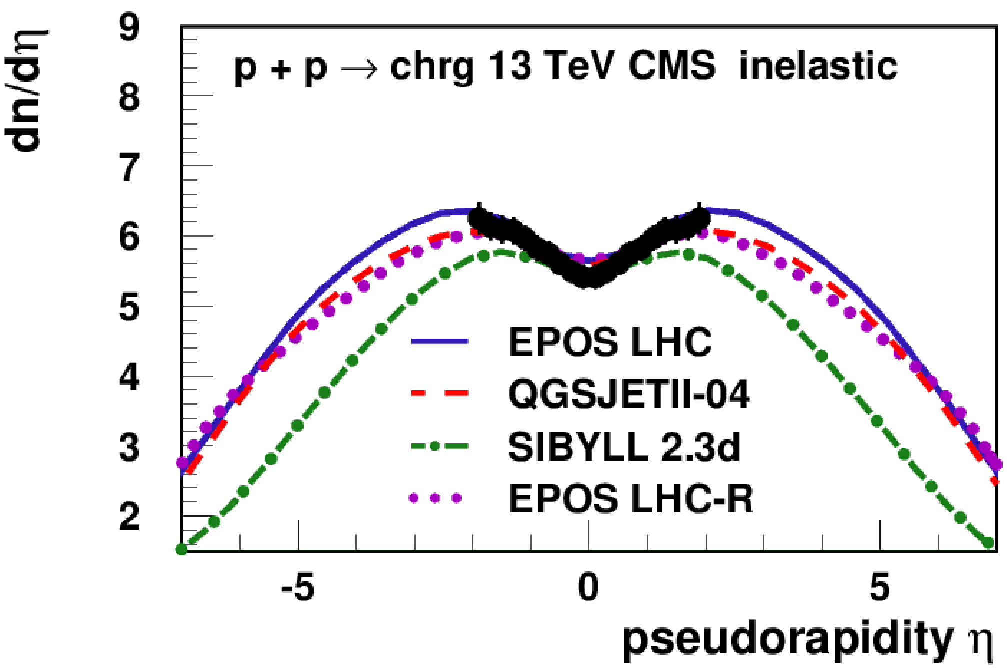
- **Probability for the particle to interact : directly related to X_{max}**
- **After TOTEM (CMS), new measurements by ALFA (ATLAS) with higher precision**
  - ➡ p-p inelastic cross-section reduced

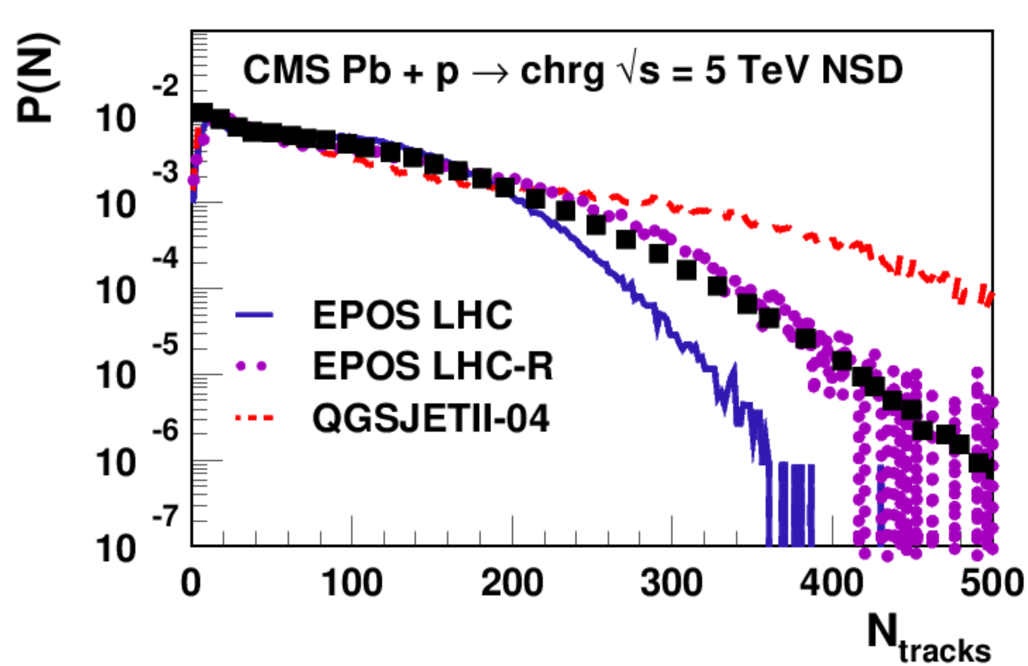




Pseudorapidity

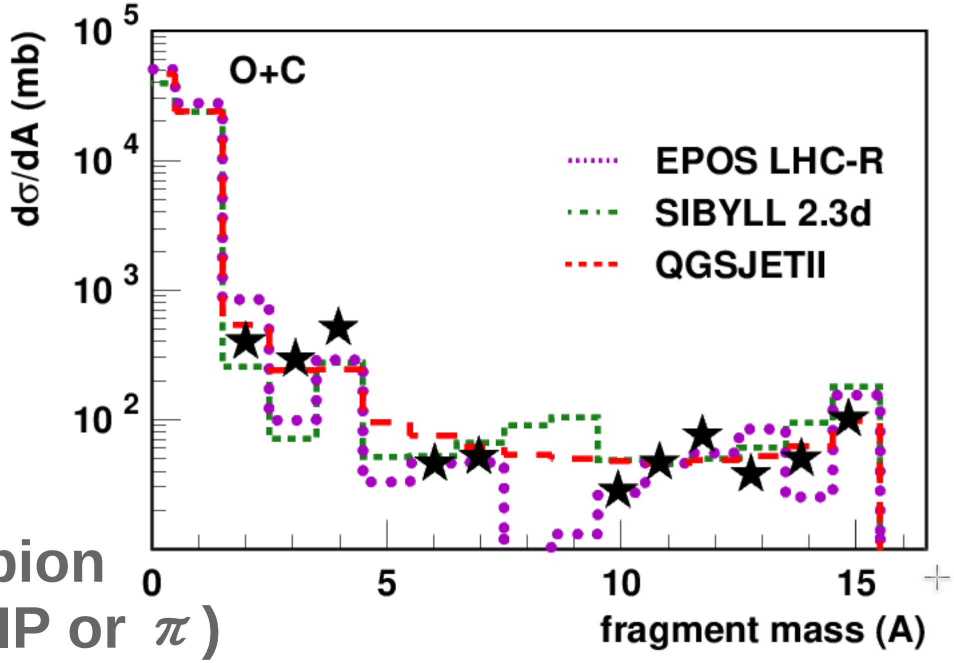
- **Angular distribution of newly produced particles**
- **New data at 13 TeV in p-p**
  - ➜ Test extrapolation with different triggers
  - ➜ Sibyll has a clear difference with other models (and data) : too narrow !
- **Detailed data at 5 TeV for p-Pb**
  - ➜ Wrong multiplicity distributions in all models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



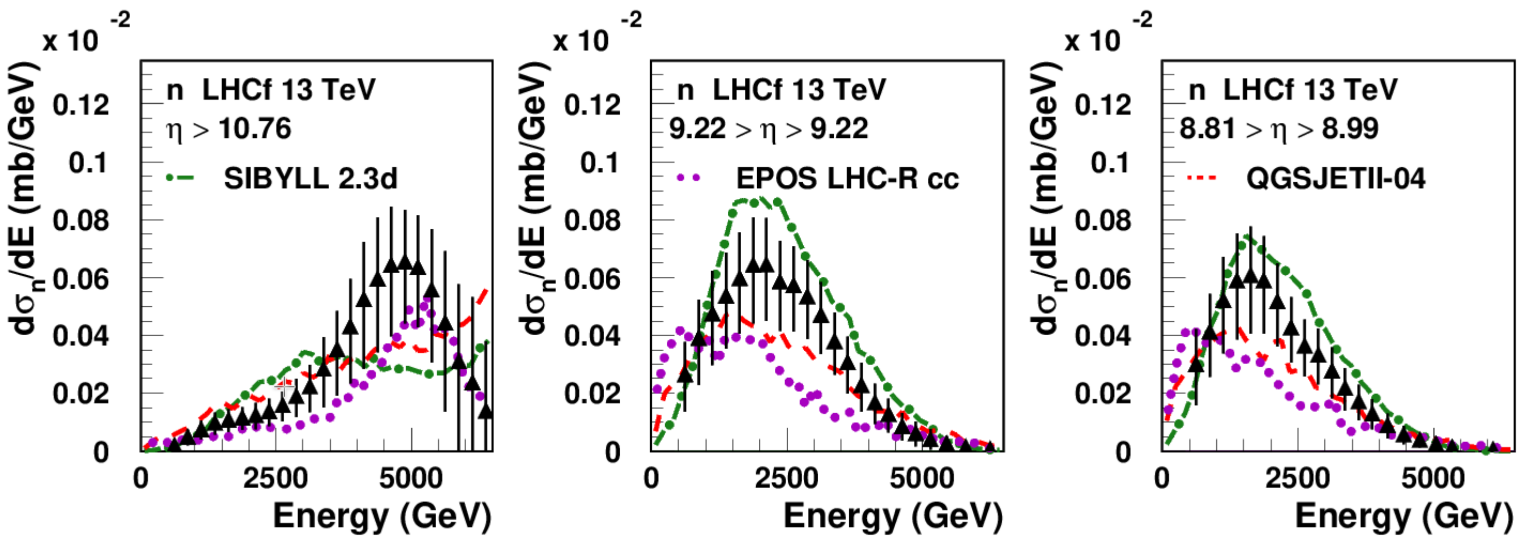


Improvements in EPOS LHC-R

- 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 nuclear fragment production cross-sections



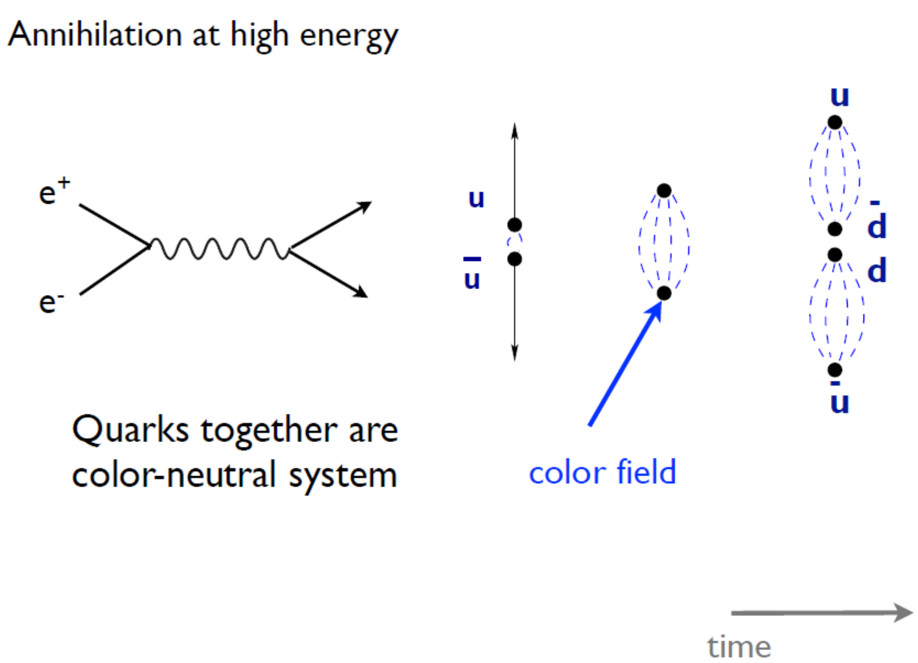
- Simplified high mass diffraction and pion exchange replaced by real emission (IP or π)

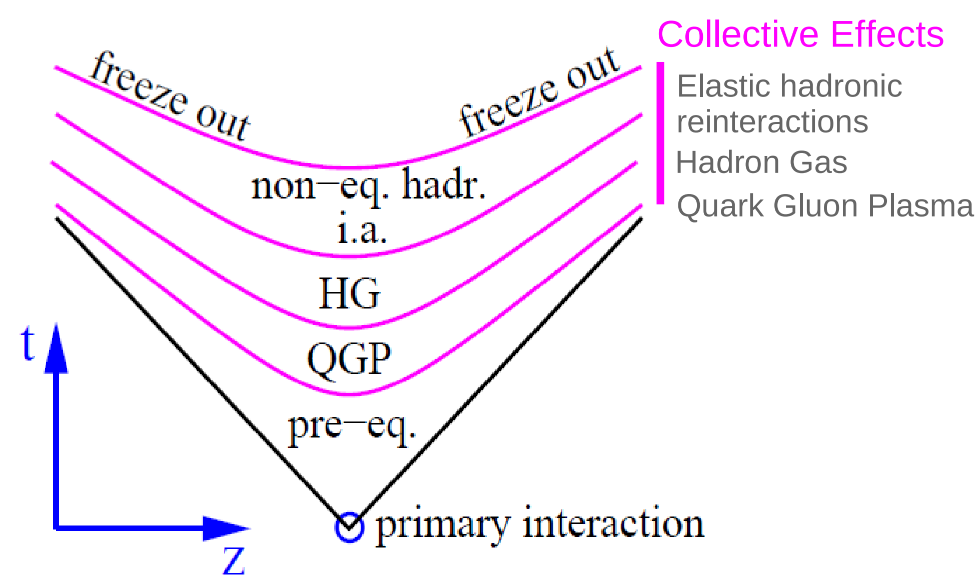


Hadronization Models

2 models well established for 2 extreme cases

➡ String Fragmentation vs Collective hadronization (statistical models)





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

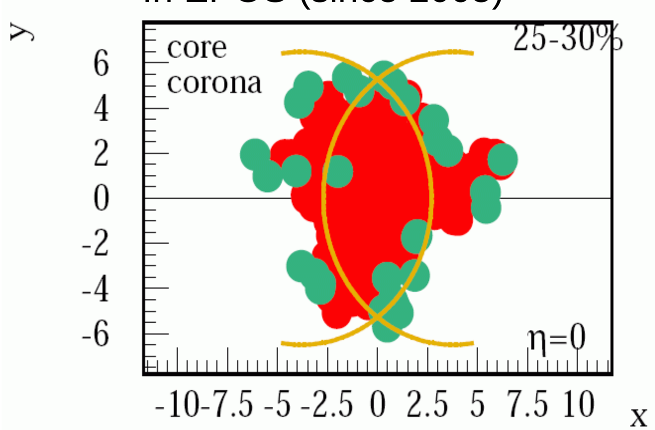
In dense systems… CORE
→ “low” π^0 fraction

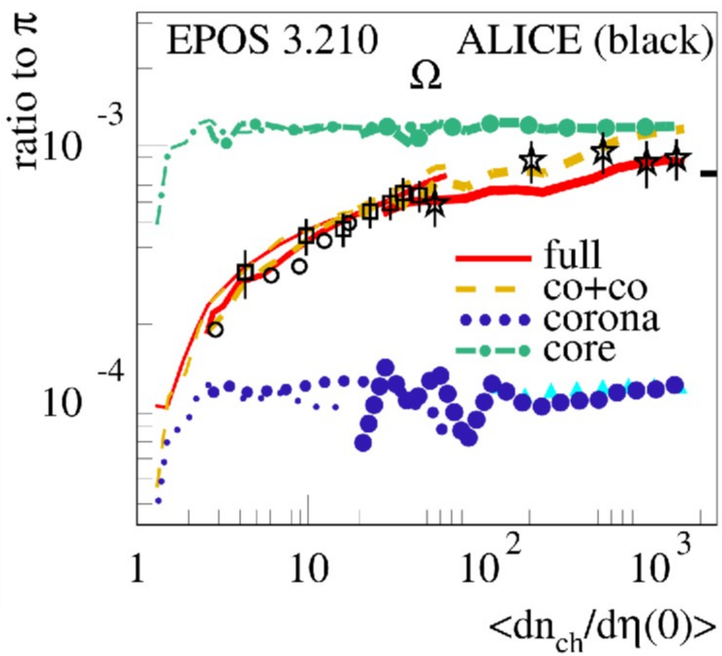
➡ What to do in between ? For proton-proton, hadron-Nucleus, ...

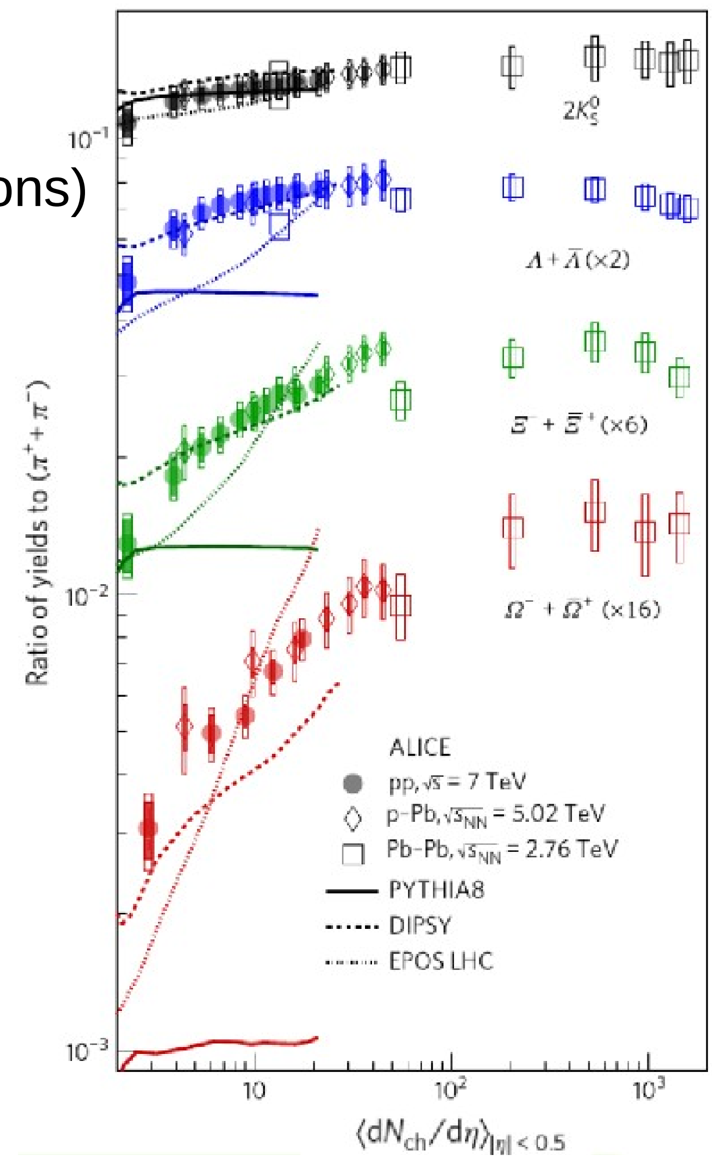
Core-Corona (CC) Approach

- **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)

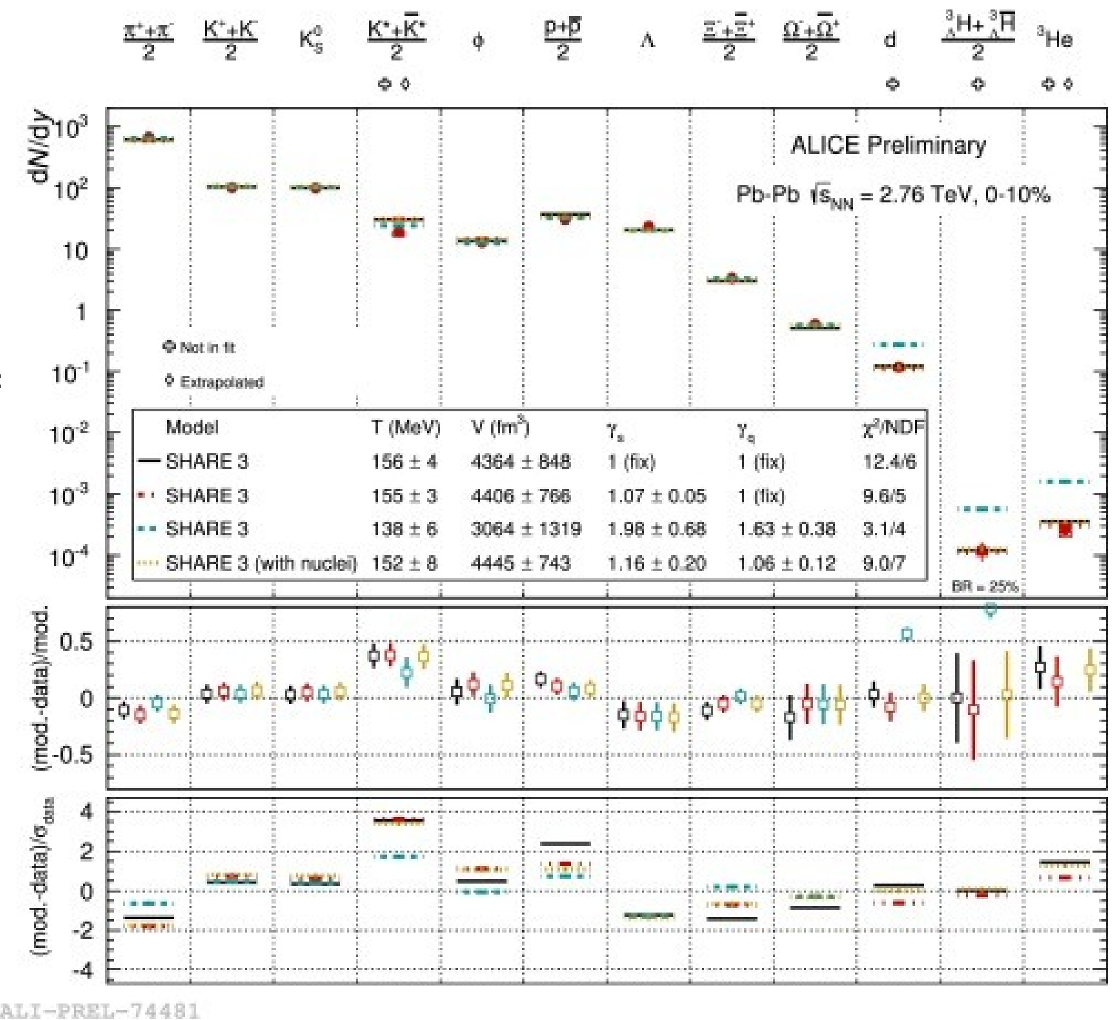






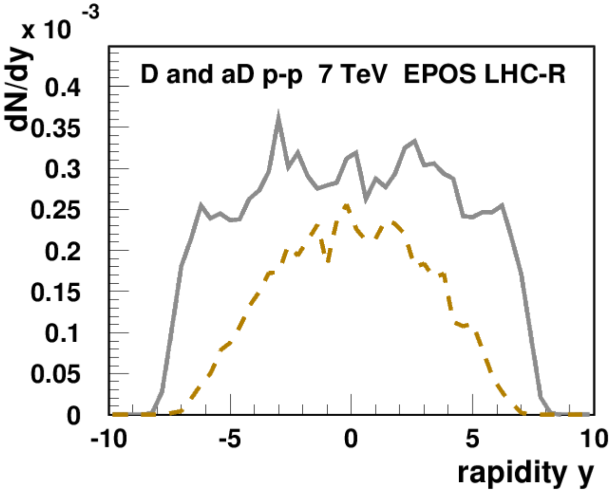
Antideuteron with Core-Corona

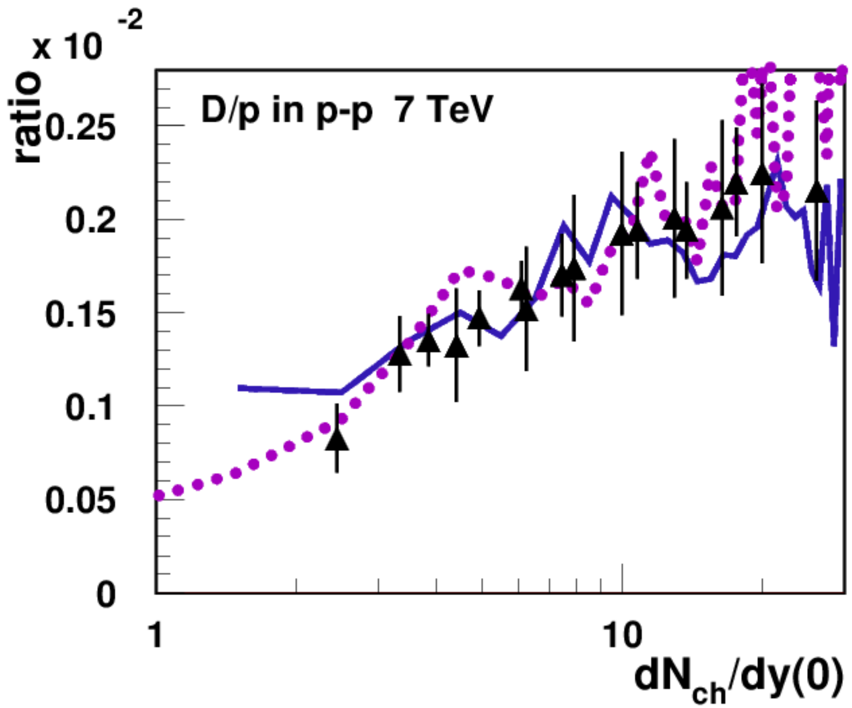
- **2 types of hadronization**
  - ➡ Corona (low density) : standard string hadronization without light (anti-)nucleus
  - ➡ Core (high density) : collective (thermal) hadronization
- **Thermal hadronization**
  - ➡ Good description of light (anti-)nuclei production in heavy ion collisions
  - ➡ Parameters fixed by other type of particles
  - ➡ No need for coalescence
- **Energy/system/centrality evolution fixed by core/corona ratio**
  - ➡ Source of different coalescence parameters ? Possible test ...

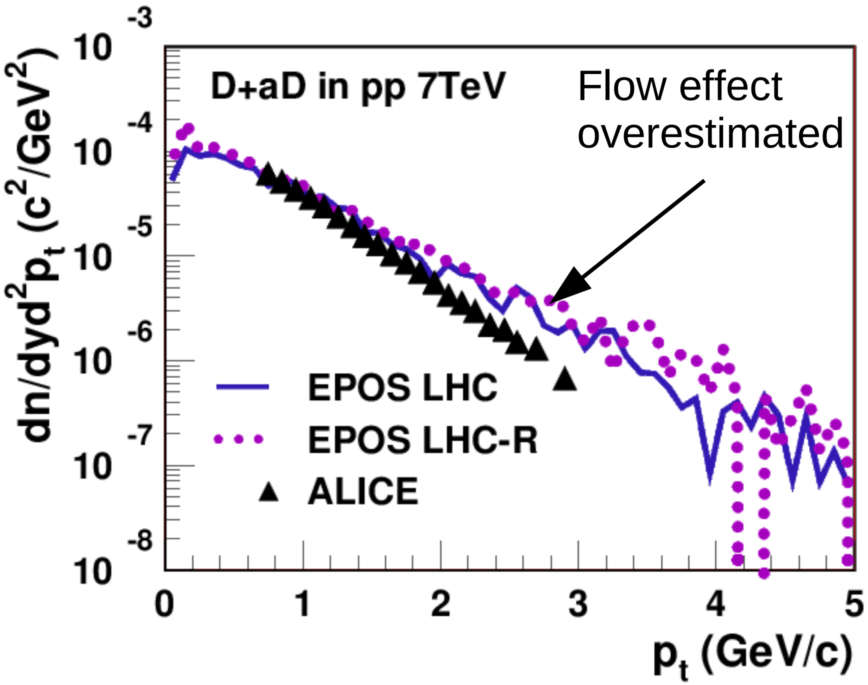


Antideuteron in EPOS

- **Core easier to produce (lower energy density) in EPOS LHC-R**
  - ➡ Core effect start at lower center of mass energy than EPOS LHC
  - ➡ Effect can be checked with more data (RHIC, SPS,...)
- **Once the core/corona fixed**
  - ➡ light (anti-)nuclei production yield fixed by thermal model



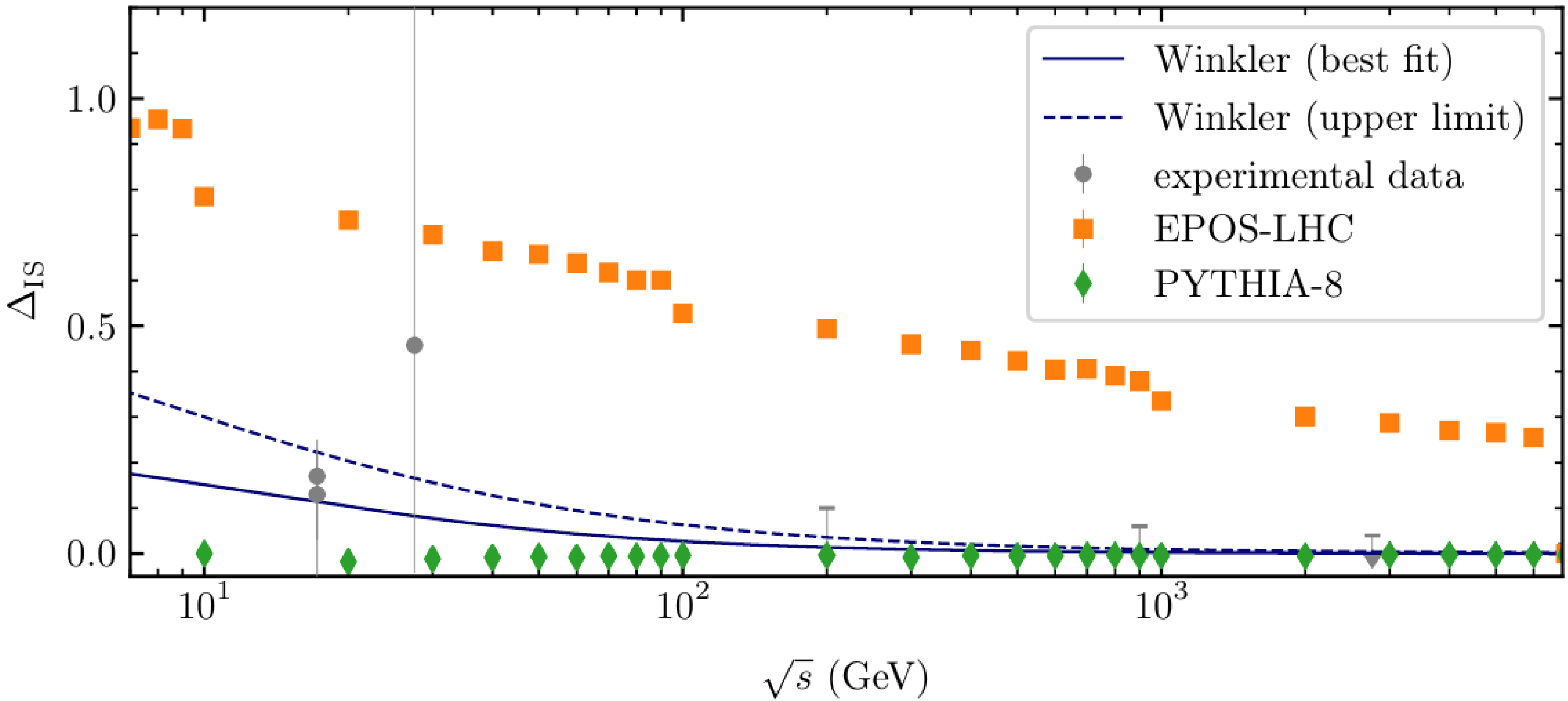




Neutron Production

- NA49 data better reproduce with more neutrons than protons, but large uncertainties
- Large isospin breaking in EPOS LHC lead to additional baryons

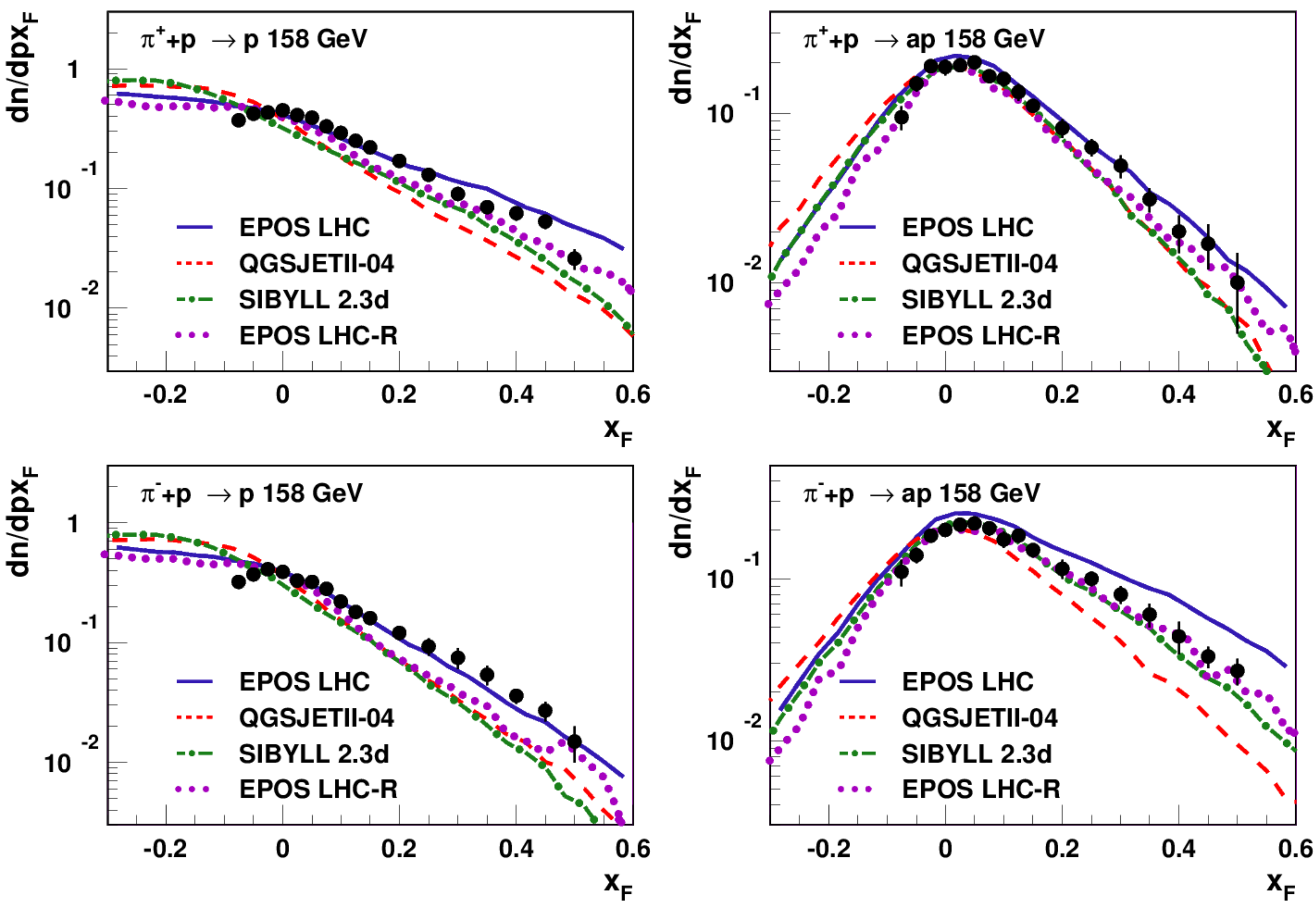
  - But TOO large → EPOS LHC-R corrected (5% assymmetry) !



Thomas Pöschl – PhD Thesis

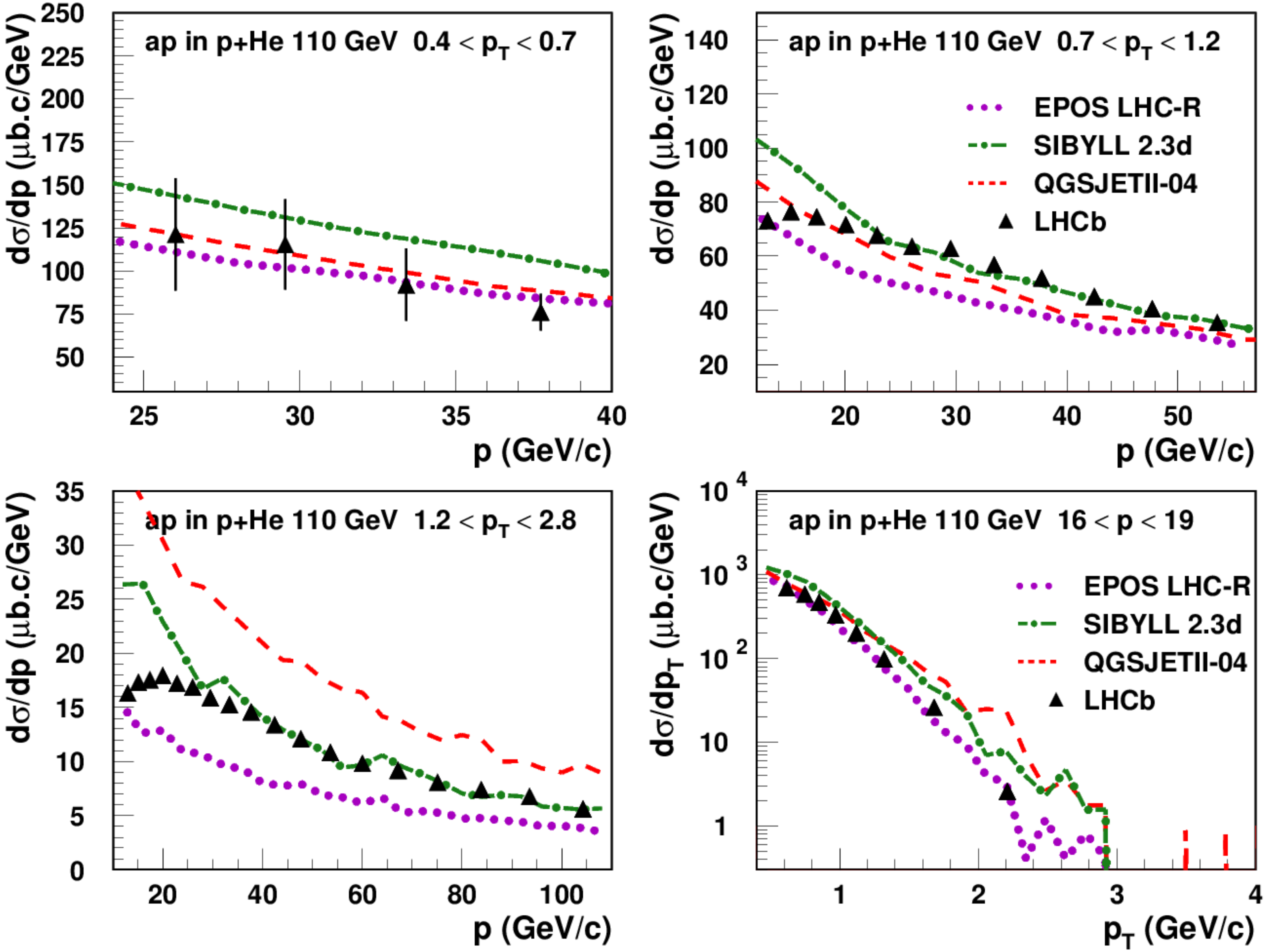
Baryons in Pion Interactions

Data from NA49 (Gabor Veres PhD) : full picture



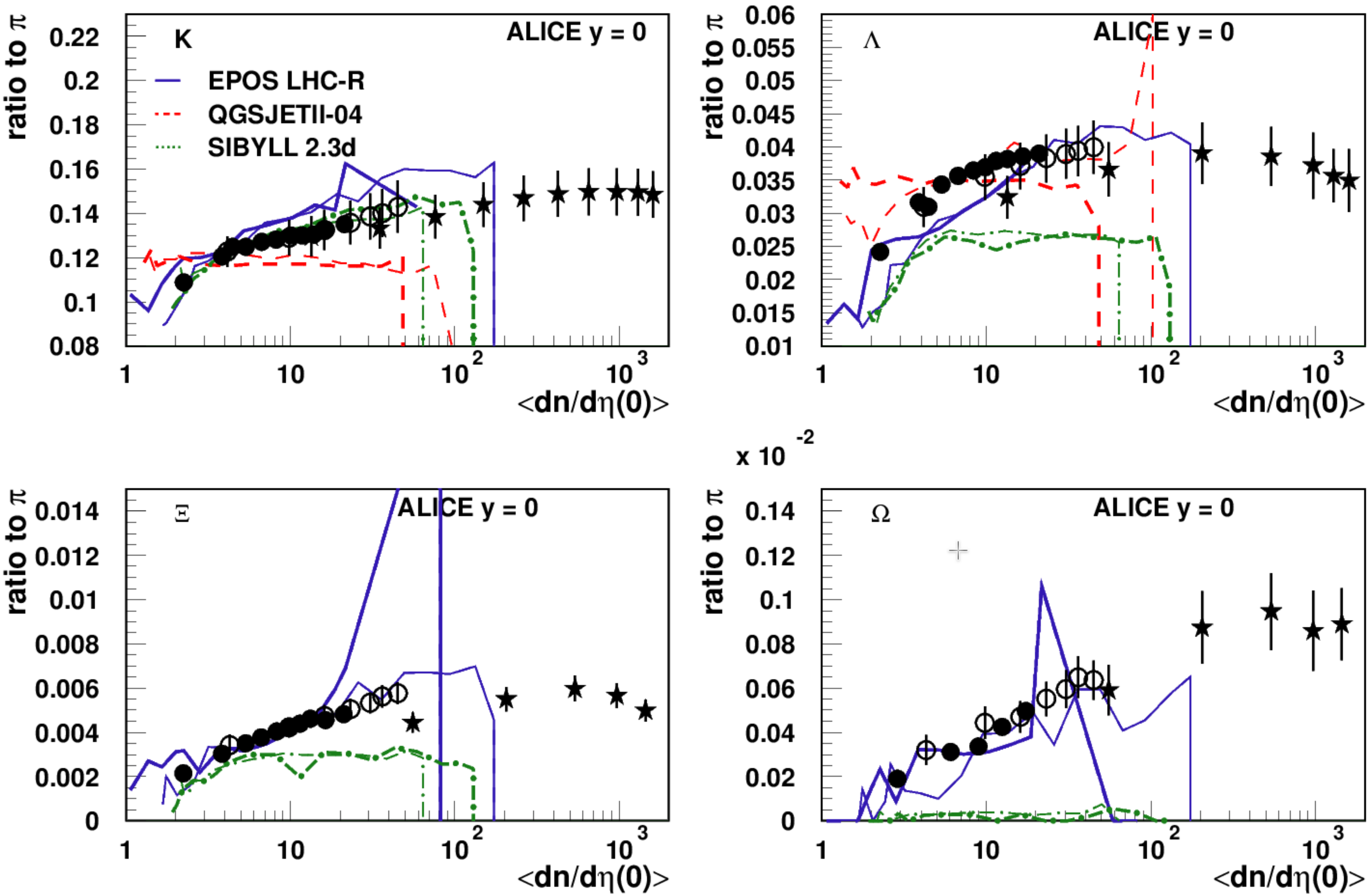
LHCb Data

p+He interaction 6.5 TeV lab energy



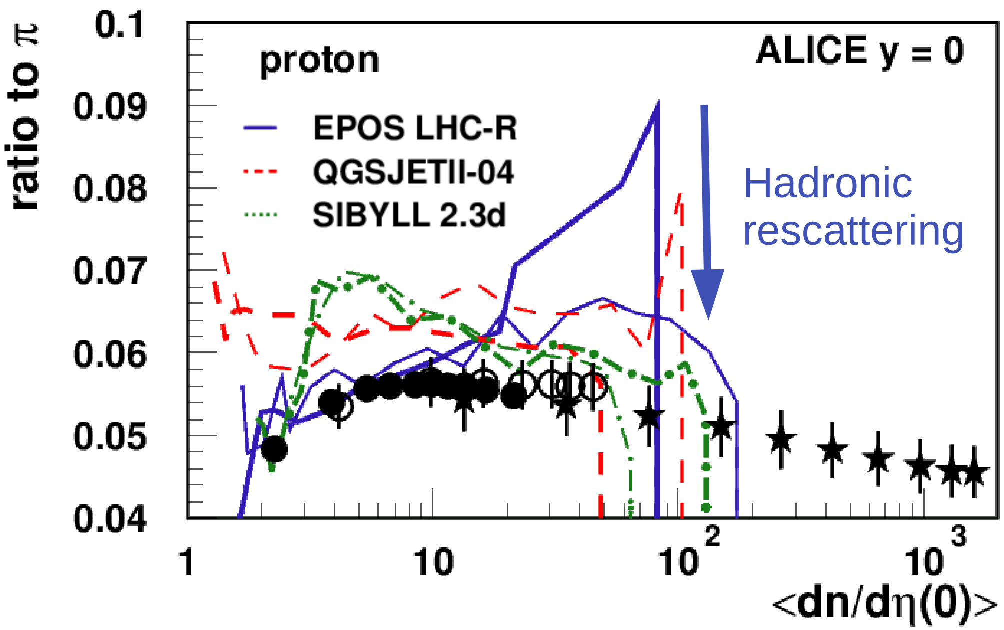
ALICE Data

pp interactions at 7 TeV (thick) or at all energies (thin)

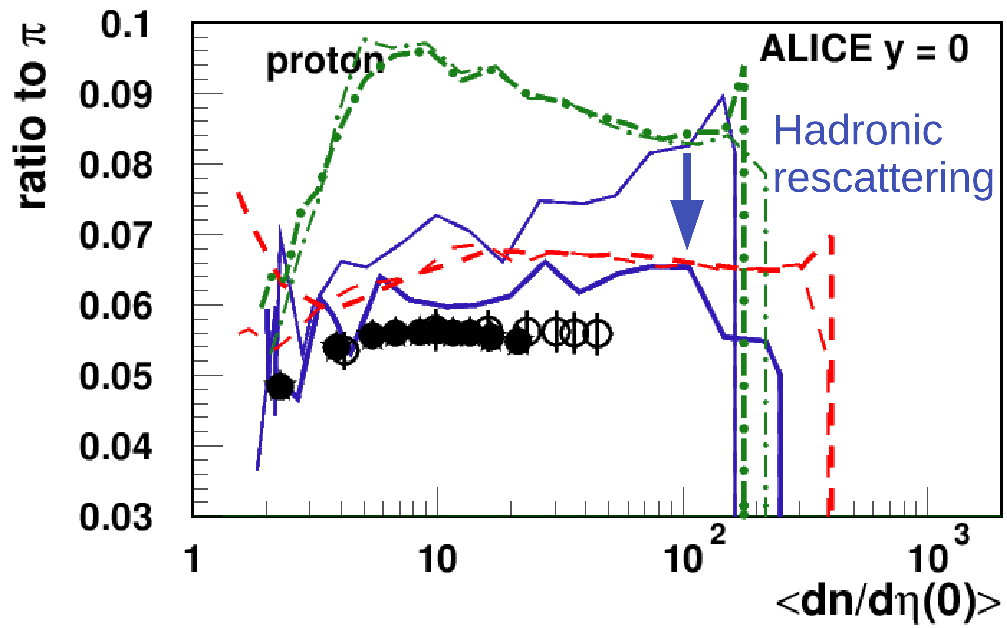


ALICE Data

pp interactions at 7 TeV (thick) or at all energies (thin)



pAir (thick) and piAir (thin) interactions at all energies



Very wide range of predictions for protons

- Weird behavior of Sibyll amplified with nuclear target
- Small energy dependence of proton cross-section in QGSJET-II-04
- Dependence only on multiplicity in EPOS
  - Important effect of hadronic rescattering on proton yield ! (difference between the lines in EPOS)

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 fragmentation**
  - Better for the propagation of CR
- **Details of hadronization matters**
  - Important role of resonance with sparse data = large uncertainty
    - Import to look at a maximum of data to better constrain the model
  - Evolution of strangeness with multiplicity
    - Different type of hadronization in core = more strangeness and baryons
  - **Core-corona provide a framework to predict light-nuclei production**

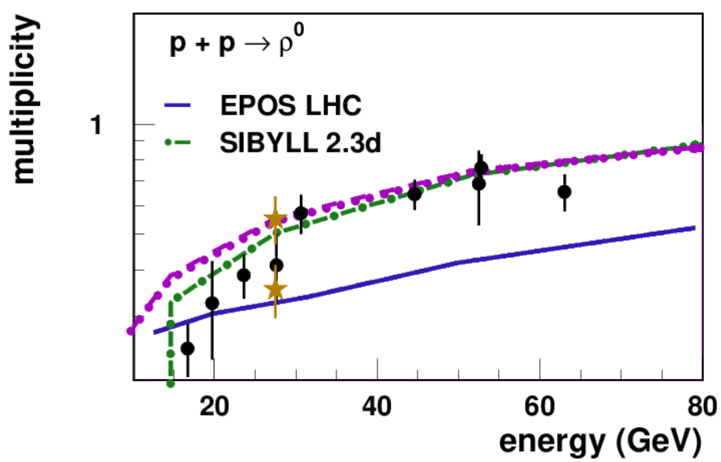
Updated EPOS LHC-R released in 2024 and then adapting EPOS 4 for CR

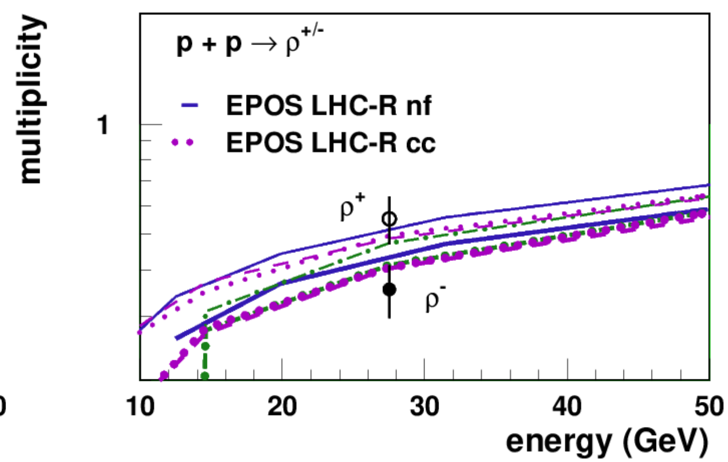
Recent LHC data provide new constraints on models changing fine details on hadronization could be more important than thought until now, impacting the particle production cross-sections.

Thank you !

Resonances Production in Corona

- **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 less μ production
  - But ρ^0 decay in $\pi^{+/-}$
    - More ρ^0 means more μ production
- **Mass asymmetry could lead to more ρ^0 than $\rho^{+/-}$**
    - Data not very constraining → use 20% asymmetry (high)

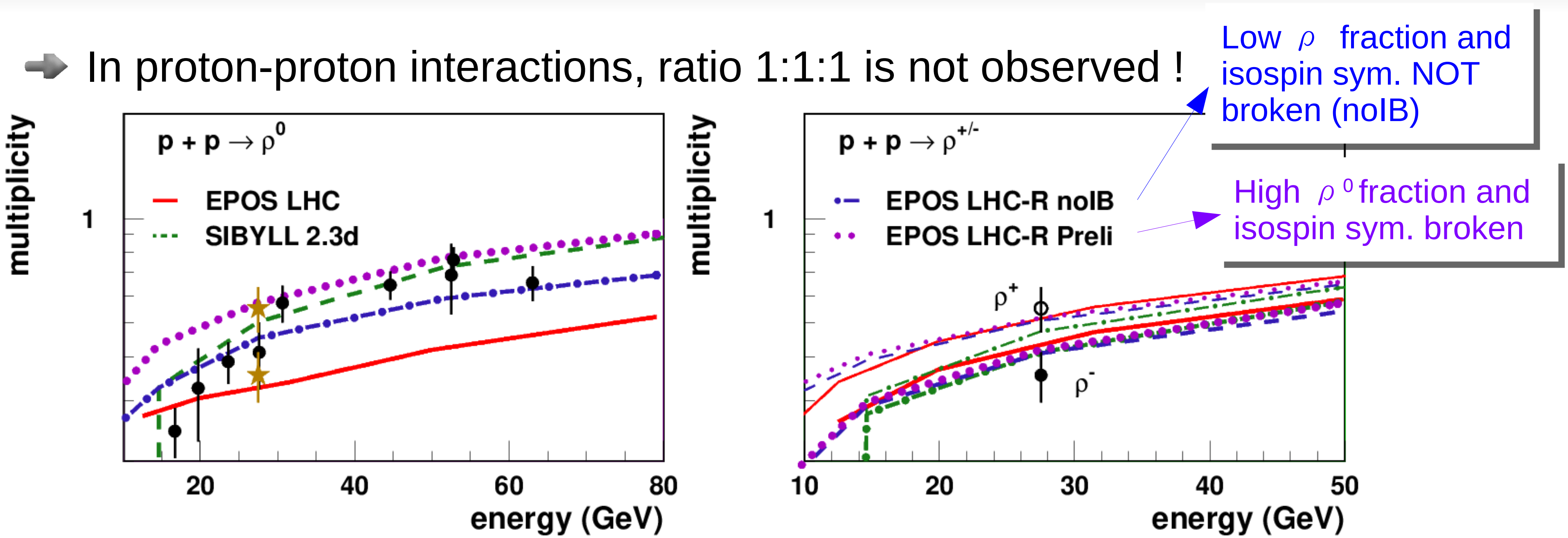




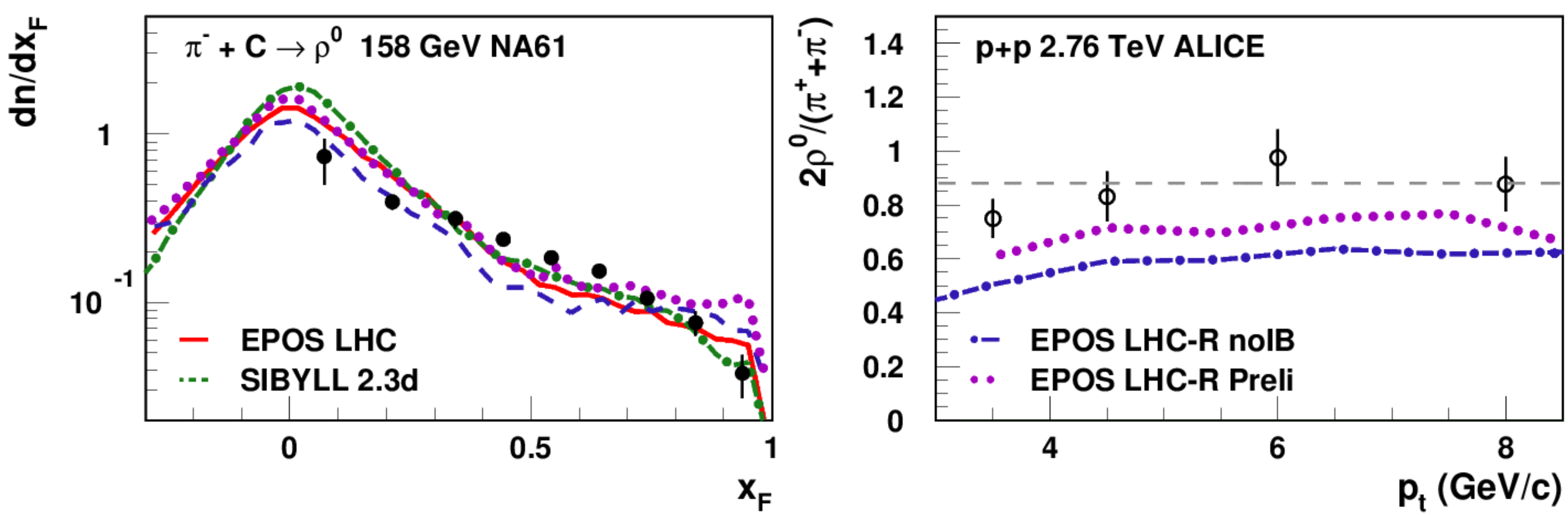
See TP ICRC 2023 contribution

Resonance Production

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

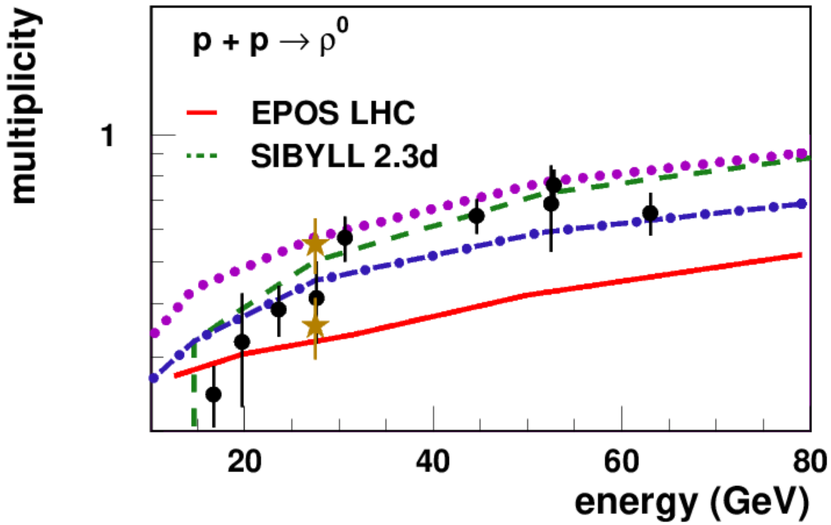


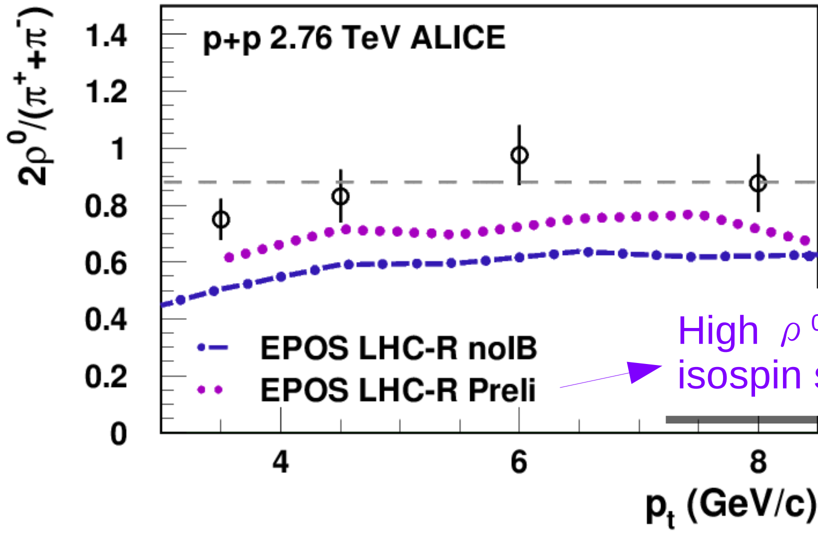
- AND high resonance fraction is favored !



Resonance Production

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

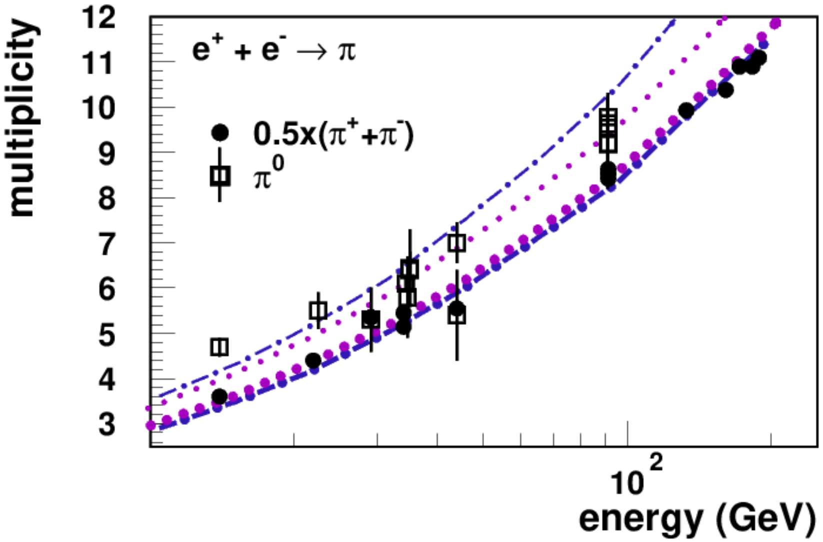


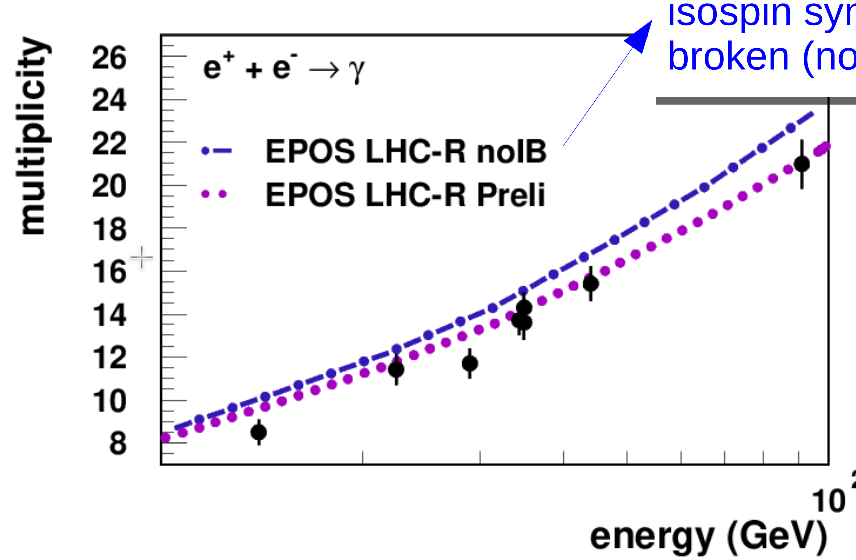


High ρ^0 fraction and isospin sym. broken

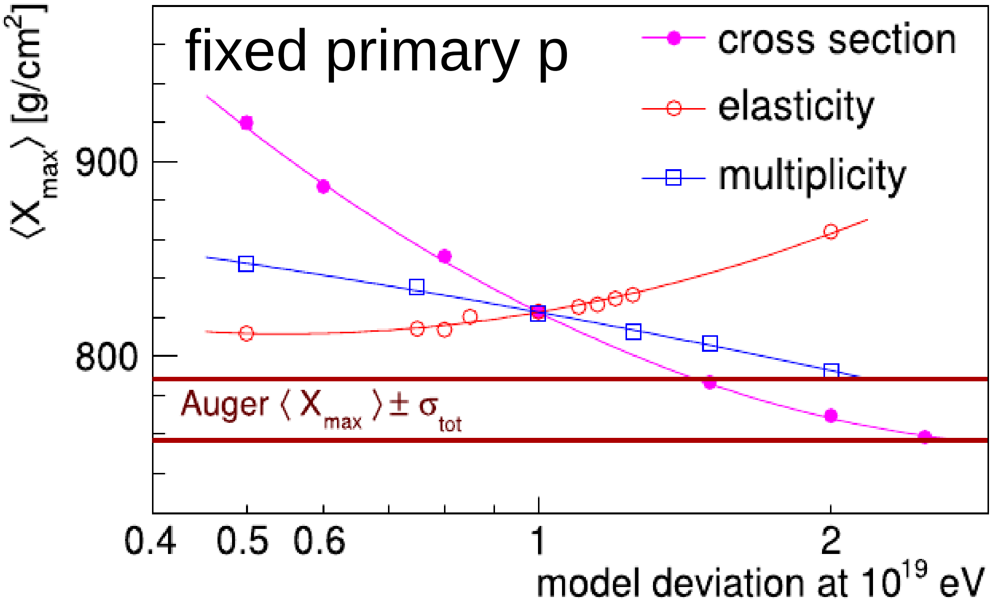
➡ Both favored in electron-positron data !

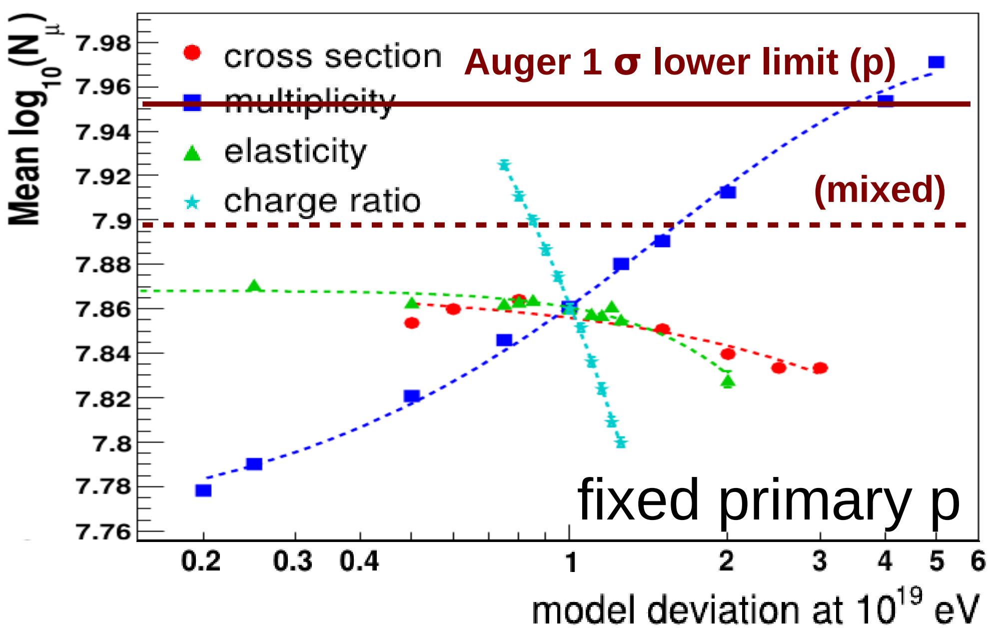
Low ρ fraction and isospin sym. NOT broken (noIB)





Sensitivity to Hadronic Interactions





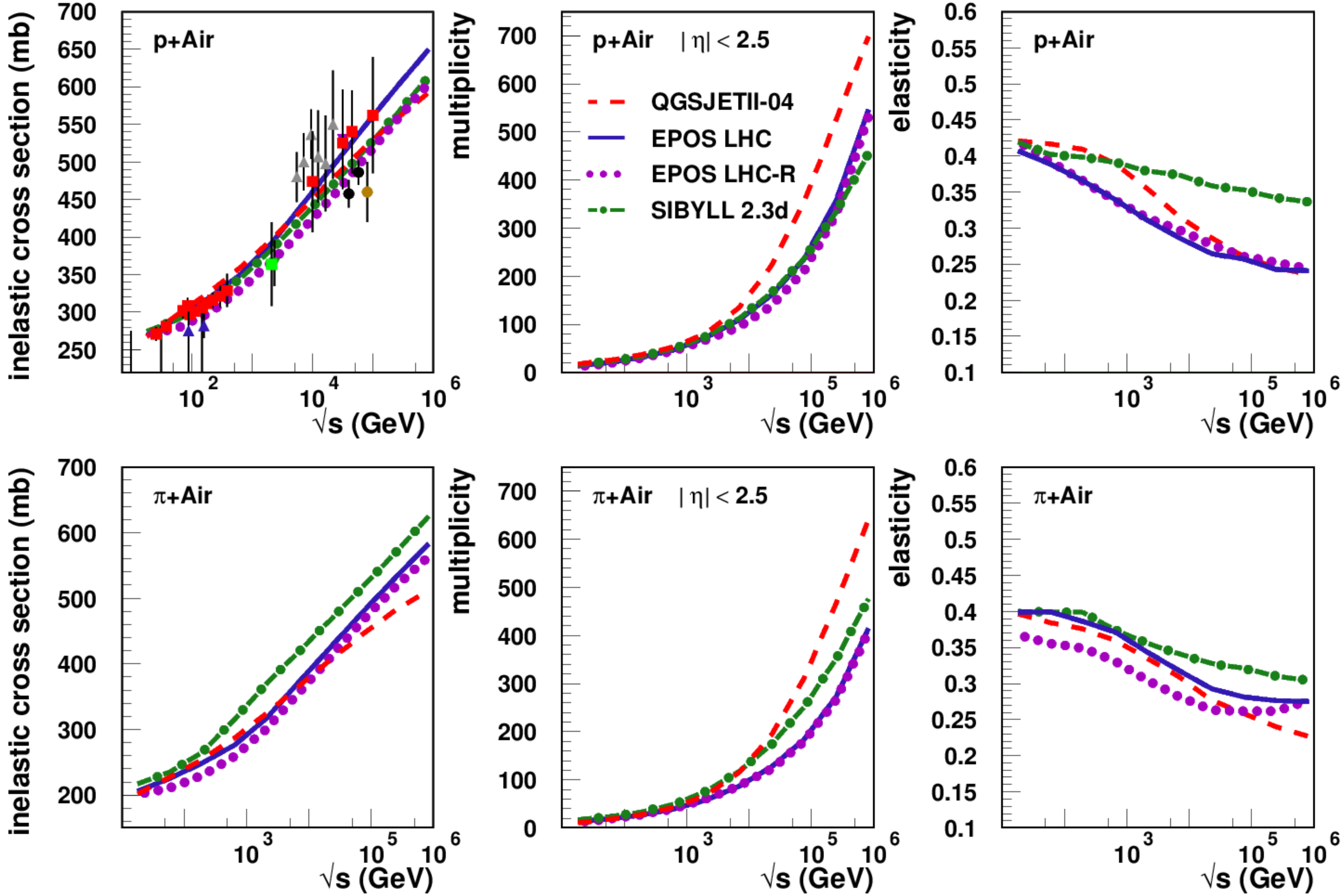
From R. Ulrich (KIT)

- **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 !

EPOS LHC-R interaction with Air

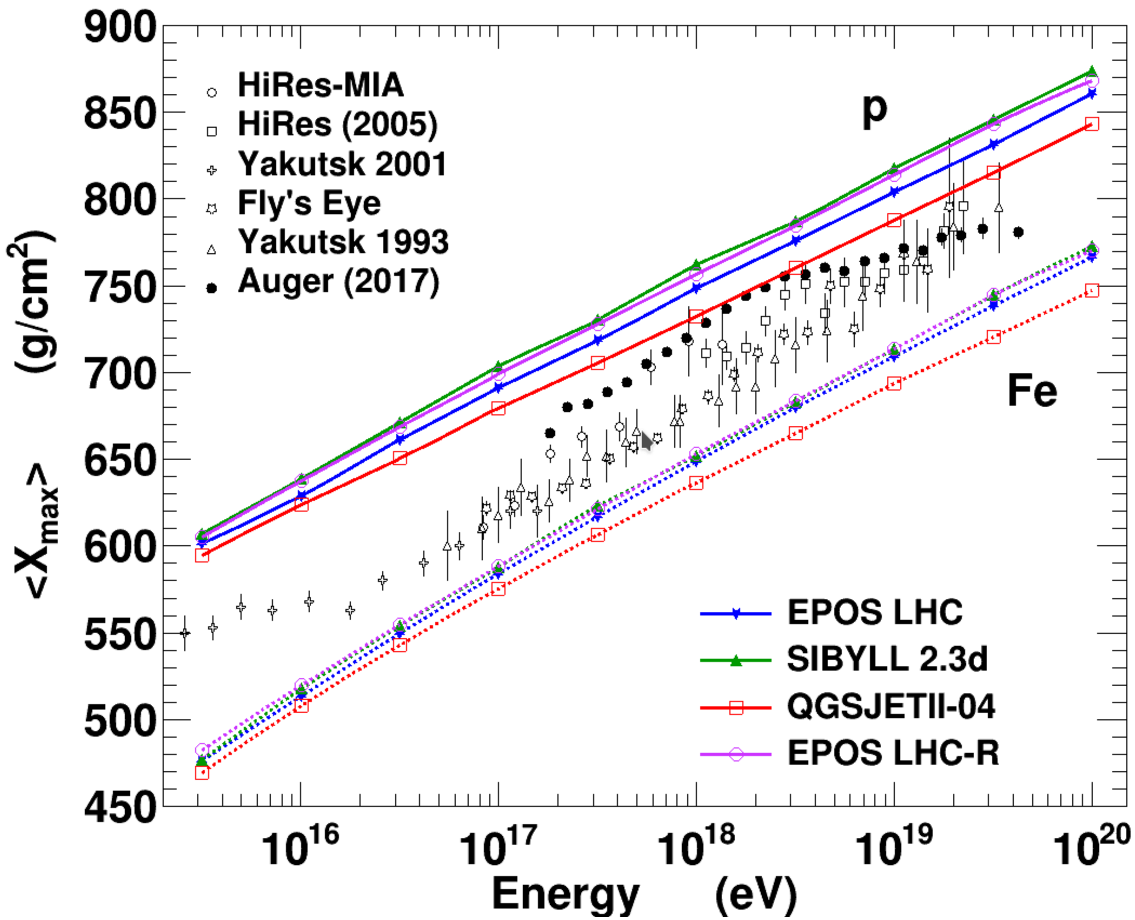
(preliminary)



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)



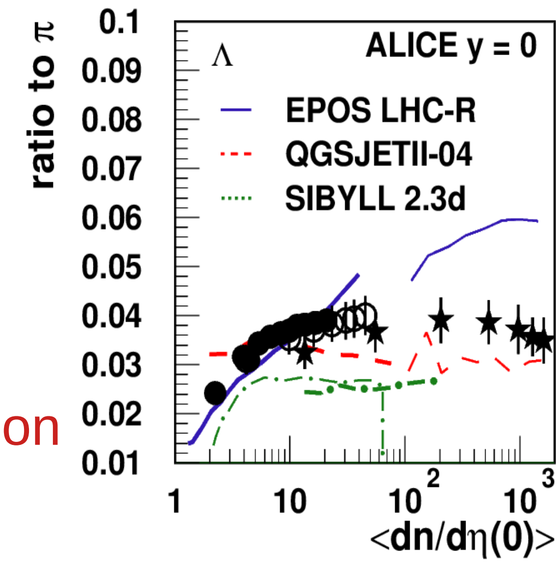
Higher <lnA> !

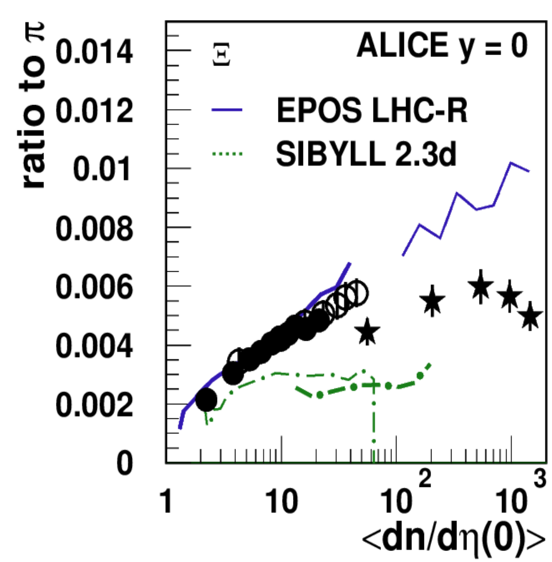
Correction of nuclear fragmentation in EPOS :
X_{max} RMS Fe
LHC=20g/cm2
LHC-R=24g/cm2
SIB=25g/cm2
QII=25g/cm2

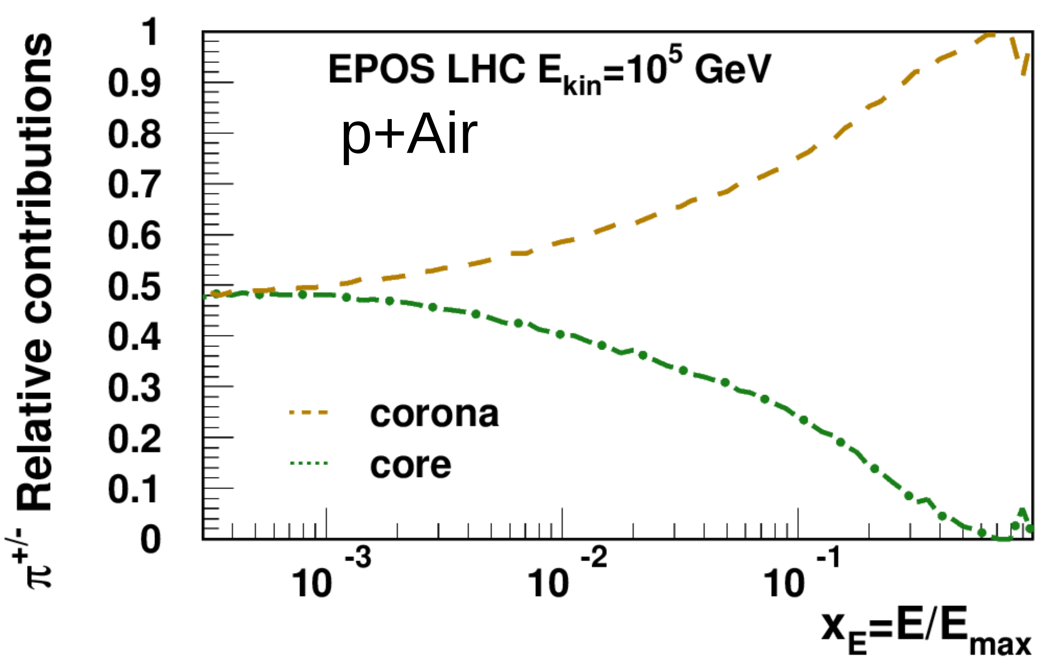
Interactions in Air Showers

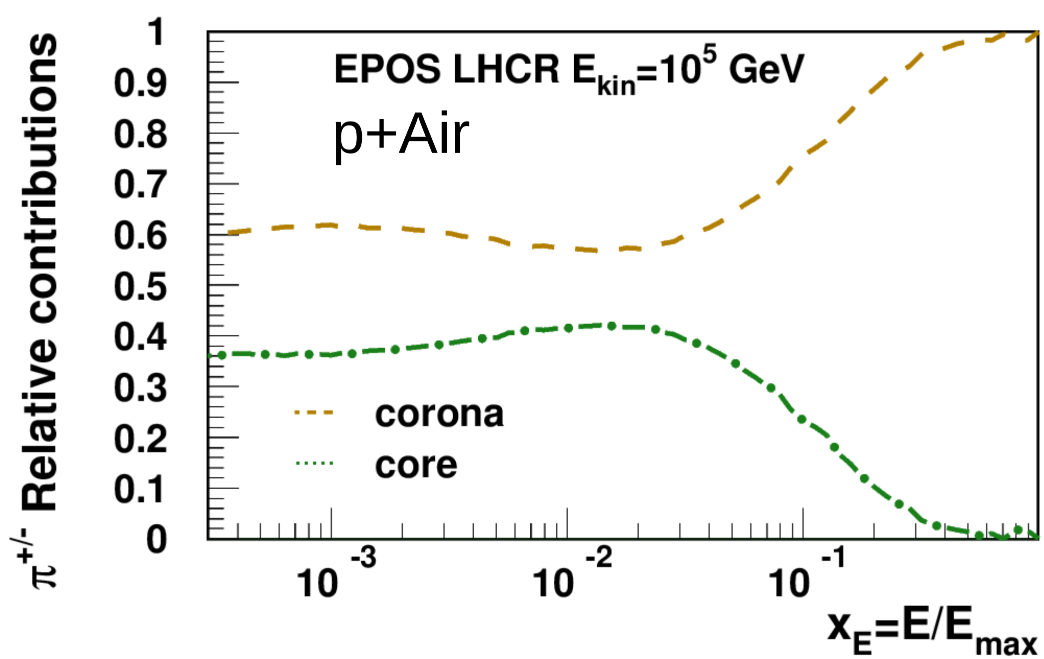
Update of EPOS to reproduce ALICE data

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





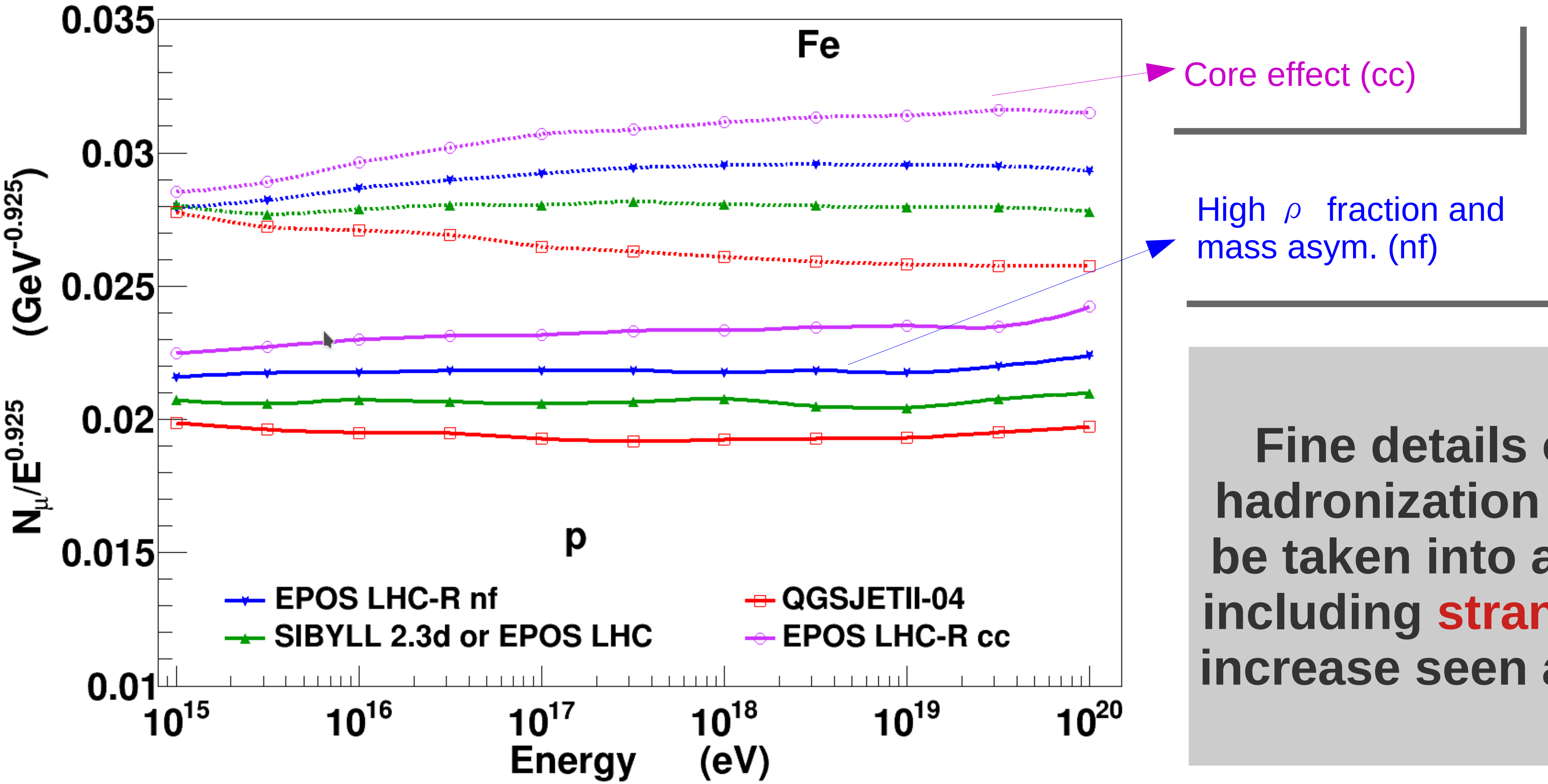




N_μ

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)

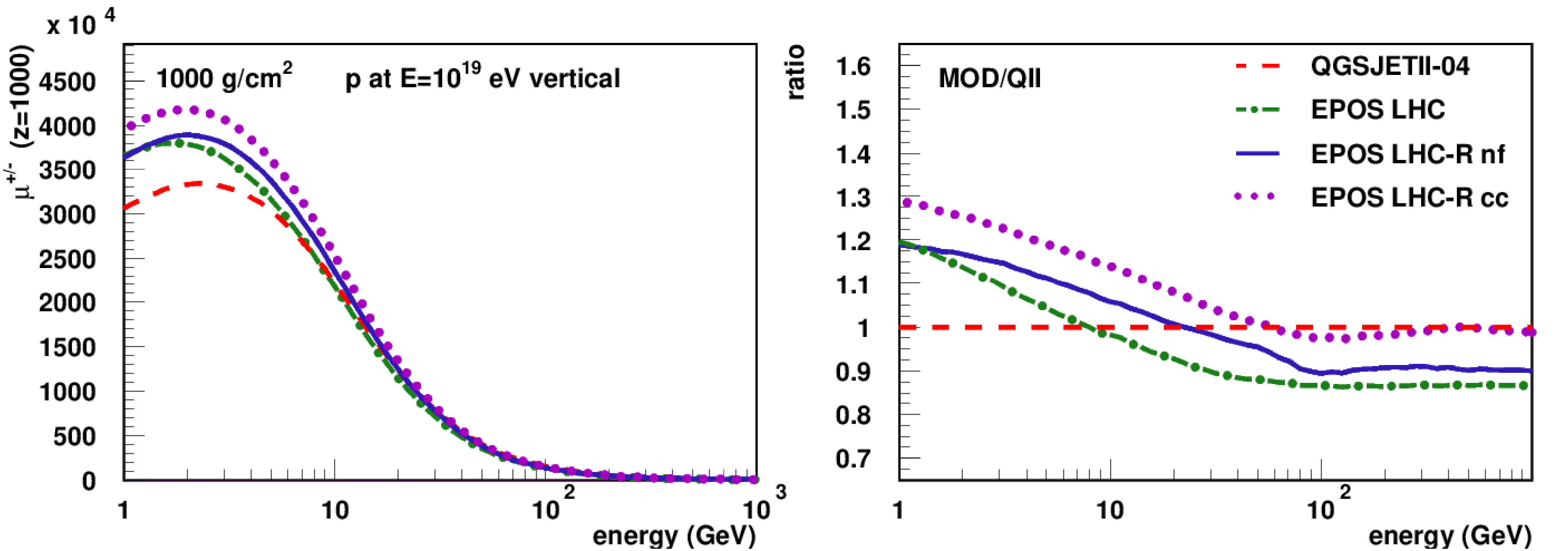


Fine details of the hadronization should be taken into account including strangeness increase seen at LHC !

E_μ

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

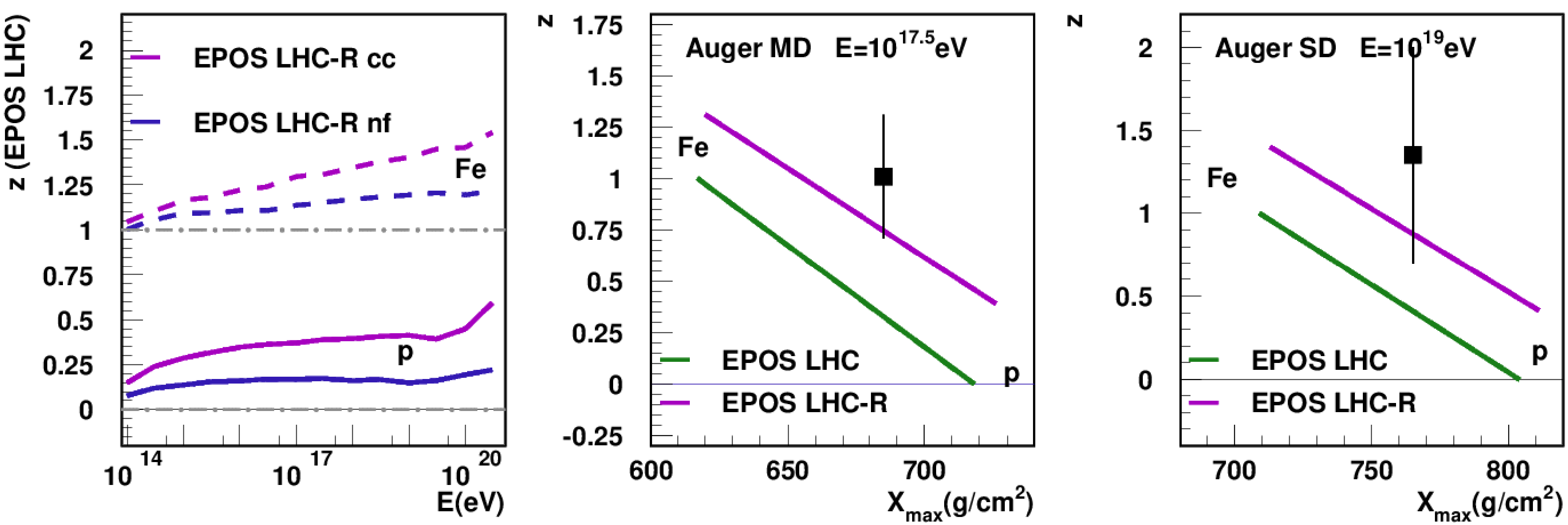
- Simulations without core-corona but ρ asymmetry already have more muons
  - Increase ~10 GeV muons
- Additional energy and mass dependent effect due to core-corona !
  - Parallel shift changing all muon energies
- First effect could be “tuned”, less freedom for core-corona (from LHC)



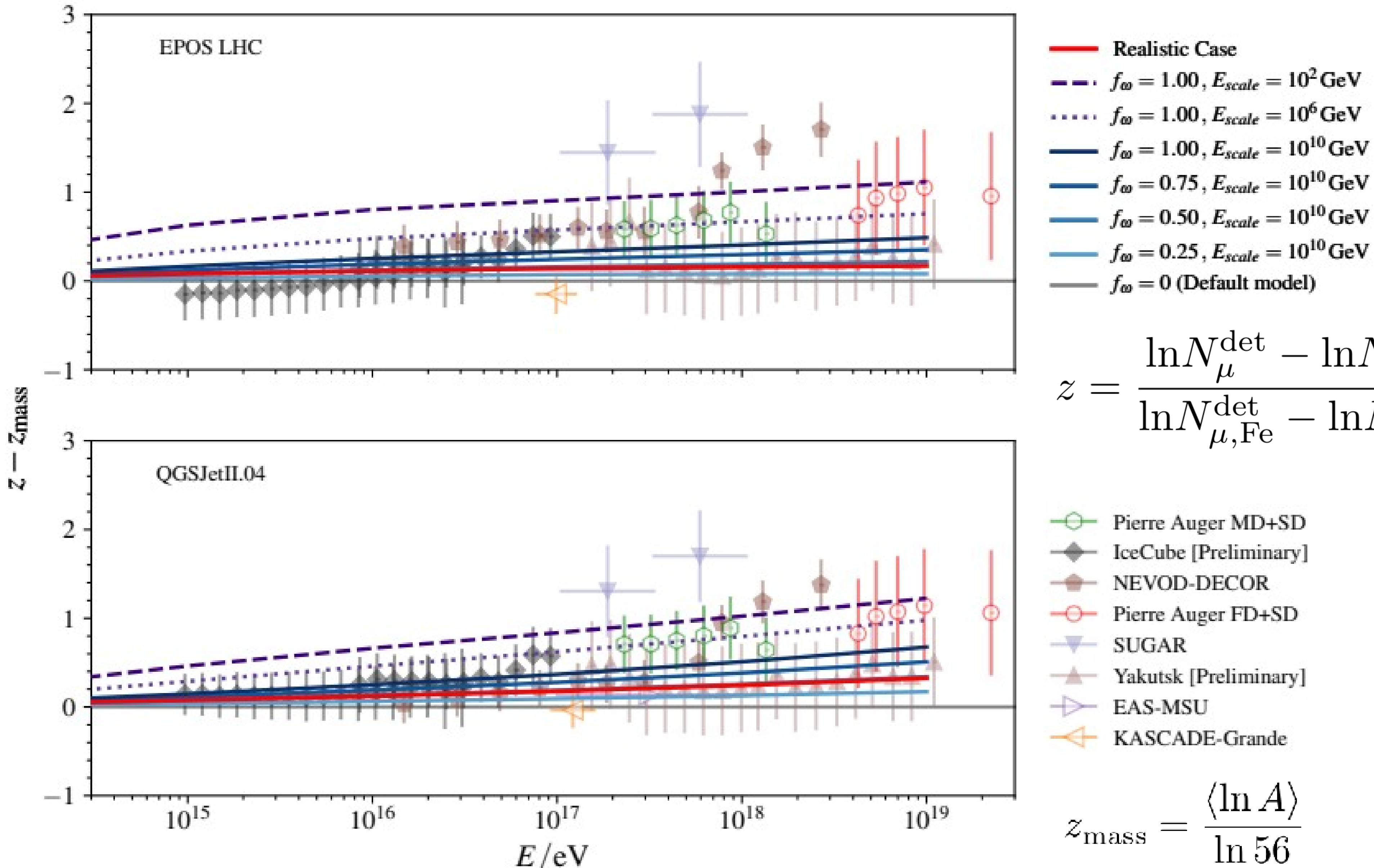
Muon Puzzle Solved ?

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



Results for z-scale



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

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

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

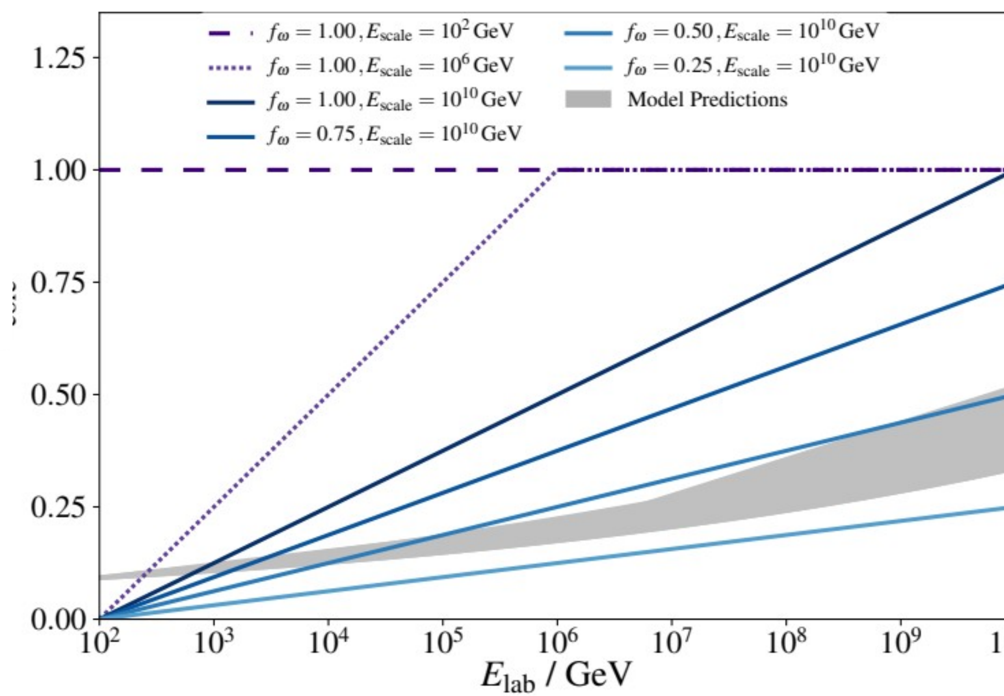
- Particle ratios from statistical model are known (tuned to PbPb) and fixed : core
- Initial particle ratios given by individual hadronic interaction models : corona
- Using CONEX, EAS can be simulated mixing corona hadronization with an arbitrary fraction ω_{core} of core hadronization: $N_i = \omega_{\text{core}}\,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

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

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

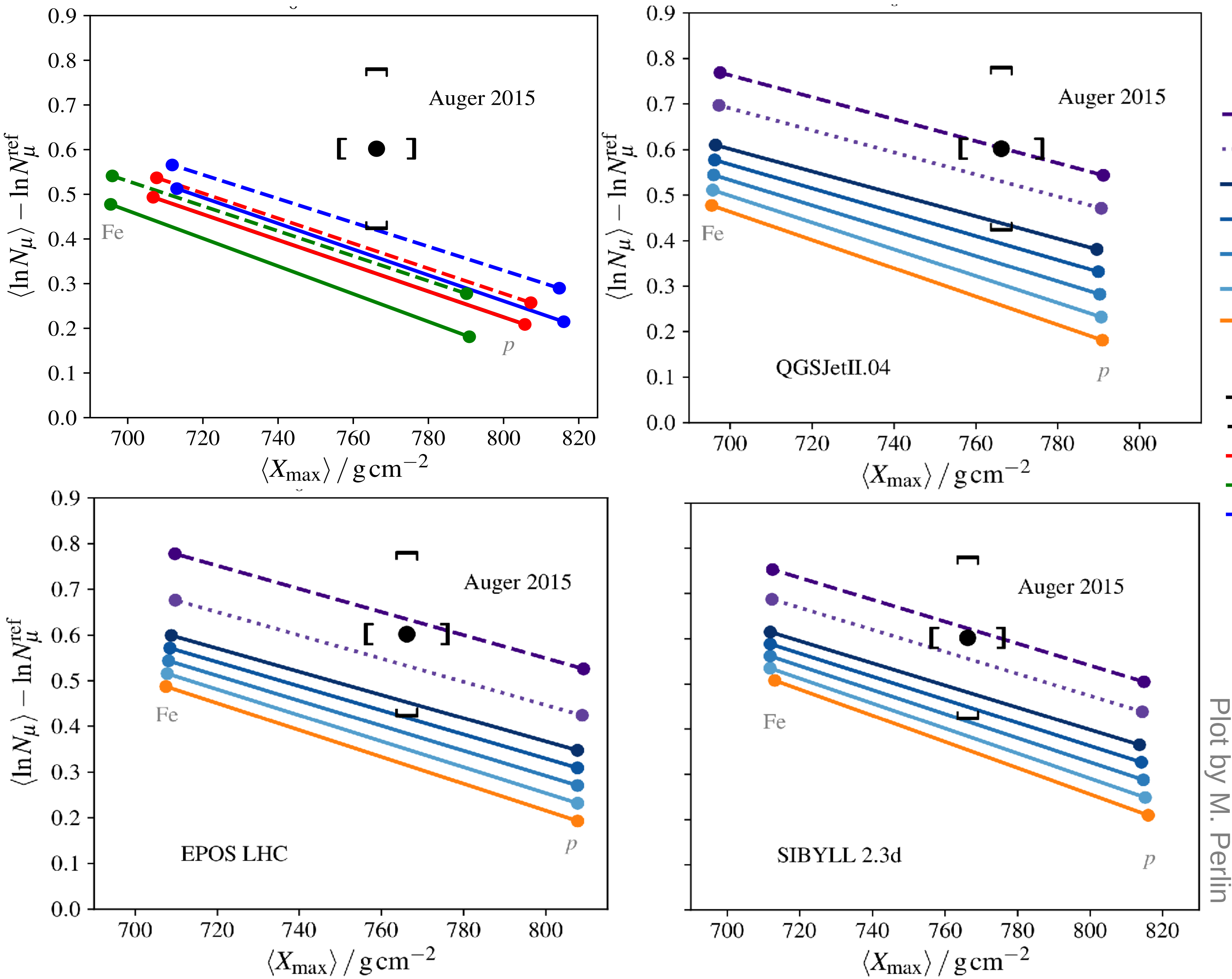
Different scenarii can be studied playing with f_ω and E_{scale}.

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)

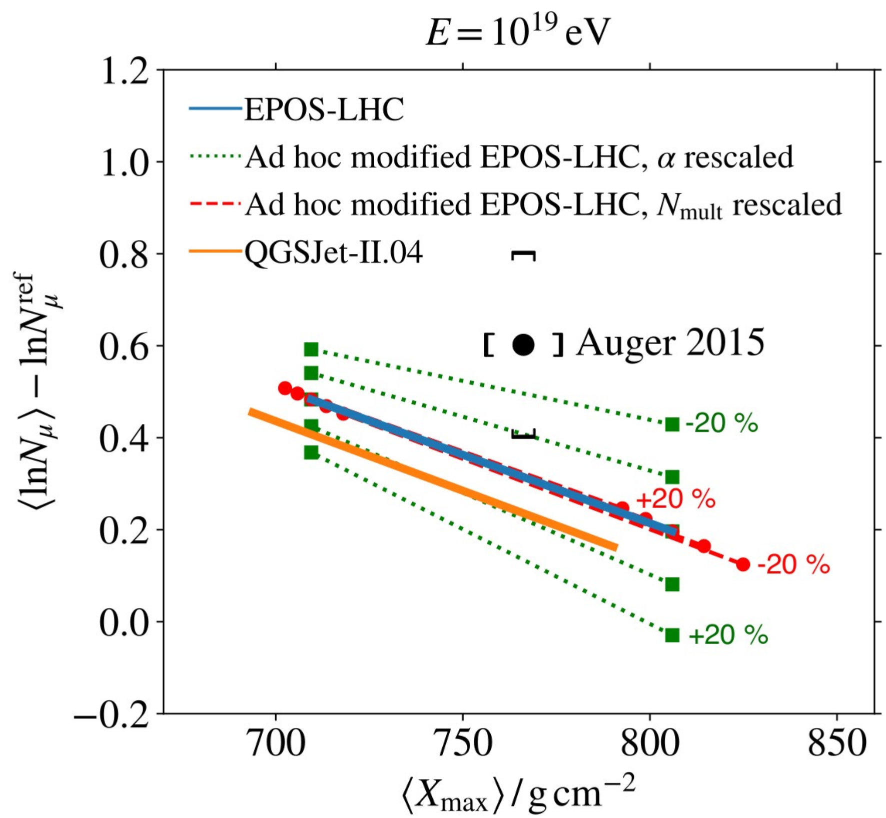
Phys.Rev.D 107 (2023) 9, 094031 1902.09265 [hep-ph]

Constraints from Correlated Change

- One needs to change energy dependence of muon production by ~+4%
- 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 $\alpha = \frac{N_{\pi^0}}{N_{mult}}$

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

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

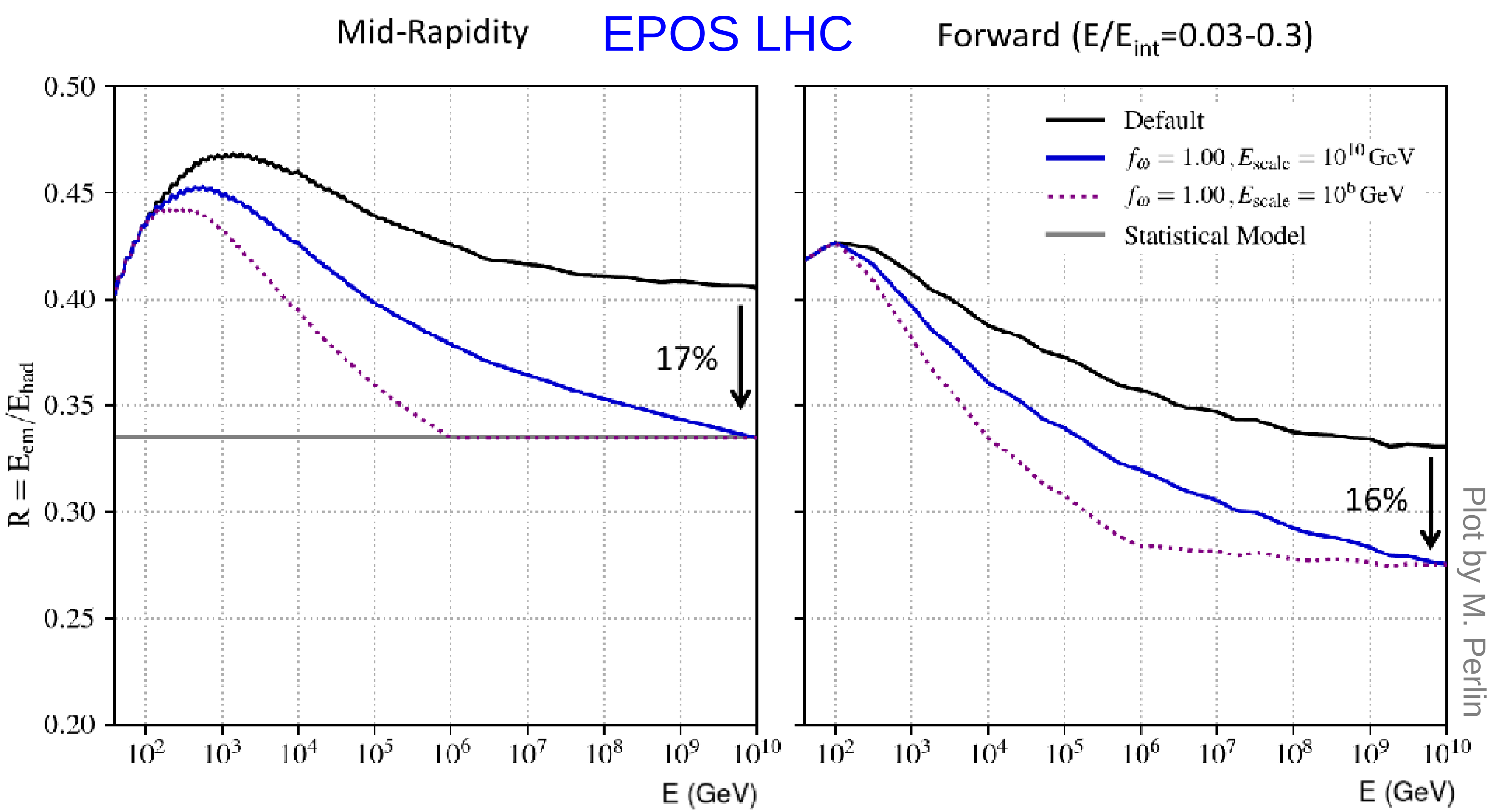


Plot by H. Dembinski

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 $R(\eta) = \frac{\langle dE_{em}/d\eta \rangle}{\langle dE_{had}/d\eta \rangle}$ which define the muon production in air showers.

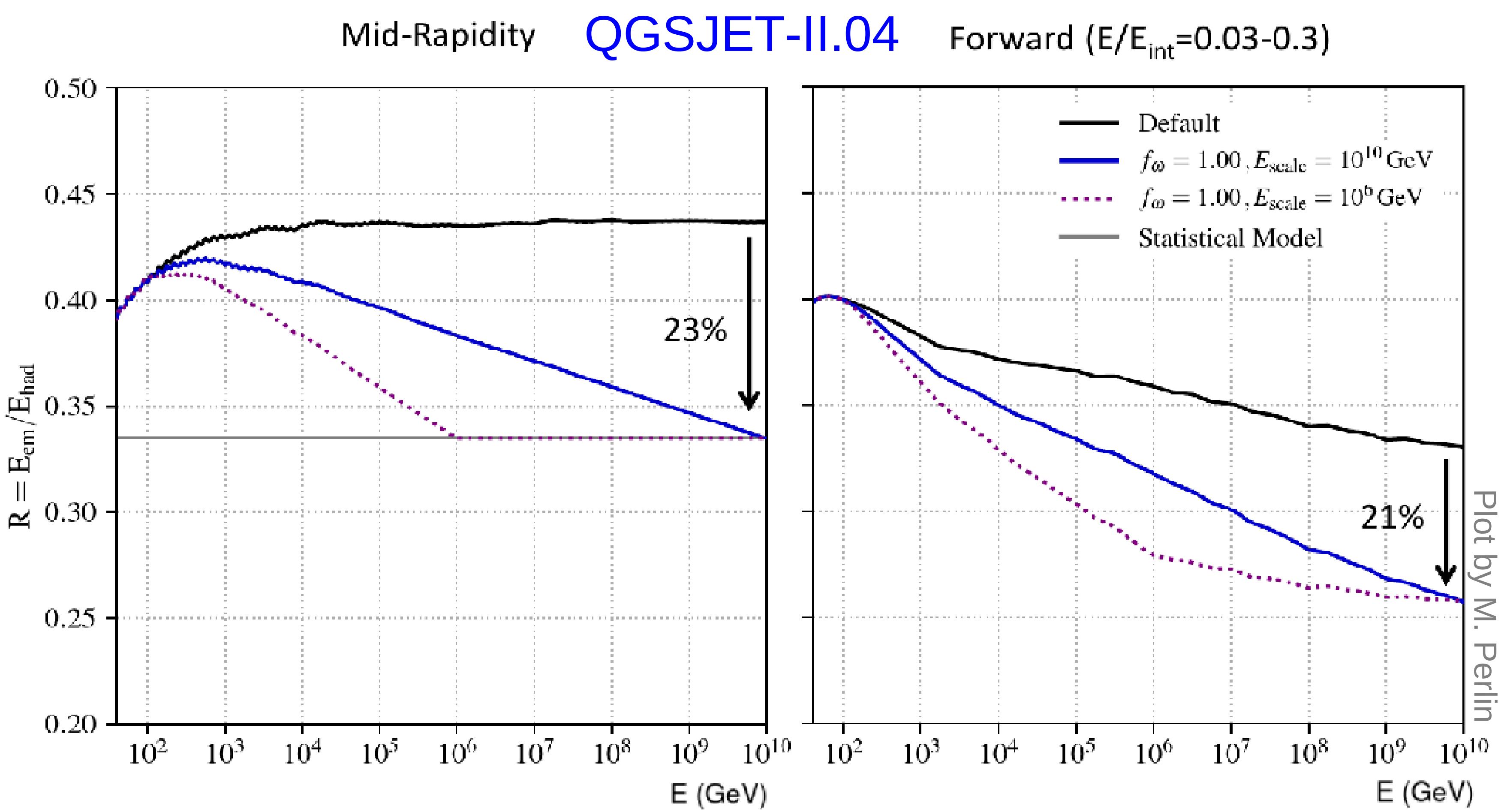


Evolution of hadronization from core to corona

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.

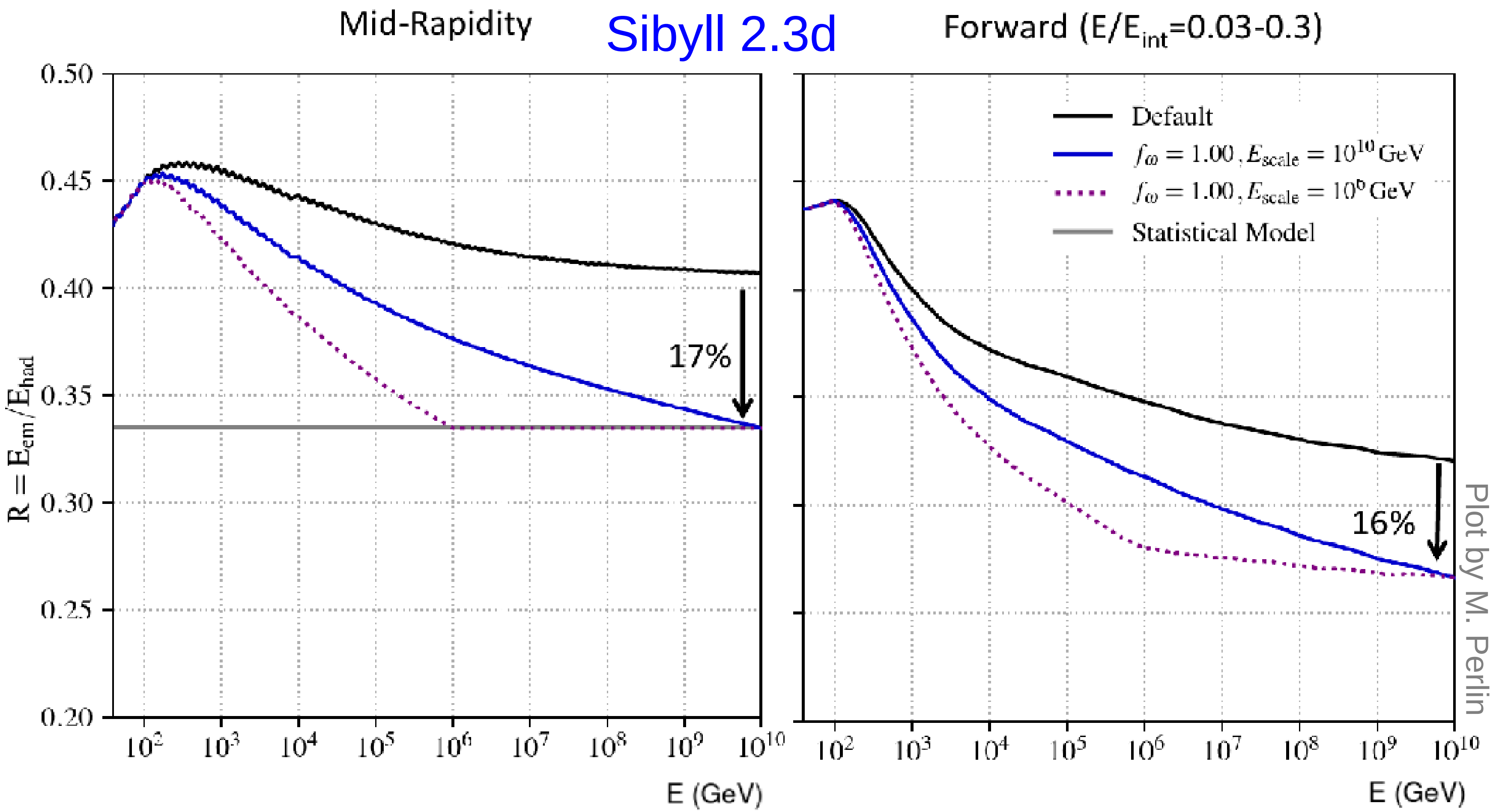


Evolution of hadronization from core to corona

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 $R(\eta) = \frac{\langle dE_{em}/d\eta \rangle}{\langle dE_{had}/d\eta \rangle}$

  which define the muon production in air showers.

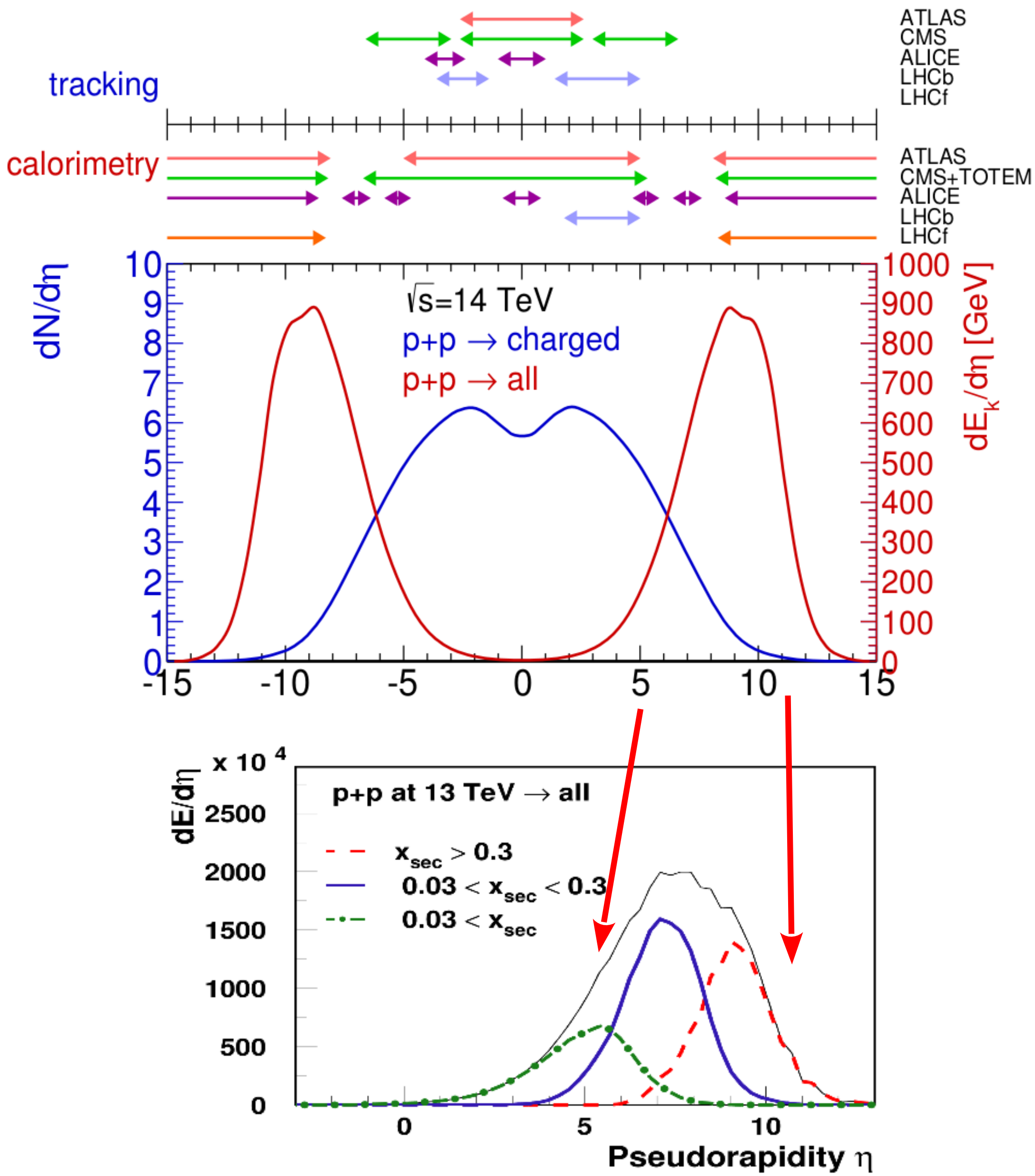


Possible Particle Physics Explanations

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

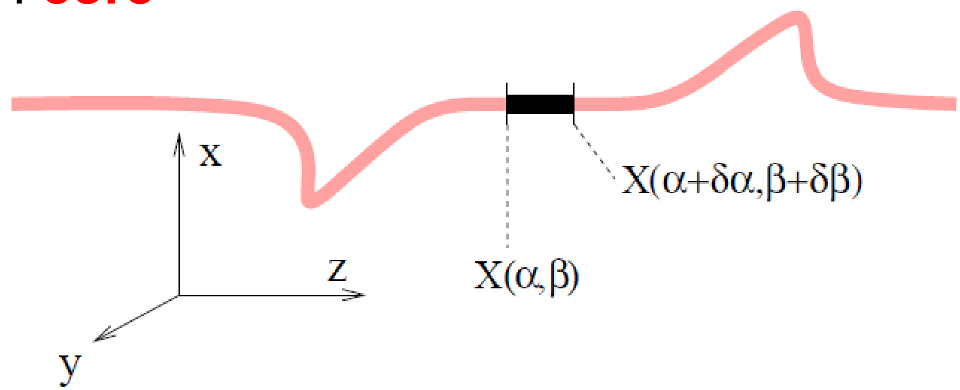


- **p-p data mainly from "central" detectors**
  - pseudorapidity $\eta=-\ln(\tan(\theta/2))$
  - $\theta=0$ is midrapidity
  - $\theta>>1$ is forward
  - $\theta<<1$ is backward
- **Different phase space for LHC and air showers**
  - most of the particles produced at midrapidity
    - important for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

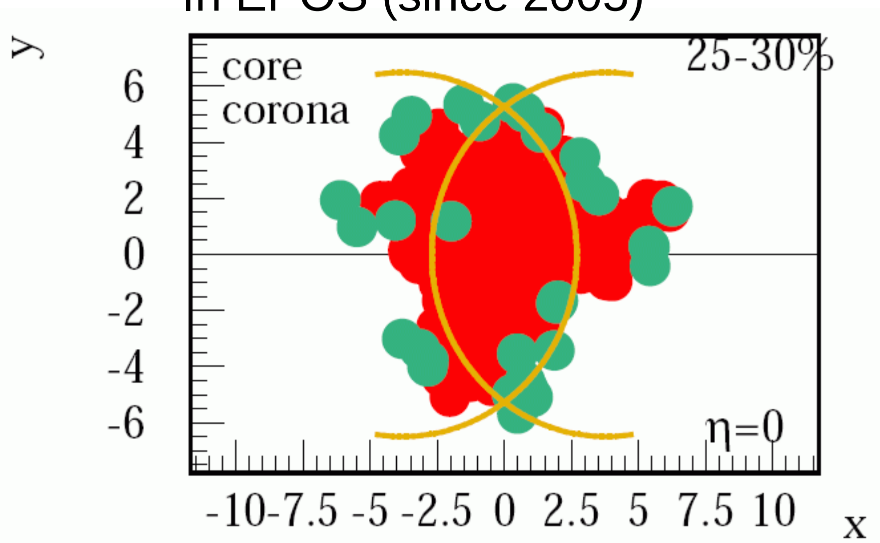
A 3rd way : the core-corona approach

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