EPOS LHC-R

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Workshop on the tuning of hadronic interaction models, Wuppertal, Germany

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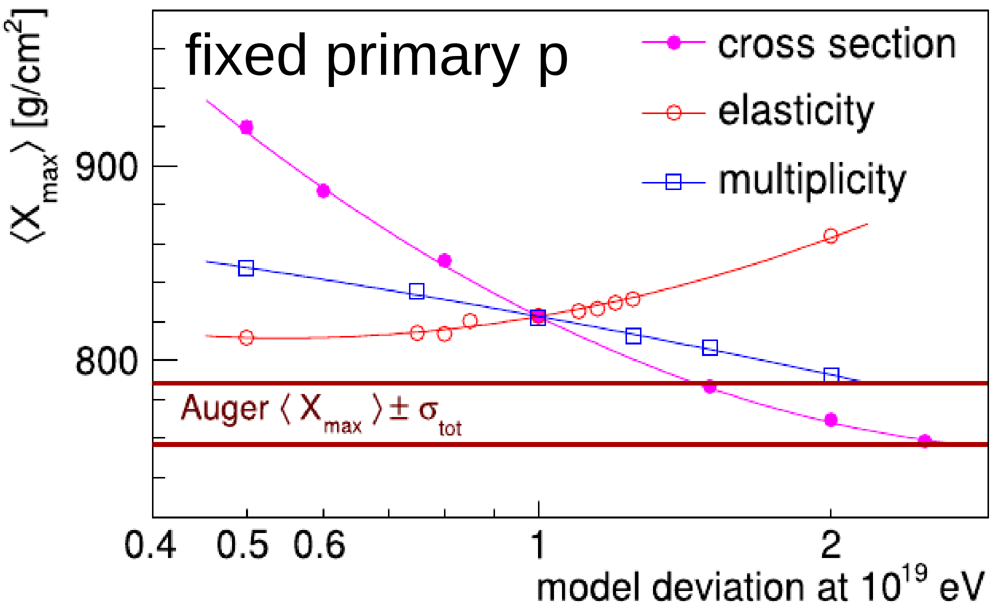
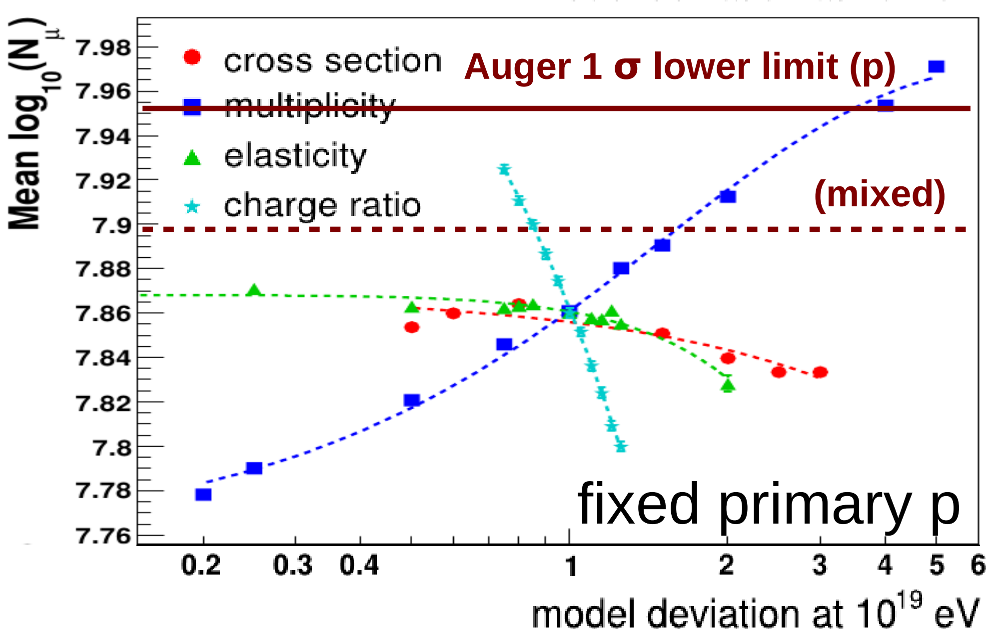
Outline

- **Introduction**
- **Updates → EPOS LHC-R**
  - ➜ Cross-section, Multiplicity, Fragmentation and Diffraction
- **Impact on X_{max}**
- **ρ, B and μ**
  - ➜ Hadronization and isospin symmetry
- **Core-corona**

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

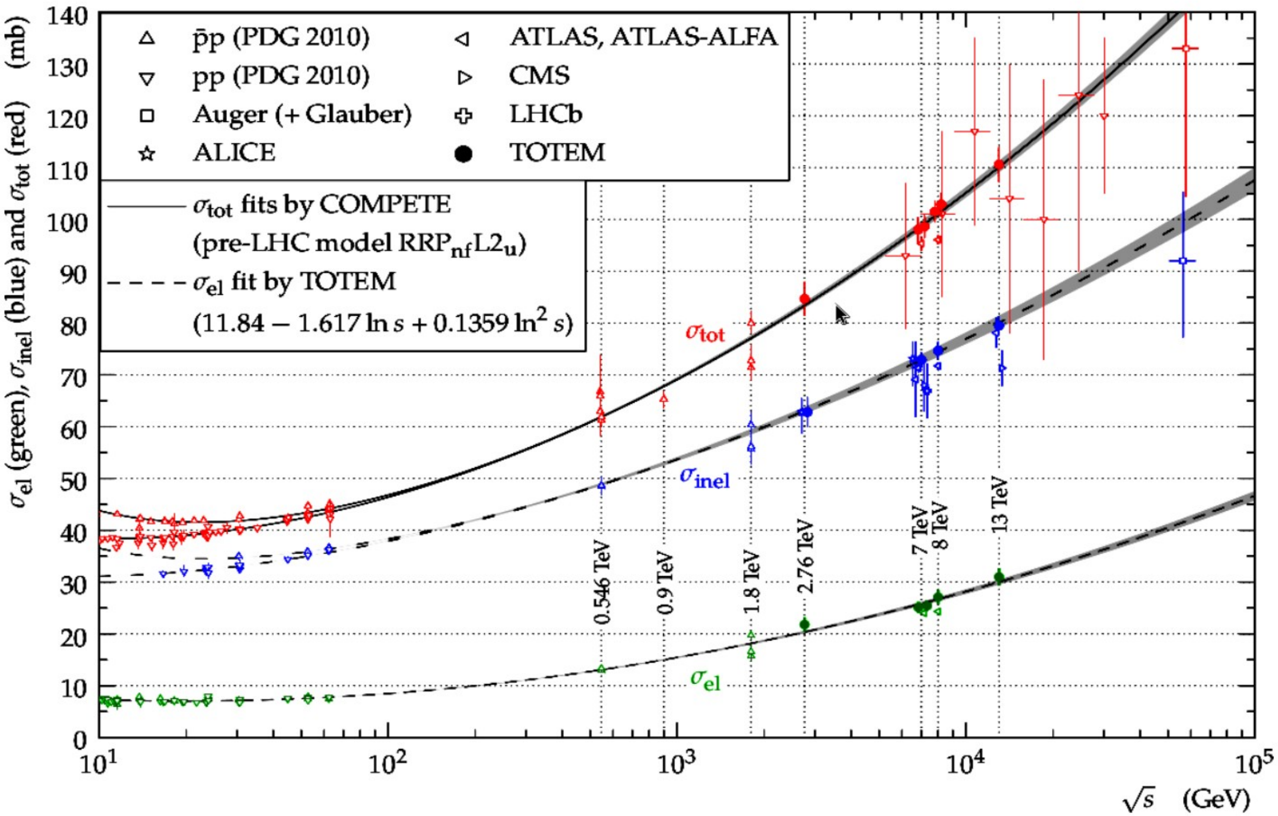
- **First LHC data lead to reduced differences between models**
- **But a number of new data since model release could be use to further improve the models :**
  - Update of the p-p cross sections (ALFA)
  - Data at 13 TeV (CMS, ATLAS, LHCf)
  - More detailed p-Pb measurements (fluctuations) CMS

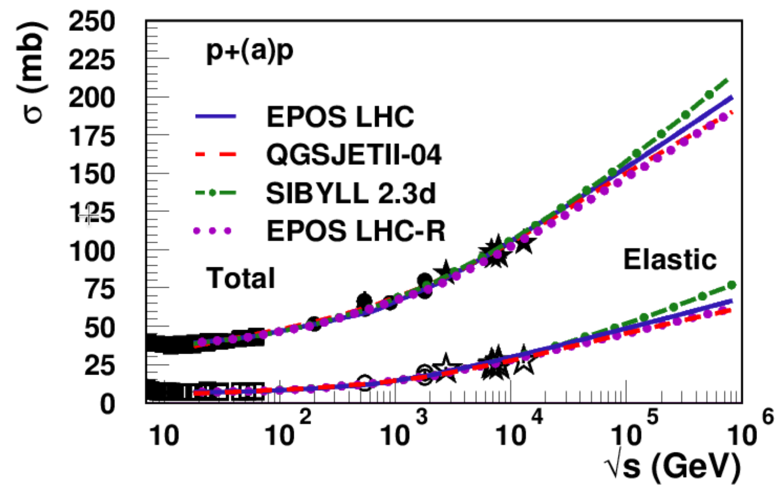
  → X_{max}
  - Particle yields as a function of multiplicity (ALICE, LHCb)
    - Very important to understand the mechanism behind particle production

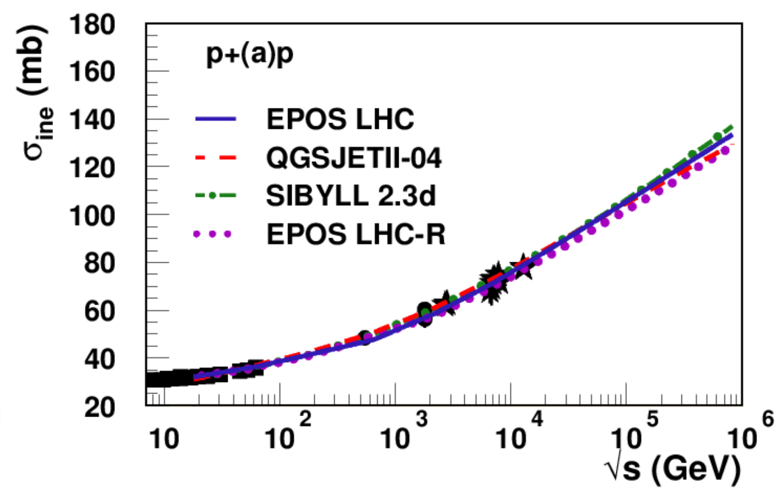
  → N_{μ}
- **Update of EPOS LHC → EPOS LHC-R**
  - New EPOS 4 available for heavy ion physics but not usable for air showers (yet)
  - Modify EPOS LHC to take into account new data and new knowledge accumulated with EPOS 4
  - Very preliminary results and here without “core-corona” !

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



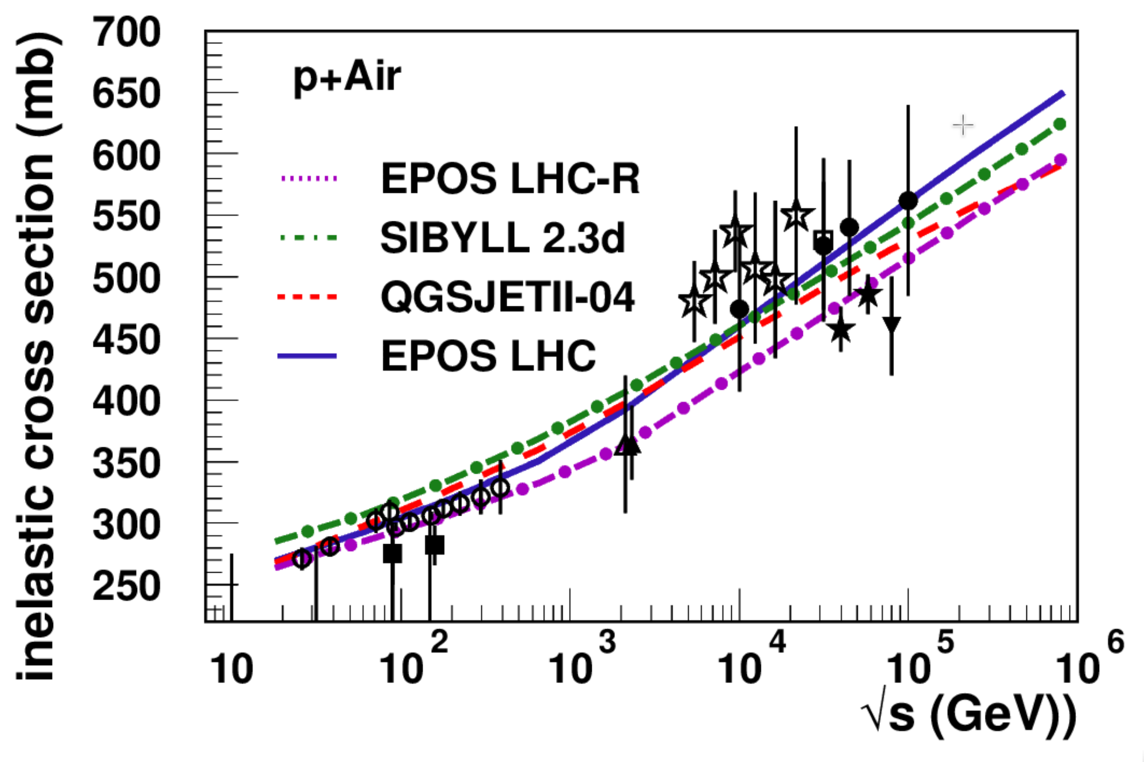


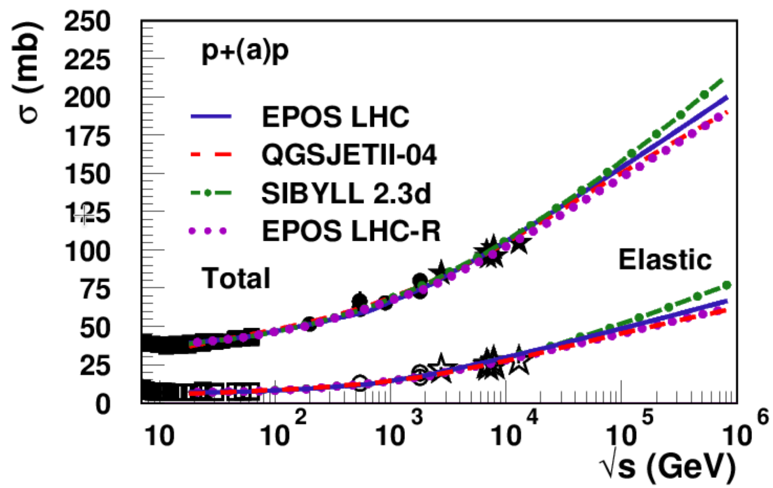


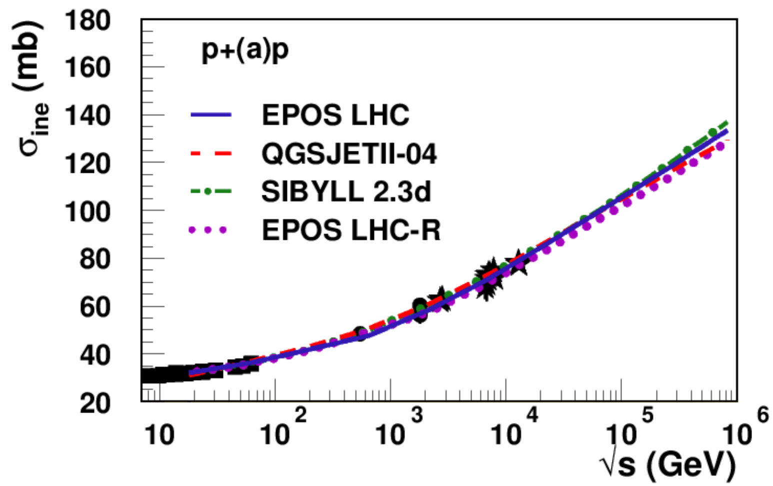
Cross-Section Reduced

- 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 too high in all models
  - ➜ Change by up to -15% at the highest energy

    using most recent CR based measurements

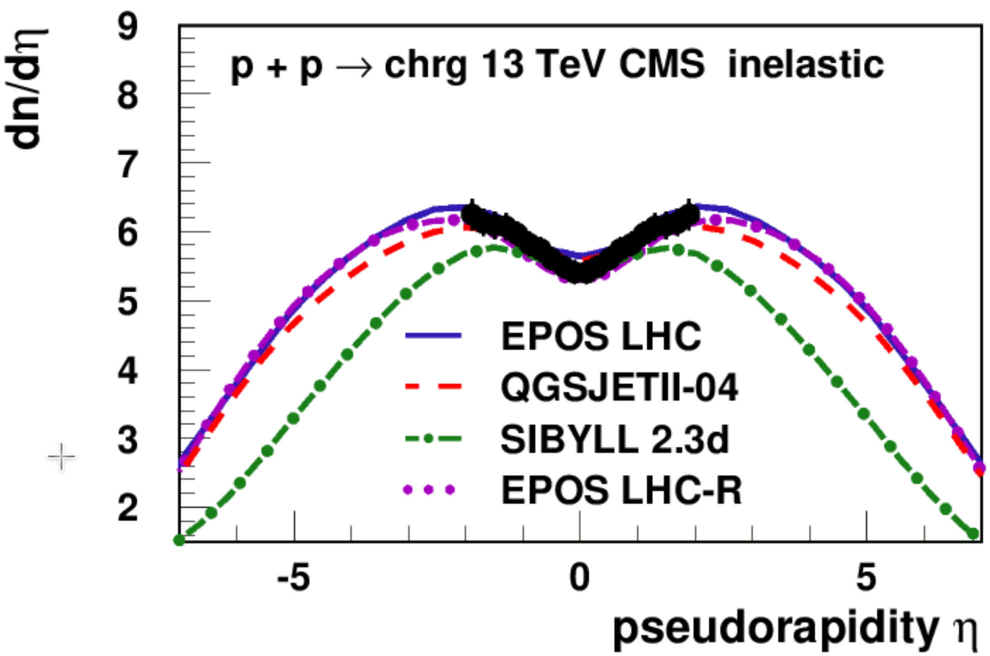


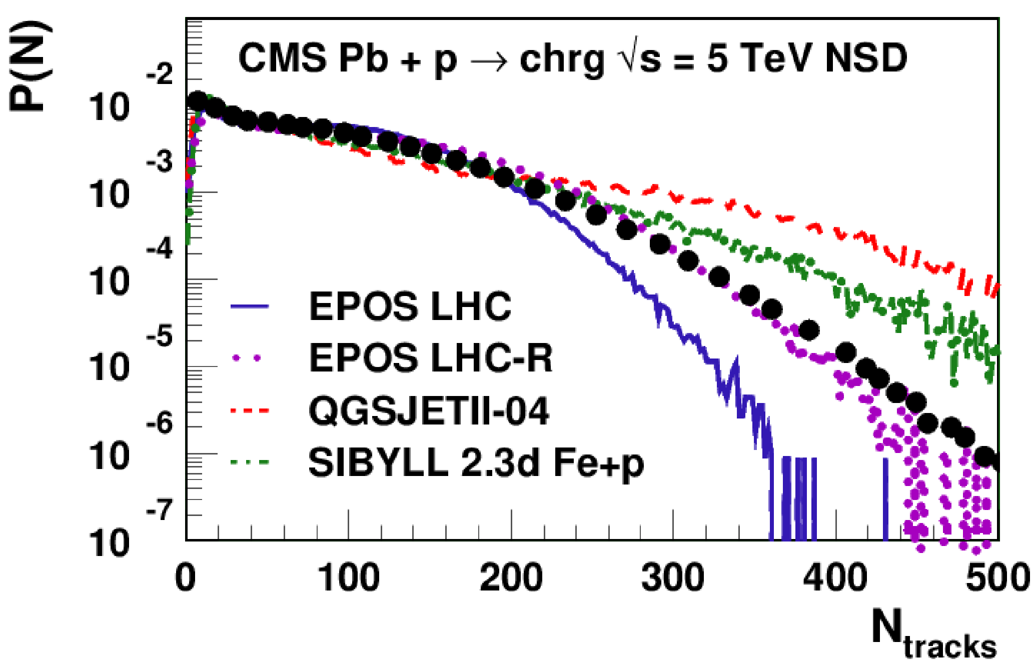




Pseudorapidity

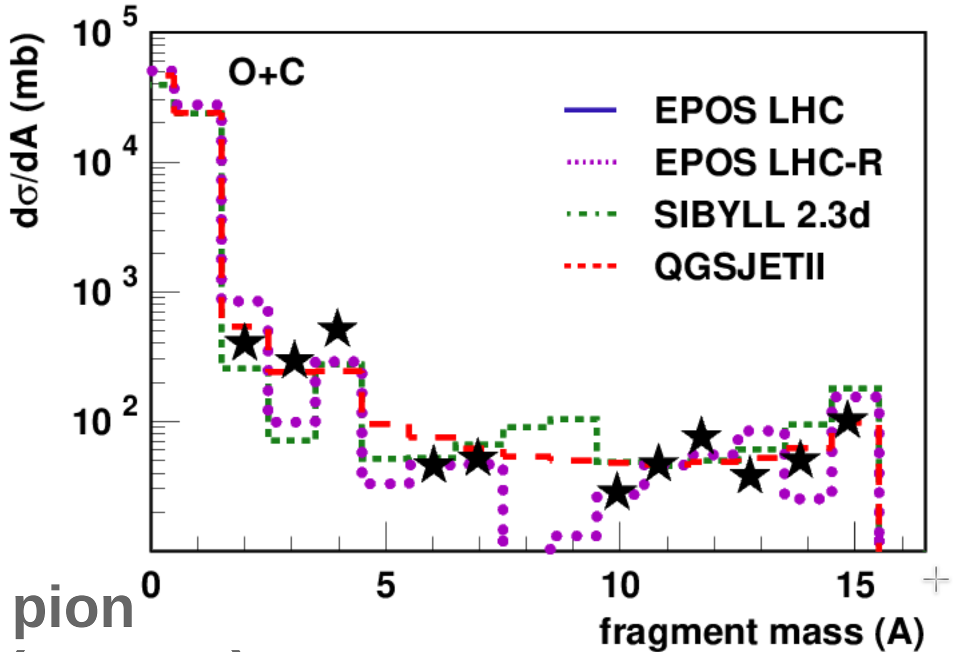
- **Angular distribution of newly produced particles**
- **New data at 13 TeV in p-p**
  - ➡ Test extrapolation with different triggers
  - ➡ Sibyll has a clear difference with other models (and data) : too narrow !
- **Detailed data at 5 TeV for p-Pb**
  - ➡ Wrong multiplicity distributions in all models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



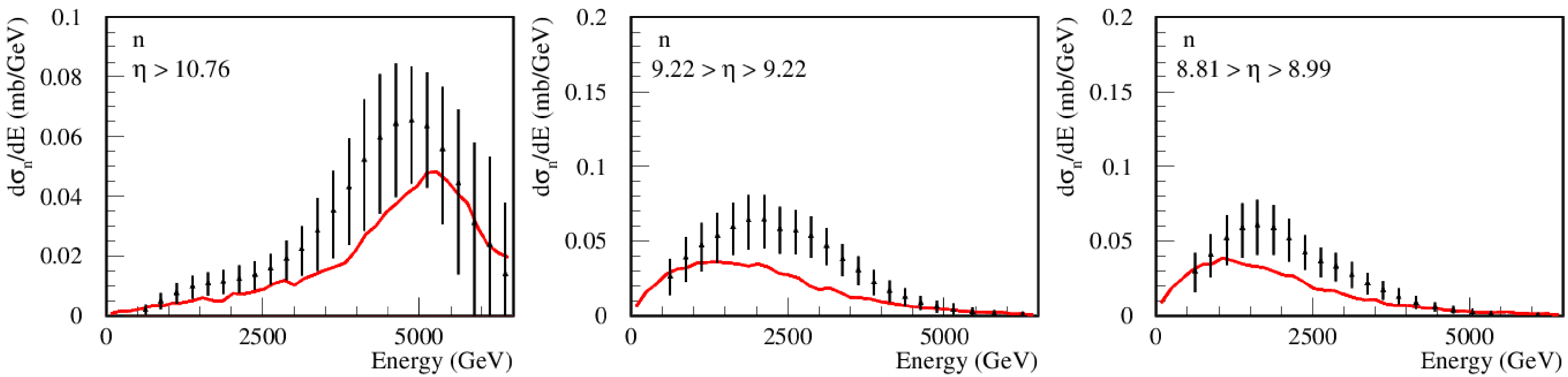


Improvements in EPOS LHC-R

- **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

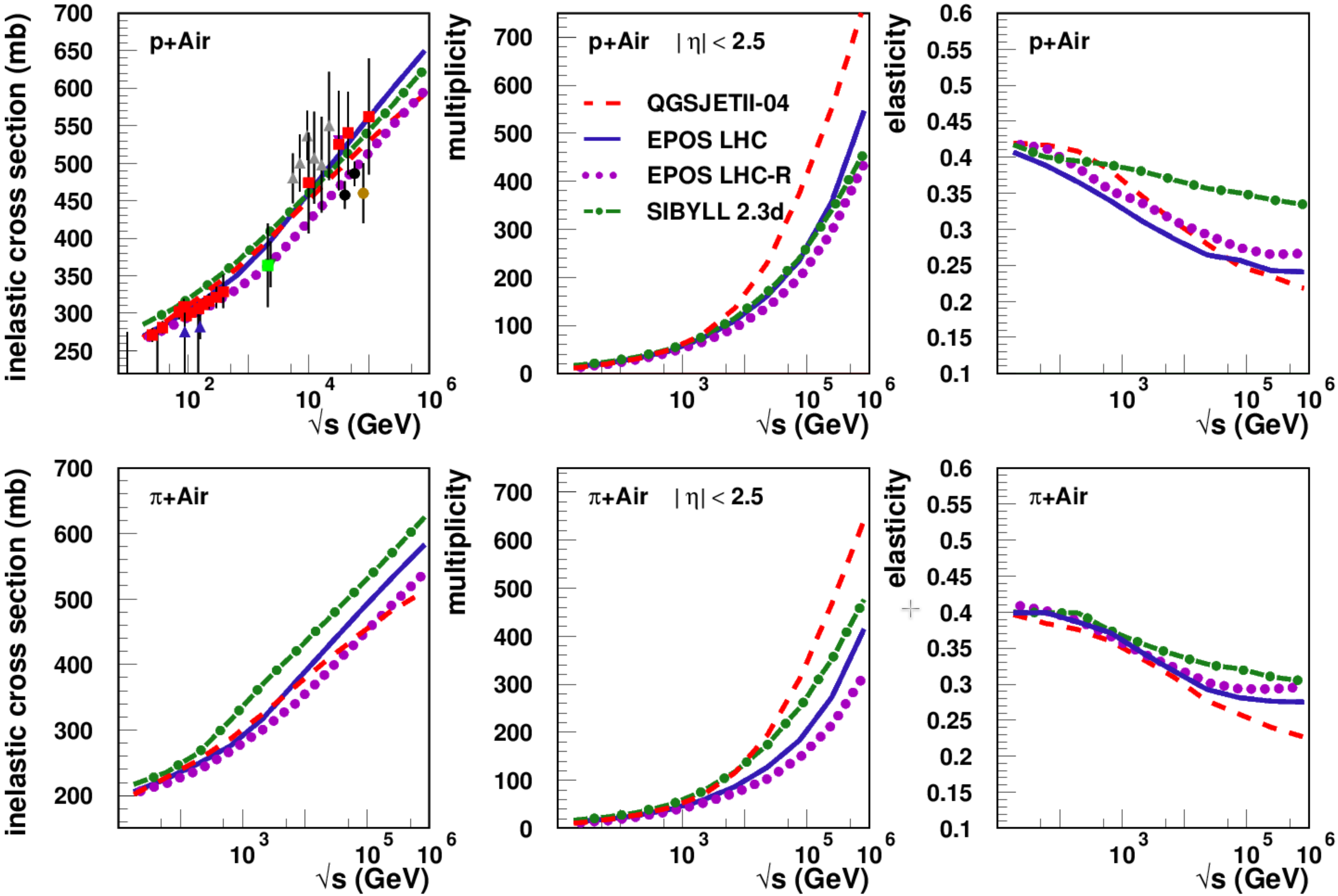


- **Simplified high mass diffraction and pion exchange replaced by real emission (IP or π)**



EPOS LHC-R interaction with Air

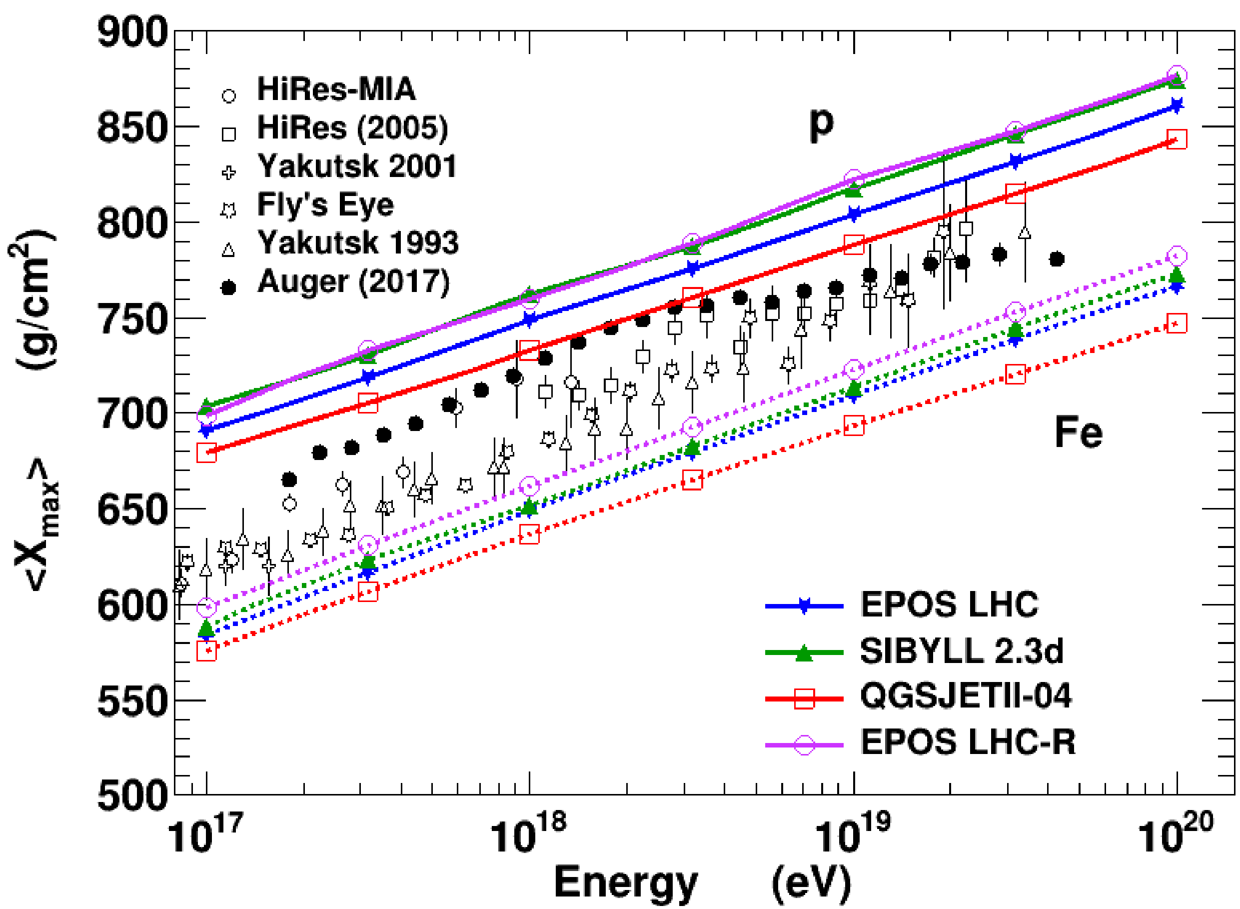
(preliminary)



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 +15g/cm² (=Sibyll for p)



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

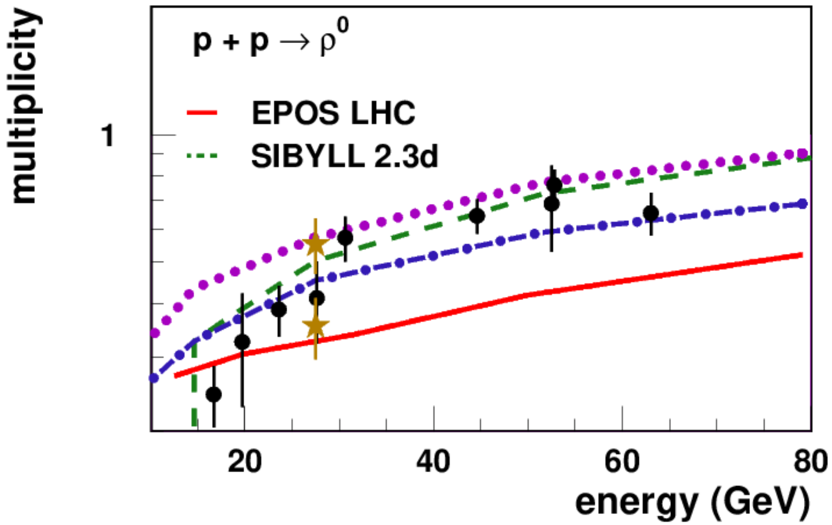
- **Isospin symmetry used as an argument in models to justify 1:1:1 ratios in π or ρ mesons** (or equal neutron/proton production)
  - ➡ But true only if u and d quarks have the same mass !
- **Pions can be produced directly or via ρ resonance decay**
  - ➡ Ratio $\pi^0/\pi^{+/-}$ very important for 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
  - ➡ Are π mesons mostly produced through ρ mesons ?
- **Isospin symmetry broken in multiparticle hadronization ?**
  - ➡ Sea u and d quark assymmetry observed in proton parton distribution function (Phys.Rev.D 71 (2005) 012003)
  - ➡ Particle masses are slightly different !
  - ➡ Can the 1:1:1 ratio be broken in particular for ρ mesons (and baryons) ?
  - ➡ What do we see in data ?

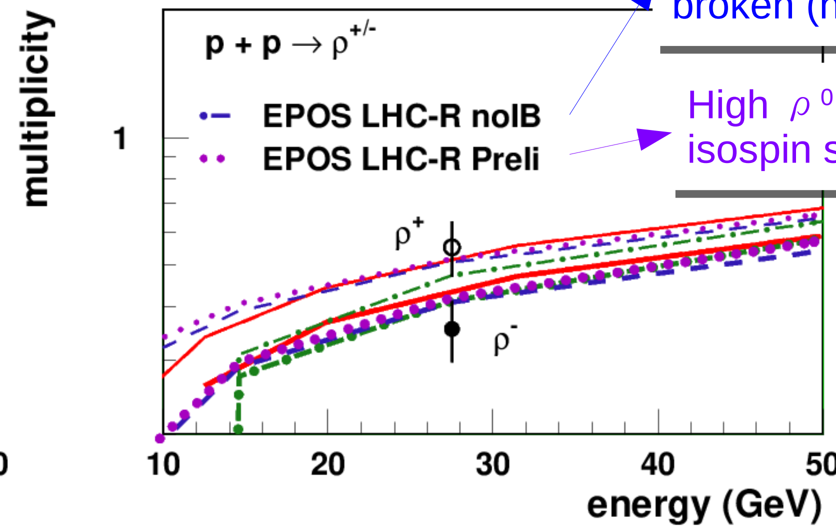
Resonance Production

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

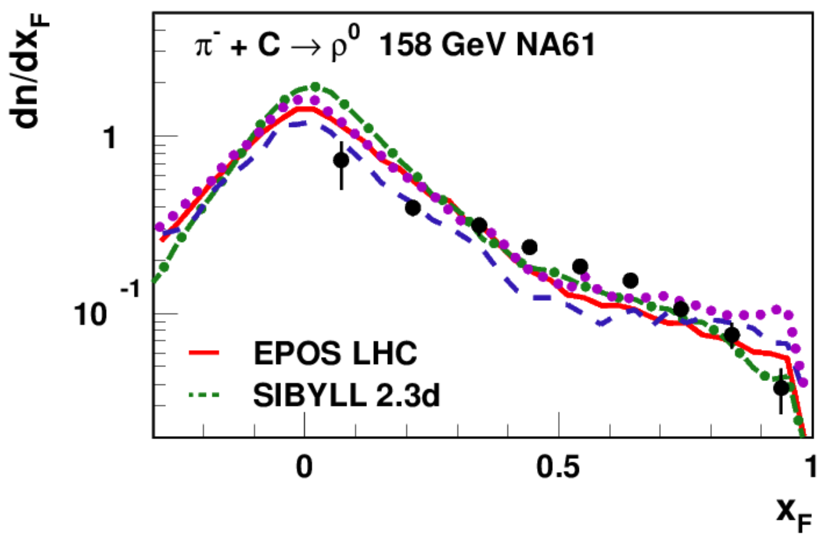
Low ρ fraction and isospin sym. NOT broken (noIB)

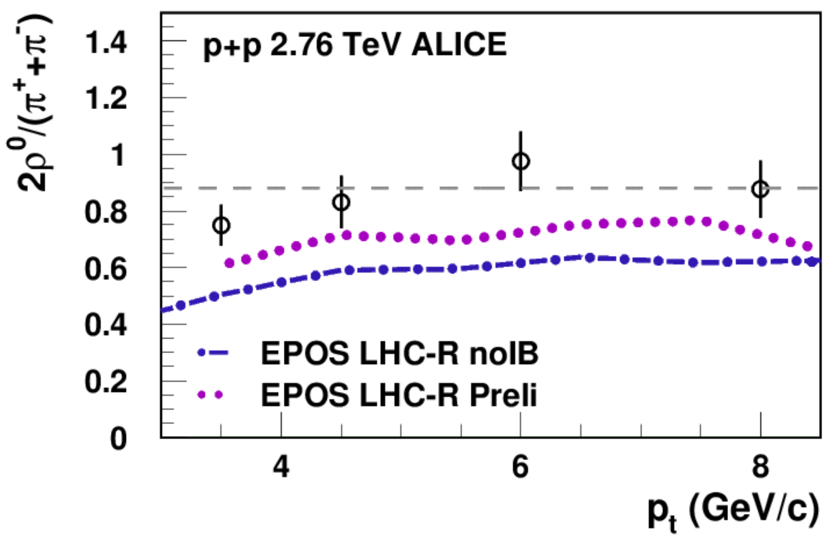
High ρ^0 fraction and isospin sym. broken





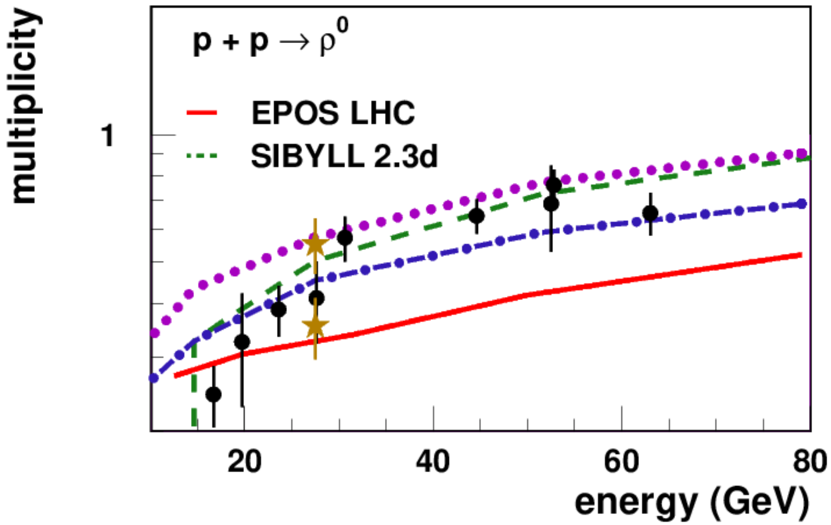
- AND high resonance fraction is favored !

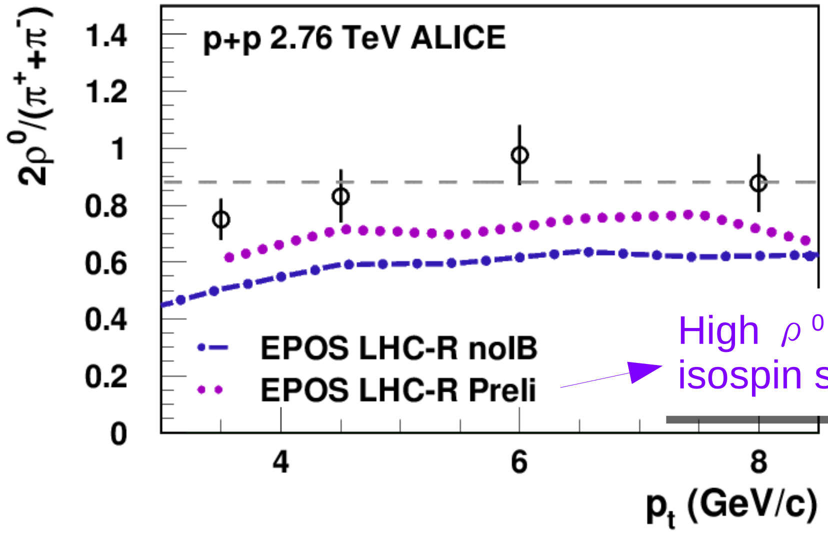




Resonance Production

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

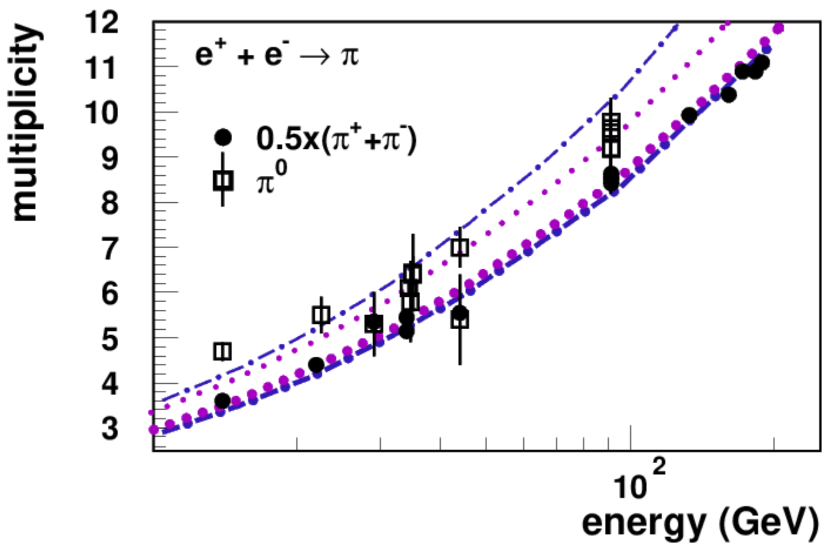


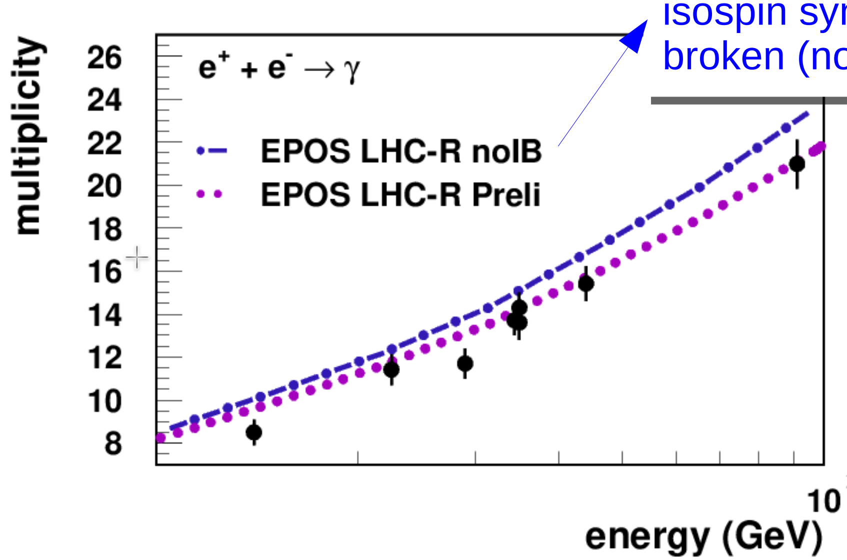


High ρ^0 fraction and isospin sym. broken

➔ Both favored in electron-positron data !

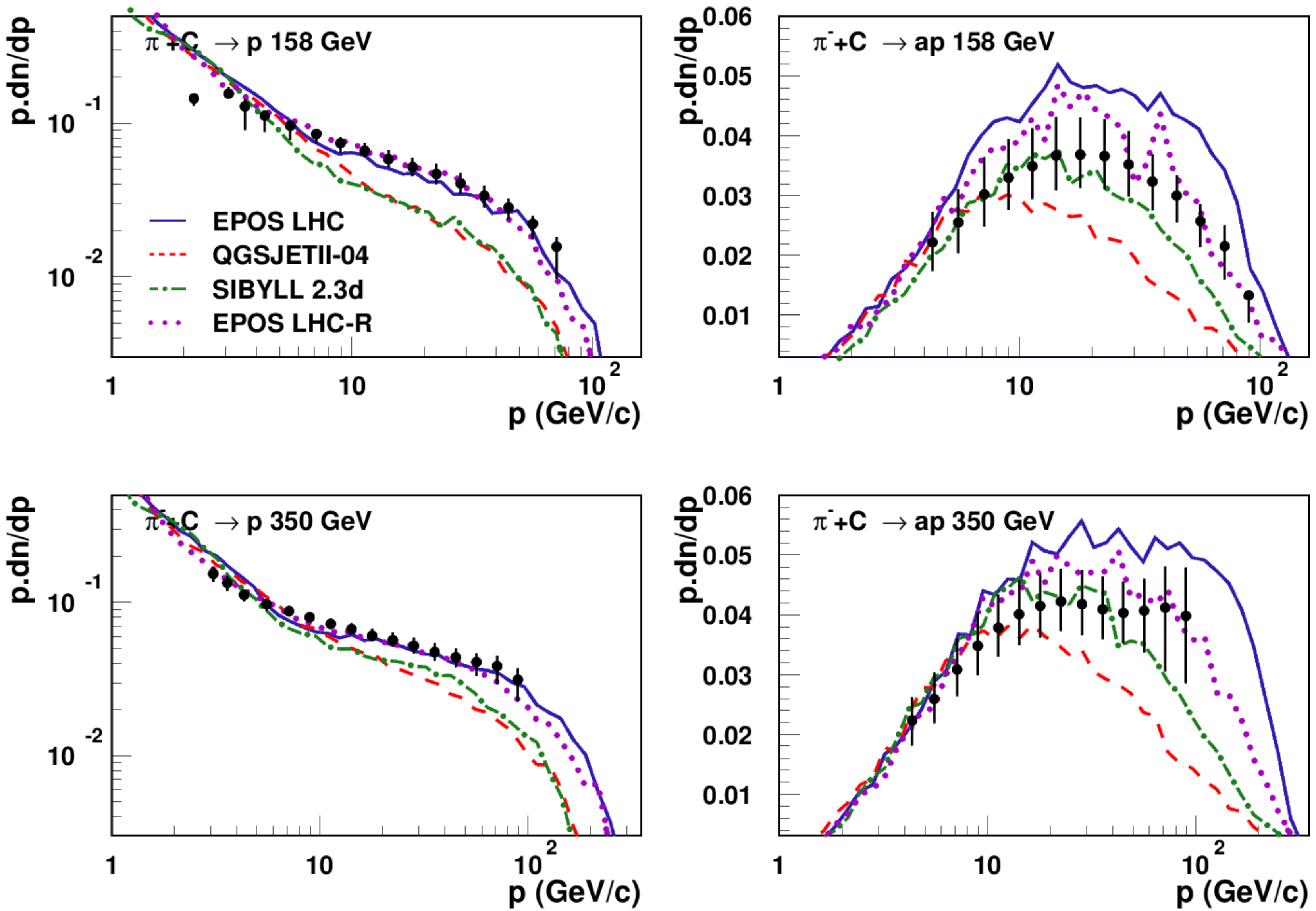
Low ρ fraction and isospin sym. NOT broken (noIB)





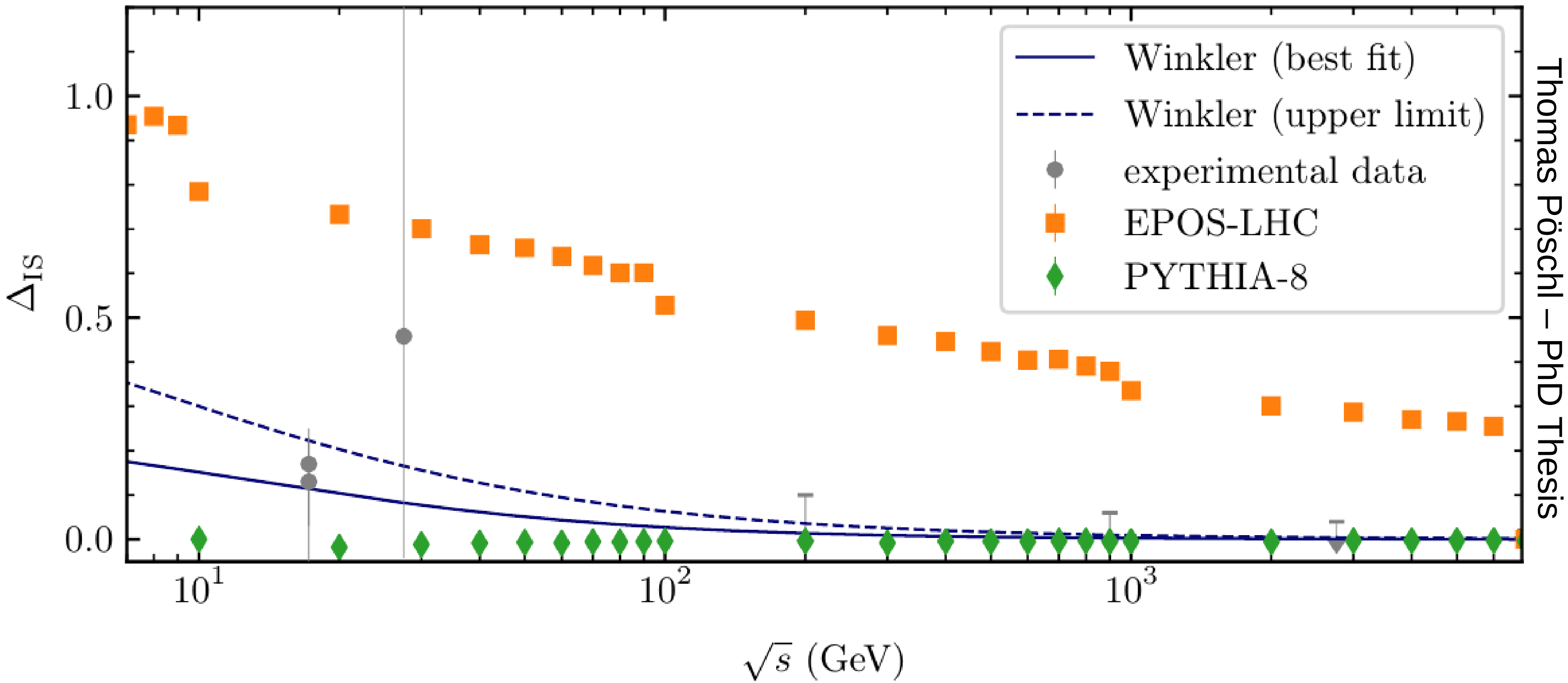
Baryon Production

➡ Corrected baryon production (here NA61 data)



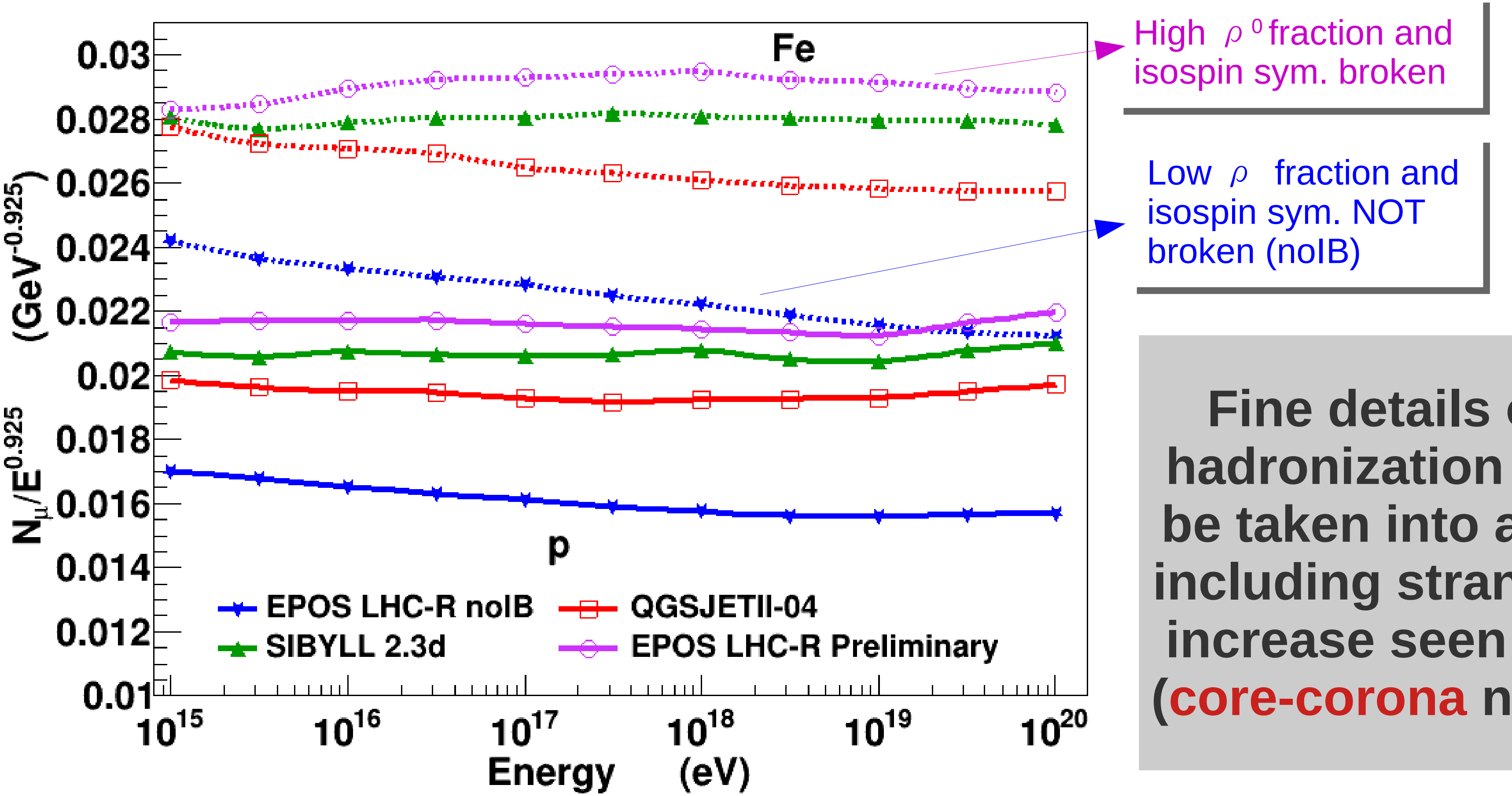
Isospin Breaking for Baryons

- 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) !



Very large differences depending on resonances (meson and baryon) :

- minimum given by low content of resonances and isospin symmetry
- maximum given by high content of resonances with isospin symmetry breaking
- Accelerator data seem to favor the 2nd option (EPOS LHC-R preliminary)



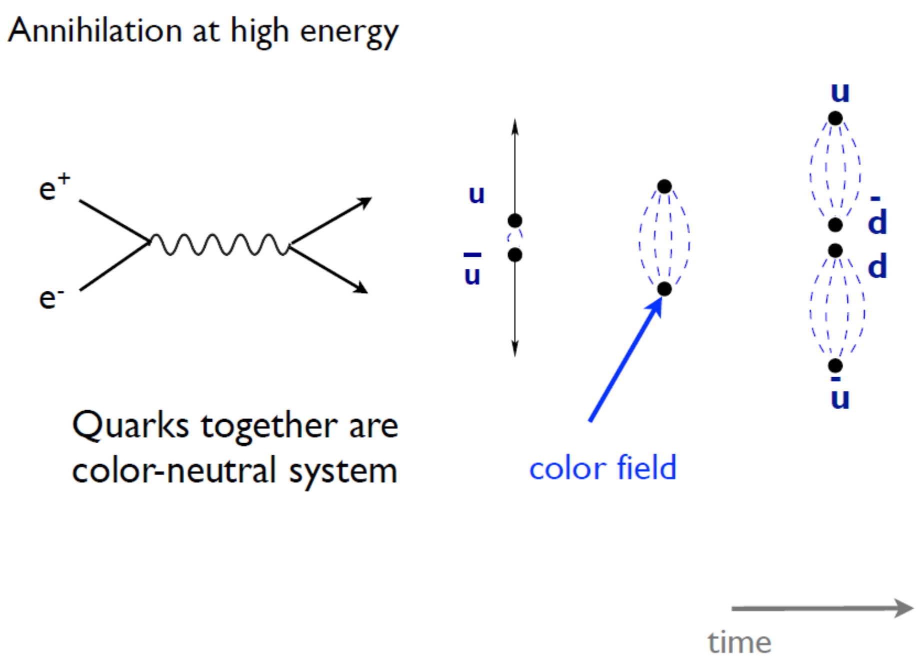
30% !

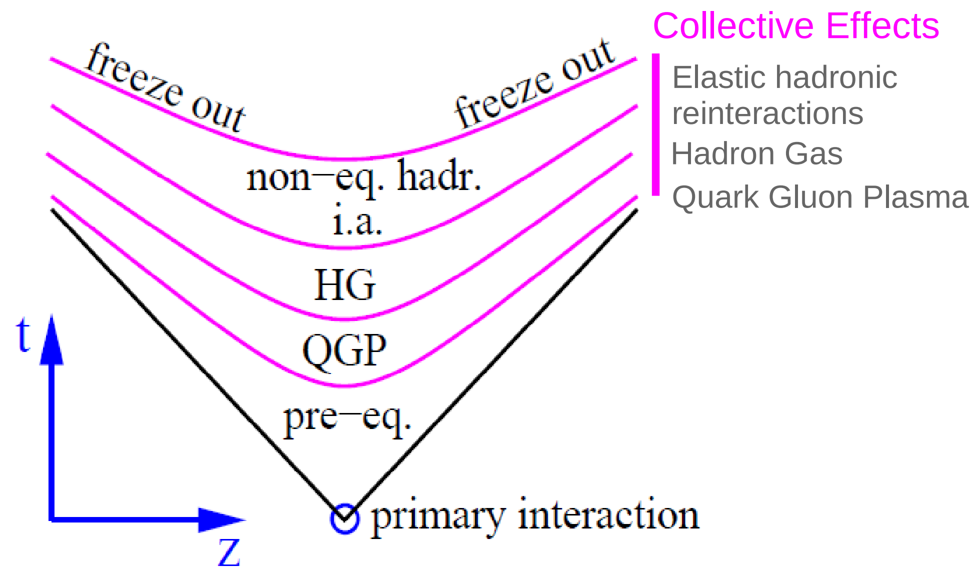
Fine details of the hadronization should be taken into account including strangeness increase seen at LHC (core-corona not here)

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 → less muons

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

➡ Core-corona → transition from one regime to the other (strangeness vs mult.)

➡ Different hadronization = different muon production in air showers !

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

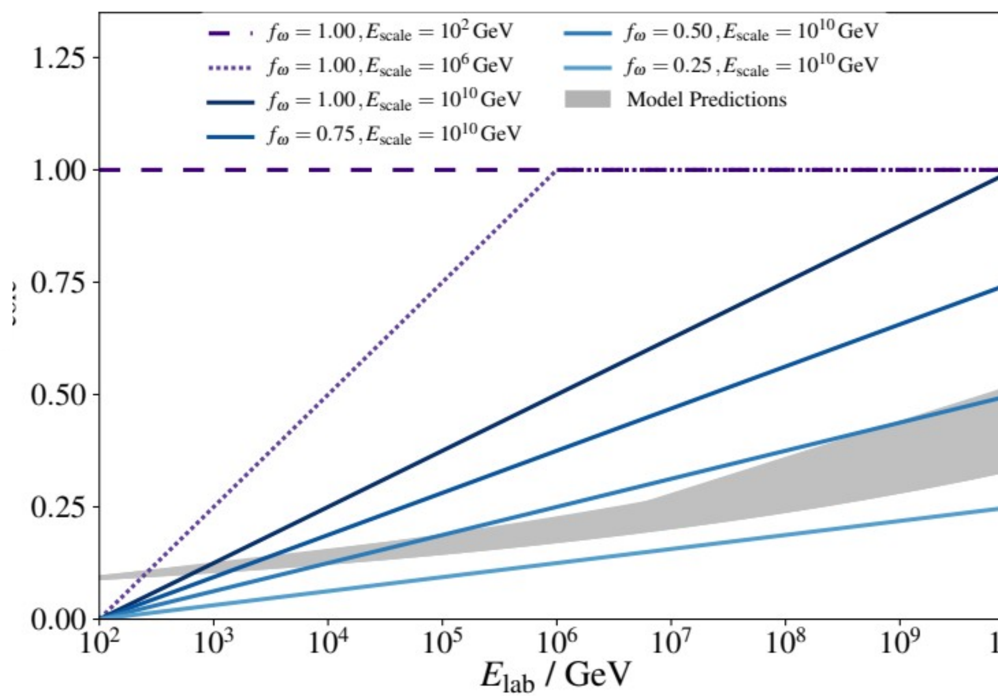
- Particle ratios from statistical model are known (tuned to PbPb) and fixed : core
- Initial particle ratios given by individual hadronic interaction models : corona
- Using CONEX, EAS can be simulated mixing corona hadronization with an arbitrary fraction ω_{core} of core hadronization: $N_i = \omega_{\text{core}}\,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

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

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

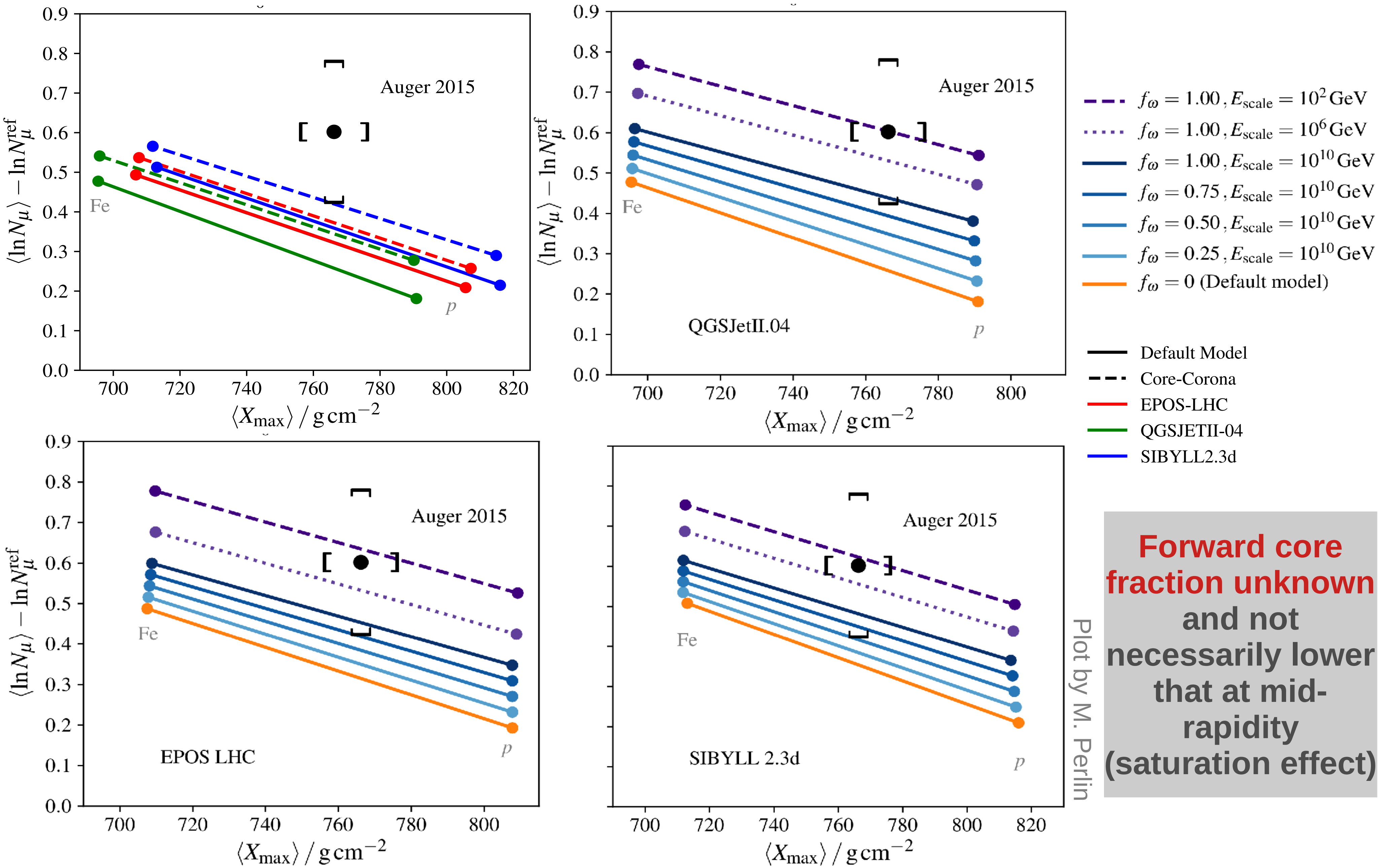
Different scenarii can be studied playing with f_ω and E_{scale}.

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]

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>
- **Details of hadronization matters**
  - Important role of resonance with sparse data = large uncertainty
    - Is Isospin symmetry broken in multiparticle production ?
  - Evolution of strangeness with multiplicity
    - Different type of hadronization (“core-corona”)
  - Carefully study “standard” physics before going to “new” physics
    - Check number of μ + energy spectra + production height (time)

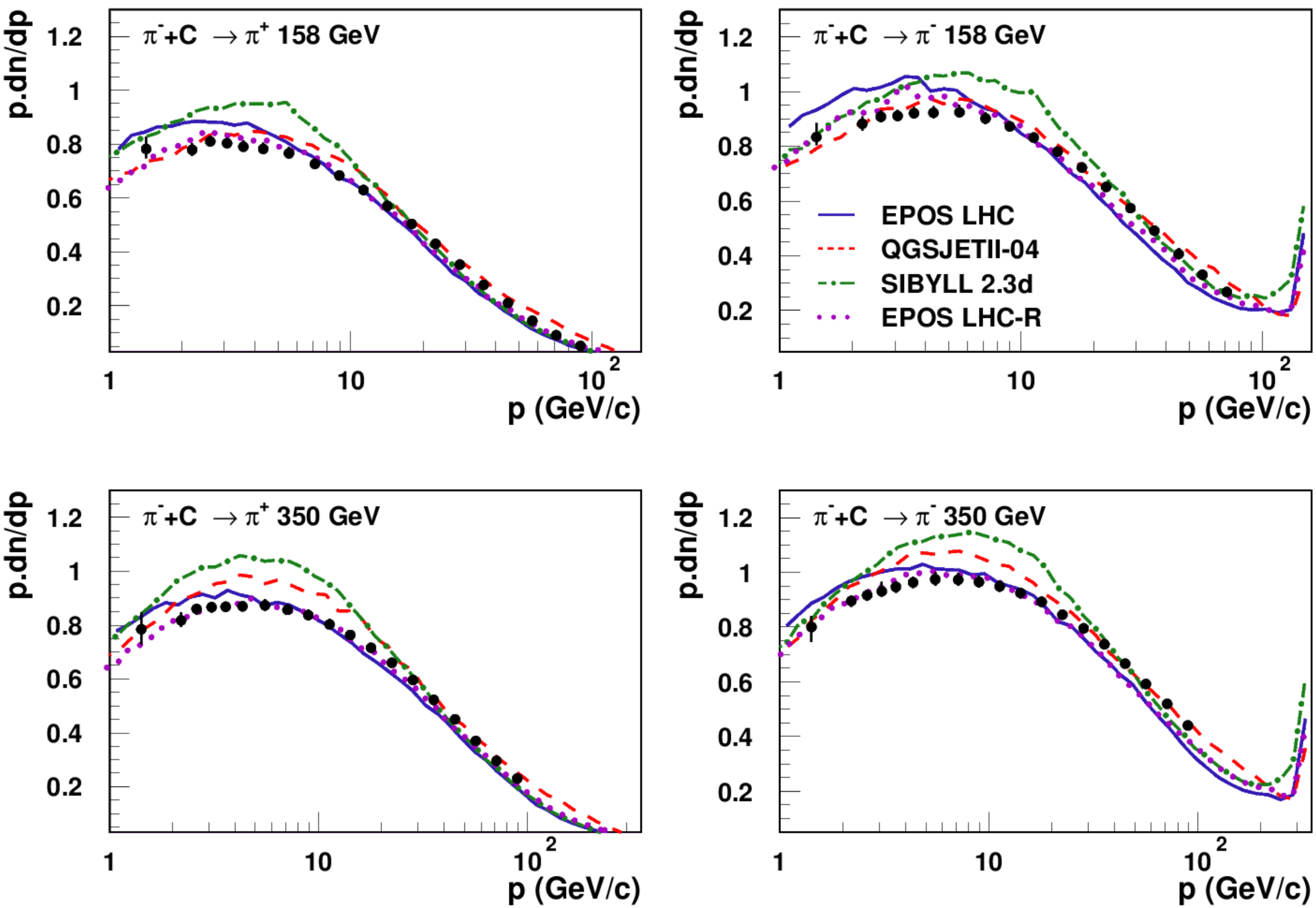
Updated EPOS LHC-R released in 2024 and then adapting EPOS 4 for CR

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.

Thank you !

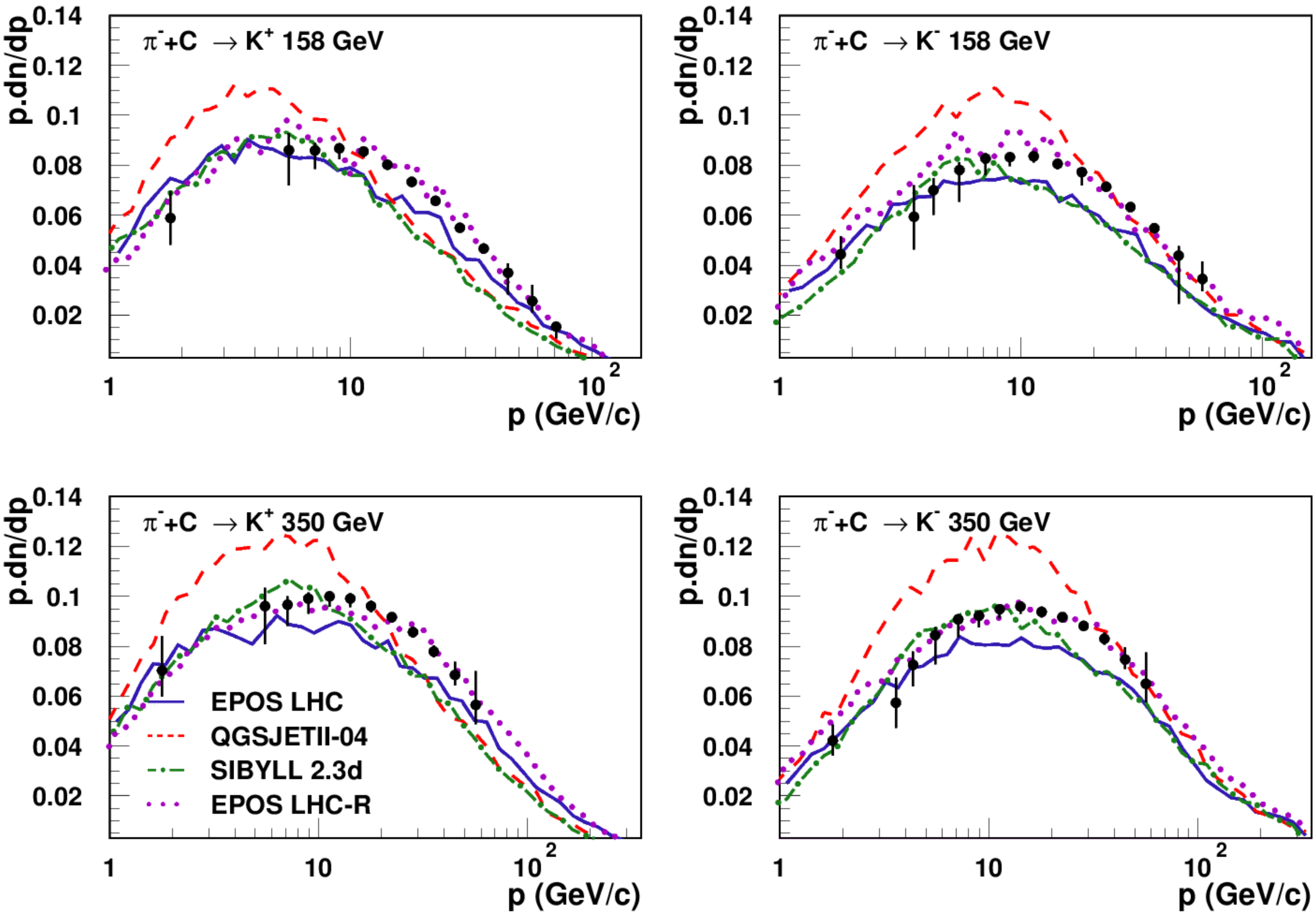
NA61

➜ Improved pion production



NA61

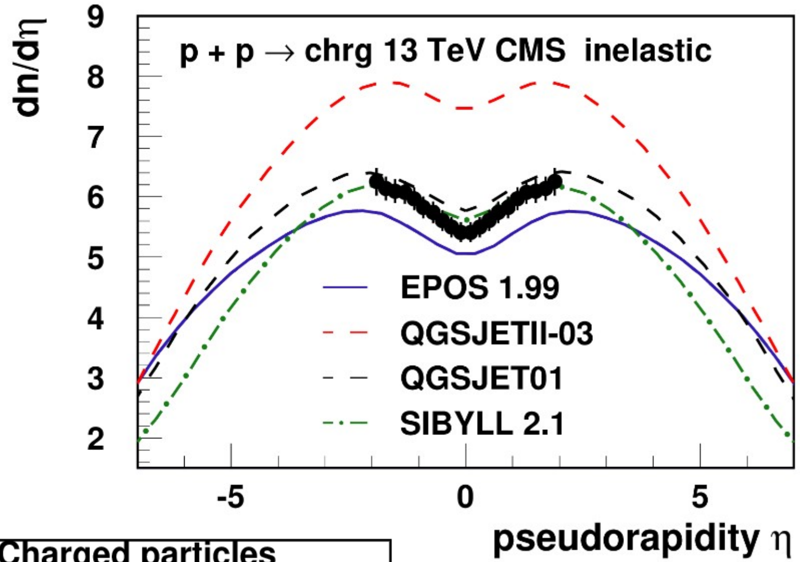
➡ Improved kaon production

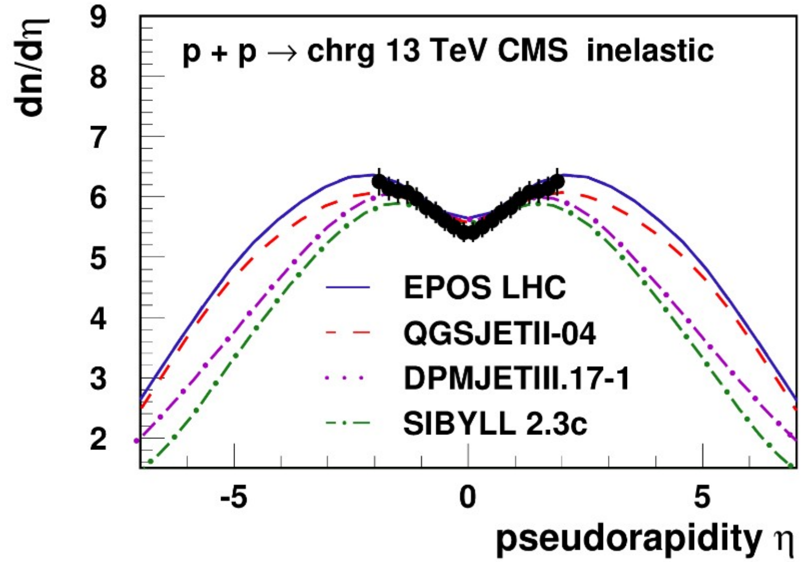


Models Uncertainties

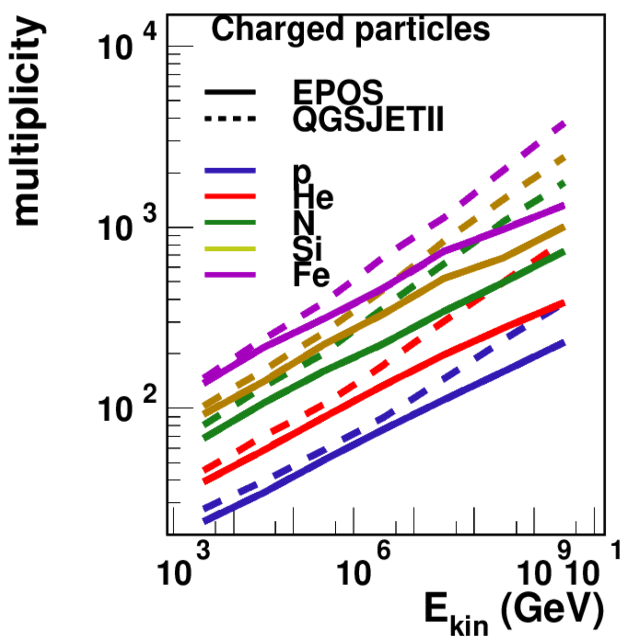
Significant improvement require new data (light ion and higher energy)

Pre - LHC





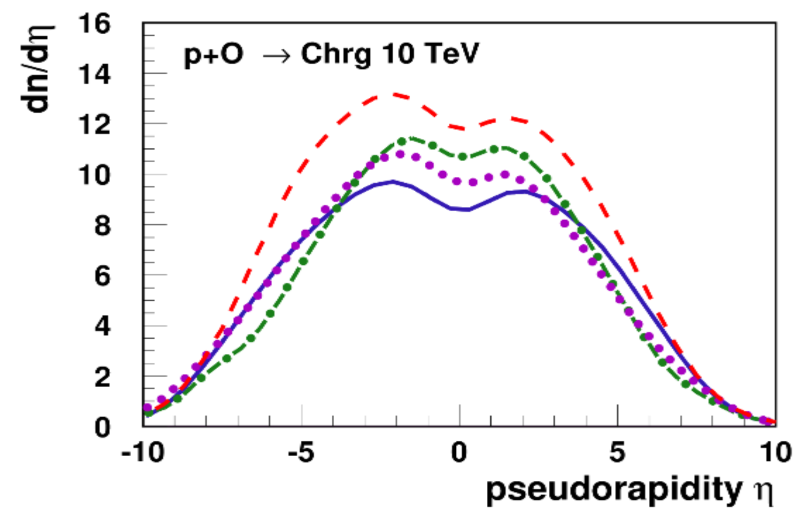
Post - LHC



After LHC, most of the model difference appear in nuclear collisions : ideal tests using p-O and O-O collisions

2024 !

Post - LHC



Hadronization in Simulations

- **Historically (theoretical/practical reasons) string fragmentation used in high energy models (Pythia, Sibyll, QGSJET, …) for proton-proton.**

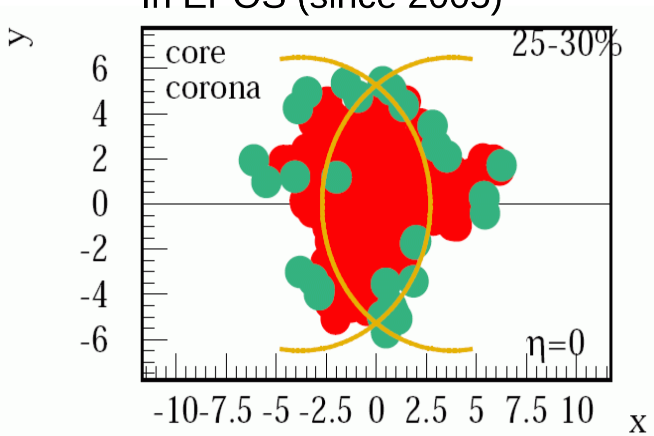
  - ➡ Light system are not “dense”
  - ➡ Works relatively well at SPS (low energy)
  - ➡ But problems already at RHIC, clearly at Fermilab, and serious at LHC :
    - Modification of string fragmentation needed to account for data
    - Various phenomenological approaches :
      - ➡ Color reconnection
      - ➡ String junction
      - ➡ String percolation, …
    - Number of parameters increased with the quality of data …

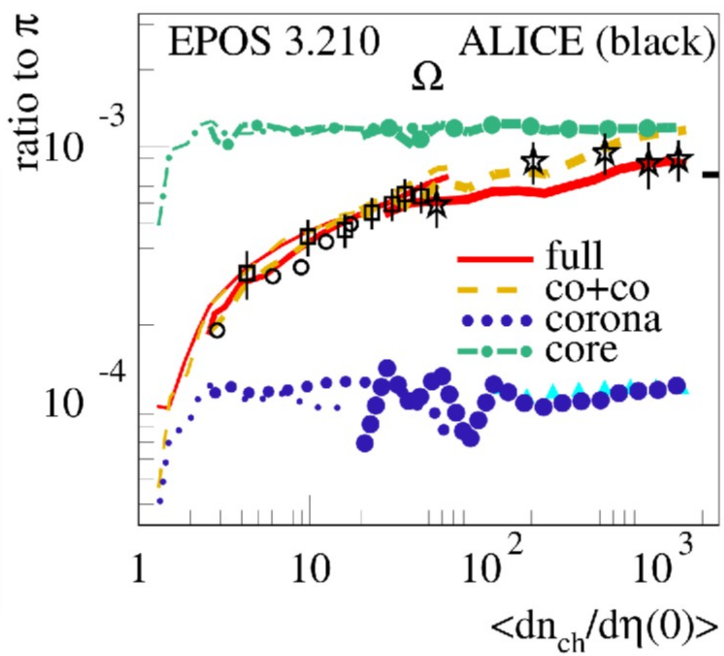
- **Statistical model only used for heavy ion (HI) in combination with hydrodynamical evolution of the dense system : QGP hadronization**
  - ➡ Account for flow effects, strangeness enhancement, particle correlations...

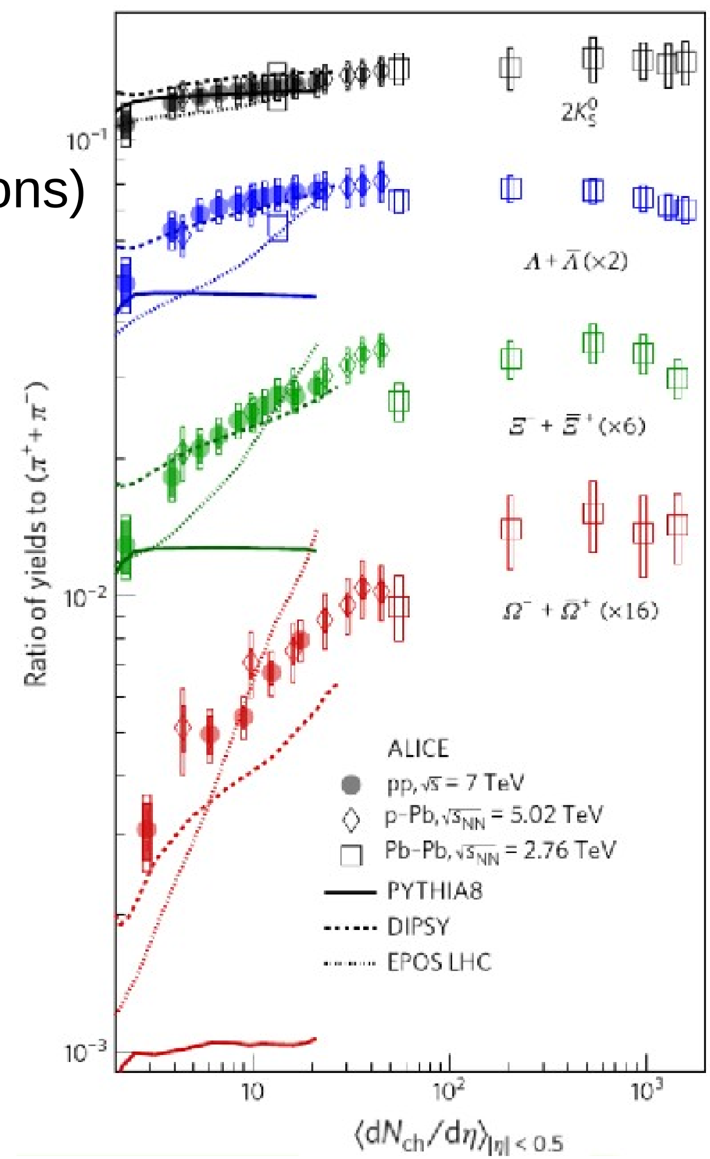
Core-Corona Approach

- **Mixing of core and corona hadronization needed to achieve detailed description of p-p data (EPOS)**
  - 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)



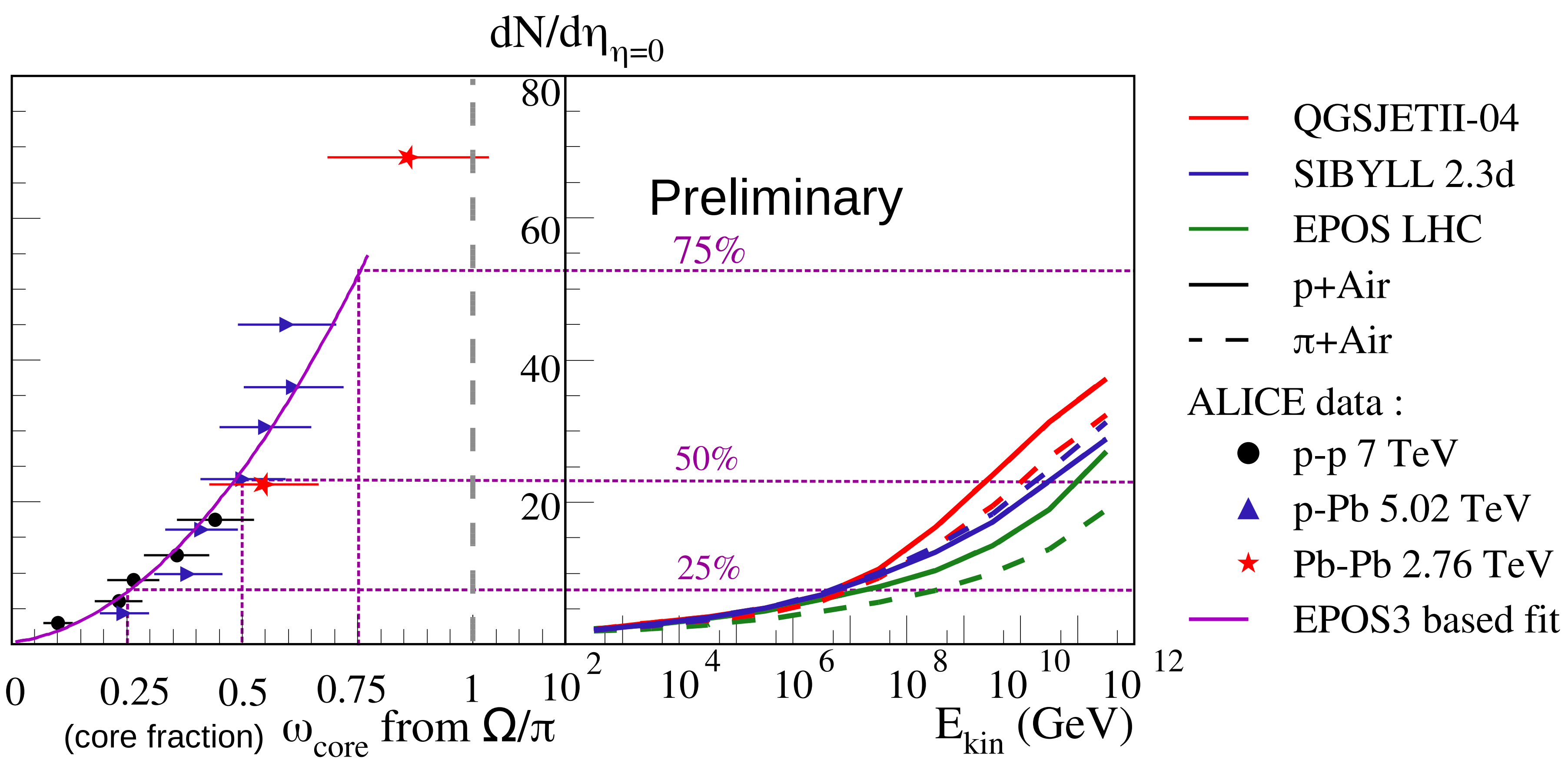




Particle Densities in Air Showers

Is particle density in air shower high enough to expect core formation ?

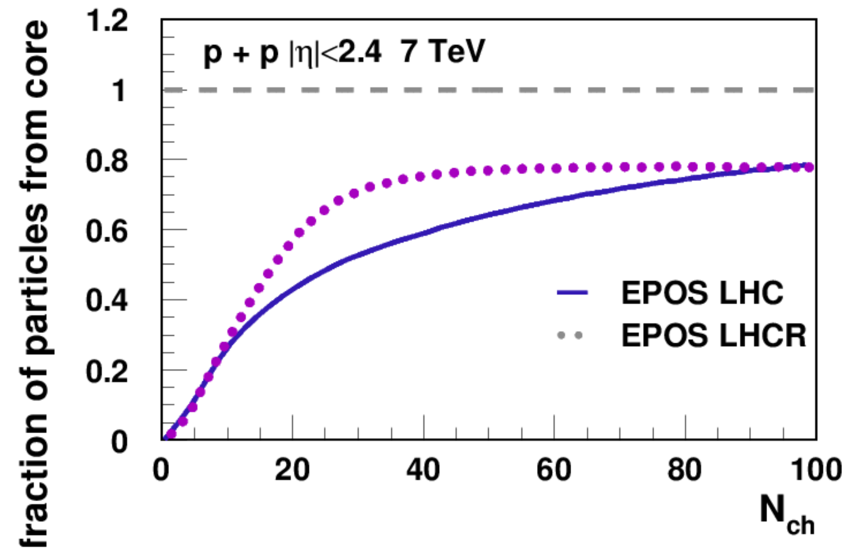
- Core formation start quite early according to ALICE data
- Cosmic ray primary interaction likely to have 50% core at mid-rapidity !

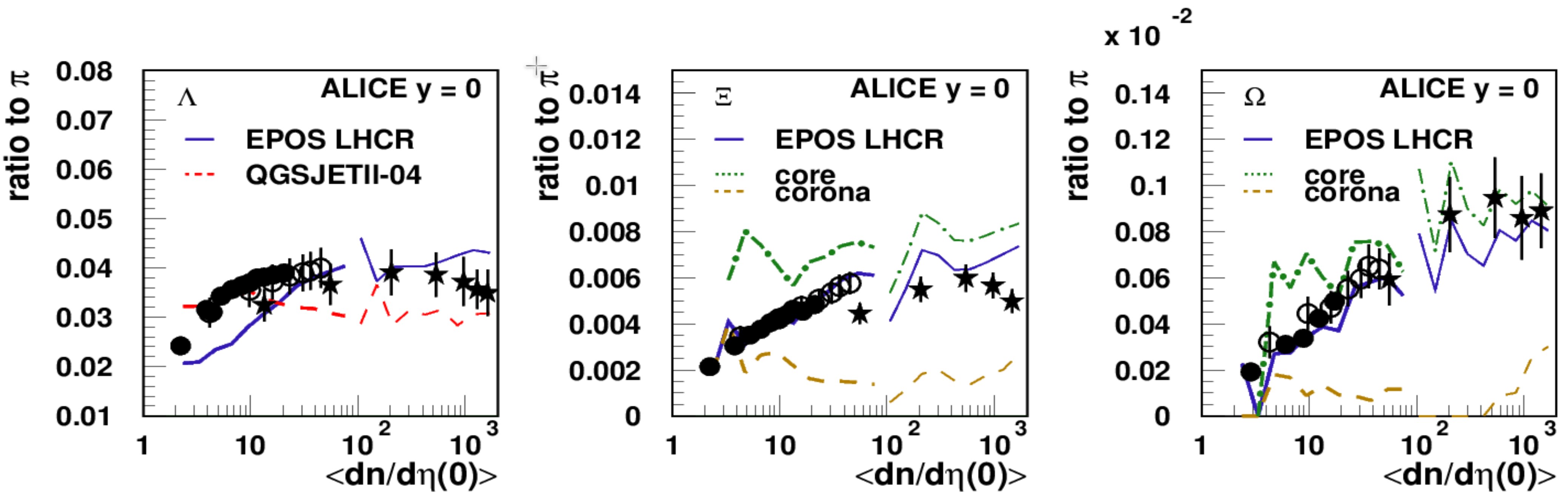


ALICE data

Update of EPOS to reproduce ALICE data

- Lower condition (particle density) to form core
- More core

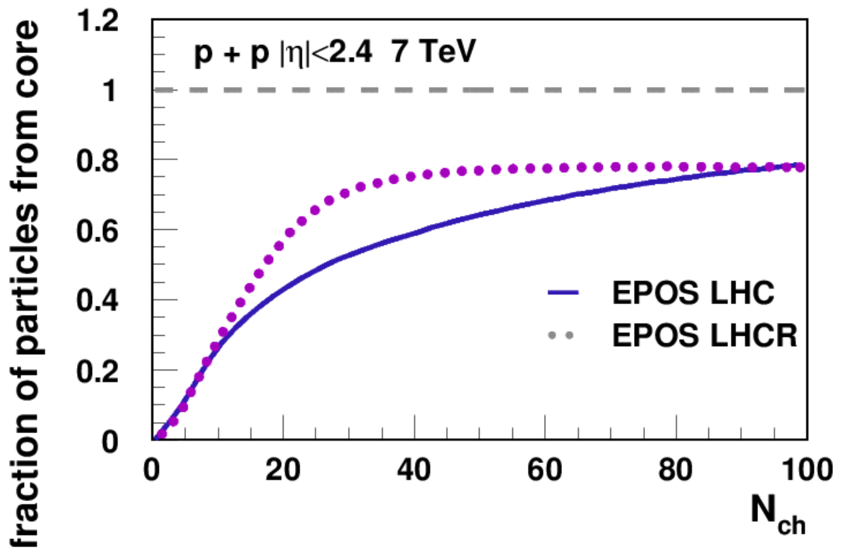


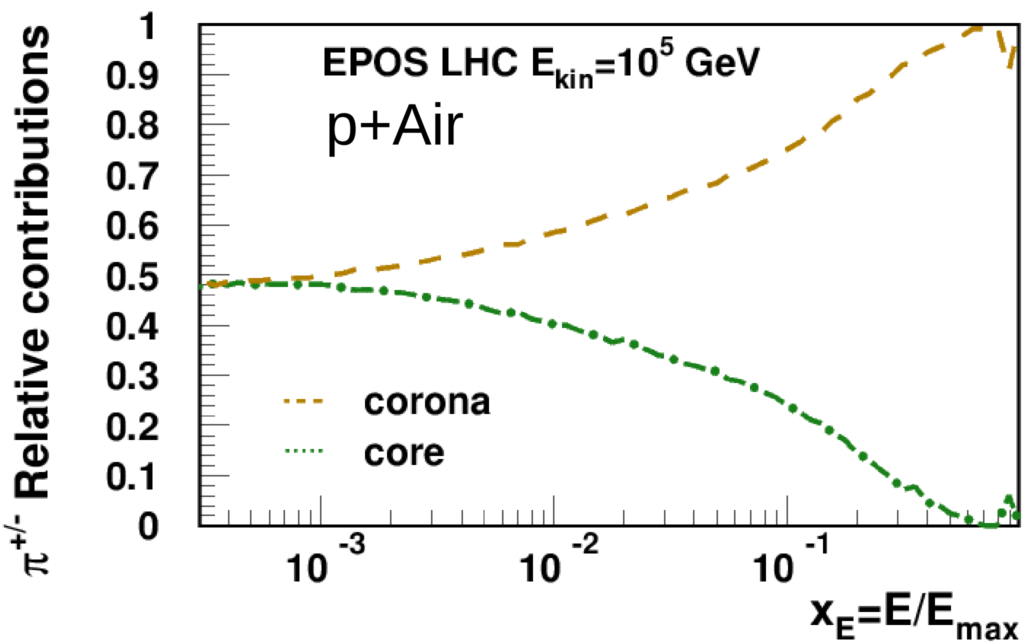


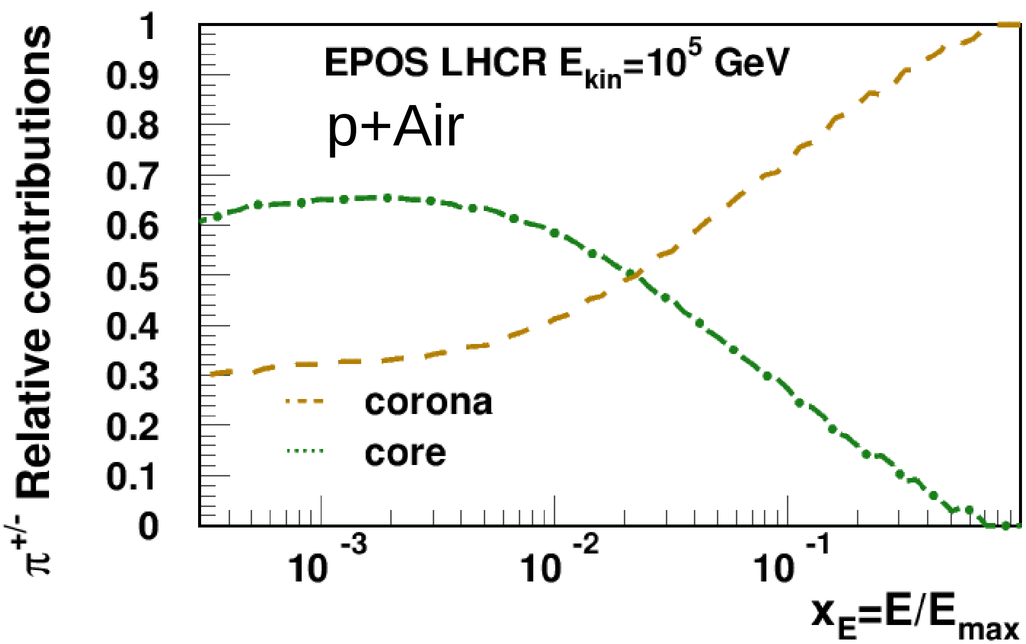
Interactions in Air Showers

Update of EPOS to reproduce ALICE data

- Lower condition (particle density) to form core
- More core and more forward
- Possible impact on muon production in air showers (lower π^0 fraction)







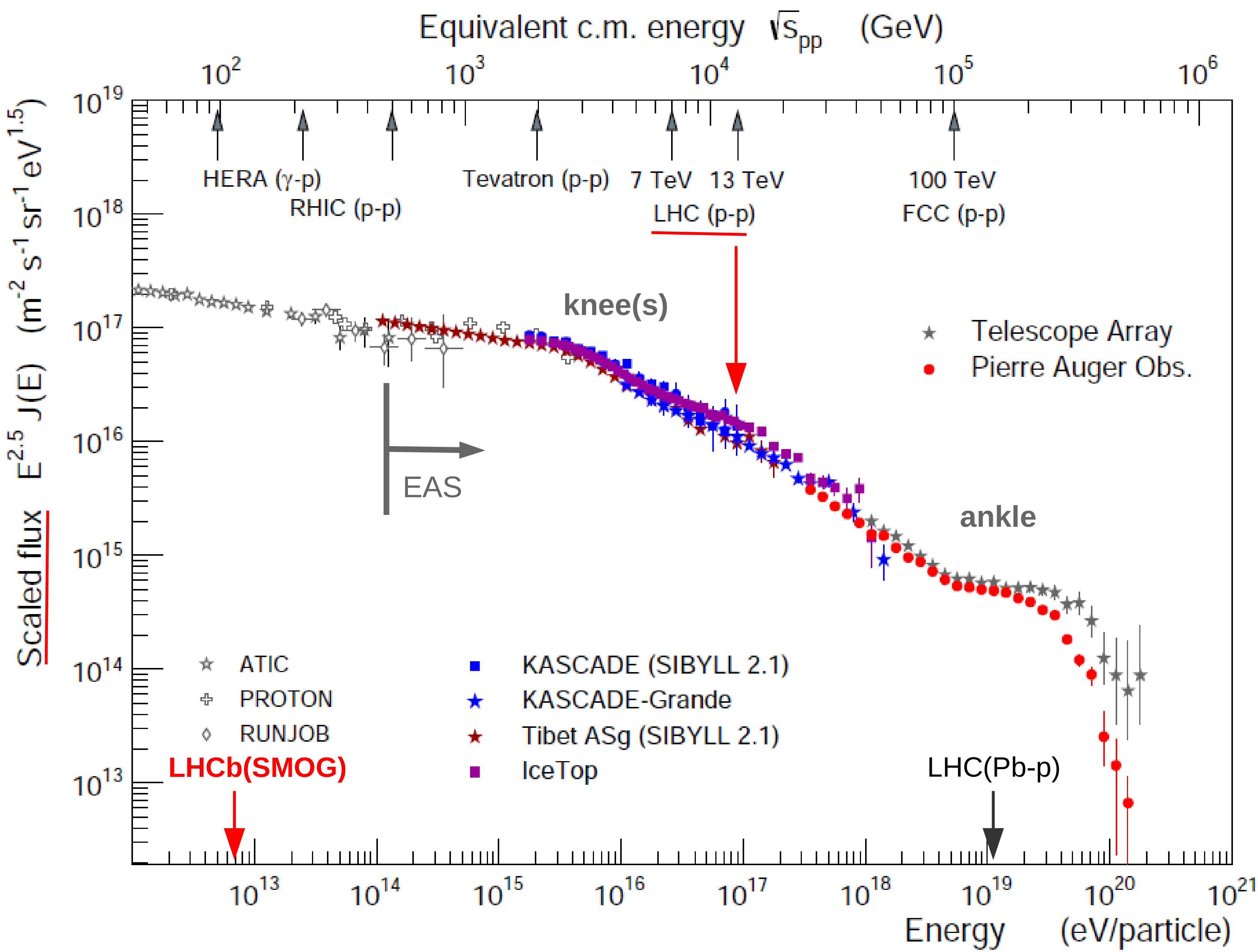
Hadronic Models for Air Showers

- **EAS simulations necessary to study high energy cosmic rays**
  - complex problem: identification of the primary particle from the secondaries

- **Hadronic models are the key ingredient !**
  - follow the standard model (QCD)
    - but mostly non-perturbative regime (phenomenology needed)
  - main source of uncertainties

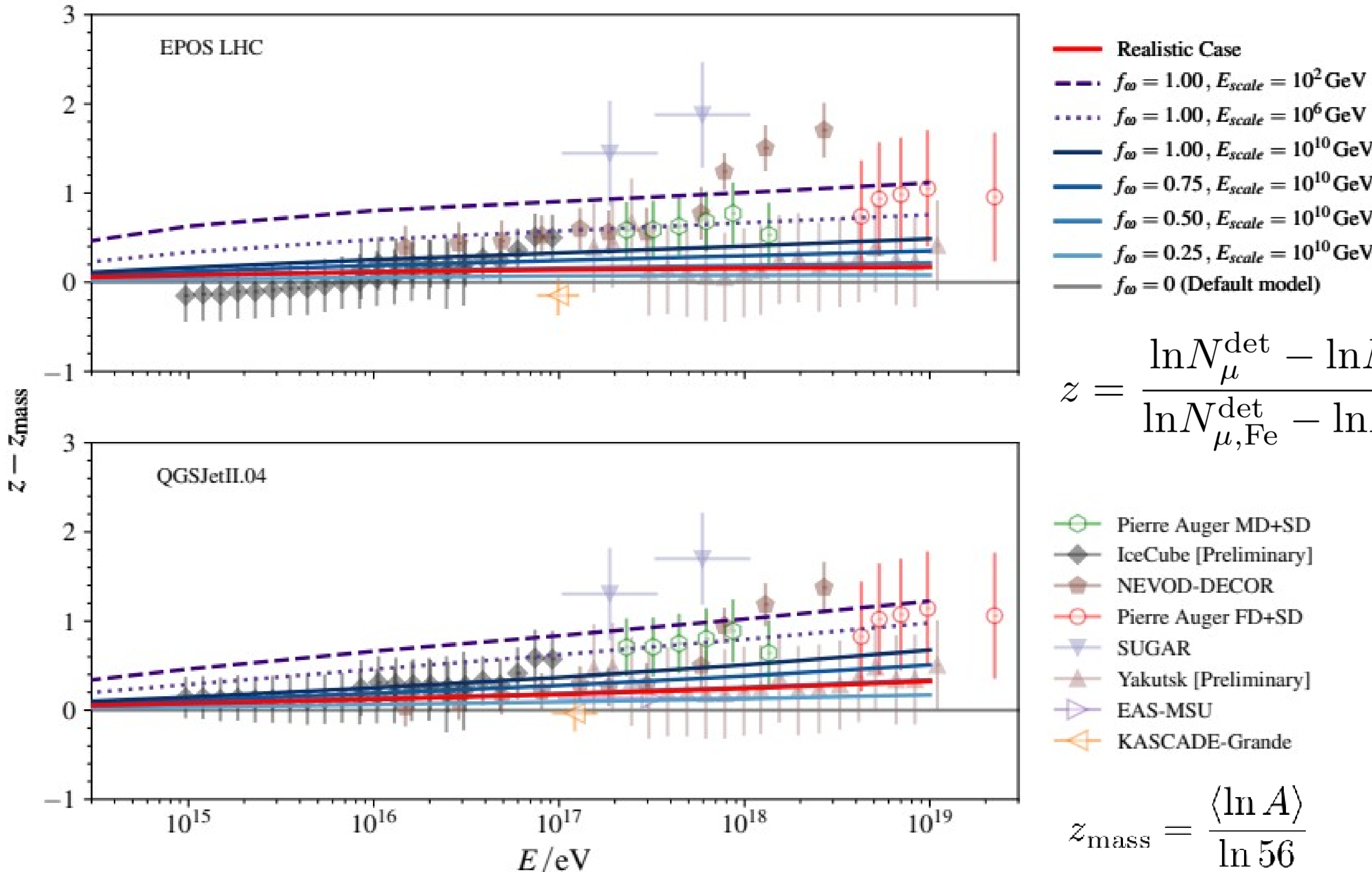
- **Which model for CR ?** (alphabetical order)
  - **DPMJETIII.17-1/19-1** by S. Roesler, A. Fedynitch, R. Engel and J. Ranft
  - **EPOS (1.99/LHC/3/4/LHC-R)** by T. Pierog and K.Werner. et al.
  - **QGSJET** (01/II-03/II-04/III) by S. Ostapchenko (starting with N. Kalmykov)
  - **Sibyll (2.1/(2.3c/)2.3d)** by E-J Ahn, R. Engel, R.S. Fletcher, T.K. Gaisser, P. Lipari, F. Riehn, T. Stanev
    - All tuned on early LHC data from 10 years ago !

Energy Spectrum



R. Engel
(KIT)

Results for z-scale



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

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

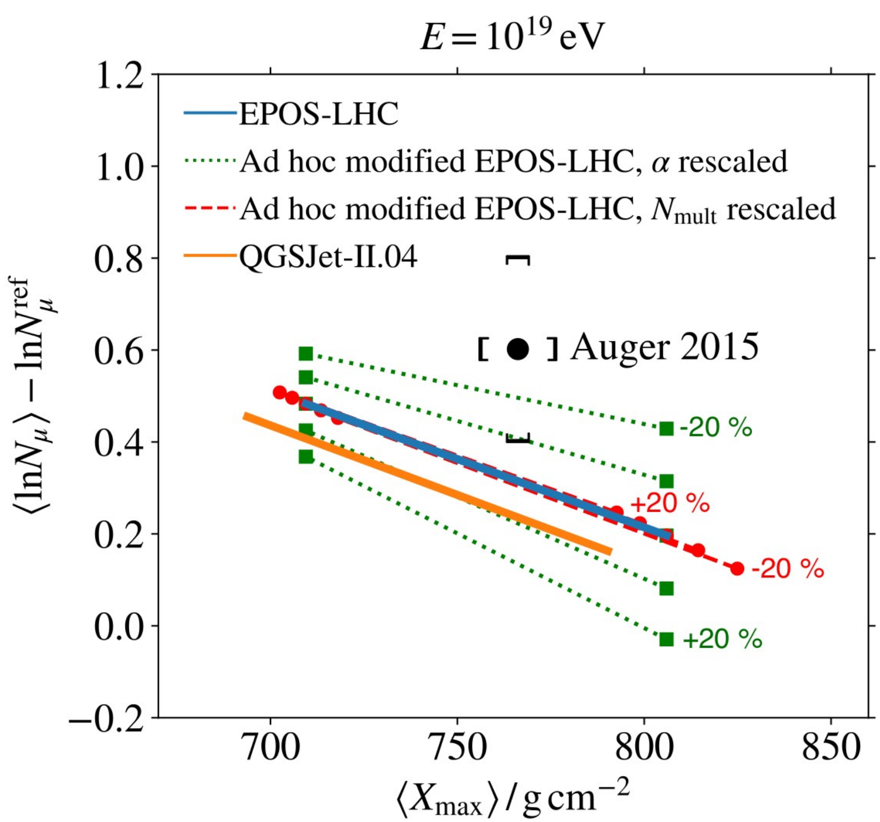
Plot by M. Perlin

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

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

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

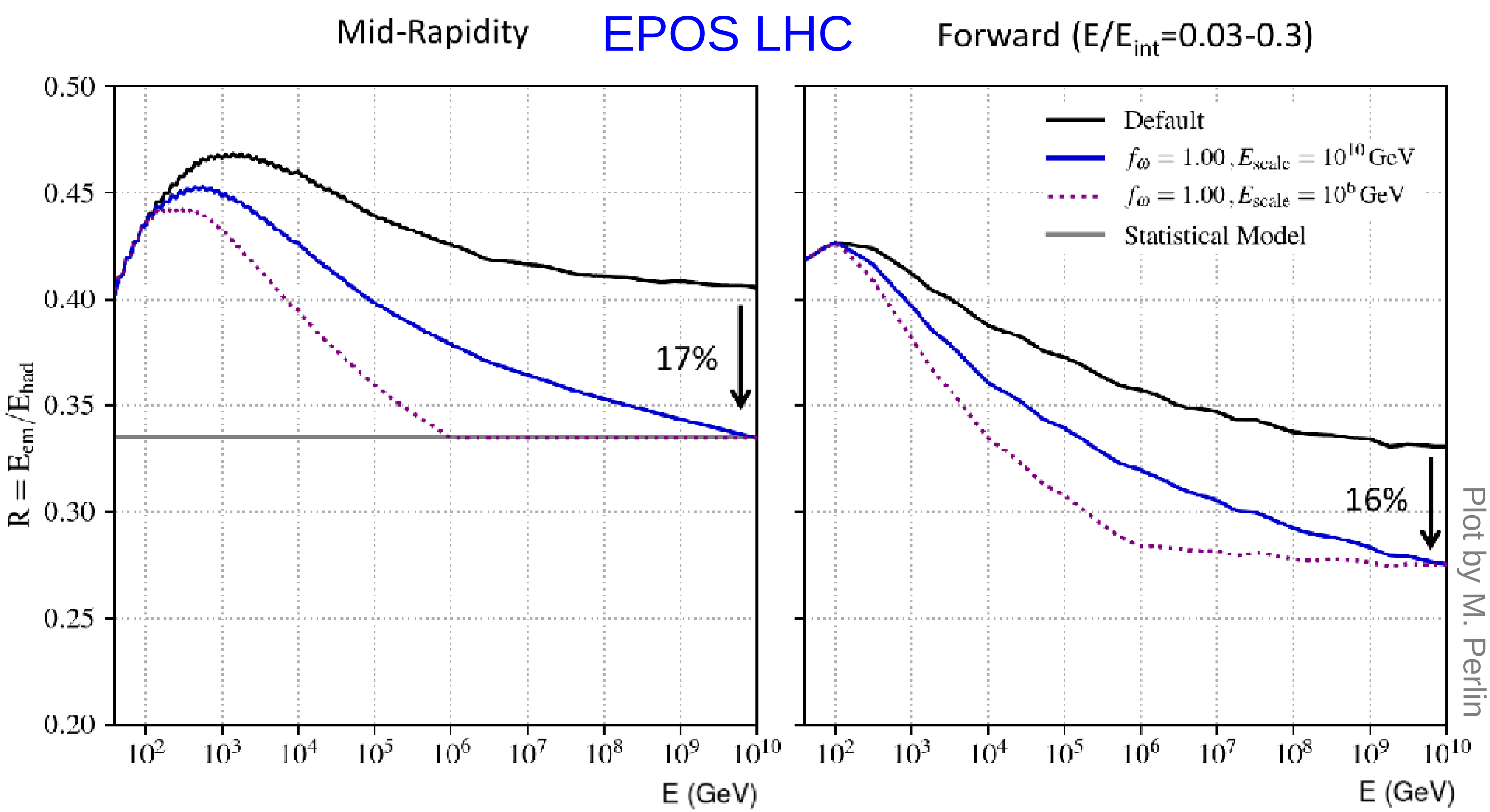


Plot by H. Dembinski

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.



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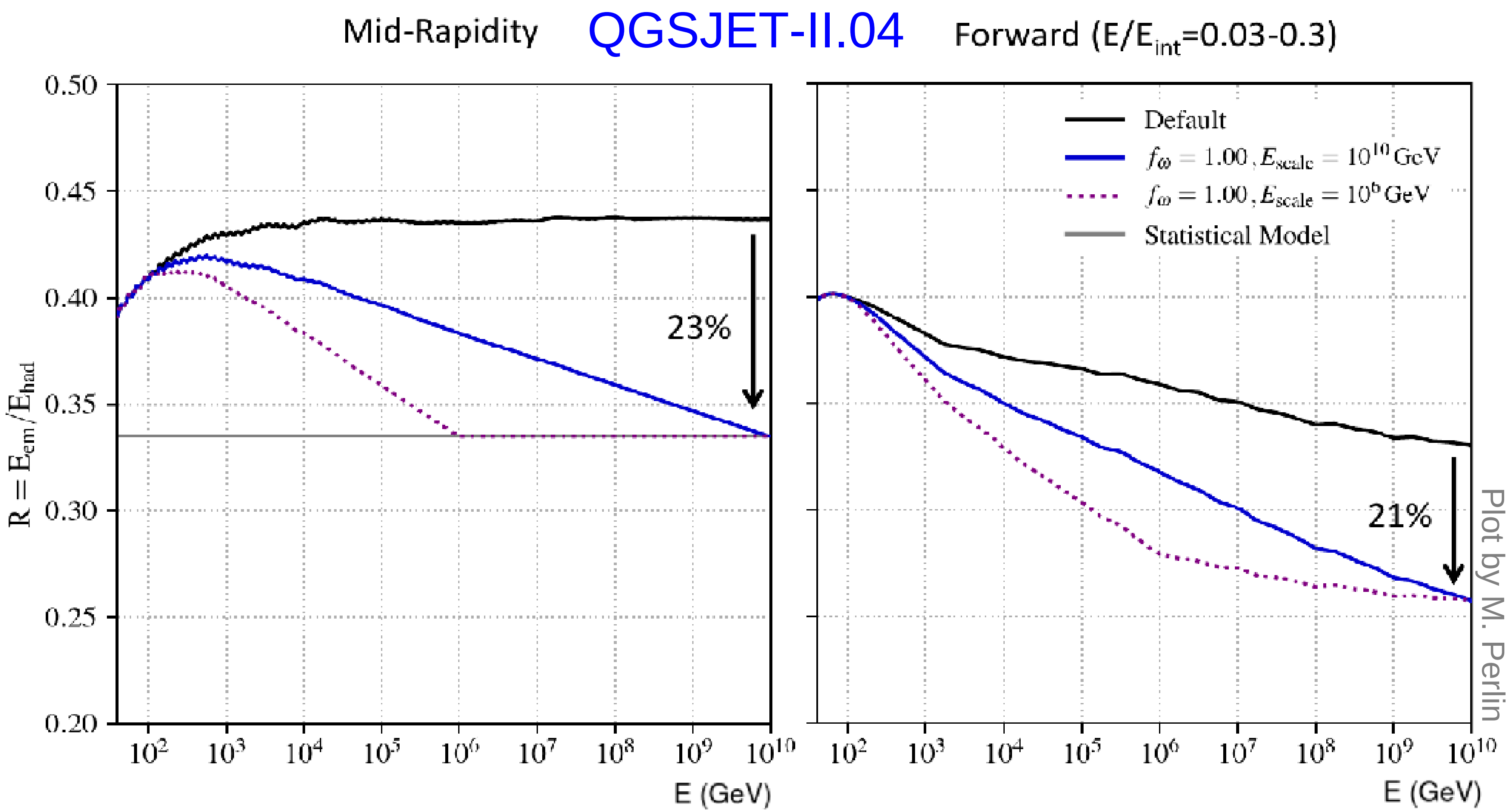

Evolution of hadronization from core to corona

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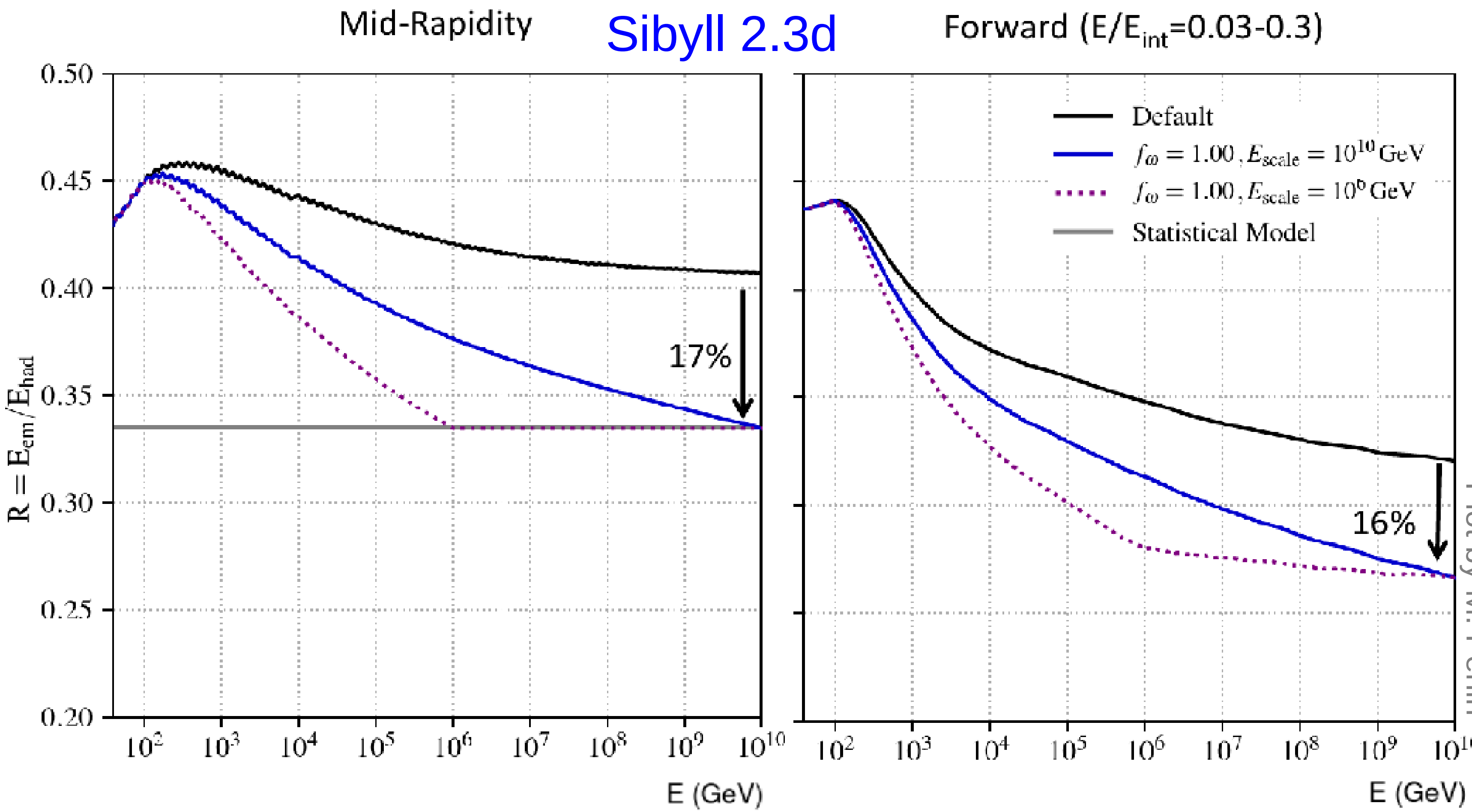
Sibyll 2.3d



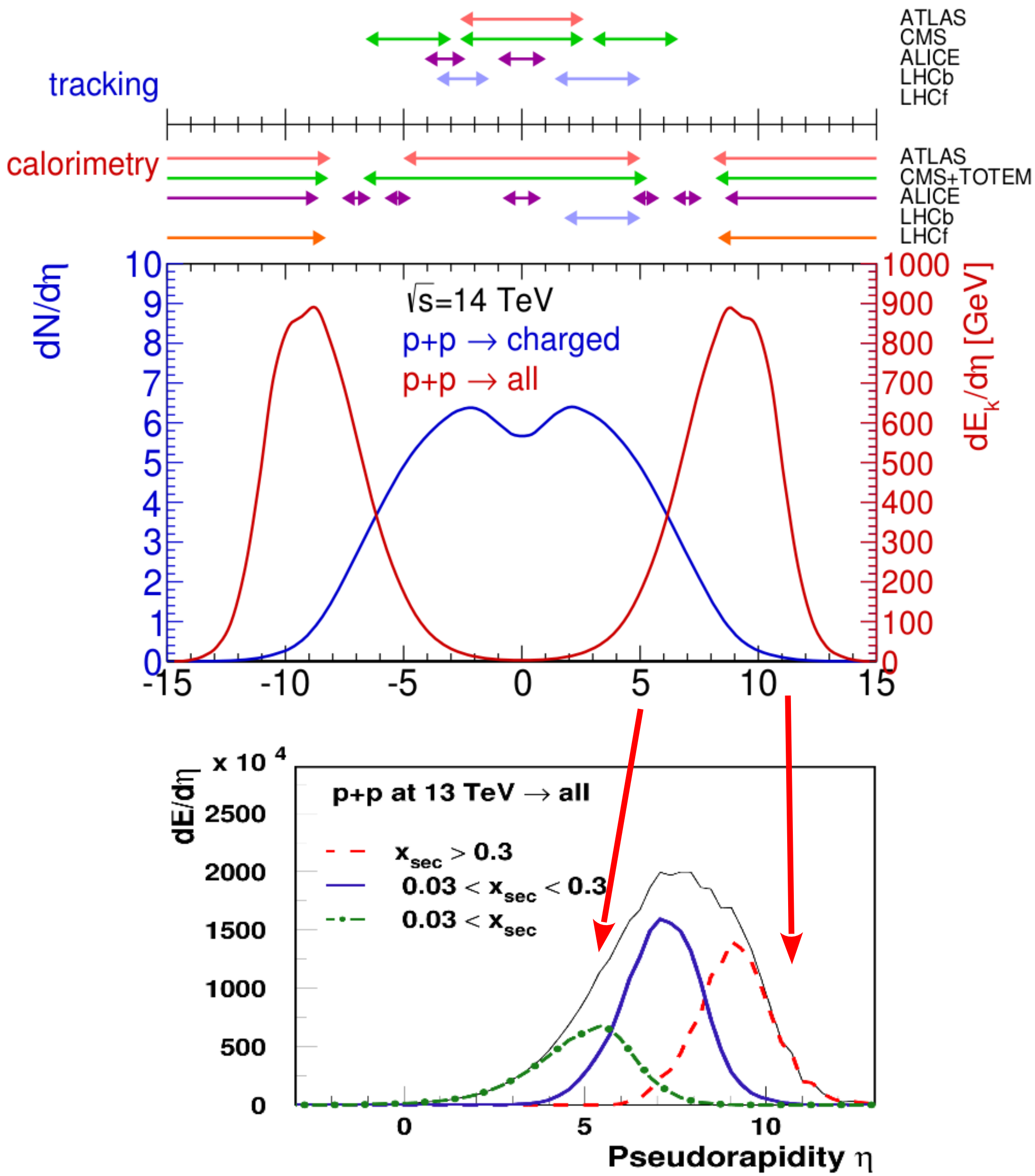
Plot by M. Perlin

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

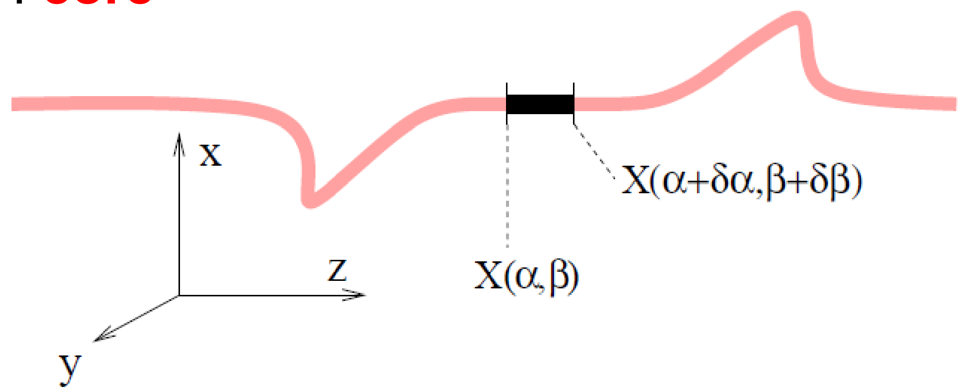


- **p-p data mainly from "central" detectors**
  - pseudorapidity $\eta=-\ln(\tan(\theta/2))$
  - $\theta=0$ is midrapidity
  - $\theta>>1$ is forward
  - $\theta<<1$ is backward
- **Different phase space for LHC and air showers**
  - most of the particles produced at midrapidity
    - important for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

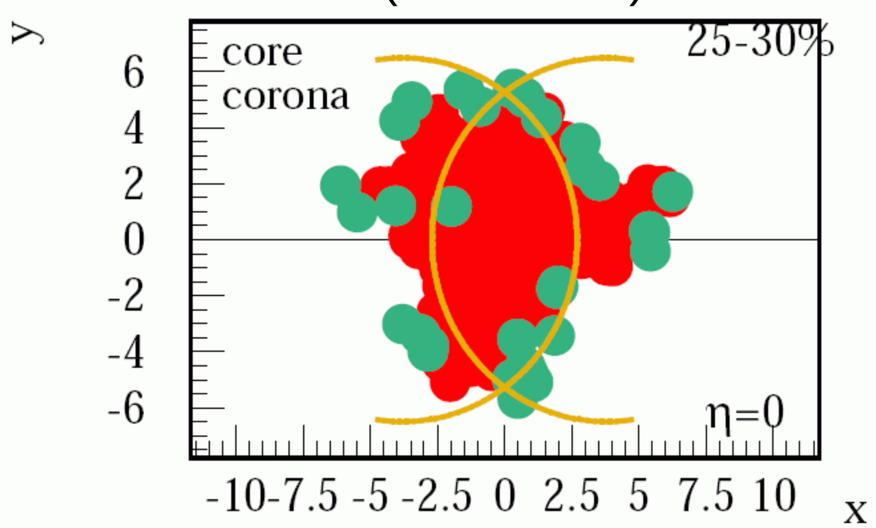
A 3rd way : the core-corona approach

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