New developments in EPOS :

Toward a global approach from Heavy Ions to Cosmic Rays

Tanguy Pierog

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

With K.Werner, SUBATECH, Nantes, France

Cosmic Ray and neutrinos in the multimessenger era, APC, Paris, France

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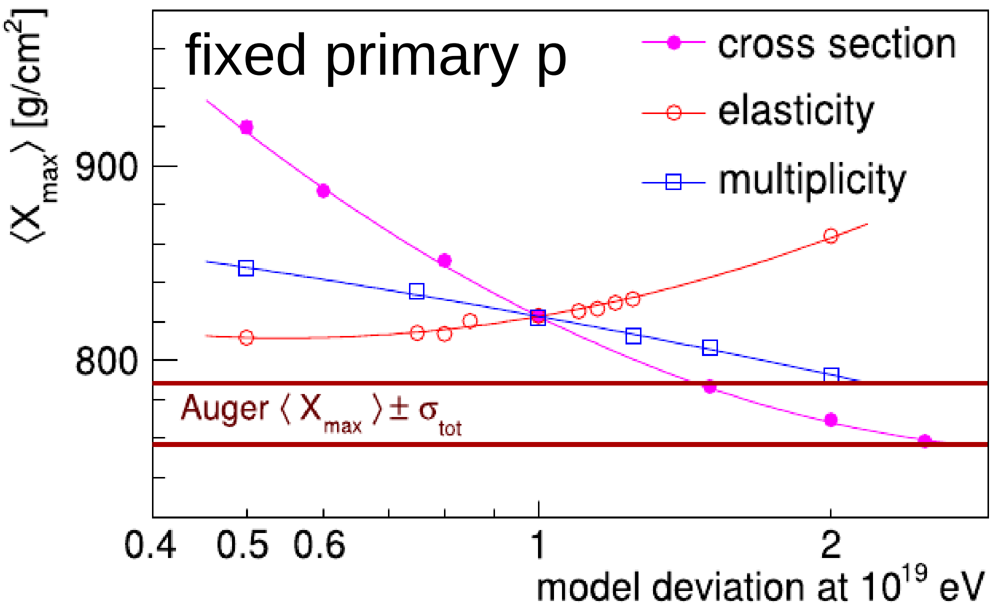
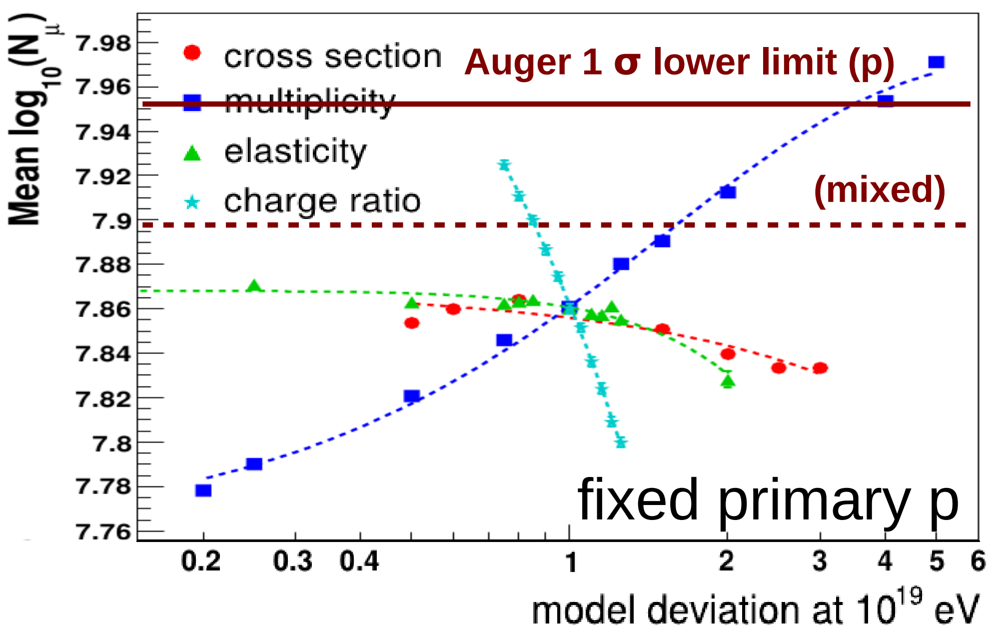
Outline

- **Introduction**
- **Updates → EPOS LHC-R**
  - ➔ A real global approach to do hadronic interactions
- **Impact of Hadronic Rescattering (HS)**
- **Predictions for air showers (EAS)**
  - ➔ X_{max} and μ
- **Muon puzzle**
  - ➔ Why collective effects impact muon production ?

Recent LHC data provide new constraints on models changing X_{max} and the muon production if a global approach is used.

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
  - ➡ <u>charge ratio</u> and baryon production
- **Change of primary = change of hadronic interaction parameters**
  - ➡ cross-section, elasticity, mult. …
- **Model tuned to accelerator data**

Theory AND data are important to constrain the hadronic model parameters.

Possible updates since EPOS LHC

- **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}

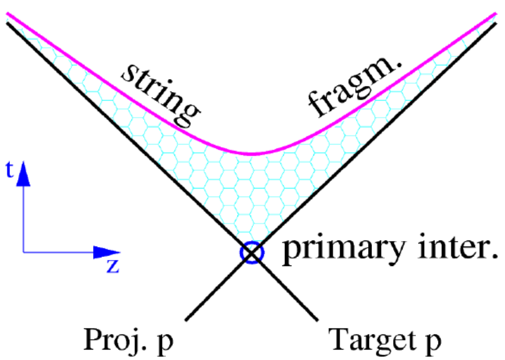
  - Particle yields as a function of multiplicity (ALICE, LHCb)
    - Very important to understand the mechanism behind particle production

  → 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
  - Almost final result (but still preliminary) including all collective effects !

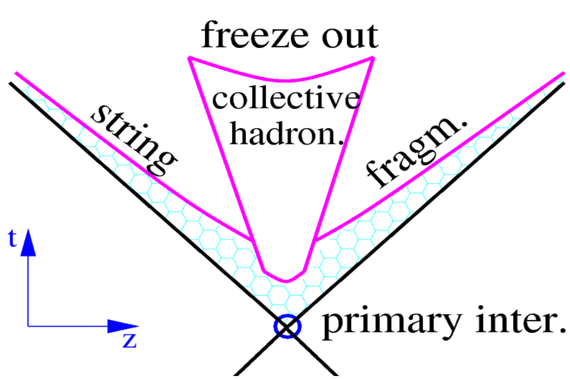
What means global approach ?

Global approach is the key !

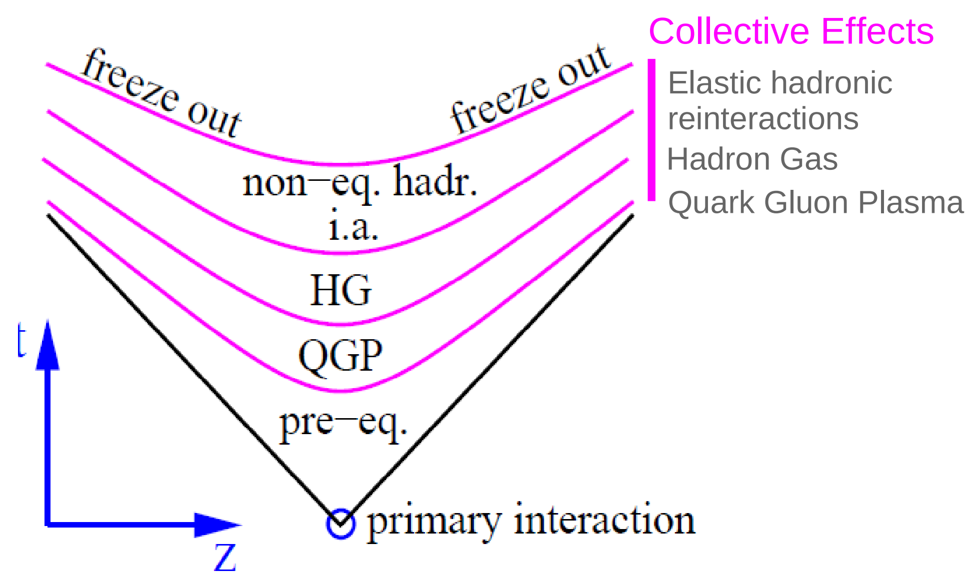
- Tuning models neglecting some physics process may lead to wrong parameters !
- Correct tune possible only if everything taken into account
- Even without a direct impact on the shower development (rare particle or not forward), it will change model parameters and the extrapolation (in energy or phase space)



Sibyll, QGSJET



EPOS LHC
(no rescattering)

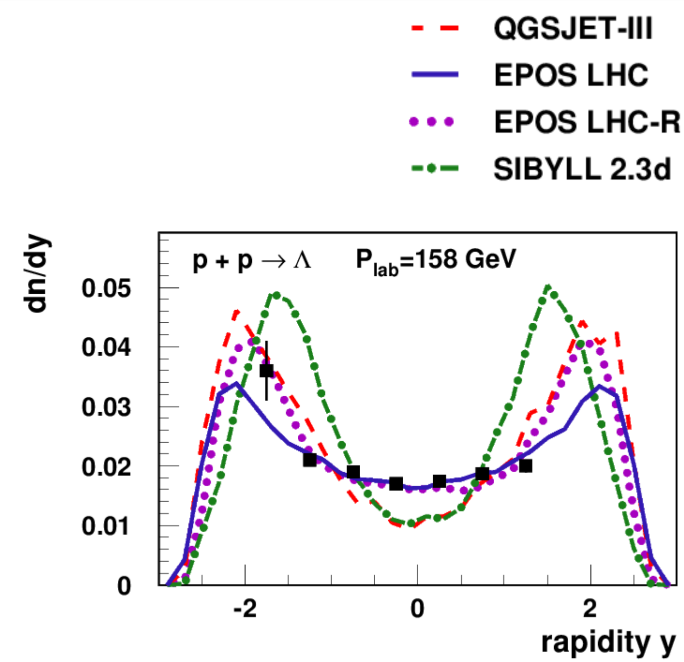


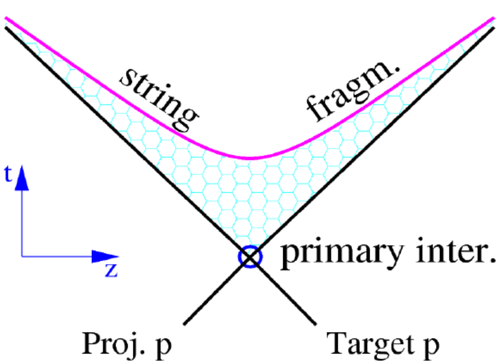
EPOS LHC-R

String Fragmentation

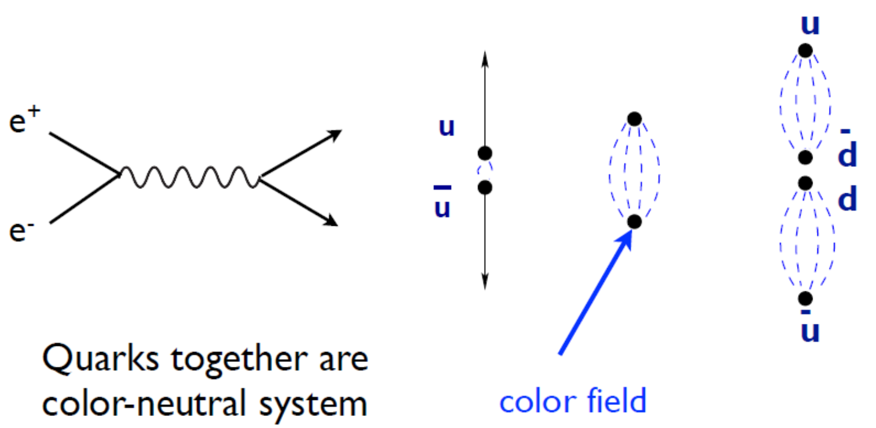
Global approach is the key !

- Common hadronization in all the models
- Parameters fixed on e+-e- only in EPOS
  - Other CR models tuned on p-p data
    - "Contamination" by beam remnant
- Very important for forward particle production (EAS)
    - Used for beam remnant hadronization

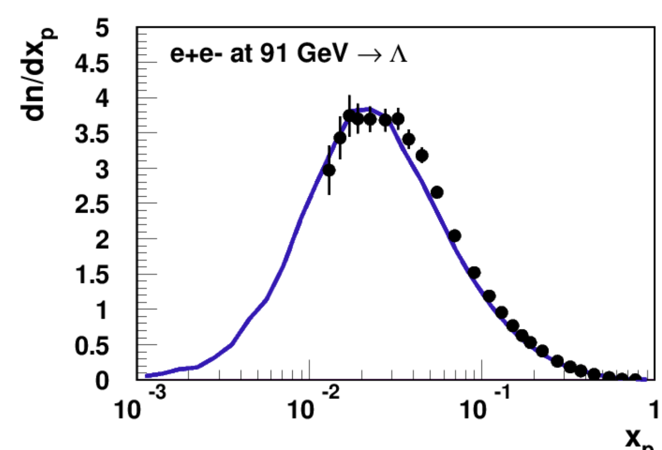




Annihilation at high energy



time

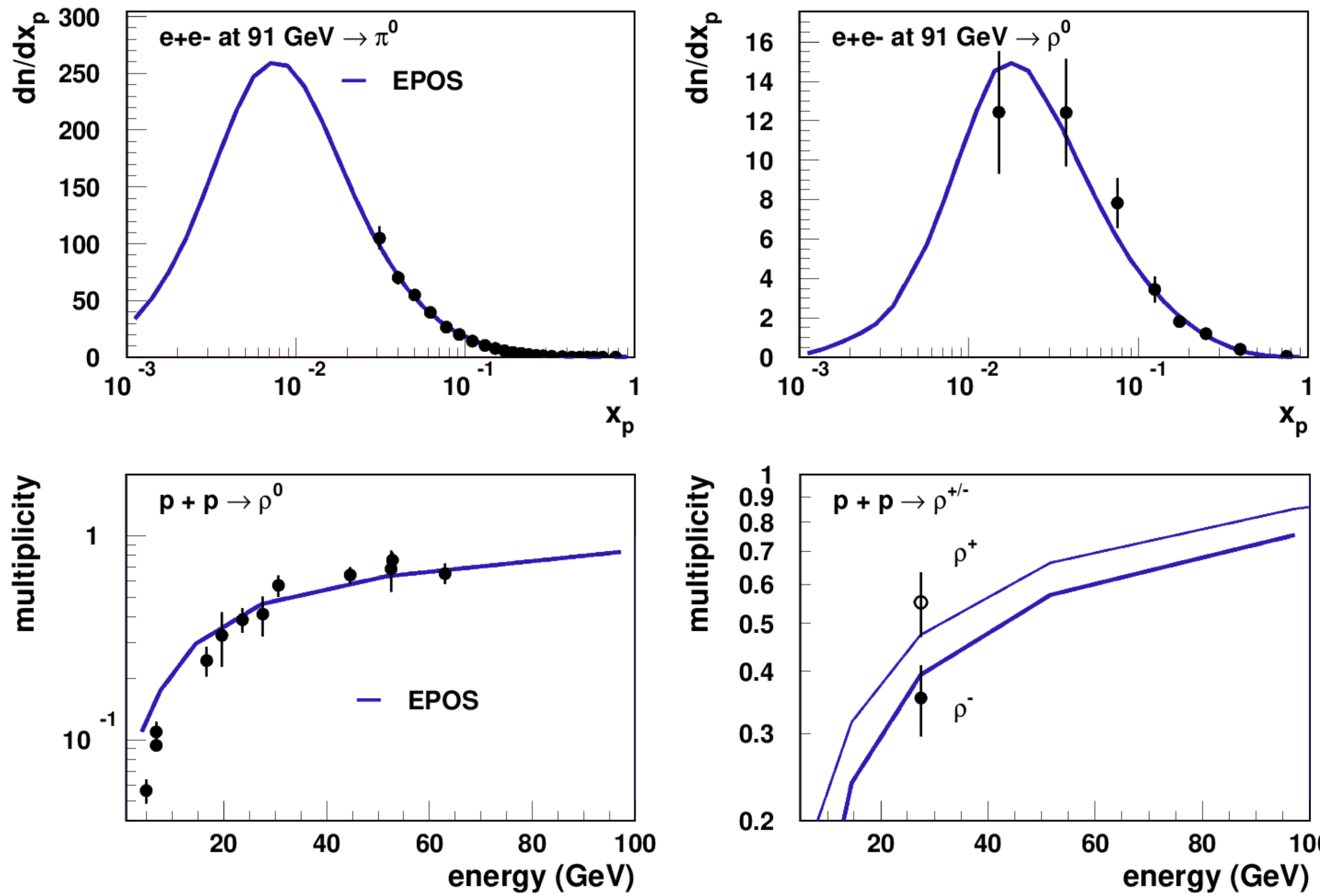


Used in dilute systems = CORONA

Generic "EPOS"

First attempt using theoretical constraints

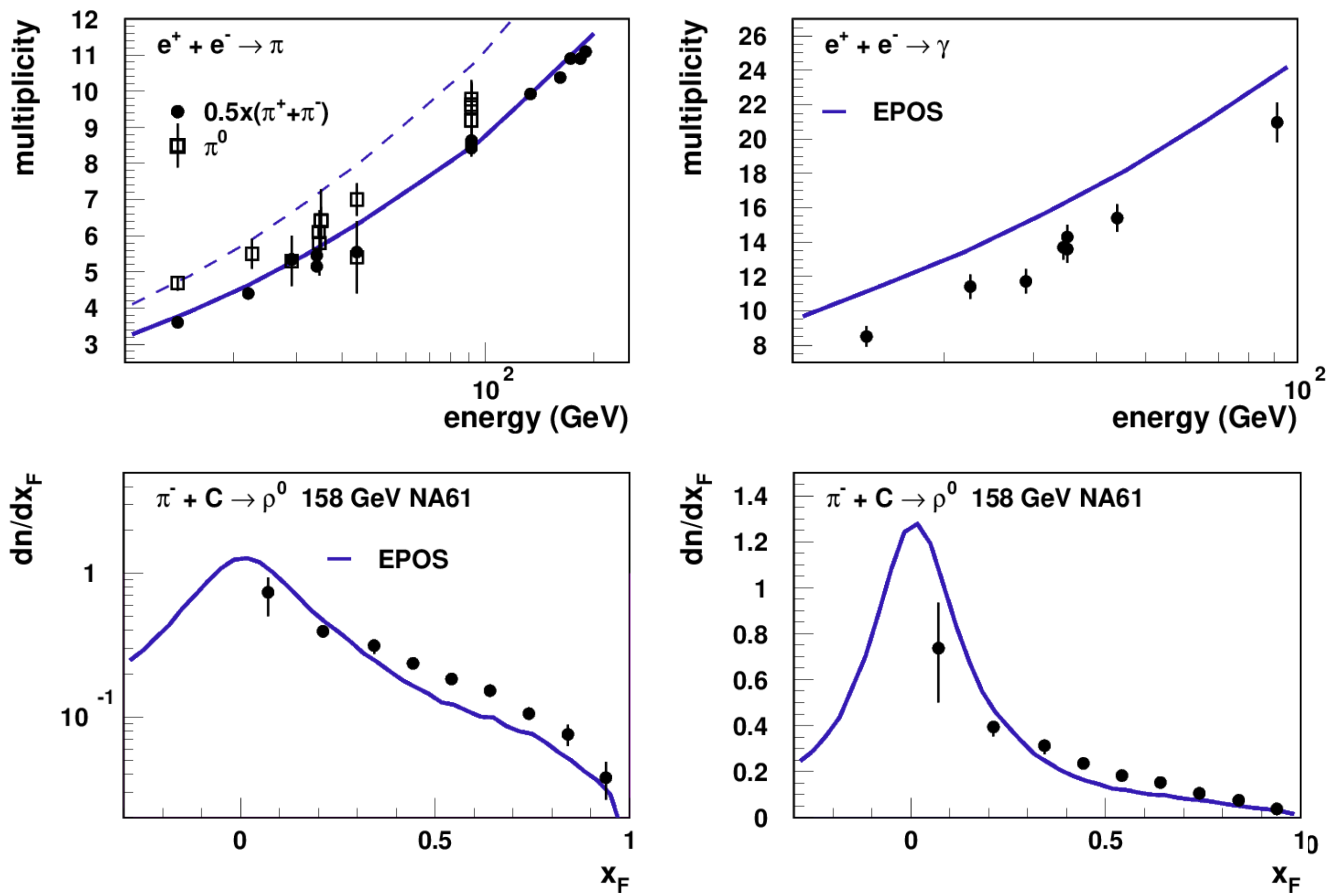
- Impose isospin symmetry (u=d) for pions, ρs and nucleons BEFORE decay
- Fix ρ^0 and multiplicity



Generic "EPOS"

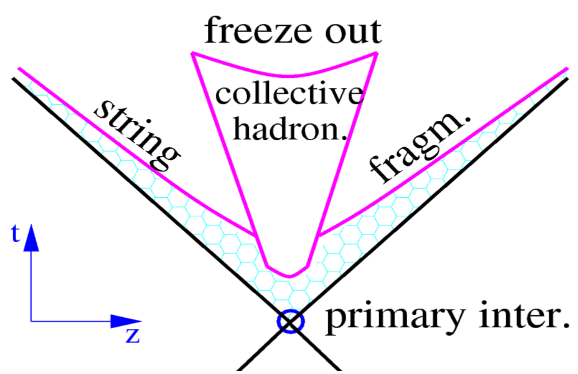
First attempt using theoretical constraints

- Impose isospin symmetry (u=d) for pions, ρs and nucleons BEFORE decay
- Fix ρ^0 and multiplicity
  - Too many neutral pions and no forward ρ^0 ! … but keep it for the moment



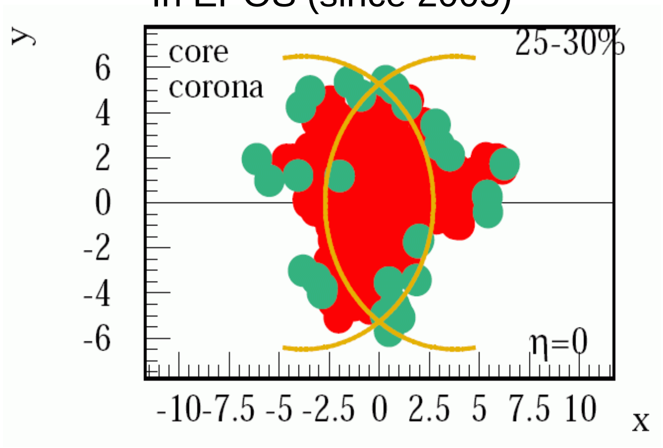
Core-Corona

- Core hadronization = thermal hadronization of Quark Gluon Plasma
- 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**

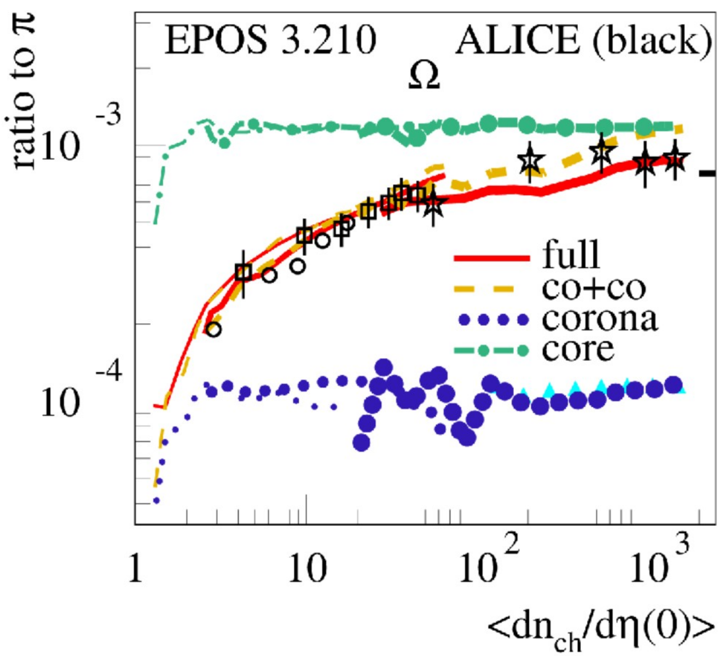


- 2 simultaneous source of particles

In EPOS (since 2005)



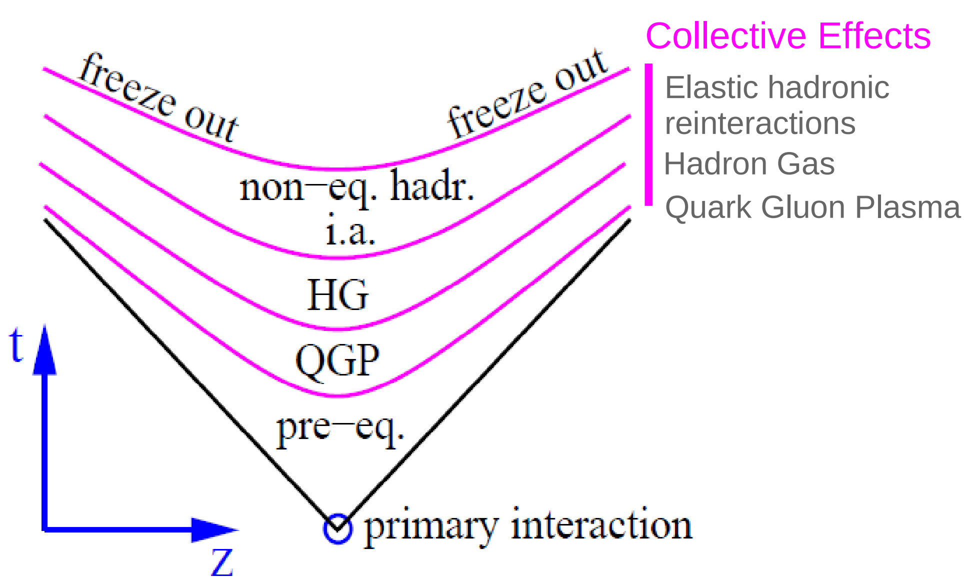
p-p ,Pb-p, Pb-Pb data

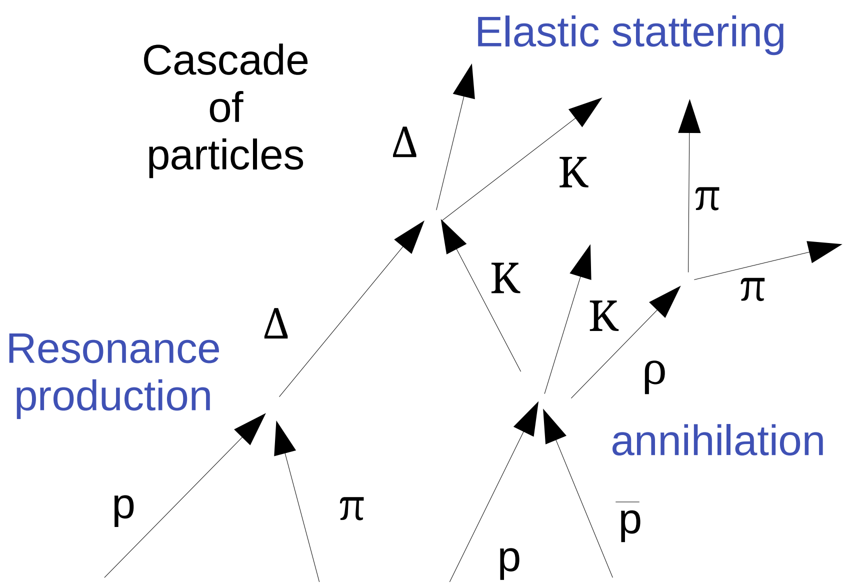


Hadronic Rescattering (HS)

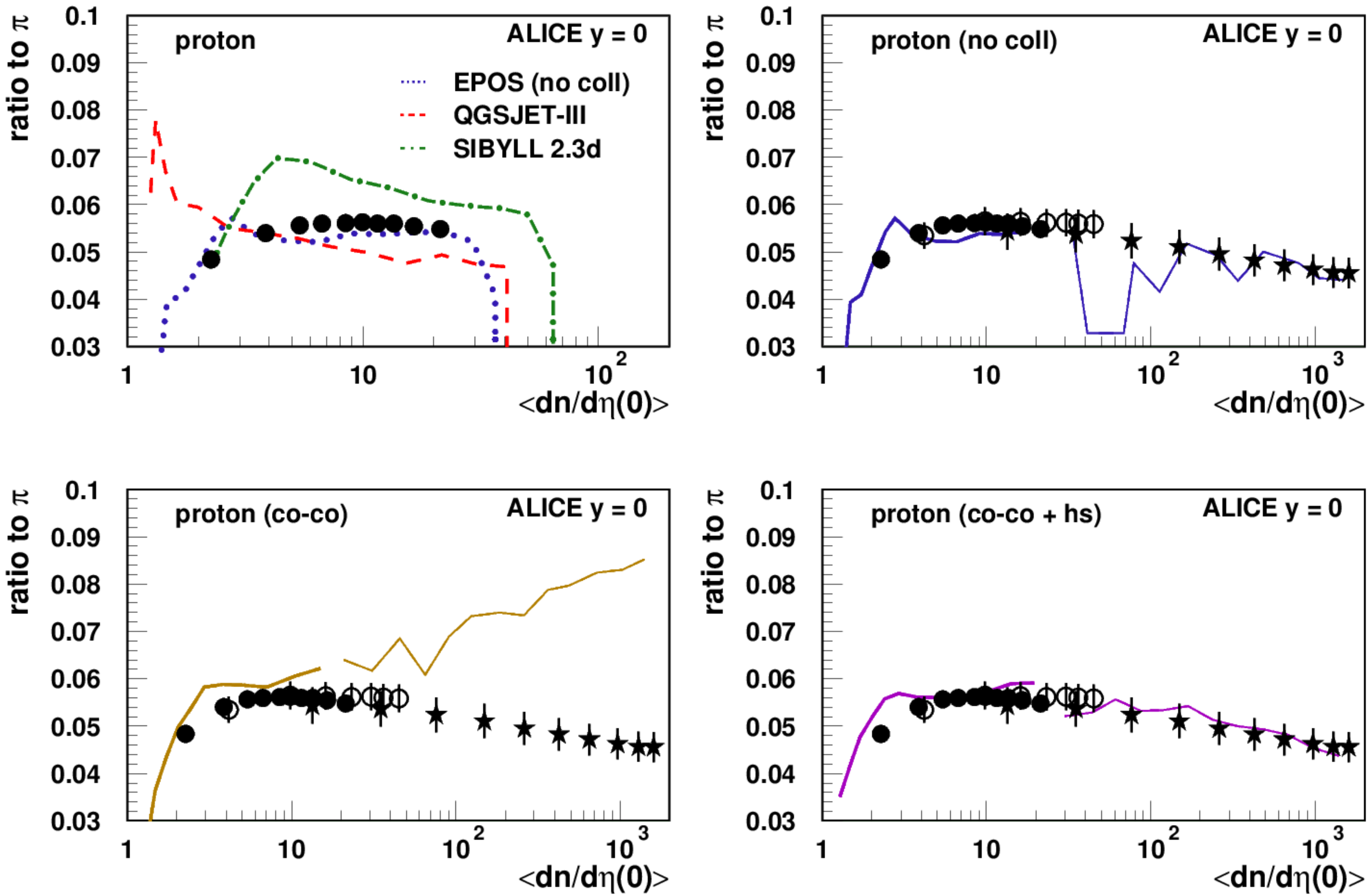
Missing effect in all CR models until now !

- Re-interaction of hadrons after parton hadronization (space-time evolution)
- “traditionally” used only for heavy ion collisions (until recently NOT in p-p)
- No direct impact on EAS development since forward particles escape
- But significant to large impact at midrapidity in heavy ion collisions !
  - Let’s apply it to all system (from e+-e- to PbPb) !





Example with protons in p-p and Pb-Pb @ LHC



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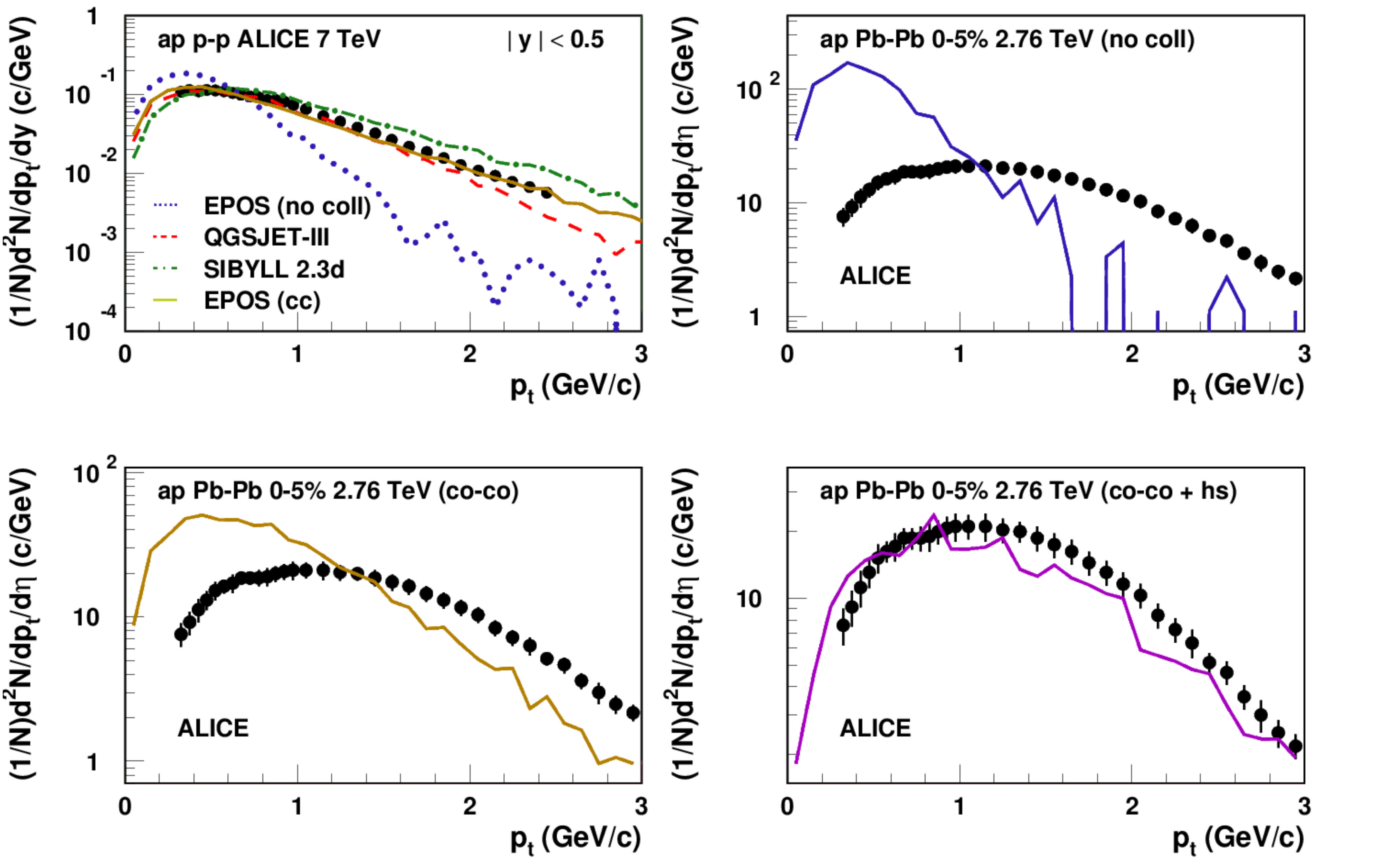
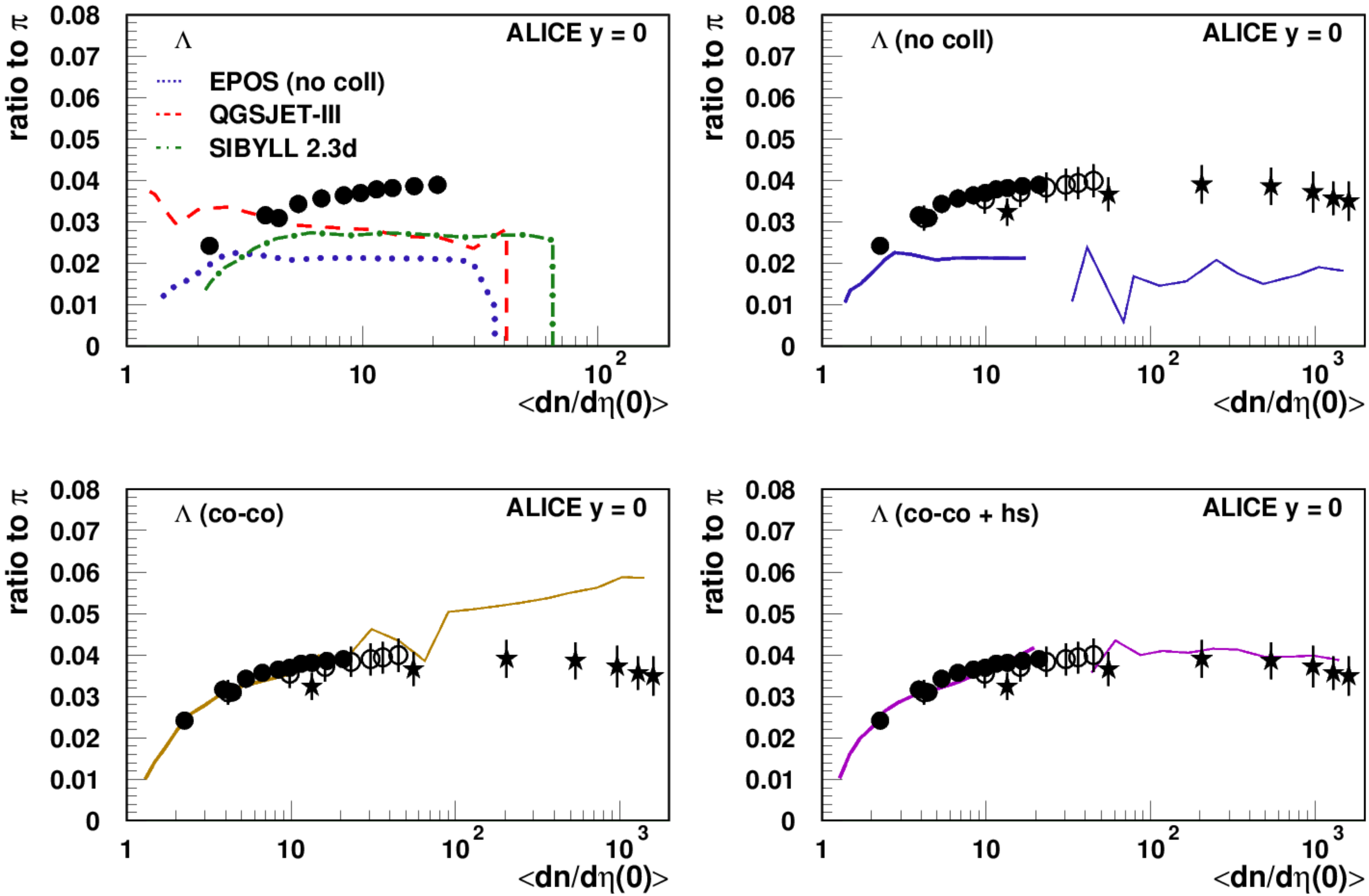
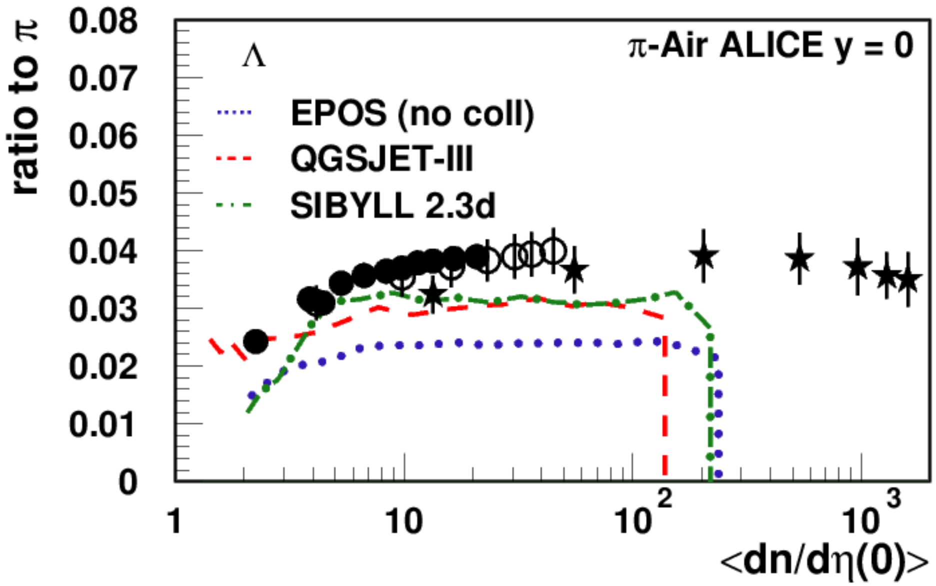
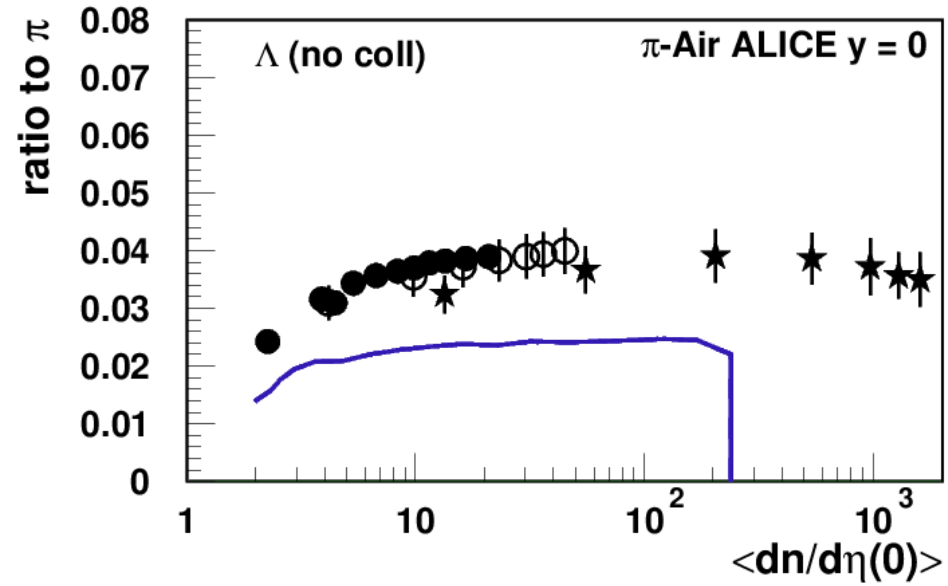


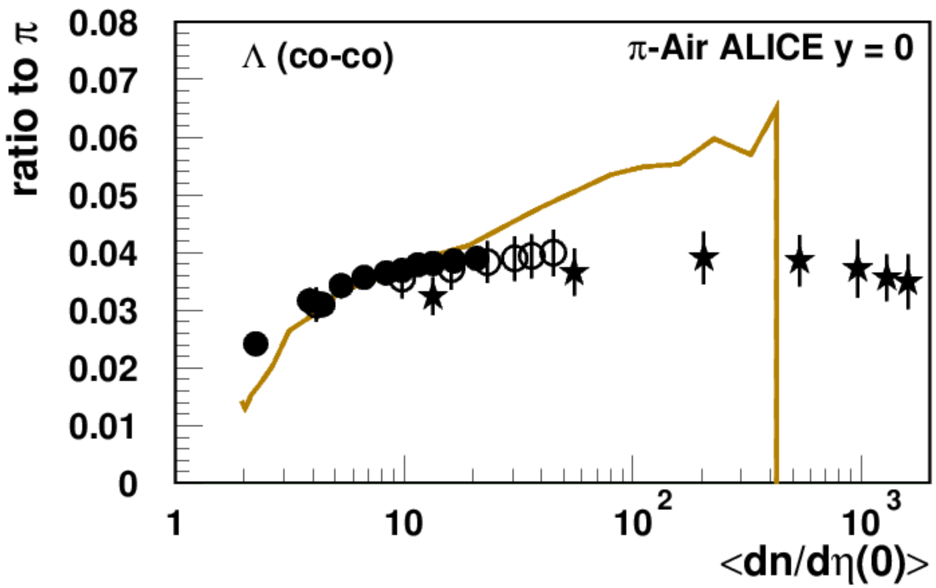
Example with Lambda particle in p-p and Pb-Pb @ LHC

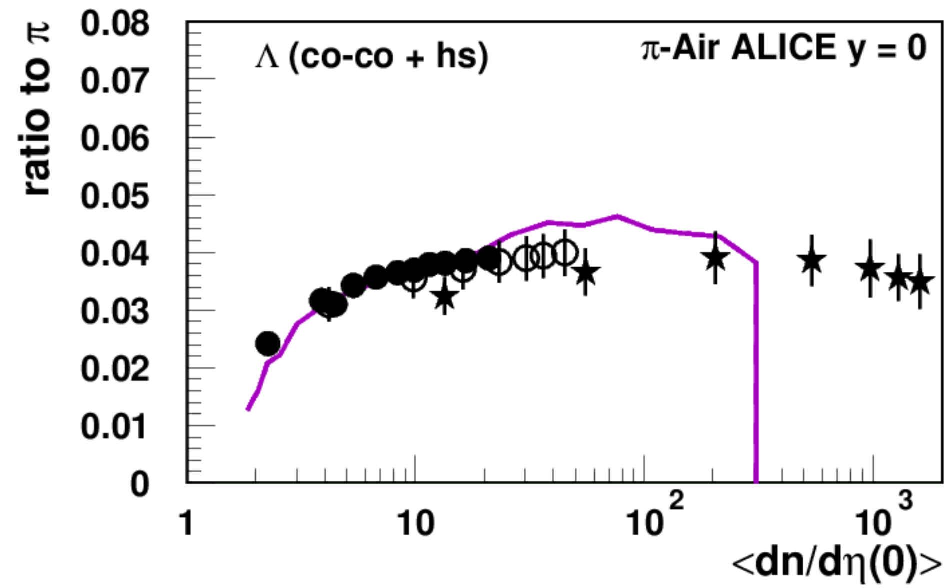


Example with Lambda particle in π-Air @ all energies





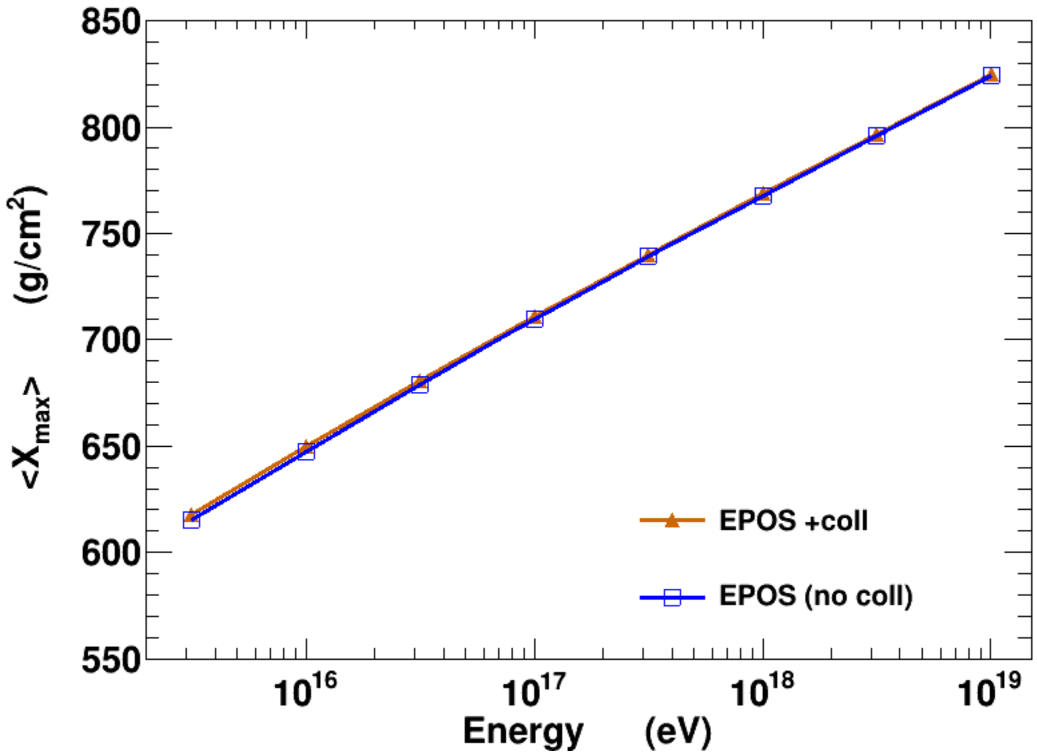


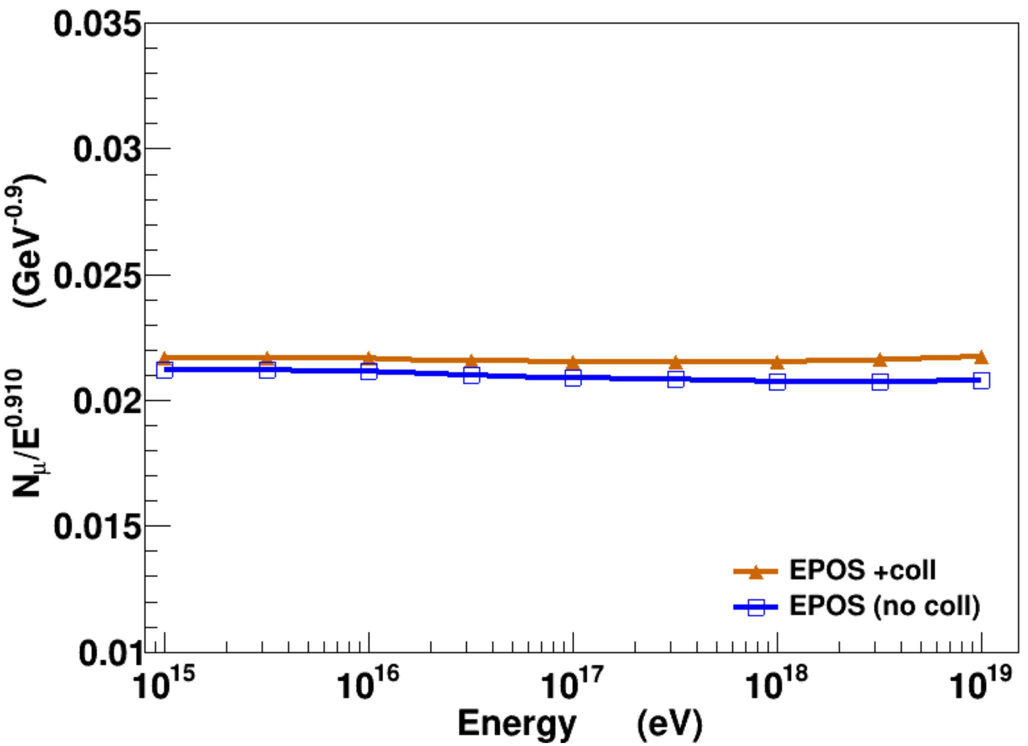


Impact on air showers

Changes applying core-corona **(same results with hadronic rescattering)**

- Same X_{max}
- Increase of the number of muons by up to 5% … only !

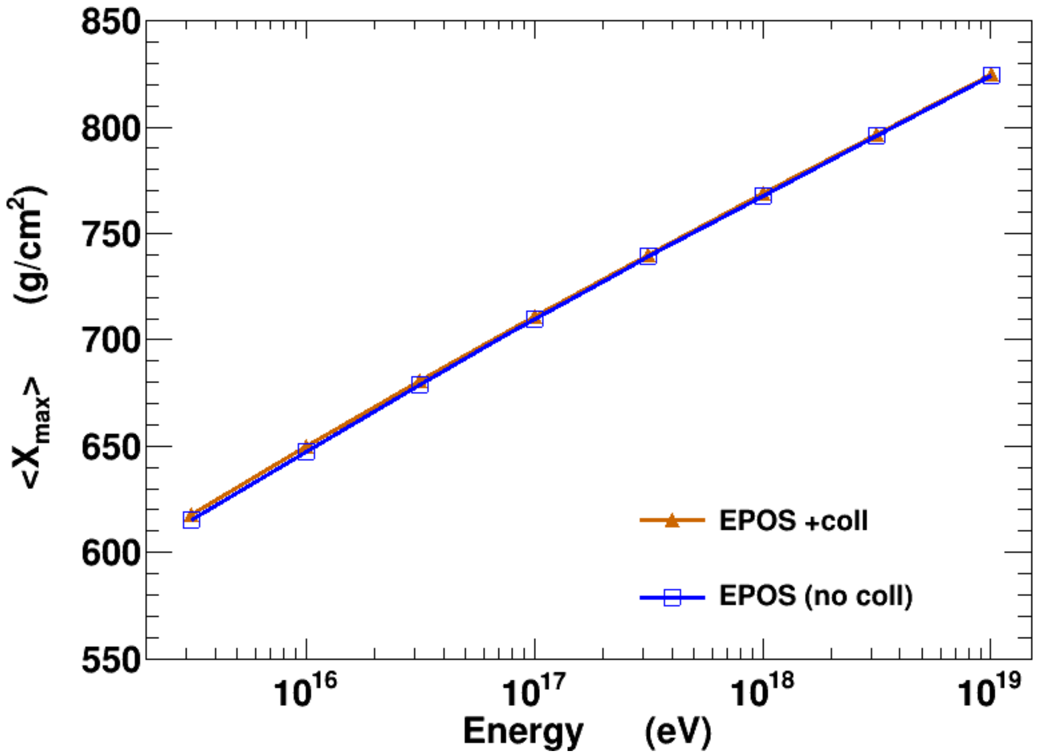


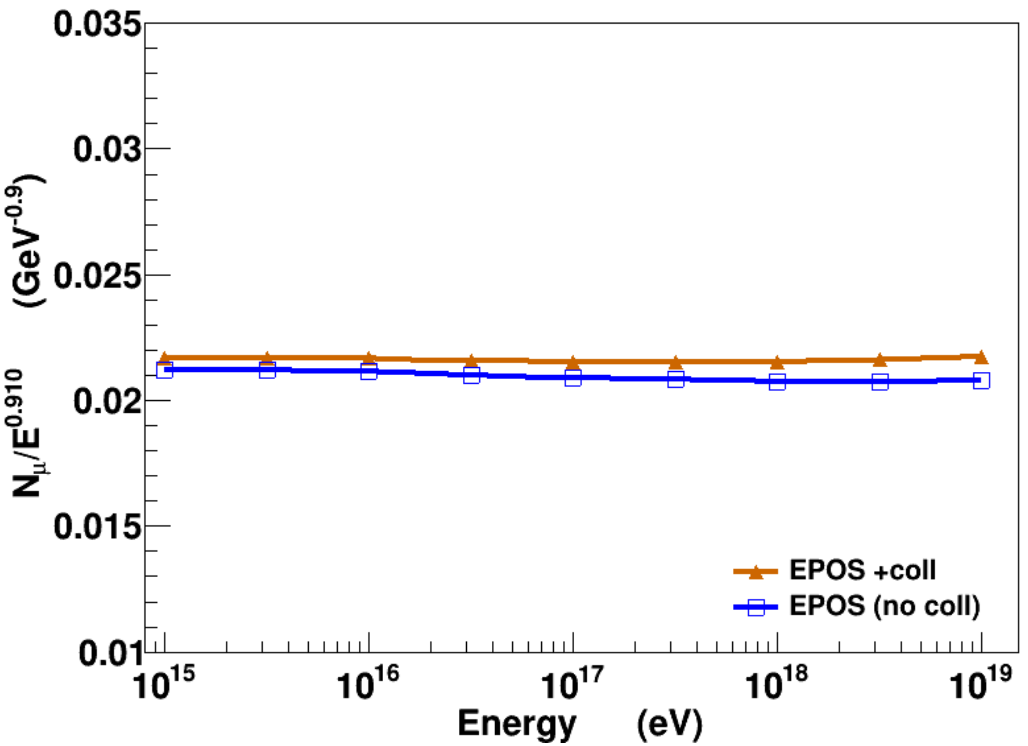


Impact on air showers

Changes applying core-corona (same results with hadronic rescattering)

- Same X_{max}
- Increase of the number of muons by up to 5% … only !
  - But what about e+-e- results after applying hadronic rescattering ?

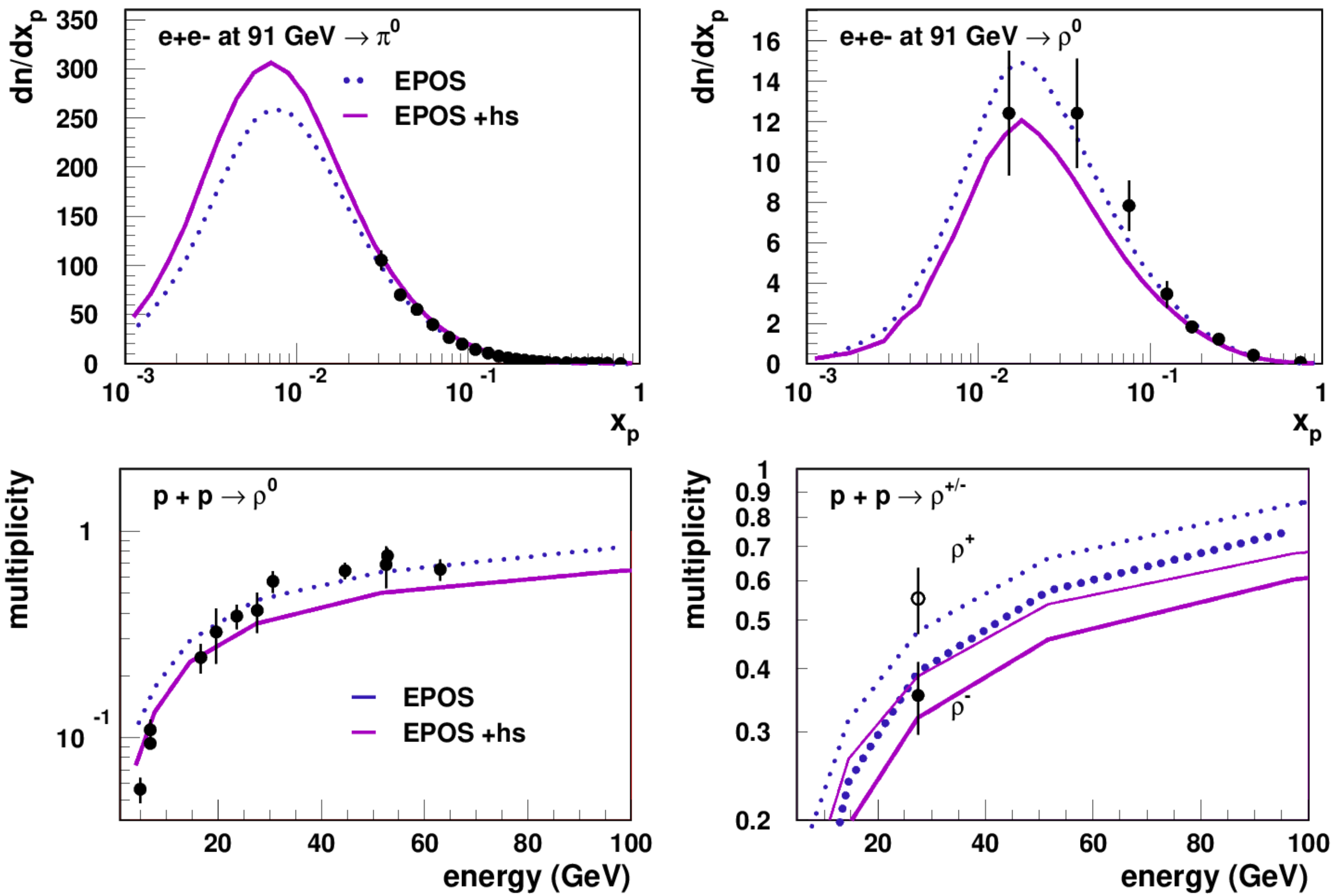




Impact of HS on light systems

If short hadronization time (<1fm/c), particles close enough to interact

- Small but significant effect even in e+e- interactions
- Reduce ρs and nucleons and increase pions



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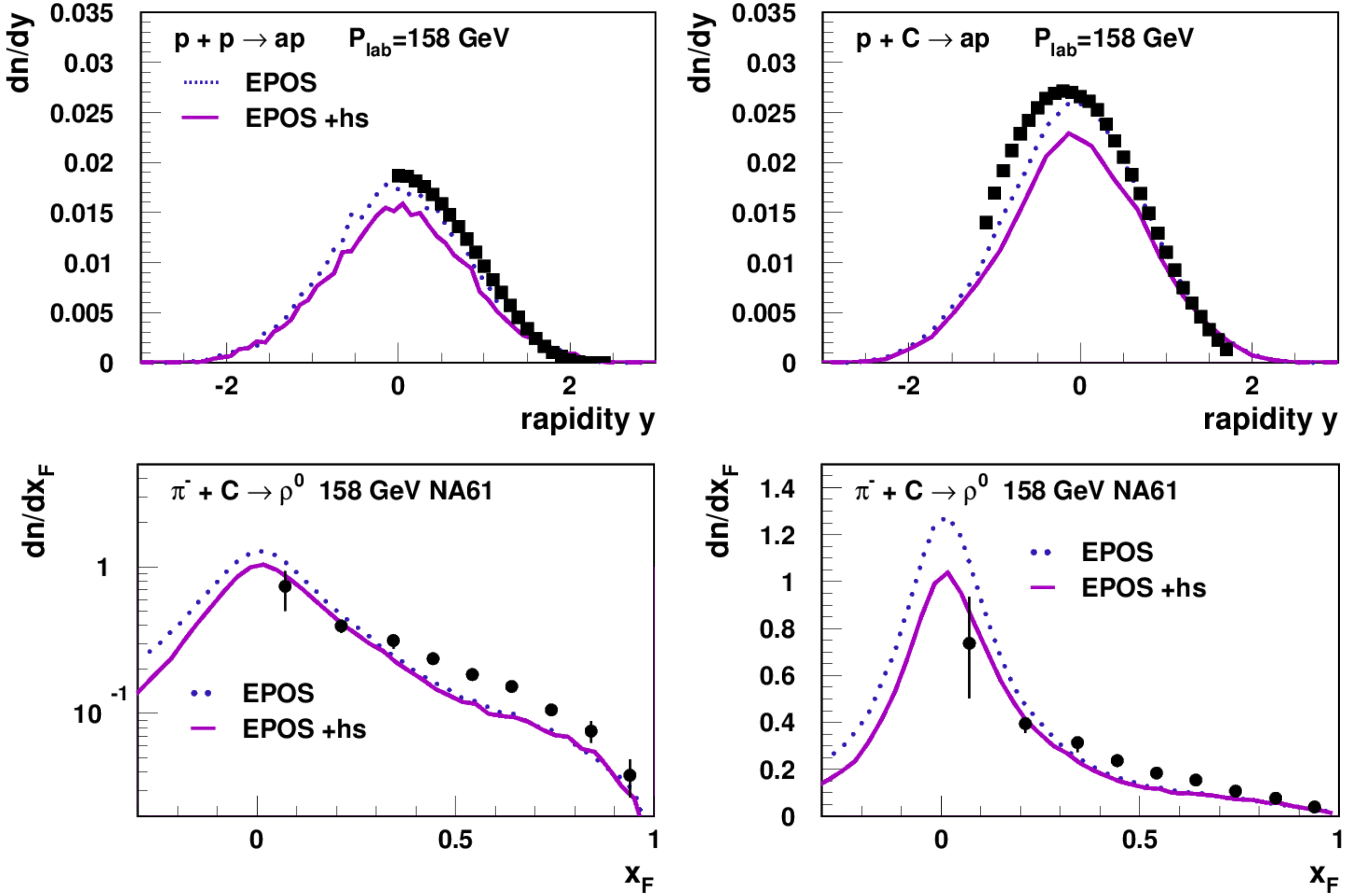
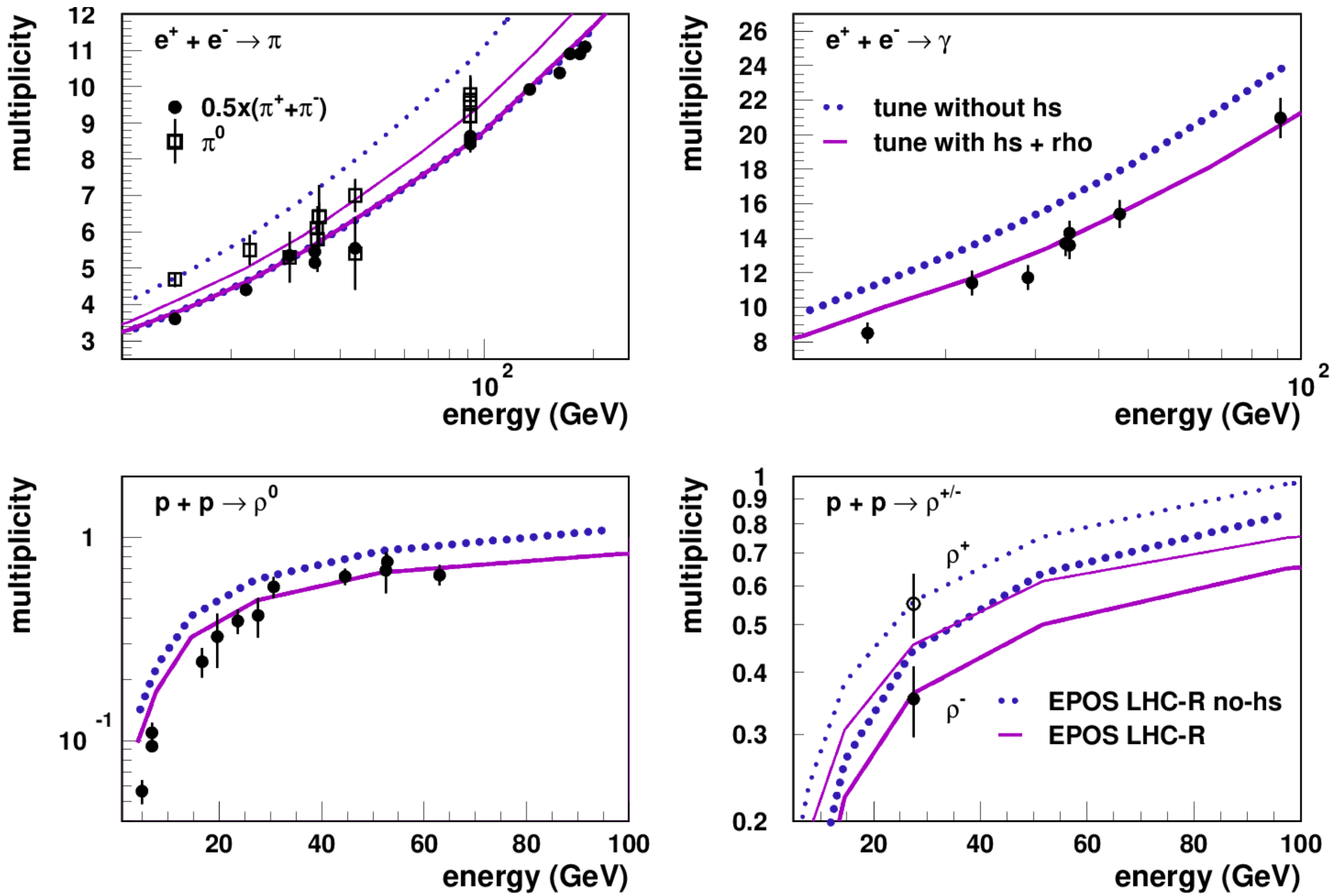


Retune basic parameters with HS

Second attempt using experimental constraints

- Keep symmetry for pions and nucleons but allow asymmetry for ρ (higher mass)
- Increase contribution of ρs and nucleon to compensate the effect of HS
  - EPOS LHC-R



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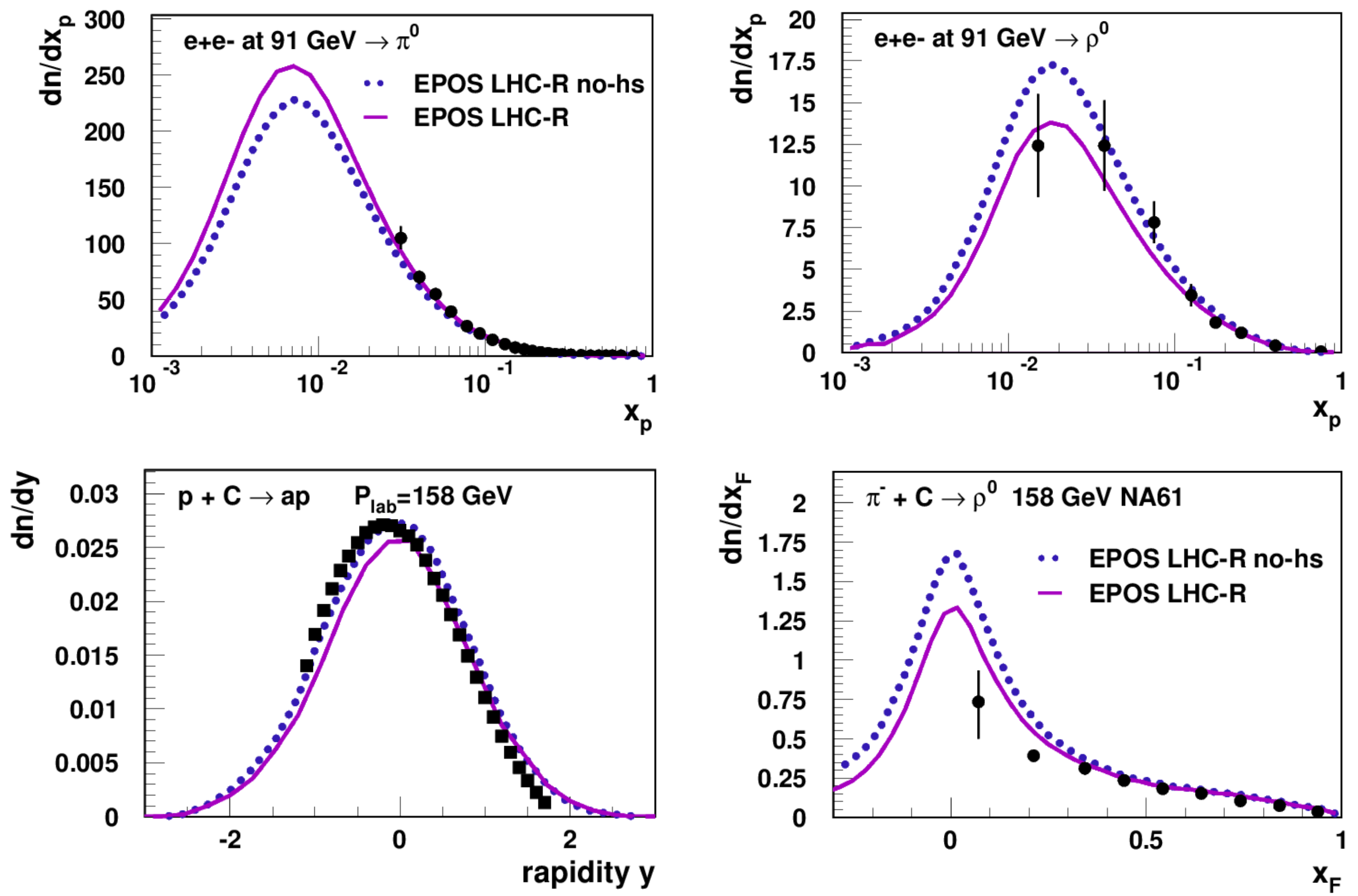
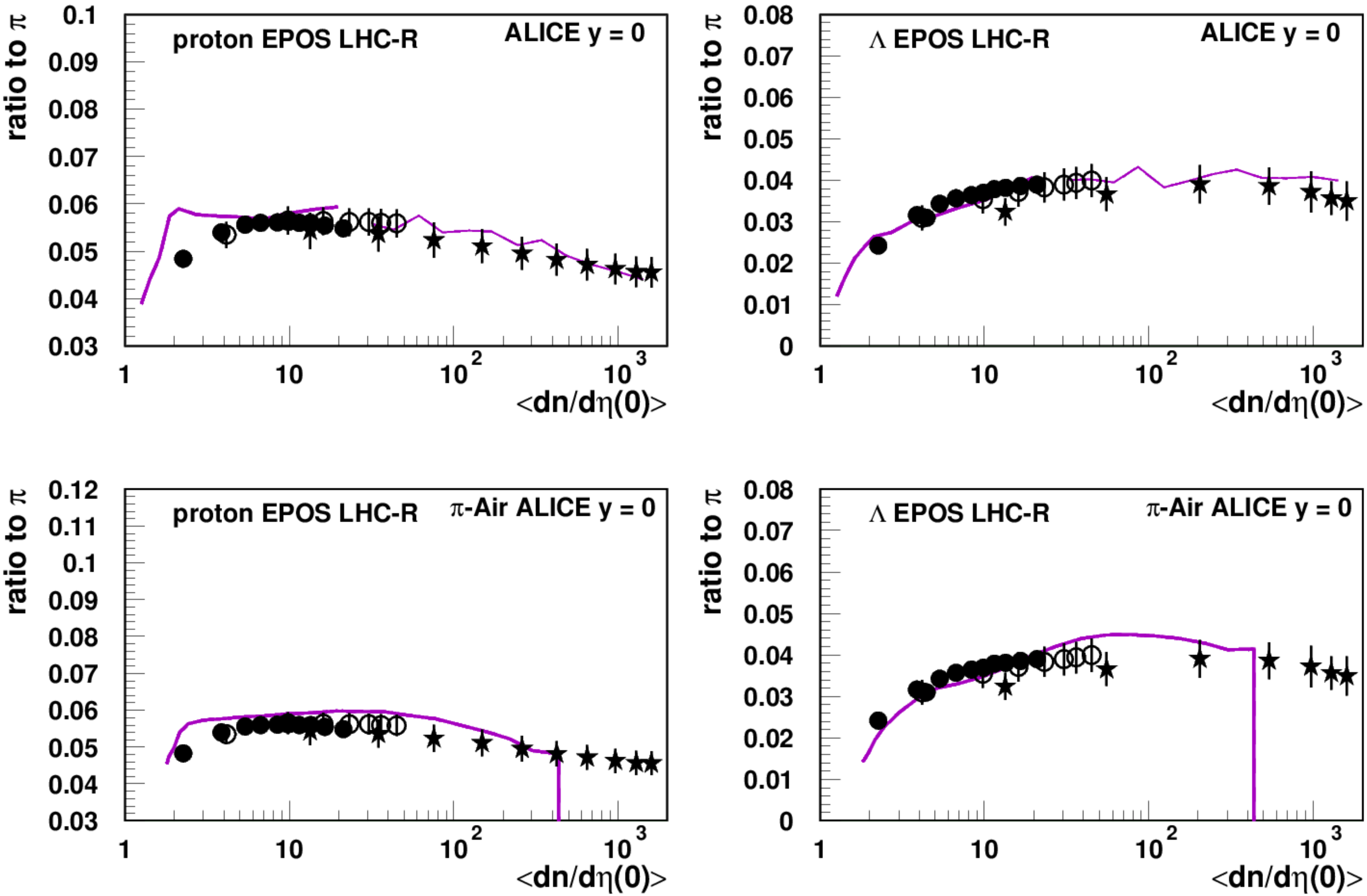


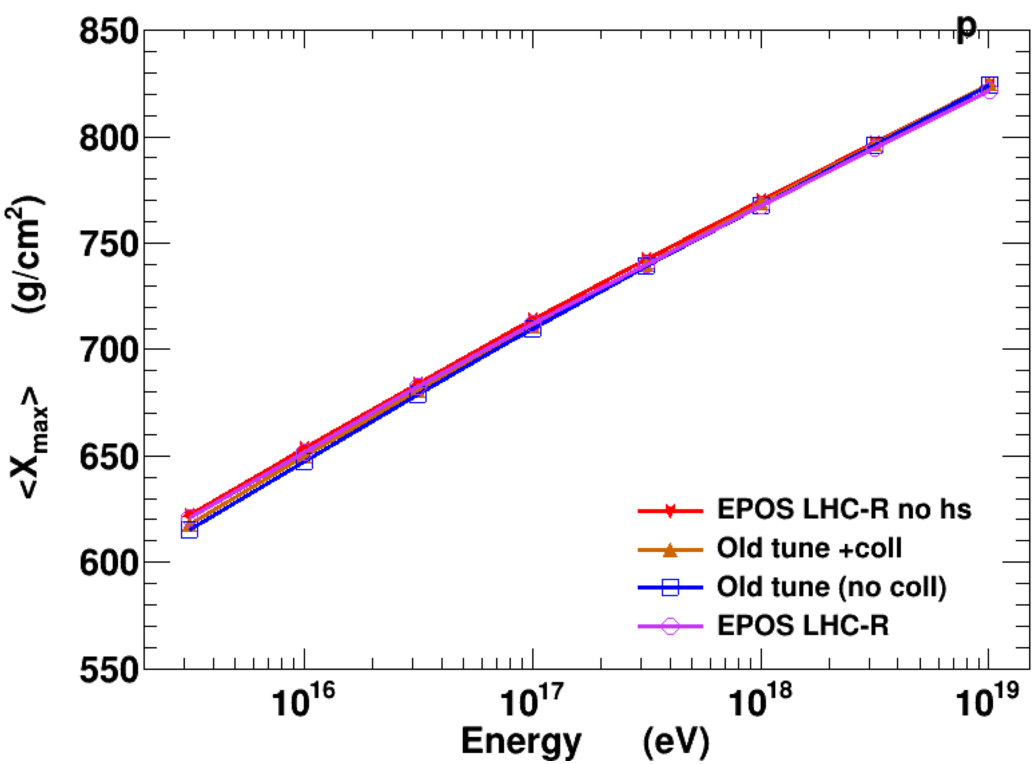
Check ALICE data

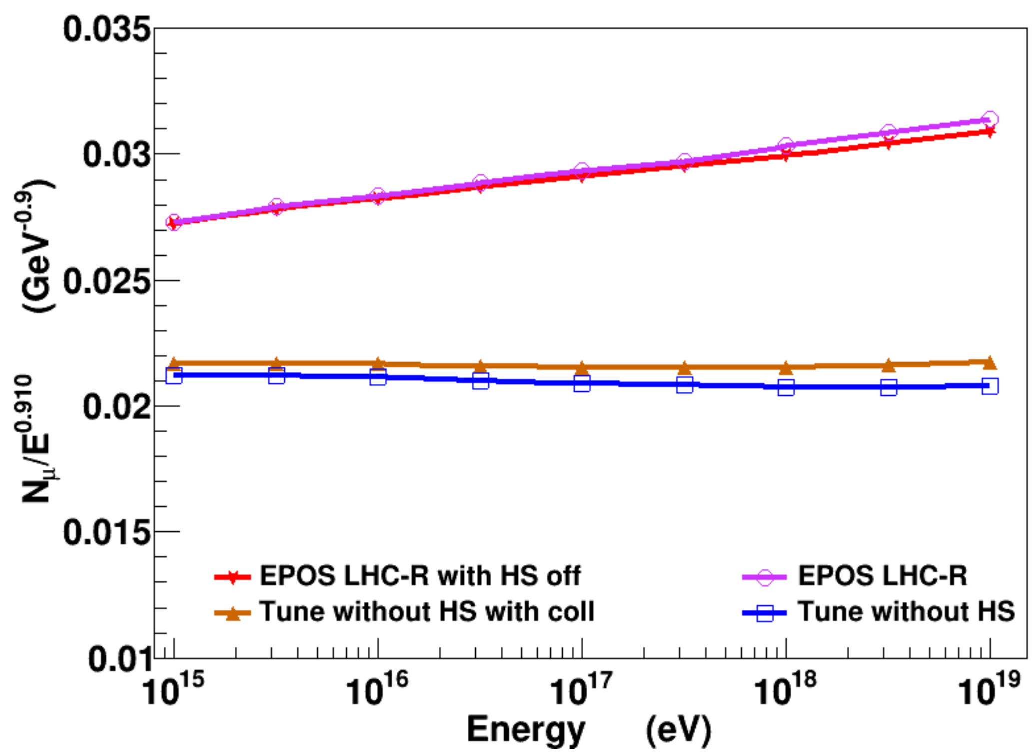


Impact on air showers (2)

Changes applying new tune taking into account hadronic rescattering

- Same X_{max} (not change applied to cross-section, multiplicity or elasticity)
- Increase the number of muons by ... 30 to 50% (different slope) !
  - Mostly due to asymmetry between charge and neutral ρs !

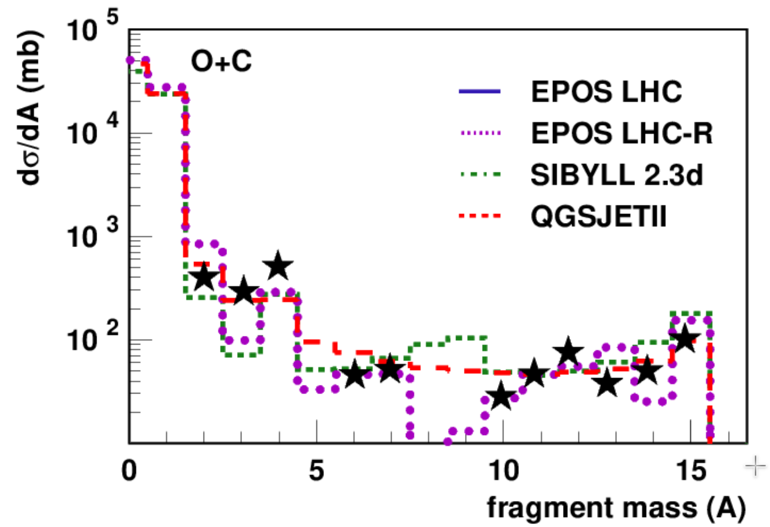


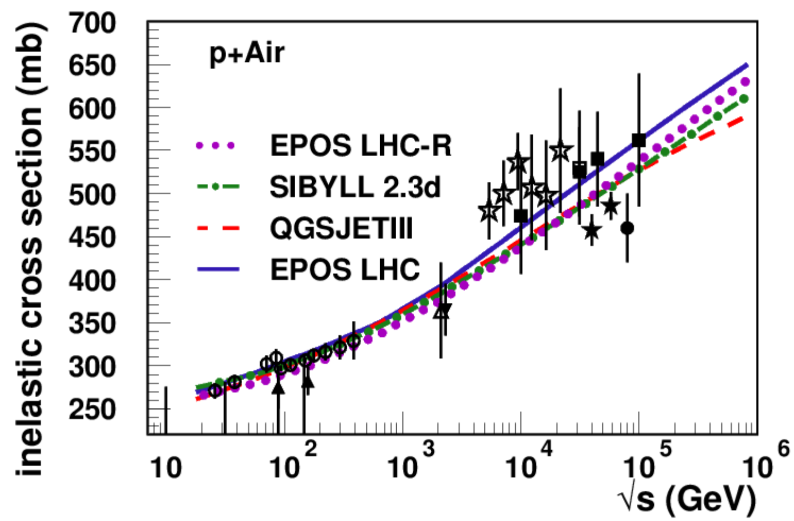


Other improvements in EPOS LHC-R

Number of limitations identified and solved compared in EPOS LHC

- Problem with nuclear fragments solved
  - Fluctuations of X_{max} for iron similar to others
- No more artificial symmetry neutron and proton
- Pion exchange and real Pomeron exchange
  - LHCf data
- Charm production
  - IceCube
- Indirect impact of core-corona (multiplicity) and hadronic rescattering (shape in pseudorapidity)
  - Higher elasticity due to smaller light cone momenta (see Sergey's talk)
- Lower cross-sections
  - X_{max} deeper

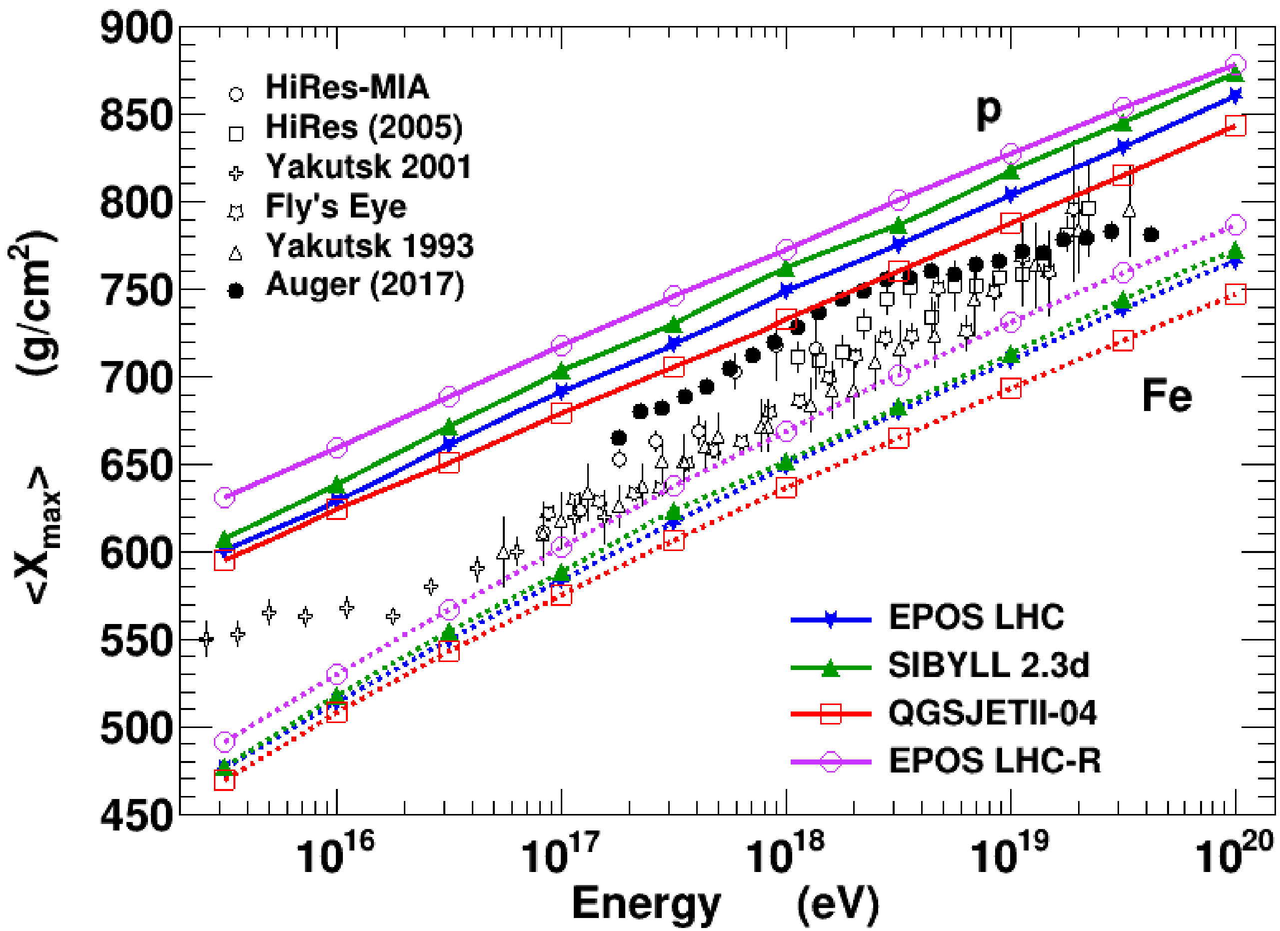




X_{max}

Global changes

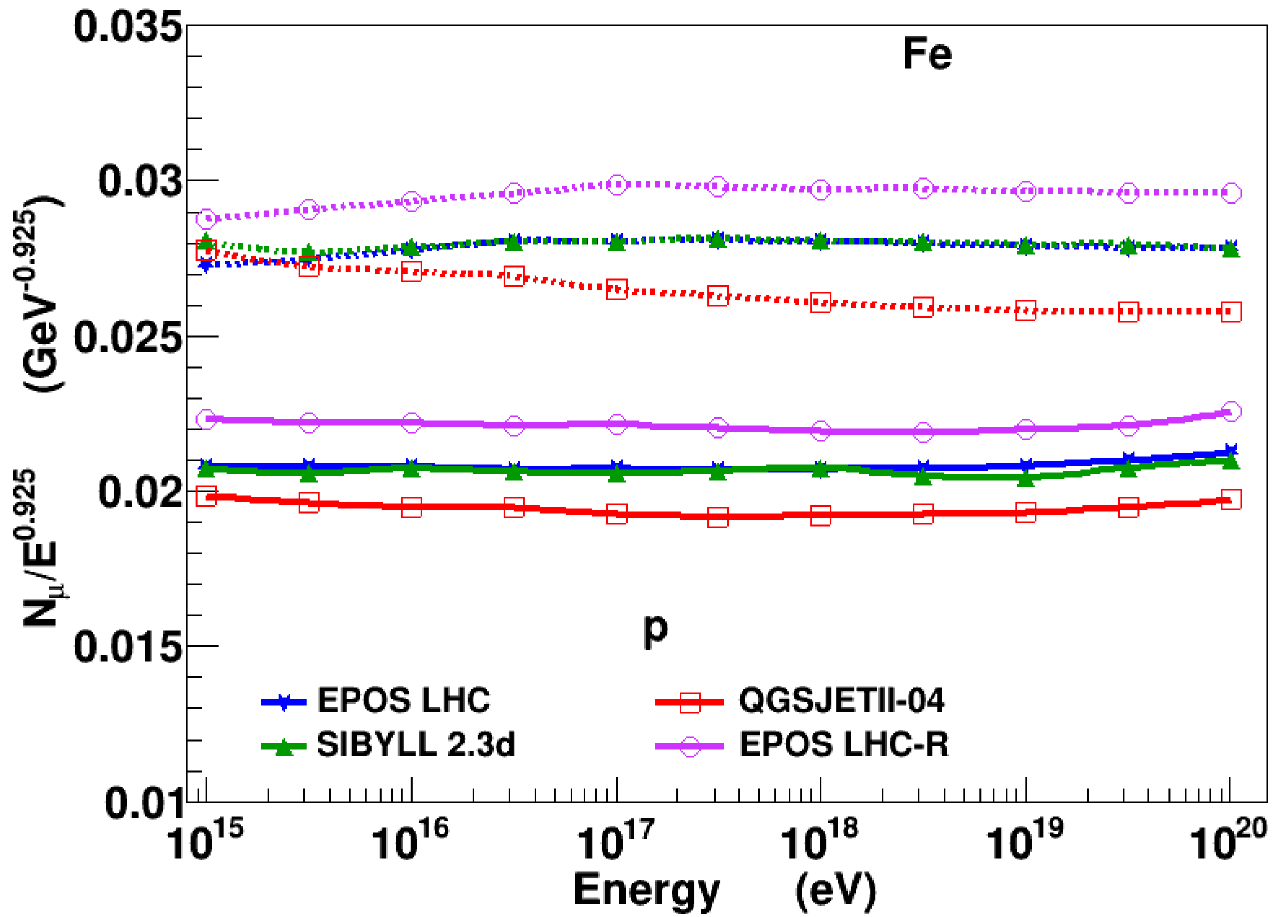
- Consequence of retuning, now EPOS shifted by +20 to 30 g/cm²
  - Still in full agreement with accelerator data !
- Same elongation rate than QGSJETII-04 for protons



N_μ

Global changes

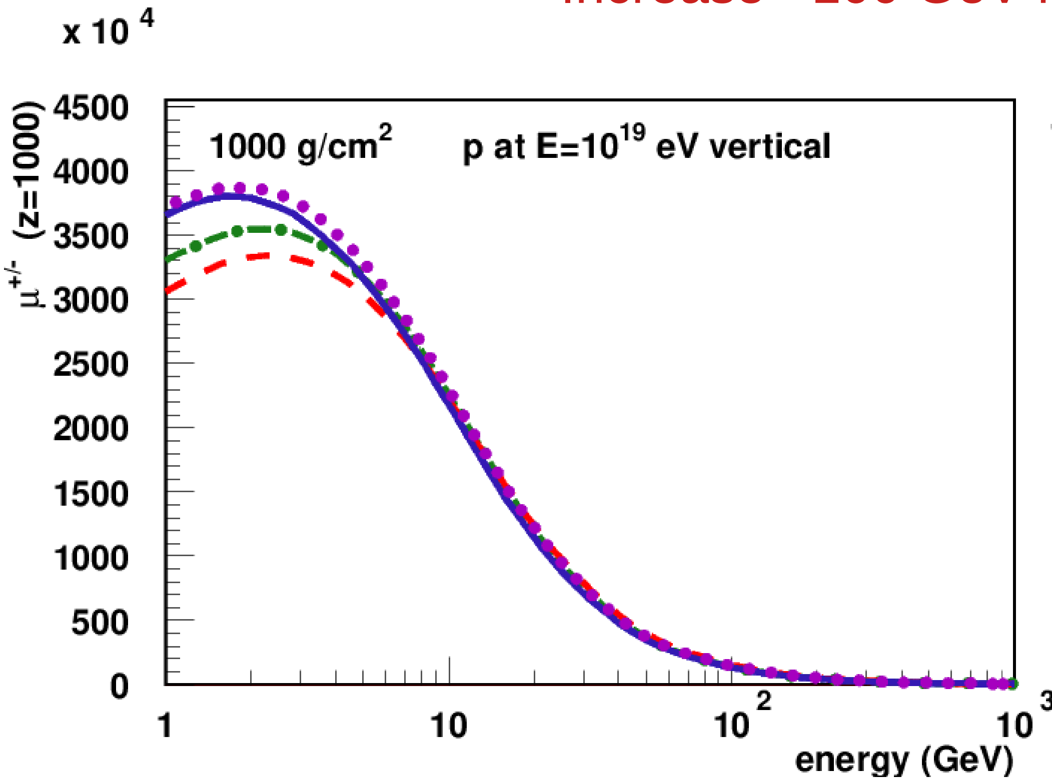
- Consequence of retuning, now EPOS shifted by +20 g/cm^2
- Increase of the number of muons by about 10%
- Change in muon spectrum !

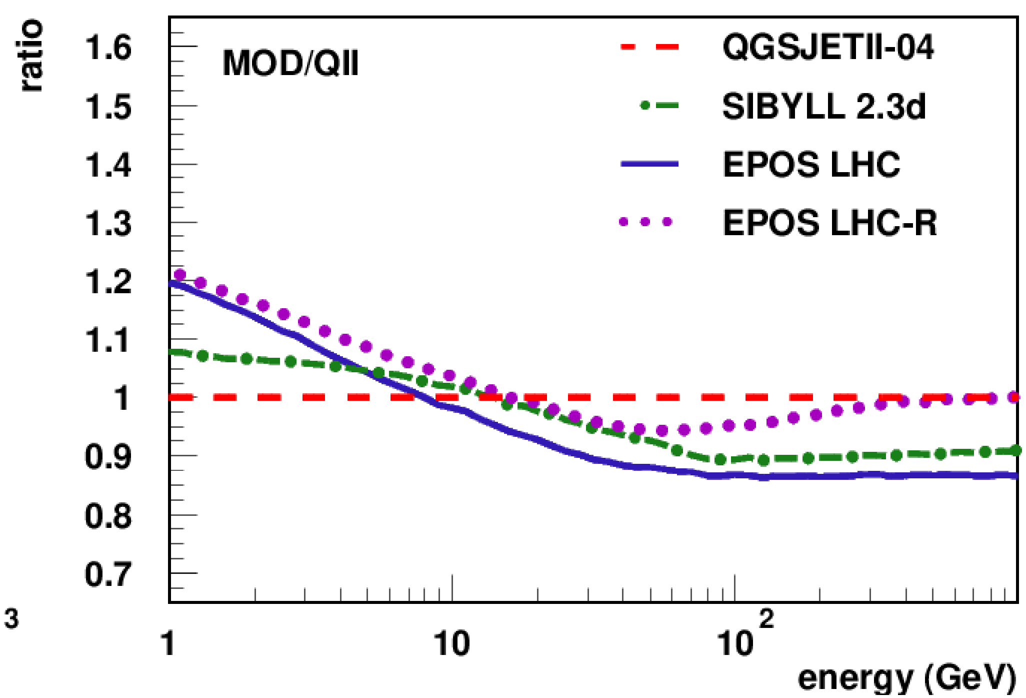


E_{μ}

First simulations with full collective effect implementation:

- Simulations without core-corona but ρ asymmetry already have more muons
  - Parallel shift changing all muon energies
- Pion-Air multiplicity impact muon energy between 10 and 100 GeV
- Better tune of kaons (indirect impact of core-corona)
  - Increase >100 GeV muons (Ice-Top/Ice-Cube)





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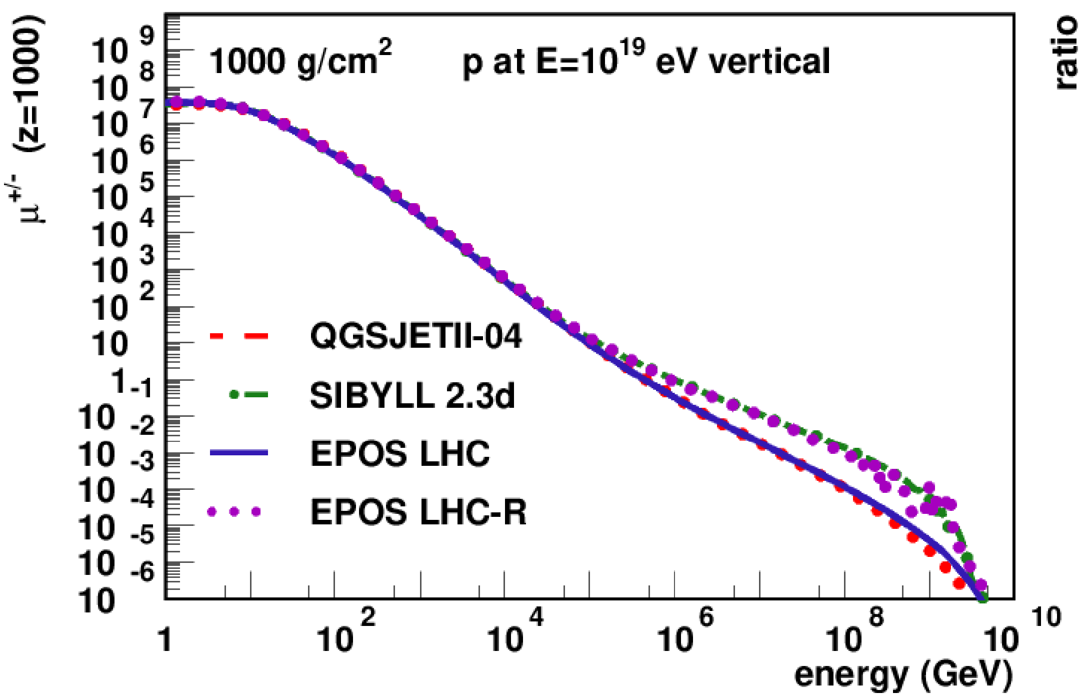
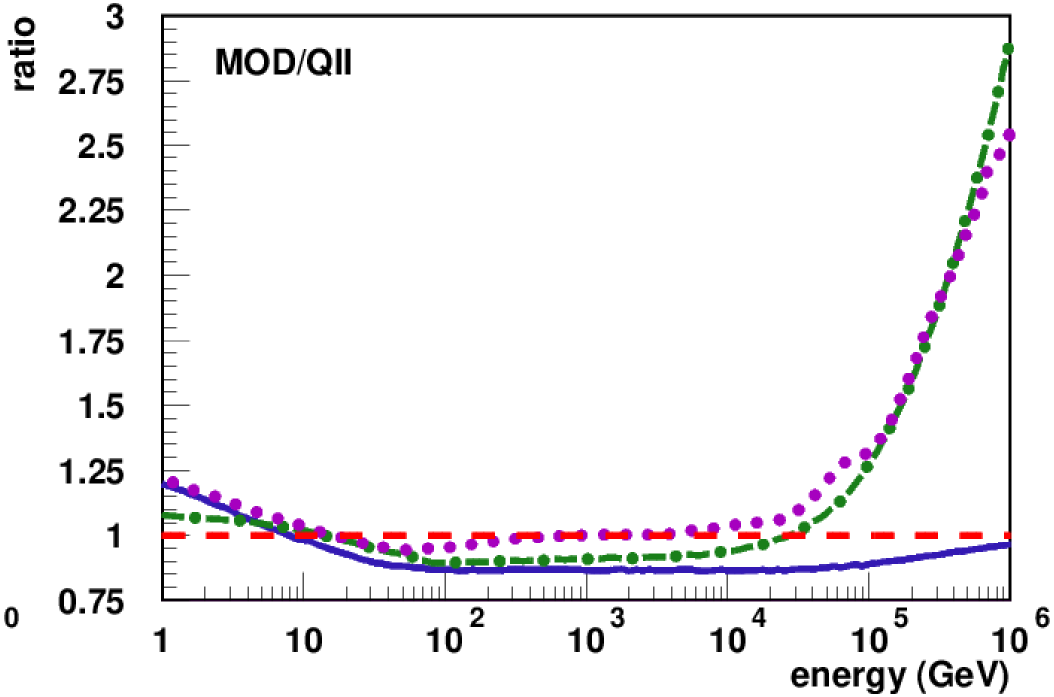
- Very high energy muons from charm ! (background for neutrino analysis)

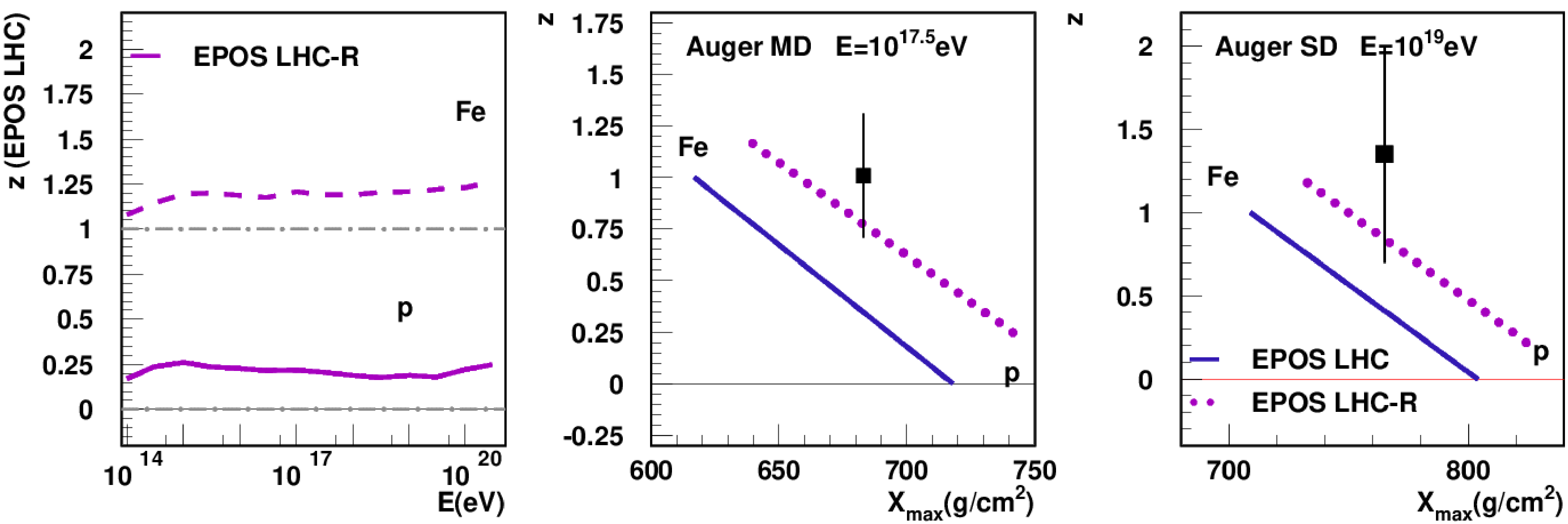




Muon Puzzle Solved ?

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

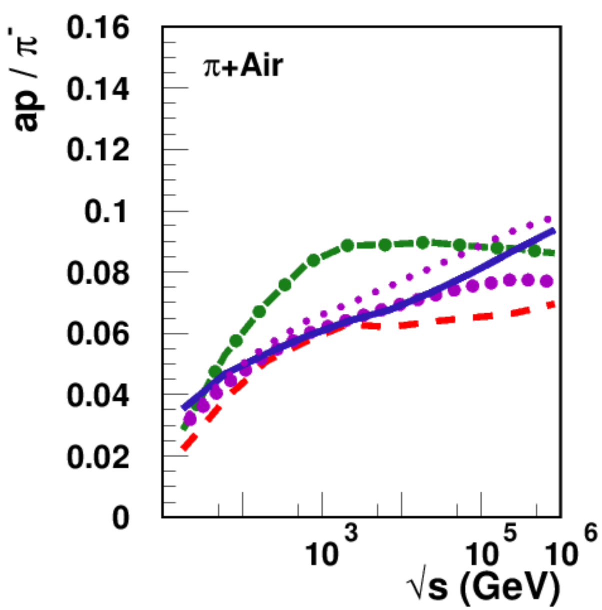
- Deeper X_{max} give larger <lnA> reducing the gap with measured muon content
- Increase of muons due to tuning taking into account collective effects further decrease the gap to reach Auger systematics
- What about low energy ? Correlation Ne-Nμ OK because of deeper X_{max} !

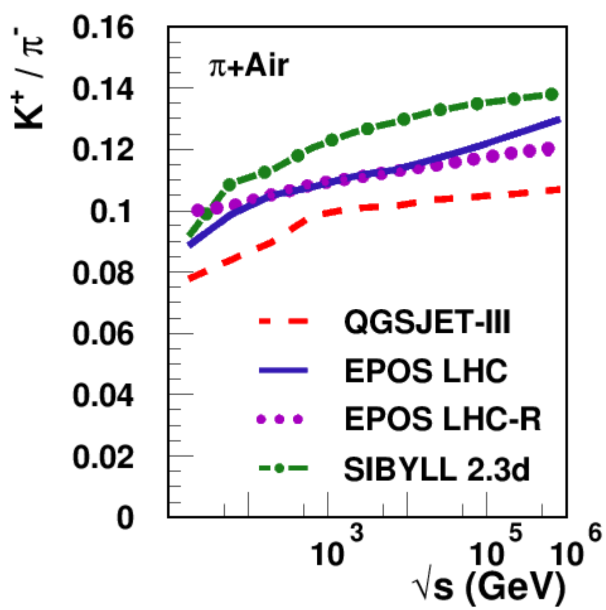


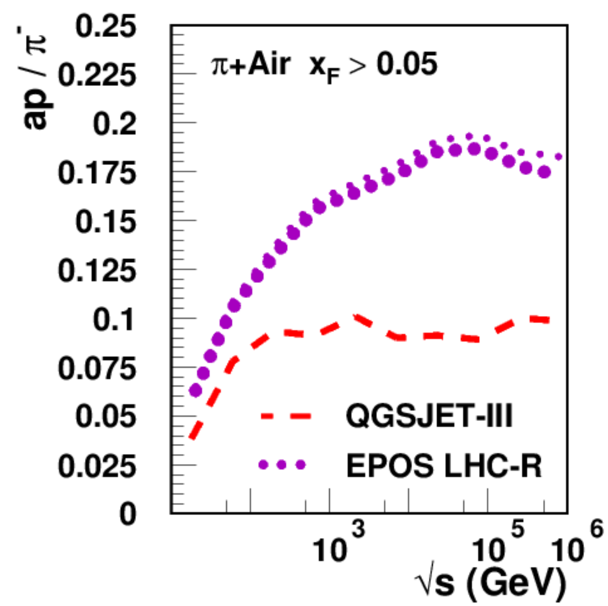
Why ?

Hadronic rescattering is important to tune properly the models !

- Change ratio between π and ρ in string fragmentation depending on phase-space
  - Forward particle production not the same than at mid-rapidity
- As seen before, if the effect is not taken into account
  - Either overestimate production compared to data (“bad tune”)
    - Sibyll*
  - Or underestimate forward production of ρ^0 to get it right with mid-rapidity data
    - All models until now !







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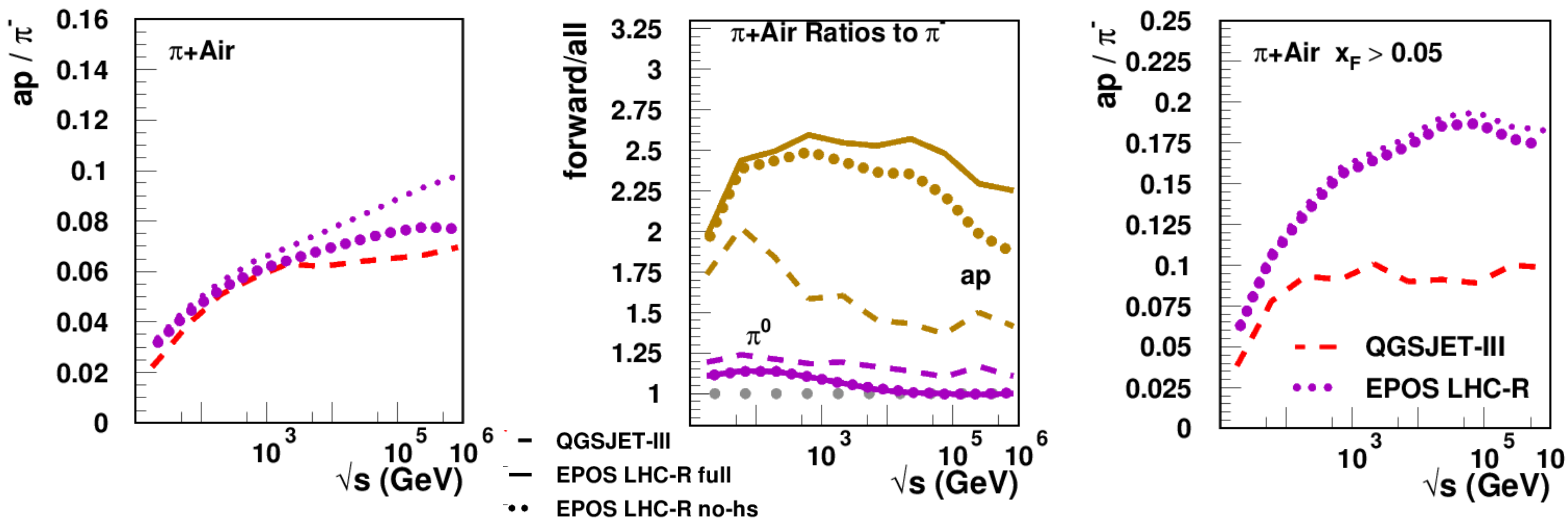


Outlook

- **Updated results of cross-sections, multiplicity and diffraction**
  - Large impact on X_{max}
  - Larger <lnA> (heavier primary mass → reduce “muon puzzle”)
- **Details of hadronization matters**
  - Important role of resonances
    - ρ^0 impacted by hadronic rescattering, important to take it into account
  - 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) !**
- **Source of muon puzzle probably due to the fact that hadron rescattering was always neglected**
  - Rescattering change the correlation between mid-rapidity (data and tuning) and forward particle production (EAS)

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

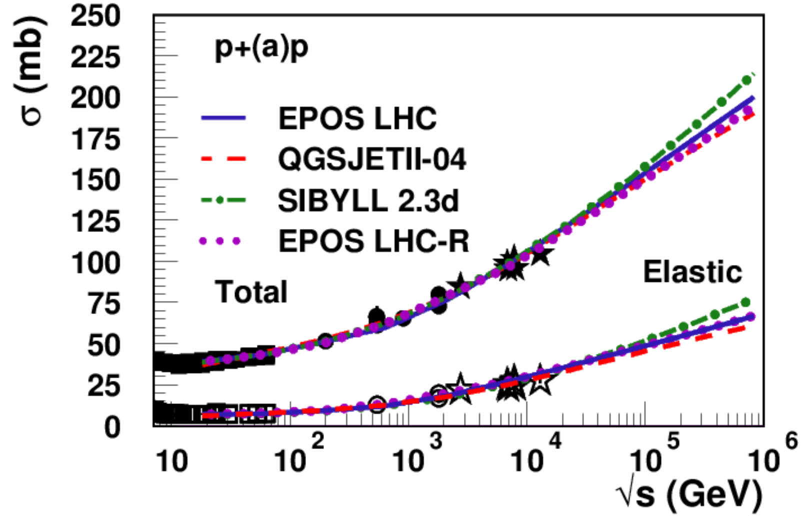
Recent LHC data provide new constraints on models, changing X_{max} and the muon production if a global approach is used.

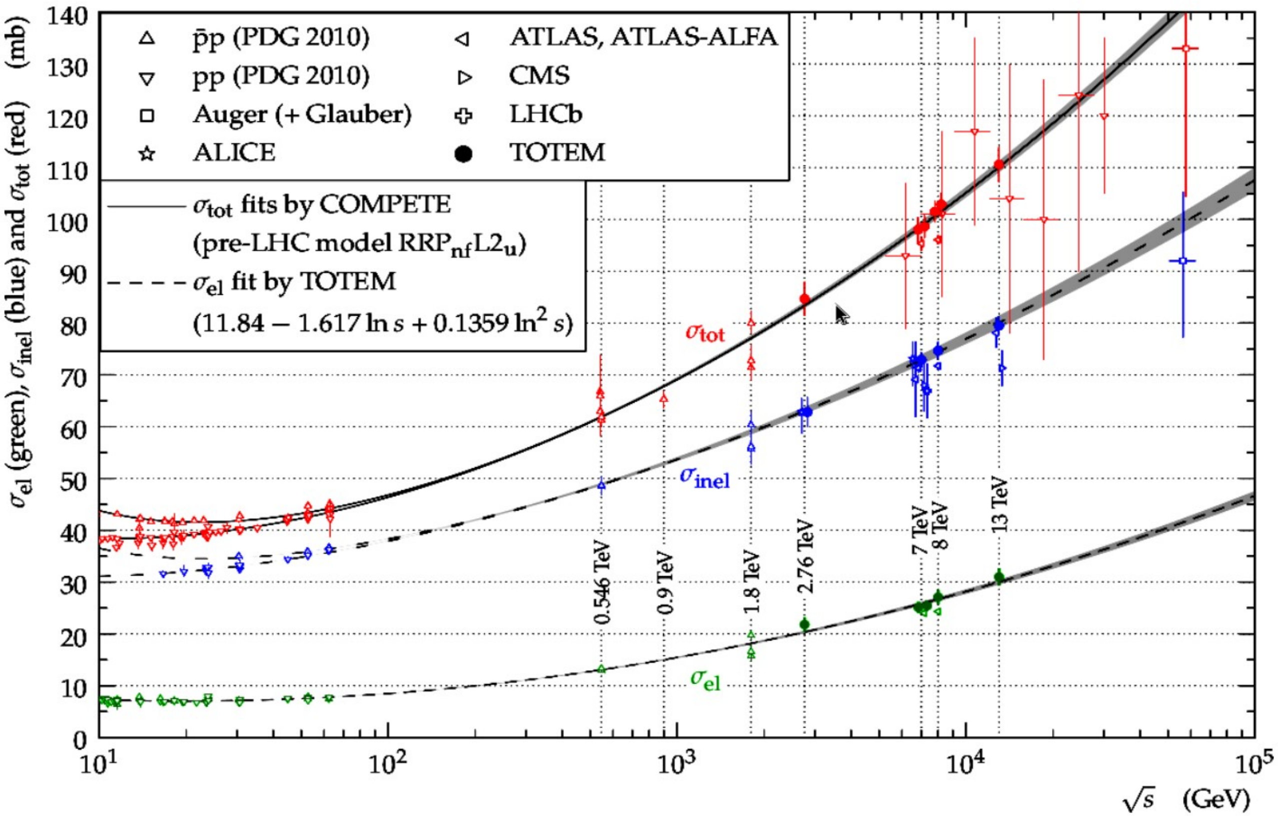
Providing a possible solution to the "muon puzzle" !

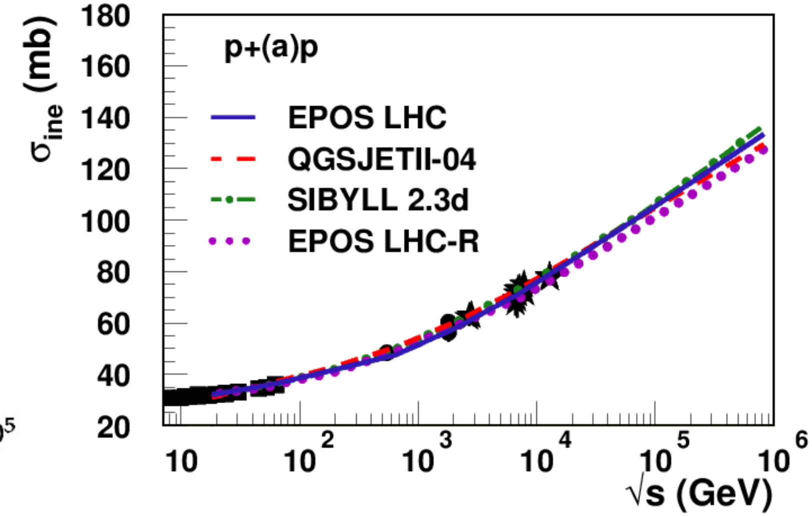
Thank you !

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

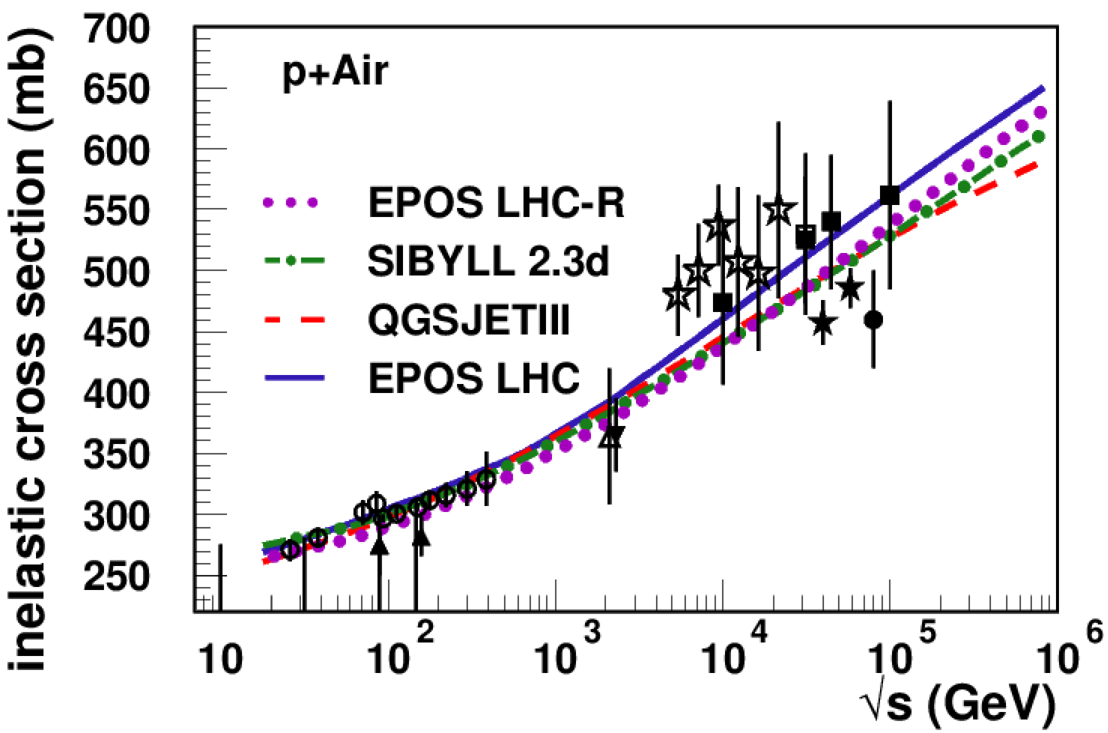


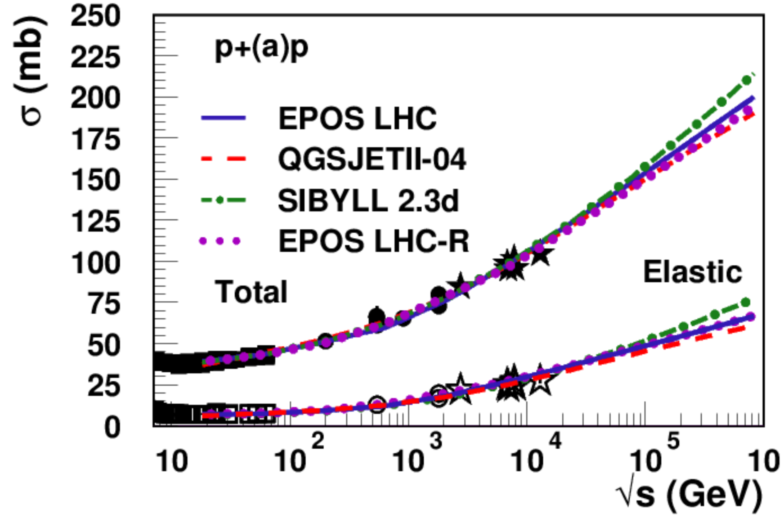


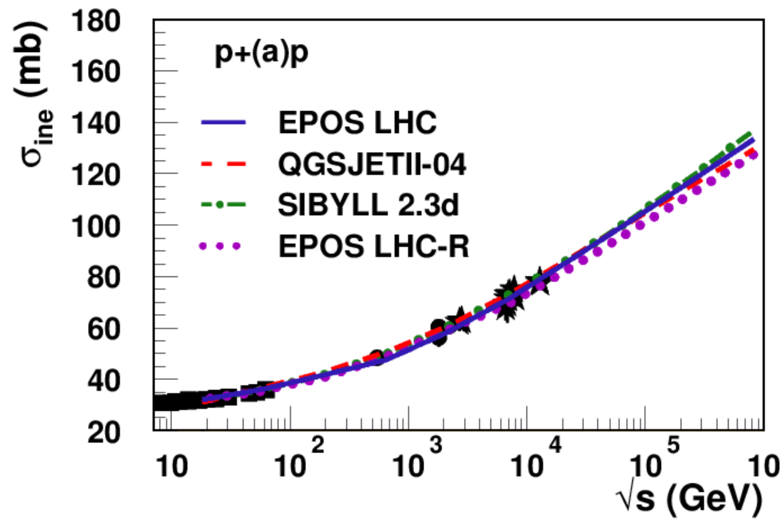


Cross-Section Reduced

- **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

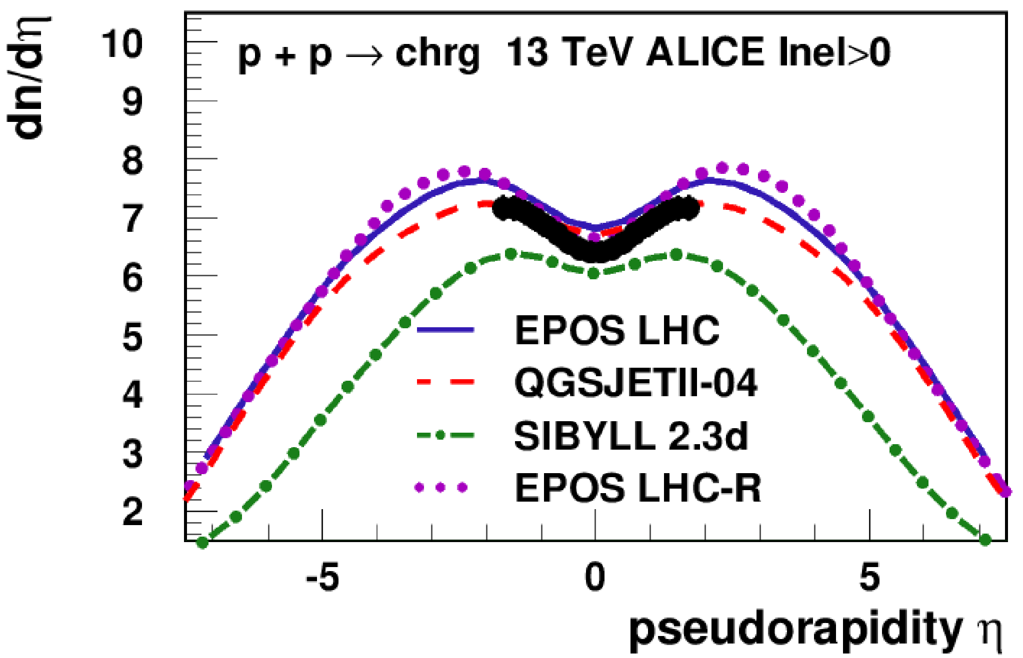


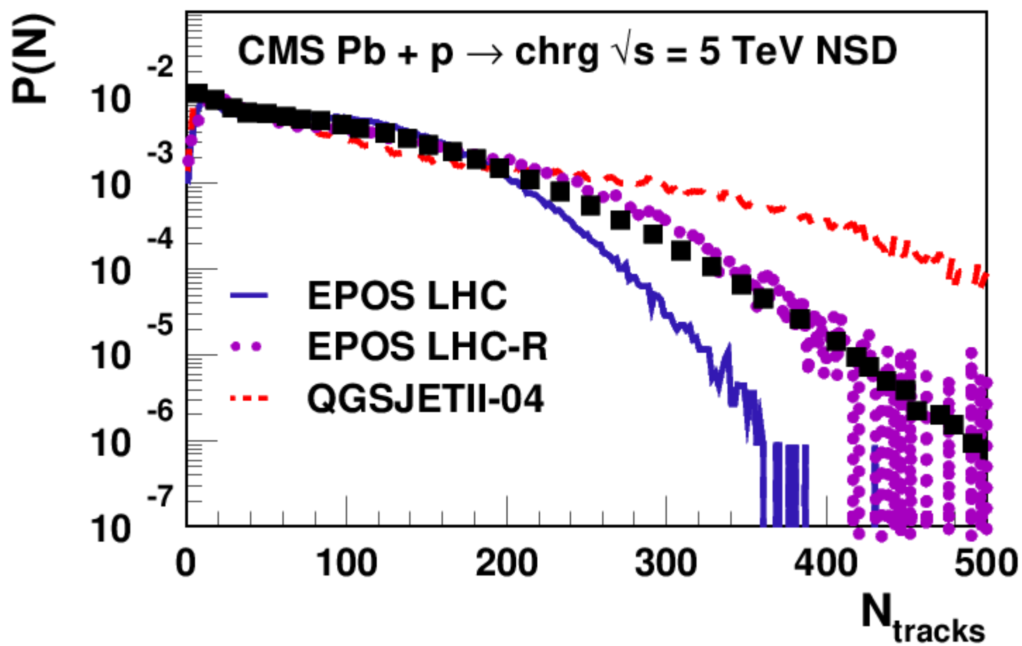




Pseudorapidity

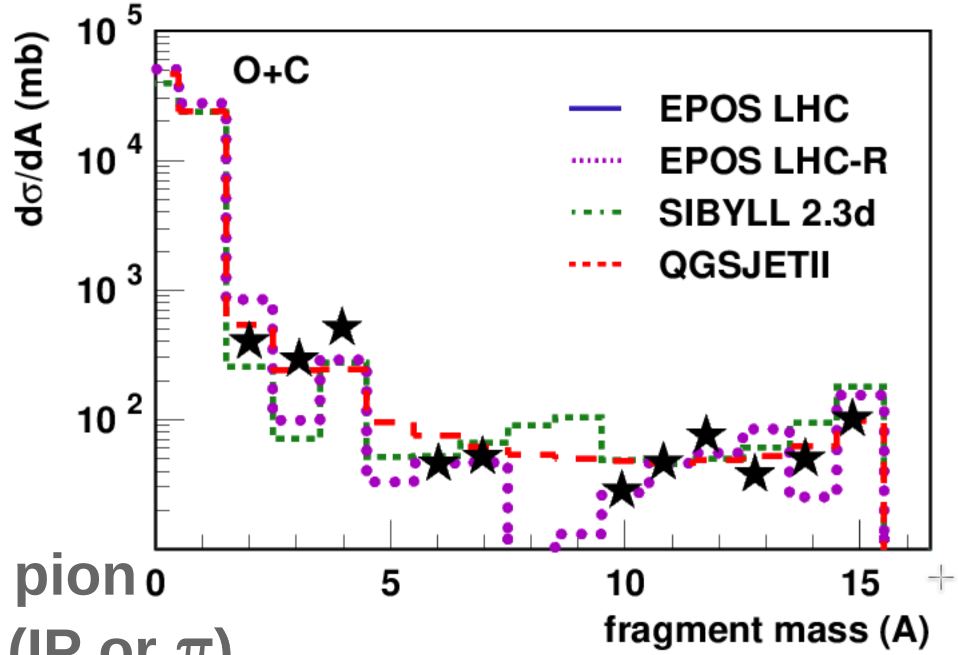
- **Angular distribution of newly produced particles**
- **New data at 13 TeV in p-p**
  - ➡ Test extrapolation with different triggers
  - ➡ Sibyll has a clear difference with other models (and data) : too narrow !
- **Detailed data at 5 TeV for p-Pb**
  - ➡ Wrong multiplicity distributions in all models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



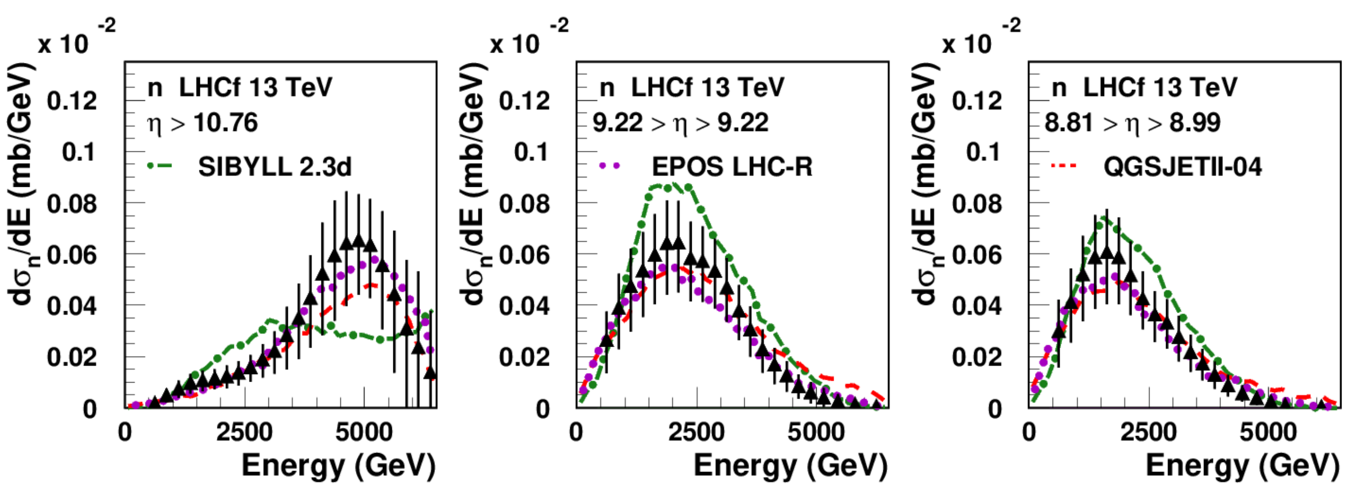


Improvements in EPOS LHC-R

- **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

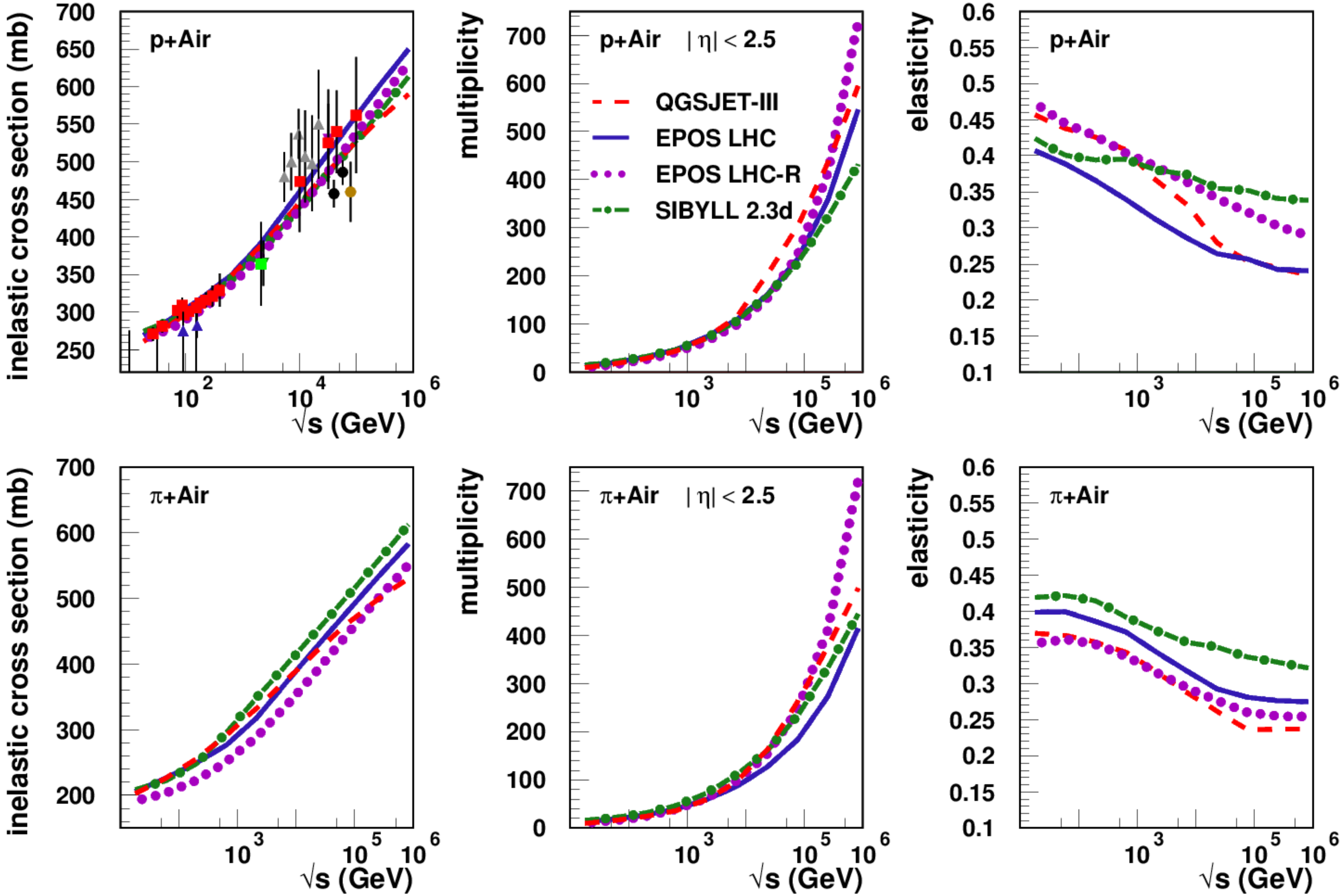


- **Simplified high mass diffraction and pion exchange replaced by real emission (IP or π)**



EPOS LHC-R interaction with Air

(preliminary)



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: $N_i = \omega_{\rm core}\, N_i^{\rm core} + (1-\omega_{\rm core})\, N_i^{\rm corona}$

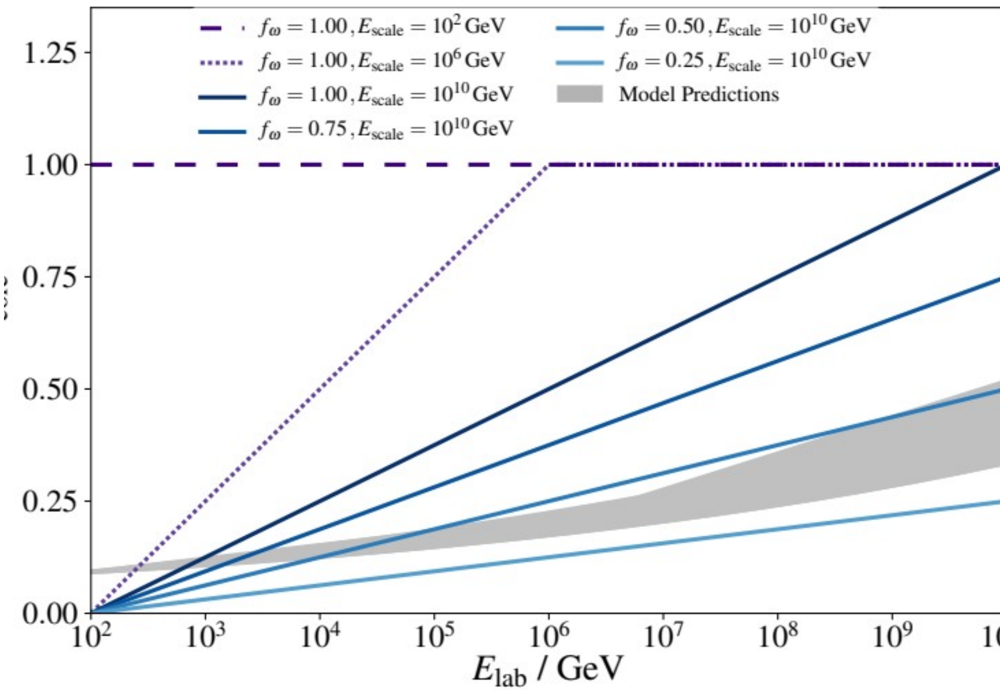
$$\omega_{\rm core}(E_{\rm lab}) = f_\omega \underbrace{F(E_{\rm lab}; E_{\rm th}, E_{\rm scale})}$$

$$\frac{\log_{10}(E_{\rm lab}/E_{\rm th})}{\log_{10}(E_{\rm scale}/E_{\rm th})} \text{ for } E_{\rm lab} > E_{\rm th}$$

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

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

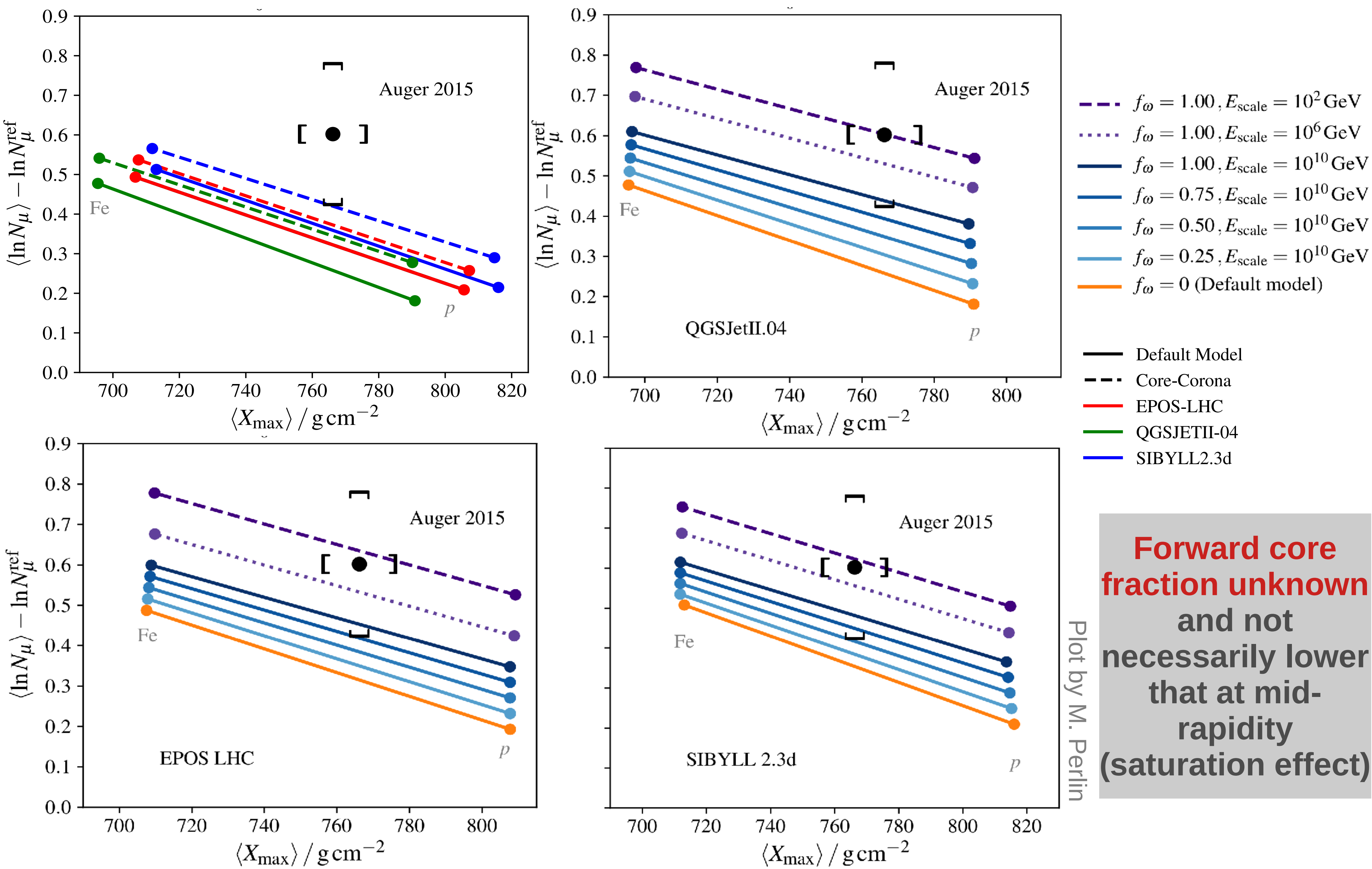
Note : the leading particle is NOT modified (projectile remnant)



Plot by M. Perlin

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

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

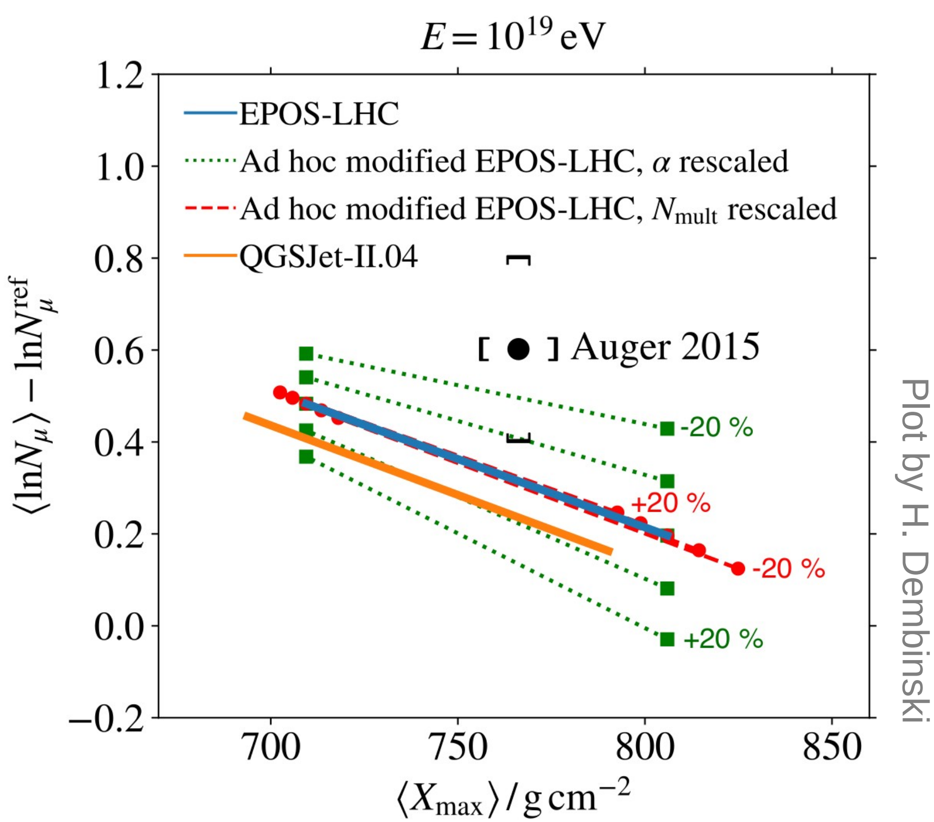
- **One needs to change energy dependence of muon production by ~+4%**

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

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

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

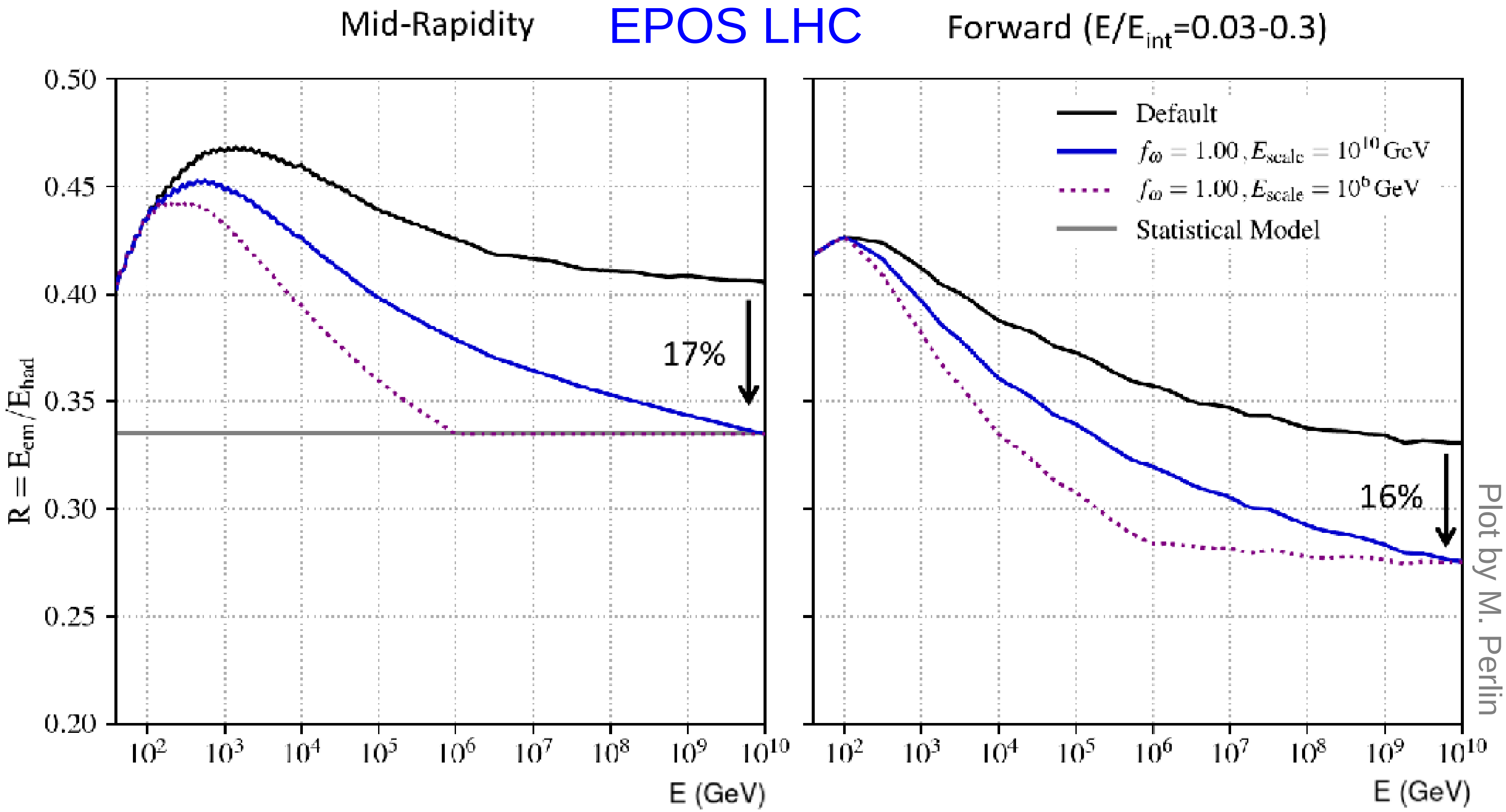


Evolution of hadronization from core to corona

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

  which define the muon production in air showers.



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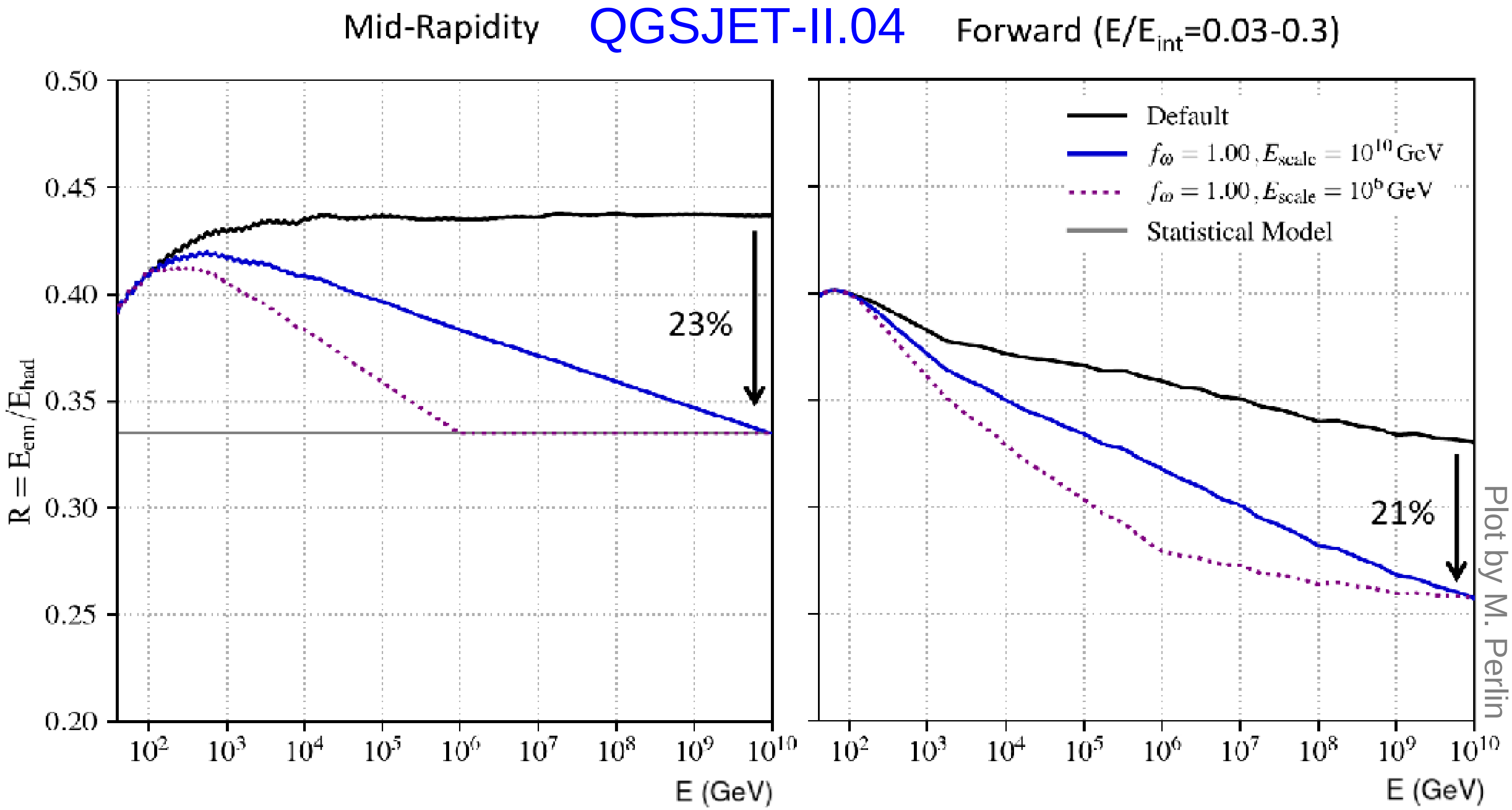

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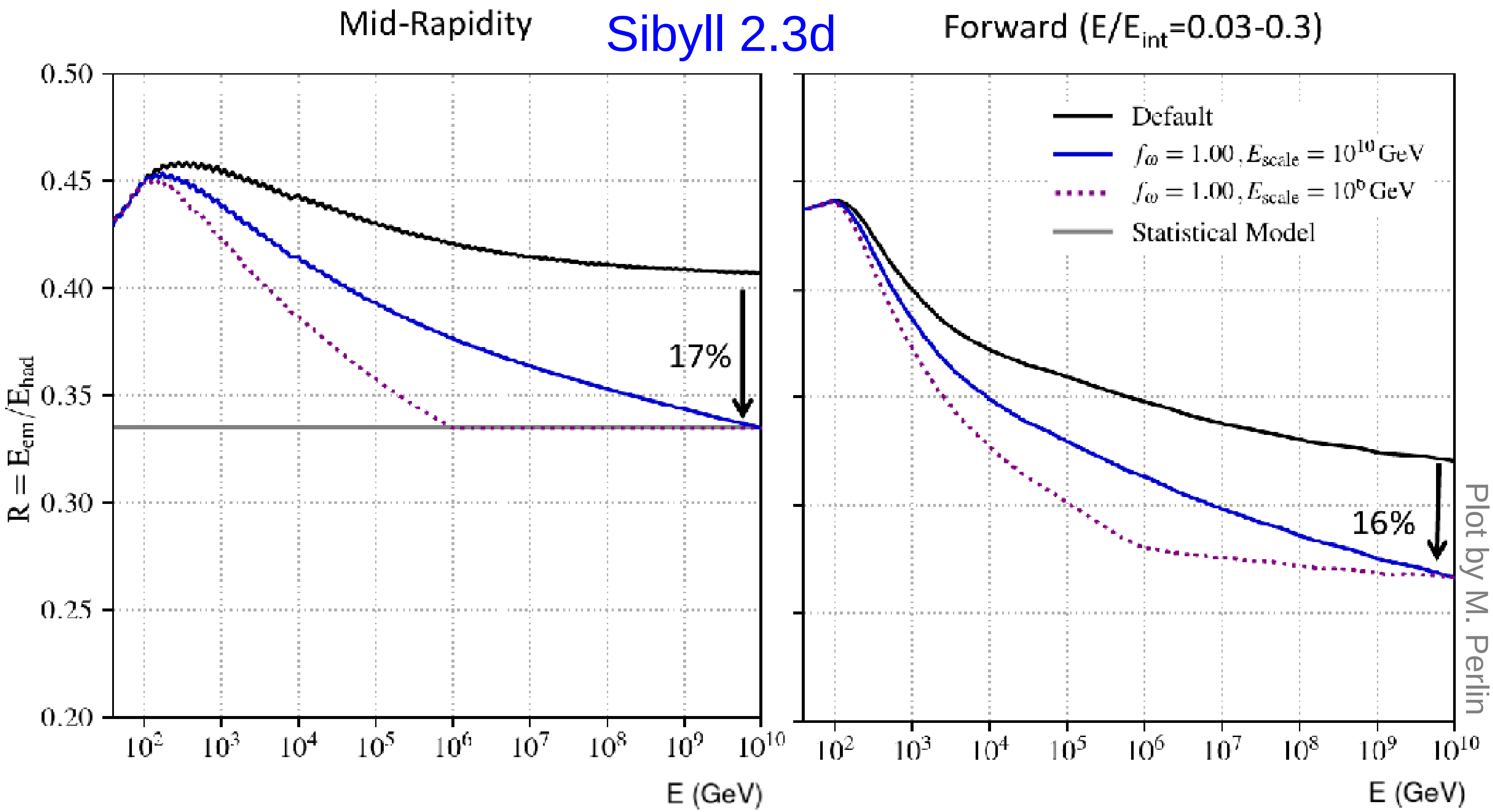
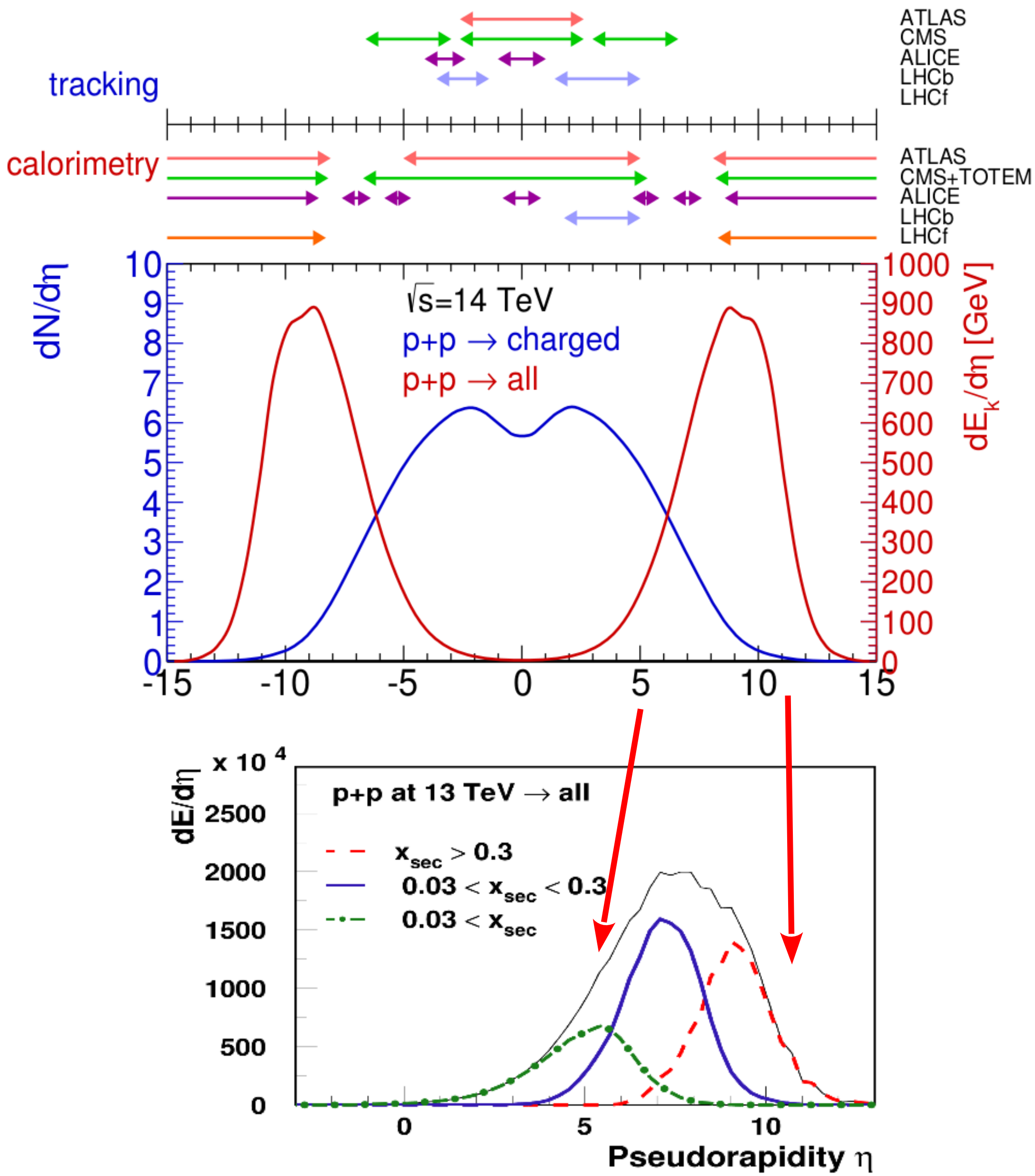


Possible Particle Physics Explanations

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

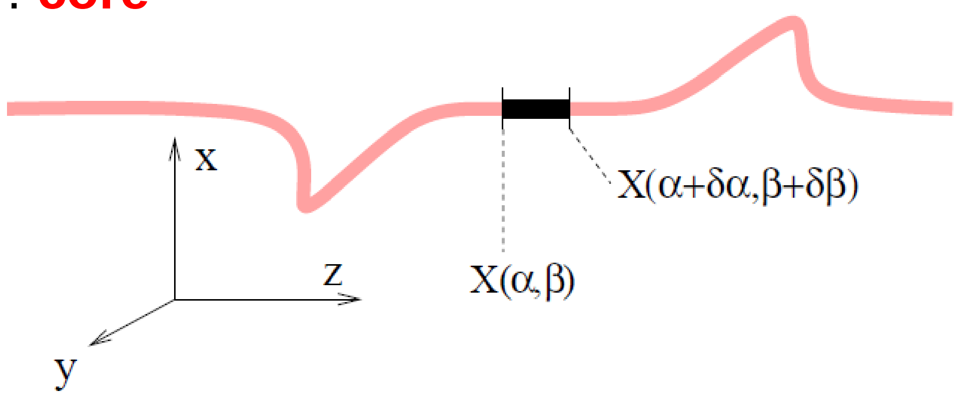


- **p-p data mainly from "central" detectors**
  - pseudorapidity η=-ln(tan(θ/2))
  - θ=0 is midrapidity
  - θ>>1 is forward
  - θ<<1 is backward
- **Different phase space for LHC and air showers**
  - most of the particles produced at midrapidity
    - important for models
  - most of the energy carried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

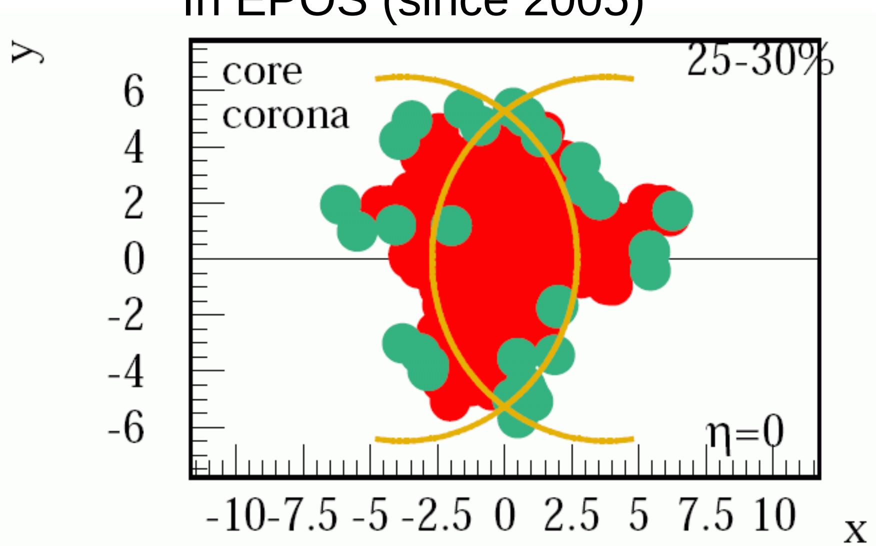
A 3rd way : the core-corona approach

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