Toward a consistent description of EAS with EPOS LHC-R

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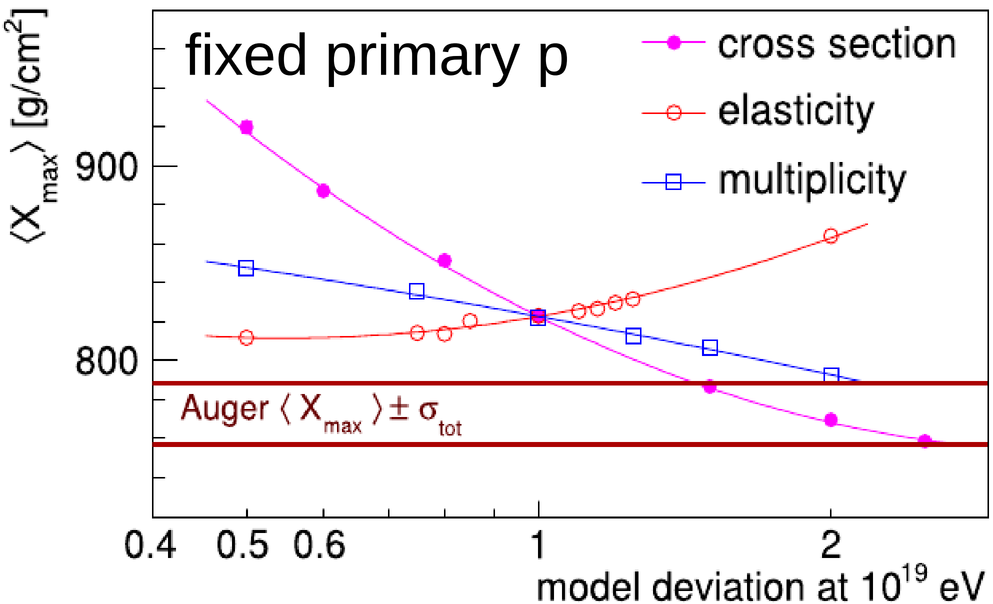
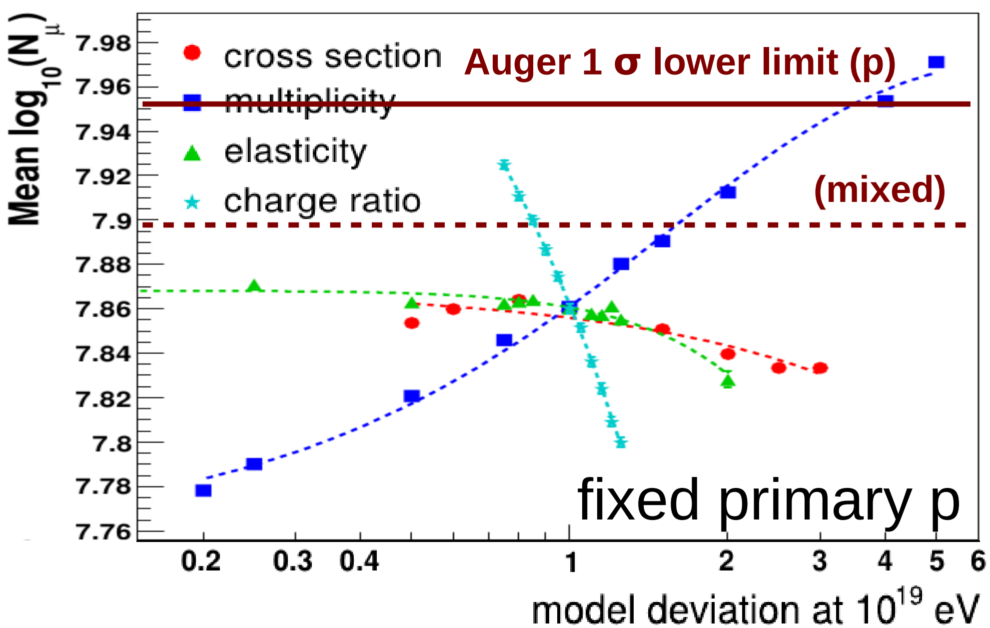
Outline

- **Introduction**
- **Updates → EPOS LHC-R**
  - ➡ A real global approach to do hadronic interactions
- **Predictions for air showers (EAS)**
  - ➡ X_{max} and μ
- **Muon puzzle**
  - ➡ Real impact of collective effects 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

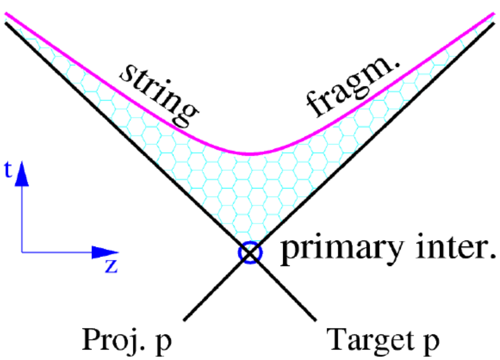
  N_{μ}

- **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
  - ➔ Almost final result (but still preliminary) including all <u>collective effects</u> !

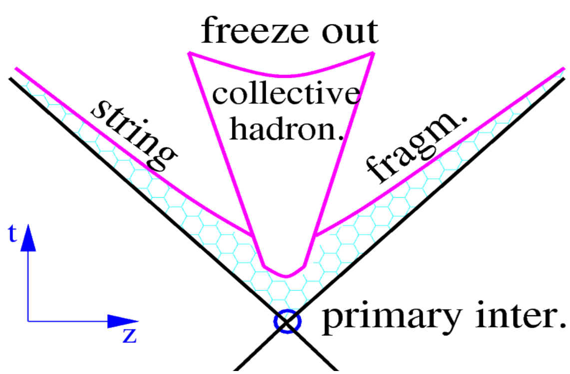
What means global approach ?

Global approach is the key !

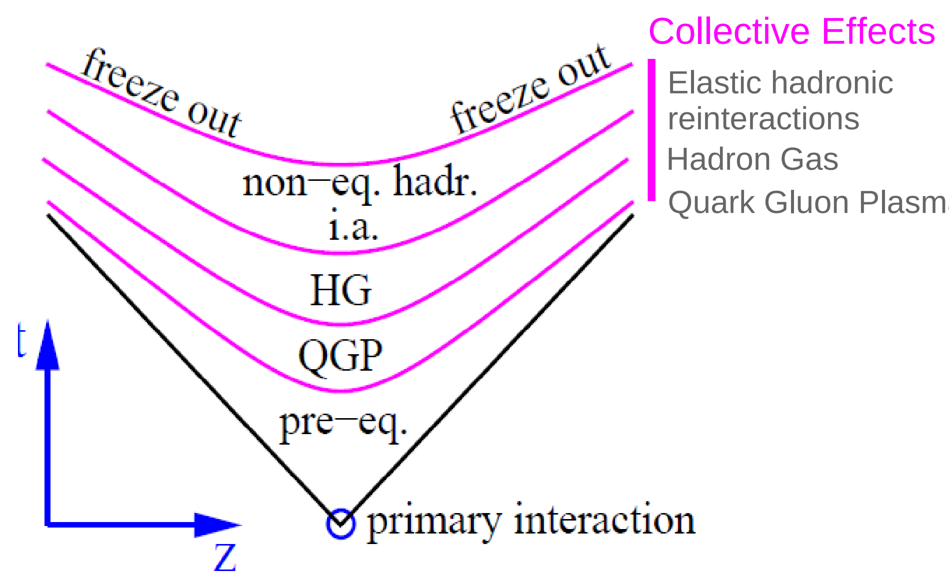
- Tuning models neglecting some physics process lead to wrong parameters !
- Correct tune possible to do only if everything taken into account
- Even without a direct impact on the shower development (rare particle or not forward), it will change model parameters and the extrapolation (in energy or phase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



Sibyll, QGSJET



EPOS LHC
(no rescattering)

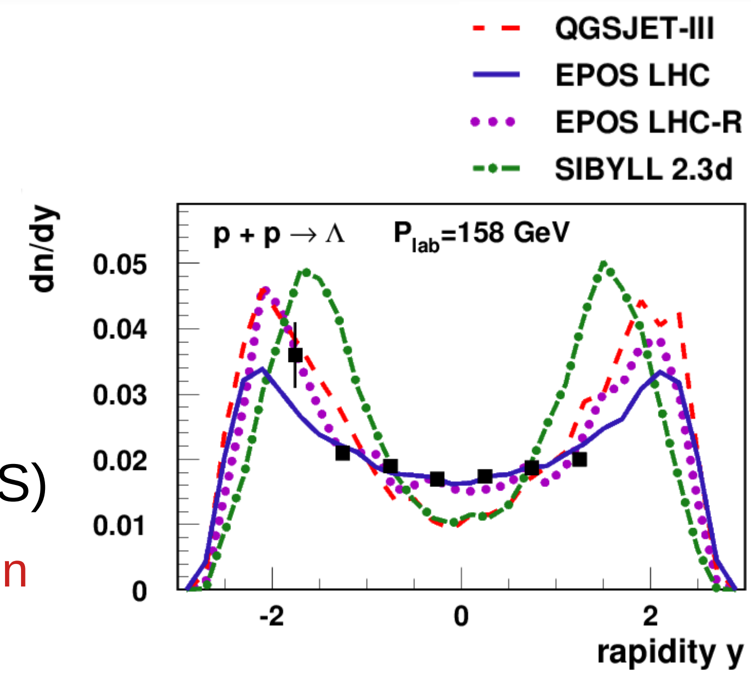


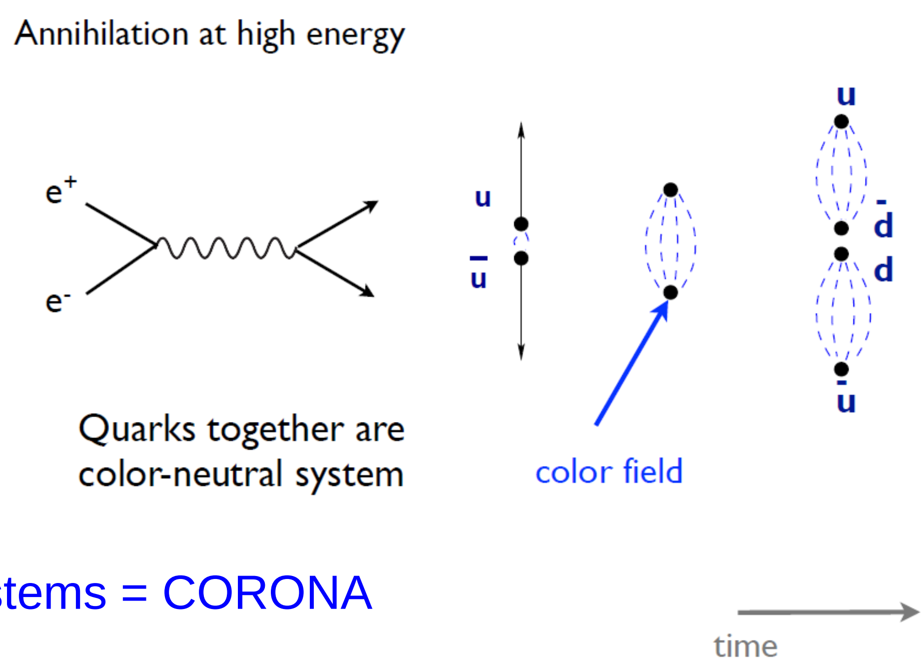
EPOS LHC-R

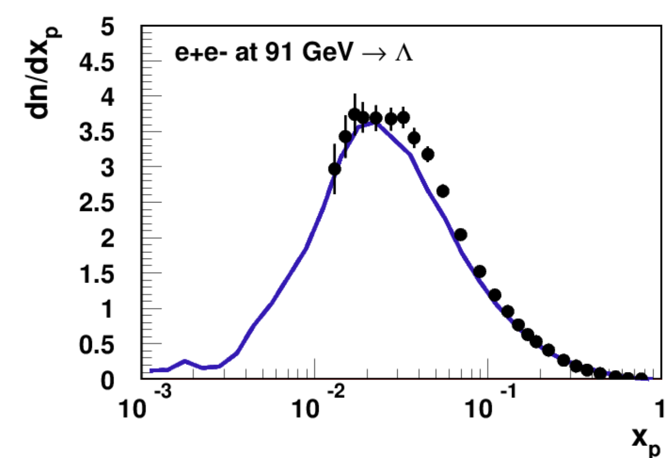
String Fragmentation

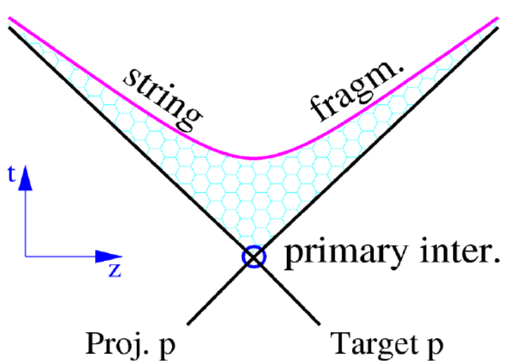
Global approach is the key !

- 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





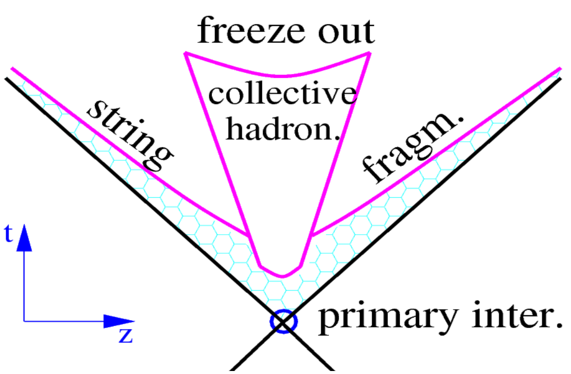




Used In dilute systems = CORONA

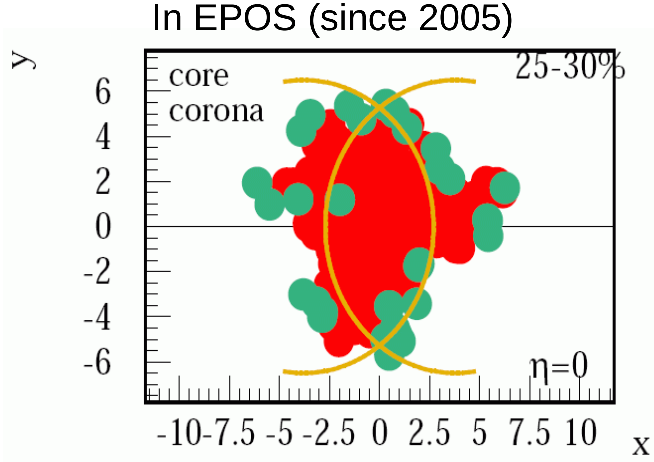
Core-Corona

- 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**

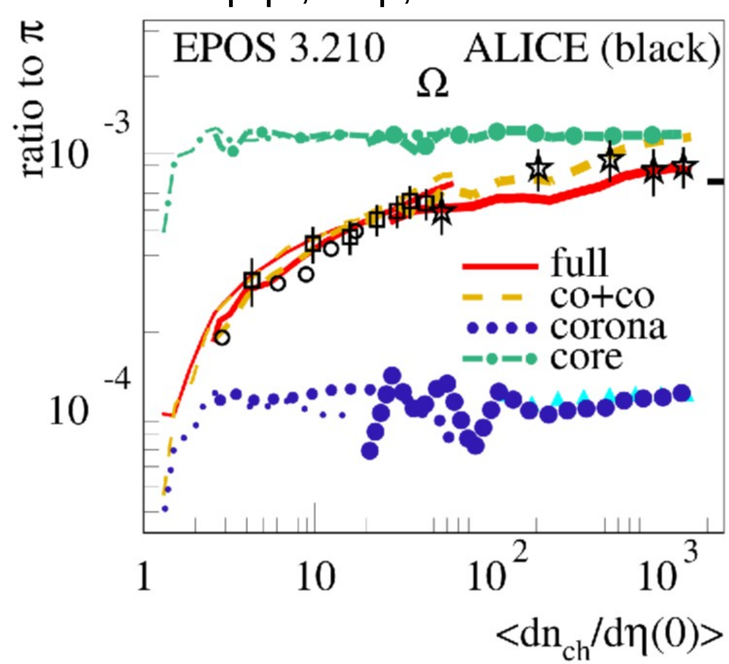


- 2 simultaneous source of particles

In EPOS (since 2005)



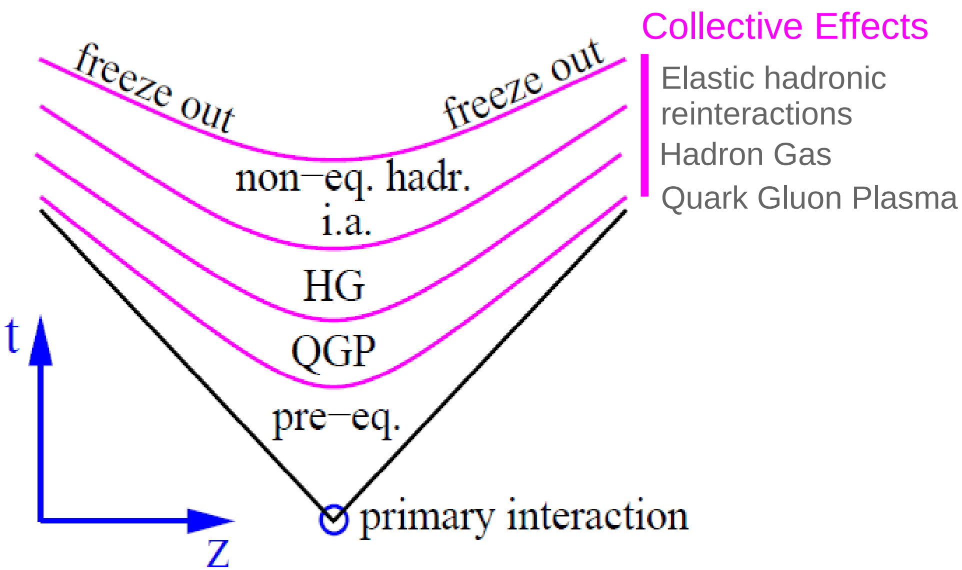
p-p ,Pb-p, Pb-Pb data

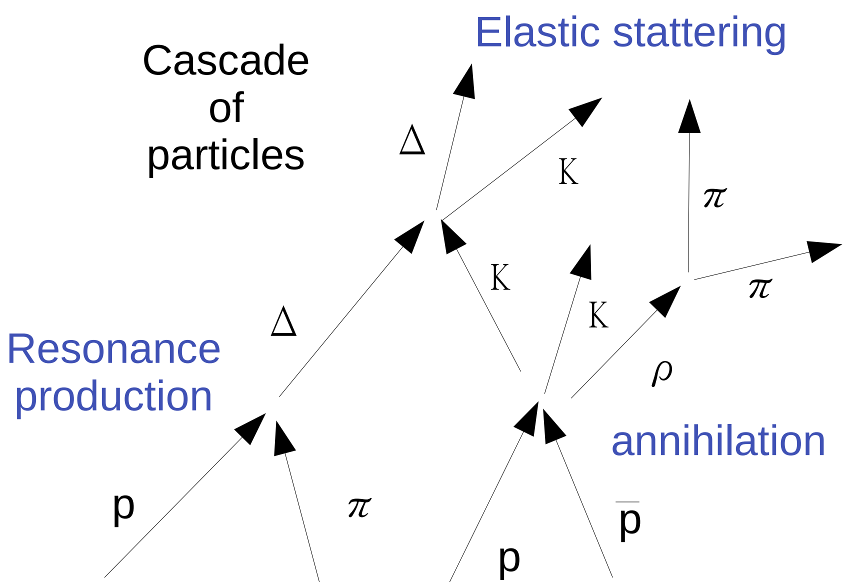


Hadronic rescattering

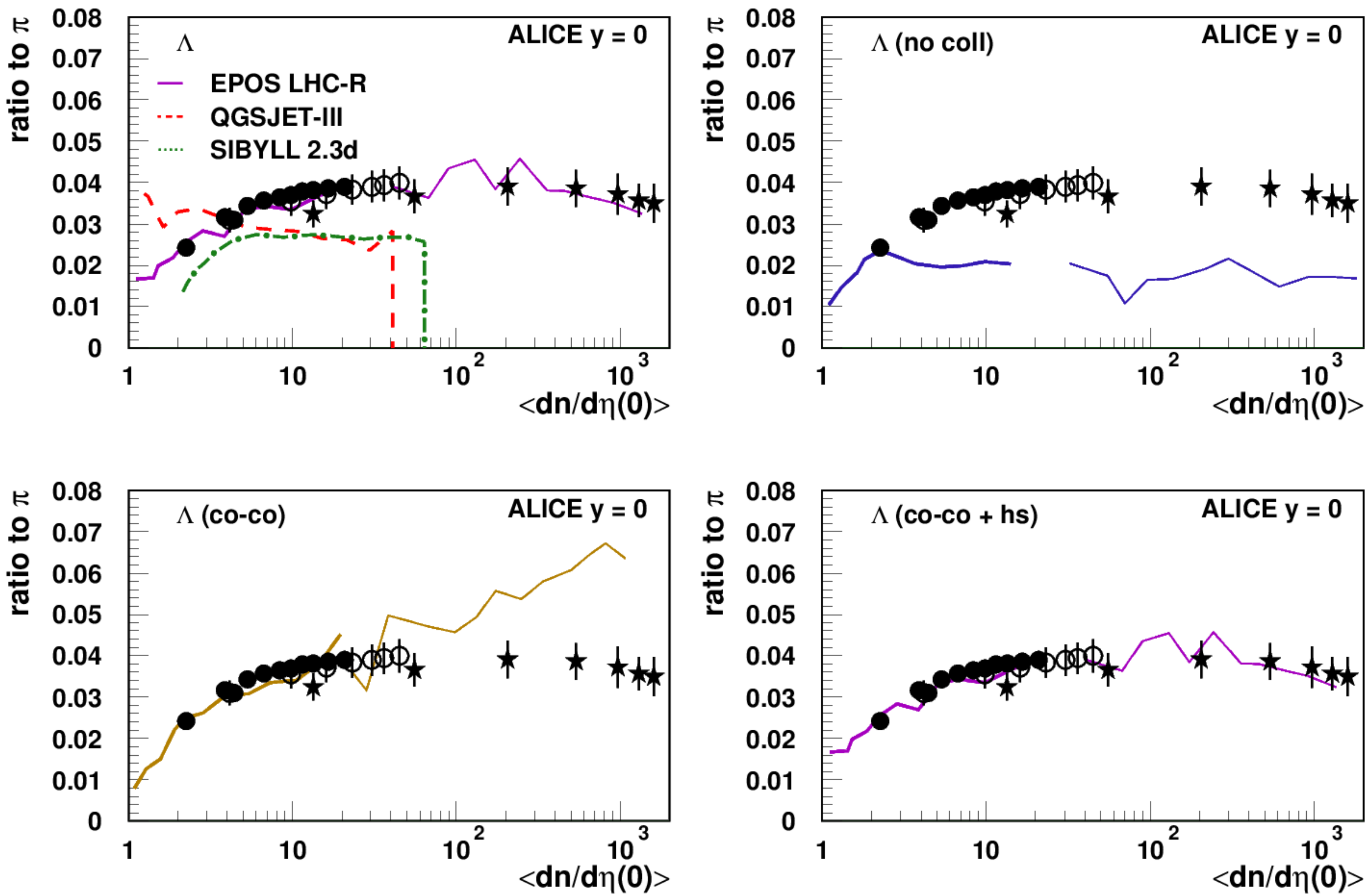
Missing effect in all CR models until now !

- 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 even in light system !
  - Change string fragmentation parameters !

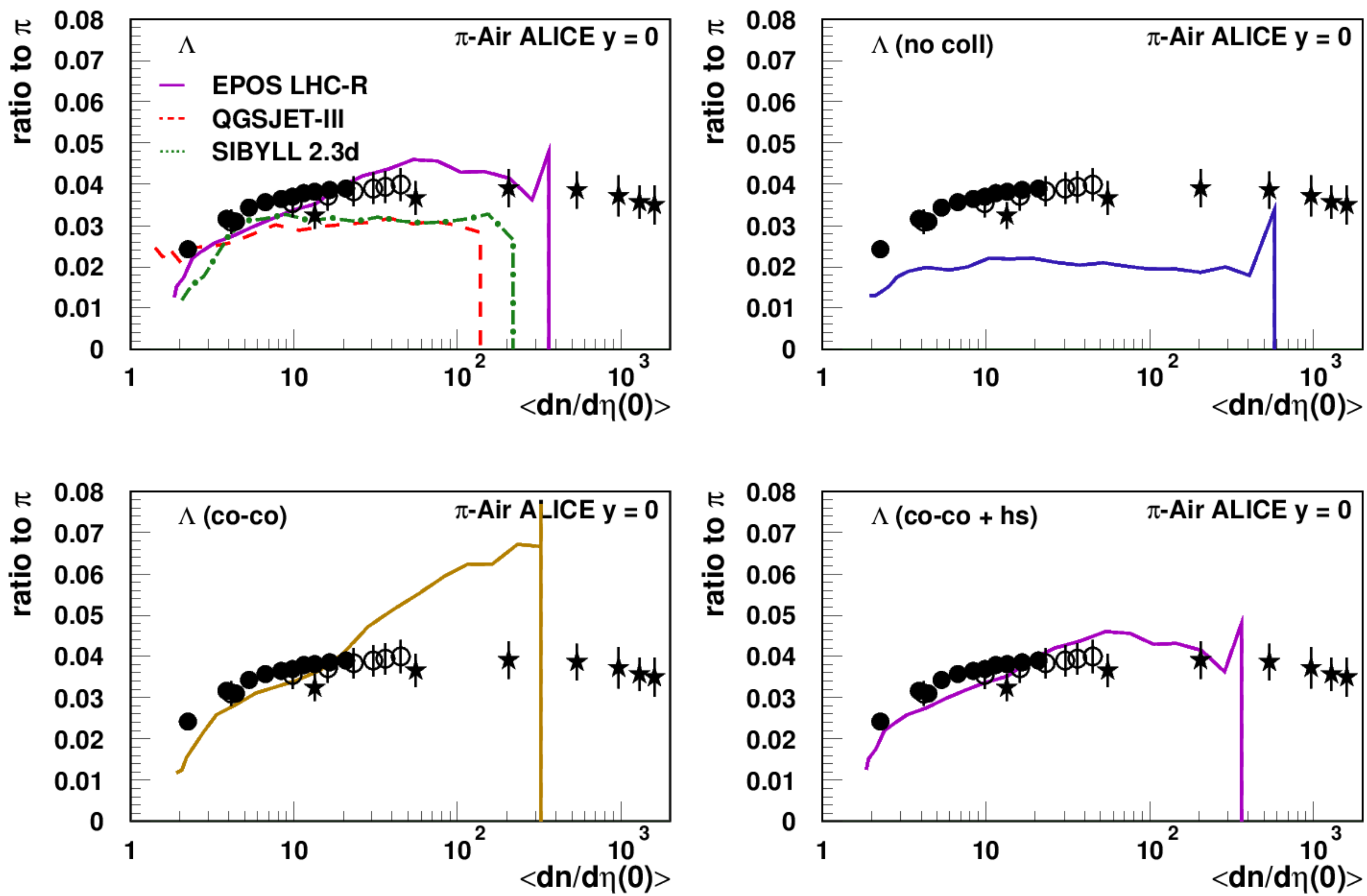




Example with Lambda particle in p-p and Pb-Pb @ LHC



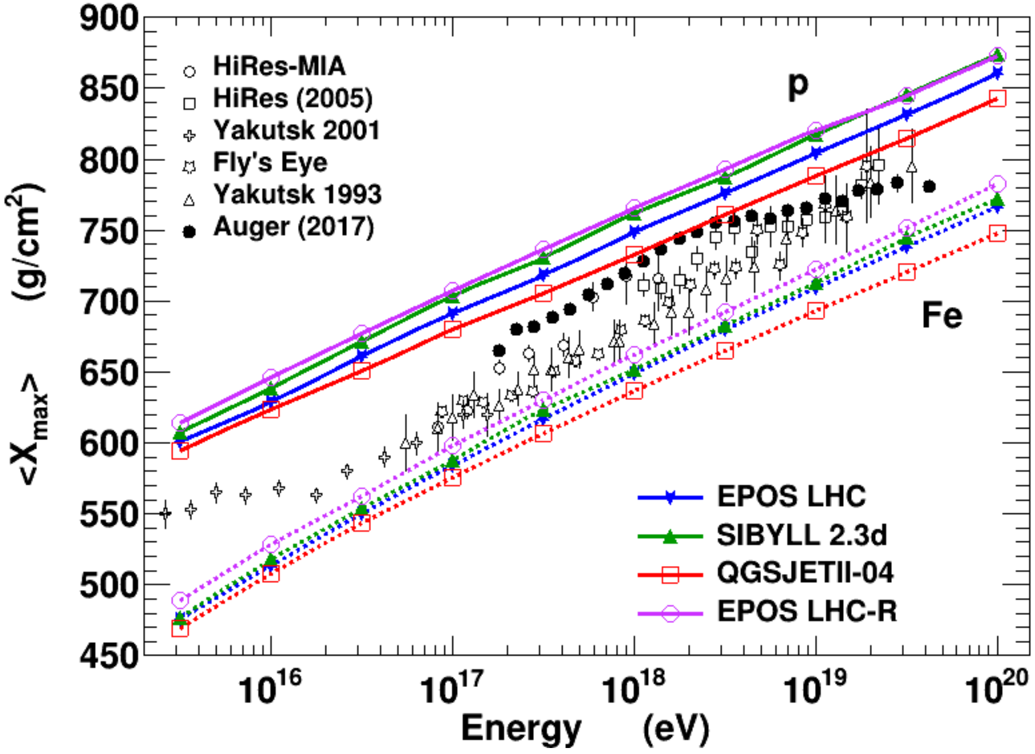
Example with Lambda particle in π-Air @ all energies

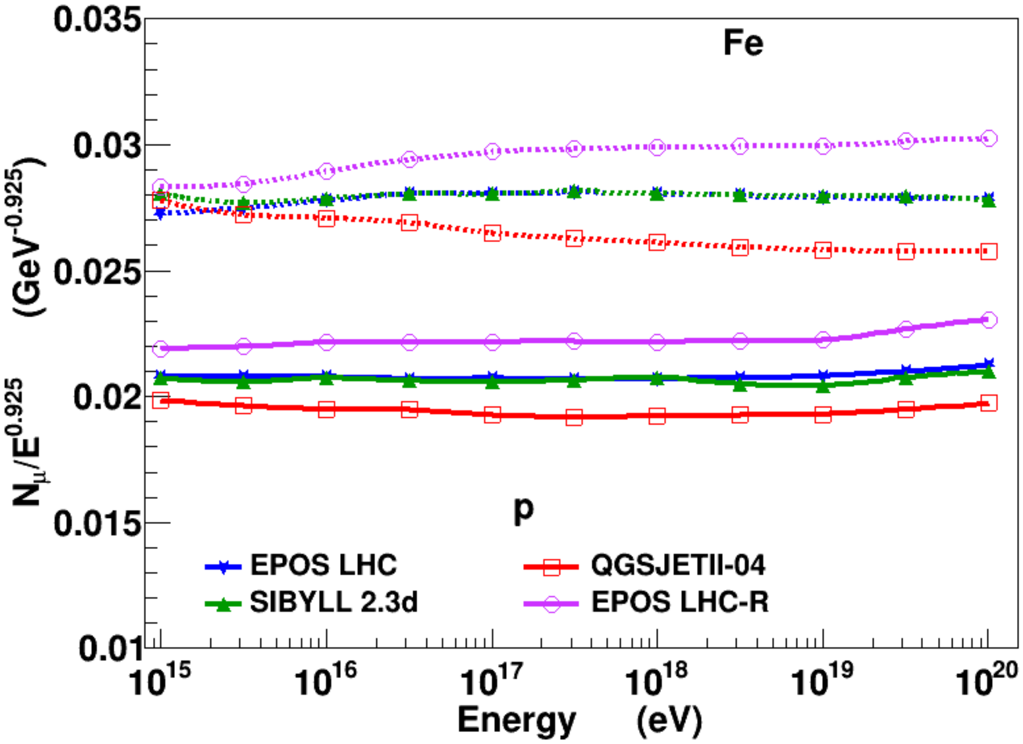


X_{max} and N_μ

Global changes

- Motivated by PAO, now EPOS shifted by +15 g/cm² (~Sibyll)
  - in full agreement with accelerator data
- Increase of the number of muons by about 10%
- LDF not tested yet but different muon energy spectrum

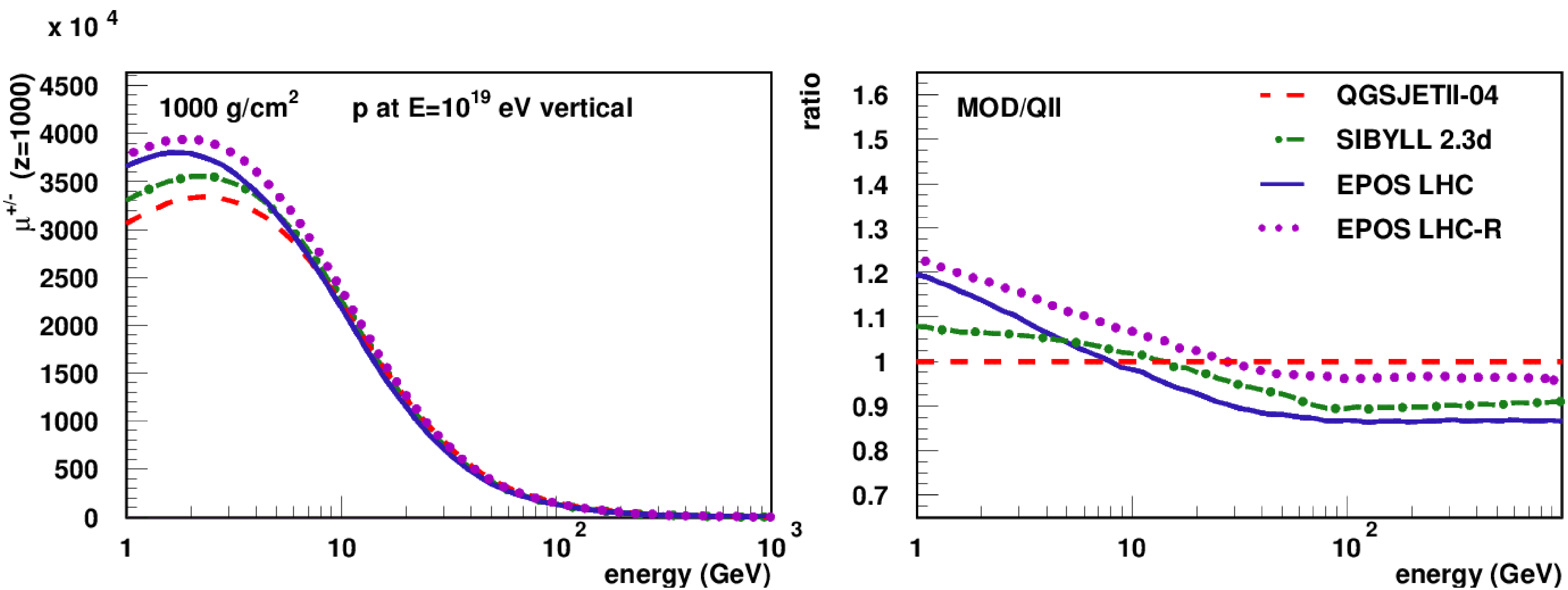




E_{μ}

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

- Simulations without core-corona but ρ asymmetry already have more muons
  - Parallel shift changing all muon energies
- Additional energy and mass dependent effect due to core-corona !
- Better tune of kaons
  - Increase ~10-100 GeV muons (Ice-Top/Ice-Cube)



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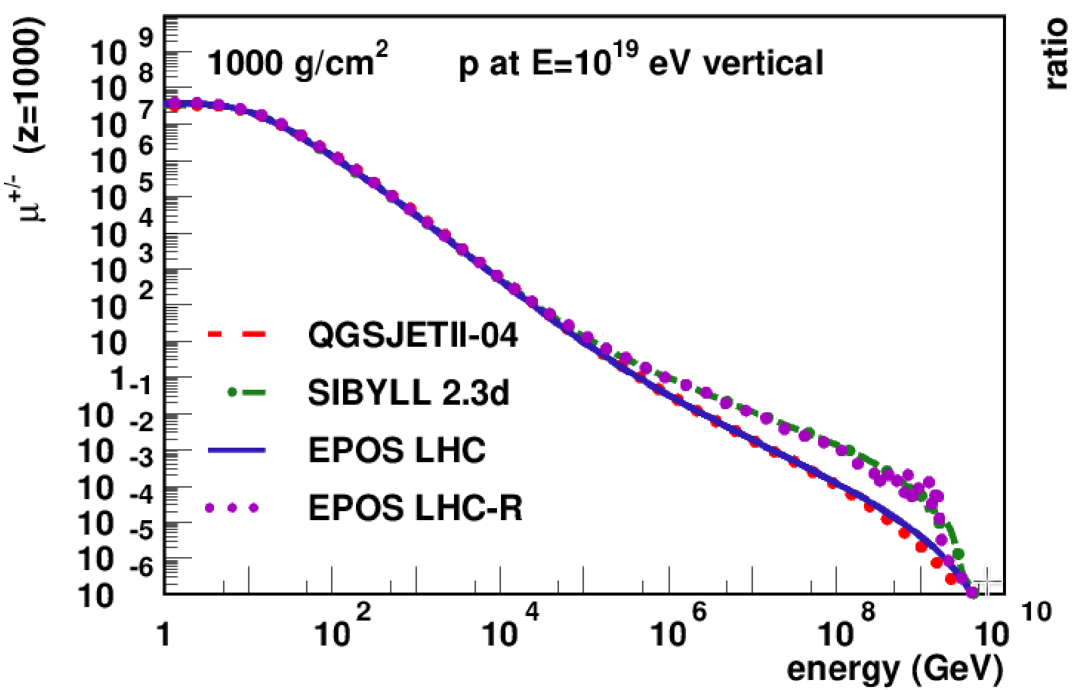
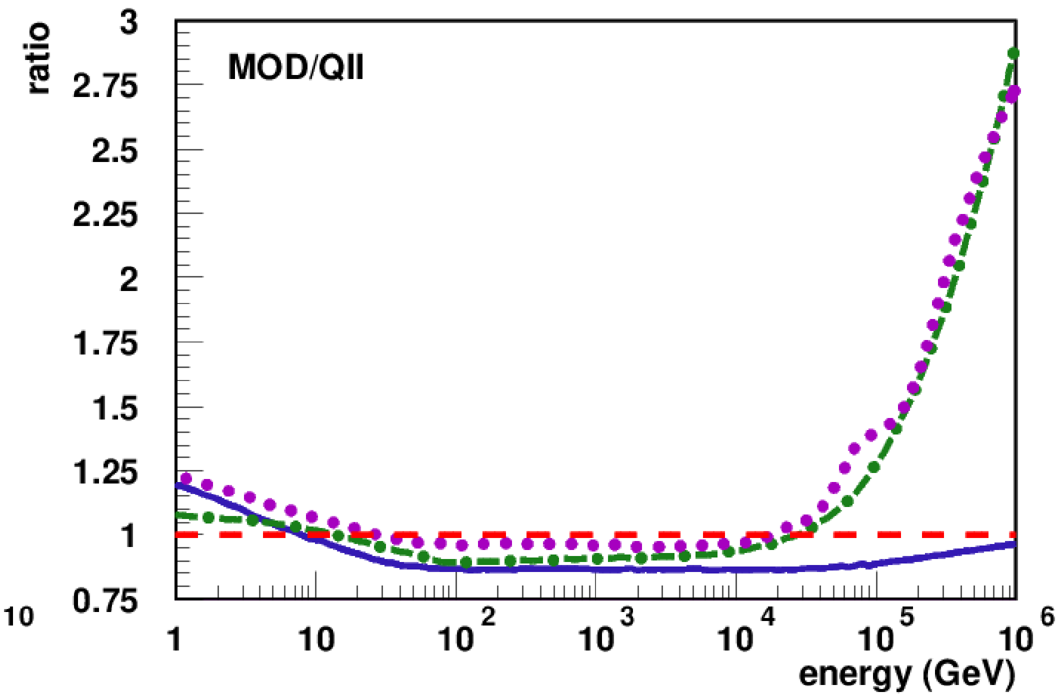
- Additional energy and mass dependent effect due to core-corona !
- Better tune of kaons
- High energy muons from charm ! (background for neutrino analysis)

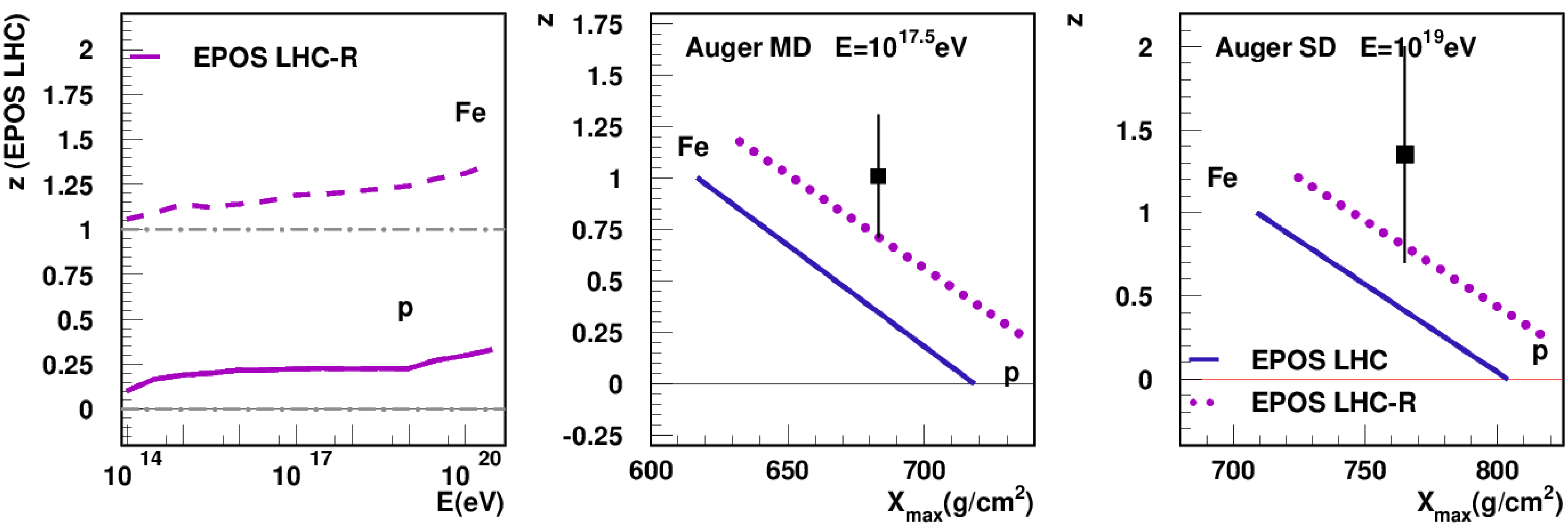




Muon Puzzle Solved ?

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
- Energy and mass dependent increase of muons due to collective effects further decrease the gap to reach Auger systematics
- What about low energy ? Correlation Ne-N μ OK because of deeper X_{max} !



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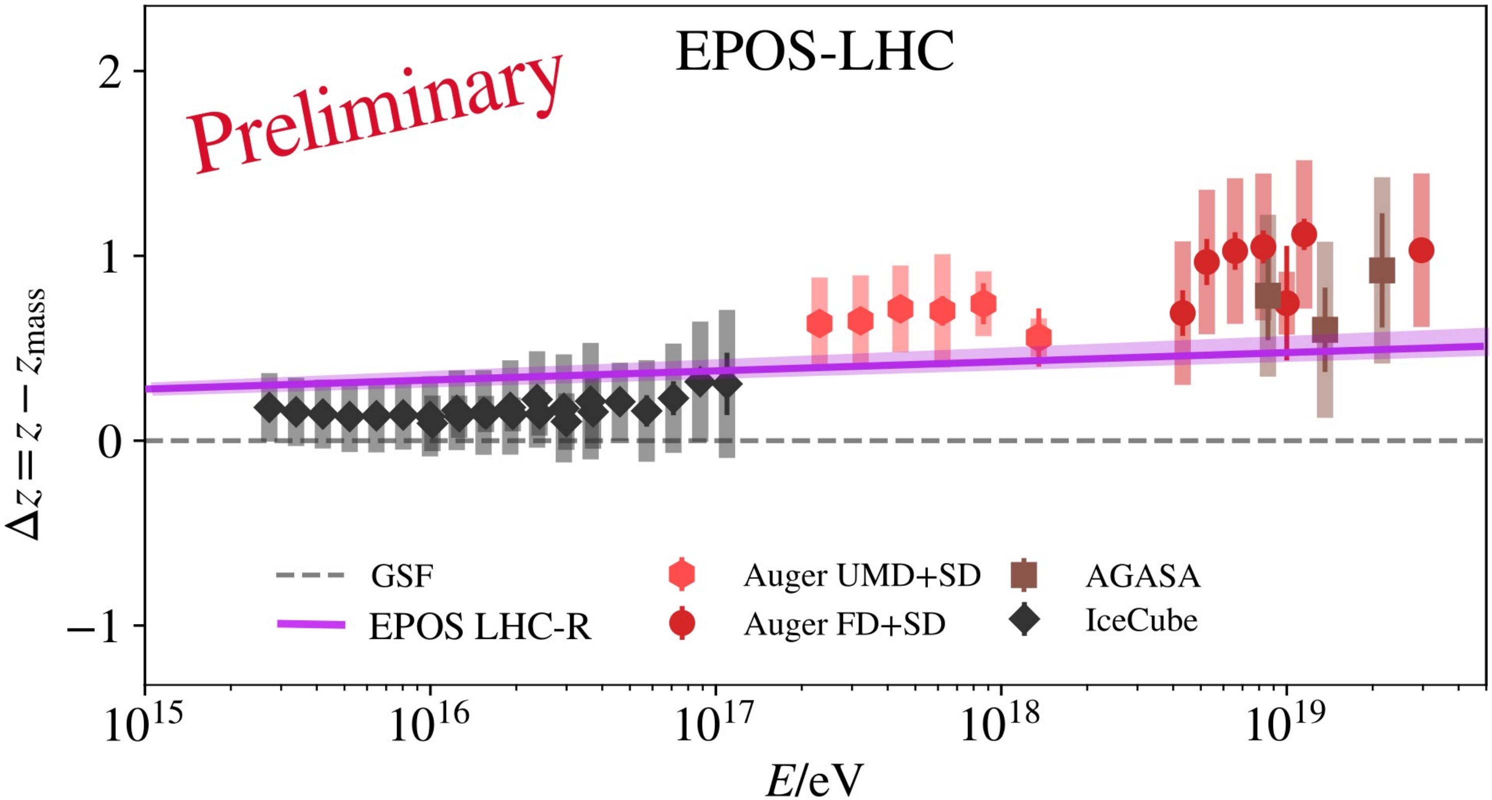
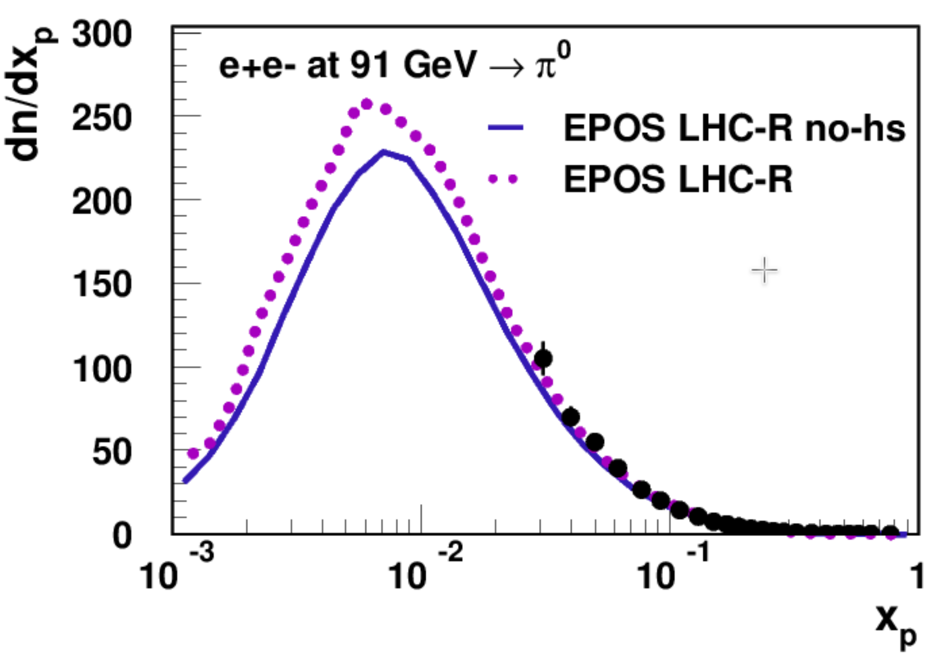
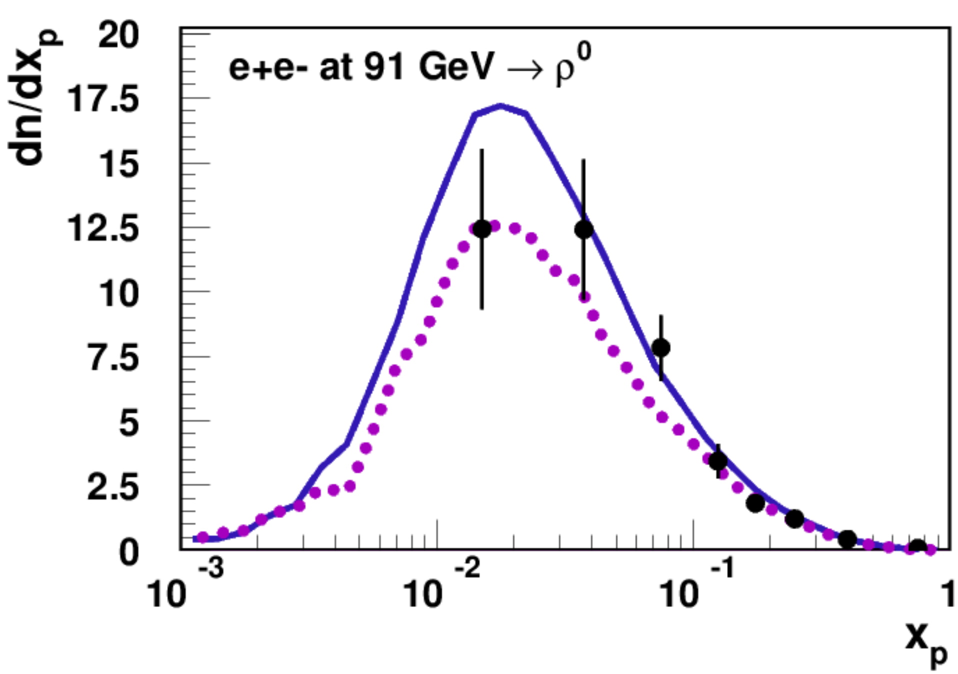


Why ?

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
- If effect is not taken into account
  - Either overestimate production compared to data ("bad tune")
    - Sibyll*
  - Or underestimate forward production of to get it right with mid-rapidity data
    - All models until now !





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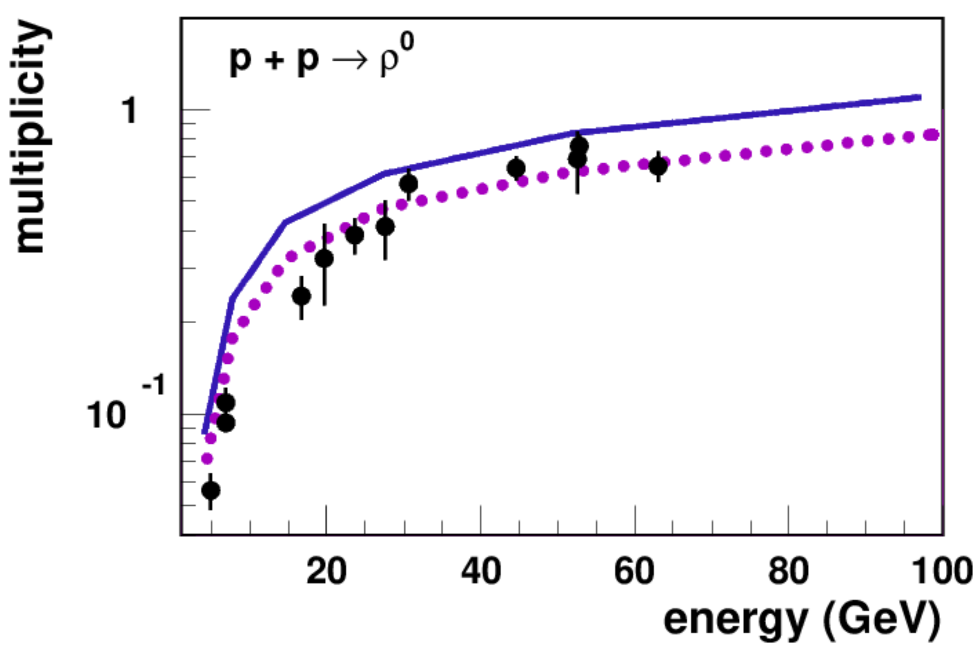

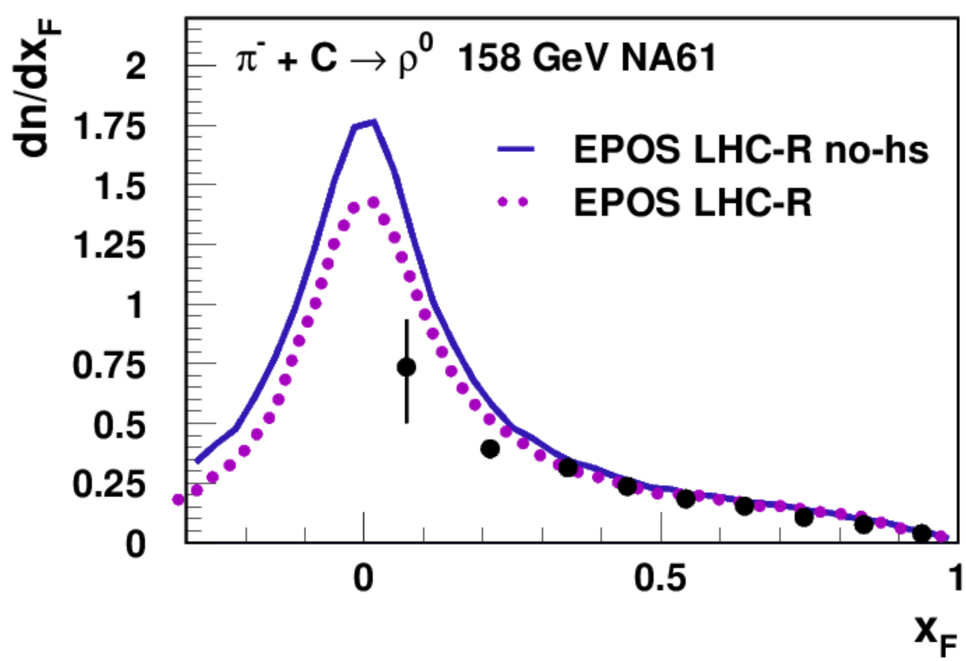

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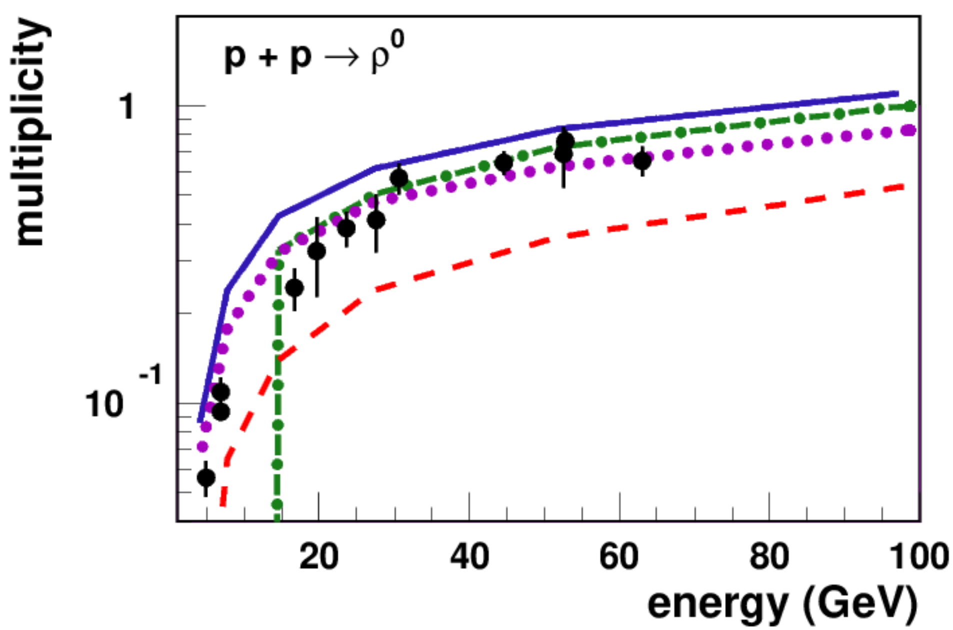

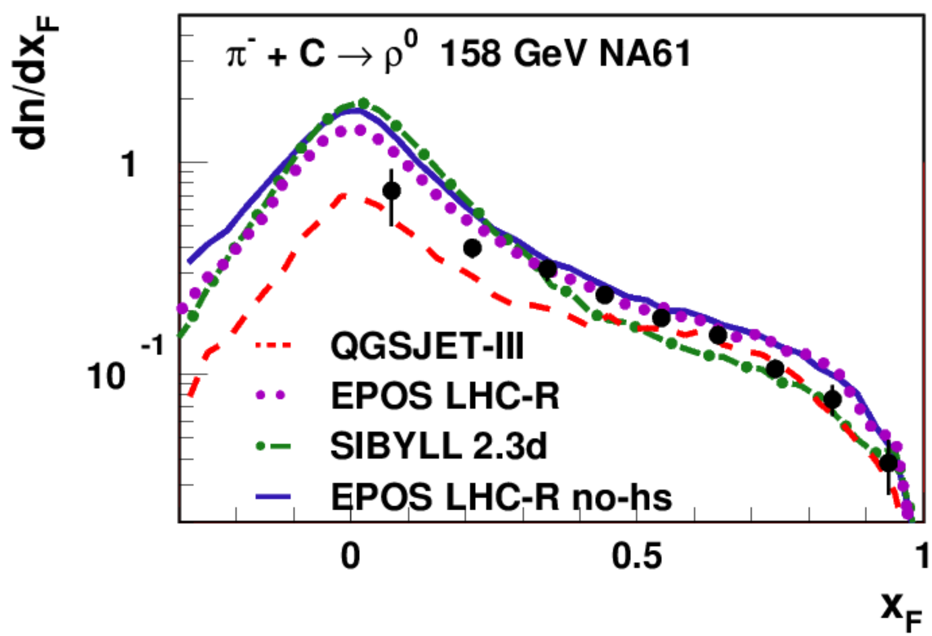

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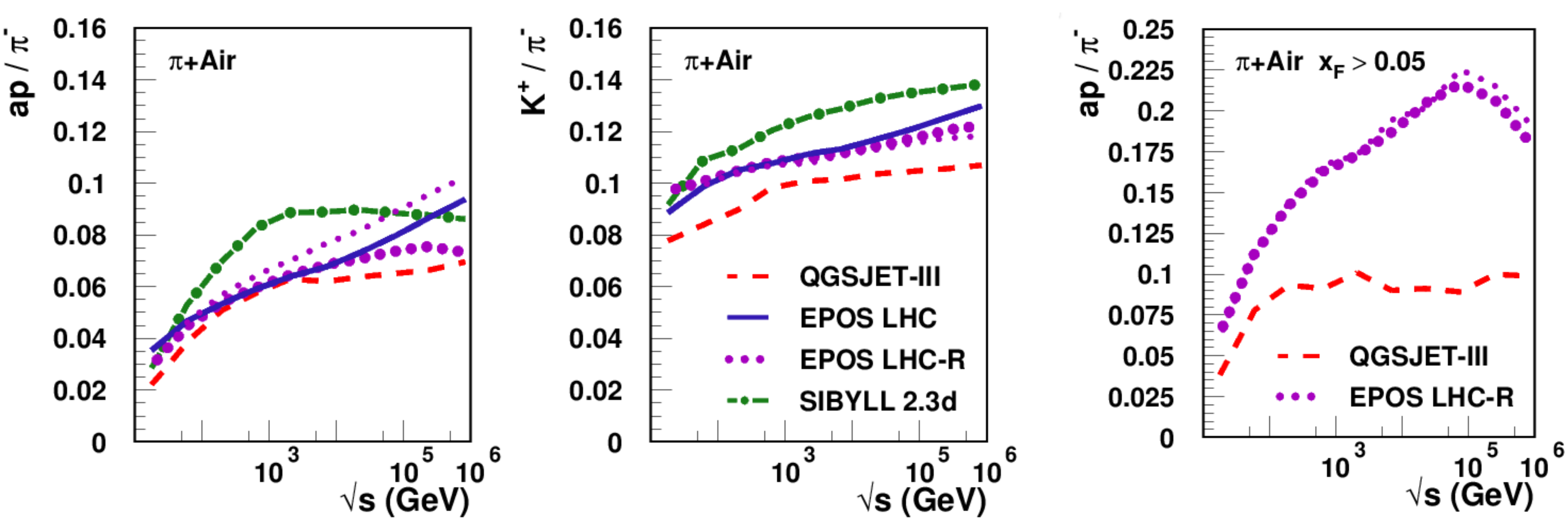

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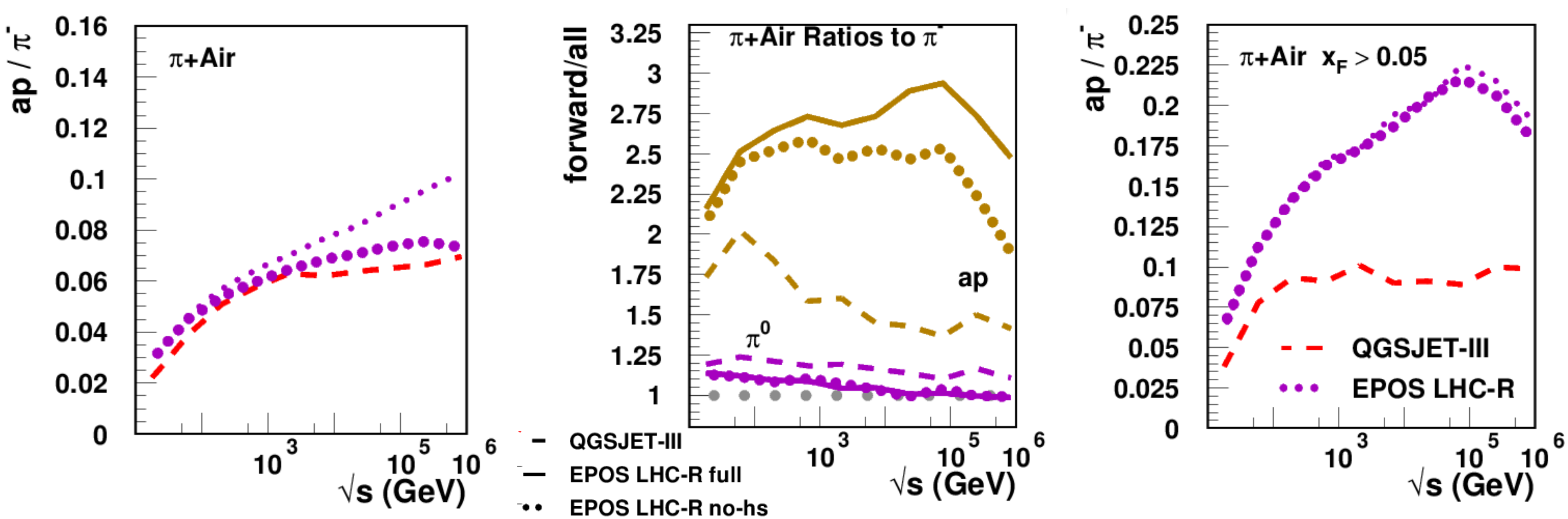


Outlook

- **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
    - 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

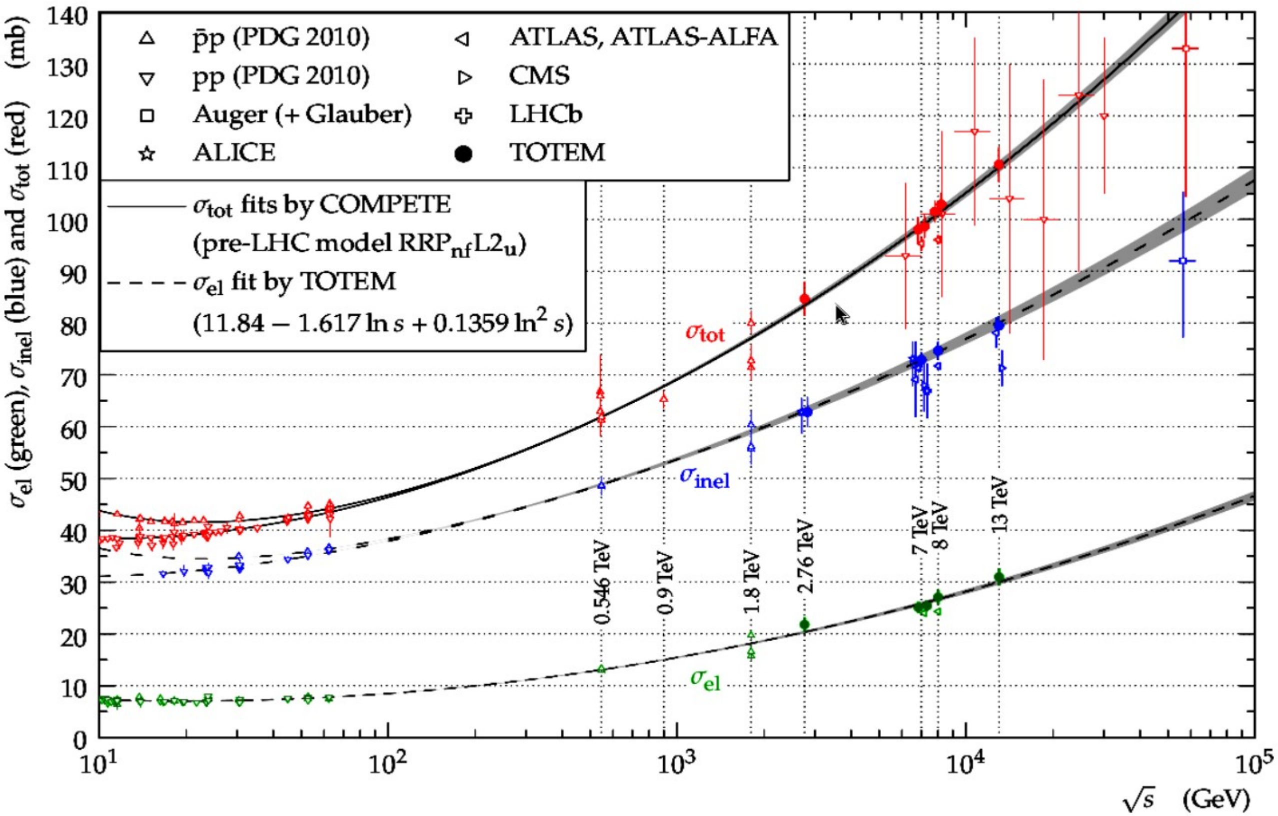
Recent LHC data provide new constraints on models changing X_{max} and fine details on hadronization could be more important than thought until now, impacting the muon production

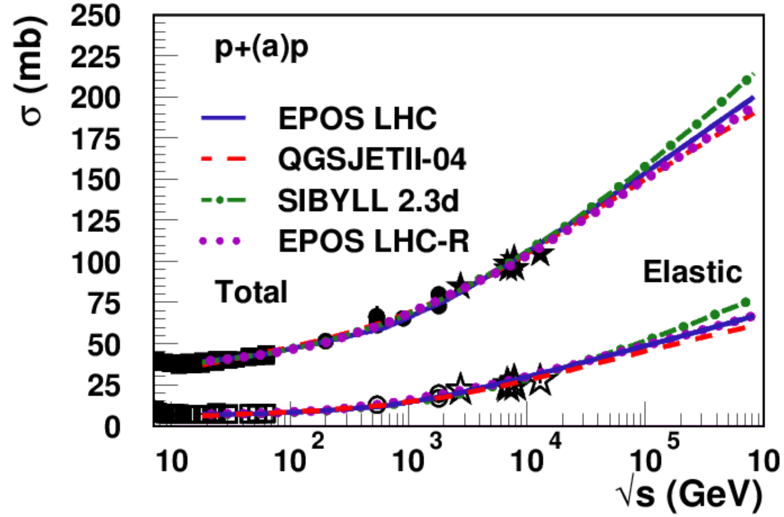
Providing solutions to the “muon puzzle” !

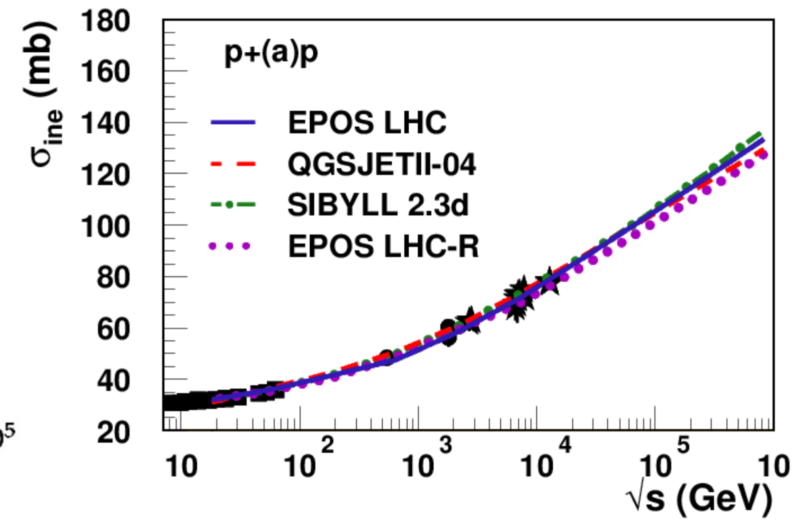
Thank you !

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

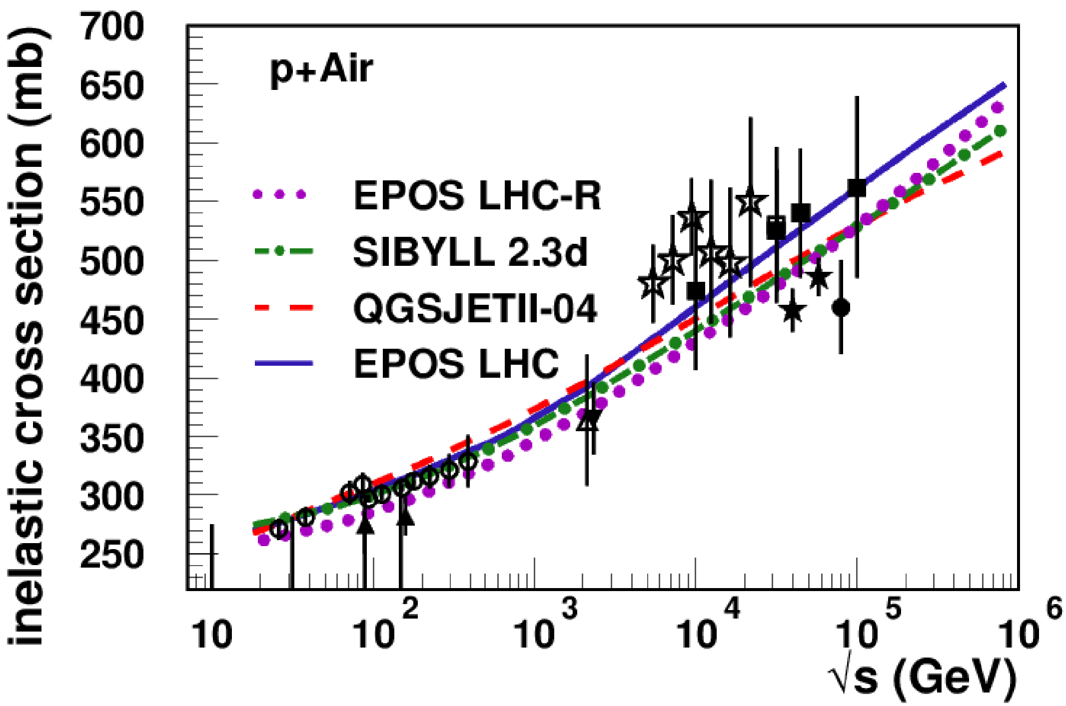


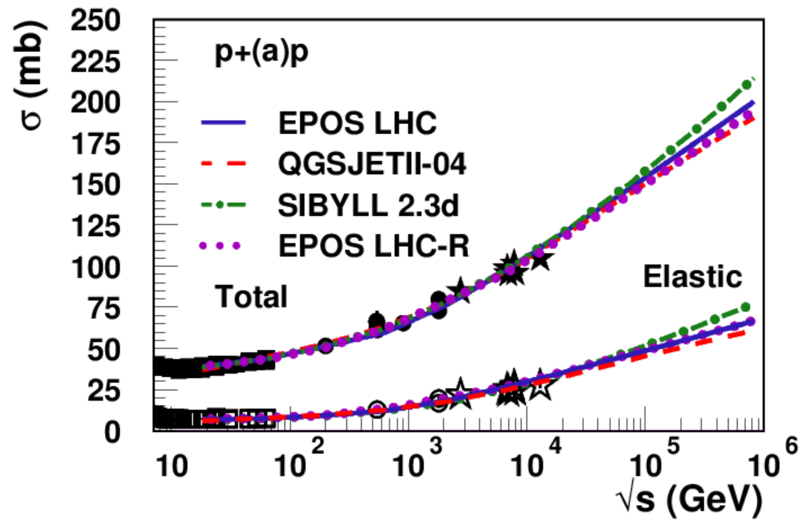


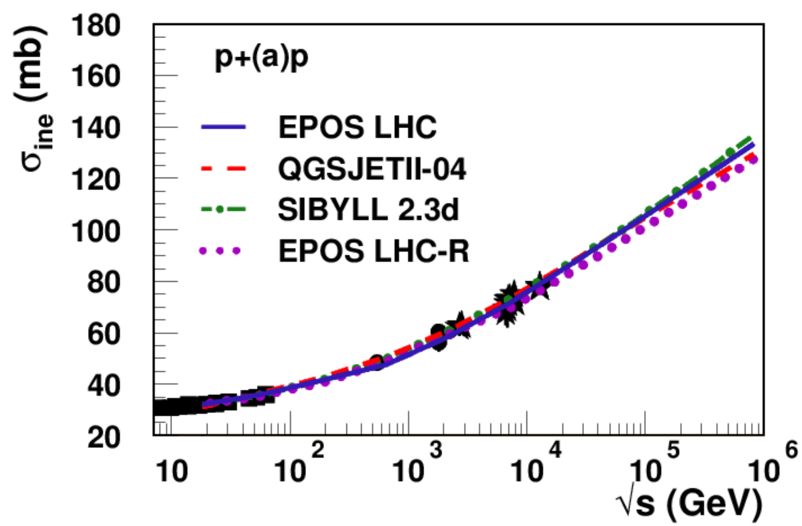


Cross-Section Reduced

- **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

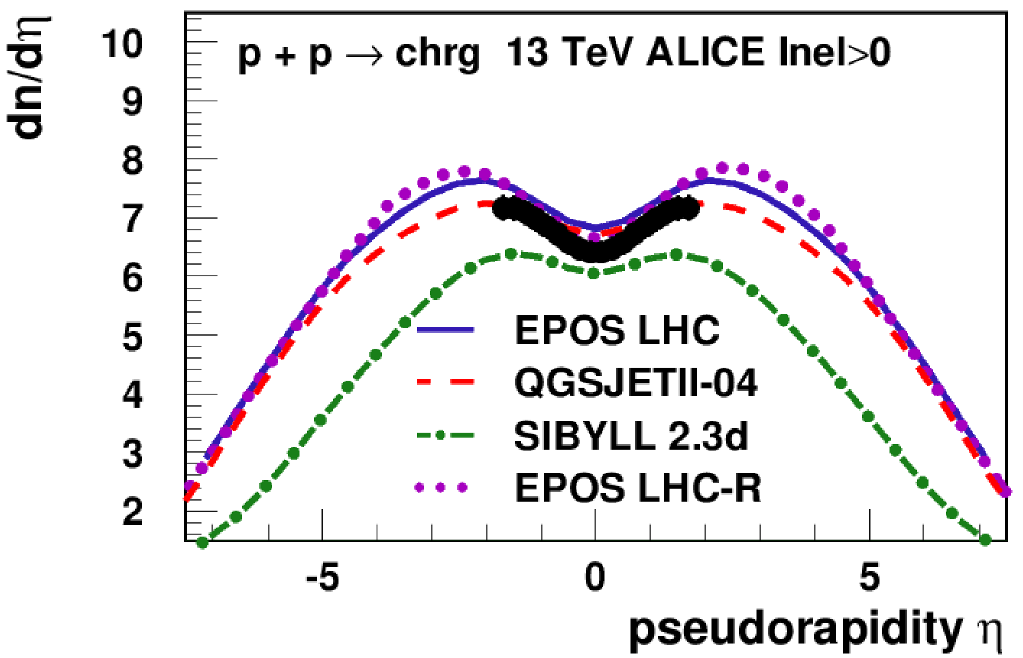


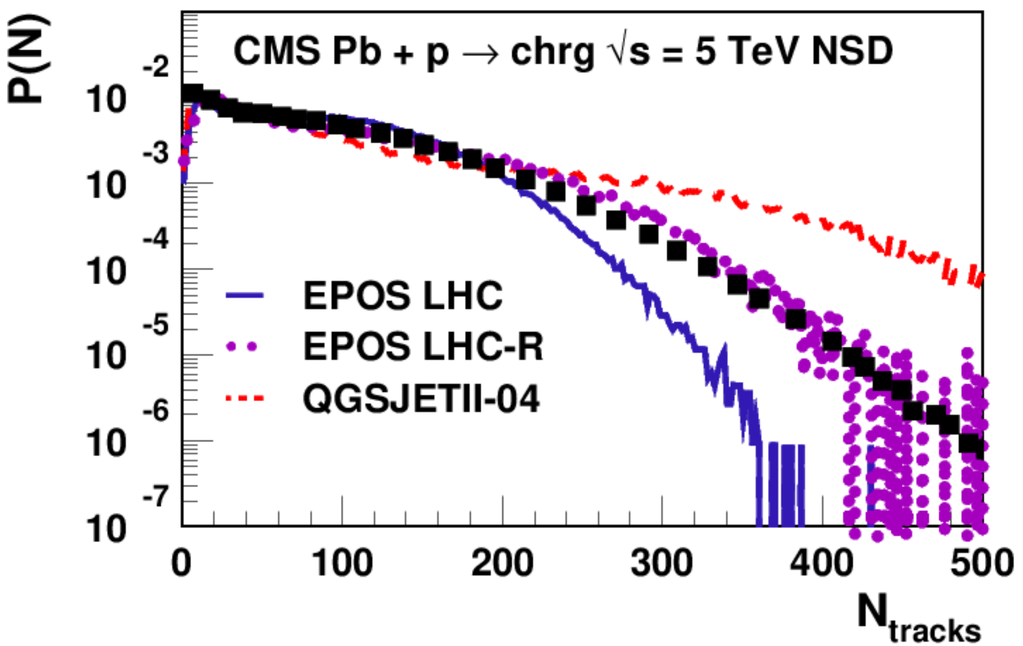




Pseudorapidity

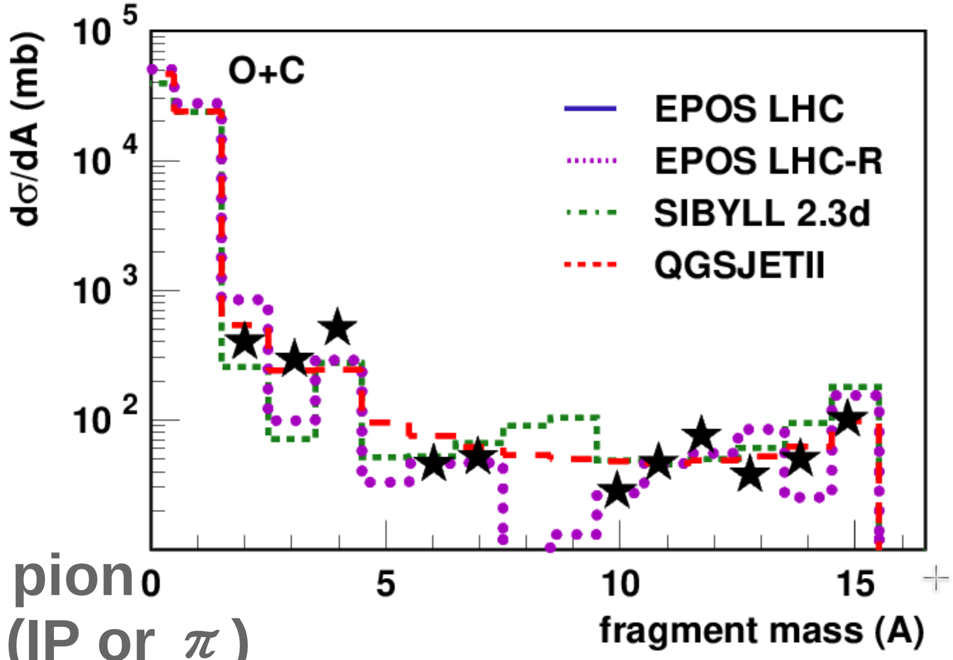
- **Angular distribution of newly produced particles**
- **New data at 13 TeV in p-p**
  - ➡ Test extrapolation with different triggers
  - ➡ Sibyll has a clear difference with other models (and data) : too narrow !
- **Detailed data at 5 TeV for p-Pb**
  - ➡ Wrong multiplicity distributions in all models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



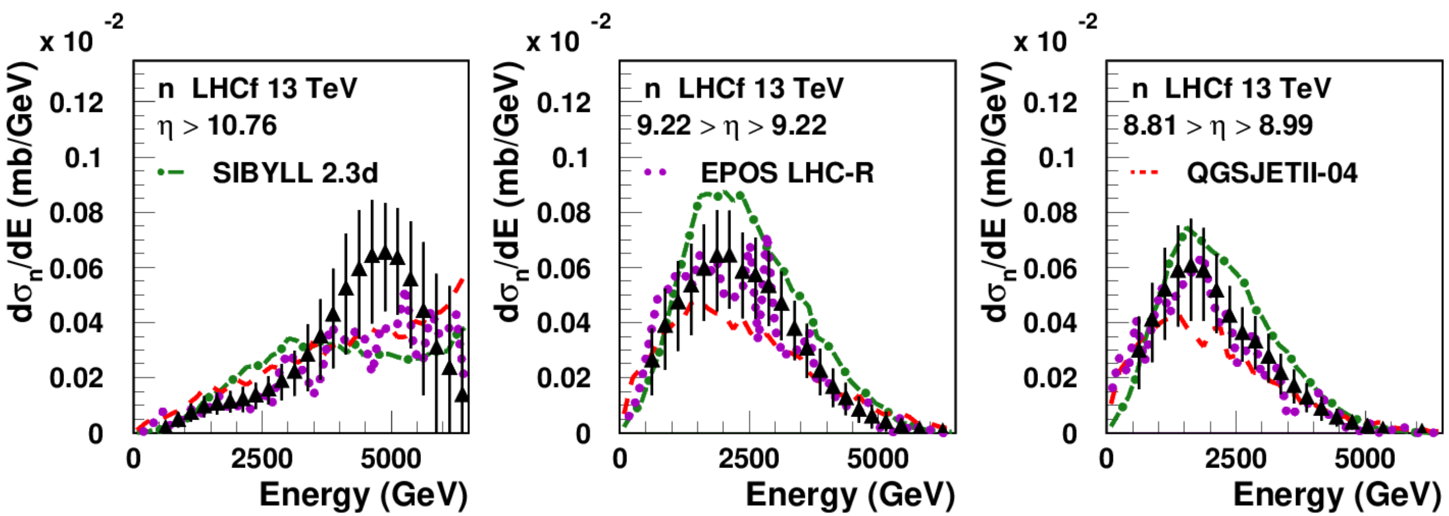


Improvements in EPOS LHC-R

- 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

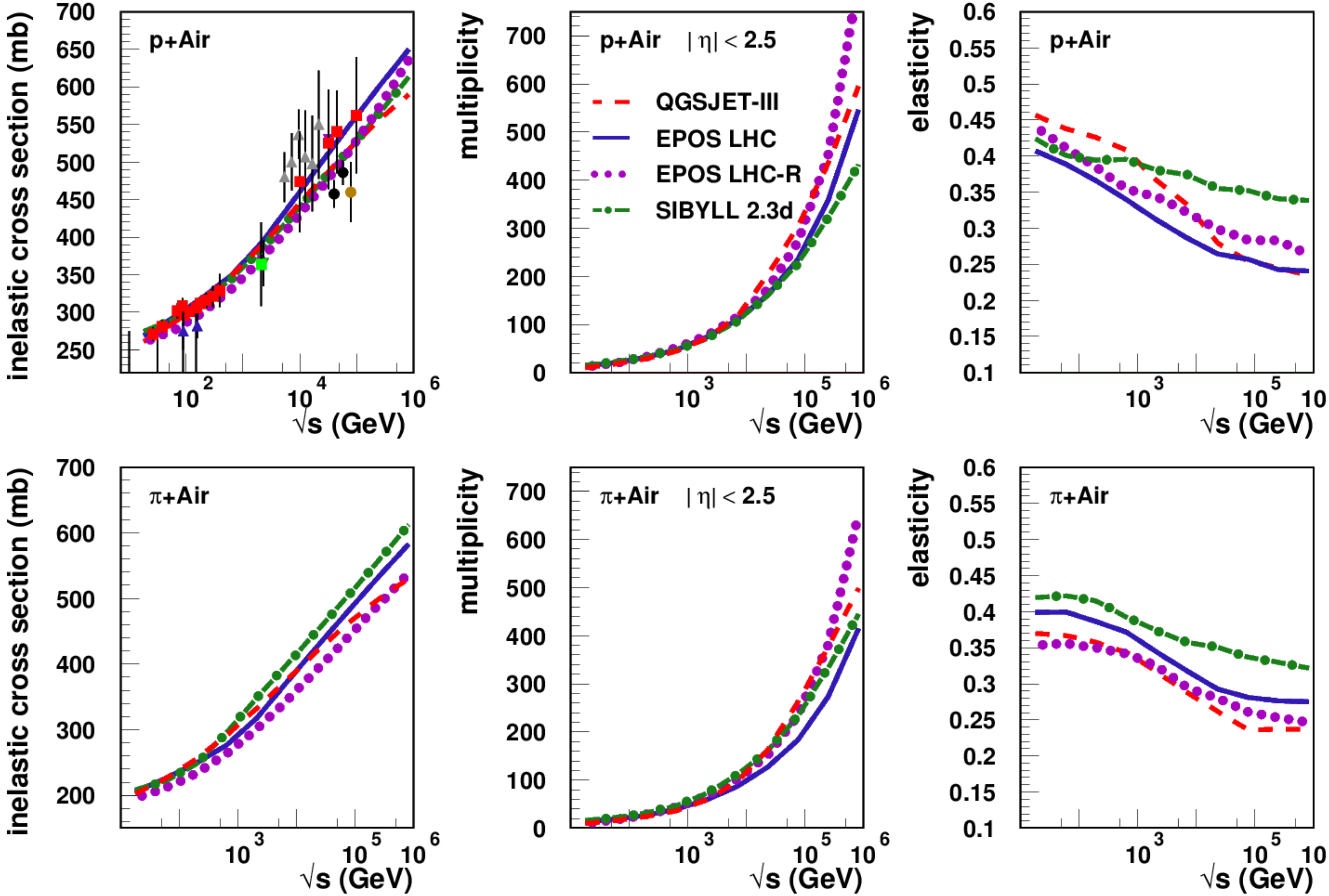


- Simplified high mass diffraction and pion exchange replaced by real emission (IP or π)

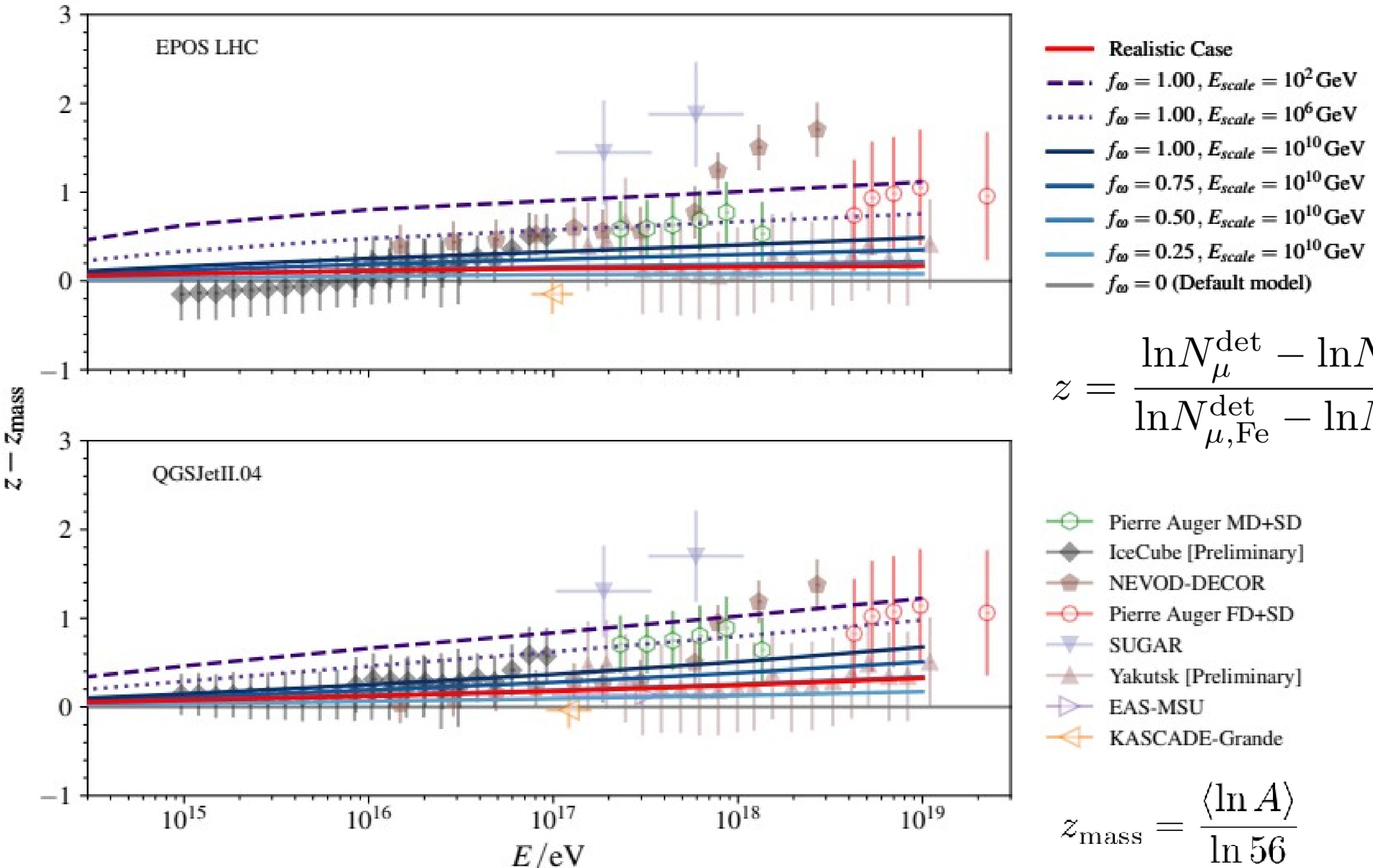


EPOS LHC-R interaction with Air

(preliminary)



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

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

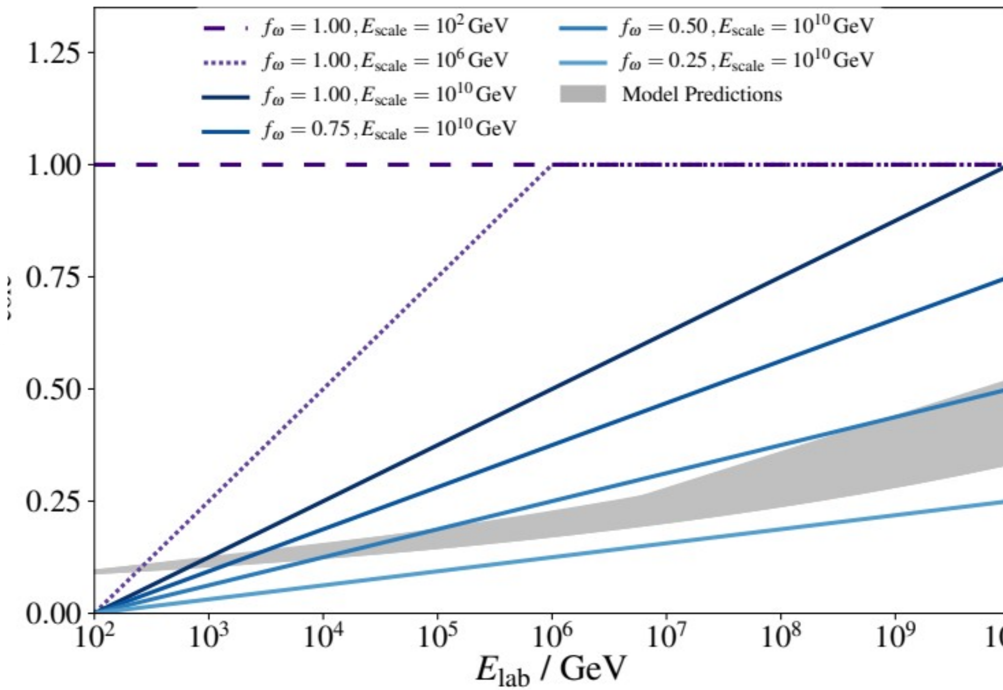
- Particle ratios from statistical model are known (tuned to PbPb) and fixed : core
- Initial particle ratios given by individual hadronic interaction models : corona
- Using CONEX, EAS can be simulated mixing corona hadronization with an arbitrary fraction ω_{core} of core hadronization: $N_i = \omega_{\mathrm{core}}\,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

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

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

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

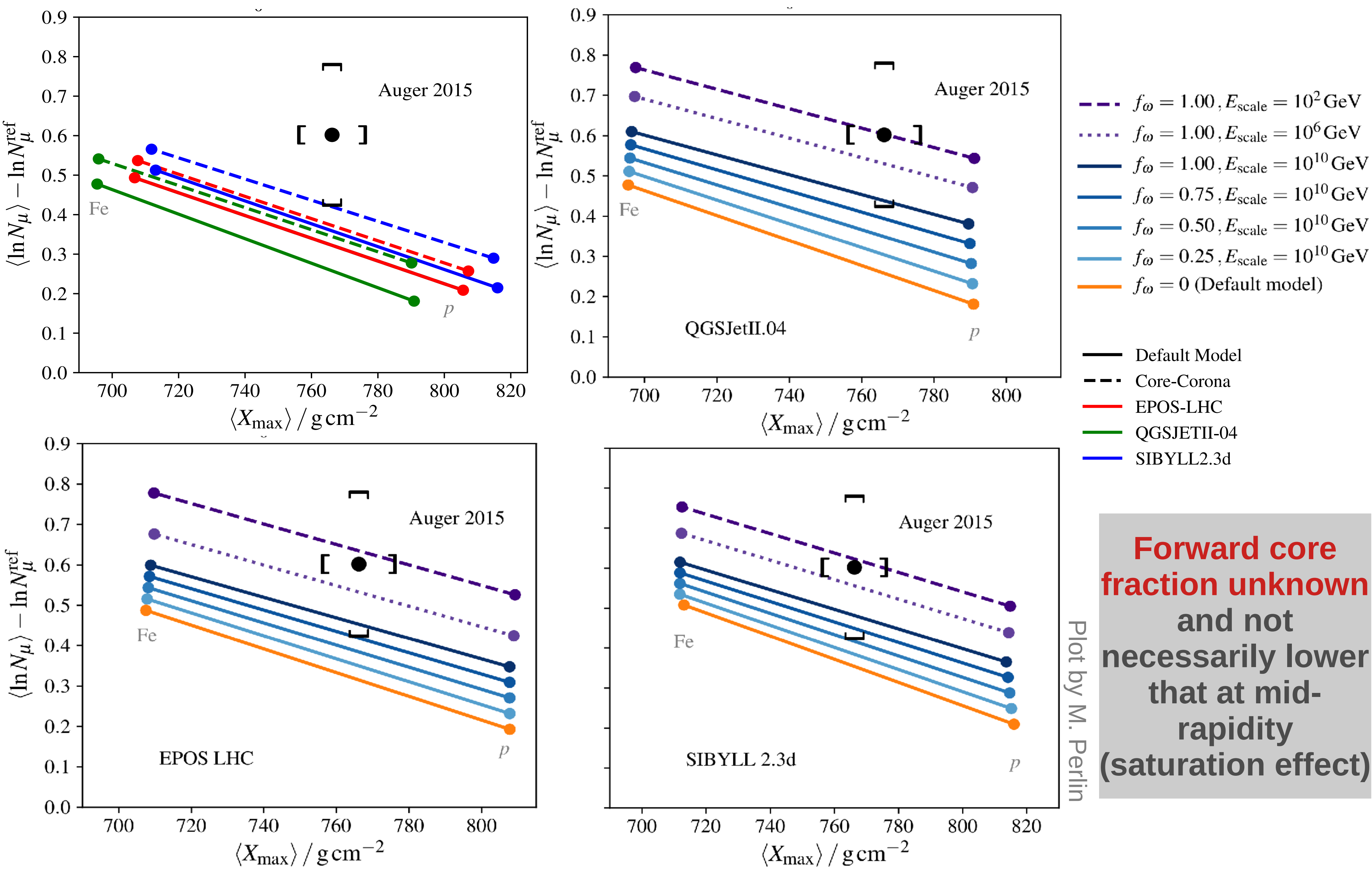
Note : the leading particle is NOT modified (projectile remnant)



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

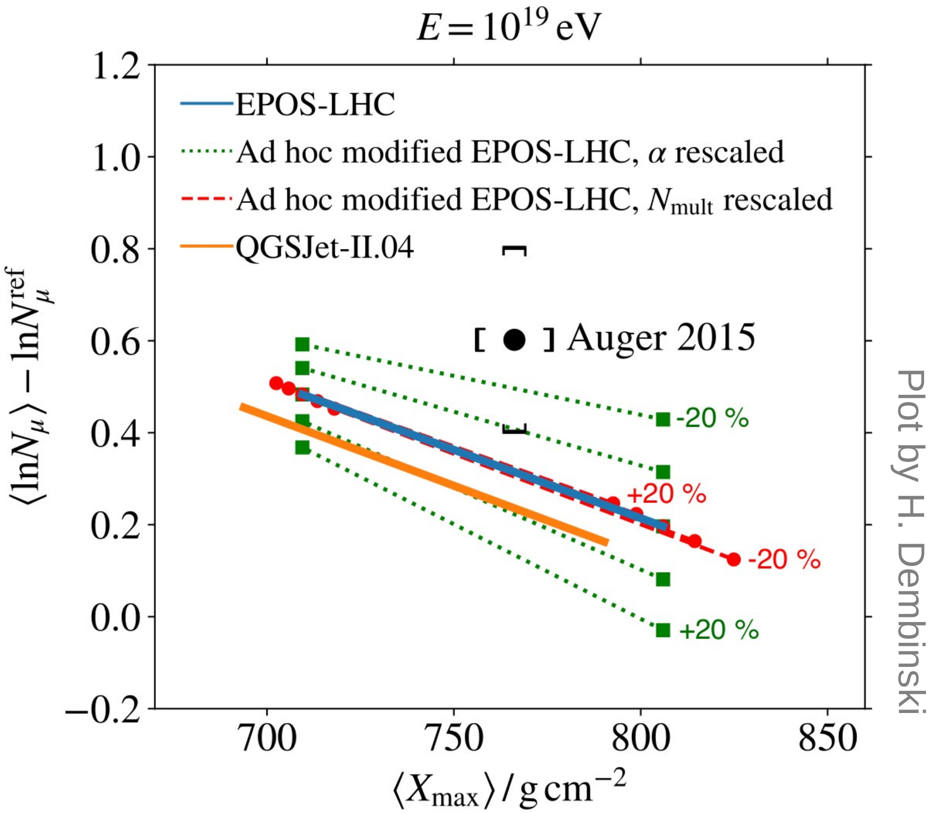
- **One needs to change energy dependence of muon production by ~+4%**

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

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

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

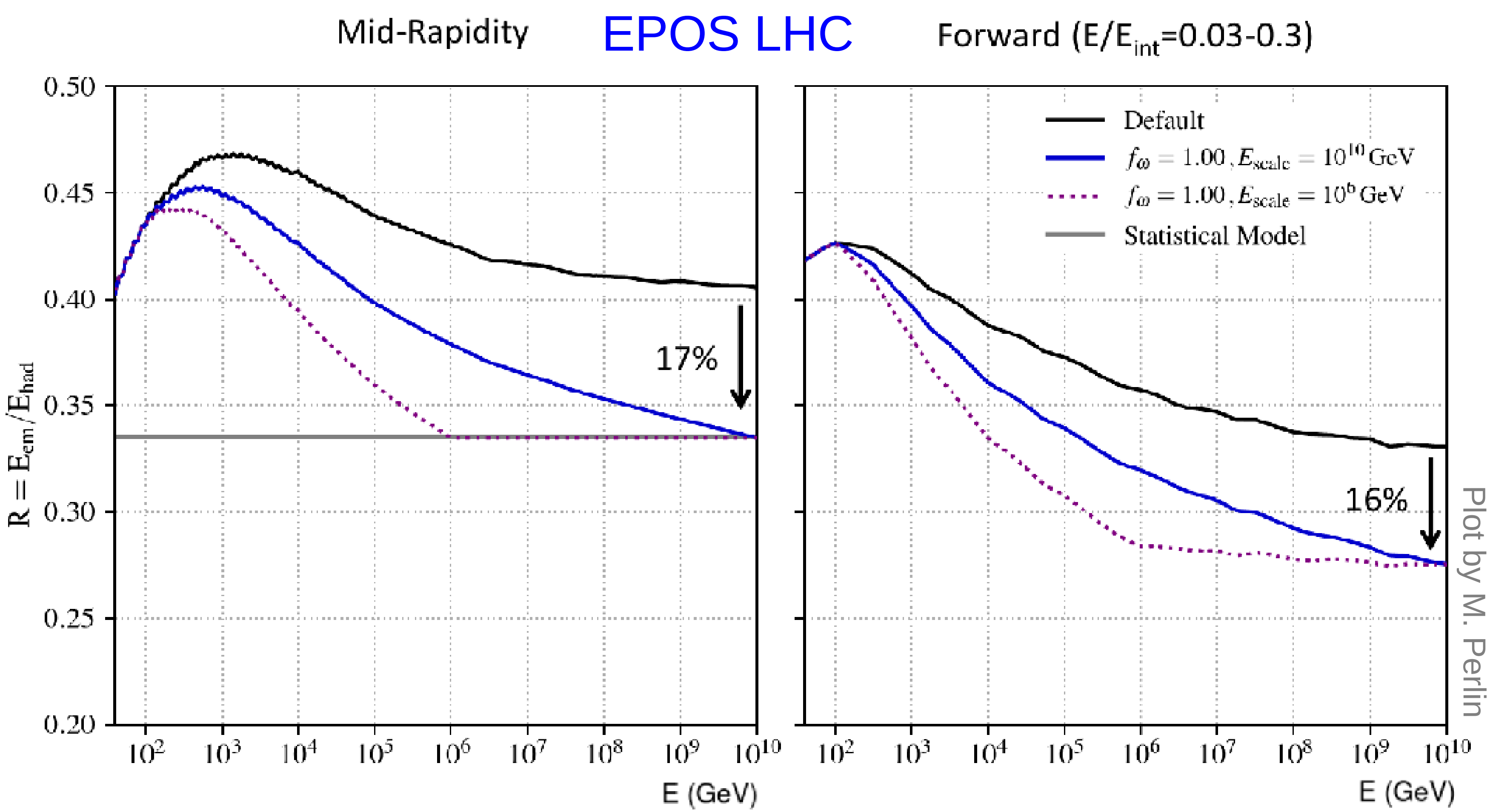


Evolution of hadronization from core to corona

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

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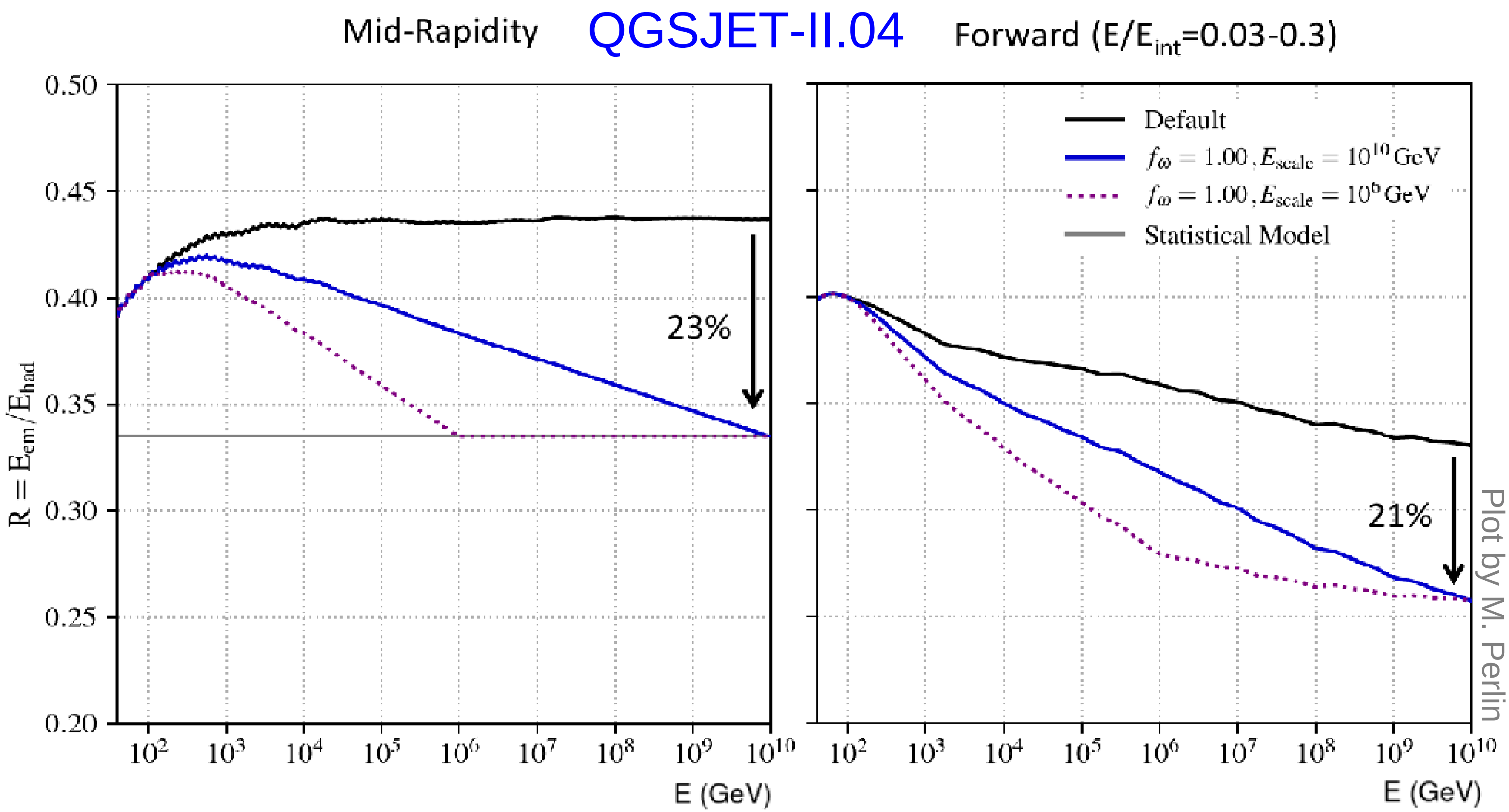

Evolution of hadronization from core to corona

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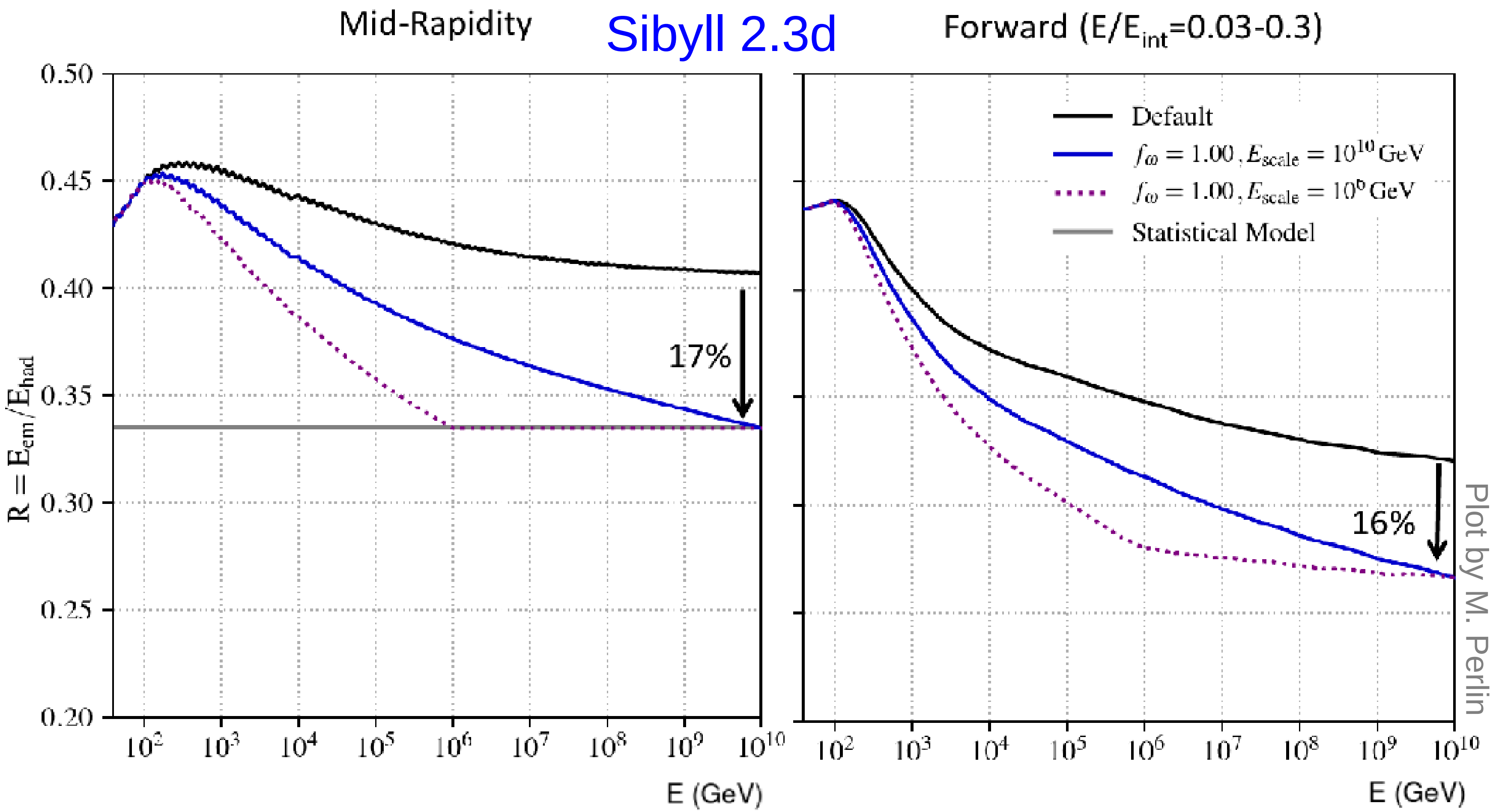
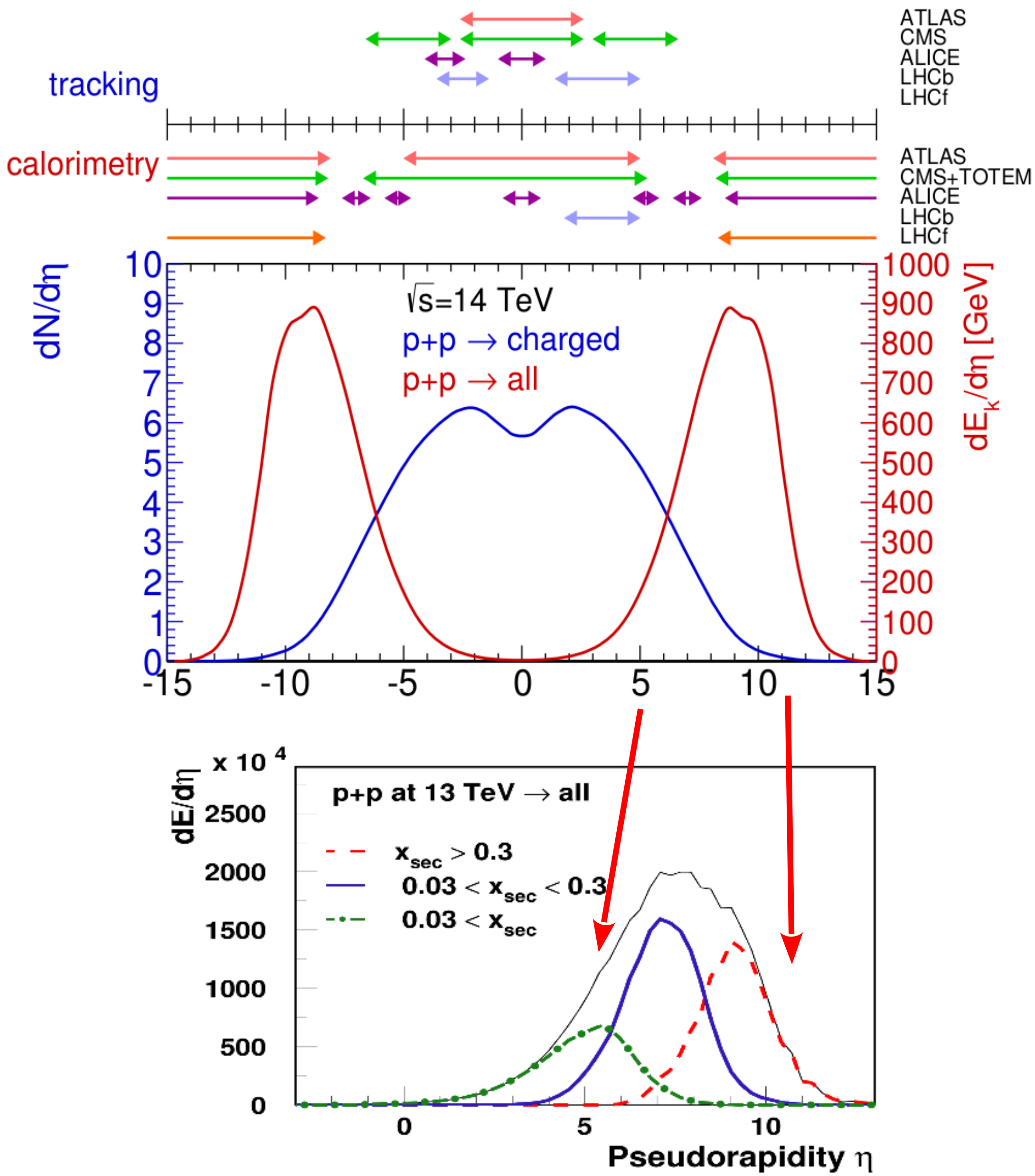


Possible Particle Physics Explanations

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

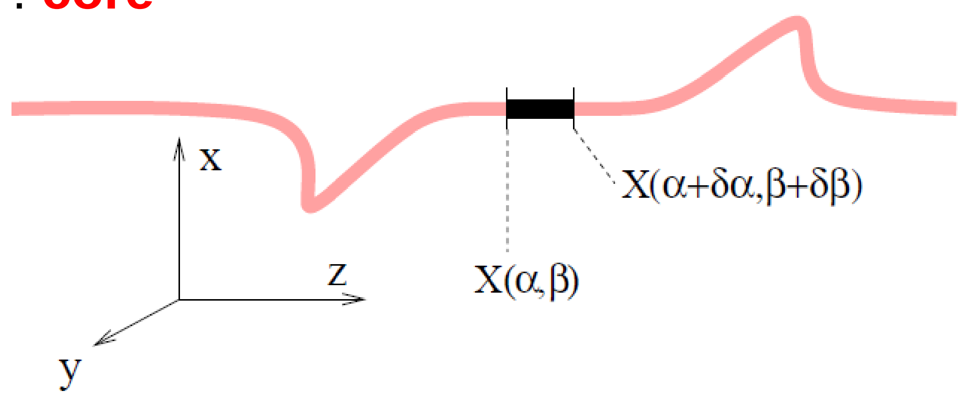


- **p-p data mainly from "central" detectors**
  - ➡ pseudorapidity $\eta=-\ln(\tan(\theta/2))$
  - ➡ $\theta=0$ is midrapidity
  - ➡ $\theta>>1$ is forward
  - ➡ $\theta<<1$ is backward
- **Different phase space for LHC and air showers**
  - ➡ most of the particles produced at midrapidity
    - important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

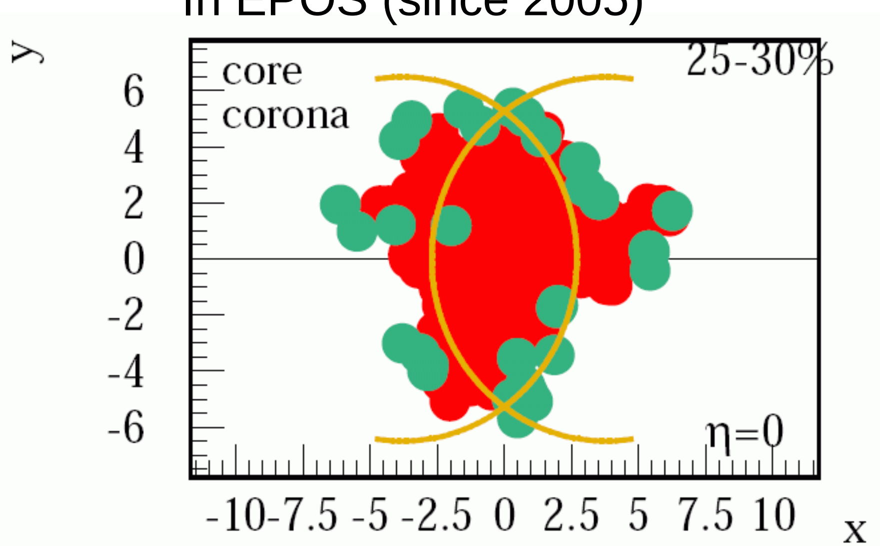
A 3rd way : the core-corona approach

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