Towards solving the muon problem in air showers :
A global approach from Heavy Ions to Cosmic Rays

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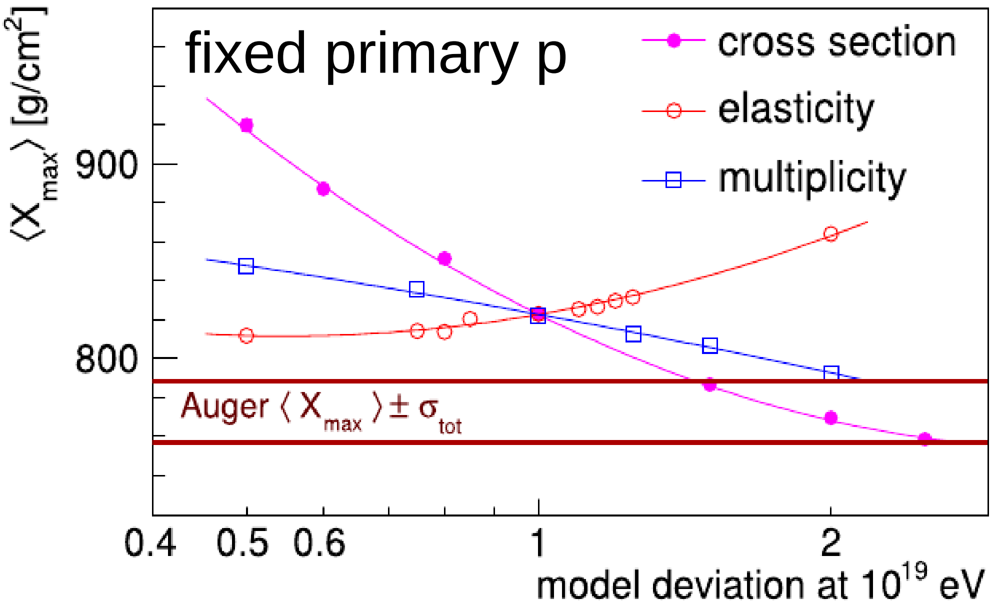
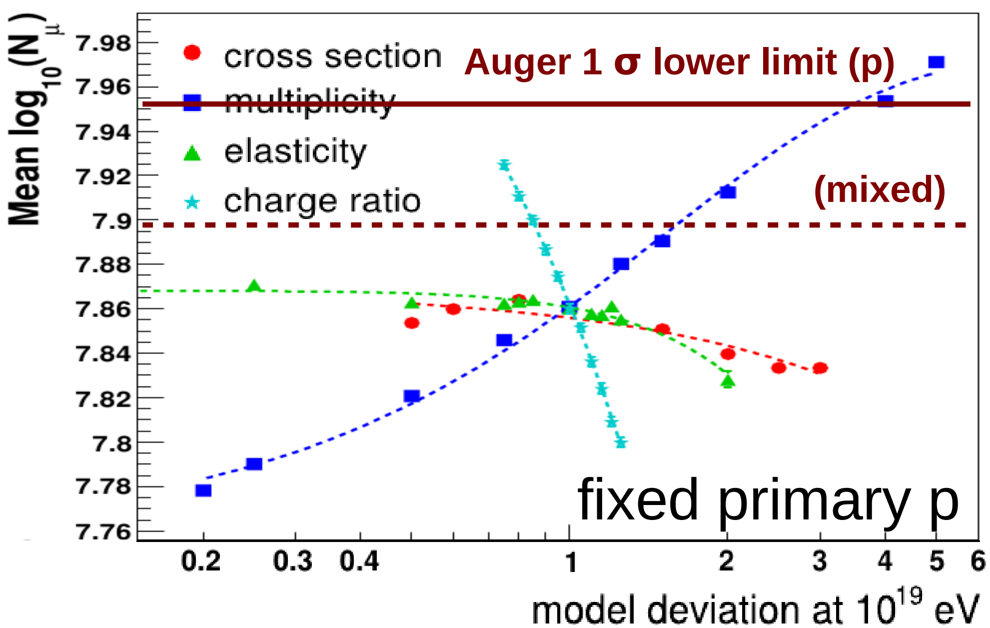
Outline

- **Introduction**
- **A 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)

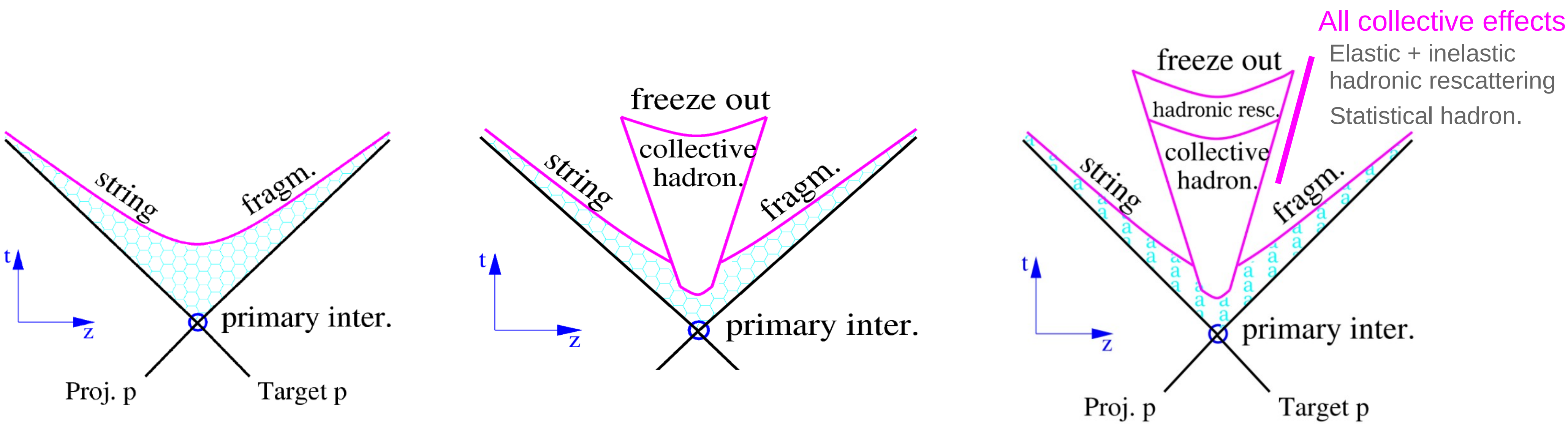
- **Air shower development dominated by few parameters**
  - ➔ mass and energy of primary CR
  - ➔ cross-sections (p-Air and (π-K)-Air)
  - ➔ (in)elasticity
  - ➔ multiplicity
  - ➔ charge ratio and baryon production
- **Change of primary = change of hadronic interaction parameters**
  - ➔ cross-section, elasticity, mult. …
- **Model tuned to accelerator data**

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

What means global approach ?

Global approach is the key !

- Tuning models neglecting some physics process lead to wrong parameters !
- Proper tune possible to do only if everything taken into account
  - All collective effects considered for the first time !
- Either with a direct impact on the shower development (new elasticity)
- Or no direct impact on the shower development but change model parameters… leading to different shower properties.



Sibyll, QGSJET

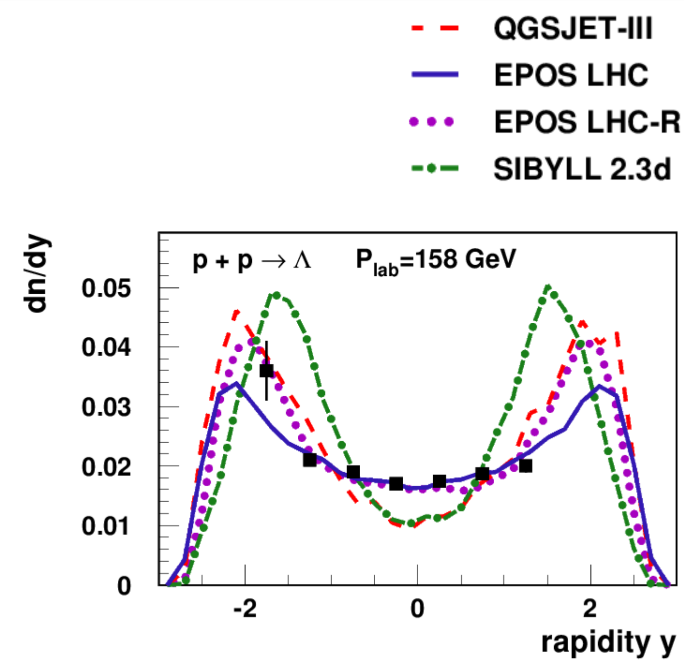
EPOS LHC
(no rescattering)

EPOS.LHC-R
(with hadronic rescattering (hs))

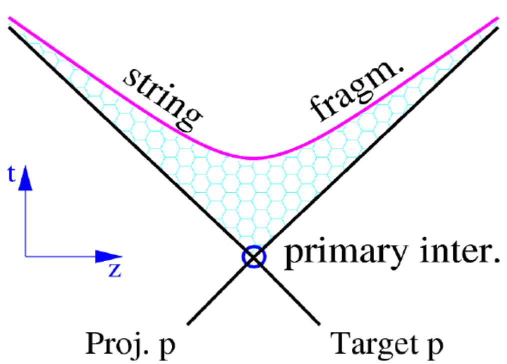
String Fragmentation

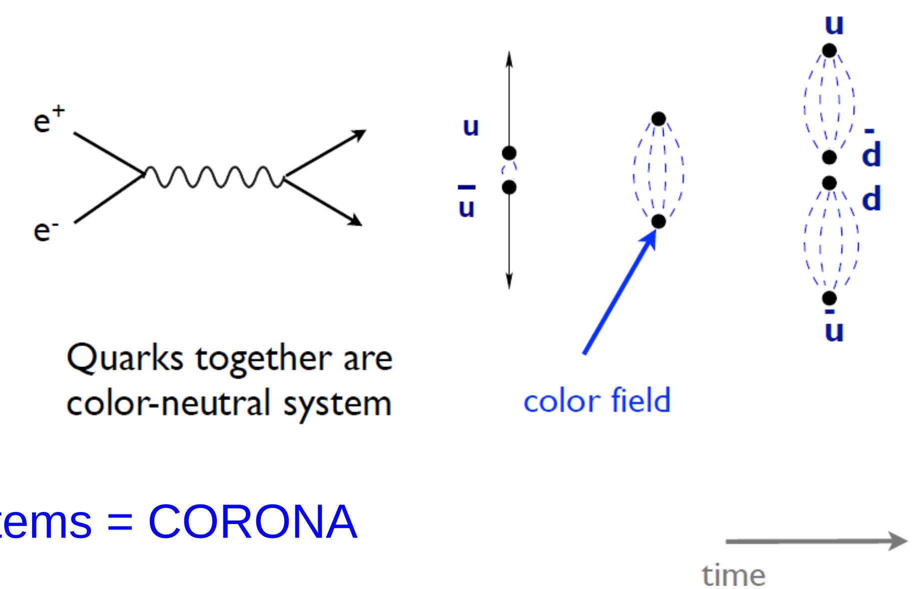
Global approach is the key !

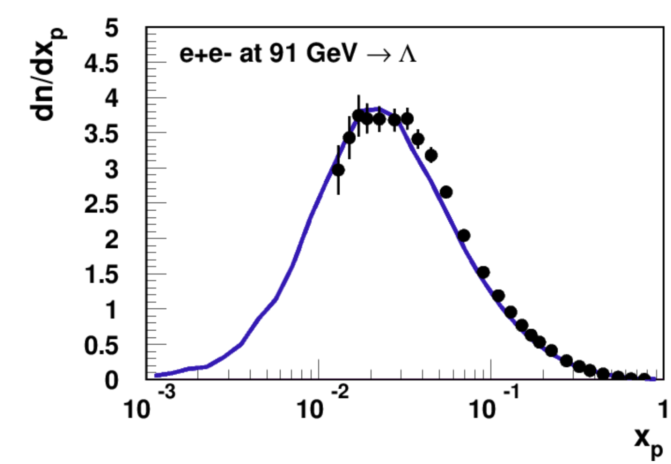
- Common hadronization in all the models
- Parameters fixed on e+-e- only in EPOS
  - Other CR models tuned on p-p data
    - "Contamination" by beam remnant
- Very important for forward particle production (EAS)
    - Used for beam remnant hadronization



Annihilation at high energy



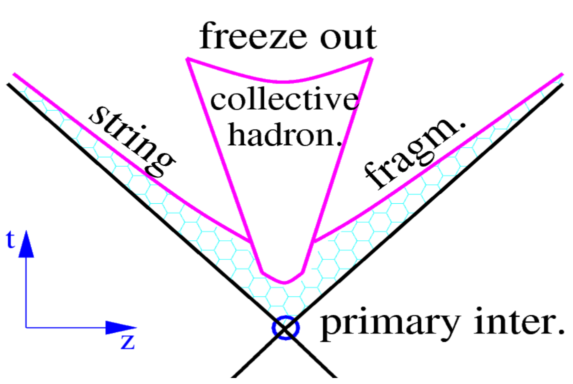




Used in dilute systems = CORONA

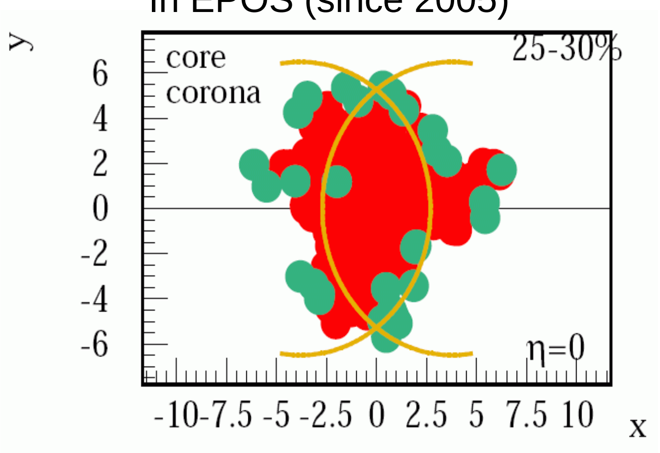
Core-Corona (co-co)

- **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**

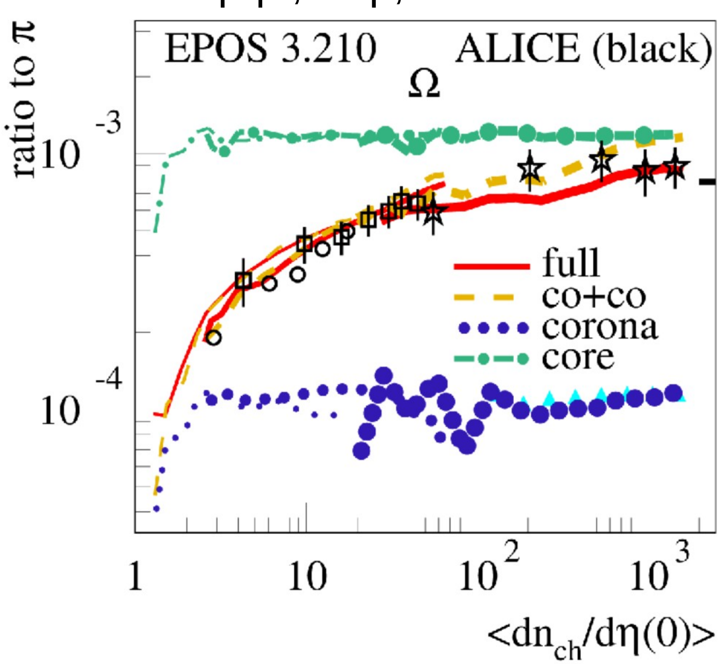


- **2 simultaneous source of particles**

In EPOS (since 2005)



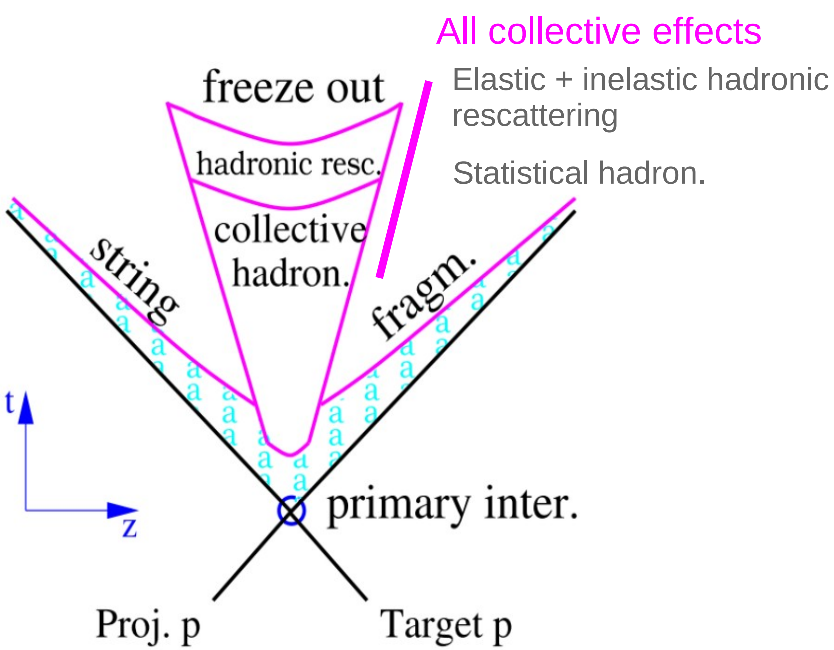
p-p ,Pb-p, Pb-Pb data

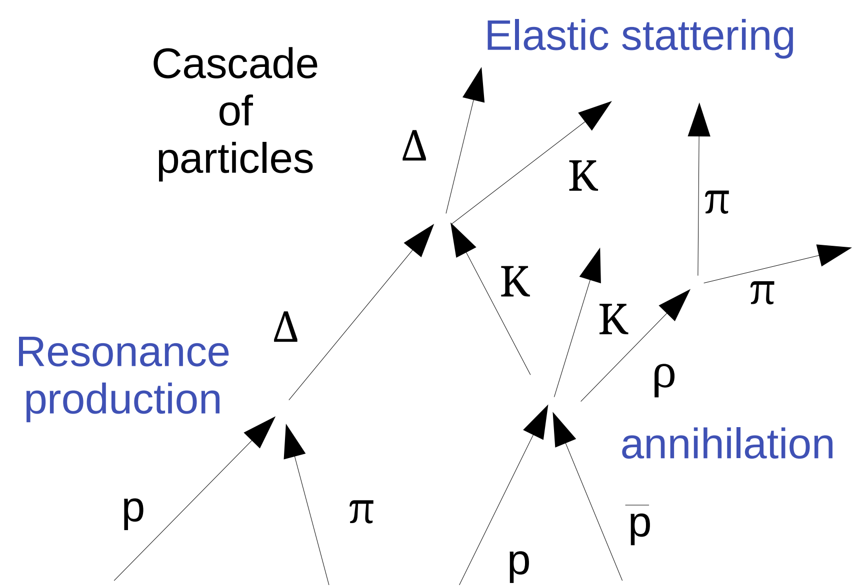


Hadronic Rescattering (HS)

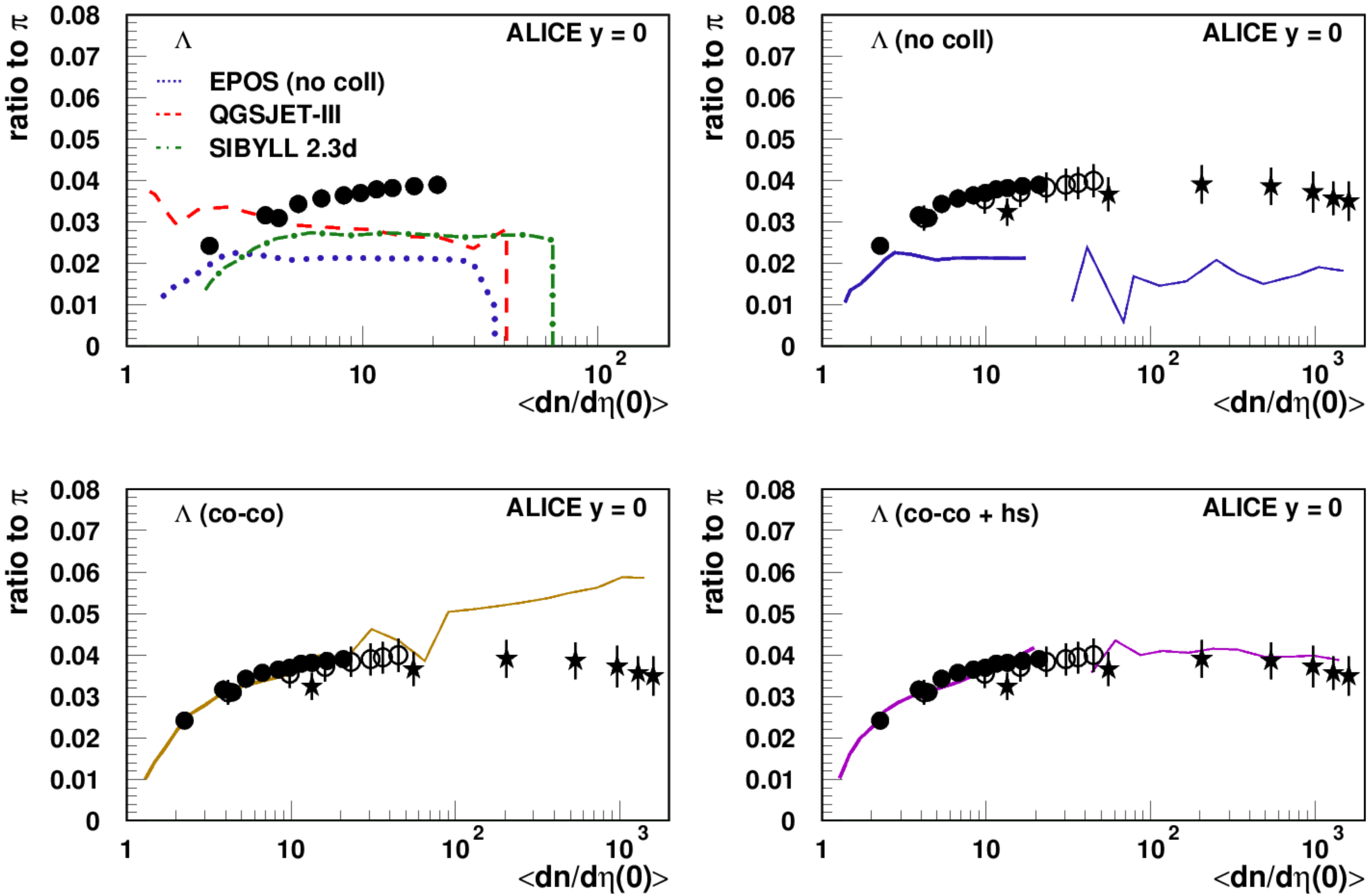
Missing effect in all CR models until now !

- 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 !
  - Applied to all system (from e+-e- to PbPb) !

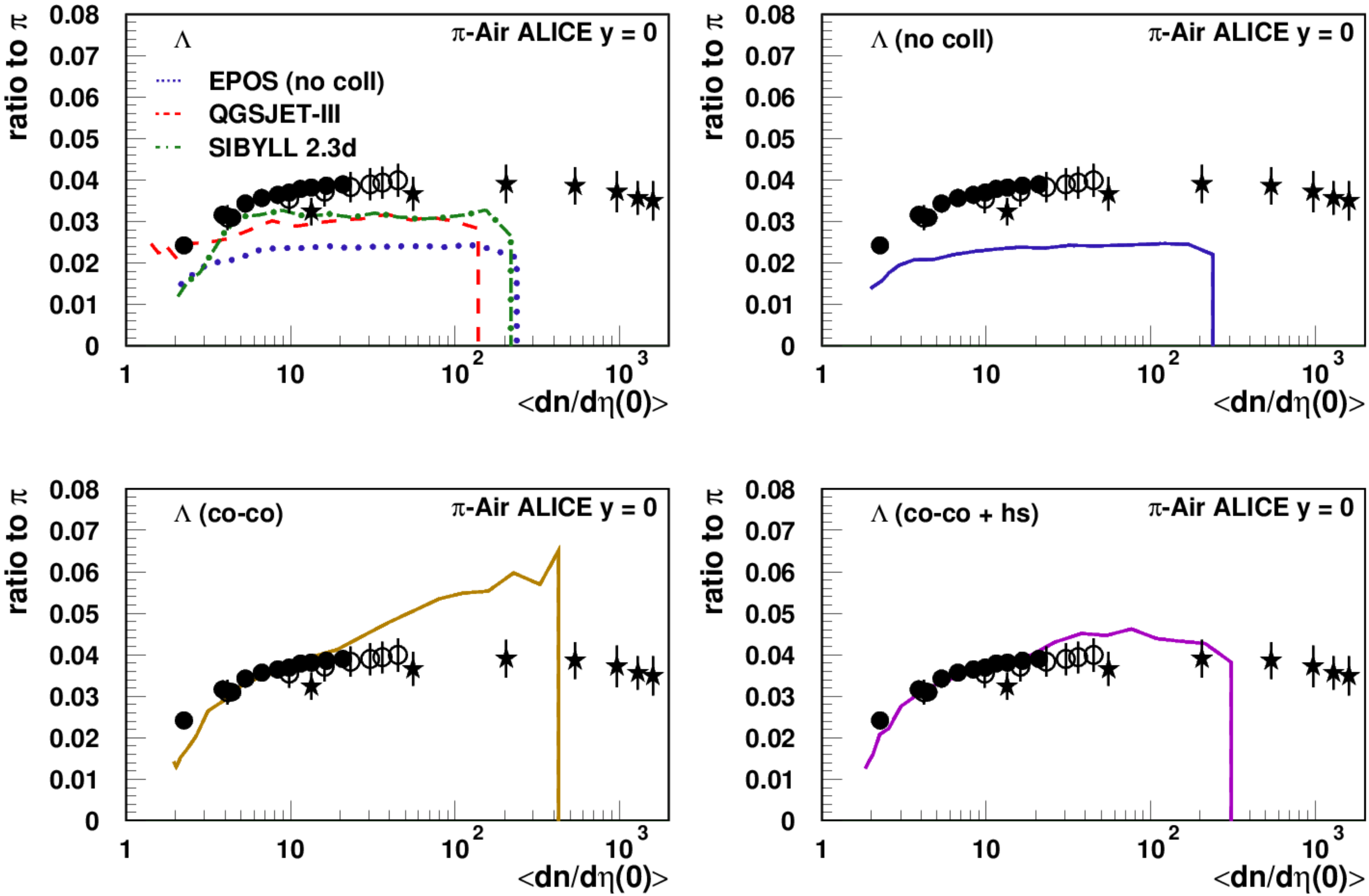




Example with Lambda particle in p-p and Pb-Pb @ LHC



Example with Lambda particle in π-Air @ all energies

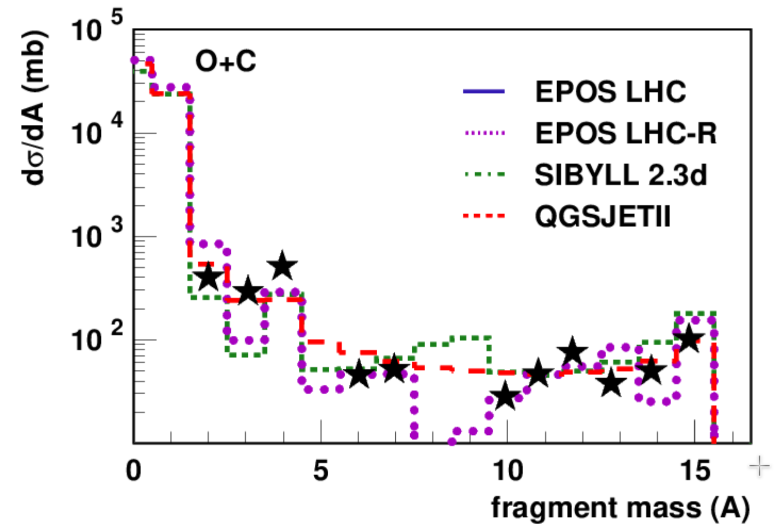


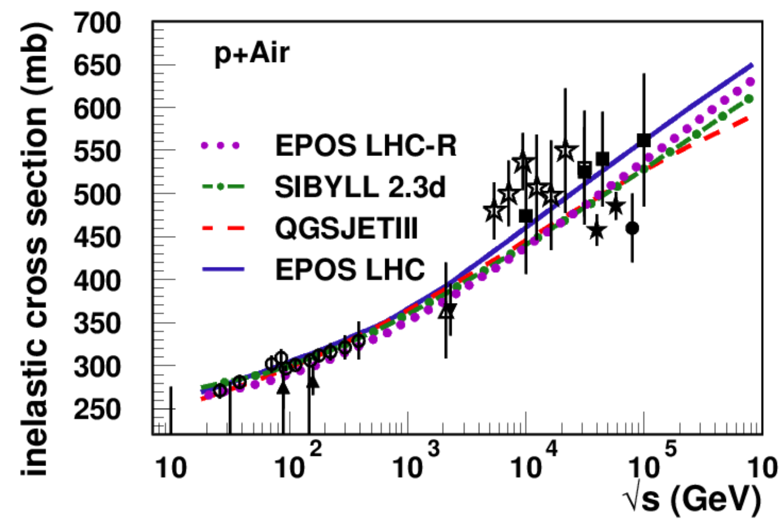
Other improvements in EPOS.LHC-R

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
- Lower cross-sections
- Indirect impact of core-corona (multiplicity) and hadronic rescattering (shape in pseudorapidity)
  - Higher elasticity due to smaller light cone momenta

→ X_{max} deeper

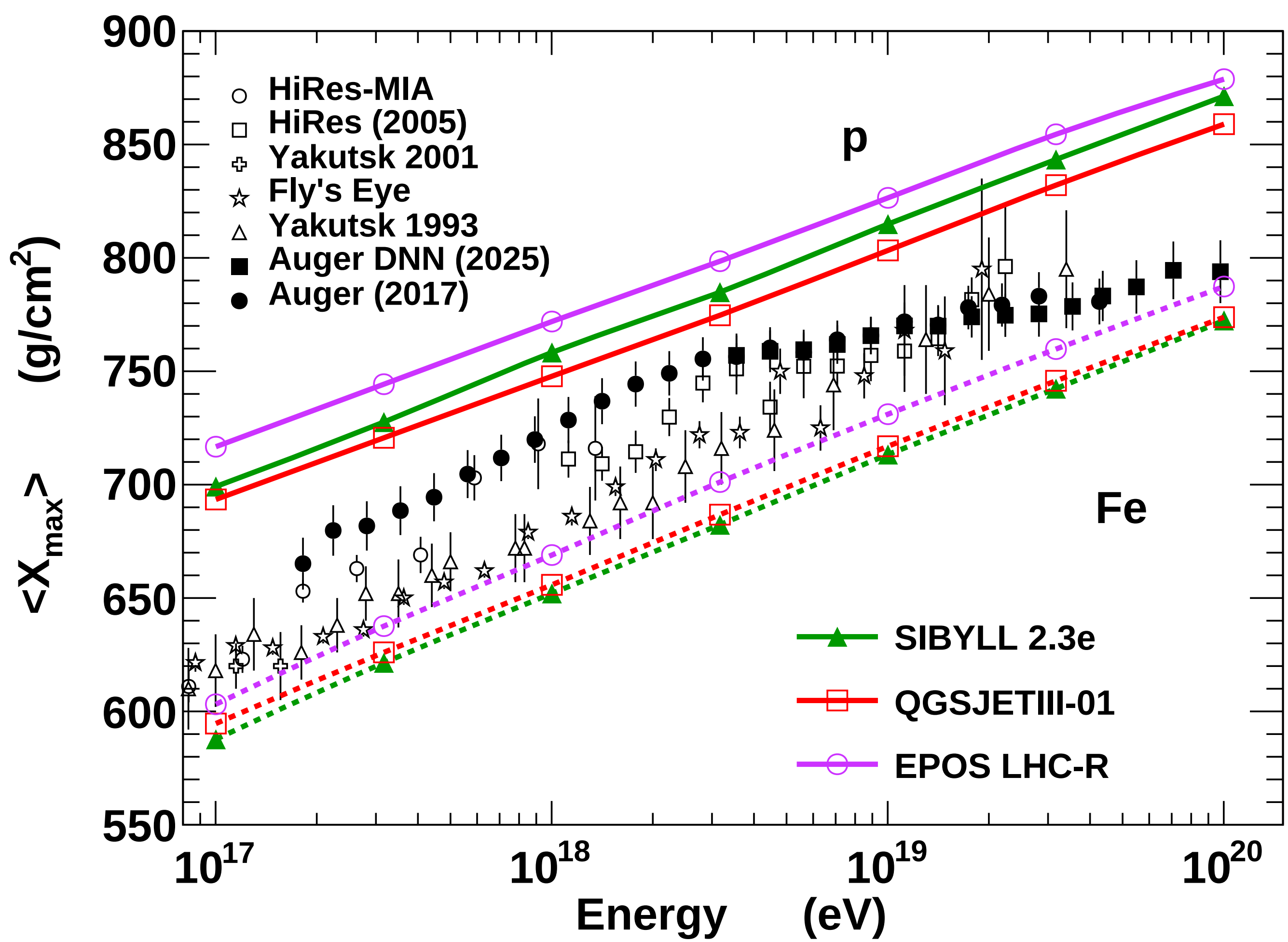




X_{max}

Global changes

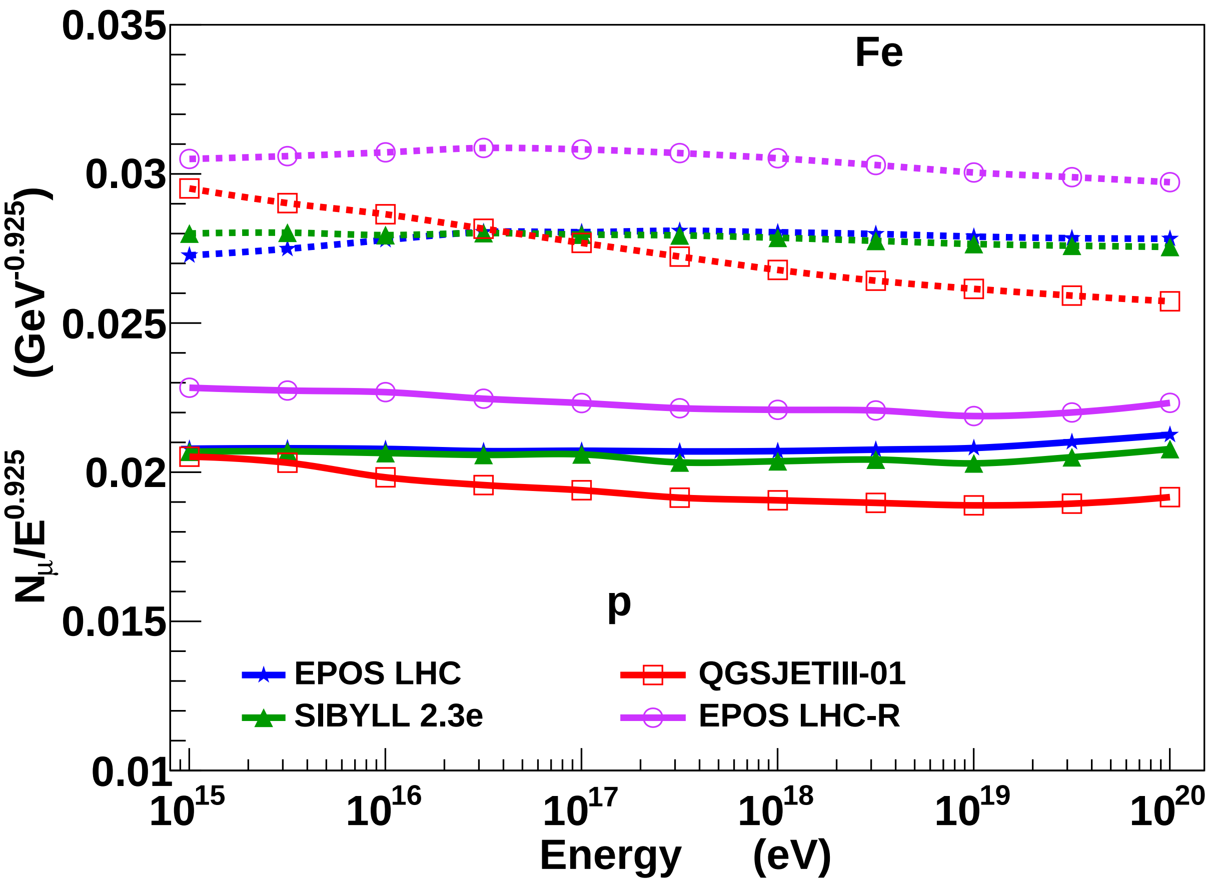
- Taking into account new data, new EPOS shifted by +20g/cm² (+/- 5g/cm²)
- QGSJETIII-01 shifted by +15g/cm² (=EPOS LHC)

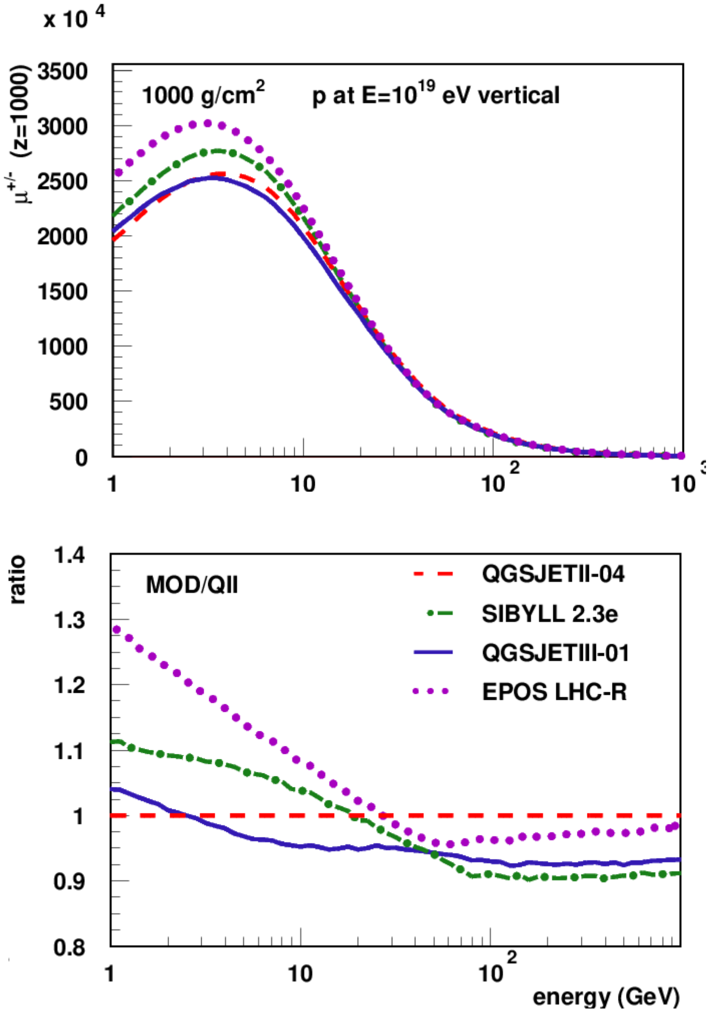


N_μ

Global changes

- Consequence of retuning, now EPOS shifted by +20 to 30 g/cm²
- Increase of the total number of muons by about 10% (+/- 5%) for EPOS.LHC-R
- Change in muon spectrum !



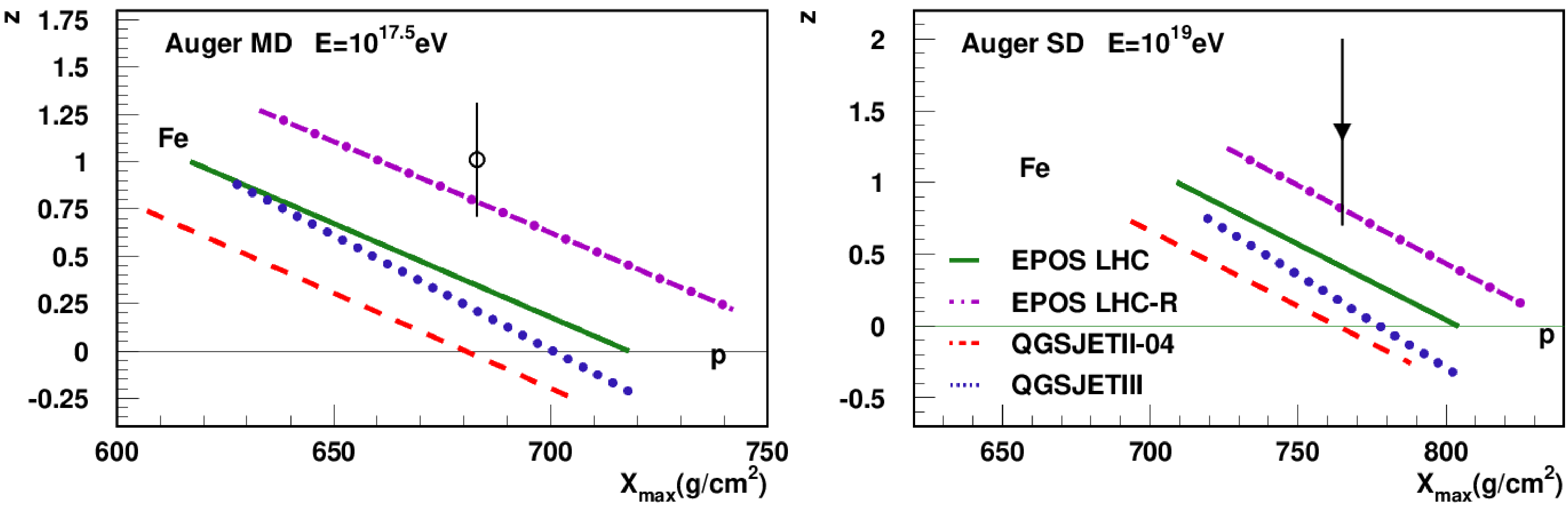


Muon Puzzle Solved ?

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

- Deeper X_{max} give larger <lnA> reducing the gap with measured muon content
- Increase of muons further decrease the gap to reach Auger systematics
- No big change for QGSJETIII
  - Impact at low energy ???

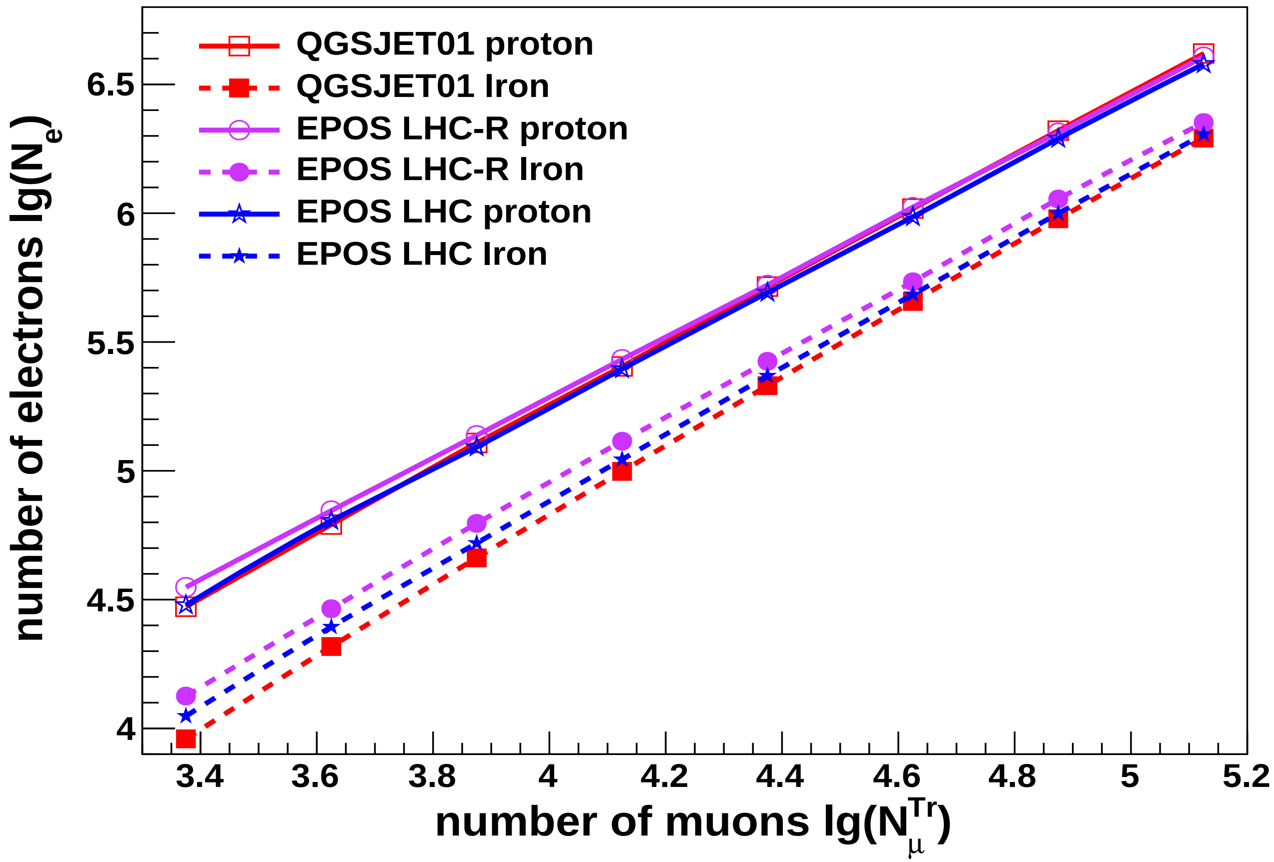
$$z = \frac{\ln N_{\mu}^{\rm det} - \ln N_{\mu,p}^{\rm det}}{\ln N_{\mu,{\rm Fe}}^{\rm det} - \ln N_{\mu,p}^{\rm det}}$$



KASCADE/LHAASO

Correlation between N_e and N_μ

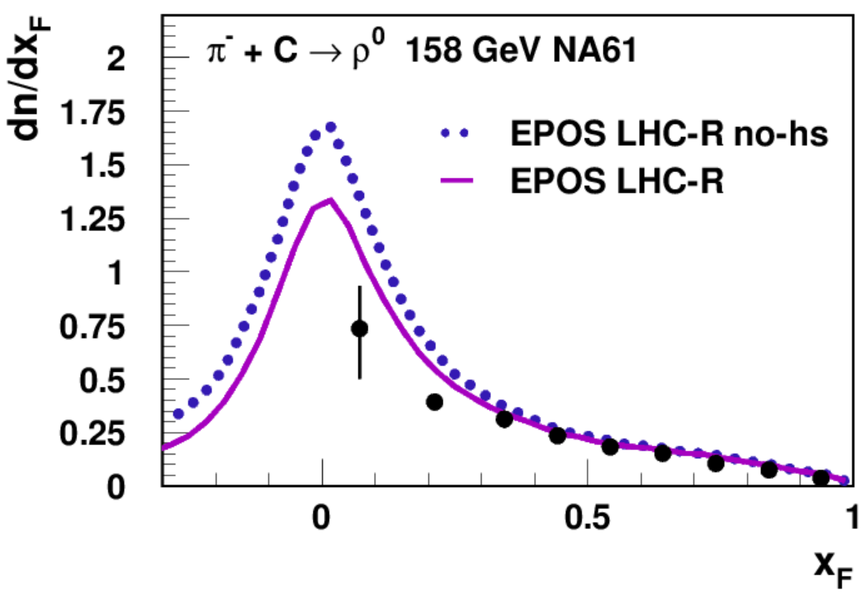
- Deeper shower development = larger Ne → compensate larger N_μ
- Very similar correlation compared to previous model
- But probably lower energy scale and larger predicted mass !

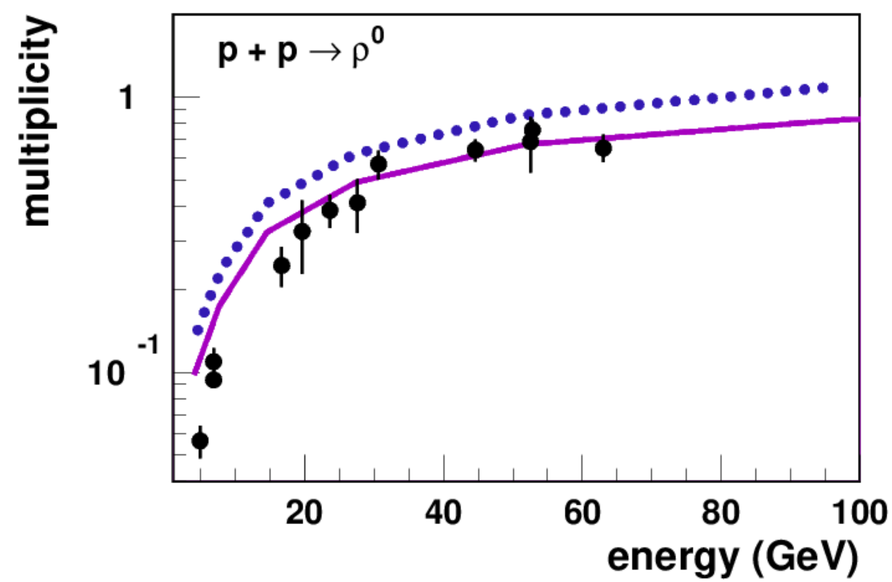


Why ?

Collective effects are 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 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 for mid-rapidity data
    - All models until now !

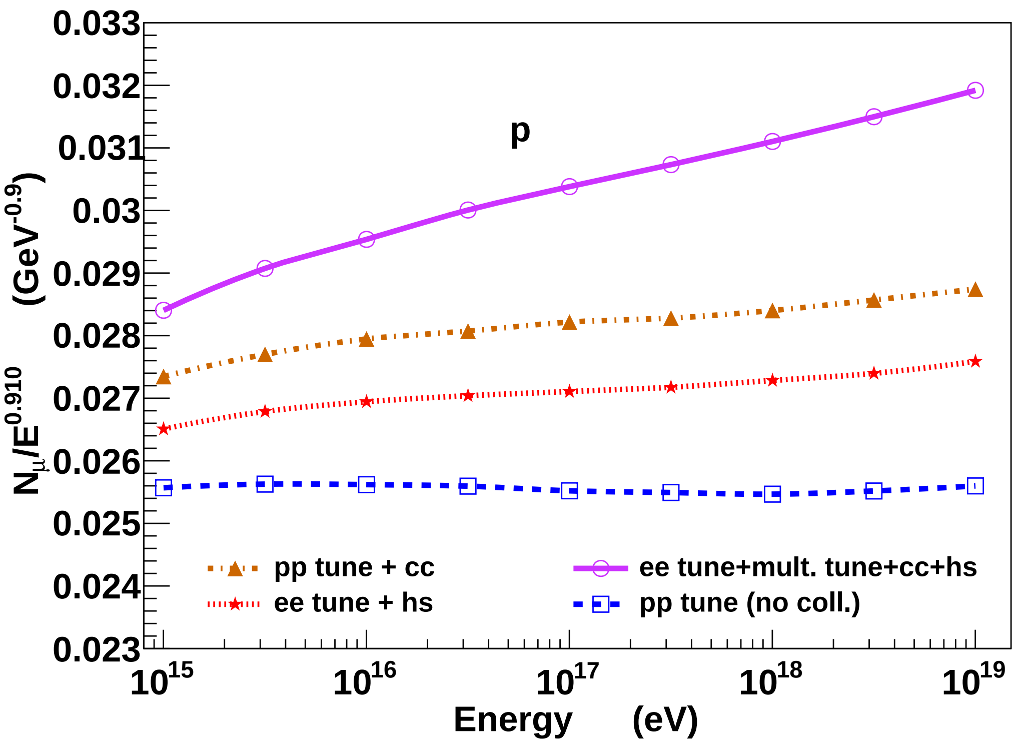


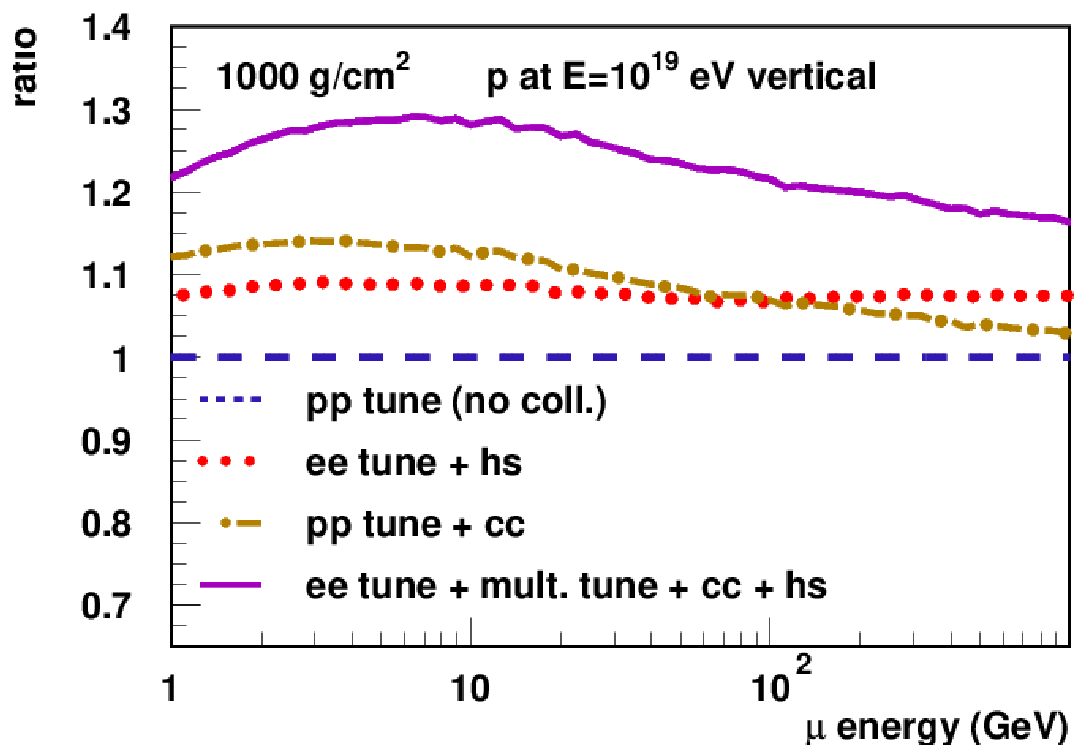


Source of differences

Changes with new tune taking into account collective effects (LHC)

- Increase the number of muons by ... 10 to 20% (different slope) !
  - Impact of core-corona on baryon/strangeness prod. AND change in multiplicity/elasticity to accommodate hydrodynamical evolution (flow)
  - Impact of tune based on full LEP data with hs instead of just p-p/p-A
- Change in muon energy spectrum !
  - More baryon from core-corona (low energy μ) and more ρ^0 (all μ)





Outlook

- **Updated results of cross-sections, multiplicity and diffraction using a global approach in EPOS LHC-R**
  - ➔ 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**
  - ➔ Hadronic rescattering change the correlation between forward and mid-rapidity !

EPOS.LHC-R and QGSJETIII-01 available in the latest CORSIKA release

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 !

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

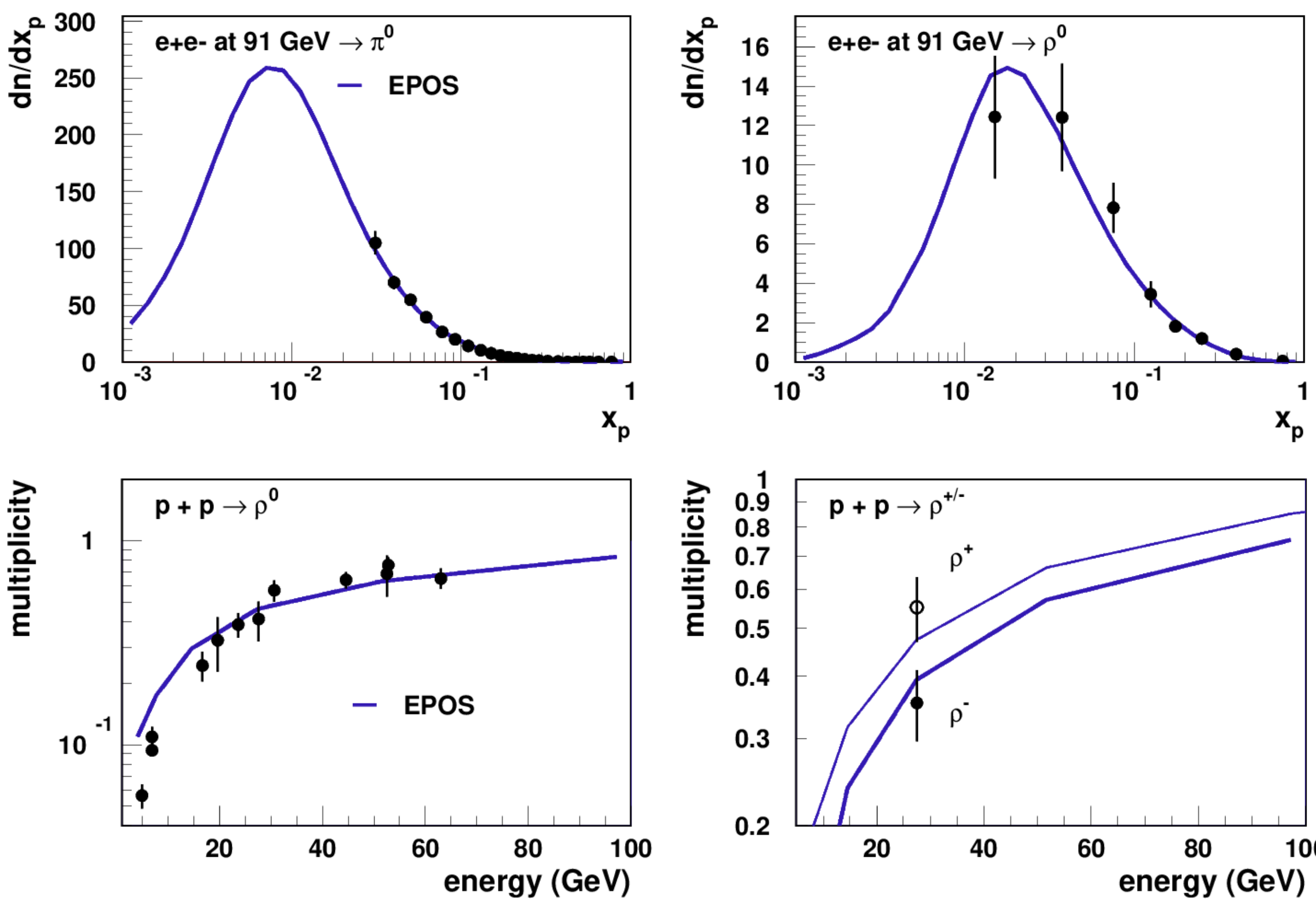
  N_{μ}

- **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 !

Generic “EPOS”

First attempt using theoretical constraints

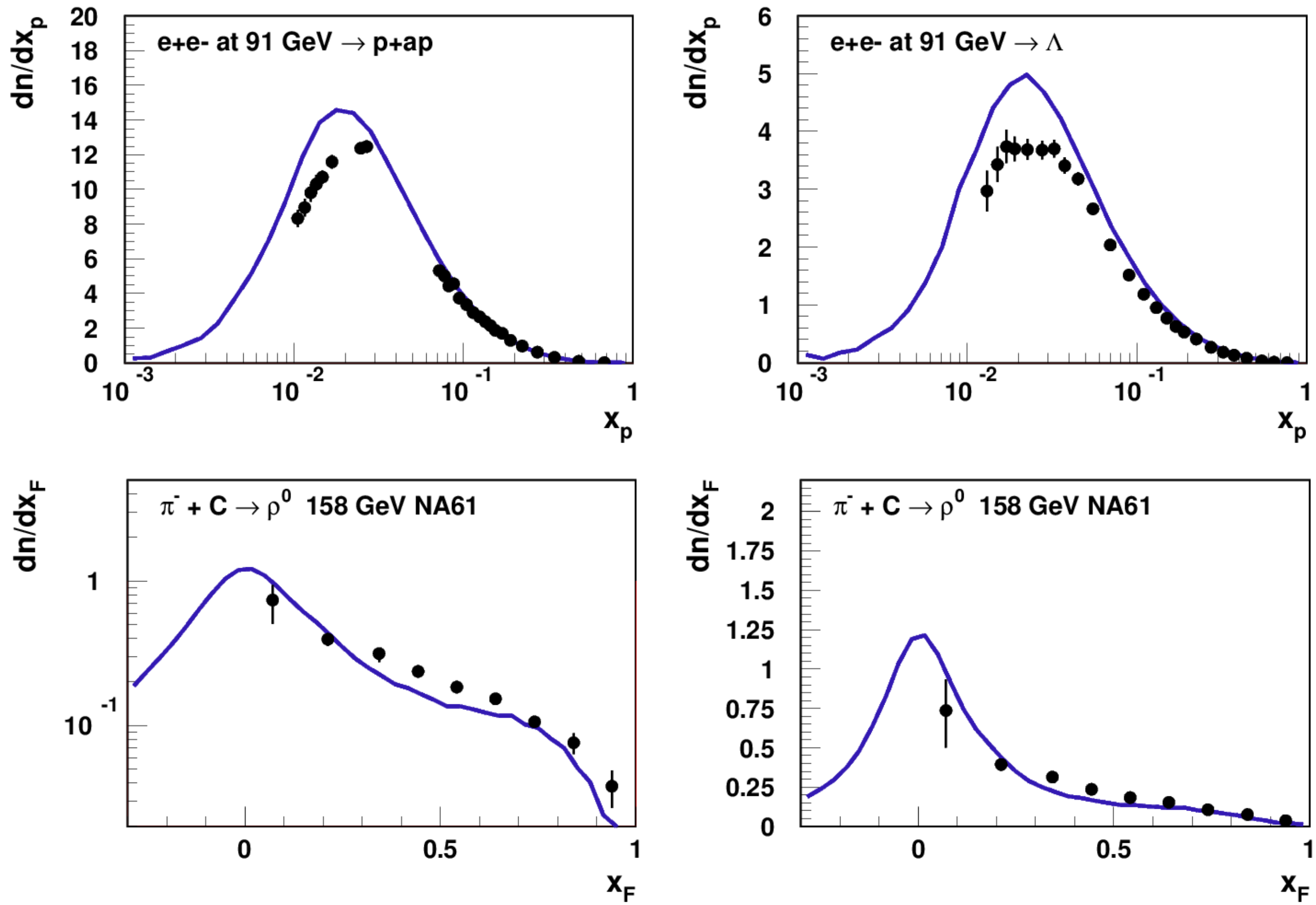
- Impose isospin symmetry (u=d) for pions, ρs and nucleons BEFORE decay
- Fix ρ^0 and multiplicity



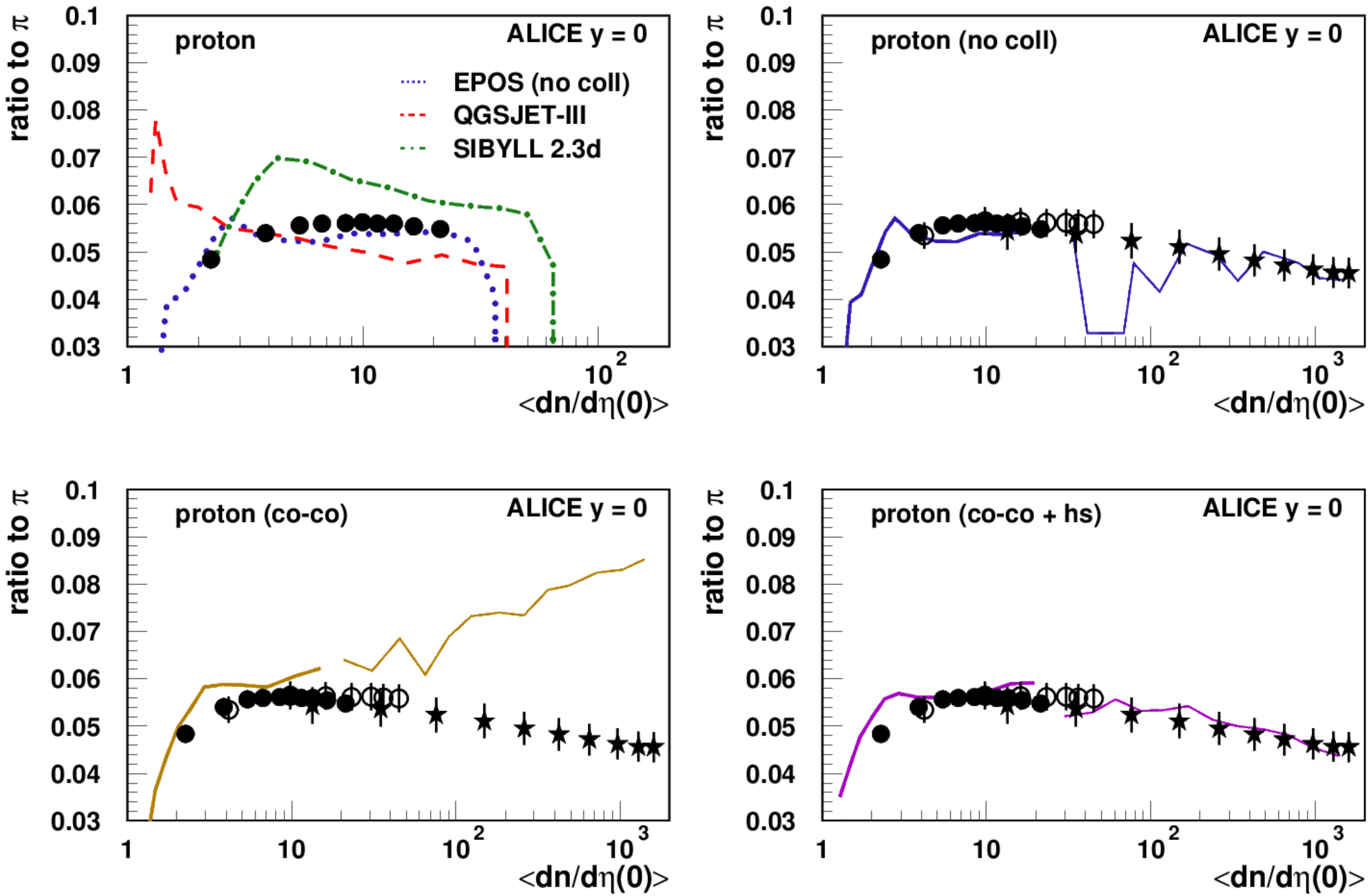
Generic CR tuning

CR models usually tuned on hadronic interactions (not LEP)

- Impose isospin symmetry (u=d) for pions, ρs and nucleons BEFORE decay
- Produce only most common particles π, ρ and η and tuned to pp data
  - LEP ~ OK but overestimate baryons and tension in h-A for ρ



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



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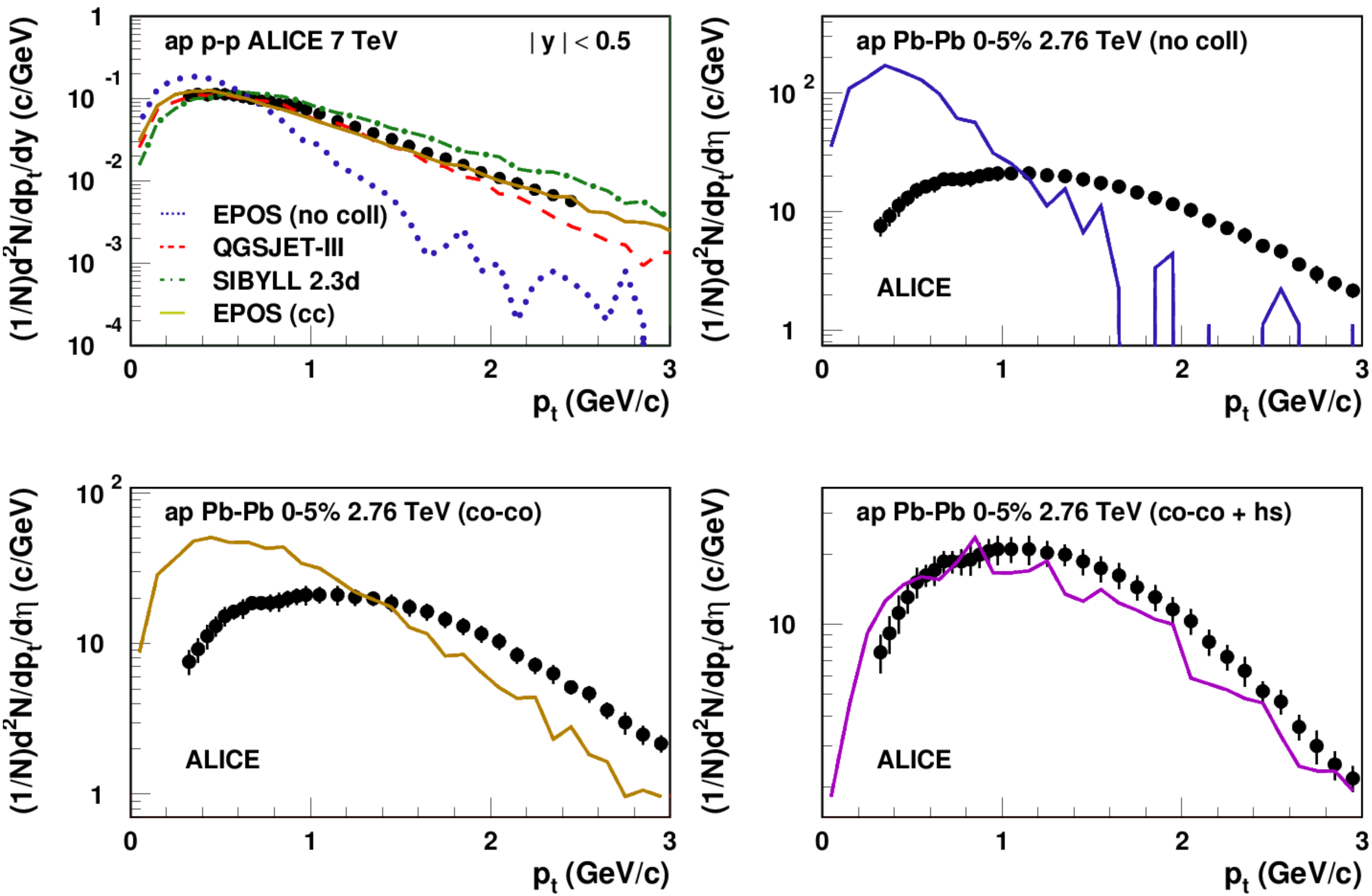
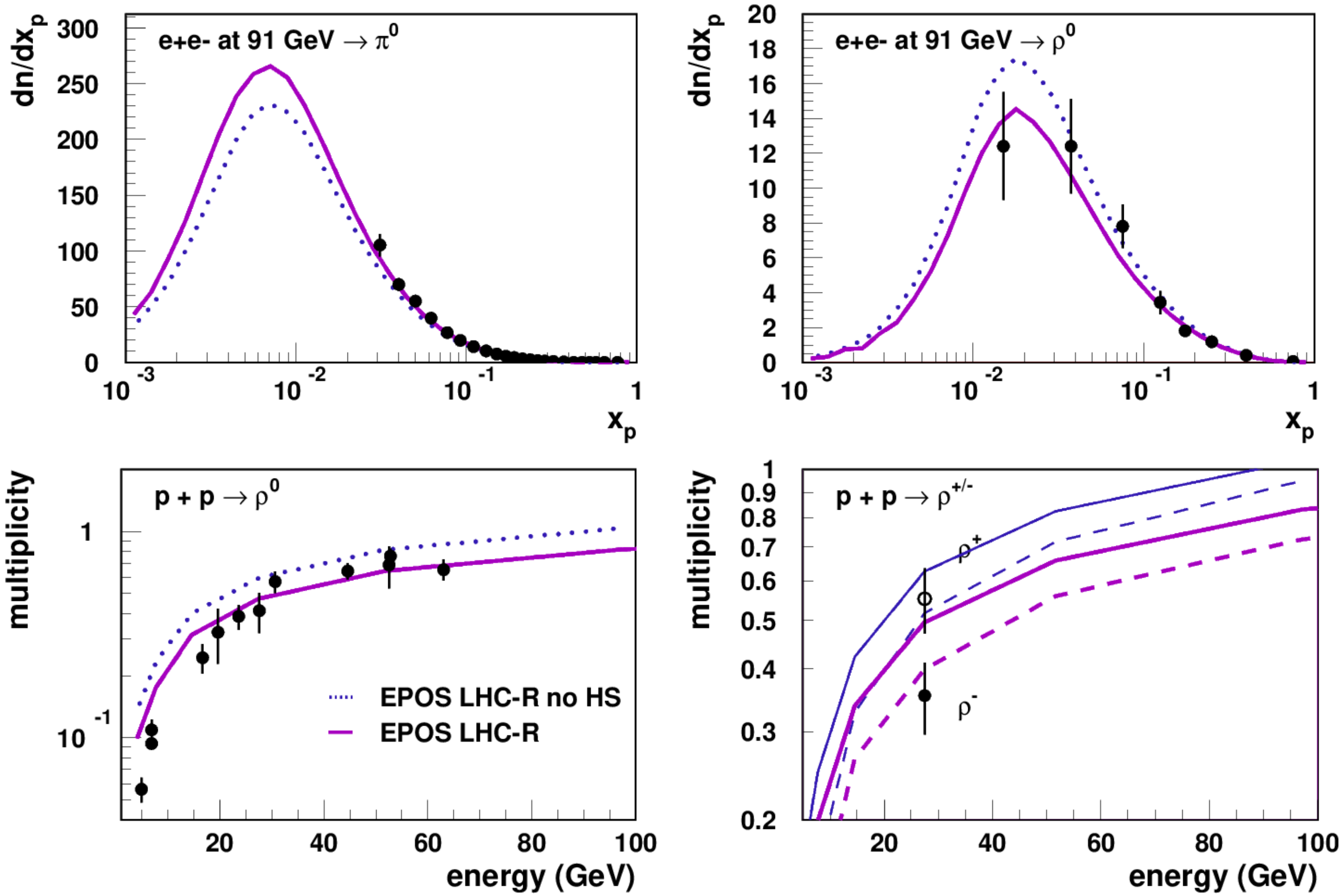


Retune basic parameters with HS and LEP

EPOS.LHC-R uses experimental constraints from LEP

➡ Increase contribution of ρs to compensate the effect of HS

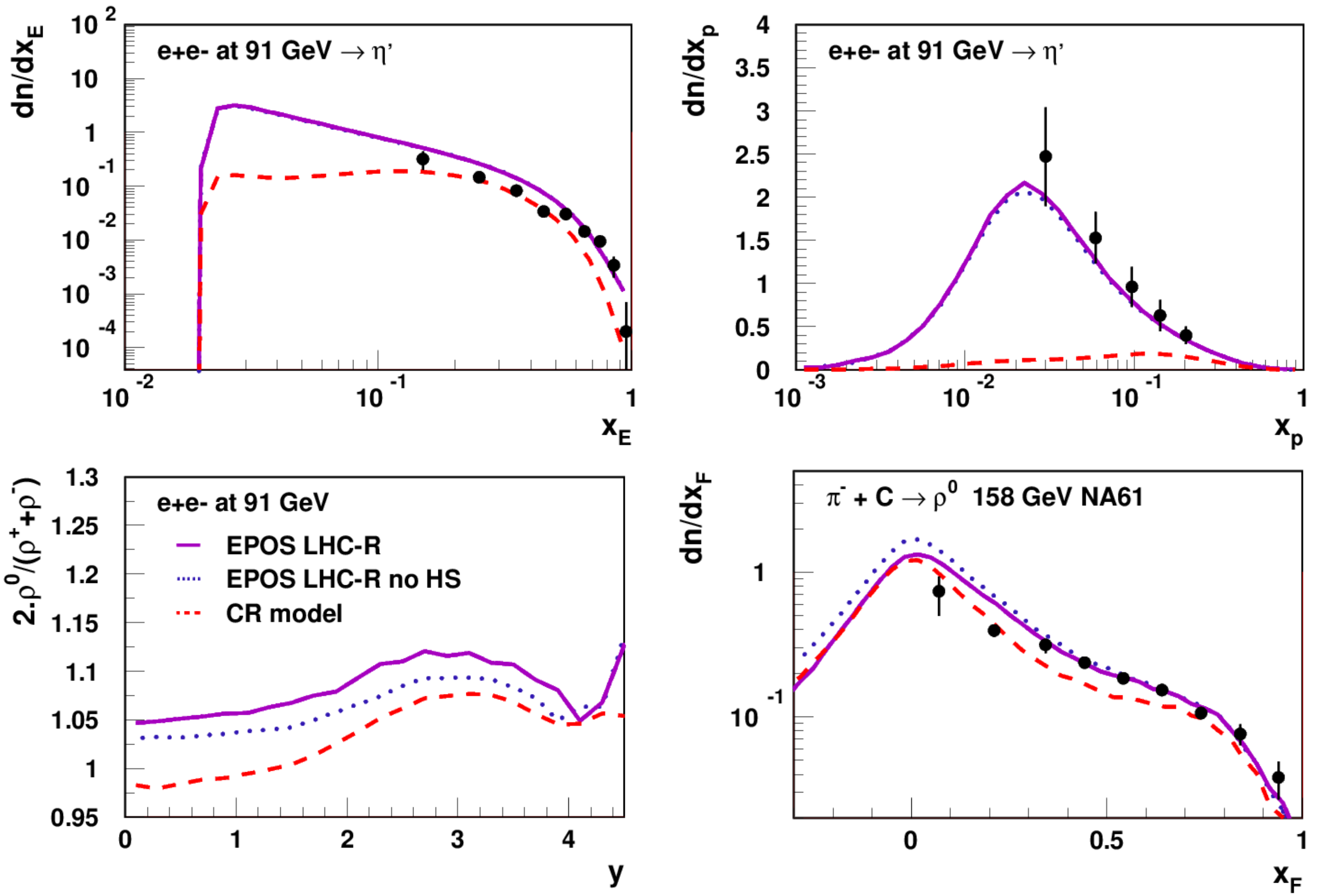


Retune basic parameters with HS and LEP

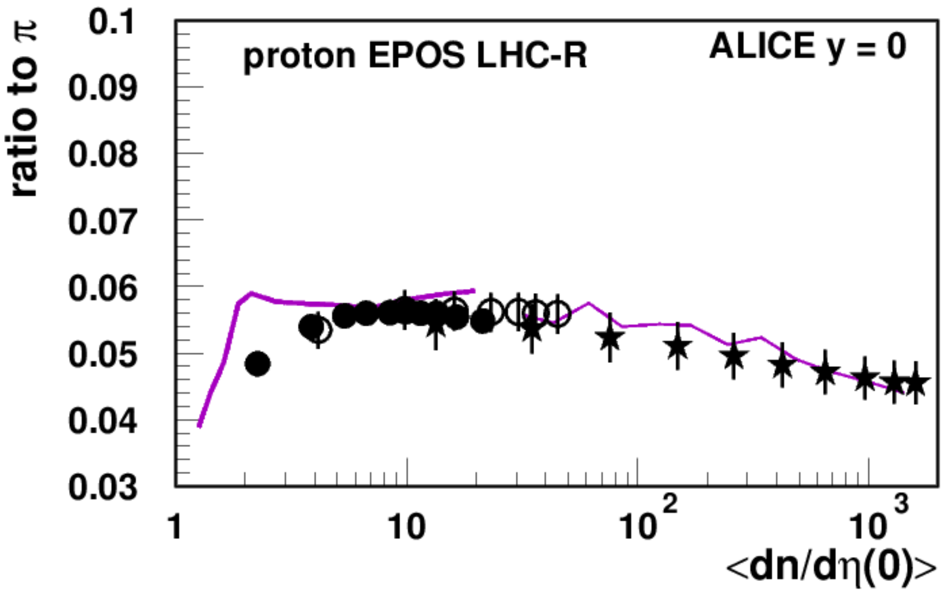
EPOS.LHC-R uses experimental constraints from LEP

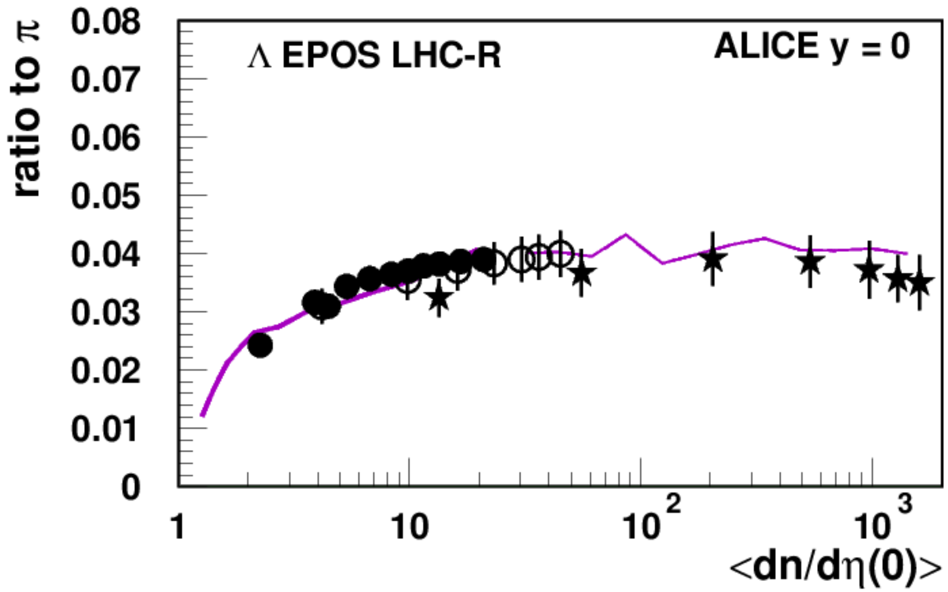
- Produce η′ and f_0 in addition to η : change asymmetry for ρ (and π)

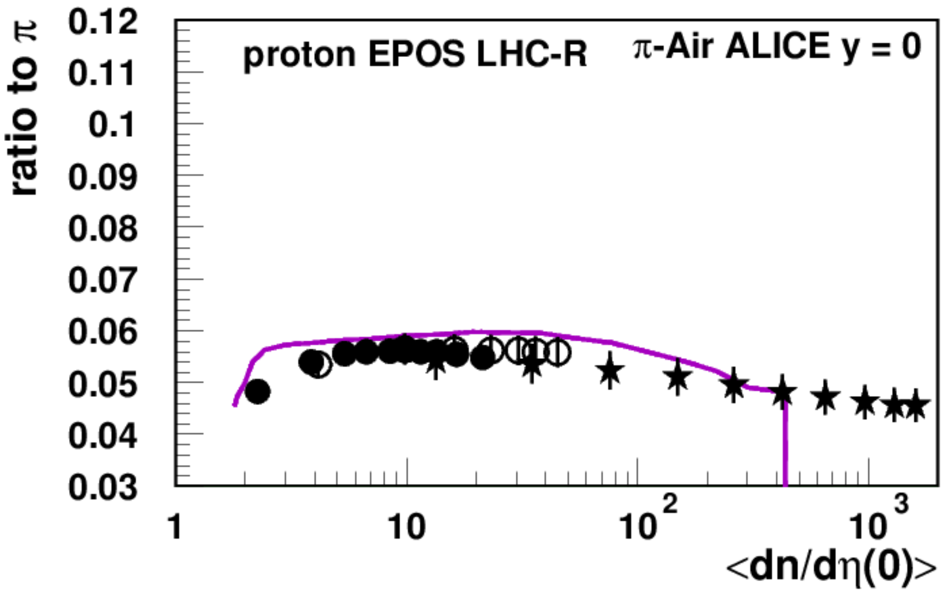
  - Effect on muon production in air showers !

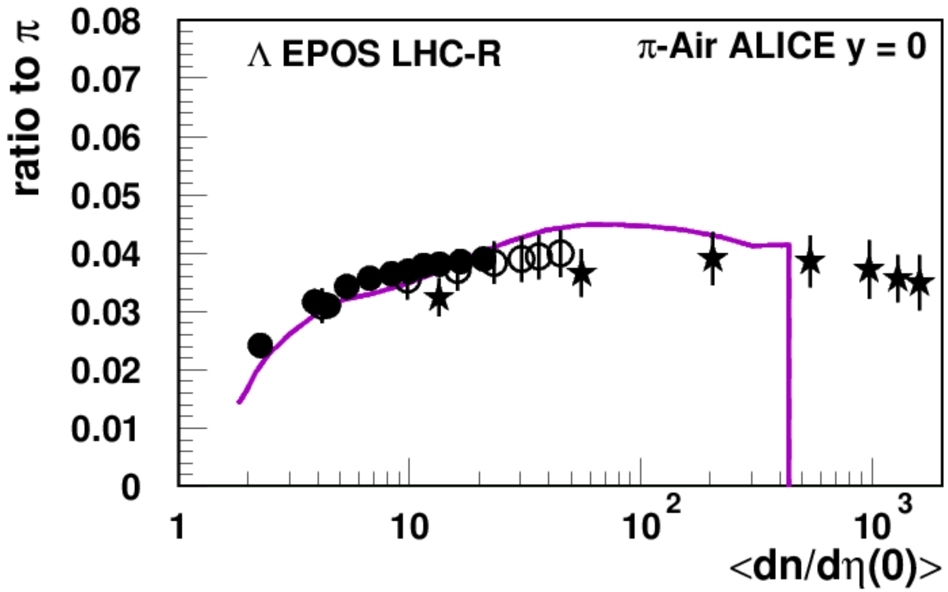


Check ALICE data





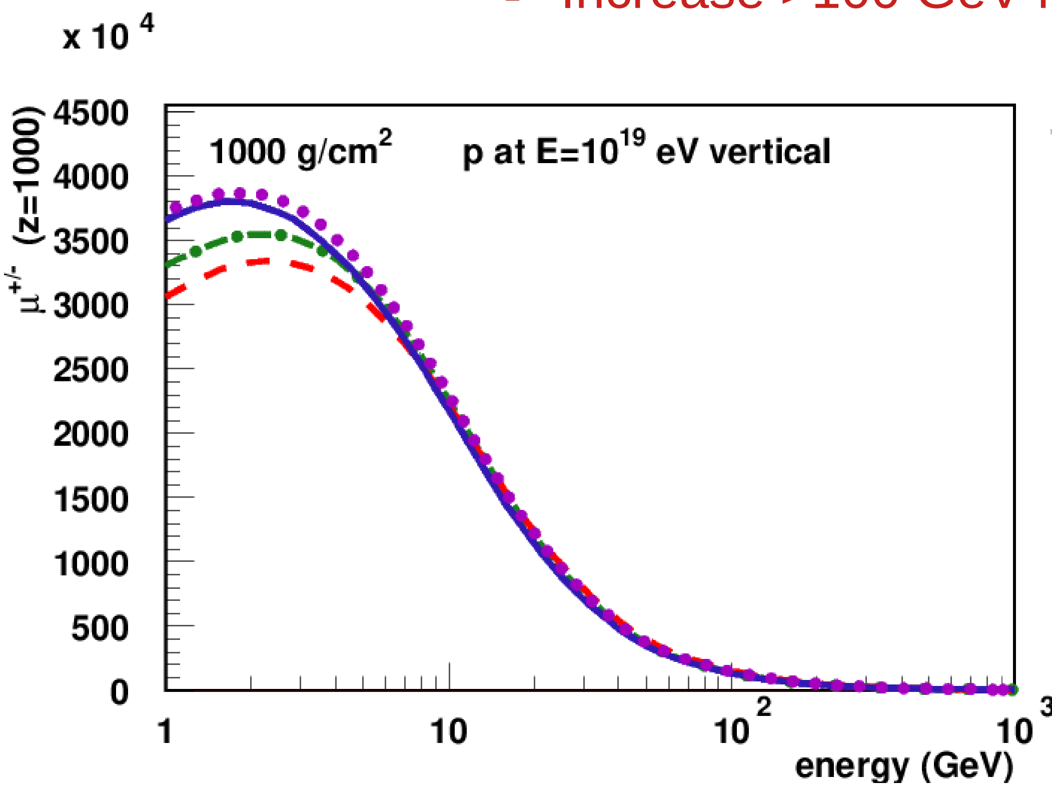


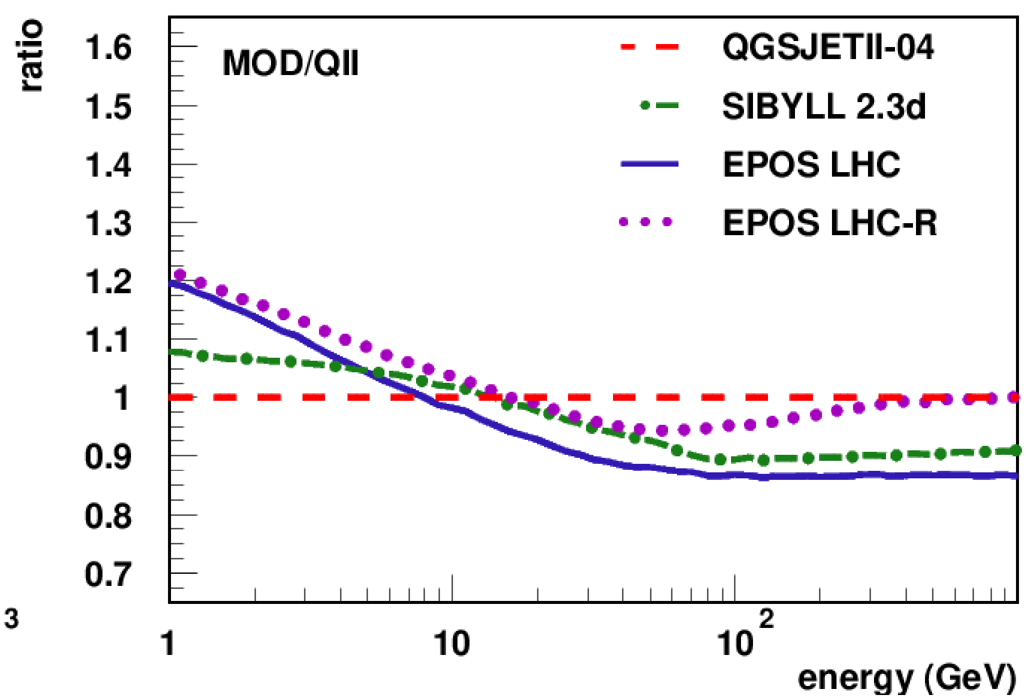


E_μ

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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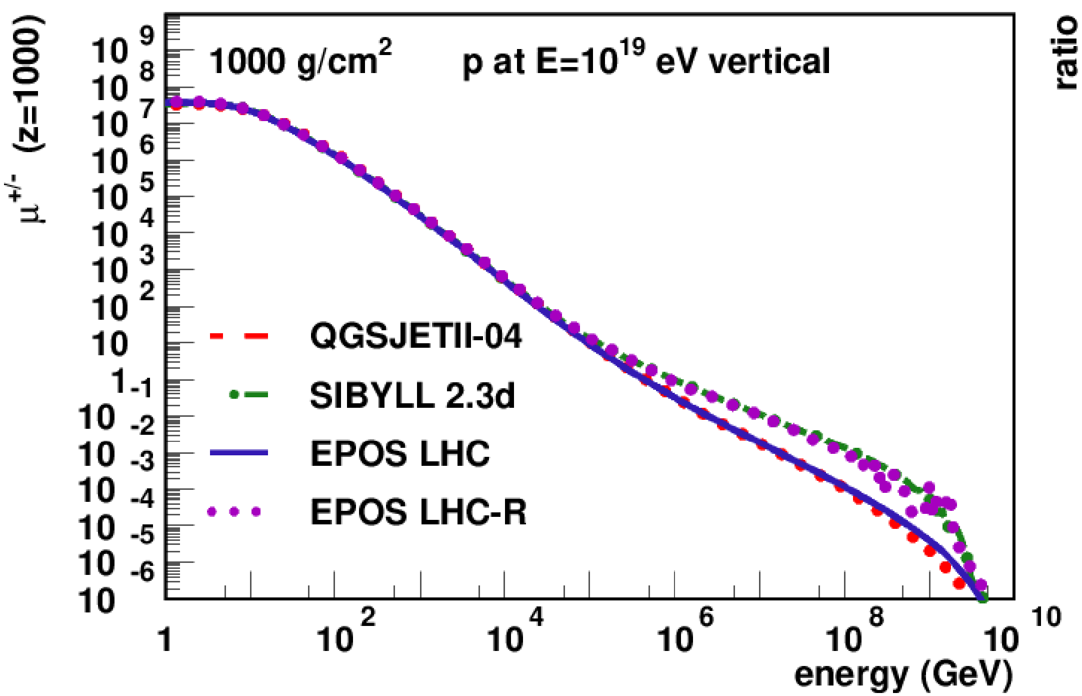
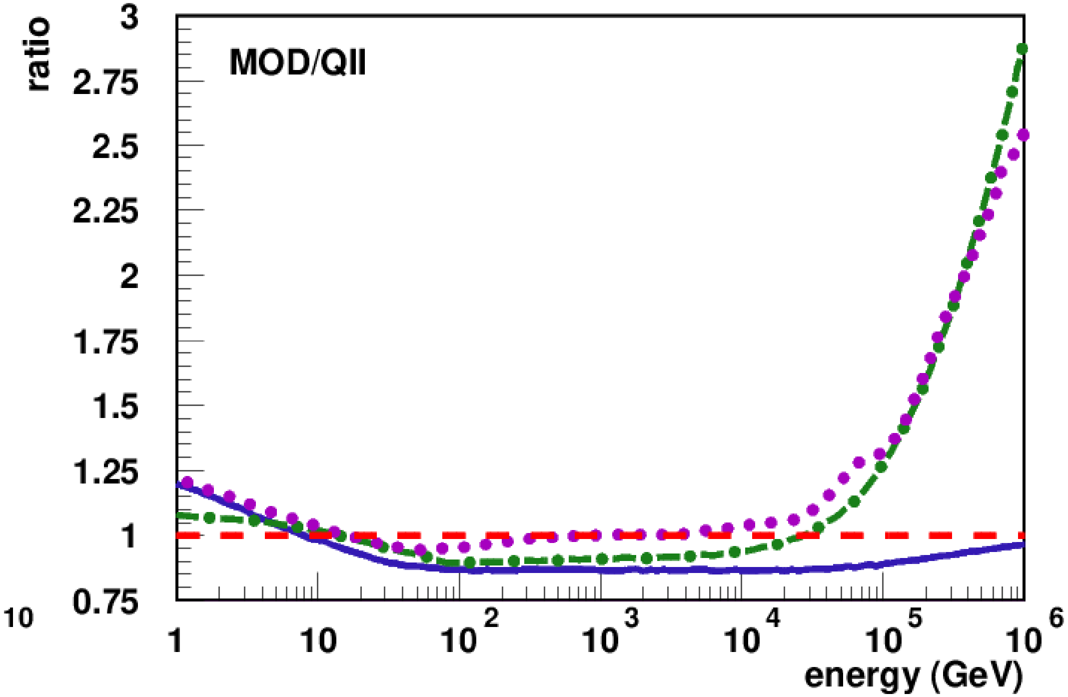
  - Parallel shift changing all muon energies
- Pion-Air multiplicity impact muon energy between 10 and 100 GeV
- Better tune of kaons (indirect impact of core-corona)
- Very high energy muons from charm ! (background for neutrino analysis)

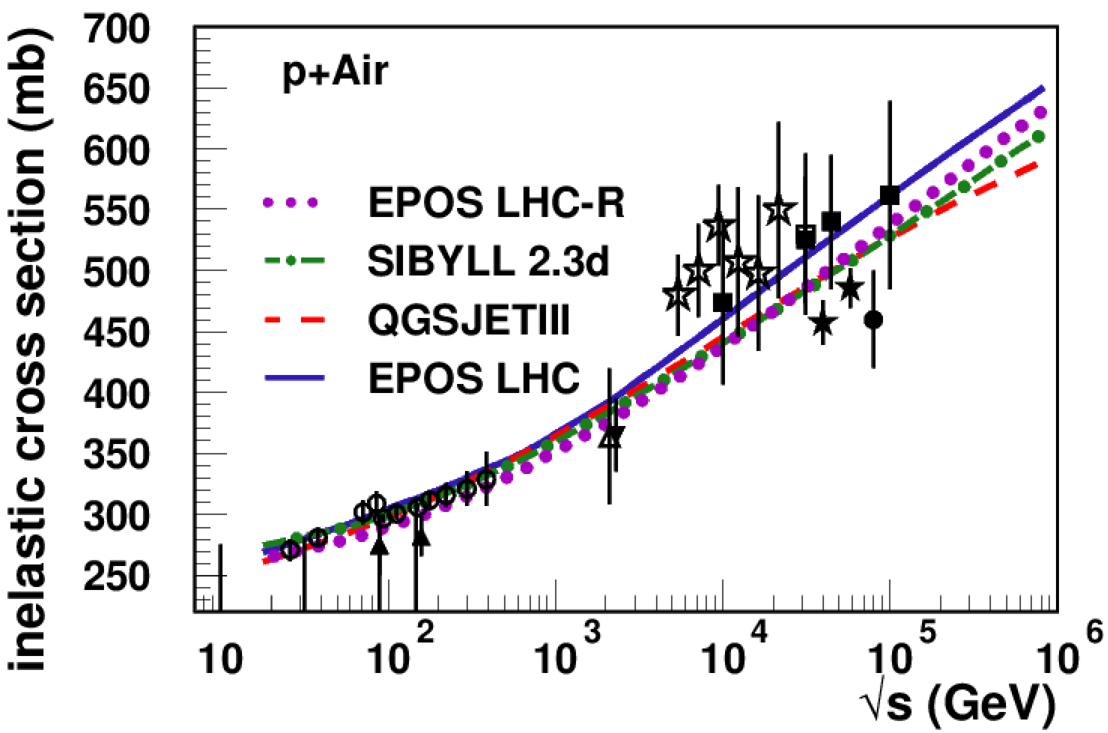


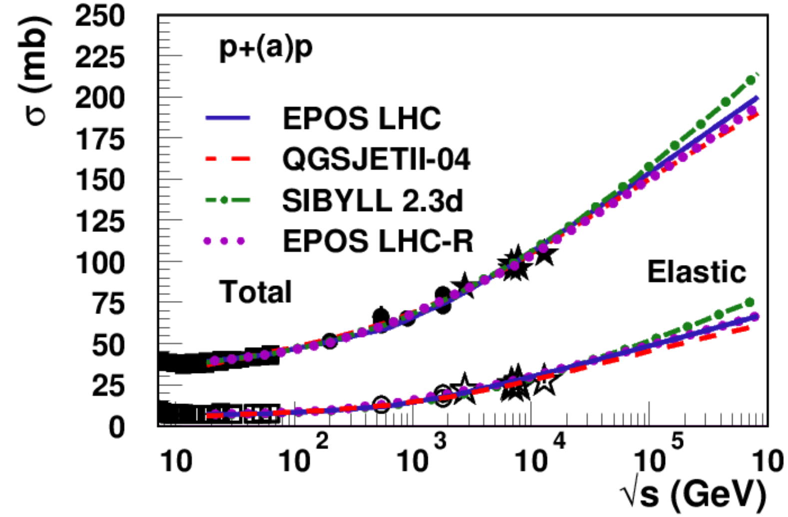


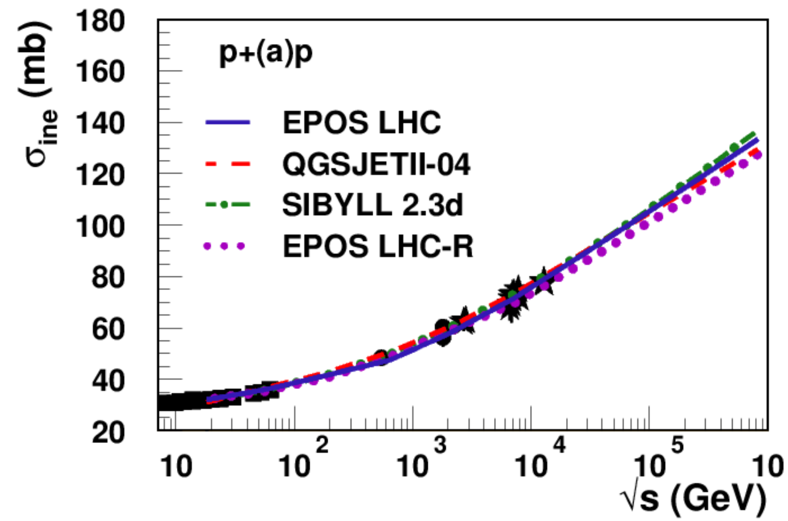
Cross-Section Reduced

- **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

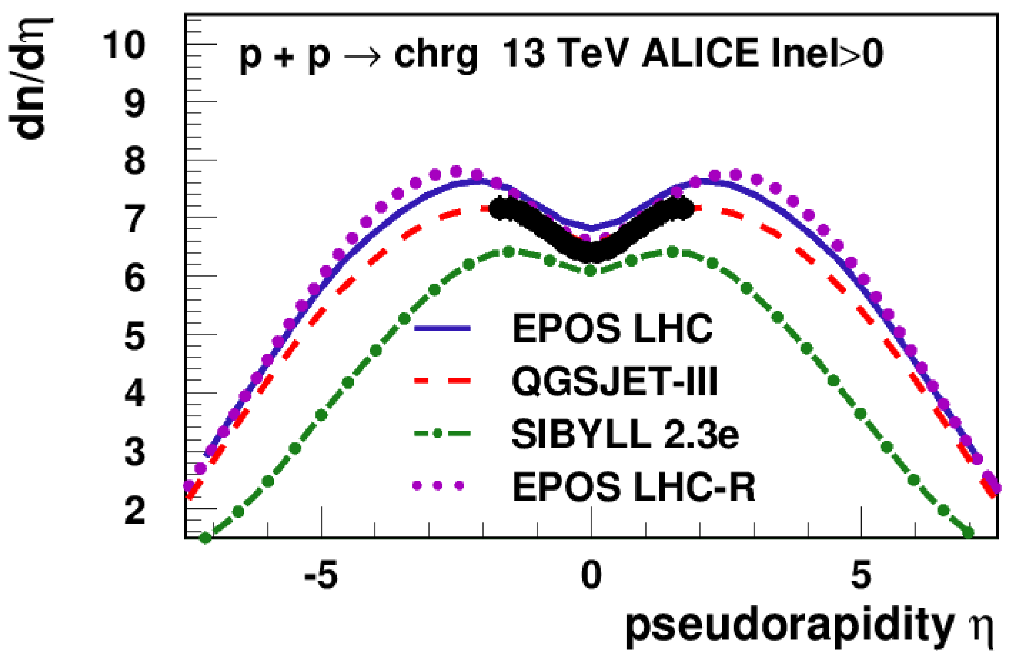


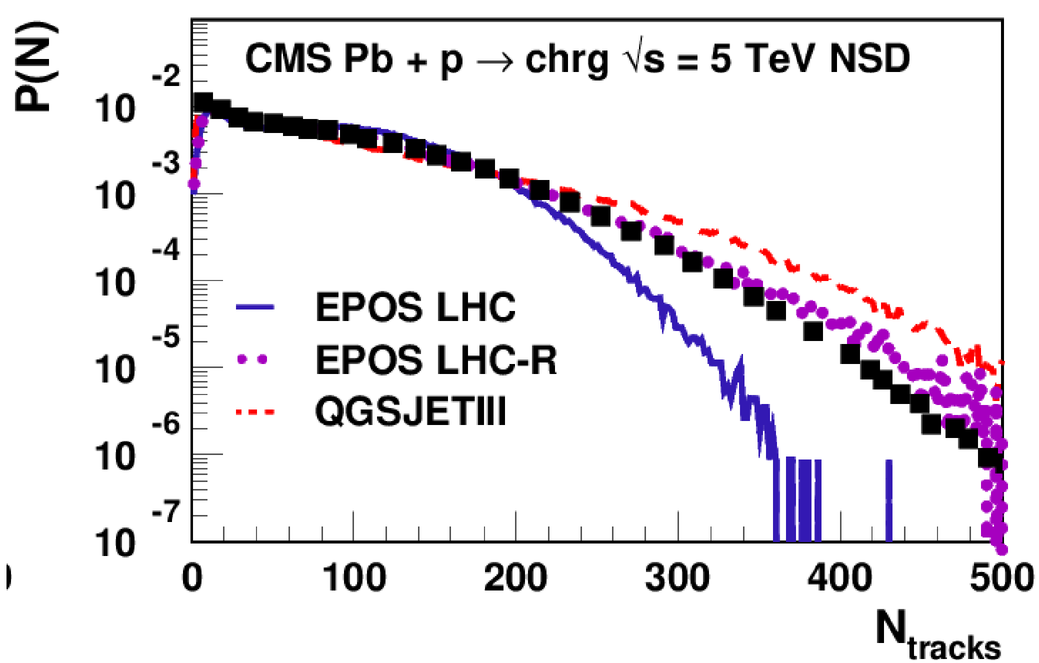




Pseudorapidity

- **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)

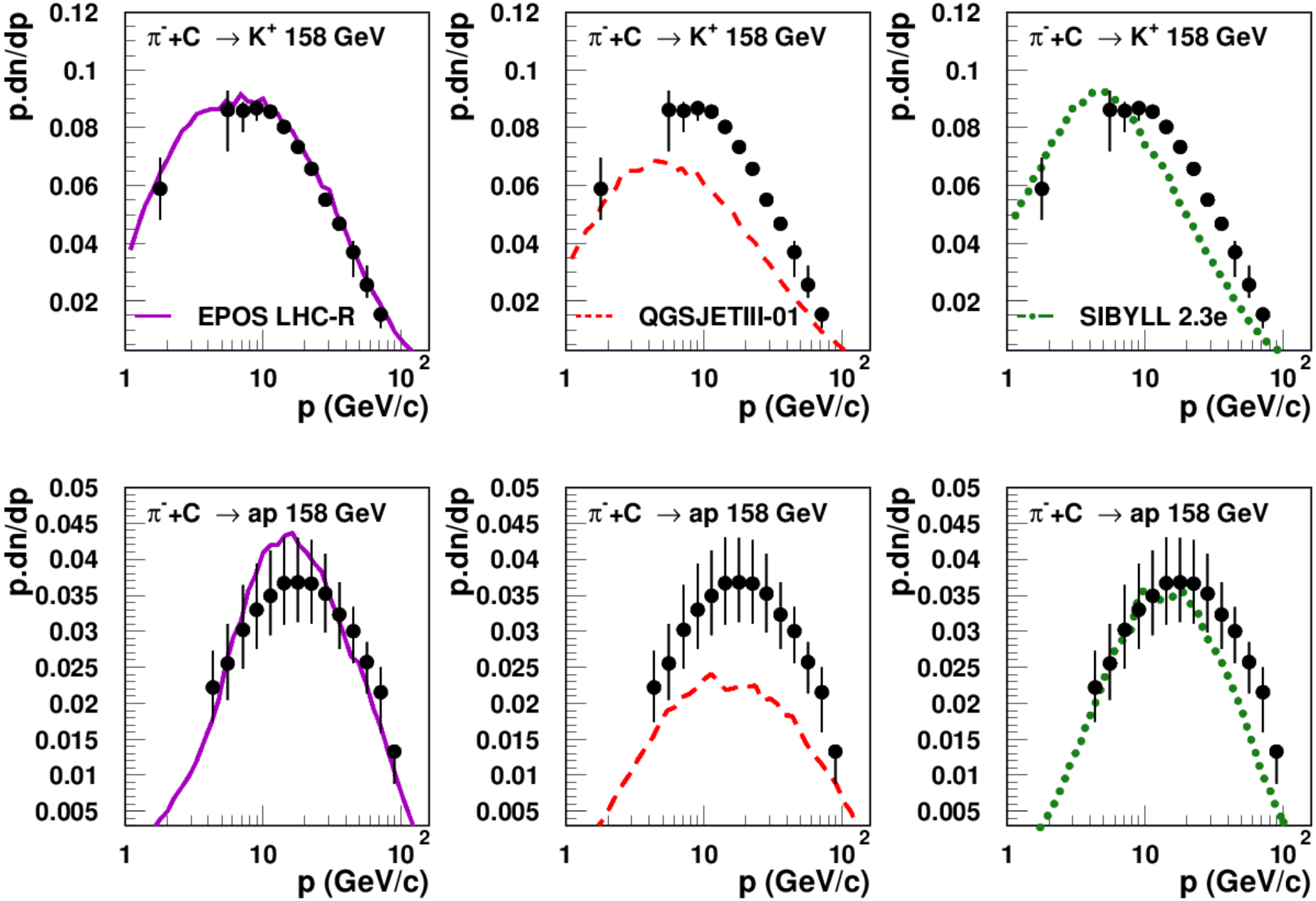




Kaons and Baryons

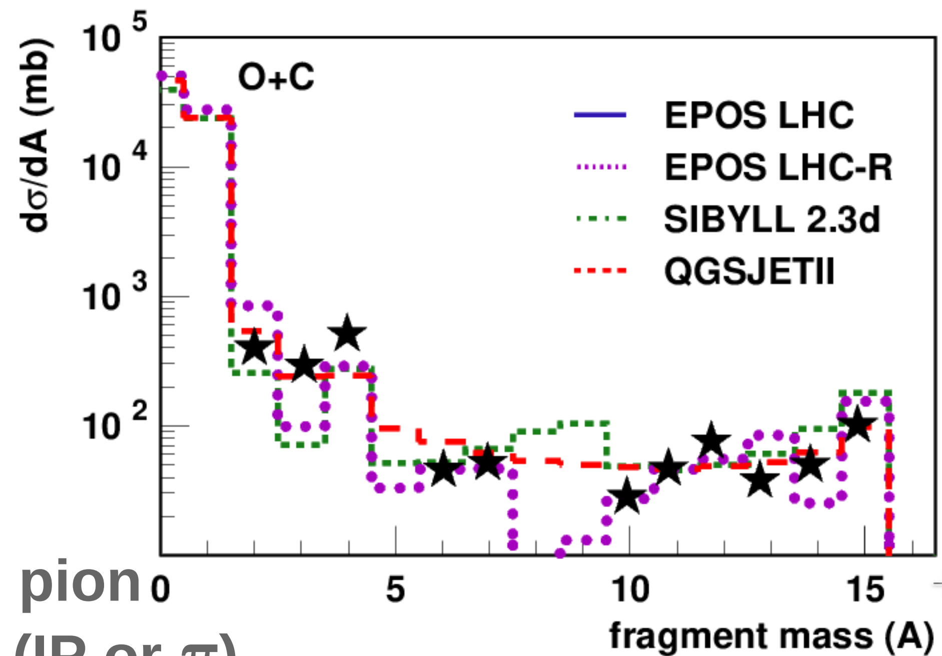
Only EPOS properly reproduce NA61 data (and many others)

➡ QGSJETIII not flexible enough !

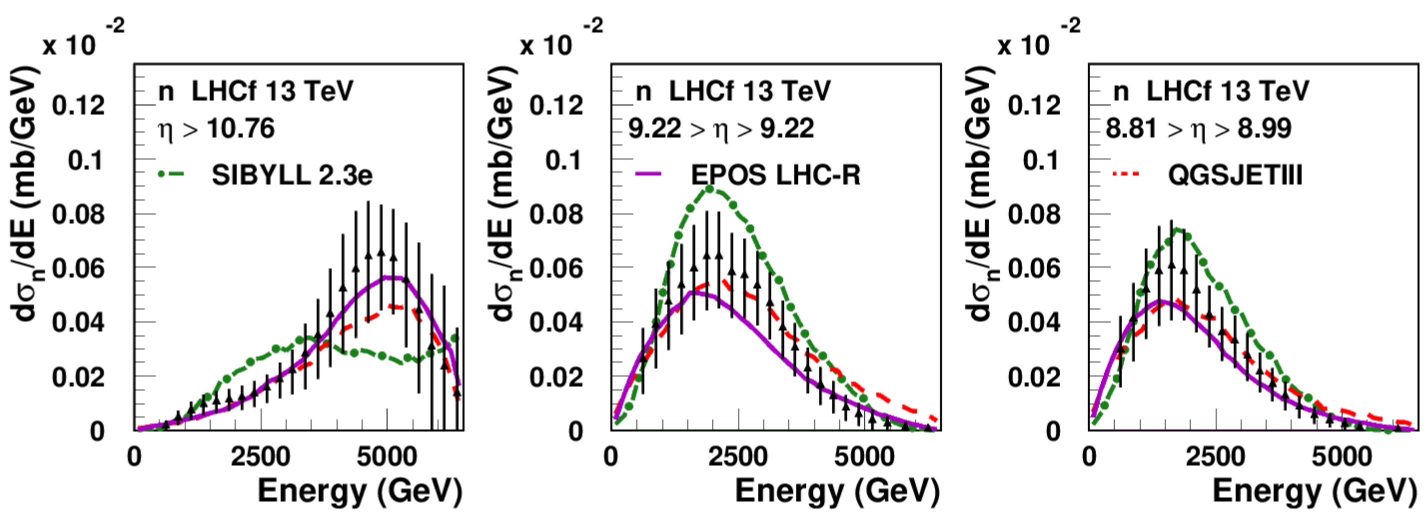


Improvements in EPOS LHC-R

- **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)**



Interaction with Air