EPOS LHC-R

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Hadronic Interaction Model workshop, Hong Kong, China

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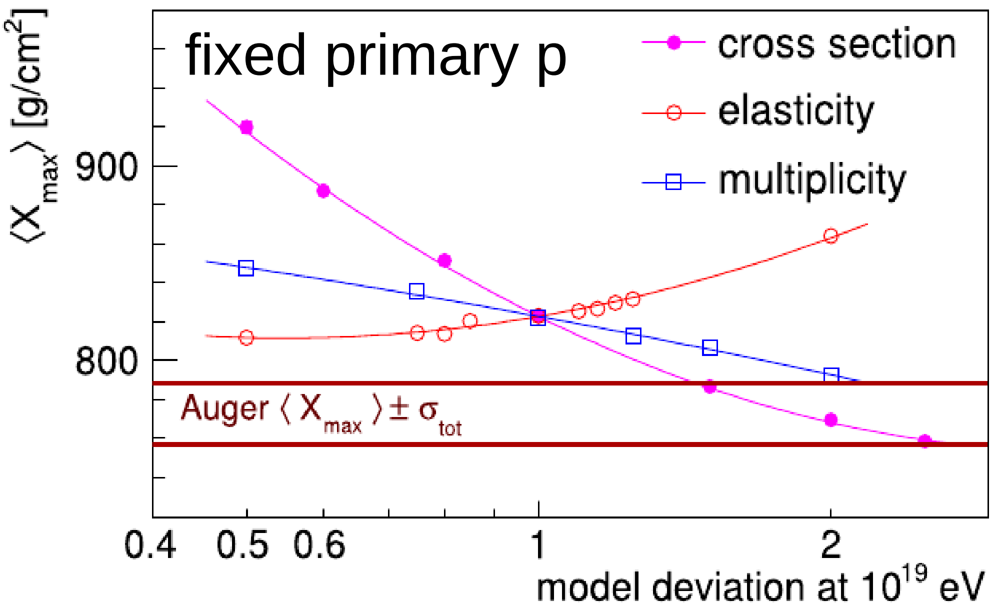
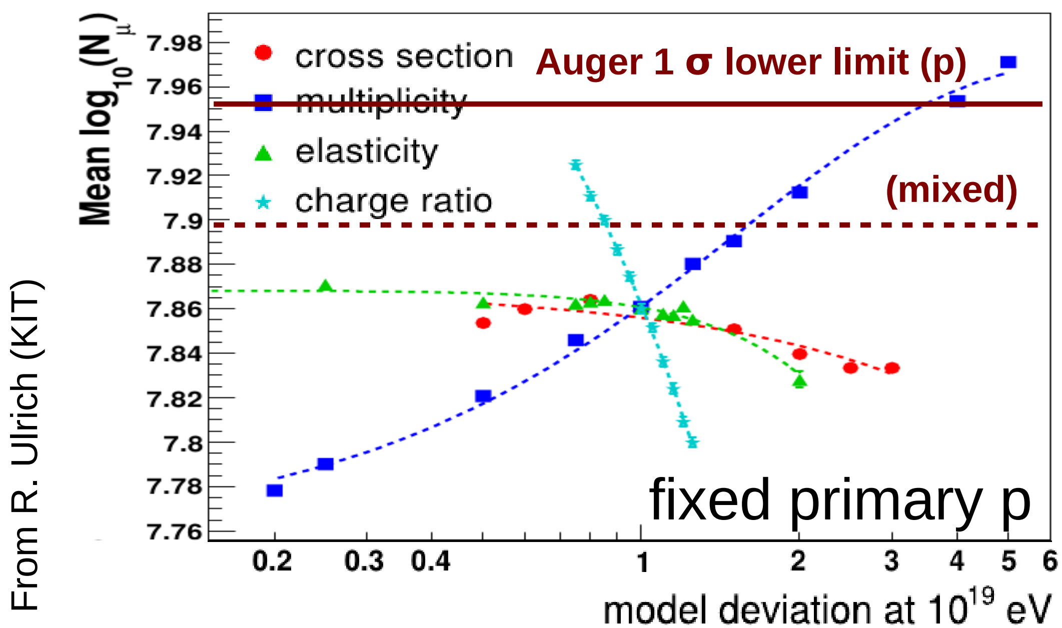
Outline

- **Introduction**
- **New LHC data → update for CR → EPOS LHC-R**
  - ➜ A real global approach to do hadronic interactions
- **Impact of collective effects and Hadronic Rescattering (HS)**
  - ➜ Role of resonances
- **Predictions for air showers (EAS)**
  - ➜ X_{max} and μ
- **Remaining uncertainties and new measurements**

Recent LHC data provide new constraints on models changing X_{max} and the muon production if a global approach is used.
More data needed to validate models and reduce uncertainties !

Hadronic Interactions and Air Showers





- **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.

Possible updates since last model release

- **A number of new data since last release has been used 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
  - ➜ Particle yields as a function of multiplicity (ALICE, LHCb)
    - Very important to understand the mechanism behind particle production
  - ➜ NA61 data

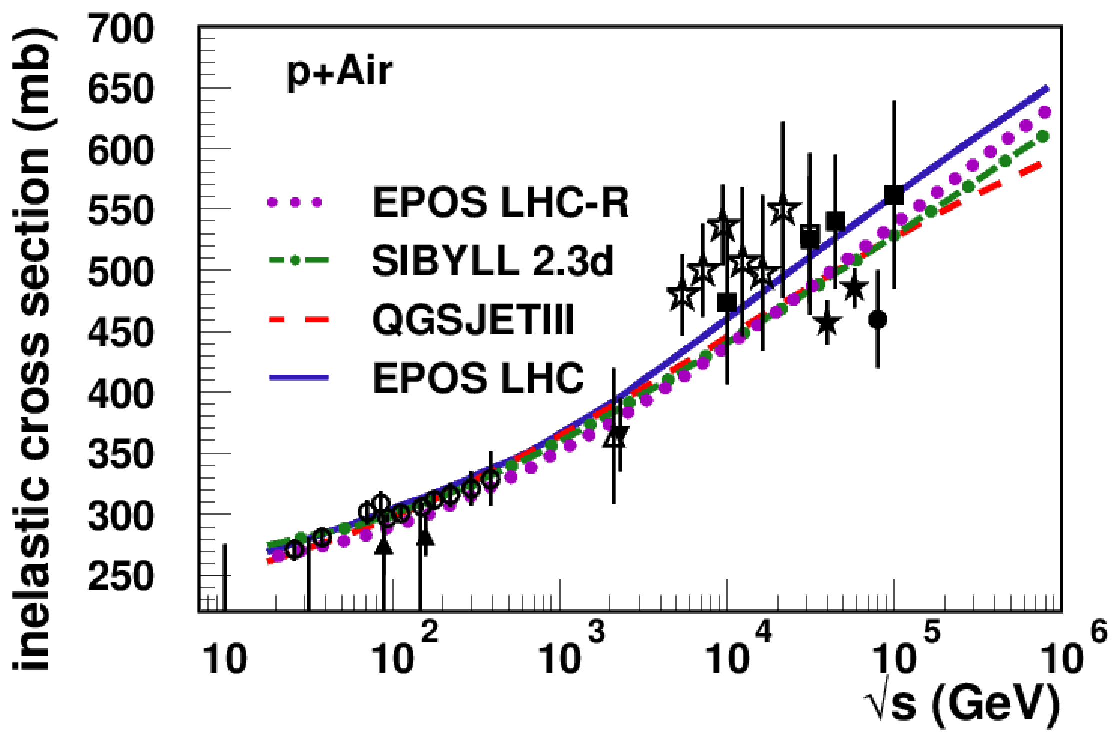
X_{max}

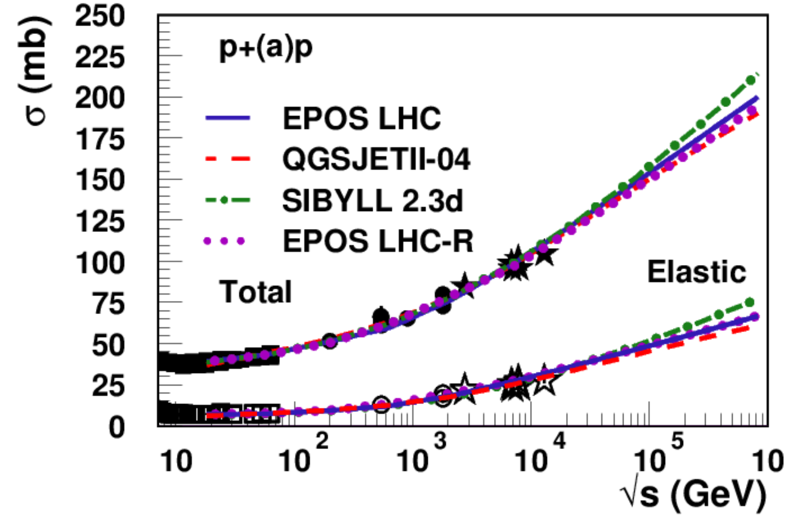
N_{μ}

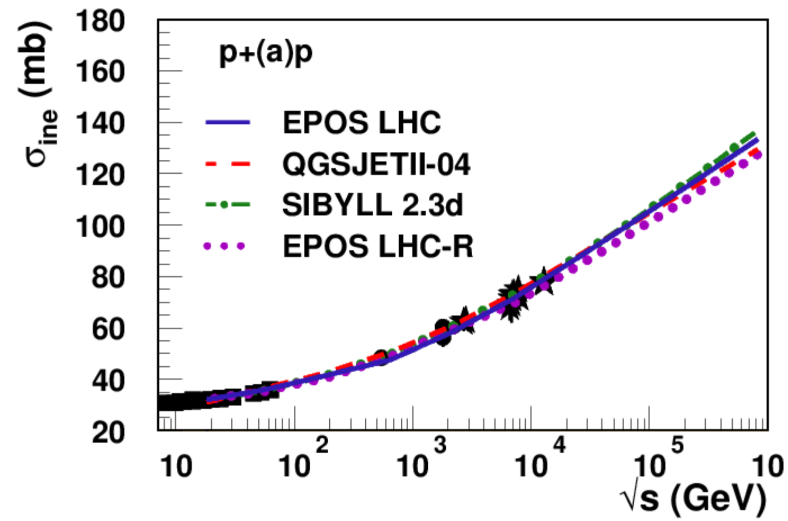
- **Update of EPOS LHC → EPOS LHC-R**
  - ➜ New EPOS 4 available for heavy ion physics but not usable for air showers (yet, cf. Klaus)
  - ➜ Modify EPOS LHC to take into account new data and new knowledge accumulated with EPOS 4 (and some code)

Inelastic 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 -5% at the highest energy using most recent CR based measurements

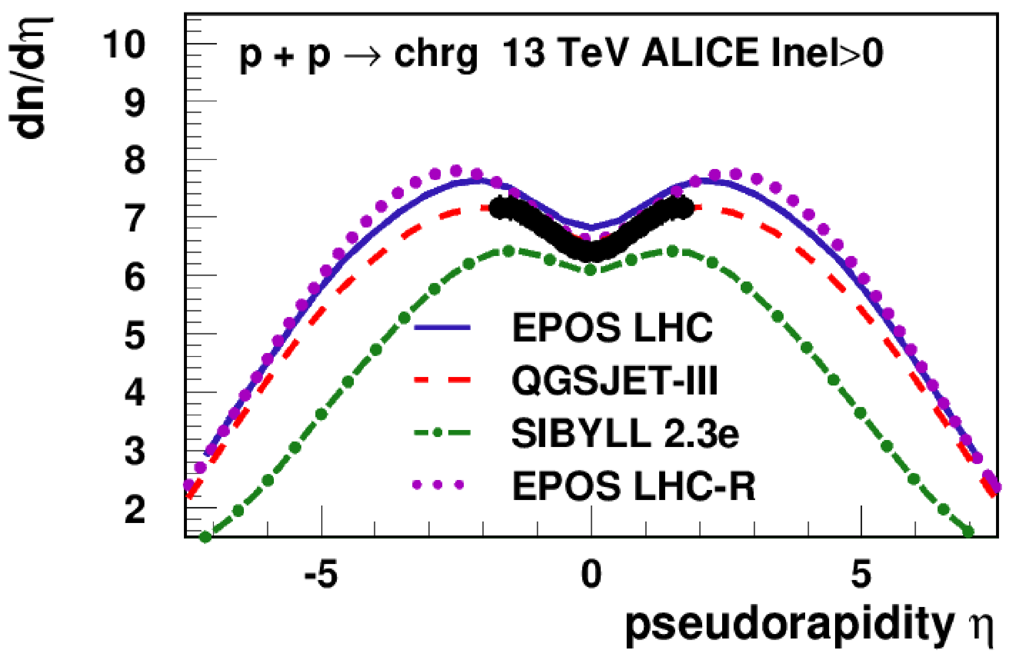


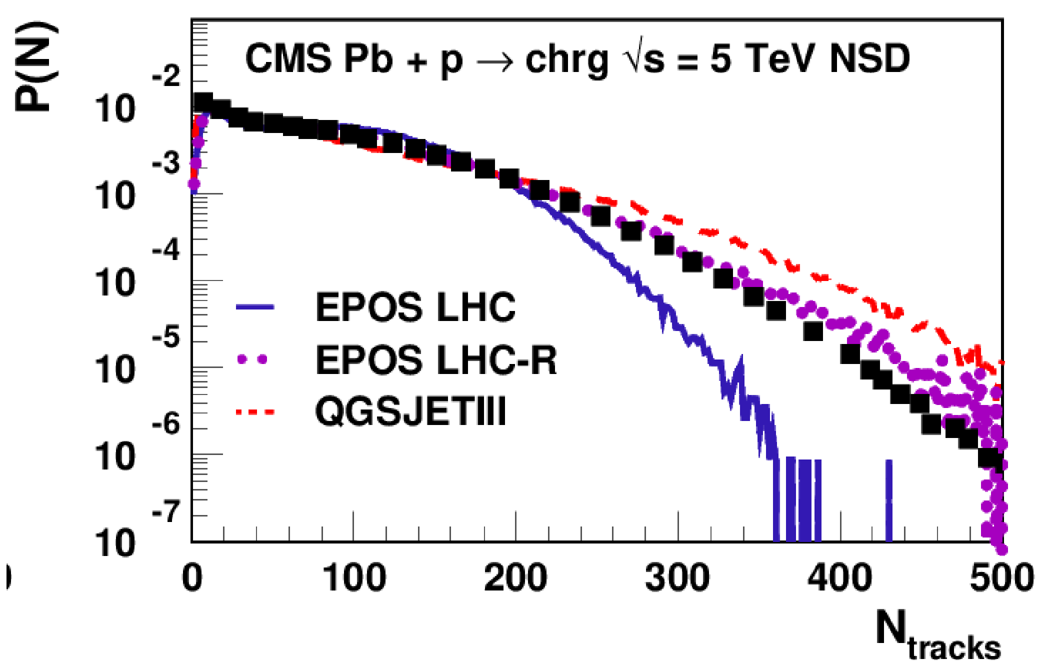




Pseudorapidity

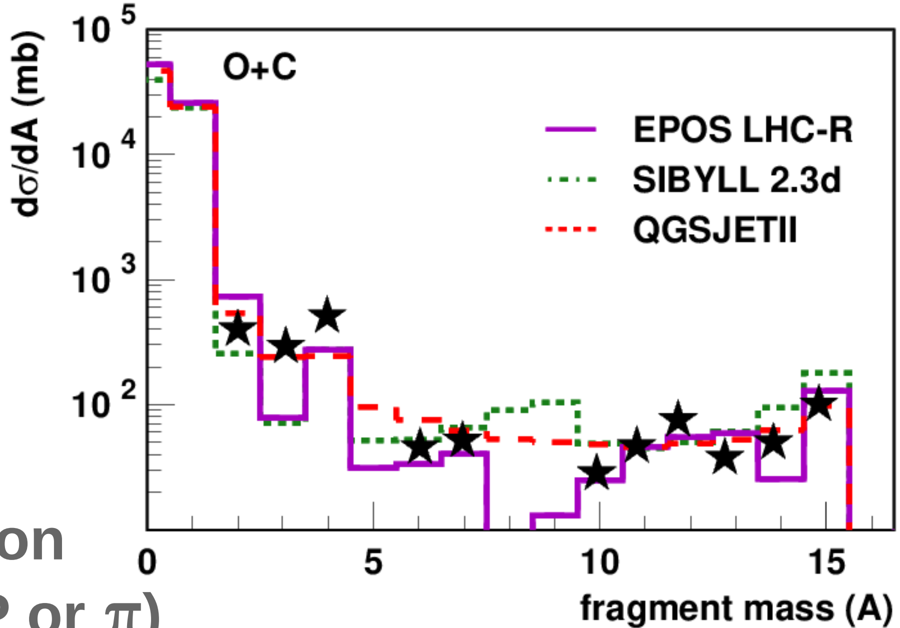
- **Angular distribution of newly produced particles**
- **New data at 13 TeV in p-p**
  - ➡ Test extrapolation with different triggers
  - ➡ Sibyll has a clear difference with other models (and data) : too narrow !
- **Detailed data at 5 TeV for p-Pb**
  - ➡ Wrong multiplicity distributions in all models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



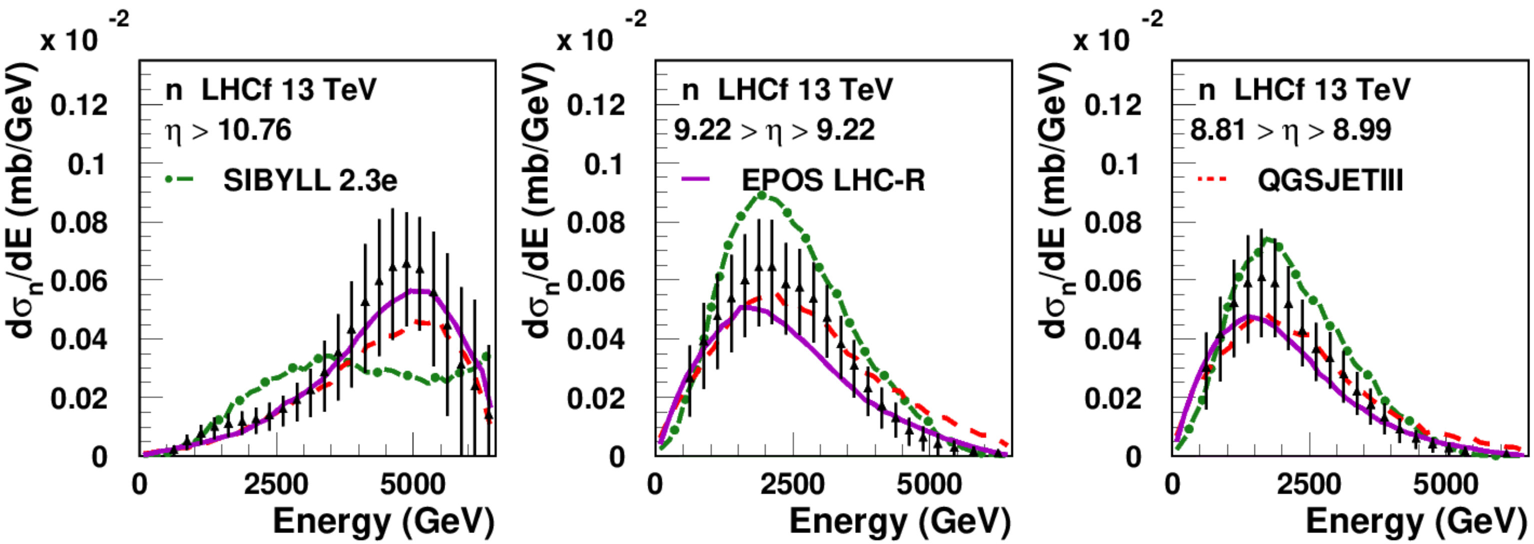


Improvements in EPOS LHC-R (1)

- Number of limitations identified in EPOS LHC
- Problem with nuclear fragments
  - ➔ Double counting for single nucleons
  - ➔ Missing multifragment production
    - Significant impact on X_{max} fluctuations for nuclei

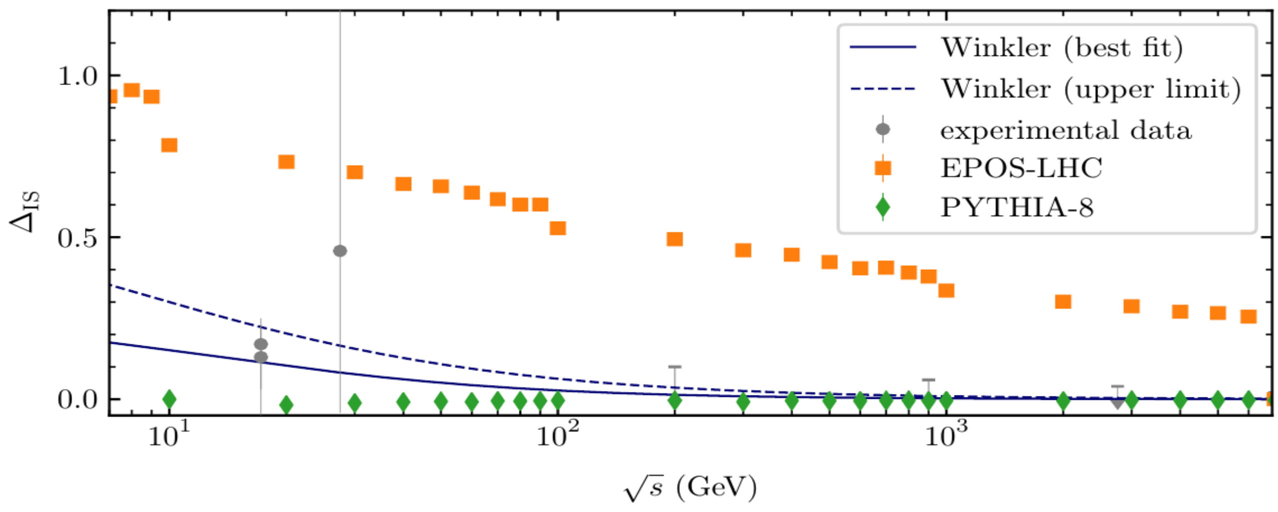


- Simplified high mass diffraction and pion exchange replaced by real emission (IP or π)



Improvements in EPOS LHC-R (2)

- **Number of limitations identified in EPOS LHC**
- **Charm production**
  - ➡ Soft (low enery and forward) and hard (high energy and mid-rapidity) prod.
- **Hard binary scaling**
  - ➡ Hard scale increase with number of MPI (inspired by EPOS 4 but simplified)
- **Large isospin breaking in EPOS LHC**
  - ➡ additional baryons and modified pion ratio



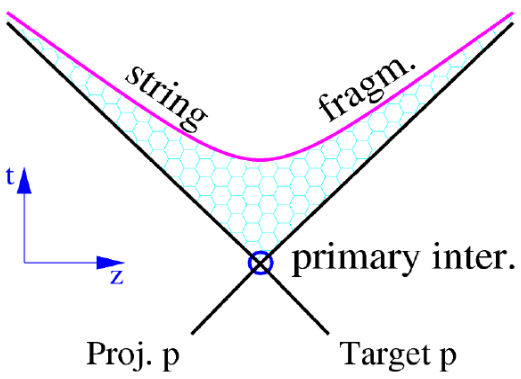
Thomas Pöschl PhD Thesis

➡ Exact isospin symmetry at production in EPOS LHC-R

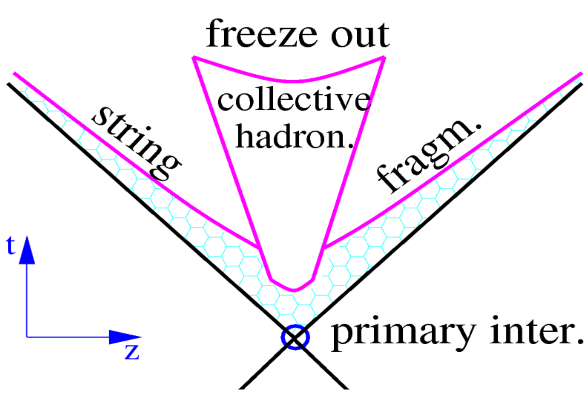
Impact of LHC data : need for a global approach

Global approach is the key !

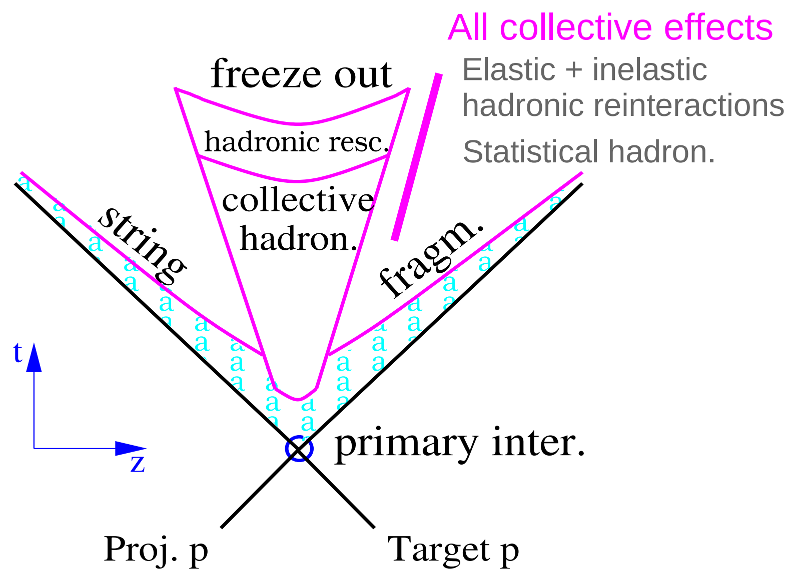
- Tuning models neglecting some physics process may lead to wrong parameters !
- Correct tune possible only if everything taken into account
- Even without a direct impact on the shower development (rare particle or not forward), it will change model parameters and the extrapolation (in energy or phase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



Sibyll, QGSJET



EPOS LHC
(no rescattering)

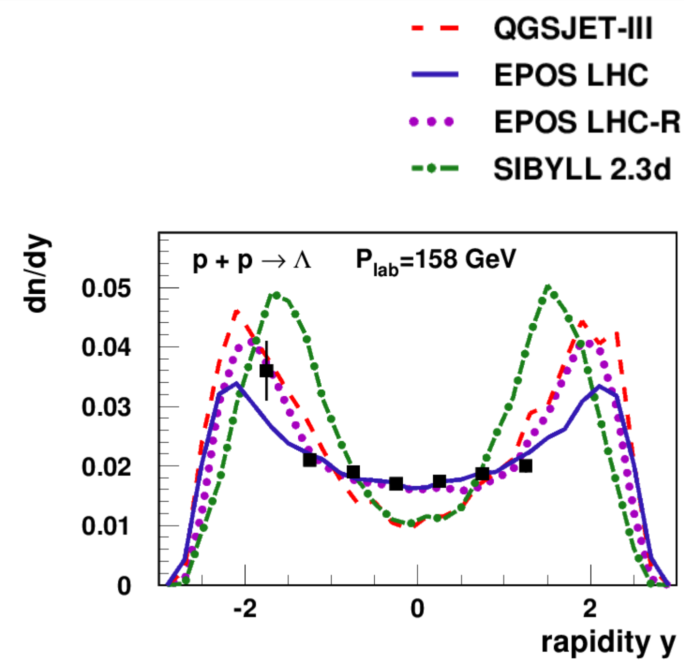


EPOS LHC-R

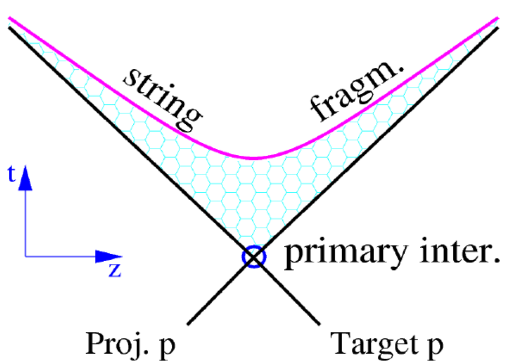
String Fragmentation

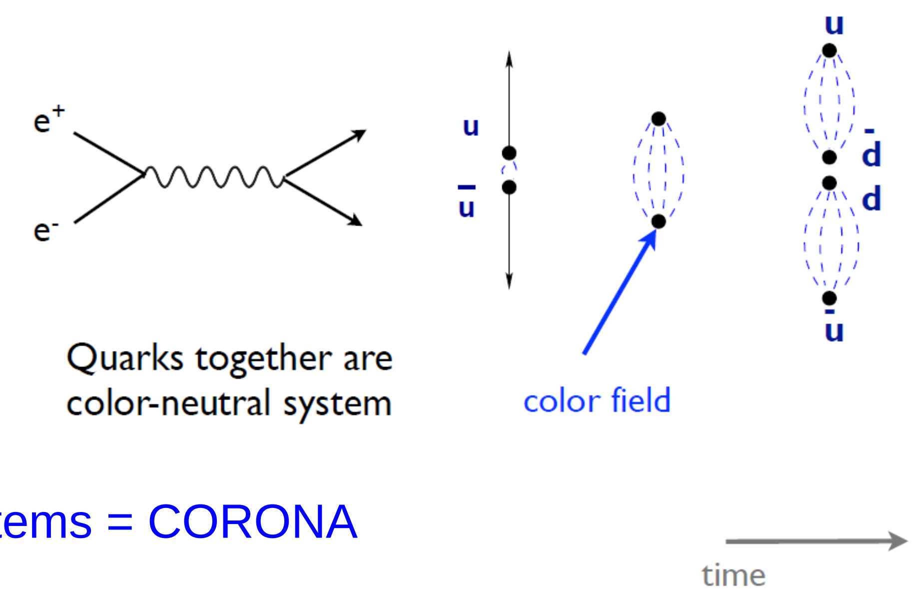
Global approach is the key !

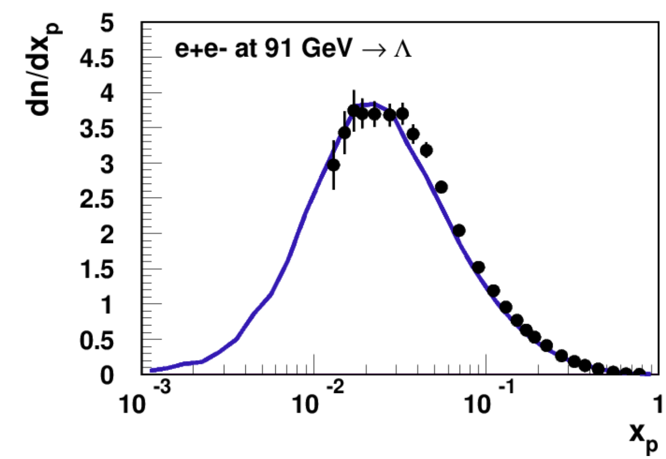
- Common hadronization in all the models
- Very important for forward particle production (EAS)
  - Used for beam remnant hadronization
- Parameters fixed on e+-e- only in EPOS
  - Other CR models tuned on p-p data
    - "Contamination" by beam remnant



Annihilation at high energy





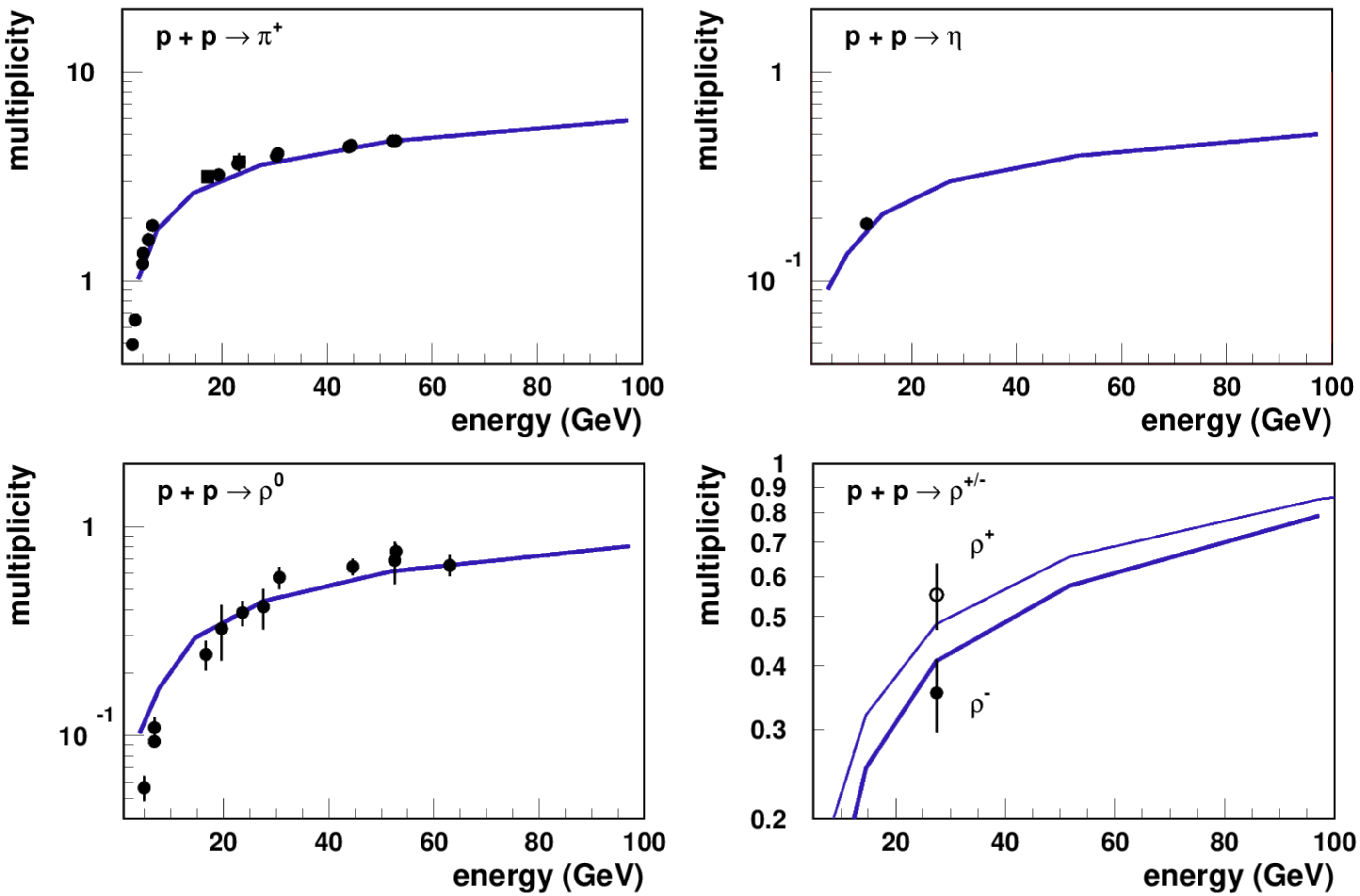


Used in dilute systems = CORONA

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



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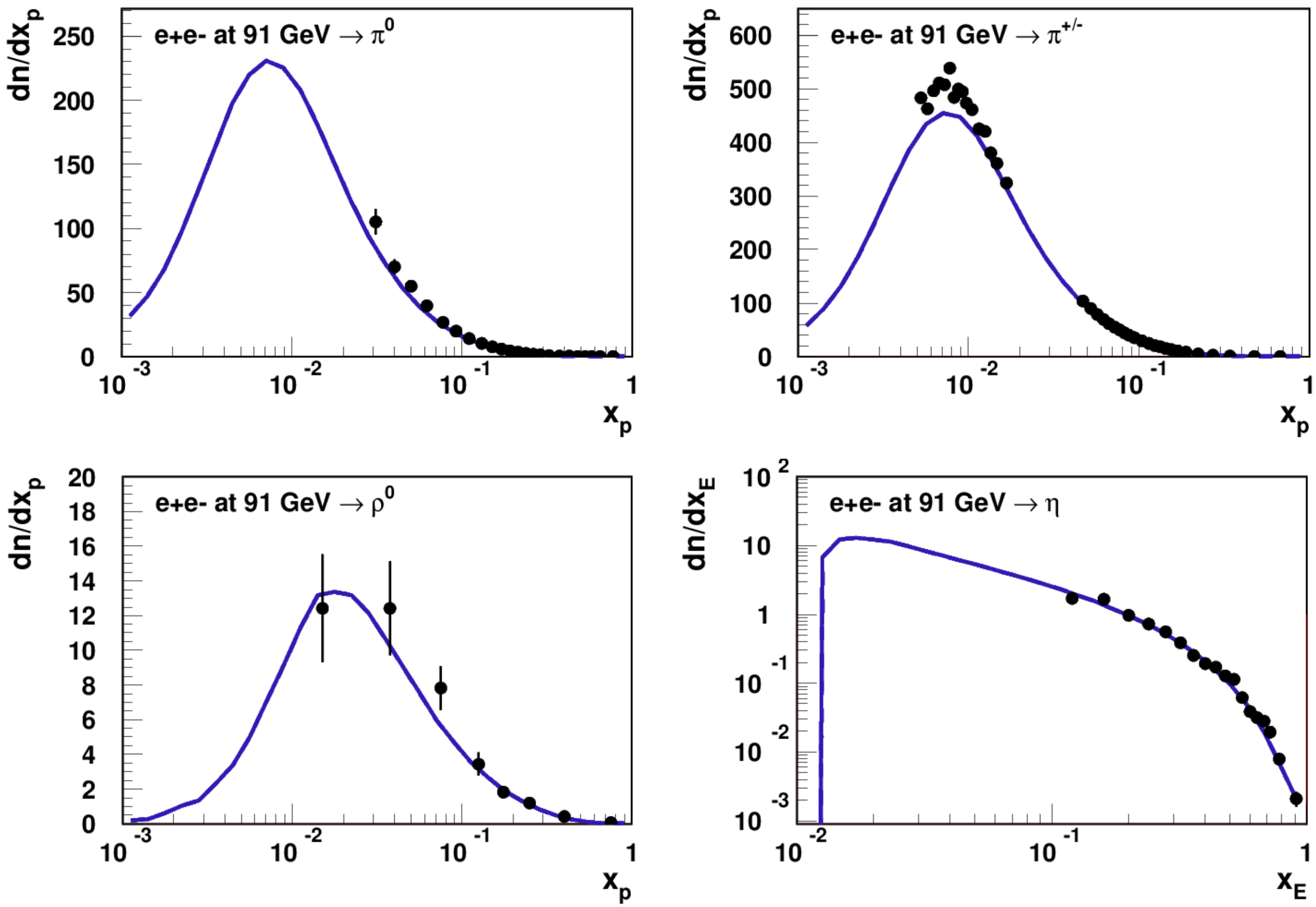
CR models usually tuned on hadronic interactions (not LEP)

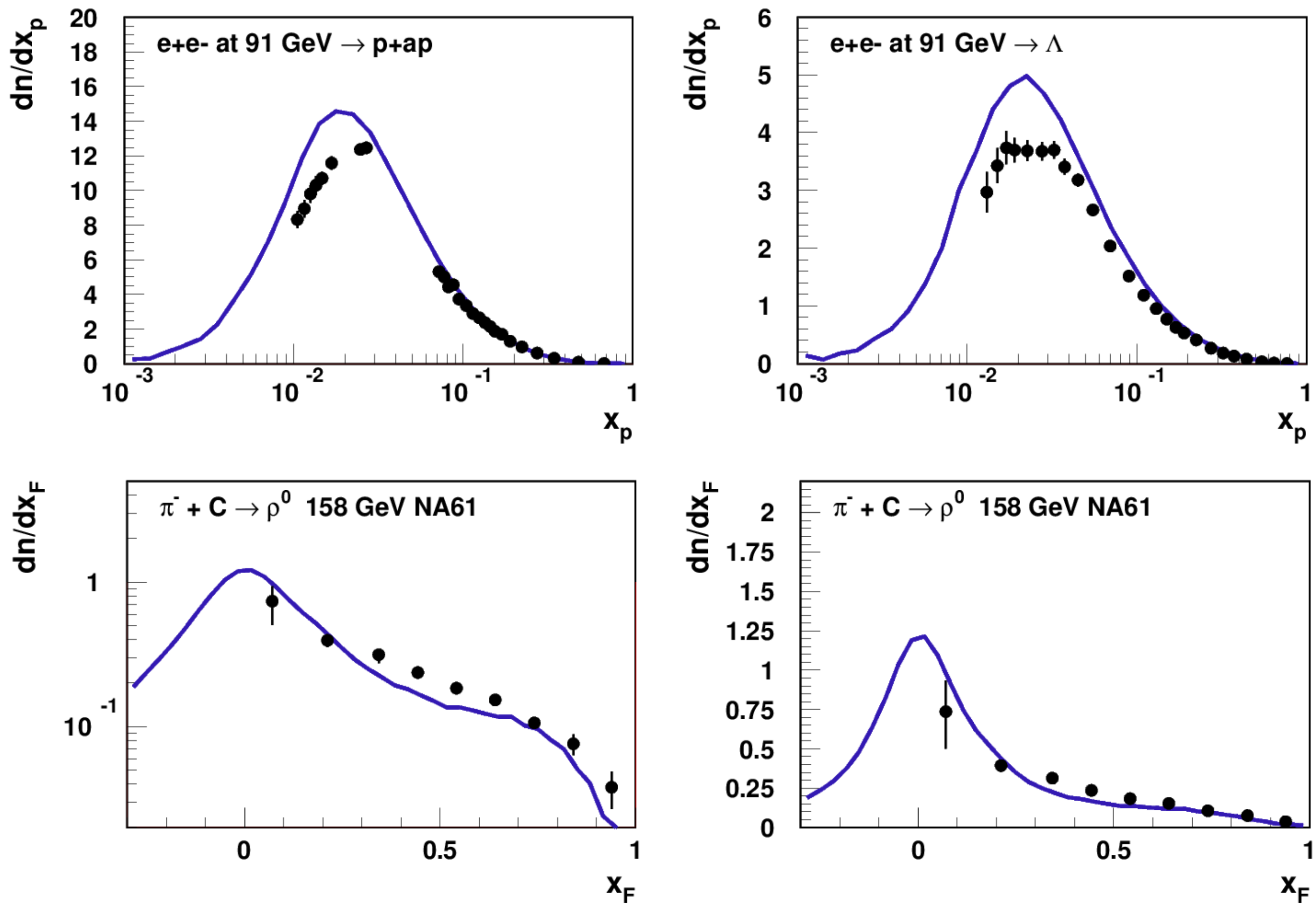
- Impose isospin symmetry (u=d) for pions, ρs and nucleons BEFORE decay
- Produce only most common particles π, ρ and η and tuned to pp data
  - Reasonable description of LEP



Generic CR tuning

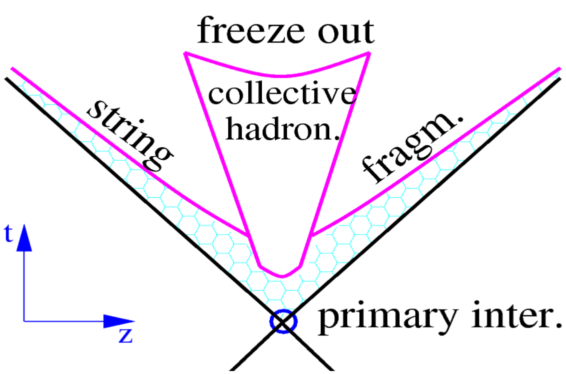
CR models usually tuned on hadronic interactions (not LEP)

- 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



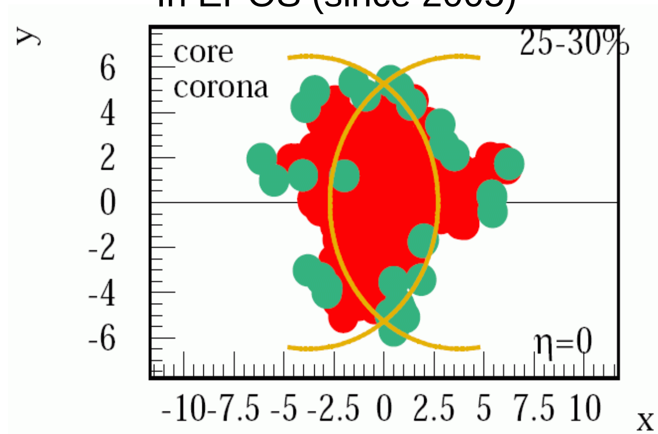
Core-Corona

- 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**

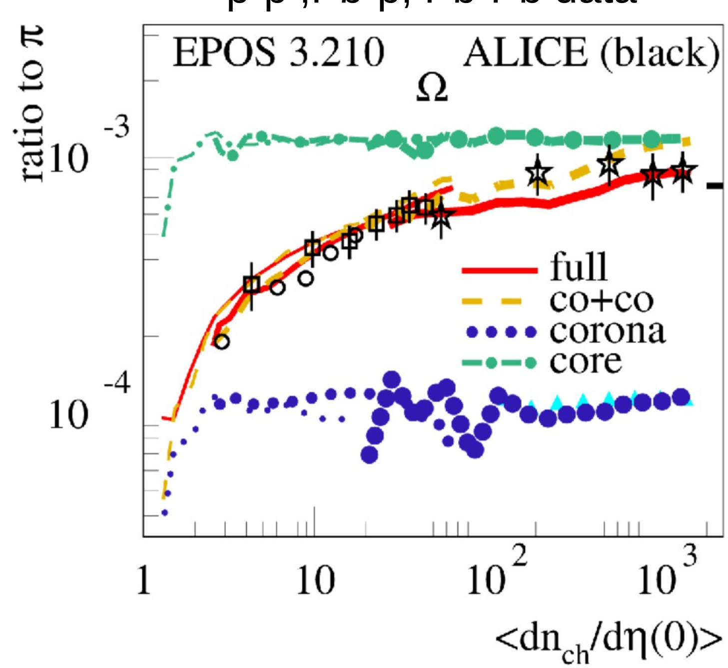


- 2 simultaneous source of particles

In EPOS (since 2005)



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

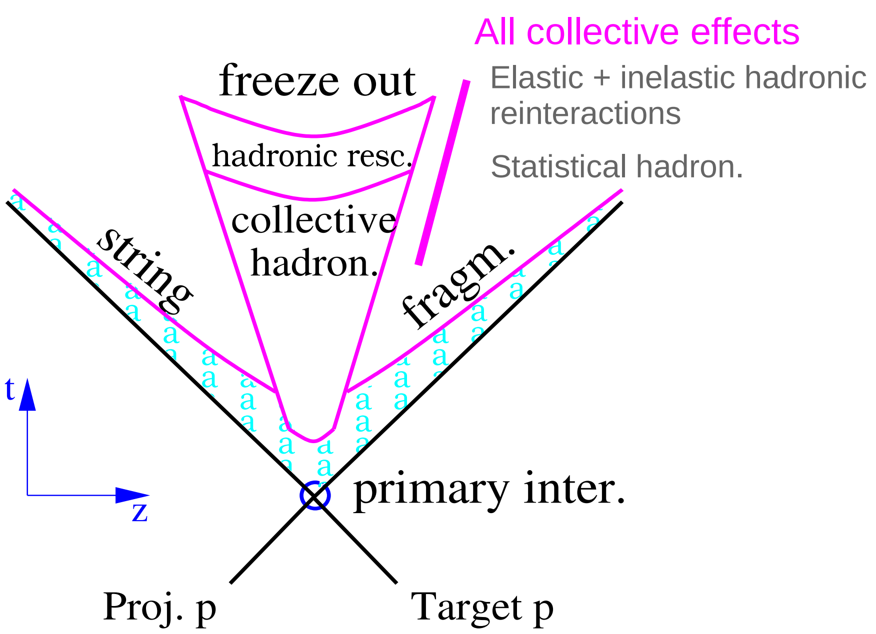


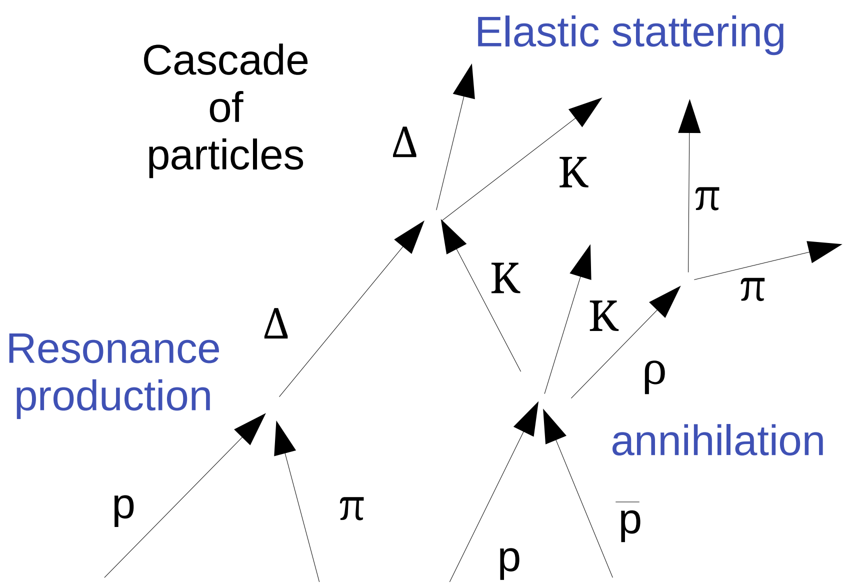
Hadronic Rescattering (HS)

Missing effect in all CR models until now !

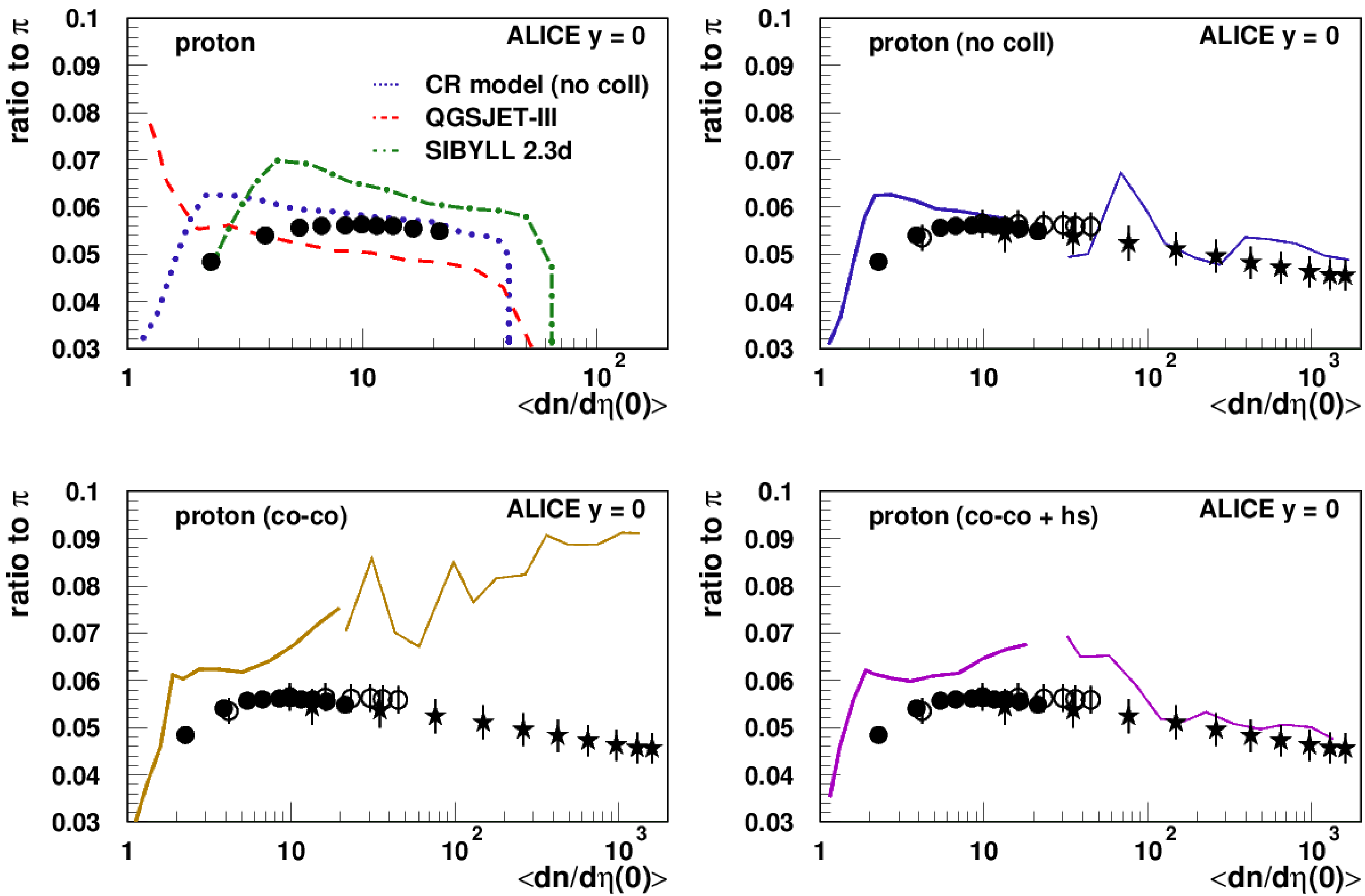
- Re-interaction of hadrons after parton hadronization (space-time evolution)
- "traditionally" used only for heavy ion collisions (until recently NOT in p-p)
- No direct impact on EAS development since forward particles escape
- But significant to large impact at midrapidity in heavy ion collisions !

  - 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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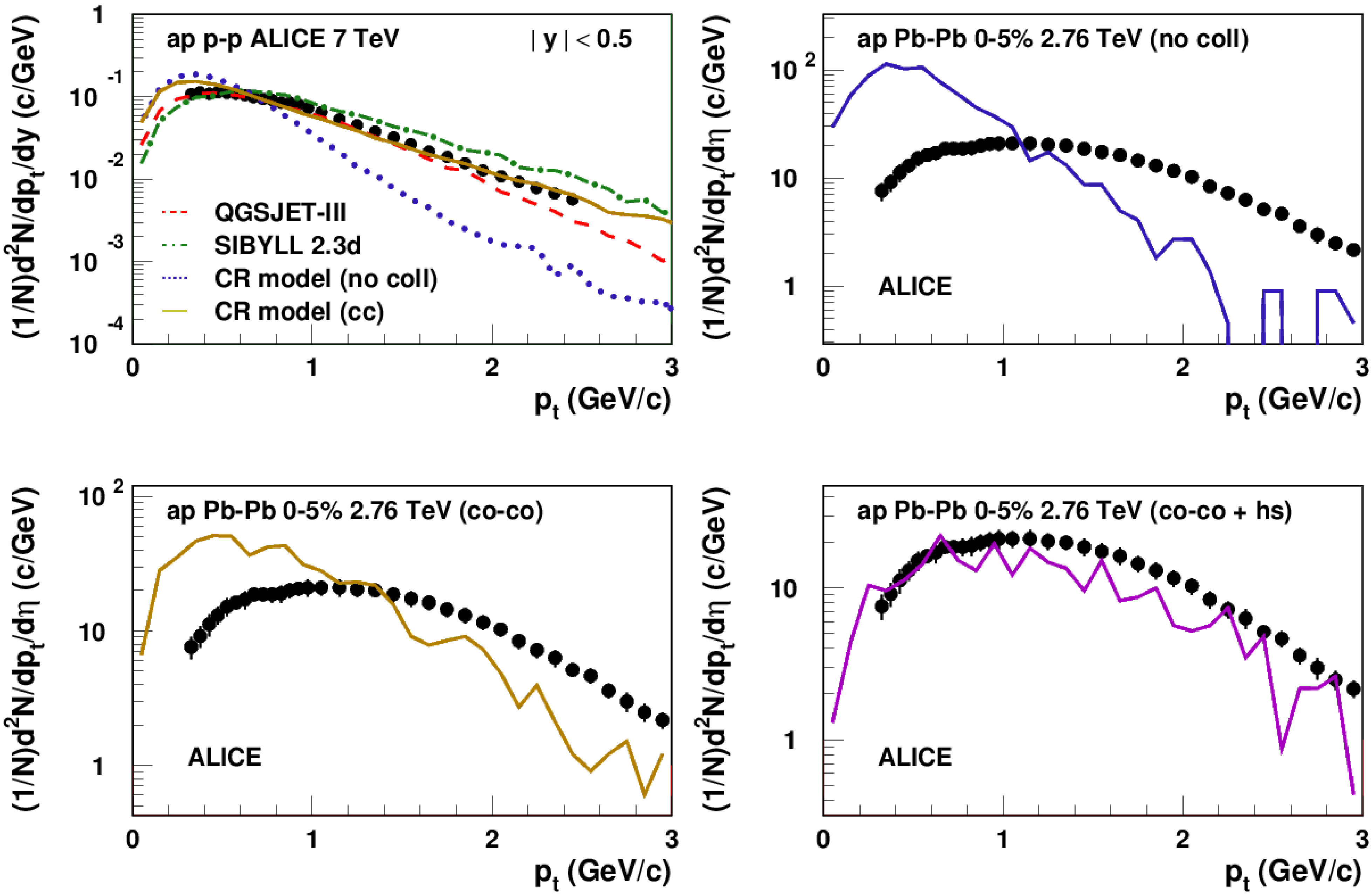
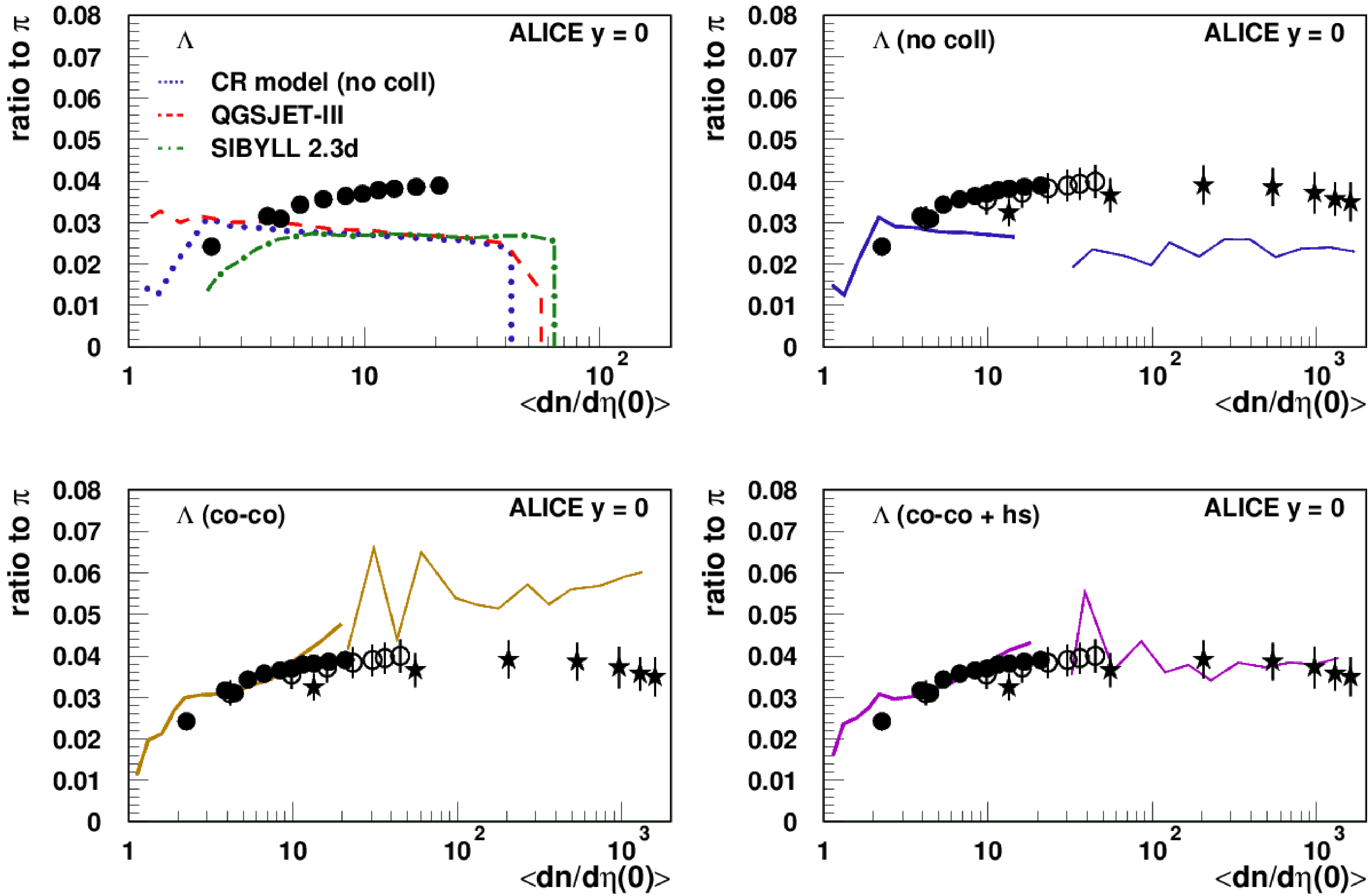
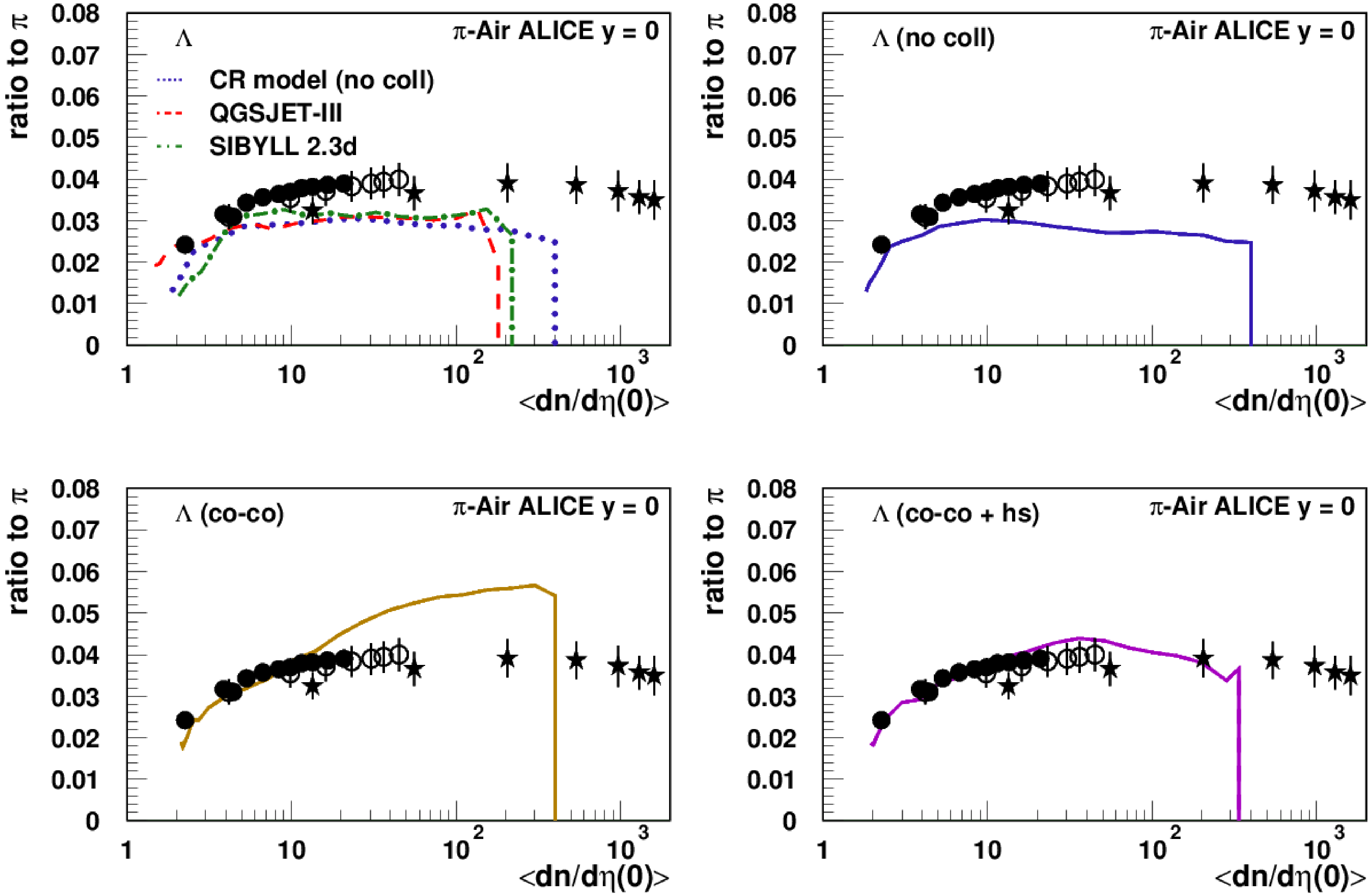


Example with Lambda particle in p-p and Pb-Pb @ LHC



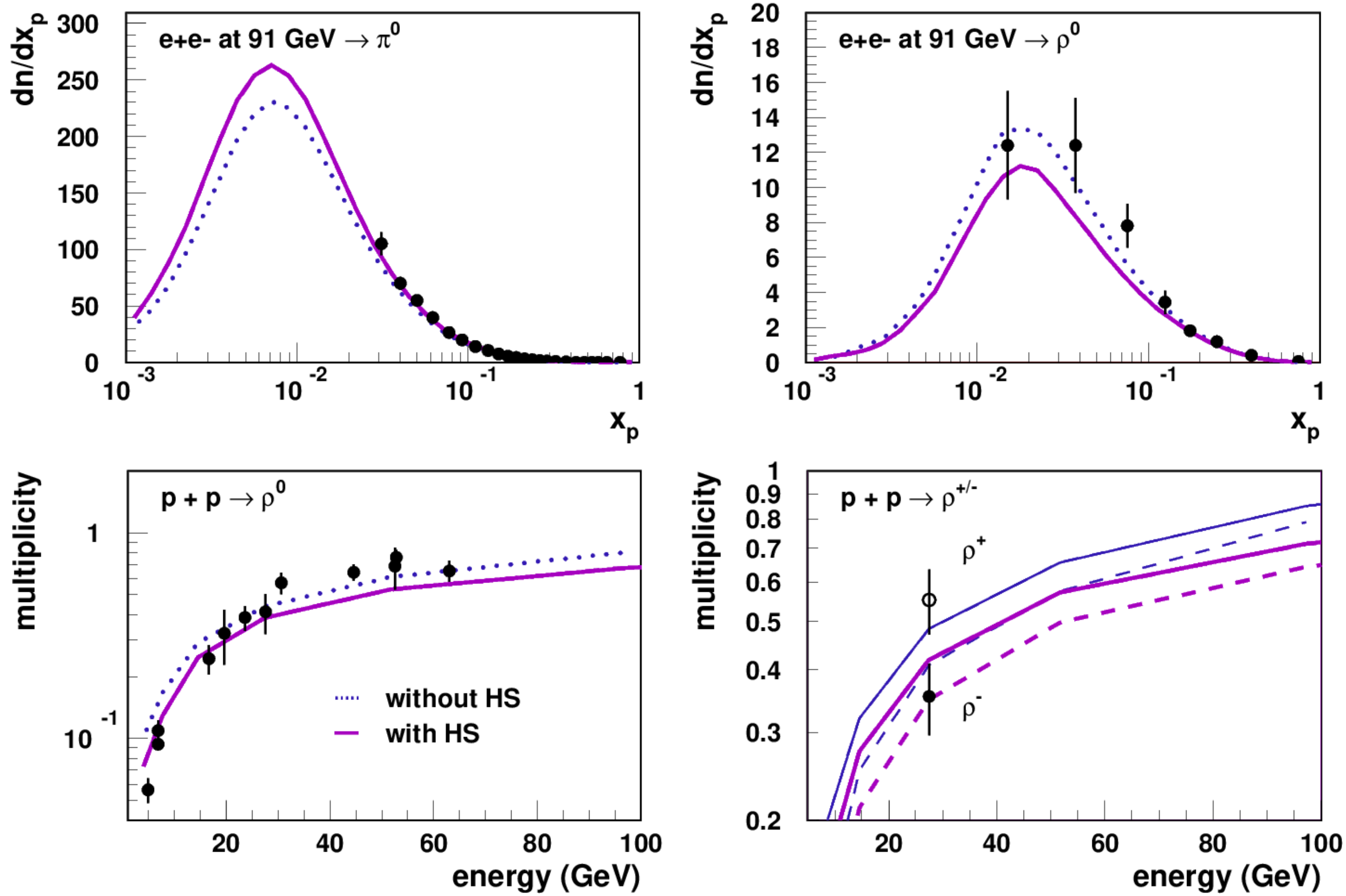
Example with Lambda particle in π-Air @ all energies



Impact of HS on light systems

If short hadronization time (~0.5 fm/c), particles close enough to interact

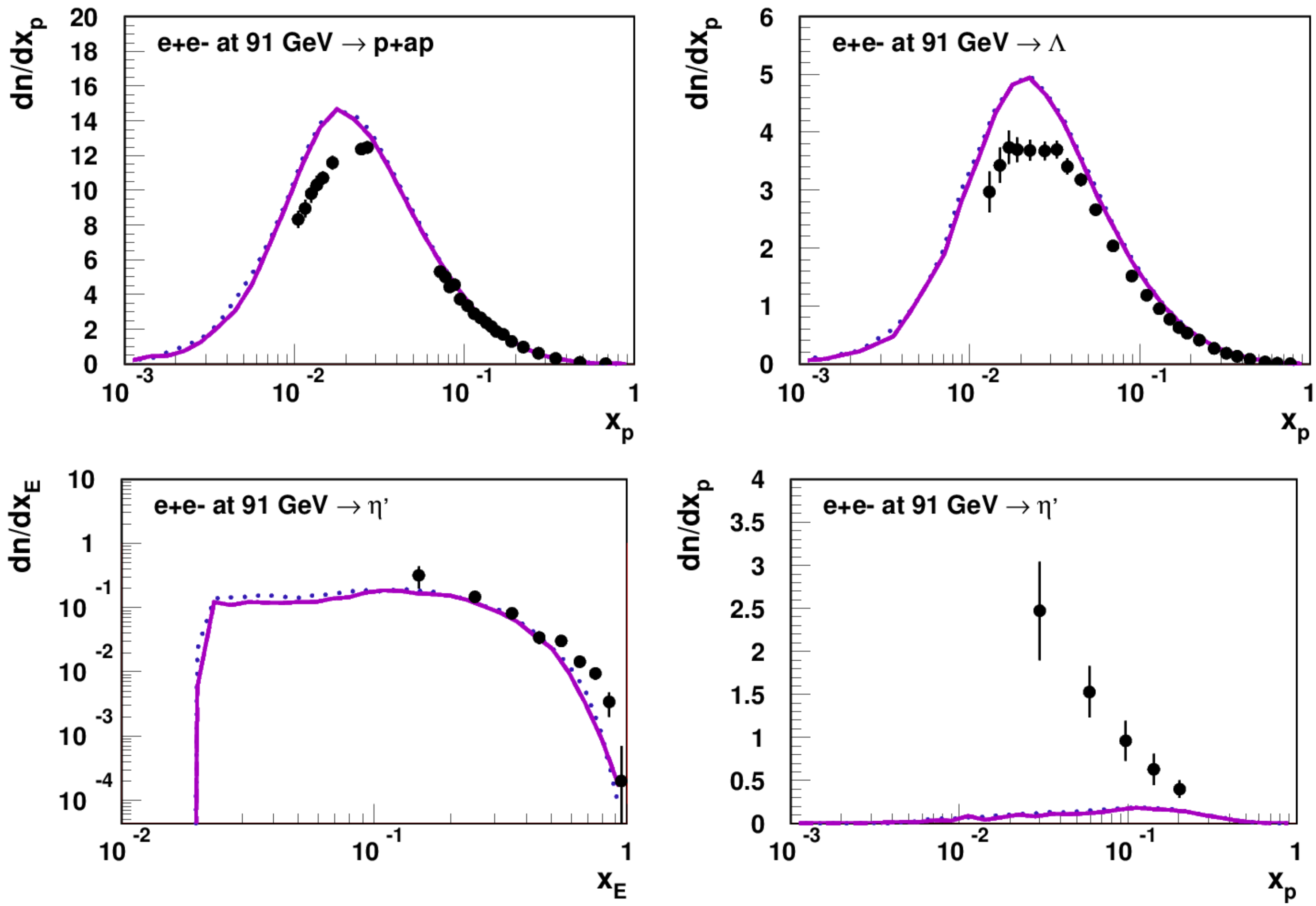
- Small but significant effect even in e+e- interactions
- Reduce ρ resonances and increase pions



LEP data

If short hadronization time (~0.5 fm/c), particles close enough to interact

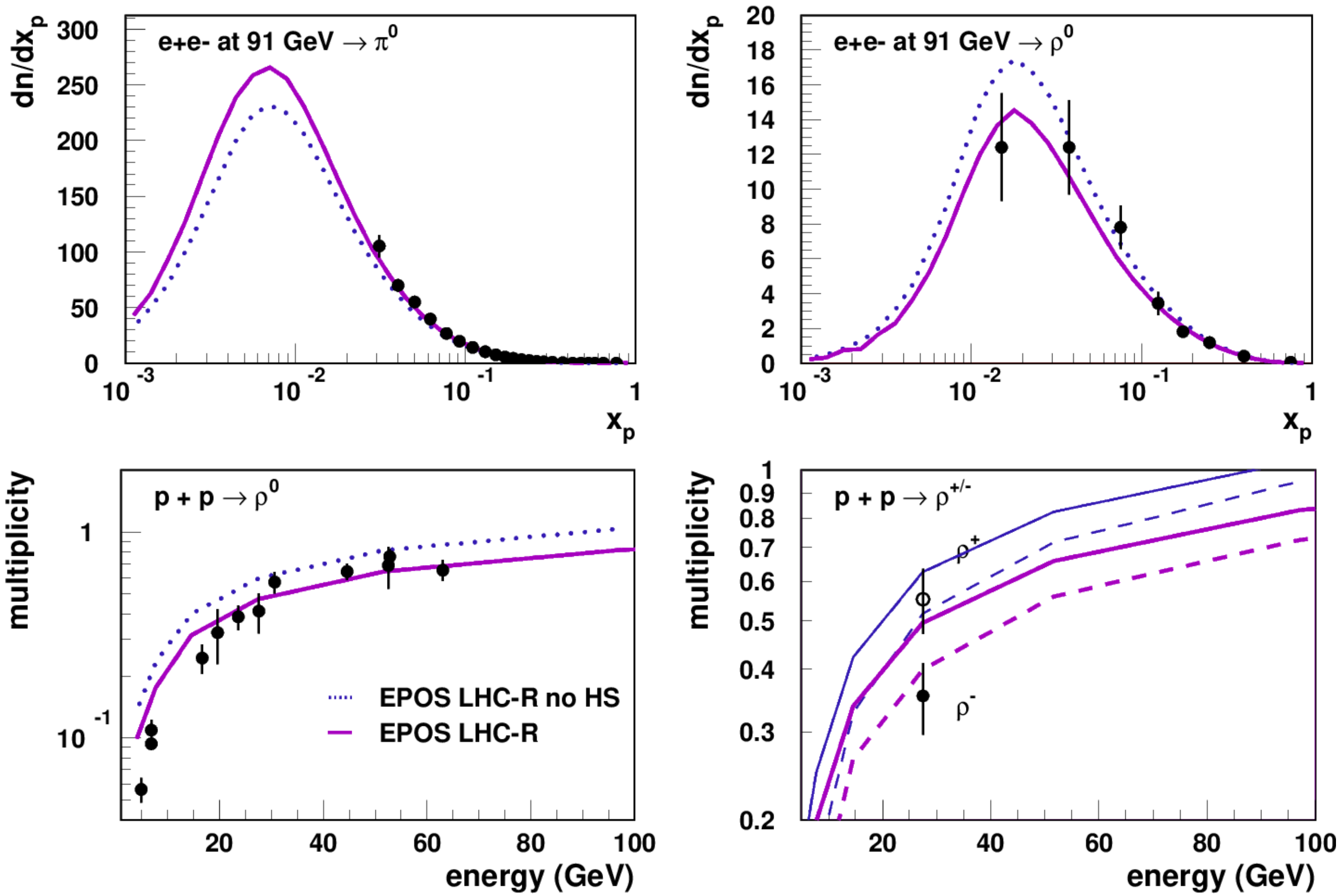
- Small but significant effect even in e+e- interactions
- More data could be considered if LEP data are used



Retune basic parameters with HS and LEP

EPOS LHC-R uses experimental constraints from LEP

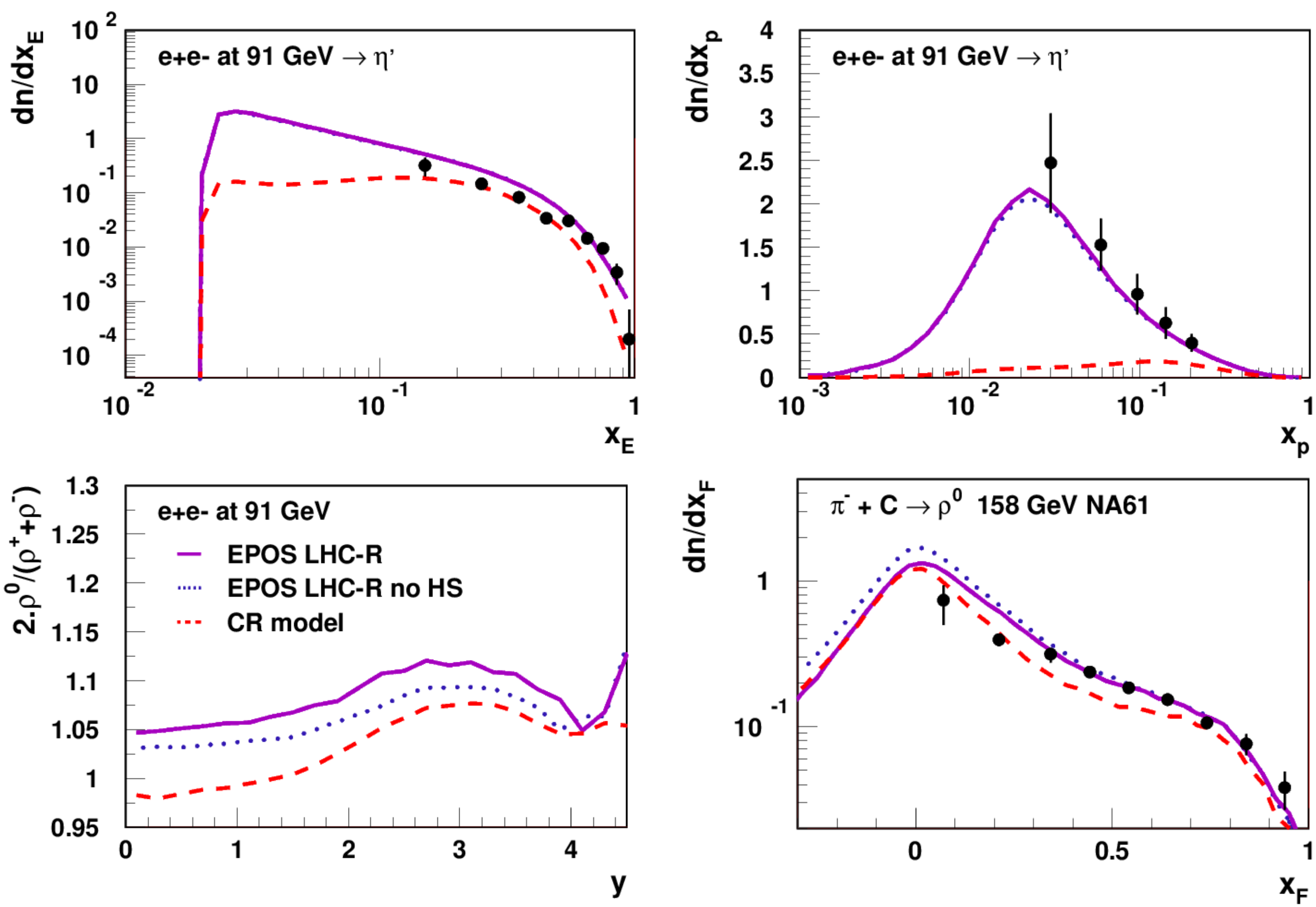
➡ Increase contribution of ρs to compensate the effect of HS



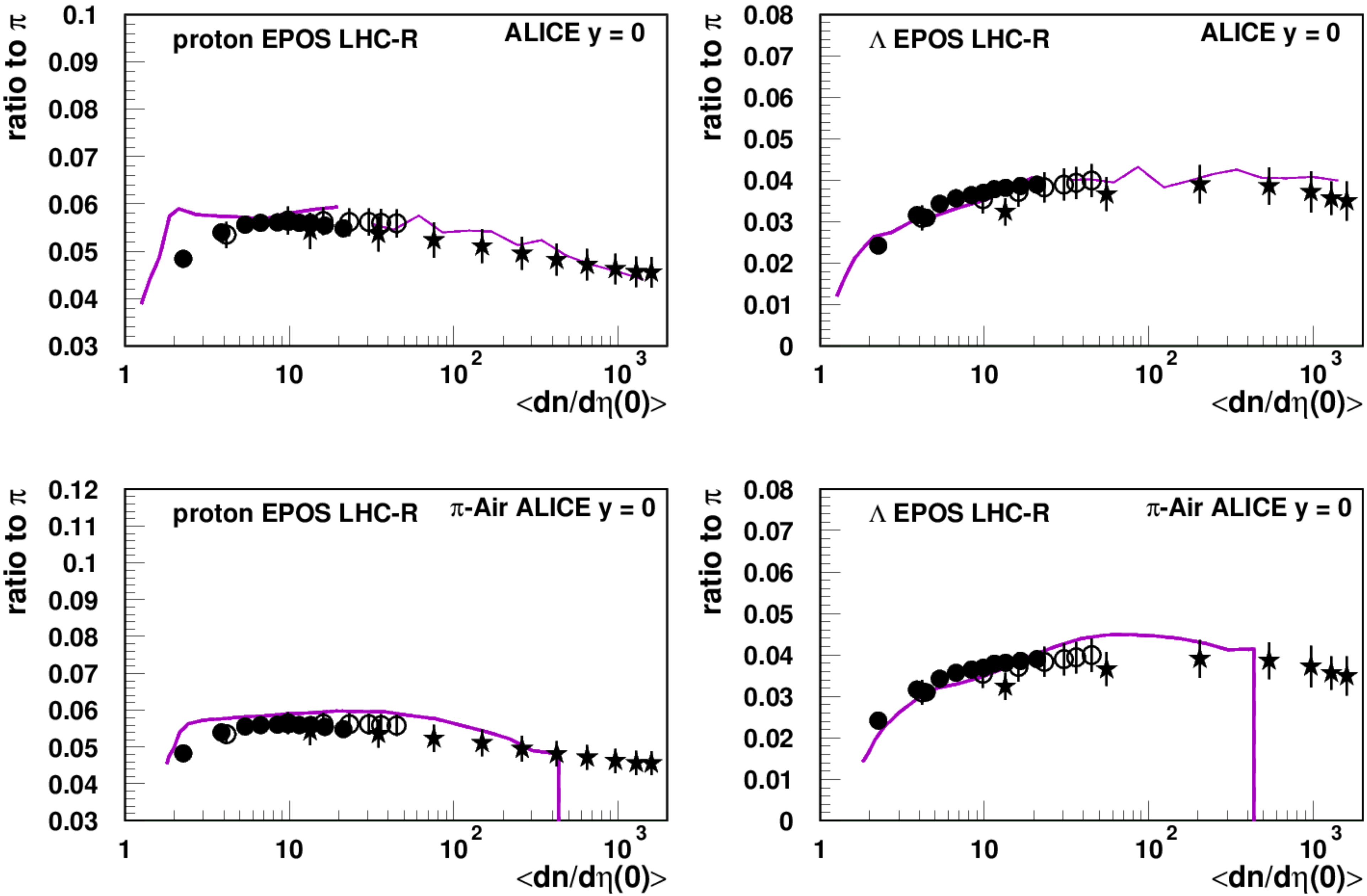
Retune basic parameters with HS and LEP

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 !



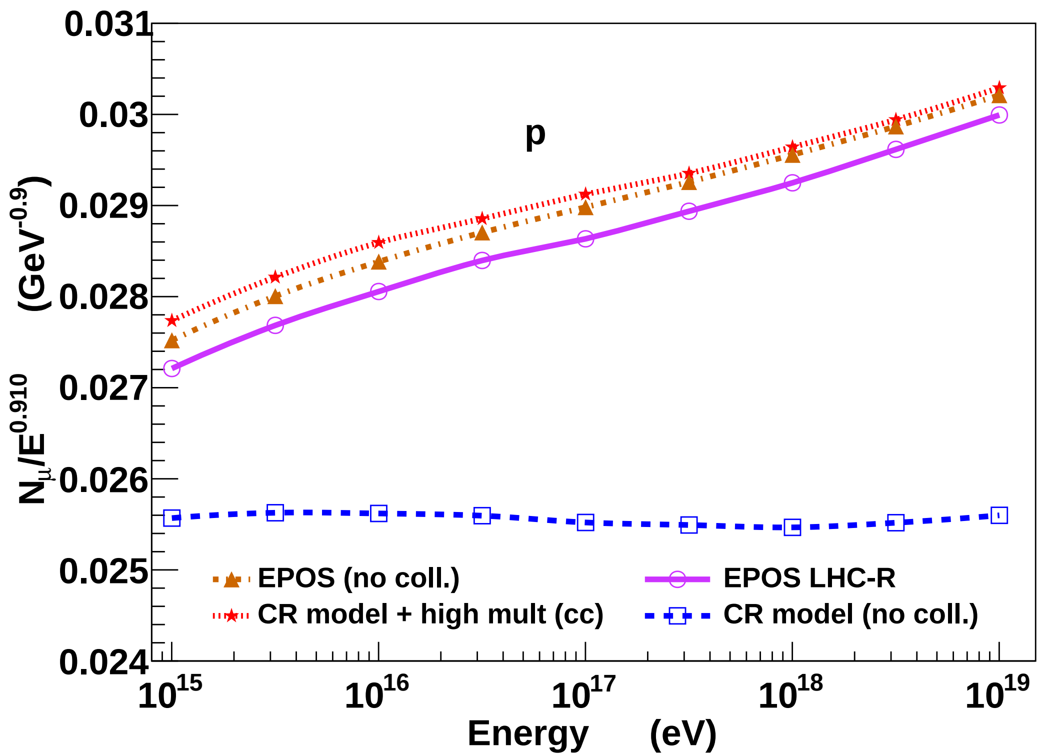
Check ALICE data

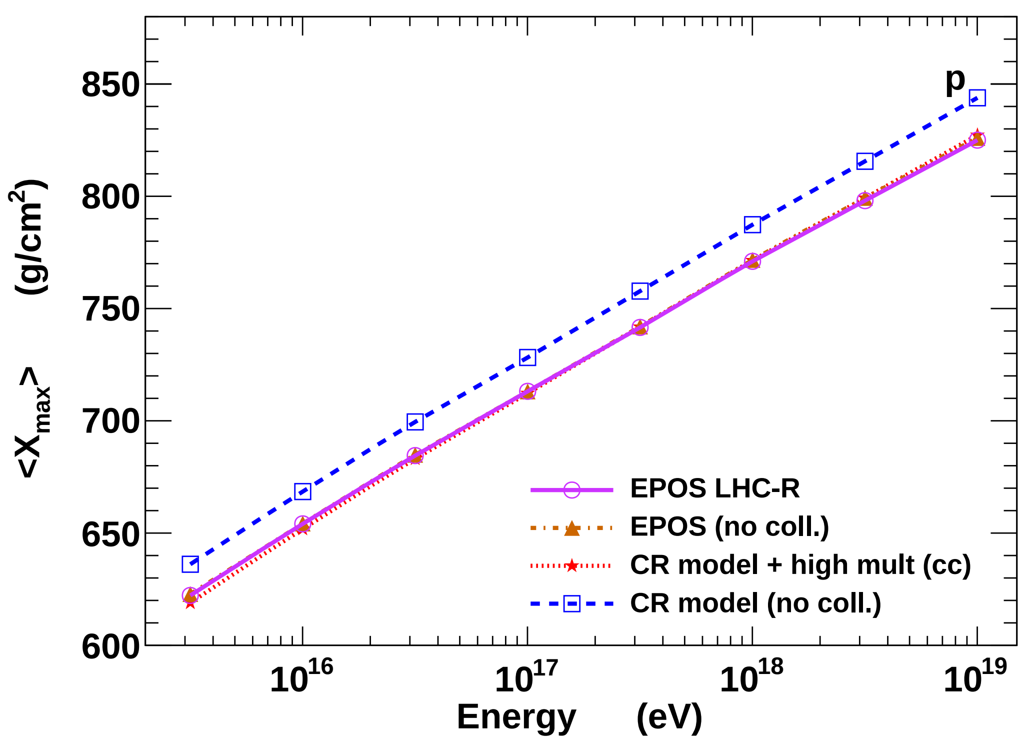


Impact on air showers

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

- Increase the number of muons by ... 10 to 20% (different slope) !
  - Large impact of the change to accommodate for core-corona (more hard)
  - But very little difference due to new tunes ????
- Change in X_{max} due to the change in multiplicity and in elasticity (anti-correlated)





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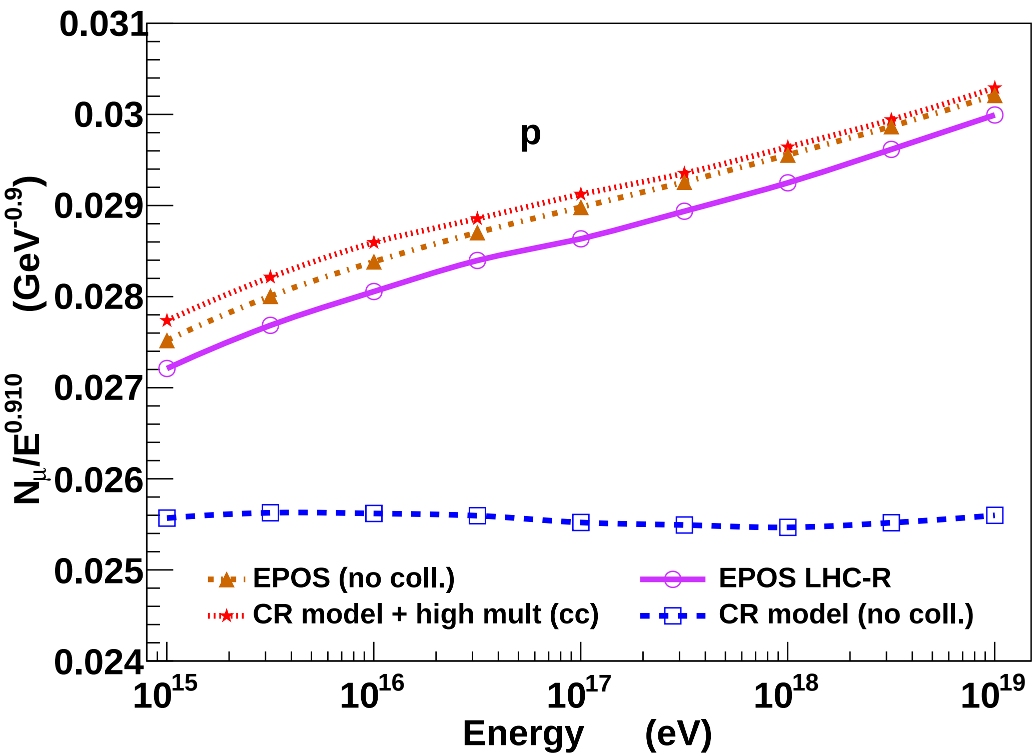
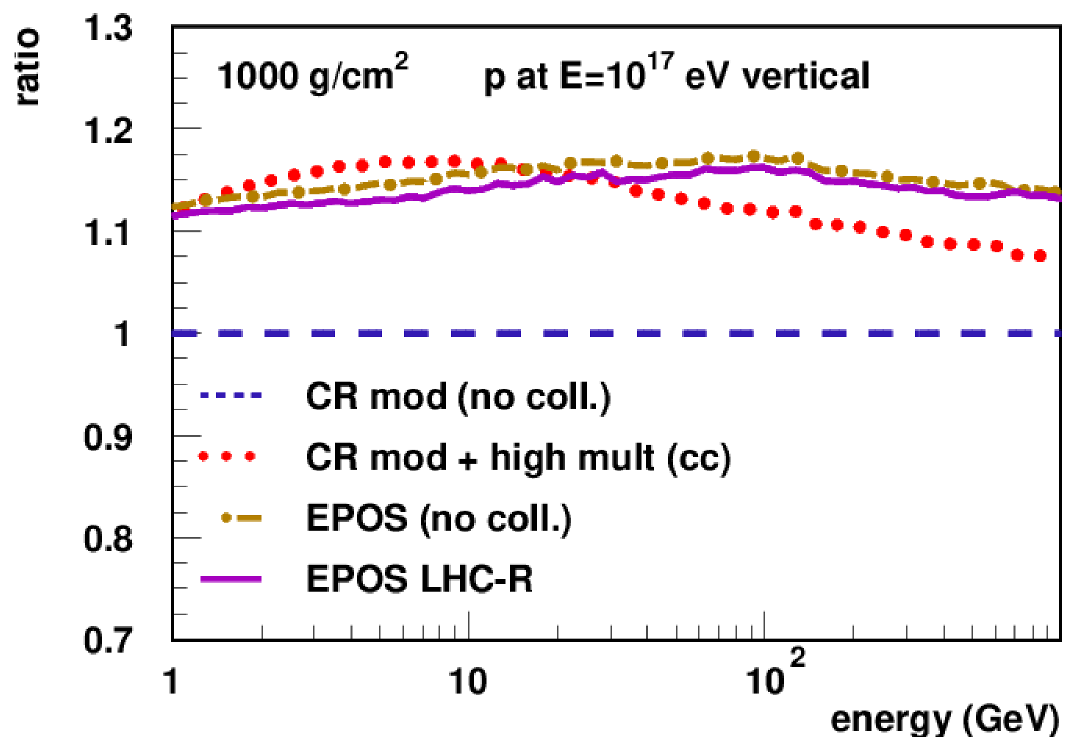
- Increase the number of muons by ... 10 to 20% (different slope) !
  - Large impact of the change in multiplicity to accommodate for core-corona
  - But very little difference due to new tunes ????
- Change in muon energy spectrum !
  - Less baryon (low energy μ) but more ρ^0 (all μ)

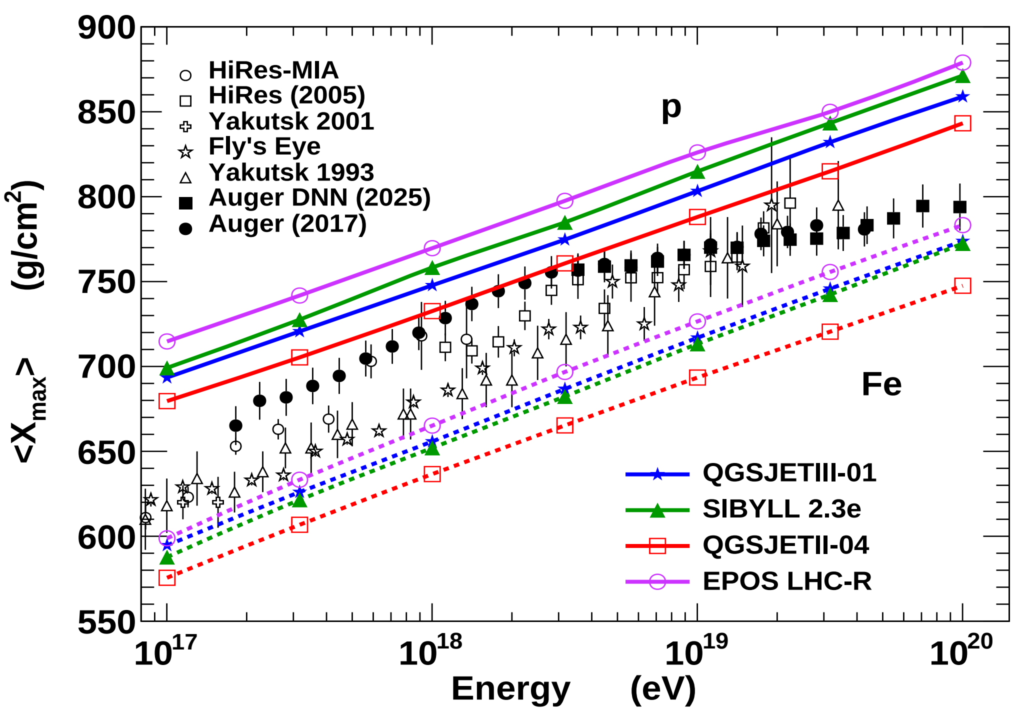


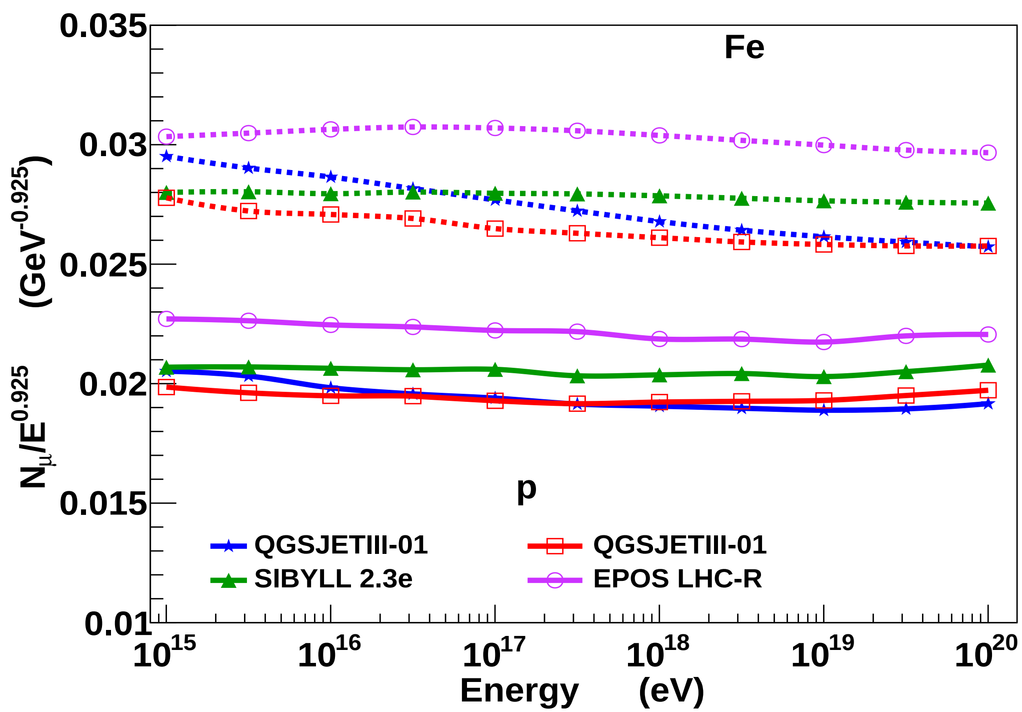


X_{max}

Global changes

- Consequence of retuning, now EPOS shifted by +20 g/cm^2
- QGSJETIII is shifted by +15 g/cm2 = EPOS LHC
- Will give heavier composition when interpreting the data
- Consequence of retuning for muons, now EPOS shifted by +7%
- Change in QGSJETIII for muons mostly at low energy (LHAASO ?)



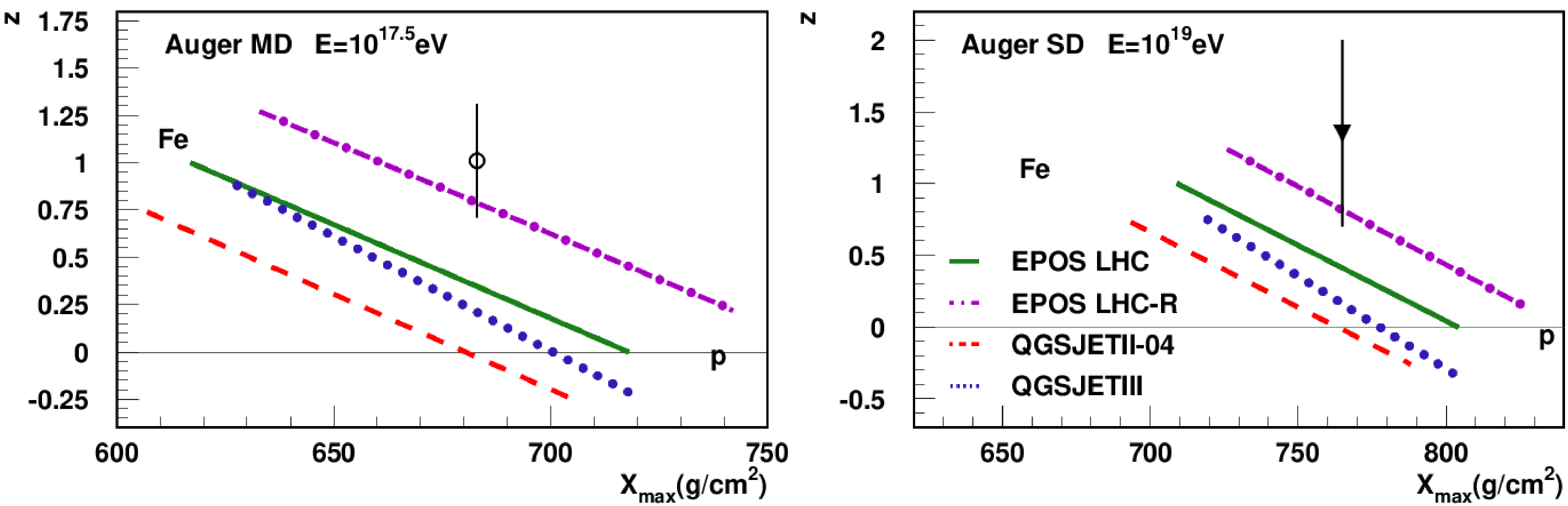


Muon Puzzle

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
  - Still no nuclear effect for hadronization !

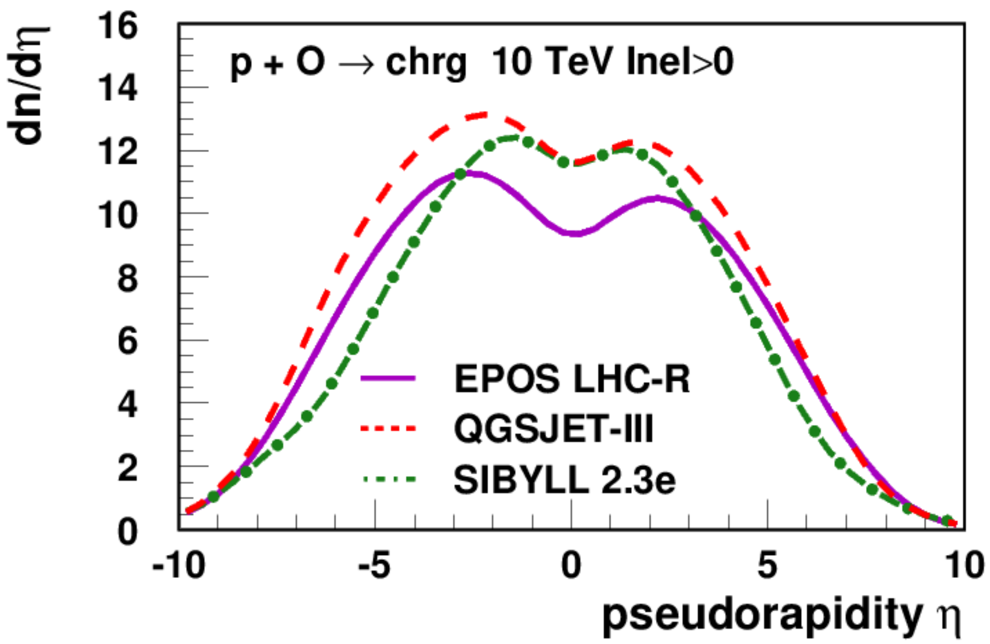
$$z = \frac{\ln N_{\mu}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}{\ln N_{\mu,\mathrm{Fe}}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}$$



Multiplicity

Collective effects are important to tune properly the models !

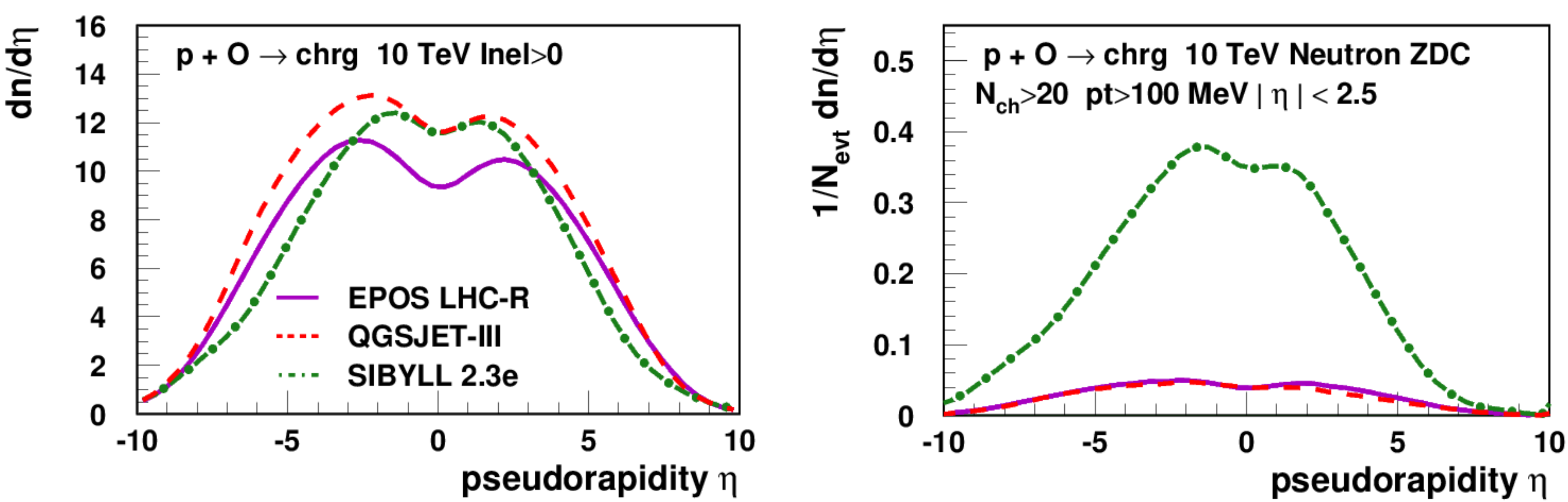
- Indirect impact on multiplicity and elasticity
  - Is it possible to predict multiplicity without collective effects ?
    - pO data
  - Is elasticity anti-correlated with multiplicity ?
    - Forward spectra vs mid-rapidity multiplicity (or # of mini-jets)



Multiplicity for pion projectile

Collective effects are important to tune properly the models !

- Still lack of constrain on pion-Air multiplicity
  - up to +/-5% uncertainty in N_μ and +/-5 g/cm^2 for X_{max}
  - Use pion exchange in p-O interactions to probe = neutron tag in ZDC (LHCf)



Multiplicity with neutron tag

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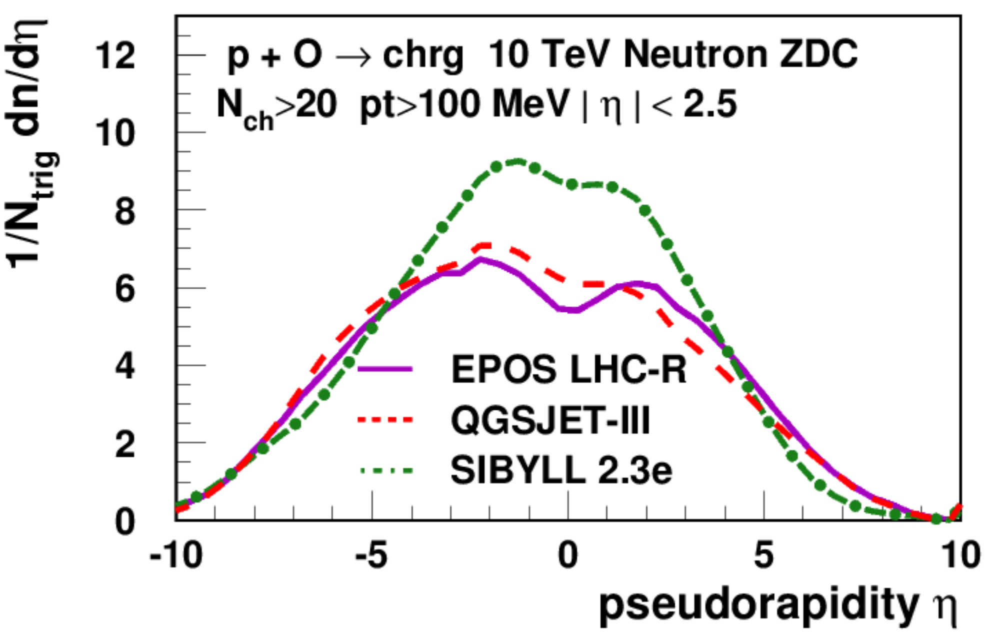
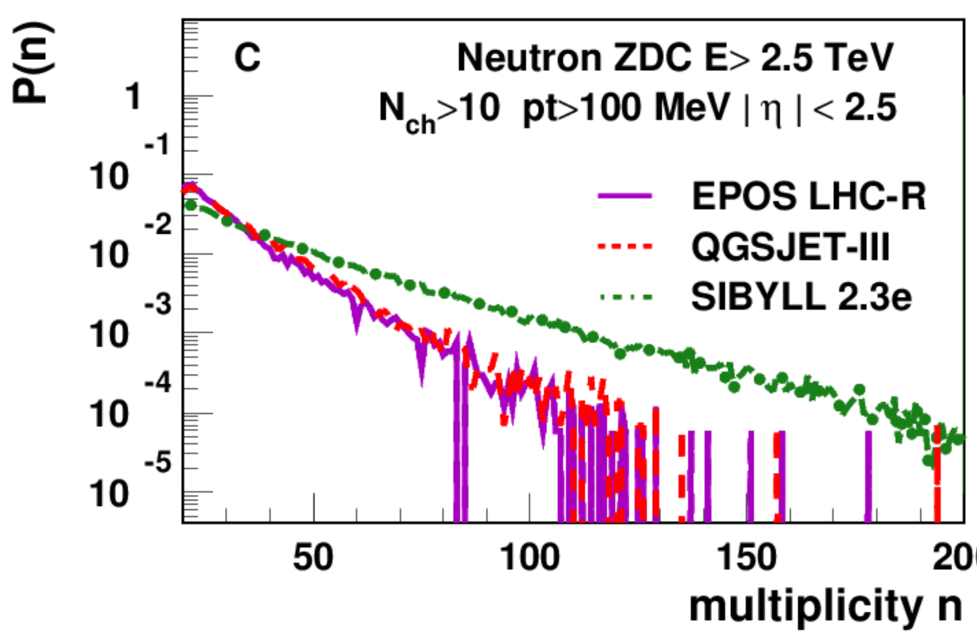
  - Use pion exchange in p-O interactions to probe = neutron tag in ZDC (LHCf)
- Trigger on forward neutron + high multiplicity at mid-rapidity to select pion exchange interaction (around 50% in EPOS)

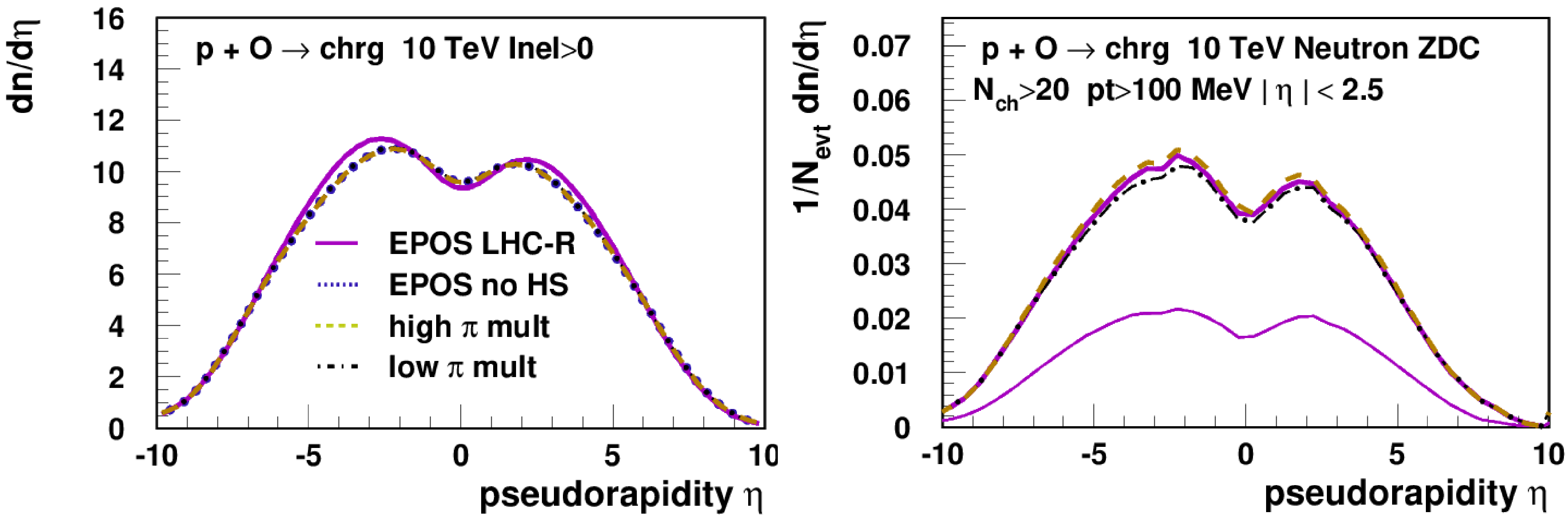




Multiplicity with neutron tag

Collective effects are important to tune properly the models !

- Still lack of constrain on pion-Air multiplicity
  - Can we get the sensitivity to test the π-O / p-O in a given model ?
- Trigger on forward neutron + high multiplicity at mid-rapidity to select pion exchange interaction (around 50% in EPOS)



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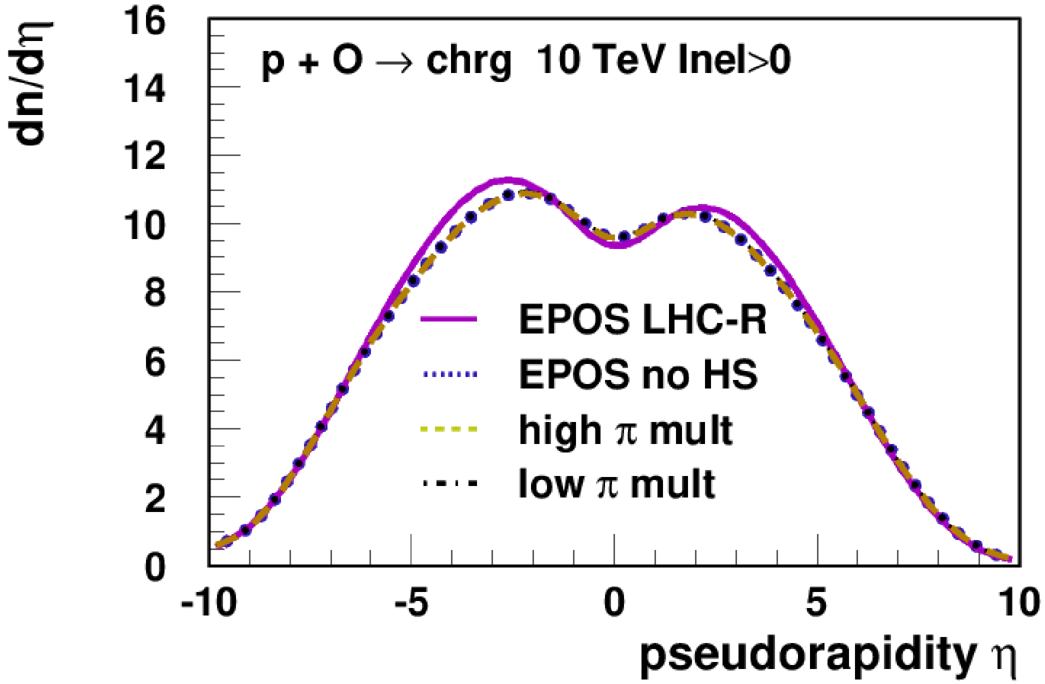
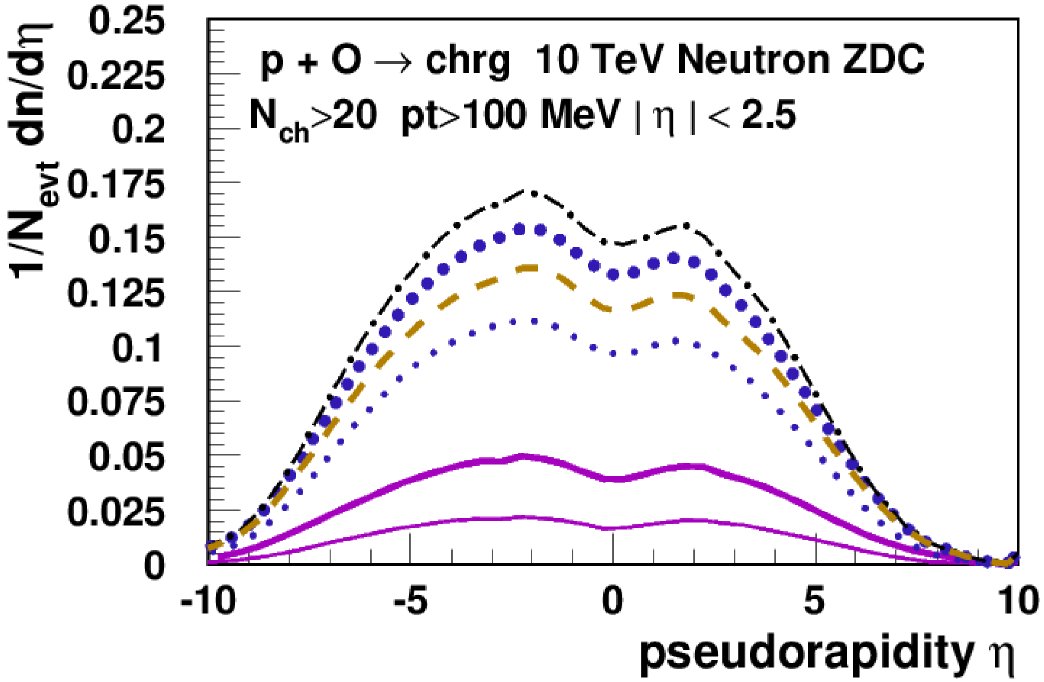
- Trigger on forward neutron + high multiplicity at mid-rapidity to select pion exchange interaction (around 50% in EPOS)
  - Dependence on hadronic rescattering in EPOS LHC-R … to be confirmed ?

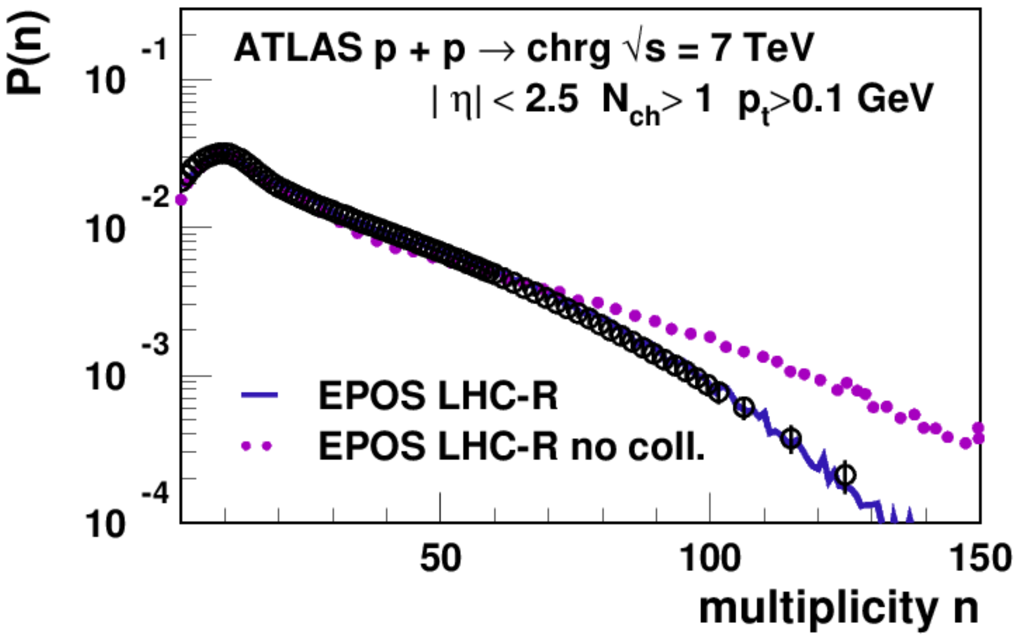




Future measurements at LHC

Hadronic rescattering and collective effects are important to tune properly the models !

- Is this approach fully correct ?
  - Need data to confirm the role/presence of hadronic rescattering even in low multiplicity system (mid-rapidity)
  - Need forward data for model validation
    - If model is validated, mid rapidity data are very constraining
- Test collective effects
  - multiplicity/hard vs soft
  - strangeness/baryon vs multiplicity
  - Pt ratios
  - How forward does it goes ?
    - LHCb !
- Measure resonances:
  - can we confirm that $\rho^0/\rho^{+/-} > 1$



Outlook

- **Updated results of cross-sections, multiplicity and diffraction/elasticity**
  - 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 as well as higher mass resonances like η′ or $f_0(980)$
  - Evolution of strangeness with multiplicity
    - Different type of hadronization and impact on apparent multiplicity
  - **Combination of the 3 effects improve significantly the description of EAS !**
- **Source of muon puzzle probably due to the fact that collective effects including hadron rescattering were always neglected**
  - Change the correlation between mid-rapidity (data and tuning) and forward particle production (EAS)
- **Fusion of EPOS LHC-R and EPOS 4 → additional constraints from hydro.**

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

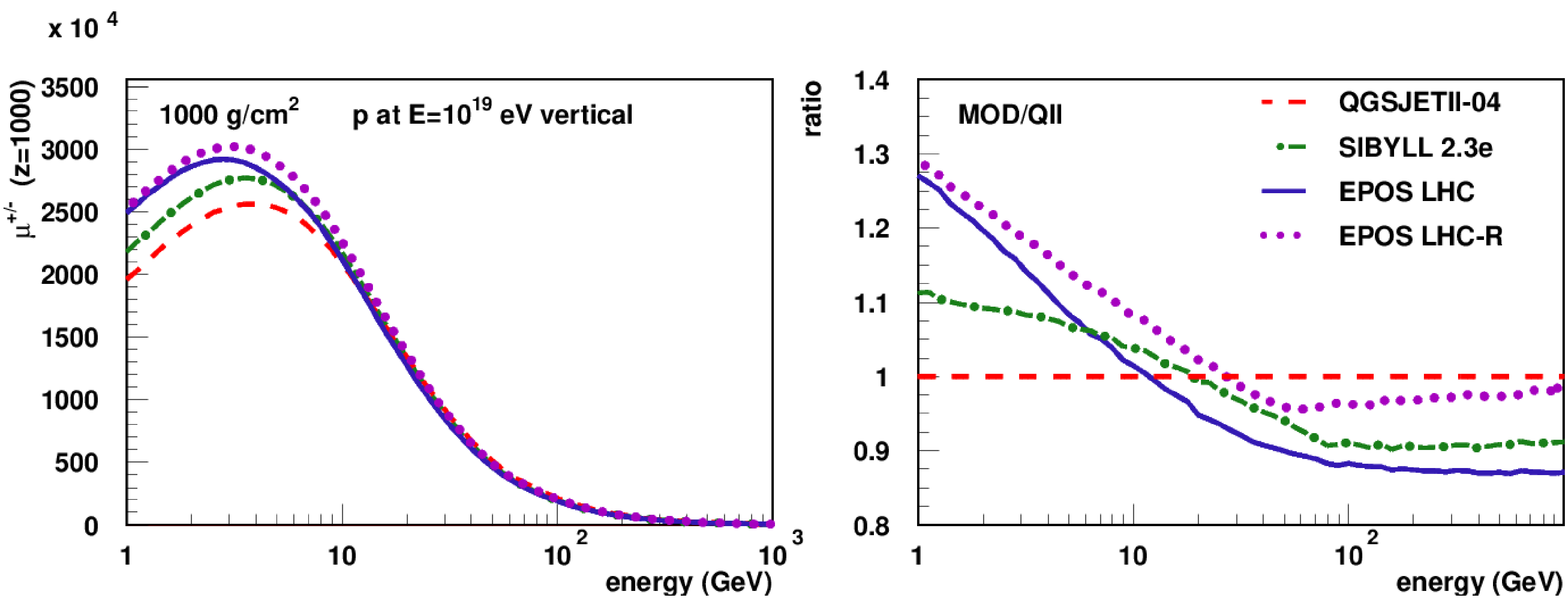
More data needed to validate models and reduce uncertainties!

Thank you !

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)



E_μ

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  - Parallel shift changing all muon energies
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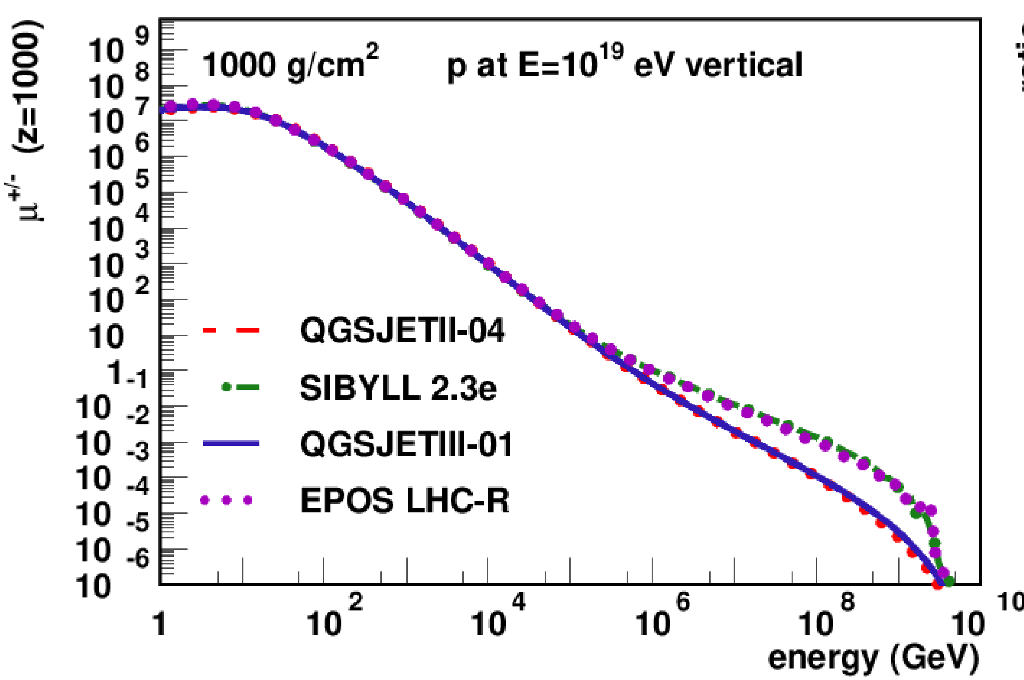
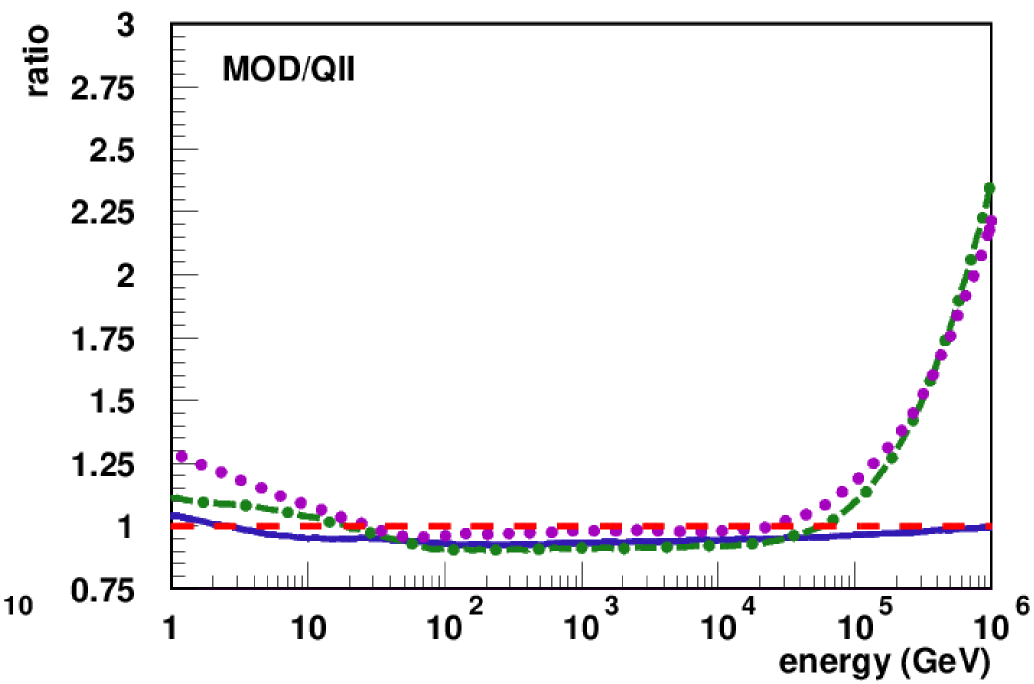
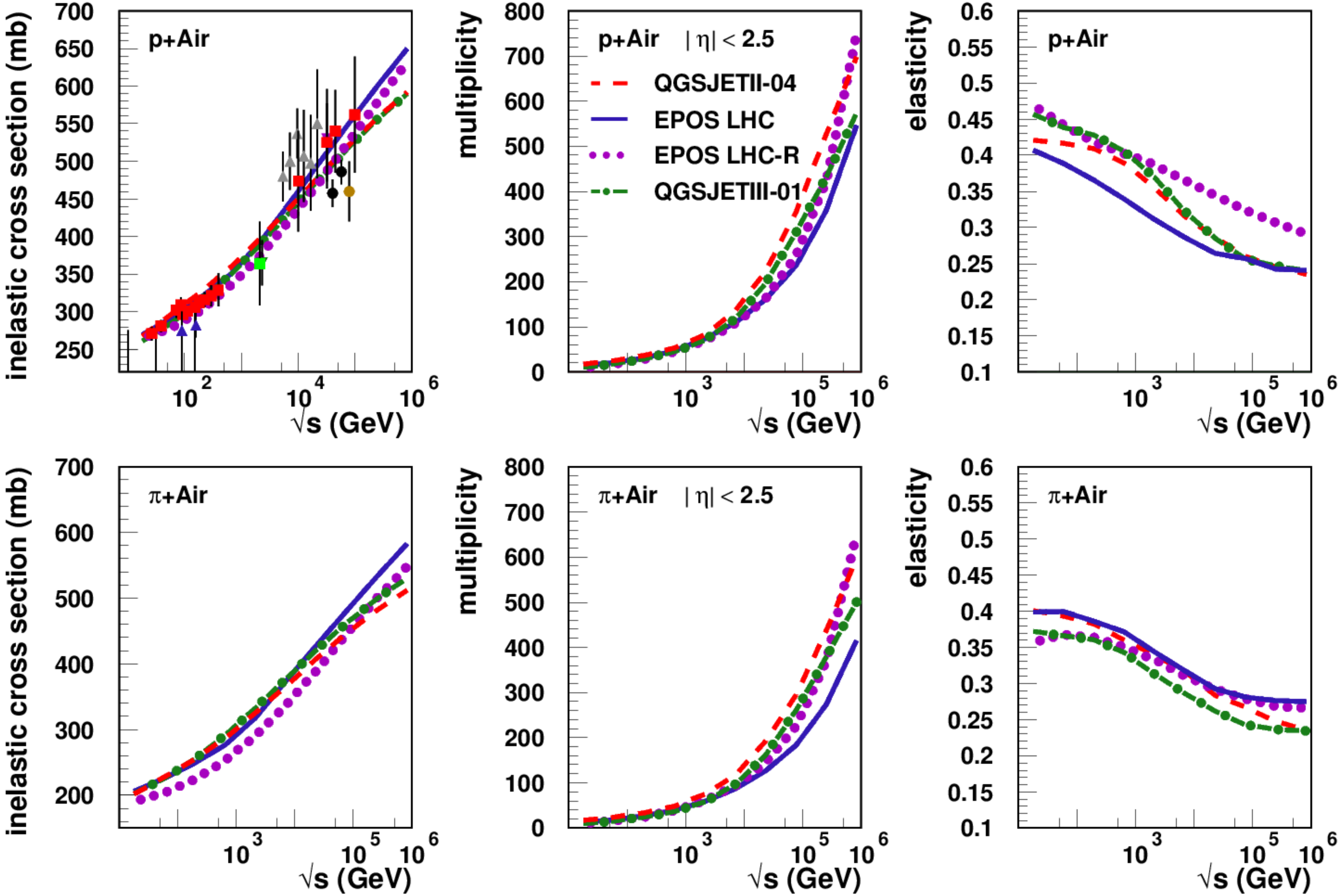
- Better tune of kaons (indirect impact of core-corona)
- Very high energy muons from charm ! (background for neutrino analysis)





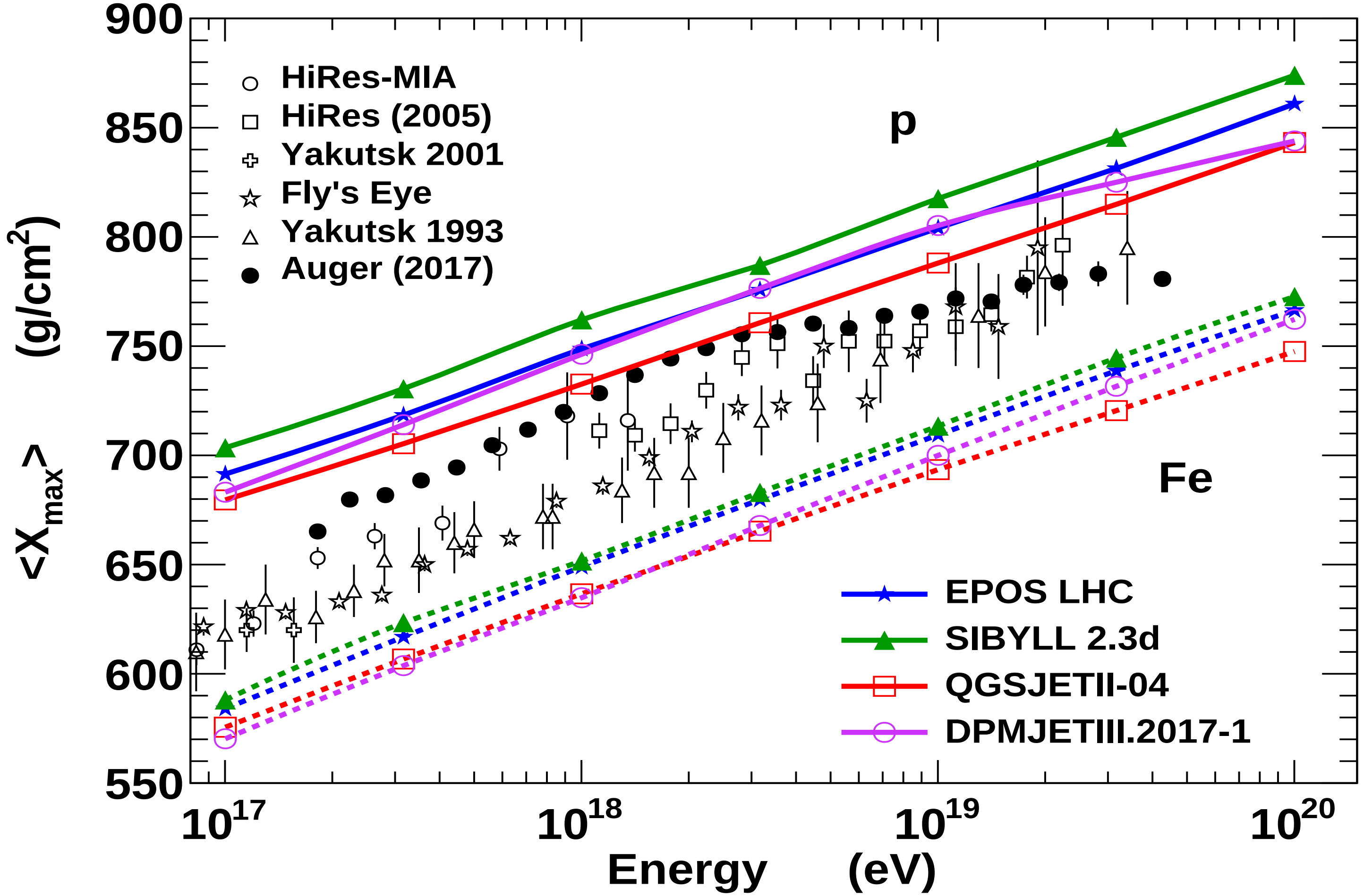
EPOS LHC-R interaction with Air



X_{max}

Old models

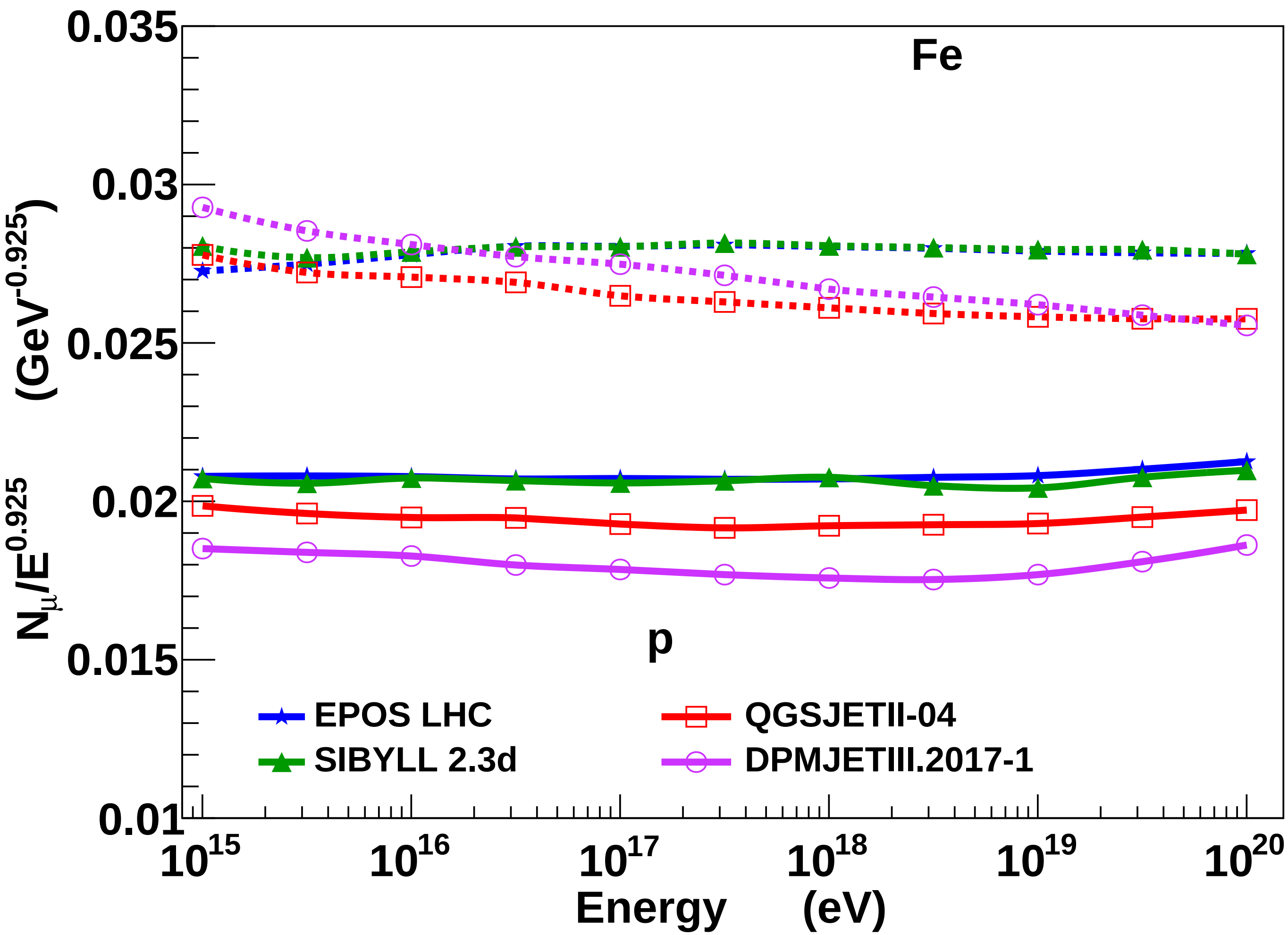
- Model range around EPOS LHC +/- 15 g/cm2
- Relatively light composition using QGSJETII-04



N_μ

Old models

- 15% difference between models (10% not counting DPMJET)
- Not enough in comparison to data ("muon puzzle")



Constraints from Correlated Change

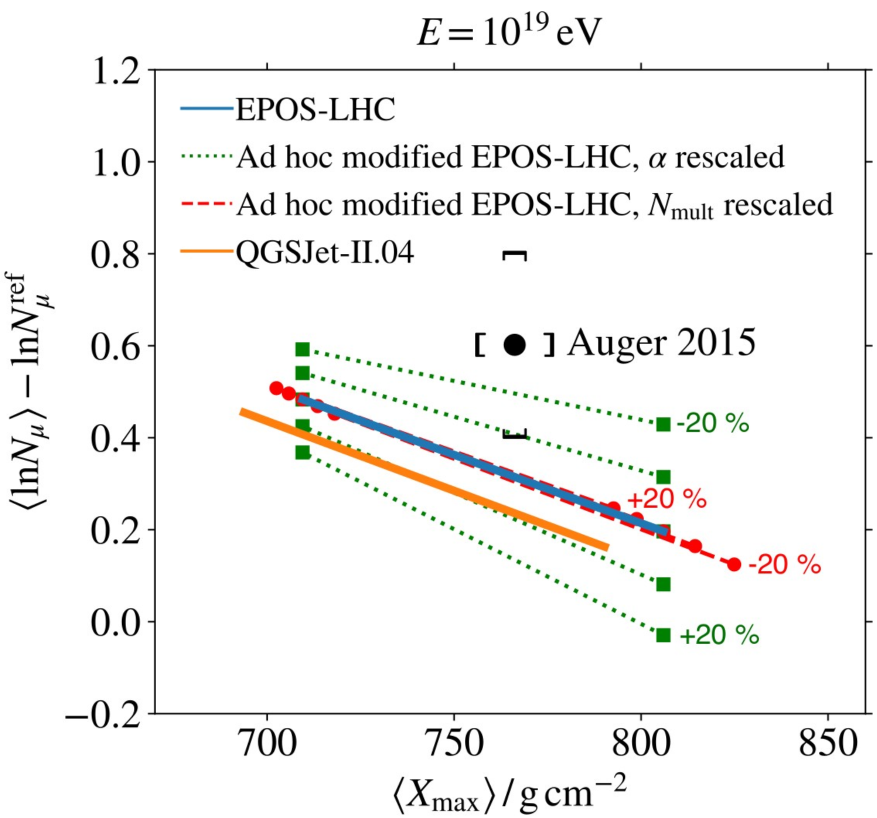
- **One needs to change energy dependence of muon production by ~+4%**

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

- **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}

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

- $$\beta = \frac{\ln\left(N_{mult}-N_{\pi^0}\right)}{\ln\left(N_{mult}\right)} = 1 + \frac{\ln\left(1-\alpha\right)}{\ln\left(N_{mult}\right)}$$
  - +4% for β ➤ -30% for $\alpha = \frac{N_{\pi^0}}{N_{mult}}$



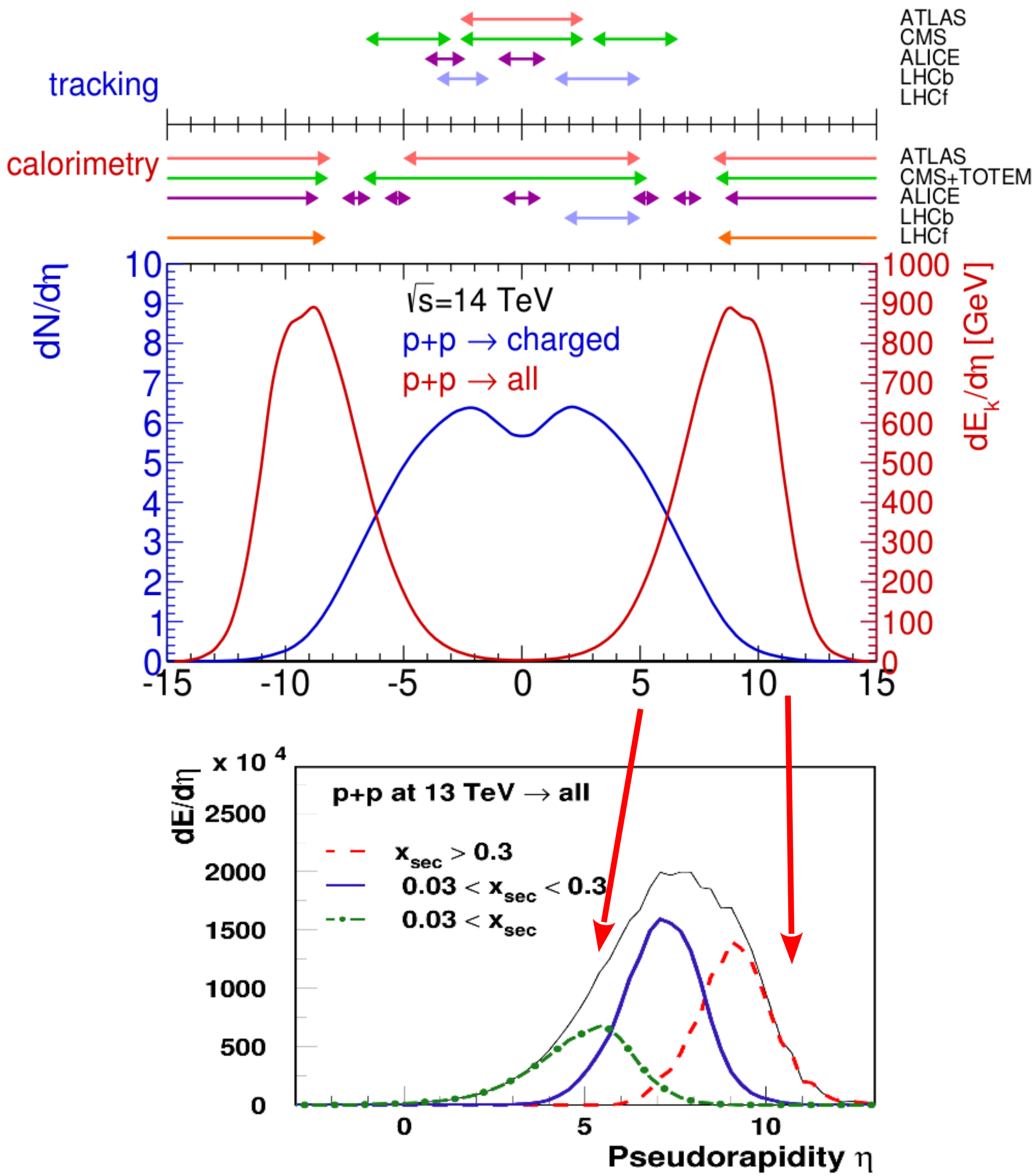
Plot by H. Dembinski

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

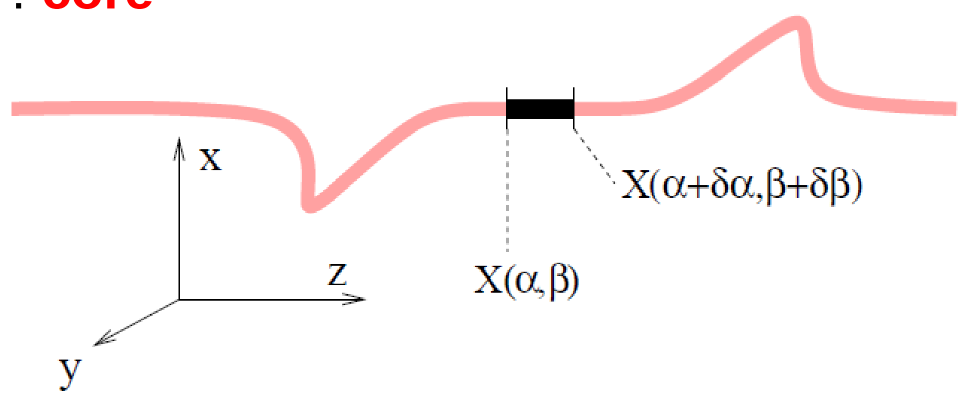


- **p-p data mainly from "central" detectors**
  - pseudorapidity η=-ln(tan(θ/2))
  - θ=0 is midrapidity
  - θ>>1 is forward
  - θ<<1 is backward
- **Different phase space for LHC and air showers**
  - most of the particles produced at midrapidity
    - important for models
  - most of the energy carried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

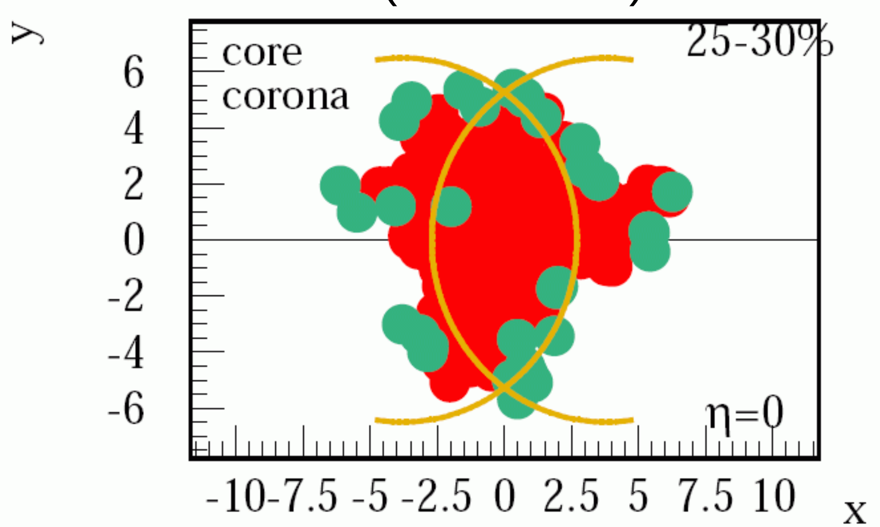
A 3rd way : the core-corona approach

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