EPOS.LHC-R :
A global approach to solve the muon puzzle

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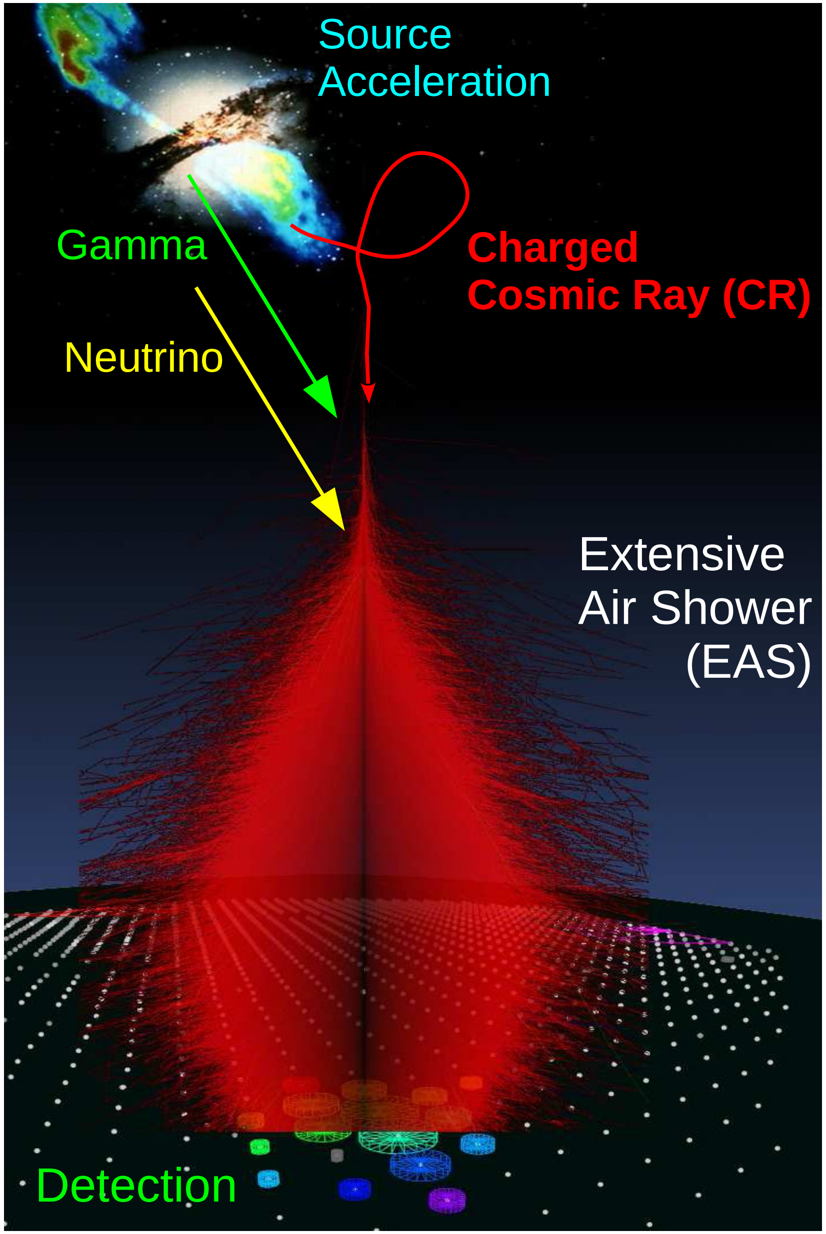
Outline

- **Introduction**
- **Muon puzzle**
- **Predictions for air showers (EAS) of the new models**
  - Model comparison
  - X_{max} and μ
- **A global approach to do hadronic interactions**
  - Impact of Hadronic Rescattering (HS)
- **Remaining uncertainties and pO run**

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

Astroparticles

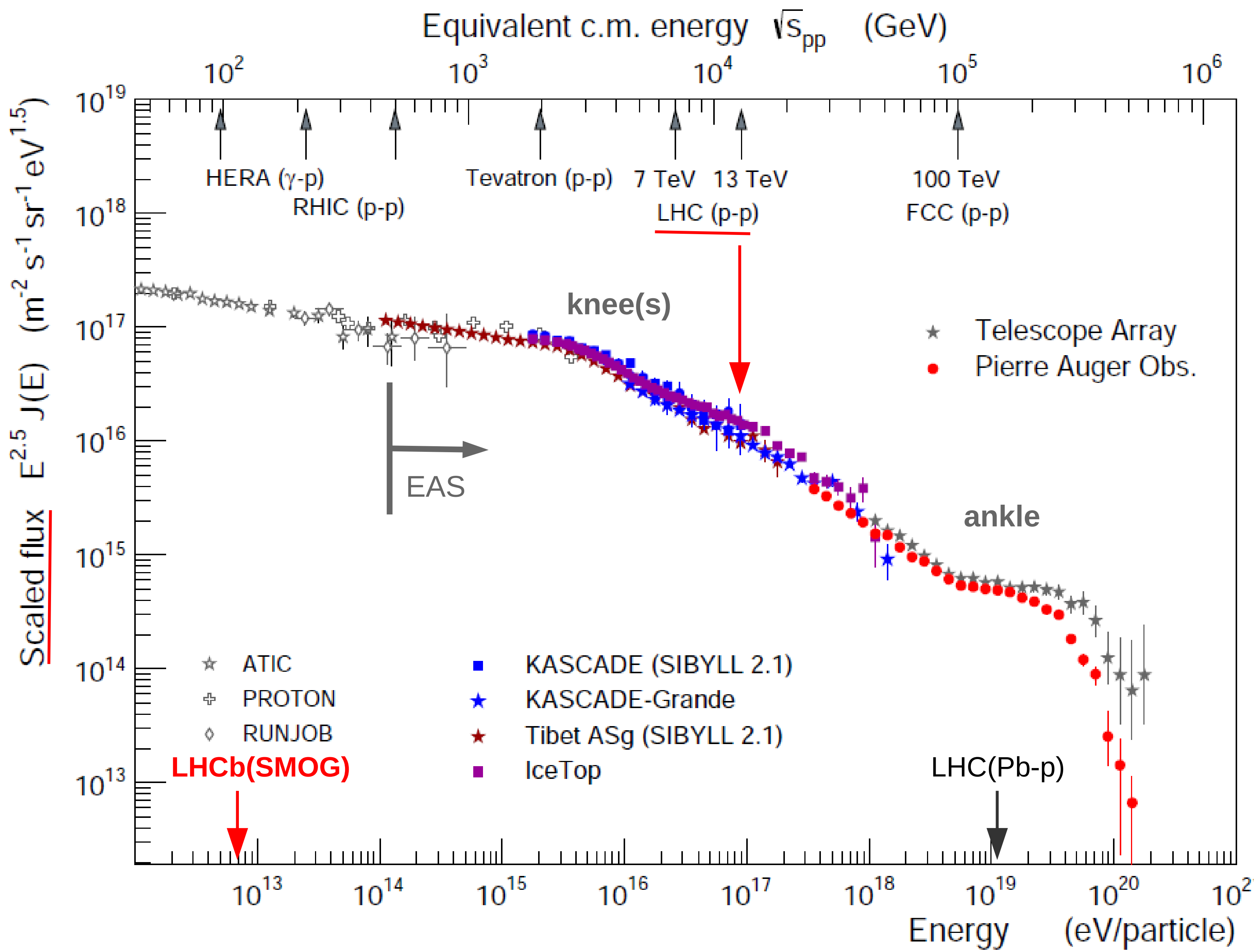


From R. Ulrich (KIT)

- **Astronomy with high energy particles**
  - gamma (straight but limited energy due to absorption during propagation)
  - neutrino (straight but difficult to detect)
  - charged ions (effect of magnetic field)
- **Measurements of charged ions**
  - source position (only for light and high E)
  - energy spectrum (source mechanism)
  - mass composition (source type)
    - light = hydrogen (proton)
    - heavy = iron (A=56)
  - test of hadronic interactions in EAS via correlations between observables.

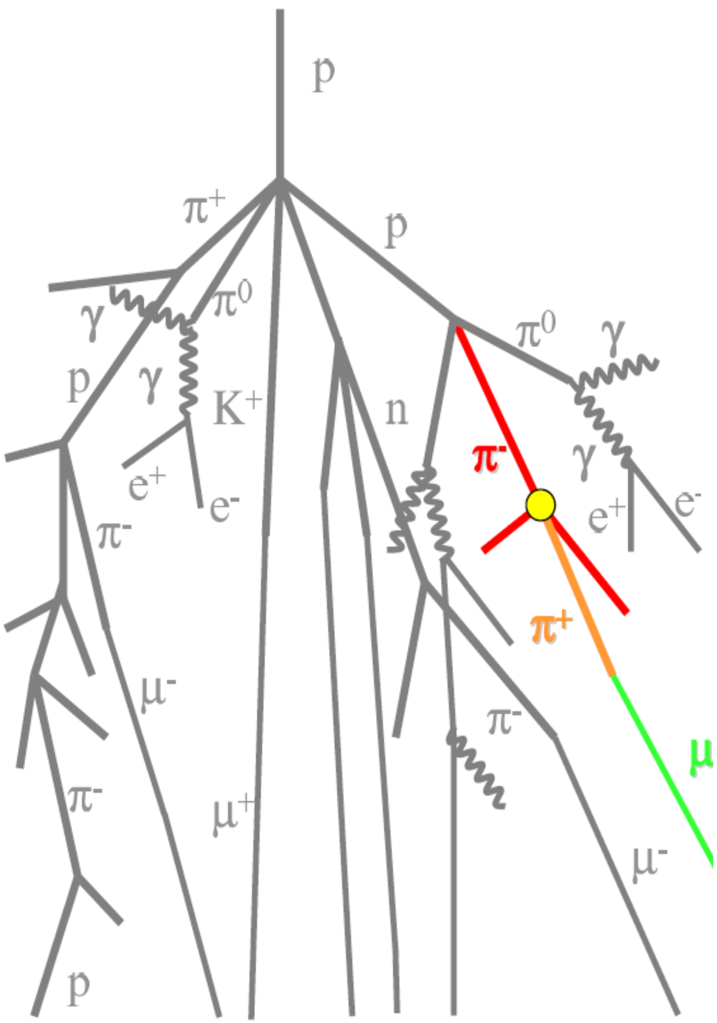
mass measurements should be consistent and lying between proton and iron simulated showers if physics is correct

Energy Spectrum



R. Engel (KIT)

Extensive Air Shower



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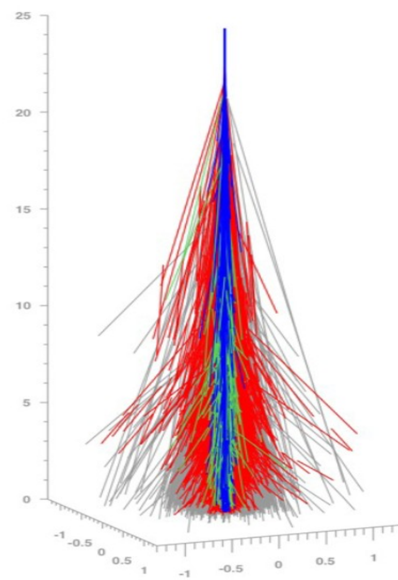


$$A + air \rightarrow \text{hadrons}$$
$$p + air \rightarrow \text{hadrons}$$
$$\pi + air \rightarrow \text{hadrons}$$

hadronic physics

initial γ from π^0 decay

$$e^{\pm} \rightarrow e^{\pm} + \gamma$$
$$\gamma \rightarrow e^{+} + e^{-}$$

well known QED

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}/\bar{\nu}_{\mu}$$

Cascade of particle in Earth's atmosphere

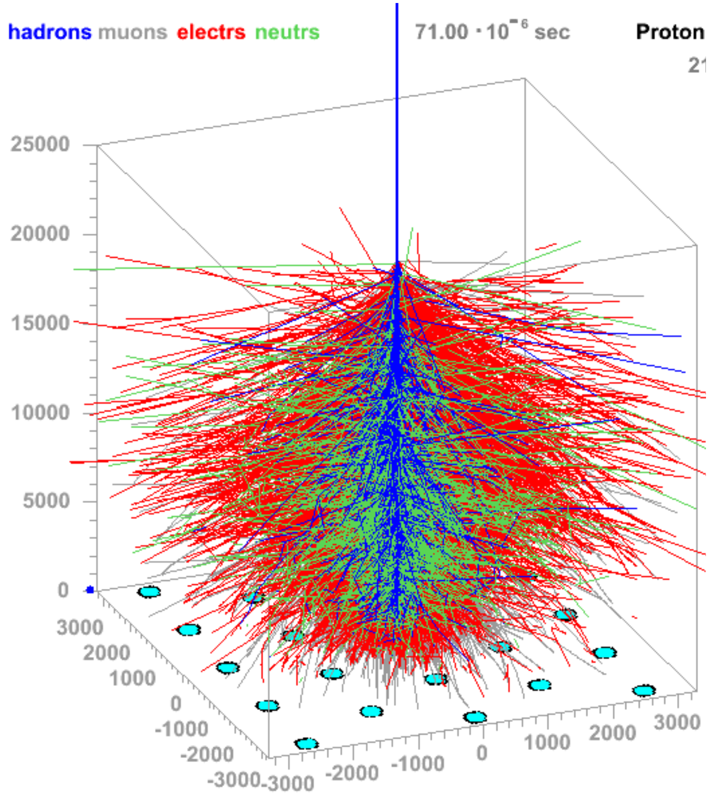
Number of particles at maximum

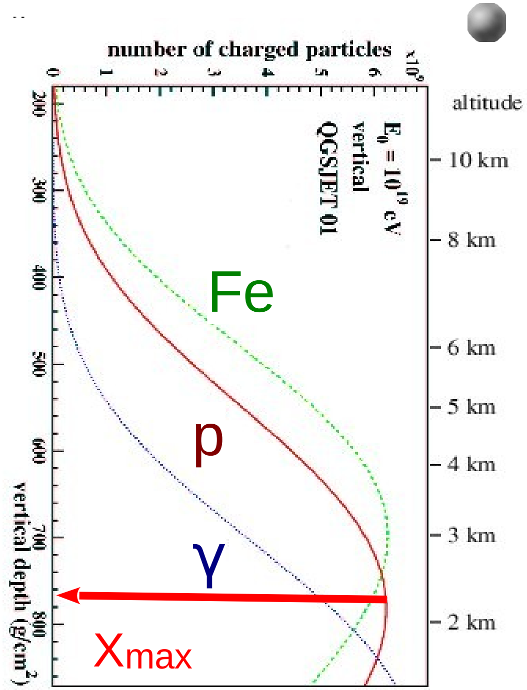
- 99,88% of electromagnetic (EM) particles
- 0.1% of muons
- 0.02% hadrons

Energy

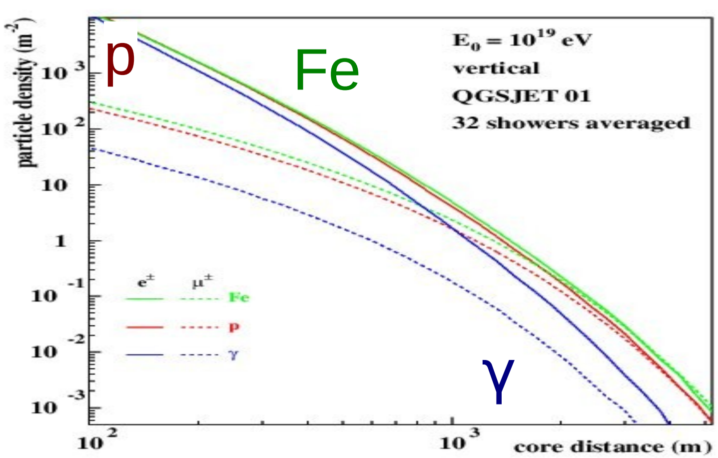
- from 100% hadronic to 90% in EM + 10% in muons at ground (vertical)

Extensive Air Shower Observables





- **Longitudinal Development**
  - number of particles vs depth
    $X = \int_h^\infty dz\, \rho(z)$
  - Larger number of particles at X_{max}
    For many showers
    - mean : $\langle X_{max} \rangle$
    - fluctuations : RMS X_{max}
    - depends on primary mass
    - depends on Hadr. Inter.



- **Lateral distribution function (LDF)**
  - particle density at ground vs distance to the impact point (core)
  - can be muons or electrons/gammas or a mixture of all.

- **Others: Cherenkov emissions, Radio signal**

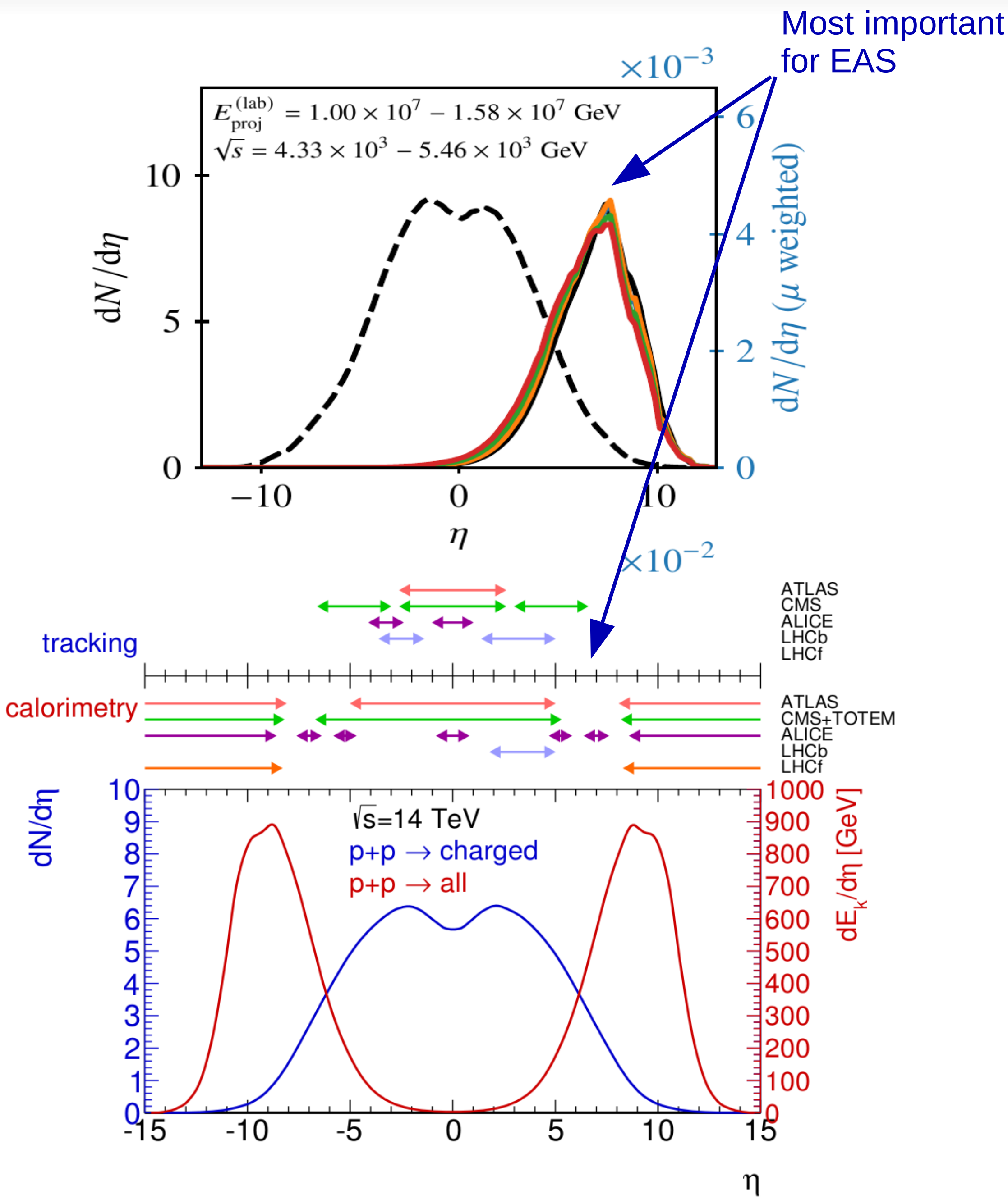
Cosmic Ray Analysis from Air Showers

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

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

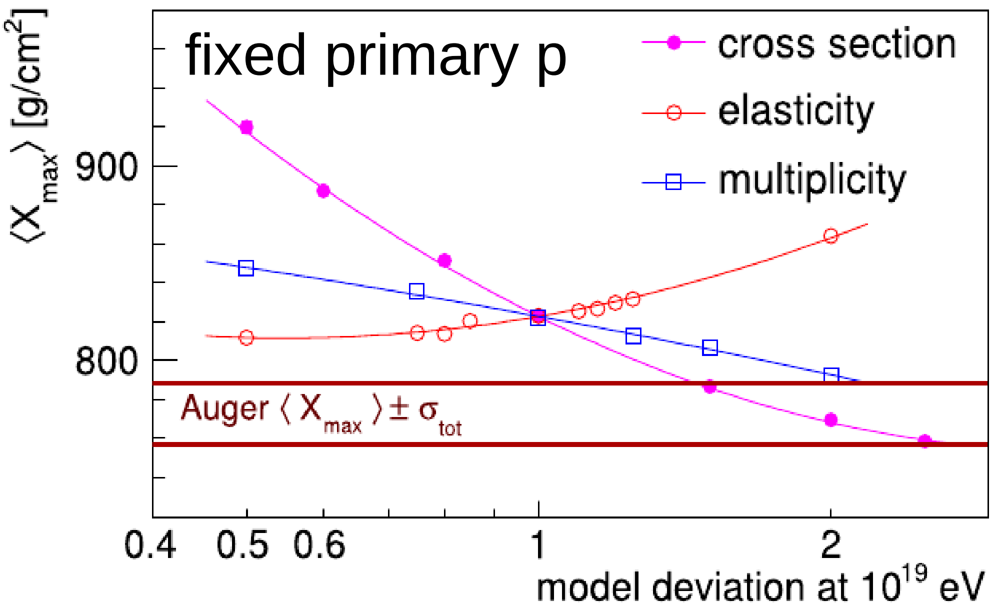
- **Which model for CR ? (alphabetical order)**
  - EPOS (1.99/**LHC**/4/**LHC-R**) (from VENUS/NEXUS before) by K. Werner, T. Pierog and al.
  - **QGSJET** (01/II-03/II-04/III-01) by S. Ostapchenko (starting with N. Kalmykov)
  - **Sibyll** (2.1/(2.3c/2.3d/)2.3e) by E-J Ahn, R. Engel, R.S. Fletcher, T.K. Gaisser, P. Lipari, F. Riehn, T. Stanev

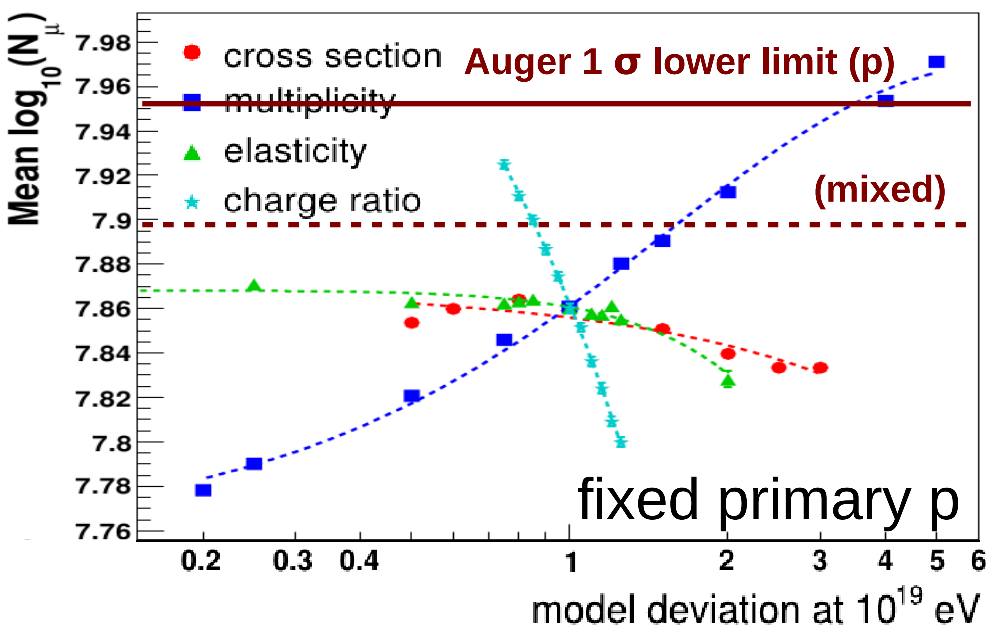
LHC acceptance and Phase Space



- **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
- **Source of uncertainties**
  - Missing data

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**

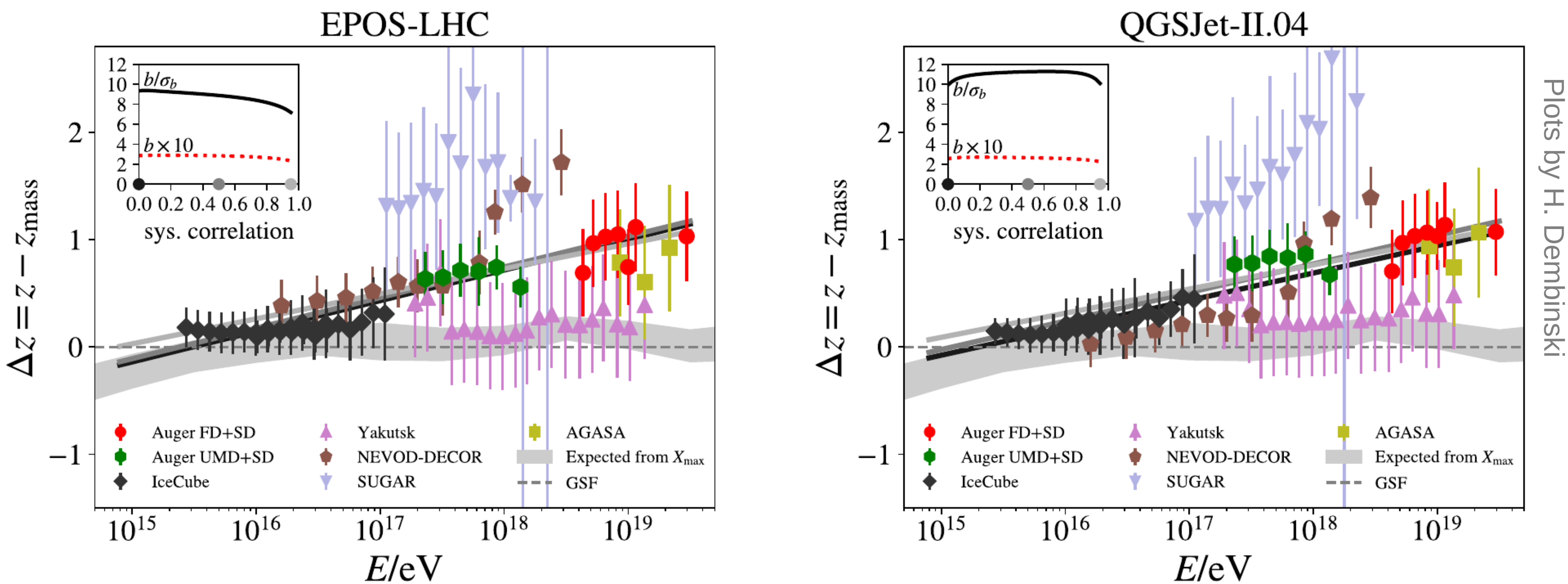
Theory AND data are important to constrain the hadronic model parameters.

WHISP Meta-Analysis (2021)

- **Clear muon excess in data compared to simulation**
  - ➡ Different energy evolution between data and simulations
    - ➡ Significant non-zero slope (>8σ)

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

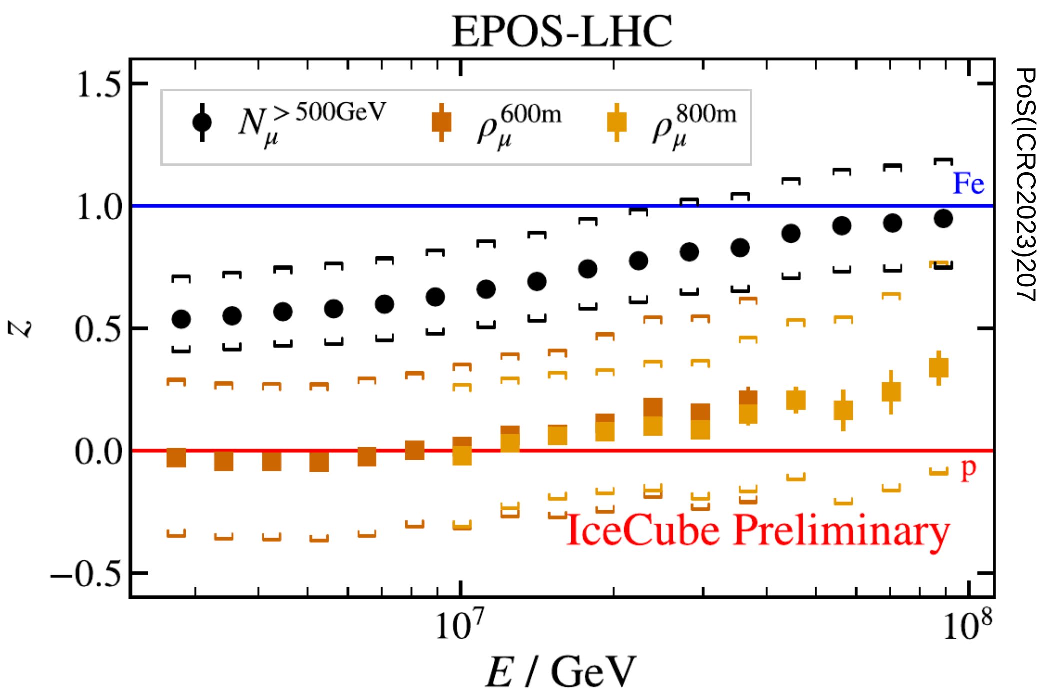
$$z_{\rm mass} = \frac{\langle \ln A \rangle}{\ln 56}$$

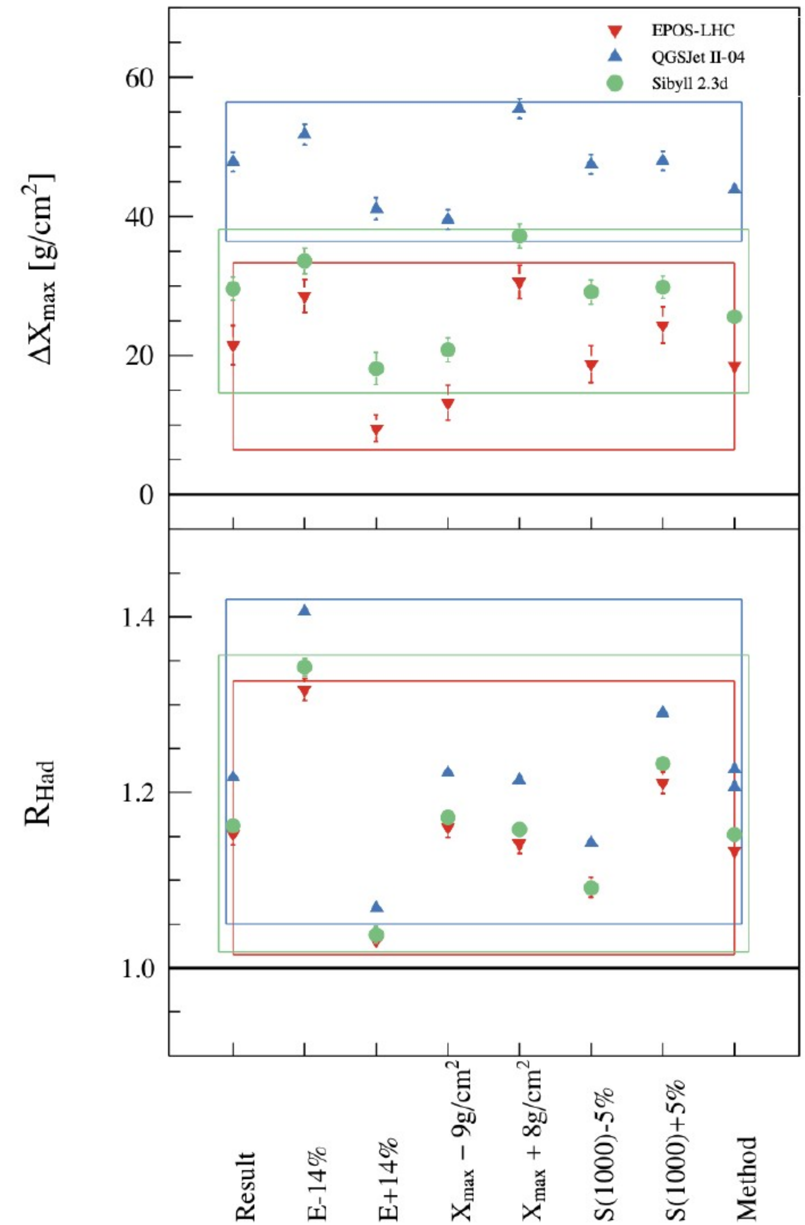


- **Different energy scale cannot change the slope**
  - ➡ Different property of hadronic interactions at least above 10^{17} eV

And more evidences

- **Air shower measurement suffer from large energy scale uncertainties**
  - ➡ But discrepancy remains within errors
- **Different muon energies are not equally reproduced**





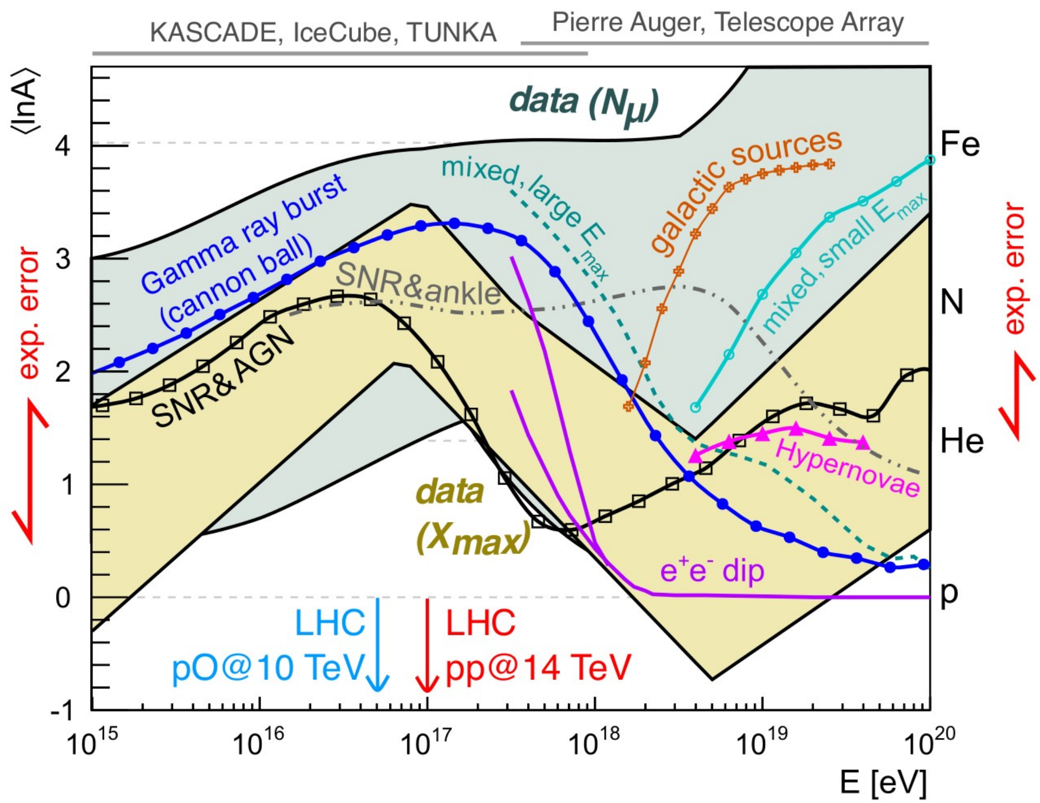
- **Other variables not well reproduced**
  - ➡ Zenith angle dependence, muon production height, ...

UHECR Composition

With current models, CR data are impossible to interpret

- Very large uncertainties in model predictions
- Mass from muon data incompatible with mass from X_{max}

Need better hadronic interaction models



Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

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) (ALICE)
  - ➡ Particle yields as a function of multiplicity (ALICE, LHCb)

X_{max}

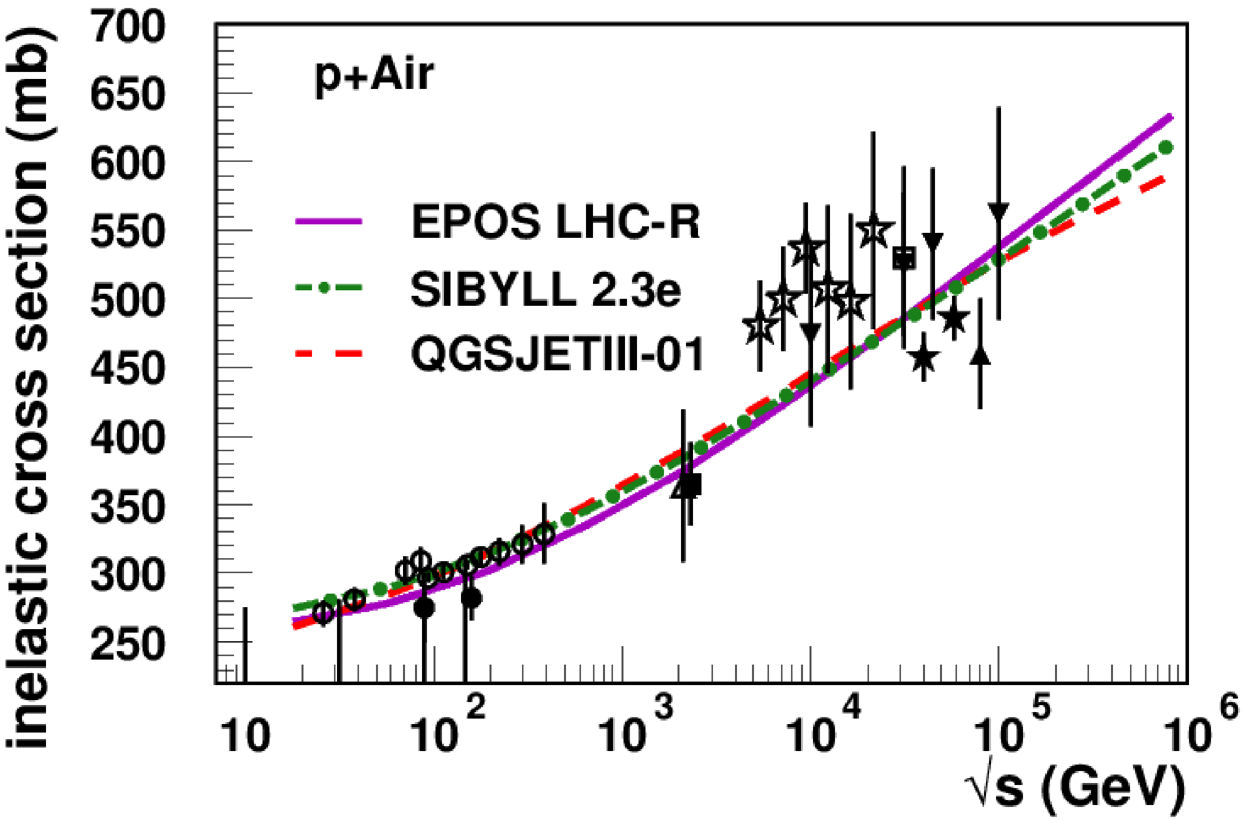
N_{μ}

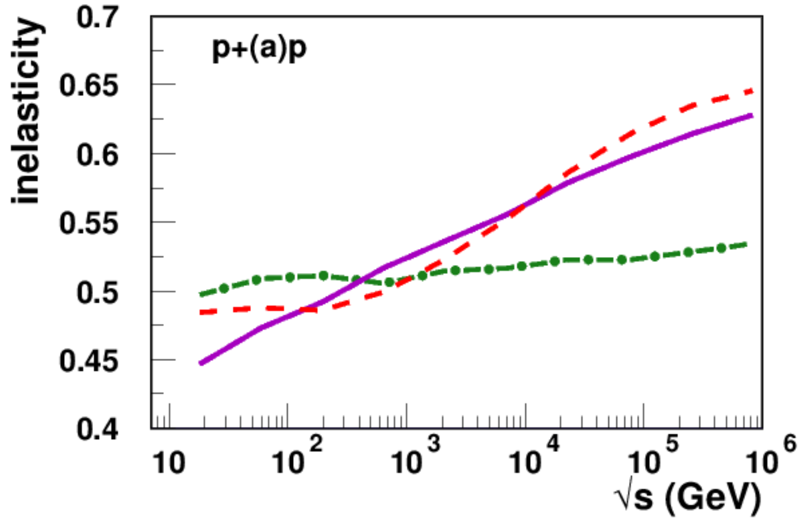
- **Update of EPOS LHC → EPOS.LHC-R**
  - ➡ Modify EPOS LHC to take into account new data and new knowledge accumulated with (and code from) EPOS 4
  - ➡ Global approach taking into account collective effects
- **Update of QGSJETII-04 → QGSJETIII-01**
  - ➡ Higher twist calculation in hard component to avoid low p_t cut-off
  - ➡ Retune to LHC and NA61 (ρ) data but nothing new in hadronization.

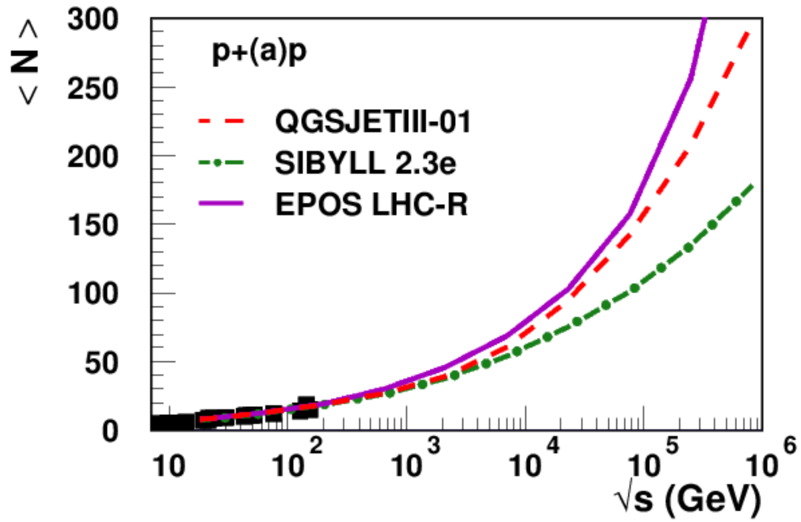
Basic Observables

Key measurements : directly related to X_{max}

- Cross-sections updated to most recent measurements
  - p-p and p-Air cross-sections very similar
- Still large differences where there is no data
  - Elasticity and total multiplicity poorly described



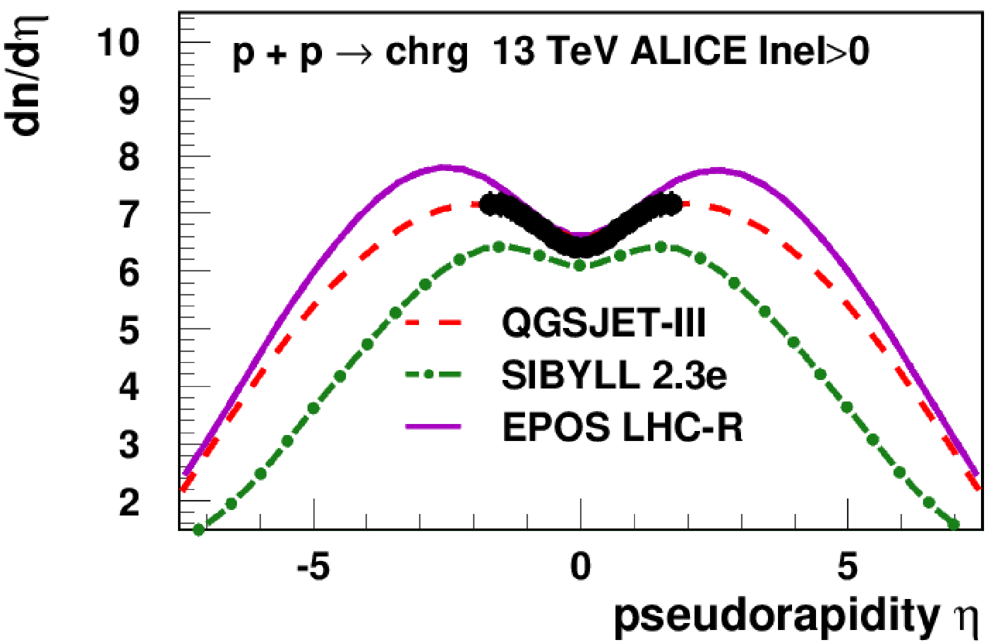


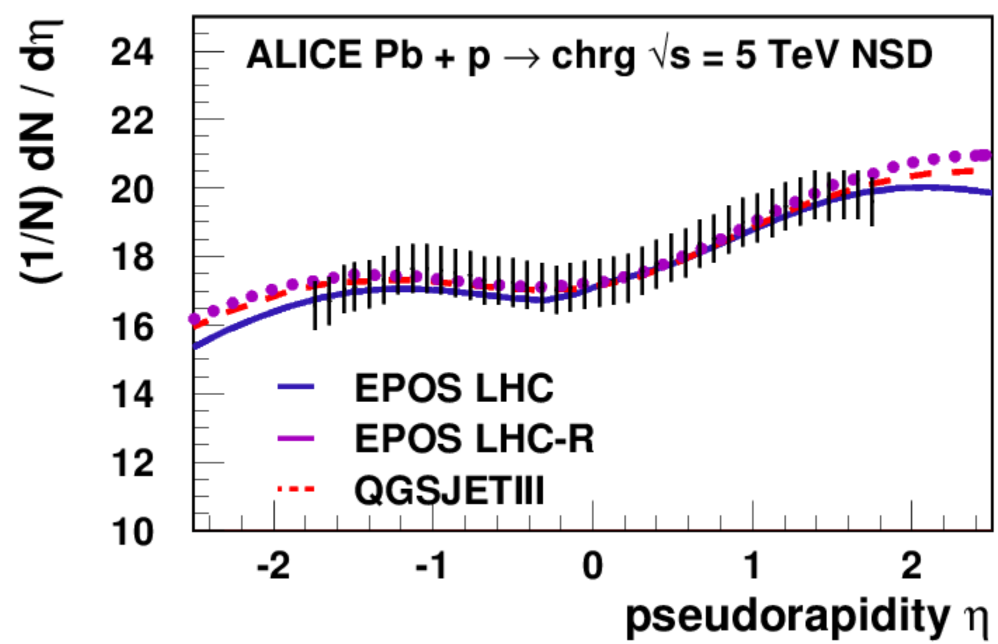


Pseudorapidity

Simple (basic) measurement still important !

- **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





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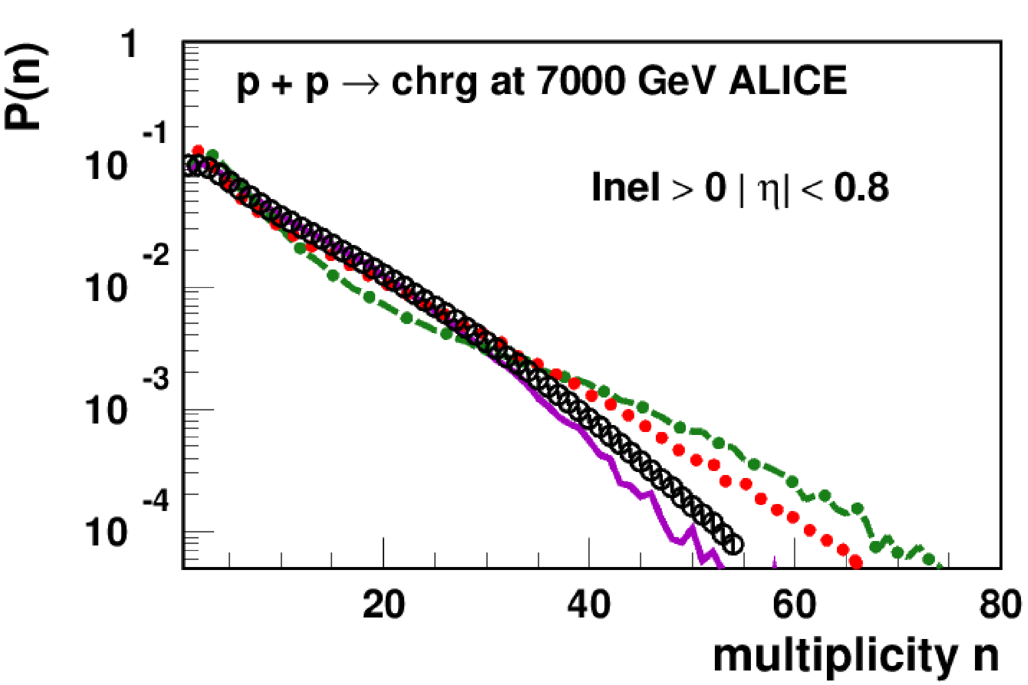

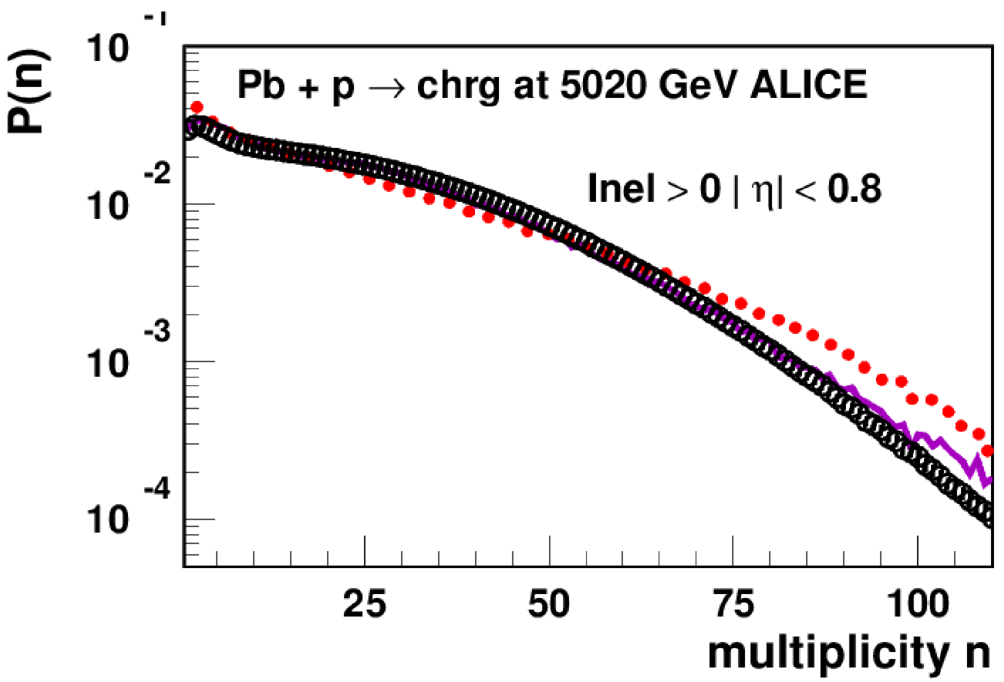

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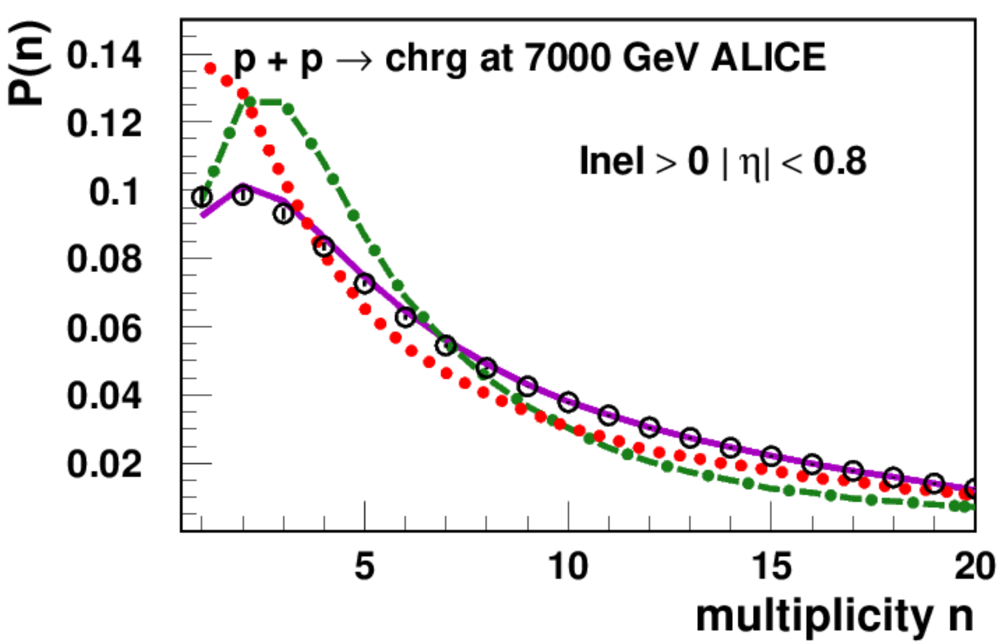
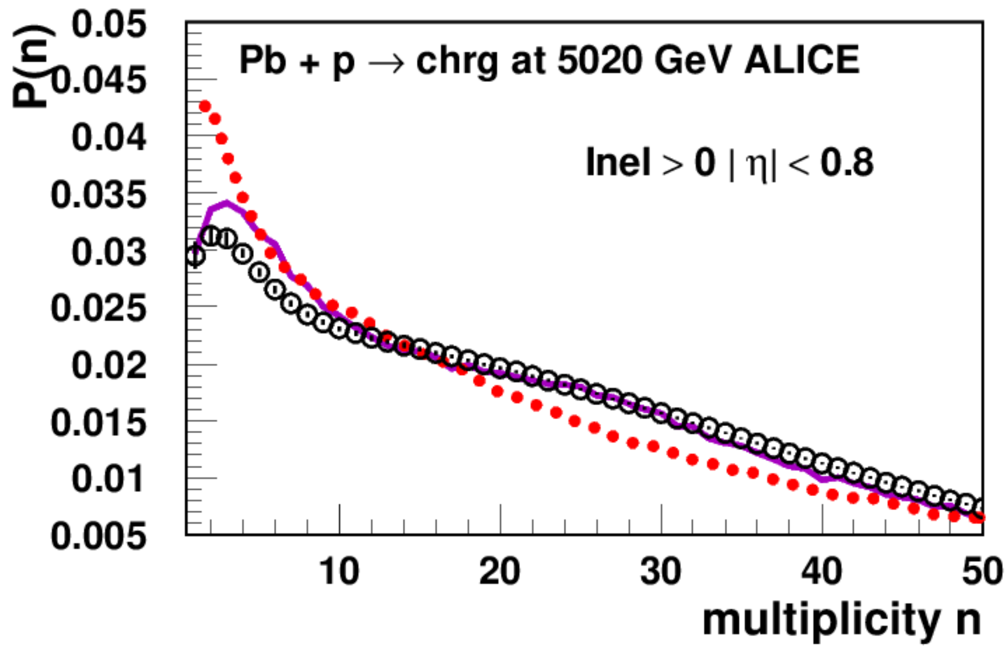
- Detailed data at 5 TeV for p-Pb
  - Problems at both high and low multiplicities
  - Correct multiplicity distribution in EPOS (large impact on X_{max})

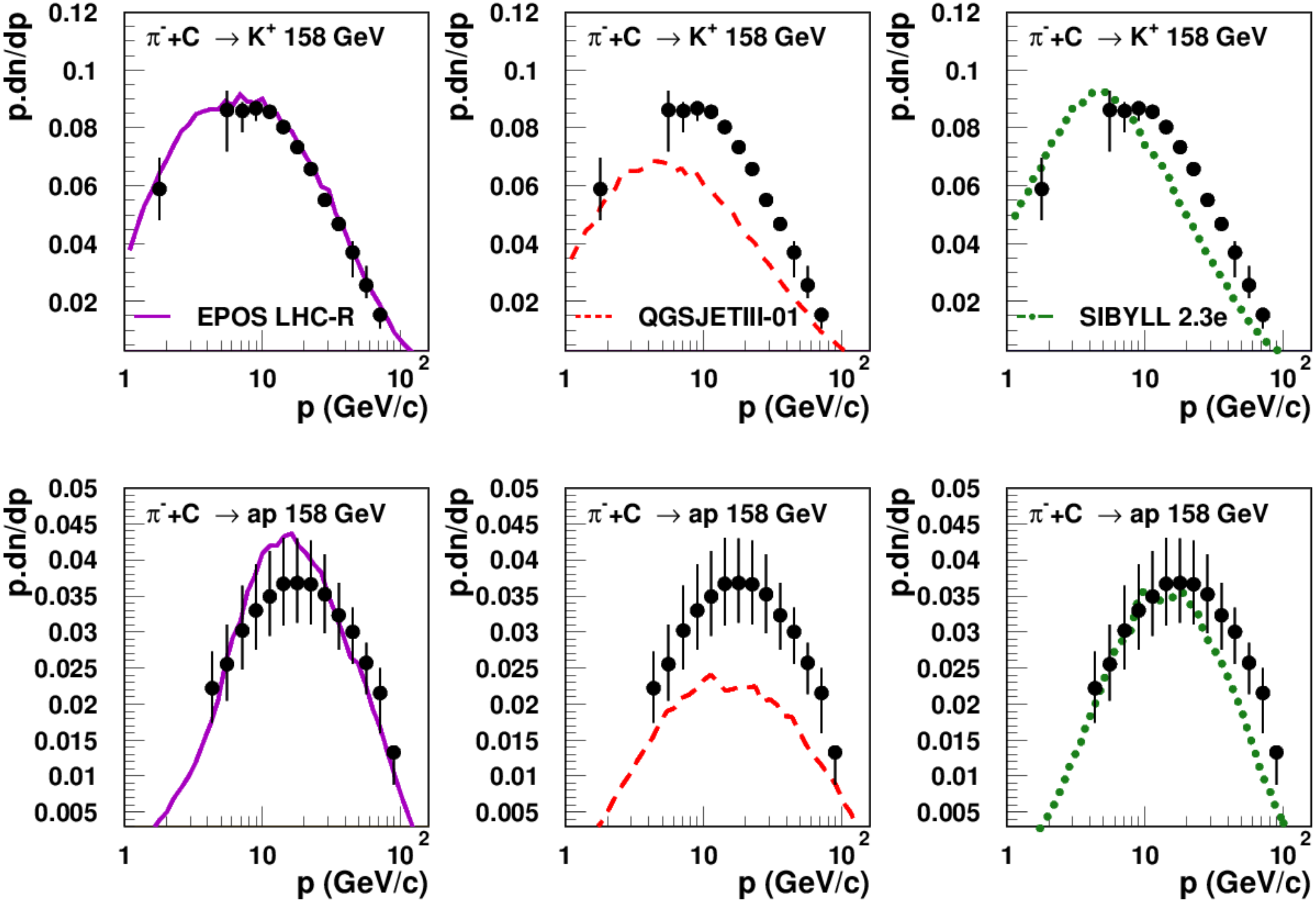




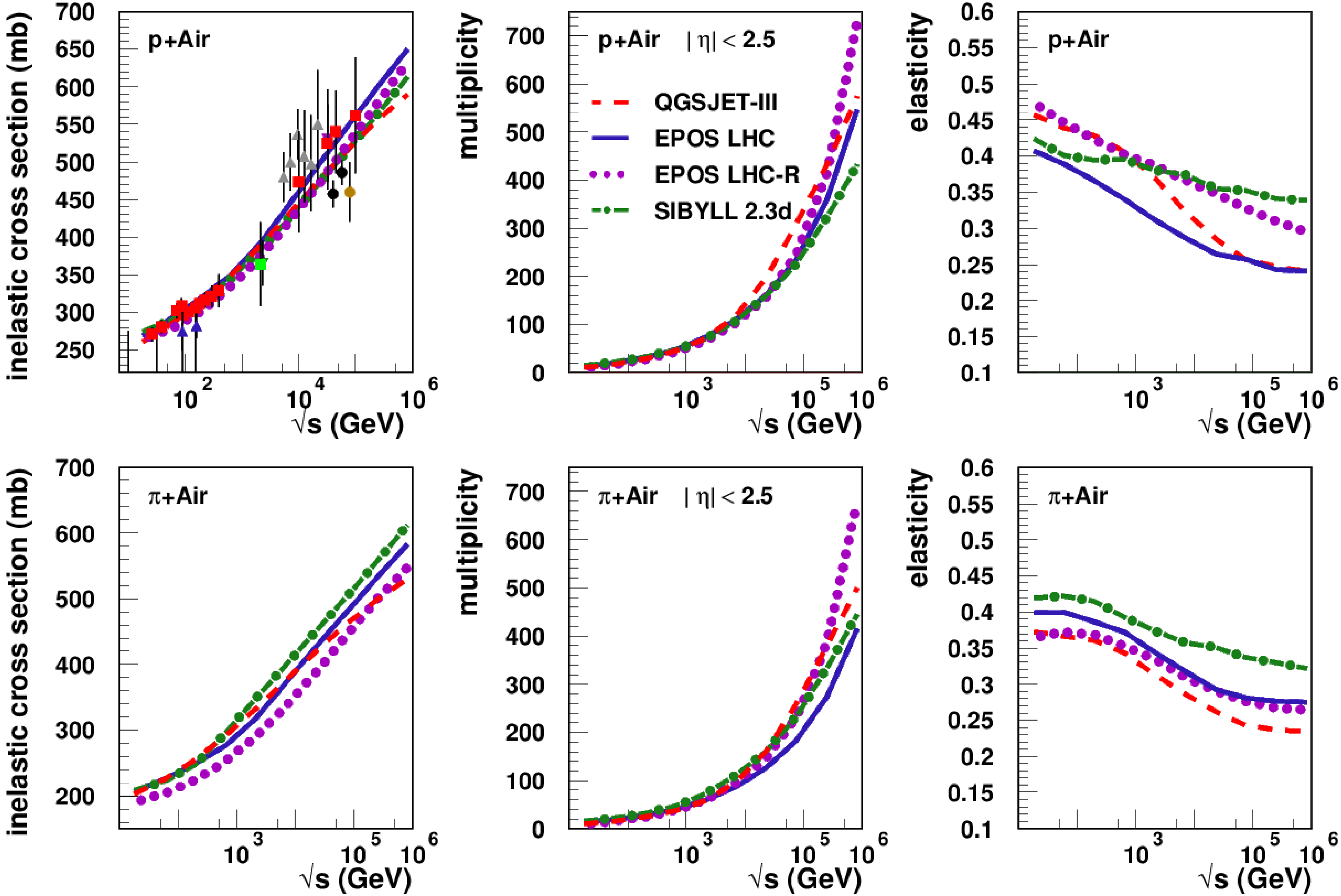
Kaons and Baryons

Only EPOS properly reproduce NA61 data (and many others)

➡ QGSJETIII not flexible enough !



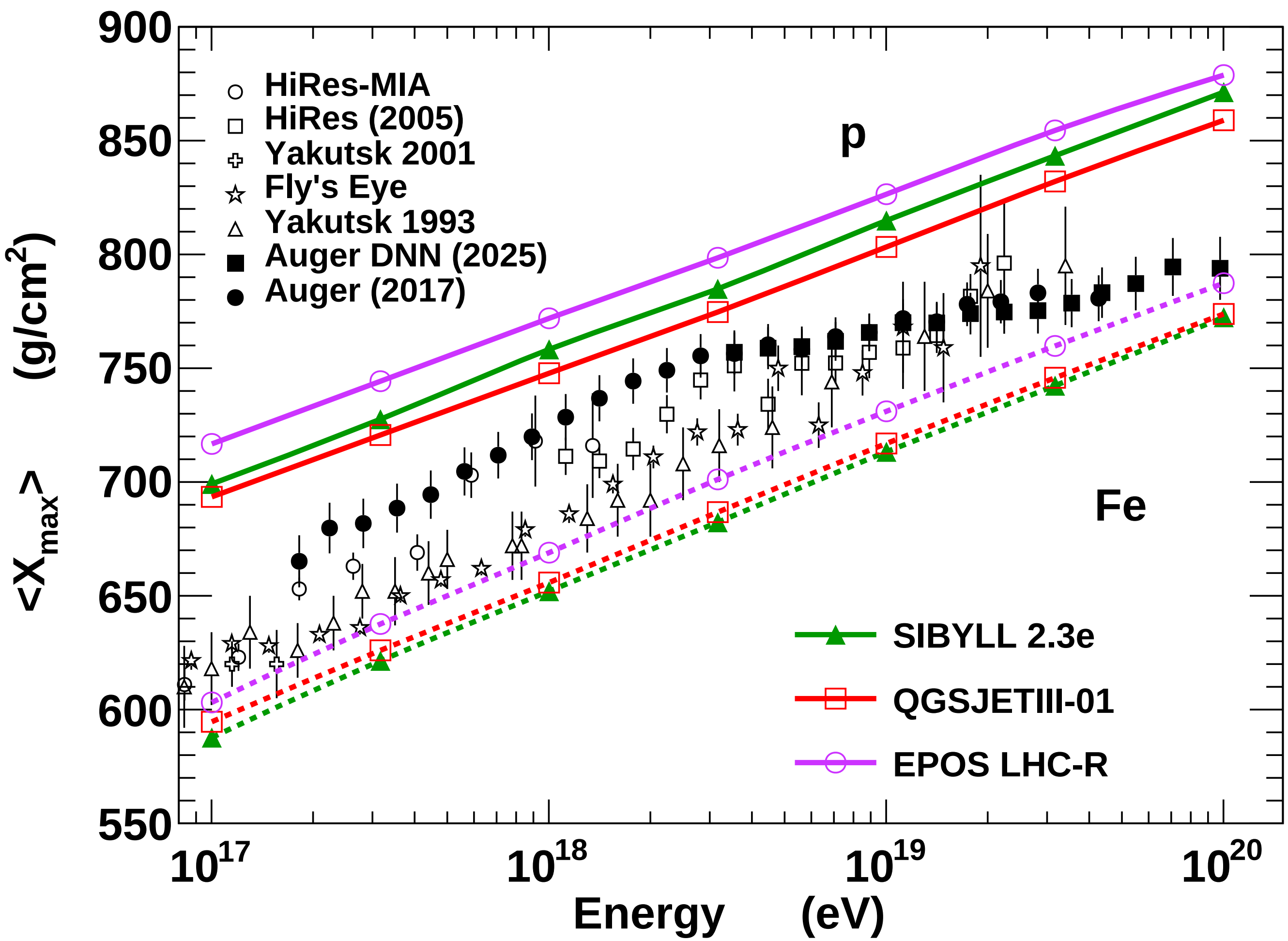
Interaction with Air



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)

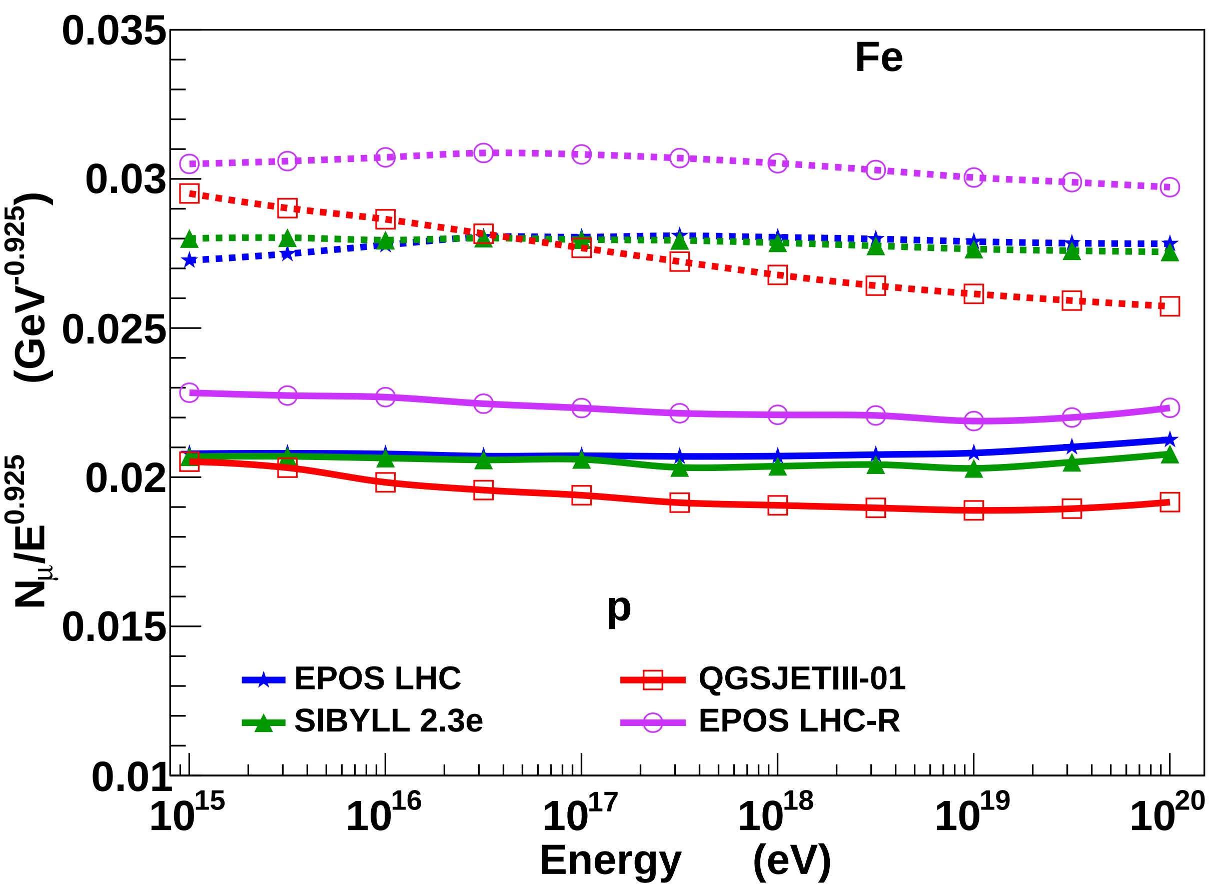


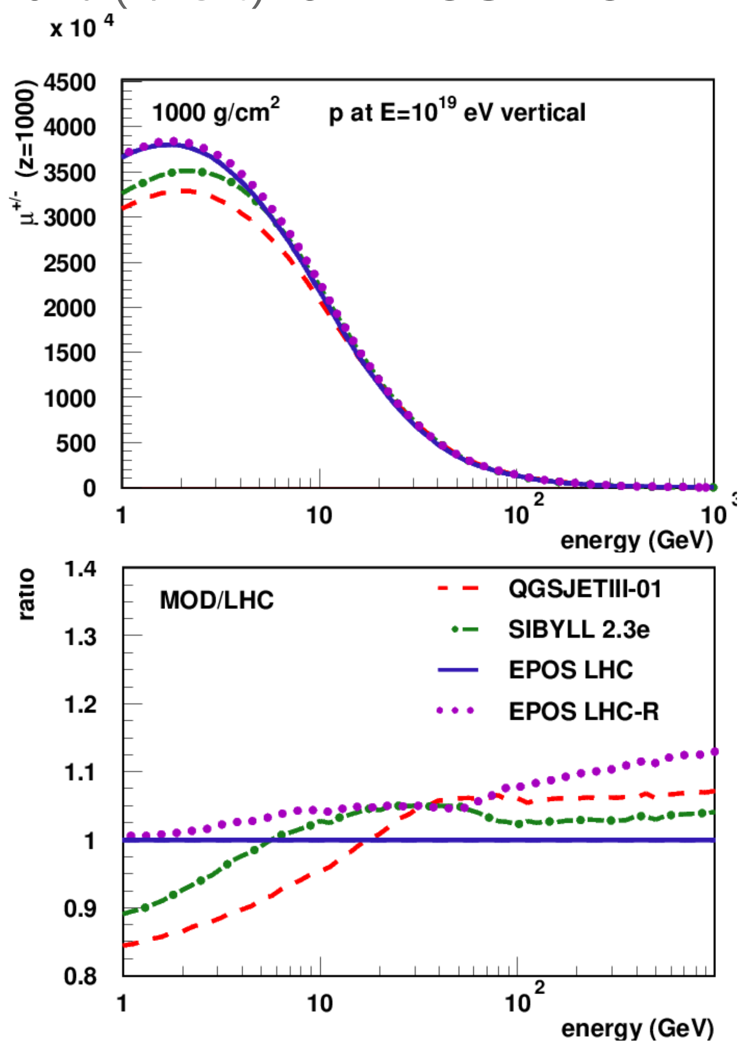
Heavier composition compared to previous generation of models

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 !



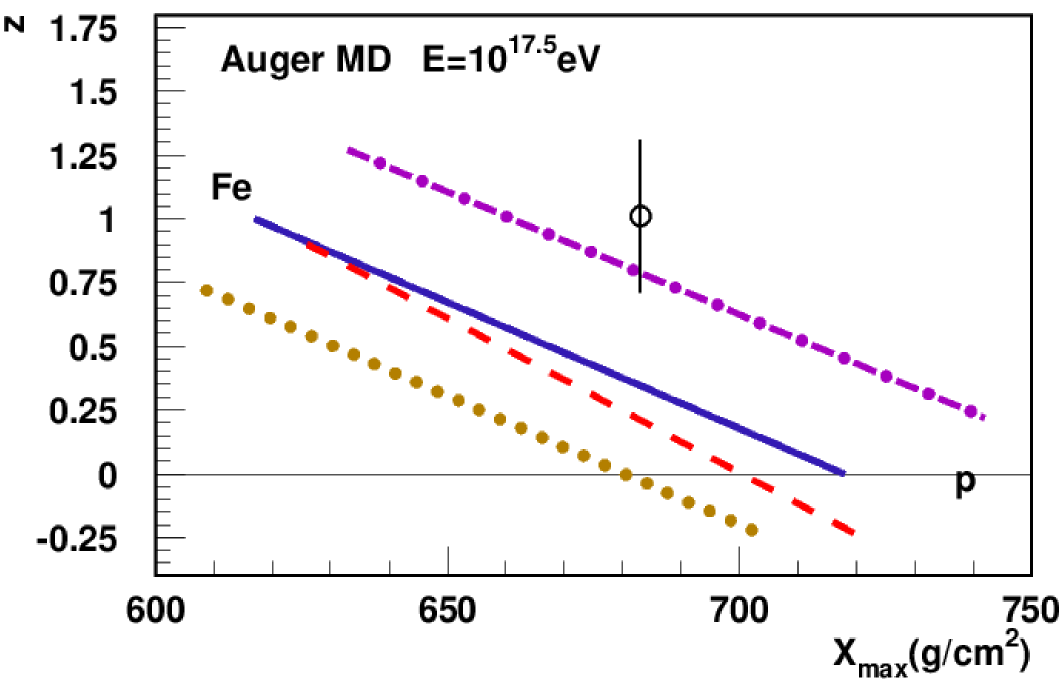


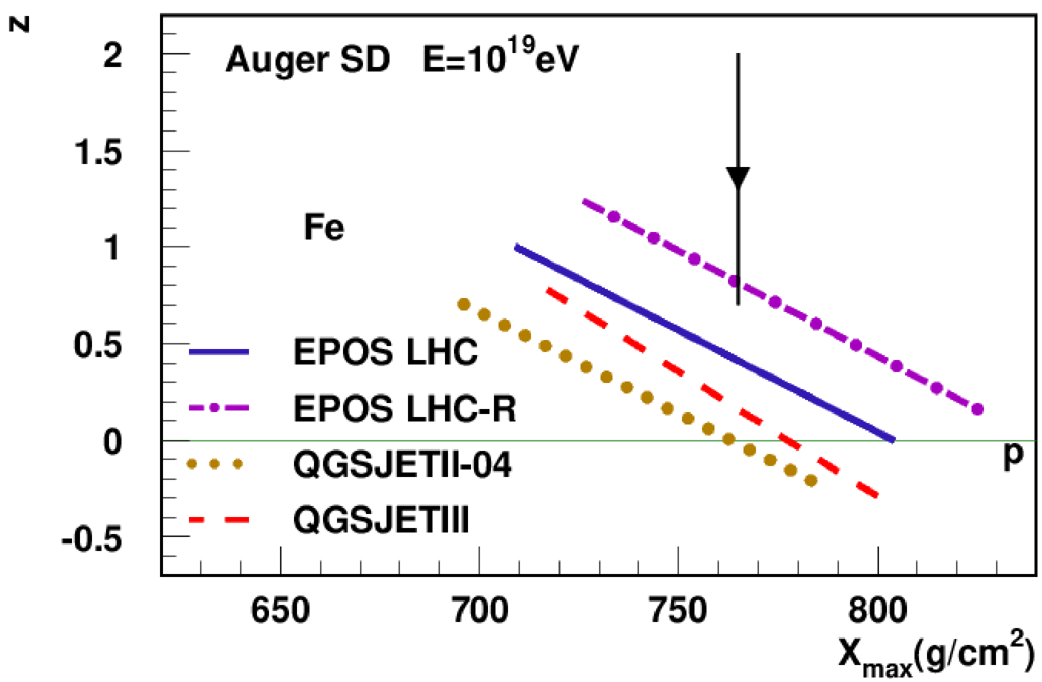
Muon Puzzle Solved ?

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
- Change not large enough for QGSJET

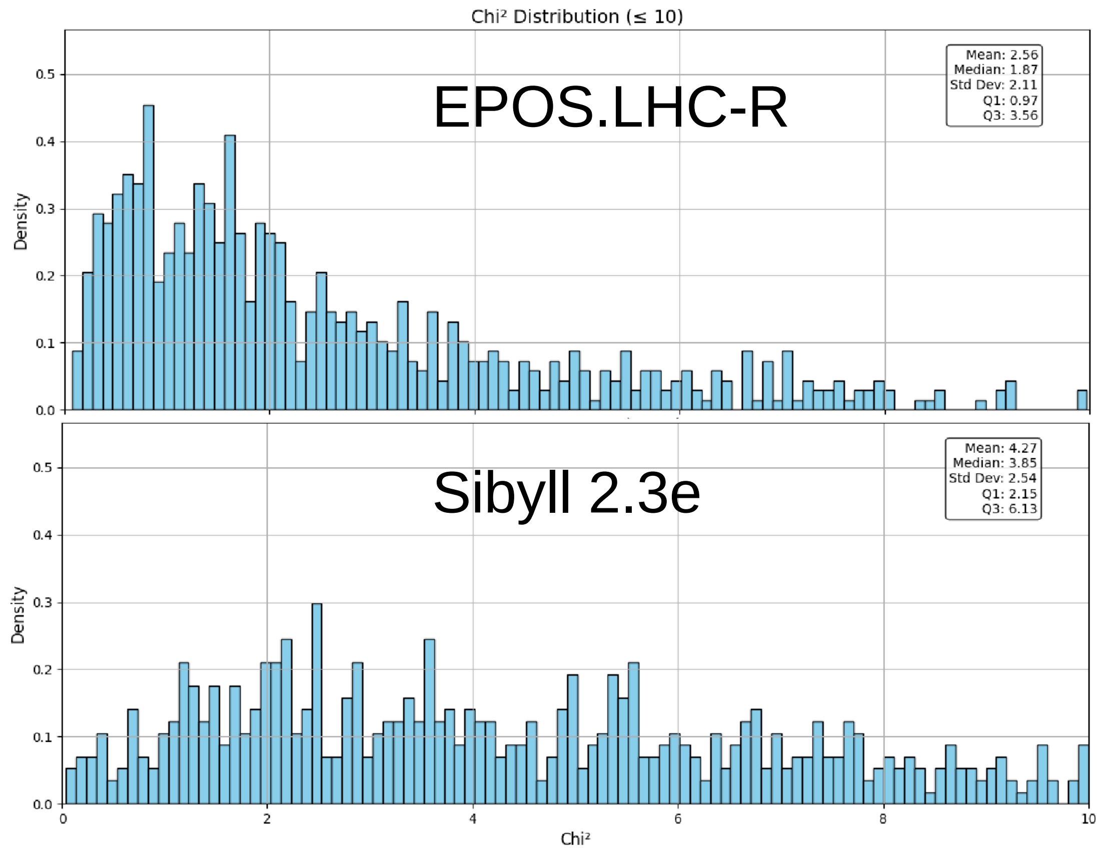
$$z = \frac{\ln N_{\mu}^{\rm det} - \ln N_{\mu,p}^{\rm det}}{\ln N_{\mu,\rm Fe}^{\rm det} - \ln N_{\mu,p}^{\rm det}}$$





Still Large Differencies

- Can the different predictions converge with simply more data ?
- Is there something missing in some models ?
    - The models do not reproduce existing data equally well

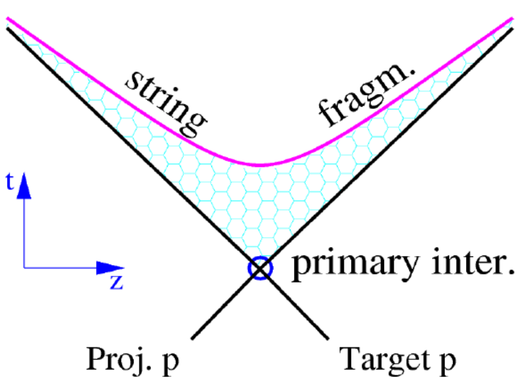


- Why is EPOS having more muons in EAS now while it doesn't over-product baryons anymore (less baryons=less muons) ?

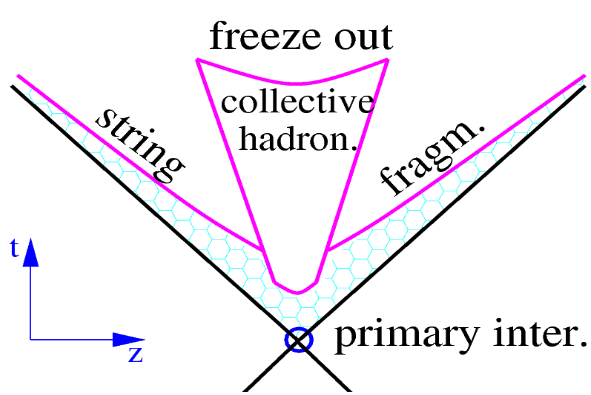
Global approach is the key !

What means global approach ?

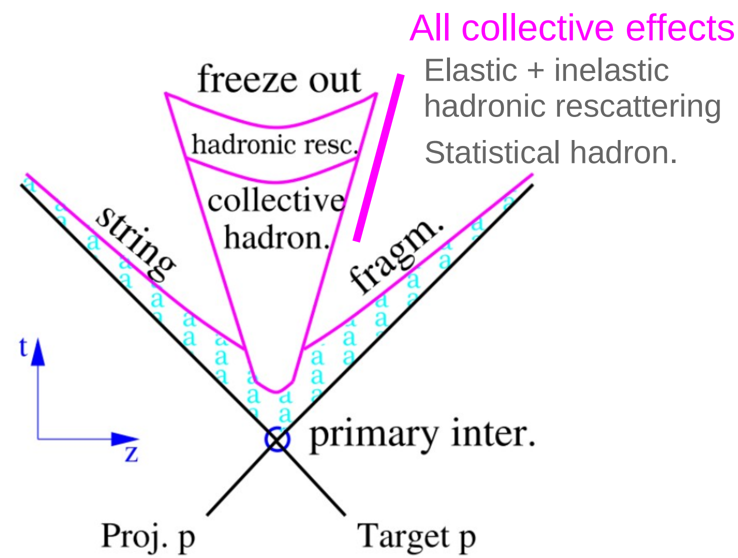
- Tuning models neglecting some physics process lead to wrong parameters !
- Proper tune possible to do only if everything taken into account
  - All collective effects considered for the first time !
- Either with a direct impact on the shower development (new elasticity)
- Or no direct impact on the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



Sibyll, QGSJET



EPOS LHC
(no rescattering)

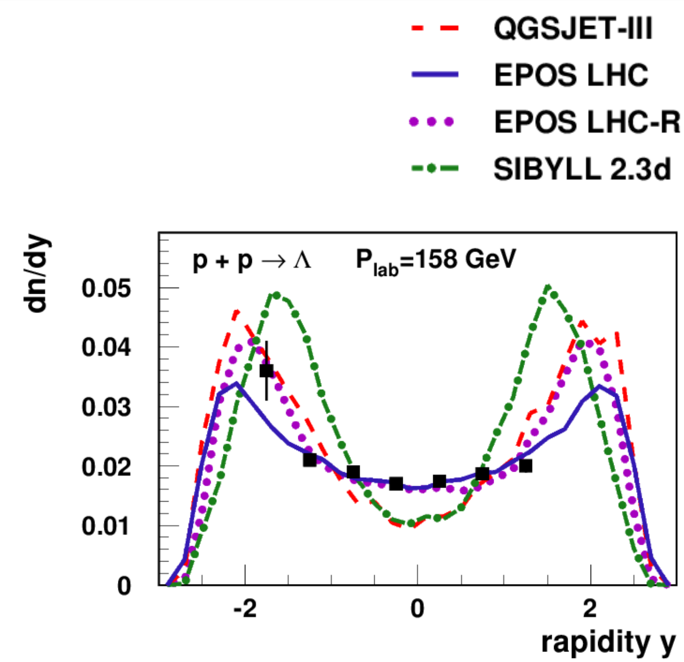


EPOS.LHC-R
(with hadronic rescattering (hs))

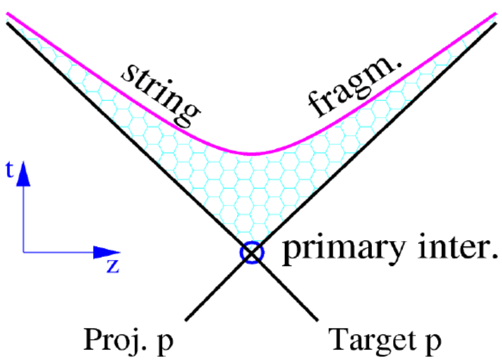
String Fragmentation

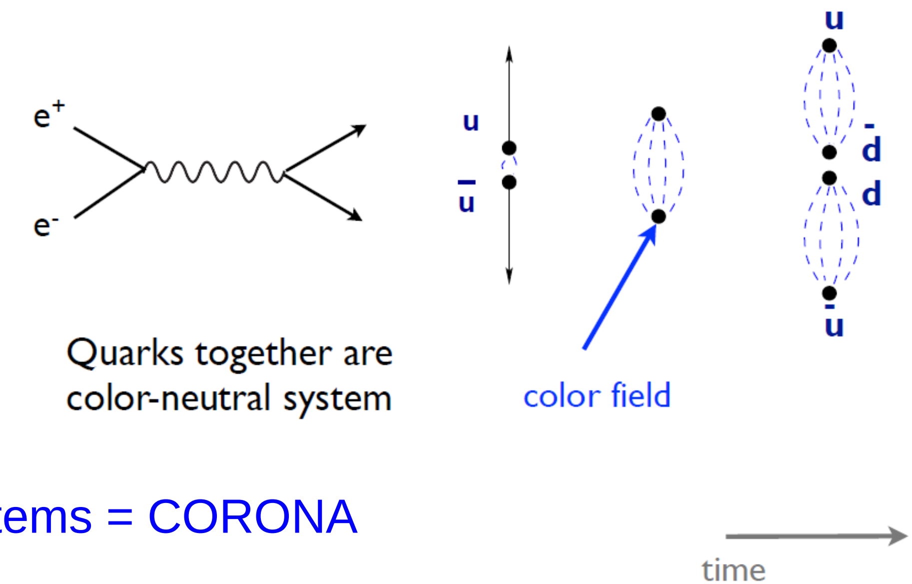
Global approach is the key !

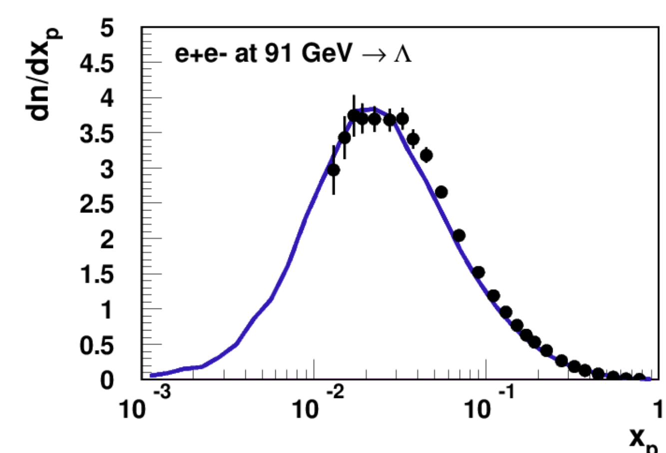
- Common hadronization in all the models
- Parameters fixed on e+-e- only possible in EPOS
  - Other CR models tuned on p-p data
    - “Contamination” by beam remnant
- Very important for forward particle production (EAS)
    - Used for beam remnant hadronization



Annihilation at high energy





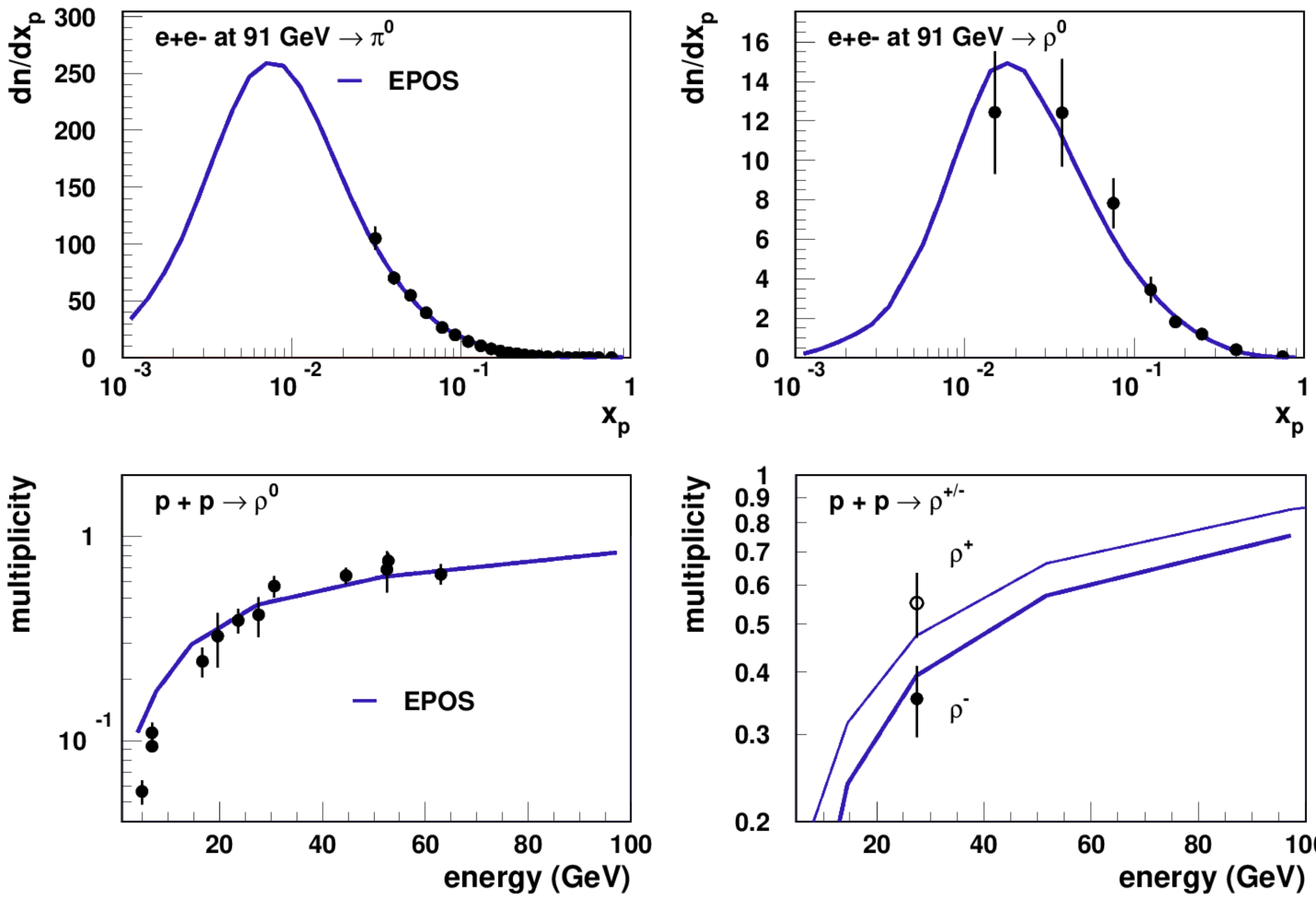


Used in dilute systems = CORONA

Generic "EPOS"

CR models usually tuned on hadronic interactions (not e+e- (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



Generic CR tuning

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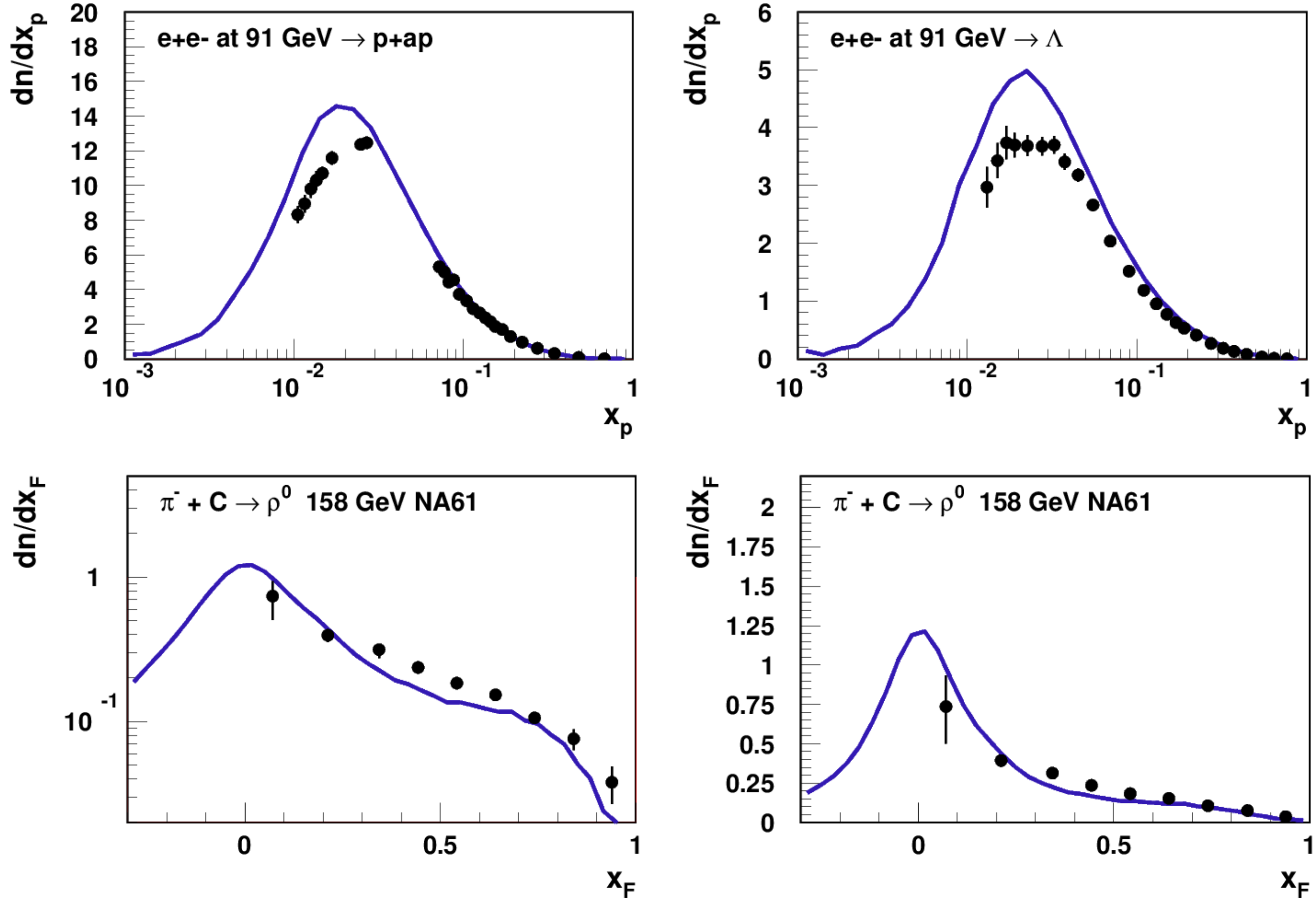
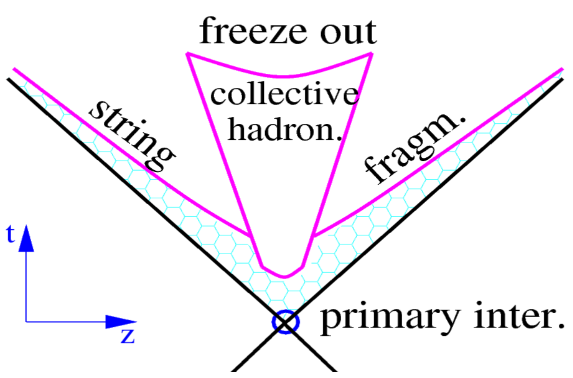


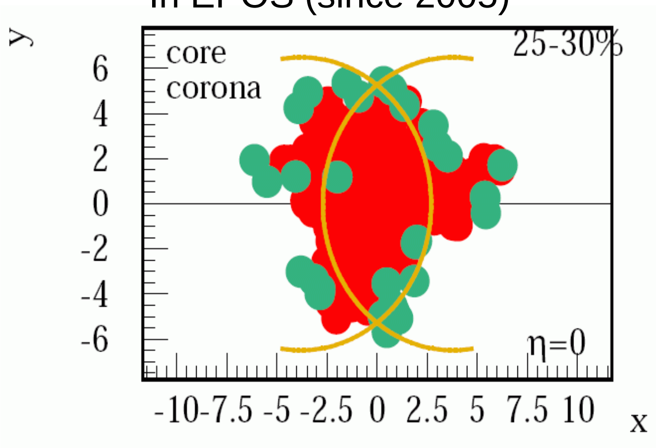
Core-Corona (co-co)

- **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**

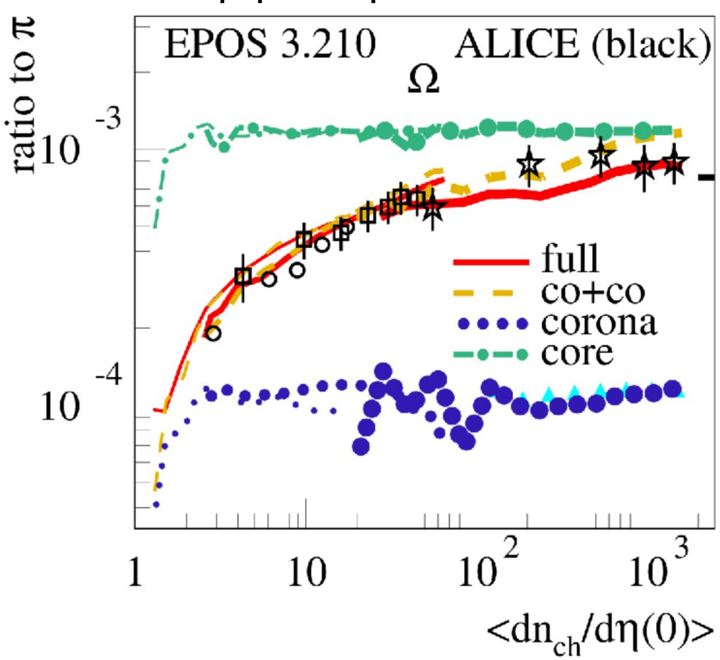


- **2 simultaneous source of particles**

In EPOS (since 2005)



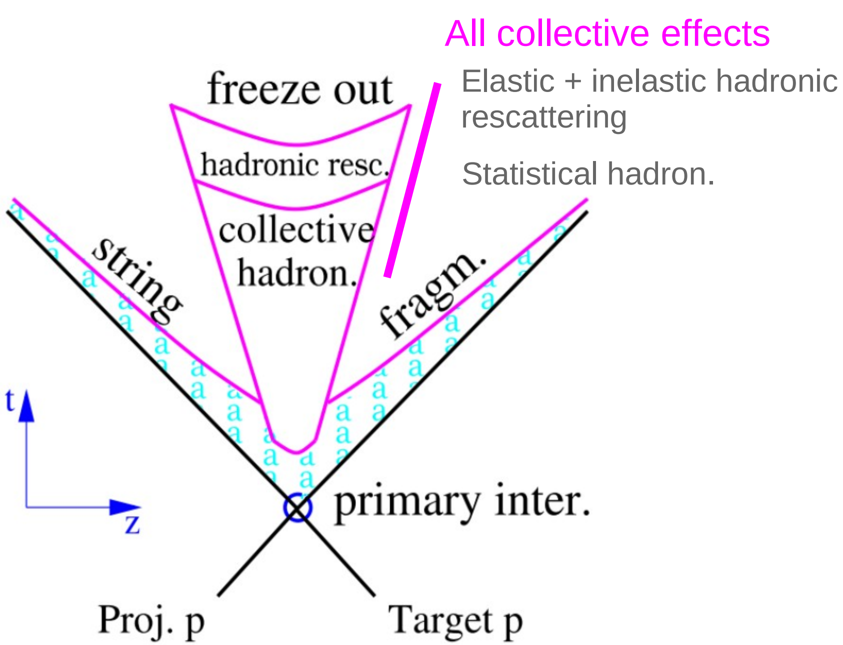
p-p ,Pb-p, Pb-Pb data

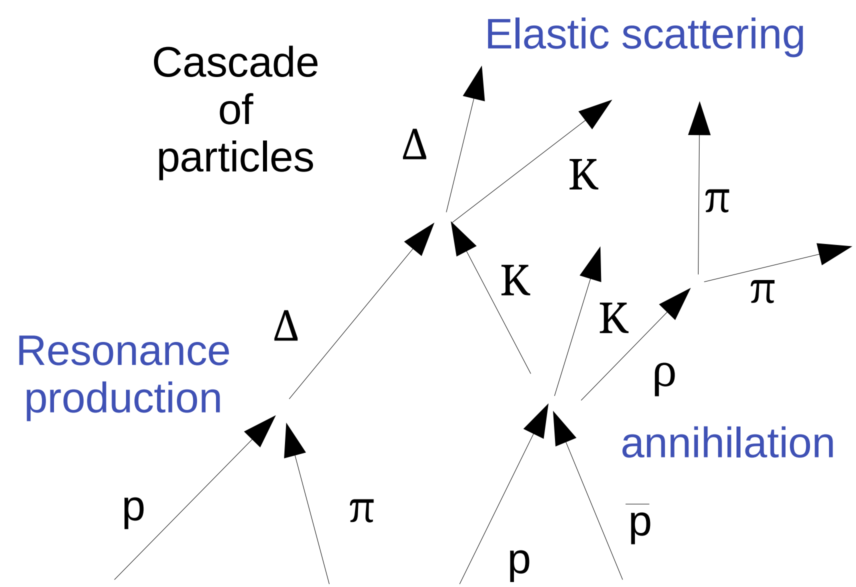


Hadronic reScattering (HS)

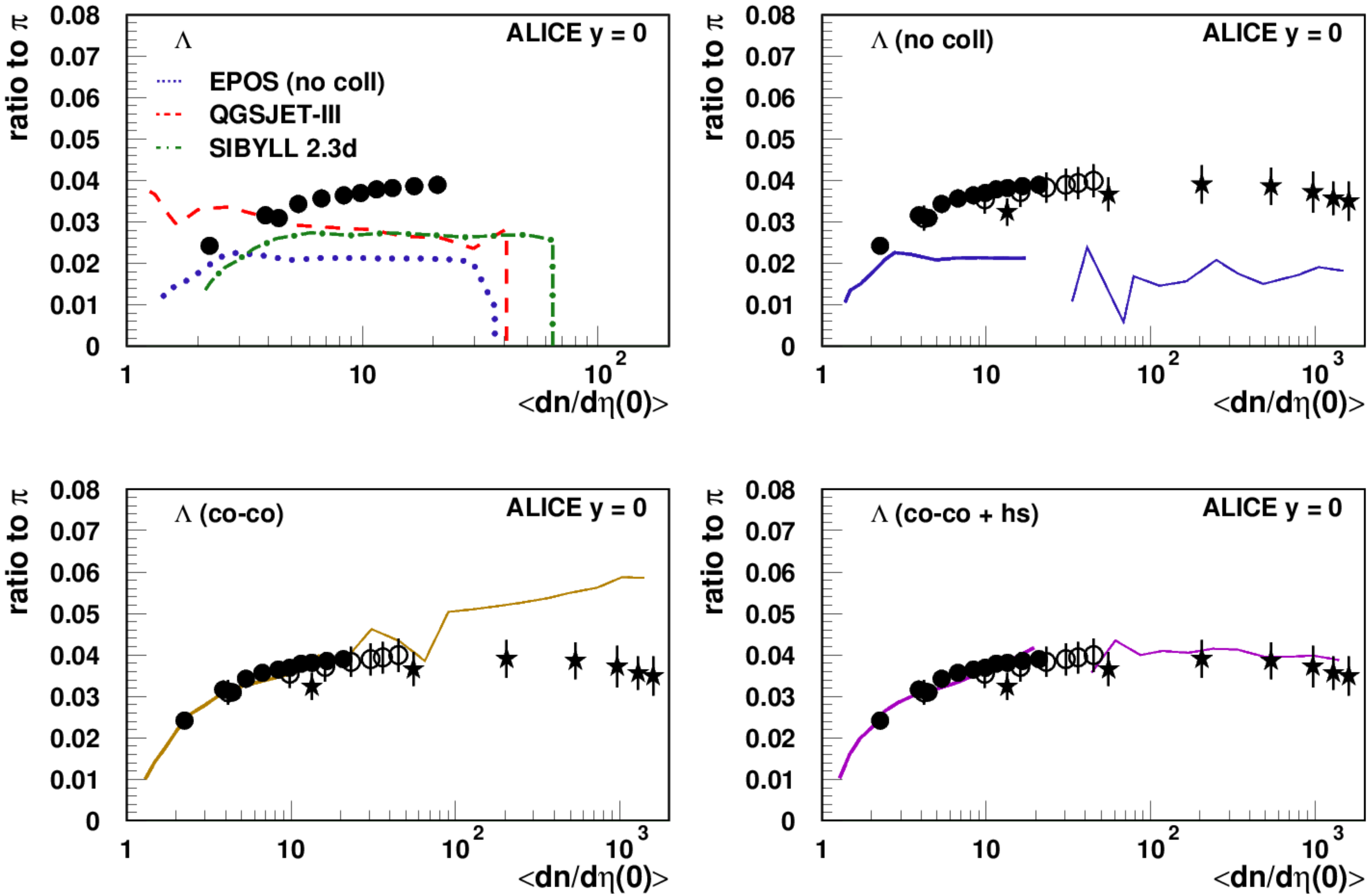
Missing effect in all CR models until now !

- 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) !

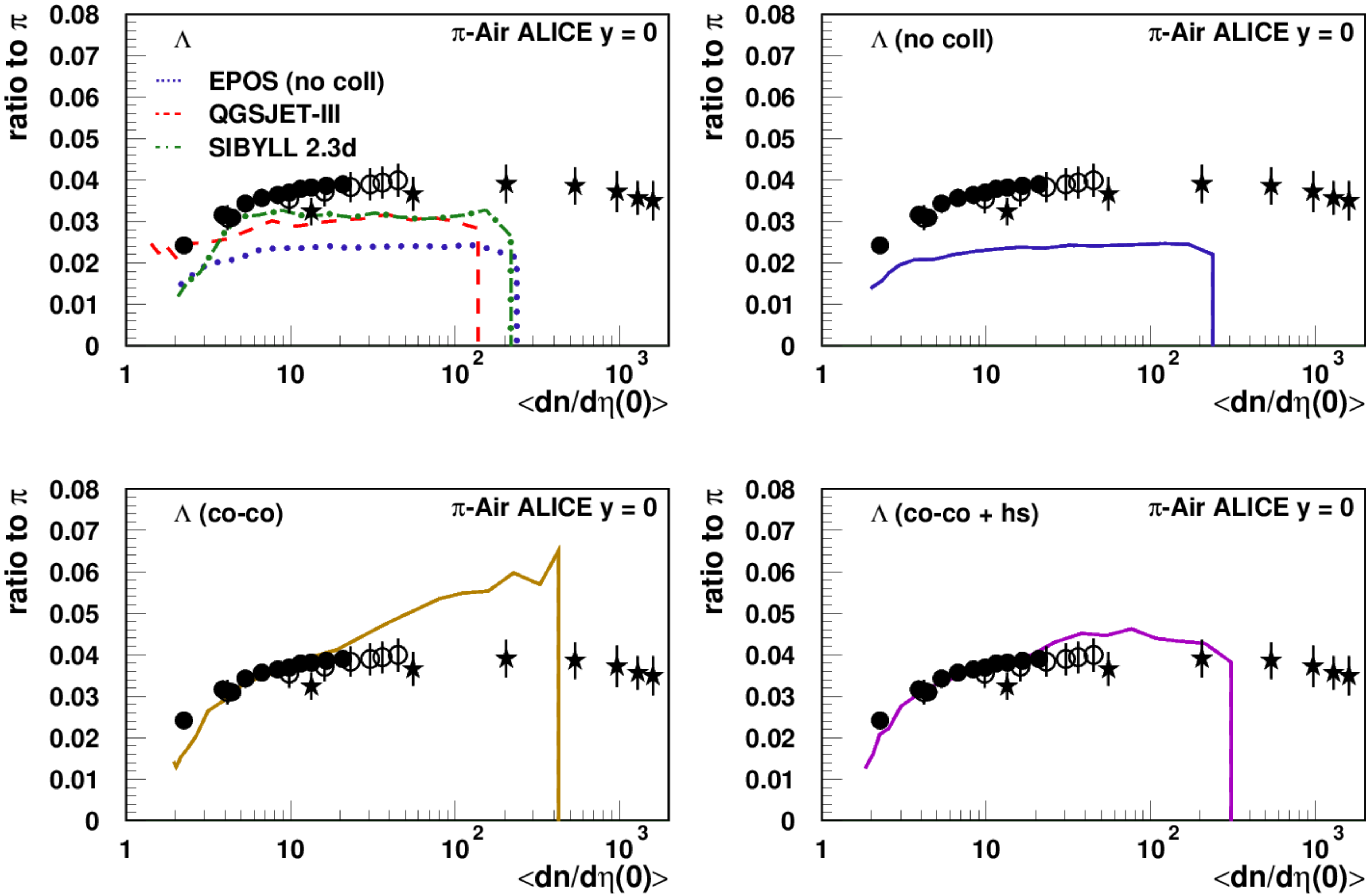




Example with Lambda particle in p-p and Pb-Pb @ LHC



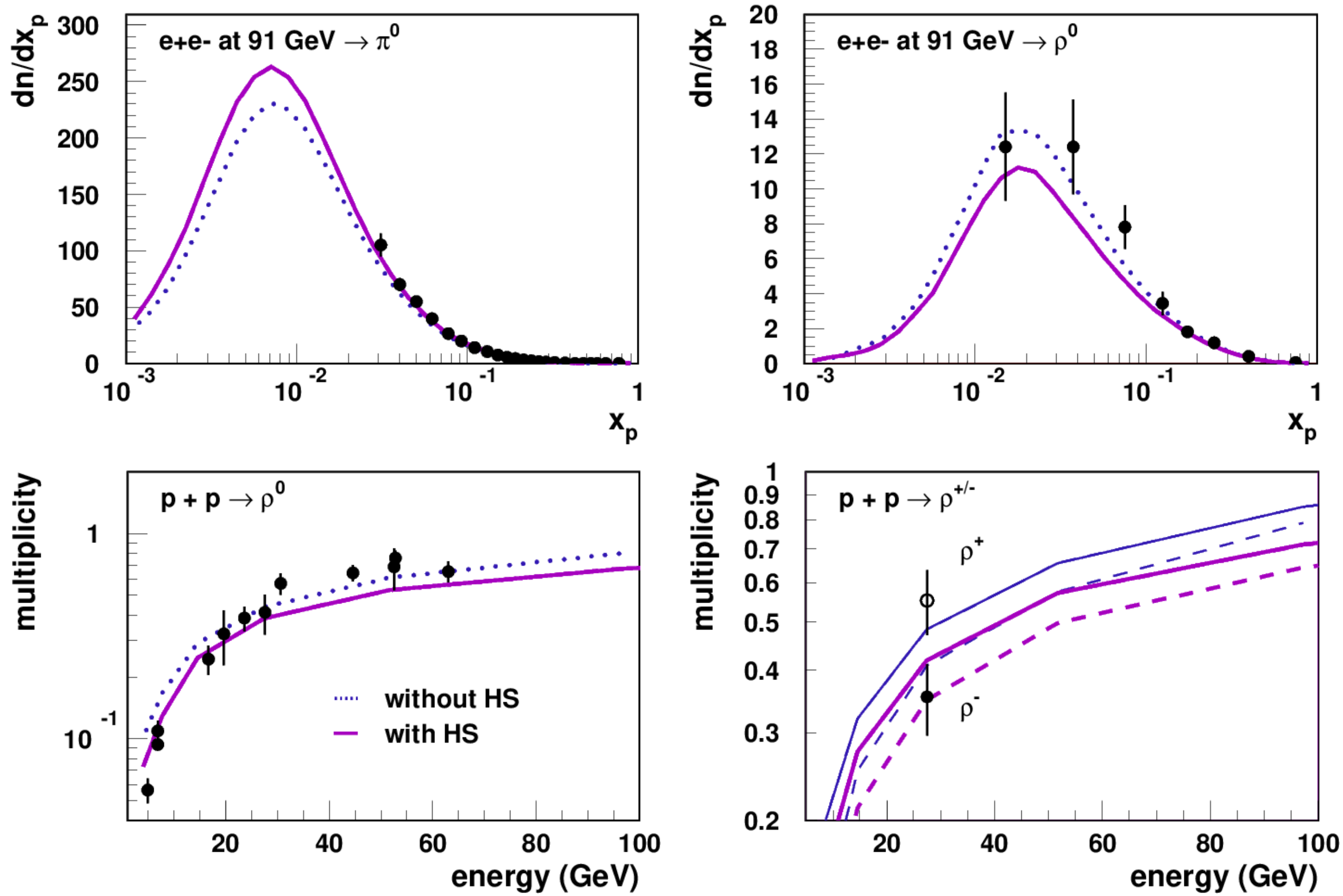
Example with Lambda particle in π-Air @ all energies



Impact of HS on light systems

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

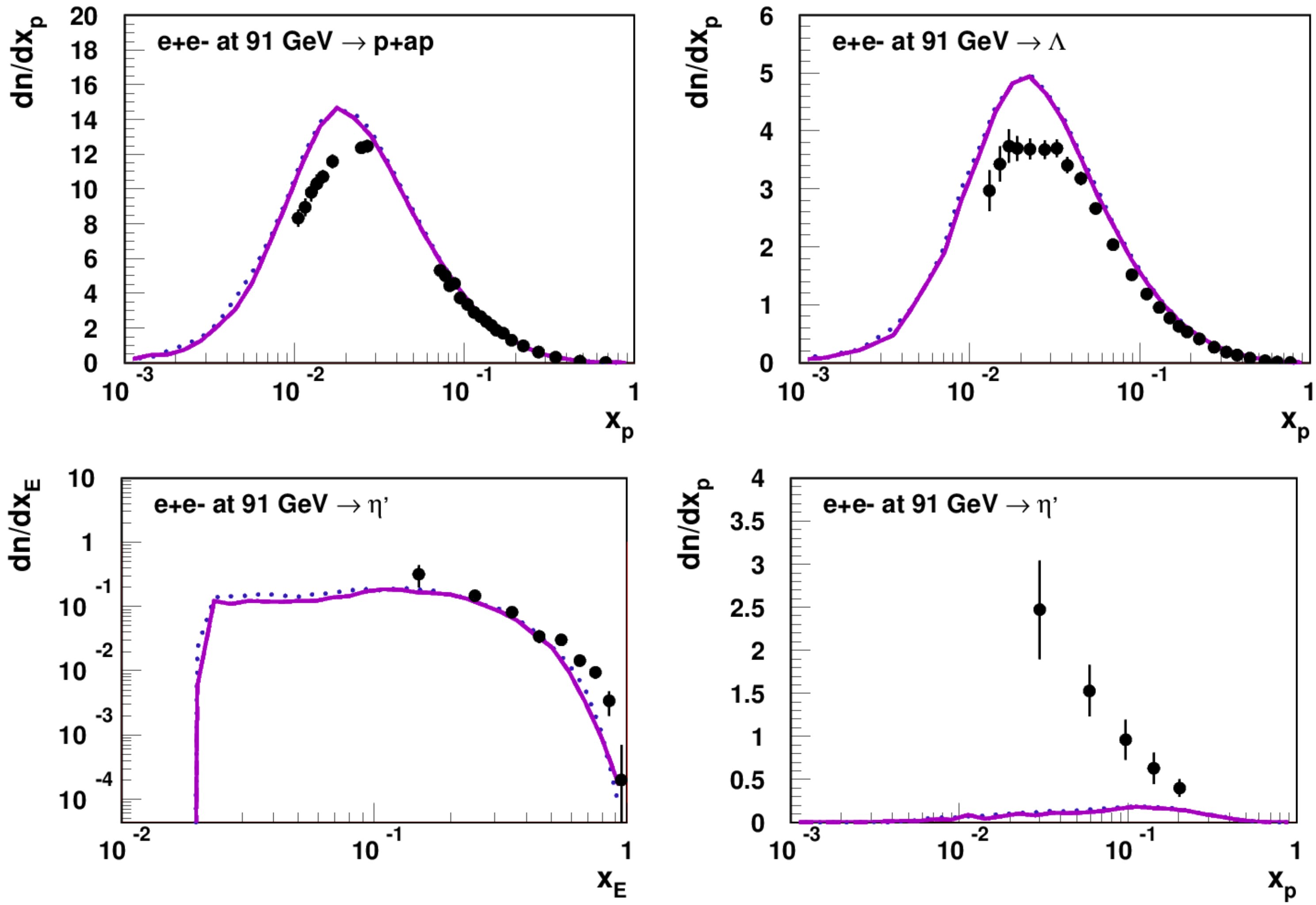
- Small but significant effect even in e+e- interactions
- Reduce ρ resonances and increase pions



LEP data

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

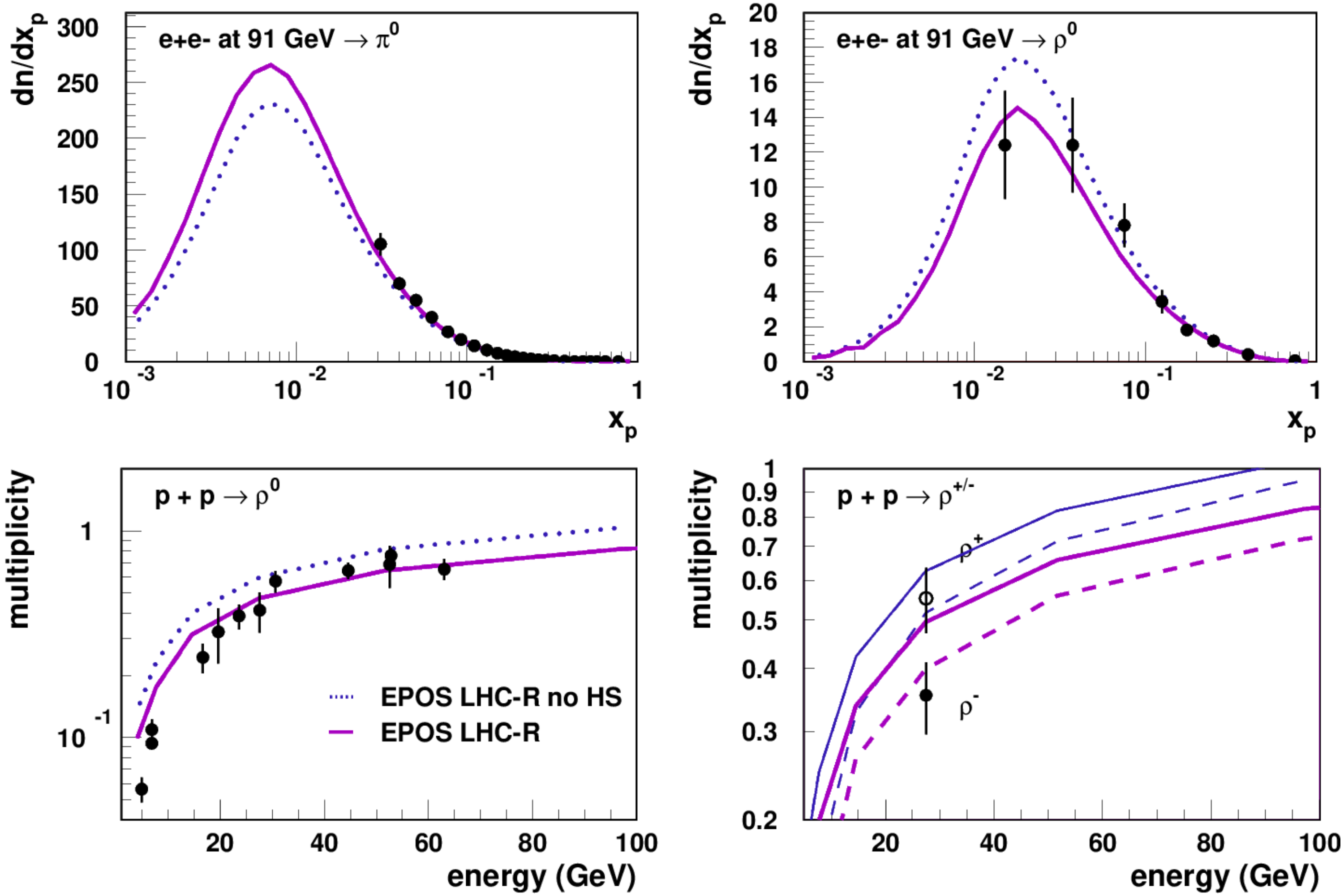
- Small but significant effect even in e+e- interactions
- More data could be considered if LEP data are used



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

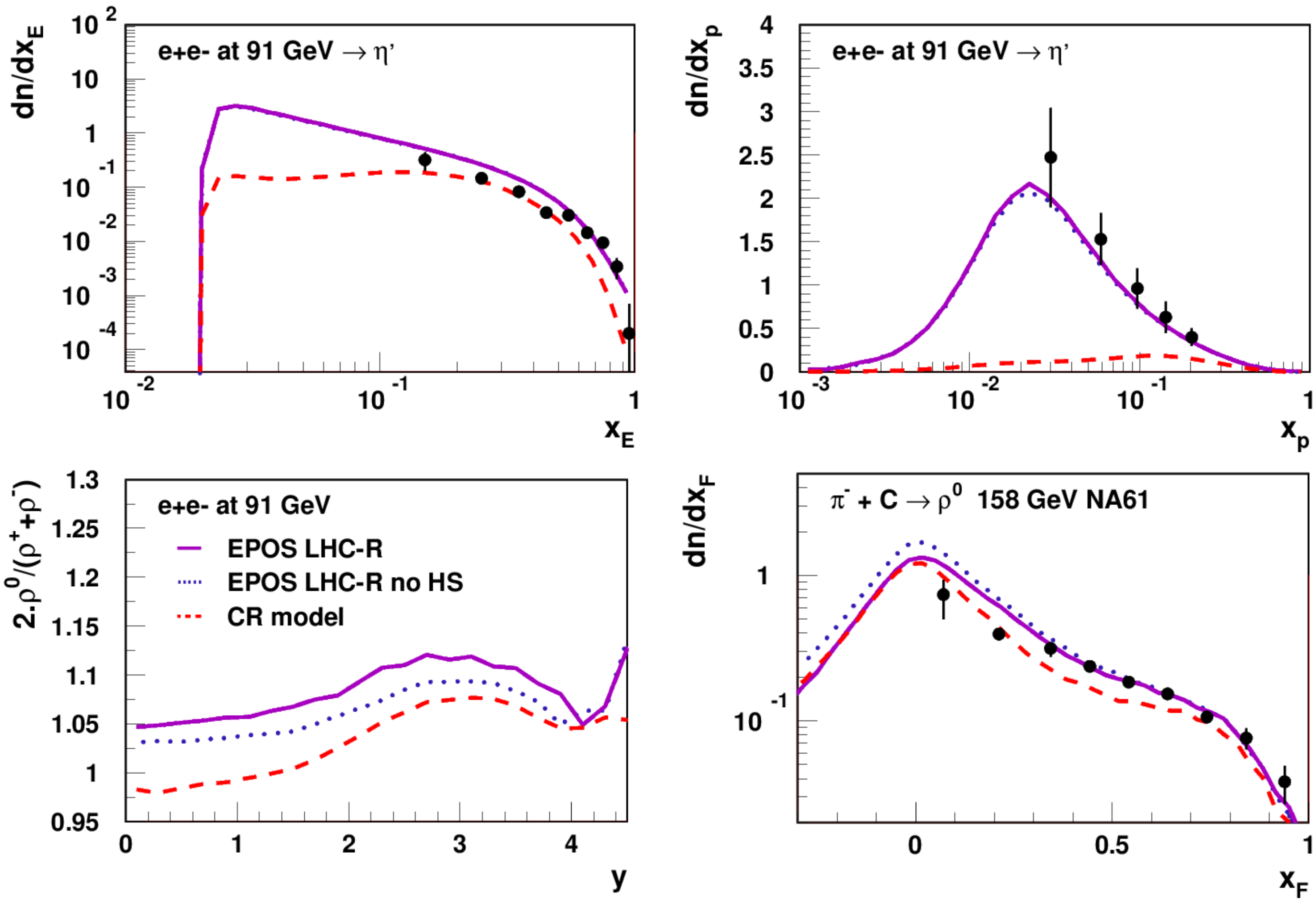


Retune basic parameters with HS and LEP

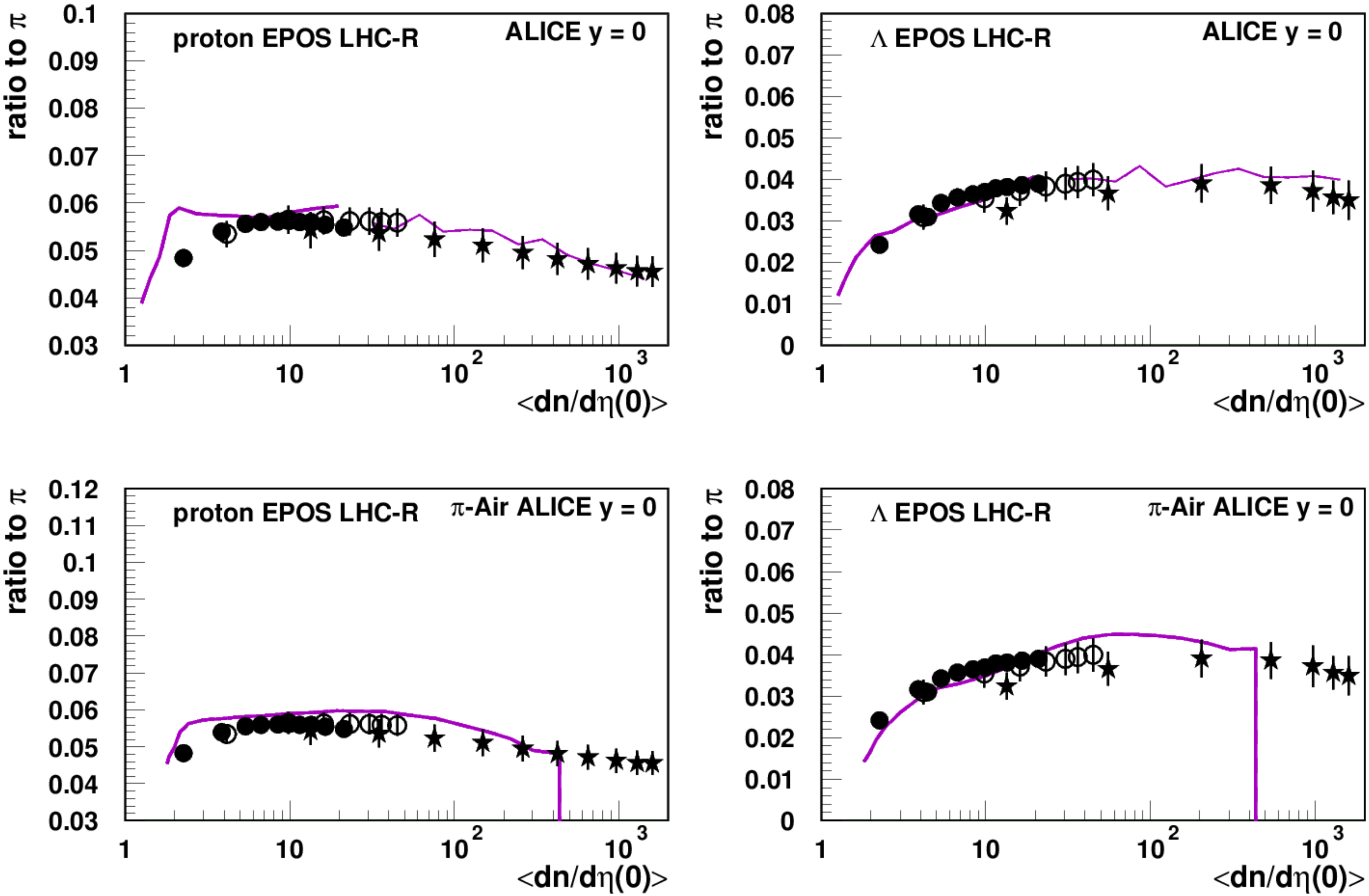
EPOS.LHC-R uses experimental constraints from LEP

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

  - Effect on muon production in air showers !



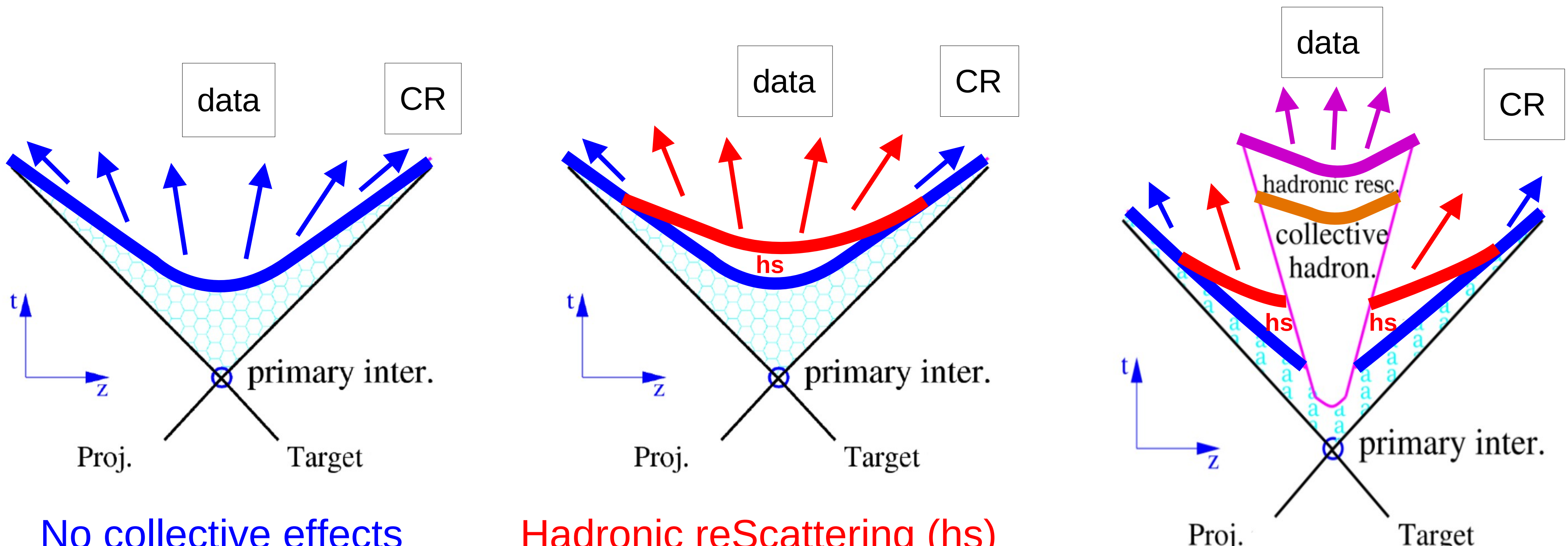
Check ALICE data



What is really new ?

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 ρ production compared to data (“bad tune”)
  - Or underestimate forward production of ρ^0 to get it right for mid-rapidity data



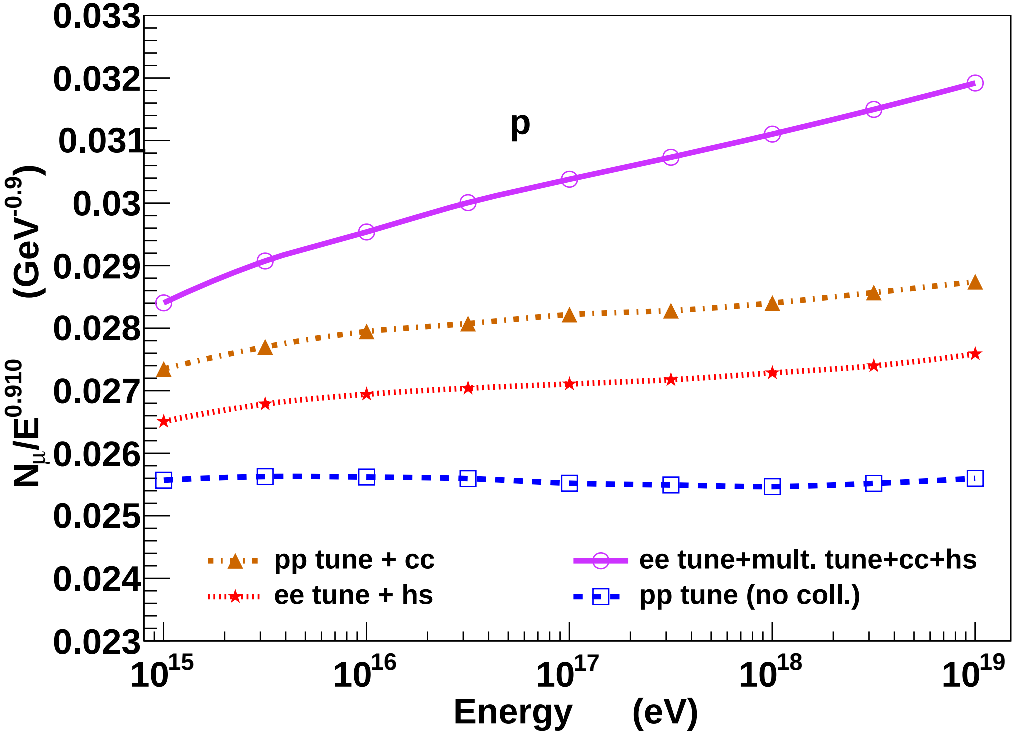
No collective effects

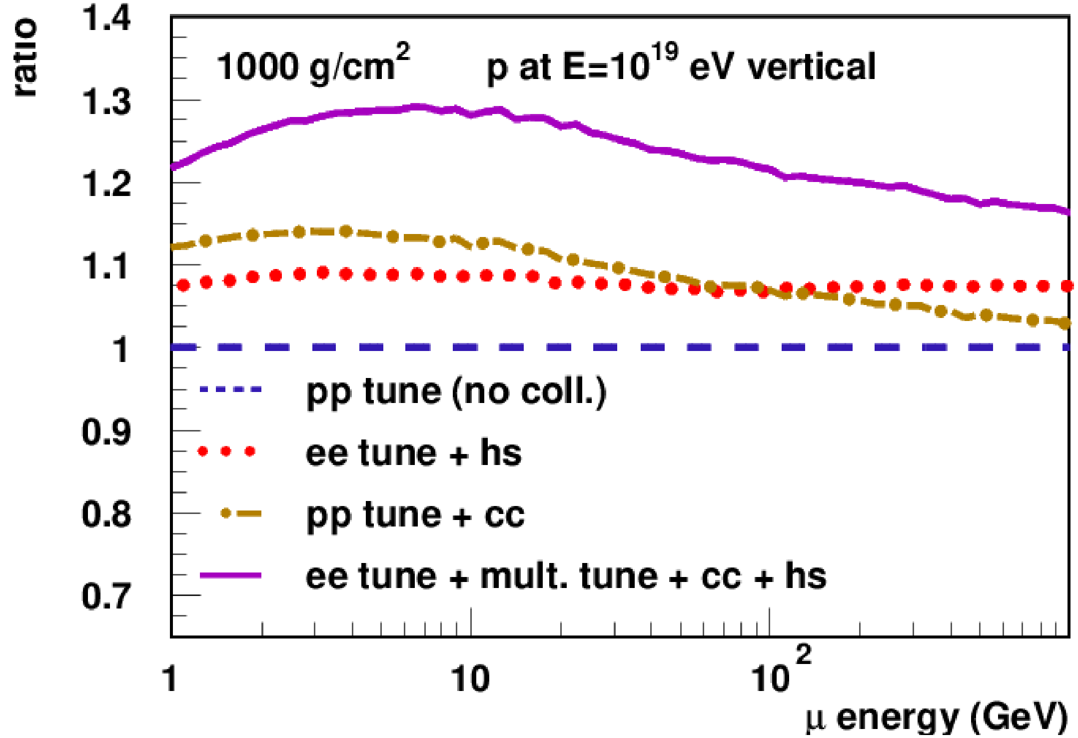
Hadronic reScattering (hs)

Impact on Air Showers

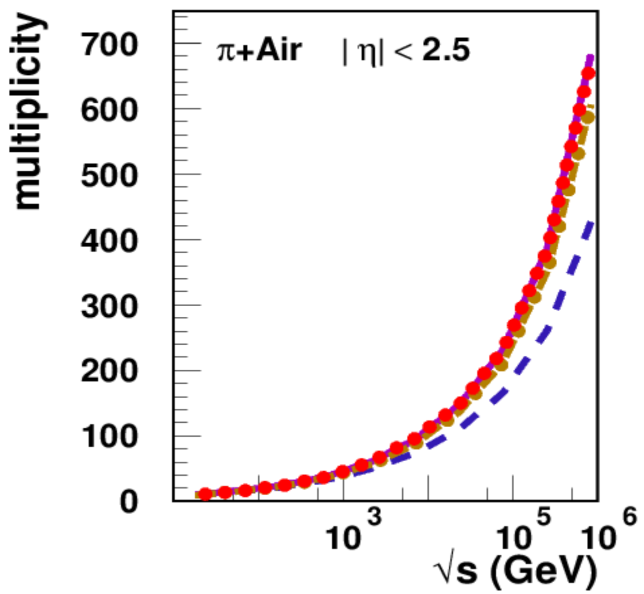
Changes with new tune taking into account collective effects (LHC)

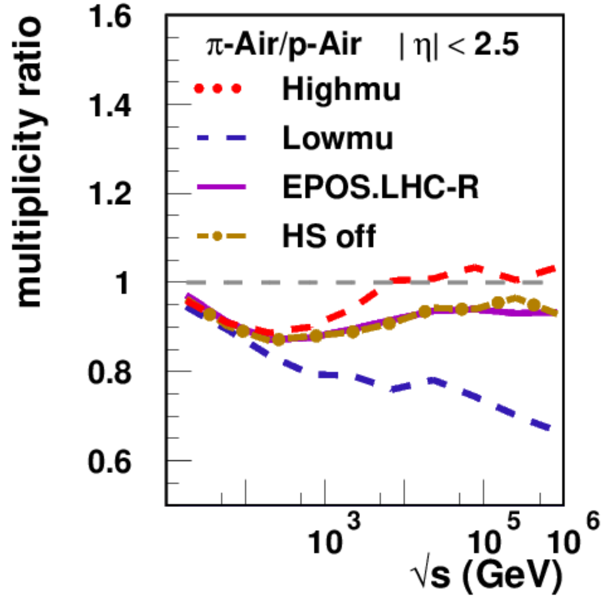
- Increase the number of muons by ... 10 to 20% (different slope) !
  - Impact of core-corona on baryon/strangeness prod. AND change in multiplicity/elasticity to accommodate hydrodynamical evolution (flow)
  - Impact of tune based on full LEP data with hs instead of just p-p/p-A
- Change in muon energy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

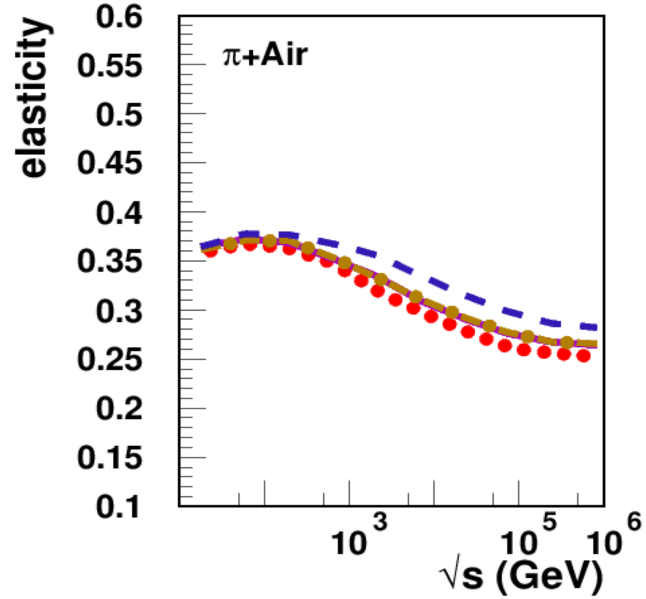


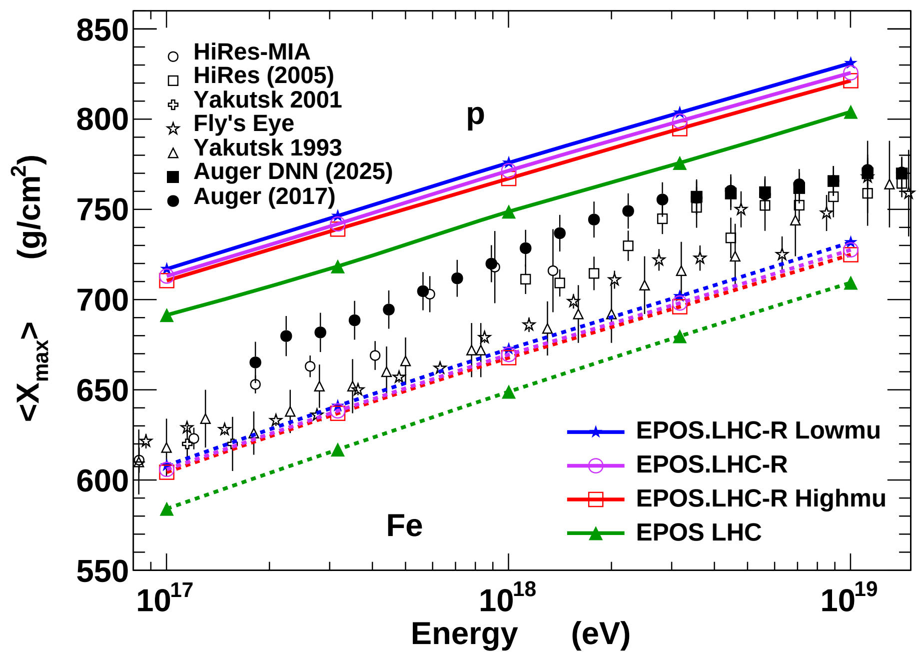


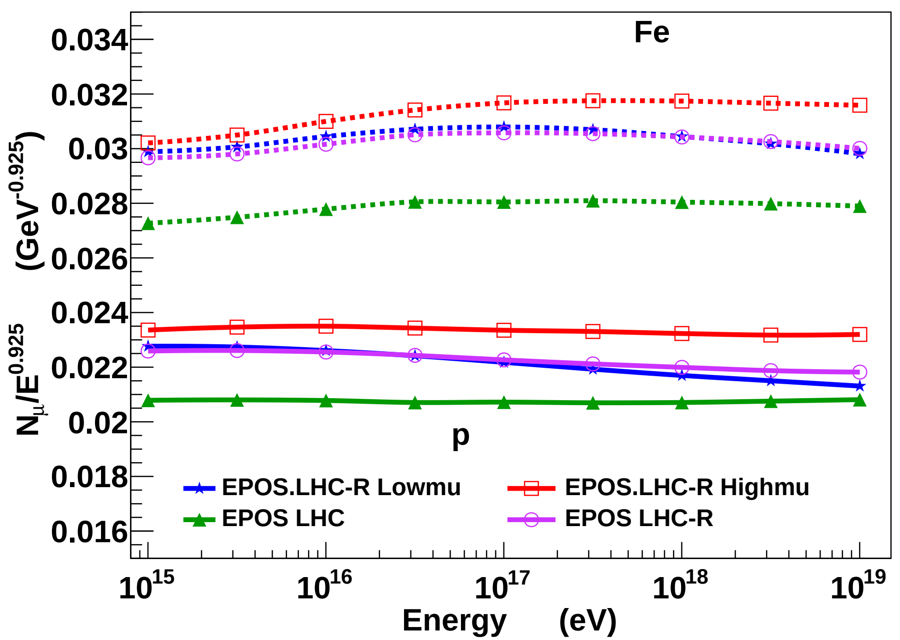
Pion-Air interaction unconstrained at high energy





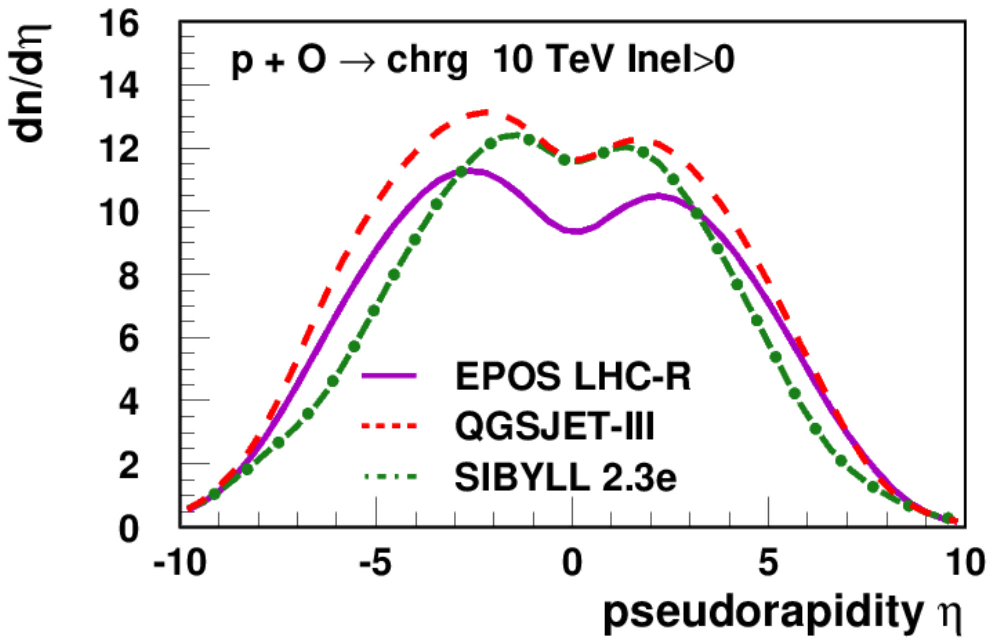


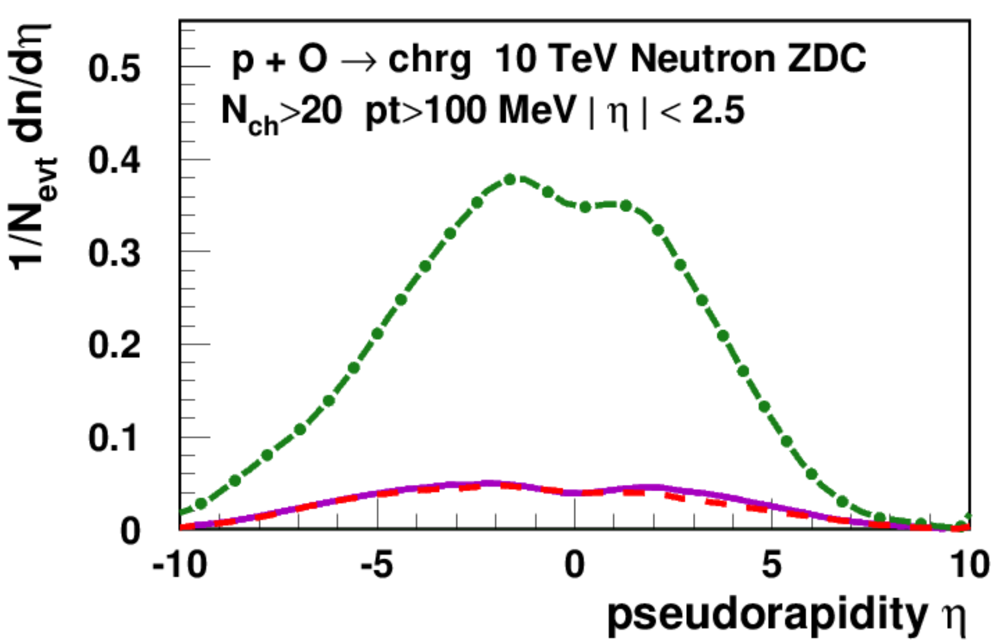




Multiplicity for pion projectile

- **Still lack of constrain on pion-Air multiplicity**
  - up to +/-5% uncertainty in N_μ and +/-5 g/cm^2 for X_{max}
- **Upcoming data for proton on Oxygen at LHC in July**
  - Use pion exchange in p-O interactions to probe pion-Oxygen
    - ➔ neutron tag in ZDC (ATLAS+LHCf/CMS)





Multiplicity with neutron tag

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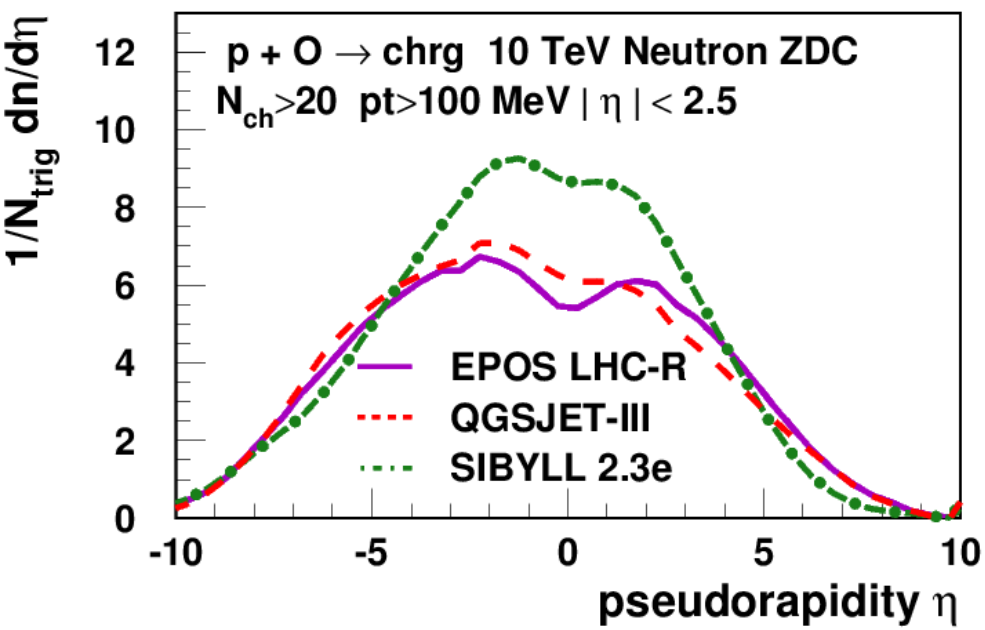
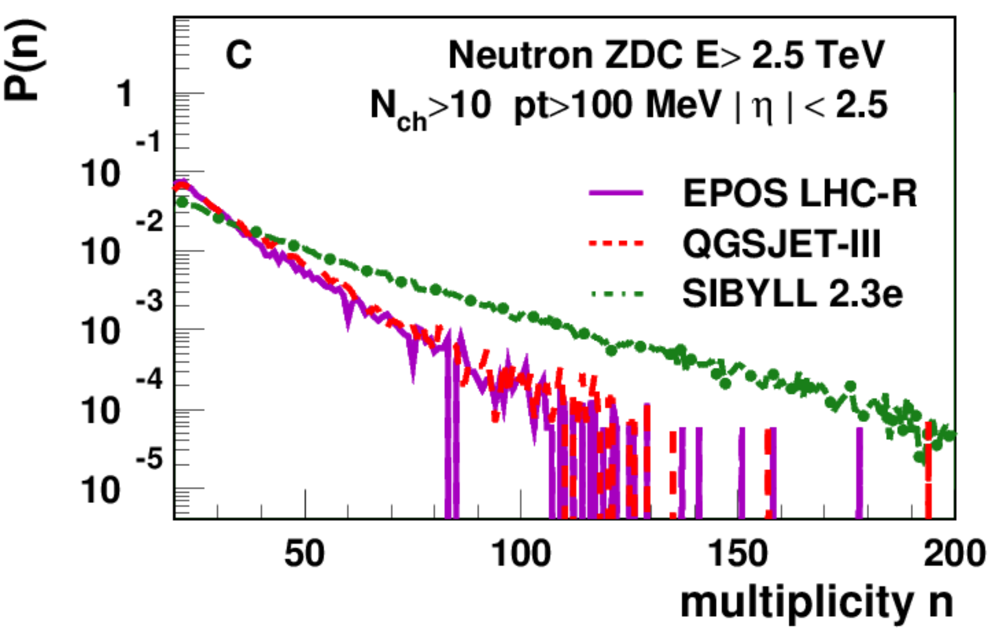
  - Use pion exchange in p-O interactions to probe pion-Oxygen
    - neutron tag in ZDC (ATLAS+LHCf/CMS)
  - Trigger on forward neutron + high multiplicity at mid-rapidity to select pion exchange interaction (around 50% in EPOS)





Multiplicity with neutron tag

- **Still lack of constrain on pion-Air multiplicity**
  - Can we get the sensitivity to test the π-O / p-O in a given model ?
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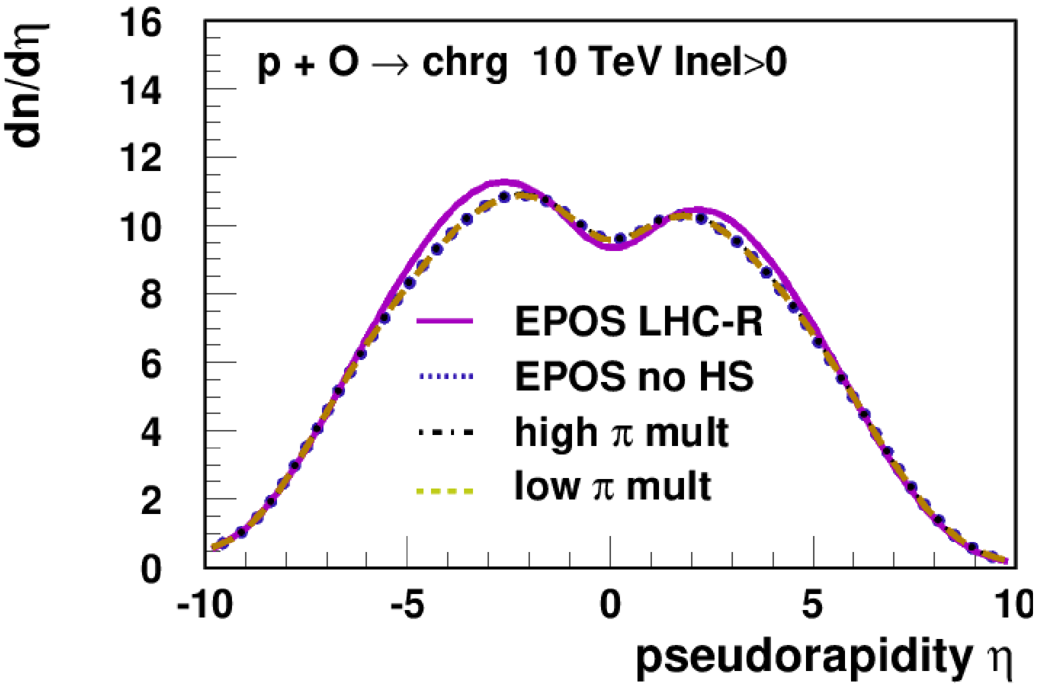

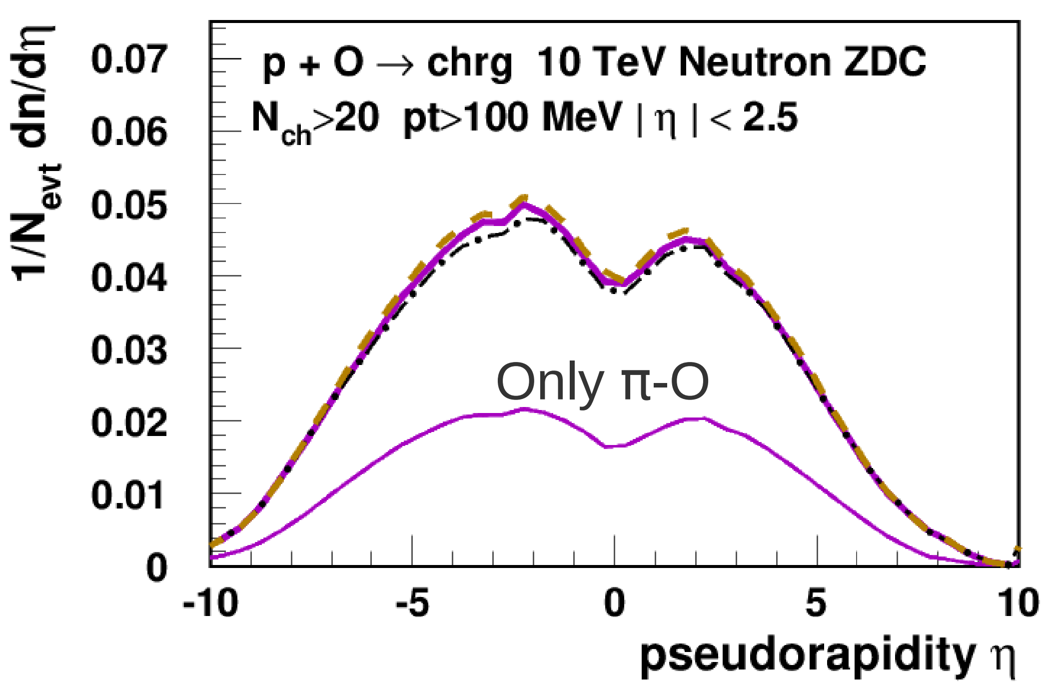

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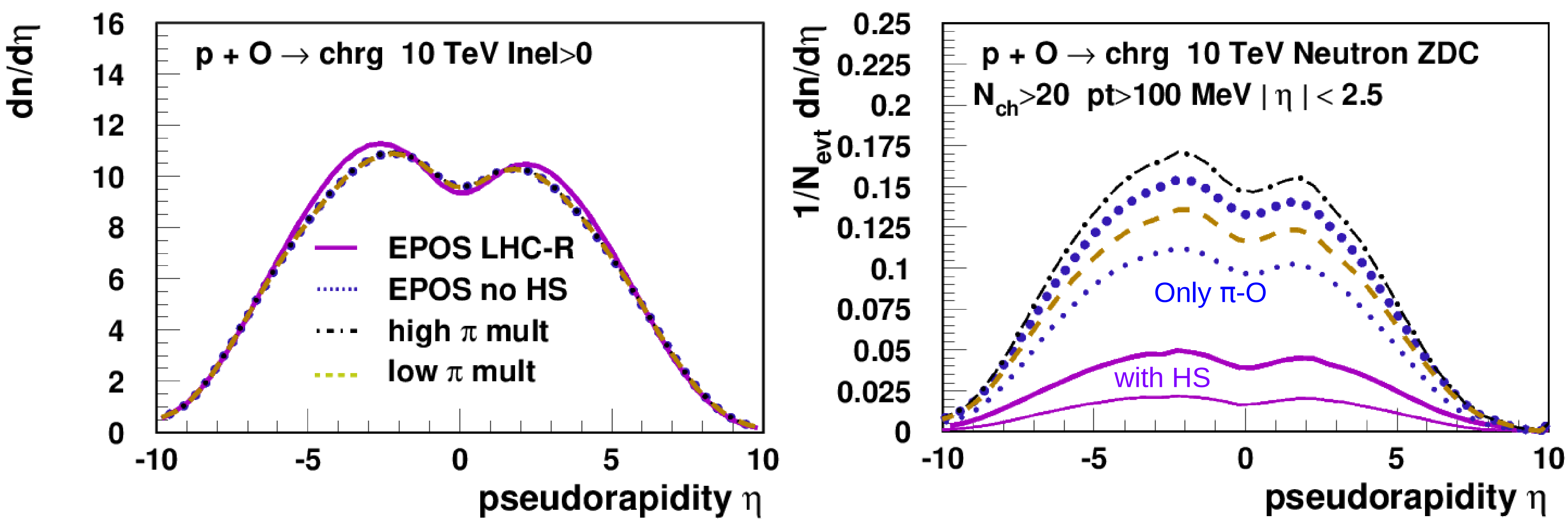
➡ Dependence on hadronic rescattering in EPOS LHC-R … to be confirmed ?



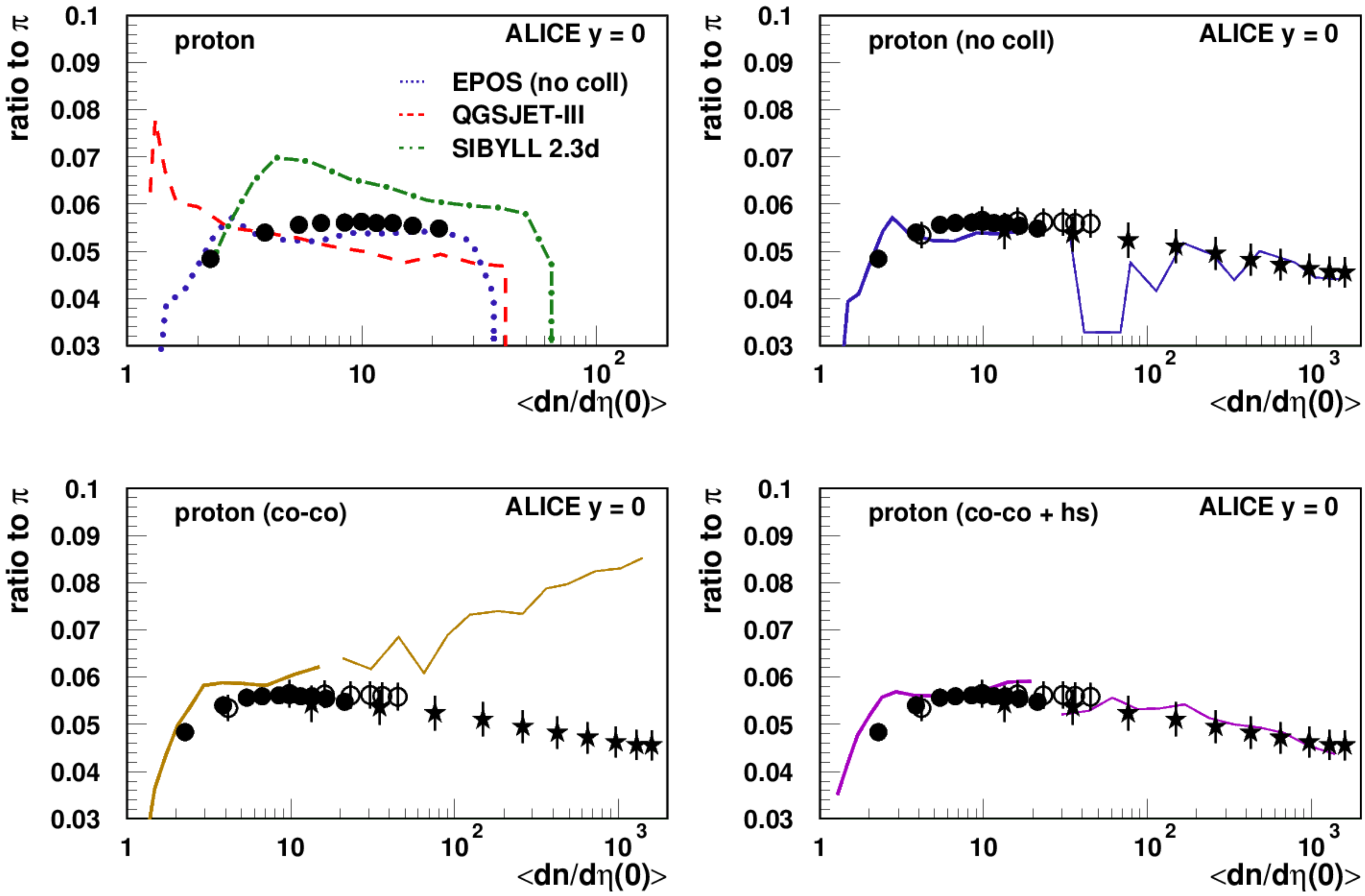
Outlook

- **Updated results of cross-sections, multiplicity and diffraction in EPOS.LHC-R and QGSJETIII-01**
  - Large impact on X_{max}
  - Larger <lnA> (heavier primary mass → reduce "muon puzzle")
- **Details of hadronization matters: importance to use a global approach**
  - 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 collective effects and in particular hadron rescattering was neglected**
  - Collective effects change the correlation between forward and mid-rapidity !
  - Different extrapolation in phase space important for EAS with same accel. data

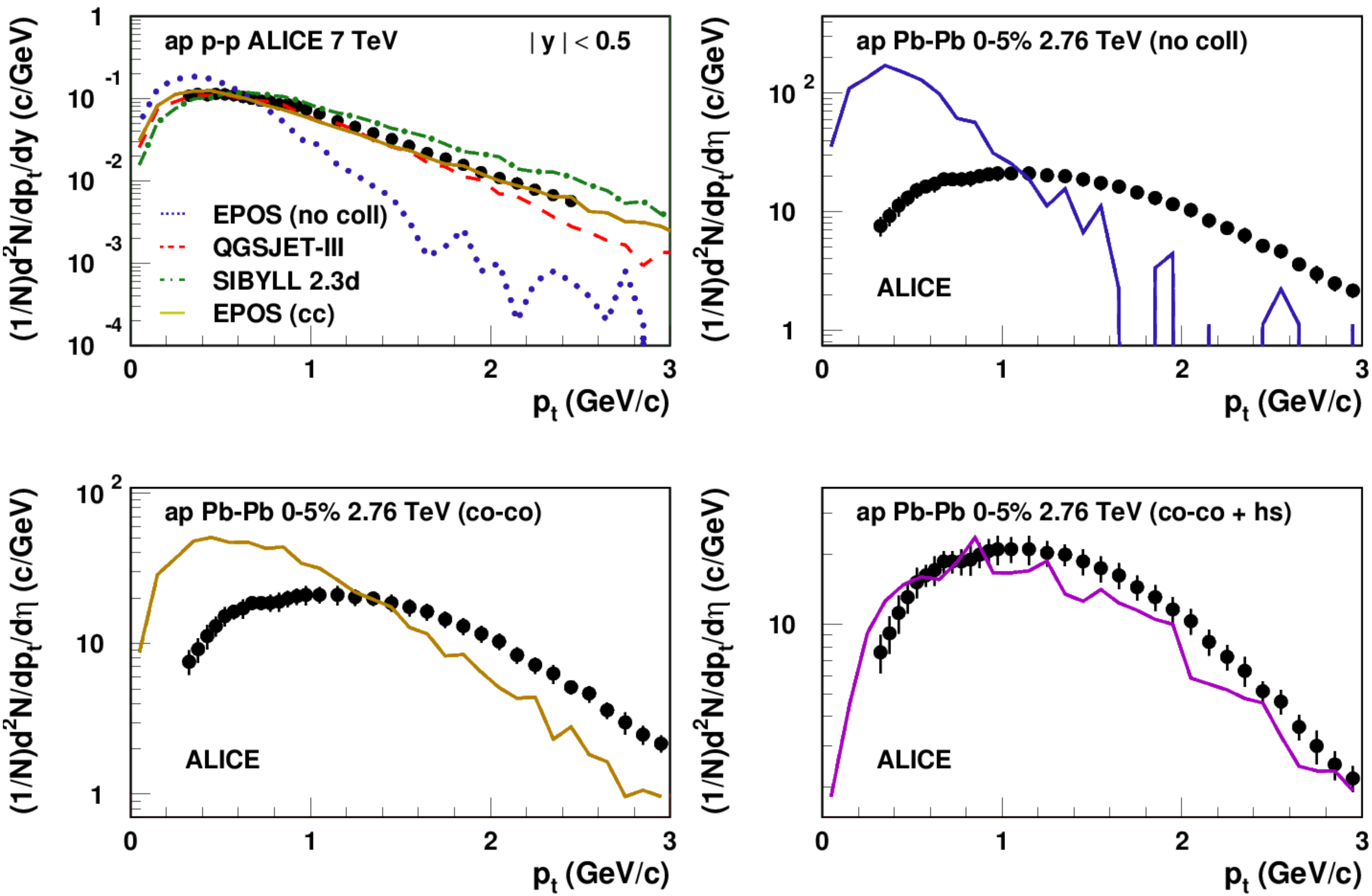
Recent LHC data provide new constraints on models changing X_{max} and the muon production, solving the muon puzzle only if a global approach is used.

Thank you !

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



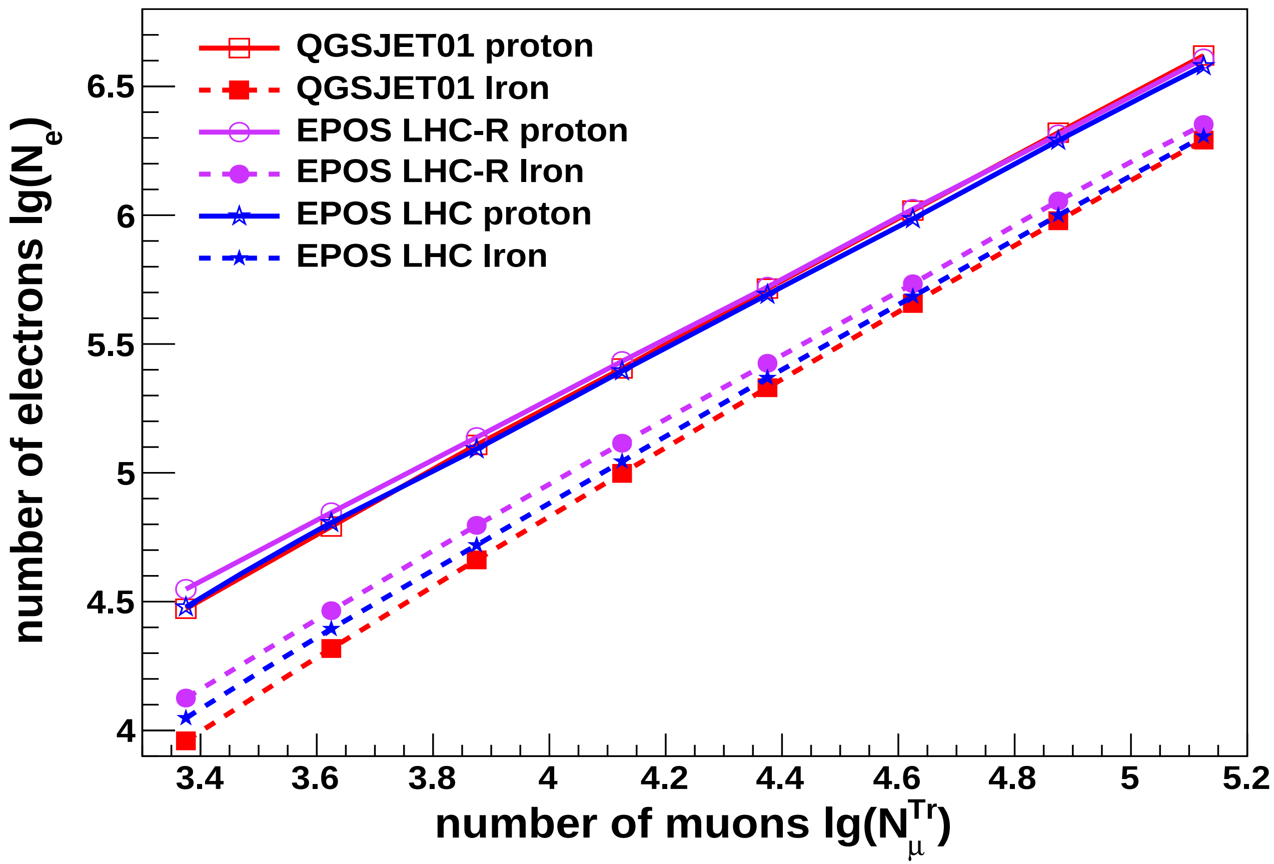
Example with protons in p-p and Pb-Pb @ LHC



KASCADE/LHAASO

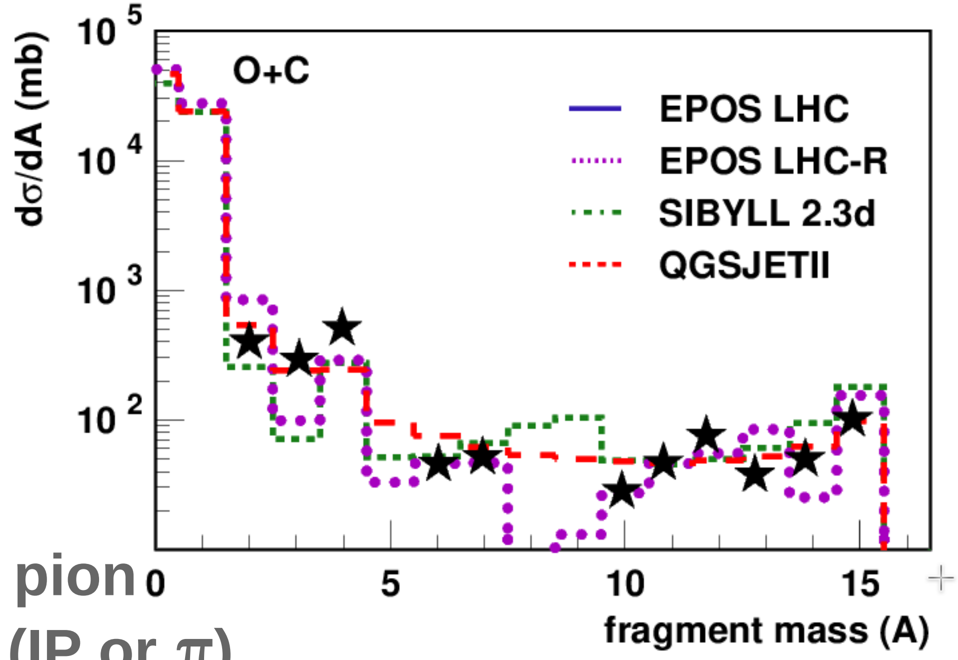
Correlation between N_e and N_μ

- 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 !

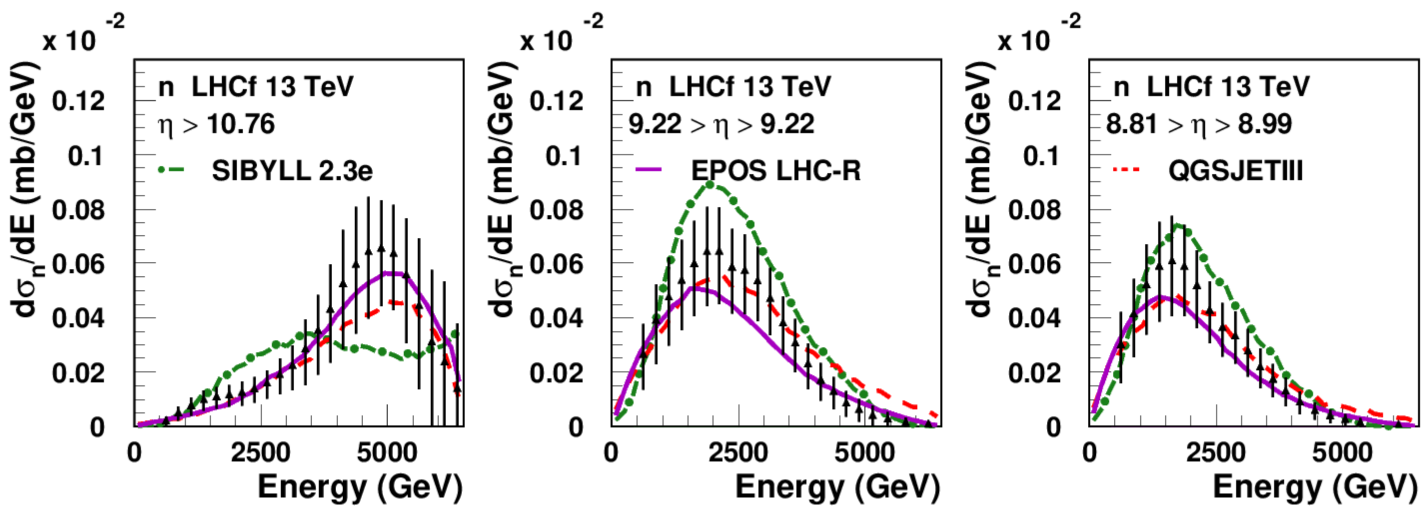


Improvements in EPOS LHC-R

- **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

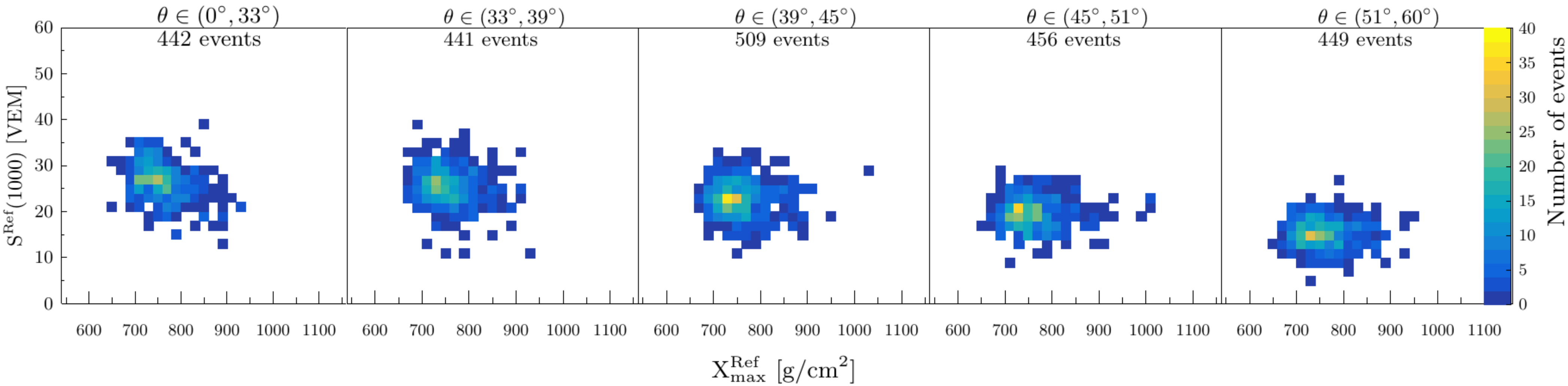


- **Simplified high mass diffraction and pion exchange replaced by real emission (IP or π)**



X_{max}-S(1000) correlation

Hybrid measurements allows to test model consistency in more details

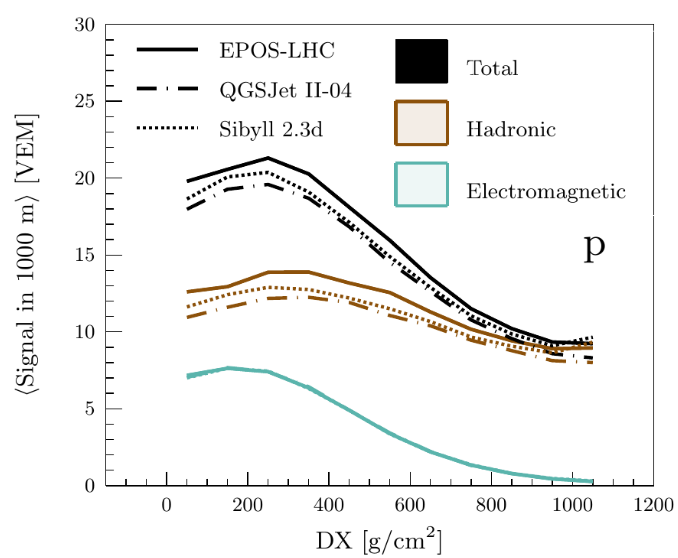


$$X^{\rm Ref}_{\rm max} \equiv \widehat{X^{\rm Ref}_{\rm max}} + \Delta X_{\rm max},$$
$$S^{\rm Ref}(1000) \equiv \widehat{S^{\rm Ref}(1000)} \cdot f_{\rm SD}(\theta)$$

Parameters:

$\Delta X_{max}, R_{Had}, R_{em}, \underbrace{\xi_1, \xi_2, \xi_3}_{\text{Describe the 4 mass fractions}}$

$$\phi = c \cdot f_{Gumbel}\left(X^{Ref}_{max}\right) \cdot f_{Gauss}\left(X^{Ref}_{max}, S^{Ref}(1000)\right)$$



The final MC templates are a sum of templates of the form of Φ of individual primary species weighted by their relative fractions.

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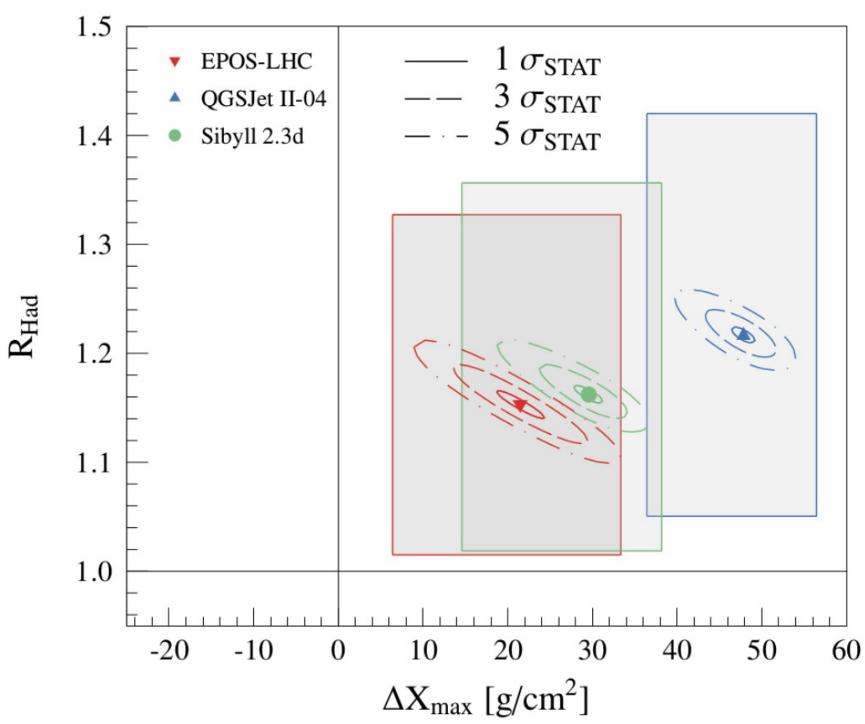
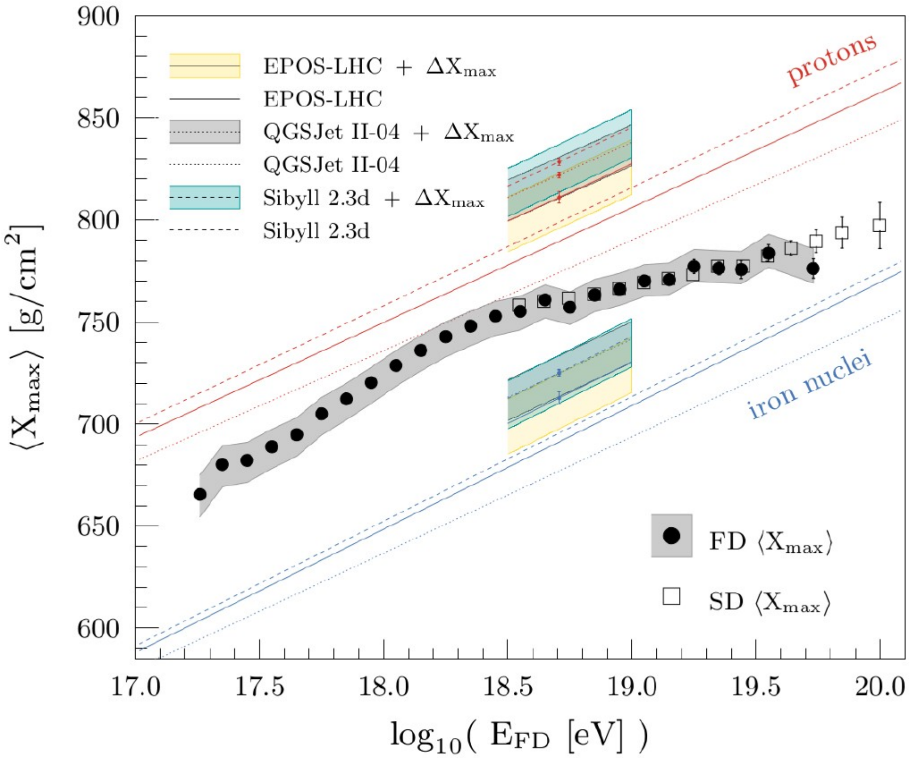
Modifications of X_{max} and signal at ground

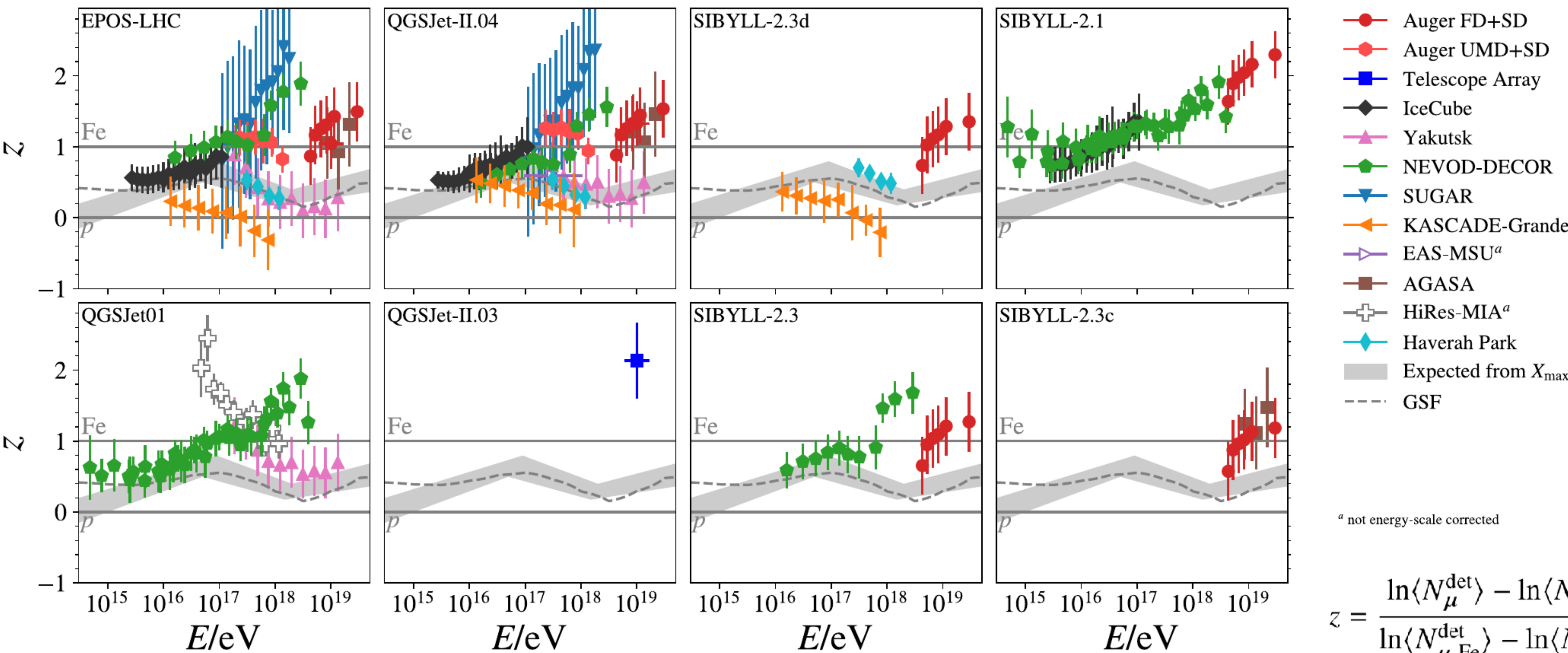
- **Best fit of data require multiple changes in hadronic models**
  - ➡ Rescaling (increase) of muons (hadronic component → confirmation)
  - ➡ Shift in X_{max} toward higher mass (electromagnetic component → new)
- **Might imply a change in mass composition**
  - ➡ Importance of LHC data to improve models (pO and forward data to reduce X_{max} and muon uncertainties)





Blurry Picture.

- **"Muon Puzzle" (<N_μ>) depends on energy measurement technique**
  - ➡ Update of WHISP analysis (2023)

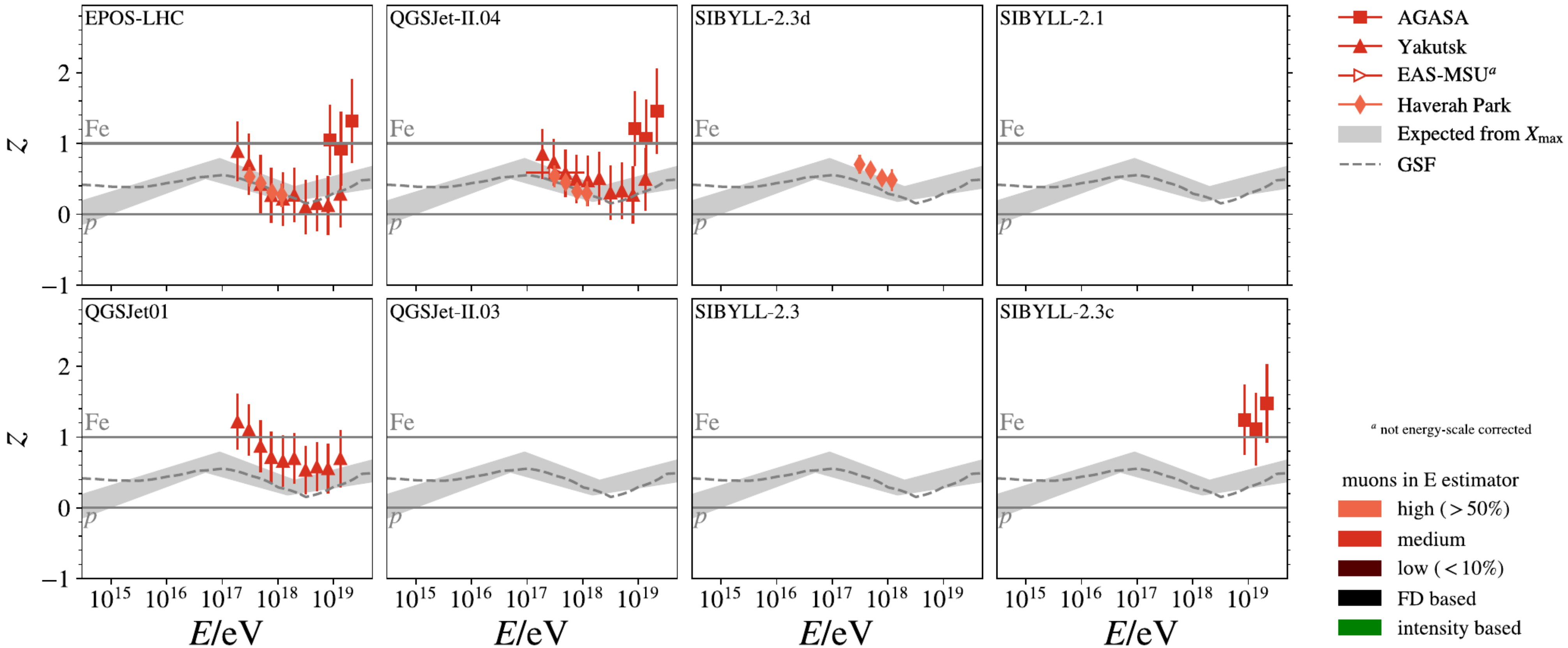


$$z = \frac{\ln\langle N_\mu^{\rm det}\rangle - \ln\langle N_{\mu,\rm p}^{\rm det}\rangle}{\ln\langle N_{\mu,\rm Fe}^{\rm det}\rangle - \ln\langle N_{\mu,\rm p}^{\rm det}\rangle}$$

J.C. Arteaga-Update on the combined analysis of μ data ICRC 2023, Nagoya, Japan 11

Blurry Picture..

- "Muon Puzzle" ($<N_\mu>$) depends on energy measurement technique
  - ➡ High muon fraction in energy estimator
    - ➡ No muon excess observed in data



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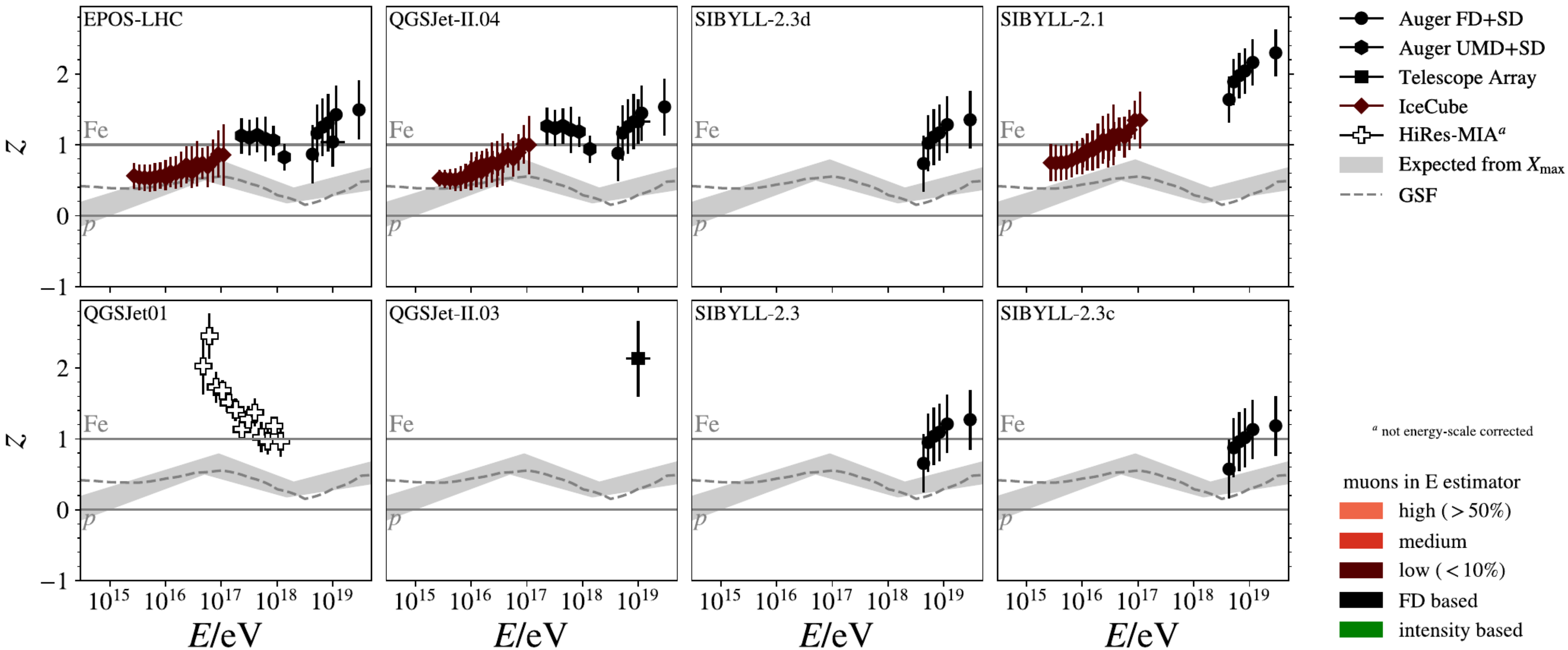
Blurry Picture...

- **"Muon Puzzle" (<N_μ>) depends on energy measurement technique**
  - ➡ Low muon fraction in energy estimator
    - ➡ Large muon deficit in simulations



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X^{μ}_{max} and N_{μ} @ 1 km (S_{μ}(1000m))

Global changes

- new EPOS shifted by +50g/cm^2 !
- QGSJETIII-01 shifted by +40g/cm^2 (=EPOS LHC)
- Very different zenith angle dependence for EPOS LHC-R !
  - Different muon energy spectrum