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

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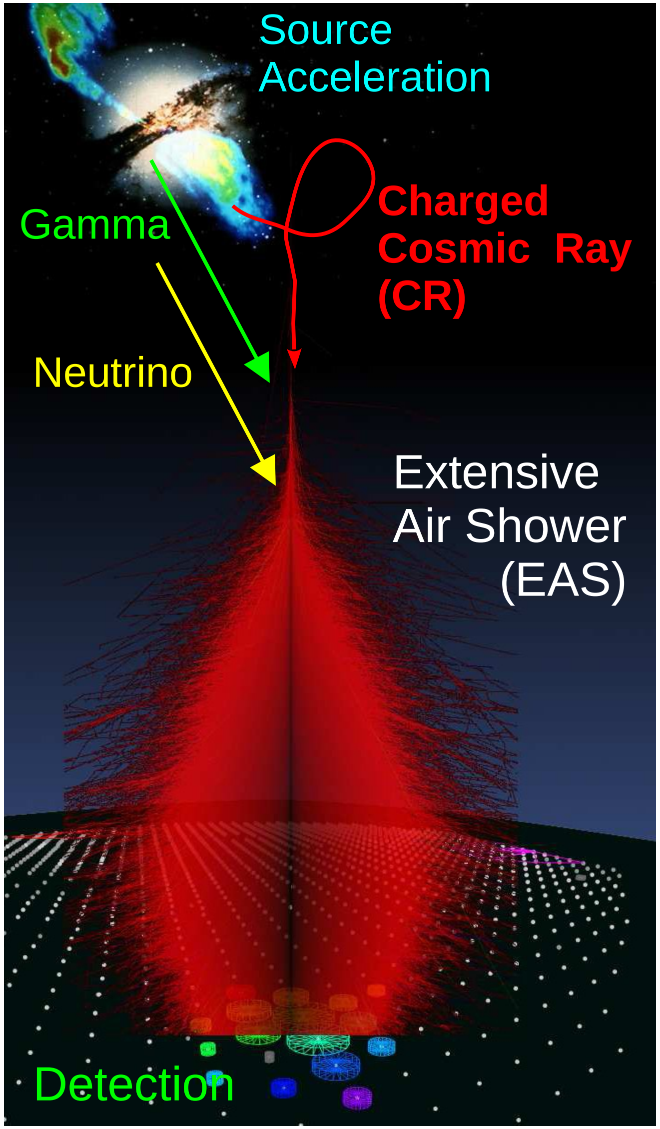
Outline

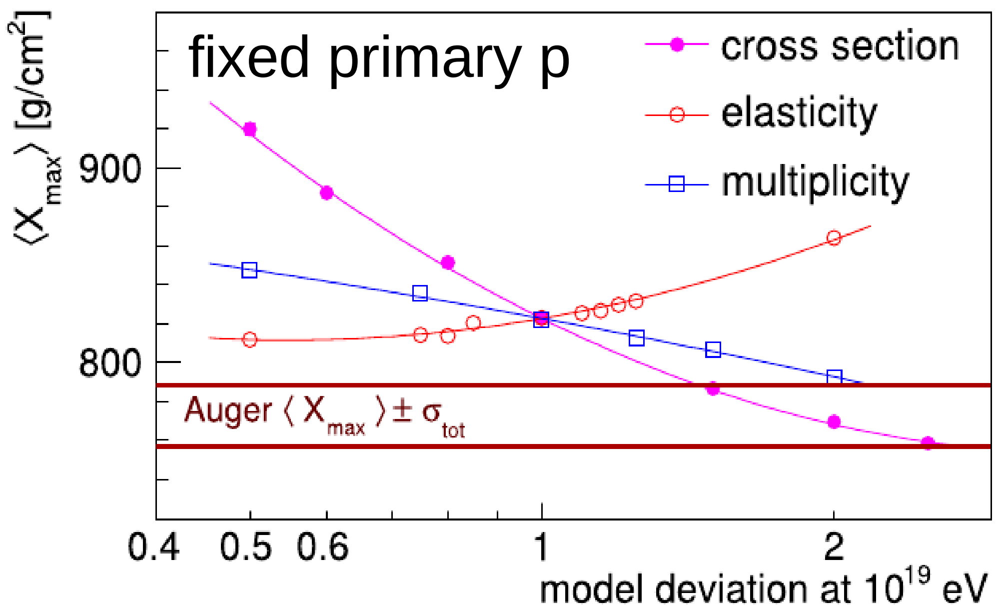


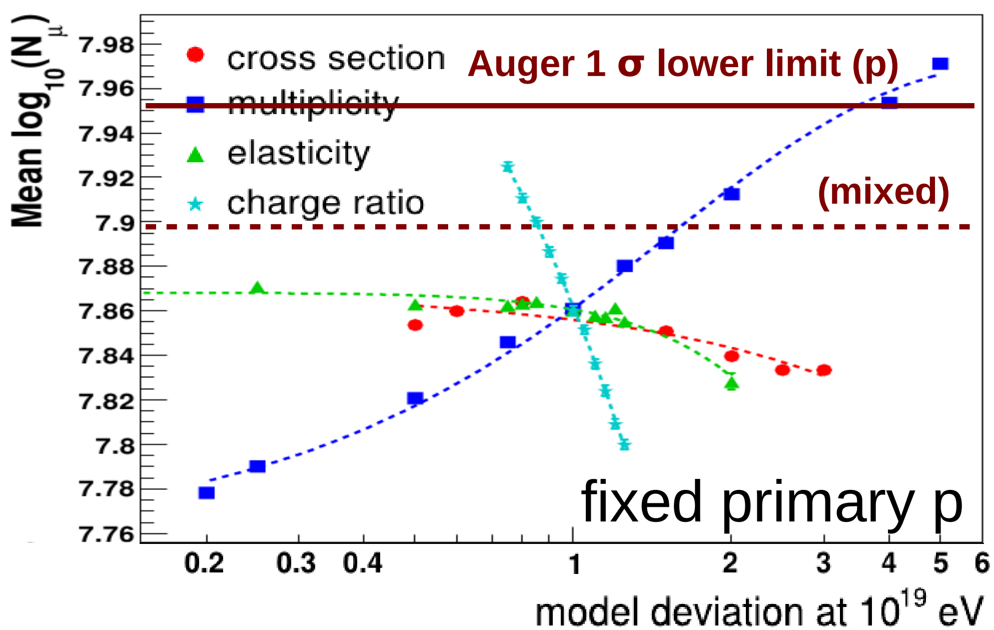
From R. Ulrich (KIT)

- **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, 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.

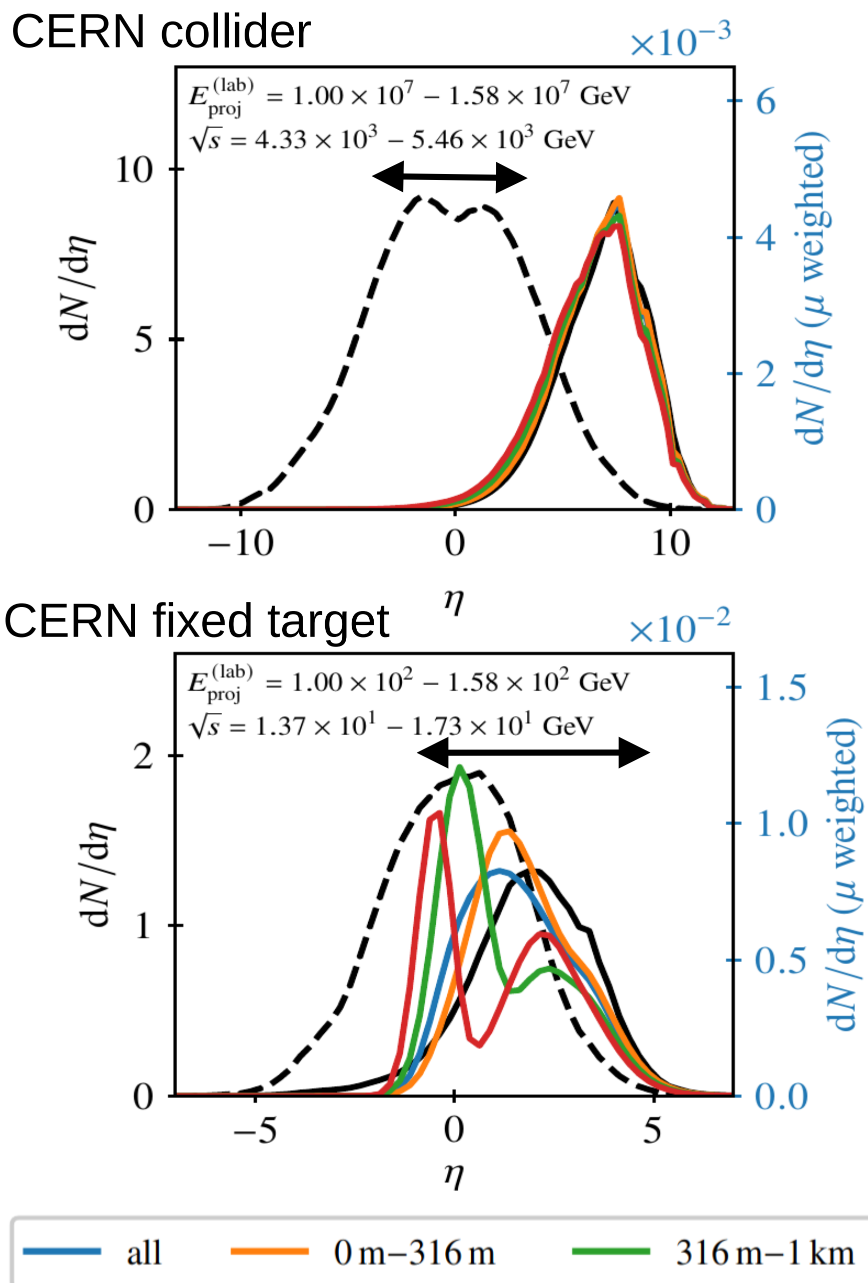
Cosmic Ray Analysis from Air Showers

- **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

Phase Space



M. Reininghaus (ICRC2021)

- **Definition** (θ=emission angle)
  - pseudorapidity η=-ln(tan(θ/2))
  - η=0 is midrapidity
  - η»1 is forward (same direction than beam)
  - η«1 is backward
- **First interaction (high energy)**
  - Muons production lead by forward particles
  - EM shower driven by most energetic π^0
- **Last generations (low energy)**
  - Muon produced from $\pi^{+/-}$ at all angles
  - EM particles impacted only at large distances
- **Most accelerator data measured in different phase space**
  - Extrapolation needed from η=0 to η»1

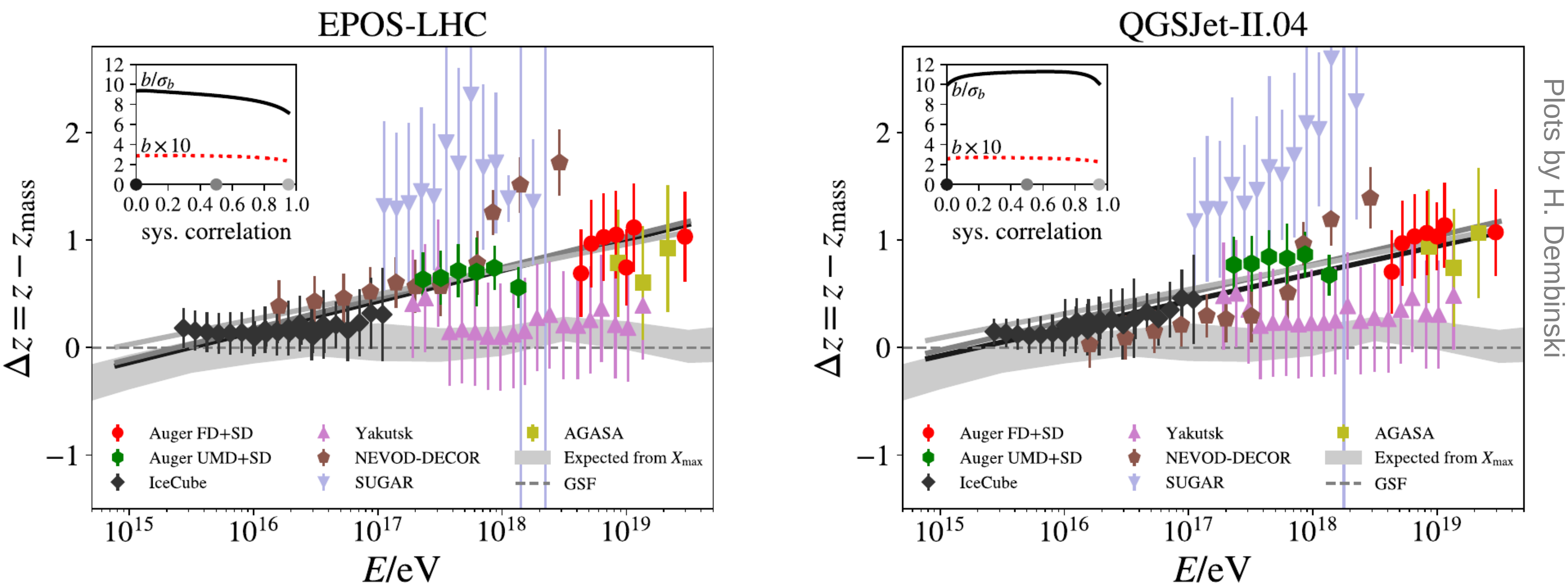
WHISP Meta-Analysis (2021)

- **Clear muon excess in data compared to simulation**
  - ➡ Different energy evolution between data and simulations

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

➡ Significant non-zero slope (>8σ)

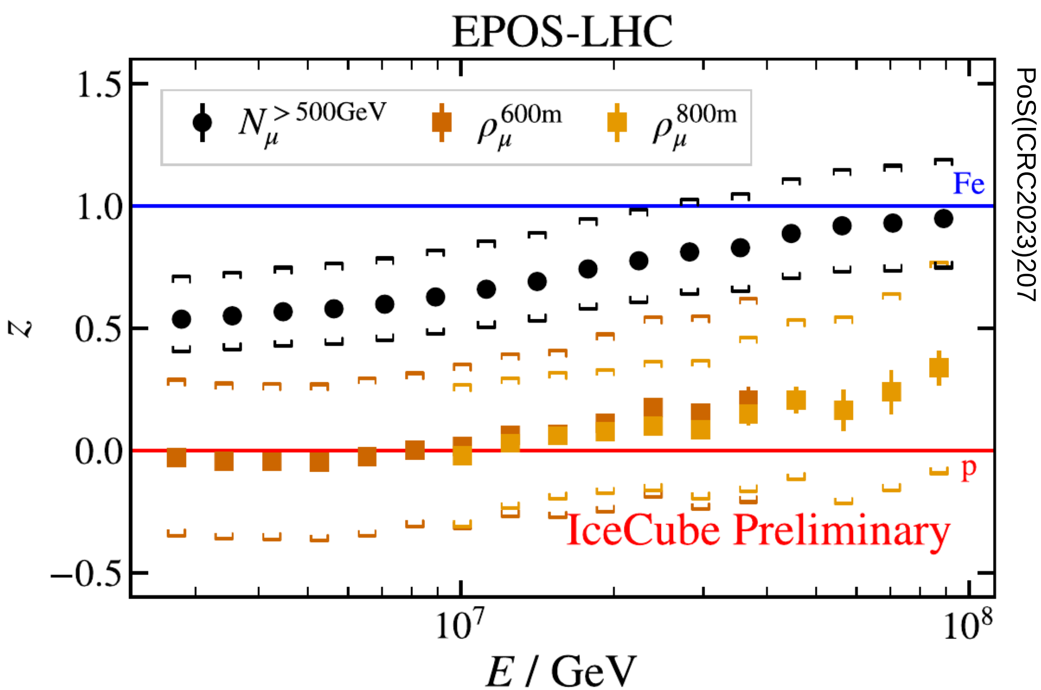
$$z_{\rm mass} = \frac{\langle \ln A \rangle}{\ln 56}$$

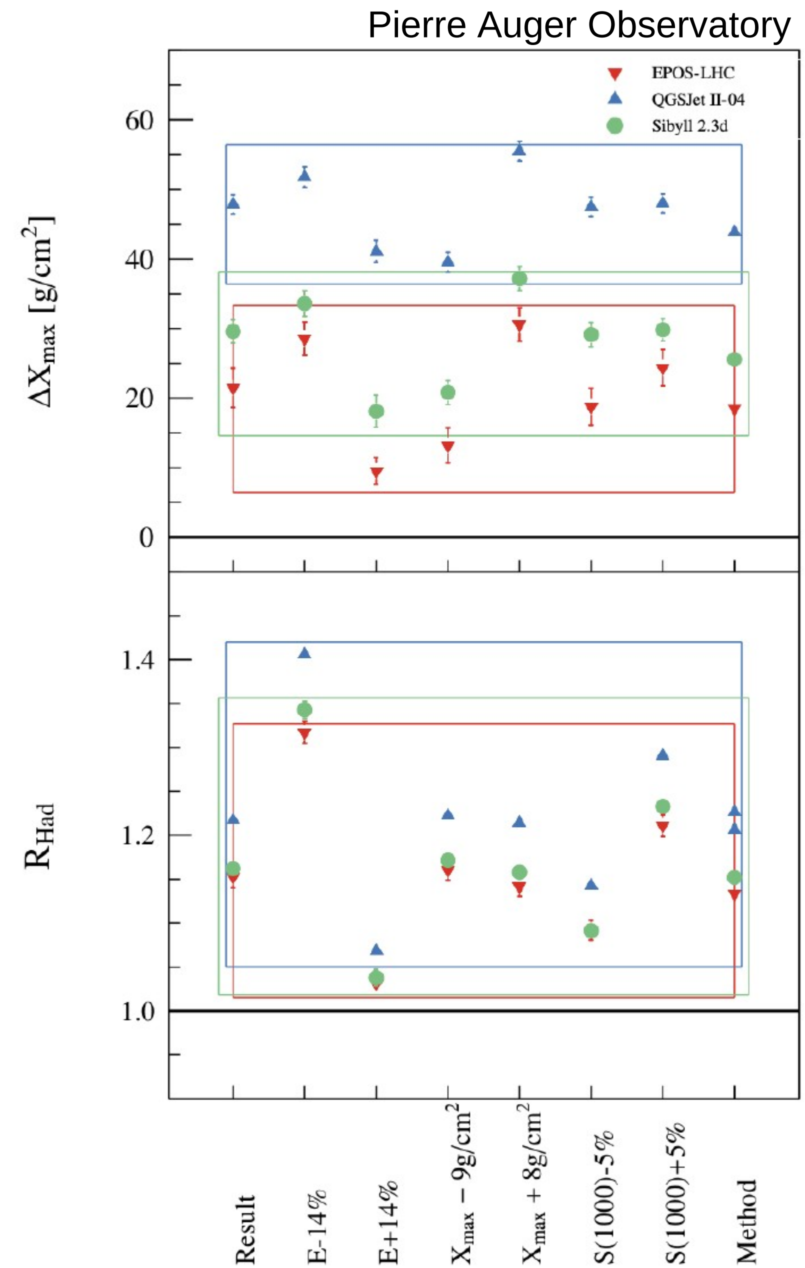


- **Different energy scale cannot change the slope**
  - ➡ Different property of hadronic interactions at least above 10^{17} eV

And more evidences

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





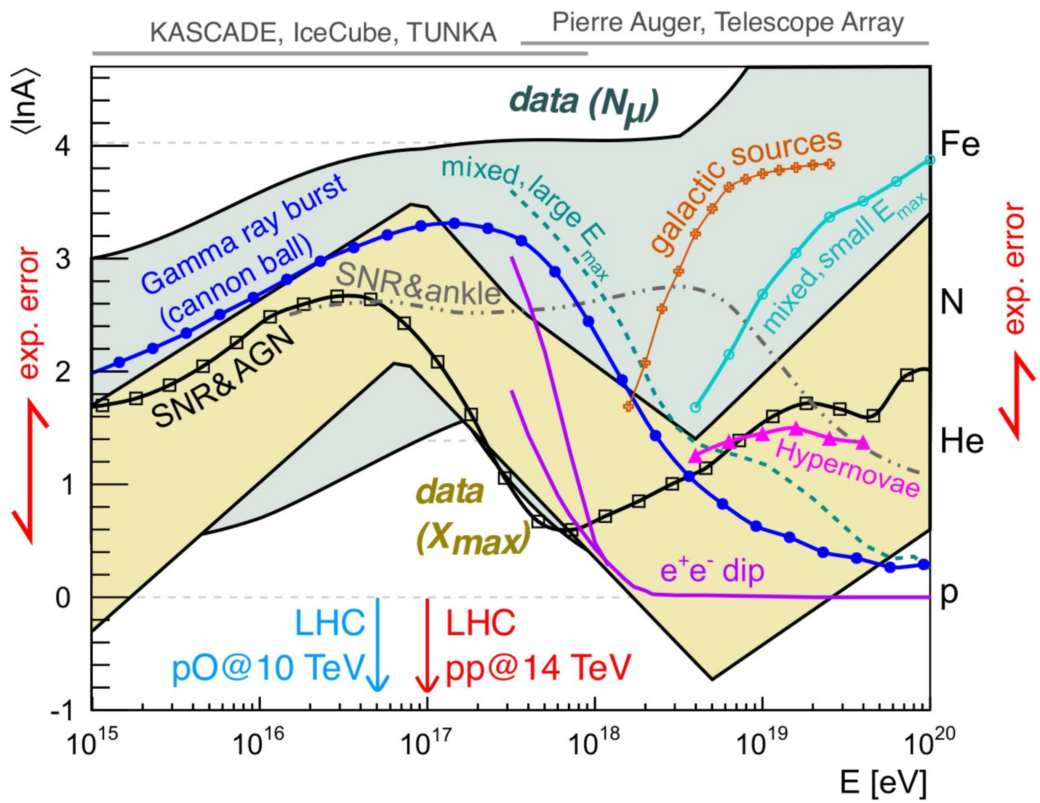
- **Other variables not well reproduced**
  - ➡ Zenith angle dependence, muon production height, ...

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)

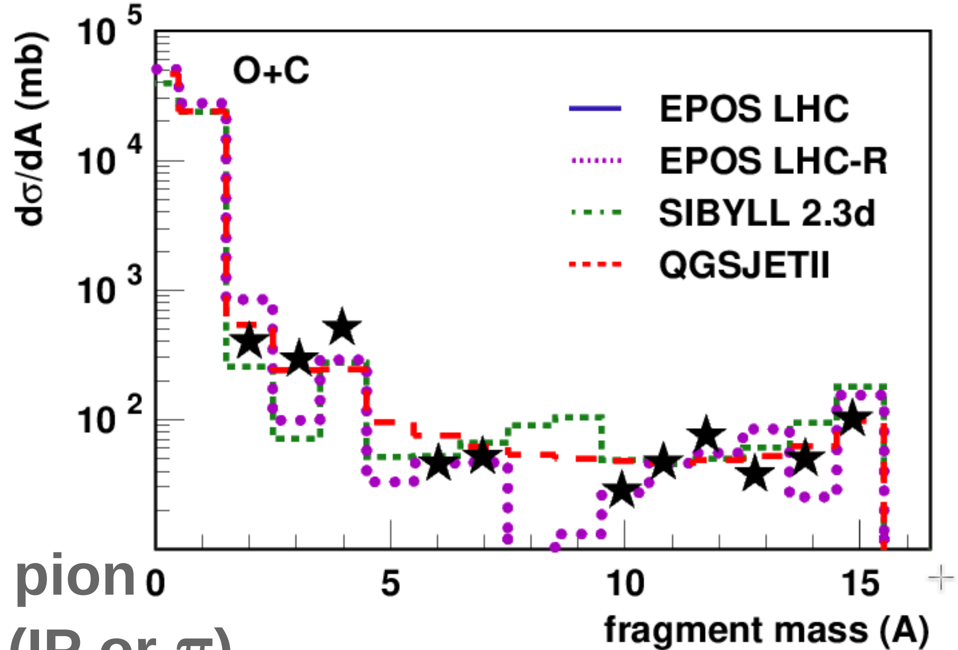
X_{max}

N_{μ}

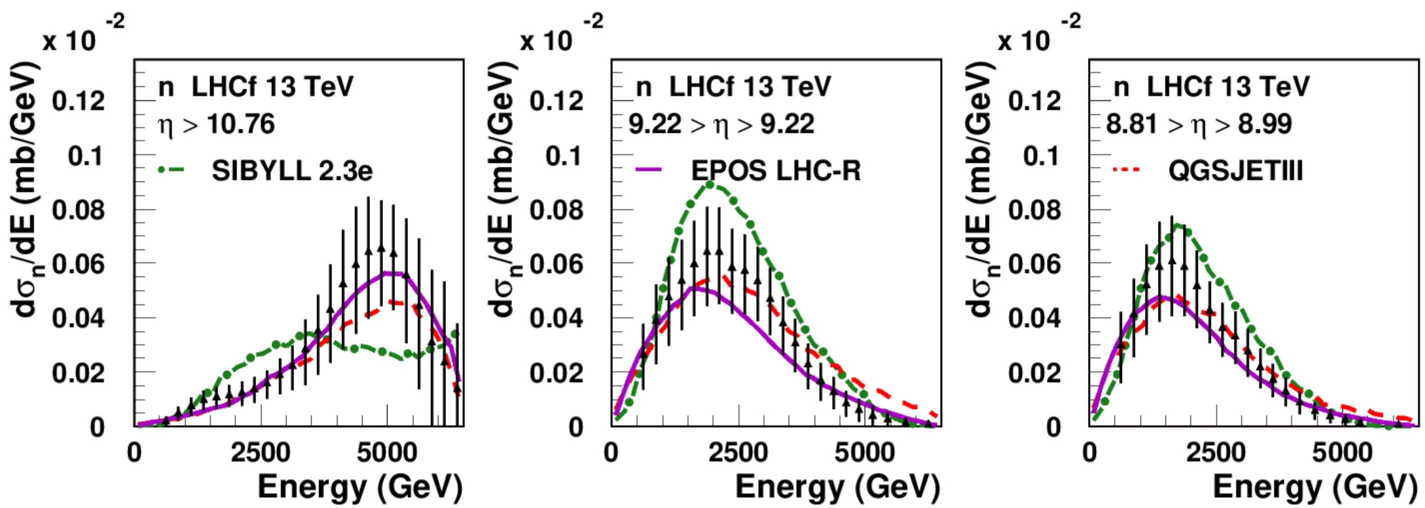
- **Update of EPOS LHC → EPOS.LHC-R**
  - Modify EPOS LHC to take into account new data and new knowledge accumulated with (and code from) EPOS 4
  - Global approach taking into account collective effects
- **Update of QGSJETII-04 → QGSJETIII-01**
  - Higher twist calculation in hard component to avoid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

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



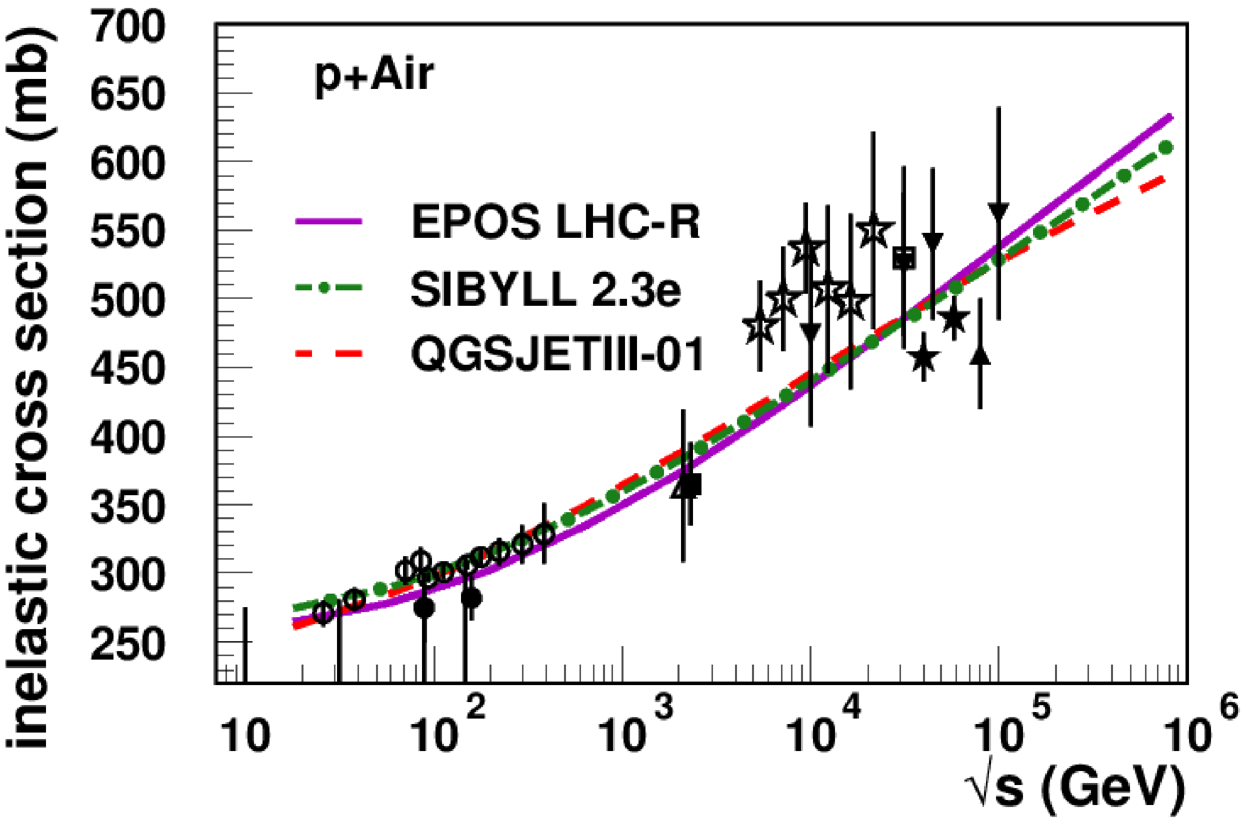
- **Simplified high mass diffraction and pion exchange replaced by real emission (IP or π)**

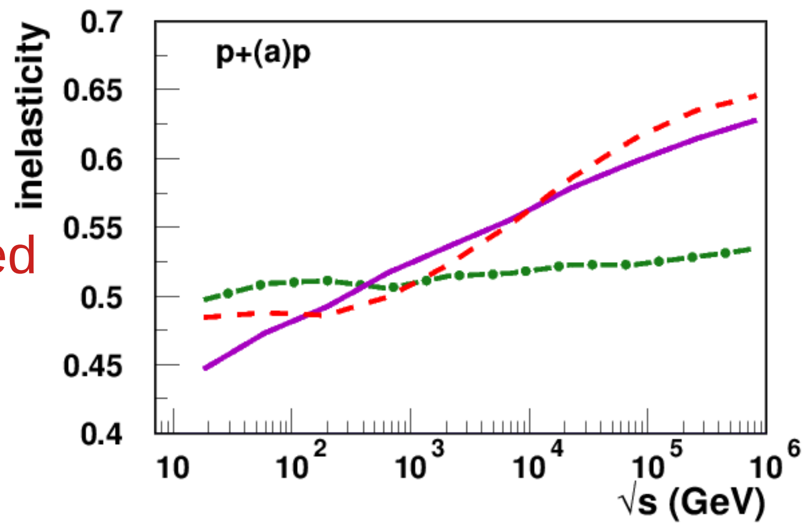


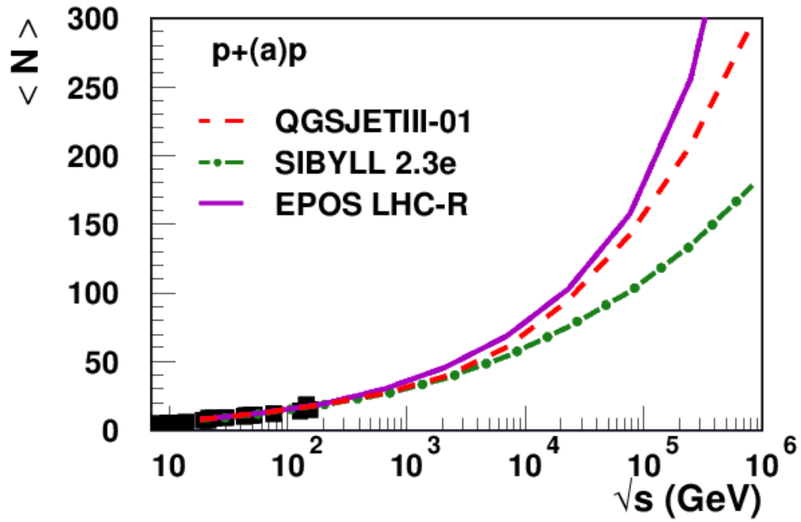
Basic Observables

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 constrained



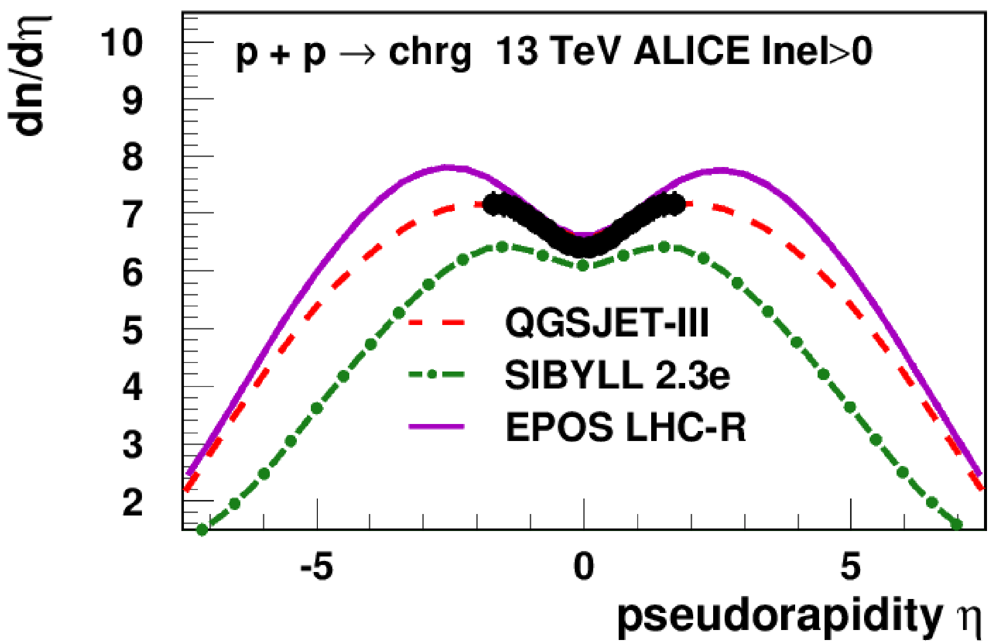


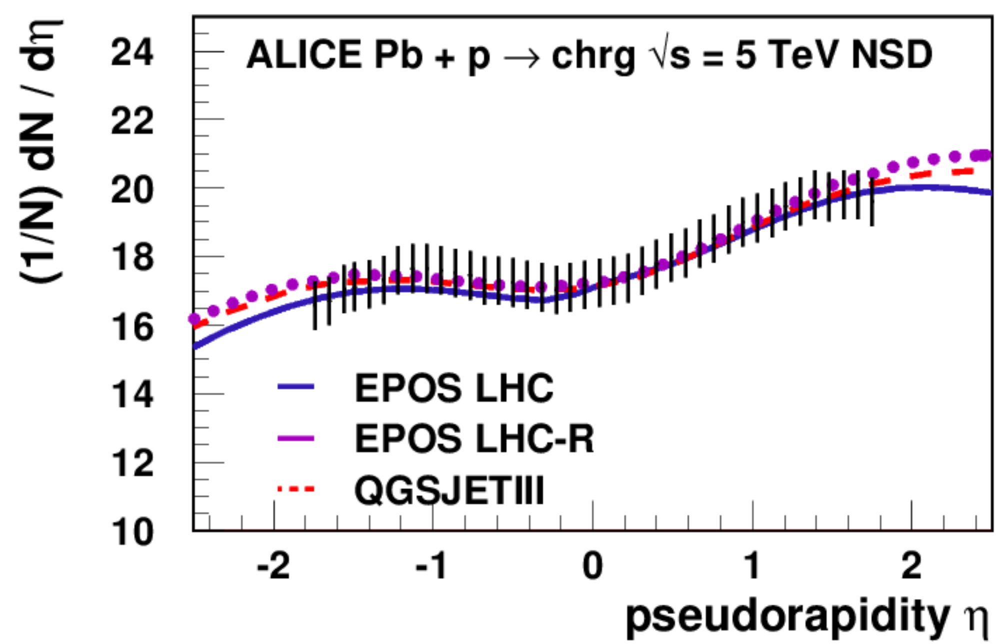


Pseudorapidity

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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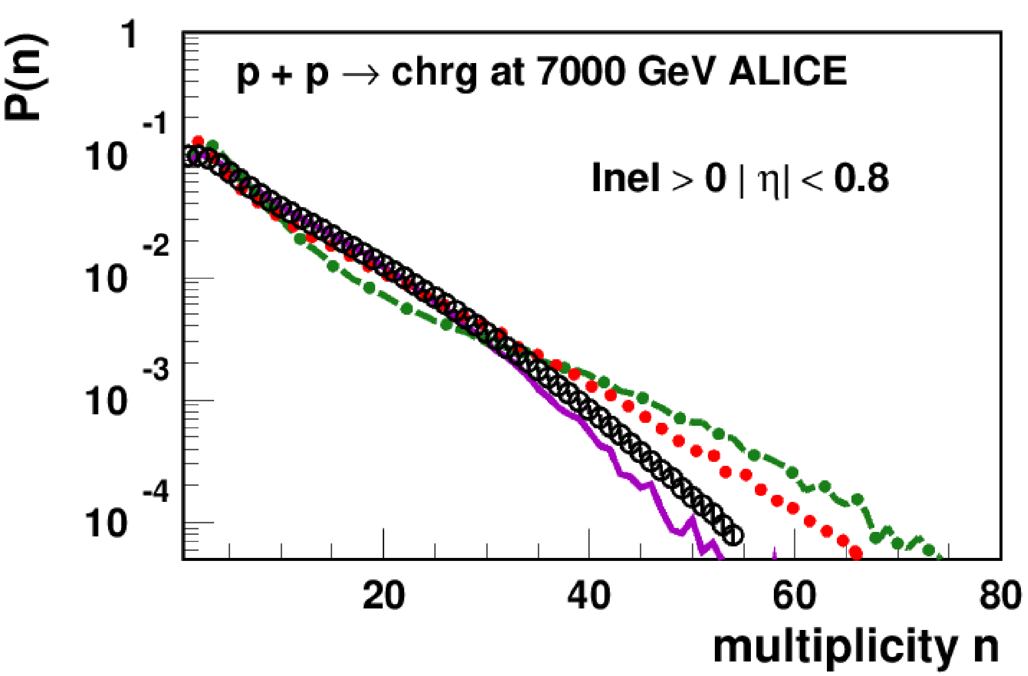

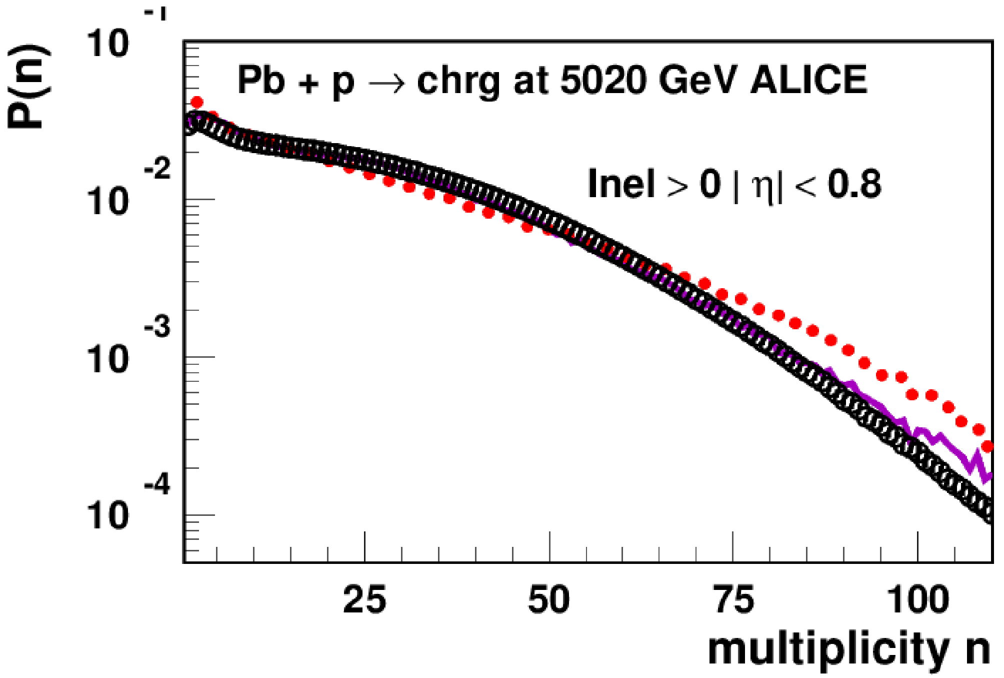

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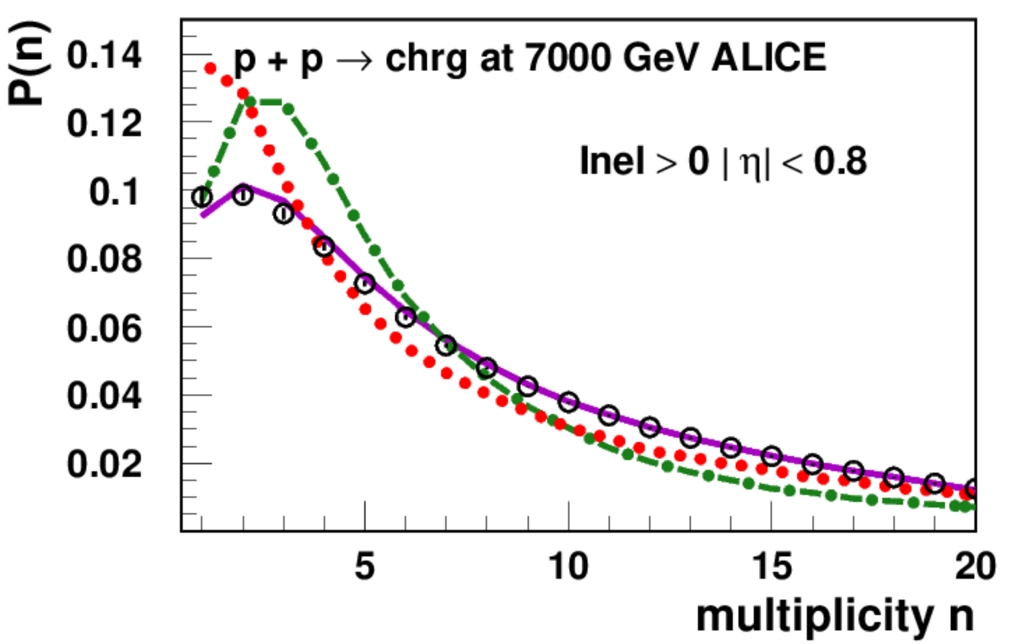
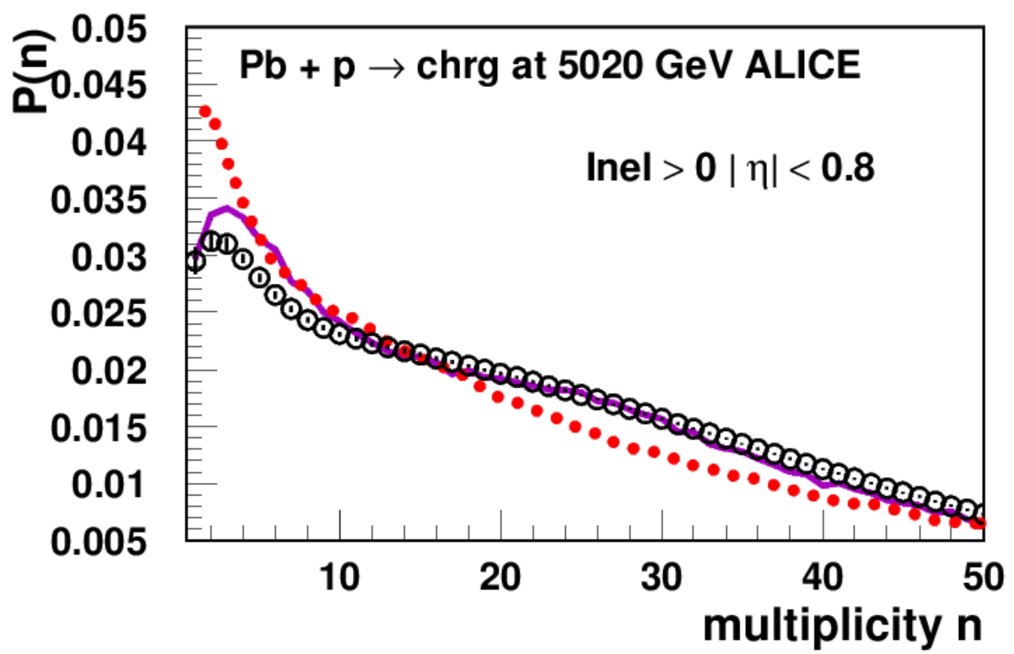
  - Correction of multiplicity distribution in EPOS (impact on X_{max})

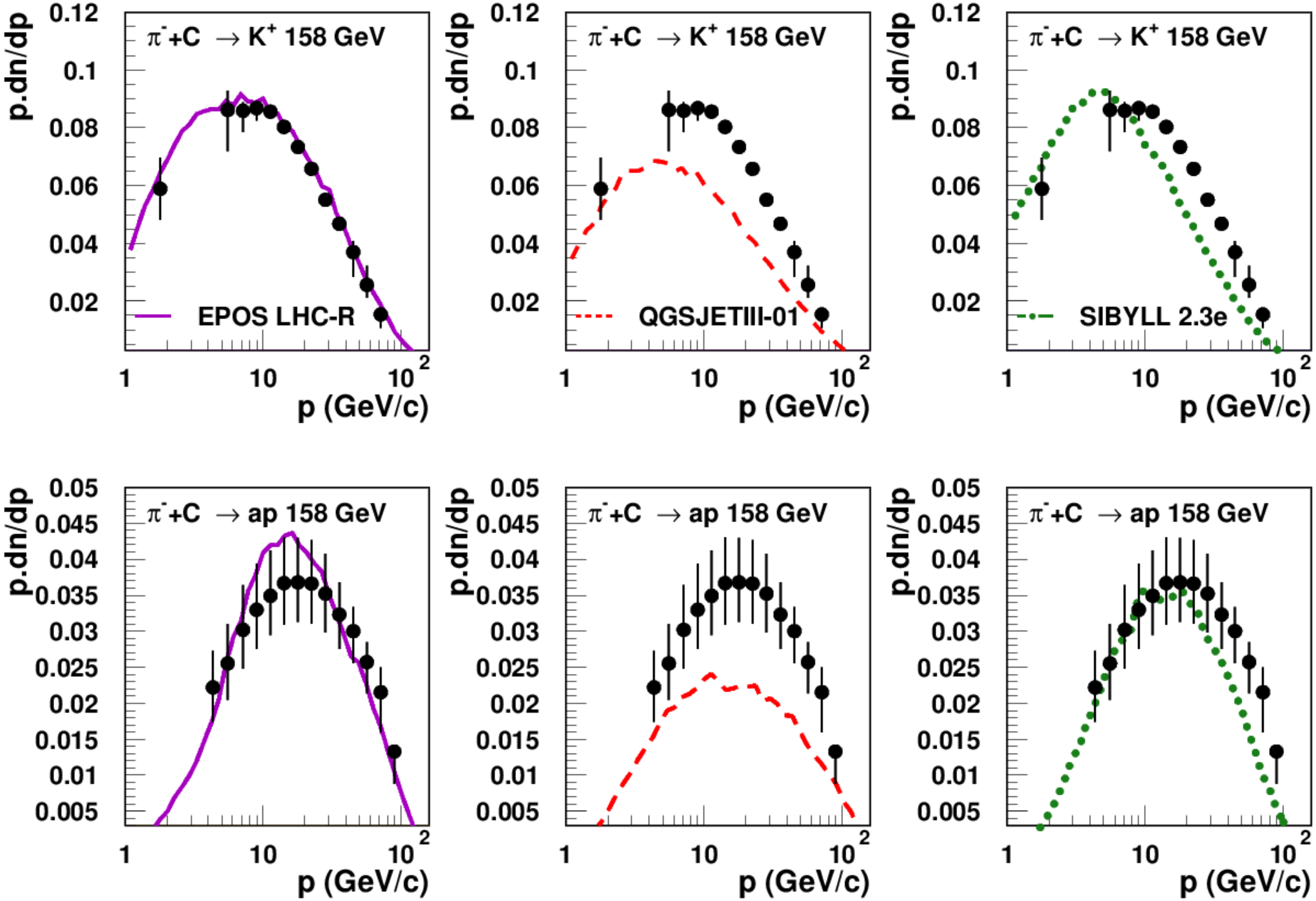




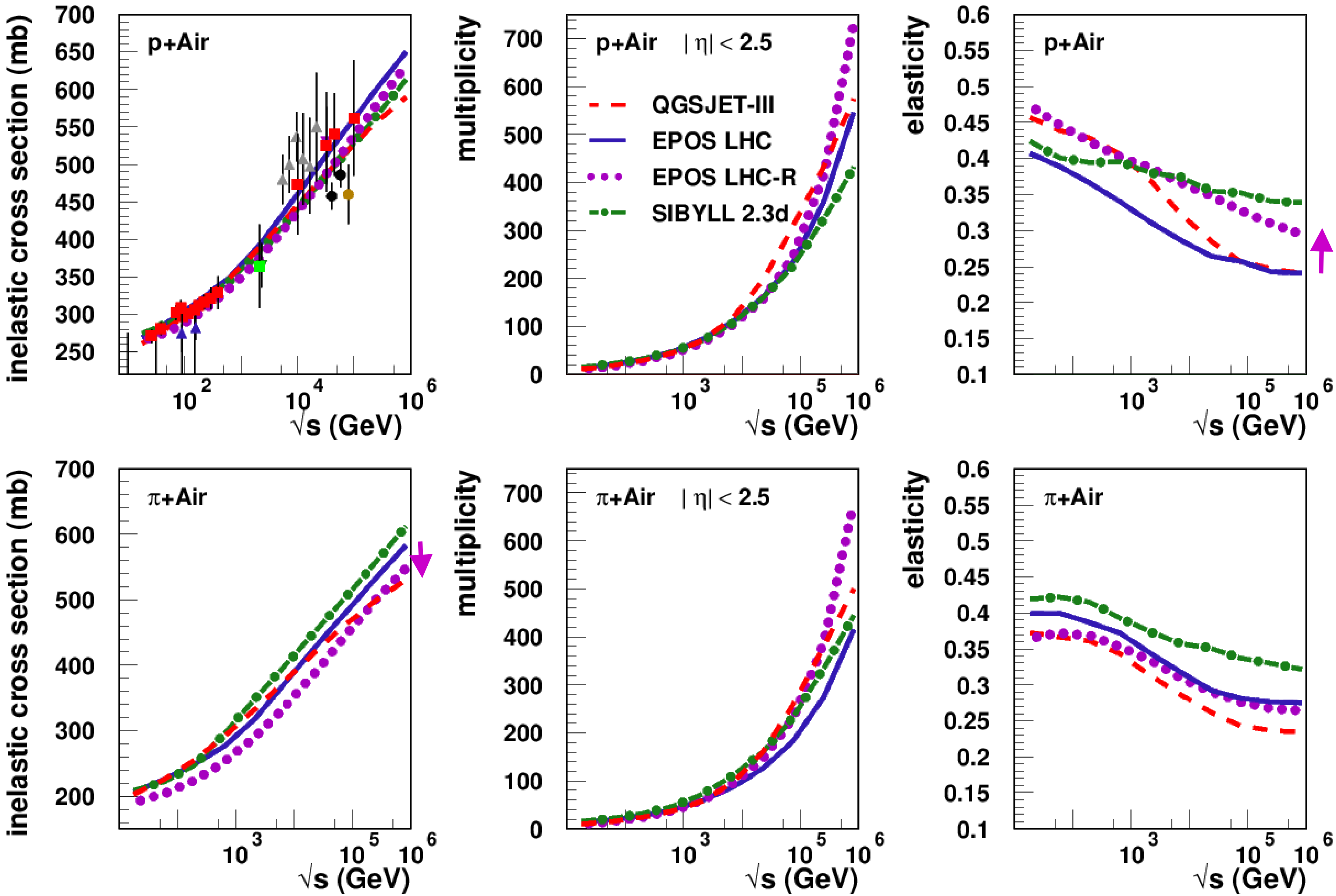
Kaons and Baryons

Only EPOS properly reproduce NA61 data (and many others)

➡ QGSJETIII not flexible enough !



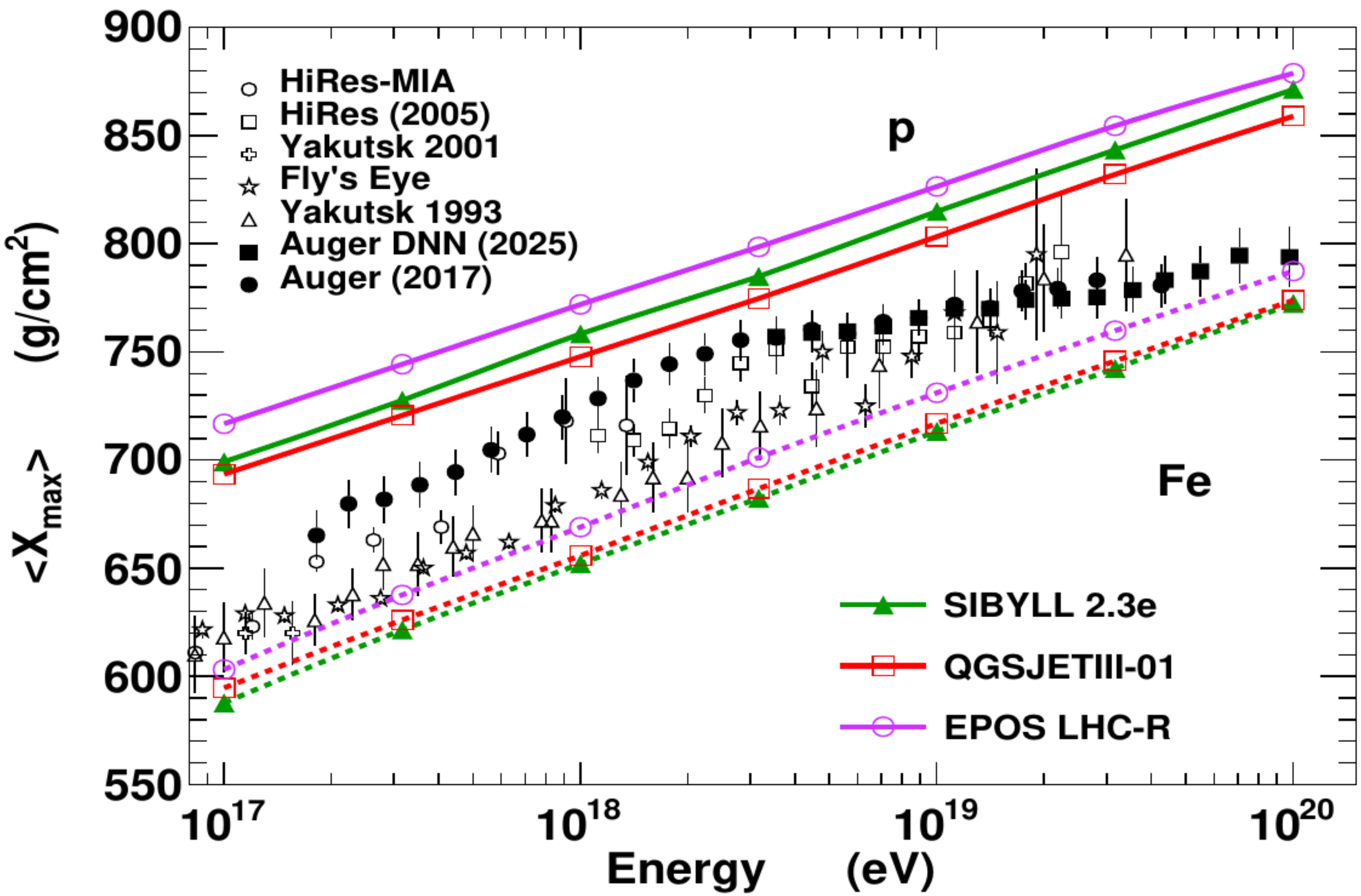
Interaction with Air



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

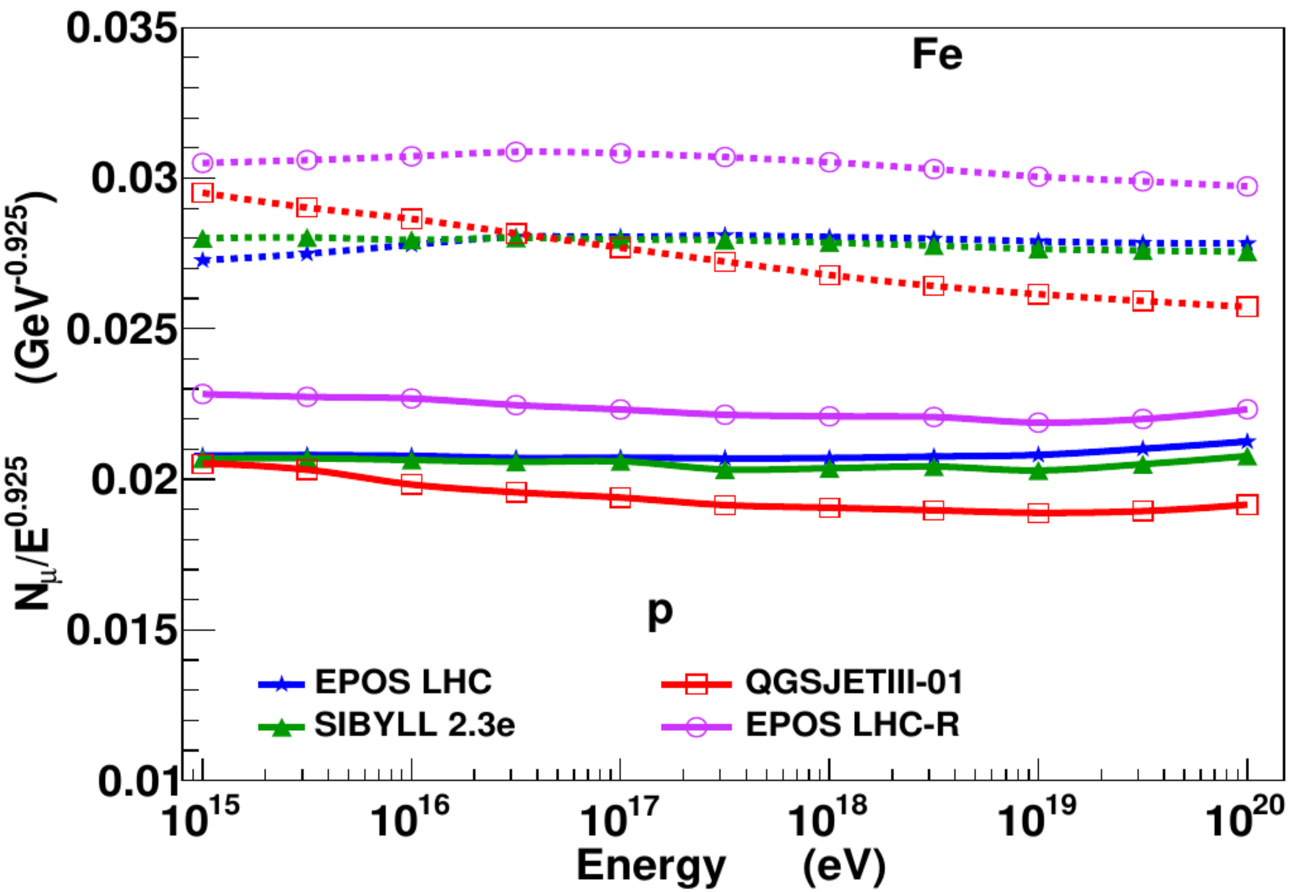
Iron at the highest energy ?

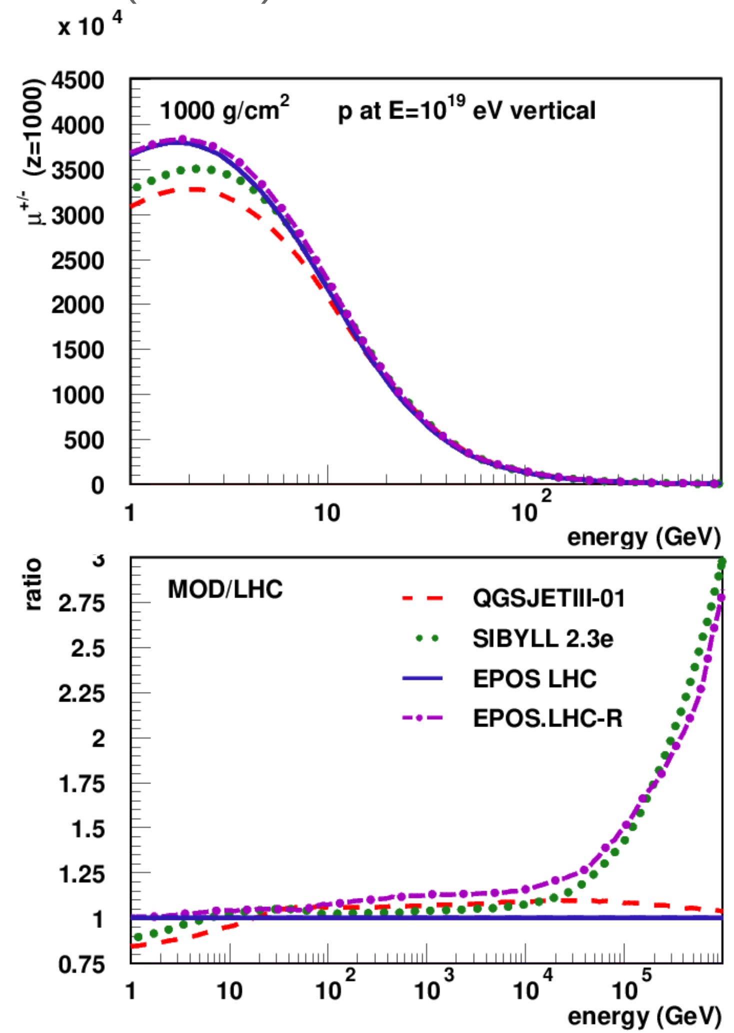
Note: Technical problem in QGSJETIII-01 leading to wrong X_{max} predictions for Iron at high energy

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 !



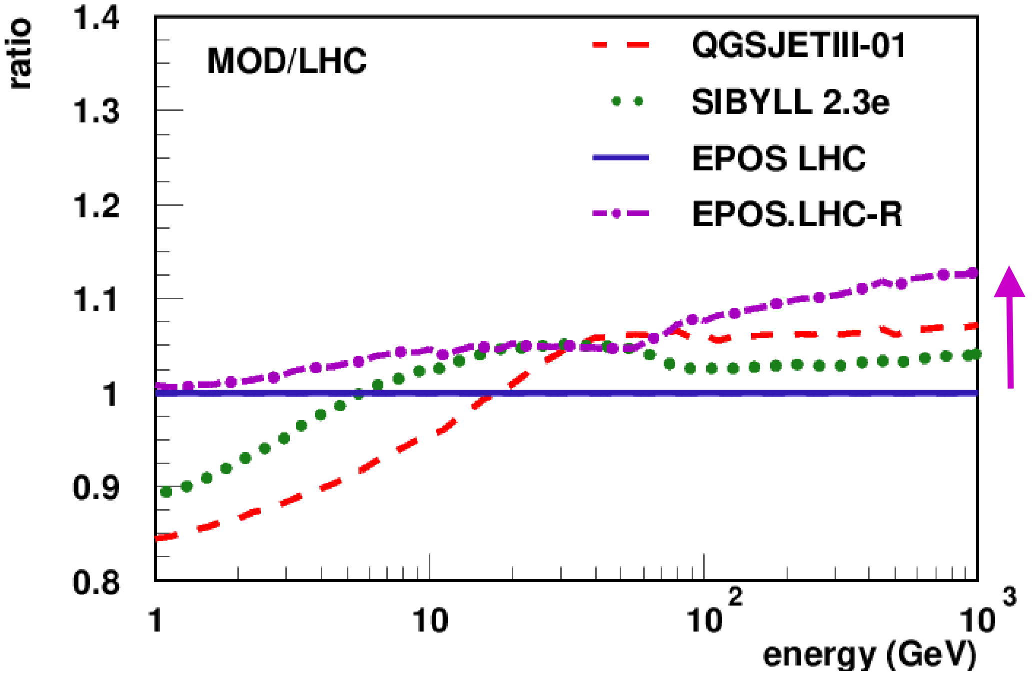


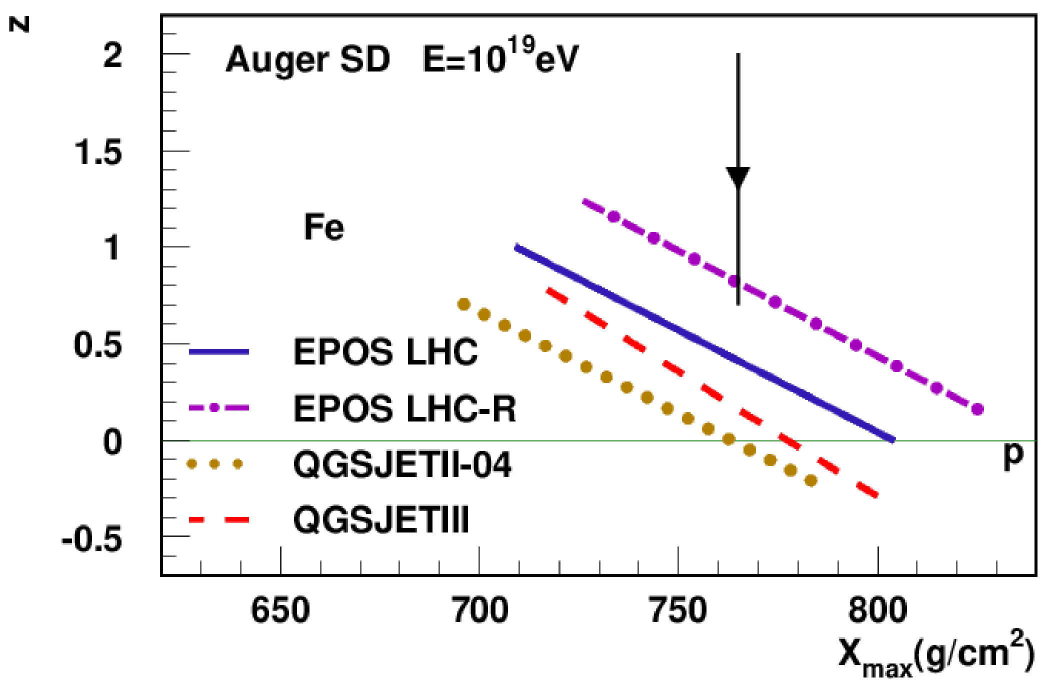
Muon Puzzle Solved ?

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
- Increased number of high energy muons
- Change not large enough for QGSJET

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



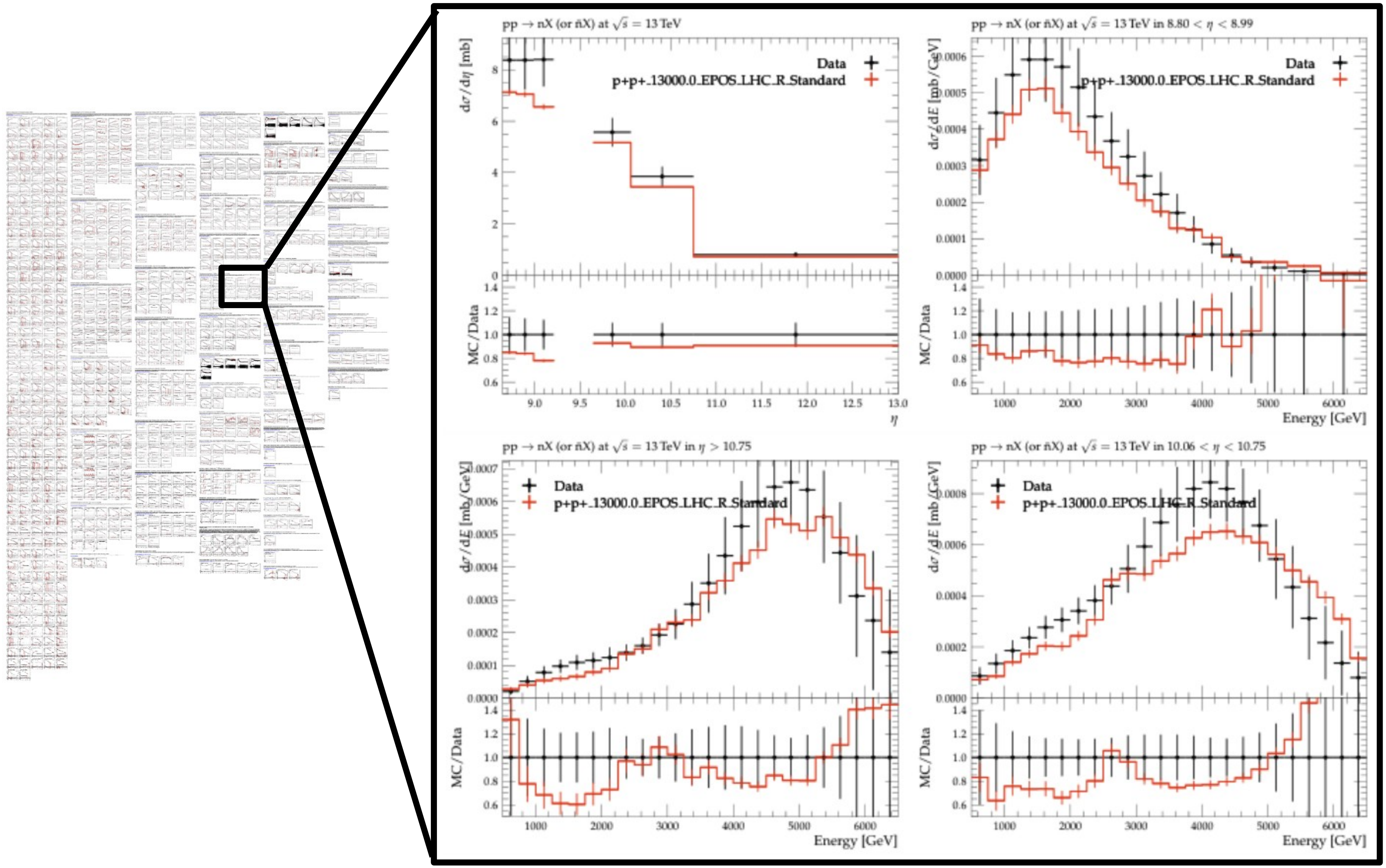


Model Quality

➡ Use all RIVET analysis (~800 plots) that EPOS, QGSJET and Sibyll can run

Inspire | HepData | Analysis reference | arXiv:2003.02192

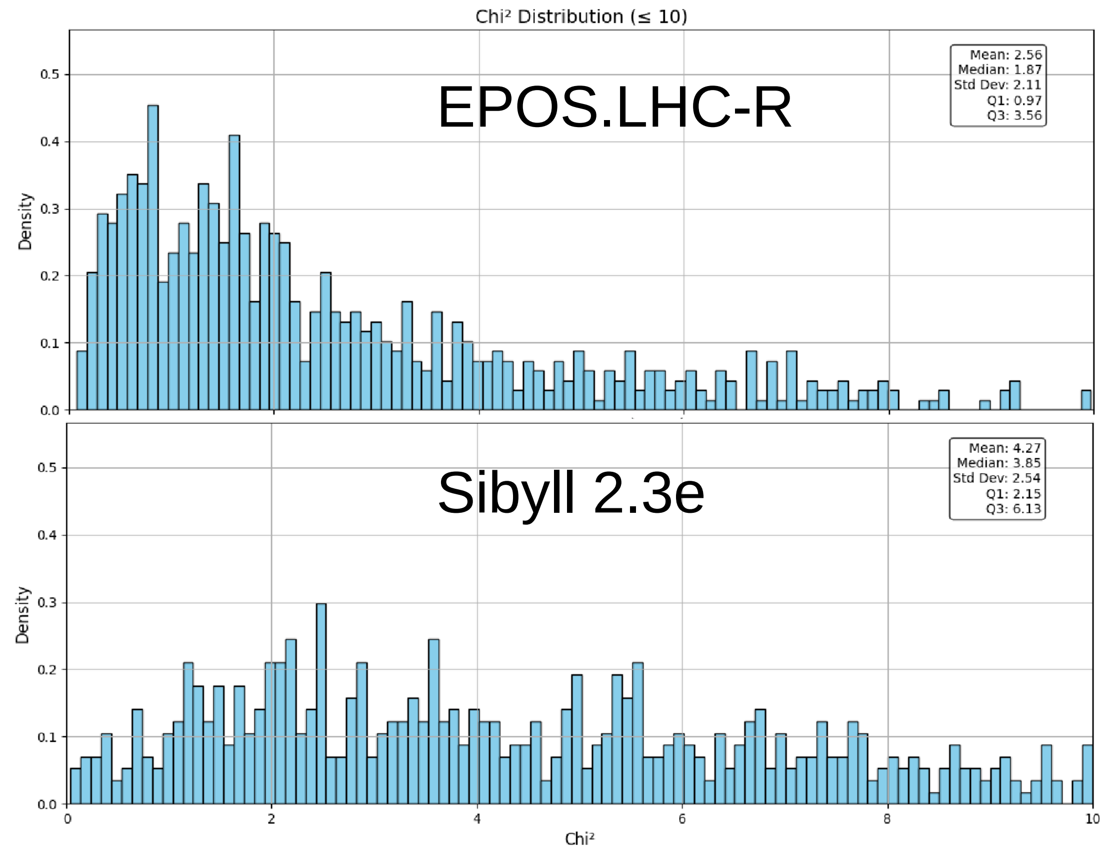
LHCf



Plots by Kamil Delassoud

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



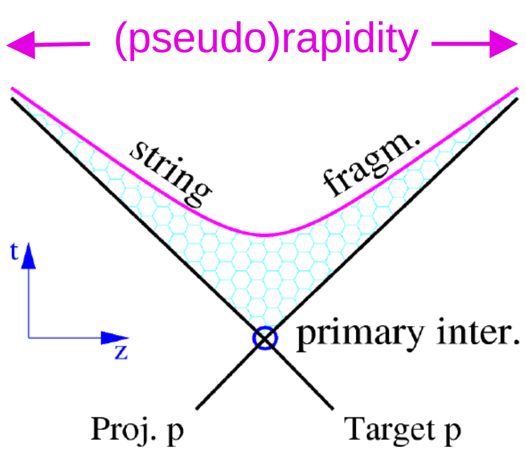
Plots by Kamil Delassoud

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

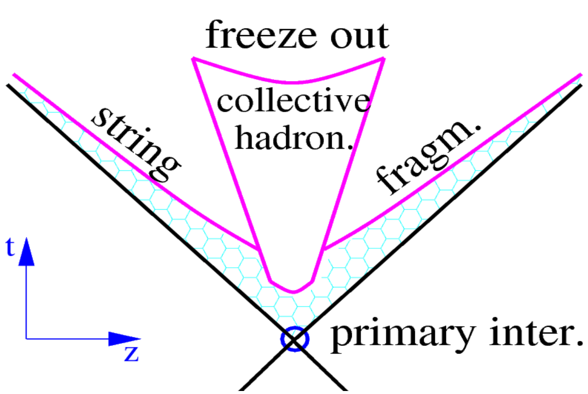
What means global approach ?

Global approach is the key !

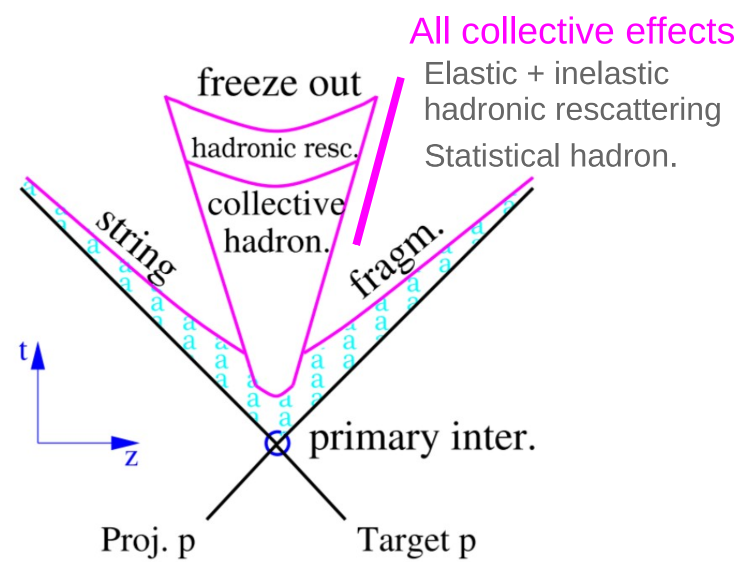
- Tuning models neglecting some physics process lead to wrong parameters !
- Proper tune possible to do, only if everything is taken into account
  - All collective effects considered for the first time in EPOS.LHC-R !
- Either with a direct impact on the shower development (new elasticity)
- Or no direct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



Sibyll, QGSJET

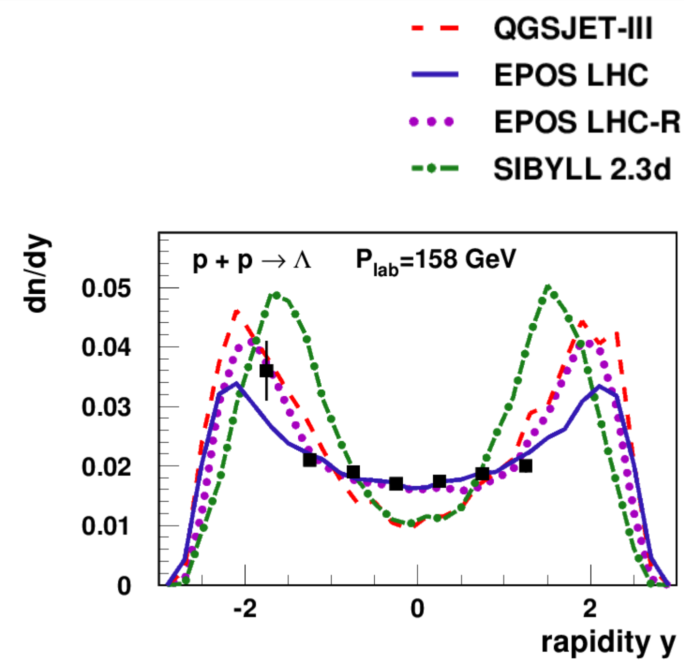


EPOS LHC
(no rescattering)



EPOS.LHC-R
(with hadronic rescattering)

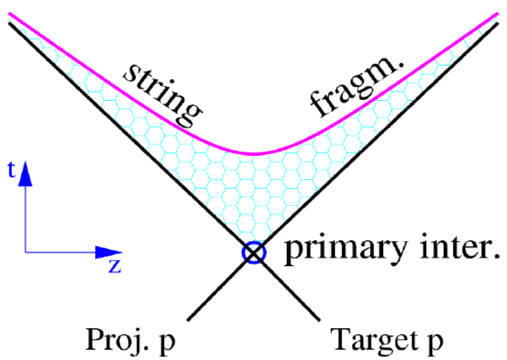
String Fragmentation

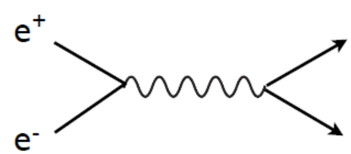


Global approach is the key !

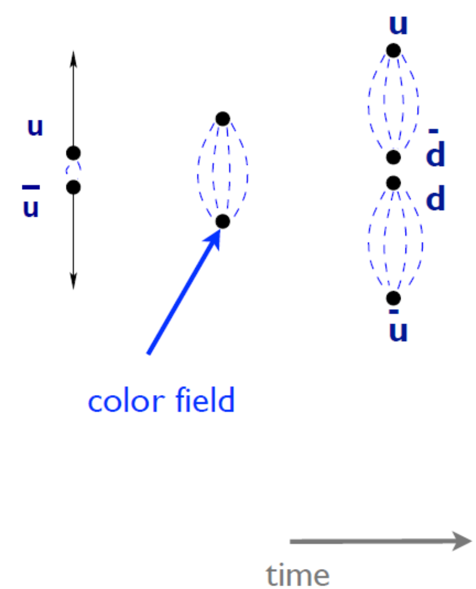
- Common hadronization in all the models
- Parameters fixed on e+-e- only possible in EPOS
  - Other CR models tuned on p-p data
    - “Contamination” by beam remnant
- Very important for forward particle production (EAS)
  - Used for beam remnant hadronization

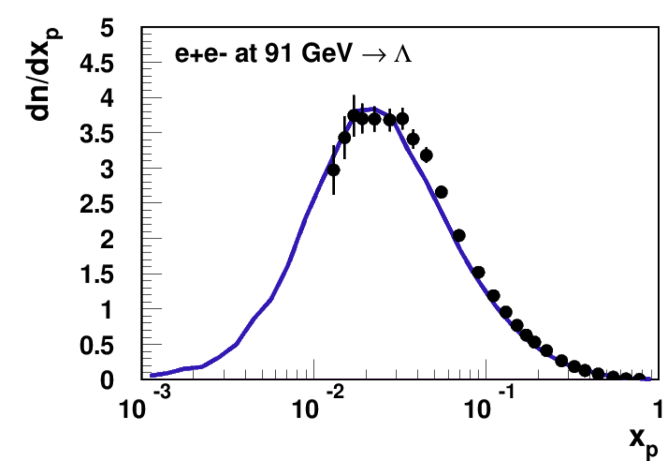
Annihilation at high energy





Quarks together are color-neutral system



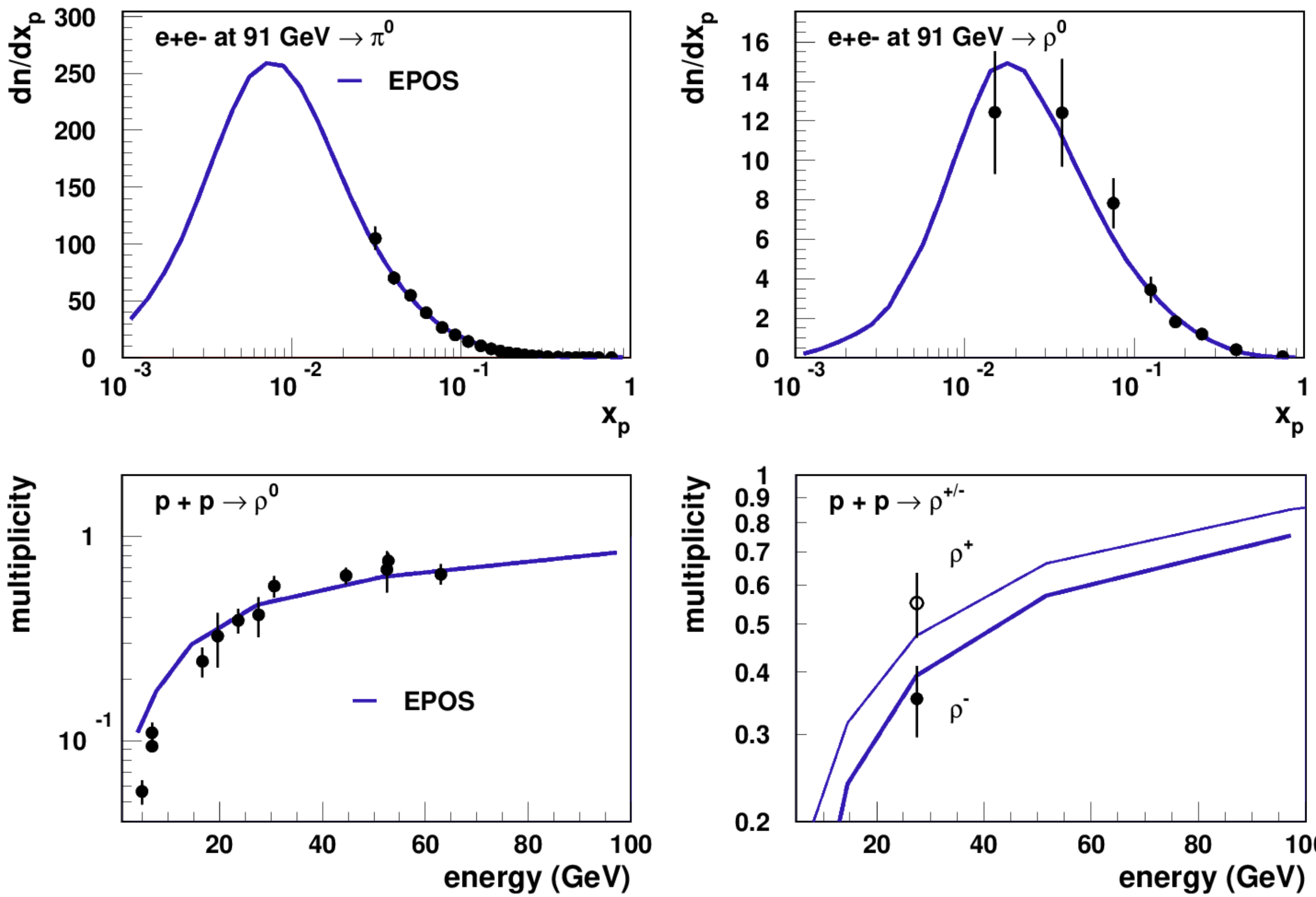


Used in dilute systems = CORONA

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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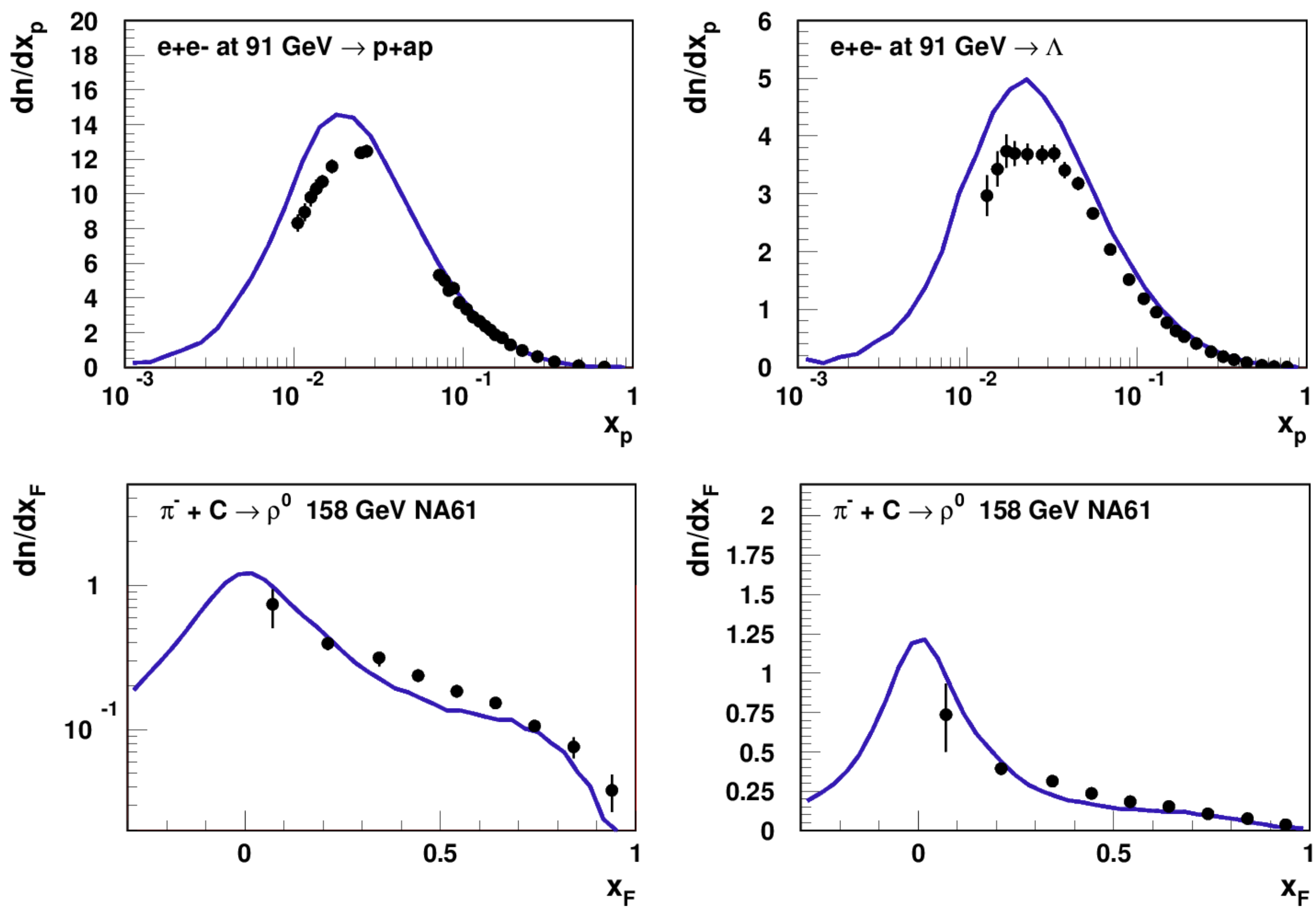
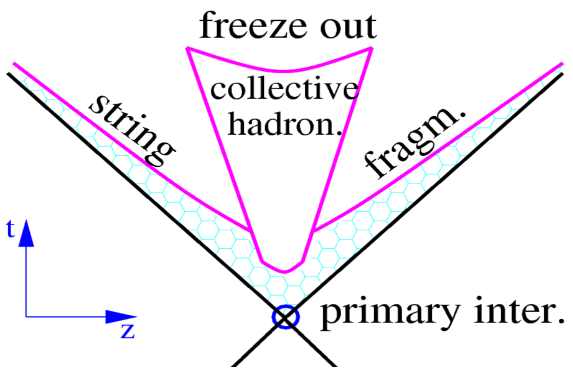


Core-Corona (co-co)

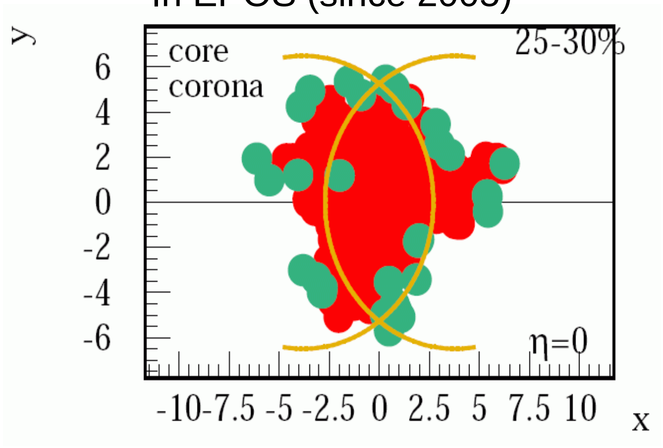
- **Core hadronization** = thermal hadronization of Quark Gluon Plasma
- **Mixing of core and corona hadronization (string) needed to achieve detailed description of p-p data** (K.Werner, Phys.Rev.C 109 (2024) 1, 014910)
  - Evolution of particle ratios from pp to PbPb
  - Particle correlations (ridge, Bose Einstein correlations)
  - Pt evolution, …
- **Both hadronizations are universal but the fraction of each change with particle density**



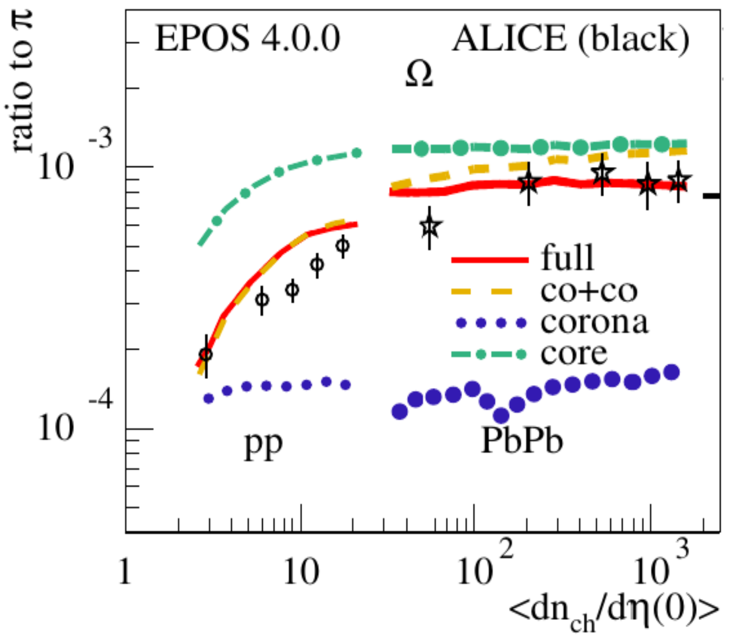
Difference high/low multiplicity

- **2 simultaneous source of particles**

In EPOS (since 2005)



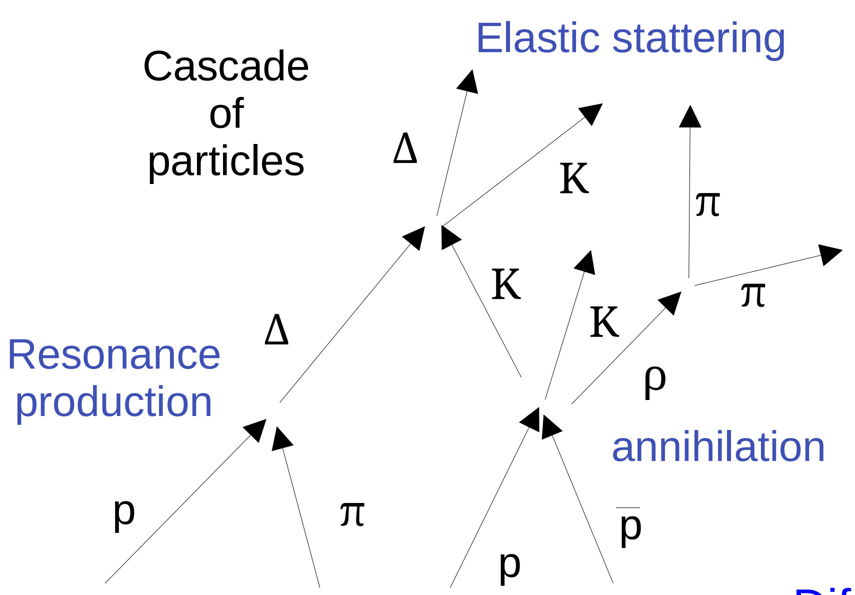
p-p ,Pb-p, Pb-Pb data

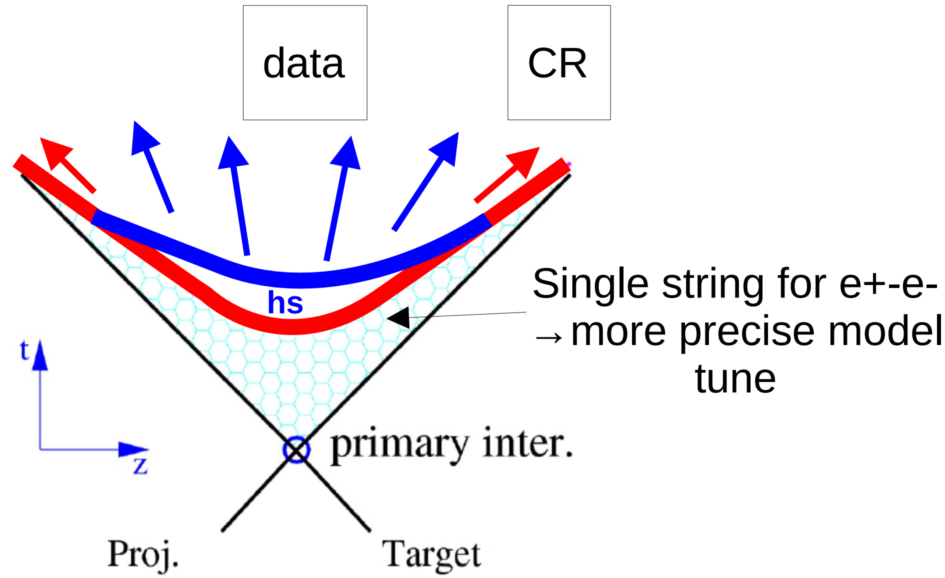


Hadronic reScattering (HS)

Important effect when particles are close to each others

- Re-interaction of hadrons* after parton hadronization (space-time evolution)
- “traditionally” used only for heavy ion collisions (even NOT in pp until recently)
- Impact “slow” particles at mid-rapidity more than “fast” forward particles
- Significant to large impact at midrapidity in heavy ion collisions !
  - Applied to all system (from e+-e- to PbPb) now !

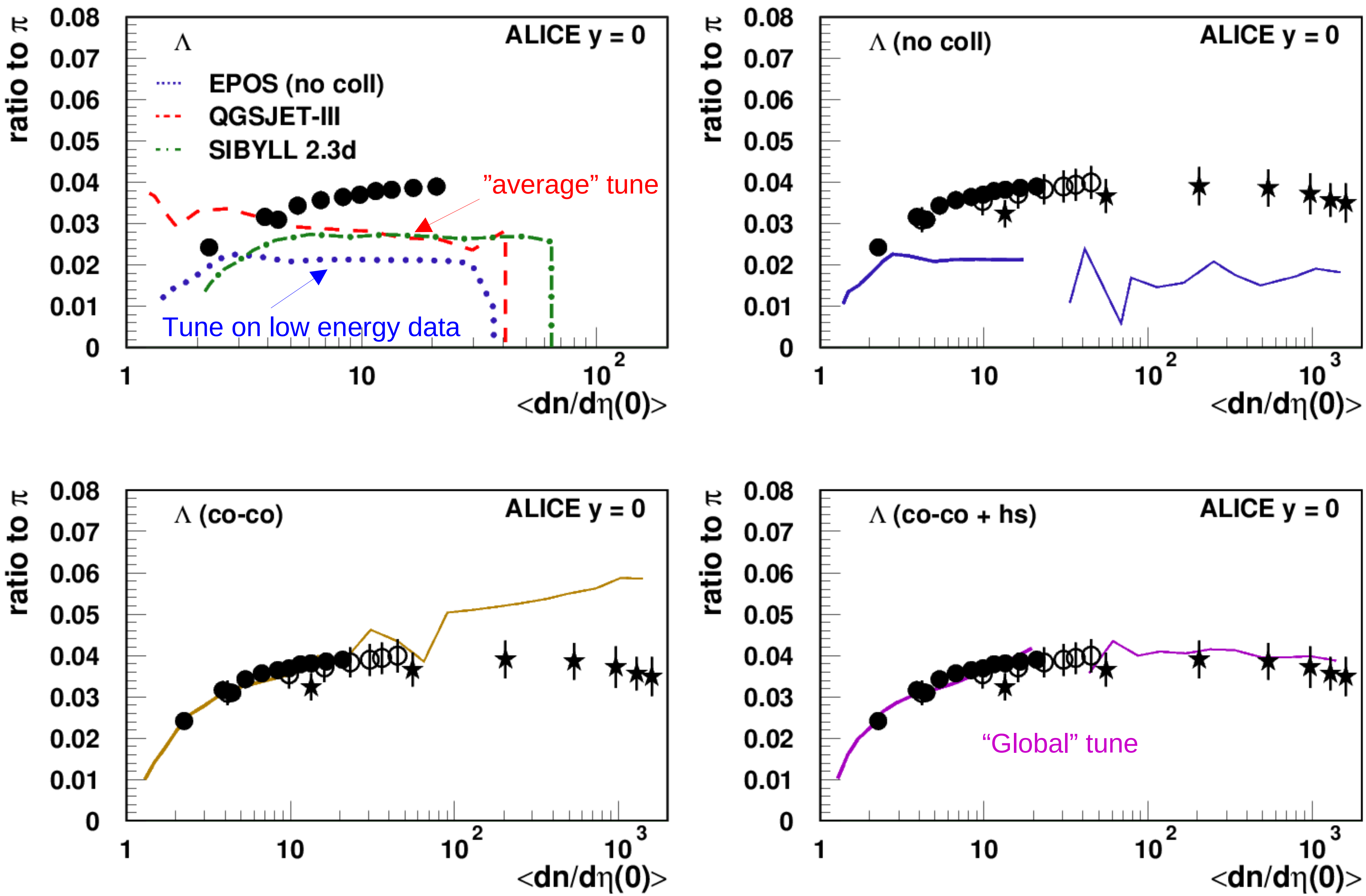




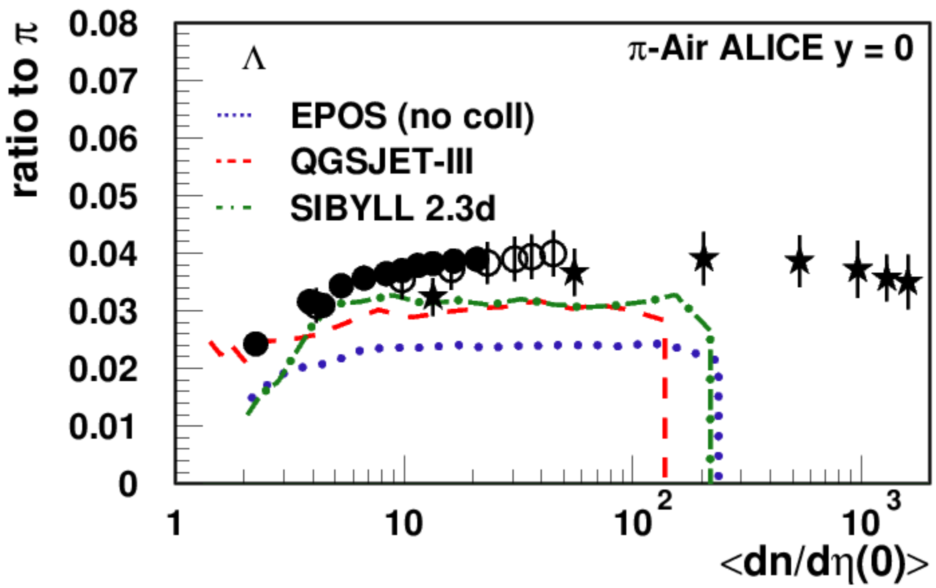
Difference small/large rapidity (emission angle)

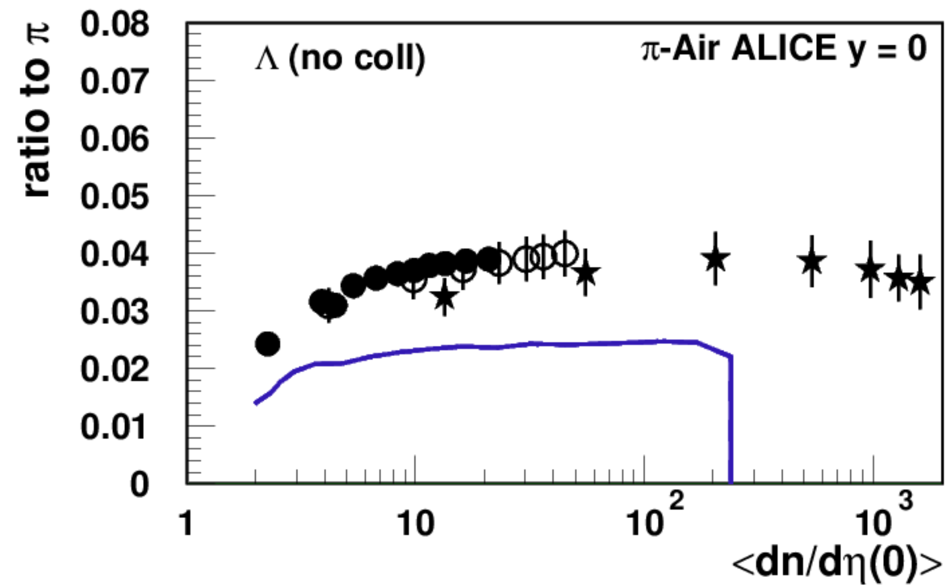
* using UrQMD 3.4, Bleicher at al., J.Phys. G25 (1999) 1859

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

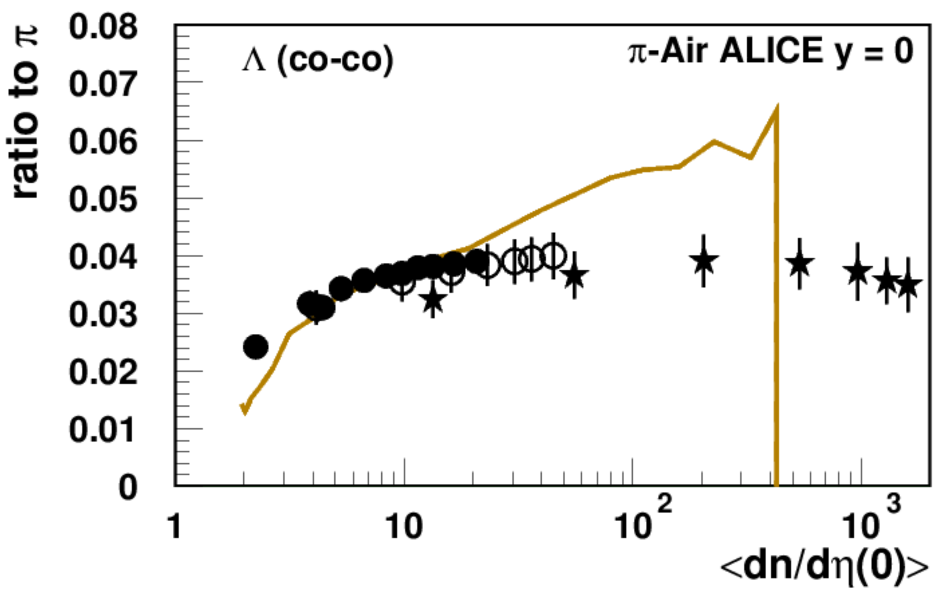


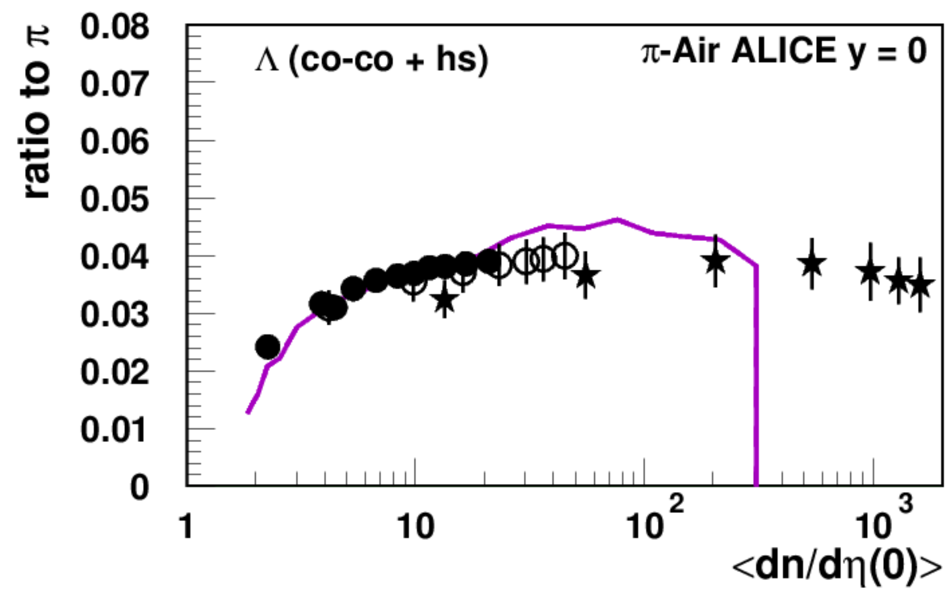
Example: Lambda particle in π-Air @ all energies





These data can be used to constrain the model only if all effects are taken into account !

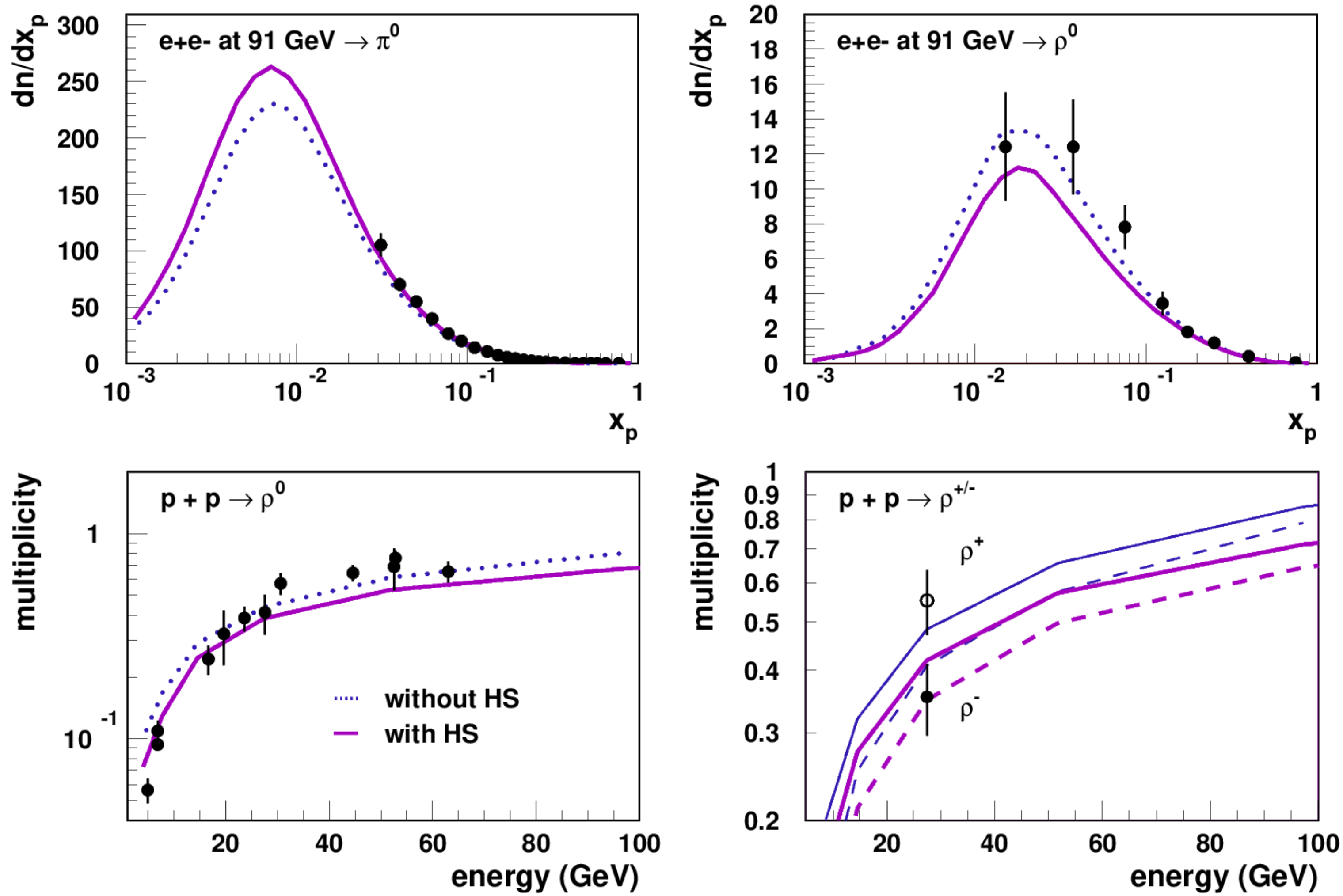




Impact of HS on light systems

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

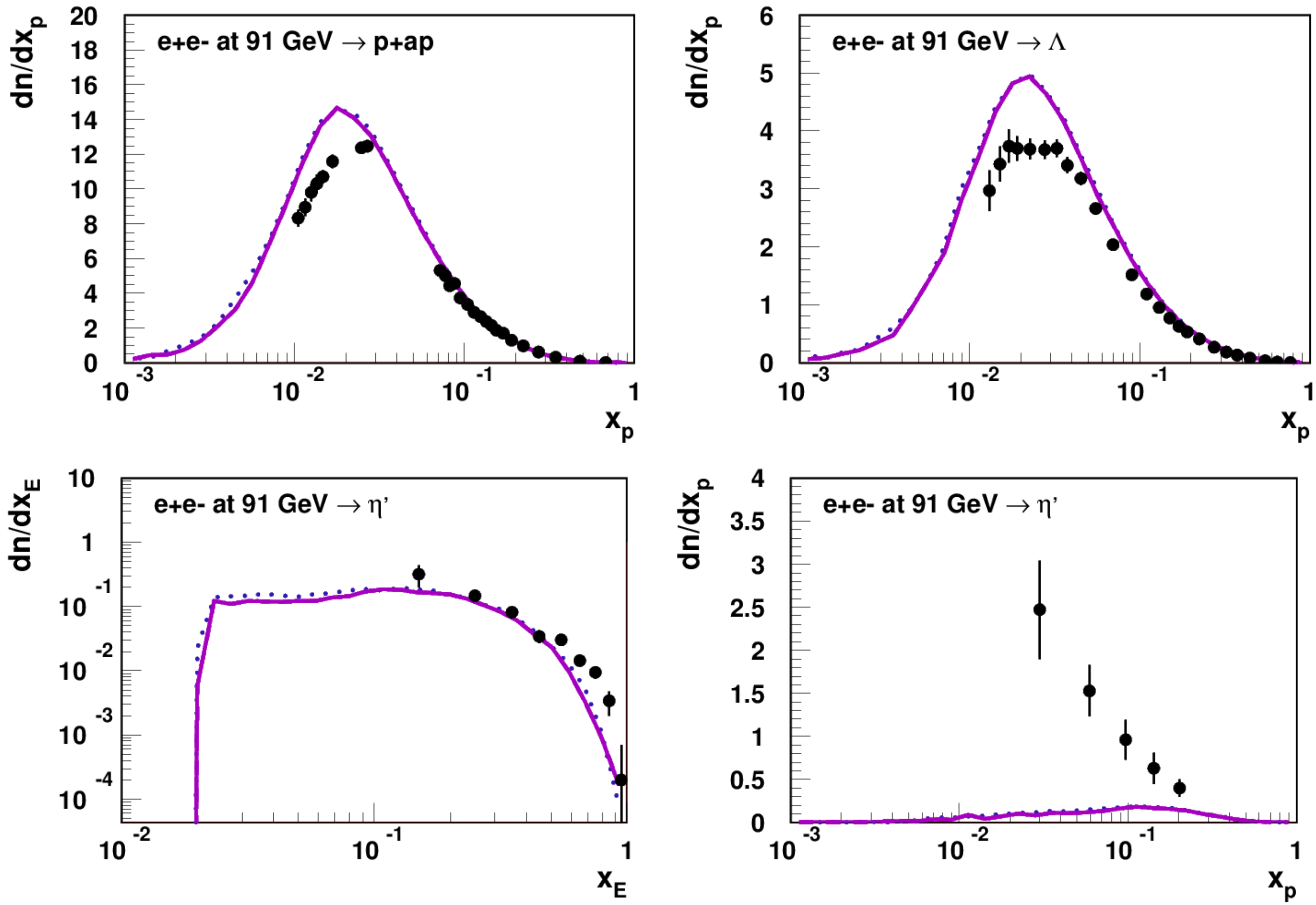
- Small but significant effect even in e+e- interactions
- Reduce ρ resonances and increase pions



LEP data

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

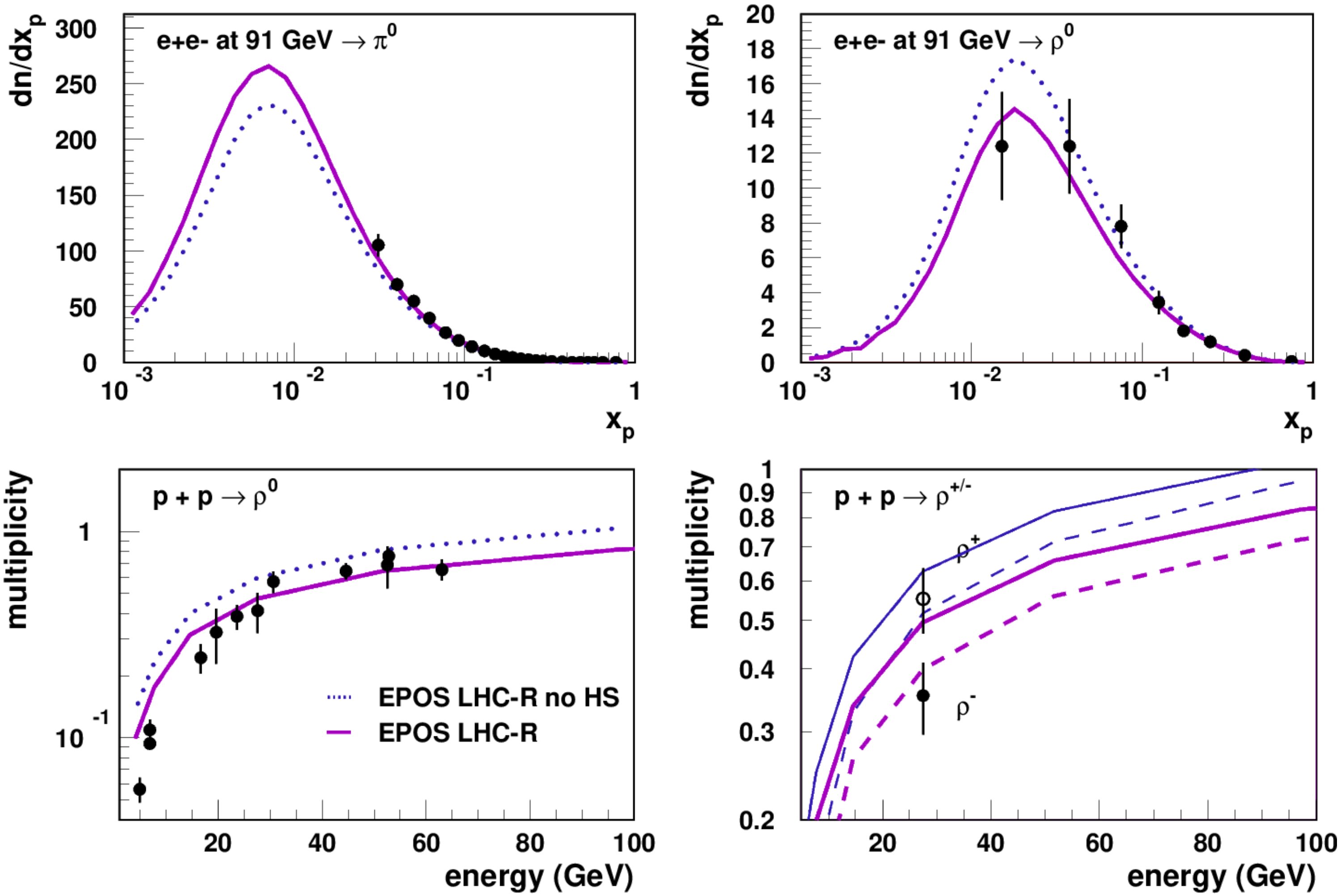
- Small but significant effect even in e+e- interactions
- More data could be considered if LEP data are used



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

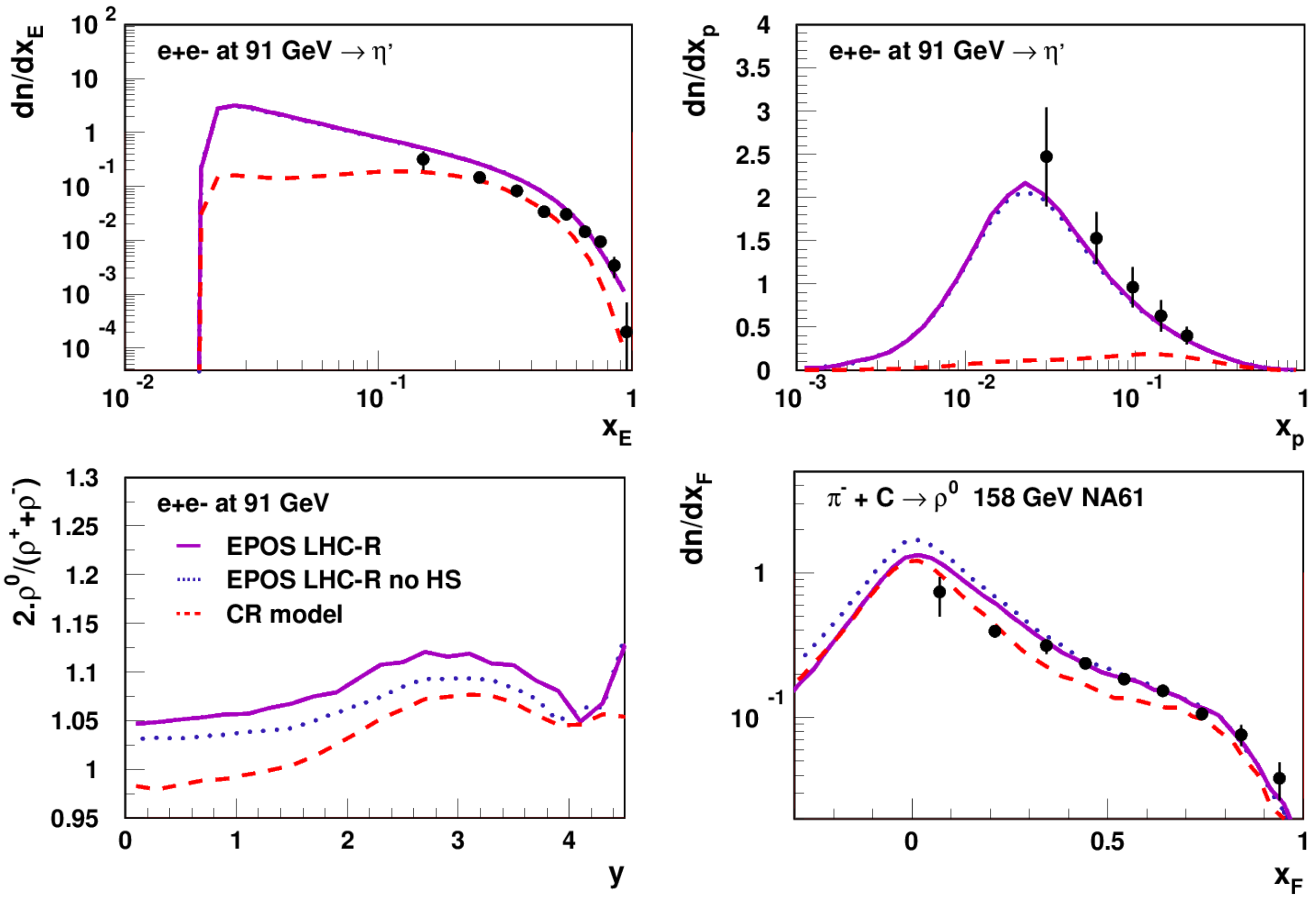


Retune basic parameters with HS and LEP

EPOS.LHC-R uses experimental constraints from LEP

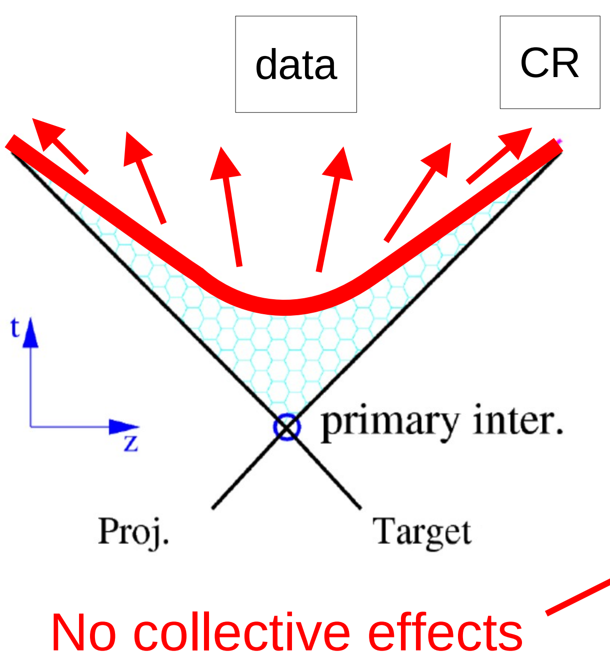
- Produce η' and f_0 in addition to η : change asymmetry for ρ (and π)

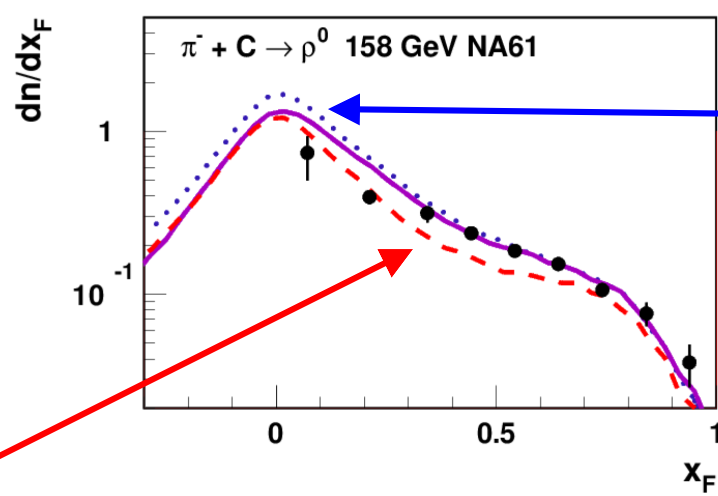
  - Effect on muon production in air showers !

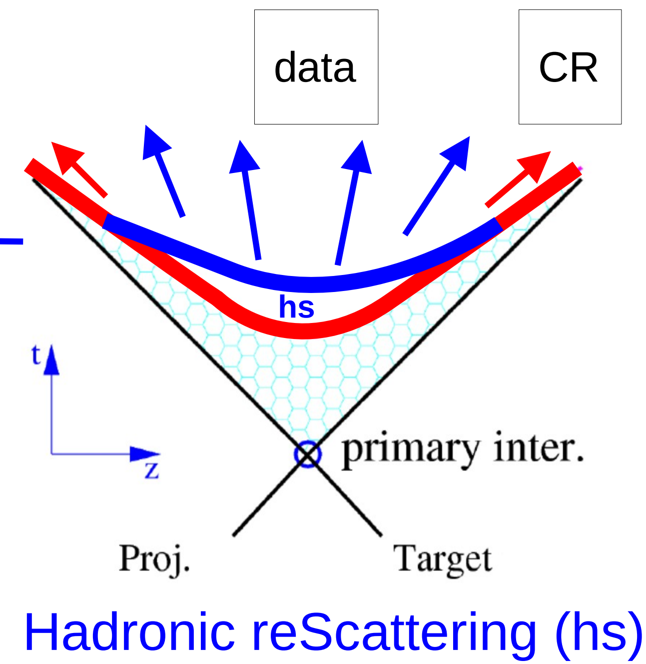


What is really new ?

- Changed 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



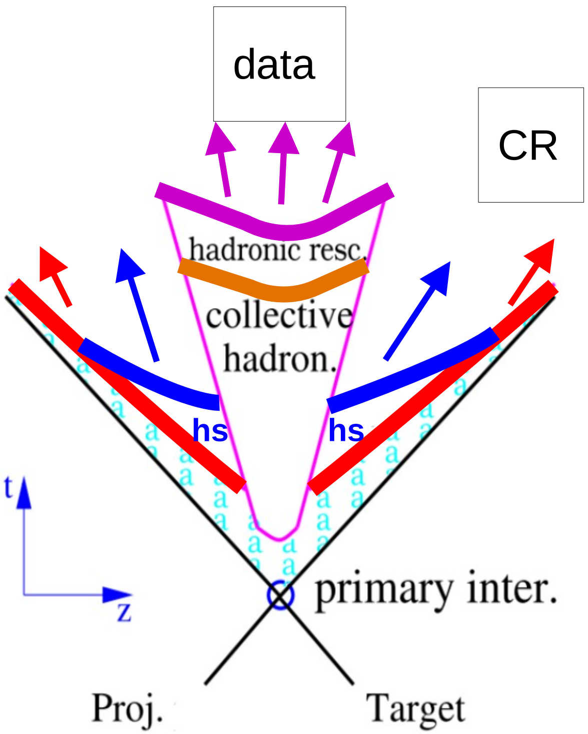


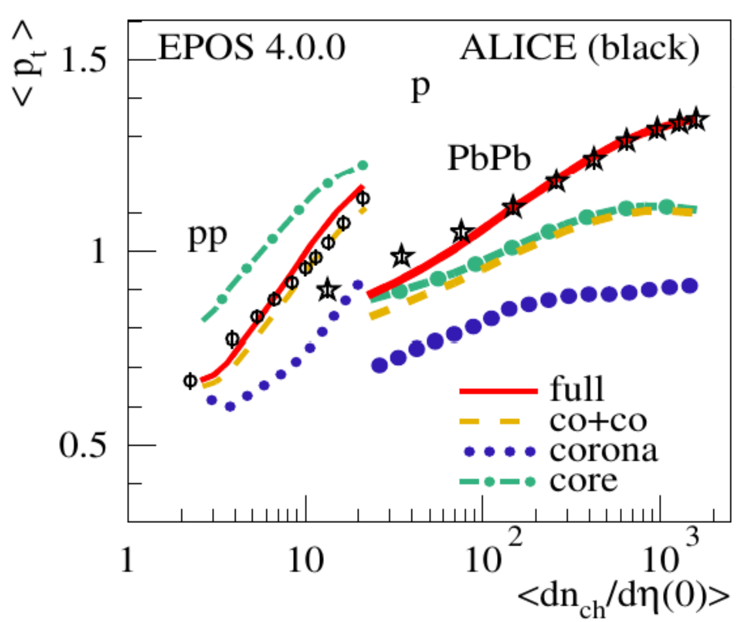


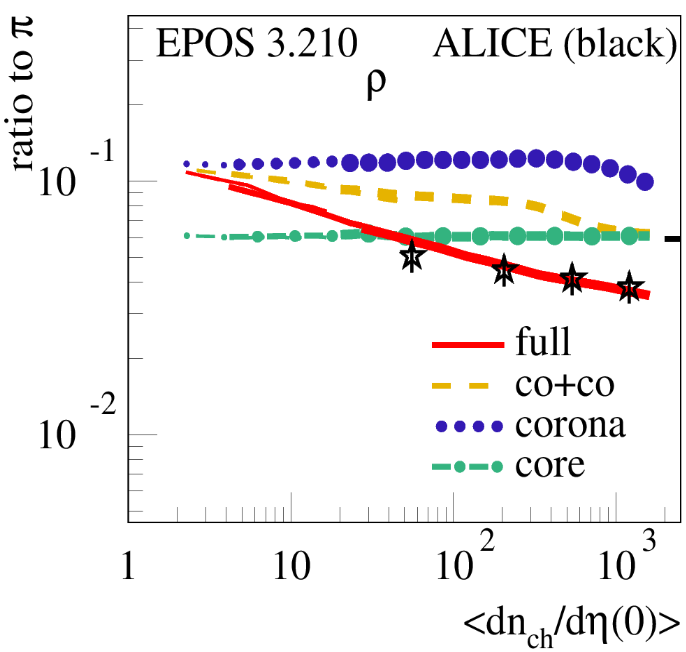
Global Approach

Collective effects are important to tune properly the models !

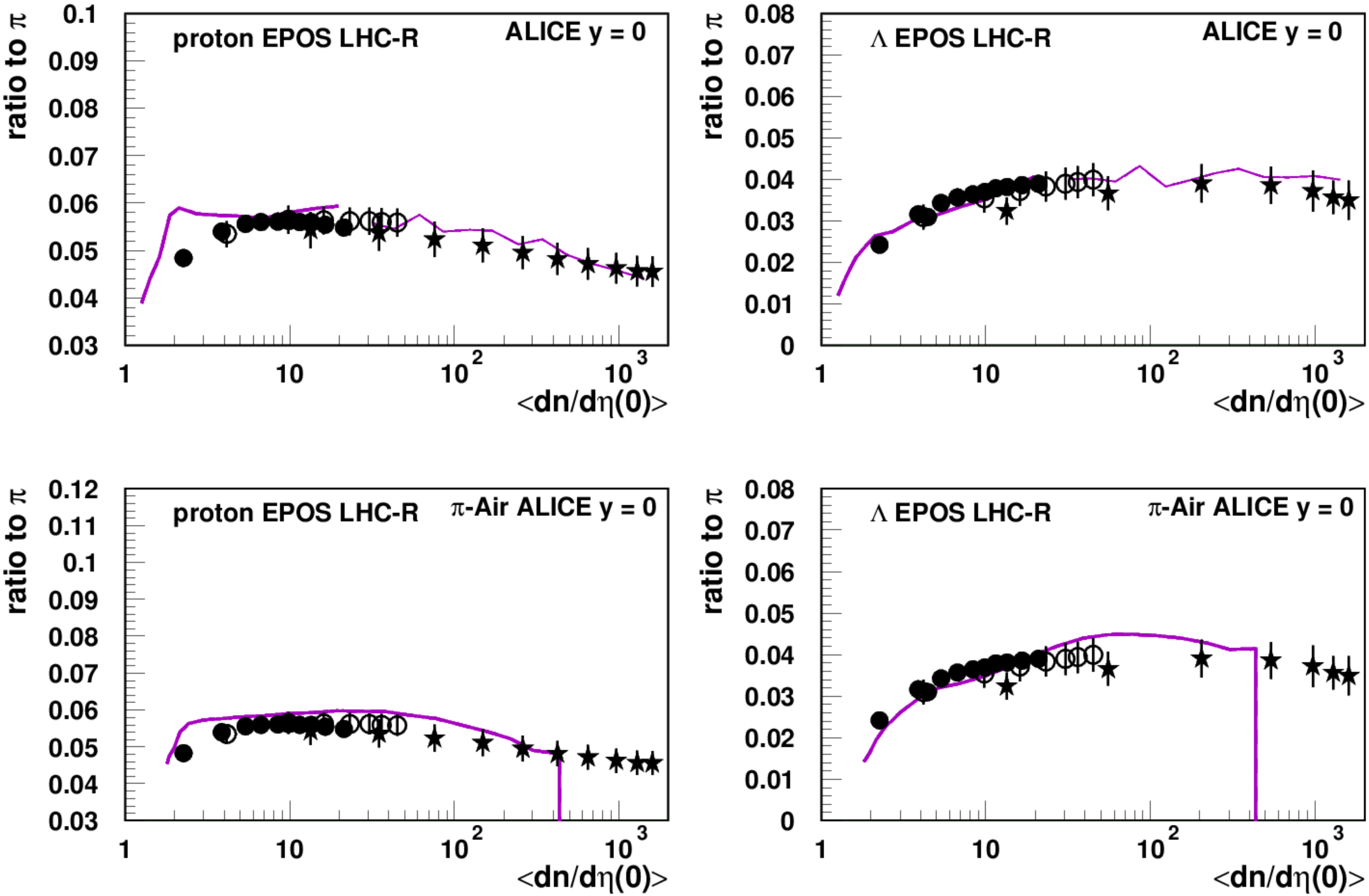
- Change multiplicity/elasticity and hadronization depending on particle density
  - Introduce energy + centrality dependence in accelerator data comparisons
  - Modify model parameters
    - Multiple mid-rapidity particle production mechanisms
- Change particle ratios in string fragmentation depending on phase-space
    - Forward particle production not the same than at mid-rapidity







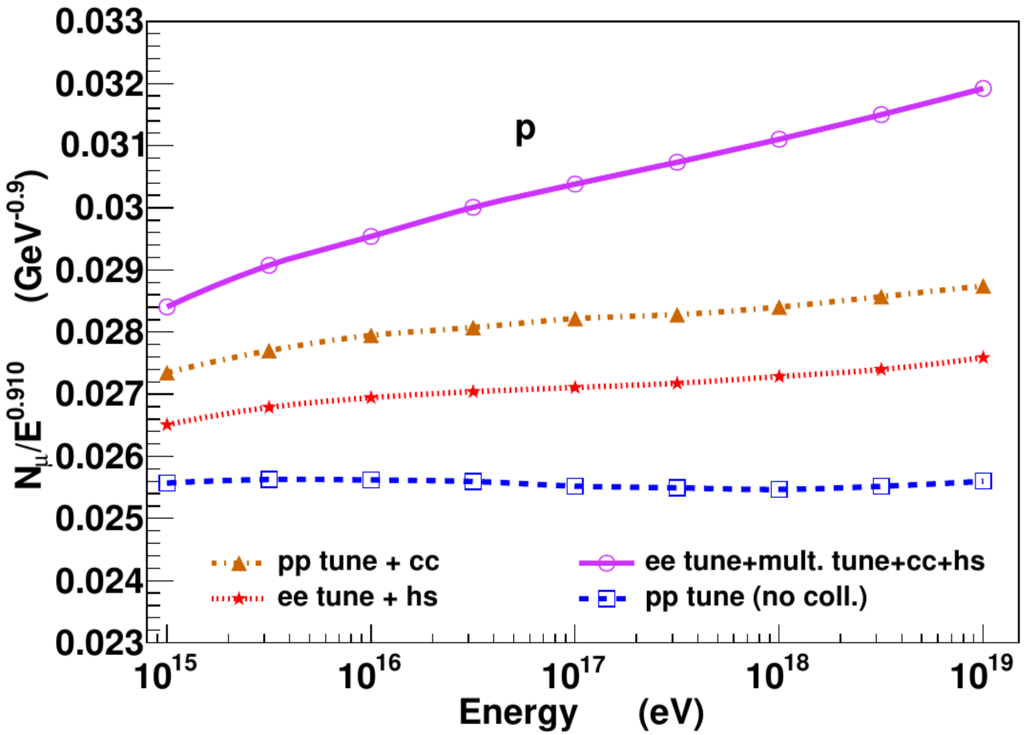
Check ALICE data

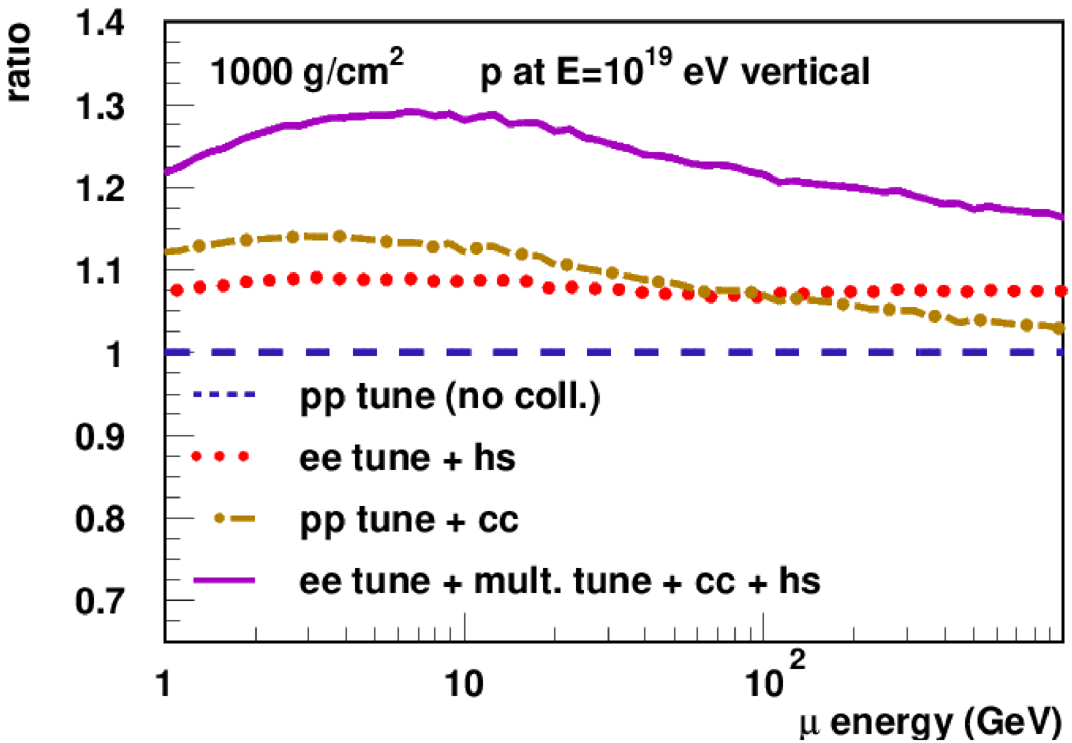


Impact on Air Showers

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

- Increase the number of muons by ... 10 to 20% (different slope) !
  - 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)

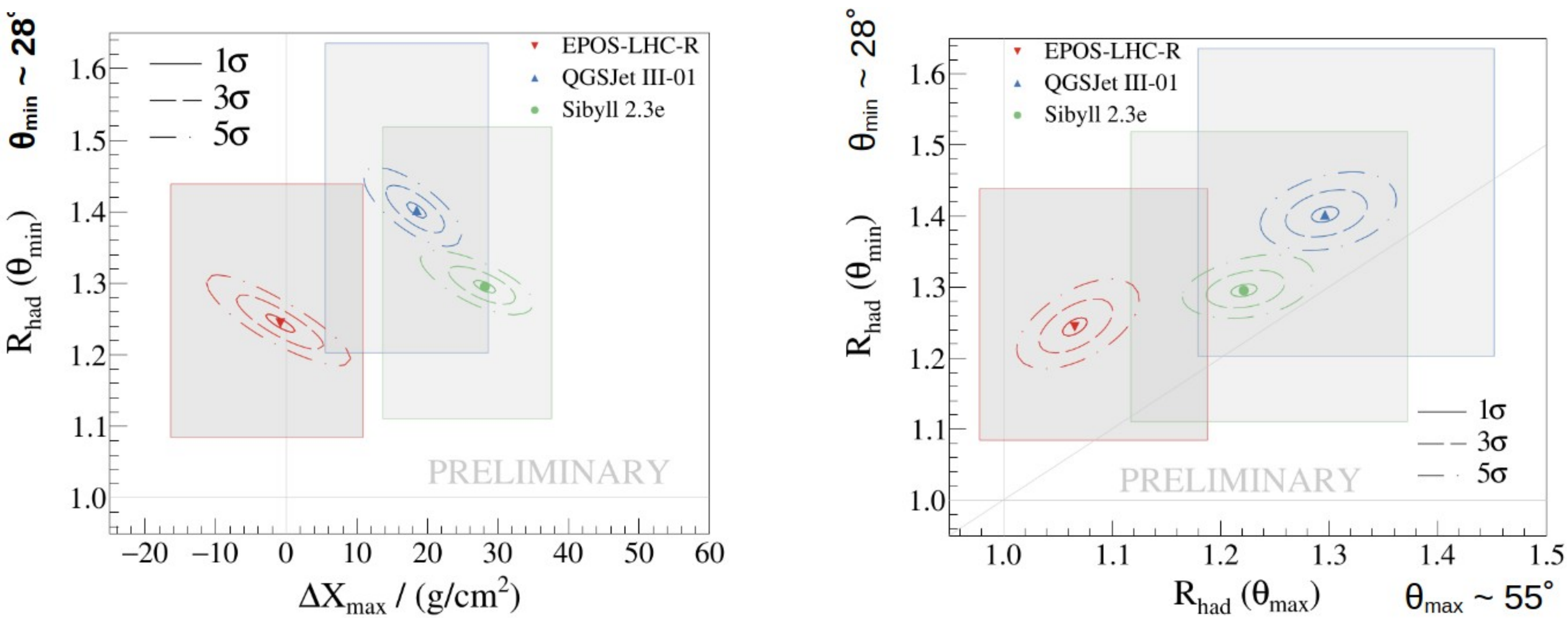




Everything Solved ?

Extensive analysis with EPOS.LHC-R on Auger data

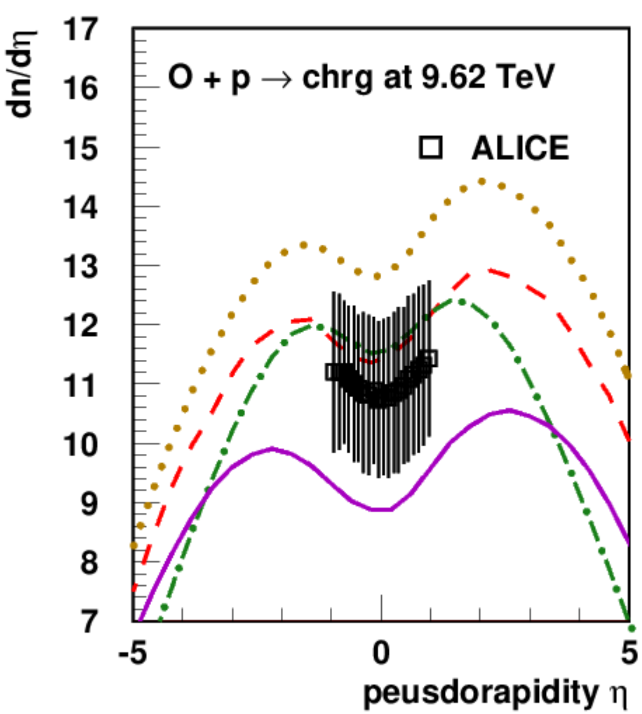
- Deep X_{max} improve data description
  - Better composition fit with X_{max}
  - Better correlation between X_{max} and ground signal
- Increased number of muons OK for inclined showers but not for vertical showers !
  - Changed zenith angle dependence compared to other models
    - Pion cross-section too low !



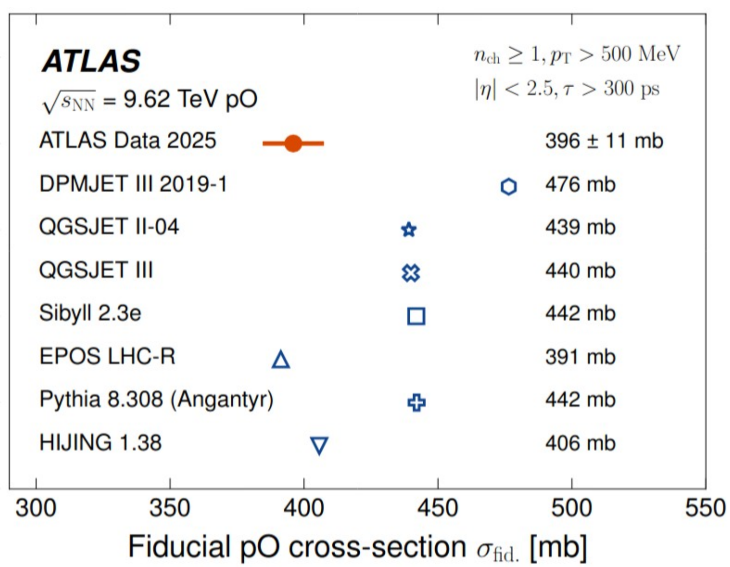
New p+O and O+O Data

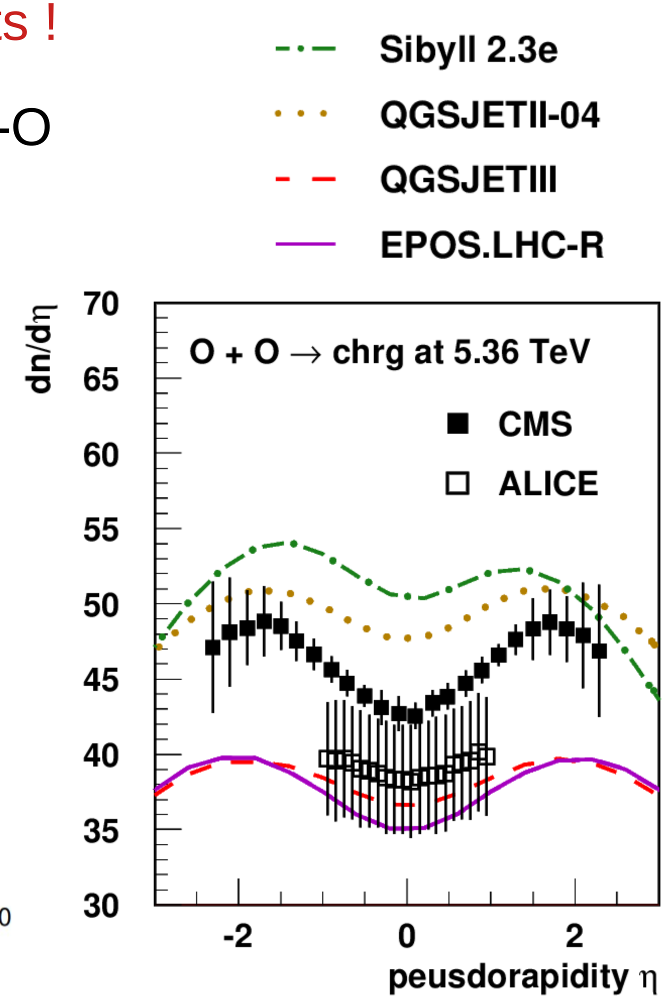
New data at 9.62 TeV for proton-Oxygen and 5.36 TeV for Oxygen-Oxygen collisions

- Data taken last July ! Not much data/analysis on p+O yet
- Preliminary comparison : tensions between data sets !
- EPOS.LHC-R a bit low for p-O, Sibyll too high for O-O
- QGSJETIII OK but bug for Iron simulations !



ATLAS p-O cross-section is low !





arXiv:2604.05512 [hep-ex]

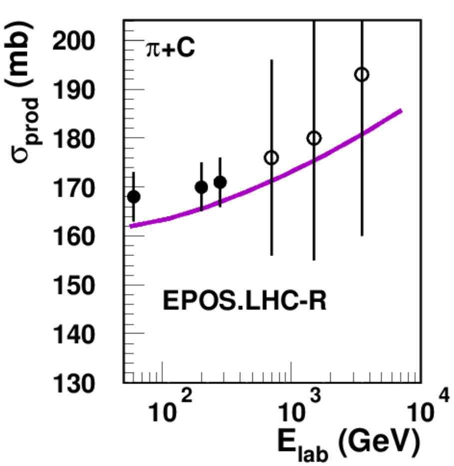
Last step toward solving the muon puzzle...

ATROPOS*, new model to do string fragmentation by Roman Nikolaenko

- Complete new model (first time since decades) taking into account angular momentum conservation (new !) introduced in EPOS: EPOS.LHC-A
  - Tuned on same data (e+e-)
  - Isospin symmetry broken by new constraint on angular momentum: $\rho^0/\rho^{+/-} > 0.6$!
    - Muon production further enhanced

Retune using p-O and O-O data and other very recent data

- ATROPOS change string multiplicity and particle phase space
  - Impact on basic parameters
  - Impact on core-corona
- Better description of low mass systems



Increase pion cross-section and inelasticity at low energy

- Higher cross-section produce more low energy muons missing in current version
- No impact on X_{max} if energy dependence can be changed (cross-section and/or elasticity)

Outlook

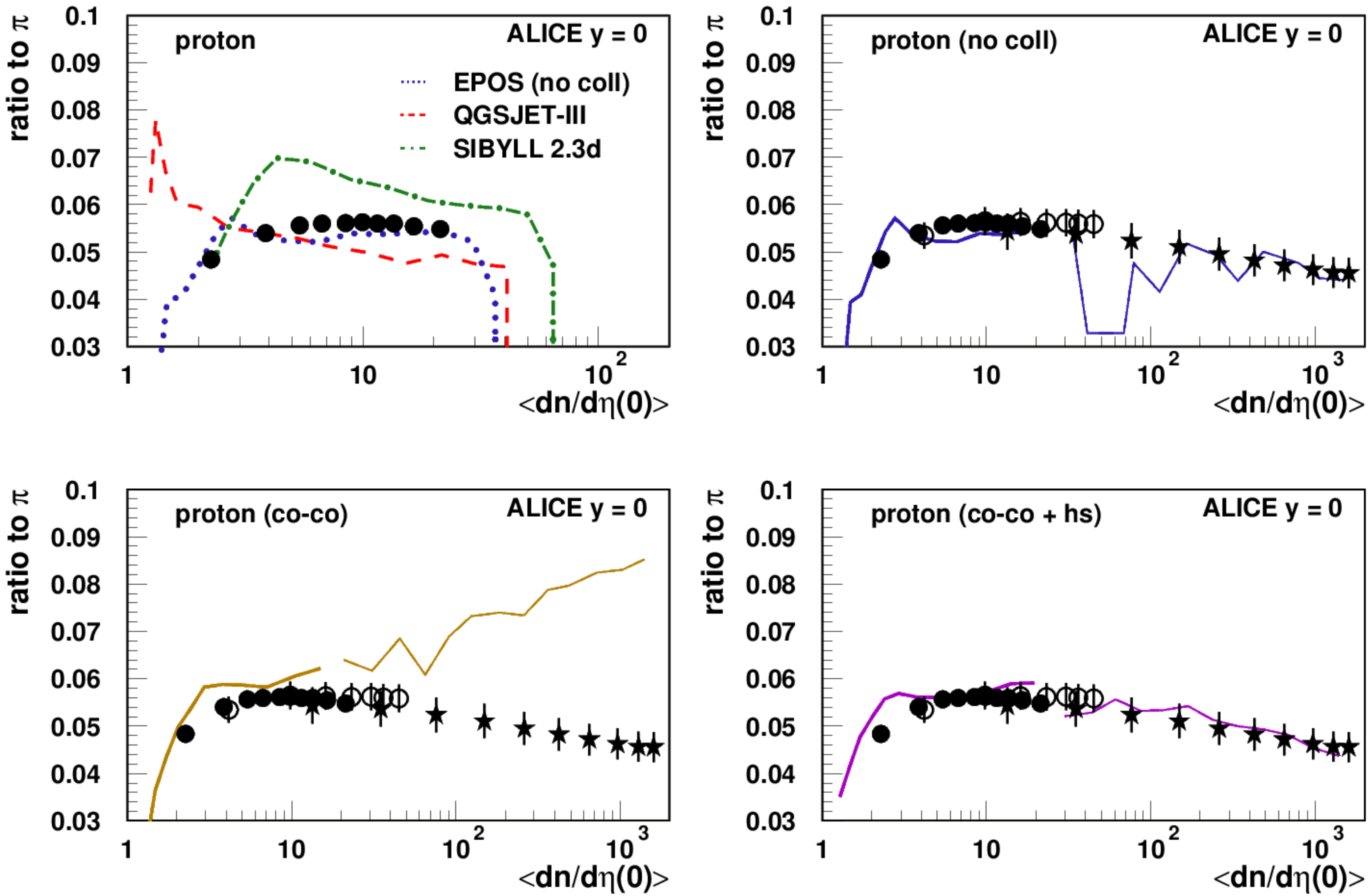
- **Updated results of cross-sections, multiplicity and diffraction using a global approach in EPOS.LHC-R**
  - Large impact on X_{max}
  - Larger <lnA> (heavier primary mass → reduce "muon puzzle")
- **Details of hadronization matters**
  - Important role of resonances
    - $\rho^0/\rho^{+/-}$ impacted by hadronic rescattering and decay of higher mass res.
  - Evolution of strangeness with multiplicity
    - Different type of hadronization in core = more muons
  - **Combination of the 3 effects necessary to solve the muon puzzle !**
- **Still uncertainties due to pion-Air interactions in EAS**
  - Cross-section, multiplicity and elasticity unknown at high energy
    - Too low pion cross-section in EPOS.LHC-R reduced muons in vertical showers
  - Some constrains using pion exchange in p-O interaction (analysis on-going)

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

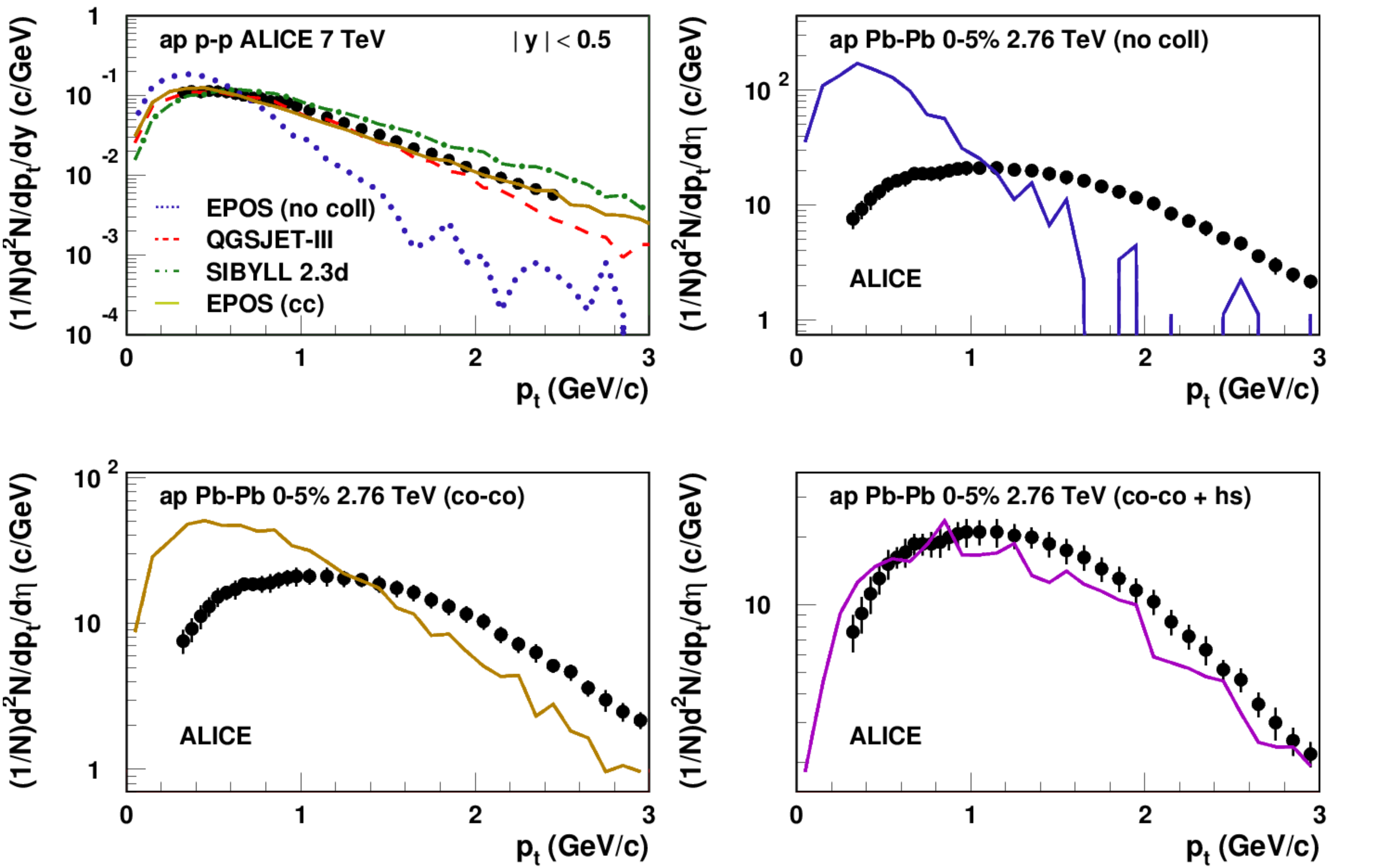
Providing a possible solution to the “muon puzzle” !

Thank you !

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



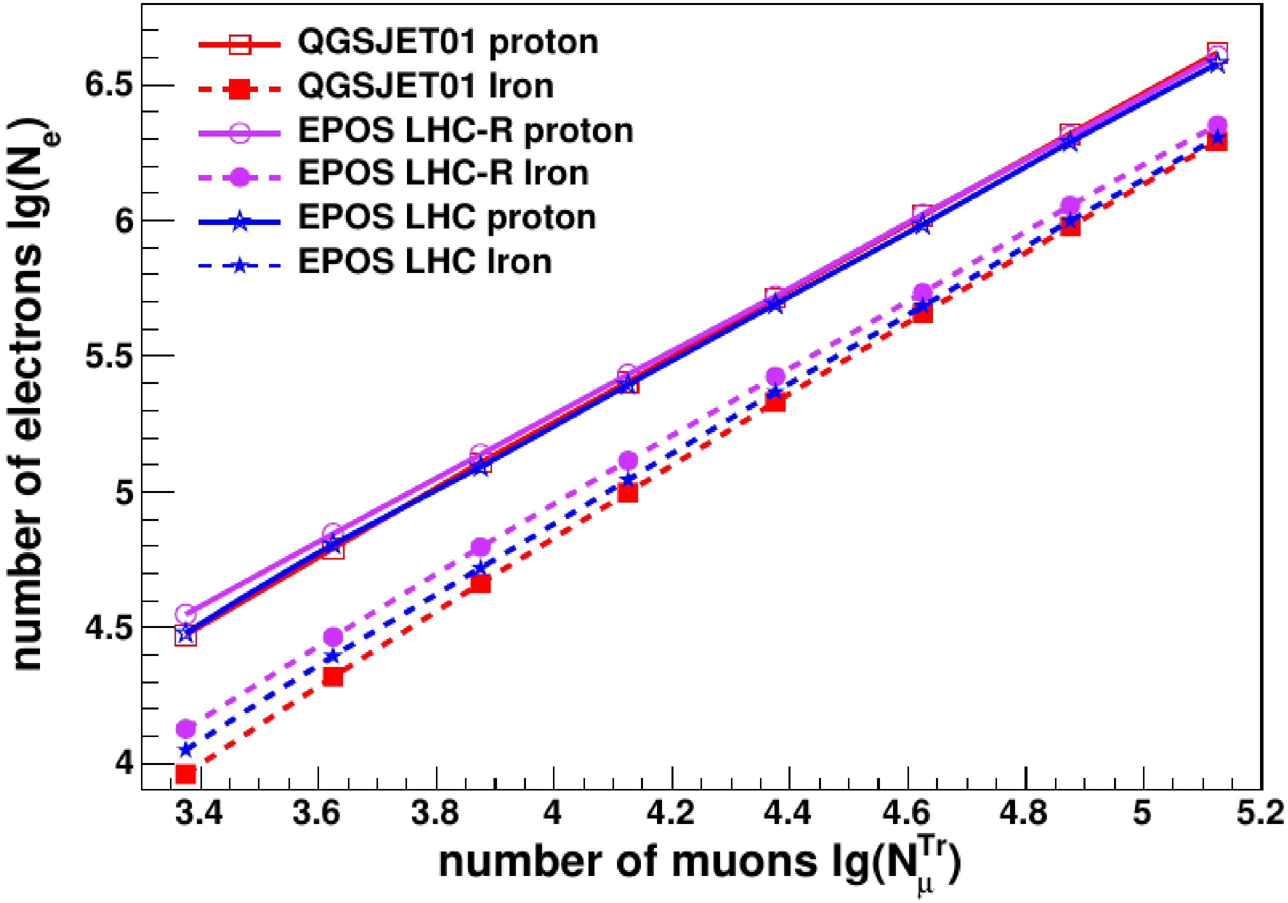
Example with protons in p-p and Pb-Pb @ LHC



KASCADE/LHAASO

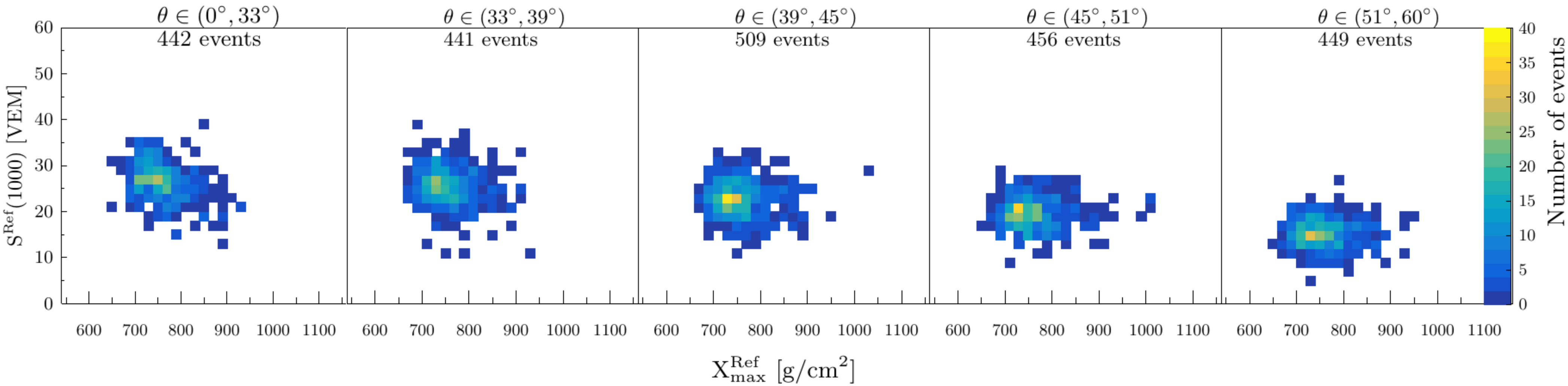
Correlation between N_e and N_μ

- ➡ 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 !



X_{max}-S(1000) correlation

Hybrid measurements allows to test model consistency in more details



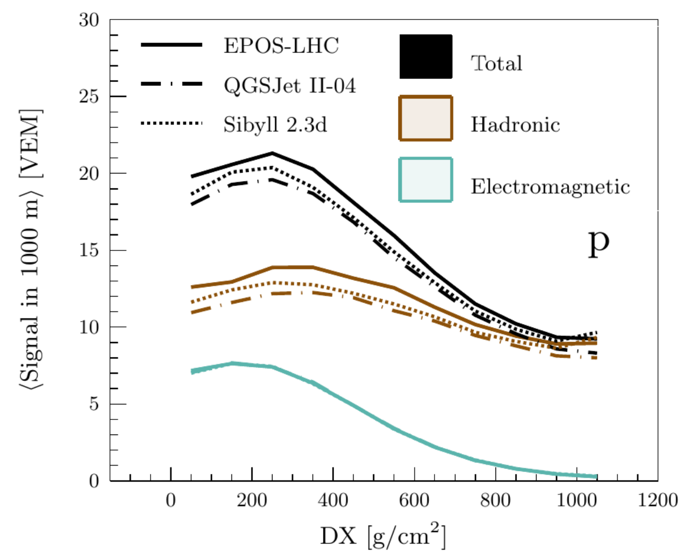
$$X^{\mathrm{Ref}}_{\mathrm{max}} \equiv \widehat{X^{\mathrm{Ref}}_{\mathrm{max}}} + \Delta X_{\mathrm{max}},$$
$$S^{\mathrm{Ref}}(1000) \equiv \widehat{S^{\mathrm{Ref}}(1000)} \cdot f_{\mathrm{SD}}(\theta)$$

Parameters:

$\Delta X_{max}, R_{Had}, R_{em}, \xi_1, \xi_2, \xi_3$

Describe the 4 mass fractions

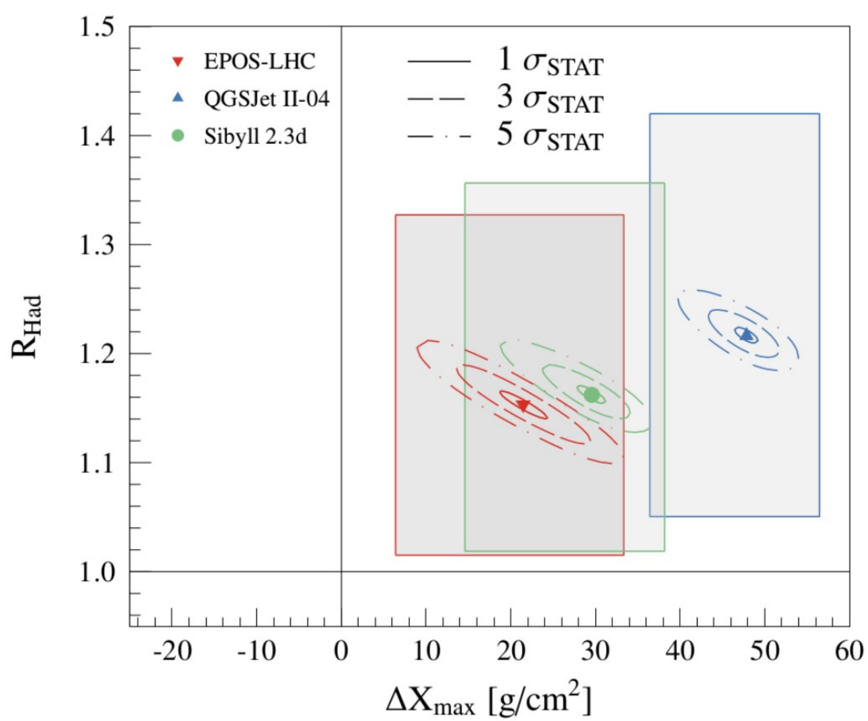
$$\phi = c \cdot f_{Gumbel}\left(X^{Ref}_{max}\right) \cdot f_{Gauss}\left(X^{Ref}_{max}, S^{Ref}(1000)\right)$$

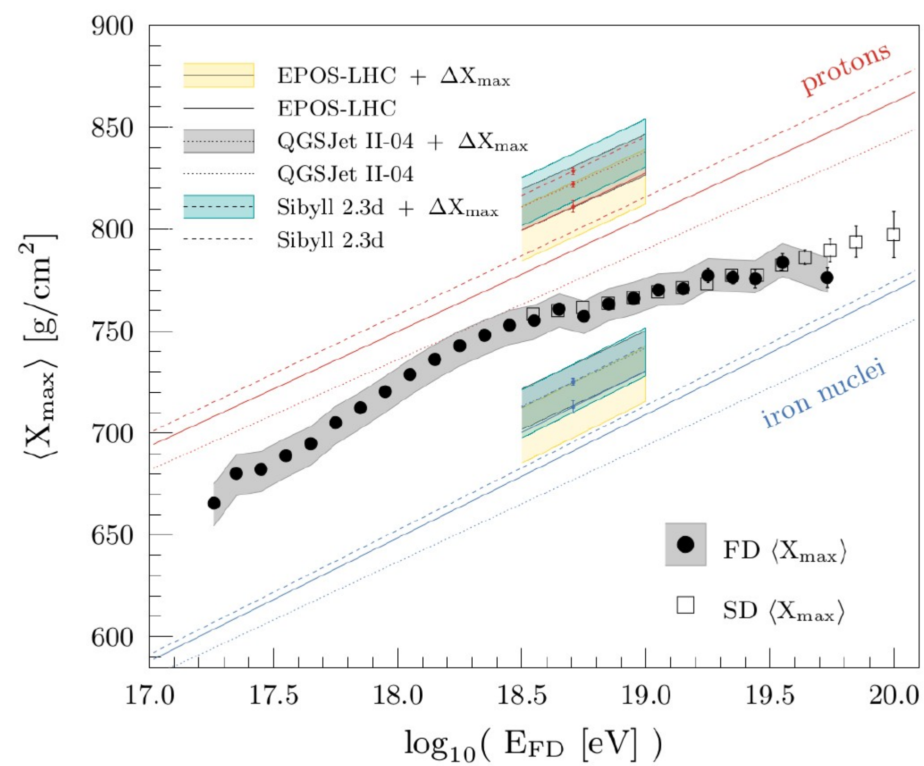


The final MC templates are a sum of templates of the form of Φ of individual primary species weighted by their relative fractions.

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)





EPJ Web Conf. 283 (2023) 02012

WHISP Working Group

- **Lots of muon measurements available**
  - ➜ Auger, EAS-MSU, KASCADE-Grande, IceCube/IceTop, HiRes-MIA, NEMOD/DECOR, SUGAR, TA, Yukutsk
- **Working group (WHISP) created to compile all results together. Analysis led and presented 1st time on behalf of all collaborations by H. Dembinski at UHECR 2018 :** **H. Dembinski (LHCb, Germany),**

L. Cazon (Auger, Portugal), R. Conceicao (AUGER, Portugal), F. Riehn (Auger, Portugal), T. Pierog (Auger, Germany),

Y. Zhezher (TA, Russia), G. Thomson (TA, USA) , S. Troitsky (TA, Russia), R. Takeishi (TA, USA),

T. Sako (LHCf & TA, Japan), Y. Itow (LHCf, Japan),

J. Gonzales (IceTop, USA), D. Soldin (IceCube, USA),

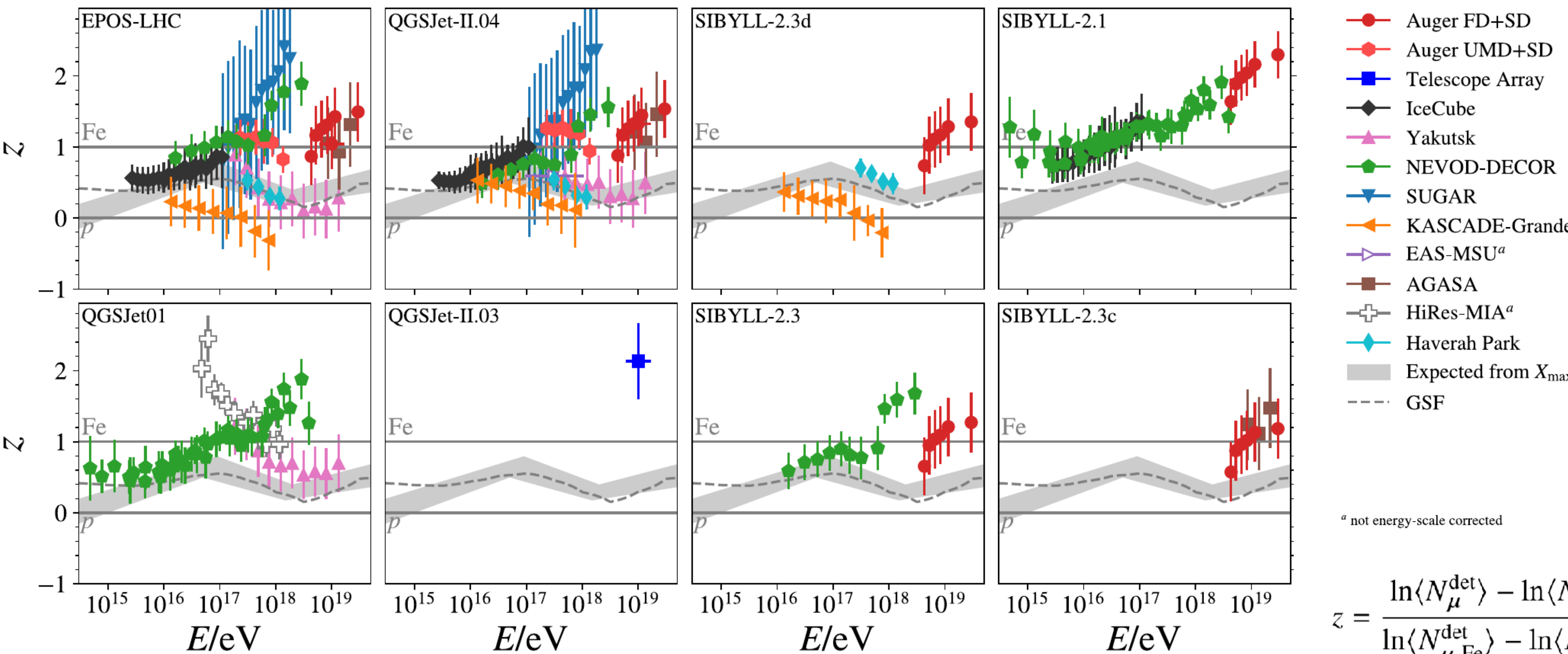
J.C. Arteaga (KASCADE-Grande, Mexico),

I. Yashin (NEMOD/DECOR, Russia). E. Zadeba (NEMOD/DECOR, Russia)

N. Kalmykov (EAS-MSU, Russia) and I.S. Karpikov (EAS-MSU, Russia)

Blurry Picture.

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

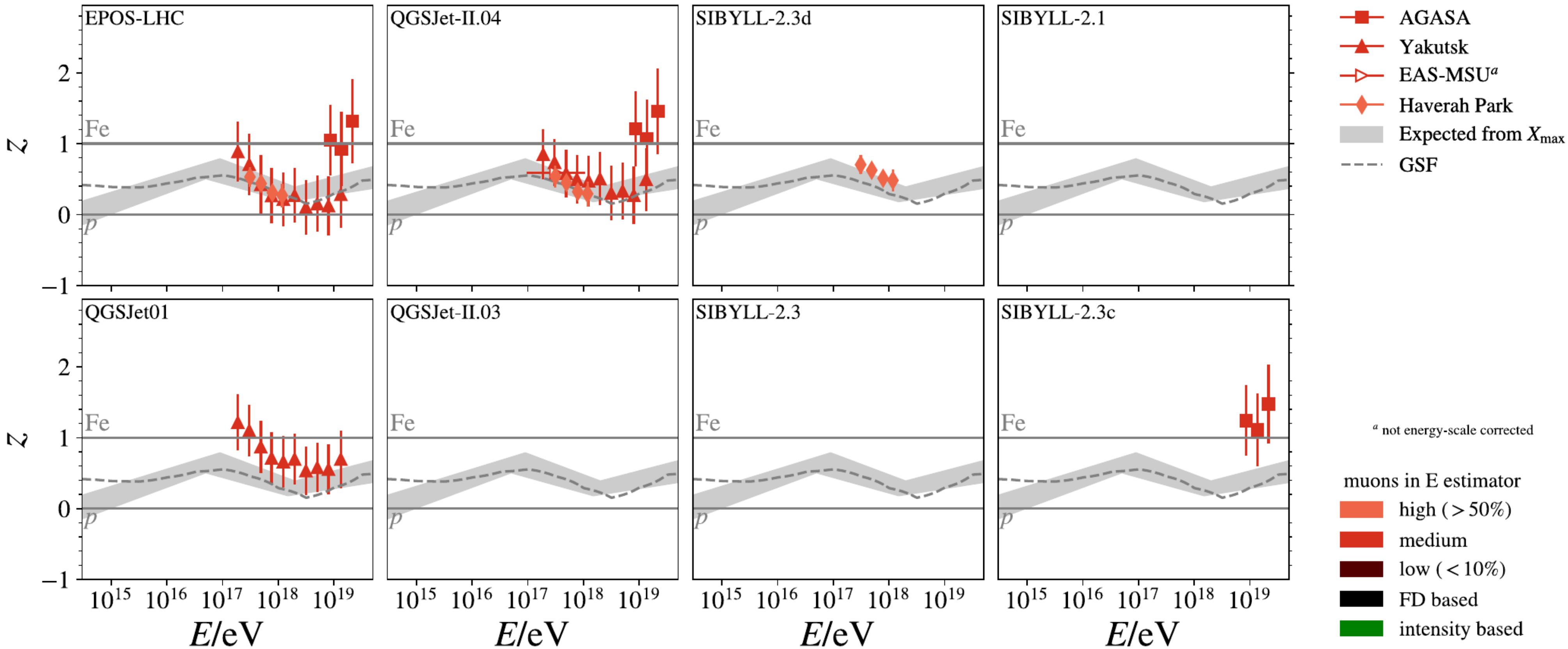


$$z = \frac{\ln\langle N_\mu^{\rm det}\rangle - \ln\langle N_{\mu,\rm p}^{\rm det}\rangle}{\ln\langle N_{\mu,\rm Fe}^{\rm det}\rangle - \ln\langle N_{\mu,\rm p}^{\rm det}\rangle}$$

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

Blurry Picture..

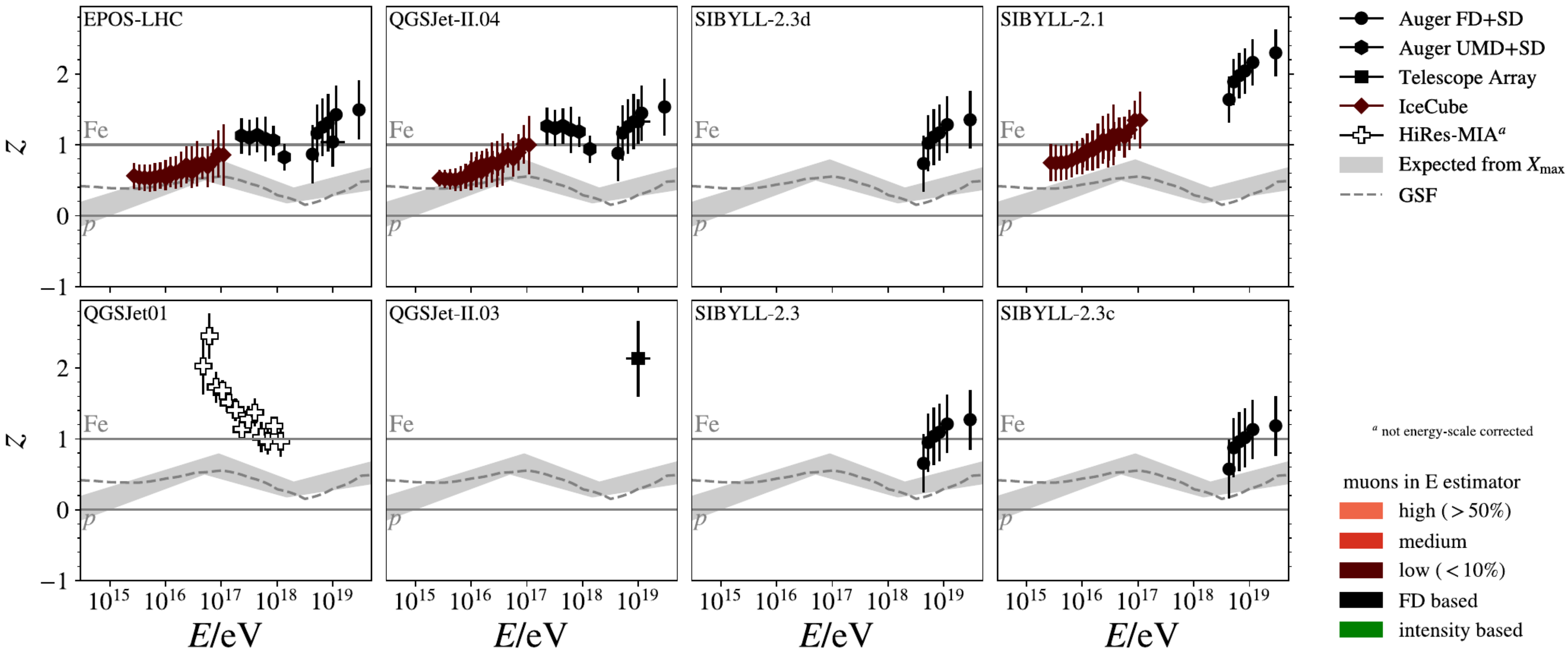
- **“Muon Puzzle” (<N_μ>) depends on energy measurement technique**
  - High muon fraction in energy estimator
    - No muon excess observed in data



J.C. Arteaga-Update on the combined analysis of μ data ICRC 2023, Nagoya, Japan 17

Blurry Picture...

- **"Muon Puzzle" ($<N_\mu>$) depends on energy measurement technique**
  - Low muon fraction in energy estimator
    - Large muon deficit in simulations



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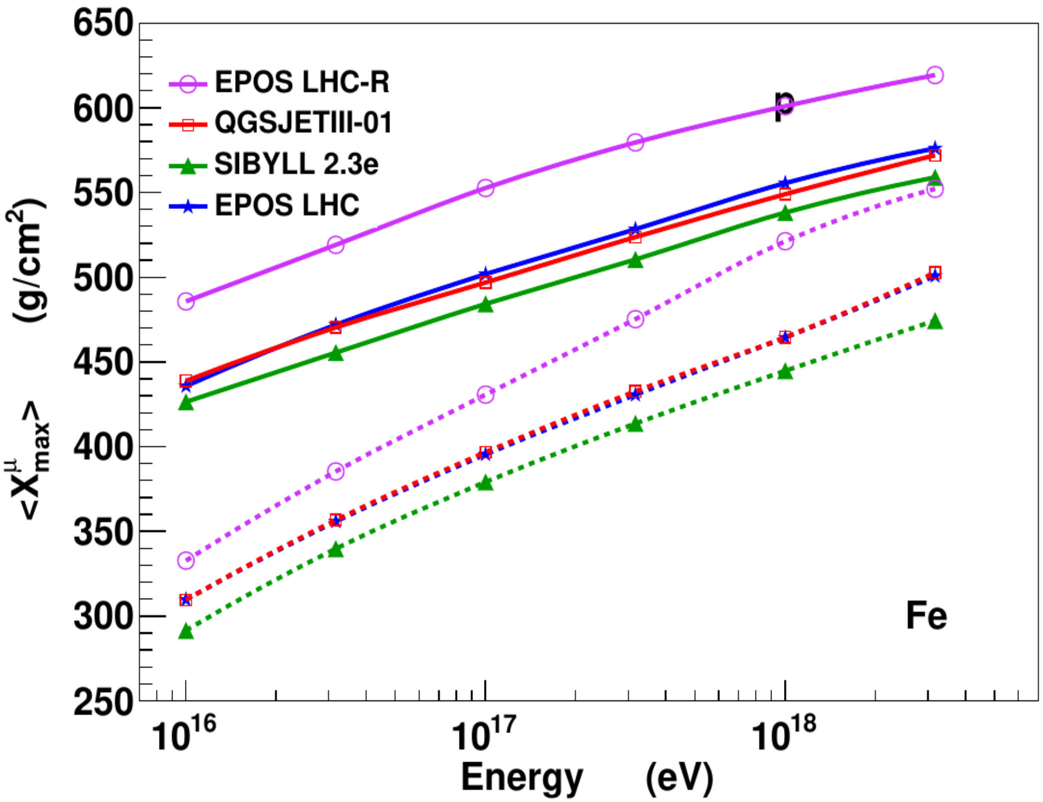
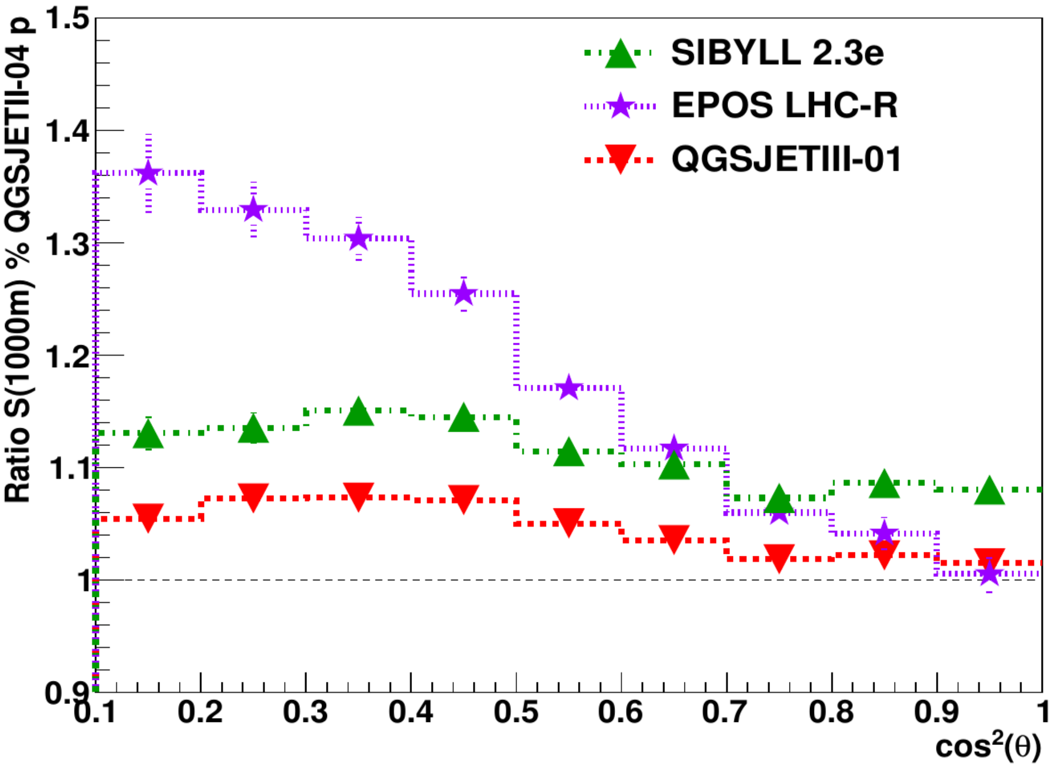
X^{μ}_{max} and N_{μ} @ 1 km (S_{μ}(1000m))

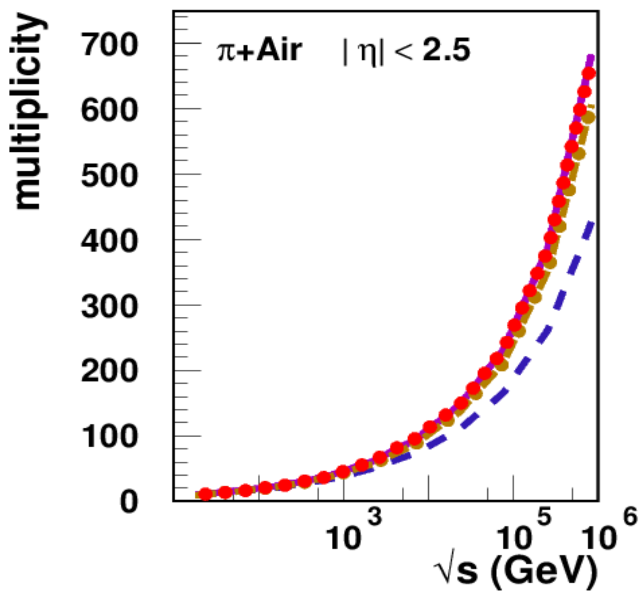
Global changes

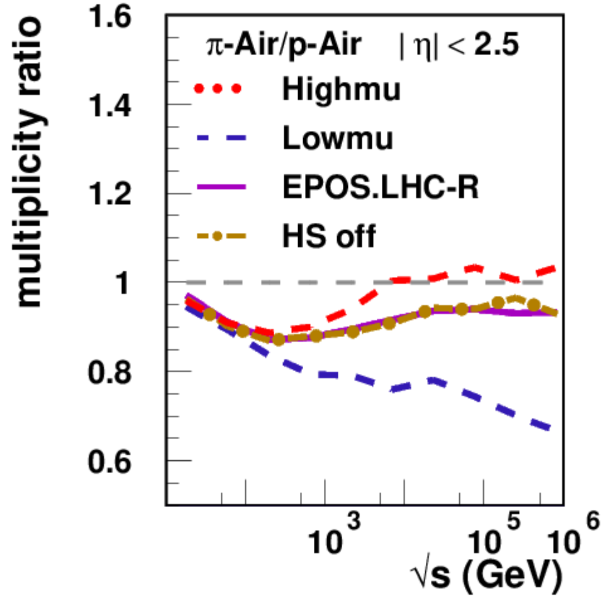
- new EPOS shifted by +50g/cm² !
- QGSJETIII-01 shifted by +40g/cm² (=EPOS LHC)
- Very different zenith angle dependence for EPOS LHC-R !
  - Different muon energy spectrum

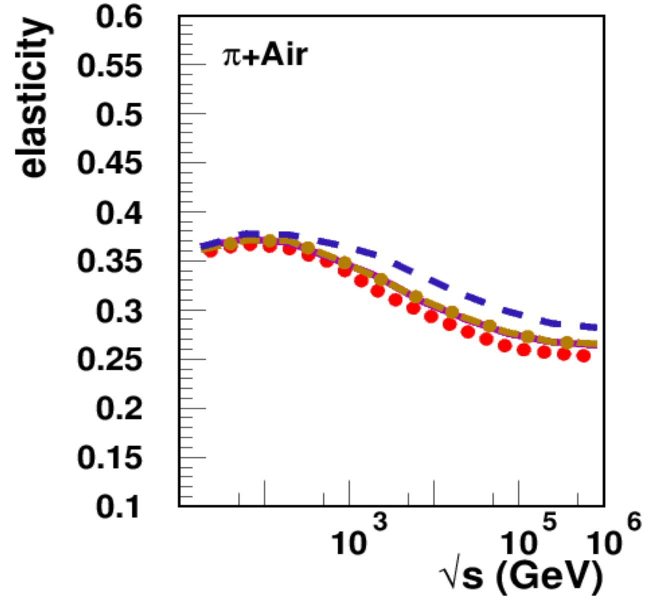


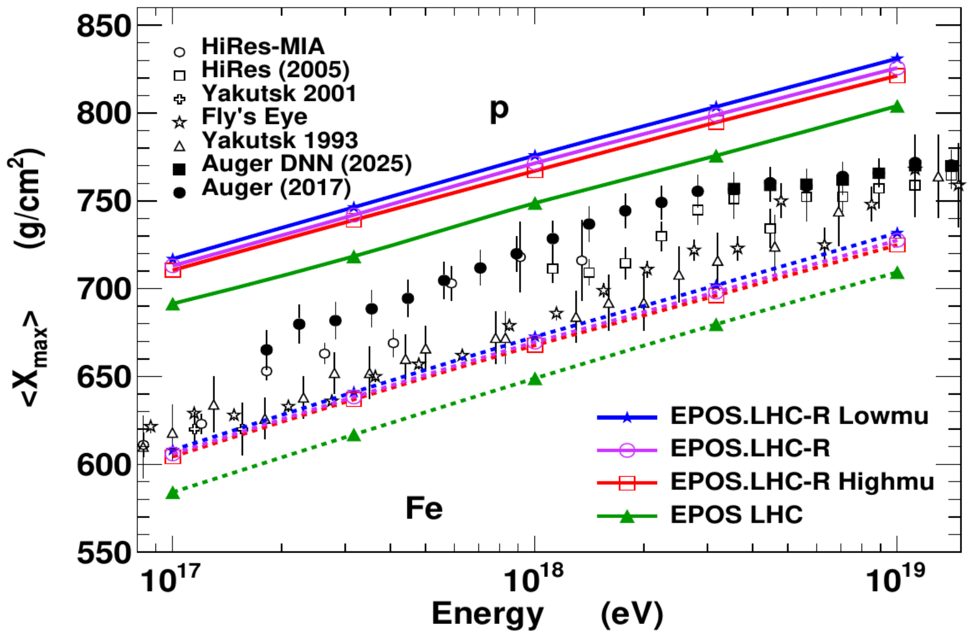


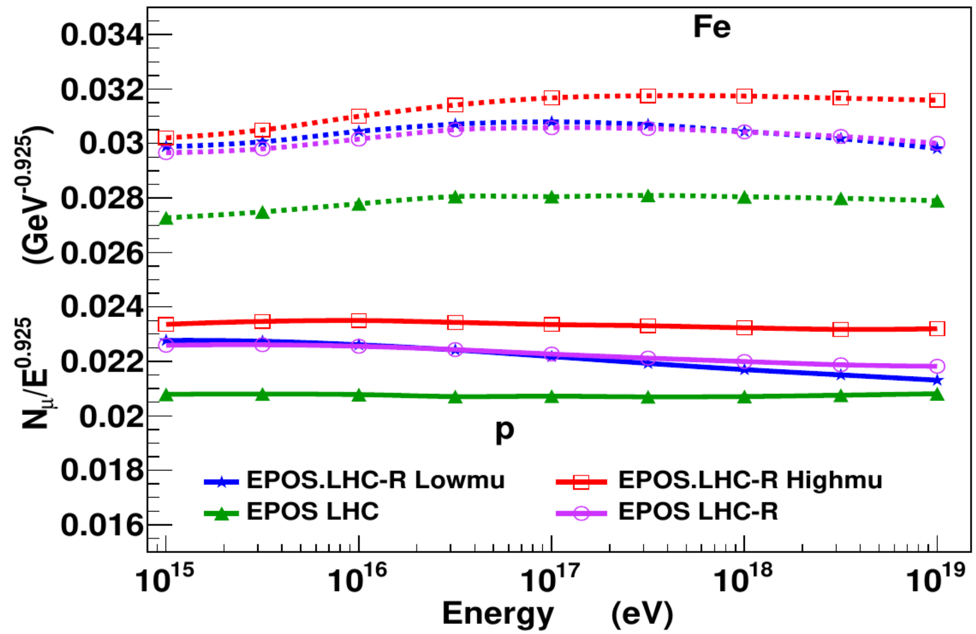
Pion-Air interaction unconstrained at high energy





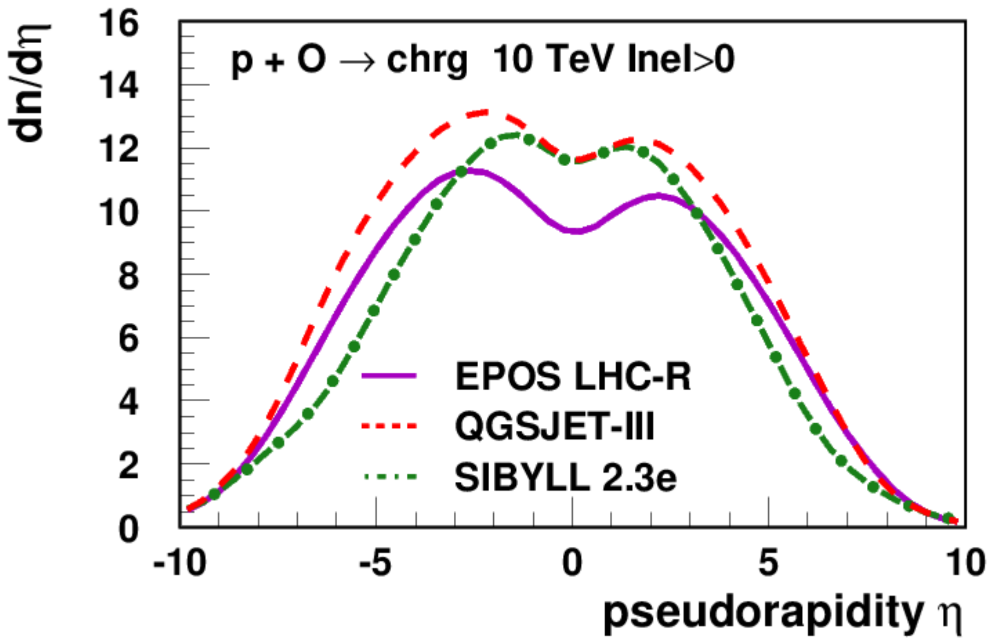


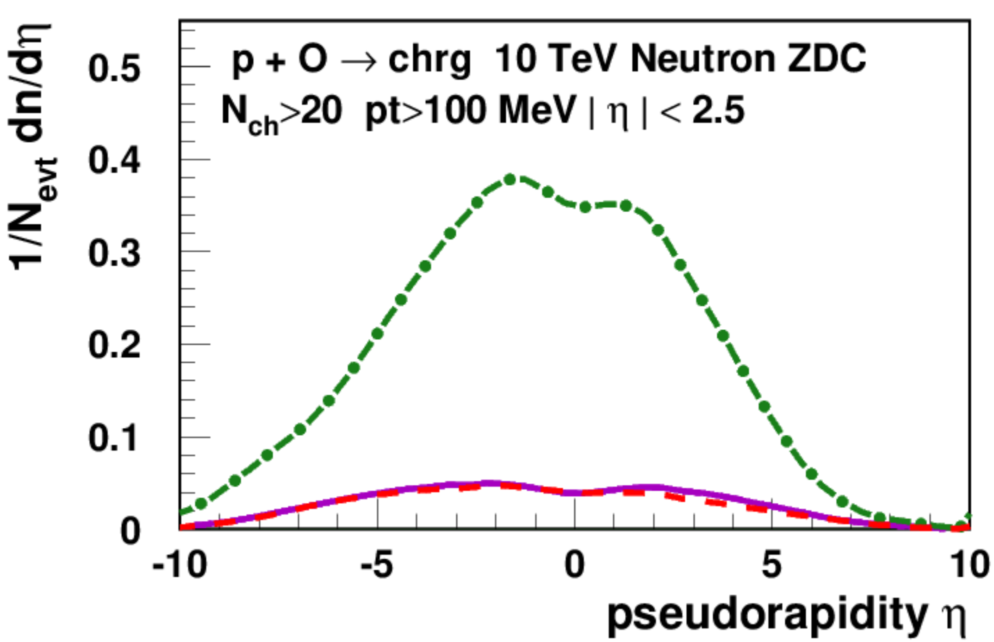




Multiplicity for pion projectile

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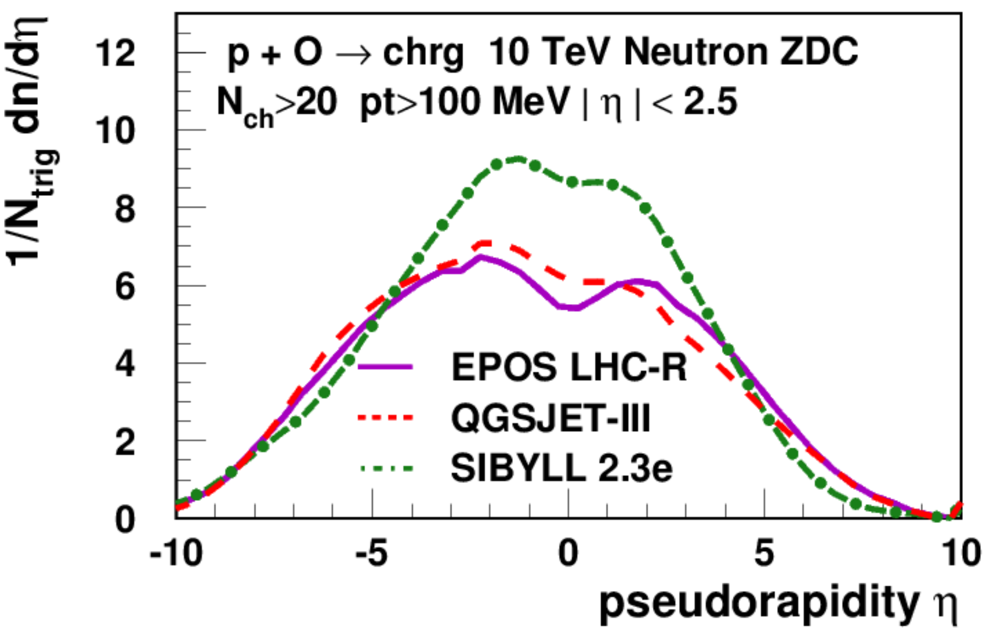
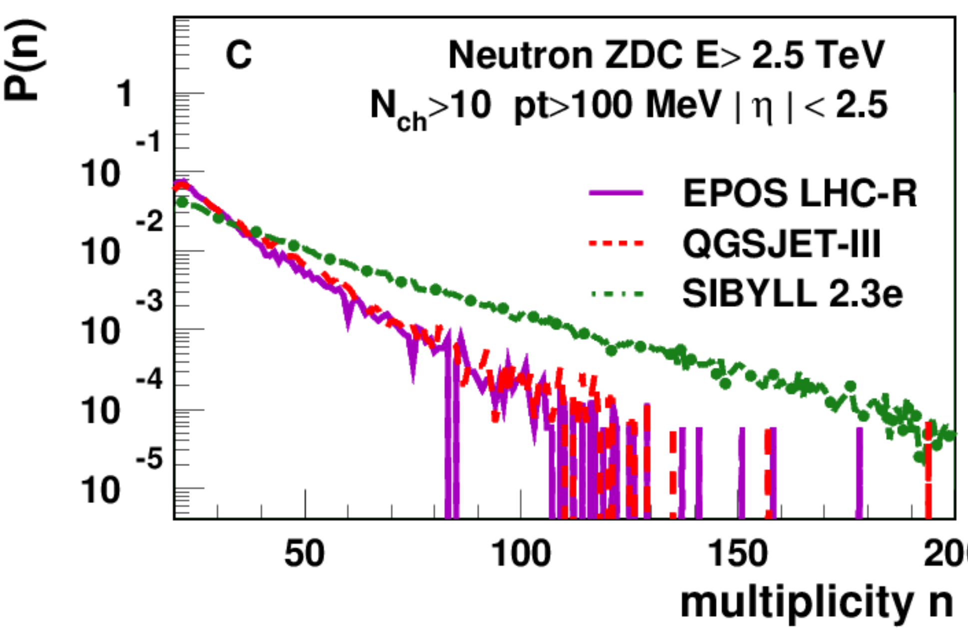
- **Upcoming data for proton on Oxygen at LHC in July**
  - Use pion exchange in p-O interactions to probe pion-Oxygen
    - ➔ neutron tag in ZDC (ATLAS+LHCf/CMS)
  - Trigger on forward neutron + high multiplicity at mid-rapidity to select pion exchange interaction (around 50% in EPOS)





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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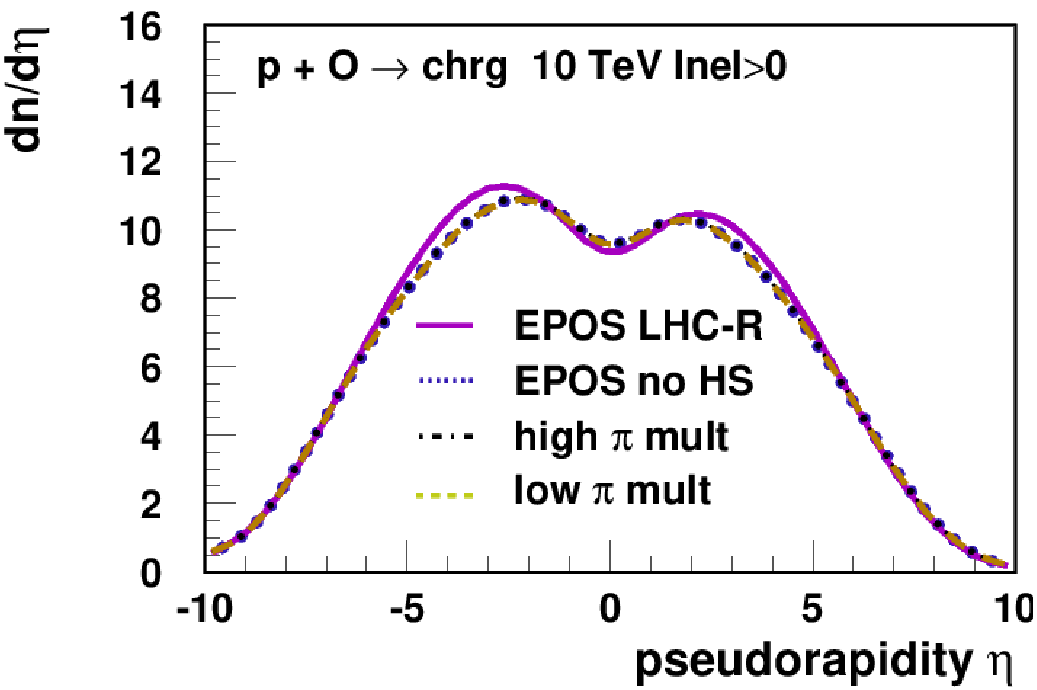

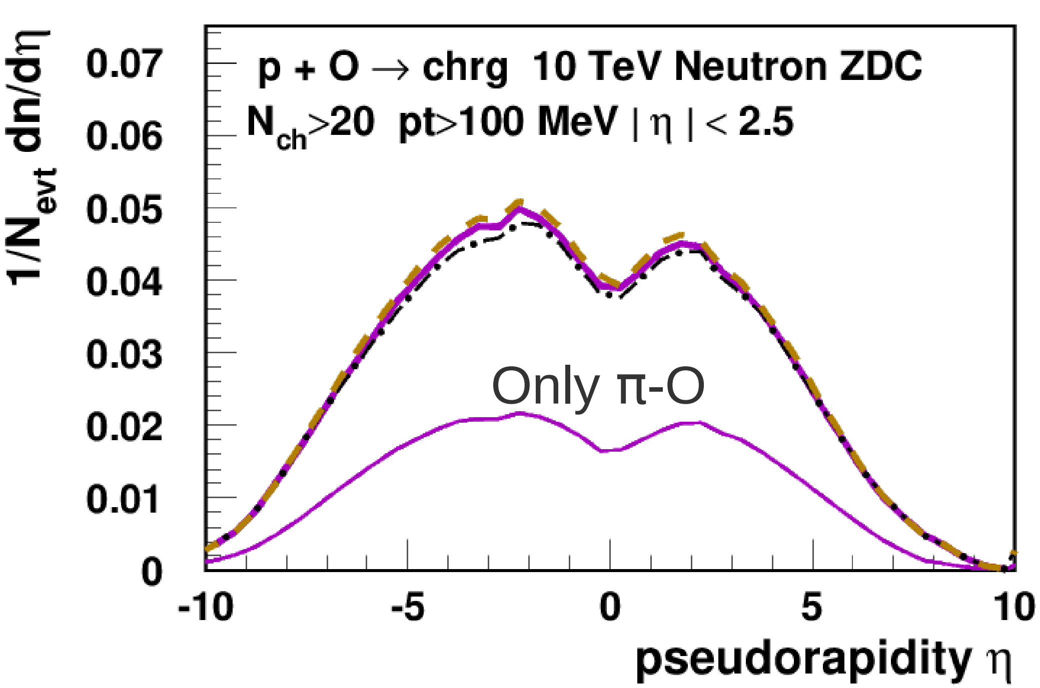

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➜ Dependence on hadronic rescattering in EPOS LHC-R … to be confirmed ?