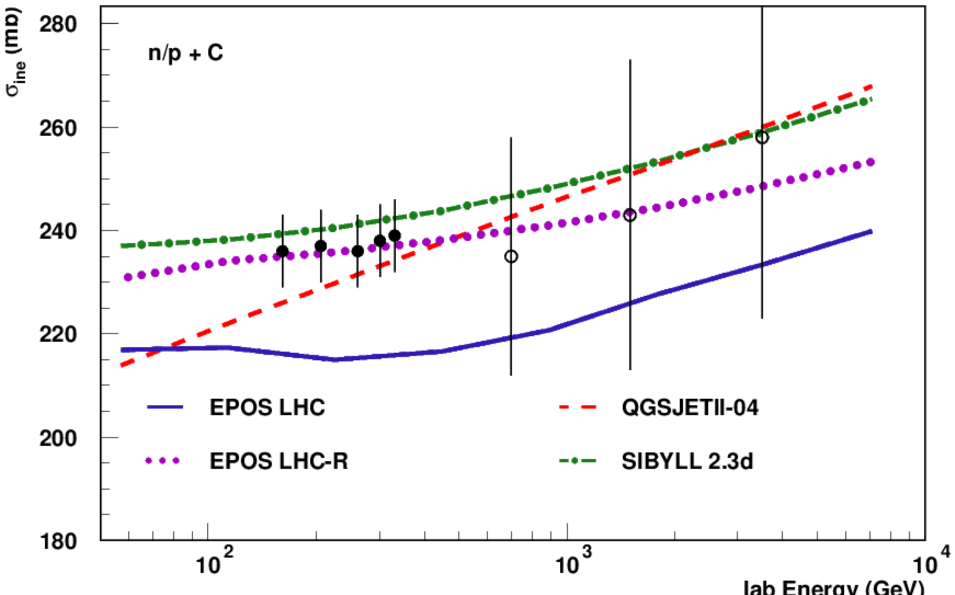
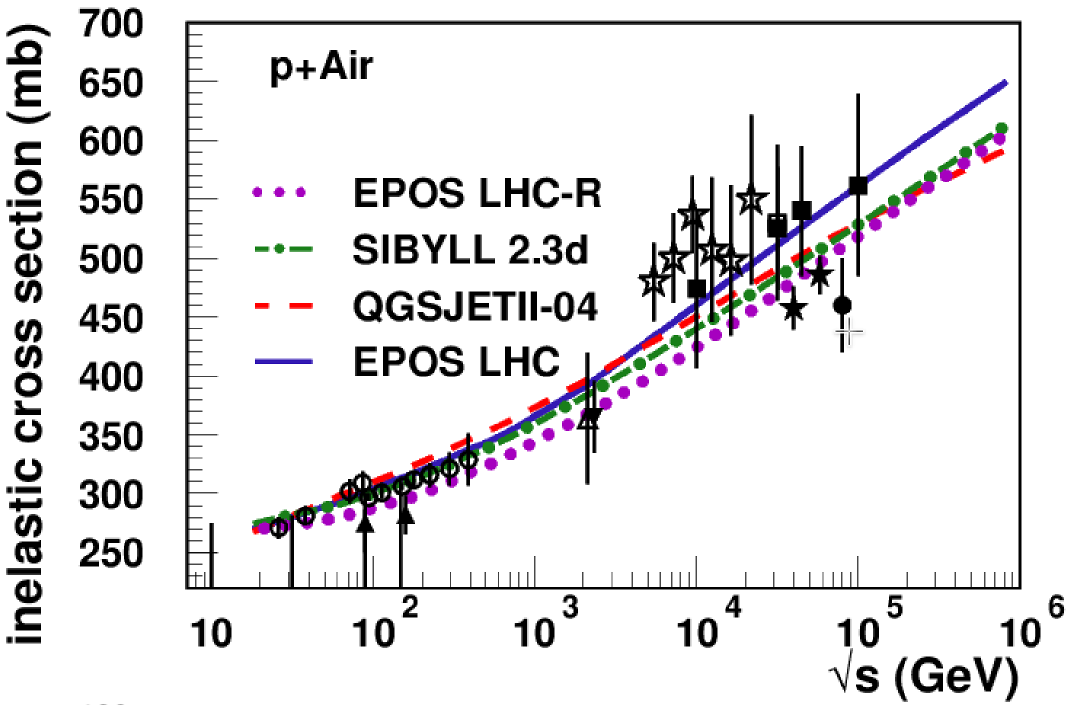
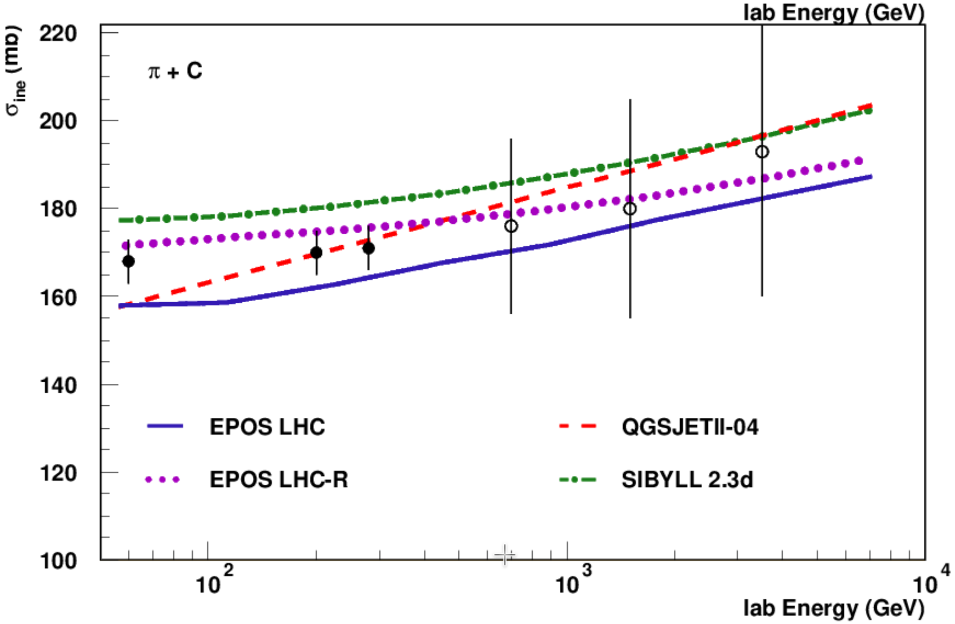
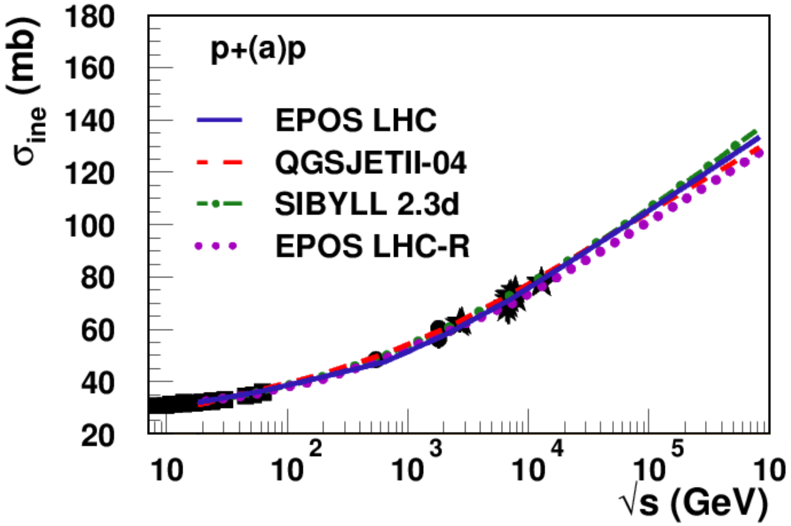
Cross-Sections

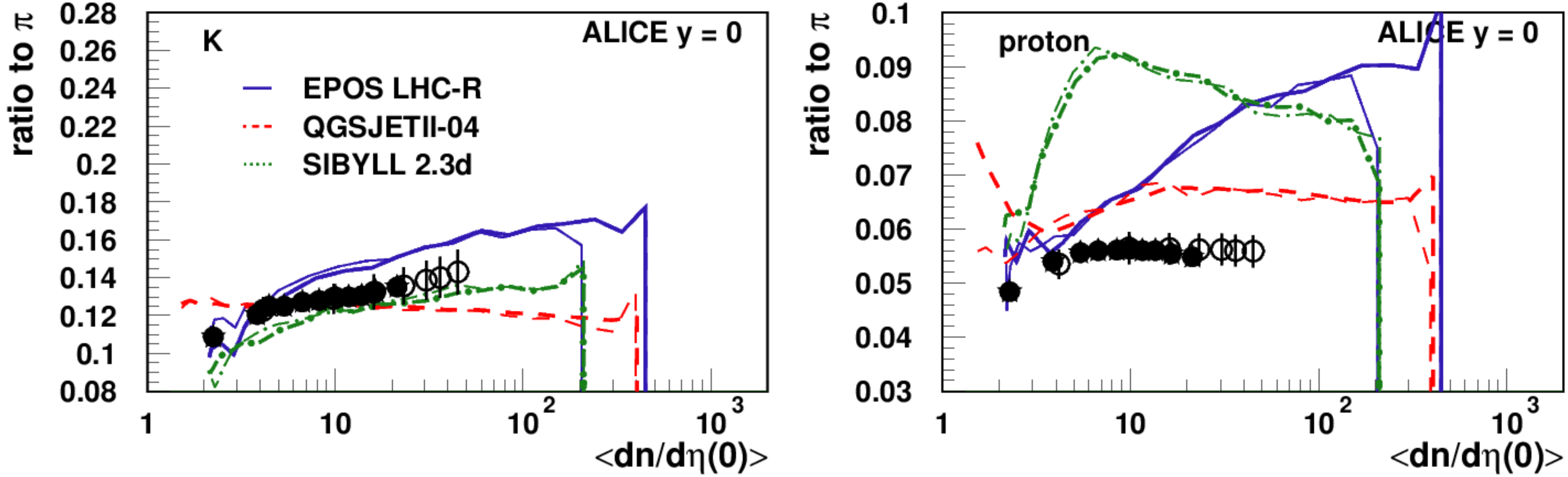




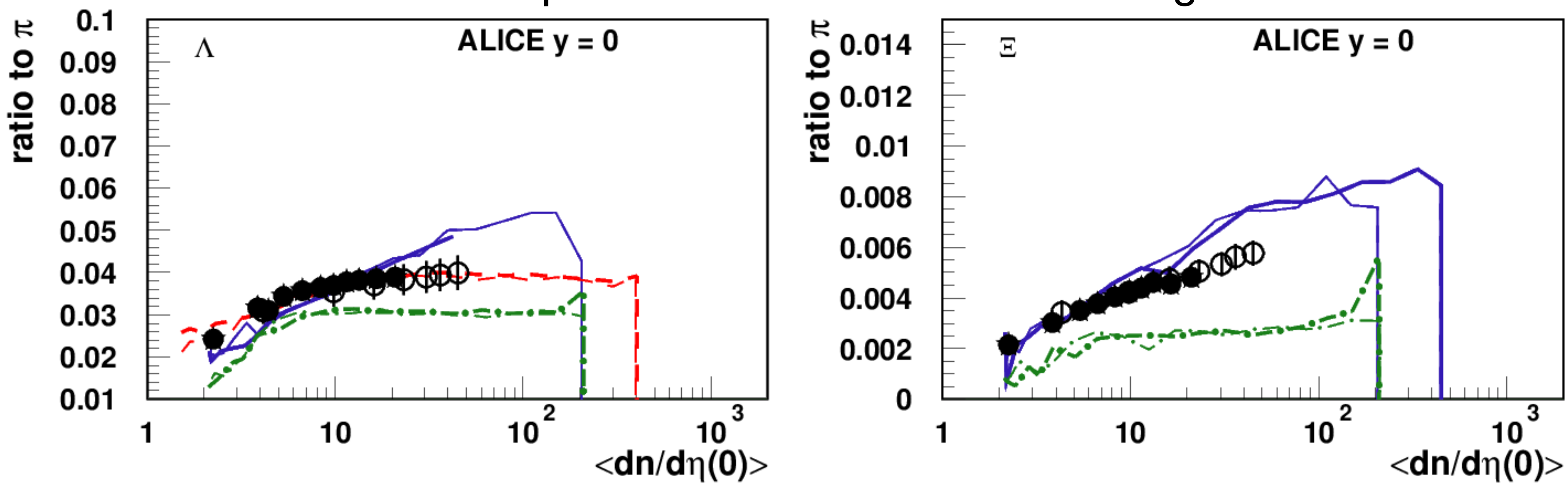




Particle Yields

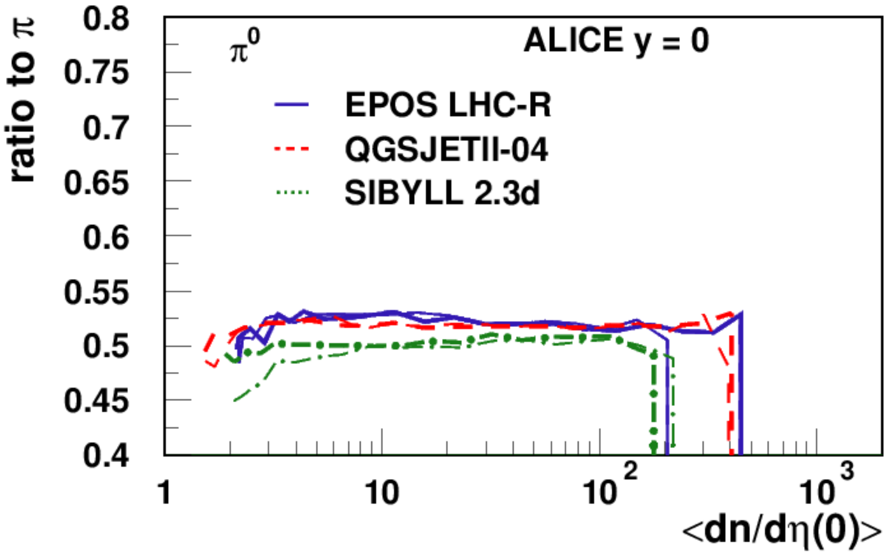


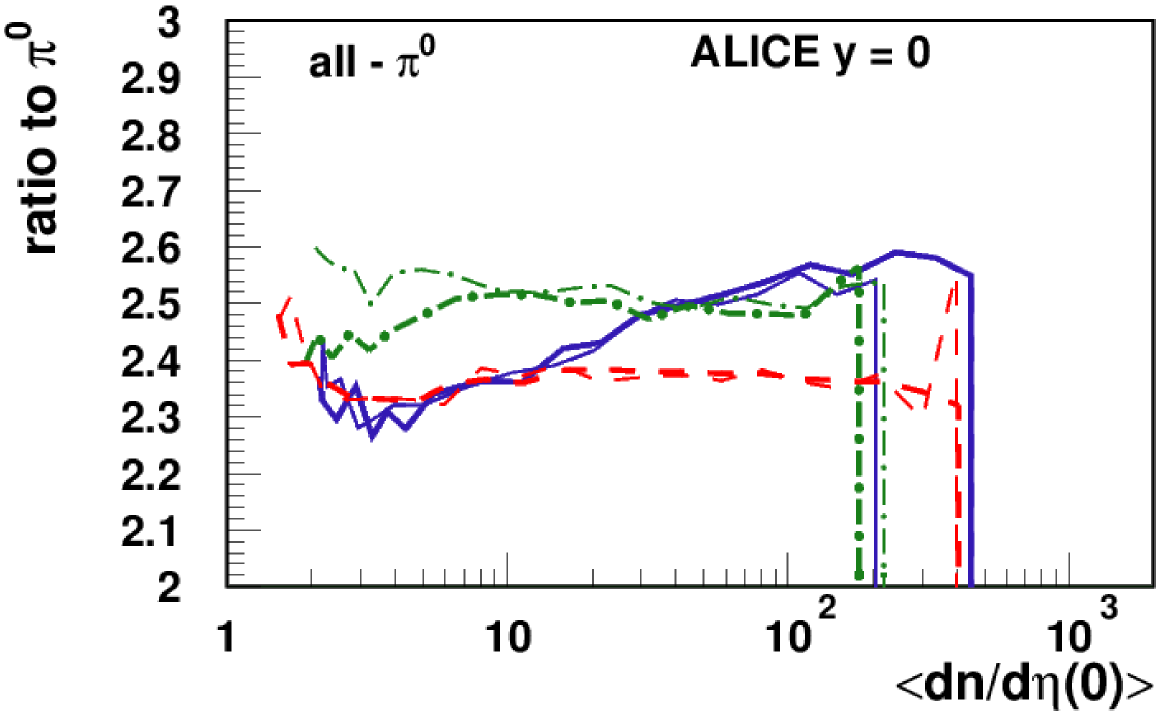
Proton and pion Air interactions at all energies



Particle Yields

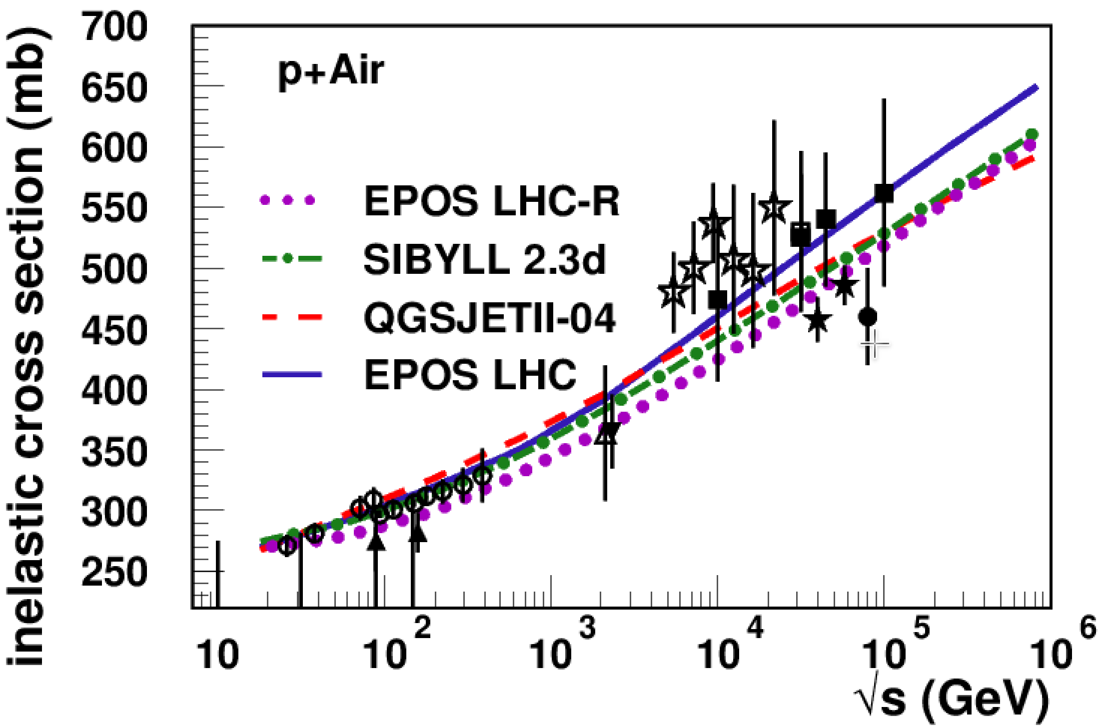
Proton and pion Air interactions at all energies

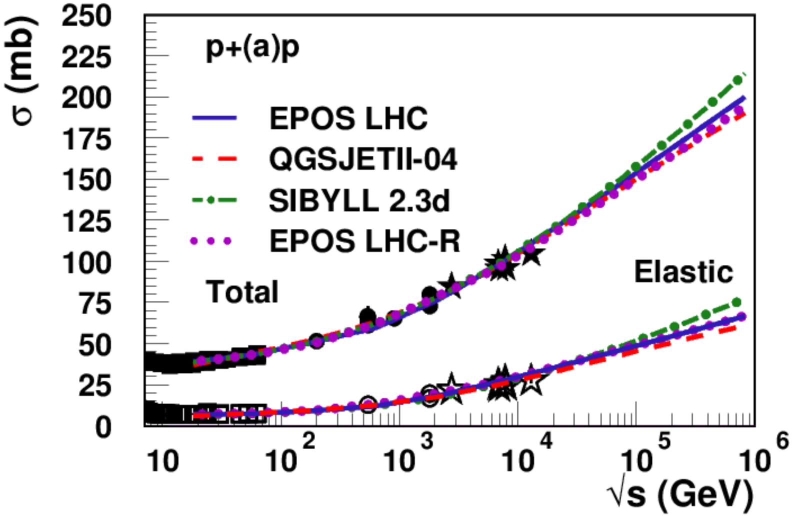


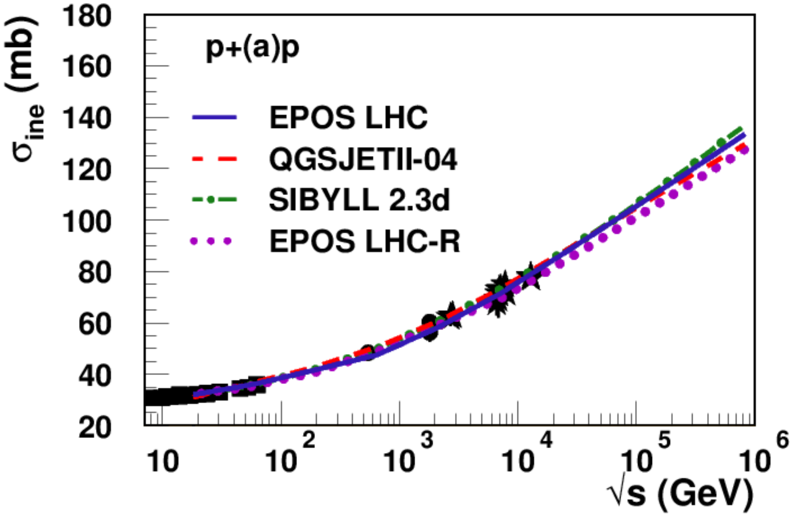


Cross-Section Reduced

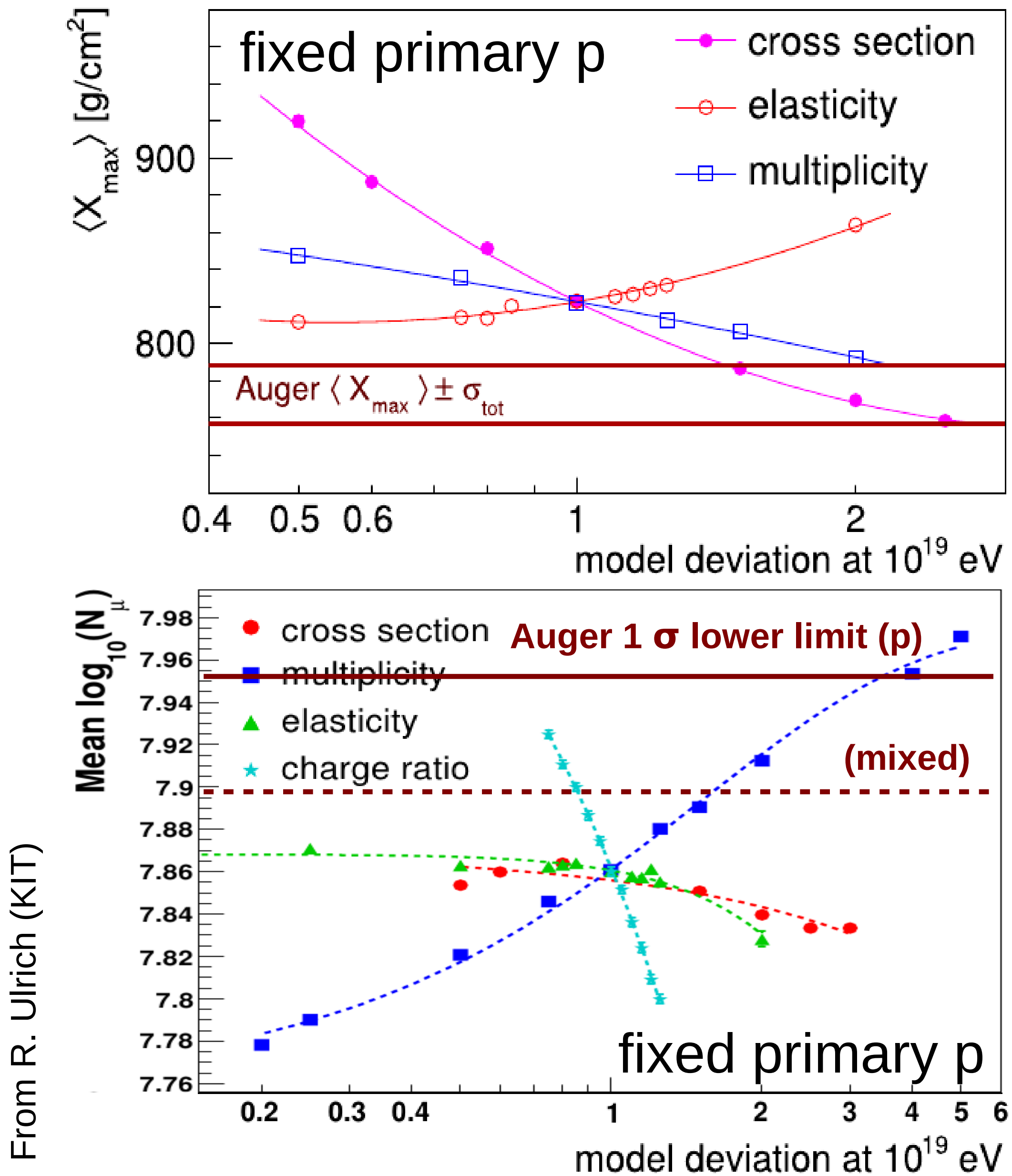
- **Probability for the particle to interact : directly related to X_{max}**
- **After TOTEM (CMS), new measurements by ALFA (ATLAS) with higher precision**
  - ➔ p-p cross-section slightly too high in all models
  - ➔ Change by up to -10% at the highest energy using most recent CR based measurements







Sensitivity to Hadronic Interactions

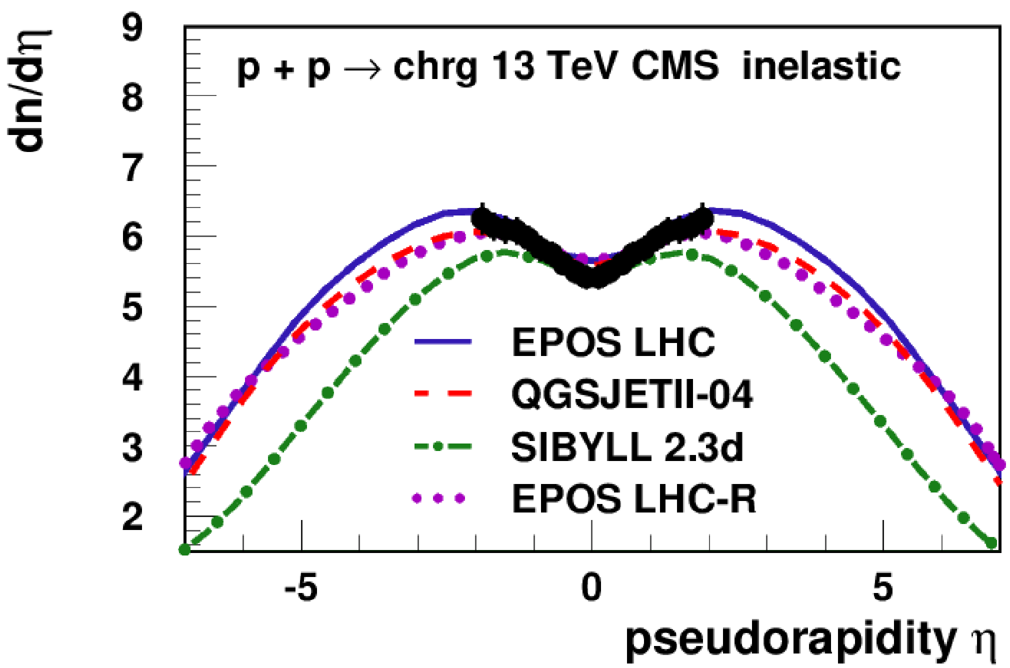


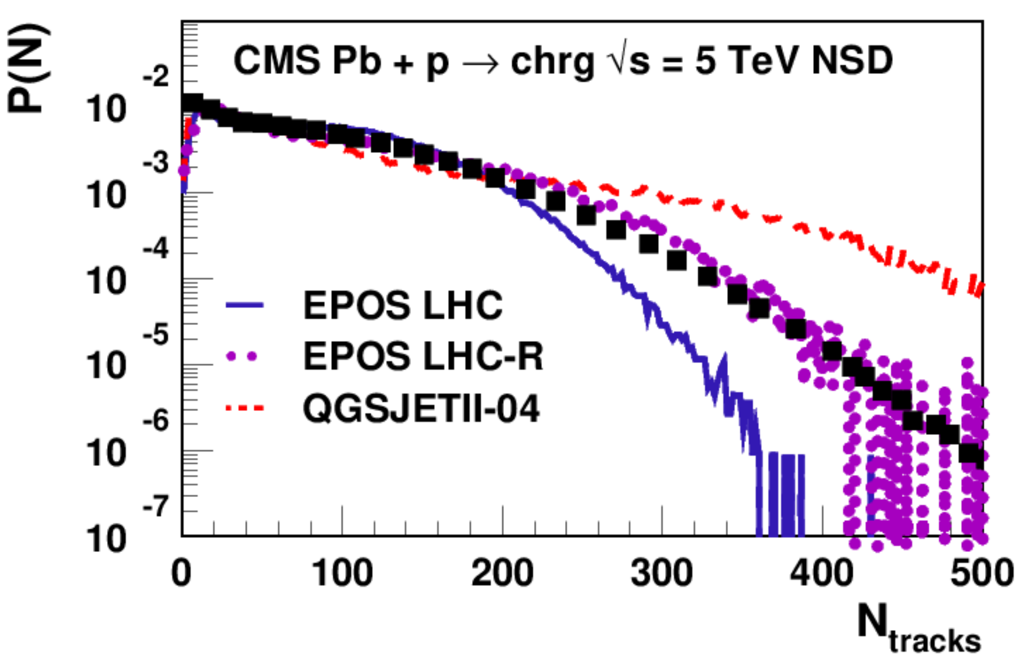
- **Air shower development dominated by few parameters**
  - mass and energy of primary CR
  - cross-sections (p-Air and (π-K)-Air)
  - (in)elasticity
  - multiplicity
  - charge ratio and baryon production
- **Change of primary = change of hadronic interaction parameters**
  - cross-section, elasticity,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

Theory AND data are important to constrain the hadronic model parameters. None of the two should be over-interpreted !

Pseudorapidity

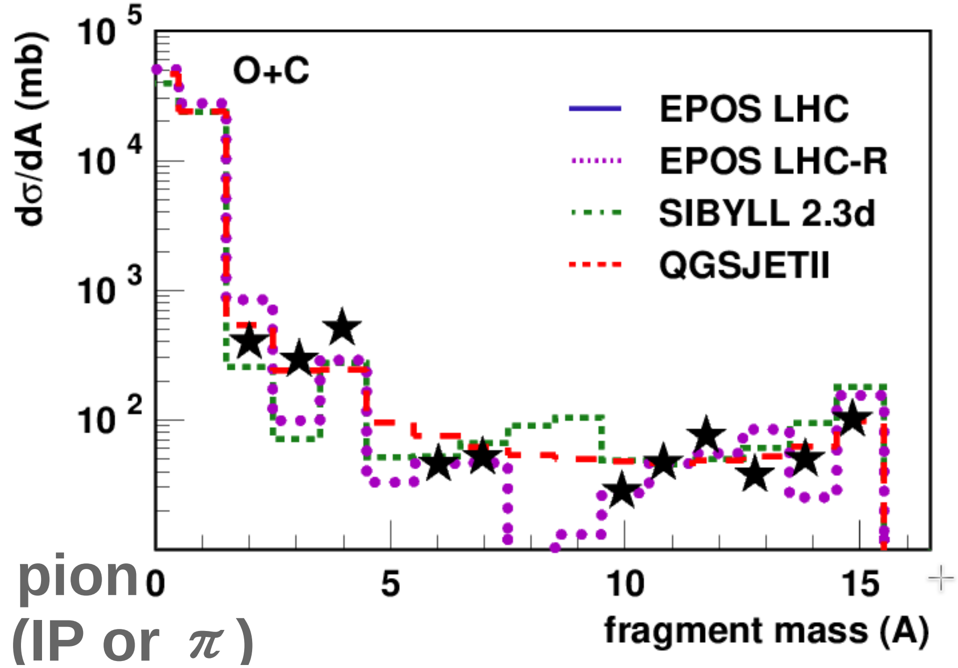
- **Angular distribution of newly produced particles**
- **New data at 13 TeV in p-p**
  - Test extrapolation with different triggers
  - Sibyll has a clear difference with other models (and data) : too narrow !
- **Detailed data at 5 TeV for p-Pb**
  - Wrong multiplicity distributions in all models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



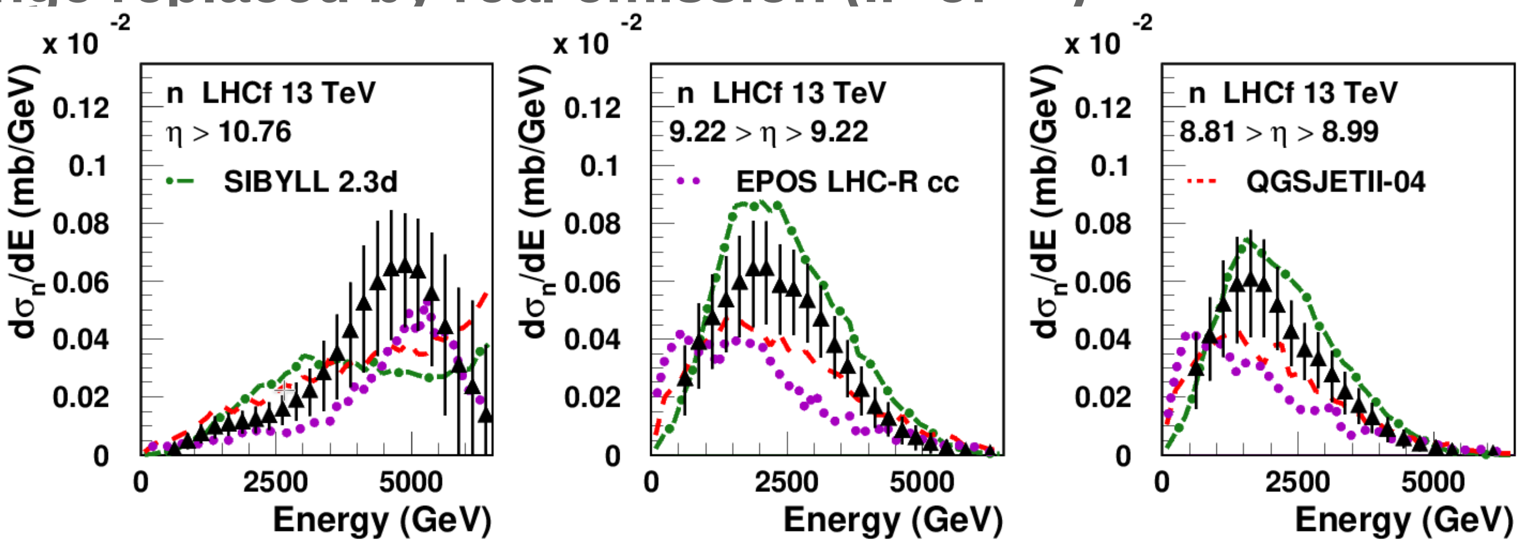


Improvements in EPOS LHC-R

- **Number of limitations identified in EPOS LHC**
- **Problem with nuclear fragments**
  - ➡ Double counting for single nucleons
  - ➡ Missing multifragment production
    - Now similar to other models
    - Significant impact on X_{max} fluctuations for nuclei

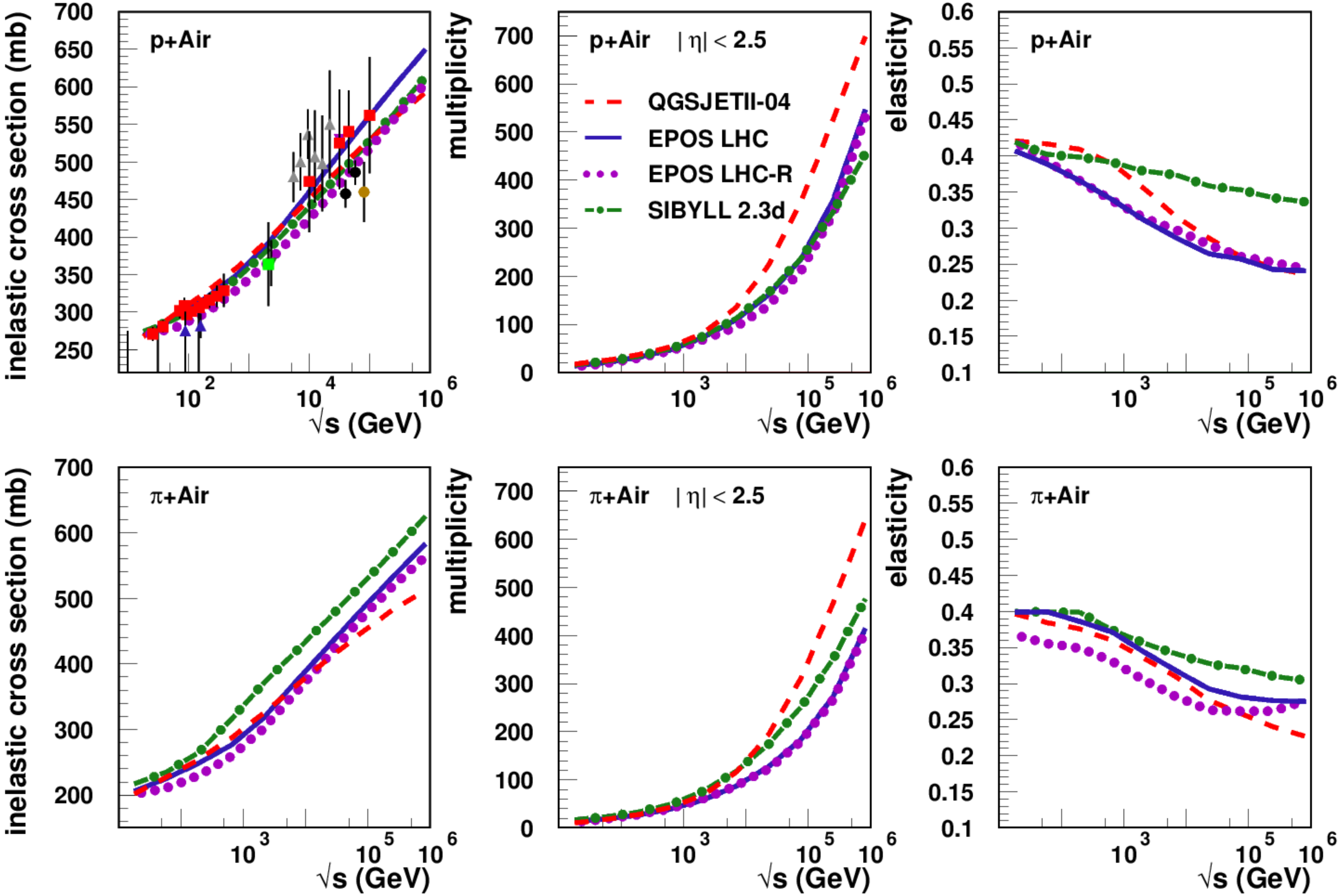


- **Simplified high mass diffraction and pion exchange replaced by real emission (IP or π)**



EPOS LHC-R interaction with Air

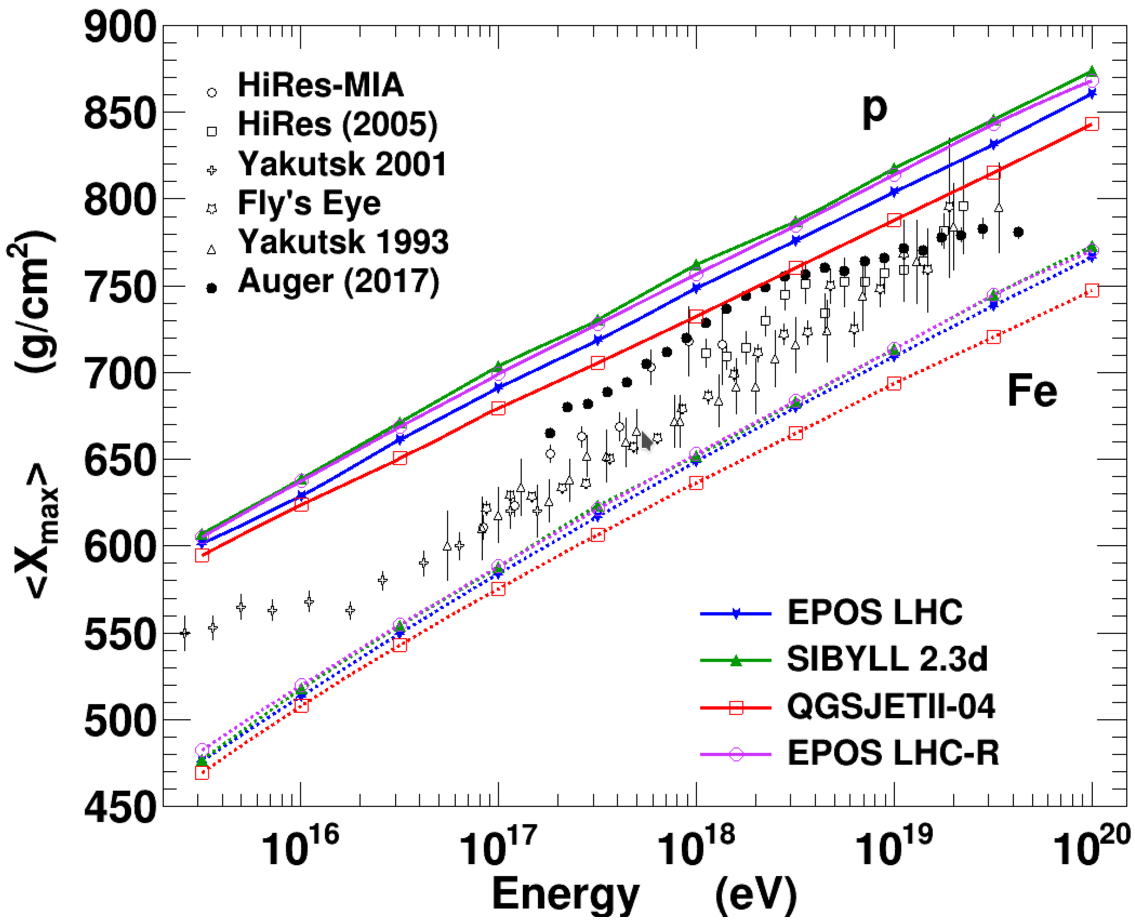
(preliminary)



X_{max}

+/- 20g/cm² is a realistic uncertainty band where is the center ?

- minimum given by QGSJETII-04 ((too) high multiplicity, low elasticity) ?
- maximum given by Sibyll 2.3d (low multiplicity, high elasticity) ?
- Taking into account new data, now EPOS shifted by +10g/cm² (~Sibyll)

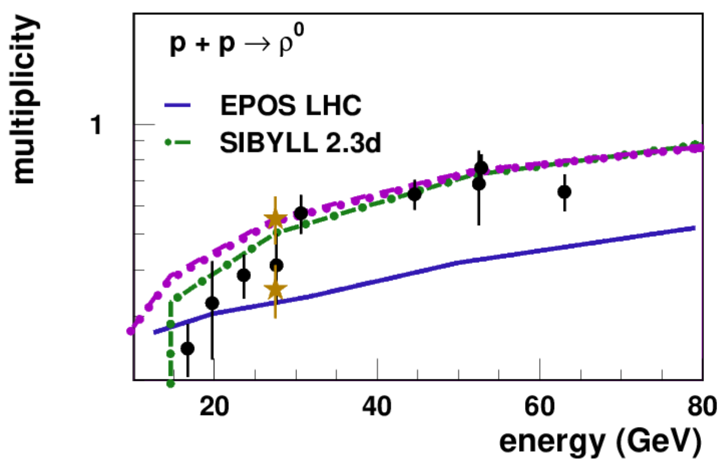


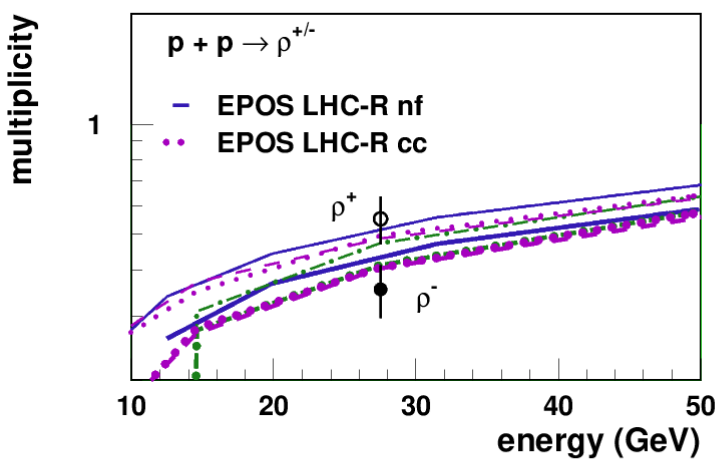
Higher <lnA> !

Correction of nuclear fragmentation in EPOS :
X_{max} RMS Fe
LHC=20g/cm2
LHC-R=24g/cm2
SIB=25g/cm2
QII=25g/cm2

Isospin Symmetry and Resonances

- **Isospin symmetry used as an argument in models to justify 1:1:1 ratios in π or ρ mesons** (or equal neutron/proton production)
  - ➜ But true only if u and d quarks have the same mass !
- **Pions can be produced directly or via ρ resonance decay**
  - ➜ Ratio $\pi^0/\pi^{+/-}$ very important for muon production
    - ➜ More π^0 means <u>less</u> μ production
  - ➜ But ρ^0 decay in $\pi^{+/-}$
    - ➜ More ρ^0 means <u>more</u> μ production
- **Mass asymmetry could lead to more ρ^0 than $\rho^{+/-}$**
    - ➜ Data not very constraining → use 20% asymmetry (high)



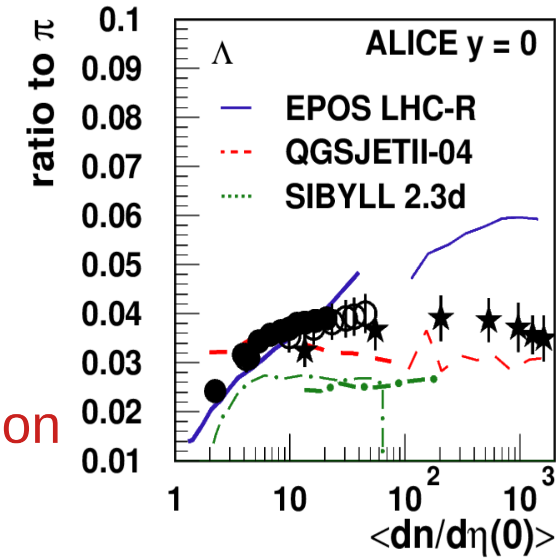


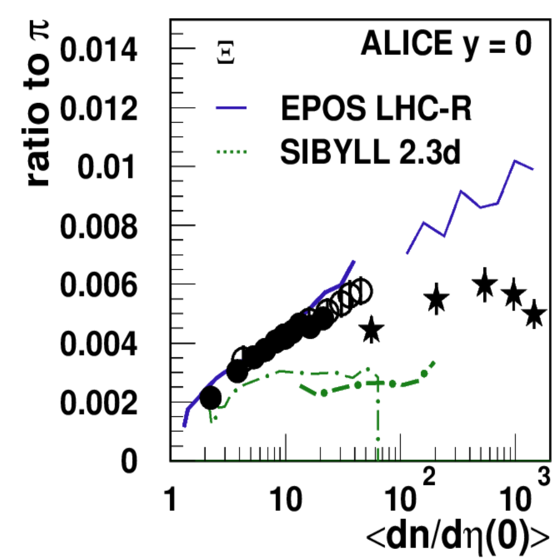
See TP ICRC 2023 contribution

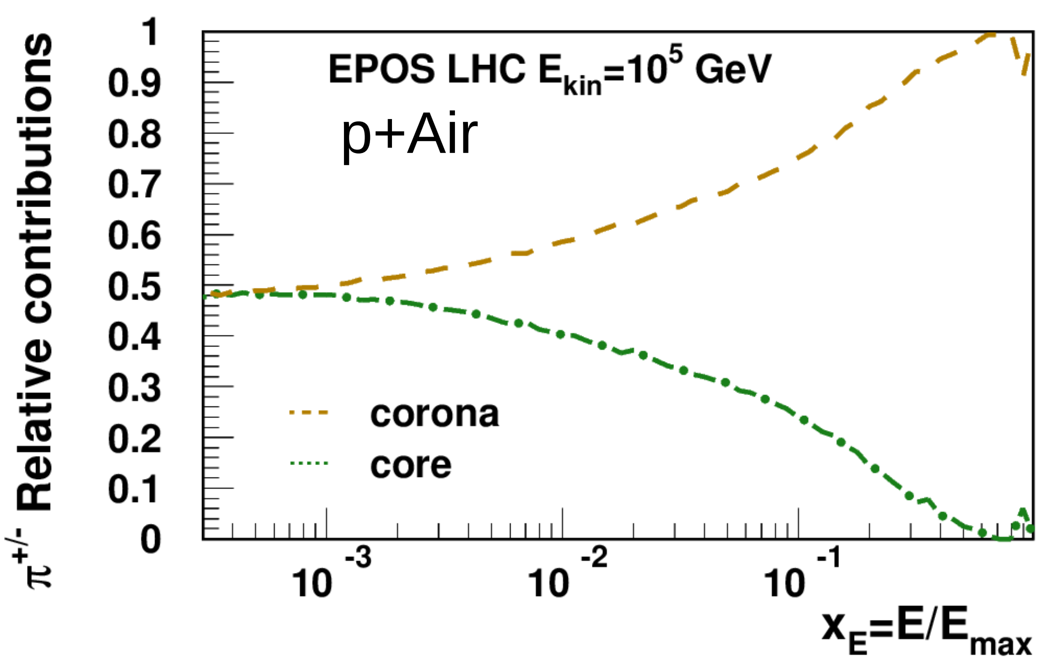
Interactions in Air Showers

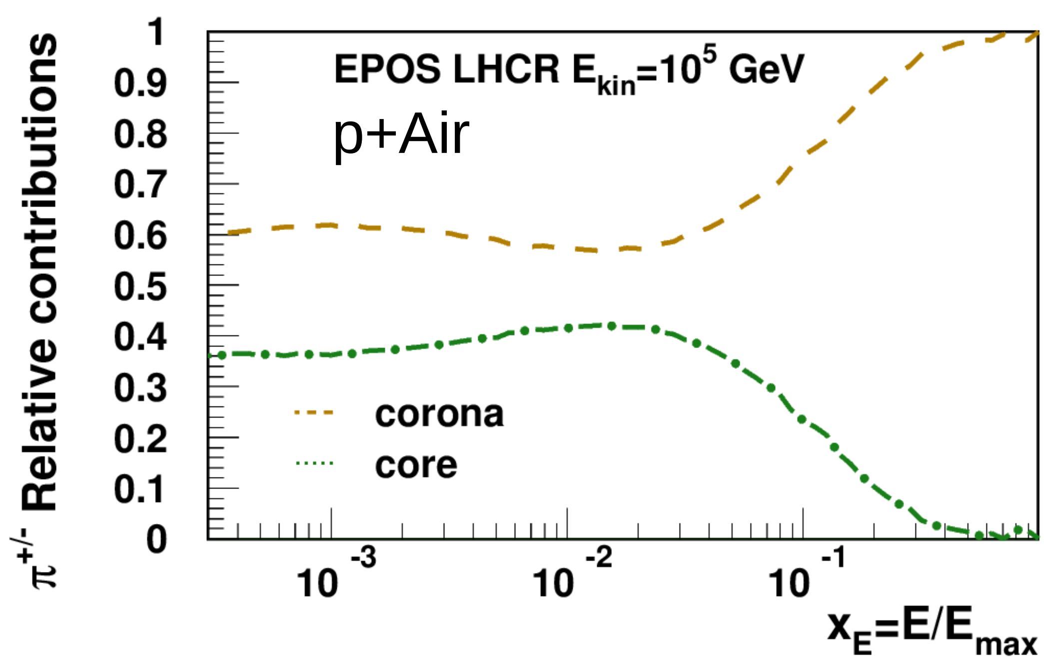
Update of EPOS to reproduce ALICE data

- Lower condition (particle density) to form core
- More core forward
- What's the impact on muon production in air showers (lower π^0 fraction) ?





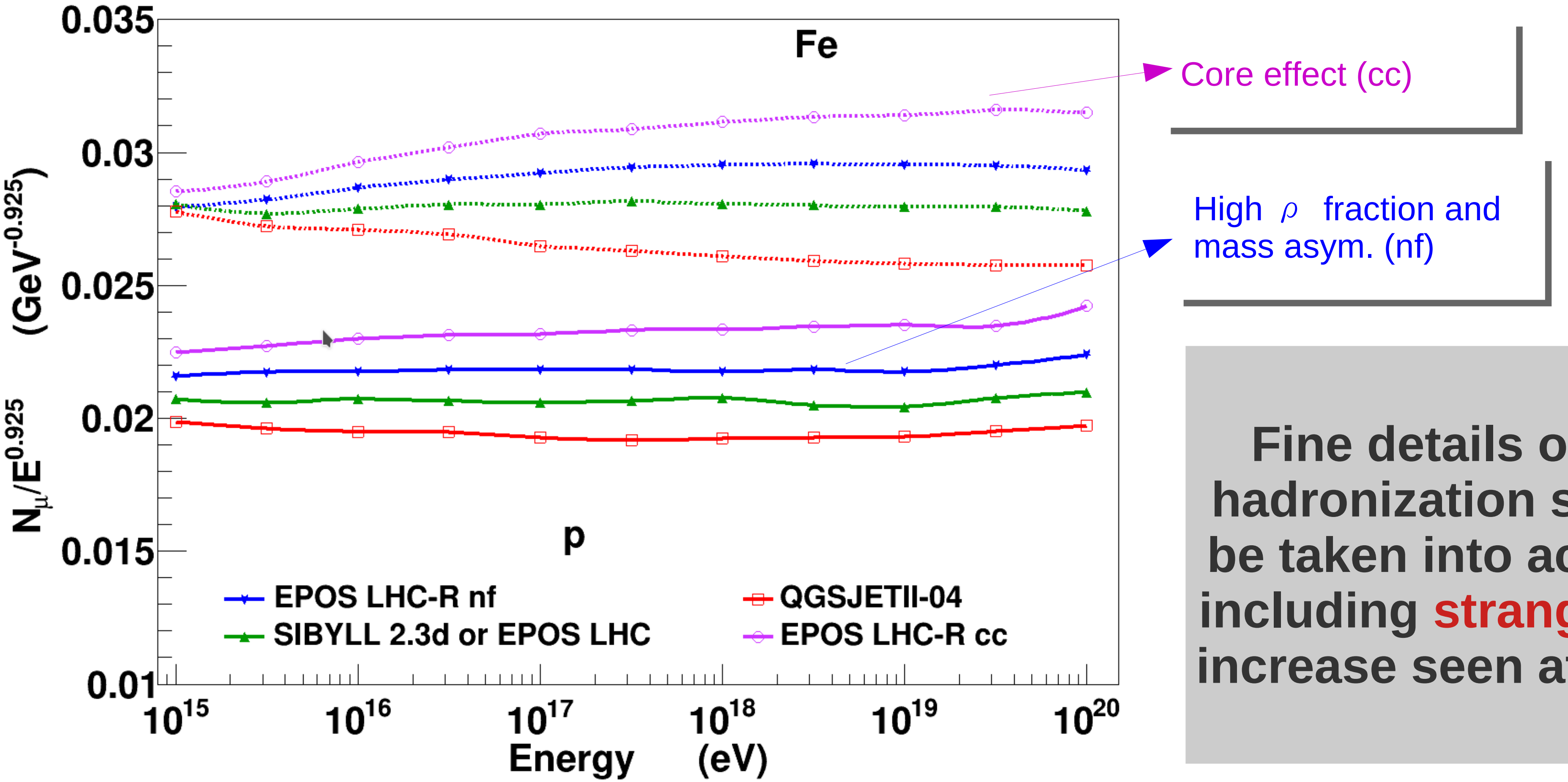




N_μ

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

- Simulations without core-corona but ρ asymmetry already have more muons
- Additional energy and mass dependent effect due to core-corona !
- First effect could be “tuned”, less freedom for core-corona (from LHC)

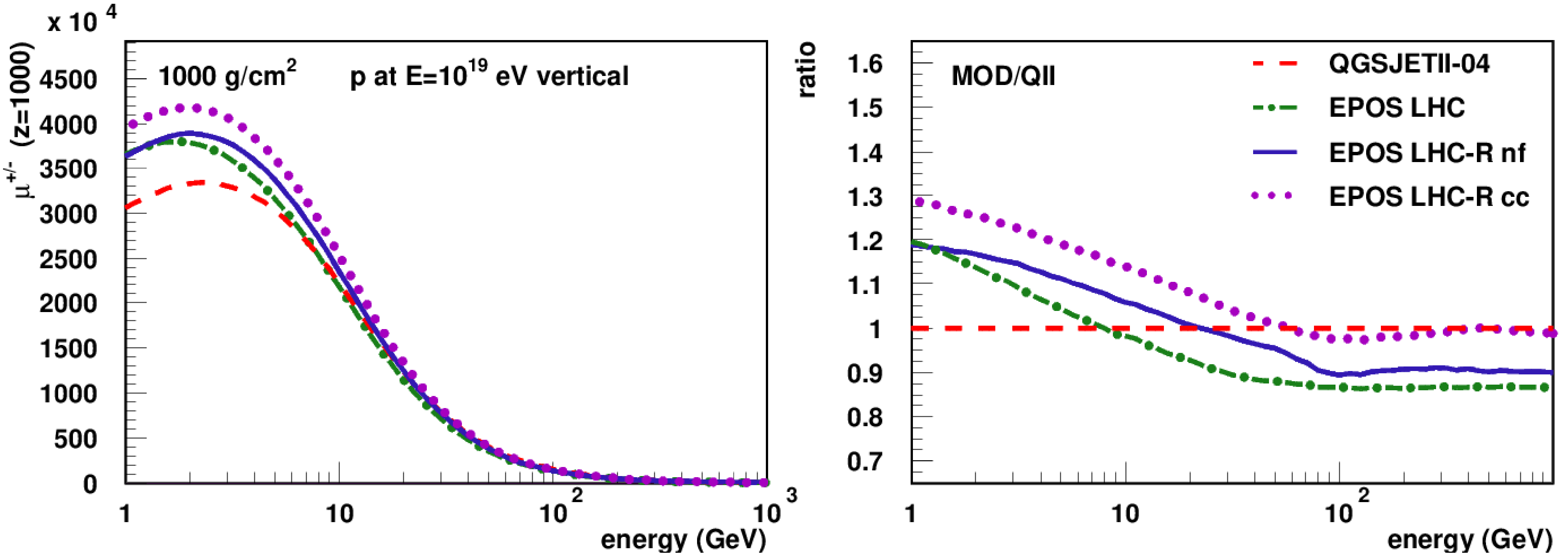


Fine details of the hadronization should be taken into account including strangeness increase seen at LHC !

E_μ

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

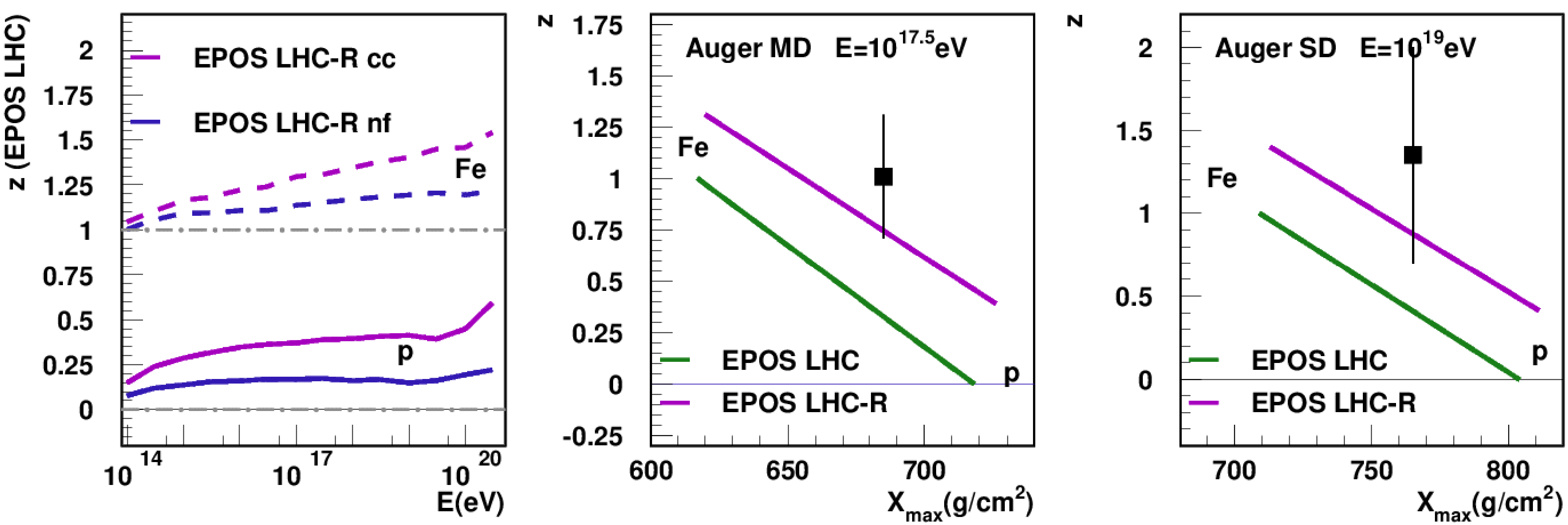
- Simulations without core-corona but ρ asymmetry already have more muons
  - Increase ~10 GeV muons
- Additional energy and mass dependent effect due to core-corona !
  - Parallel shift changing all muon energies
- First effect could be “tuned”, less freedom for core-corona (from LHC)



Muon Puzzle Solved ?

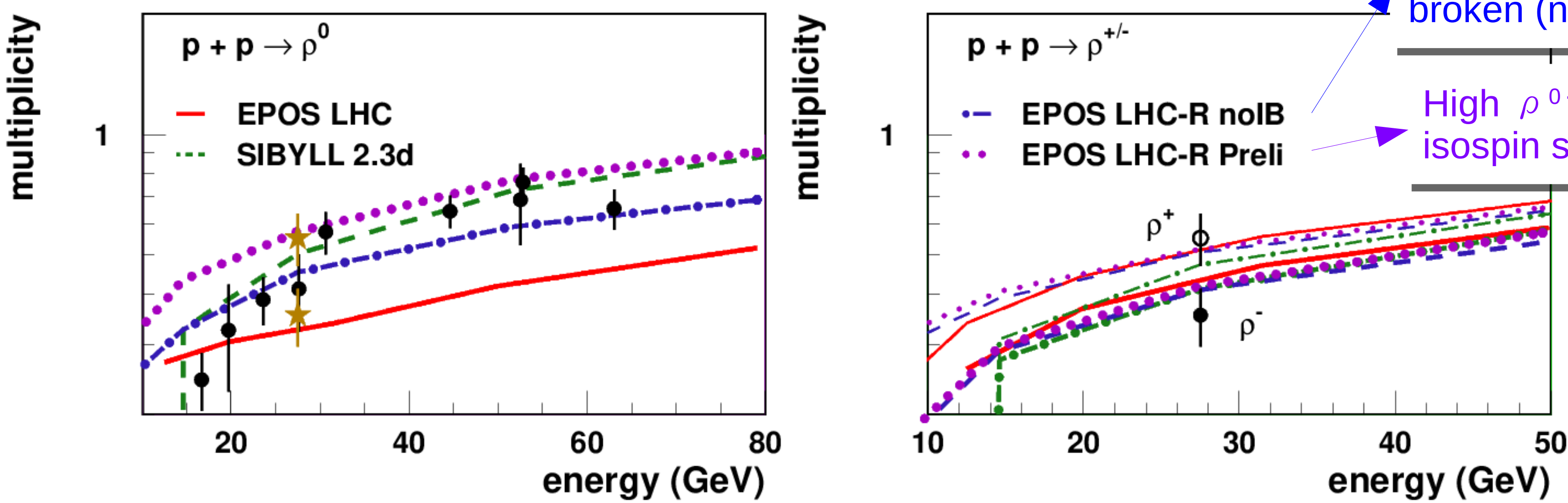
EPOS LHC-R, first model producing a deeper X_{max} and more muons and being compatible with measured accelerator data (better at LHC) :

- Deeper X_{max} give larger <lnA> reducing the gap with measured muon content
- Energy and mass dependent increase of muons due to core-corona further decrease the gap to reach Auger systematics
- What about low energy ? Less ρ^0 may be better not to have “too many” muons

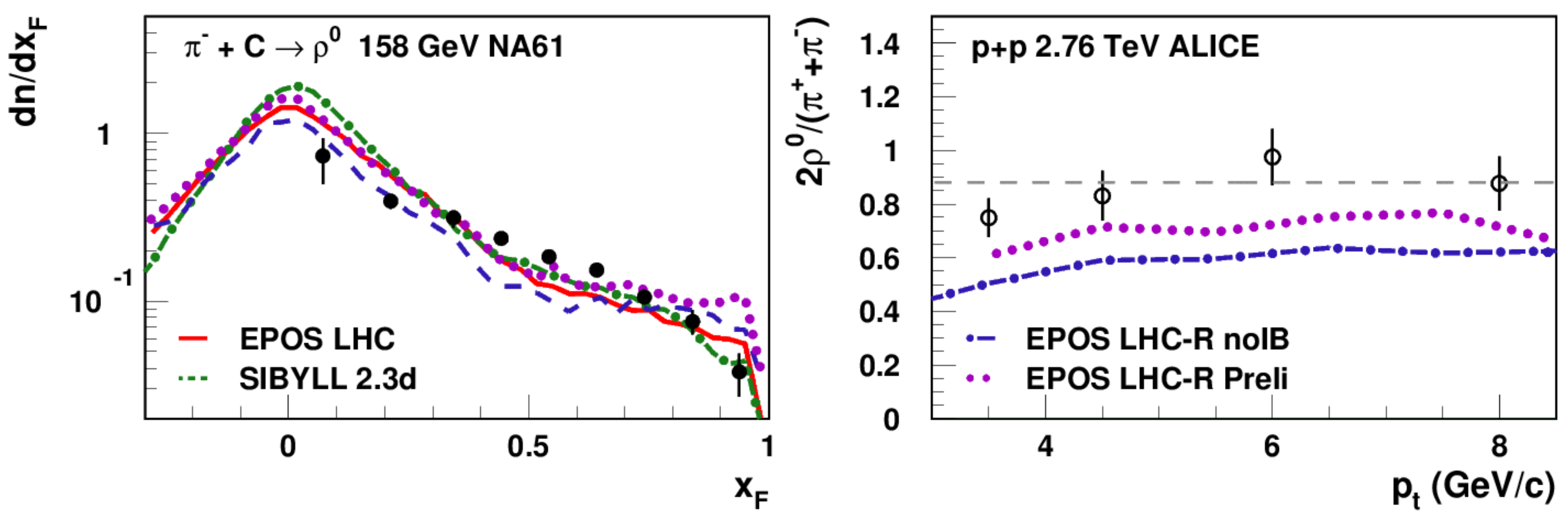


Resonance Production

- In proton-proton interactions, ratio 1:1:1 is not observed !

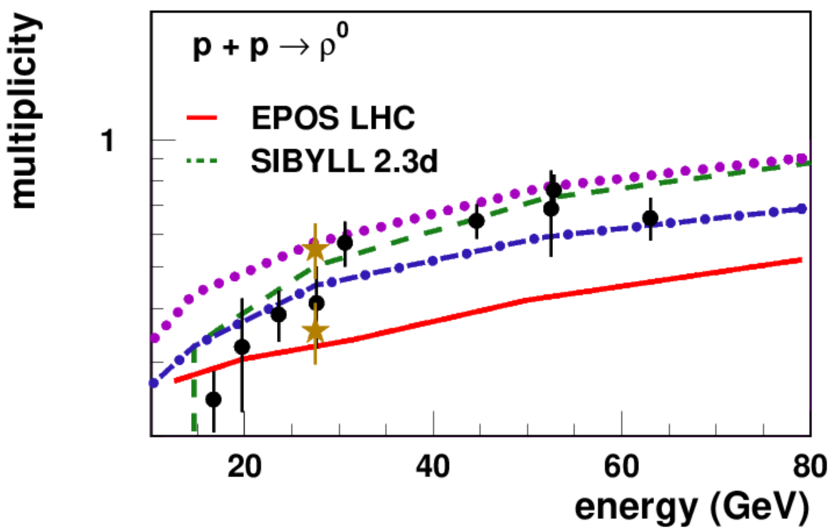


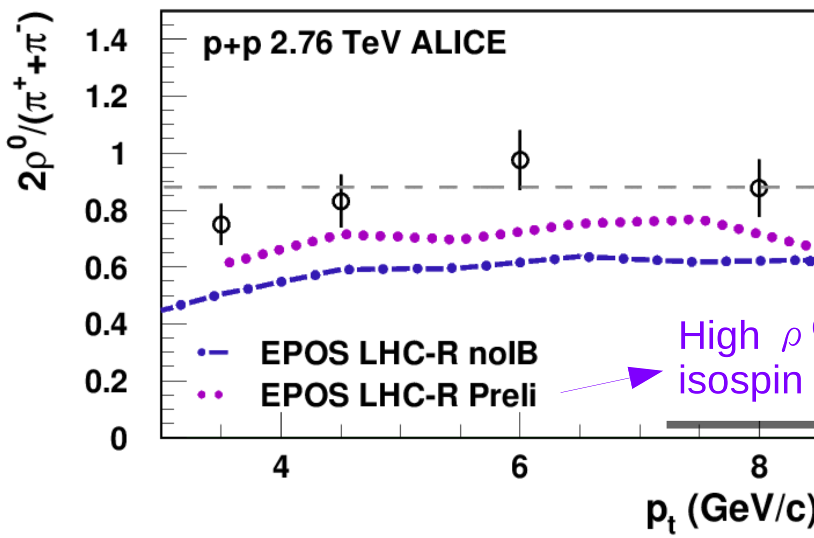
- AND high resonance fraction is favored !



Resonance Production

- In proton-proton interactions, ratio 1:1:1 is not observed and high ρ ...

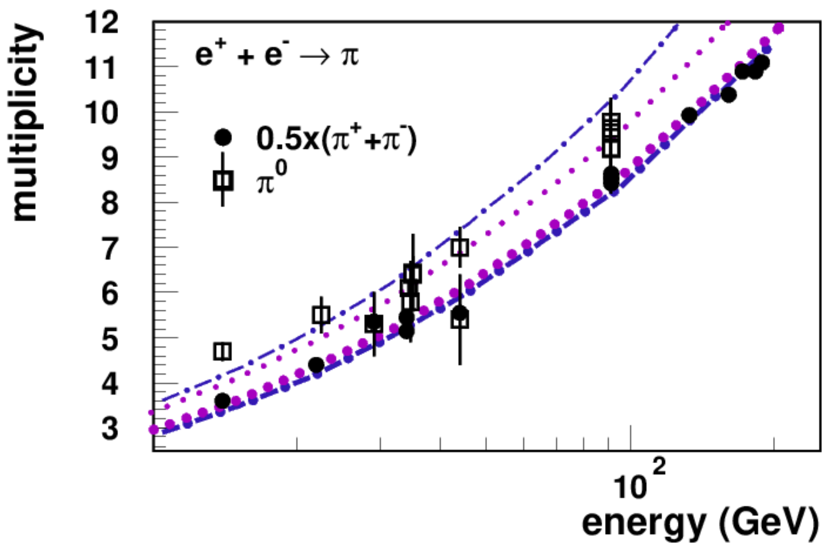


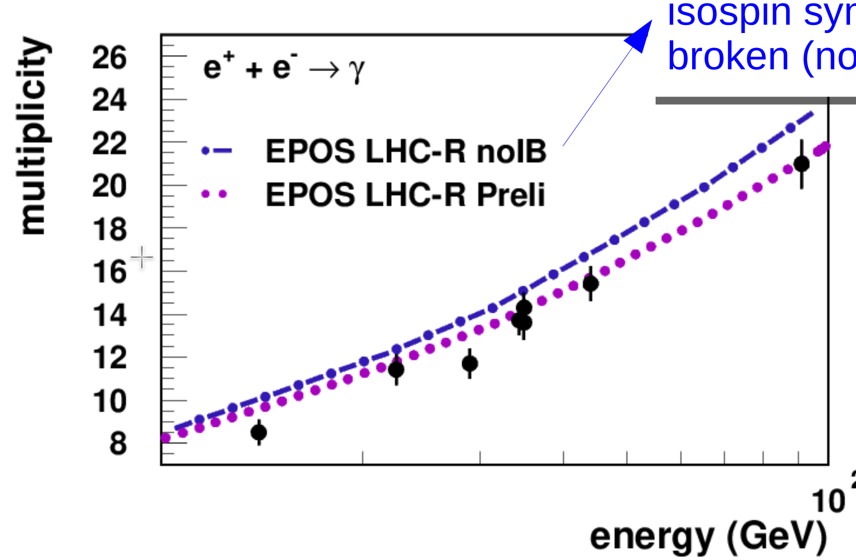


High ρ^0 fraction and isospin sym. broken

- Both favored in electron-positron data !

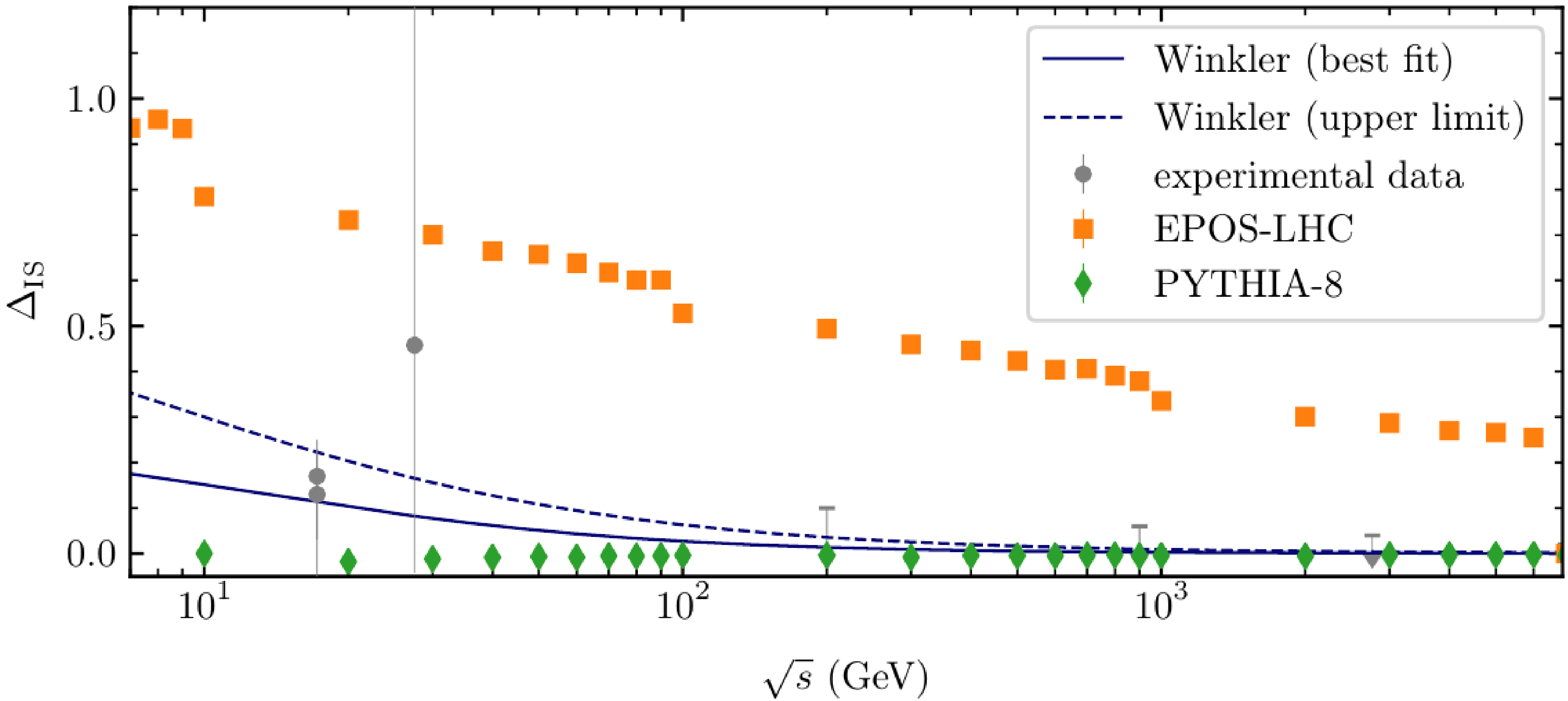
Low ρ fraction and isospin sym. NOT broken (noIB)





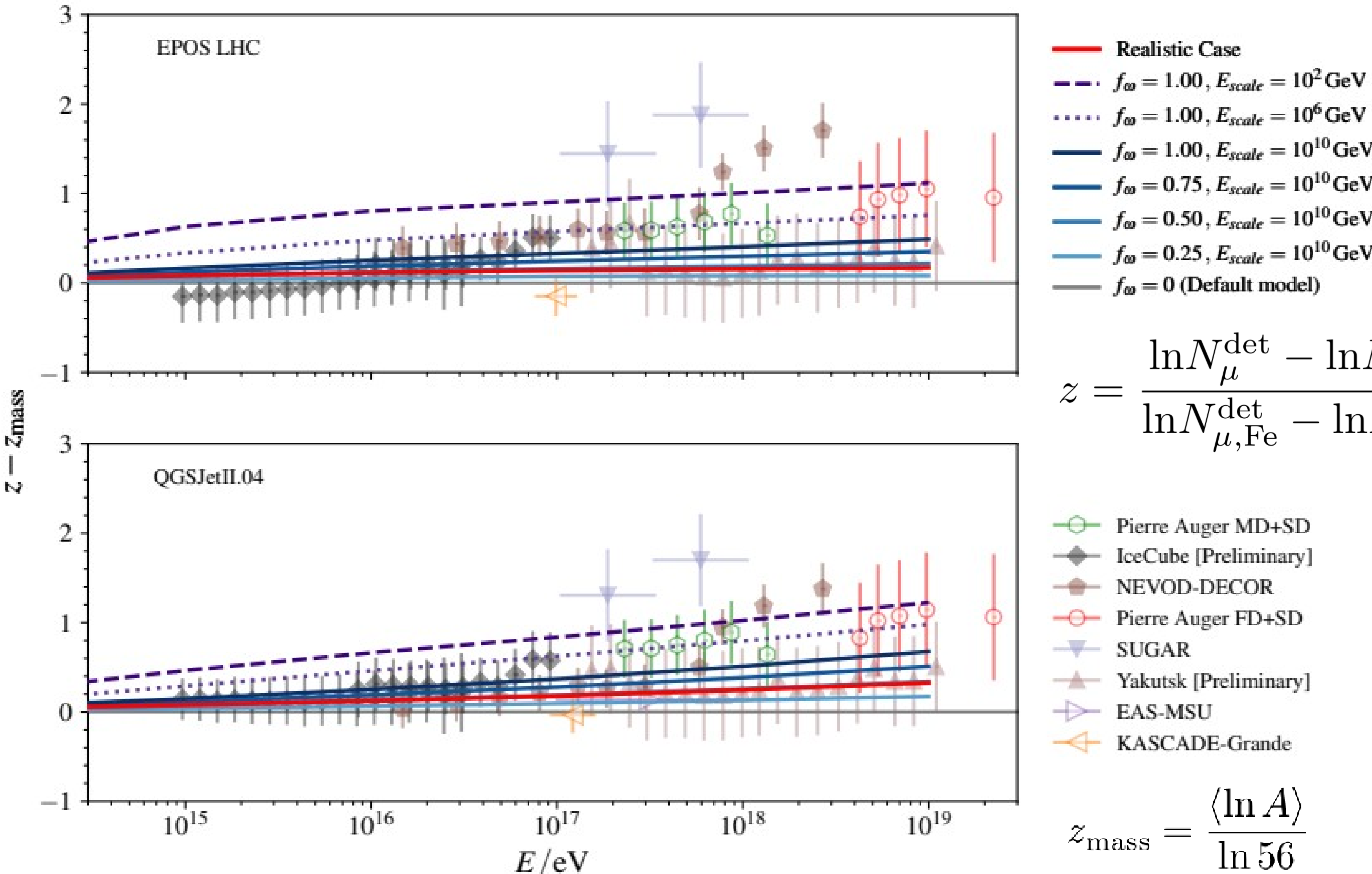
Isospin Breaking for Baryons

- NA49 data better reproduce with more neutrons than protons, but large uncertainties
- Large isospin breaking in EPOS LHC lead to additional baryons
  - But TOO large → EPOS LHC-R corrected (5% assymmetry) !



Thomas Pöschl – PhD Thesis

Results for z-scale



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

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

Plot by M. Perlin