Experimental Constraints to High Energy Hadronic Interaction Models using the Pierre Auger Observatory Part III

Tanguy Pierog

Karlsruhe Institute of Technology, Institut für Kernphysik, Karlsruhe, Germany

QCD at Cosmic Energies VII, Chalkida, Greece

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Outline

- **Monte-carlo for Cosmic Ray analysis**
  - ➡ Sibyll 2.3
- **Muon Production Depth and hadronic interactions**
  - ➡ baryons
- **Nuclear Interactions**
  - ➡ model differences

Hadronic Interaction Models in CORSIKA

(HDPM)

Old generation : SIBYLL 2.1 (QGSJET01 DPMJET 2.55 VENUS) (<2001)

All Glauber based

But differences in hard, remnants, diffraction …

Engel et al.

semi-hard

soft

NEXUS 3.97

Attempt to get everything described in a consistent way (energy sharing)

New generation : (QGSJET II-03)(DPMJET III) (EPOS 1.99) (2005-2012)

LHC tuned : QGSJET II-04 EPOS LHC (2013-)

Ostapchenko

Pierog & Werner

Riehn & Engel

LHC inspired : SIBYLL 2.3 QGSJET III (?) EPOS 3 (2016-)

Motivation :

- **update with latest LHC results in simple model**

Motivation :

- **Hard Pomeron-Pomeron connexion**

Motivation :

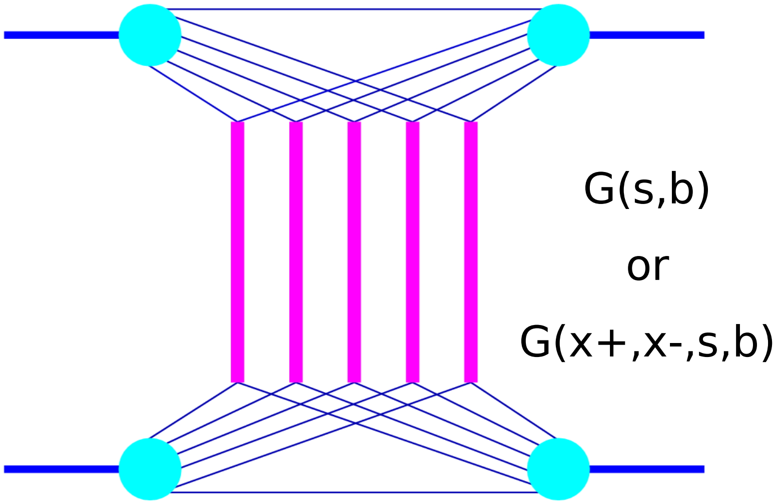
- **binary scaling in hard probes**

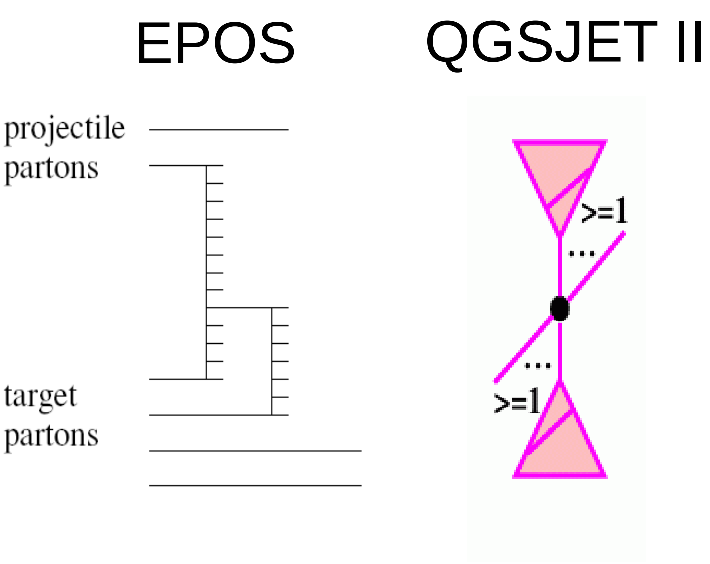
Cosmic Ray Hadronic Interaction Models

- **Theoretical basis :**
  - pQCD (large p_t)
  - Gribov-Regge (cross section with multiple scattering)
  - energy conservation
- **Phenomenology (models) :**
  - hadronization
    - string fragmentation
    - EPOS : high density effects (statistical hadronization and flow)
  - diffraction (Good-Walker, ...)
  - higher order effects (multi-Pomeron interactions)
  - remnants
- **Comparison with data to fix parameters**

Better predictive power than HEP models thanks to link between total cross section and particle production (GRT) tested on a broad energy range (including EAS)

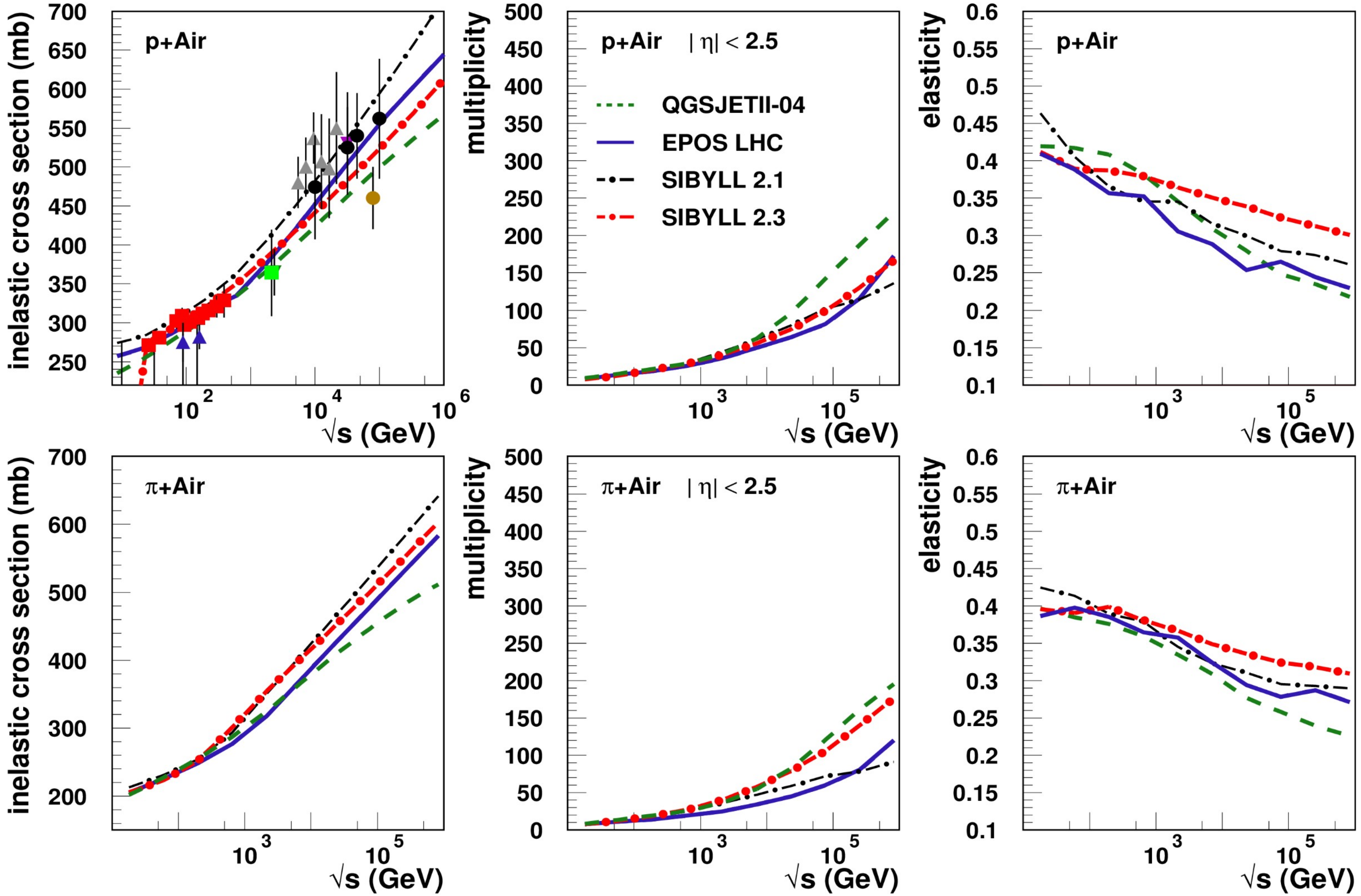
Cross Section and Multiplicity in Models



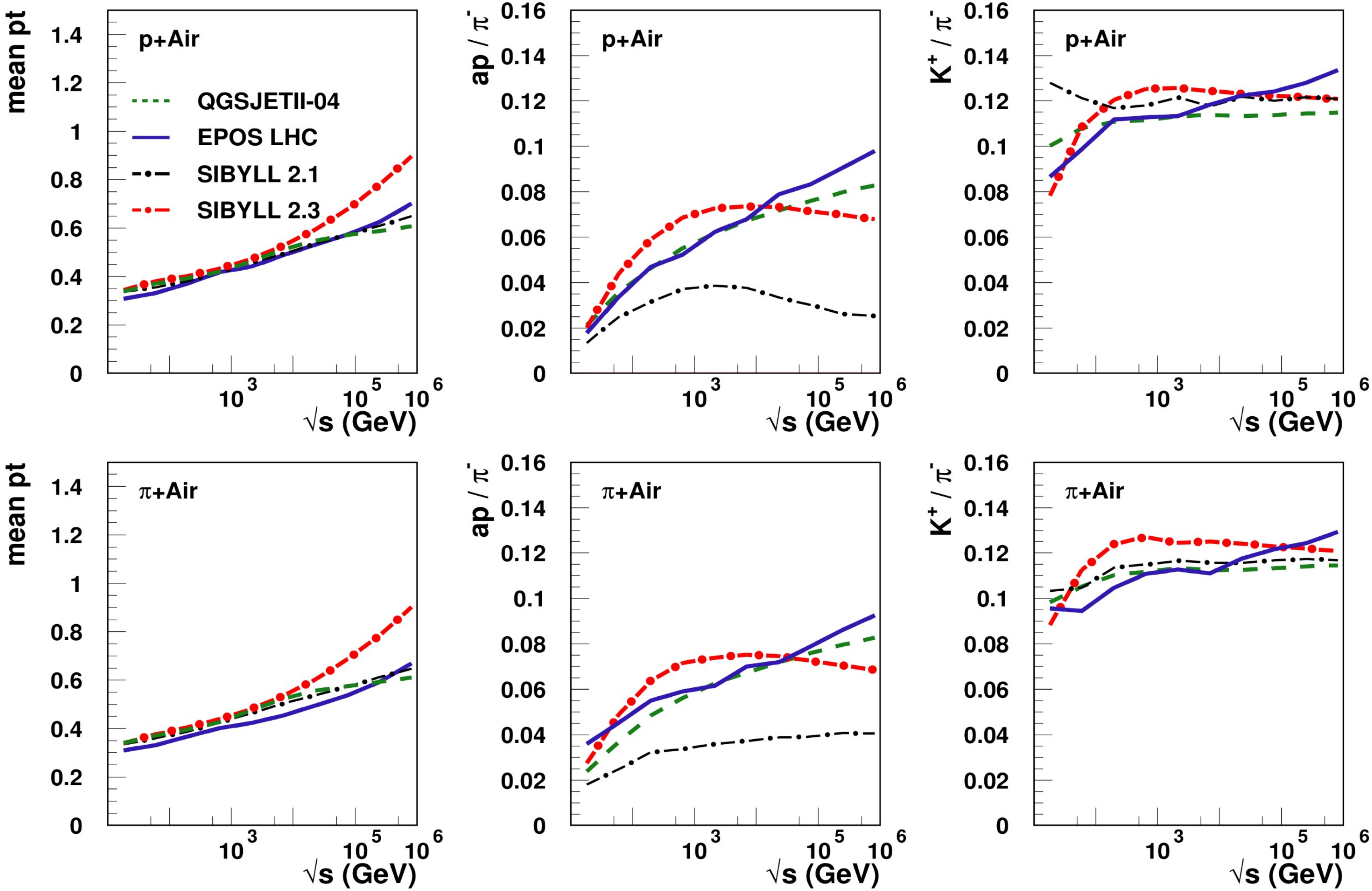


- **Gribov-Regge and optical theorem**
  - ➔ Basis of all models (multiple scattering) but
    - Classical approach for QGSJET and SIBYLL (no energy conservation for cross section calculation)
    - Parton based Gribov-Regge theory for EPOS (energy conservation at amplitude level)
- **pQCD**
  - ➔ Minijets with cutoff in SIBYLL
  - ➔ Same hard Pomeron (DGLAP convoluted with soft part : no cutoff) in QGSJET and EPOS but
    - Generalized enhanced diagram in QGSJET-II
    - Simplified non linear effect in EPOS
      - Phenomenological approach

Model Predictions (1)



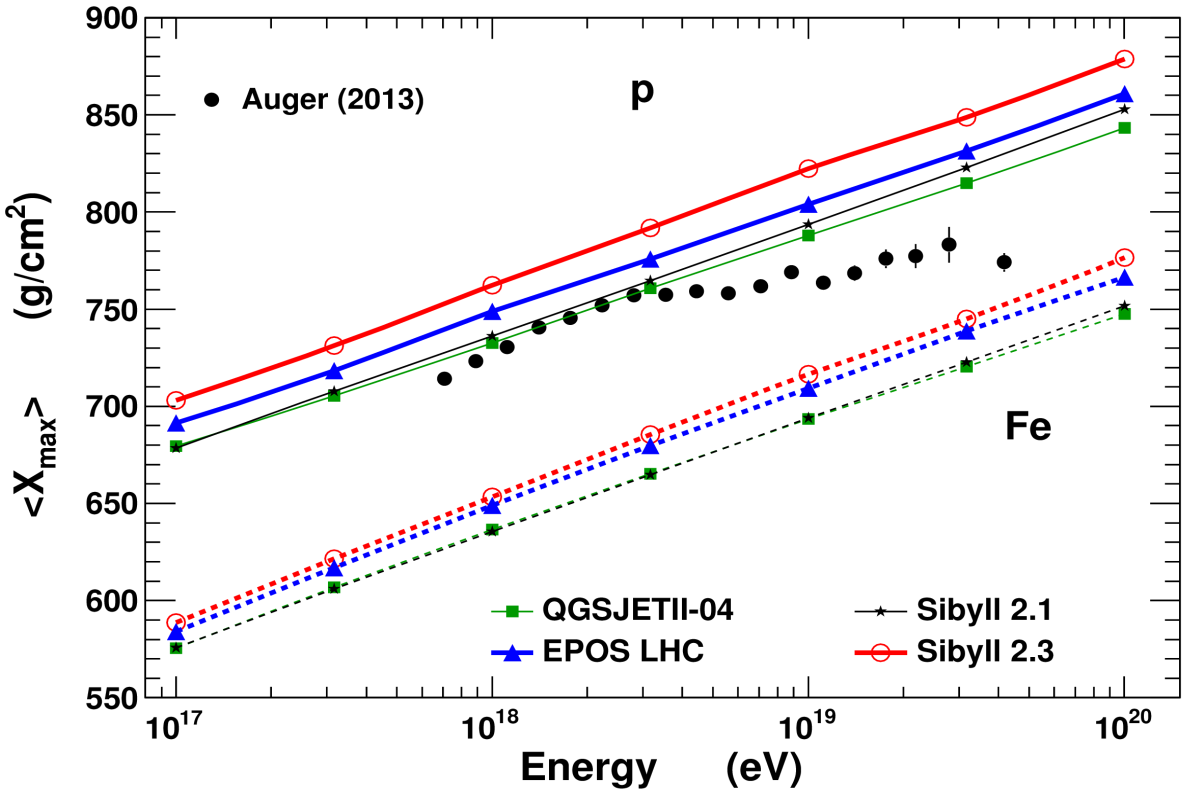
Model Predictions (2)

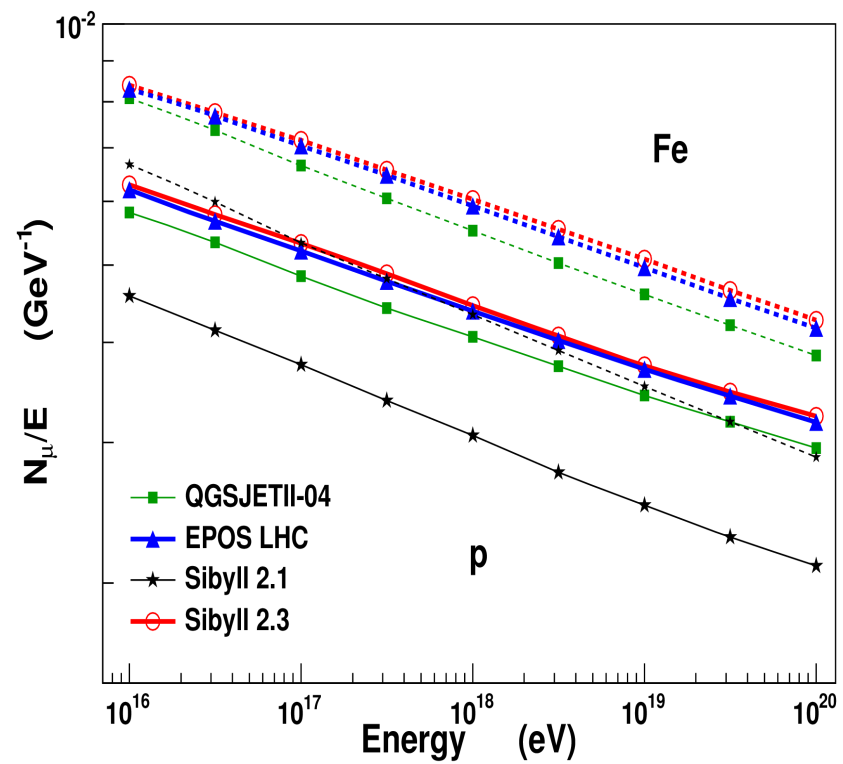


Air Shower Observables

Post-LHC models have very similar energy evolution for X_{max} and N_{mu} and small difference in absolute value but

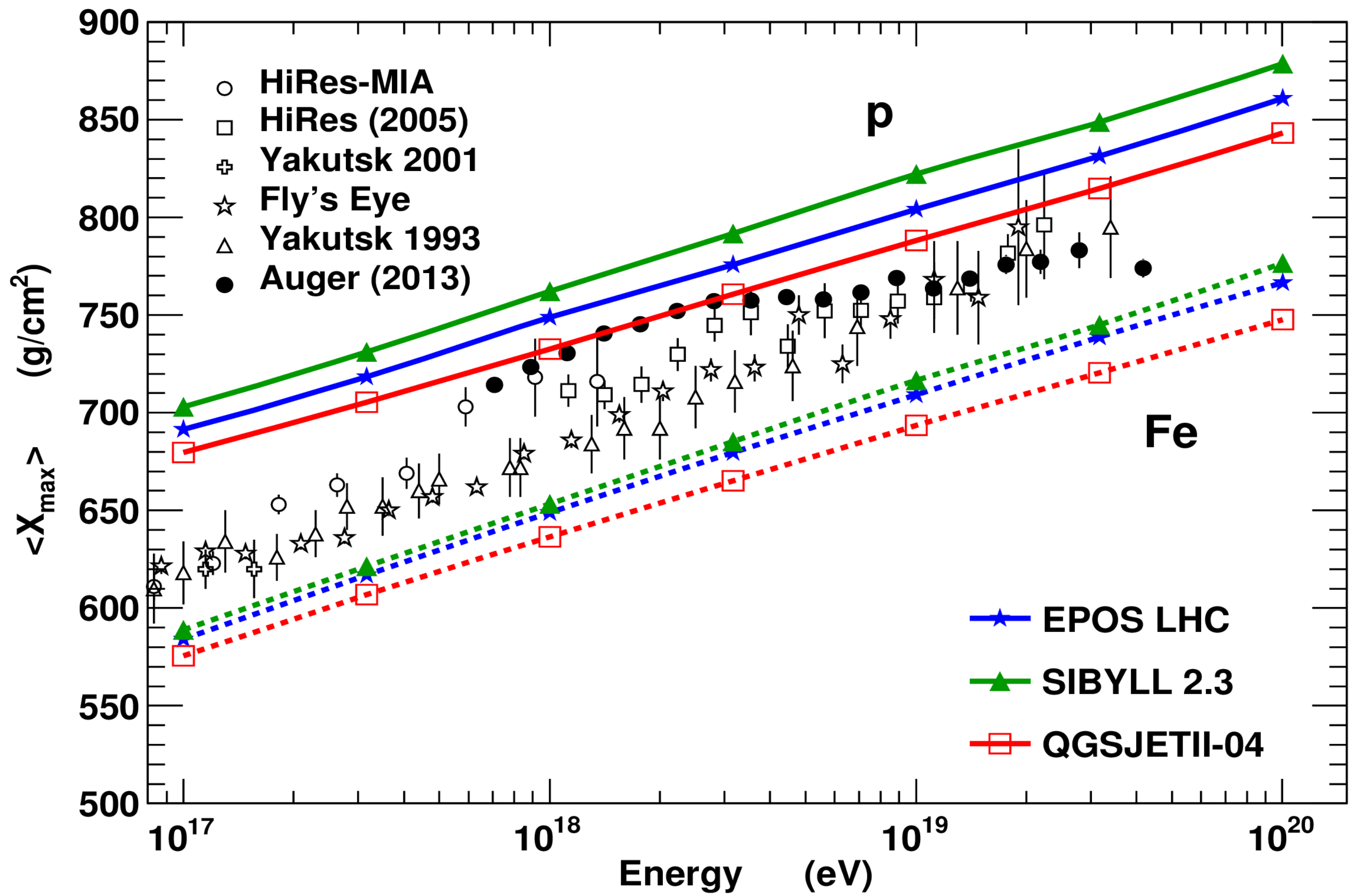
- Sibyll 2.3 have quite large X_{max} for proton
- different muon spectra between models





X_{max} Model Uncertainties

After LHC still about 20g/cm² (40g/cm²) difference between EPOS LHC (Sibyll 2.3) and QGSJETII-04 while only ~10g/cm² by changing p-Air within LHC uncertainties (see S. Ostapchenko, Phys. Rev. D 89, 074009 (2014))



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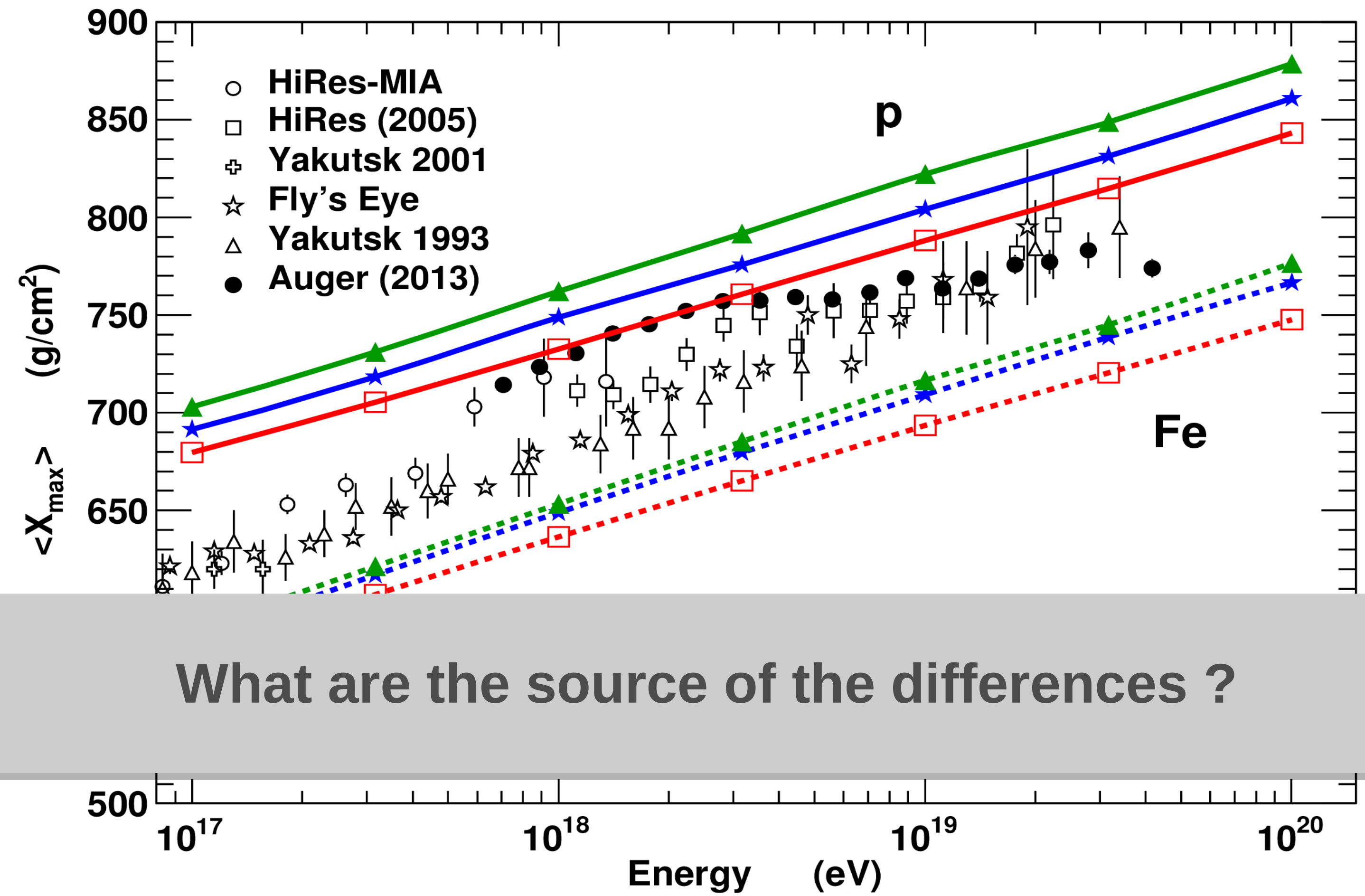
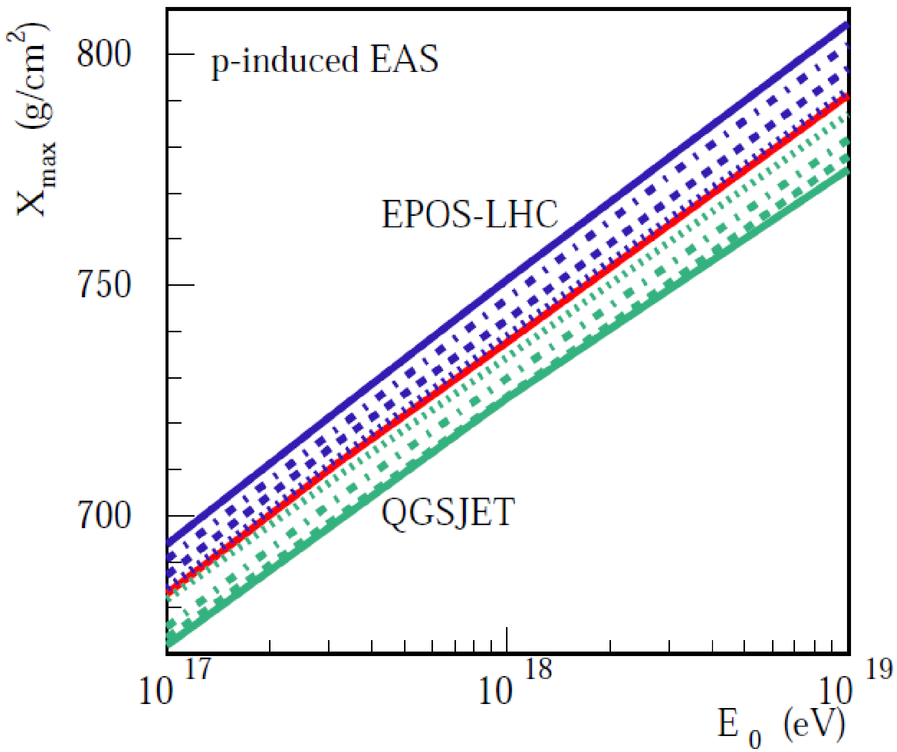
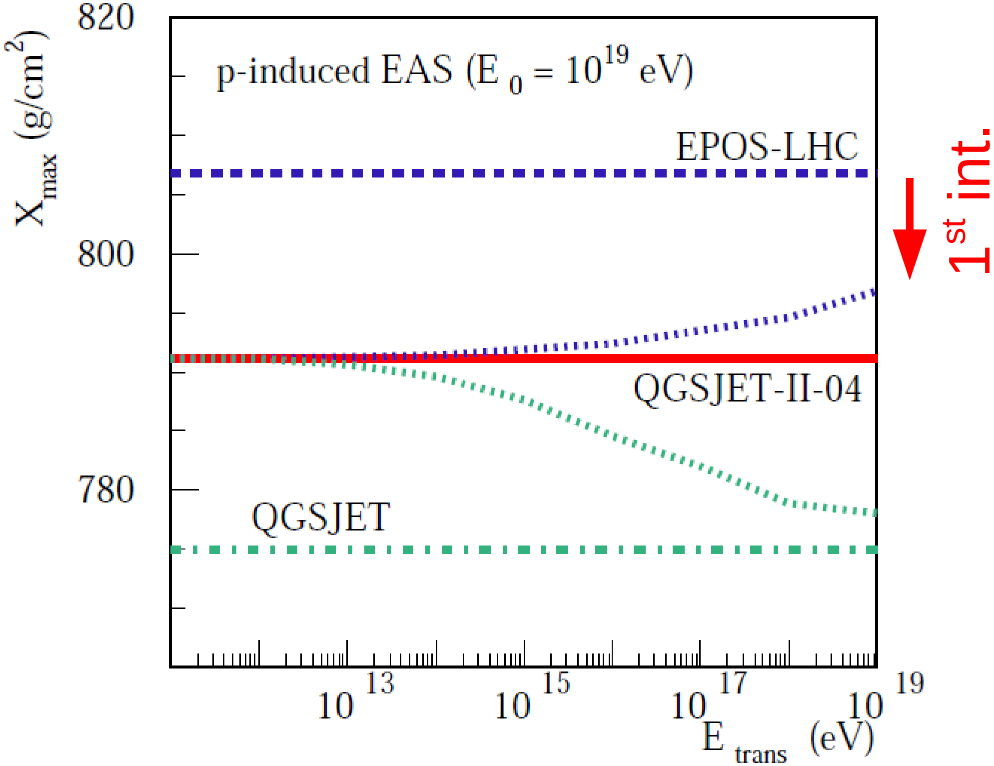


What are the source of the differences ?

Mix models to identify source of differences

- **Different mixing to extract useful information on X_{max}**
  - QII only for cross-section and nucleon spectra of 1st int. : dot-dashed
  - QII complete 1st int : dashed
  - QII complete 1st int and all nucleon prod. in the shower: dotted
  - For energy dependence, QII for $E>E_{trans}$, other model below

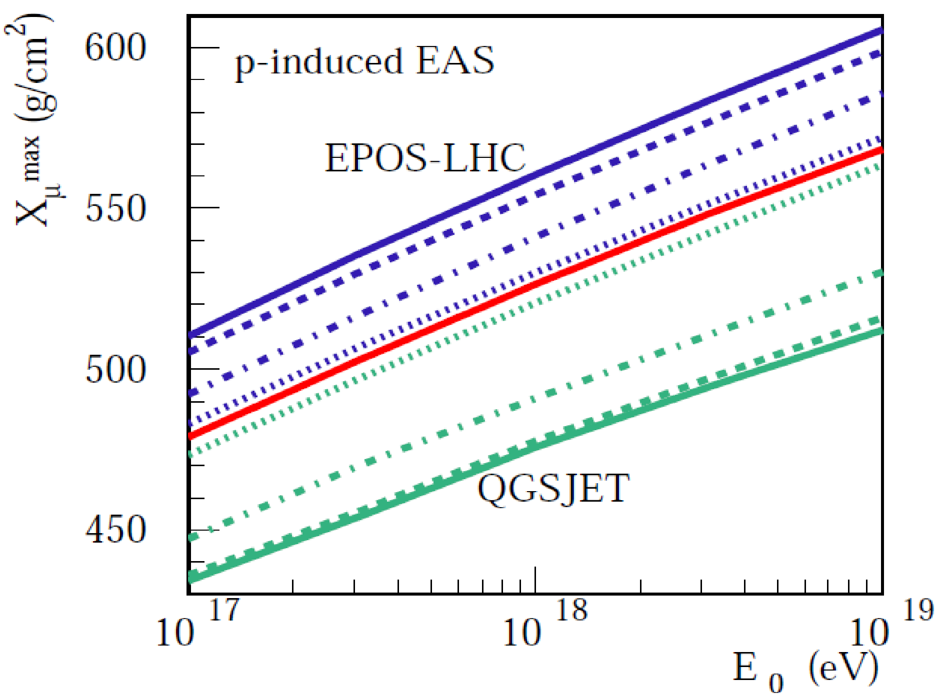


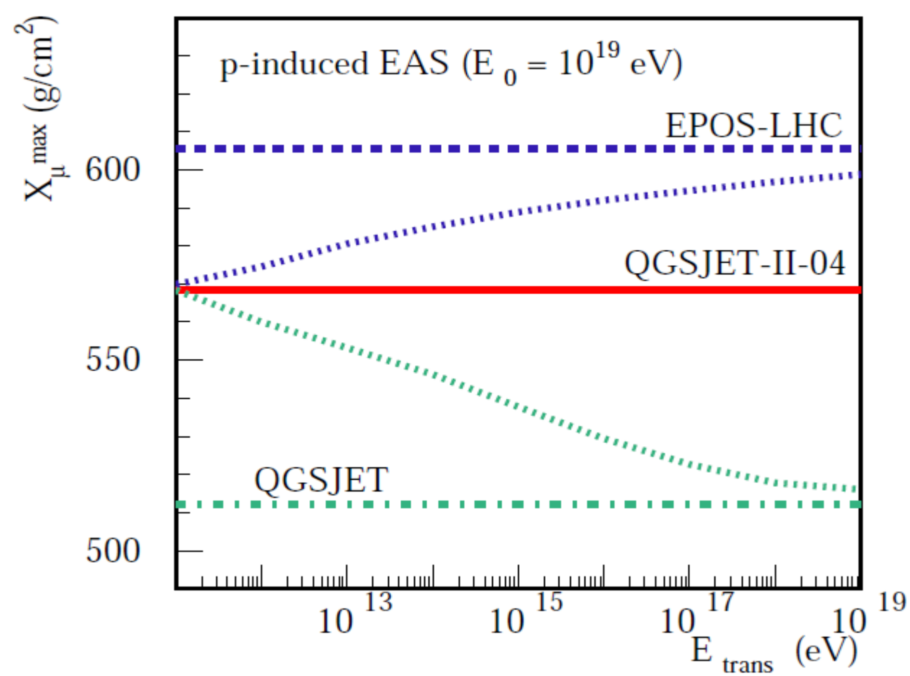


From arXiv:1601.06567 by S. Ostapchenko and M. Bleicher

Mix models to identify source of differences

- **Different mixing to extract useful information on X^{μ}_{max}**
  - QII complete 1st int. : dashed
  - QII complete 1st int. and all nucleon prod. in the shower: dot-dashed
  - QII complete 1st int. and hadron spectra in pion and kaon int.: dotted
  - For energy dependence, QII for E>E_{trans}, other model below





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Summary of arXiv:1601.06567

Modifications	X_{max}	X^{μ}_{max}
cross-section and nucleon spectra of 1st interaction	5 g/cm²	
rest of 1st interaction	5 g/cm²	5 g/cm²
nucleon spectra in all int.	5 g/cm²	15 g/cm²
all pion and kaon interactions		15 g/cm²
Model difference fractions		
1st interaction	70%	10%
pion interactions	30%	90%

Conclusions on Hadronic Interactions

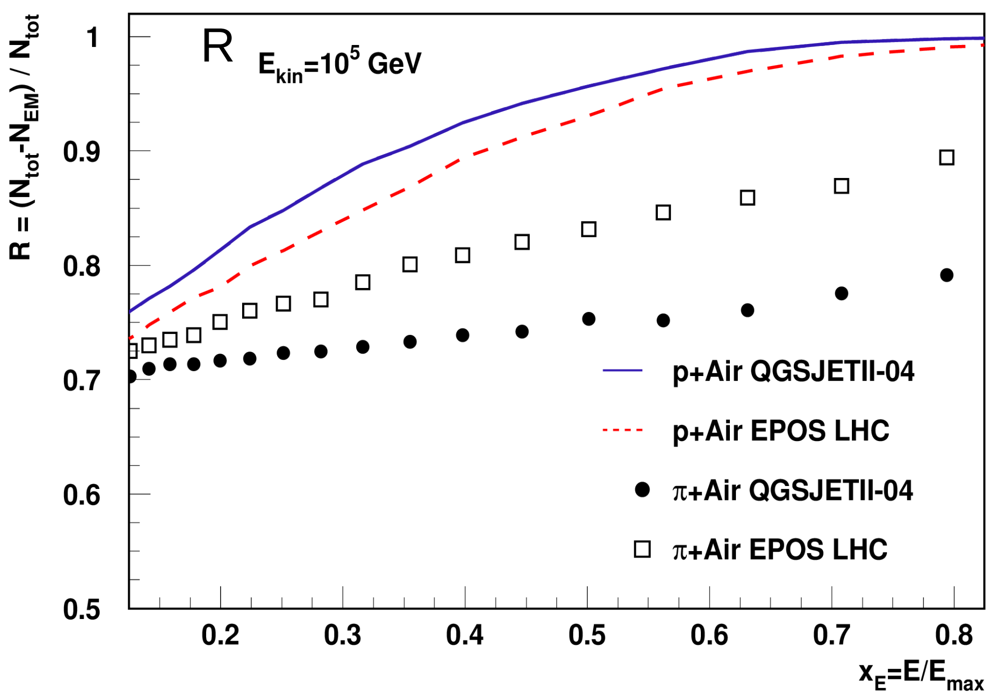
- **Differences in first interaction dominates X_{max} uncertainties**
  - ➡ from where ? results at LHC are very similar ...
- **Remaining uncertainties in X_{max} due to different results for pion-air interactions at high energy**
  - ➡ Problem : no data for pion interactions at high energy
- **X^{μ}_{max} very sensitive to pion interactions at all energies (incl. high energies) so MPD can be use to probe pion interactions and limit uncertainties on X_{max}**
  - ➡ Role of baryons
  - ➡ pion spectra ?
- **Test using EPOS LHC and Sibyll 2.3**

Muon Number

- From Heitler

$$N_\mu = \left(\frac{E_0}{E_{dec}}\right)^\alpha, \quad \alpha = \frac{\ln N_{had}}{\ln(N_{had}+N_{em})}$$

➡ In real shower, not only pions : Kaons, (anti)Baryons and resonances



$$\alpha = \frac{\ln(N_{had})}{\ln(N_{tot})} = 1 + \frac{\ln(R)}{\ln(N_{tot})}$$

$$R = \frac{N_{had}}{N_{tot}} \approx \frac{N_{\pi^{ch}} + N_B}{N_{\pi^{ch}} + N_B + N_{\pi^0}} < 1$$

Very important :
in (a)Baryon-Air interactions, no leading neutral pion !
R~1

R depends on the number of (anti)B and ρ^0 in p- or π-Air interactions

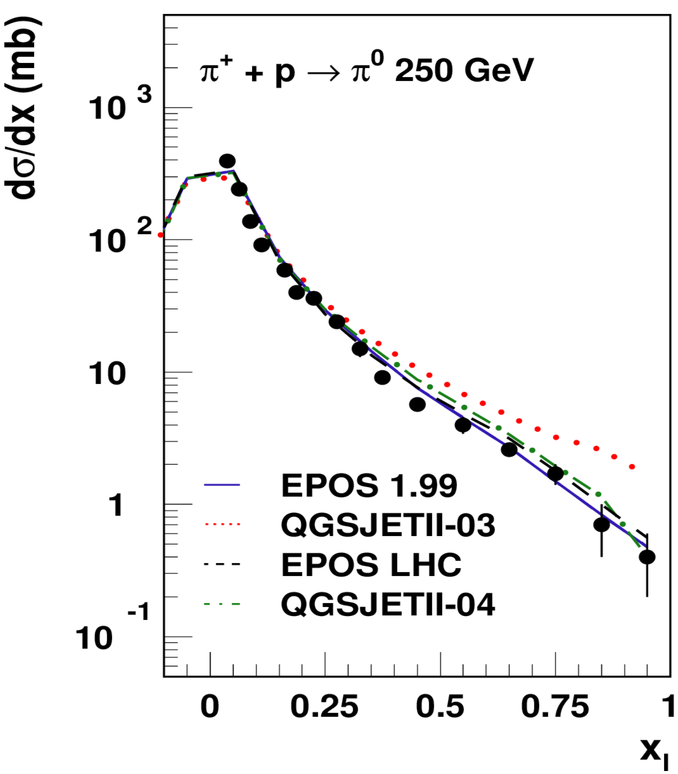
More fast (anti)baryons or ρ^0 or larger N_{tot} = $\alpha \rightarrow 1$ = more muons

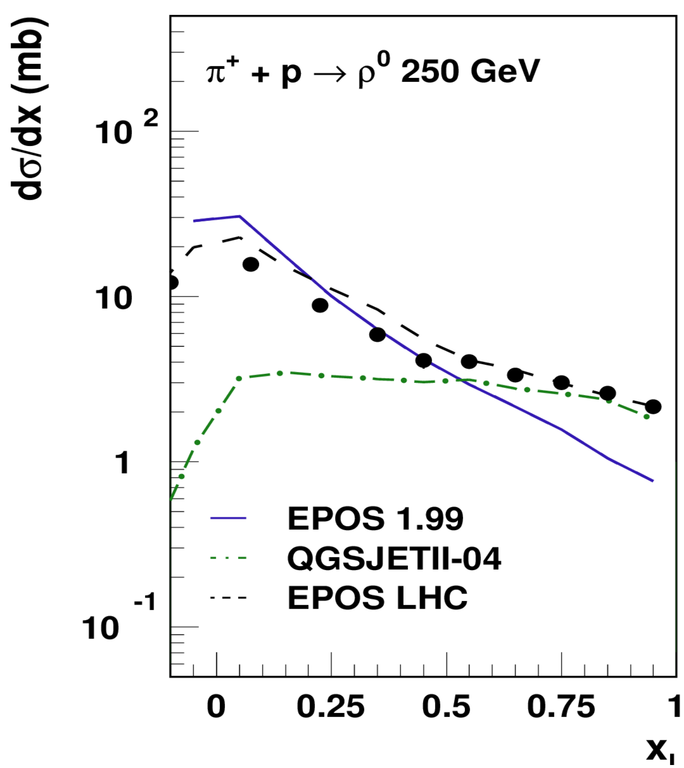
T. Pierog et al.,Phys.Rev.Lett. 101 (2008) 171101

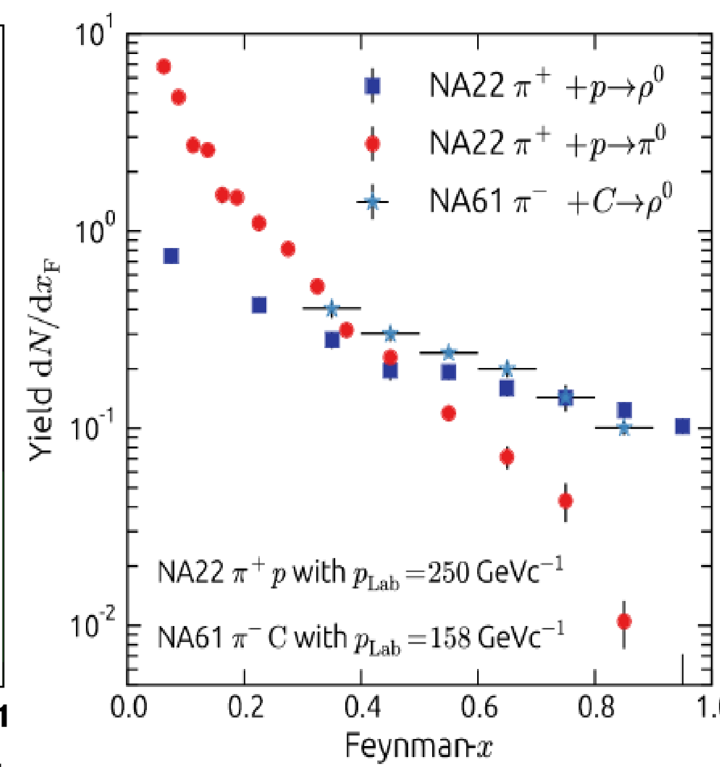
Pion Leading Particle Effect

Rho meson production added in QGSJETII (and Sibyll 2.3) to take into account leading particle effect in pion-Air interaction

- ➡ same effect as baryon production : forward π^0 replaced by charged pions (reduced leading π^0)
- ➡ increase muon production
- ➡ higher minimum muon energy (less generations) compared to baryons





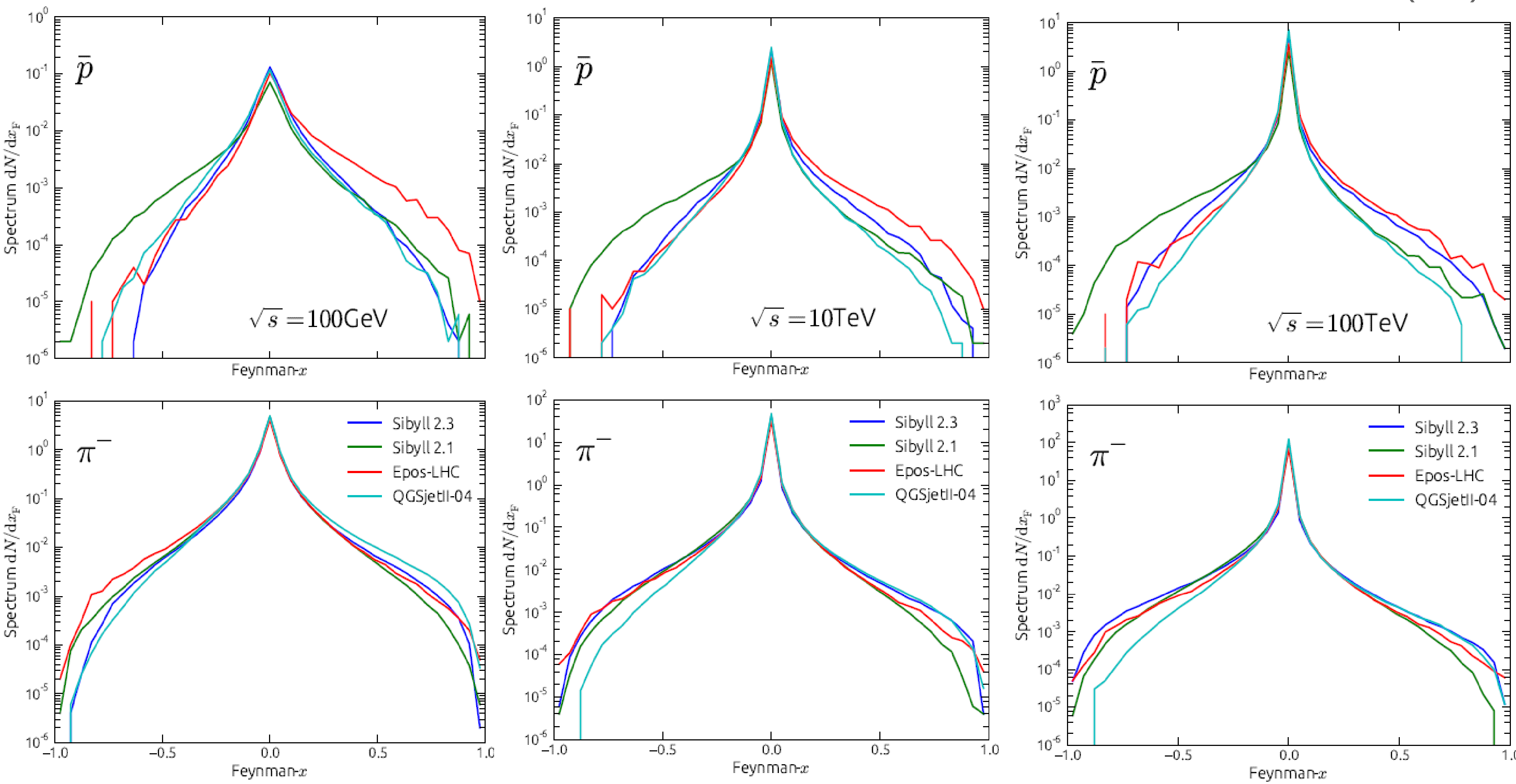


Plot from F. Riehn (KIT)

Pion(+)-Carbon Interactions

Different model predictions as a function of energy:

Plots from F. Riehn (KIT)

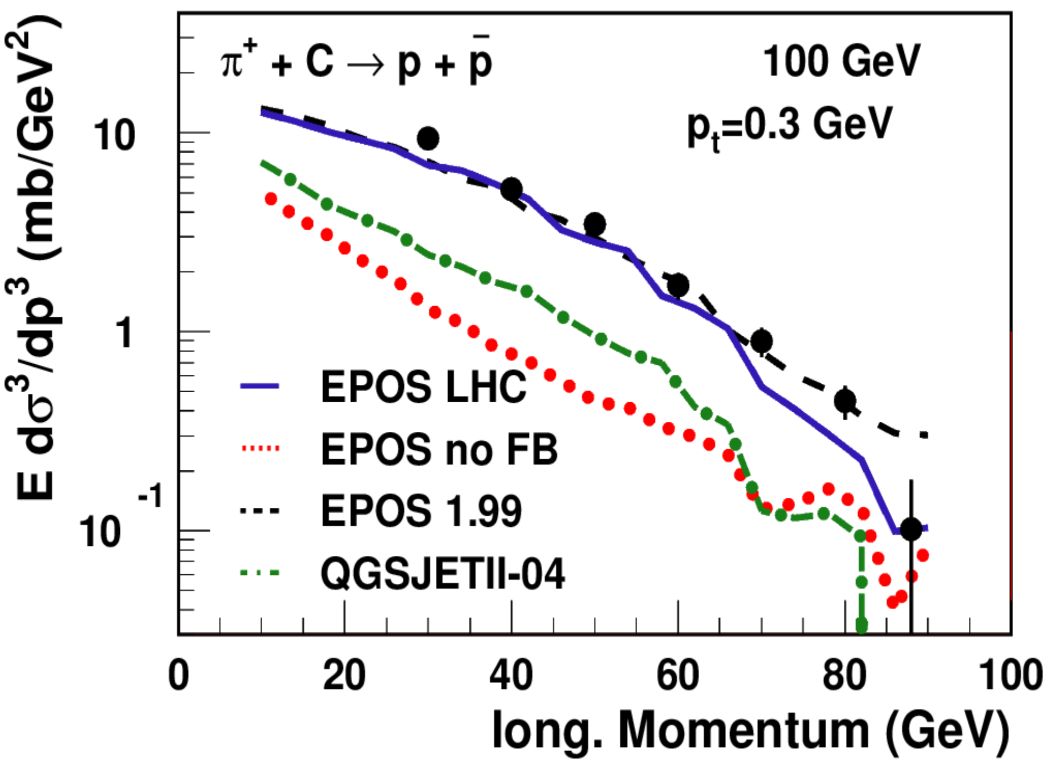


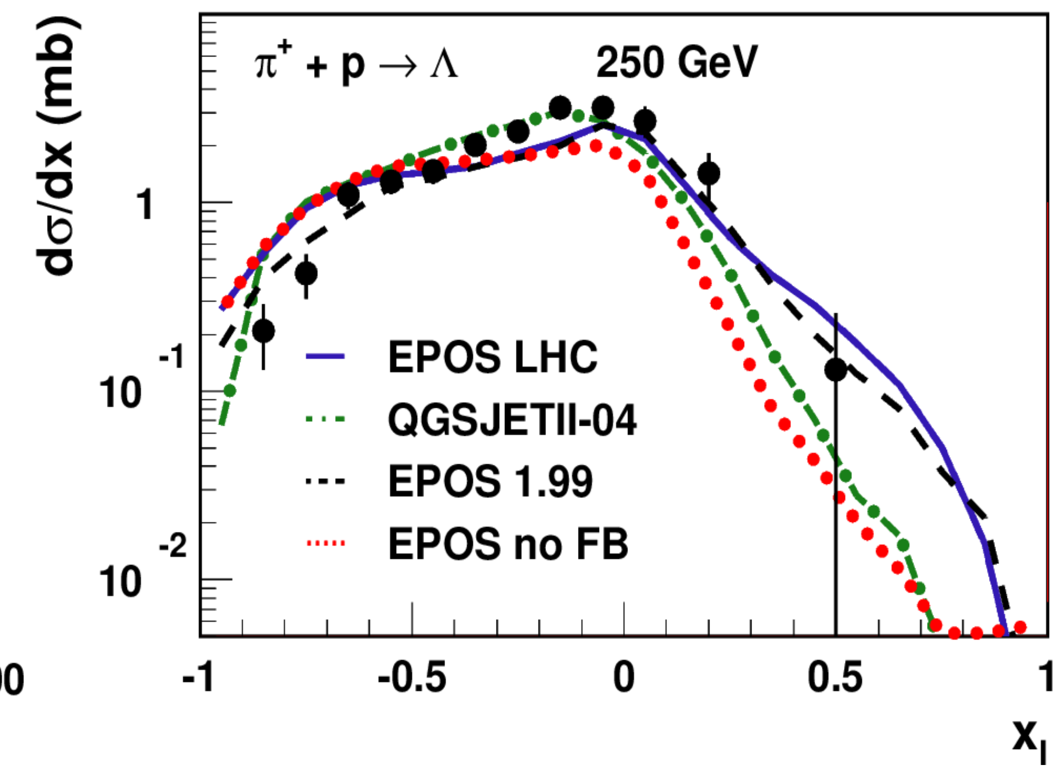
Baryons in Pion-Carbon

Very few data for baryon production from meson projectile, but for all :

- strong baryon acceleration (probability ~20% per string end)
- proton/antiproton asymmetry (valence quark effect)
- target mass dependence

➡ NA61 Data to check !

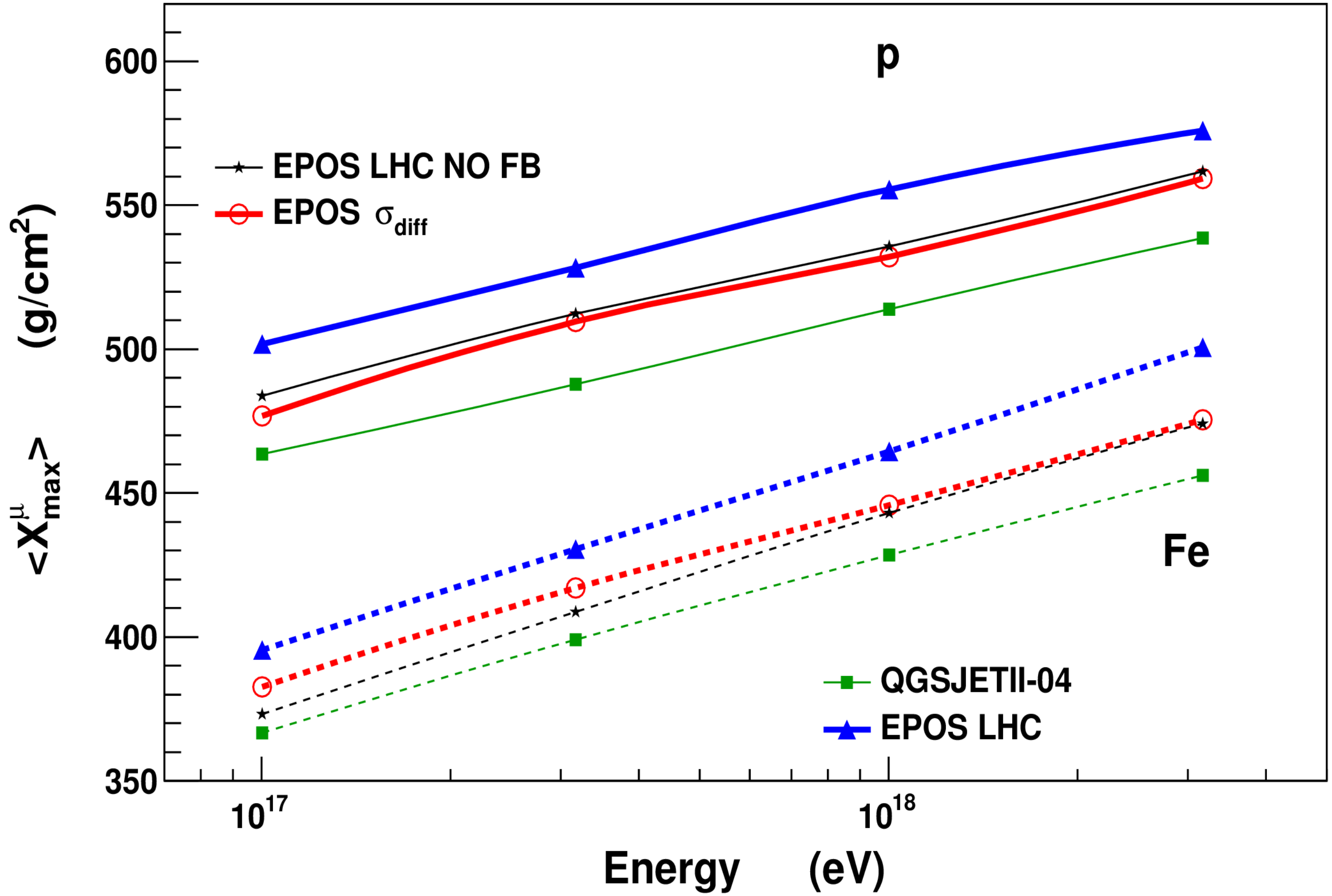




$<X^{\mu}_{max}>$ with modified EPOS LHC

Same than in mixed models

- softer meson spectra (lower elasticity) : lower X^{μ}_{max}
- less forward baryons: lower X^{μ}_{max}



-25 g/cm² for diff

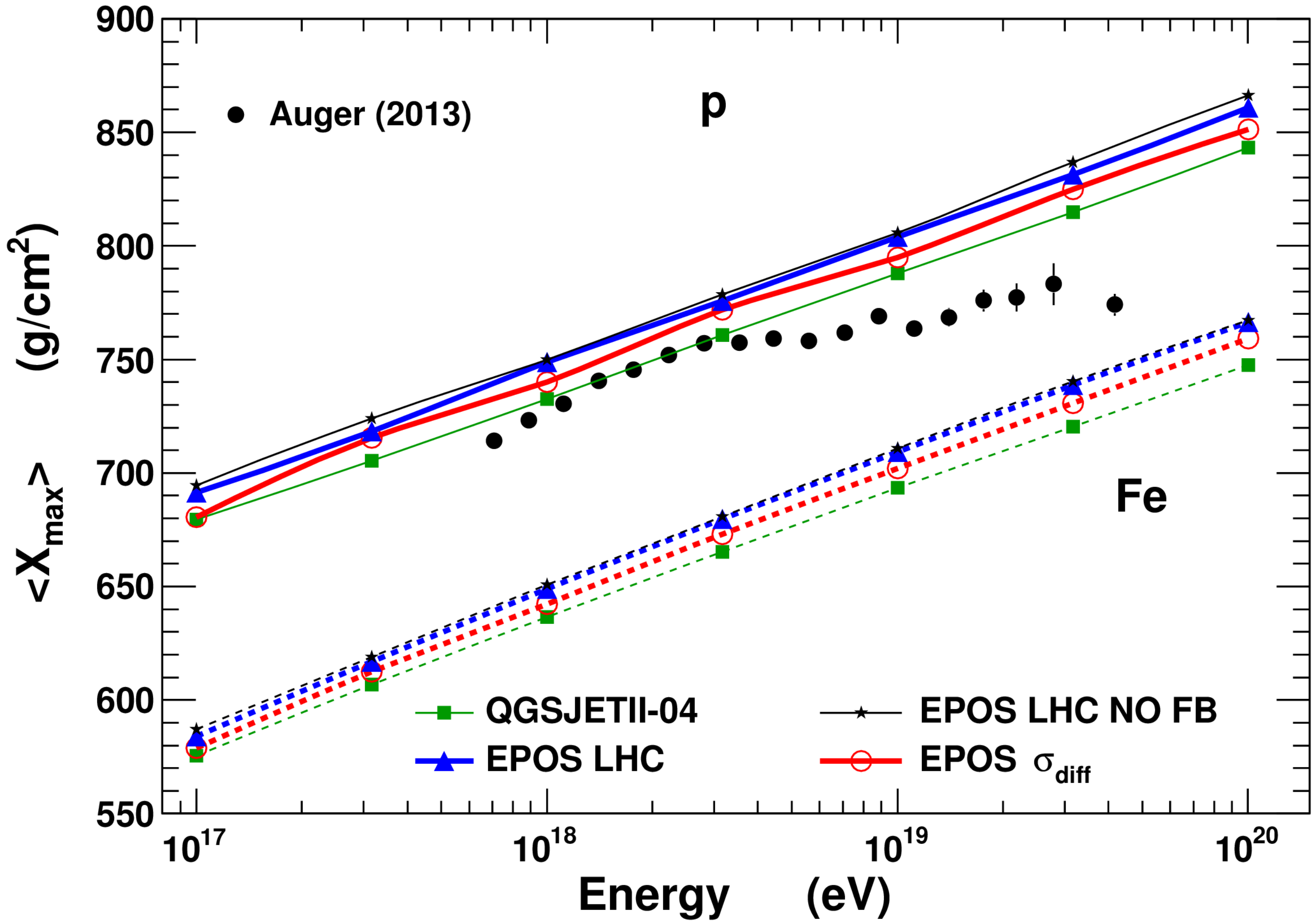
-20 g/cm² for baryons

MPDs sensitive to baryon (less generation) and meson spectra in pion interactions

<X_{max}> with Modified EPOS

Same than in mixed models

- softer meson spectra: lower X_{max}
- forward baryons: small effect



-10 g/cm^2 for diff

~0 g/cm^2 for baryons

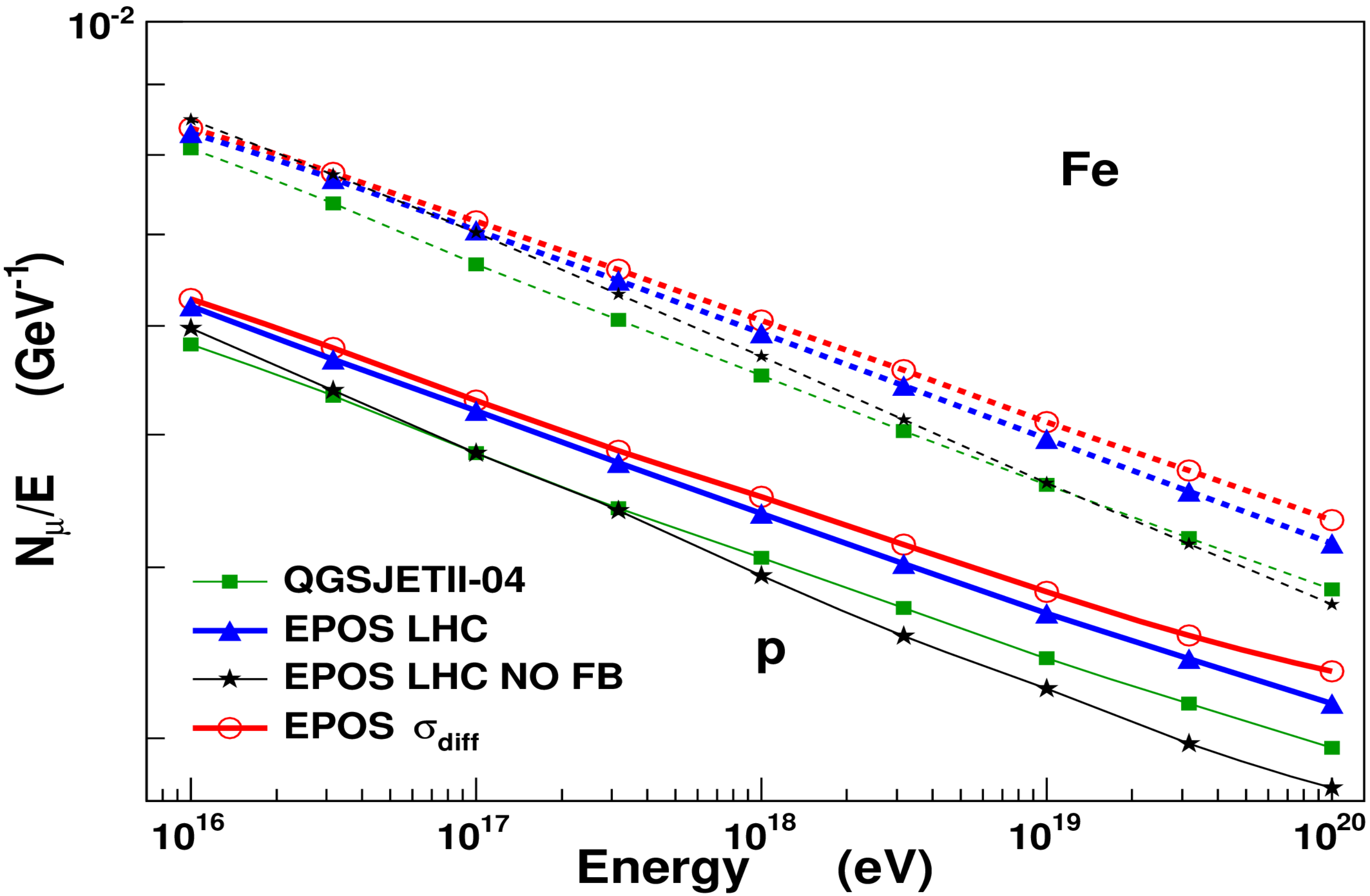
X_{max} less sensitive to baryon spectra than to pion spectra in pion interactions

In Sergey's model, energy is not conserved (baryons not replaced by mesons)

N_μ with Modified EPOS

Number of muons depends on the same parameters

- softer meson spectra: larger N_μ
- forward baryons: lower N_μ but could be compensated by ρ^0 (keep energy to produce muons but doesn't change the number of generations: lower MPD)



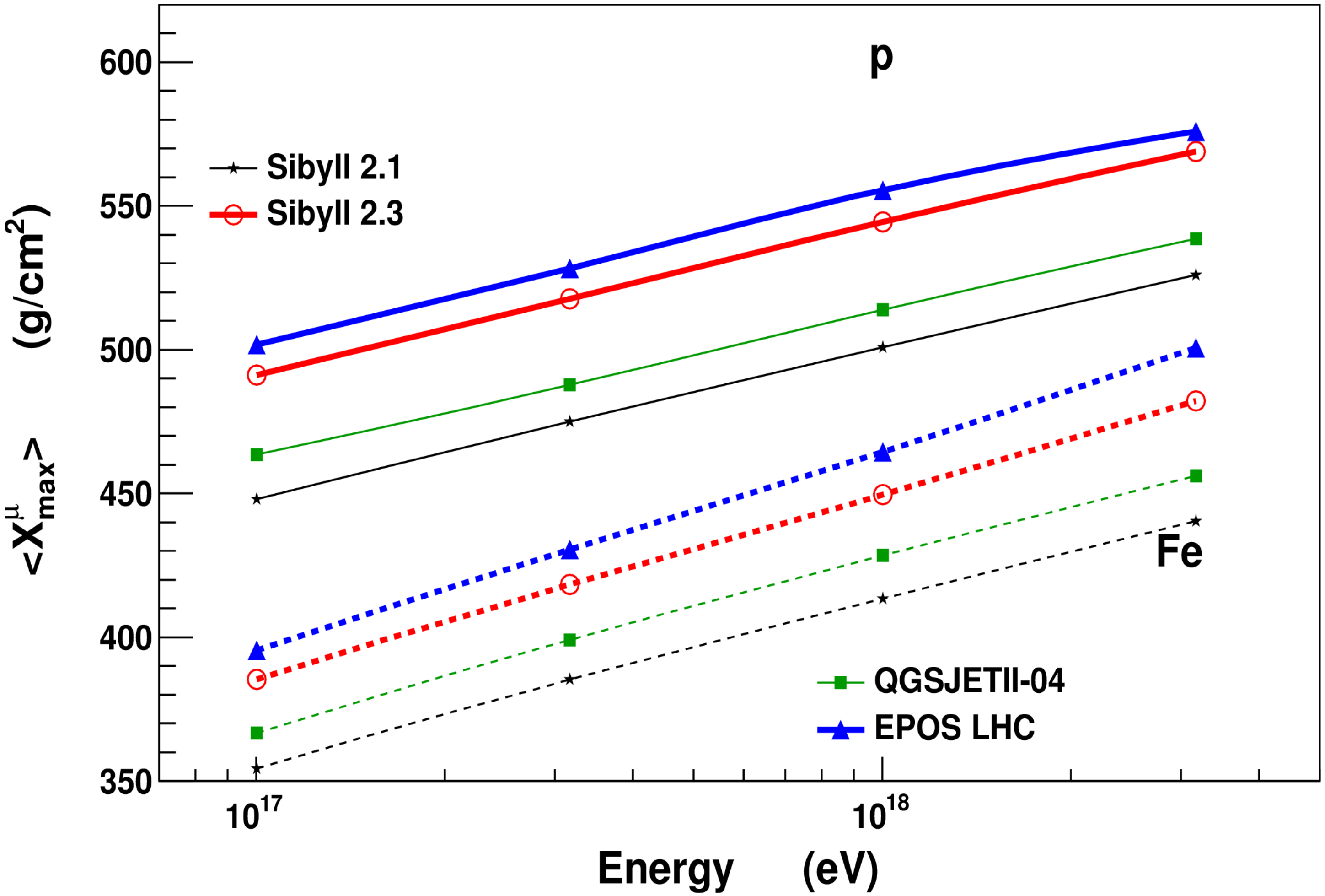
N_μ sensitive to baryon (less generation) and meson spectra in pion interactions

+5% for diff

-15% without forward baryons

$<X^{\mu}_{max}>$ with new Sibyll 2.3

- **Same than for EPOS LHC**
  - low pion-air elasticity: higher X^{μ}_{max}
  - more forward baryons: higher X^{μ}_{max}



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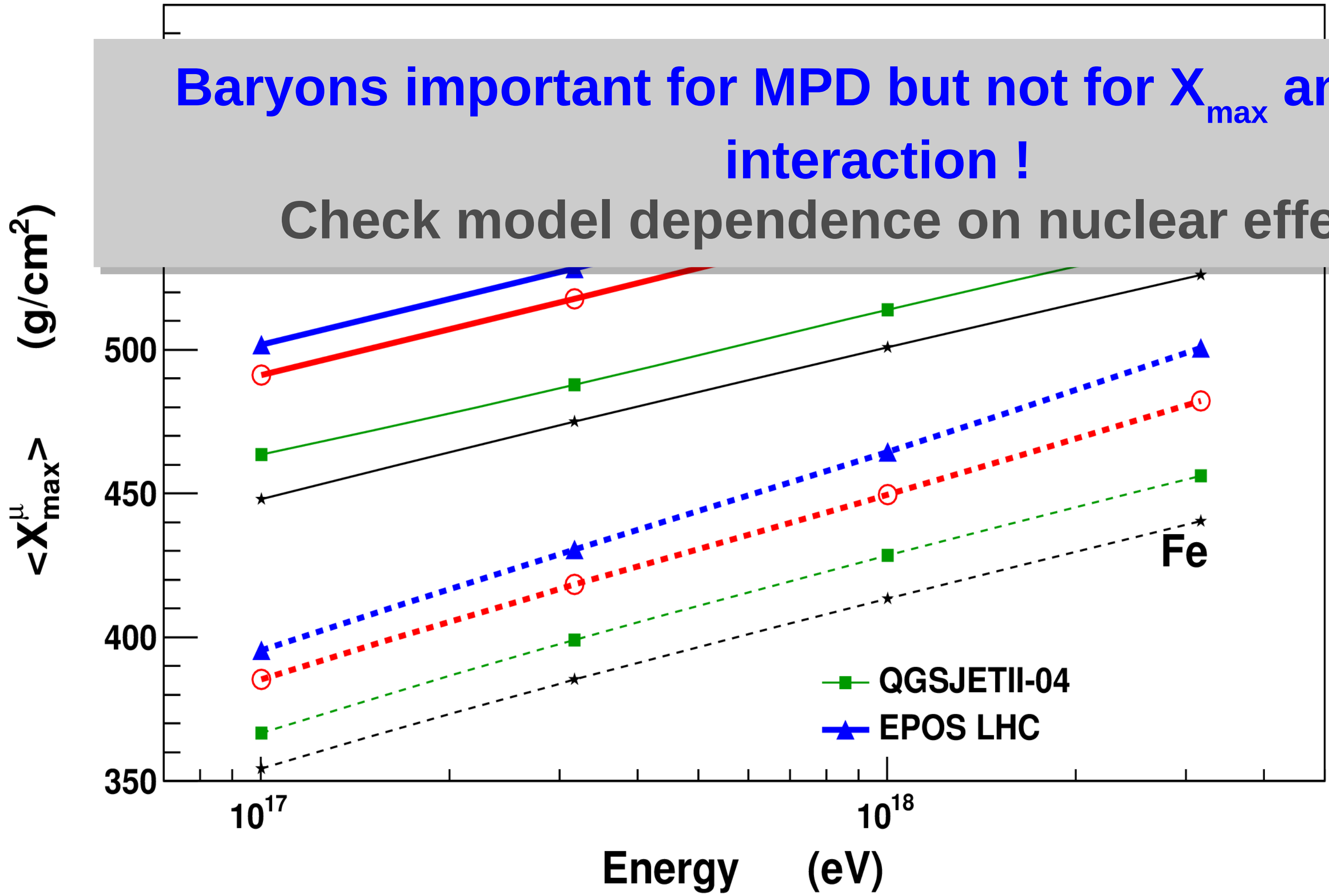
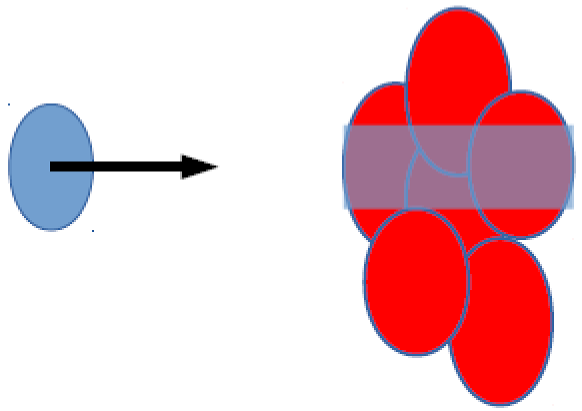


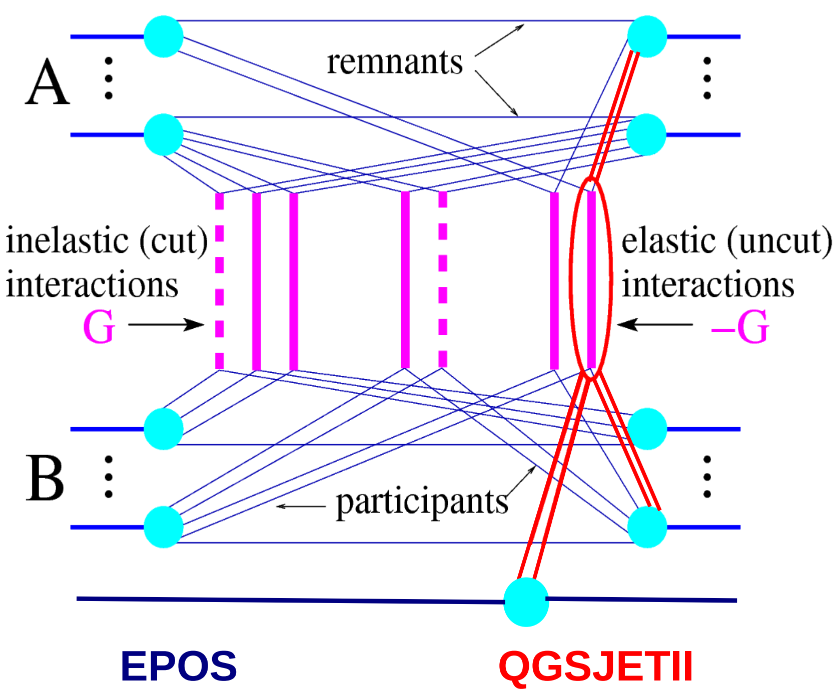
Baryons important for MPD but not for X_{max} and for first interaction !

Check model dependence on nuclear effects ...

MPDs sensitive to baryon (less generation) and meson spectra in pion interactions

Nuclear Interactions



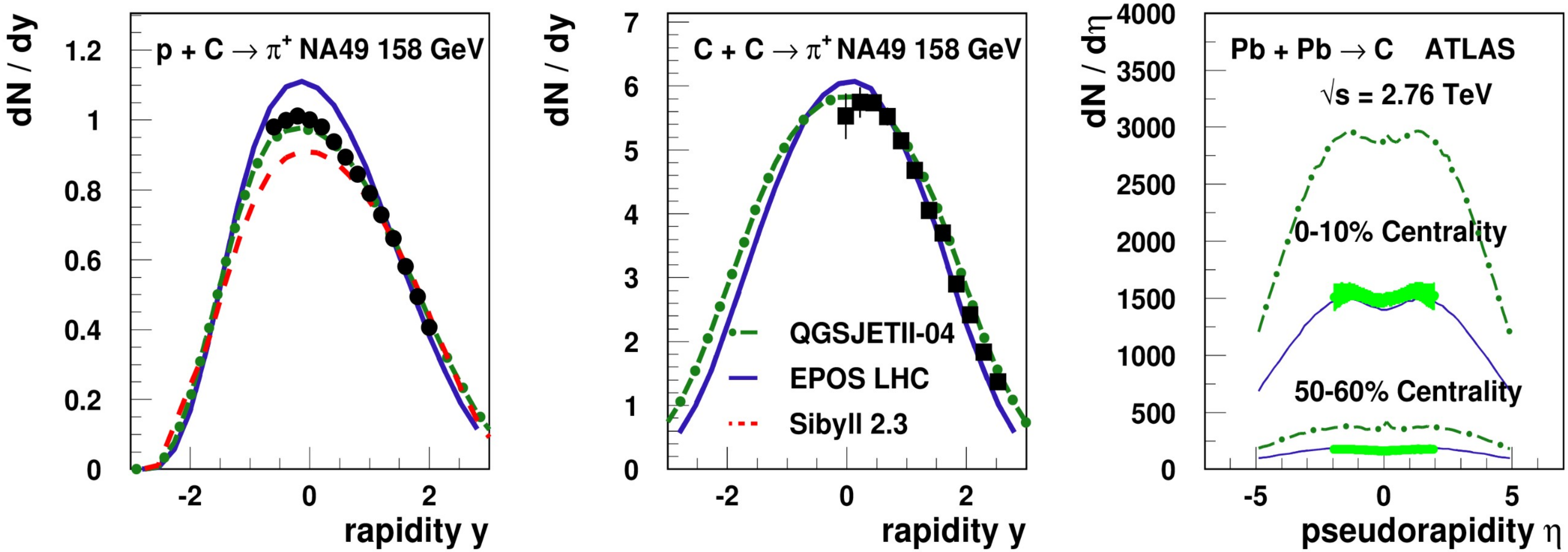


- Sibyll
  - Glauber for pA
    - with inelastic screening for diffraction in new Sibyll 2.3 (only nuclear effect)
  - superposition model for AA (A x pA)
- QGSJETII
  - Pomeron configuration based on A projectiles and A targets
  - Nuclear effect due to multi-leg Pomerons
- EPOS
  - Pomeron configuration based on A projectiles and A targets
  - screening corrections depend on nuclei
  - final state interactions (core-corona approach and collective hadronization with flow for core)

Light Ion Data

Very few data to compare with all CR models :

- ➡ strong limitations in Sibyll (projectile up to Fe only and target up to O !)
- ➡ no final state interactions exclude heavy nuclei for QGSJETII
- ➡ no light ion at high energy



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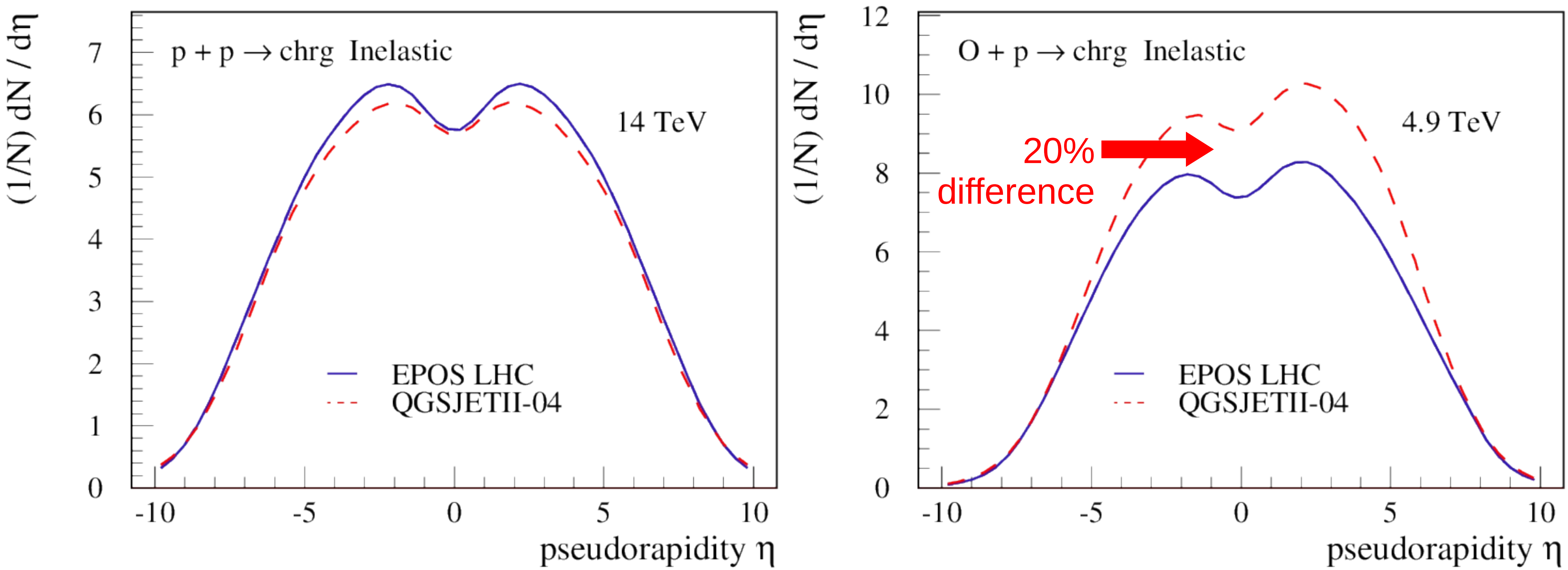
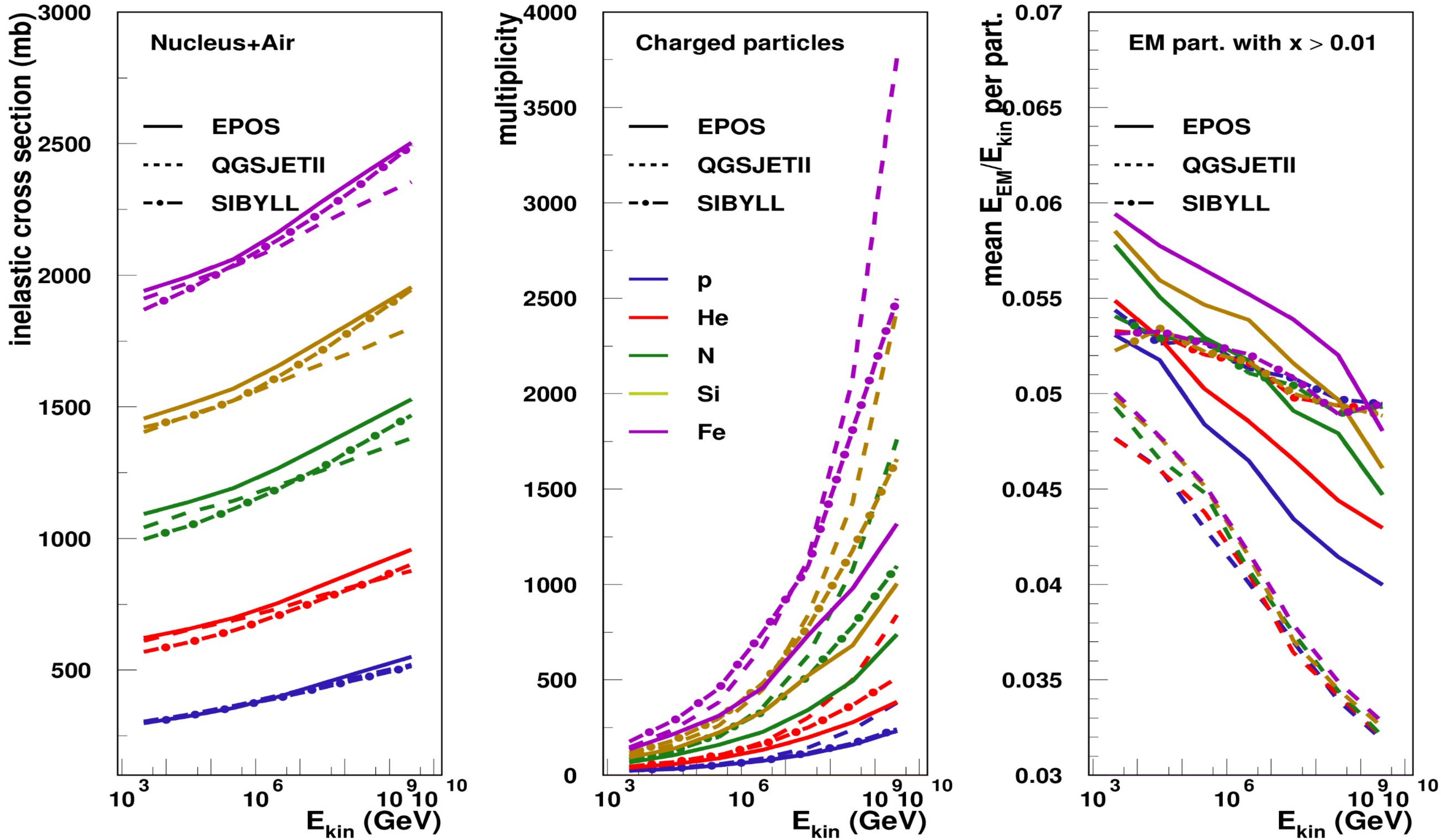
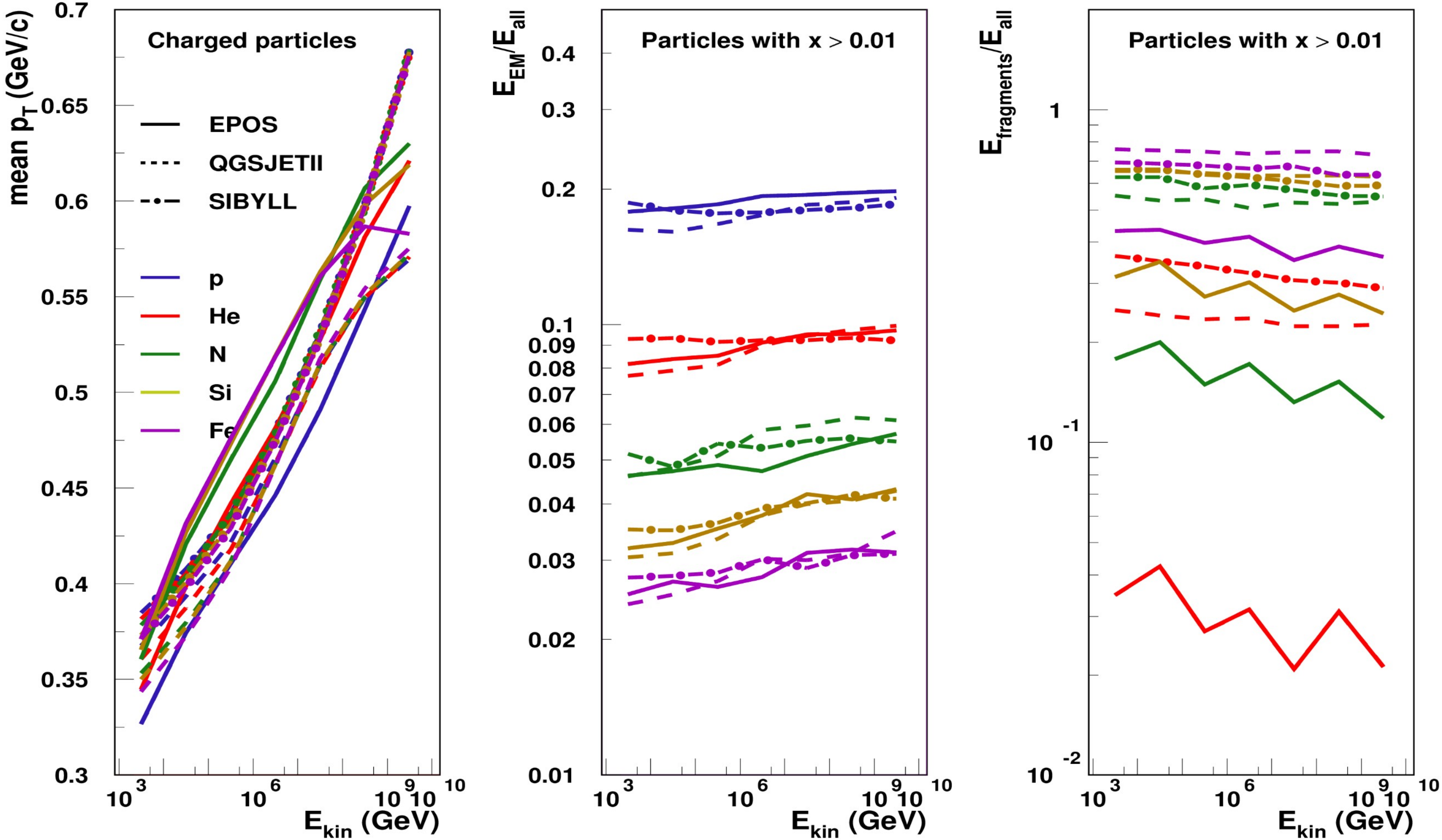
→ pO@LHC to check models at high energy



Model Comparison (1)



Model Comparison (2)



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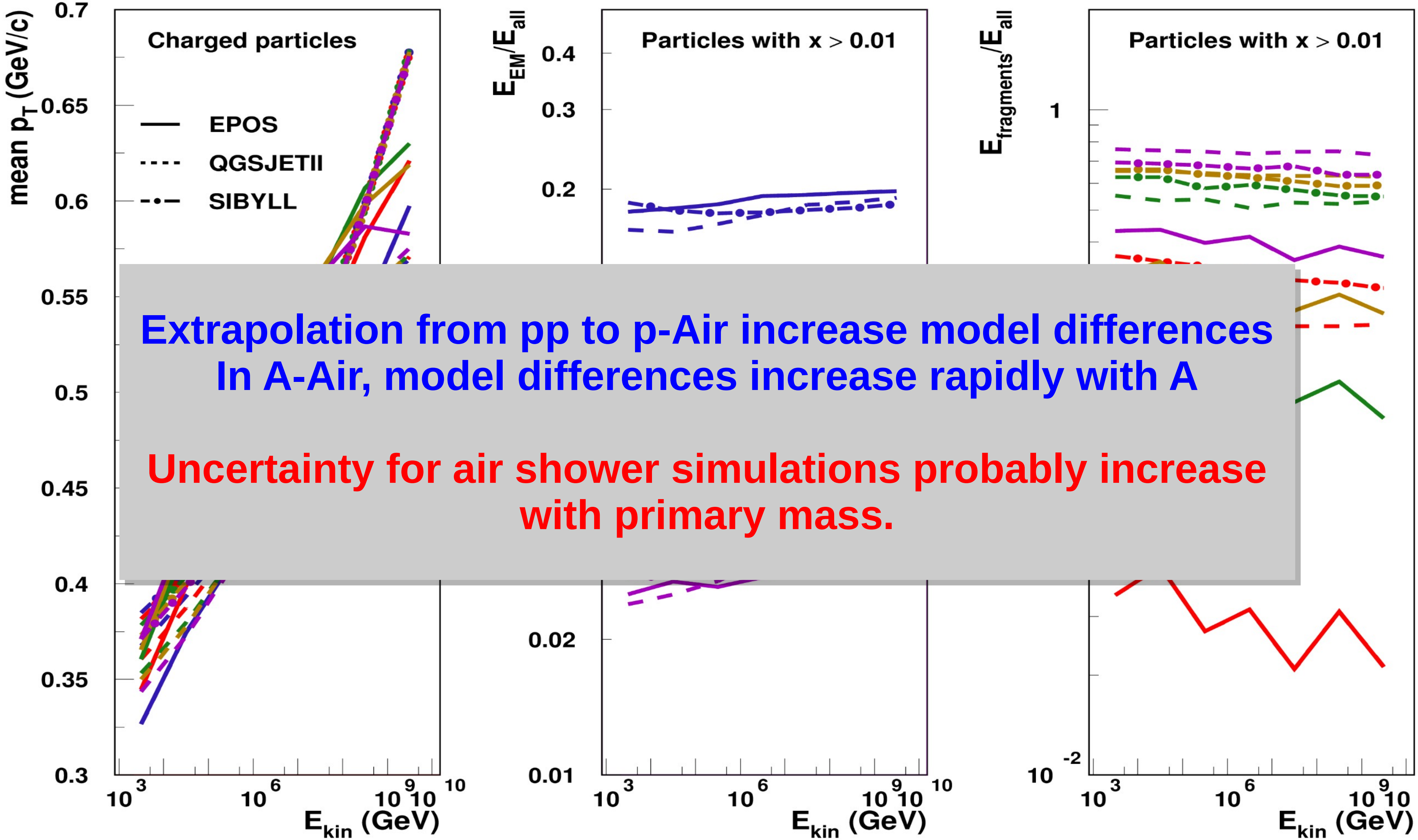


Extrapolation from pp to p-Air increase model differences
In A-Air, model differences increase rapidly with A

Uncertainty for air shower simulations probably increase with primary mass.

Summary

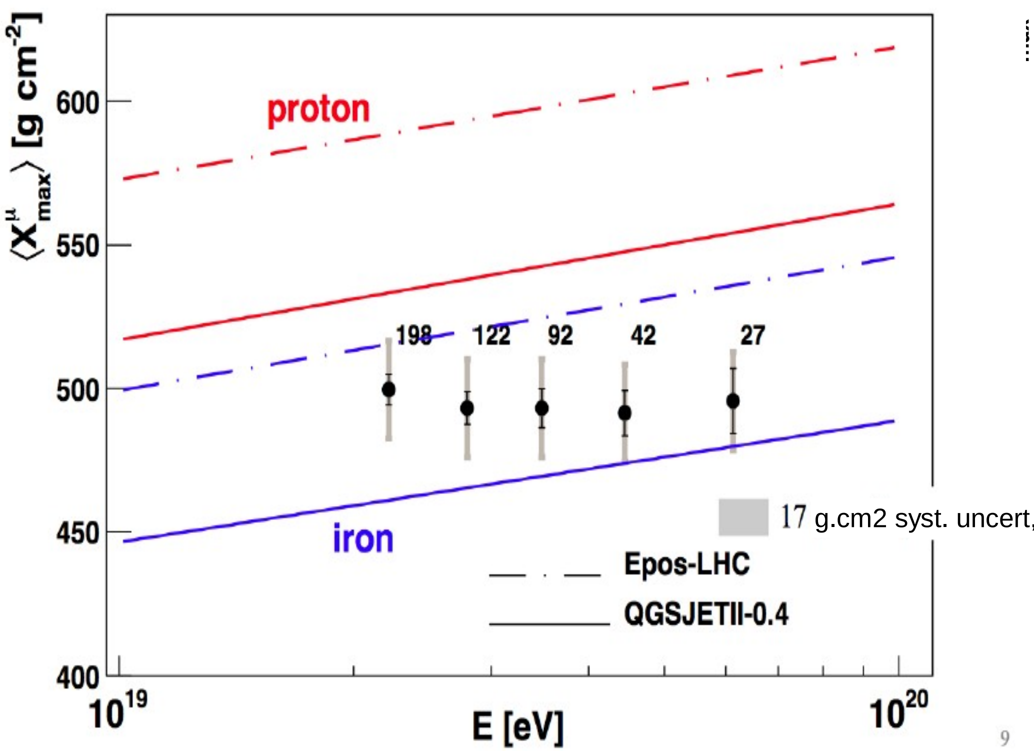
- **Very strong sensitivity of MPD on pion interactions which is badly measured**
  - MPD can be used to constrain models
  - then MPD can not be used for mass composition (X_{max} less sensitive to details) unless more accelerator data can constrain the models

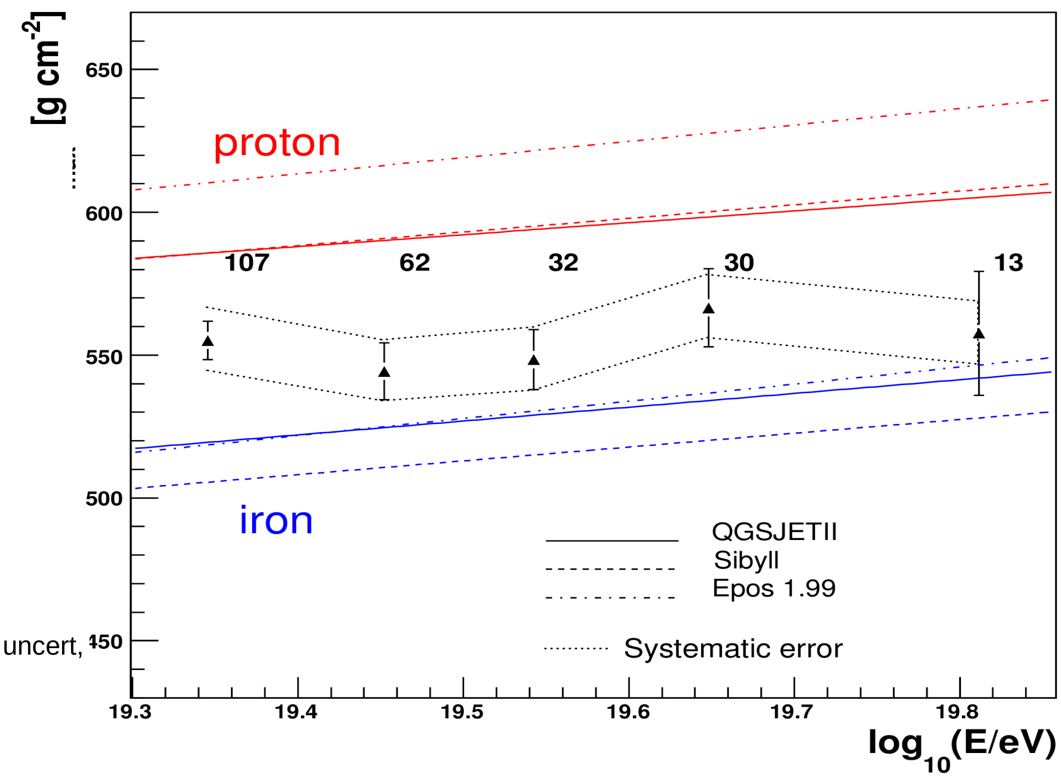
- **Better MPD = better X_{max} ?**
  - ➡ YES
    - meson spectra influence both MPD and X_{max}
  - ➡ NO
    - forward baryons change MPD but X_{max} only if meson spectra is not changed
    - in EPOS LHC if forward baryons are suppressed, we get harder meson spectra and X_{max} do not change

- **Remaining main source of uncertainty in X_{max} probably related to extrapolations due to nuclear interactions** (lack of data at high energy and forward). **See David D'enterria talk for more hint on that.**

MPD and EPOS

- **2 independent mass composition measurements**
  - both results should be between p and Fe
  - both results should give the same mean logarithmic mass for the same model
  - problem with EPOS appears after corrections motivated by LHC data

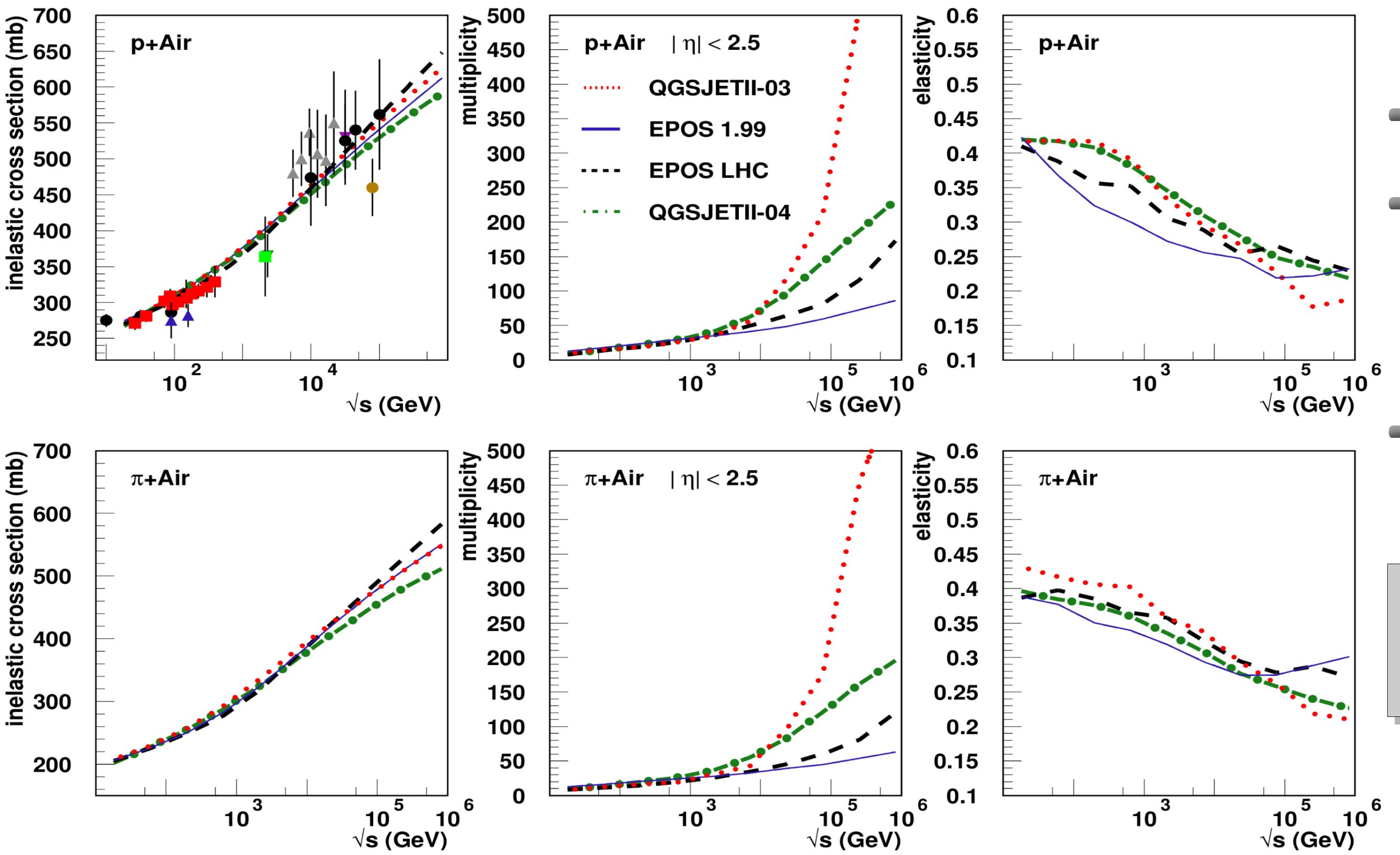




EPOS 1.99 used as reference for the rest of the talk

Difference EPOS 1.99/EPOS LHC

- **EPOS 1.99 to EPOS LHC**
  - ➔ tune cross section to TOTEM value
  - ➔ ~~change old flow calculation to a more realistic one~~
  - ➔ introduce central diffraction and improve rapidity gap distributions

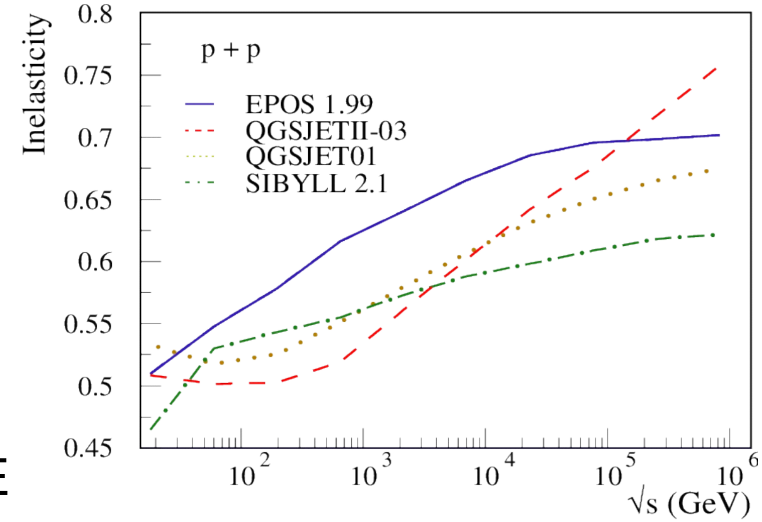


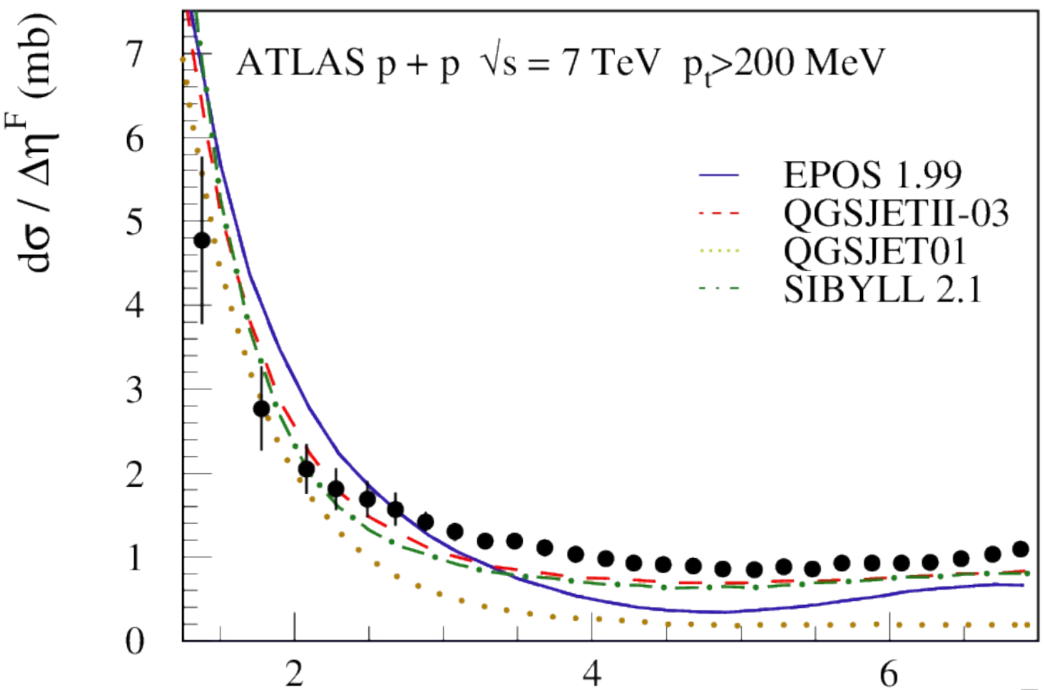
- shallower MPD
- ➔ larger multiplicity
- ➔ larger cross-section (small)
- deeper MPD
- ➔ larger elasticity

Elasticity should be the source of the difference

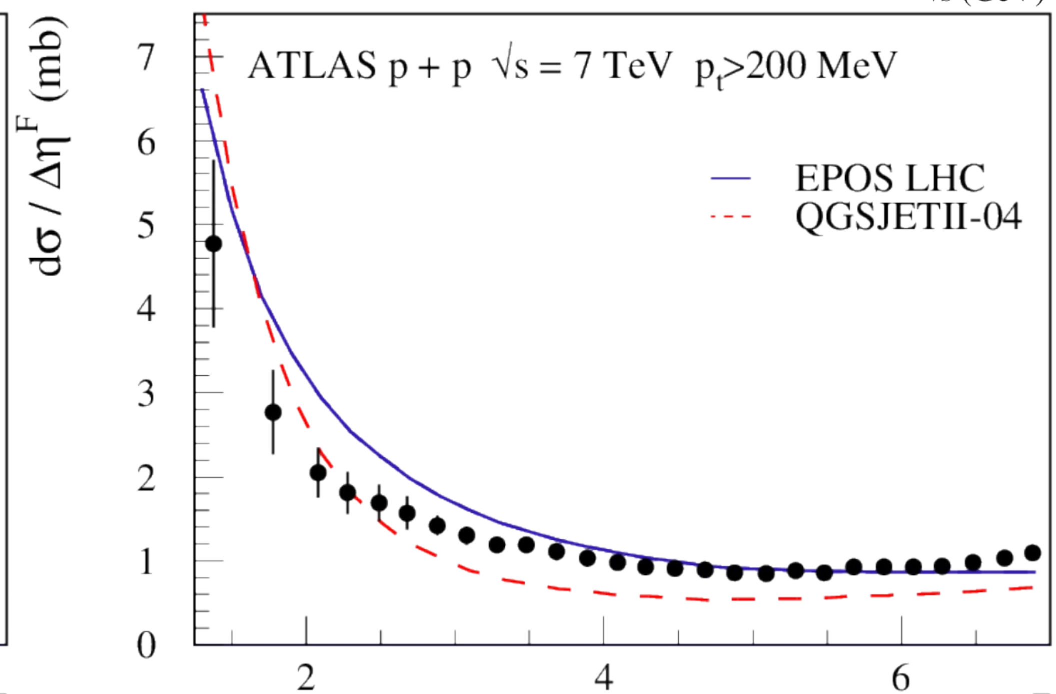
(In)elasticity

- **Difficult to measure : larger uncertainty**
  - Difference in diffraction
    - low mass / high mass / central diffraction
  - difference for pions/Kaons/nucleons
    - very few data (and at low energy)
  - Rapidity gap : first precise measurement at high E





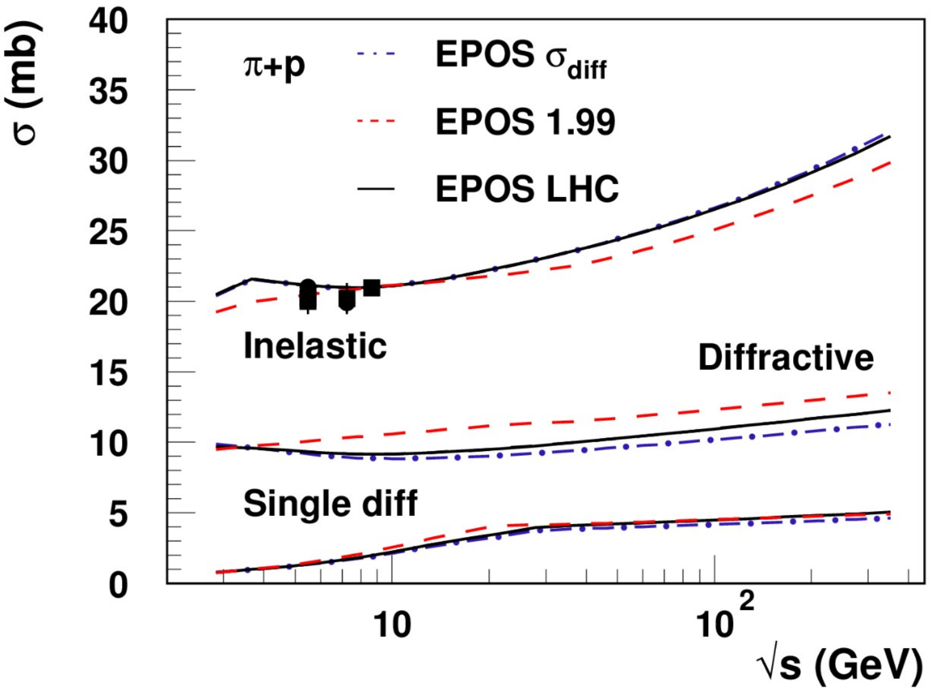
Pre - LHC



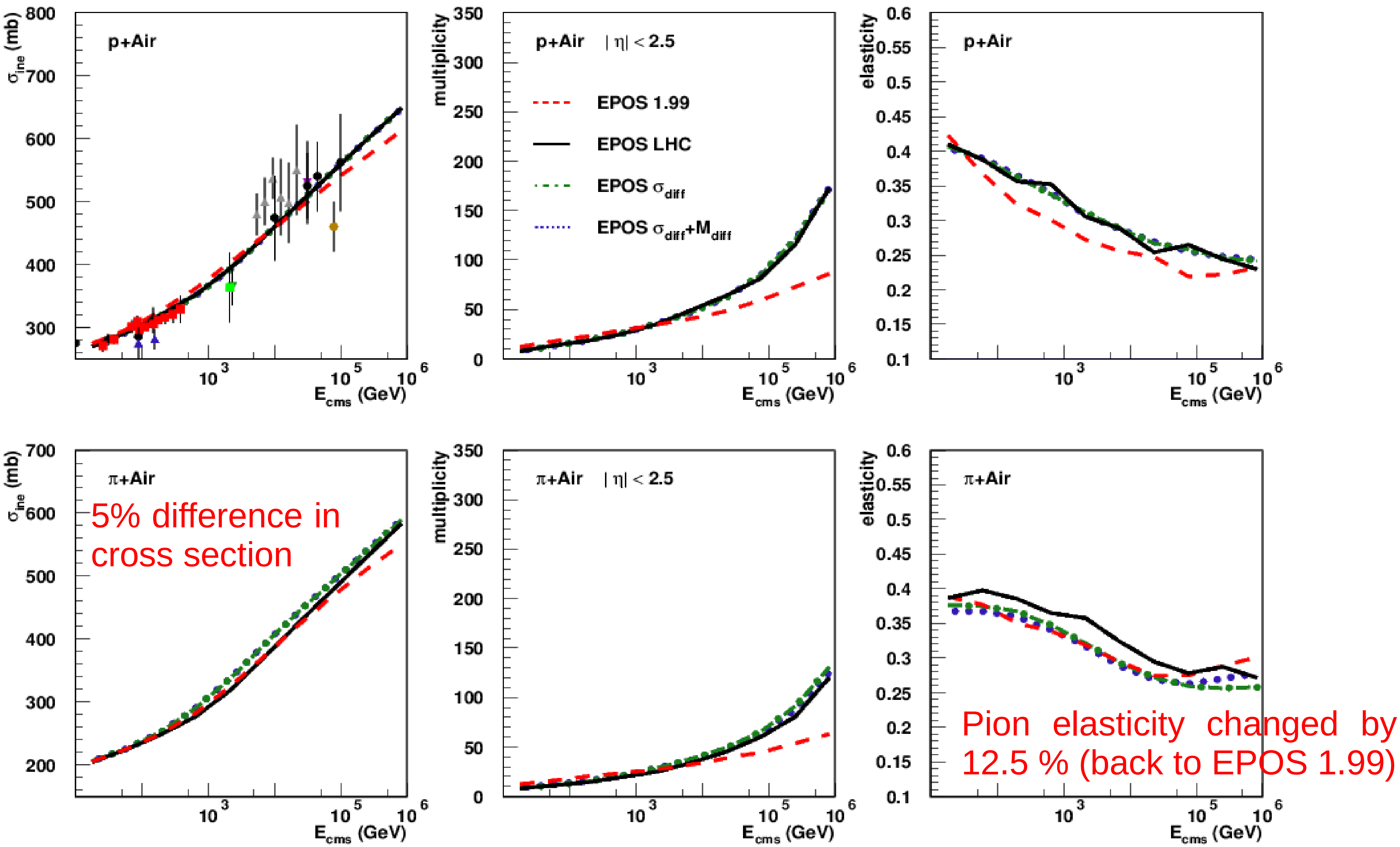
Post - LHC

Pion Diffraction and MPD

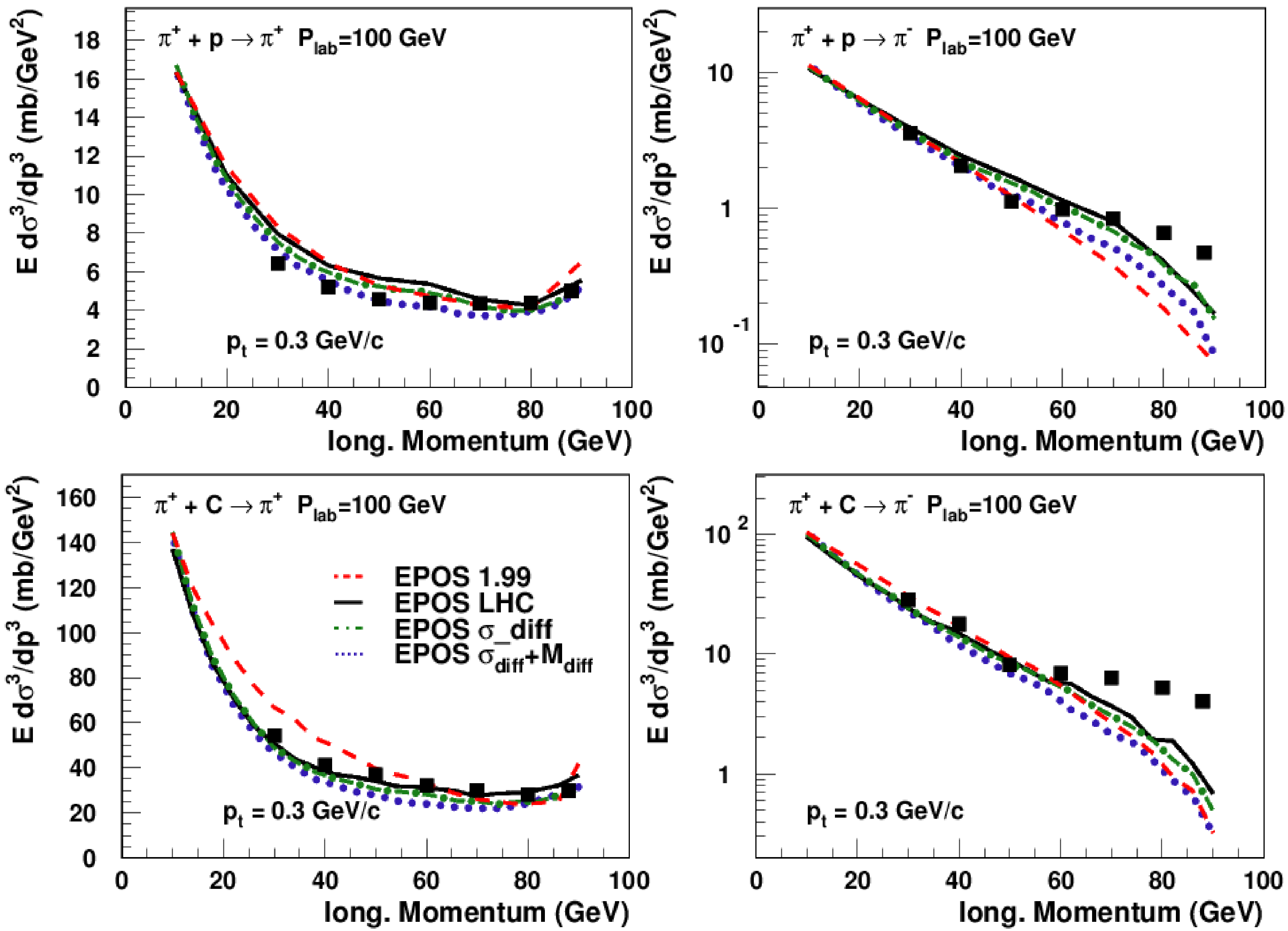
- **Rapidity gap measurement fixed by LHC**
  - ➜ should not change proton interactions
- **MPD driven by long chain of pion-Air interaction**
  - ➜ Modify in EPOS pion diffraction only
  - ➜ Test cross-section and diffractive mass distribution
  - ➜ first check existing pion data to tune parameter to REDUCE pion diffraction and INCREASE diffractive mass
- **2 "tunes"**
  - ➜ EPOS (LHC) σ_{diff} : diffractive cross section reduced
  - ➜ EPOS (LHC) σ_{diff} + M_{diff}: diffractive cross-section reduced and mass increased



Extrapolation to CR interactions



Test with accelerator data



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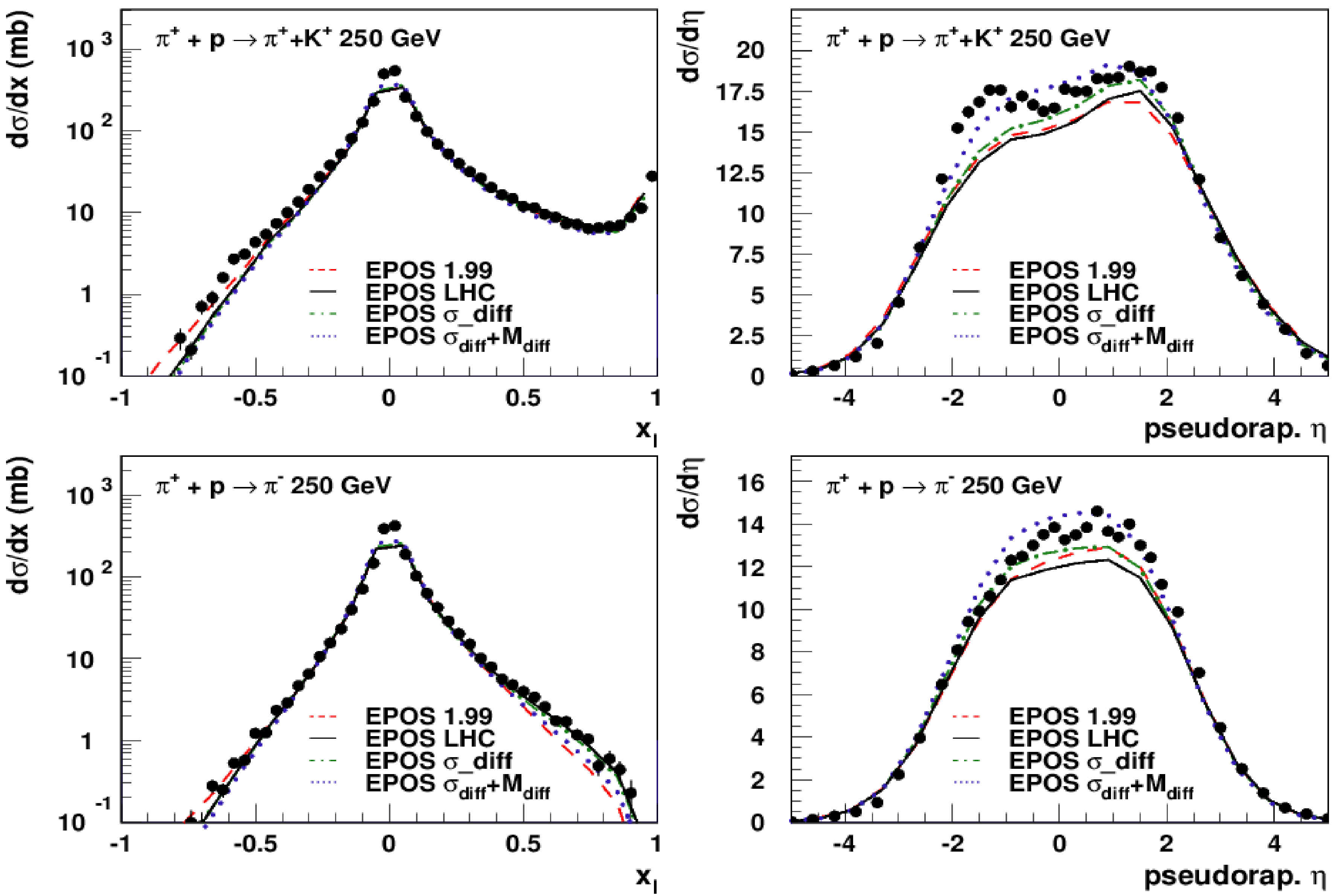
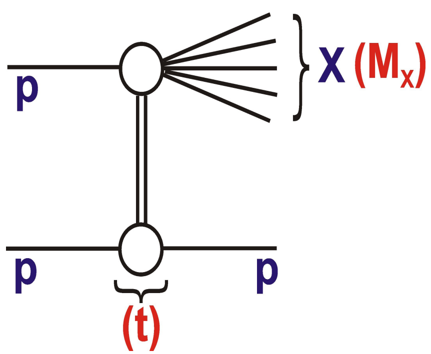
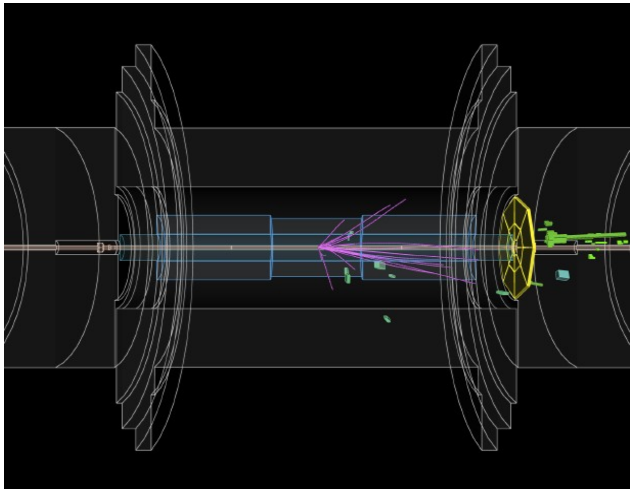


Rapidity Gap and (In)elasticity

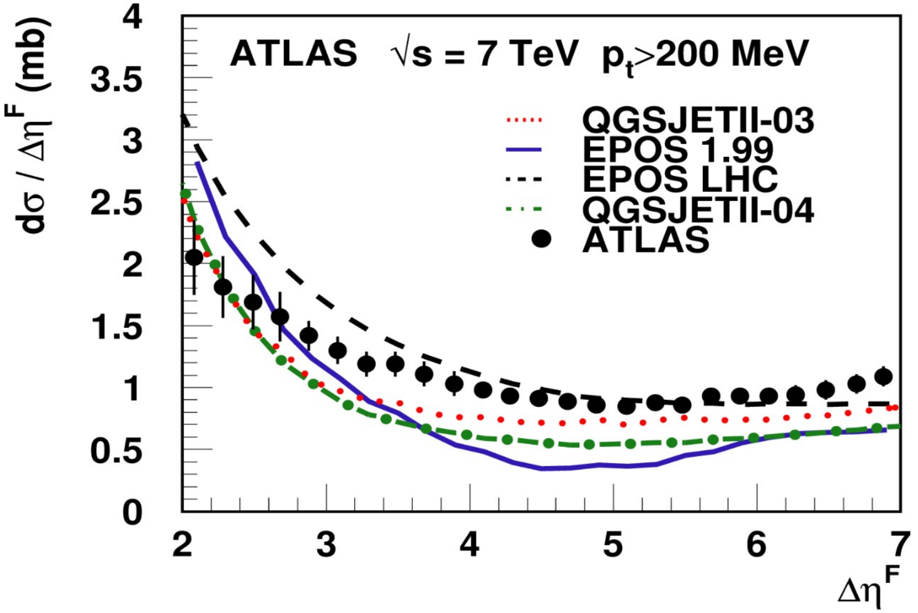
diffractive process

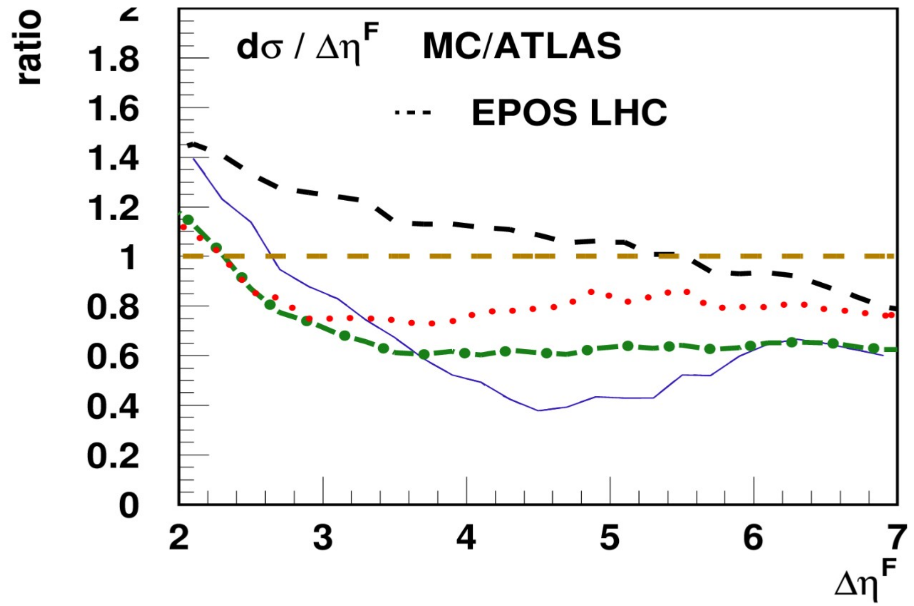


ATLAS detector



ATLAS Collaboration

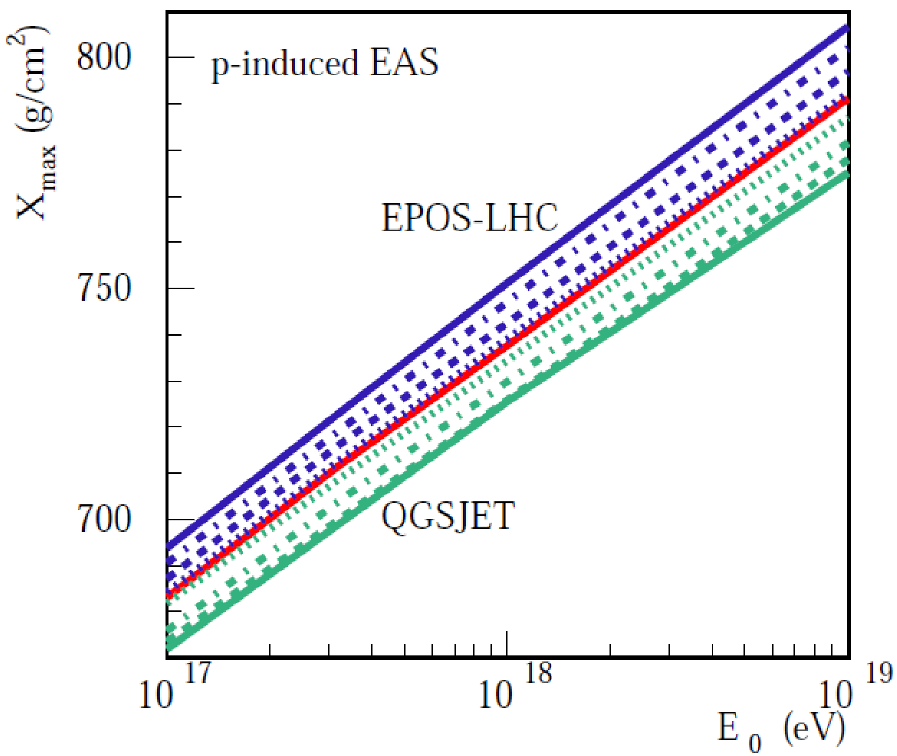


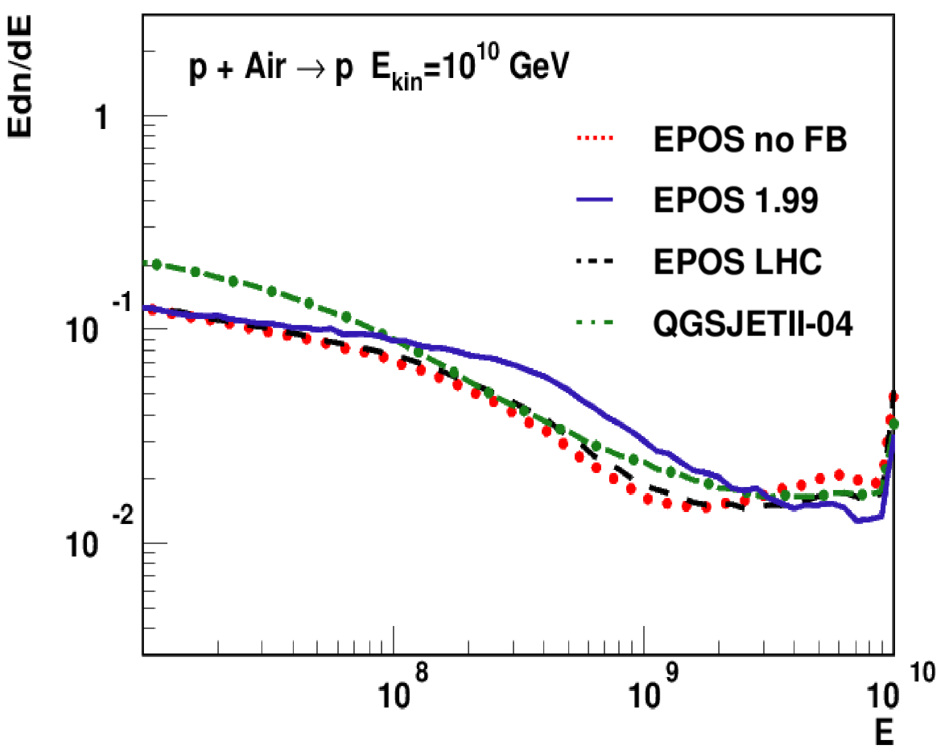


- **Rapidity gap closely related to diffraction**
  - diffractive cross-section
  - AND diffractive mass distribution
- **Hard constraint for CR**
  - change (in)elasticity

Mix models to identify source of differences

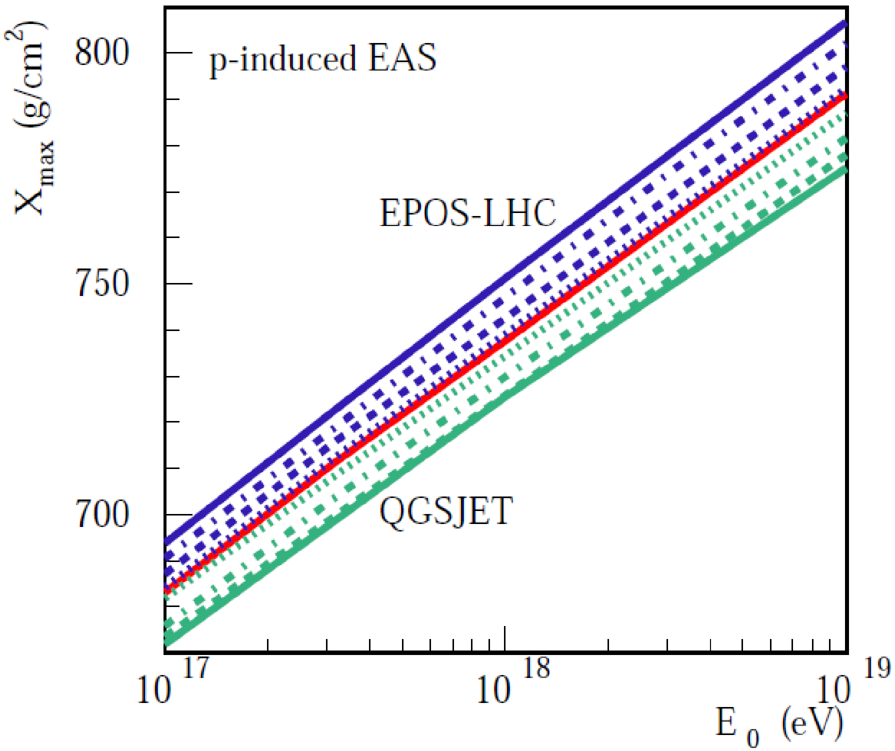
- **Different mixing to extract useful information on X_{max}**
  - ➡ QII only for cross-section and nucleon spectra of 1^{st} int. : dot-dashed

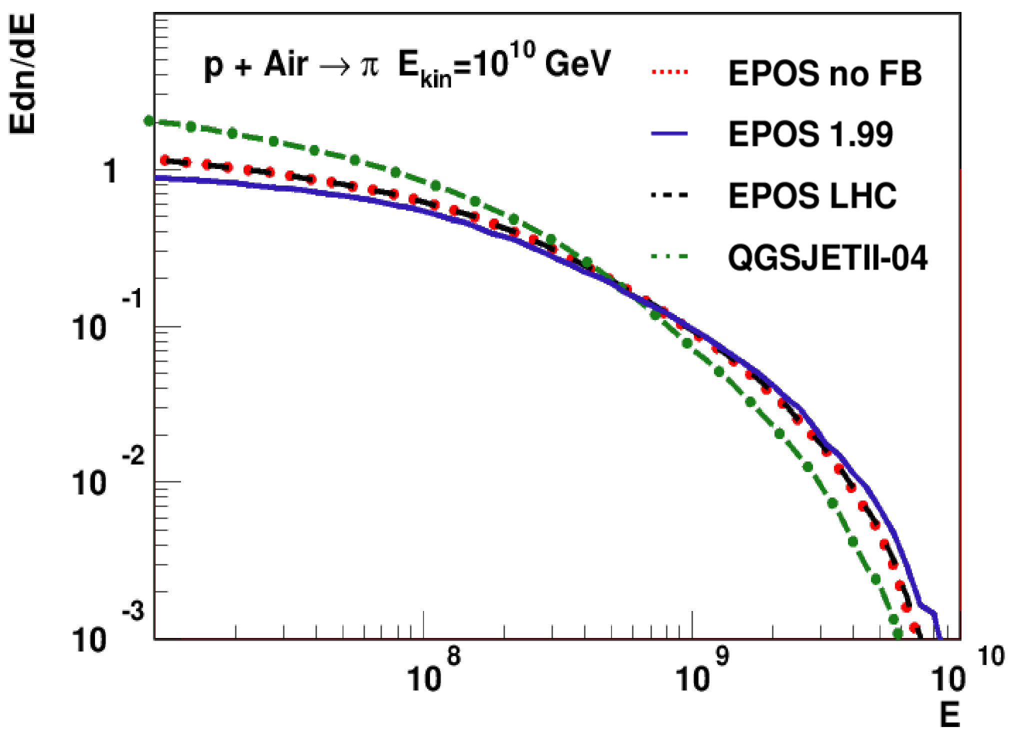




Mix models to identify source of differences

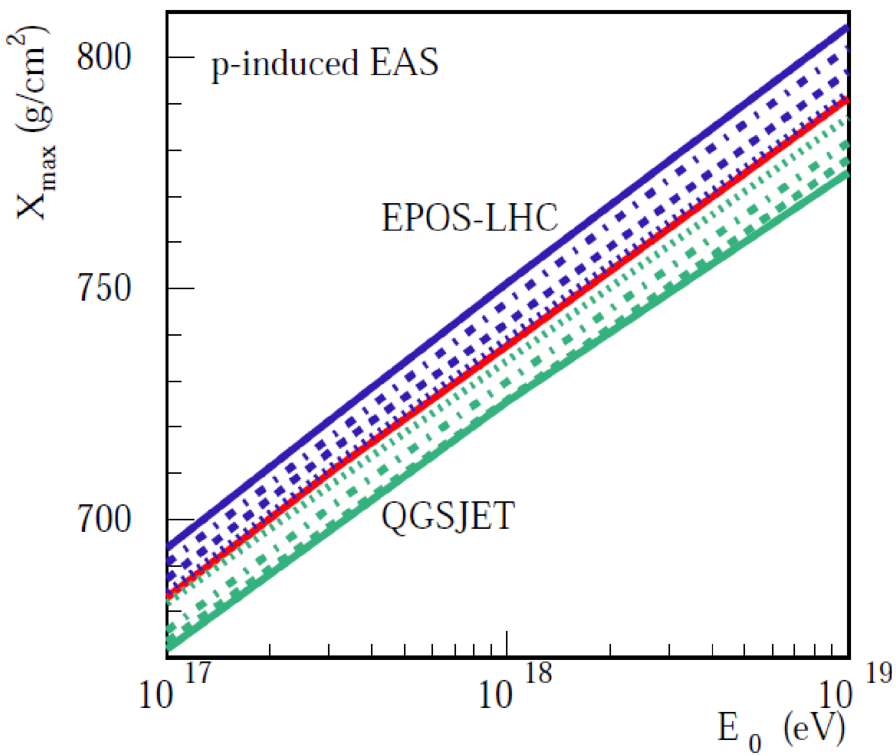
- **Different mixing to extract useful information on X_{max}**
  - QII only for cross-section and nucleon spectra of 1st int. : dot-dashed
  - QII complete 1st int : dashed

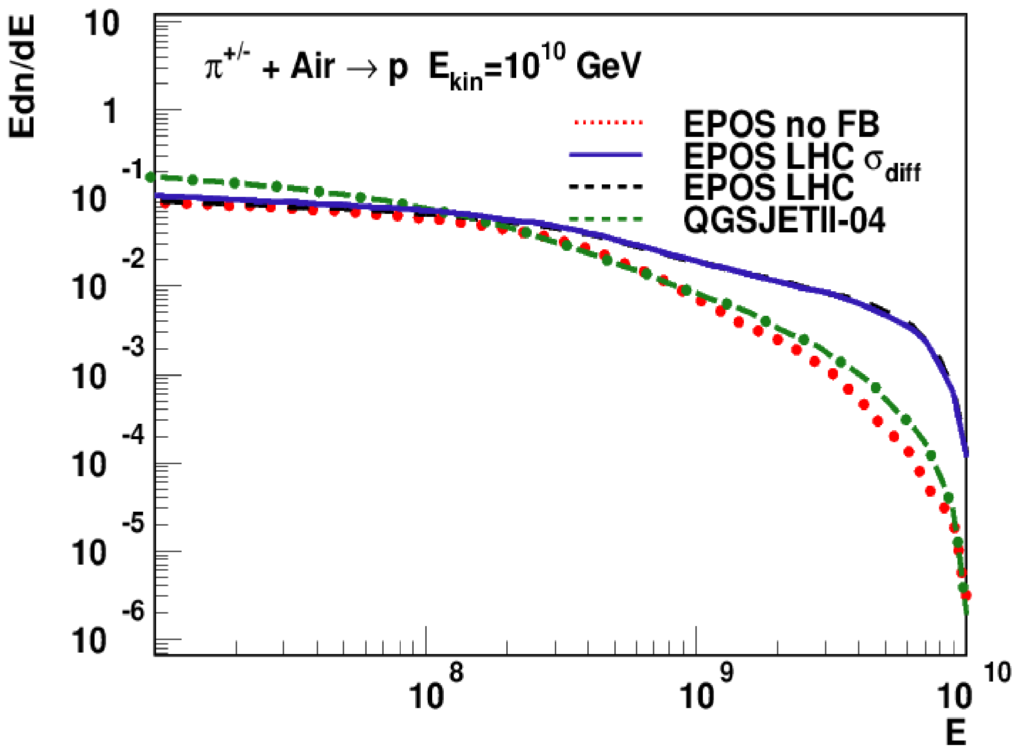




Mix models to identify source of differences

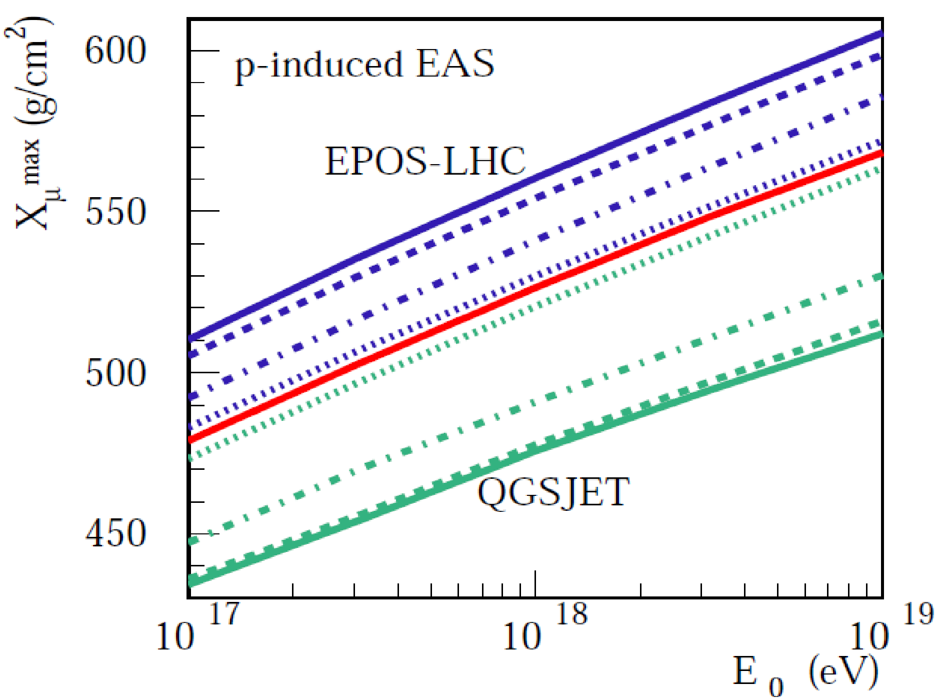
- Different mixing to extract useful information on X_{max}
  - QII only for cross-section and nucleon spectra of 1st int. : dot-dashed
  - QII complete 1st int : dashed
  - QII complete 1st int and all nucleon prod. in the shower: dotted

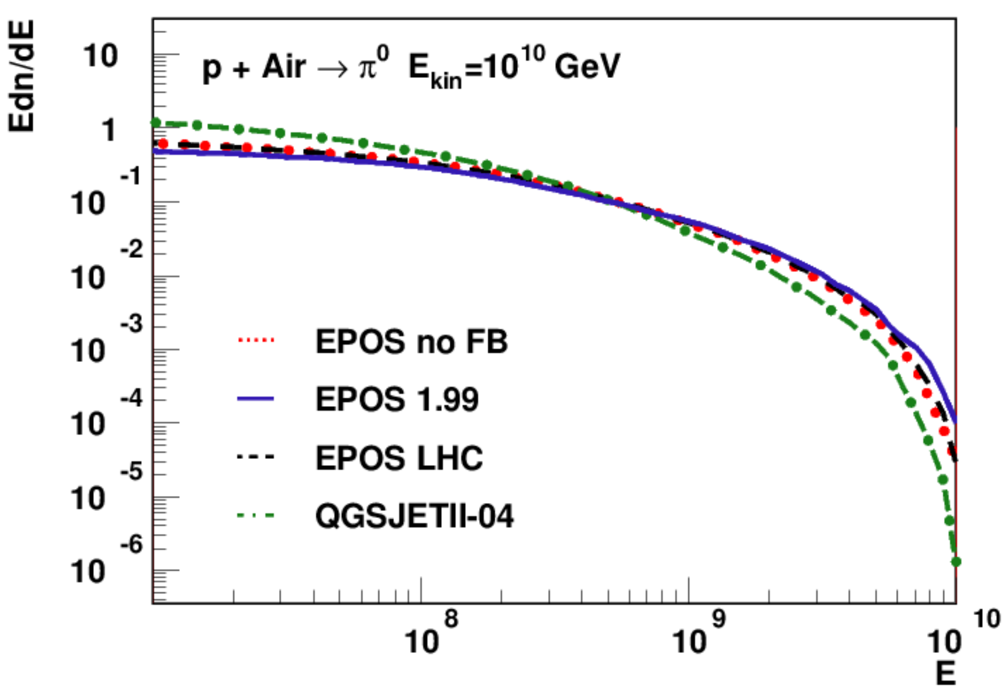




Mix models to identify source of differences

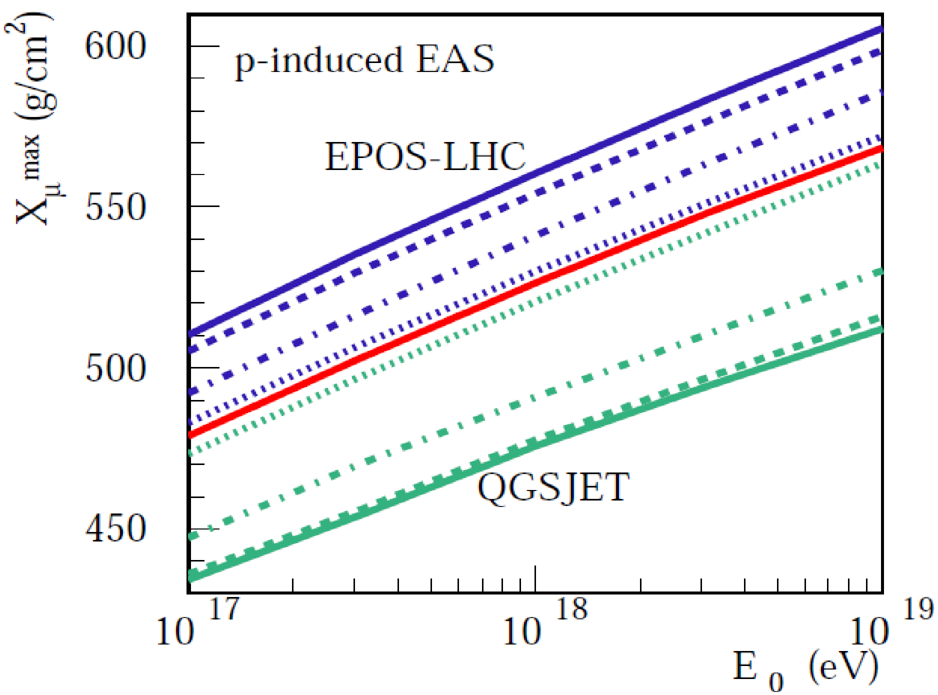
- **Different mixing to extract useful information on X^{μ}_{max}**
  - ➡ QII complete 1^{st} int. : dashed

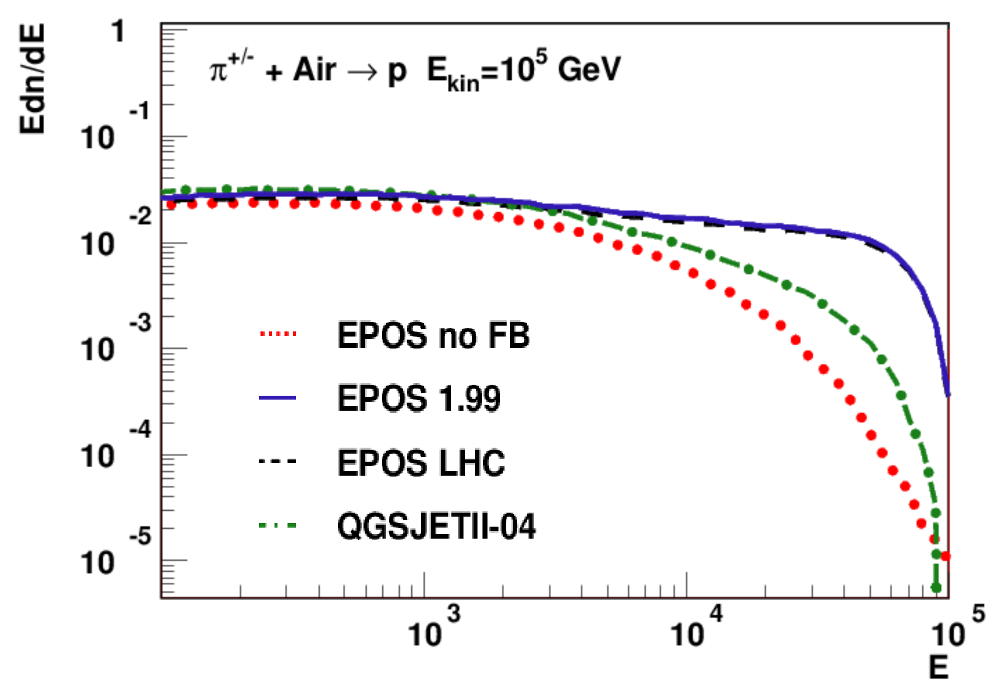




Mix models to identify source of differences

- **Different mixing to extract useful information on X^{μ}_{max}**
  - QII complete 1st int. : dashed
  - QII complete 1st int. and all nucleon prod. in the shower: dot-dashed





Mix models to identify source of differences

- **Different mixing to extract useful information on X^{μ}_{max}**
  - QII complete 1st int. : dashed
  - QII complete 1st int. and all nucleon prod. in the shower: dot-dashed
  - QII complete 1st int. and hadron spectra in pion and kaon int.: dotted