# Air Shower Development and Pion Interactions in the EPOS Model (and other MCs)

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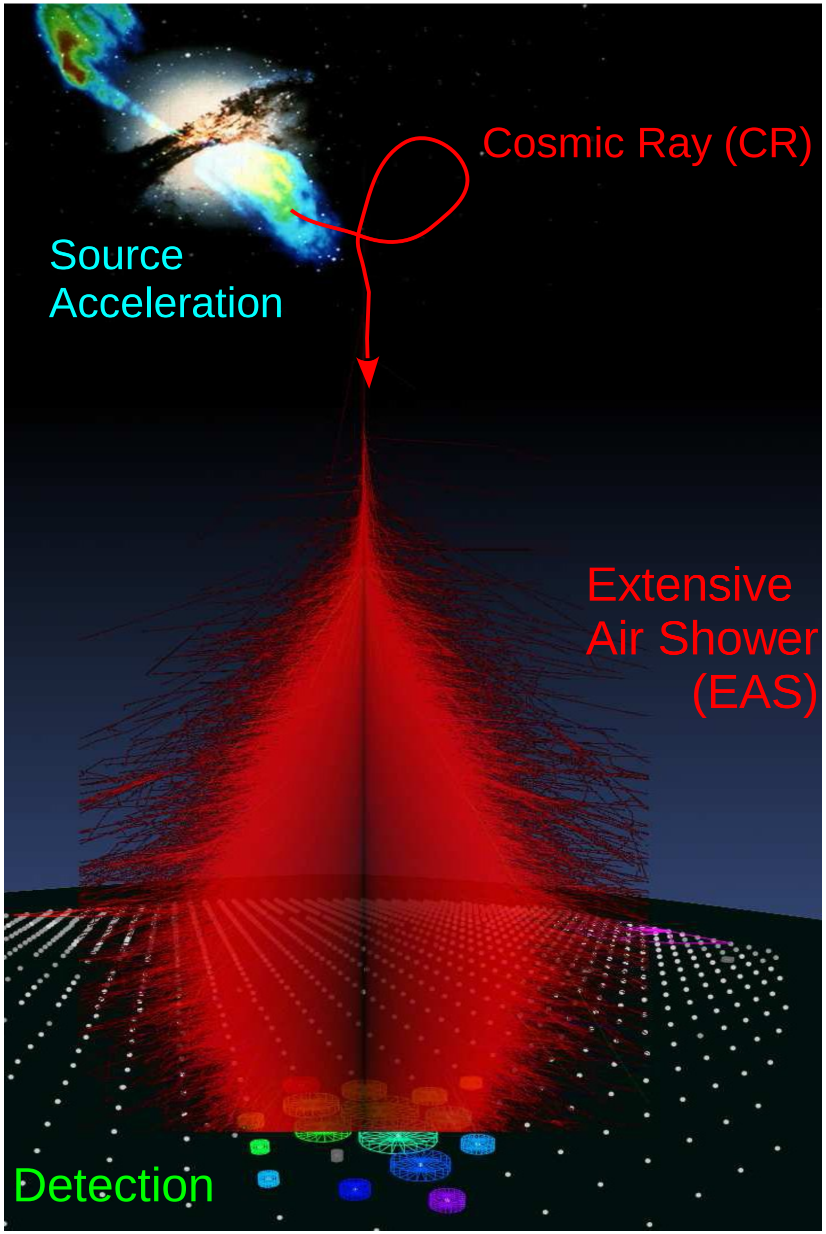
# Outline

- **Inconsistancies between models and PAO measurements**
- **New monte-carlo for Cosmic Ray analysis**
  - ➔ Sibyll 2.3
- **Muon Production Depth and hadronic interactions**
  - ➔ baryons in pion interactions
- **Nuclear Interactions**
  - ➔ model differences

# Preamble




From R. Ulrich (KIT)

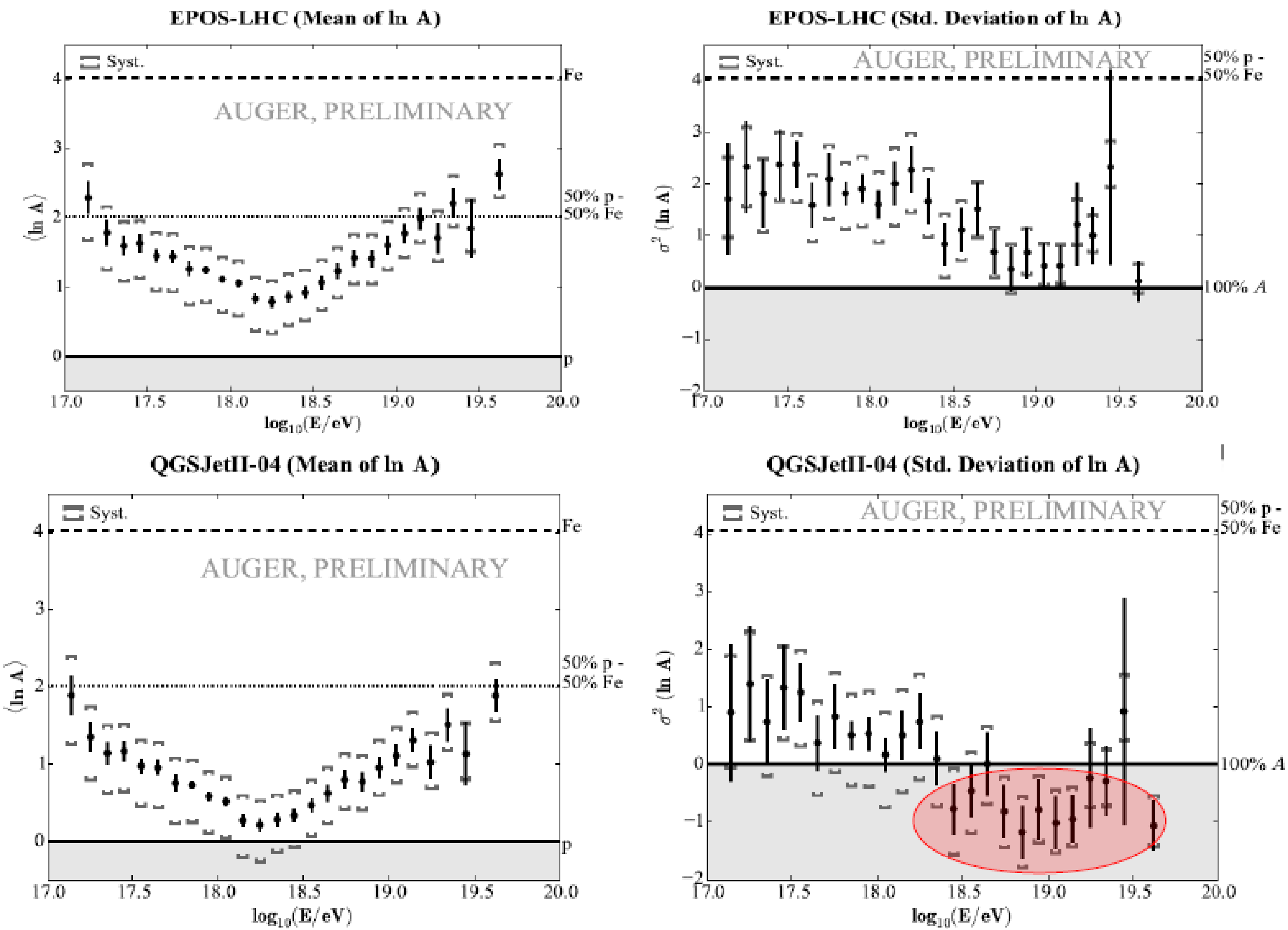
- **Goal of Astroparticle Physics :**
  - astronomy with high energy particles
- **How to test hadronic interactions ?**
  - if the source mechanism is well understood we could have a known beam at ultra-high energy ($10^{10}$ GeV and more)
    - unlikely situation
  - reasonable minimum limits from CR abundance :
    - low = hydrogen (proton)
    - high = 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 : tests with PAO**

# Model Consistency using Electromagnetic Component

## Details on following results shown by A. Yushkov

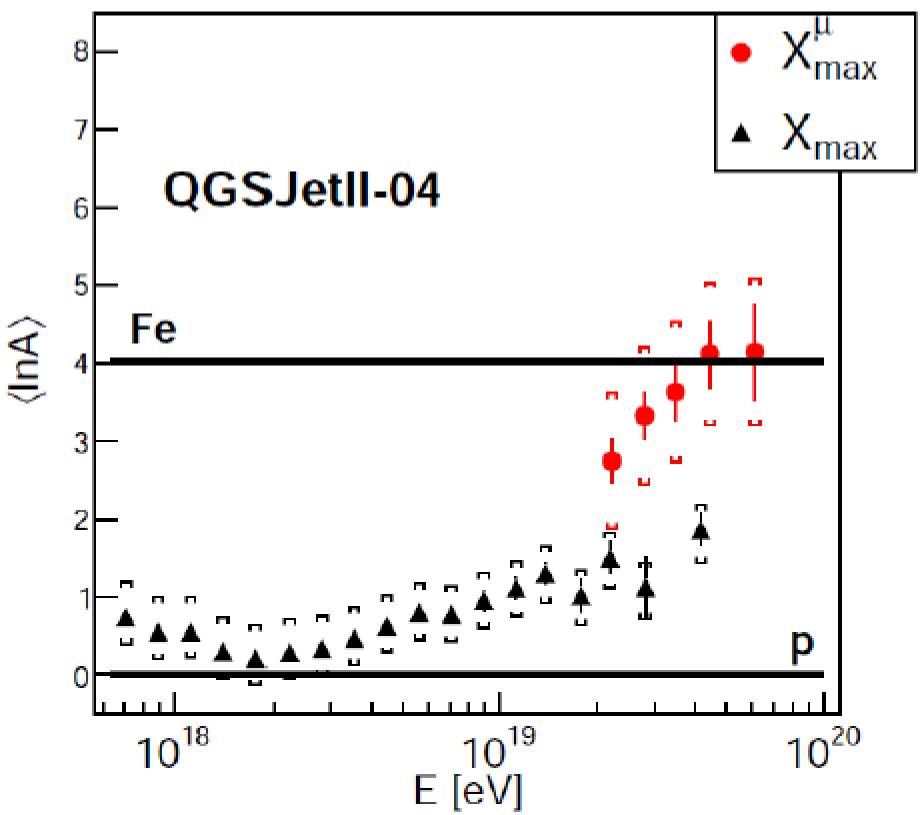
- std deviation of lnA allows to test model consistency.

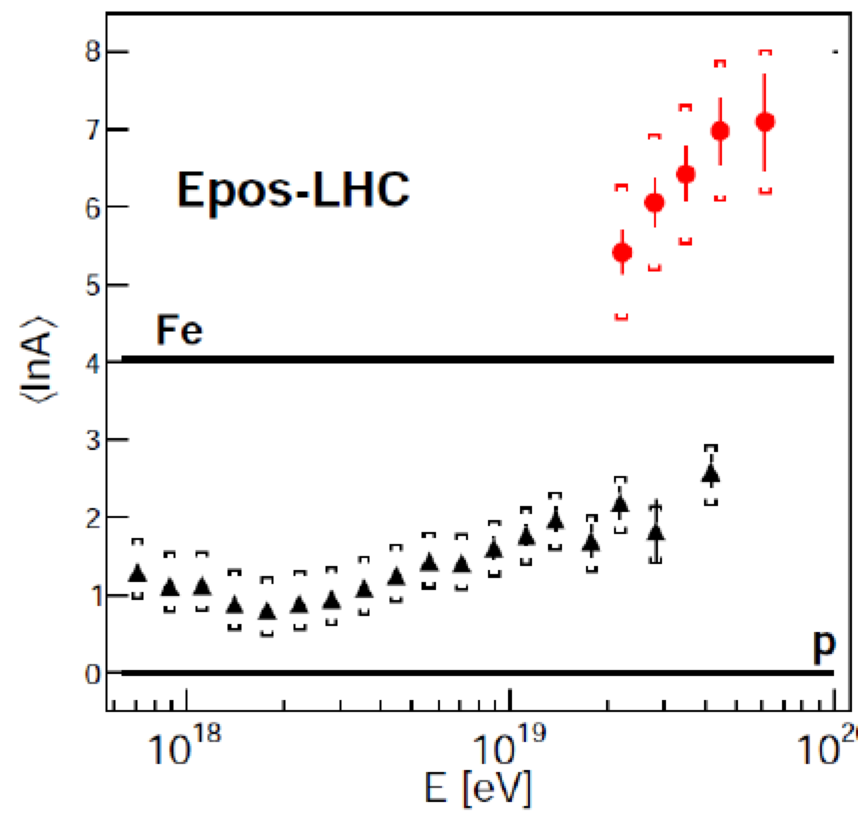


# Muon Production Depth (MPD)

## 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 (low mass diffraction) and model consistency (forward baryon production at high energy): direct constraint on hadronic interactions.



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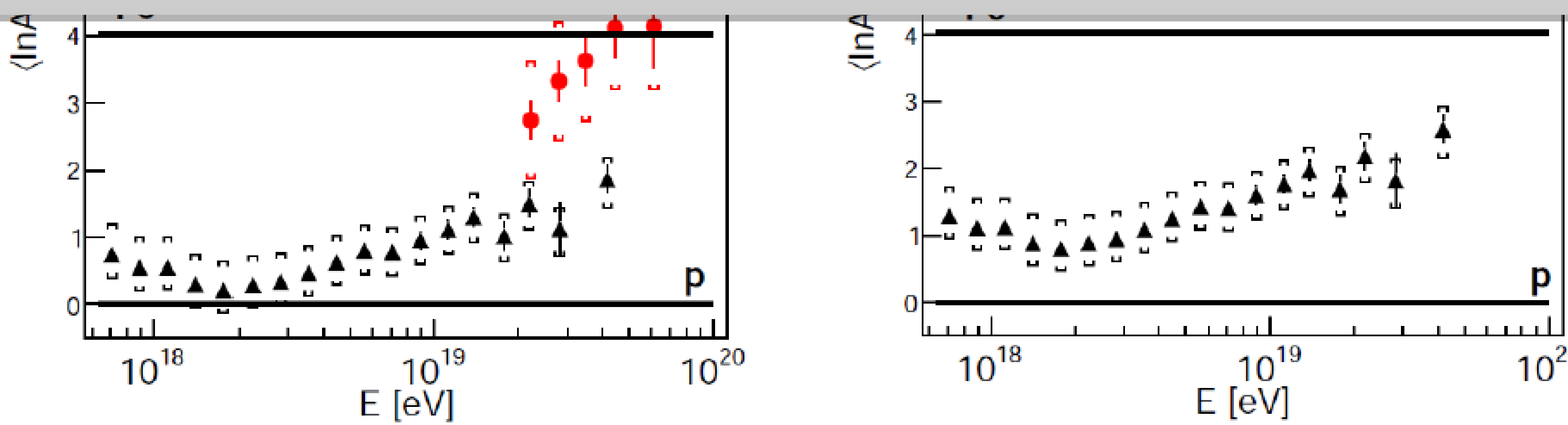
**No MC model compatible with Pierre Auger Observatory data !**

**Can we improve the current situation ?**



# 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 (2017-)

**Motivation :**

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

**Motivation :**

- **Hard Pomeron-Pomeron connexion**

**Motivation :**

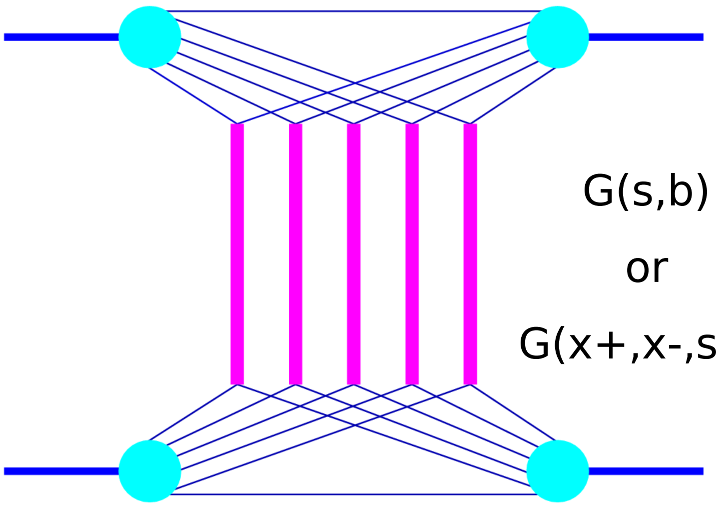
- **binary scaling in hard probes**

# Cosmic Ray Hadronic Interaction Models

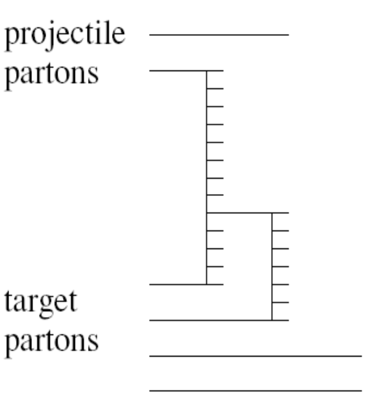
- **Theoretical basis :**
  - pQCD (large $p_t$)
  - Gribov-Regge (cross section with multiple scattering)
  - energy conservation
- **Phenomenology (models) :**
  - hadronization
    - string fragmentation
    - EPOS : high density effects (statistical hadronization and flow)
  - diffraction (Good-Walker, ...)
  - 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)**

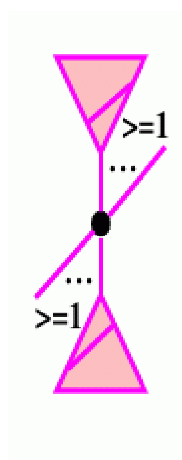
# Cross Section and Multiplicity in Models




EPOS

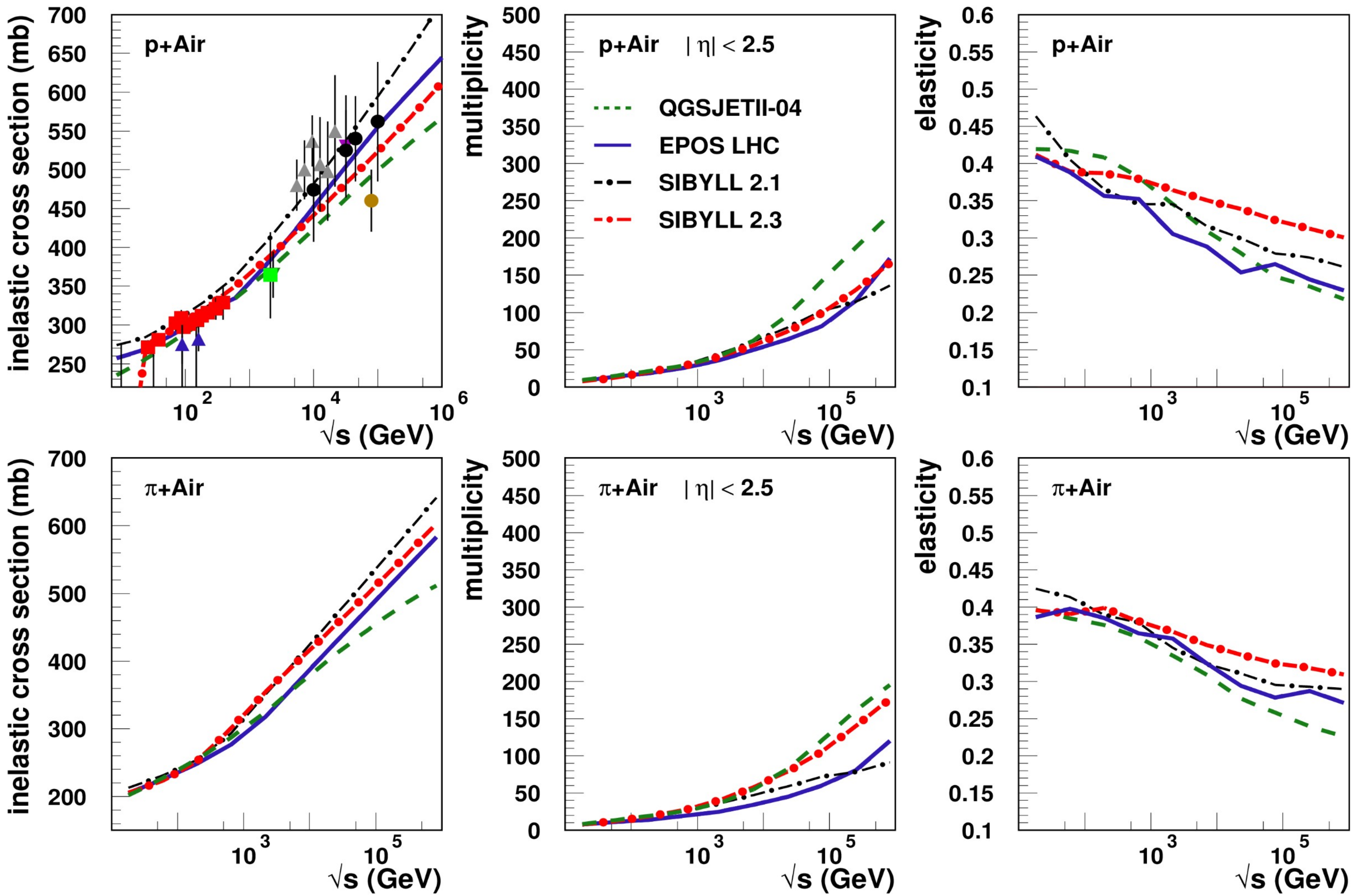



QGSJET II

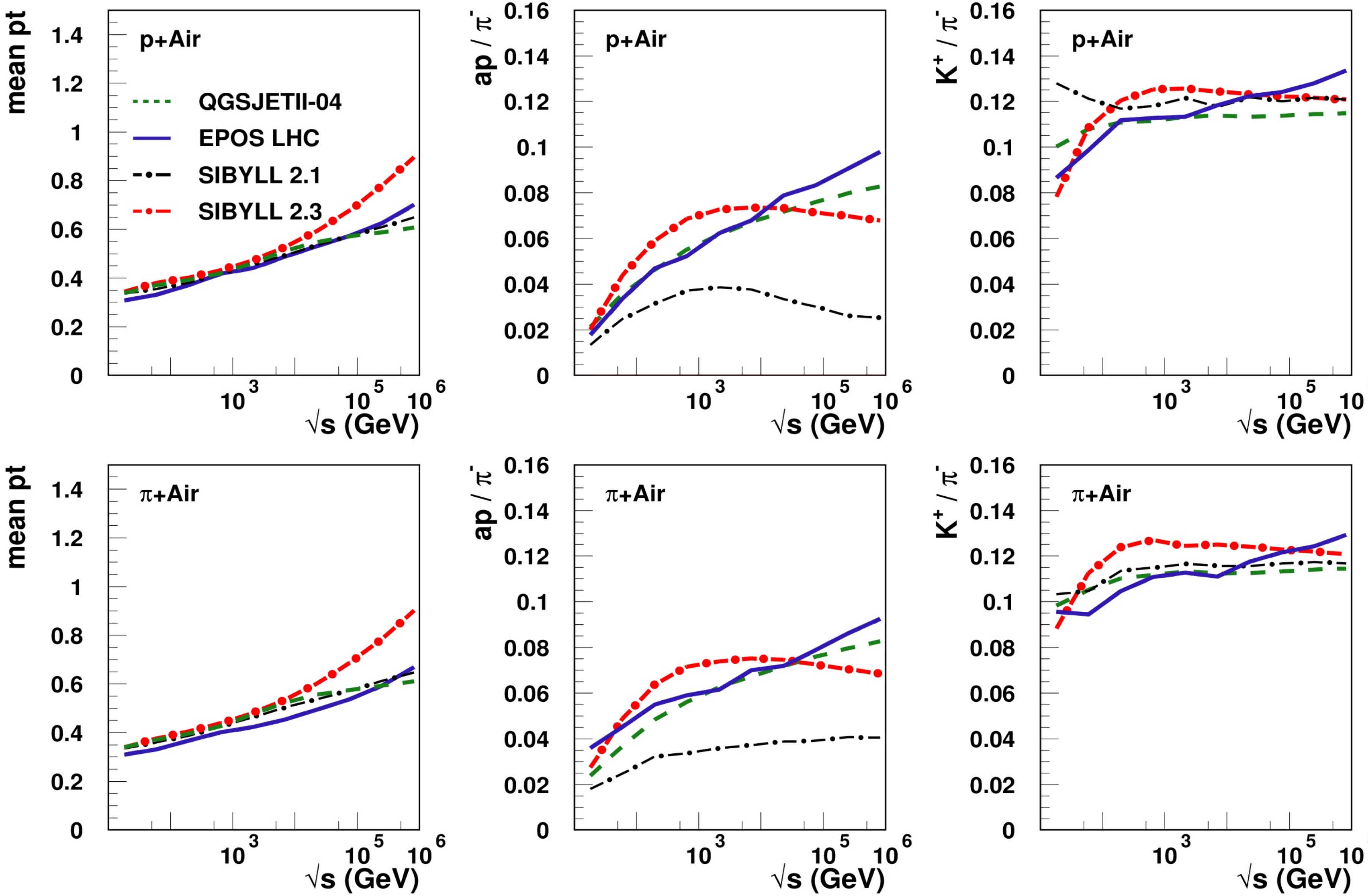



- **Gribov-Regge and optical theorem**
  - Basis of all models (multiple scattering) but
    - Classical approach for QGSJET and SIBYLL (no energy conservation for cross section calculation)
    - Parton based Gribov-Regge theory for EPOS (energy conservation at amplitude level)
- **pQCD**
  - Minijets 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)



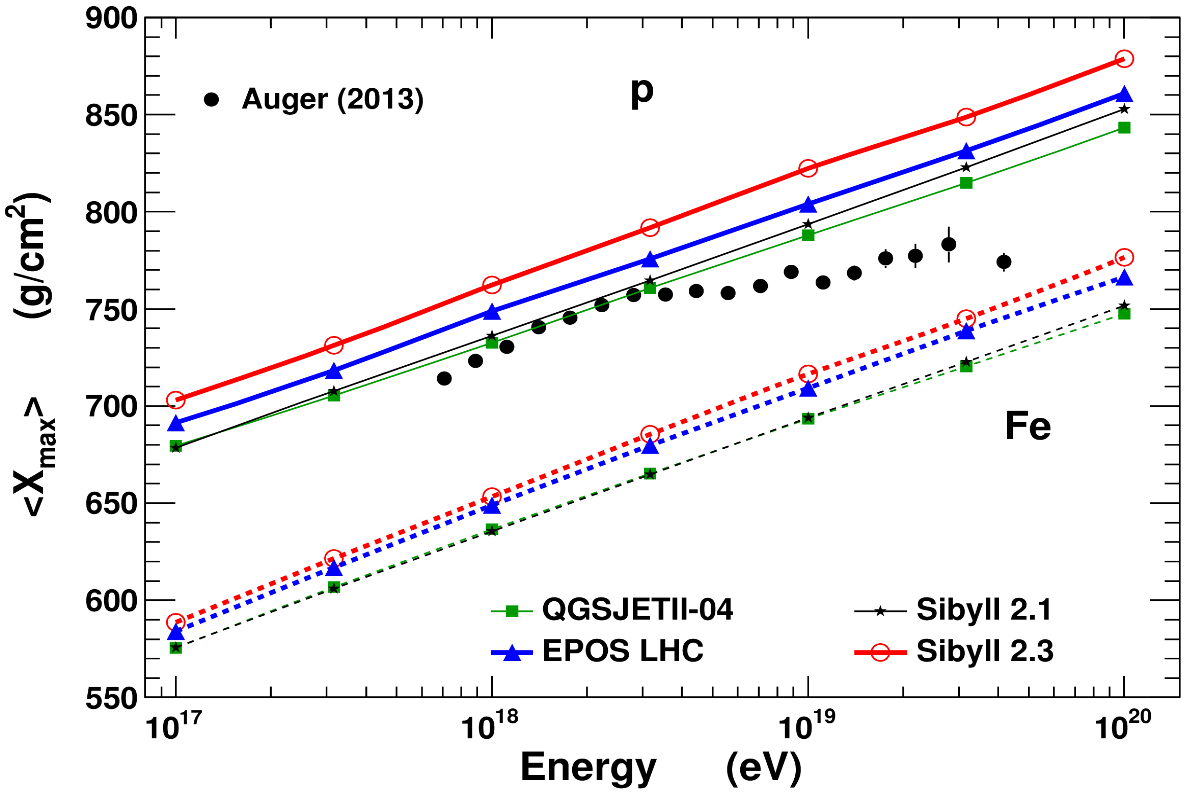
# Model Predictions (2)

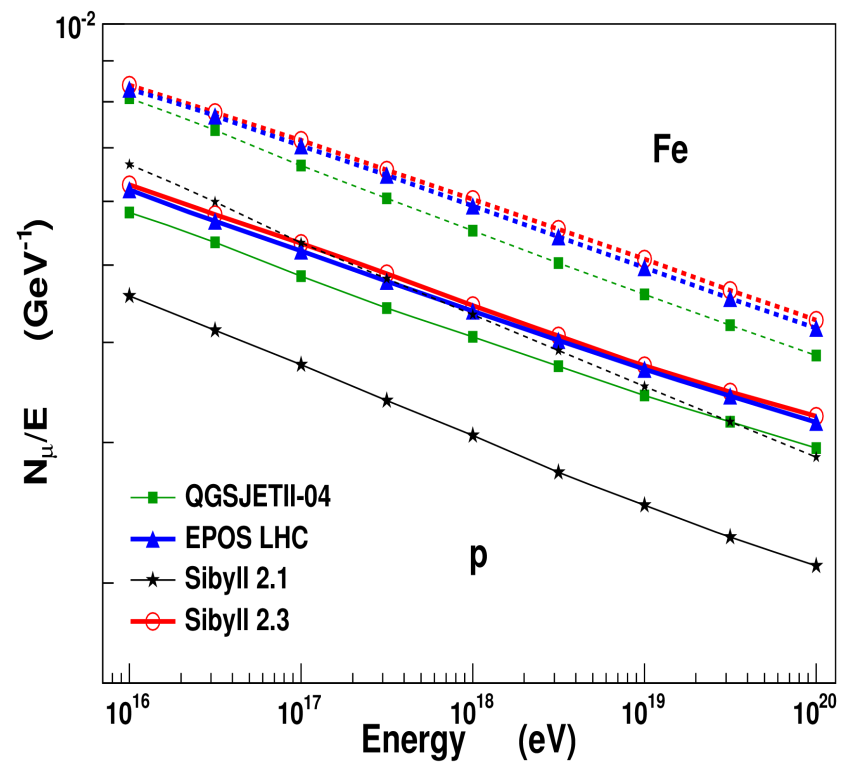


# Air Shower Observables

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

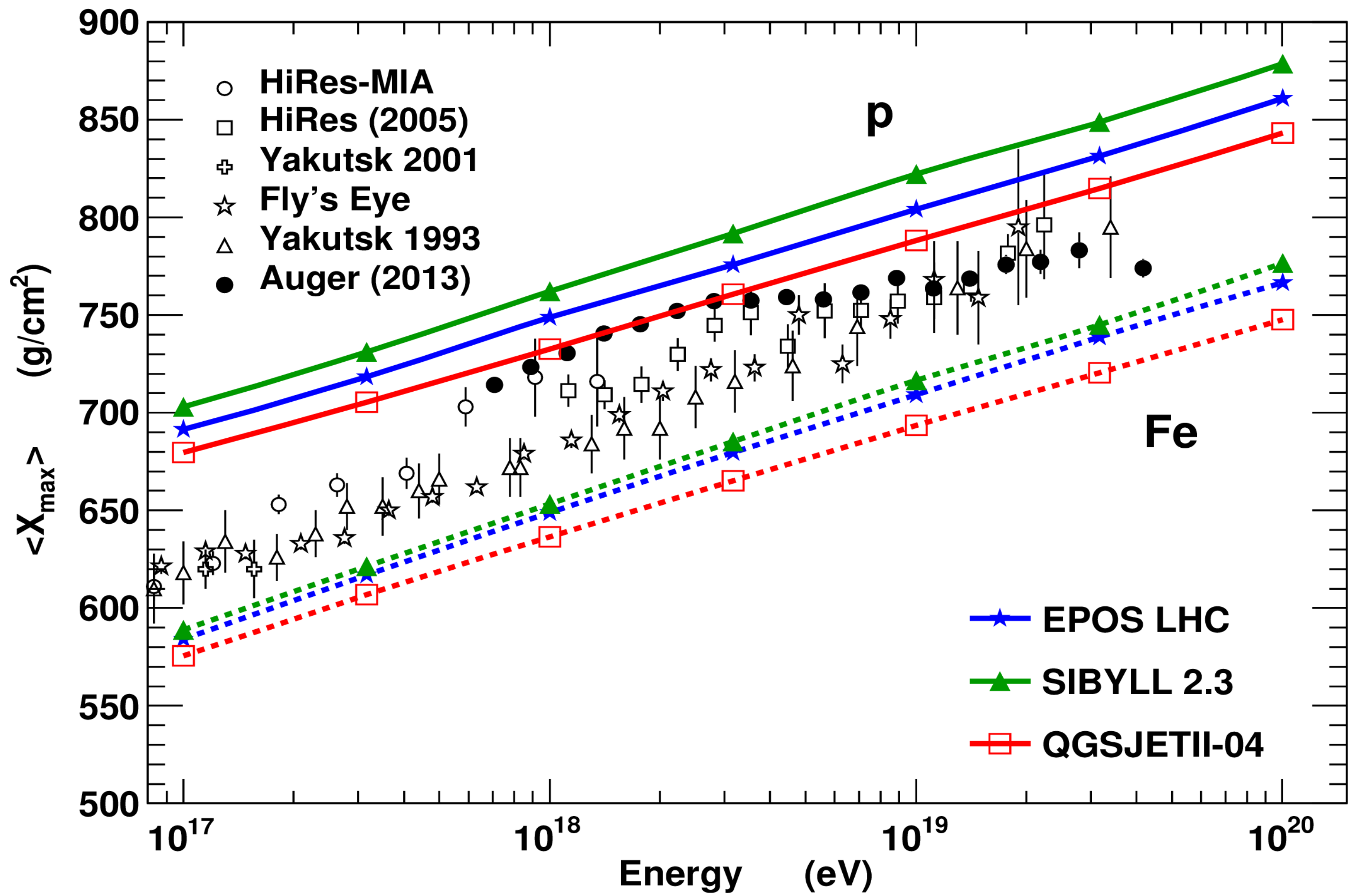
- Sibyll 2.3 have quite large $X_{max}$ for proton
- different muon spectra between models



# $X_{max}$ Model Uncertainties

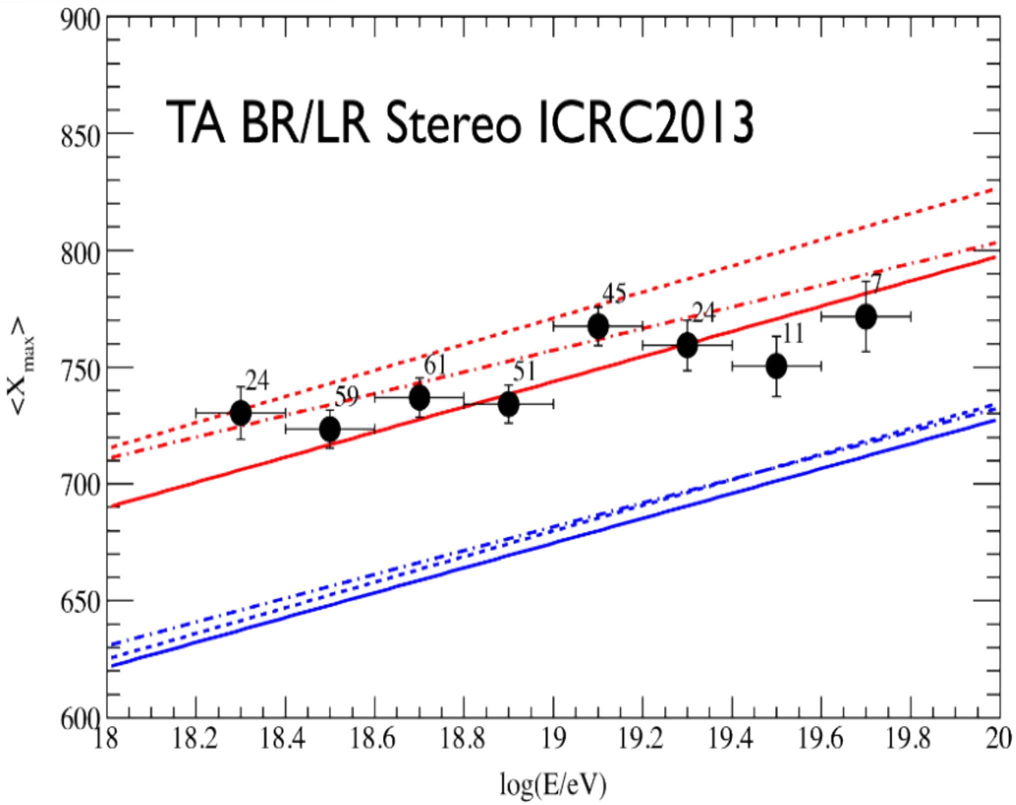
**After LHC still about 20g/cm² (40g/cm²) difference between EPOS LHC (Sibyll 2.3) and QGSJETII-04 while only ~10g/cm² by changing p-Air within LHC uncertainties** (see S. Ostapchenko, Phys. Rev. D 89, 074009 (2014))

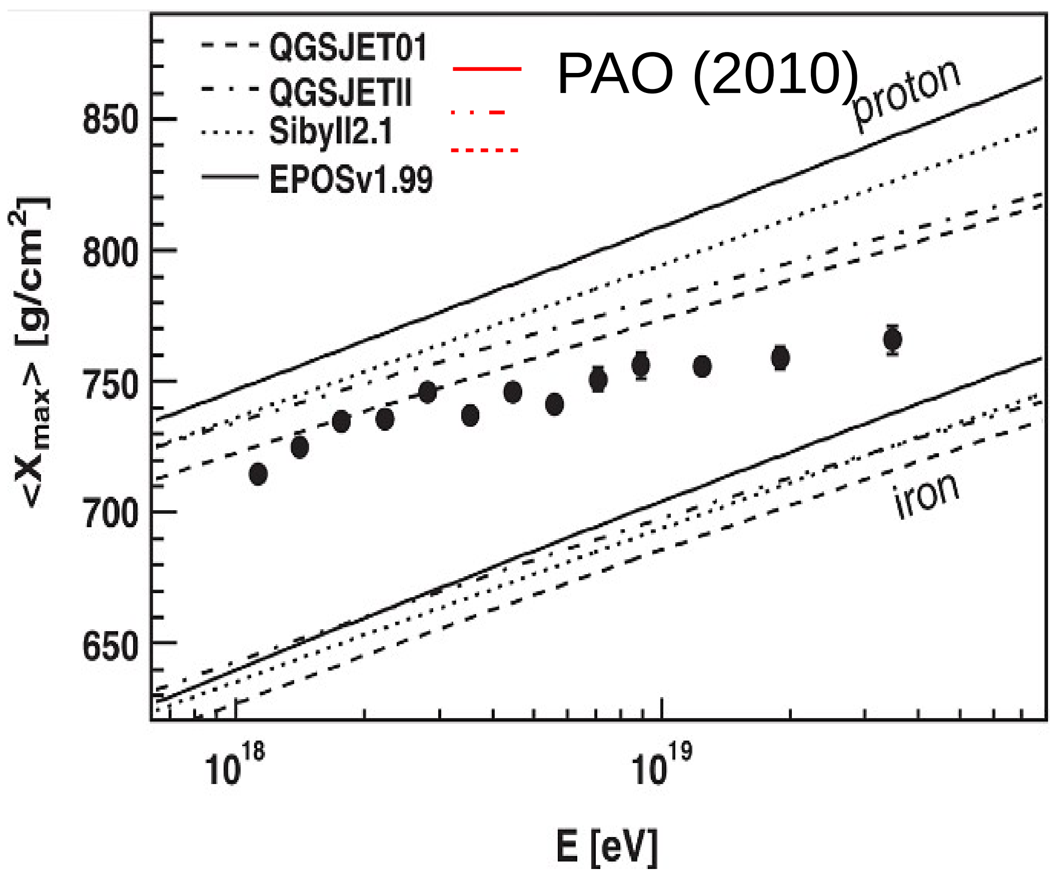


# PAO vs TA before LHC

## Data very similar but different models used

- TA data tested against QGSJETII-03 (only) : compatible with proton
- PAO data best described by EPOS 1.99 (<$X_{max}$> vs RMS consistency)
  - not compatible with pure proton (neither with pure iron) : mixed

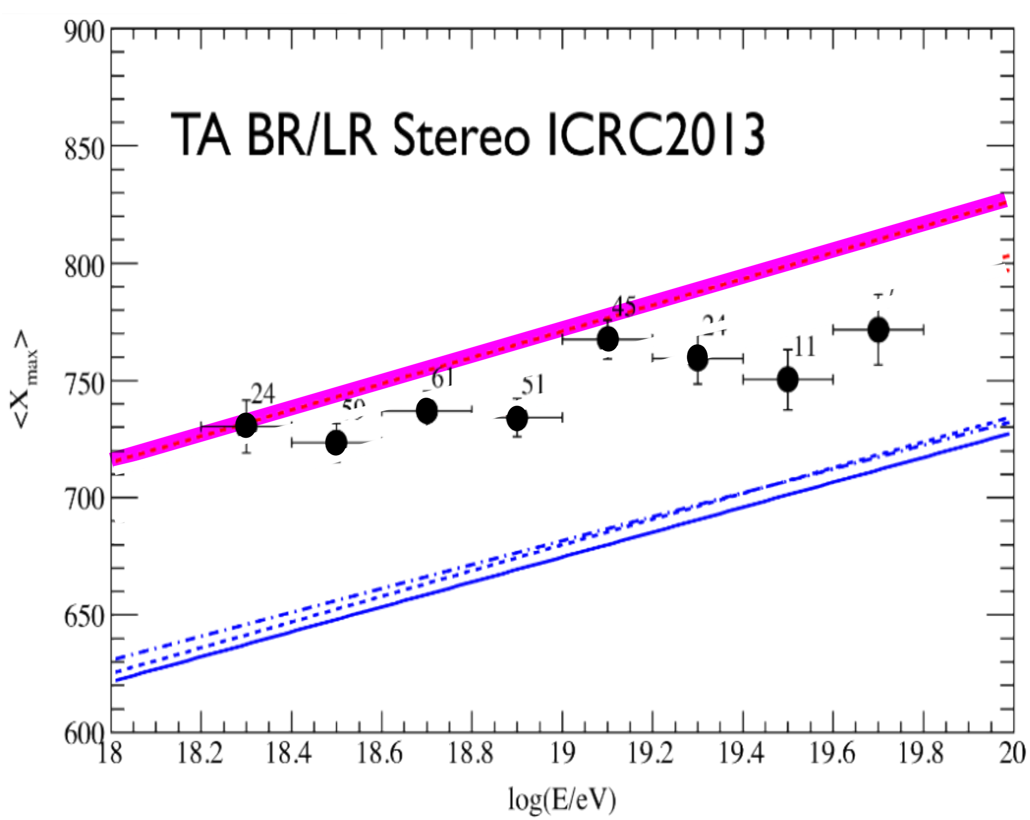


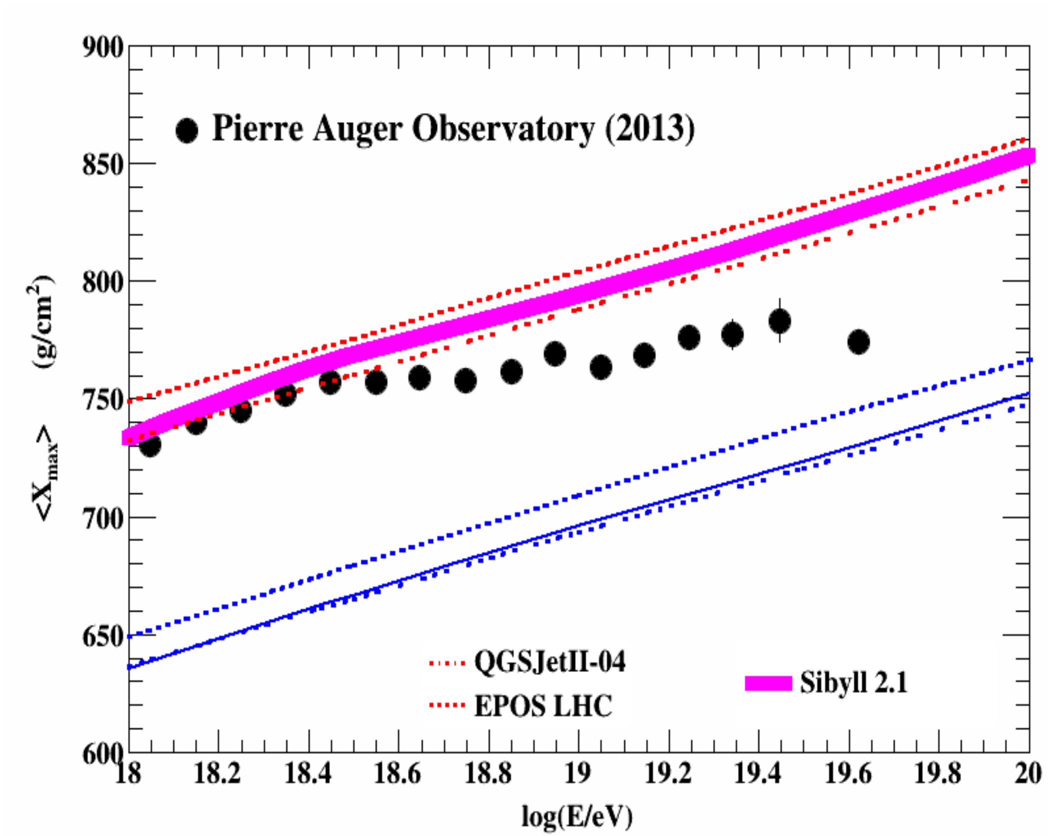



# PAO vs TA after LHC

## Composition with TA and PAO are similar

- light composition below the Ankle
- change toward heavier composition above the Ankle



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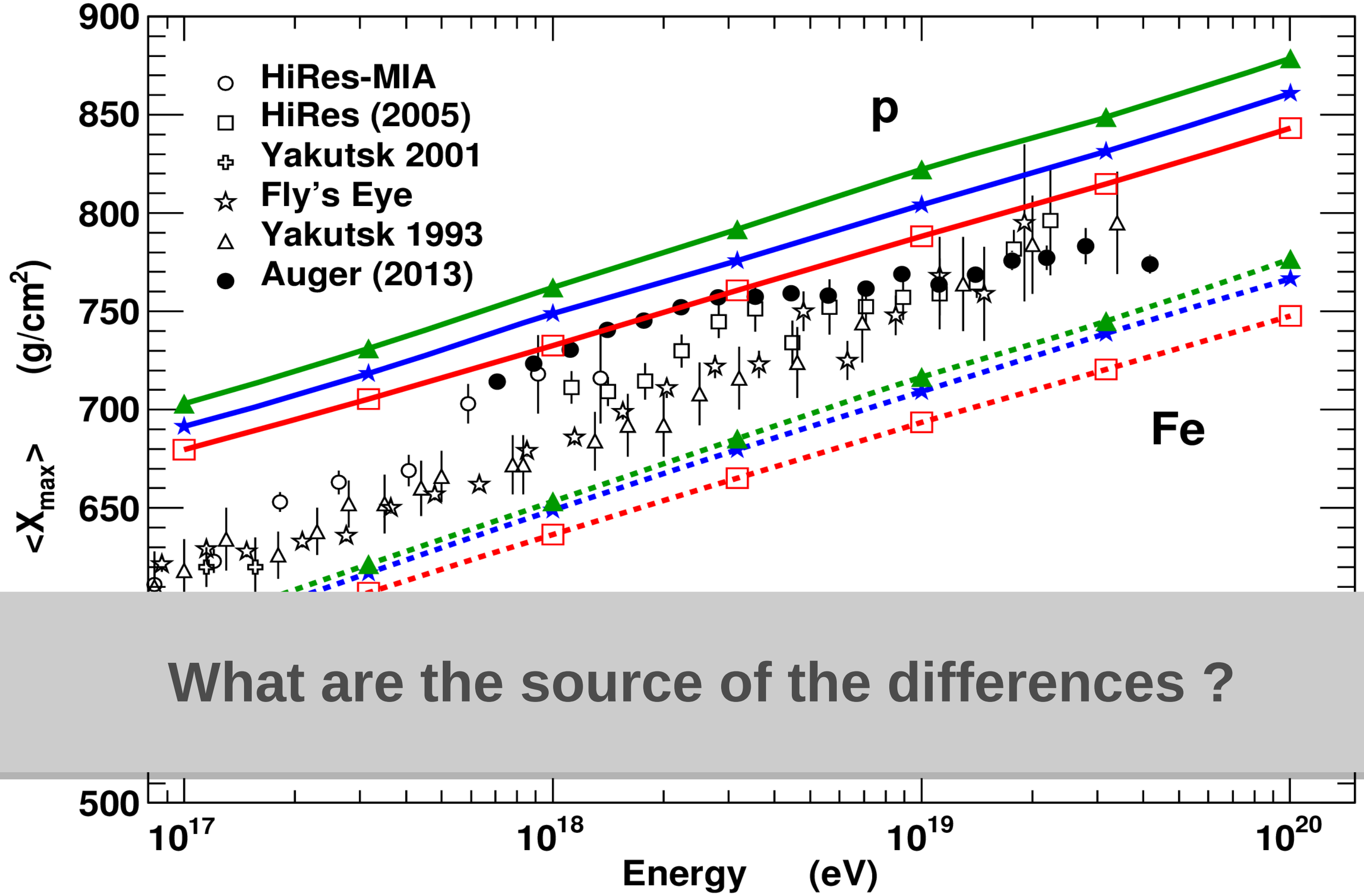
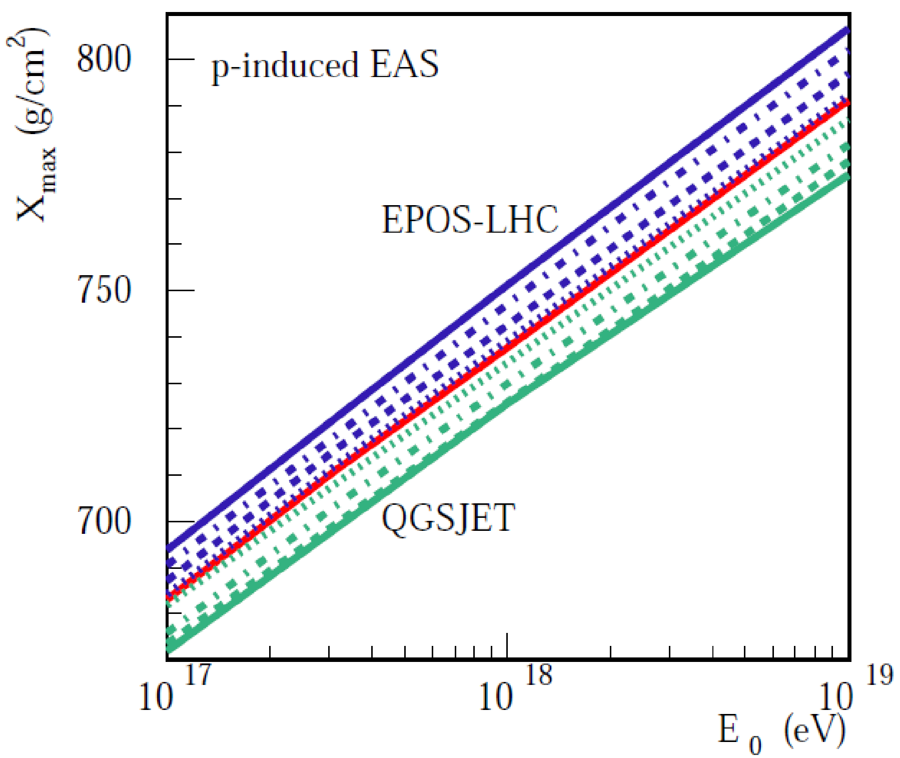
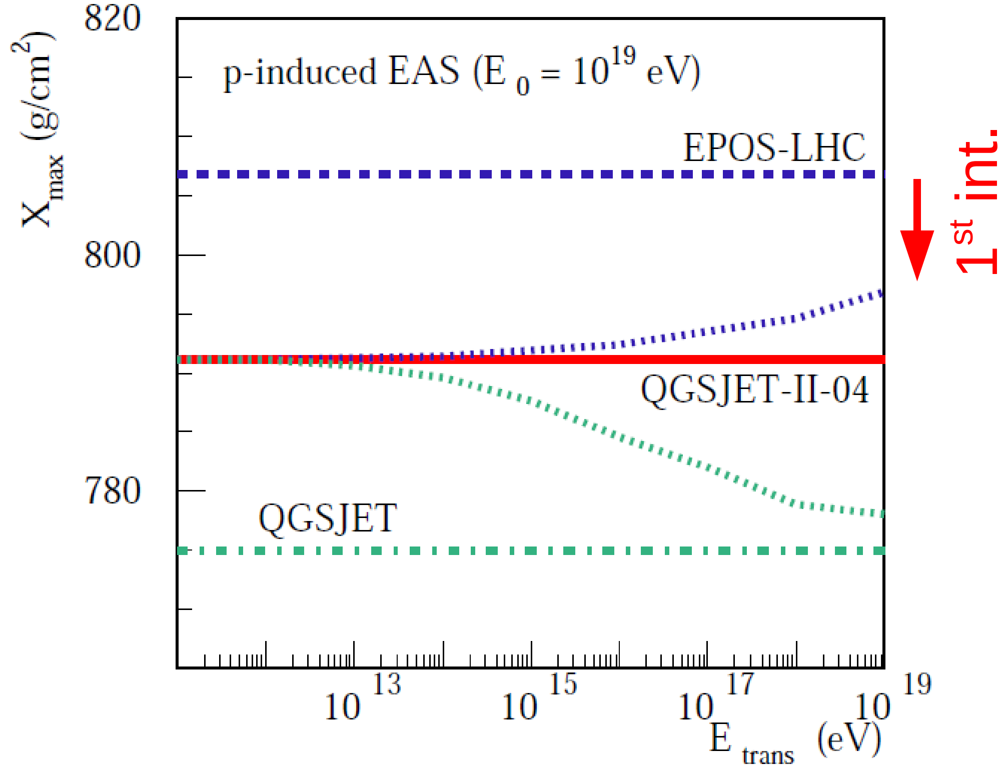



**What are the source of the differences ?**

# 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

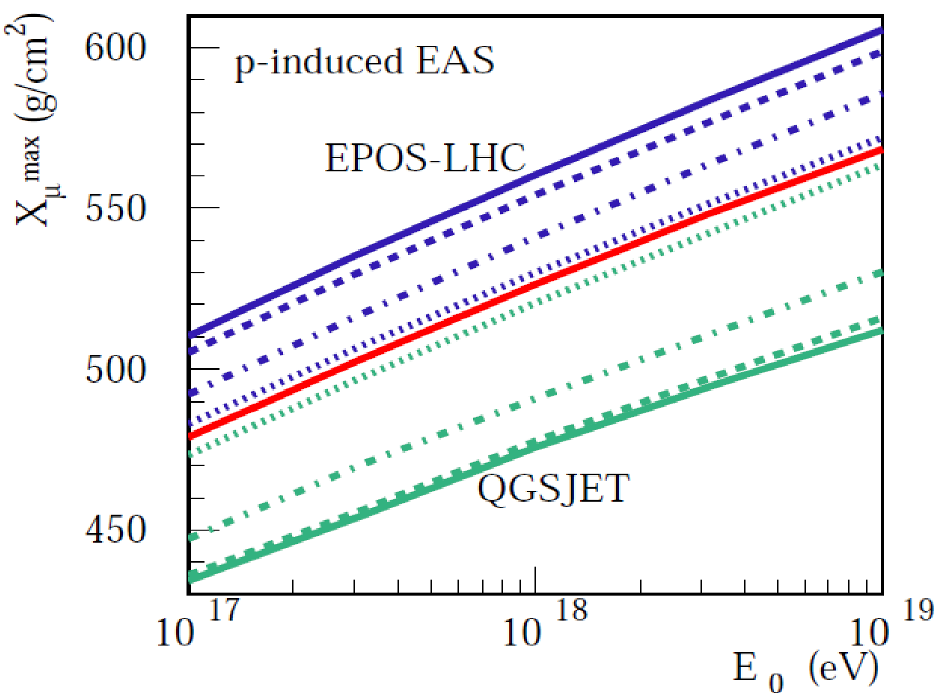


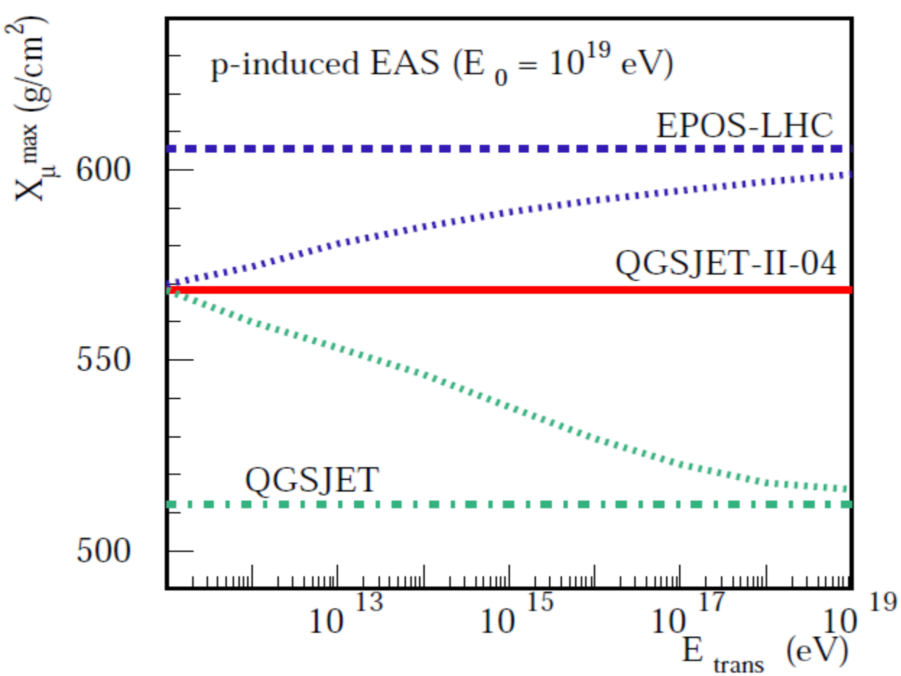




From arXiv:1601.06567 by S. Ostapchenko and M. Bleicher

# Mix models to identify source of differences

- **Different mixing to extract useful information on $X^{\mu}_{max}$**
  - 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 | $X_{max}$ | $X^{\mu}_{max}$ |
|---|---|---|
| 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

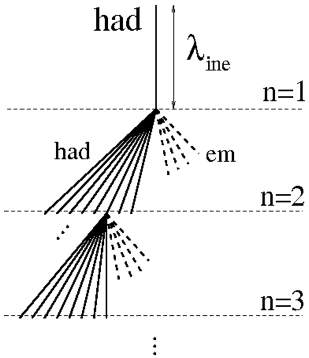
- **Differences in first interaction dominates $X_{max}$ uncertainties**
  - ➔ from where ? results at LHC are very similar ...
- **30% of remaining uncertainties in $X_{max}$ due to different results for pion-air interactions at high energy**
  - ➔ Problem : no data for pion interactions at high energy
- **$X^{\mu}_{max}$ 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 ? ... other effect ?
- **Test using EPOS LHC and Sibyll 2.3**

# Muon Number

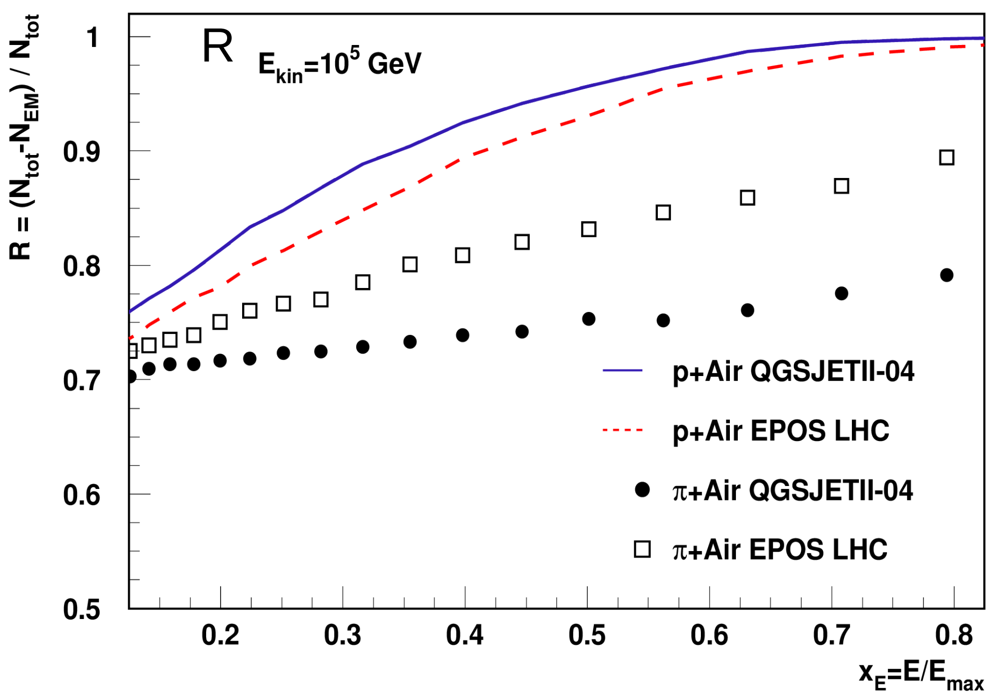
- From Heitler

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

$$N_{tot} = N_{had} + N_{em}$$




➡ 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 $\rho^0$ in p- or $\pi$-Air interactions**

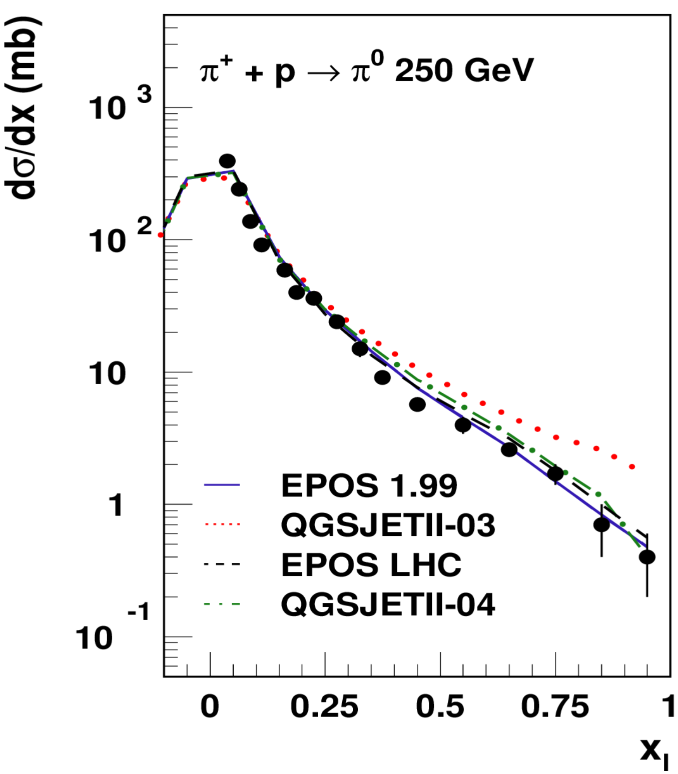
More fast (anti)baryons or $\rho^0$ or larger $N_{tot}$ = $\alpha \rightarrow 1$ = more muons

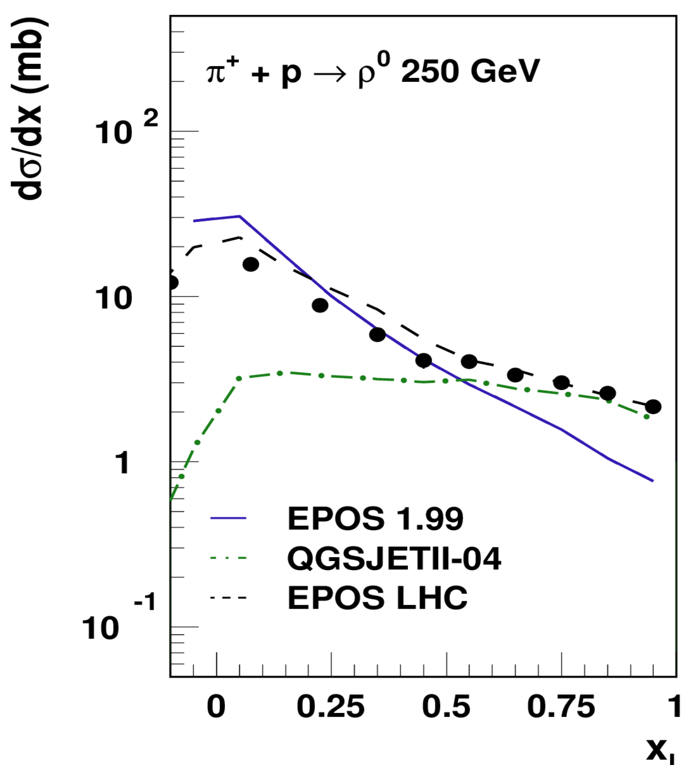
T. Pierog et al.,Phys.Rev.Lett. 101 (2008) 171101

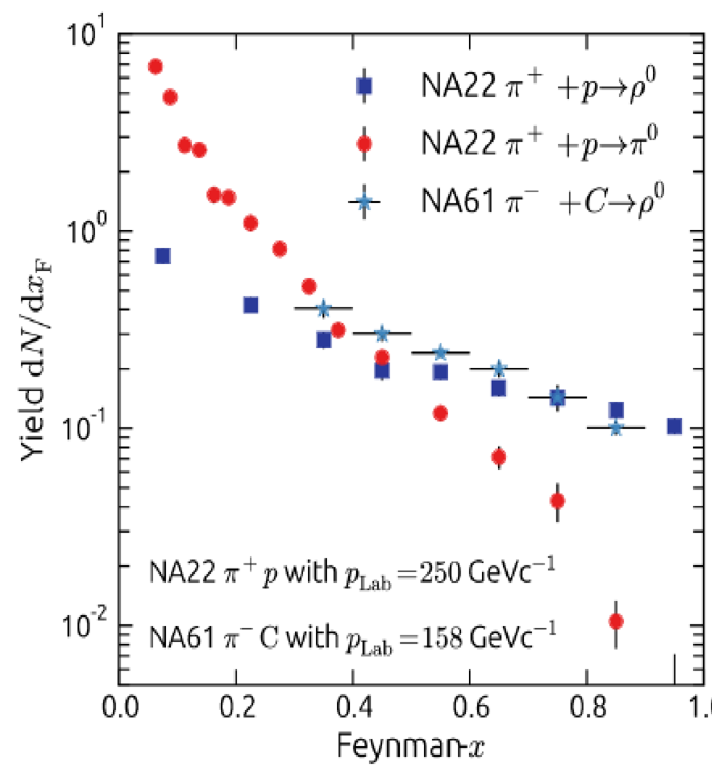
# Pion Leading Particle Effect

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

- same effect as baryon production : forward $\pi^0$ replaced by charged pions (reduced leading $\pi^0$)
- increase muon production
- higher minimum muon energy (less generations) compared to baryons
  - different effect on MPD for resonance (shallow) or baryon (deep)



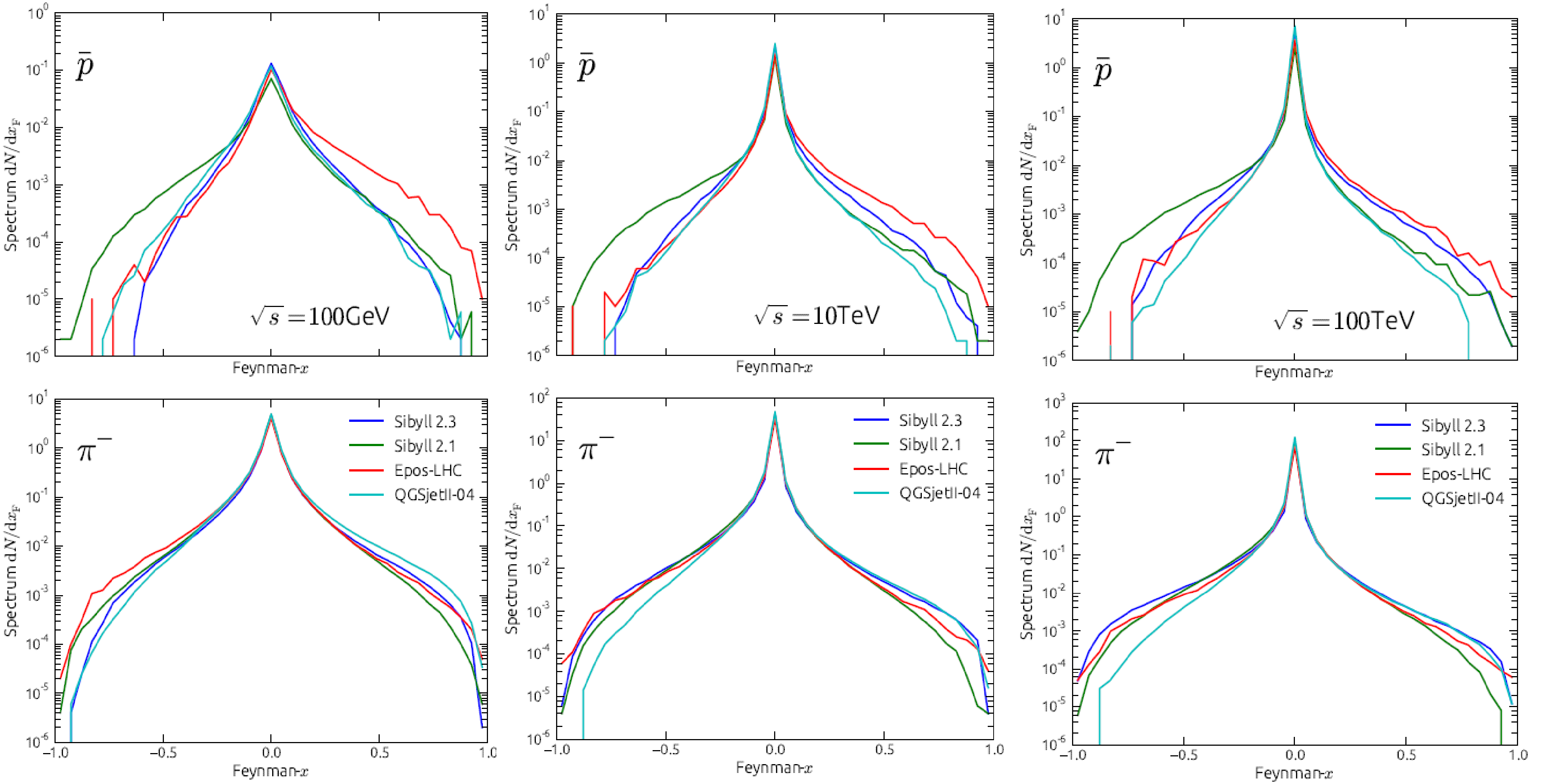




Plot from F. Riehn (KIT)

# Pion(+)-Carbon Interactions

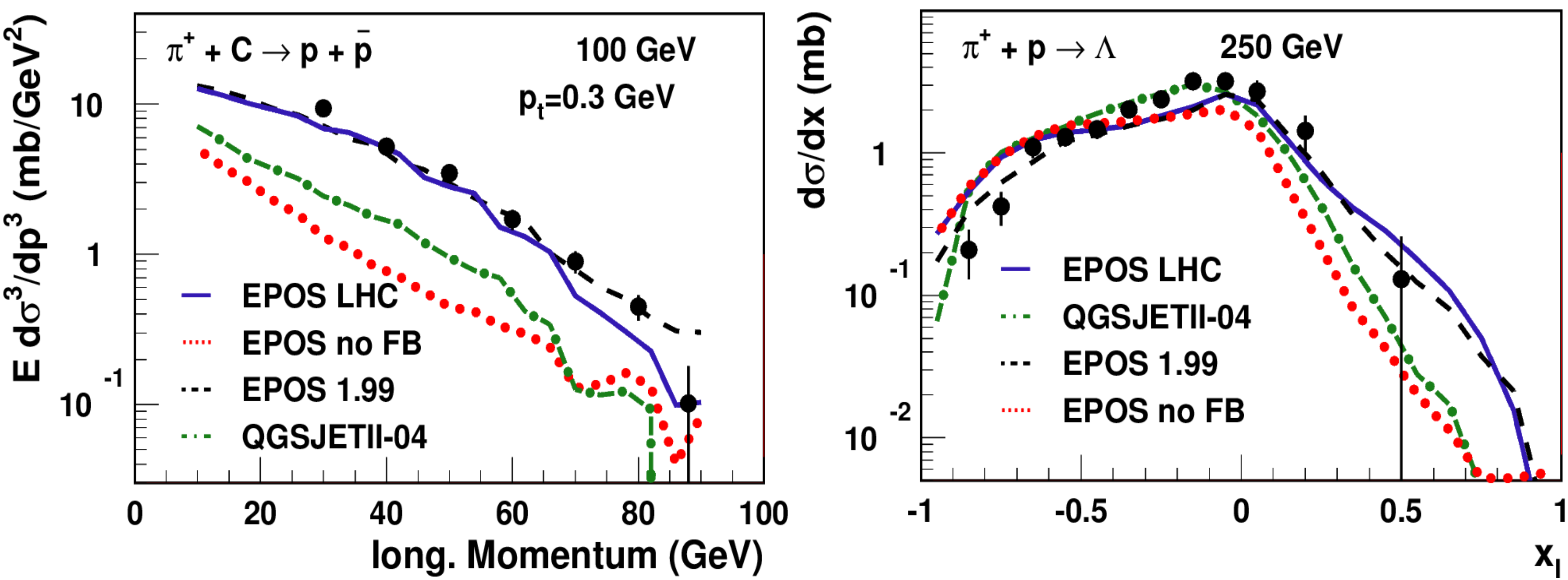
## Different model predictions as a function of energy:

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
    - ◆ Forward Baryon production added in EPOS to reproduce low energy data



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  - target mass dependence

- **New data set from NA49 (G. Veres' PhD)**
  - test $\pi^+$ and $\pi^-$ interactions and productions at 158 GeV with C and Pb target
  - confirm large forward proton production in $\pi^+$ and $\pi^-$ interactions but not for anti-protons
    - forward protons in pion interactions are due to strong baryon stopping (nucleons from the target are accelerated in projectile direction)
    - strong effect only at low energy

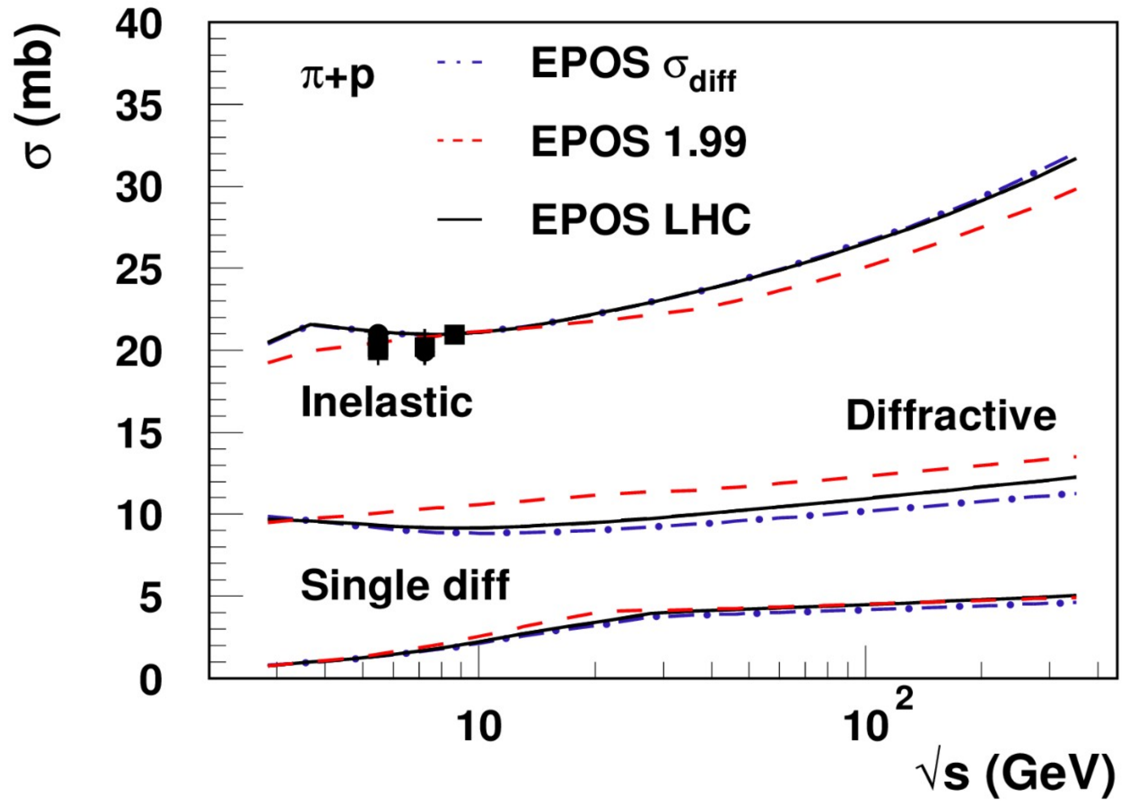
→ EPOS overestimate forward baryon production at high energy

# Modified Pion Interactions in EPOS

- **Rapidity gap measurement fixed by LHC**
  - ➡ should not change proton diffraction
- **MPD driven by long chain of pion-Air interaction**
  - ➡ Modify in EPOS pion diffraction only
  - ➡ Test change of reduced diffractive cross-section
- **2 "tunes"**
  - ➡ EPOS (LHC) $\sigma_{diff}$ :

    diffractive cross section reduced
  - ➡ EPOS (LHC) NO FB :

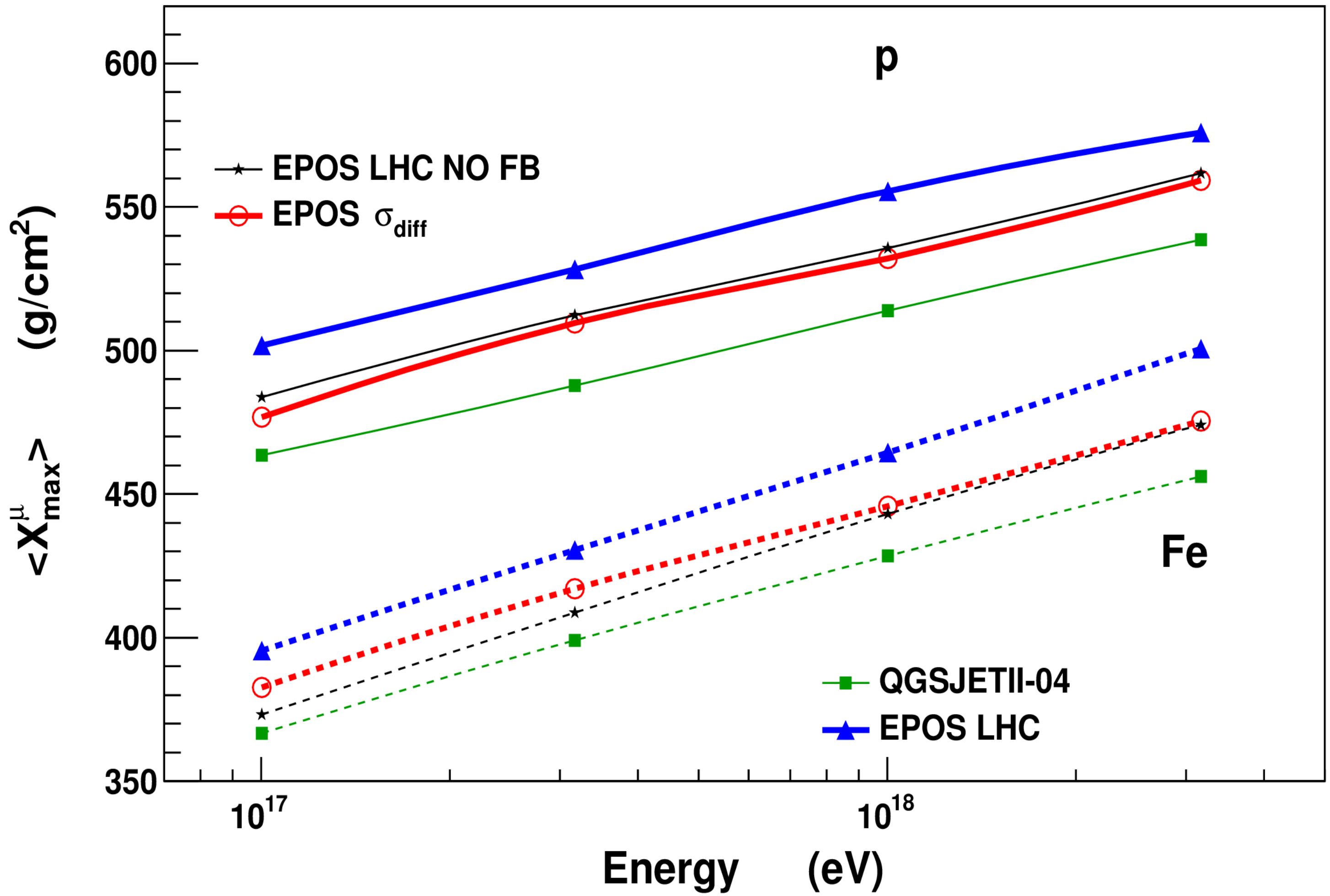
    no additionnal forward baryon production (not retuned to data)



# $\langle X^{\mu}_{max} \rangle$ with modified EPOS LHC

## Same than in mixed models

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




-25 g/cm² for diff

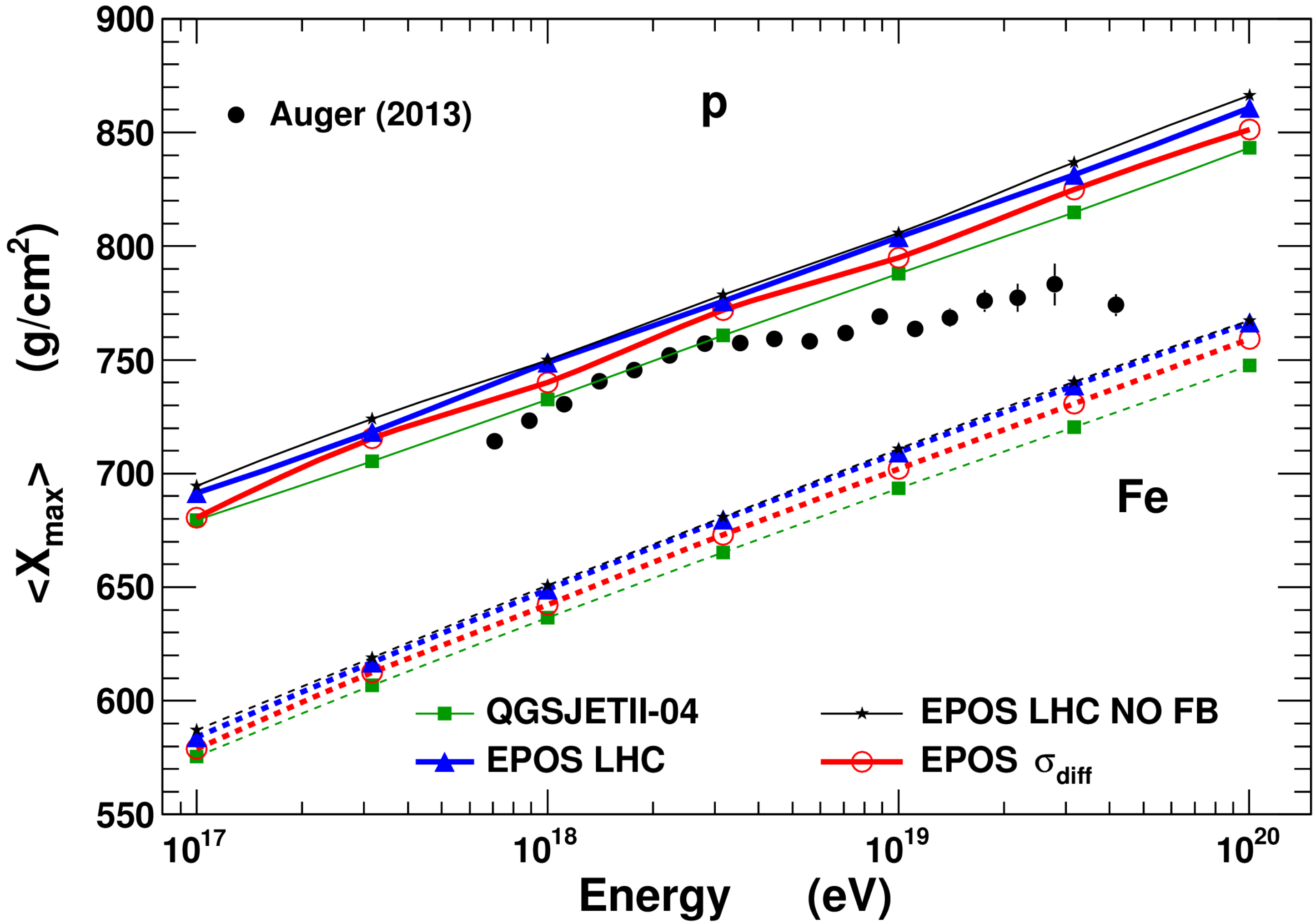
-20 g/cm² for baryons

**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/cm² for diff

~0 g/cm² for baryons

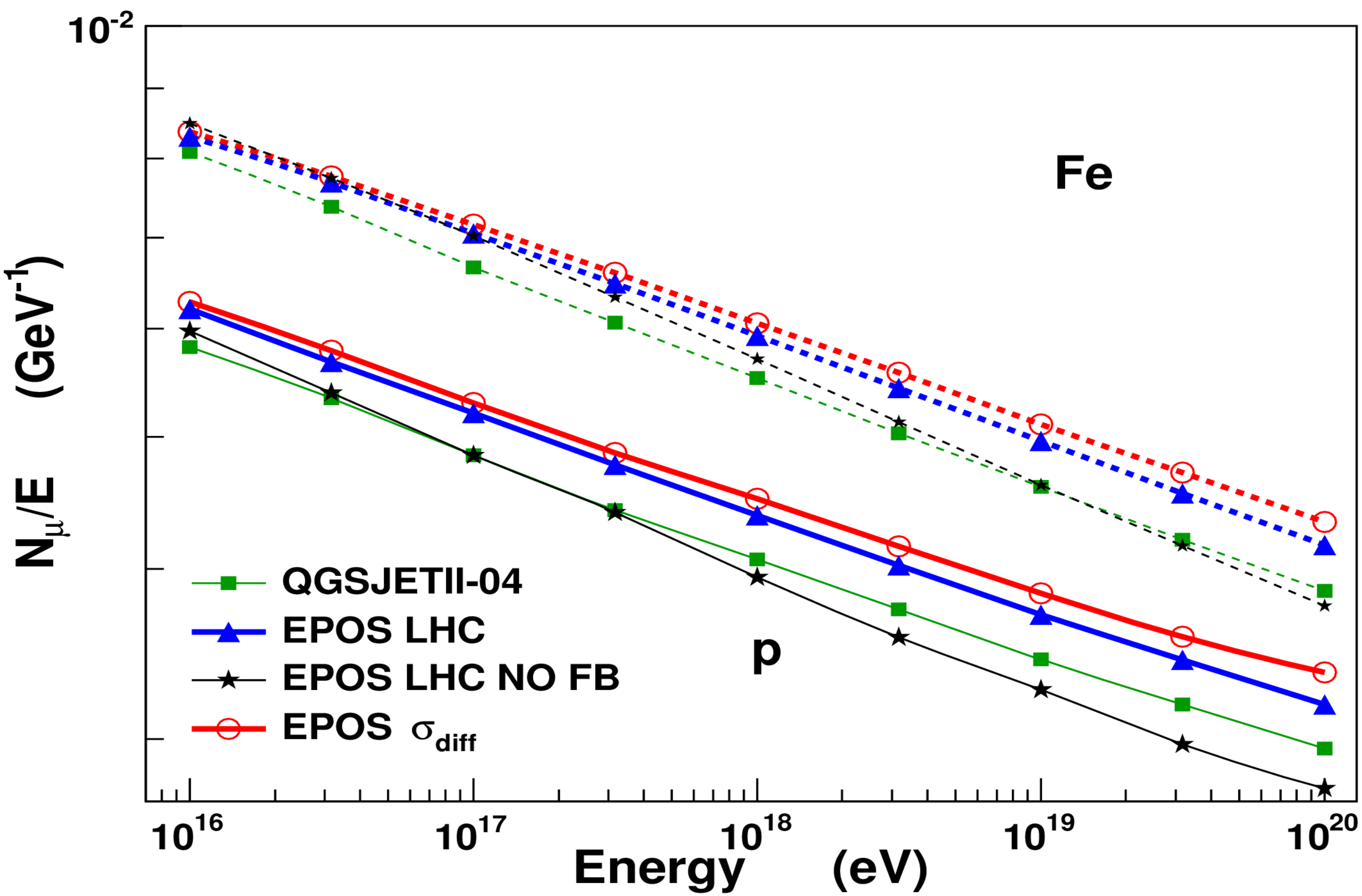
**$X_{max}$ less sensitive to baryon spectra than to pion spectra in pion interactions**

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

# $N_\mu$ with Modified EPOS

## Number of muons depends on the same parameters

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



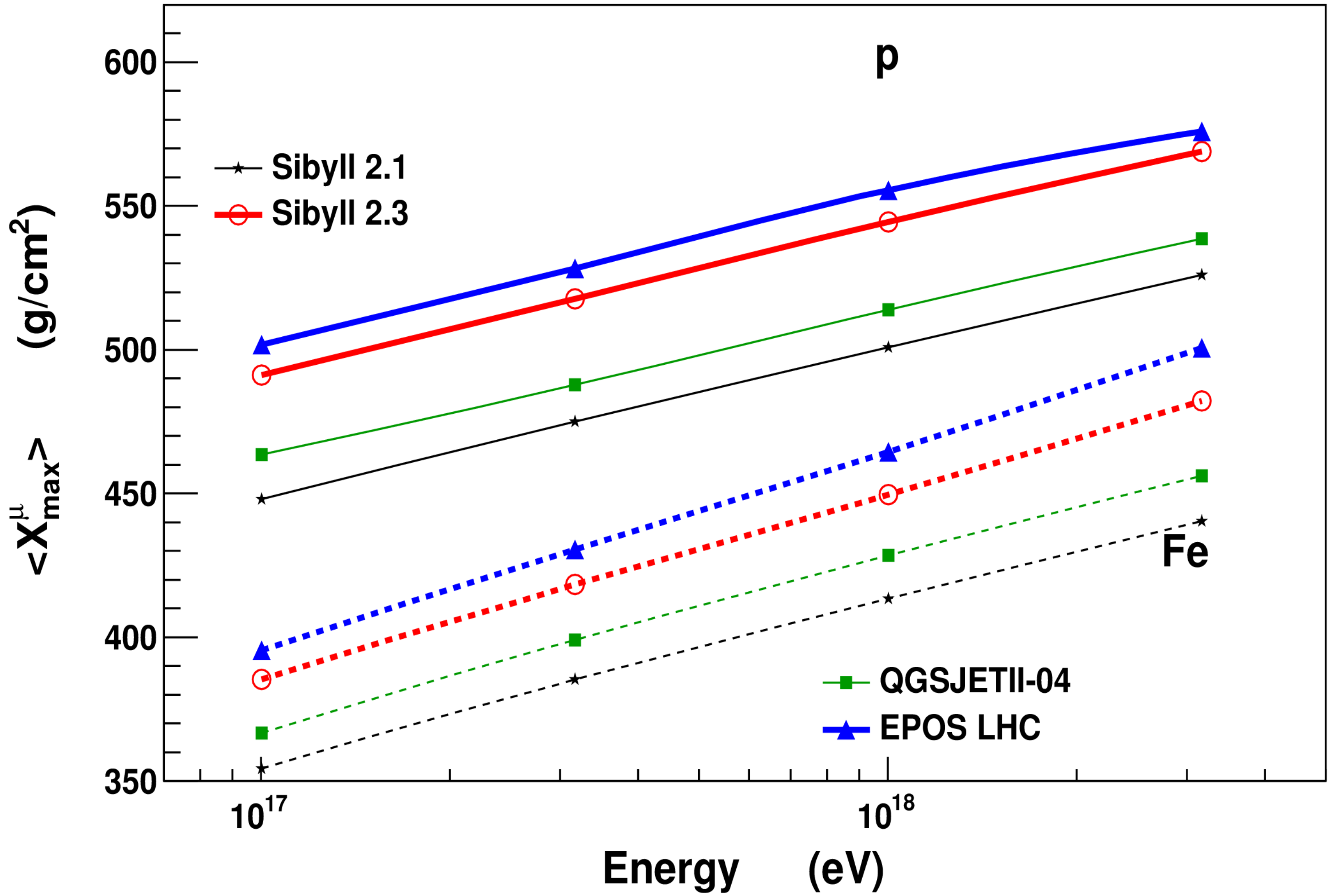

**$N_\mu$ sensitive to baryon (less generation) and meson spectra in pion interactions**

+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 $X^{\mu}_{max}$
  - more forward baryons: higher $X^{\mu}_{max}$

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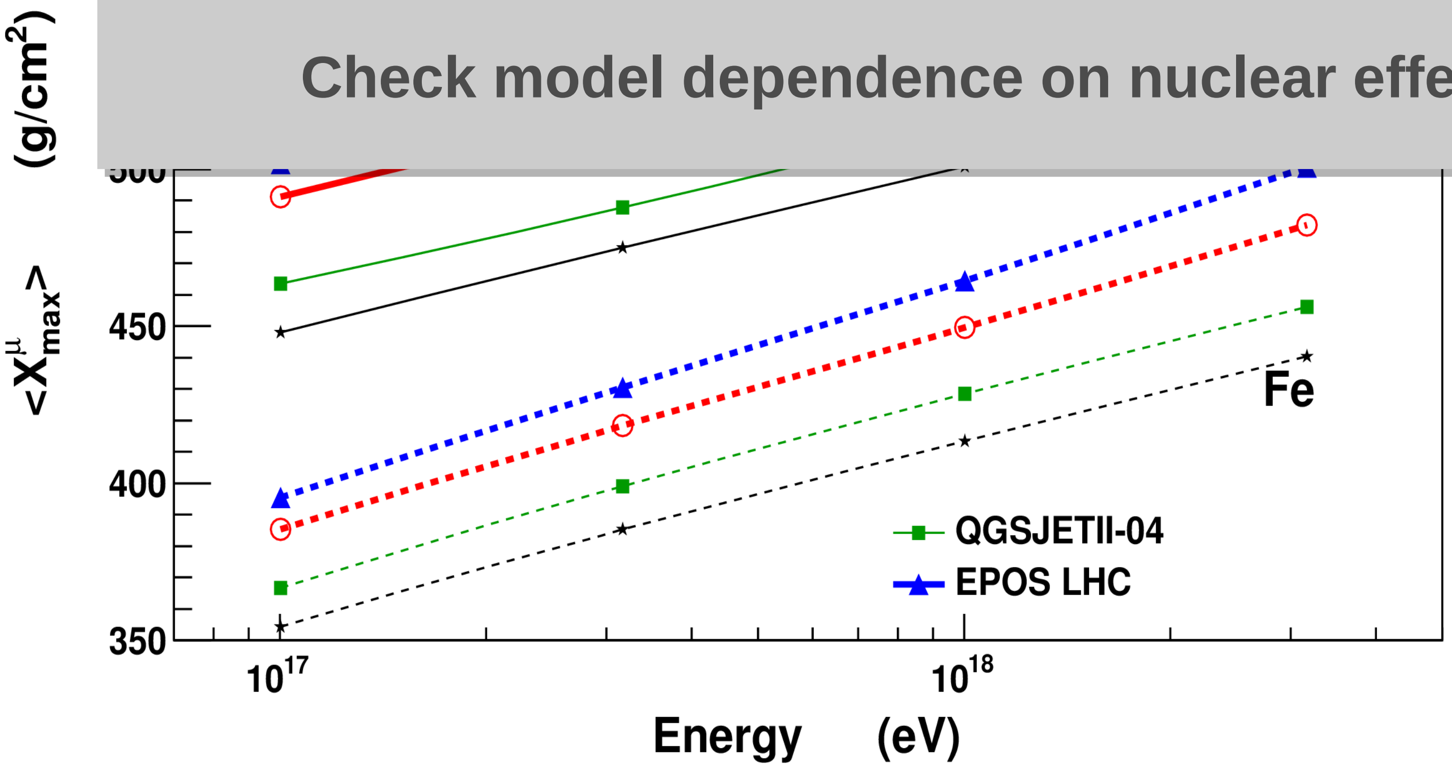
# $<X^{\mu}_{max}>$ with new Sibyll 2.3

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

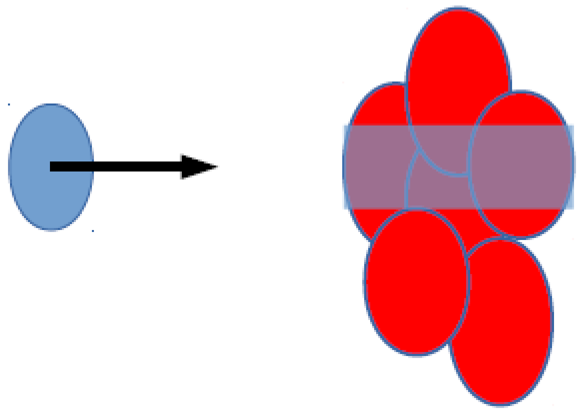
**Baryons important for MPD but not for $X_{max}$ and for first interaction (70% of model difference) !**

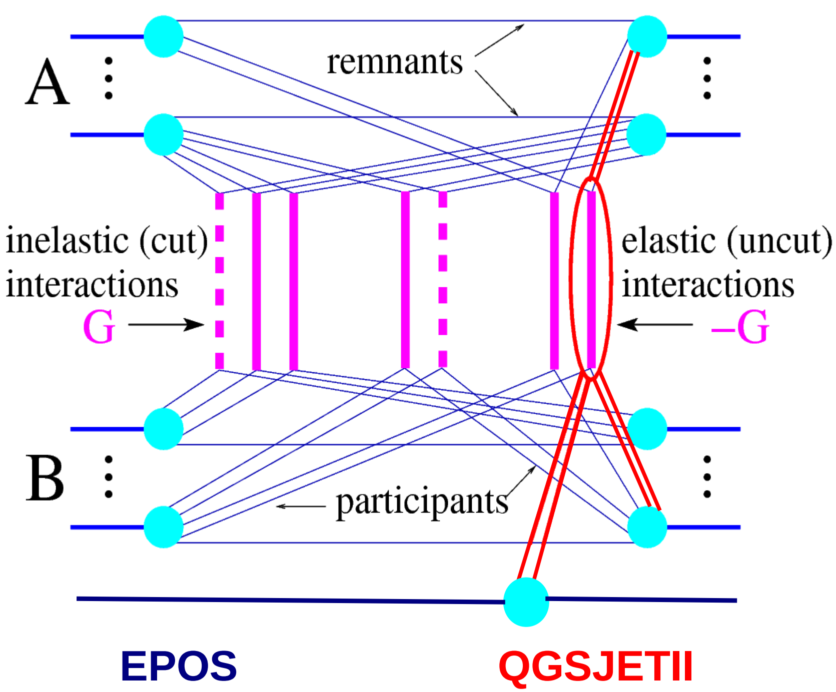
**Check model dependence on nuclear effects ...**




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

# Nuclear Interactions



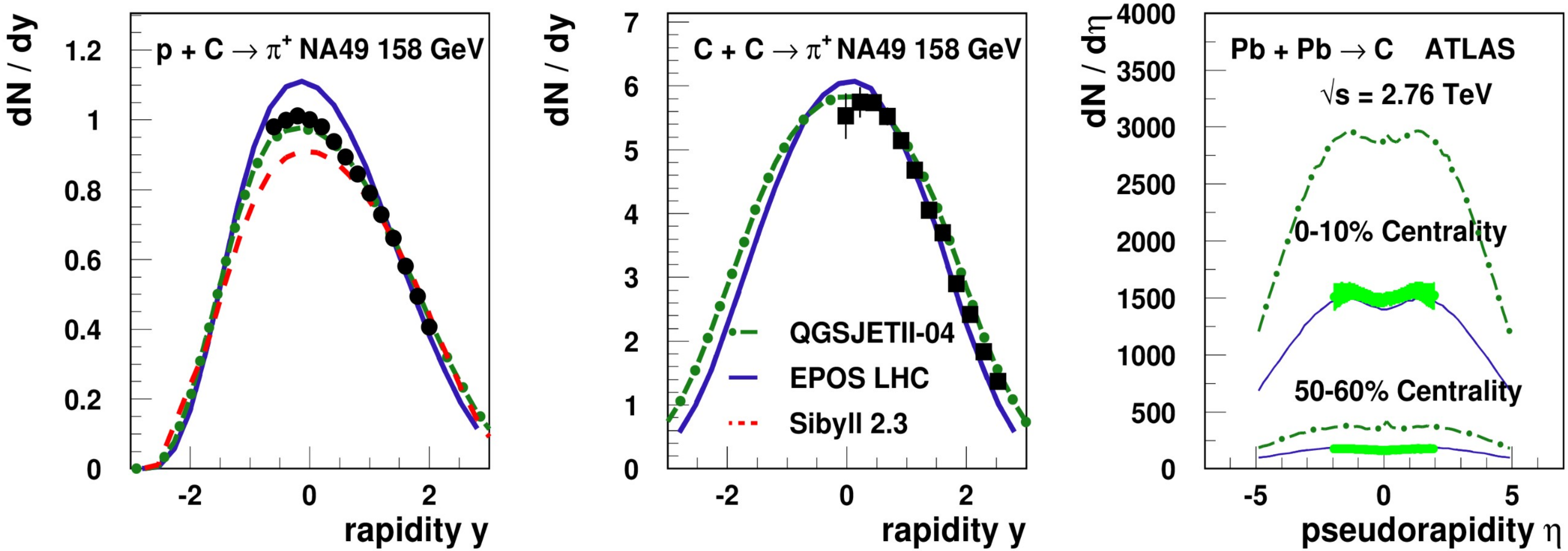



- **Sibyll**
  - Glauber for pA
    - with inelastic screening for diffraction in new Sibyll 2.3 (only nuclear effect)
  - superposition model for AA (A x pA)
- **QGSJETII**
  - Pomeron configuration based on A projectiles and A targets
  - Nuclear effect due to multi-leg Pomerons
- **EPOS**
  - Pomeron 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 data at high energy



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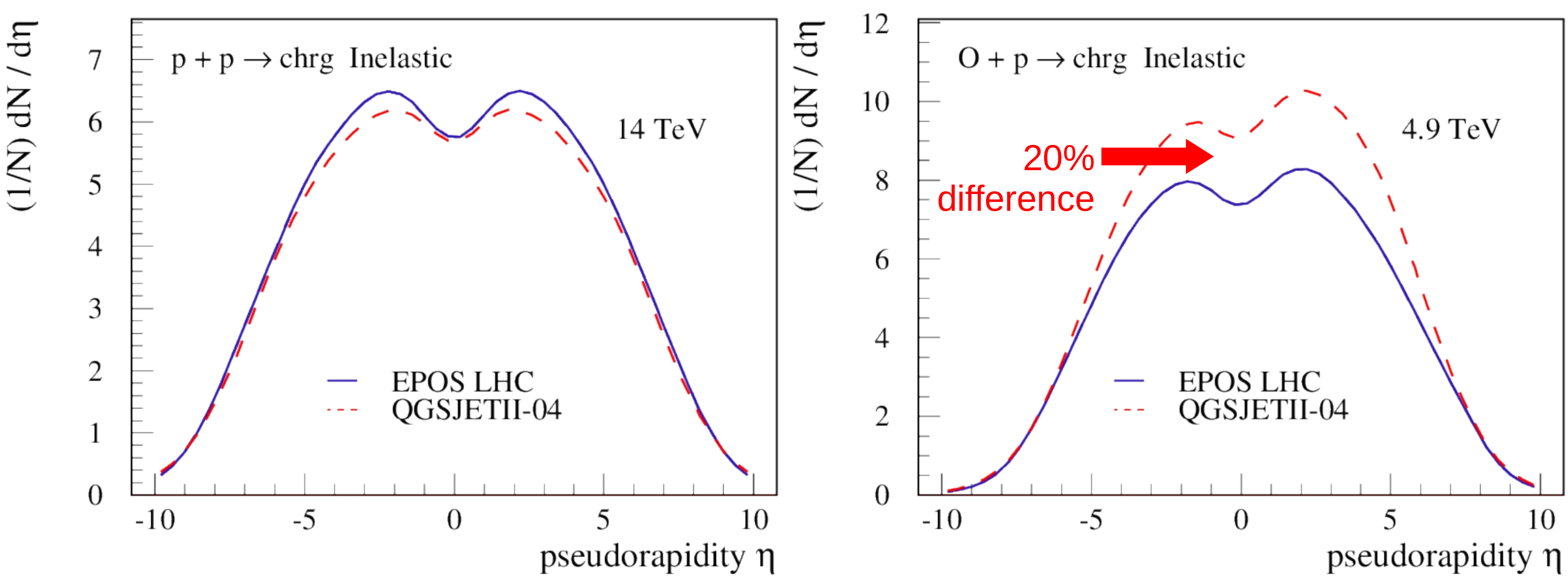
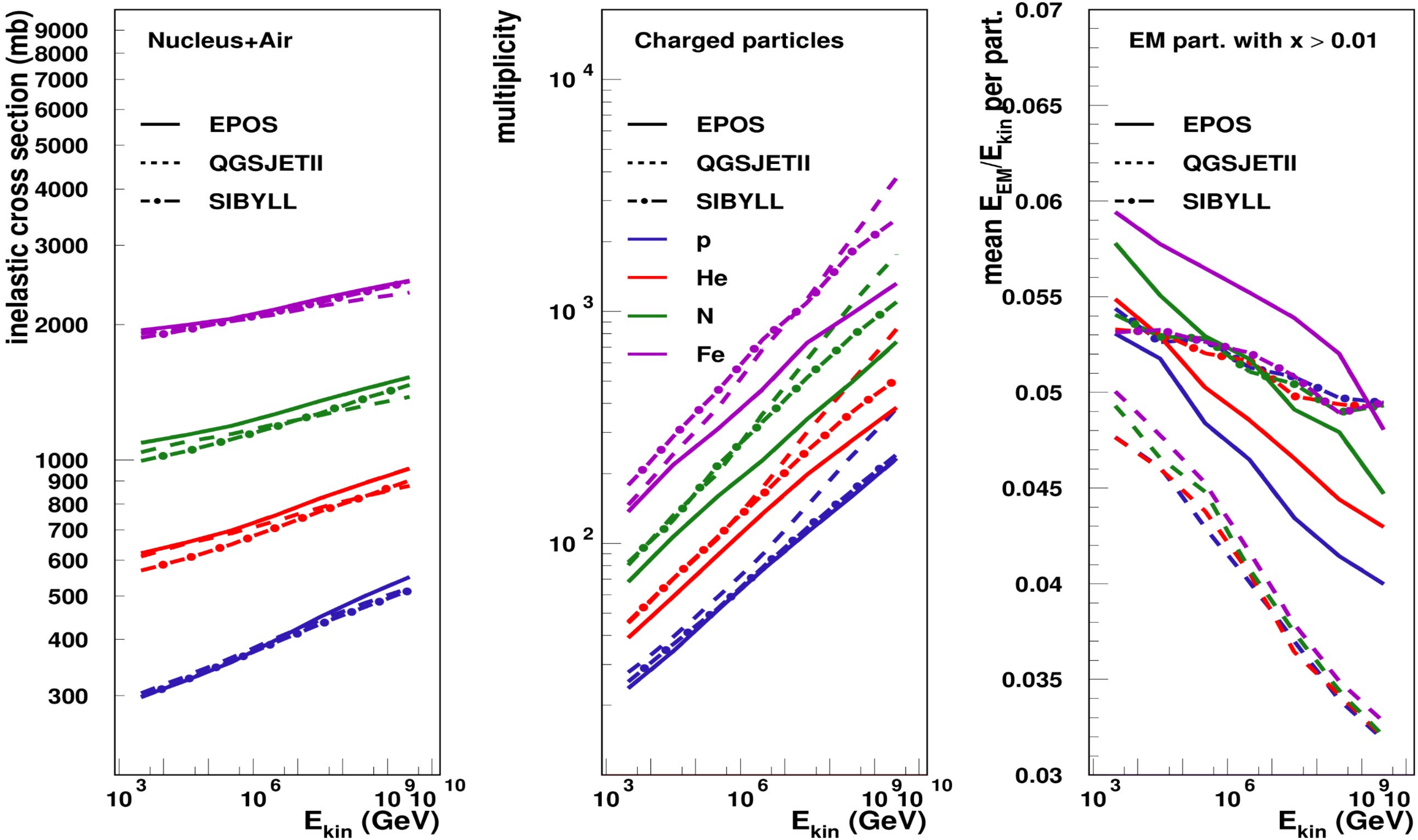
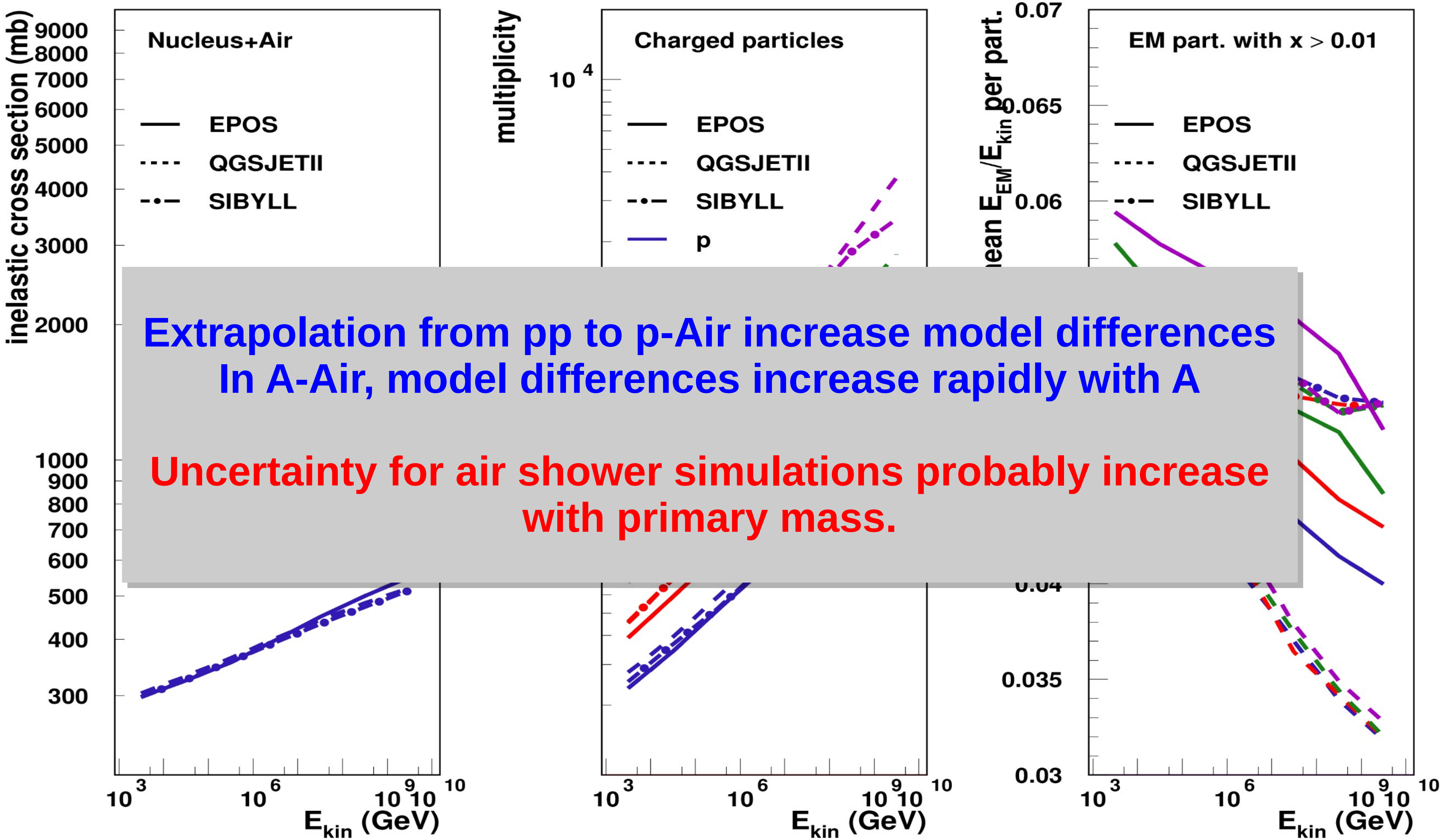
➡ pO@LHC to check models at high energy



# Model Comparison



# Model Comparison

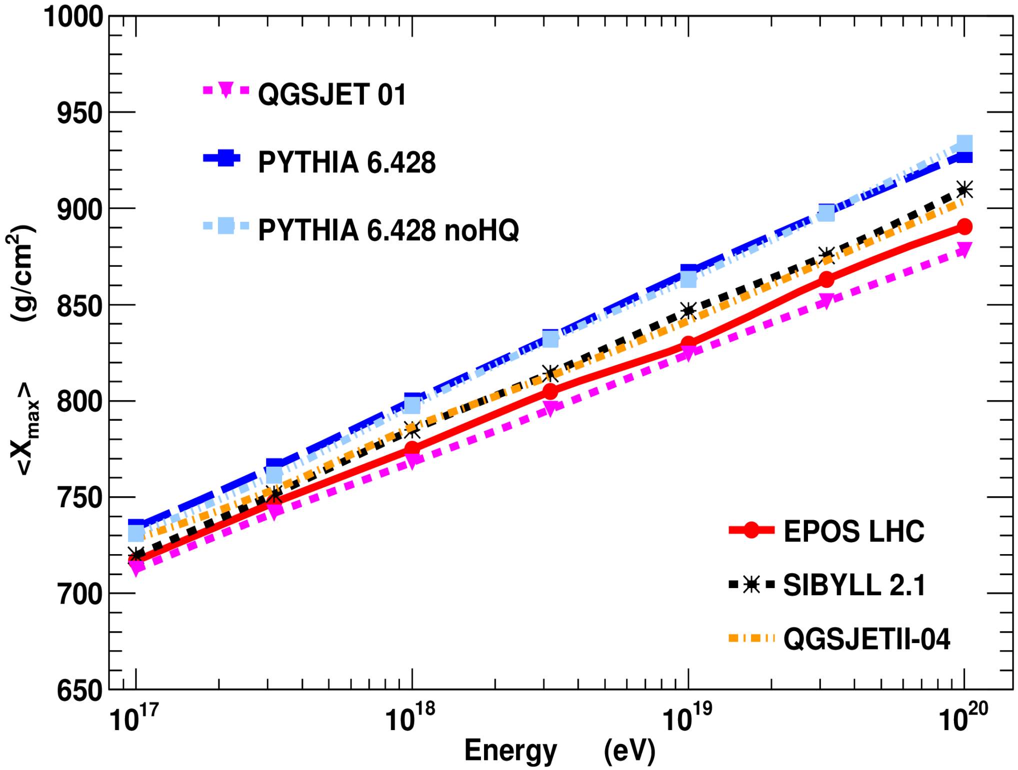


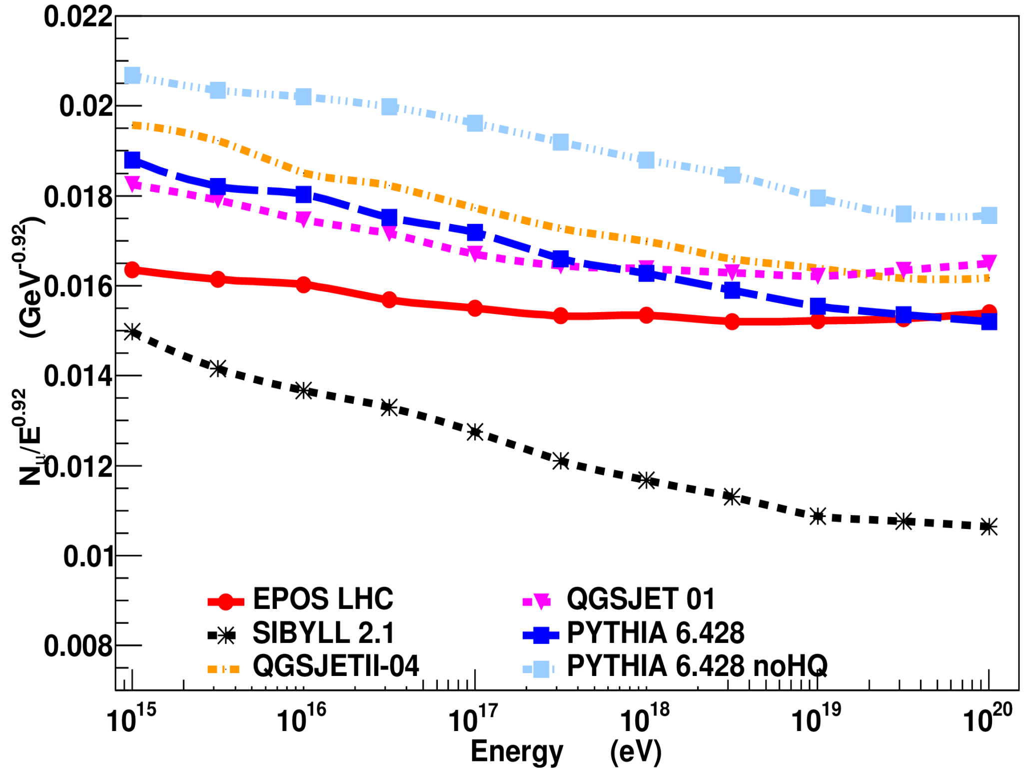

**Extrapolation from pp to p-Air increase model differences**
**In A-Air, model differences increase rapidly with A**

**Uncertainty for air shower simulations probably increase with primary mass.**

# Tests using hydrogen atmosphere

- Work done with David D'Enterria (CERN) and Sun Guanhao
  - ➡ test of Pythia event generator
- Modified air shower simulations with air target replaced by hydrogen
  - ➡ for interactions only (no change in density)
  - ➡ no nuclear effect



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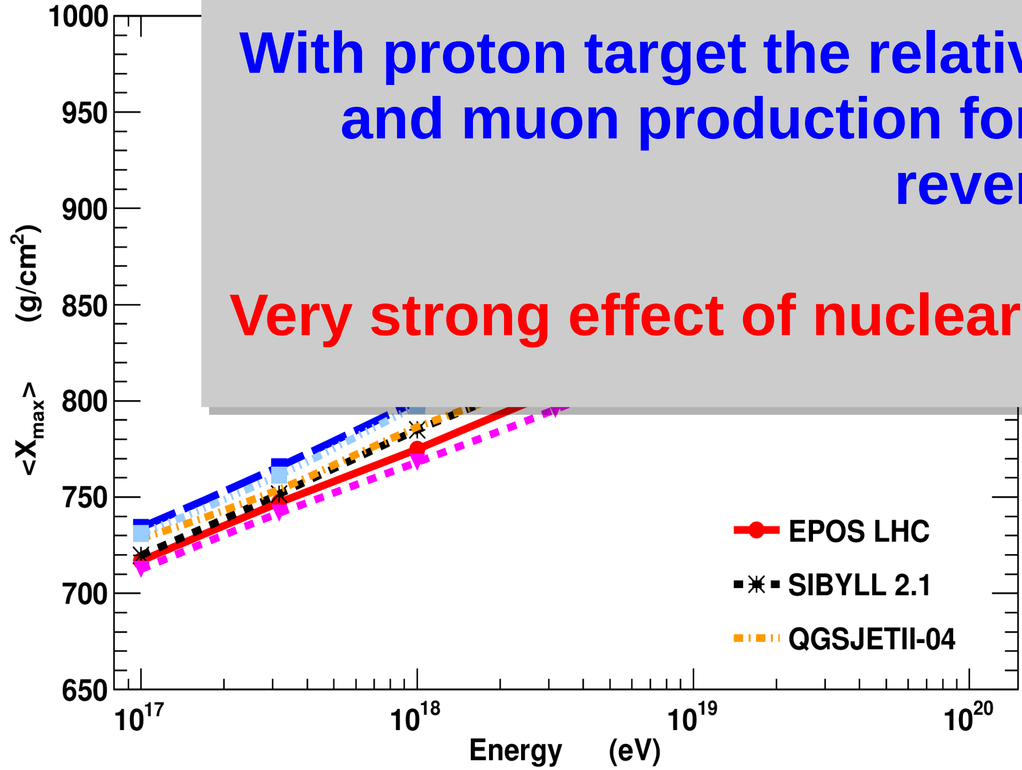
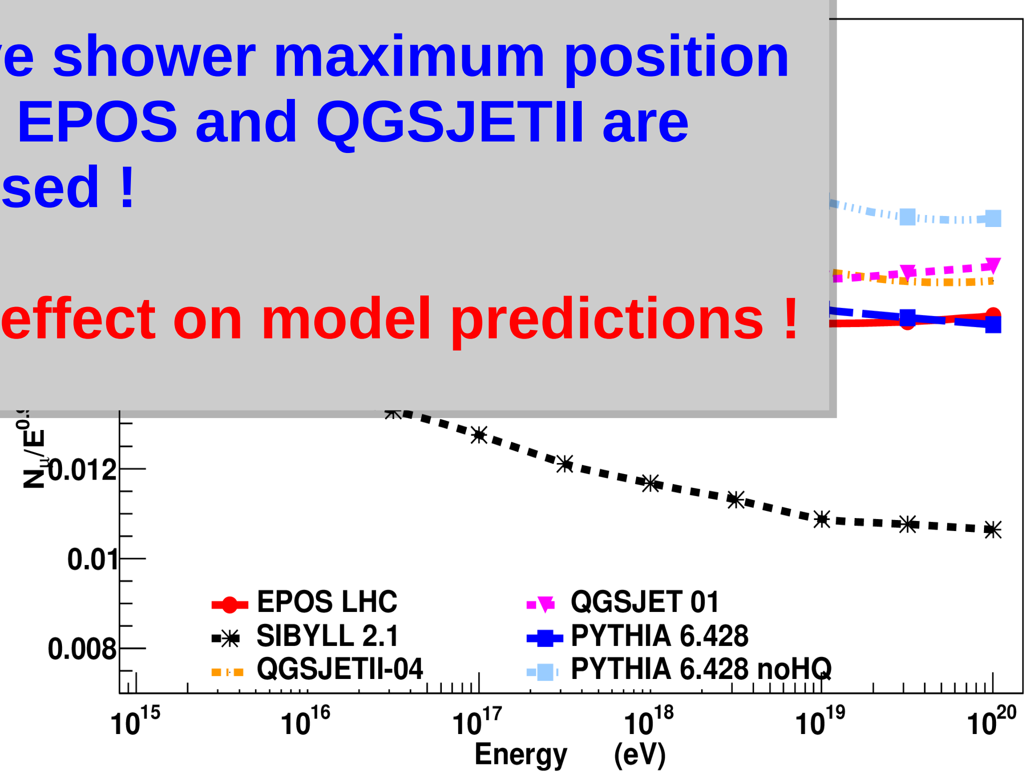



**With proton target the relative shower maximum position and muon production for EPOS and QGSJETII are reversed !**

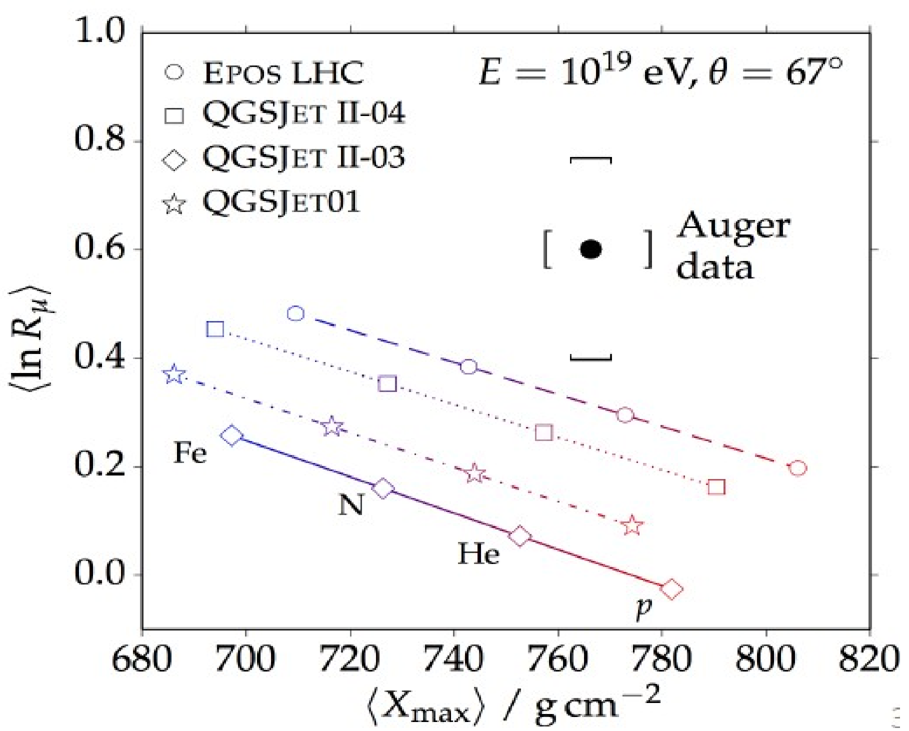
**Very strong effect of nuclear effect on model predictions !**

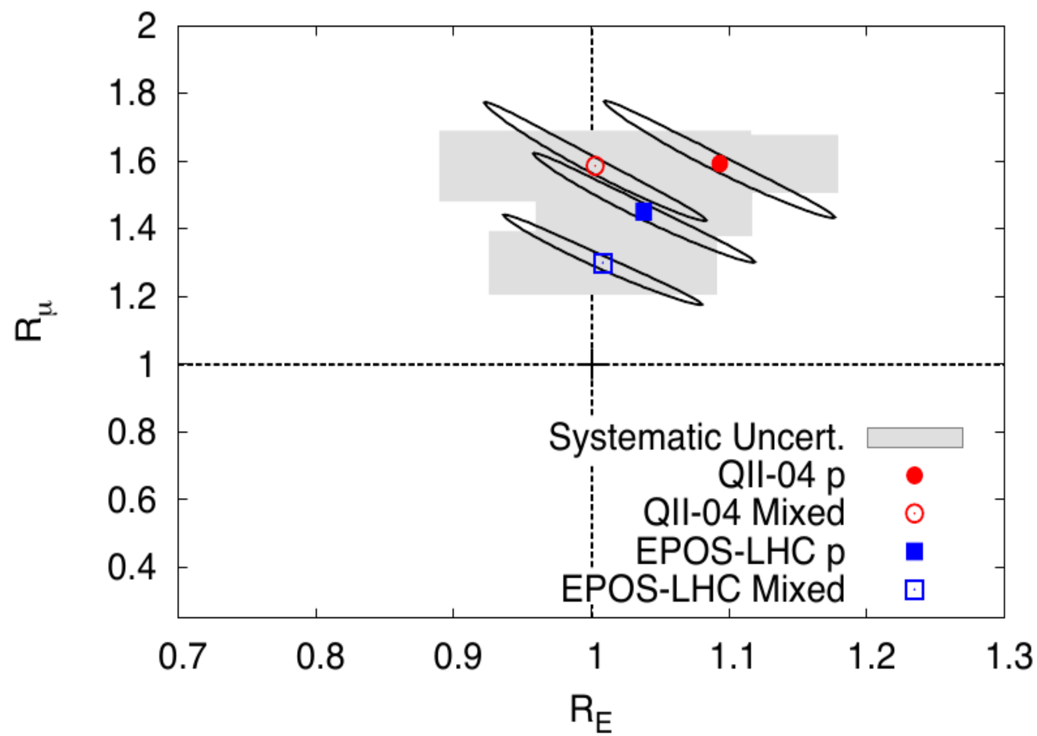
# Summary

- **PAO data (and other low energy experiments) not consistently described by hadronic interaction models (even post LHC)**
  - $<X_{max}>$ and fluctuations
  - number of muons and muon production depth (MPD) ...
- **New Sibyll 2.3 not really improving the picture**
- **Role of pion interactions**
  - crucial to describe muons (MPD and total number) but not so much for $X_{max}$
  - NA49 and NA61 data indicate some problems in hadronic models
    - diffraction
    - baryon stopping
    - resonances
- **Remaining main source of uncertainty in $X_{max}$ probably related to extrapolations due to nuclear interactions**
  - lack of data at high energy and forward for light ion interaction
  - effect increasing with nuclear mass of the projectile (primary CR)

# Muon Number

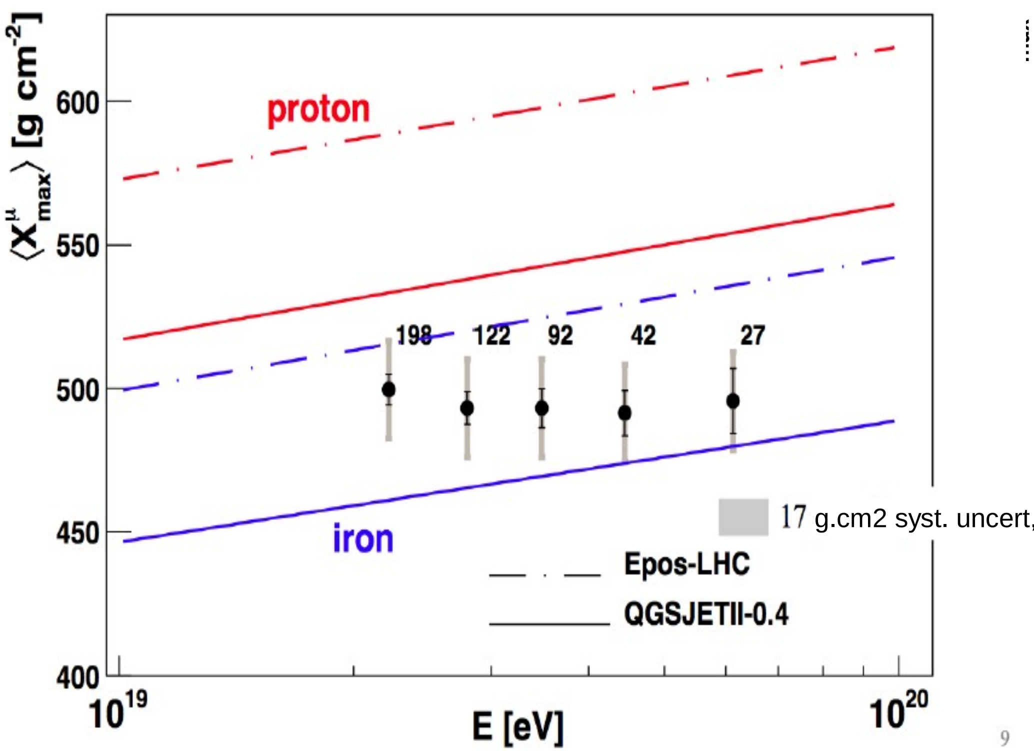
- **Simulations don't reproduce direct muon measurement**
  - inclined showers
  - EPOS-LHC and QGSJETII-04 about 1.5 sigma from PAO measurement if composition is taken into account
- **To reproduce data simulations have to be rescaled**
  - for mixed composition, only muon component has to be changed
    - correct energy scale
  - 30% muon deficit for EPOS-LHC and 59% for QGSJETII-04.

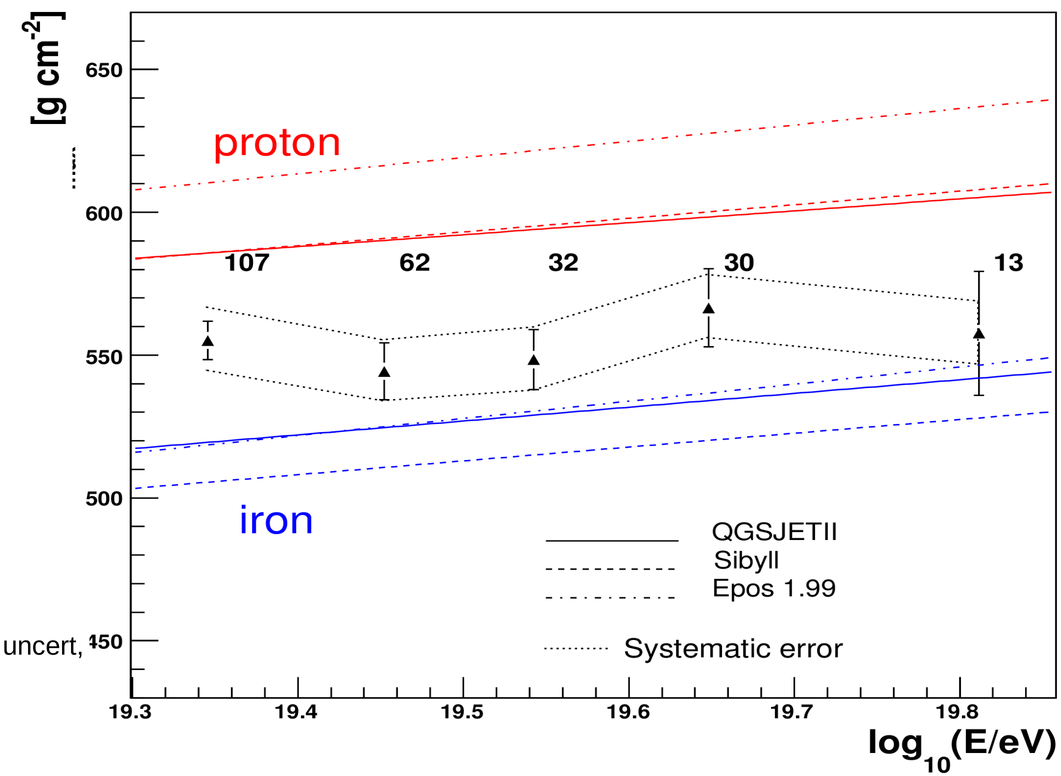


# MPD and EPOS

- **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

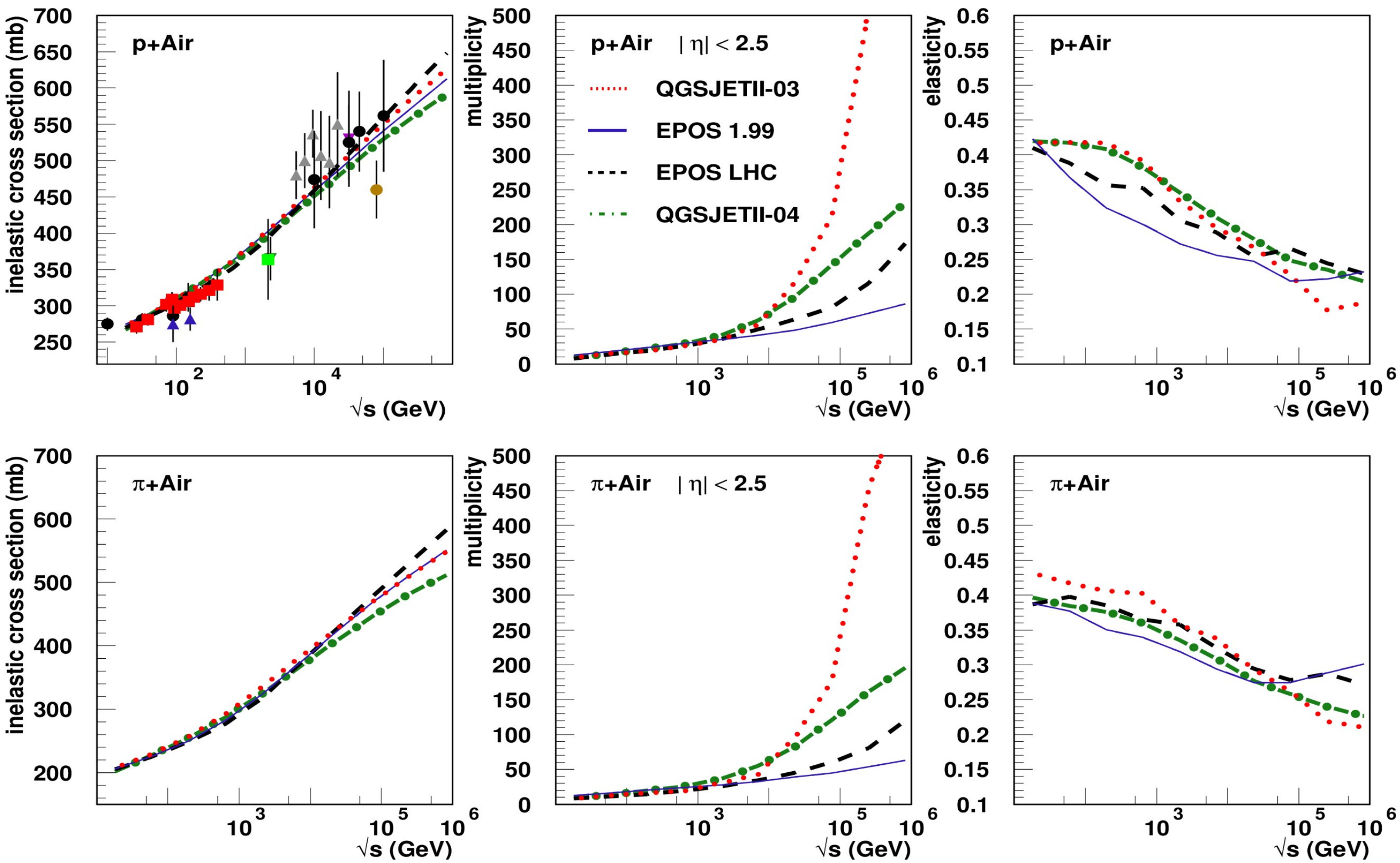



**EPOS 1.99 used as reference for the rest of the talk**

# 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

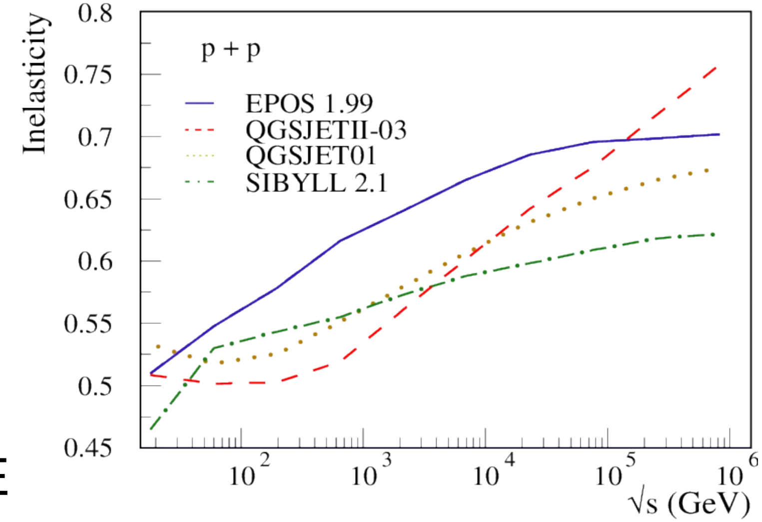


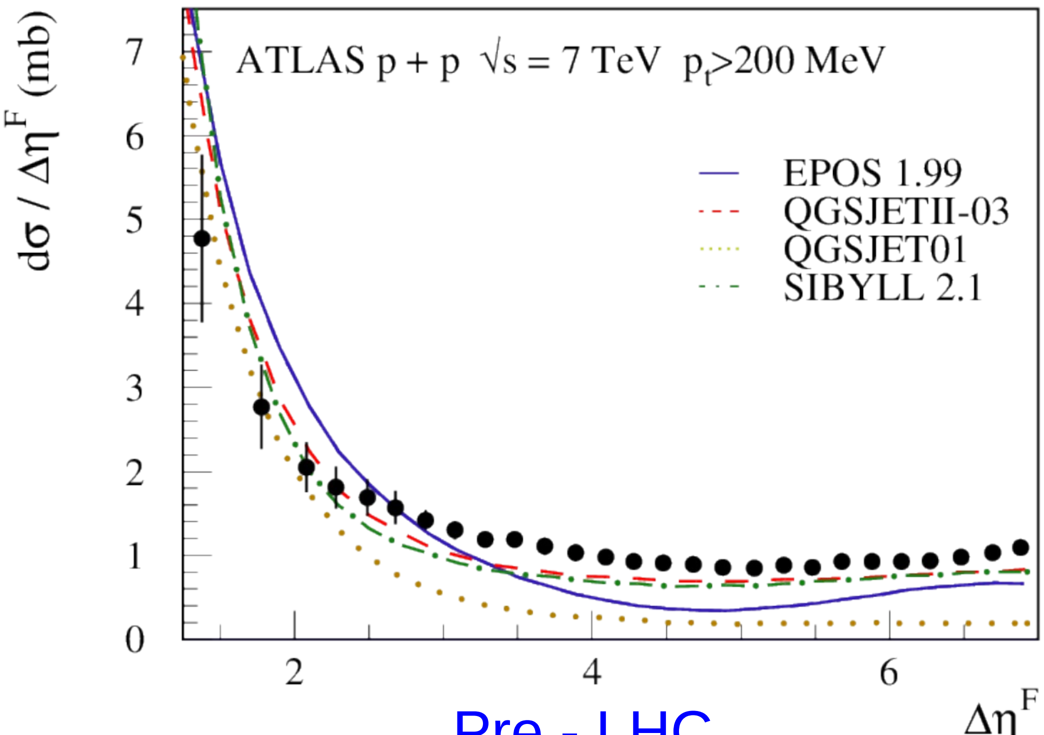

- shallower MPD
  - ➡ larger multiplicity
  - ➡ larger cross-section (small)
- deeper MPD
  - ➡ larger elasticity

**Elasticity should be the source of the difference**

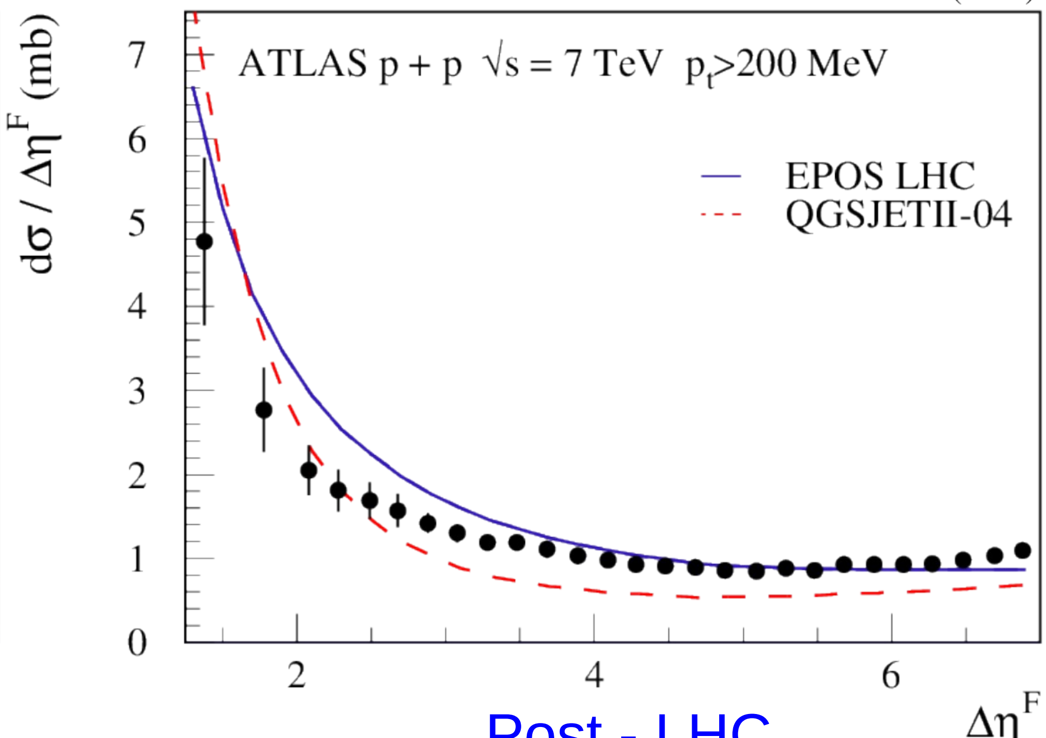
# (In)elasticity

- **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



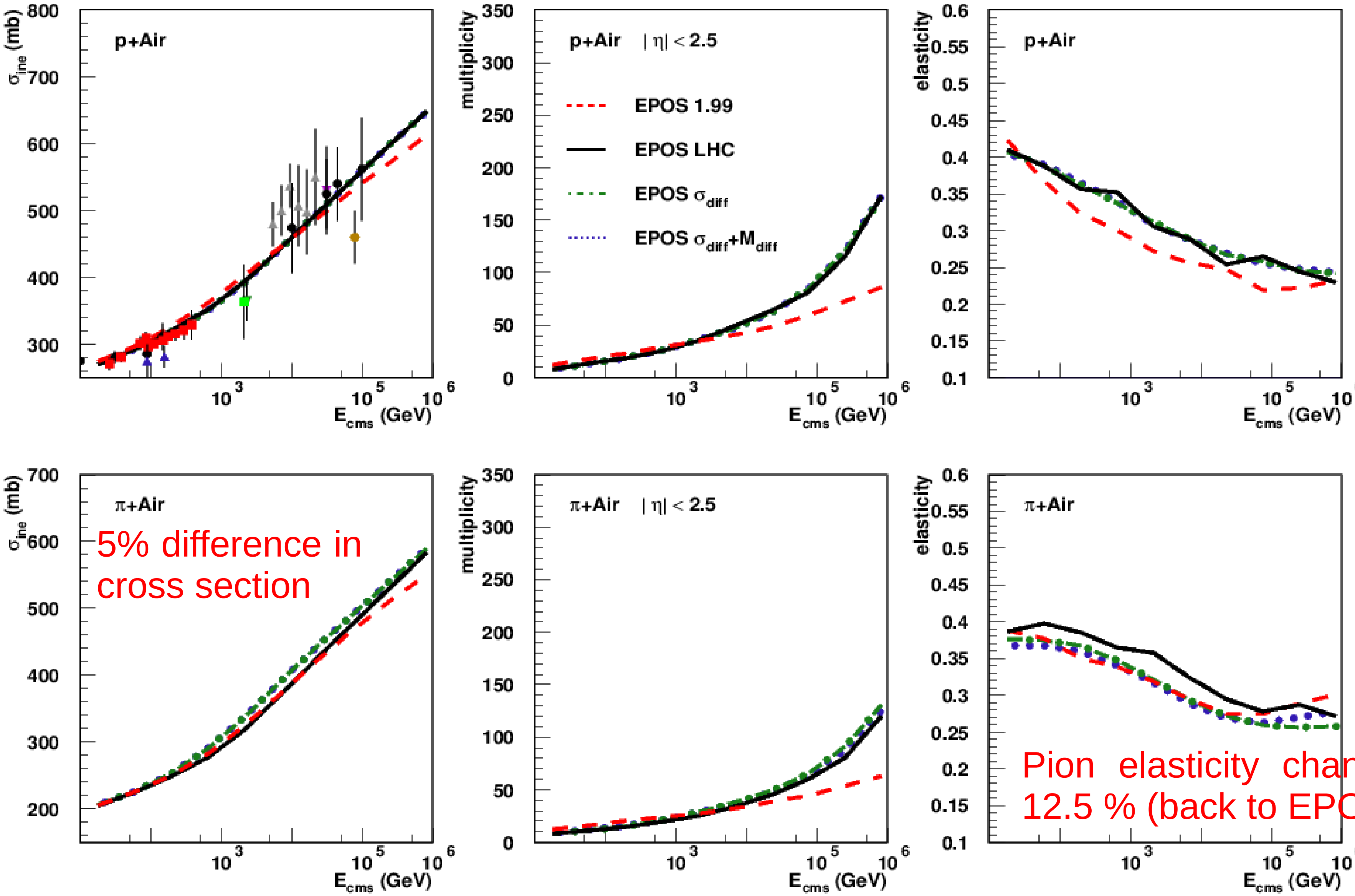




Pre - LHC




Post - LHC

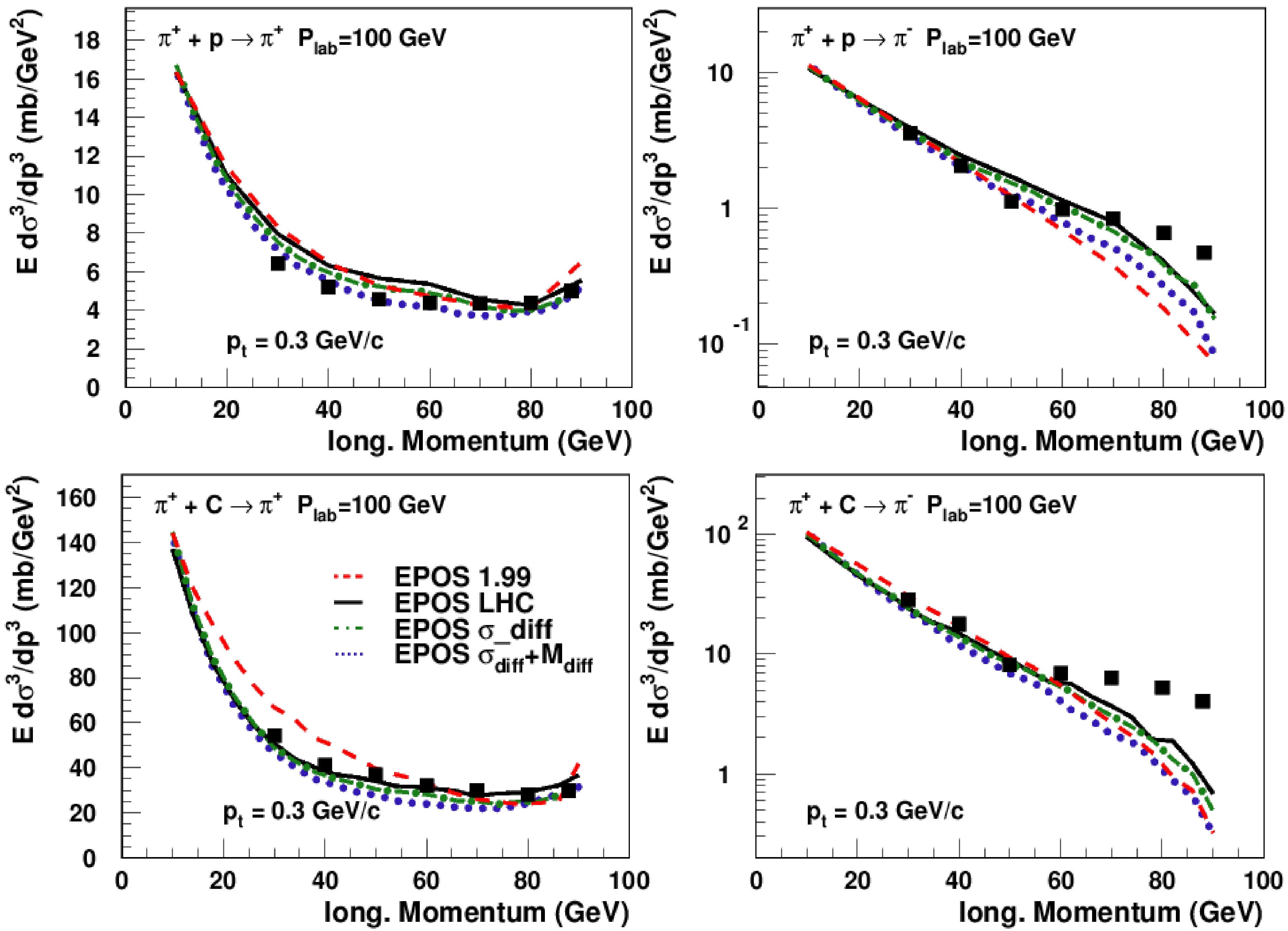
# Extrapolation to CR interactions




5% difference in cross section

Pion elasticity changed by 12.5 % (back to EPOS 1.99)

# Test with accelerator data



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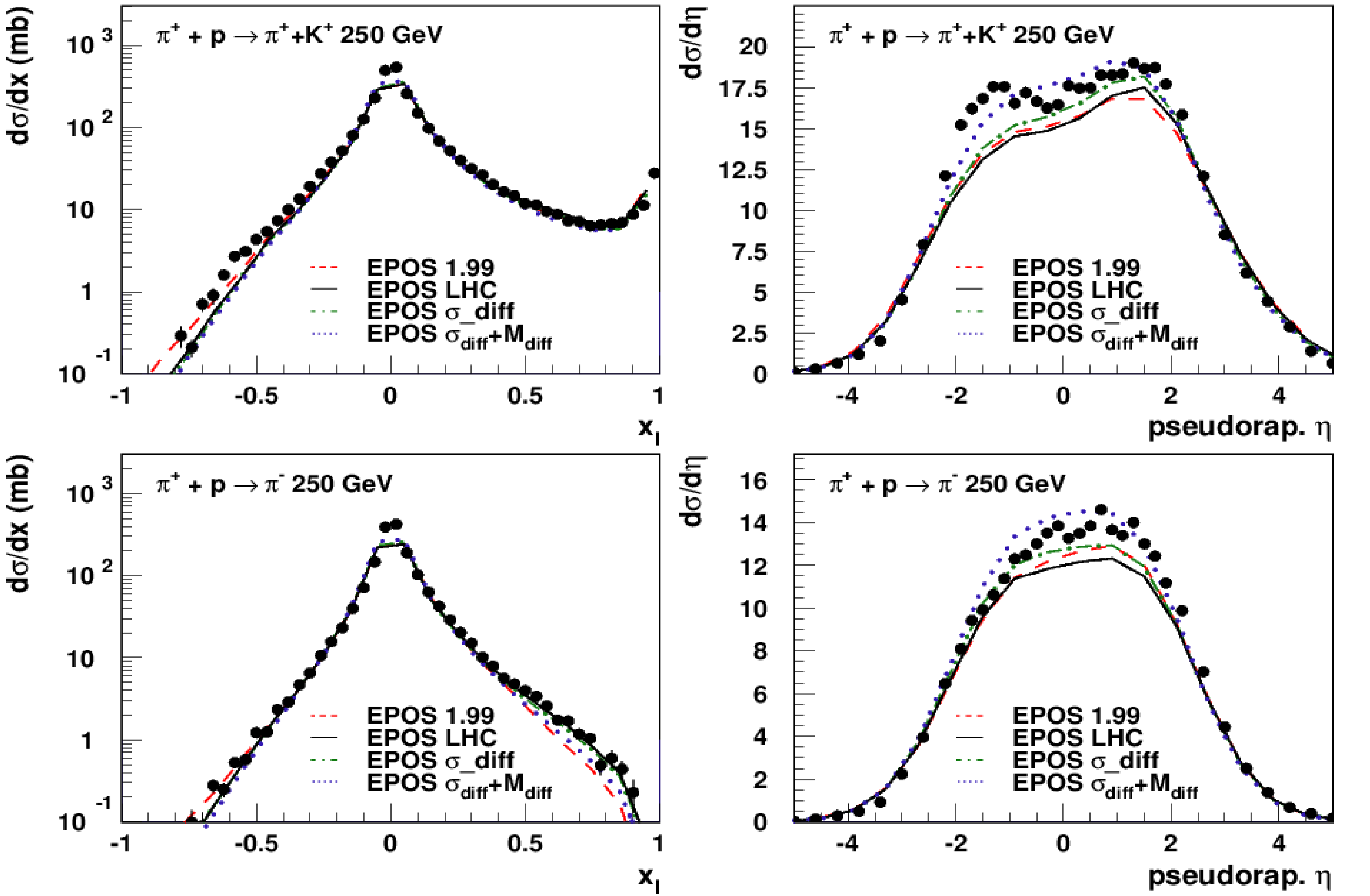
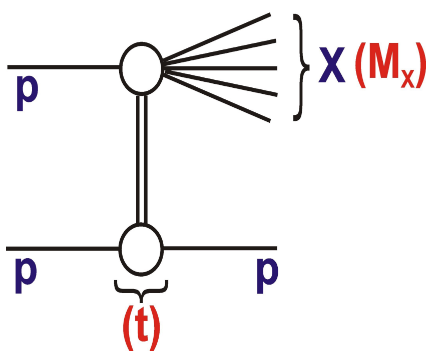
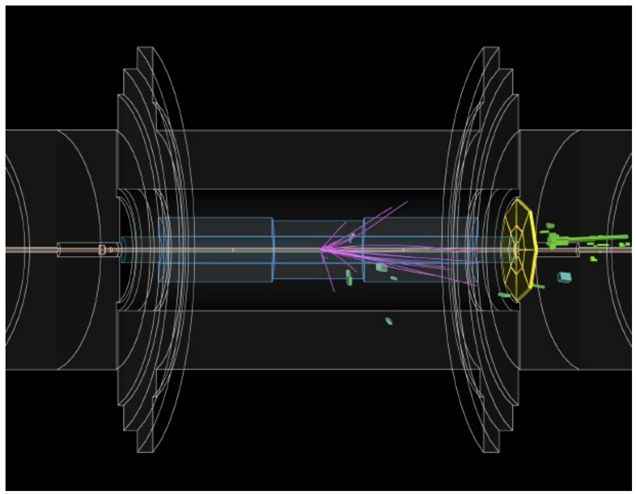


# Rapidity Gap and (In)elasticity

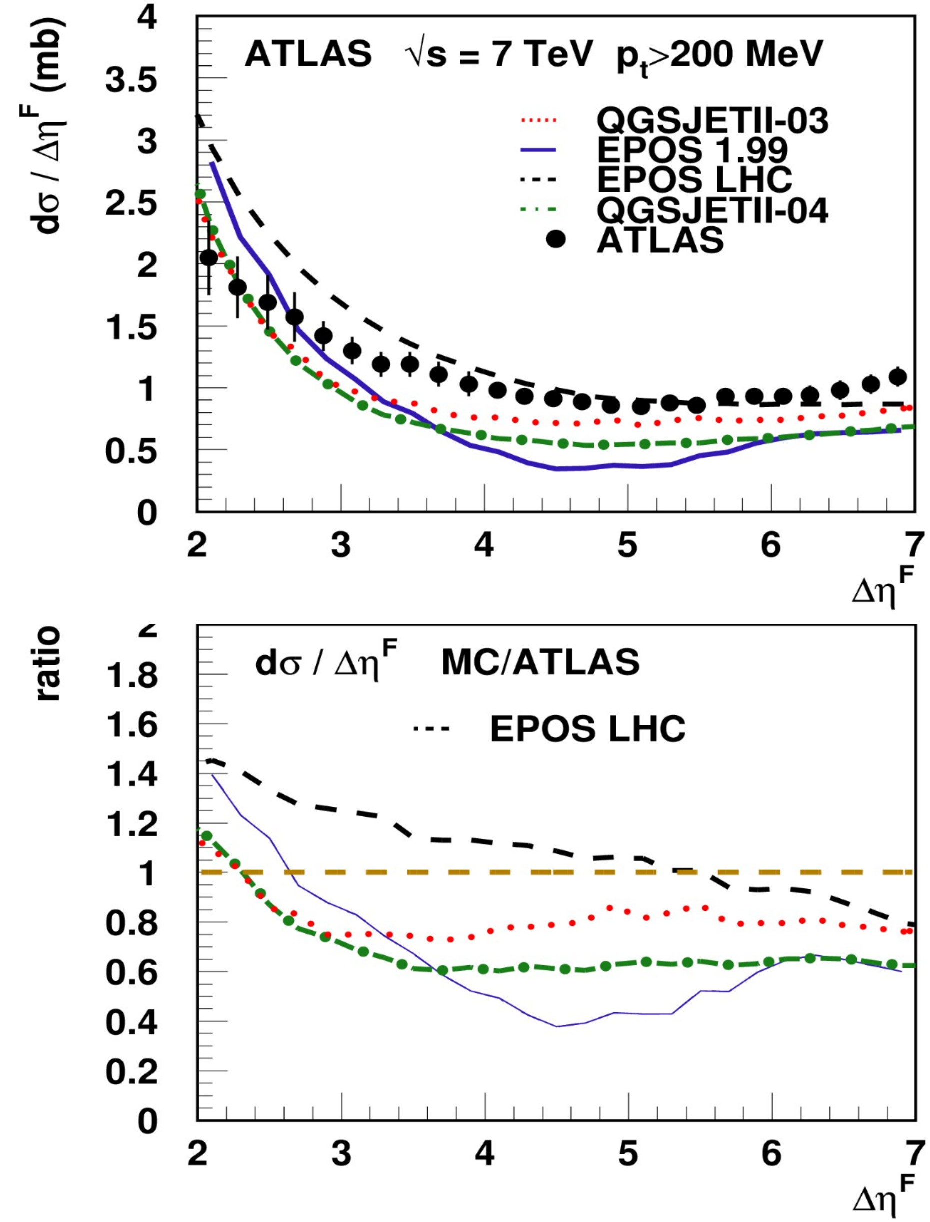
diffractive process




ATLAS detector



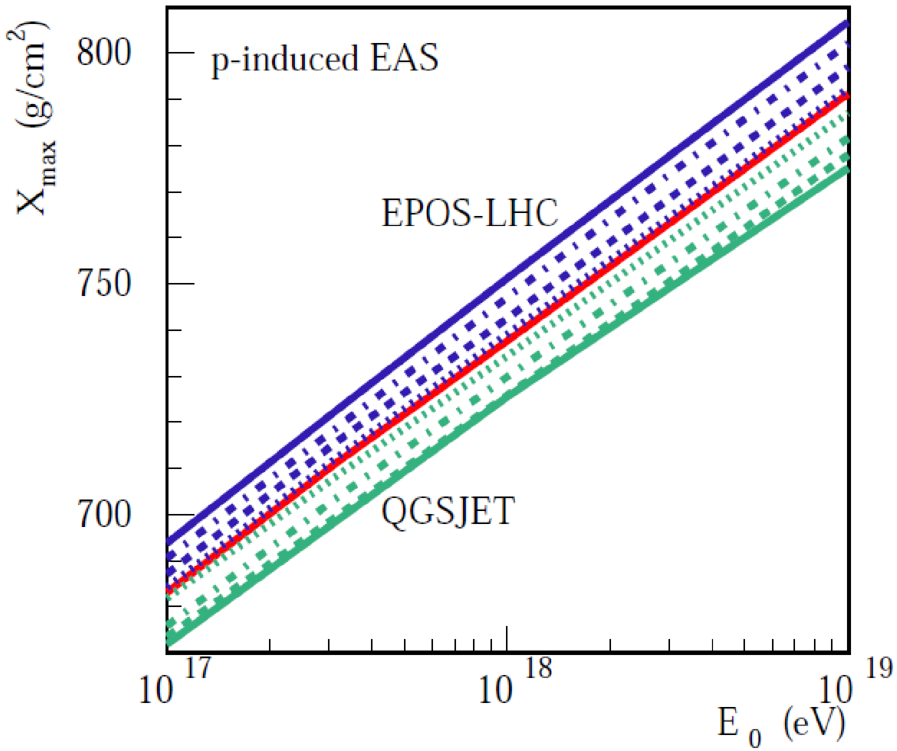
ATLAS Collaboration

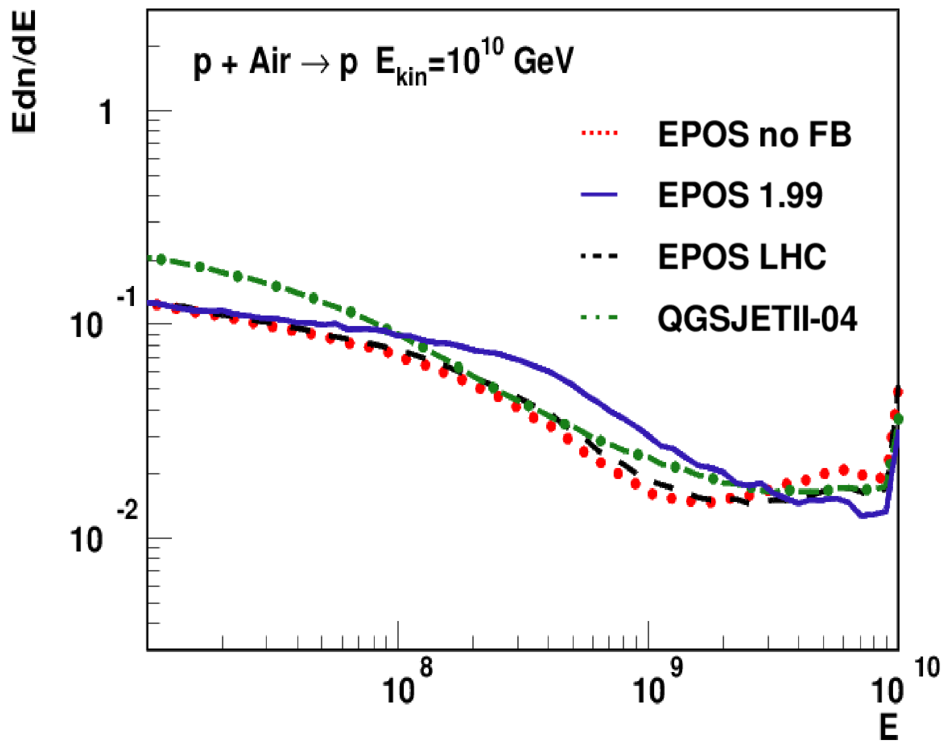



- **Rapidity gap closely related to diffraction**
  - ➔ diffractive cross-section
  - ➔ AND diffractive mass distribution
- **Hard constraint for CR**
  - ➔ change (in)elasticity

# 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 1st int. : dot-dashed



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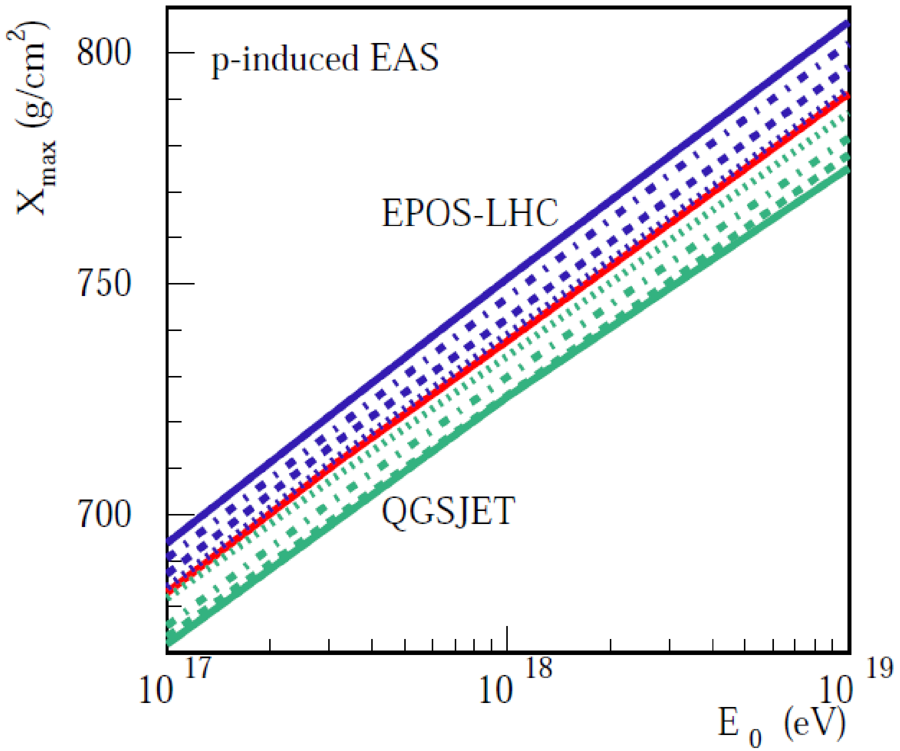


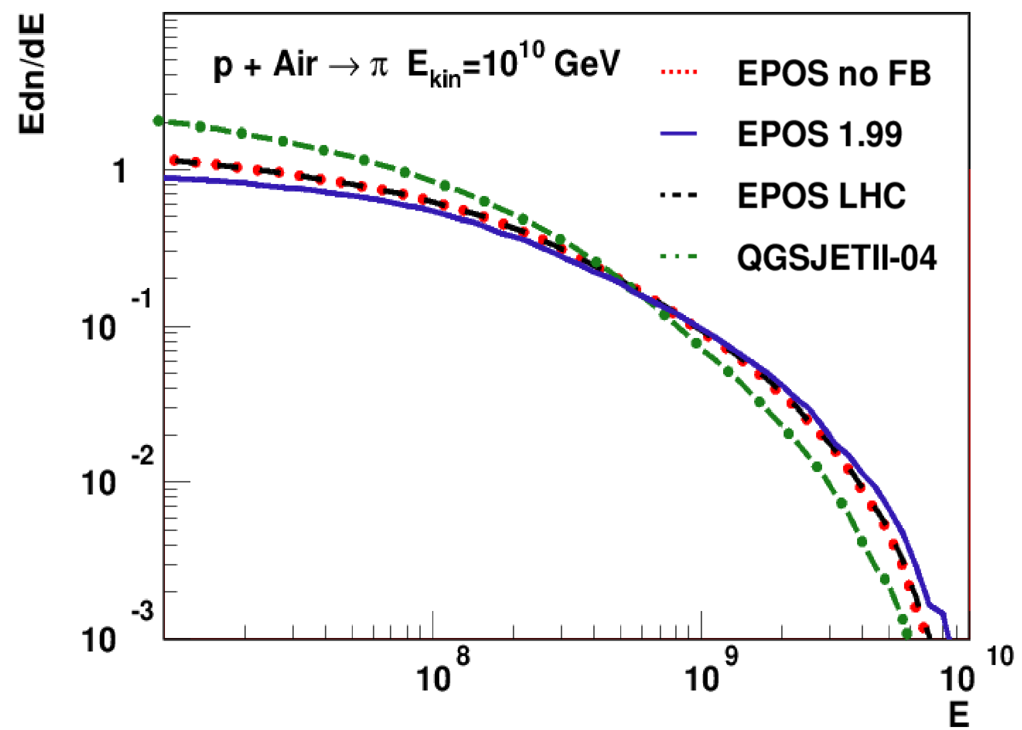

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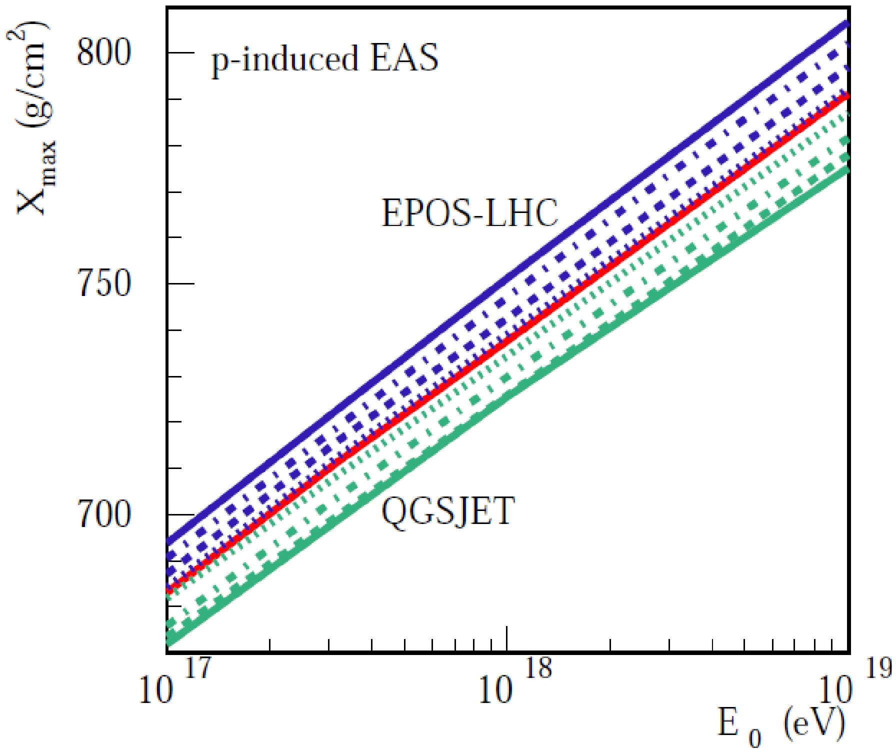
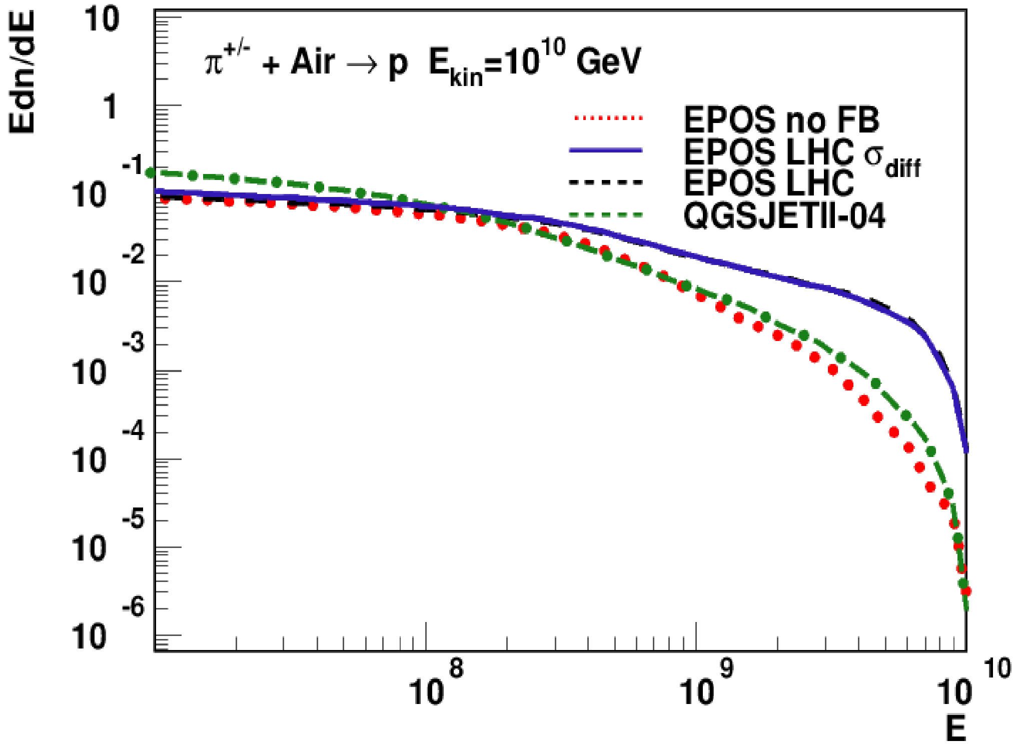
  - QII complete 1st int and all nucleon prod. in the shower: dotted



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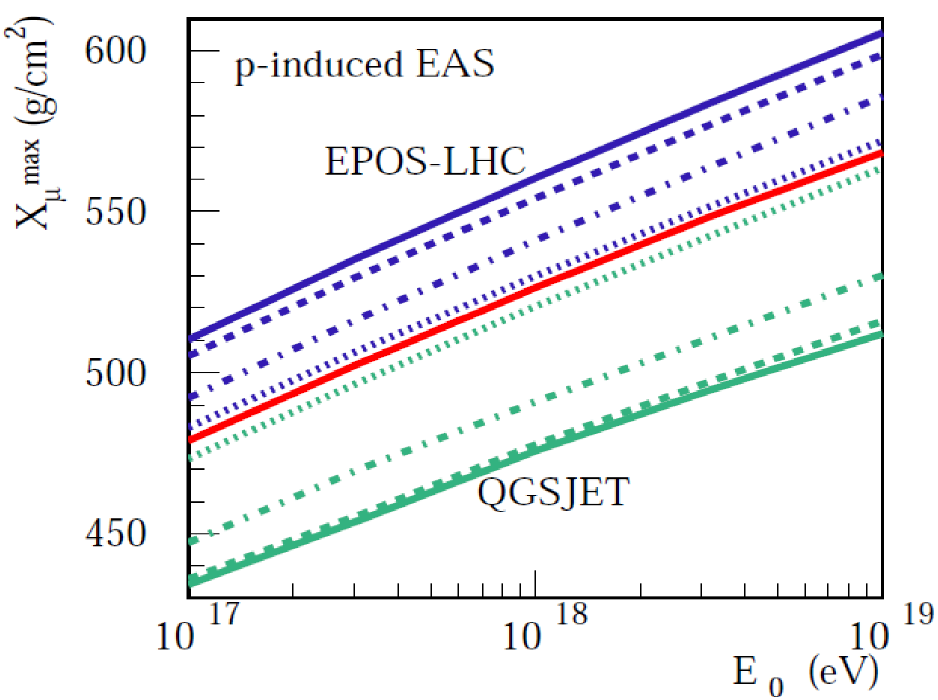


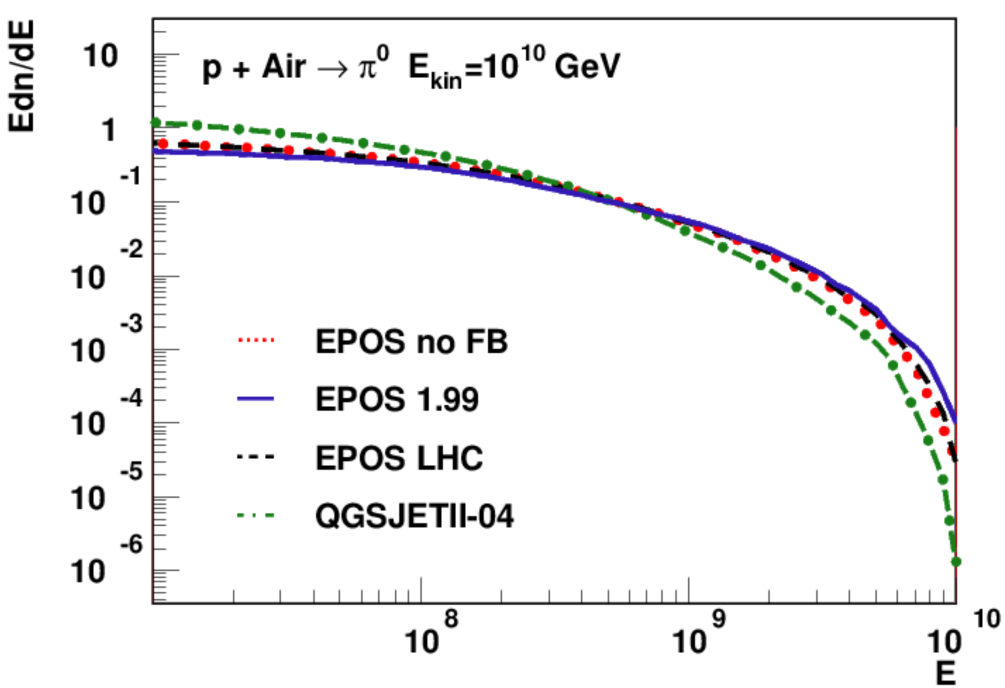

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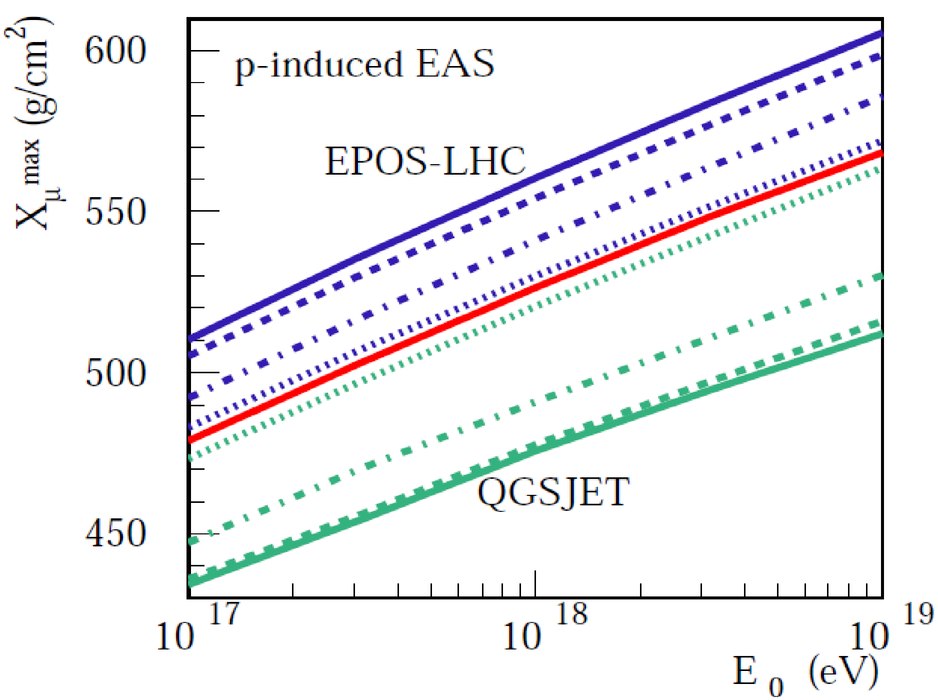


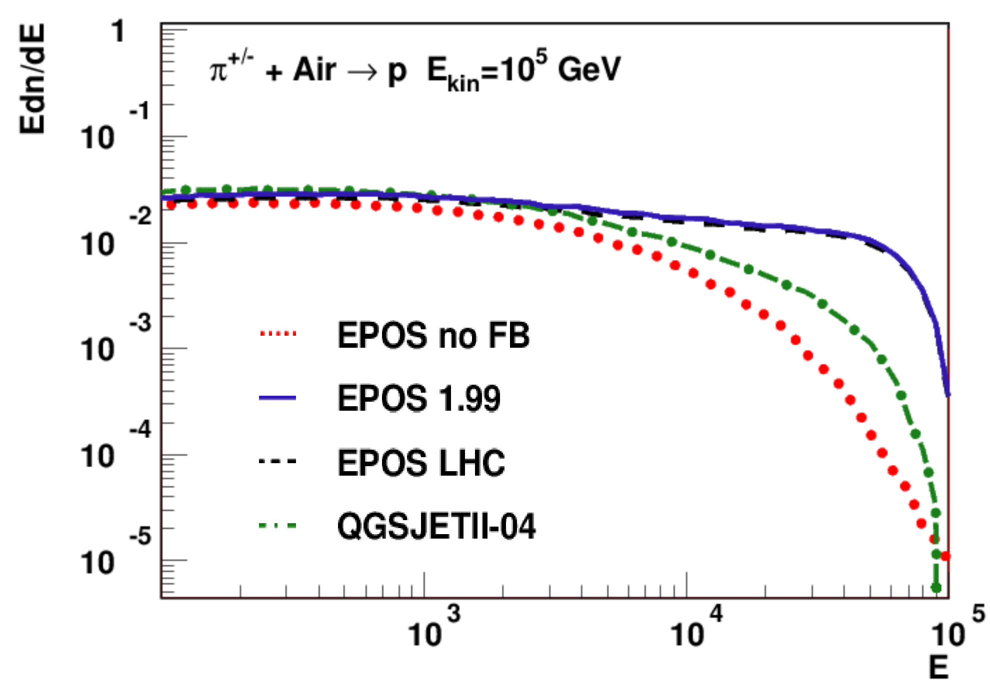

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