Review of Model Predictions for Extensive Air Showers

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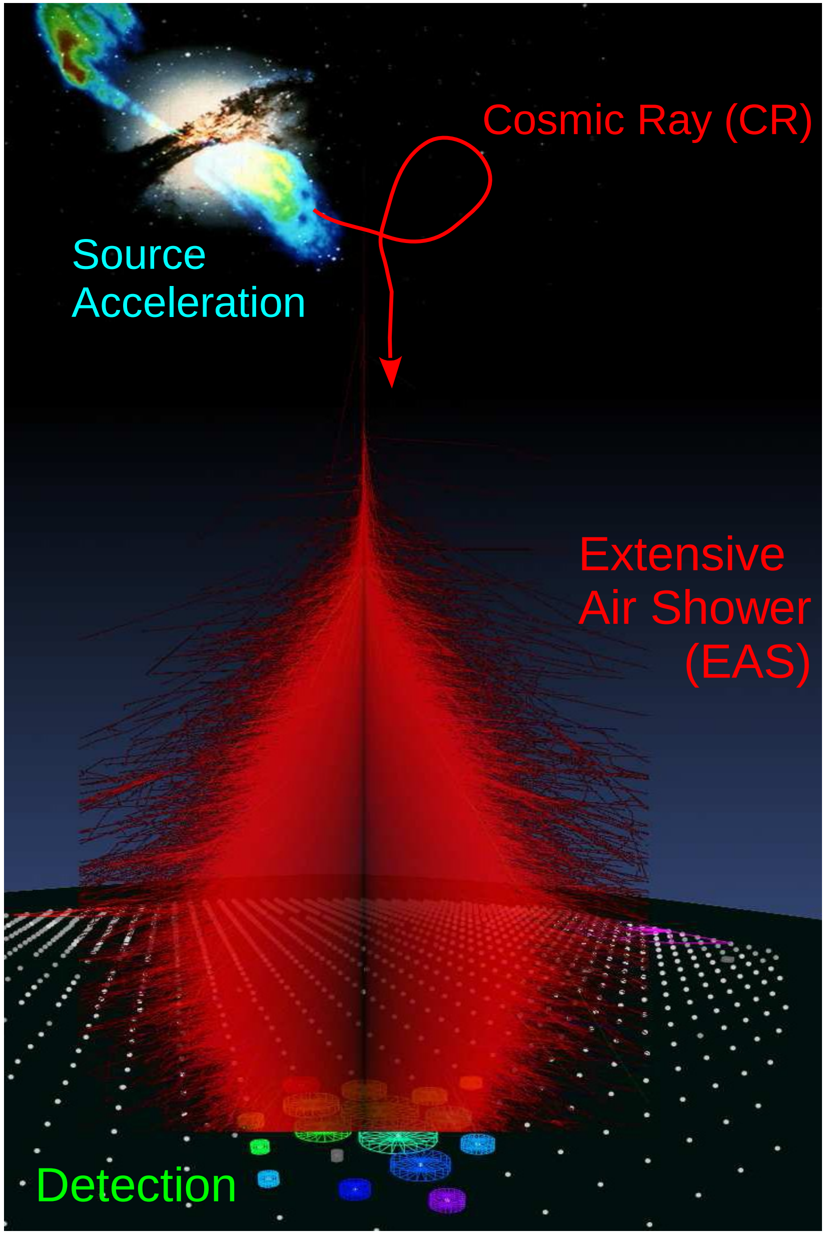
Outline

- **Monte-carlo for Cosmic Ray analysis**
- **MC comparison to accelerator data**
- **Electromagnetic (EM) signal in extended air showers**
  - ➜ source of uncertainties
- **Muon signal**

LHC data reduced the model uncertainties and exclude old models for mass composition of cosmic rays. Remaining uncertainties can be further reduced taking into account forward measurements AND using (light) nuclear target.

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 (10^6 GeV and more)
    - improving but not very precise
  - 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 if physics is correct

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) (EPOS 1.99) (2005-2012)

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

Ostapchenko

Pierog & Werner

Riehn & Engel

Fedinitch & Engel

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

Motivation :

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

Motivation :

- **Hard Pomeron-Pomeron connexion**

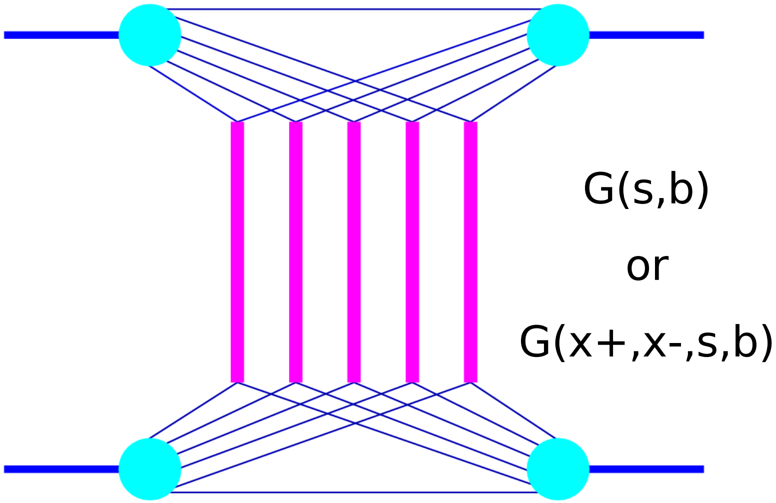
Motivation :

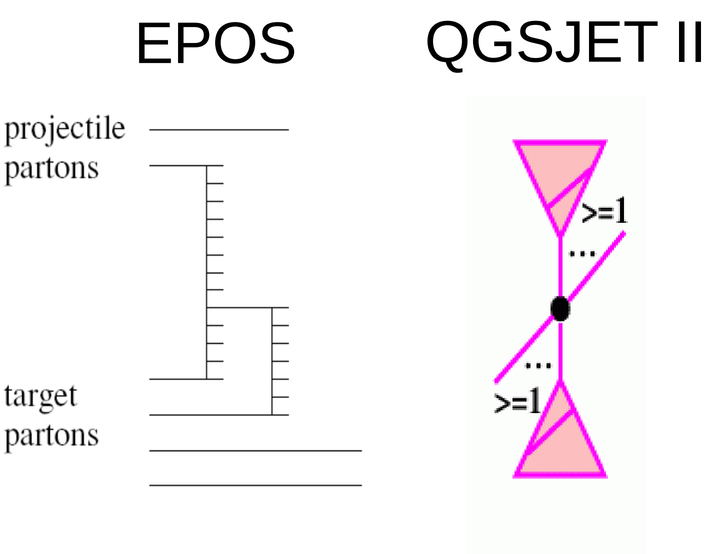
- **update with LHC results**
- **fix high energy**

Motivation :

- **binary scaling in hard probes**

Cross Section and Multiplicity in Models



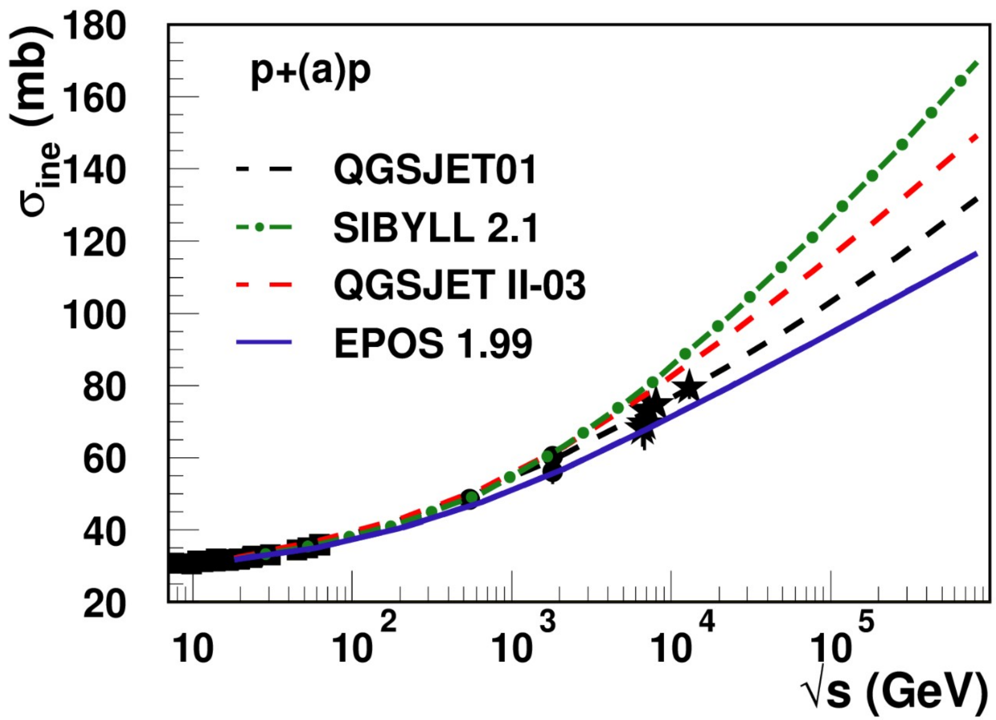


- **Gribov-Regge and optical theorem**
  - Basis of all models (multiple scattering) but
    - Classical approach for QGSJET, SIBYLL and DPMJET (no energy conservation for cross section calculation)
    - Parton based Gribov-Regge theory for EPOS (energy conservation at amplitude level)
- **pQCD**
 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

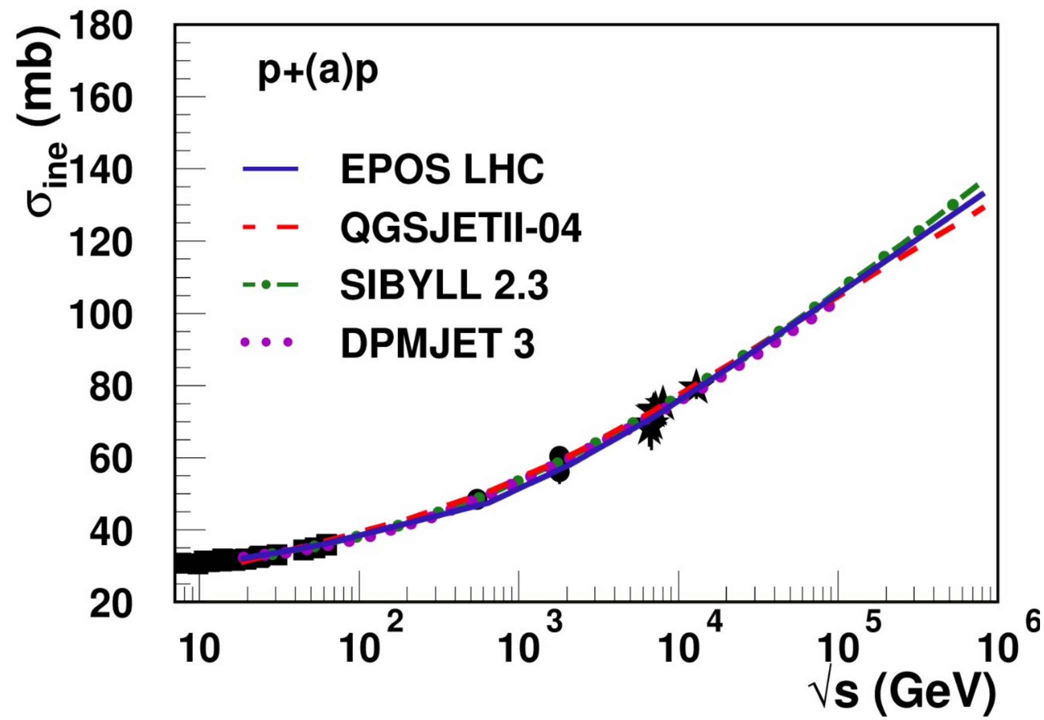
Cross Sections

- Same cross section prediction at pp level and low energy (data for tuning)
- extrapolation to high energy looks settled
  - different amplitude and scheme
    - same extrapolations

Pre - LHC



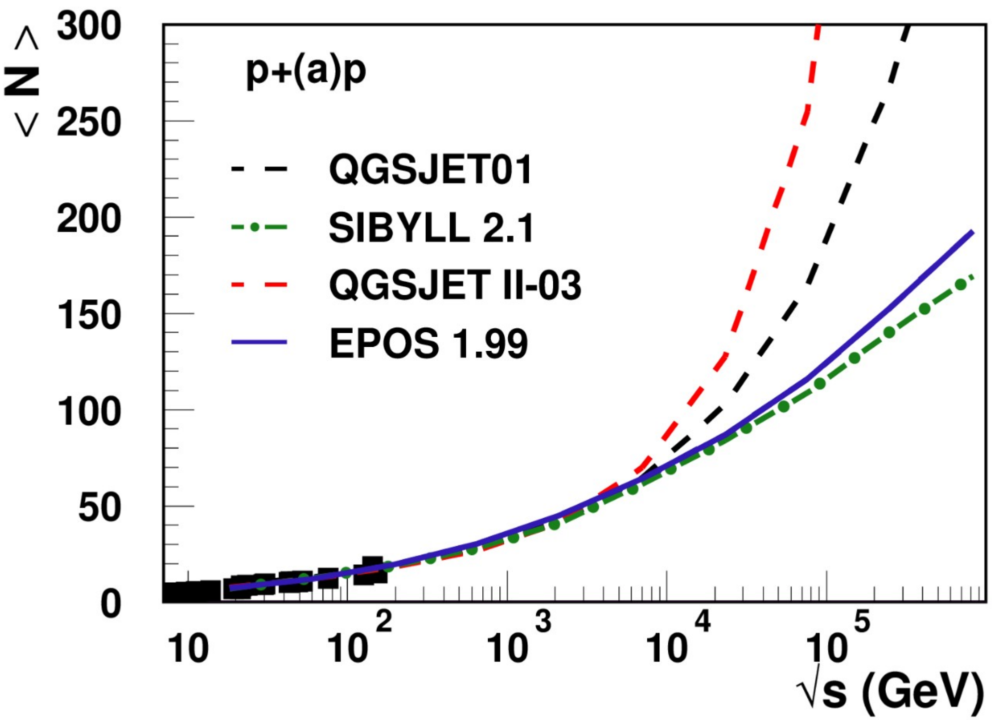
Post - LHC



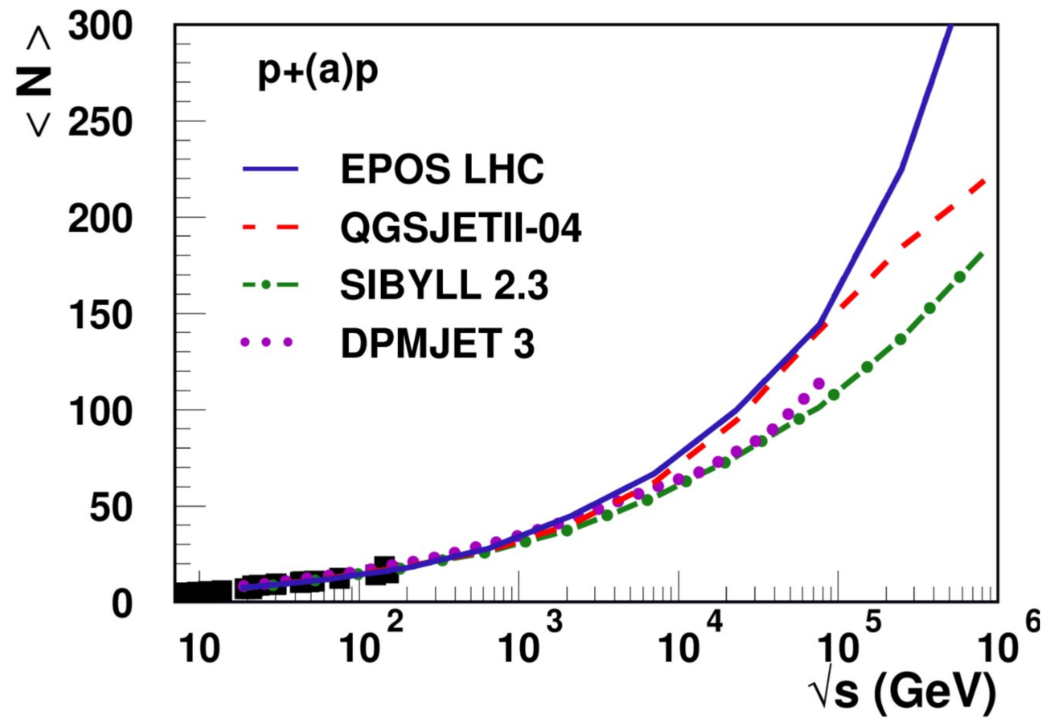
Multiplicity

- Multiplicity fixed by data up to 900 GeV
- extrapolation to high energy is still model dependent ?

Pre - LHC



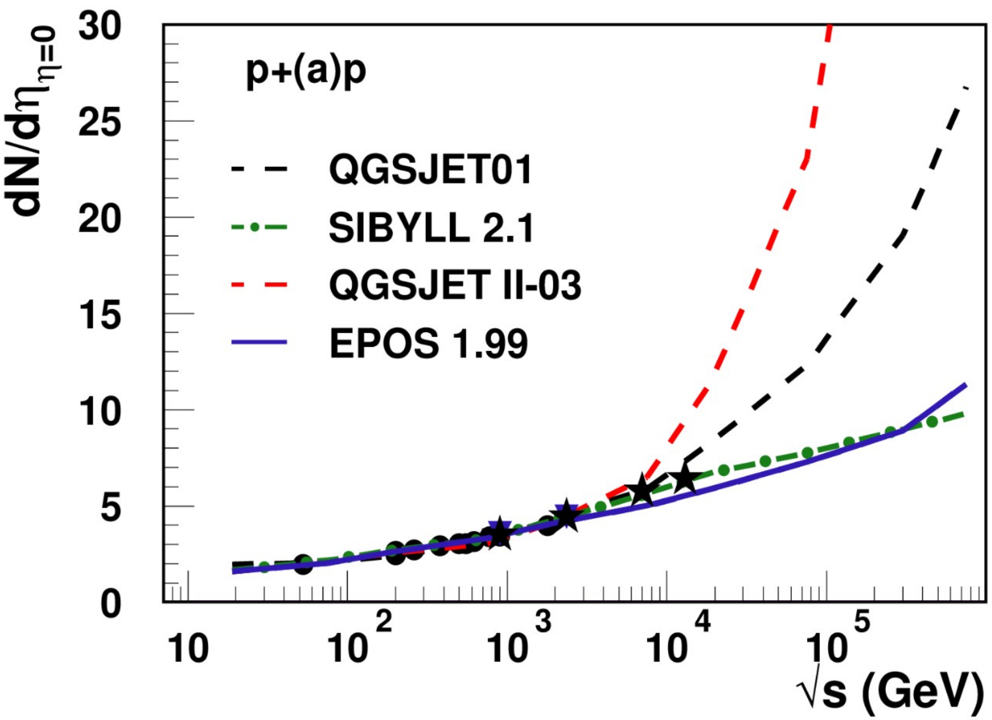
Post - LHC



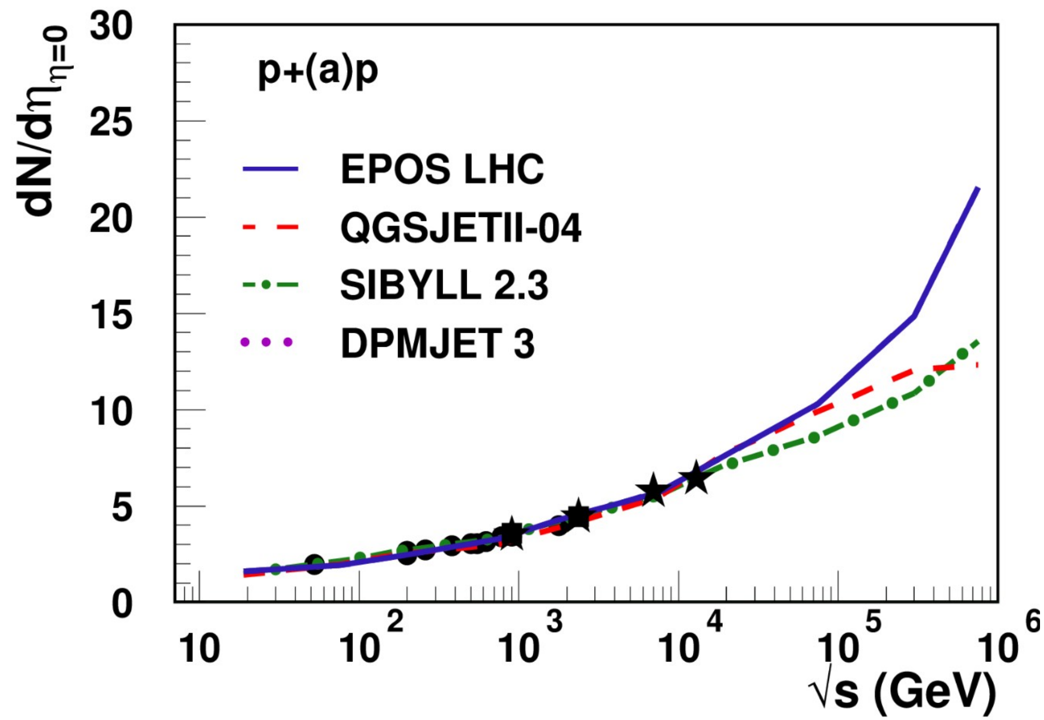
Multiplicity at mid-rapidity

- Multiplicity fixed by data up to 13 TeV
- extrapolation to high energy less model dependent after LHC
- QGSJET01 and QGSJETII-03 extrapolation excluded

Pre - LHC



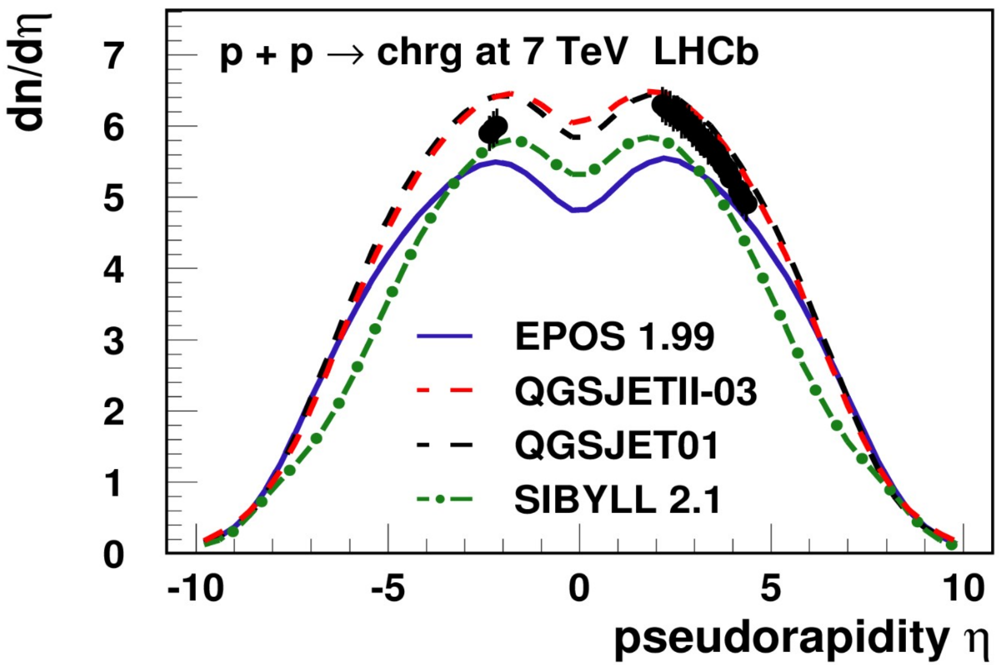
Post - LHC



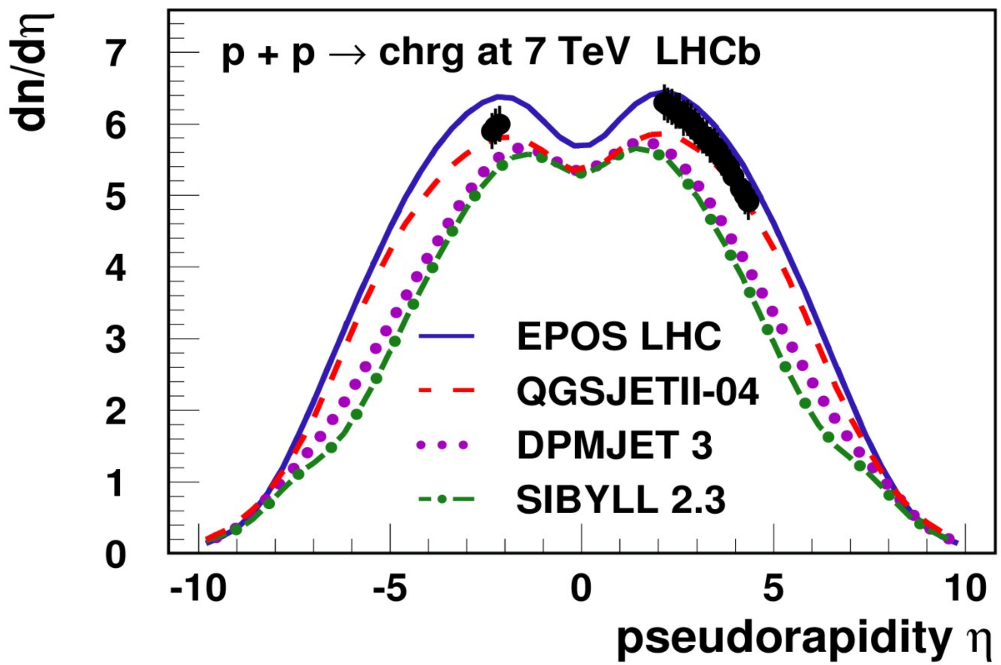
Pseudorapidity

- Difference between mid-rapidity and full multiplicity coming from the width of the pseudorapidity distributions
- From LHC data
  - DPMJET 3 and SIBYLL 2.3 too narrow
  - QGSJETII-04 ~ OK
  - EPOS LHC a bit too large

Pre - LHC

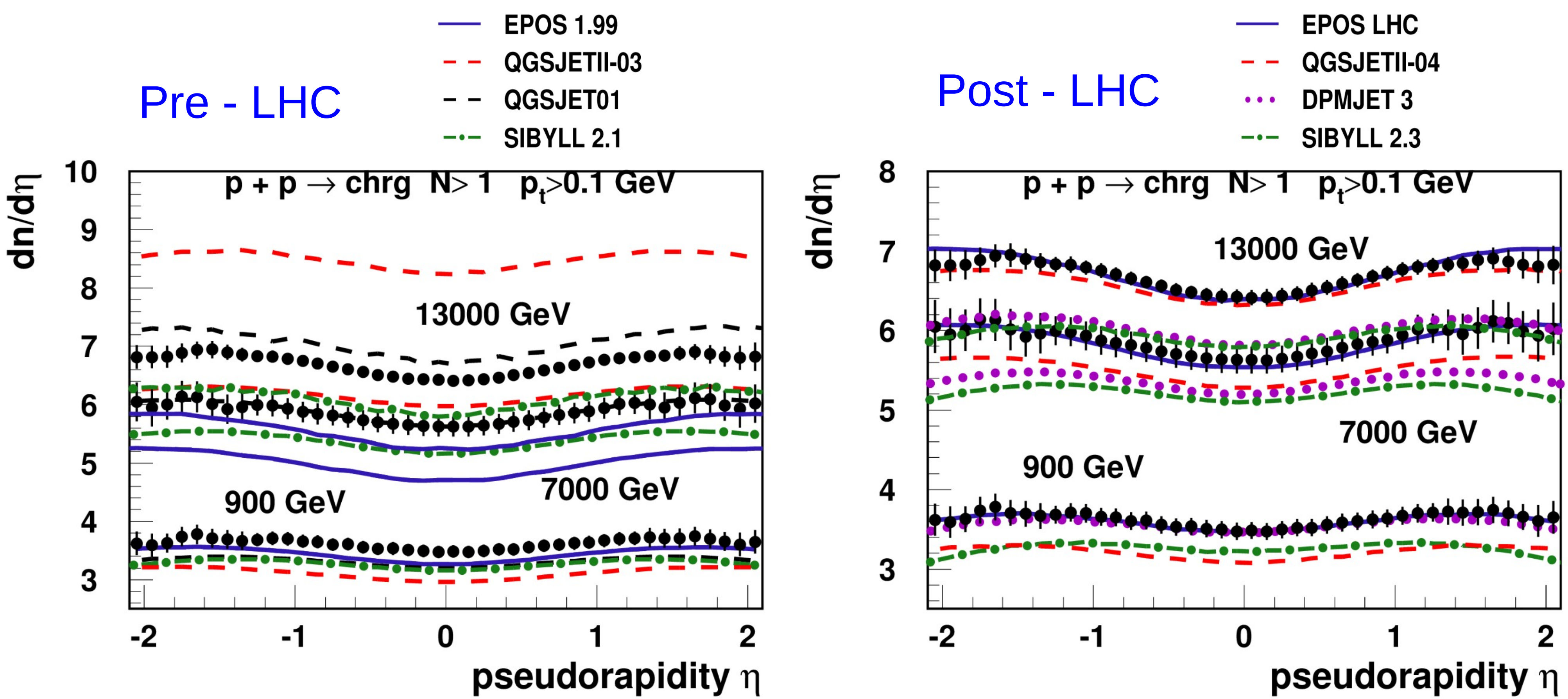


Post - LHC

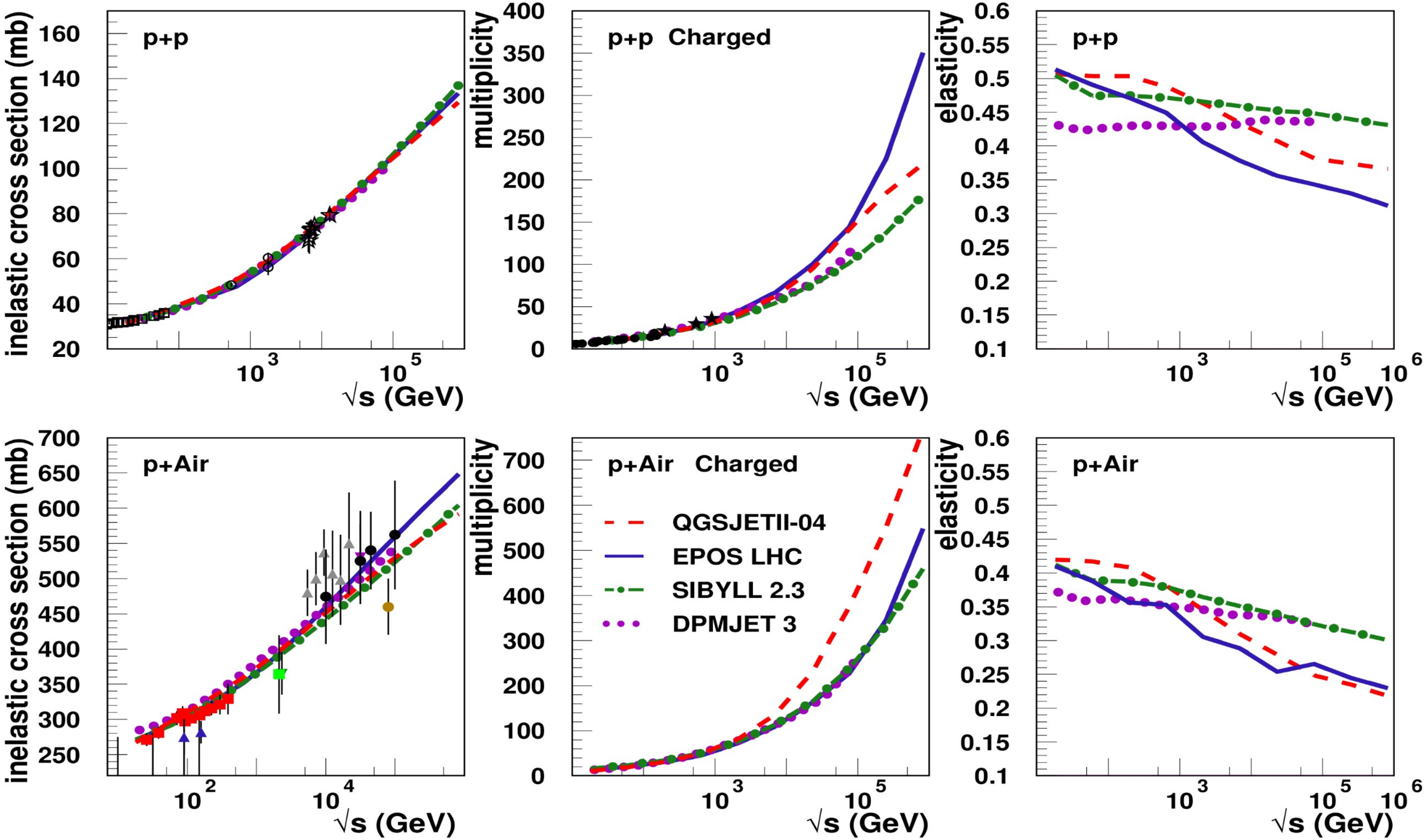


Test of Models vs Accelerator Data

- From LHC data
  - All pre-LHC models extrapolation excluded
  - DPMJET 3 and SIBYLL 2.3 underestimate multiplicity
  - QGSJETII-04 and EPOS LHC ~ OK (and similar to Pythia 8)



Ultra-High Energy Hadronic Model Predictions p-Air



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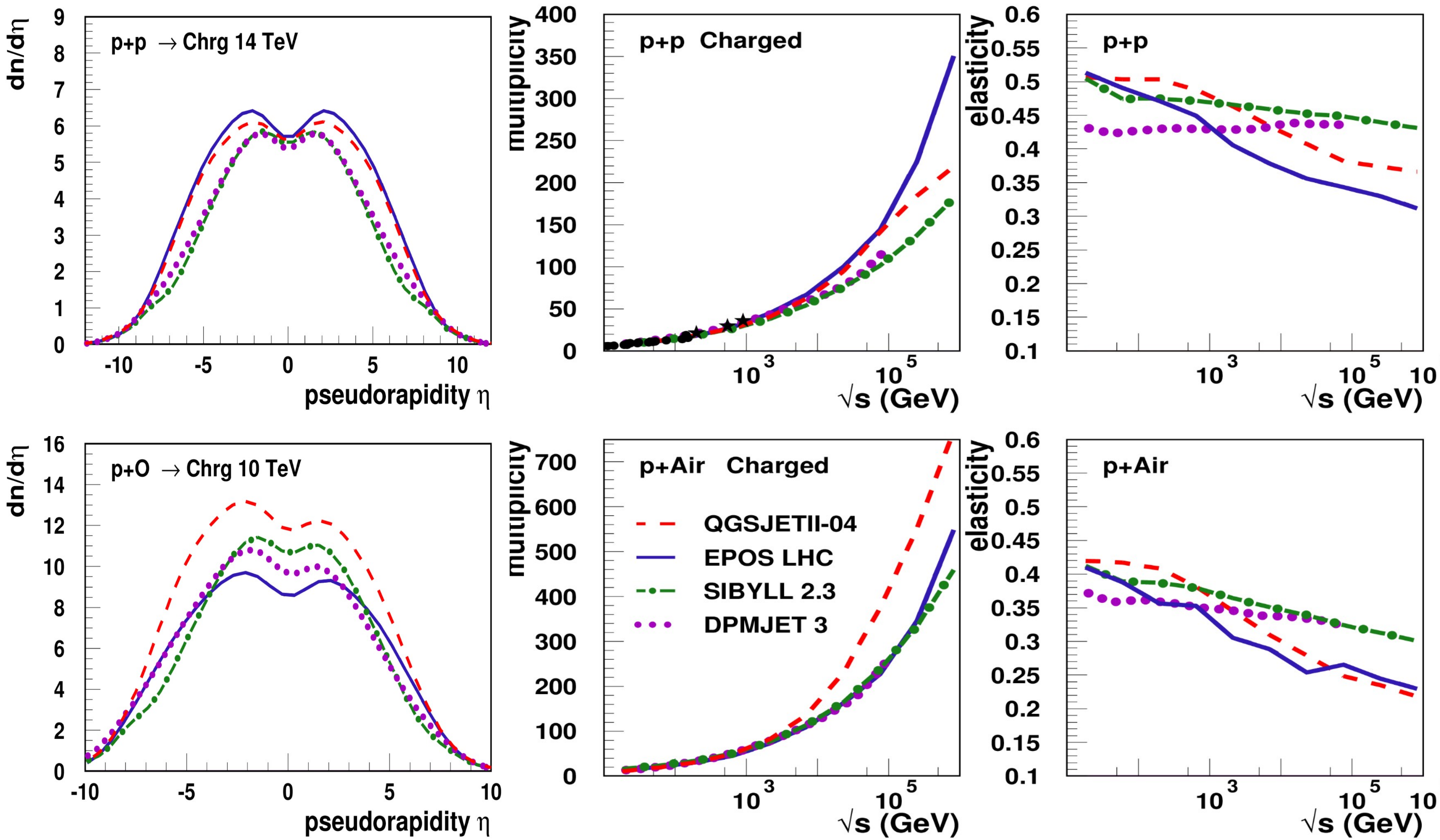
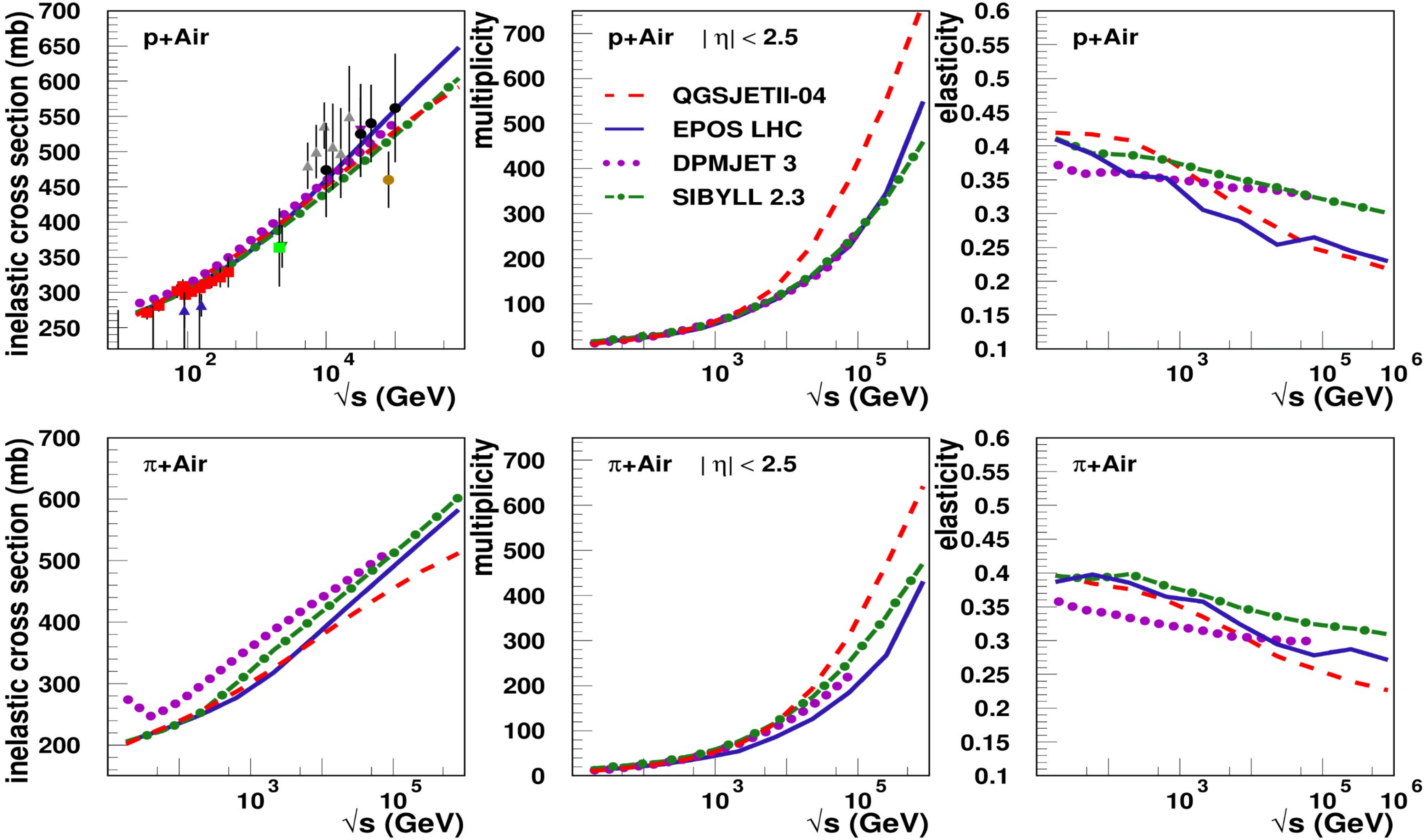
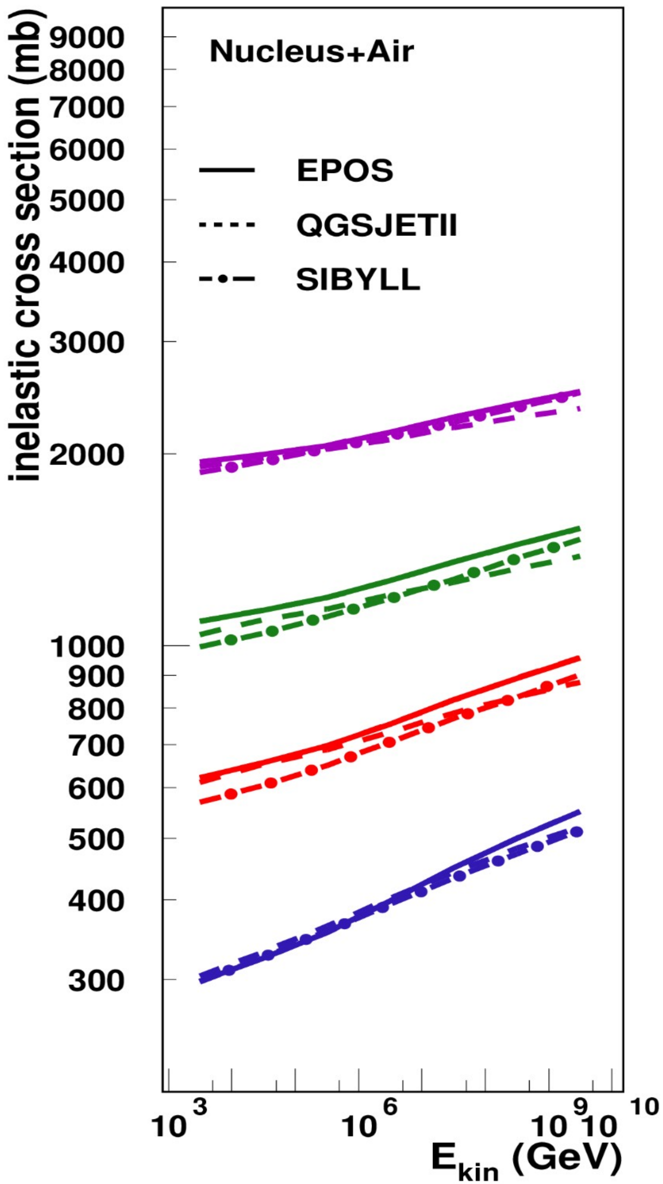
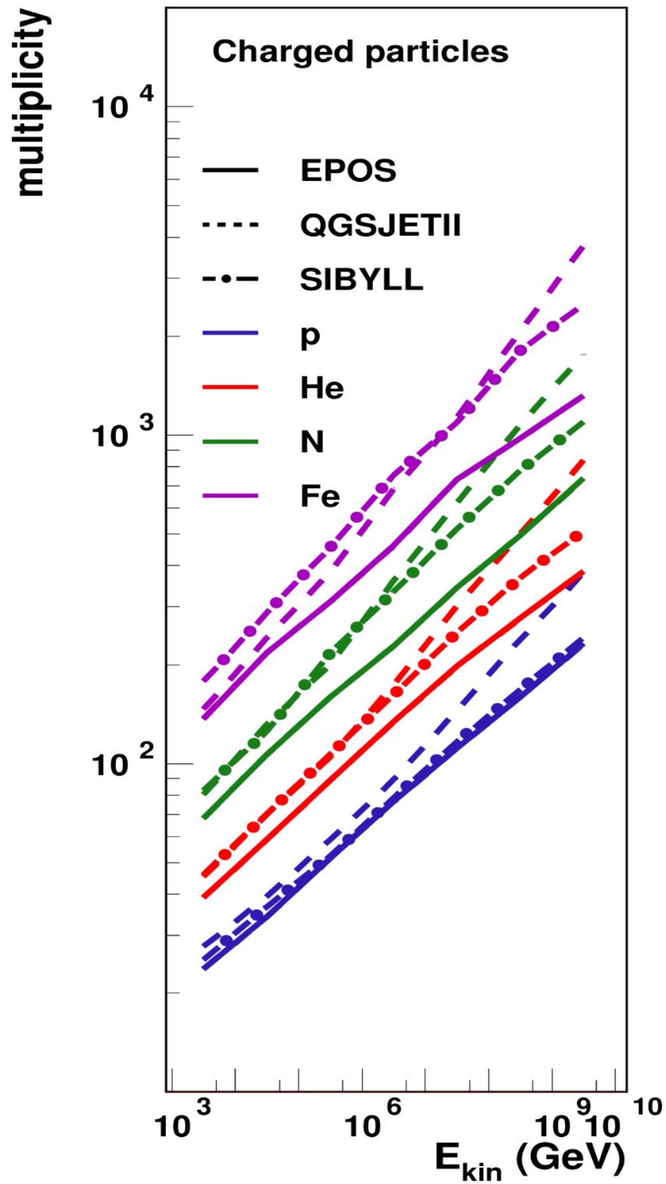


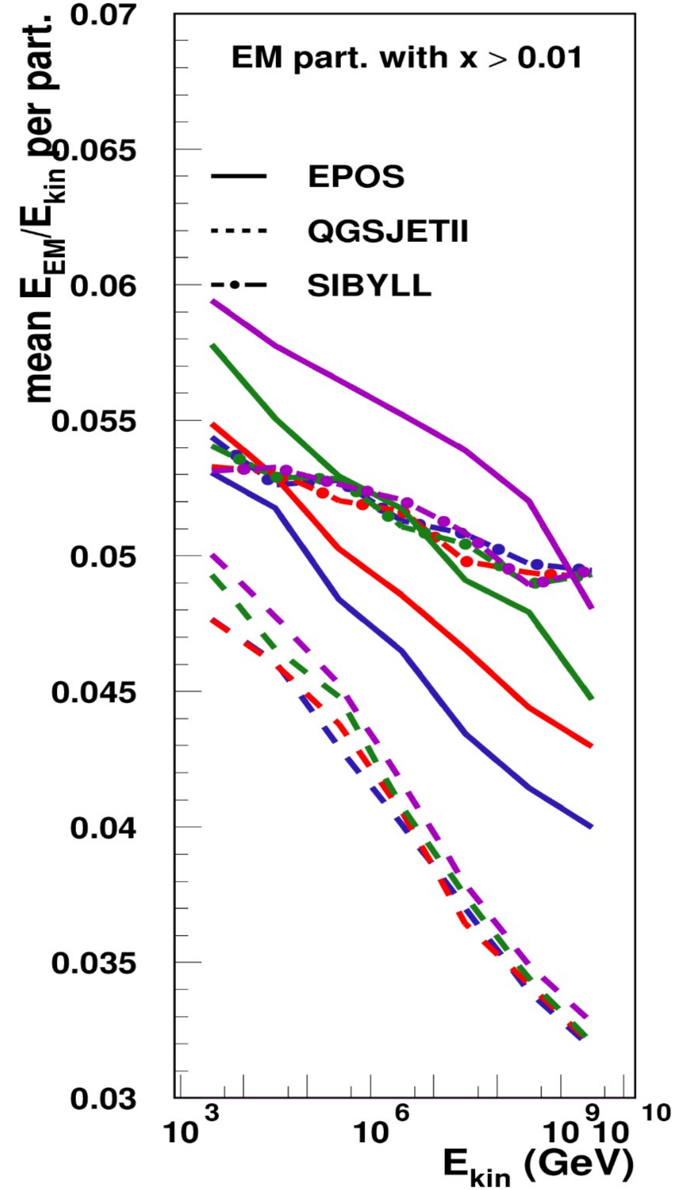
Ultra-High Energy Hadronic Model Predictions π-Air



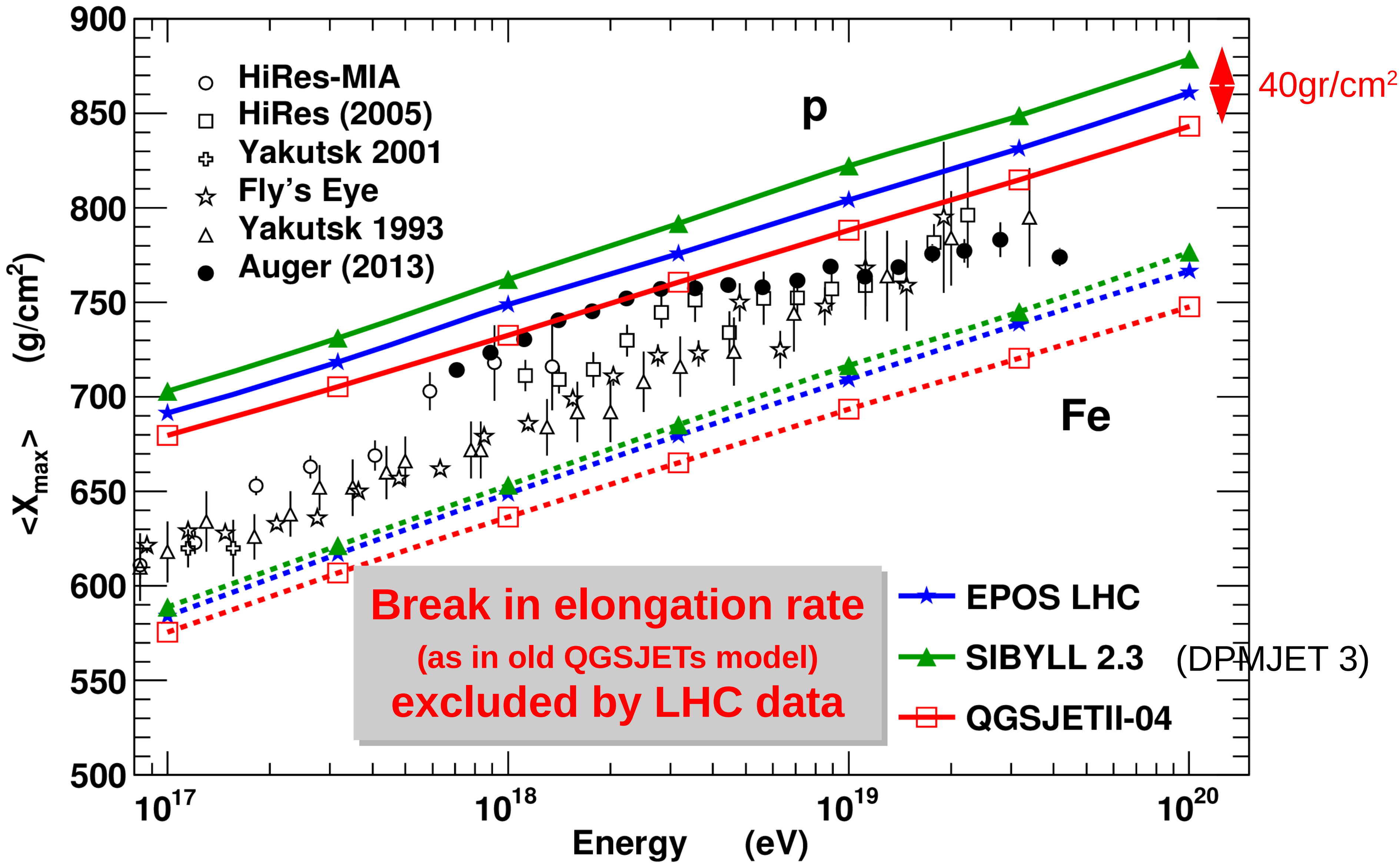
Ultra-High Energy Hadronic Model Predictions A-Air





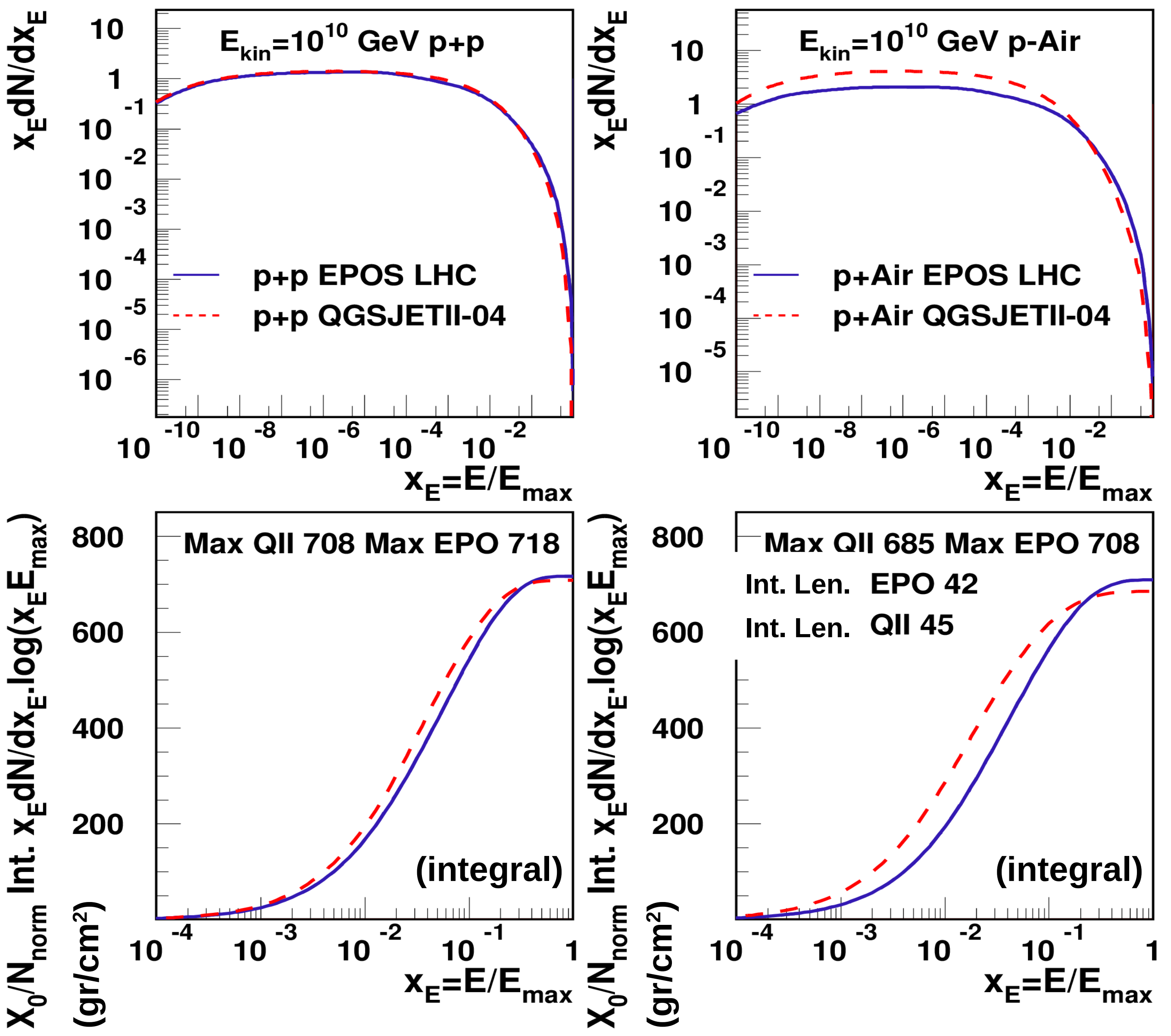


EAS with Re-tuned CR Models : X_{max}



Photon Energy Spectra

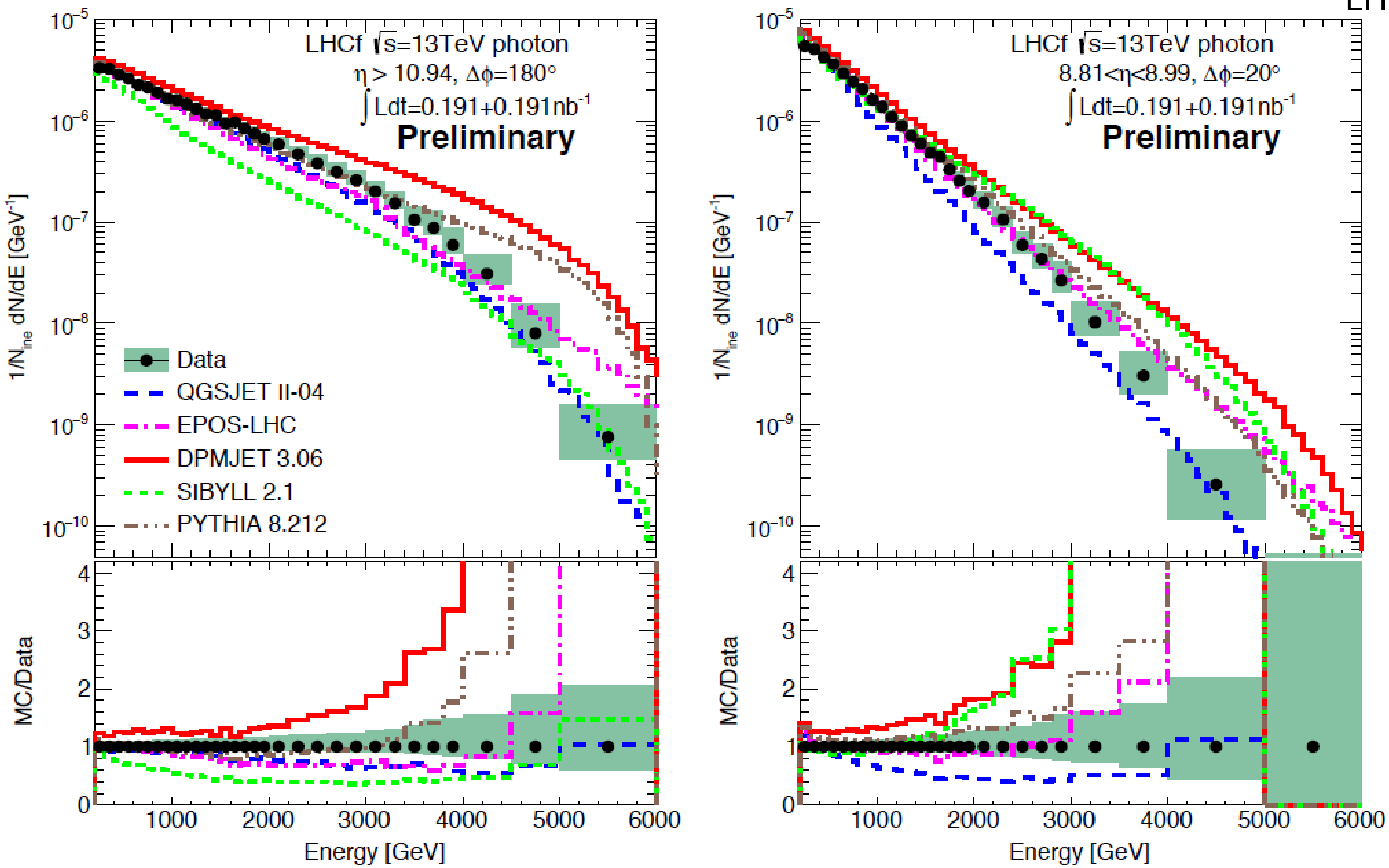
- **Uncertainties in X_{max}**
  - photon energy spectra
  - elasticity (for 2[d] interaction)
  - extrapolation to nuclear interactions
- **Use directly energy spectra from first interaction**
  - which energy is important ?



Comparison with LHCf

- LHCf favor not too soft photon spectra (EPOS LHC, SIBYLL 2.3) : deep X_{max}
- No model compatible with all LHCf measurements : room for improvments !
- Can p-Pb data be used to mimic light ion (Air) interactions ?

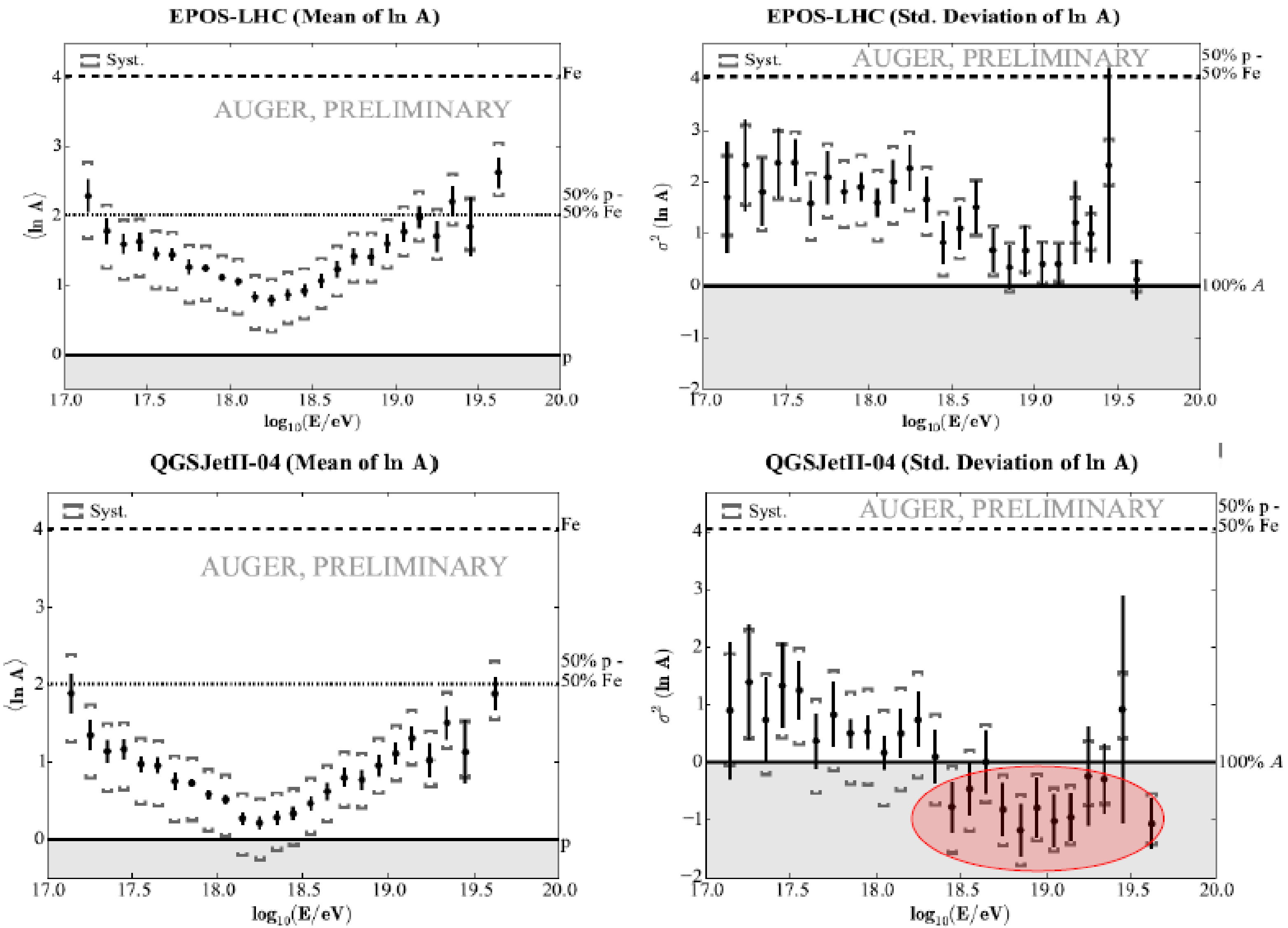
T.Sako for the LHCf collaboration



Model Consistency using Electromagnetic Component

Study by Pierre Auger Collaboration

➡ std deviation of lnA allows to test model consistency.

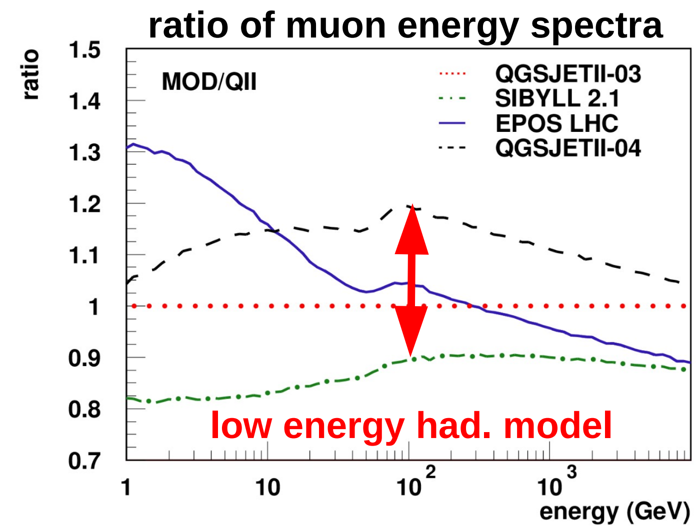


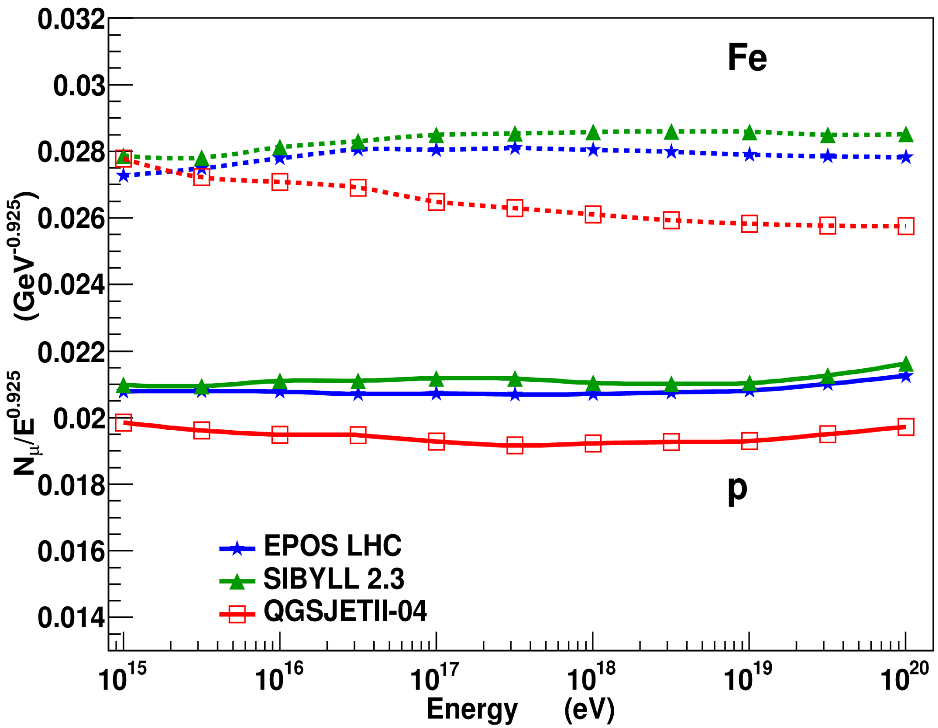
tensions if <X_{max}> too small

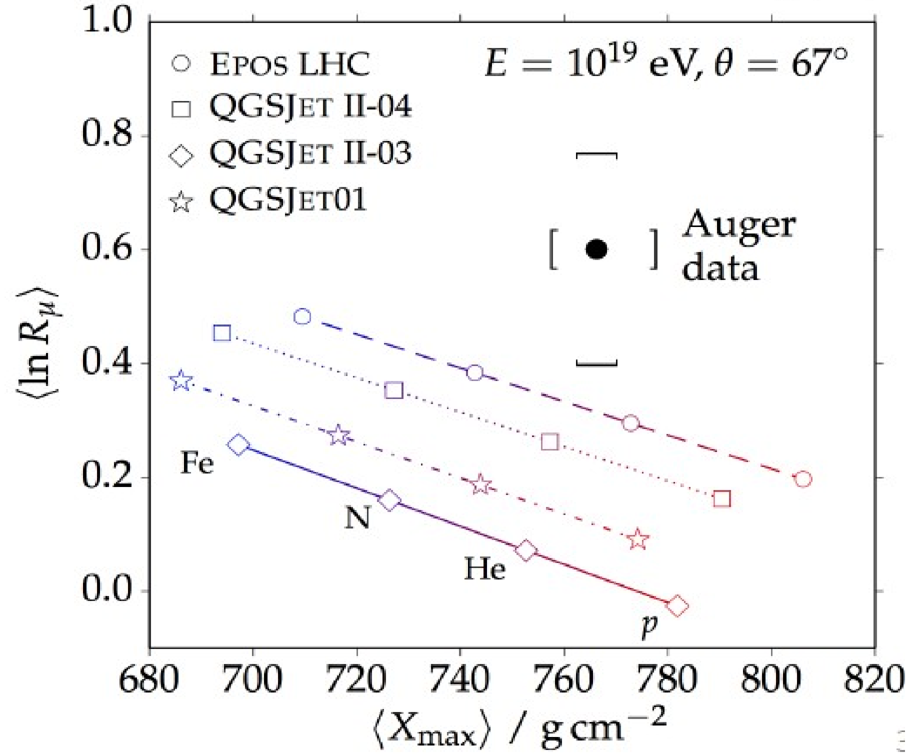
QGSJETII-04 is a lower limit for X_{max}

Muons at Ground

- Muon production depends on all int. energies
- Muon production dominated by pion interactions (LHC indirectly important)
- Resonance and baryon production important
- Post-LHC Models ~ agrees on numbers but with different production height and spectra

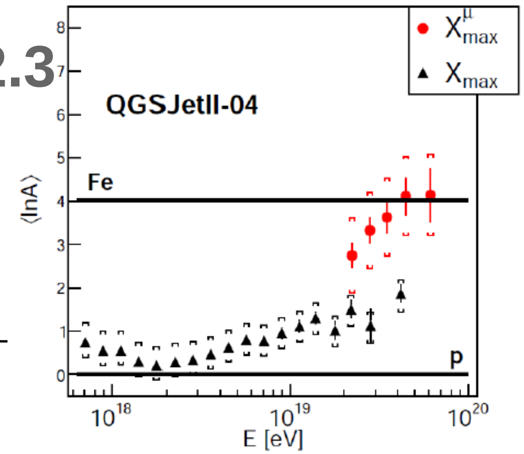


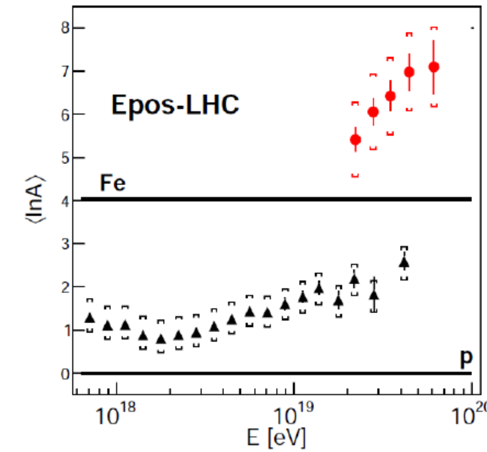


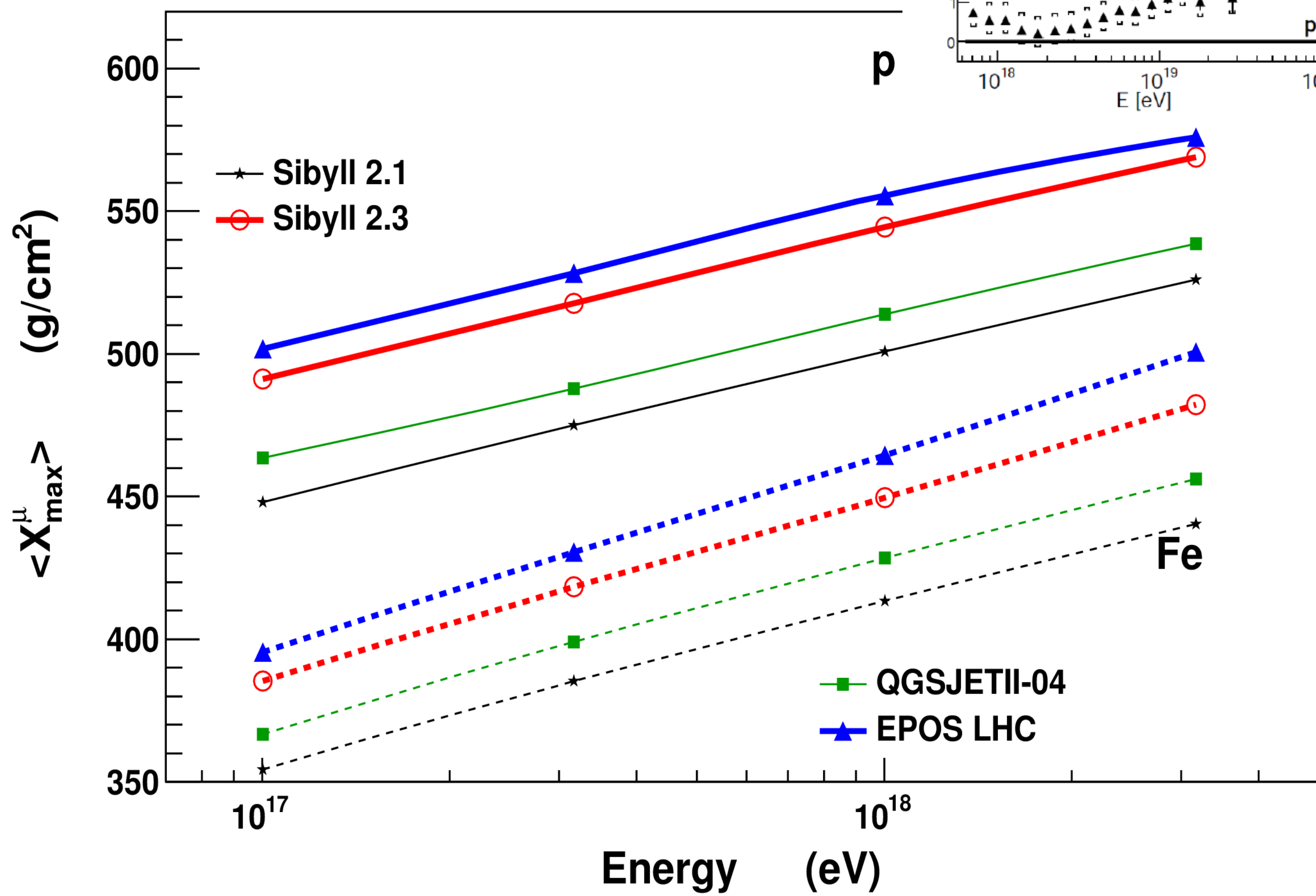


Muon Production Depth

- **Same for EPOS LHC and SIBYLL 2.3**
  - low pion-air elasticity: higher X^{μ}_{max}
  - more forward baryons: higher X^{μ}_{max}







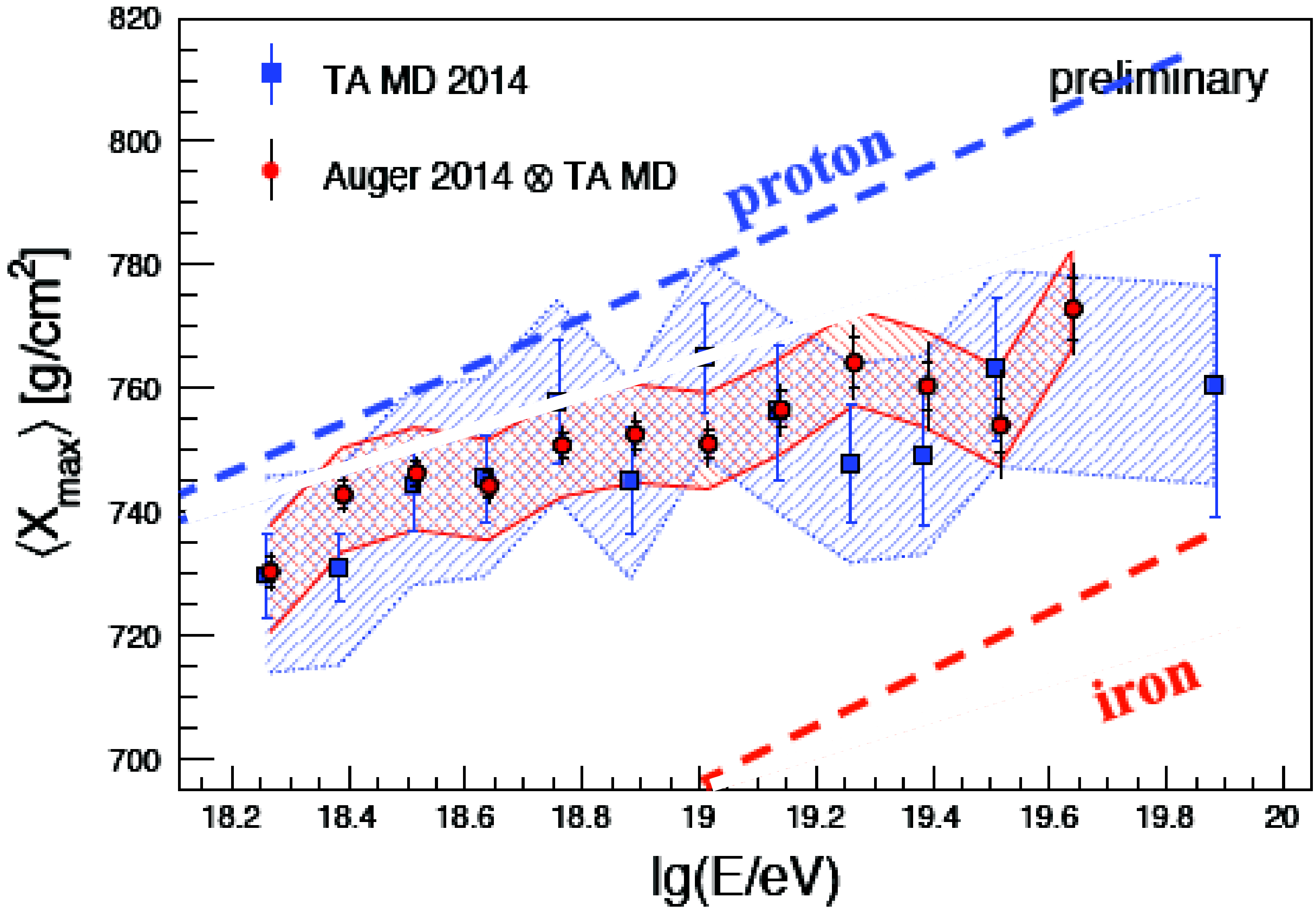
MPDs sensitive to baryon (less generation) and meson spectra in pion interactions so small effect on X_{max}

Source of discrepancy understood and will be corrected in EPOS 3.

Summary

- **Auger data (and other low energy cosmic ray experiments) not consistently described by hadronic interaction models (even post LHC)**
  - <X_{max}> and fluctuations, number of muons and muon production depth …
  - ➡ but it has never been so good ! only 1 to 2 sigma difference in most of the cases
- **Central particle production at LHC reduced model uncertainties in slope of X_{max}**
  - ➡ same energy evolution in models important for mass of primary cosmic rays
  - ➡ all pre-LHC models in contradiction with LHC data (central and forward prod.)
  - ➡ using latest model version reduce uncertainties and avoid unphysical behavior
- **Remaining 20 gr/cm^2 difference for X_{max} predictions**
  - ➡ linked to forward physics (photon spectra and diffraction measured at LHC) not yet taken into account in models used for EAS simulation (coming...)
  - ➡ effect of extrapolation to p-Air interaction
    - p-O beam necessary to check that p-p properly extrapolated
    - p-Pb measurements can be used but need change in most models (only EPOS reproduces p-Pb data for the moment)

Conclusion ...



From Roberto Aloiso talk (2015 working group)

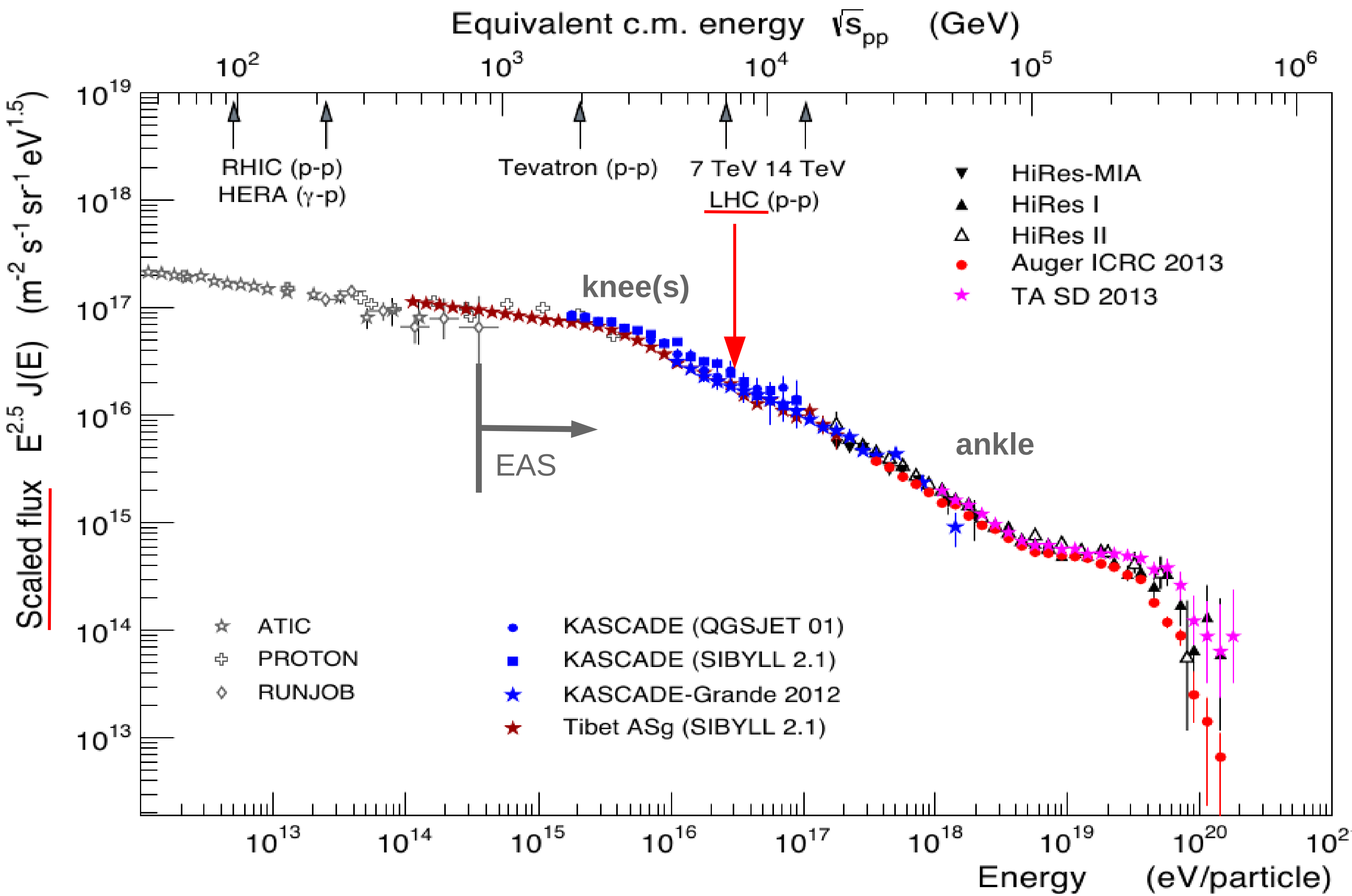
Baryons in Pion-Carbon

- **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

- **New data set from NA49 (G. Veres' PhD)**
  - ➔ test π^+ and π^- interactions and productions at 158 GeV with C and Pb target
  - ➔ confirm large forward proton production in π^+ and π^- 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

Cosmic Ray Spectrum



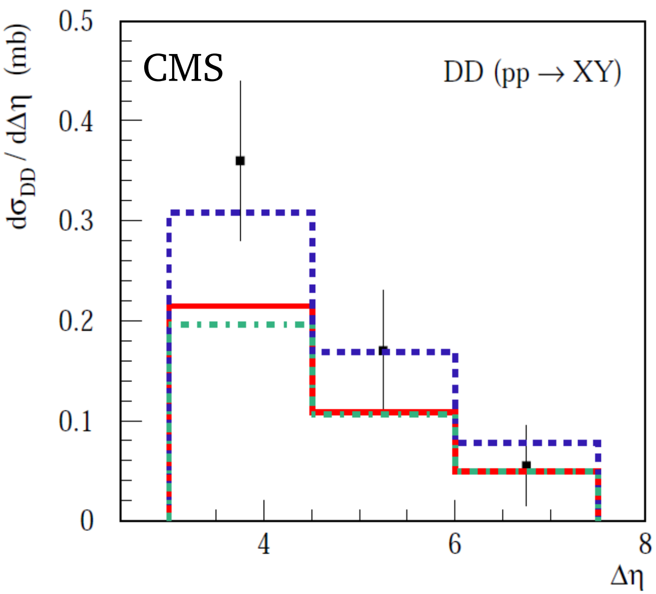
R. Engel (KIT)

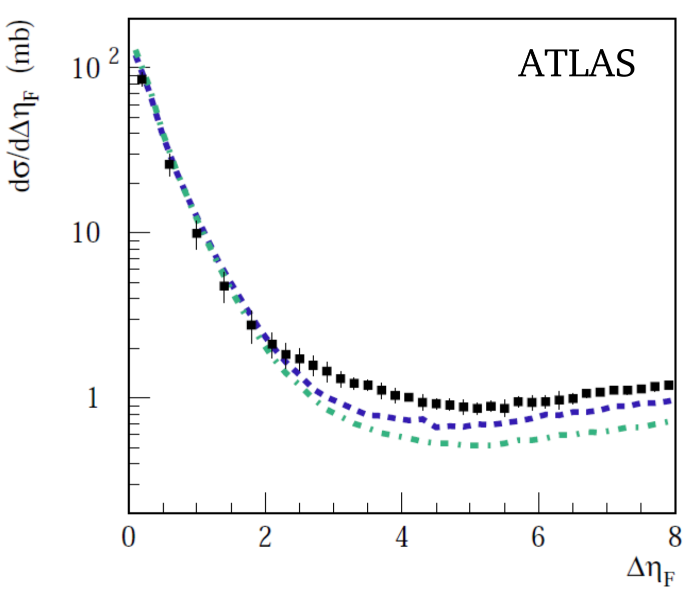
Diffraction measurements

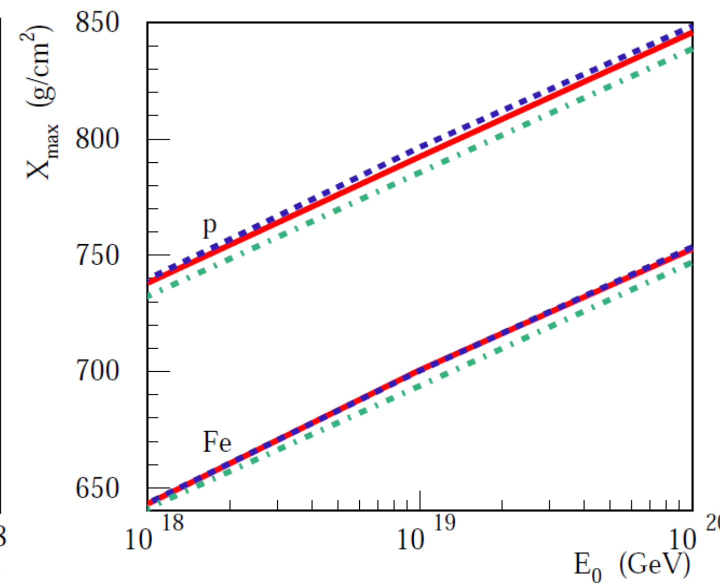
- **TOTEM and CMS diffraction measurement not fully consistent**
- **Tests by S. Ostapchenko using QGSJETII-04 (PRD89 (2014) no.7, 074009)**
  - ➔ SD+ option compatible with CMS
  - ➔ SD- option compatible with TOTEM

M_X range	< 3.4 GeV	$3.4 - 1100$ GeV	$3.4 - 7$ GeV	$7 - 350$ GeV	$350 - 1100$ GeV
TOTEM [13, 24]	2.62 ± 2.17	6.5 ± 1.3	$\simeq 1.8$	$\simeq 3.3$	$\simeq 1.4$
QGSJET-II-04	3.9	7.2	1.9	3.9	1.5
option SD+	3.2	8.2	1.8	4.7	1.7
option SD-	2.6	7.2	1.6	3.9	1.7

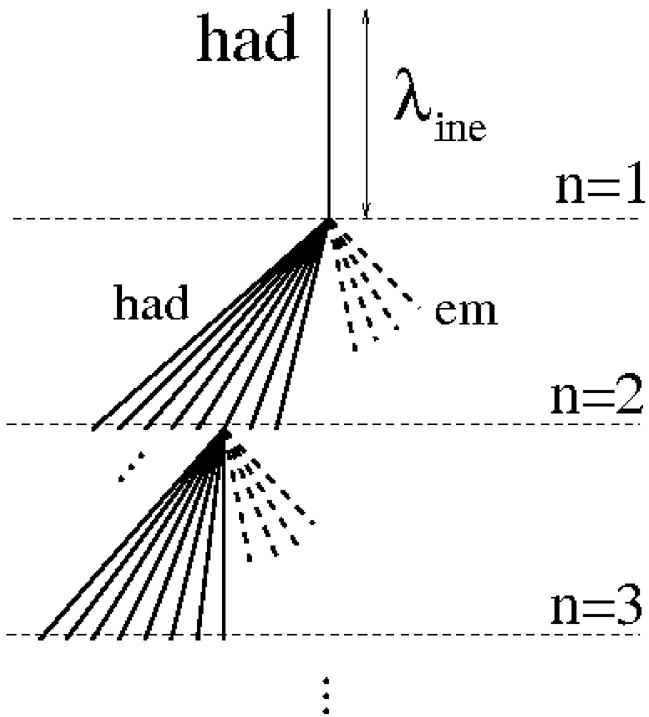
  - ➔ difference of ~10 gr/cm^2 between the 2 options







Simplified Shower Development



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

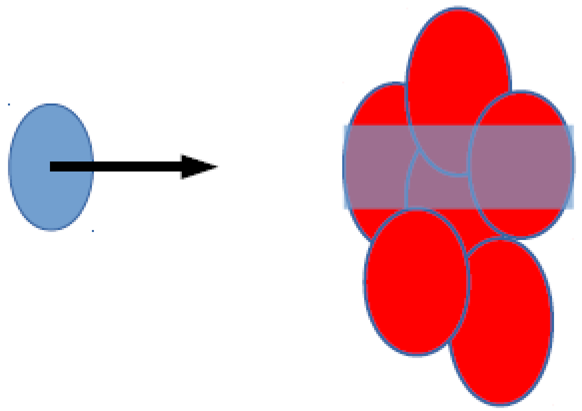
J. Matthews, Astropart.Phys. 22 (2005) 387-397

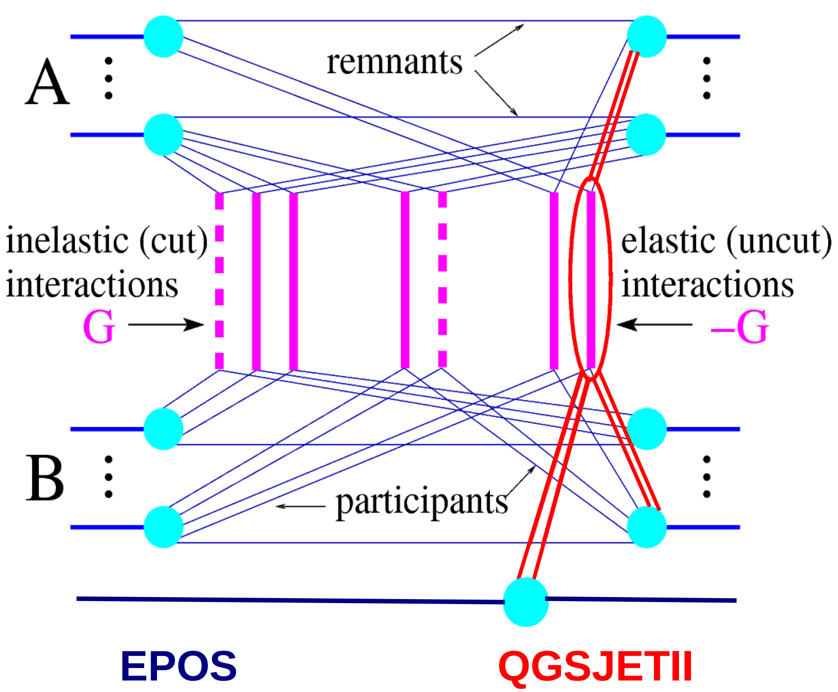
Using generalized Heitler model and superposition model :

$$X_{max} \sim \lambda_e \ln\left((1-k) . E_0 / (2.N_{tot} . A)\right) + \lambda_{ine}$$

- Model independent parameters :
  - E_0 = primary energy
  - A = primary mass
  - λ_e = electromagnetic mean free path
- Model dependent parameters :
  - k = elasticity
  - N_{tot} = total multiplicity
  - λ_{ine} = hadronic mean free path (cross section)

Nuclear Interactions



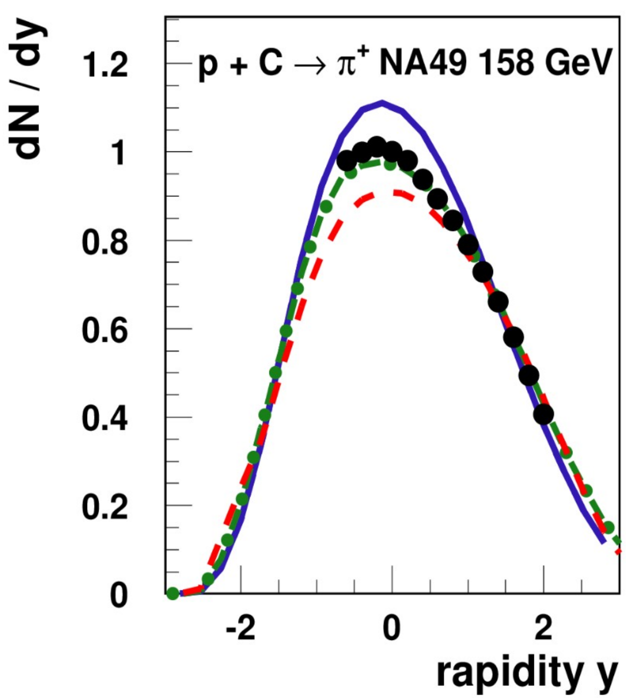


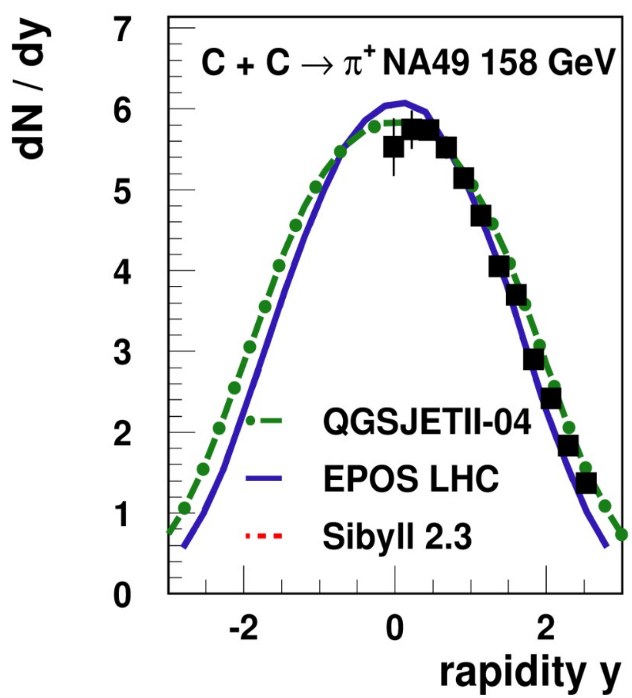
- **Sibyll**
  - Glauber for pA
    - with inelastic screening for diffraction in new Sibyll 2.3 (only nuclear effect)
  - superposition model for AA (A x pA)
- **QGSJETII**
  - Pomeron configuration based on A projectiles and A targets
  - Nuclear effect due to multi-leg Pomerons
- **EPOS**
  - Pomeron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

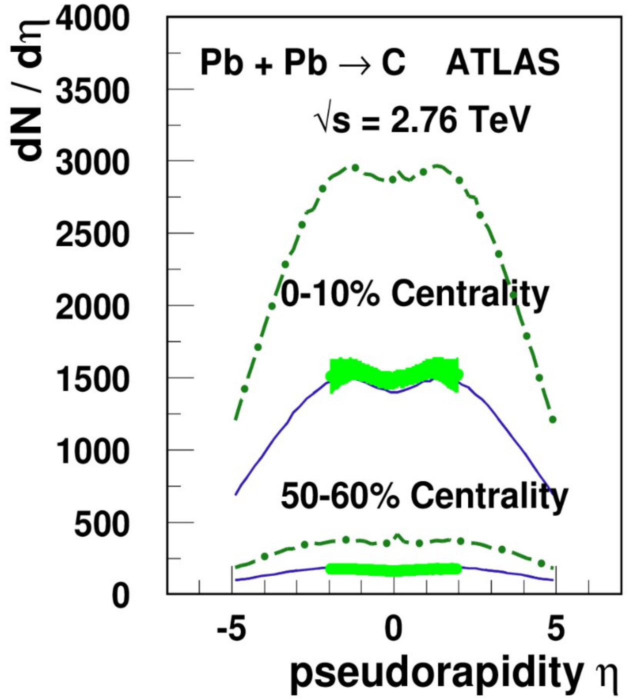
Light Ion Data

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

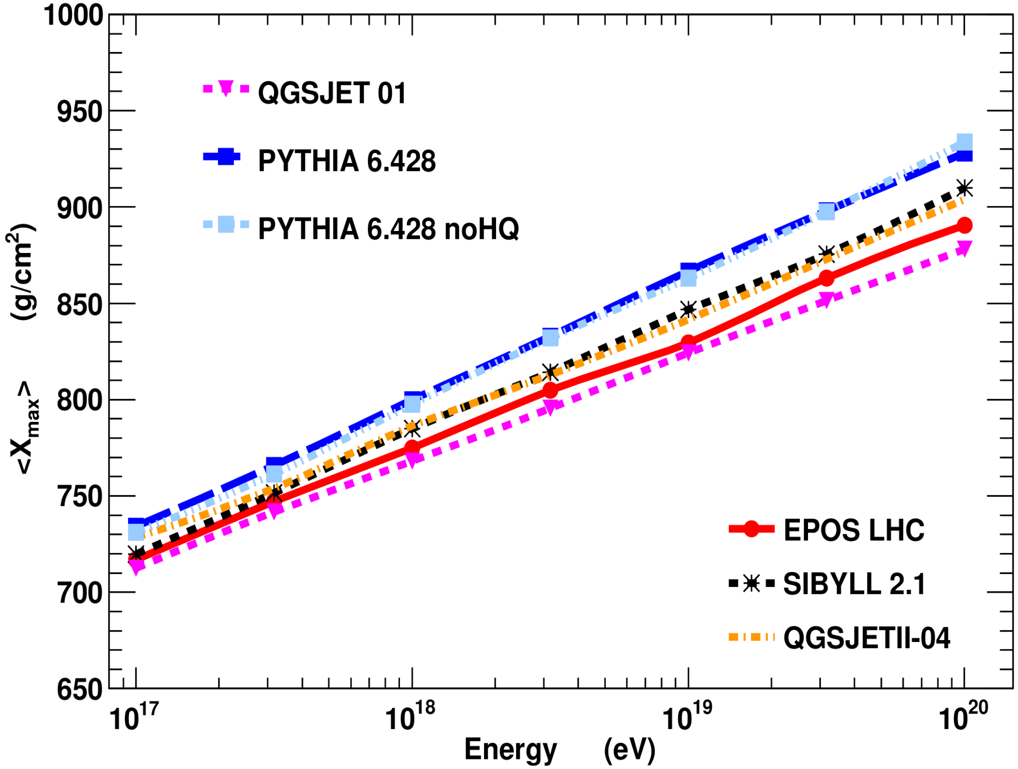


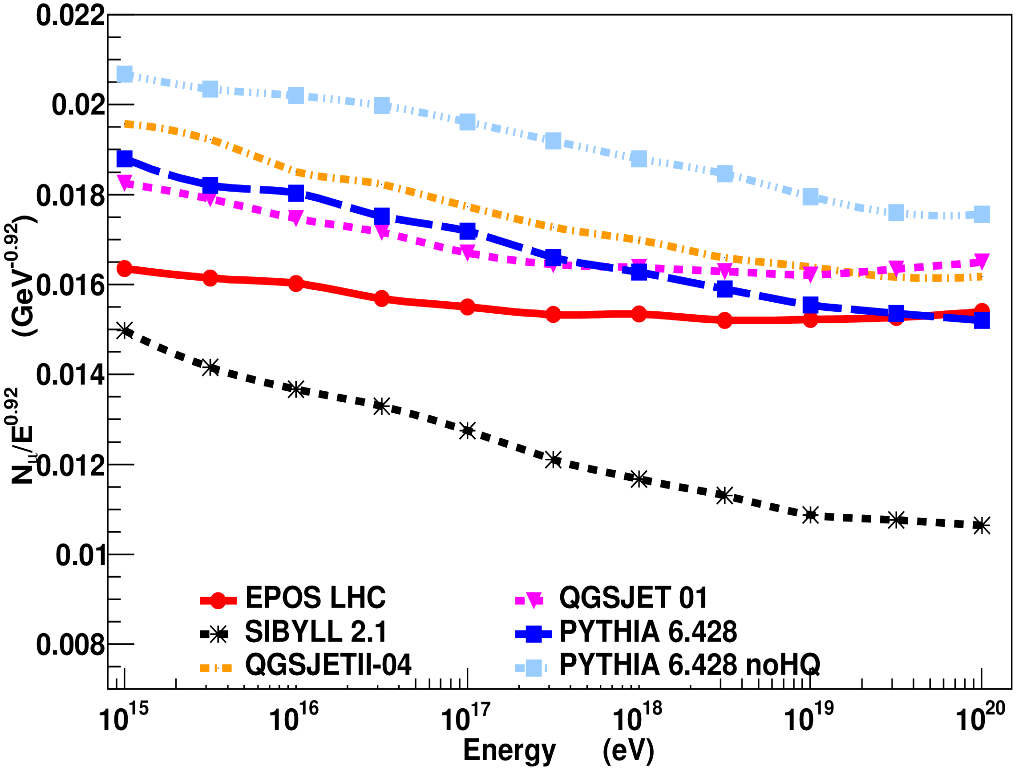




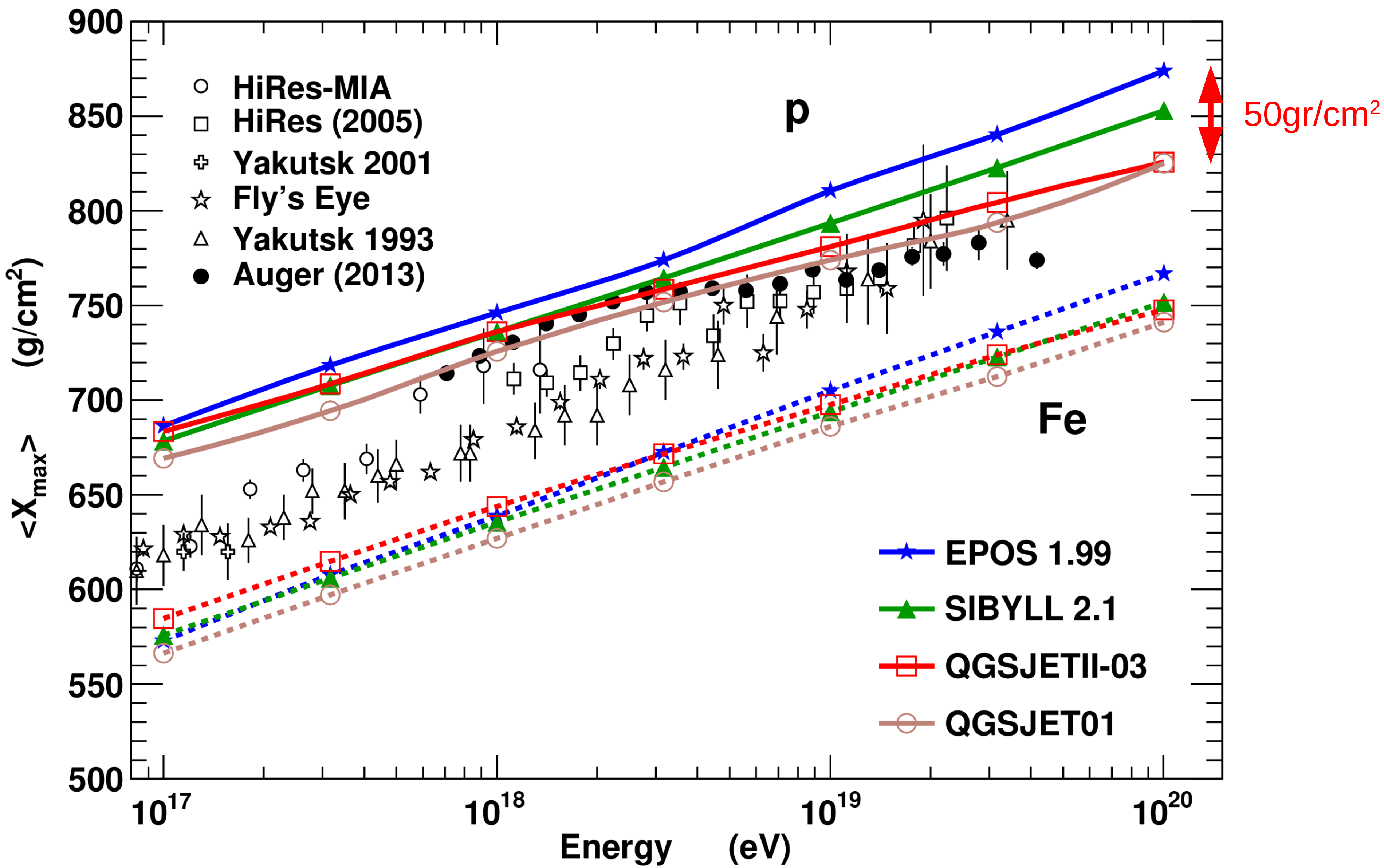
Tests using hydrogen atmosphere

- **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

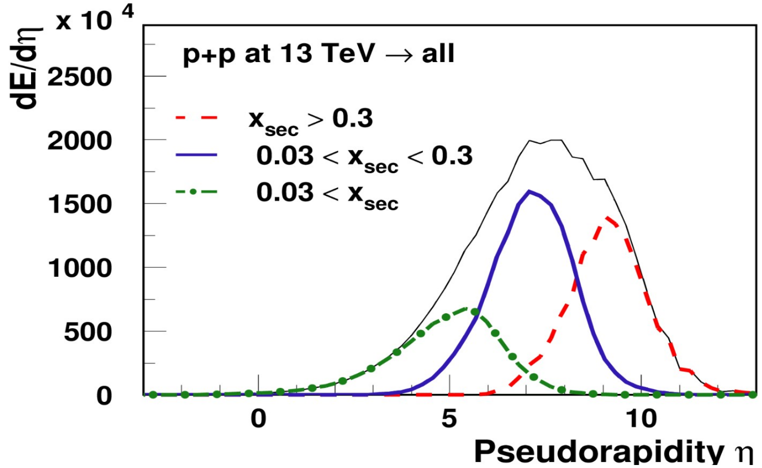


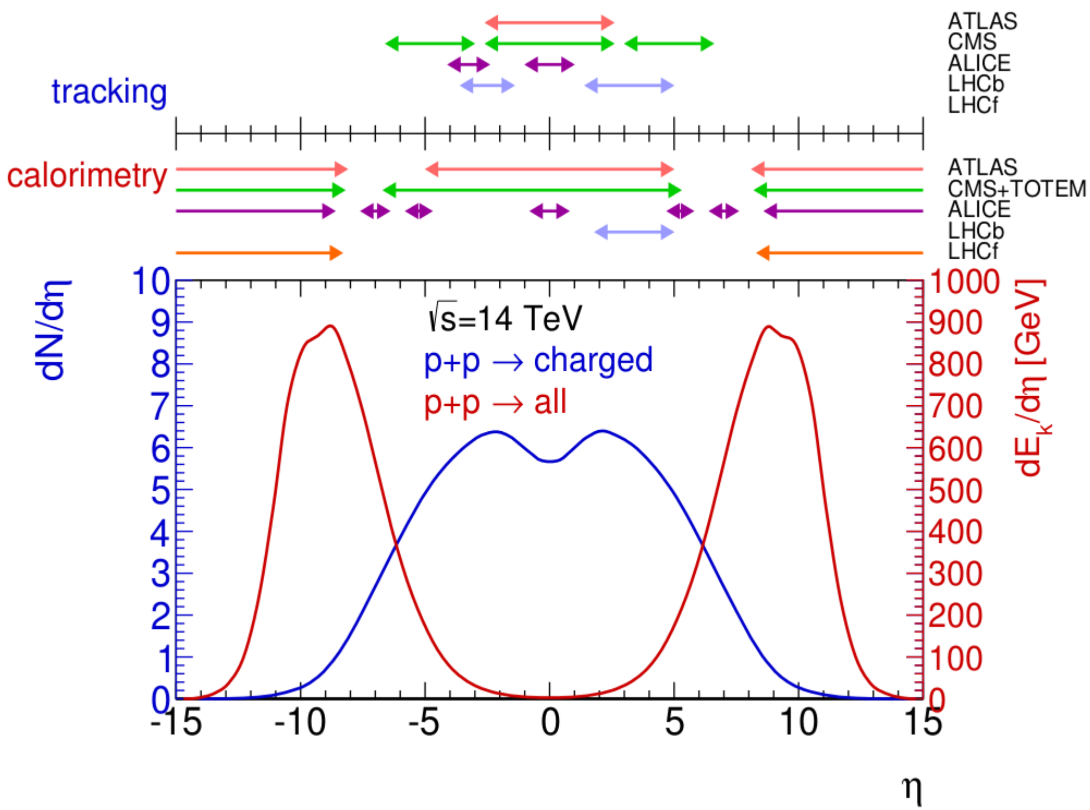


EAS with Old CR Models : X_{max}



LHC acceptance





- **p-p data of central detectors used to reduce uncertainty by factor ~2**
  - p-Pb difficult to compare to CR models (only EPOS)
  - special centrality selection
  - pO ?
- **Direct photon energy spectra from LHCf**
  - small phase space but relevant for X_{max}
  - p-Pb (O) and correlation with ATLAS
- **Average elasticity/inelasticity** (energy fraction of the leading particle)
  - all diffraction measurement to be taken into account