Air Shower Simulation with a New (the first) Generation of post-LHC Hadronic Interaction Models in CORSIKA

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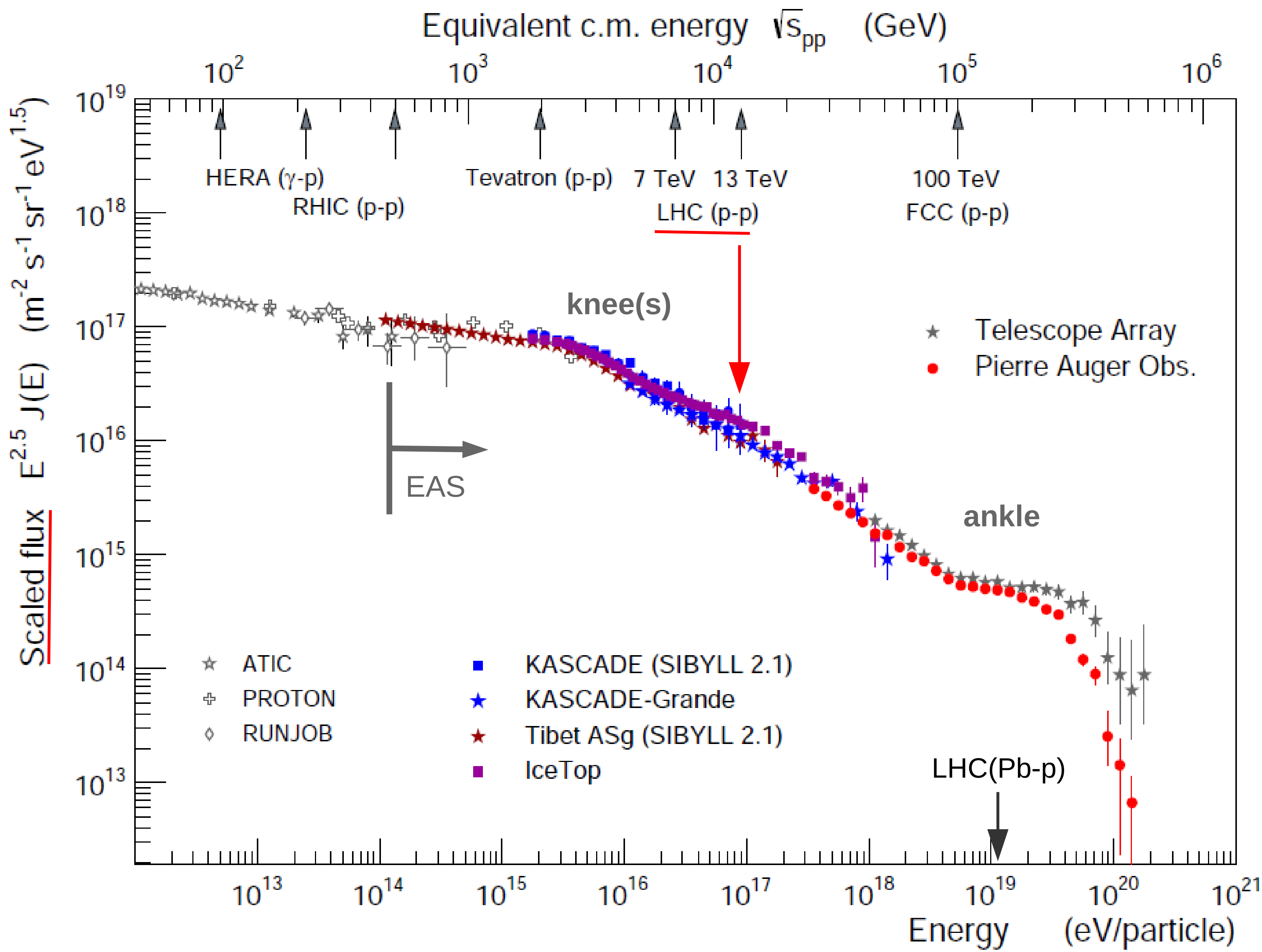
Outline

- **Hadronic Interactions and Monte-carlo (MC) for Cosmic Ray (CR) analysis**
- **General MC comparison of model extrapolations**
- **Electromagnetic (EM) signal in extended air showers**
- **Muon signal**

LHC data reduced the model uncertainties and exclude old models for mass composition of cosmic rays. Remaining uncertainties linked to model limitations and lack of (light) nuclear target.

Energy Spectrum



R. Engel (KIT)

Hadronic Interaction Models

- **What are the hadronic model suppose to do ?**
  - ➡ Transfer part of the energy of a fast projectile to slower newly produced particles when a target is hit
  - ➡ excite the vacuum to produce new particles (quantum number conservation)
  - ➡ conserve the total energy of the system
  - ➡ follow the standard model (QCD)
    - ➡ but mostly non-perturbative regime (phenomenology needed)

- **Which model for CR ? (alphabetical order)**
  - ➡ **DPMJETIII.17-1** by S. Roesler, A. Fedynitch, R. Engel and J. Ranft
  - ➡ **EPOS (1.99/LHC)** (from VENUS/NEXUS before) by H.J. Drescher, F. Liu, T. Pierog and K.Werner.
  - ➡ **QGSJET** (01/II-03/II-04) by S. Ostapchenko (starting with N. Kalmykov)
  - ➡ **Sibyll (2.1/2.3c)** by E-J Ahn, R. Engel, R.S. Fletcher, T.K. Gaisser, P. Lipari, F. Riehn, T. Stanev

When does a projectile interact ?

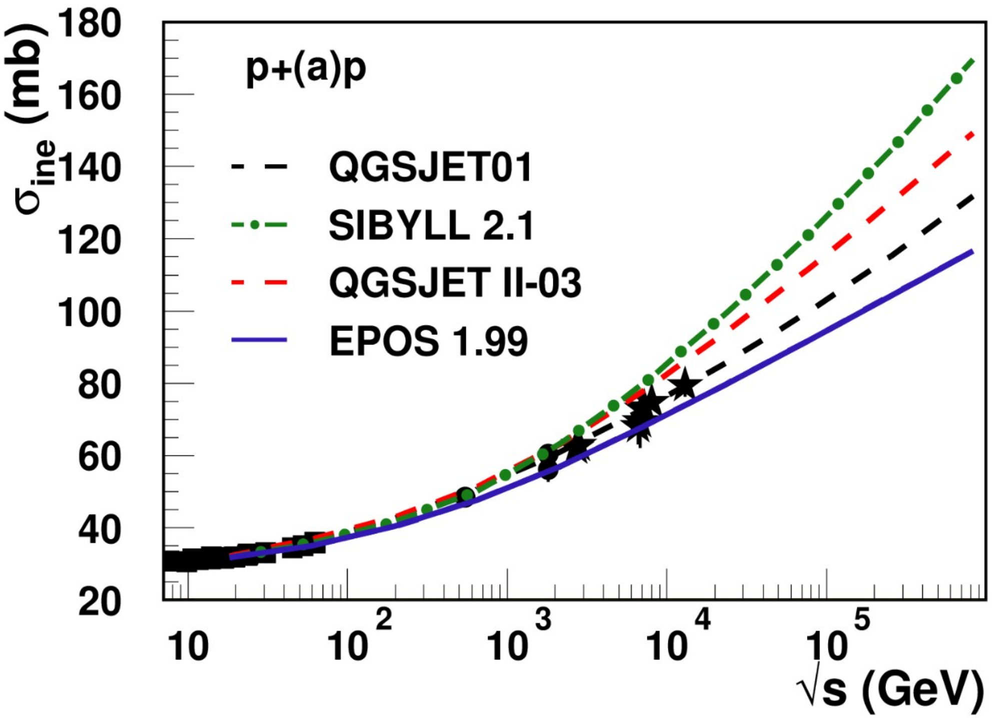
For all models cross-section calculation based on optical theorem

- total cross-section given by elastic amplitude

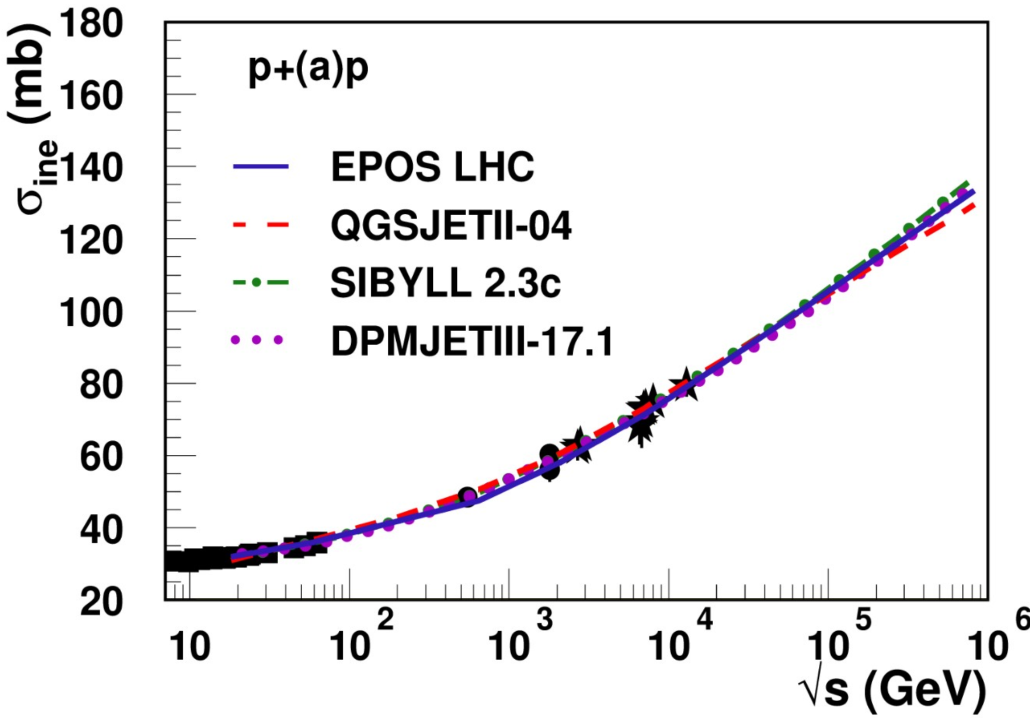
$$\sigma_{tot} = \frac{1}{s}\Im m(A(s,t \to 0))$$

- different amplitudes in the models but free parameters set to reproduce all p-p cross-sections
- basic principles + high quality LHC data = same extrapolation

Pre - LHC



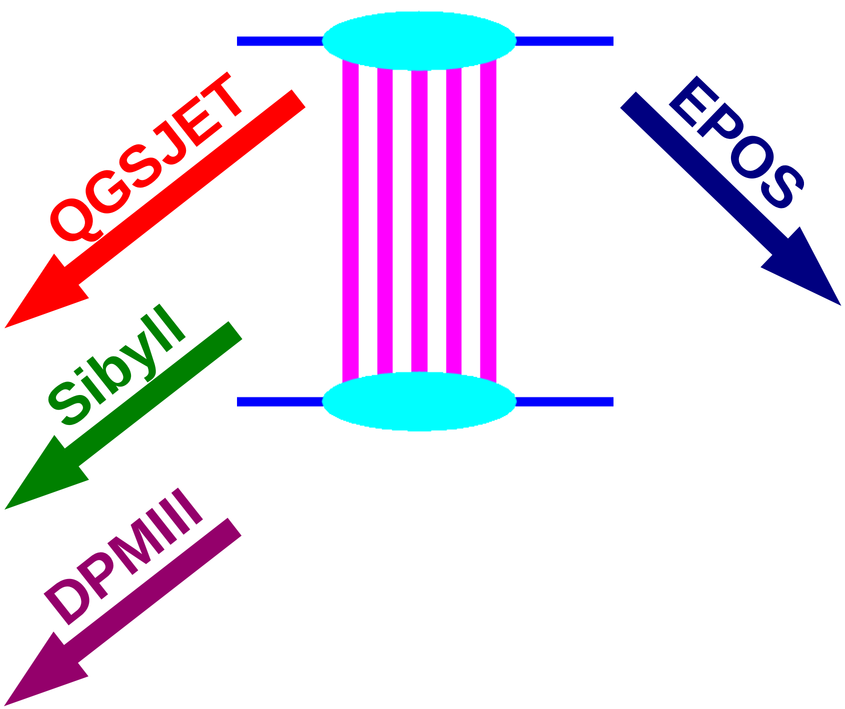
Post - LHC



How does the projectile interact ?

- **Field theory : scattering via the exchange of an excited field**
  - parton, hadron, quasi-particle = Reggeon or Pomeron (vacuum excitation)
- **Gribov-Regge Theory and cutting rules : multiple scattering associated to cross-section via sum of inelastic states**
  - different ways of dealing with energy conservation

- sum all scatterings with full energy to get cross-section
- get number of elementary scattering without energy sharing (Poissonian distribution)
- share energy between scattering afterwards



- cross-section calculated with energy sharing
- get the number of scattering taking into account energy conservation
- consistent approach

Does energy sharing order matter ?

- **Field theory : scattering via the exchange of an excited field**
  - ➜ parton, hadron, quasi-particle = Reggeon or Pomeron (vacuum excitation)
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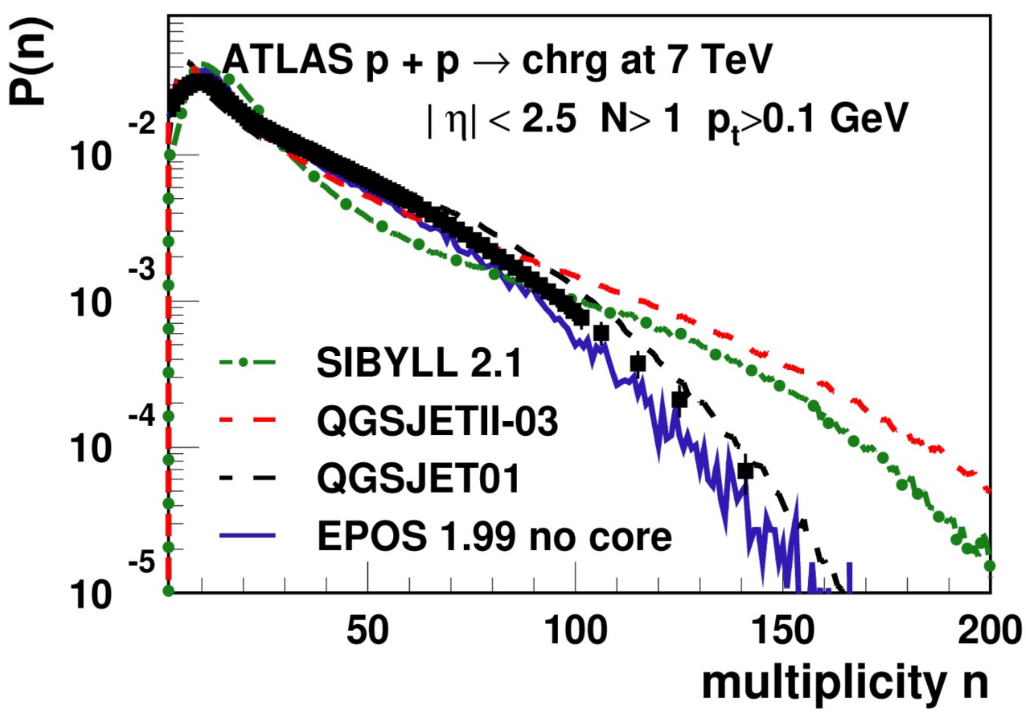
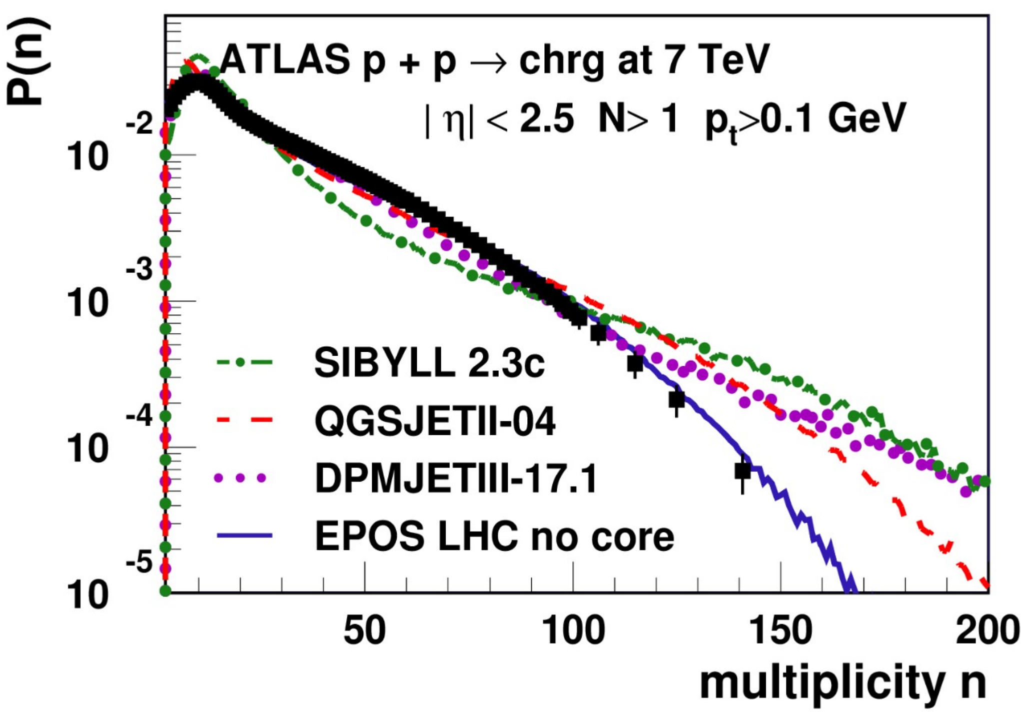
Pre - LHC

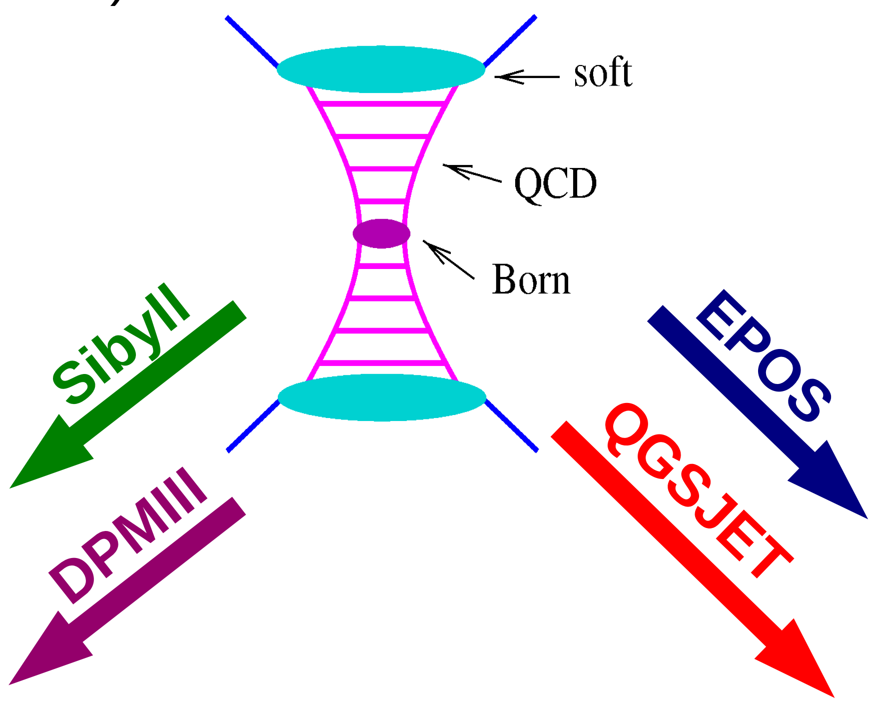


Post - LHC



How to build the amplitude ?

- **Field theory : scattering via the exchange of an excited field**
  - parton, hadron, quasi-particle = Reggeon or Pomeron (vacuum excitation)
- **QCD based theory so at high energy, perturbative QCD can be used to build the field amplitude (amplitude used for the cross-section)**
  - all minijet based (parton cascade and pQCD born process hadronized using string fragmentation) but different definitions



- soft+hard in different components
- external parton distribution functions (**GRV98**,**cteq14**)
- connection to projectile/target with small “x”

- soft+hard in the same amplitude
- own parton distribution function compatible with HERA data (not for QGSJET01: pre-HERA time)
- connection to projectile/target with large “x”

Ostapchenko et al. Phys.Rev. D94 (2016) no.11, 114026

Does the minijet definition matter ?

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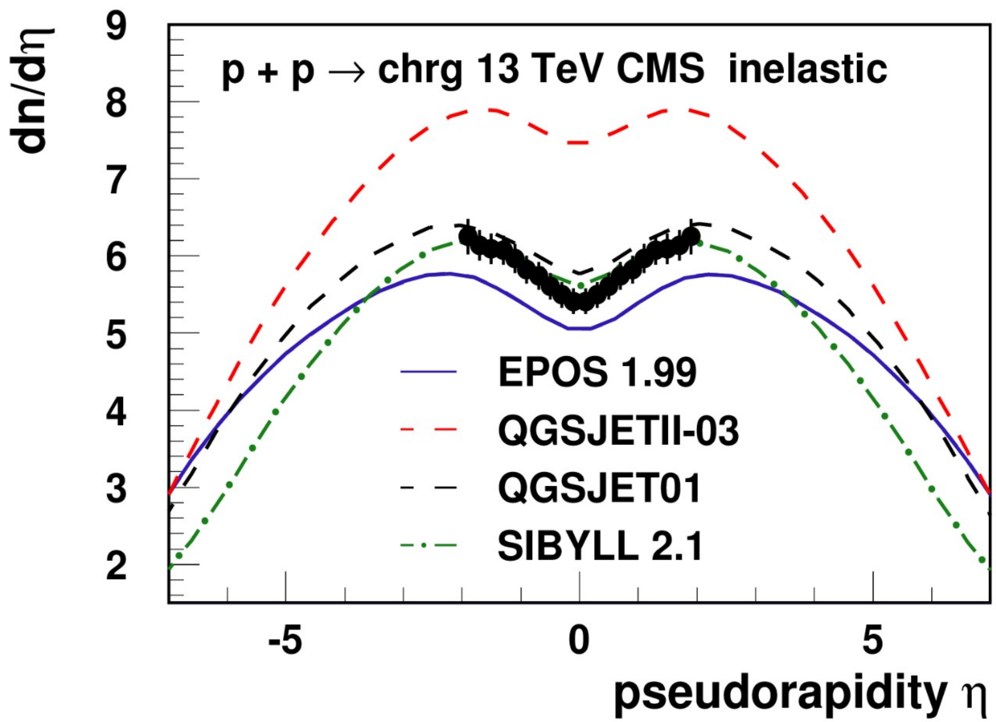
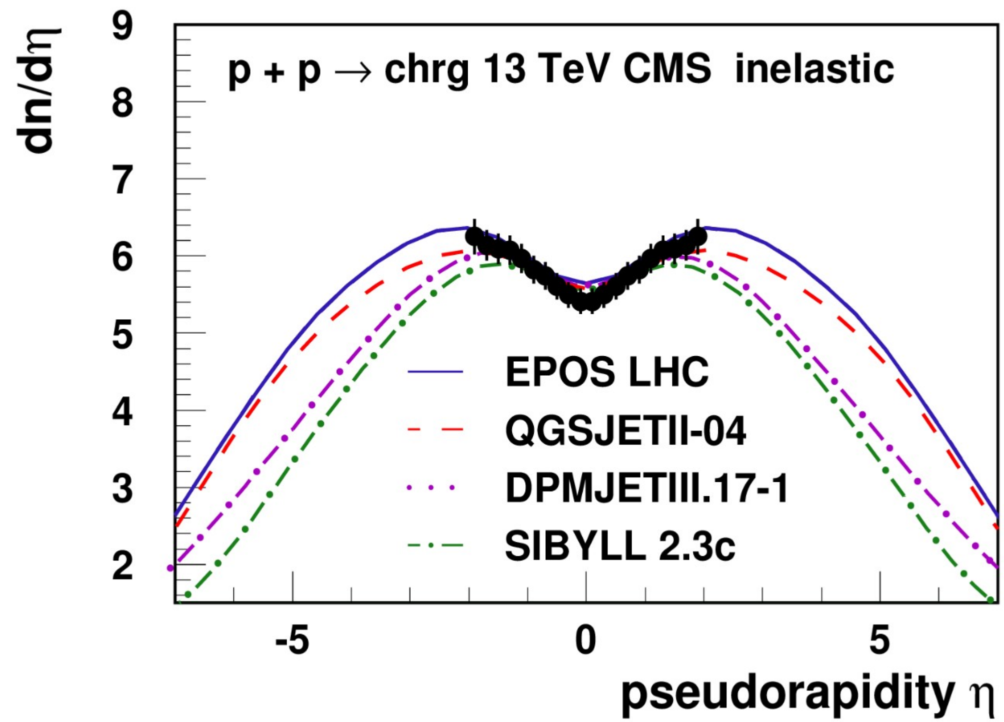


Post - LHC



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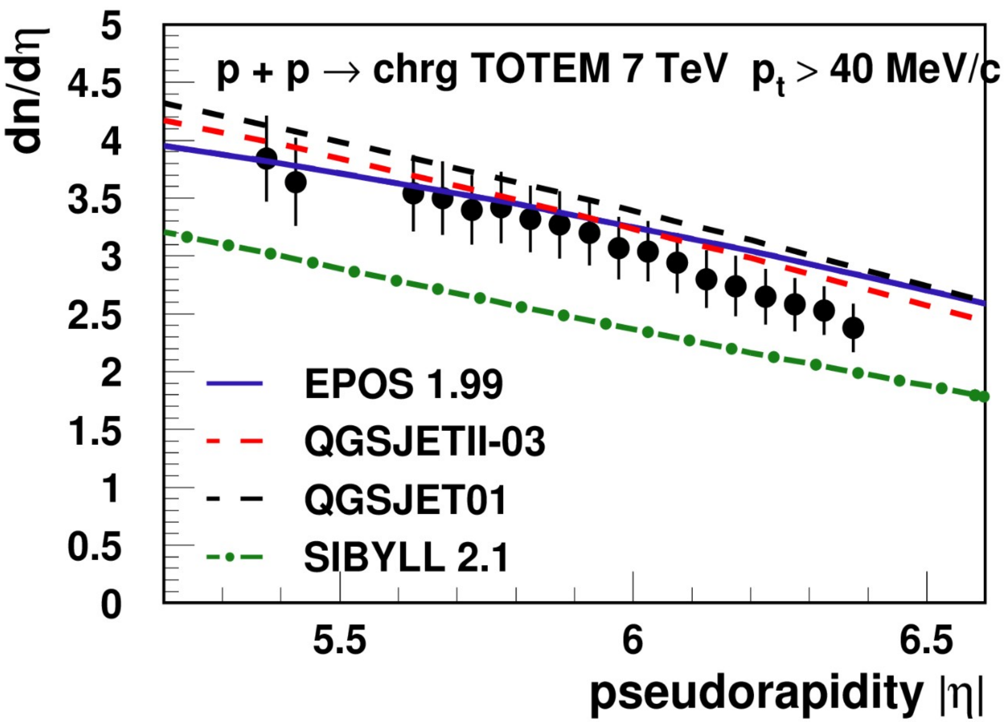
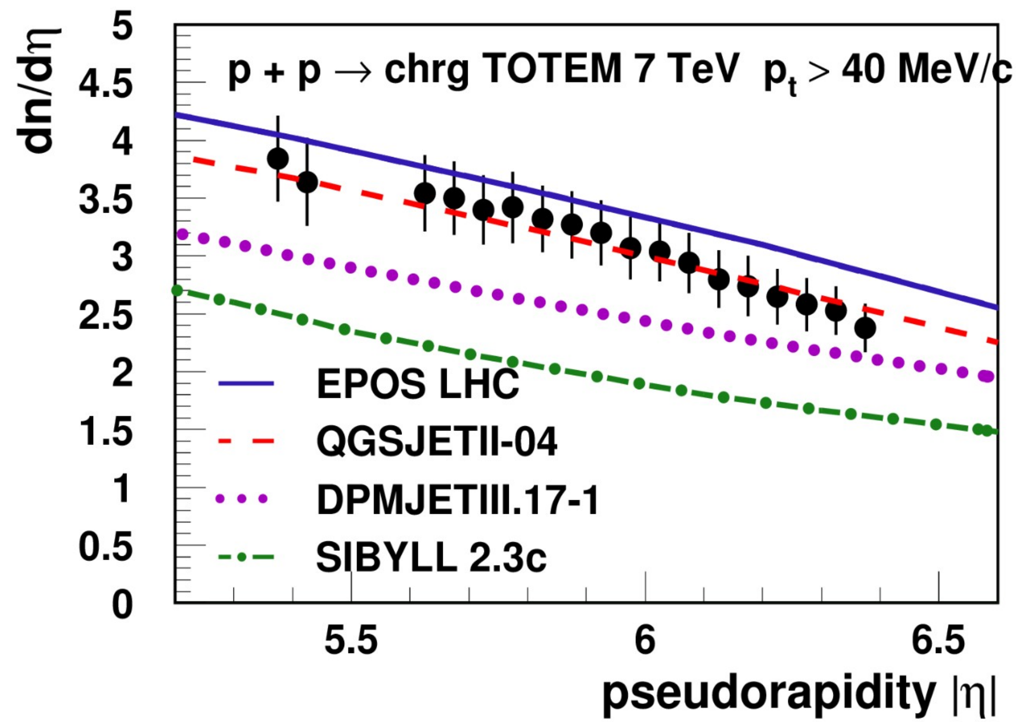
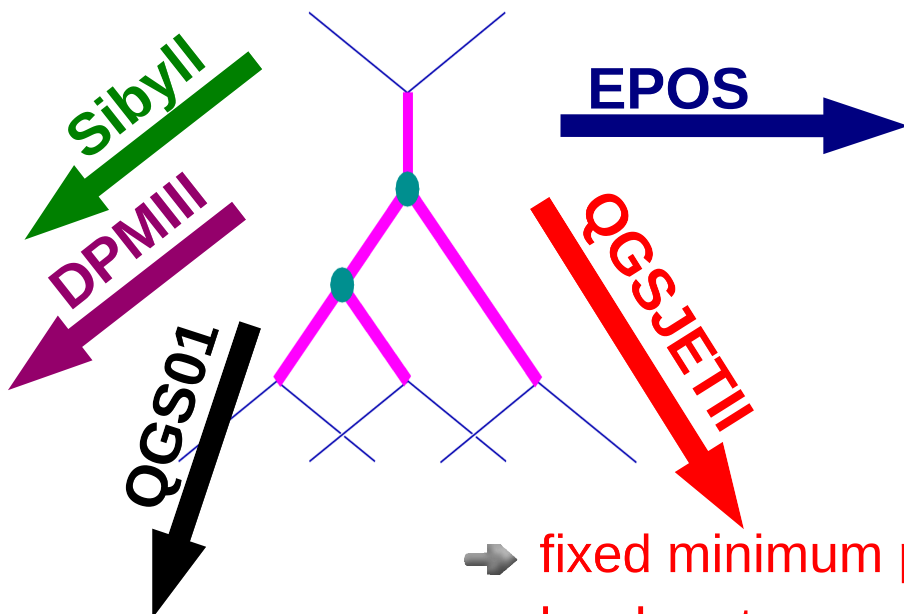


Post - LHC



How to take into account energy evolution ?

- **Multiple scattering not enough to reconcile pQCD minijet cross-section and total cross-section**
  - ➡ non-linear effect should be taken into account (interaction between scatterings)
- **Solution depends on amplitude definition**



- ➡ hard amplitude depend on minimum p_t
- ➡ parametrize minimum p_t as a function of energy (and impact parameter for DPMJETIII)
- ➡ fit to data (multiplicity and cross-section)

- ➡ not needed because of <u>wrong</u> parton distribution function

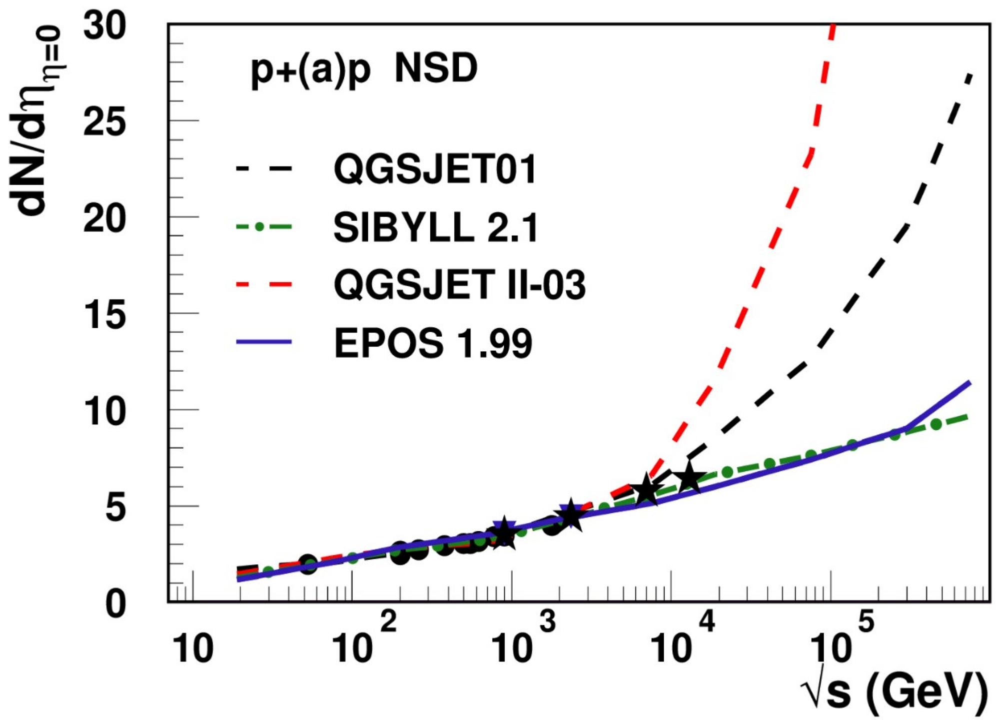
- ➡ fixed minimum p_t in hard part
- ➡ theory based “fan diagrams” resumed to infinity without energy sharing

- ➡ fixed minimum p_t in hard part
- ➡ enhanced diagrams not compatible with energy sharing
- ➡ modification of vertex function to take into account non linear effects (data driven phenomenological approach)

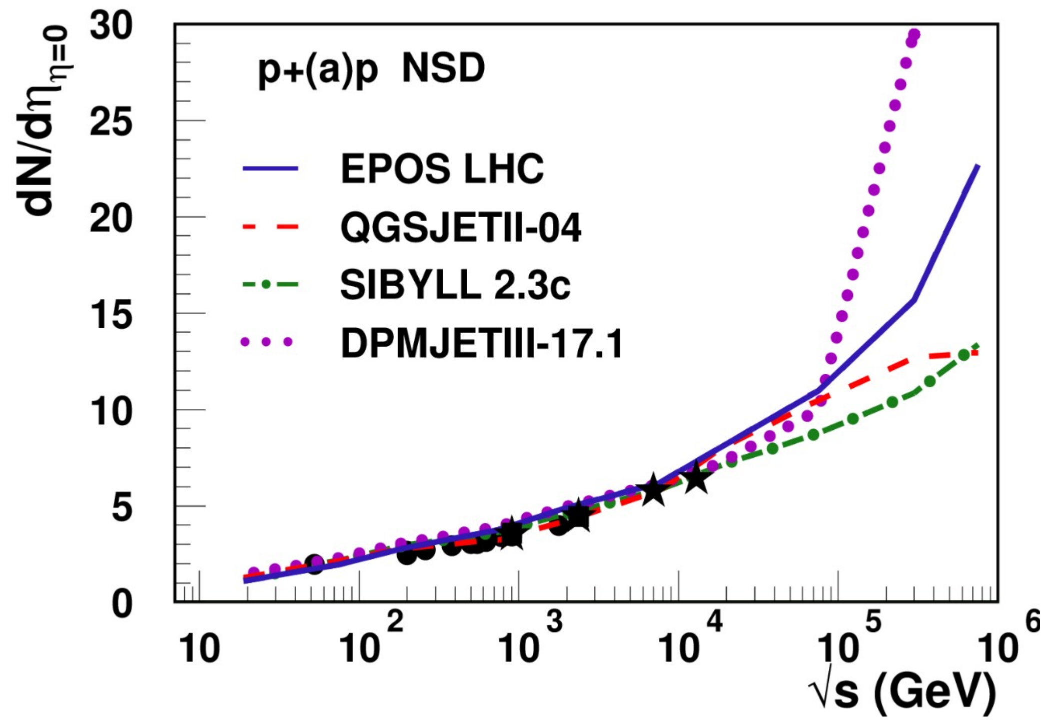
Do non linear effects matters ?

- **Multiple scattering not enough to reconcile pQCD minijet cross-section and total cross-section**
  - ➡ non-linear effect should be taken into account (interaction between scatterings)
- **Solution depends on amplitude definition**
  - ➡ large uncertainties at high energy but reduced after LHC

Pre - LHC

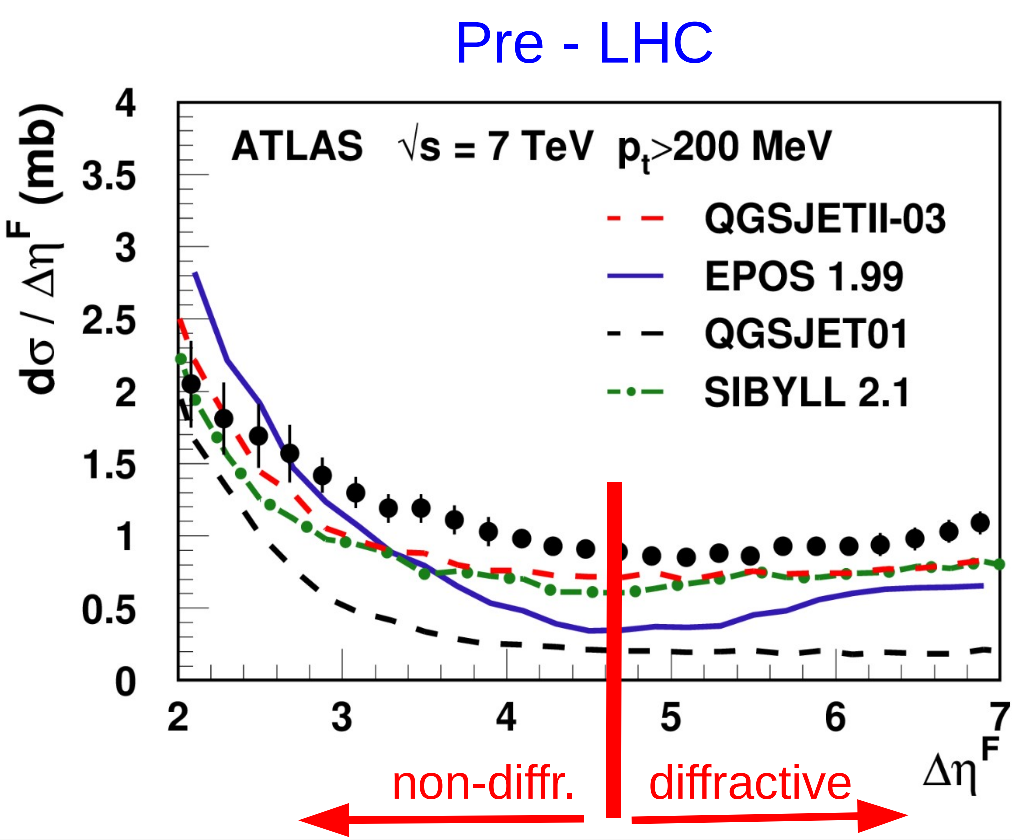


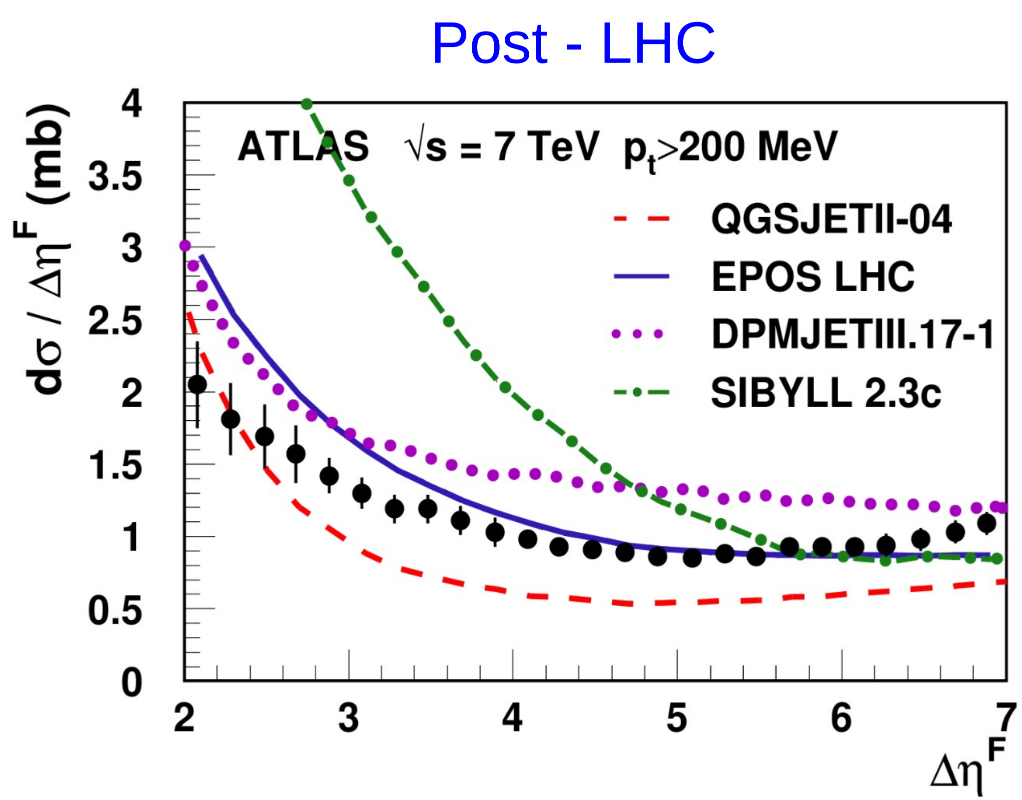
Post - LHC



What if only energy is transferred ?

- **In most of the cases, the projectile is destroyed by the collision**
  - ➔ non-diffractive scattering : high energy loss for leading particle, high multiplicity
- **In 10-20% of the time, the projectile have a small energy loss (high elasticity) and is unchanged**
  - ➔ diffractive scattering : low energy loss, low multiplicity on target side
- **Model difference mostly at technical level (and choice of data)**



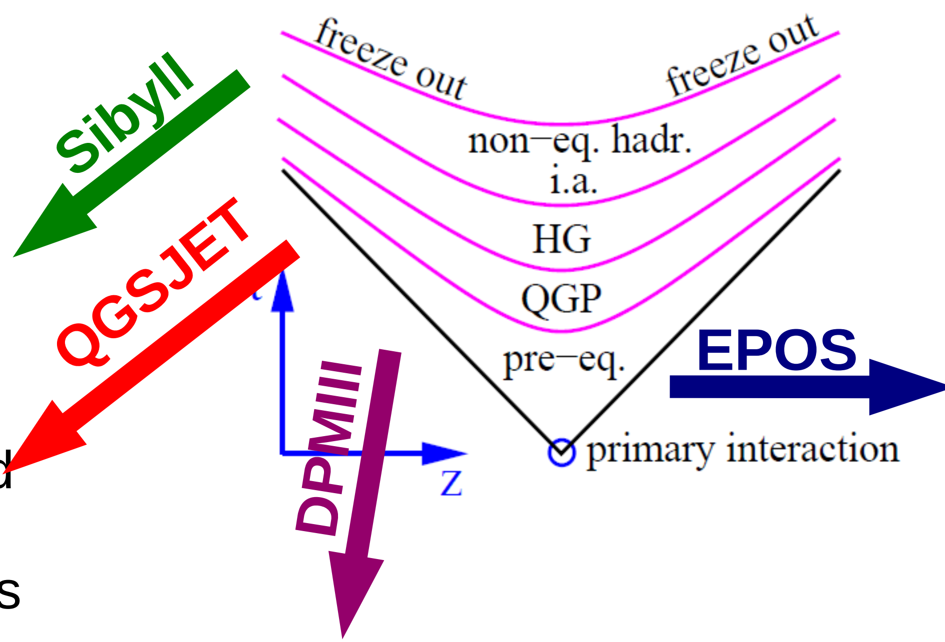


Should everything be taken into account ?

Models have different philosophies !

- number of parameters increase with data set to reproduce
- predictive power may decrease with number of parameters
- predictive power increase if we are sure not to neglect something

- models for CR only
- fast and not suppose to describe everything
- no detailed hard scattering or collective effects

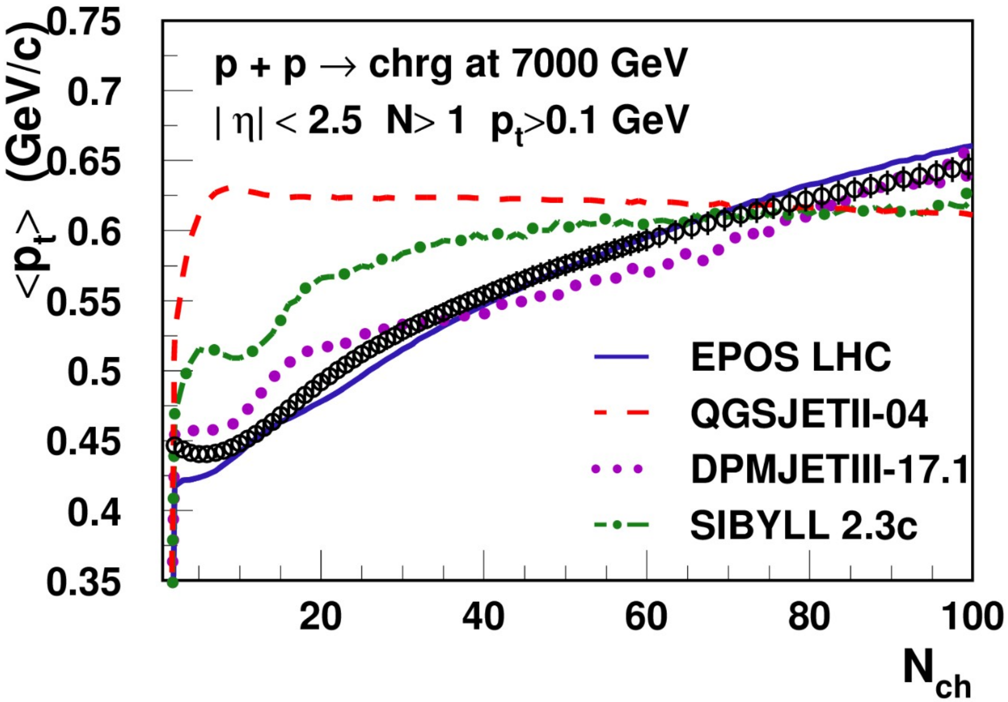


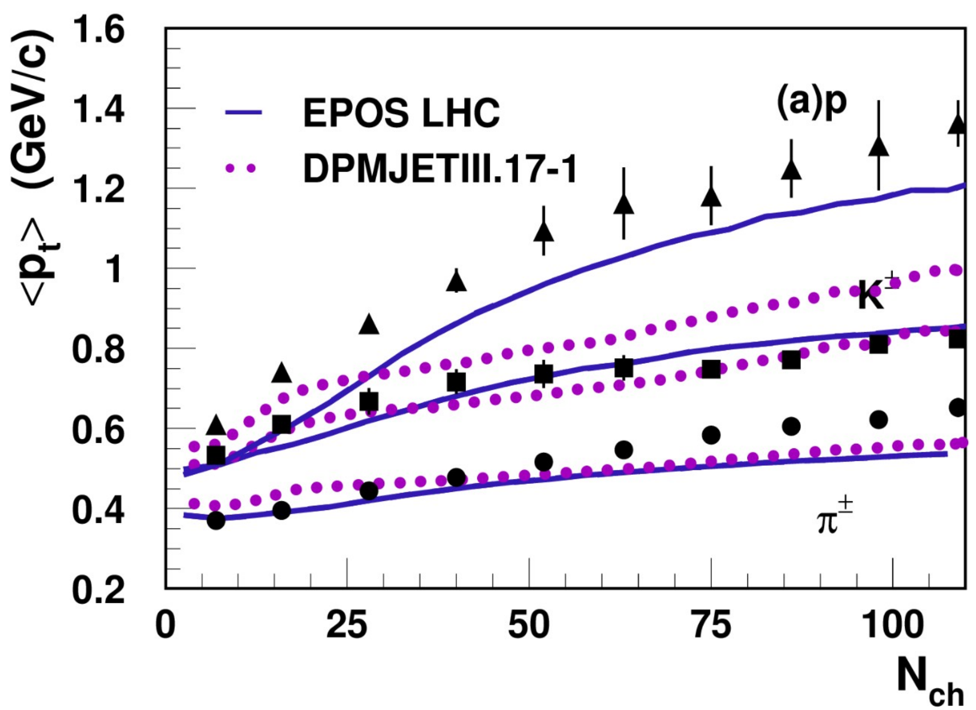
- developed first for heavy ion interactions
- detailed description of every possible “soft” observable (not good for hard scattering yet)
- sophisticated collective effect treatment (real hydro for EPOS 2 and 3)
- very large complete data set (LEP, HERA, SPS, RHIC, LHC)

- heavy ion model intended to be used for high energy physics
- limited development for collective effects but correct hard scattering

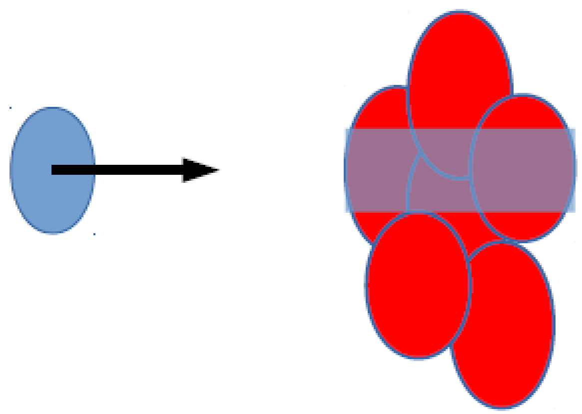
Should everything be taken into account ?

- **Models have different philosophies !**
  - ➡ number of parameters increase with data set to reproduce
  - ➡ predictive power may decrease with number of parameters
  - ➡ predictive power increase if we are sure not to neglect something
- **No direct influence on air showers but different parameters and extrapolations ?**





How to do nuclear interactions ?

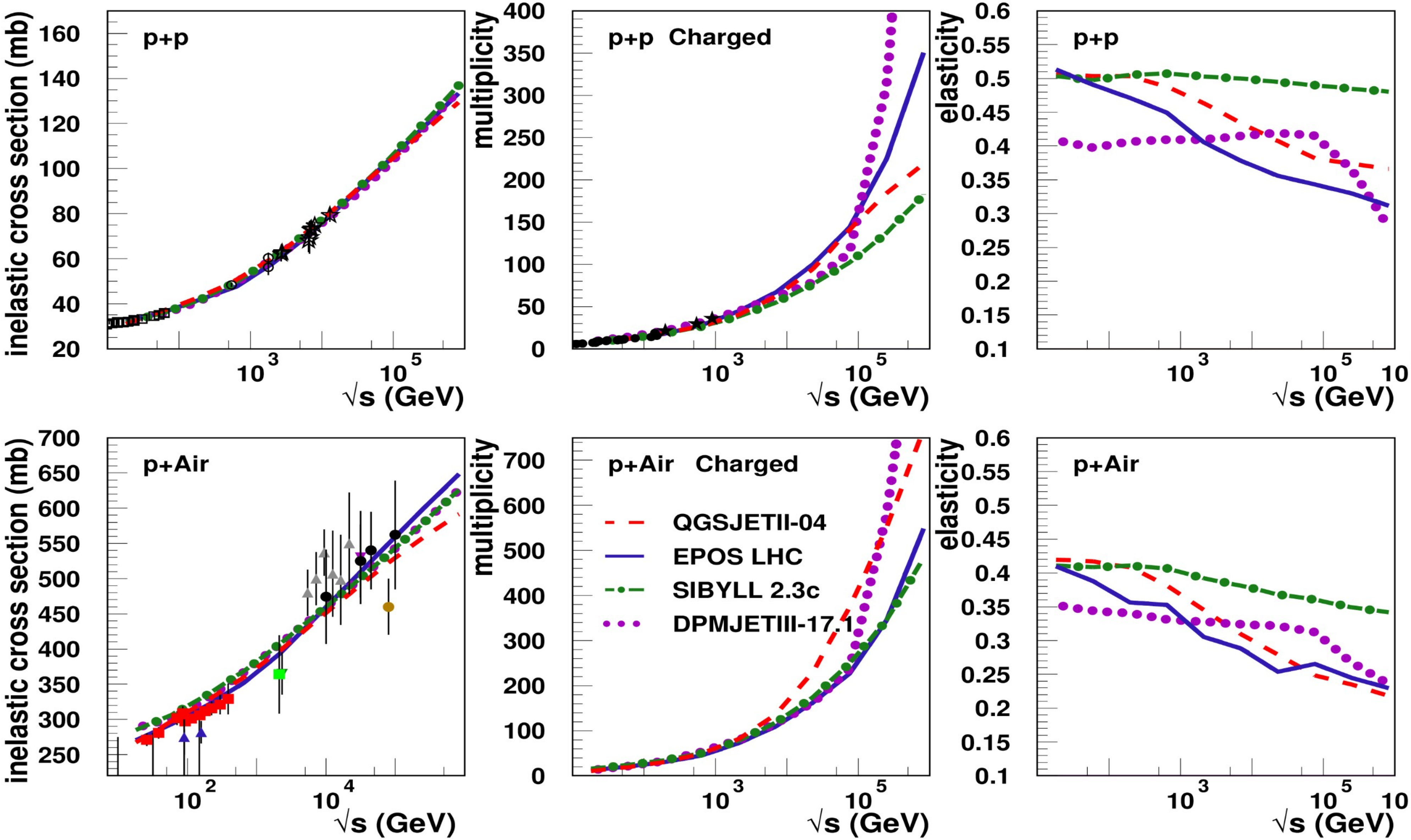


Main source of uncertainty in extrapolation :

- **very different approaches**
- **limited available data set**
- **limited models capabilities**

- **Sibyll** (light ion only)
  - corrected Glauber for pA
  - superposition model for AA (A x pA)
- **QGSJETII** (all masses but not all data)
  - Scattering configuration based on A projectiles and A targets
  - Nuclear effect due to multi-leg Pomerons
- **DPMJETIII (all masses)**
  - Glauber
  - limited collective effects treatment
- **EPOS** (all masses)
  - Scattering 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)

Ultra-High Energy Hadronic Model Predictions p-Air



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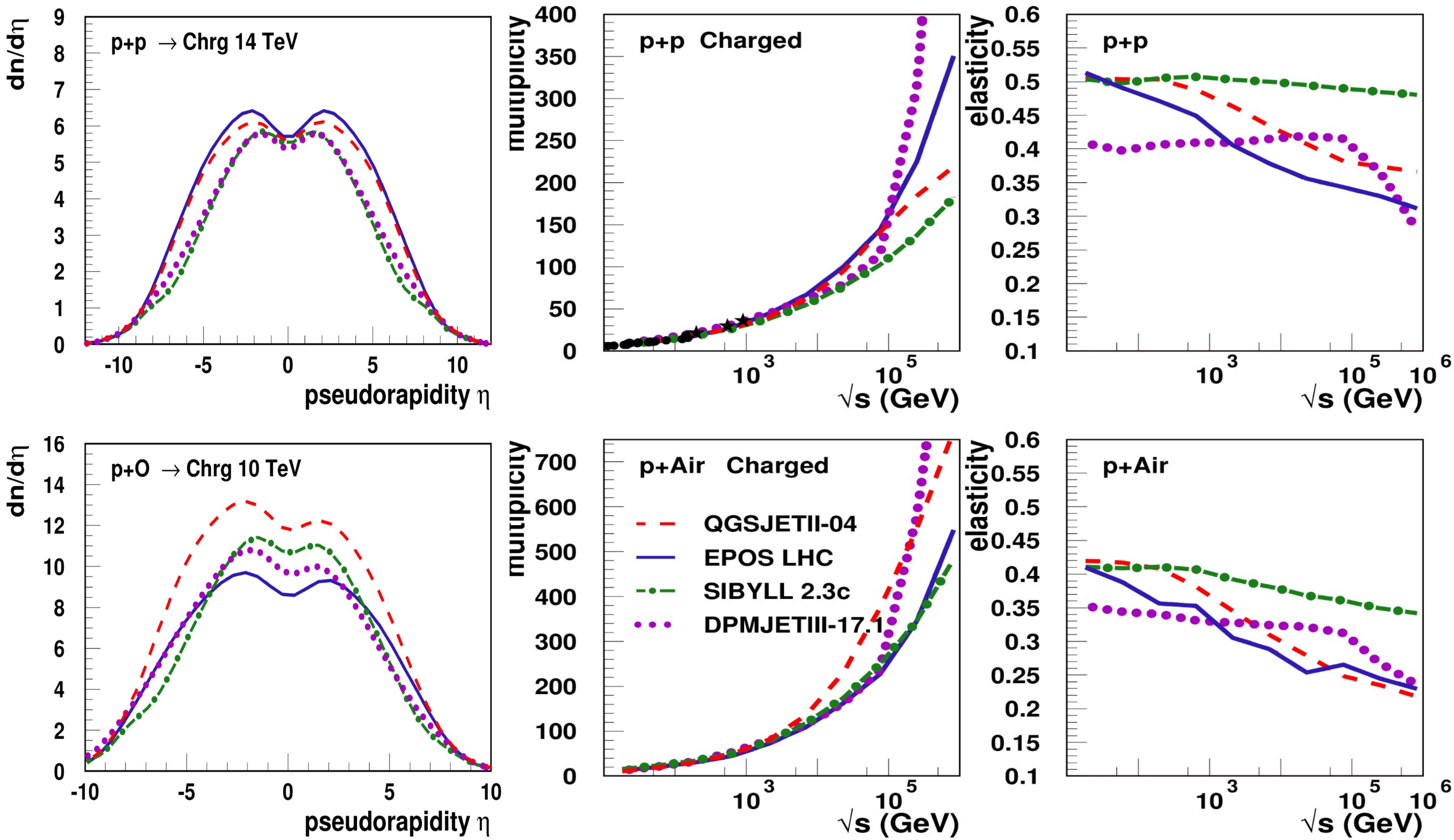
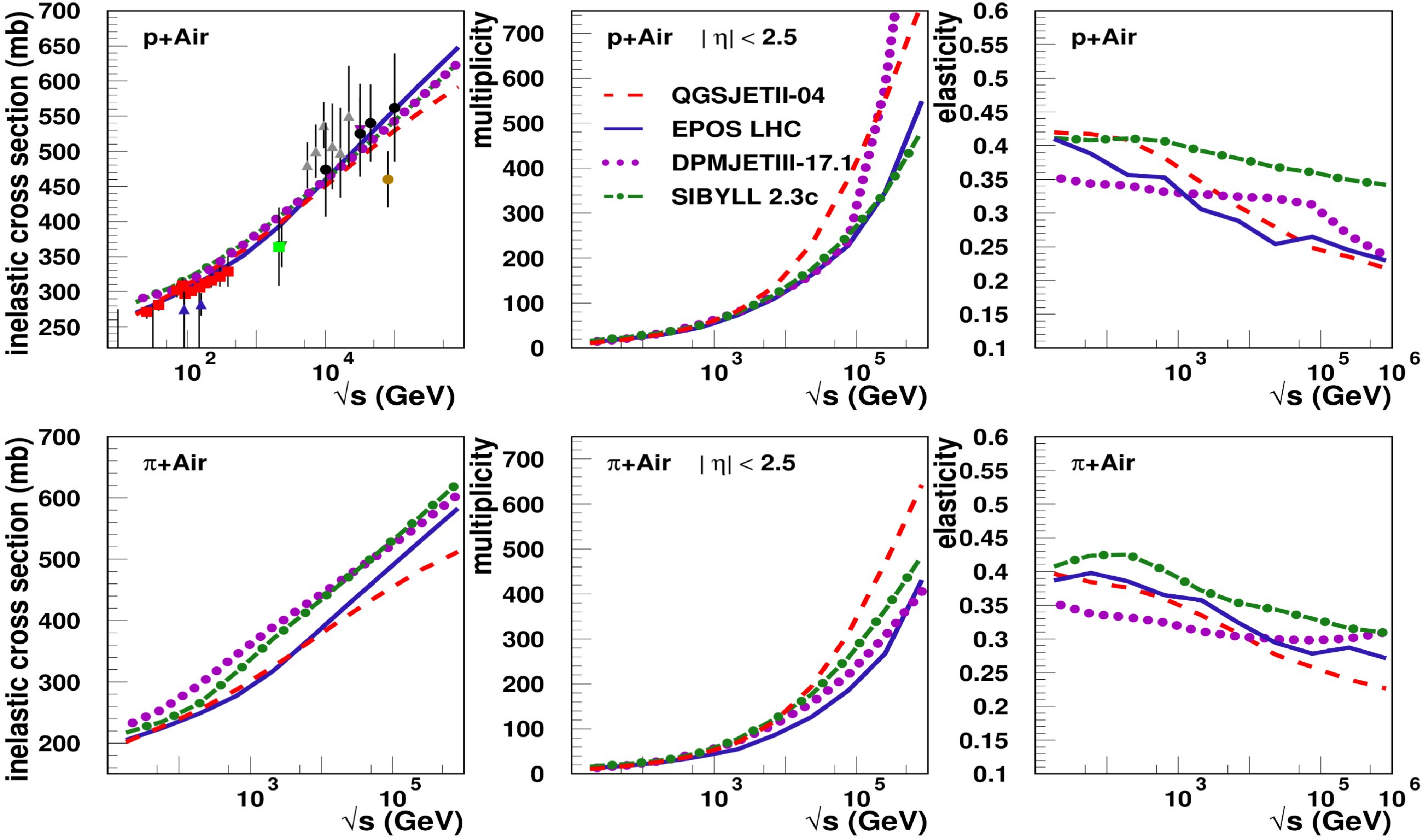


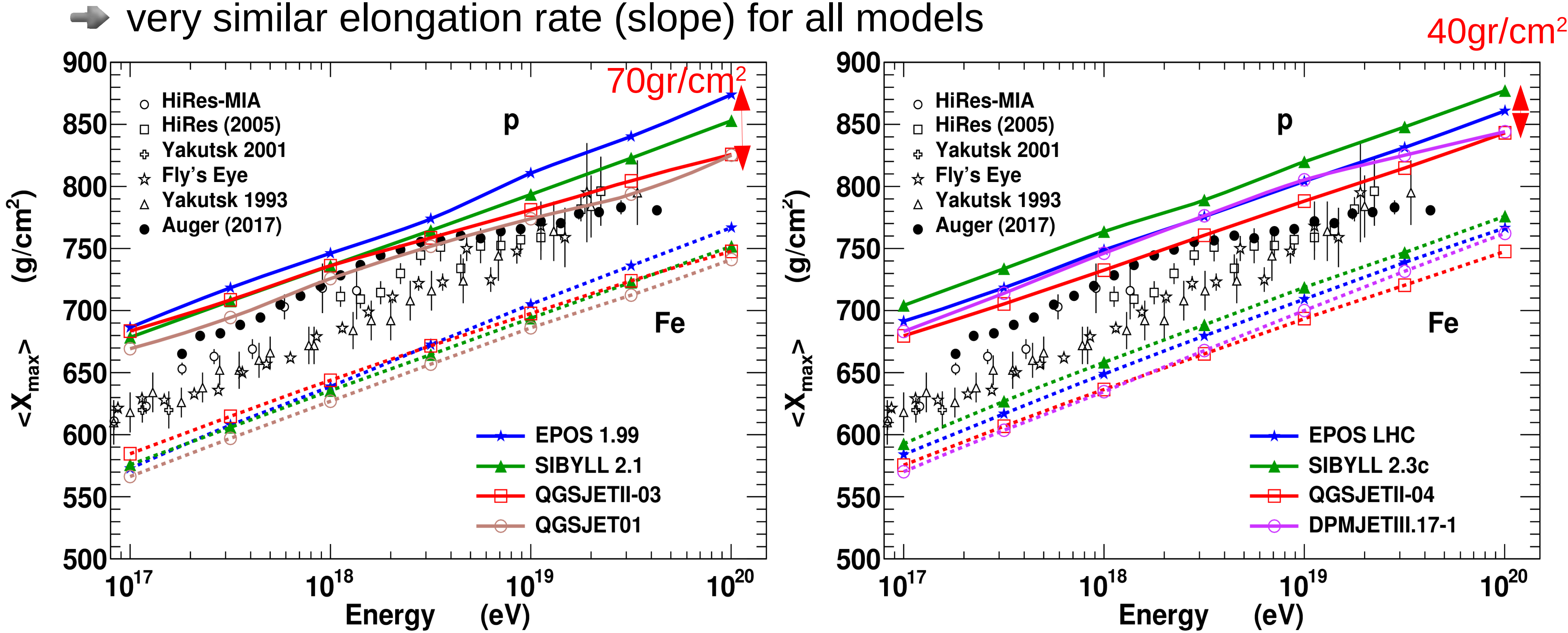
Ultra-High Energy Hadronic Model Predictions π-Air



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

After LHC :

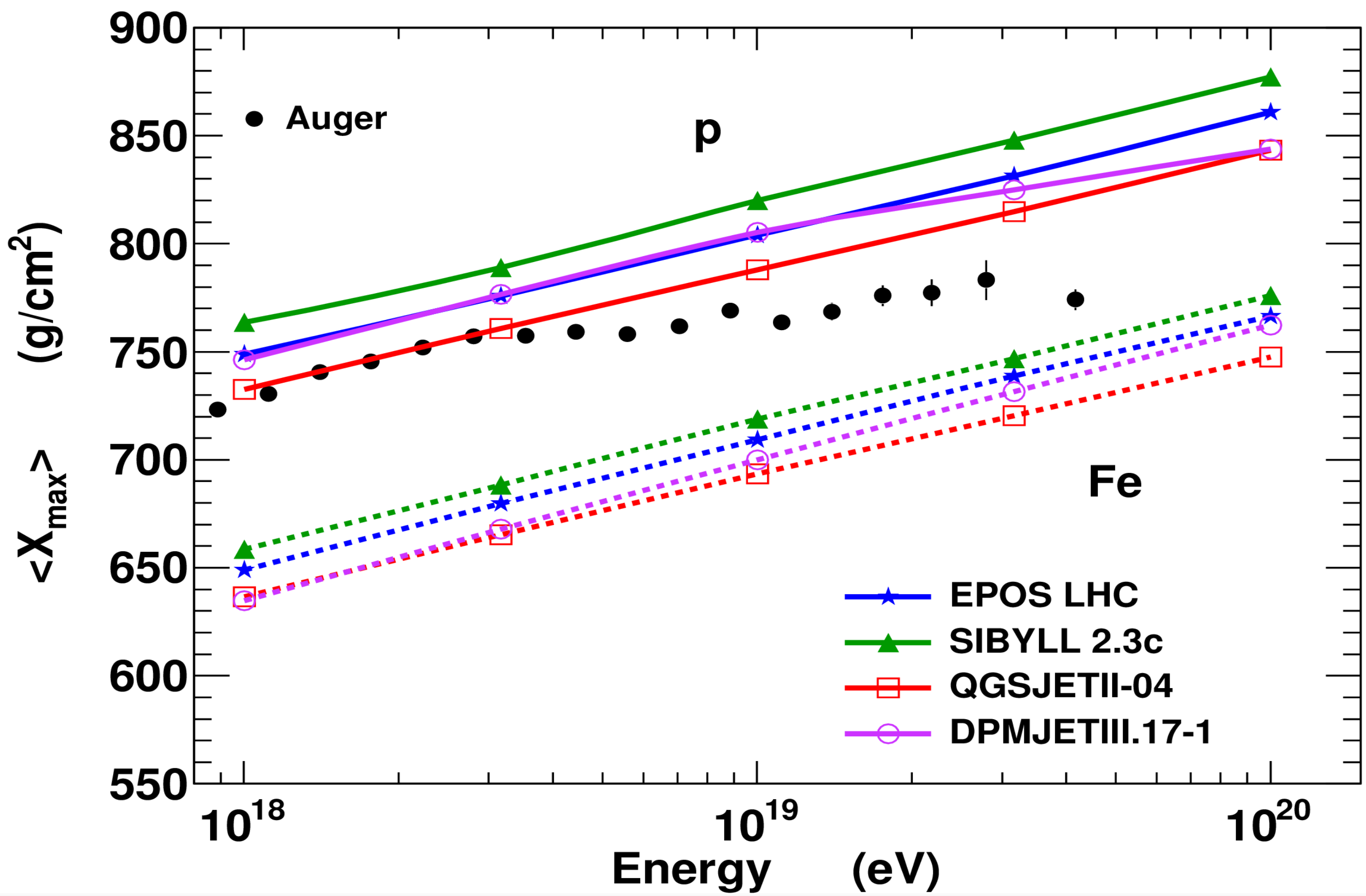
- Sibyll shifted by ~+20 g/cm²
- for other models about the same $\langle X_{max} \rangle$ value at 10^{18} eV but
  - slope increased for QGSJETII
  - slope decreased for EPOS
- very similar elongation rate (slope) for all models



X_{max}

+/- 20g/cm2 is a realistic uncertainty band but :

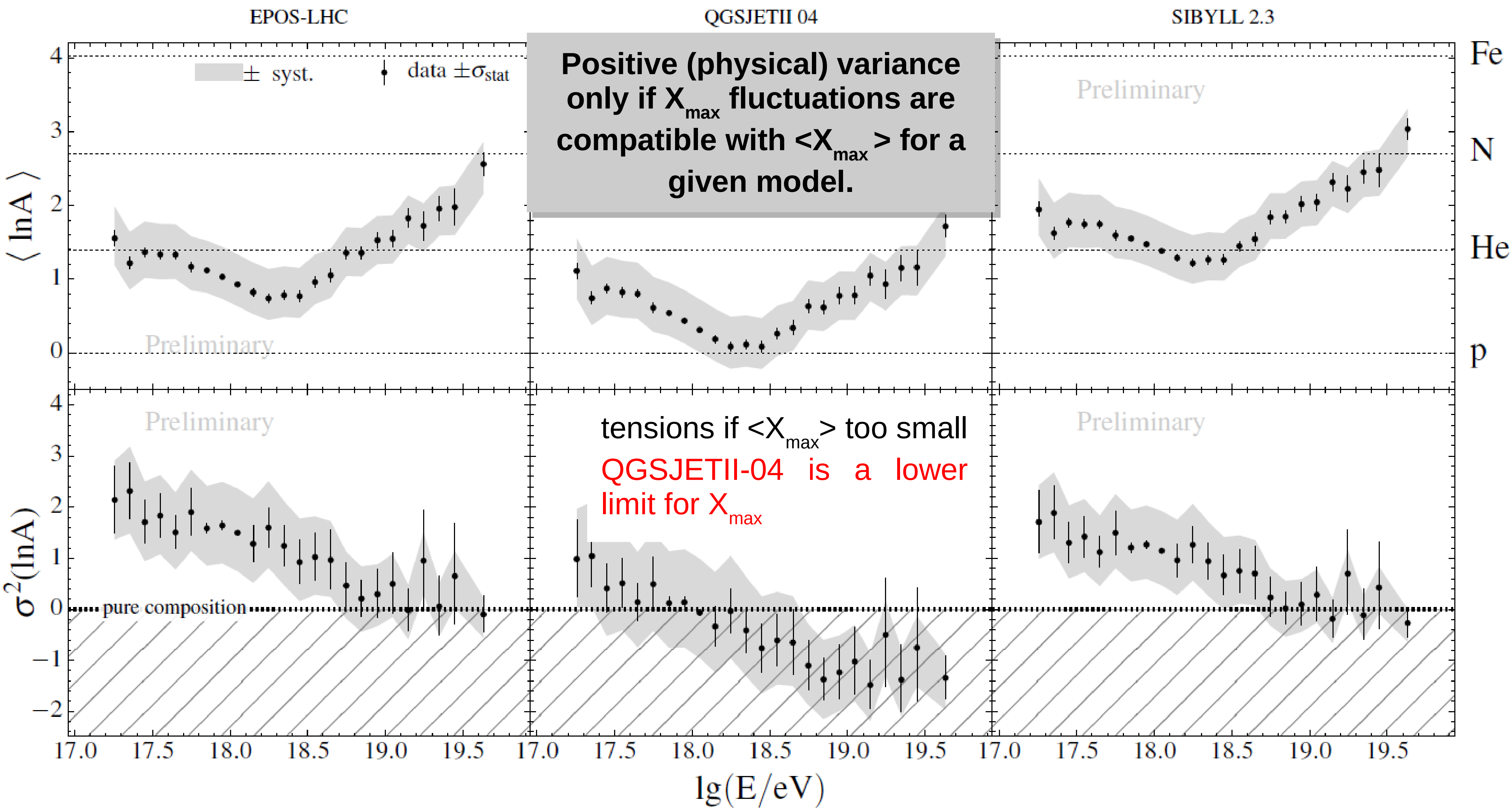
- minimum given by QGSJETII-04 (high multiplicity, low elasticity)
- maximum given by Sibyll 2.3c (low multiplicity, high elasticity)
- anything below or above won't be compatible with LHC data



Model Consistency using Electromagnetic Component

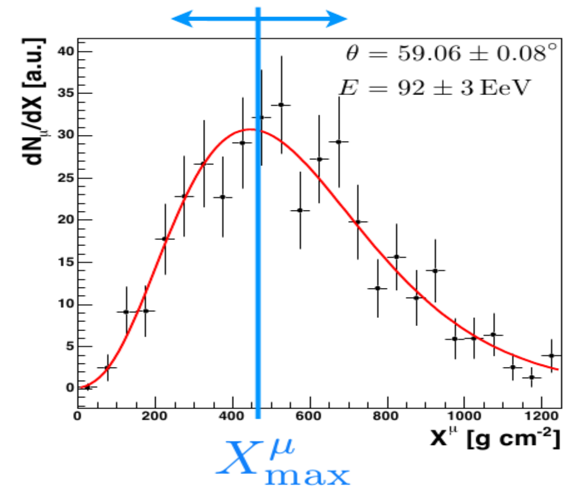
Study by Pierre Auger Collaboration

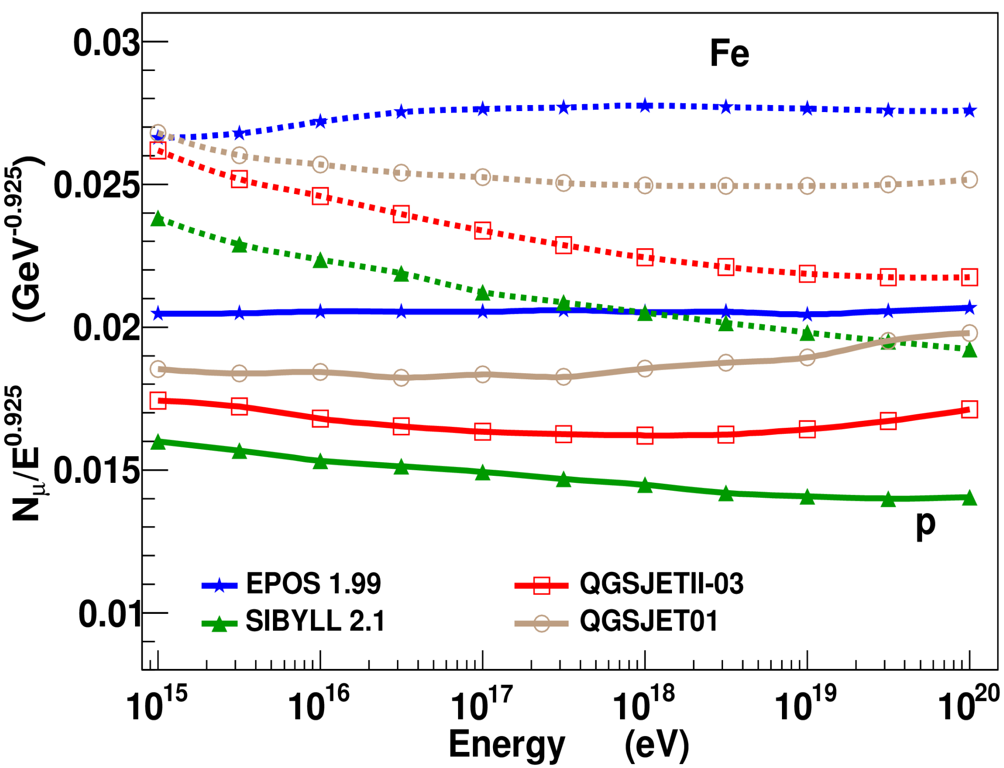
- std deviation of lnA allows to test model consistency.

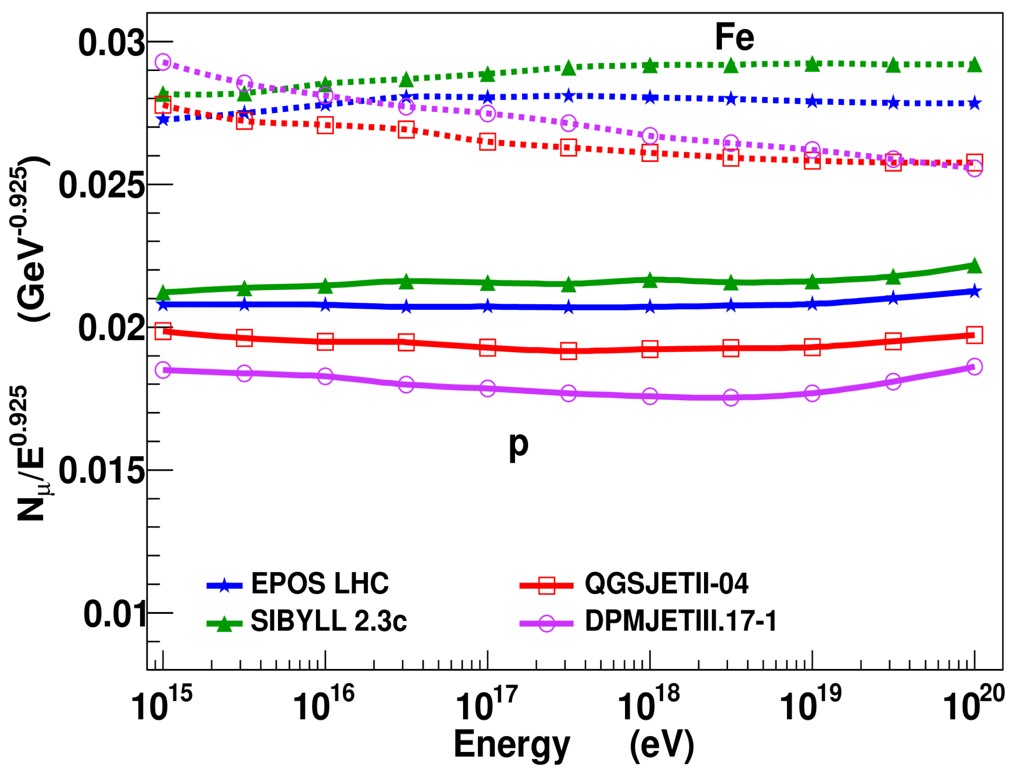


Muons at Ground

- 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 (MPD) and spectra

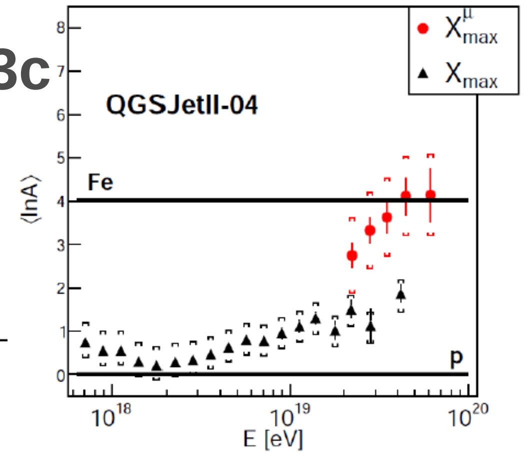


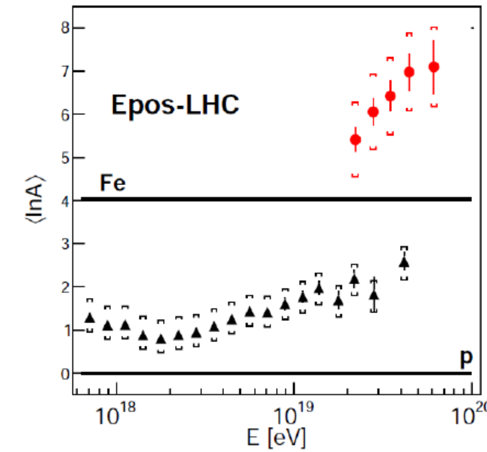


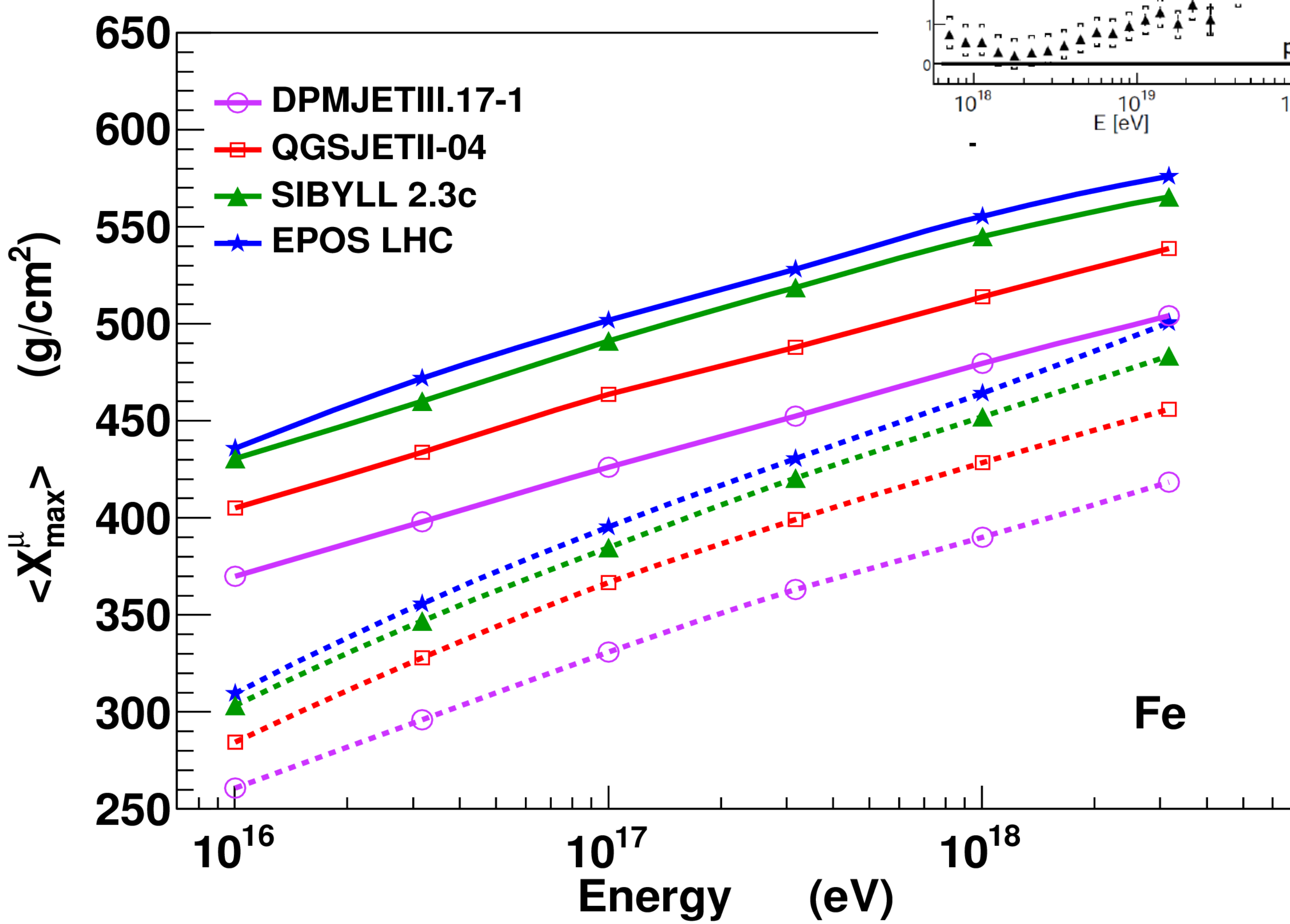


Muon Production Depth

- Same for EPOS LHC and SIBYLL 2.3c
- Very shallow for DPMJETIII
  - ➜ but same X_{max} than EPOS LHC







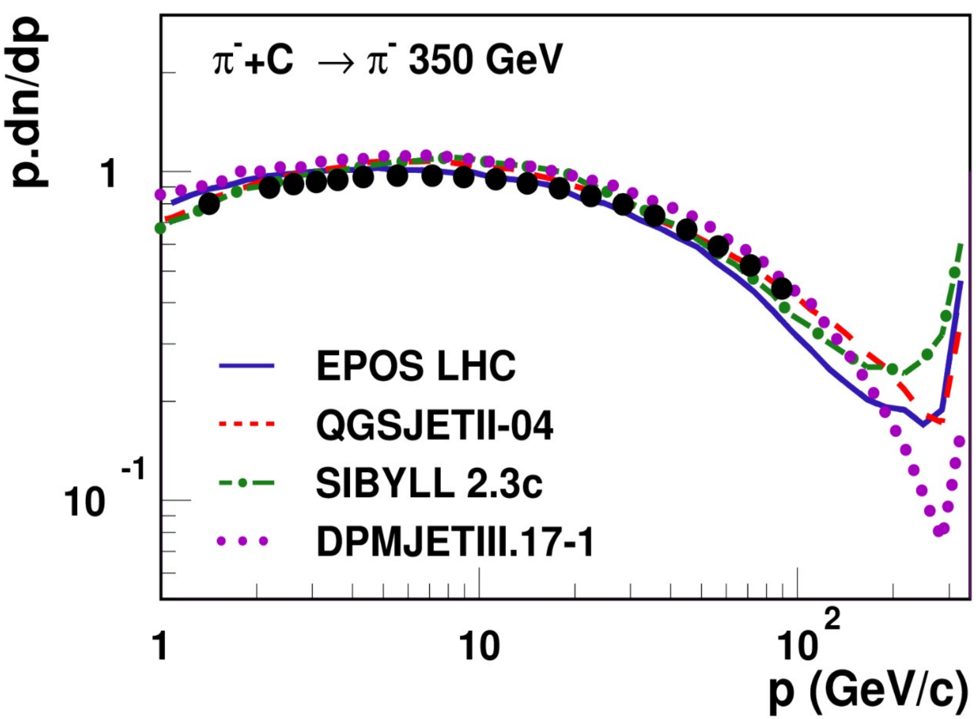
MPDs sensitive to baryon (less generation) and meson spectra in pion interactions so small effect on X_{max}

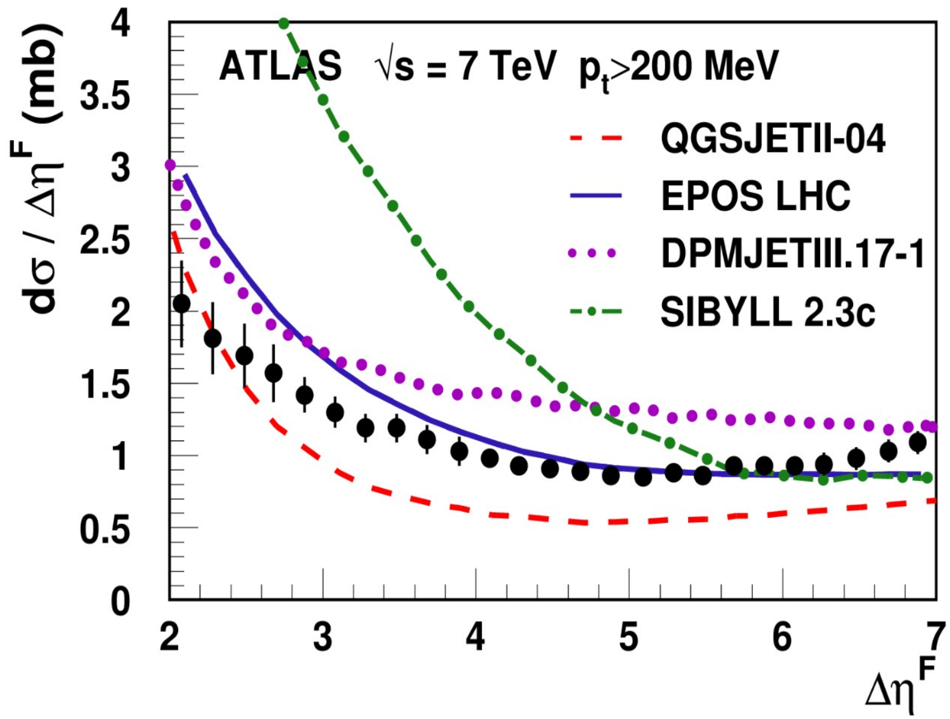
Ostapchenko et al. Phys.Rev. D93 (2016) no.5, 051501

Pion Interactions

MPD measurement helped to understand the importance of pion interactions (lack of accelerator data until NA61) and baryon effect on propagation

- low pion elasticity in DPMJETIII
- high pion elasticity (diffraction) in EPOS and Sibyll driven by LHC data (and high baryon number (Ostapchenko et al. Phys.Rev. D93 (2016) no.5, 051501))
- diffraction with pion projectile or proton projectile are different





Summary

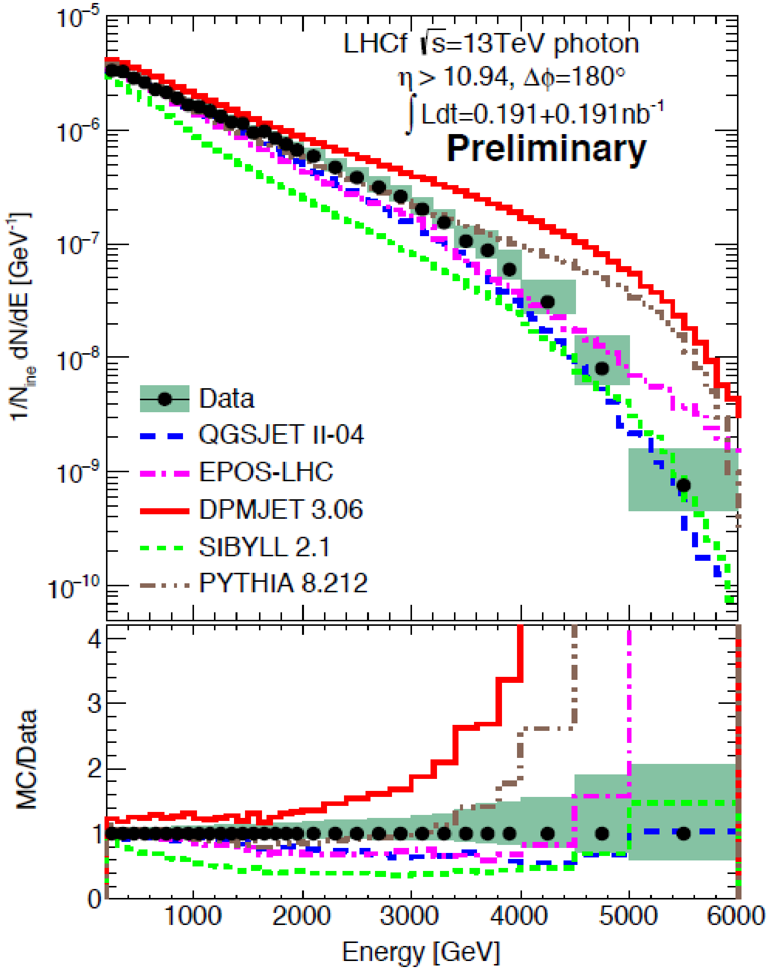
- **Central particle production at LHC reduced model uncertainties in X_{max} range ("truth" ~ between QGSJETII-04 and Sibyll 2.3c)**
  - ➡ same energy evolution in models important for mass of primary cosmic rays
  - ➡ all pre-LHC models in contradiction with LHC data (central and forward prod.)
  - ➡ using latest model version reduce uncertainties and avoid unphysical behavior
- **Remaining 40 gr/cm² range 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) and cross-section or forward spectra are different event for the same multiplicity

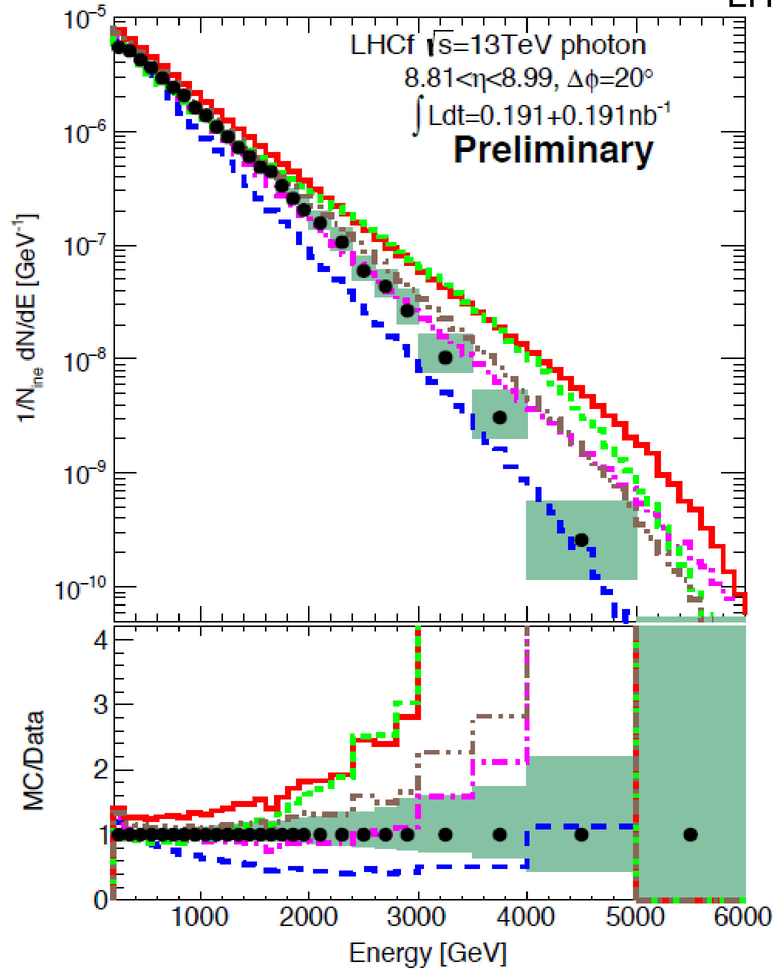
LHC data reduced the model uncertainties and exclude old models for mass composition of cosmic rays. Remaining uncertainties linked to model limitations and lack of (light) nuclear target.

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

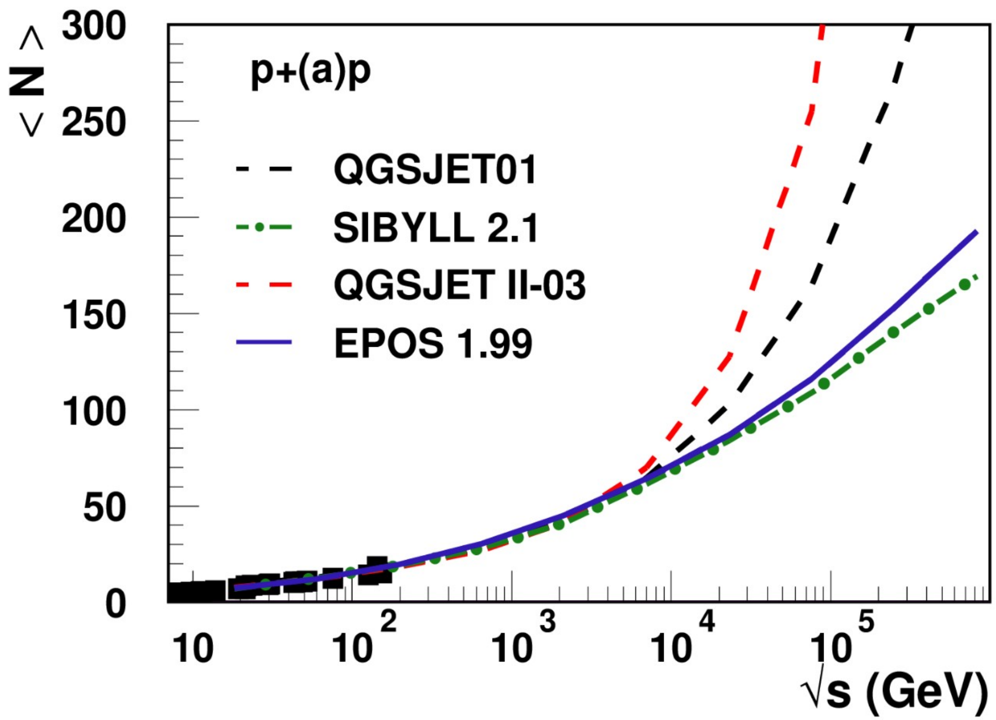




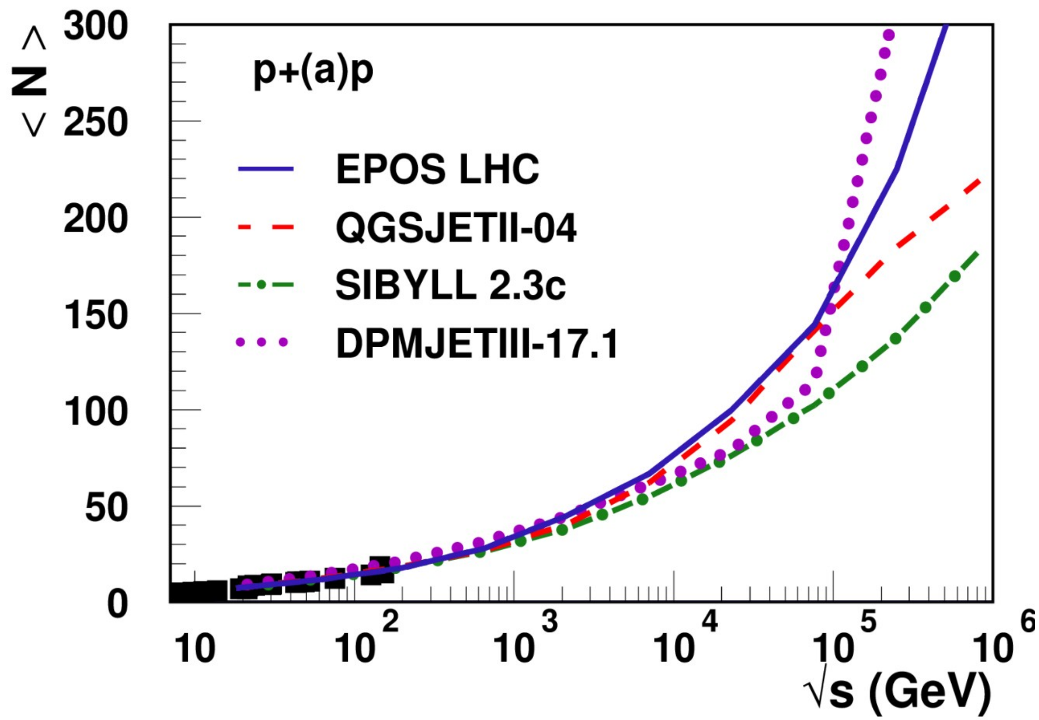
Multiplicity

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

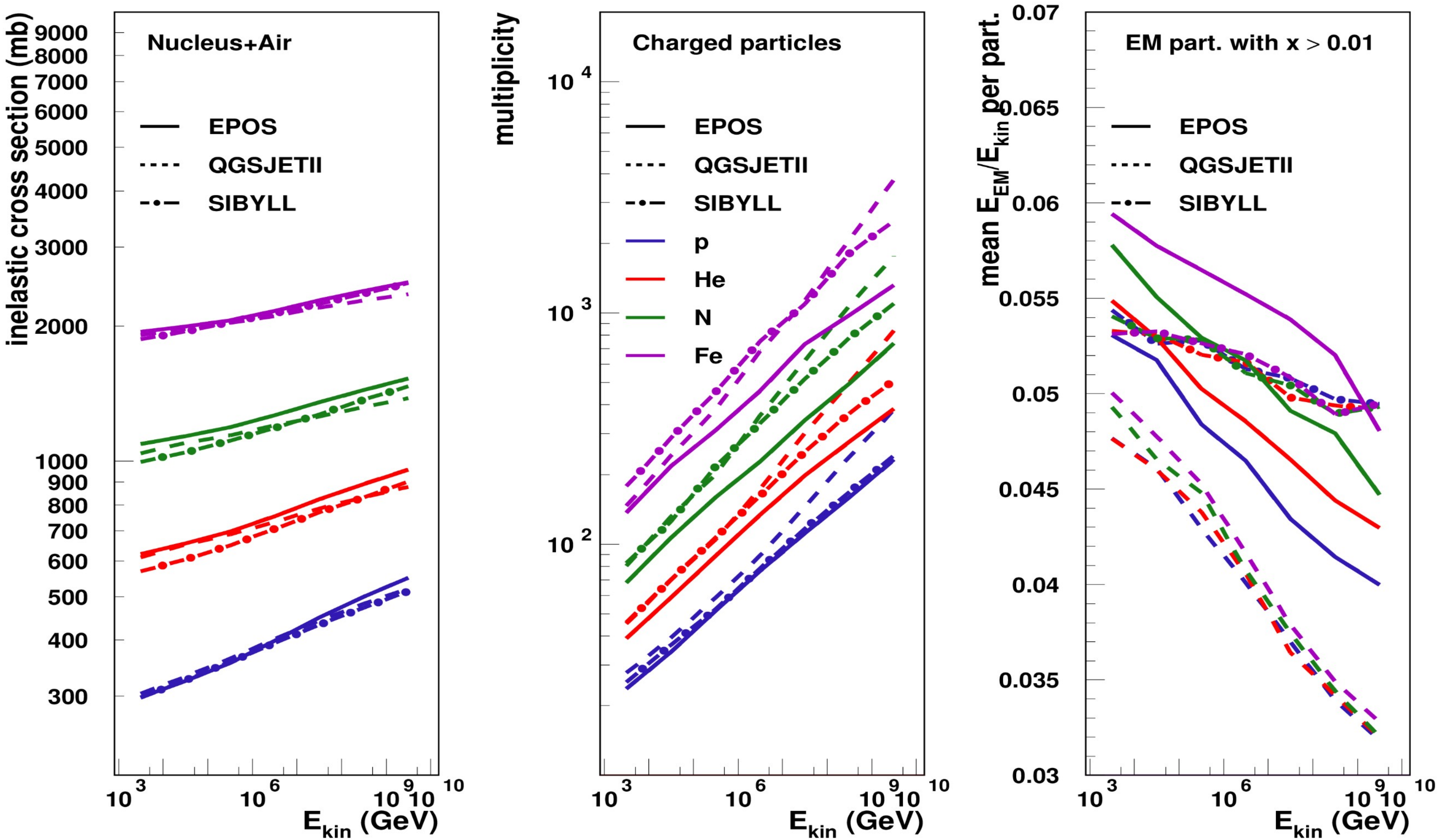
Pre - LHC



Post - LHC

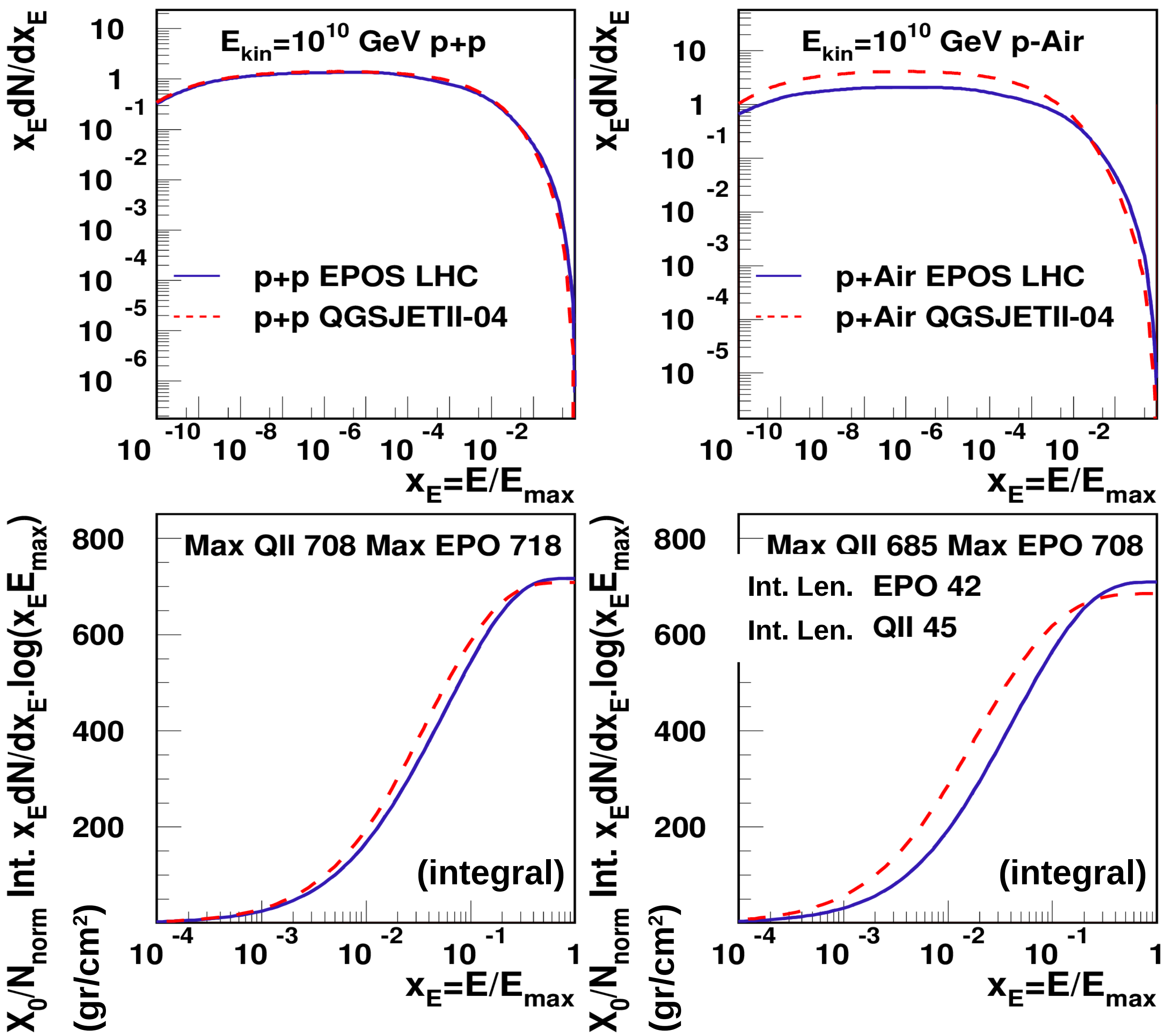


Ultra-High Energy Hadronic Model Predictions A-Air

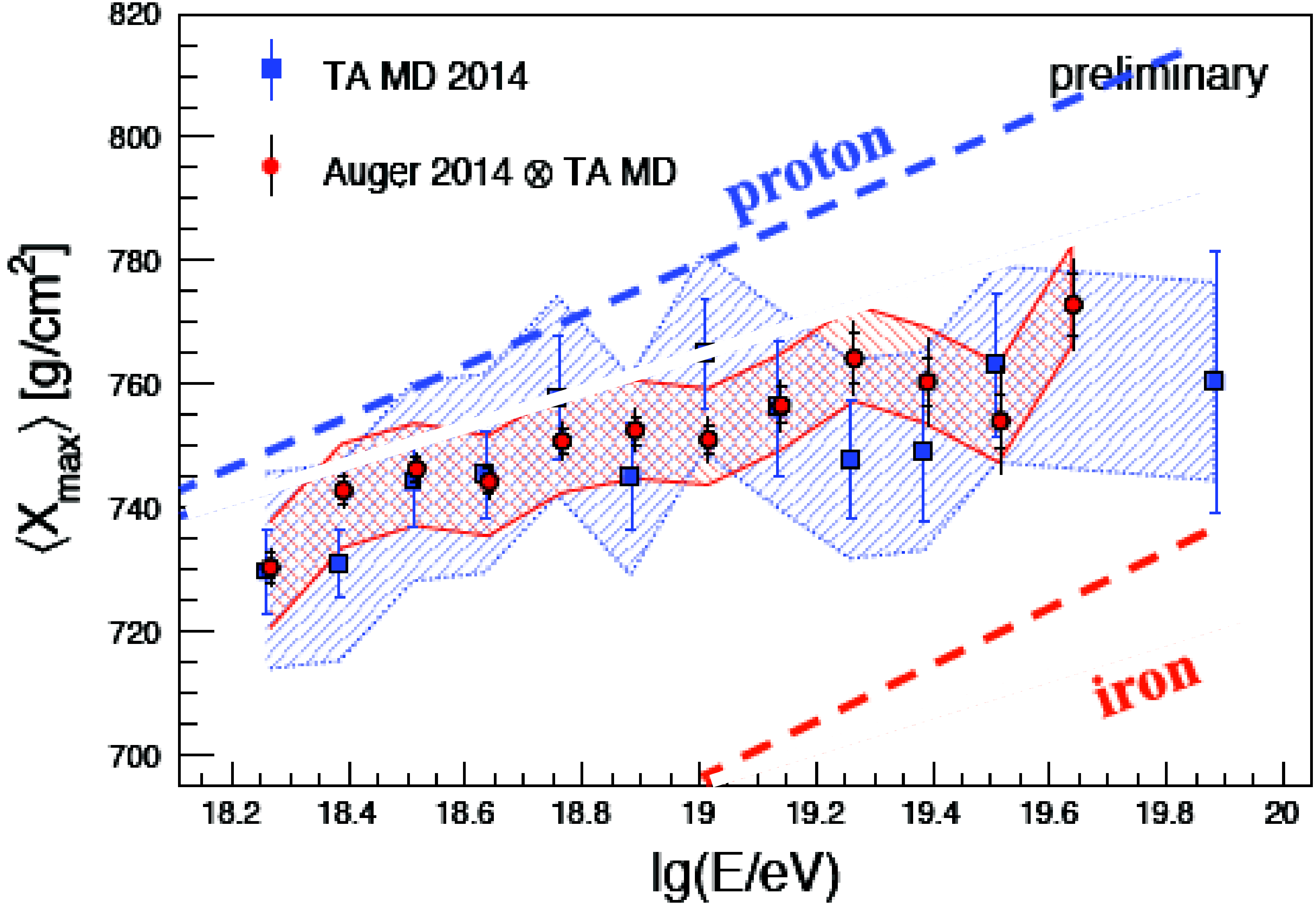


Photon Energy Spectra

- **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 ?



PAO vs TA



From Roberto Aloiso UHECR 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

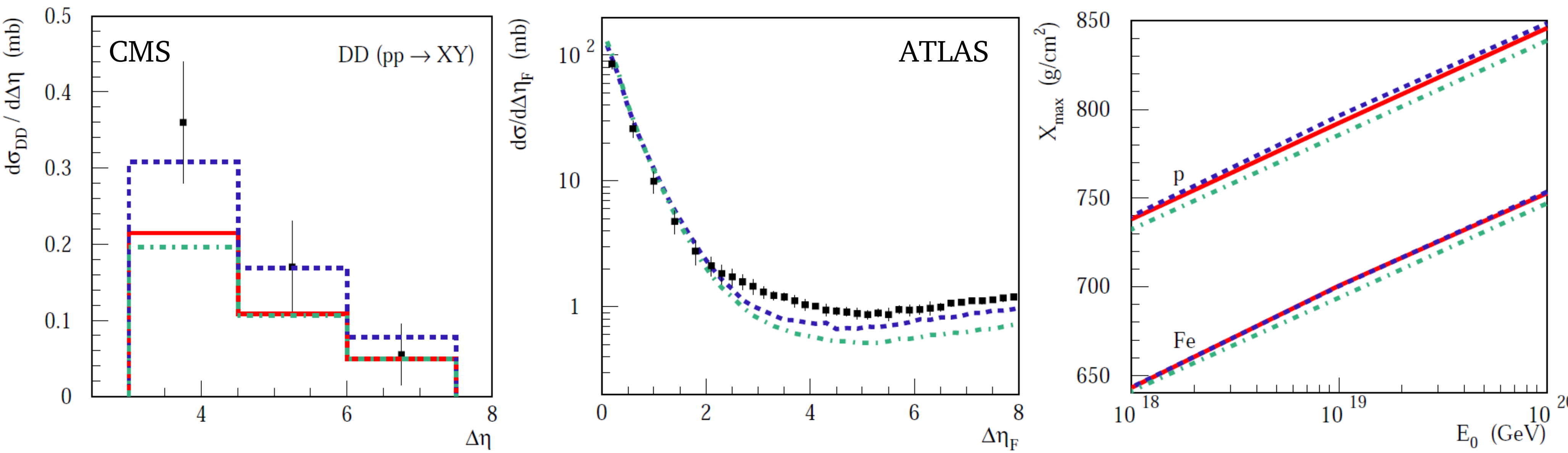
➡ EPOS overestimate forward baryon production at high energy

Diffraction measurements

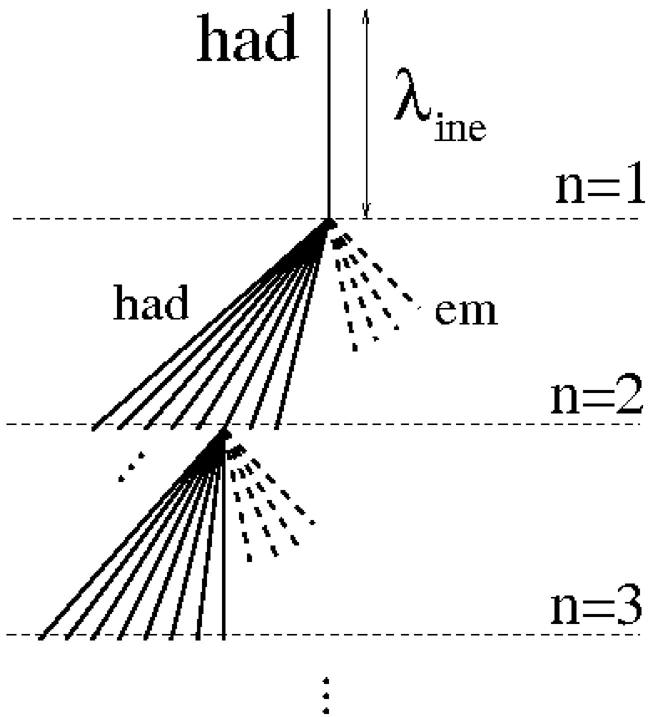
- **TOTEM and CMS diffraction measurement not fully consistent**
- **Tests by S. Ostapchenko using QGSJETII-04 (PRD89 (2014) no.7, 074009)**
  - ➡ SD+ option compatible with CMS
  - ➡ SD- option compatible with TOTEM

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 :

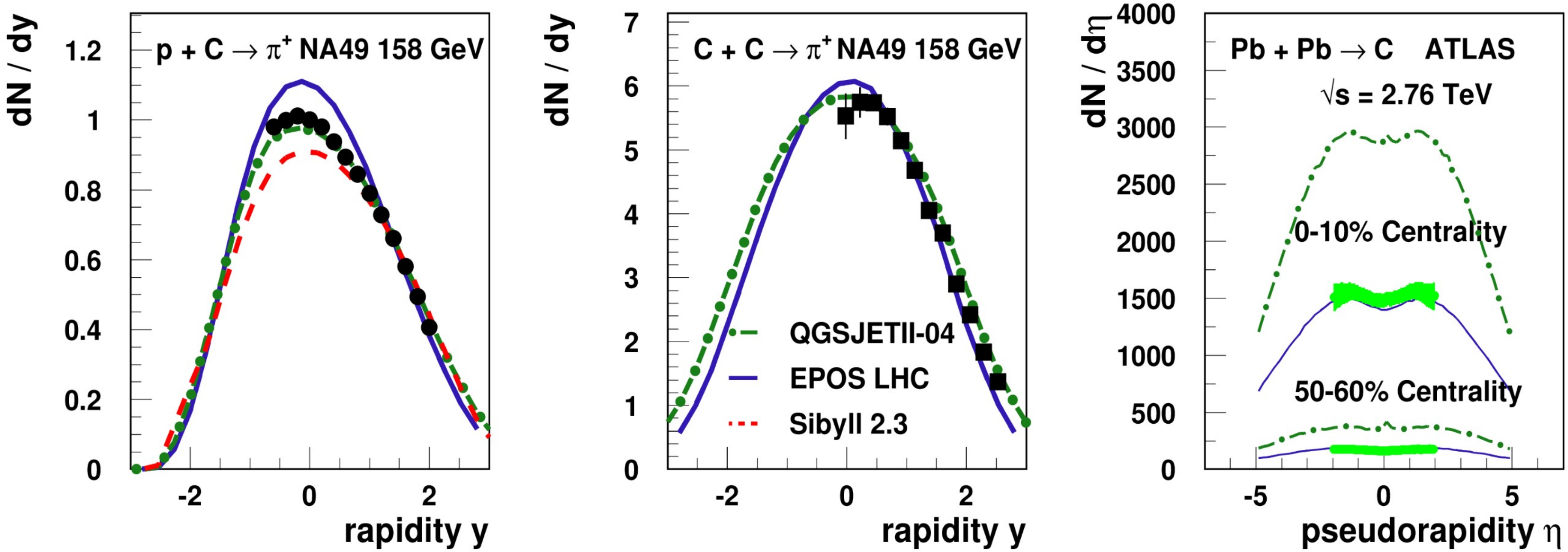
$$X_{max} \sim \lambda_e \ln\left(\left(1-k\right).E_0/\left(2.N_{tot}.A\right)\right) + \lambda_{ine}$$

- 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)

Light Ion Data

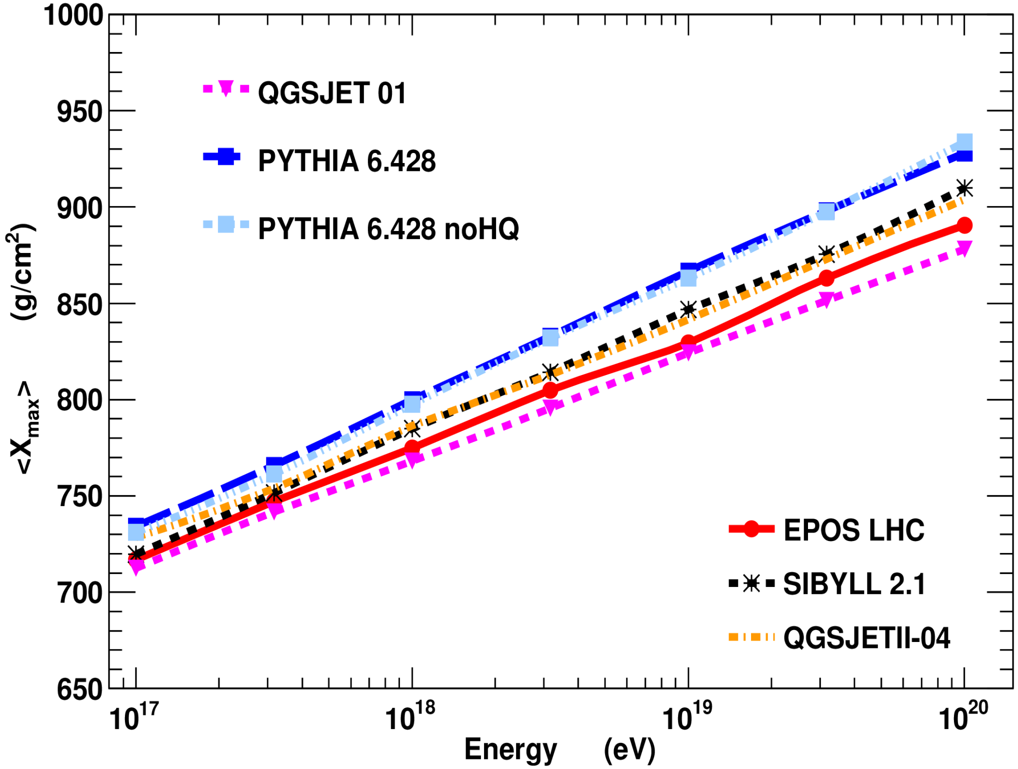
Very few data to compare with all CR models :

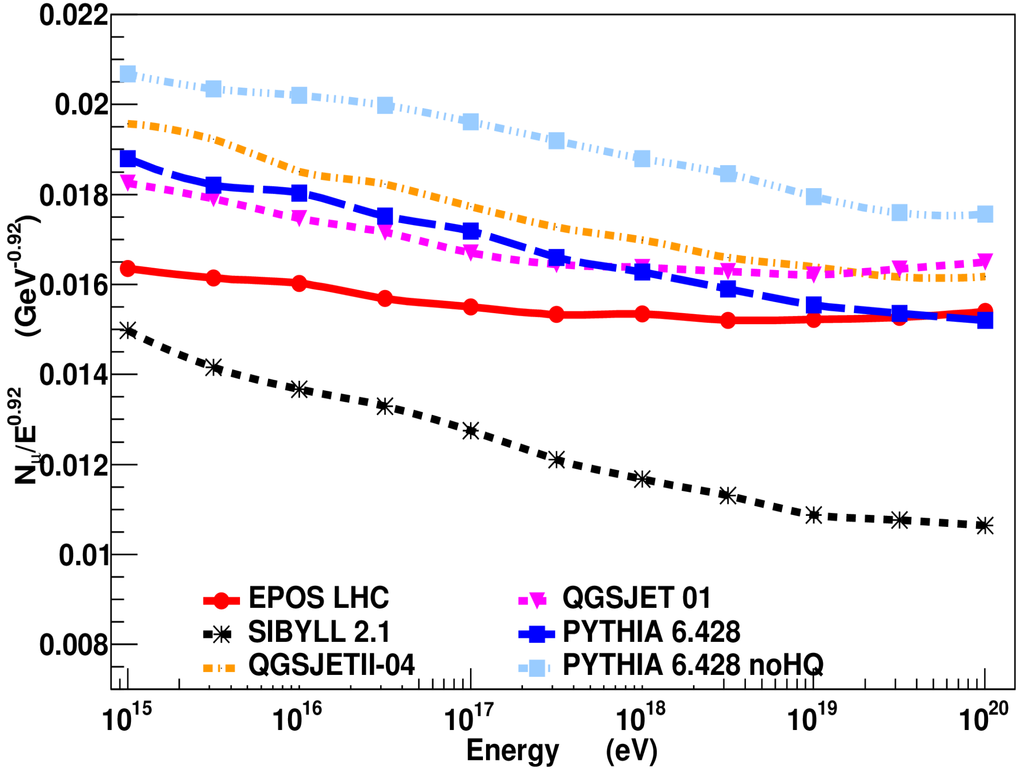
- strong limitations in Sibyll (projectile up to Fe only and target up to O !)
- no final state interactions exclude heavy nuclei for QGSJETII
- no light ion data at high energy



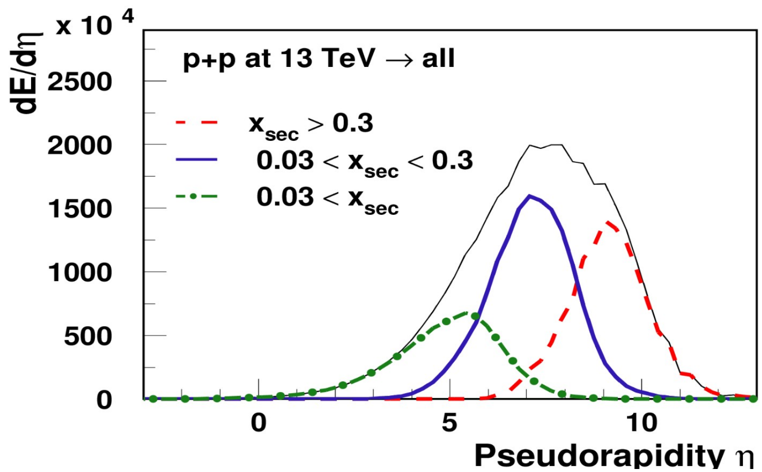
Tests using hydrogen atmosphere

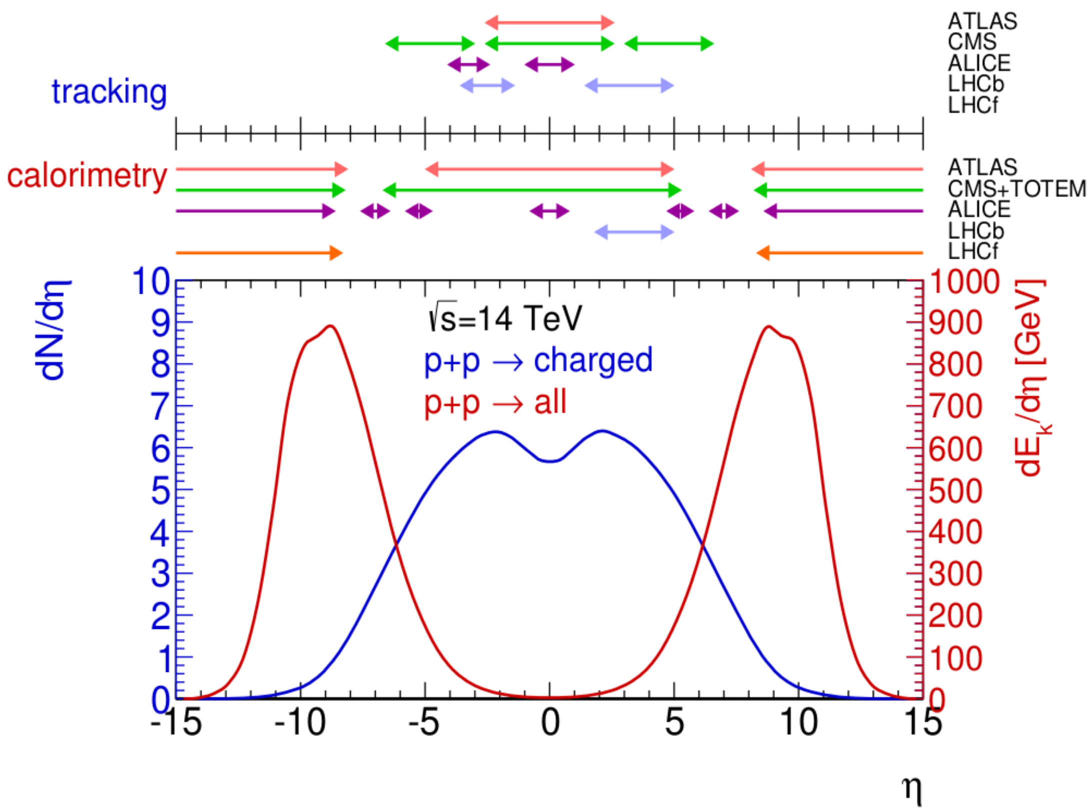
- **Work done with David D'Enterria (CERN) and Sun Guanhao**
  - test of Pythia event generator
- **Modified air shower simulations with air target replaced by hydrogen**
  - for interactions only (no change in density)
  - no nuclear effect





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

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**