Cosmic Rays and Forward LHC Physics

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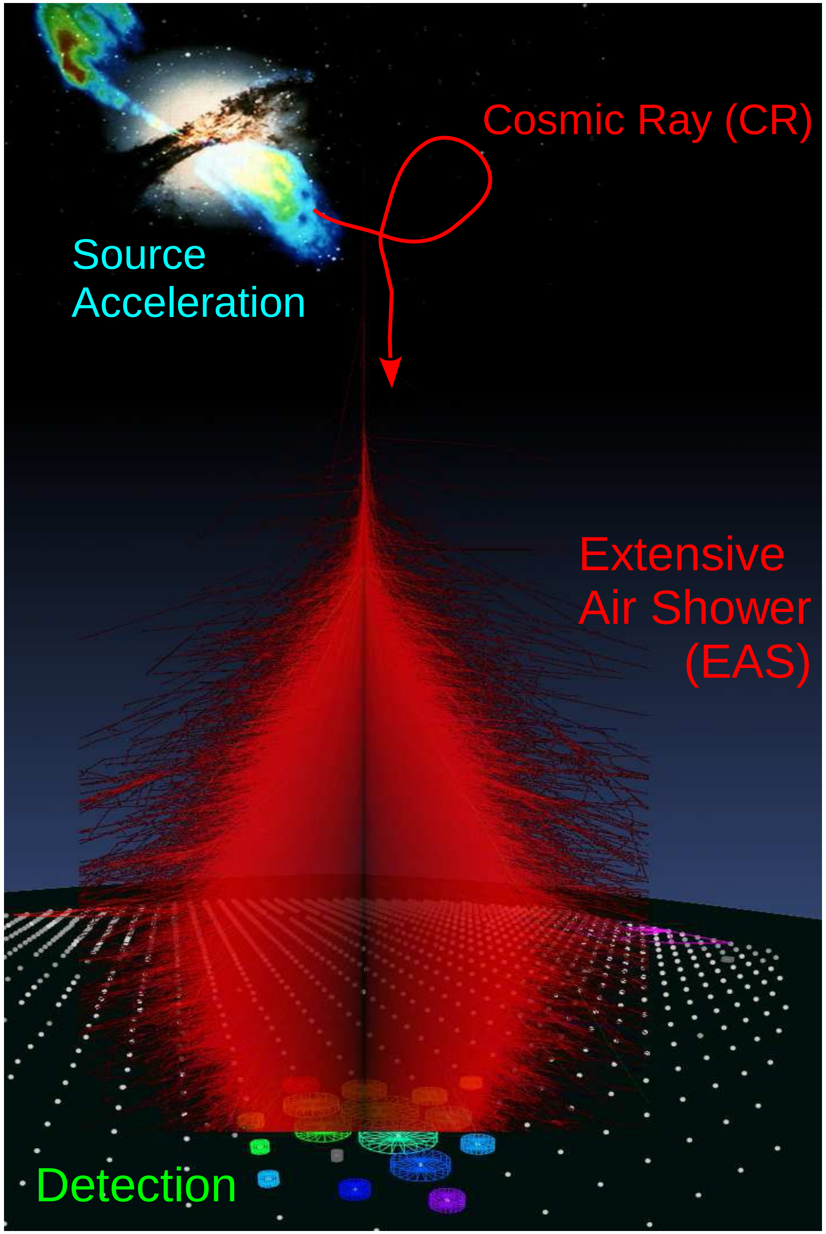
Outline

- **Introduction on Extended Air Showers (EAS)**
- **Monte-carlo for Cosmic Ray analysis and LHC data**
  - ➡ MC tuned to central data only
- **Remaining uncertainties**
  - ➡ Forward production in nuclear Interactions
- **Forward LHC Physics**

Central production at LHC reduced the model uncertainties for mass composition of cosmic rays. Remaining uncertainties can be reduced taking into account forward measurements AND using (light) nuclear target.

Preamble

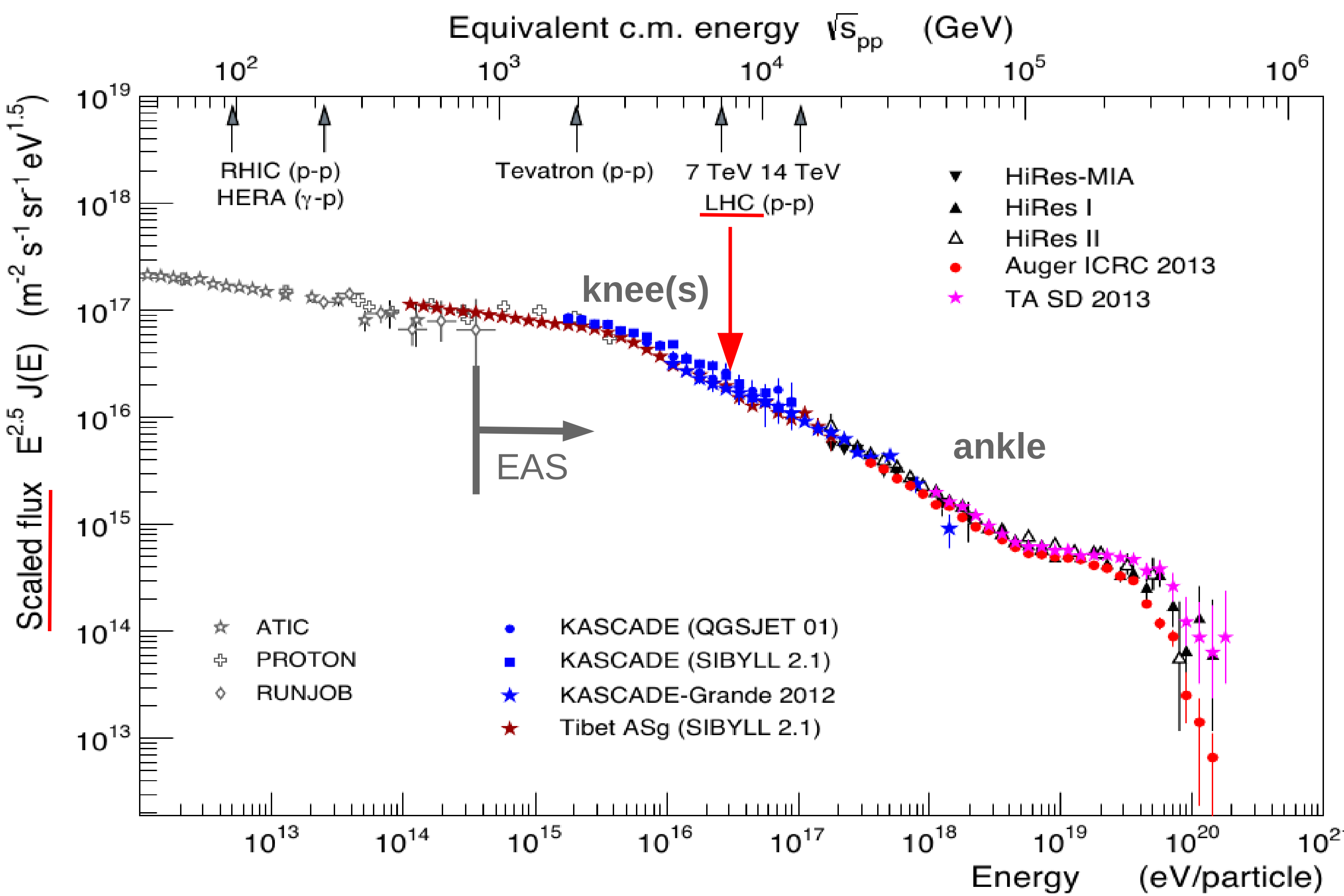


From R. Ulrich (KIT)

- **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

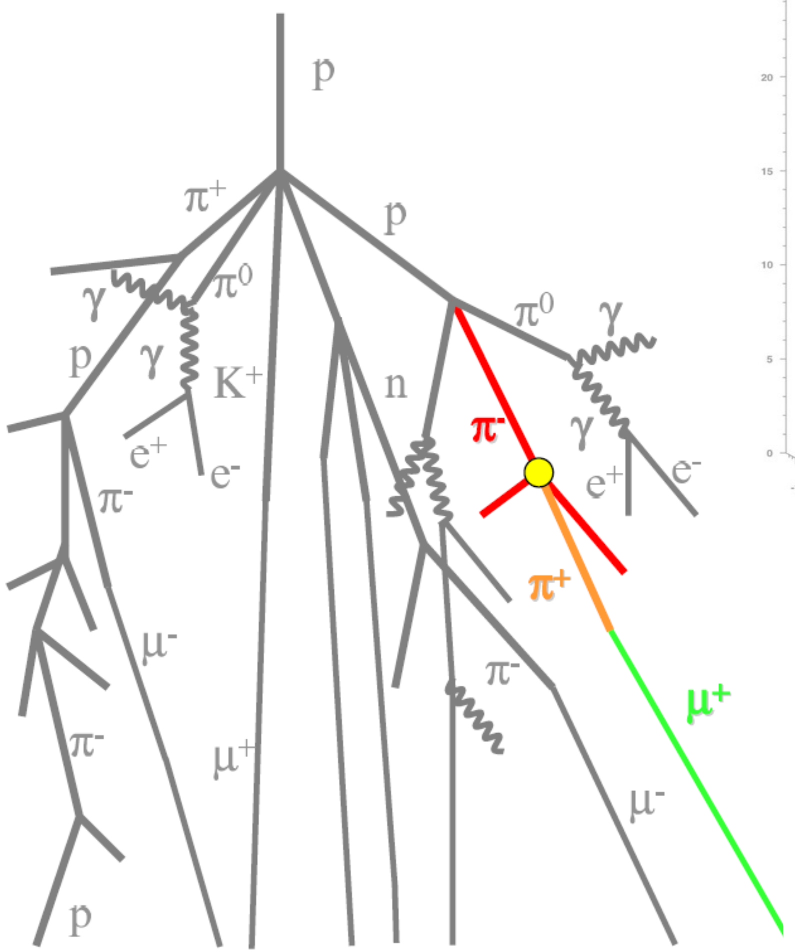
Cosmic Ray Spectrum



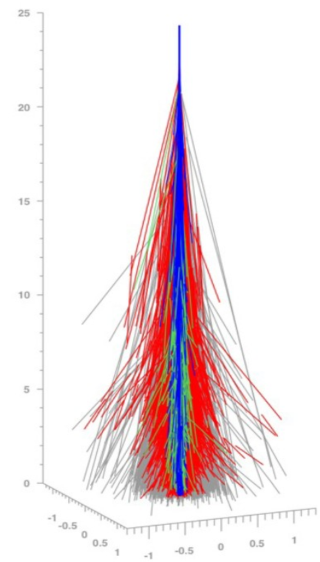
R. Engel (KIT)

- **Origins of spectrum properties**
  - ➡ mostly unknown
  - ➡ depend on primary CR mass
- **Astroparticle Physics**
  - ➡ Origin of cosmic rays (source, acceleration, ...)
  - ➡ Physics of EAS (mass vs hadronic interactions)

Extensive Air Shower



From R. Ulrich (KIT)



$A + air \rightarrow \text{hadrons}$

$p + air \rightarrow \text{hadrons}$

$\pi + air \rightarrow \text{hadrons}$

main source of uncertainties

intial γ from π^0 decay

$e^\pm \rightarrow e^\pm + \gamma$

$\gamma \rightarrow e^+ + e^-$

well known

$\pi^\pm \rightarrow \mu^\pm + \nu_\mu/\bar{\nu_\mu}$

- **Cascade of particle in Earth's atmosphere**

  Number of particles at maximum

  ➡ 99,88% of electromagnetic (e/m) particles

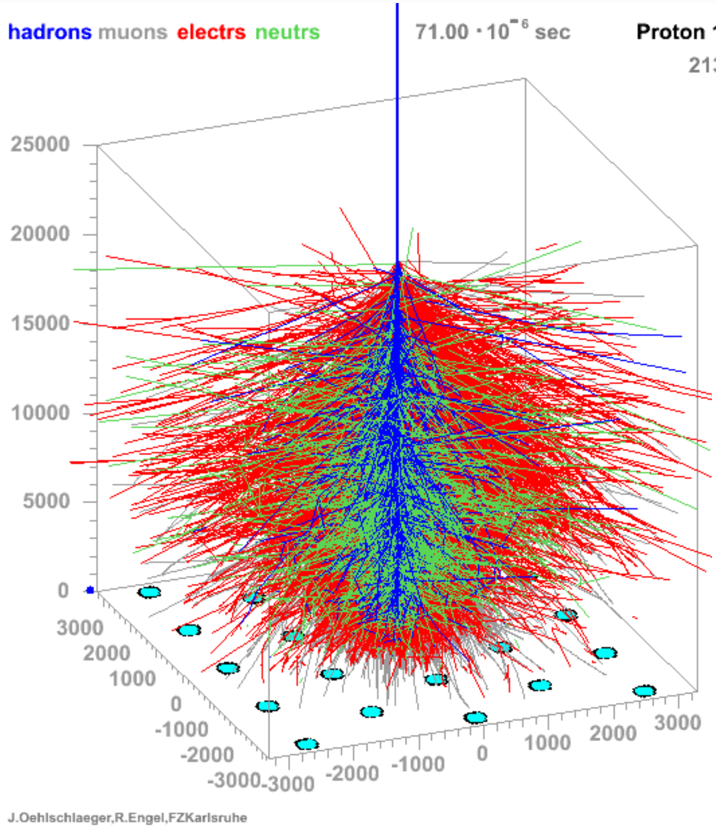
  ➡ 0.1% of muons

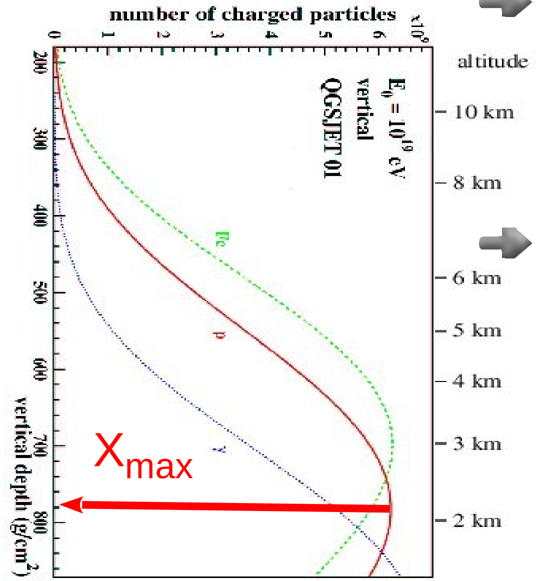
  ➡ 0.02% hadrons

  Energy

  ➡ from 100% hadronic to 90% in e/m + 10% in muons at ground (vertical)

Extensive Air Shower Observables



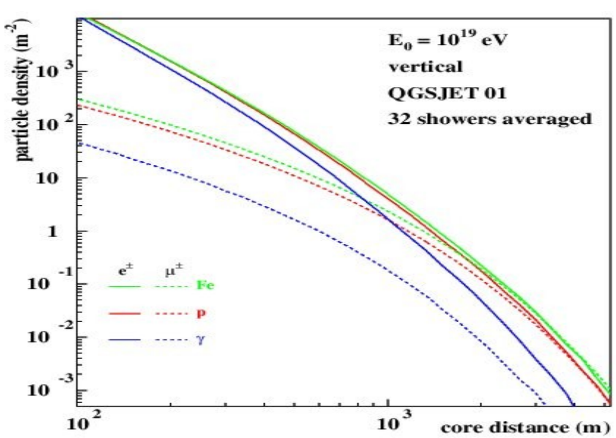


- **Longitudinal Development**
  - number of particles vs depth

$$X = \int_h^\infty dz\, \rho(z)$$

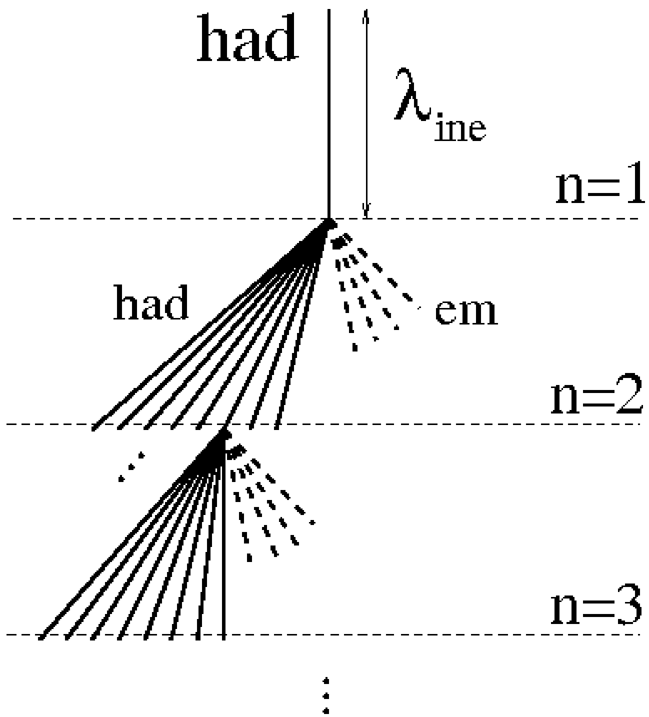
  - larger number of particles at X_{max}

    for many showers
    - mean : $<X_{max}>$
    - fluctuations : RMS X_{max}
  - mostly fixed by first interaction(s)



- **Lateral distribution function (LDF)**
  - particle density at ground vs distance to the impact point (core)
  - can be muons or electrons/gammas or a mixture of all
  - depends on all interactions in the shower

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)

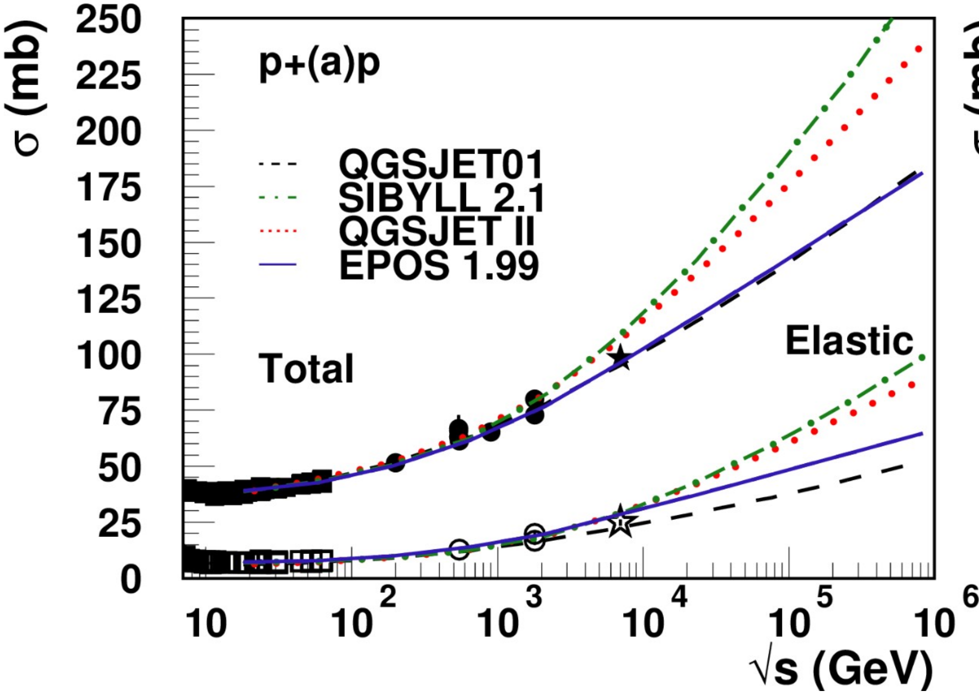
Hadronic Models for EAS

- **High Energy Physics model (PYTHIA)**
  - <n_{jet}> and cross-section (fit) are independent
  - no soft multiple scattering
  - no constrain from total cross-section to have independent access of inclusive class of events
- **Hadronic interaction models used for EAS**
  - Gribov Regge Theory (GRT) used to compute total cross-section
  - Sibyll (Engel et al.)
    - fix σ_{hard} (pQCD) and σ_{tot} (data)
    - GRT using <n_{jet}> as final goal to reach
  - QGSJETII (Ostapchenko) and EPOS (Pierog&Werner et al,)
    - first built the Pomeron from soft and hard component
    - then add corrections to the bare amplitude to fit the total cross-section using GRT
    - <n> is a consequence of the Pomeron choice and the cross-section.

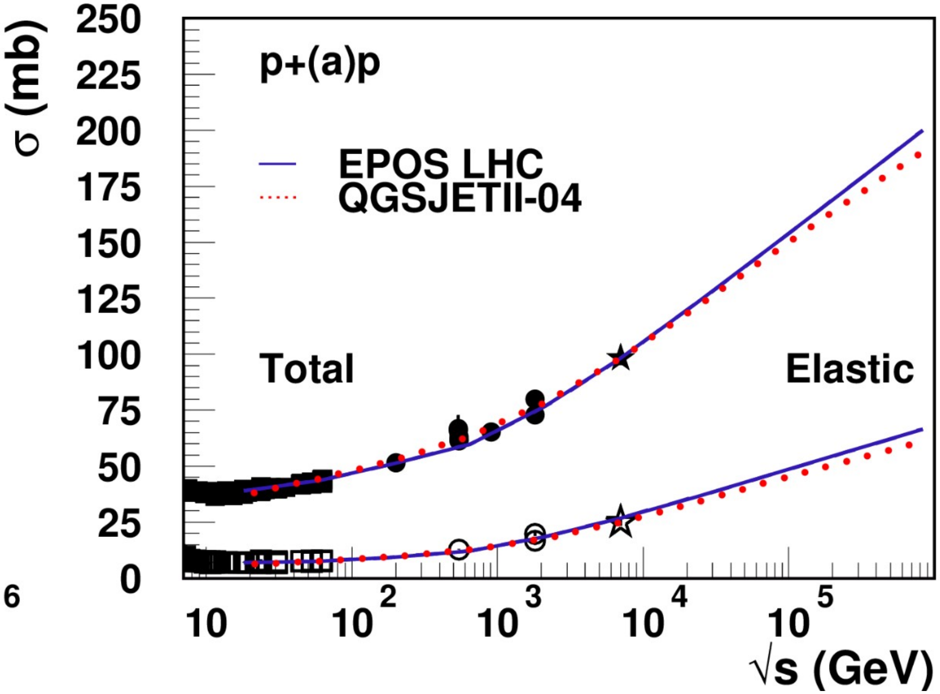
Cross Sections

- Same cross section at pp level and low energy for models (data for tuning)
- extrapolation to pA or to high energy (model dependent)
  - different amplitude and scheme
    - different extrapolations

Pre - LHC

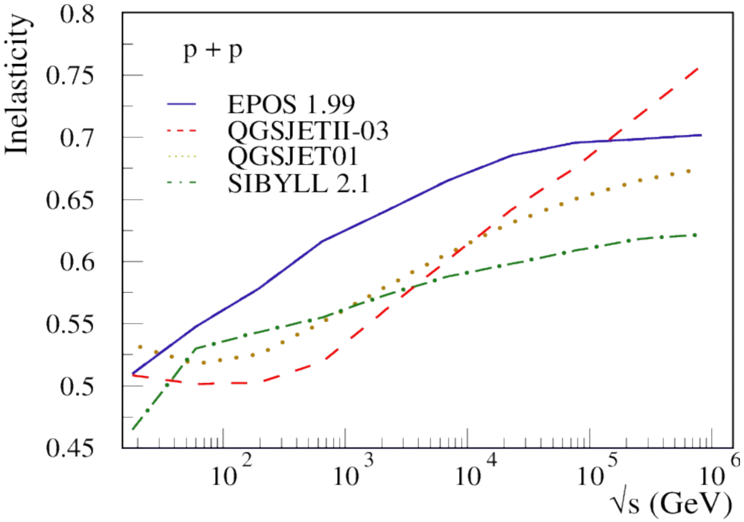


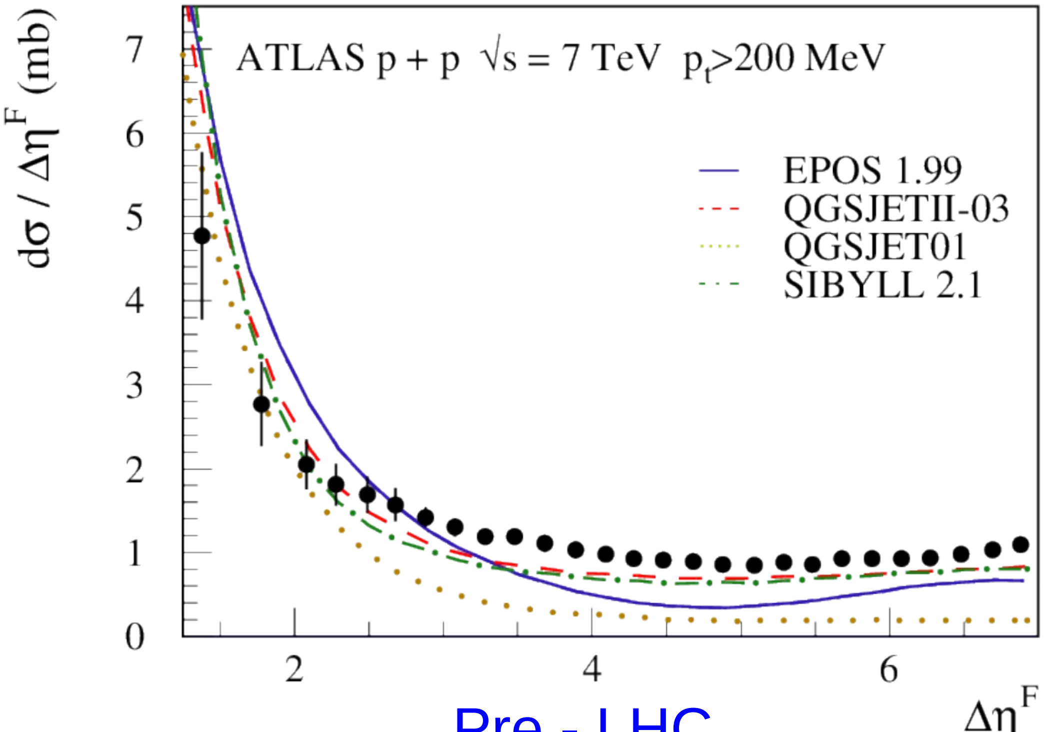
Post - LHC



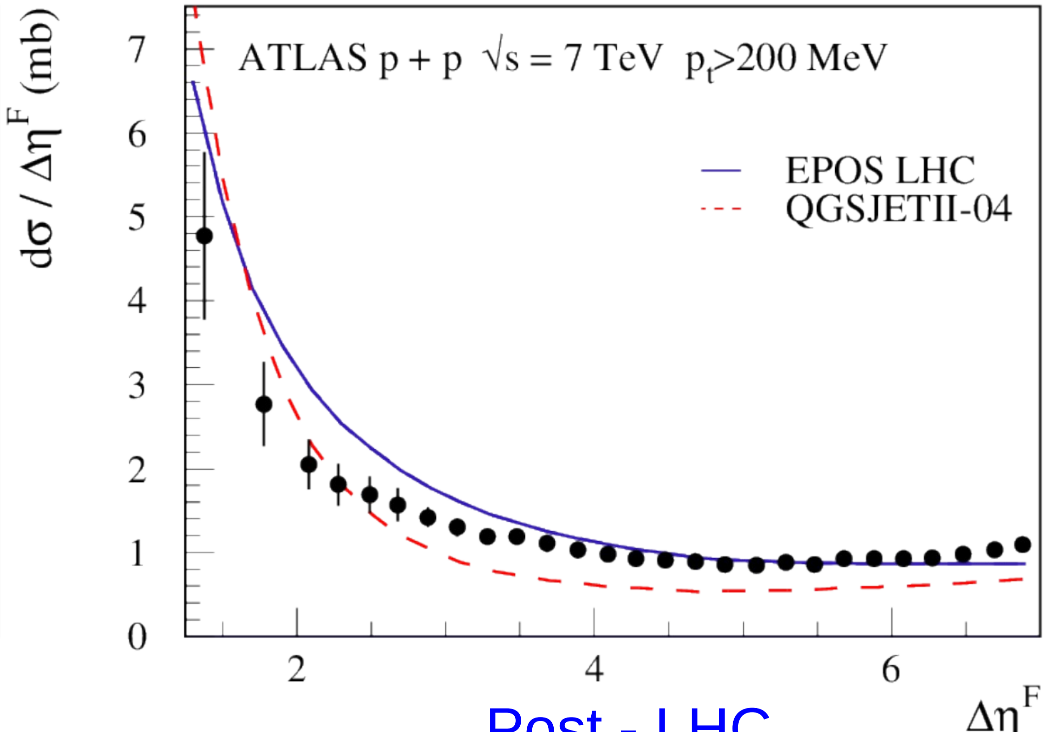
(In)elasticity

- **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

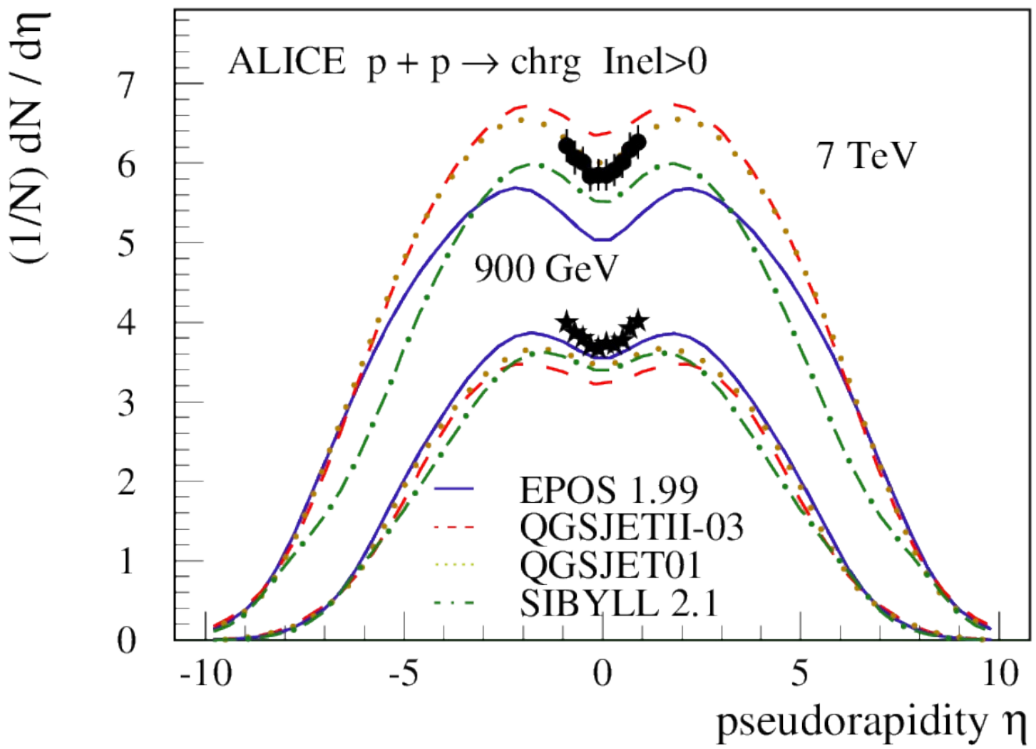
Pseudorapidity

Consistent results

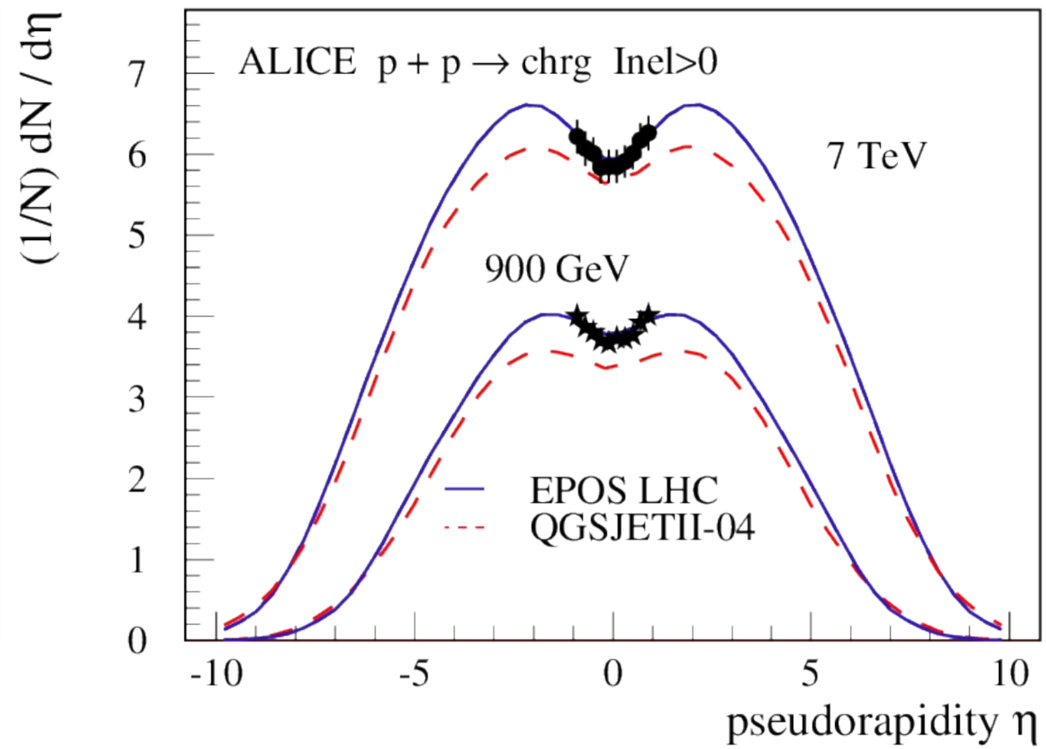
➡ Better mean after corrections
- difference remains in shape

LHC data in the range defined by Pre-LHC models : no unexpected results in basic distributions

Pre - LHC



Post - LHC



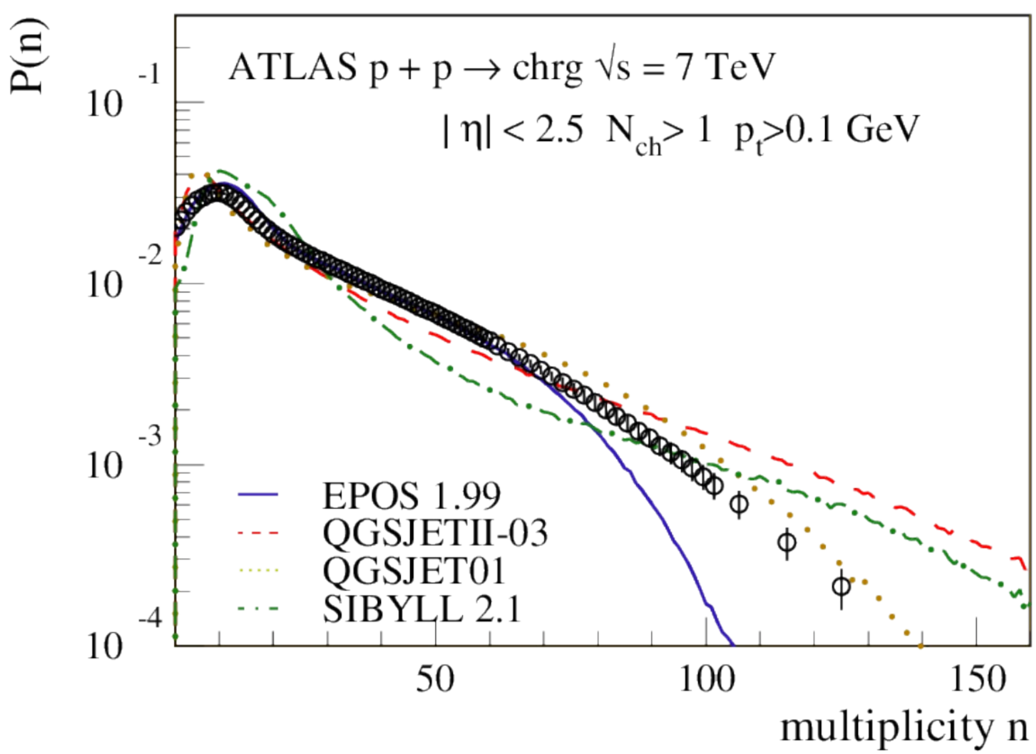
Multiplicity Distribution

Consistent results

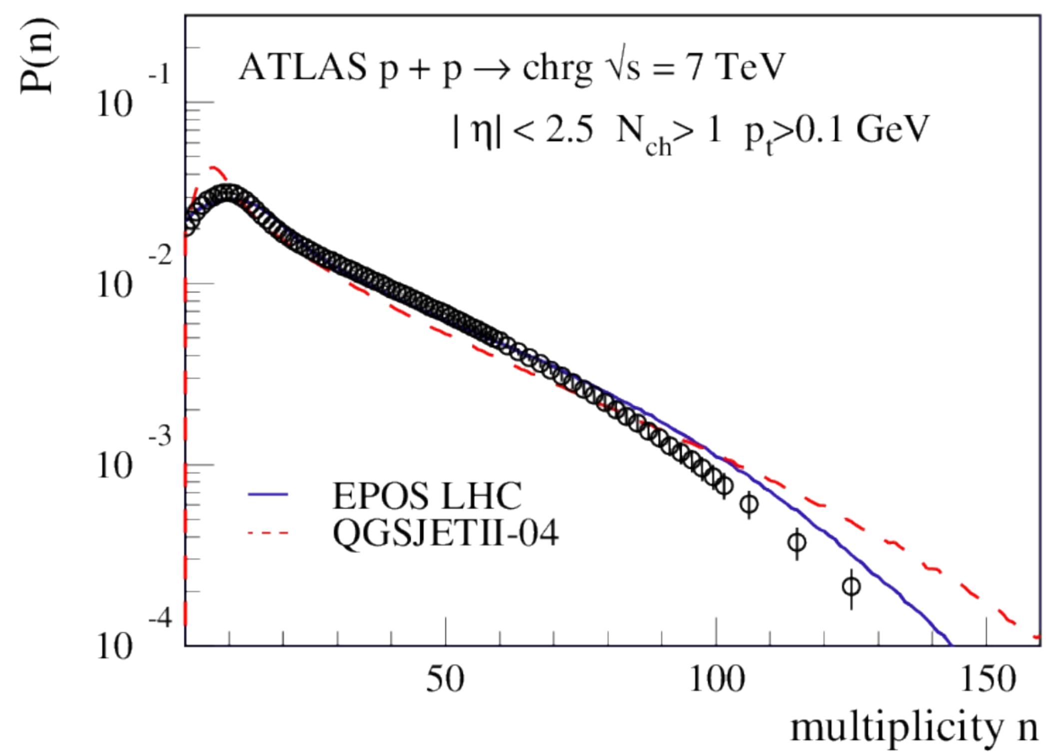
- Better mean after corrections
  - difference remains in shape
- Better tail of multiplicity distributions
  - corrections in EPOS LHC (flow) and QGSJETII-04 (minimum string size)

LHC data in the range defined by Pre-LHC models : no unexpected results in basic distributions

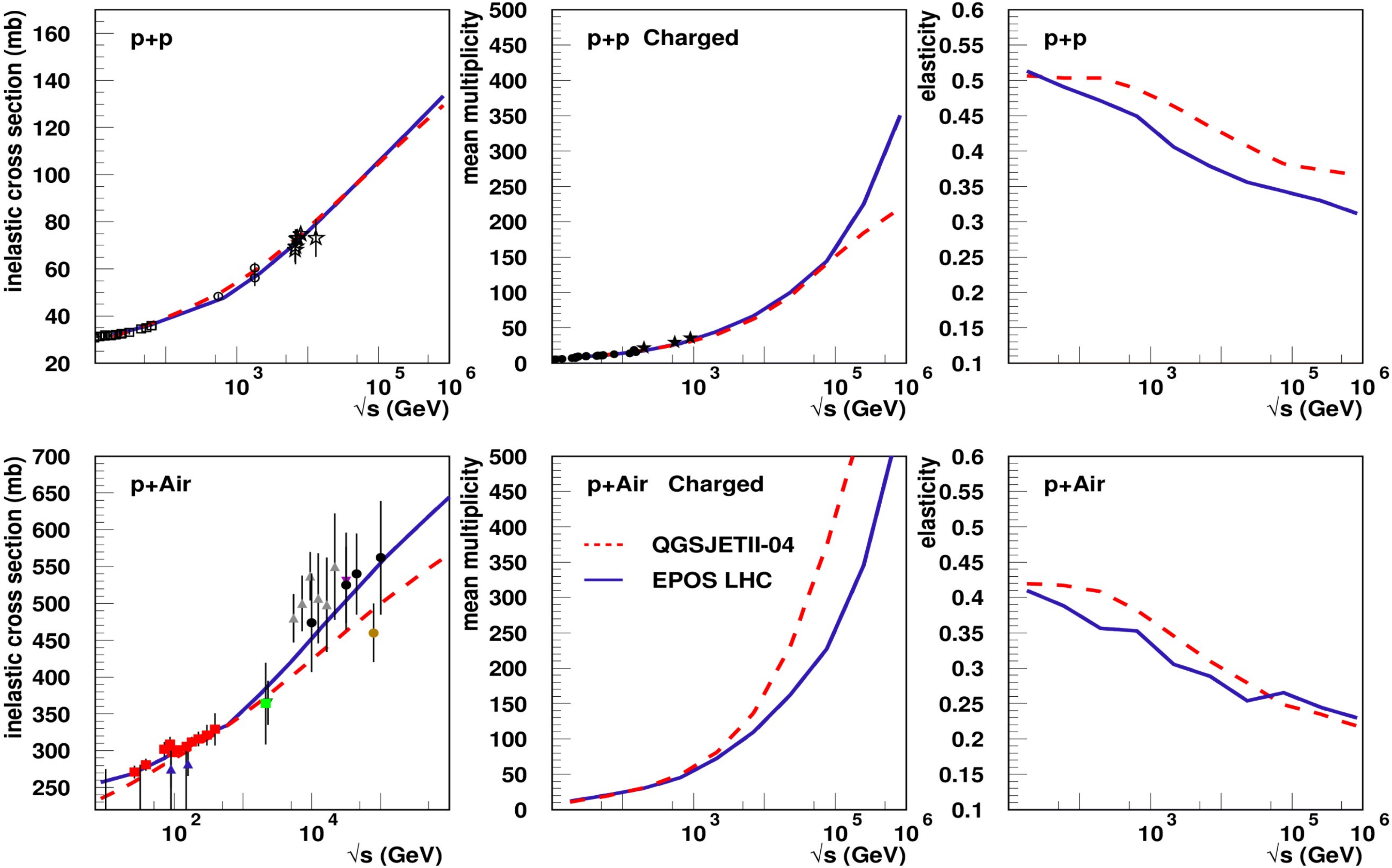
Pre - LHC



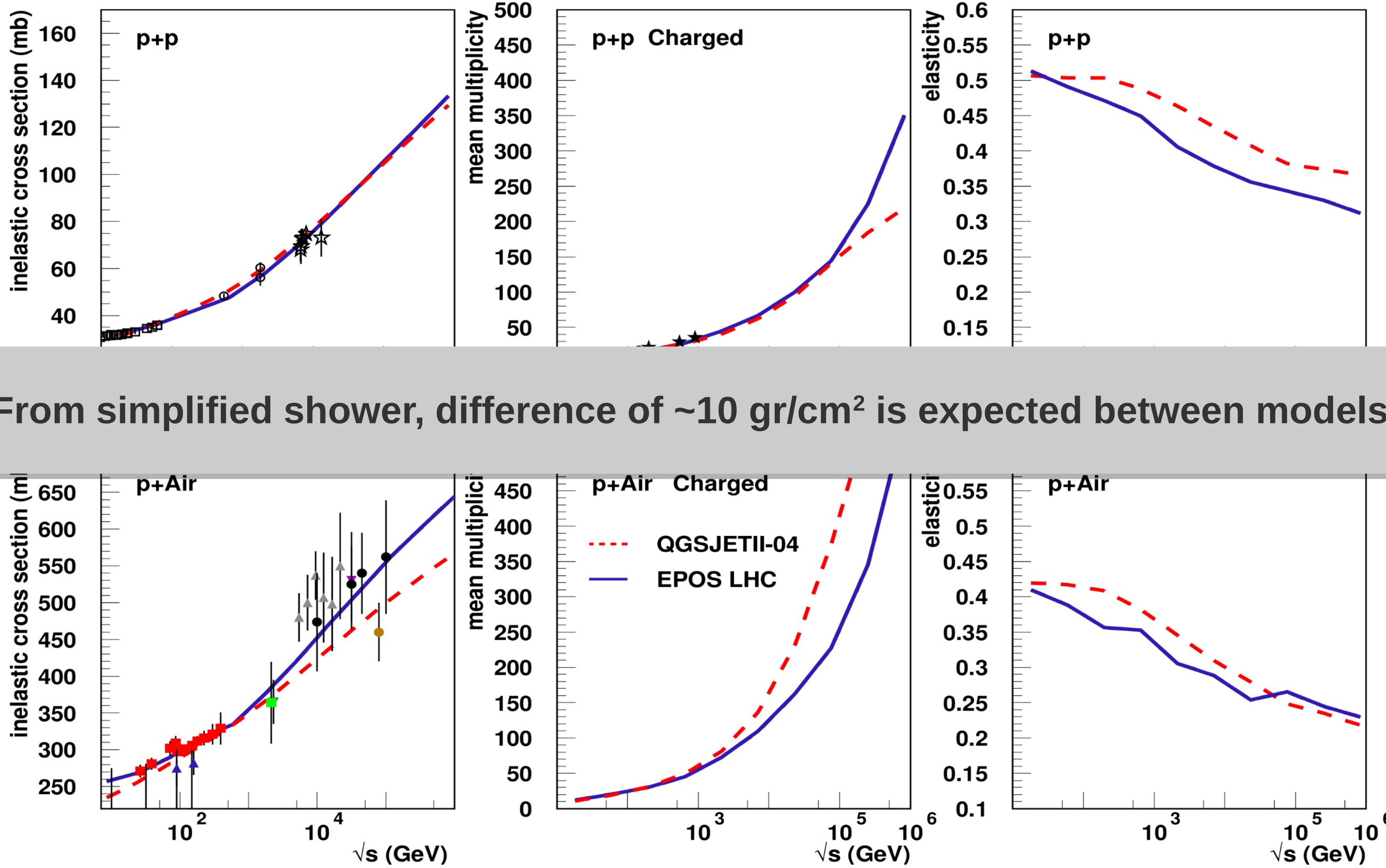
Post - LHC



Ultra-High Energy Hadronic Model Predictions

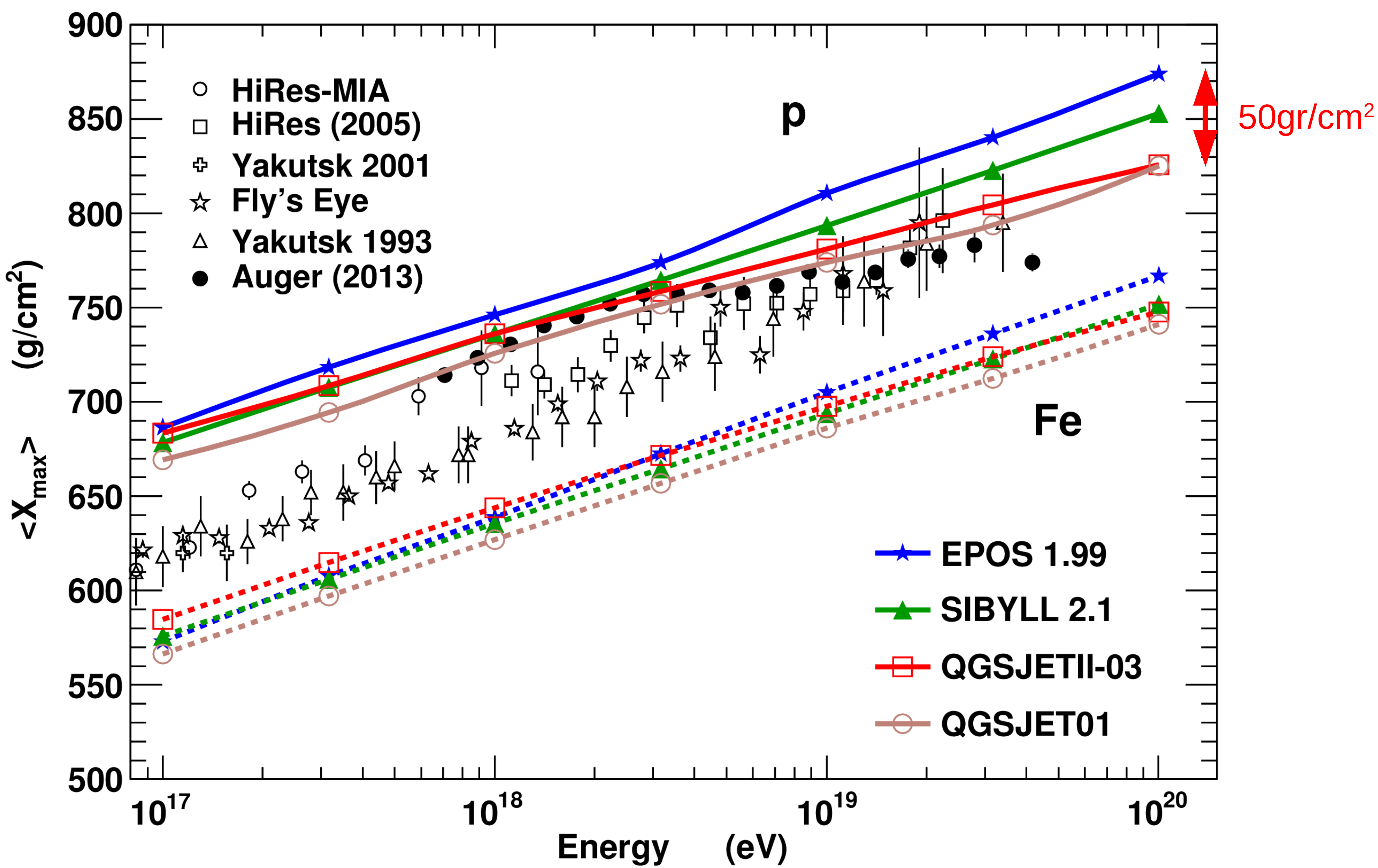


Ultra-High Energy Hadronic Model Predictions

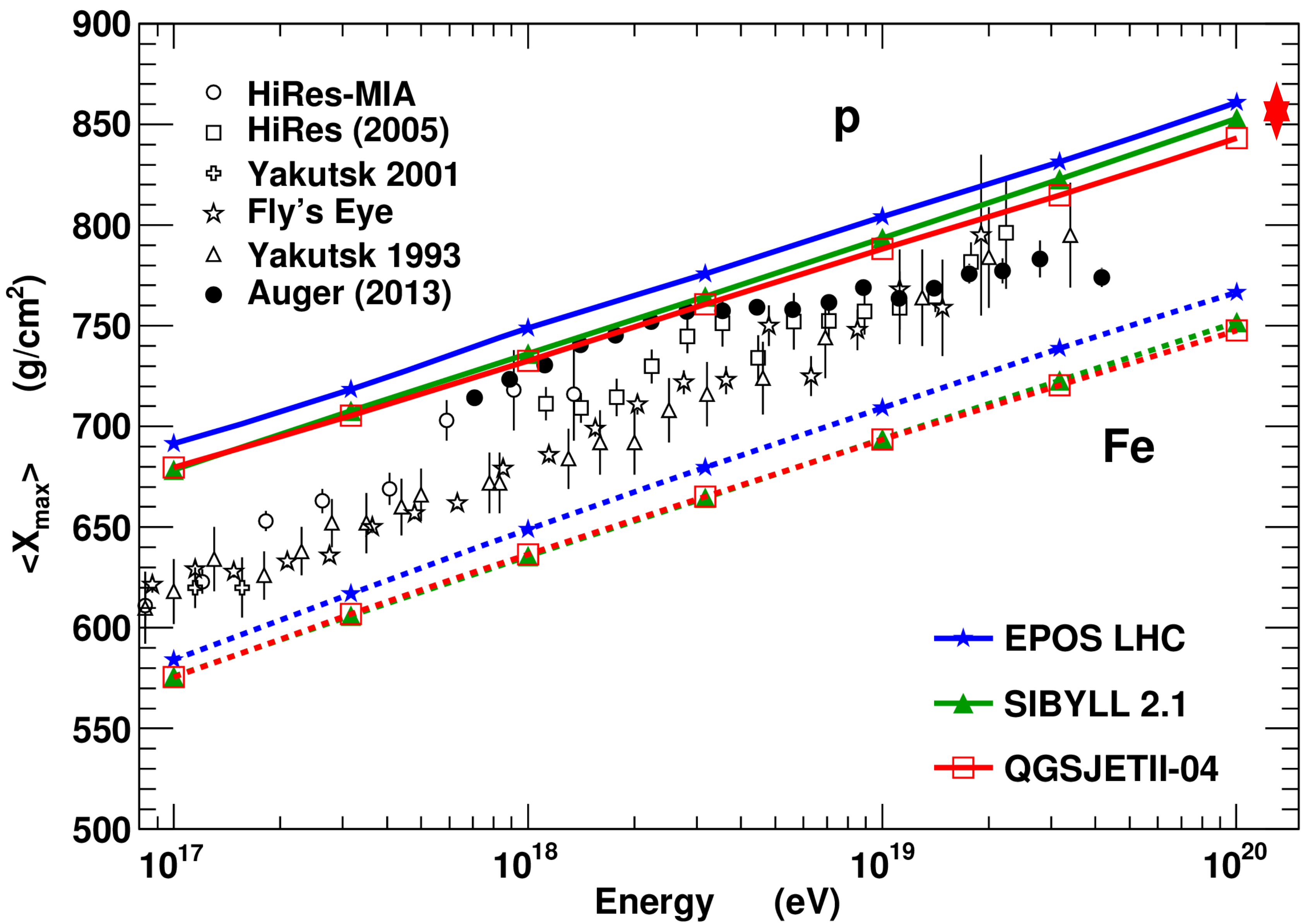


From simplified shower, difference of ~10 gr/cm² is expected between models.

EAS with Old CR Models : X_{max}



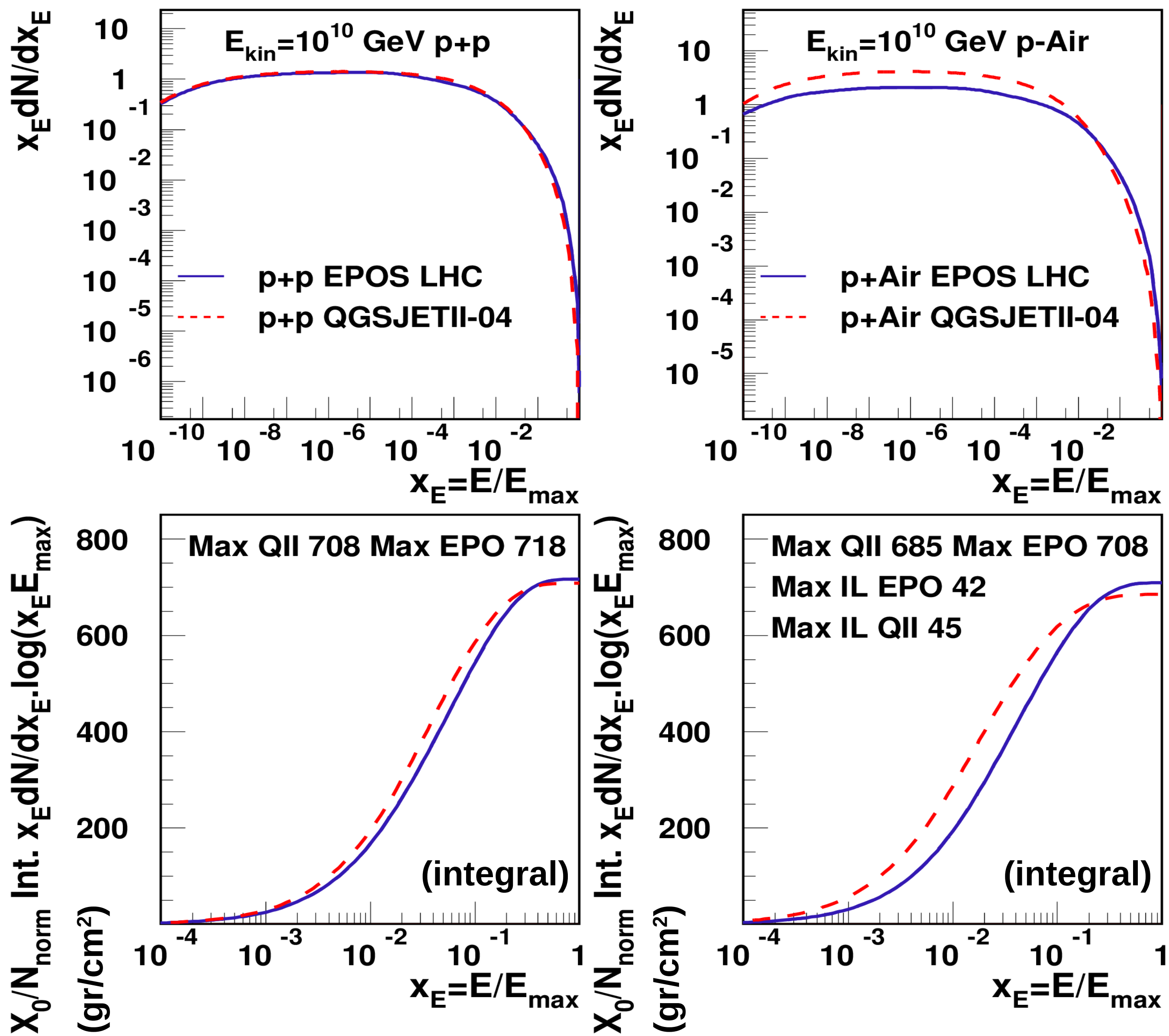
EAS with Re-tuned CR Models : X_{max}



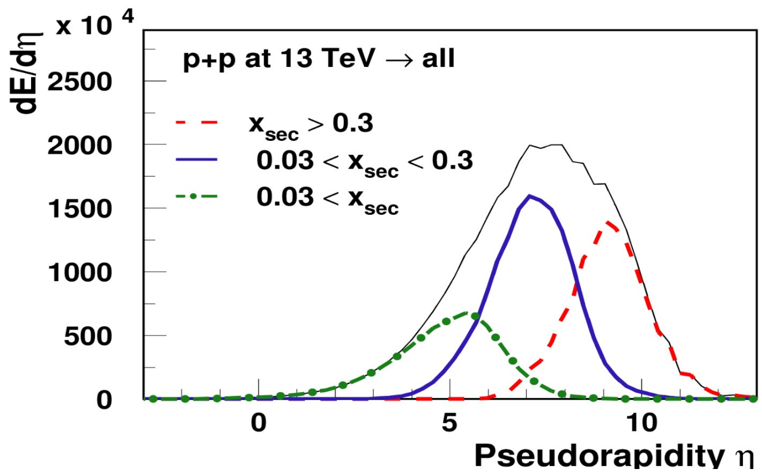
20gr/cm2

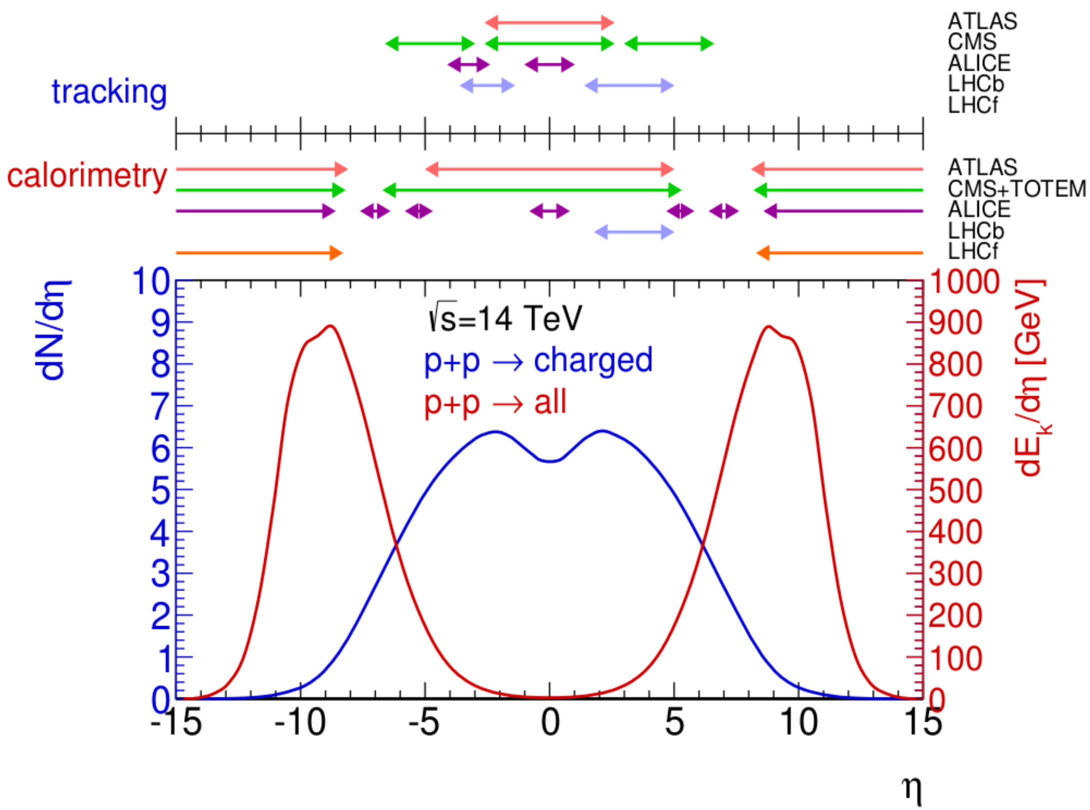
Photon Energy Spectra

- **In simplified model**
  - multiplicity used to get average energy of first (and highest energy) photon induced sub-showers
  - neglect energy spectra
- **Use directly energy spectra from first interaction**
  - which energy is important ?



LHC acceptance



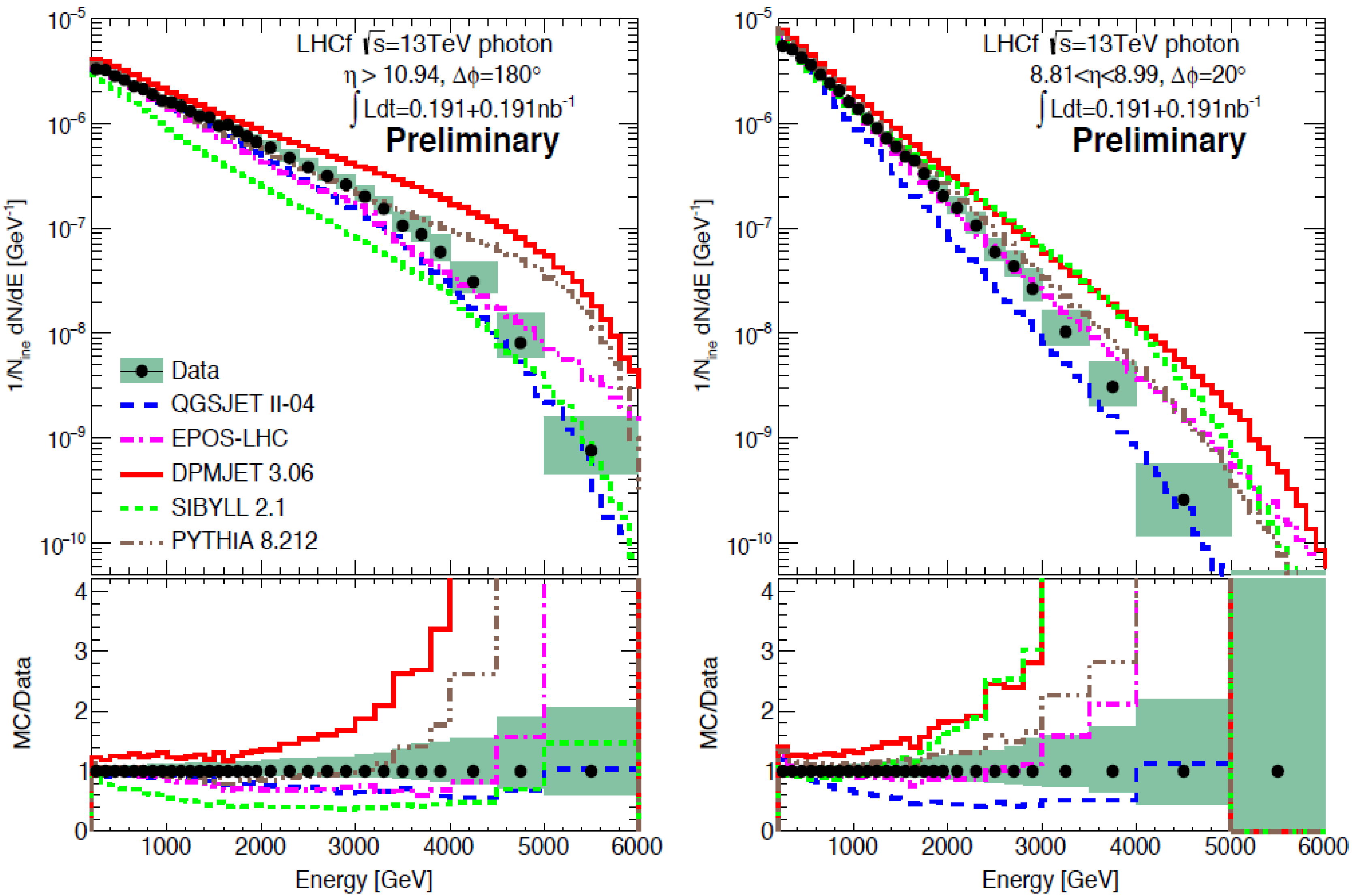


- **p-p data of central detectors used to reduce uncertainty by factor ~2**
  - p-Pb difficult to compare to CR models (only EPOS)
  - special centrality selection
  - pO ?
- **Direct photon energy spectra from LHCf**
  - small phase space but relevant for X_{max}
  - p-Pb (O) and correlation with ATLAS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

Comparison with LHCf

- **LHCf favor not too soft photon spectra**
- **No model compatible with all LHCf measurements**

T.Sako for the LHCf collaboration

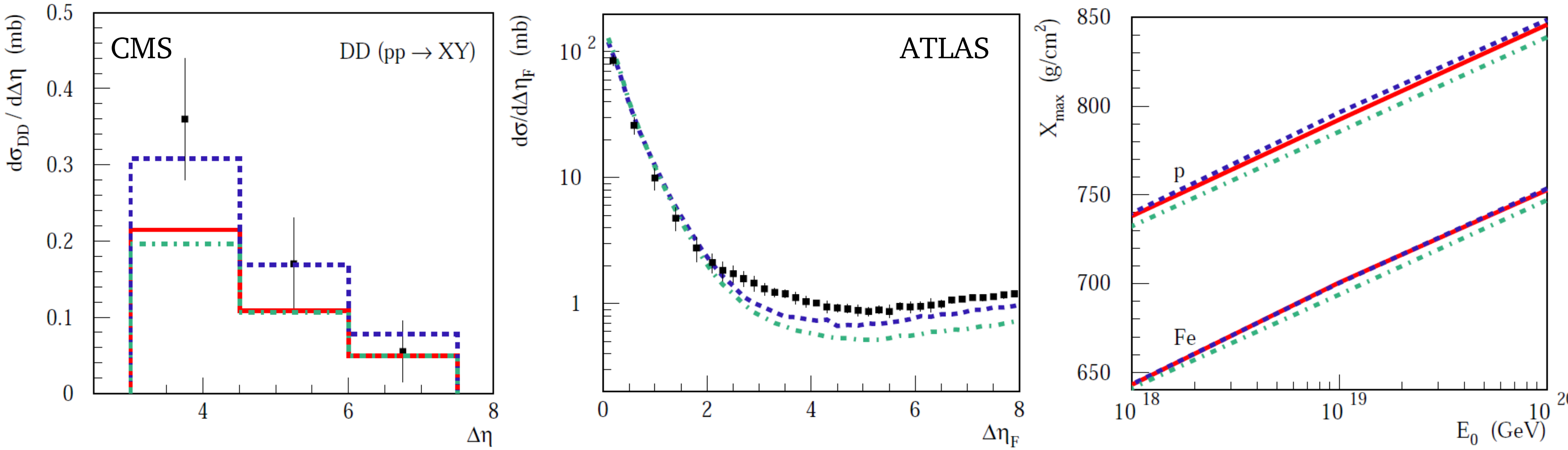


Diffraction measurements

- **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



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 ...

See talk by R. Conceicao

- **Central particle production at LHC reduced model uncertainties in X_{max} by a factor ~2**
  - ➔ same energy evolution in models important for mass of primary cosmic rays

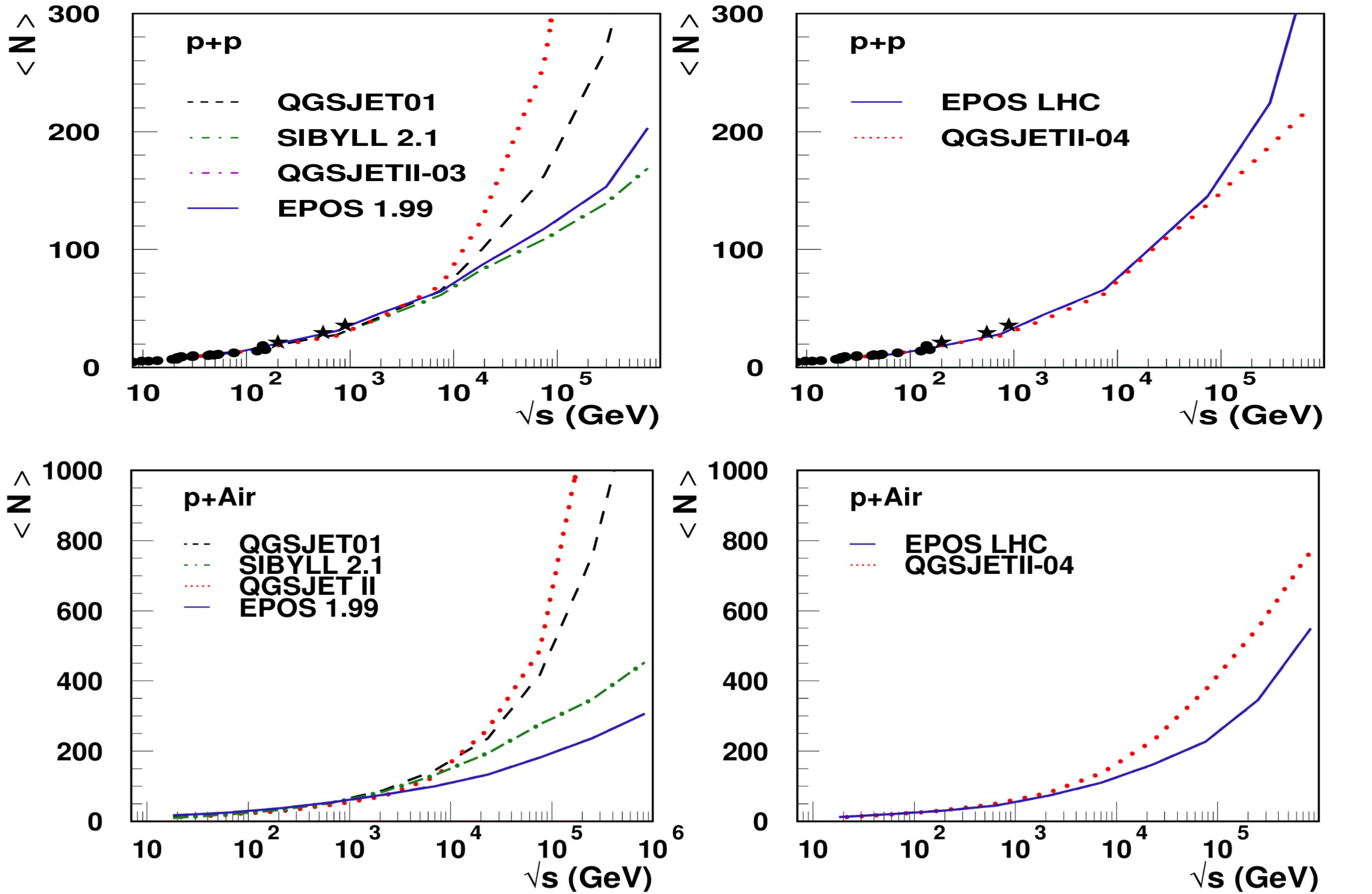
- **Remaining 20 gr/cm^2 difference for X_{max} predictions**
  - ➔ linked to forward physics (photon spectra and diffraction measured at LHC) not yet taken into account in models used for EAS simulation (coming...)
  - ➔ effect of extrapolation to p-Air interaction
    - p-O beam necessary to check that p-p properly extrapolated
    - p-Pb forward measurement can be used but need change in most models
      - ➔ peripheral p-Pb (not selected on multiplicity ! …) could give approximate results of p-O (but not exactly the same...)

Cosmic Ray Hadronic Interaction Models

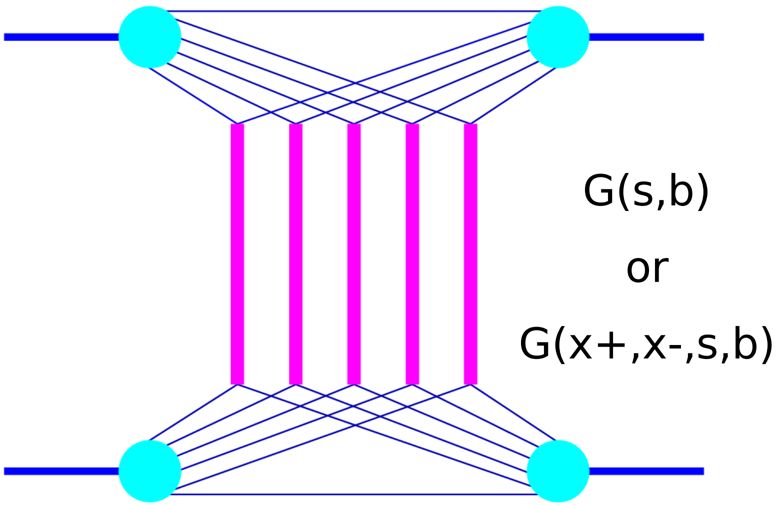
- **Theoretical basis :**
  - pQCD (large p_t)
  - Gribov-Regge (cross section with multiple scattering)
  - energy conservation
- **Phenomenology (models) :**
  - hadronization
    - string fragmentation
    - EPOS : high density effects (statistical hadronization and flow)
  - diffraction (Good-Walker,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

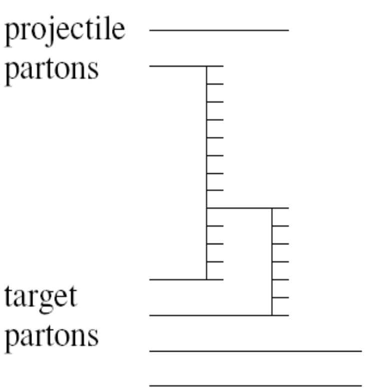
Ultra-High Energy Hadronic Model Predictions



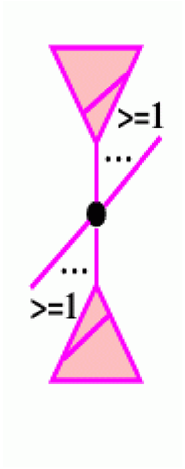
Cross Section and Multiplicity in Models



EPOS

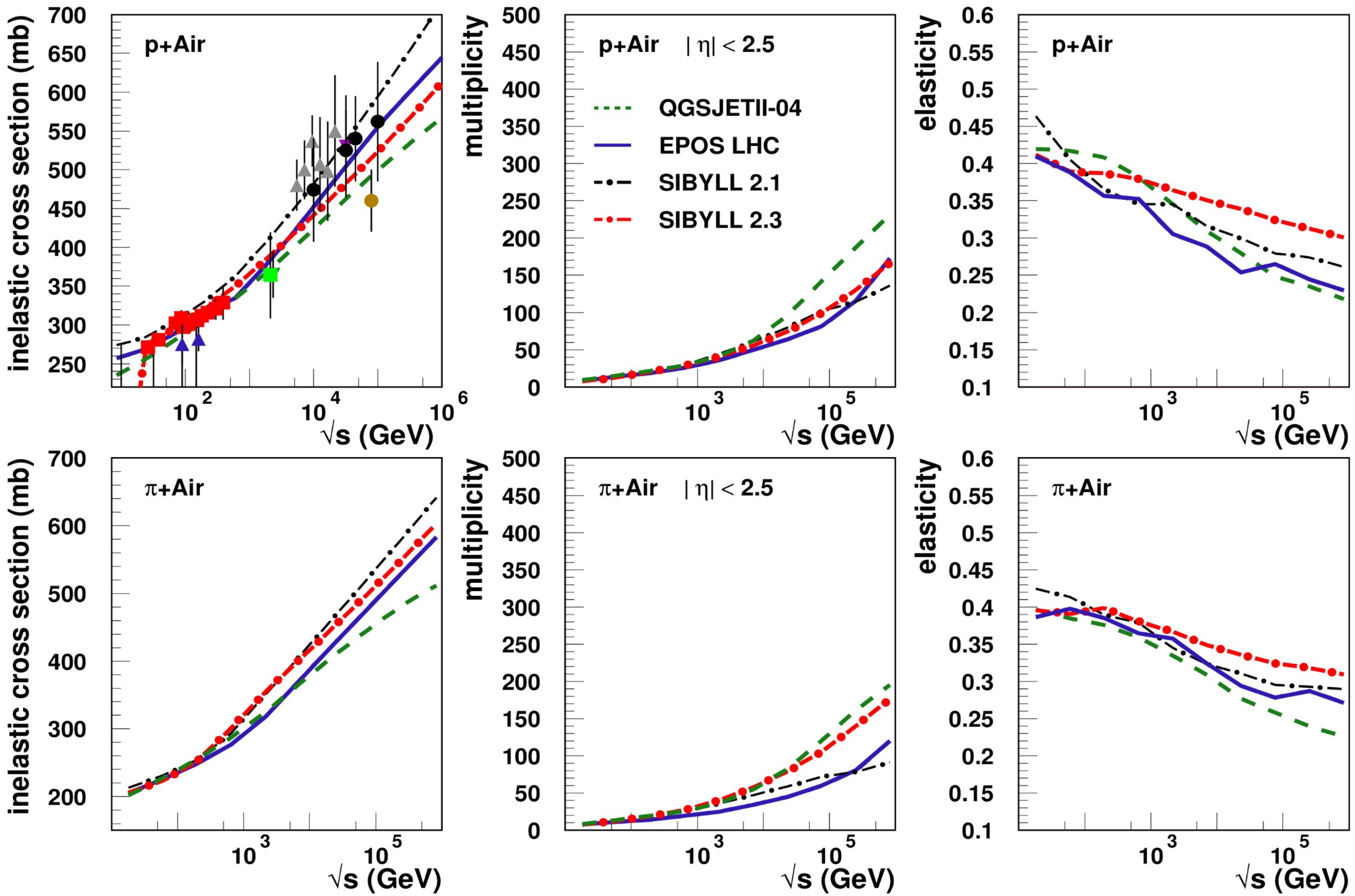


QGSJET II

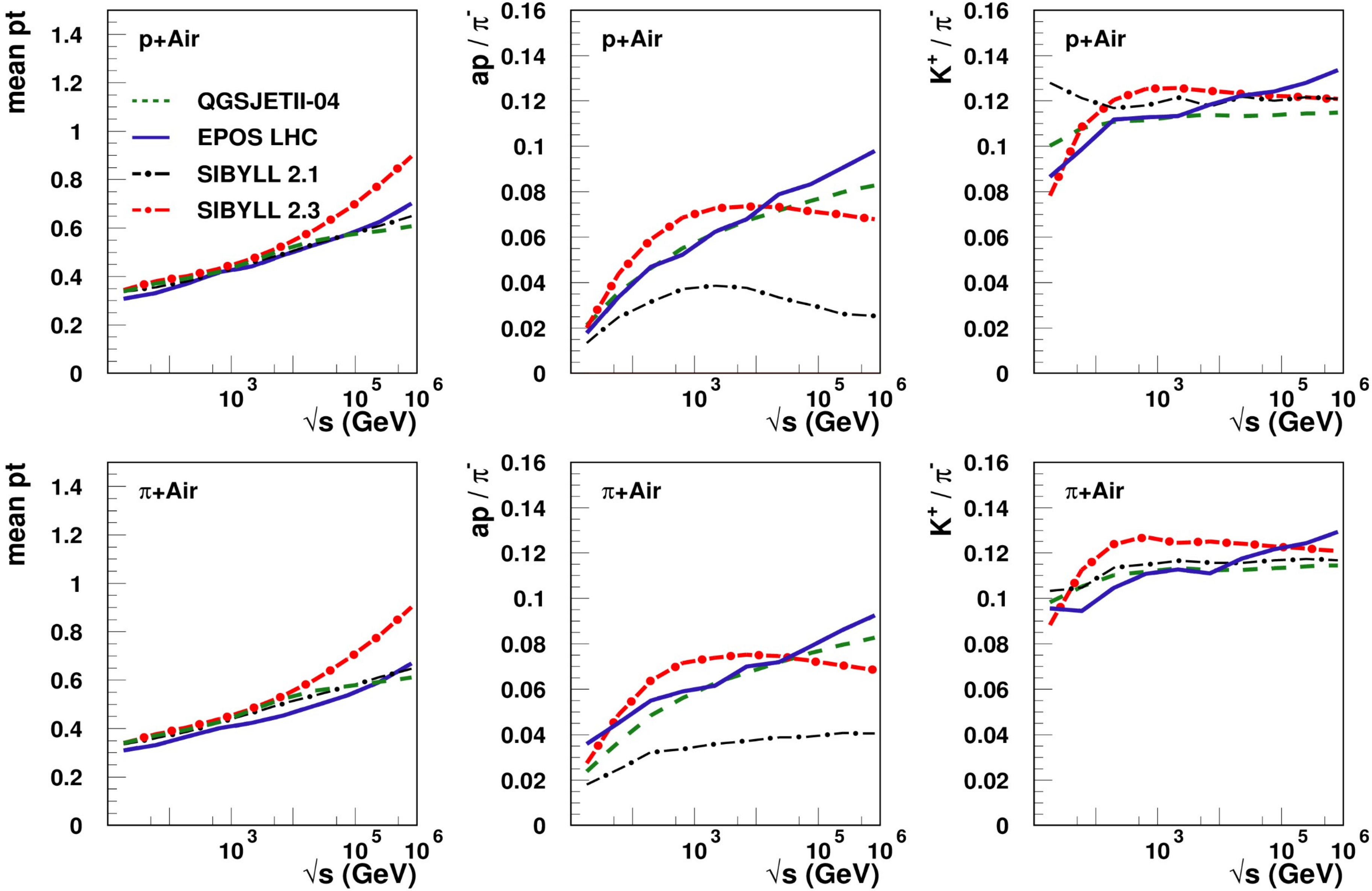


- **Gribov-Regge and optical theorem**
  - Basis of all models (multiple scattering) but
    - Classical approach for QGSJET and SIBYLL (no energy conservation for cross section calculation)
    - Parton based Gribov-Regge theory for EPOS (energy conservation at amplitude level)
- **pQCD**
  - Minijets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



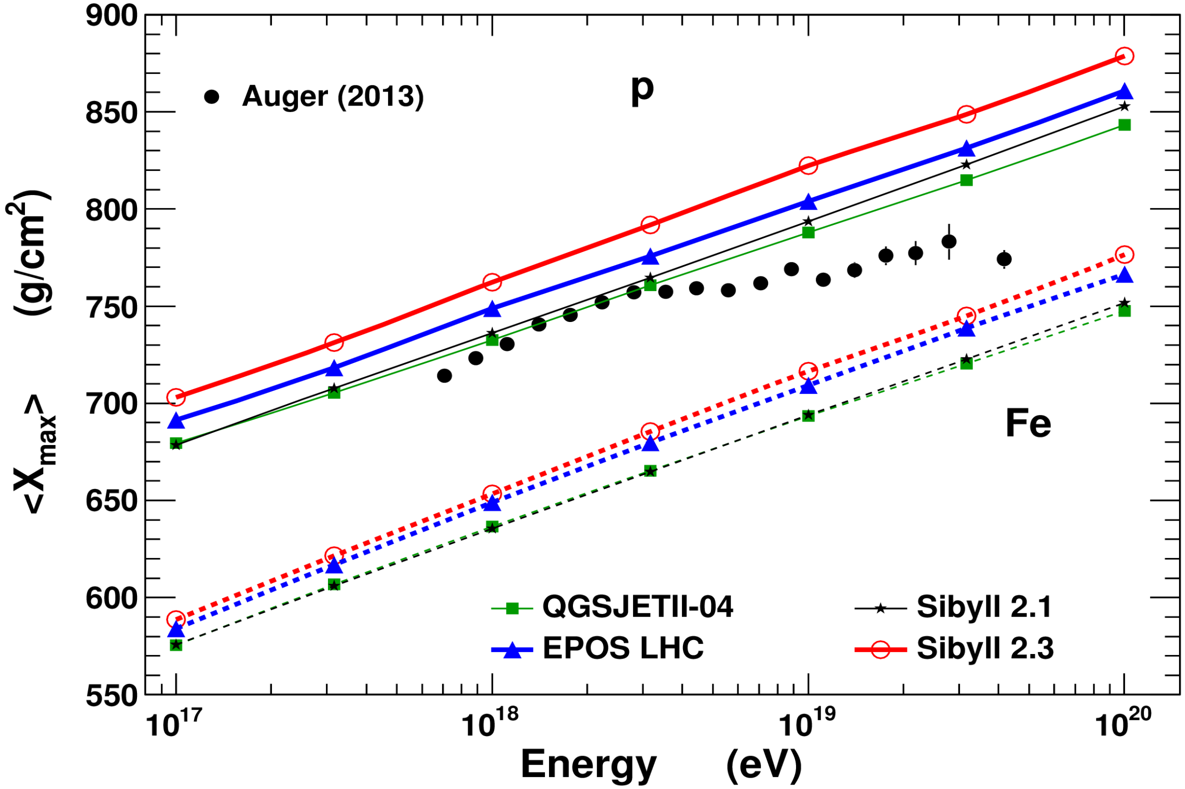
Model Predictions (2)

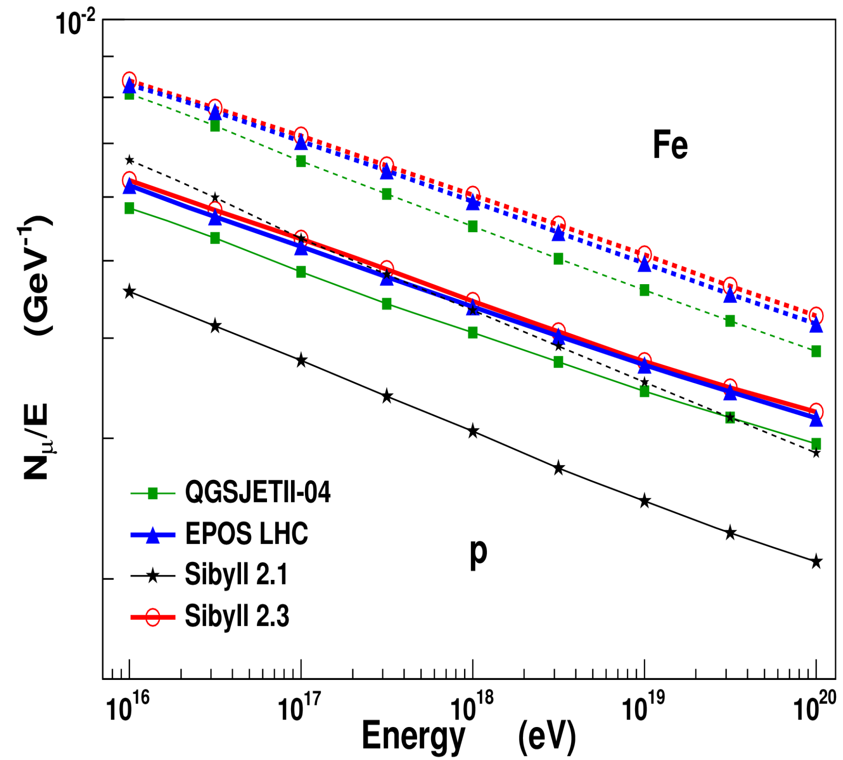


Air Shower Observables

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

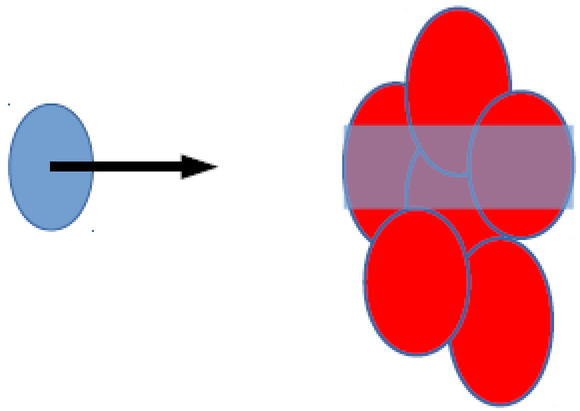


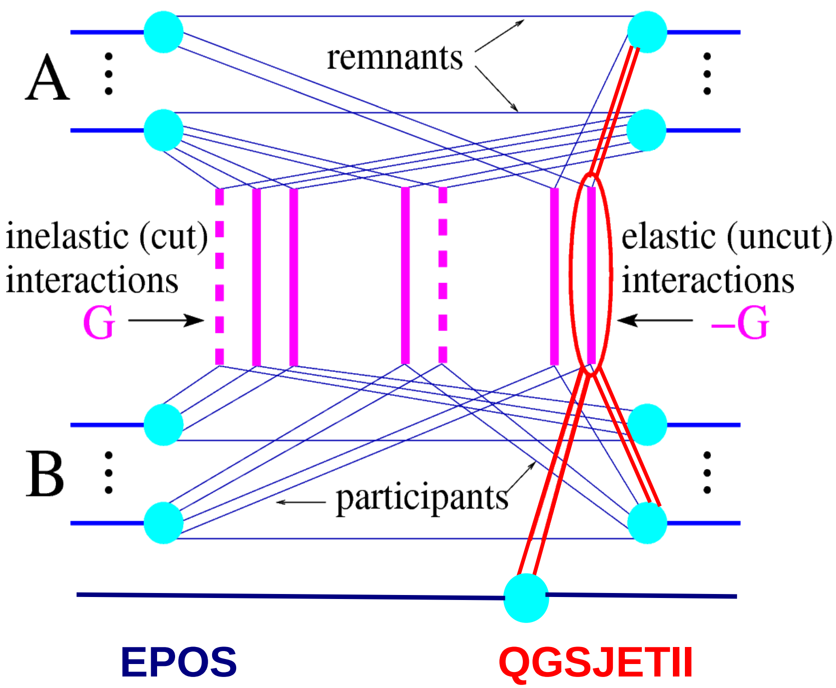


Summary of arXiv:1601.06567

Modifications	X_{max}	X^{μ}_{max}
cross-section and nucleon spectra of 1st interaction	5 g/cm^2	
rest of 1st interaction	5 g/cm^2	5 g/cm^2
nucleon spectra in all int.	5 g/cm^2	15 g/cm^2
all pion and kaon interactions		15 g/cm^2
Model difference fractions		
1st interaction	70%	10%
pion interactions	30%	90%

Nuclear Interactions



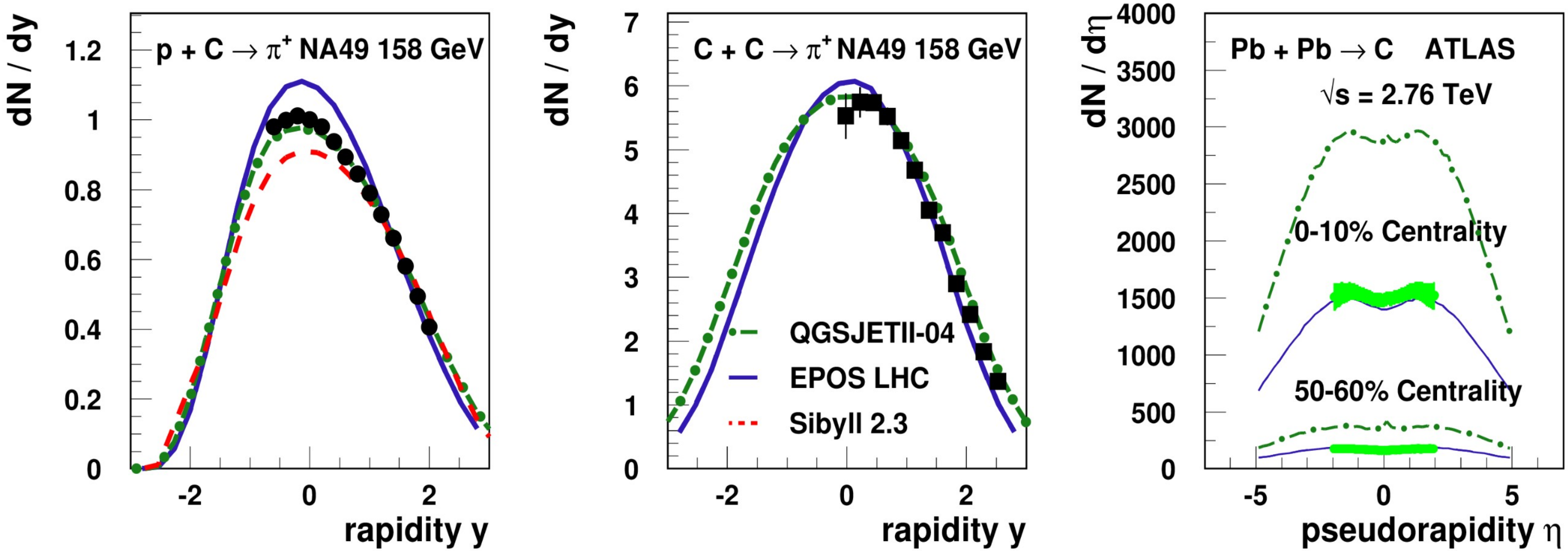


- **Sibyll**
  - ➜ Glauber for pA
    - with inelastic screening for diffraction in new Sibyll 2.3 (only nuclear effect)
  - ➜ superposition model for AA (A x pA)
- **QGSJETII**
  - ➜ Pomeron configuration based on A projectiles and A targets
  - ➜ Nuclear effect due to multi-leg Pomerons
- **EPOS**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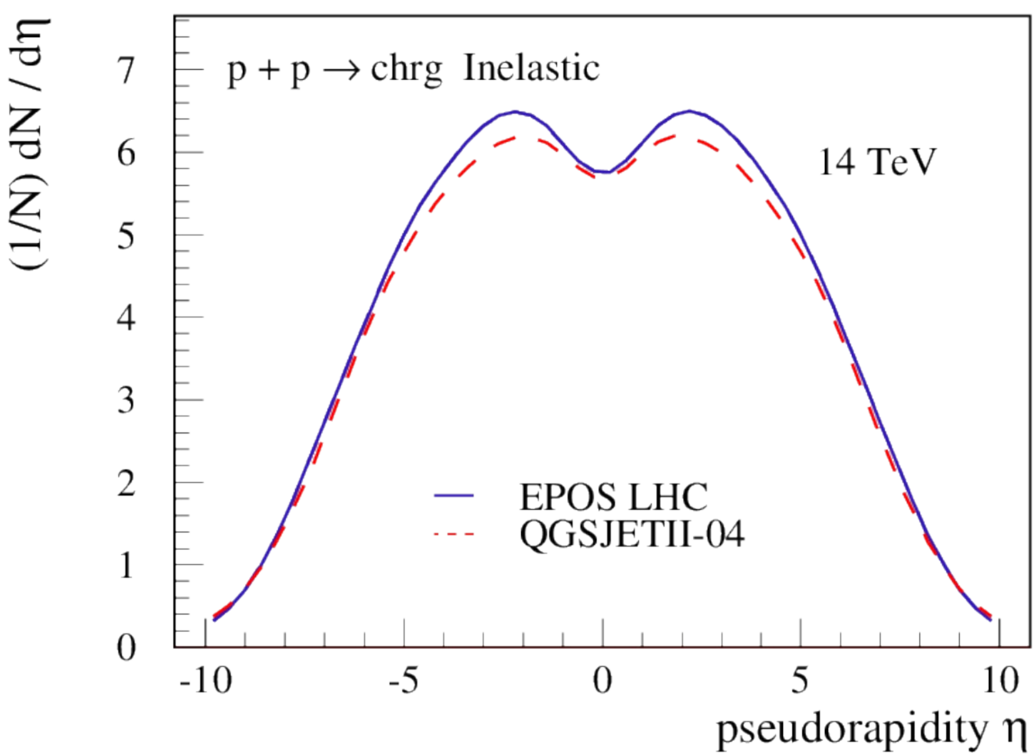
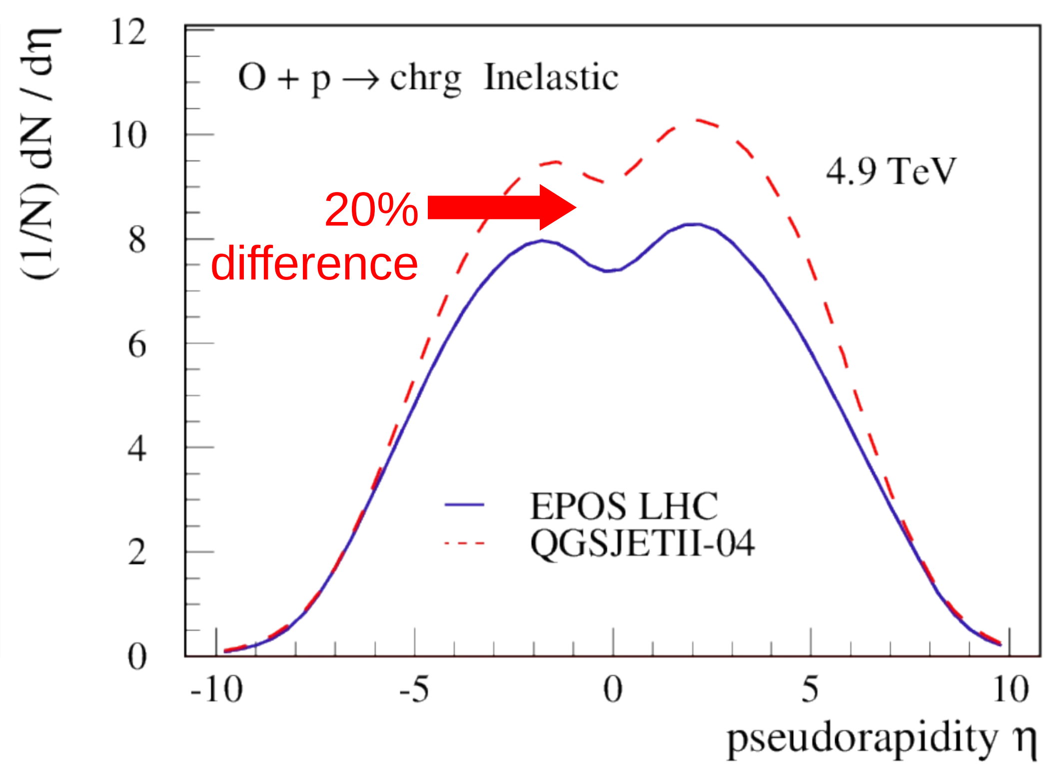
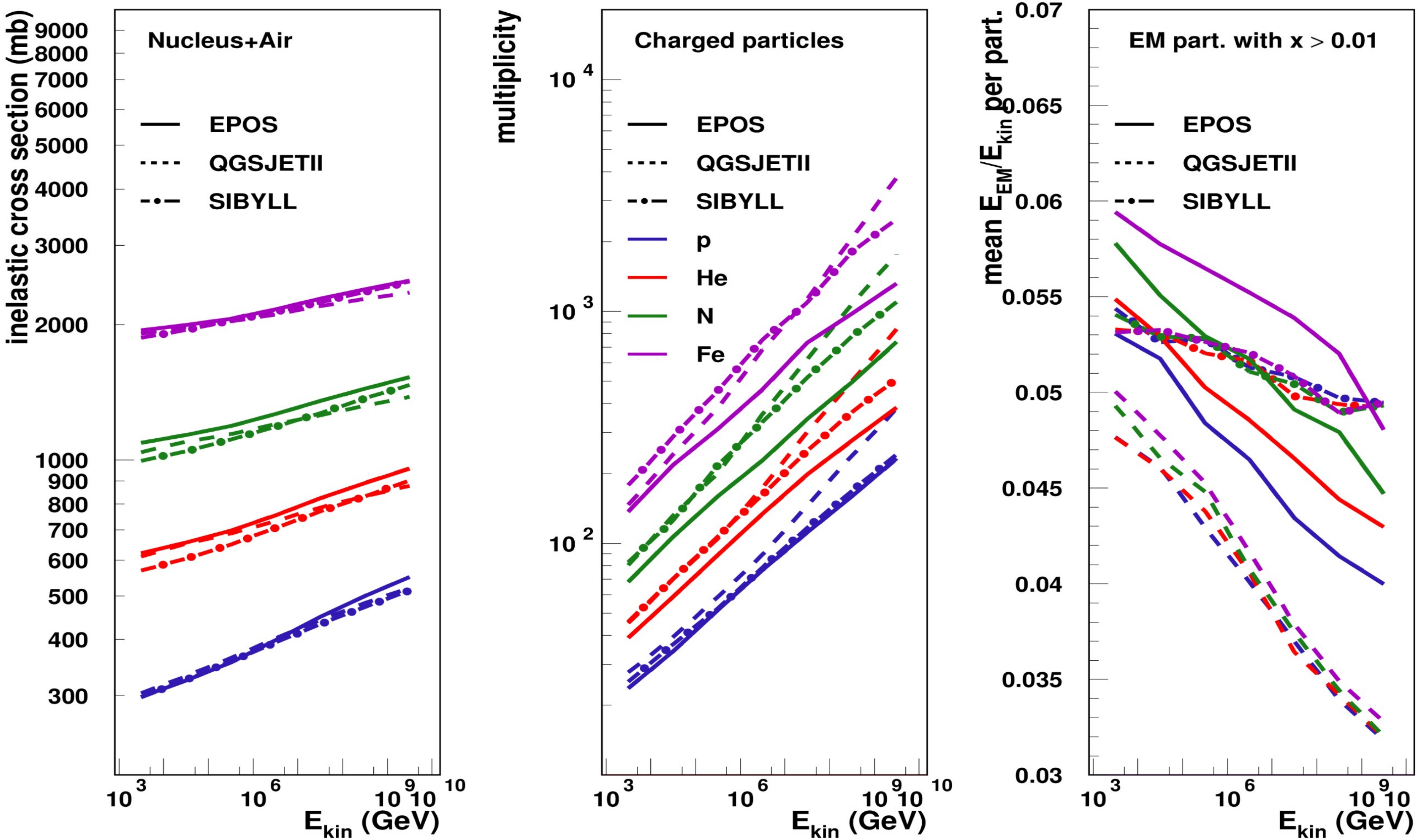
➡ pO@LHC to check models at high energy





Model Comparison



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