Hadronic Interaction Models

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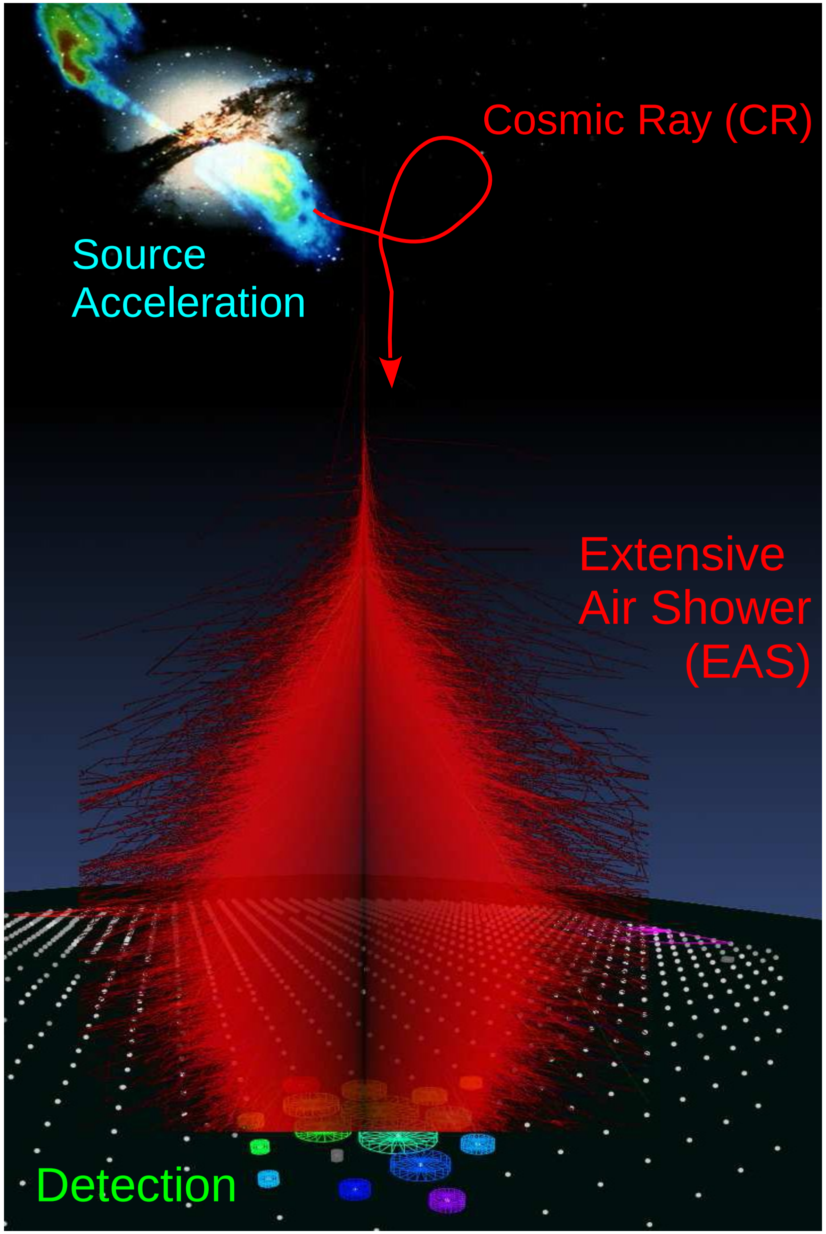
Outline

- **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

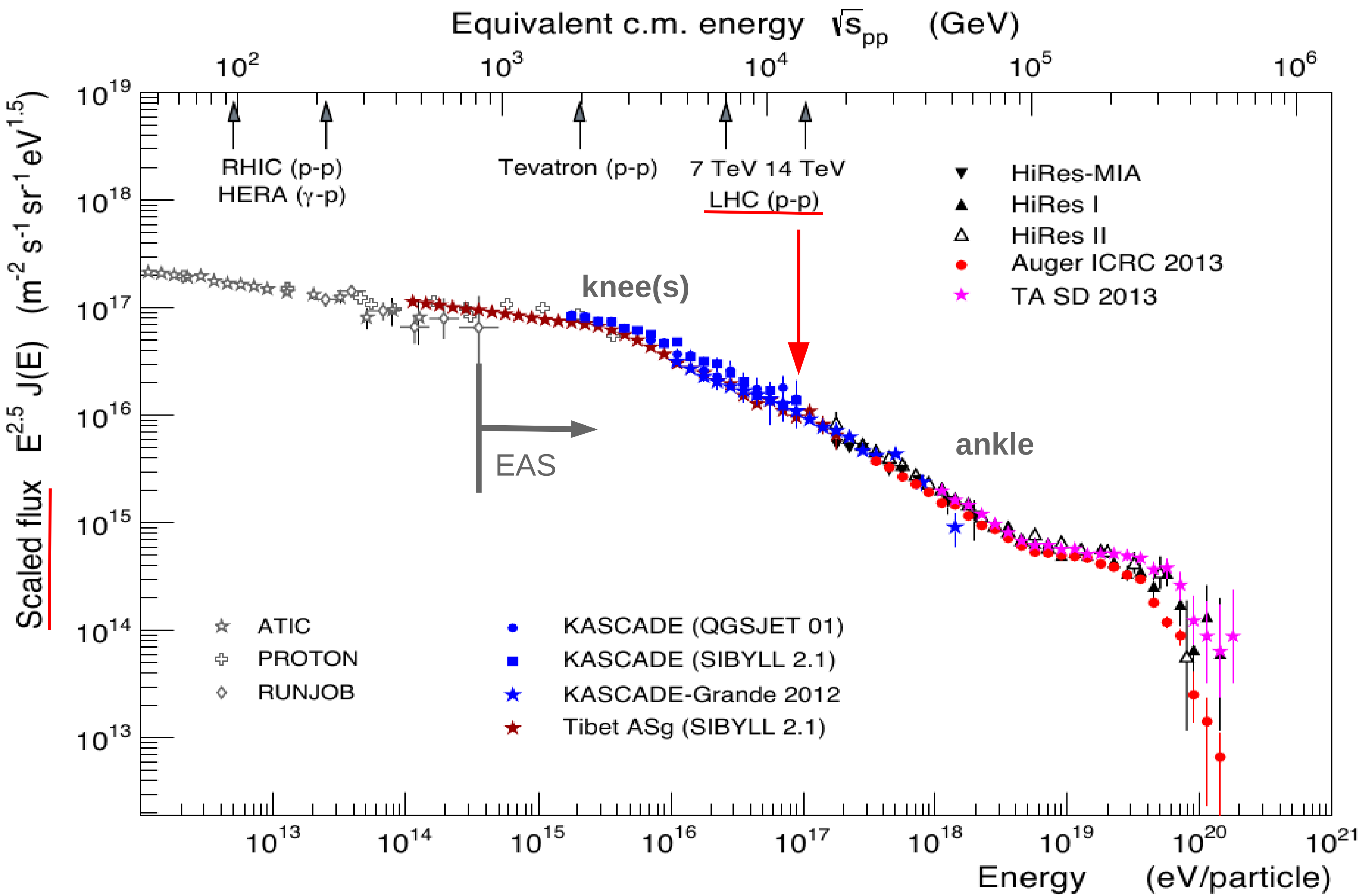


From R. Ulrich (KIT)

- **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

Cosmic Ray Spectrum



R. Engel (KIT)

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 (2017-)

Motivation :

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

Motivation :

- **Hard Pomeron-Pomeron connexion**

Motivation :

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

Motivation :

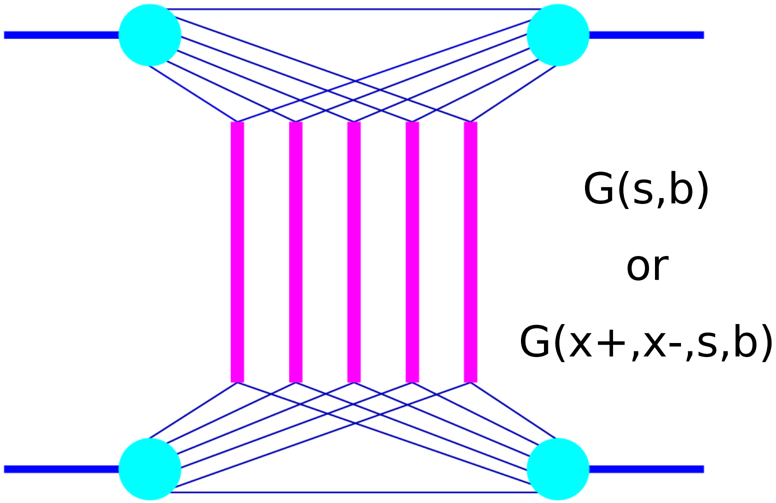
- **binary scaling in hard probes**
- **better diffraction**

Cosmic Ray Hadronic Interaction Models

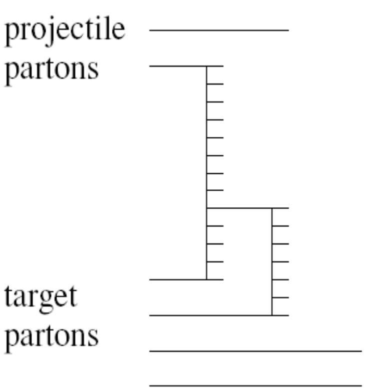
- **Theoretical basis :**
  - pQCD (large p_t)
  - Gribov-Regge (cross section with multiple scattering)
  - energy conservation
- **Phenomenology (models) :**
  - hadronization
    - string fragmentation
    - EPOS : high density effects (statistical hadronization and flow)
  - diffraction (Good-Walker,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

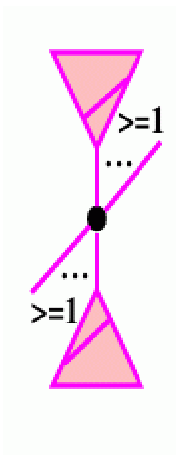
Cross Section and Multiplicity in Models



EPOS



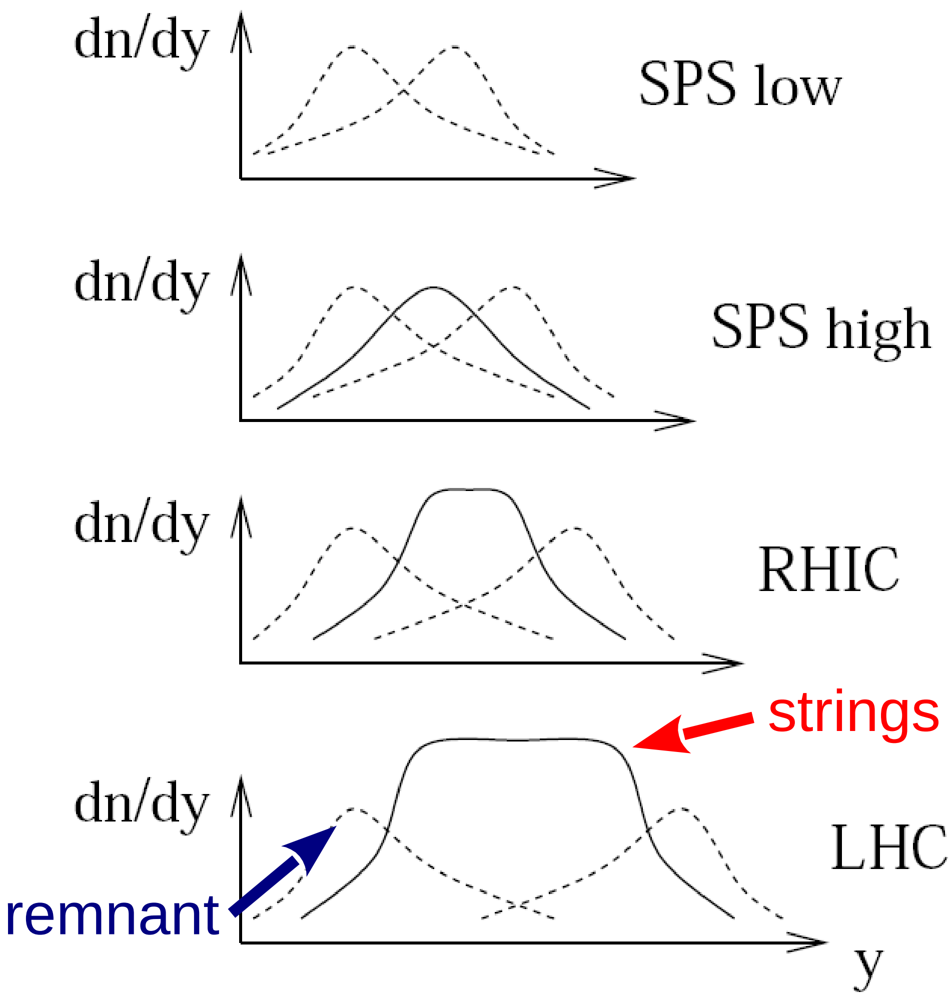
QGSJET II



- **Gribov-Regge and optical theorem**
  - Basis of all models (multiple scattering) but
    - Classical approach for QGSJET, 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

Remnants

Forward particles mainly from projectile remnant



The (in)elasticity is closely related to diffraction and forward spectra

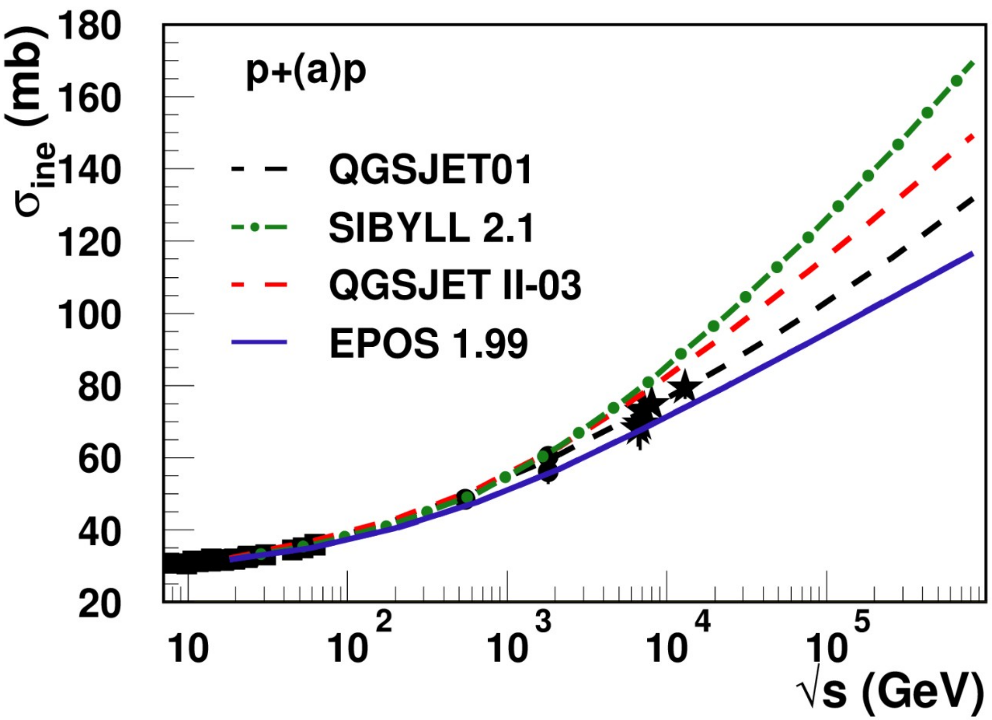
- SIBYLL
  - No remnant except for diffraction
  - Leading particle from string ends
- QGSJET
  - Low mass remnants
  - Leading particle similar to proj.
- EPOS
  - Low and high mass remnants
  - Any type of leading particle
    - from resonance
    - from string
    - from statistical decay

Cross Sections

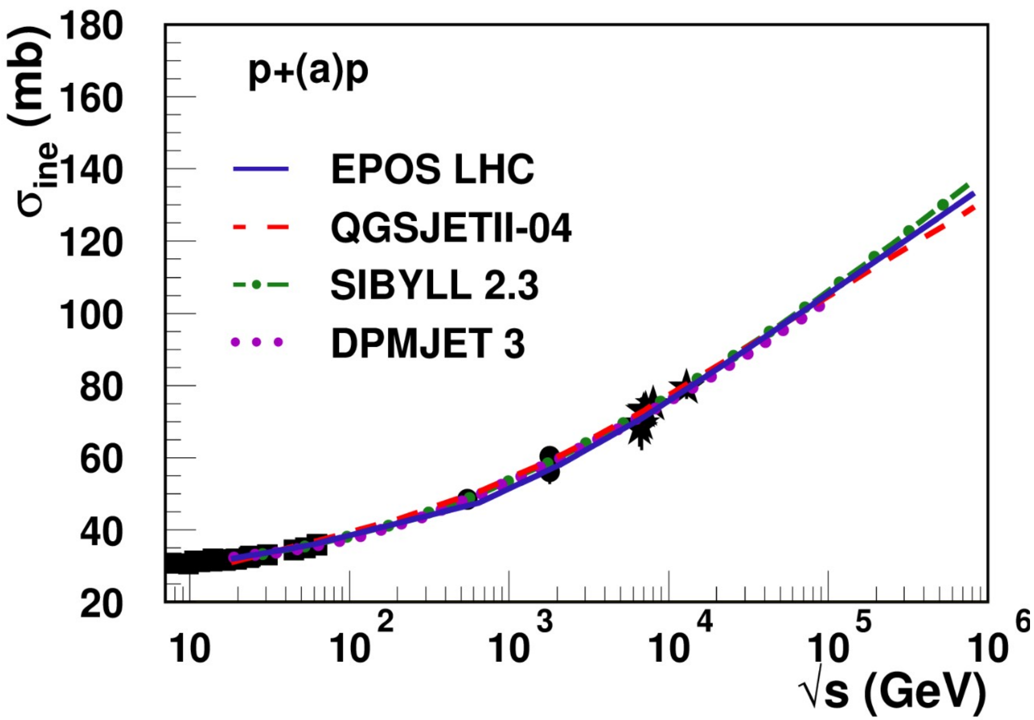
- Same cross section prediction at pp level and low energy (data for tuning)

- extrapolation to high energy looks settled
  - different amplitude and scheme
    - same extrapolations

Pre - LHC



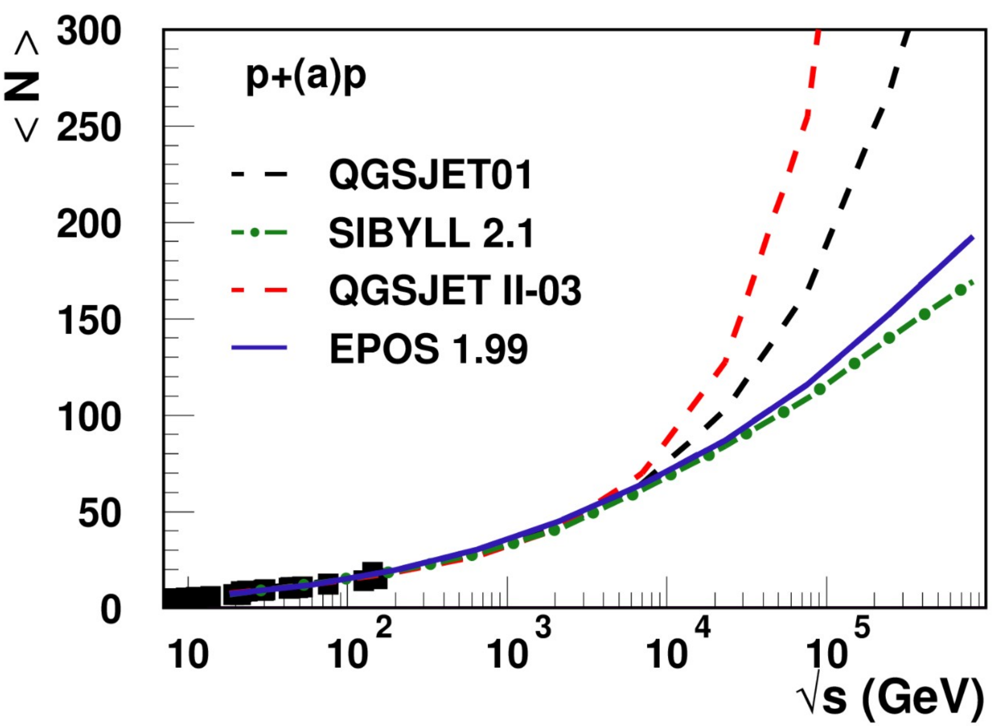
Post - LHC



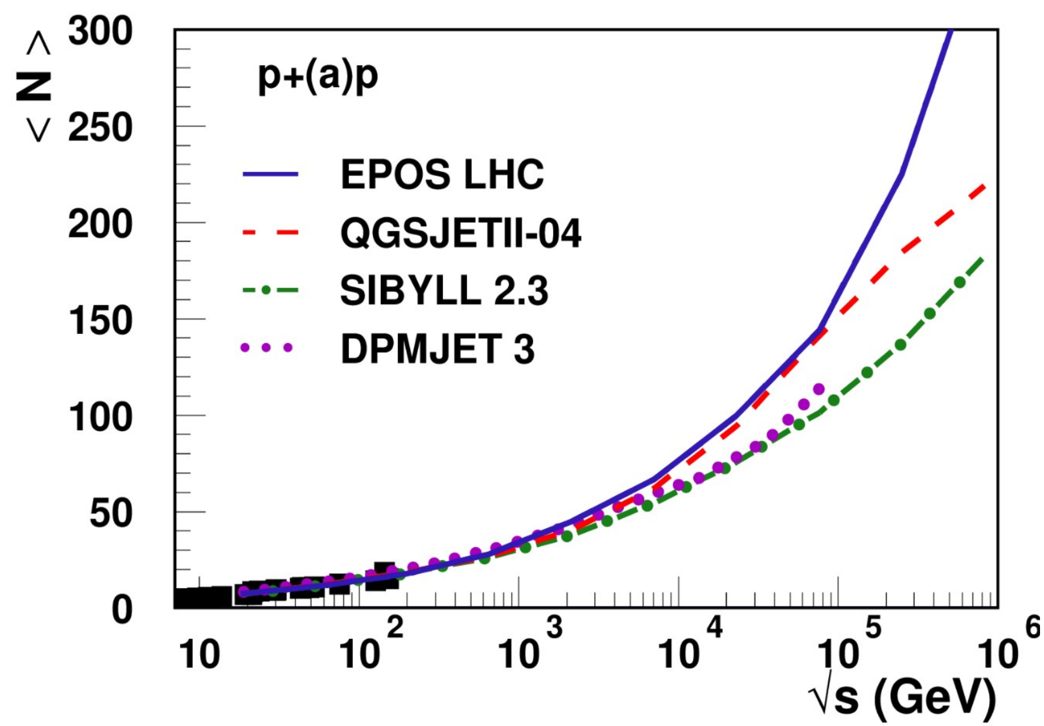
Multiplicity

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

Pre - LHC



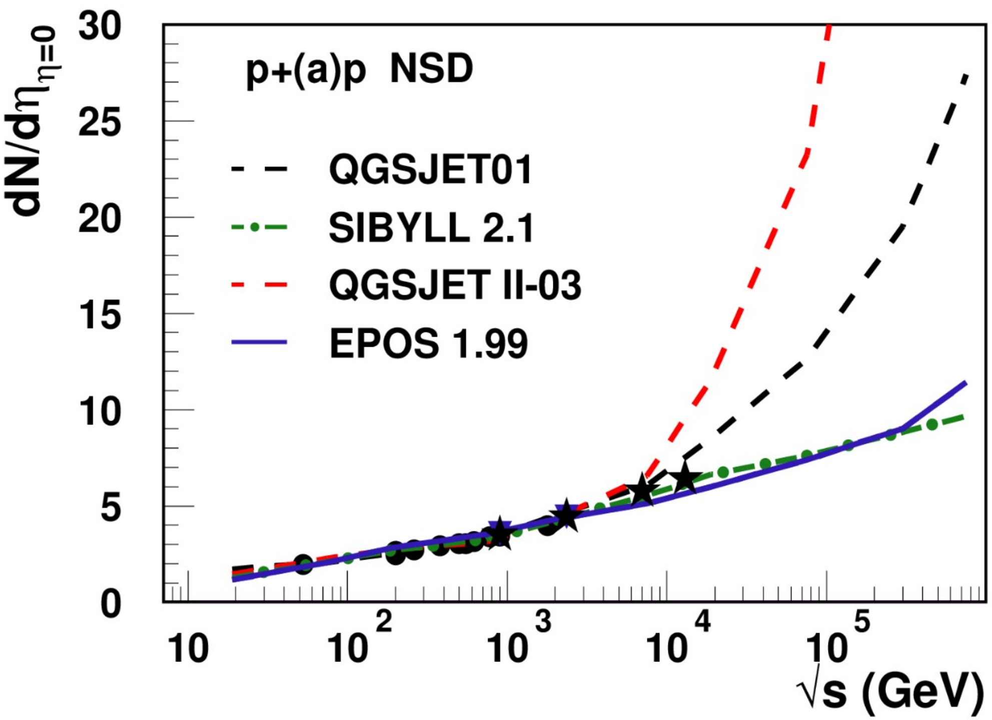
Post - LHC



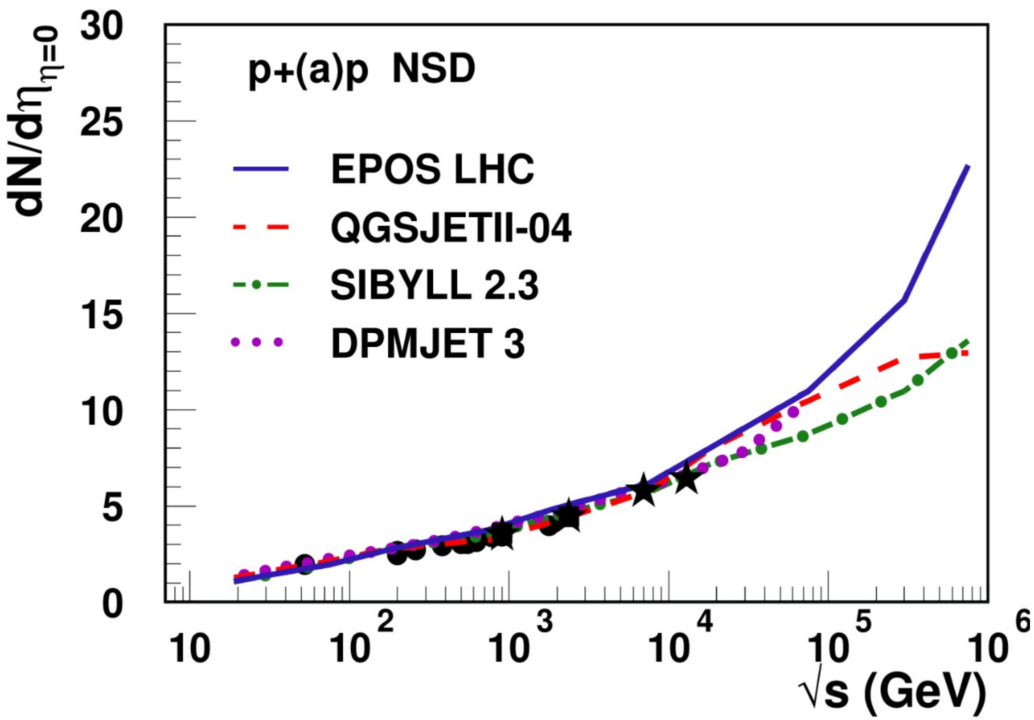
Multiplicity at mid-rapidity

- 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



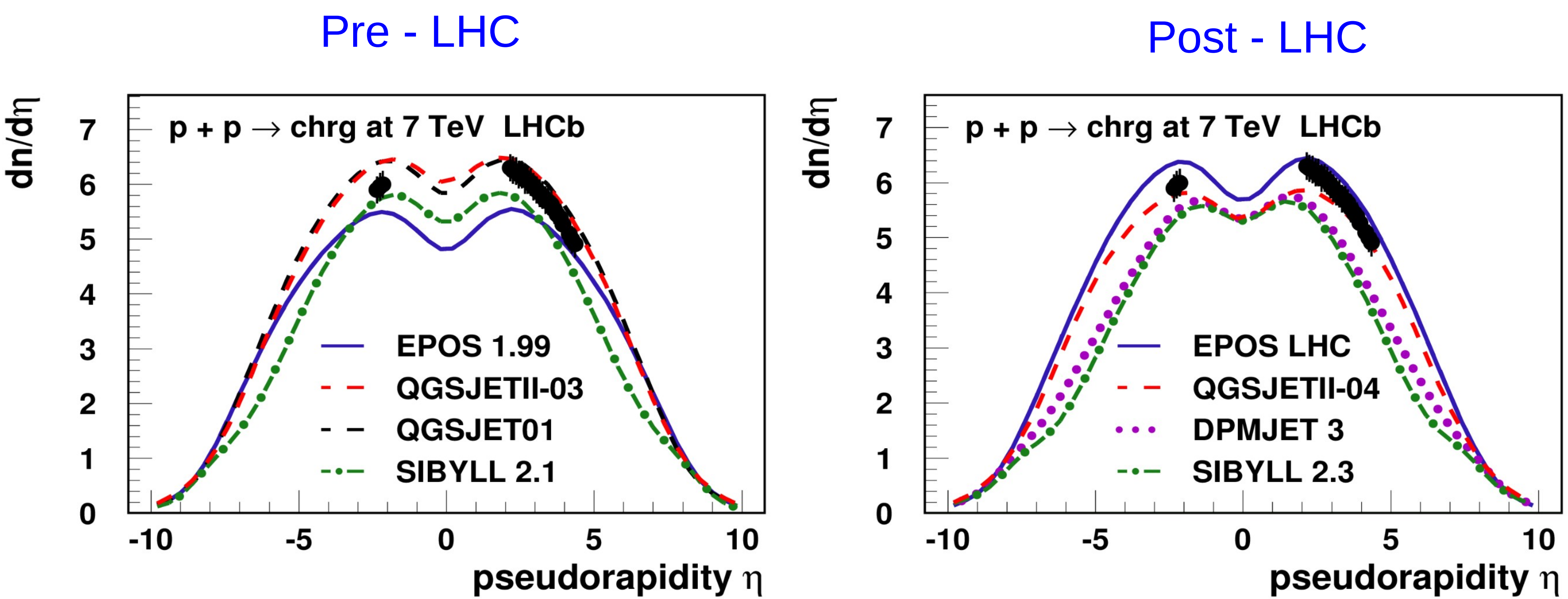
Post - LHC



Pseudorapidity

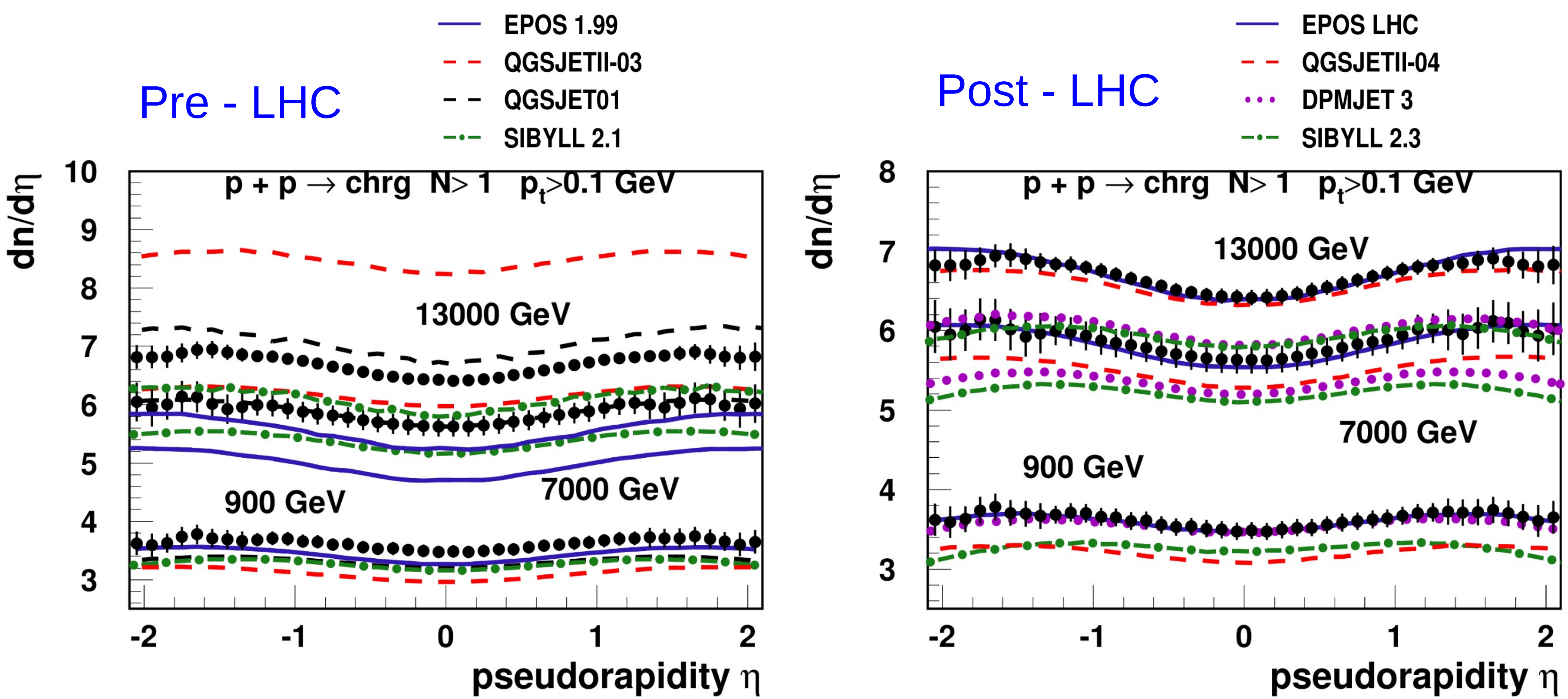
- Difference between mid-rapidity and full multiplicity coming from the width of the pseudorapidity distributions

- From LHC data
  - DPMJET 3 and SIBYLL 2.3 too narrow
  - QGSJETII-04 ~ OK
  - EPOS LHC a bit too large

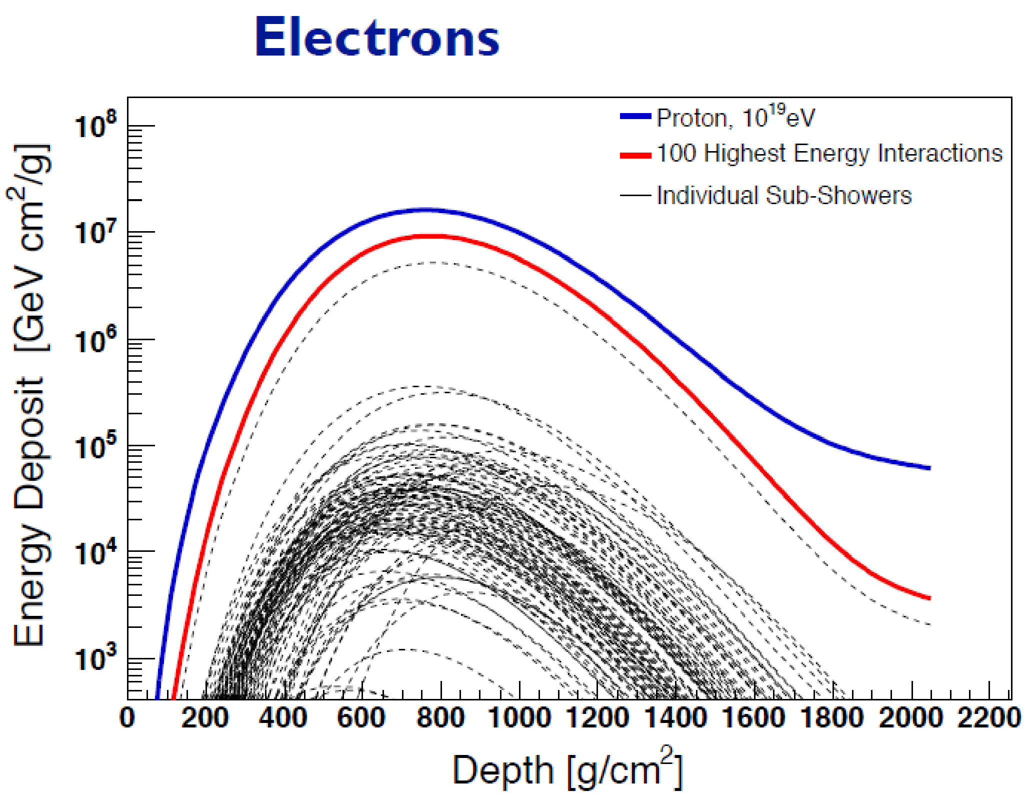


Test of Models vs Accelerator Data

- 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)

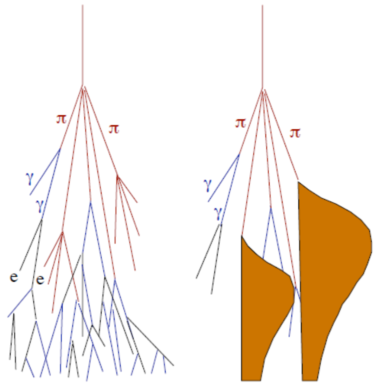


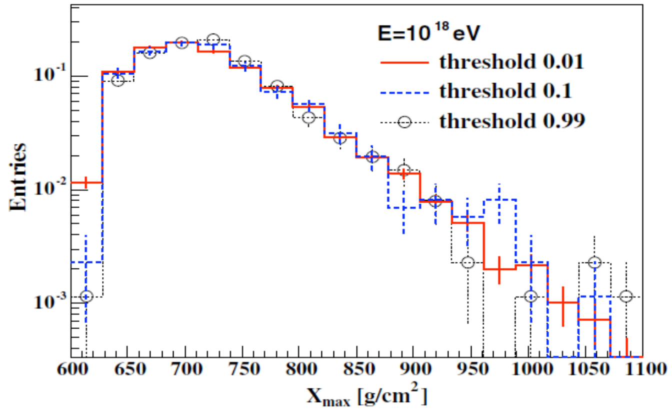
Energy of hadronic interactions for X_{max}



Shower particles produced in 100 interactions of highest energy

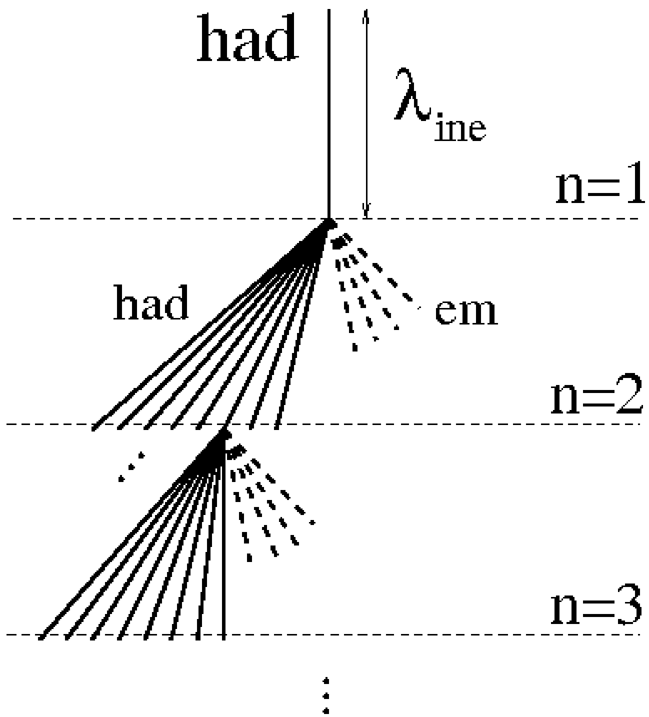
X_{max} dominated by first (high energy) interaction(s) : proton (nucleus)-Air





Fluctuations mainly coming from the first hadronic interaction.

Simplified Shower Development



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

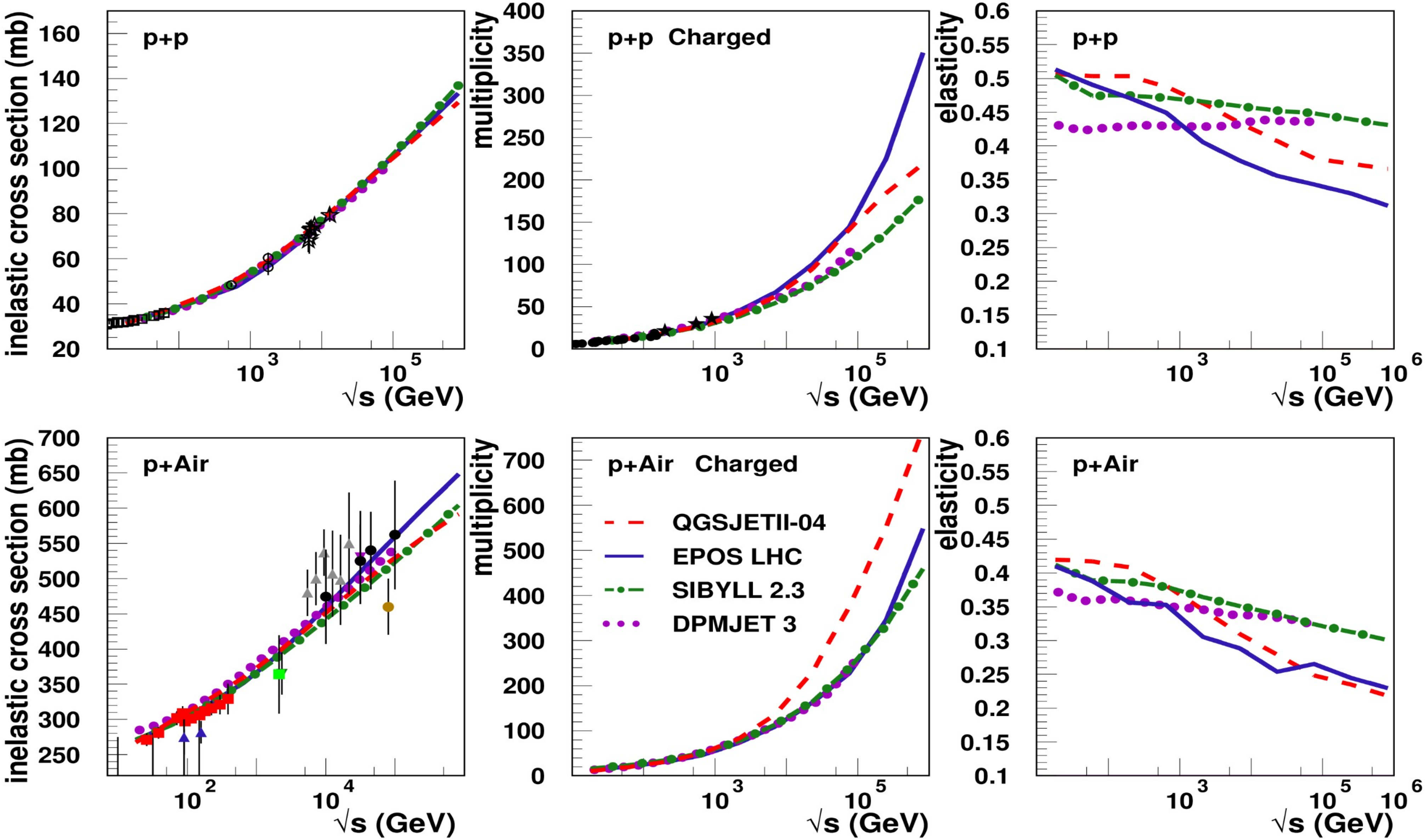
J. Matthews, Astropart.Phys. 22 (2005) 387-397

Using generalized Heitler model and superposition model :

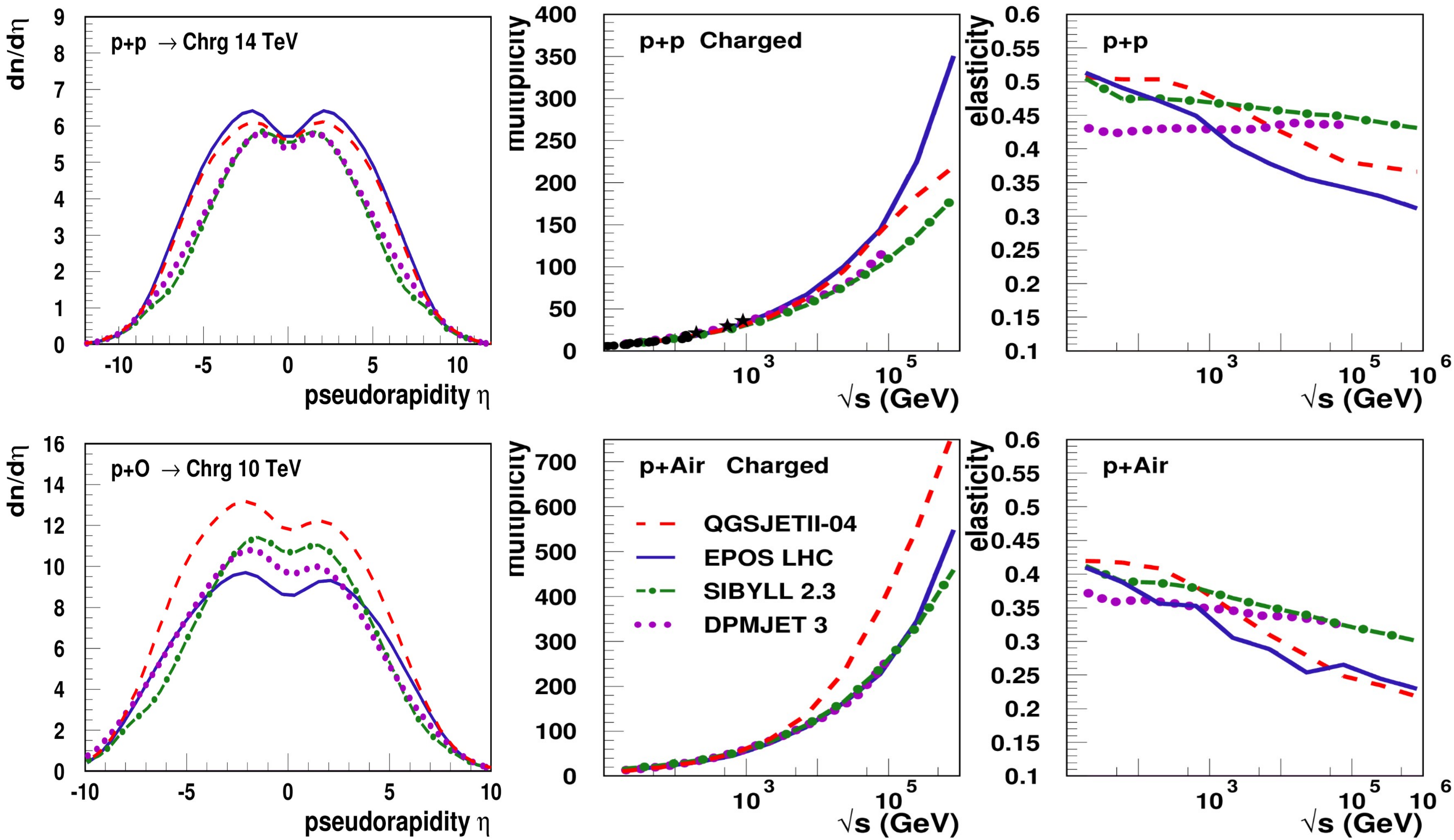
$$X_{max} \sim \lambda_e \ln\left((1-k).E_0/(2.N_{tot}.A)\right) + \lambda_{ine}$$

- 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)

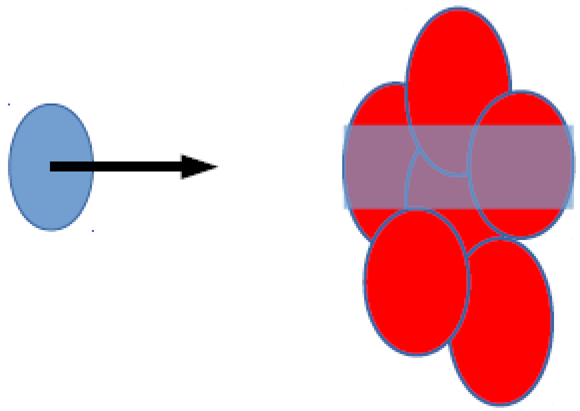
Ultra-High Energy Hadronic Model Predictions p-Air

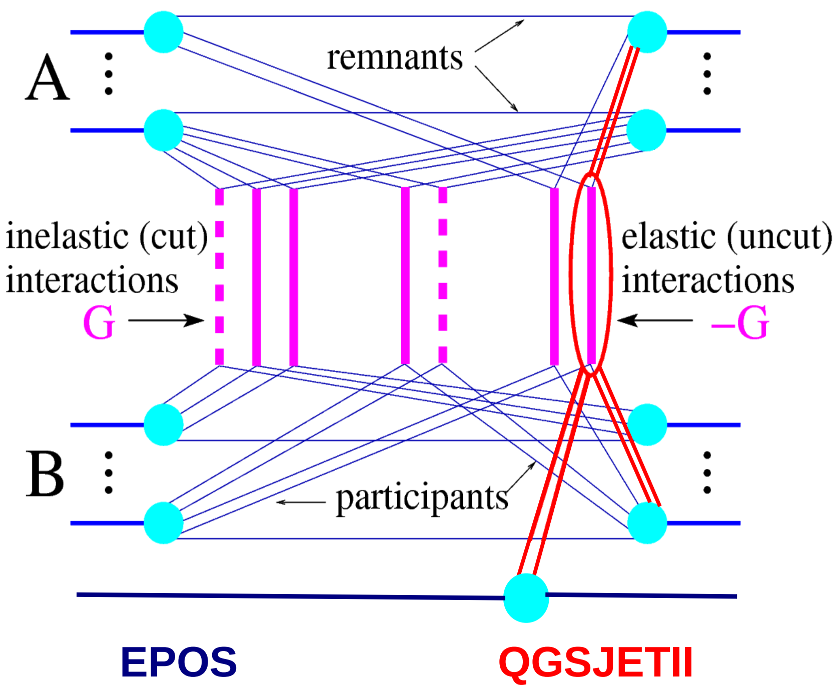


Ultra-High Energy Hadronic Model Predictions p-Air



Nuclear Interactions



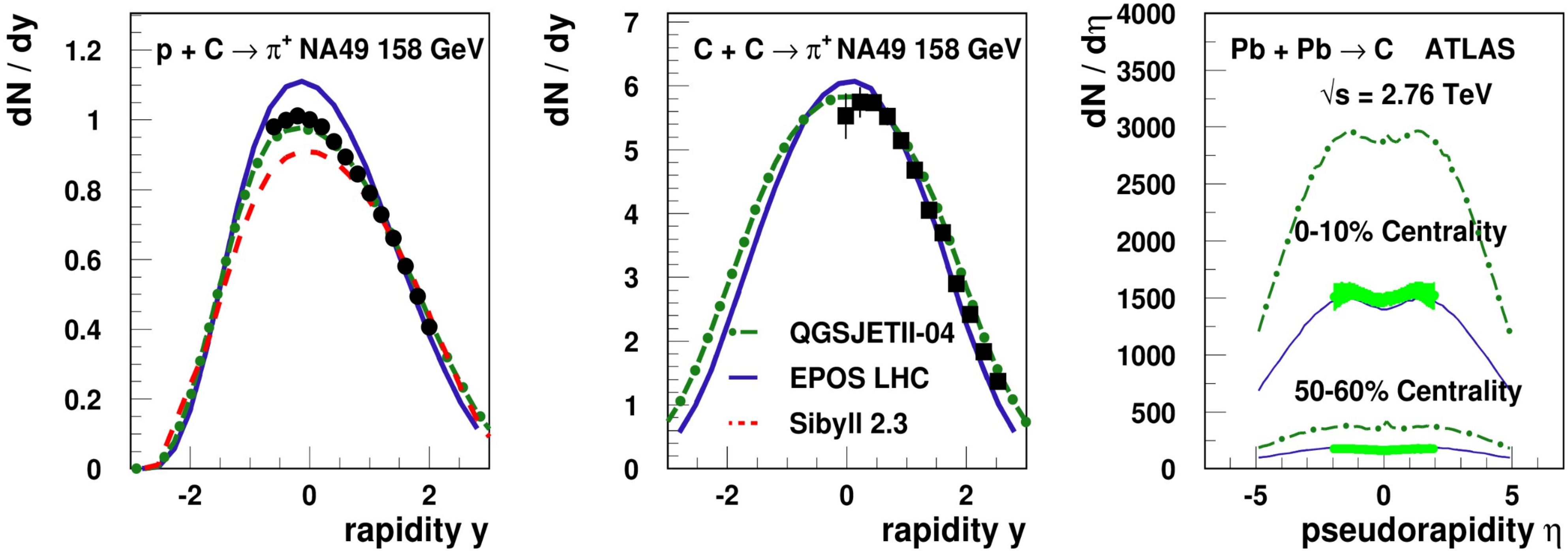


- **Sibyll**
  - Glauber for pA
    - with inelastic screening for diffraction in new Sibyll 2.3 (only nuclear effect)
  - superposition model for AA (A x pA)
- **QGSJETII**
  - Pomeron configuration based on A projectiles and A targets
  - Nuclear effect due to multi-leg Pomerons
- **EPOS**
  - Pomeron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

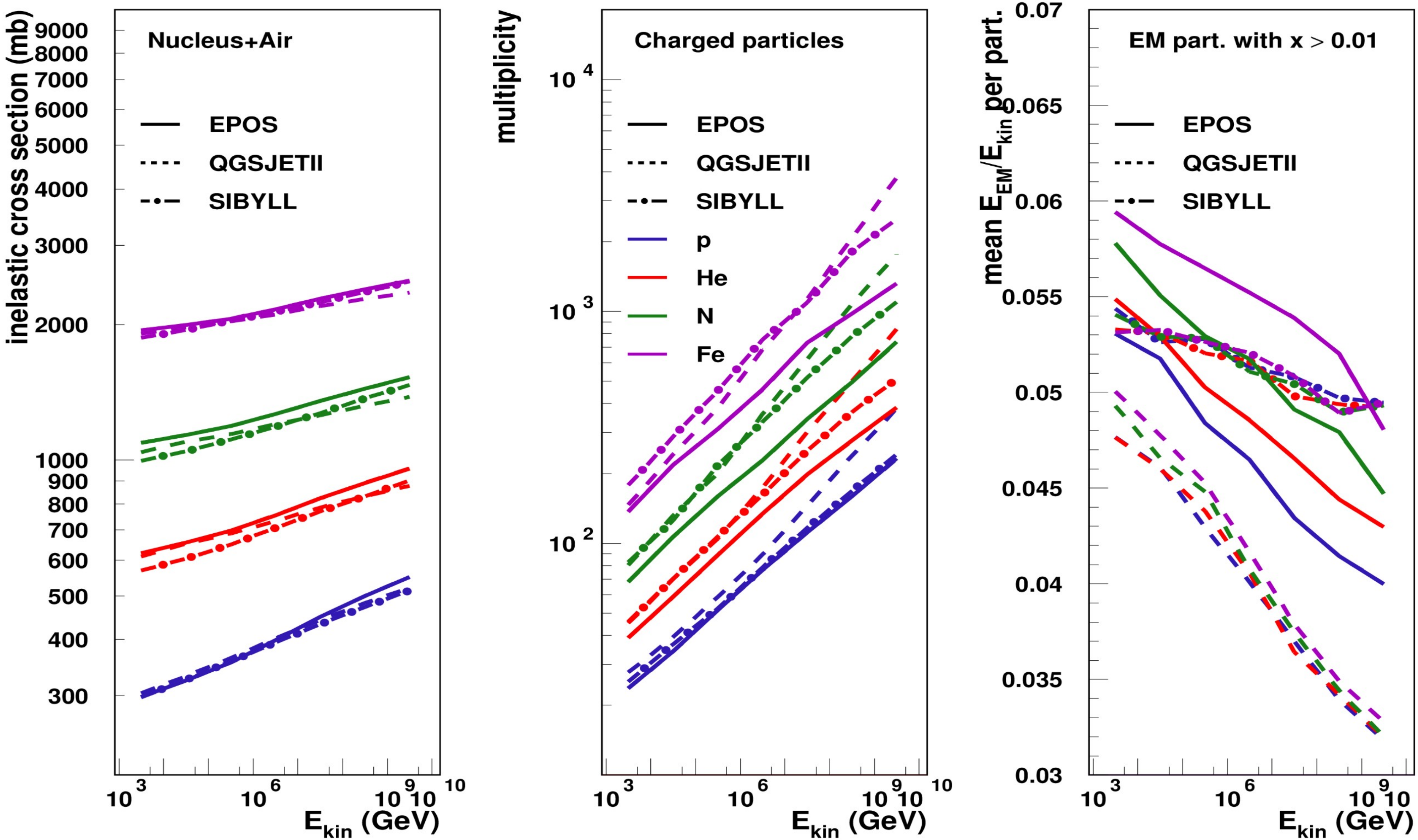
Light Ion Data

Very few data to compare with all CR models :

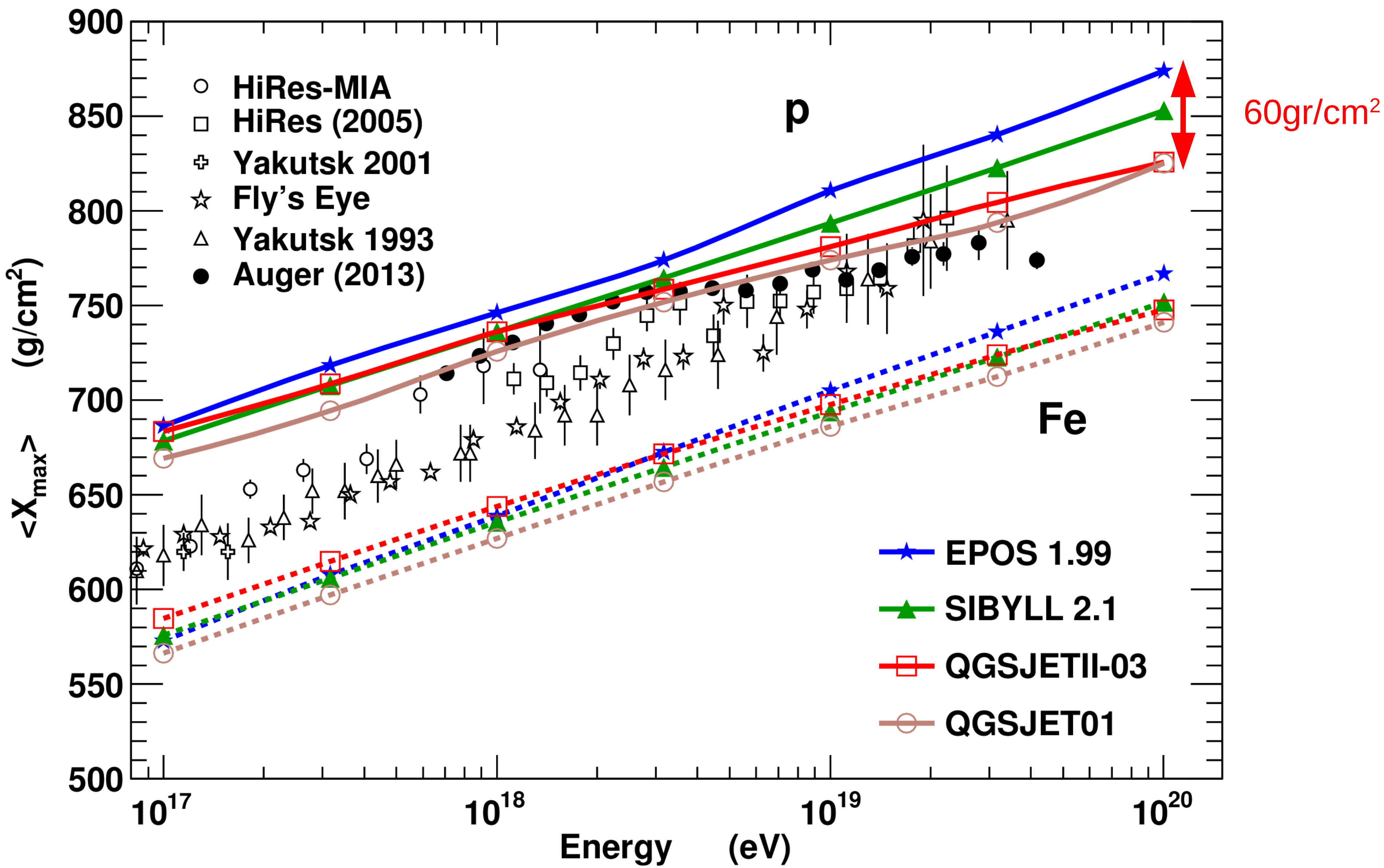
- strong limitations in Sibyll (projectile up to Fe only and target up to O !)
- no final state interactions exclude heavy nuclei for QGSJETII
- no light ion data at high energy



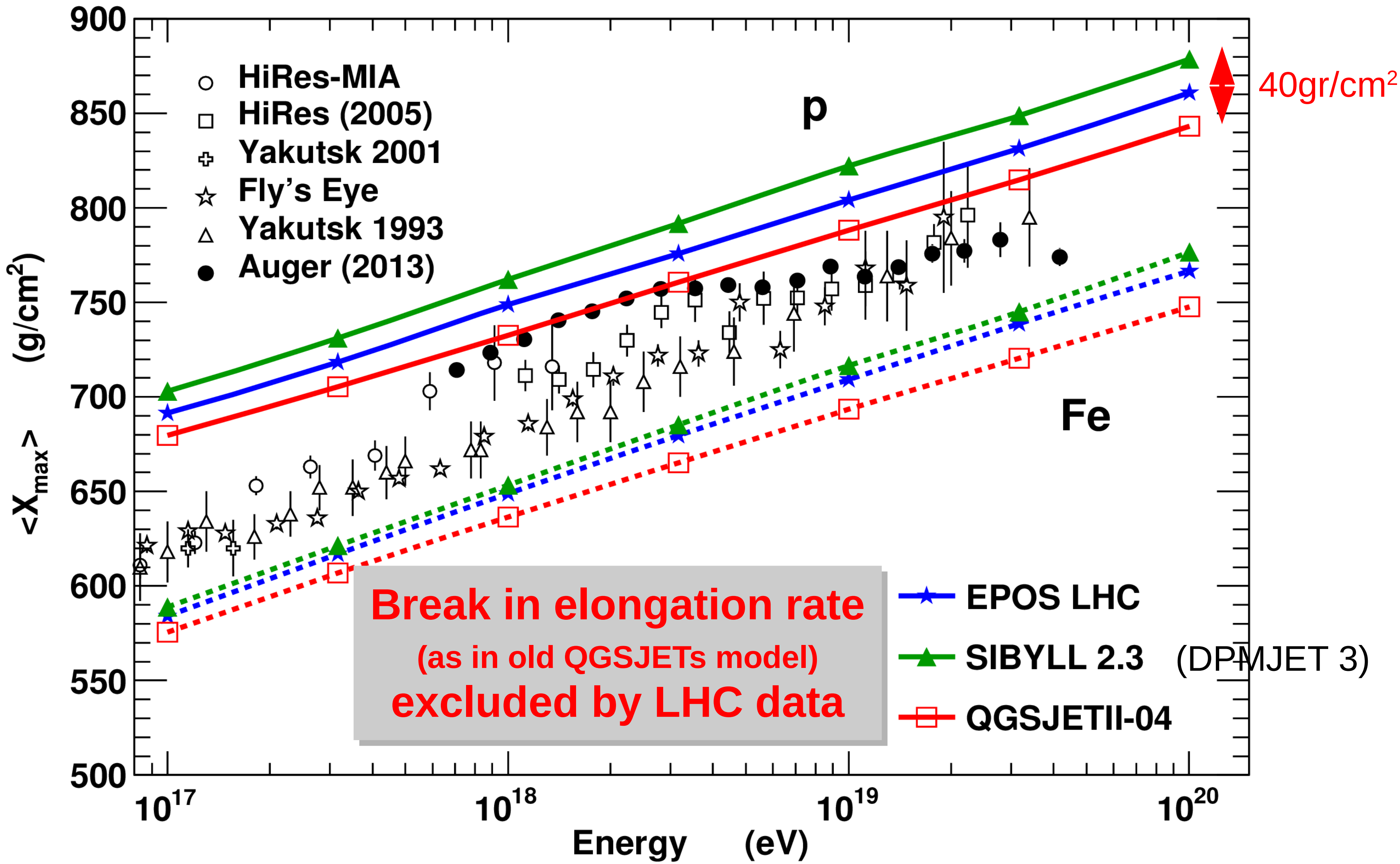
Ultra-High Energy Hadronic Model Predictions A-Air



EAS with Old CR Models : X_{max}

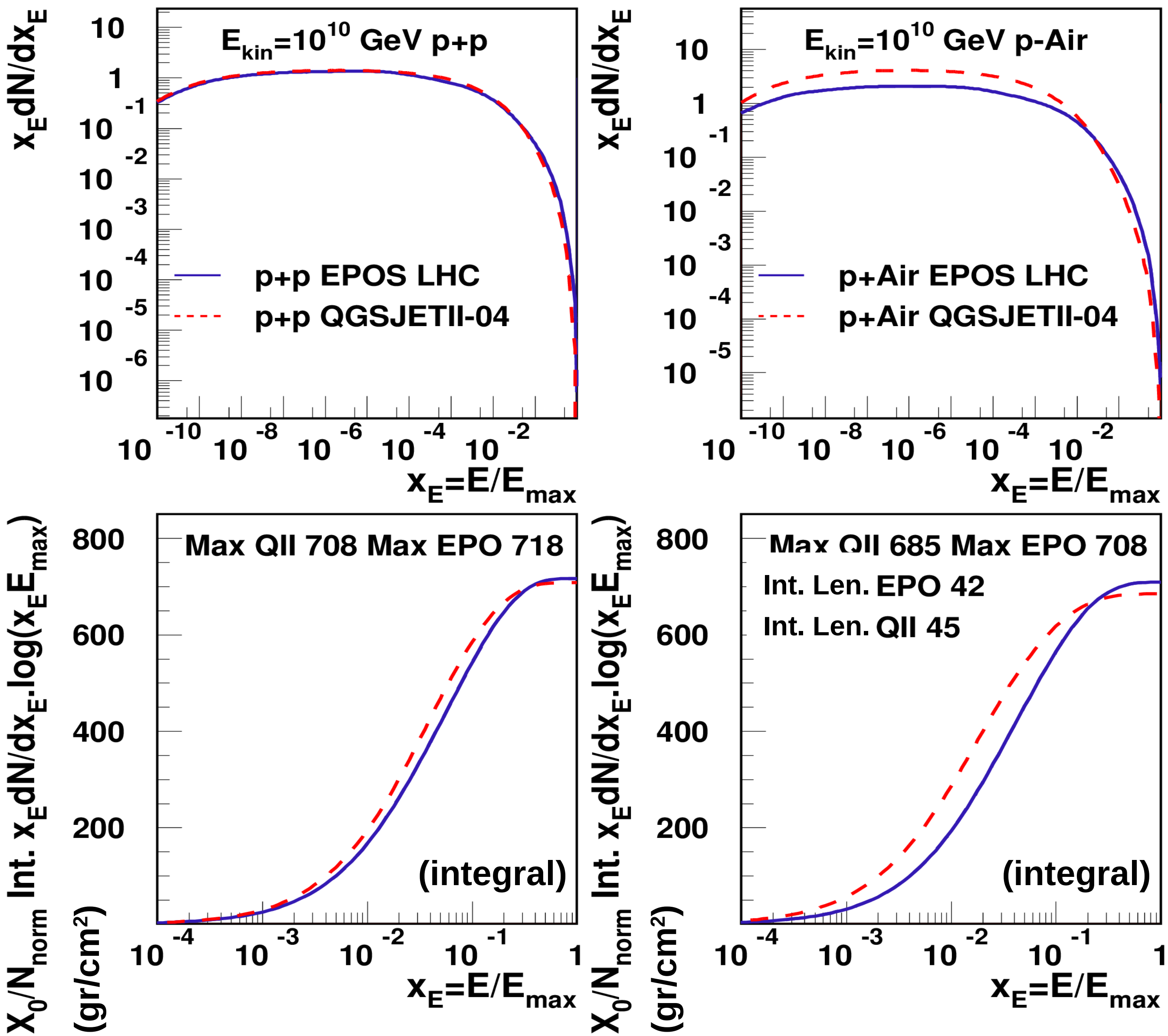


EAS with Re-tuned CR Models : X_{max}



Photon Energy Spectra

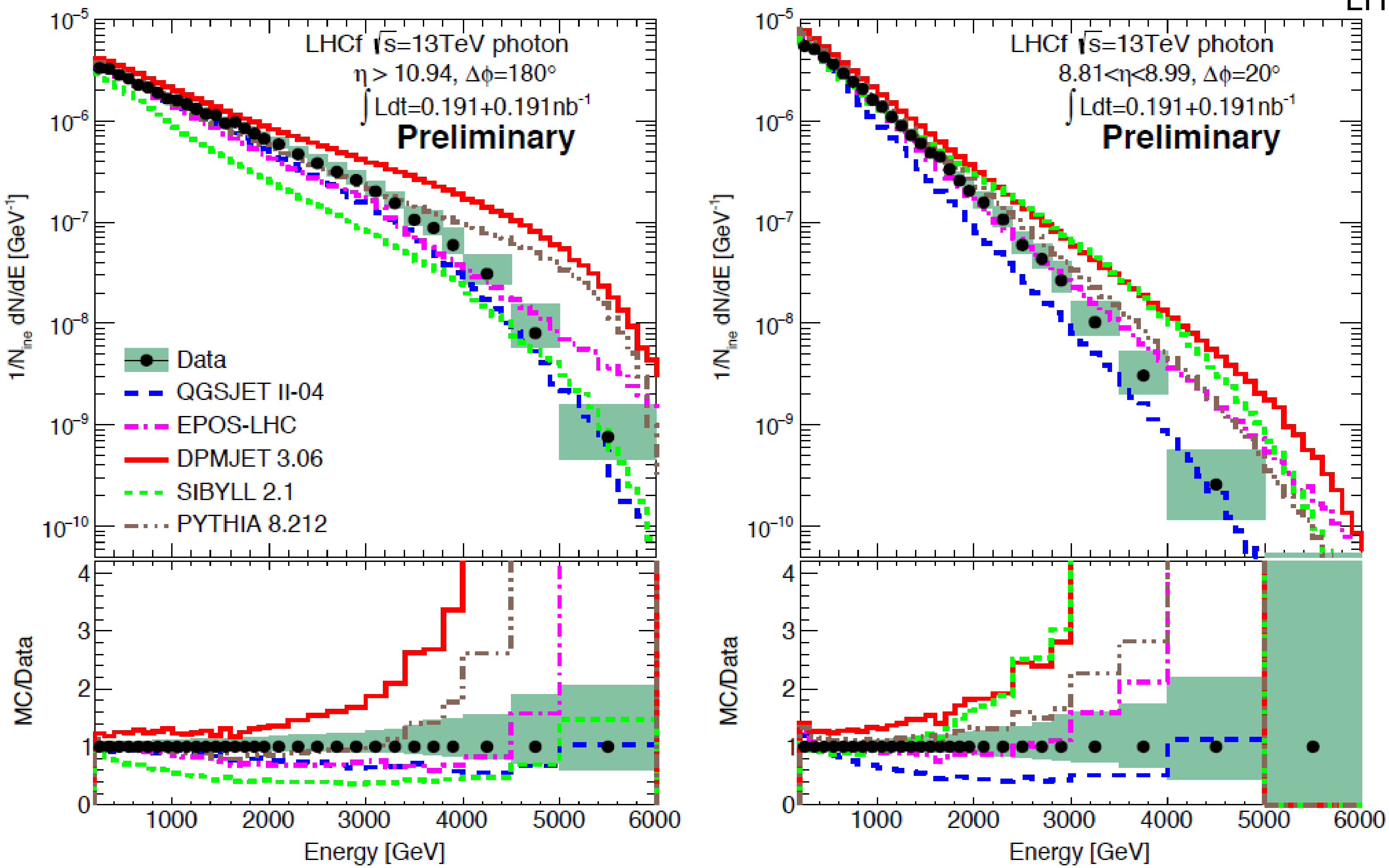
- **Uncertainties in X_{max}**
  - photon energy spectra
  - elasticity (for 2[d] interaction)
  - extrapolation to nuclear interactions
- **Use directly energy spectra from first interaction**
  - which energy is important ?



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

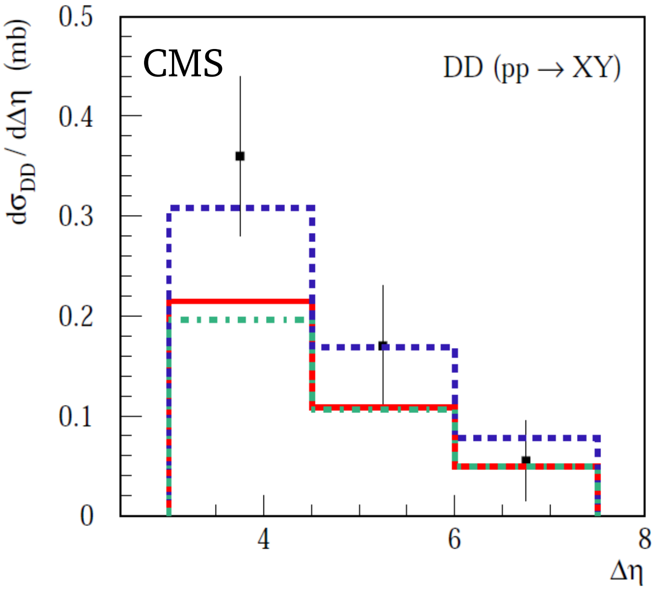


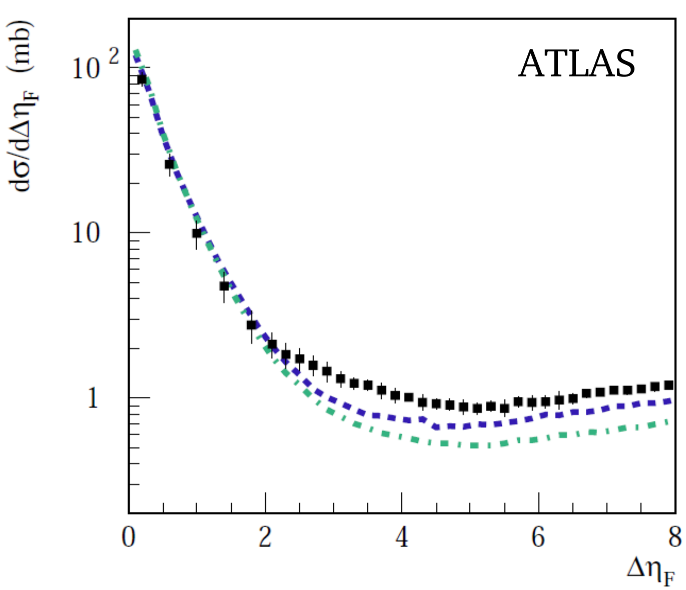
Diffraction measurements

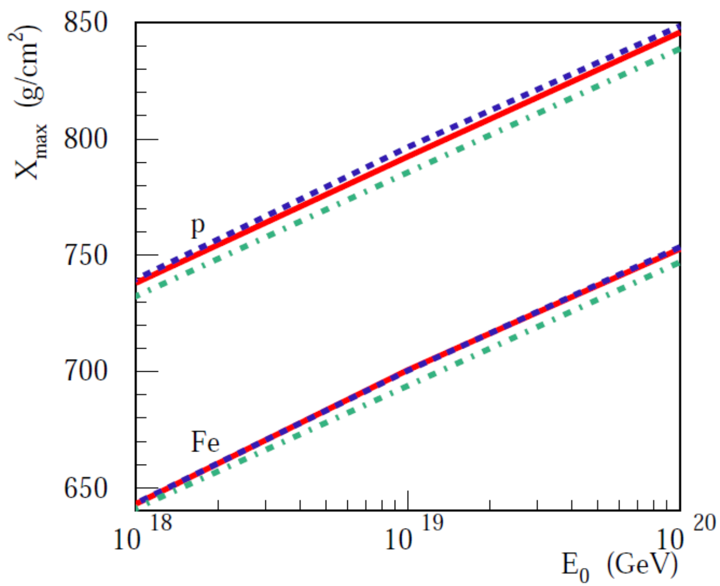
- **TOTEM and CMS diffraction measurement not fully consistent**
- **Tests by S. Ostapchenko using QGSJETII-04** **(PRD89 (2014) no.7, 074009)**
  - ➡ SD+ option compatible with CMS
  - ➡ SD- option compatible with TOTEM

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



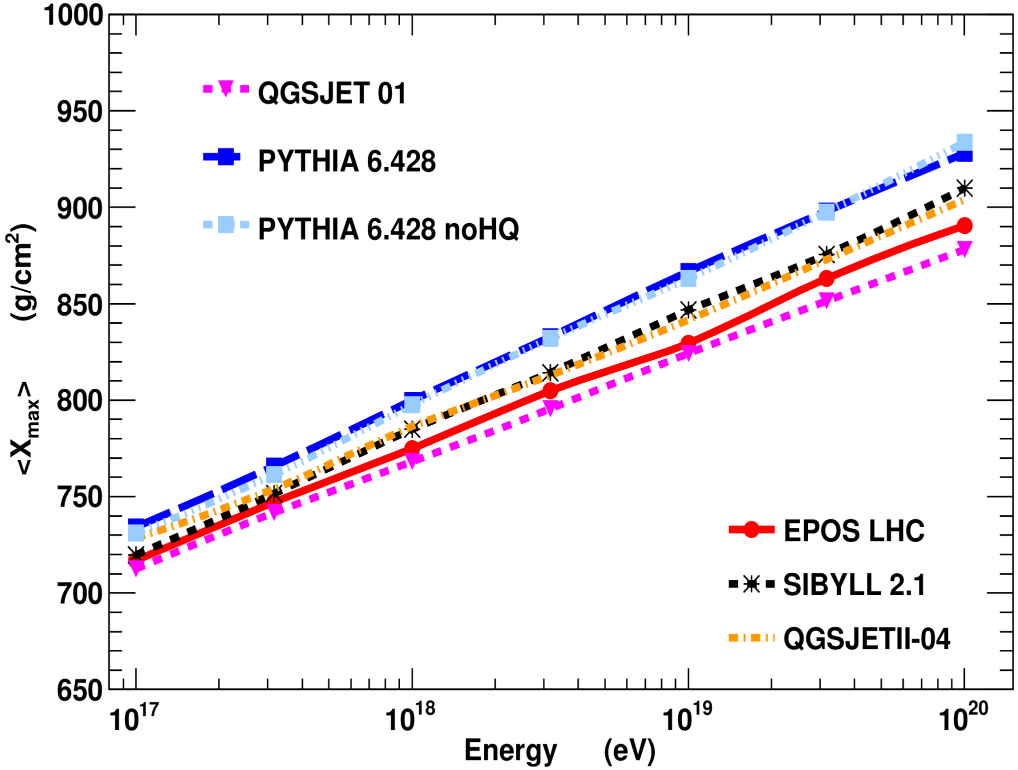


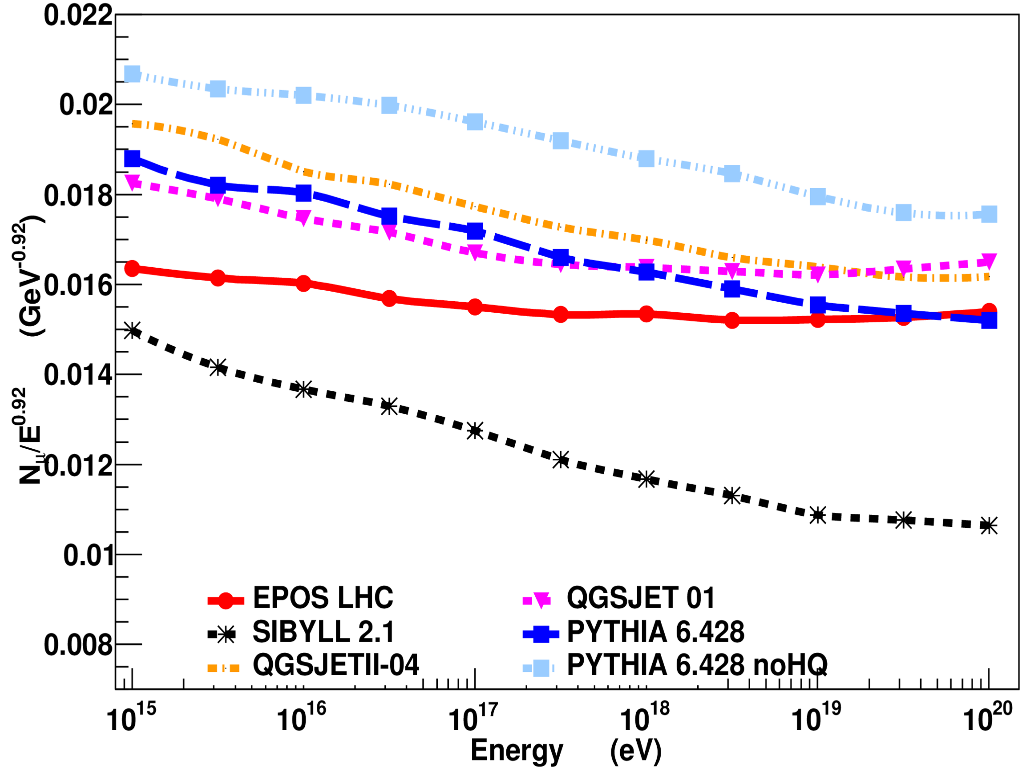


Tests using hydrogen atmosphere

- **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
  - Without nuclear effect relative order of the models is changed

    - Nuclear effects are the main remaining source of uncertainty

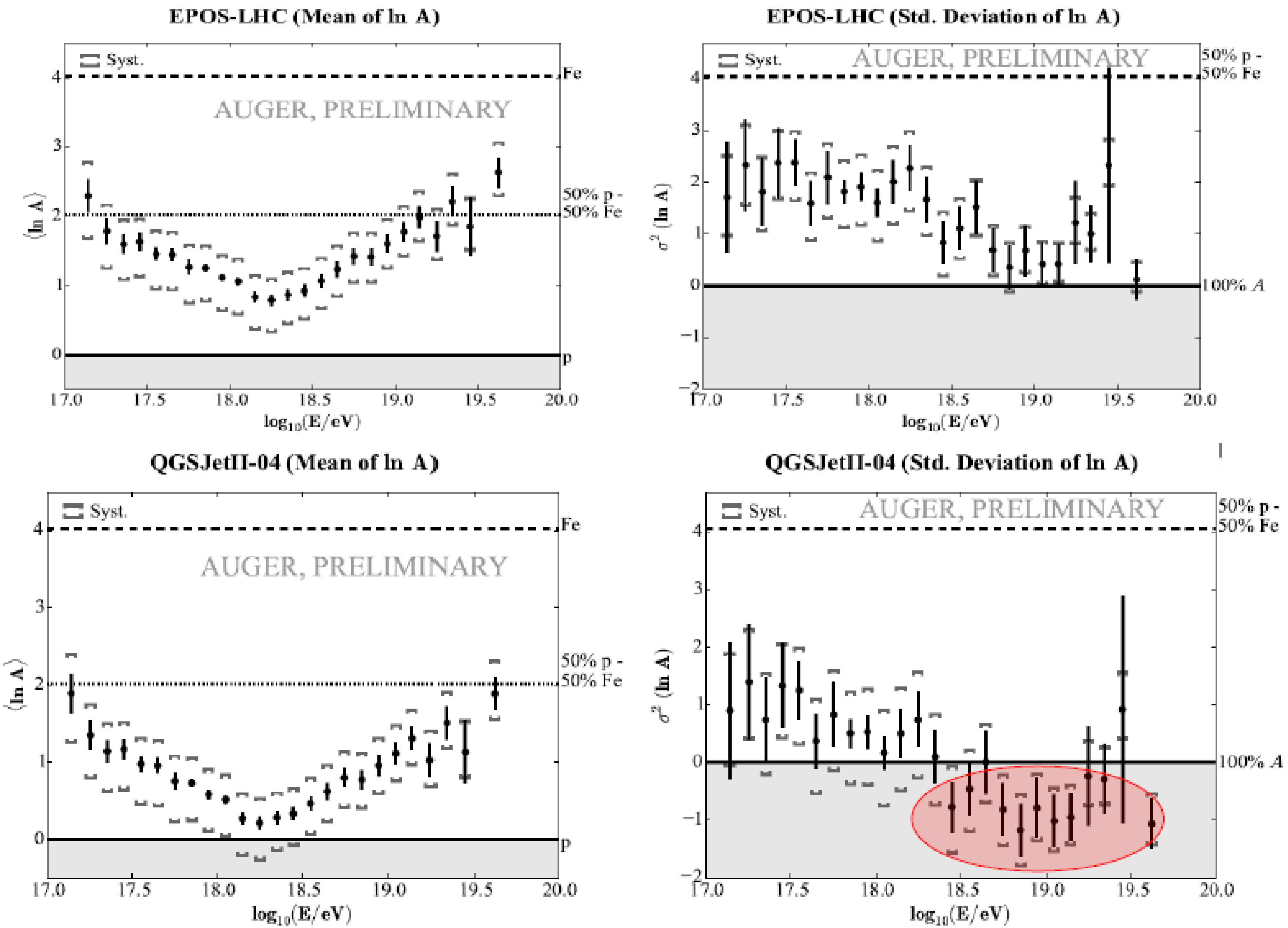




Model Consistency using Electromagnetic Component

Study by Pierre Auger Collaboration

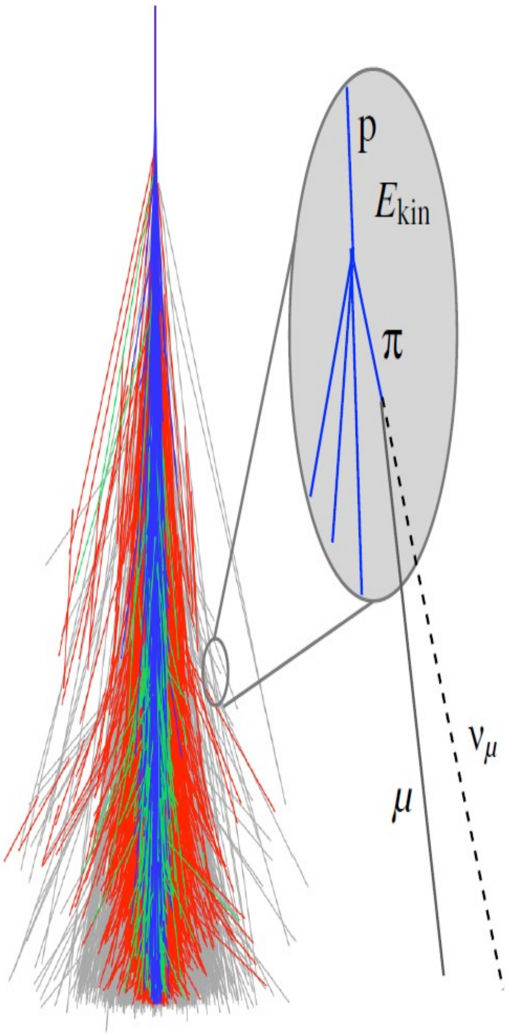
➡ std deviation of lnA allows to test model consistency.

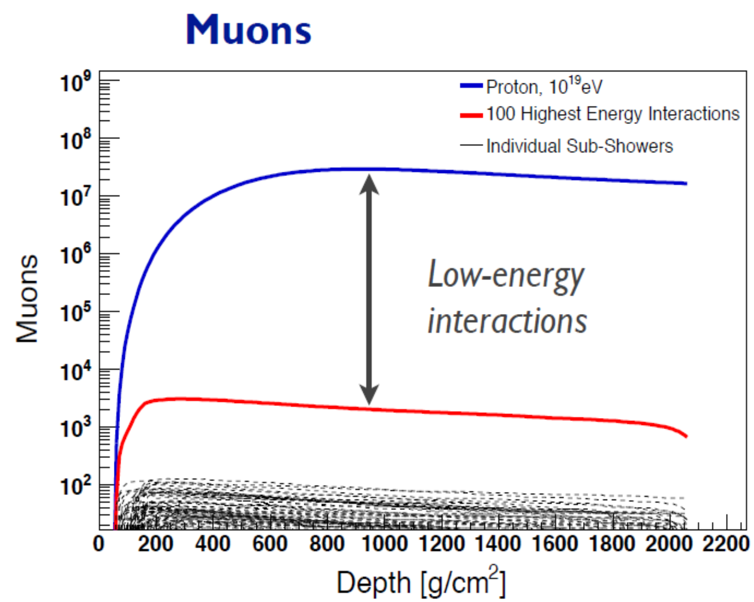


tensions if <X_{max}> too small

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

Muon production by low energy interactions

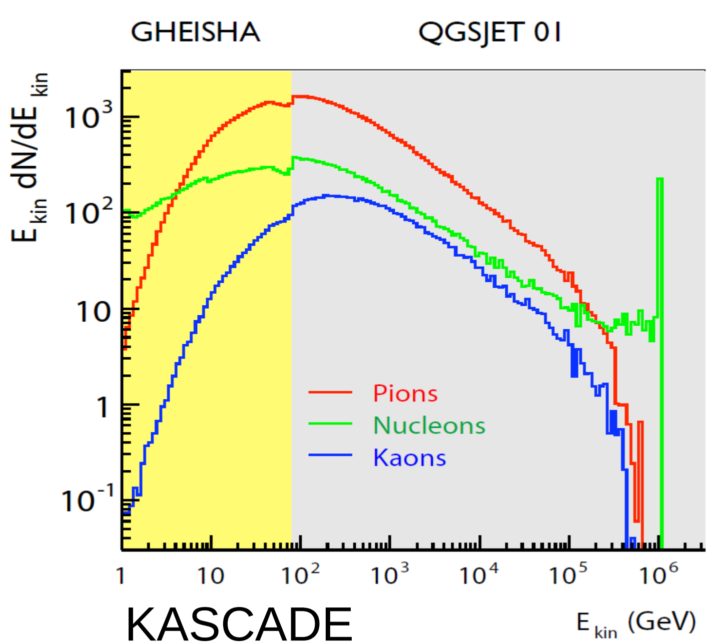




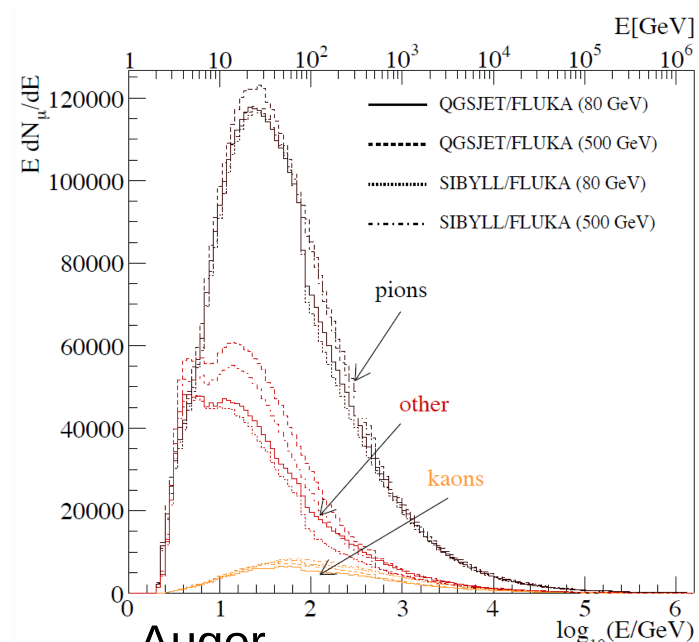
Energy of Last generation:

~ 100 GeV for KASCADE
~ 30 GeV for Auger

N_{mu} generated by all (low energy) interactions : pion-Air



KASCADE



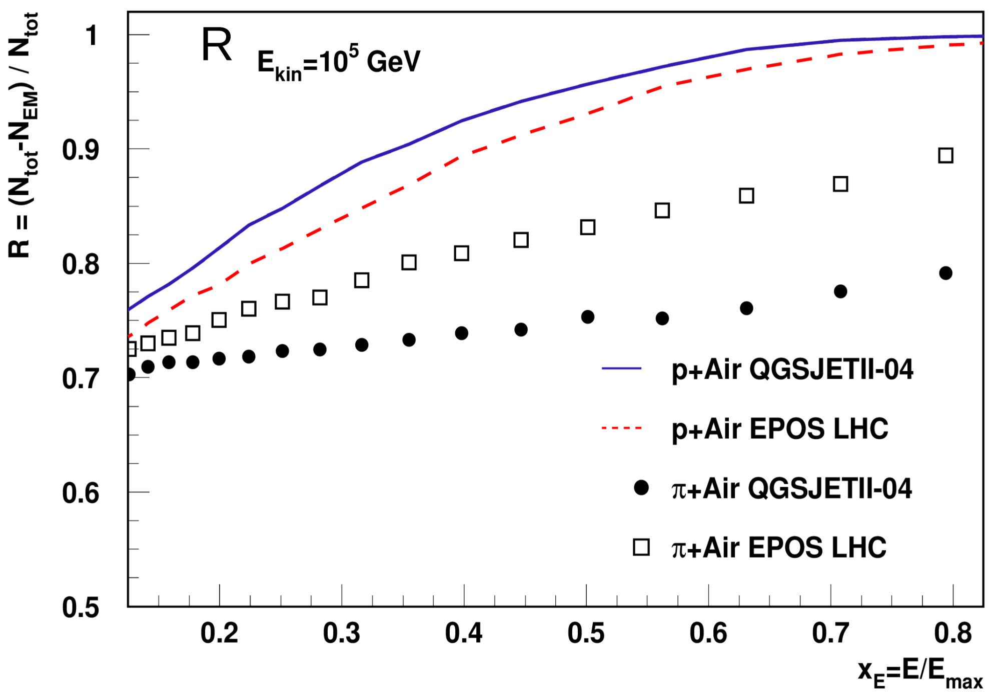
Auger

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

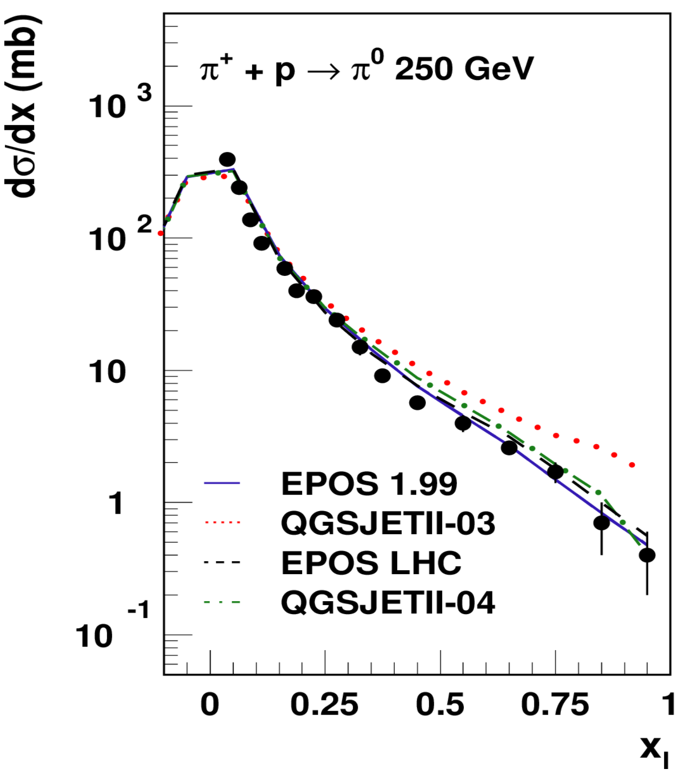
More fast (anti)baryons or ρ^0 or larger N_{tot} = $\alpha \rightarrow 1$ = more muons

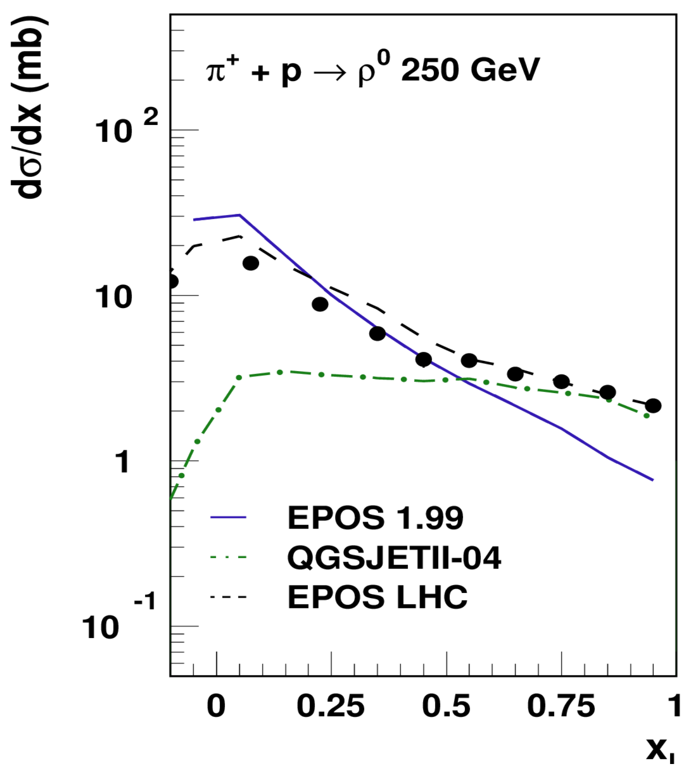
T. Pierog et al.,Phys.Rev.Lett. 101 (2008) 171101

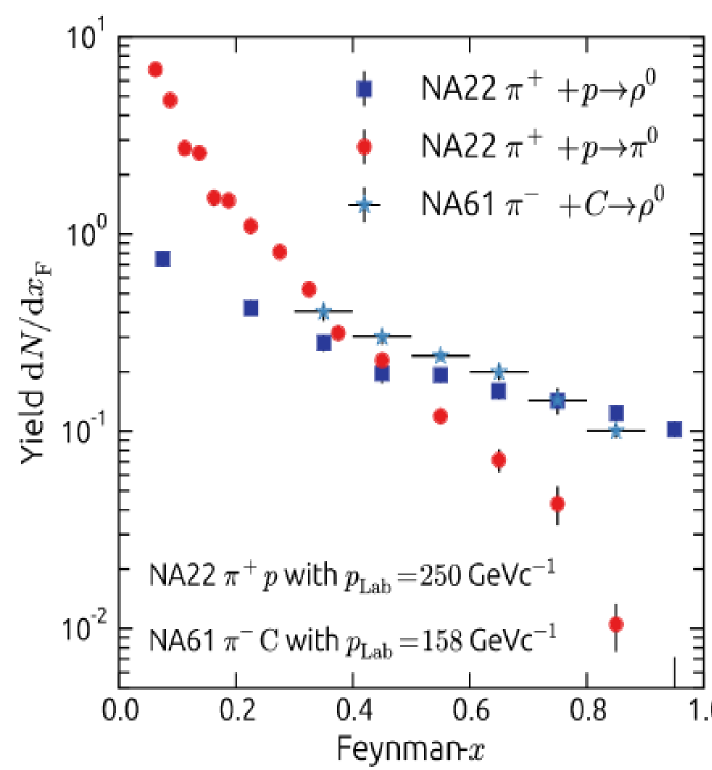
Pion Leading Particle Effect

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





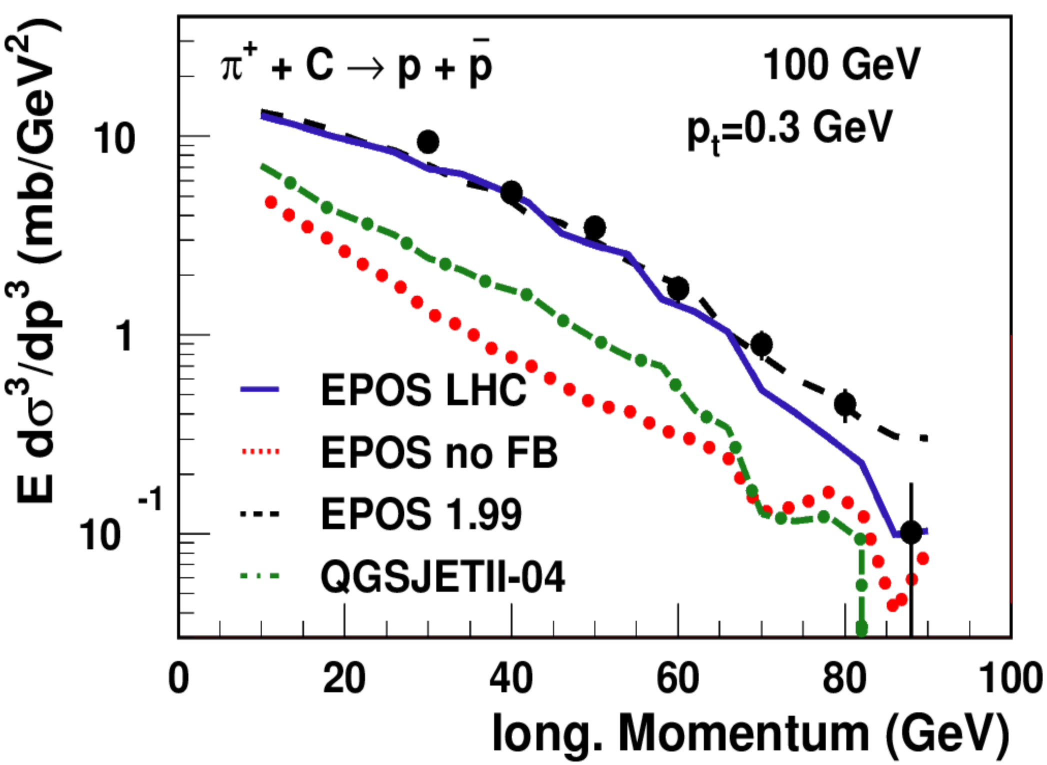


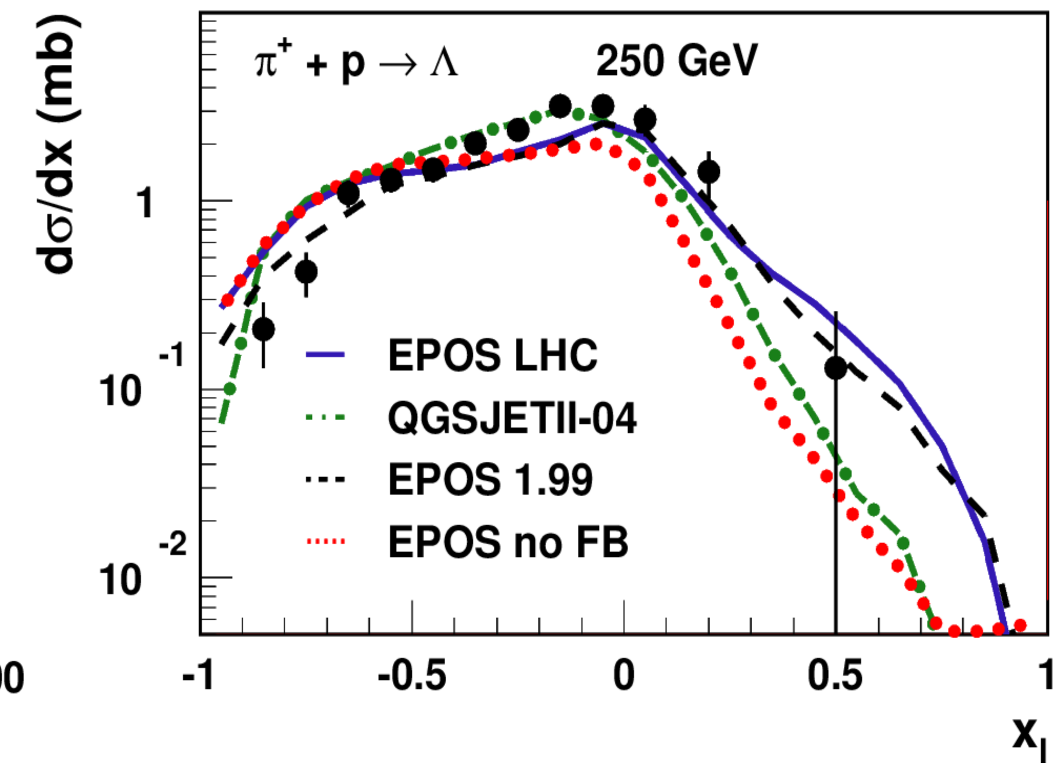
Plot from F. Riehn (KIT)

Baryons in Pion-Carbon

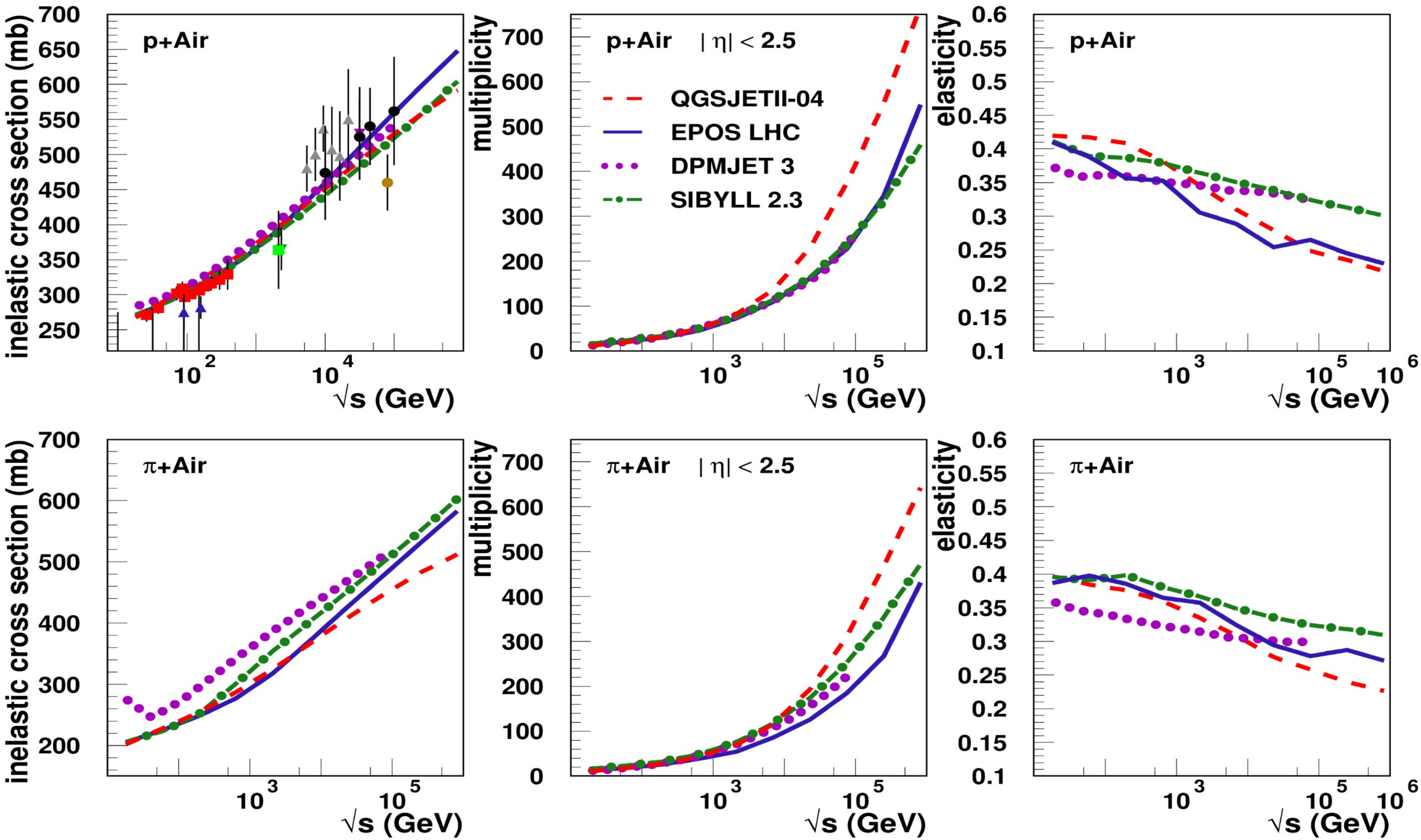
Very few data for baryon production from meson projectile, but for all :

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



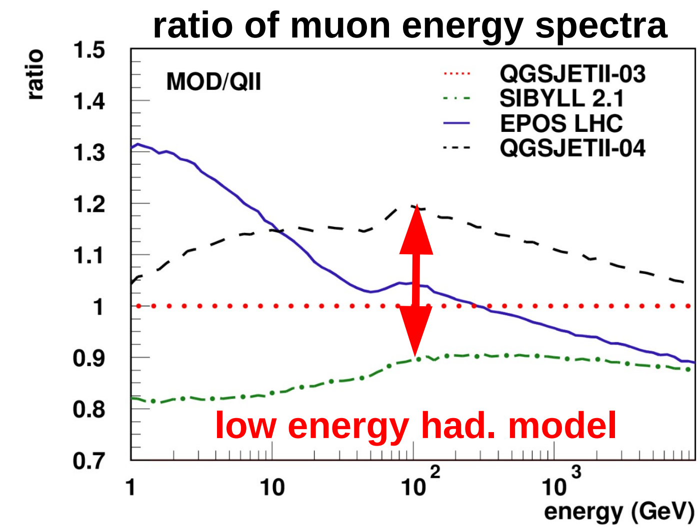


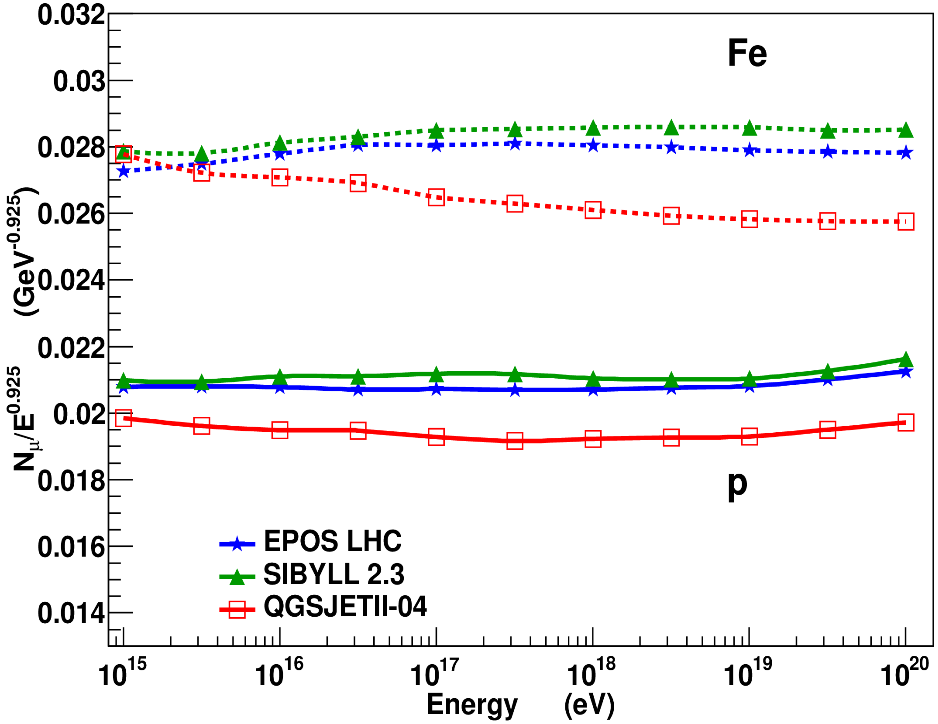
Ultra-High Energy Hadronic Model Predictions π-Air

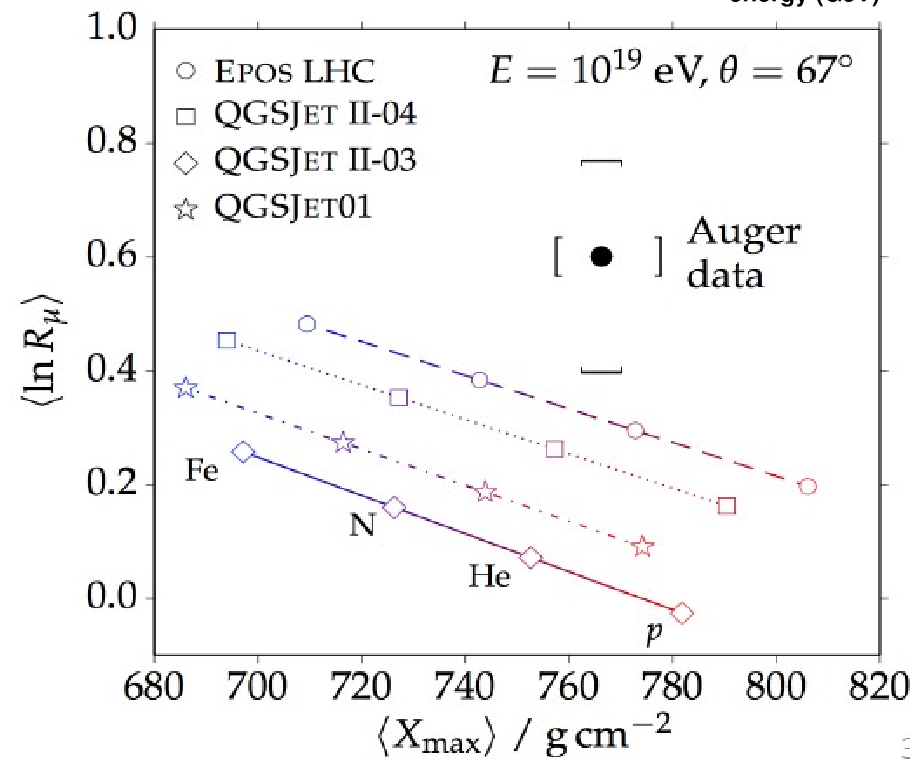


Muons at Ground

- 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



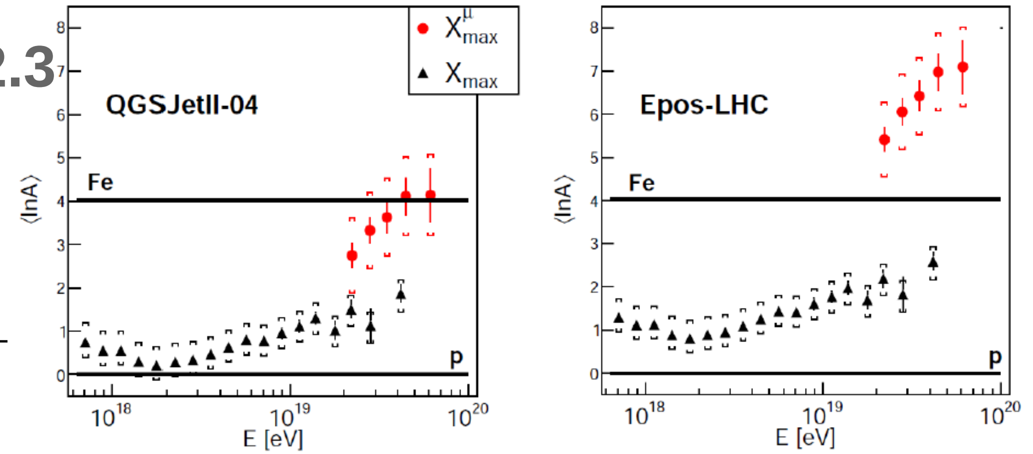


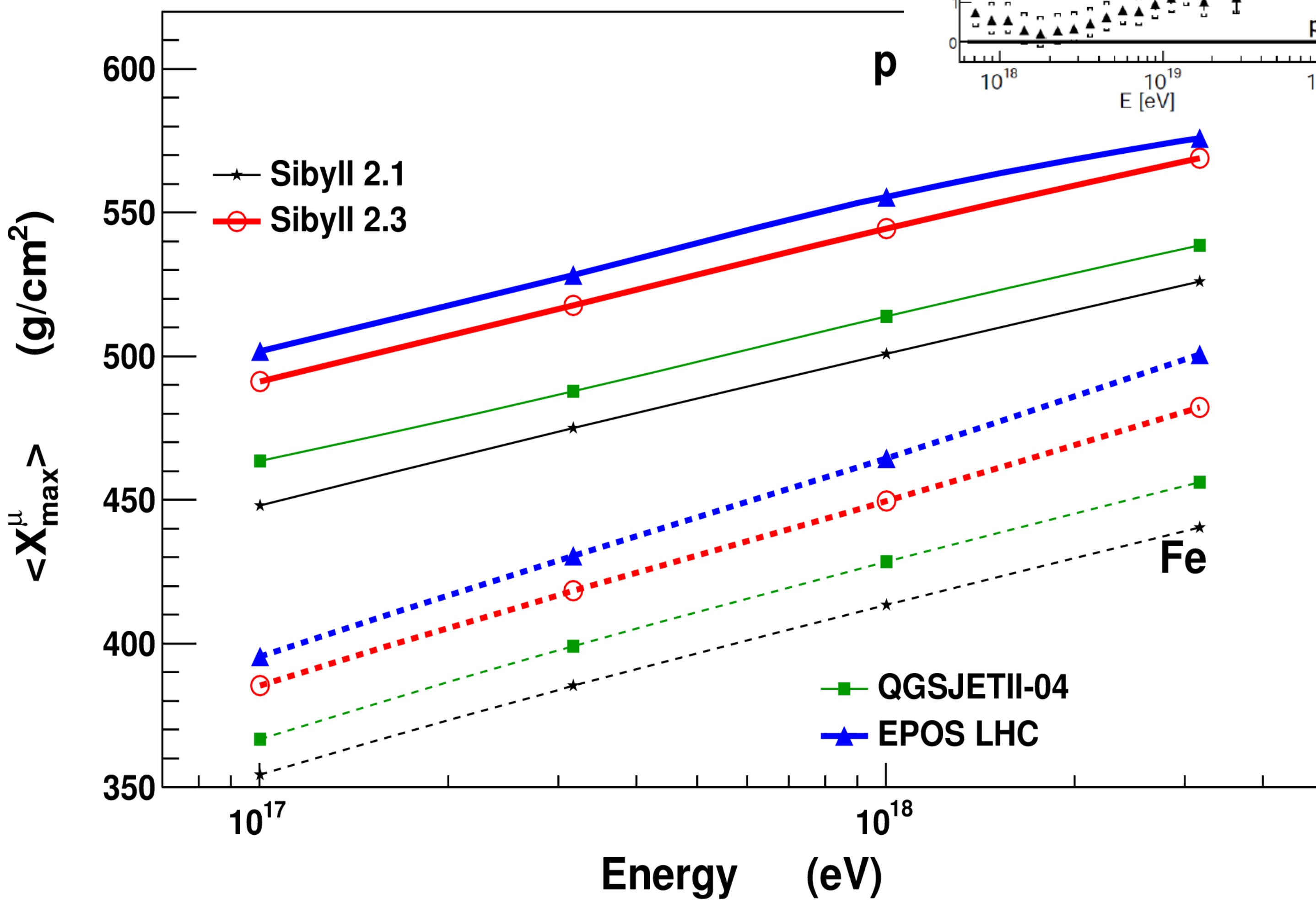


Muon Production Depth

Same for EPOS LHC and SIBYLL 2.3

- low pion-air elasticity: deeper X^{μ}_{max}
- more forward baryons: deeper X^{μ}_{max}

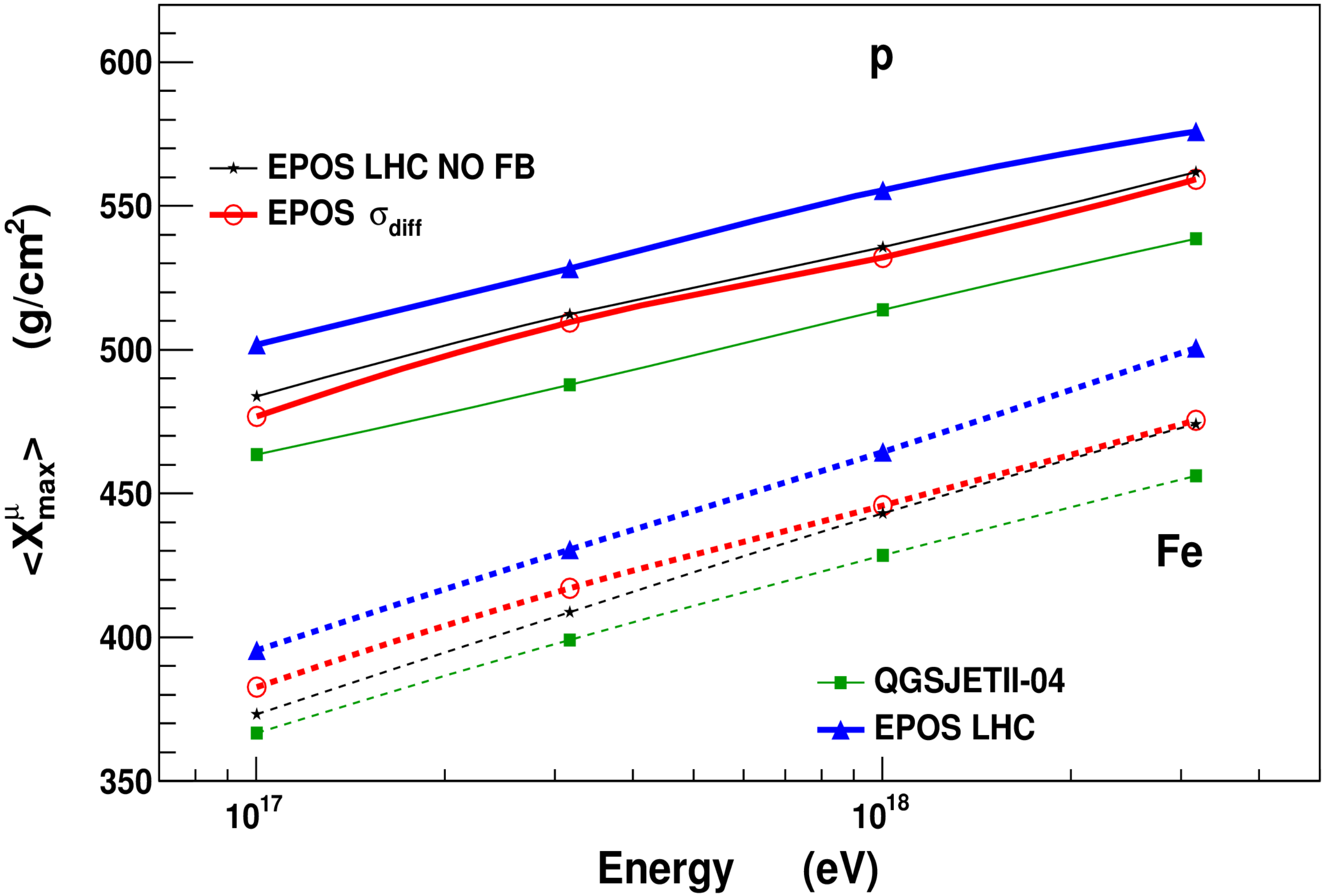




$\langle X^{\mu}_{max} \rangle$ with modified EPOS LHC

EPOS LHC without forward baryons or more inelastic pion int.

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



-25 g/cm² for diff

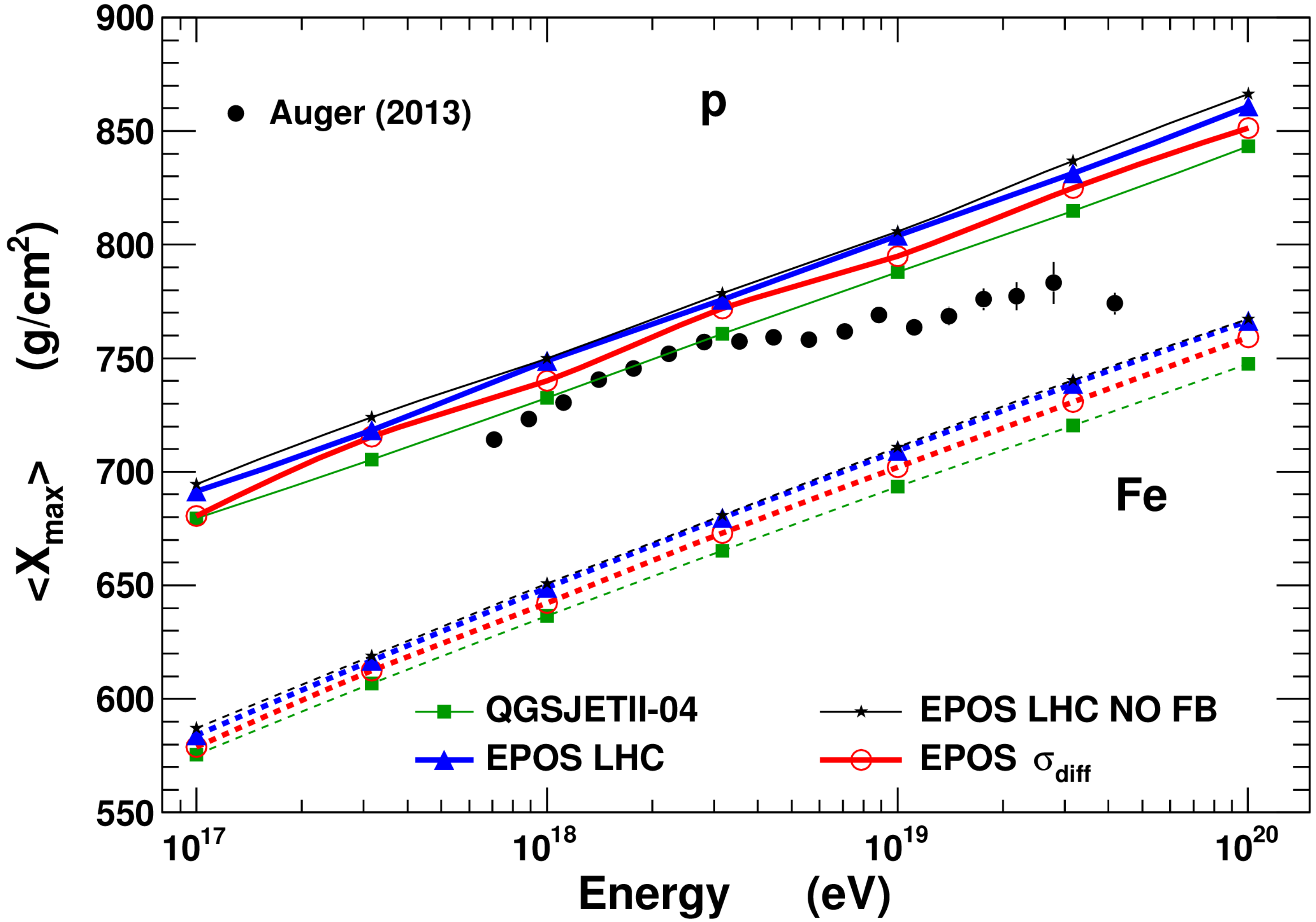
-20 g/cm² for baryons

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

$<X_{max}>$ with Modified EPOS LHC

EPOS LHC without forward baryons or more inelastic pion int.

- softer meson spectra: smaller X_{max}
- forward baryons: negligeable effect



-10 g/cm^2 for diff

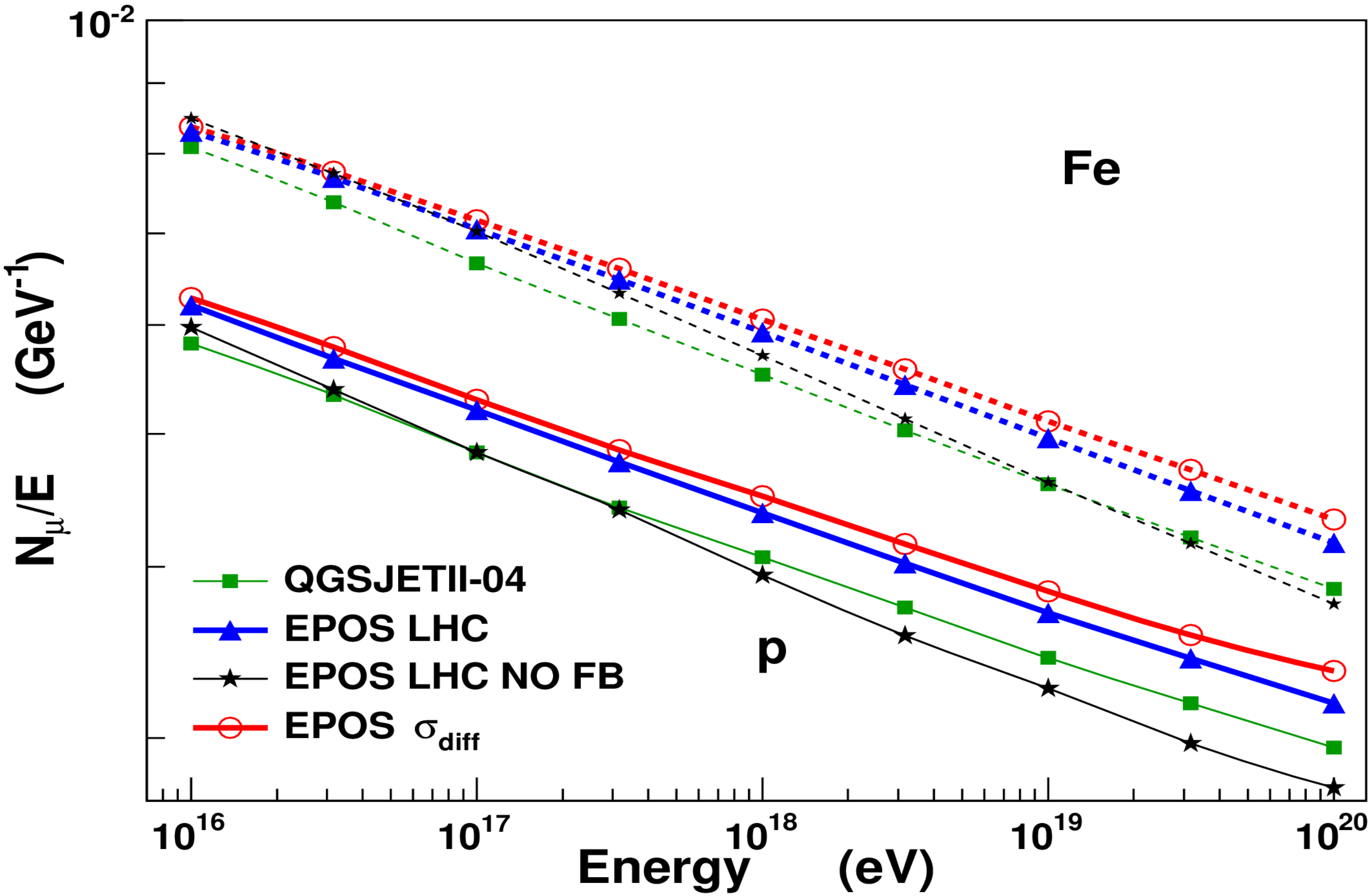
~0 g/cm^2 for baryons

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

N_μ with Modified EPOS LHC

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

New Baryon Measurement

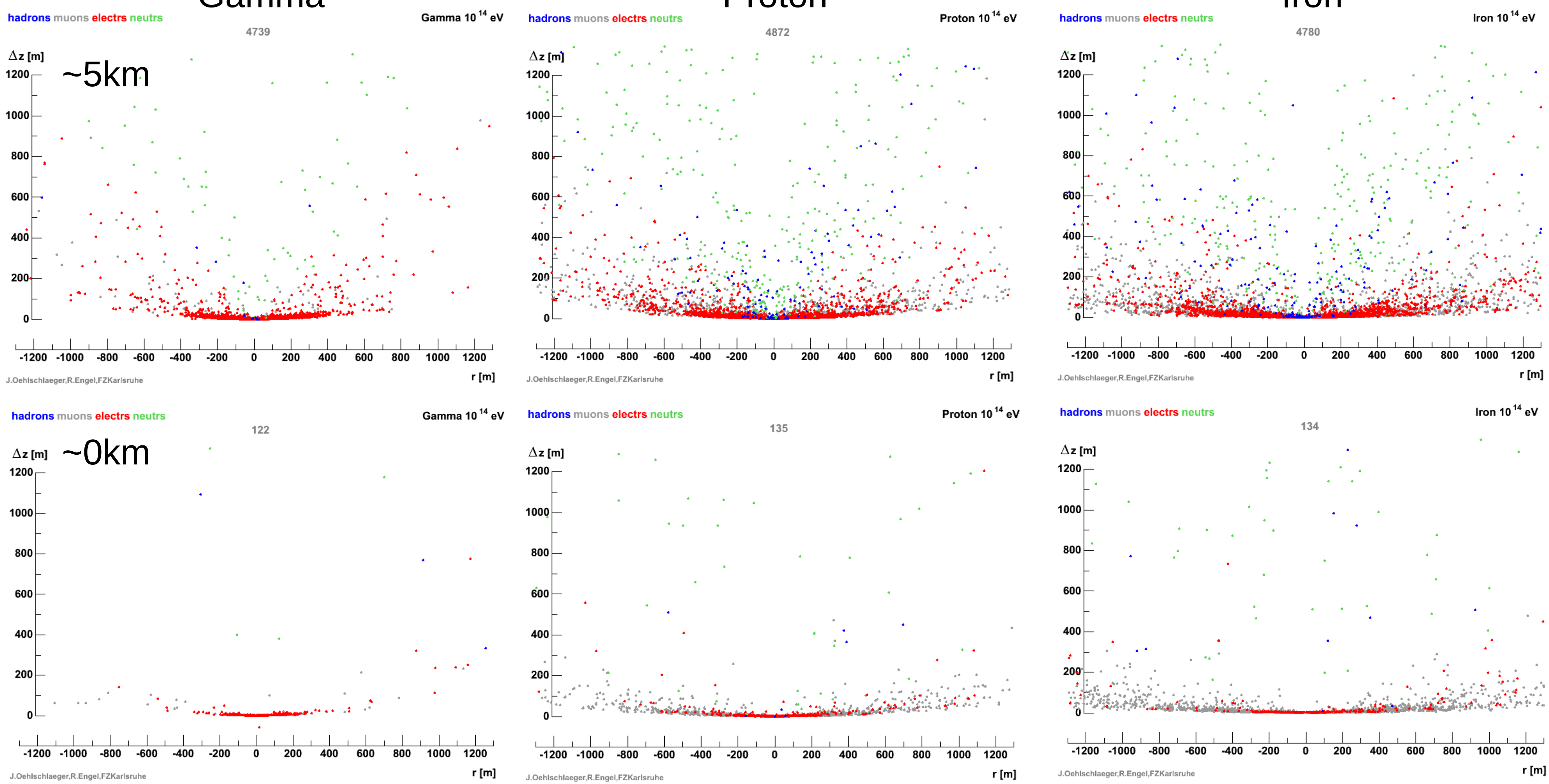
- **Very few data for baryon production from meson projectile, but for all :**
  - strong baryon acceleration (probability ~20% per string end)
  - proton/antiproton asymmetry (valence quark effect)
  - target mass dependence
- **New data set from NA49 (G. Veres' PhD)**
  - test π^+ and π^- interactions 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
      - Source of discrepancy understood and will be corrected in EPOS 3.
- **New measurements by NA61 can be used to confirm this result**

Air Showers at High Altitude

Thick shower front (close to maximum) : ➔ more particles and less fluctuations

➔ sensitive to details of nuclear int. ? ➔ shell structure detection ?

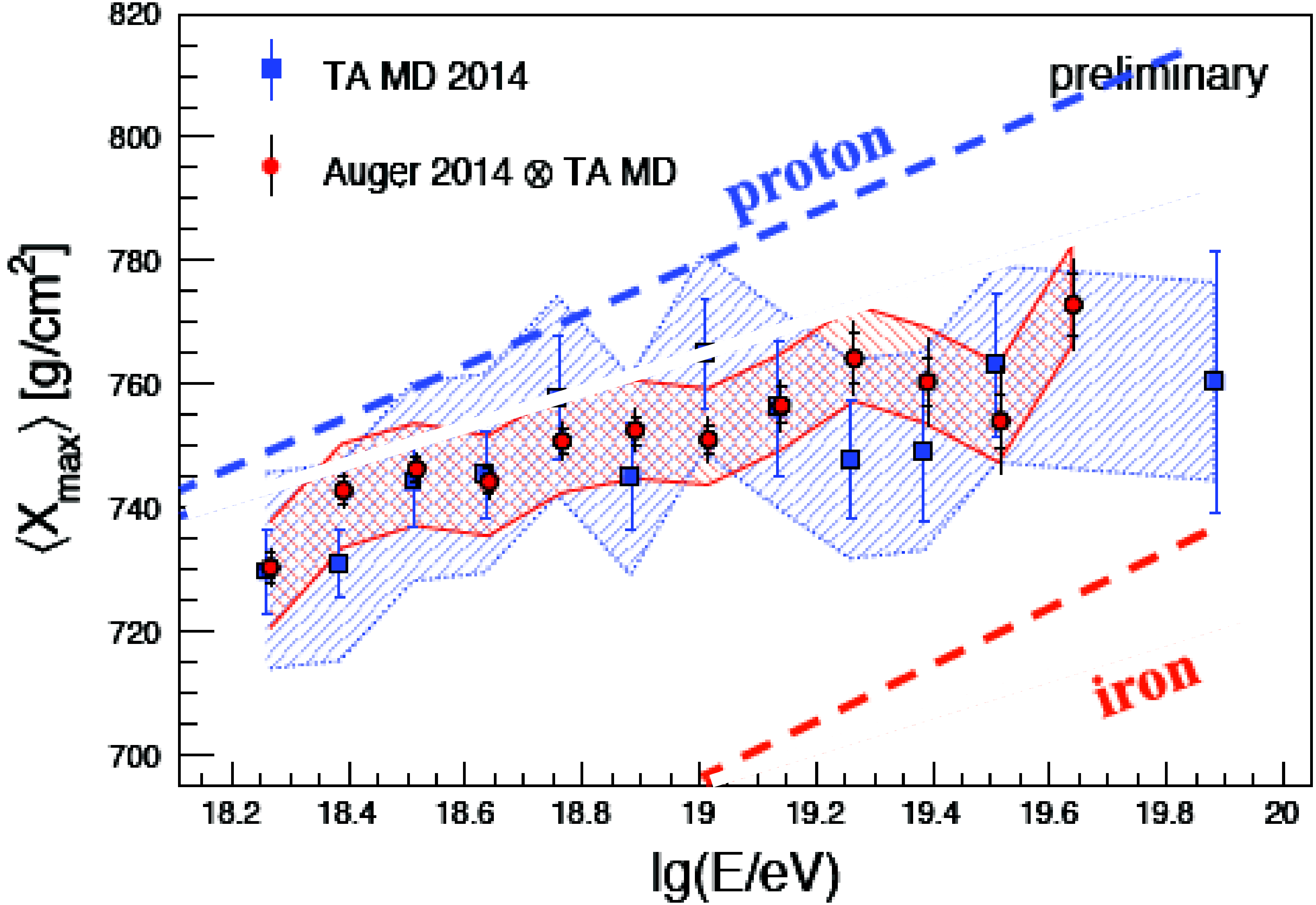
Gamma Proton Iron



Summary

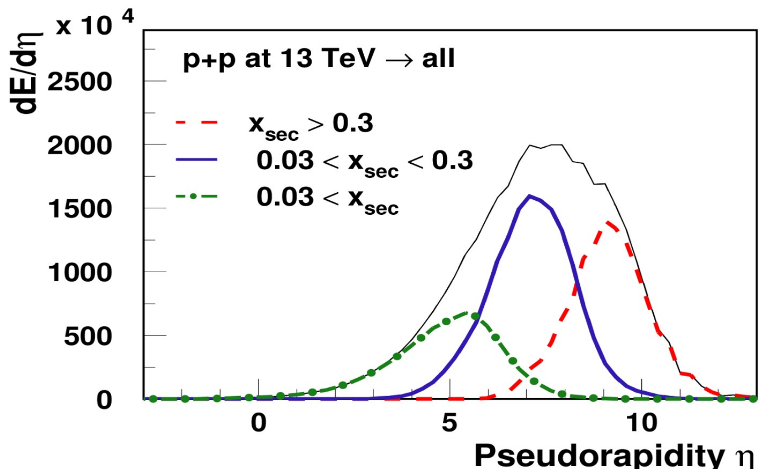
- **Auger data (and other low energy cosmic ray experiments) not consistently described by hadronic interaction models (even post LHC)**
  - $<X_{max}>$ and fluctuations, number of muons and muon production depth …
  - ➔ but it has never been so good ! only 1 to 2 sigma difference in most of the cases
- **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
- **Improvments to come (EPOS 3 for ICRC 2017, others ?)**
  - ➔ forward physics: photon and neutron spectra and diffraction measured at LHC, and baryon stopping and resonance production at SPS
  - ➔ effect of extrapolation to p-Air interaction: p-Pb measurements can be used to constrain nuclear effects (p-O would be the best check).
  - ➔ effect of (very) low energy: extension to very low energy (few GeV) to have a better control on the muon production.

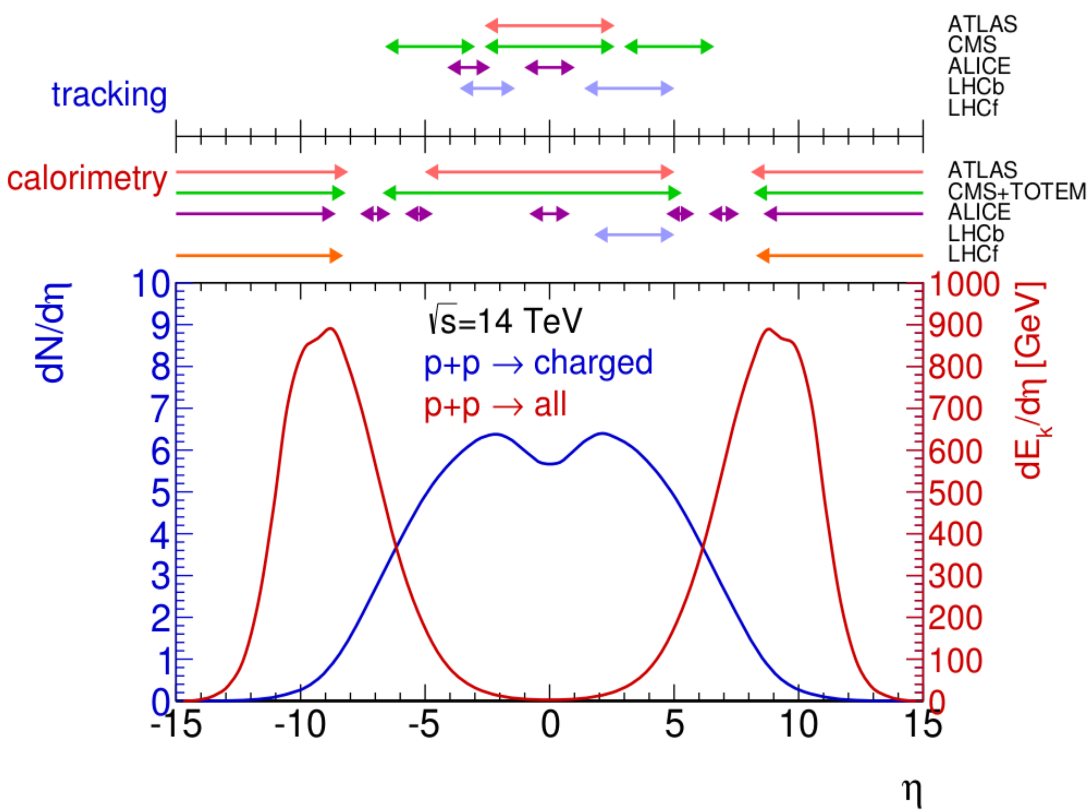
TA ...



From Roberto Aloiso talk (2015 working group)

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