What Have We Learnt From LHC About Air Showers?

Tanguy Pierog

Karlsruhe Institute of Technology, Institut für Kernphysik,
Karlsruhe, Germany

Karlsruhe Institute of Technology

MU Programmtag, Mainz, Germany

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Outline

- Monte-carlo for Cosmic Ray (CR) analysis

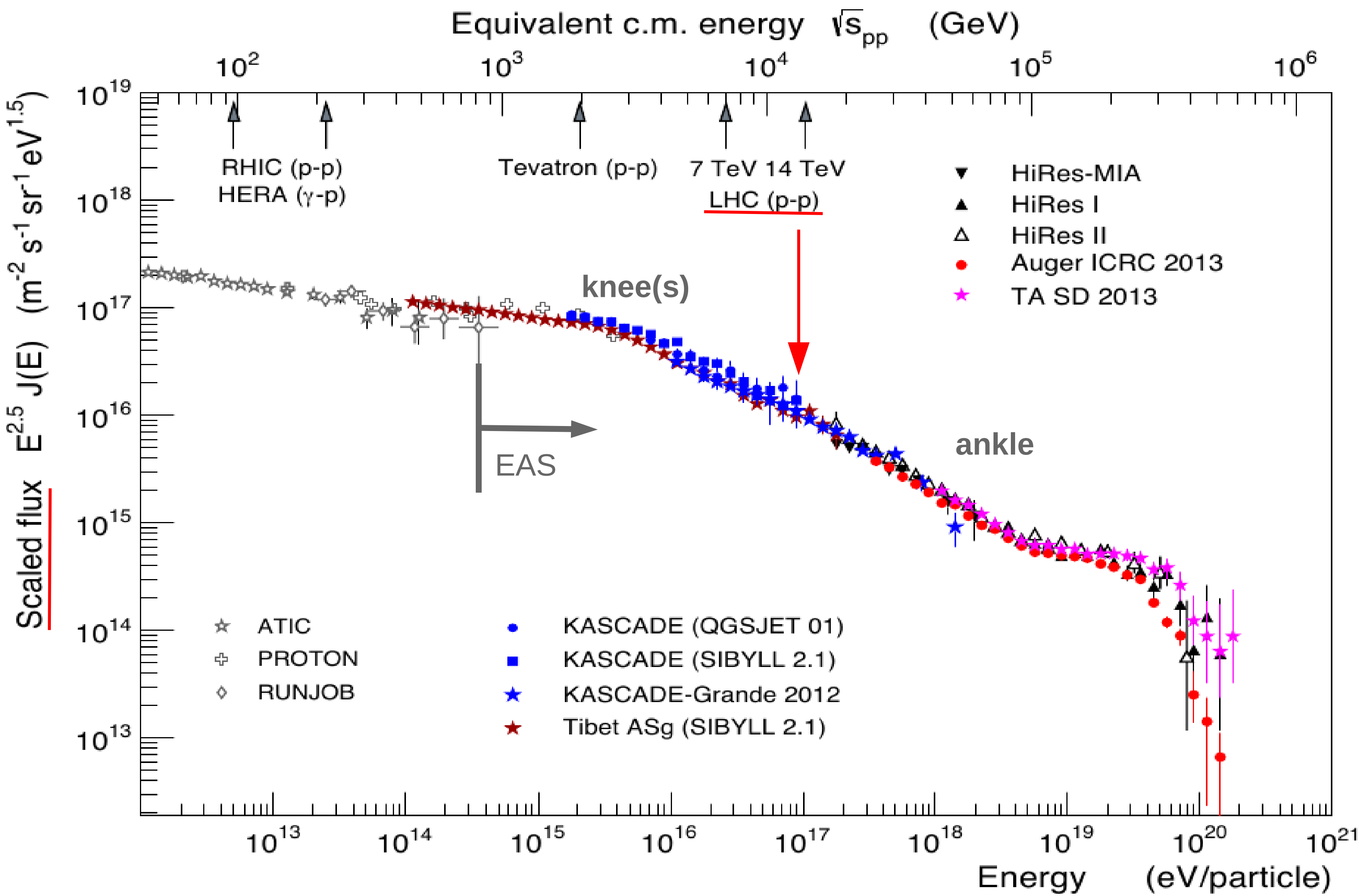
- Monte-carlo (MC) comparison to LHC data

- Electromagnetic (EM) signal in extended air showers
  - ➡ X_{max}

- Muon signal
  - ➡ X^{mu}_{max}

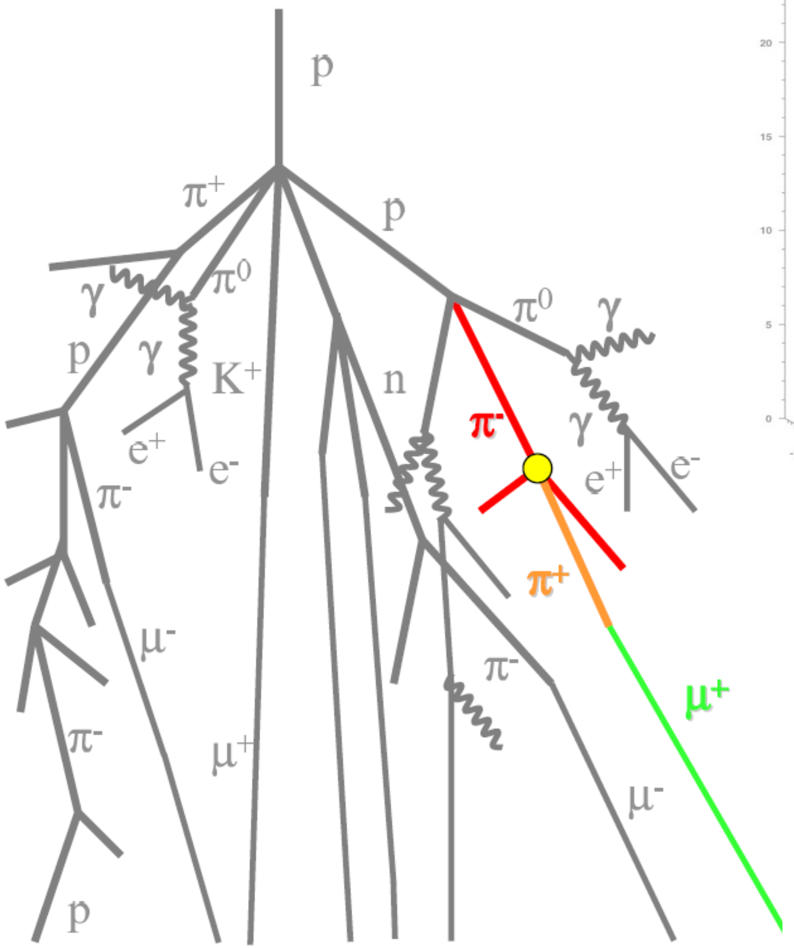
LHC data reduced the model uncertainties and exclude exotic models for CR spectrum. Indirectly the measurement of diffraction at LHC for protons used in air showers gives information on pion interactions.

Cosmic Ray Spectrum

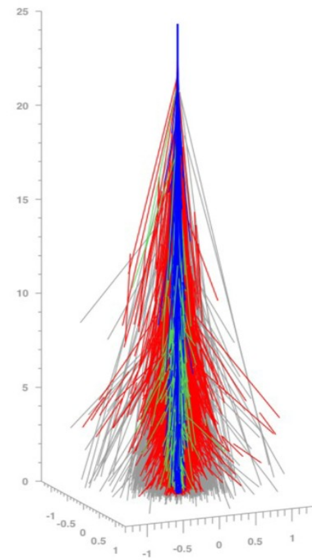


R. Engel (KIT)

Extensive Air Shower



From R. Ulrich (KIT)



$A + air \to$ hadrons
$p + air \to$ hadrons
$\pi + air \to$ hadrons

main source of uncertainties

intial γ from π^0 decay

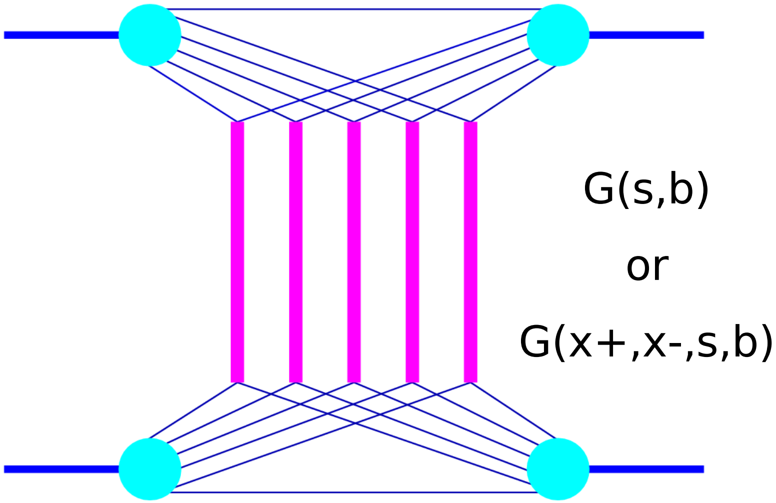
$e^{\pm} \to e^{\pm} + \gamma$
$\gamma \to e^{+} + e^{-}$

well known

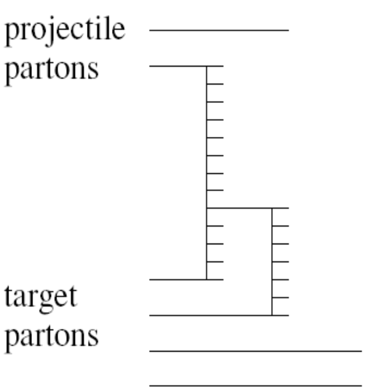
$\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}/\bar{\nu_{\mu}}$

- **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)

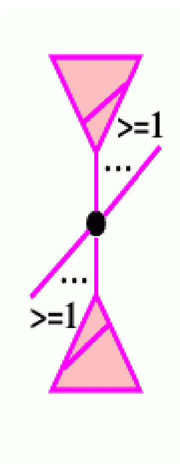
Cross Section and Multiplicity in Models



EPOS



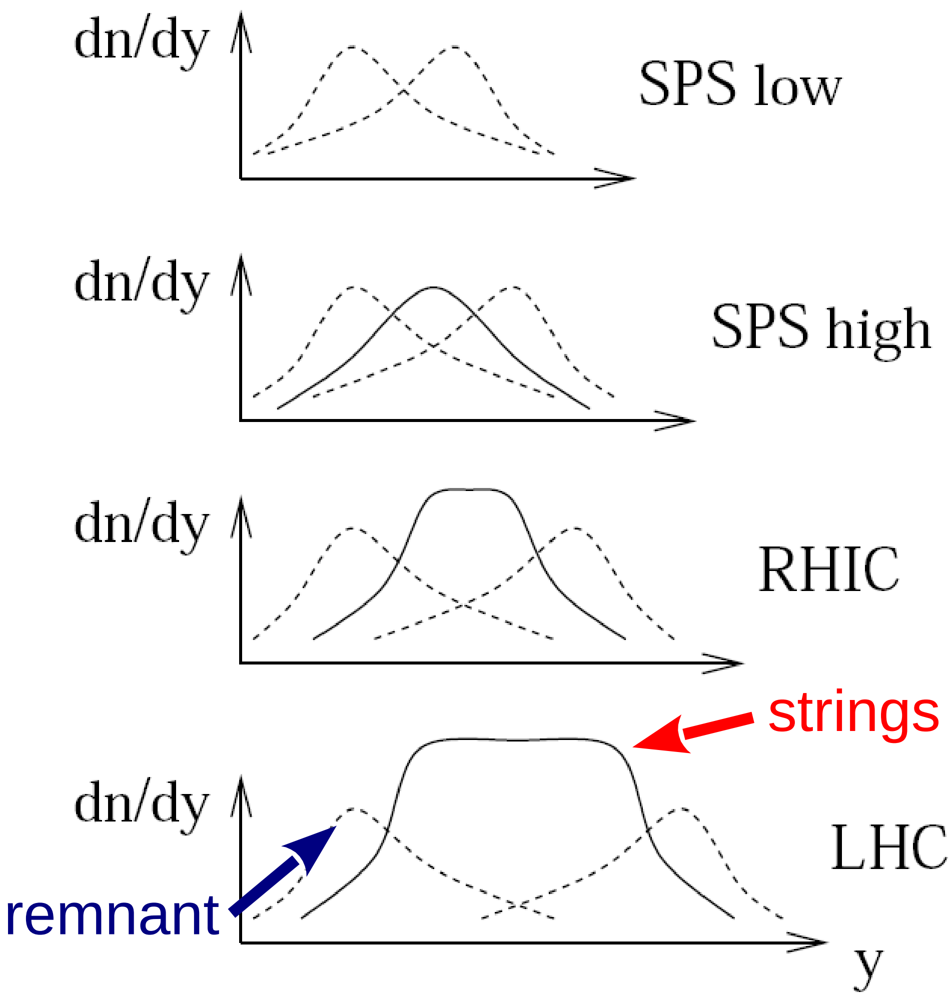
QGSJET II



- **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

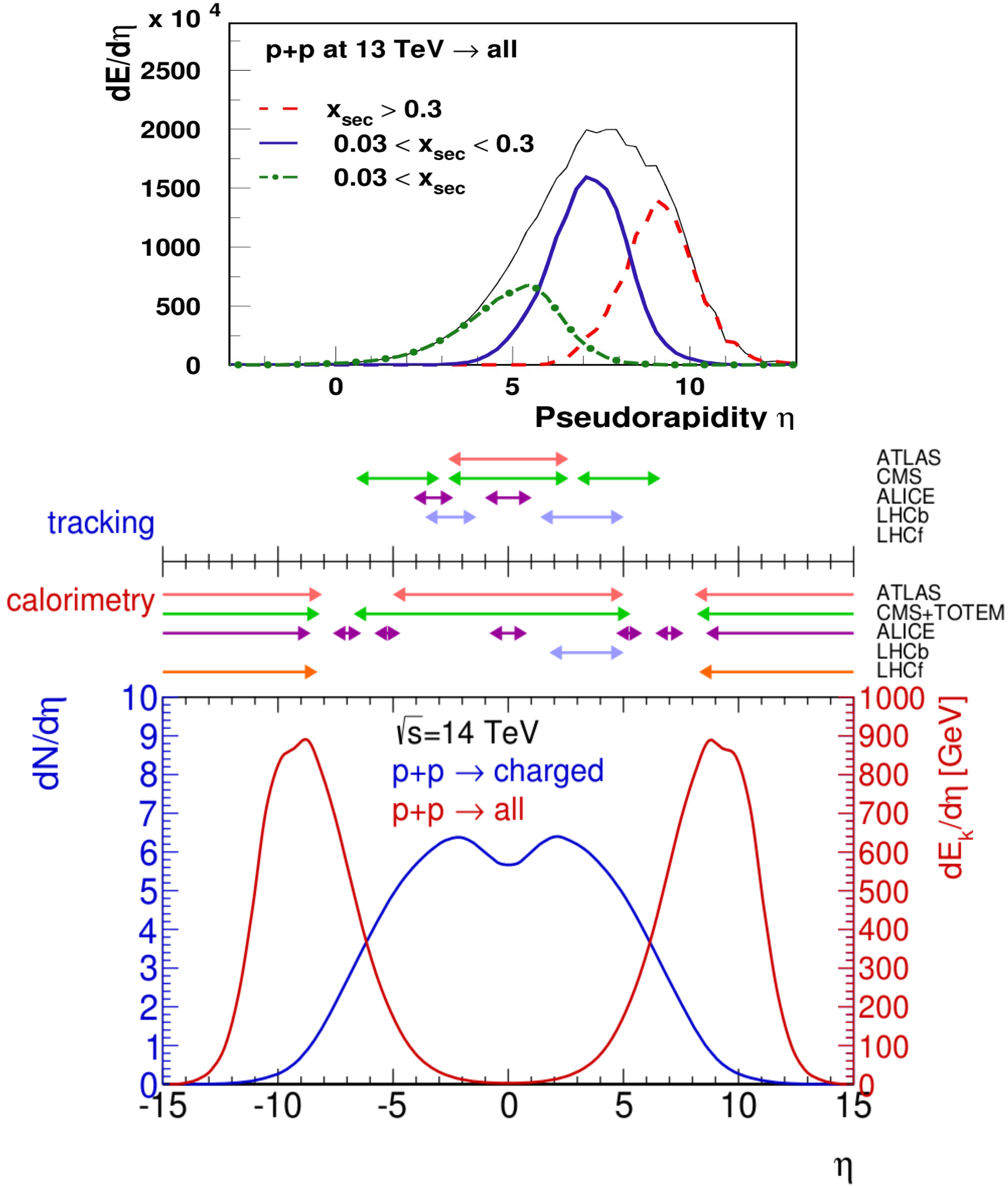
Forward particles mainly from projectile remnant



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

LHC acceptance



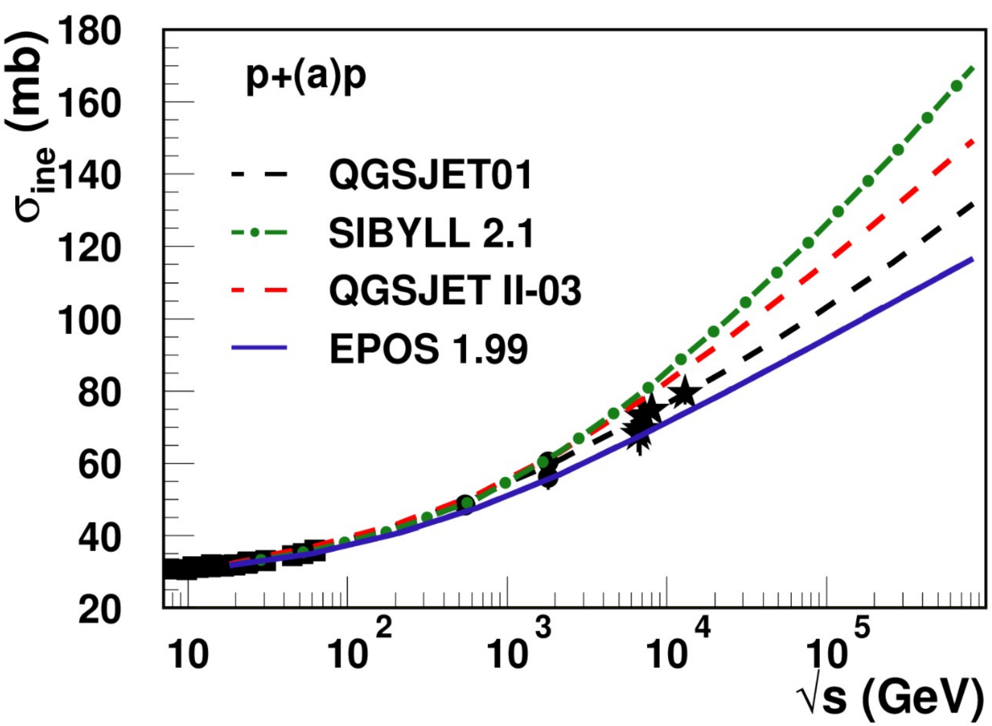
- **p-p data of central detectors used to update the models**
  - p-Pb difficult to compare to CR models (only EPOS)
  - special centrality selection
  - mostly new tuning of models
- **Direct photon energy spectra from LHCf**
  - small phase space but relevant for X_{max}
  - not yet taken into account into models
- **Average elasticity/inelasticity** (energy fraction of the leading particle)
  - all diffraction measurement to be taken into account

Cross Sections

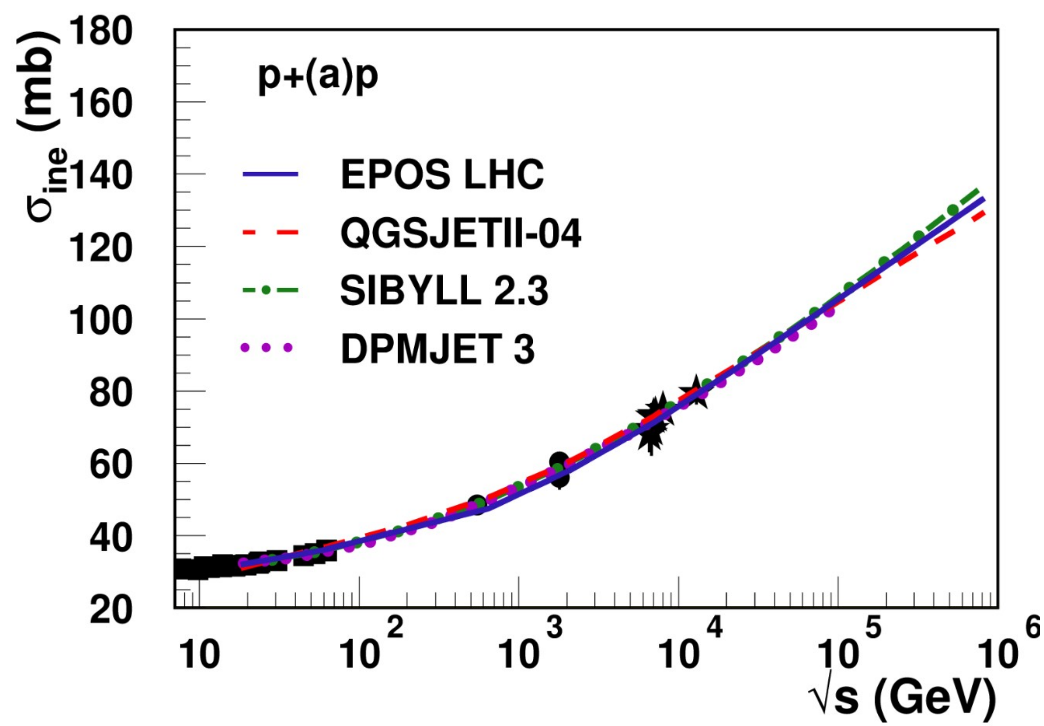
- same cross section prediction at pp level and low energy (data for tuning)

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

Pre - LHC



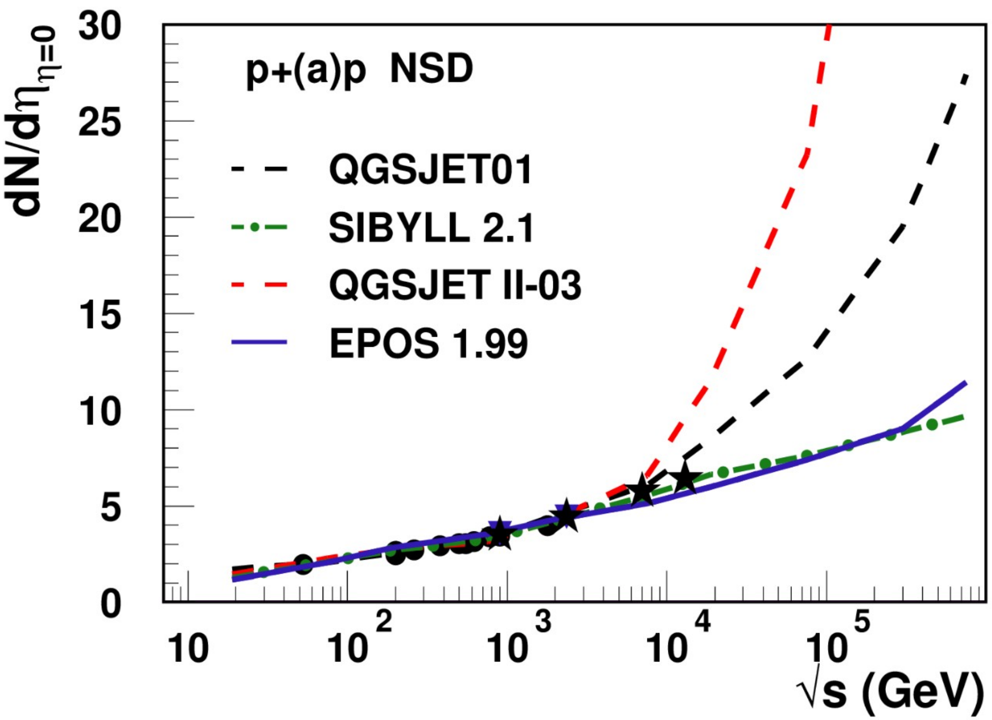
Post - LHC



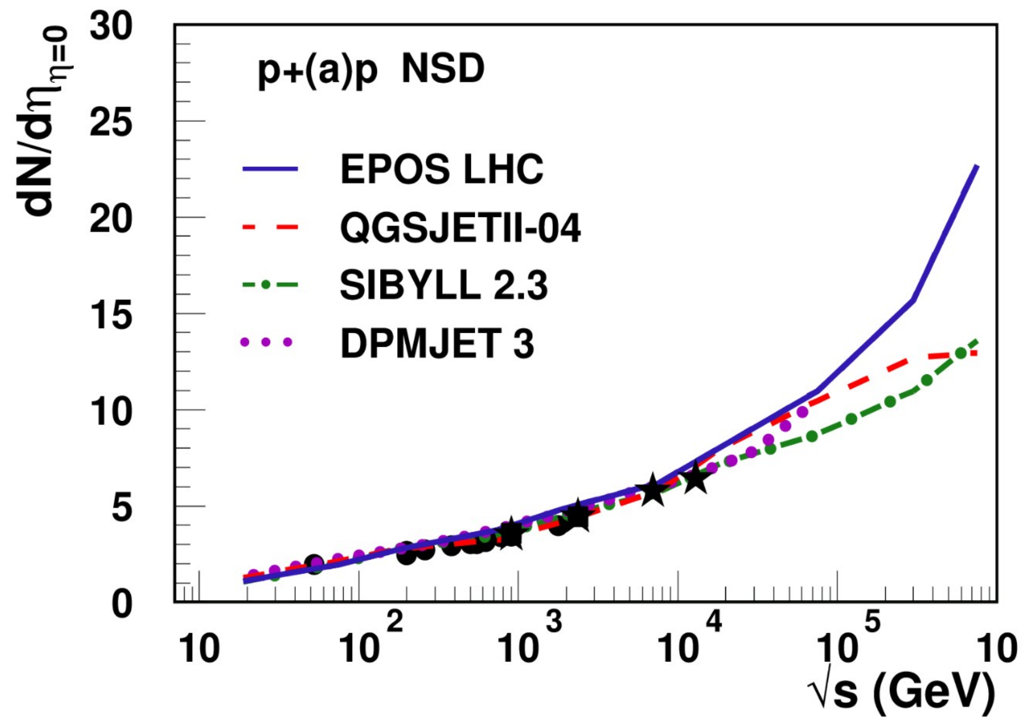
Multiplicity at mid-rapidity

- 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

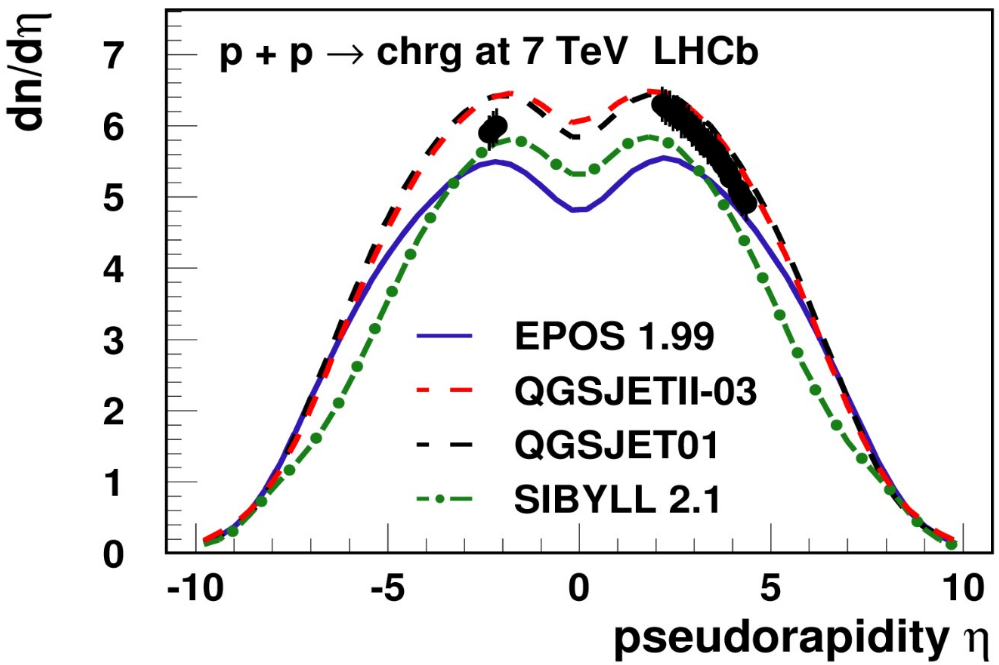


Pseudorapidity

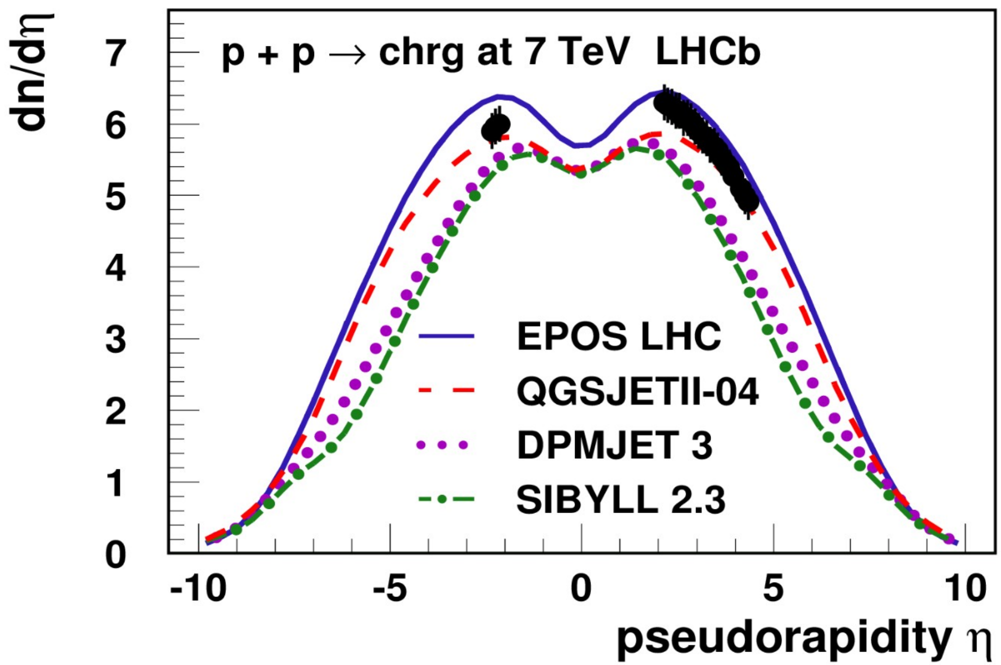
- The width of the pseudorapidity distributions introduce a difference between mid-rapidity and full multiplicity.

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

Pre - LHC



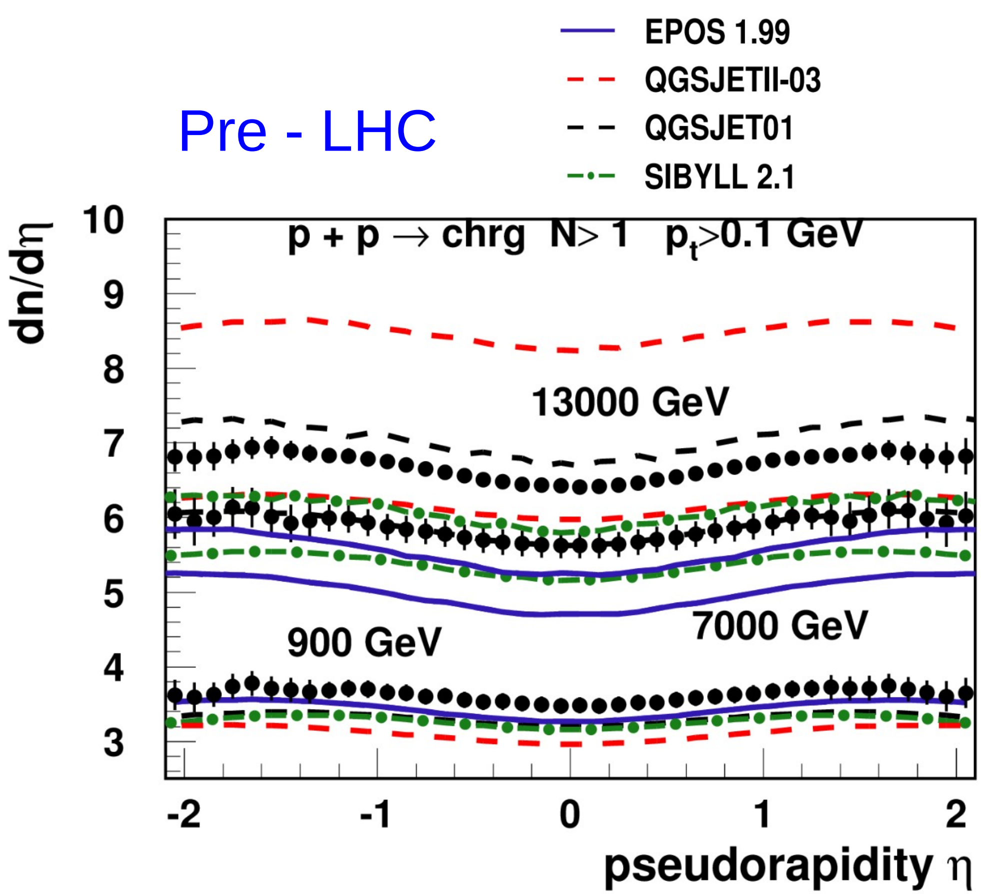
Post - LHC

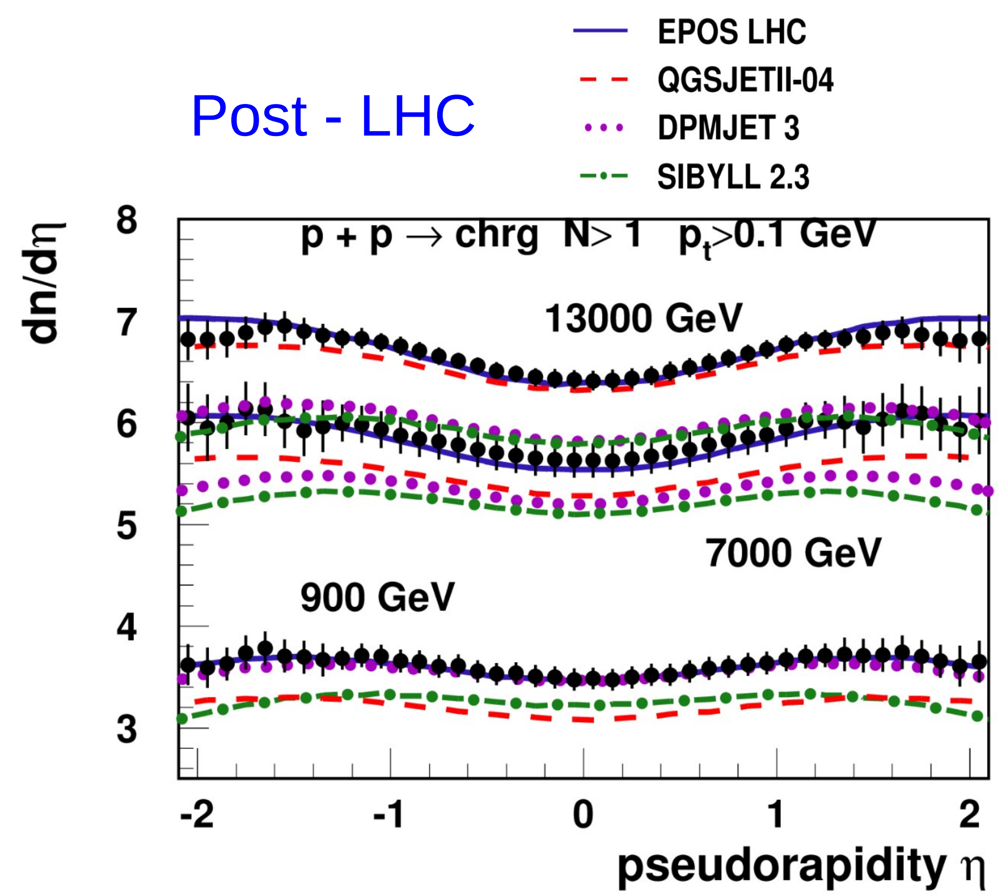


Test of Models vs Accelerator Data

- From LHC data

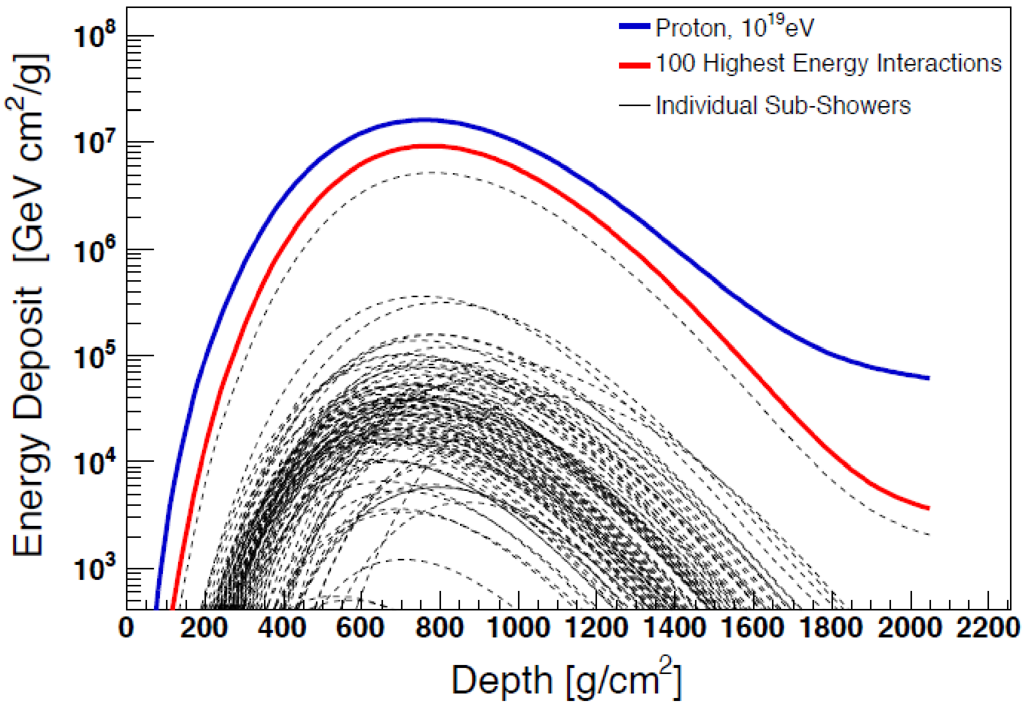
  - All pre-LHC models extrapolation excluded
  - DPMJET 3 and SIBYLL 2.3 underestimate multiplicity
  - QGSJETII-04 and EPOS LHC ~ OK (and similar to Pythia 8)





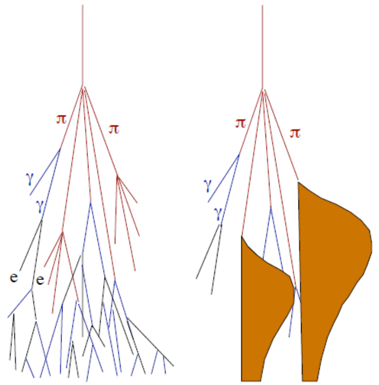
Hadronic Interactions for X_{max}

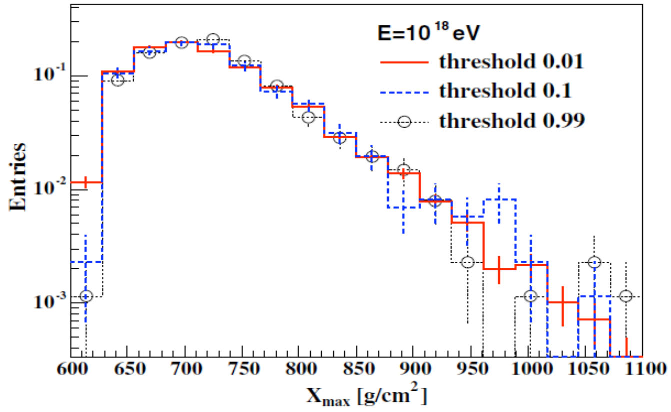
Electrons



Shower particles produced in 100 interactions of highest energy

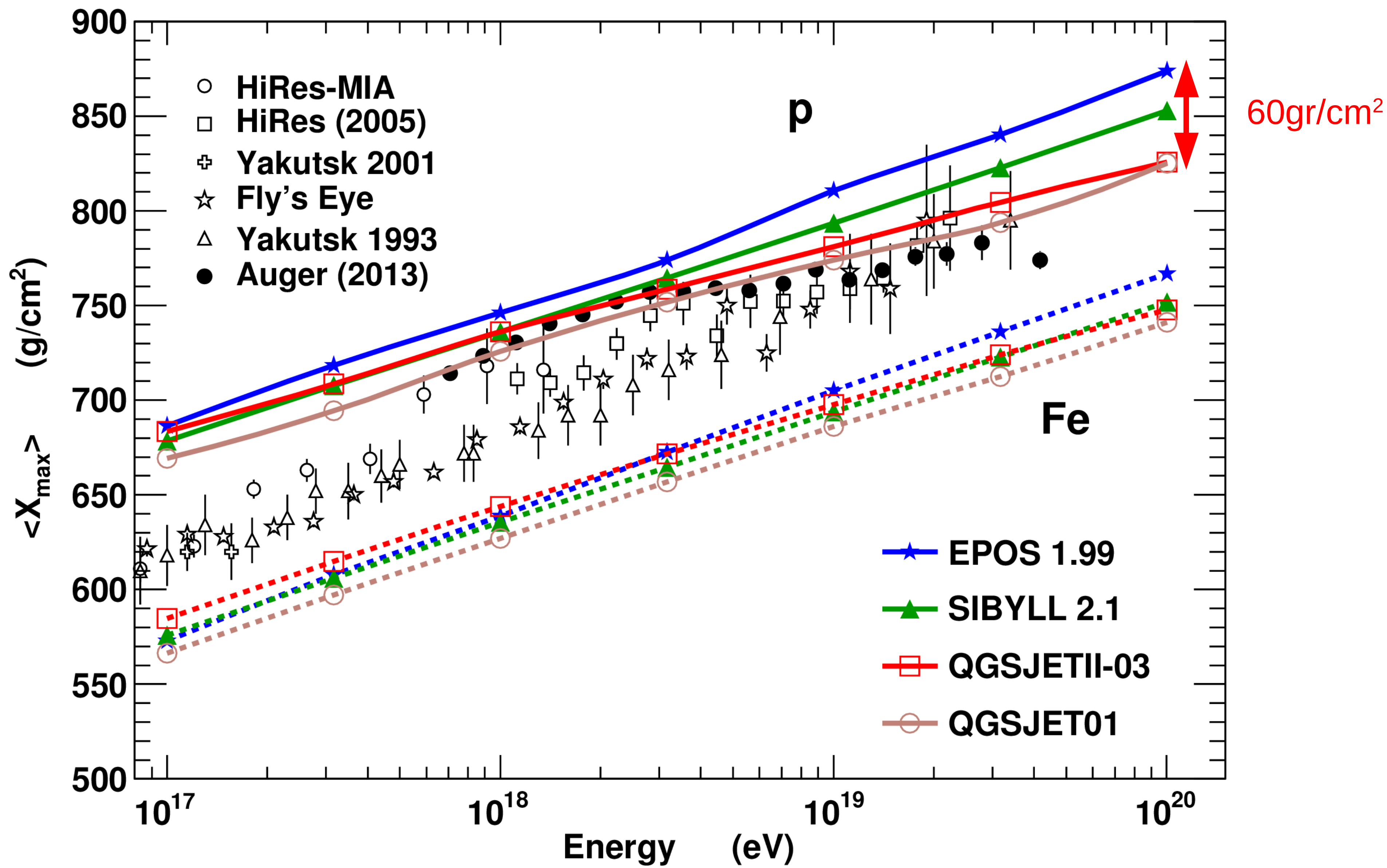
X_{max} dominated by first (high energy) interaction(s) : proton (nucleus) - Air



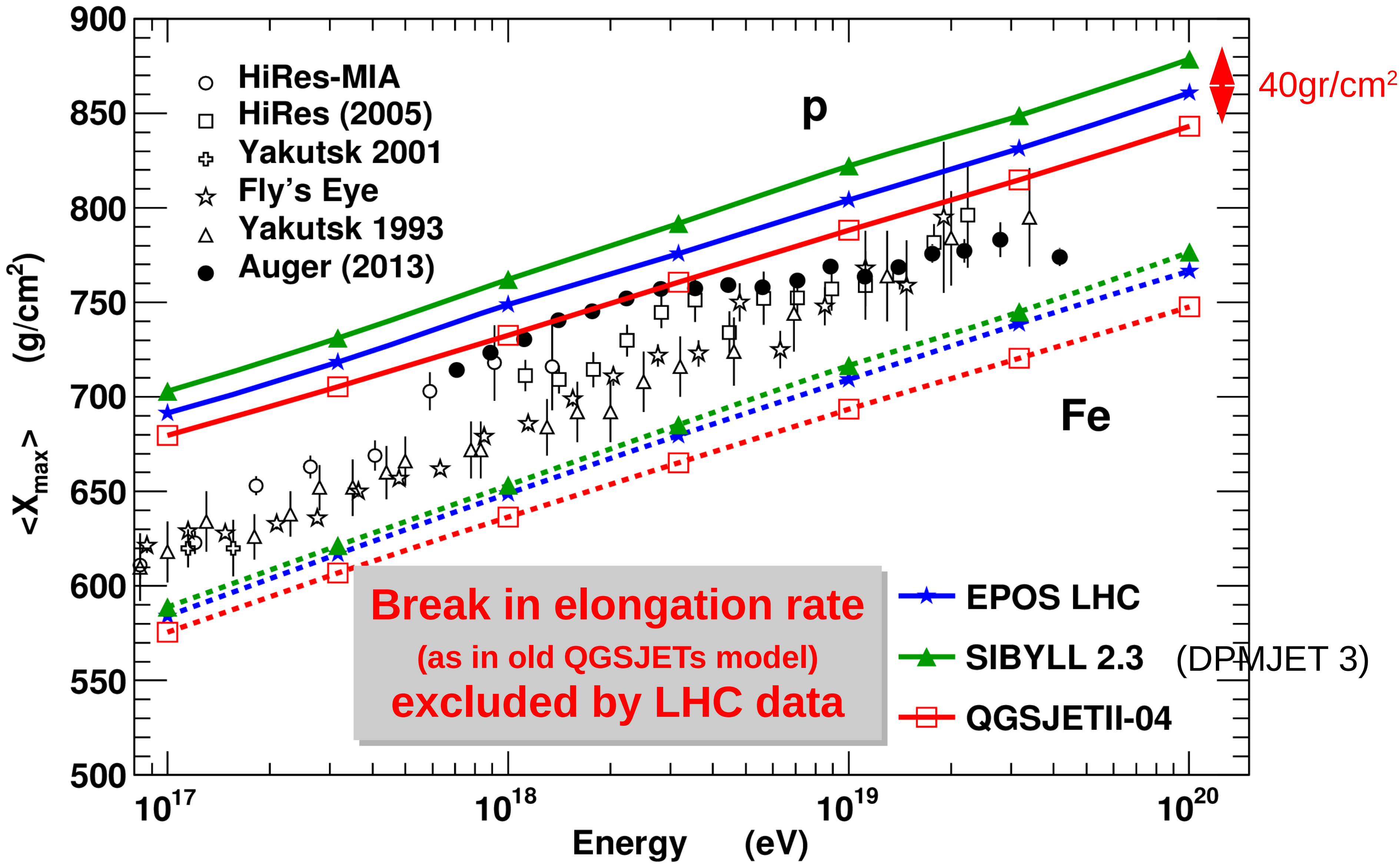


Fluctuations mainly coming from the first hadronic interaction.

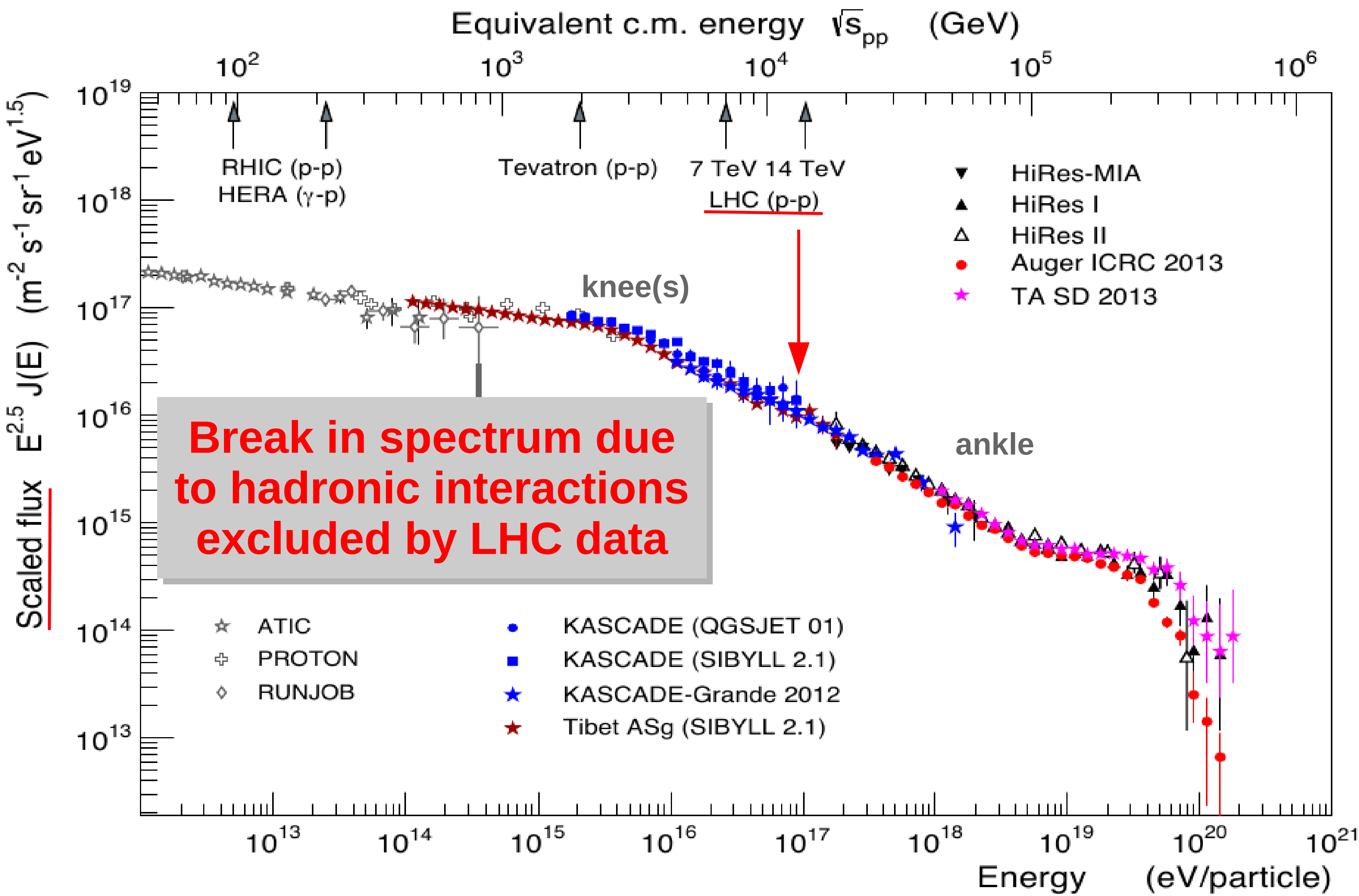
EAS with Old CR Models : X_{max}



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

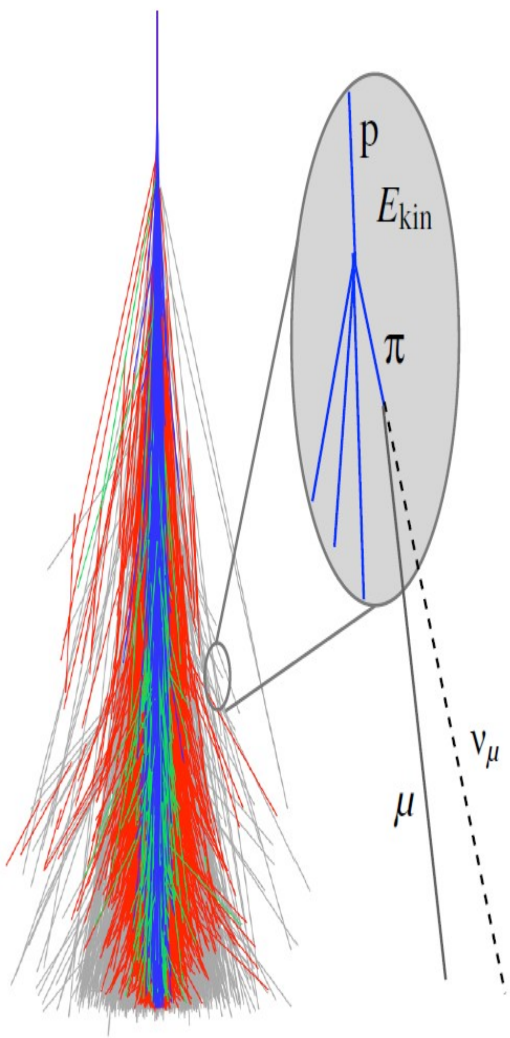


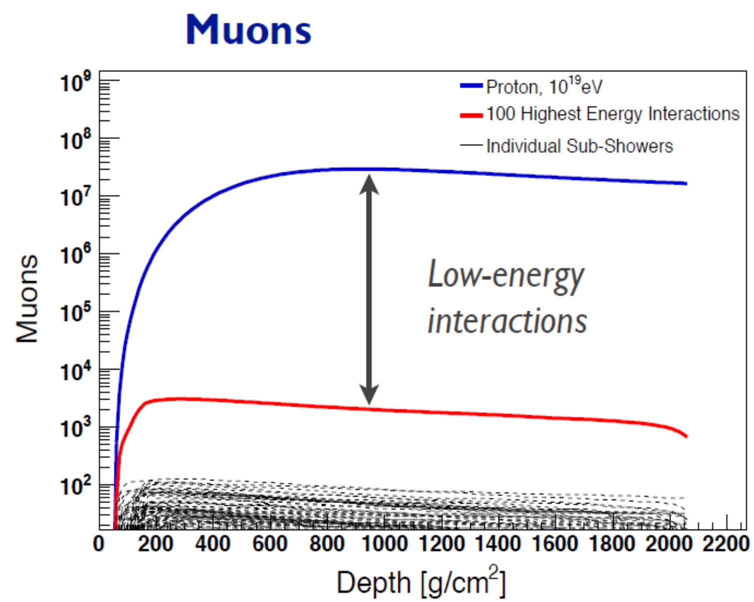
Cosmic Ray Spectrum



R. Engel (KIT)

Muon production by low energy interactions

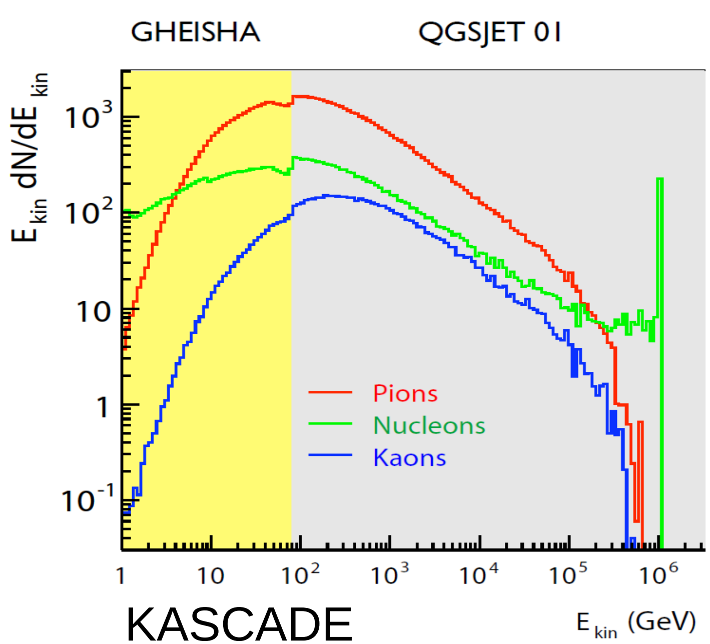


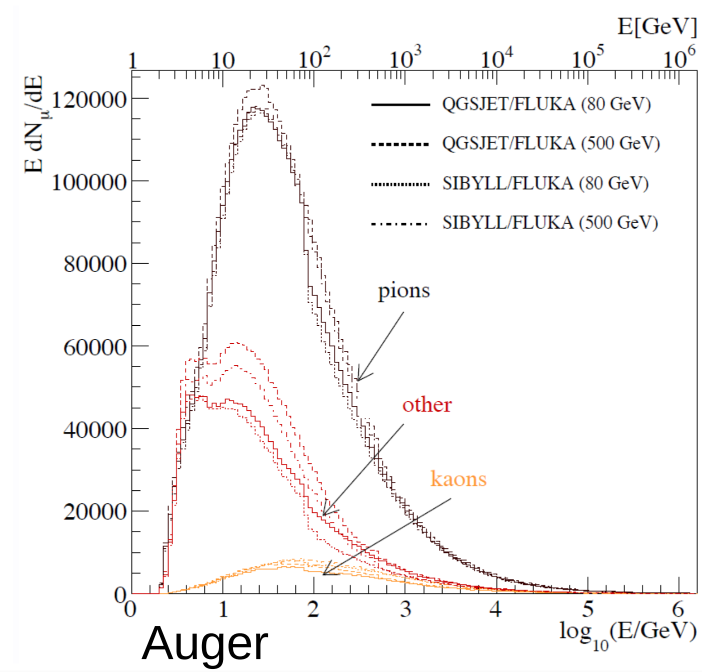


Energy of Last generation:

~ 100 GeV for KASCADE
~ 30 GeV for Auger

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

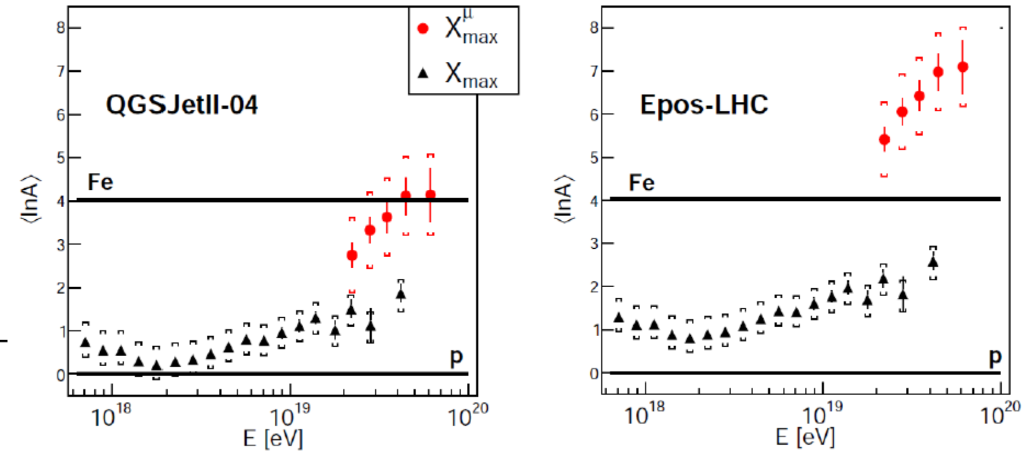


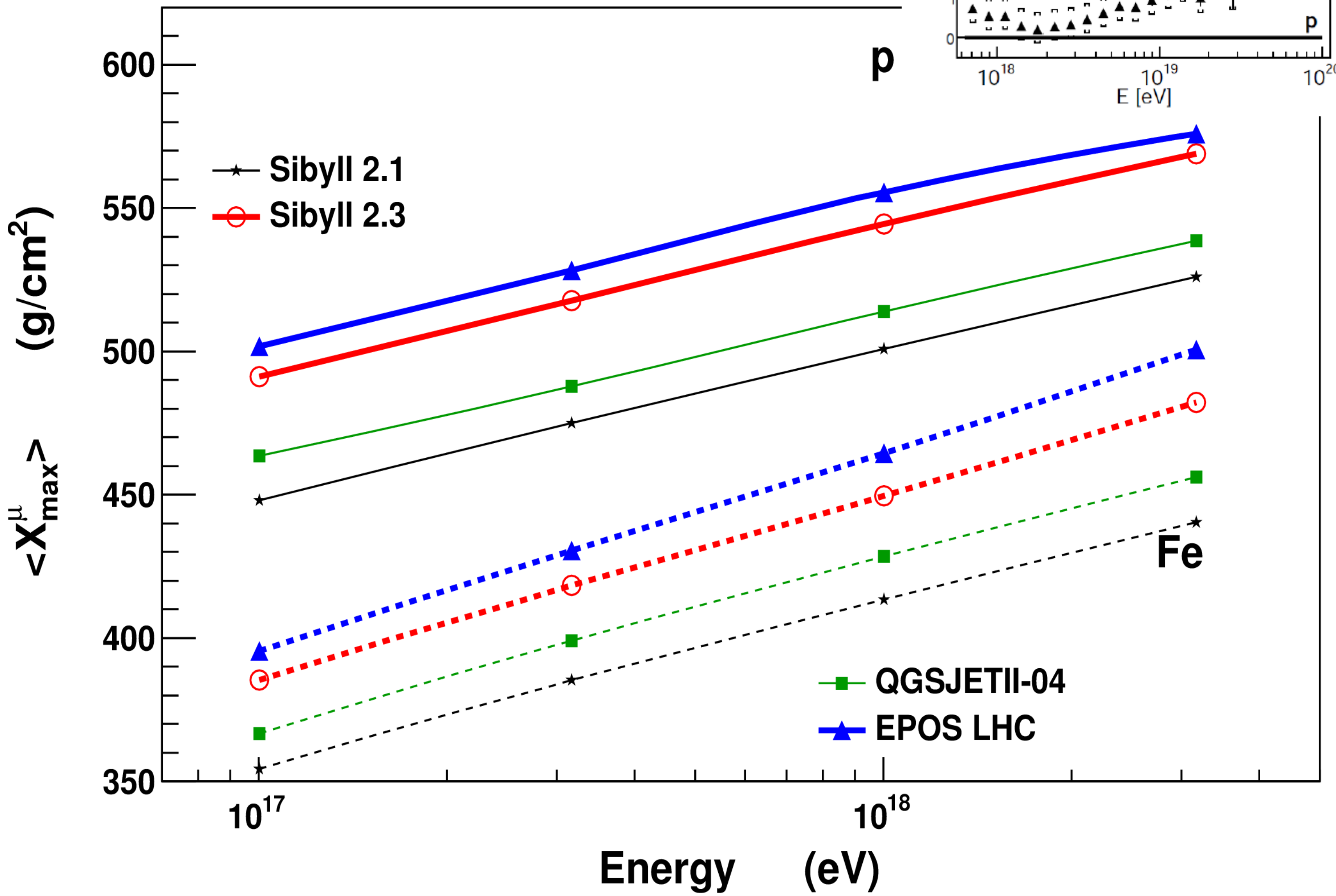


Muon Production Depth

Same for EPOS LHC and SIBYLL 2.3

- deeper X^{μ}_{max}
- link to rapidity gap measurement

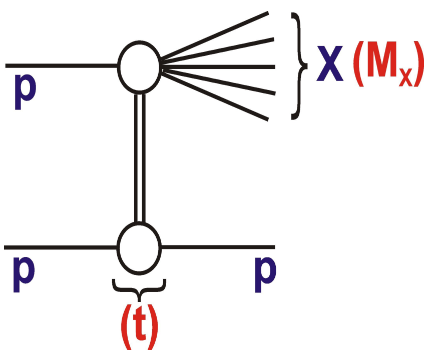




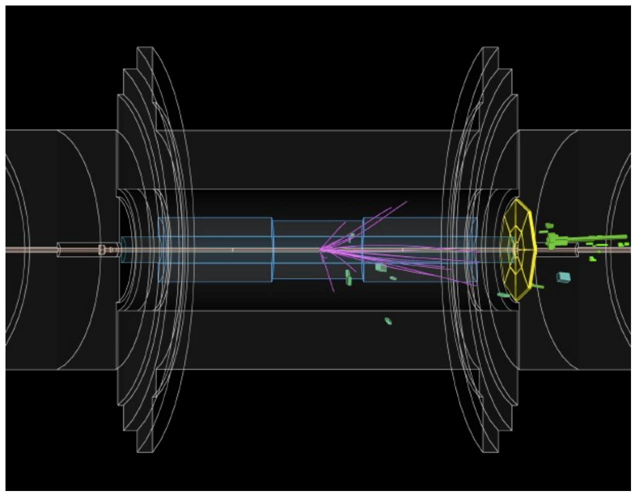
MPD changed in EPOS and SIBYLL after LHC data

Rapidity Gap

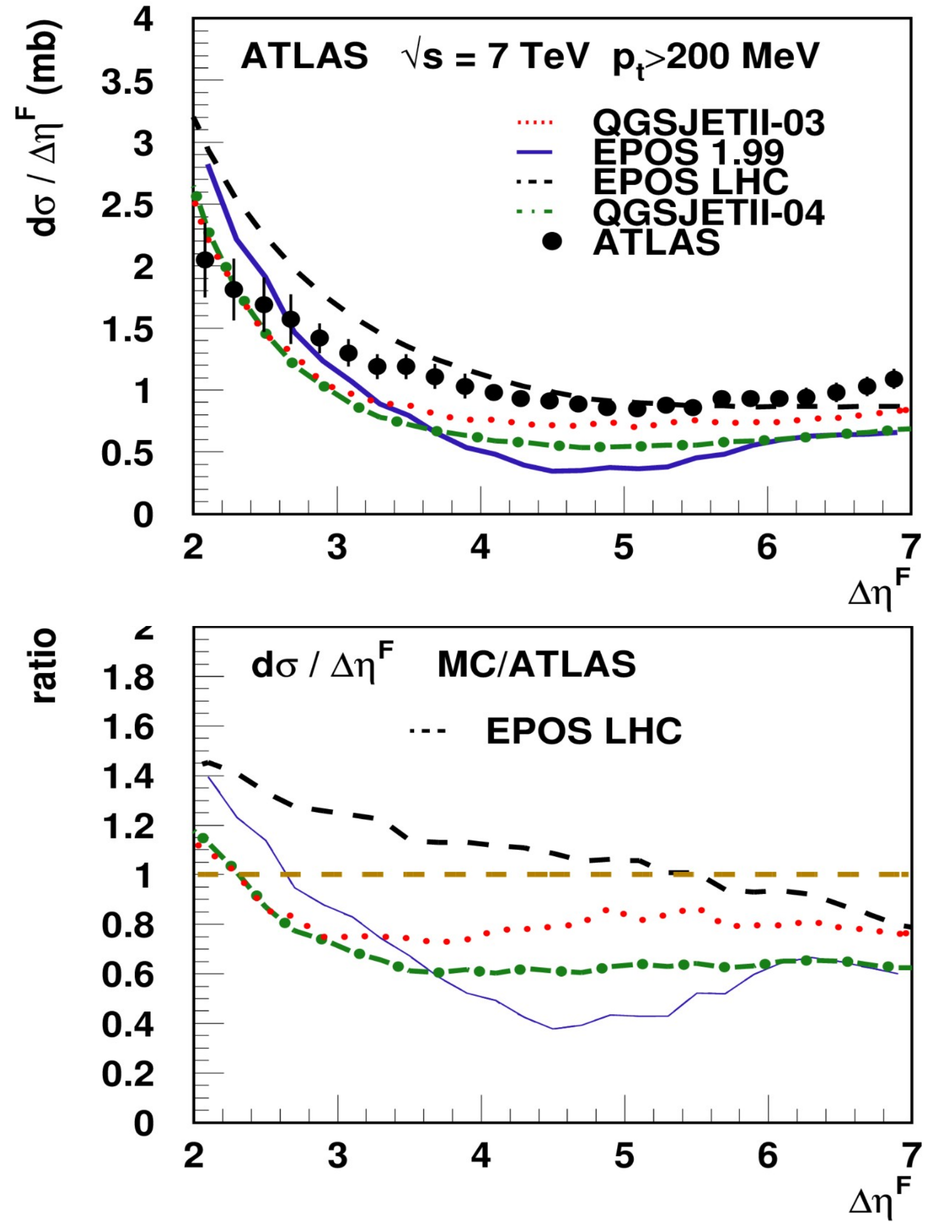
diffractive process



ATLAS detector



ATLAS Collaboration

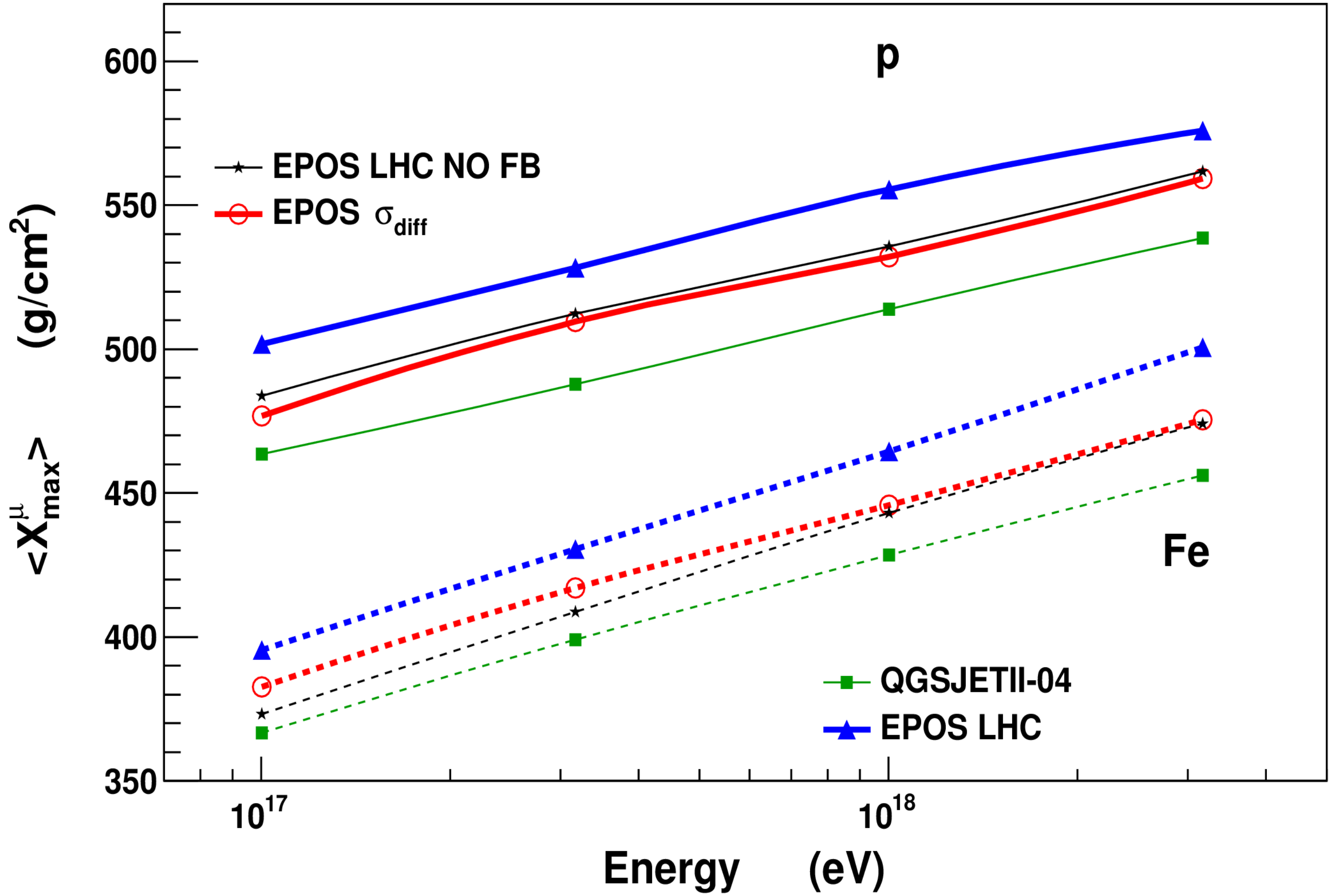


- **Rapidity gap closely related to diffraction**
  - ➡ diffractive cross-section
  - ➡ AND diffractive mass distribution
- **Hard constraint for CR**
  - ➡ high elasticity for proton seen at LHC not compatible with low value needed in air showers : pion inter.

$<X^{\mu}_{max}>$ 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

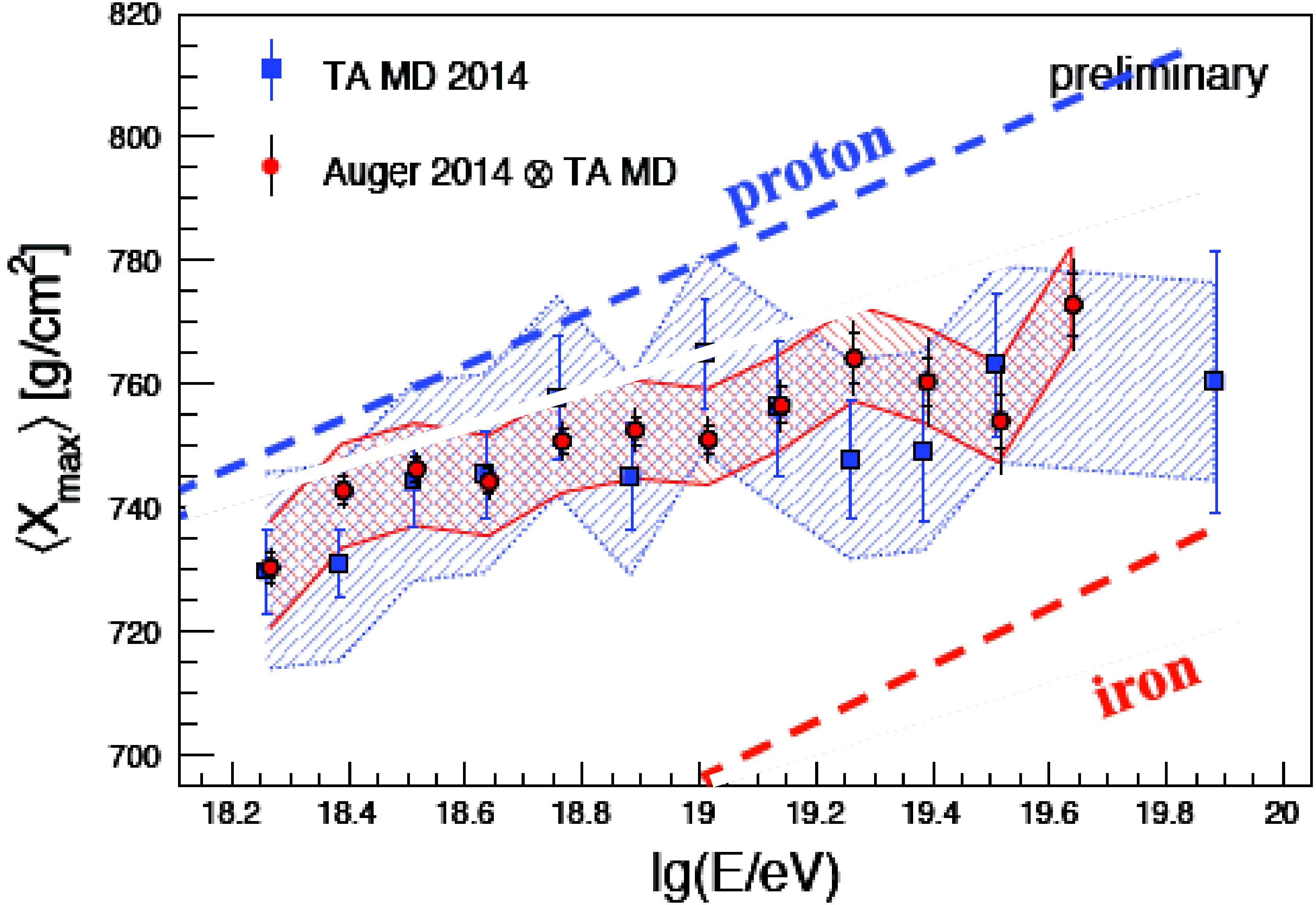
-20 g/cm² for baryons

MPD sensitive to pion interactions which should have a lower elasticity than in proton inter.

Summary

- **LHC data show no special feature and soft increase**
  - ➡ data bracketted by pre-LHC models : break in CR not due to hadronic inter.
  - ➡ post LHC models EPOS LHC and QGSJETII-04 predicted new 13 TeV correctly
- **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 ...

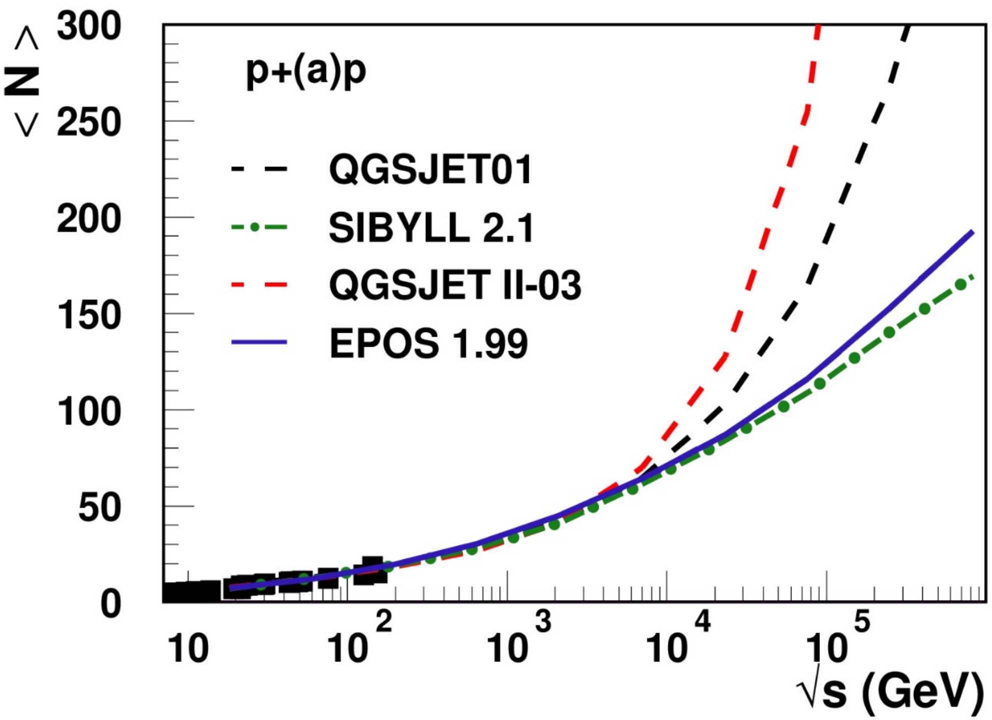


From Roberto Aloiso talk (2015 working group)

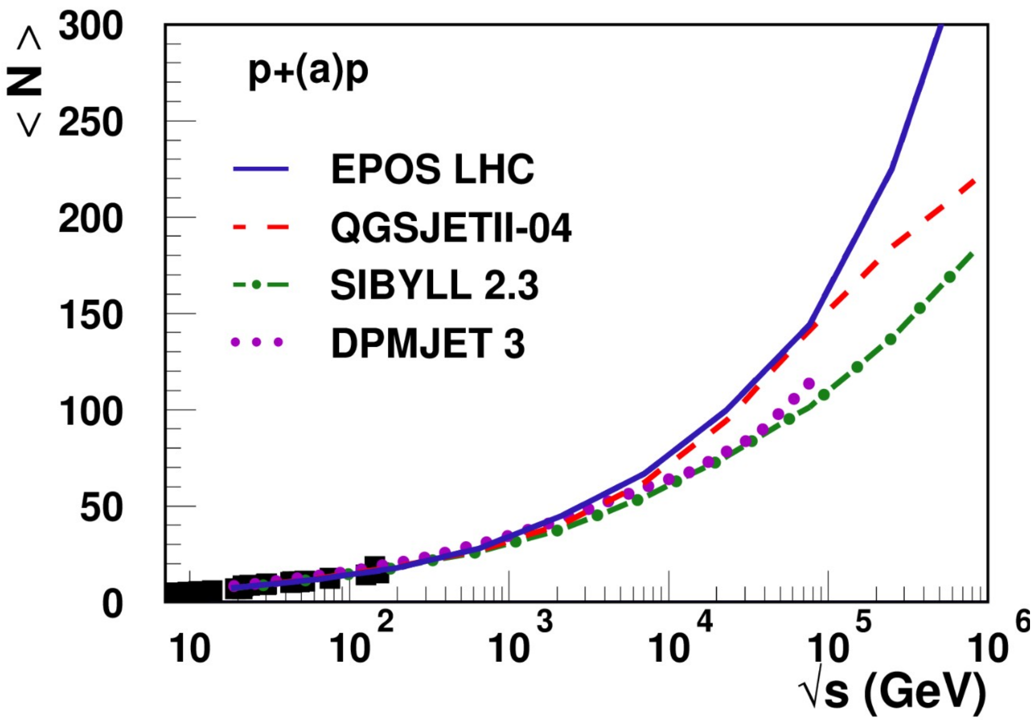
Multiplicity

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

Pre - LHC



Post - LHC



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

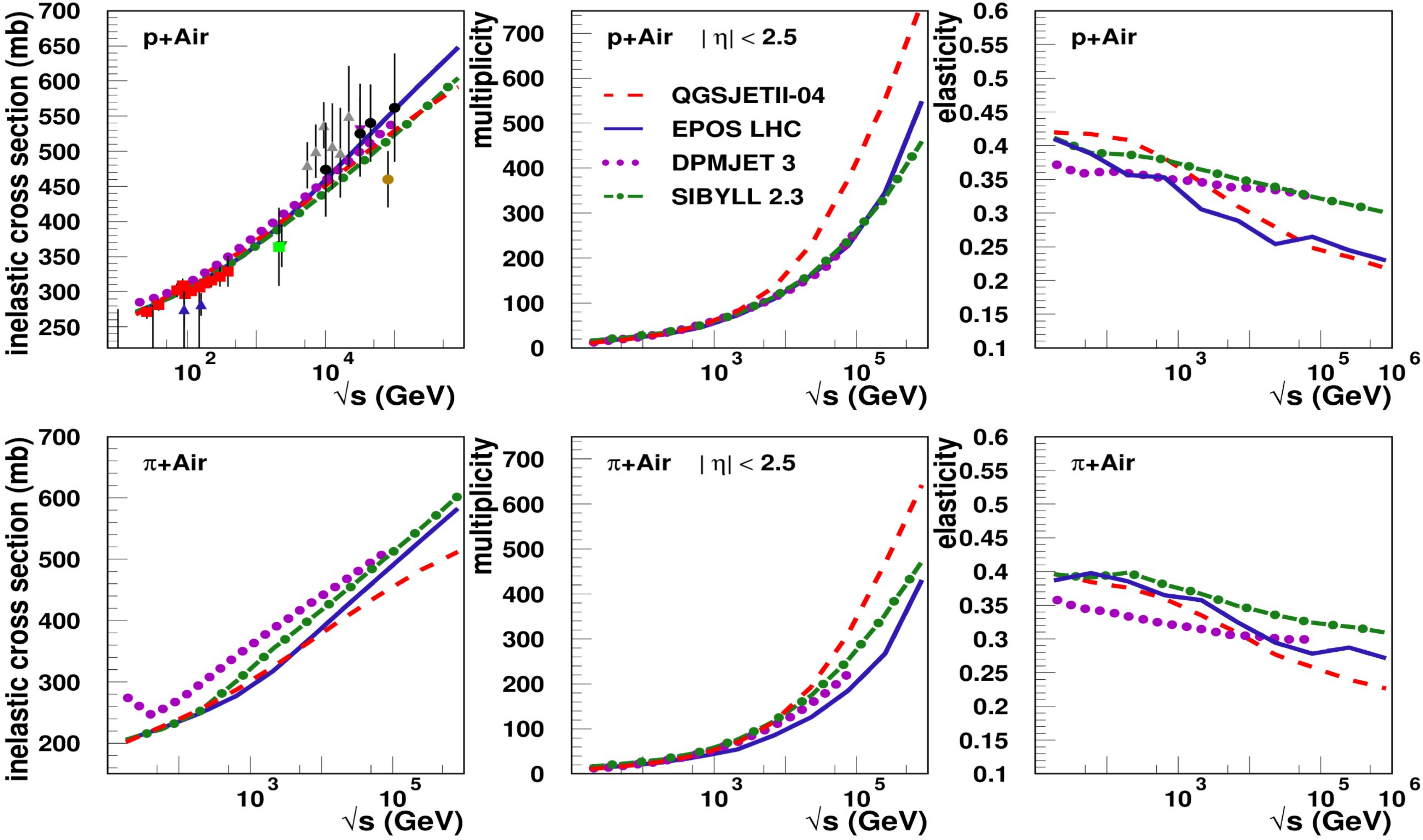
Motivation :

- update with LHC results
-fix high energy

Motivation :

- binary scaling in hard probes
-better diffraction

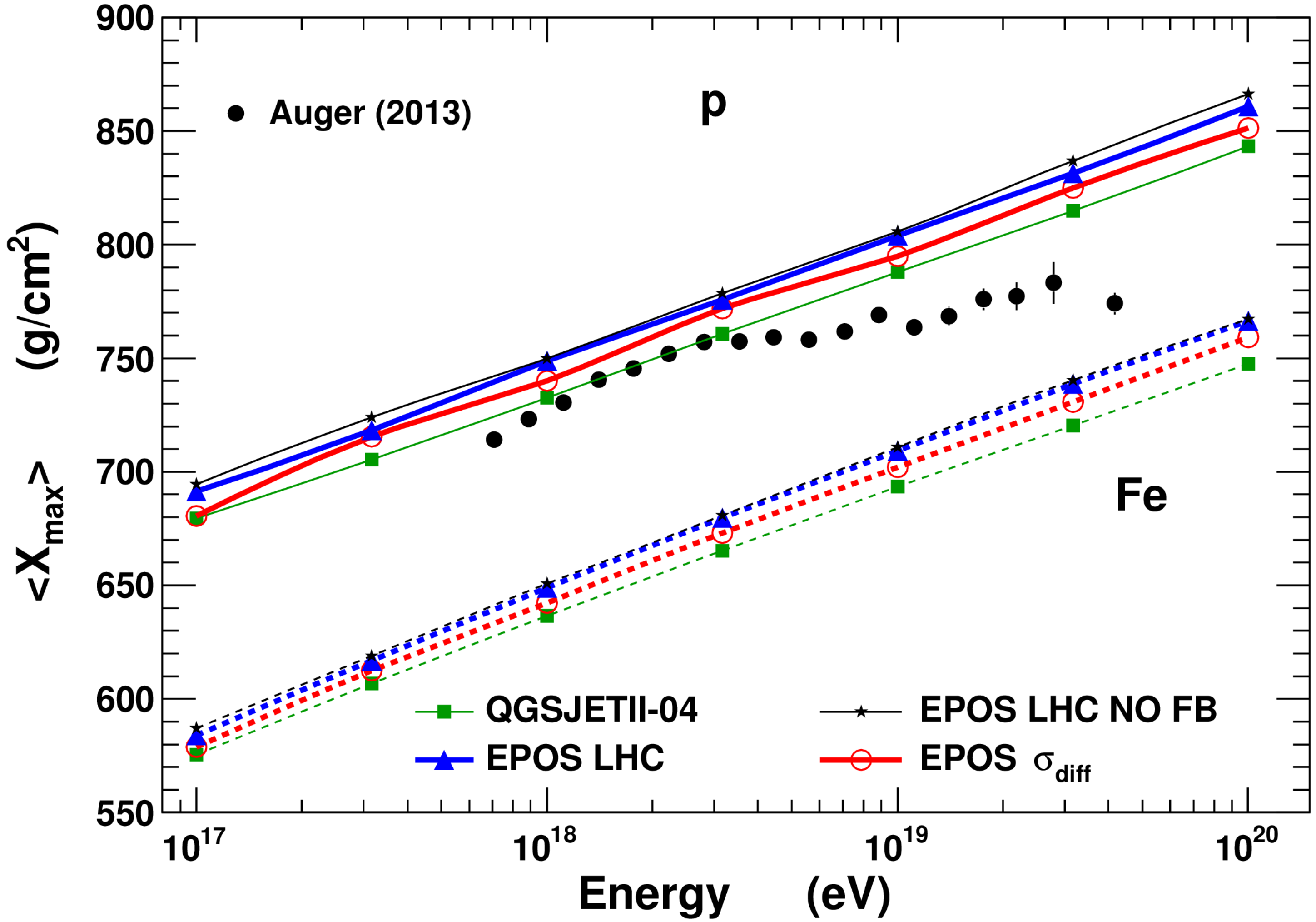
Ultra-High Energy Hadronic Model Predictions π-Air



$<X_{max}>$ 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/cm² for diff

~0 g/cm² for baryons

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