Hadronic Models and Ultra-High Energy Cosmic Ray Composition

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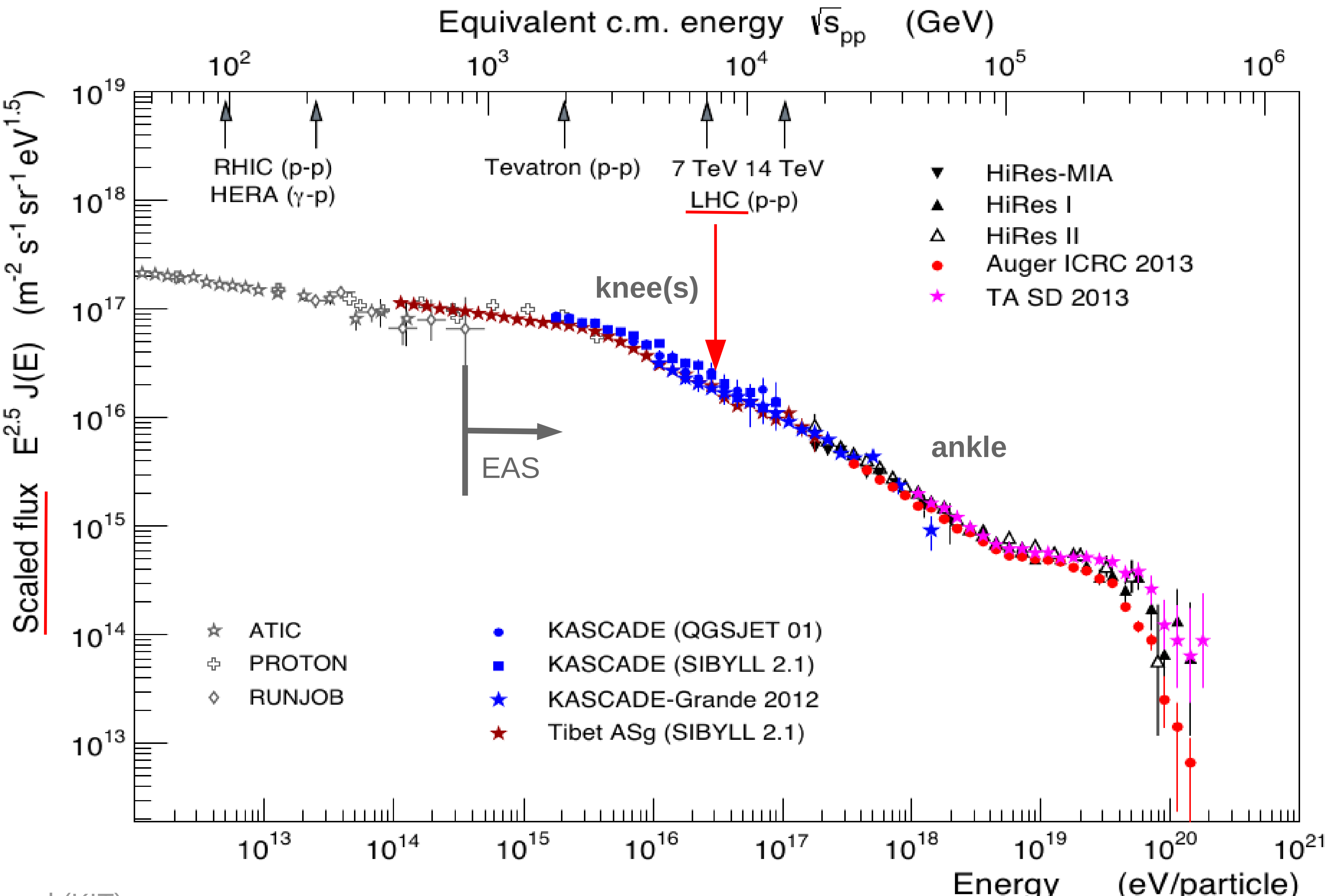
Outline

- Air showers and hadronic interactions
- Consequences of current LHC data
- Mass composition : PAO vs TA
- Summary

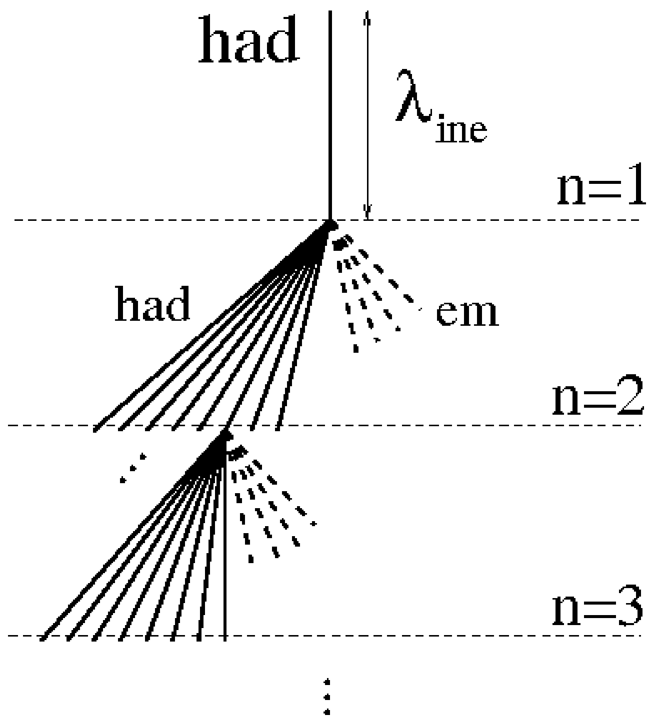
Post-LHC hadronic models increase mass composition of UHECR for both TA and PAO measurements above the Ankle.

Cosmic Ray Spectrum



R. Engel (KIT)

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)

Cosmic Ray Hadronic Interaction Models

- **Theoretical basis :**
  - pQCD (large p_t)
  - Gribov-Regge (cross section with multiple scattering)
  - energy conservation

EPOS 1.99/LHC
QGSJet01/II-03/II-04
Sibyll 2.1

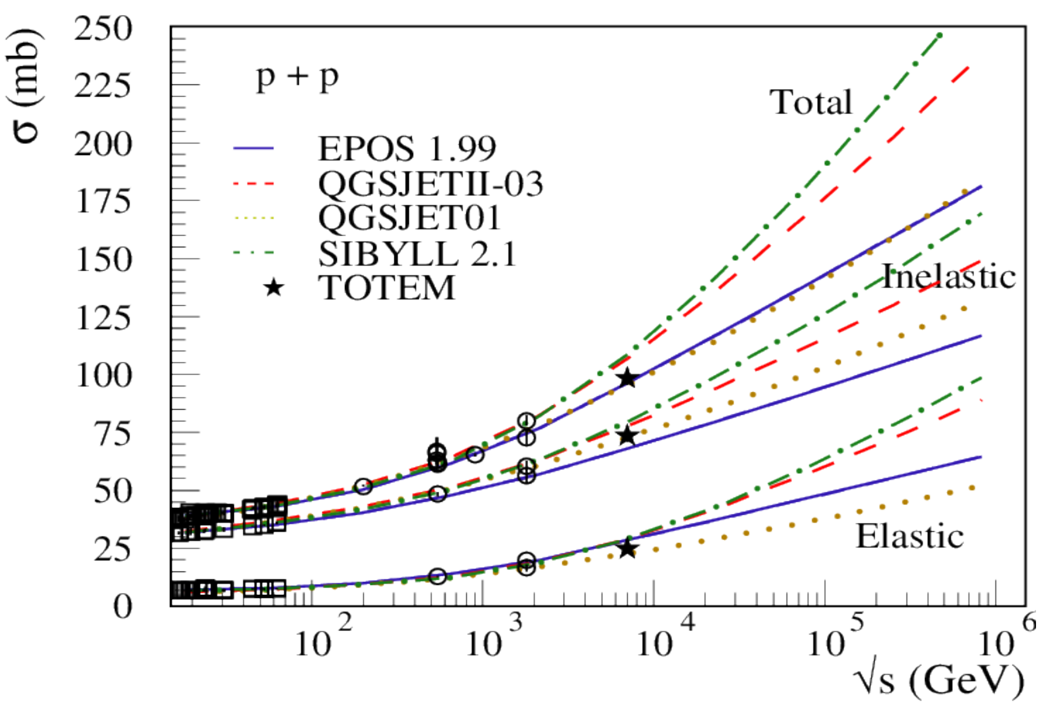
- **Phenomenology (models) :**
  - hadronization
    - string fragmentation — **EPOS modif. for LHC**
    - EPOS : high density effects (statistical hadronization and flow)
  - diffraction (Good-Walker, ...) — **QII and EPOS modif. for LHC**
  - higher order effects (multi-Pomeron interactions) — **QII modif. for LHC**
  - 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)

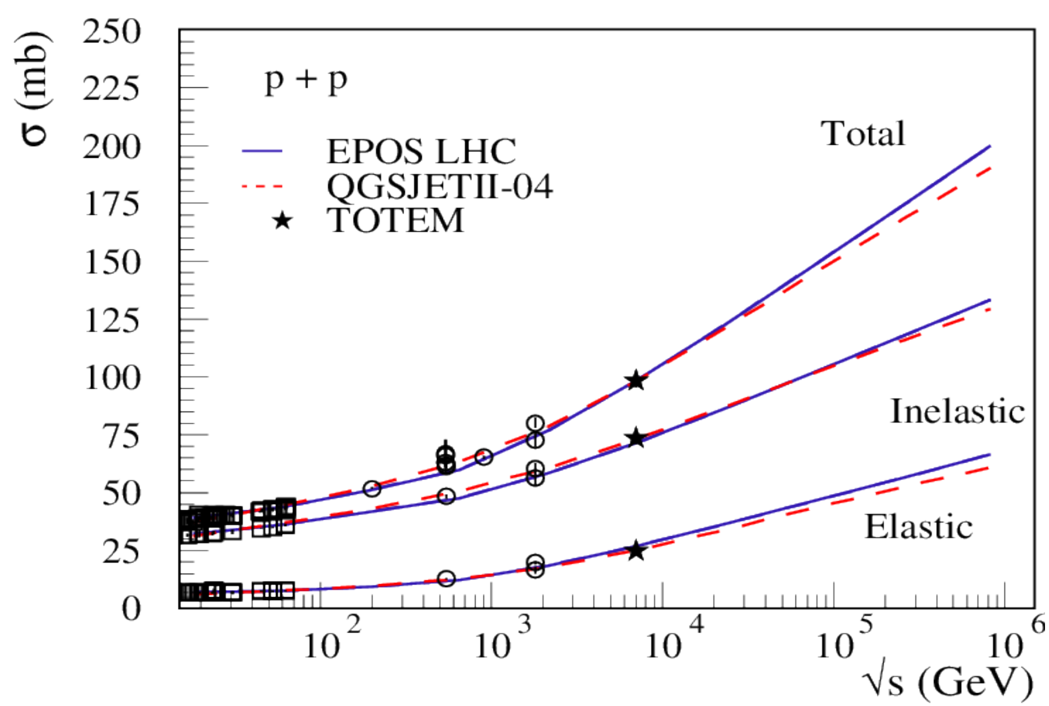
Cross Sections

- Same cross sections at pp level up to LHC
  - weak energy dependence : no room for large change beyond LHC
- other LHC measurements of inelastic cross-section (ALICE, ATLAS, CMS) test the difference between models (diffraction)

Pre - LHC



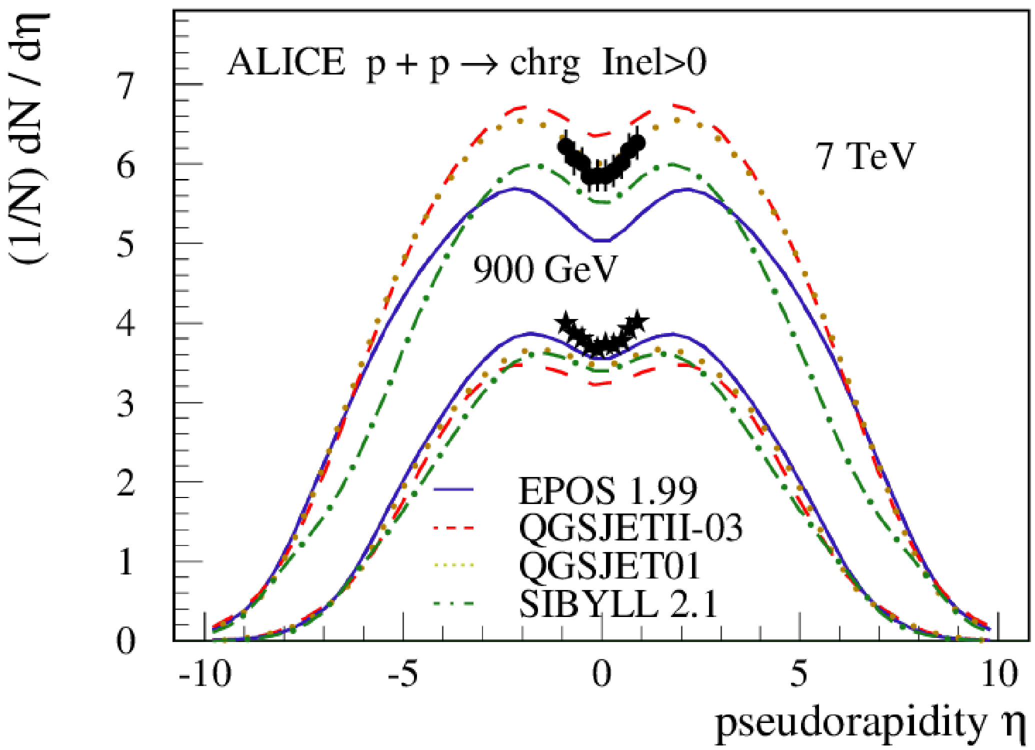
Post - LHC



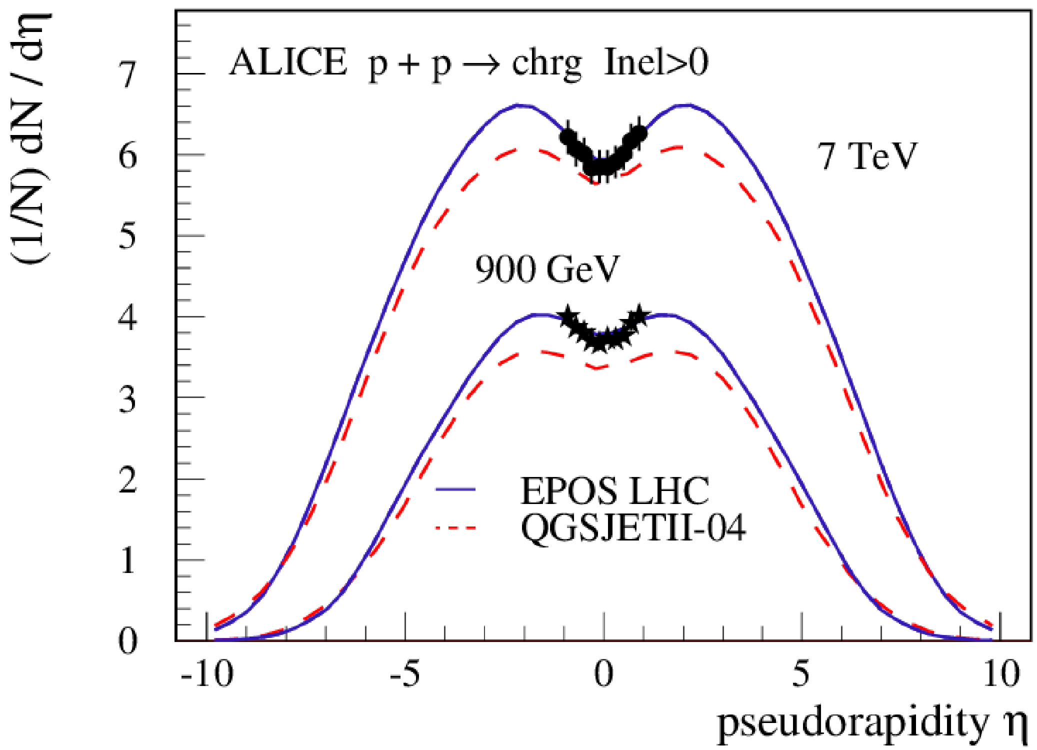
Pseudorapidity (Angular (long.) distribution)

- **Consistent results**
  - ➔ Better mean after corrections
    - difference remains in shape

Pre - LHC



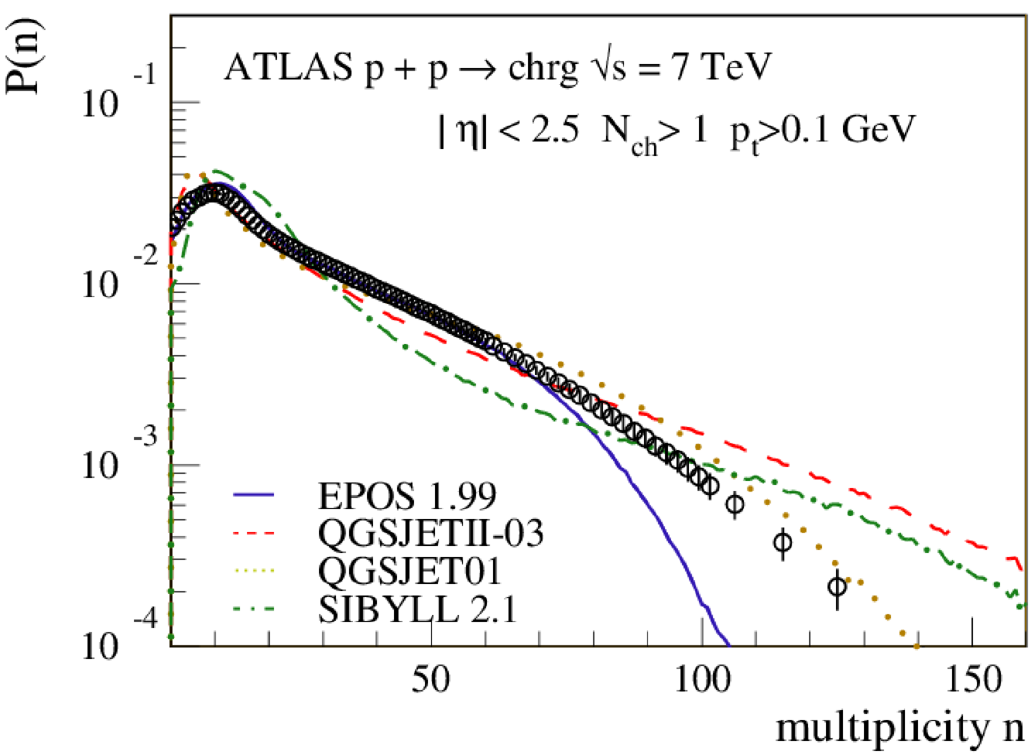
Post - LHC



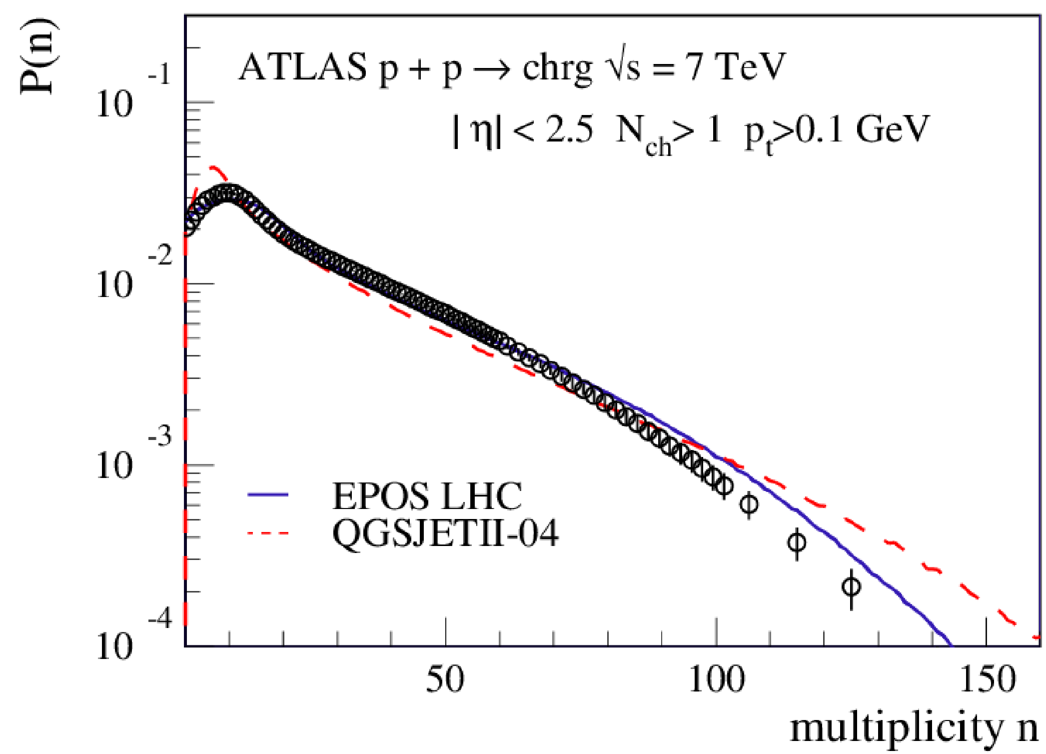
Multiplicity Distribution

- **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)

Pre - LHC

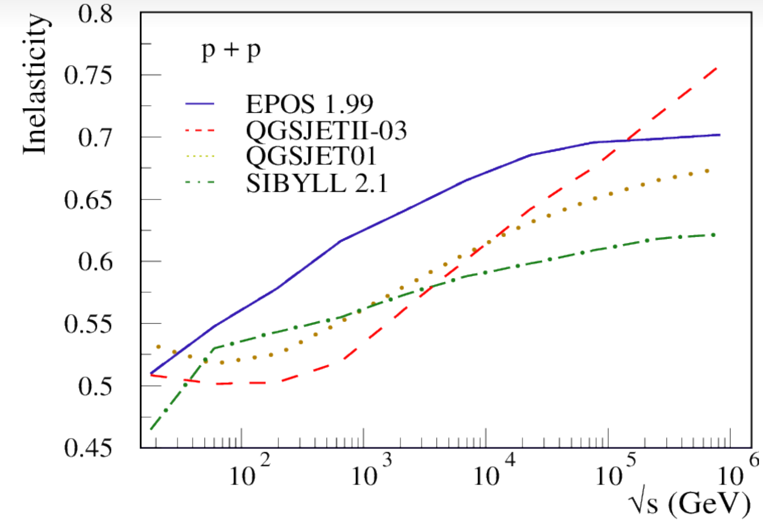


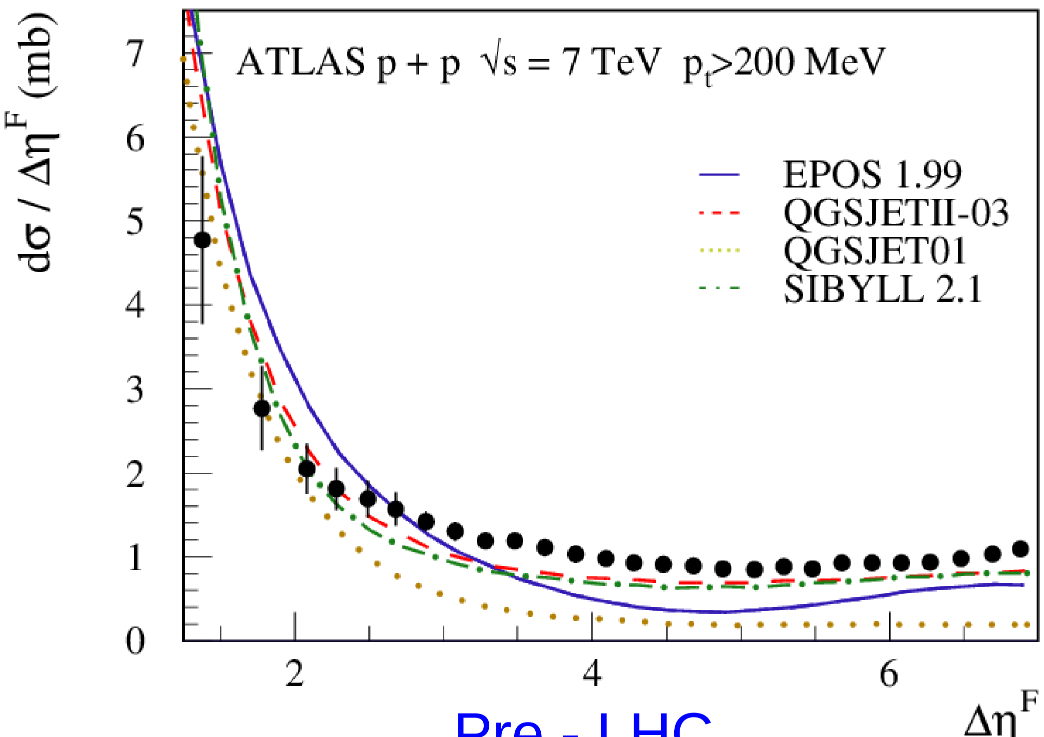
Post - LHC



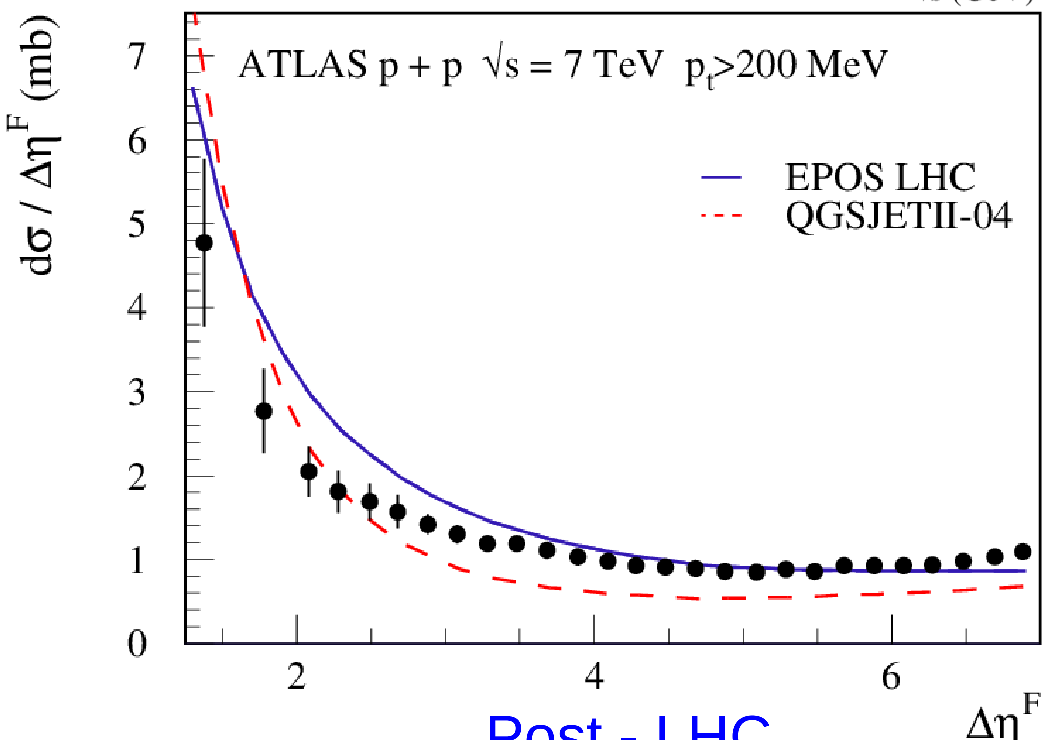
Inelasticity

- **Difficult to measure : larger uncertainty**
  - ➜ Difference in diffraction
    - low mass / high mass / central diffraction





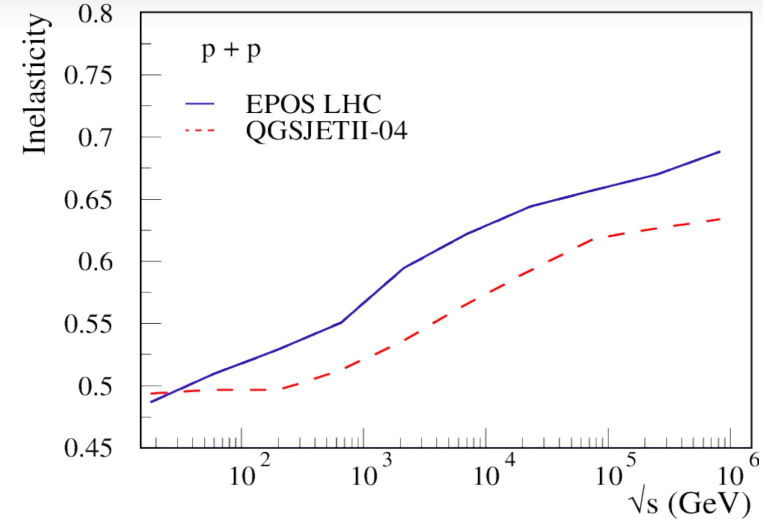
Pre - LHC

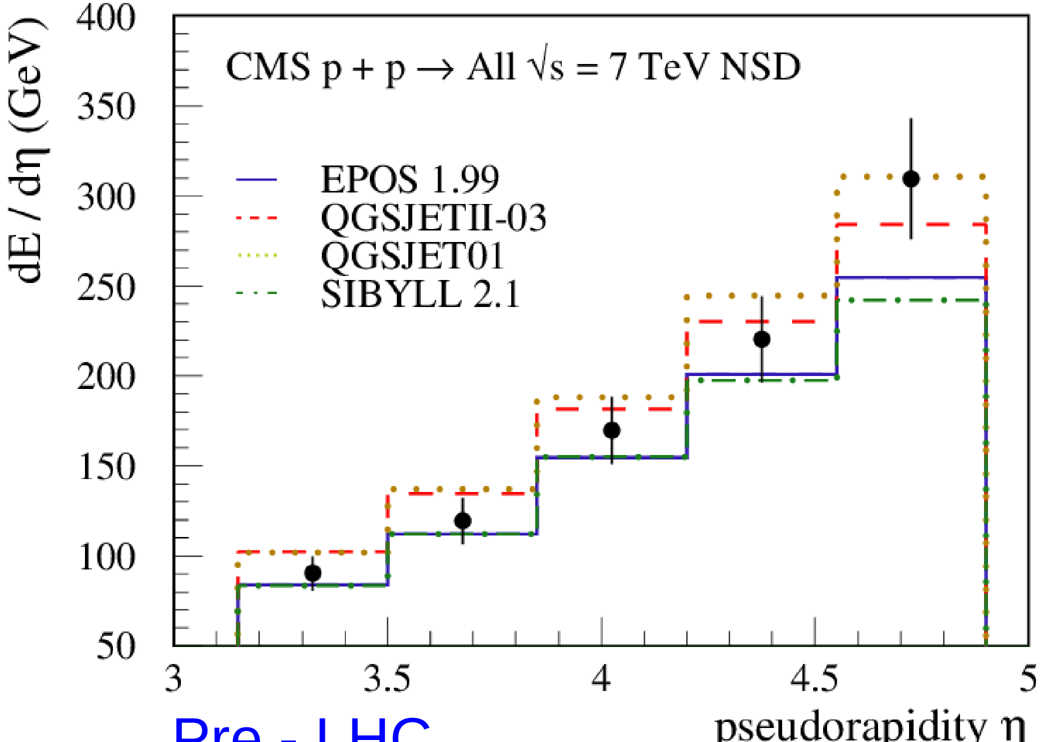


Post - LHC

Inelasticity

- **Difficult to measure : larger uncertainty**
  - ➡ Difference in diffraction
    - low mass / high mass / central diffraction
  - ➡ very similar energy flow





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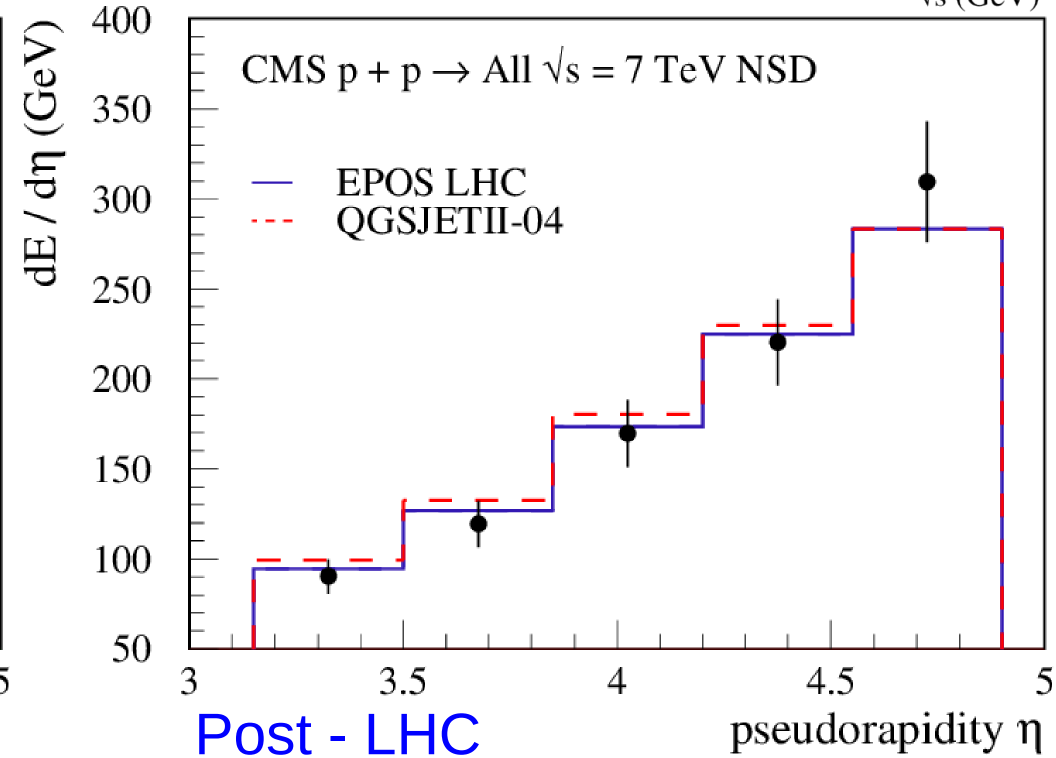
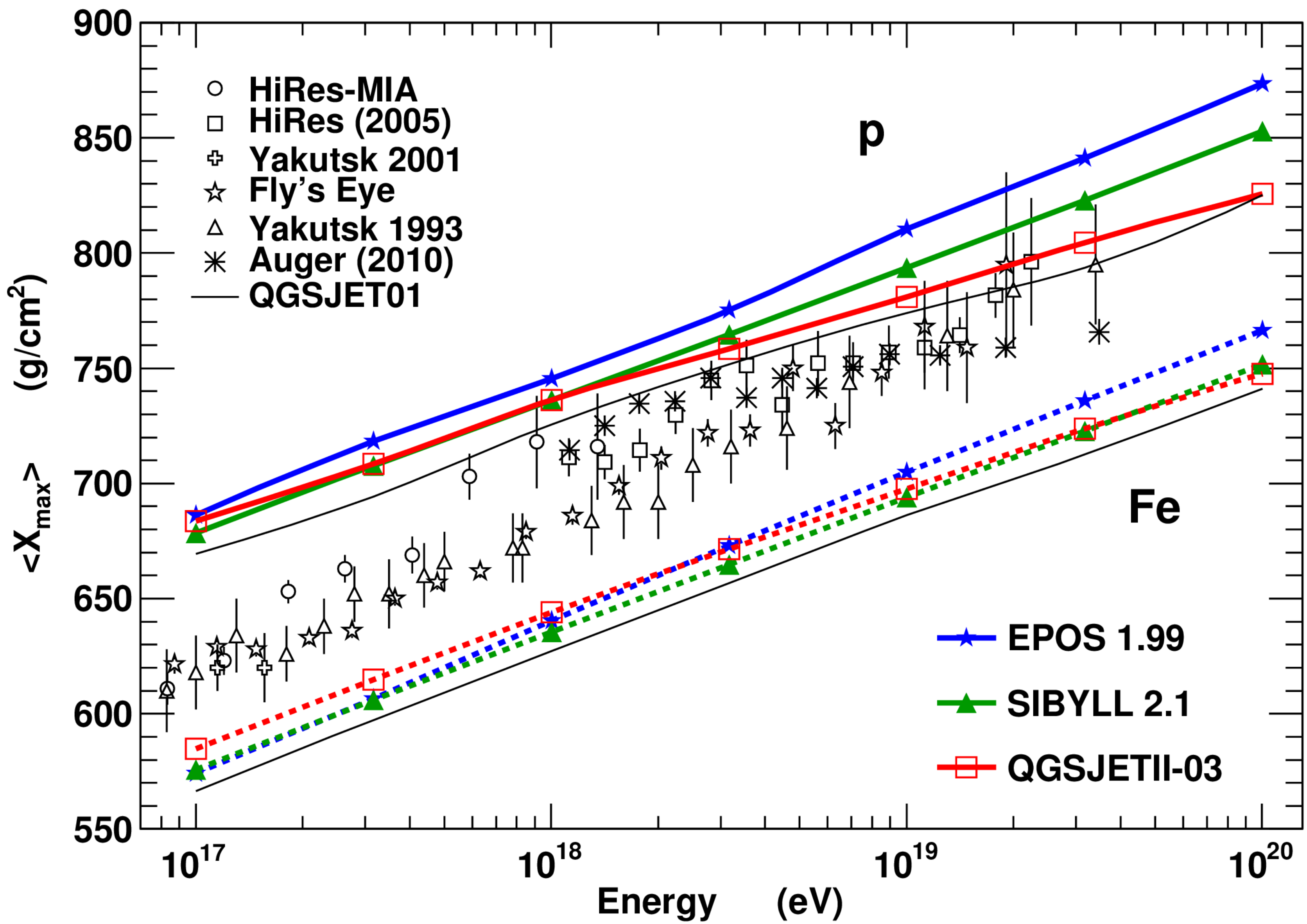
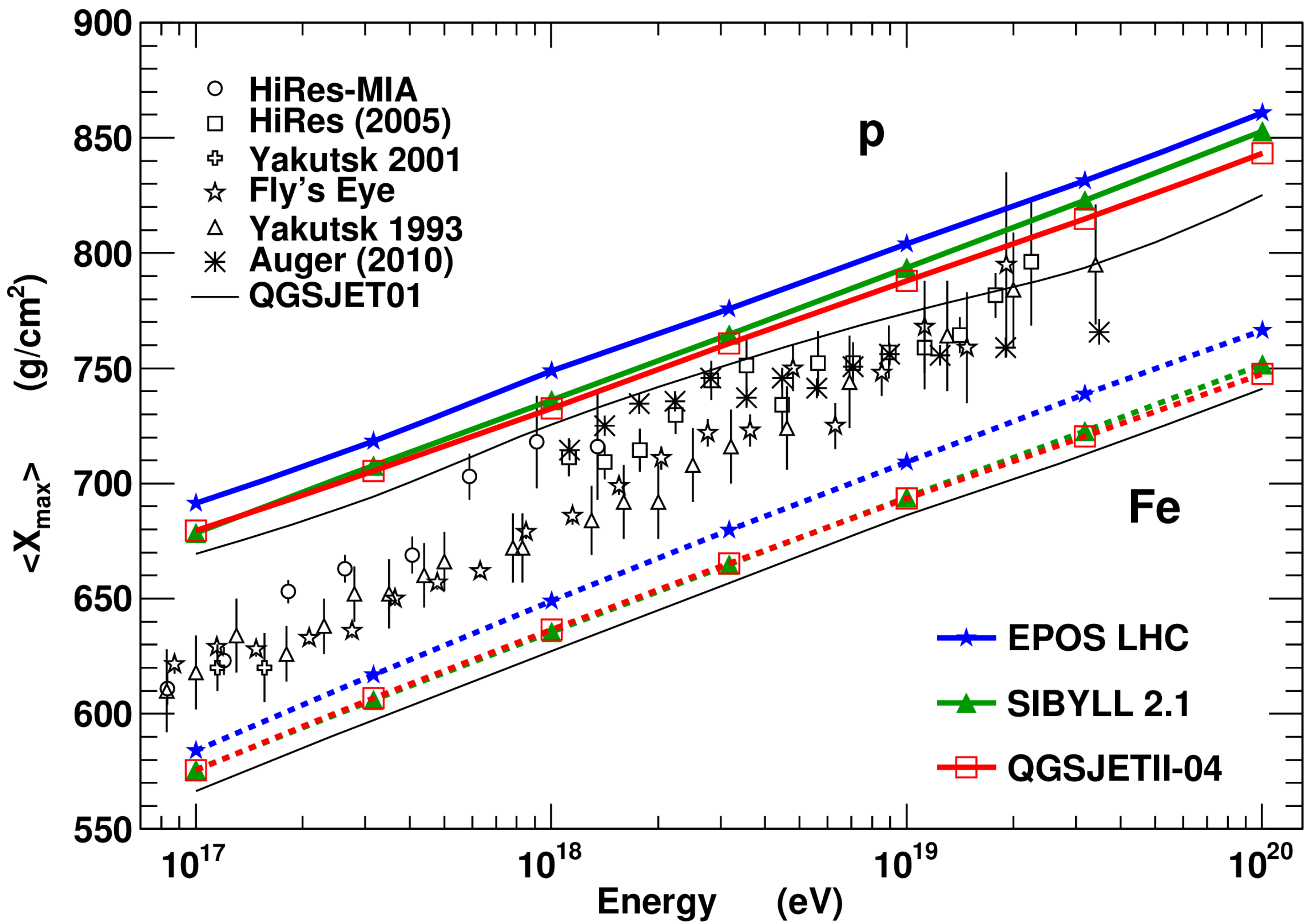


Post - LHC

EAS with Old CR Models : X_{max}

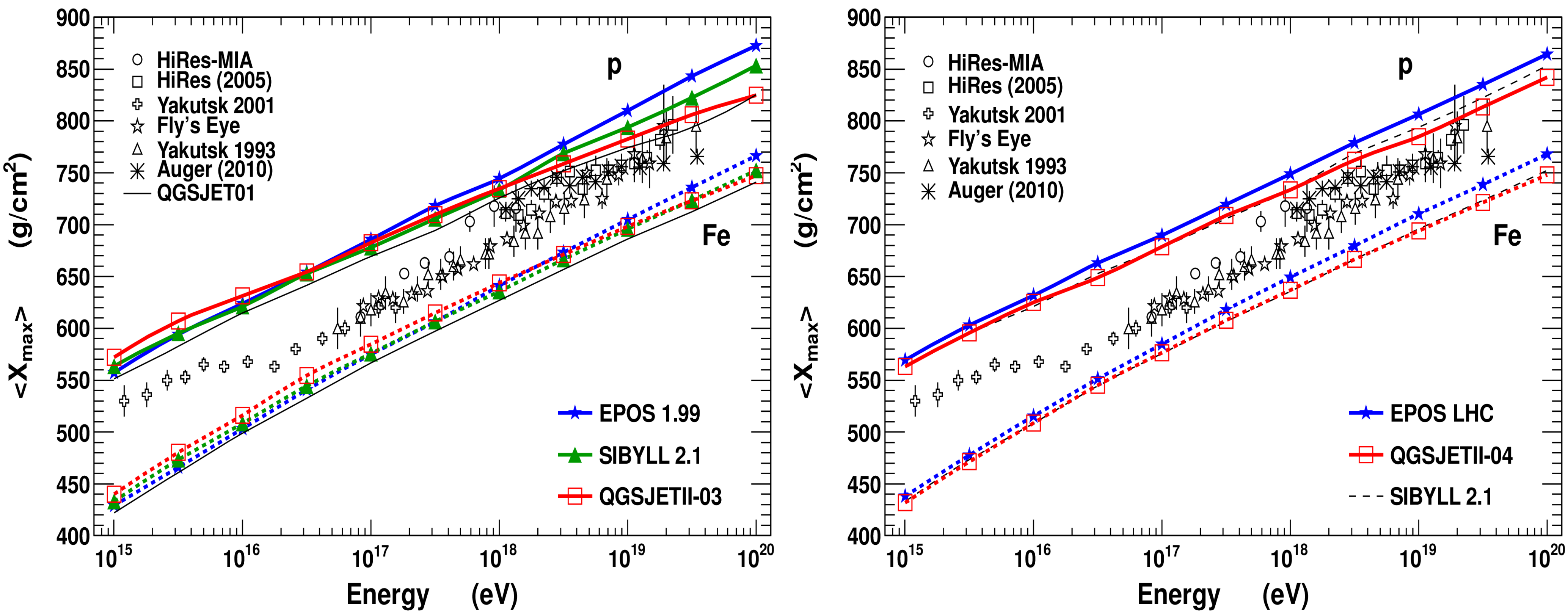


EAS with Re-tuned CR Models : X_{max}



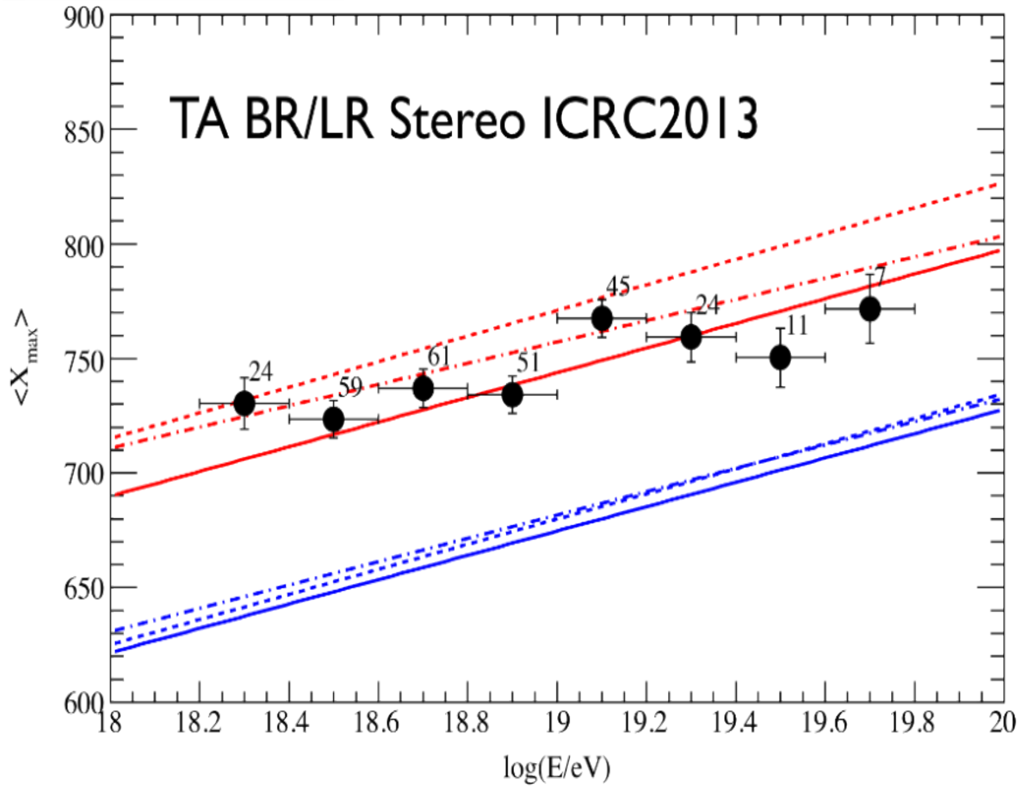
EAS with Re-tuned CR Models : X_{max}

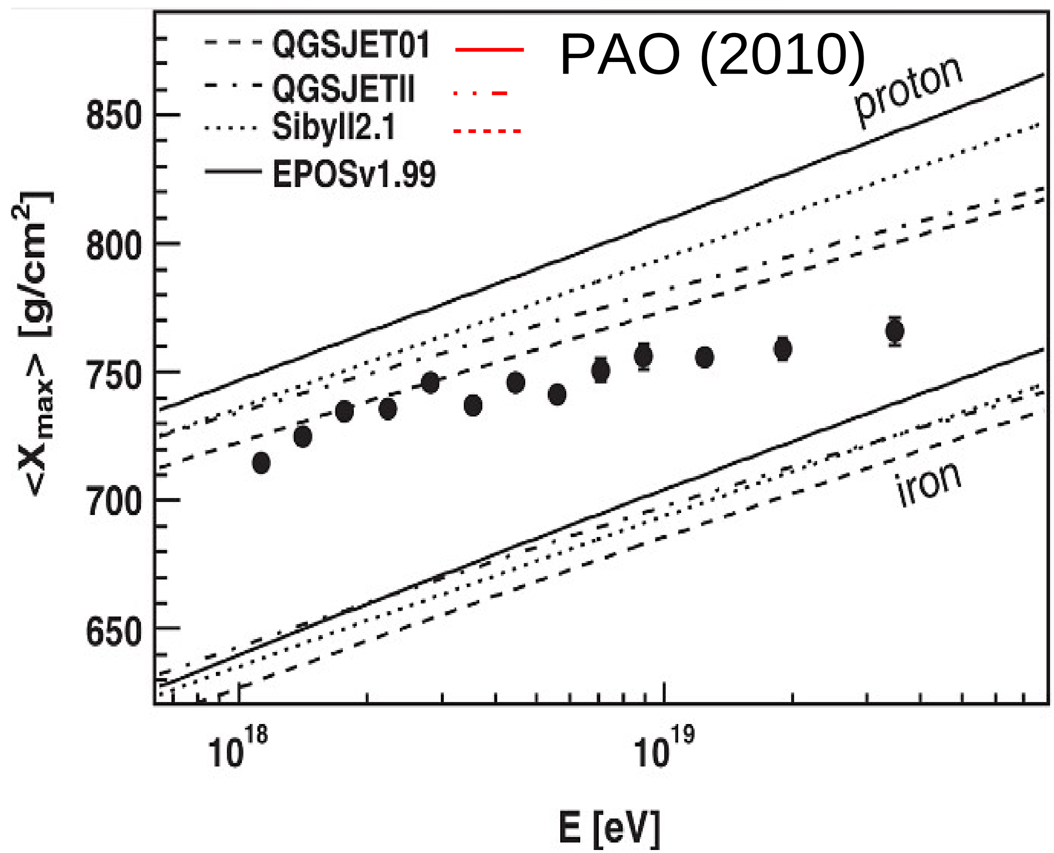
- **Cross section and multiplicity fixed at 7 TeV**
  - ➡ smaller slope for EPOS and larger for QGSJETII
  - ➡ re-tuned model converge to old Sibyll 2.1 predictions
    - ◆ reduced uncertainty from ~50 g/cm² to ~20 g/cm² (difference proton/iron is about 100 g/cm²)



PAO vs TA before LHC

- **Data very similar but different models used**
  - TA data tested against QGSJETII-03 (only) : compatible with proton
  - PAO data best described by EPOS 1.99 (<X_{max}> vs RMS consistency)
    - not compatible with pure proton (neither with pure iron) : mixed





PAO vs TA before LHC

- **Data very similar but different models used**
  - ➡ TA data tested against QGSJETII-03 data : compatible with proton
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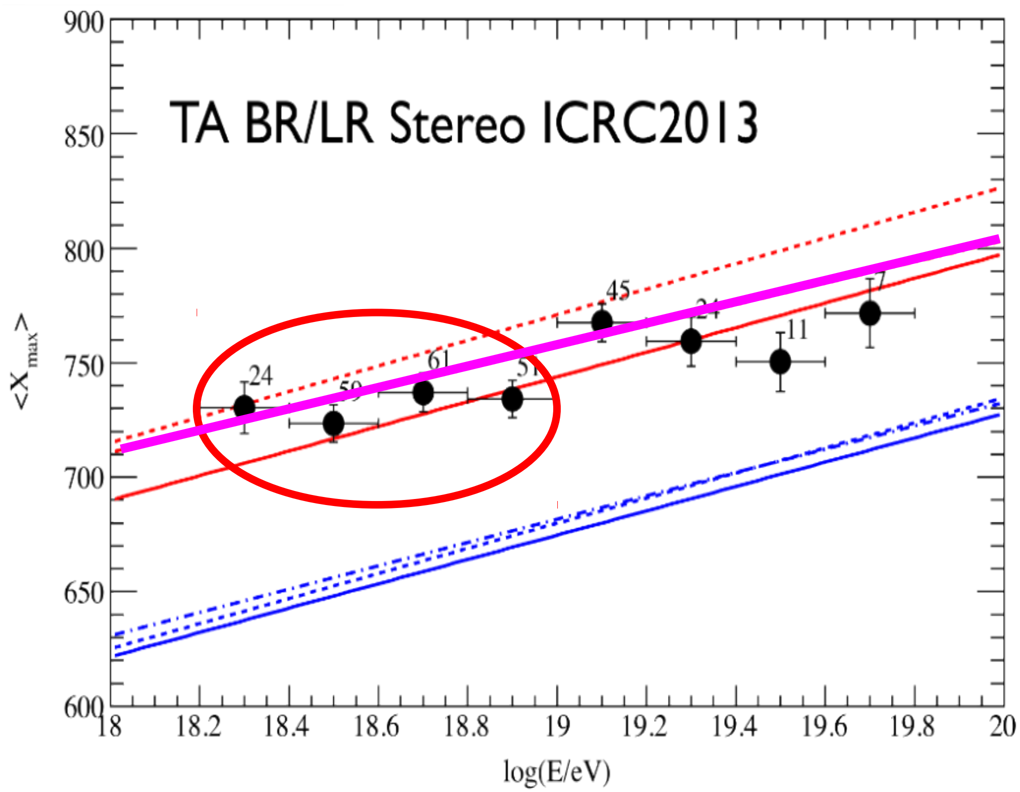
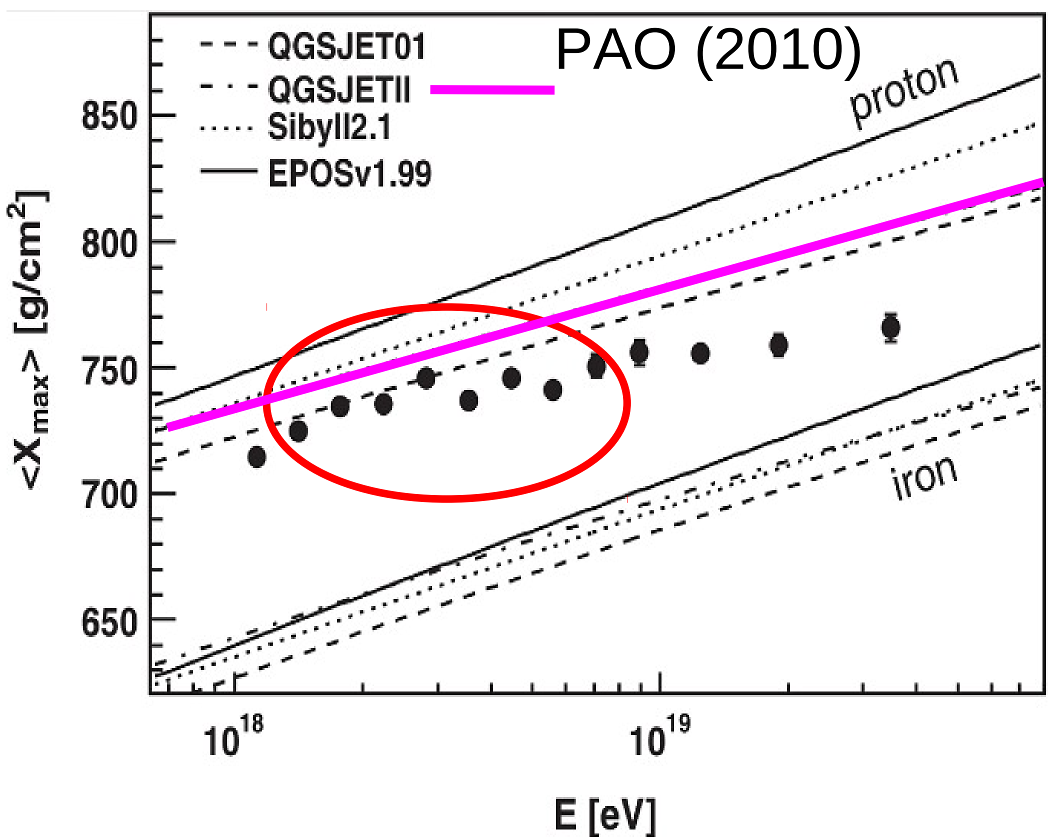


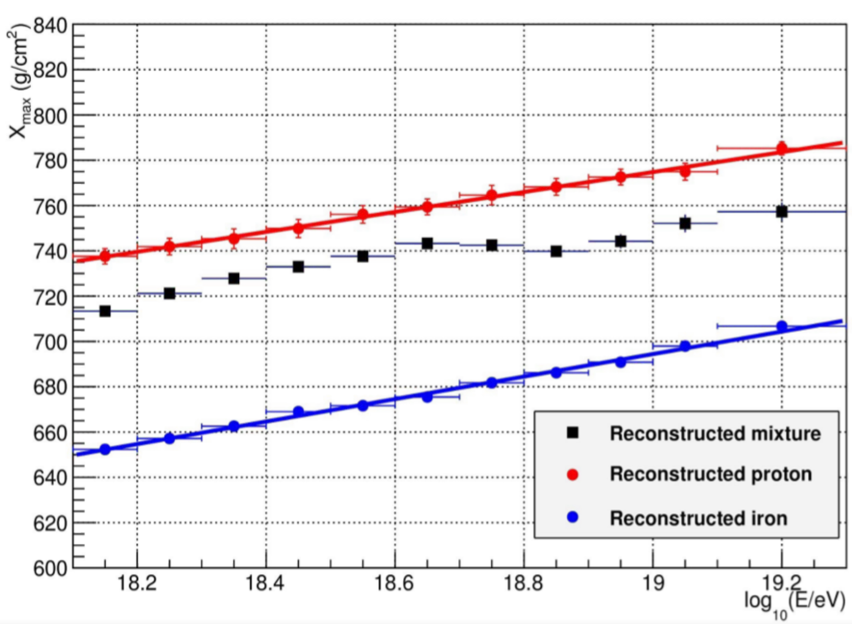


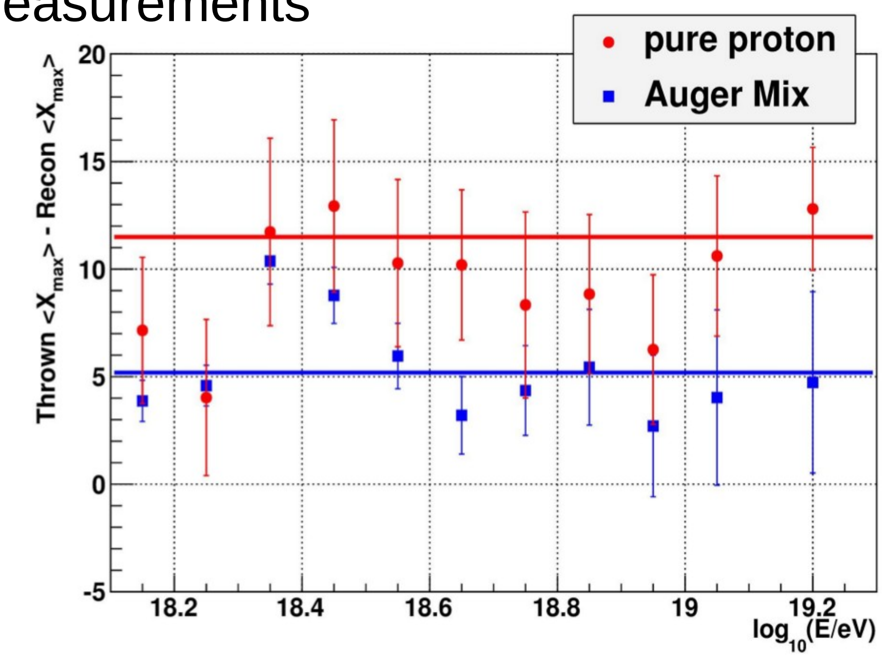
Measurement Bias in TA

- **Different model curves on $<X_{max}>$ plots**
  - PAO : fiducial field of view cuts : data can be compared to model simulation without detector geometry simulations
  - TA : statistic too low to apply cuts on data : simulations take into account field of view bias

    model curves in PAO and TA are different !

- **TA field of view bias is a non-linear correction vs mass**
  - TA/PAO working group to compare measurements





Official Statement without LHC models

- **PAO data are mixed composition going to heavier mass at high energy**
  - ➔ not compatible with proton at all energies (only at low energy with QII-03)
  - ➔ not compatible with iron at all energies
- **TA data are :**
  - ➔ compatible with proton at all energies
  - ➔ not compatible with iron at all energies
- **TA statistic is more than 10 times smaller than PAO :**

Roadmap for Ultra-High Energy Cosmic Ray Physics and Astronomy (whitepaper for Snowmass 2013)

Luis A. Anchordoqui,[1] Glennys R. Farrar,[2] John F. Krizmanic,[3,4] Jim Matthews,[5] John W. Mitchell,[3] Dave Nitz,[6] Angela V. Olinto,[7,8] Thomas C. Paul,[1,9] Pierre Sokolsky,[10] Gordon B. Thomson,[11] and Thomas J. Weiler[12]

An additional intriguing twist in the present observational situation is that the HiRes and TA results are consistent with a proton dominated flux everywhere above the ankle [19, 20], although with present statistics the TA and Auger elongation rates agree within errors [21]. Since the sources seen by the HiRes and TA in the Northern hemisphere may not the same sources as seen by the Auger Observatory in the South, the composition need not be the same.

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- **TA data are :**
  - ➡ compatible with proton at all energies
  - ➡ not compatible with iron at all energies

TA data compatible with pure proton AND mixed composition (PAO) using QGSJetII-03

- **TA statistic is more than 10 times smaller than PAO :**

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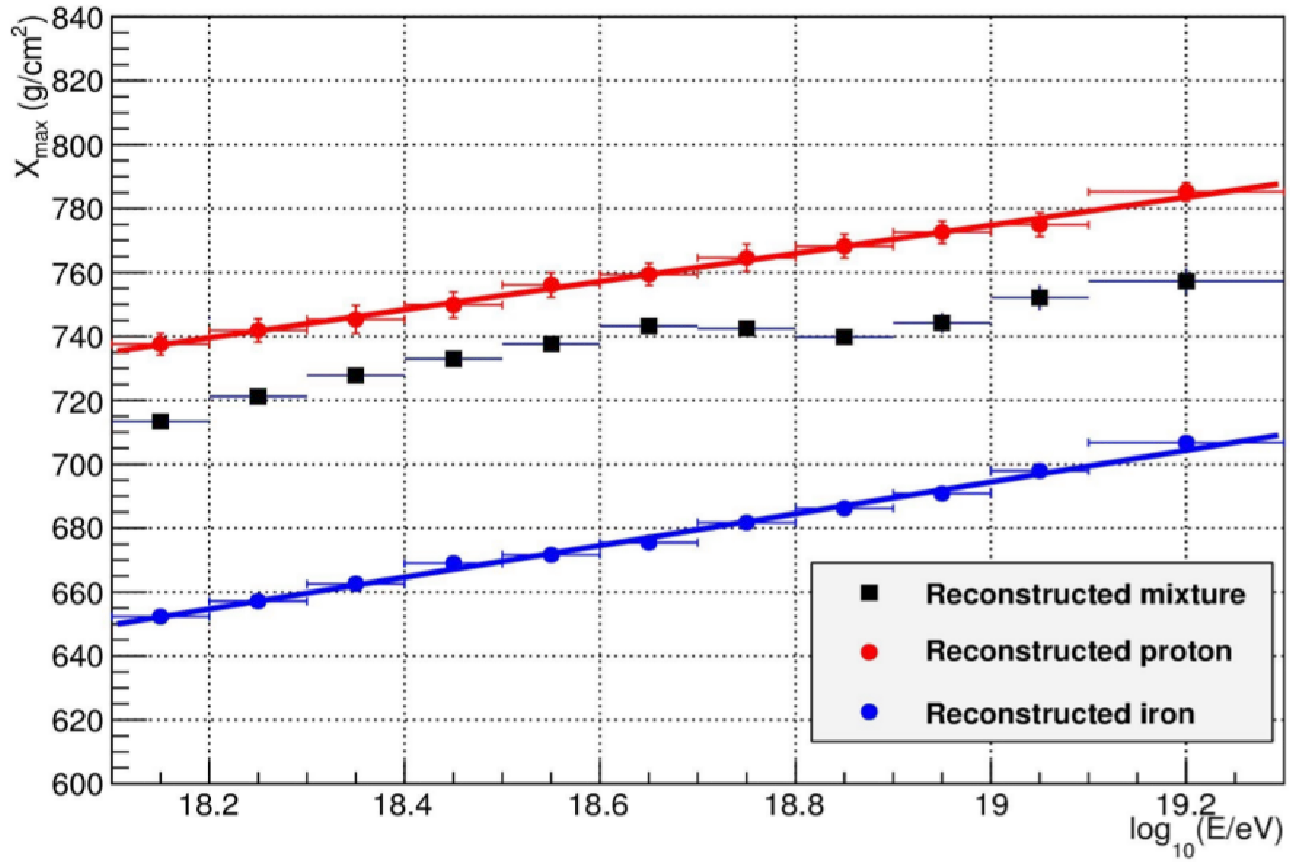
Tests using TA/PAO Working Group Results

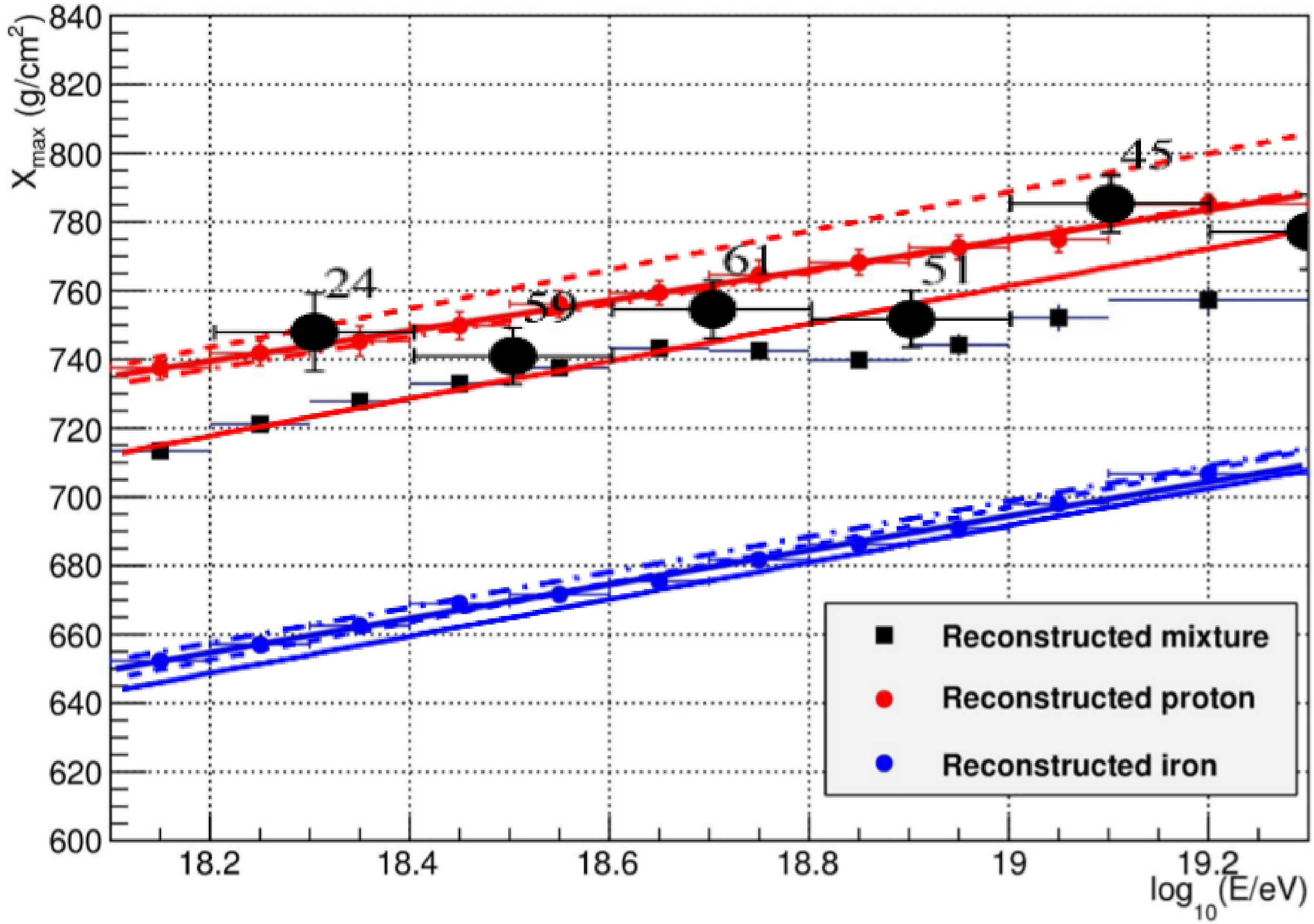
- **PAO X_{max} distributions simulated using QGSJETII-03 model with mixed composition and reconstructed as data by TA**
  - ➜ conclusion : with high statistic, TA can disentangle proton and mixed (PAO type) composition



Tests using TA/PAO Working Group Results

- **Test : overlay stereo data on top of reconstructed PAO data**
  - ➜ not done by TA or PAO !

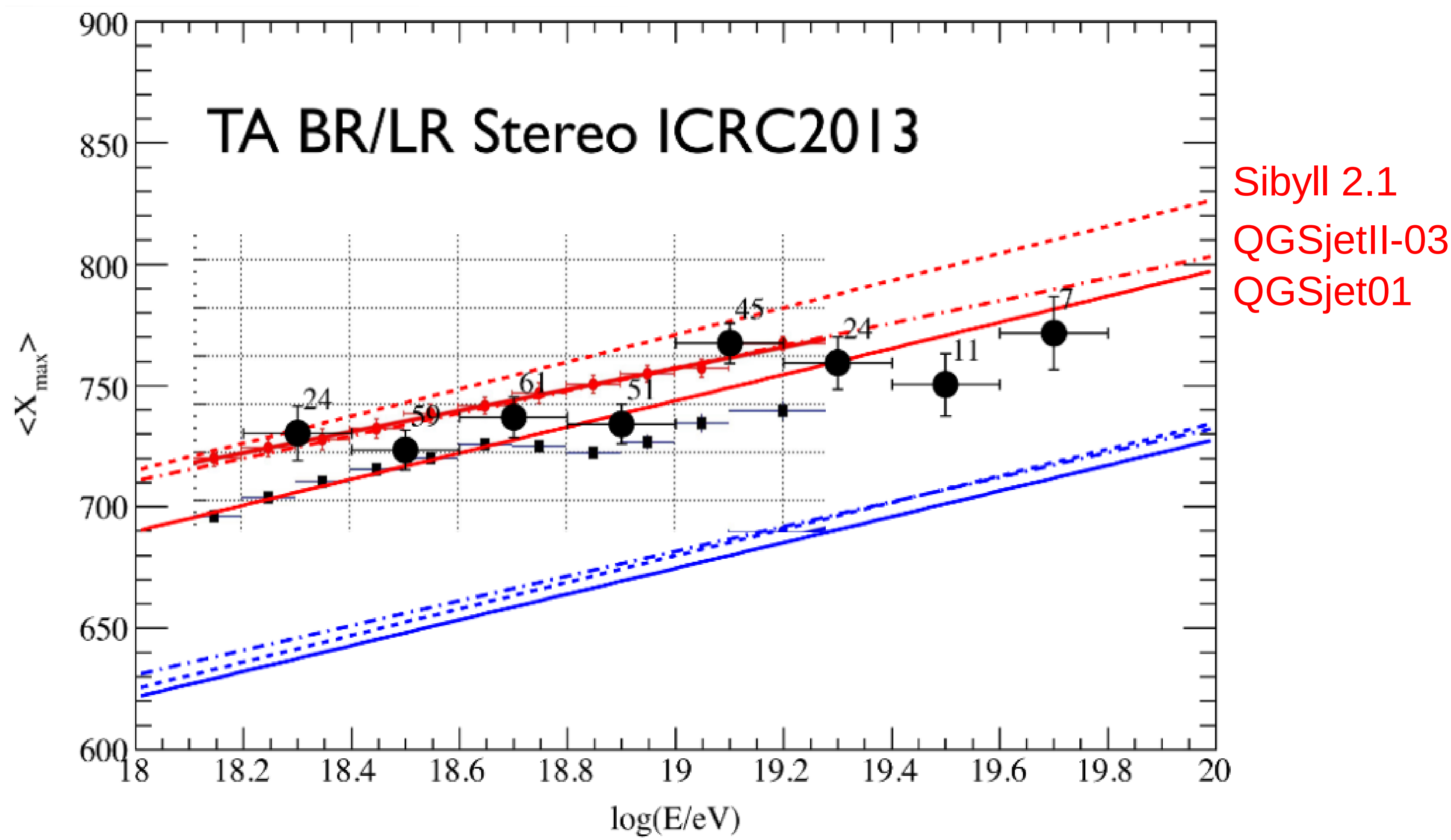
(my own test : model used as reference ➡ data shifted by +20 g/cm²)



Sibyll 2.1
QGSjetII-03
QGSjet01

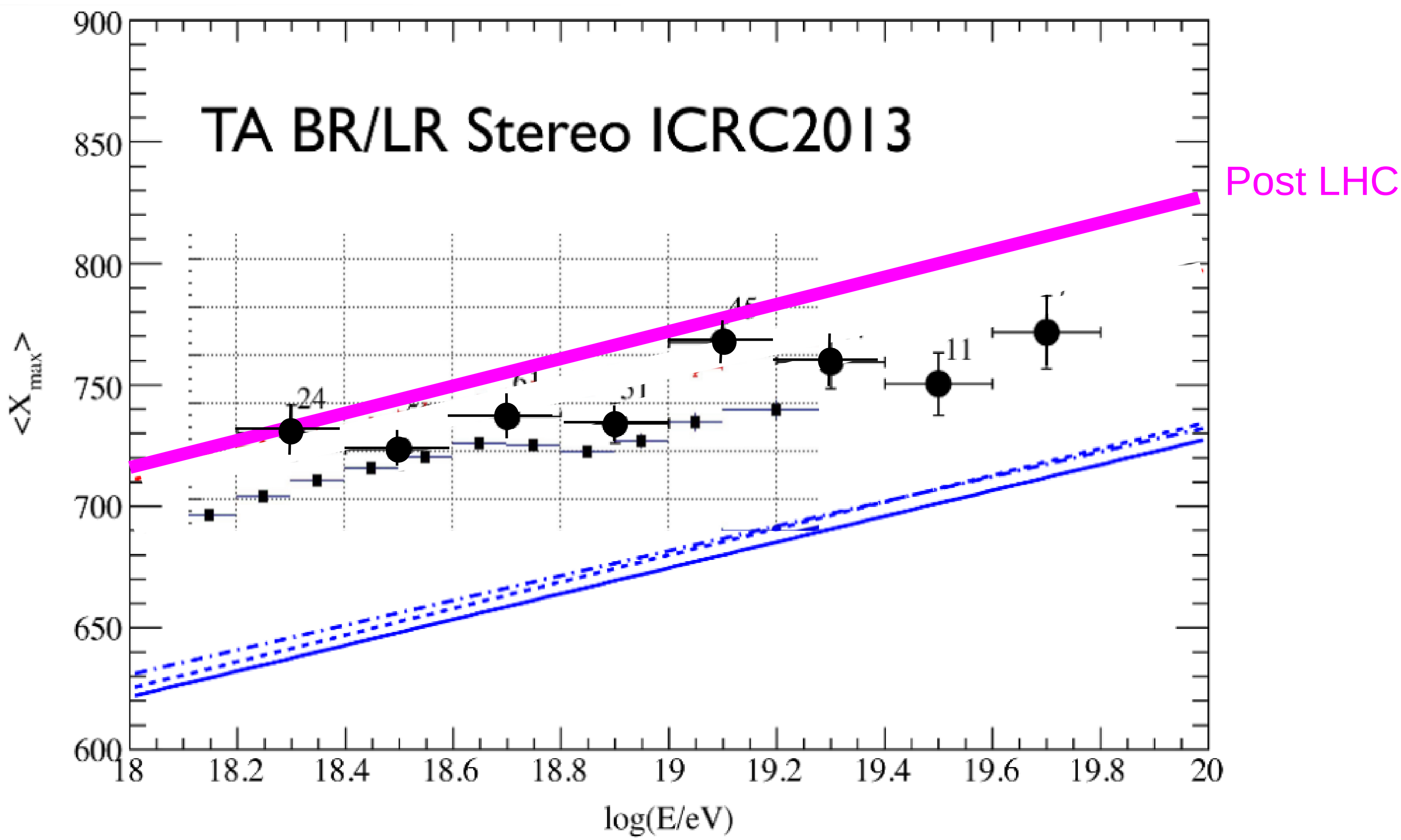
Tests using TA/PAO Working Group Results

- **Test : overlay stereo data on top of reconstructed PAO data**
  - ➡ not done by TA or PAO ! (my own test)
  - ➡ check that TA as compatible with proton (QII-03) than PAO mixed



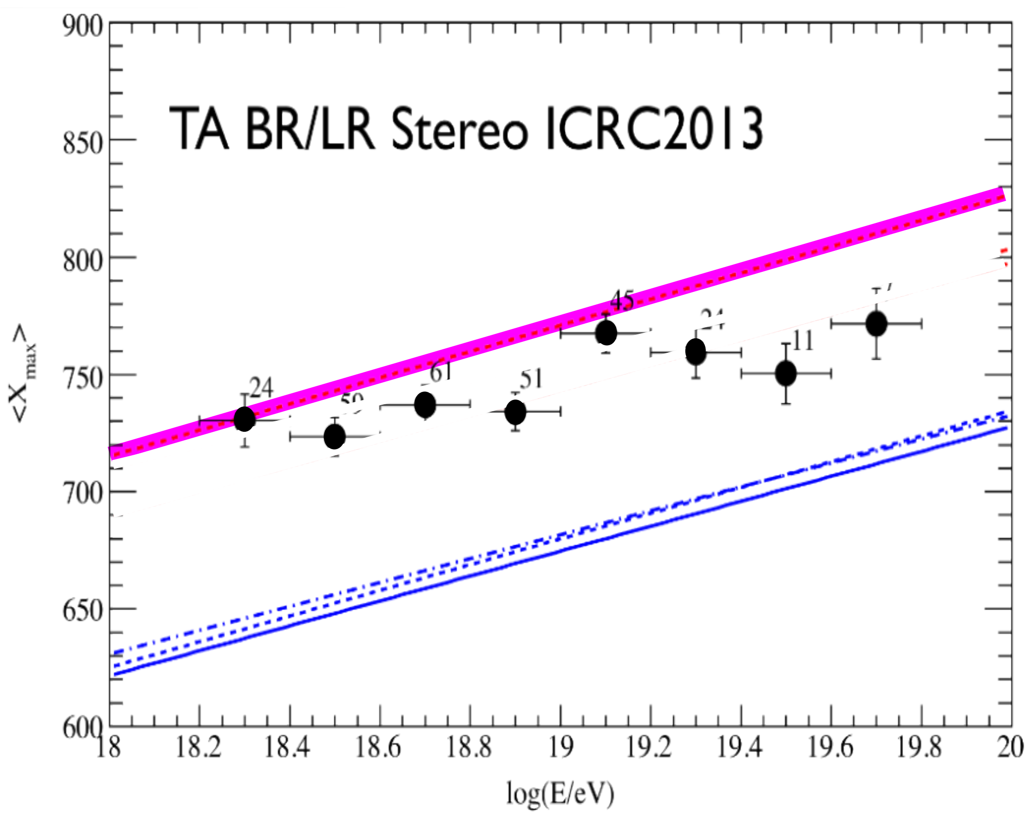
Tests using TA/PAO Working Group Results

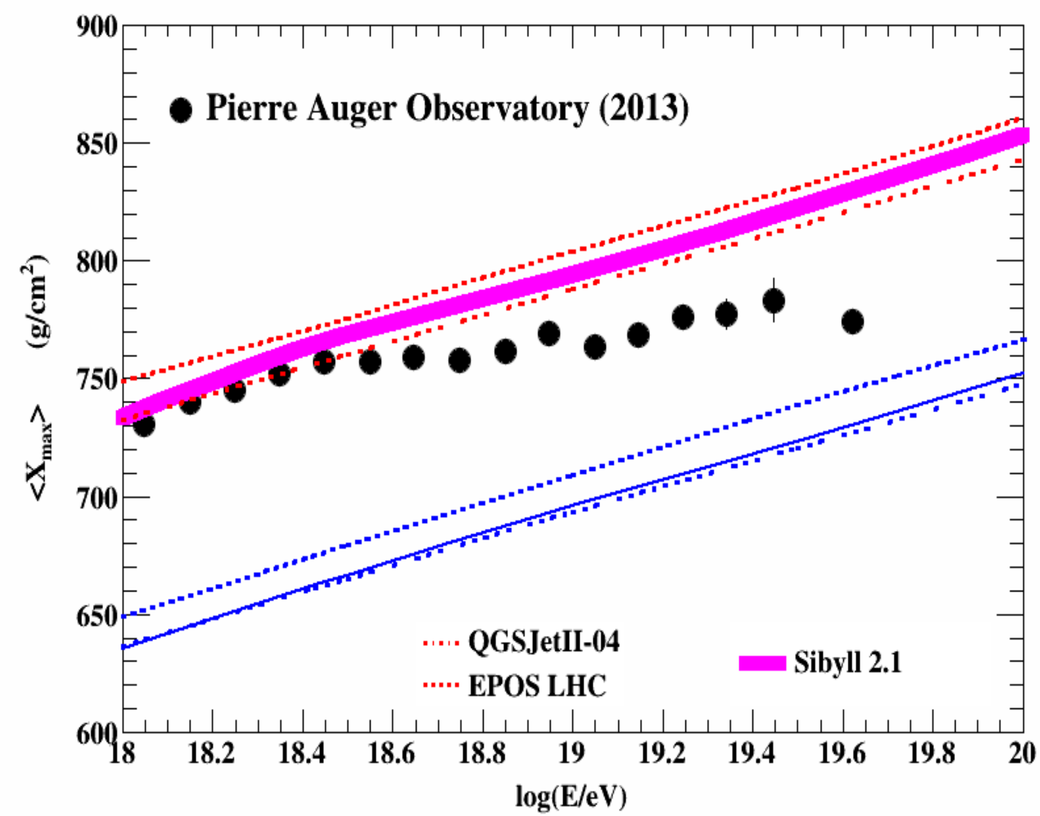
- **Test : keep only model compatible with LHC data**
  - EPOS LHC and QGSJetII-04 not used by TA yet : Sibyll 2.1 ~ QGSJetII-04
  - TA data NOT as compatible with proton at high E anymore ! (no shift here)



PAO vs TA after LHC

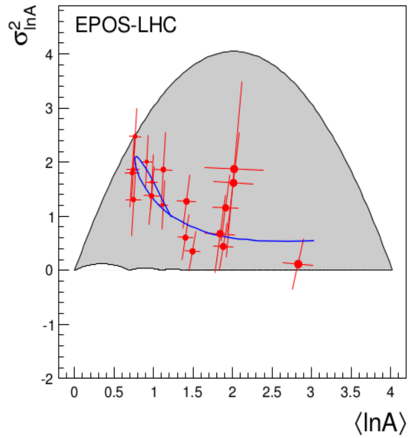
- **Composition with TA and PAO are similar**
  - ➜ light composition below the Ankle
  - ➜ change toward heavier composition above the Ankle

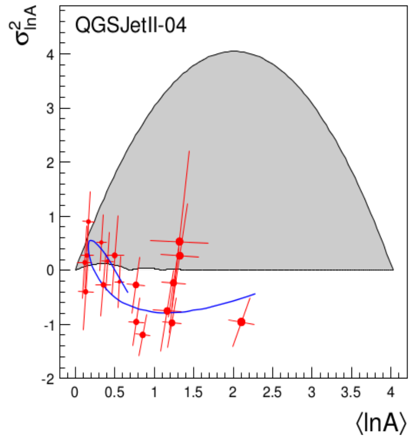


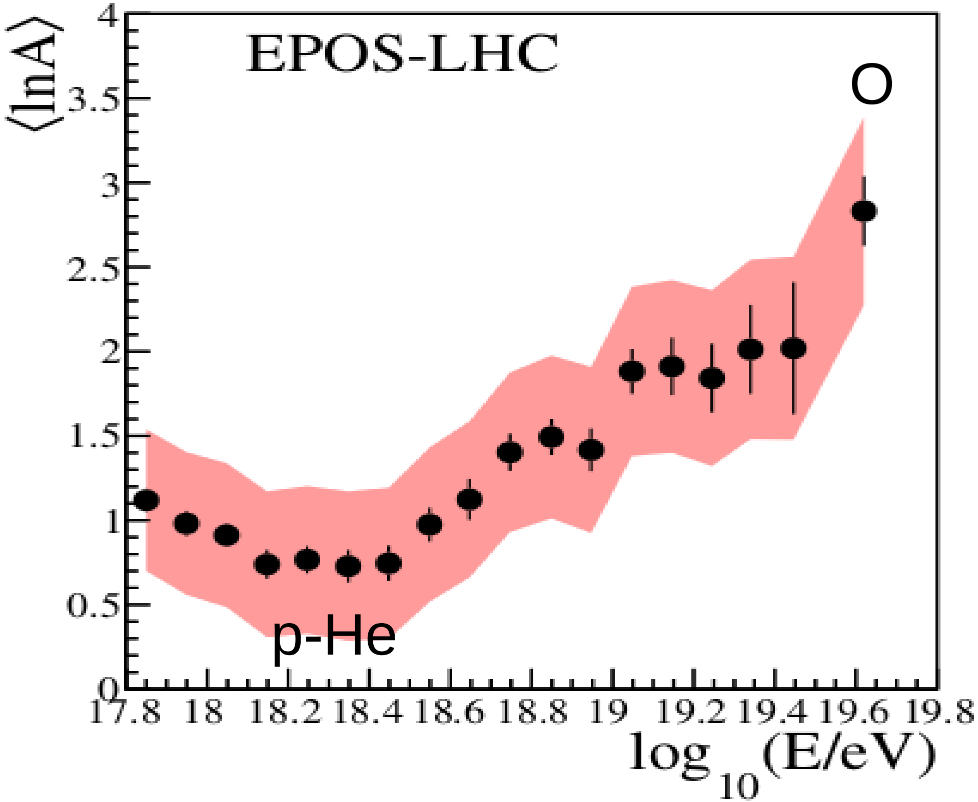


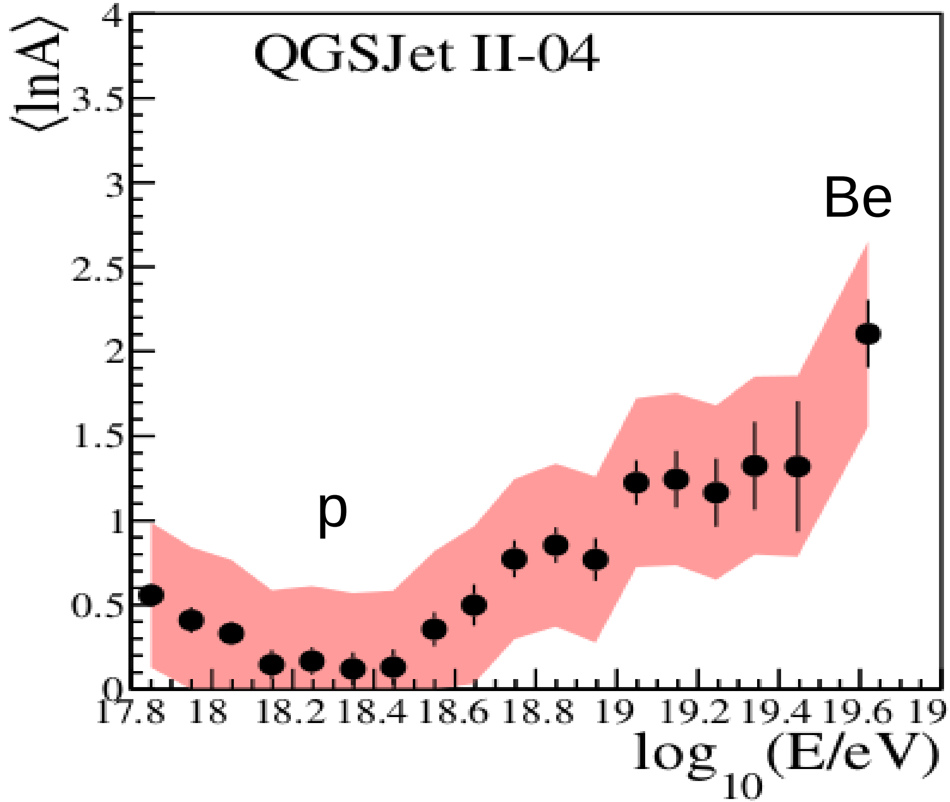
PAO composition after LHC

- **<lnA> can be measured using post LHC models**
  - ➡ Note : only EPOS LHC reproduce consistently $<X_{max}>$ and RMS.





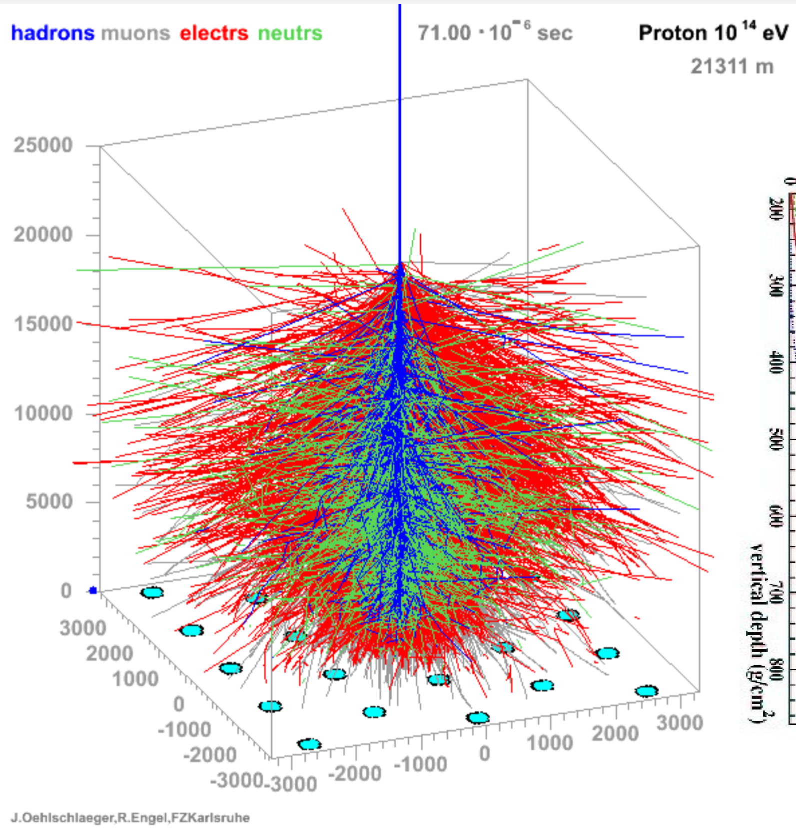


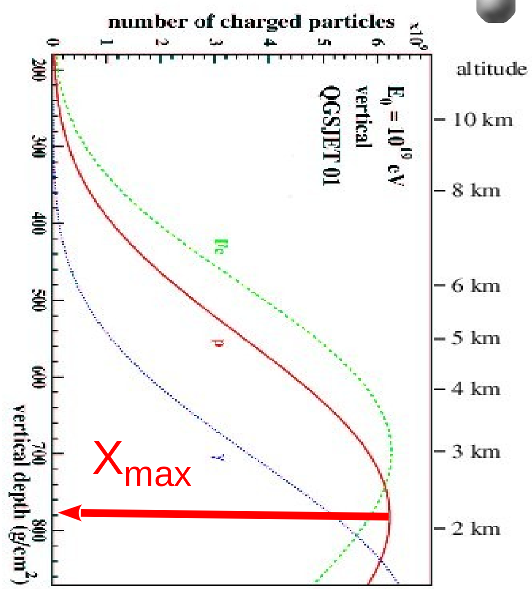


Summary

- **Correction of high energy hadronic interaction models after LHC data**
  - ➡ uncertainty reduced by a factor of 2 at the highest energies
  - ➡ same elongation rate for all models
    - ➡ QGSJeII-03 and QGSJet01 change in slope excluded
  - ➡ same improvement for number of muons : only 7% difference between EPOS LHC and QGSJetII-04 (QII-04 number of muons increased).
- **For PAO no big change in mass composition**
  - ➡ mixed light to mixed heavy when energy increase (with a break at the Ankle)
  - ➡ consistent results from FD $<X_{max}>$ and RMS X_{max}, and SD based method.
- **For TA, results are now closer to PAO interpretation**
  - ➡ data were always compatible between each other within statistical error
  - ➡ peculiar behavior of model used for interpretation (QGSJetII-03) excluded by LHC data
    - ➡ using same model, same composition is obtained

Extensive Air Shower Observables



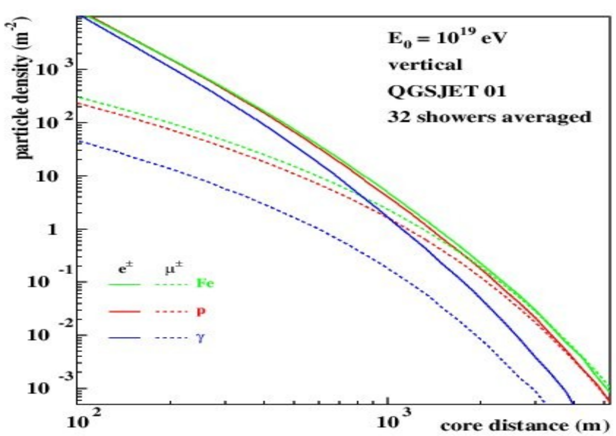


- **Longitudinal Development**
  - number of particles vs depth

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

  - Larger number of particles at X_{max}

    For many showers
    - mean : $<X_{max}>$
    - fluctuations : RMS X_{max}



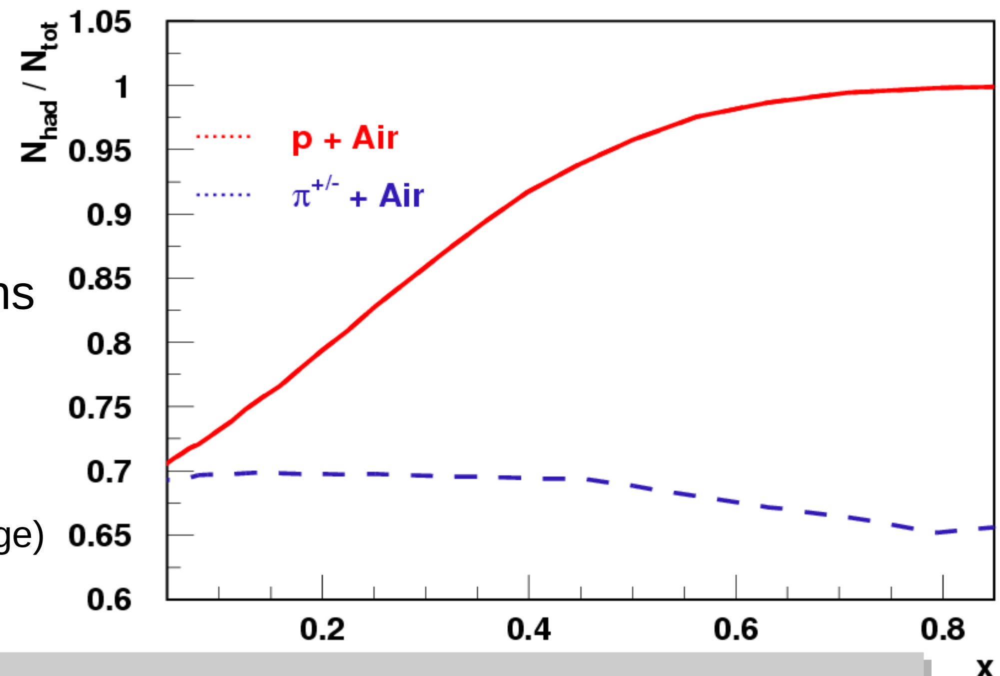
- **Lateral distribution function (LDF)**
  - particle density at ground vs distance to the impact point (core)
  - can be muons or electrons/gammas or a mixture of all.

Muon Number

- **From Heitler**

$$N_\mu = \left(\frac{E_0}{E_{dec}}\right)^\alpha, \quad \alpha = \frac{\ln N_{\pi^{ch}}}{\ln(N_{\pi^{ch}} + N_{\pi^0})}$$

- In real shower, not only pions : Kaons and (anti)Baryons (but 10 times less …)
- Baryons do not produce leading π^0
- With leading baryon, energy kept in hadronic channel = muon production
- Cumulative effect for low energy muons
- High energy muons
  - important effect of first interactions and baryon spectrum (LHC energy range)



Muon number depends on the number of (anti)B in p- or π-Air interactions at all energies

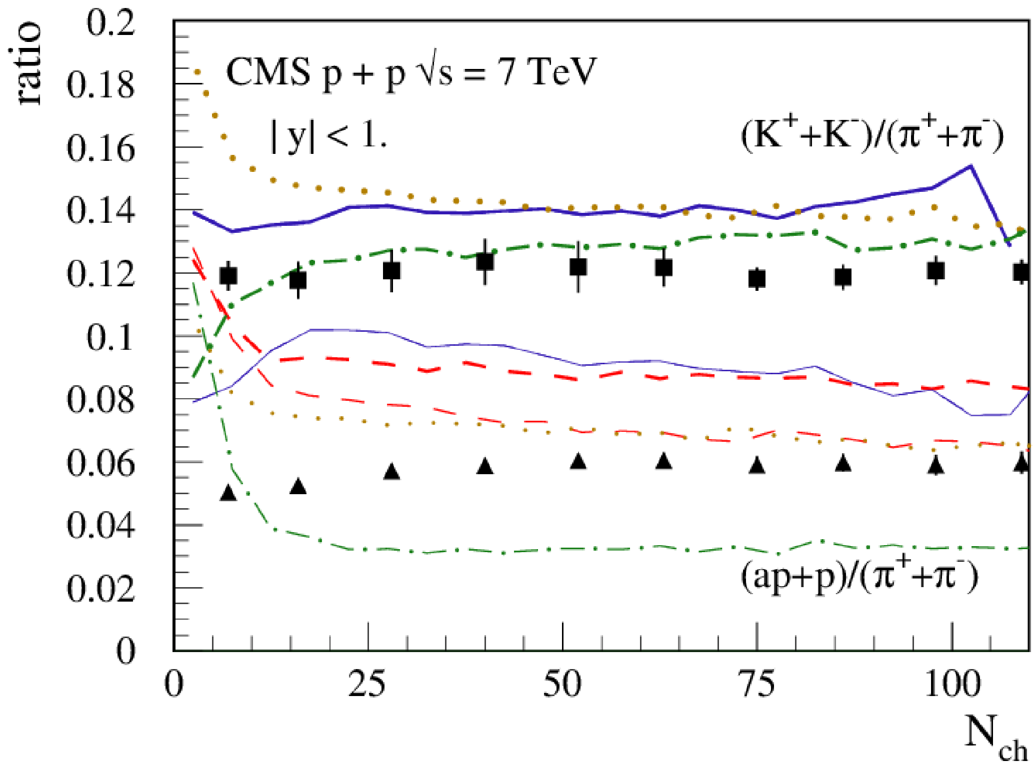
More fast (anti)baryons = more muons

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

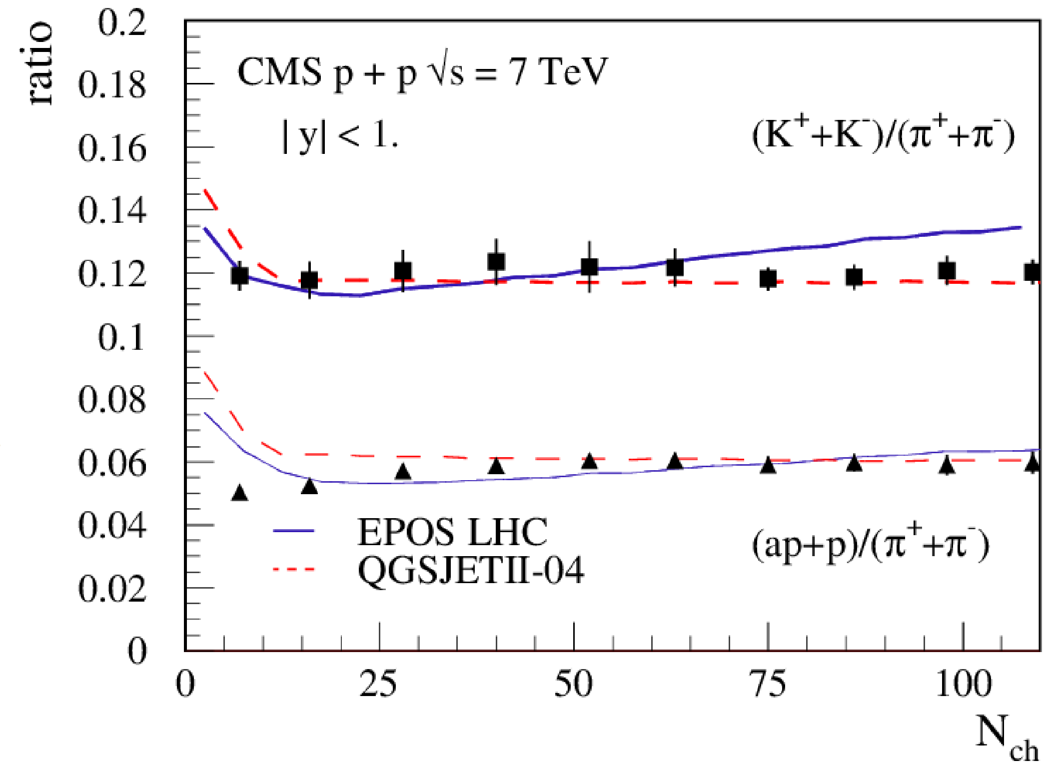
Identified particles

- **Large improvement at mid-rapidity**
  - very similar results for particle ratios
  - overestimation of baryon production before due to wrong interpretation of Tevatron data

Pre - LHC

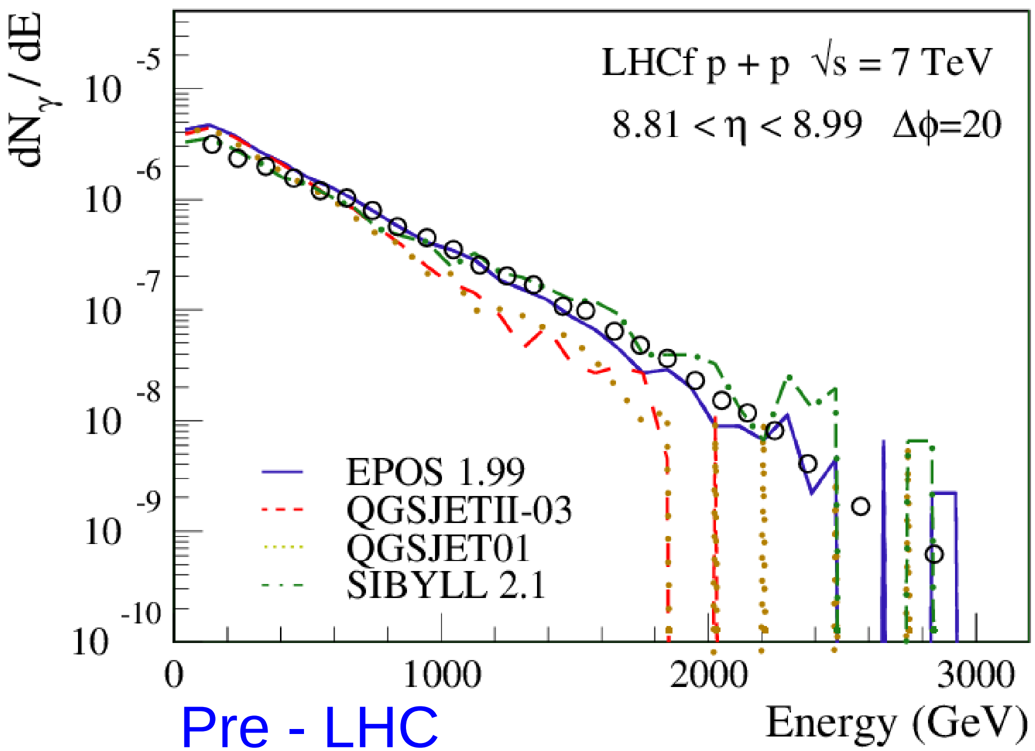


Post - LHC

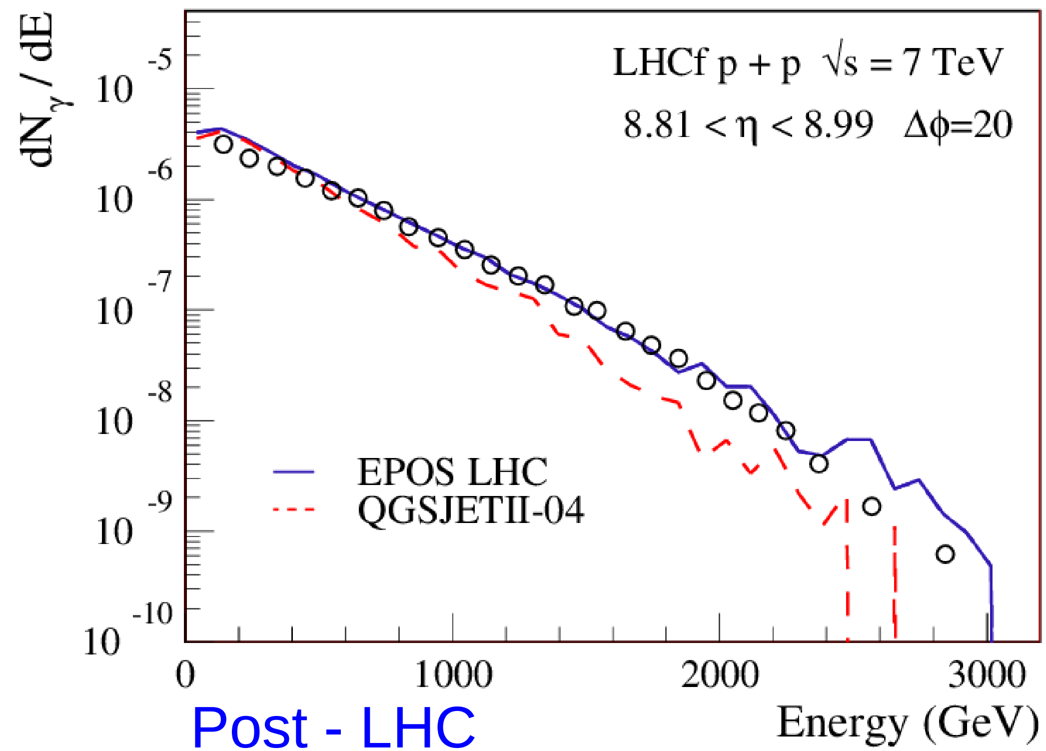


Identified particles

- **Large improvement at mid-rapidity**
  - very similar results for particle ratios
  - overestimation of baryon production before due to wrong interpretation of Tevatron data
- **Only small changes very forward**
  - no try to tune LHCf data yet (difficult)

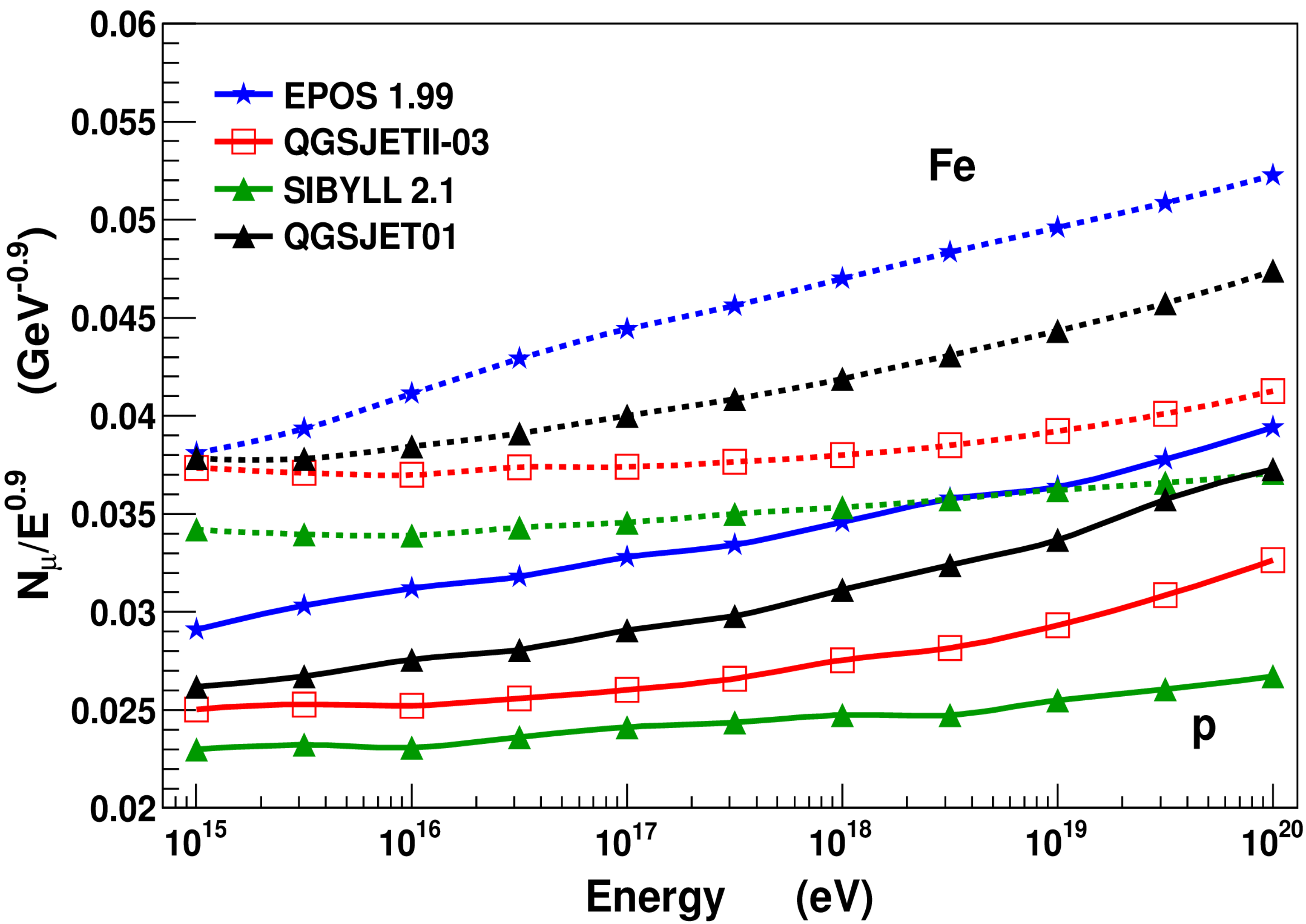


Pre - LHC

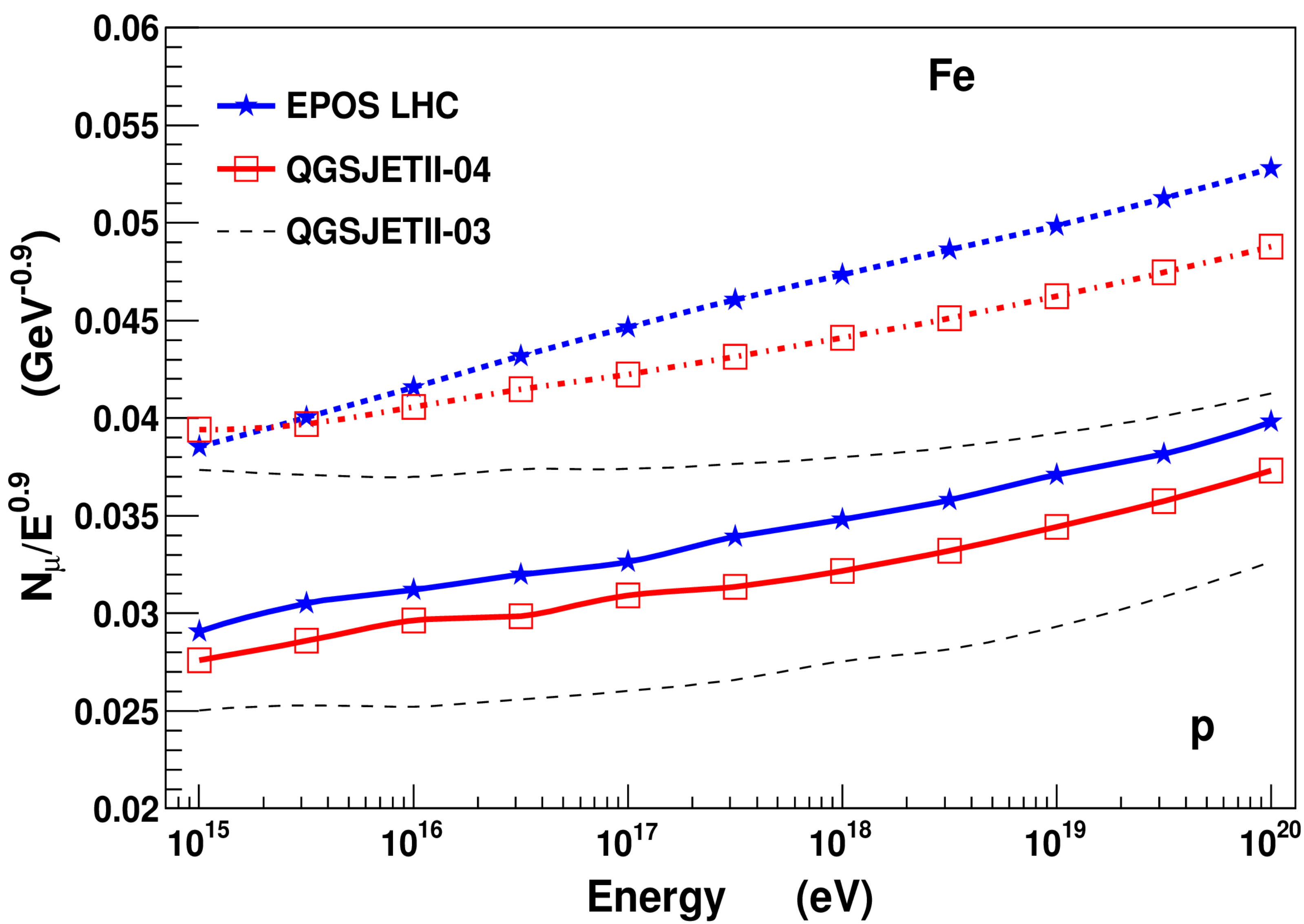


Post - LHC

EAS with Re-tuned CR Models : Muons

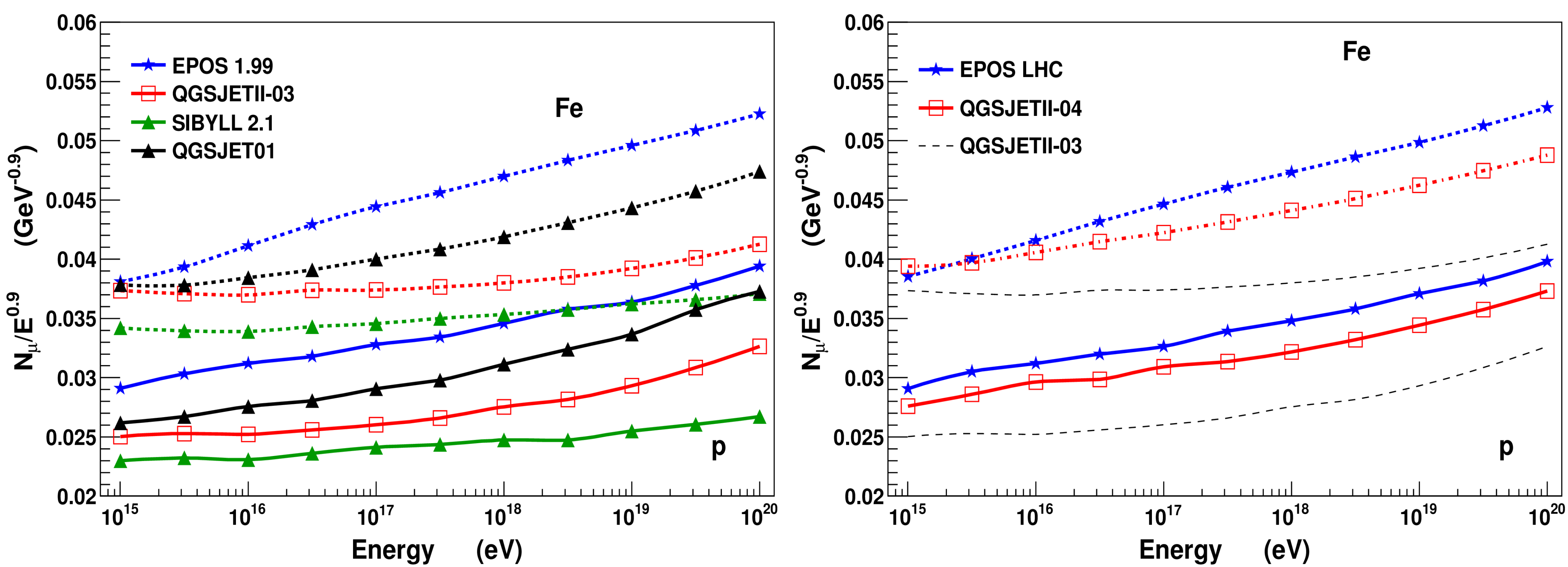


EAS with Re-tuned CR Models : Muons



EAS with Re-tuned CR Models : Muons

- Effect of LHC hidden by other changes
  - Corrections at mid-rapidity only for EPOS
  - Changes in QGSJET motivated by pion induced data
  - EPOS LHC ~ EPOS 1.99 and only -7% for QGSJETII-04



Hadronic Interaction Models in CORSIKA

(HDPM)

Old generation : QGSJET01 SIBYLL 2.1 DPMJET 2.55 VENUS (<1999)

All Glauber based

But differences in hard, remnants, diffraction …

semi-hard

soft

NEXUS 3.97

Attempt to get everything described in a consistent way (energy sharing)

New generation : (QGSJET II-03) (DPMJET III) (EPOS 1.99) (2005-2012)

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

Theory ++ :

- **Loop diagrams**
- **rho0 resonance**
- **optimized for CR**

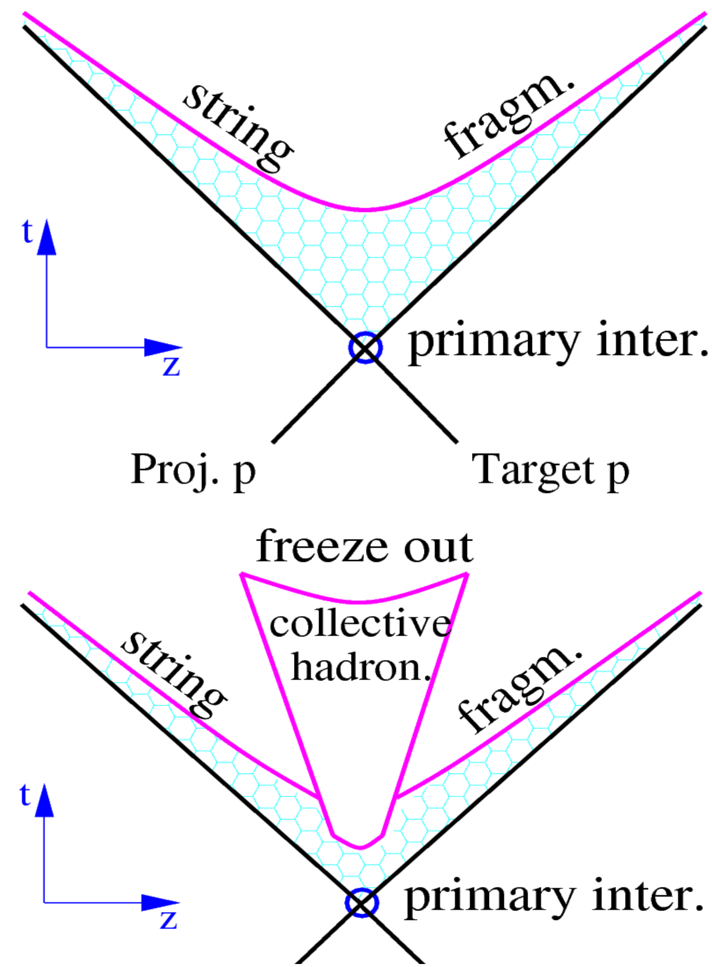
Phenomenology ++ :

- **Nuclear effect**
- **High density effect (QGP)**
- **all type of data studied**

Only model used in HEP (SPS, RHIC, LHC)

New Models

- **QGSJETII-03 to QGSJETII-04 :**
  - loop diagrams
  - rho0 forward production in pion interaction
  - re-tuning some parameters for LHC and lower energies

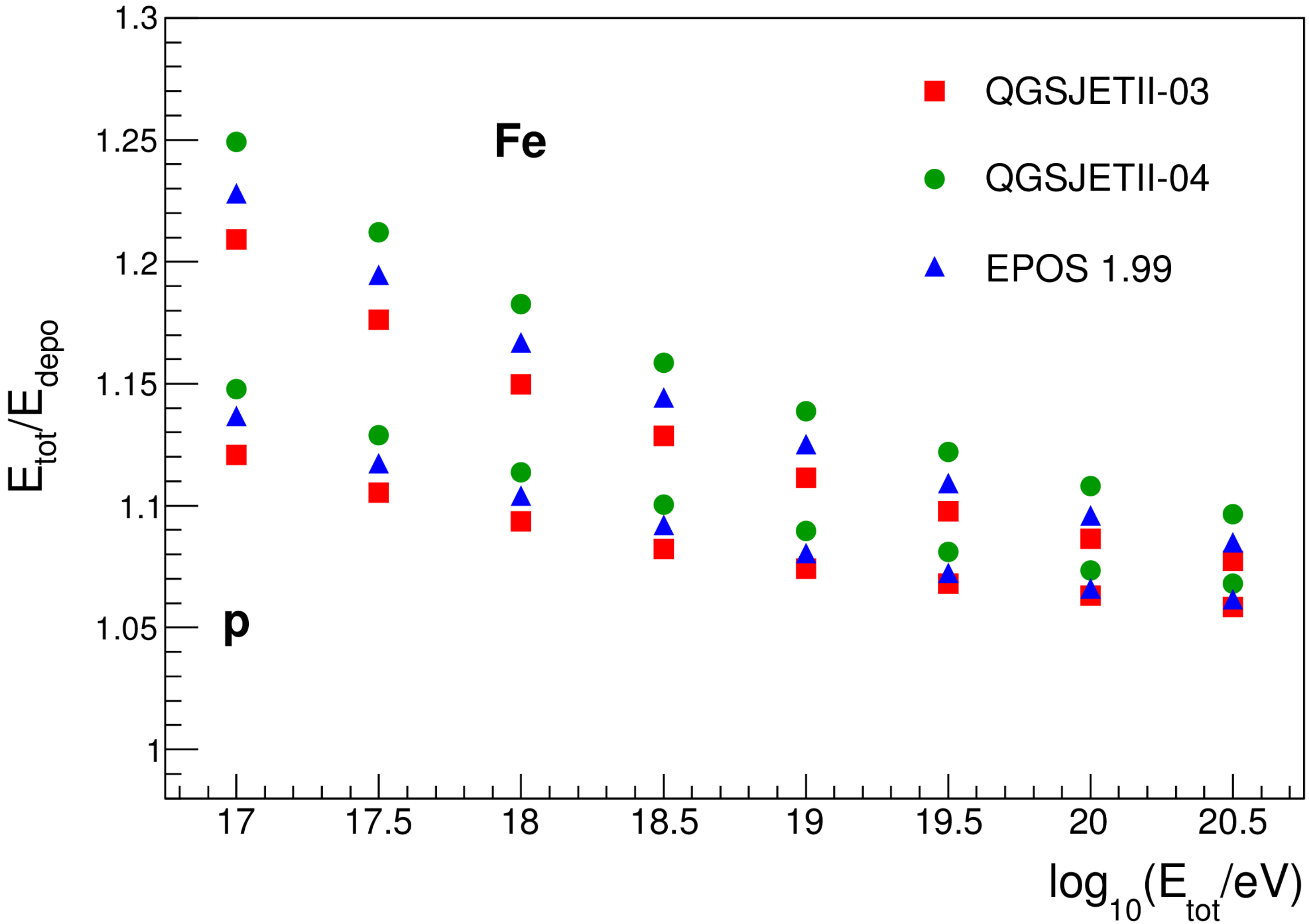


- **EPOS 1.99 to EPOS LHC**
  - tune cross section to TOTEM value
  - change old flow calculation to a more realistic one
  - introduce central diffraction
  - keep compatibility with lower energies

Direct influence of collective effects on EAS simulations has to be shown but important to compare to LHC and set parameters properly (<pt>, ...).

EAS Energy Deposit

- **Increase of muons in QII04**
  - ➔ larger correction factor from missing energy



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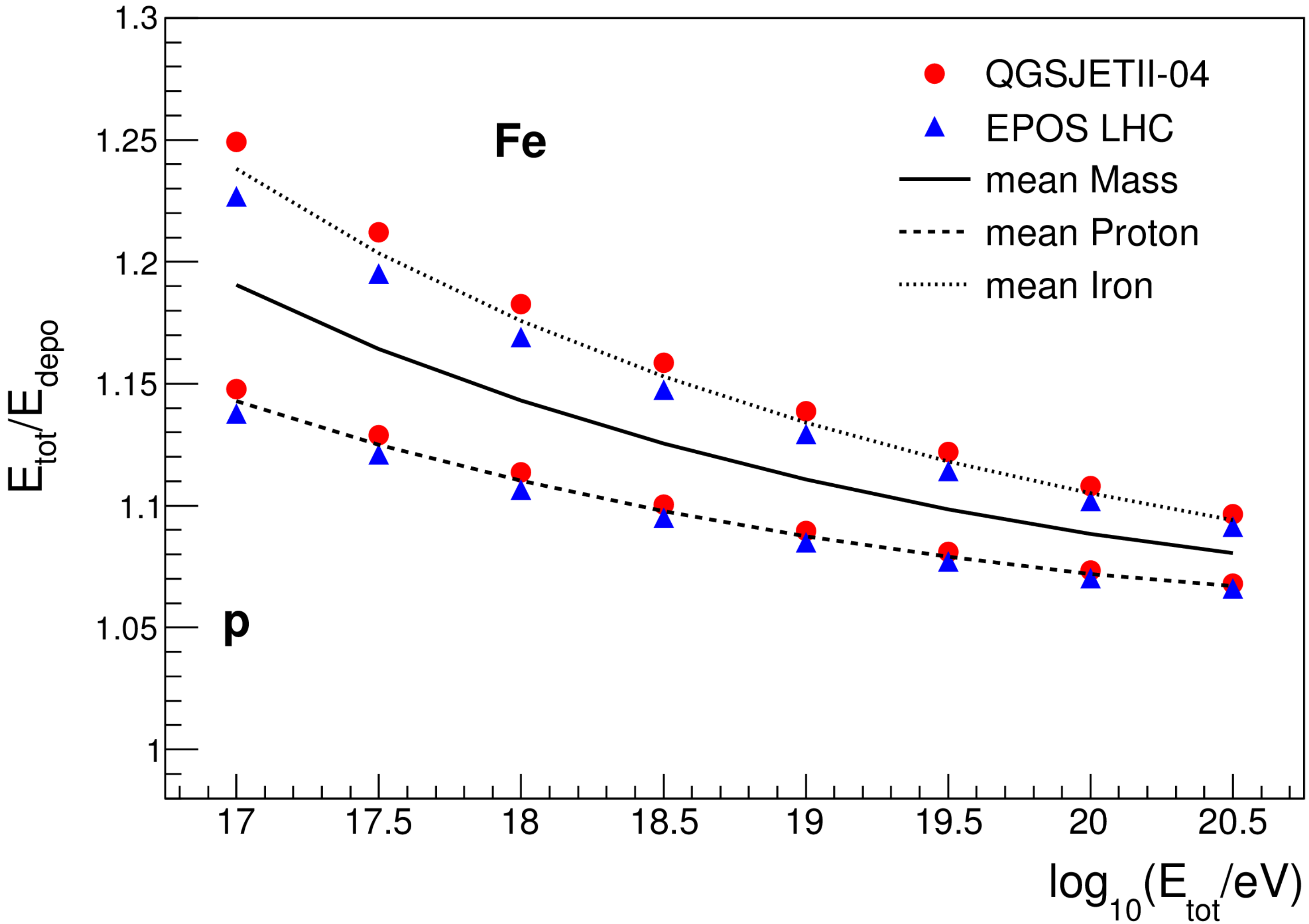
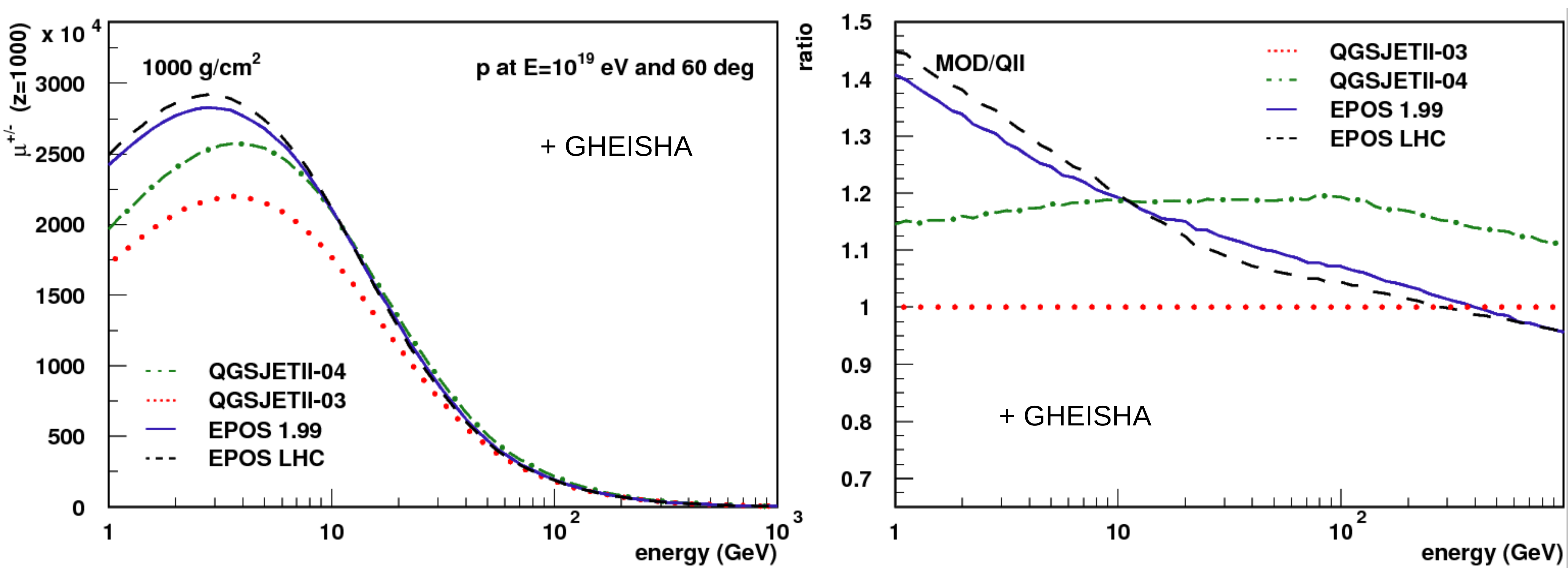


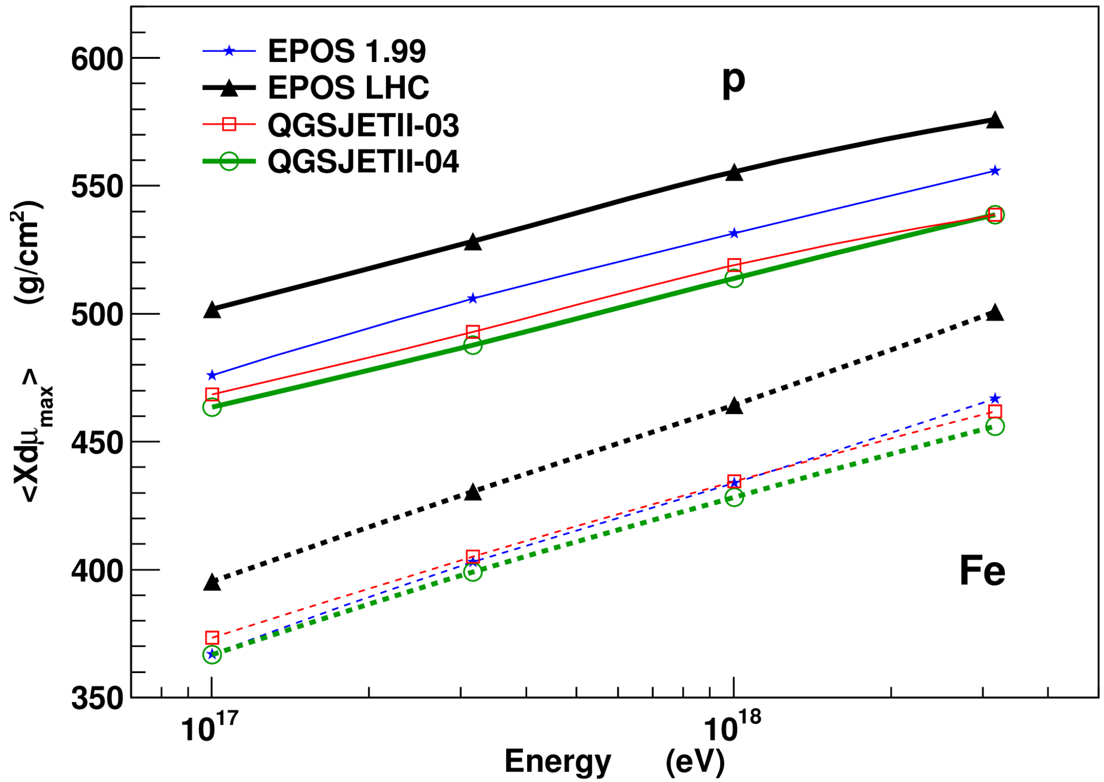
Muon Energy Spectra

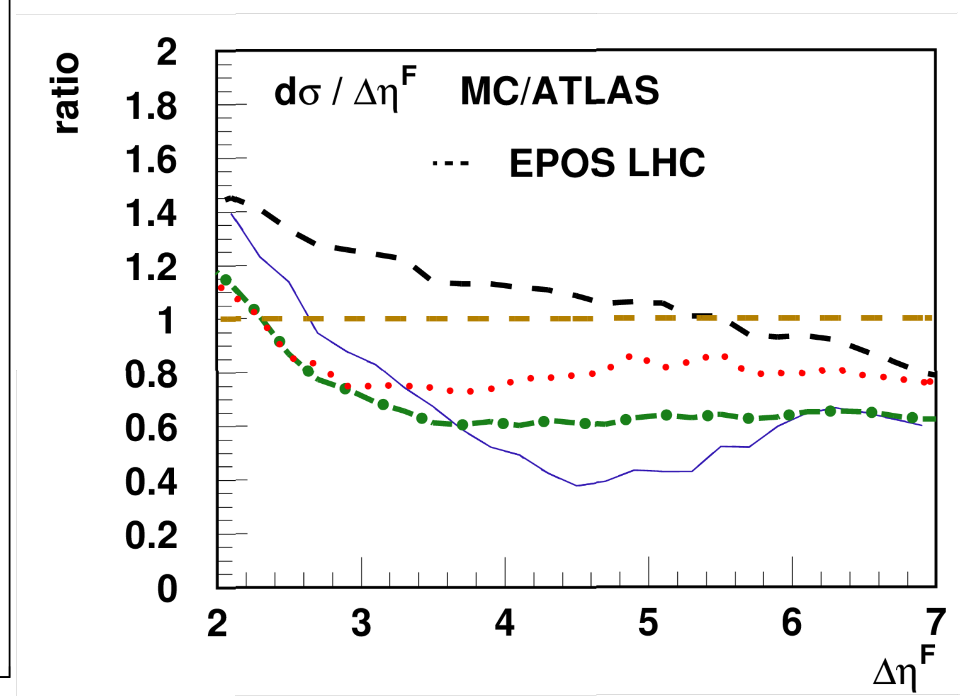
- **Total number of muons in QGSJETII-04 (@60°) closer to EPOS BUT**
  - muons with different energy (hadronic energy stored in mesons or baryons ?)
  - different zenith angle dependence (attenuation length depends on muon energy spectrum)
  - effect of low energy hadronic interaction models (Gheisha, Fluka, UrQMD) ?
    - muon production dominated by last hadronic interaction(s) !



Muon Production Depth

- **Pierre Auger Observable** (Cazon and Garcia-Gomez)
  - Depth of maximum muon production rate
  - link to hadronic shower core
  - very sensitive to inelasticity
    - rapidity gap measurement (diffraction)





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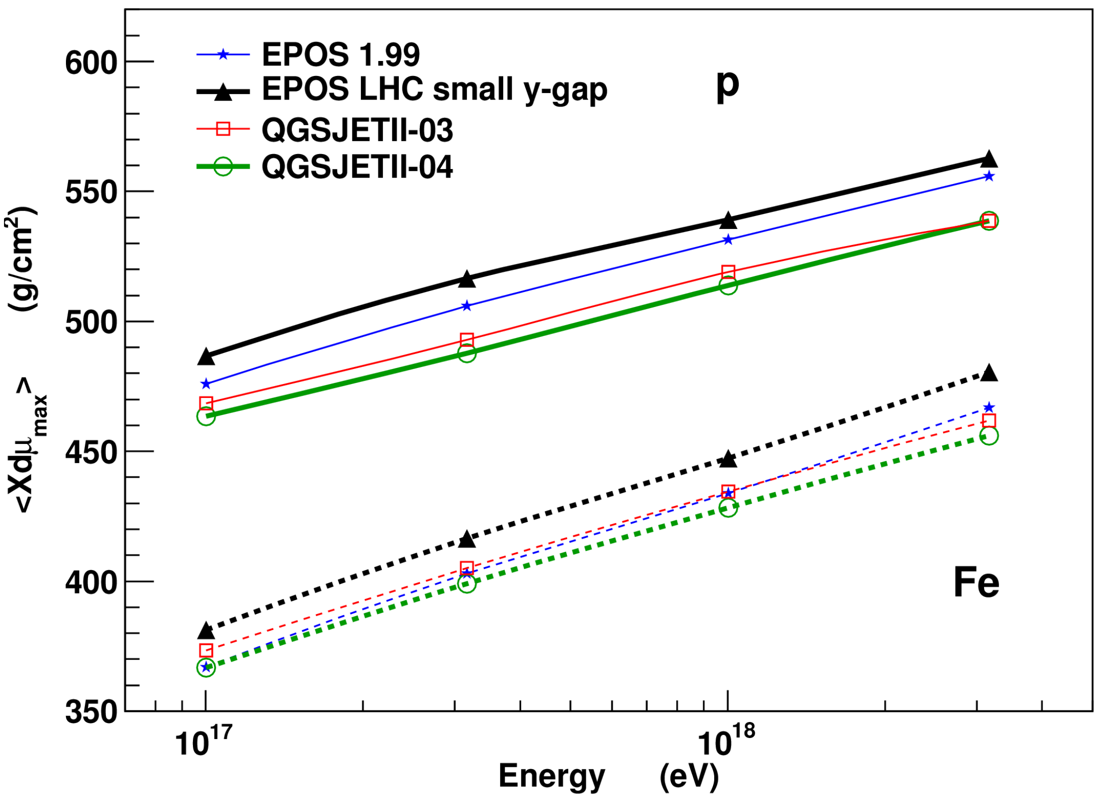

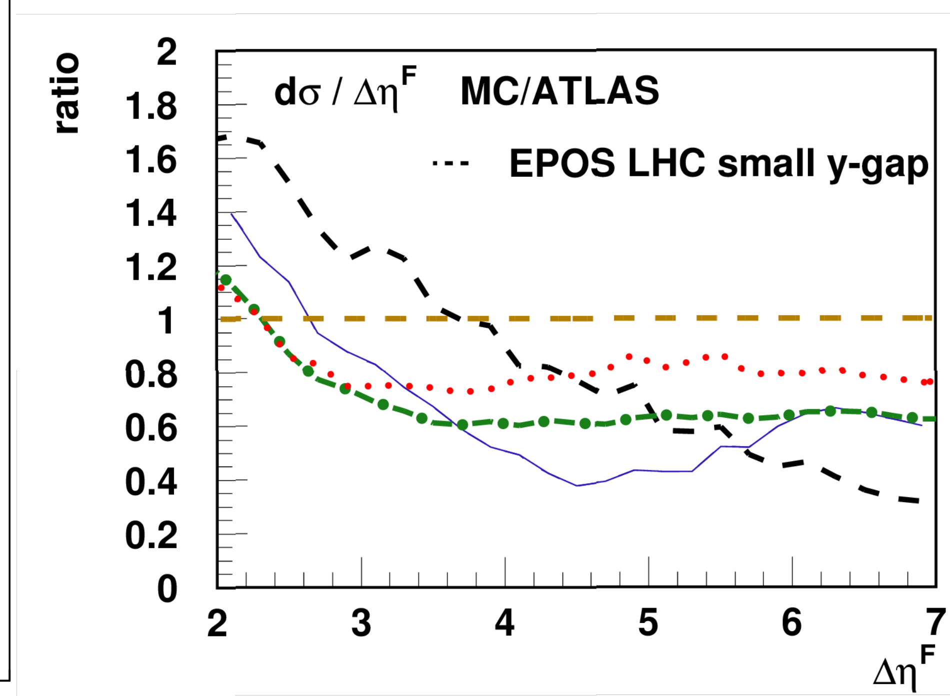

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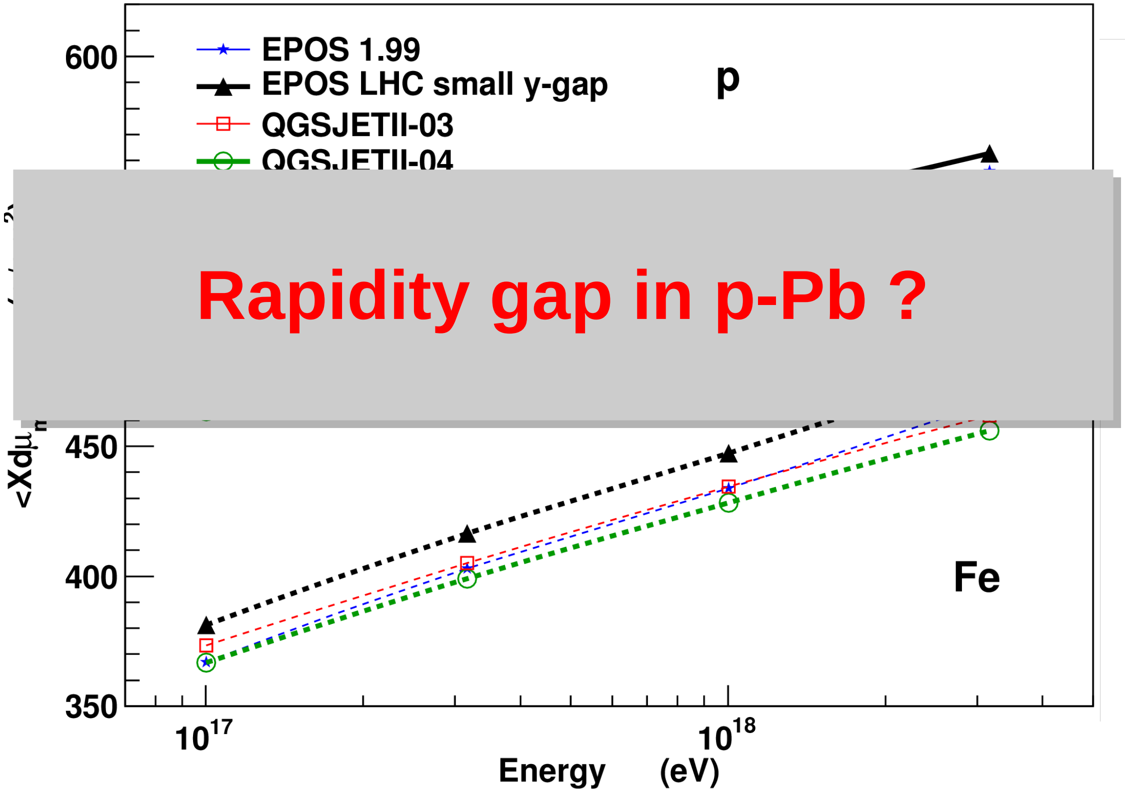
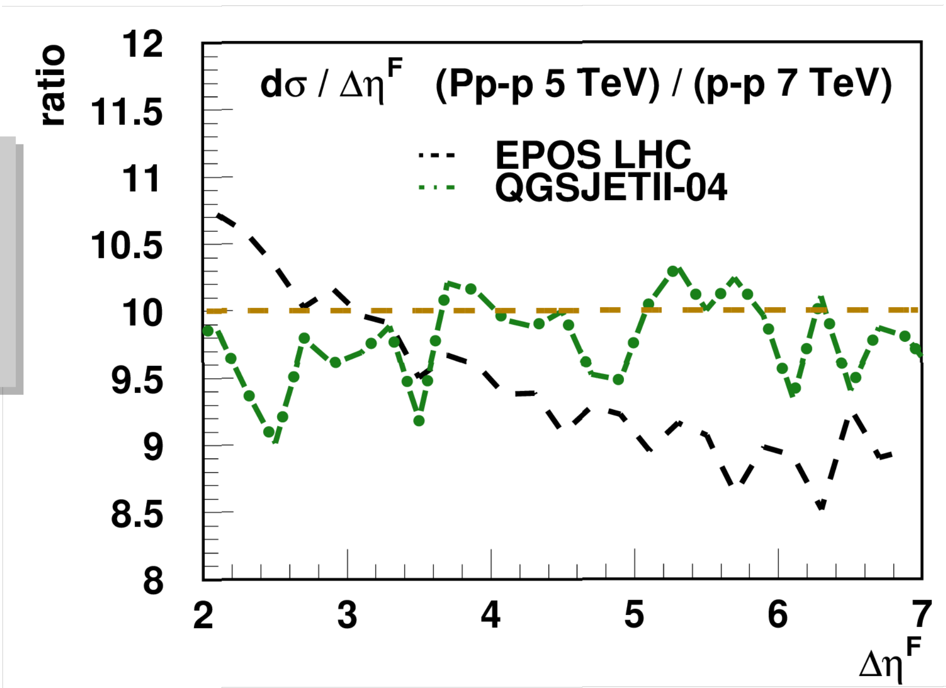
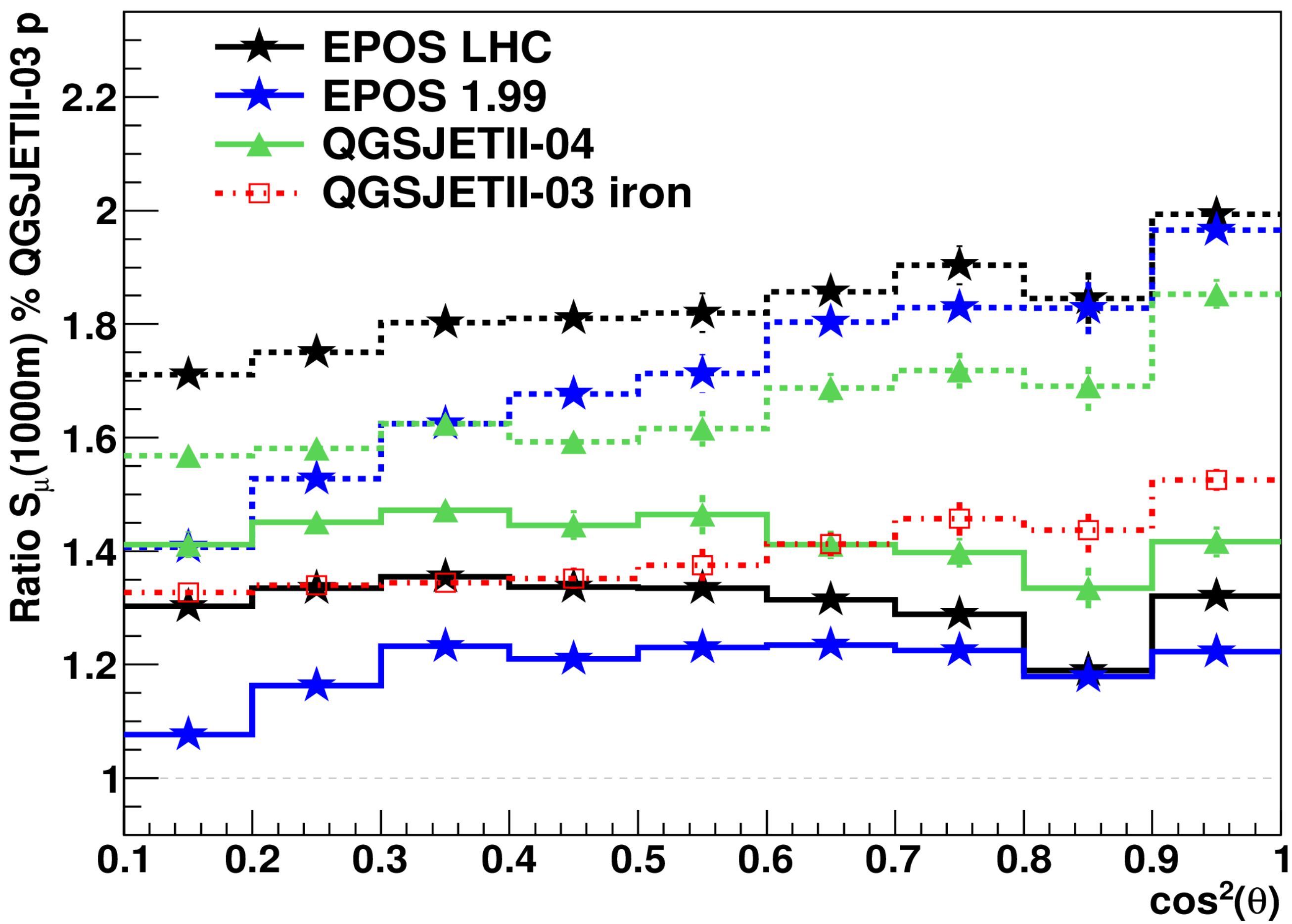


Rapidity gap in p-Pb ?

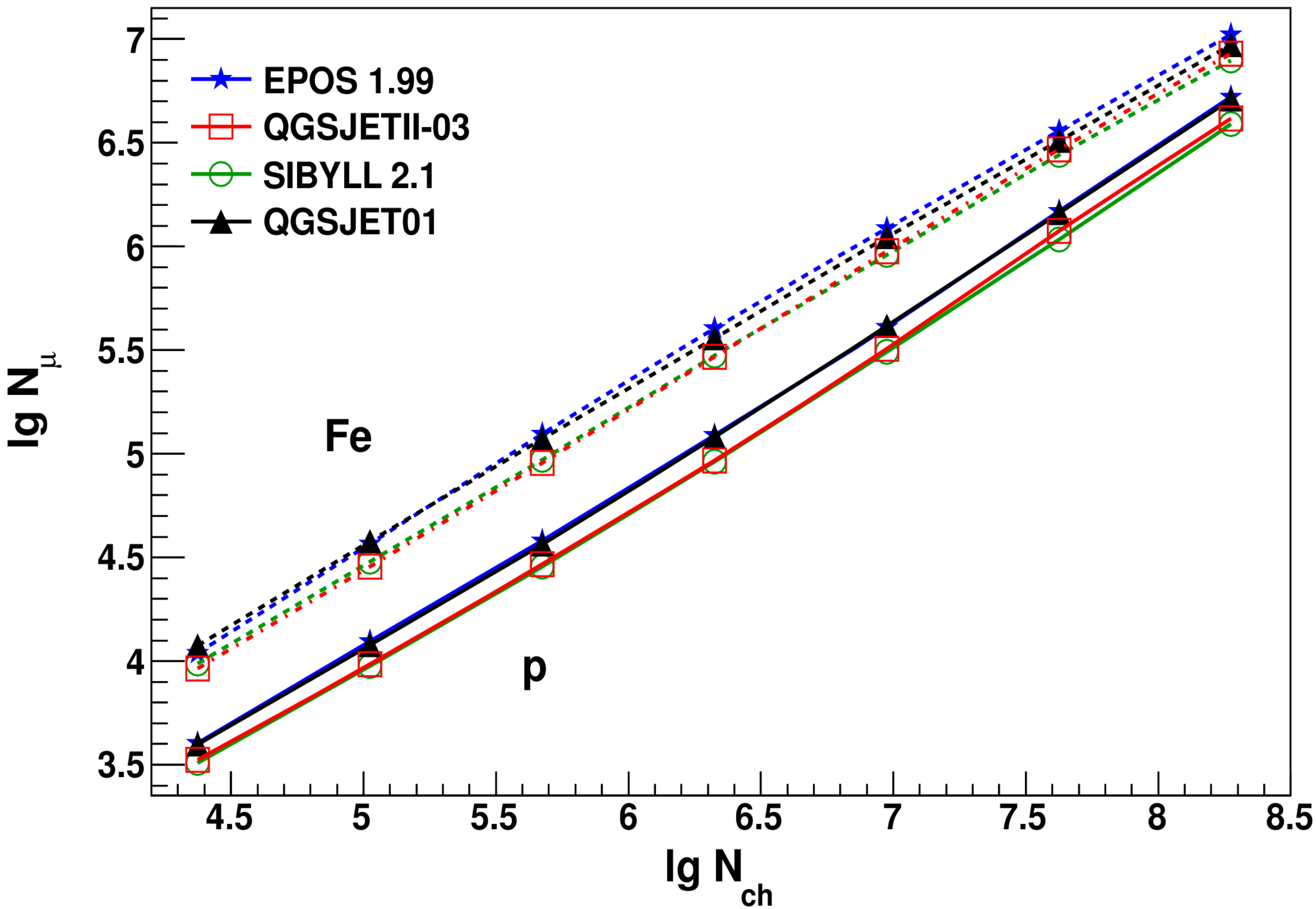


Muon Signal at 1000m for PAO

- **Different zenith angle dependence**
  - ➔ probably better description of muon number for PAO using heavy composition consistent with X_{max}



EAS with Re-tuned CR Models : Correlations



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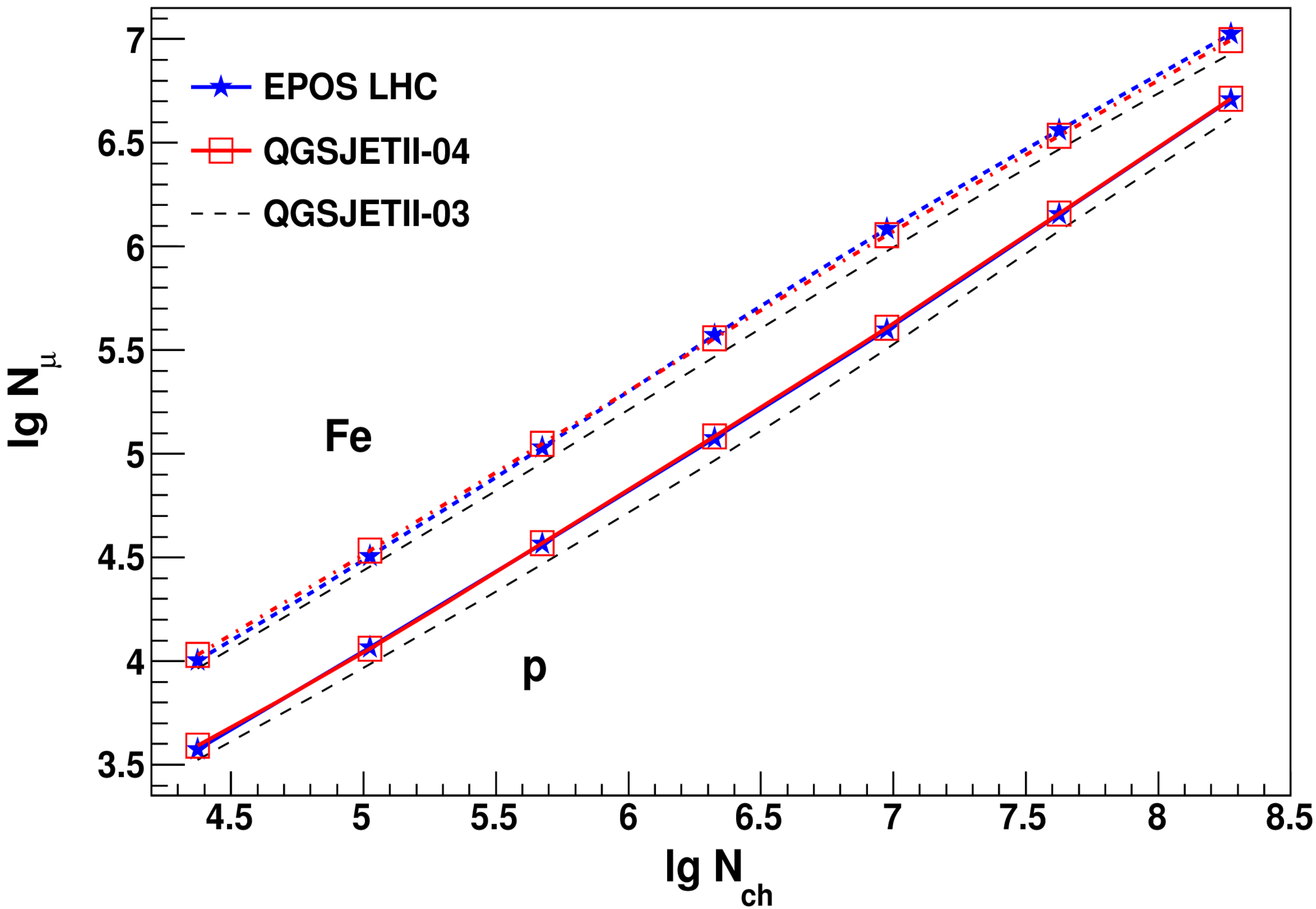
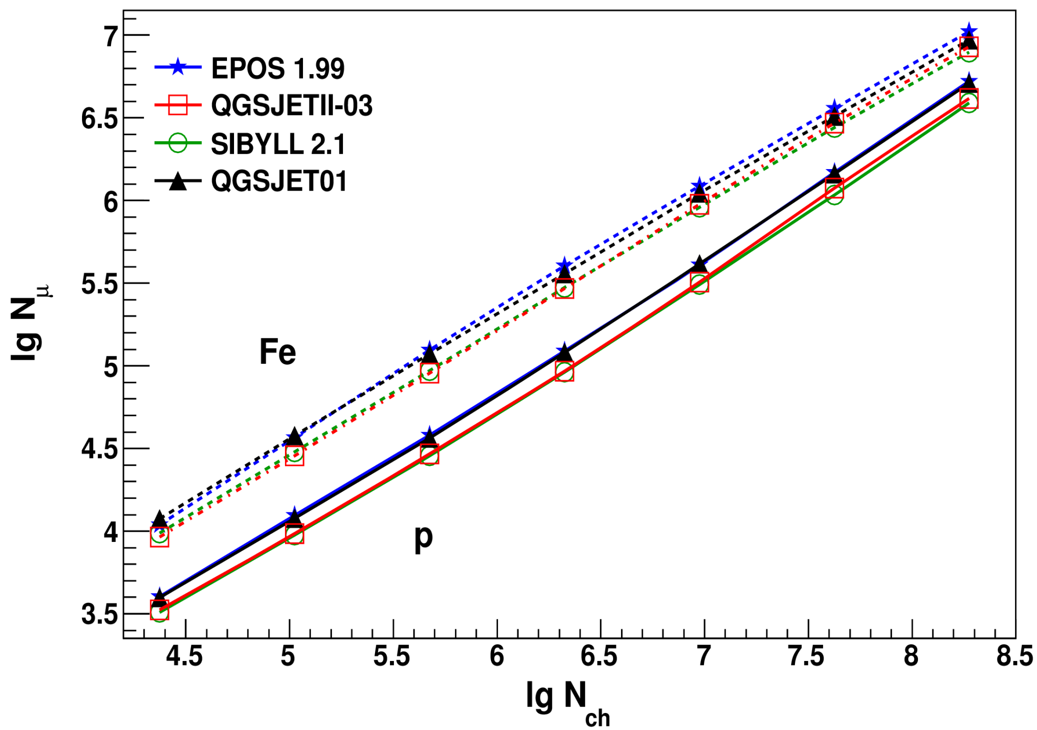
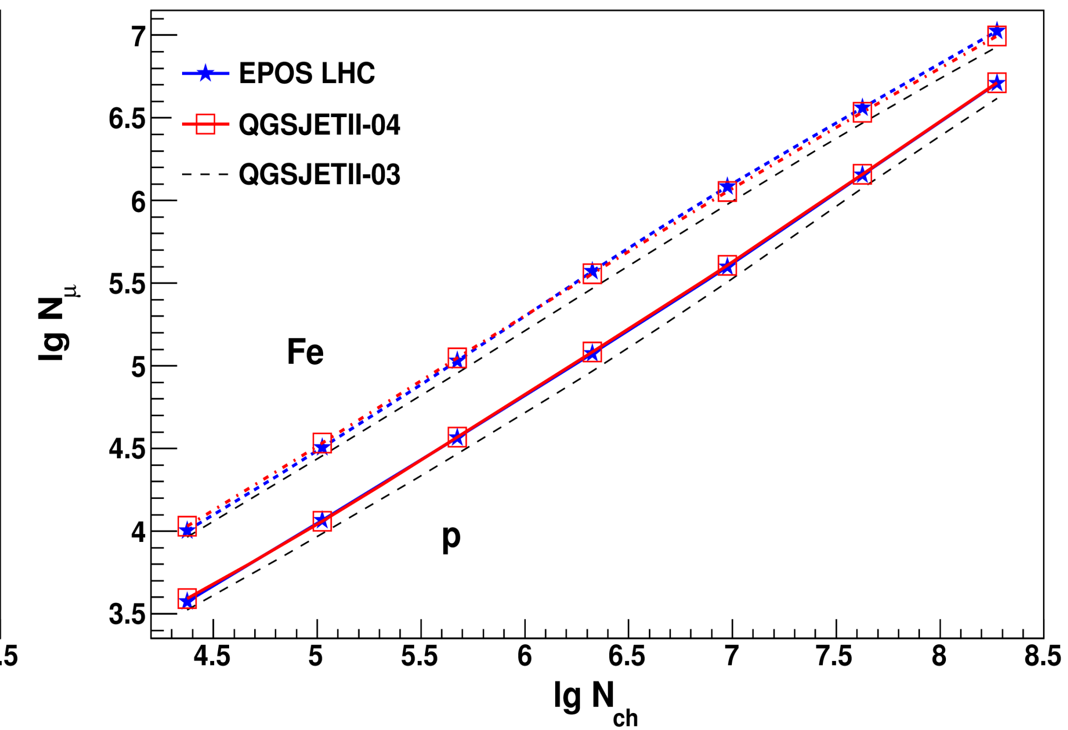


EAS with Re-tuned CR Models : Correlations

- **QGSJETII-04 and EPOS LHC similar to EPOS 1.99**
  - ➡ More muons AND more electrons with EPOS LHC compared to QGSJETII-04
  - ➡ More muons and less electrons with QGSJETII-04 compared to QGSJETII-03
  - ➡ Same correlations with EPOS LHC and QGSJETII-04
  - ➡ Lighter composition compared to QGSJETII-03





Effects of Parameters

- **Sensibility depends on observable and parameter :**
  - ➔ effect of uncertainties at LHC on air shower observables
    - $f_{LHC\text{-}pO}$ = modification factor@LHC
  - ➔ 20% difference in multiplicity is about
    - ➔ 10% muons
    - ➔ 20 gr/cm^2 $\langle X_{max} \rangle$

Plots with Sibyll model