LHC Data and Ultra-High Energy Cosmic Rays

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Cracow, Poland**

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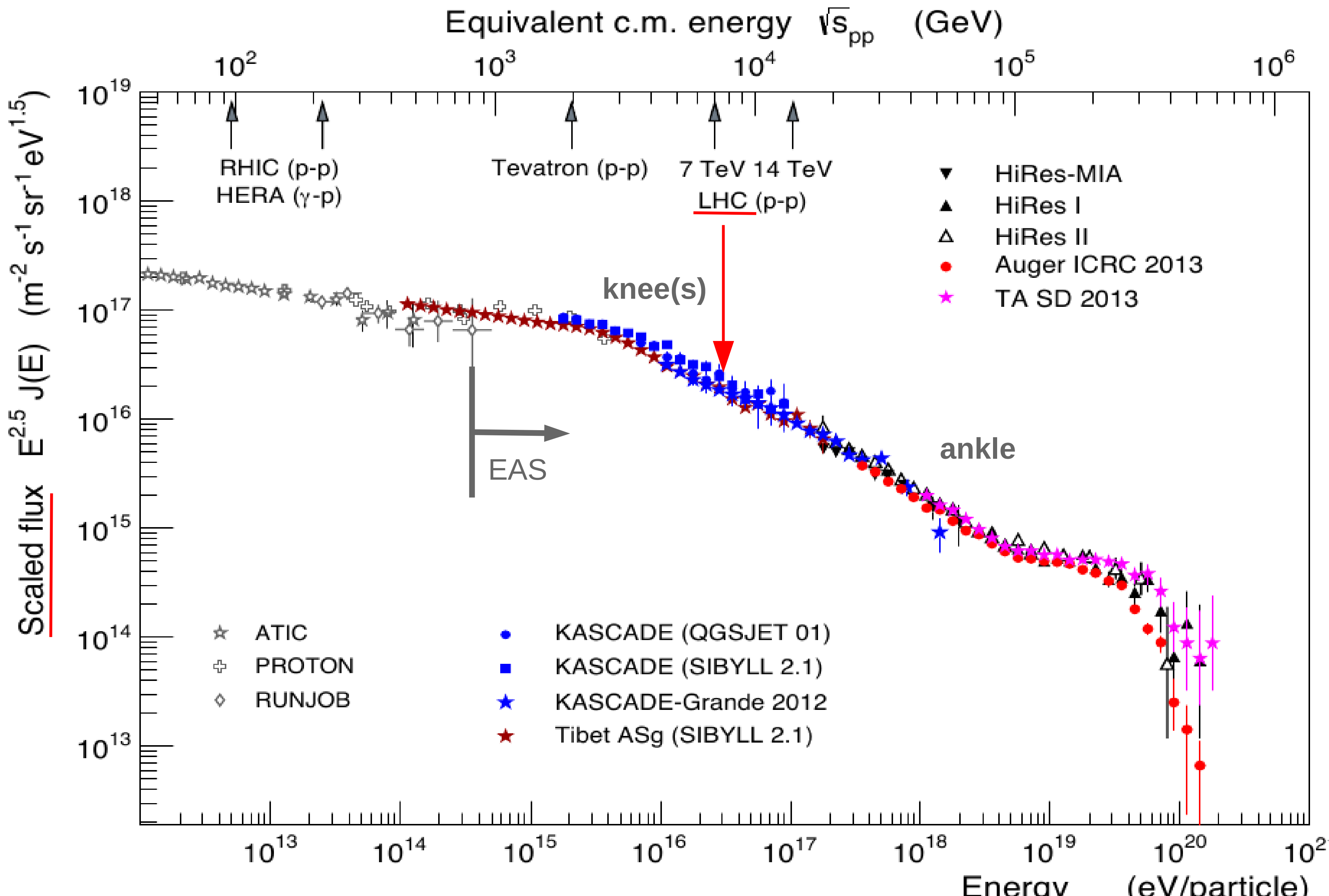
Outline

- Air showers and hadronic interactions
- Consequences of current LHC data
- Needs for further improvement: p-O
- Summary

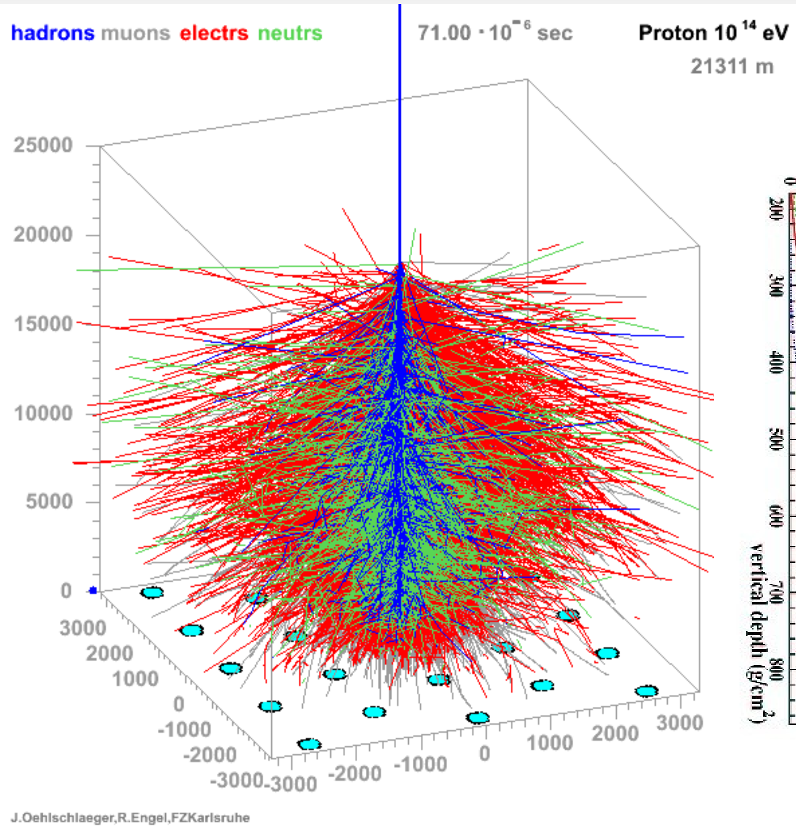
Proton-Oxygen beam is needed to reduce uncertainties in air shower simulations.

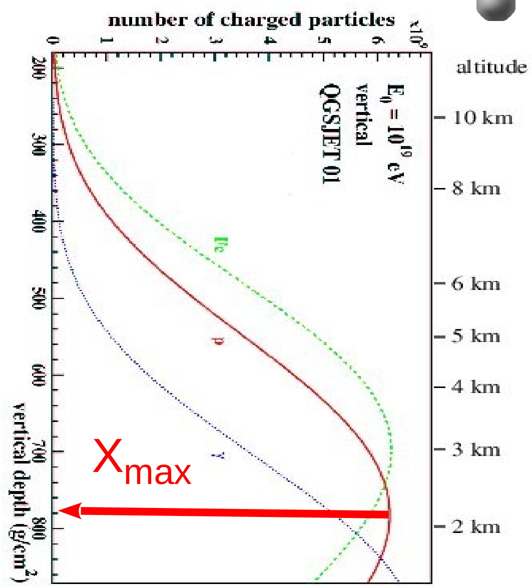
Cosmic Ray Spectrum



R. Engel (KIT)

Extensive Air Shower Observables





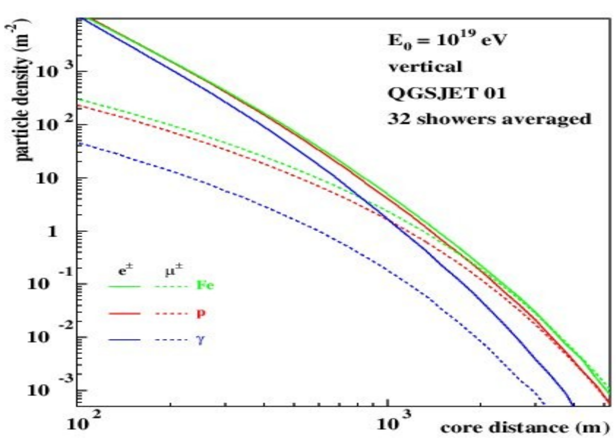
- **Longitudinal Development**
  - number of particles vs depth

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

  - Larger number of particles at X_{max}

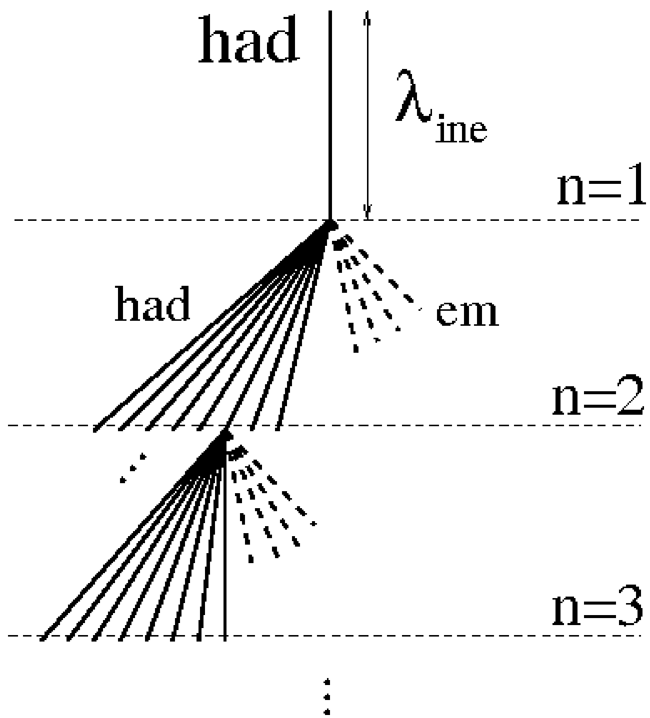
    For many showers

    - mean : $\langle X_{max} \rangle$
    - 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.

Simplified Shower Development



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

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

- **Using generalized Heitler model and superposition model :**

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

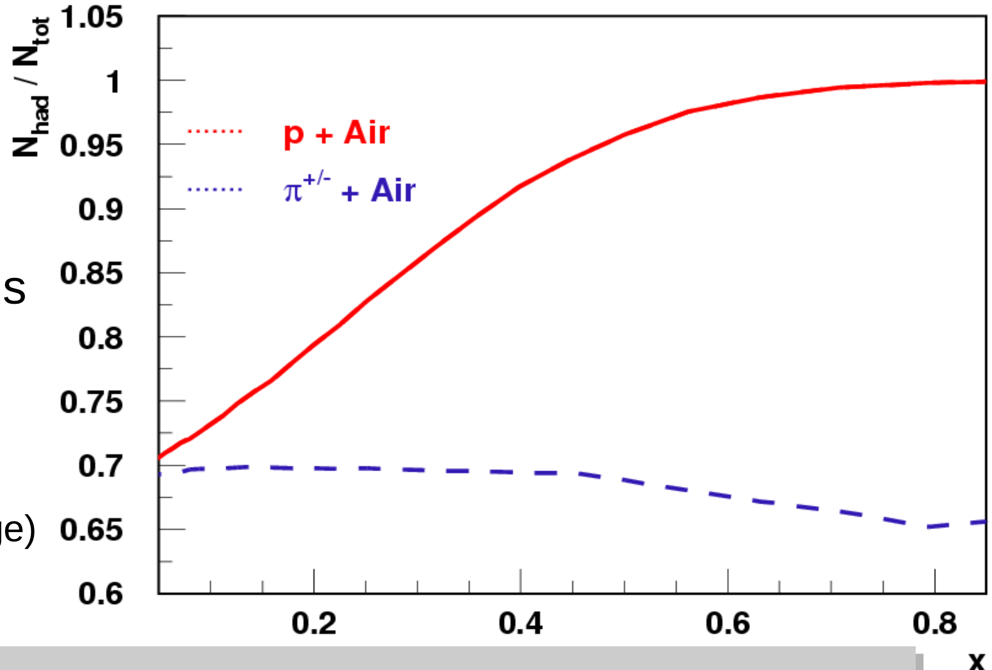
- Model independent parameters :
  - E_0 = primary energy
  - A = primary mass
  - λ_e = electromagnetic mean free path
- Model dependent parameters :
  - k = elasticity
  - N_{tot} = total multiplicity
  - λ_{ine} = hadronic mean free path (cross section)

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

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

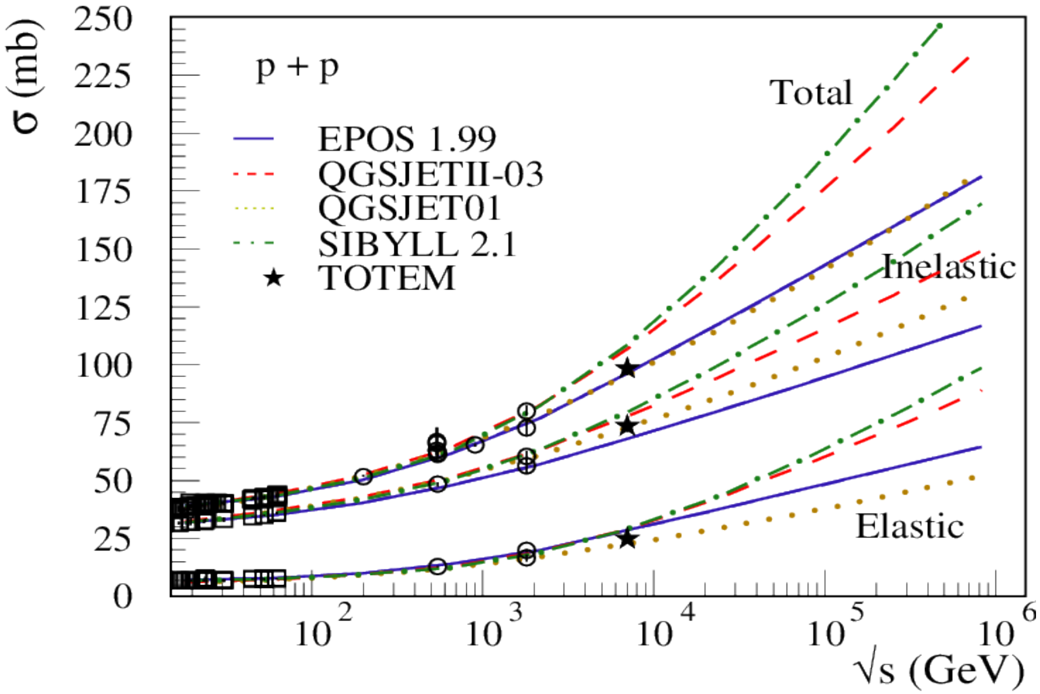
- **Phenomenology (models) :**
  - hadronization
    - string fragmentation — **EPOS modif. for LHC**
    - EPOS : high density effects (statistical hadronization and flow)
  - diffraction (Good-Walker, ...) — **QII and EPOS modif. for LHC**
  - higher order effects (multi-Pomeron interactions) — **QII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

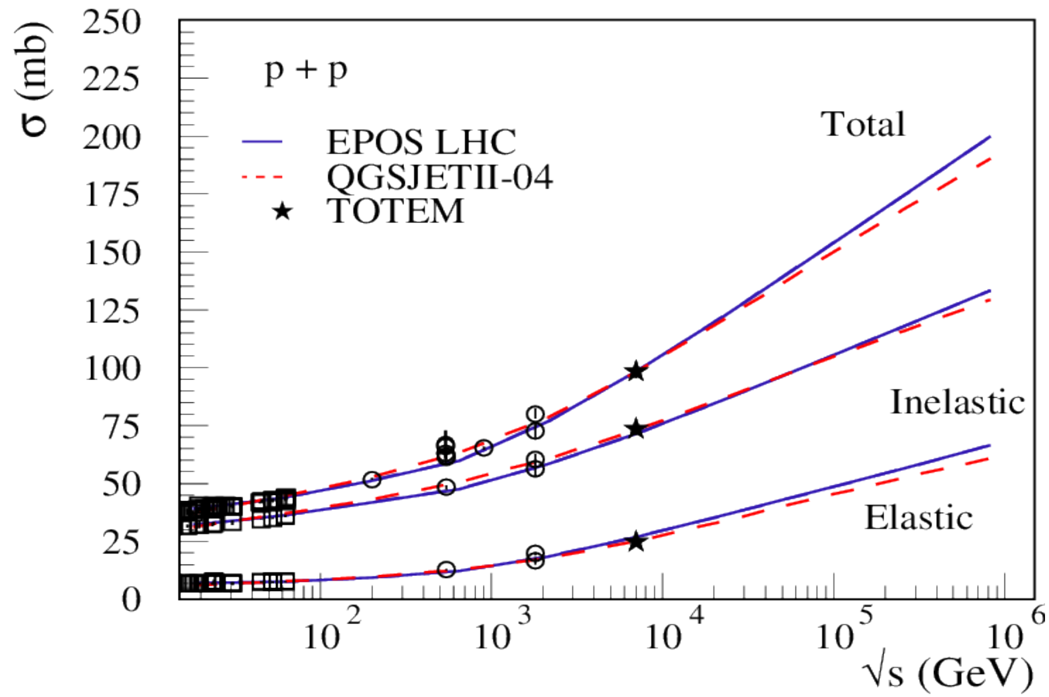
Cross Sections

- 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

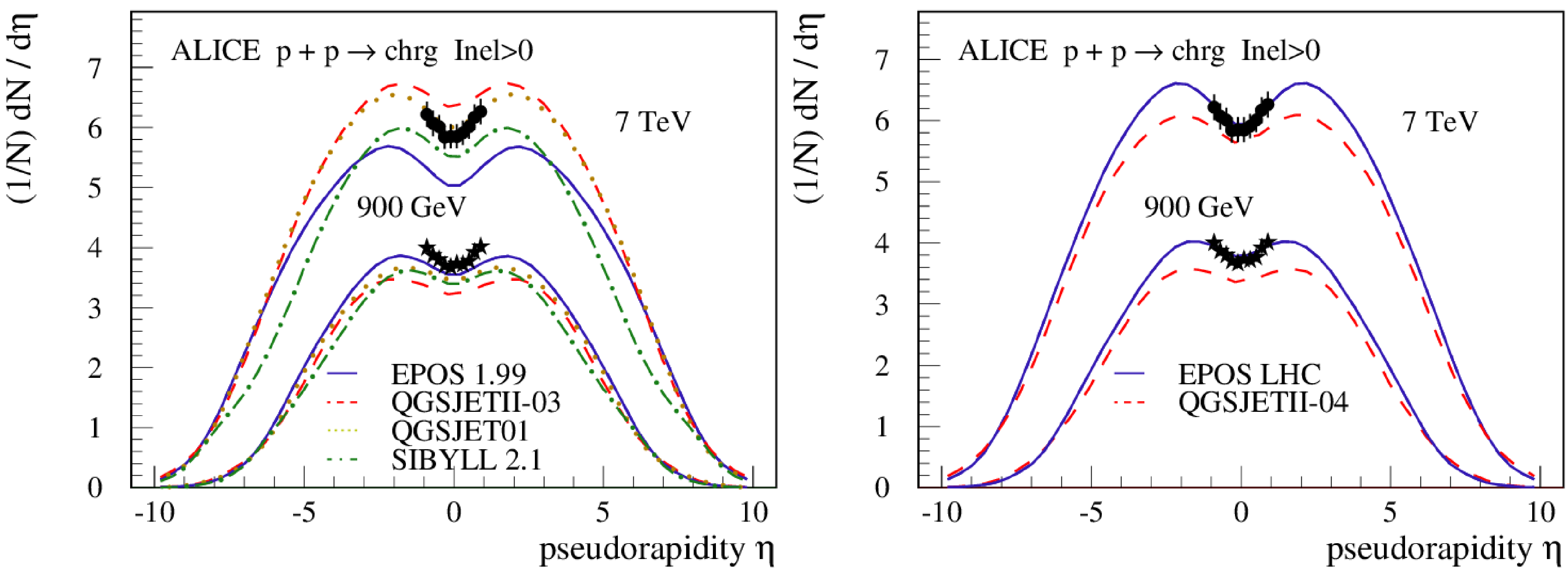


Multiplicity

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

Pre - LHC

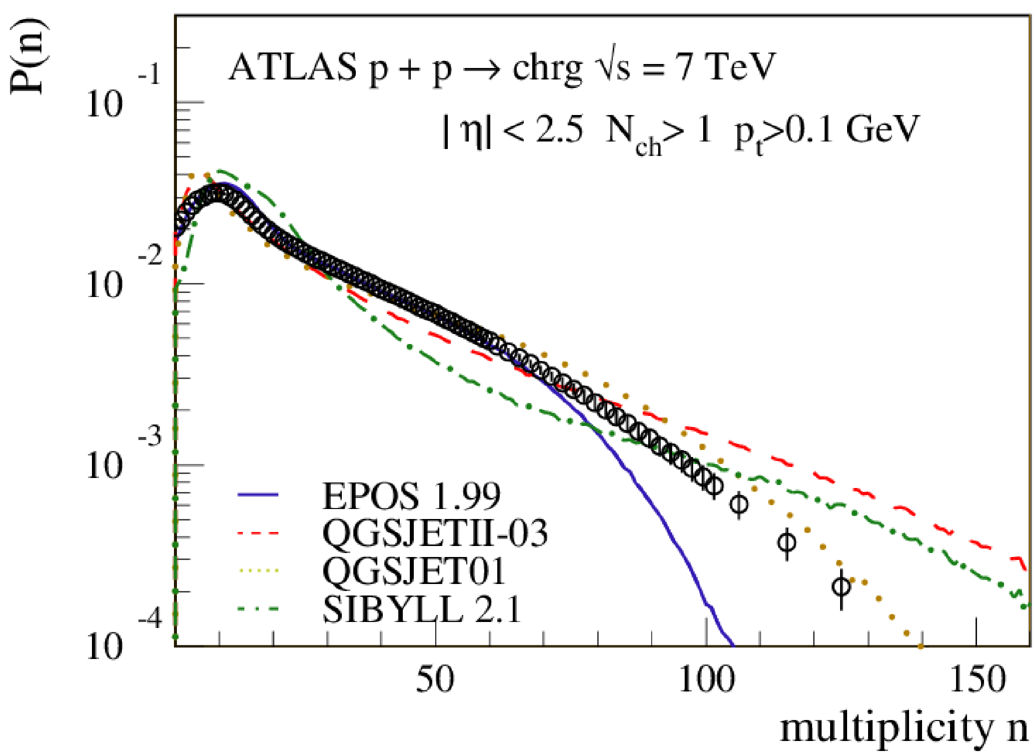
Post - LHC



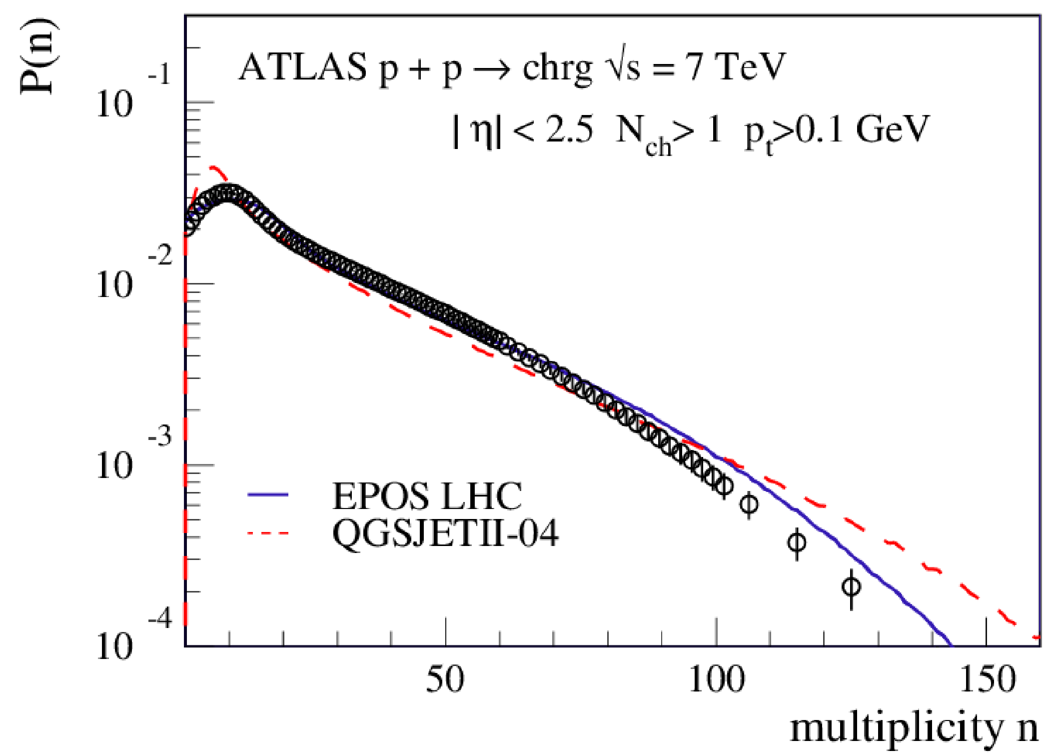
Multiplicity

- **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

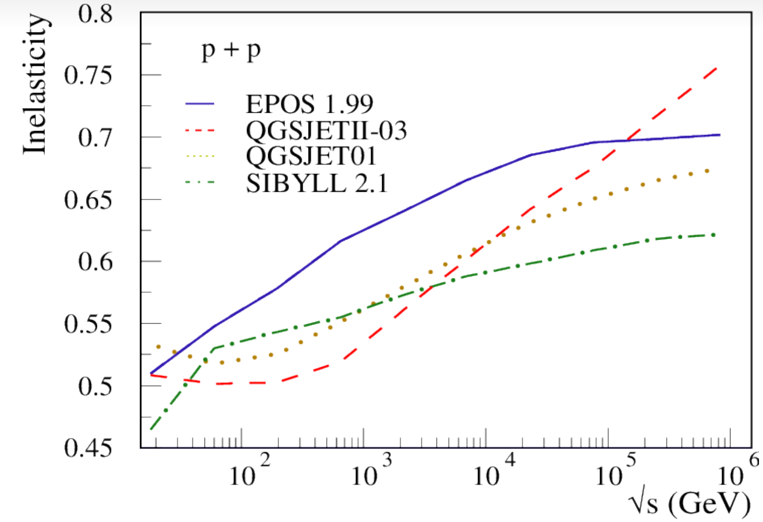


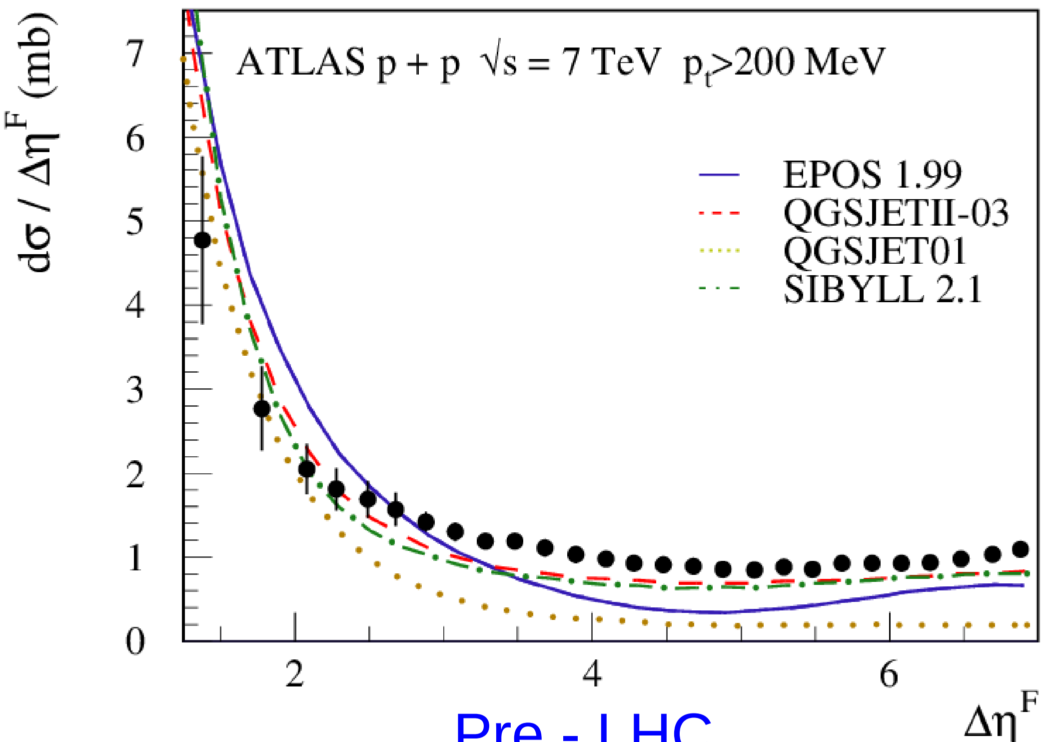
Post - LHC



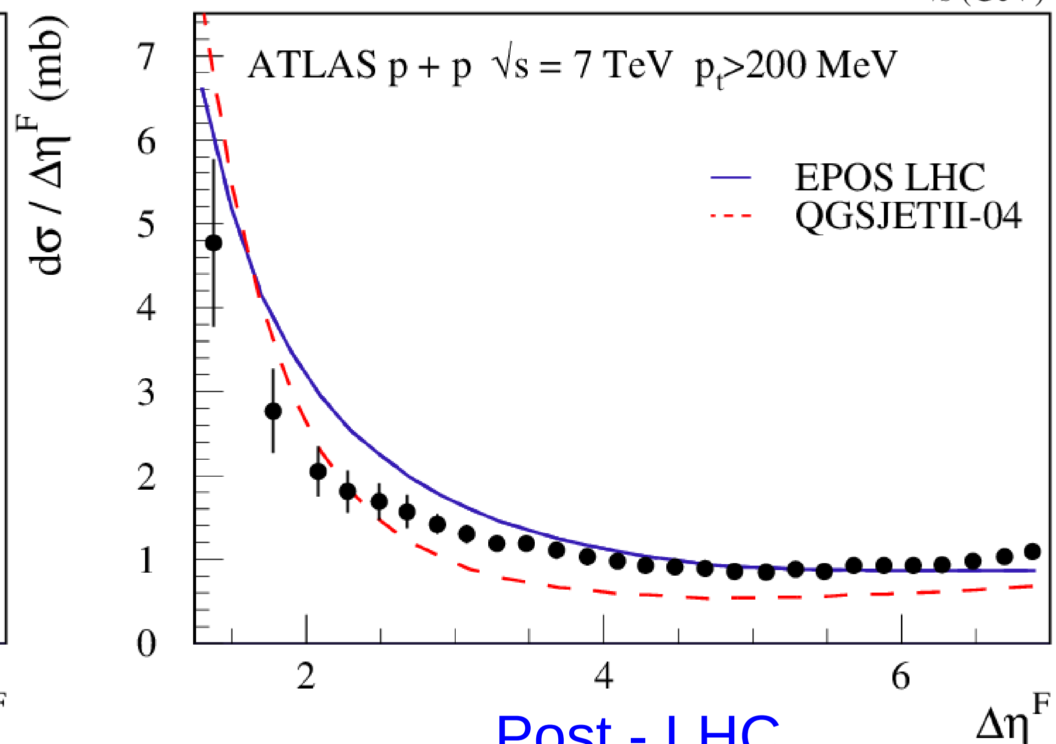
Inelasticity

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





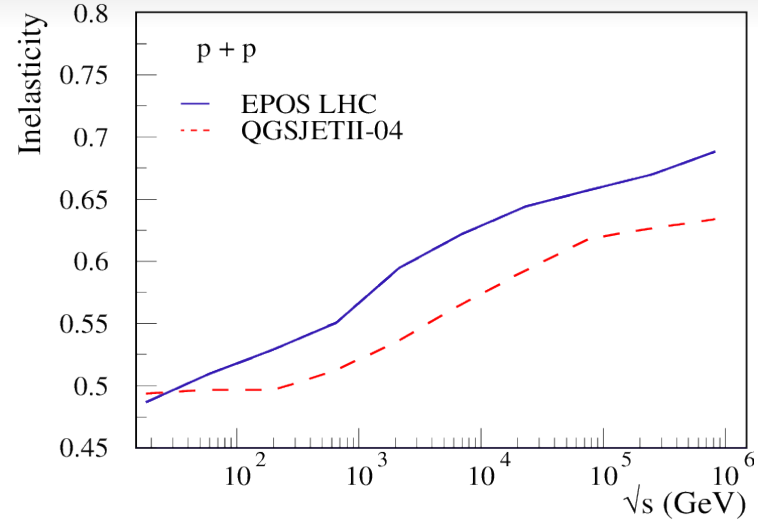
Pre - LHC

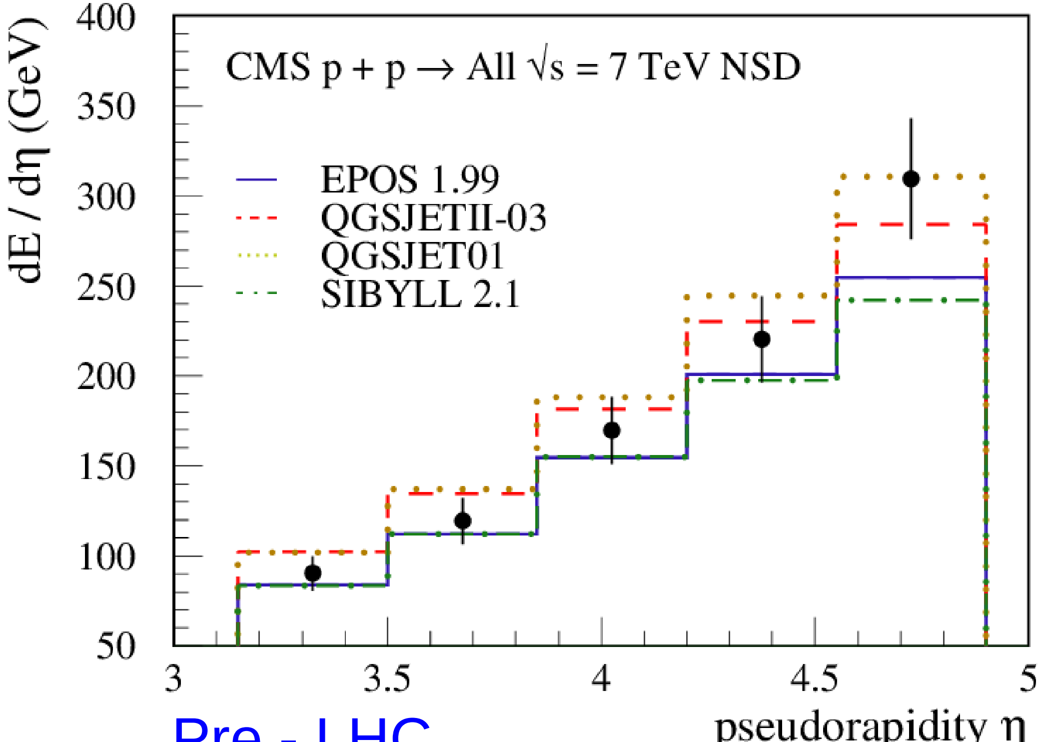


Post - LHC

Inelasticity

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





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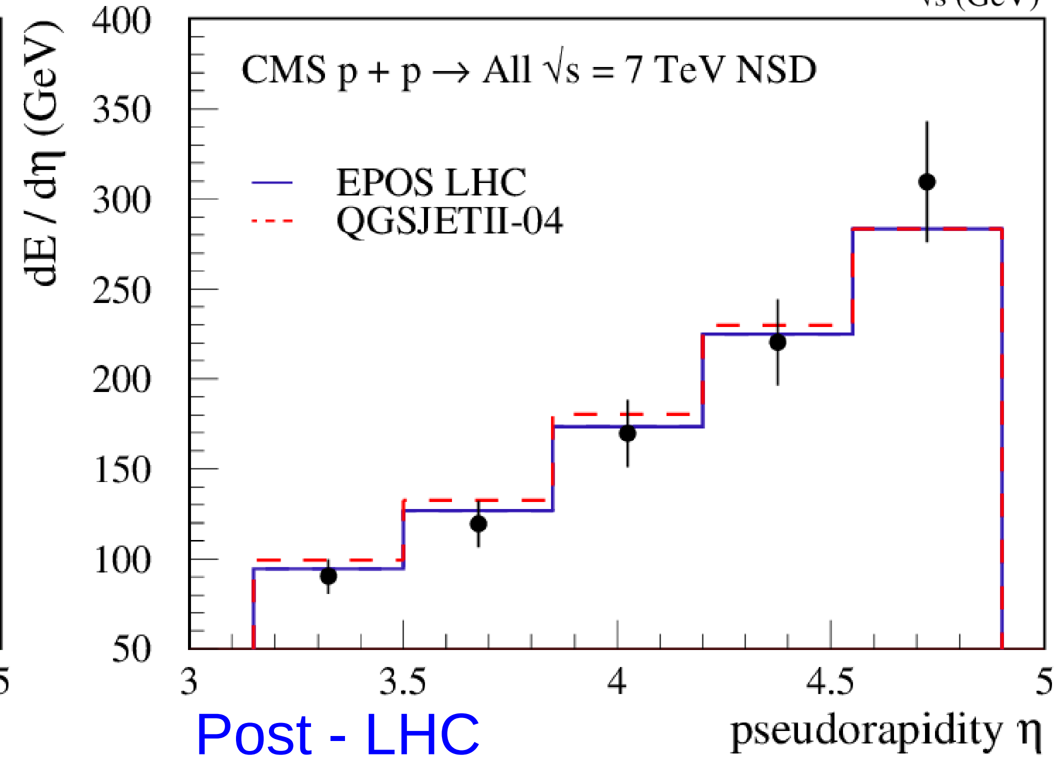
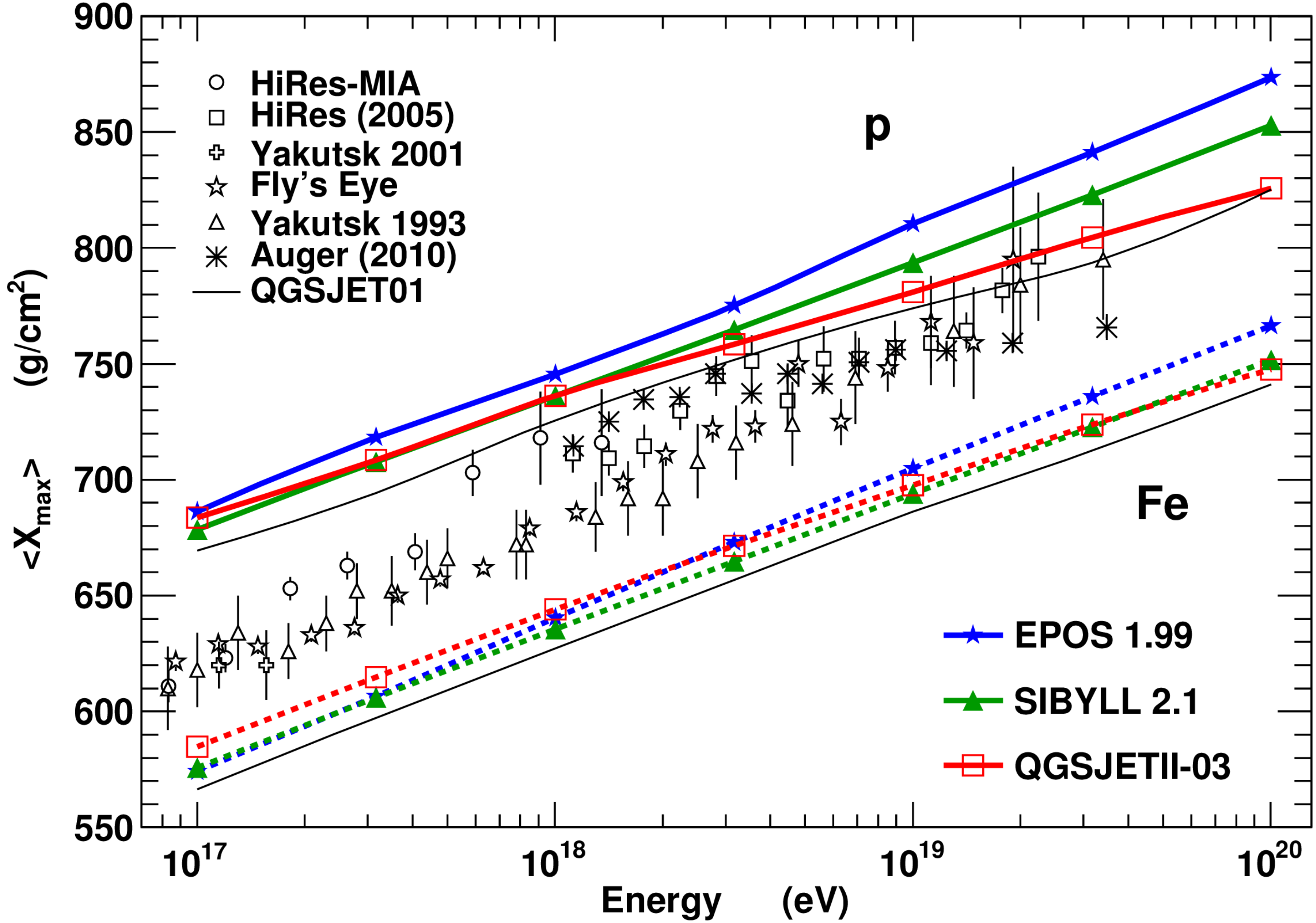
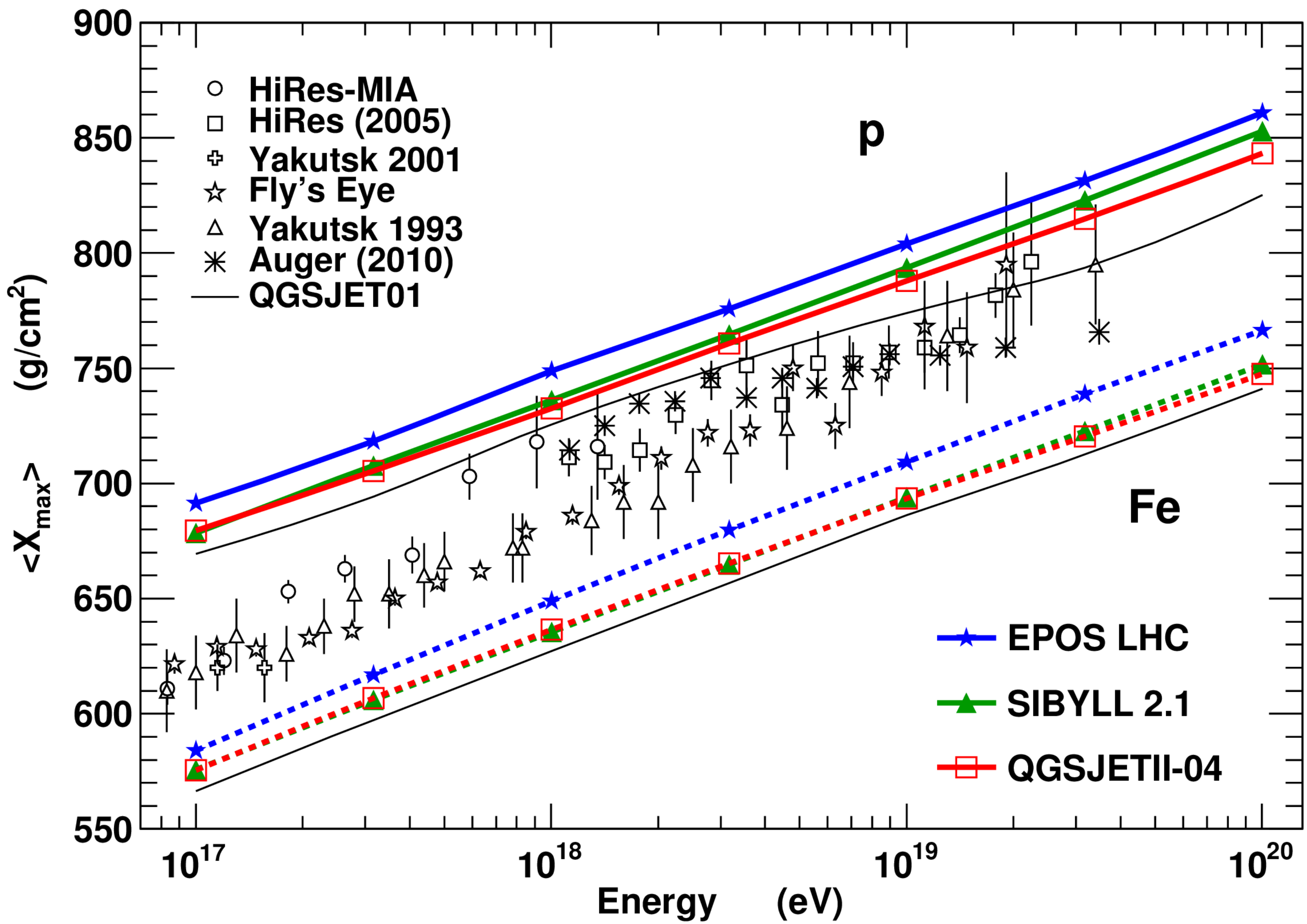


Post - LHC

EAS with Old CR Models : X_{max}

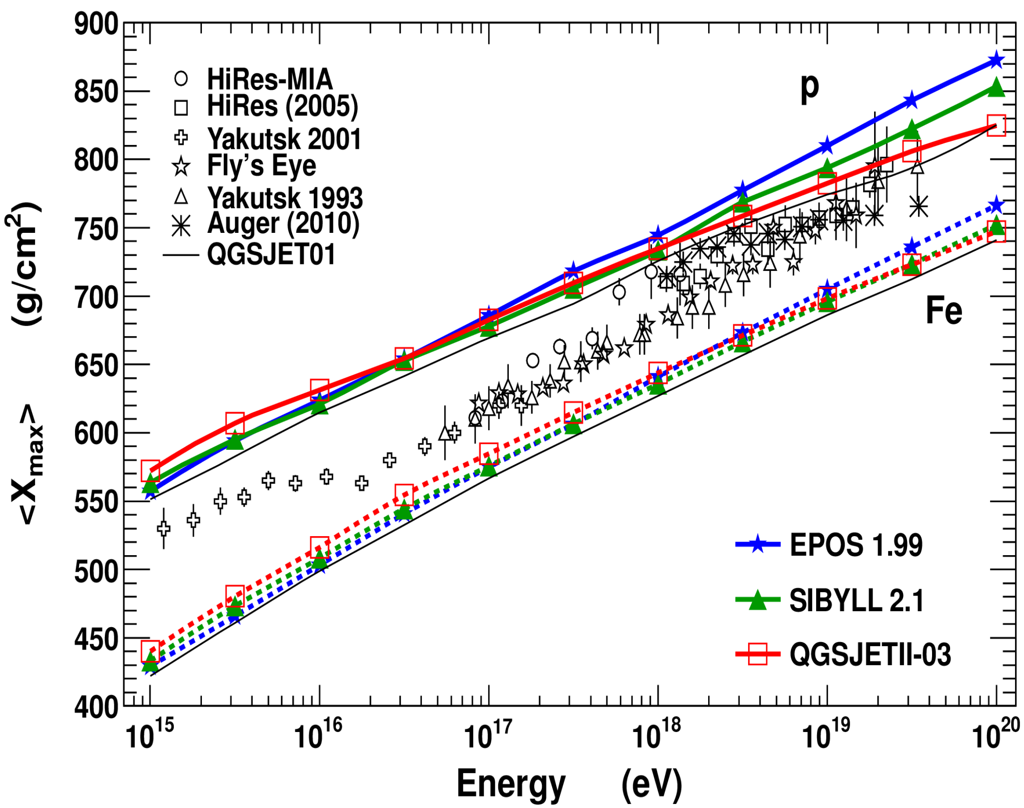


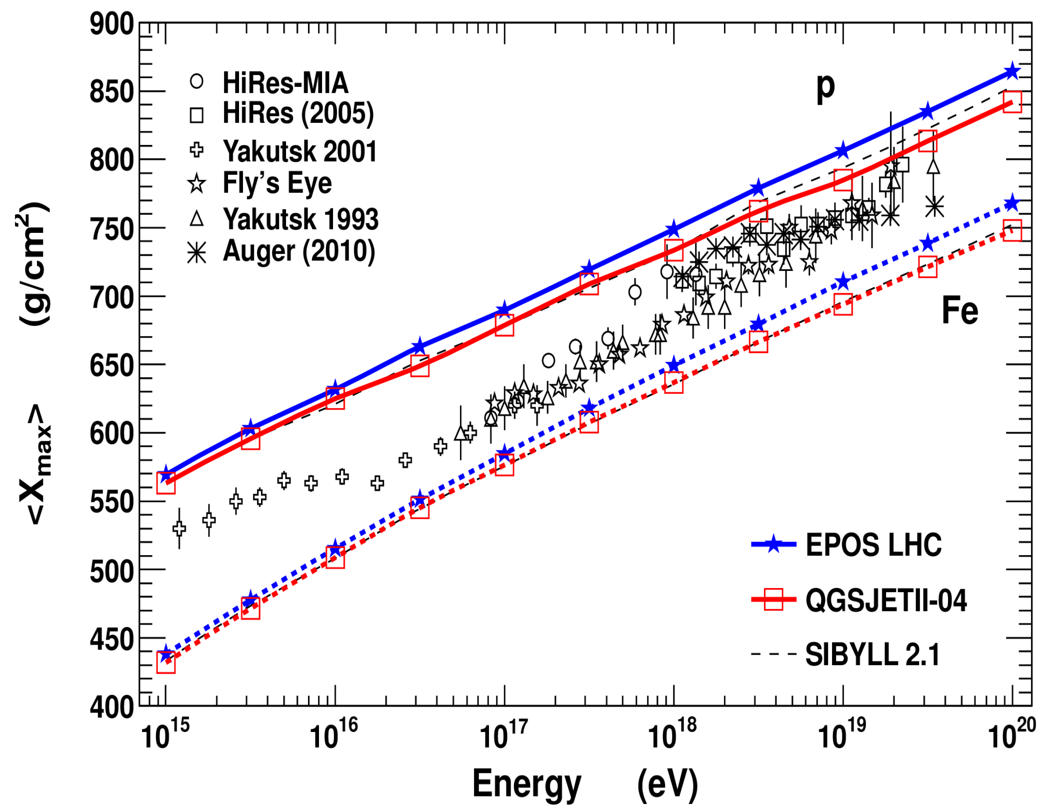
EAS with Re-tuned CR Models : X_{max}



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/cm^2 to ~20 g/cm^2 (difference proton/iron is about 100 g/cm^2)

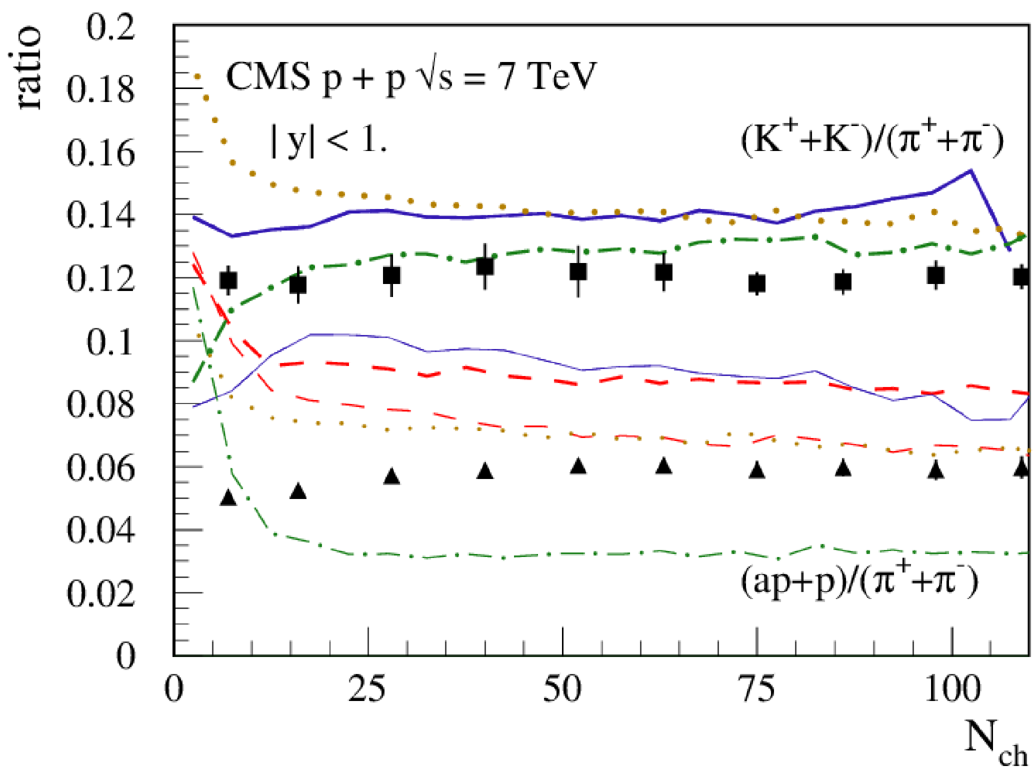




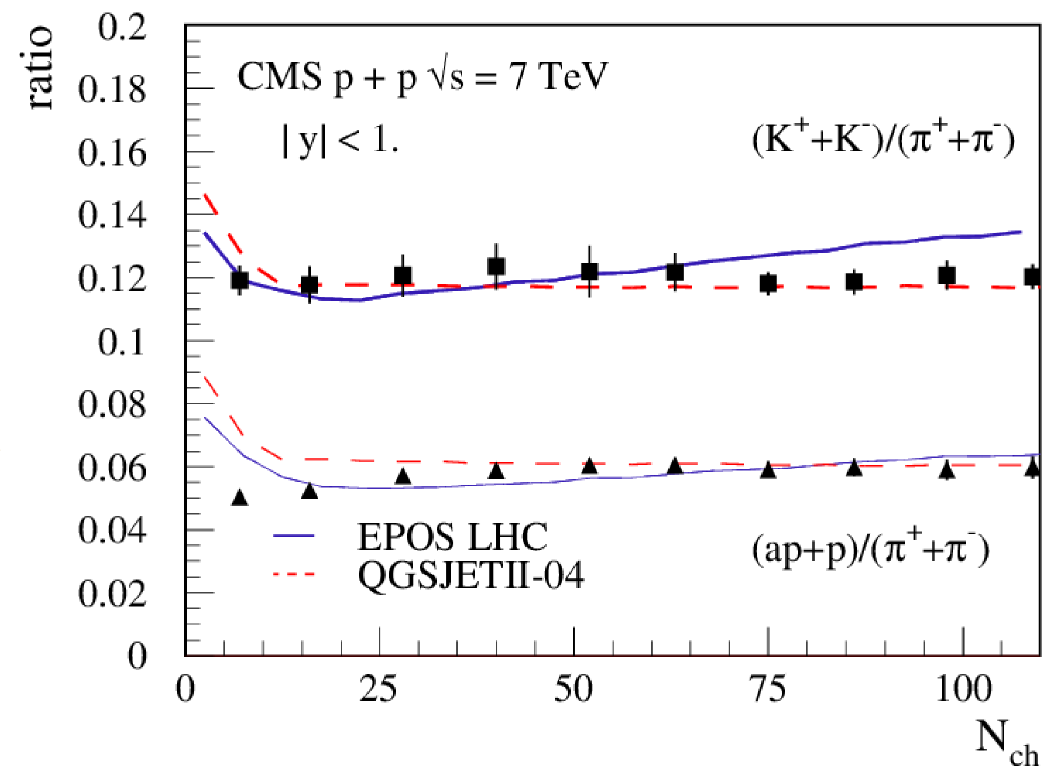
Identified particles

- **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

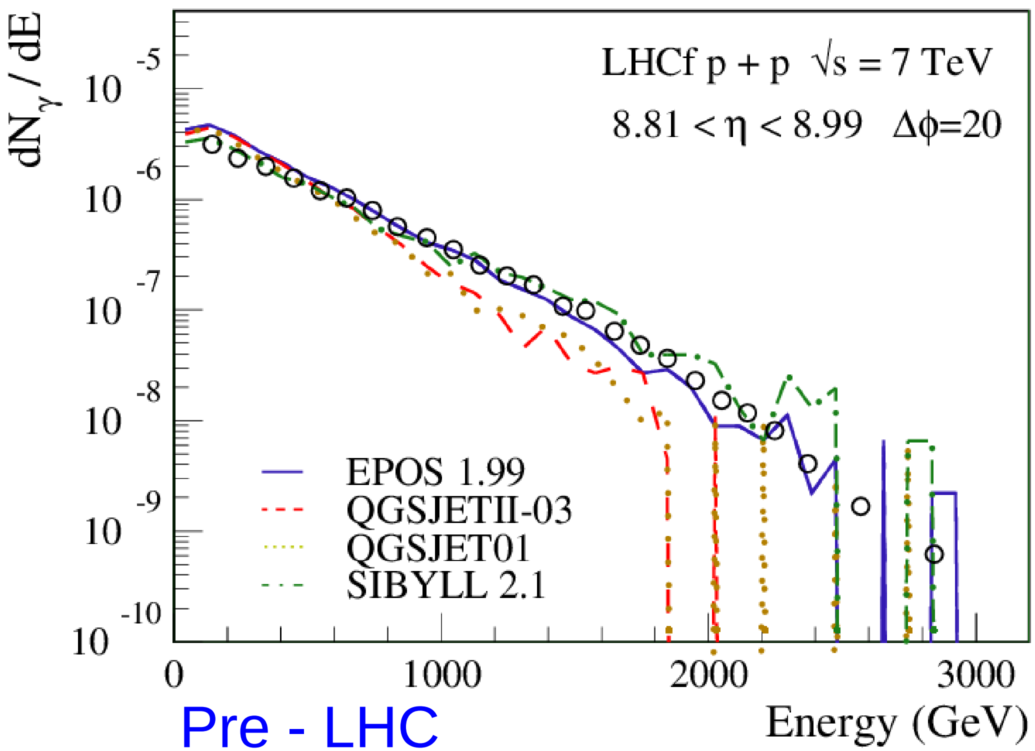


Post - LHC



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)



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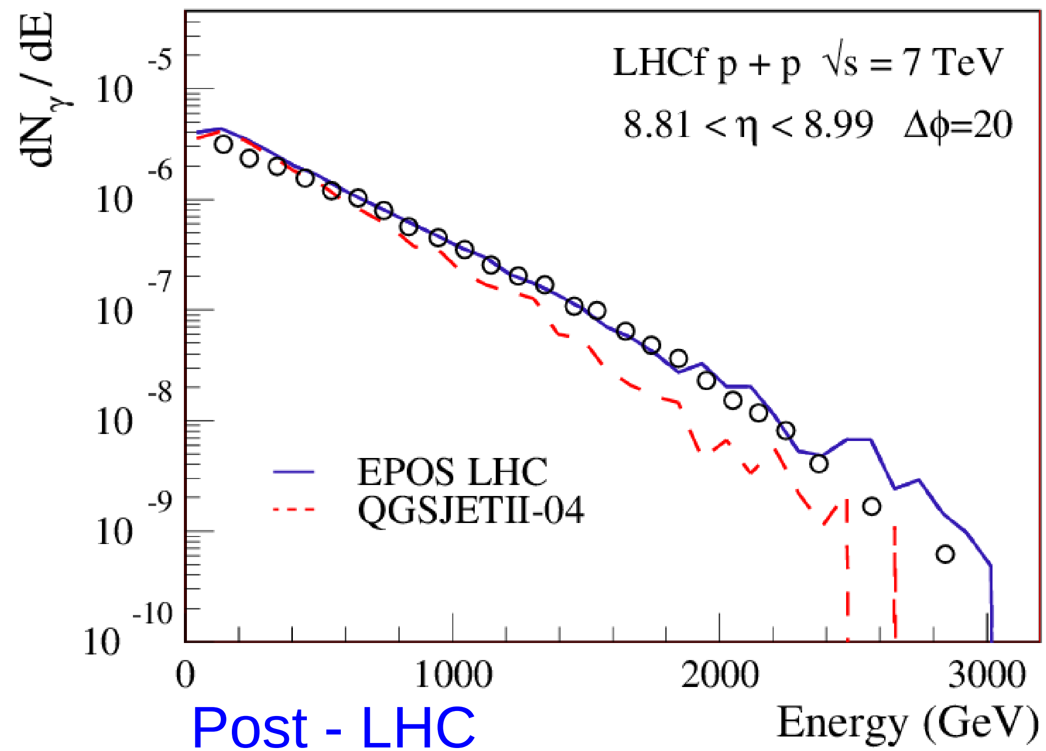
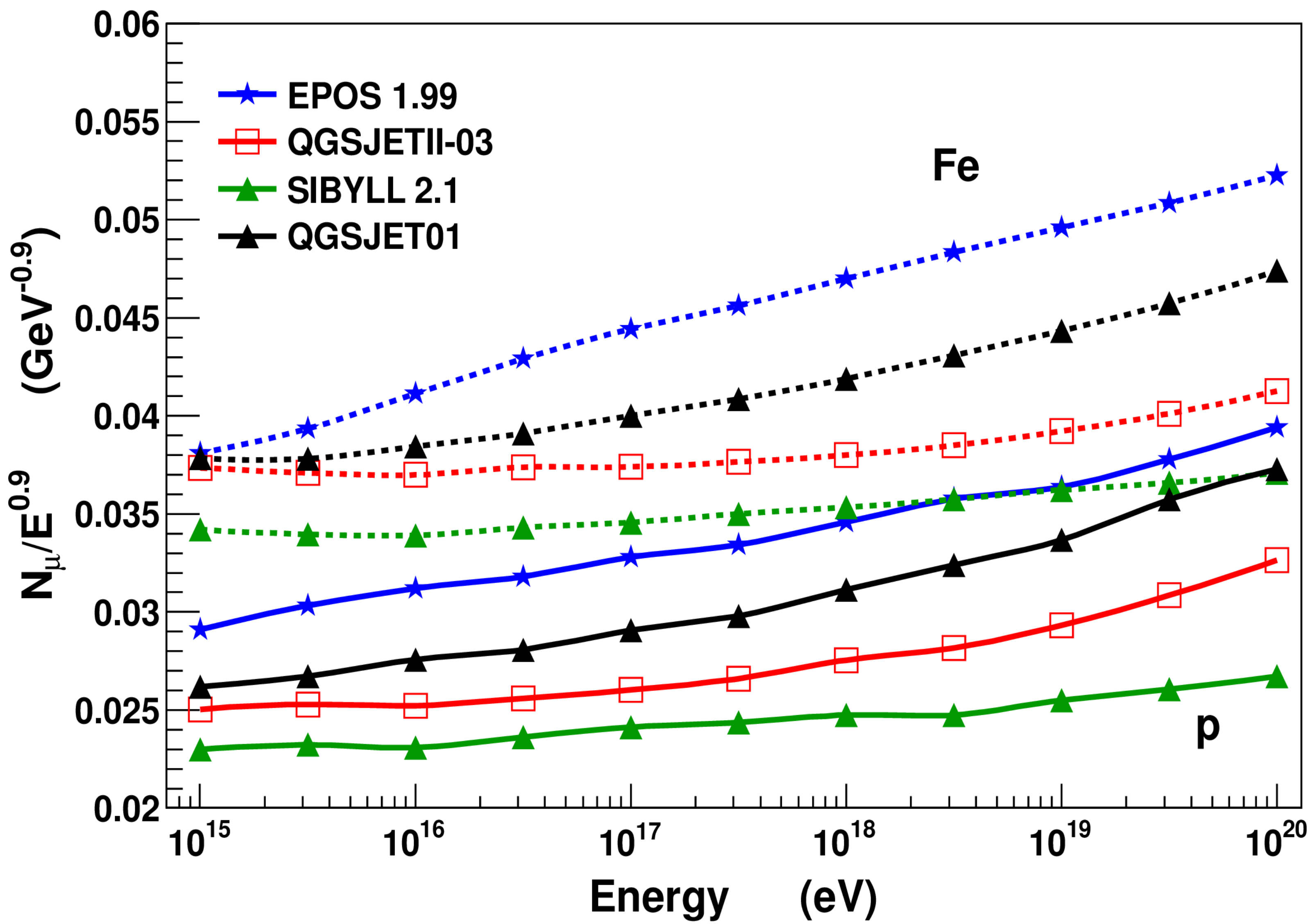


Post - LHC

EAS with Re-tuned CR Models : Muons



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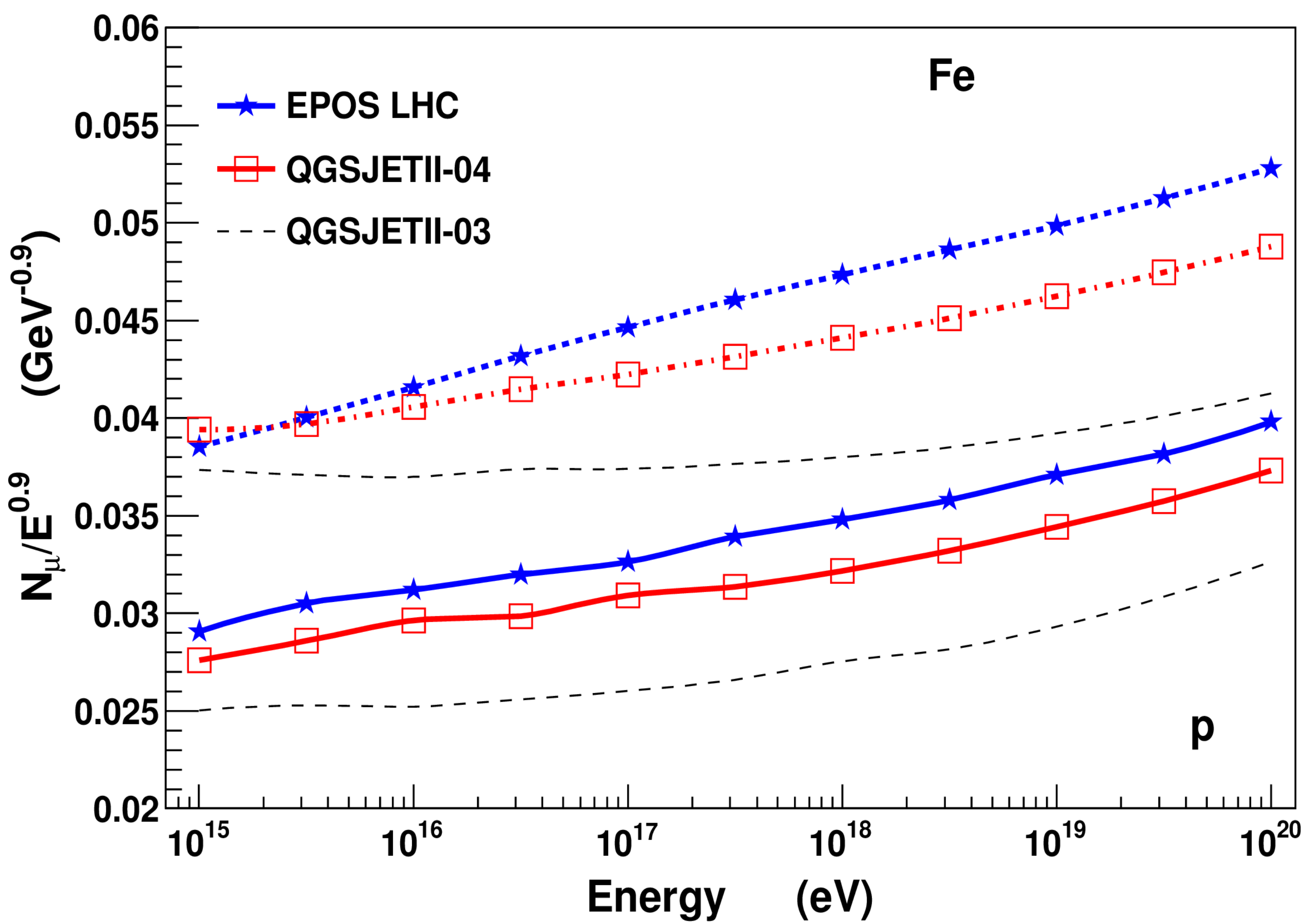
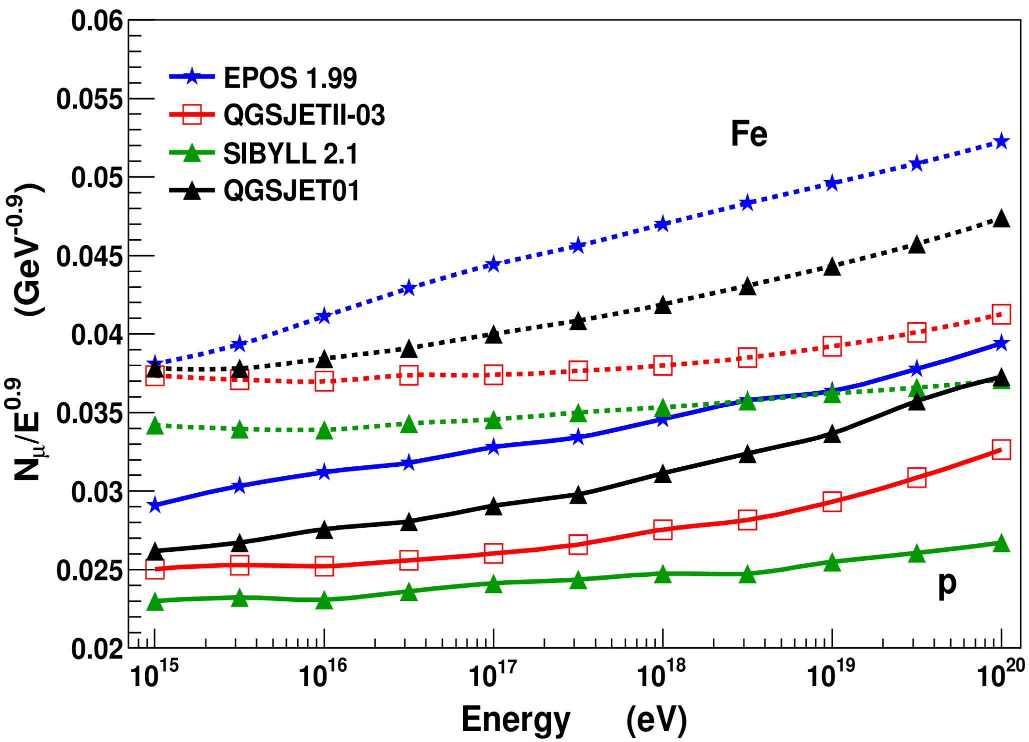
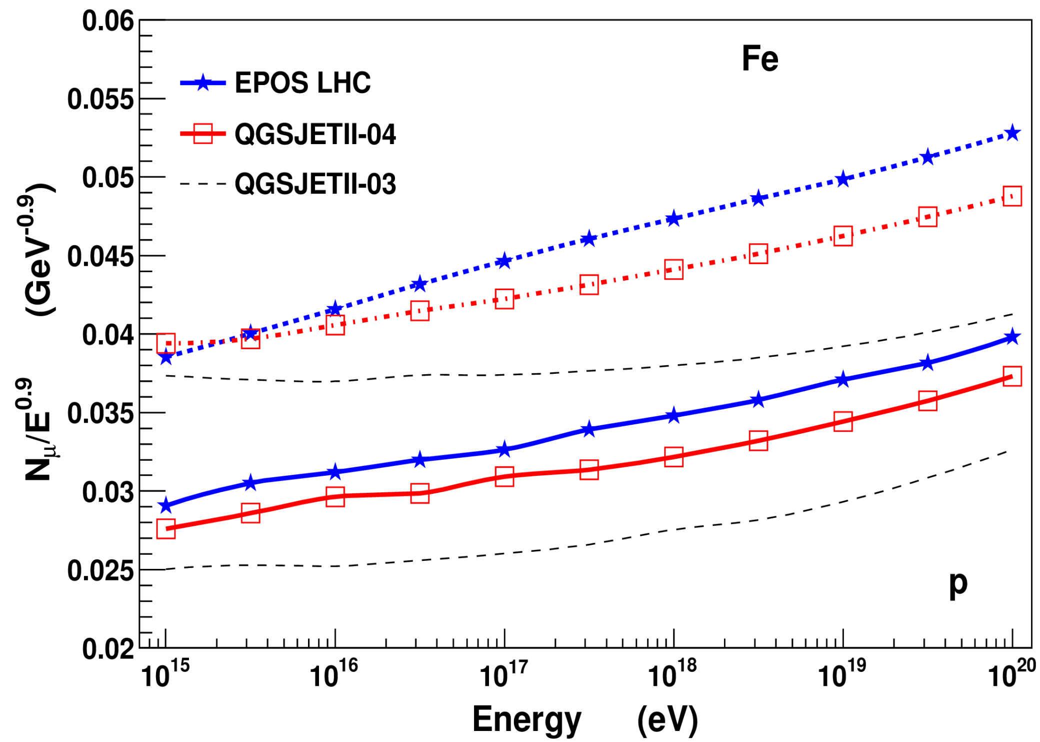


EAS with Re-tuned CR Models : Muons

- **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

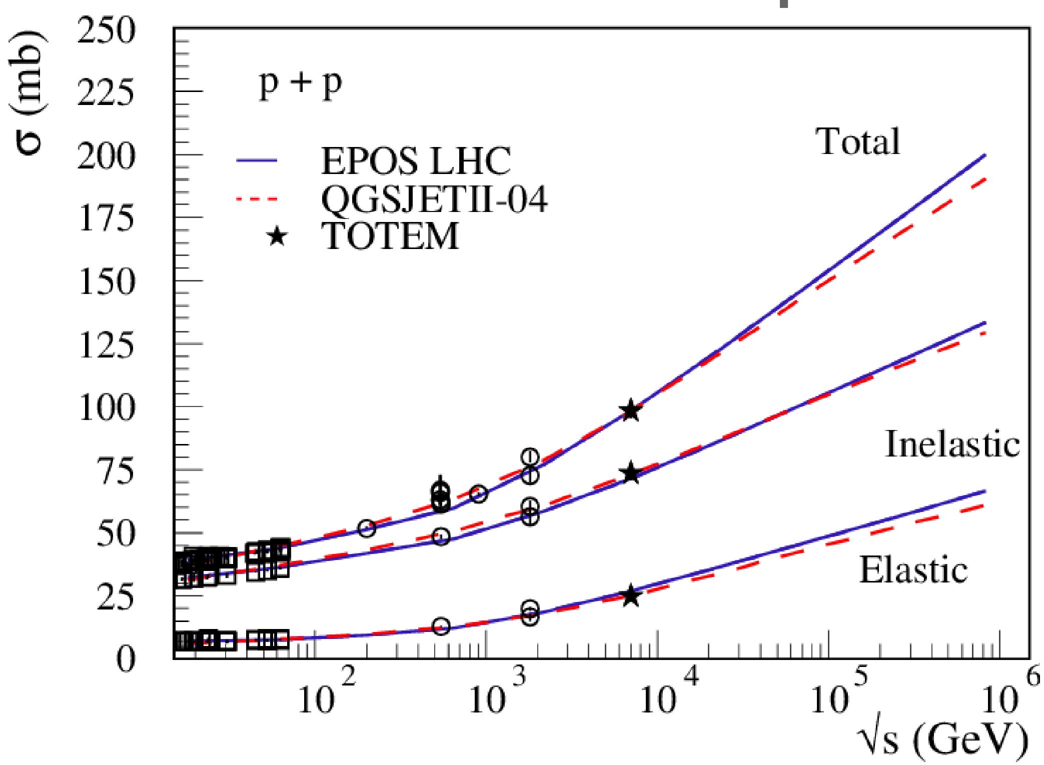


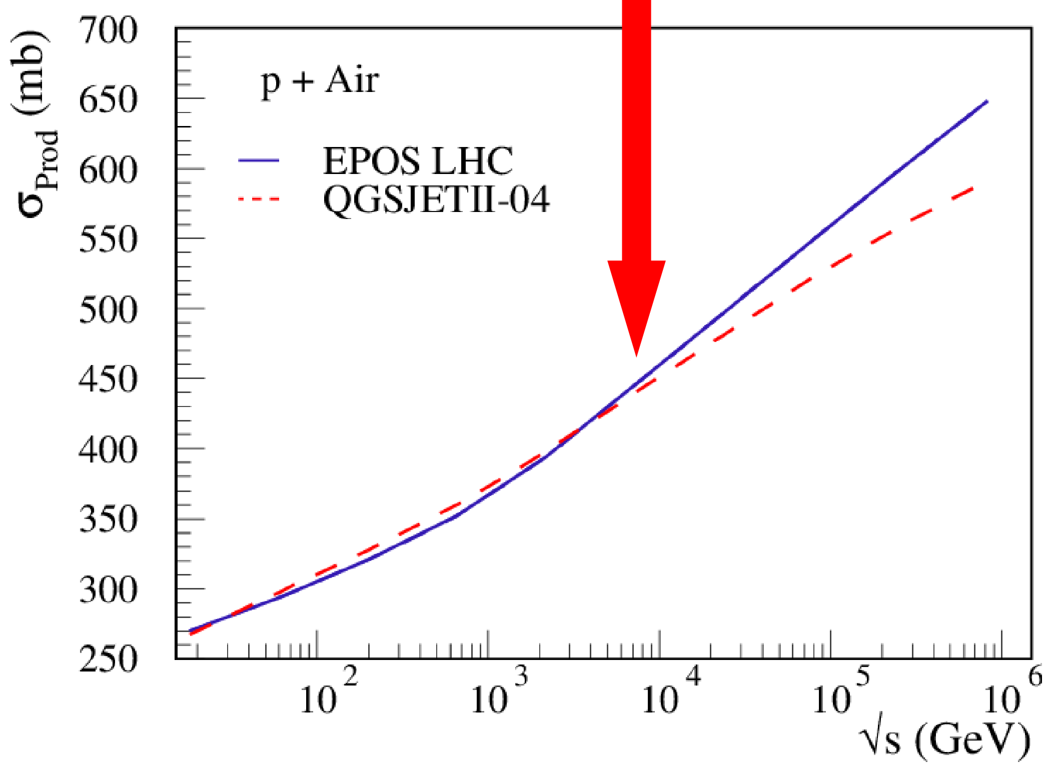


Interactions in Air Shower : p-Air

- **Source of uncertainties : extrapolation**
  - to higher energies
    - strong constraints by current LHC data
  - from p-p to p-Air
    - current main source of uncertainty
- **Needs for new data : p-O**

No big difference @ LHC but larger uncertainty in extrapolation





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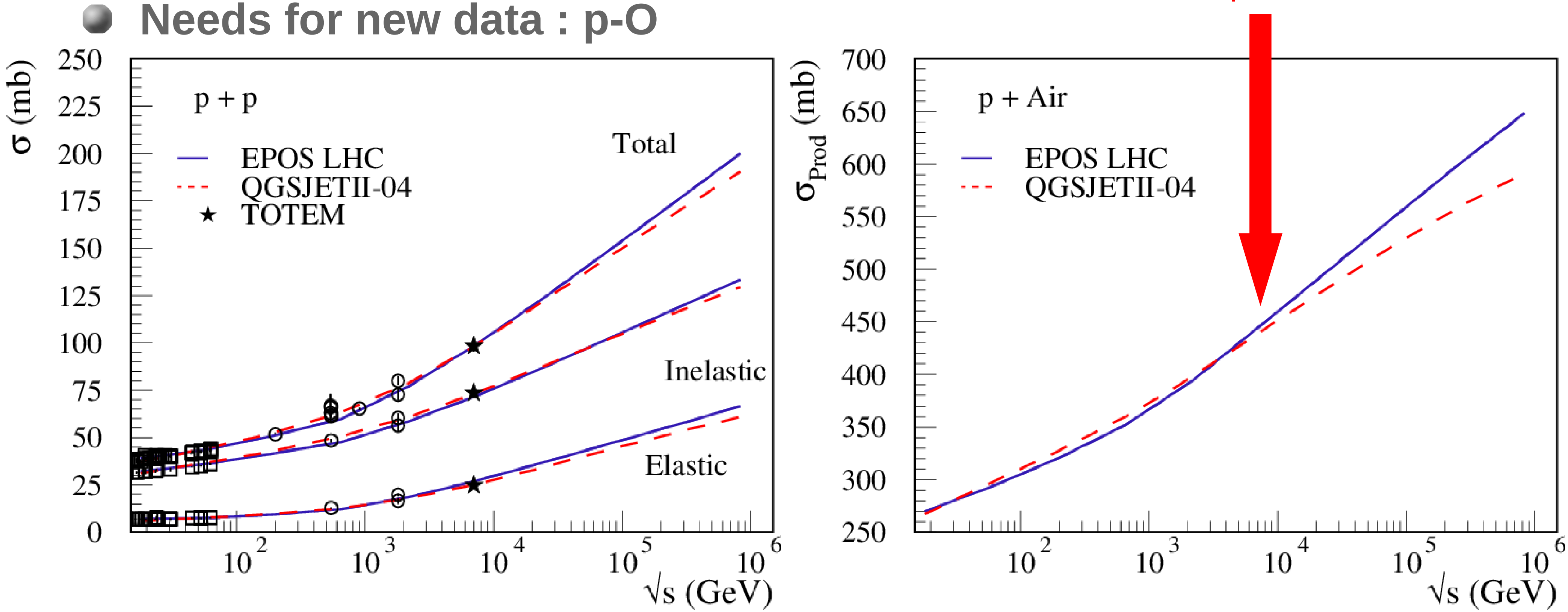
Compare p-p@14TeV and p-O@4.9TeV
(same beam energy than p-p@7TeV)

No big difference @ LHC but larger uncertainty in extrapolation



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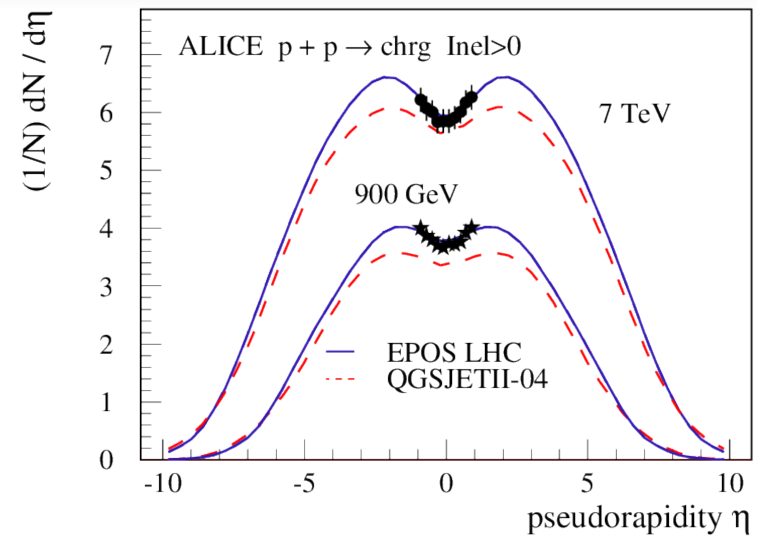

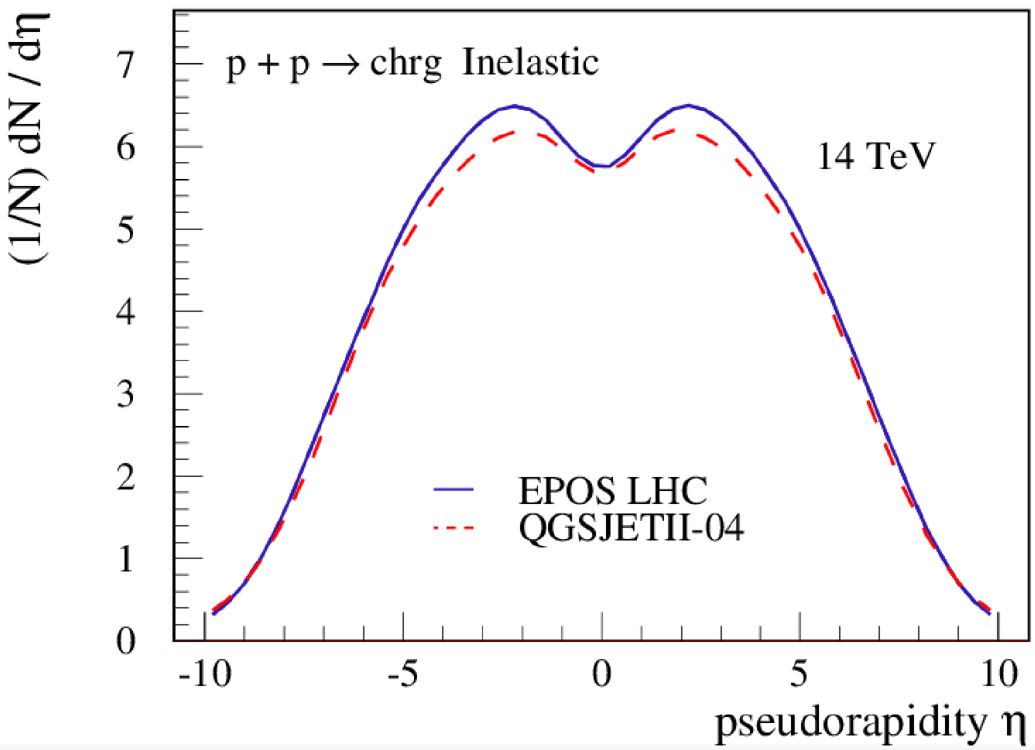

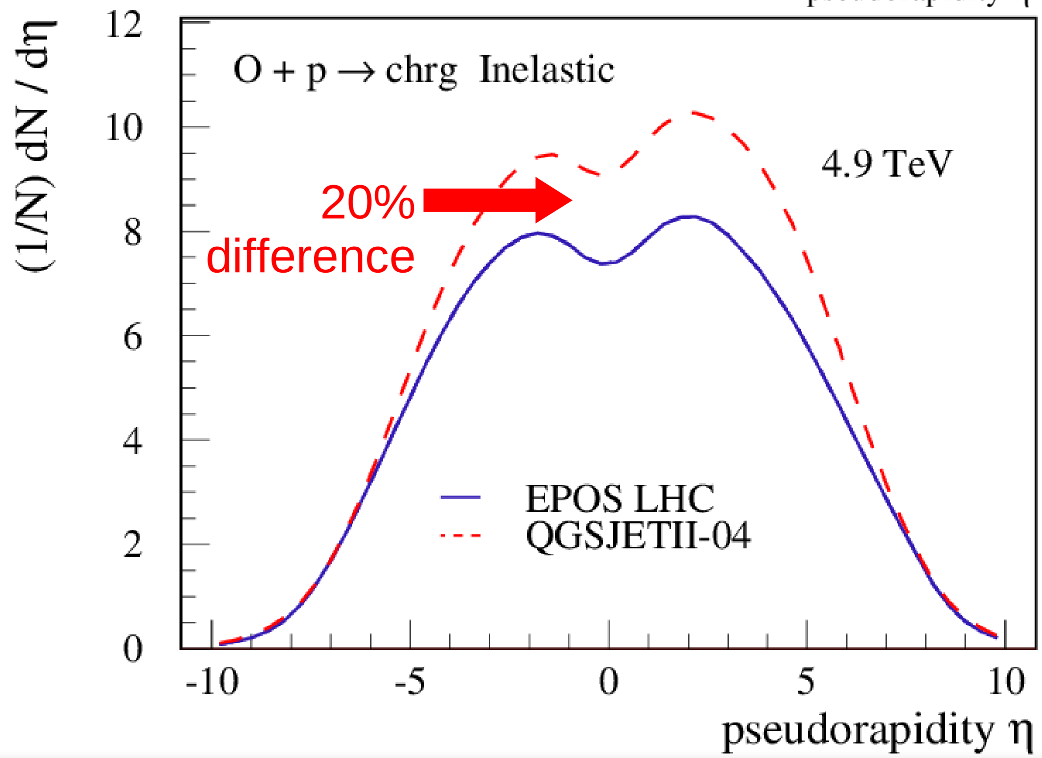

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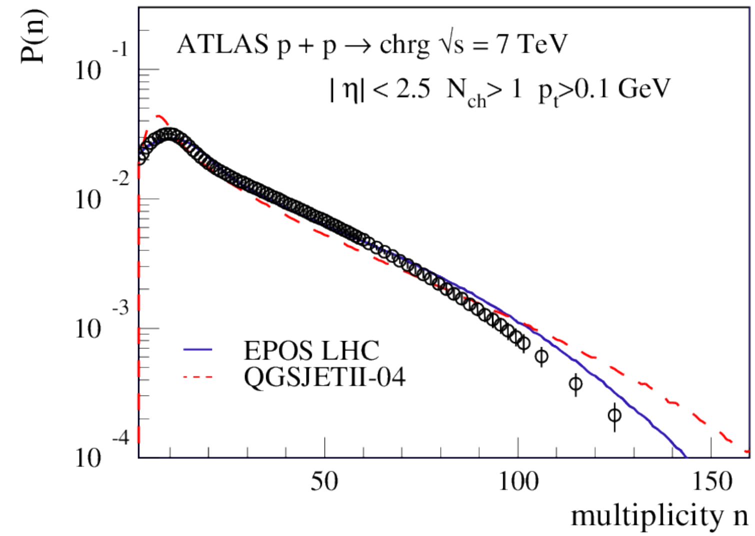

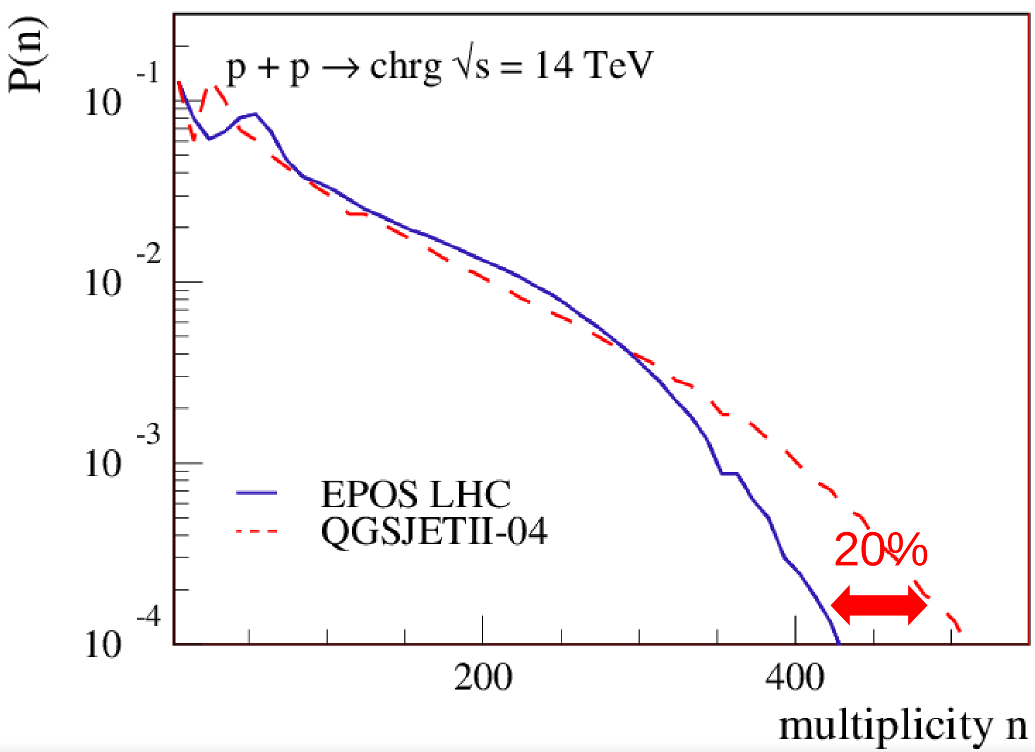

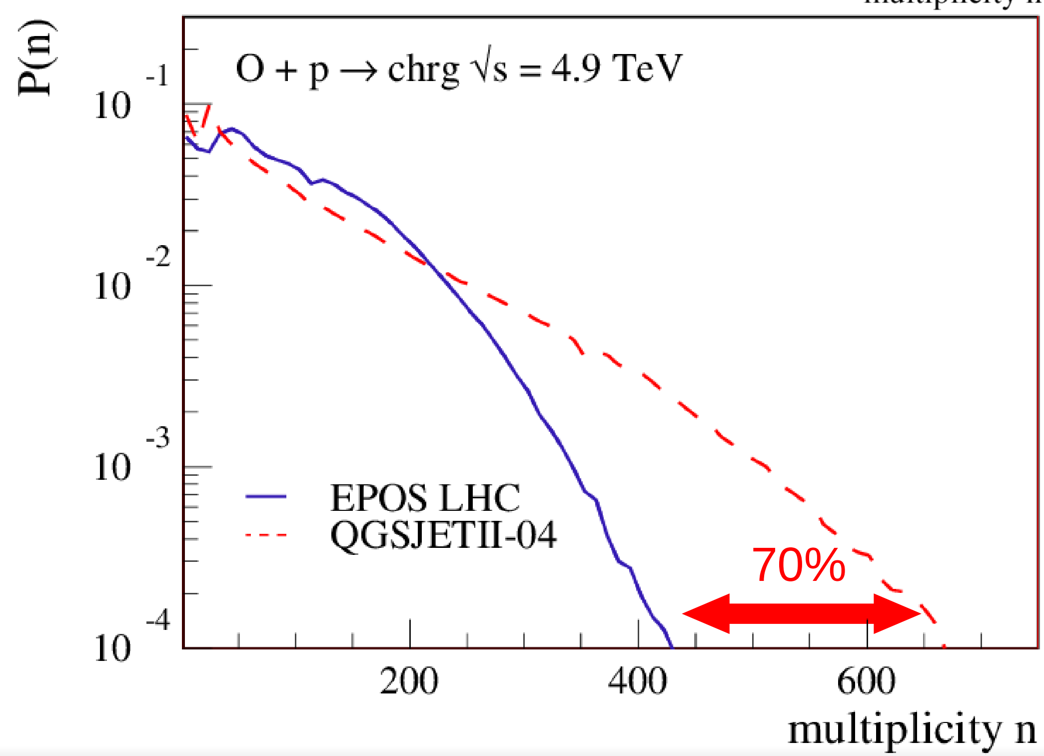

Interactions in Air Shower : p-Air

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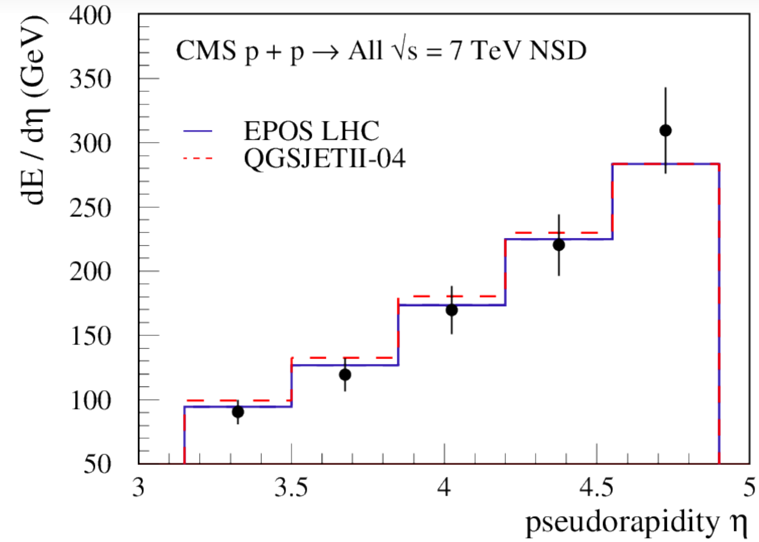
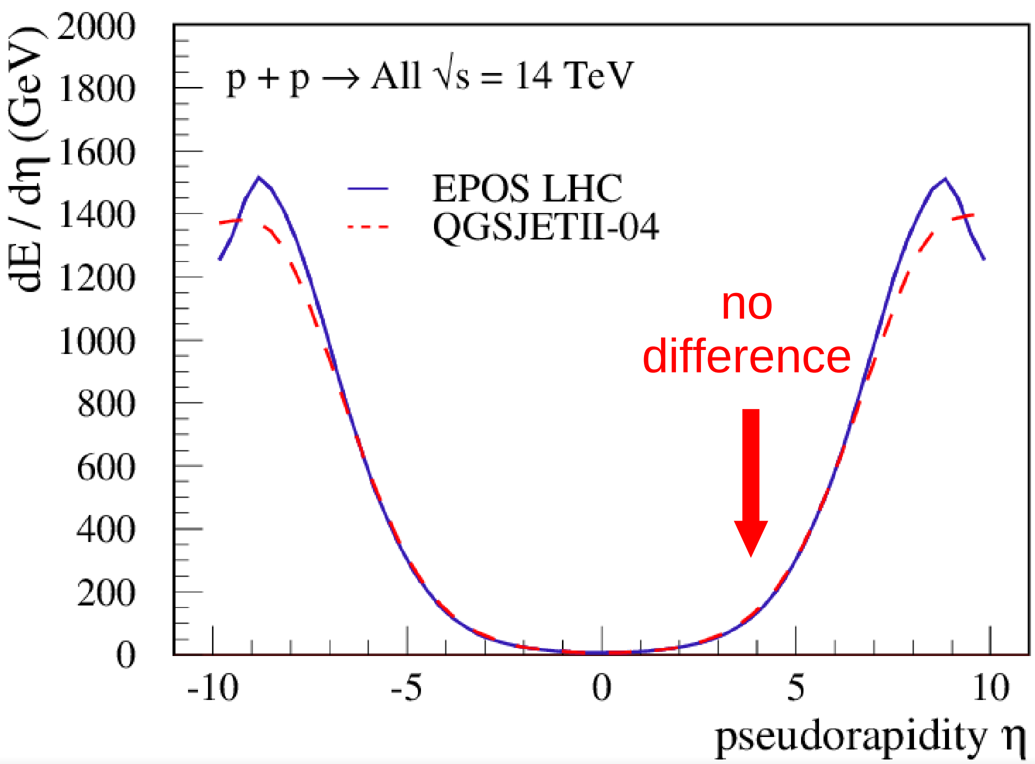
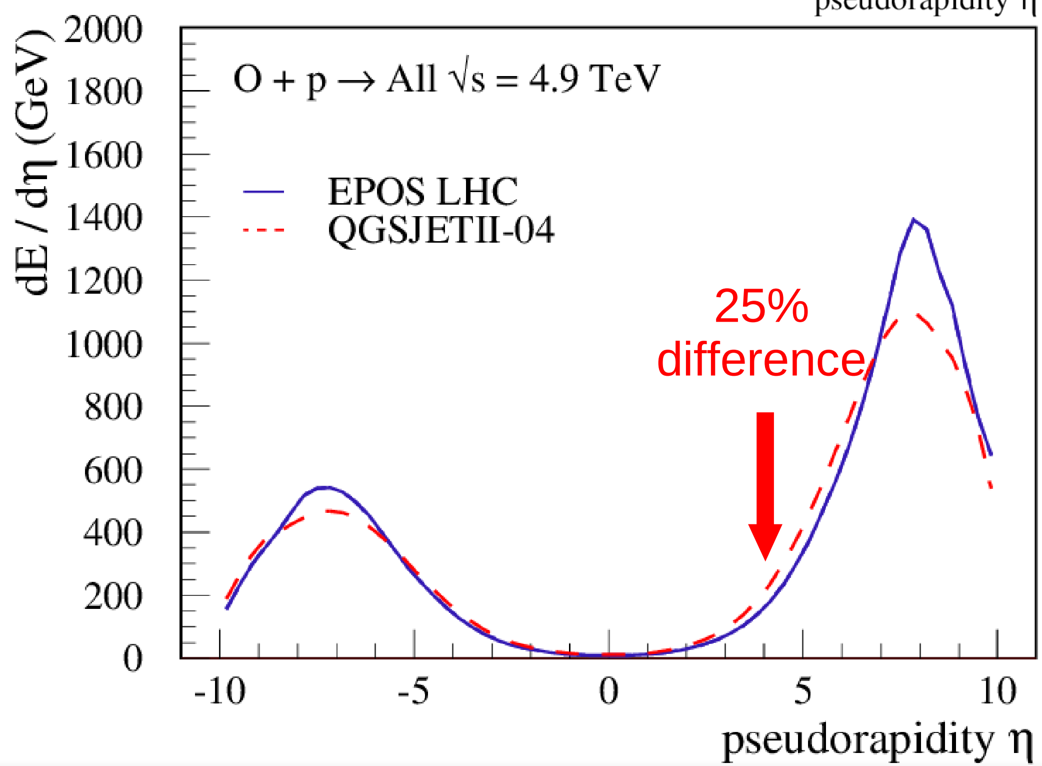
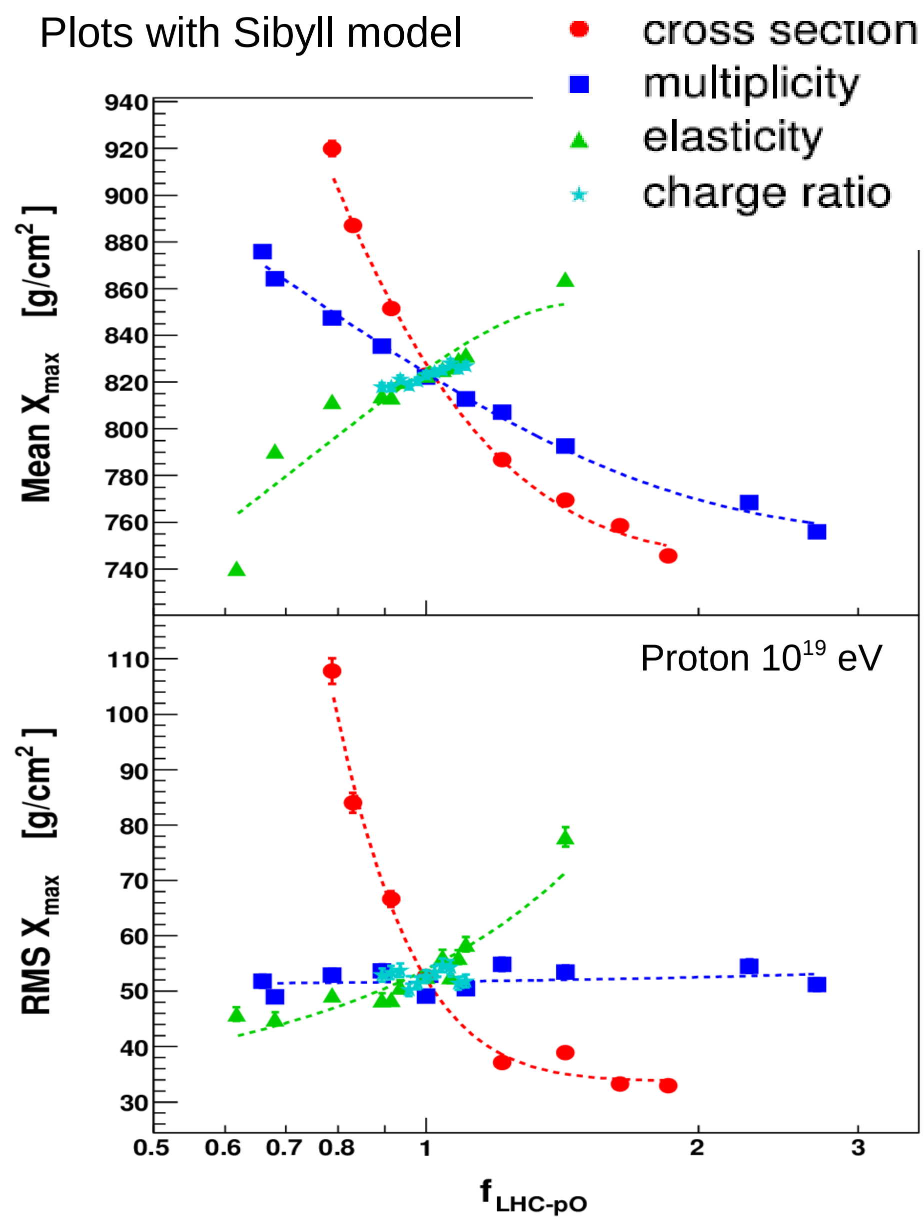


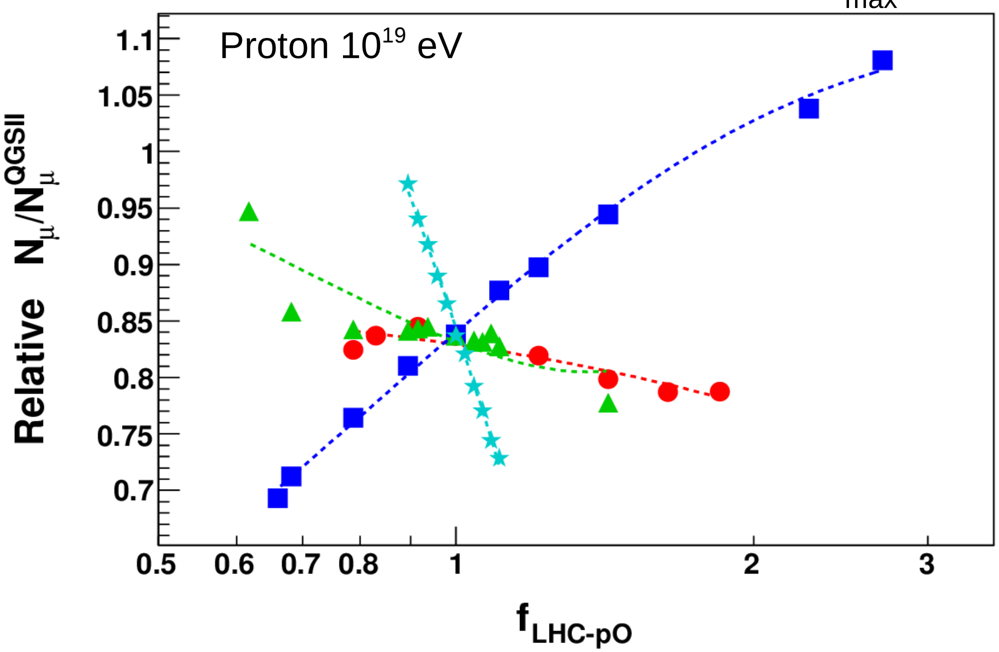




Effects of Parameters

- **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 $<X_{max}>$





Summary

- **First LHC run :**
  - ➡ Min bias analysis provide plenty of useful data to constrain hadronic interactions models used for air shower simulation
    - strong constrains on energy evolution of particle production and cross-section
  - ➡ results converge between models both air shower observable like X_{max} and number of muons at ground (differences reduced by a factor of 2)

- **Next LHC run :**
  - ➡ little further improvement by larger energy (unless new Physics appear)
  - ➡ more constrain if new beam is used : p-O would be a perfect test for hadronic interaction models
    - reduction of the larger remaining source of uncertainty in air shower simulations
  - ➡ other useful measurements : very forward particle identification, ...

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**

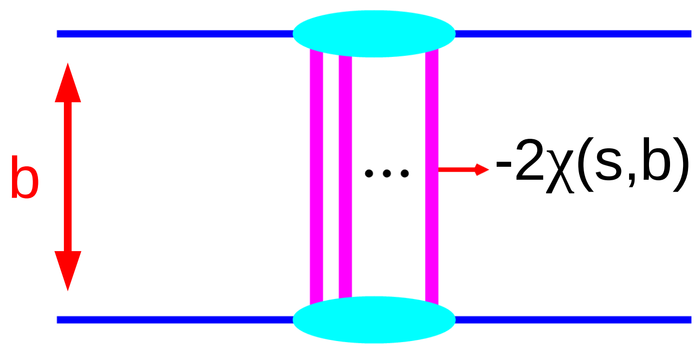
Only model used in HEP (SPS, RHIC, LHC)

Cross Section Calculation : SIBYLL / QGSJET

Interaction amplitude given by parameterization (soft) or pQCD (hard) and Gribov-Regge for multiple scattering :

- elastic amplitude : $-2\chi(s,b)$
- sum n interactions :
  - optical theorem : $\frac{(-2\chi)^n}{n!} \rightarrow \exp(-2\chi)$

s = (cms energy)^2
b = impact parameter

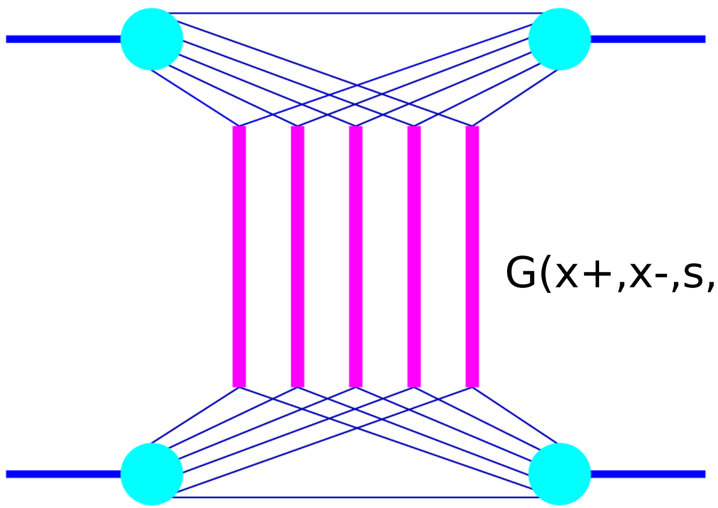


$$\sigma \sim 1 - \exp(-2\chi)$$

Not the same χ in QGSJET01, QGSJETII and SIBYLL

- $\chi(s,b)$ parameters for a given model fixed by pp cross-section
- pp to pA or AA cross section from Glauber
- energy conservation not taken into account at this level

Cross Section Calculation : EPOS



Different approach in EPOS :

- Gribov-Regge but with energy sharing at parton level : MPI with energy conservation !
- amplitude parameters fixed from QCD and pp cross section
- cross section calculation take into account interference term

$$\Phi_{\mathrm{pp}}\left(x^{+},x^{-},s,b\right) = \sum_{l=0}^{\infty}\int dx_1^+ dx_1^- \ldots dx_l^+ dx_l^- \left\{\frac{1}{l!}\prod_{\lambda=1}^{l} -G(x_\lambda^+,x_\lambda^-,s,b)\right\}$$
$$\times \; F_{\mathrm{proj}}\left(x^+ - \sum x_\lambda^+\right) F_{\mathrm{targ}}\left(x^- - \sum x_\lambda^-\right).$$

$$\sigma_{\mathrm{ine}}(s) = \int d^2b\,(1-\Phi_{\mathrm{pp}}(1,1,s,b))$$

- can not use complex diagram like QII with energy sharing
  - non linear effects taken into account as correction of single amplitude G

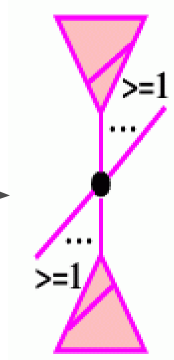
Particle Production in SIBYLL and QGSJET

Number n of exchanged elementary interaction per event fixed from elastic amplitude (cross section) :

- n from :

$$P(n)=\frac{(2\chi)^n}{n!}.\exp(-2\chi)$$

  - no energy sharing accounted for (interference term)
- $2n$ strings formed from the n elementary interactions
  - in QGSJET II, n is increased by the sub-diagrams
  - energy conservation : energy shared between the $2n$ strings
  - particles from string fragmentation



- inconsistency : energy sharing should be taken into account when fixing n

→ EPOS approach

Particle Production in EPOS

m number of exchanged elementary interaction per event fixed from elastic amplitude taking into account energy sharing :

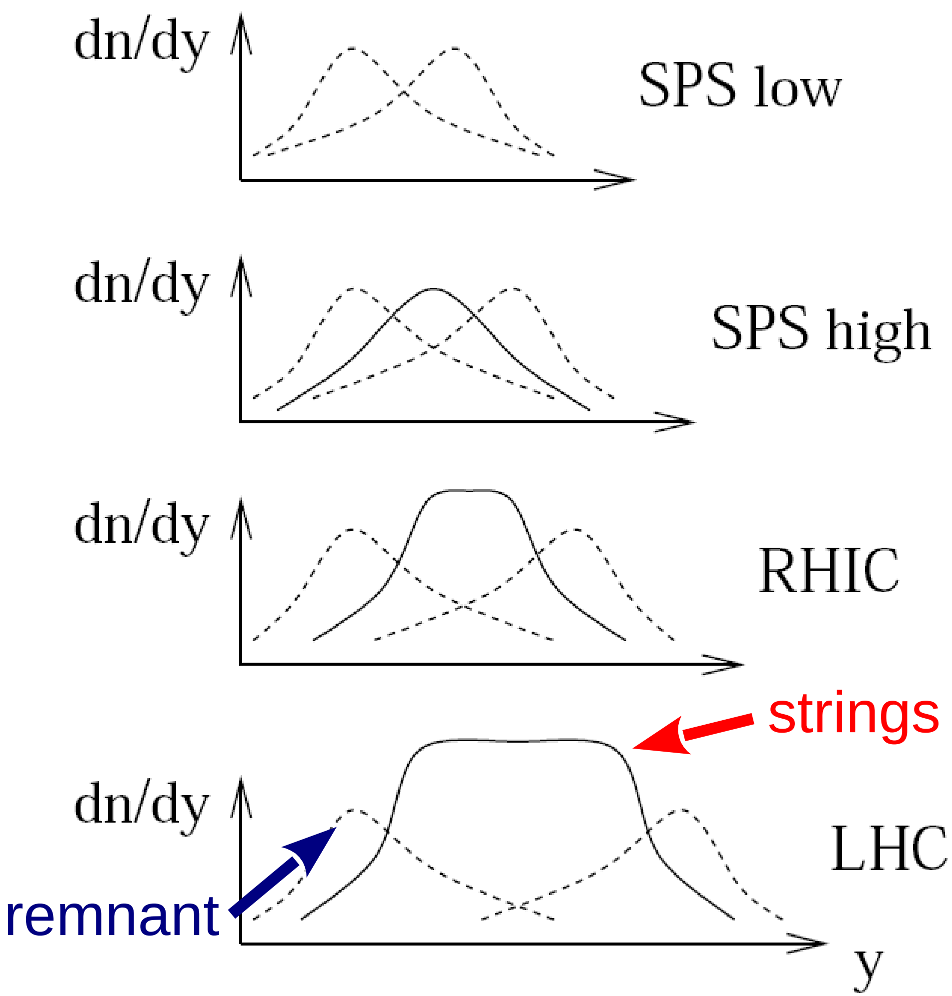
- m from :

$$\Omega_{AB}^{(s,b)}(m, X^+, X^-) = \prod_{k=1}^{AB} \left\{ \frac{1}{m_k!} \prod_{\mu=1}^{m_k} G(x_{k,\mu}^+, x_{k,\mu}^-, s, b_k) \right\} \Phi_{AB}\left(x^{\text{proj}}, x^{\text{targ}}, s, b\right)$$

  - m and X fixed together by a complex Metropolis (Markov Chain)
- 2m strings formed from the m elementary interactions
  - energy conservation : energy fraction of the 2m strings given by X
- consistent scheme : energy sharing reduce the probability to have large m
- modified hadronization due to high density effect
  - statistical hadronization instead of string fragmentation
    - larger Pt (flow)

Forward Spectra

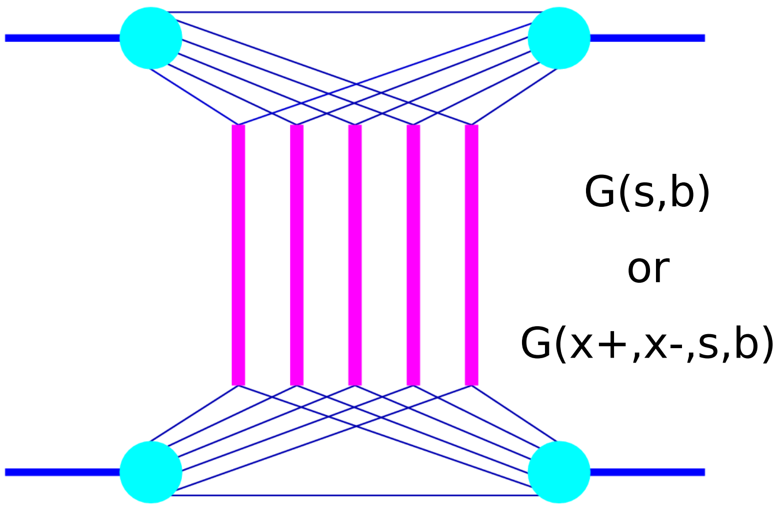
Forward particles mainly from projectile remnant



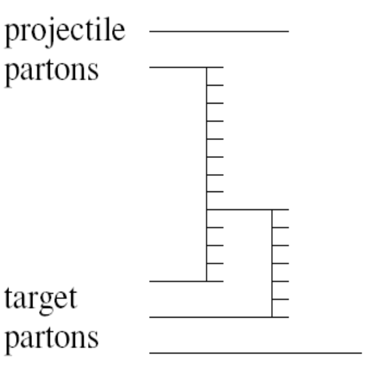
The inelasticity is closely related to diffraction and forward spectra

- 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

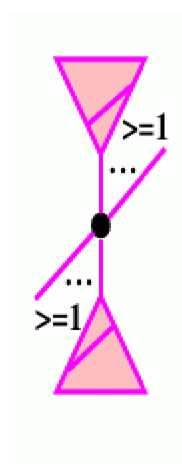
Cross Section and Multiplicity in Models



EPOS



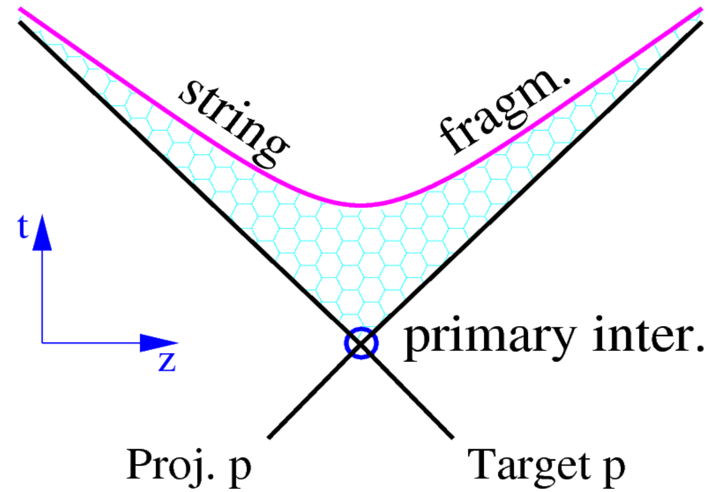
QGSJET II



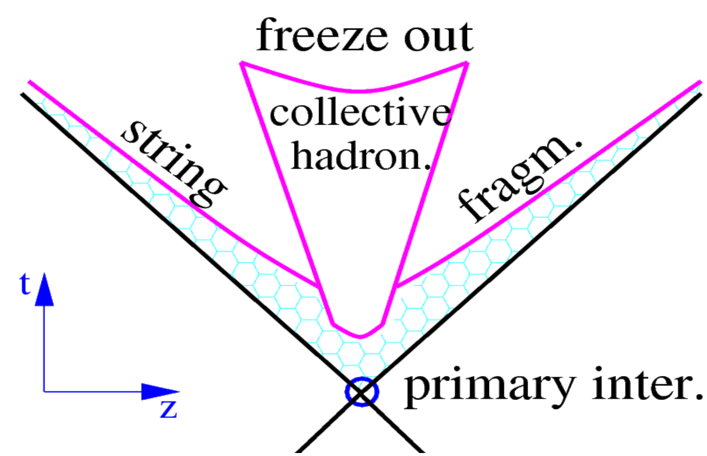
- **Gribov-Regge and optical theorem**
  - Basis of all models (multiple scattering) but
    - Classical approach for QGSJET and SIBYLL (no energy conservation for cross section calculation)
    - Parton based Gribov-Regge theory for EPOS (energy conservation at amplitude level)
- **pQCD**
  - Minijets with cutoff in SIBYLL
  - Same hard Pomeron (DGLAP convoluted with soft part : no cutoff) in QGS and EPOS but
    - No enhanced diagram in Q01
    - Generalized enhanced diagram in QII
    - Simplified non linear effect in EPOS
      - Phenomenological approach

New Models

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



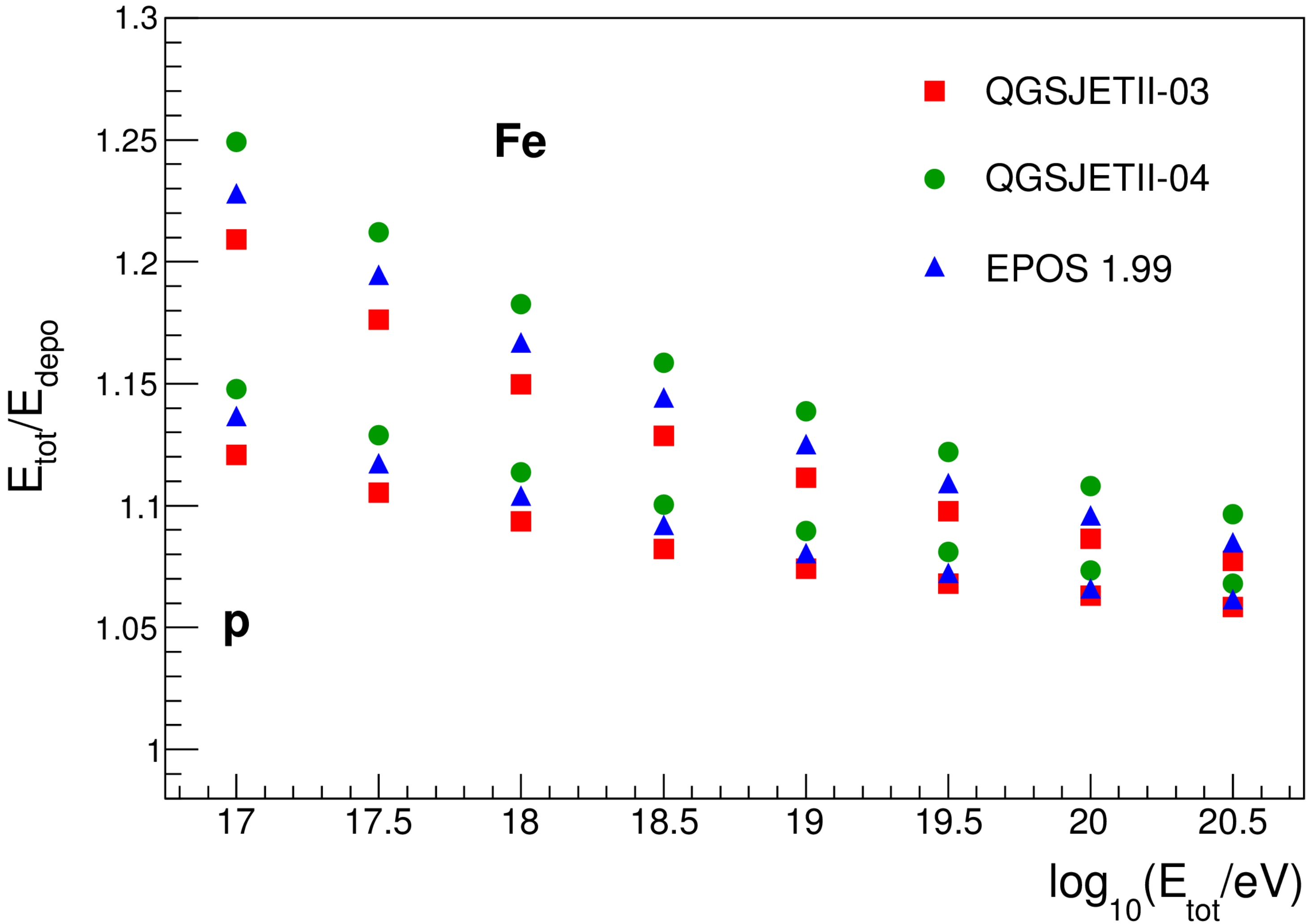
- **EPOS 1.99 to EPOS LHC**
  - tune cross section to TOTEM value
  - change old flow calculation to a more realistic one
  - introduce central diffraction
  - keep compatibility with lower energies



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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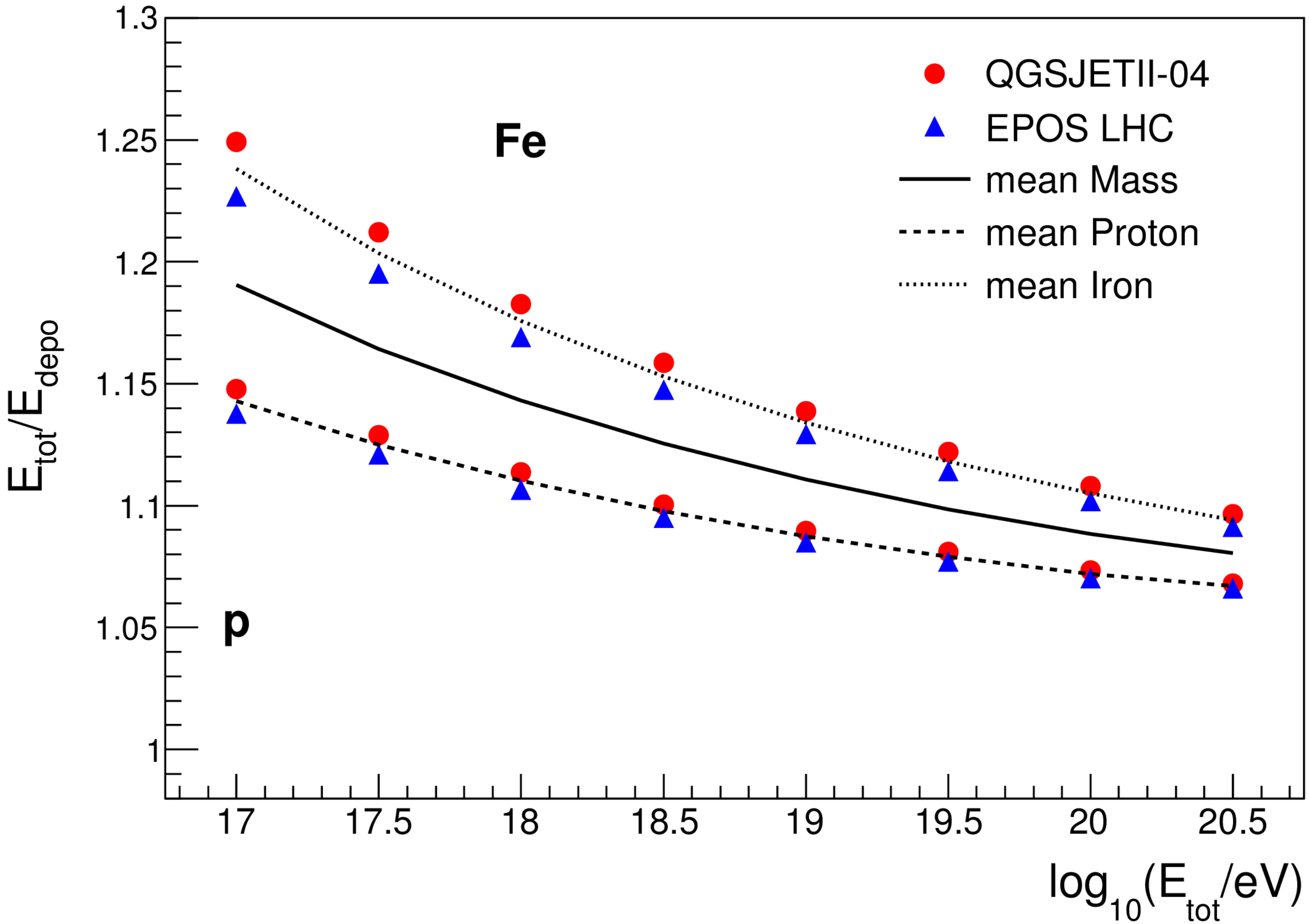
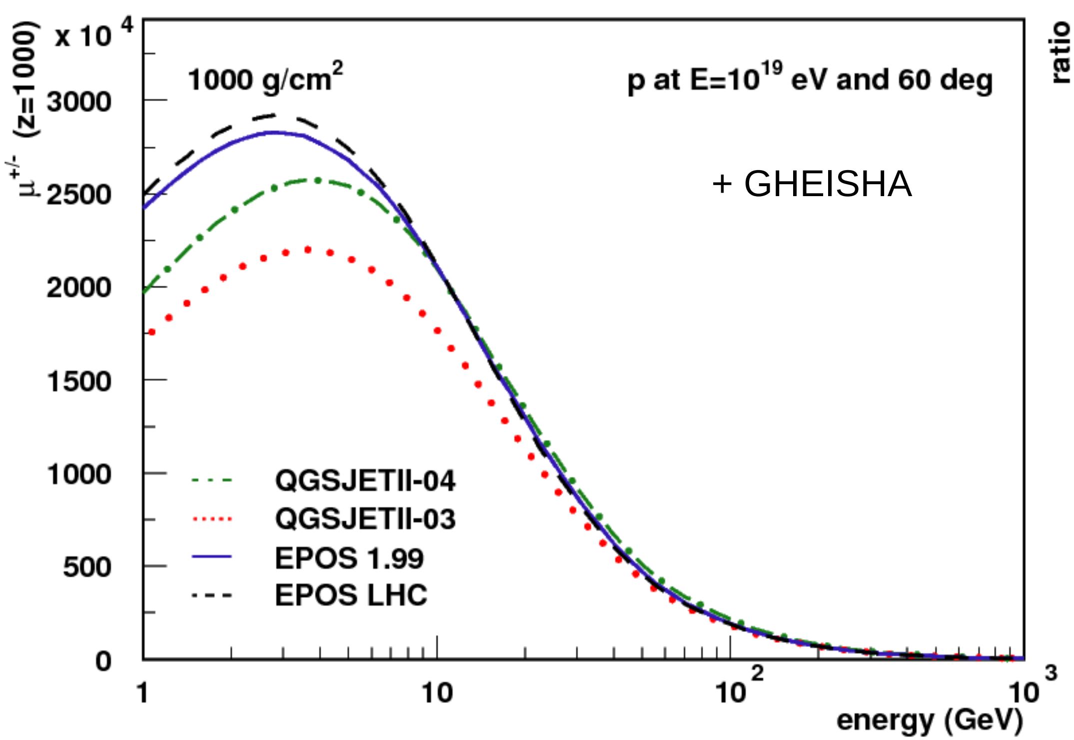
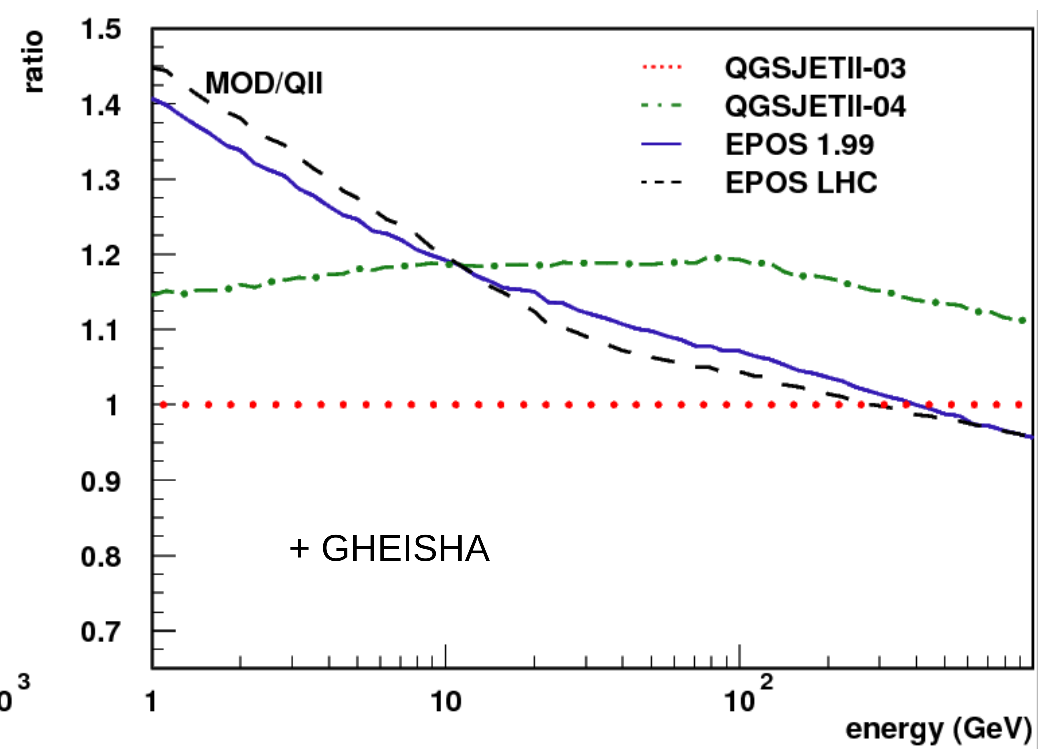


Muon Energy Spectra

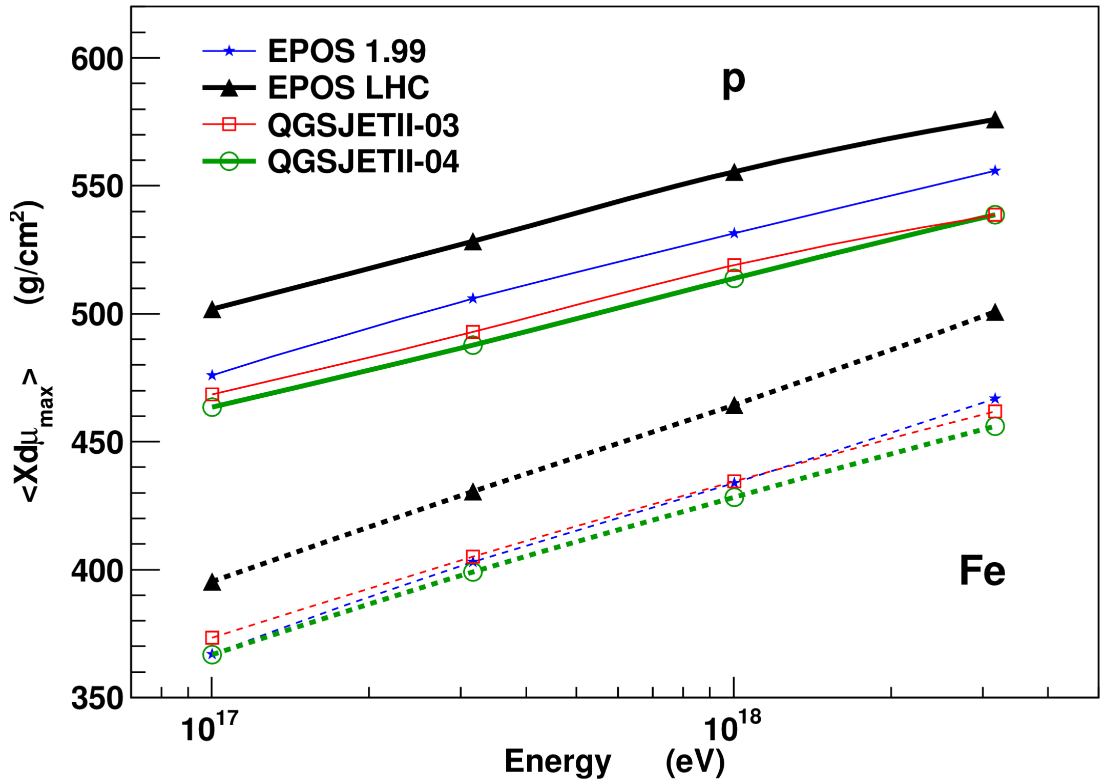
- **Total number of muons in QGSJETII-04 (@60°) closer to EPOS BUT**
  - ➡ muons with different energy (hadronic energy stored in mesons or baryons ?)
  - ➡ different zenith angle dependence (attenuation length depends on muon energy spectrum)
  - ➡ effect of low energy hadronic interaction models (Gheisha,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

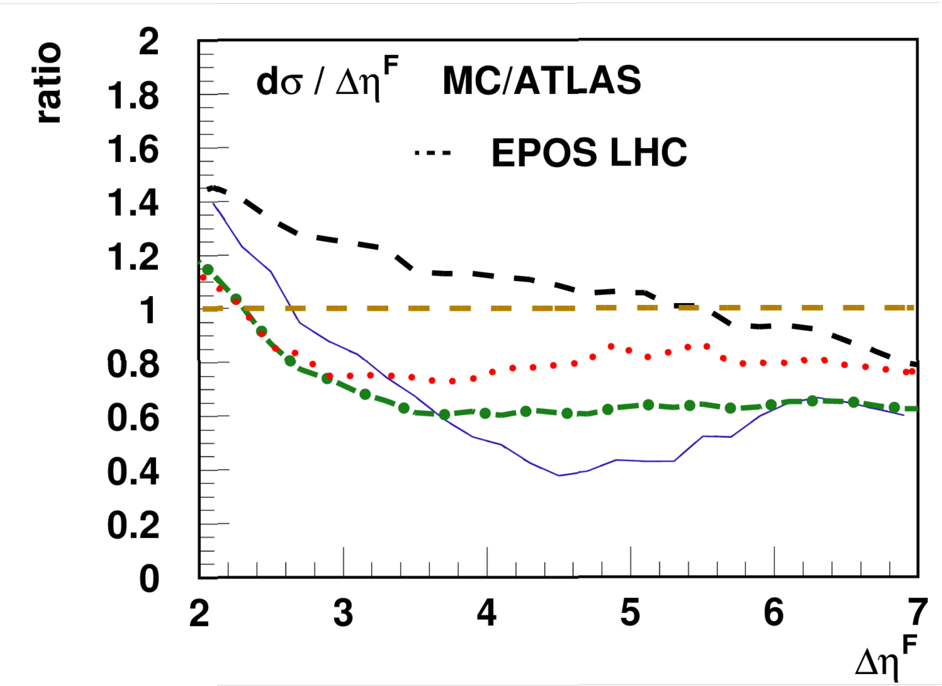




Muon Production Depth

- **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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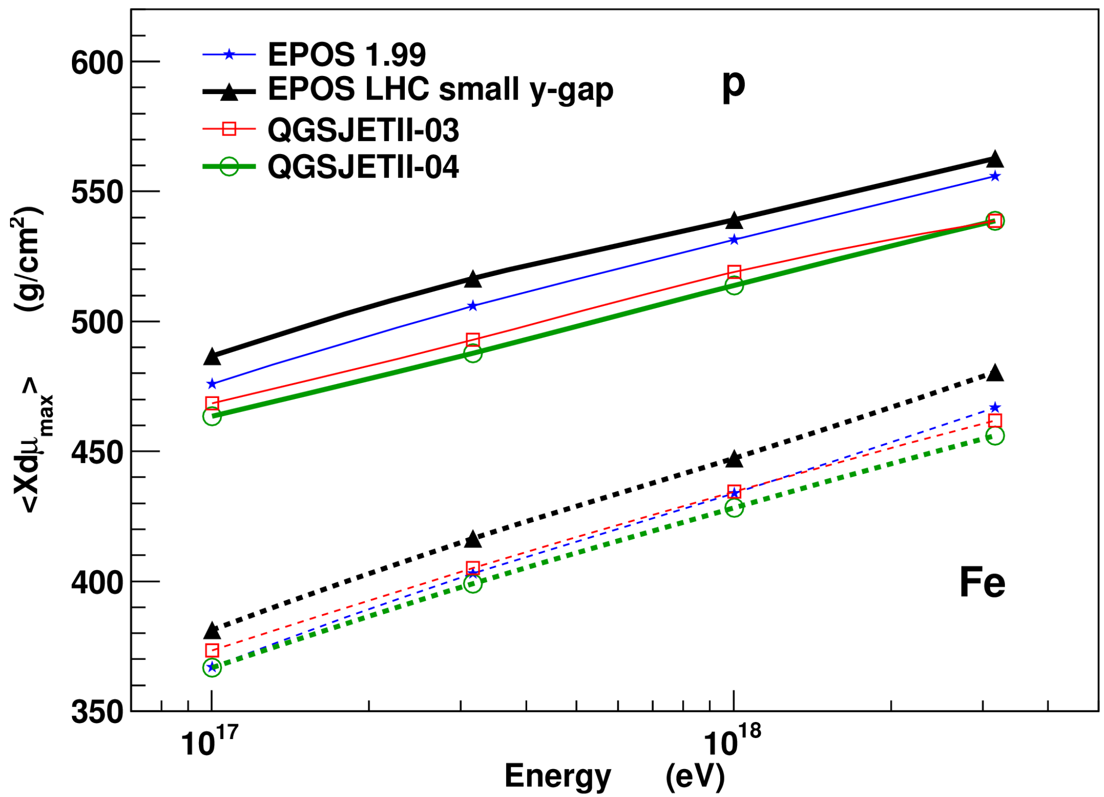

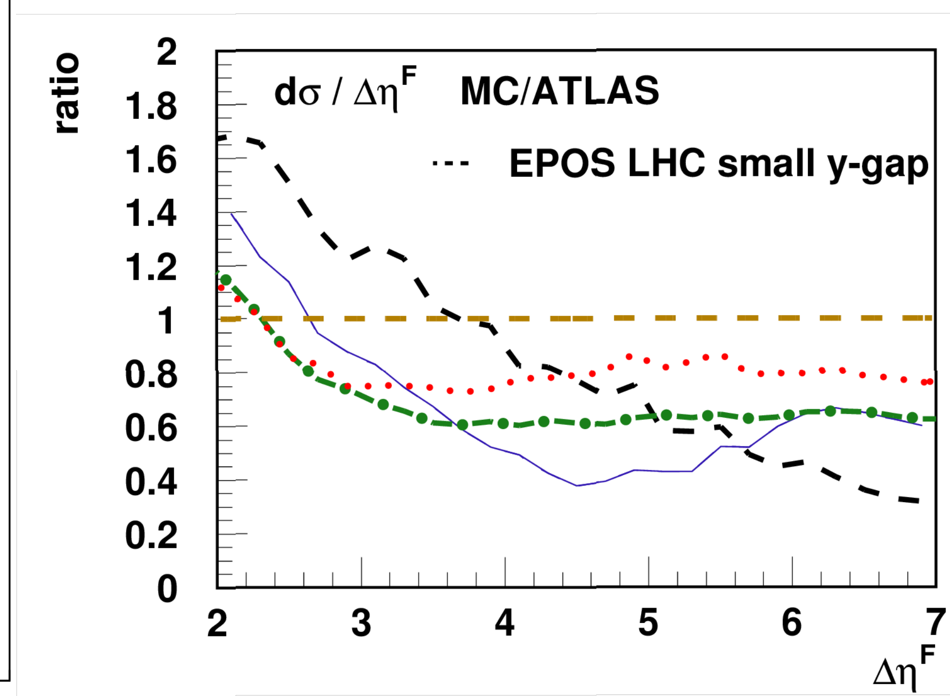

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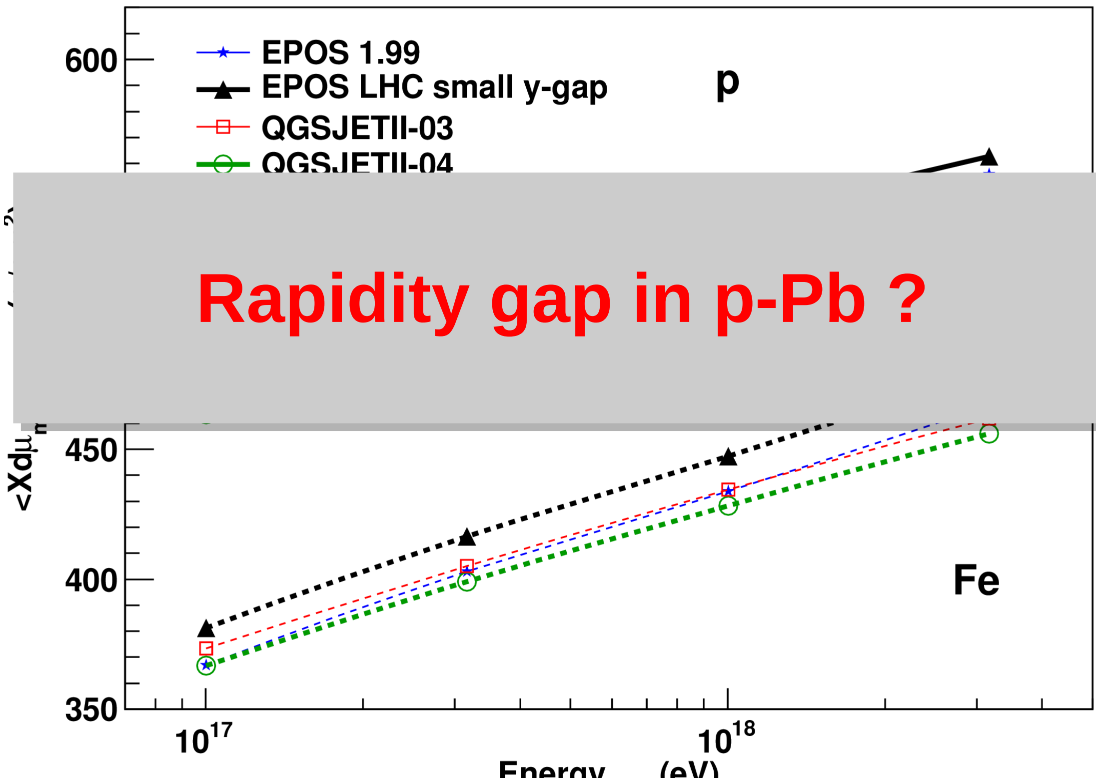
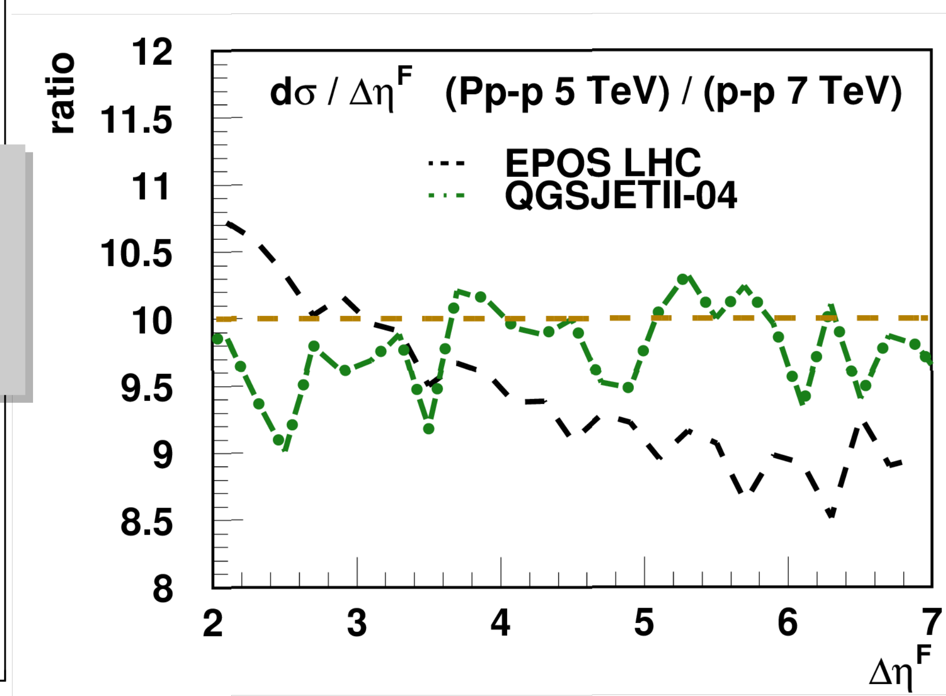
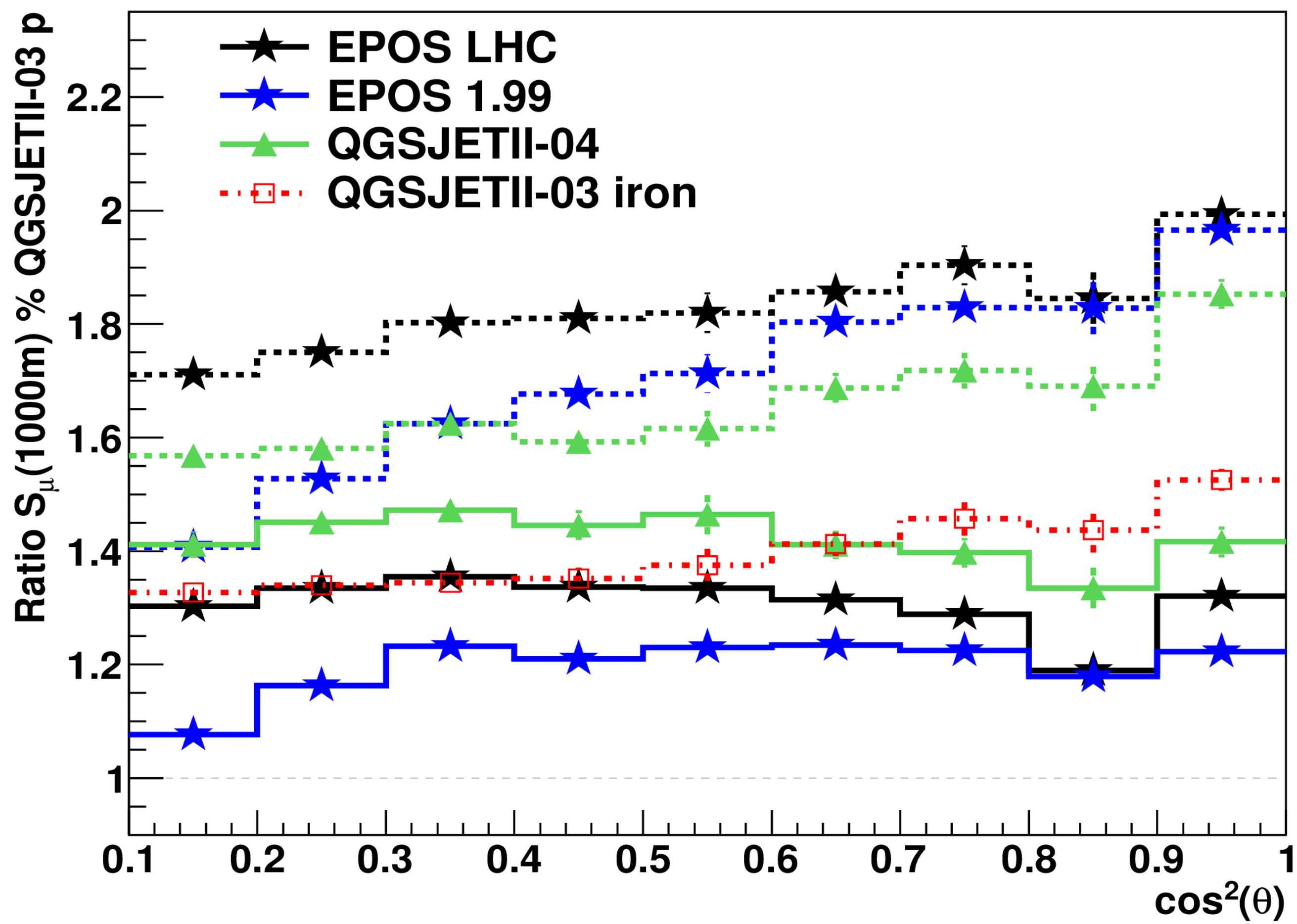


Rapidity gap in p-Pb ?

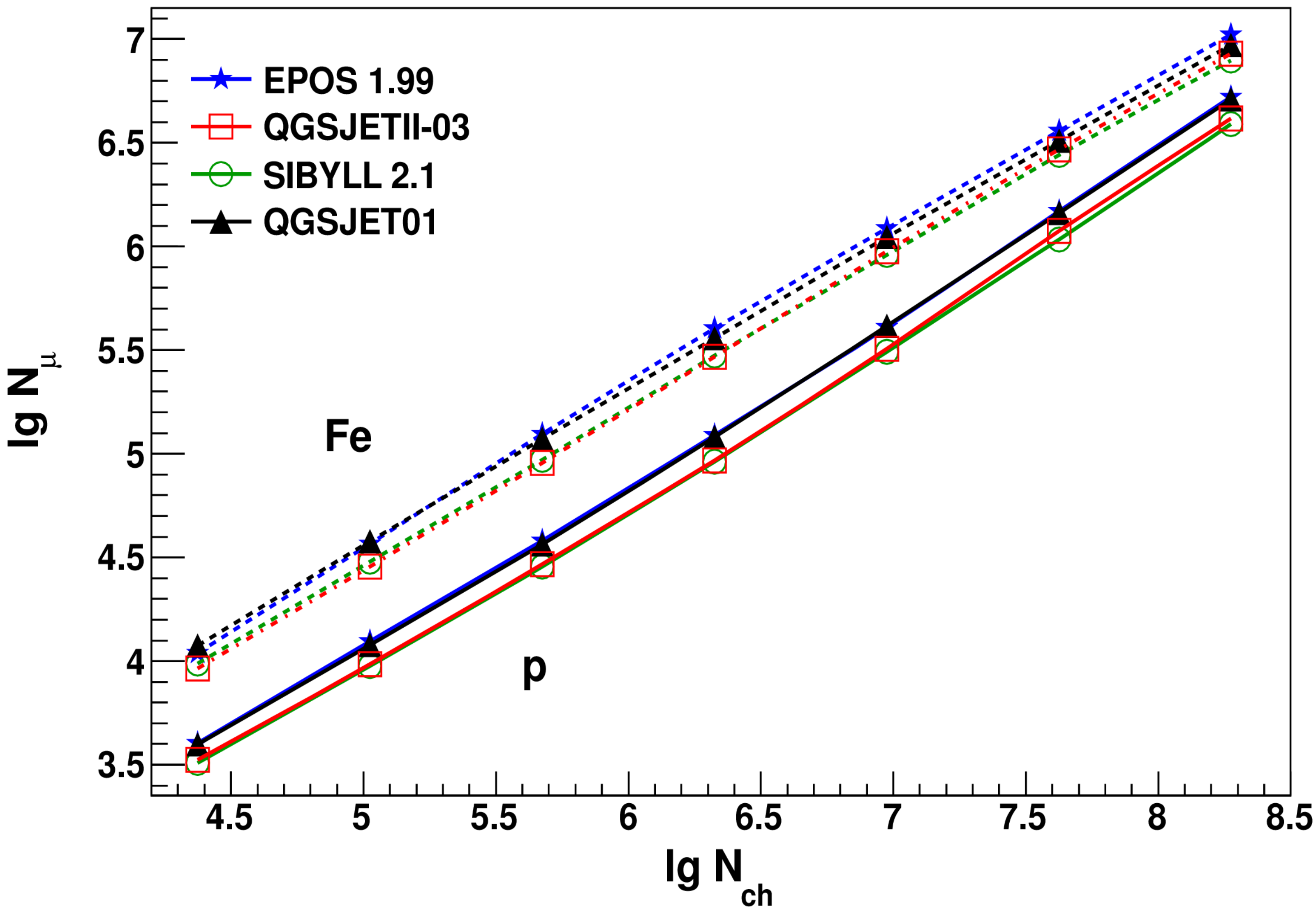


Muon Signal at 1000m for PAO

- **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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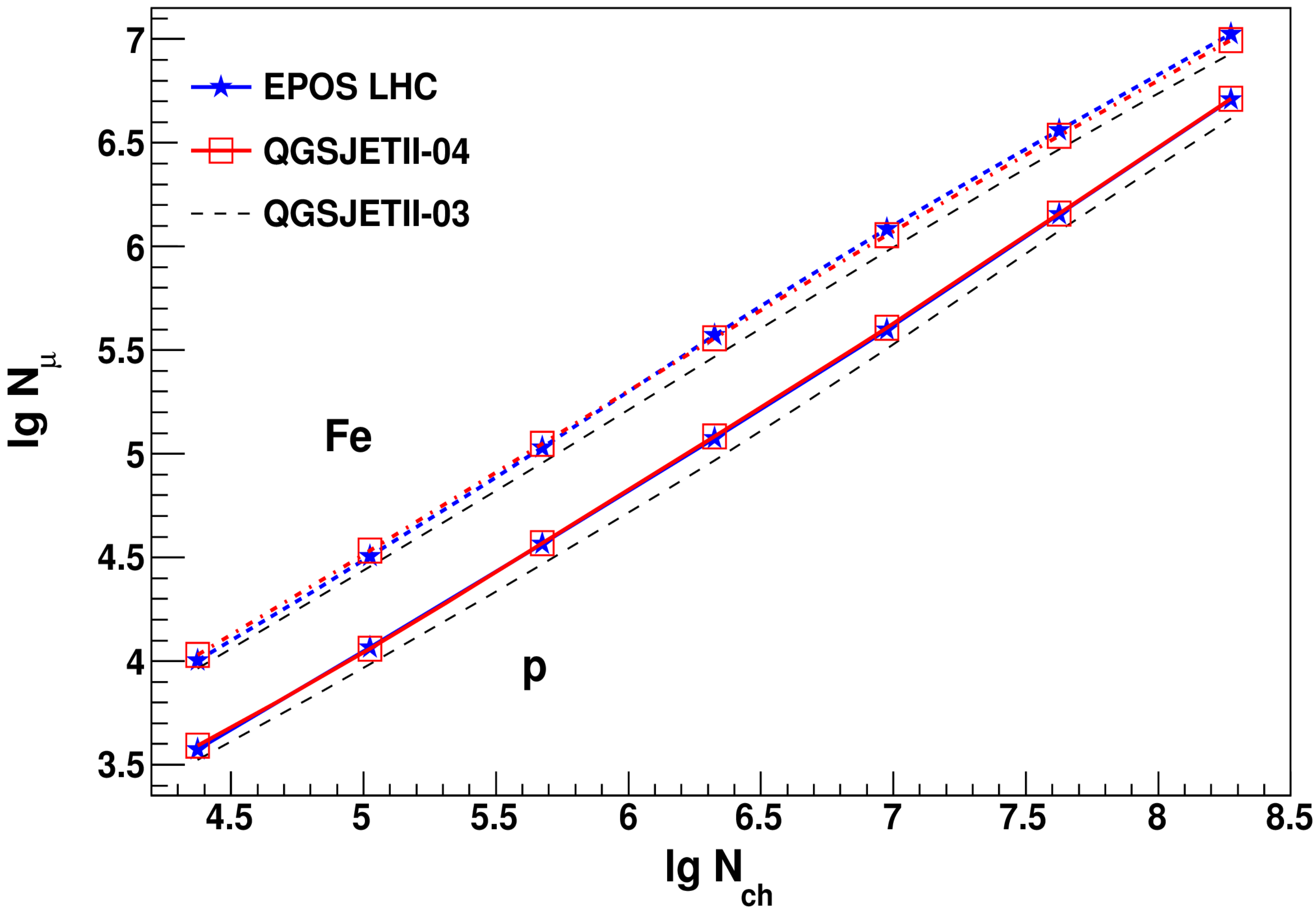

EAS with Re-tuned CR Models : Correlations

- **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