Forward Measurement in p-O at LHC and Cosmic Ray Physics

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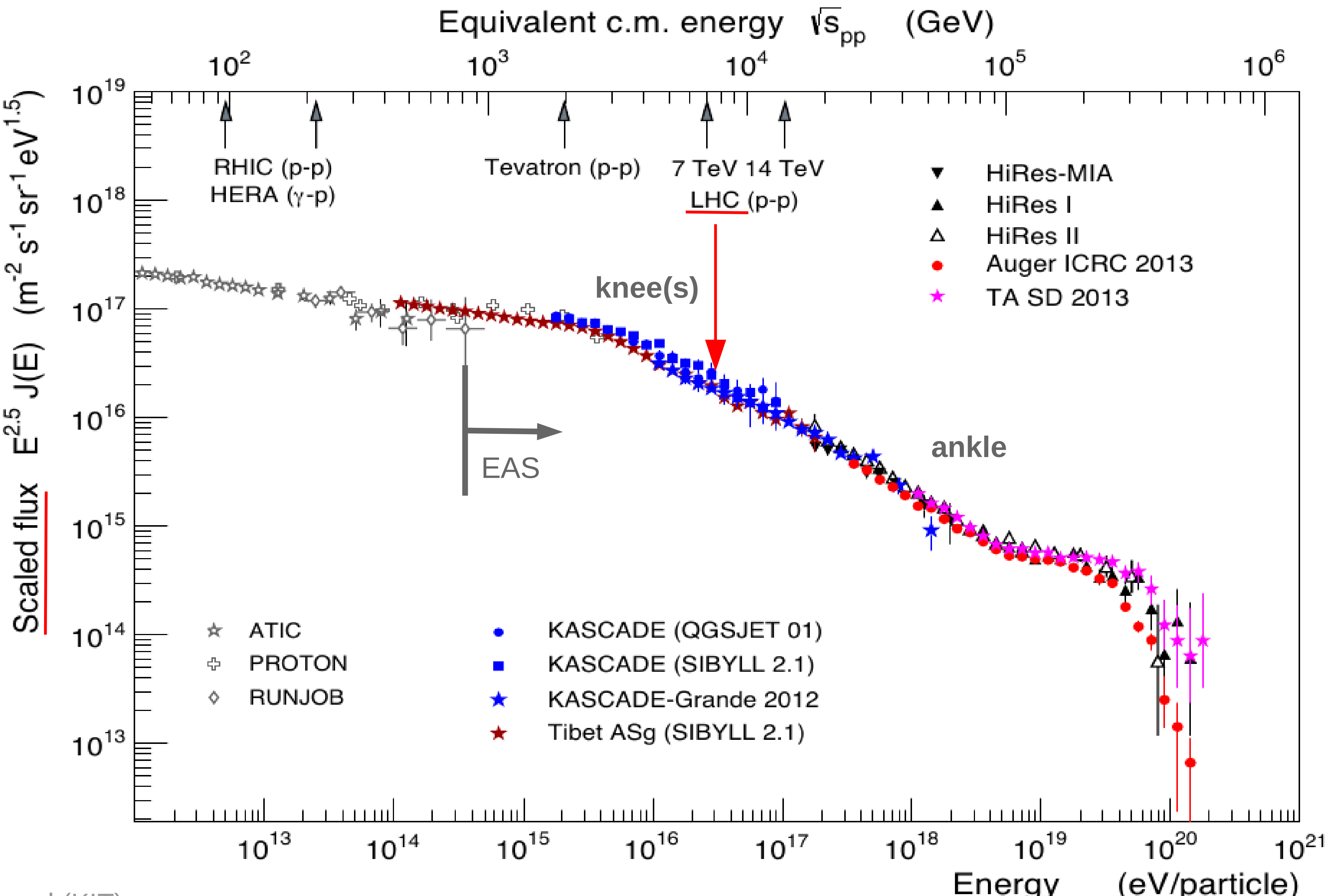
Outline

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

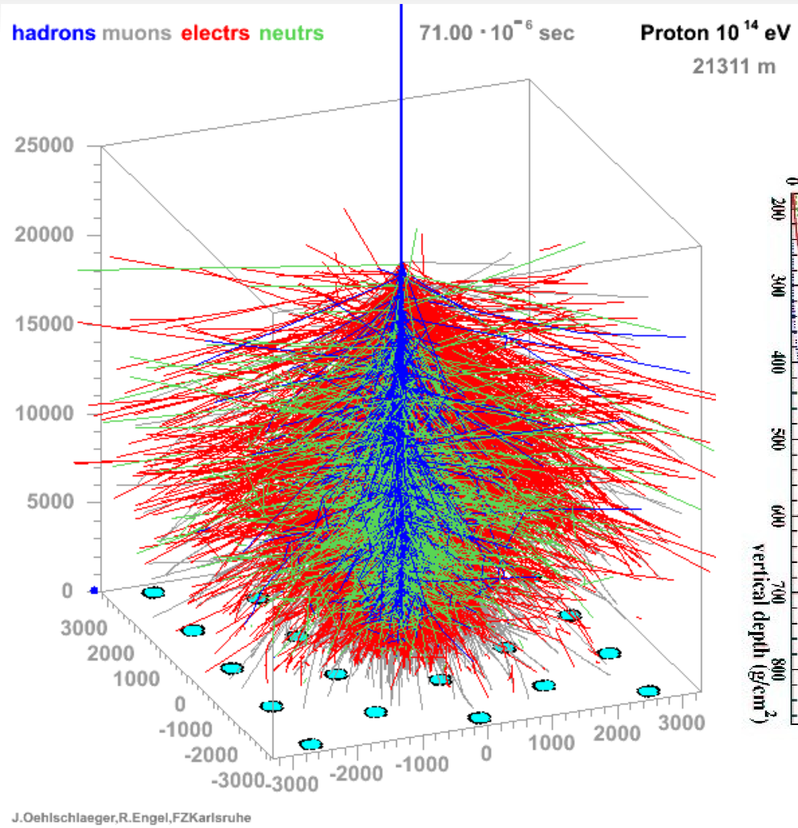
Proton-Oxygen beam is needed to reduce uncertainties in air shower simulations.

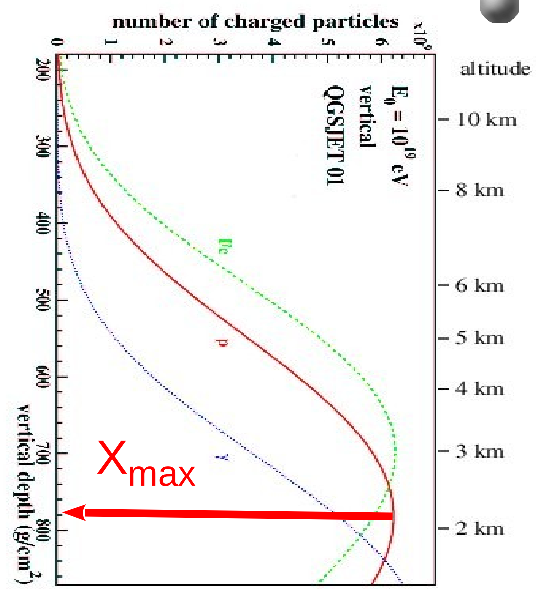
Cosmic Ray Spectrum

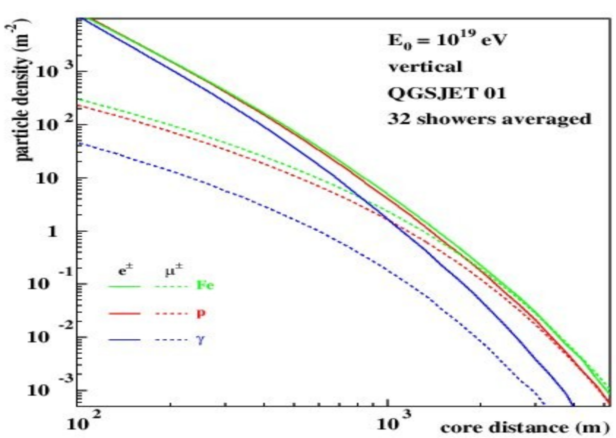


R. Engel (KIT)

Extensive Air Shower Observables







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

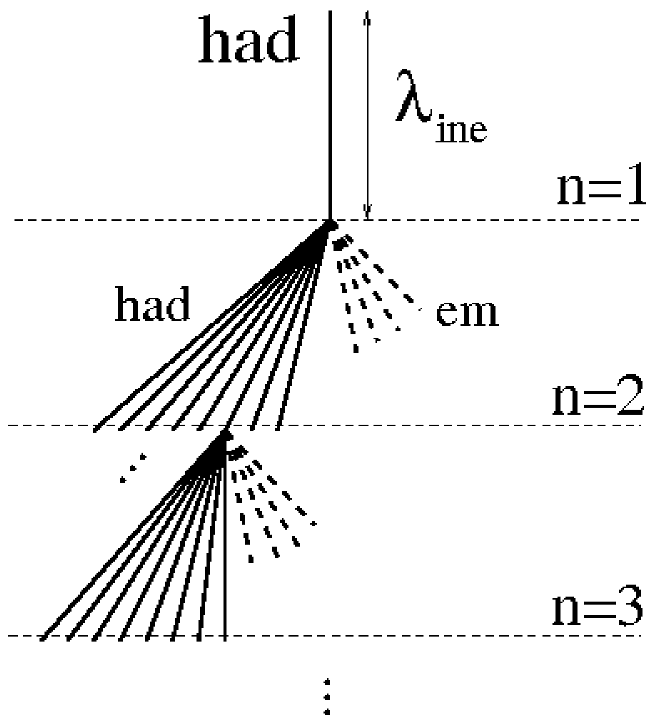
$$X = \int_h^\infty dz\, \rho(z)$$

  - 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 :**

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

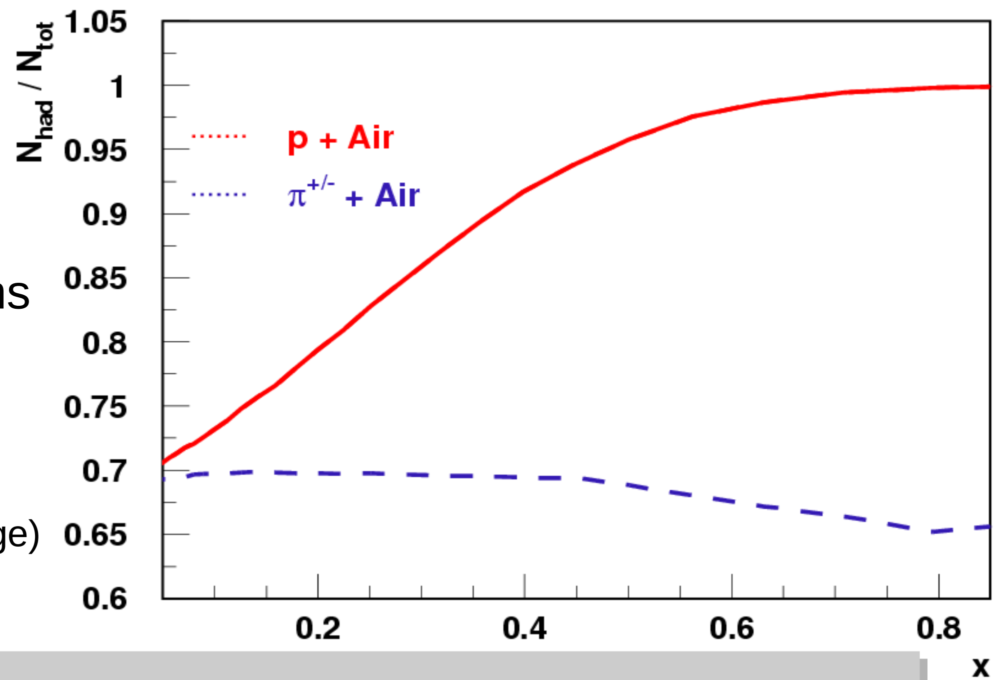
- Model independent parameters :
  - E_0 = primary energy
  - A = primary mass
  - λ_e = electromagnetic mean free path
- Model dependent parameters :
  - k = elasticity
  - N_{tot} = total multiplicity
  - λ_{ine} = hadronic mean free path (cross section)

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)

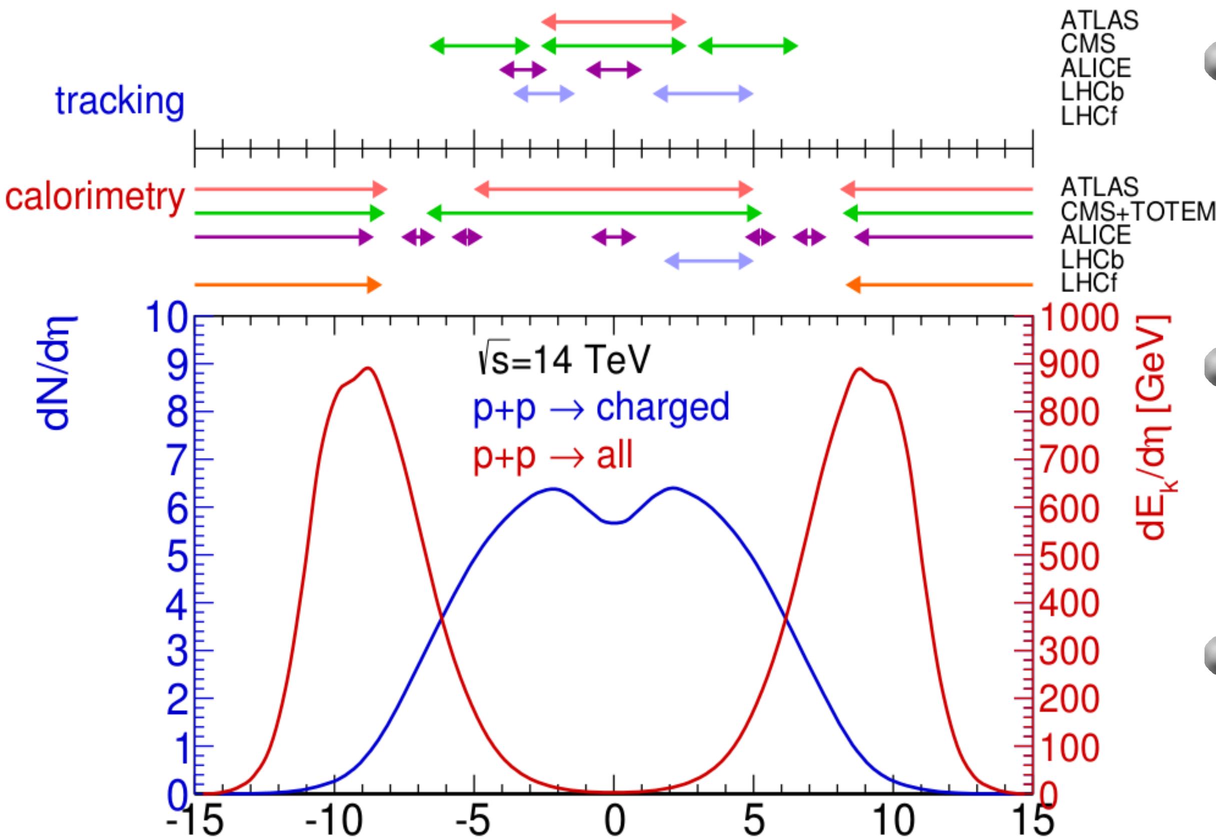


Muon number depends on the number of (anti)B in p- or π-Air interactions at all energies

More fast (anti)baryons = more muons

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

Ideal Measurements for CR



More direct measurement of particles important for air shower development not really possible at LHC !
(excluded by kin. and techn. limits)

- **Inelastic cross-section (and all other obs.) for p-Air and pion-Air**
  - ➡ LHC: p-p or p-Pb … pO ?
- **Average elasticity/inelasticity** (energy fraction of the leading particle)
  - ➡ LHC: SD with proton tagging only
- **Multiplicity of id. particles in forward region (x_F~0.1)**
  - ➡ LHC: tracking for eta<7 (id<5)
- **EM/Had Forward Energy flow (x_F>0.1)**
  - ➡ LHC: ZDCs for neutral particles
    - add tracking in ZDC ?

Example : Inclusive Muon Spectra

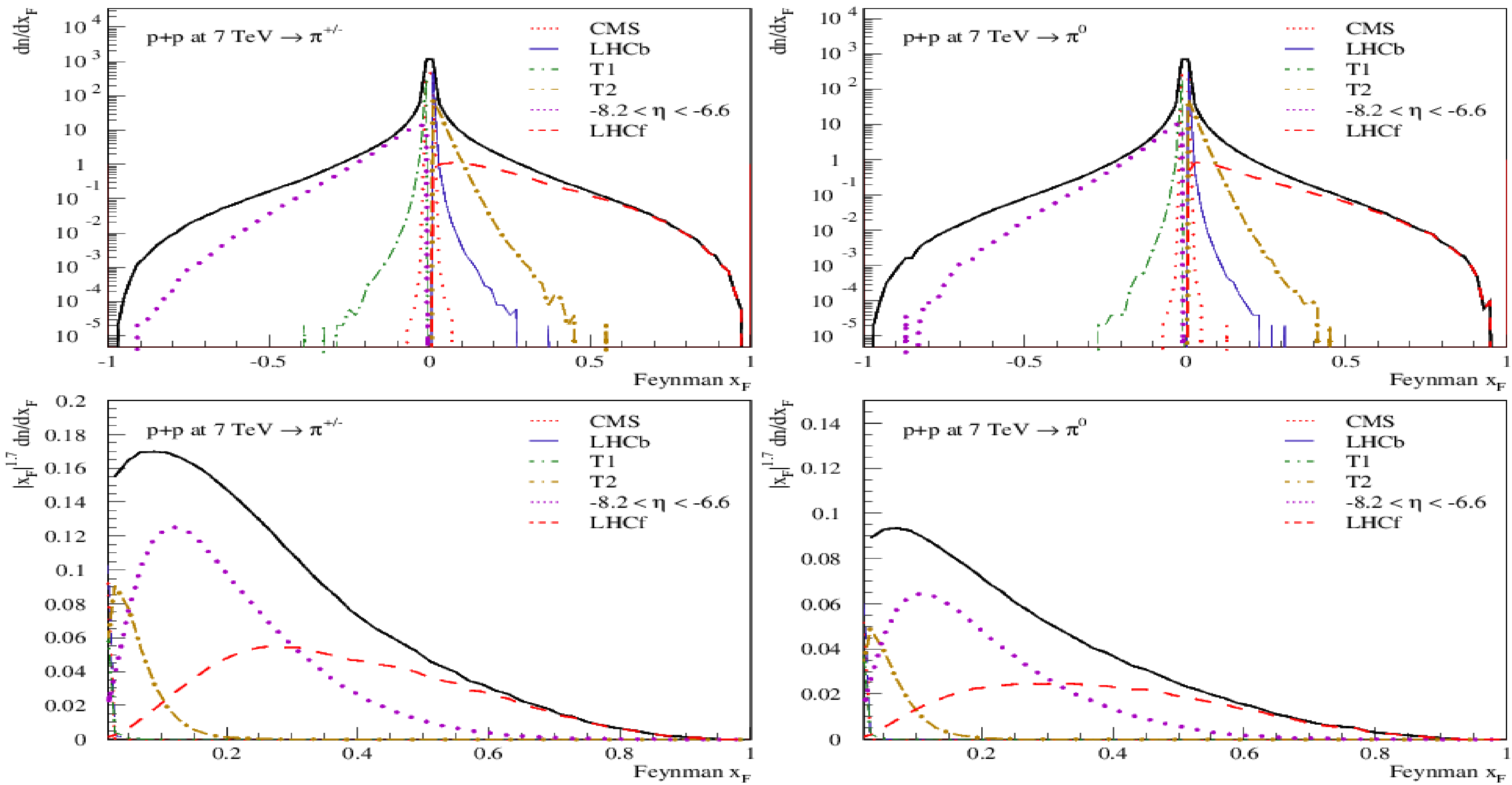
- **Energy spectrum of all muons arriving at ground**
  - ➜ convolution of CR spectrum, composition of primary and hadronic interactions
  - ➜ important for neutrino experiment like Ice-Cube (atmospheric neutrino flux is the background of astrophysical neutrinos)

- **Can be calculated if muon weighted spectra is known :**

$$|x_F|^{1.7}\, dn/dx_F$$

- **dn/dx_F should be known for π^+,π^-,K^+,K^-,D^+,D^-…**

Example : Inclusive Muon Spectra (2)



- In the range of LHCf … but charged particles not seen by LHCf !
  - extrapolation needed
  - **LHC data important to fix hadronic models**

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**
  - one set of parameter for all systems/energies

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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)

Data for Hadronic Interaction Models

- **Theoretical basis :**
  - pQCD : **PDF and jets**
  - Gribov-Regge : **All cross-sections and particle multiplicities**
  - energy conservation : **Correlations (various triggers, proton tagging, multiplicity windows or dependence)** **Model killer !**
- **Phenomenology :**
  - hadronization : **Particle identification and pt and multiplicity dep.**
  - diffraction : **Energy loss, rapidity gaps**
  - higher order effects : **Nuclear modification factor**
  - remnants : **Baryon stopping (baryon ratio)**
- **Comparison with data to fix parameters**
  - all type of min bias data are welcome to constrain hadronic interaction models for air showers
  - specific interest in forward measurement to check extrapolation for air showers

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Already done or planned analysis cover most of the need to improve hadronic models for air shower simulations

Wish : more results as function of event multiplicity

  - remnants : **Baryon stopping (baryon ratio)**
- **Comparison with data to fix parameters**
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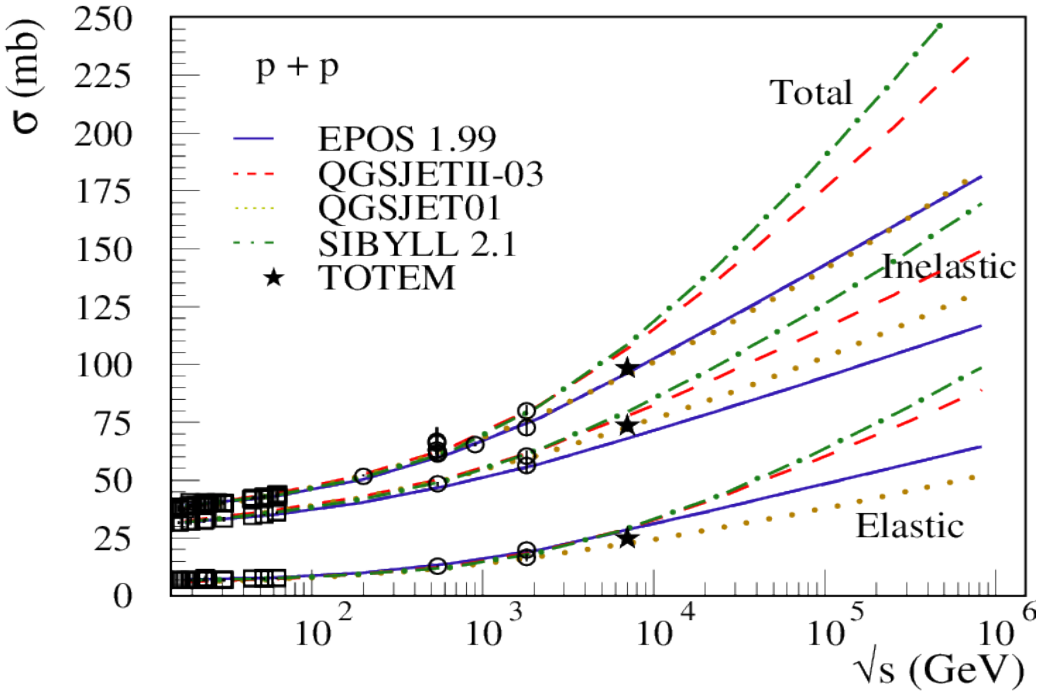
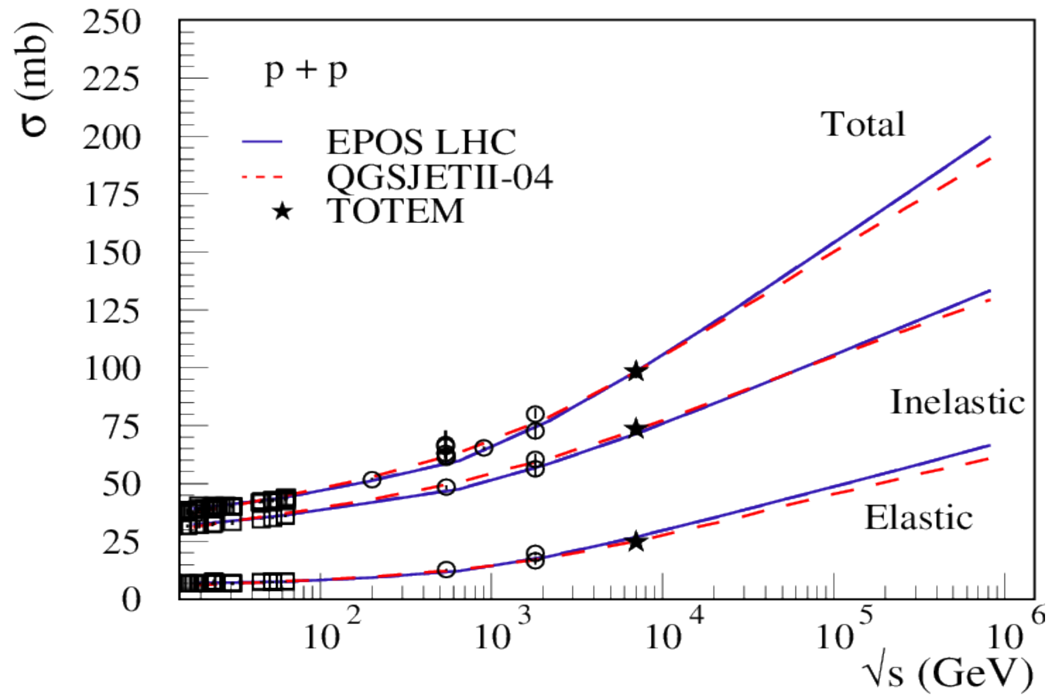
Cross Sections

- 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

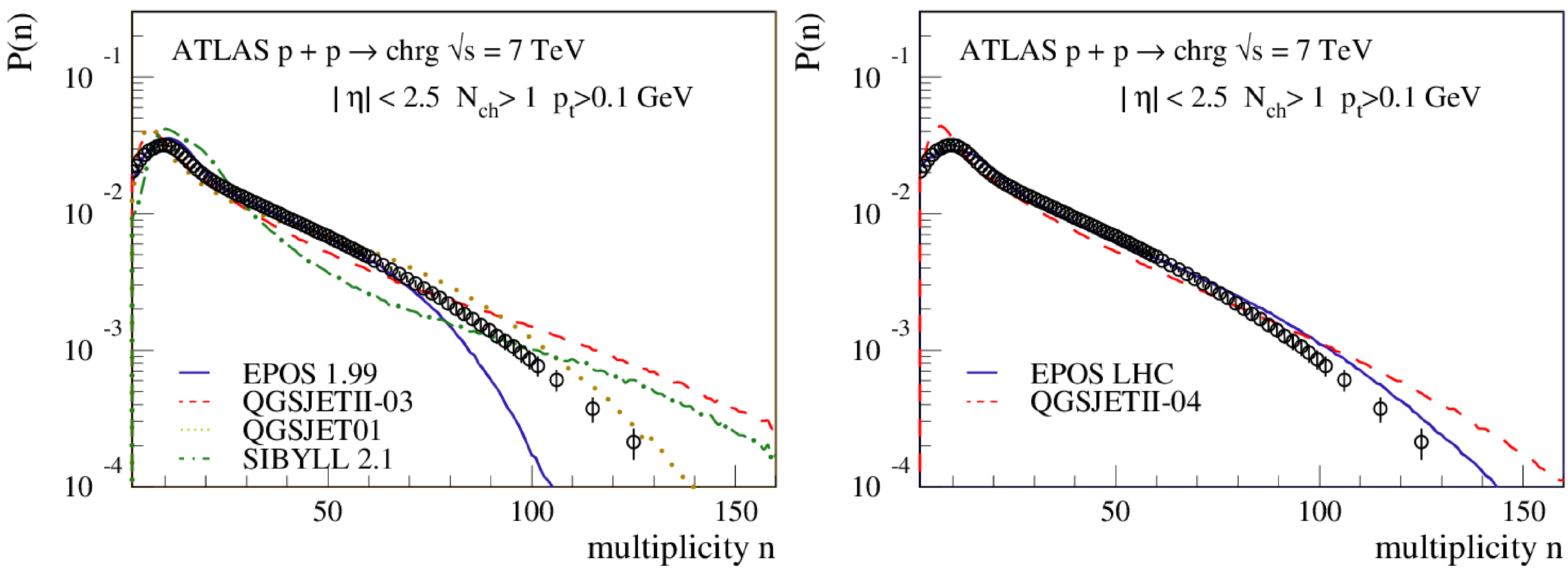


Multiplicity

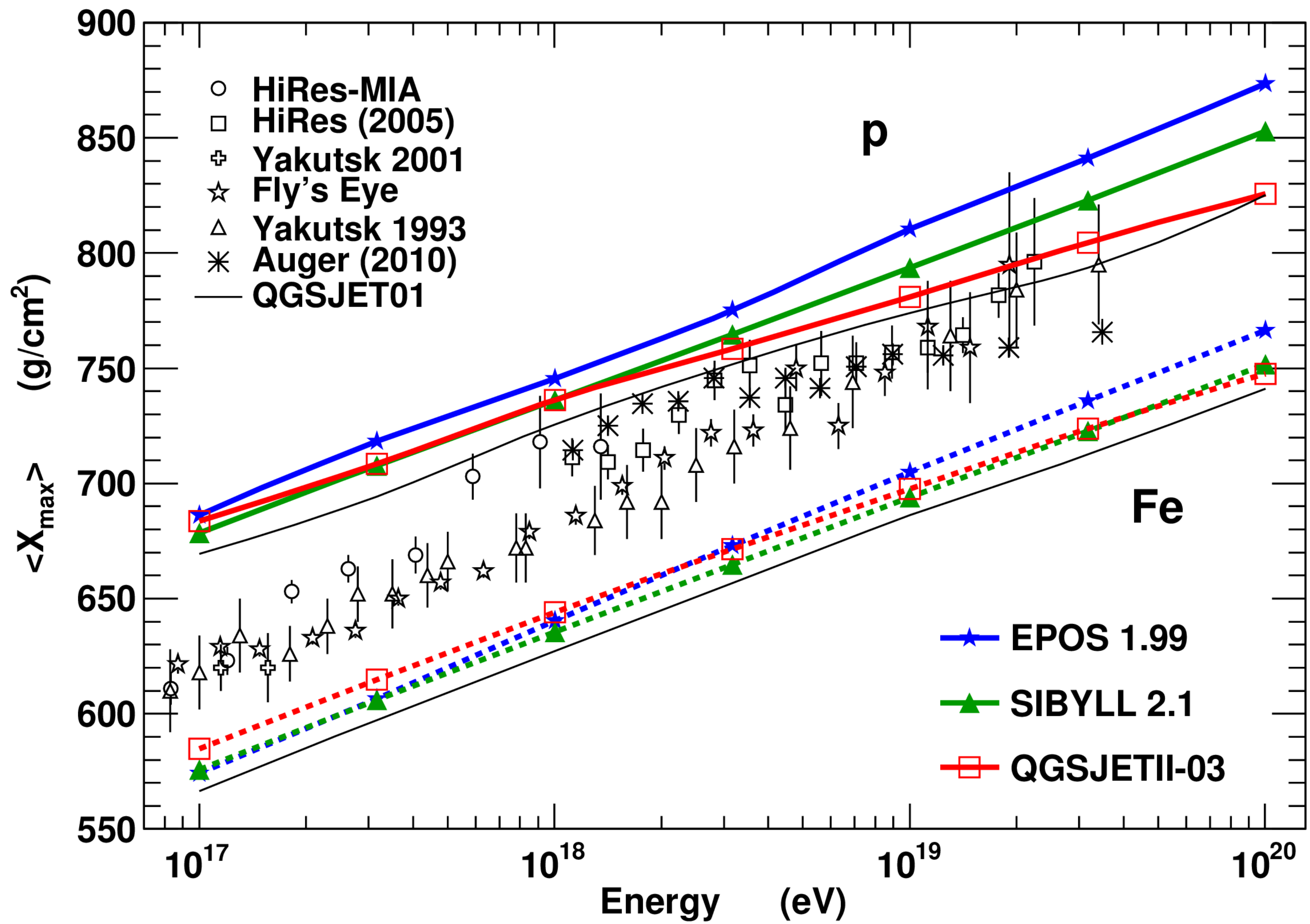
- **Consistent results**
  - Better mean after corrections
    - difference remains in shape
  - Better tail of multiplicity distributions
    - corrections in EPOS LHC (flow) and QGSJETII-04 (minimum string size)

Pre - LHC

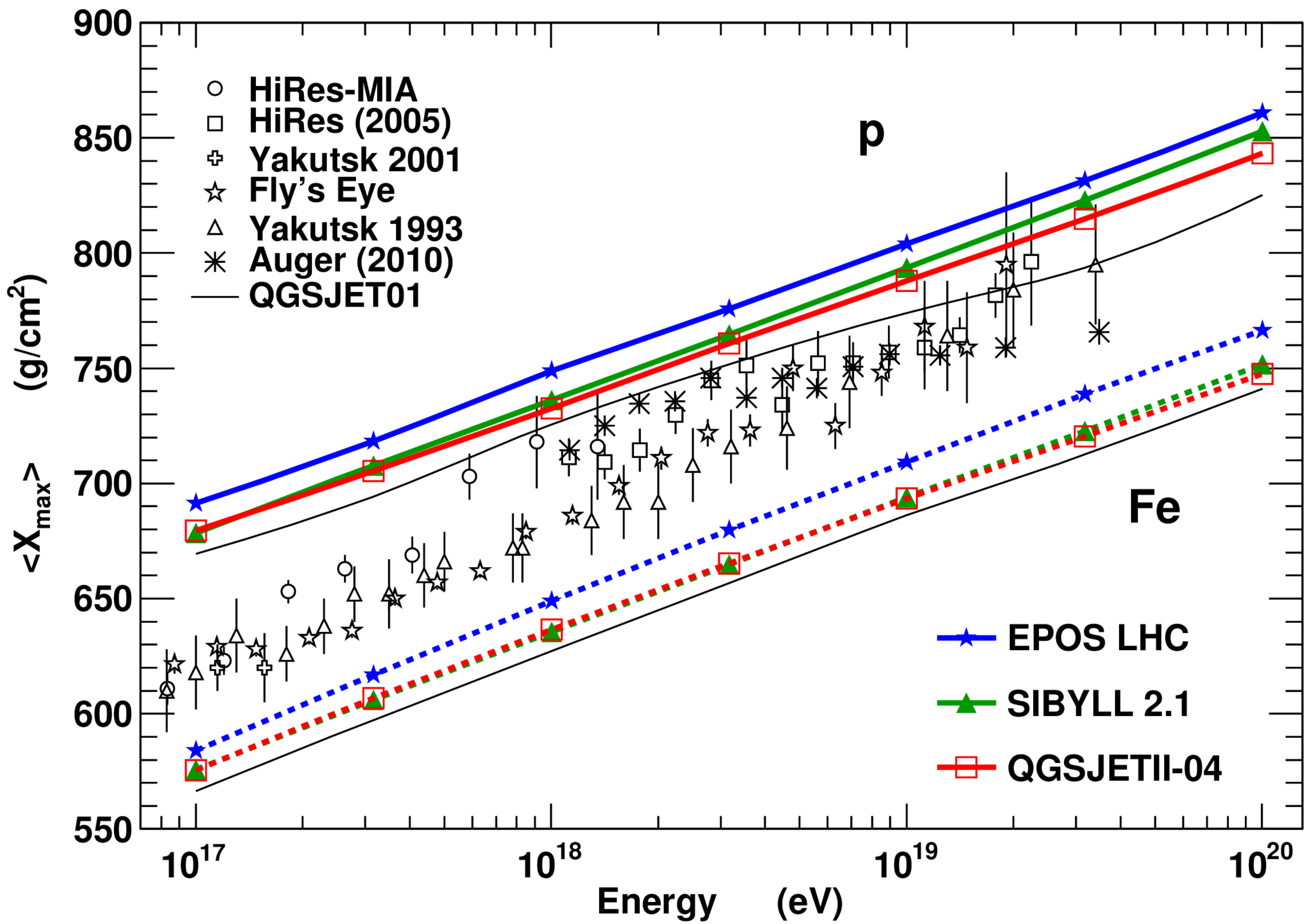
Post - LHC



EAS with Old CR Models : X_{max}

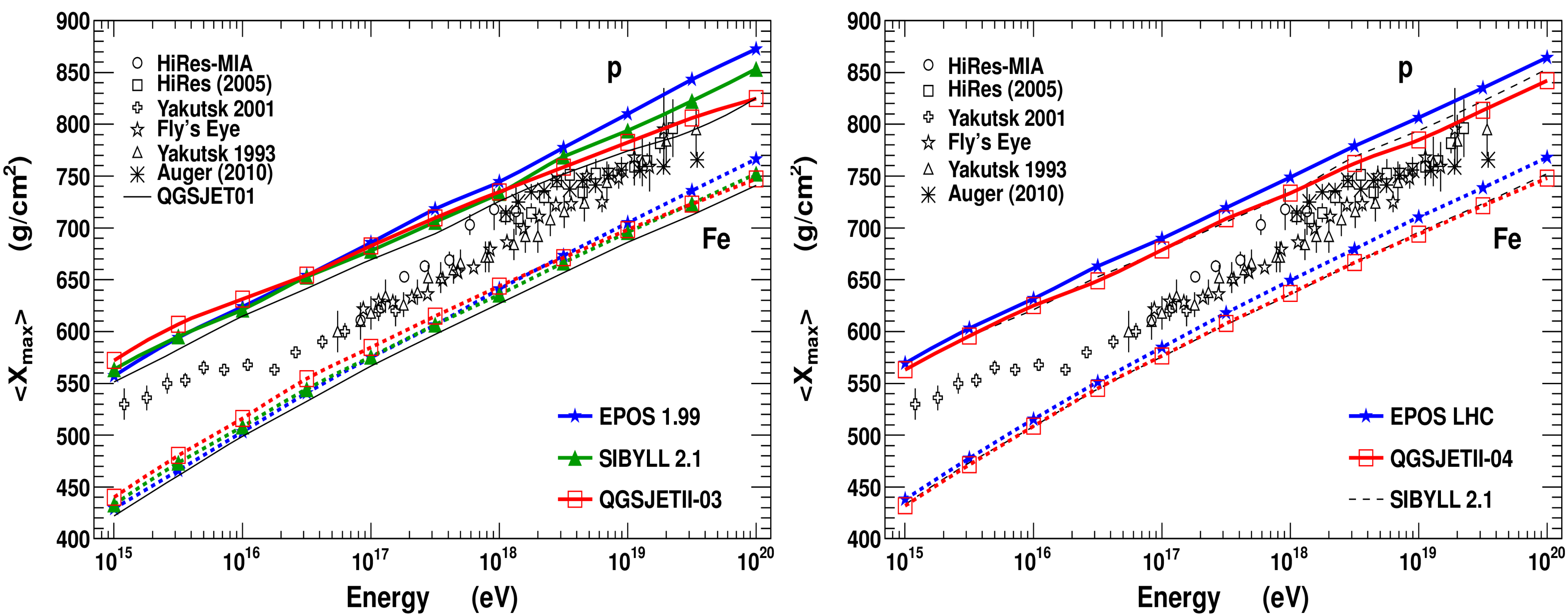


EAS with Re-tuned CR Models : X_{max}



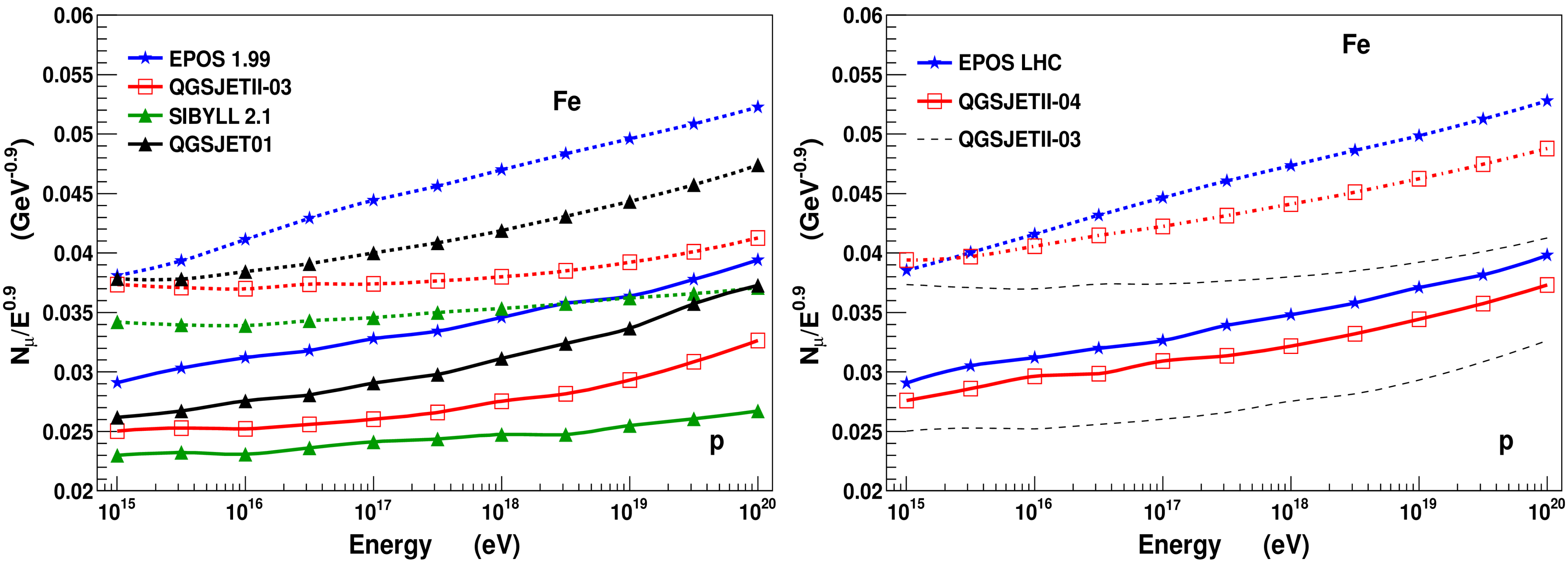
EAS with Re-tuned CR Models : X_{max}

- **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)



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



Counterexample : Muon Production Depth

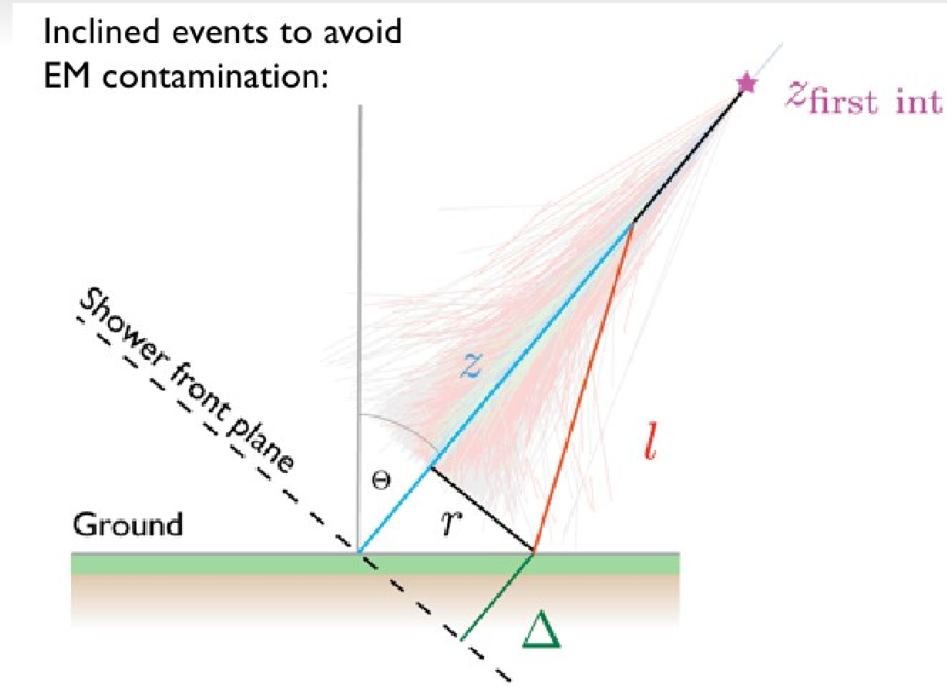
- **Independent SD mass composition measurement**
  - geometric delay of arriving muons

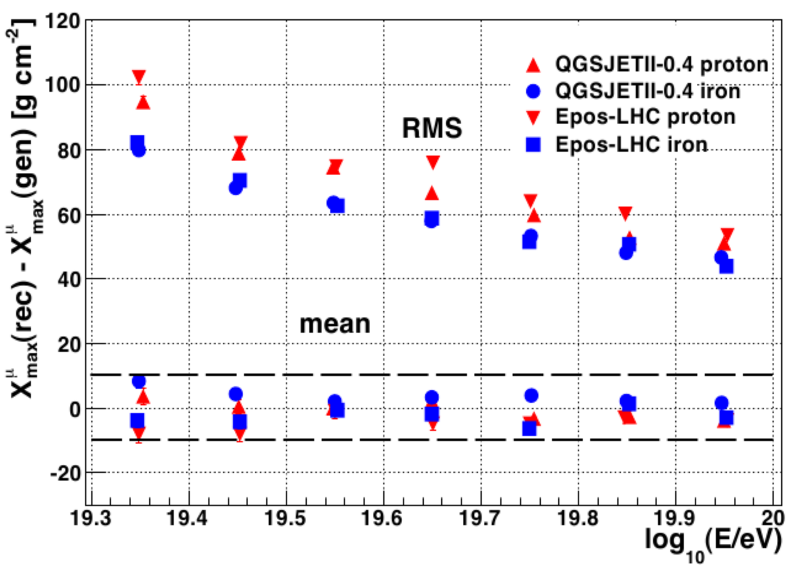
$$c \cdot t_{\mathrm{g}} = l - (z - \Delta) = \sqrt{r^2 + (z-\Delta)^2} - (z - \Delta)$$

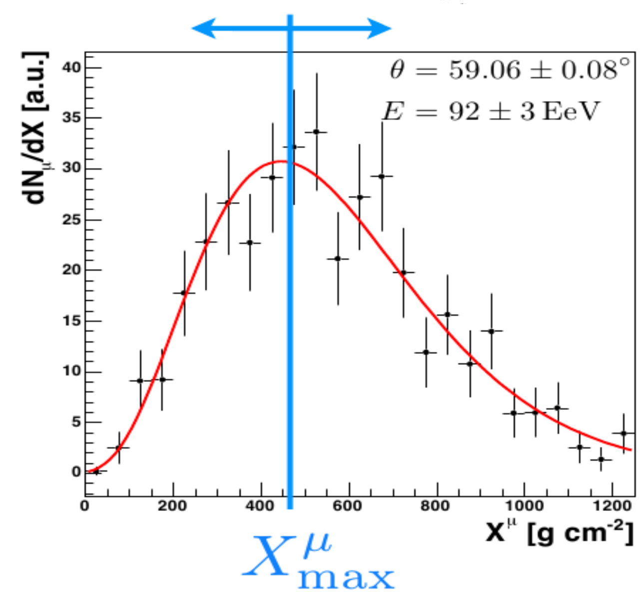
  - mapped to muon production distance

$$z = \frac{1}{2}\left(\frac{r^2}{ct_{\mathrm{g}}} - ct_{\mathrm{g}}\right) + \Delta$$

  - decent resolution and no bias

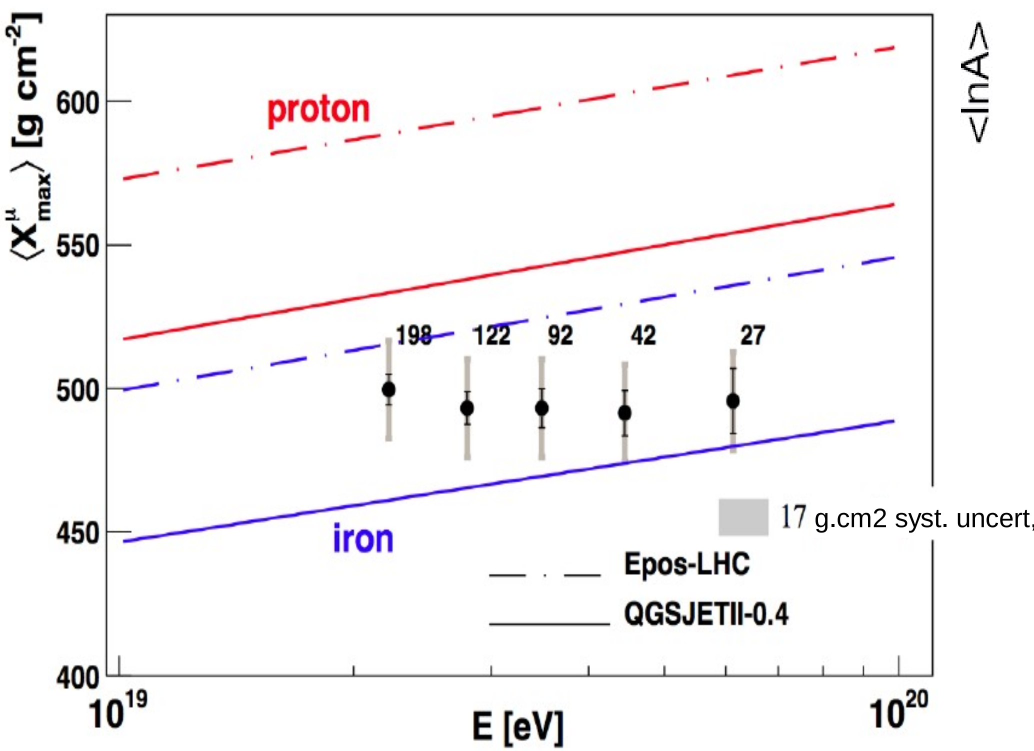


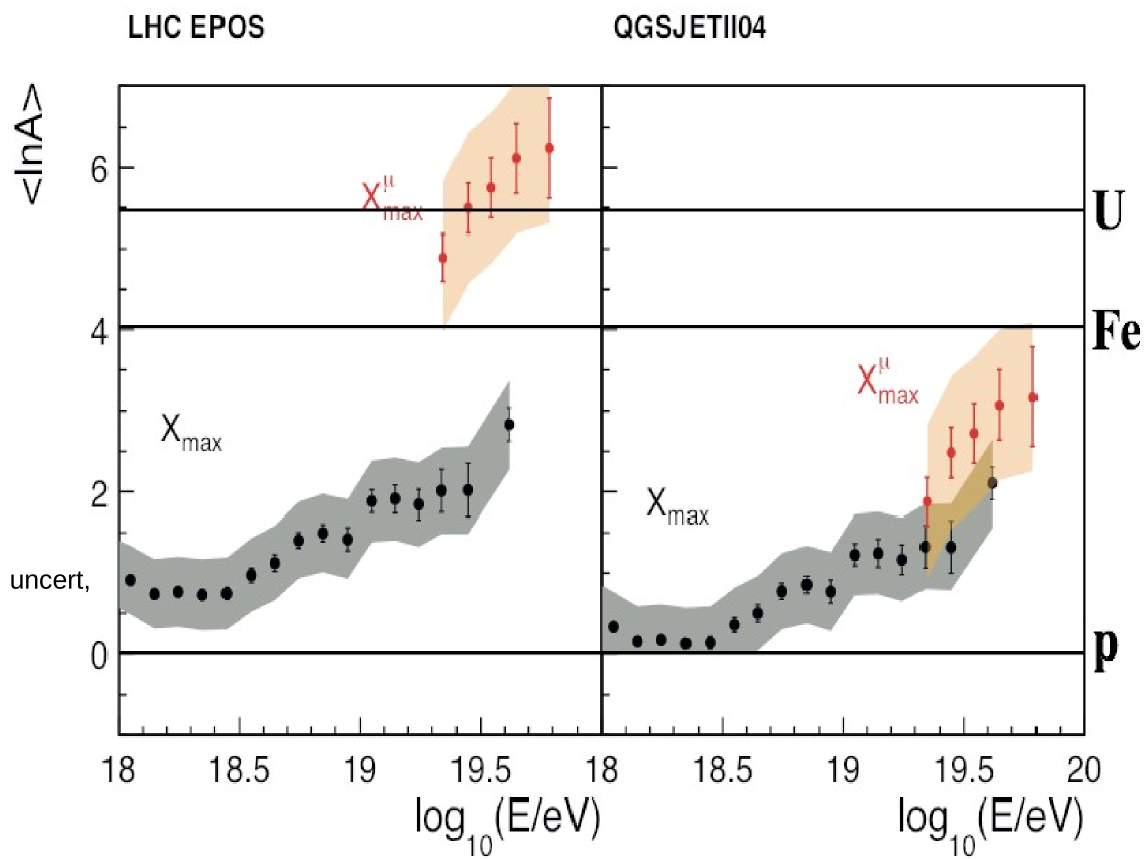




MPD and Models

- **2 independent mass composition measurements**
  - ➡ both results should be between p and Fe
  - ➡ both results should give the same mean logarithmic mass for the same model
  - ➡ problem with EPOS appears after corrections motivated by LHC data
    - ➡ lower diffractive mass motivated by rapidity gap cross-section !

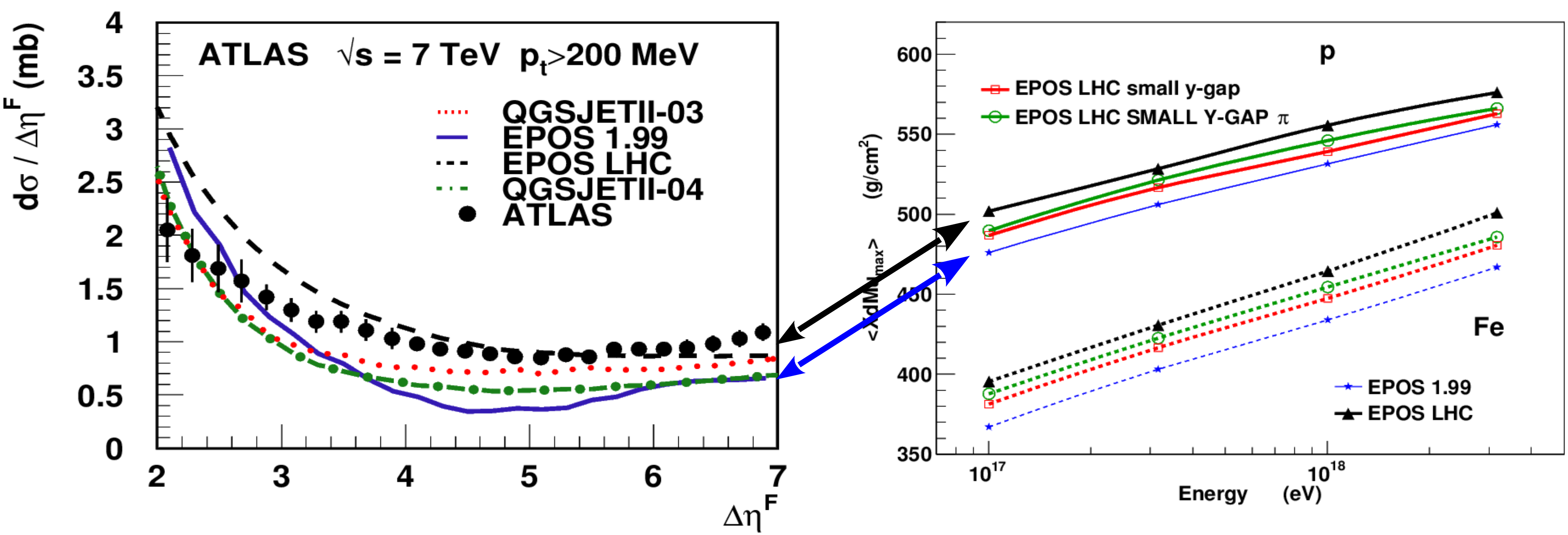




MPD and Diffraction

- **Inelasticity linked to diffraction (cross-section and mass distribution)**
  - weak influence on EM X_{max} since only 1st interaction really matters
  - cumulative effect for X^{μ}_{max} since muons produced at the end of hadr. subcasc.
  - rapidity-gap in p-p @ LHC not compatible with measured MPD
  - harder mass spectrum for pions reduce X^{μ}_{max} and increase muon number !

probably different diffractive mass distribution for mesons and baryons



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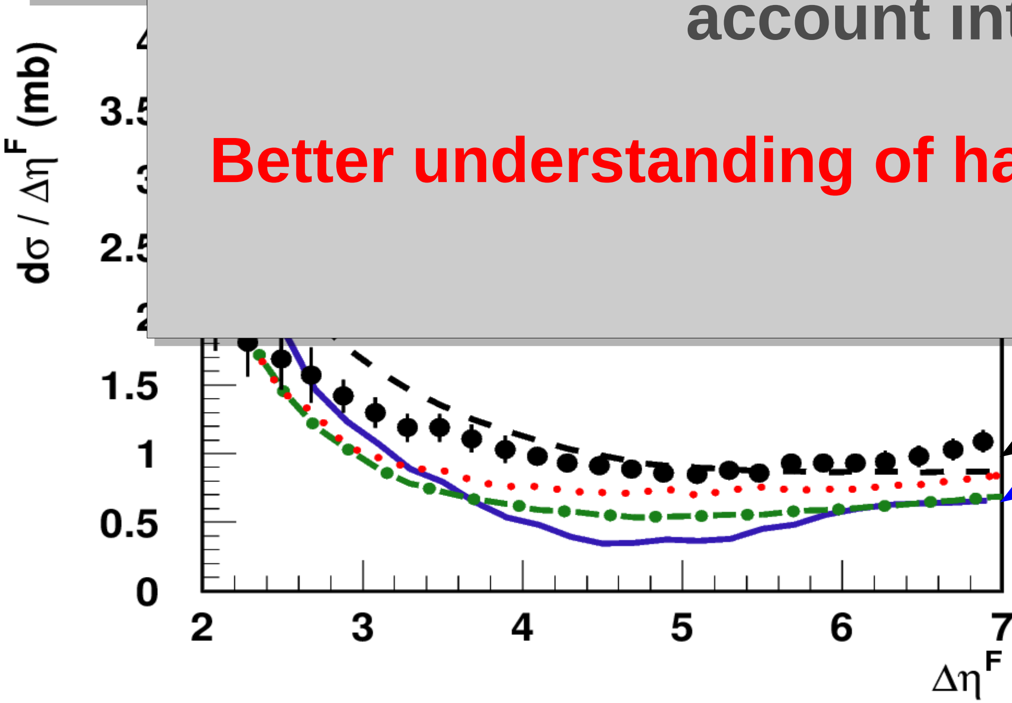
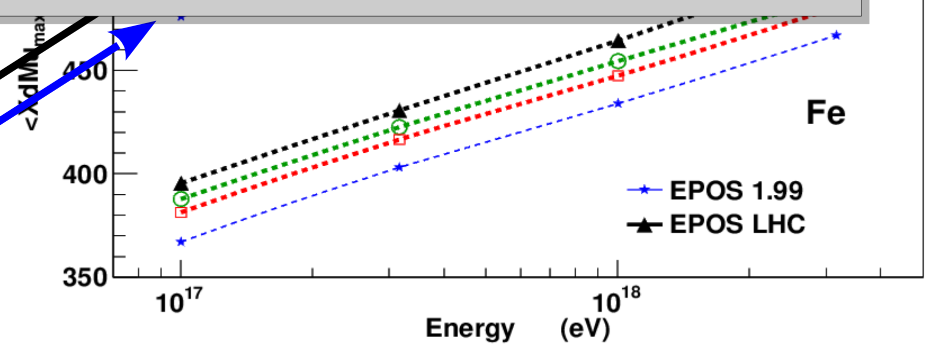
pro … ons

New measurements can in fact increase (temporarily) model uncertainties until these data are taken into account into all models

=

Better understanding of hadronic physics in air shower

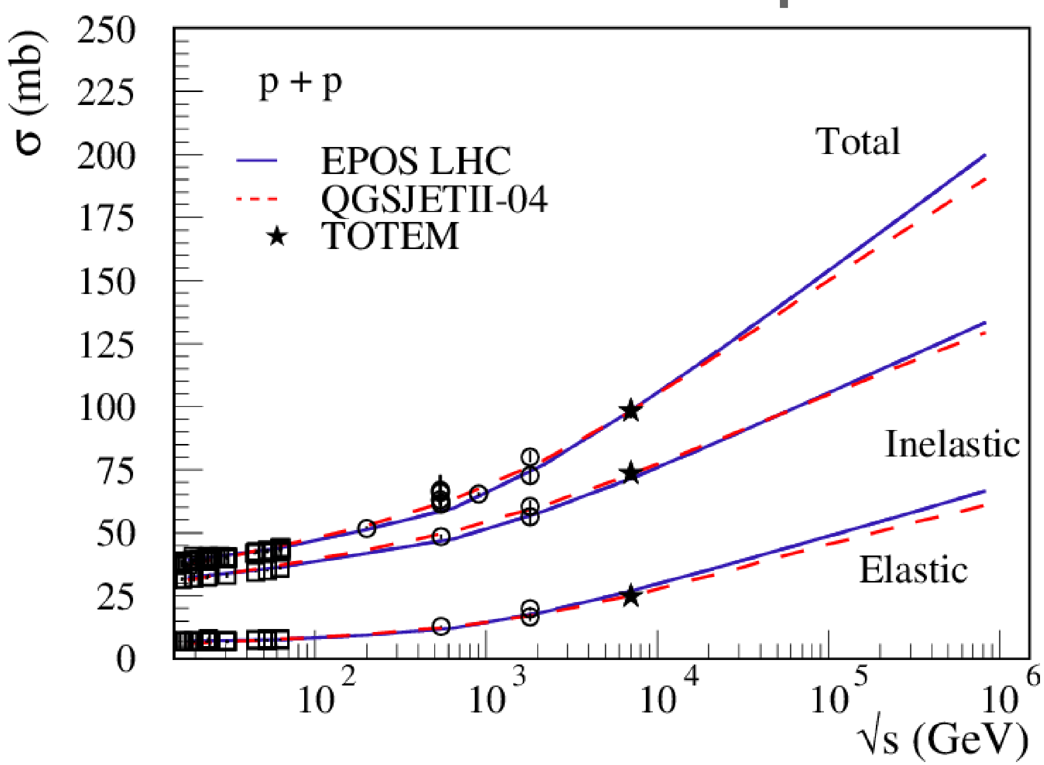


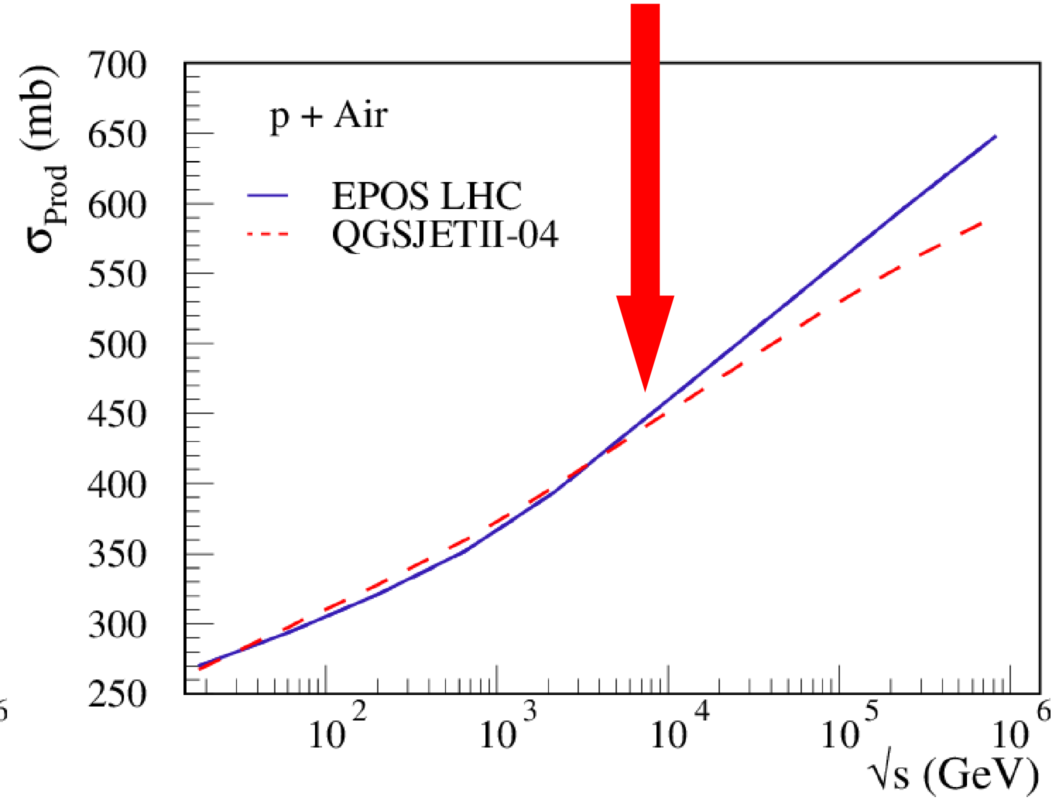


Interactions in Air Shower : p-Air

- **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)

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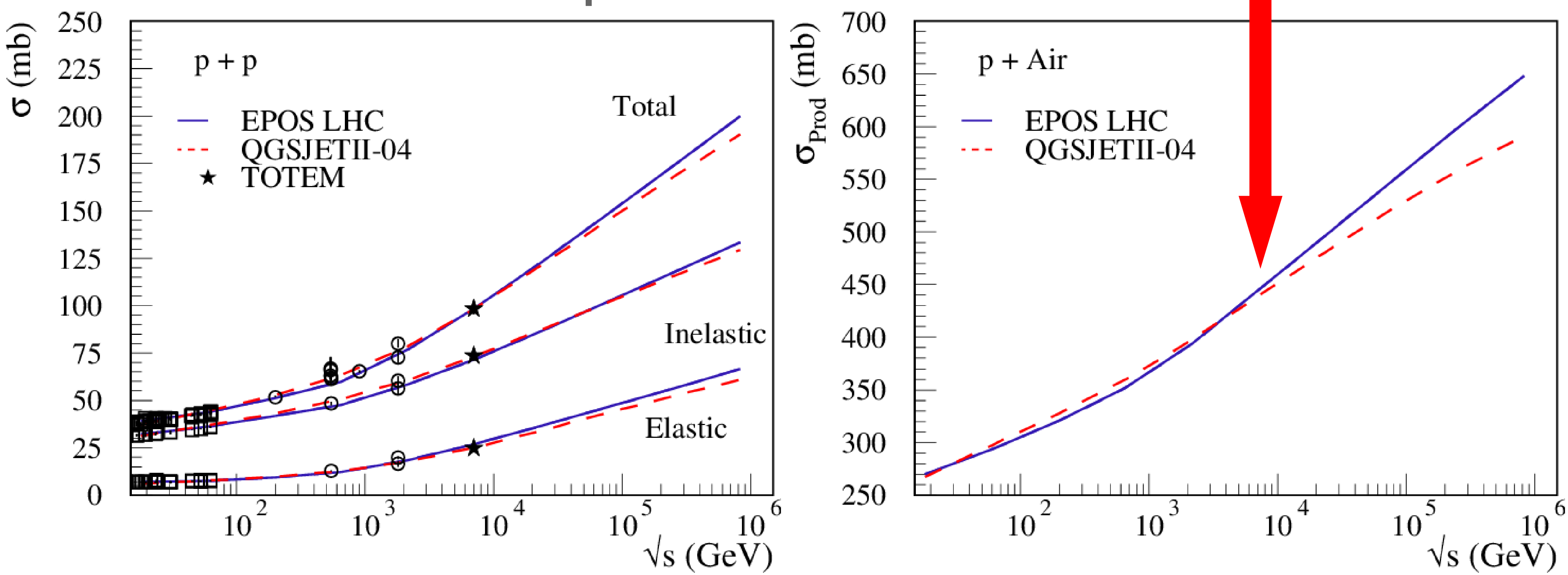

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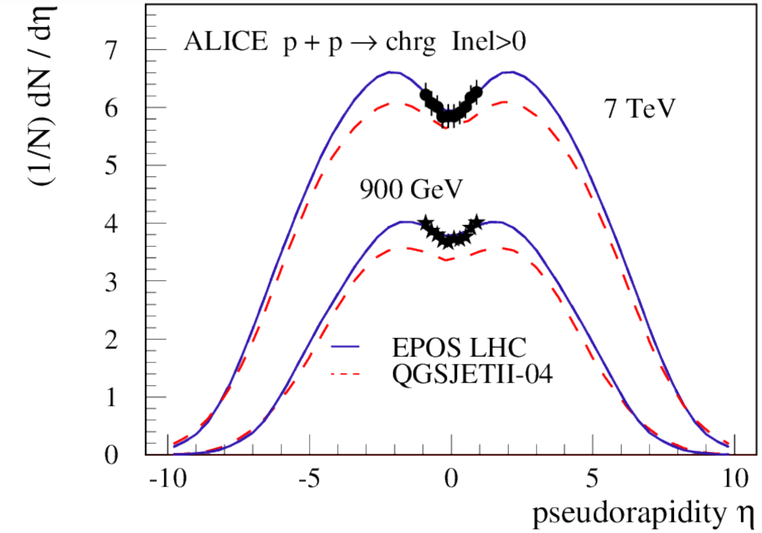

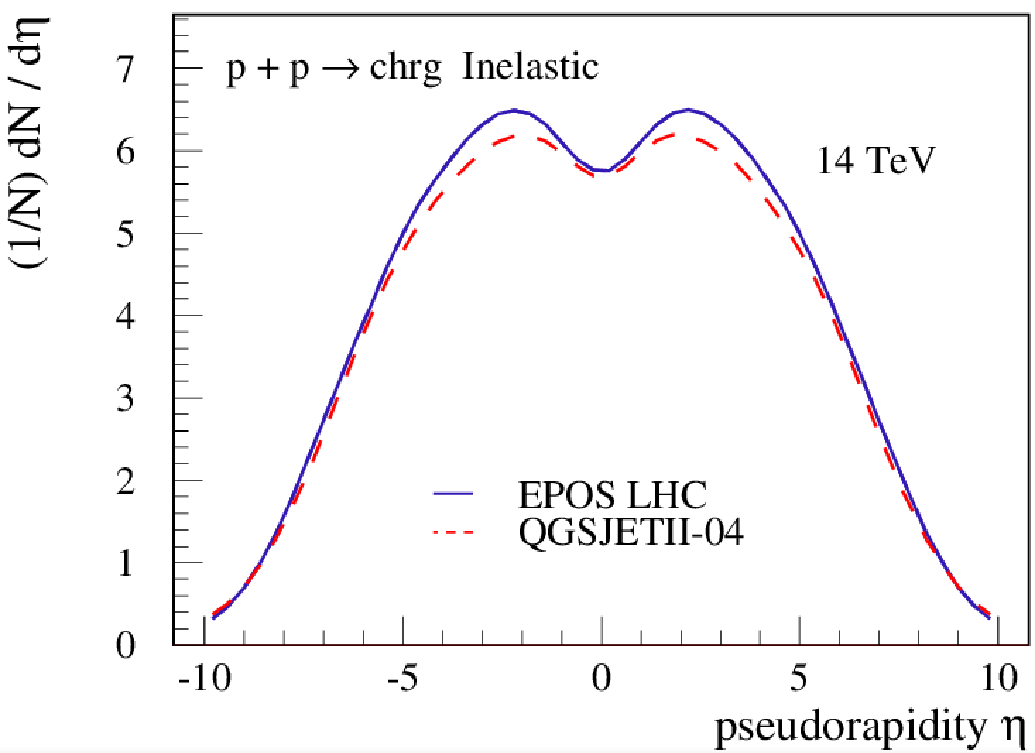

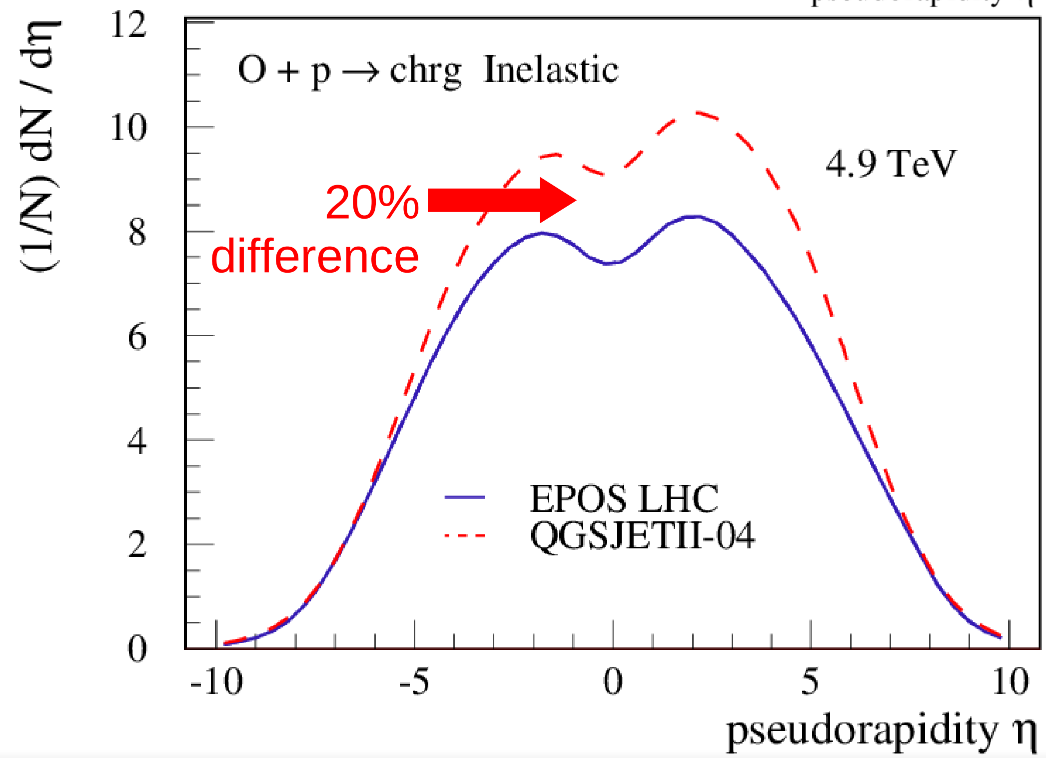

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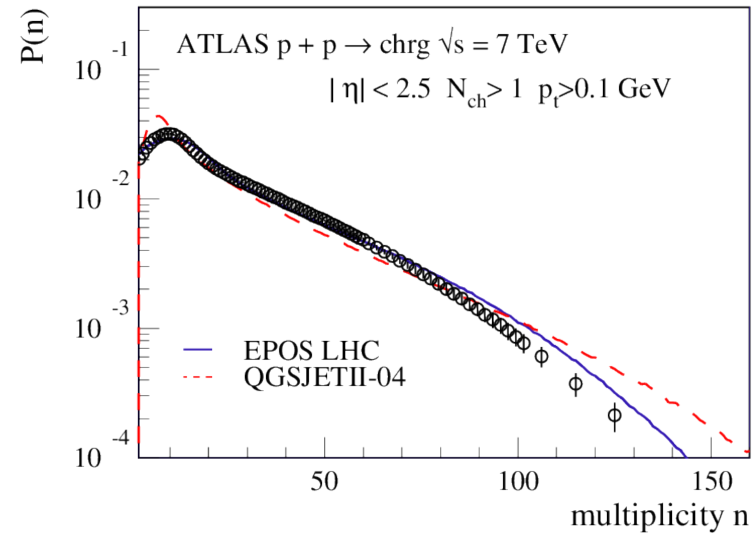

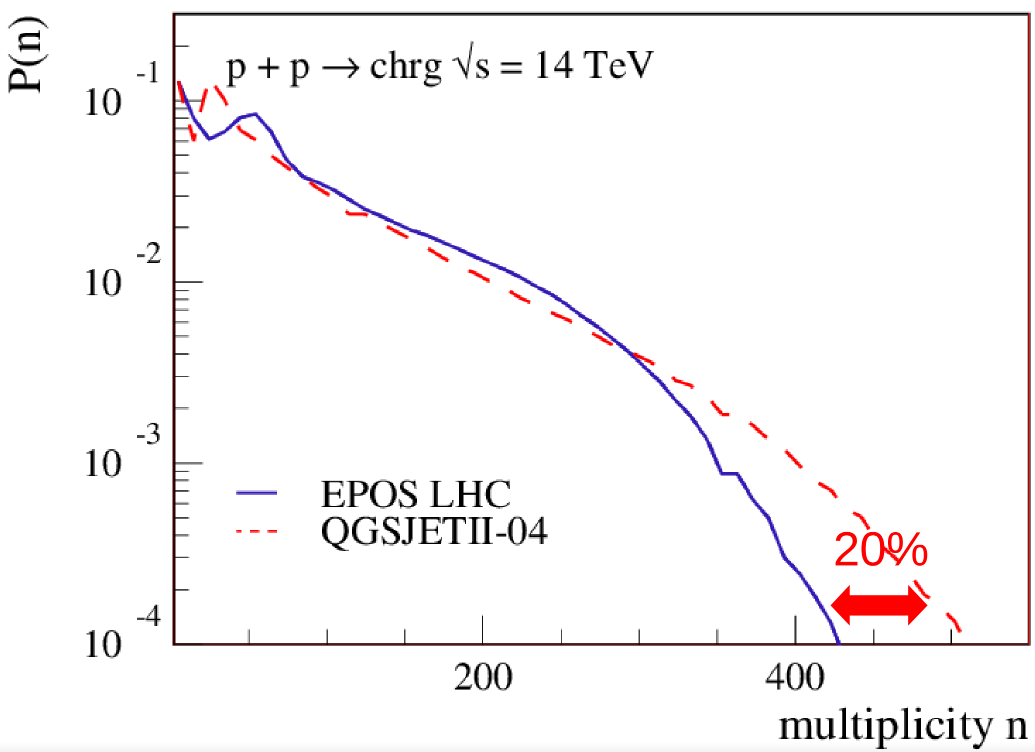

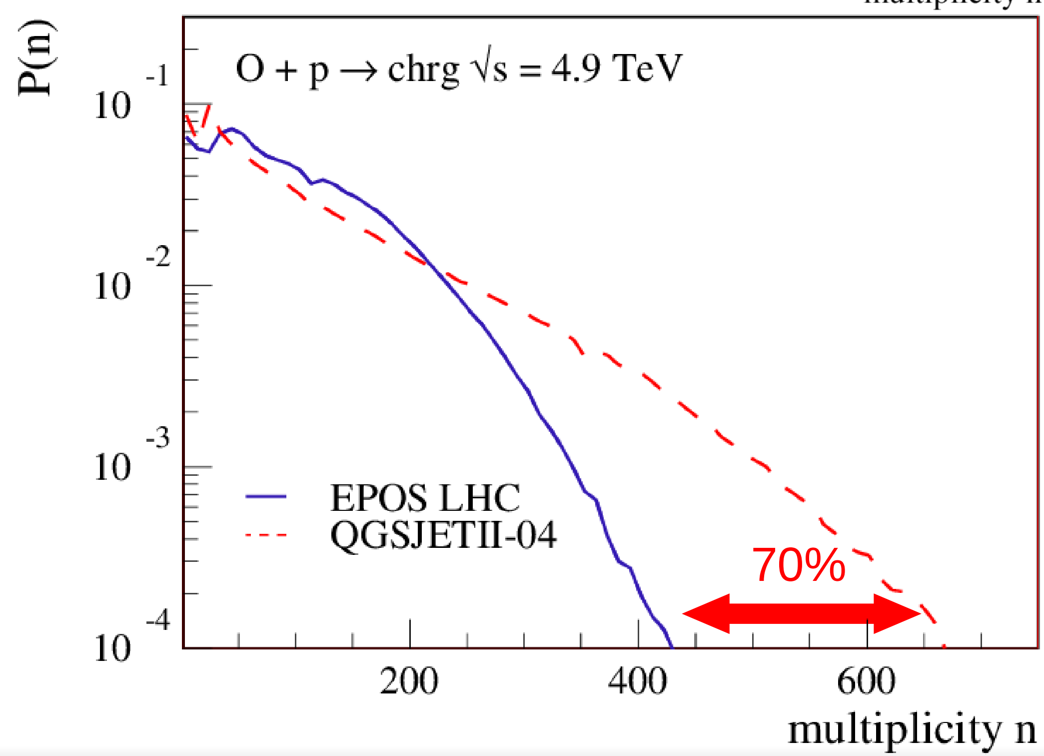

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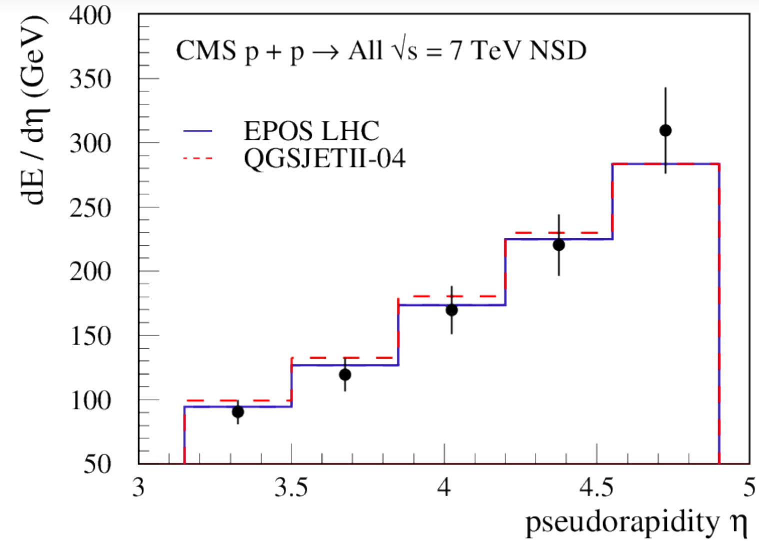
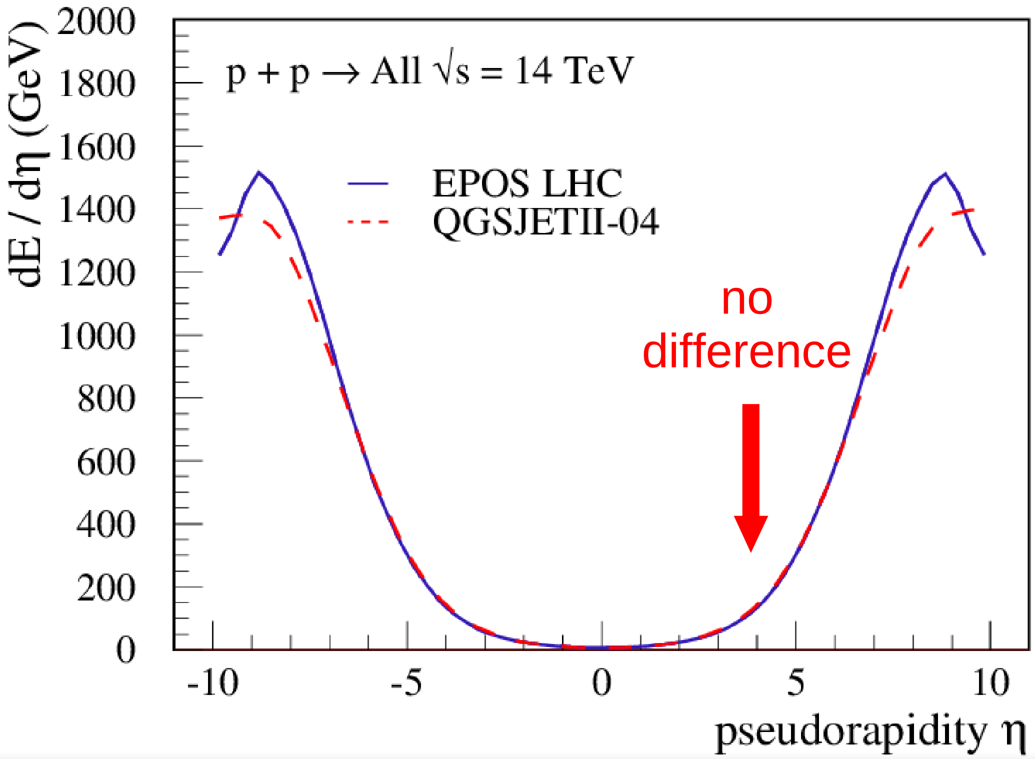
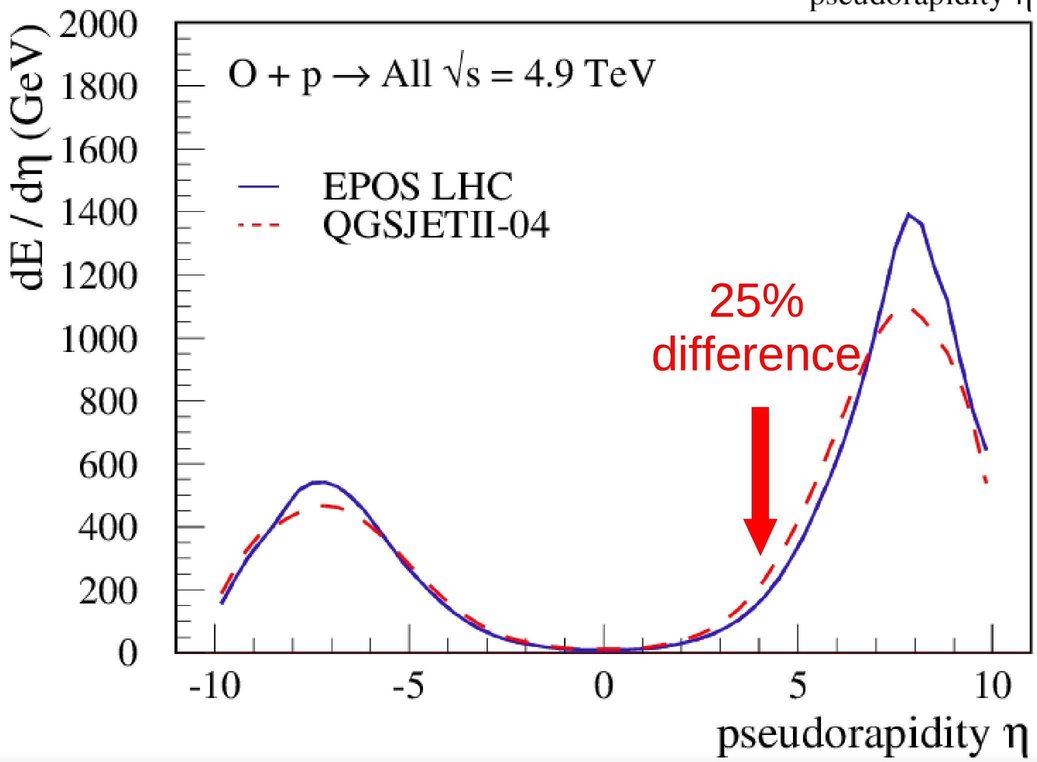
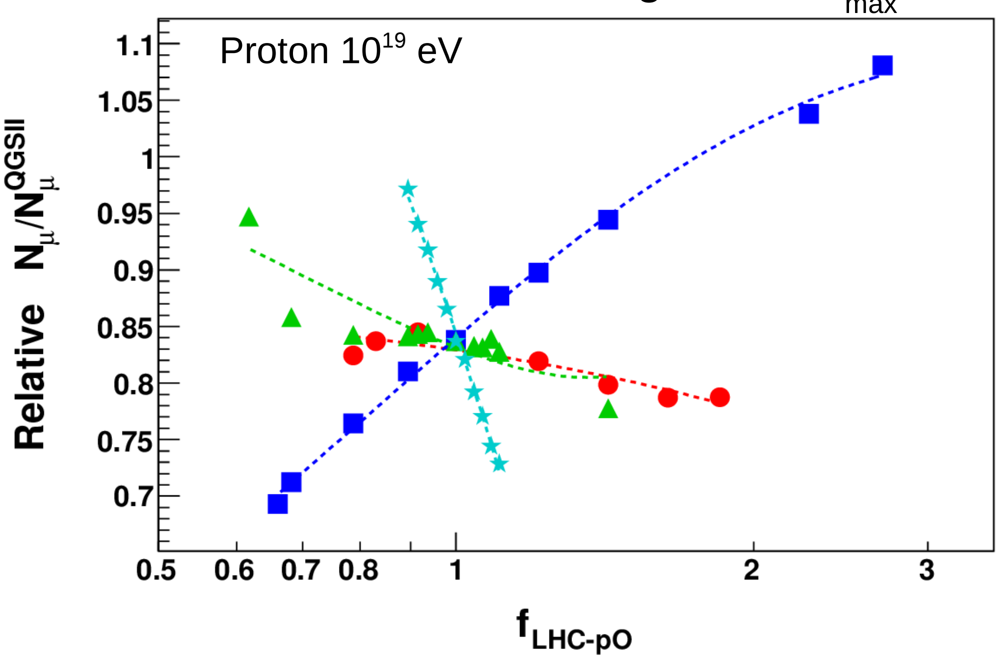


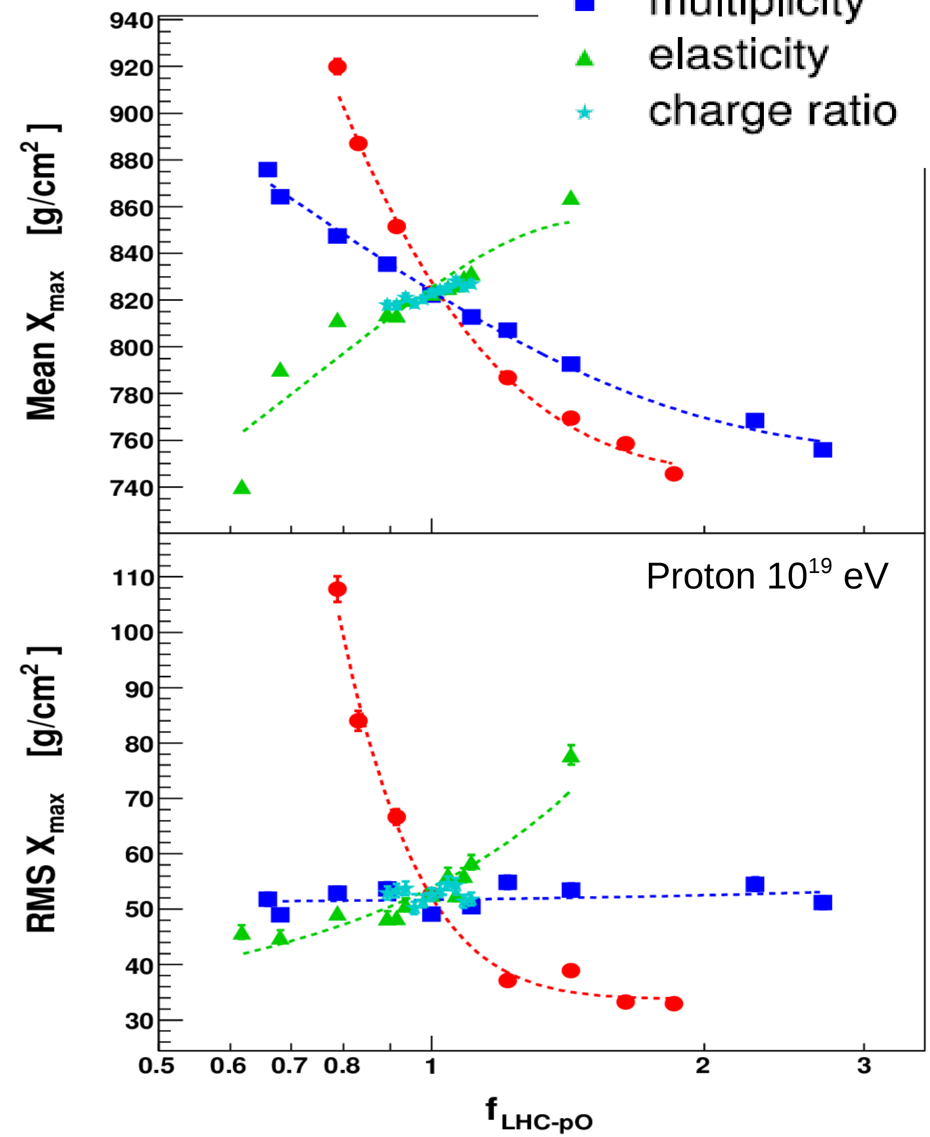




Effects of Parameters

- **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 $\langle X_{max} \rangle$



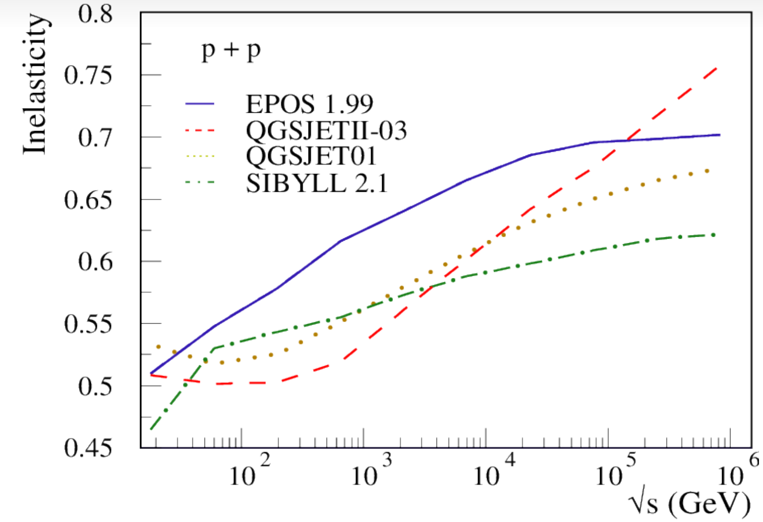


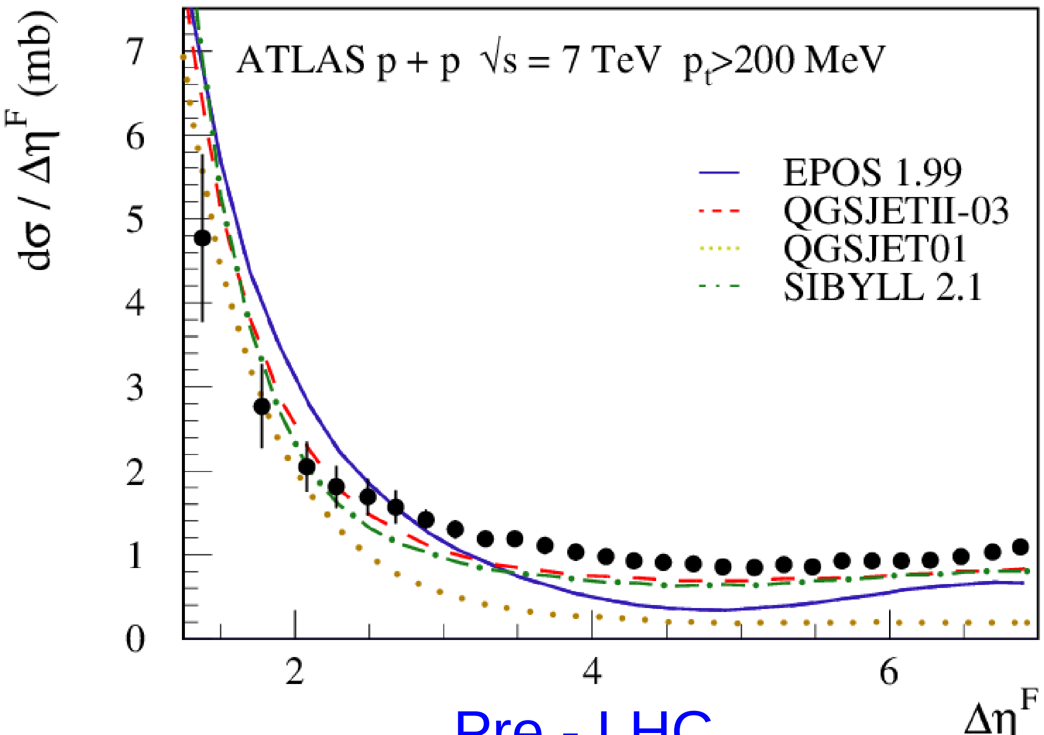
Summary

- **LHC data not usable directly to analyze air showers but important to constrain hadronic models used to analyze data !**
  - ➜ any min-bias measurement is useful and correlation with forward emission are even more constraining
- **First LHC run :**
  - ➜ 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, ...

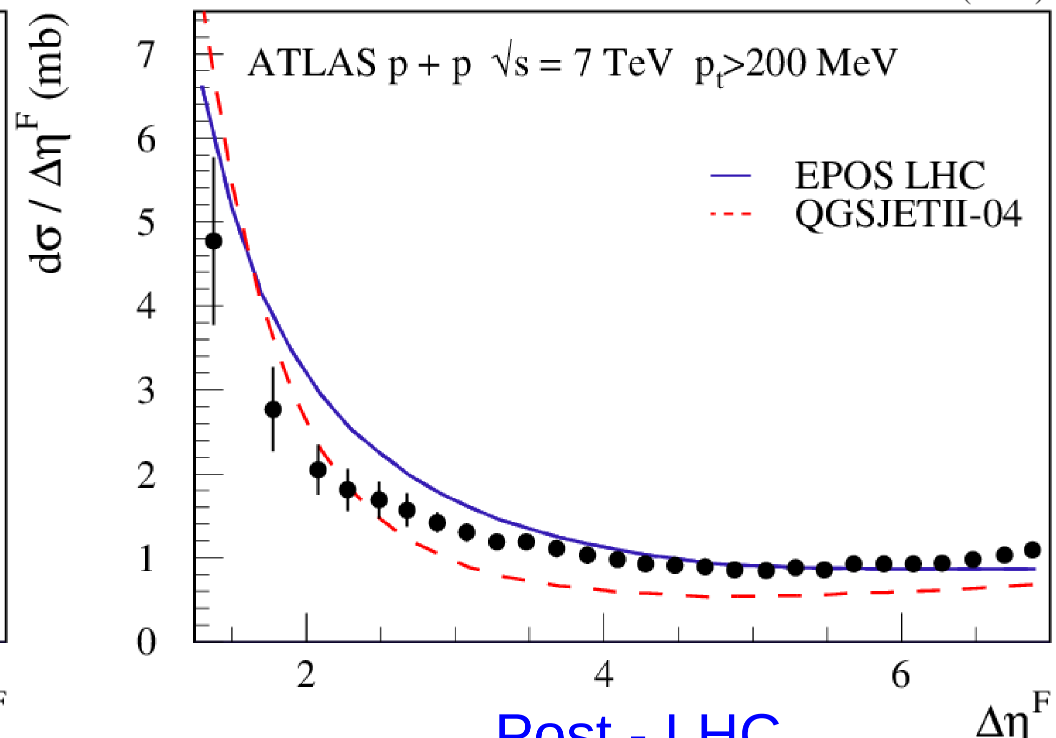
Inelasticity

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





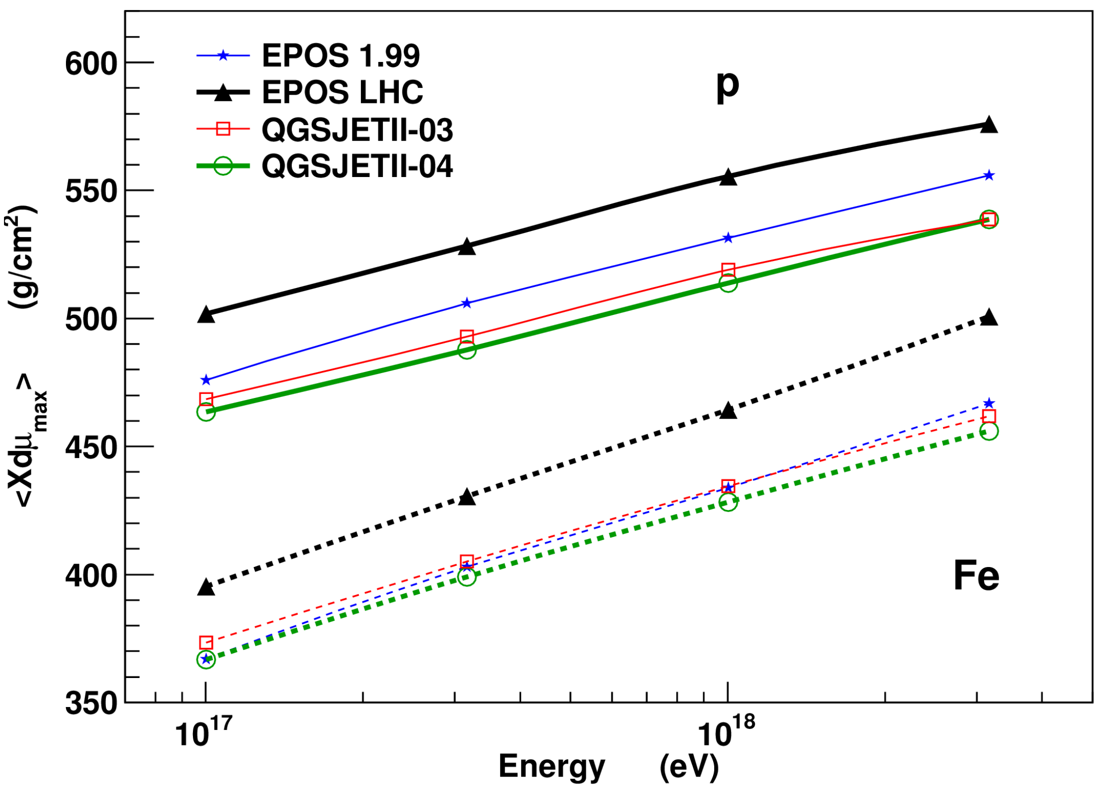
Pre - LHC

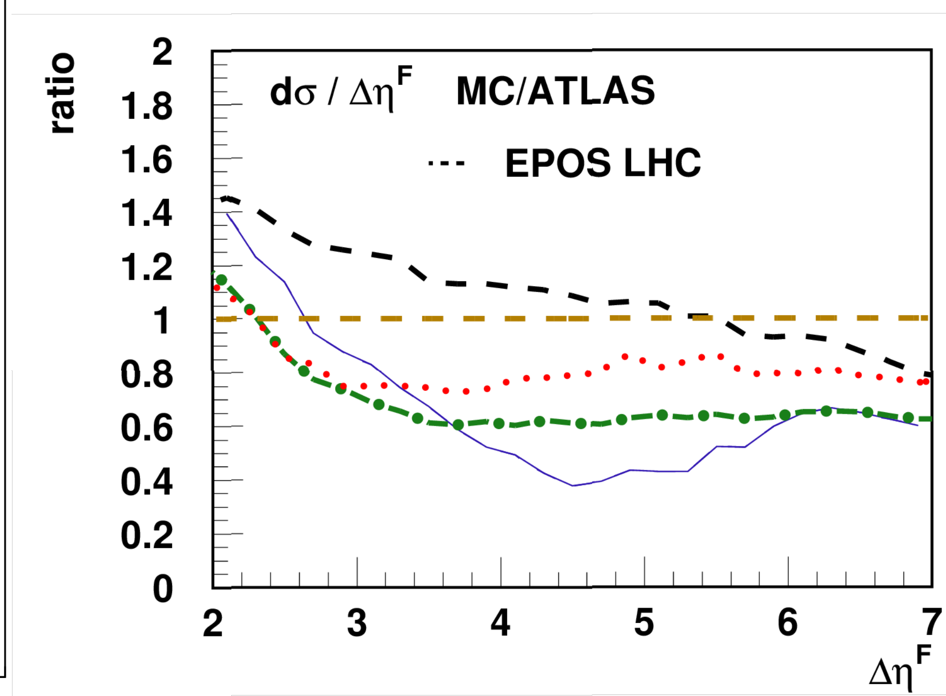


Post - LHC

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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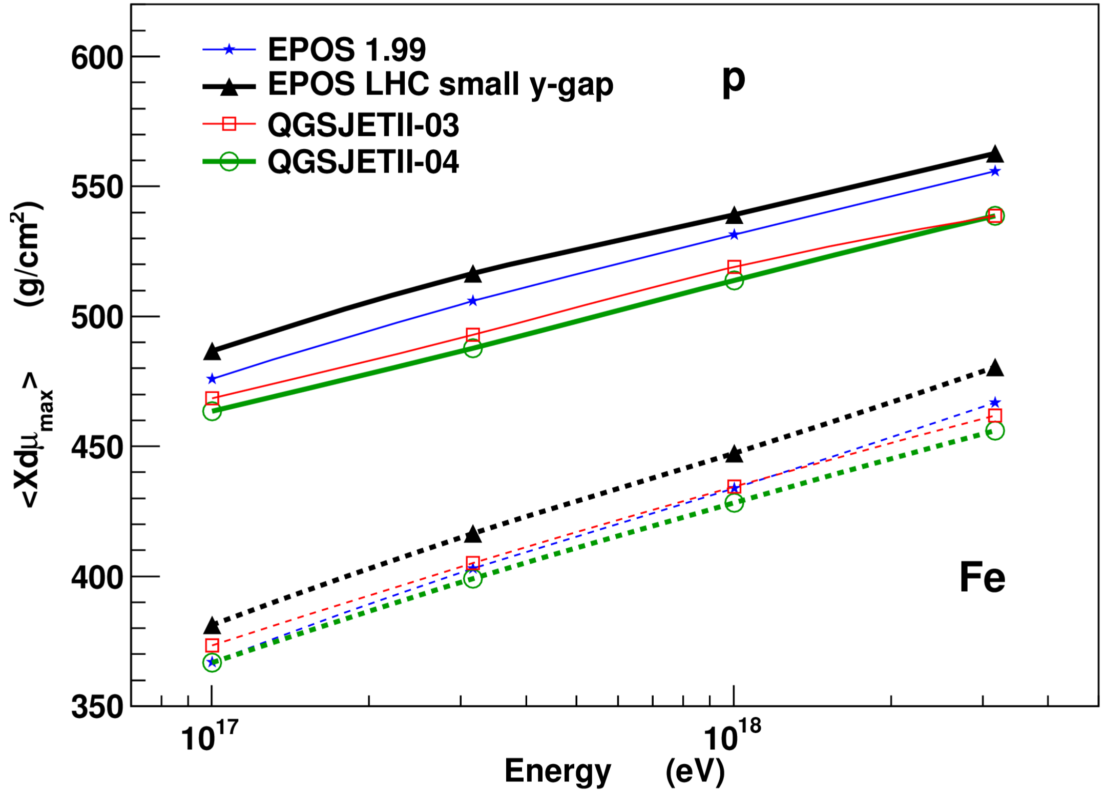
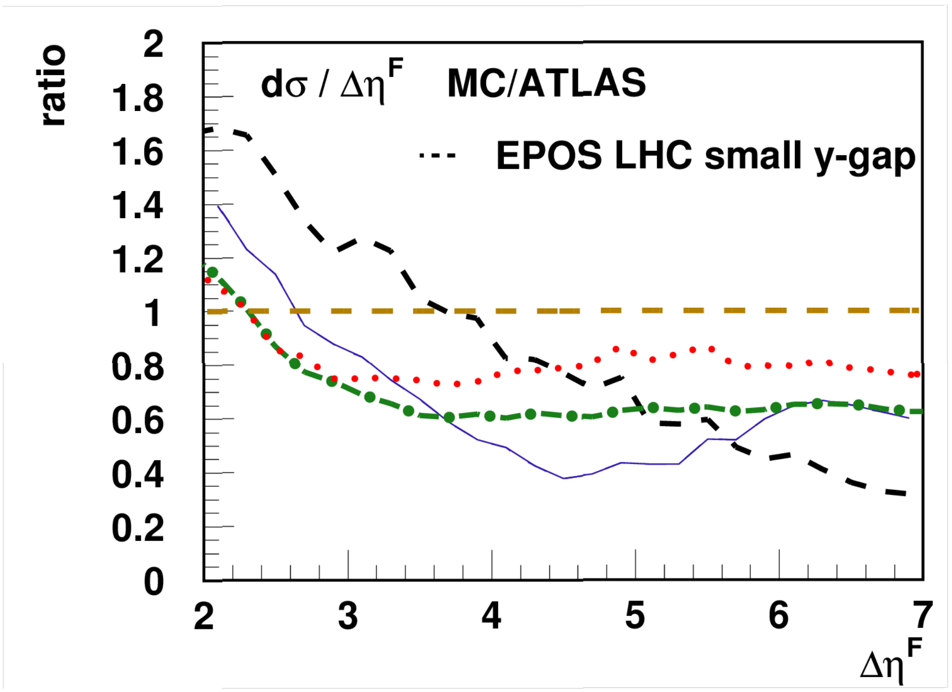
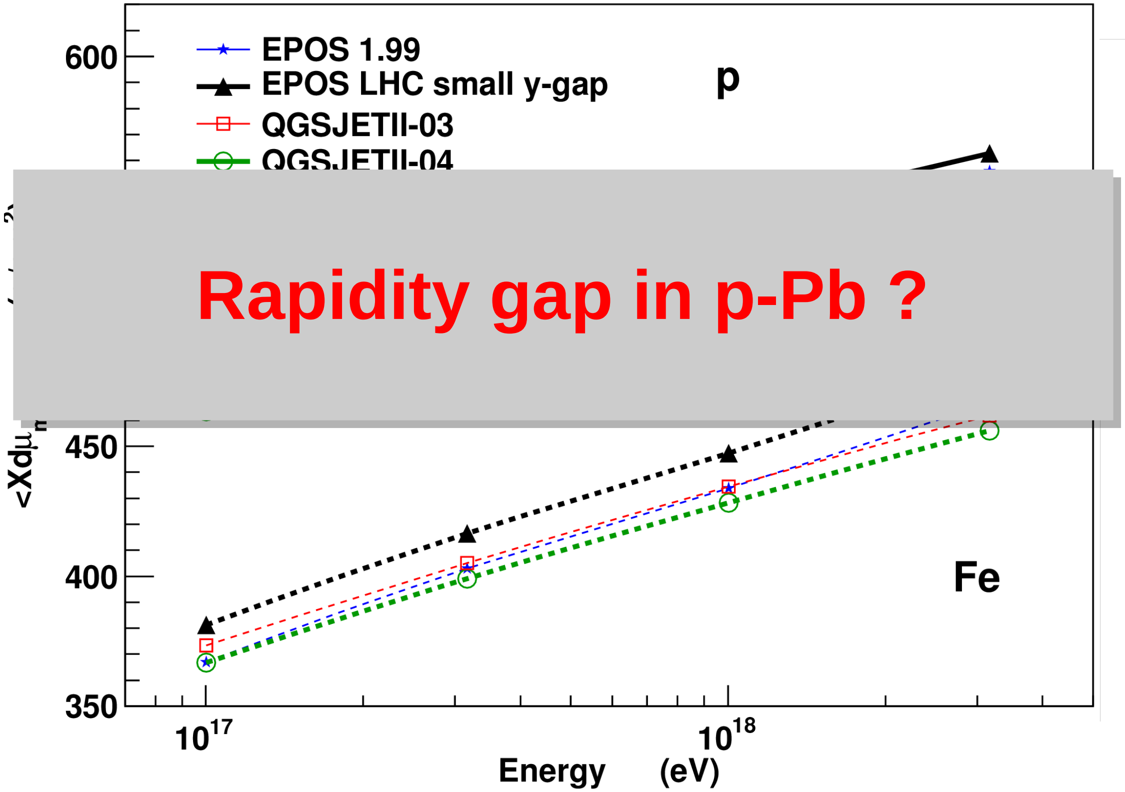


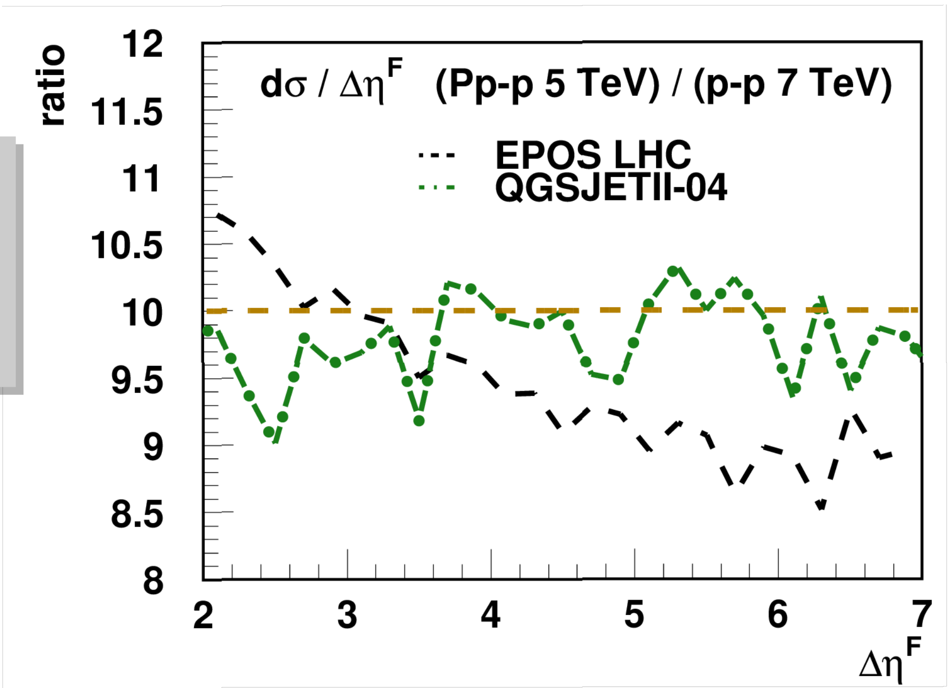


Muon Production Depth

- **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)



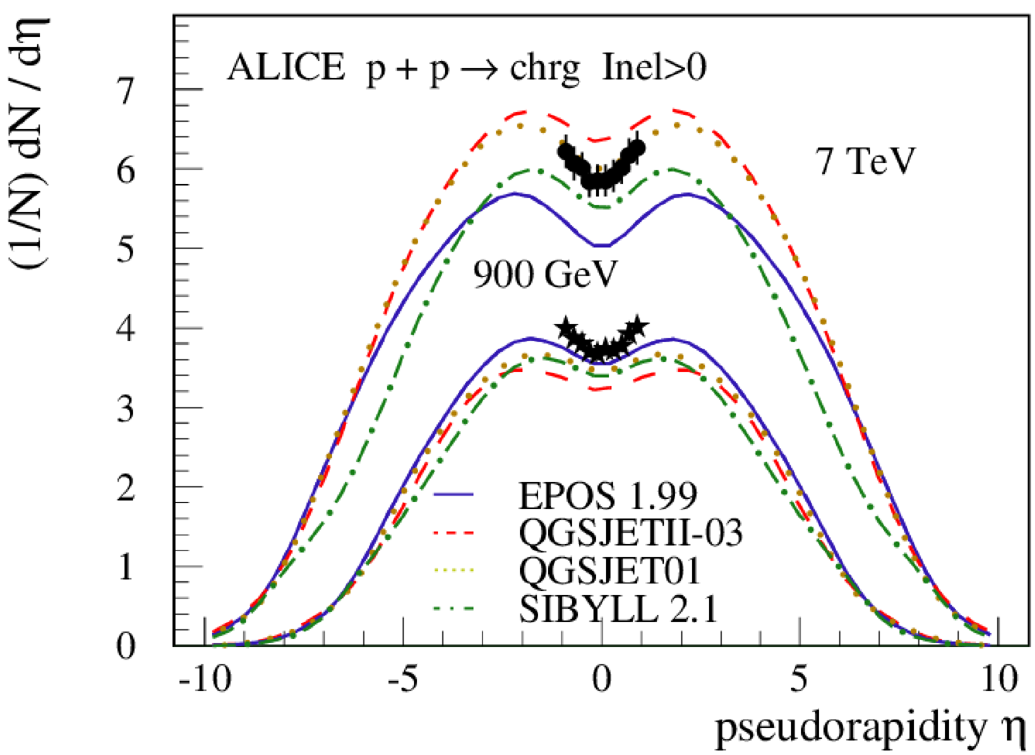
Rapidity gap in p-Pb ?



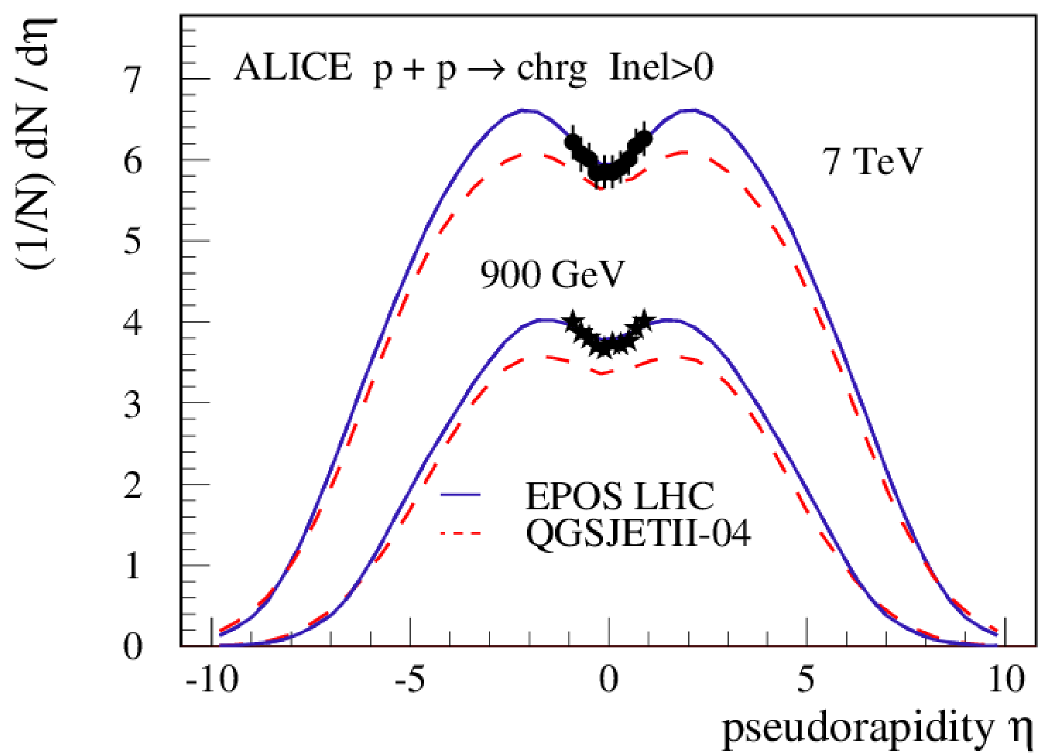
Multiplicity

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

Pre - LHC

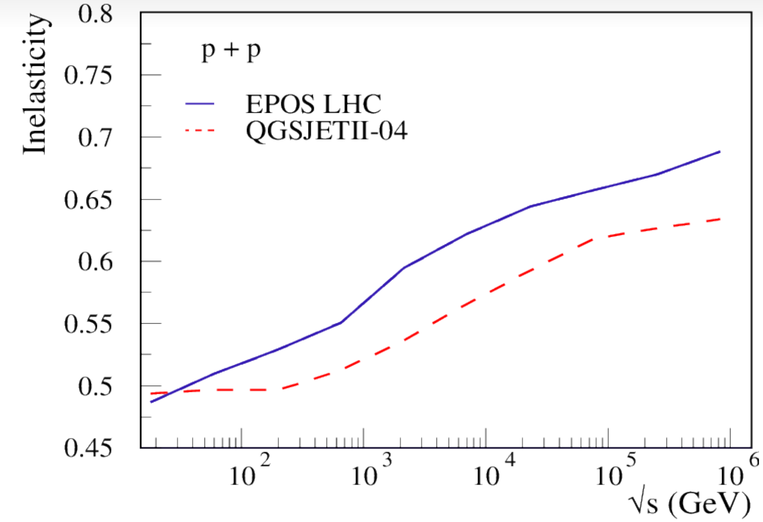


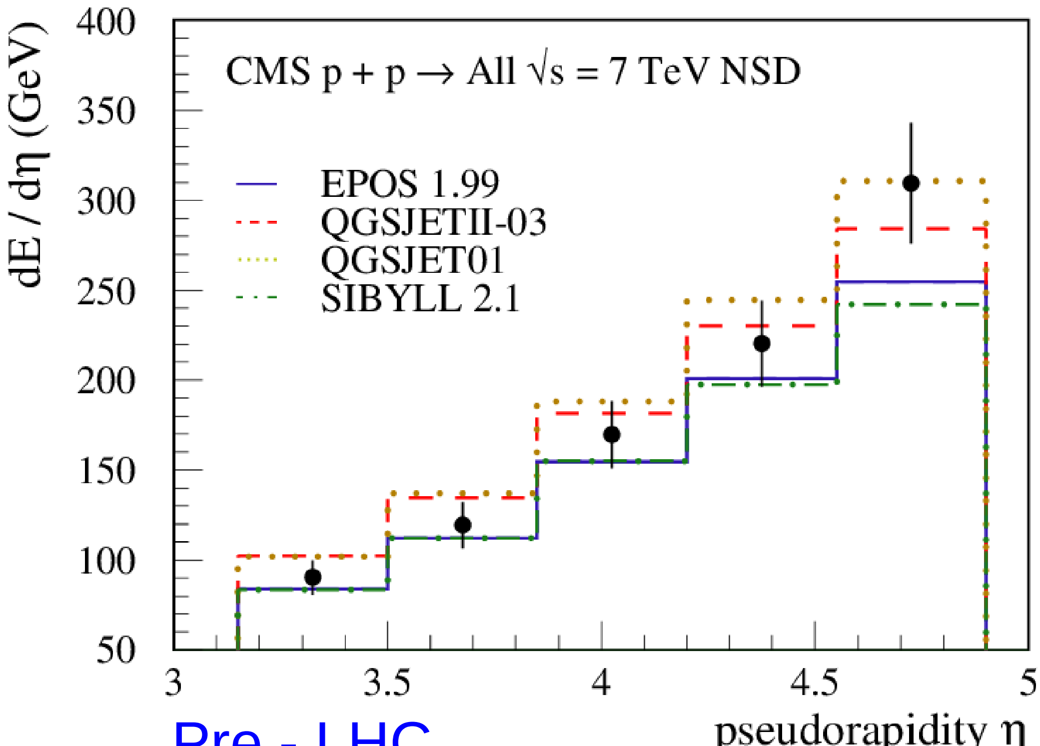
Post - LHC



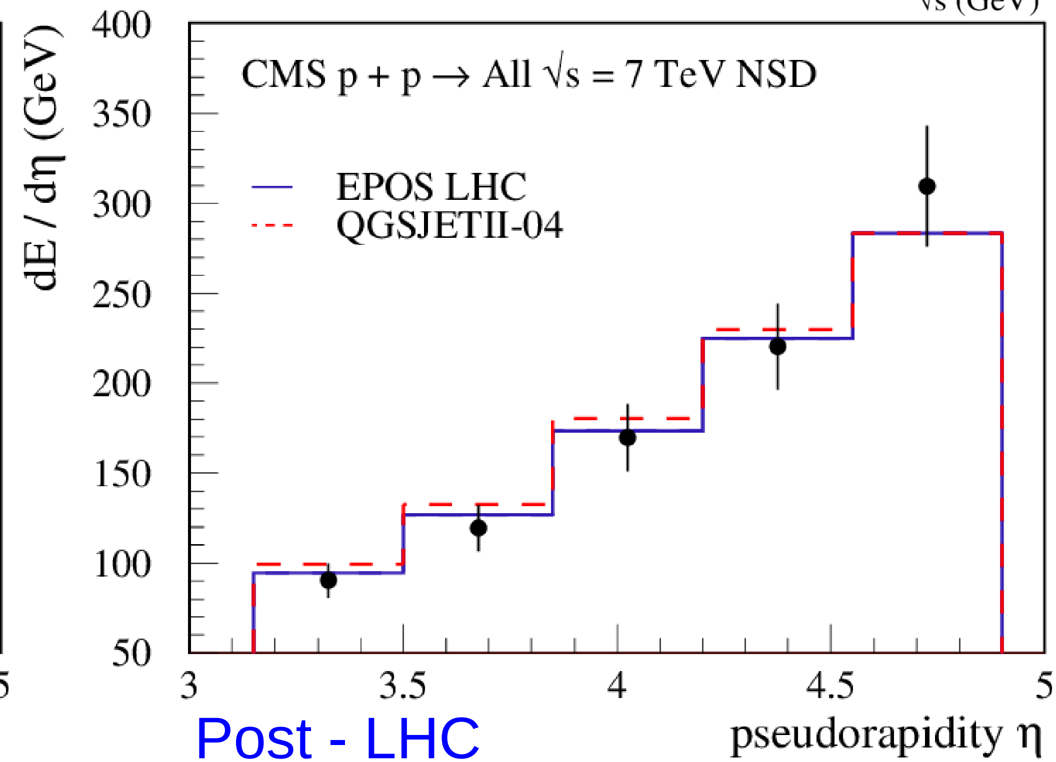
Inelasticity

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





Pre - LHC

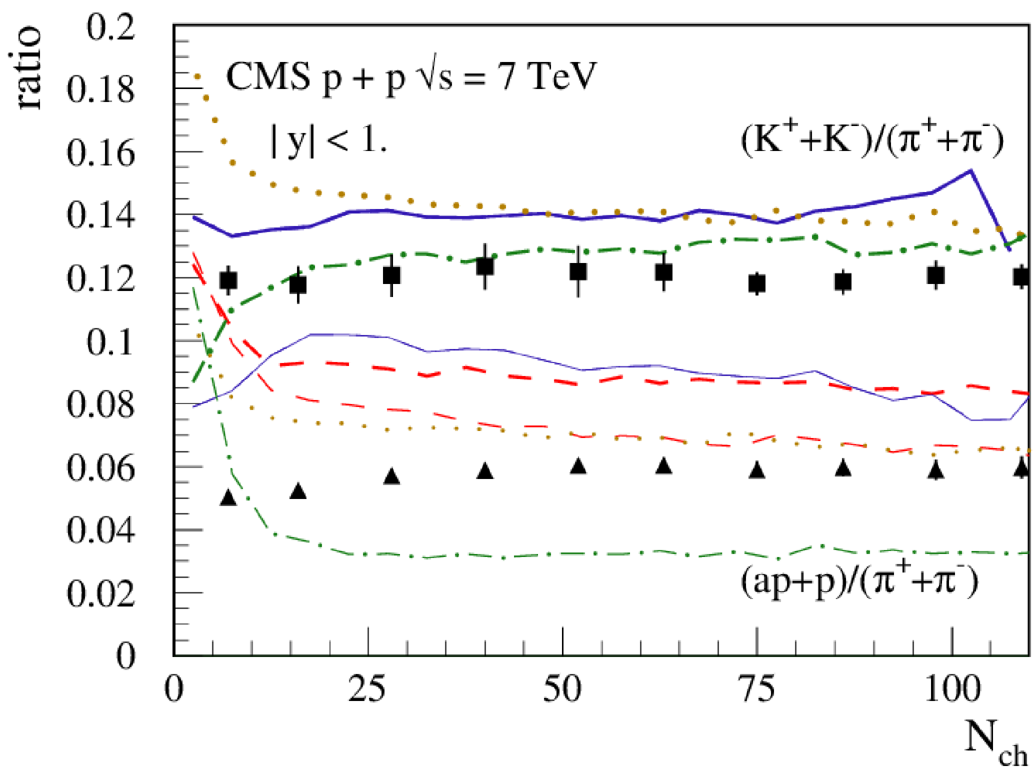


Post - LHC

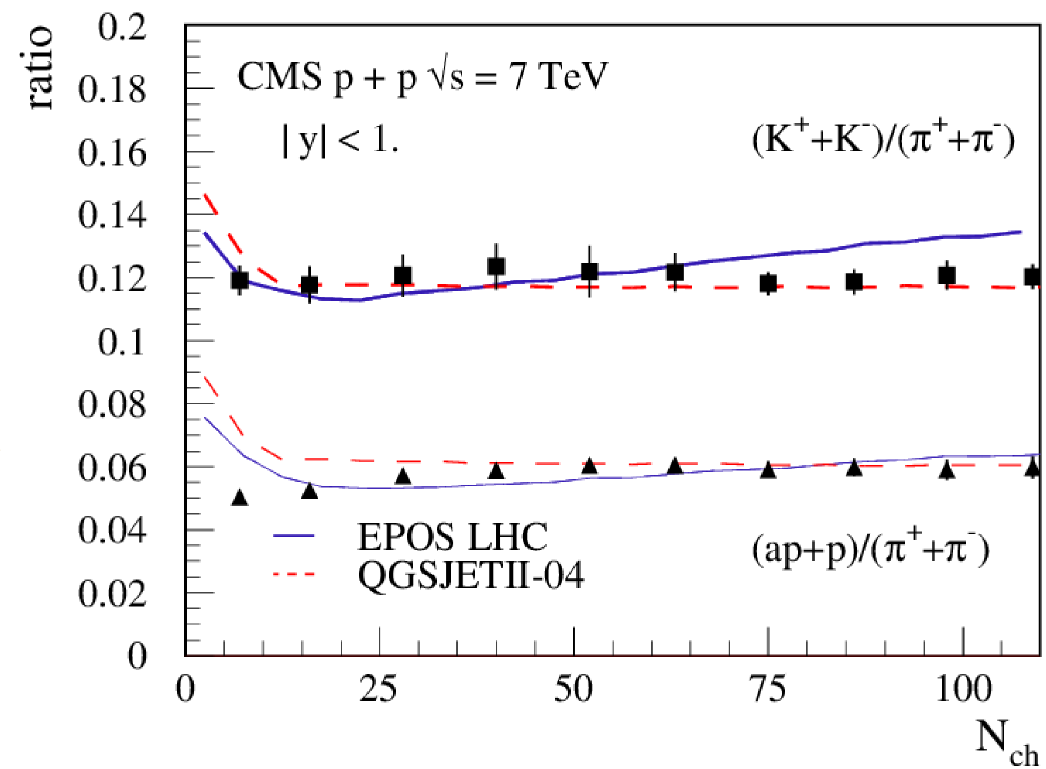
Identified particles

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

Pre - LHC

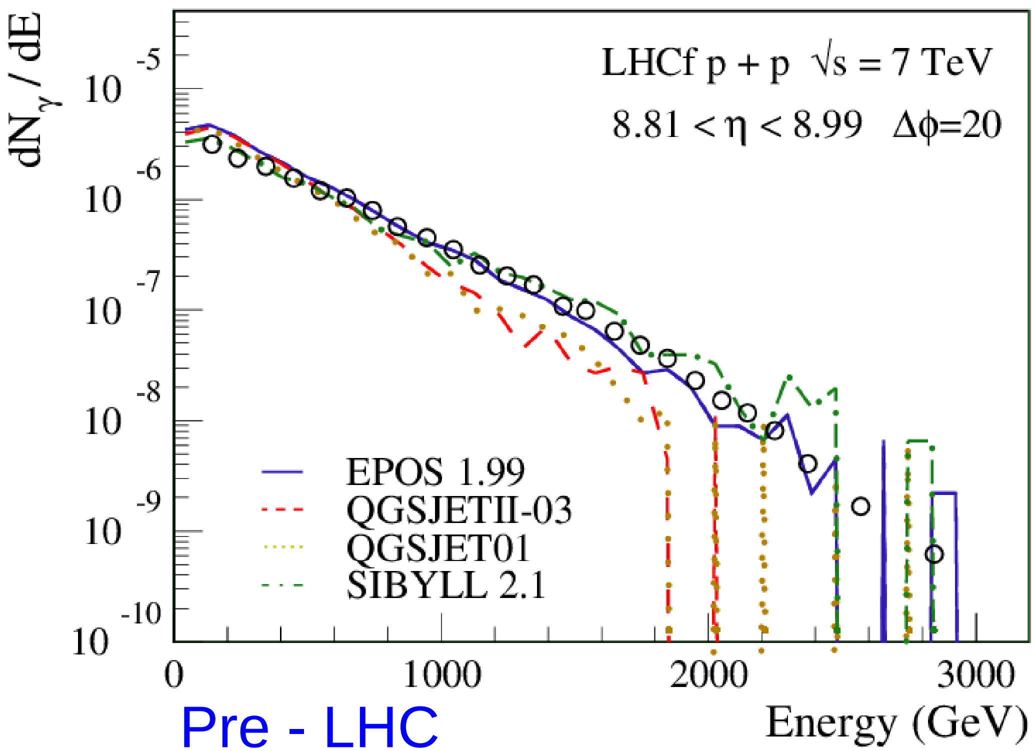


Post - LHC

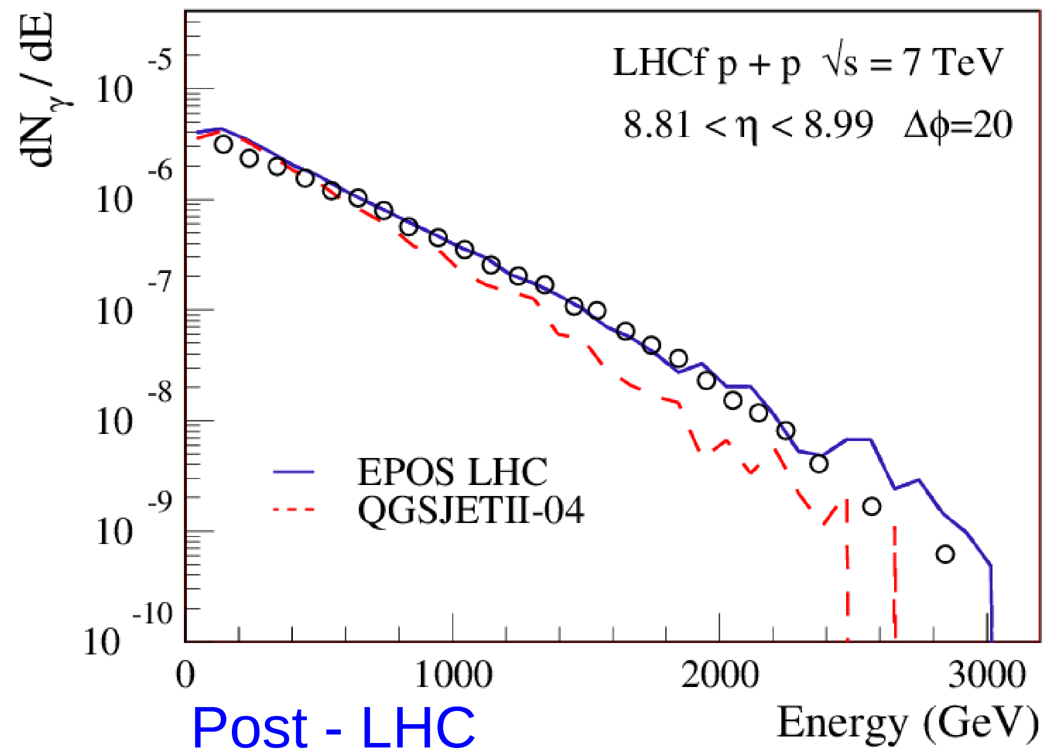


Identified particles

- **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)

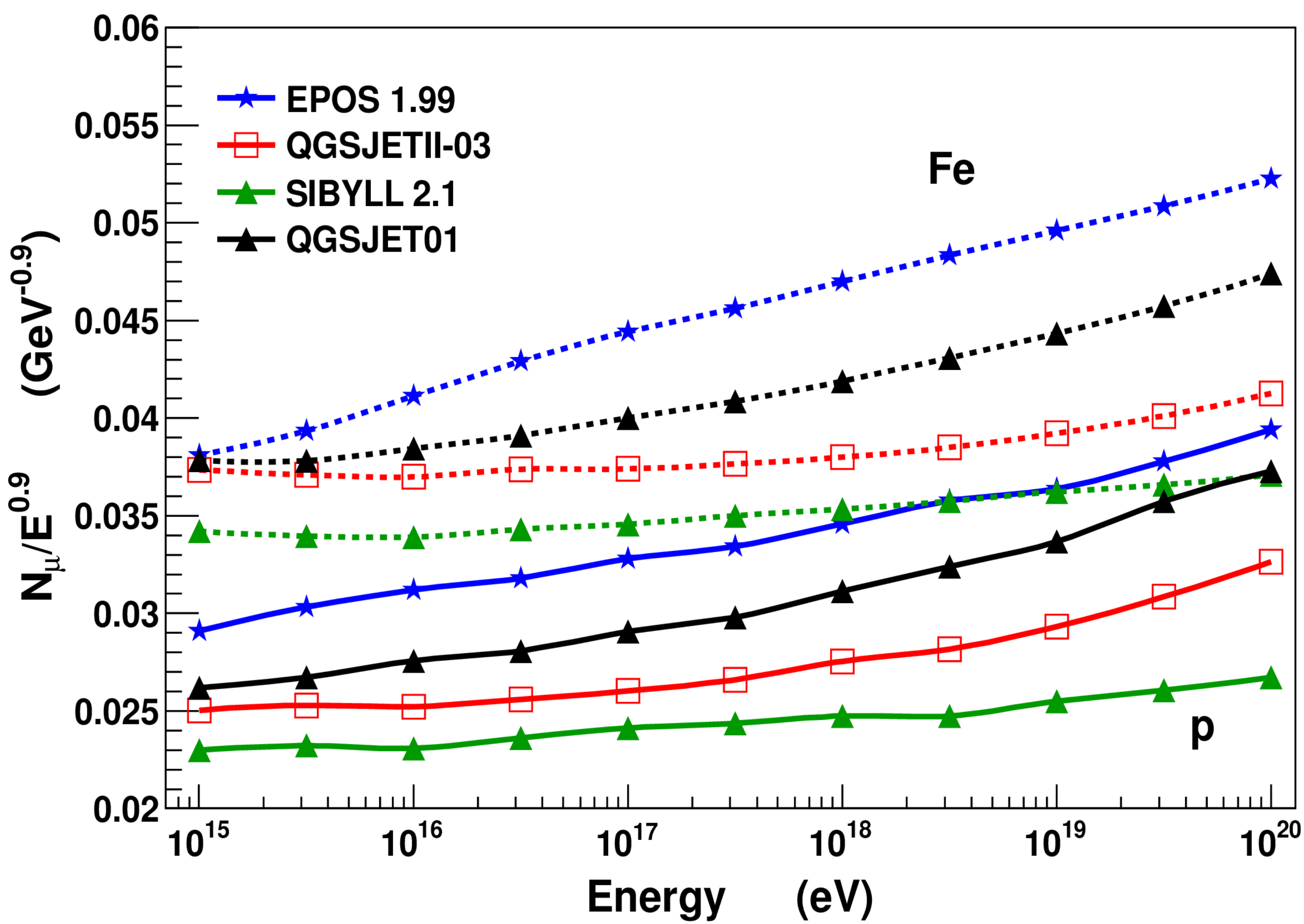


Pre - LHC

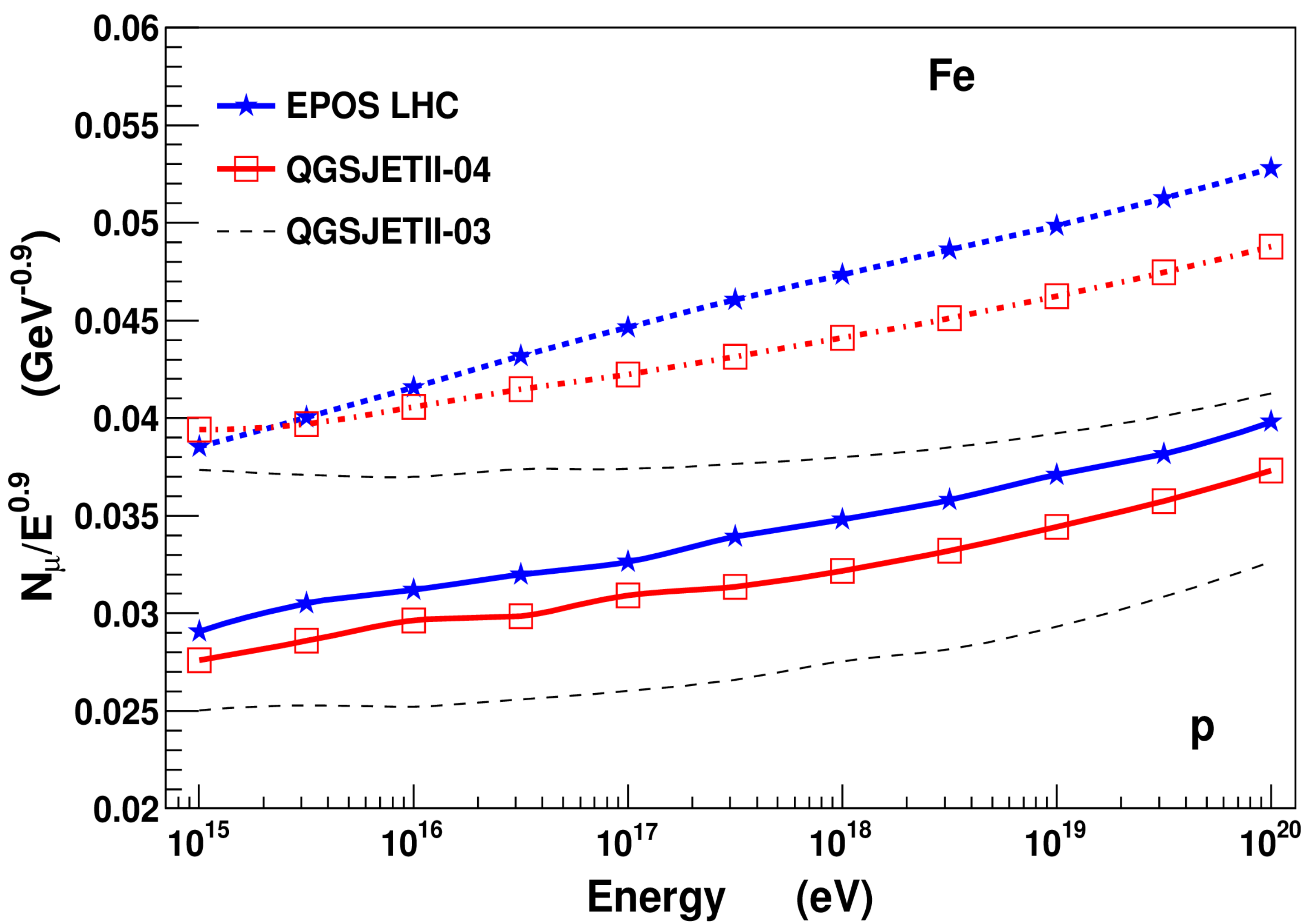


Post - LHC

EAS with Re-tuned CR Models : Muons



EAS with Re-tuned CR Models : Muons



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**

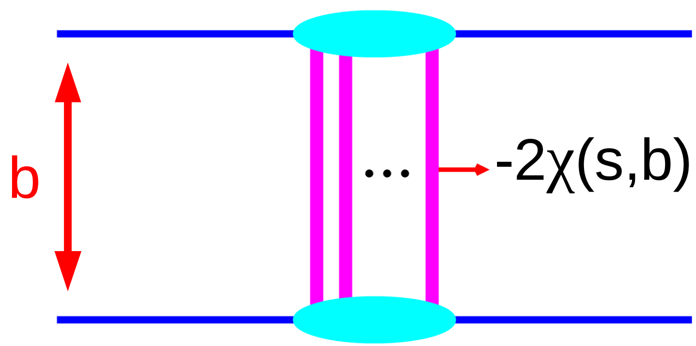
Only model used in HEP (SPS, RHIC, LHC)

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

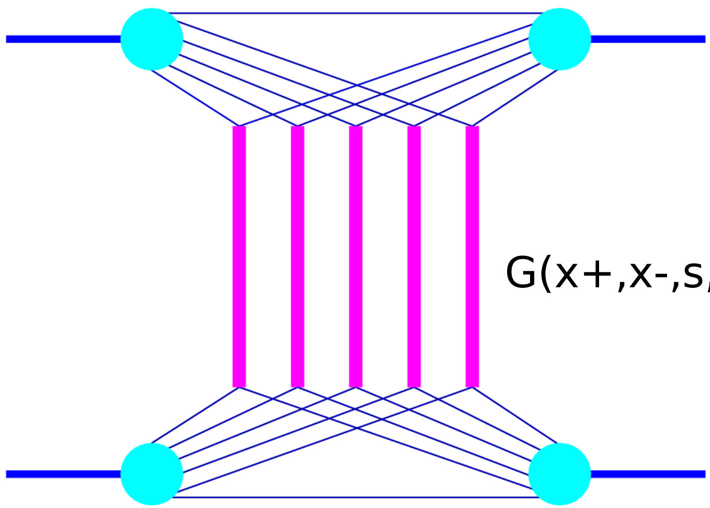


$$\sigma \sim 1 - \exp(-2\chi)$$

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

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

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

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

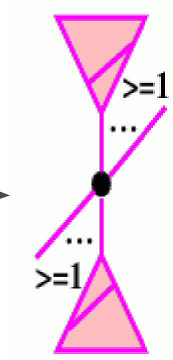
Particle Production in SIBYLL and QGSJET

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 :

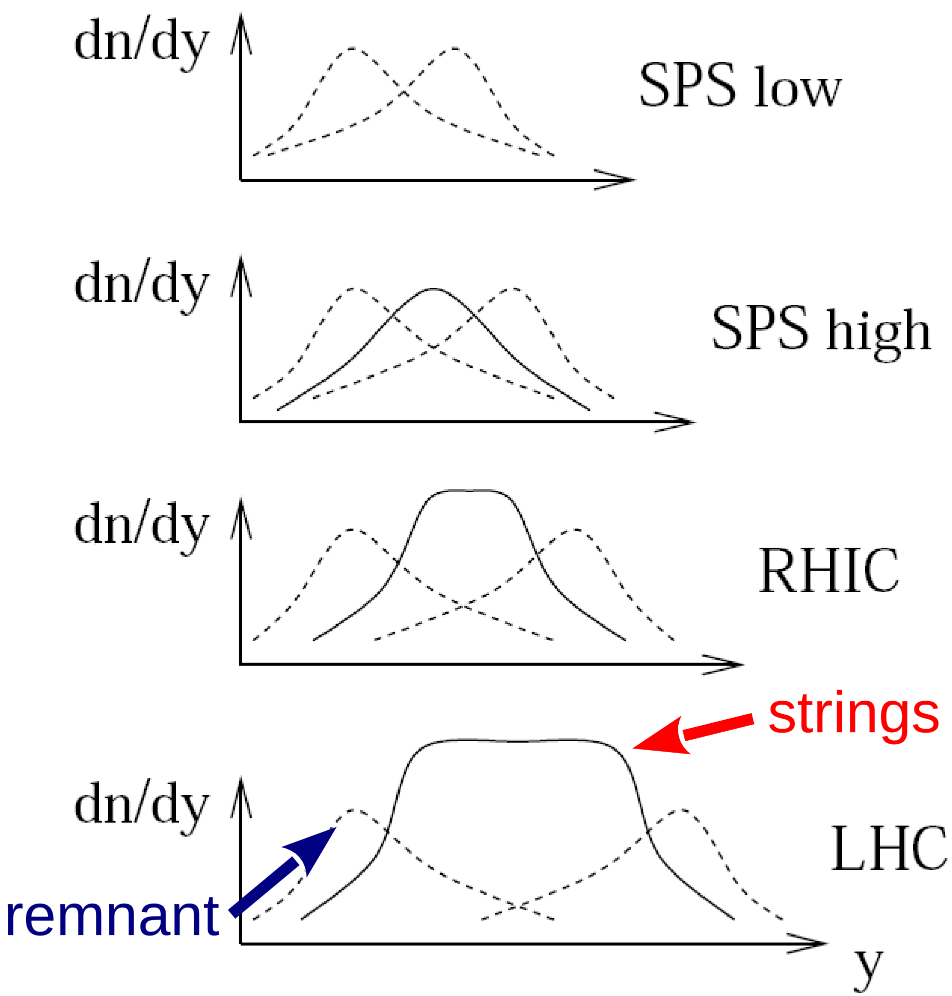
- m from :

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

  - 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

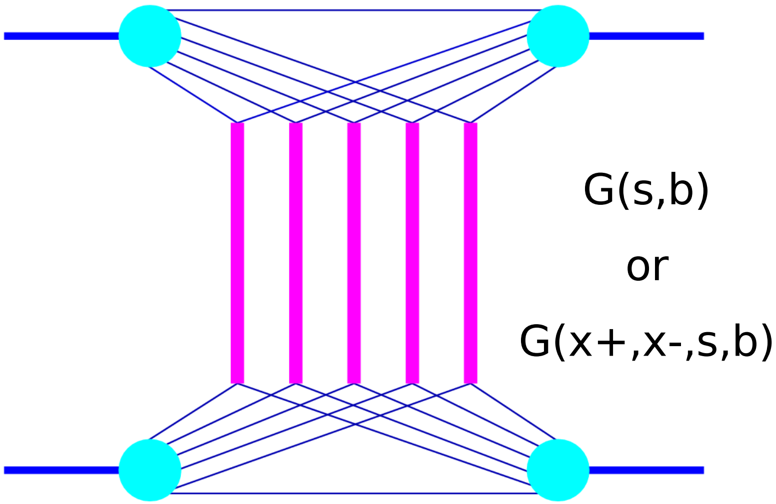
Forward particles mainly from projectile remnant



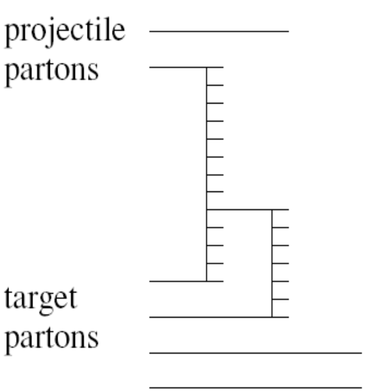
The inelasticity is closely related to diffraction and forward spectra

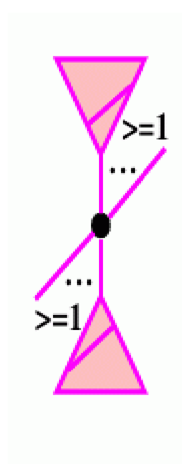
- SIBYLL
  - No remnant except for diffraction
  - Leading particle from string ends
- QGSJET
  - Low mass remnants
  - Leading particle similar to proj.
- EPOS
  - Low and high mass remnants
  - Any type of leading particle
    - from resonance
    - from string
    - from statistical decay

Cross Section and Multiplicity in Models



EPOS QGSJET II



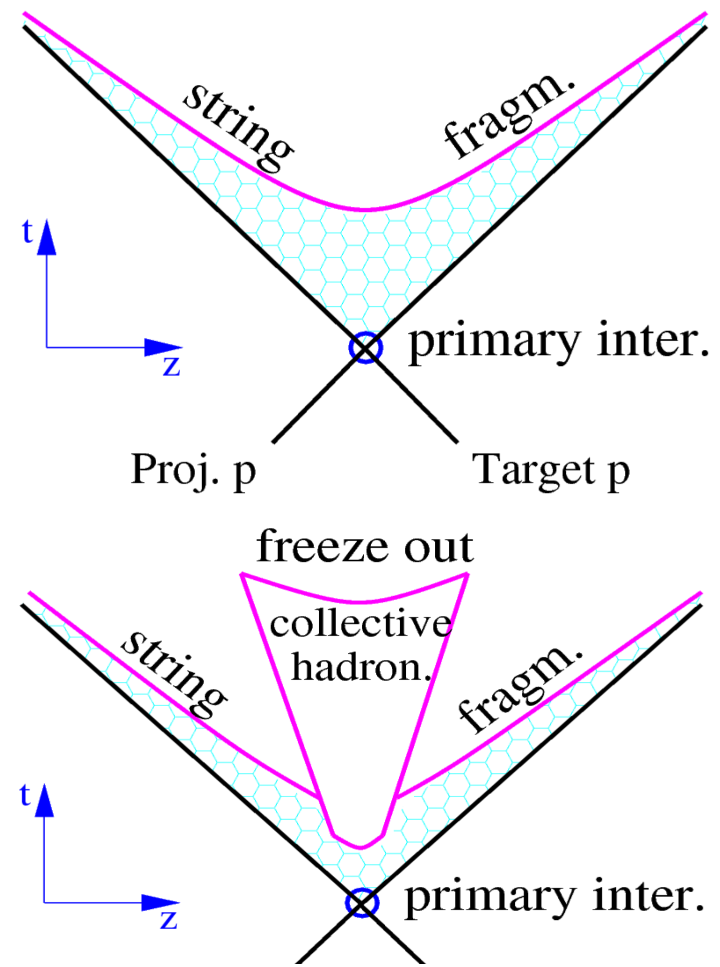


- **Gribov-Regge and optical theorem**
  - ➜ Basis of all models (multiple scattering) but
    - Classical approach for QGSJET and SIBYLL (no energy conservation for cross section calculation)
    - Parton based Gribov-Regge theory for EPOS (energy conservation at amplitude level)
- **pQCD**
  - ➜ Minijets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

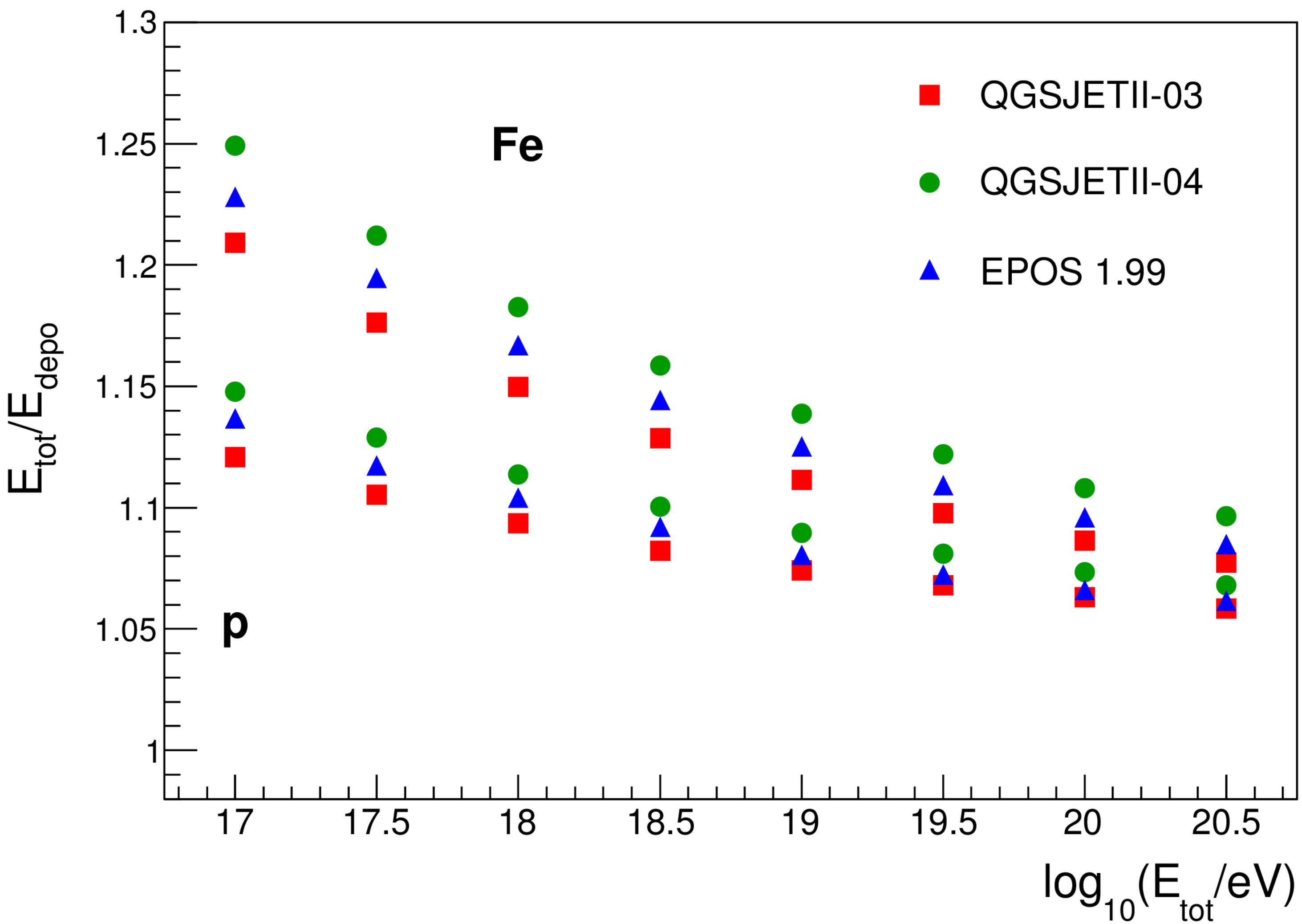
- **EPOS 1.99 to EPOS LHC**
  - tune cross section to TOTEM value
  - change old flow calculation to a more realistic one
  - introduce central diffraction
  - keep compatibility with lower energies



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



EAS Energy Deposit

- **Increase of muons in QII04**
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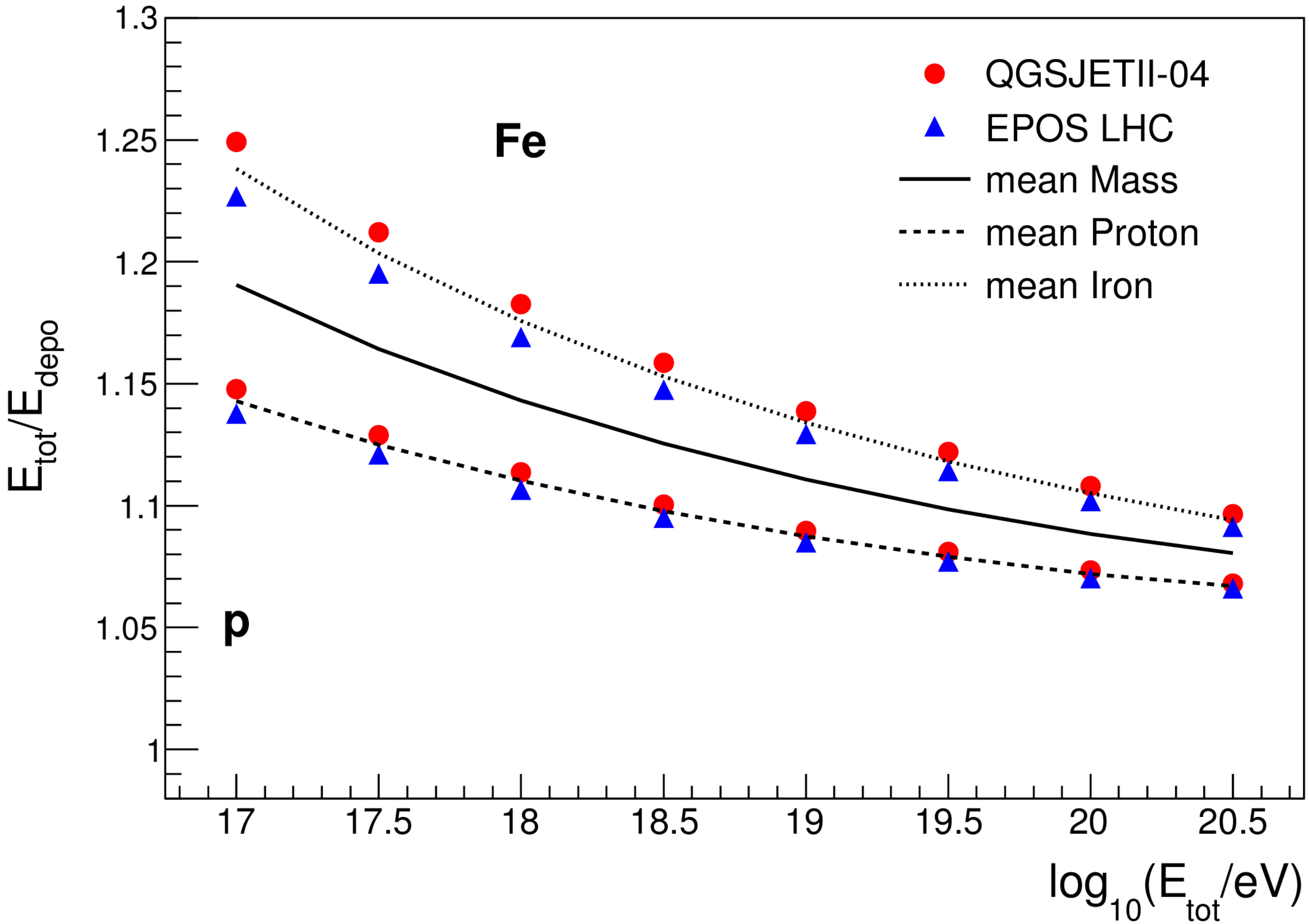
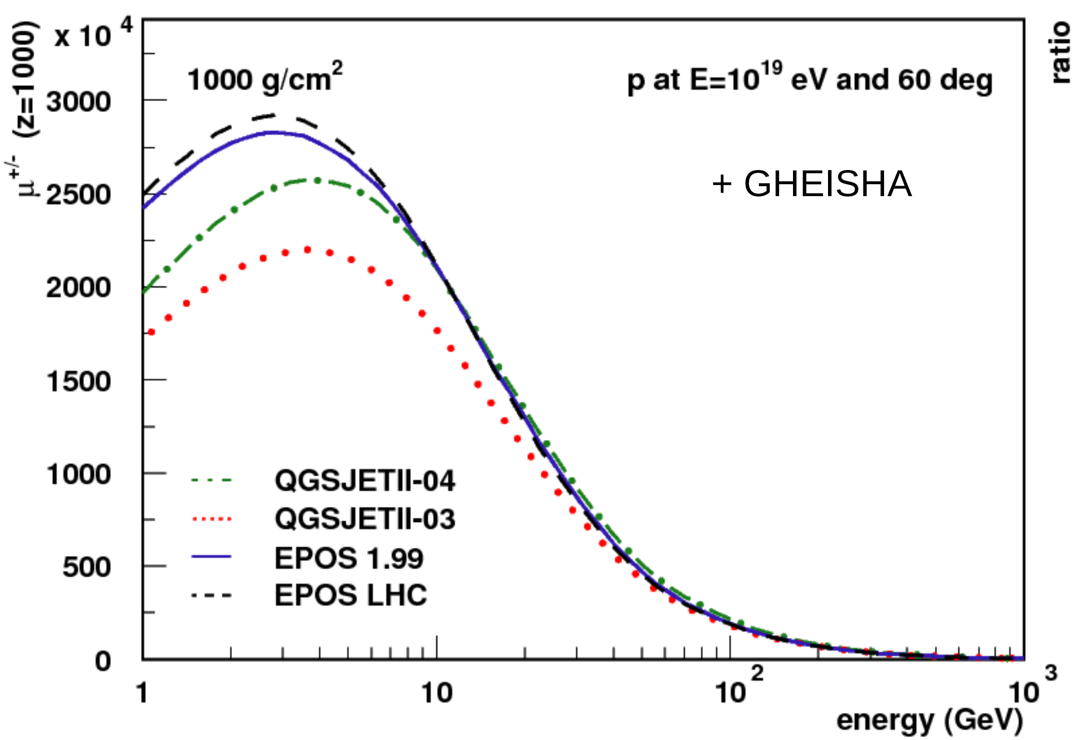
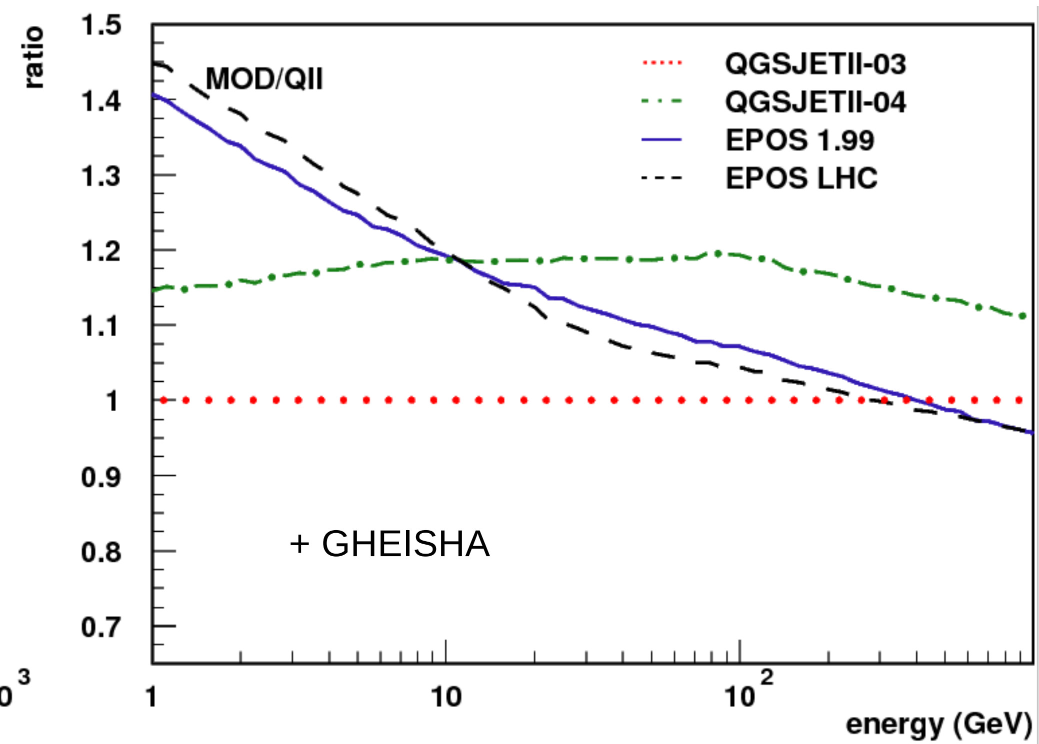


Muon Energy Spectra

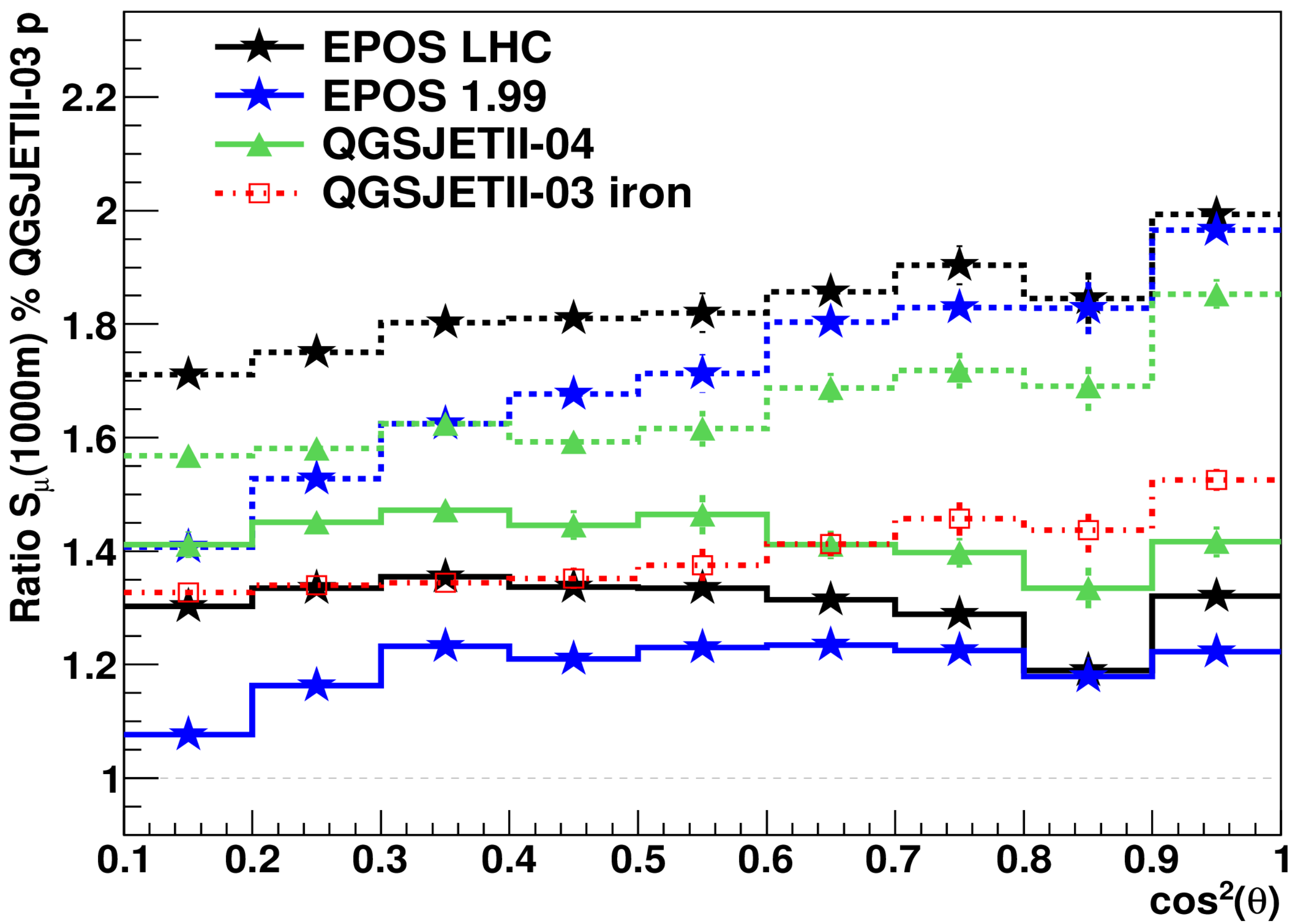
- **Total number of muons in QGSJETII-04 (@60°) closer to EPOS BUT**
  - ➡ muons with different energy (hadronic energy stored in mesons or baryons ?)
  - ➡ different zenith angle dependence (attenuation length depends on muon energy spectrum)
  - ➡ effect of low energy hadronic interaction models (Gheisha,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



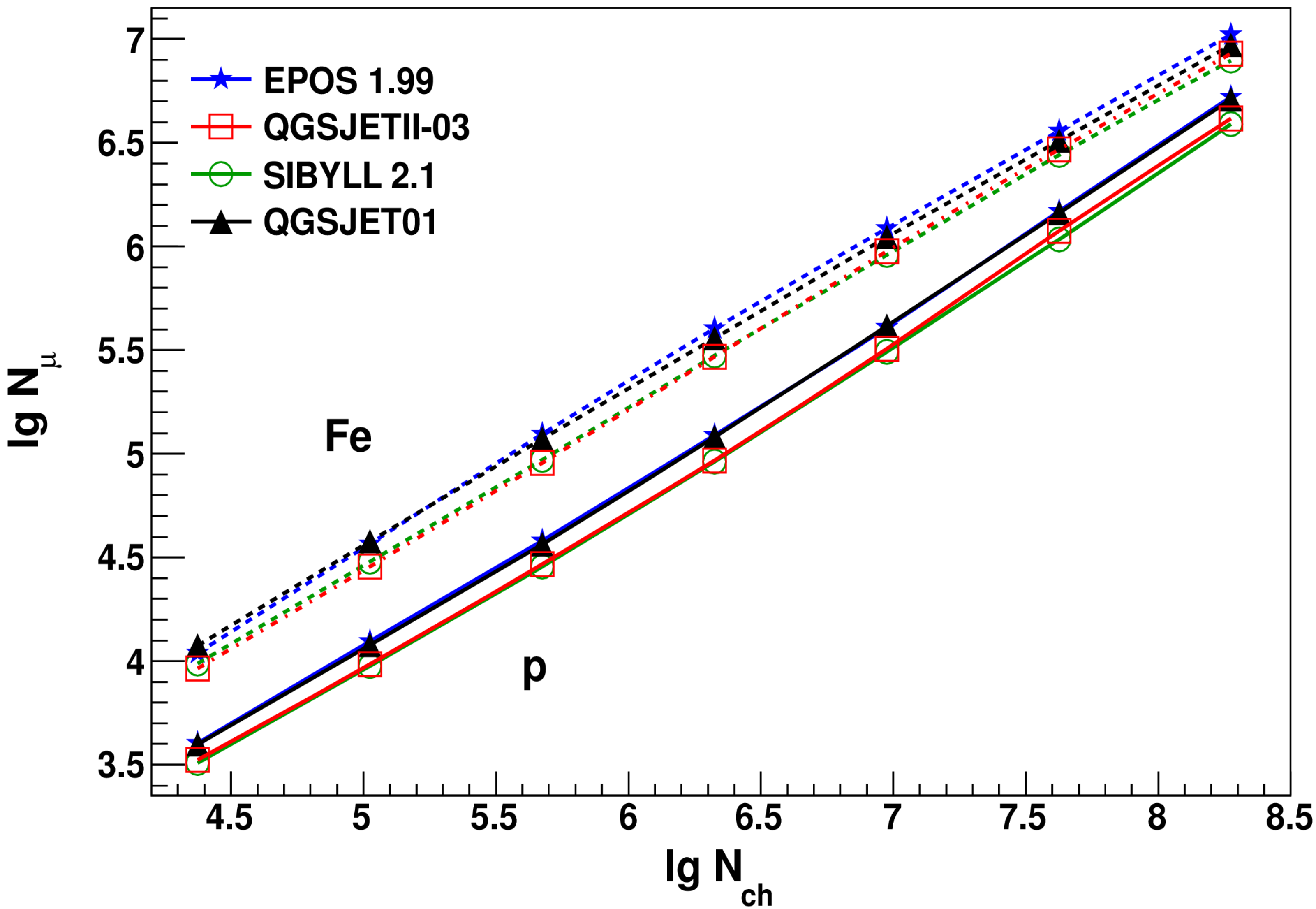


Muon Signal at 1000m for PAO

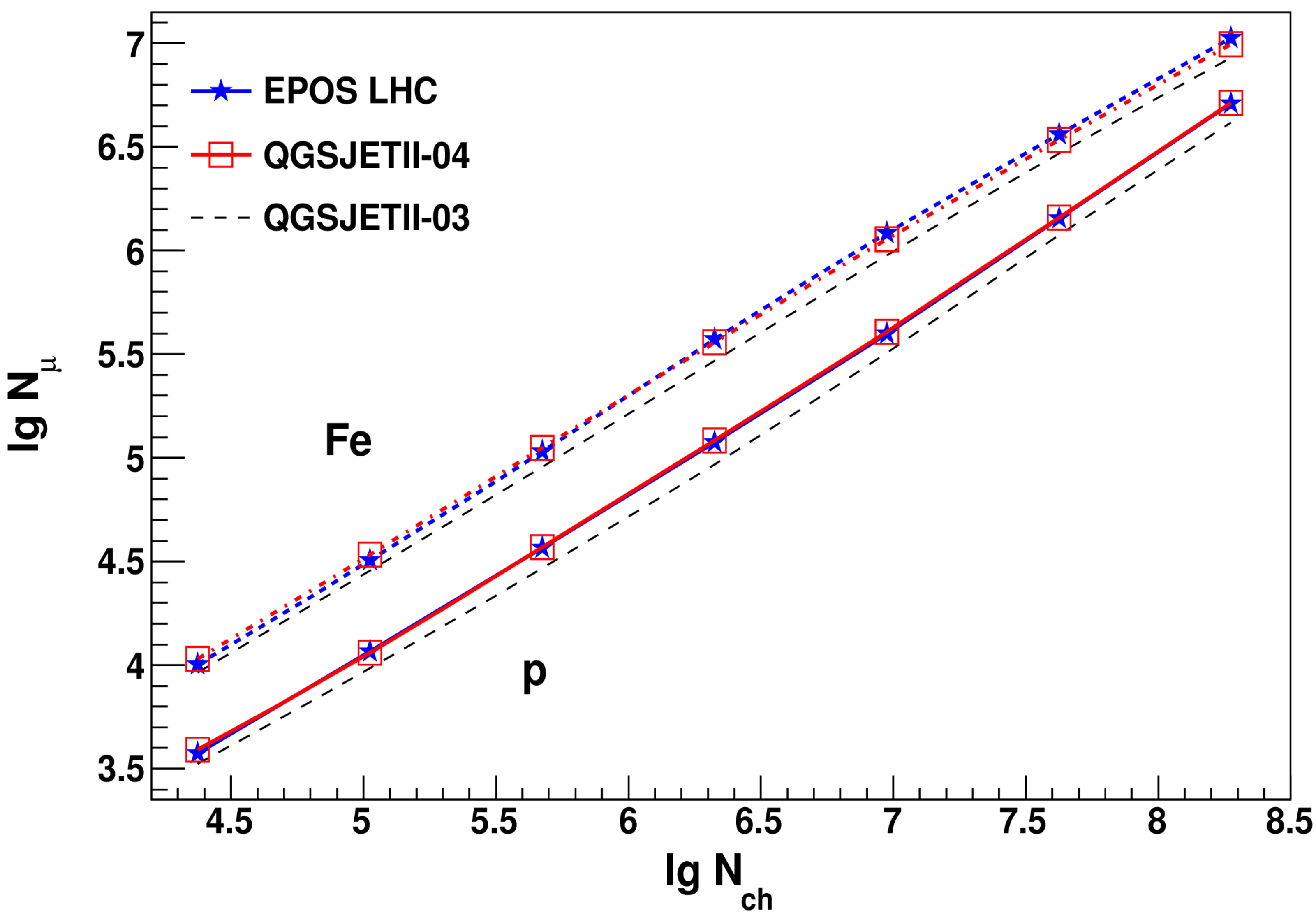
- **Different zenith angle dependence**
  - ➡ probably better description of muon number for PAO using heavy composition consistent with X_{max}



EAS with Re-tuned CR Models : Correlations



EAS with Re-tuned CR Models : Correlations



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