Modeling Hadronic Interactions in Cosmic Ray MC generators

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ISVHECRI 2014, CERN, Switzerland

August the 21th 2014

Outline

- **Hadronic interaction models for air showers**
- **Cross-section and Multiplicity**
  - ➨ air shower maximum
- **Particle spectra**
  - ➨ number of muons
- **Constraints from air showers**

LHC (accelerator) data : constrain hadronic models used for EAS simulations.

Cosmic ray (EAS) data : additional constraints on models leading to better predictive power.

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  - ➔ air shower maximum
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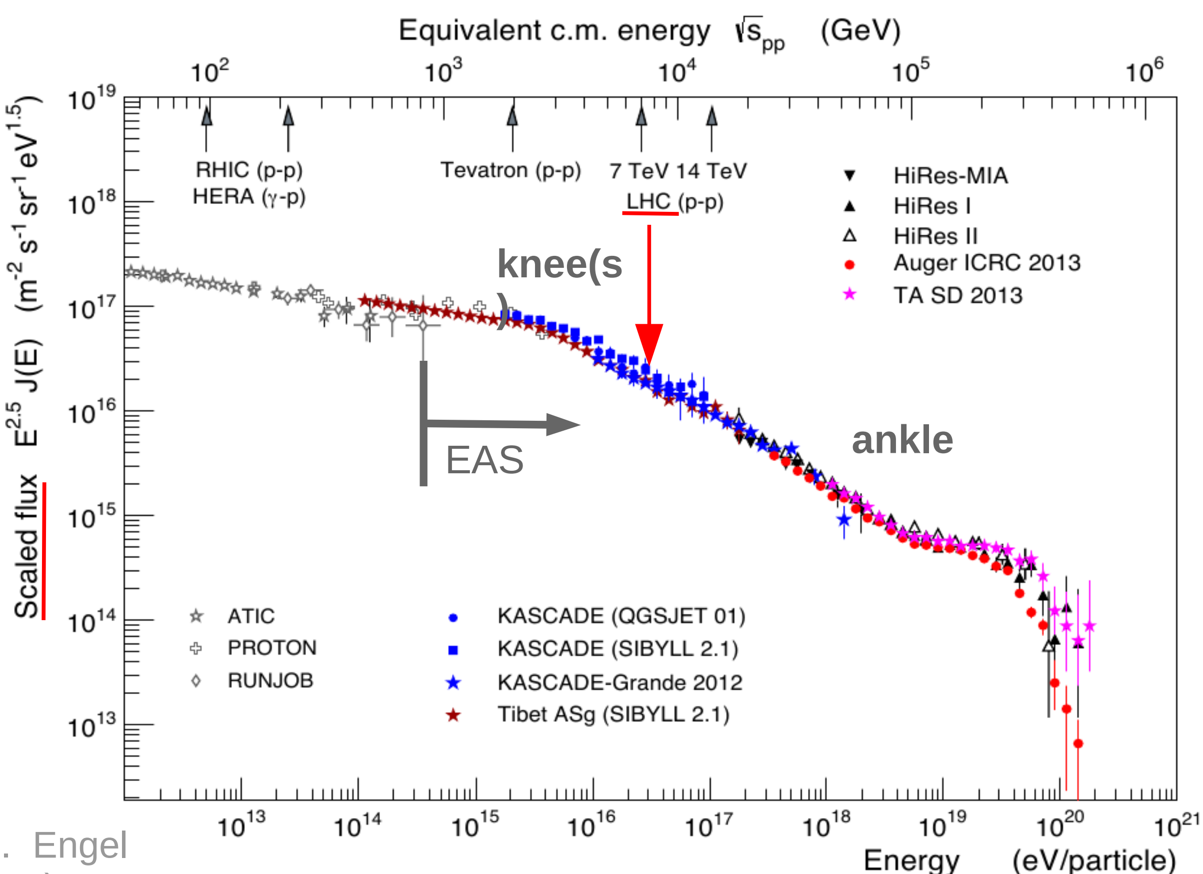
See R. Ulrich talk

<u>LHC (accelerator) data</u> : constrain hadronic models used for EAS simulations.

<u>Cosmic ray (EAS) data</u> : additional constraints on models leading to better predictive power.

Models for Air Shower Simulation



R. Engel (KIT)

- **Hadronic models for Simulations**
  - mainly soft (low p_t (< 2 GeV/c)) physics + diffraction (forward region)
  - should handle p-, π-Air, K-Air and A-Air interactions
  - should be able to run at 10^6 GeV center-of-mass (cms) energy
  - Single set of parameters
  - models used for EAS analysis :
    - QGSJET01/II
    - SIBYLL 2.1
    - EPOS
    - DPMJET, ...

Main source of uncertainties in EAS analysis !

Hadronic Interaction Models in CORSIKA

(HDPM)

Old generation : SIBYLL 2.1 (QGSJET01 DPMJET 2.55 VENUS) (<2001)

All Glauber based

Engel et al.

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-)

Ostapchenko

Pierog & Werner

LHC inspired : SIBYLL 2.3 QGSJET III EPOS 3 (2015-)

Motivation :

- update with latest LHC results in simple model

Motivation :

- Hard Pomeron-Pomeron connexion

Motivation :

- binary scaling in hard probes

Cosmic Ray Hadronic Interaction Models

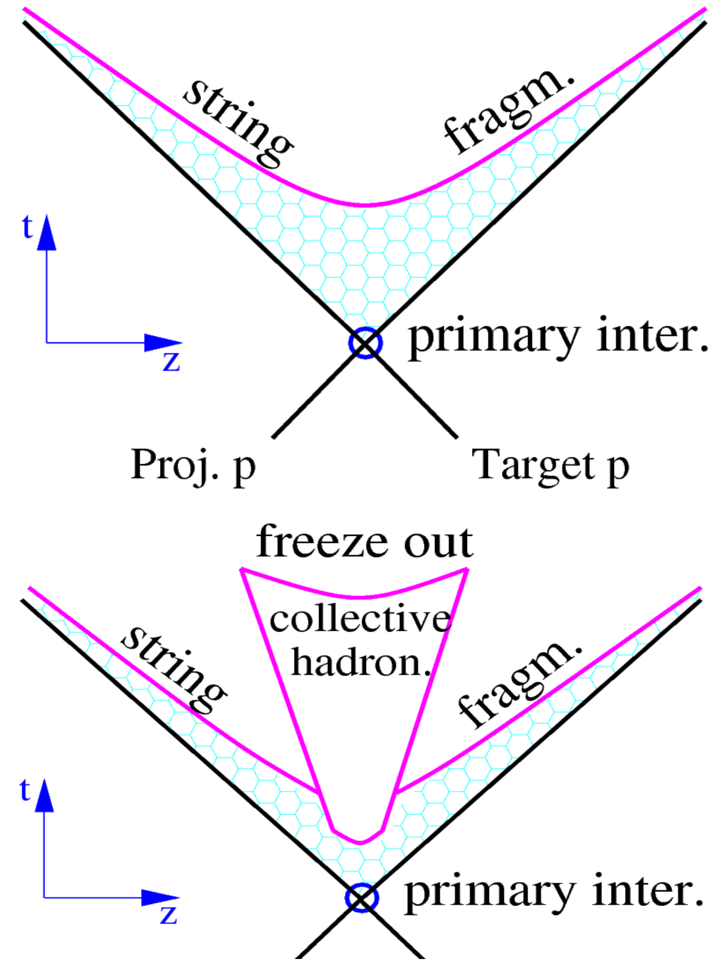
- **Theoretical basis :**
  - pQCD (large p_t)
  - Gribov-Regge (cross section with multiple scattering)
  - energy conservation
- **Phenomenology (models) :**
  - hadronization
    - string fragmentation
    - EPOS : high density effects (statistical hadronization and flow)
  - diffraction (Good-Walker, ...)
  - higher order effects (multi-Pomeron interactions)
  - remnants
- **Comparison with data to fix parameters**
  - one set of parameter for all systems/energies

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)**
- **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

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
- **Both models used in (some) LHC analysis**



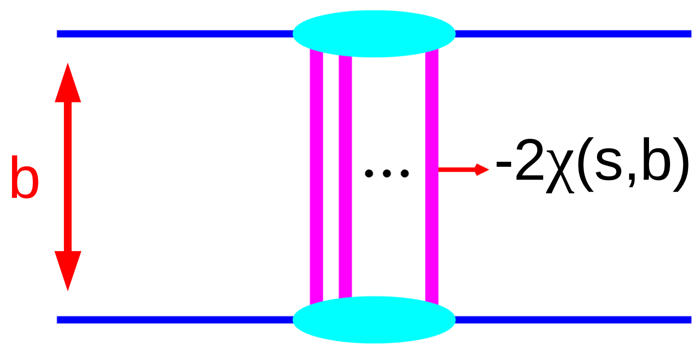
Direct influence of collective effects on EAS simulations has to be shown but important to compare to LHC and set parameters properly (<pt>, ...).

Cross Section Calculation : SIBYLL / QGSJET

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

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

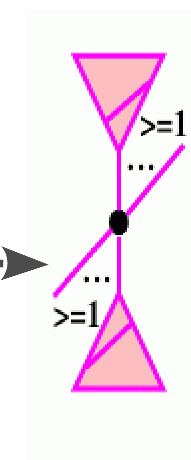
- elastic amplitude : $-2\chi(s,b)$
- sum n interactions : $\frac{(-2\chi)^n}{n!} \rightarrow \exp(-2\chi)$
  - optical theorem :



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

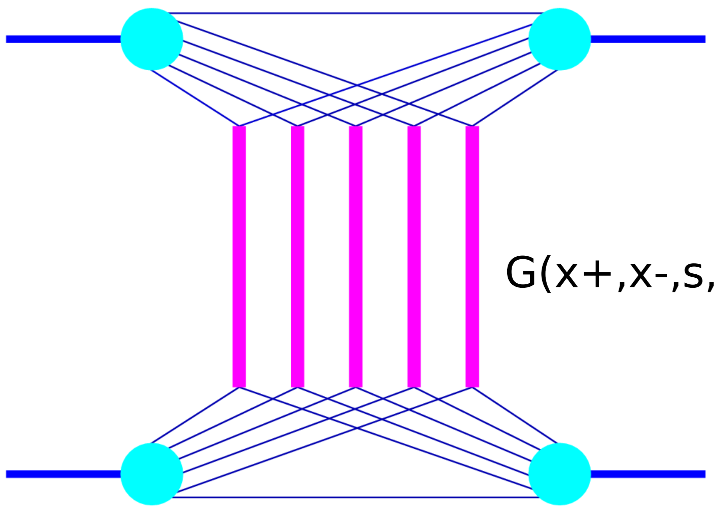
Not the same χ in QGSJET01, QGSJETII and SIBYLL

- $\chi(s,b)$ parameters for a given model fixed by pp cross-section
  - SIBYLL: pQCD mini-jet with energy dependent cut-off
  - QGSJETII: pQCD + infinite re-summation of (soft) triple Pomeron coupling



- 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

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

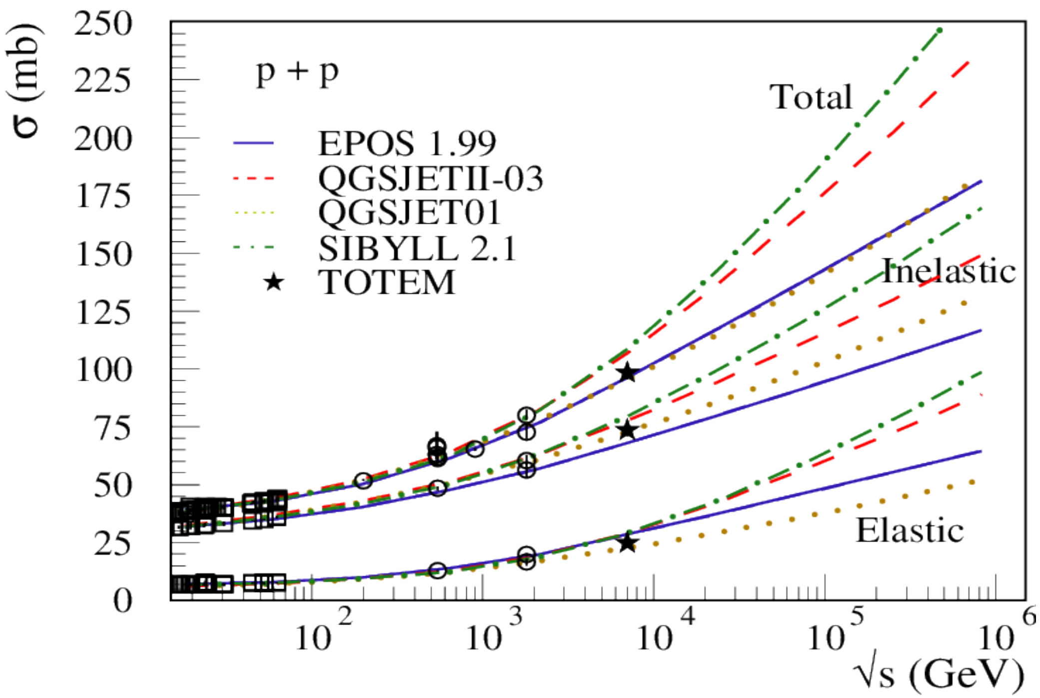
$$\sigma_{\rm ine}(s) \;=\; \int d^2b\,(1-\Phi_{\rm pp}(1,1,s,b))$$

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

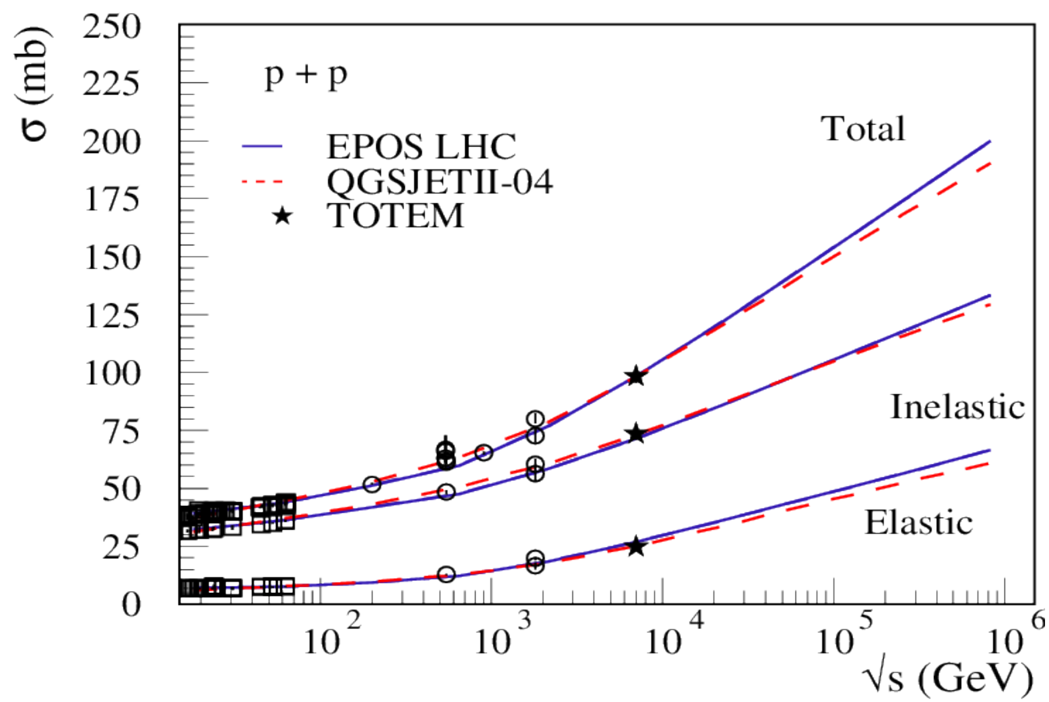
Cross Sections

- 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



Particle Production in SIBYLL and QGSJET

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

- n from (Poisson distribution):

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

  - 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 :

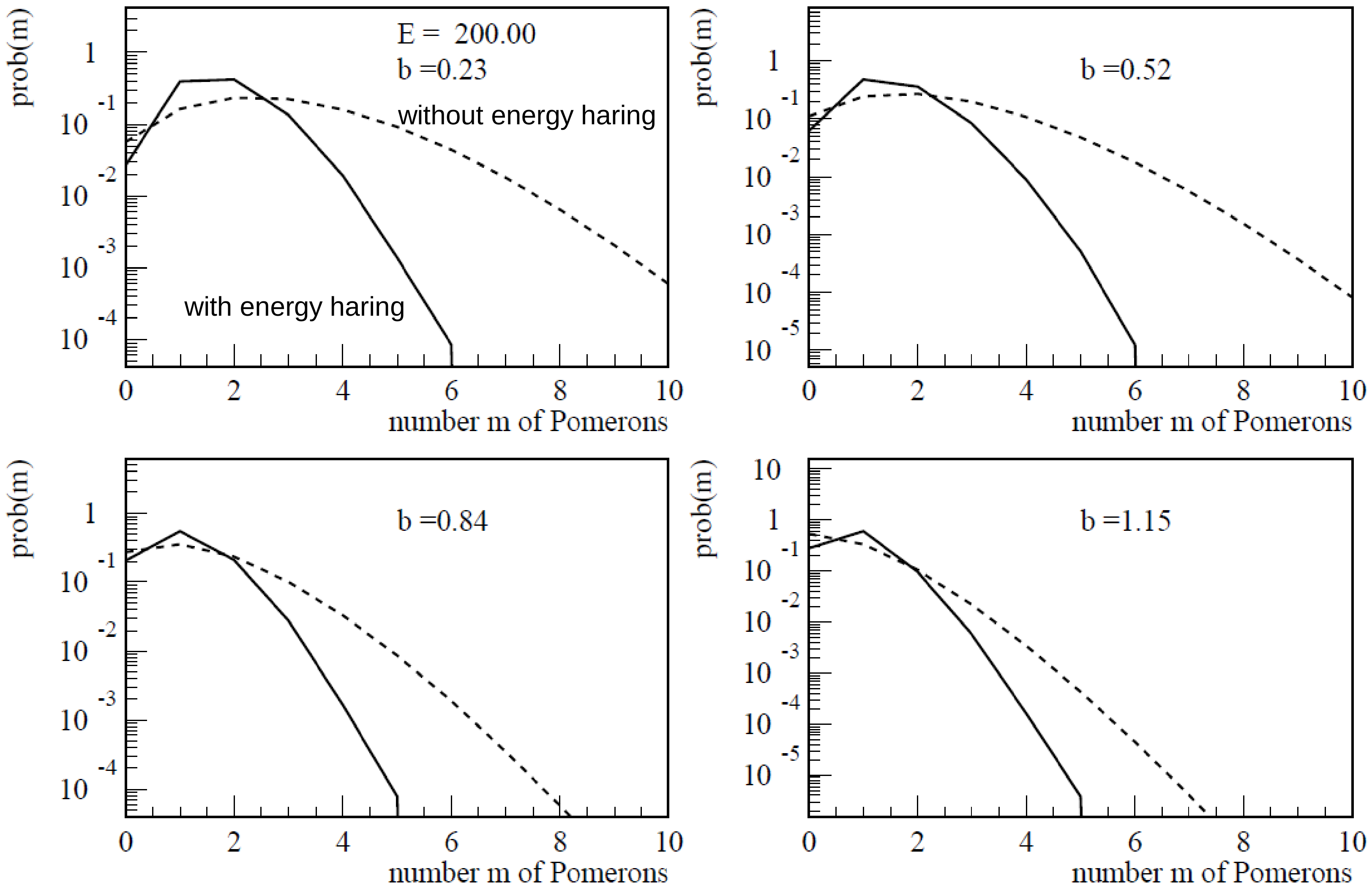
- m from :

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

  - m and X fixed together by a complex Metropolis (Markov Chain)
- $2\mathrm{m}$ strings formed from the m elementary interactions
  - energy conservation : energy fraction of the $2\mathrm{m}$ 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)

Number of cut Pomerons

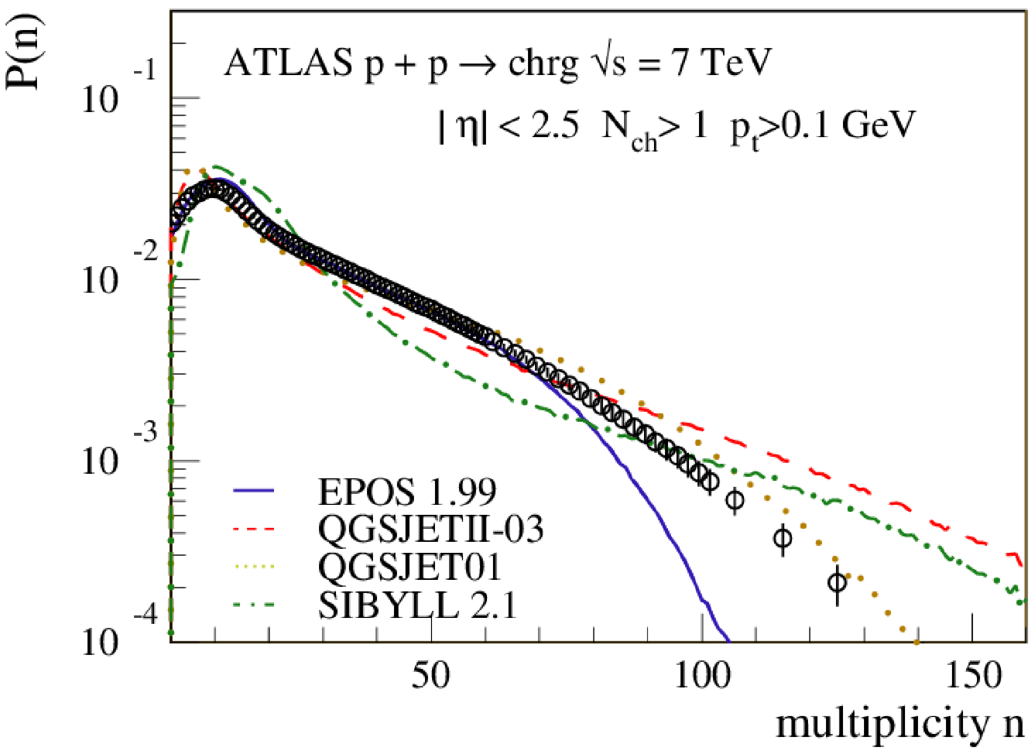
Fluctuations reduced by energy sharing (mean can be changed by parameters)



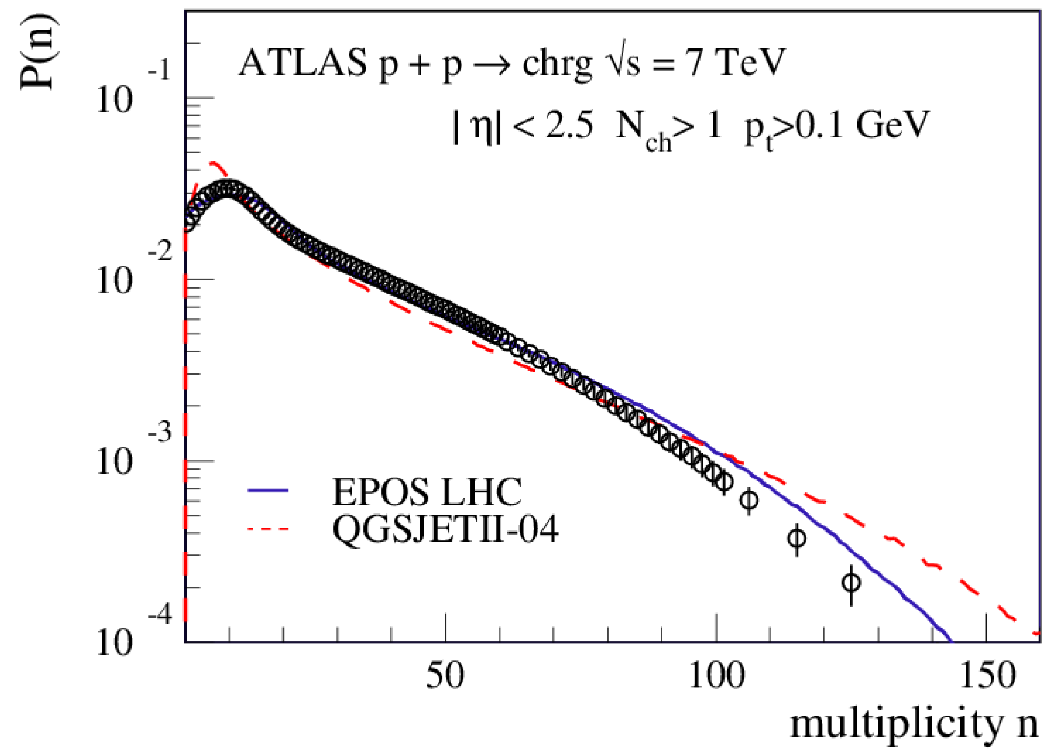
Multiplicity

- **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

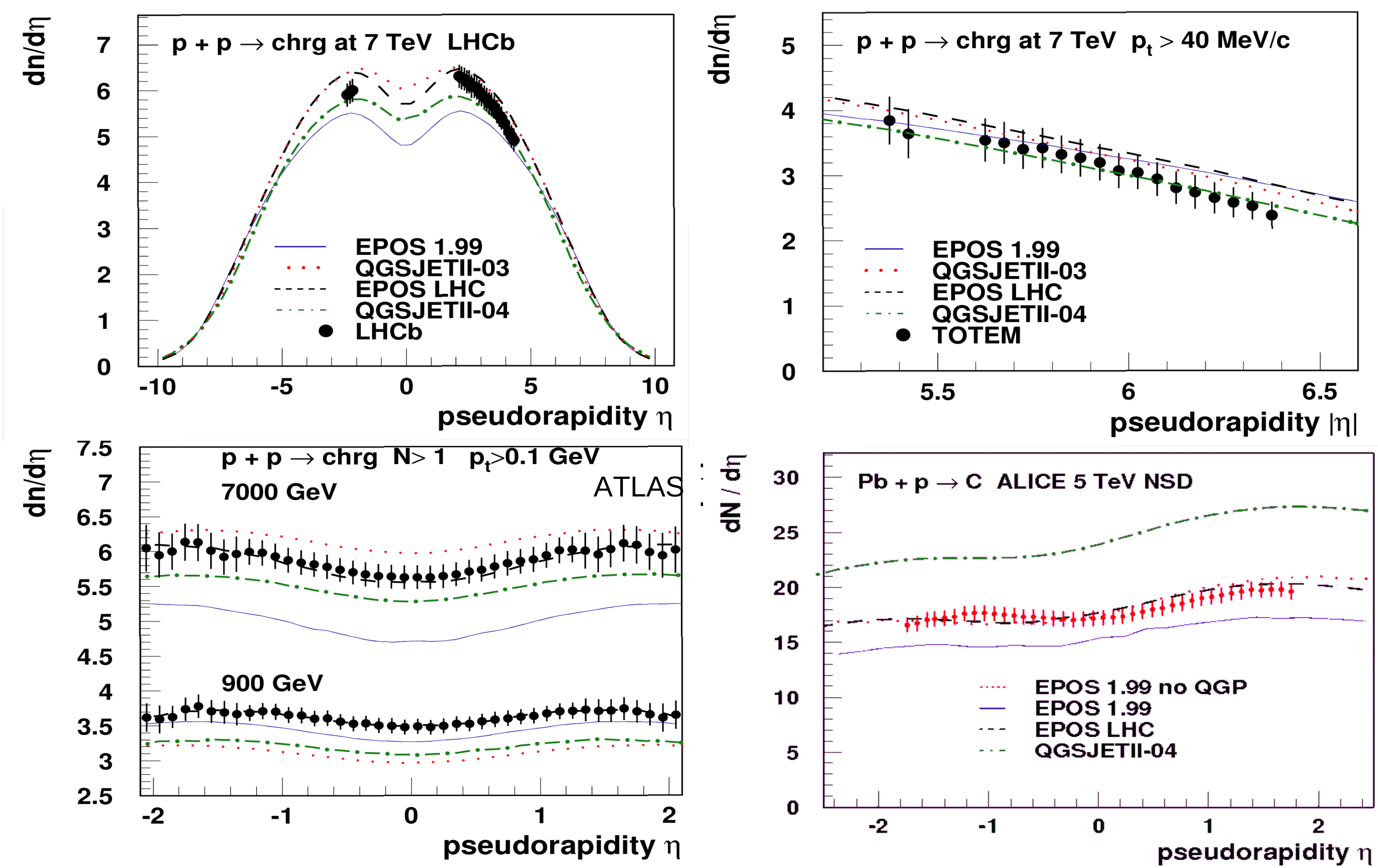


Post - LHC

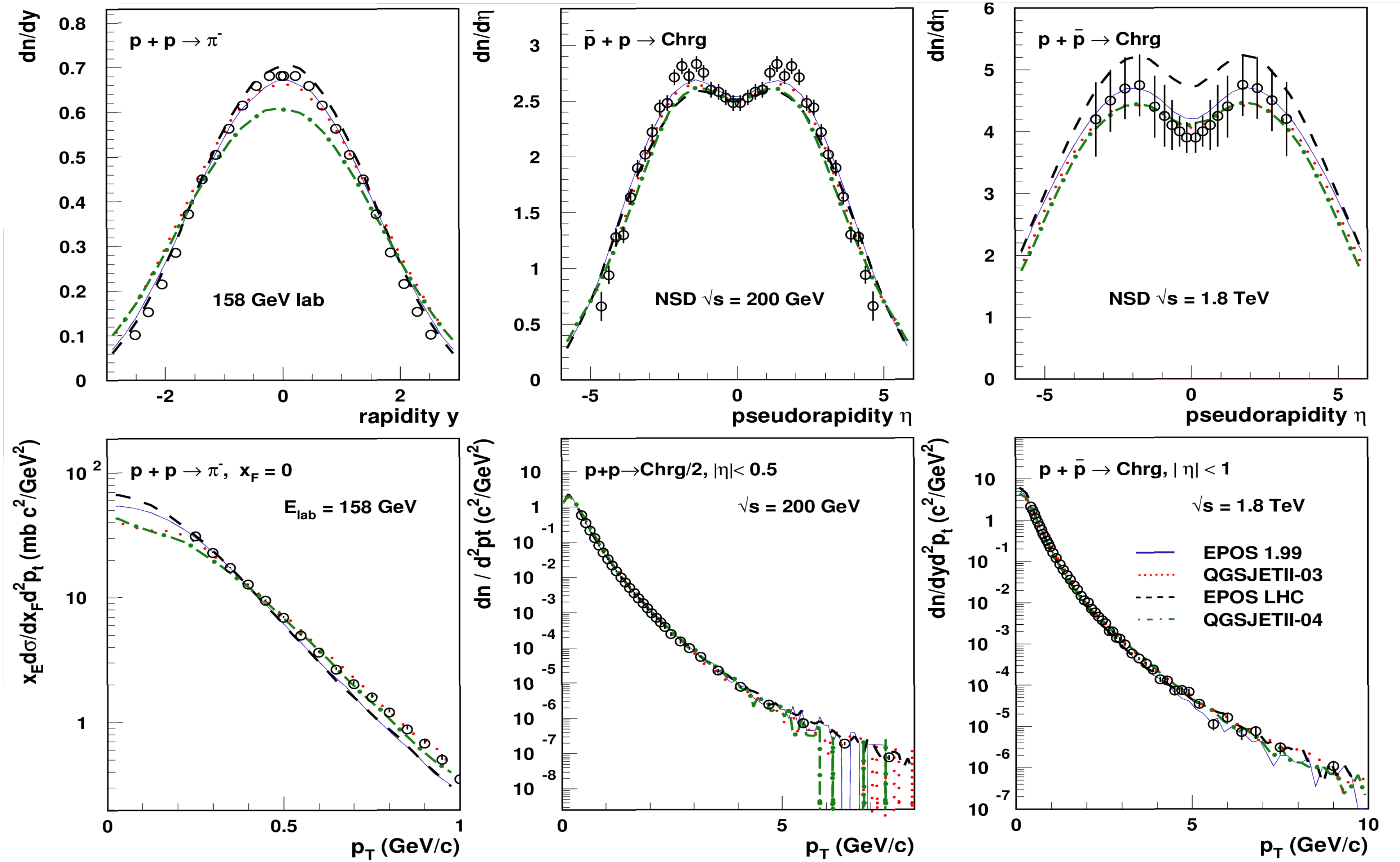


Pseudorapidity Distributions

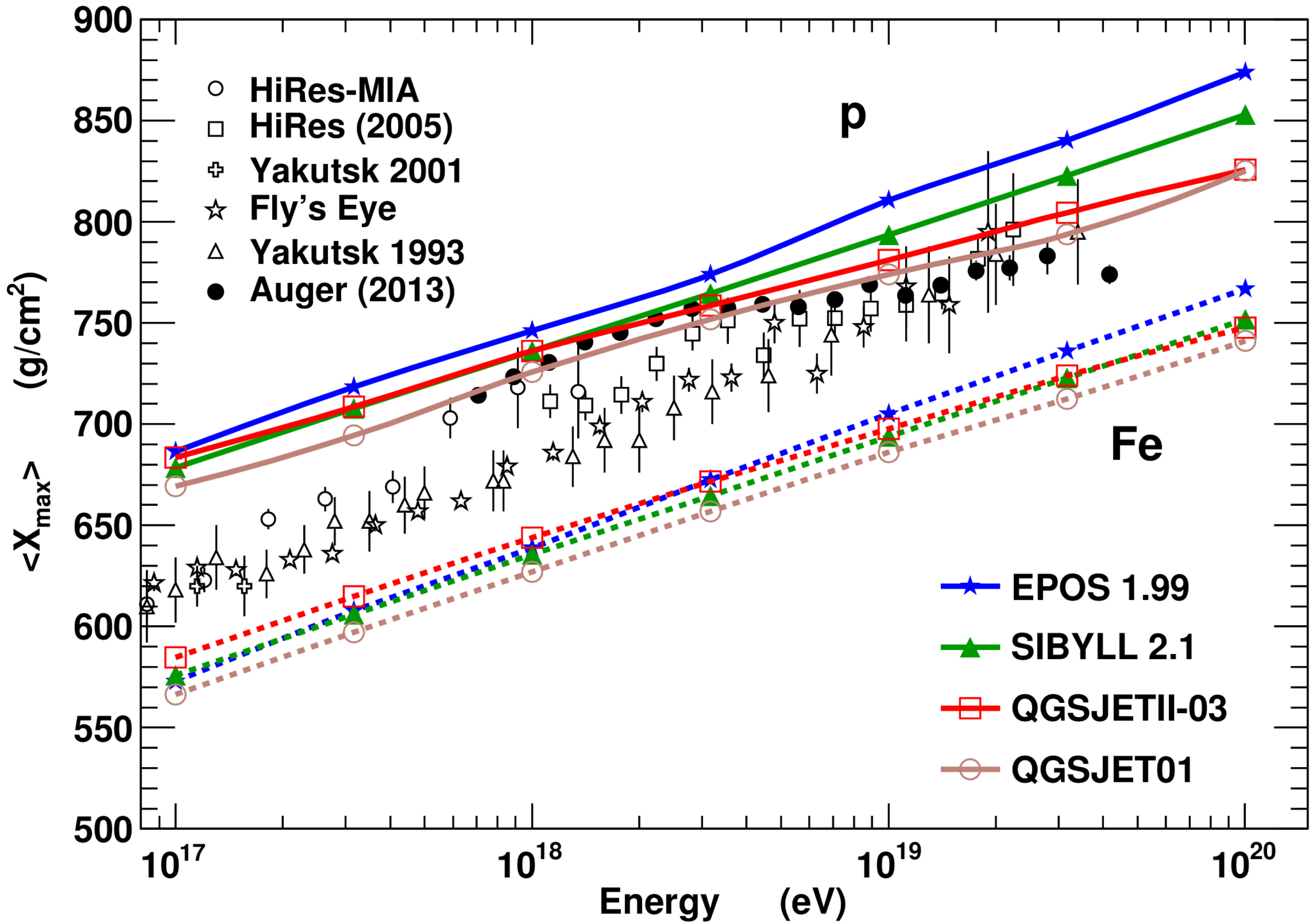
- Nice agreement for new models



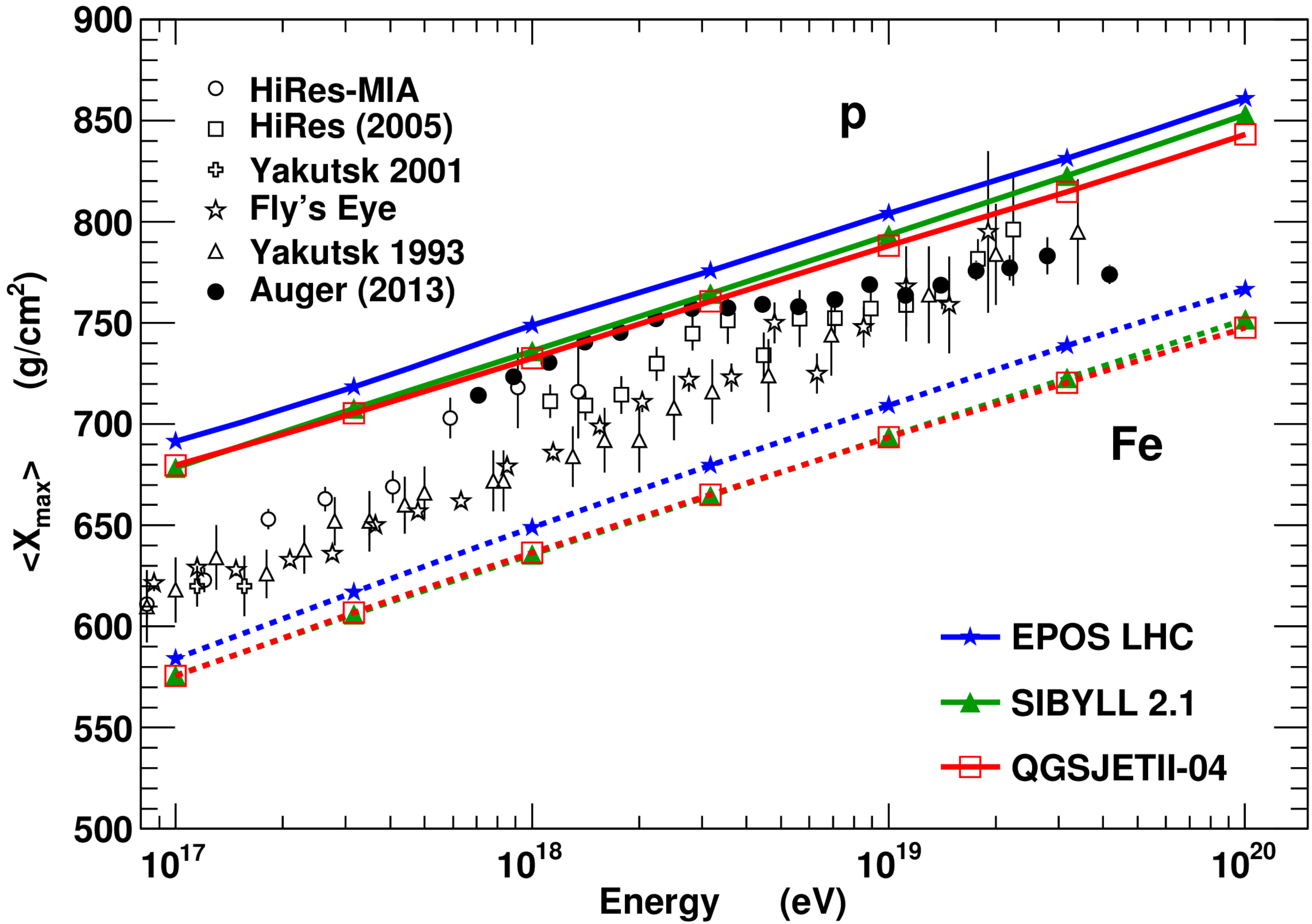
Low Energy Data



EAS with Old CR Models : X_{max}

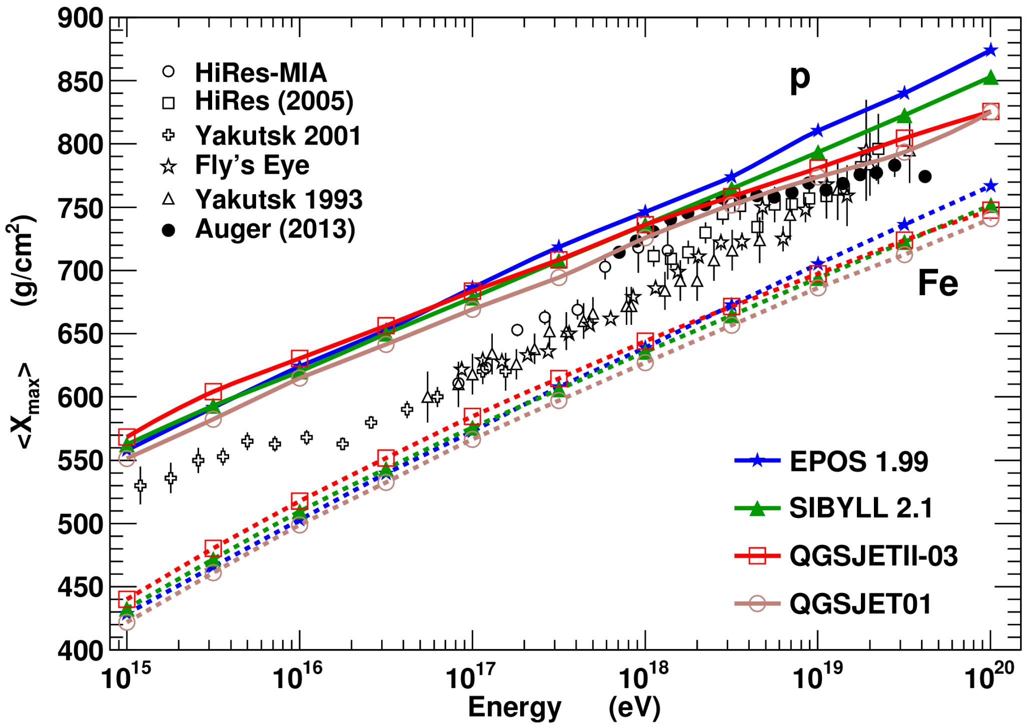


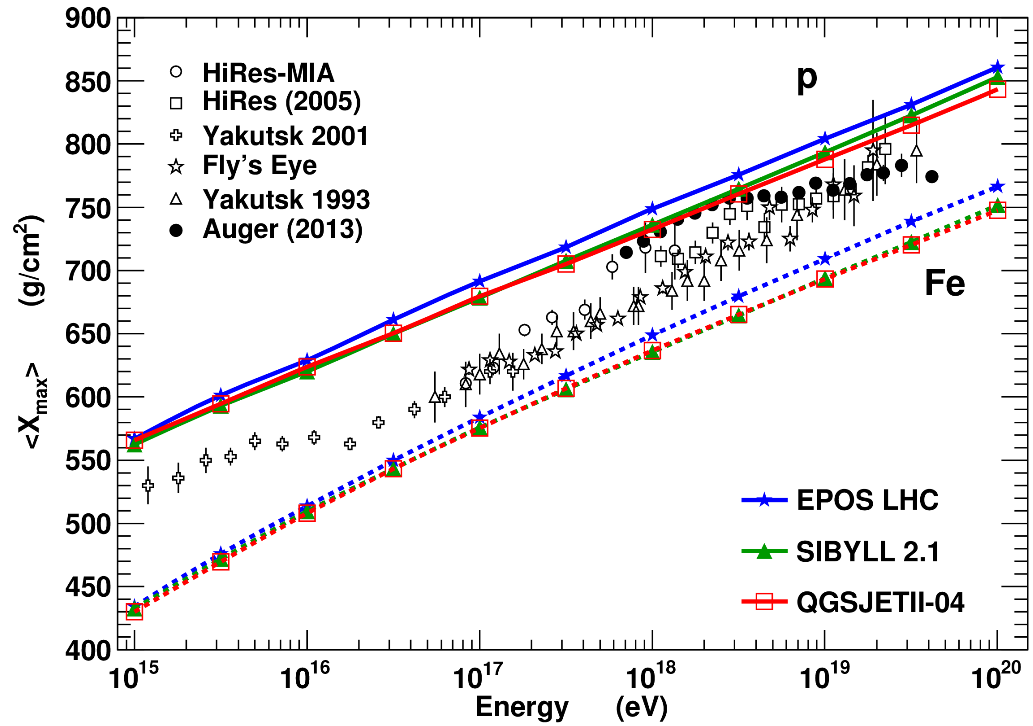
EAS with Re-tuned CR Models : X_{max}



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

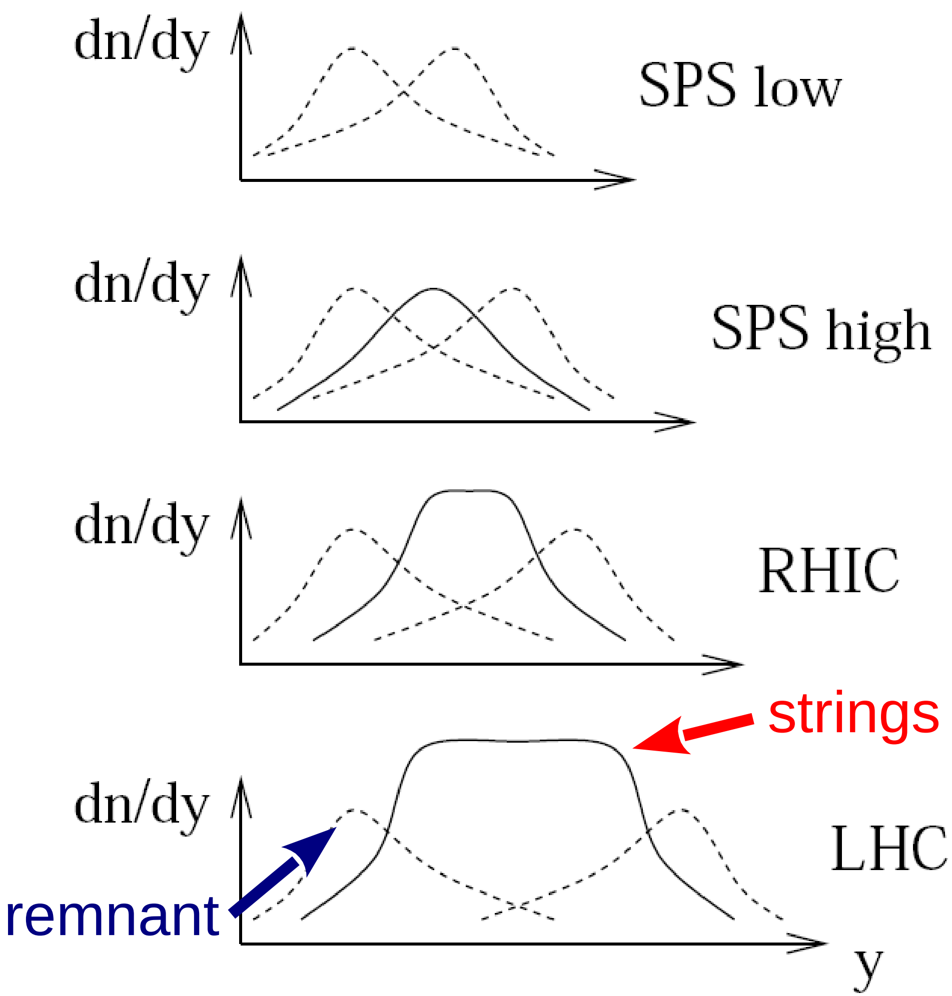
- **Cross section and multiplicity fixed at 7 TeV**
  - ➡ smaller slope for EPOS and larger for QGSJETII
  - ➡ re-tuned model converge to old Sibyll 2.1 predictions
    - ◆ reduced uncertainty from ~50 g/cm² to ~20 g/cm² (difference proton/iron is about 100 g/cm²)





Particle Spectra

Forward particles mainly from projectile remnant

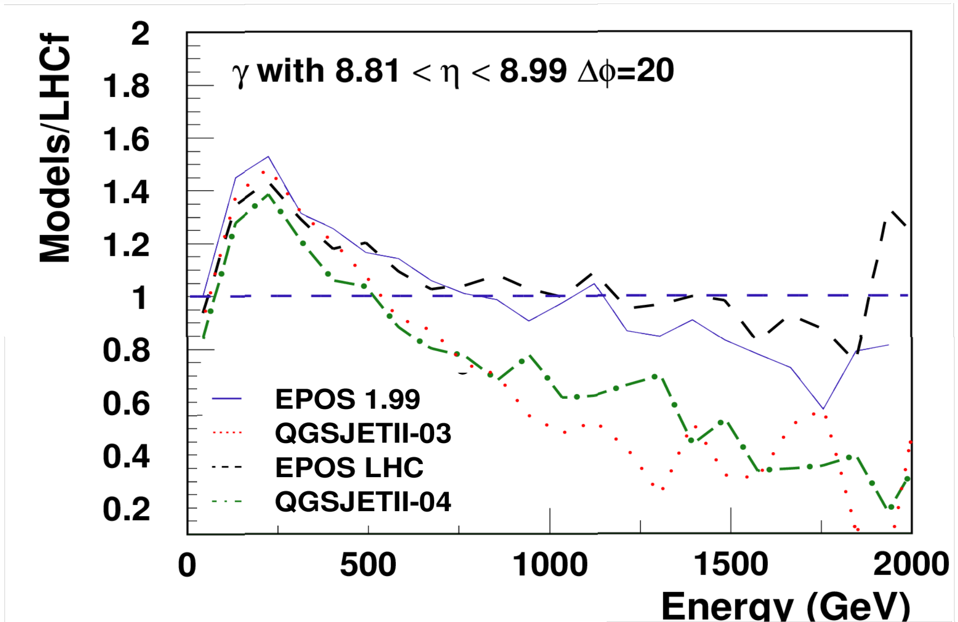


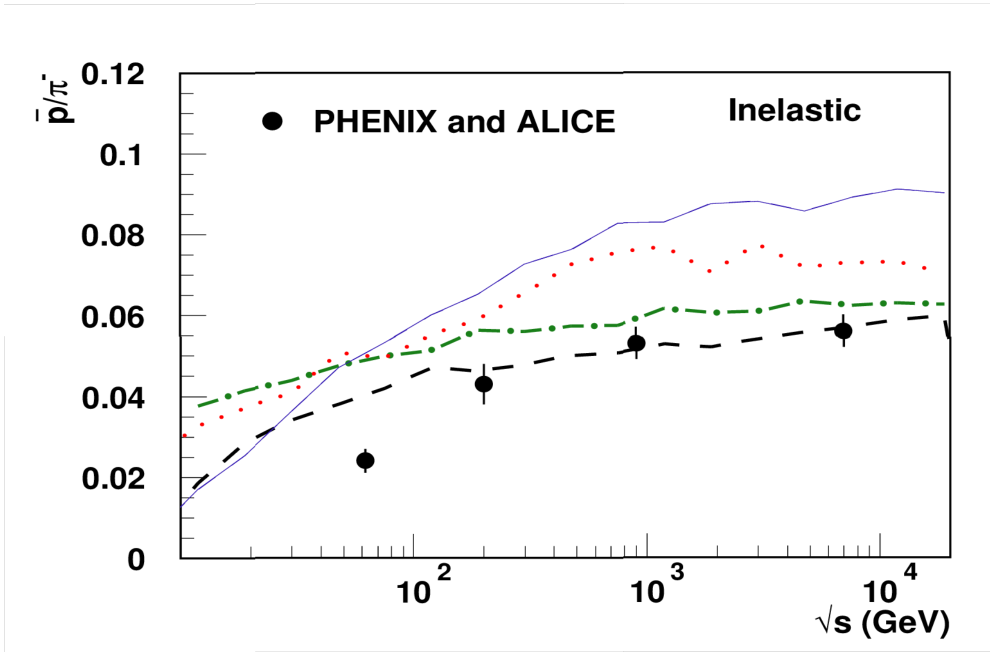
Particle production from string (mini-jets) and remnants:

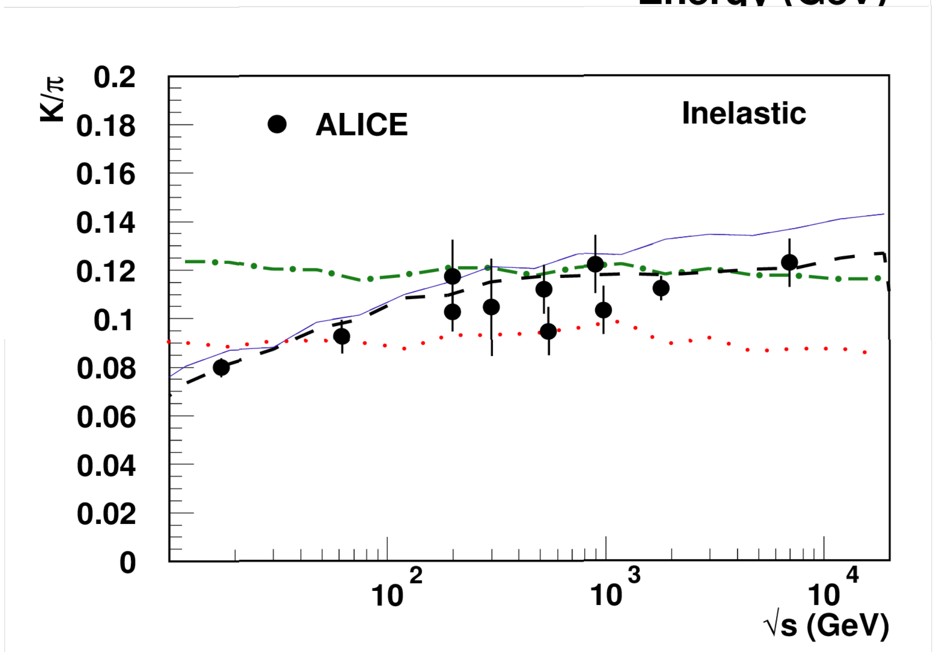
- SIBYLL
  - No remnant except for diffraction
  - Leading particle from string ends
  - Lund string fragmentation
- QGSJET
  - Low mass remnants
  - Leading particle similar to proj.
  - Simplified string fragmentation
- EPOS
  - Low and high mass remnants
  - Any type of leading particle (from resonance, string, cluster)
  - Corona: string fragm. from area law
  - Core: micro-canonical decay+flow

Identified particles

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

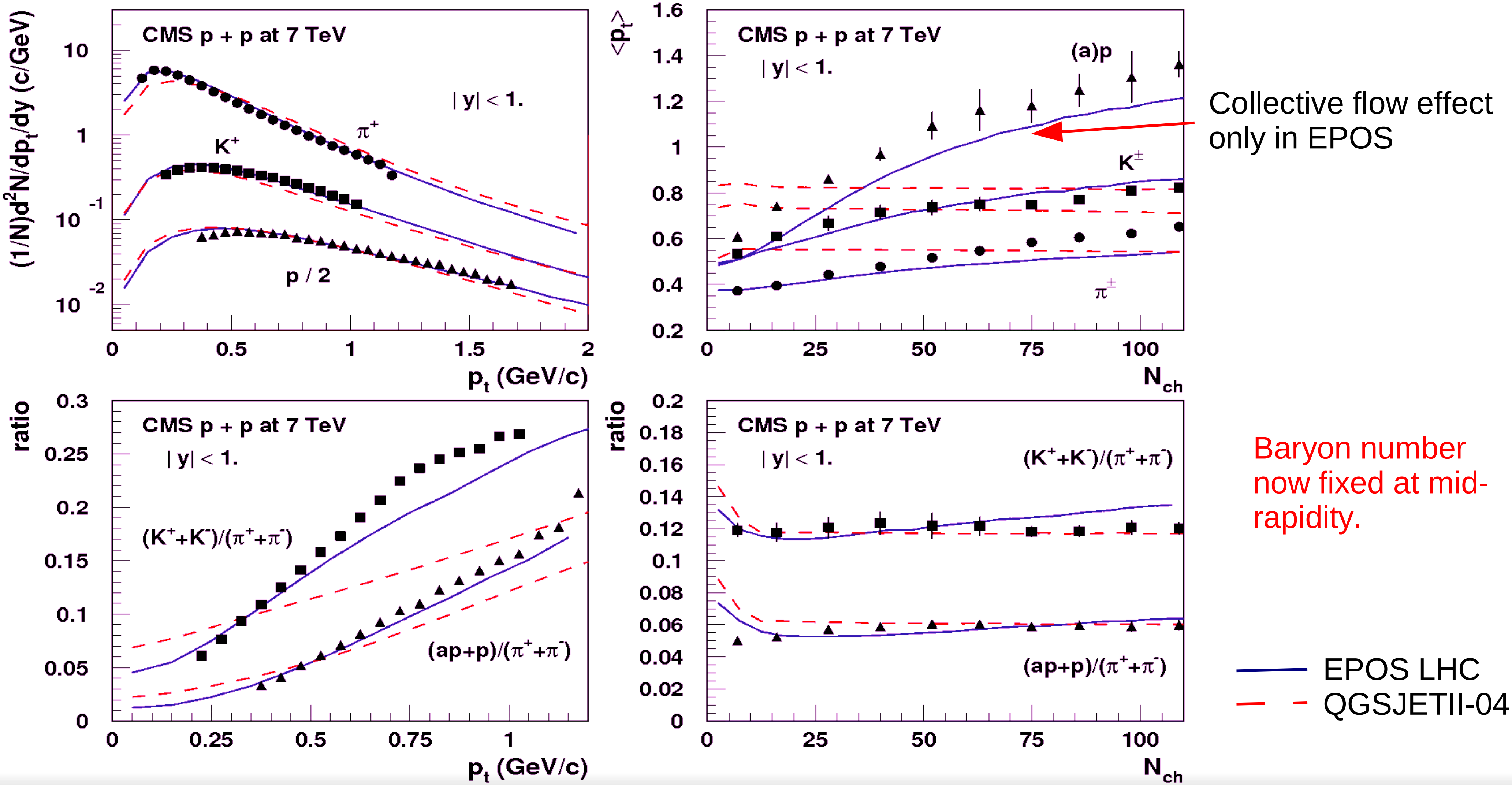






Identified Particle Spectra

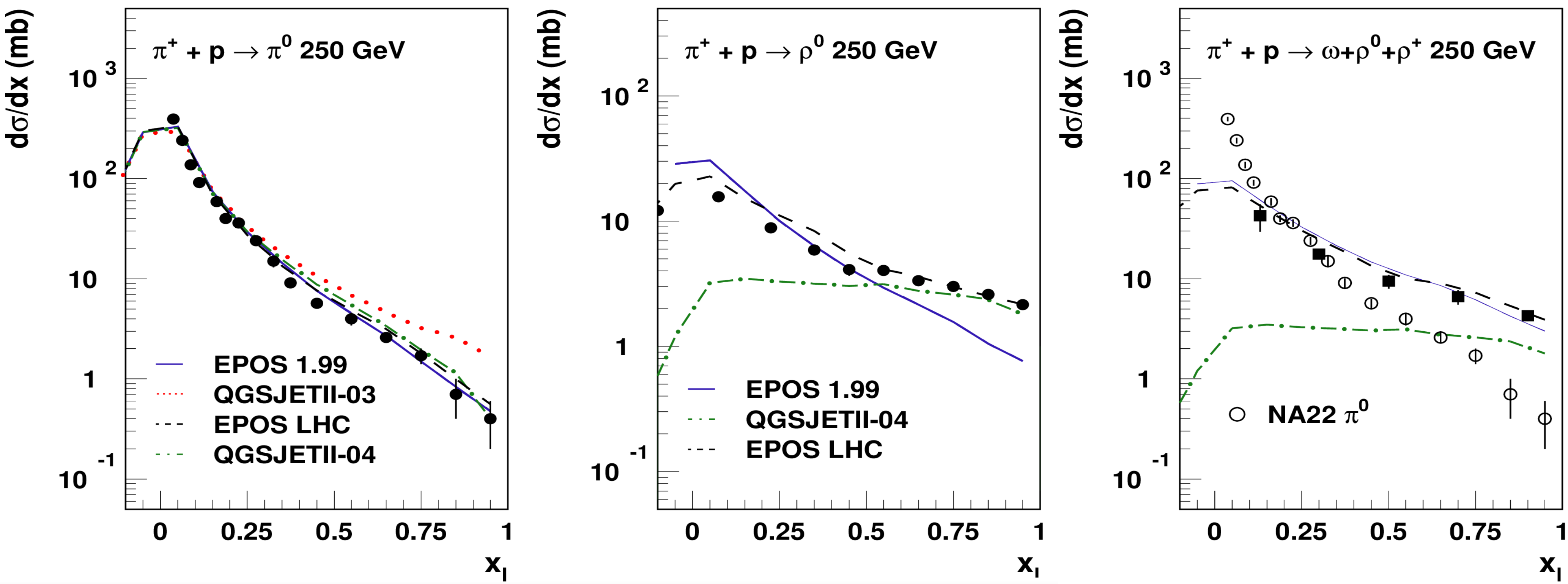
- **Detailed description can be achieved**
  - identified spectra
  - p_t behavior driven by collective effects (in EPOS statistical hadronization + flow)



Pion Leading Particle Effect

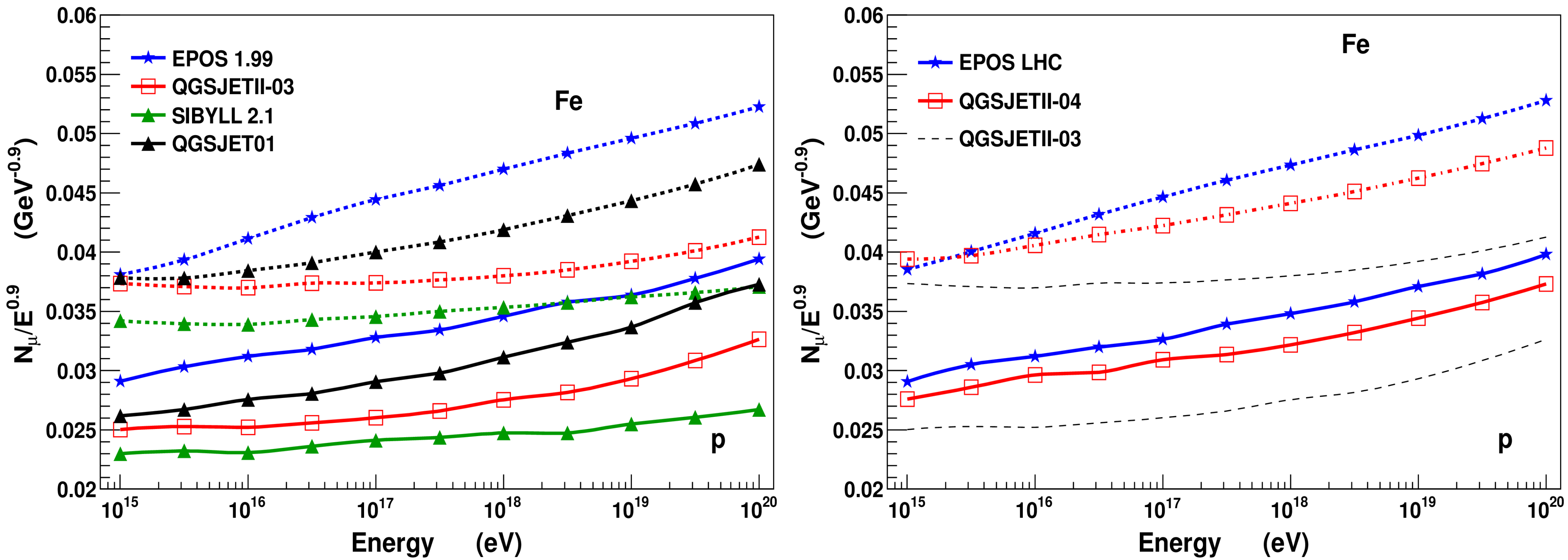
- **Rho meson production added in QGSJETII to take into account leading particle effect in pion-Air interaction**
  - same effect as baryon production : forward π^0 replaced by charged pions (reduced leading π^0)
  - increase muon production

Not only Rho0 should be taken into account !



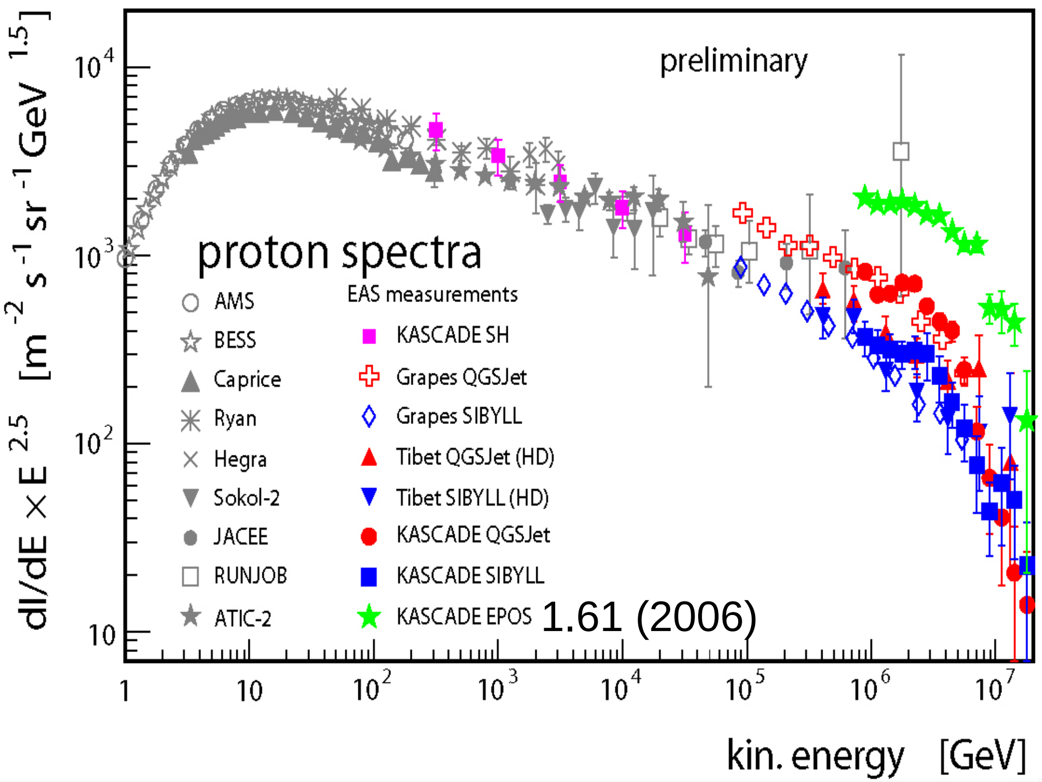
EAS with Re-tuned CR Models : Muons

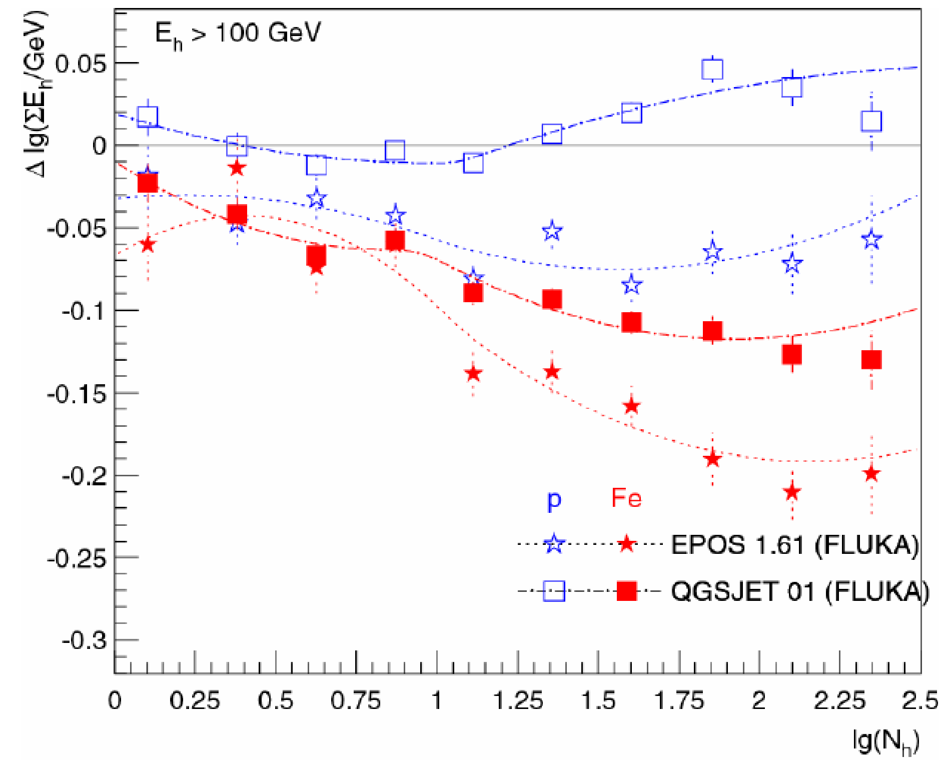
- **Effect of LHC hidden by other changes**
  - Corrections at mid-rapidity only for EPOS
  - Changes in QGSJET motivated by pion induced data
  - EPOS LHC ~ EPOS 1.99 and only -7% for QGSJETII-04



EAS constraints on Models

- **A model used for EAS simulation can be highly constrain from low energy data**
  - predicted mass between p and Fe
    - at low energy link with direct measurements
  - KASCADE measured correlations between hadrons, electrons and muons
    - hard test for all models (but no man power to study new models ...)





Muon Production Depth

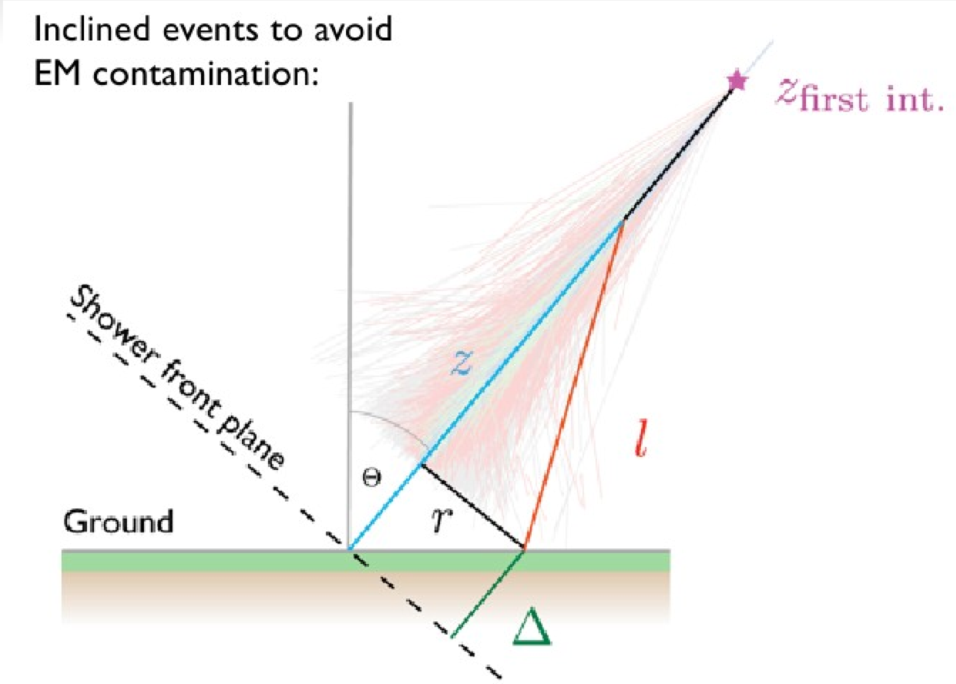
- **Independent SD mass composition measurement**
  - ➡ geometric delay of arriving muons

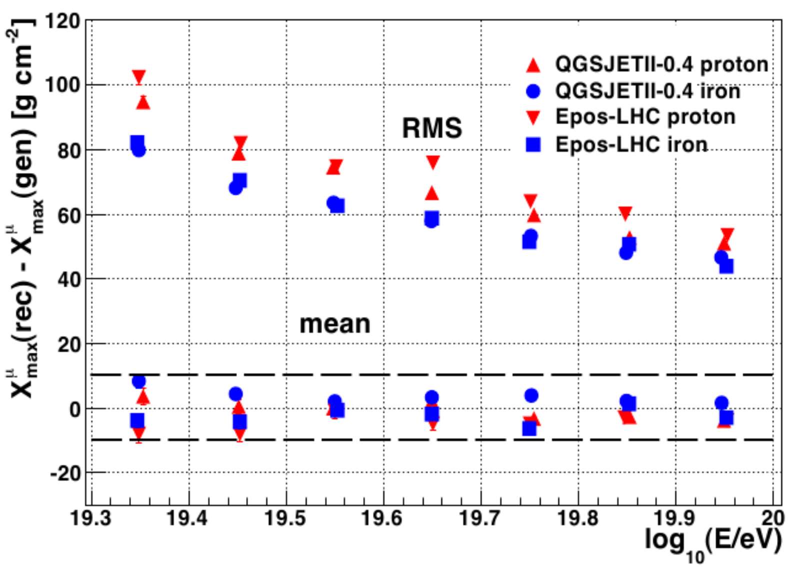
$$c \cdot t_g = l - (z - \Delta) = \sqrt{r^2 + (z-\Delta)^2} - (z - \Delta)$$

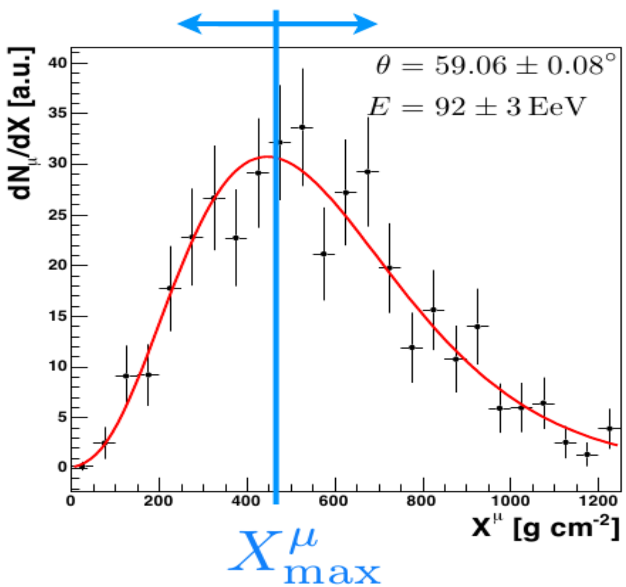
  - ➡ mapped to muon production distance

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

  - ➡ decent resolution and no bias

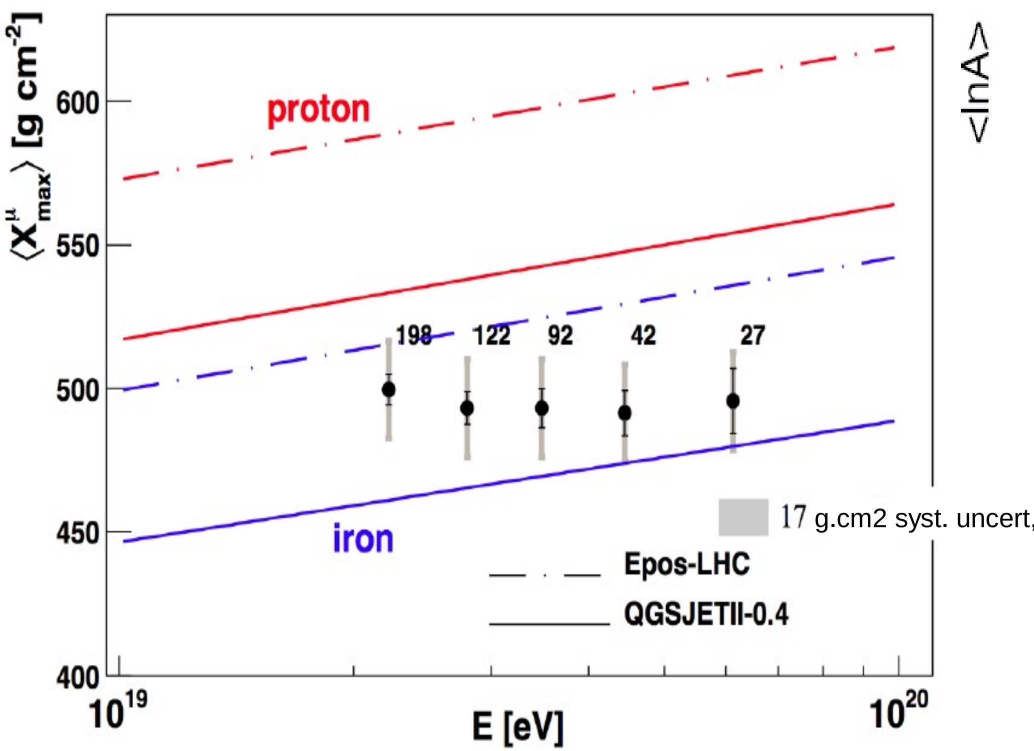


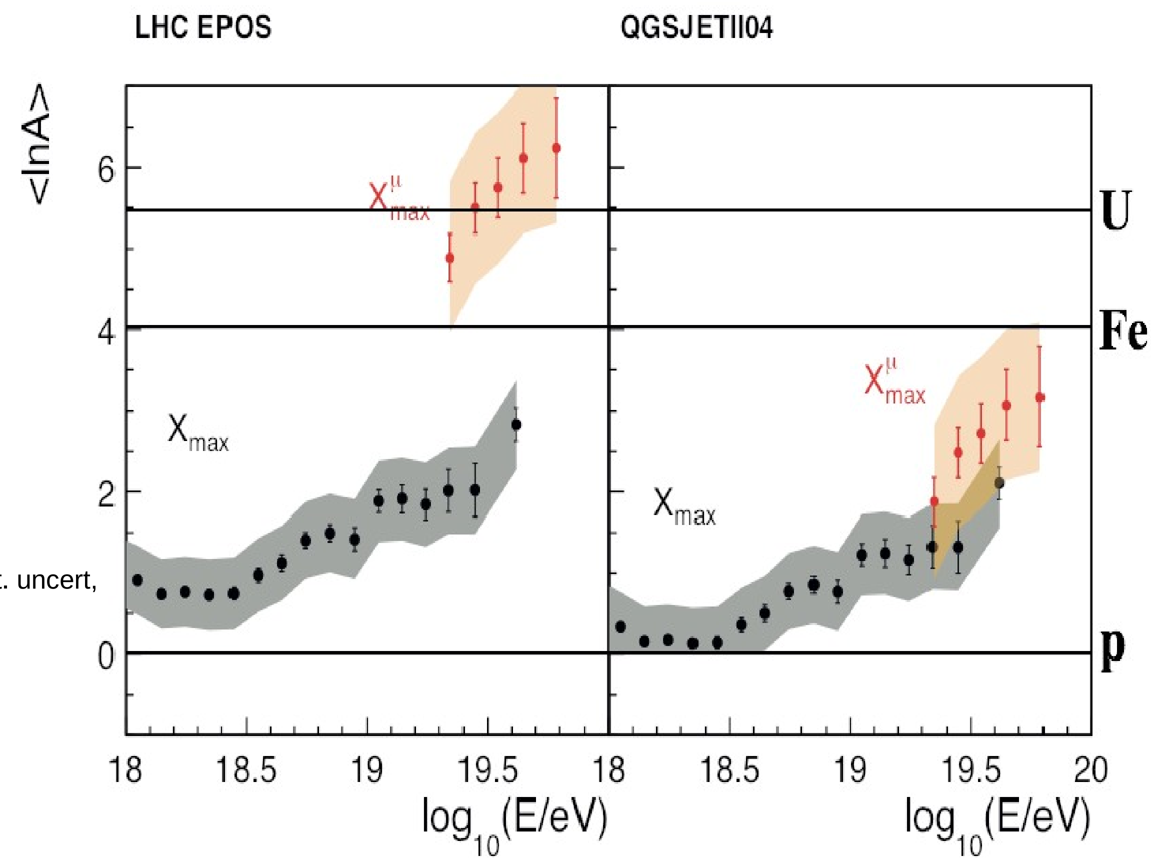




MPD and Models

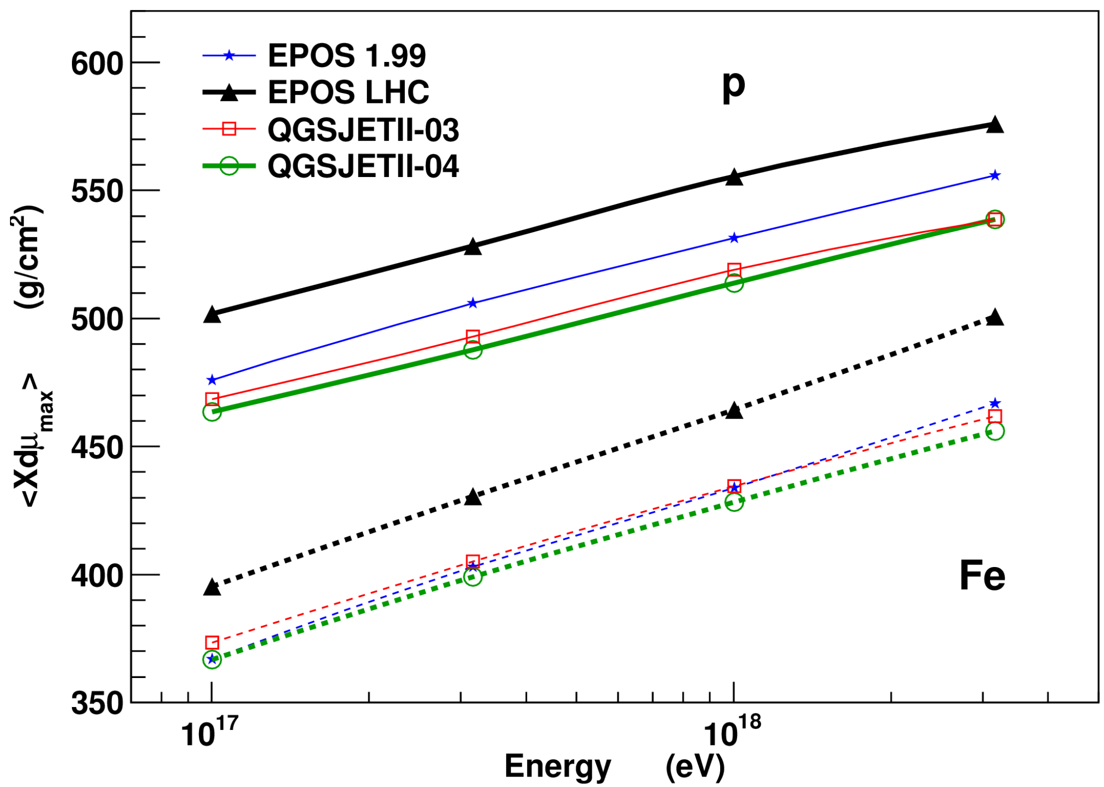
- **2 independent mass composition measurements**
  - both results should be between p and Fe
  - both results should give the same mean logarithmic mass for the same model
  - problem with EPOS appears after corrections motivated by LHC data
    - lower diffractive mass motivated by rapidity gap cross-section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

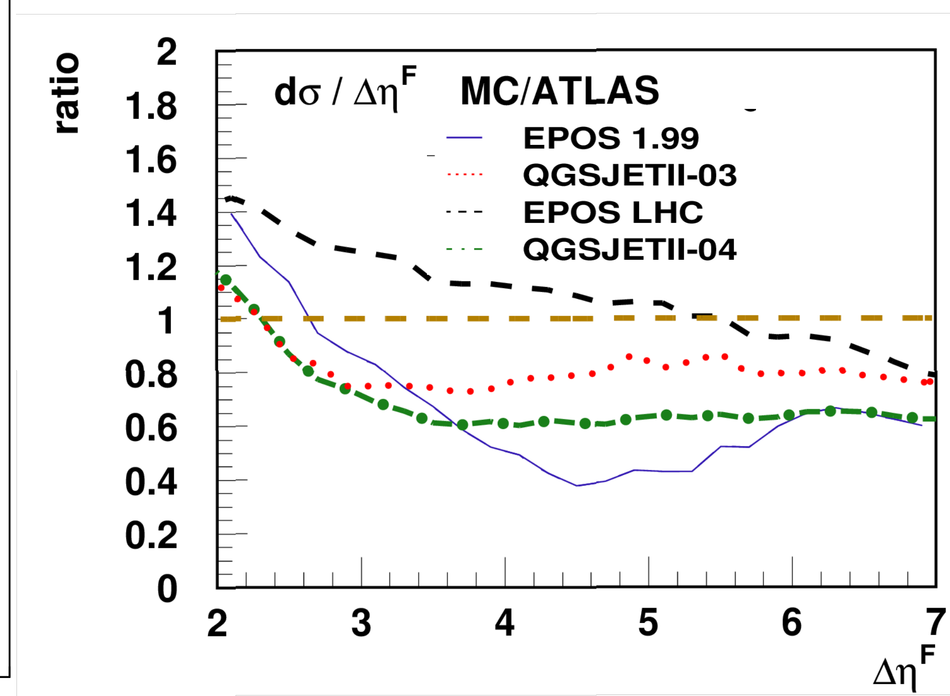




Muon Production Depth

- **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





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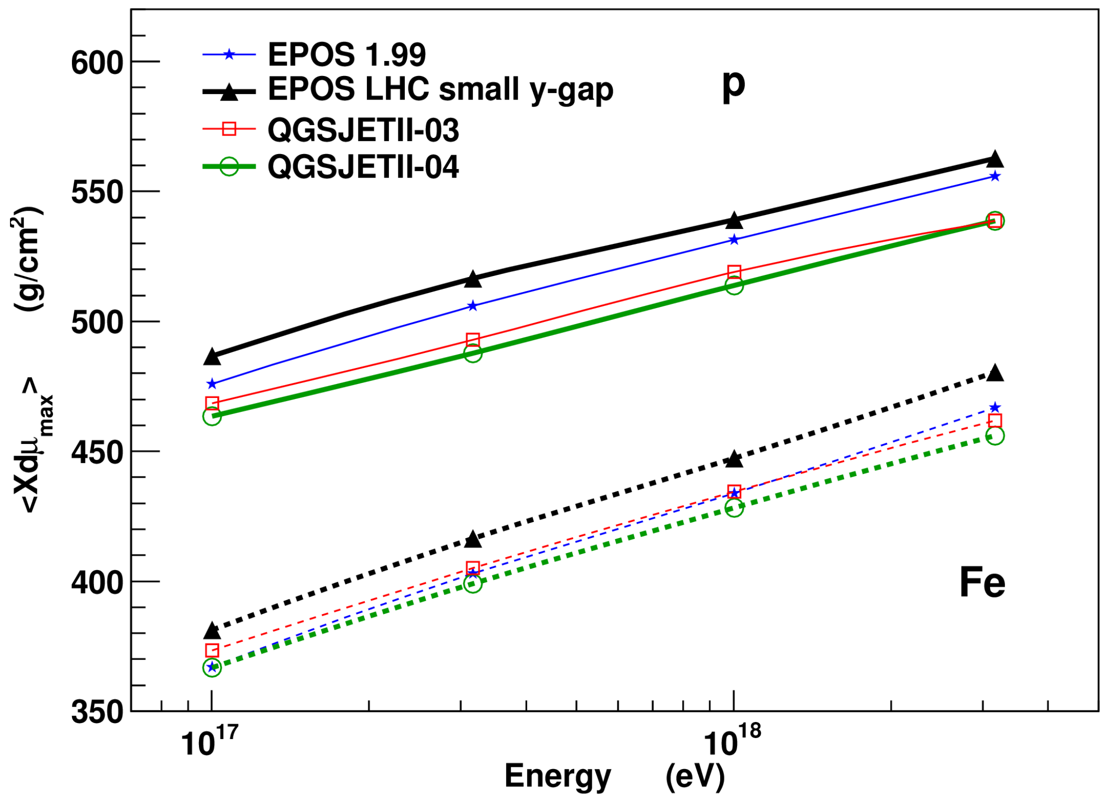

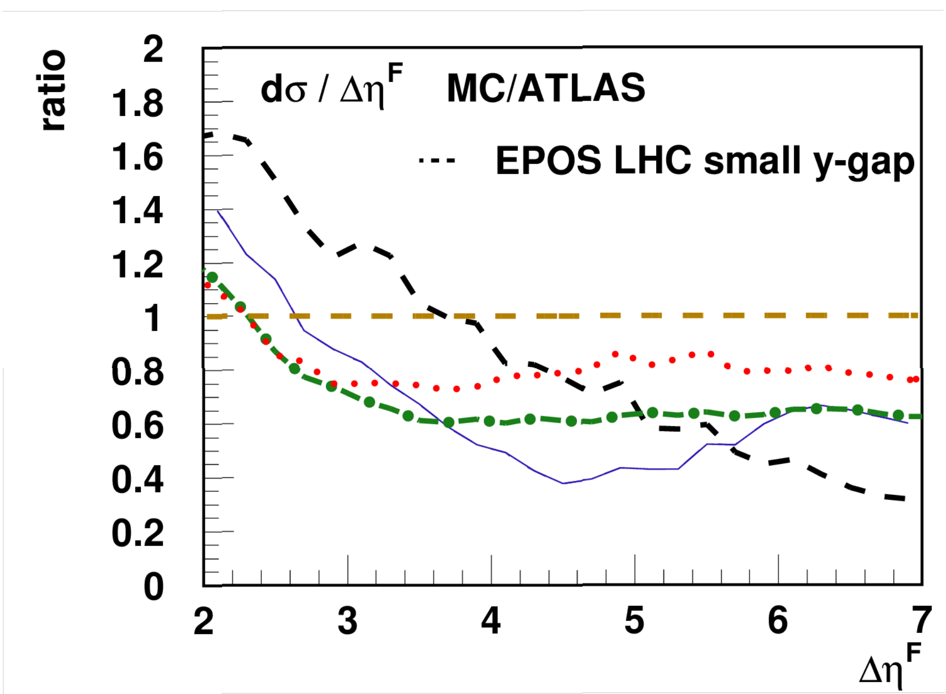

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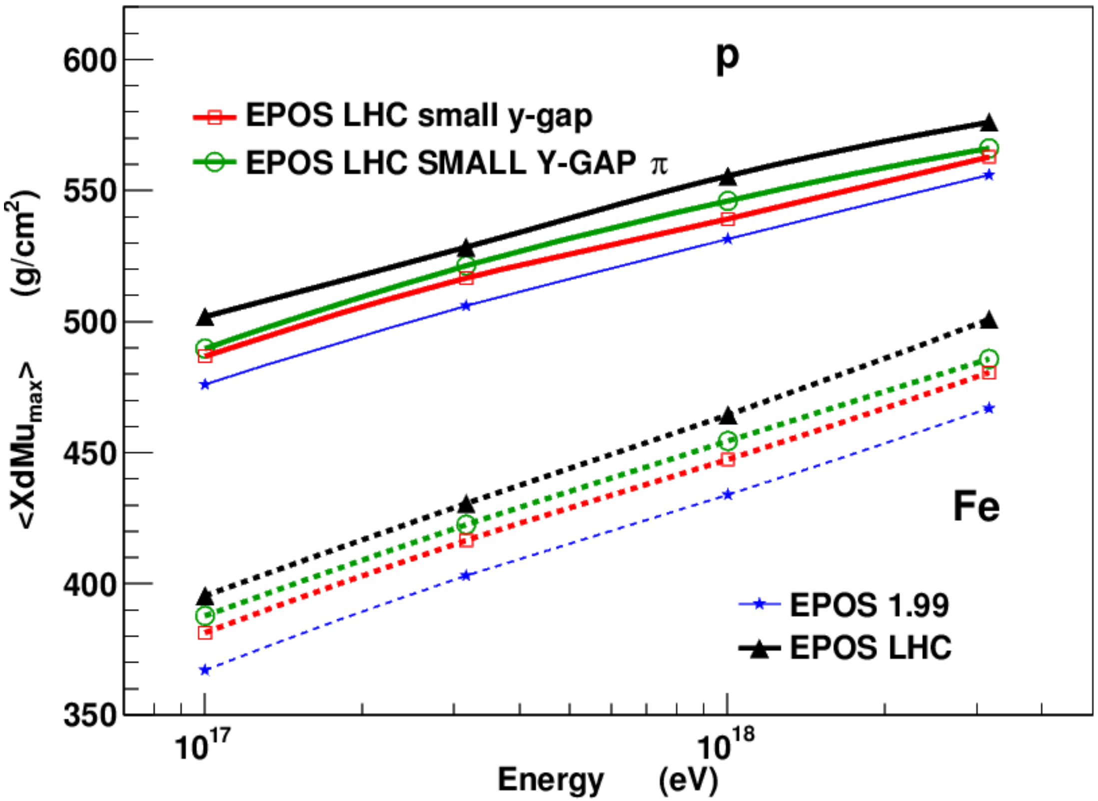
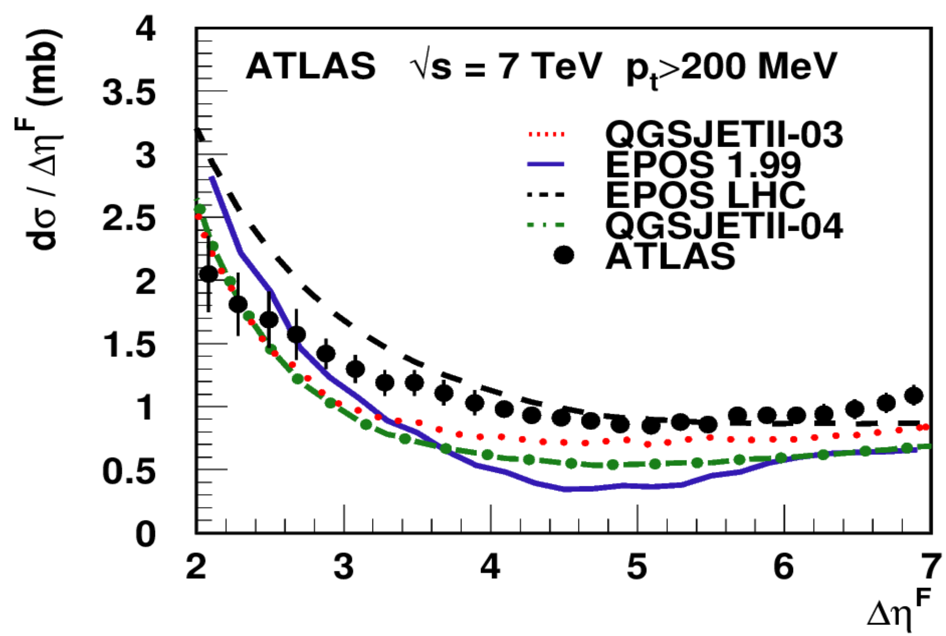
  - harder mass spec. for pions reduce X^{μ}_{max} and increase muon for same X_{max} !





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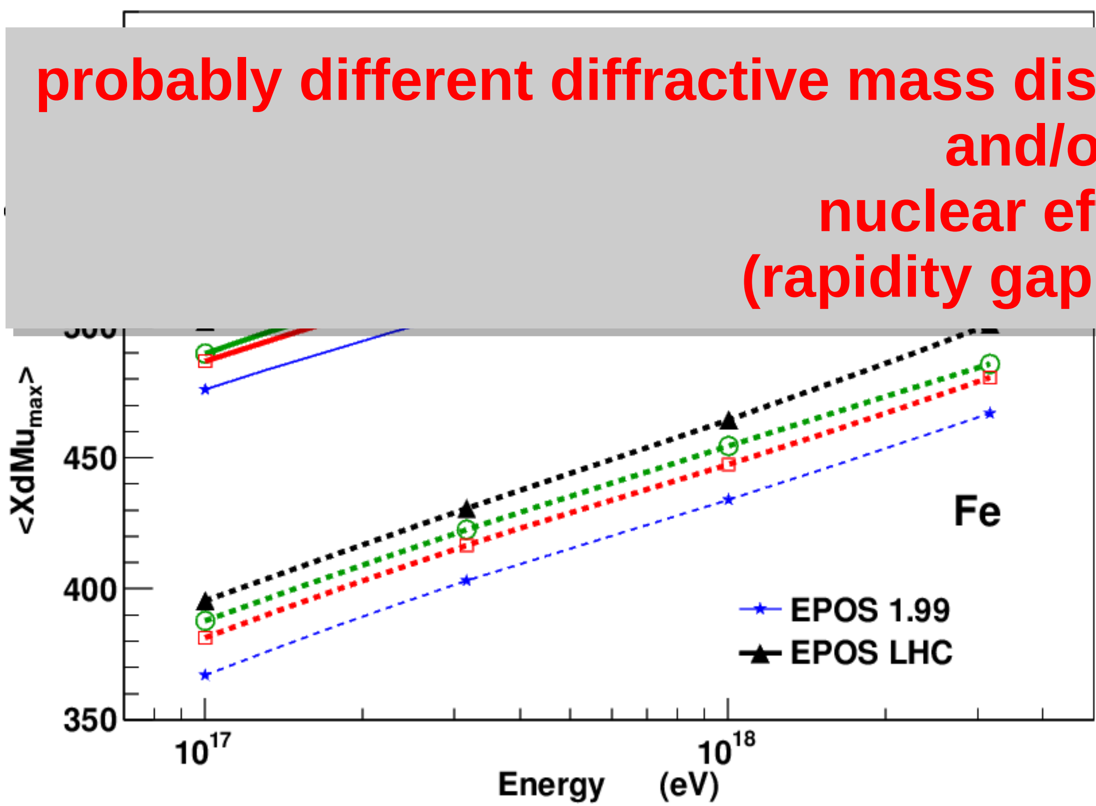
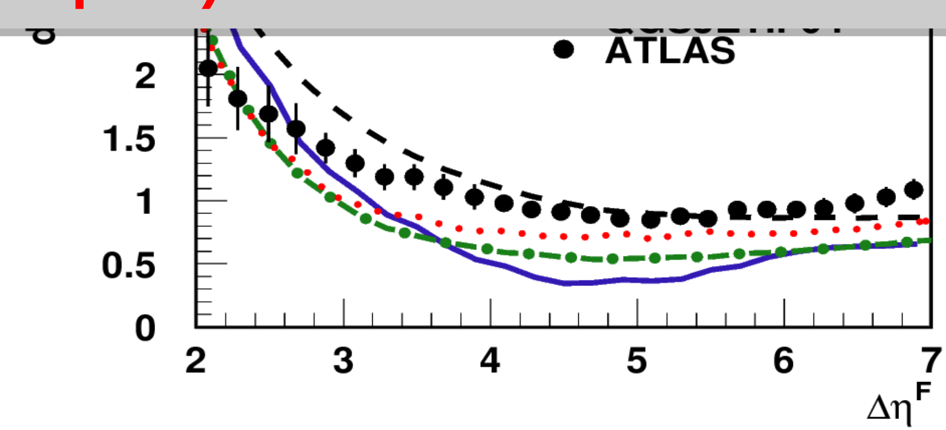


probably different diffractive mass distribution for mesons and baryons
and/or
nuclear effect ?
(rapidity gap in p-Pb)



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
- **LHC and models for air showers :**
  - strong constrains on energy evolution of particle production and cross-section
  - results converge between models for both air shower observable X_{max} and number of muons at ground (differences reduced by a factor of 2)
  - further improvements by taking into account all new important results
    - saturation effects, collective effects, forward/mid-rapidity correlations, ...
- **EAS :**
  - Models can be tested using EAS data by checking consistency of mass composition with different methods
    - high sensitivity on hadronic interactions of MPD
  - more direct tests : cross-section measurement, muon number, ...

Final Conclusions

Tests of the hadronic interaction models EPOS 1.6 and QGSJET-II

Jörg R. Hörandel, RU Nijmegen
Jens Milke, IWR, FZK

2007

- EPOS 1.6 is not compatible with KASCADE measurements
  → can not be recommended for air shower simulations
- QGSJET-II has some deficiencies
  → should be used for simulations with care
- QGSJET 01 and SIBYLL 2.1 still most compatible models

And a final petition:
New interaction models should be tested first carefully and then applied to reconstruct primary spectra to not undermine the reputation of KASCADE

QGSJET 98
~~VENUS~~
~~SIBYLL 1.6~~

~~DPMJET II.5~~
DPMJET II.55
QGSJET 01
SIBYLL 2.1
~~NEXUS 2~~

~~EPOS 1.6~~
(QGSJET II)

Final Conclusions

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2014
(LHC and PAO)

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New interaction models should be tested first carefully
and then applied to reconstruct primary spectra
to not undermine the reputation of ~~KASCADE~~ cosmic ray physics ...

~~QGSJET 98~~
~~VENUS~~
~~SIBYLL 1.6~~

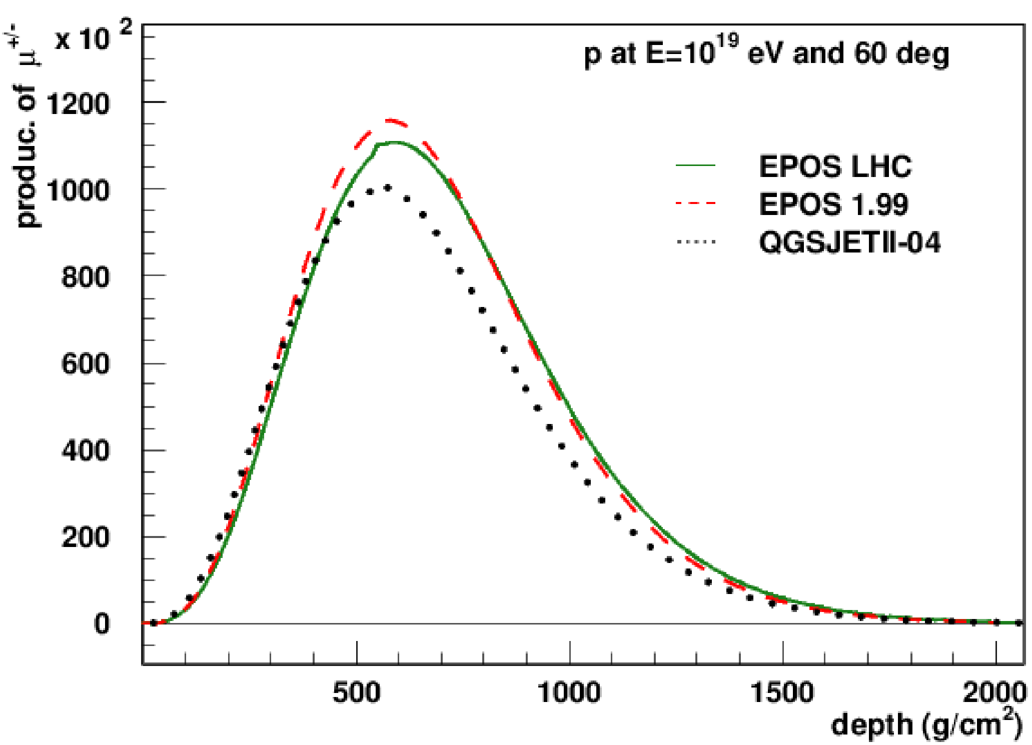
~~DPMJET II.5~~
~~DPMJET II.55~~
~~QGSJET 01~~
~~SIBYLL 2.1~~
~~NEXUS 2~~

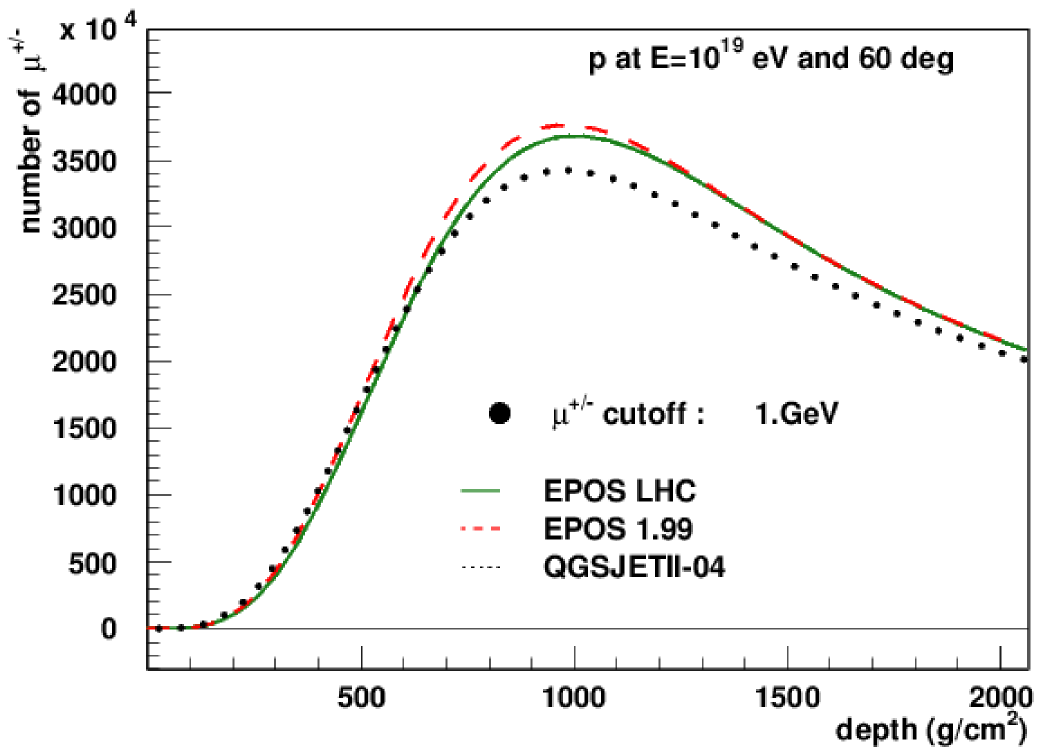
~~EPOS 1.6~~
(~~QGSJET II~~)

Backup

Is X^{μ}_{max} Important for Muons at Ground ?

- **For EM particles : shift in X_{max} ≈ change in EM at ground**
  - strong atmospheric absorption
- **For muons : shift in X^{μ}_{max} ≉ change in muons at ground**
  - weak atmospheric absorption
  - model dependent energy spectra
  - distance to core dependence





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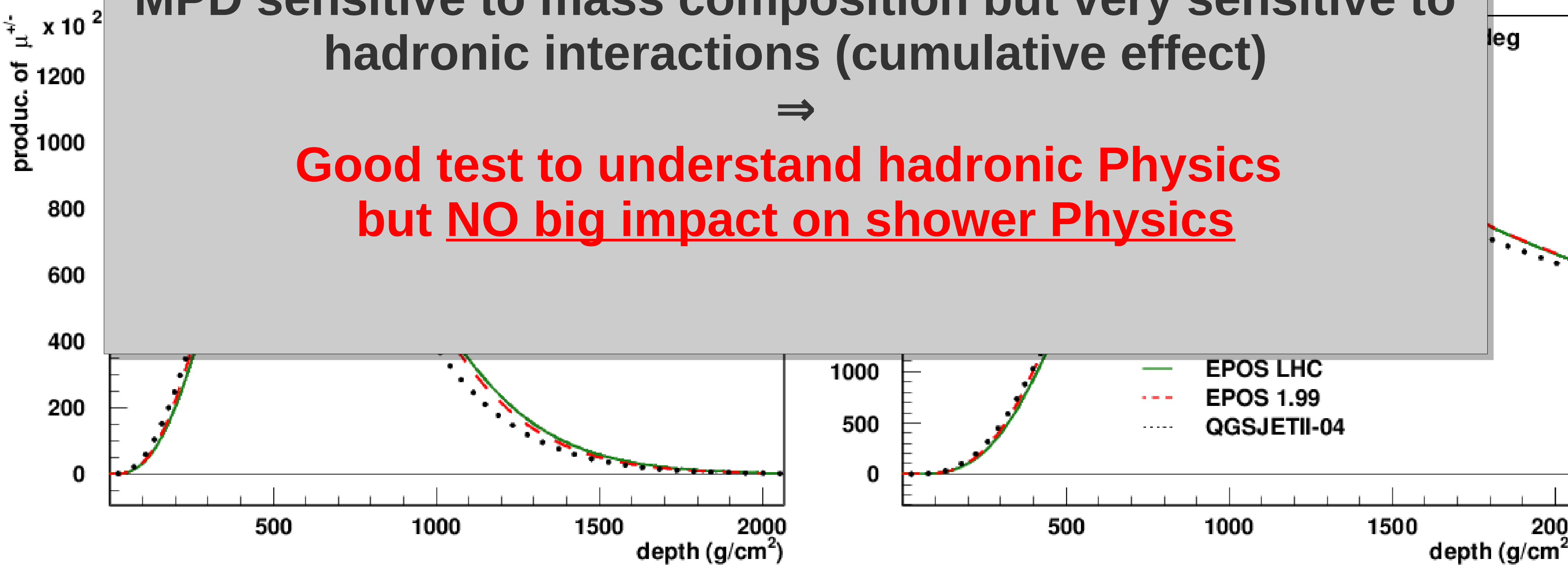


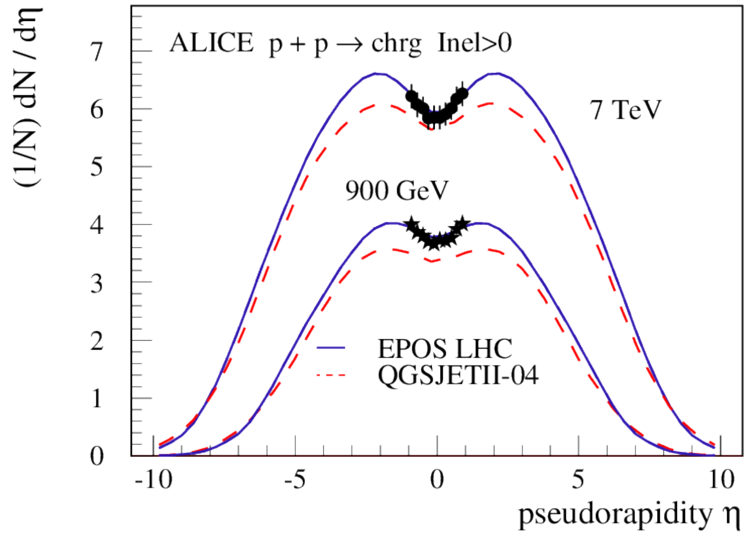
MPD sensitive to mass composition but very sensitive to hadronic interactions (cumulative effect)

⇒

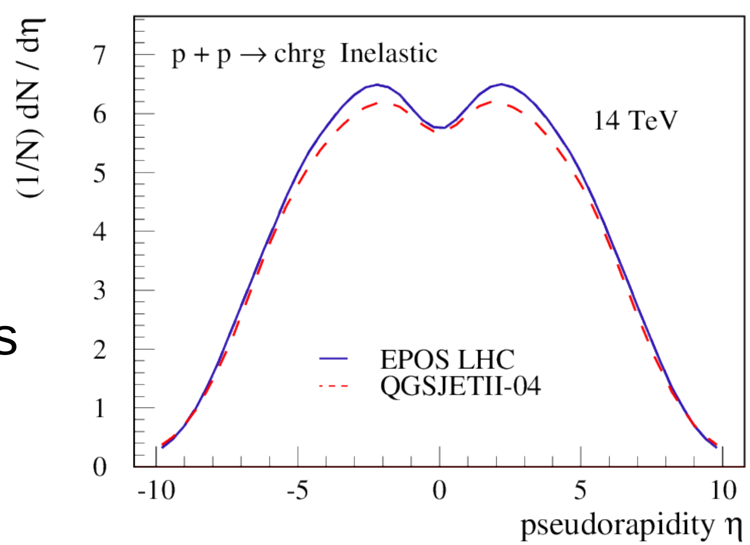
Good test to understand hadronic Physics
but <u>NO big impact on shower Physics</u>

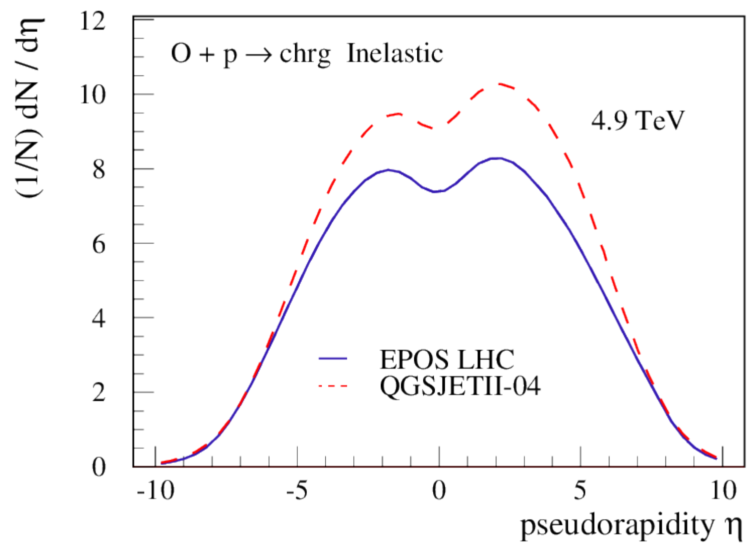
Extrapolation and LHC Results

- **Source of uncertainties : extrapolation**
  - to higher energies
    - strong constraints by current LHC data
  - from p-p to p-Air and pi-Air
    - current main source of uncertainty



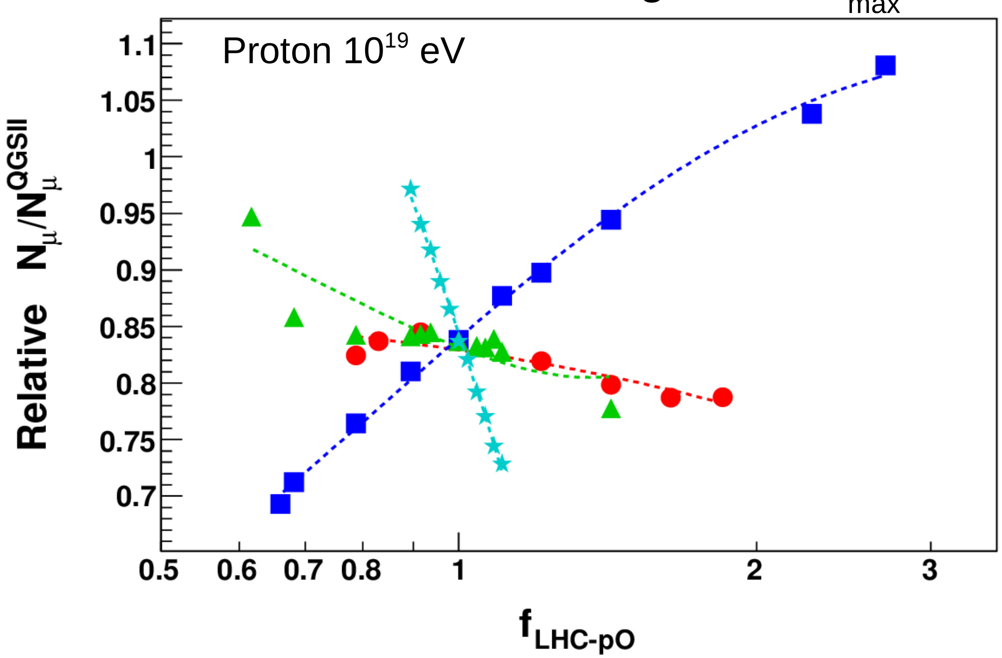
- **Needs to better take into account last LHC results :**
  - hard scale saturation
  - collective effects in small system
  - detailed diffractive measurements
  - particle correlations
    - EPOS 3
    - QGSJETxxx

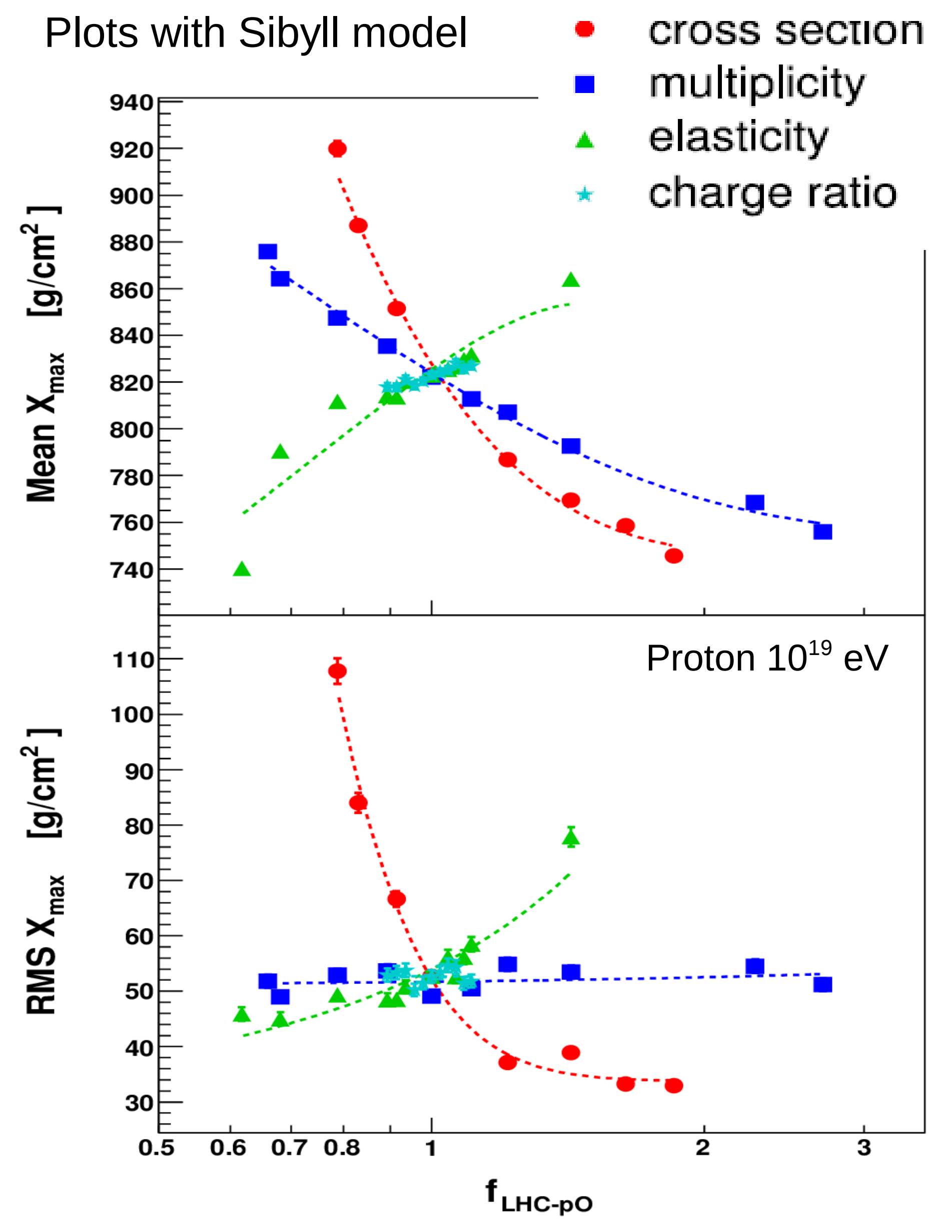




Effects of Parameters

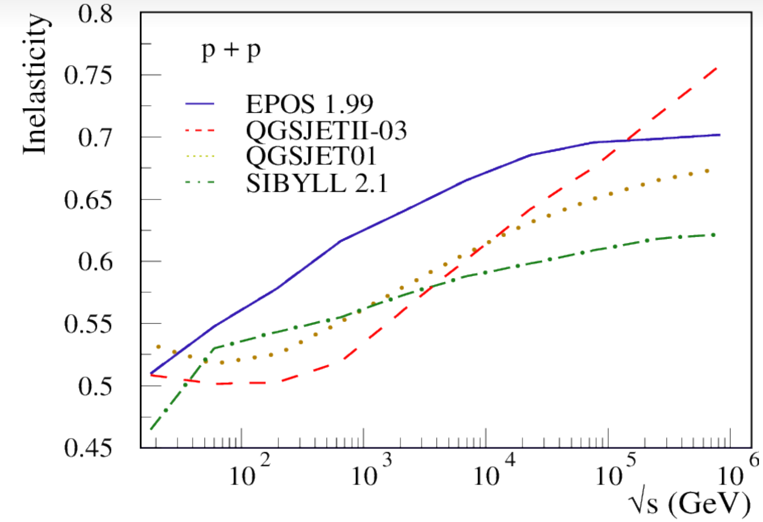
- **Sensibility depends on observable and parameter :**
  - ➜ effect of uncertainties at LHC on air shower observables
    - $f_{LHC\text{-}pO}$ = modification factor@LHC
  - ➜ 20% difference in multiplicity is about
    - 10% muons
    - 20 gr/cm² <X_{max}>

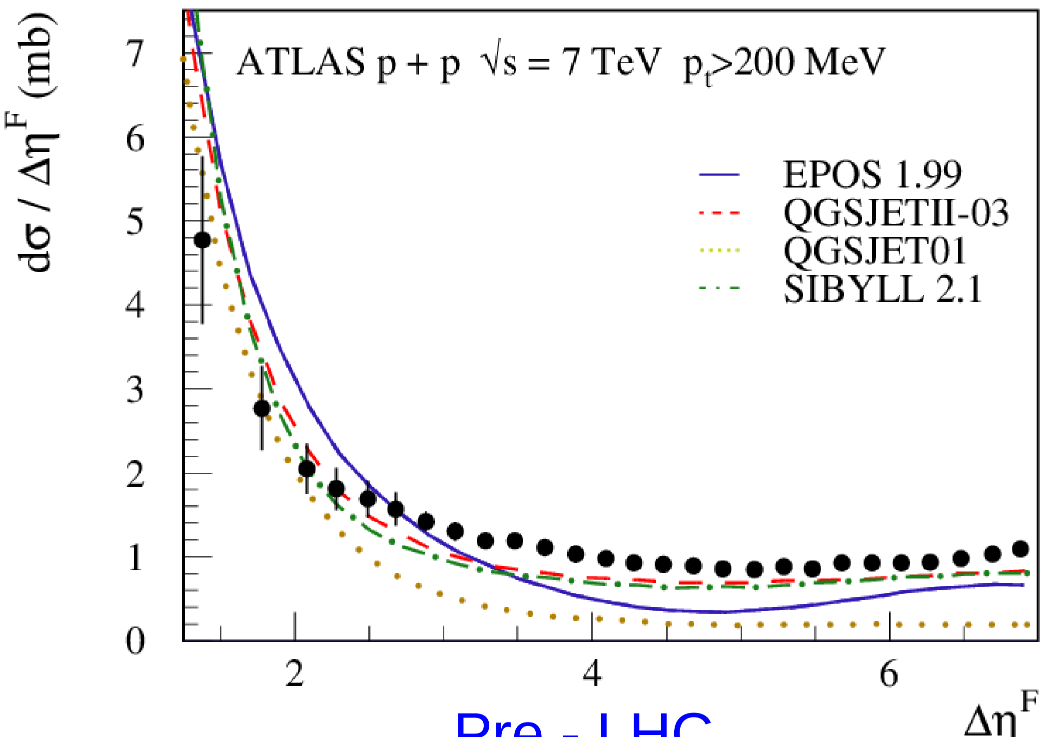




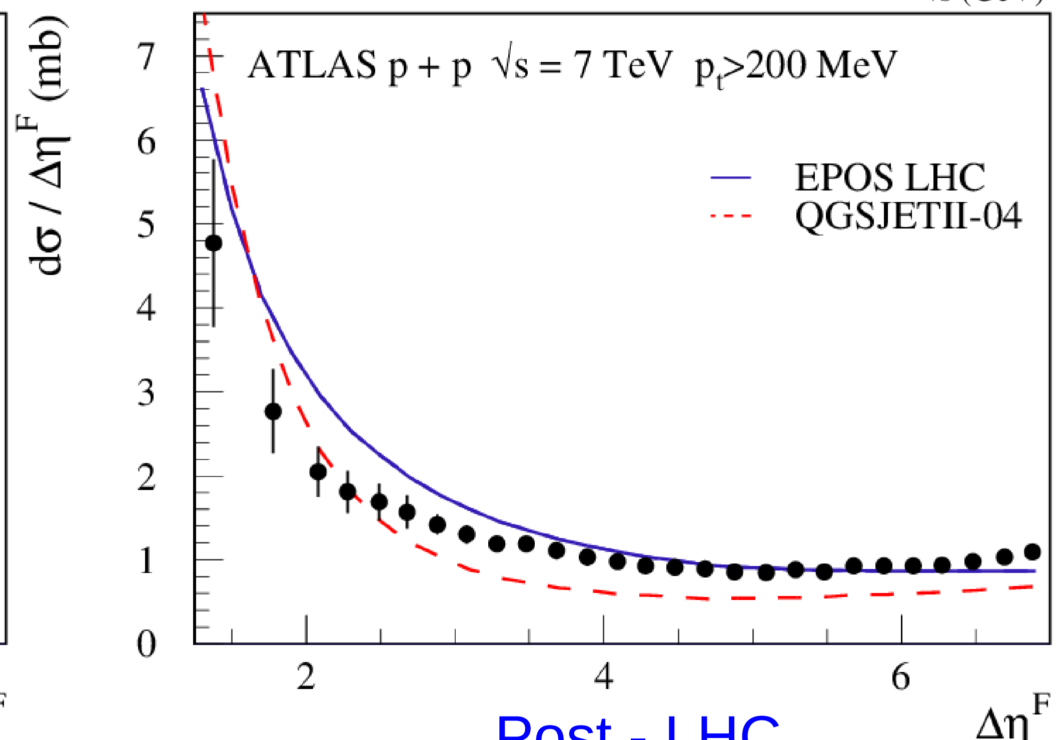
Inelasticity

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





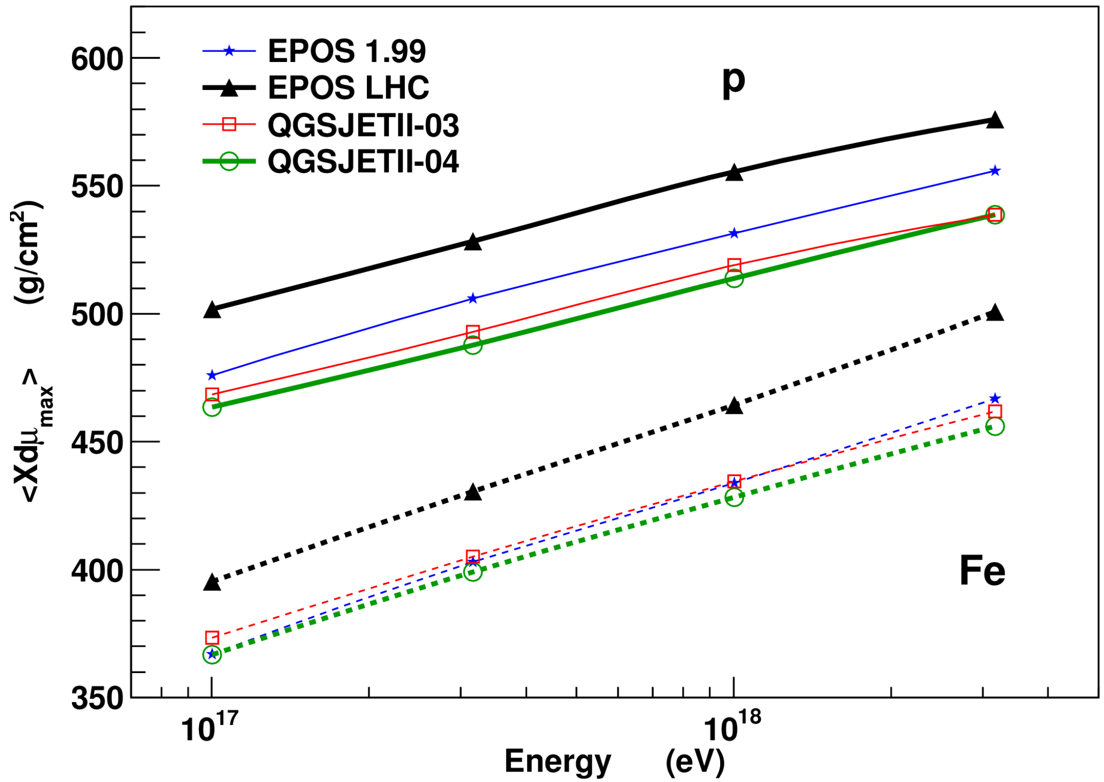
Pre - LHC

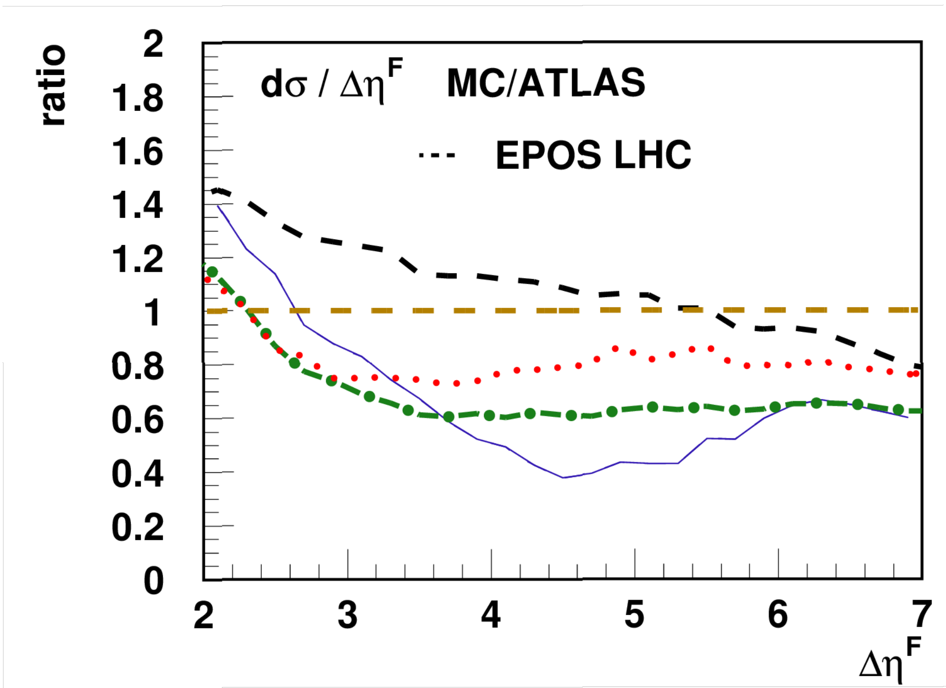


Post - LHC

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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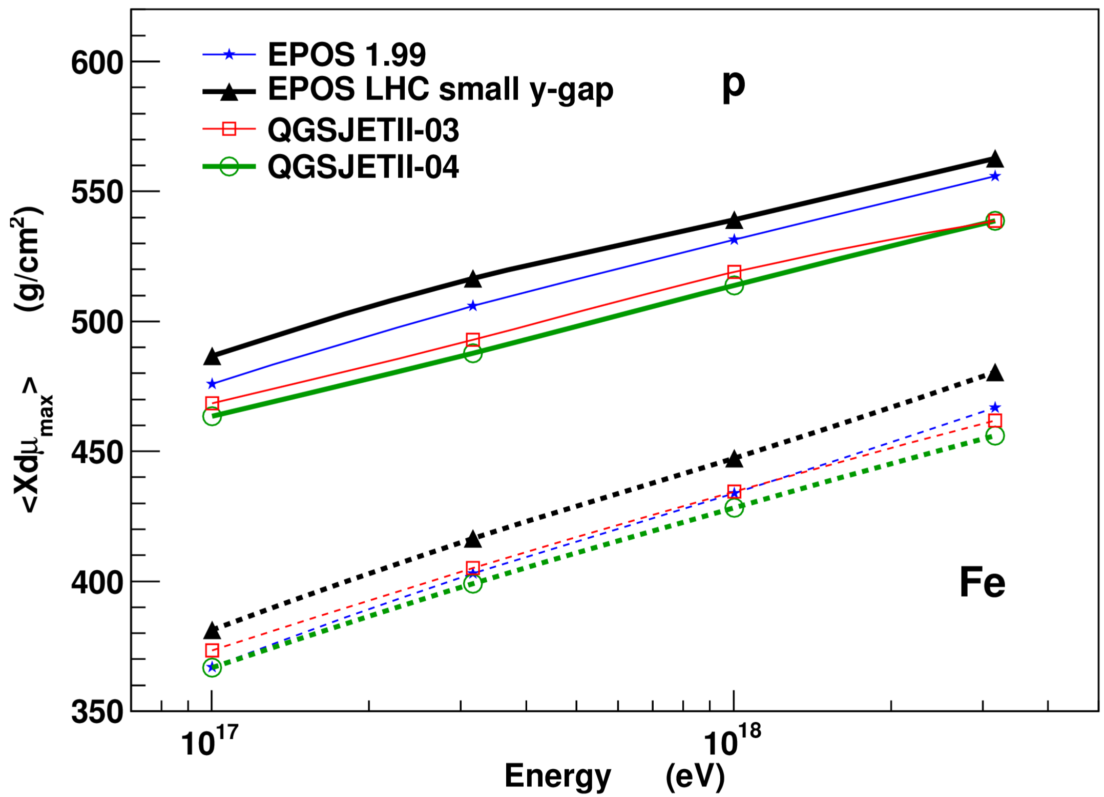

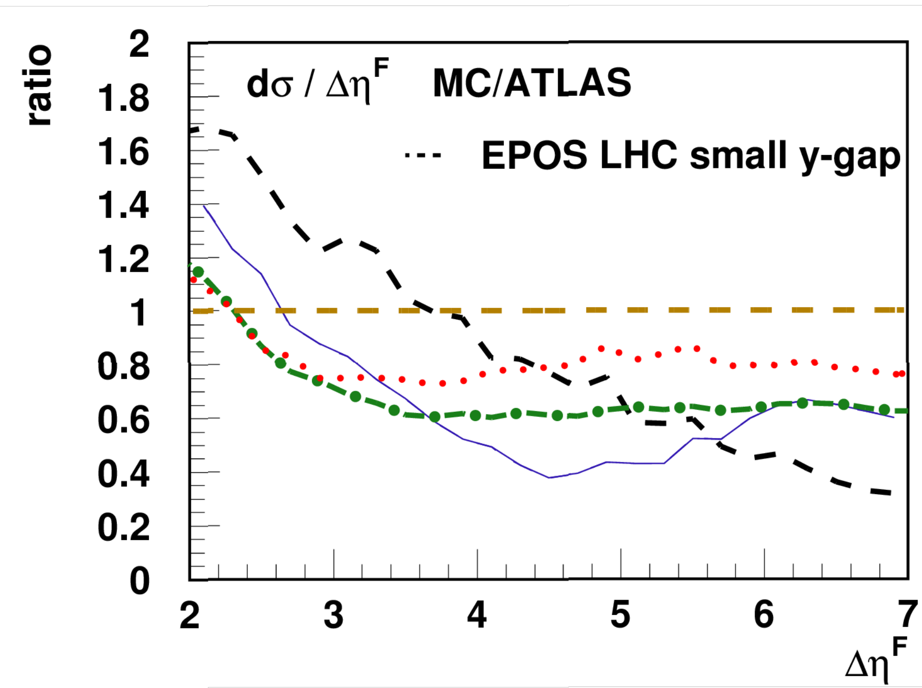

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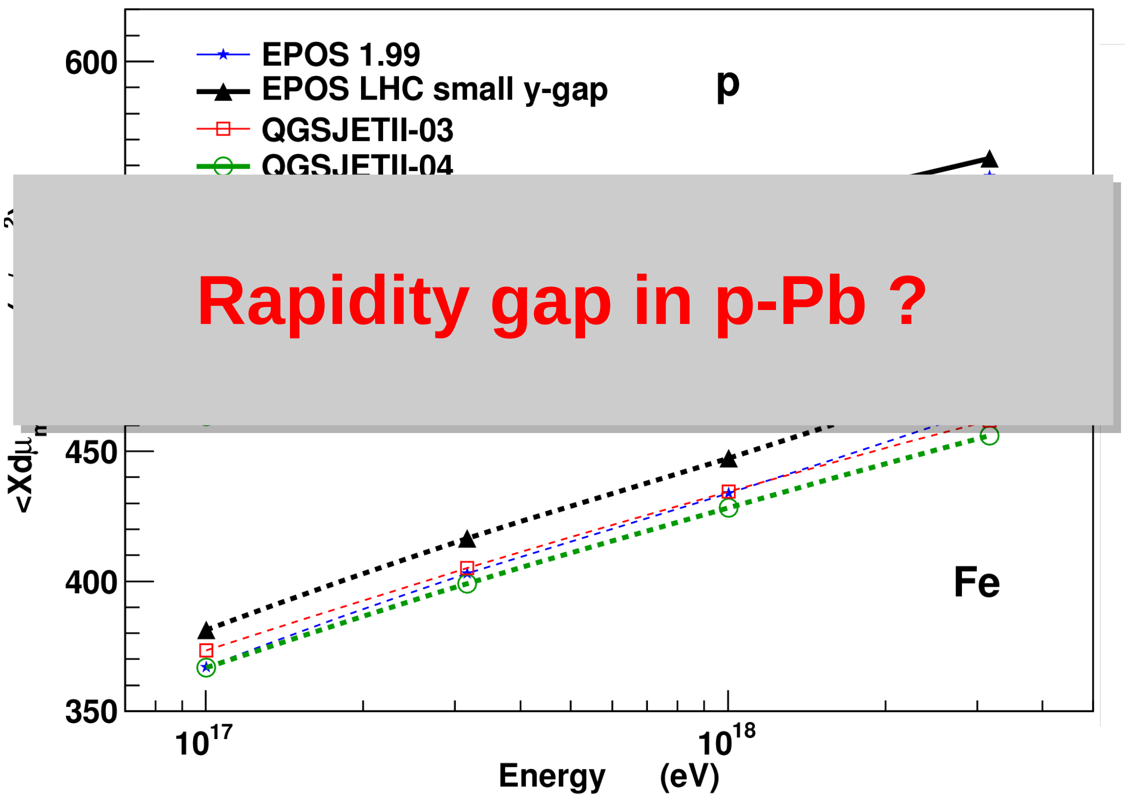
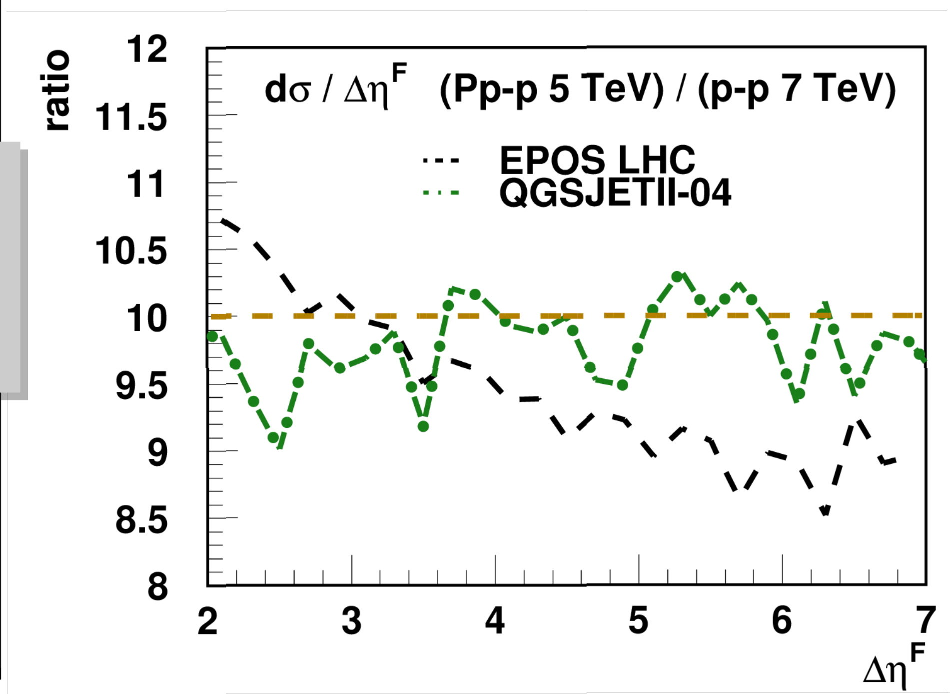
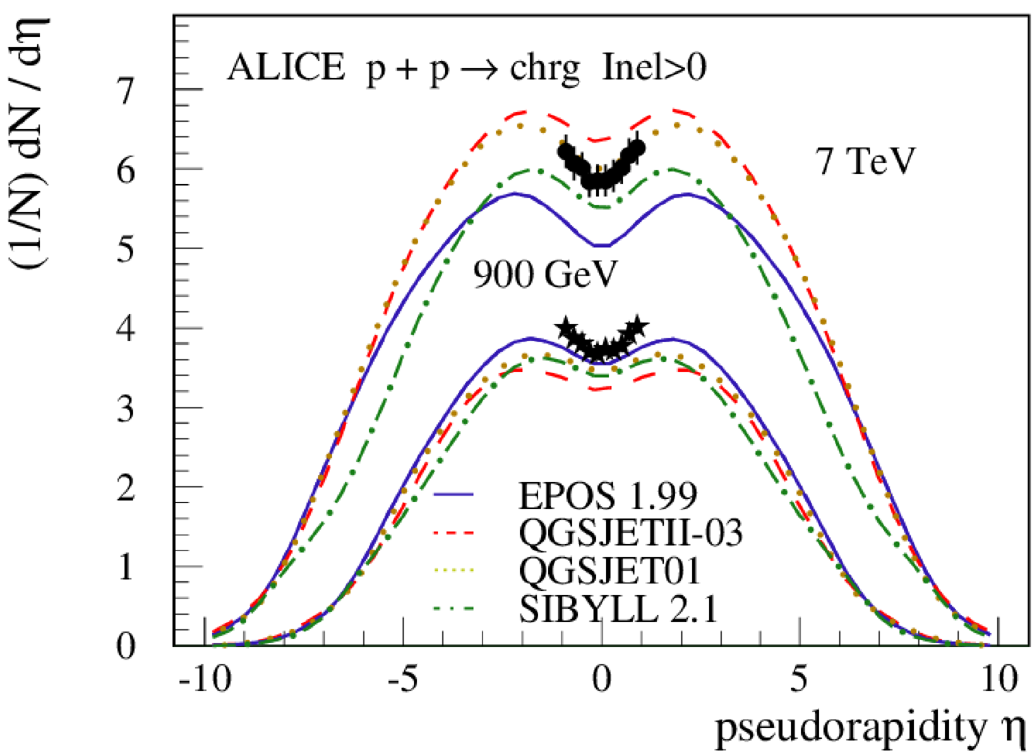




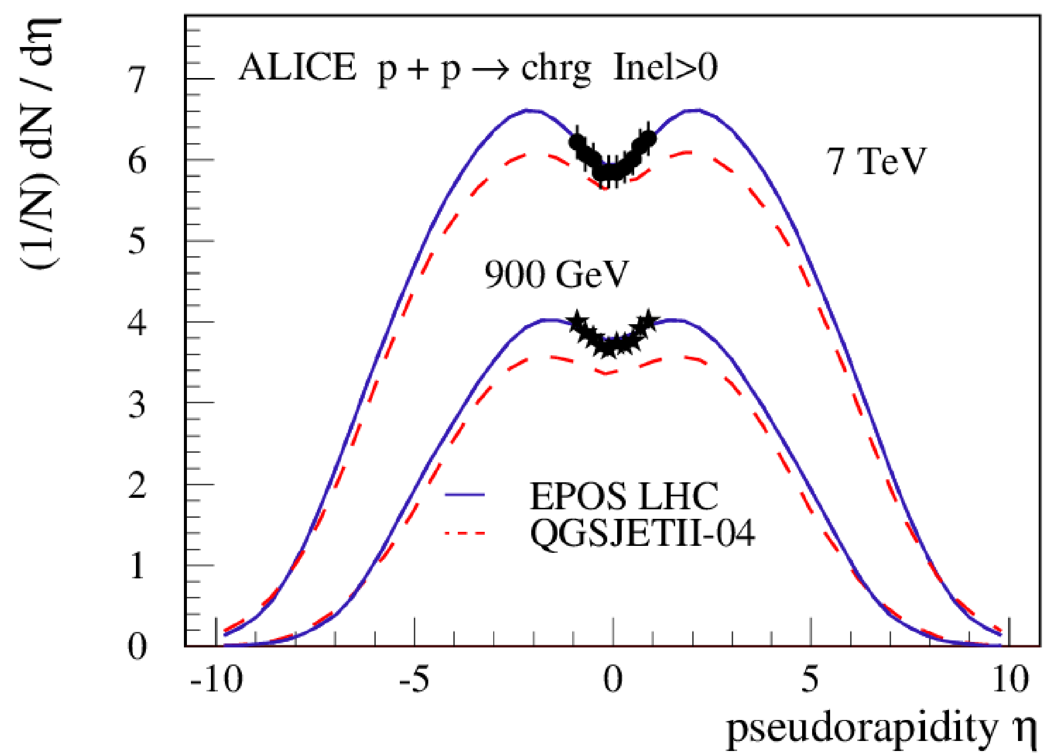
Multiplicity

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

Pre - LHC

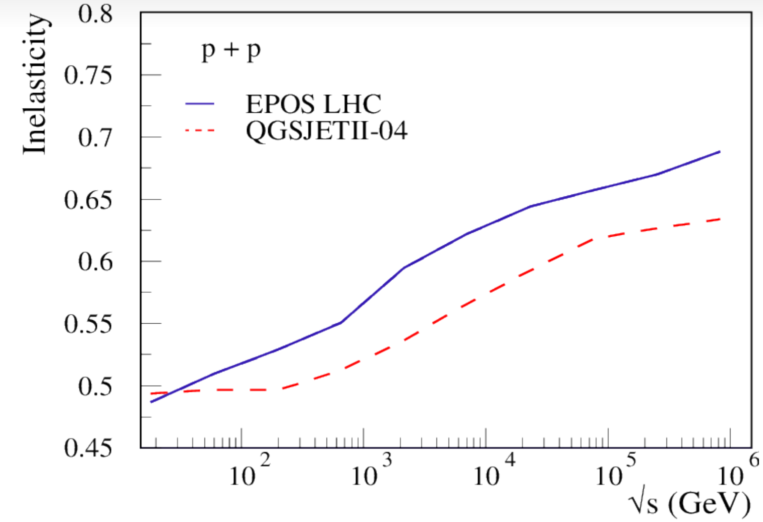


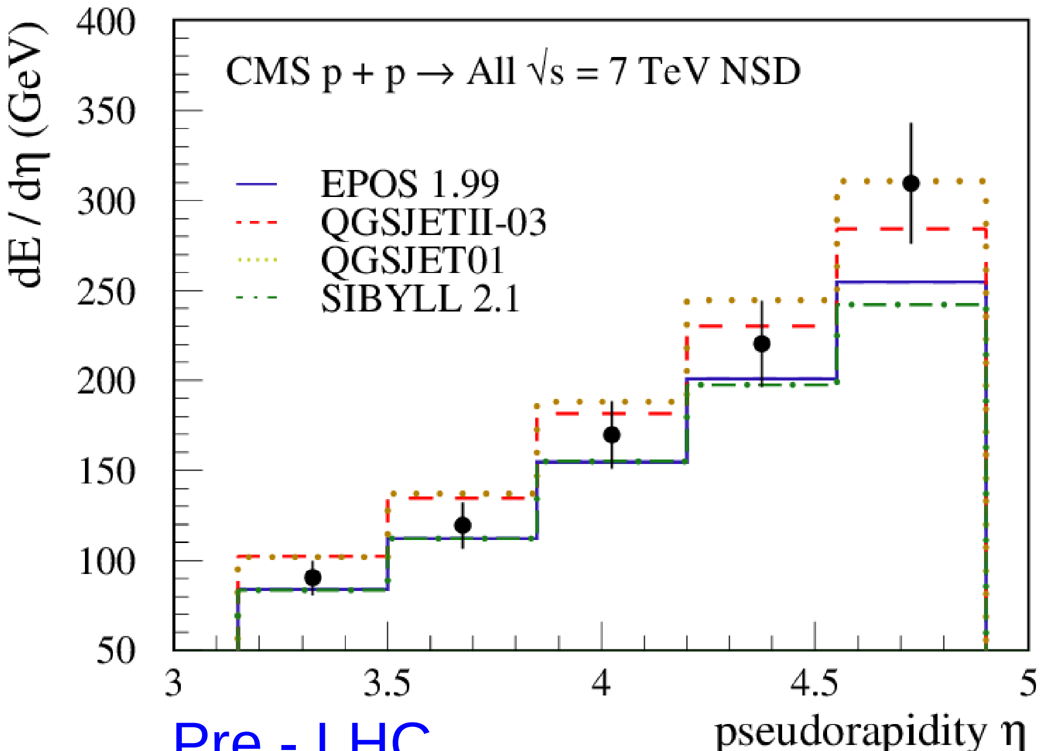
Post - LHC



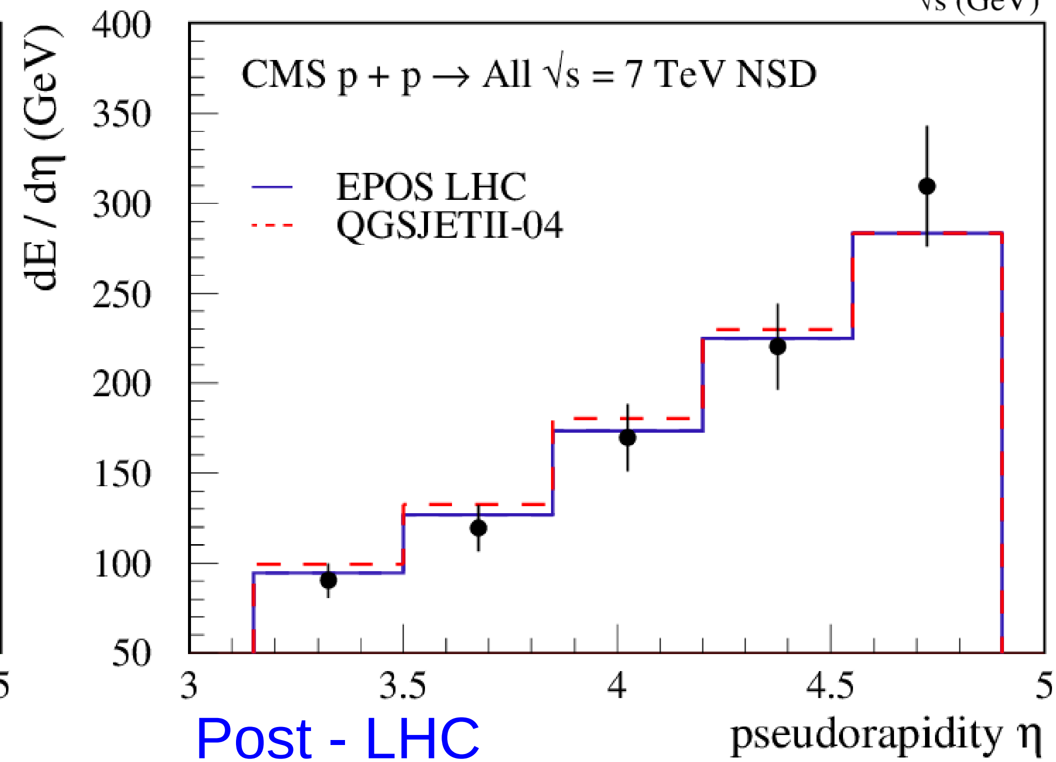
Inelasticity

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





Pre - LHC

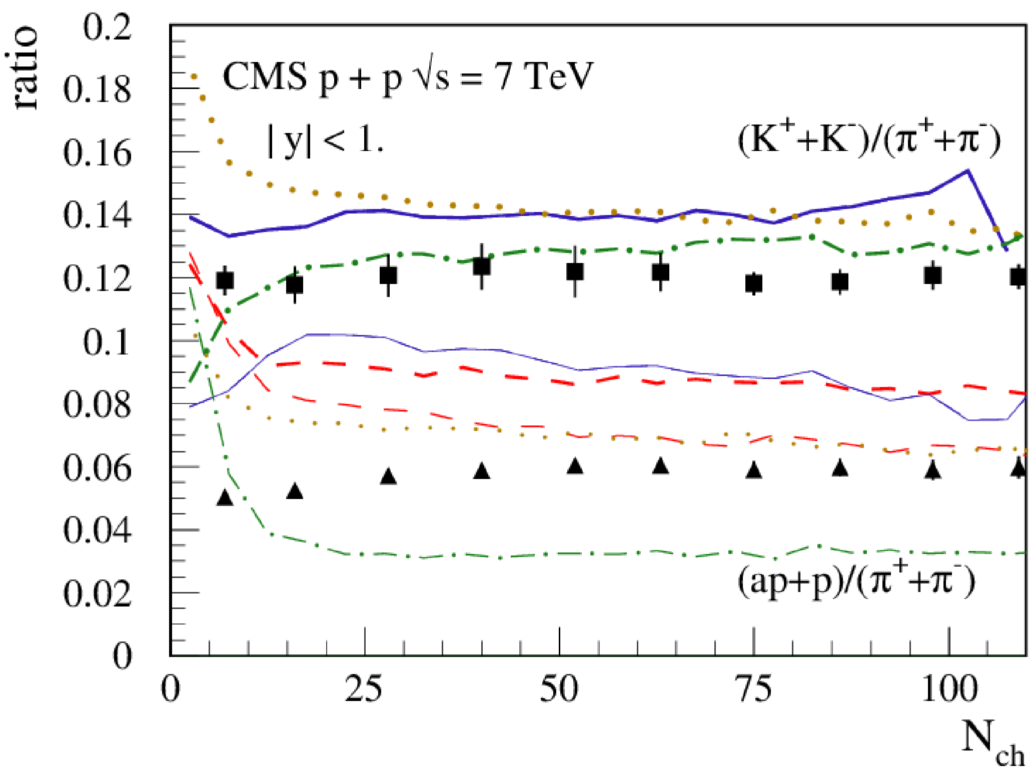


Post - LHC

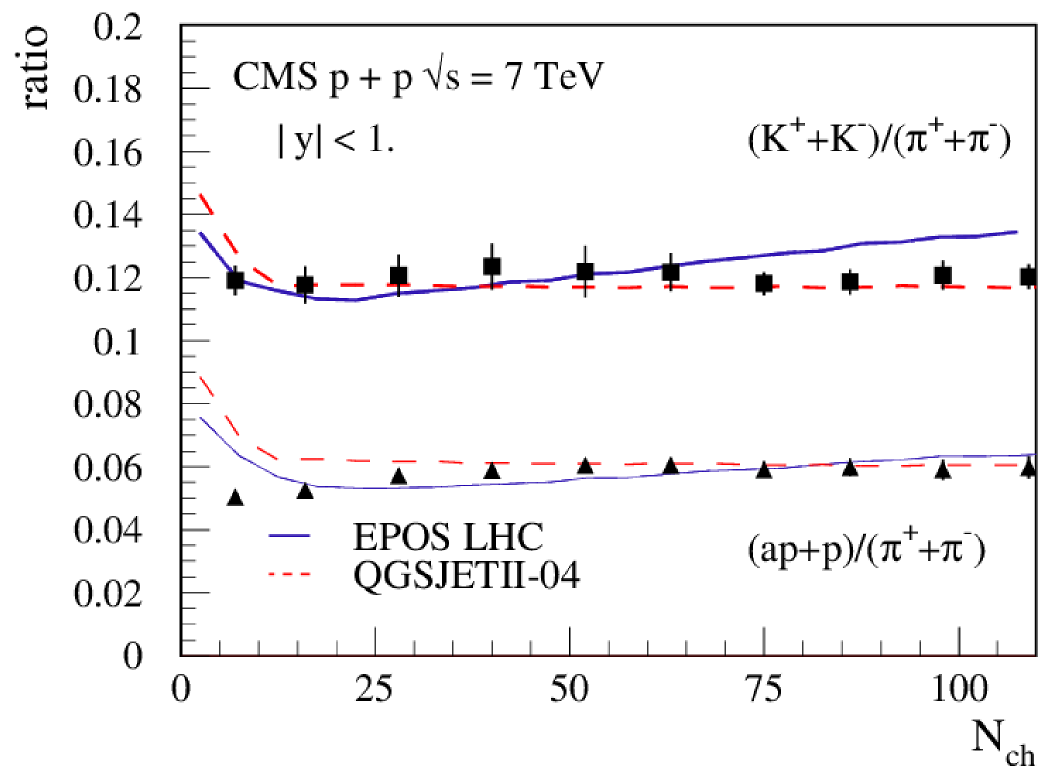
Identified particles

- **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

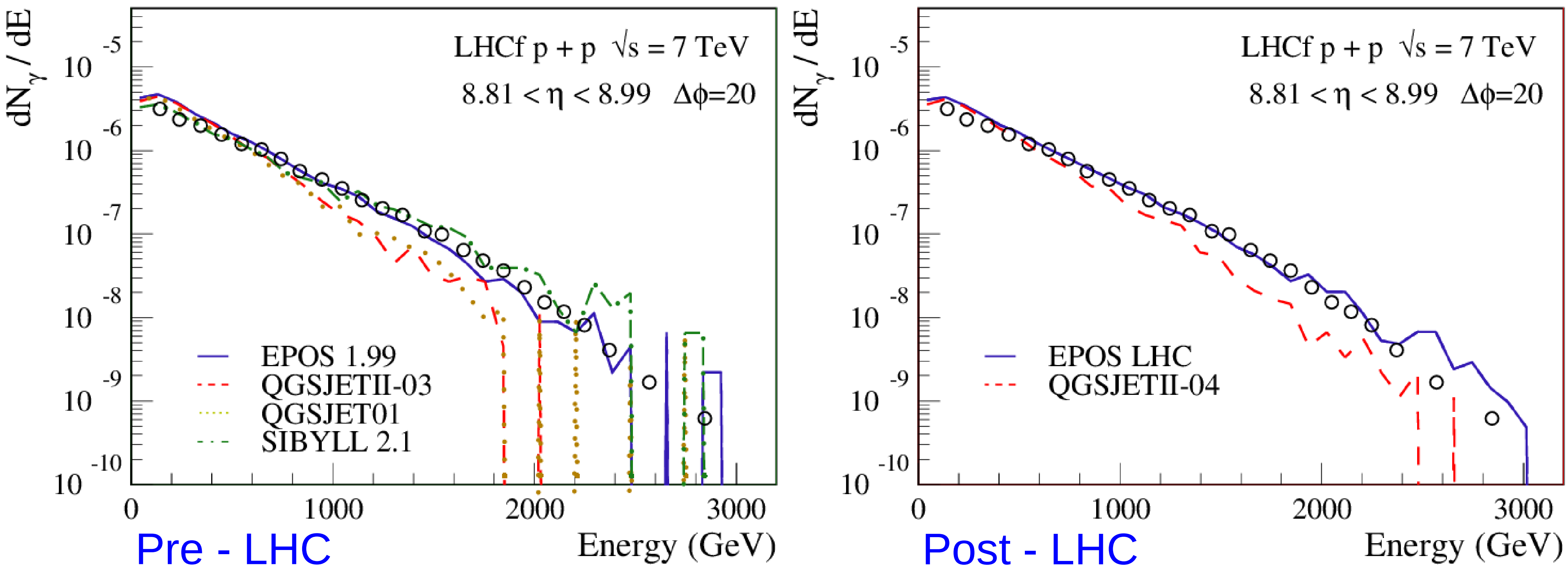


Post - LHC

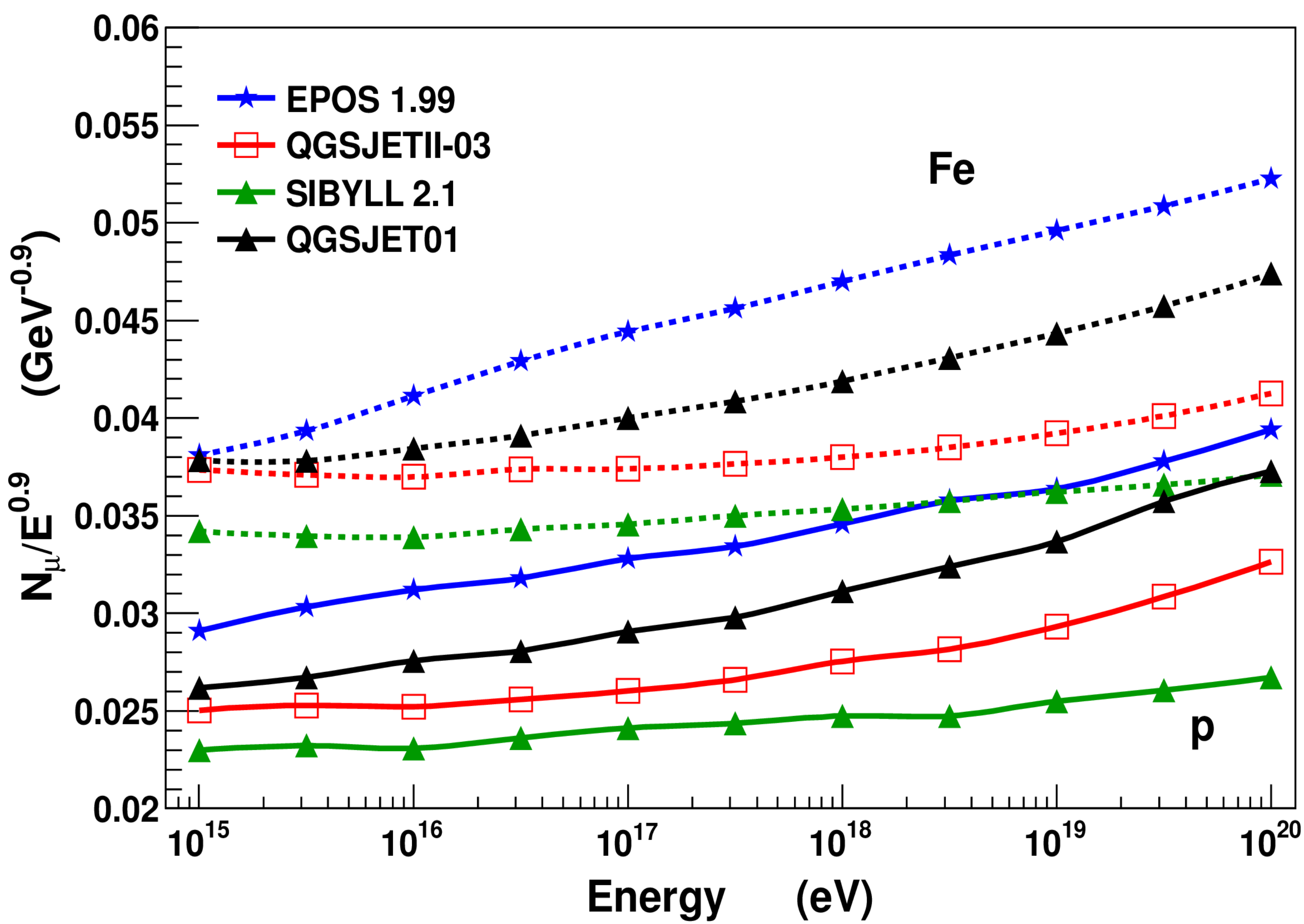


Identified particles

- **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)



EAS with Re-tuned CR Models : Muons



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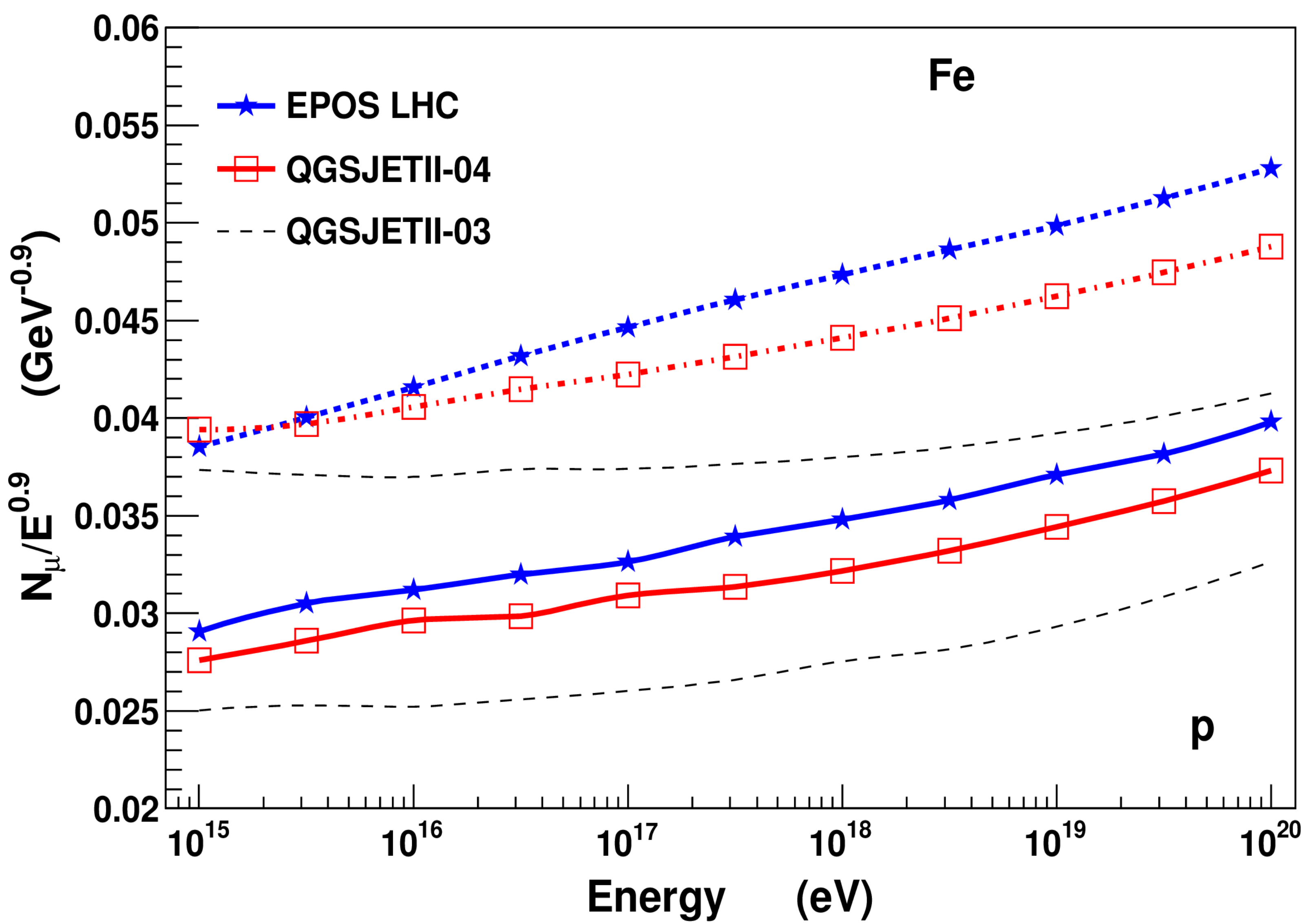
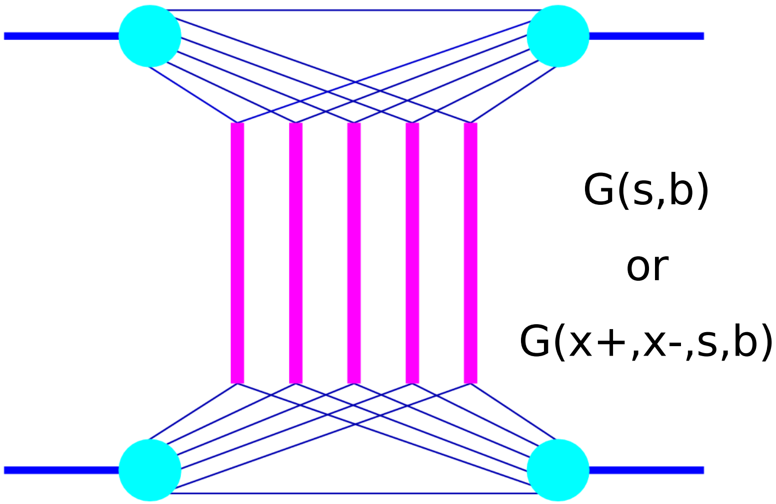
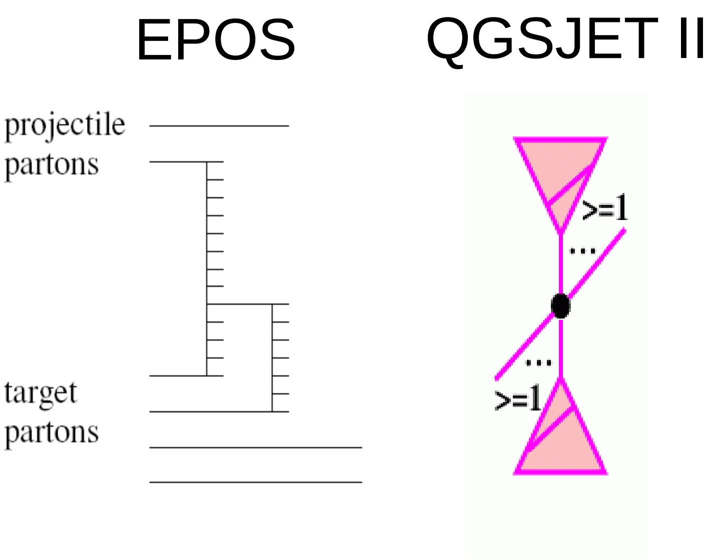


Cross Section and Multiplicity in Models

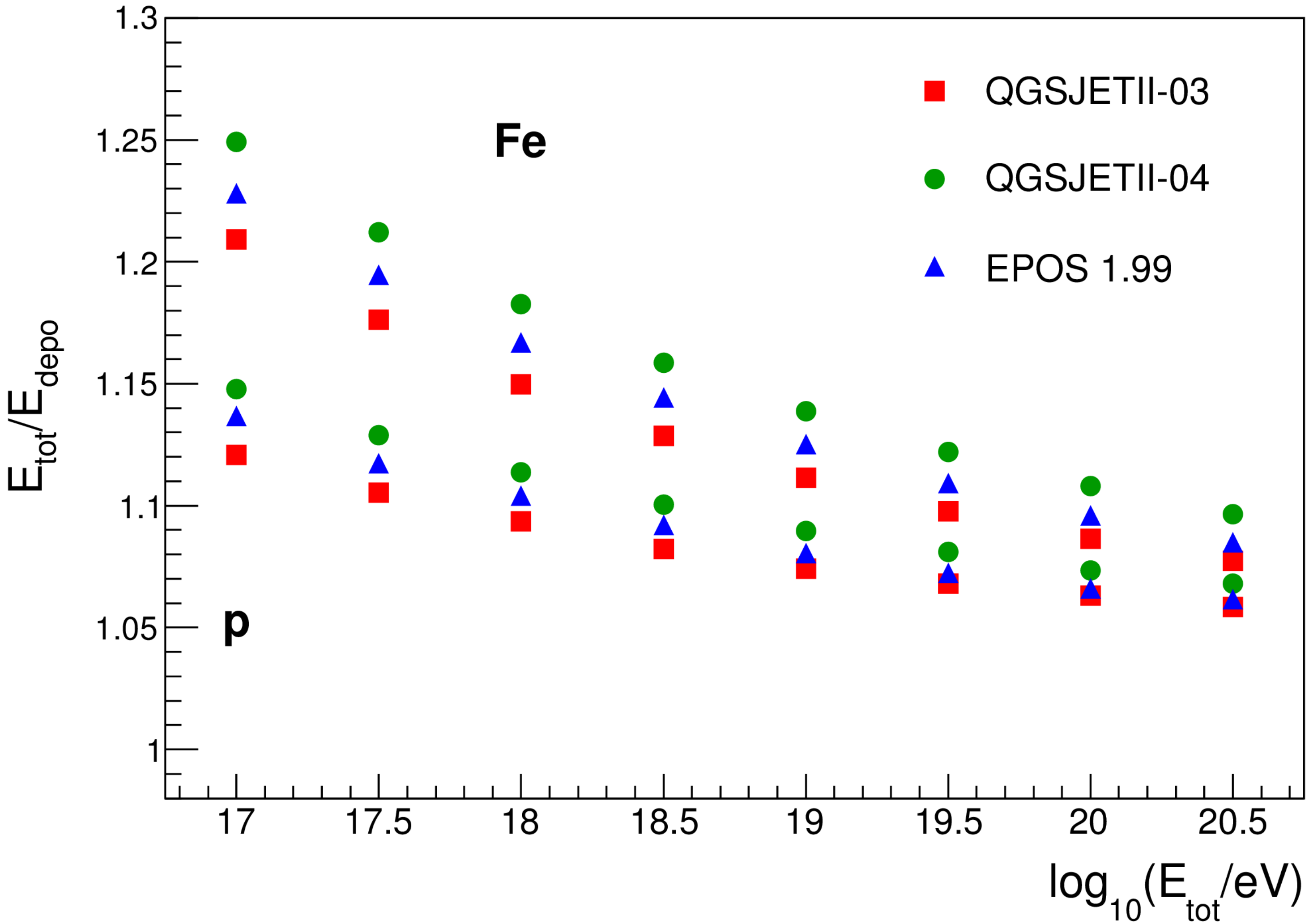




- **Gribov-Regge and optical theorem**
  - Basis of all models (multiple scattering) but
    - Classical approach for QGSJET and SIBYLL (no energy conservation for cross section calculation)
    - Parton based Gribov-Regge theory for EPOS (energy conservation at amplitude level)
- **pQCD**
  - Minijets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

EAS Energy Deposit

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



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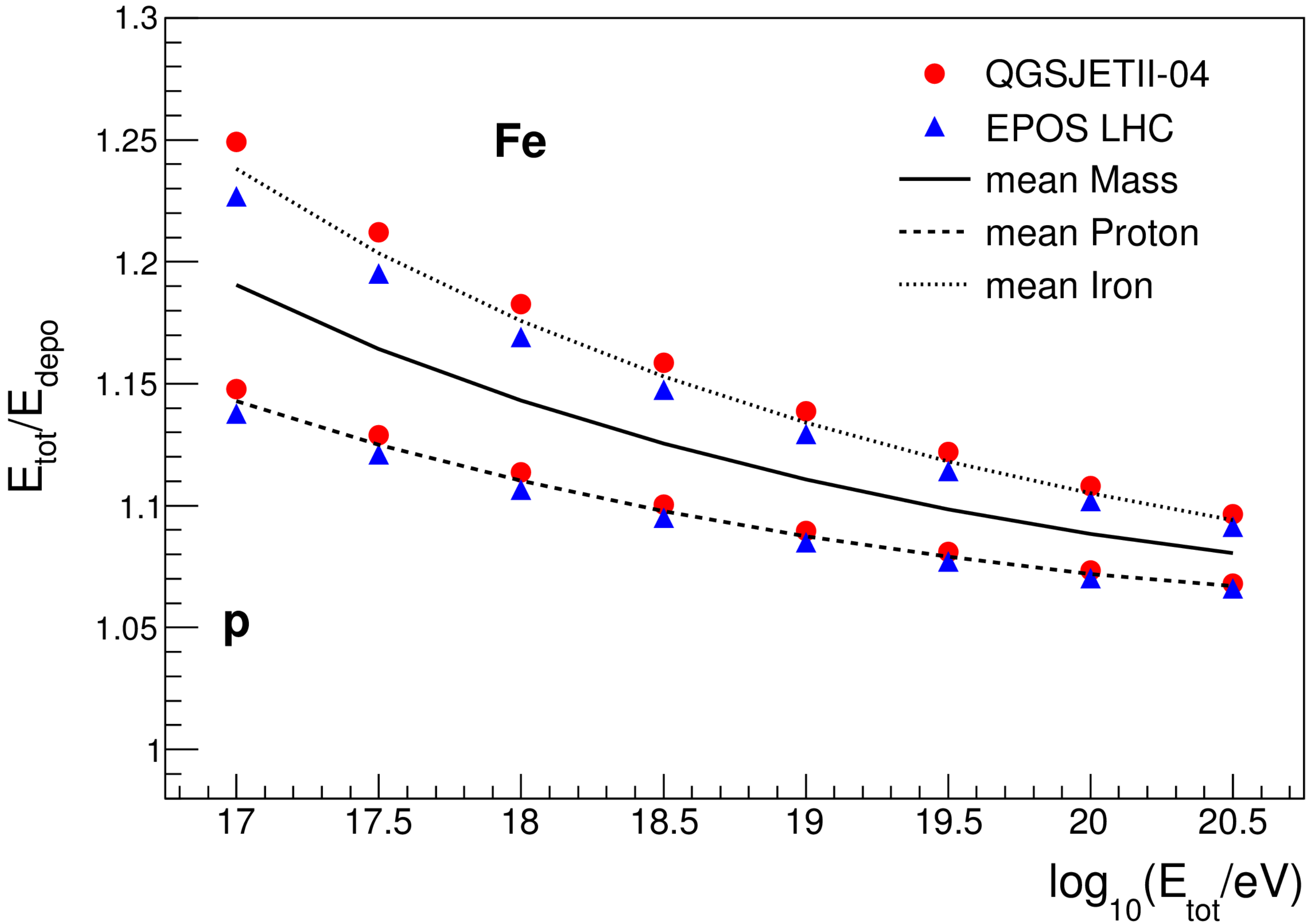
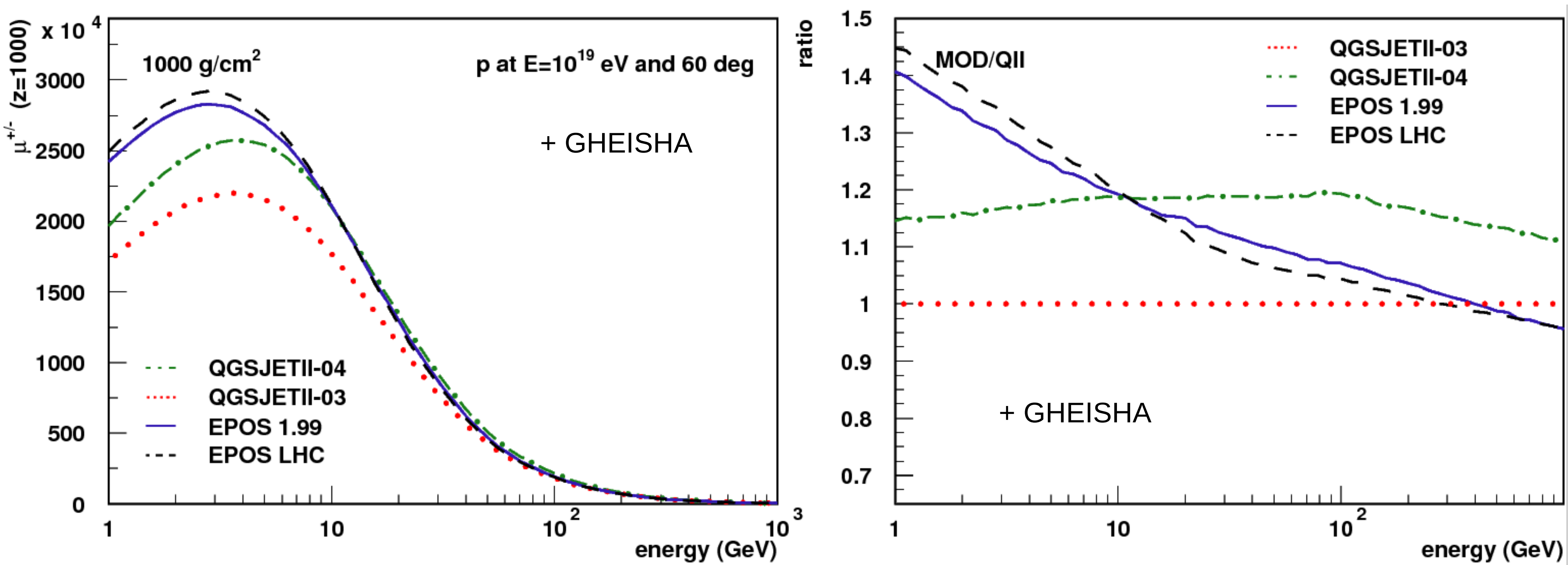


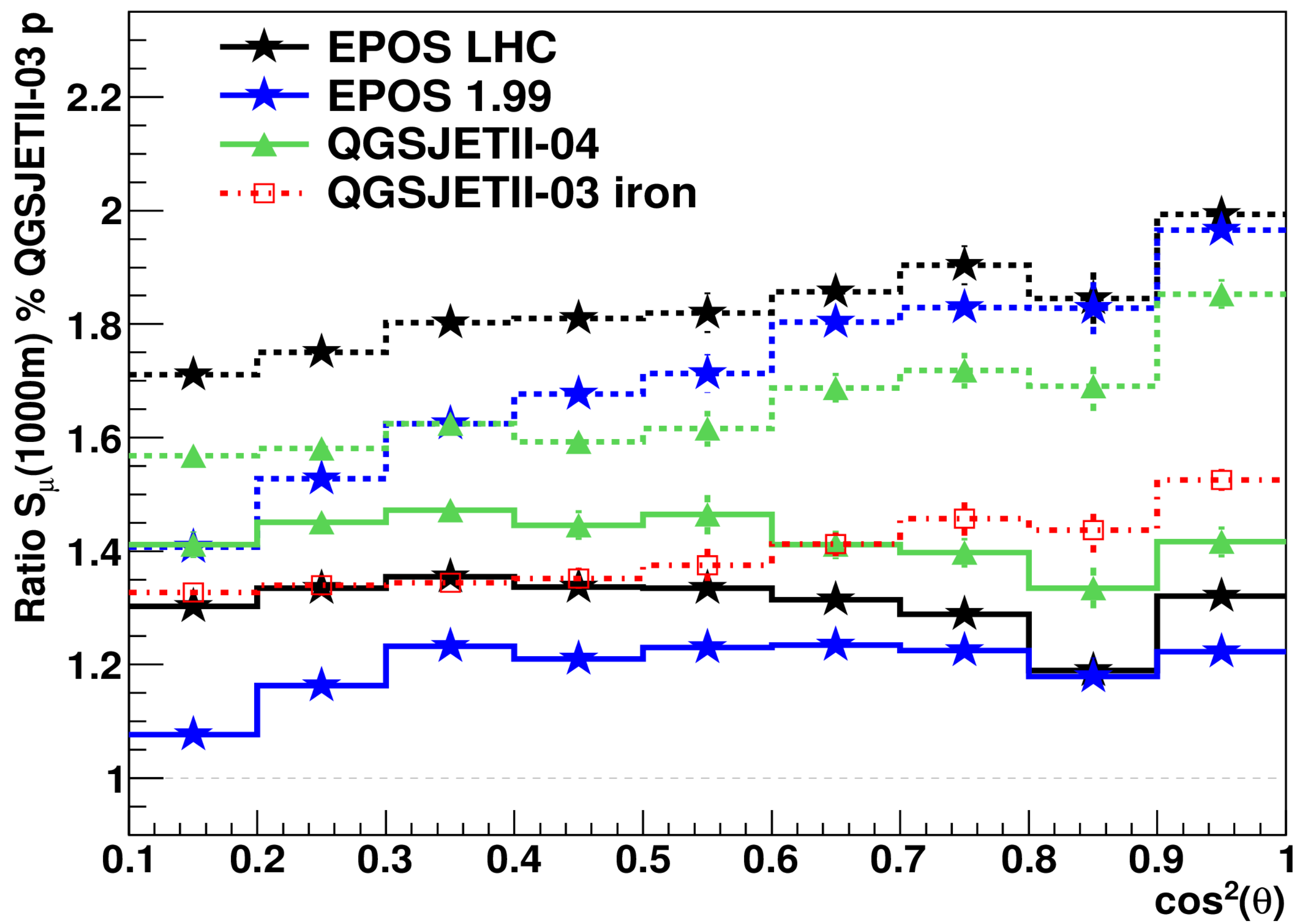
Muon Energy Spectra

- **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) !

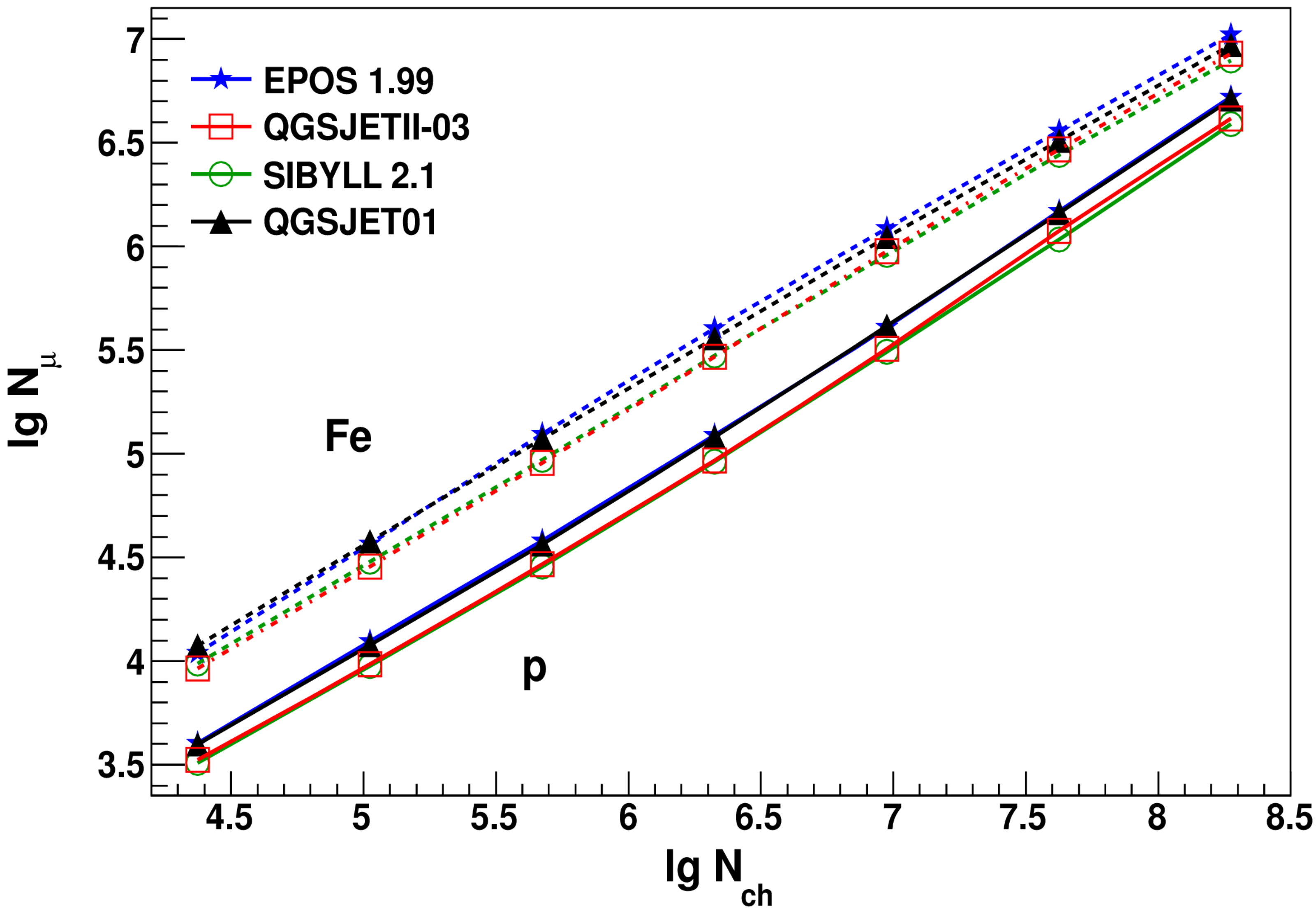


Muon Signal at 1000m for PAO

- **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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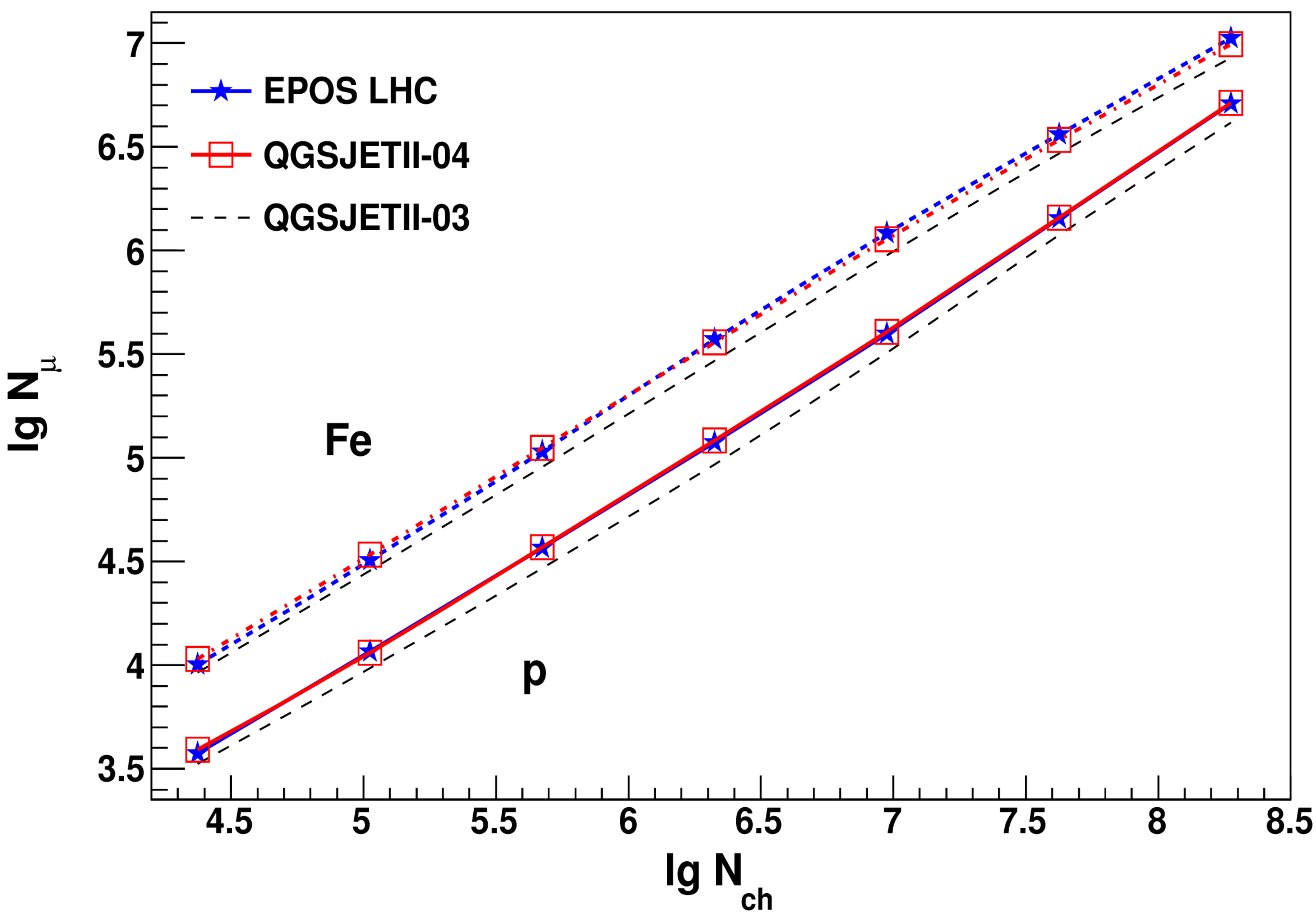
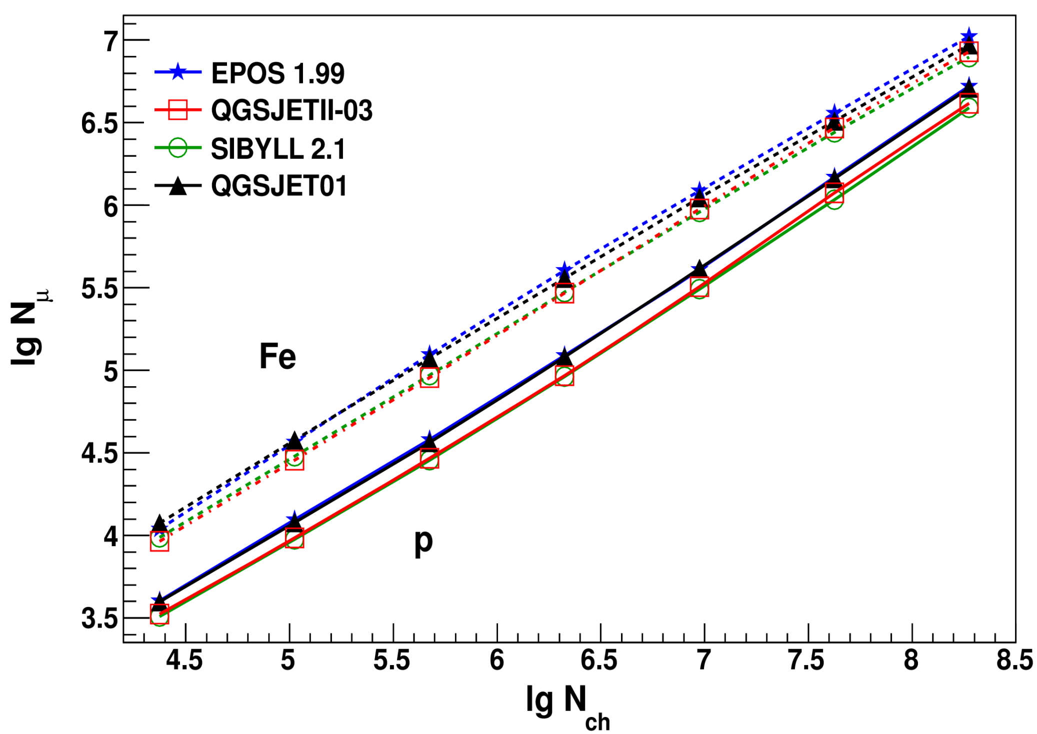
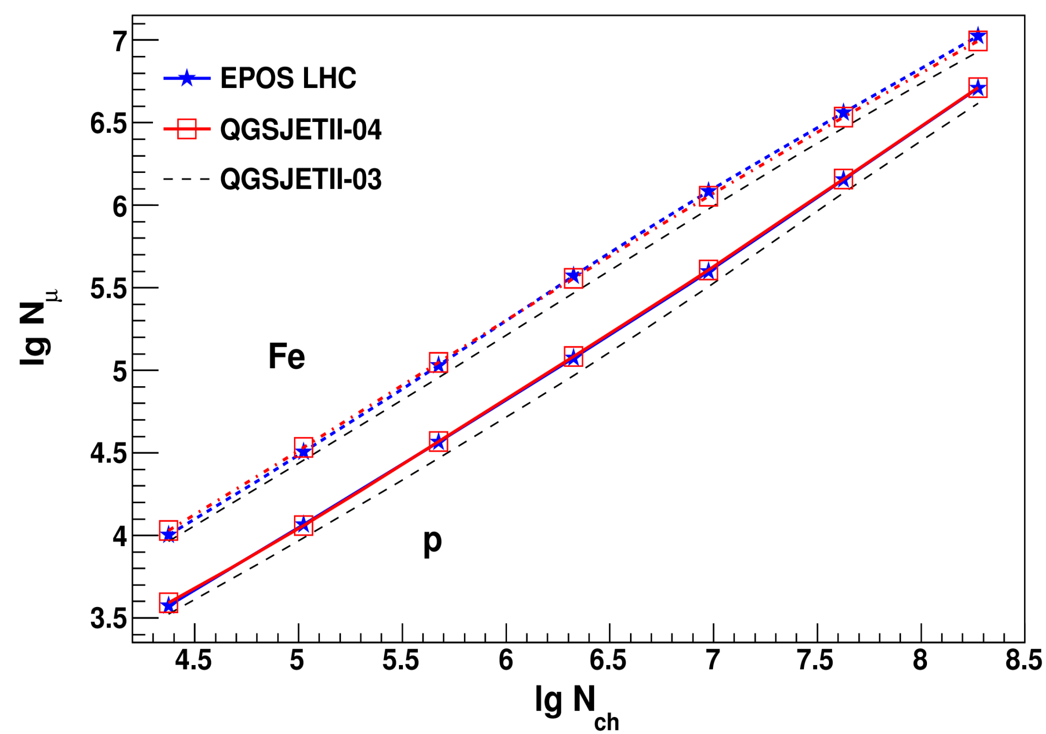


EAS with Re-tuned CR Models : Correlations

- **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





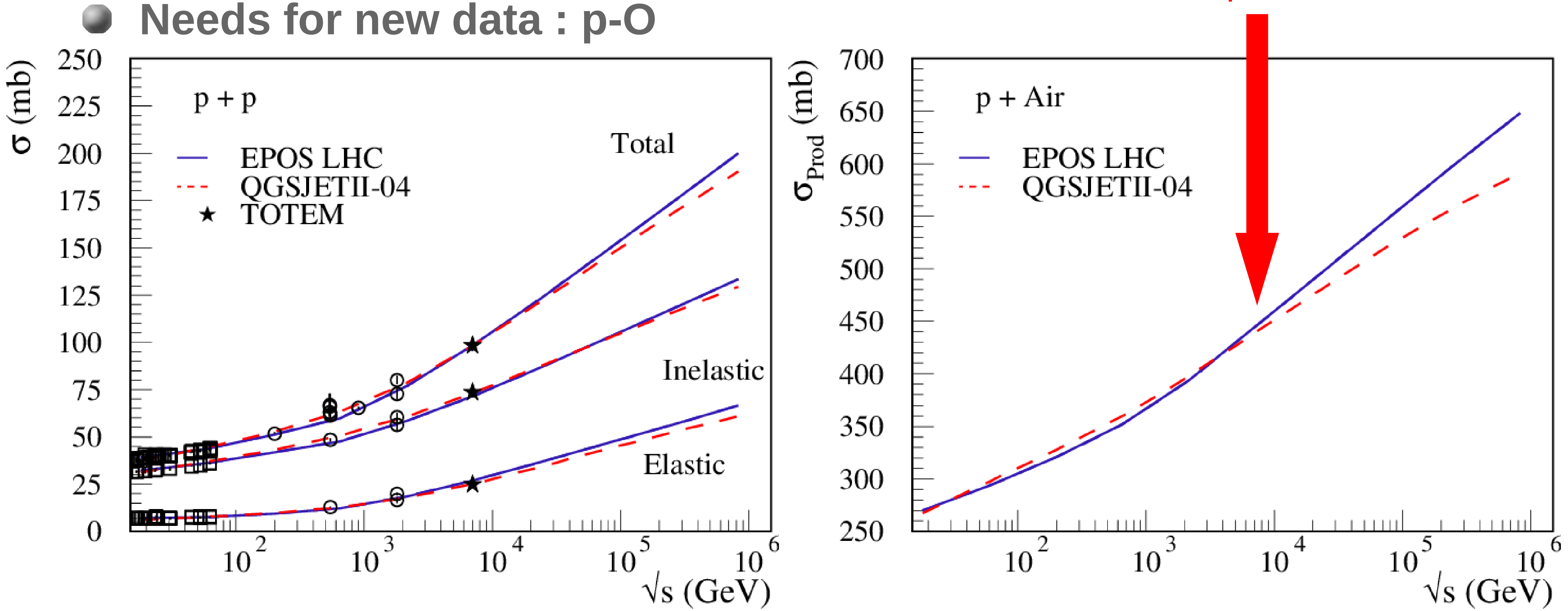
Data for Hadronic Interaction Models

- **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

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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  - ➜ to higher energies
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  - ➜ from p-p to p-Air
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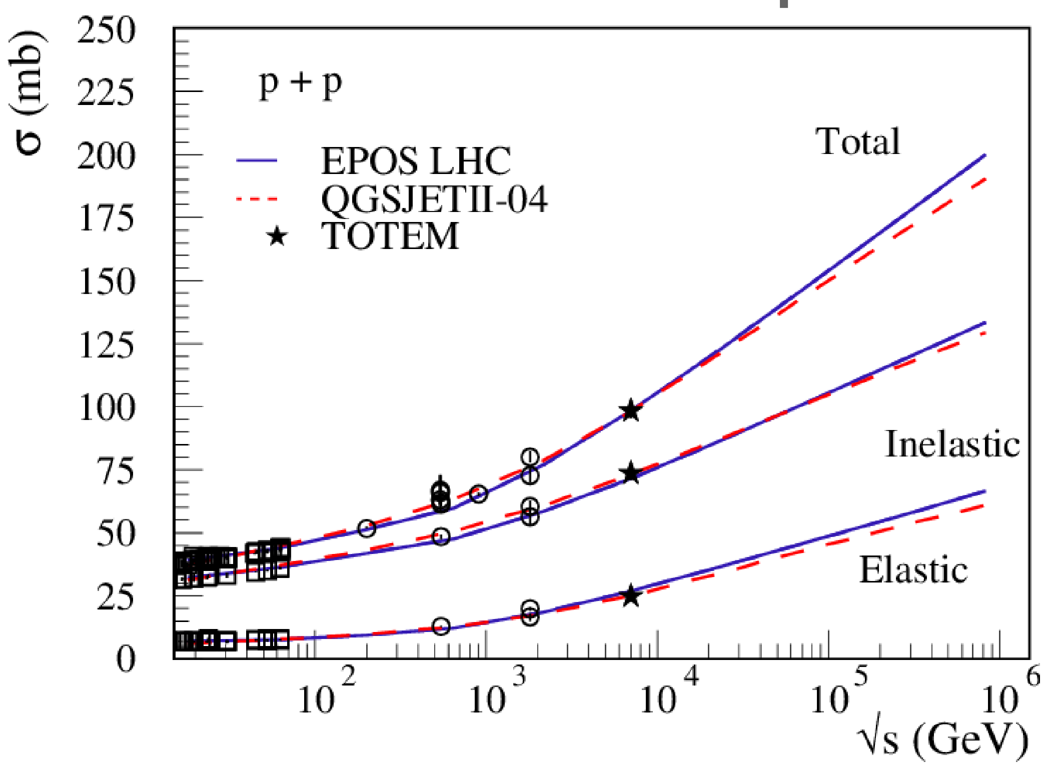
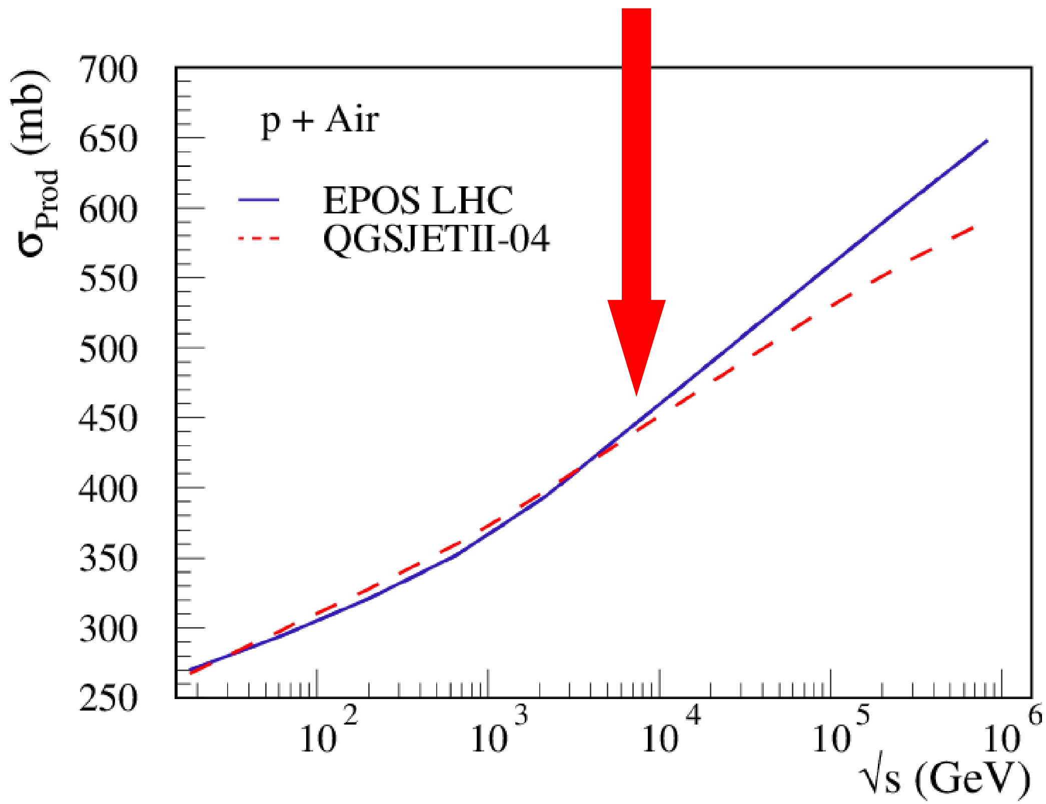
- **Needs for new data : p-O**

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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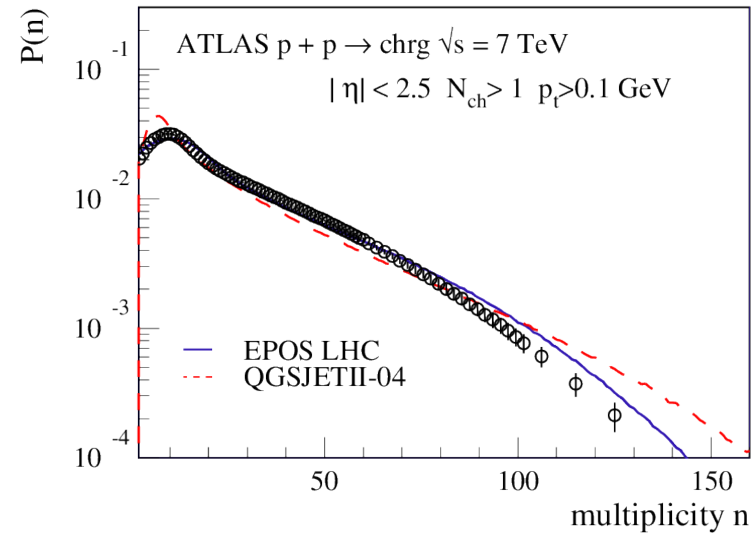

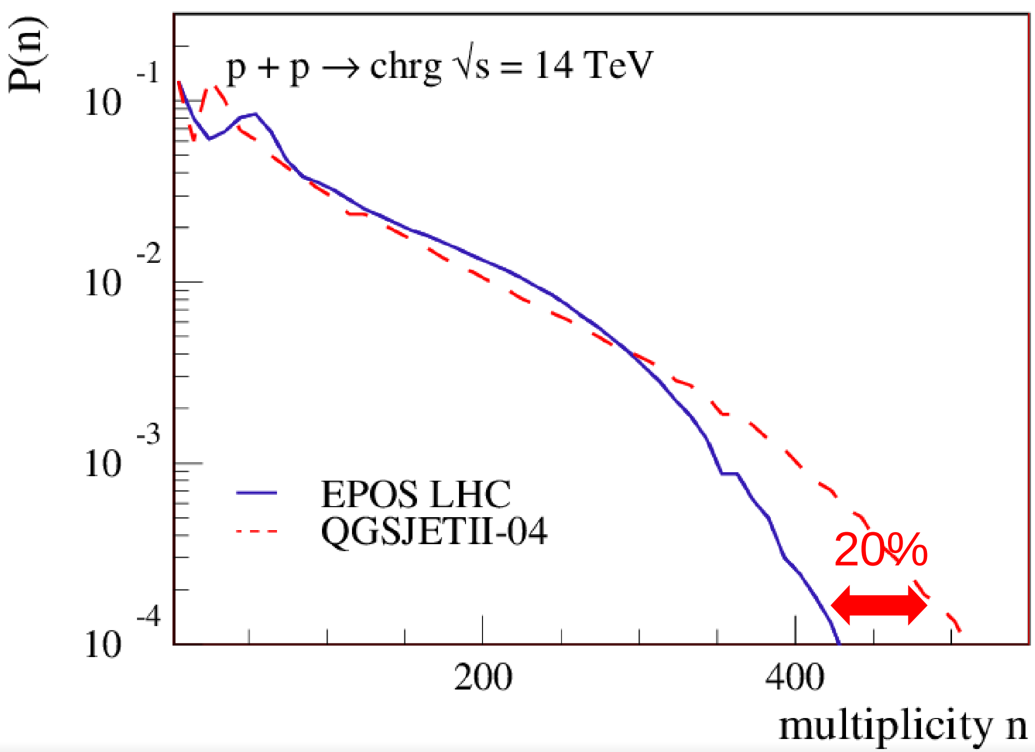

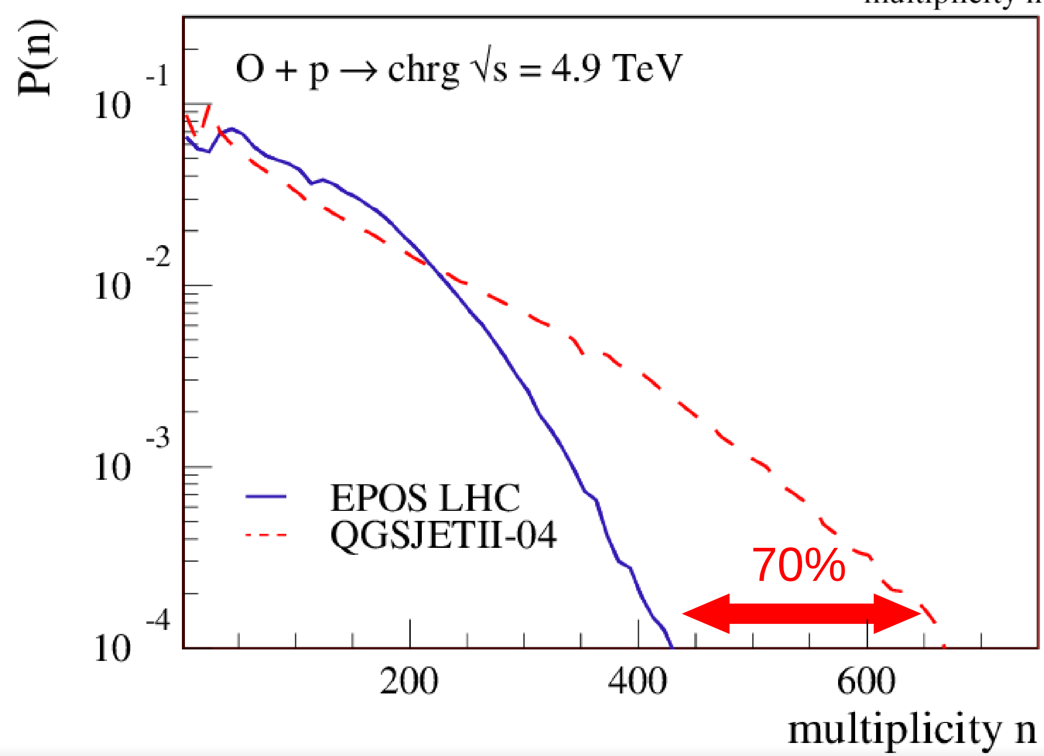

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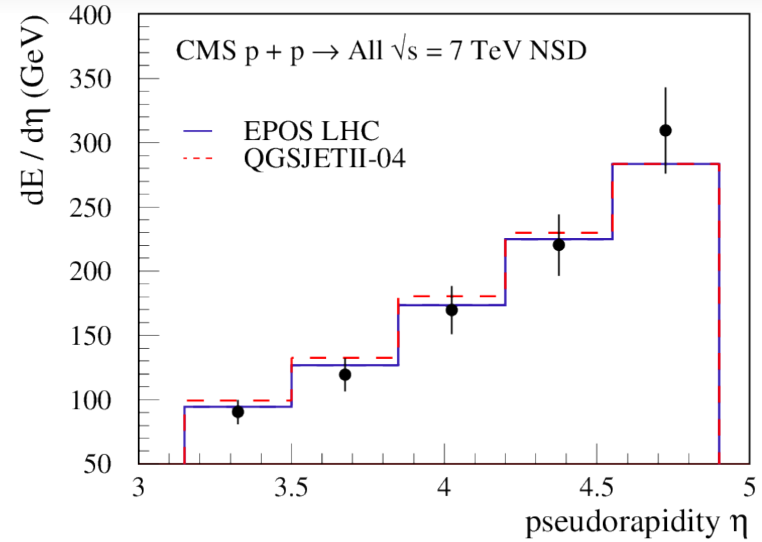
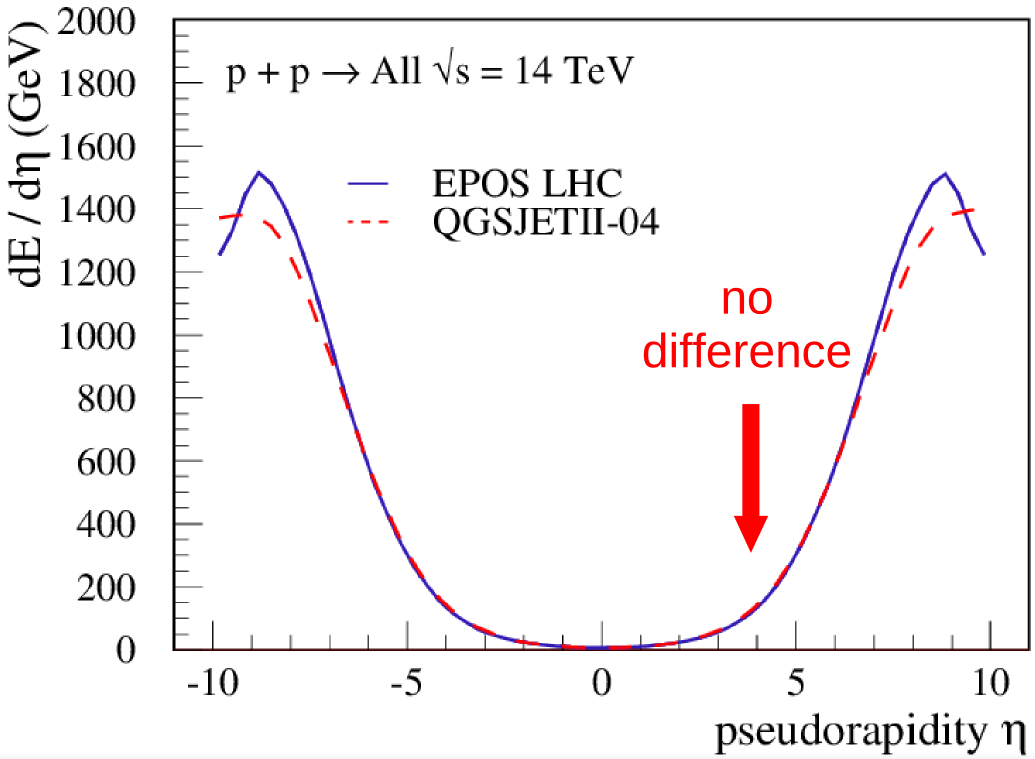
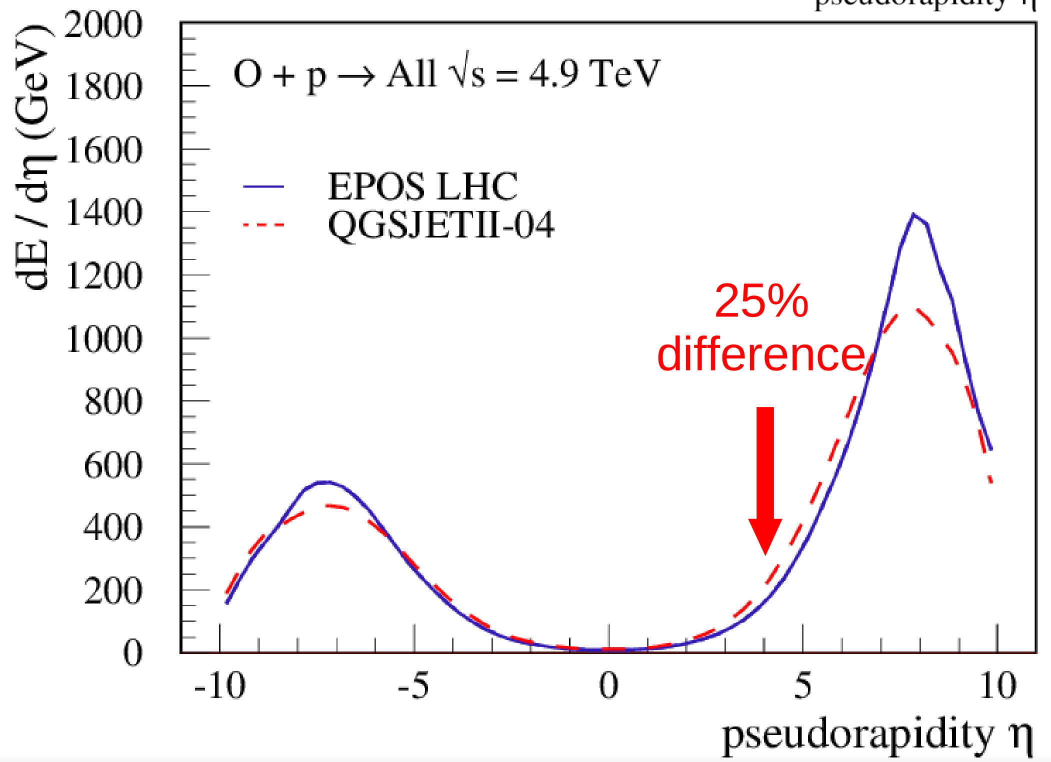
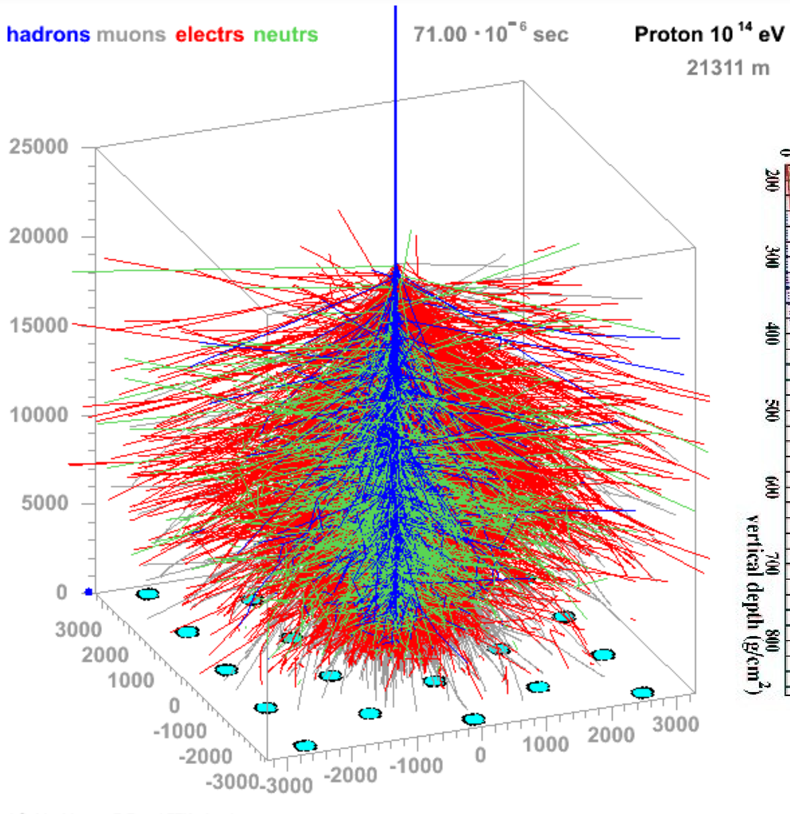
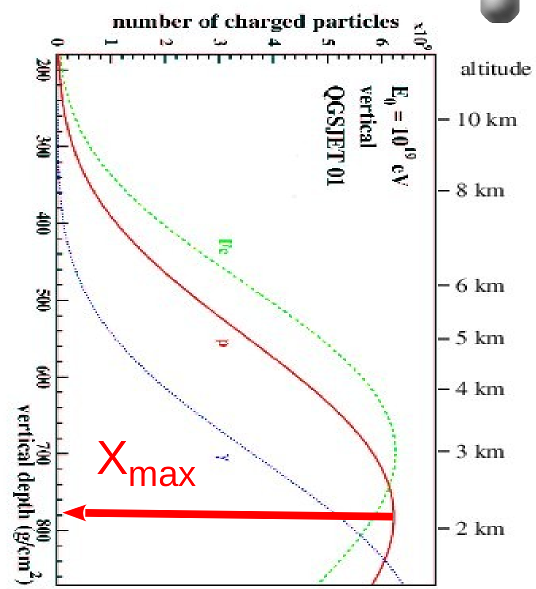


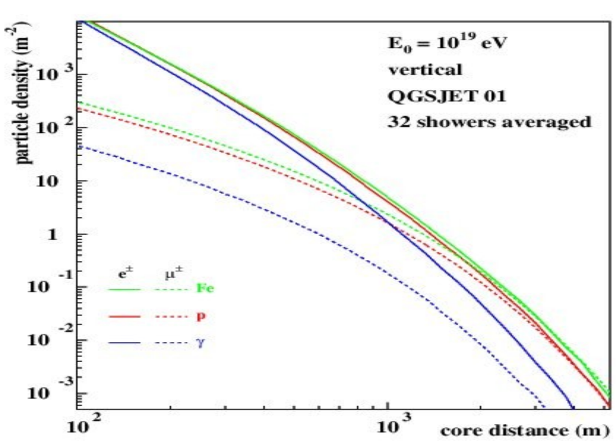




Extensive Air Shower Observables







- **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

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

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

- 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)

First hadronic generation only !

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

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

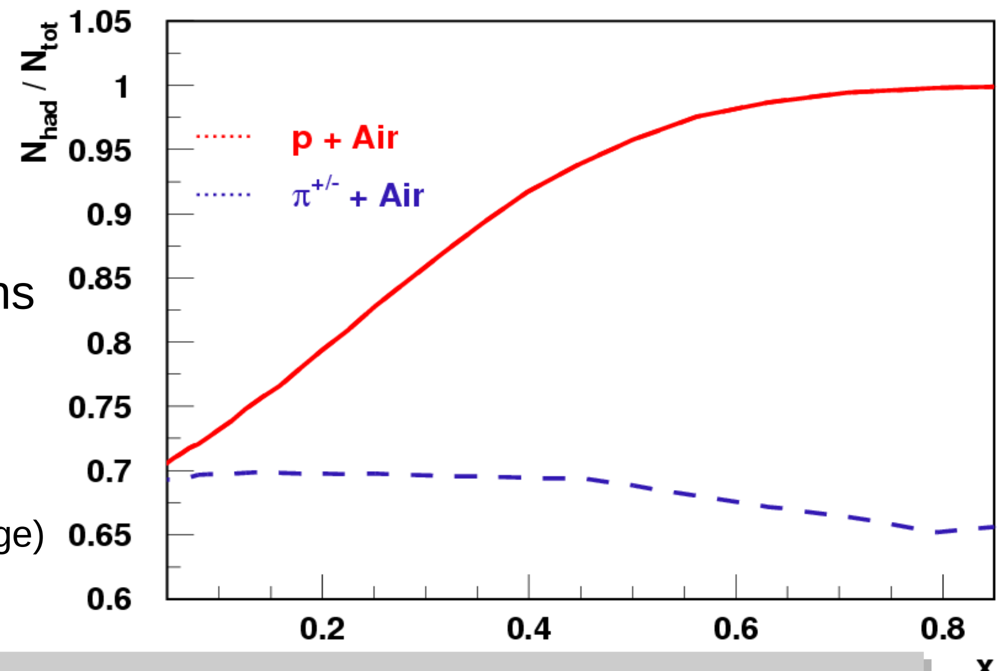
Muon Number

- **From Heitler**

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

→ after n generations

- 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)

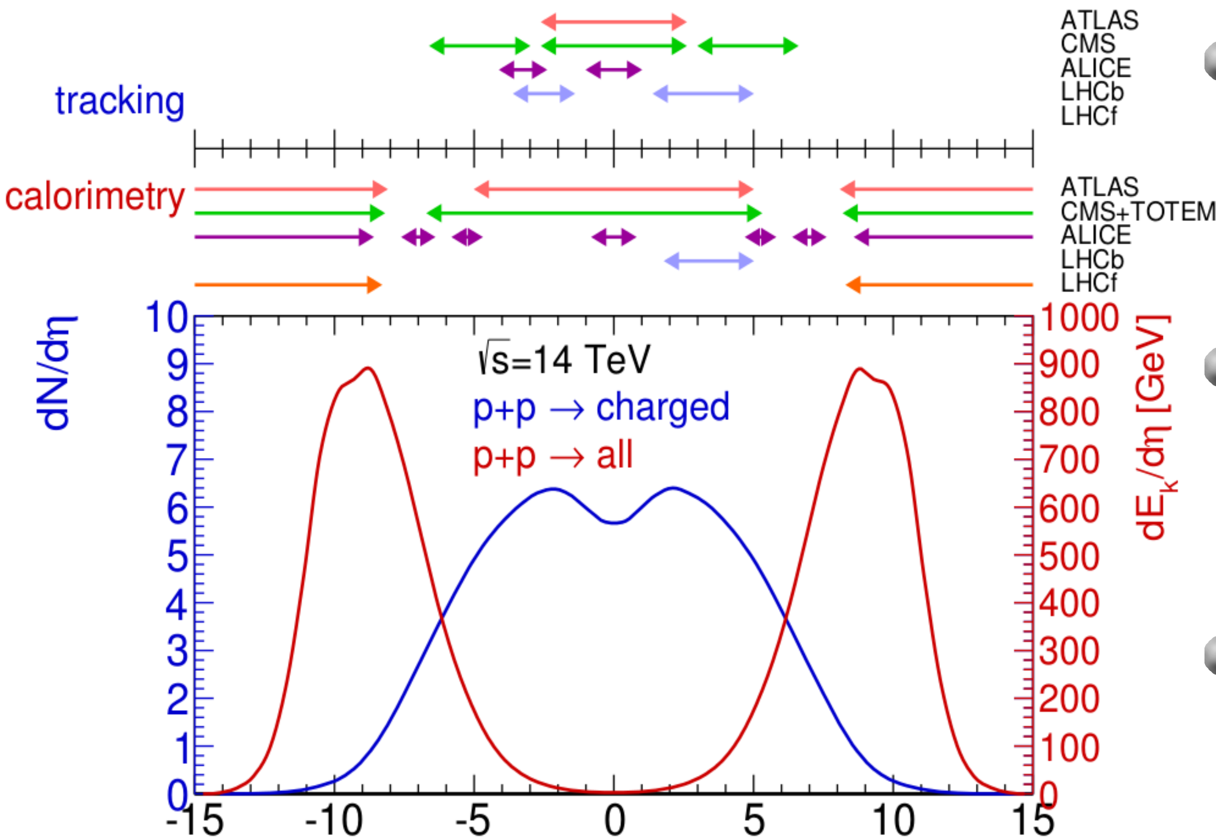


Muon number depends on the number of (anti)B in p- or π-Air interactions at all energies

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

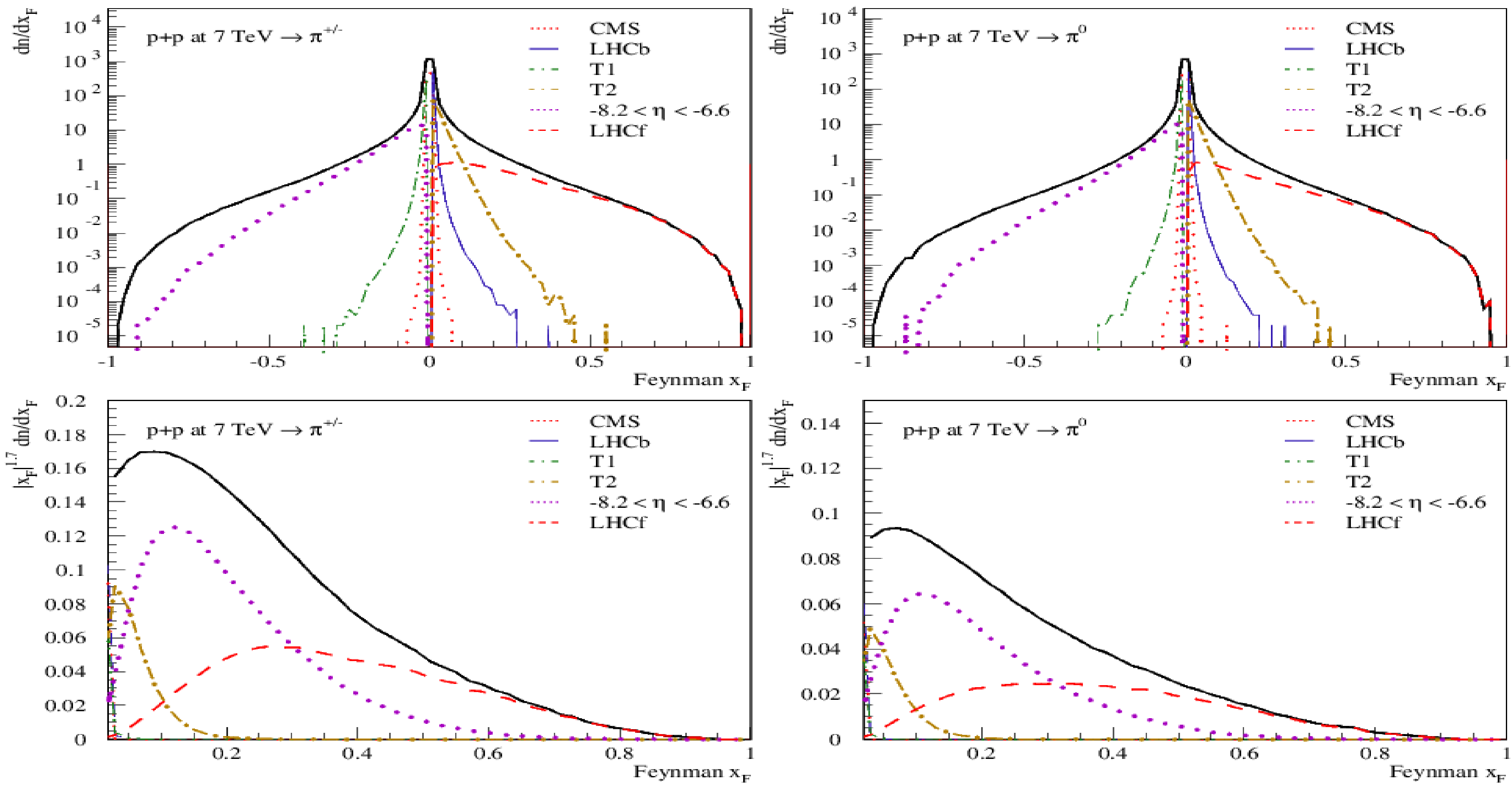
- **Energy spectrum of all muons arriving at ground**
  - convolution of CR spectrum, composition of primary and hadronic interactions
  - important for neutrino experiment like Ice-Cube (atmospheric neutrino flux is the background of astrophysical neutrinos)

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

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

- **dn/dx_F should be known for $\pi^+,\pi^-,K^+,K^-,D^+,D^-\ldots$**

Example : Inclusive Muon Spectra (2)



- In the range of LHCf … but charged particles not seen by LHCf !
  - extrapolation needed
  - **Hadronic models are needed even for incl. flux.**

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)