pA at the LHC and Extensive Air Shower Development

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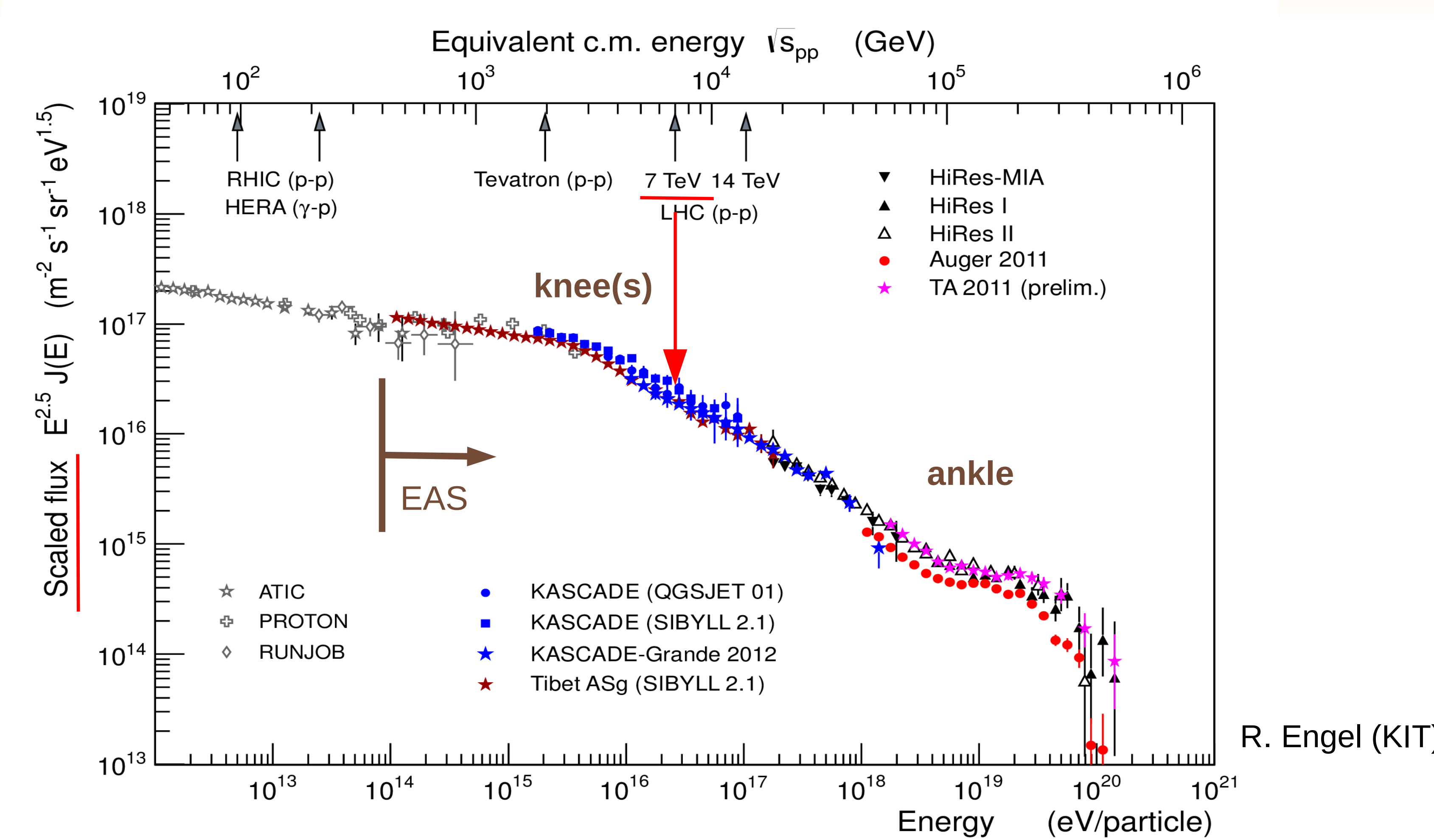
Cosmic Ray Spectrum



- **Origins of spectrum properties**
  - mostly unknown
  - depend on primary CR mass
- **Most of analysis based on EAS simulations**
  - CORSIKA
  - AIRES
  - COSMOS
  - CONEX, ...

Outline

- **Hadronic Interaction Models for CR**
  - New models
- **Connection with Cosmic Rays (CR)**
  - Heitler model
- **LHC and Xmax**
  - Longitudinal development
- **LHC and muons in Extensive Air Showers (EAS)**
  - Particles at ground
- **Summary**

Hadronic Interaction Models

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

Pb : CR physic dominated by soft interactions

Pb : Gribov-Regge do not take into account energy conservation ...

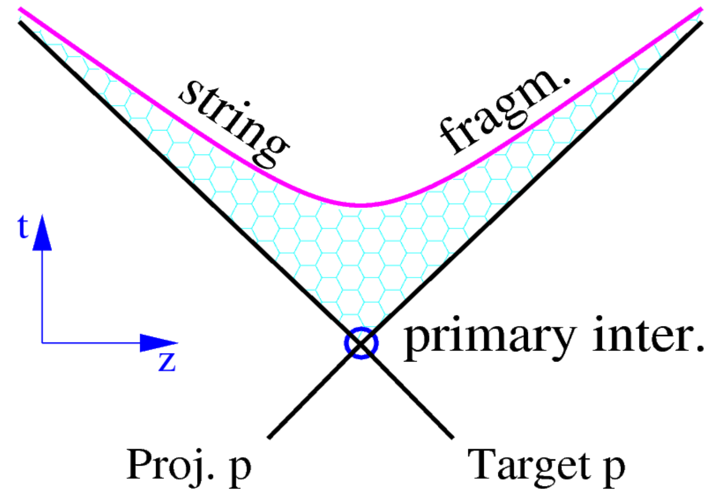
- **Phenomenology (models) :**
  - string fragmentation
  - beam remnants
  - diffraction (Good-Walker, ...)
  - higher order effects

Need Parameters !

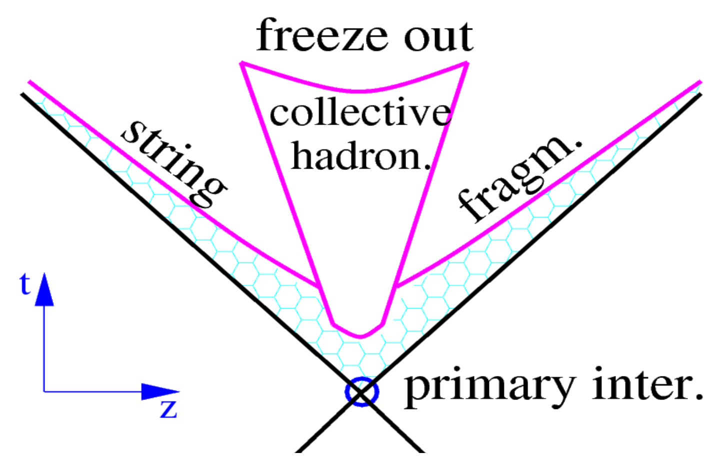
- **Models corrected to take into account LHC data (pp) :**
  - QGSJETII-04 : minimum theory requirement with few parameters and limited data set : optimized for CR (S. Ostapchenko).
  - EPOS LHC : more detailed data with more parameters : complete picture (even heavy ion) (K. Werner and TP).

New Models after LHC

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

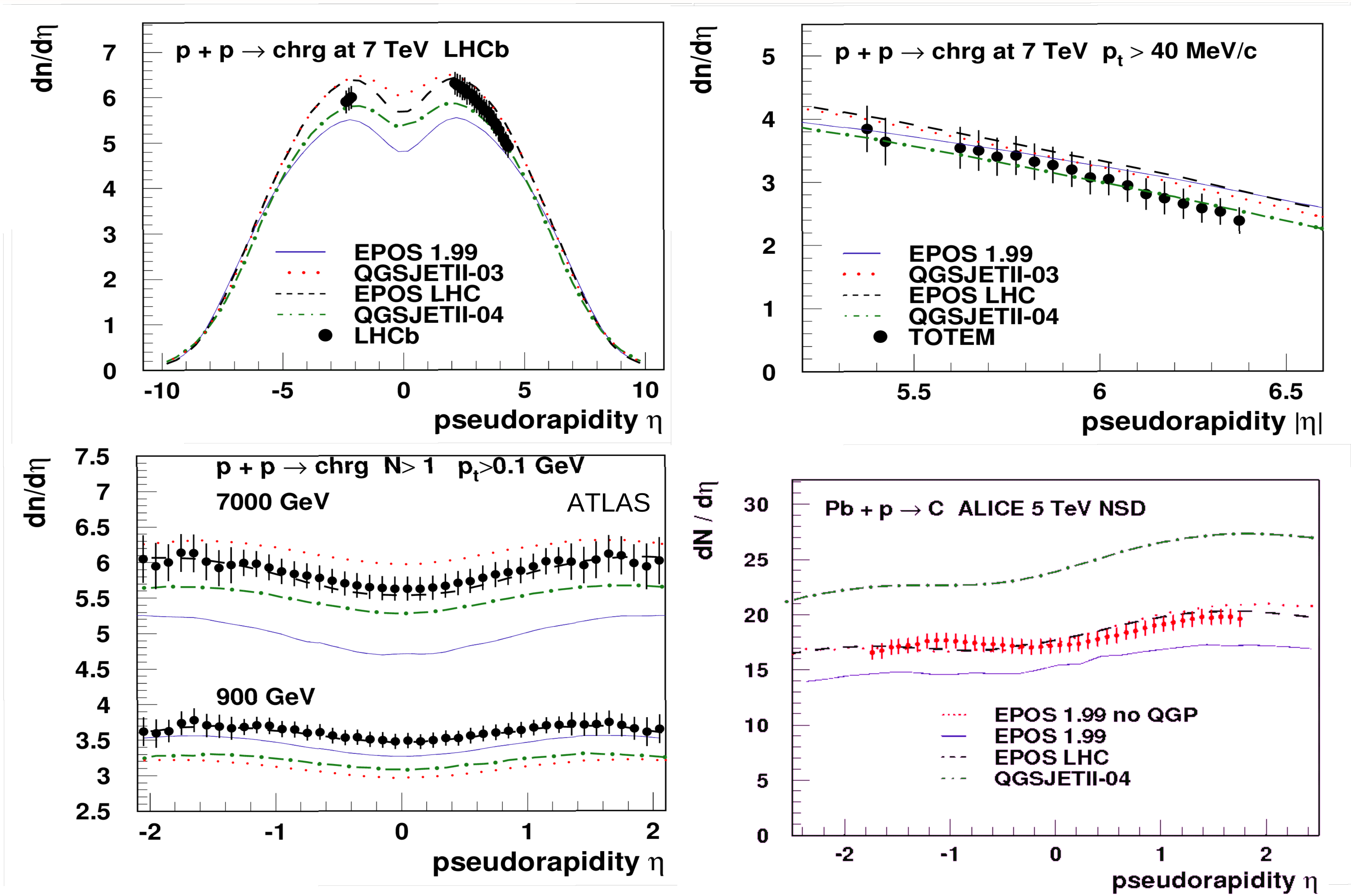


- **EPOS 1.99 to EPOS LHC**
  - tune cross section to TOTEM value
  - change old flow calculation to a more realistic one
  - introduce central diffraction
  - keep compatibility with lower energies

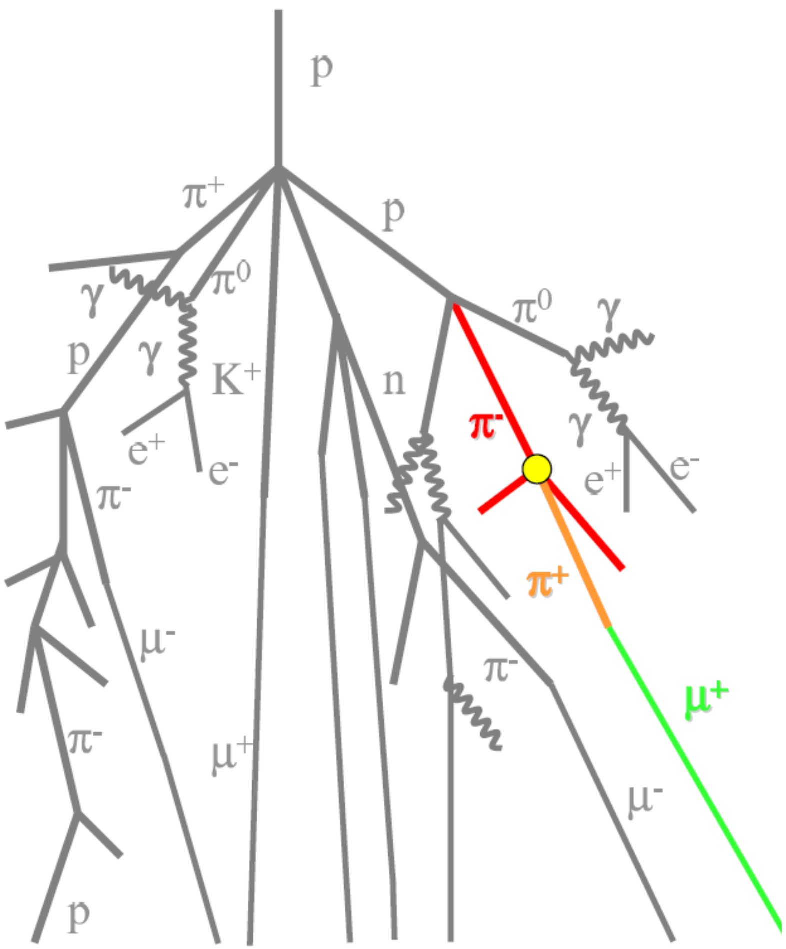


Direct influence of collective effects on EAS simulations to be shown but important to compare to LHC and set parameters properly (<pt>, ...).

Pseudorapidity Distributions



Extensive Air Shower



From R. Ulrich (KIT)

$$A + air \rightarrow \text{hadrons}$$
$$p + air \rightarrow \text{hadrons}$$
$$\pi + air \rightarrow \text{hadrons}$$

main source of uncertainties

intial γ from π^0 decay

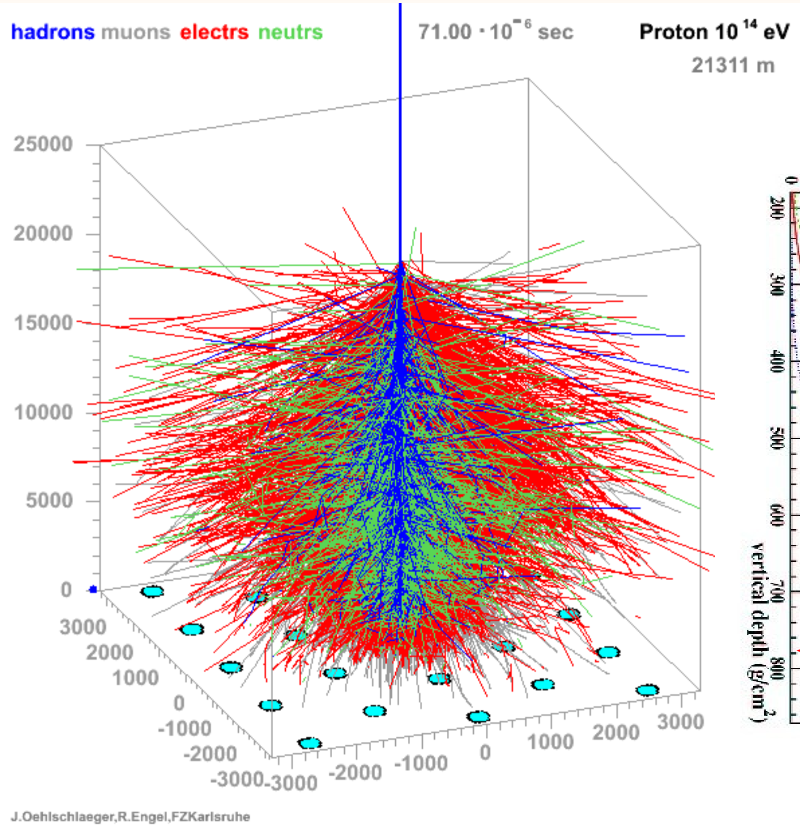
$$e^{\pm} \rightarrow e^{\pm} + \gamma$$
$$\gamma \rightarrow e^{+} + e^{-}$$

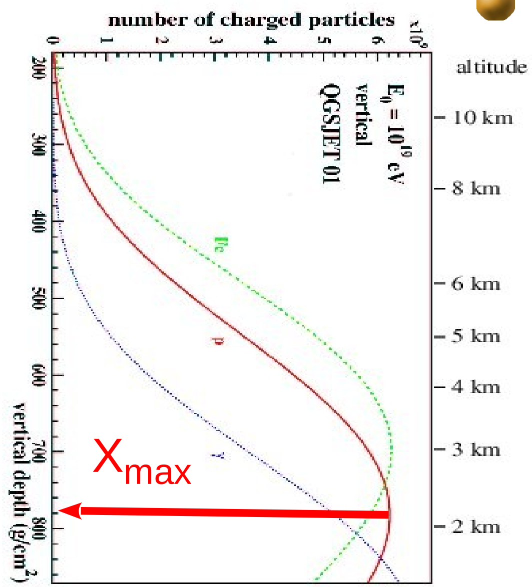
well known

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

- **Cascade of particle in Earth's atmosphere**
  - Number of particles at maximum
    - 99,88% of electromagnetic (e/m) particles
    - 0.1% of muons
    - 0.02% hadrons
  - Energy
    - from 100% hadronic to 90% in e/m + 10% in muons at ground (vertical)

Extensive Air Shower Observables



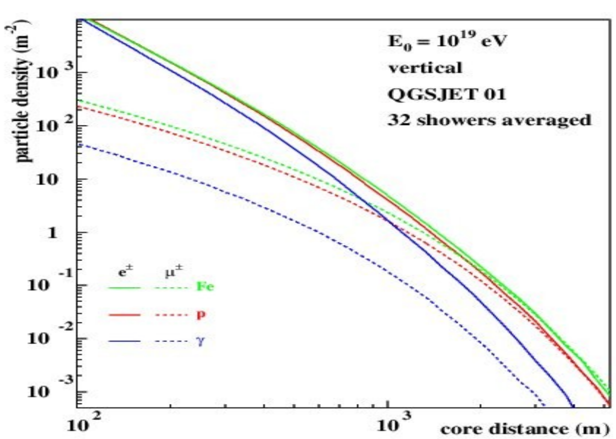


- **Longitudinal Development**
  - number of particles vs depth

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

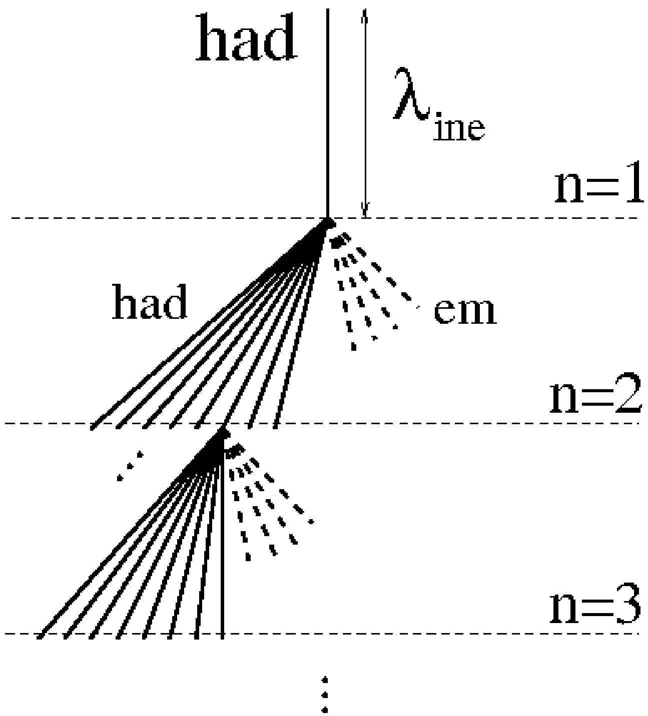
  - Larger number of particles at X_{max}

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



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

Simplified Shower Development



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

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

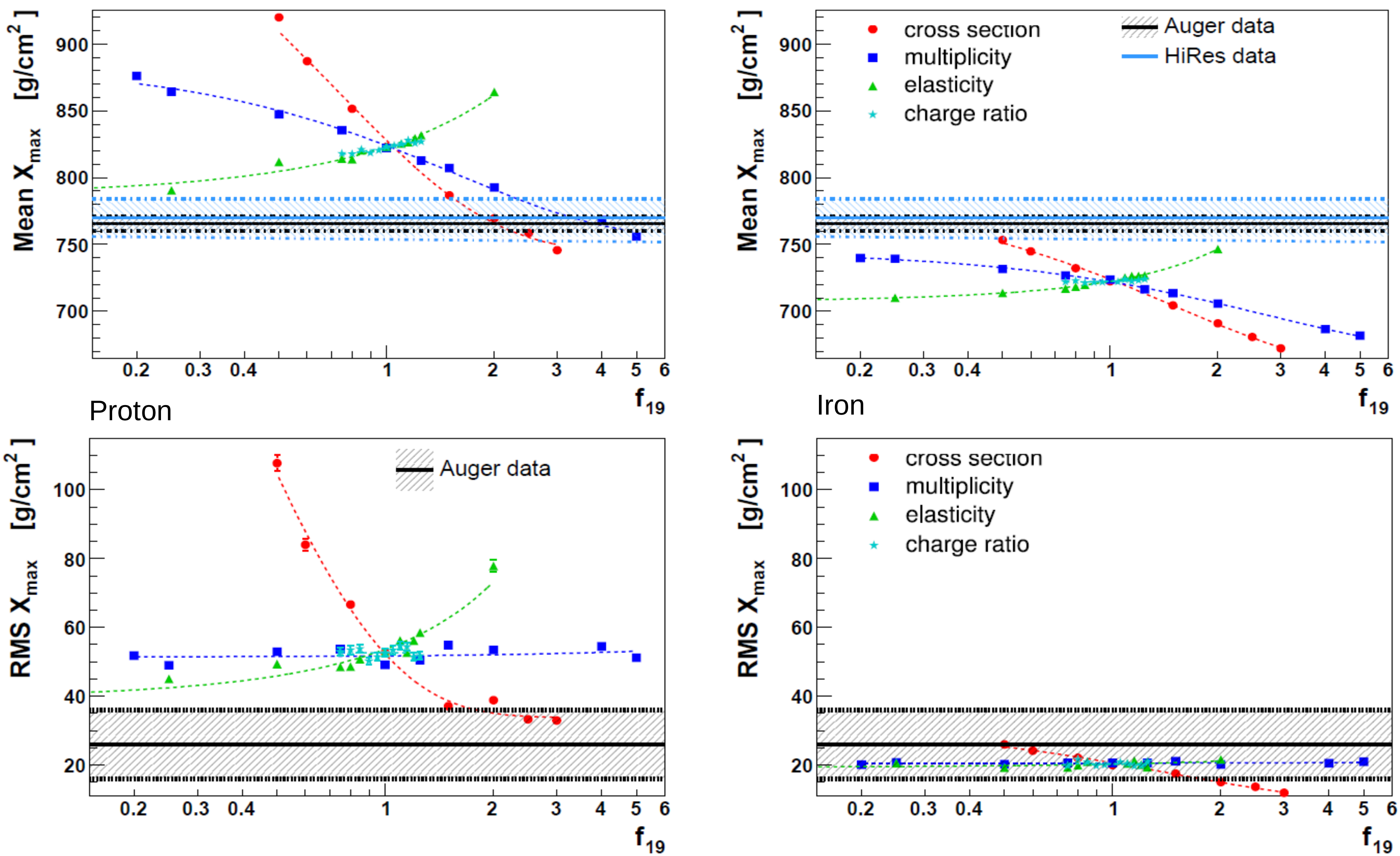
- **Using generalized Heitler model and superposition model :**

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

- 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)

Effects of Parameters

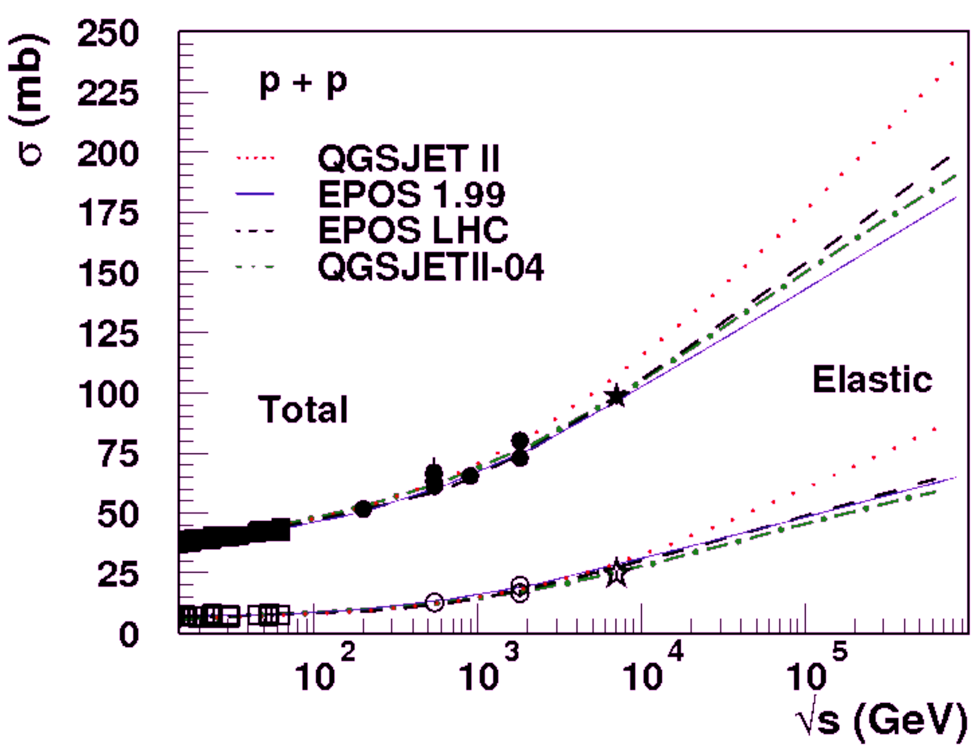
Sensibility depends on observable and parameter :

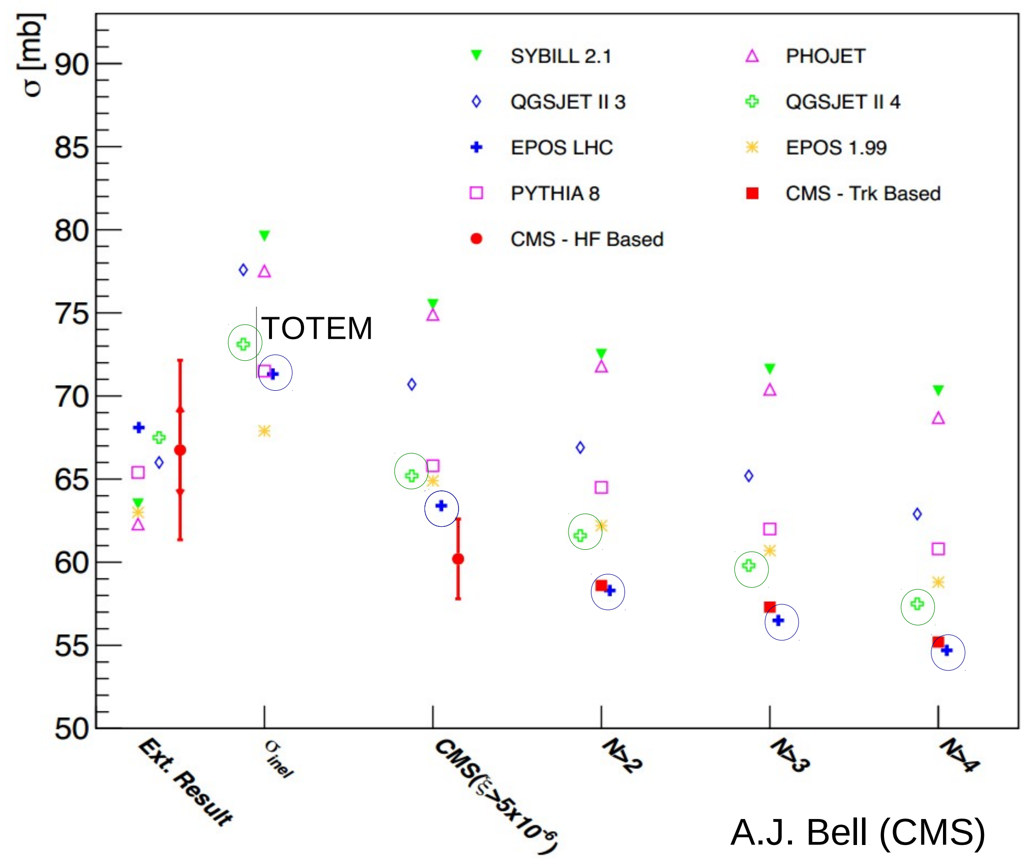


Plots by R. Ulrich (KIT) with Sibyll model and PAO data @ 10^{19} eV

Cross Sections

- Same cross sections at pp level up to LHC
- extrapolation to pA or to high energy
  - weak energy dependence : no room for large change beyond LHC
- LHC measurements test the difference between models (diffraction)

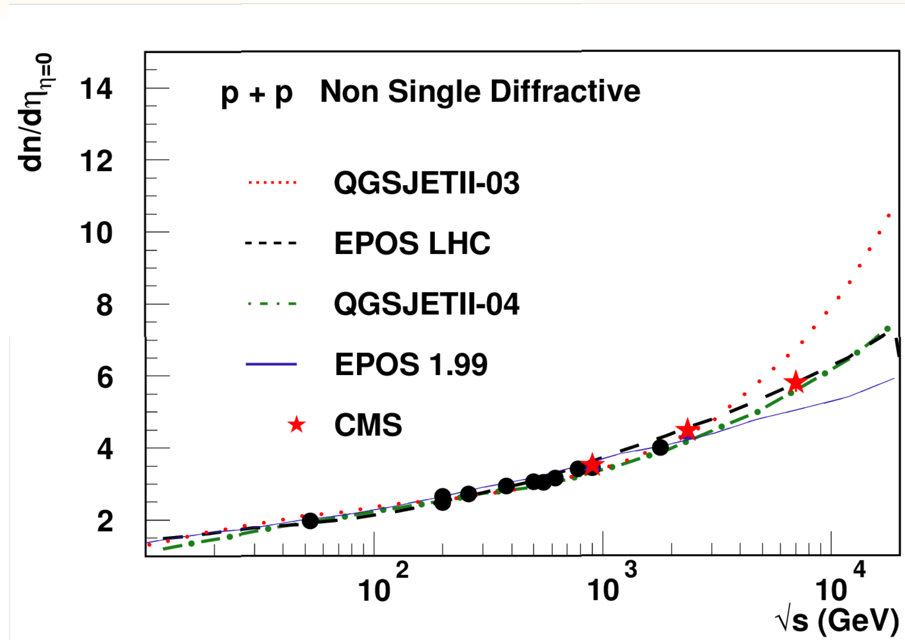


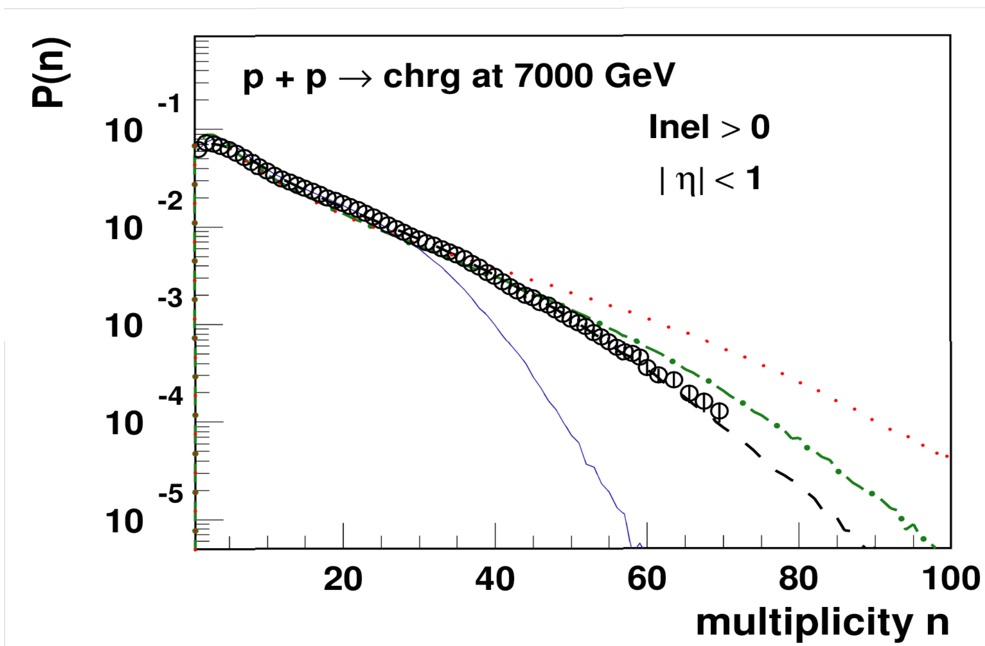


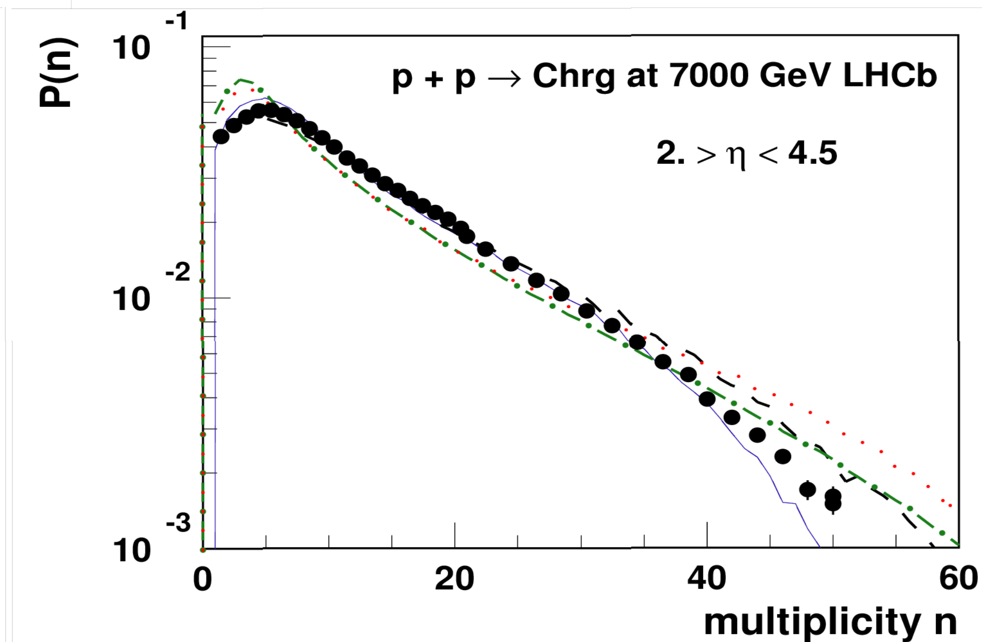
A.J. Bell (CMS)

Multiplicity

- **Consistent results**
  - Better energy evolution
    - TOTEM cross section
  - Better tail of multiplicity distributions
    - corrections in EPOS LHC (flow) and QGSJETII-04 (minimum string size)

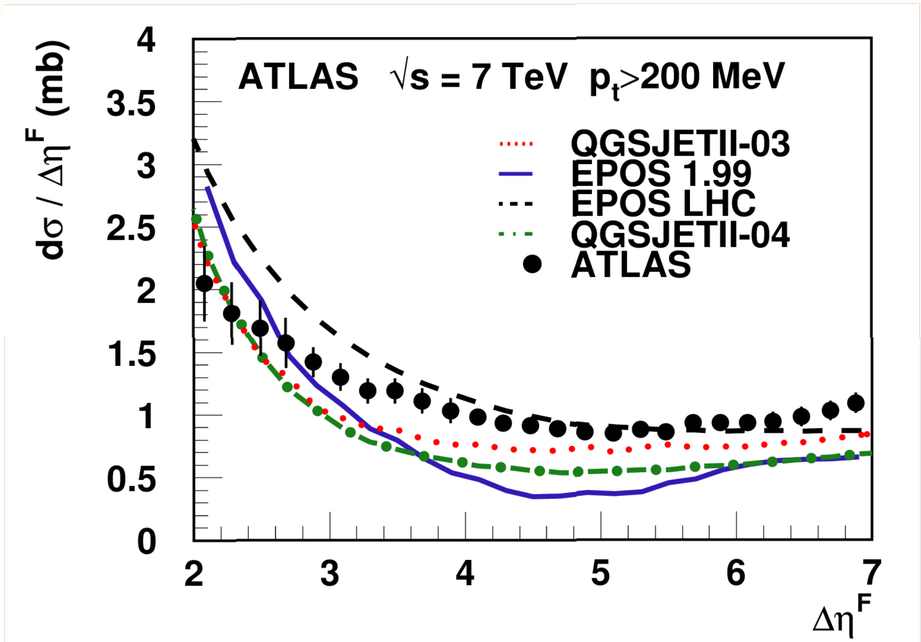


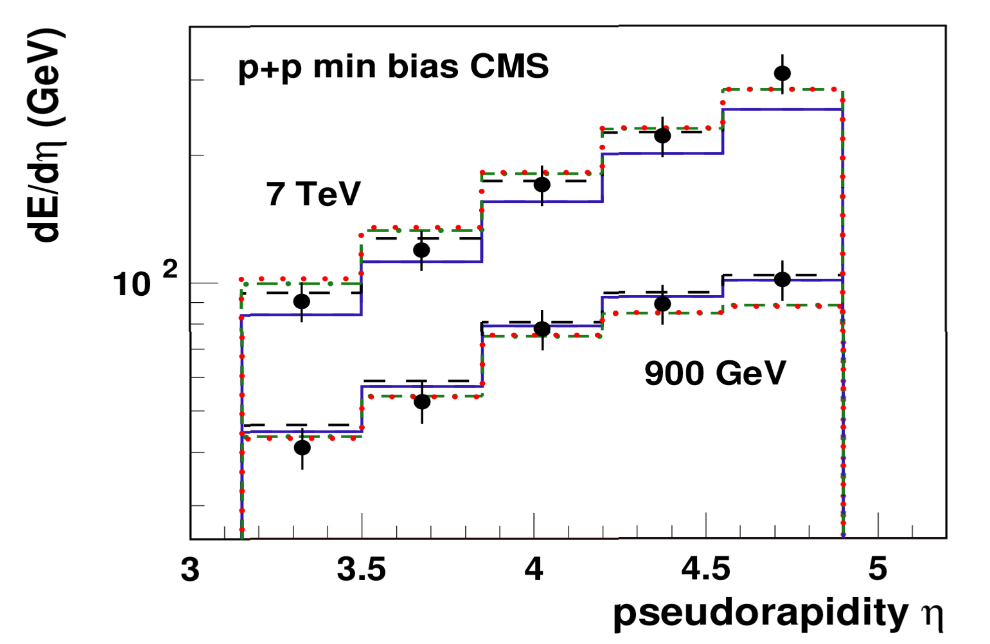


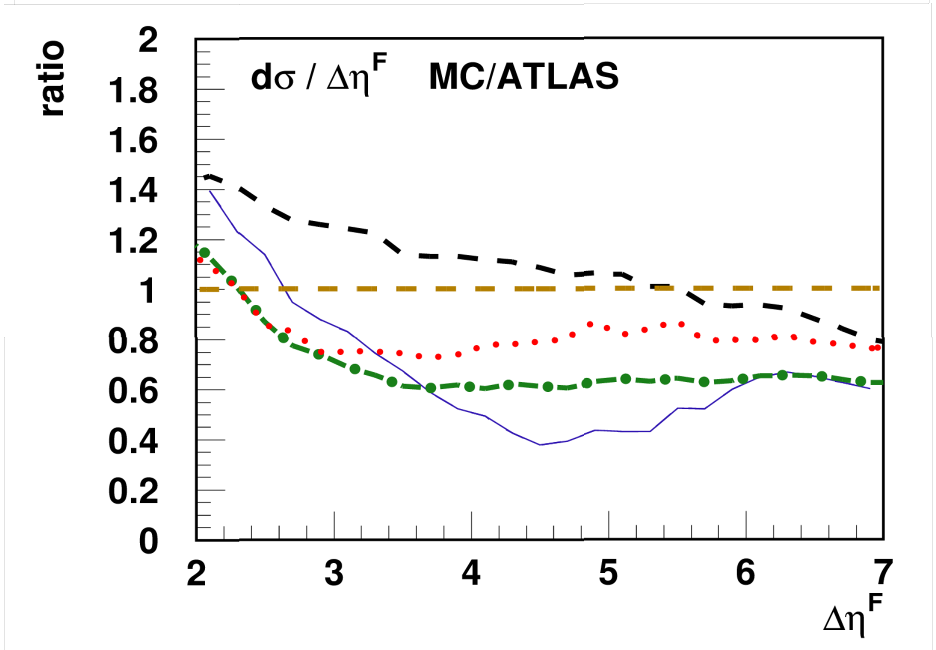


Inelasticity

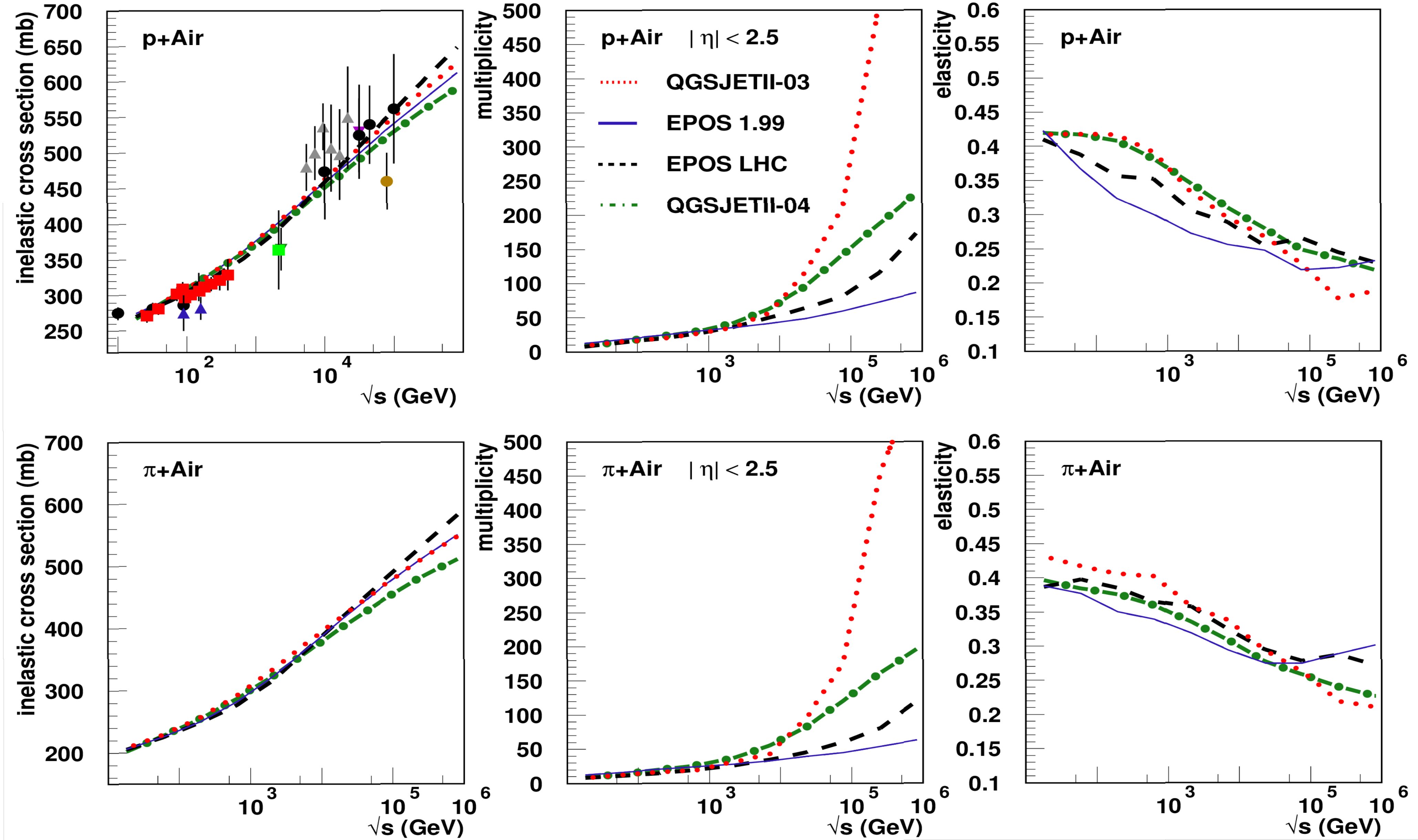
- **More uncertainty**
  - Difference in diffraction
    - low mass
    - high mass
    - central
  - very similar energy flow



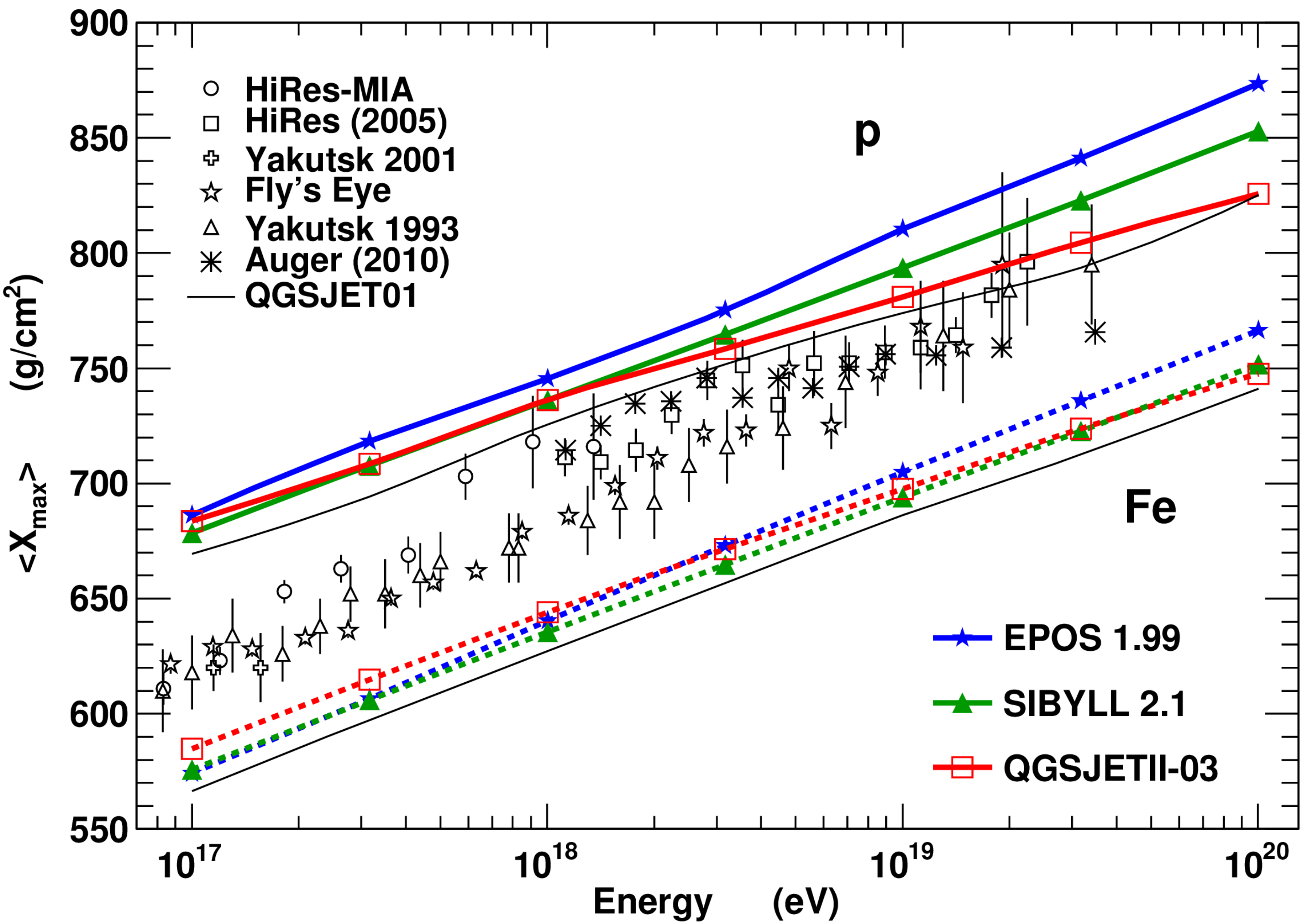




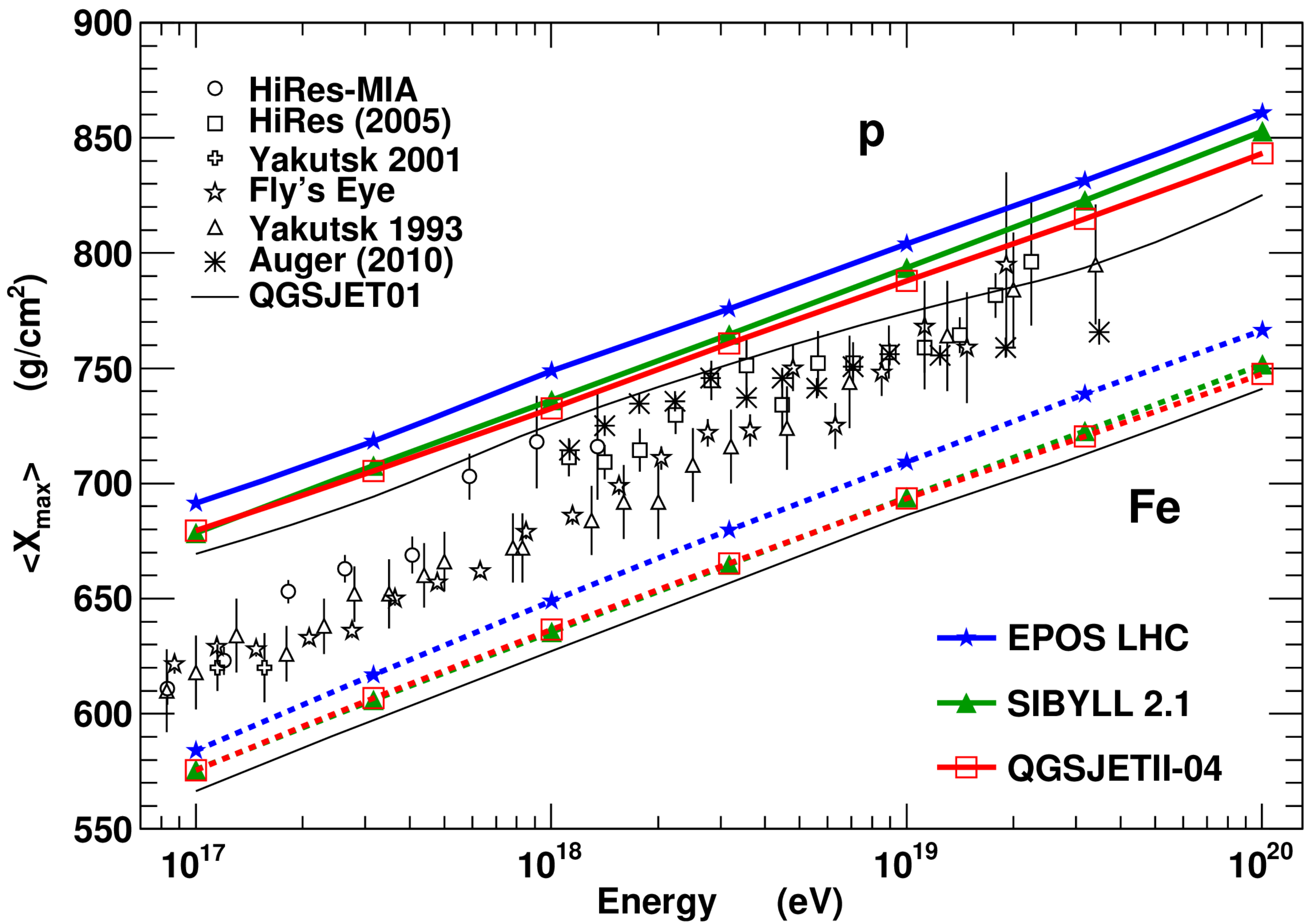
Predictions with retuned models



EAS with old CR Models : X_{max}

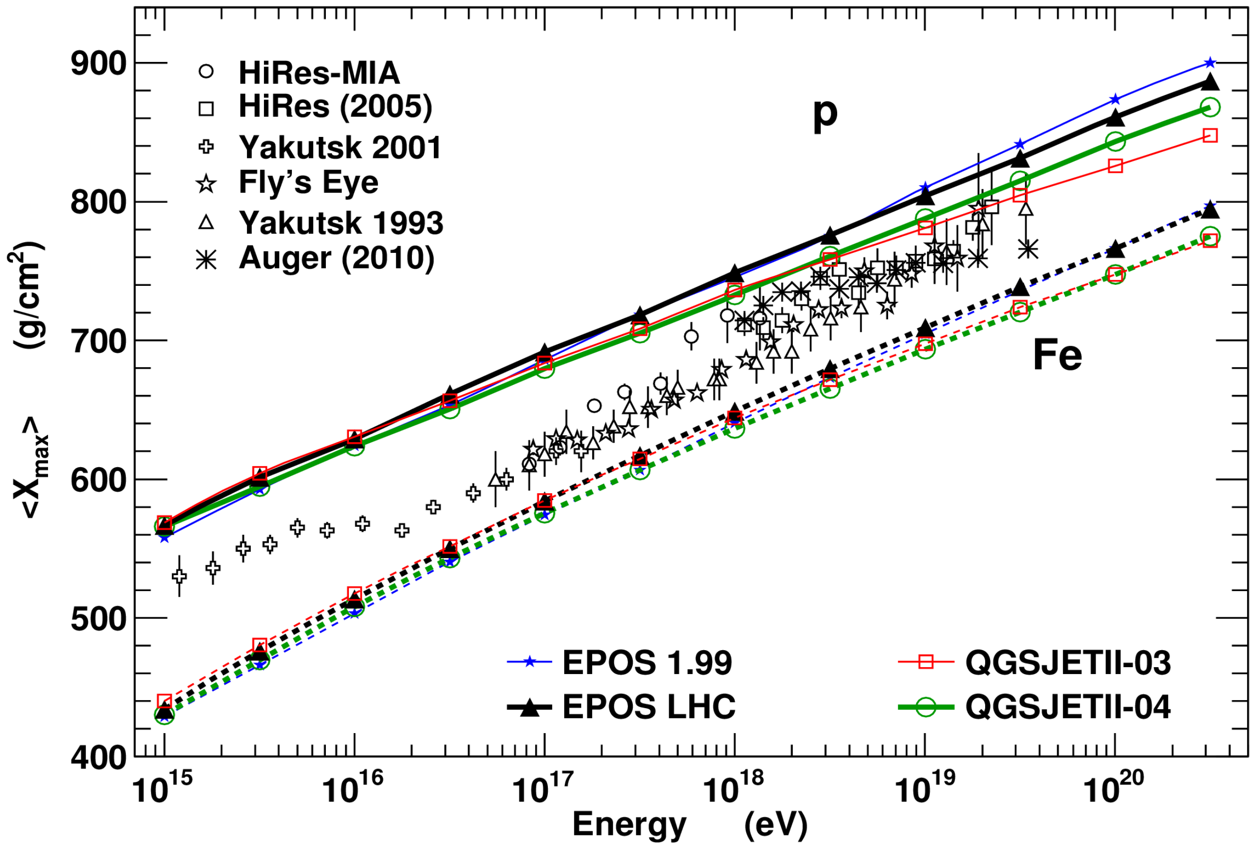


EAS with Re-tuned CR Models : X_{max}



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)

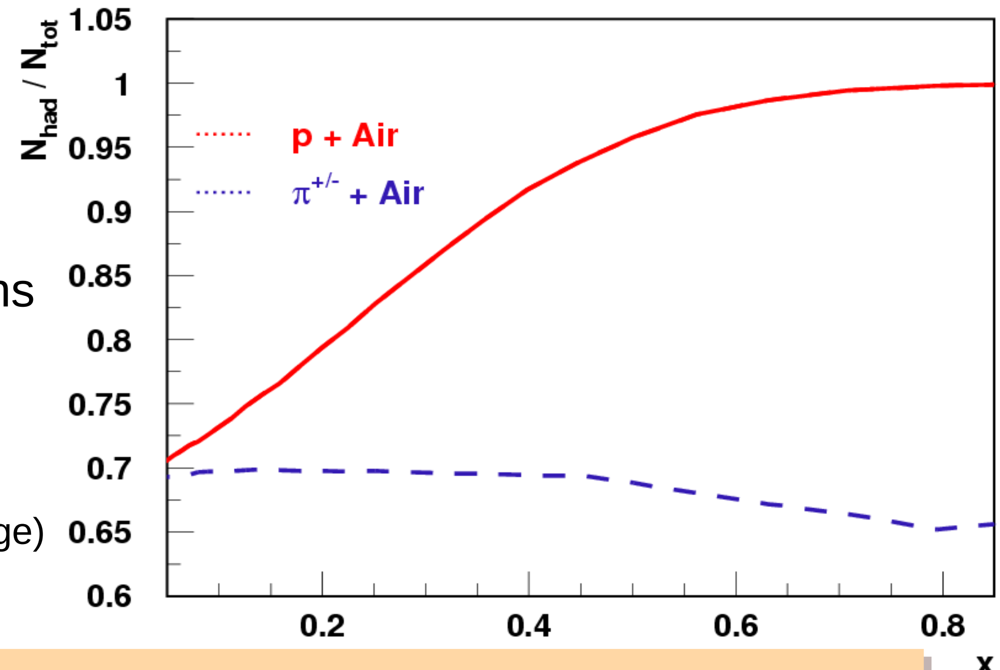


Muon Number

- **From Heitler**

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

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



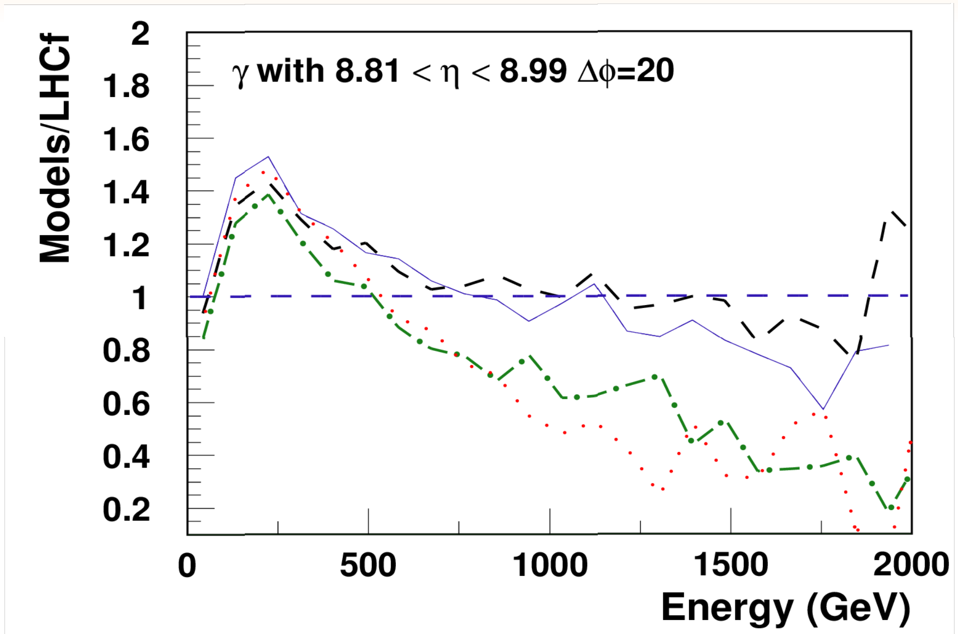
Muon number depends on the number of (anti)B in p- or π-Air interactions at all energies

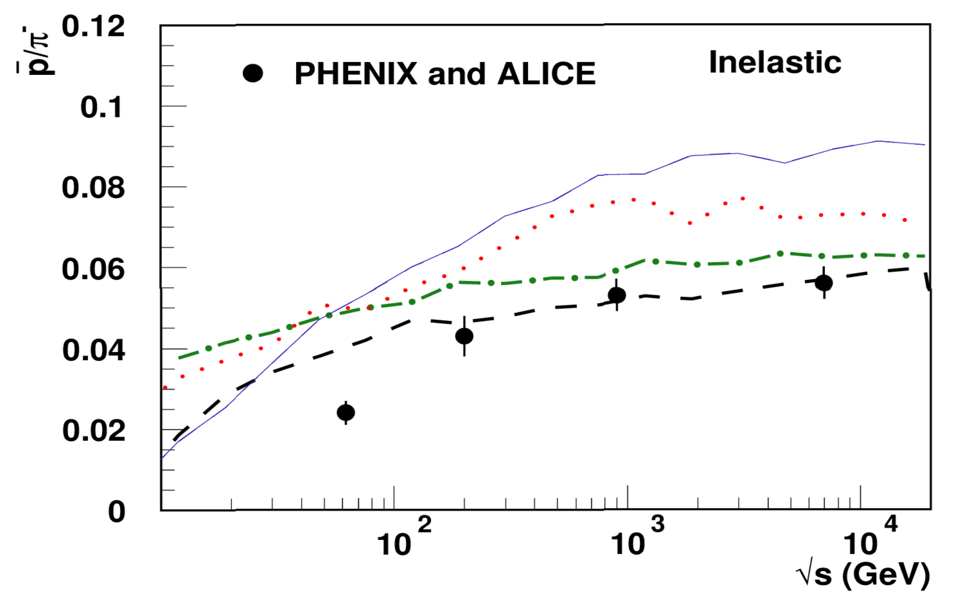
More fast (anti)baryons = more muons

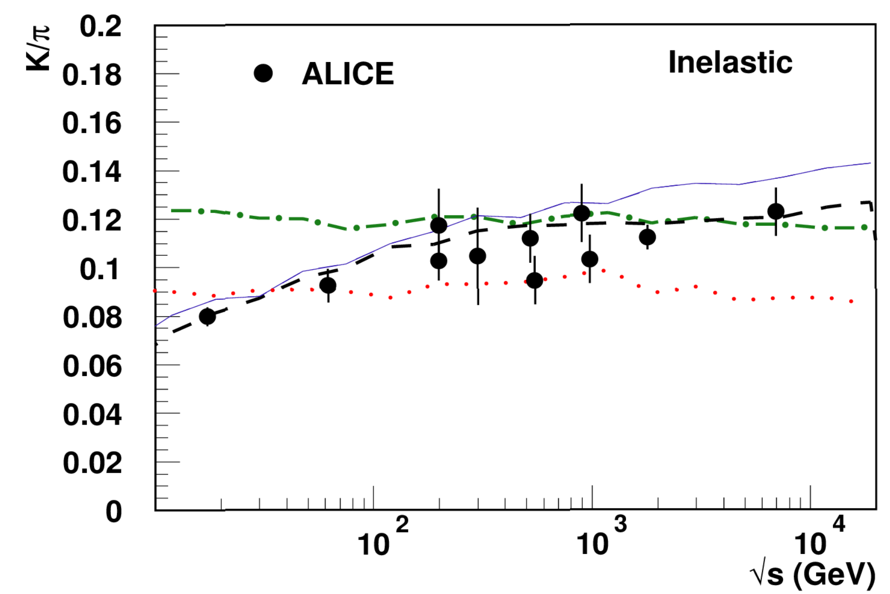
T. Pierog et al.,Phys.Rev.Lett. 101 (2008) 171101

Identified particles

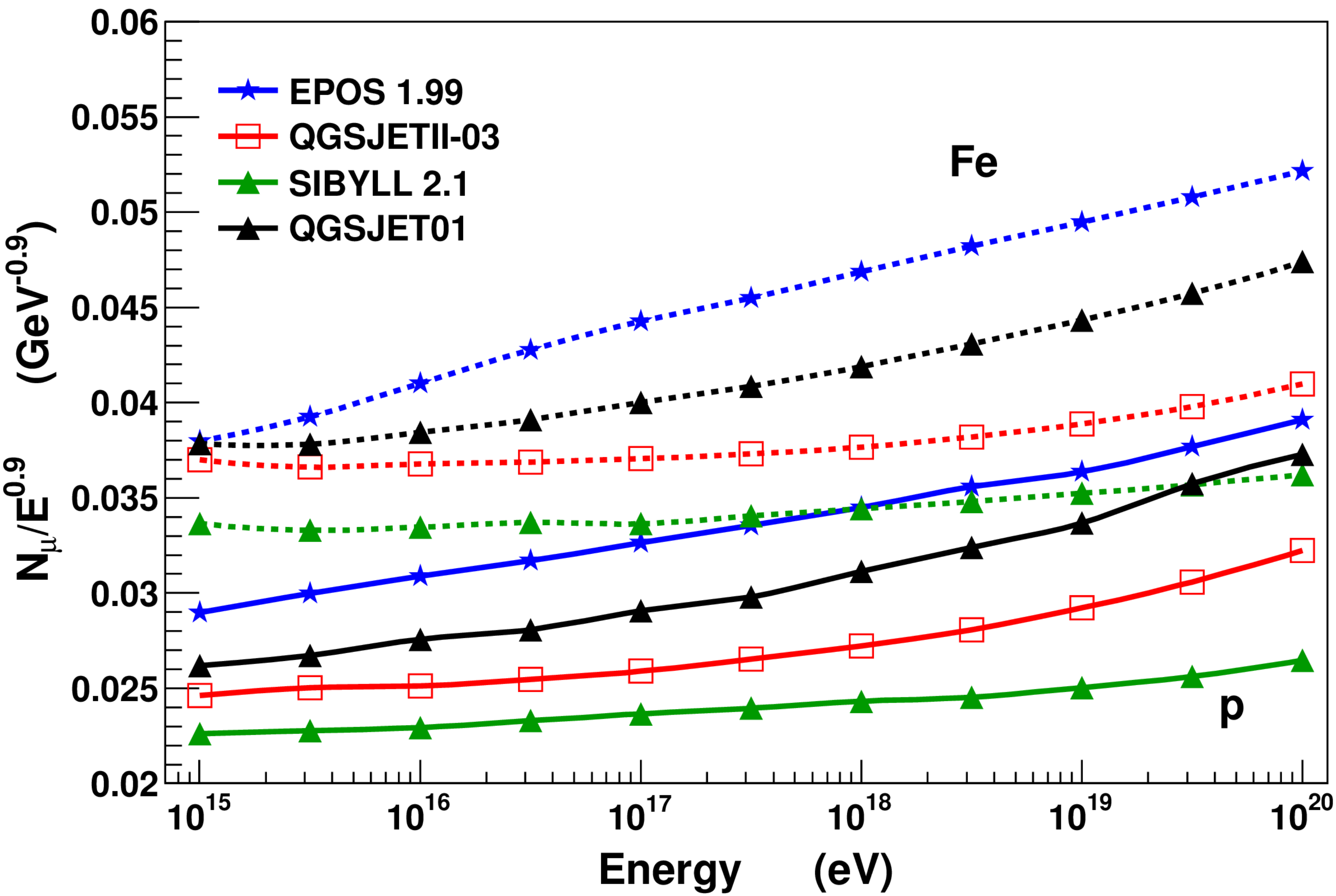
- **Large improvement at mid-rapidity**
  - very similar results for particle ratios
  - overestimation of baryon production before due to wrong interpretation of Tevatron data
- **Only small changes very forward**
  - no try to tune LHCf data yet (difficult)



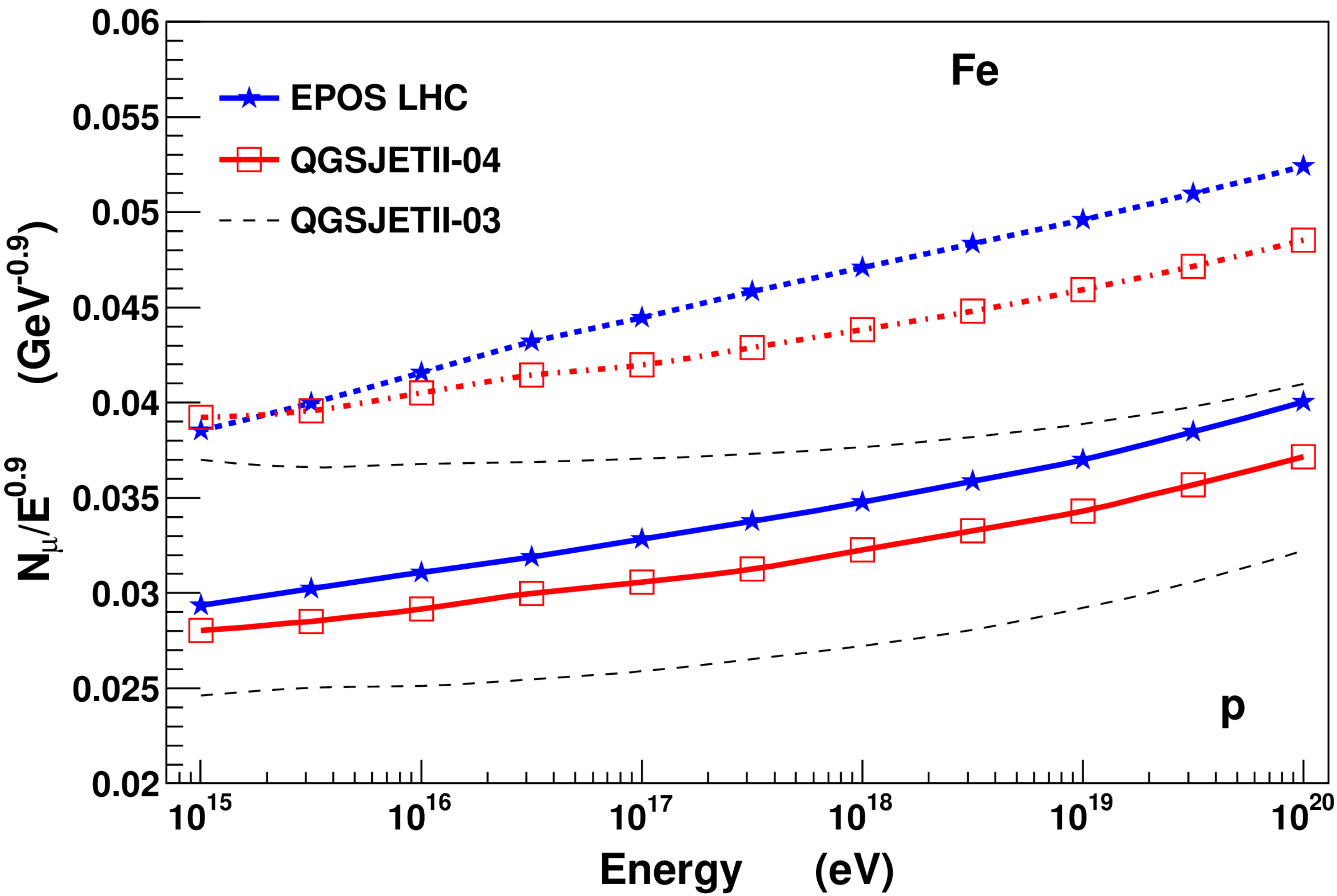




EAS with old CR models : Muons

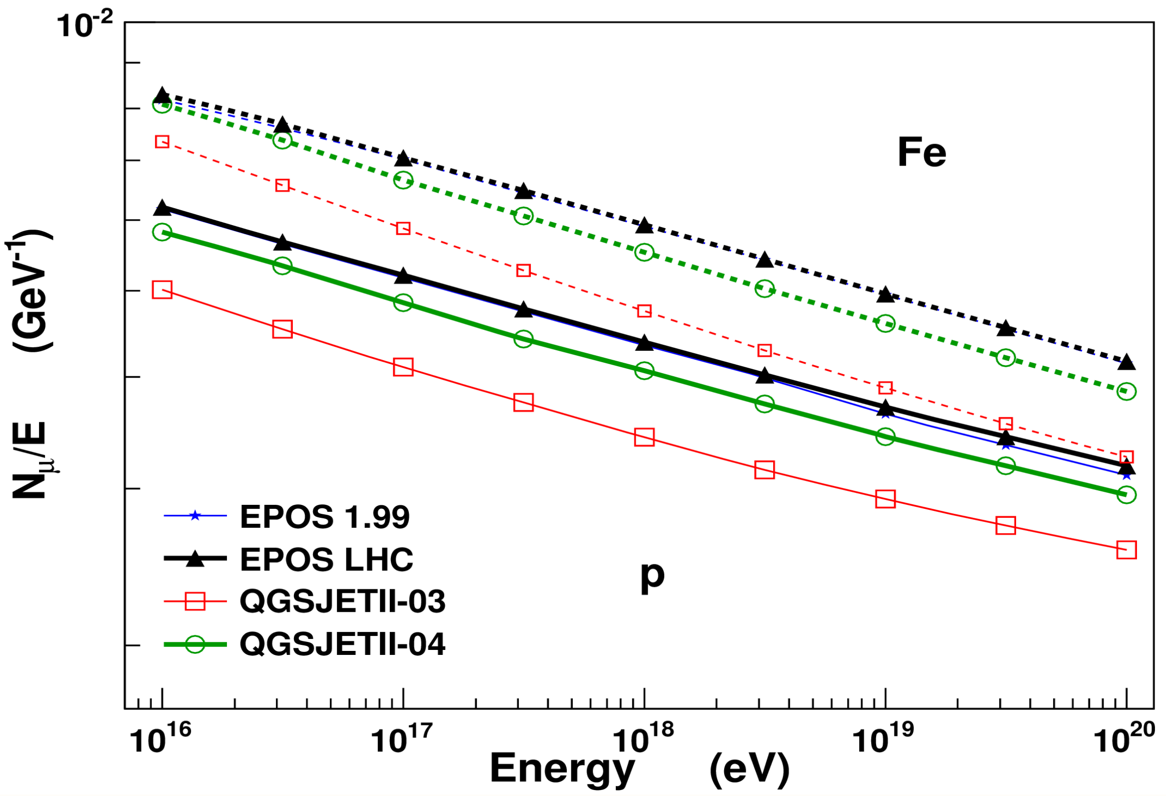


EAS with Re-tuned CR models : Muons



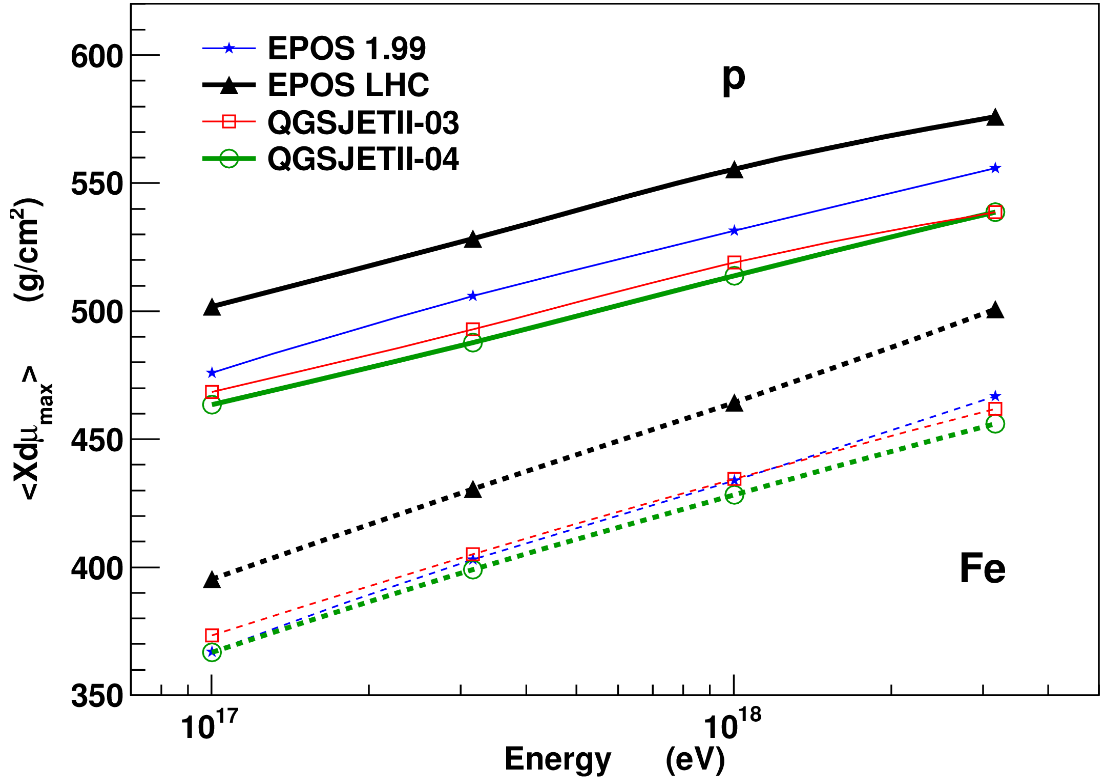
EAS with Re-tuned CR models : Muons

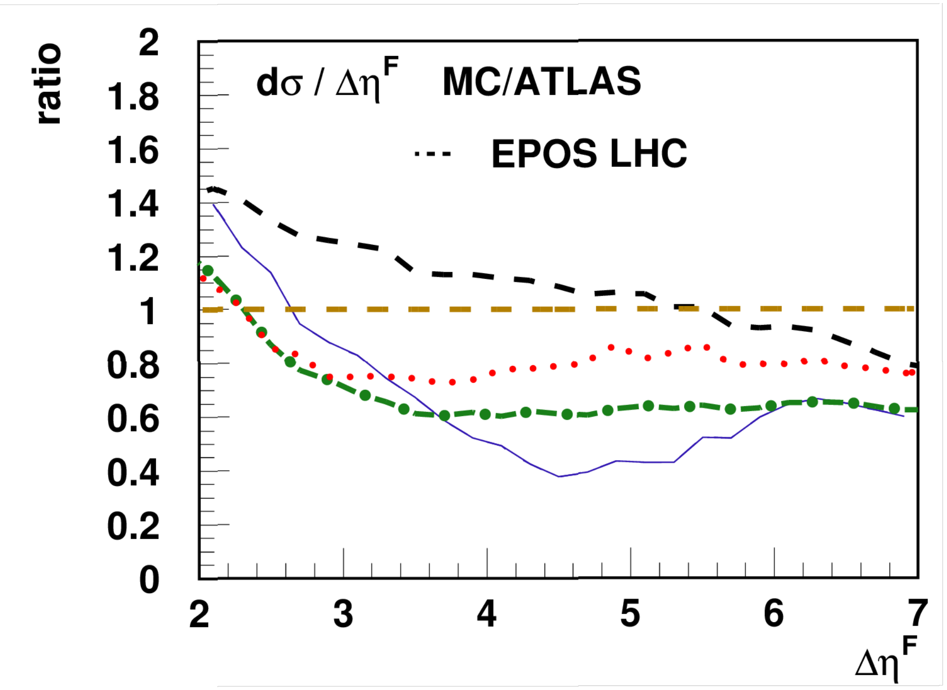
- **Weak effect of LHC**
  - Corrections at mid-rapidity thanks to LHC
  - Changes in QGSJETII motivated by pion induced data (SPS)
  - Changes for forward production in EPOS LHC can not be checked by LHC (yet ?) (motivated by model consistency)
- **NA61 data wanted to check old data set**



Muon Production Depth

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





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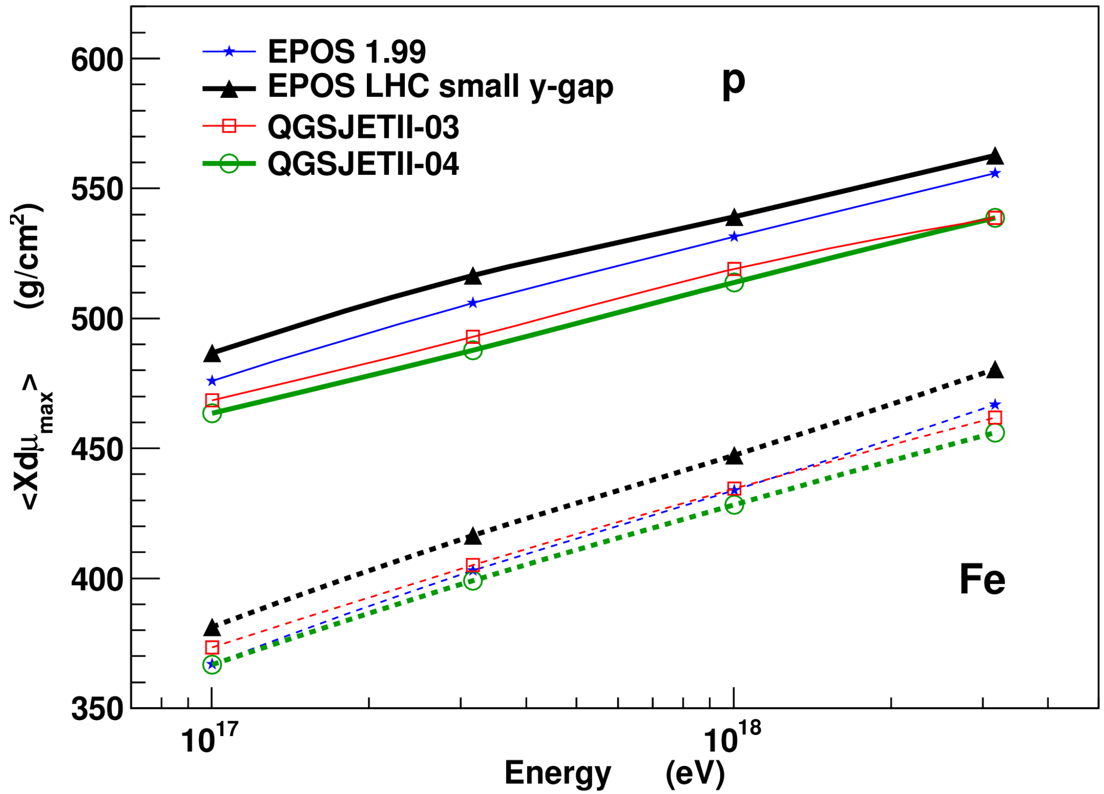

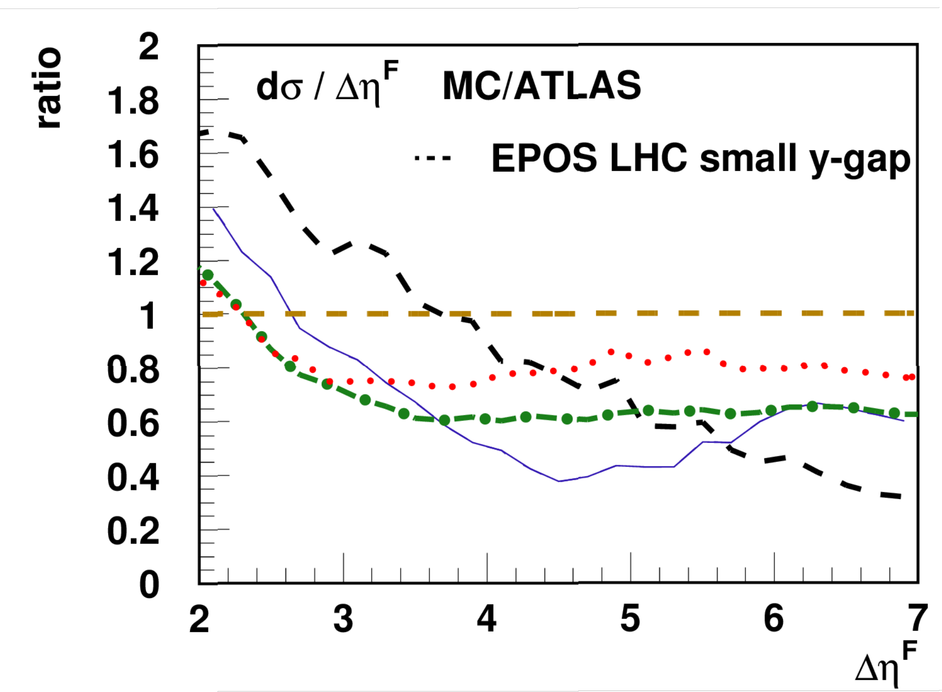

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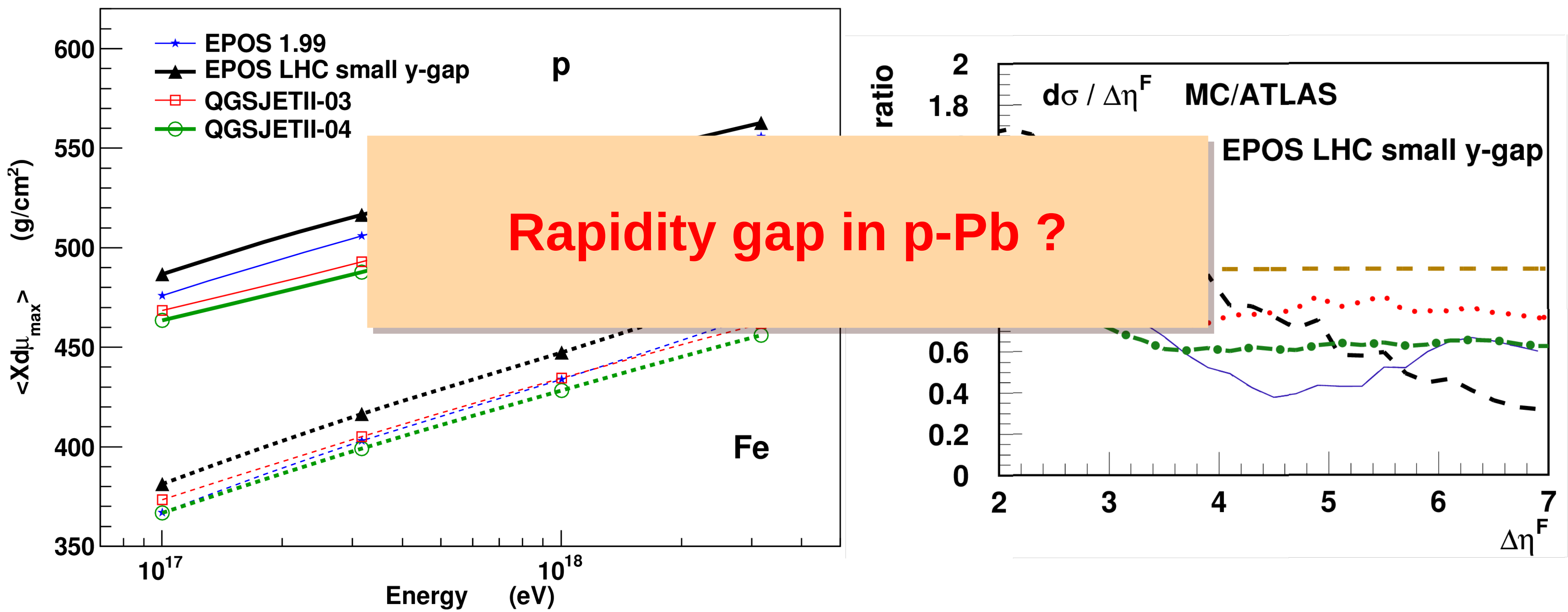
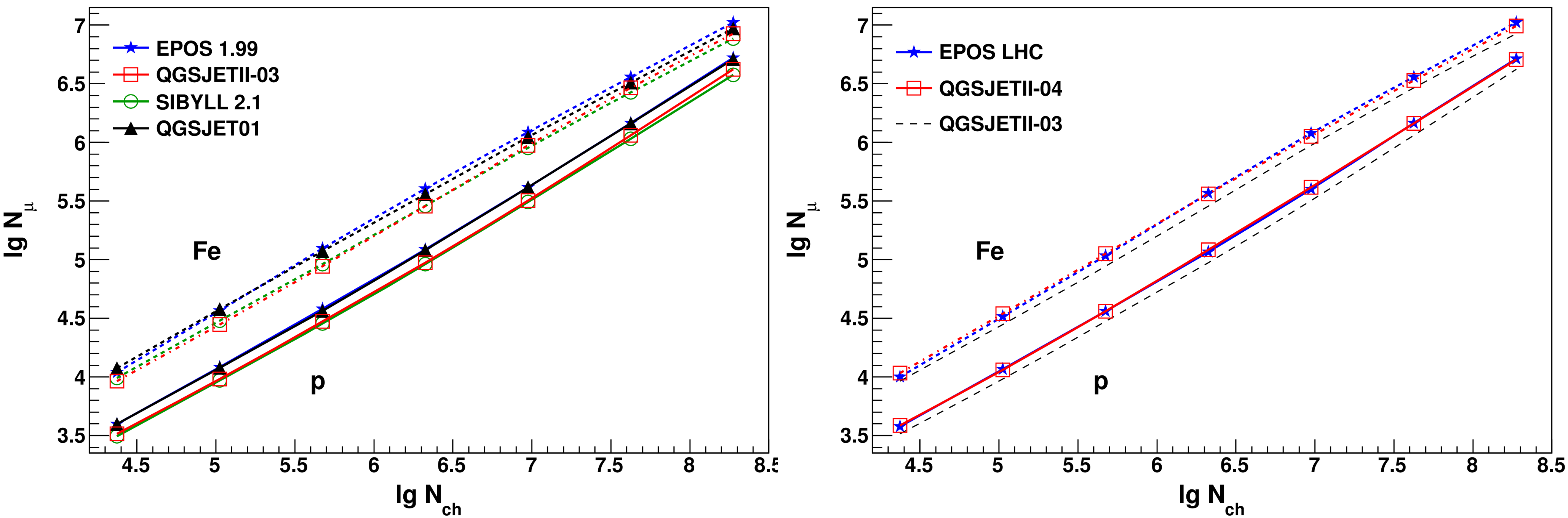


Summary

- **Hadronic interaction models for CR reproduce LHC data in a reasonable way**
  - No change of hadronic physics around the knee (10^{15} eV)
  - Large uncertainties in <X_{max}> simulations due to hadronic models reduced by precise fit of LHC data to the value of the exp. resolution
    - Low mass composition UNLIKELY at highest energy (PAO)
  - Muon number converging to high value
    - NA61 will help for precise muon energy spectrum below 100 GeV.
    - LHC energies important for high energy muons and muon production depth
    - Low mass composition LIKELY at lowest energy (KASCADE)
- **Hadronic interaction models for CR can be re-tuned to LHC data without too many changes**
  - Better predictive power than HEP MC models
  - All CR models available with hepMC interface to be compared with LHC !
    - CR models for LHC

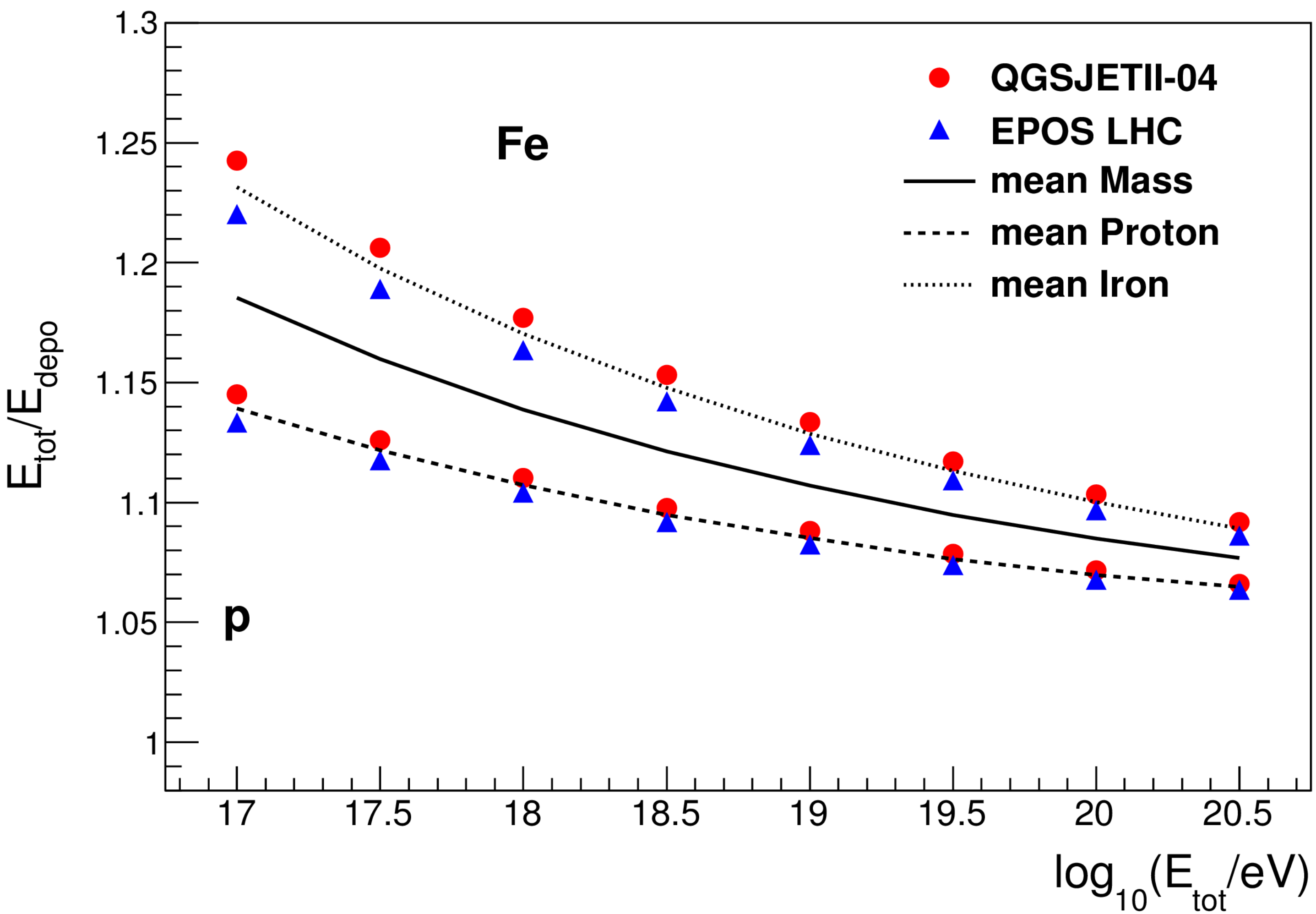
EAS with Re-tuned CR Models : Correlations

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



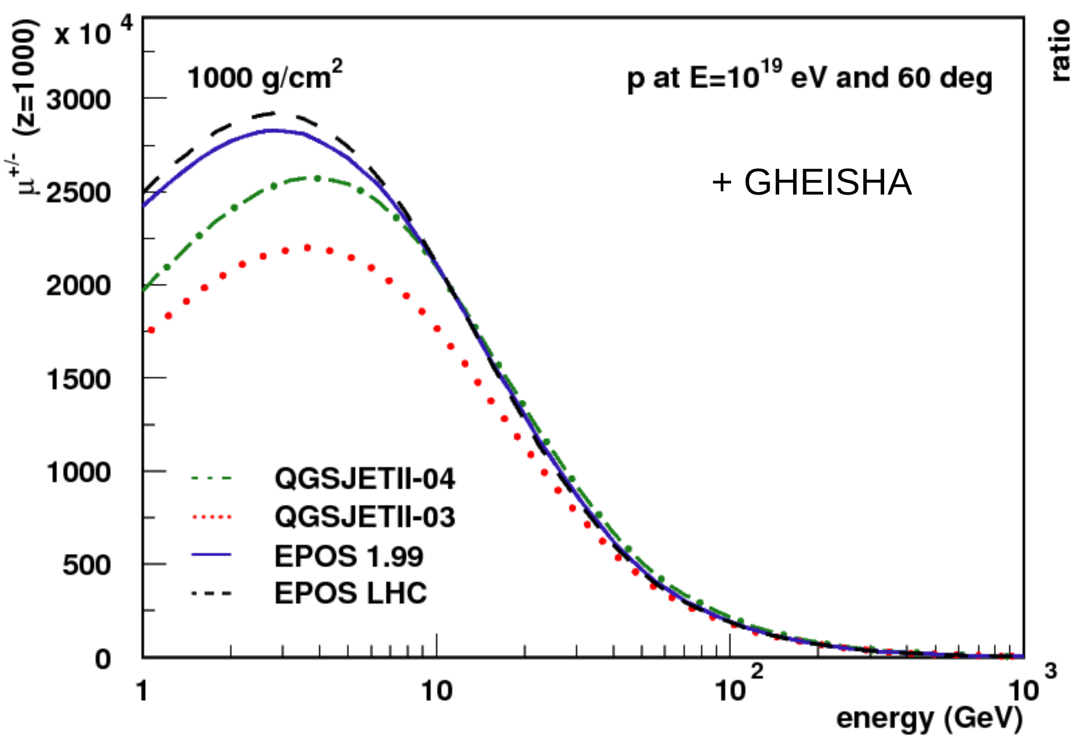
EAS Energy Deposit

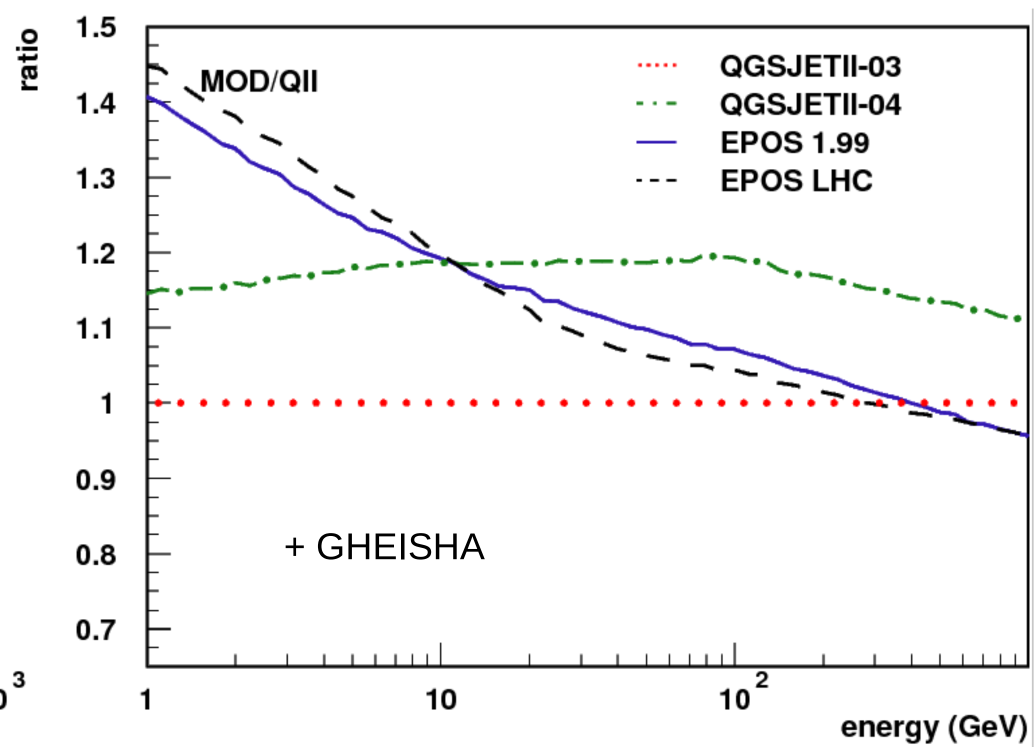
- **Increase of muons in QII04**
  - ➔ larger correction factor from missing energy



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) !





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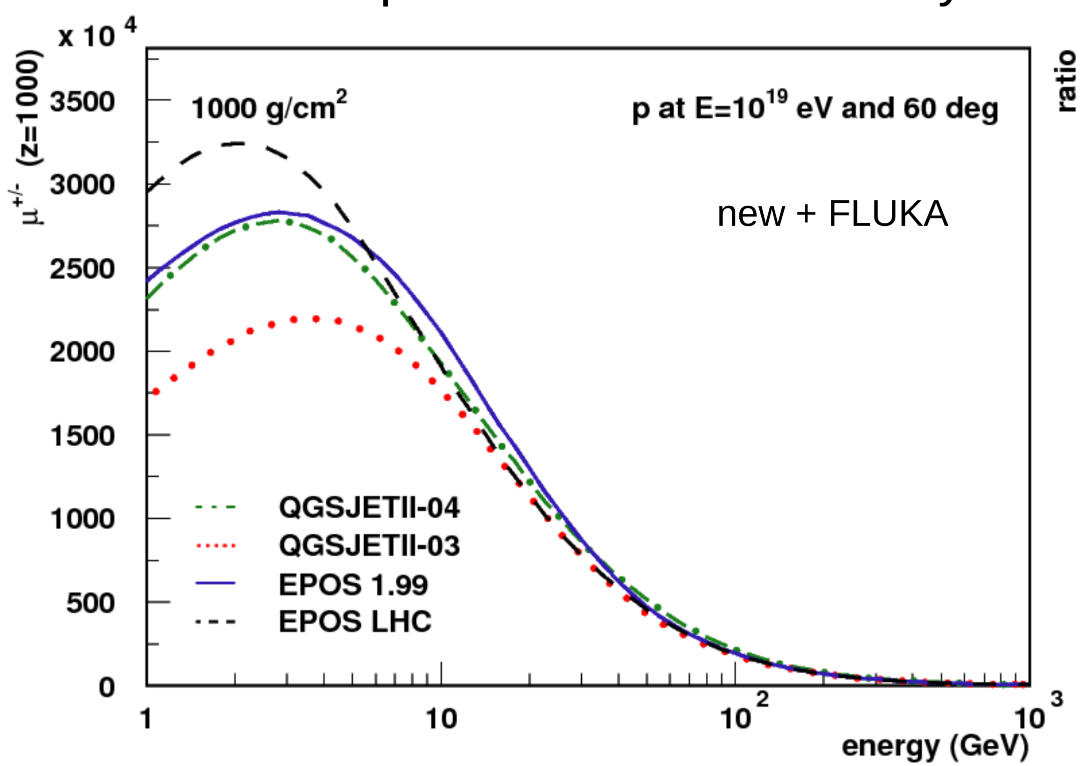
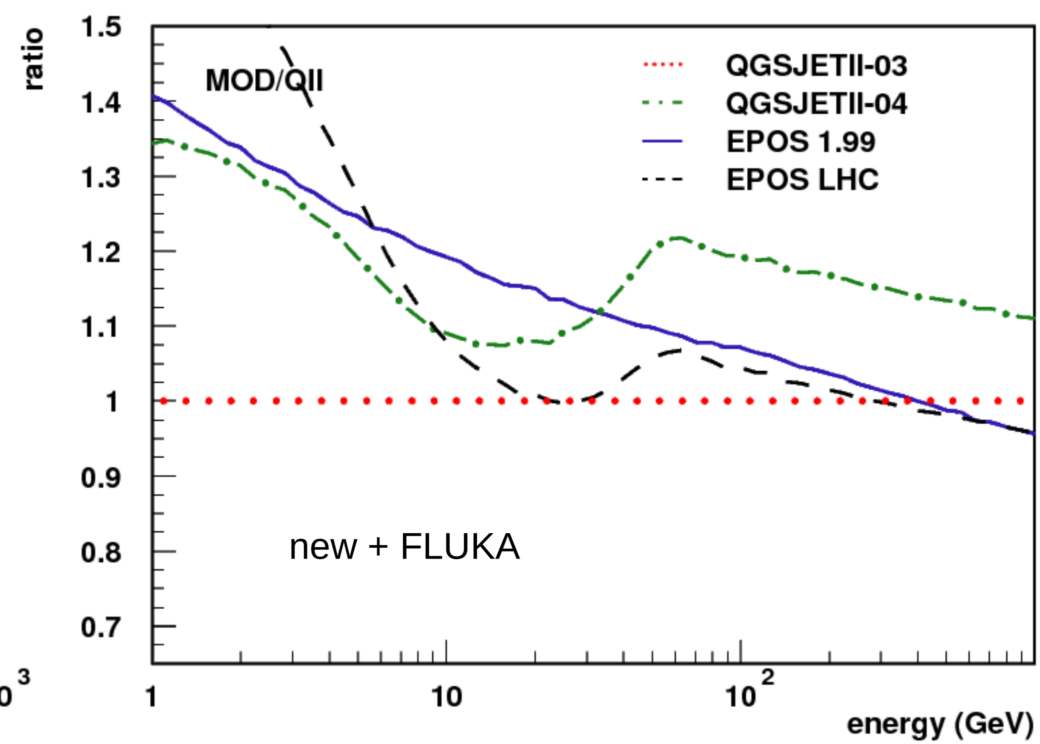
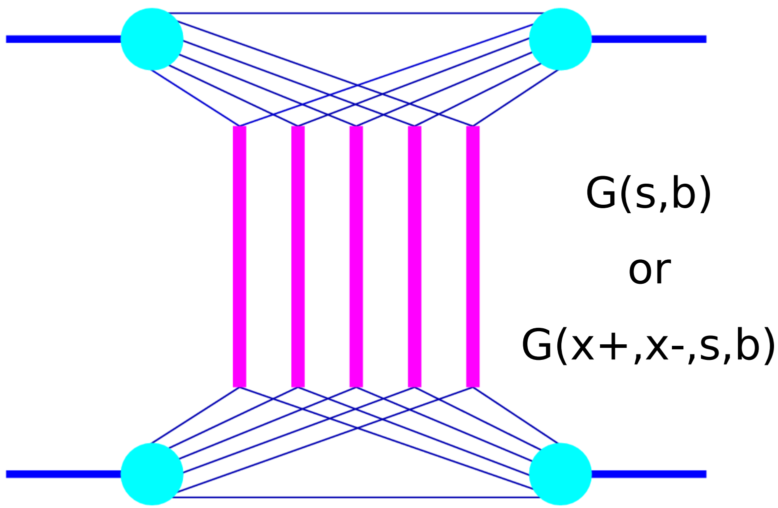
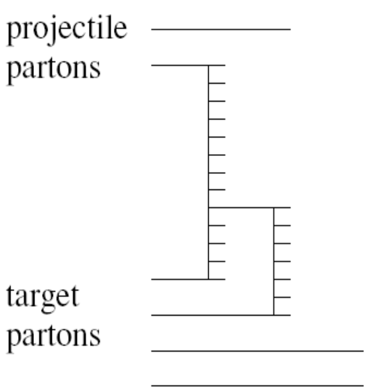


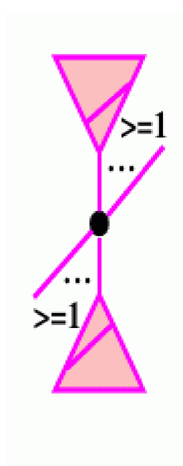


Differences between Models



EPOS QGSJET II





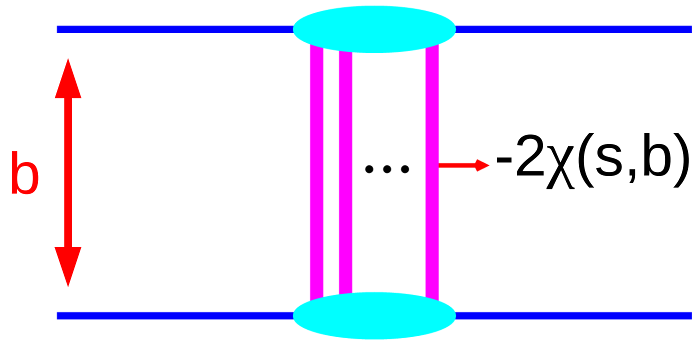
- **Gribov-Regge and optical theorem**
  - Basis of all models (multiple scattering) but
    - Classical approach for QGSJET and SIBYLL (no energy conservation for cross section calculation)
    - Parton based Gribov-Regge theory for EPOS (energy conservation at amplitude level)
- **pQCD**
  - Minijets with cutoff in SIBYLL
  - Same semi-hard Pomeron (DGLAP convoluted with soft part : not cutoff) in QGS and EPOS but
    - No enhanced diagram in Q01 (old PDF)
    - Generalized enhanced diagram in QII
    - Simplified non linear effect in EPOS
      - Phenomenological approach

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

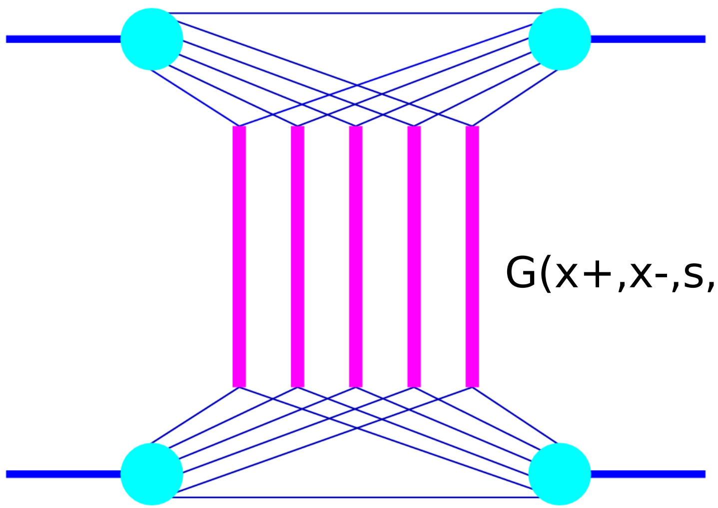


$$\sigma \sim 1-\exp(-2\chi)$$

Not the same χ in QGSJET01, QGSJETII and SIBYLL

- χ(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

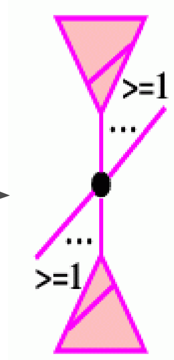
Particle Production in SIBYLL and QGSJET

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

- n from :

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

  - 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 :

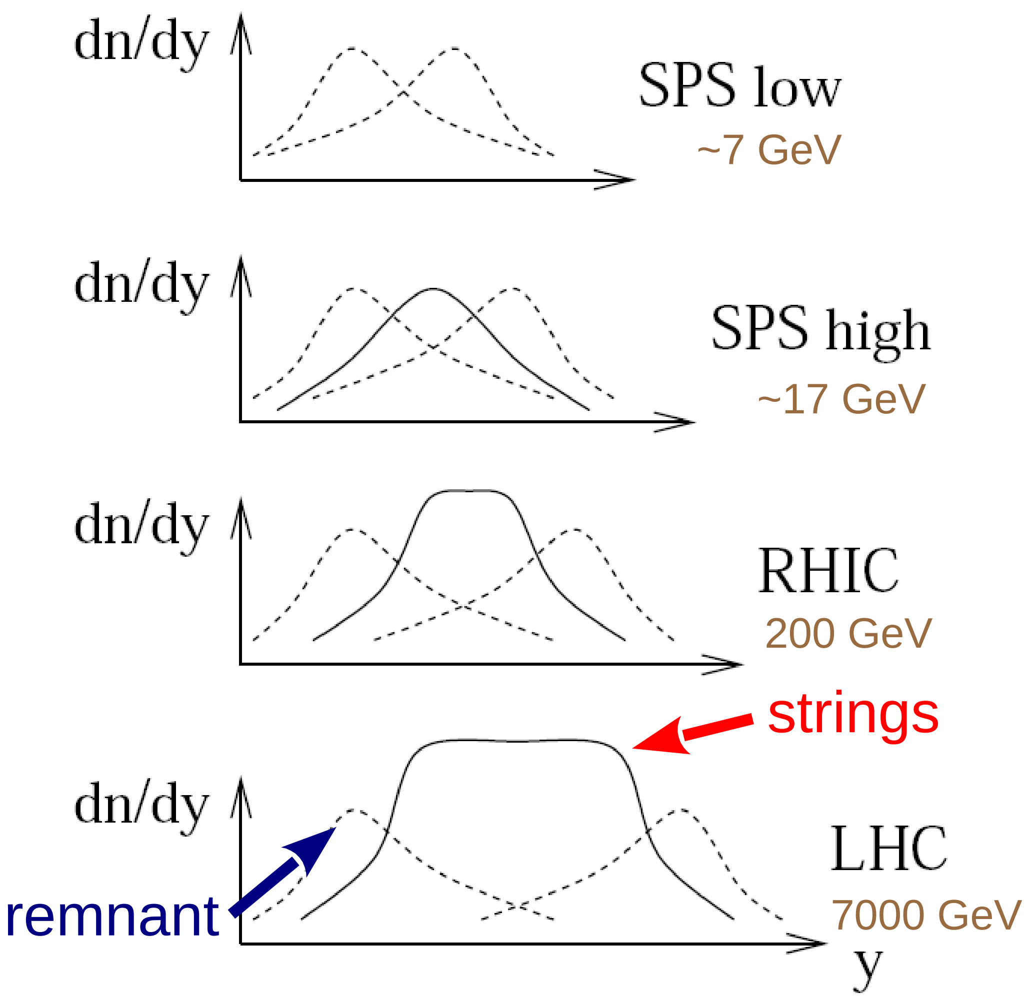
$$\Omega_{AB}^{(s,b)}(m, X^+, X^-) = \prod_{k=1}^{AB} \left\{ \frac{1}{m_k!} \prod_{\mu=1}^{m_k} G(x_{k,\mu}^+, x_{k,\mu}^-, s, b_k) \right\} \Phi_{AB}\left(x^{\text{proj}}, x^{\text{targ}}, s, b\right)$$

  - 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 (in)elasticity is closely related to diffraction and forward spectra



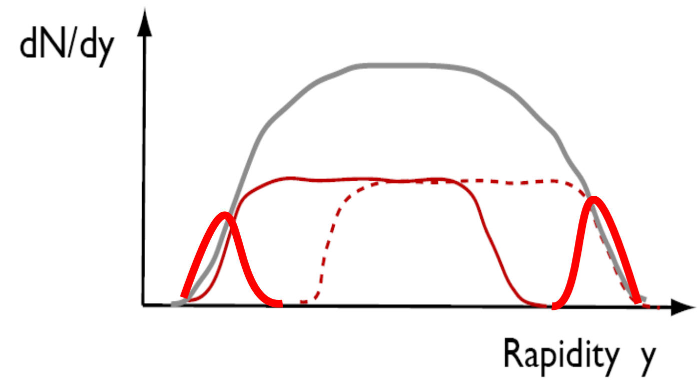
- At very low energy only particles from remnants
- At low energy (fixed target experiments) (SPS) strong mixing
- At intermediate energy (RHIC) mainly string contribution at mid-rapidity with tail of remnants.
- At high energy (LHC) only strings at mid-rapidity (baryon free)

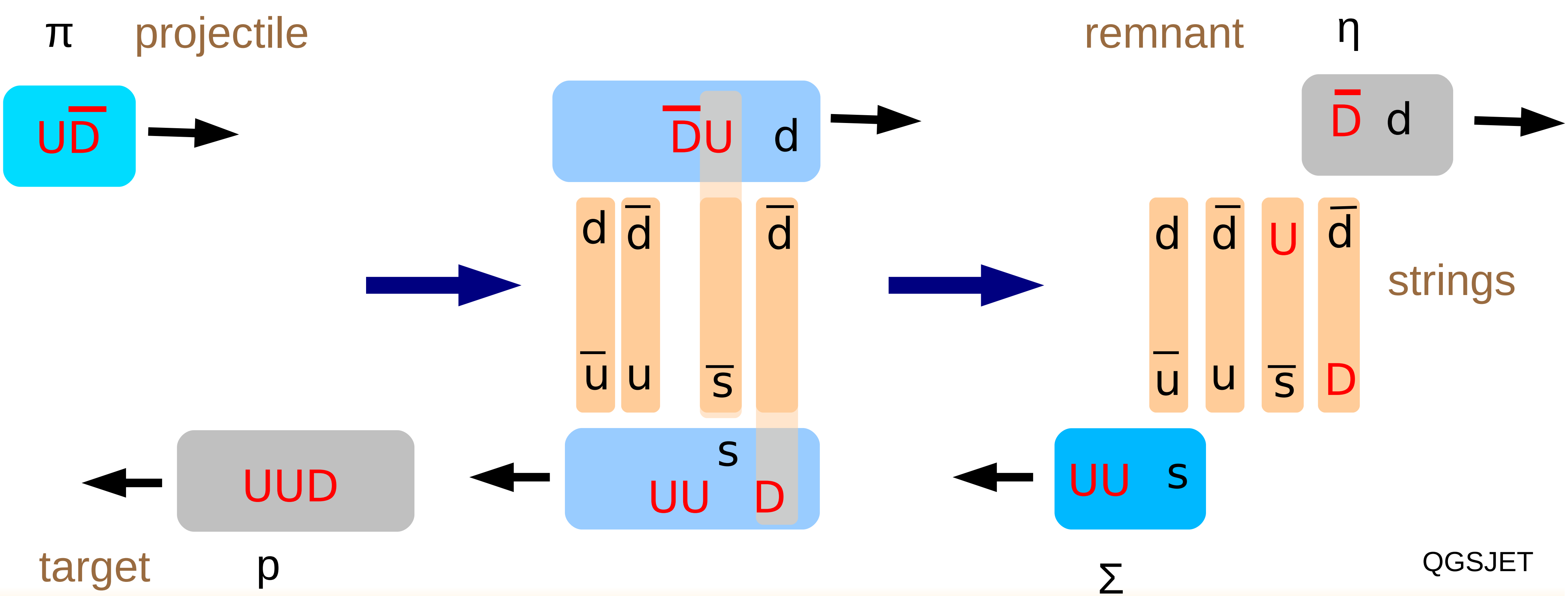
Different contributions of particle production at different energies or rapidities

Beam Remnants

Forward particle production dominated by beam remnants

- No strong theory
- Each model has its own approach
- Can be tested at low energy

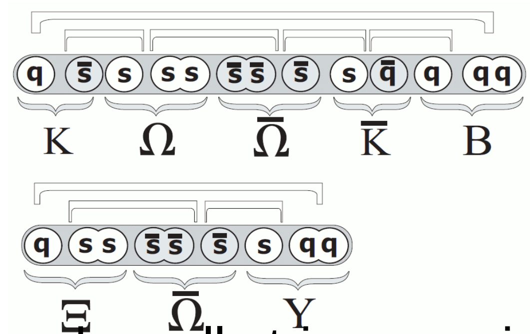




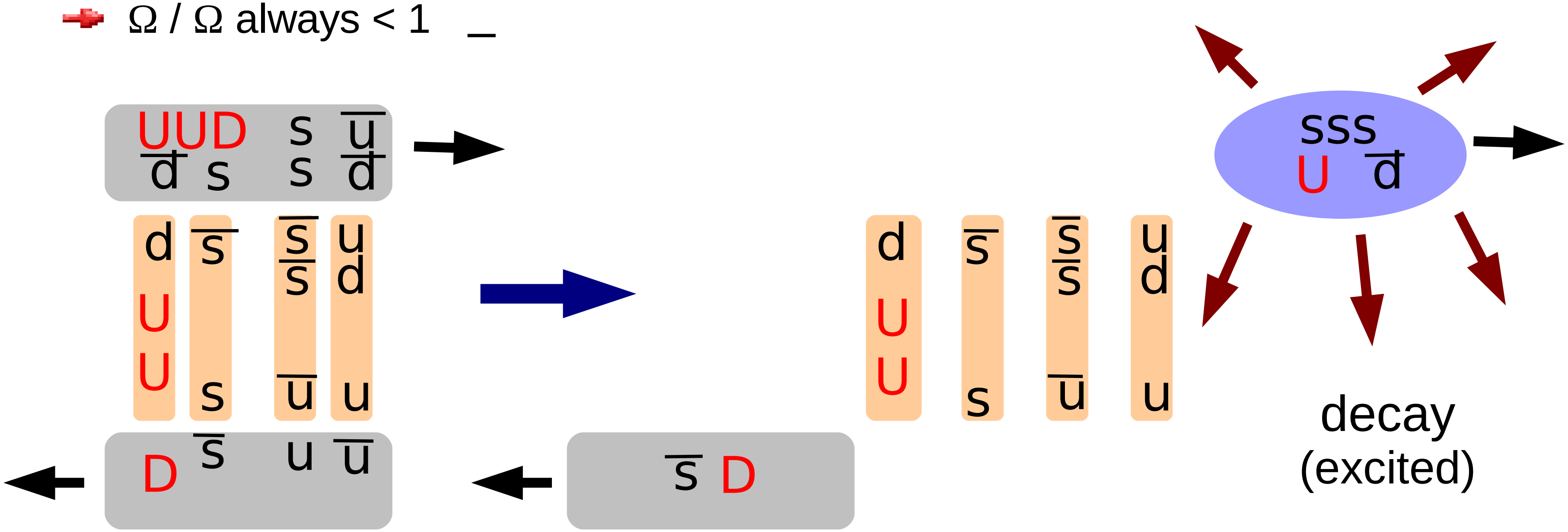
Baryons and Remnants

Parton ladder string ends :

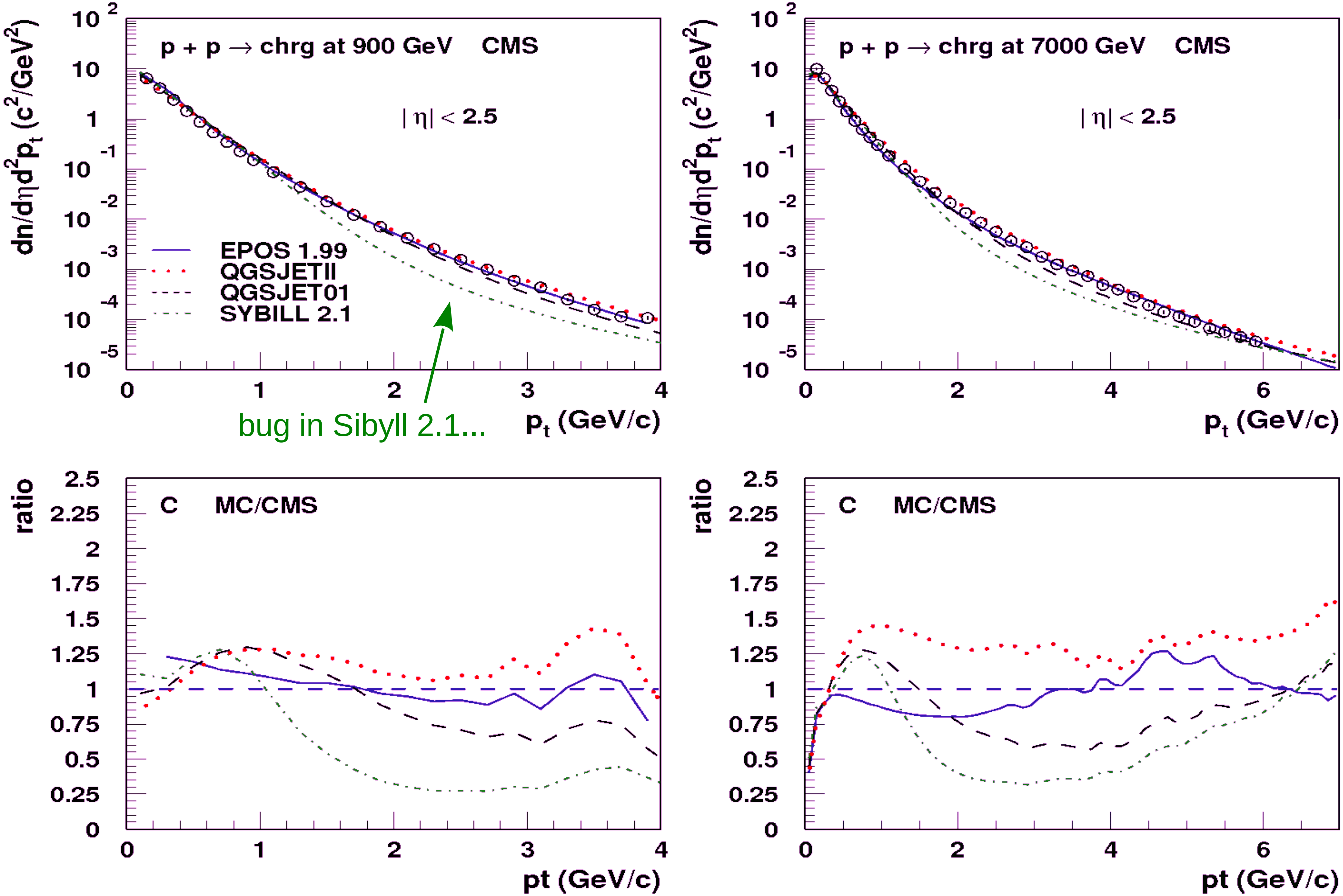
- Problem of multi-strange baryons at low energy (Bleicher et al., Phys.Rev.Lett.88:202501,2002)
  - 2 strings approach :
    - Ω / $\bar{\Omega}$ always > 1
    - But data < 1 (Na49)



- EPOS
  - No “first string” with valence quarks : all strings equivalent
  - Wide range of excited remnants (from light resonances to heavy quark-bag)
    - Ω / $\bar{\Omega}$ always < 1

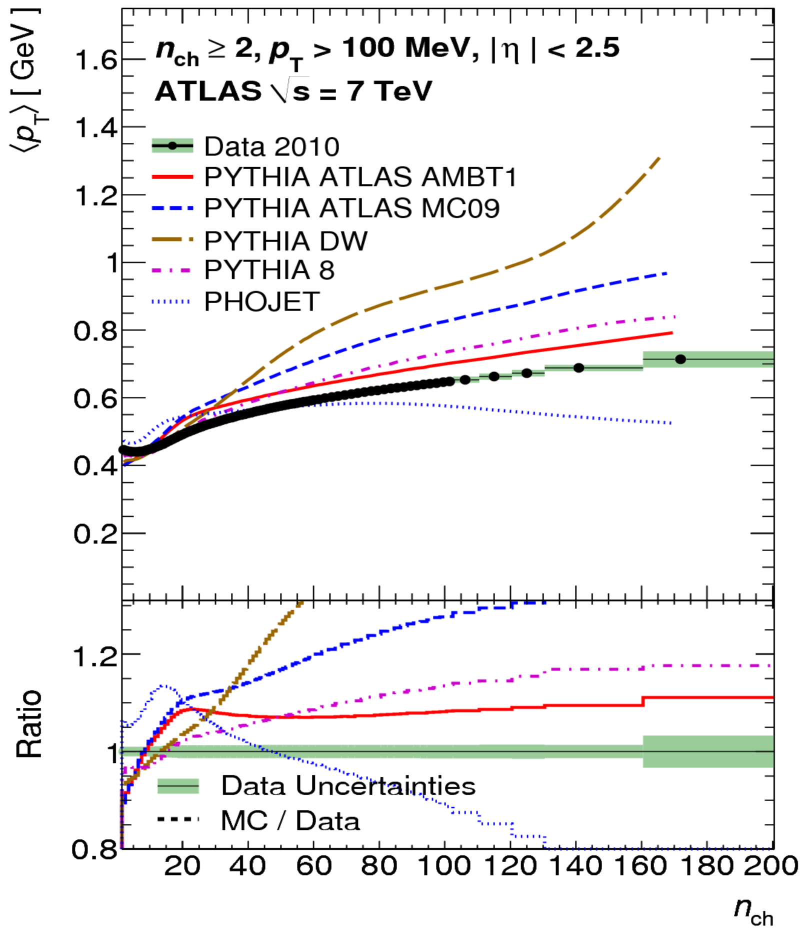


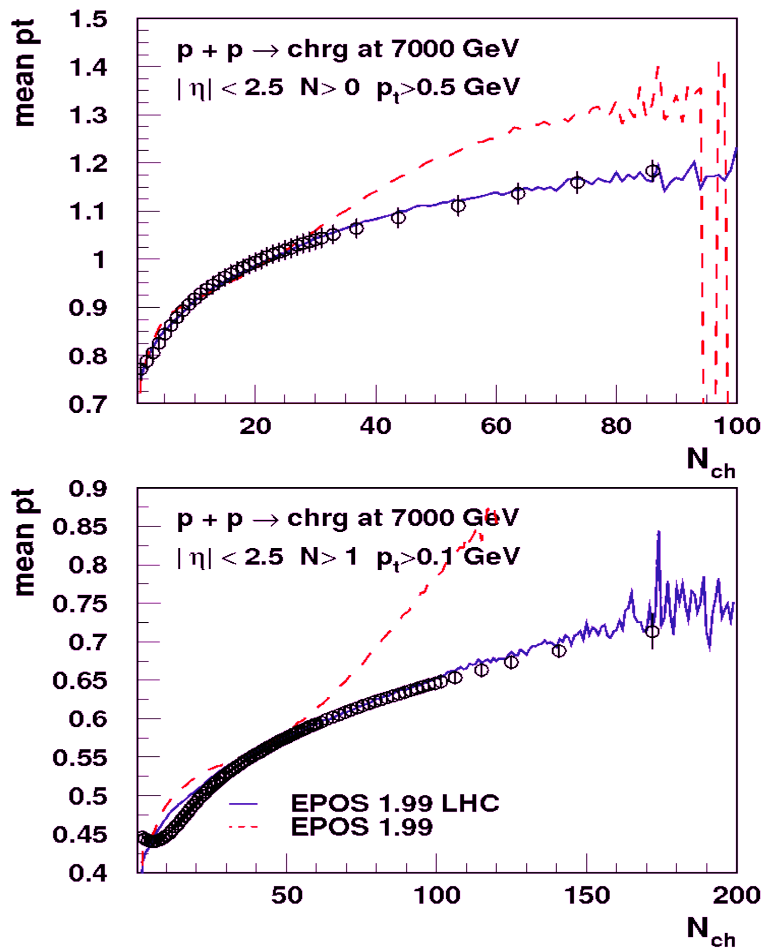
Pt @ LHC


p + p → chrg at 900 GeV CMS
|η| < 2.5
EPOS 1.99
QGSJETII
QGSJET01
SYBILL 2.1
bug in Sibyll 2.1...
p + p → chrg at 7000 GeV CMS
|η| < 2.5
$dn/d\eta d^2p_t$ (c^2/GeV^2)
p_t (GeV/c)
C MC/CMS
ratio
pt (GeV/c)

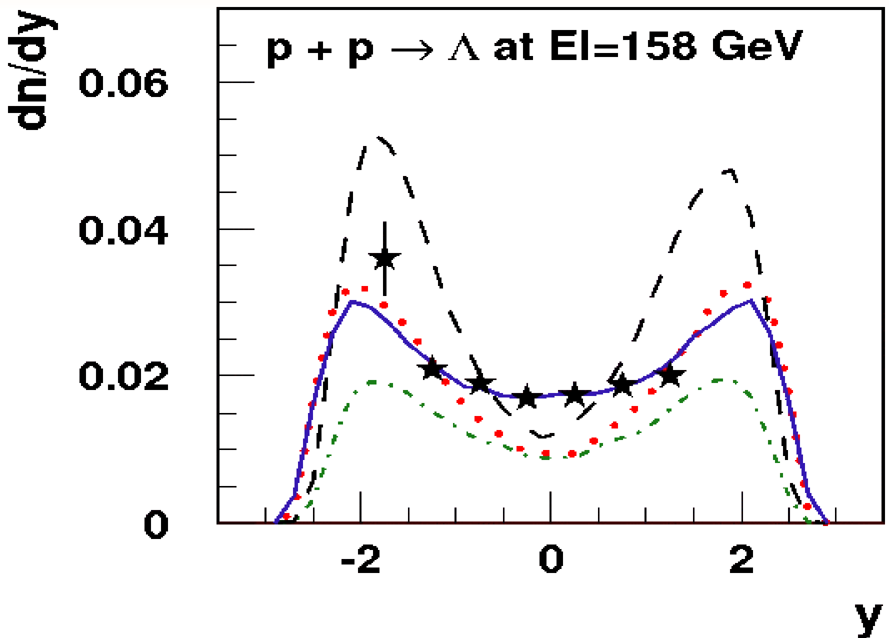
EPOS LHC

- **Detailed description can be achieved**
  - better than HEP MC used by LHC collaborations
  - can be used as min bias generator at LHC
    - not suitable for rare events (high p_t jets or electroweak)

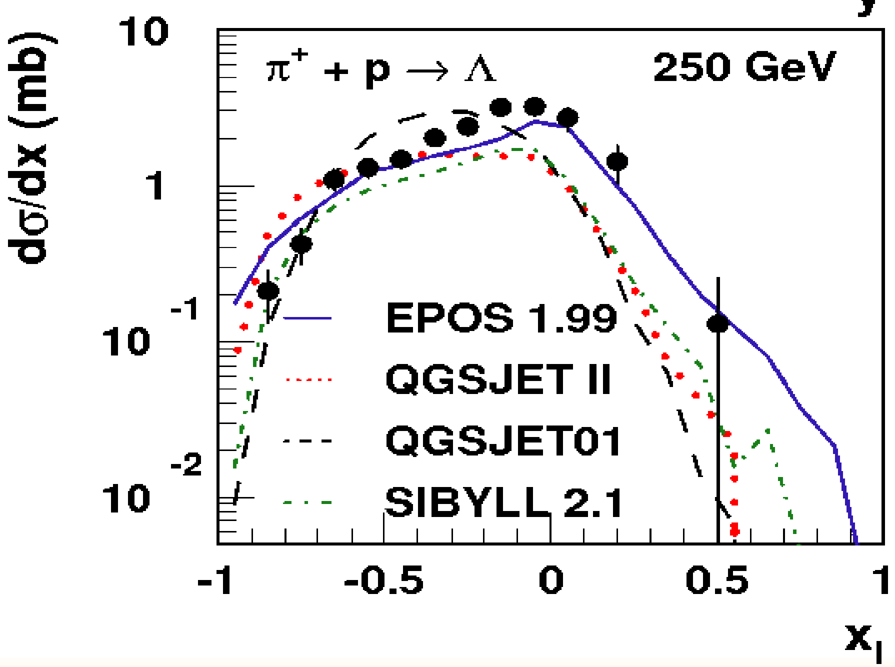


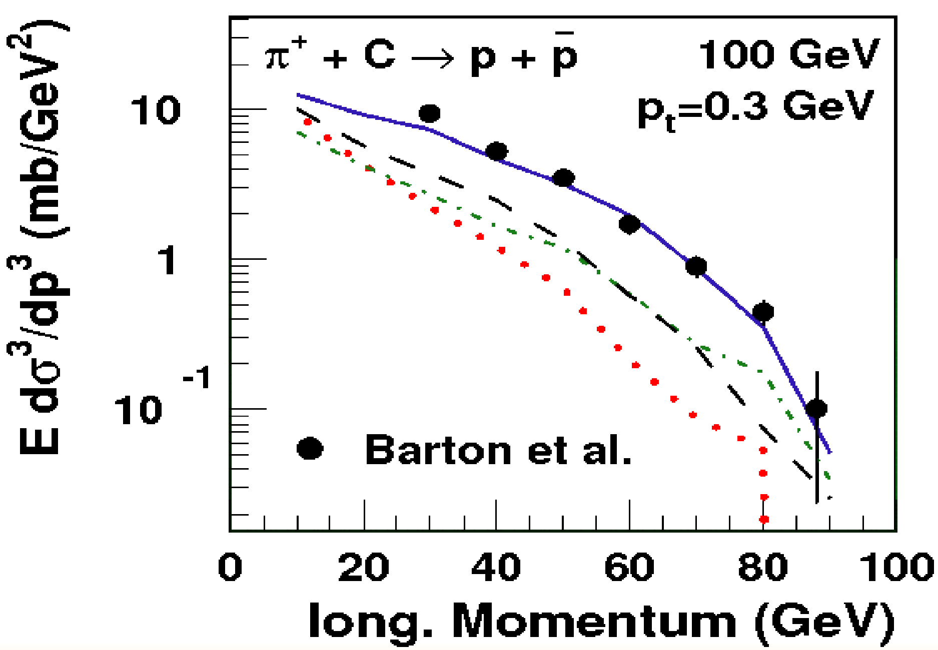


Baryon Forward Spectra



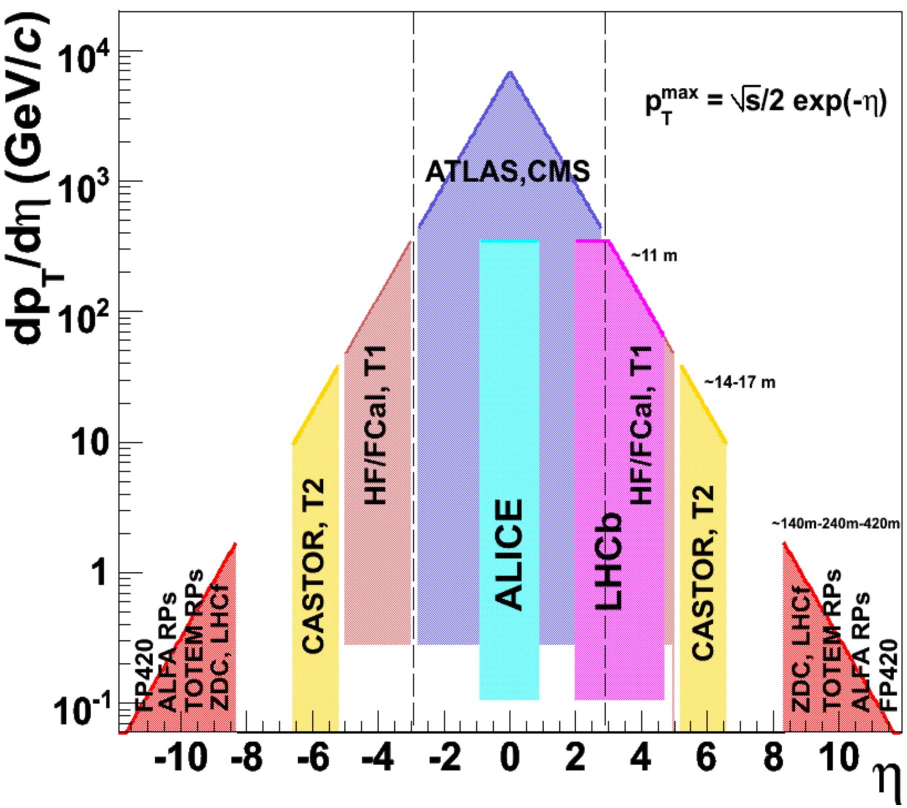
- Large differences between models
- Need a new remnant approach for a complete description (EPOS)
- Problems even at low energy
- No measurement at high energy !





Basic Observables

mid-rapidity



forward

LHC : First hadron collider with full coverage.

- **Pseudorapidity**
  - emission angle of a particle from interaction point ("mid-rapidity" : $\eta=0$) :

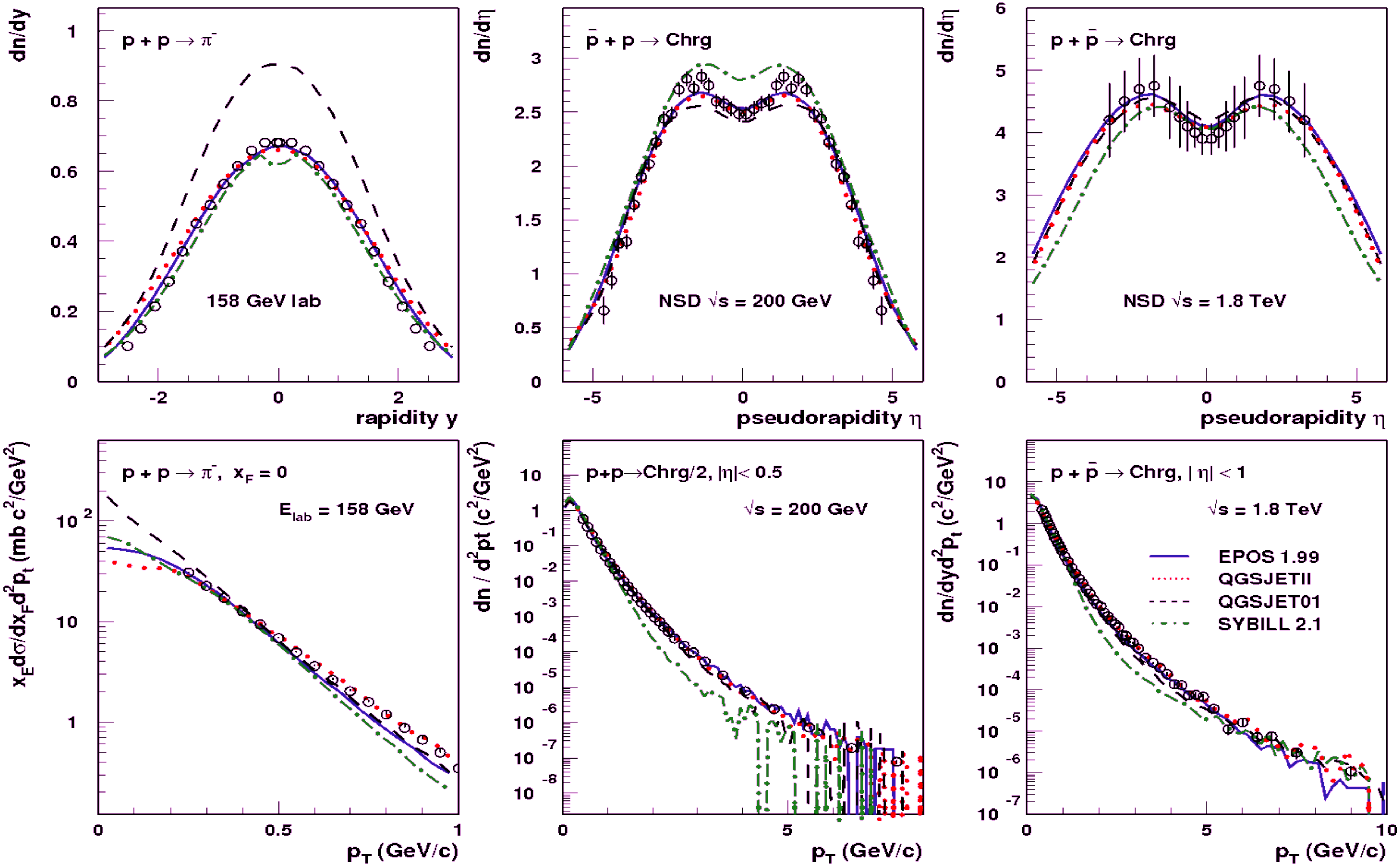
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right] \qquad \eta = \frac{1}{2}\ln\left(\frac{|\mathbf{p}|+p_L}{|\mathbf{p}|-p_L}\right)$$

  - when the mass of the particle is known the rapidity is used :

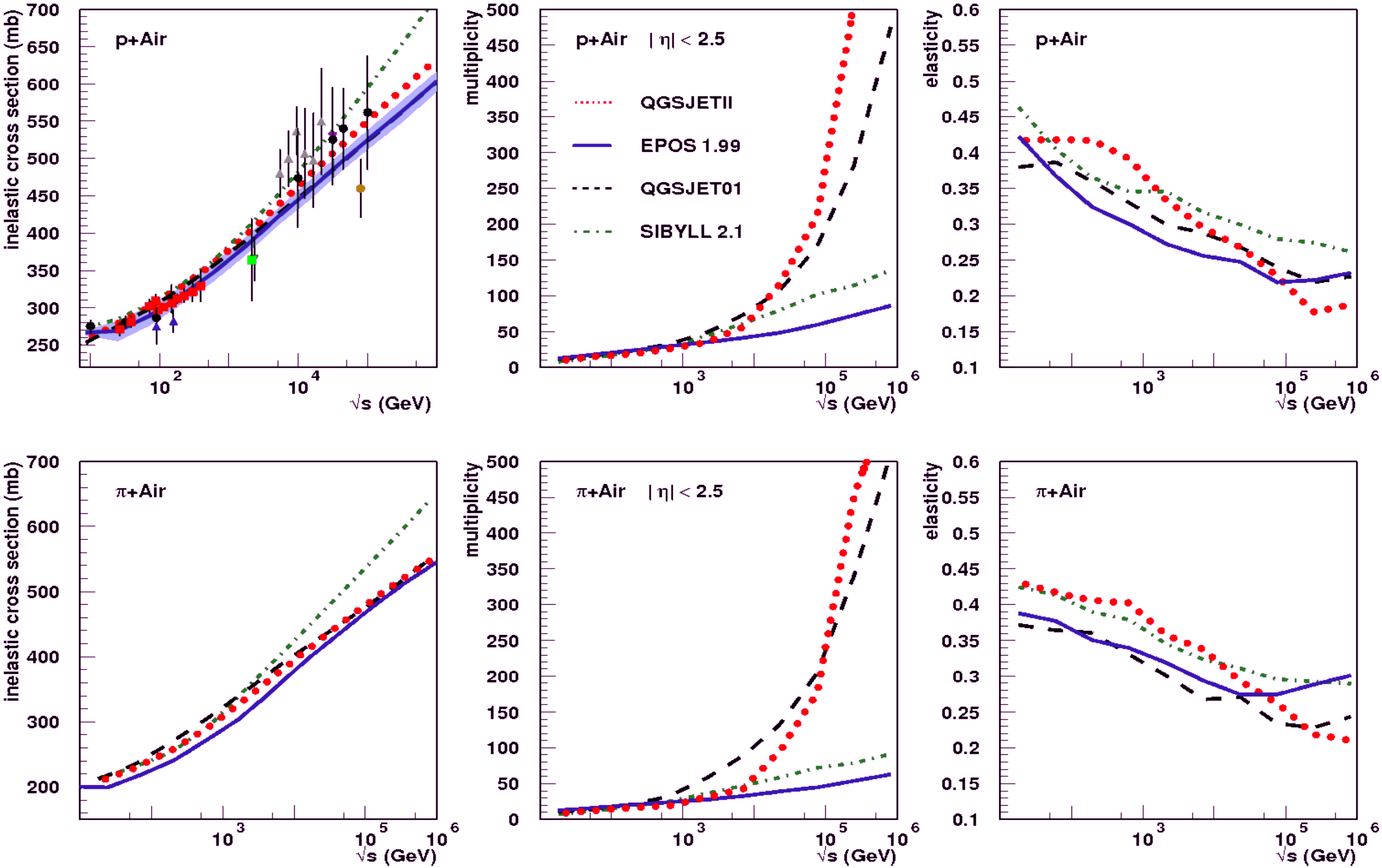
$$y = \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right)$$

  - for EAS development, "forward" particles (with large η) are most important
- **Transverse momentum**
  - $p_t = \sqrt{p_x^2 + p_y^2}$
- **Multiplicity**
  - number of particles in a given η and p_t range

Pseudorapidity and p_T

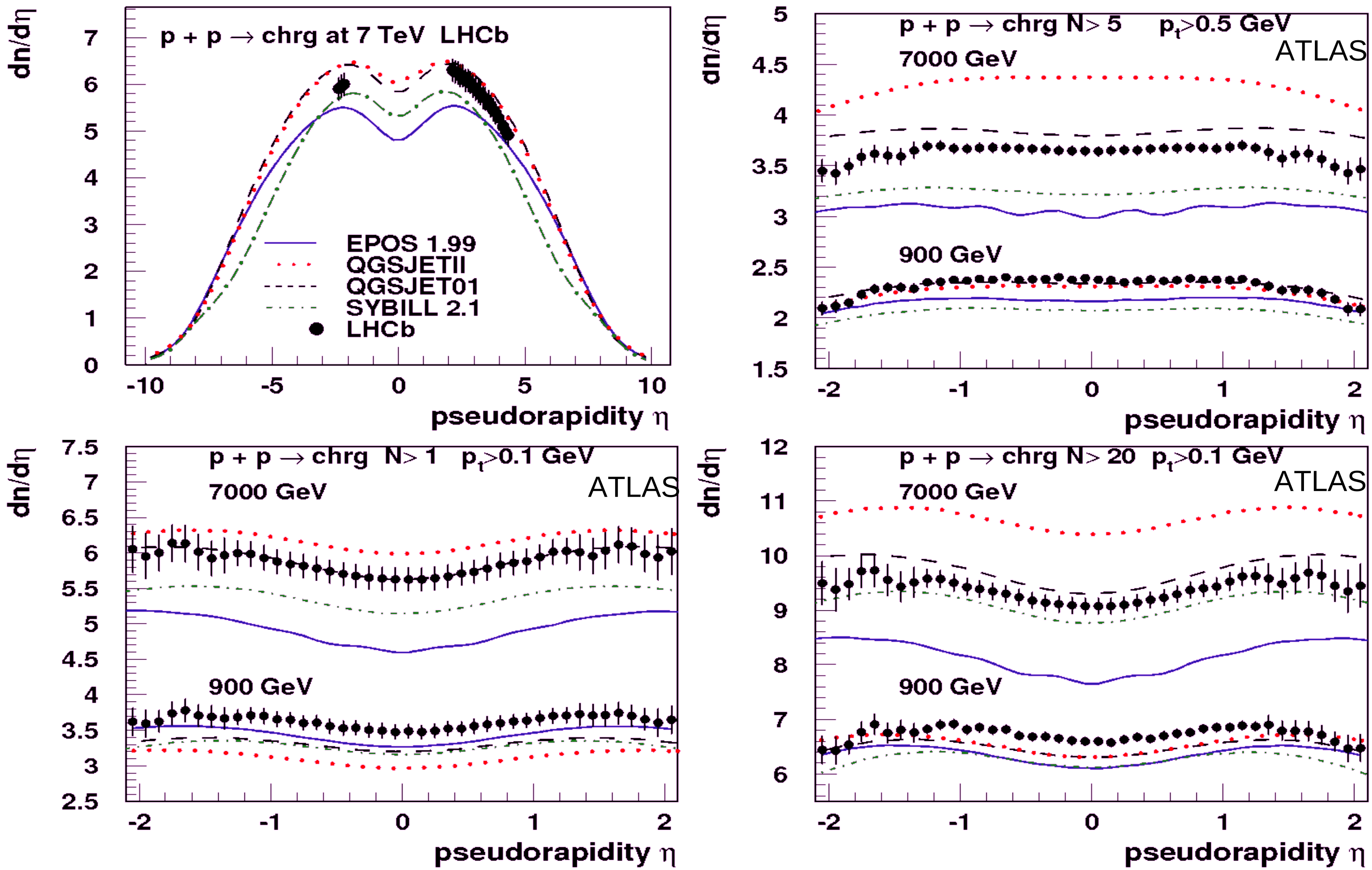


Ultra-High Energy Hadronic Model Predictions



Pseudorapidity Distributions

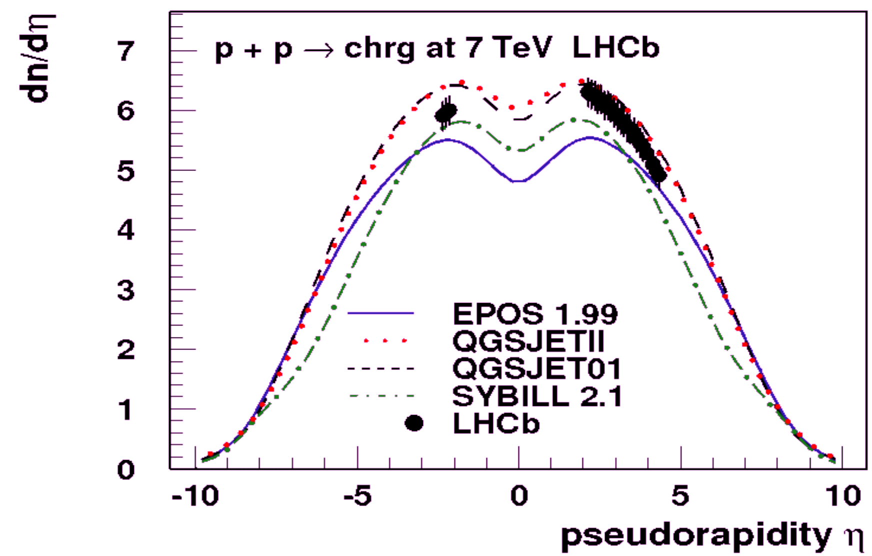
- No model with perfect prediction : **but data well bracketed**

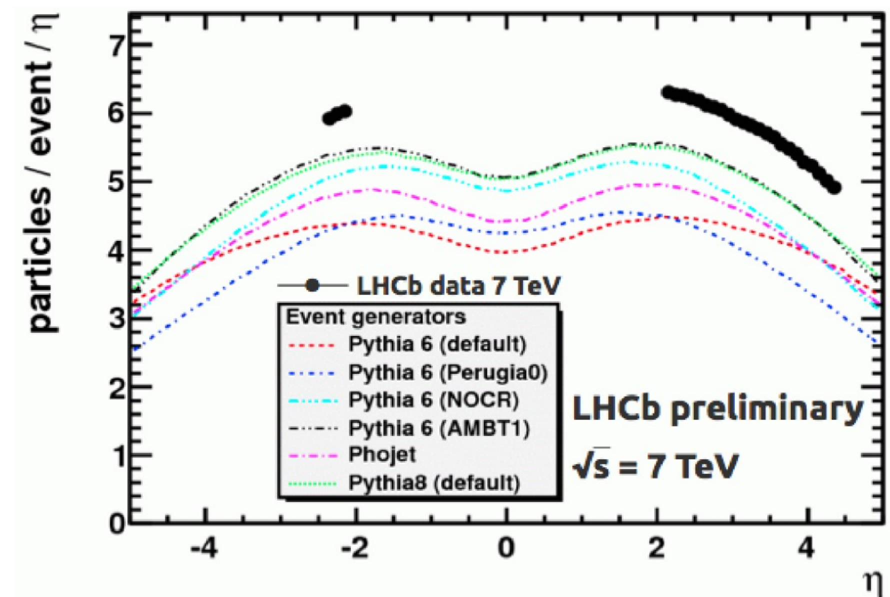


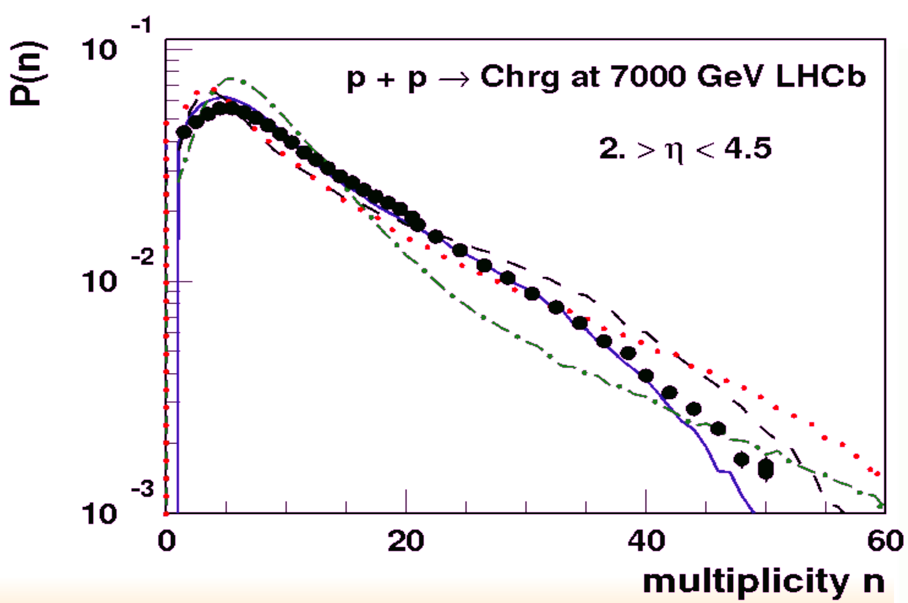
Predictions ! … newest model released in march 2009

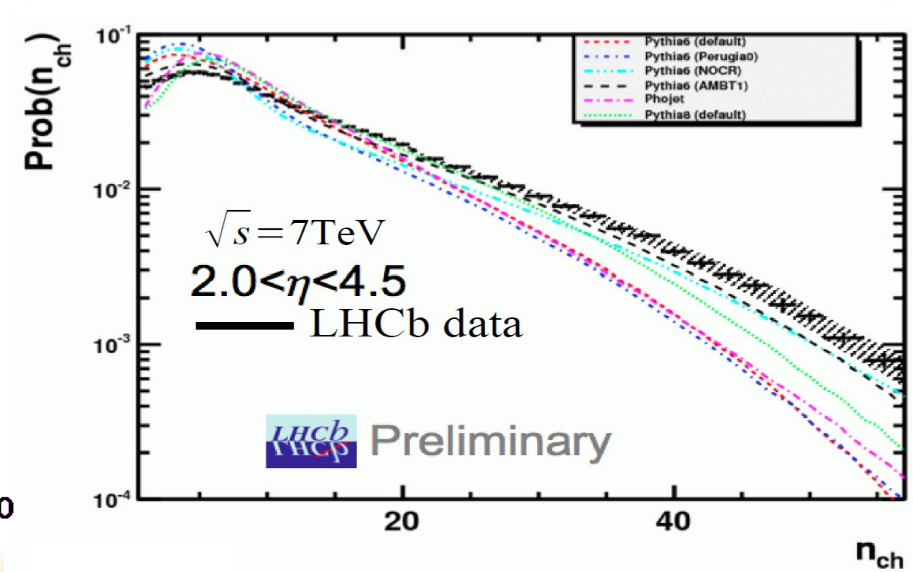
Pseudorapidity Distributions

- No model with perfect prediction : **but better than HEP MC**

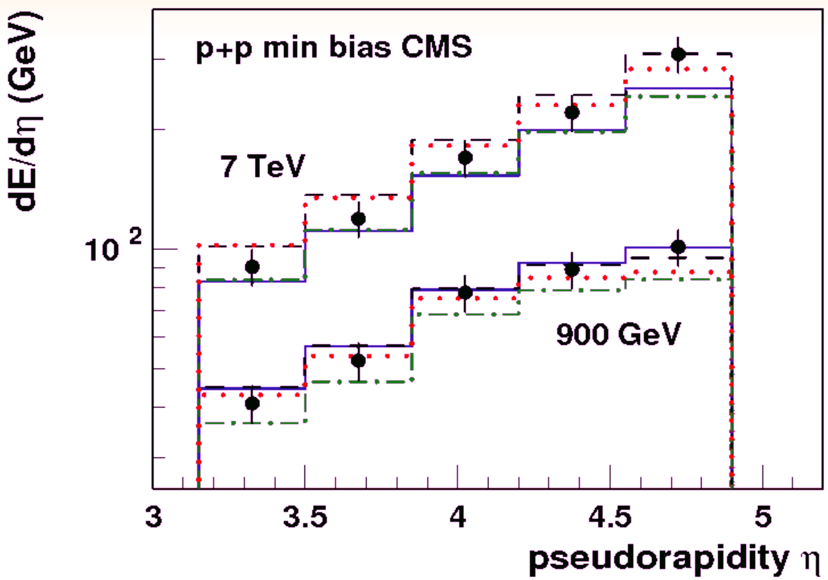


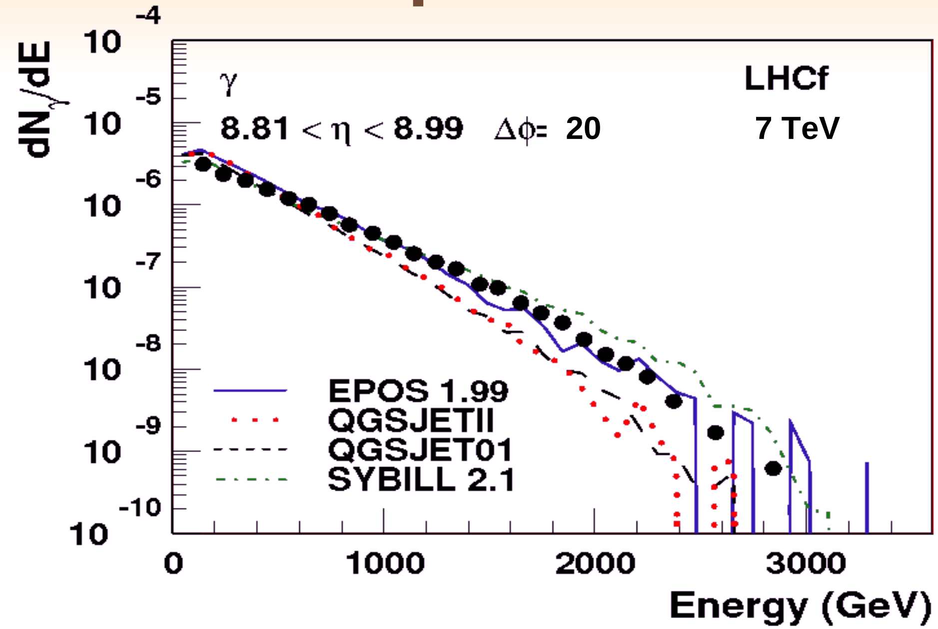


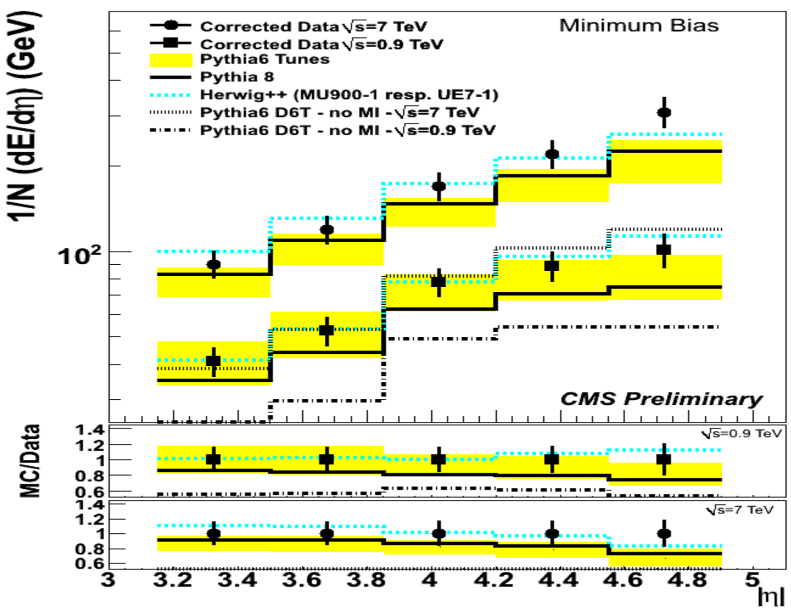


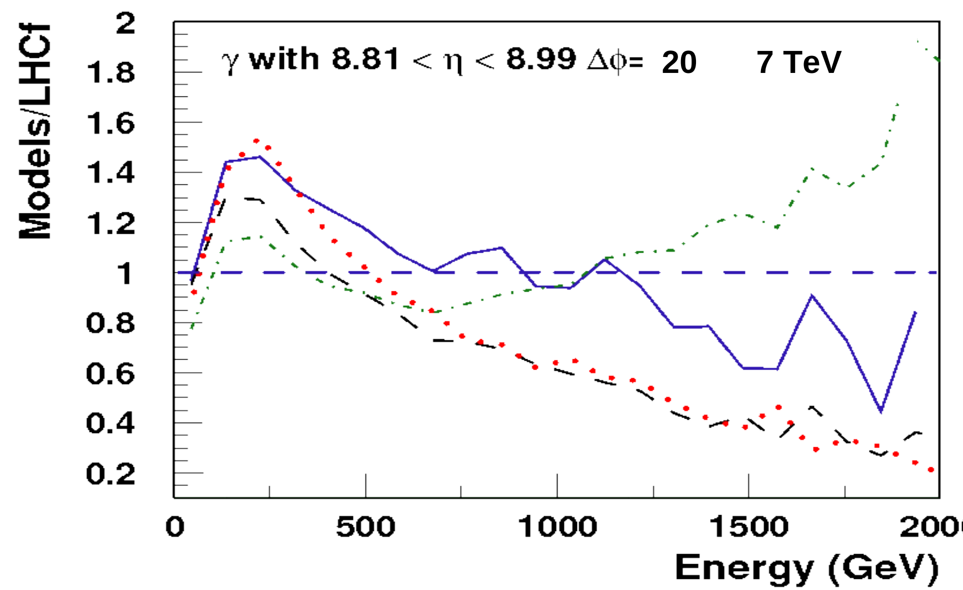


CMS and LHCf Forward Spectra





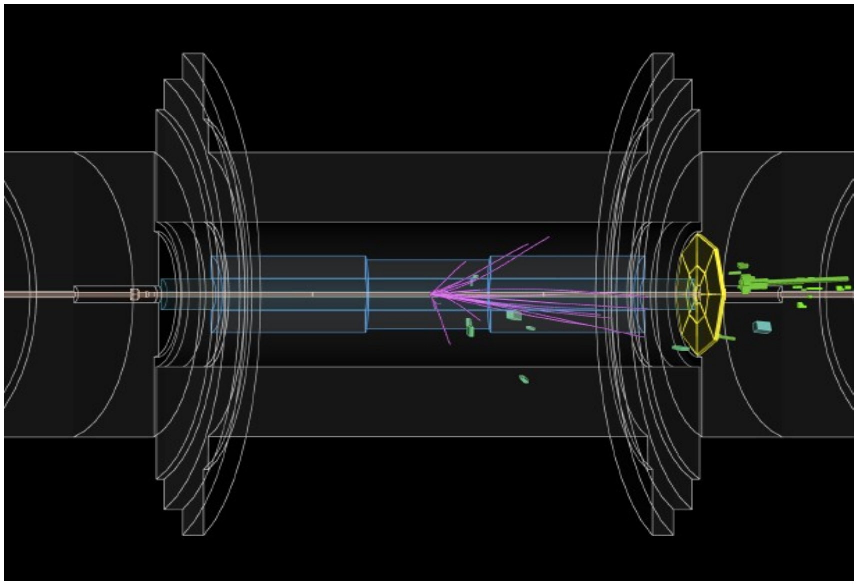




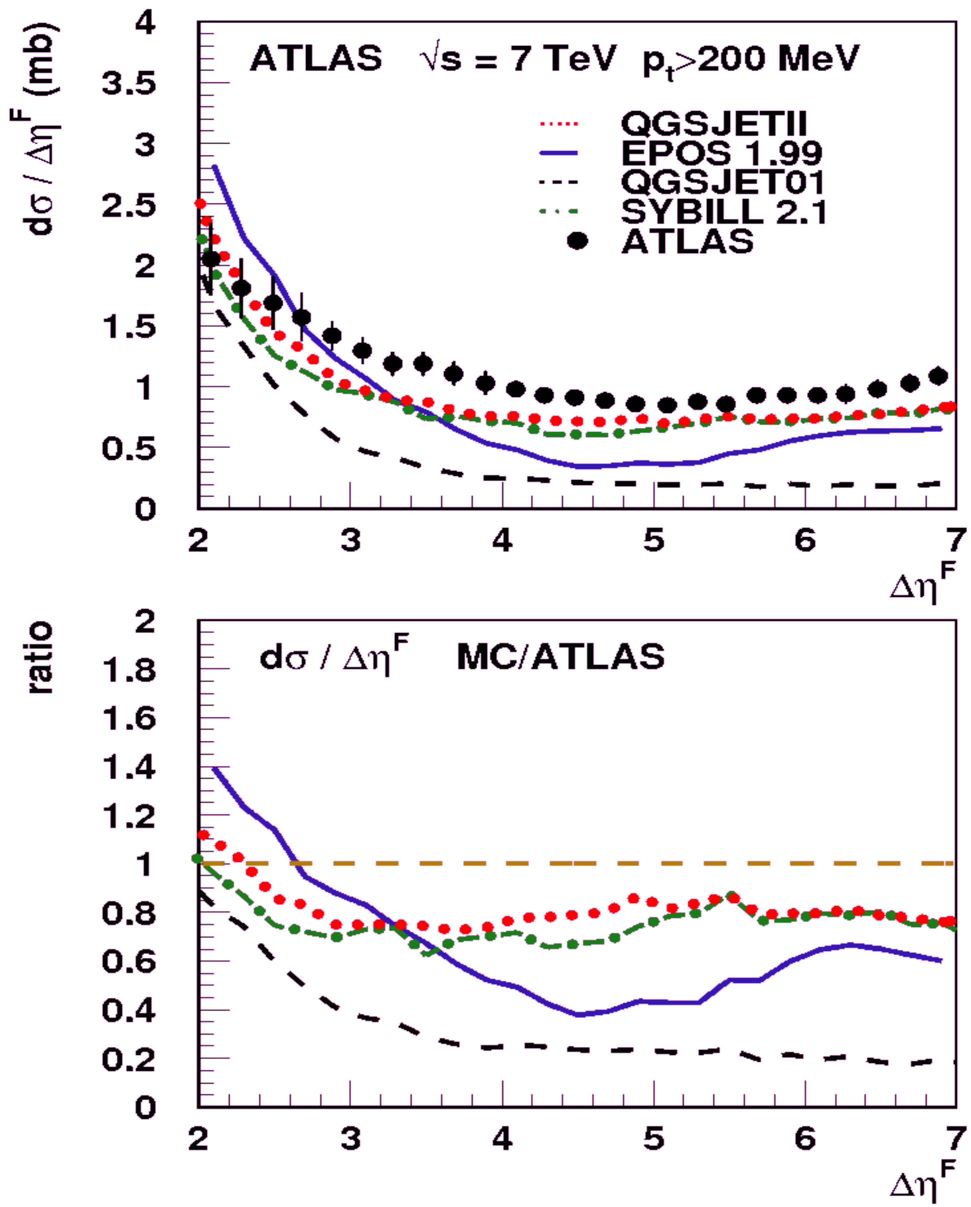
- **Forward calorimeter → better than HEP models**

Rapidity Gap

ATLAS detector



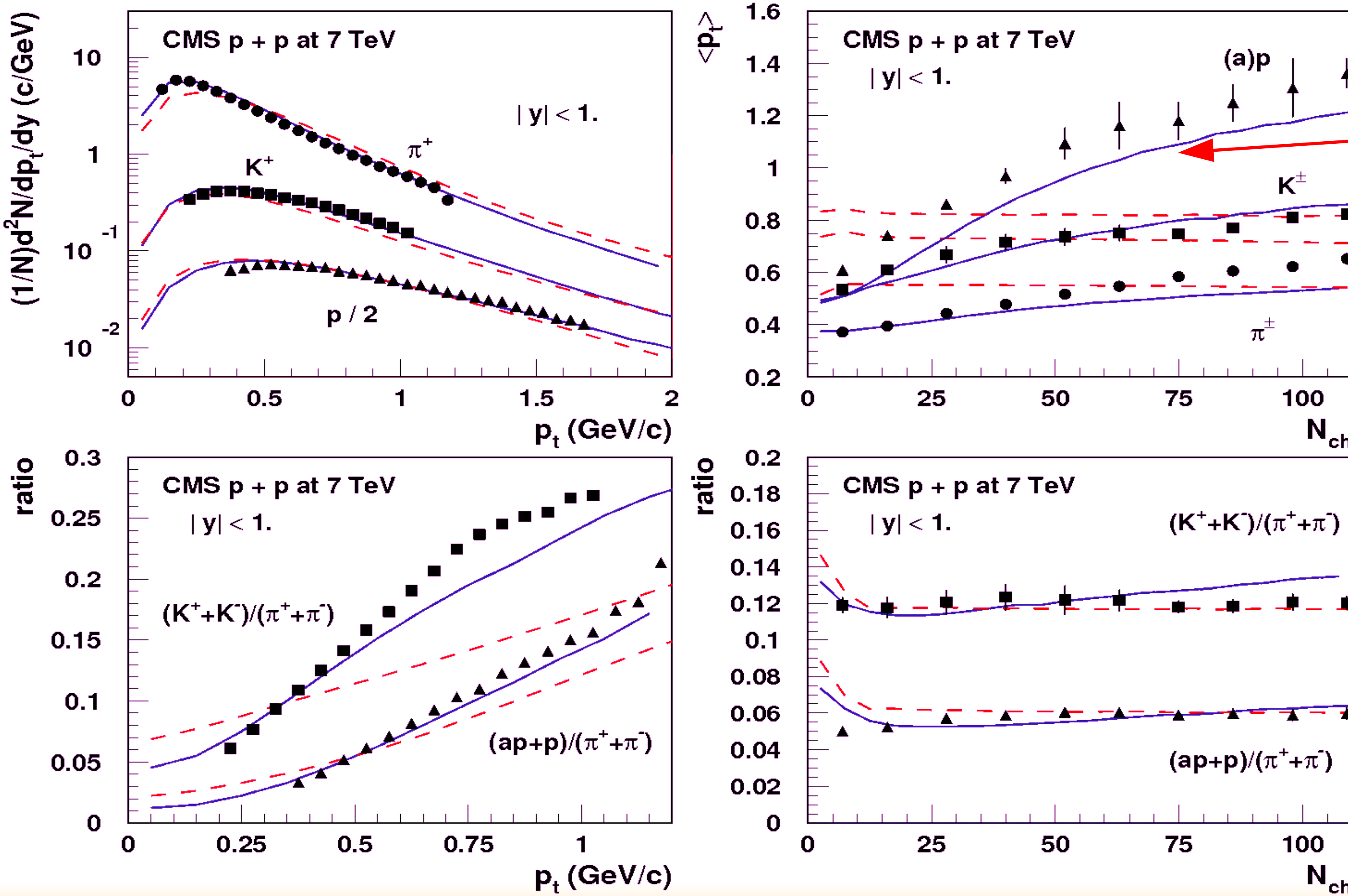
ATLAS Collaboration



- **Rapidity gap closely related to diffraction**
  - diffractive cross-section
  - AND diffractive mass distribution
- **Hard constraint for CR**
  - change elasticity

Identified Particle Spectra

- **Detailed description can be achieved (tested by ATLAS for publications)**
  - identified spectra
  - p_t behavior driven by collective effects (statistical hadronization + flow)

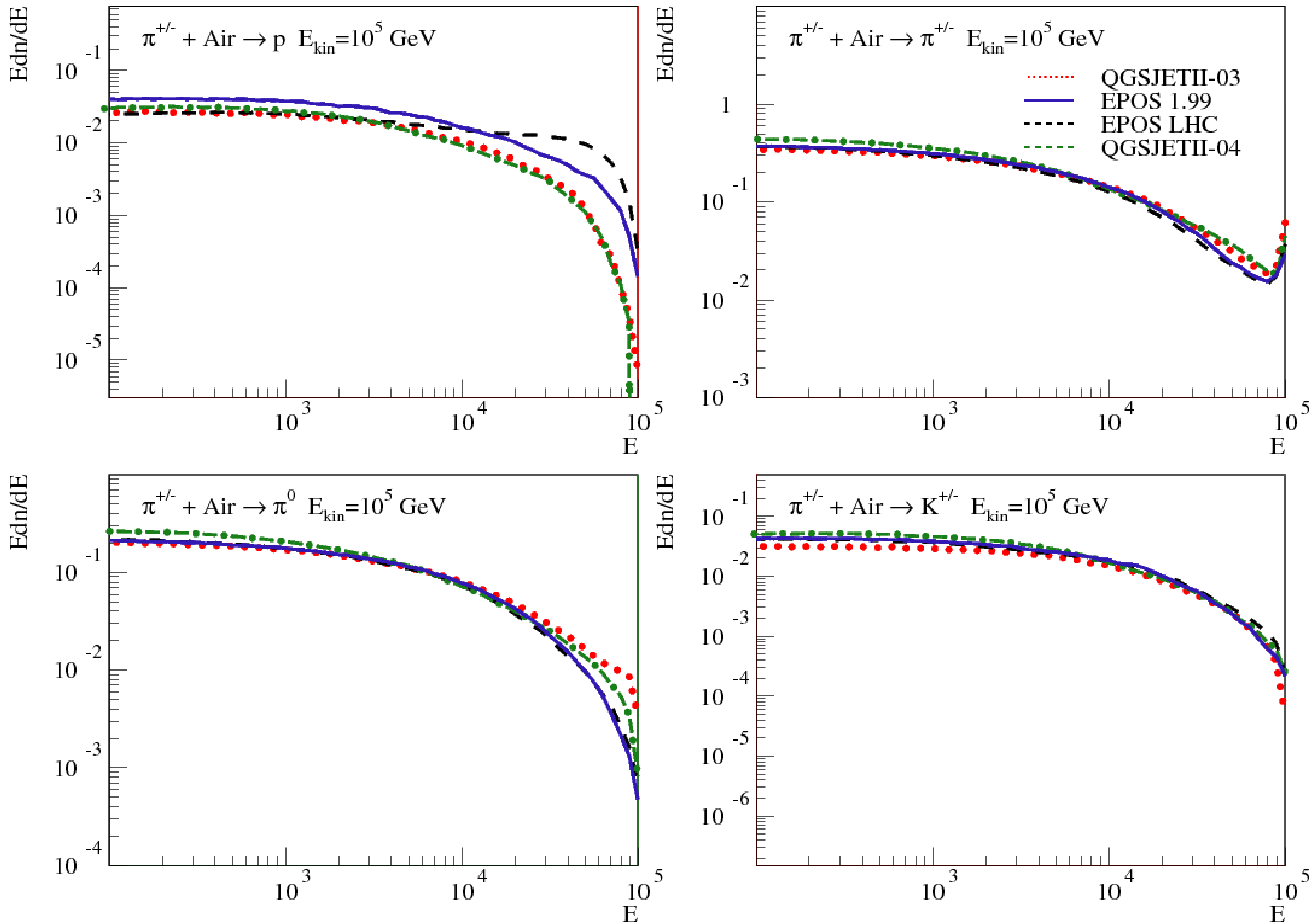


Collective flow effect only in EPOS

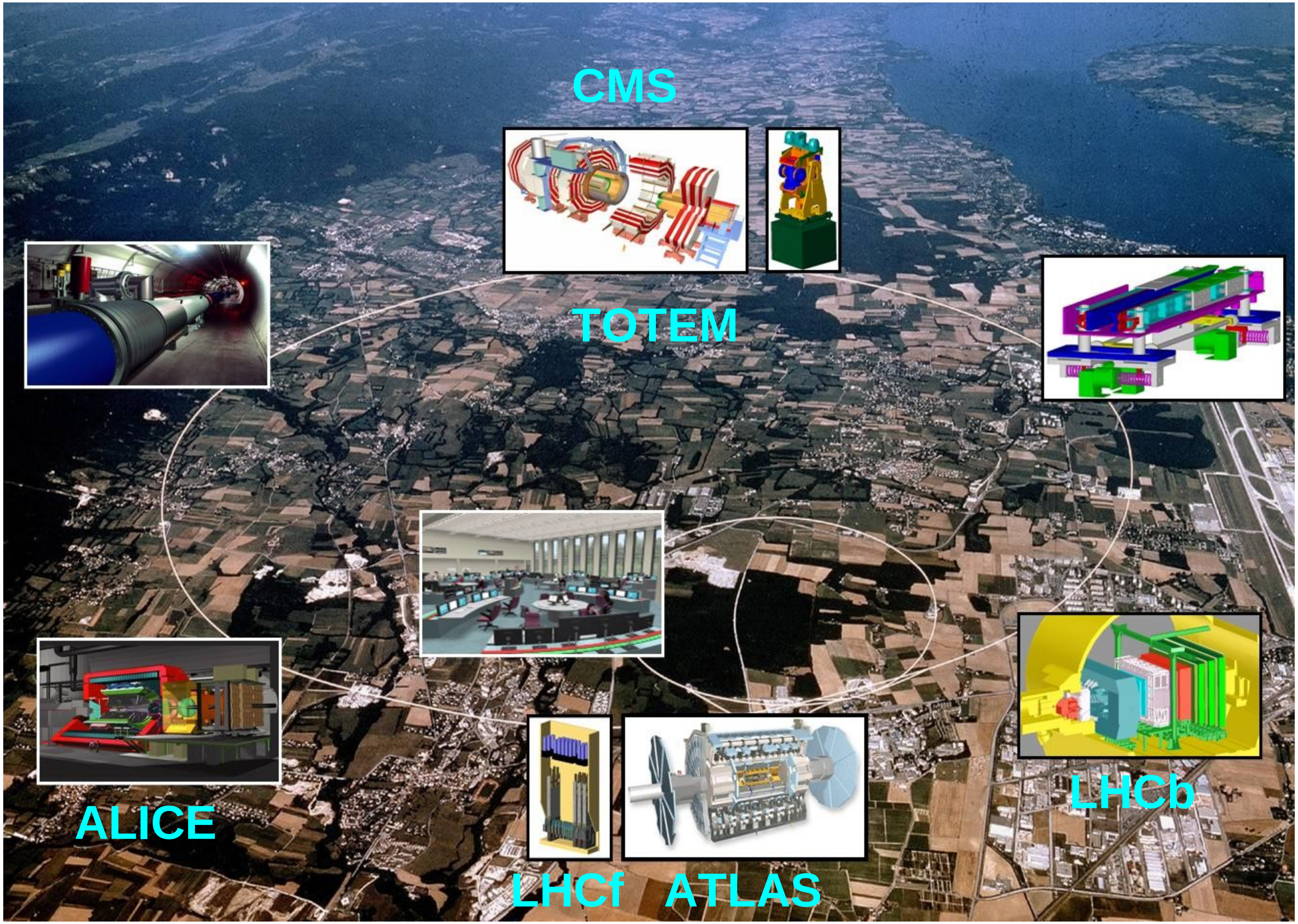
Baryon number now fixed at mid-rapidity.

EPOS LHC
QGSJETII-04

Particle Spectra



LHC Detectors



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-)

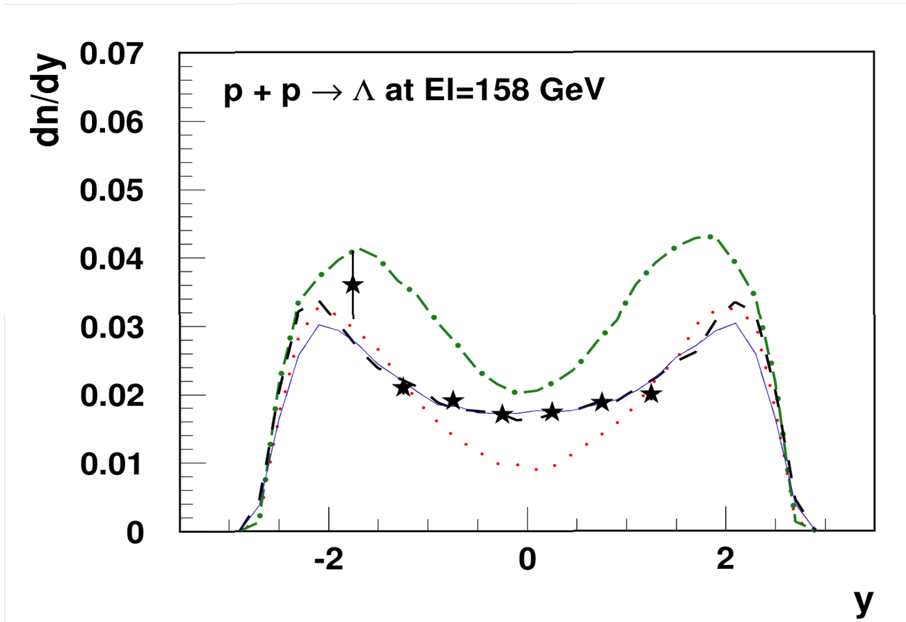
Theory ++ :

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

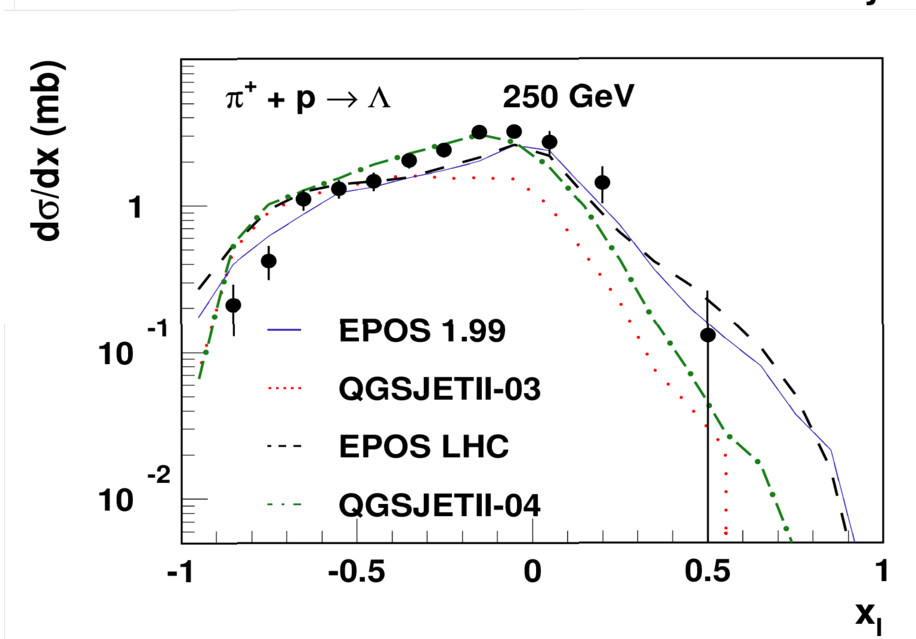
Phenomenology ++ :

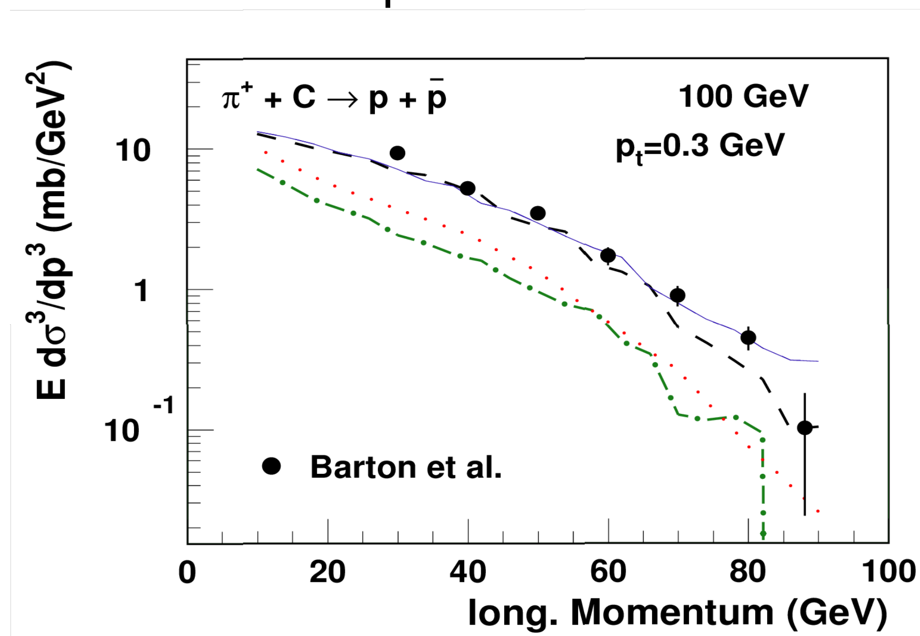
- **all type of data studied**
- **high density effect (QGP)**
- **multi-purpose model (SPS, RHIC, LHC analysis)**

Baryon Forward Spectra



- Large differences between models
- Need a new remnant approach for a complete description (EPOS)
- Problems even at low energy
  - check data with NA61
- No measurement at high energy !
  - neutron spectra from LHCf ?





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
  - already in EPOS

Not only Rho0 should be taken into account !