Connecting Collider Data with Air-Shower Physics

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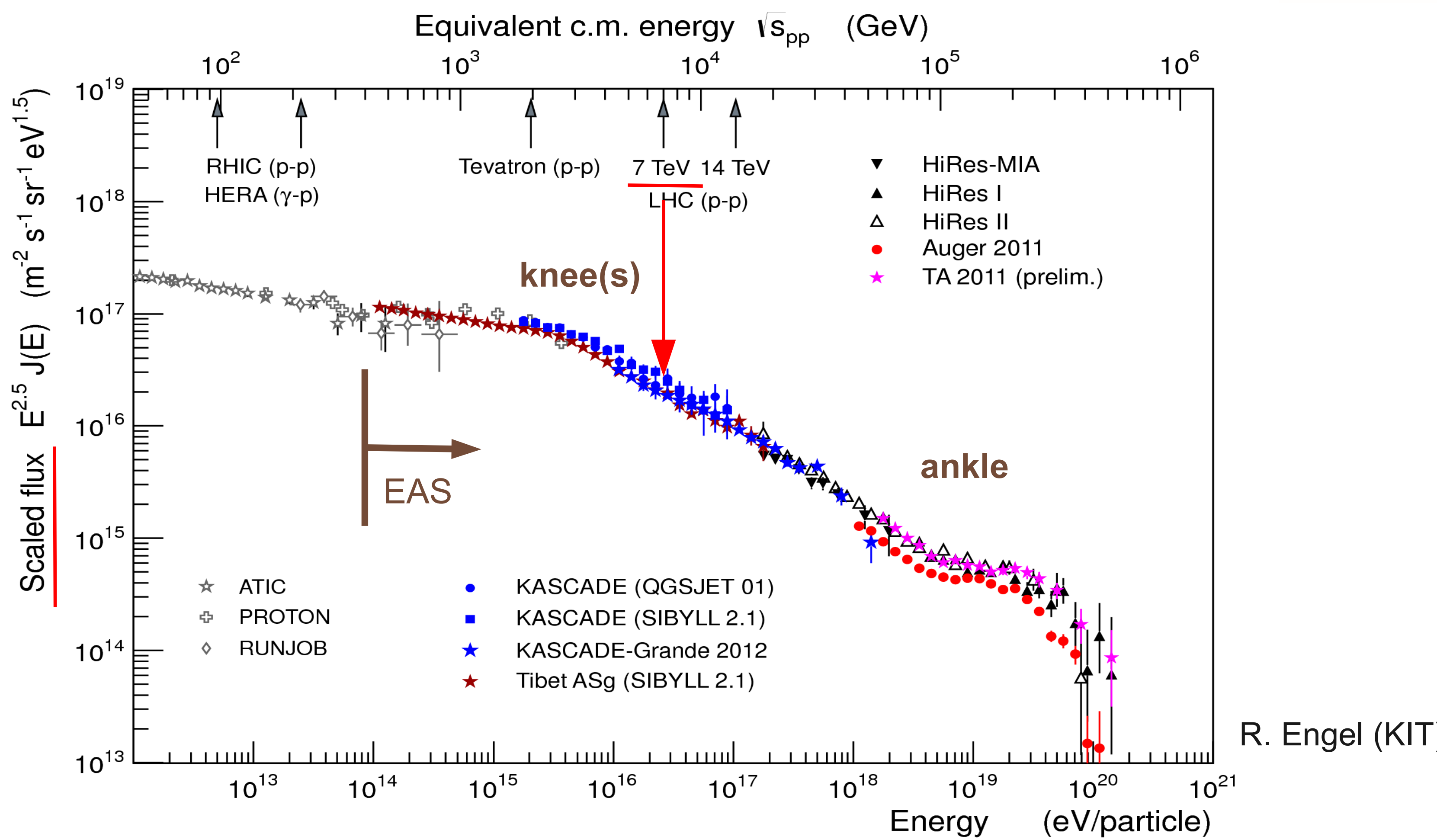
Cosmic Ray Spectrum



- **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 !

- **Comparison with data to fix parameters :**
  - minimum theory requirement with few parameters and limited data set (QGSJET approach) : better predictive power (if nothing forgotten...)

... or ...

  - more detailed data with more parameters (EPOS approach) : nothing neglected (but more uncertainties in extrapolation)

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 ++ :

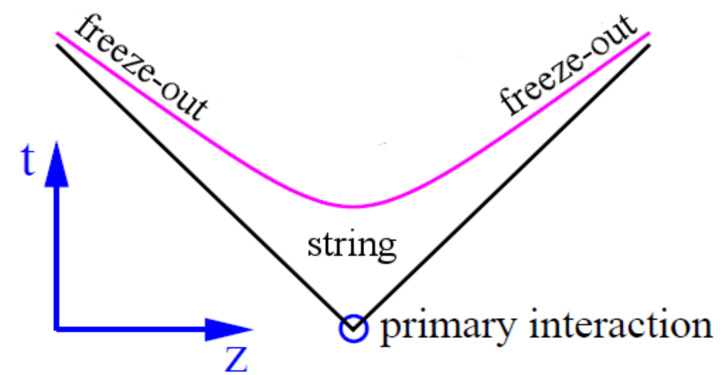
- **Loop diagrams**
- **rho0 resonance**
- **optimized for CR**

Phenomenology ++ :

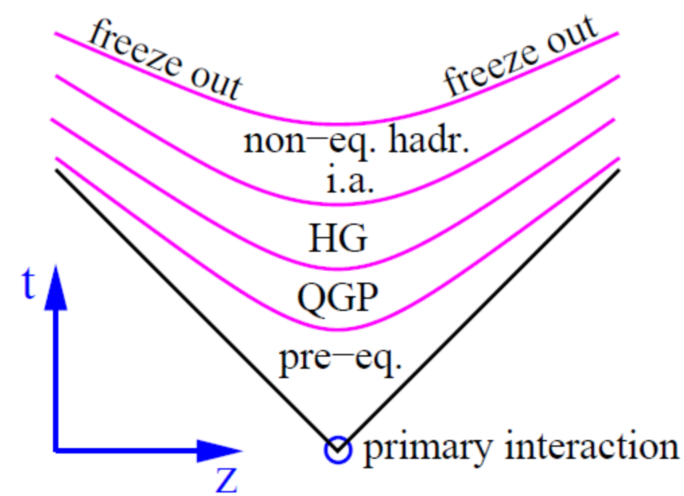
- **all type of data studied**
- **high density effect (QGP)**
- **multi-purpose model (SPS, RHIC, LHC analysis)**

New Models

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

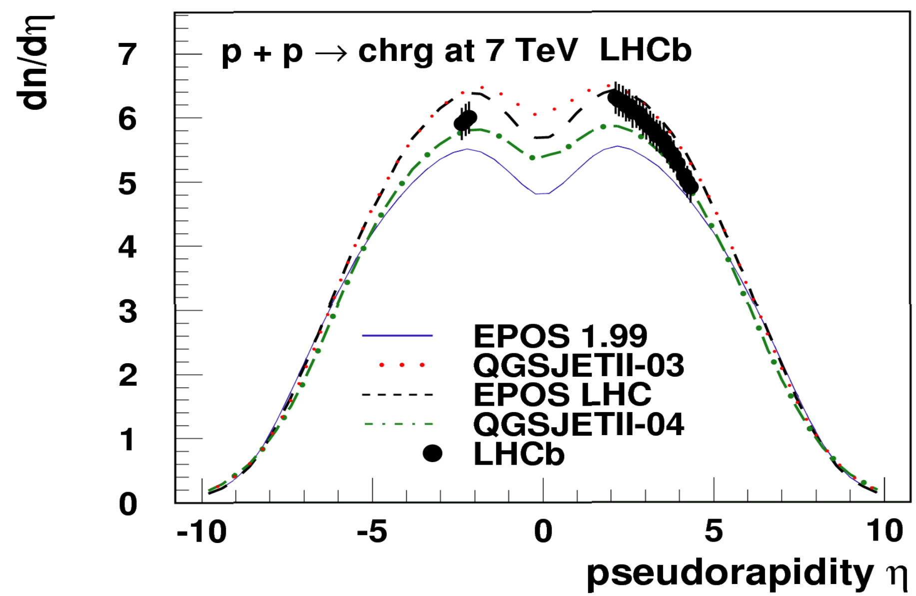


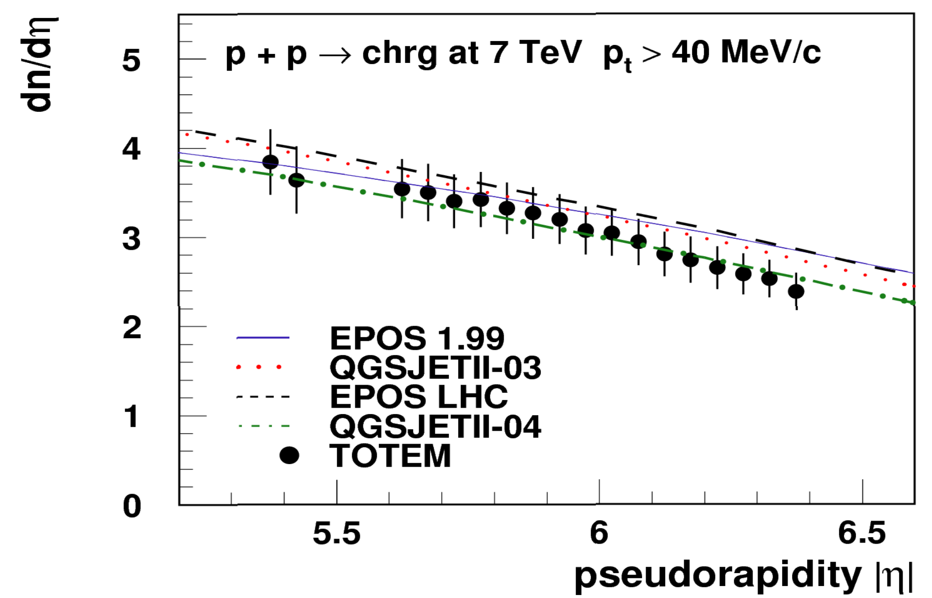
- **EPOS LHC**
  - tune cross section to TOTEM value
  - change old flow calculation to a more realistic one
  - introduce central diffraction
  - keep compatibility with lower energies

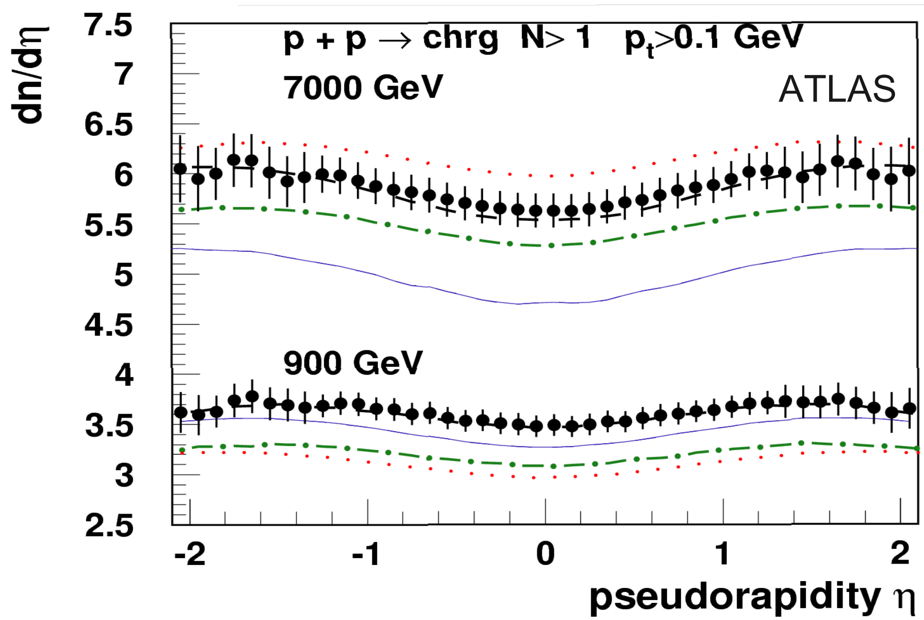


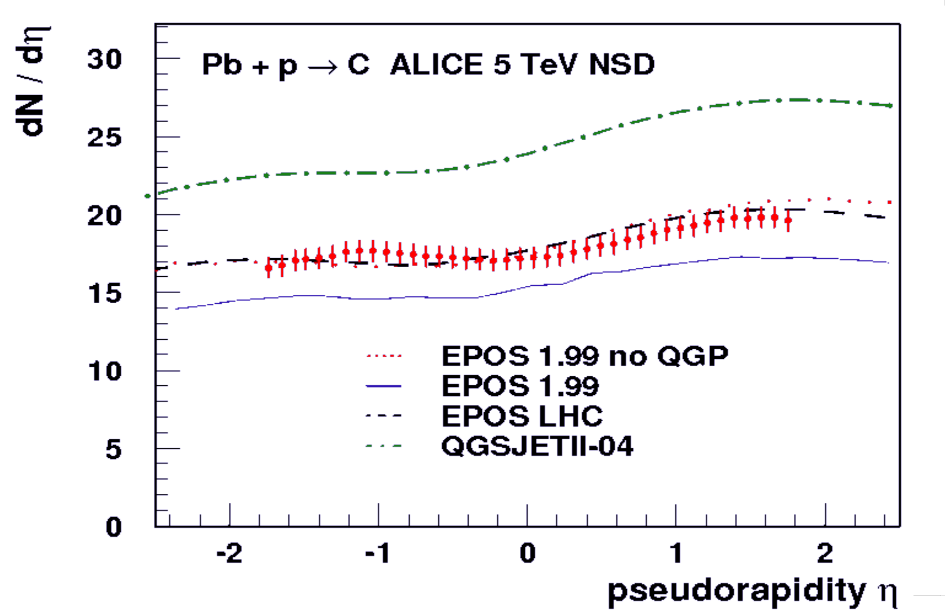
Direct influence on EAS simulations to be shown but important to compare to LHC and set parameters properly (<pt>, ...).

Pseudorapidity Distributions

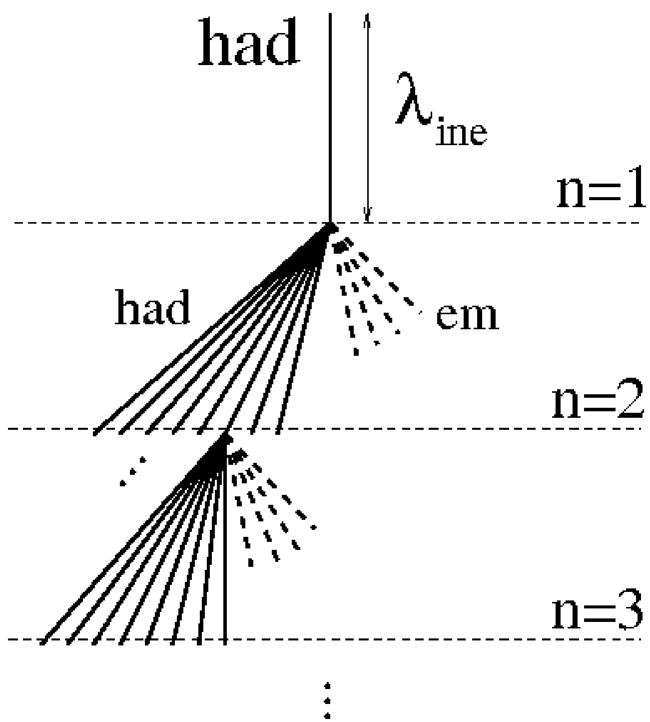








Simplified Shower Development



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

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

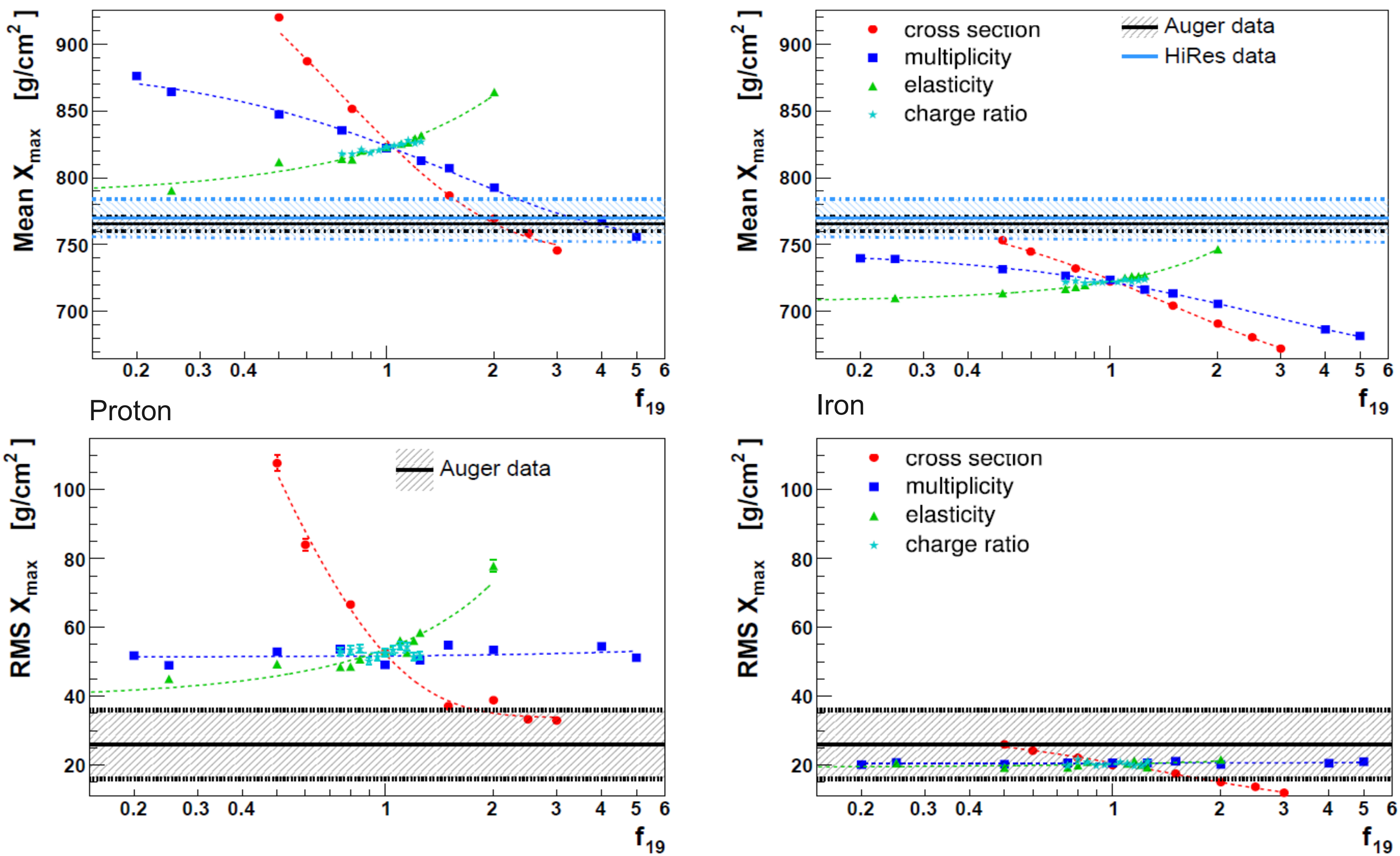
- Using generalized Heitler model and superposition model :

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

- 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)

Effects of Parameters

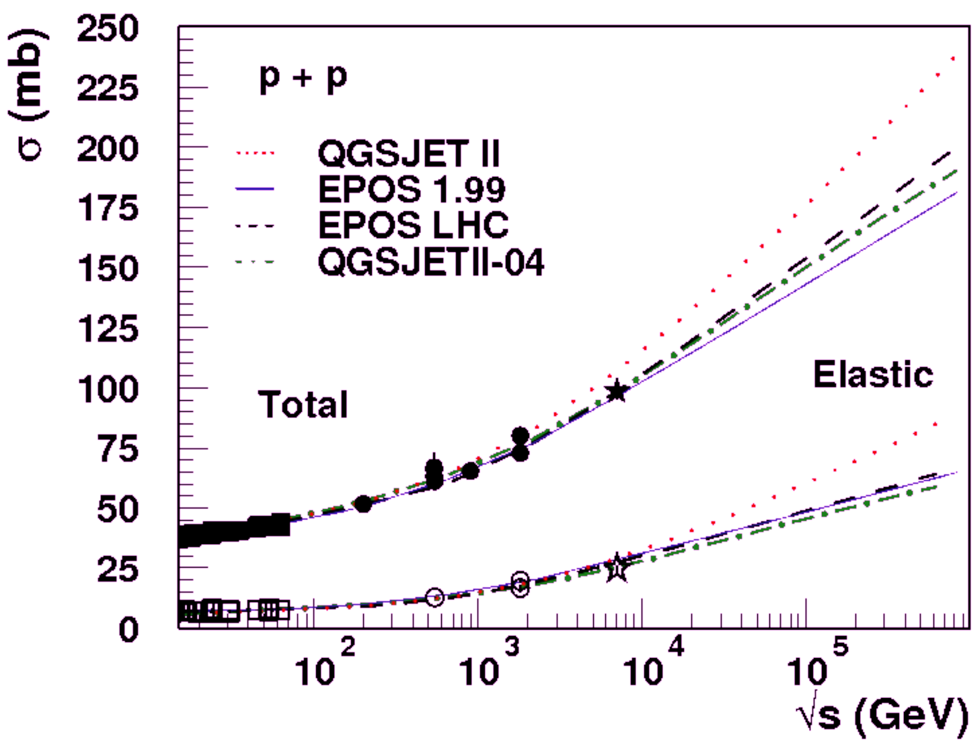
- **Sensibility depends on observable and parameter :**

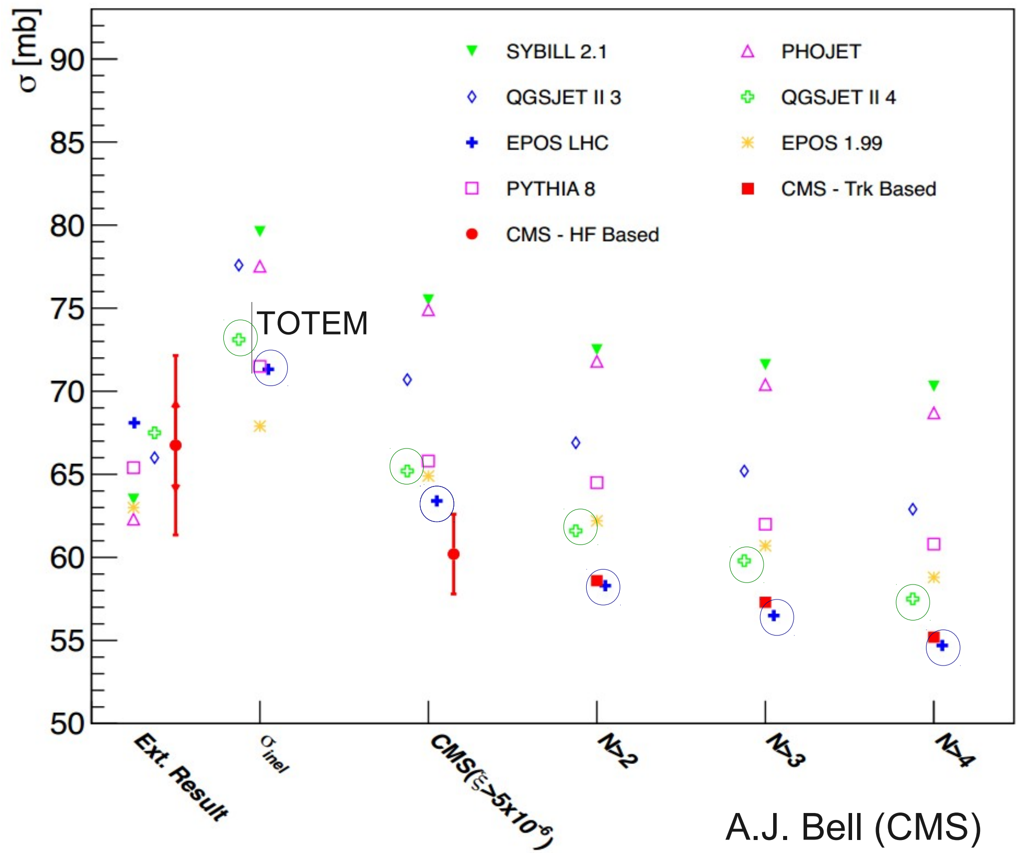


Plots by R. Ulrich (KIT) with Sibyll model and PAO data @ 10^{19} eV

Cross Sections

- Same cross sections at pp level up to LHC
- extrapolation to pA or to high energy
  - different amplitude and scheme : different extrapolations
- LHC measurements test the difference between models (diffraction)

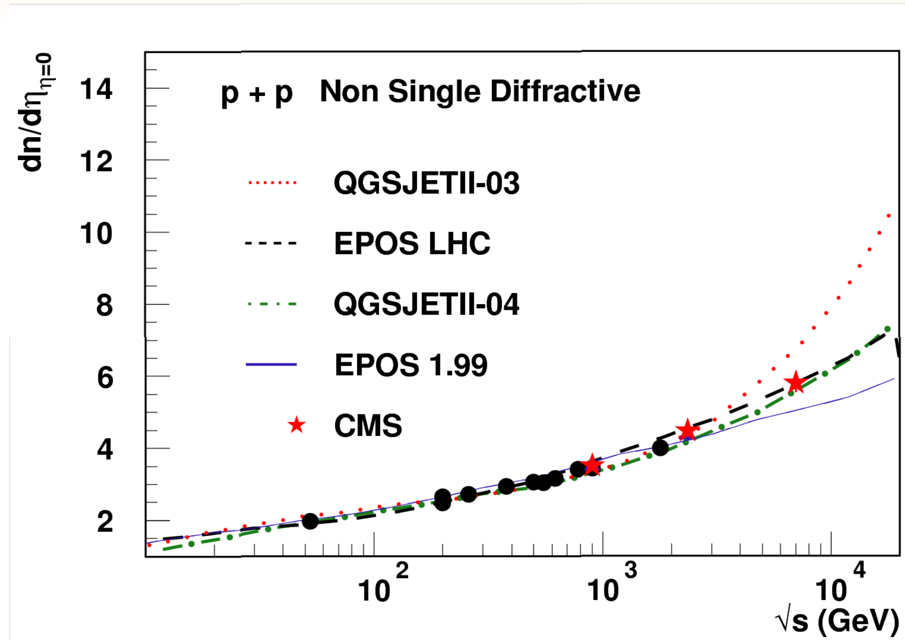


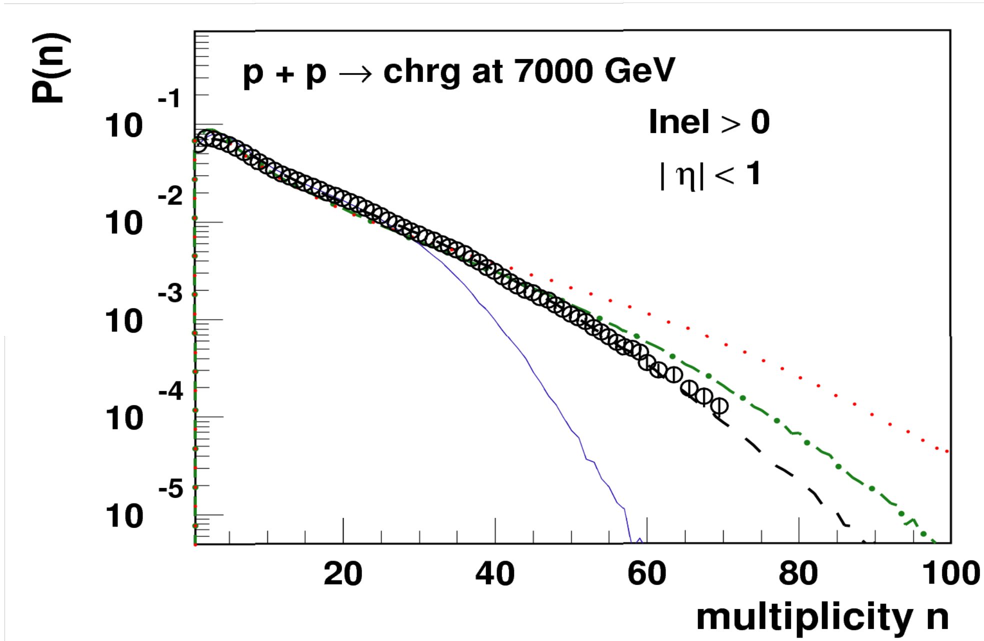


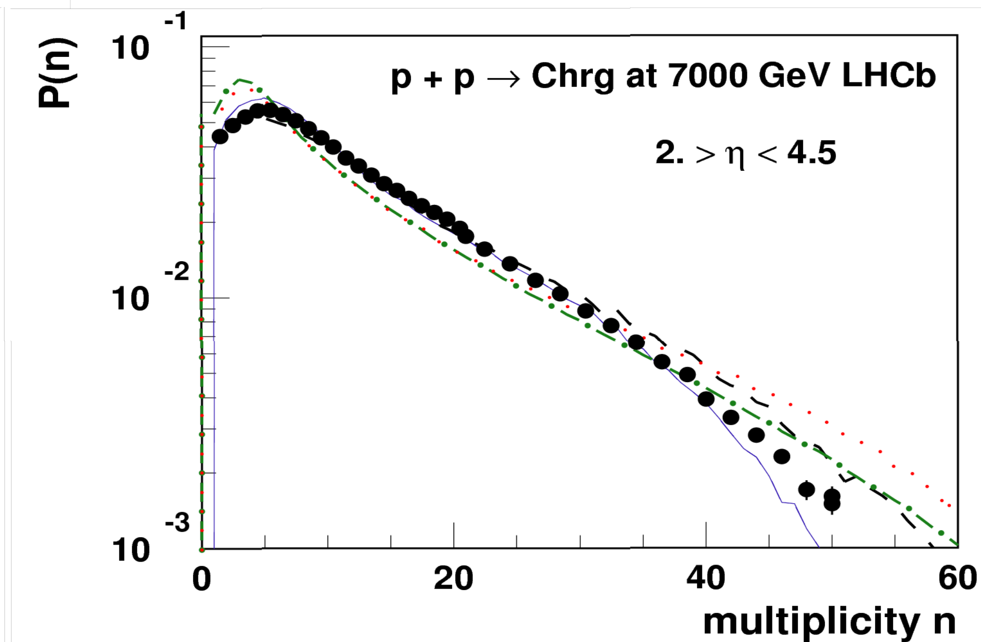
A.J. Bell (CMS)

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)

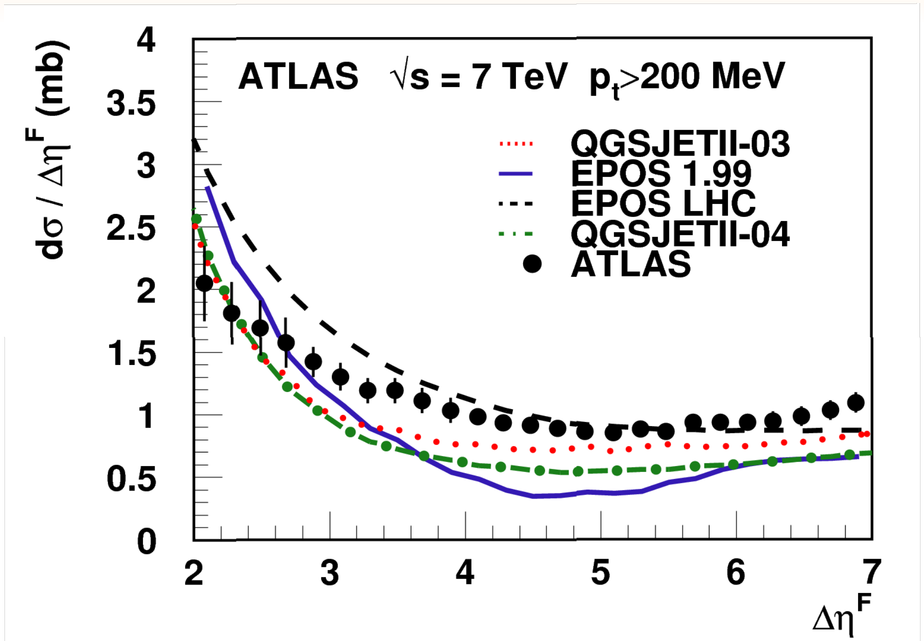


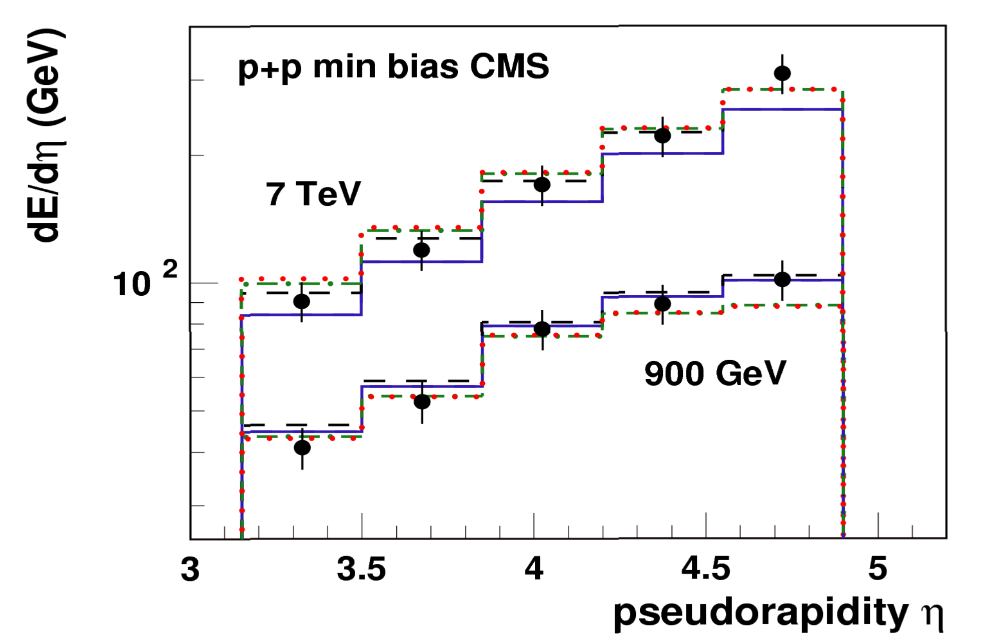


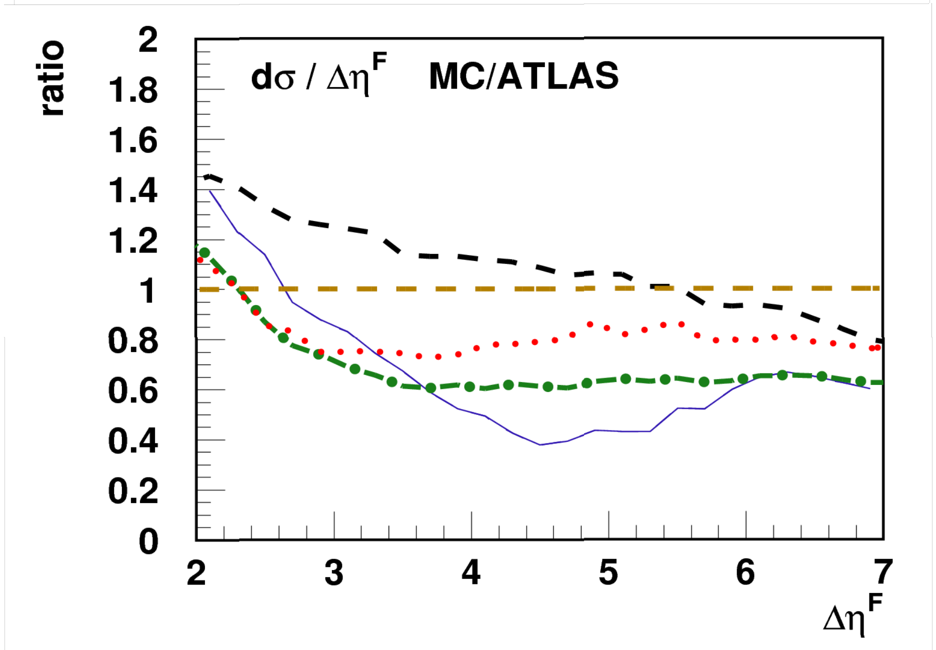


Inelasticity

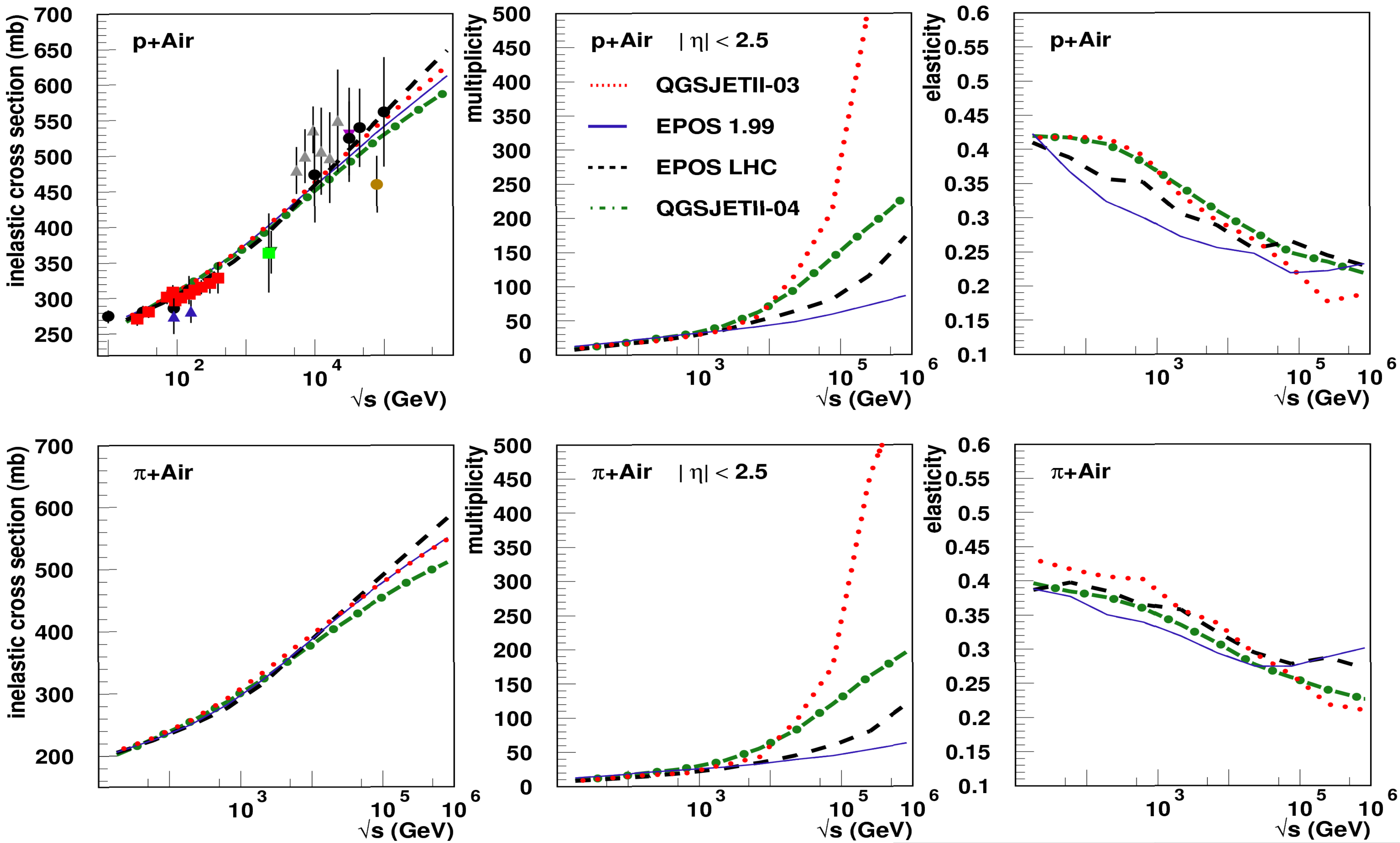
- **More uncertainty**
  - Difference in diffraction
    - low mass
    - high mass
    - central
  - very similar energy flow



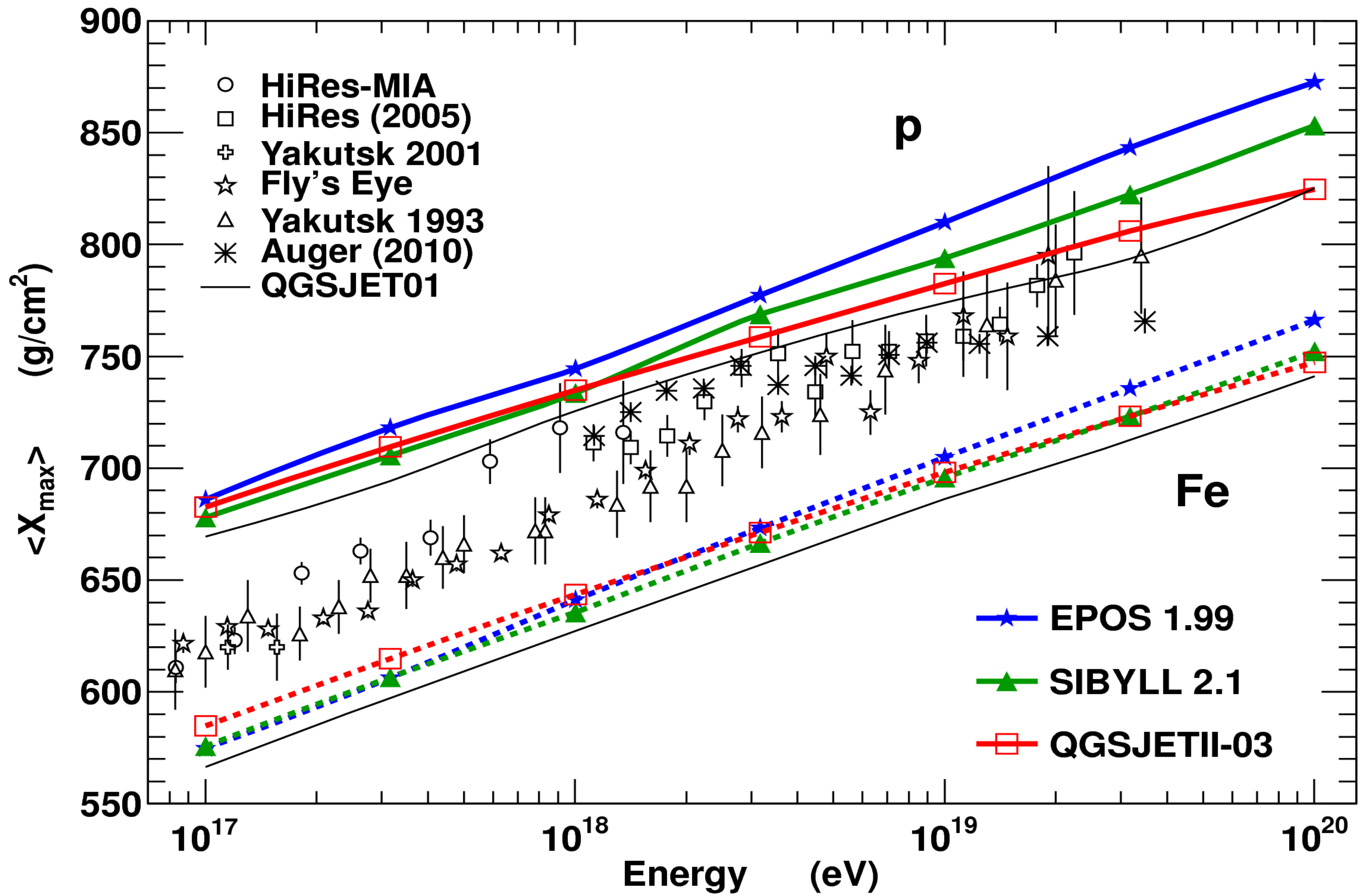




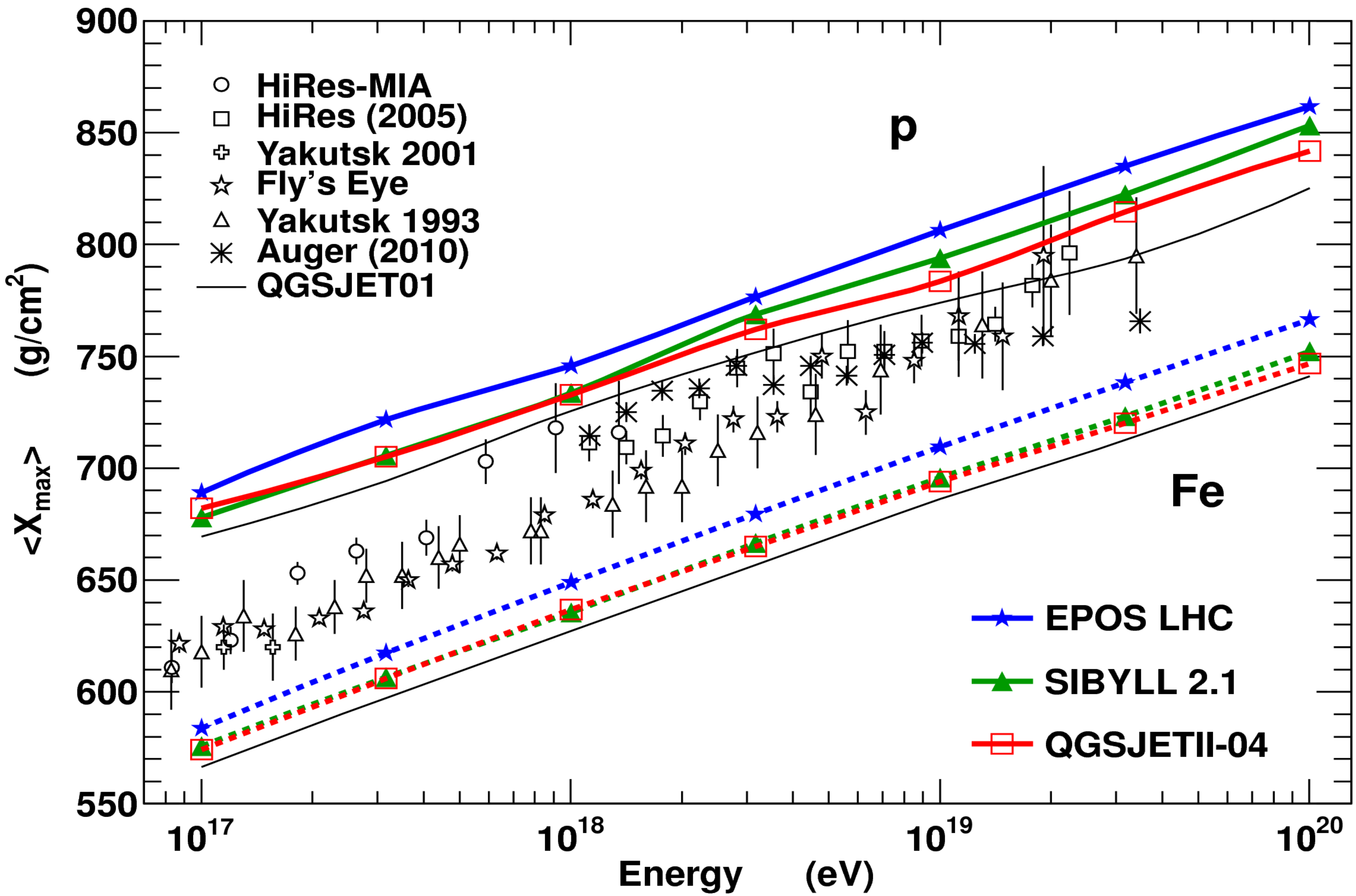
Predictions with retuned models



EAS with old CR Models : X_{max}

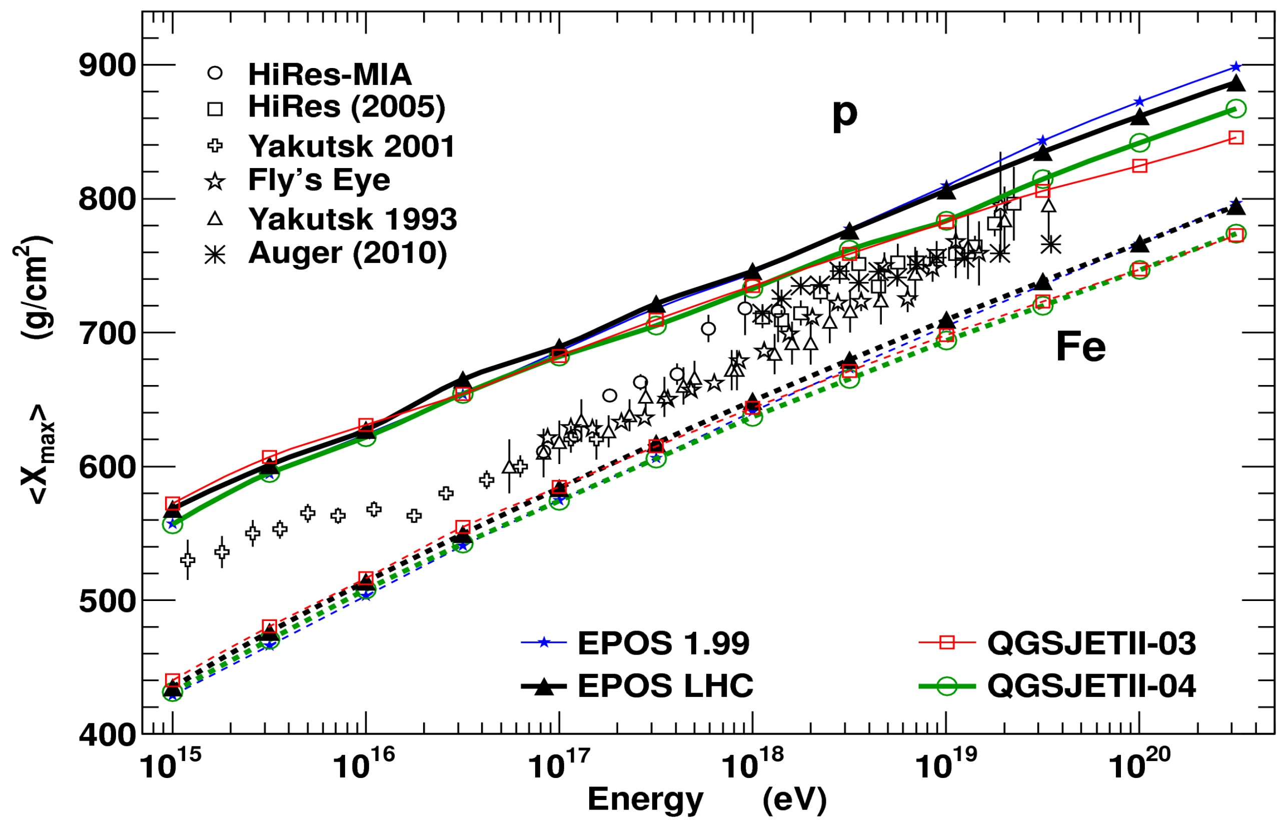


EAS with Re-tuned CR Models : X_{max}



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)

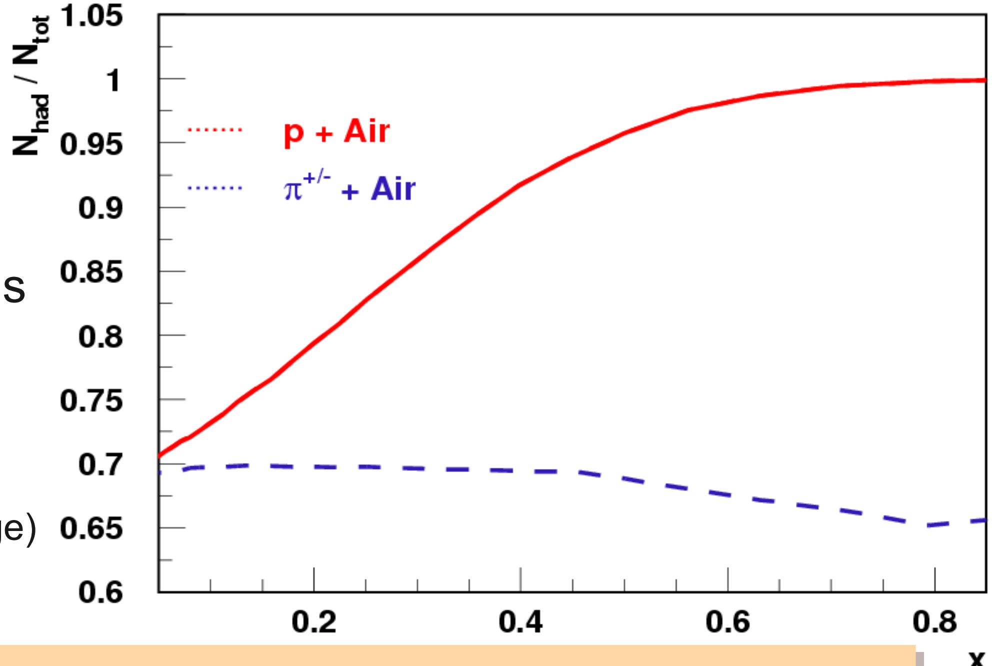


Muon Number

- **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)

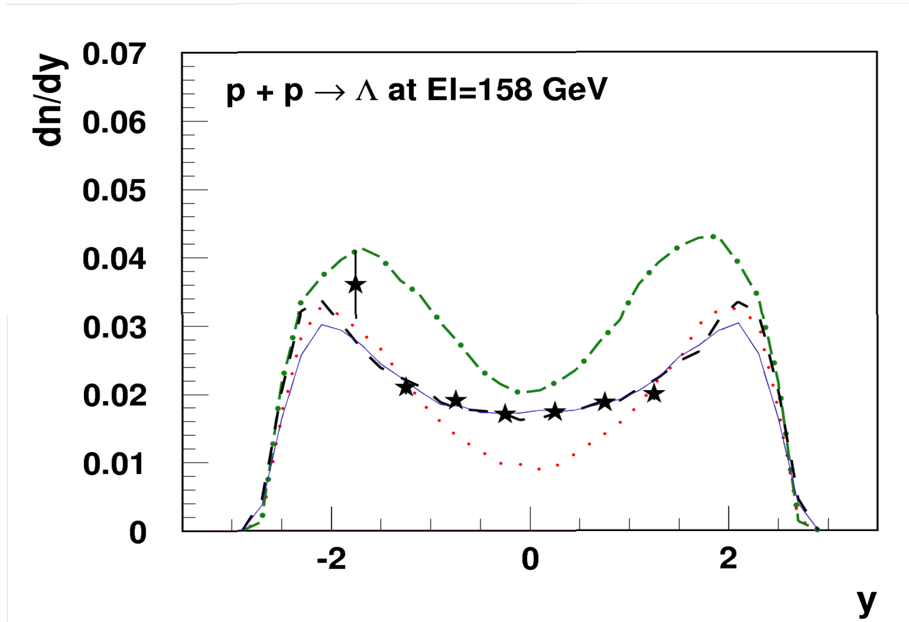


Muon number depends on the number of (anti)B in p- or π-Air interactions at all energies

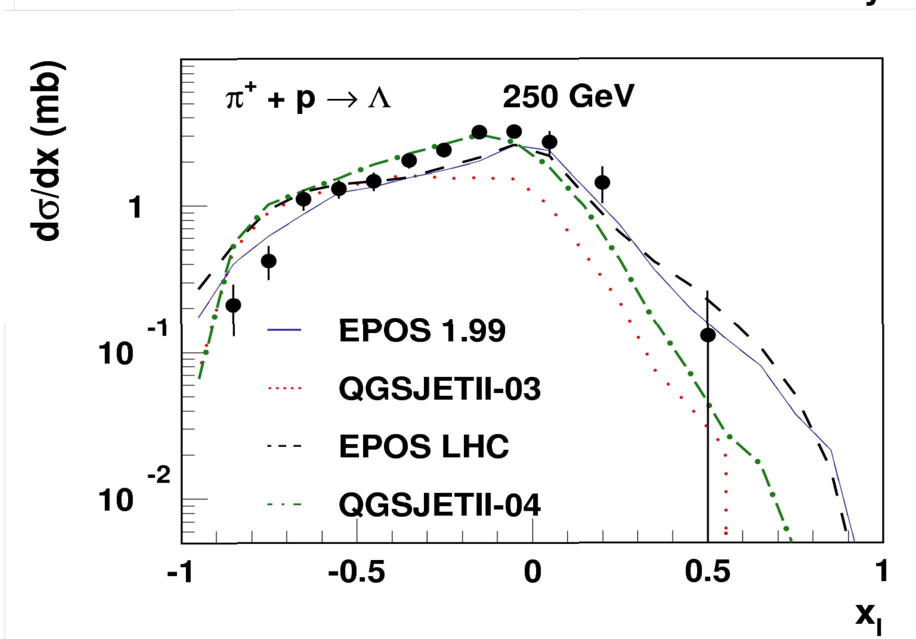
More fast (anti)baryons = more muons

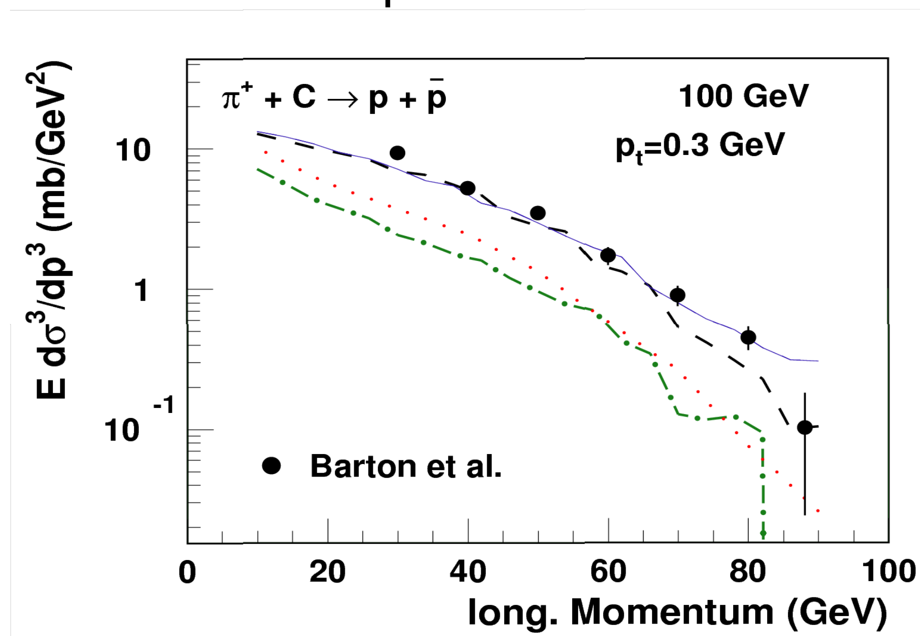
T. Pierog et al.,Phys.Rev.Lett. 101 (2008) 171101

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 ?

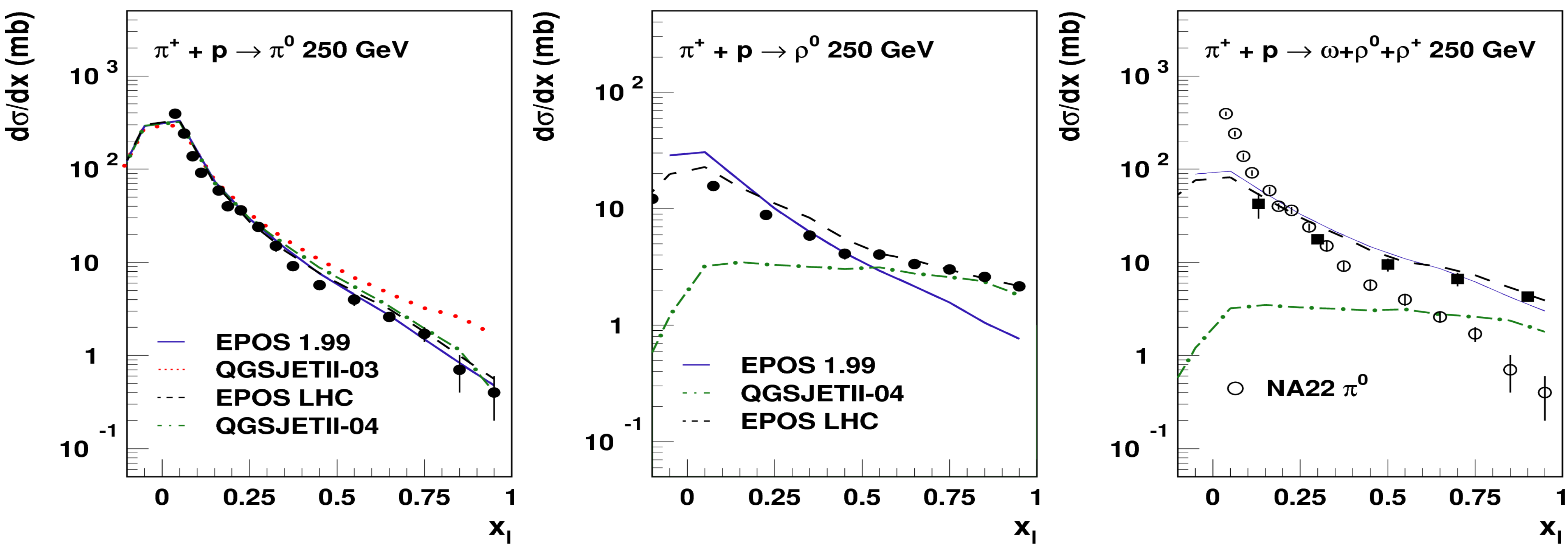




Pion Leading Particle Effect

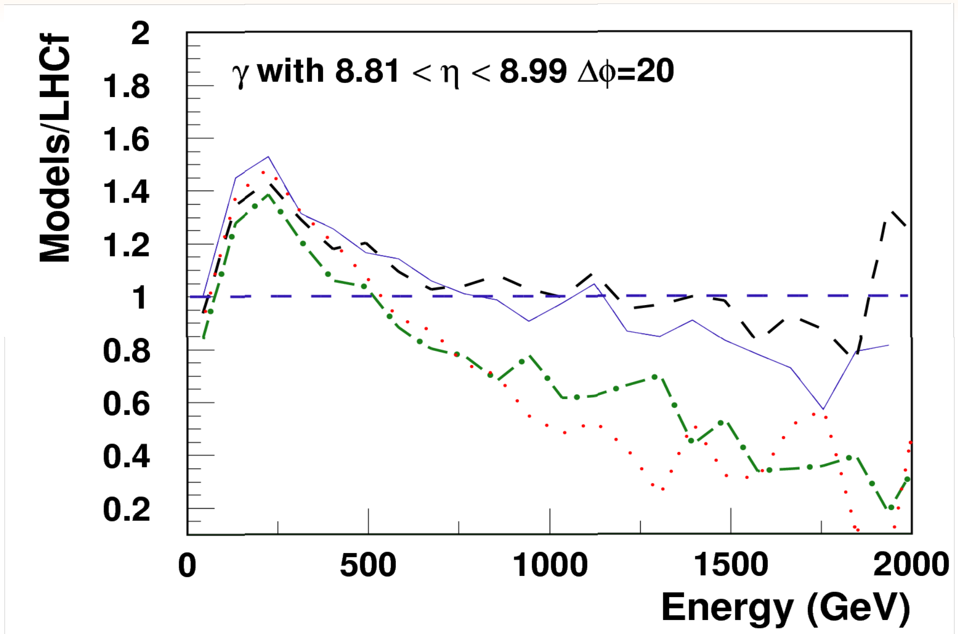
- **Rho meson production added in QGSJETII to take into account leading particle effect in pion-Air interaction**
  - same effect as baryon production : forward π^0 replaced by charged pions (reduced leading π^0)
  - increase muon production
  - already in EPOS

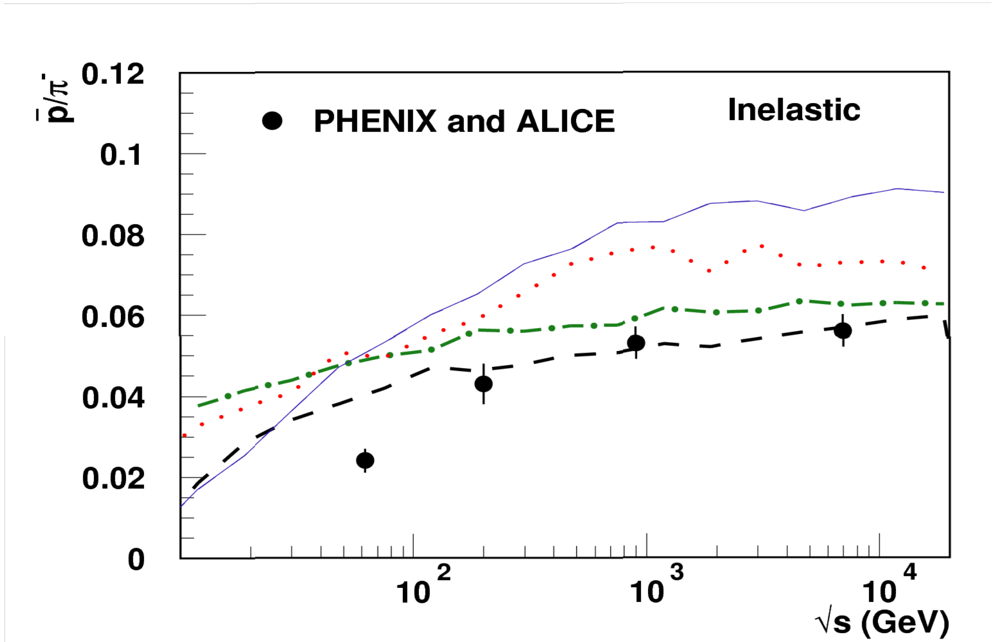
Not only Rho0 should be taken into account !

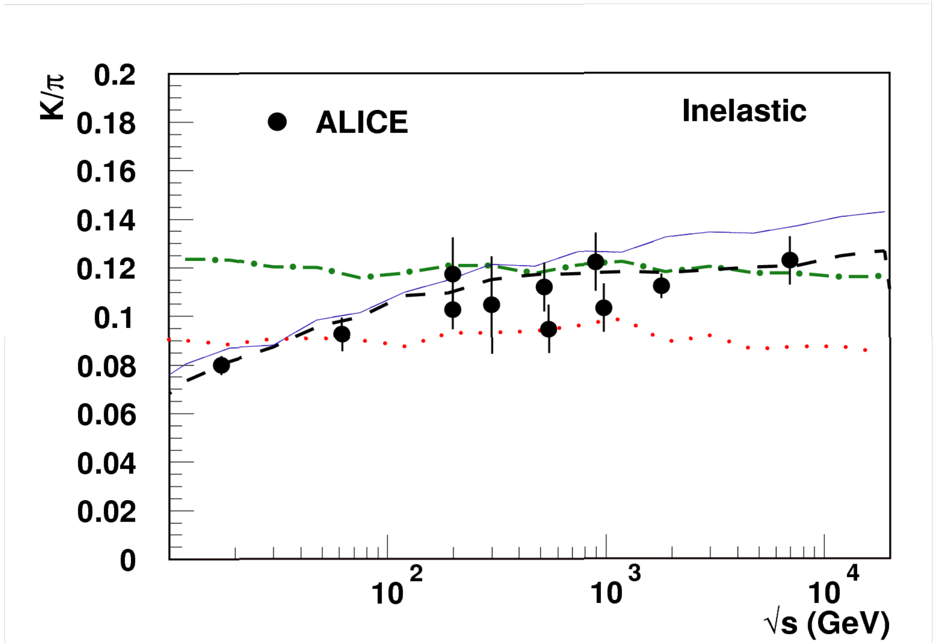


Identified particles

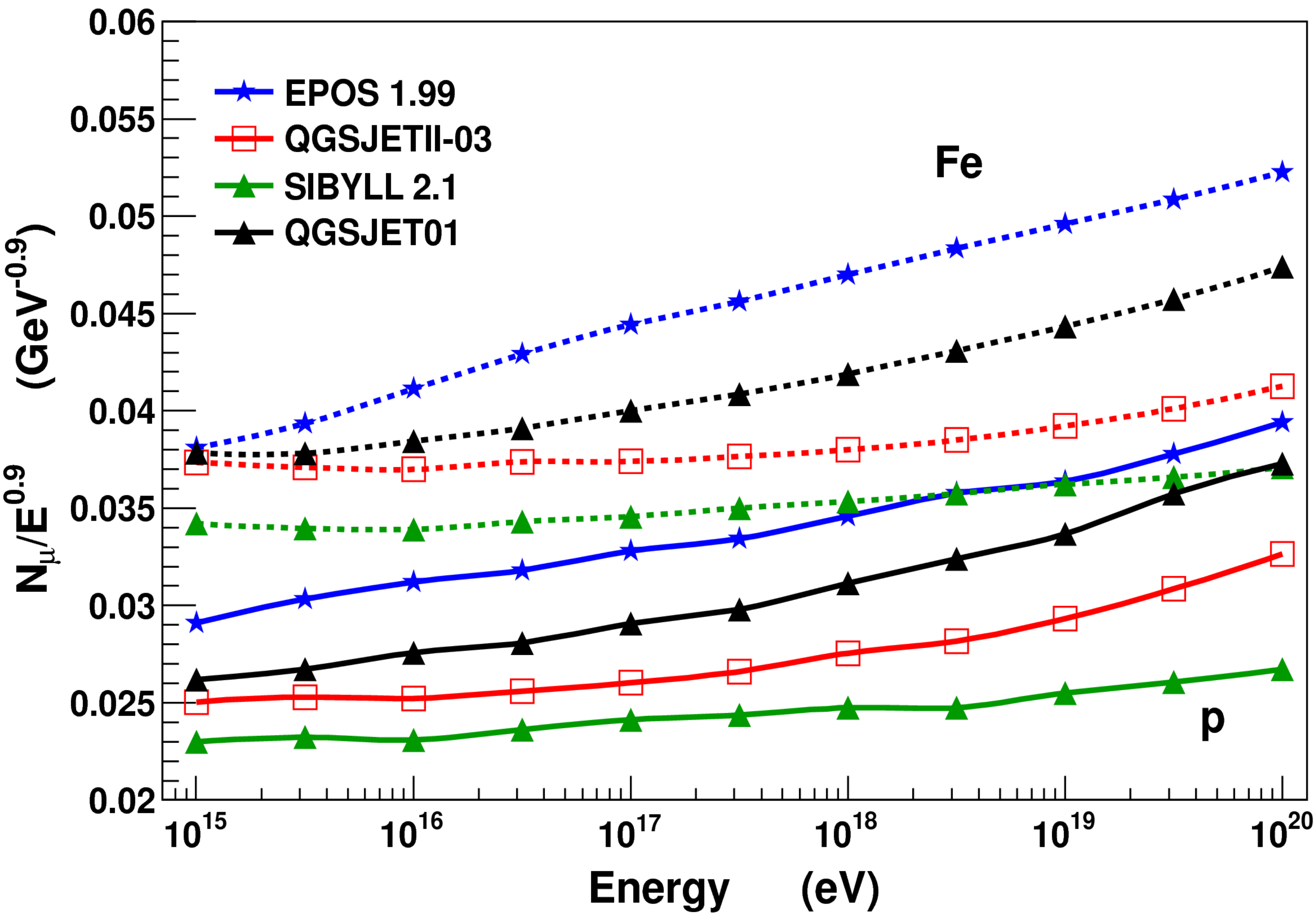
- **Large improvement at mid-rapidity**
  - very similar results for particle ratios
  - overestimation of baryon production before due to wrong interpretation of Tevatron data
- **Only small changes very forward**
  - no try to tune LHCf data (difficult)



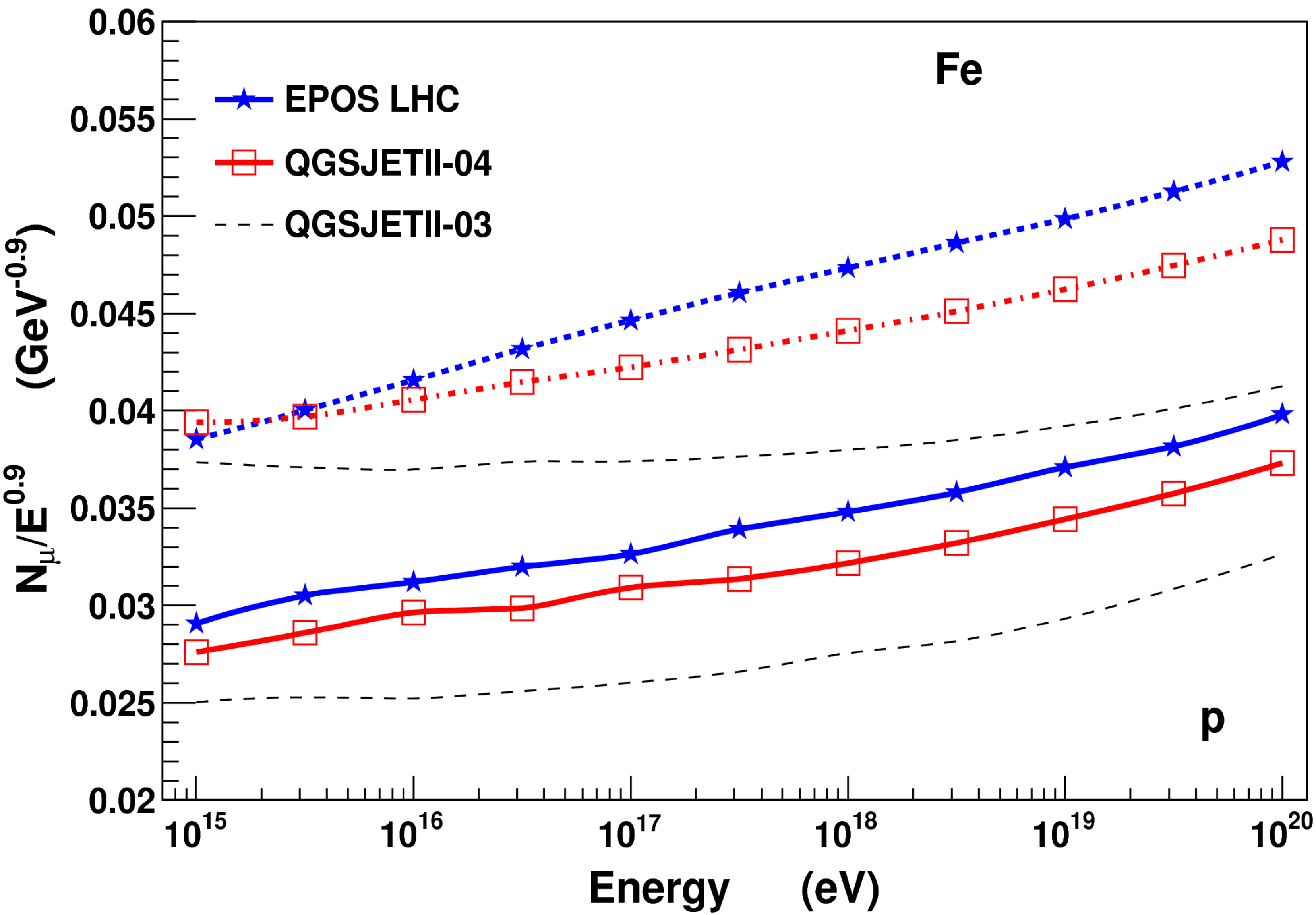




EAS with old CR models : Muons

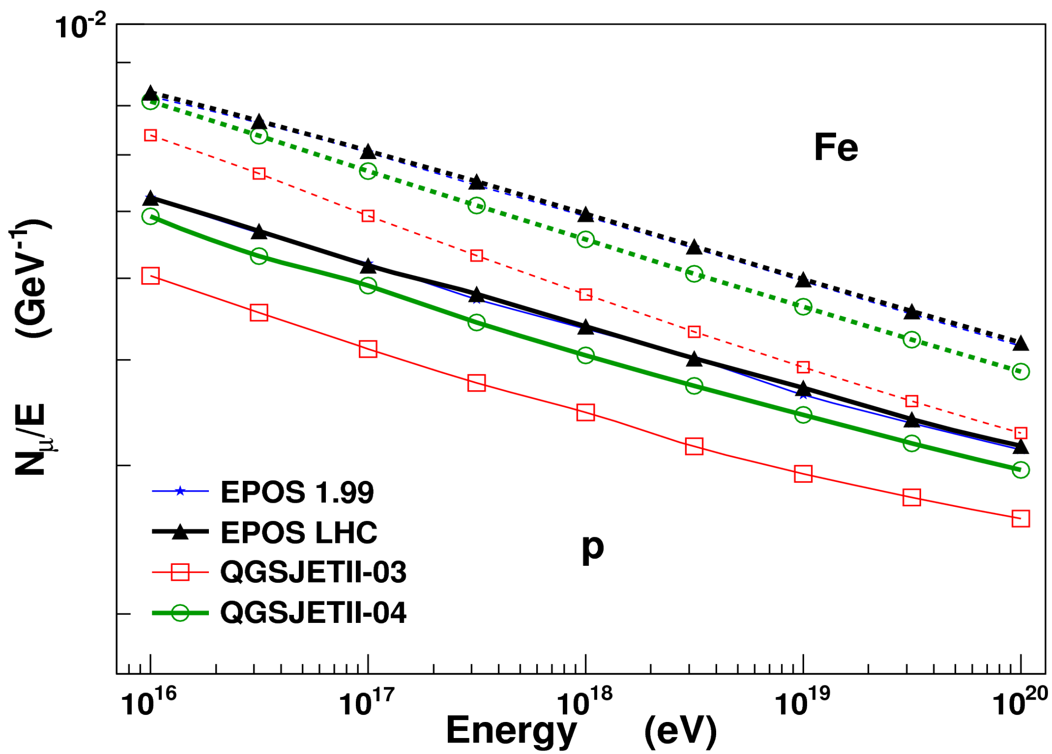


EAS with Re-tuned CR models : Muons



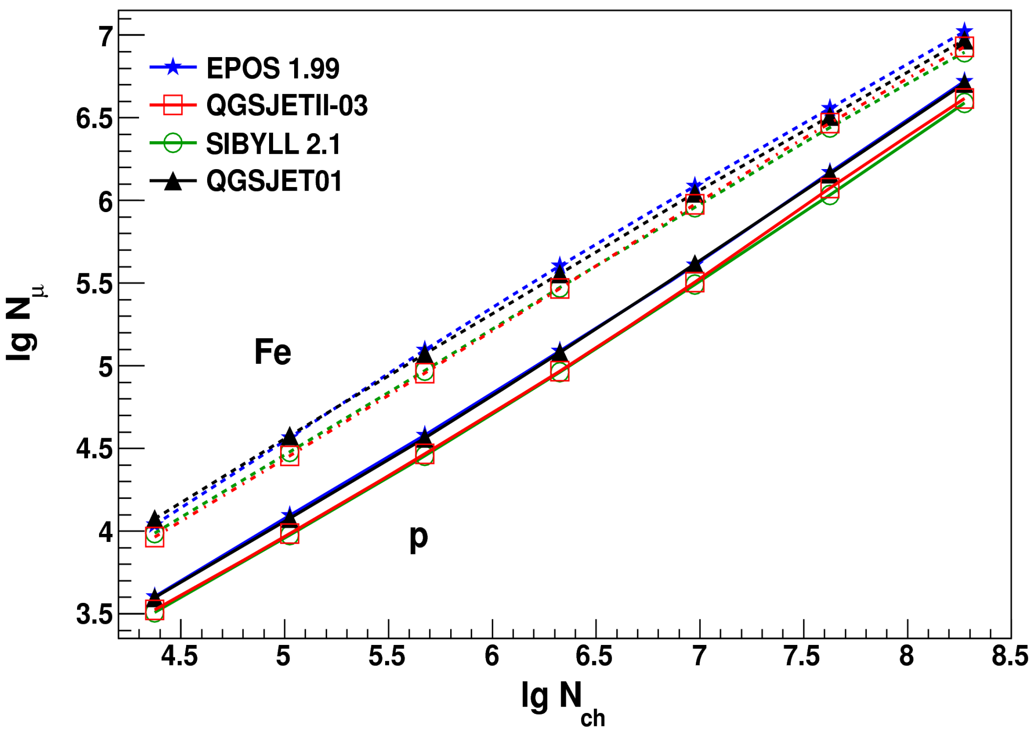
EAS with Re-tuned CR models : Muons

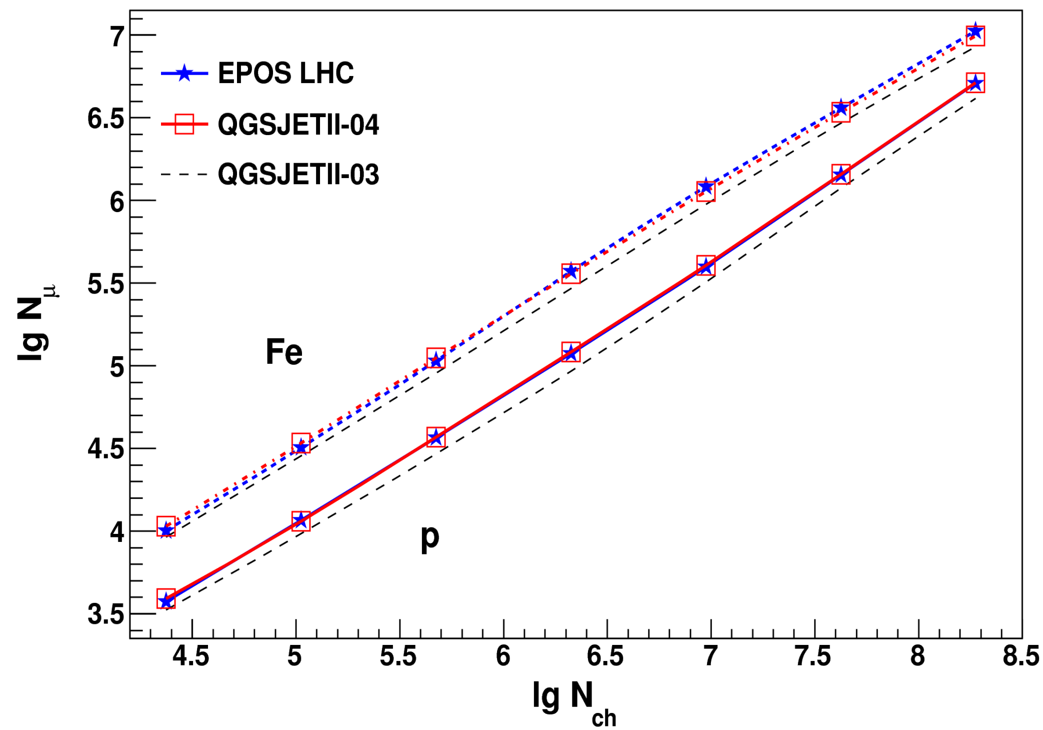
- **Weak effect of LHC**
  - Corrections at mid-rapidity thanks to LHC
  - Changes in QGSJETII motivated by pion induced data
  - Changes for forward production in EPOS LHC can not be checked by LHC (yet ?) (motivated by model consistency)
- **NA61 data wanted to check old data set**



EAS with Re-tuned CR Models : Correlations

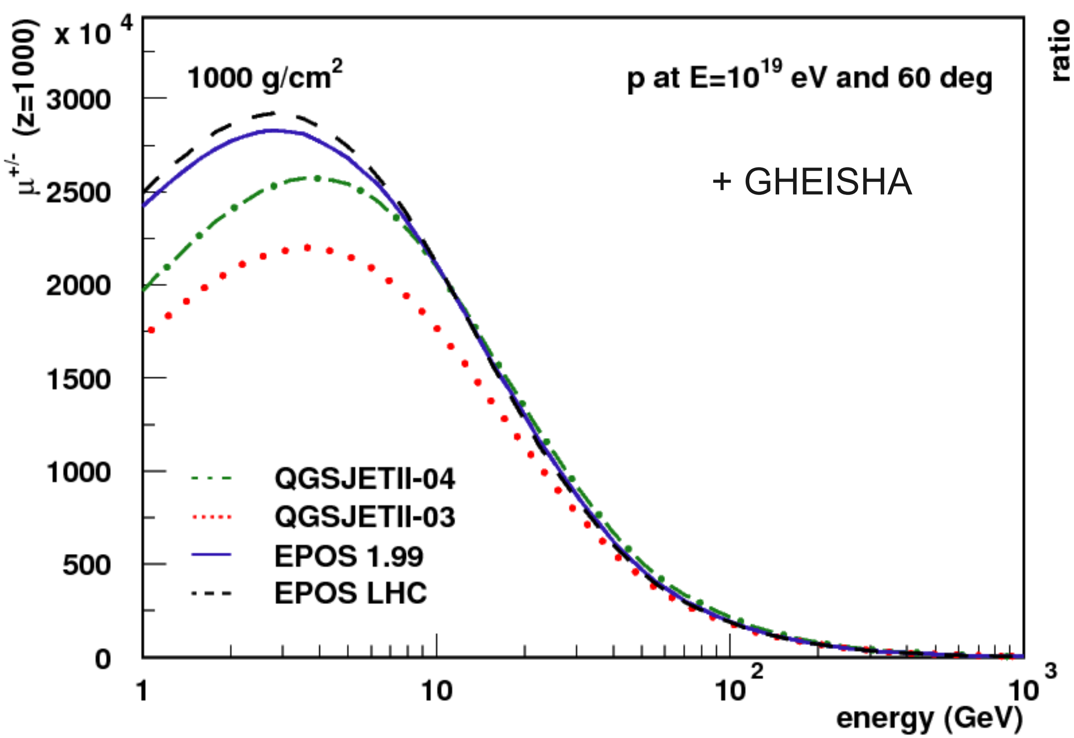
- **QGSJETII-04 and EPOS LHC similar to EPOS 1.99**
  - More muons AND more electrons in EPOS LHC than in QGSJETII-04
  - More muons and less electrons in QGSJETII-04 than in QGSJETII-03
  - Same correlations in EPOS LHC and QGSJETII-04
  - Lighter composition than with QGSJETII-03

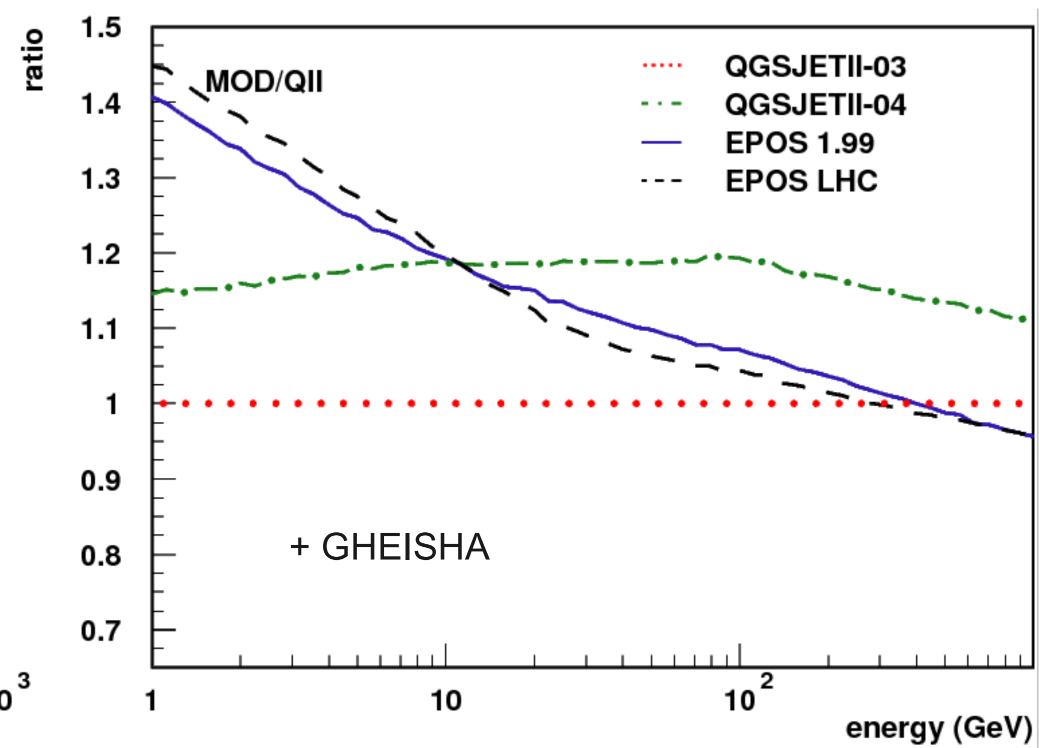




Muon Energy Spectra

- **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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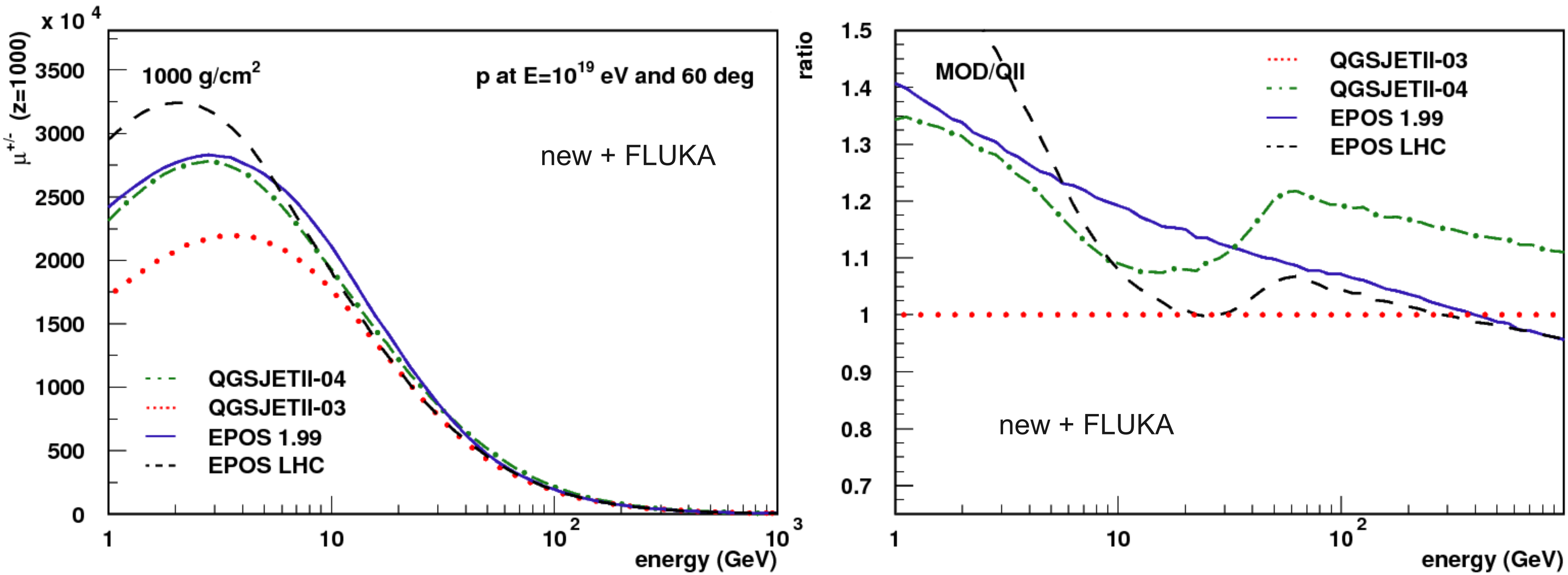
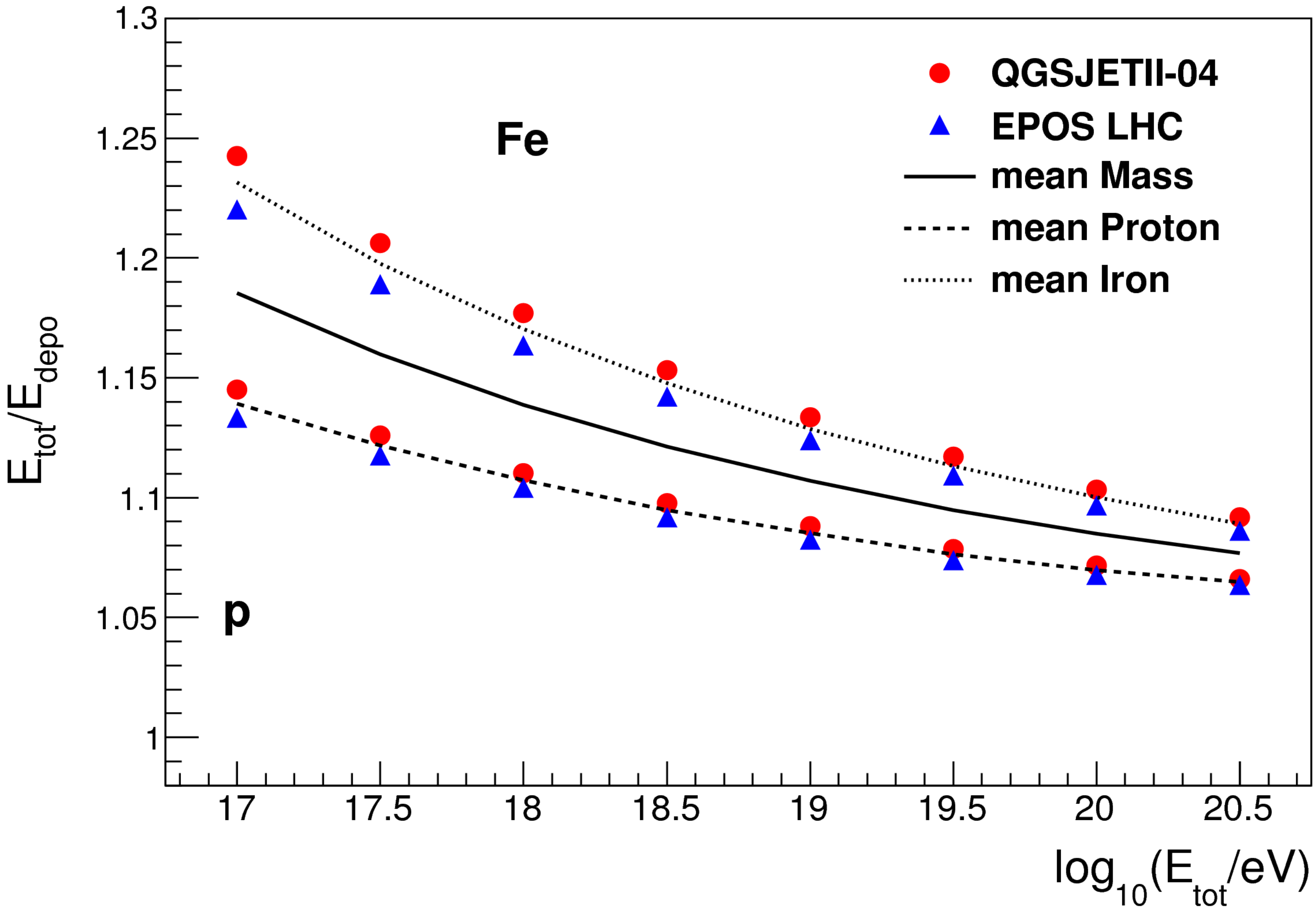


Summary

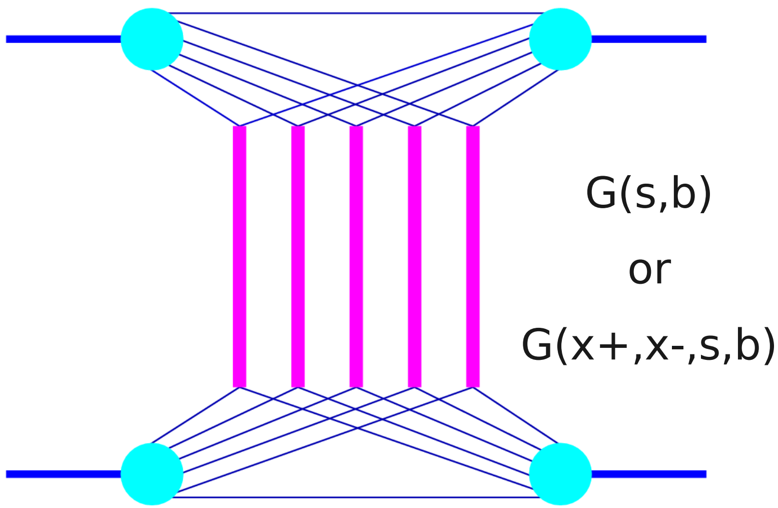
- **Hadronic interaction models for CR reproduce LHC data in a reasonable way**
  - No change of hadronic physics around the knee (10^{15} eV)
  - Large uncertainties in $<X_{max}>$ simulations due to hadronic models reduced by precise fit of LHC data to the value of the exp. resolution
    - Low mass composition UNLIKELY at highest energy
  - Muon number converging to high value
    - NA61 will help for precise muon energy spectrum below 100 GeV.
    - LHC energies important for high energy muons
    - Low mass composition LIKELY at lowest energy
- **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 Energy Deposit

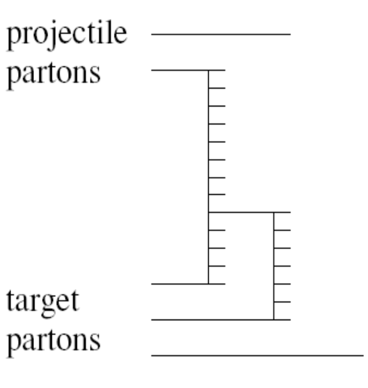
- **Increase of muons in QII04**
  - ➔ larger correction factor from missing energy



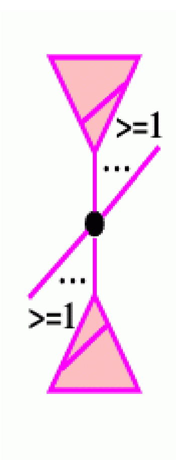
Differences between Models



EPOS



QGSJET II



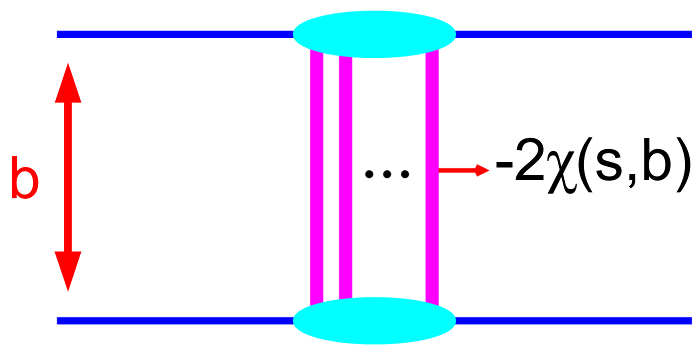
- **Gribov-Regge and optical theorem**
  - Basis of all models (multiple scattering) but
    - Classical approach for QGSJET and SIBYLL (no energy conservation for cross section calculation)
    - Parton based Gribov-Regge theory for EPOS (energy conservation at amplitude level)
- **pQCD**
  - Minijets 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 : $-2\chi(s,b)$
- sum n interactions :
  - optical theorem : $\frac{(-2\chi)^n}{n!} \rightarrow \exp(-2\chi)$

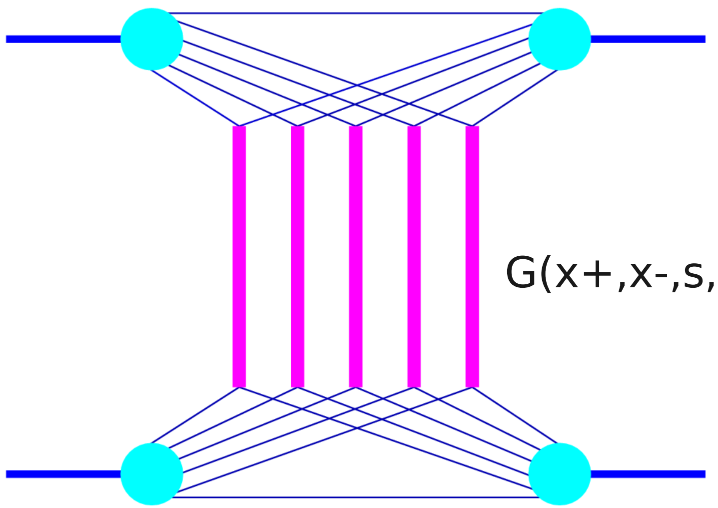


$$\sigma \sim 1 - \exp(-2\chi)$$

Not the same χ in QGSJET01, QGSJETII and SIBYLL

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

Cross Section Calculation : EPOS



Different approach in EPOS :

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

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

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

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

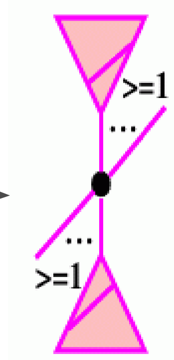
Particle Production in SIBYLL and QGSJET

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

- n from :

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

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



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

  - EPOS approach

Particle Production in EPOS

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

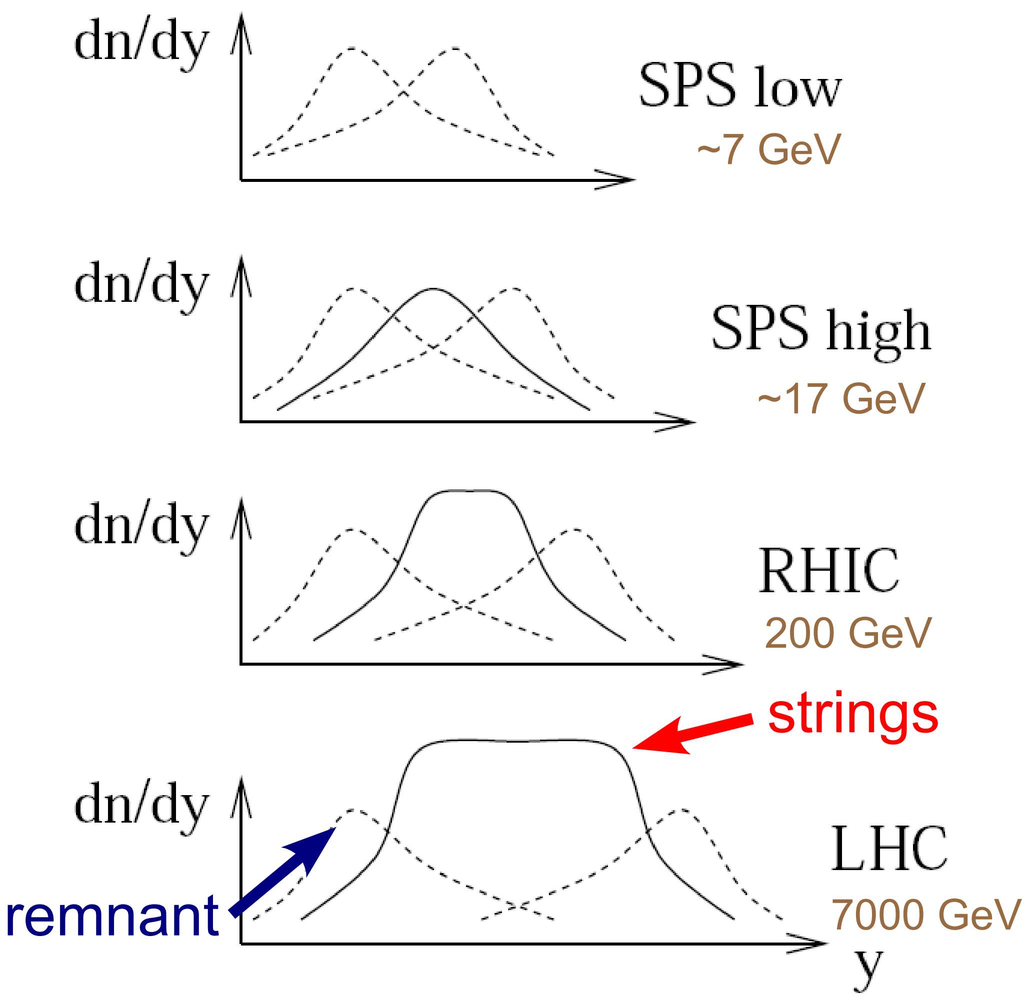
- m from :

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

  - 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)

Forward Spectra

Forward particles mainly from projectile remnant



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

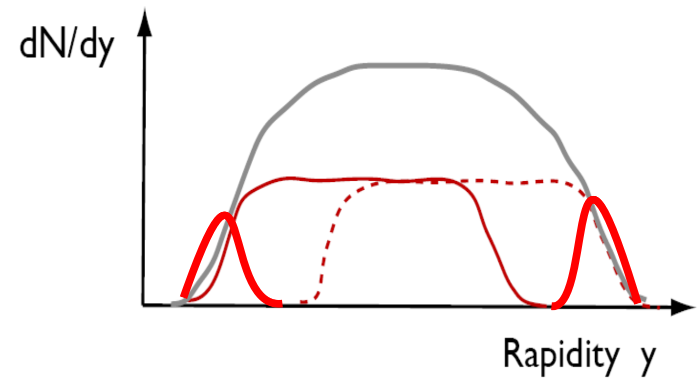
- At very low energy only particles from remnants
- At low energy (fixed target experiments) (SPS) strong mixing
- At intermediate energy (RHIC) mainly string contribution at mid-rapidity with tail of remnants.
- At high energy (LHC) only strings at mid-rapidity (baryon free)

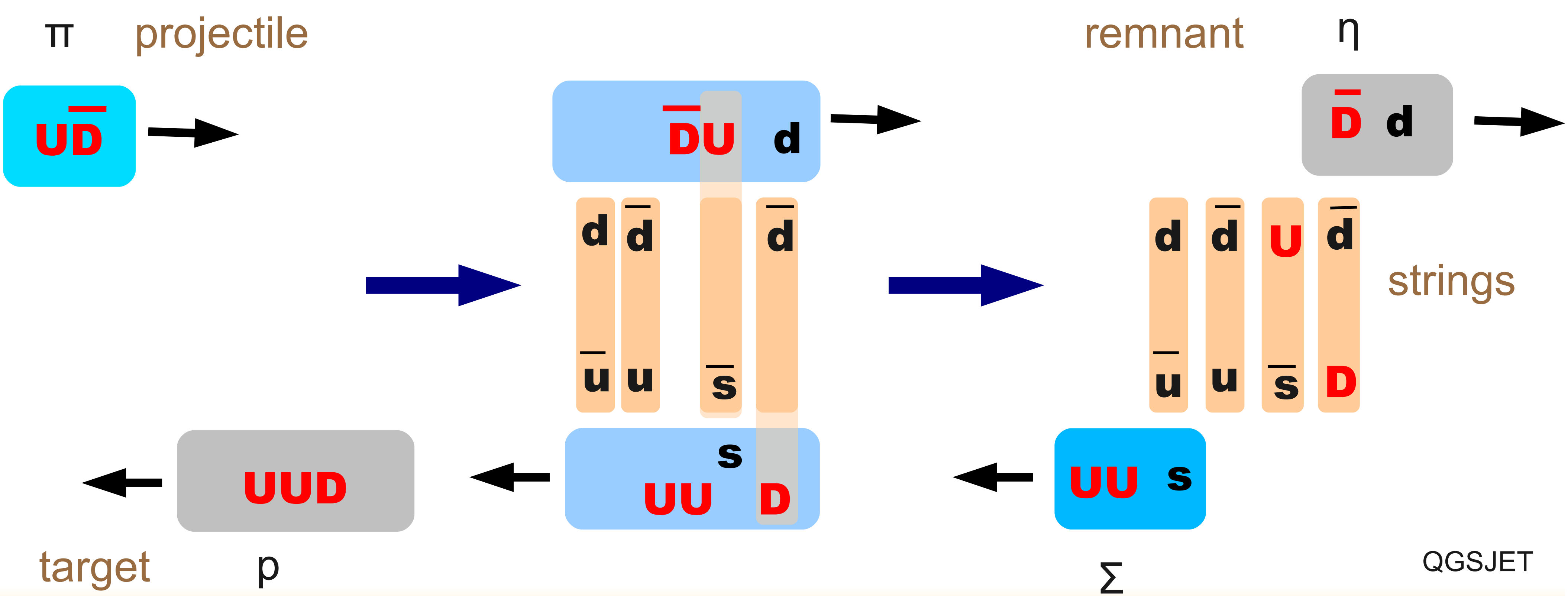
Different contributions of particle production at different energies or rapidities

Beam Remnants

Forward particle production dominated by beam remnants

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

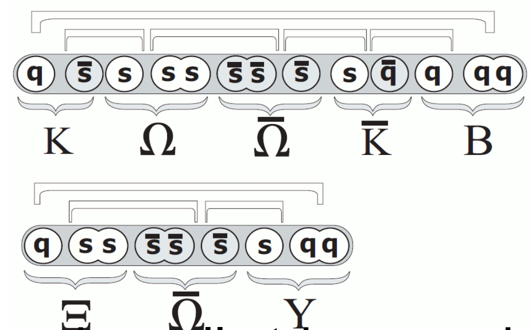




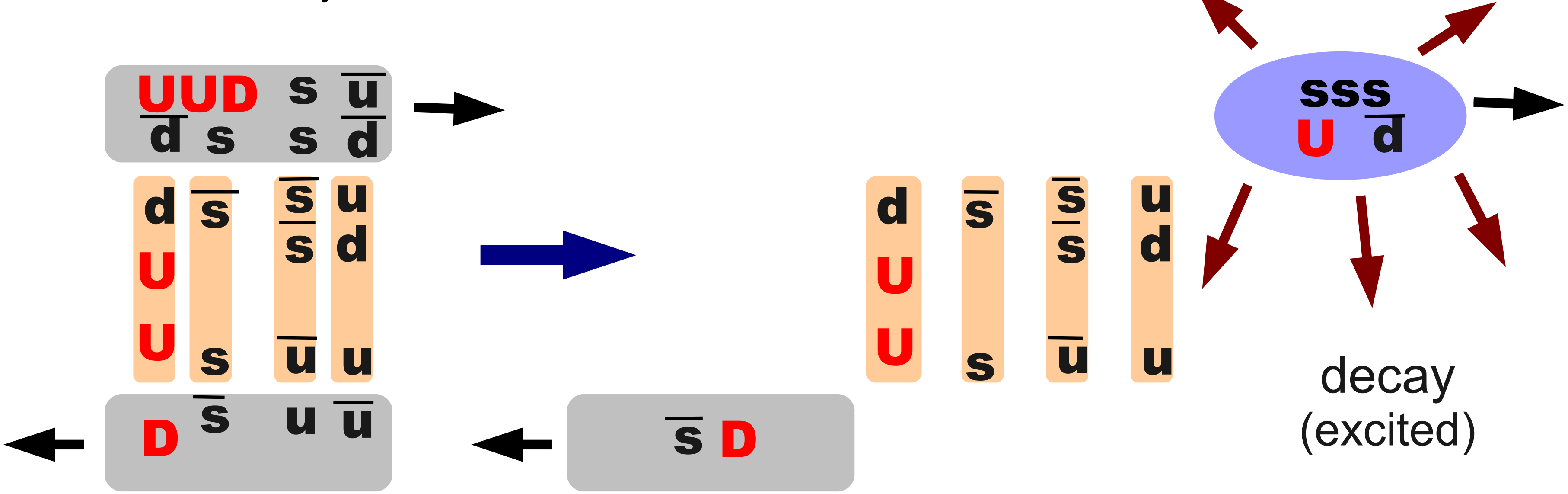
Baryons and Remnants

Parton ladder string ends :

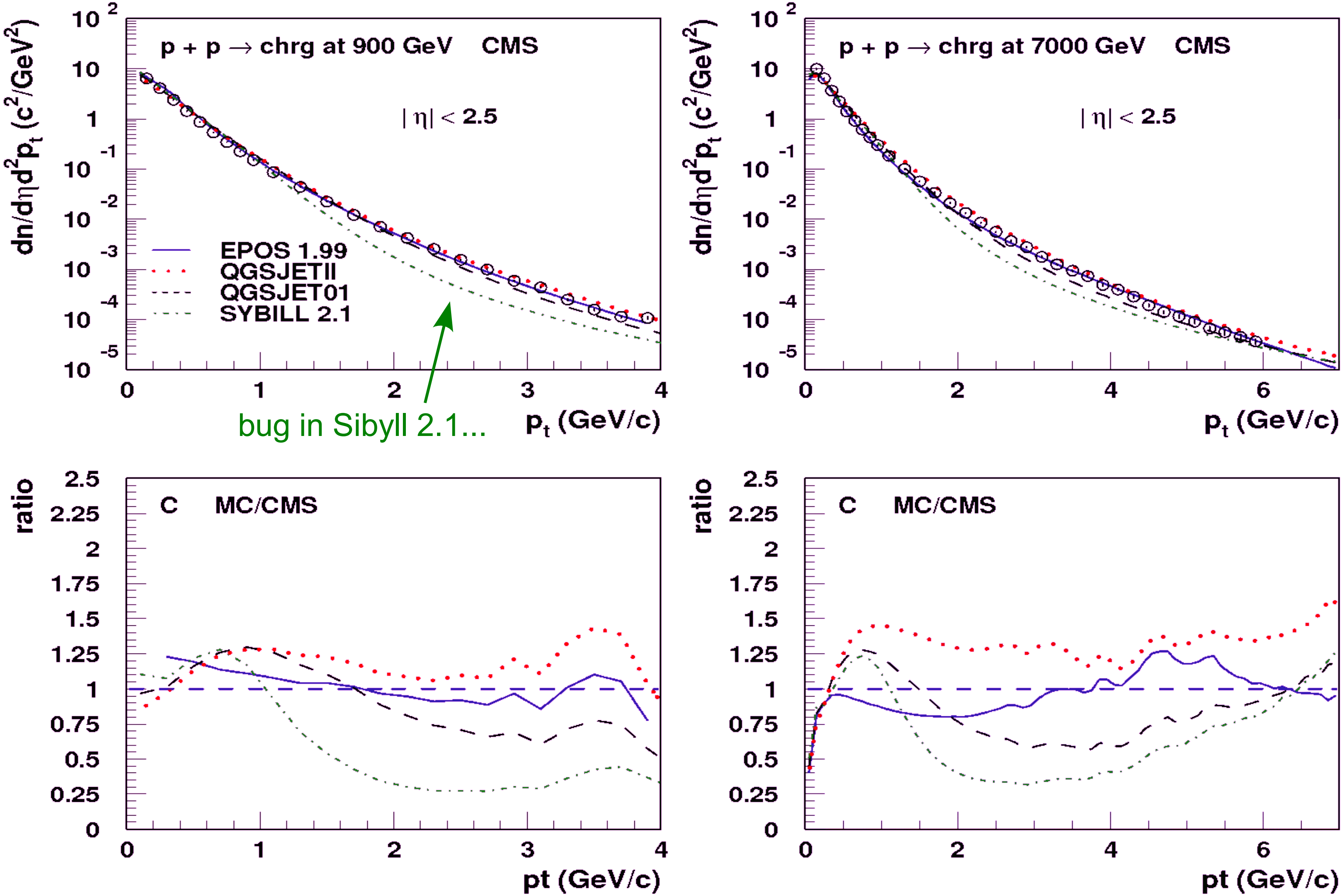
- Problem of multi-strange baryons at low energy (Bleicher et al., Phys.Rev.Lett.88:202501,2002)
  - 2 strings approach :



- $\Omega / \bar{\Omega}$ 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)
- $\Omega / \bar{\Omega}$ always < 1

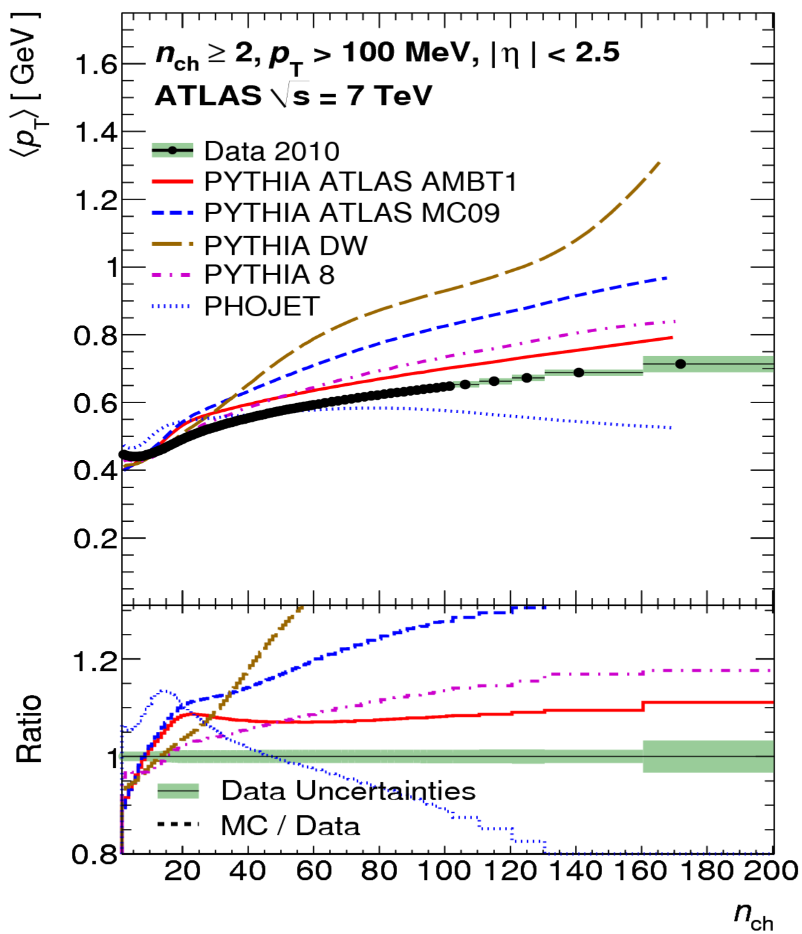


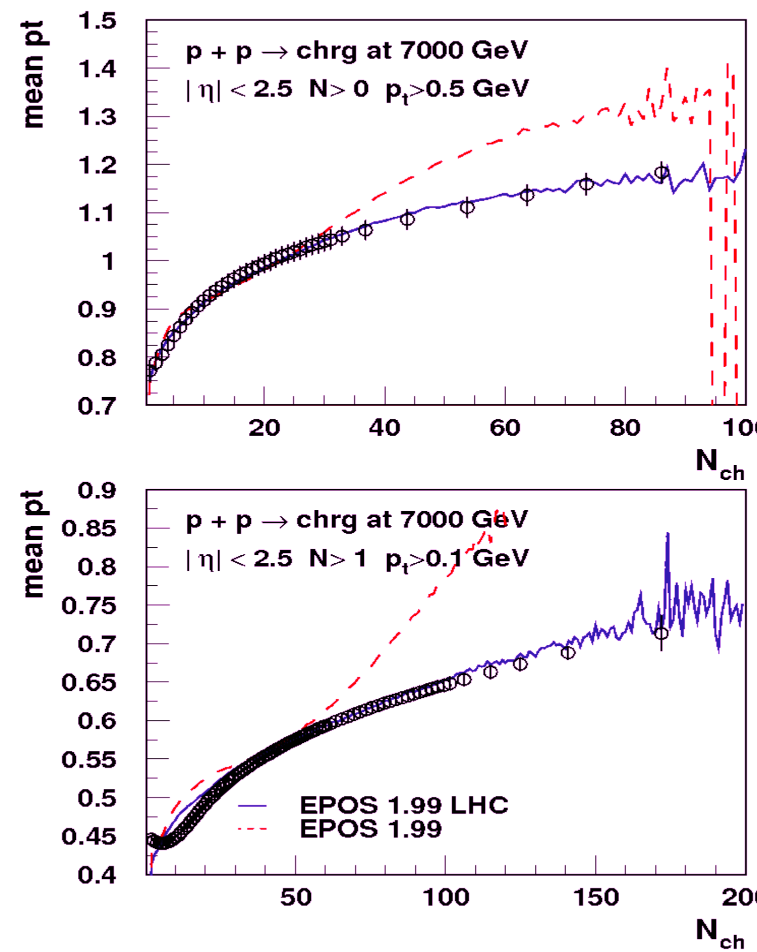
Pt @ LHC


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/dηd²pt (c²/GeV²)
pt (GeV/c)
ratio
C MC/CMS
pt (GeV/c)

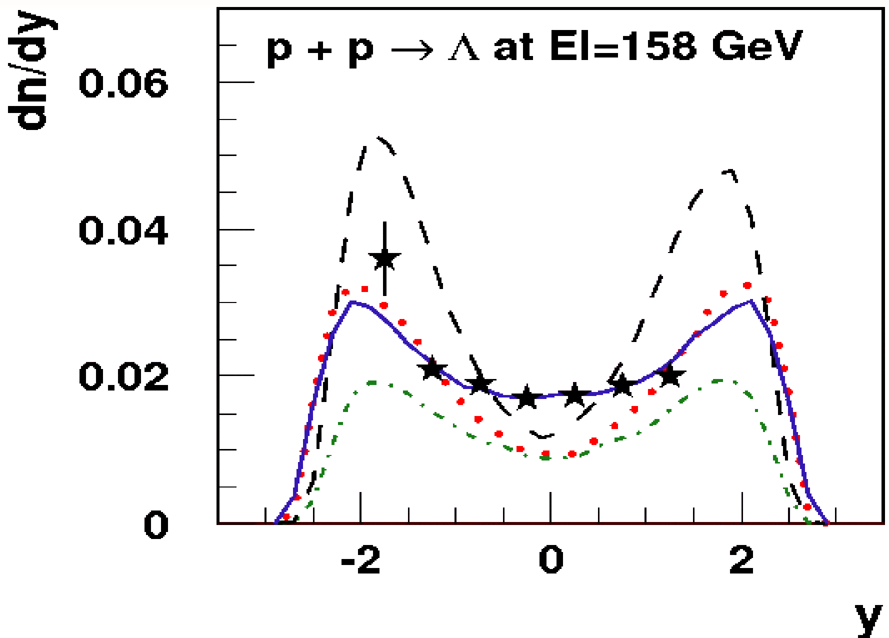
EPOS LHC

- **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)

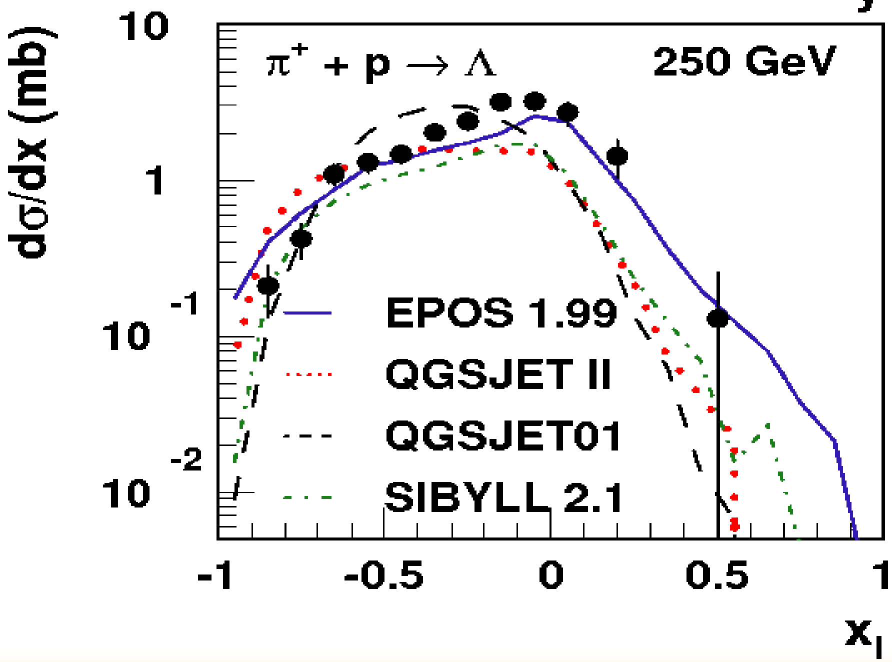


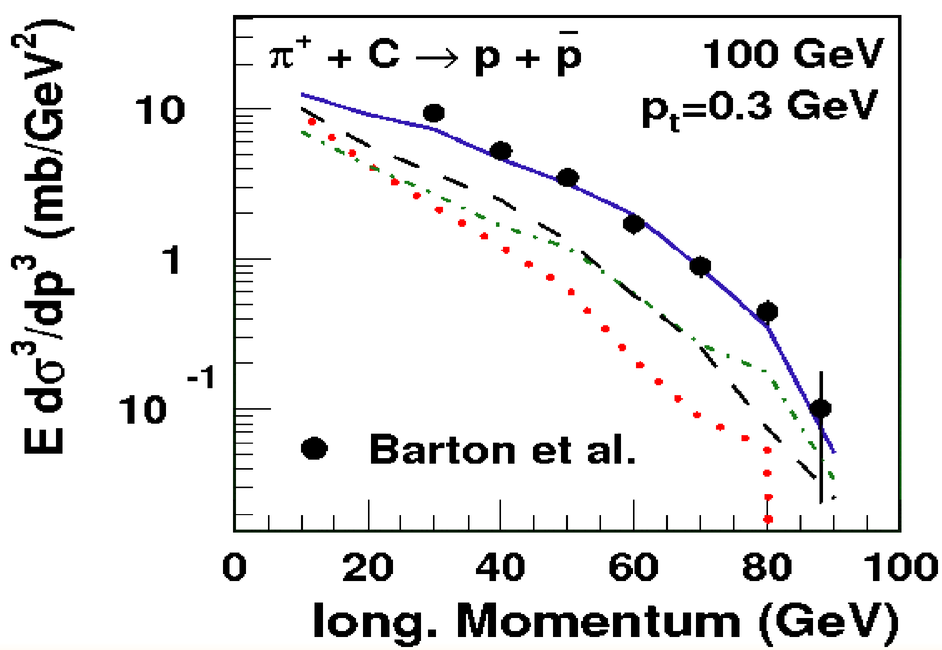


Baryon Forward Spectra



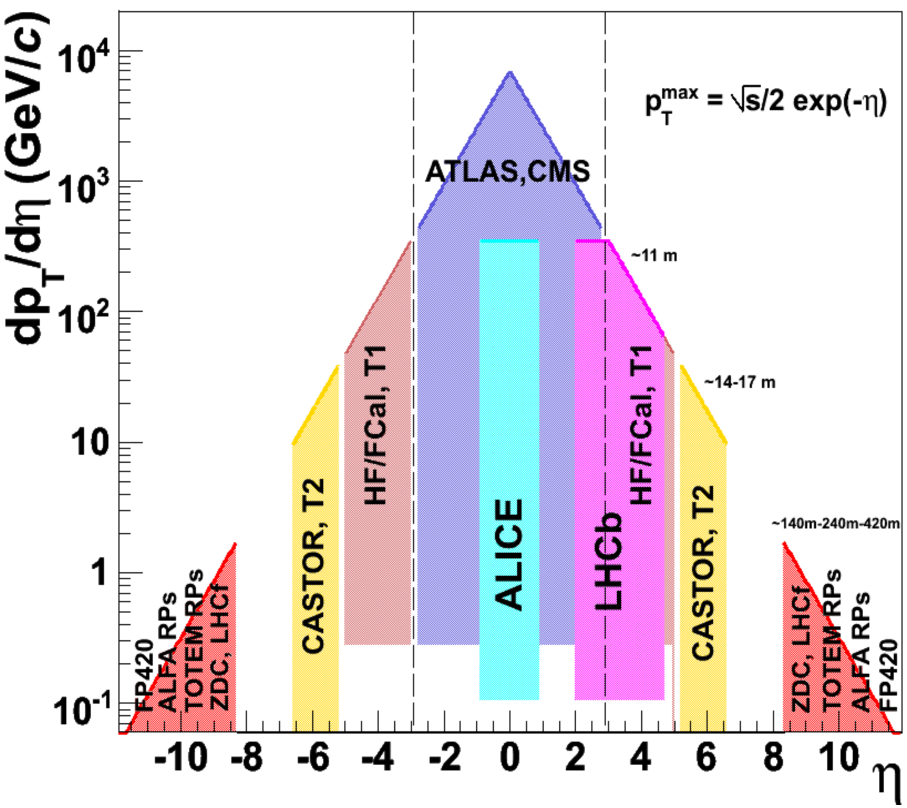
- Large differences between models
- Need a new remnant approach for a complete description (EPOS)
- Problems even at low energy
- No measurement at high energy !





Basic Observables

mid-rapidity



forward

LHC : First hadron collider with full coverage.

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

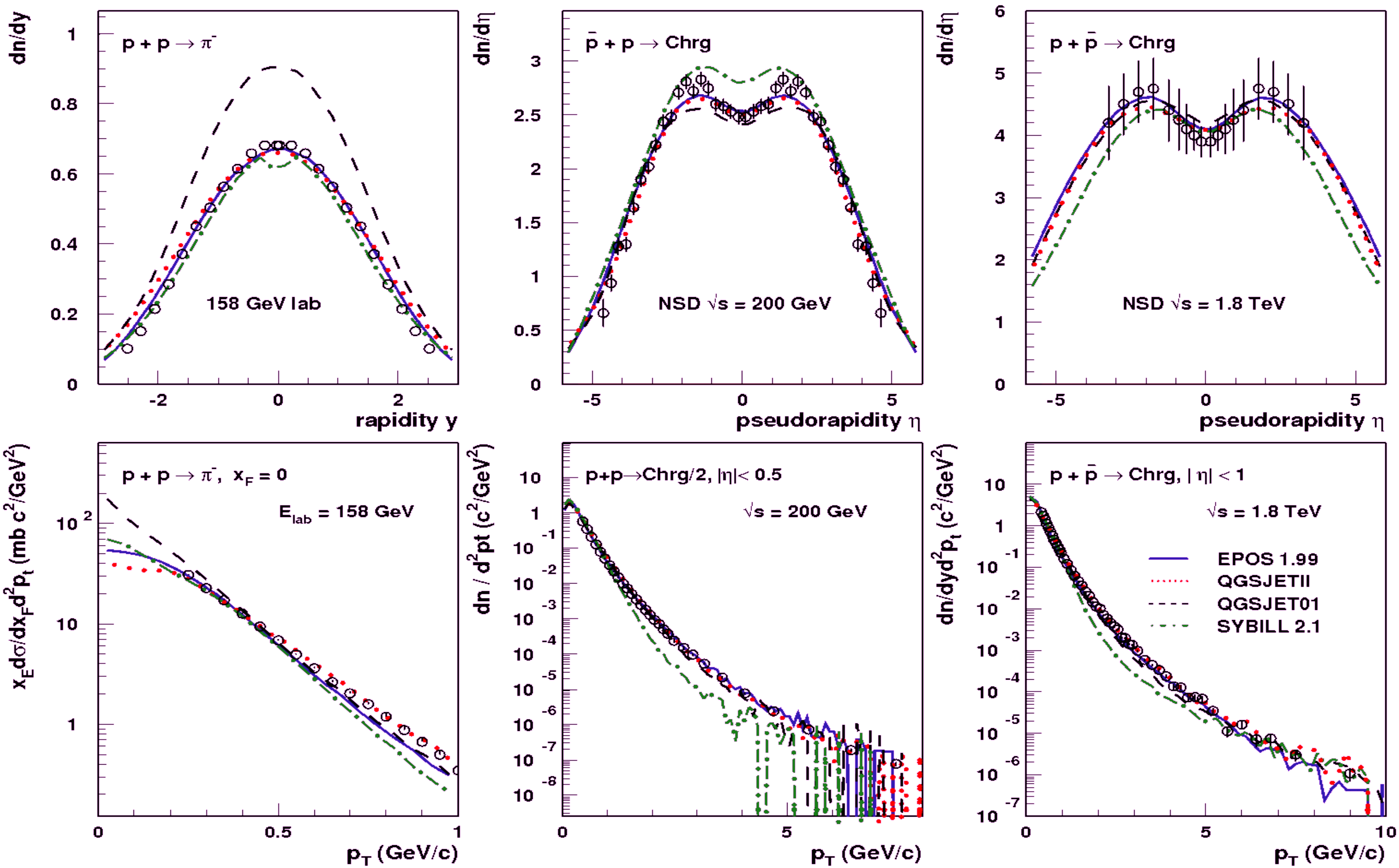
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right] \qquad \eta = \frac{1}{2}\ln\left(\frac{|\mathbf{p}|+p_L}{|\mathbf{p}|-p_L}\right)$$

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

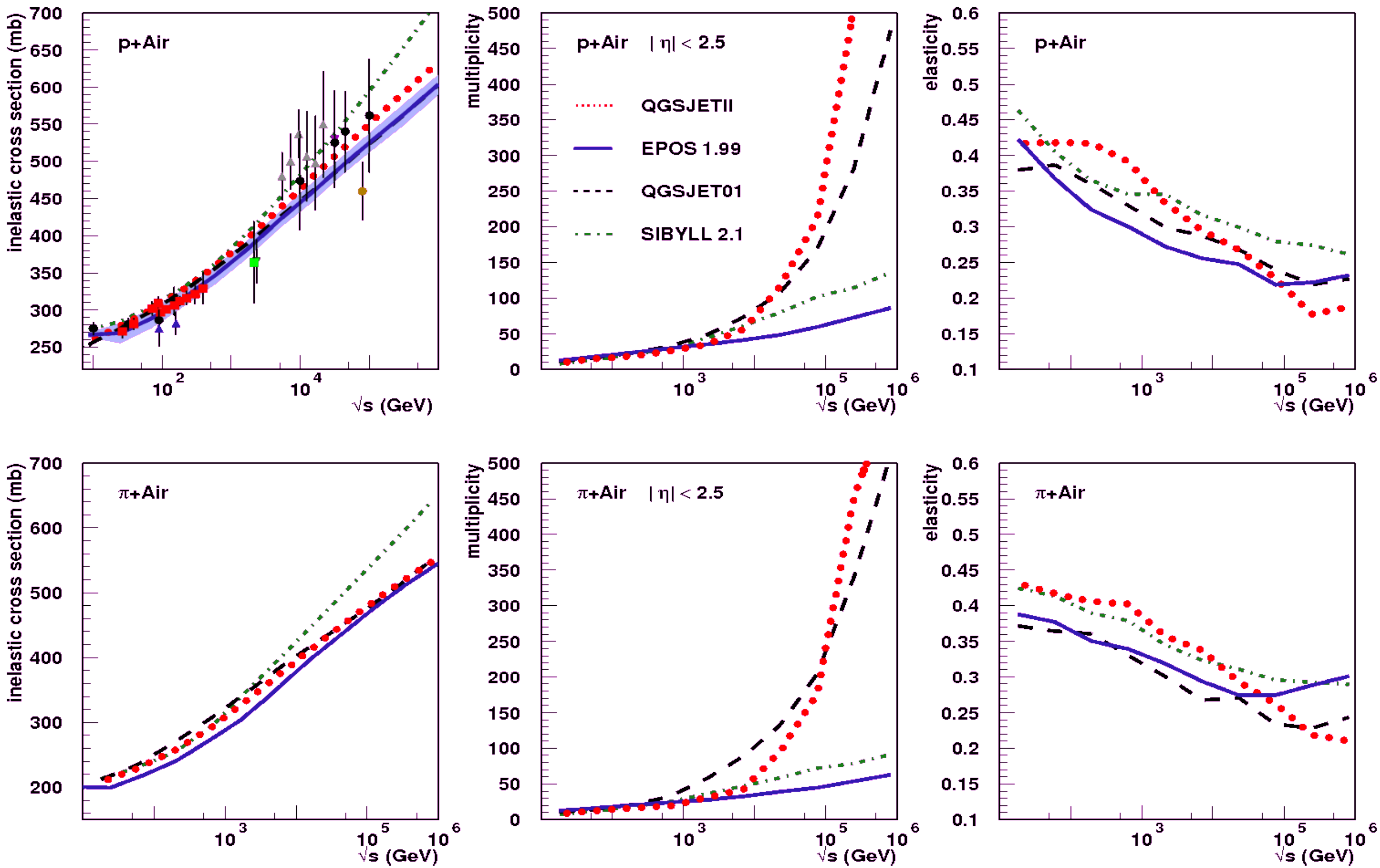
$$y = \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right)$$

  - 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

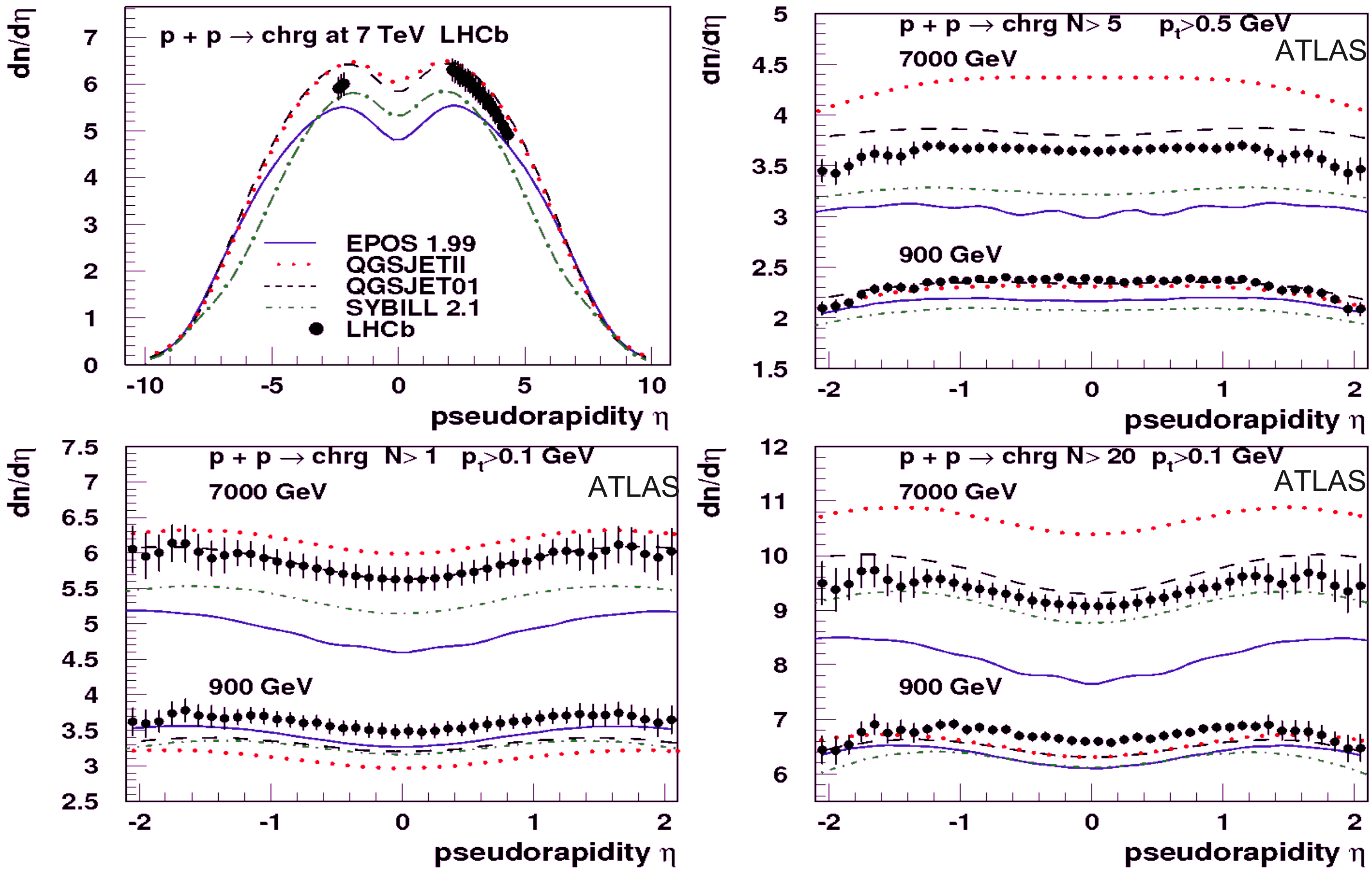


Ultra-High Energy Hadronic Model Predictions



Pseudorapidity Distributions

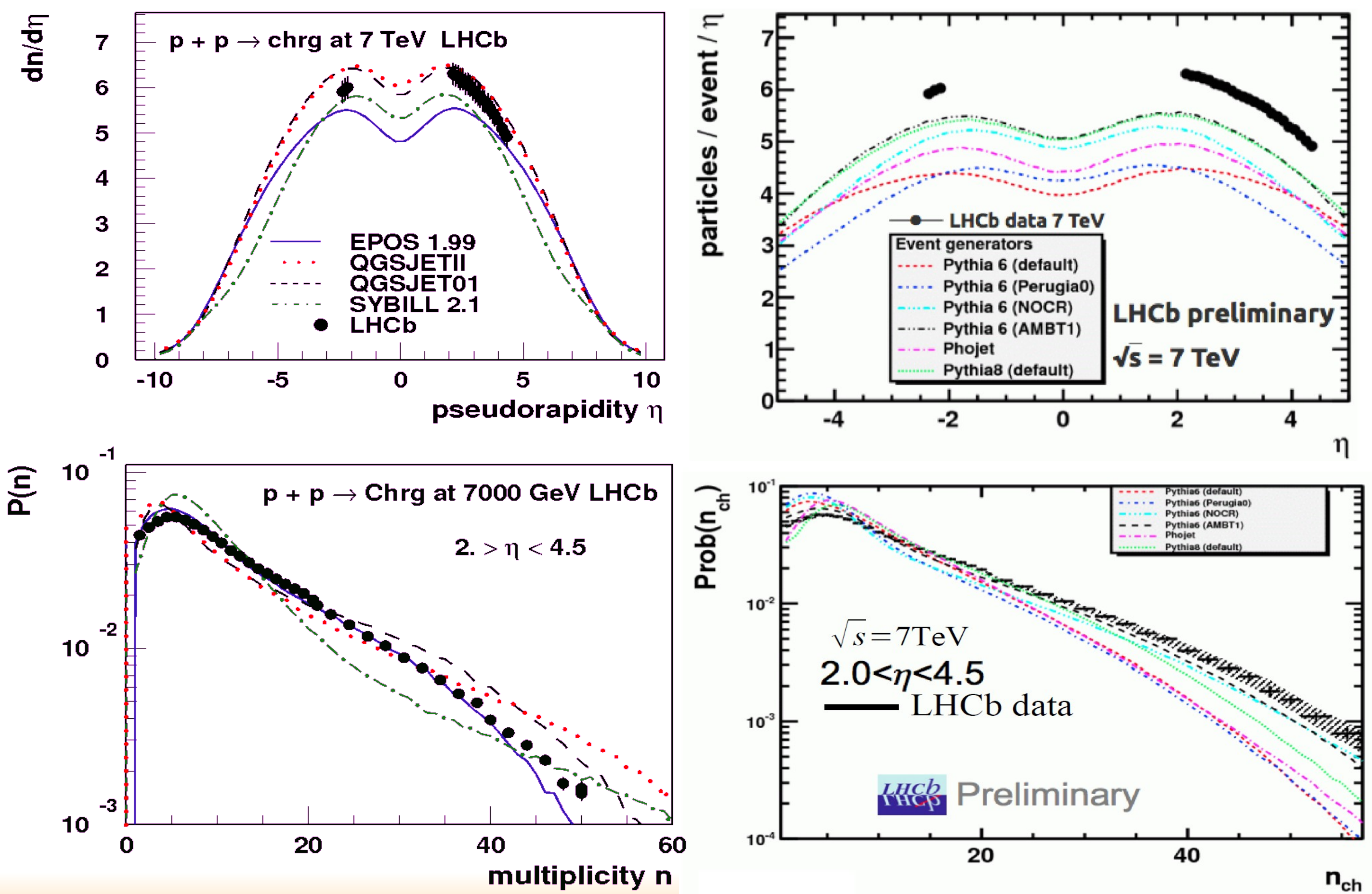
- No model with perfect prediction : **but data well bracketed**



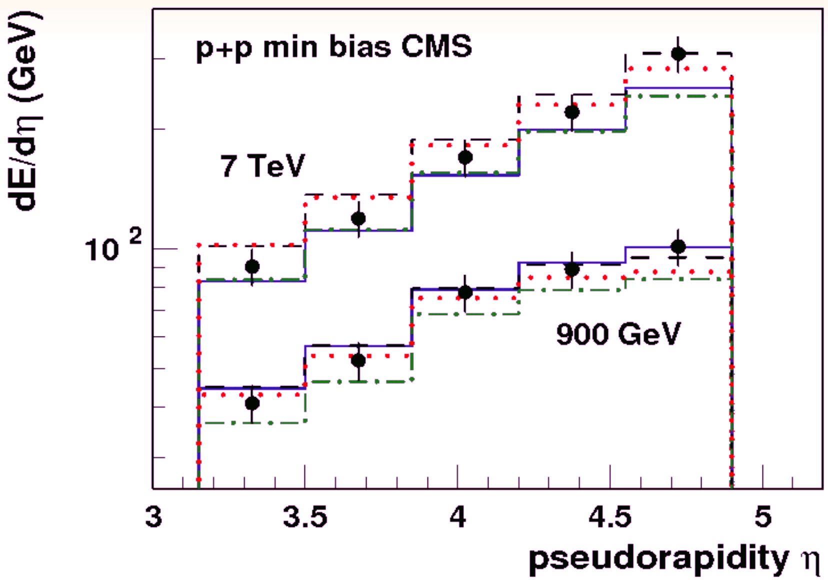
Predictions ! … newest model released in march 2009

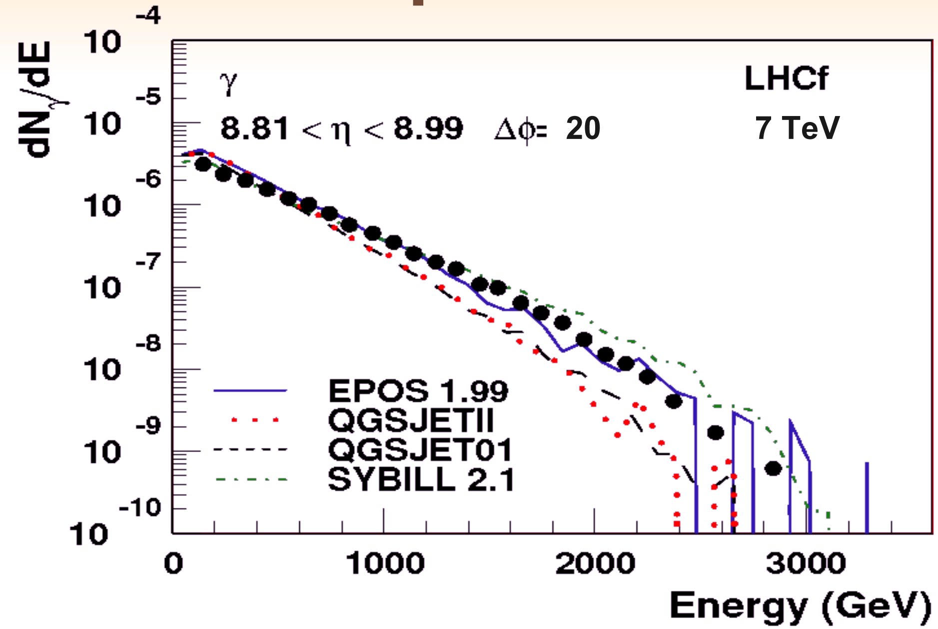
Pseudorapidity Distributions

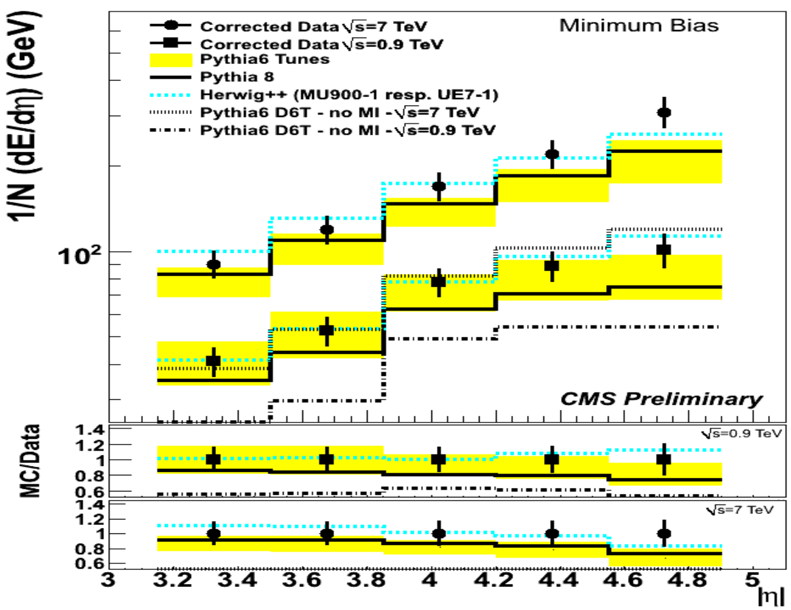
- No model with perfect prediction : **but better than HEP MC**

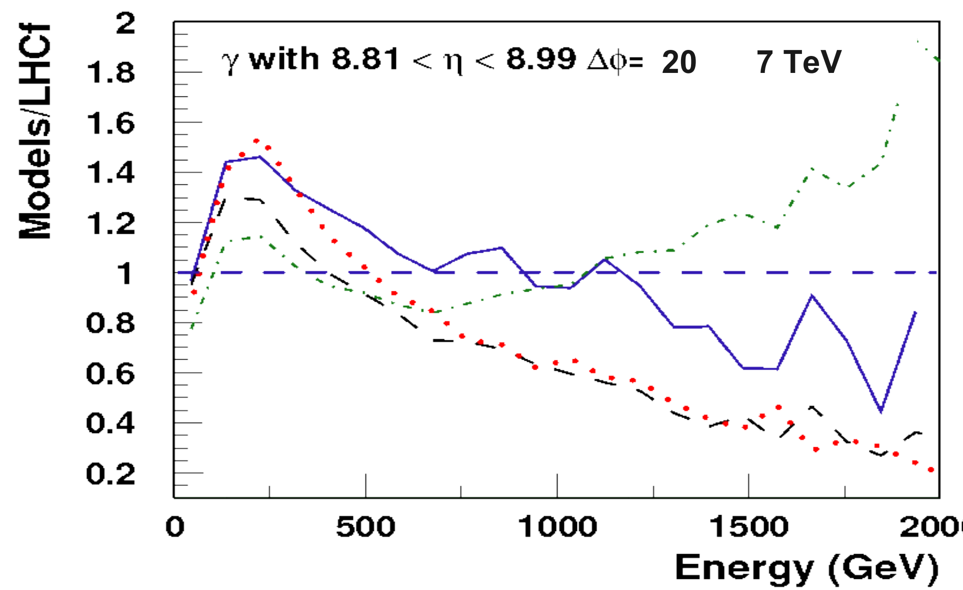


CMS and LHCf Forward Spectra





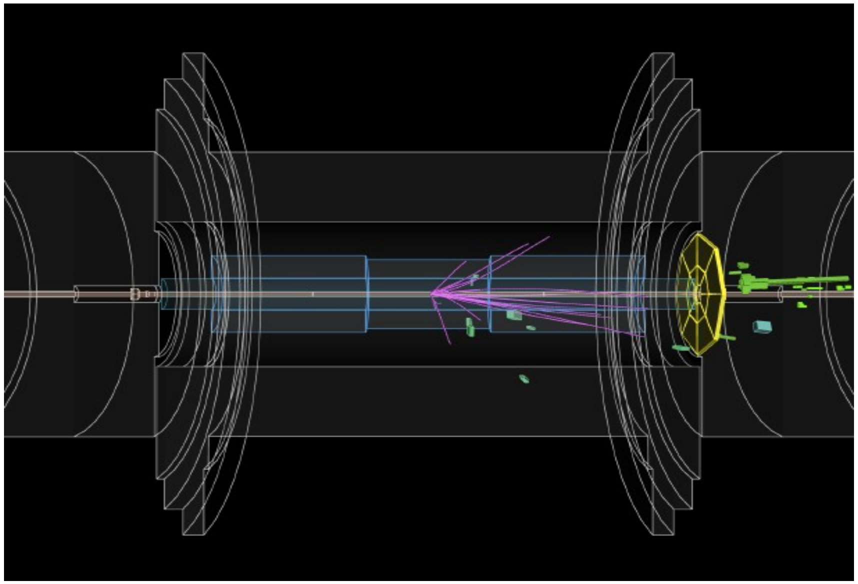




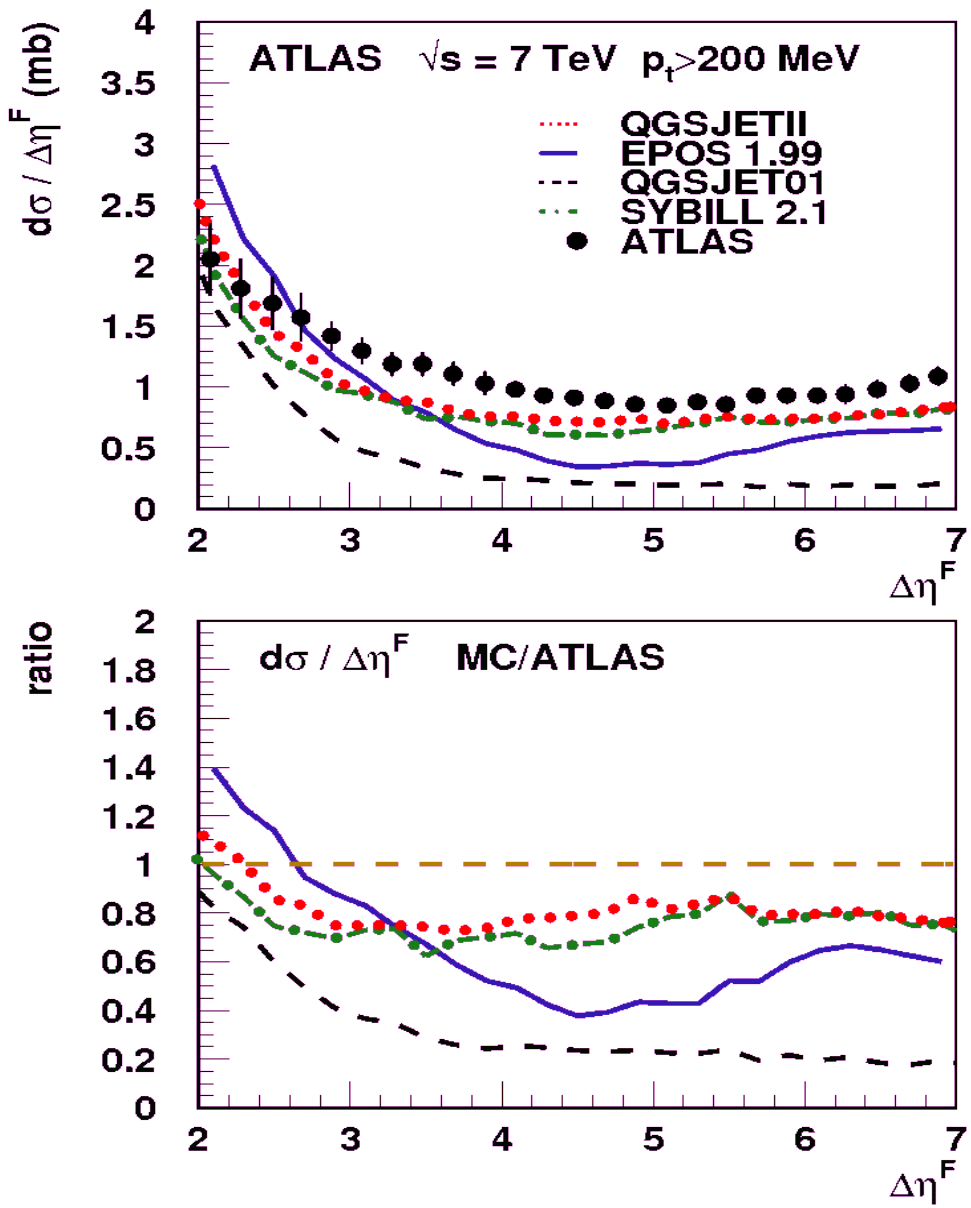
- Forward calorimeter → better than HEP models

Rapidity Gap

ATLAS detector



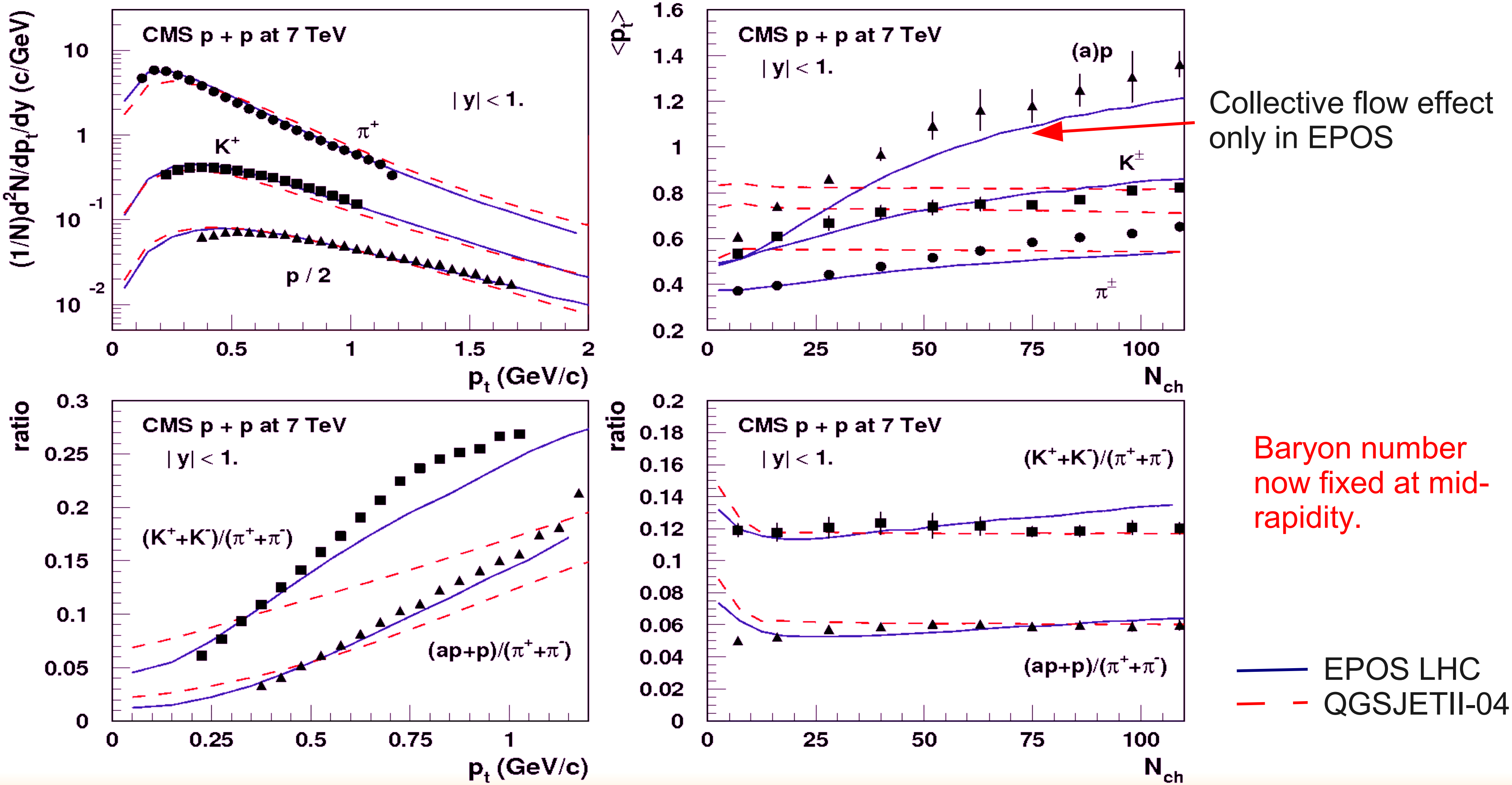
ATLAS Collaboration



- **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)



Particle Spectra