Hadronic interaction models in air showers simulations

Updates based on recent LHC data

Hans Dembinski, Tanguy Pierog

Karlsruhe Institute of Technology, Institut für Kernphysik,
Karlsruhe, Germany

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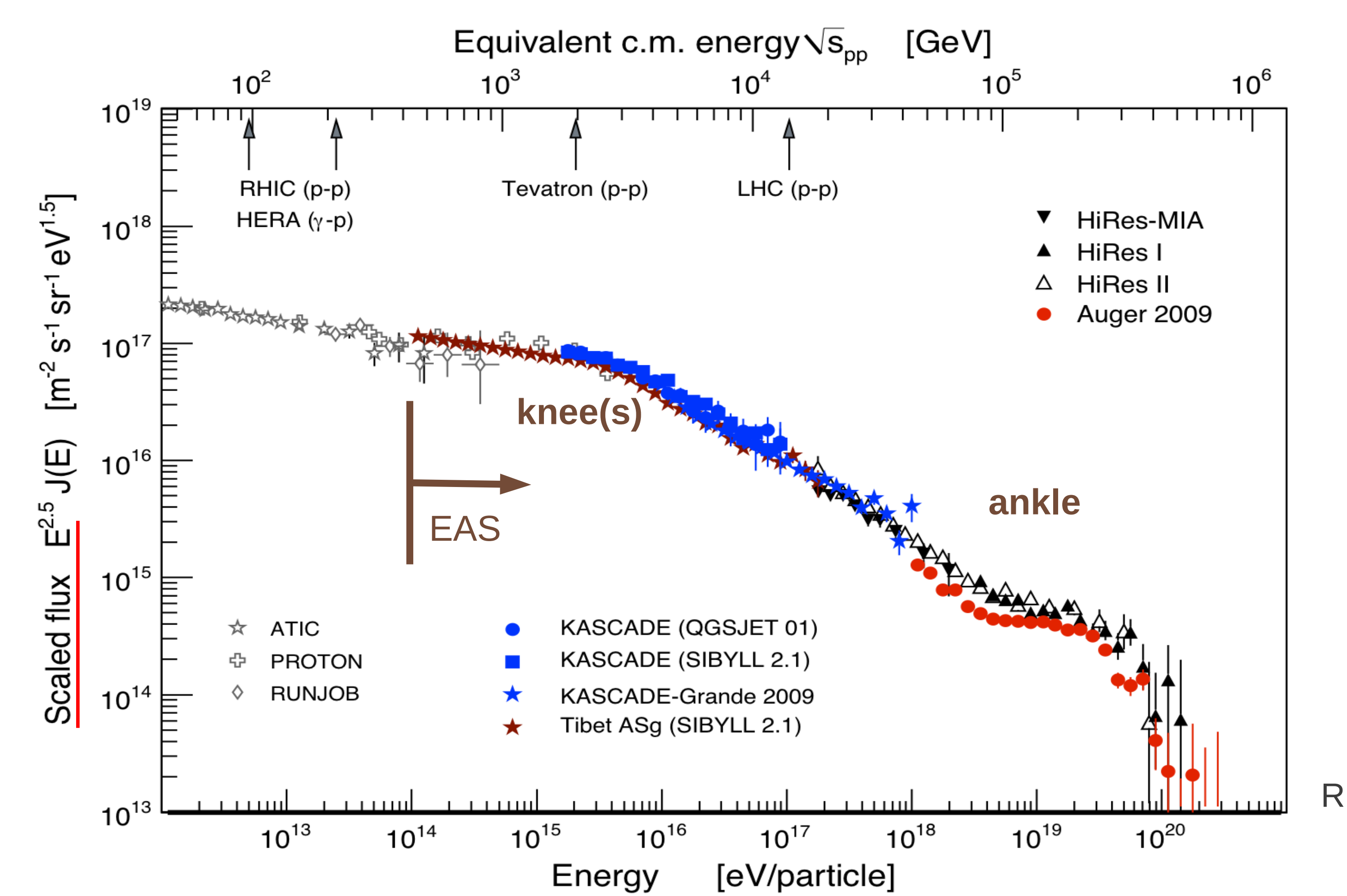
Outline

- **Hadronic Interaction Models for CR**
  - Ingredients
  - Differences
- **Model Performance**
  - Before LHC
  - Current status
- **Extensive Air Shower (EAS)**
  - Depth of shower maximum X_{max}
  - Number of muons

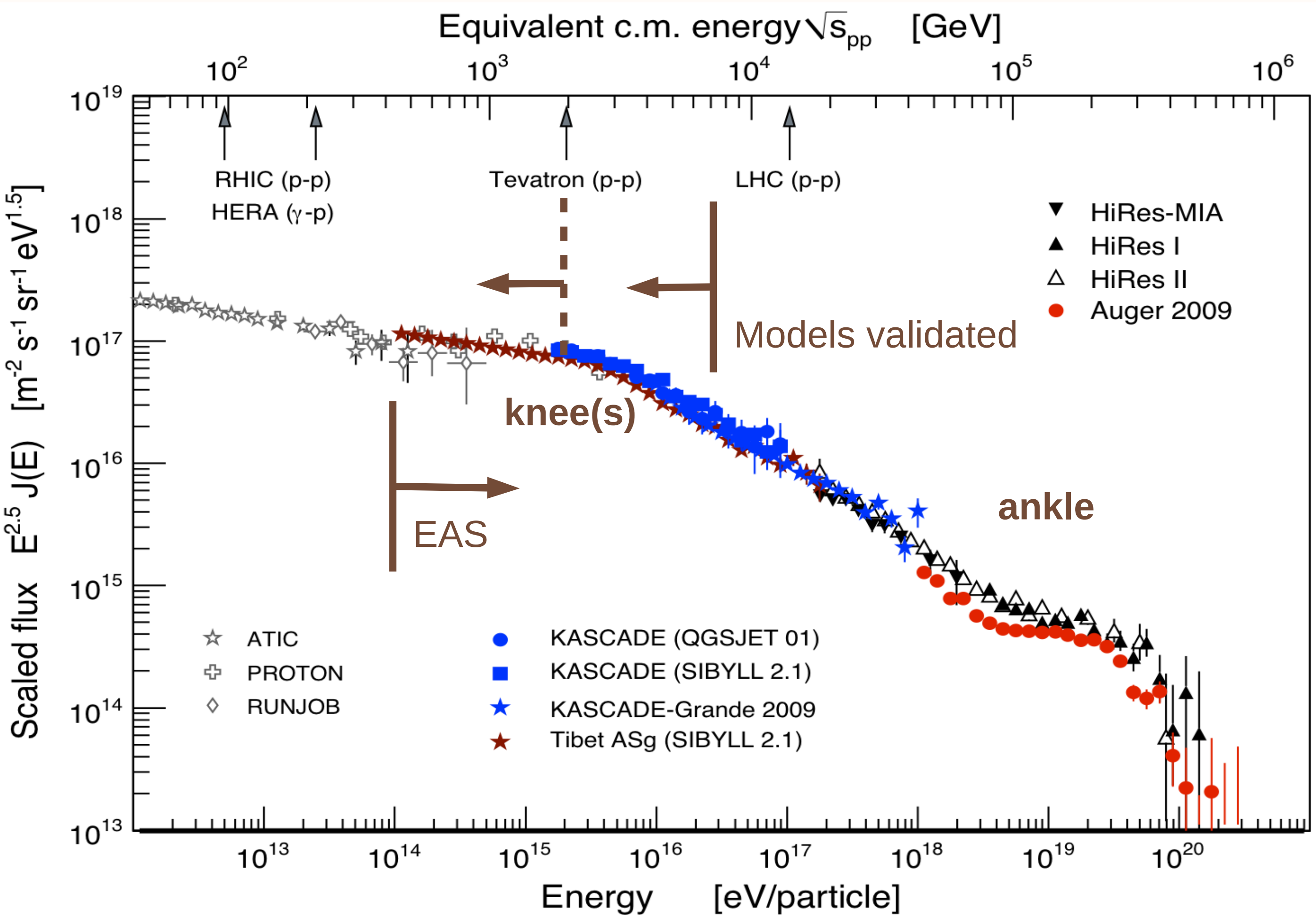
Cosmic Ray Spectrum



R. Engel (KIT)

- **Cosmic ray properties of interest**
  - Direction — **No model-depency**
  - Energy — **Some model-depency**
  - Mass — **Model-dependent**
- **Mass composition analyses depend on air shower simulation programs**
  - CORSIKA, CONEX
  - SENECA
  - COSMOS
  - AIRES, ...

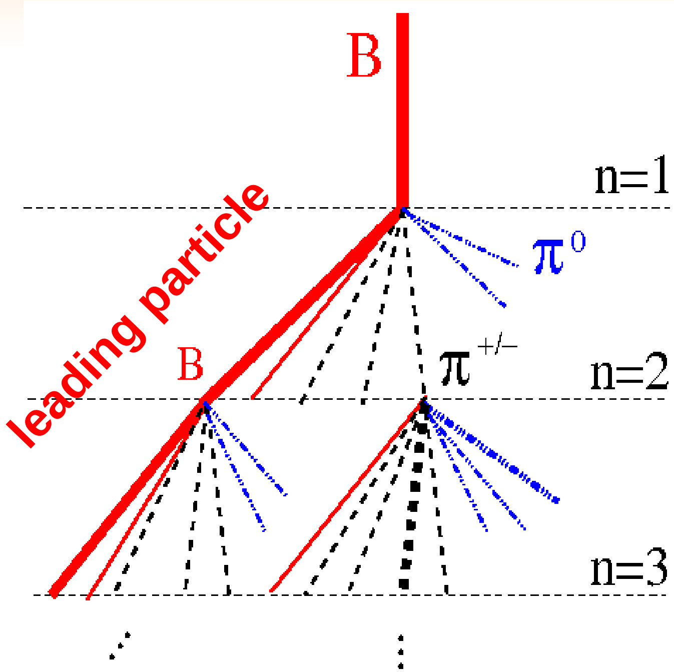
CR Knee and Hadronic Interactions

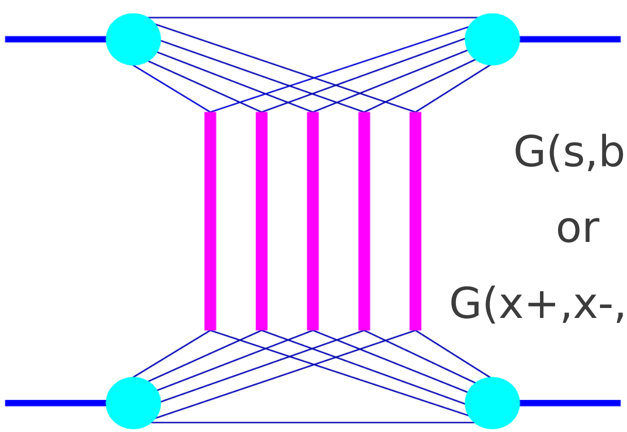


R. Engel (KIT)

- **CR models validated by LHC data**
  - Collider data bracketed by CR models
  - Model spread ~ systematic uncertainty
- **Origin of the knee**
  - most likely NOT due to exotic hadronic interaction (D'Enterria et al., Astro. Phys 35,98 (2011))
  - probable dependence on primary CR composition (KASCADE-Gr PRL.107.171104)

Hadronic Interaction Models





- **Theoretical basis :**
  - pQCD (large p_t)

  CR physic dominated by soft interactions

  - Gribov-Regge (cross section with multiple scattering)
  - Energy conservation

  Standard Gribov-Regge does not take energy conservation into account

- **Phenomenology (models) :**
  - String fragmentation
  - Beam remnants
  - Diffraction (Good-Walker, ...)
  - High density effects (Pomeron interactions, QGP)
- **Comparison with data to fix parameters**

Main source of uncertainties in EAS analysis !

History of Models

(HDPM)

Old generation :

Ostapchenko et al.	Engel et al.	Ranft et al.	Werner et al.	
QGSJet01	SIBYLL	DPMJet 2	VENUS	~1995

All Glauber based

But differences in hard, remnants, diffraction …

semi-hard

soft

NEXUS

Ostapchenko, Werner, et al.

Attempt to get everything describe in a consistent way (energy sharing)

New generation :

Ostapchenko et al.	Ranft et al.	Werner and Pierog	
QGSJet II	(DPMJet III)	**EPOS**	~2005-now

Fan diagrams (pomeron self-interaction)

Diffraction

Optimized for CR

Consistent energy sharing

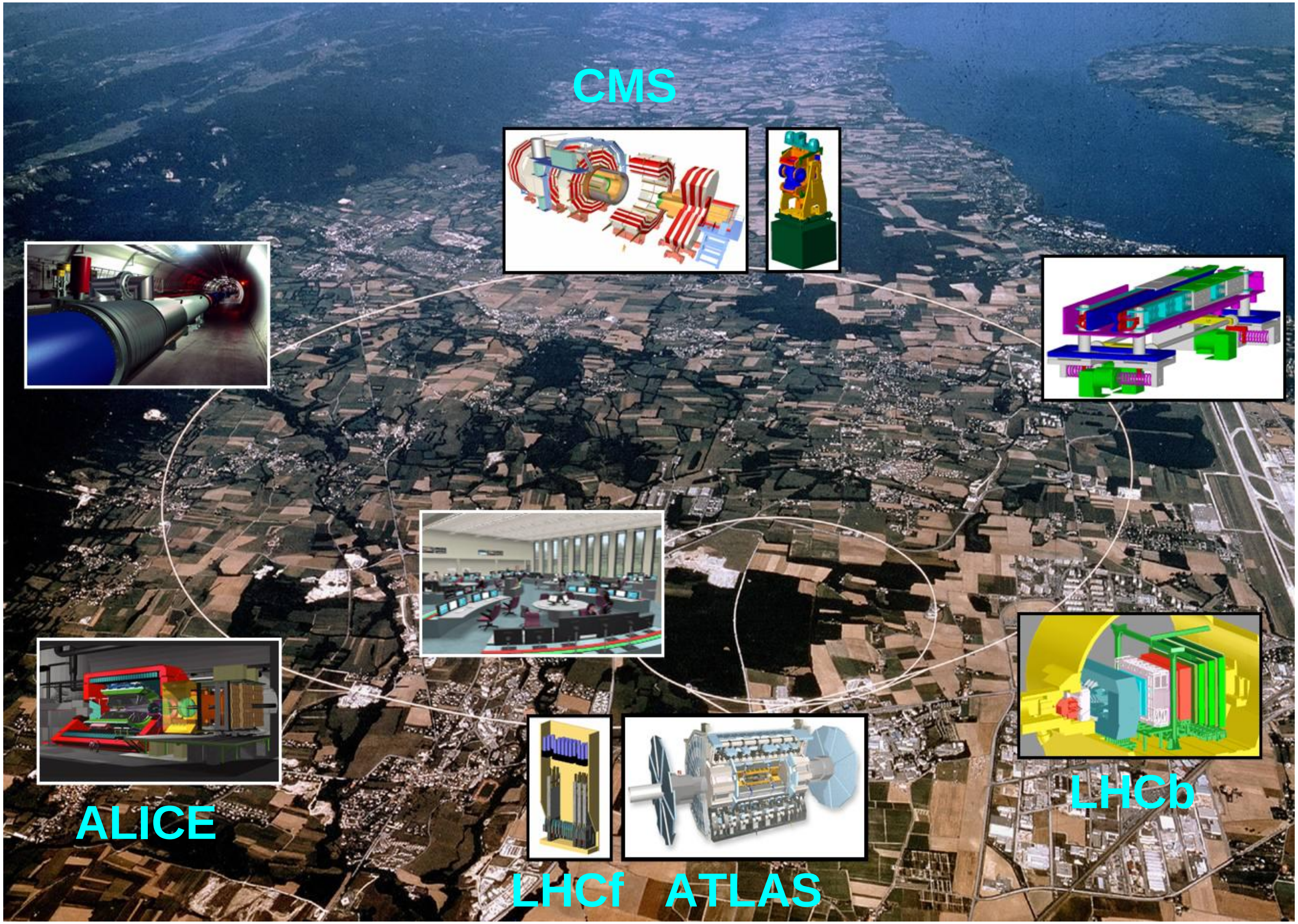
High density effect (QGP)

All type of data studied

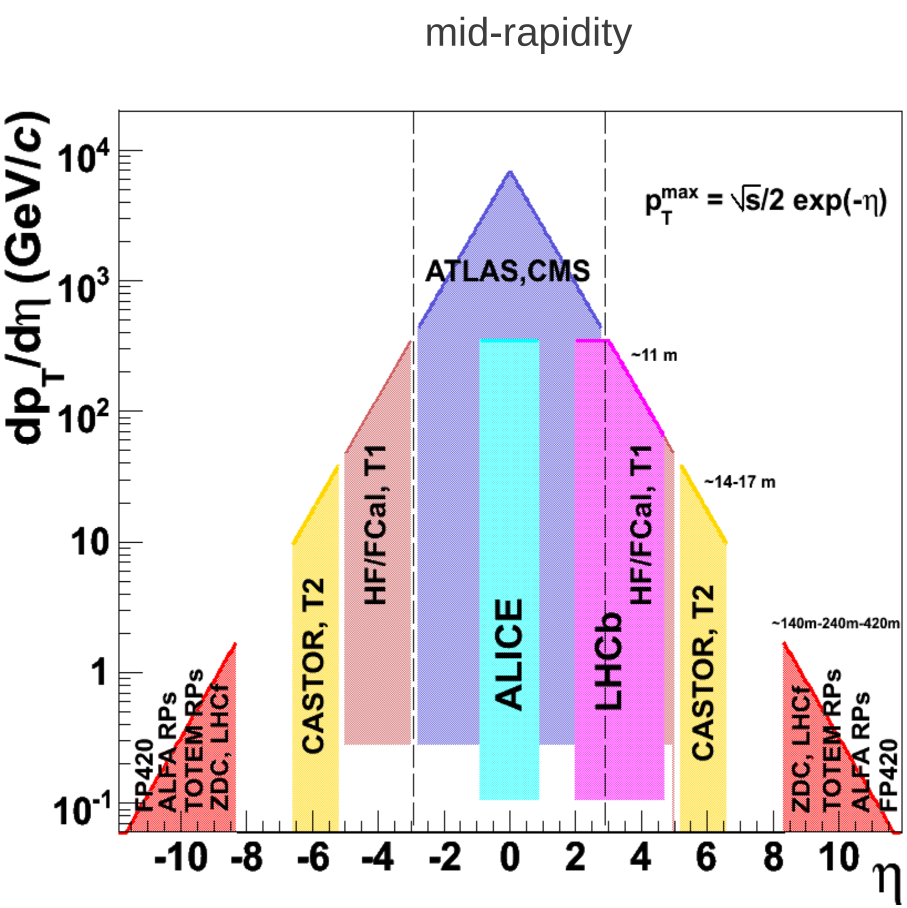
Model used in HEP/HI (SPS, RHIC, LHC)

???

LHC Detectors



Basic Observables



LHC : First hadron collider with full coverage

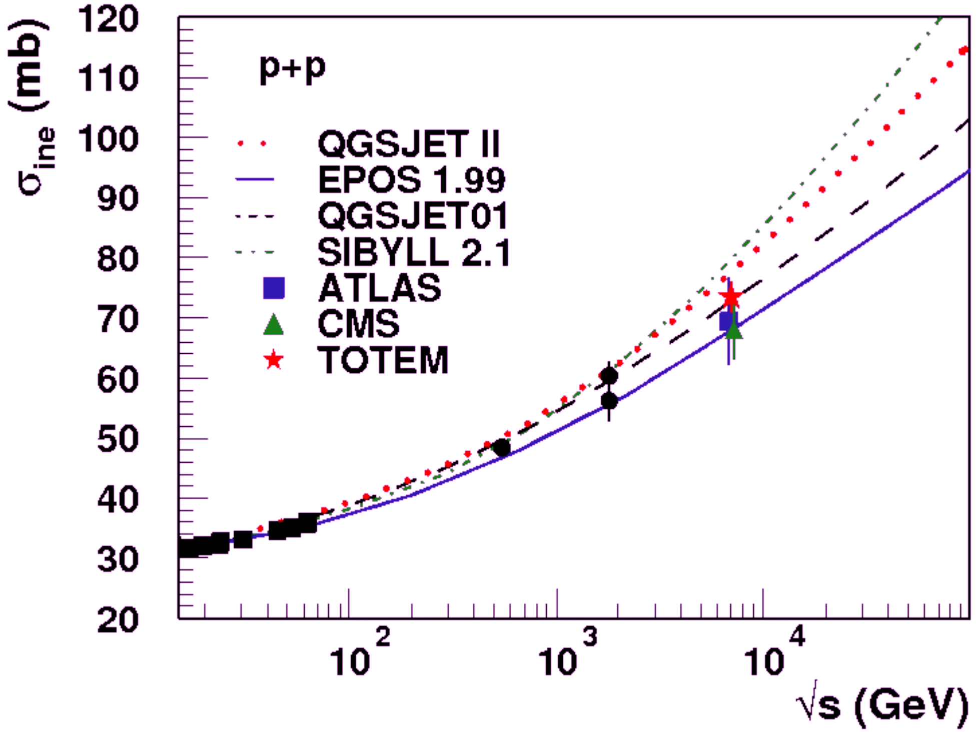
- **Pseudorapidity**
  - emission angle of a particle from interaction point ("mid-rapidity" : $\eta=0$) :

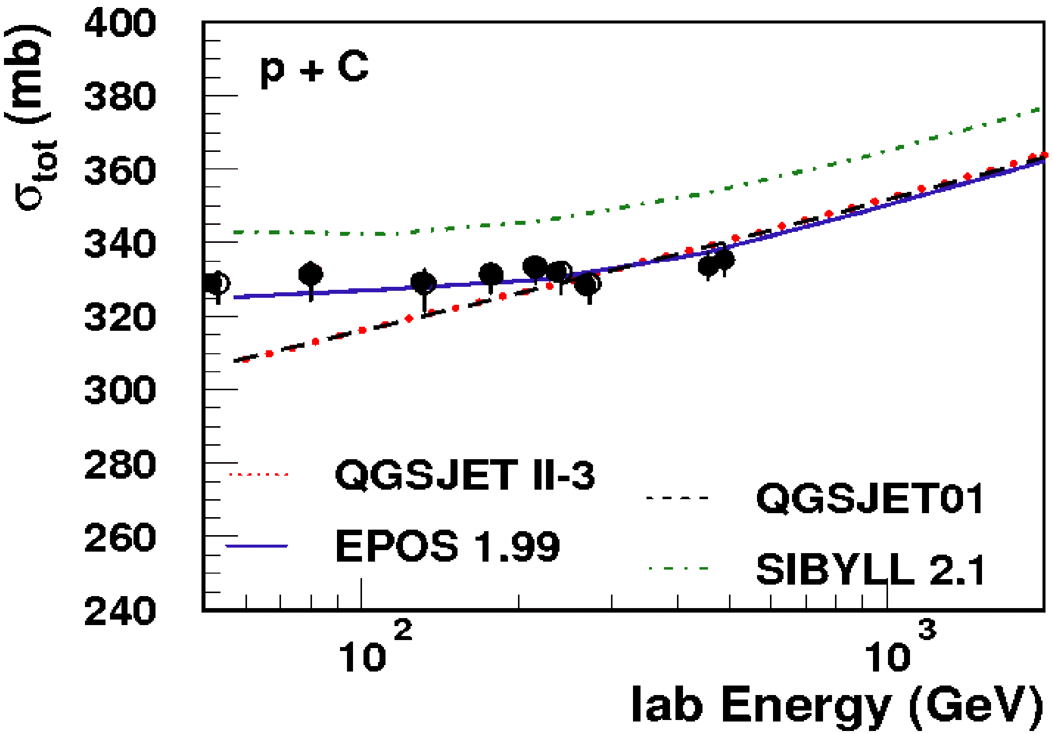
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right] \qquad \eta = \frac{1}{2}\ln\left(\frac{|\mathbf{p}|+p_L}{|\mathbf{p}|-p_L}\right)$$

  - 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 scattered into a given η and p_t range

Cross Section

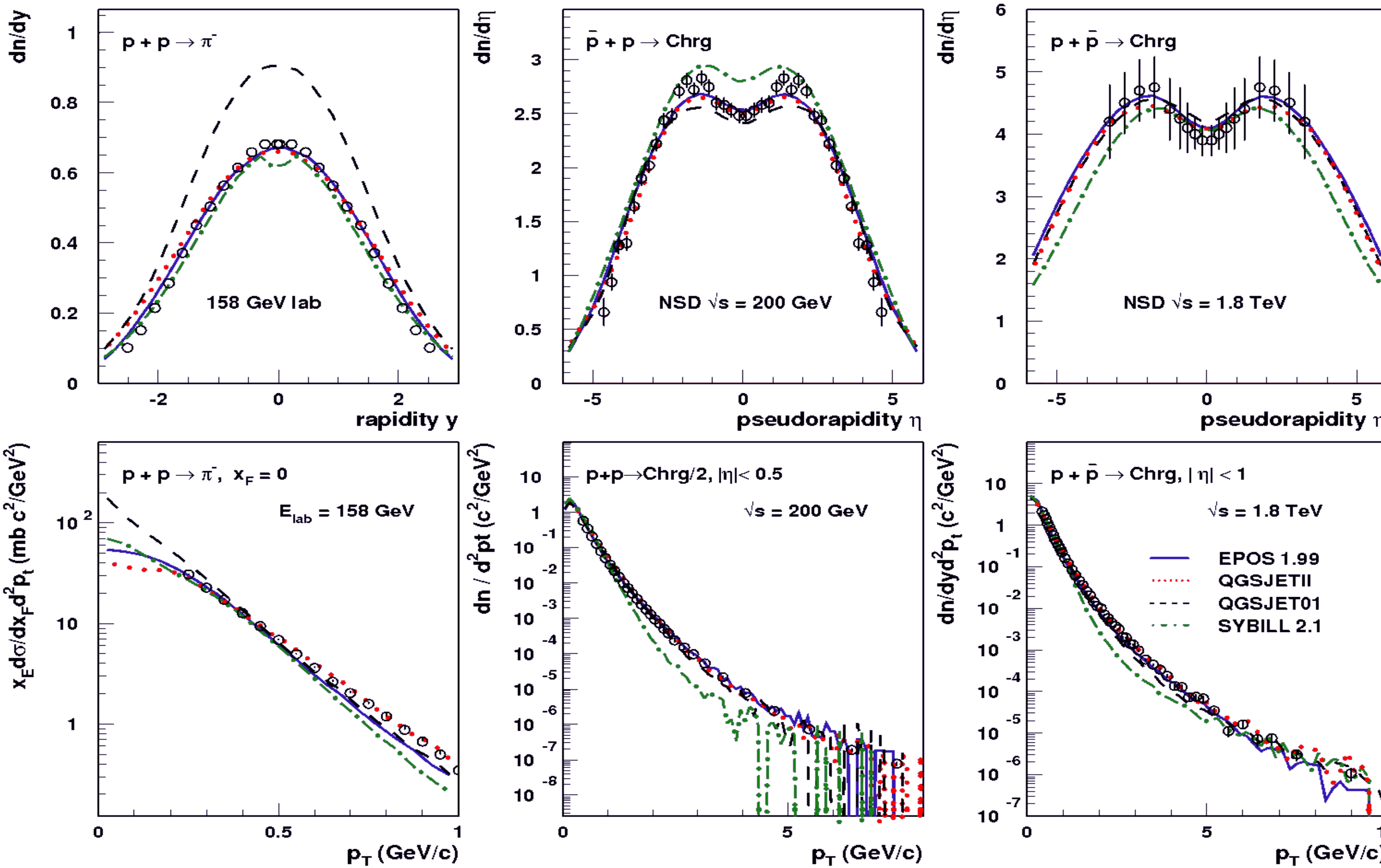
- Same cross section at pp level and low energy (data)
- Prediction of pA and pp at high energy
  - Theoretical approaches differ → extrapolations differ
- Best/most direct high energy measurement from TOTEM





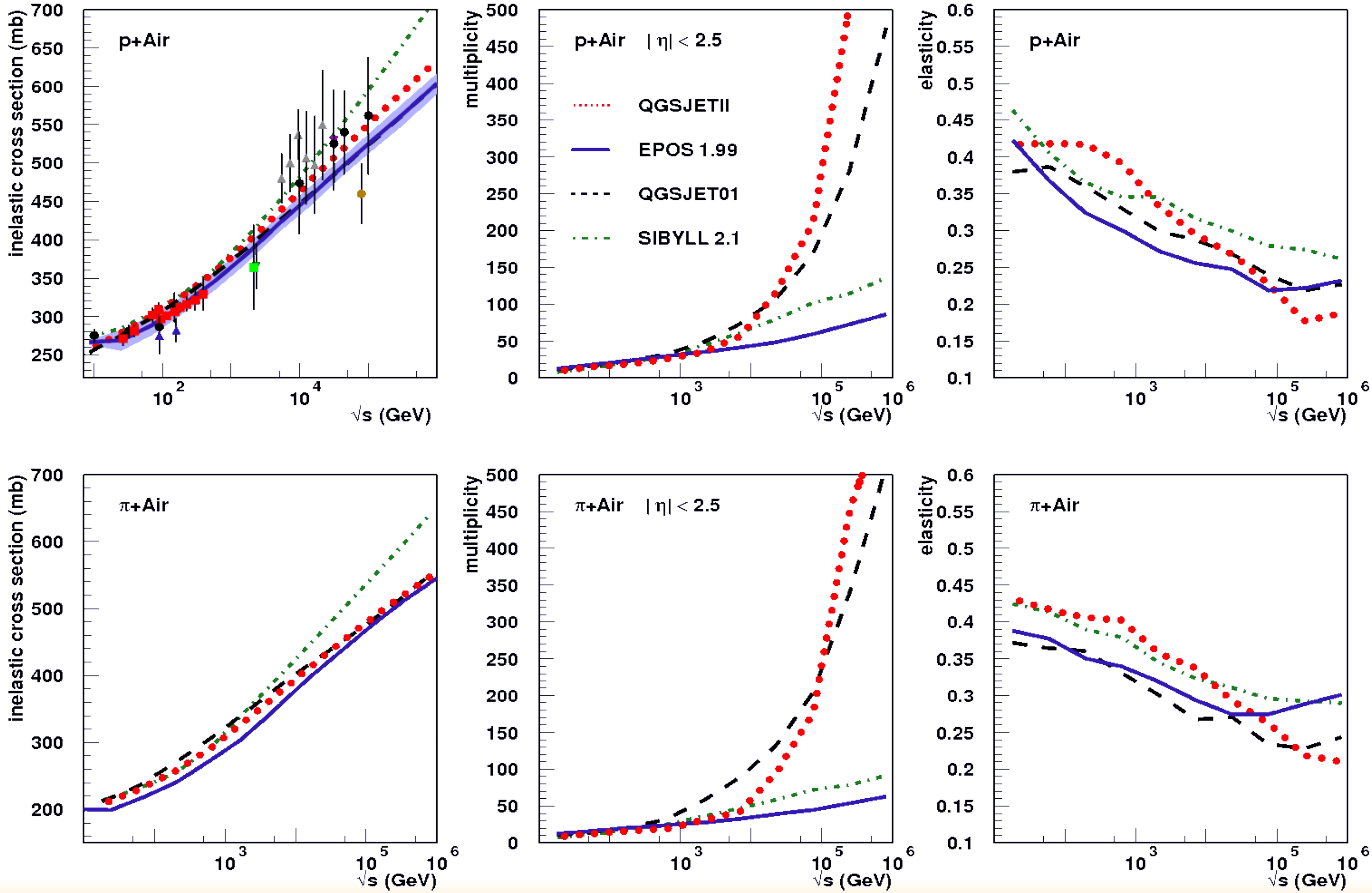
Pseudorapidity and p_T up to 1.8 TeV

Models describe previous measurements (SPS, Tevatron, ...) well



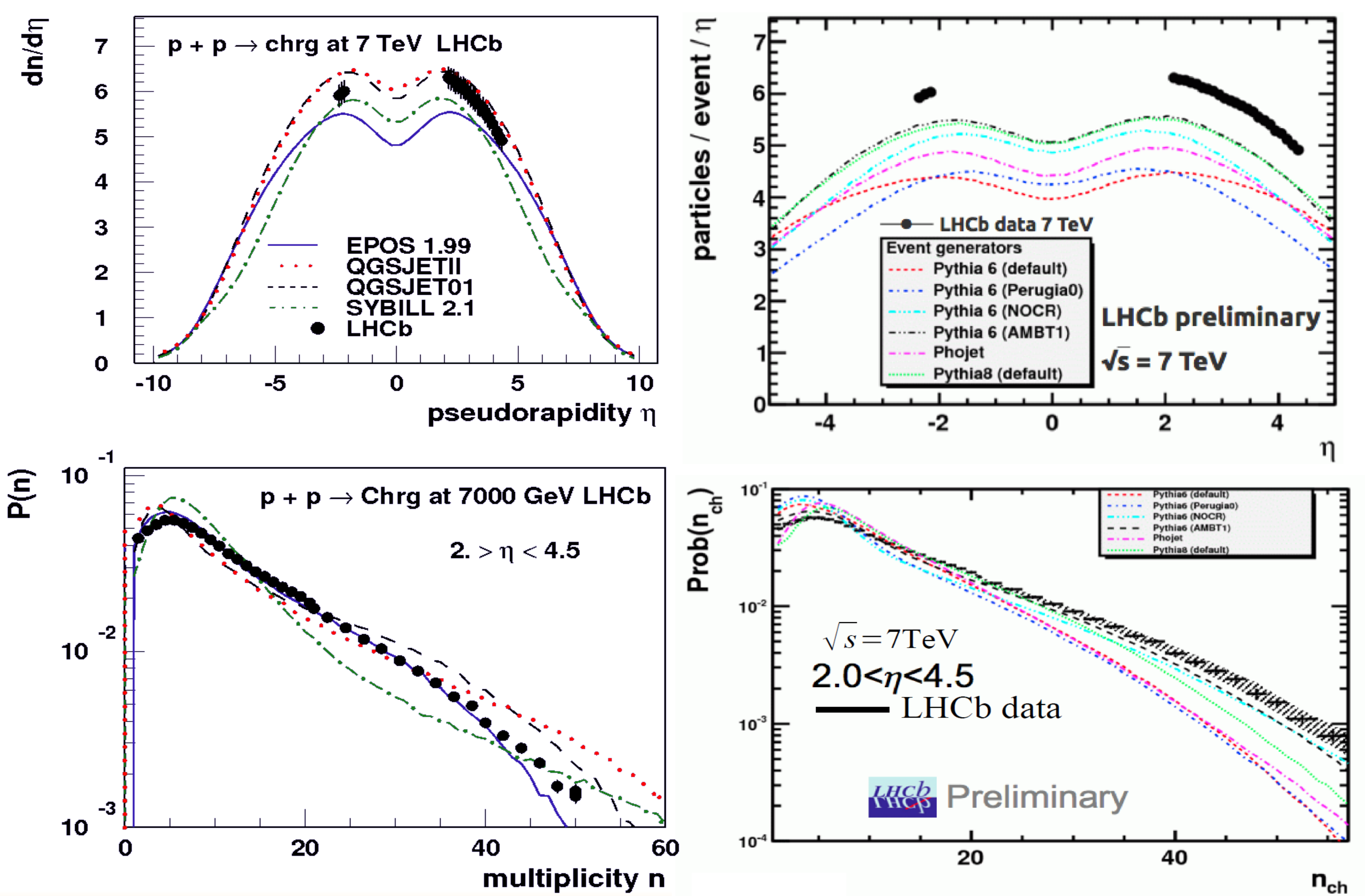
Ultra-High Energy Hadronic Model Predictions

Systematic uncertainties arise from extrapolations



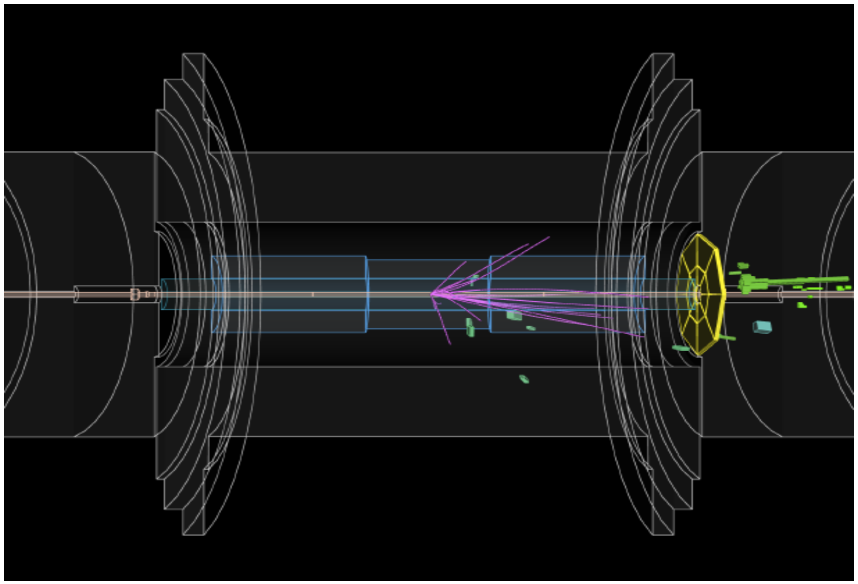
Pseudorapidity at 7 TeV: Predictions before re-tuning

- CR models bracket data, better than dedicated HEP models

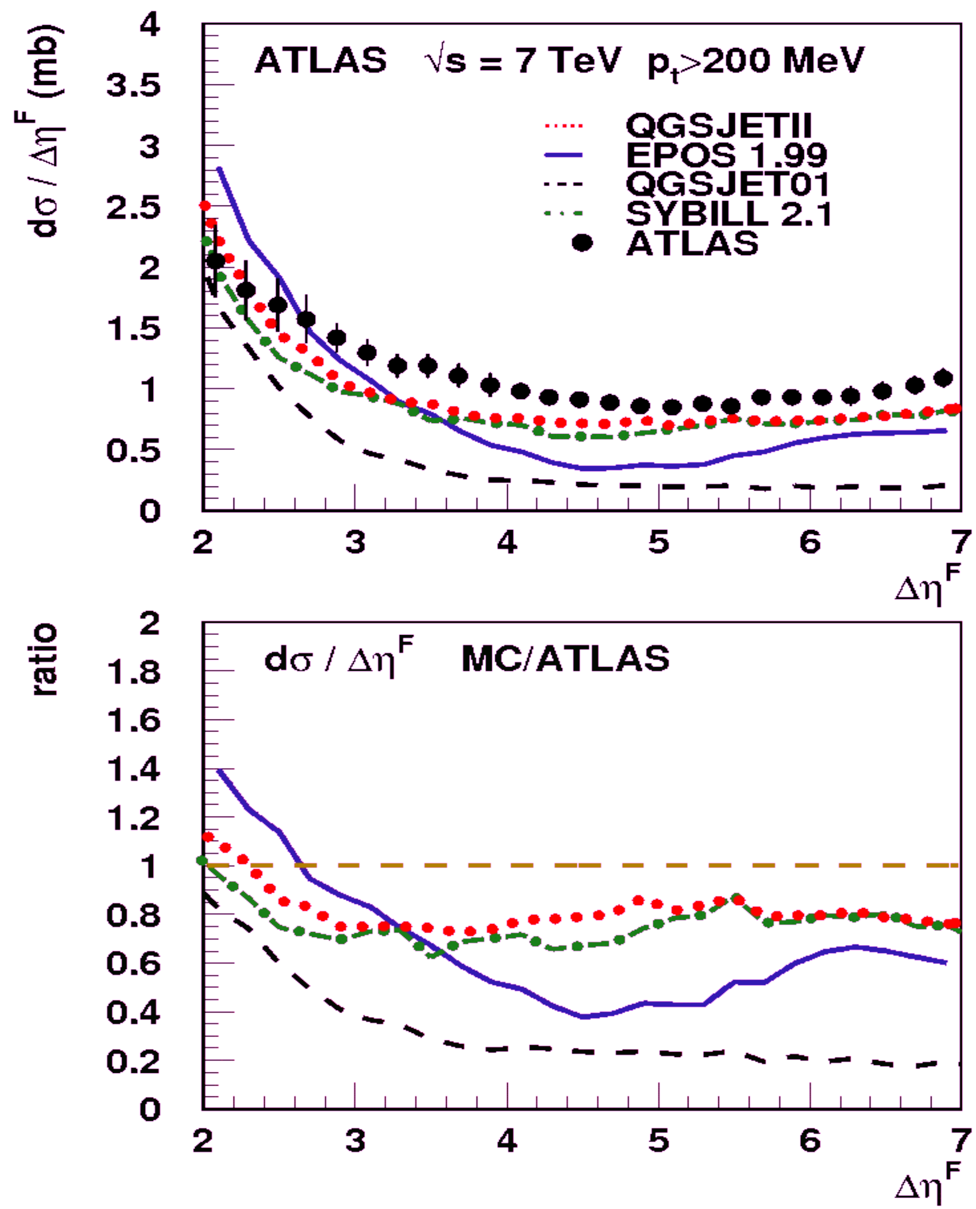


Rapidity Gap

ATLAS detector



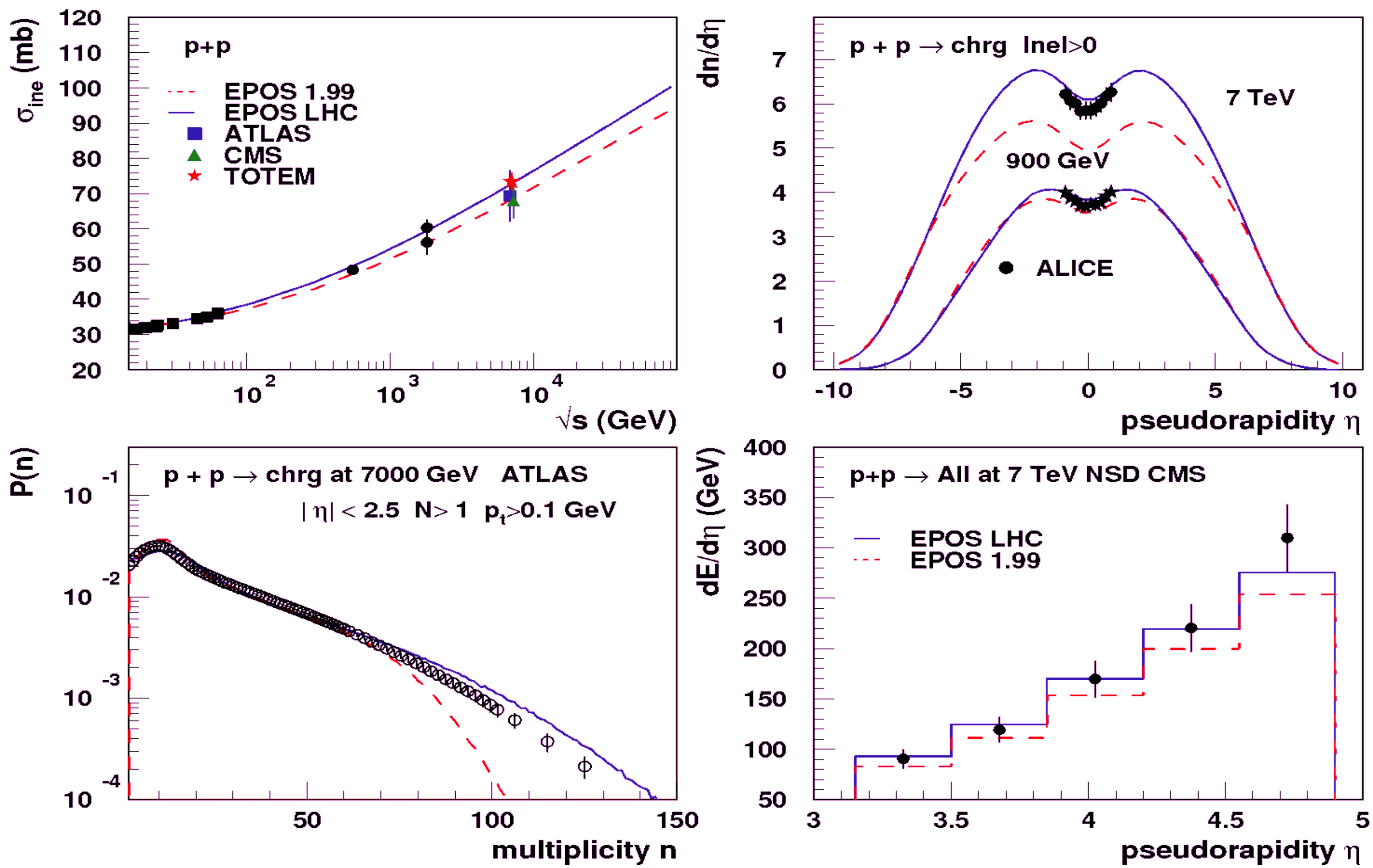
ATLAS Collaboration



- **Rapidity gap closely related to diffraction**
  - Diffractive cross-section
  - Diffractive mass distribution
- **Important effect for CR**
  - Changes elasticity

EPOS LHC

- **Small changes needed**
  - Cross-section tuned to TOTEM value
  - Old flow calculation refined to a more realistic one

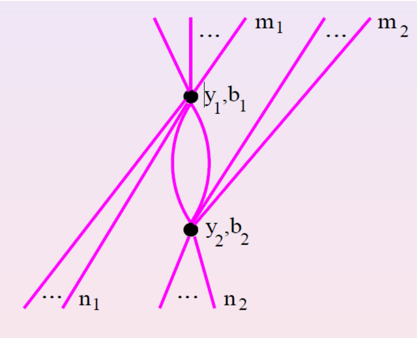


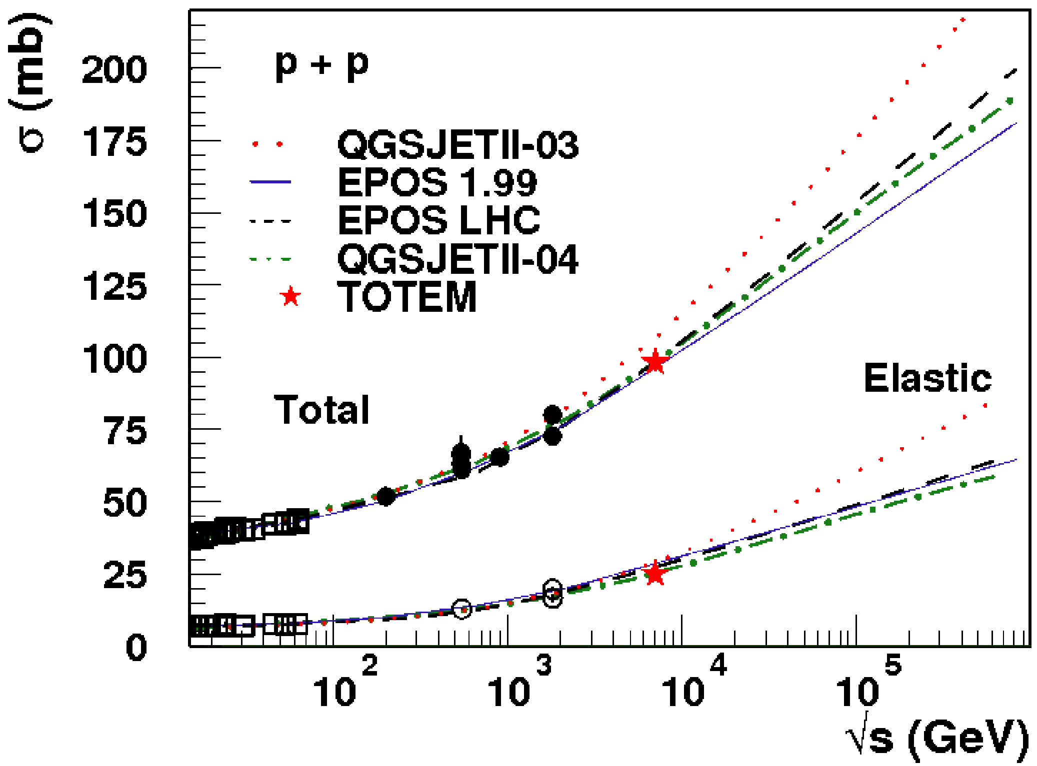
X-Section

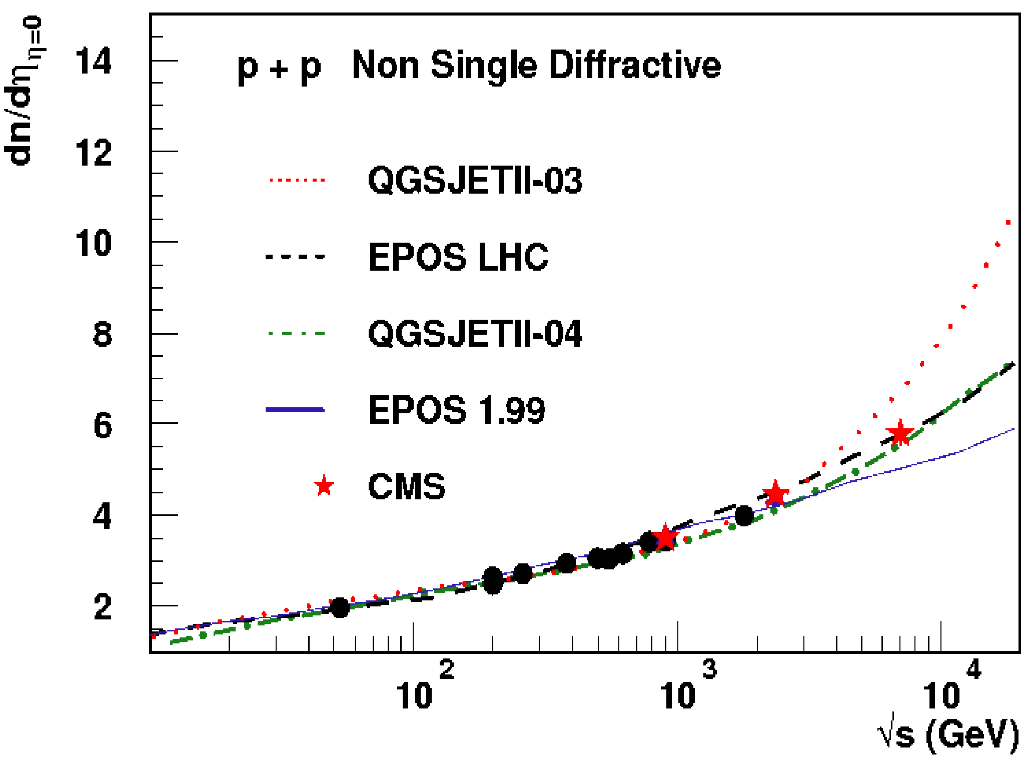
Flow

QGSJetII-04

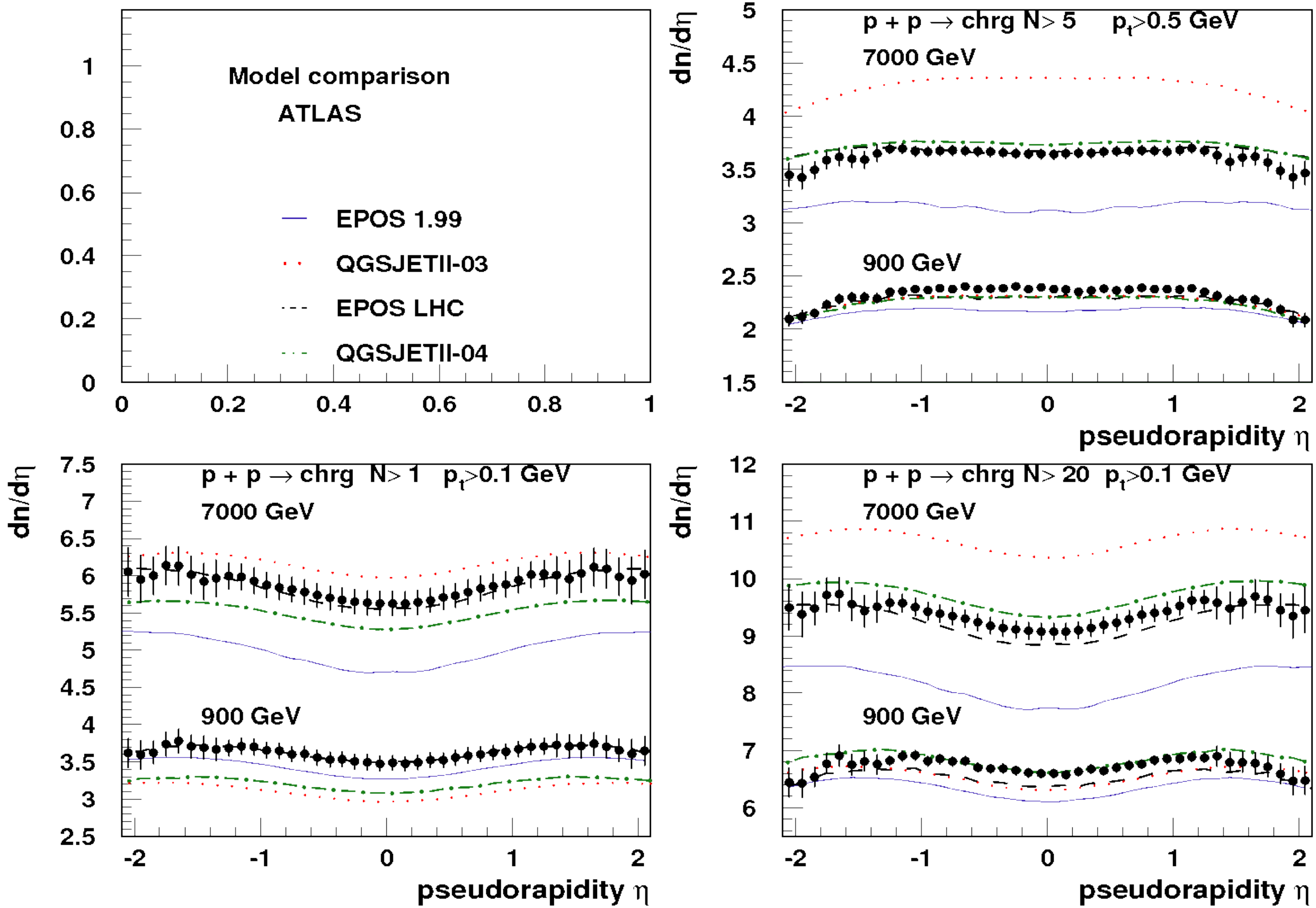
- Some parameters with loop diagrams included
- Rapidity-threshold for particle production revised
- ρ-production included (big effect on muons!)
- General re-tuning



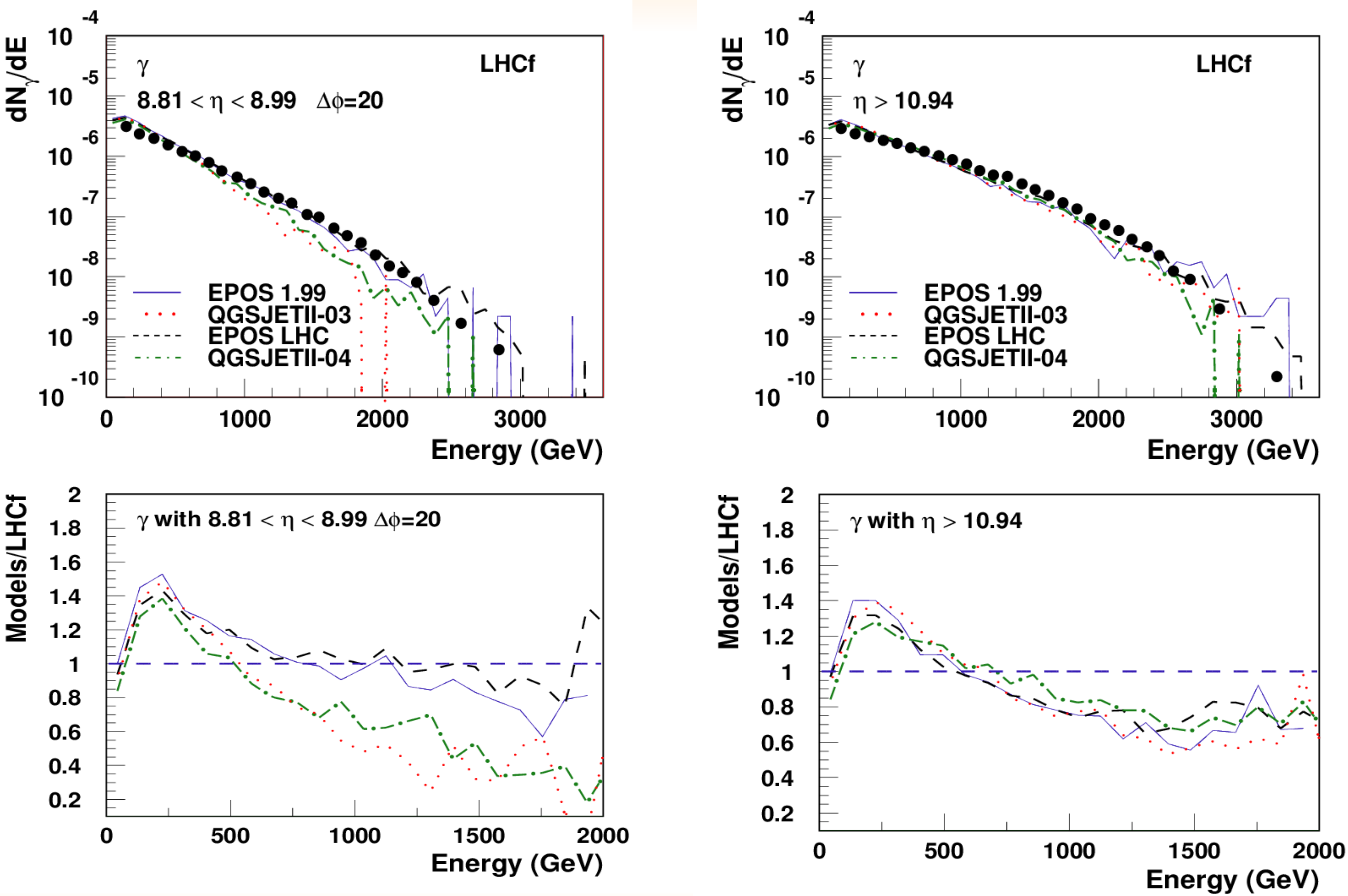




Charged particle production at mid-rapidity

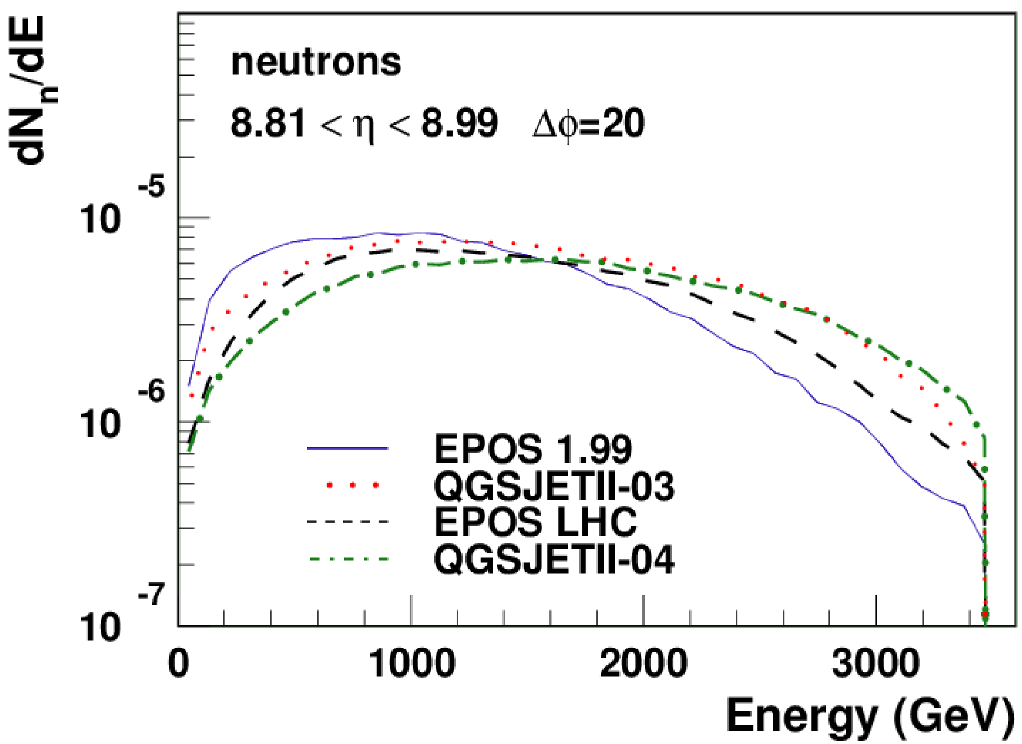


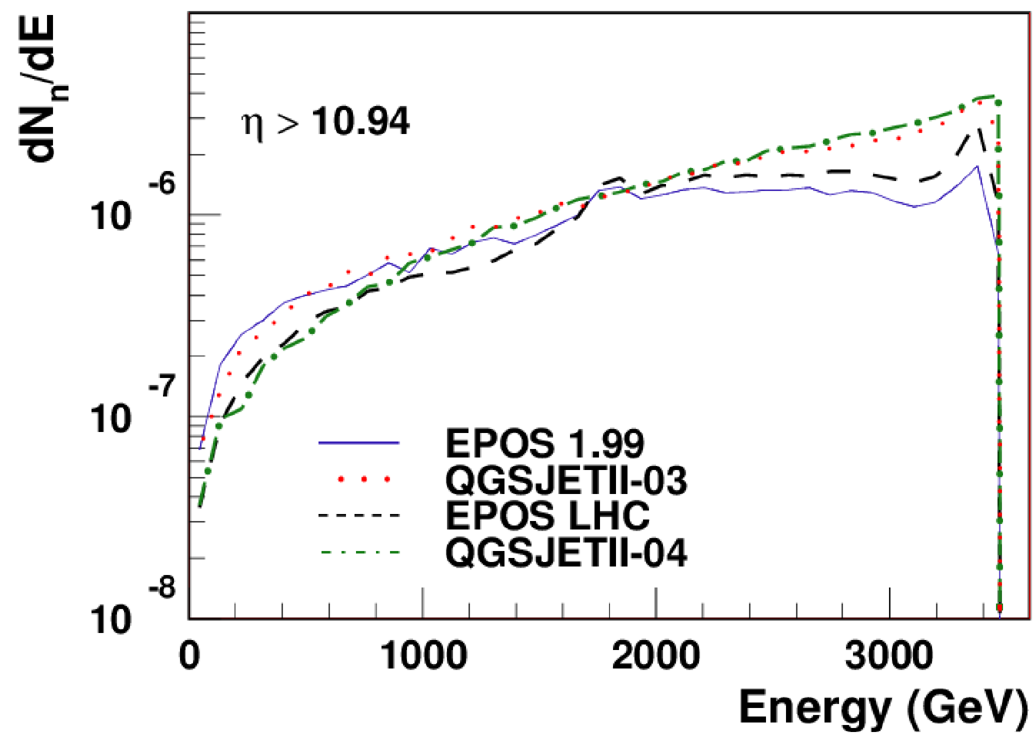
Photon production in forward direction at 7 TeV



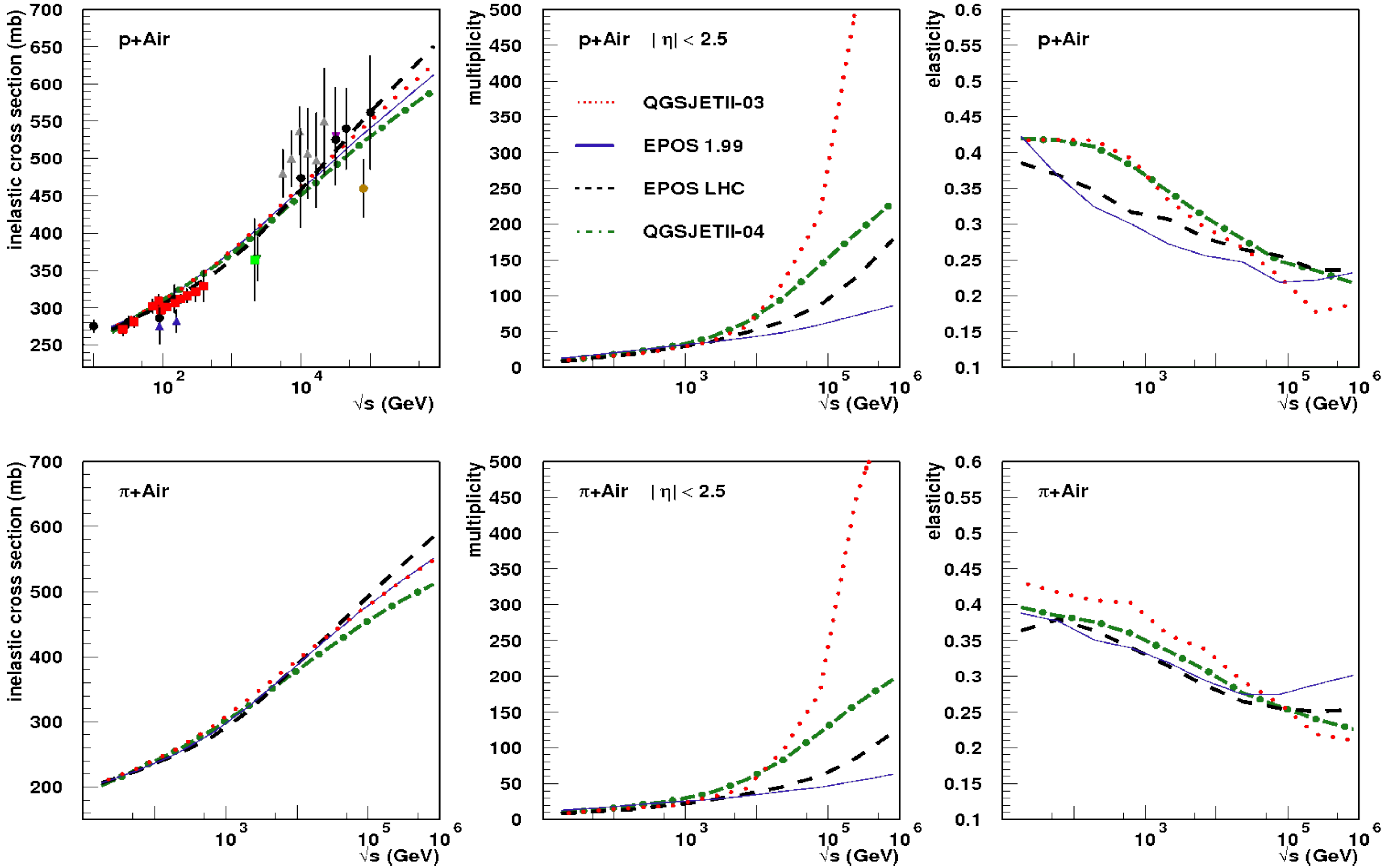
Neutron production in forward direction at 7 TeV

- **No data yet**



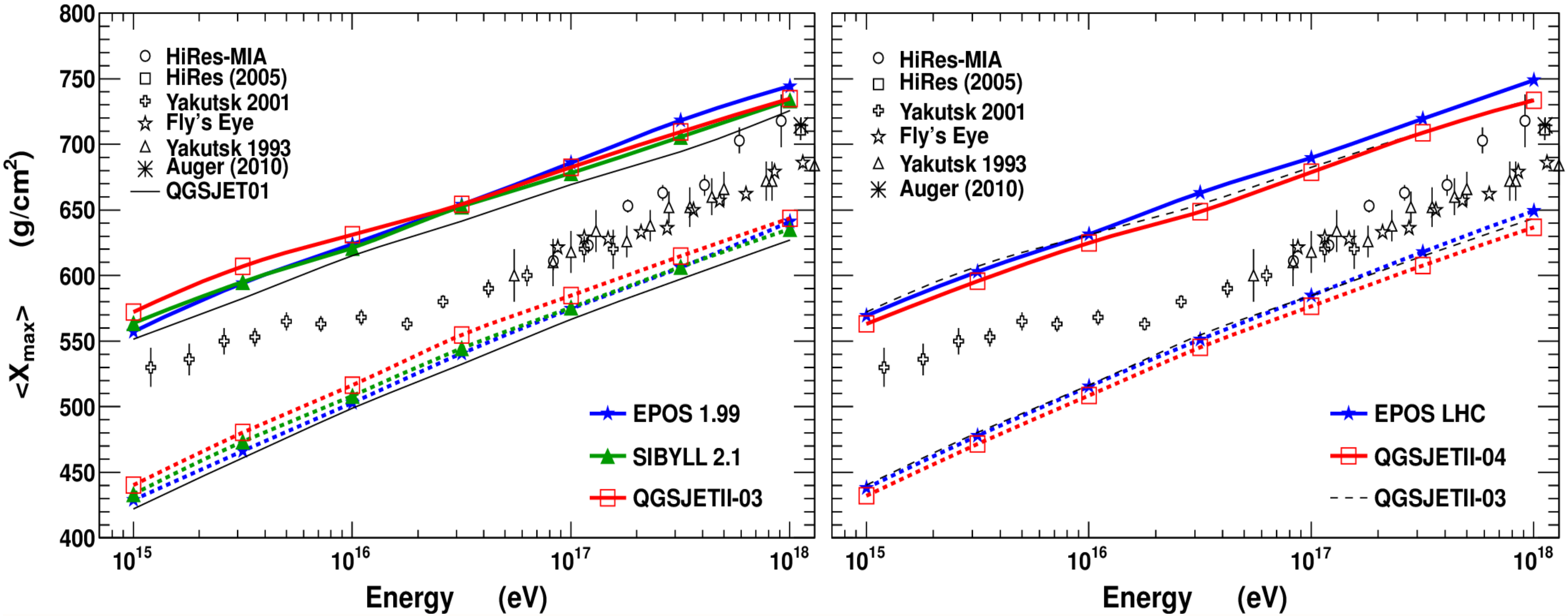


Predictions with retuned models



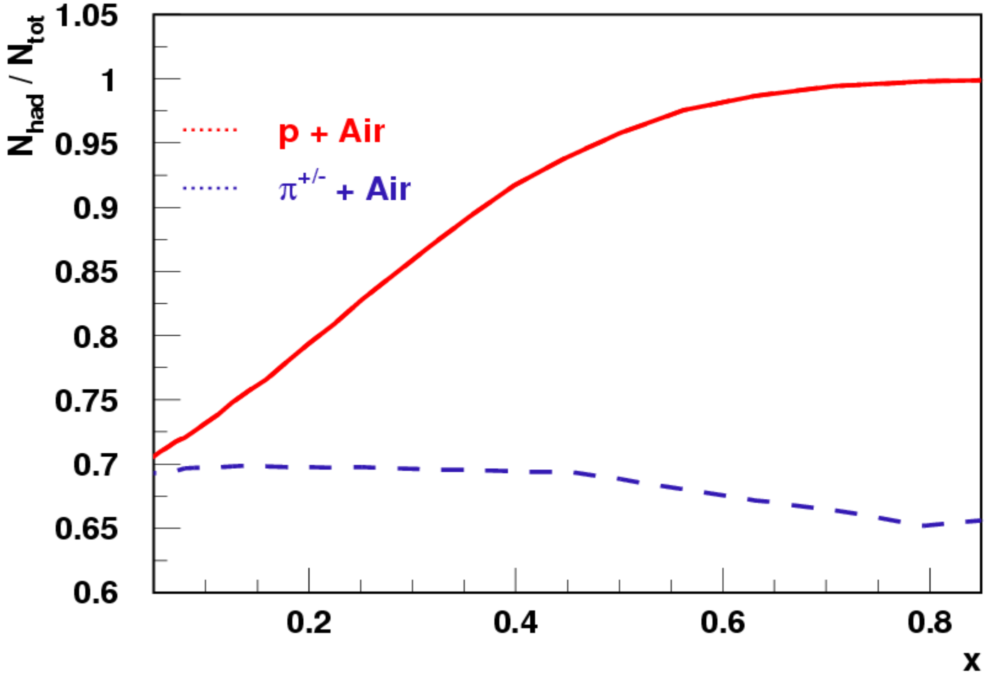
Depth of shower maximum X_{max}

- **Cross section and multiplicity fixed at 7 TeV**
  - Smaller $\langle X_{max} \rangle$ for EPOS and larger for QGSJetII
  - Updated models converge to old Sibyll 2.1 predictions
    - Model spread reduced from ~25 g/cm² to ~15 g/cm² (difference proton/iron about 100 g/cm²)



Muon Number: Background

- **Number of muons driven by energy in cascade not lost to π^0s**
  - Multiplicity, elasticity, type of leading particle important
  - Leading particles not only pions: also kaons and (anti)baryons (but 10 times less …)
  - Baryons do not produce leading π^0, energy kept in hadronic channel (EPOS ++)
  - Some excited meson-states decay preferably into charged pions (ρ^0!), energy kept in hadronic channel

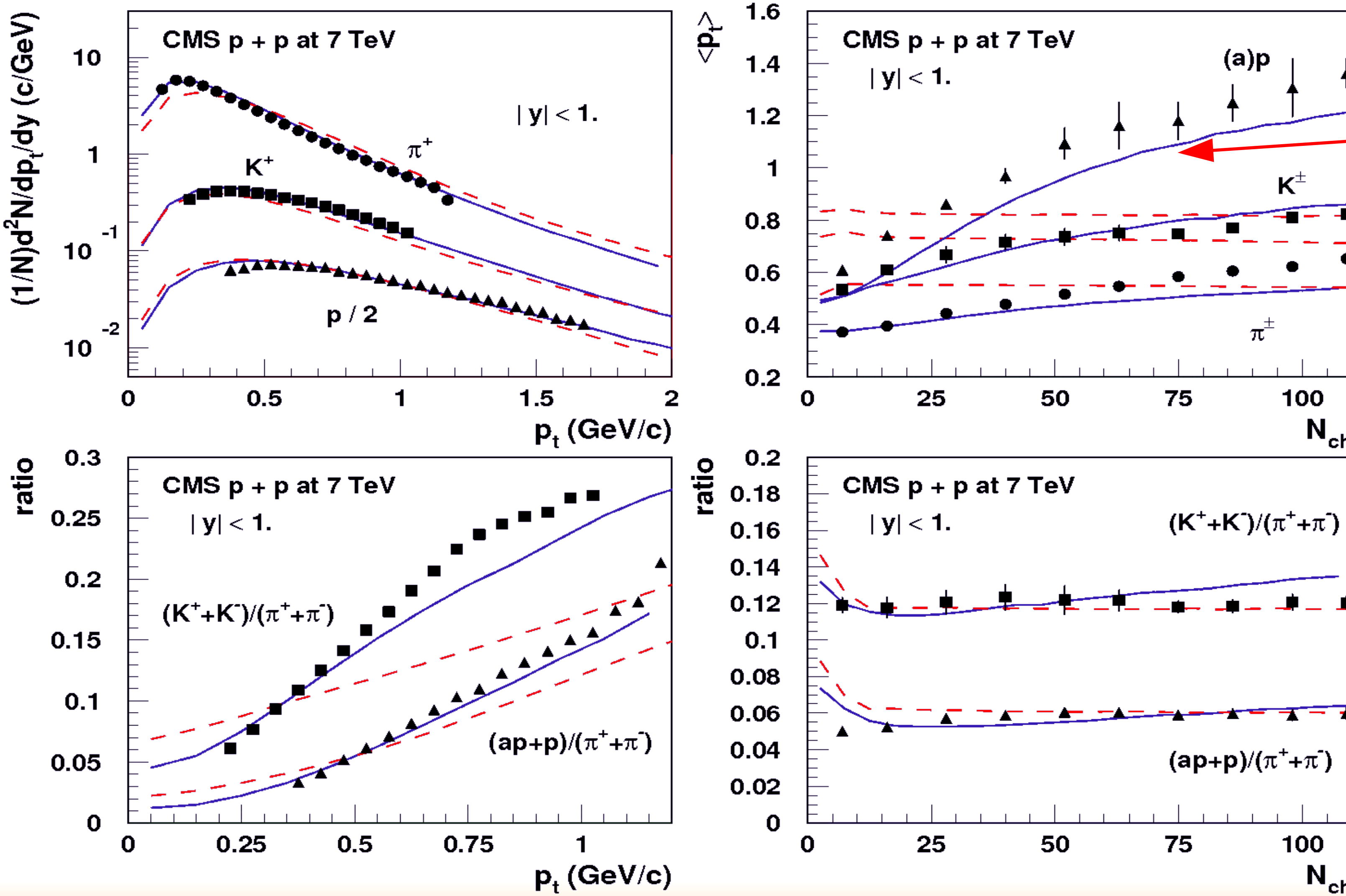


Need to check baryon, kaon, rho... production in forward direction, but particle identification difficult

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

Identified Particle Spectra at mid-rapidity

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



Collective flow effect only in EPOS

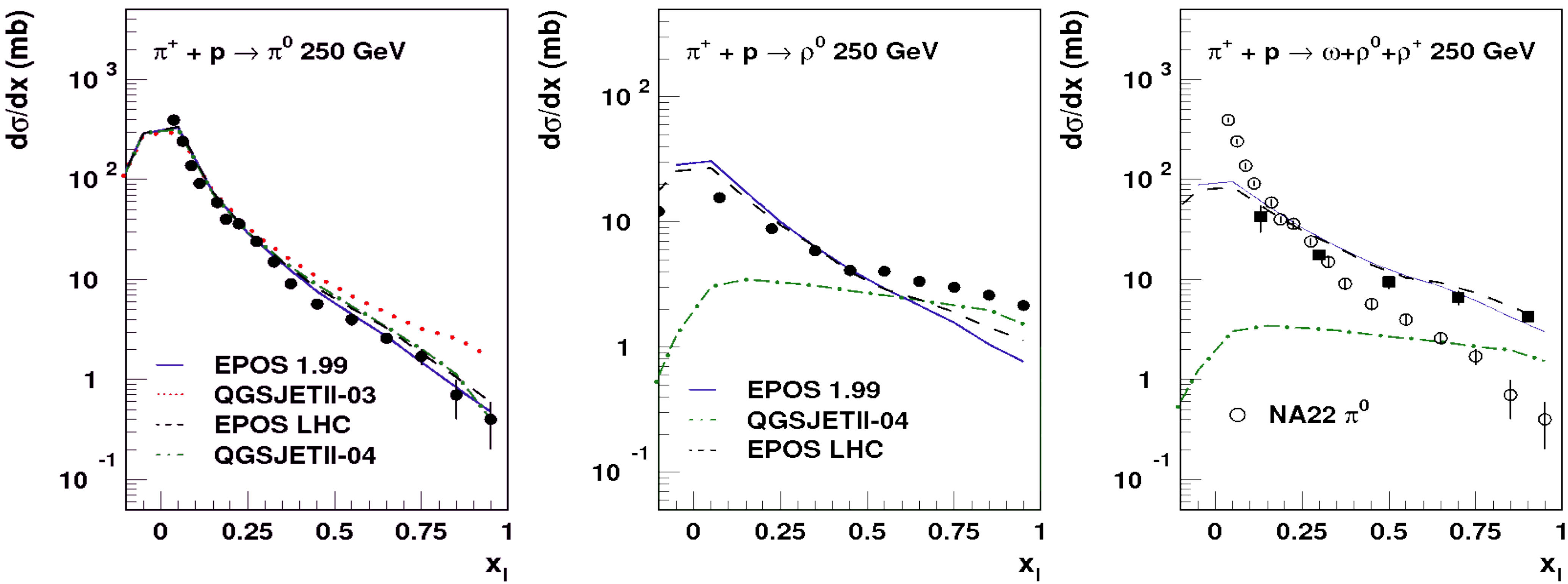
Baryon number now fixed at mid-rapidity.

EPOS LHC
QGSJETII-04

Pion Leading Particle Effect

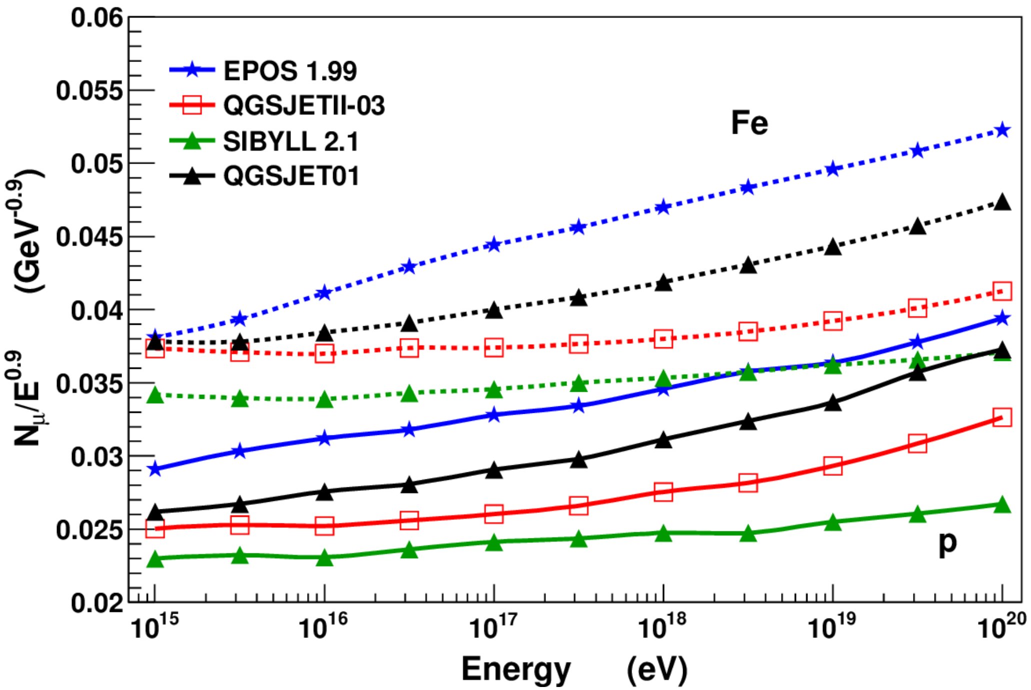
- **ρ-meson production added in QGSJetII**
  - Not only ρ^0 should be taken into account!

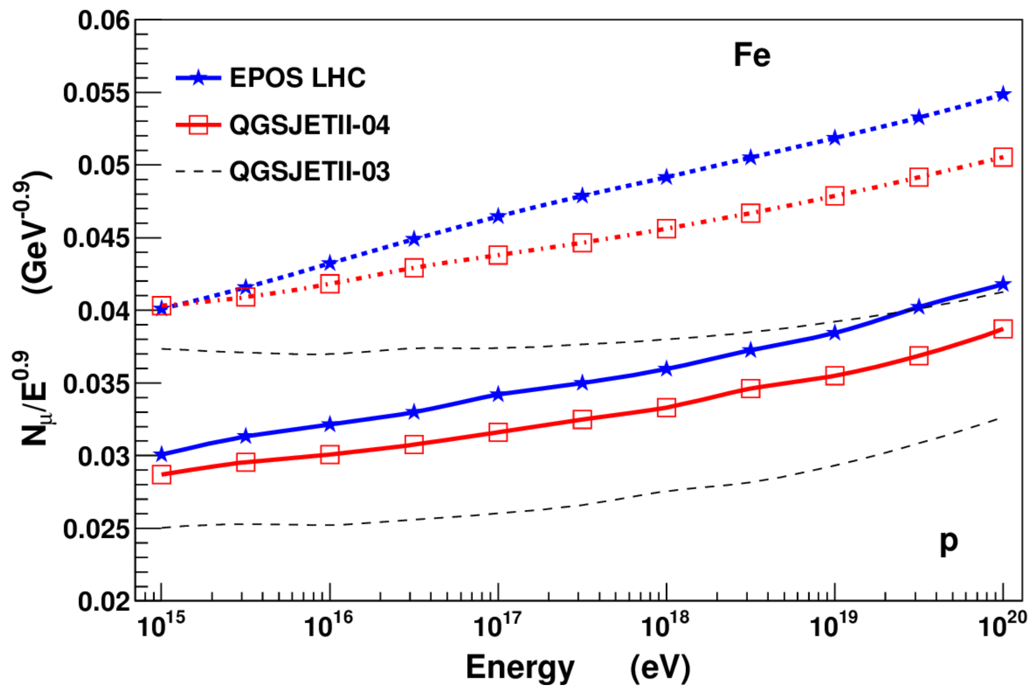
similar cross-section



Number of Muons vs. Cosmic Ray Energy

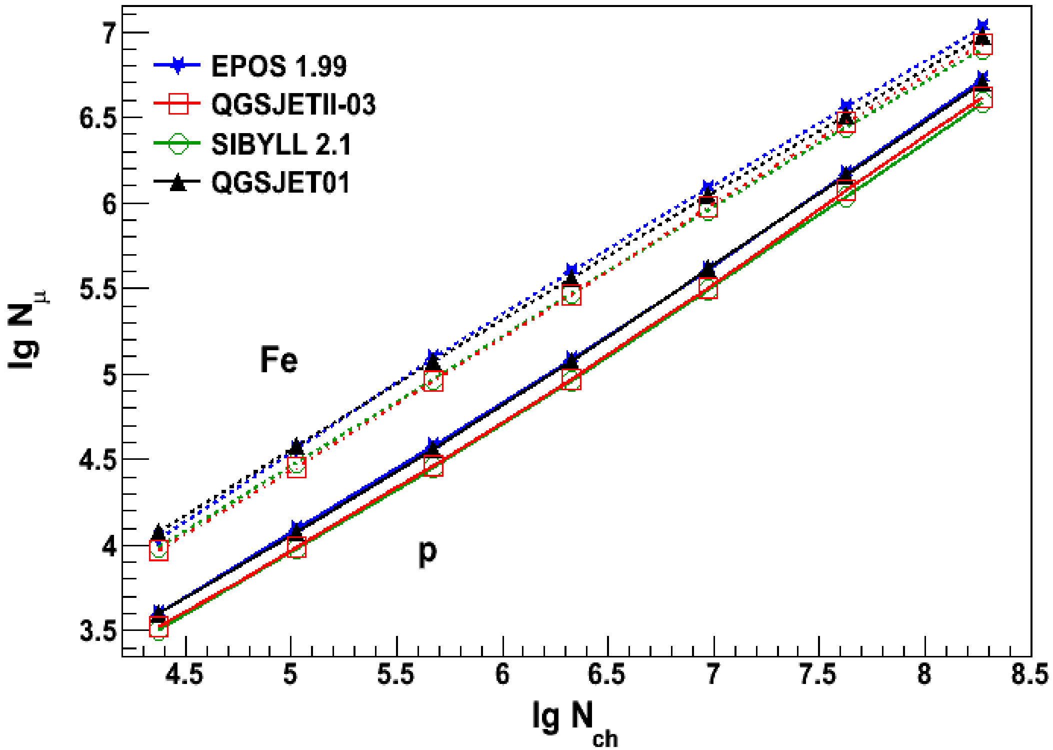
- **Weak effect of LHC**
  - Corrections at mid-rapidity only for EPOS
  - Changes in QGSJetII motivated by pion induced data at low energies
  - Changes for forward production in EPOS LHC cannot be checked by LHC (yet ?) (motivated by model consistency)
- **NA61 data wanted to check old data set**

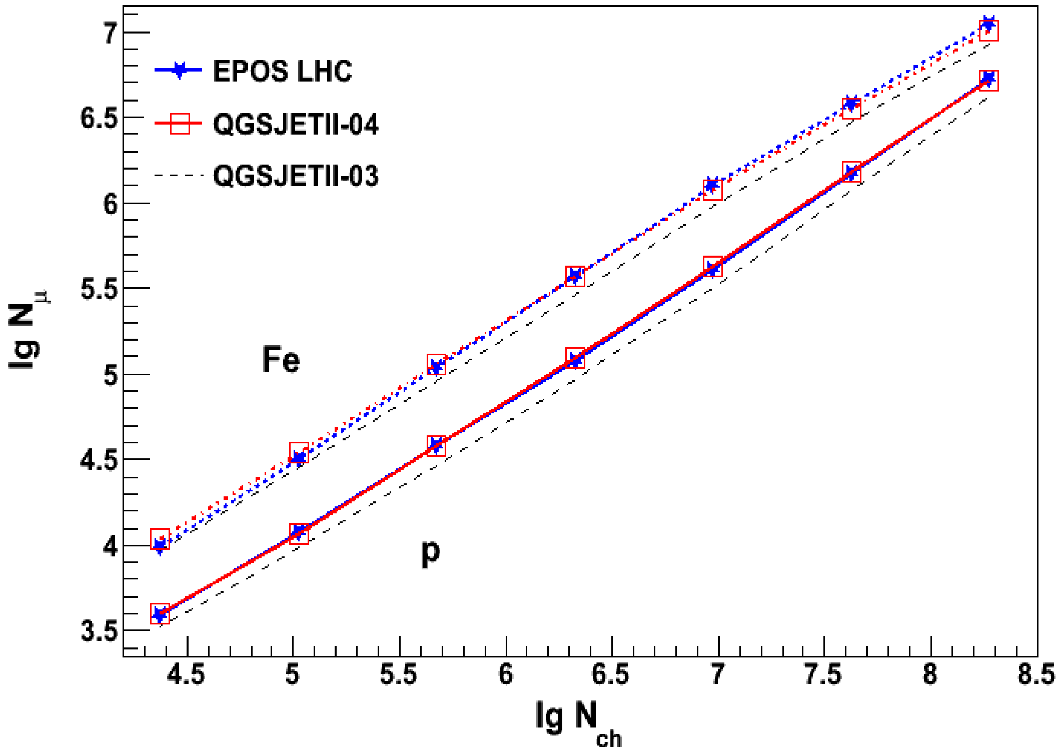




Number of Muons vs. Charged Particles

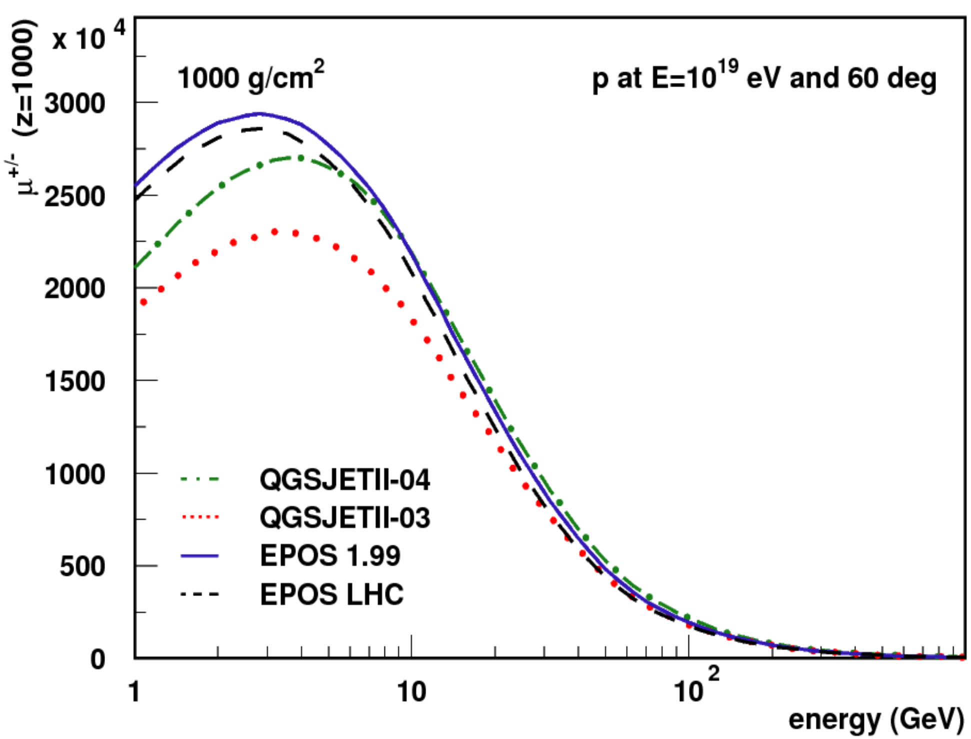
- **QGSJetII-04 and EPOS LHC in close agreement**
  - EPOS has more muons, but also more charged particles: ratio cancels
- **Mass composition derived from KASCADE-like data will change**
  - More muons per charged particle predicted, therefore...
  - Mass composition will become lighter in light of models

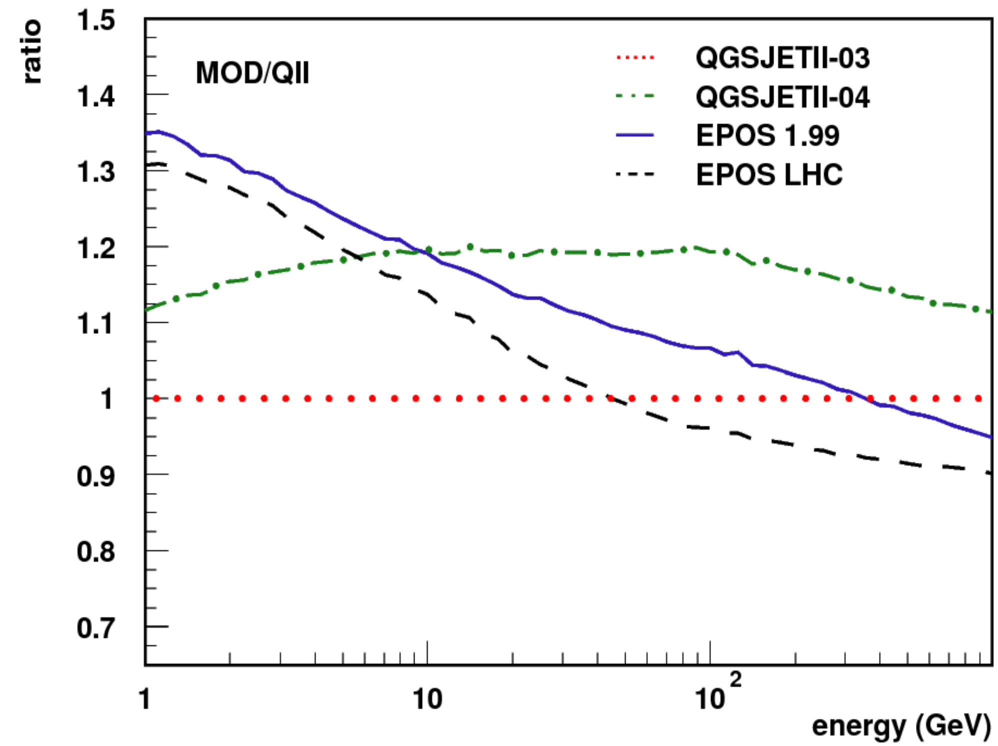




Muon Energy Spectra

- **Total number of muons similar in EPOS and QGSJETII-04 (@60°) BUT**
  - Energy spectrum differs, related to enhanced baryon production in EPOS
  - Zenith angle dependence differs (attenuation length depends on muon energy spectrum)



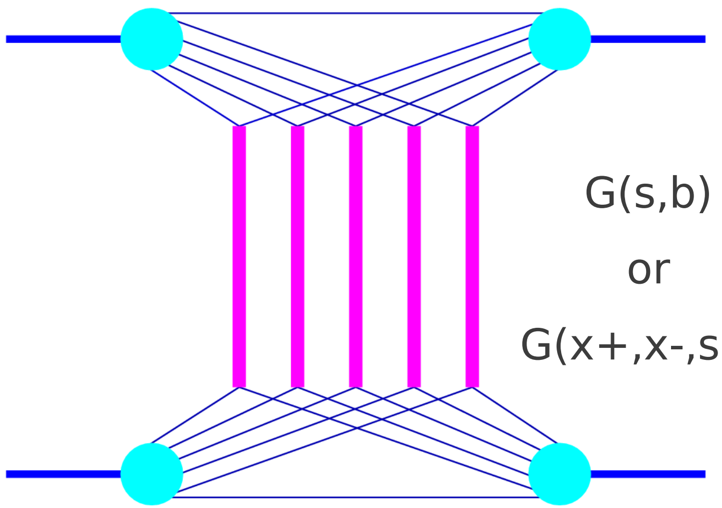


Summary

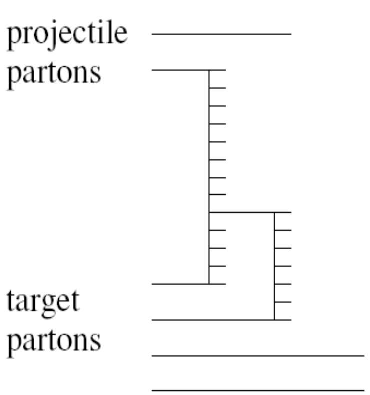
- **Hadronic interaction models for CR reproduce LHC data in a reasonable way**
  - No sudden change in hadronic physics around the knee (10^{15} eV)
  - Model uncertainties in $<X_{max}>$-simulations reduced by LHC data to ~15 g/cm^2
  - Number of muons drastically increased in QGSJetII-04, following EPOS 1.99
    - Difference between EPOS, QGSJetII down to ~10 % at 10^{20} eV, less at lower energies
    - Better understanding from forward baryon and p_t measurements: NA61 will help further
    - LHC energies important for high energy muons
- **Hadronic interaction models for CR are 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 !

    → Demand of CR models from LHC

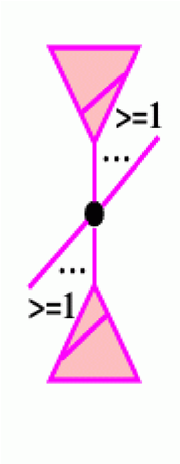
Differences between Models



EPOS

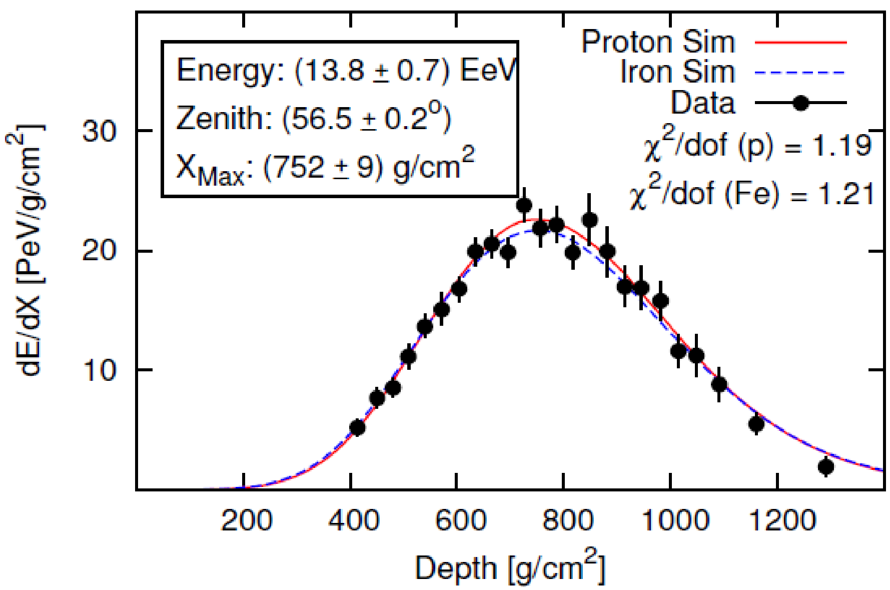


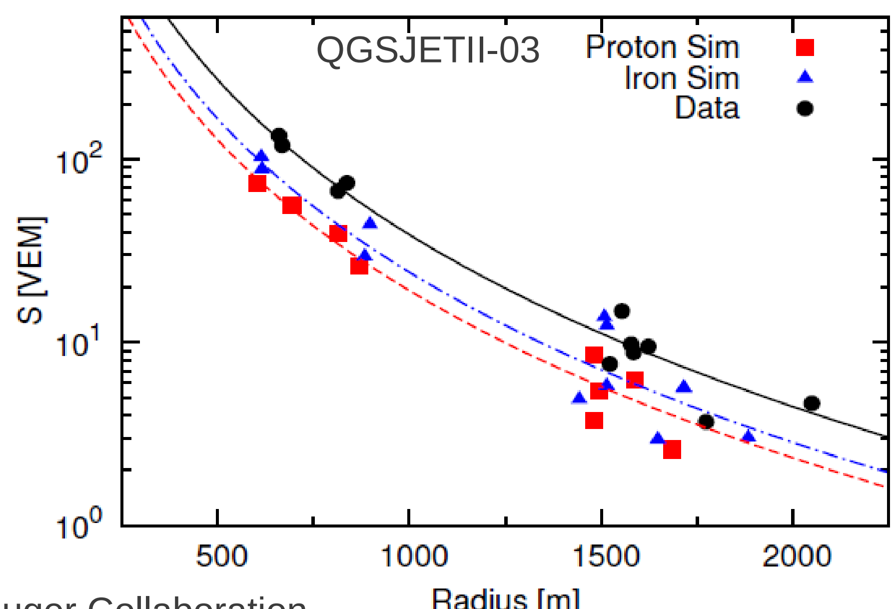
QGSJET II



- **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 + Glauber
  - 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

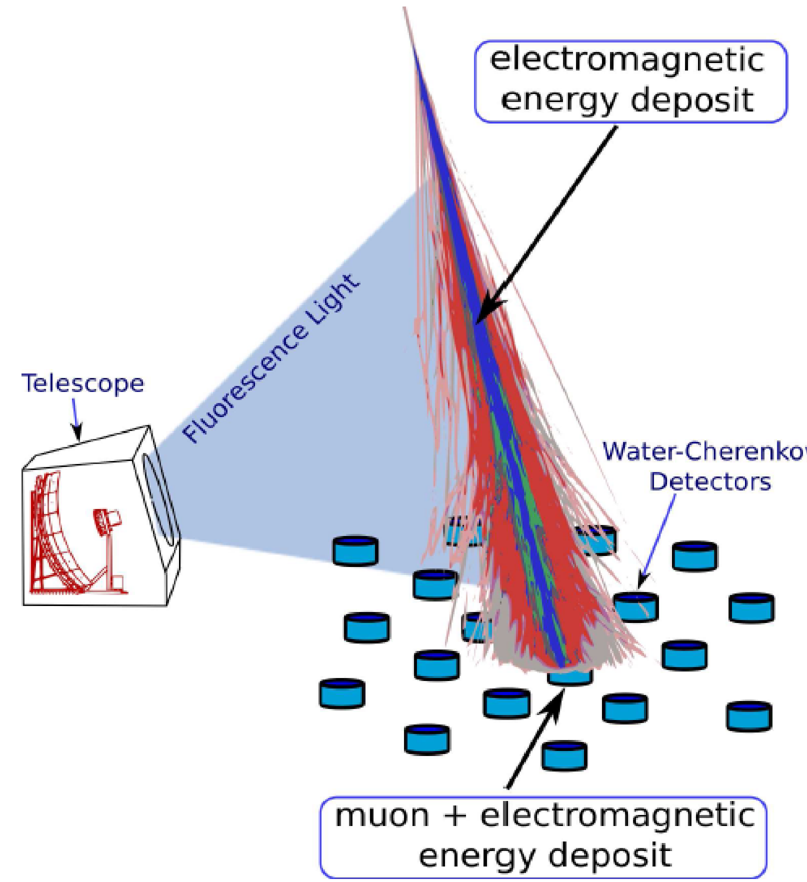
Hybrid Measurements





Pierre Auger Collaboration

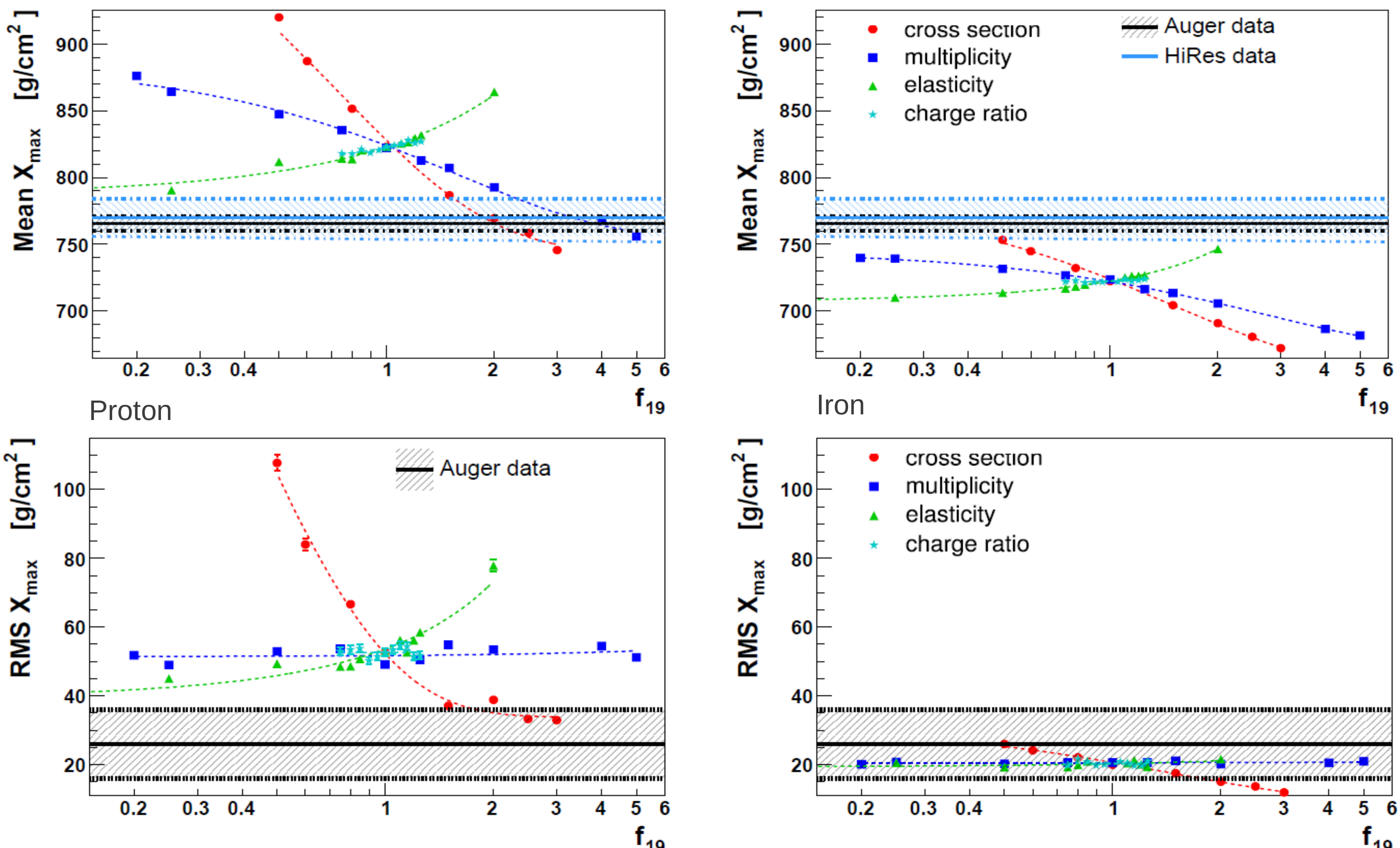
fix initial conditions : mass + energy



missing component = muons

Effects of Parameters

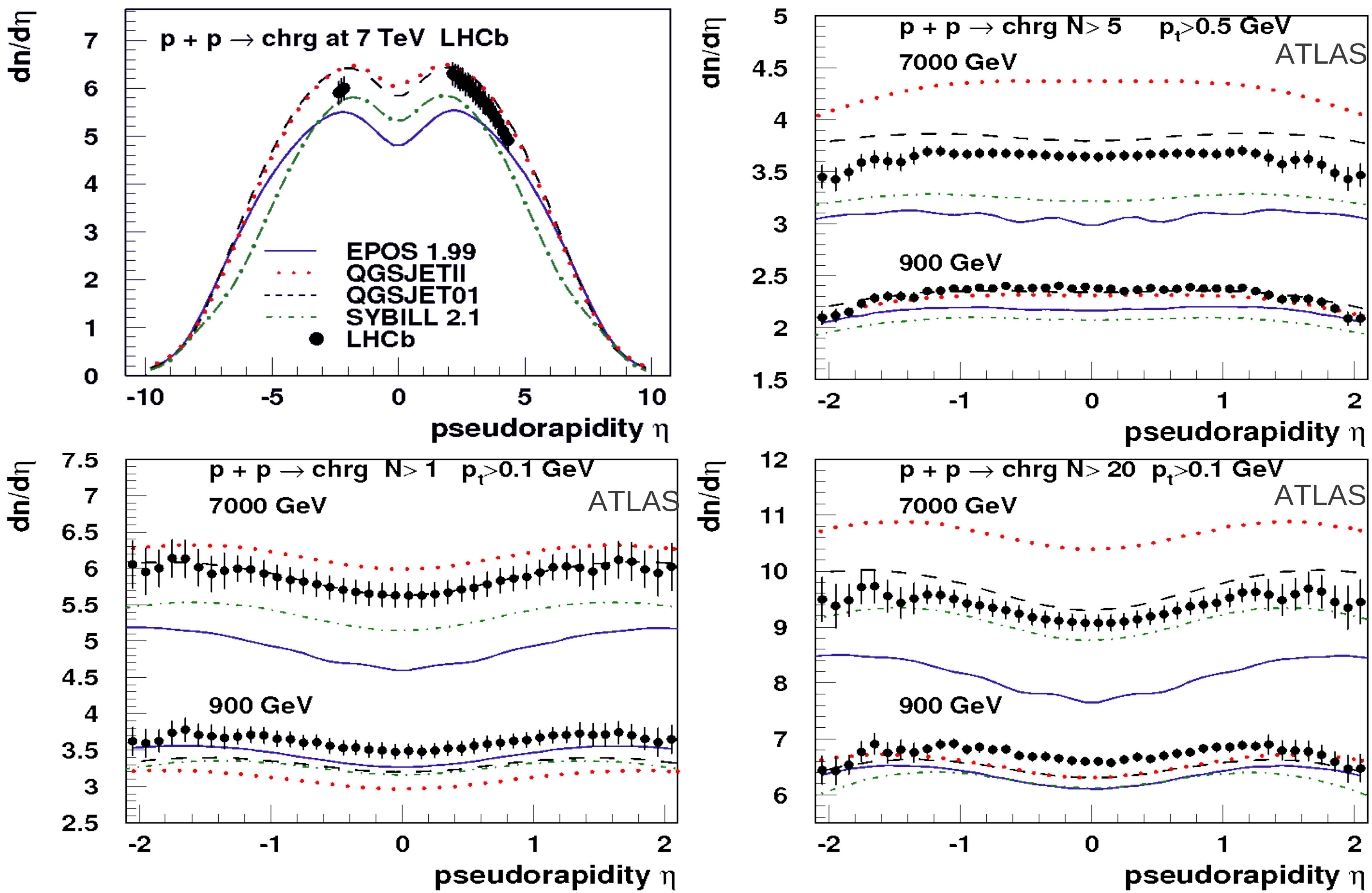
- **Sensibility depends on observable and parameter :**



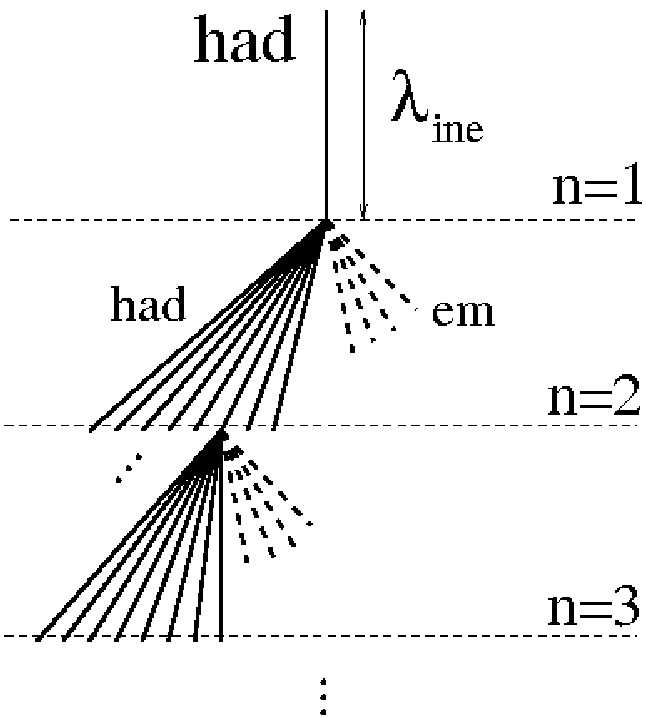
Plots by R. Ulrich (KIT) with SIBYLL model and PAO data @ 10^{19} eV

Pseudorapidity at 7 TeV: Predictions before re-tuning

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



Simplified Shower Development



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

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

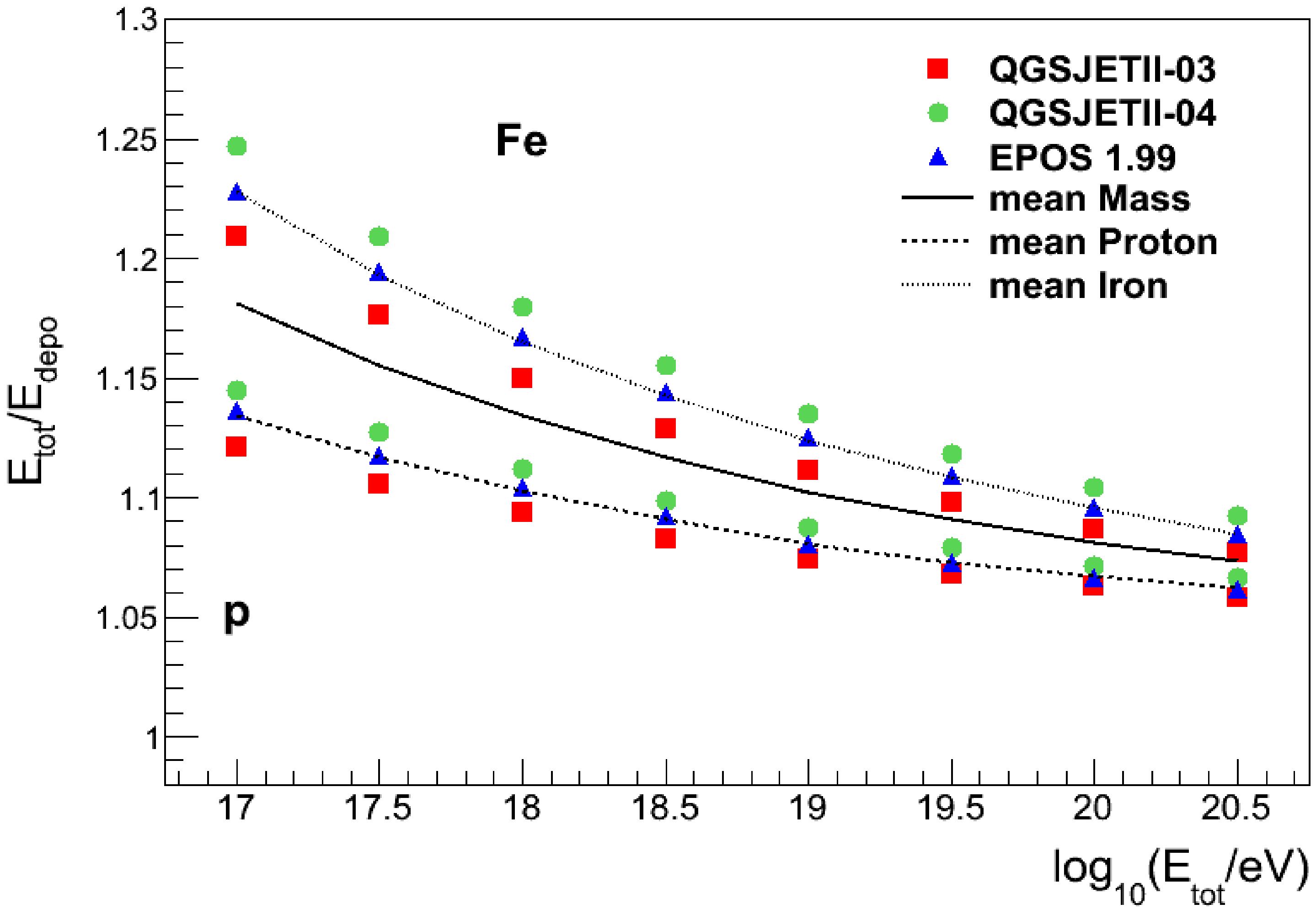
- **Using generalized Heitler model and superposition model :**

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

- 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)

EAS Energy Deposit

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

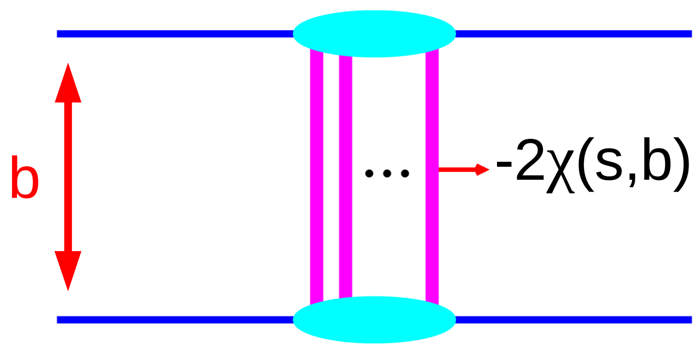


Cross Section Calculation : SIBYLL / QGSJET

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 : $\frac{(-2\chi)^n}{n!} \rightarrow \exp(-2\chi)$

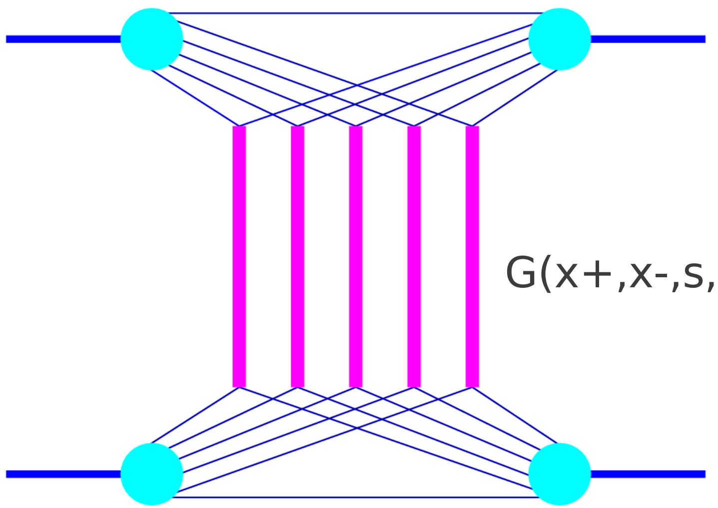


$$\sigma \sim 1 - \exp(-2\chi)$$

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

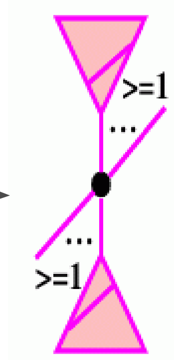
Particle Production in SIBYLL and QGSJET

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

- n from :

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

  - 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 :

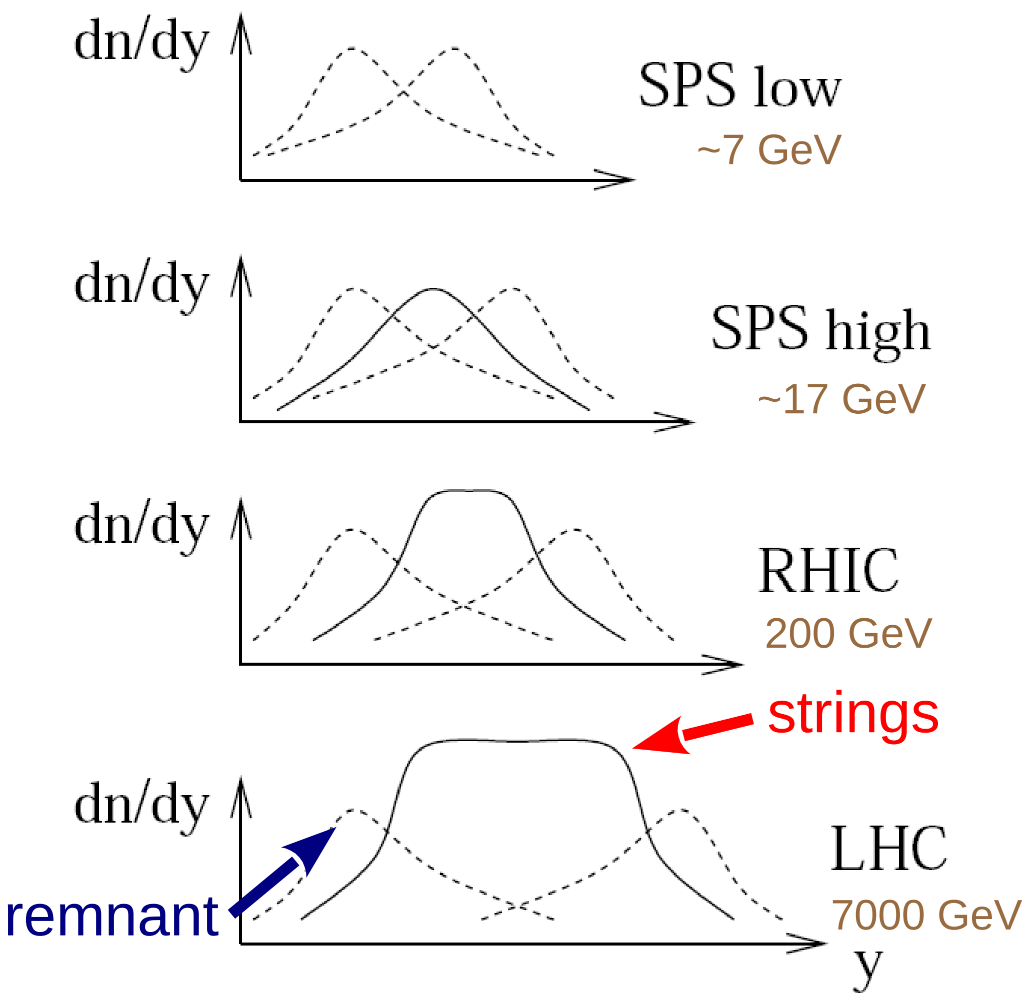
- m from :

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

  - m and X fixed together by a complex Metropolis (Markov Chain)
- 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

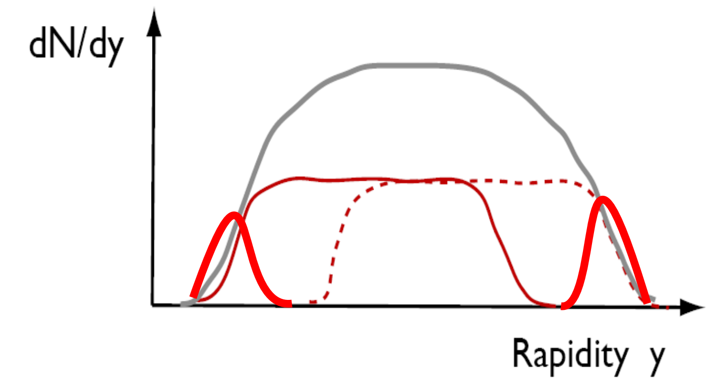
- At very low energy only particles from remnants
- At low energy (fixed target experiments) (SPS) strong mixing
- At intermediate energy (RHIC) mainly string contribution at mid-rapidity with tail of remnants.
- At high energy (LHC) only strings at mid-rapidity (baryon free)

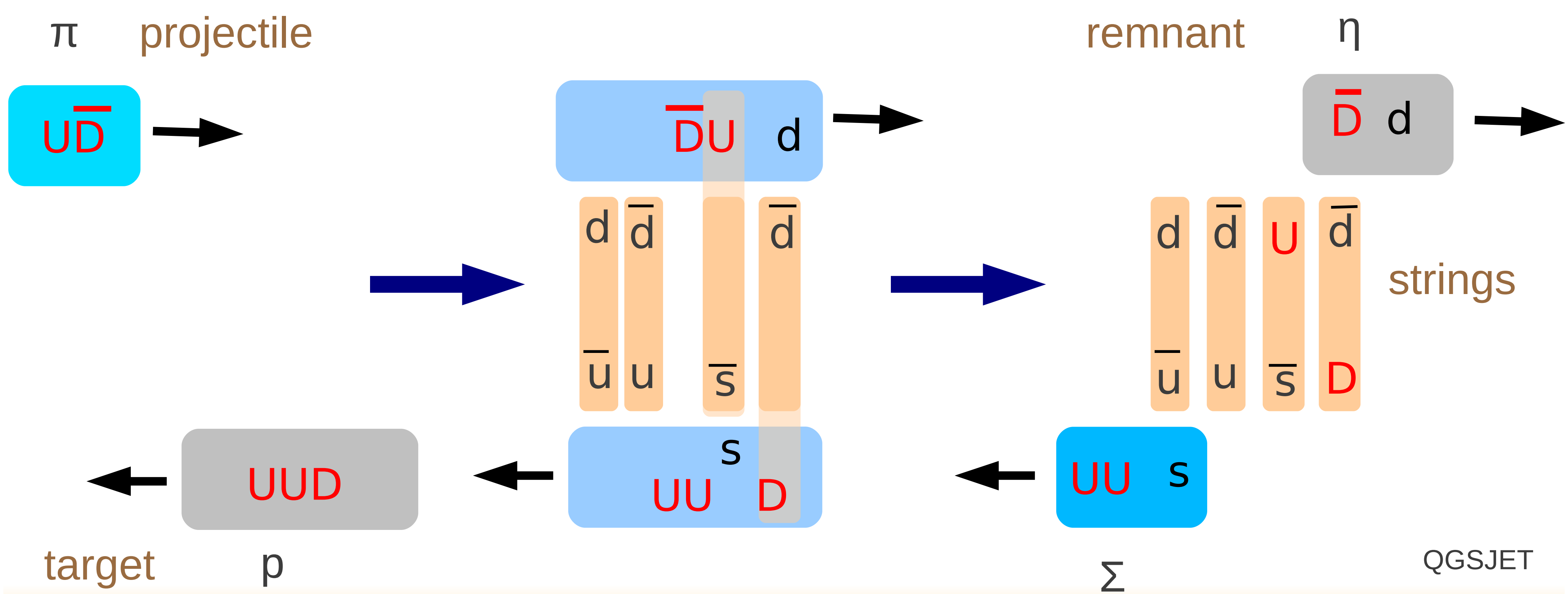
Different contributions of particle production at different energies or rapidities

Beam Remnants

Forward particle production dominated by beam remnants

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

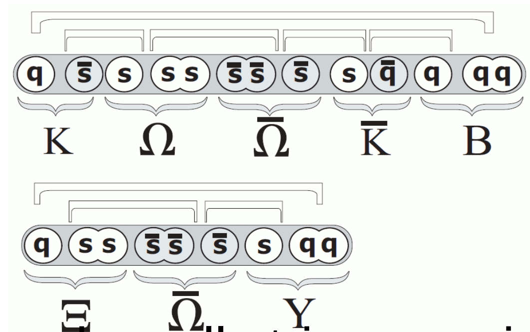




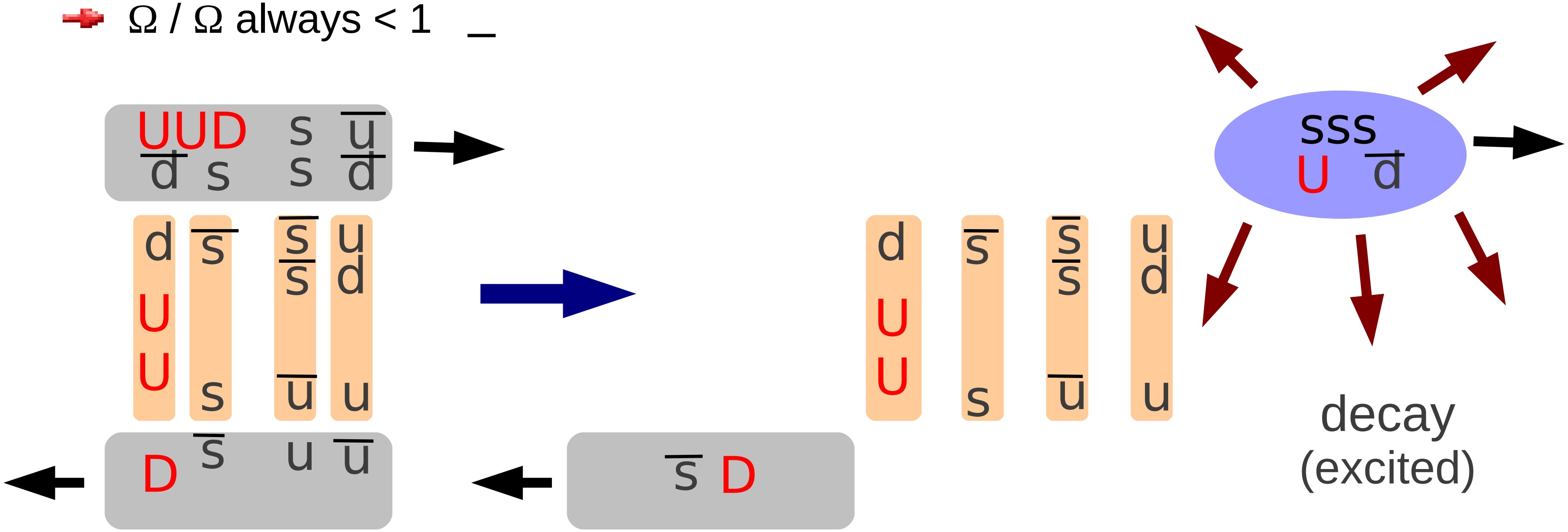
Baryons and Remnants

Parton ladder string ends :

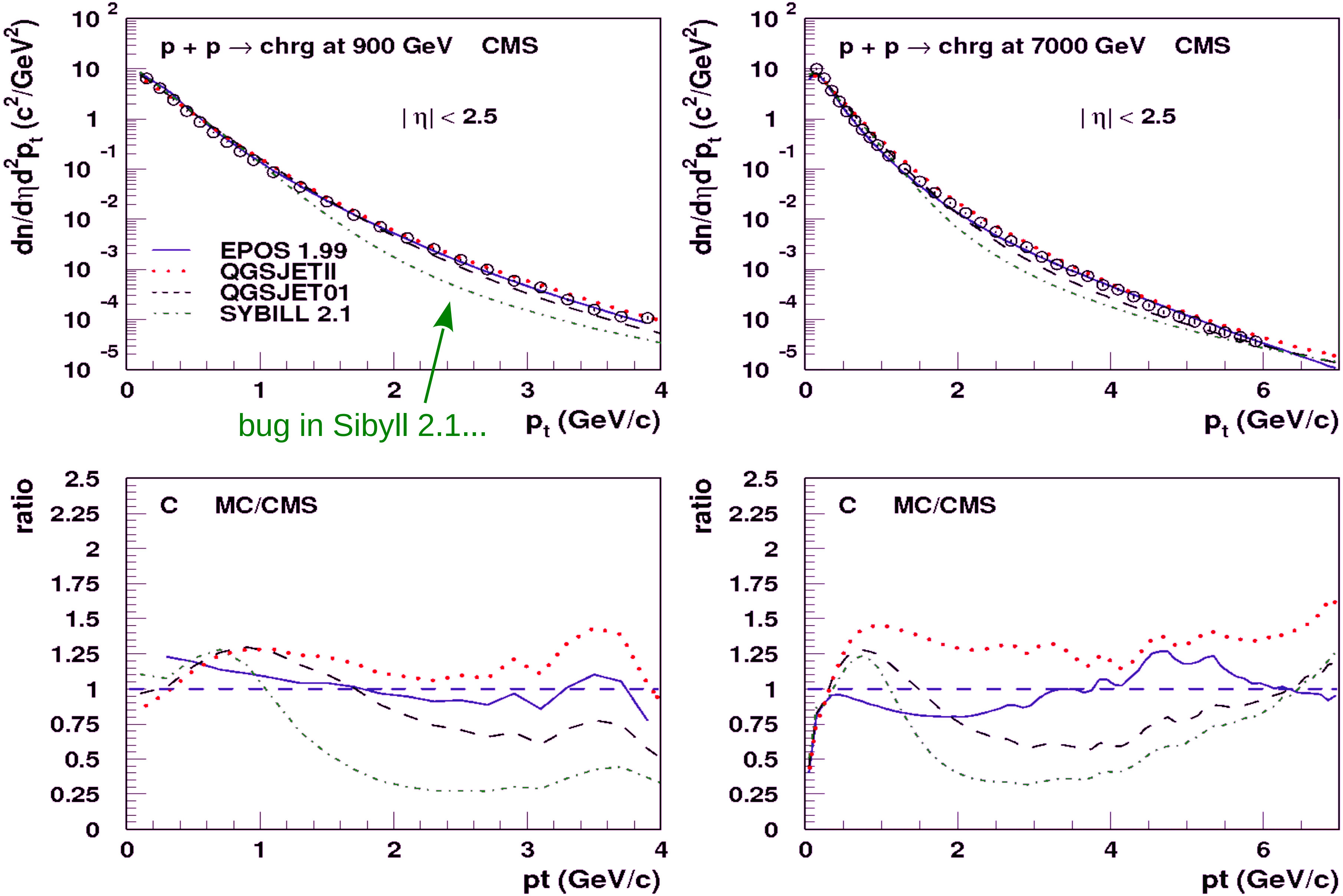
- Problem of multi-strange baryons at low energy (Bleicher et al., Phys.Rev.Lett.88:202501,2002)
  - 2 strings approach :
- $\Omega / \bar{\Omega}$ always > 1
- But data < 1 (Na49)



- 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



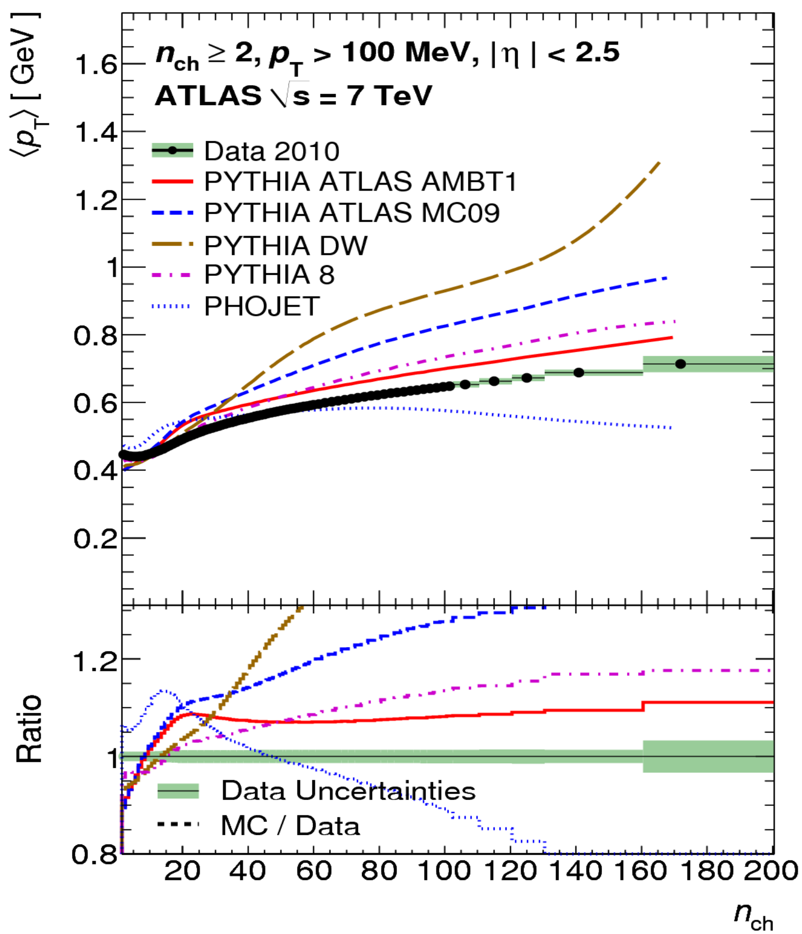
Pt @ LHC

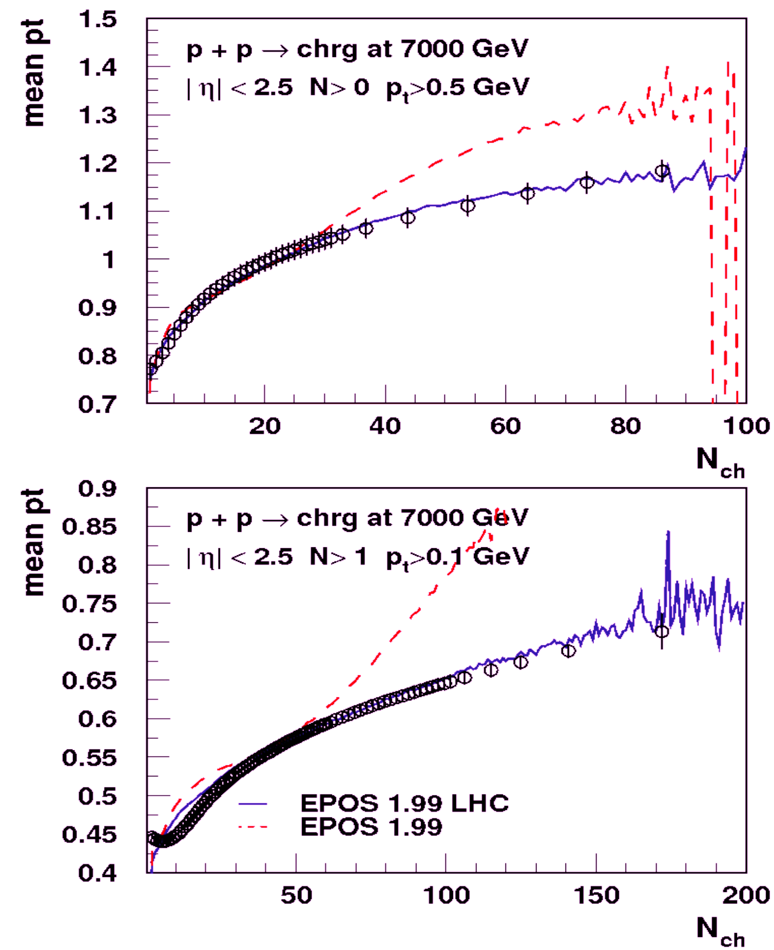


p + p → chrg at 900 GeV CMS
|η| < 2.5
EPOS 1.99
QGSJETII
QGSJET01
SYBILL 2.1
bug in Sibyll 2.1...
p + p → chrg at 7000 GeV CMS
|η| < 2.5
C MC/CMS
C MC/CMS
ratio
pt (GeV/c)

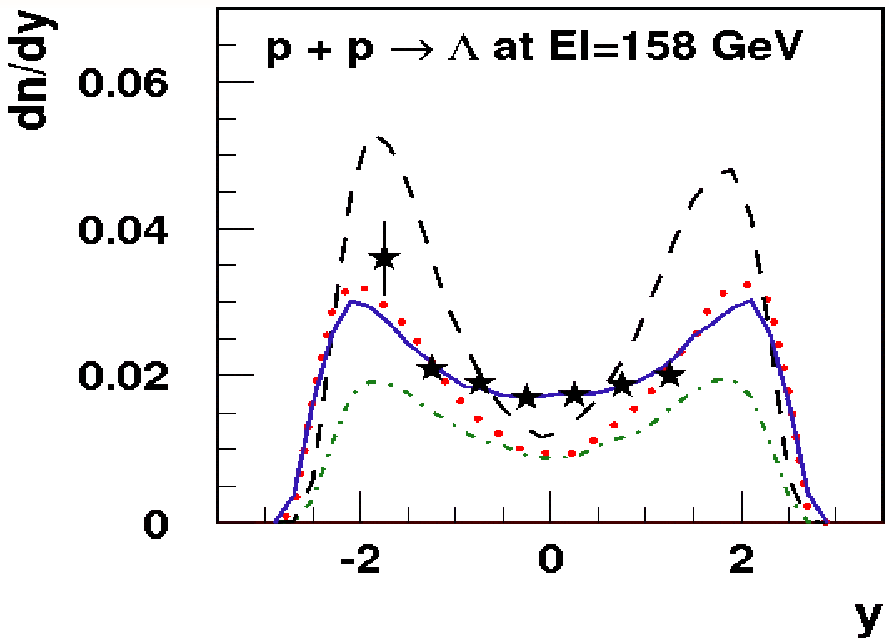
EPOS LHC

- **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 !