Constraints for the Modeling of Multi Parton Interactions in Astroparticle Physics

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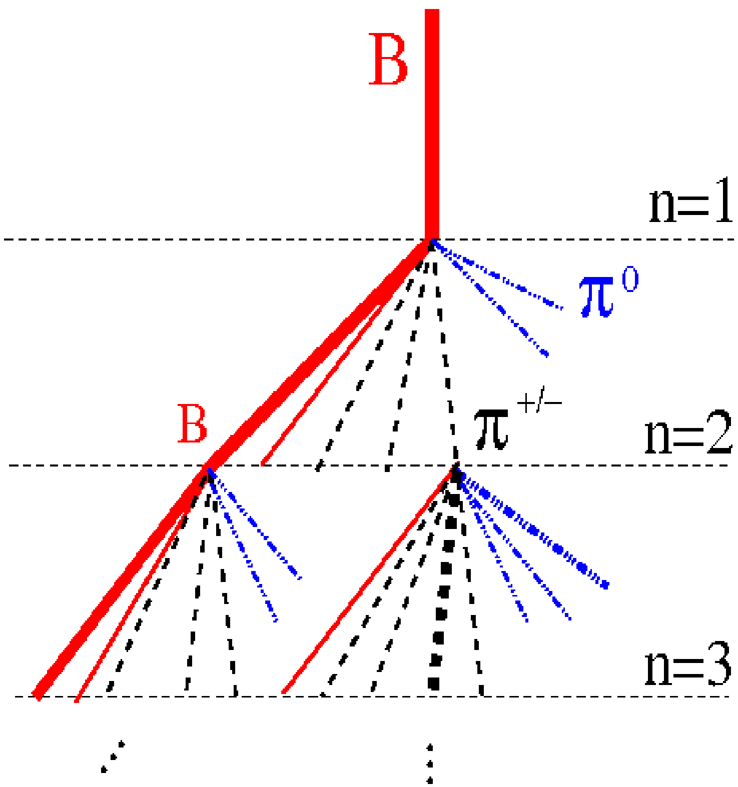
Outline

- Introduction
- Hadronic Models for CR
  - ➜ Cross section
  - ➜ Multiplicity
  - ➜ Forward spectra
- Constraints from EAS
- Comparison to LHC
- Summary

MPI needed to reproduce data at all energies with a single set of parameters. EAS simulations improve models' predictive power.

Air Shower Simulation



Thickness = amount of energy

- **Hadronic models for simulations :**
  - ➜ mainly soft 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 1.99
    - ...

Hadronic Interaction Models

- **Theoretical basis :**
  - ➡ pQCD
  - ➡ Gribov-Regge
  - ➡ energy conservation

Pb : CR physic dominated by soft interactions

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

- **Phenomenology (models) :**
  - ➡ string fragmentation
  - ➡ diffraction
  - ➡ higher order effects

Need Parameters !

- **Comparison with data to fix parameters :**
  - ➡ the more parameters, the more data you need

... or ...

  - ➡ the more data, the more parameters you need !

Hadronic Interaction Models in CORSIKA

(HDPM)

Old generation : QGSJET01 SIBYLL DPMJET 2 VENUS (<1999)

All Glauber based

But differences in hard, remnants, diffraction …

semi-hard

soft

NEXUS

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

New generation : **QGSJET II** (DPMJET III) **EPOS** (2005<)

Theory ++ :

- **Fan diagrams**
- **diffraction**
- **optimized for CR**

Phenomenology ++ :

- **Nuclear effect**
- **High density effect (QGP)**
- **all type of data studied**

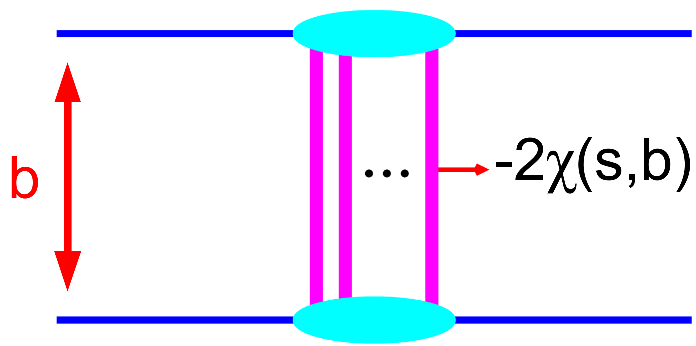
Only model used in HEP (SPS, RHIC, LHC)

Cross Section Calculation : SIBYLL / QGSJET

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

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

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

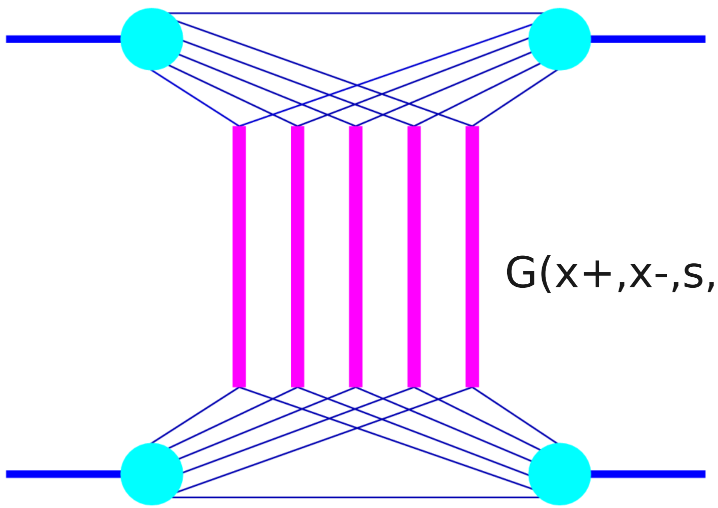


$$\sigma \sim 1 - \exp(-2\chi)$$

Not the same χ in QGSJET01, QGSJETII and SIBYLL

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

Cross Section Calculation : EPOS



Different approach in EPOS :

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

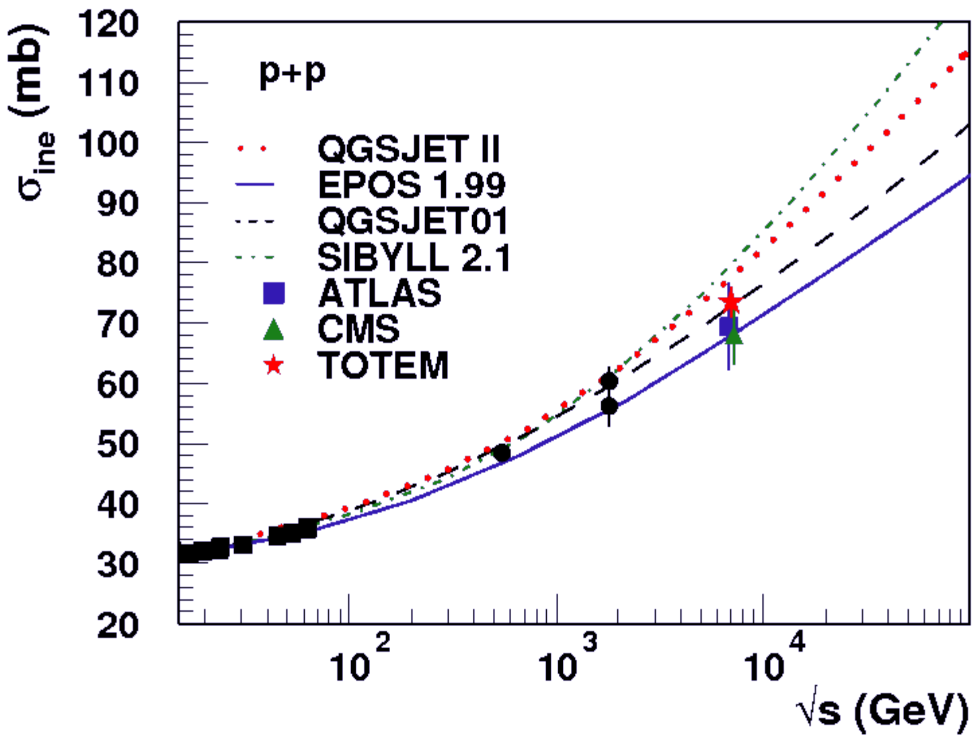
$$\Phi_{\mathrm{pp}}\left(x^+,x^-,s,b\right) = \sum_{l=0}^{\infty}\int dx_1^+dx_1^-\ldots dx_l^+dx_l^-\left\{\frac{1}{l!}\prod_{\lambda=1}^{l}-G(x_\lambda^+,x_\lambda^-,s,b)\right\}$$
$$\times\; F_{\mathrm{proj}}\left(x^+-\sum x_\lambda^+\right)F_{\mathrm{targ}}\left(x^--\sum x_\lambda^-\right).$$

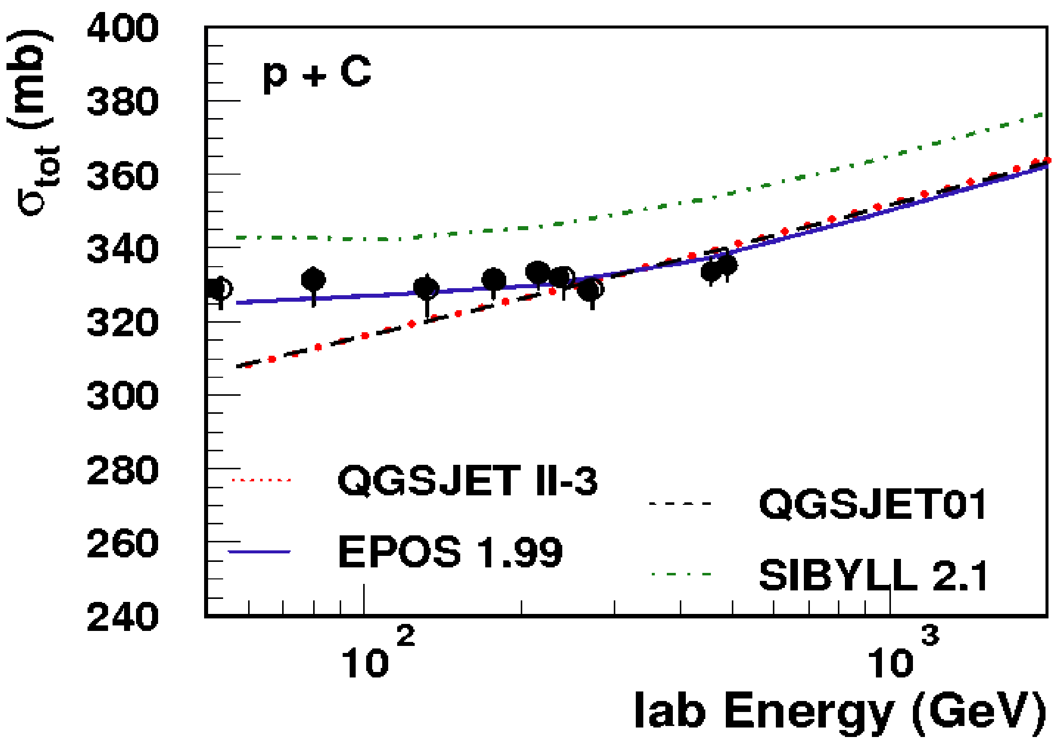
$$\sigma_{\mathrm{ine}}(s) = \int d^2b\,(1-\Phi_{\mathrm{pp}}(1,1,s,b))$$

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

Cross Section

- Same cross section at pp level and low energy (data)
- extrapolation to pA or to high energy
  - different amplitude and scheme : different extrapolations
- multiple scattering + screening (=MPI) needed to use pQCD hard amplitude in inelastic cross section calculation ($\sigma_{hard}>\sigma_{ine}$)





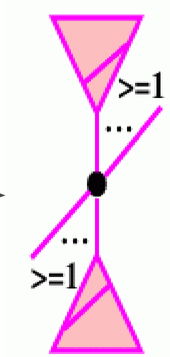
Particle Production in SIBYLL and QGSJET

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

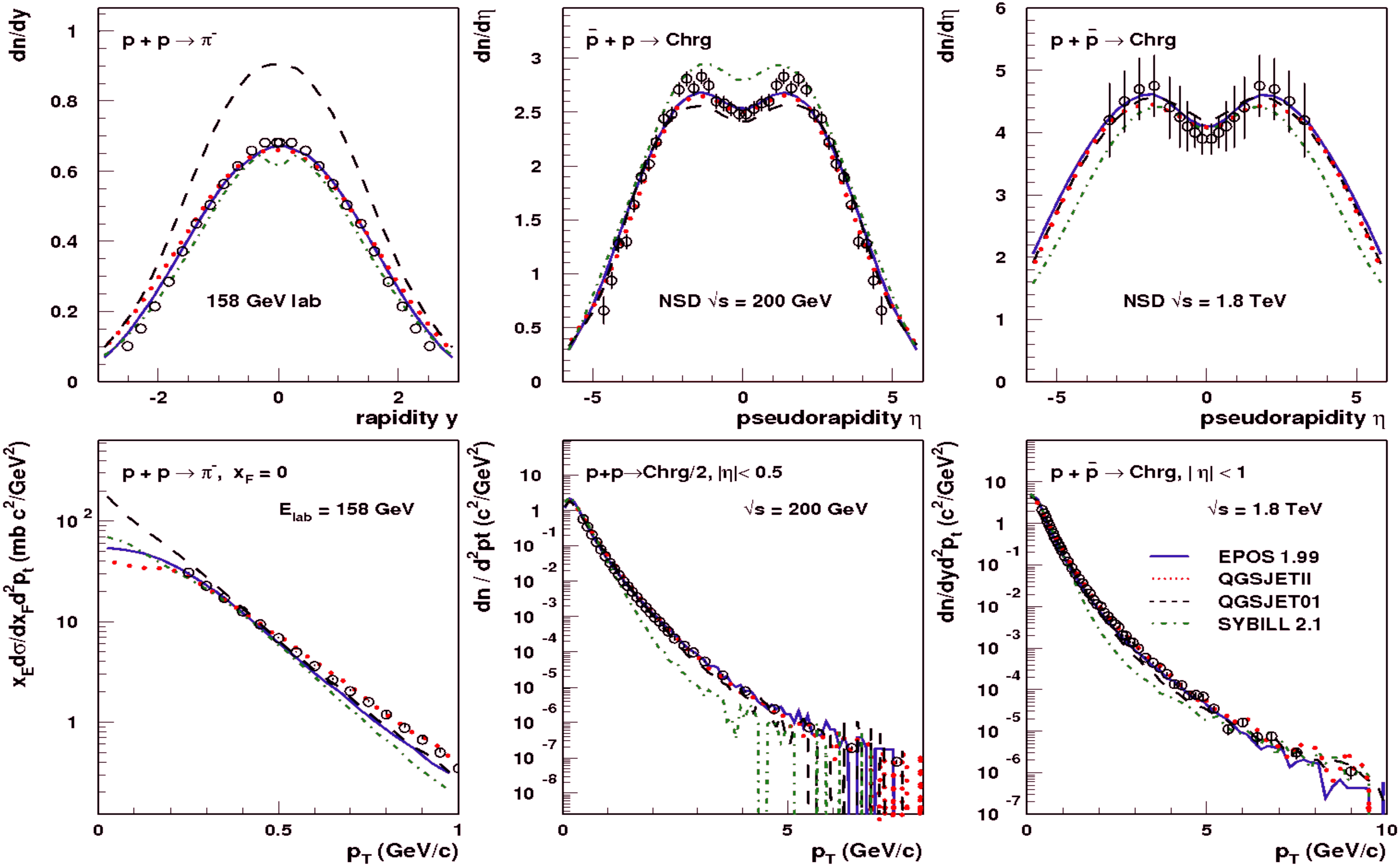
m number of exchanged elementary interaction per event fixed from elastic amplitude taking into account energy sharing :

- m from :

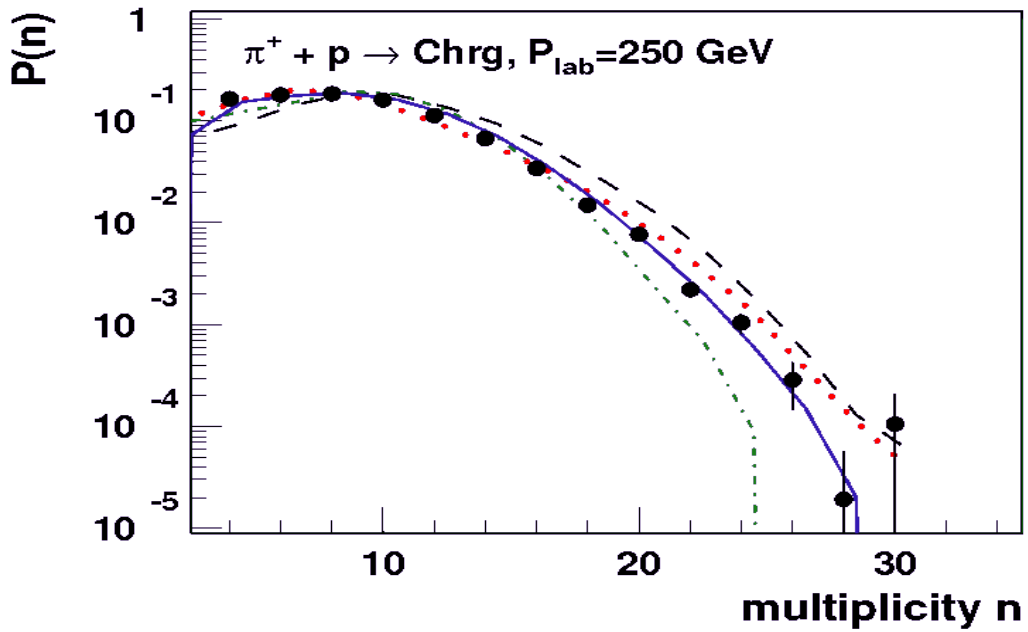
$$\Omega_{AB}^{(s,b)}(m, X^+, X^-) = \prod_{k=1}^{AB} \left\{ \frac{1}{m_k!} \prod_{\mu=1}^{m_k} G(x_{k,\mu}^+, x_{k,\mu}^-, s, b_k) \right\} \Phi_{AB}\left(x^{\mathrm{proj}}, x^{\mathrm{targ}}, s, b\right)$$

  - 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)

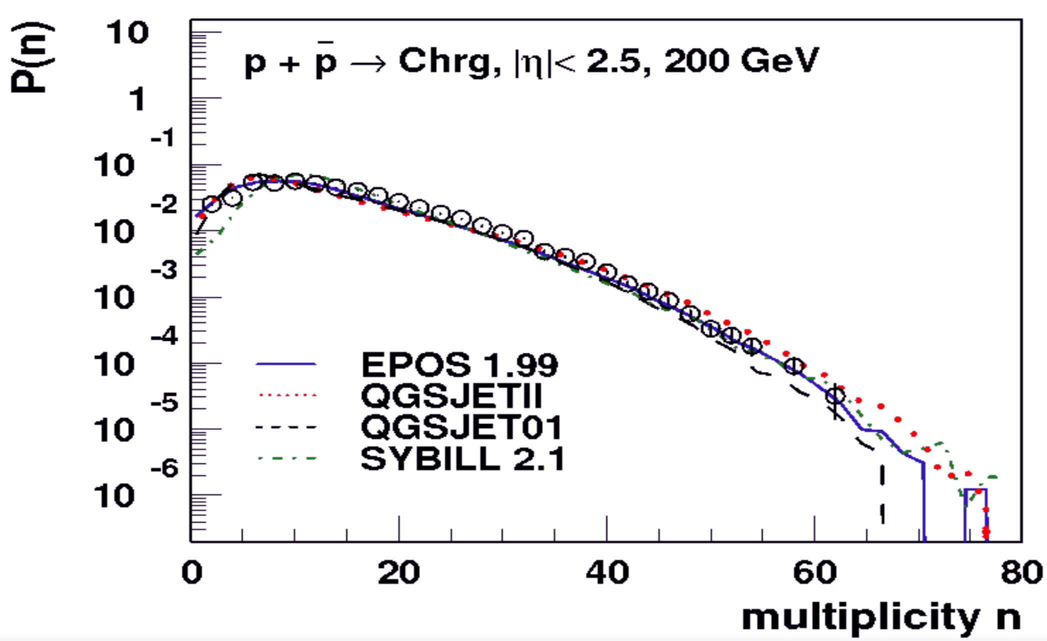
Pseudorapidity and p_T

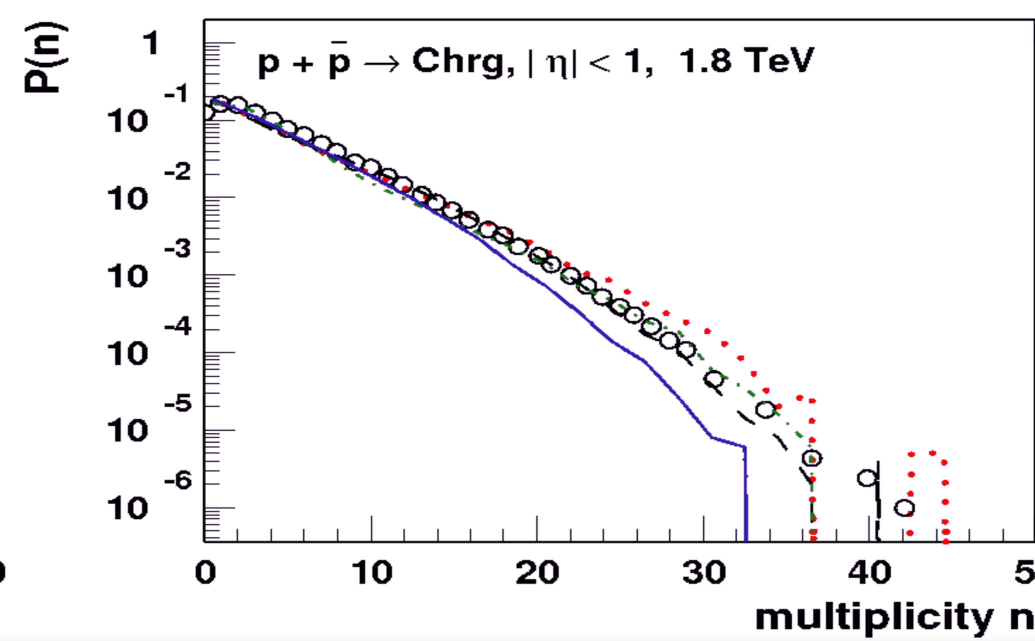


Multiplicity



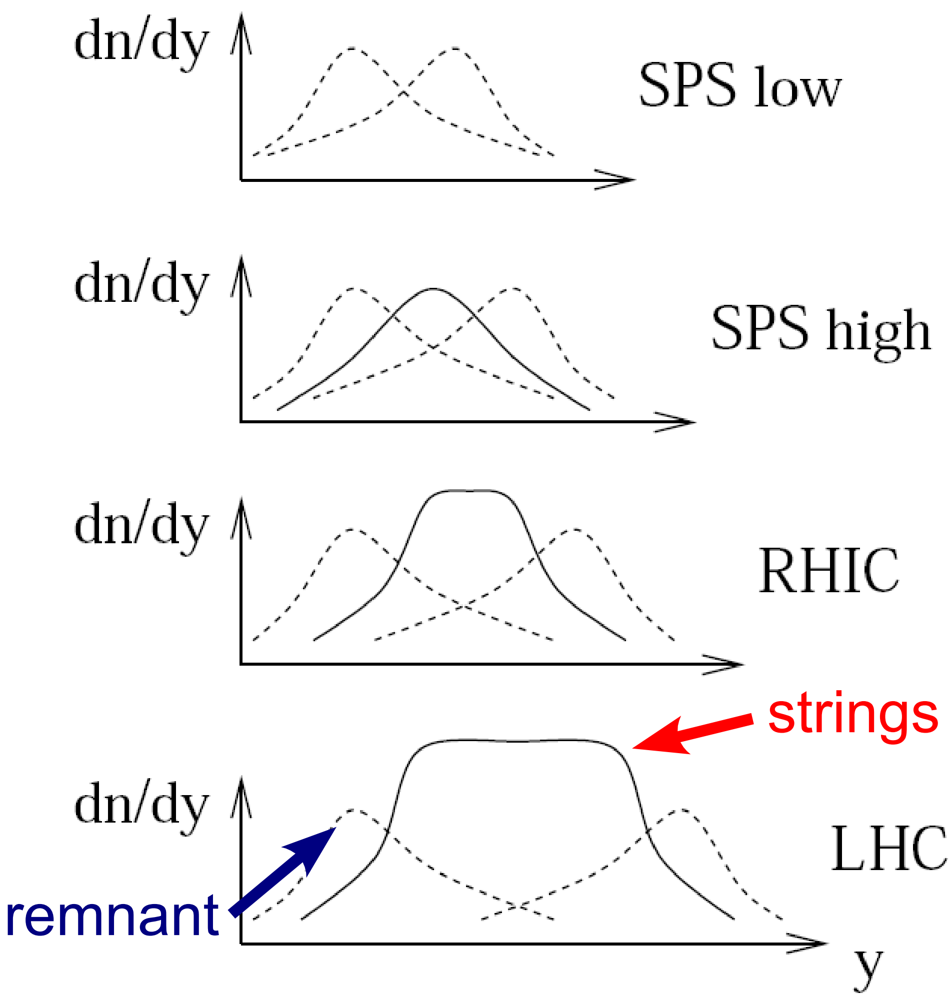
- Shape of distribution correct
- Agreement with existing data
- Effect of multiple scattering already visible at 200 GeV (but mainly soft)





Forward Spectra

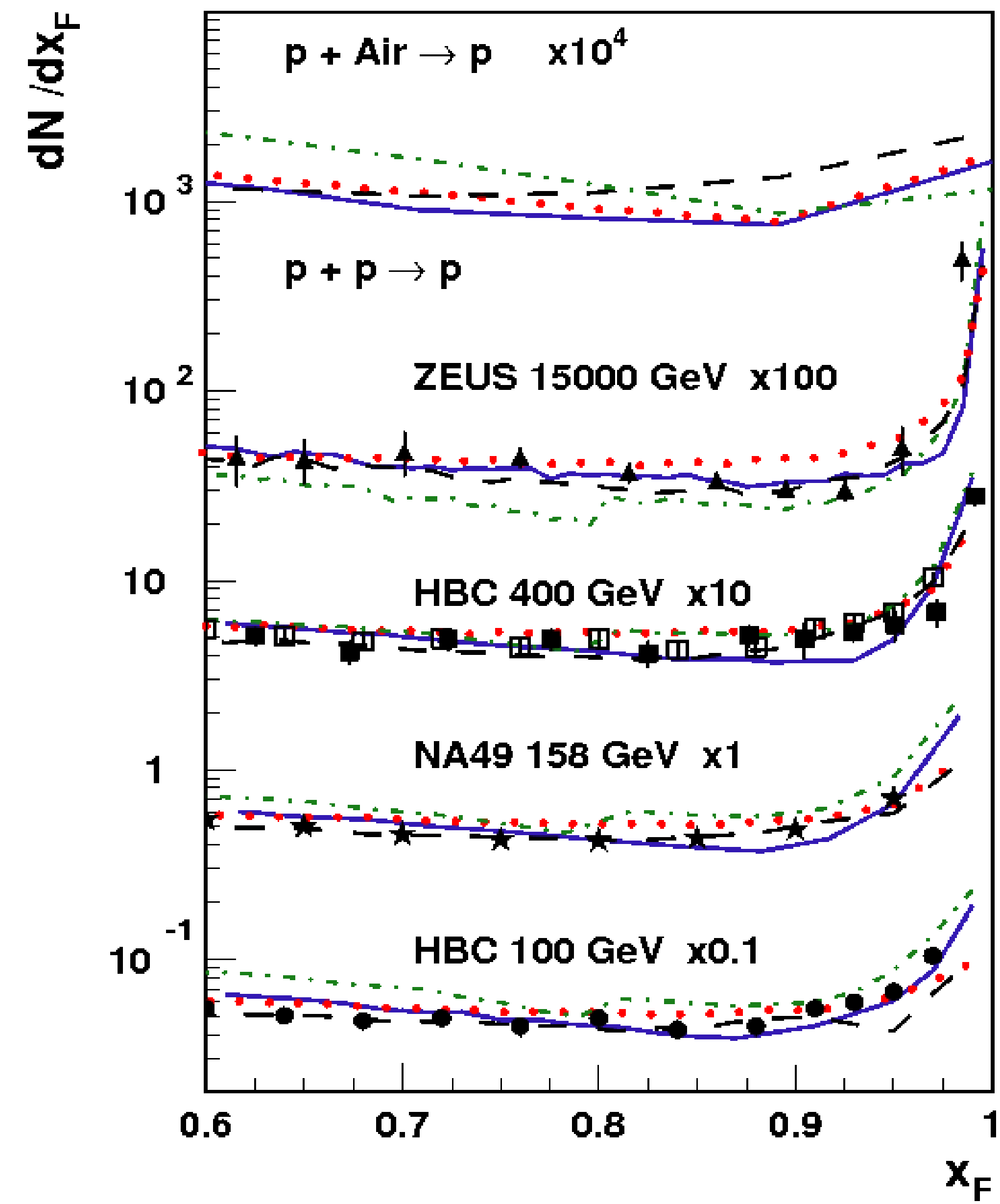
Forward particles mainly from projectile remnant



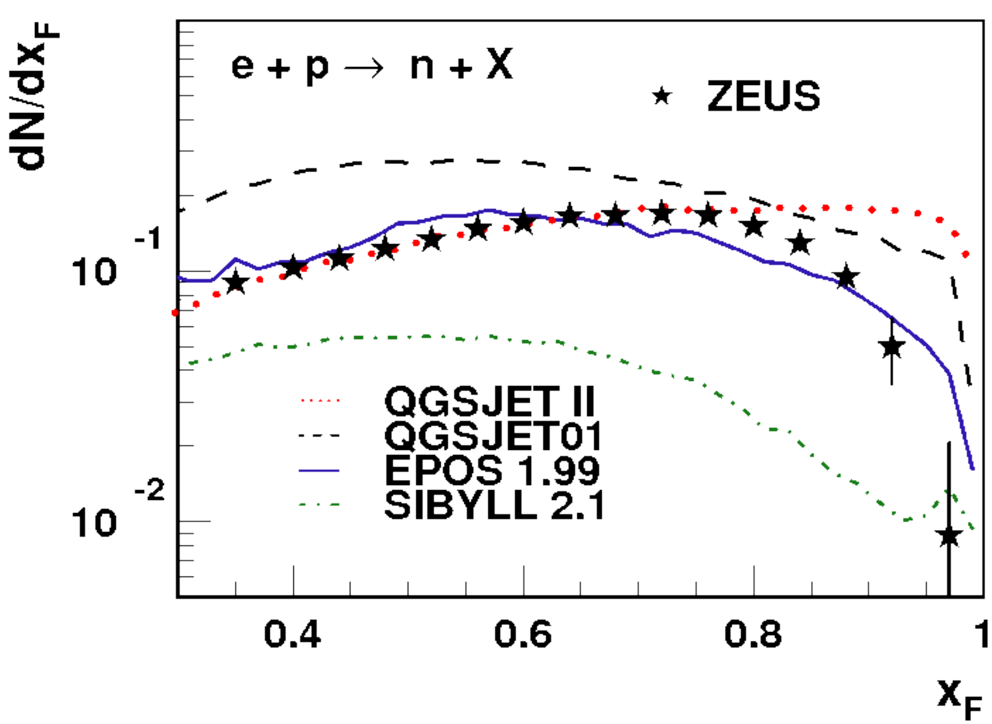
The inelasticity is closely related to diffraction and forward spectra

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

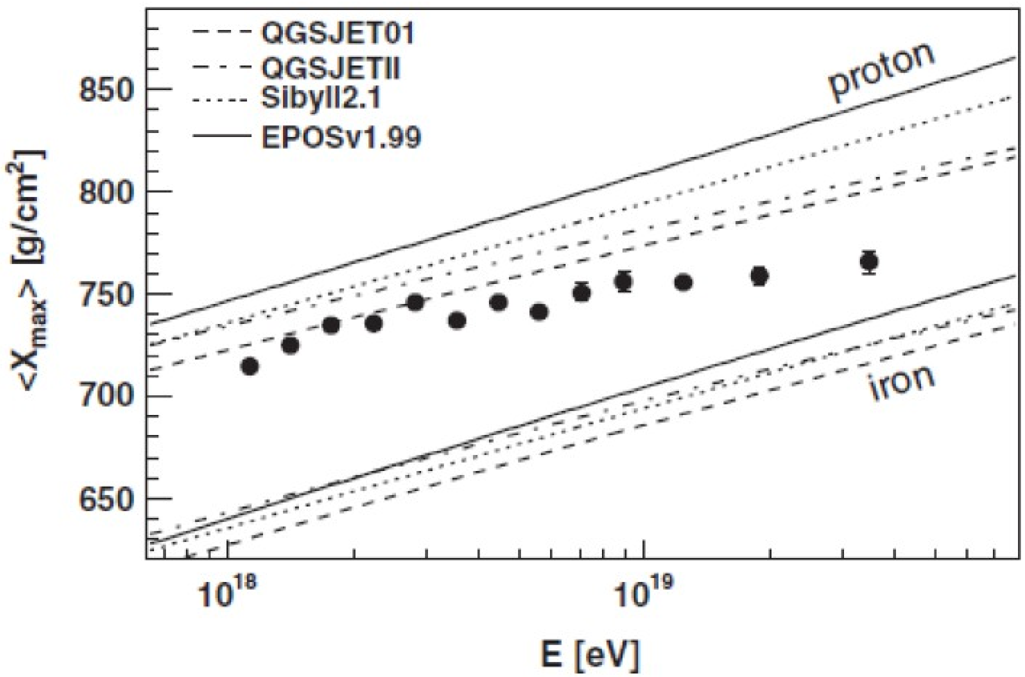
Diffraction and x Distributions

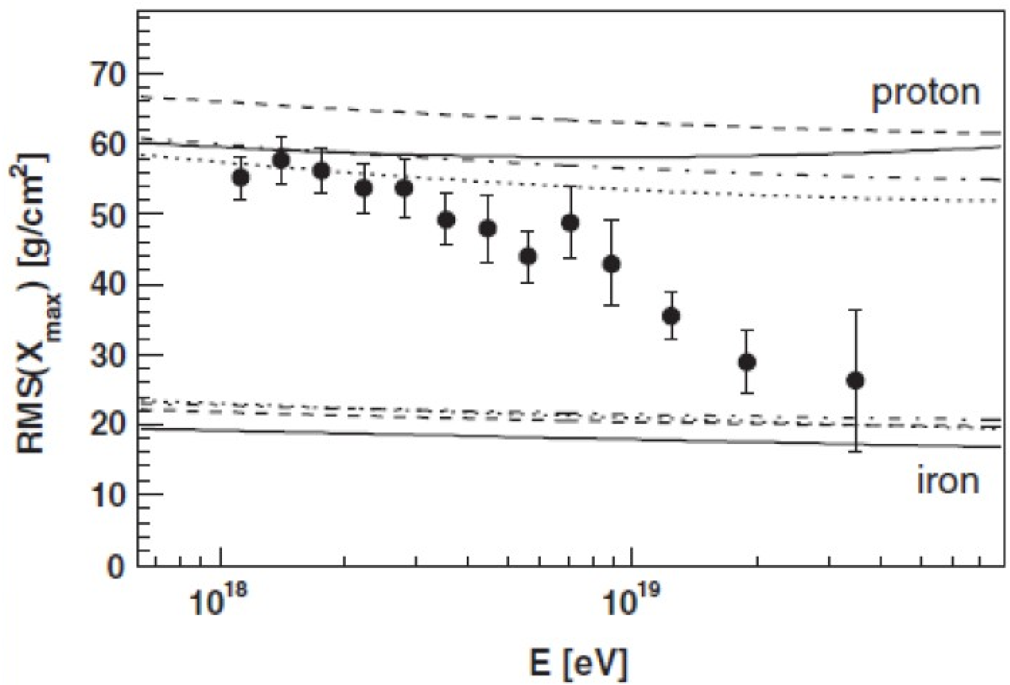


- ➔ most of the data at low energy (fixed target experiment)
- ➔ extrapolation tested with HERA data
  - more data available now (gamma)
- ➔ large differences for neutrons



Xmax Auger



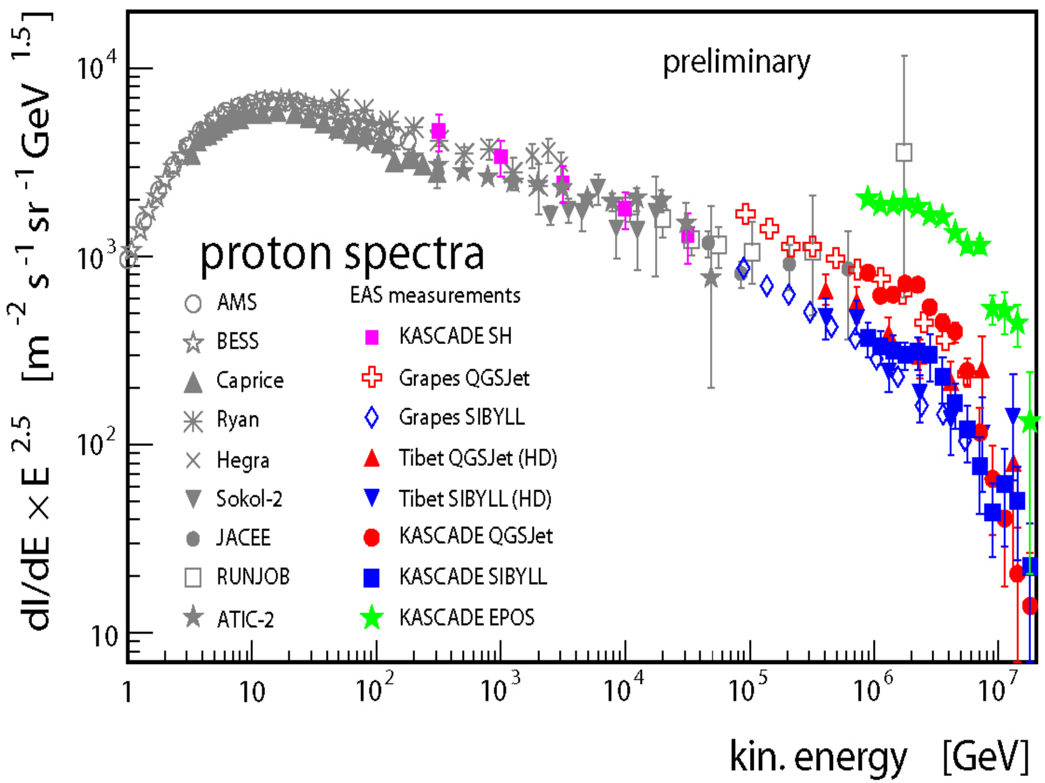


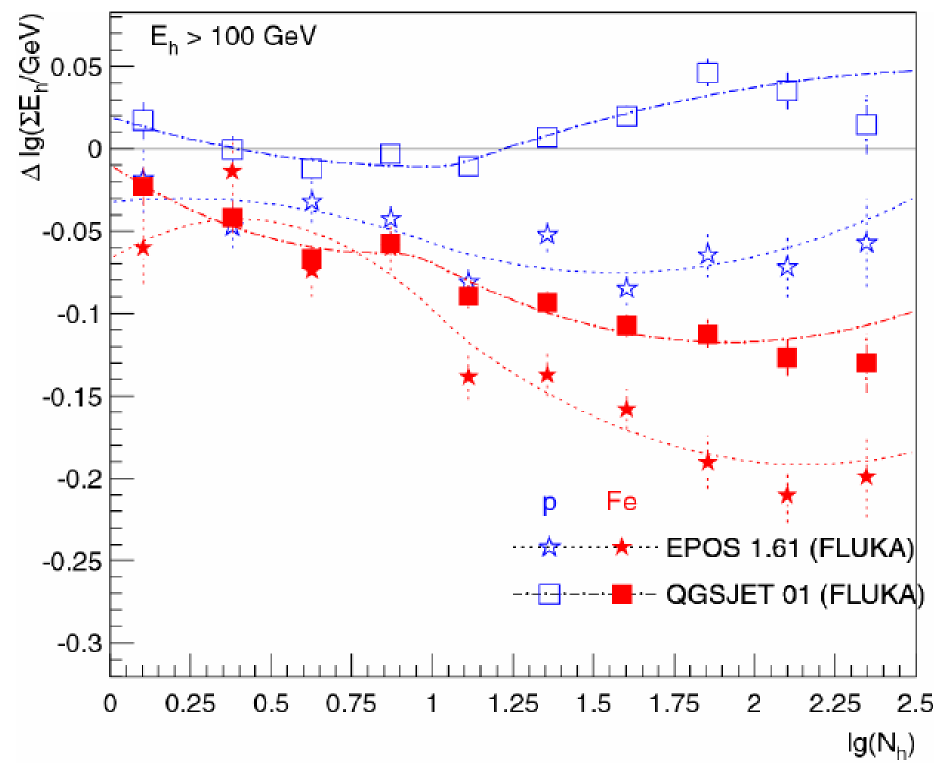
- **EPOS and SIBYLL (almost)**
  - ➡ consistent light mix to heavy mix <Xmax> and RMS
- **QGSJETII**
  - ➡ very light at low E, but inconsistent <Xmax> and RMS at high E
- **QGSJET01**
  - ➡ inconsistent description of <Xmax> and RMS

EPOS 2006 problems with KASCADE

- Large muon number :
  - proton flux to high: not enough electron at ground
- not enough energy per hadron

Showers develop to fast using EPOS 1.6





KASCADE Hadron Correlation

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

- 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

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

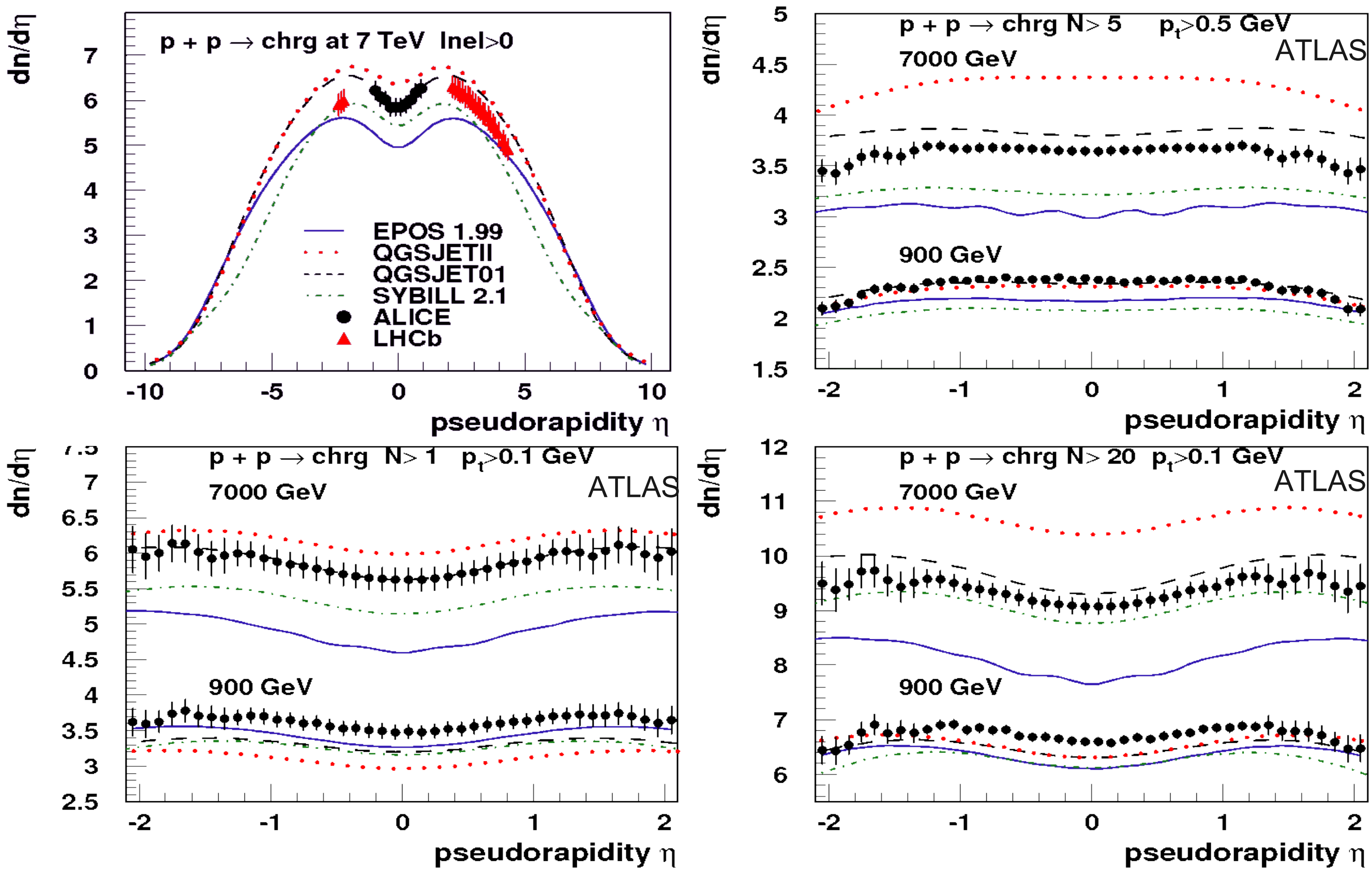
~~DPMJET II.5~~
DPMJET II.55
QGSJET 01
SIBYLL 2.1
~~NEXUS 2~~

~~EPOS 1.6~~
(QGSJET II)

- EPOS 1.99
  - these data used to understand problem with cross section and inelasticity
  - KASCADE results should come soon
  - preliminary tests OK.

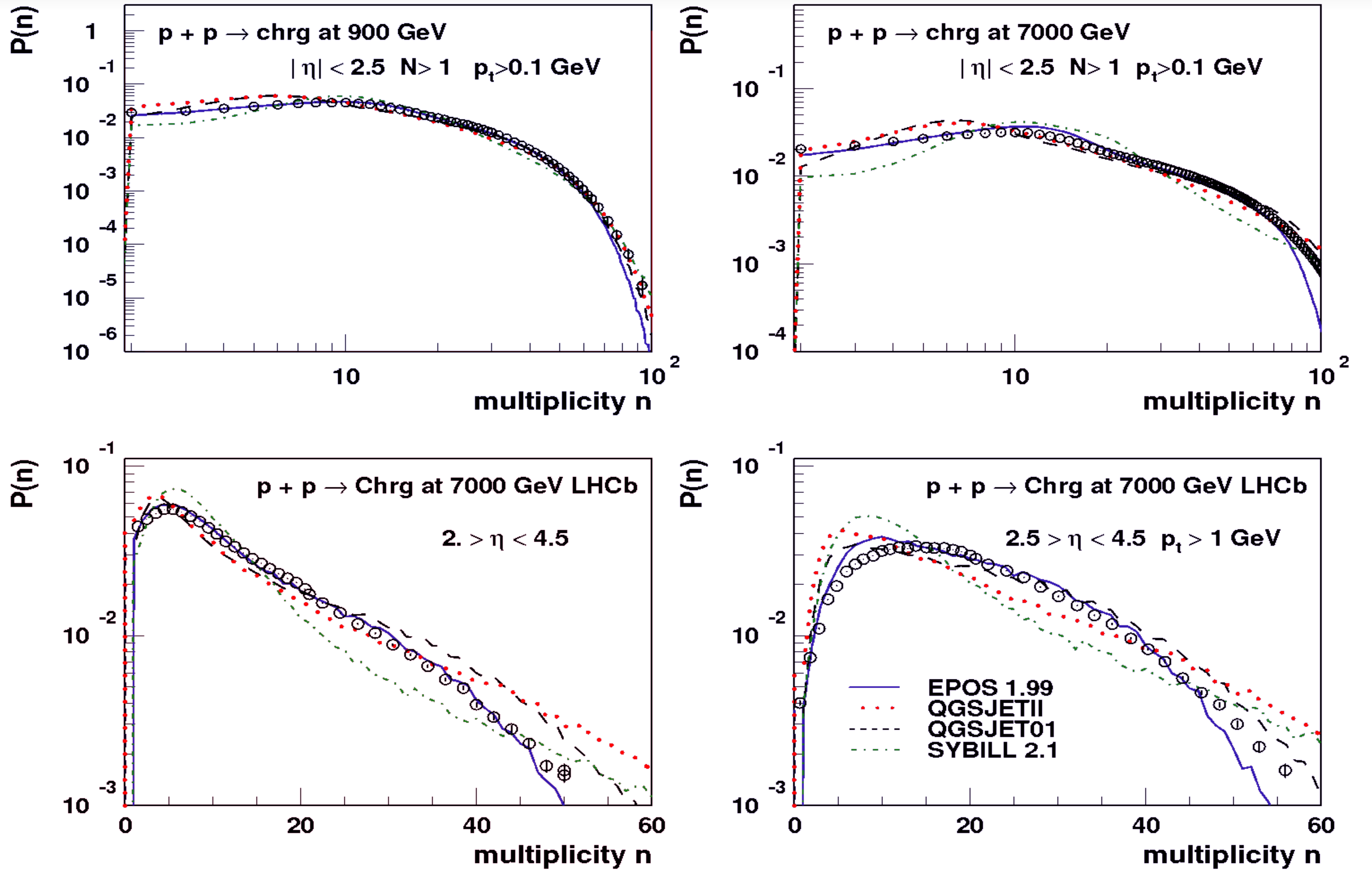
Pseudorapidity Distributions

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



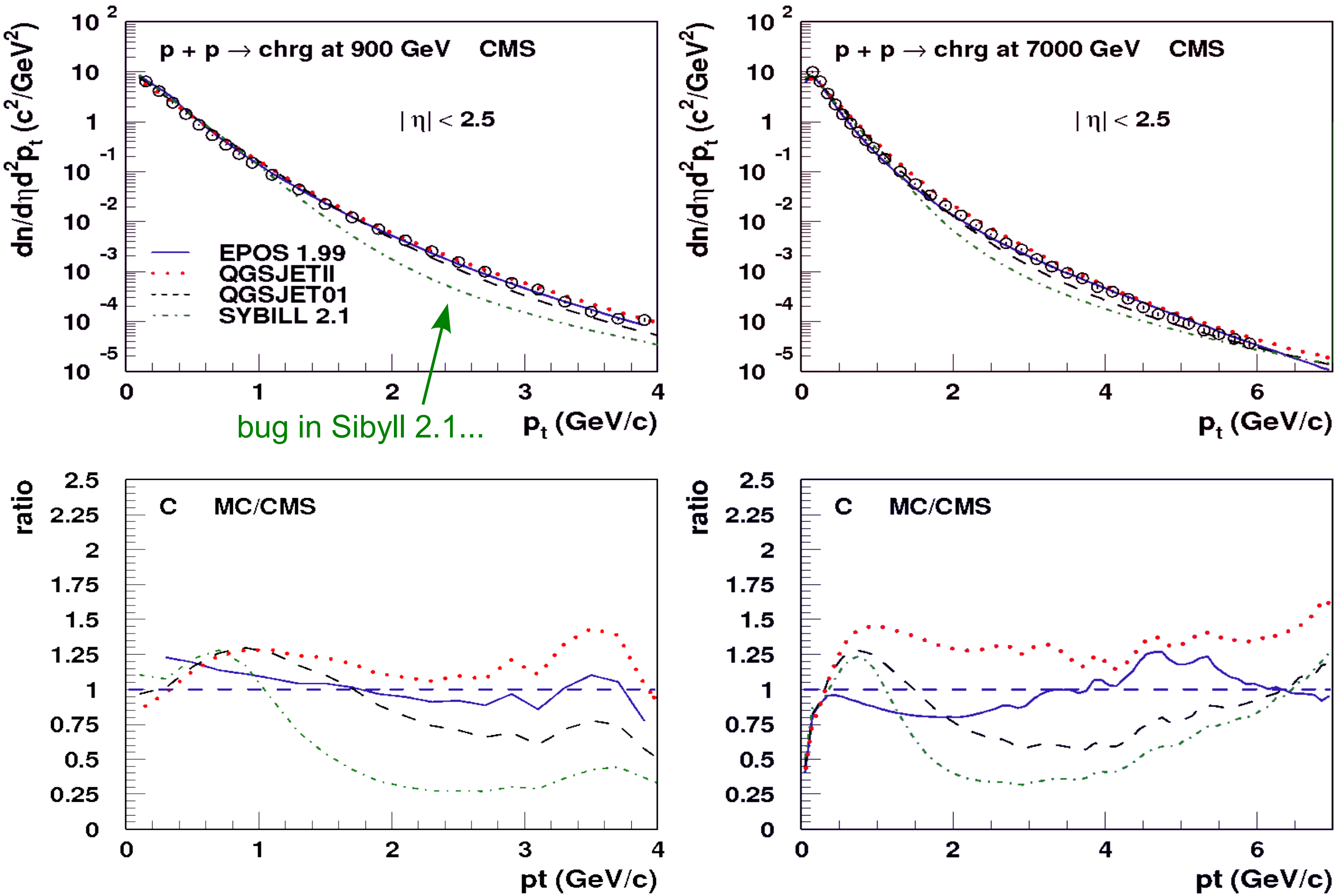
Predictions ! … newest model released in march 2009

Multiplicity Distributions



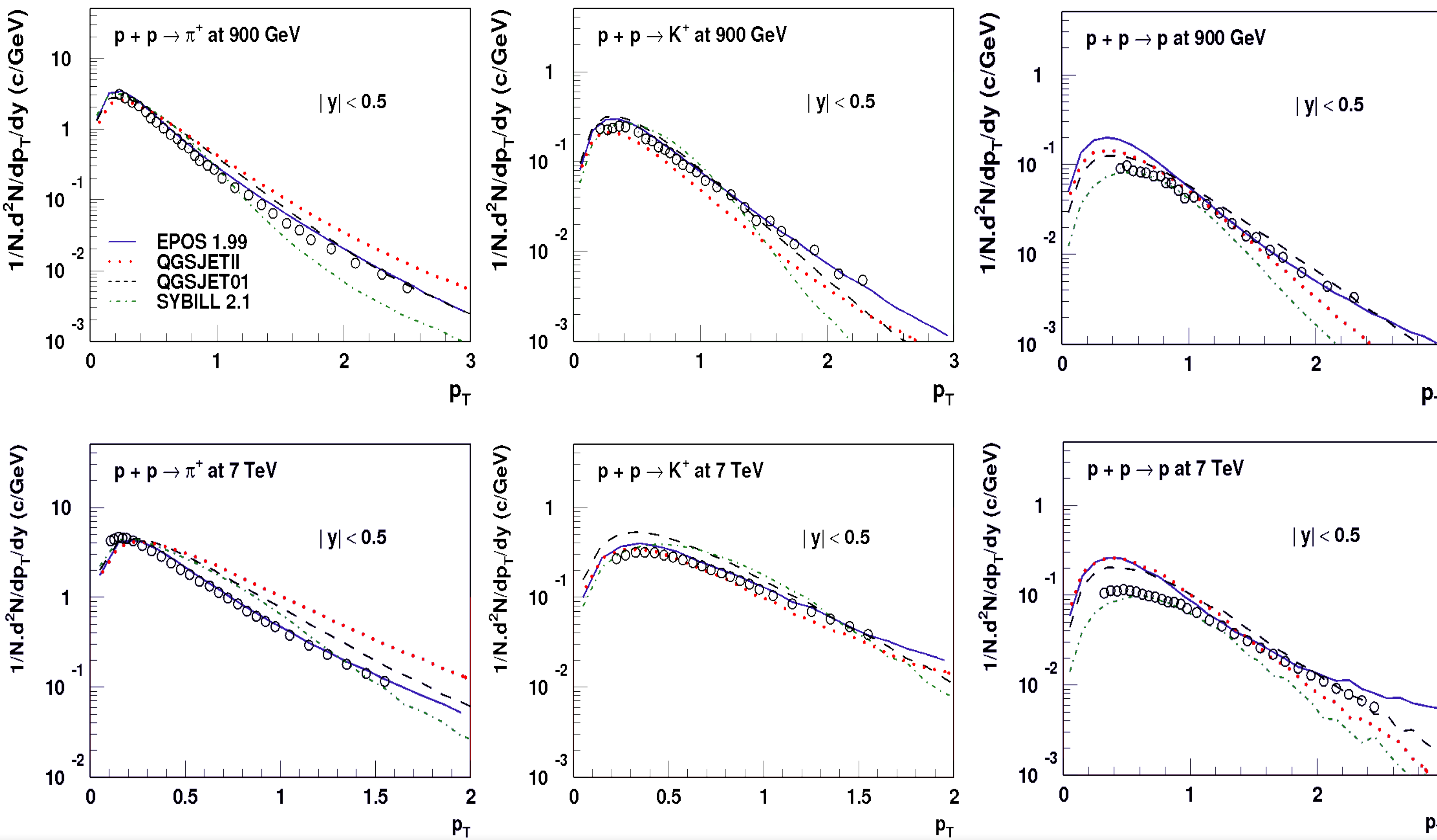
- Forward multiplicity from LHCb : **new test for models**

Pt @ LHC

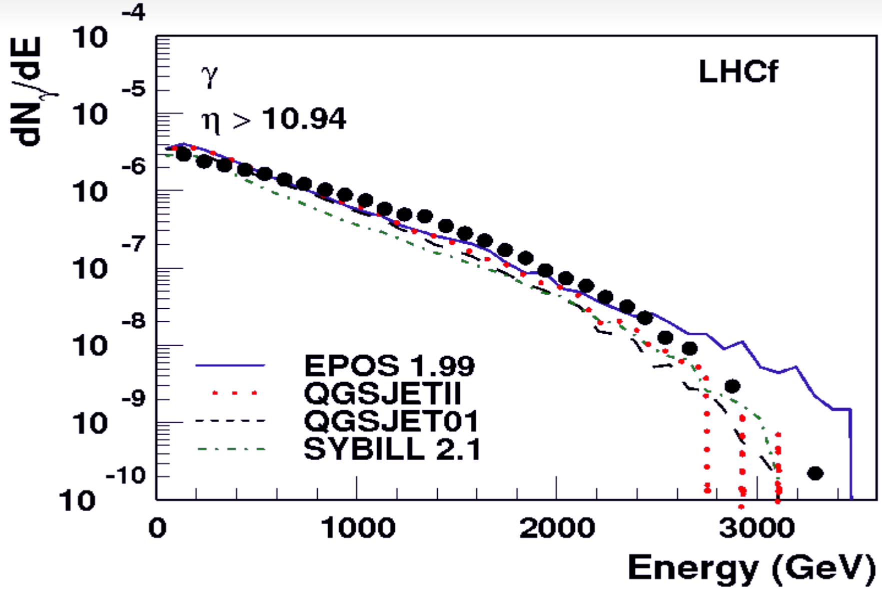

p + p → chrg at 900 GeV CMS
|η| < 2.5
EPOS 1.99
QGSJETII
QGSJET01
SYBILL 2.1
bug in Sibyll 2.1...
p + p → chrg at 7000 GeV CMS
|η| < 2.5
dn/dηd²pt (c²/GeV²)
pt (GeV/c)
C MC/CMS
ratio
pt (GeV/c)

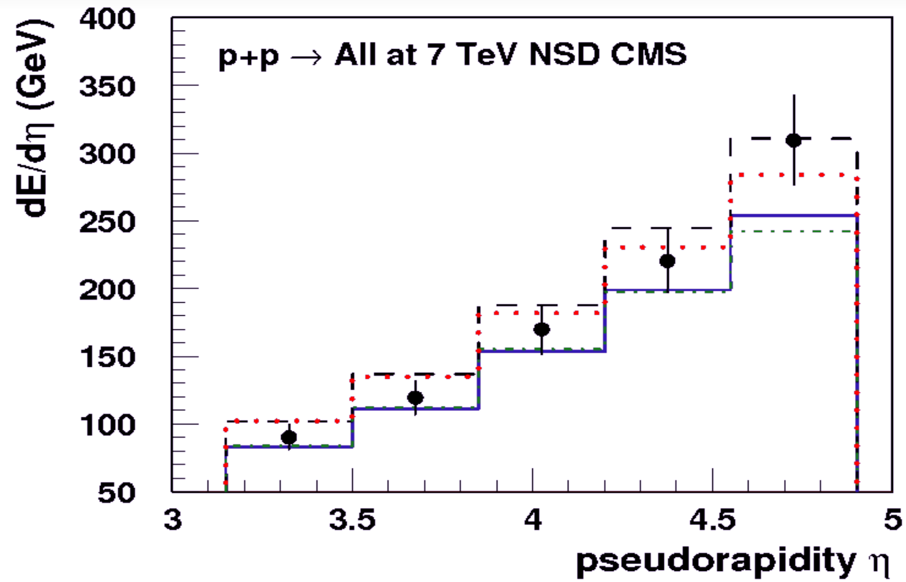
Identified Pt @ LHC

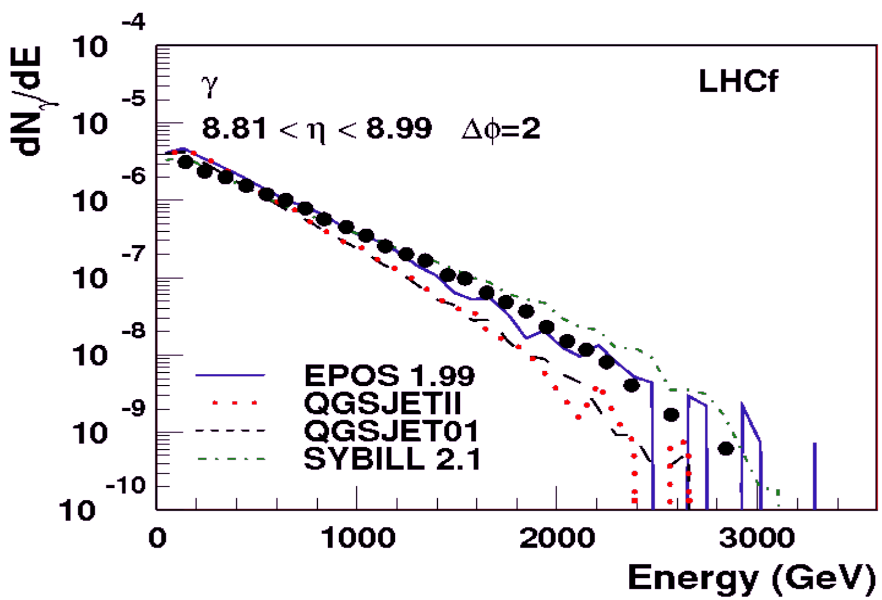
- Preliminary results from ALICE : **(a)proton looks strange ???**

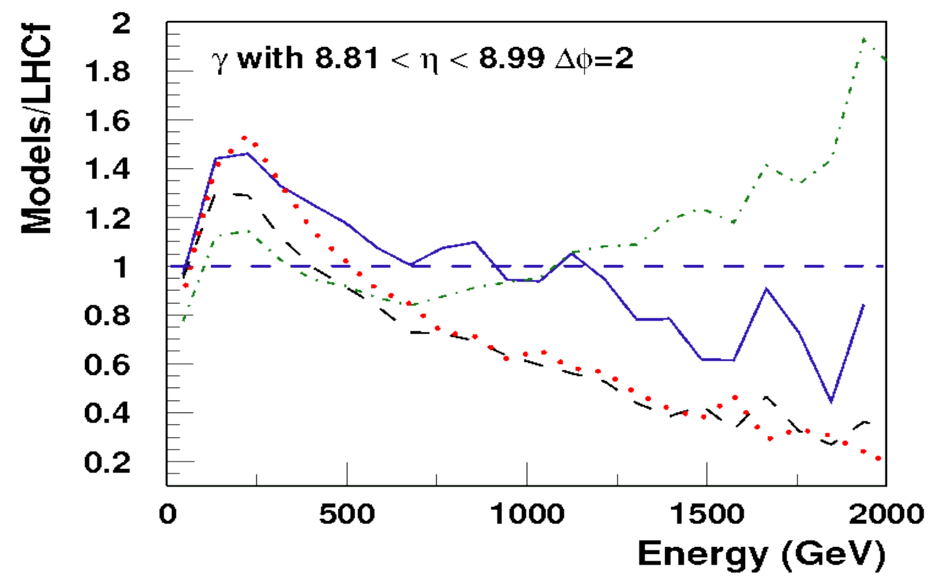


Forward Spectra



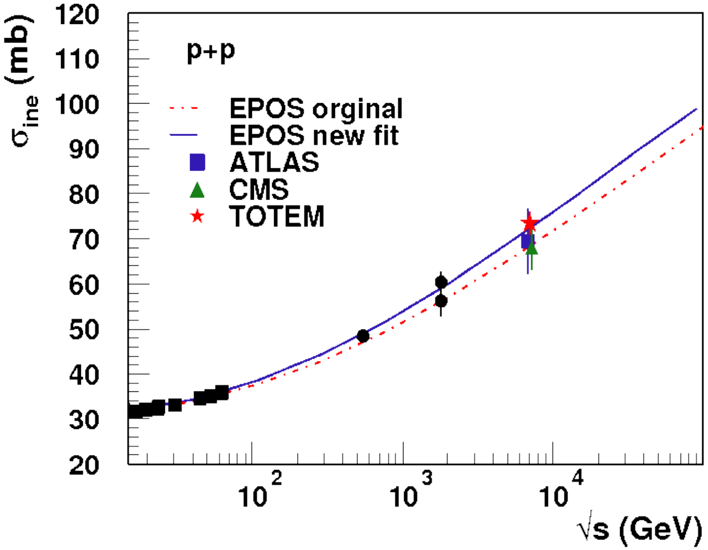


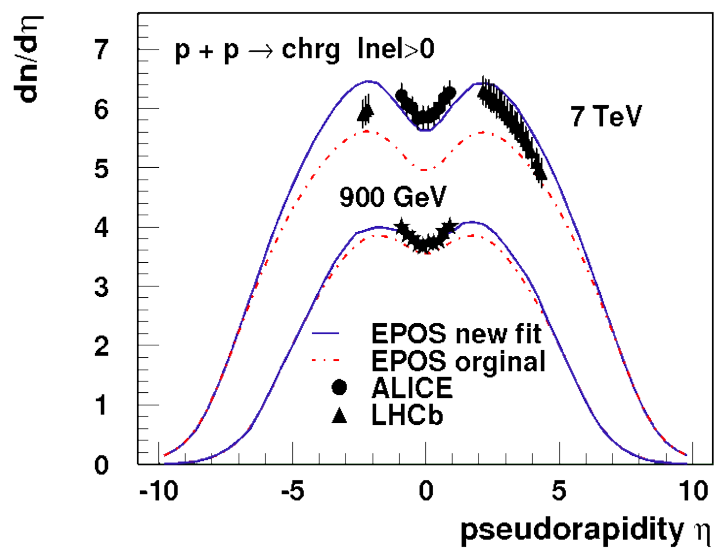




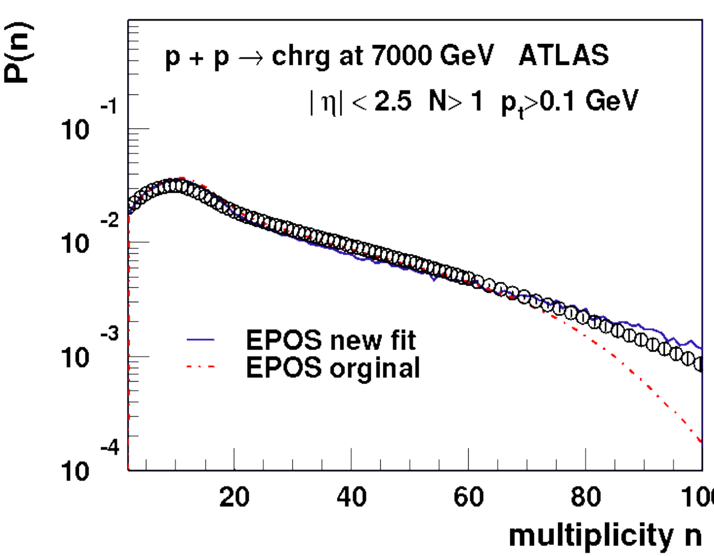
- Fitting of LHCf data → **effect on air shower development under investigation**

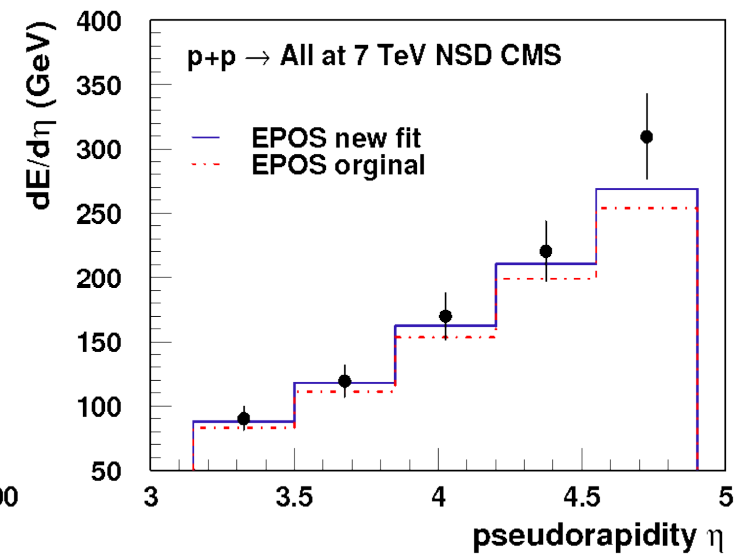
Predictive Power ?





- With TOTEM cross section:
  - ➡ new xsection fit
  - ➡ only 1 parameter changed (max screening (saturation) lowered by 10%)
    - Multiplicity OK
    - Energy flow OK





- ➡ Example with EPOS but the same with QGSJETII (opposite effect)

Summary

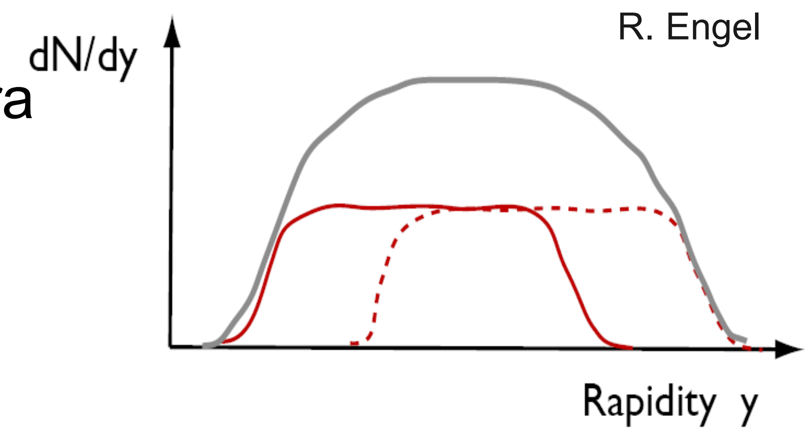
- **Hadronic models used for CR physics need a consistent treatment:**
  - correlation between inelastic cross section and particle production
  - soft/hard/semi-hard included in amplitude
  - same parameters at all energy
- ➜ need multiple scattering + non-linear effect (MPI=NOT independent multiple interaction)
- ➜ general implementation in CR models such that min bias results OK
  - “soft” particle production
  - underlying events
- ➜ effect on specific hard topology probably limited
  - only effective correction to PDF (EPOS) or soft triple Pomeron vertex (QII)
  - min bias models and only 2 to 2 pQCD cross section implemented

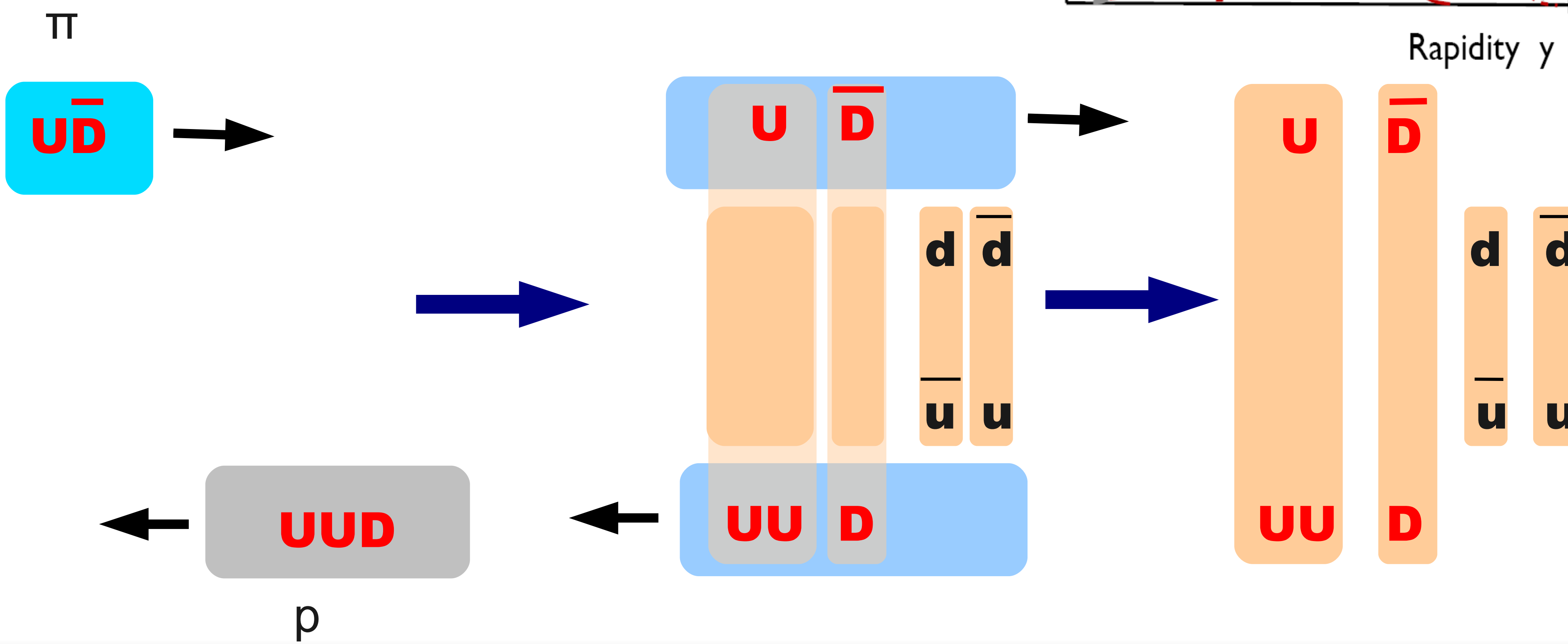
MPI needed to reproduce data at all energies with a single set of parameters. EAS simulations improve models' predictive power.

Remnants in SIBYLL

In SIBYLL : valence quarks attached to main string

- limited quark exchange
- very hard baryon and meson spectra
- string fragmentation
  - forward particle can be anything

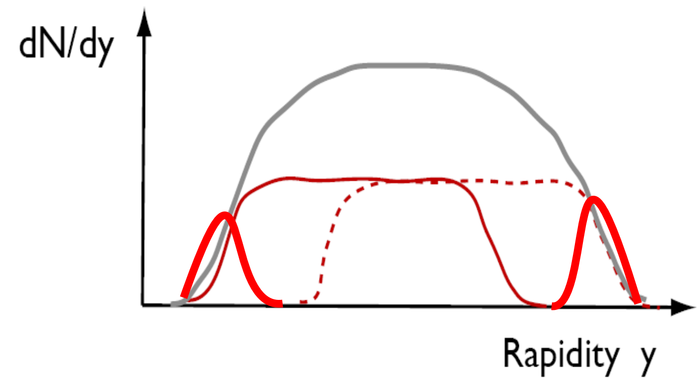


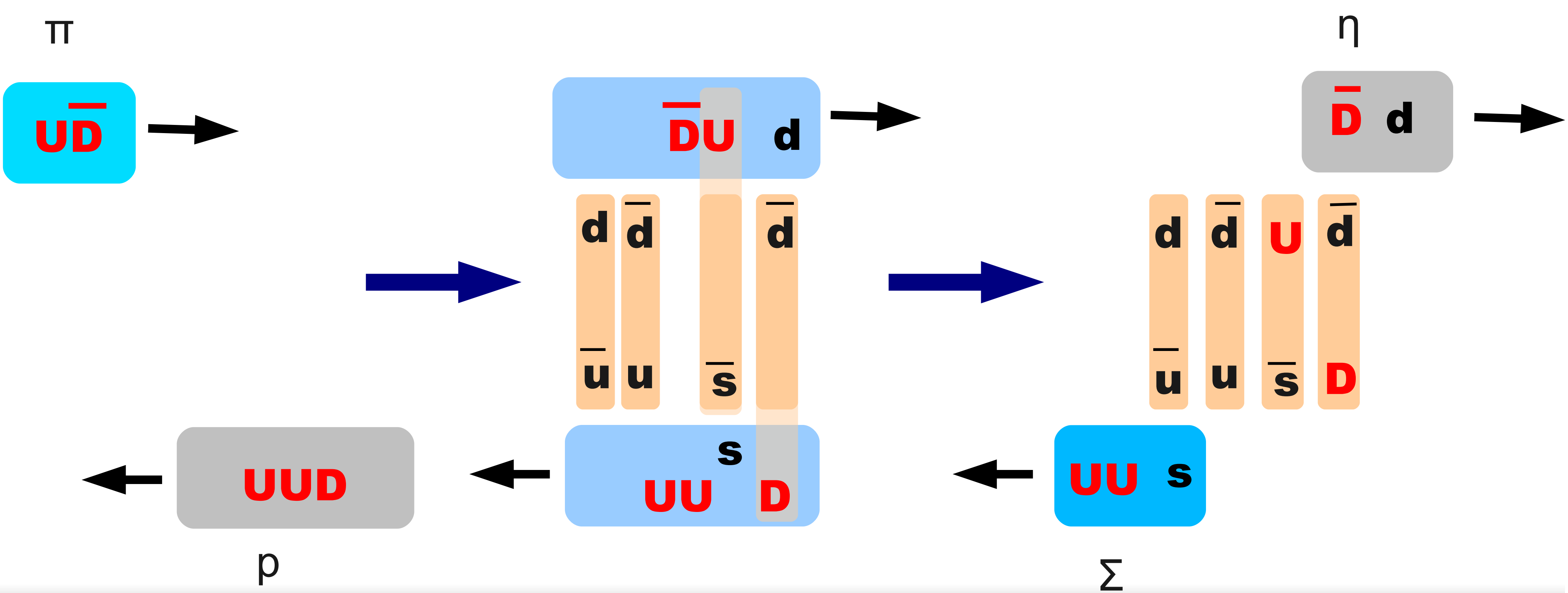


Remnants in QGSJET

In QGSJET : One quark exchange and leading remnant

- Limited quark exchange
  - forward particle same type than proj/targ
- low mass remnant (resonances)
- soft spectra

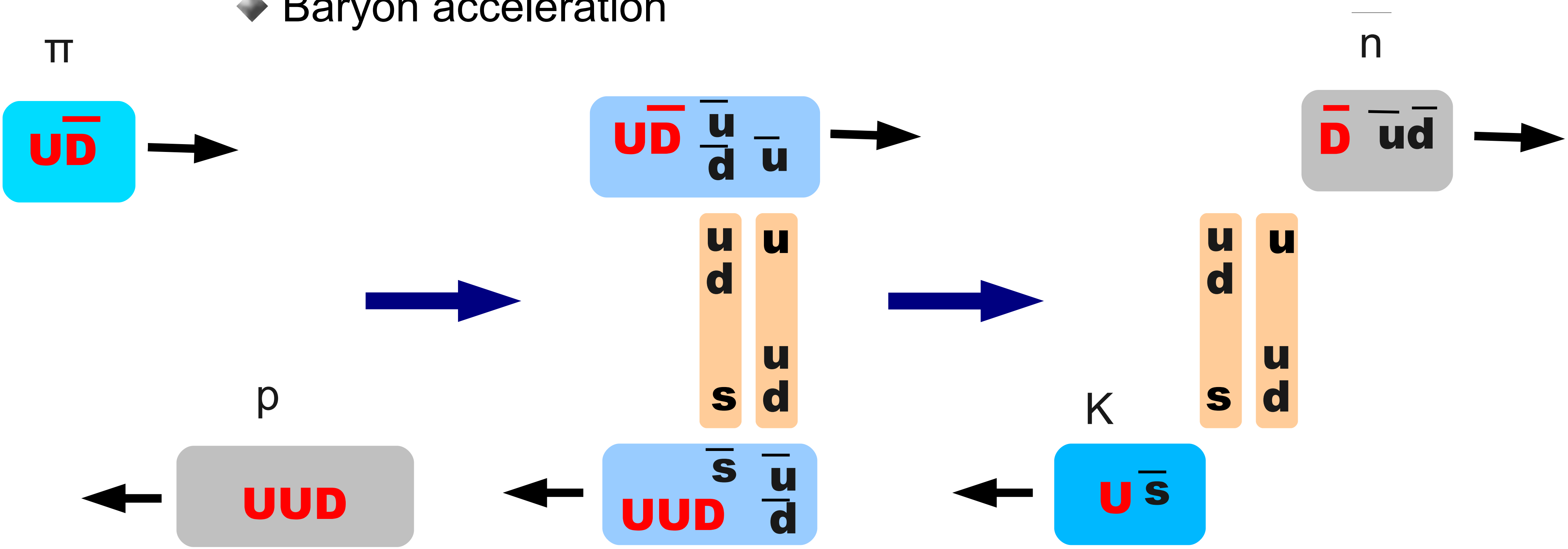




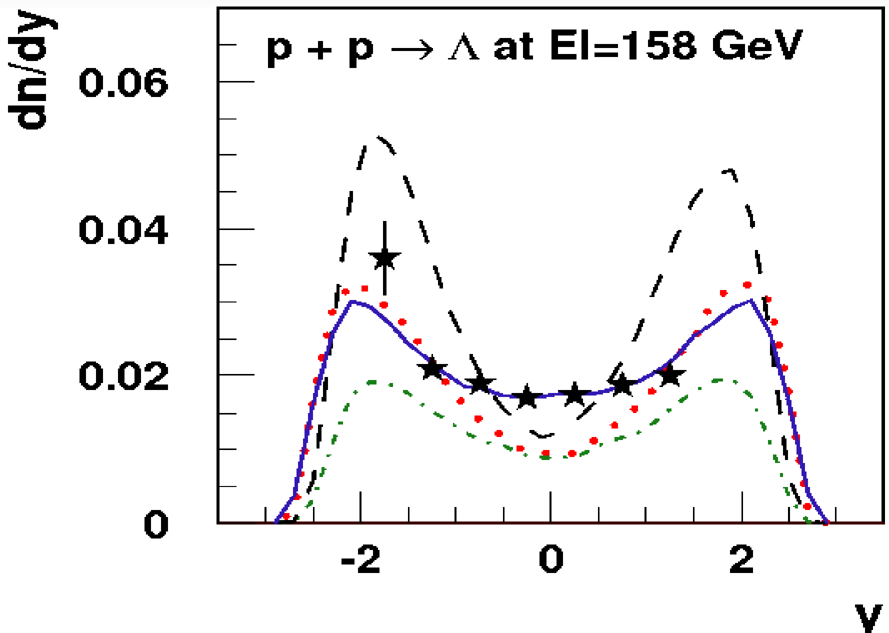
Remnants in EPOS

In EPOS : any possible quark/diquark transfer

- Diquark transfer between string ends and remnants
- Baryon number can be removed from nucleon remnant :
  - Baryon stopping
- Baryon number can be added to pion/kaon remnant :
  - Baryon acceleration



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 !