EPOS and EAS

Tanguy Pierog

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

Karlsruhe Institute of Technology

CORSIKA School, Ooty, India

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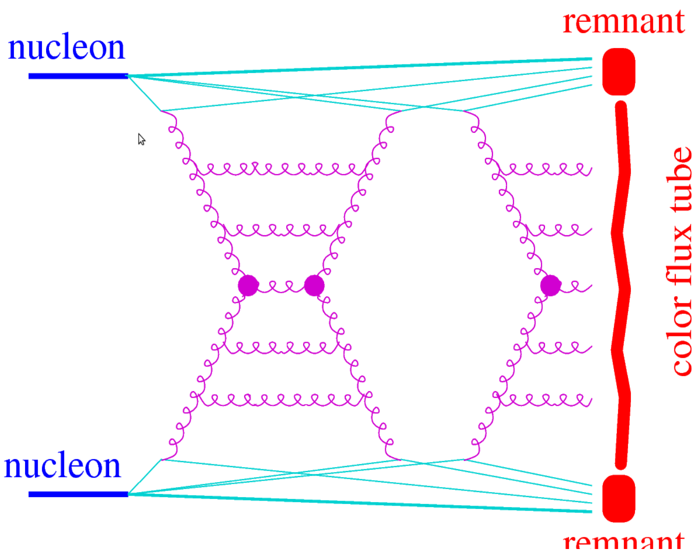
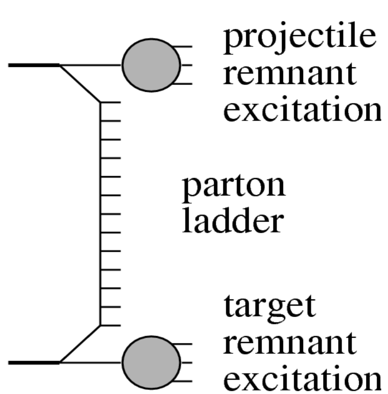
Outline

- **The EPOS model**
- **<Xmax>**
  - cross section
  - multiplicity
- **Muons**
  - remnants
  - baryons
- **LDF**
  - Pt

The EPOS Model





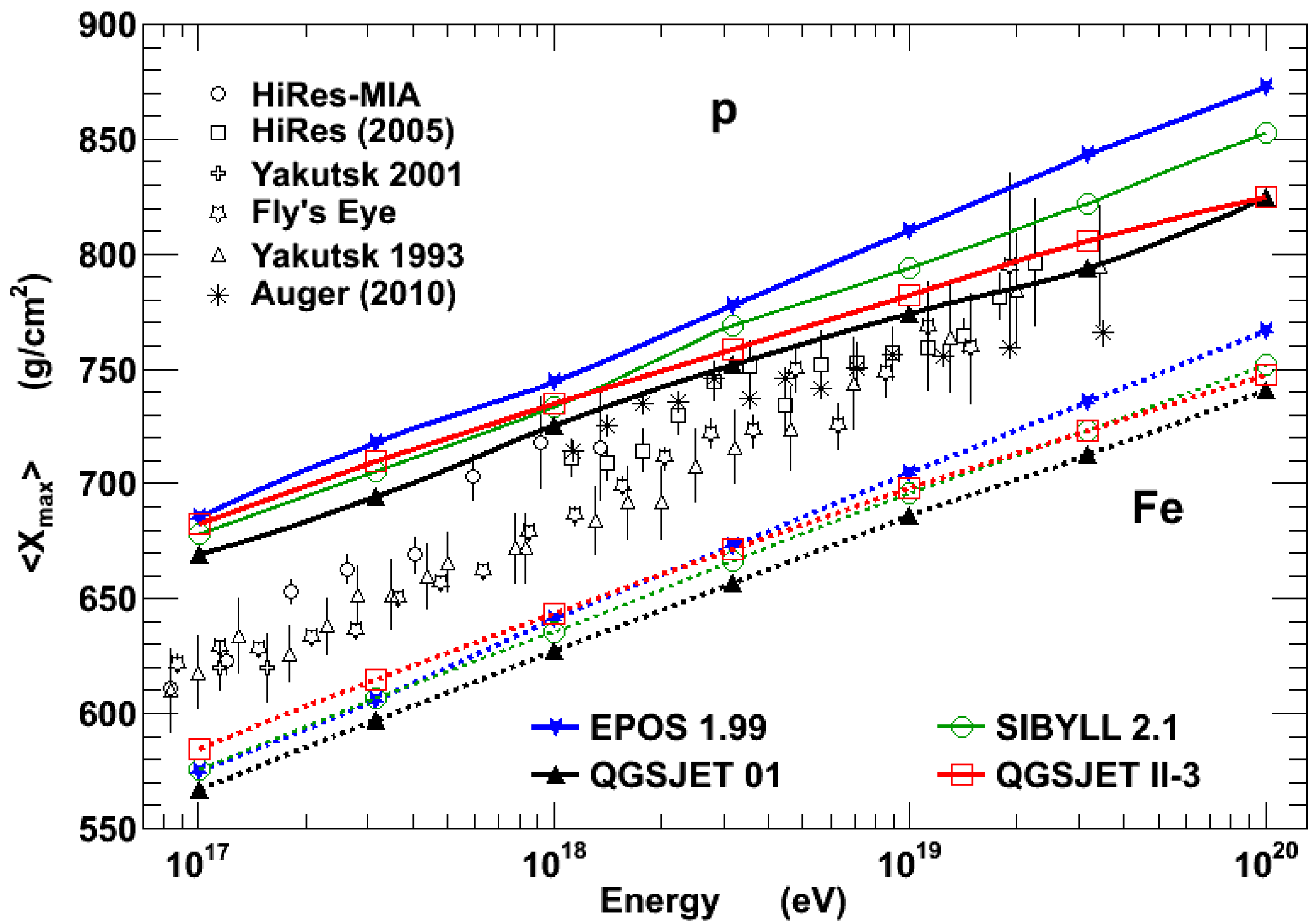
EPOS* is a parton model, with many binary parton-parton interactions, each one creating a parton ladder.

- **E**nergy-sharing : for cross section calculation AND particle production
- **P**arton Multiple scattering
- **O**utshell remnants
- **S**creening and shadowing via unitarization and splitting
- Collective effects for dense systems

EPOS can be used for minimum bias hadronic interaction generation (h-p to A-B) from 100 GeV (lab) to 1000 TeV (cms) : used for air shower !

EPOS designed to be used for particle physics experiment analysis (SPS, RHIC, LHC)

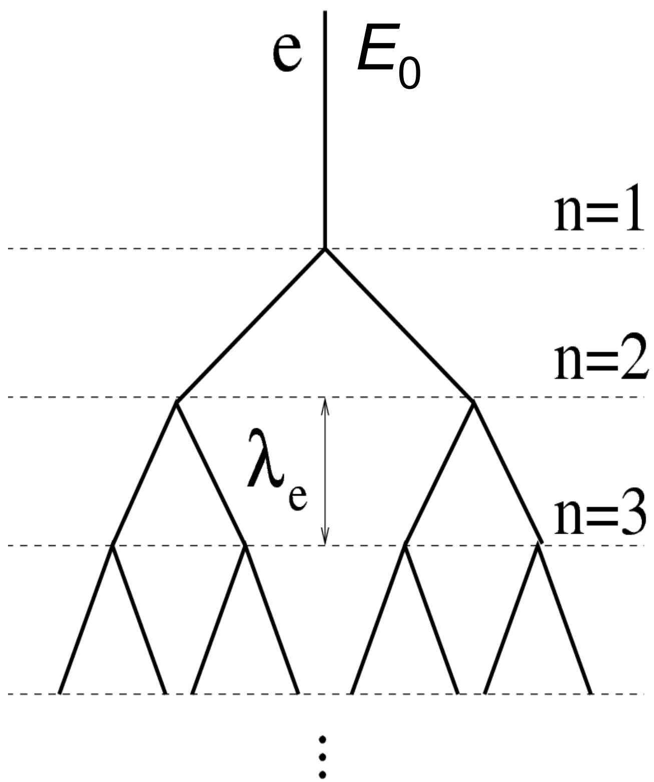
<Xmax>



Large spread of model predictions !

EPOS showers very deep ...

Toy Model for Electromagnetic Cascade



Primary particle : photon/electron

Heitler toy model :

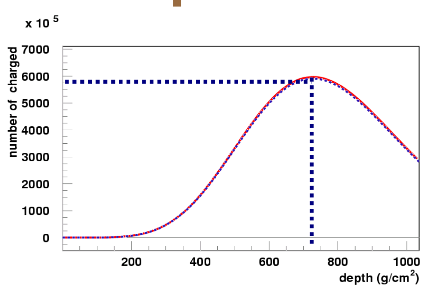
- 2 particles produced with equal energy

2^n particles after *n* interactions

$$n = X/\lambda_e$$

$$N(X) = 2^n = 2^{X/\lambda_e} \qquad E(X) = E_0/2^{X/\lambda_e}$$

Assumption: shower maximum reached if $E(X_{max}) = E_c$ (critical energy)

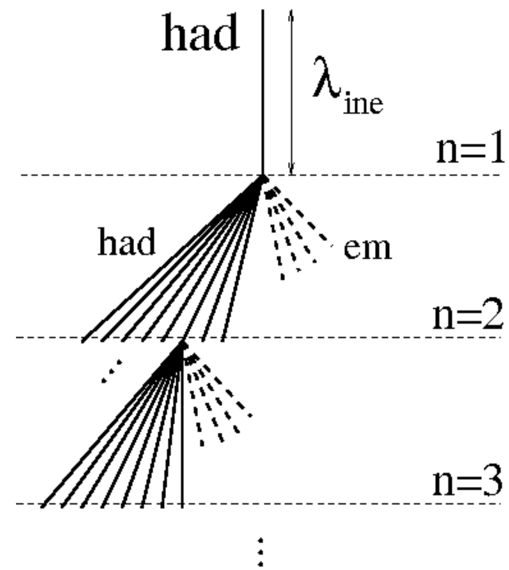


$$N_{max} = E_0/E_c \qquad X_{max} \sim \lambda_e \ln(E_0/E_c)$$

<Xmax> Theory

Using a simple generalized Heitler model to understand EAS characteristics :

- fixed interaction length
- equally shared energy
- 2 types of particles :
  - N_{had} continuing hadronic cascade until decay at E_{dec} producing muons (charged pions).
  - N_{em} transferring their energy to electromagnetic shower (neutral pions).



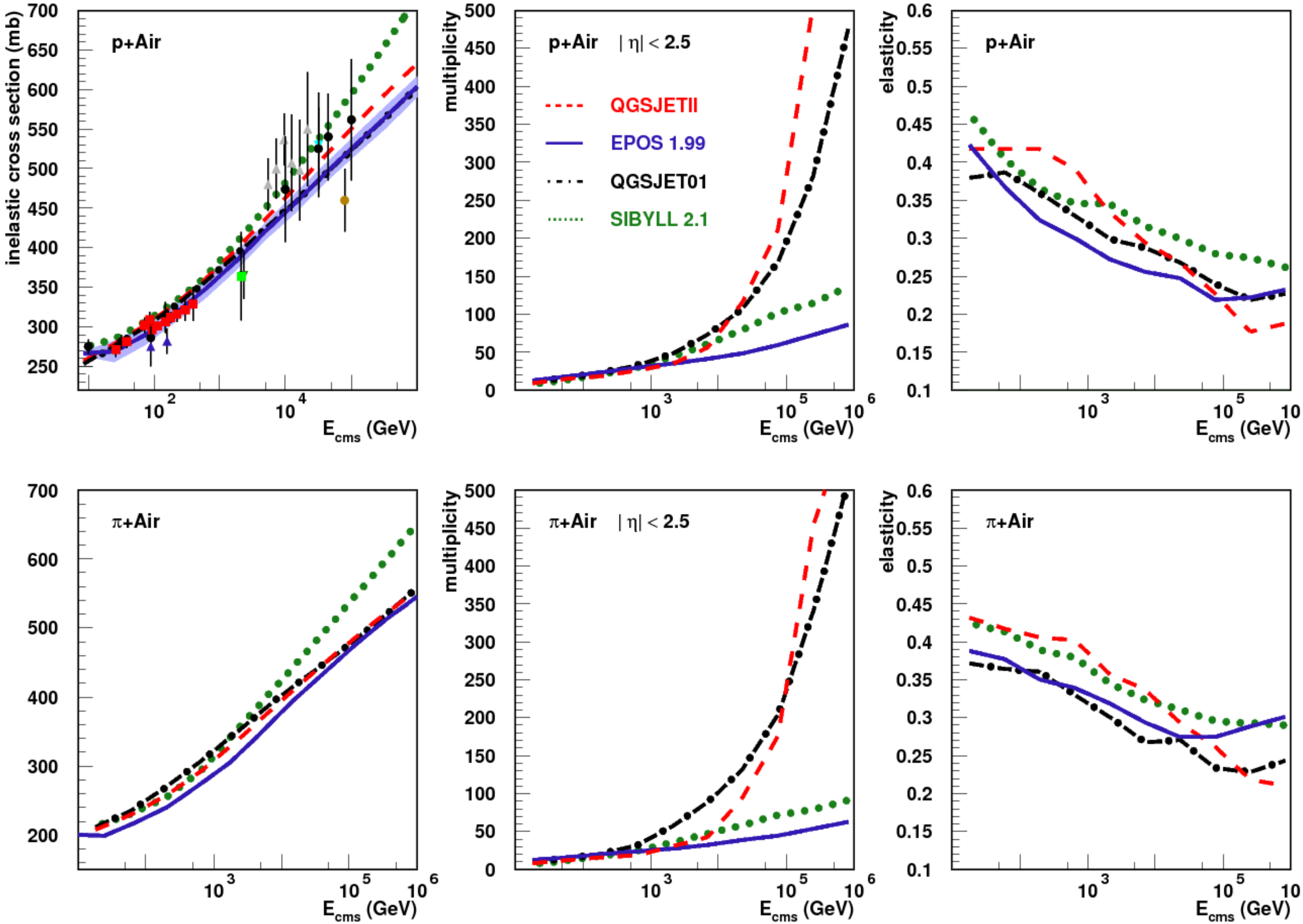
$$N_{tot} = N_{had} + N_{em}$$

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

- Model independent parameters :
  - E_0 = primary energy
  - λ_e = electromagnetic mean free path
- Model dependent parameters :
  - N_{tot} = total multiplicity
  - λ_{ine} = hadronic mean free path

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

Hadronic Model Predictions

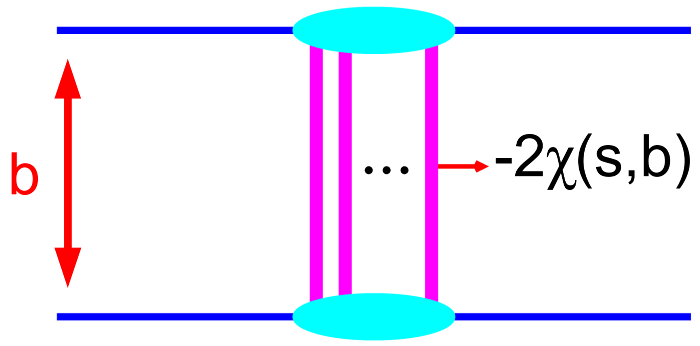


Cross Section Calculation : SIBYLL / QGSJET

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

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

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

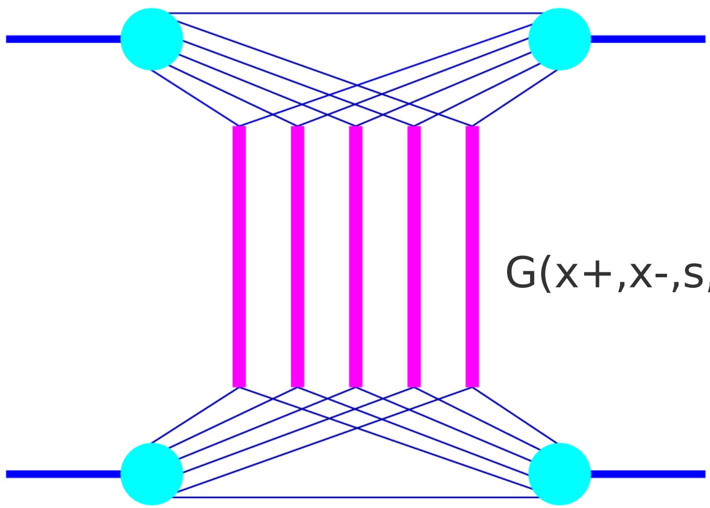


$$\sigma \sim 1 - \exp(-2\chi)$$

Not the same χ in QGSJET01, QGSJETII and SIBYLL

- $\chi(s,b)$ parameters 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
- amplitude parameters fixed from QCD and pp cross section
- cross section calculation take into account interference term

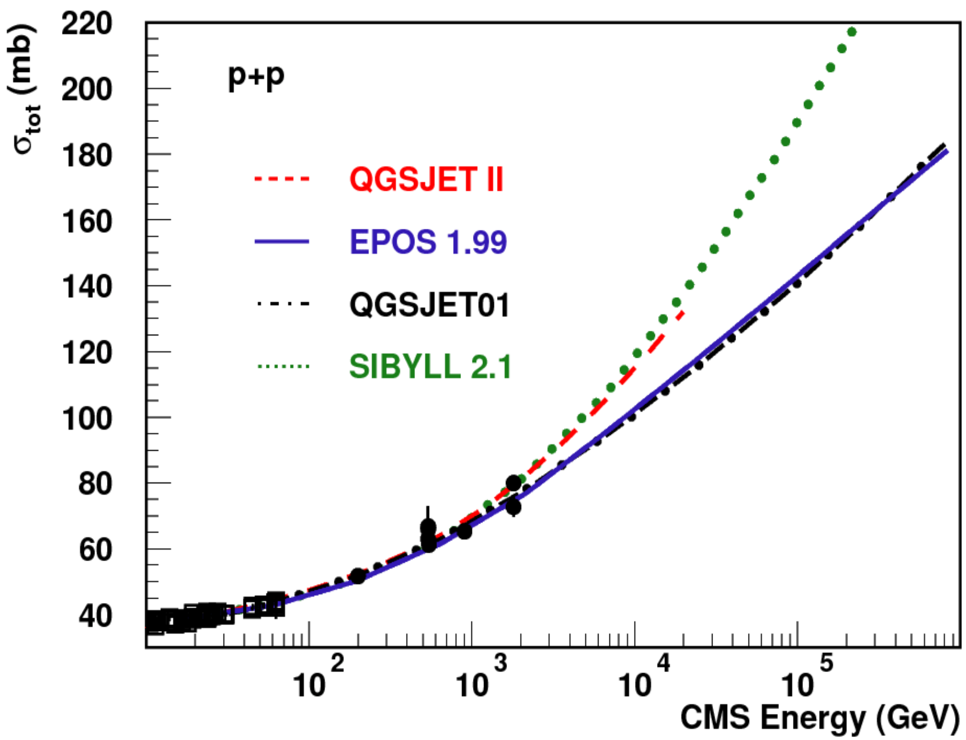
$$\Phi_{\rm pp}\left(x^+,x^-,s,b\right) = \sum_{l=0}^{\infty}\int dx_1^+dx_1^-\dots dx_l^+dx_l^-\left\{\frac{1}{l!}\prod_{\lambda=1}^{l}-G(x_\lambda^+,x_\lambda^-,s,b)\right\}$$
$$\times\; F_{\rm proj}\left(x^+-\sum x_\lambda^+\right)F_{\rm targ}\left(x^--\sum x_\lambda^-\right).$$

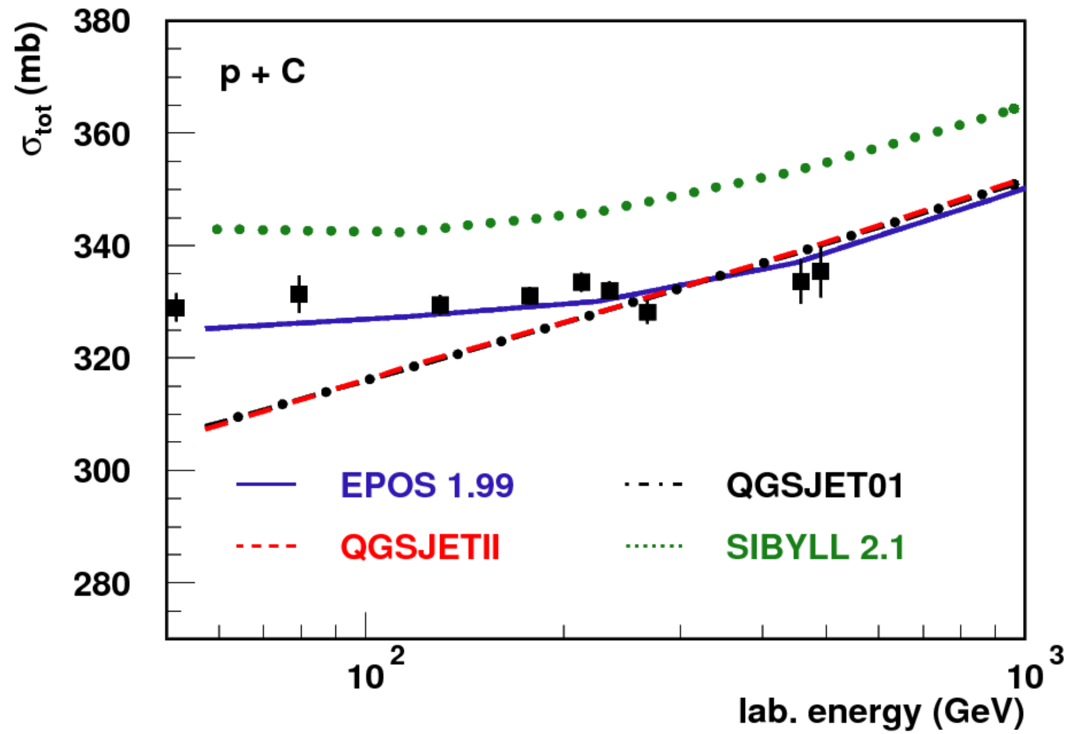
$$\sigma_{\rm ine}(s) = \int d^2b\,(1-\Phi_{\rm pp}(1,1,s,b))$$

- can not use complex diagram like QII with energy sharing (only Y and X)
  - 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





Low cross section in EPOS

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 subdiagrams
  - 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

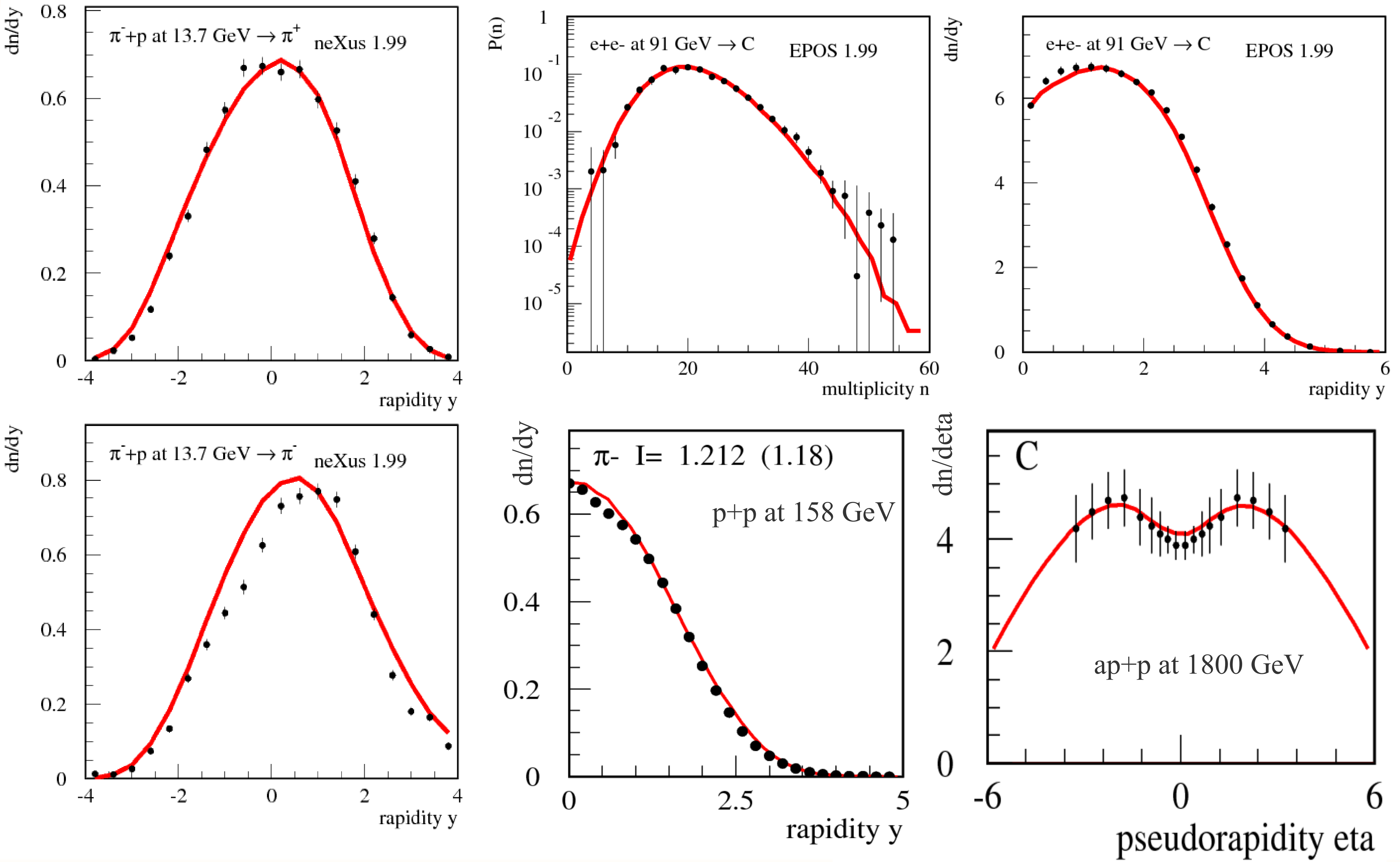
m number of exchanged elementary interaction per event fixed from elastic amplitude taking into account energy sharing :

- m from :

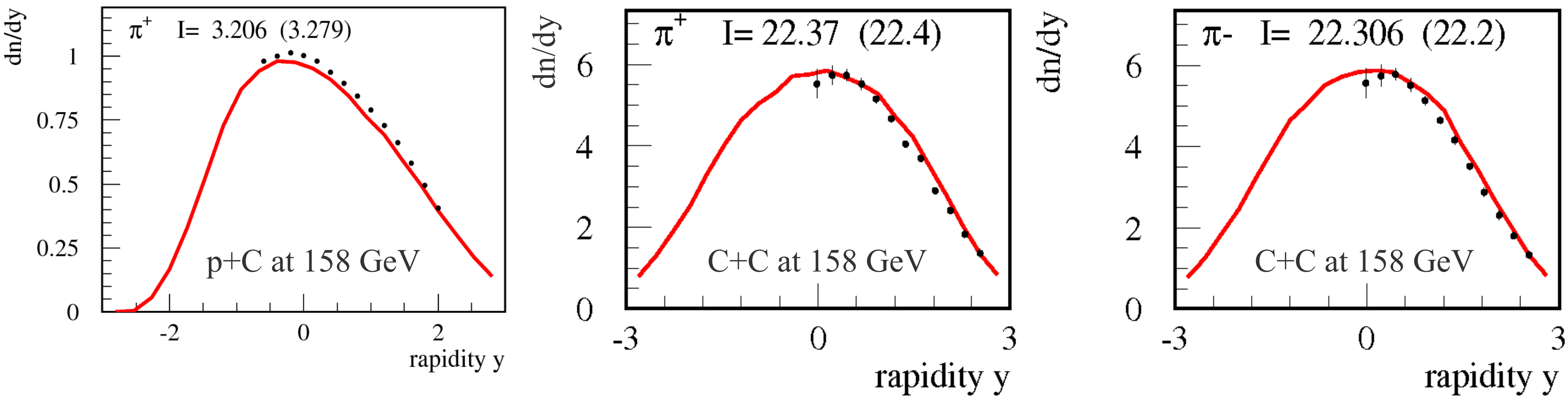
$$\Omega_{AB}^{(s,b)}(m,X^+,X^-)=\prod_{k=1}^{AB}\left\{\frac{1}{m_k!}\prod_{\mu=1}^{m_k}G(x_{k,\mu}^+,x_{k,\mu}^-,s,b_k)\right\}\Phi_{AB}\left(x^{\mathrm{proj}},x^{\mathrm{targ}},s,b\right)$$

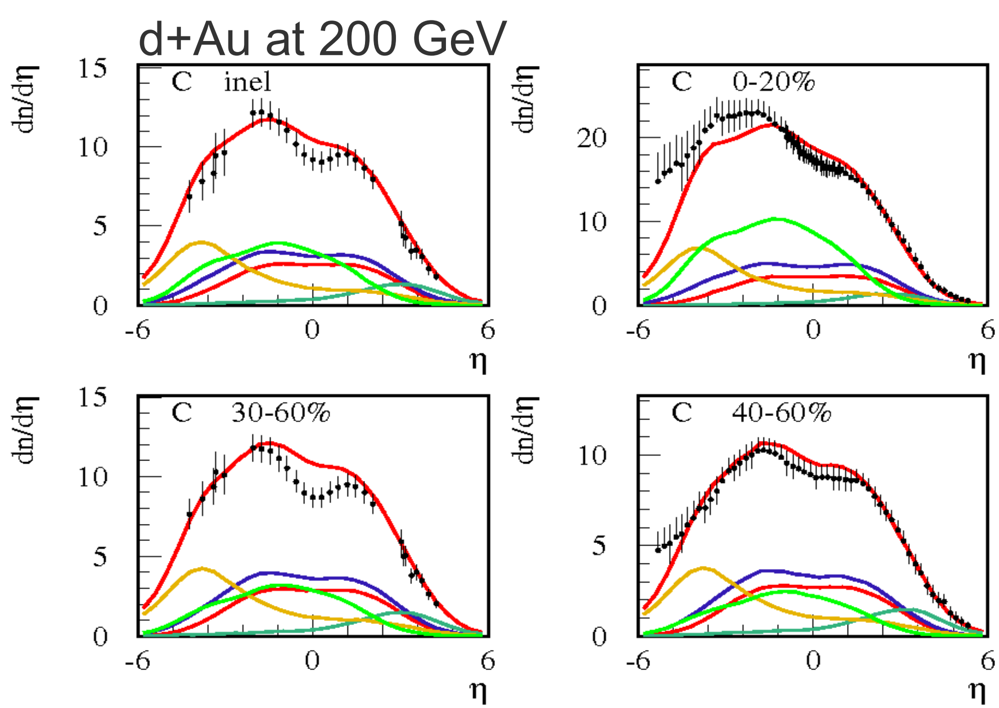
  - m and X fixed together by a complex Metropolis
- $2m$ strings formed from the m elementary interactions
  - energy conservation : energy fraction of the $2m$ strings given by X
- consistent scheme : energy sharing reduce the probability to have large m
- additional multiplicity reduction due to high density effect
  - statistical hadronization instead of string fragmentation
    - larger Pt (flow)

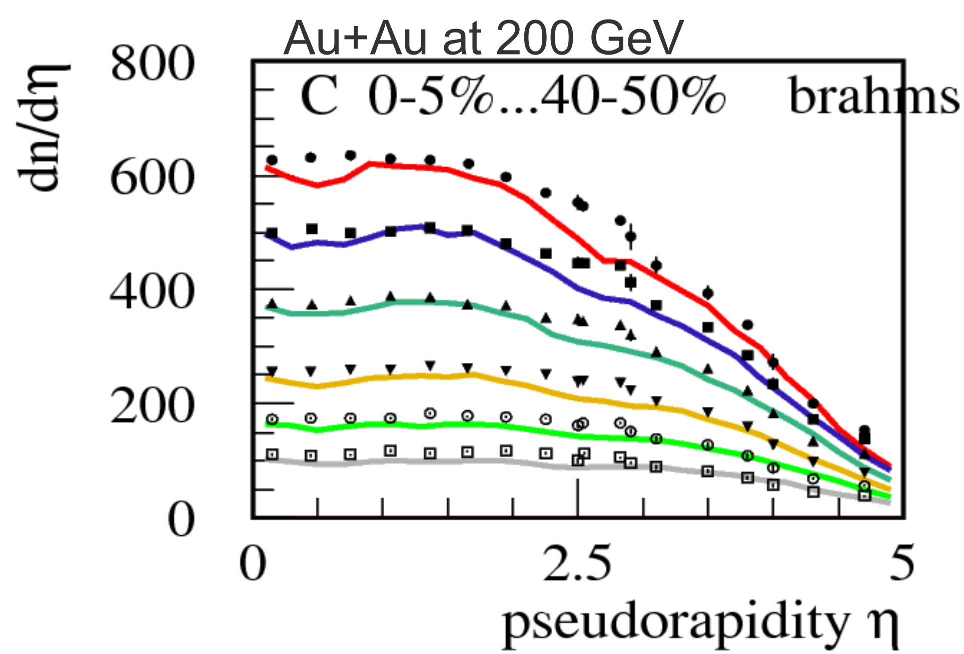
EPOS Basic Distributions



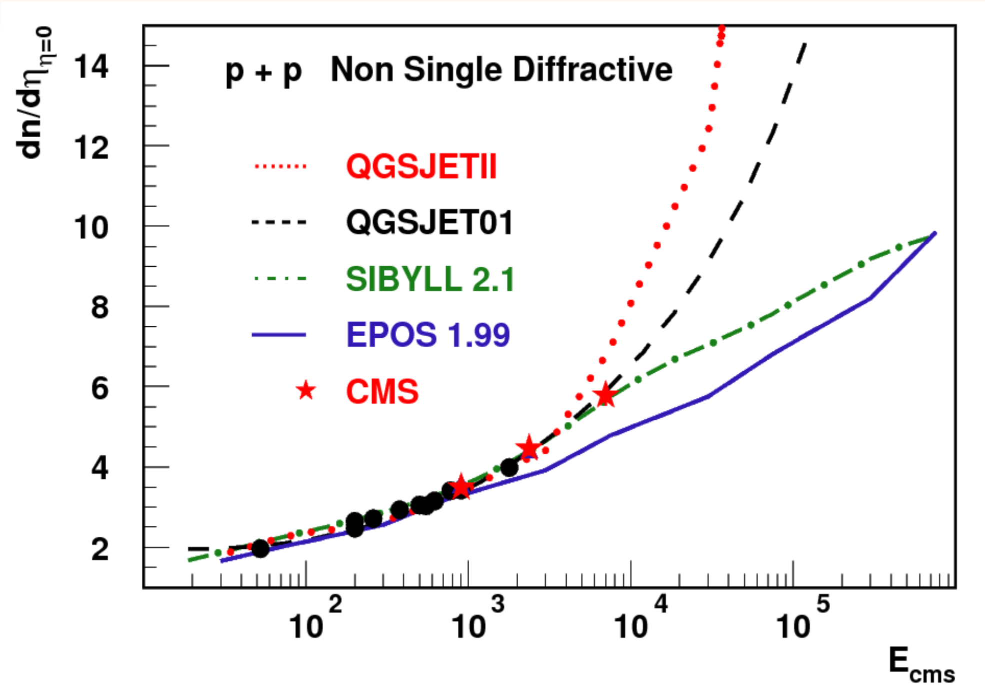
EPOS Nuclear Interactions





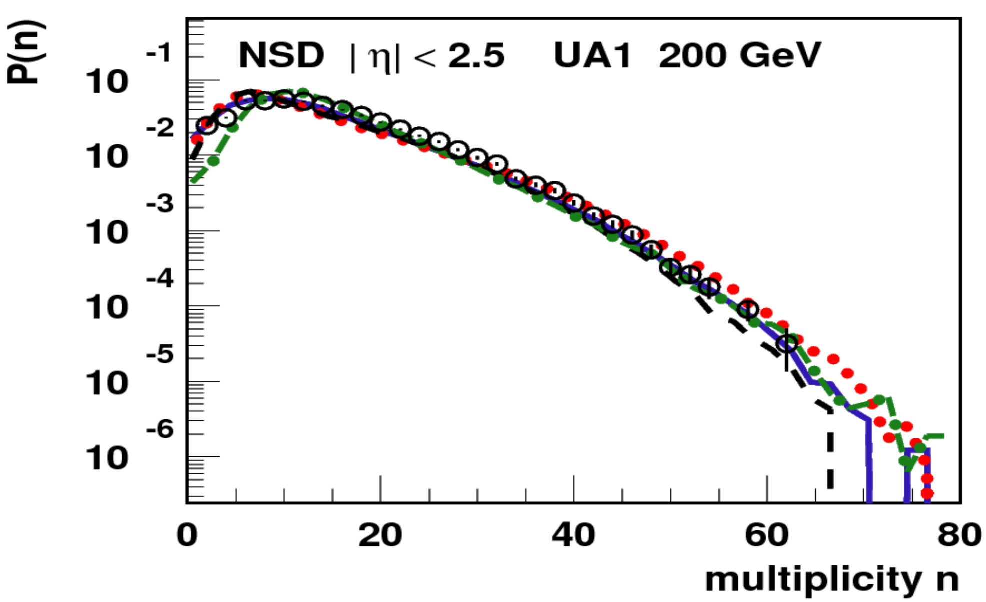


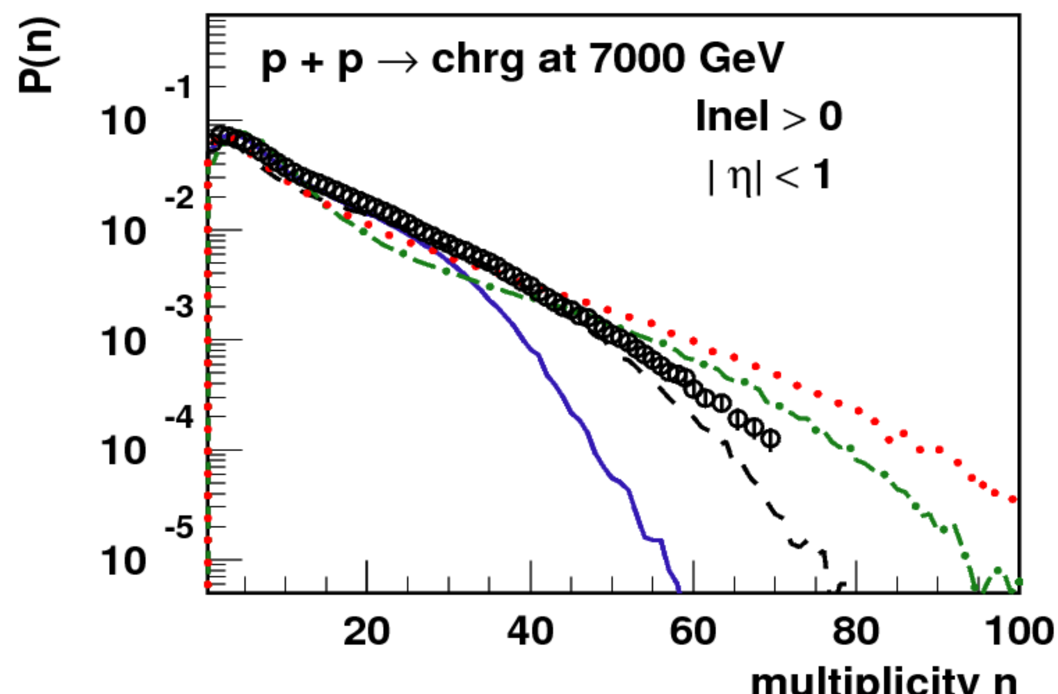
Multiplicity



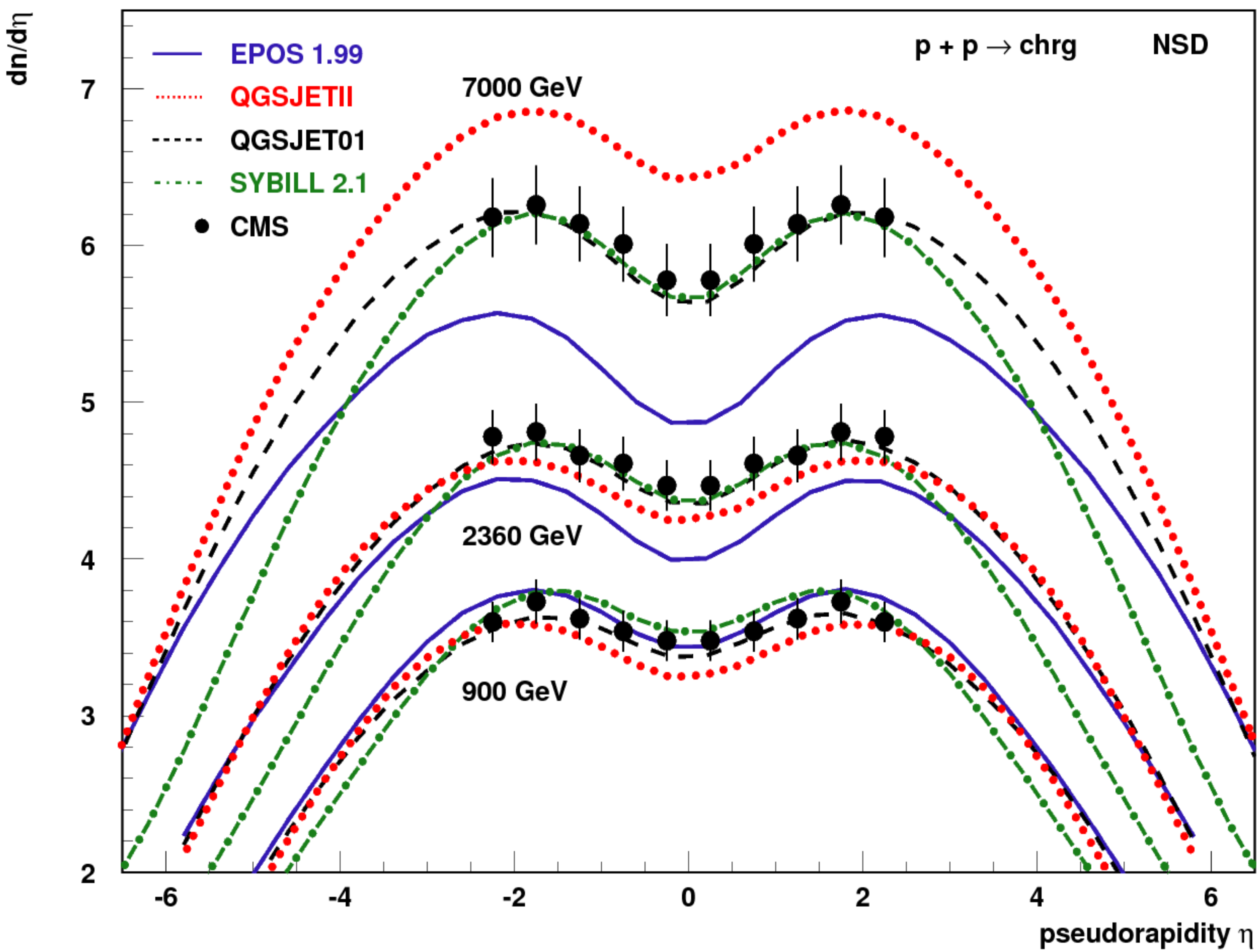
- Low multiplicity in EPOS at midrapidity
- Shape of distribution correct
- large differences at LHC
  - EPOS too low due to missing hard diffraction and core fusion
  - not due to energy sharing

  (cf EPOS 2)

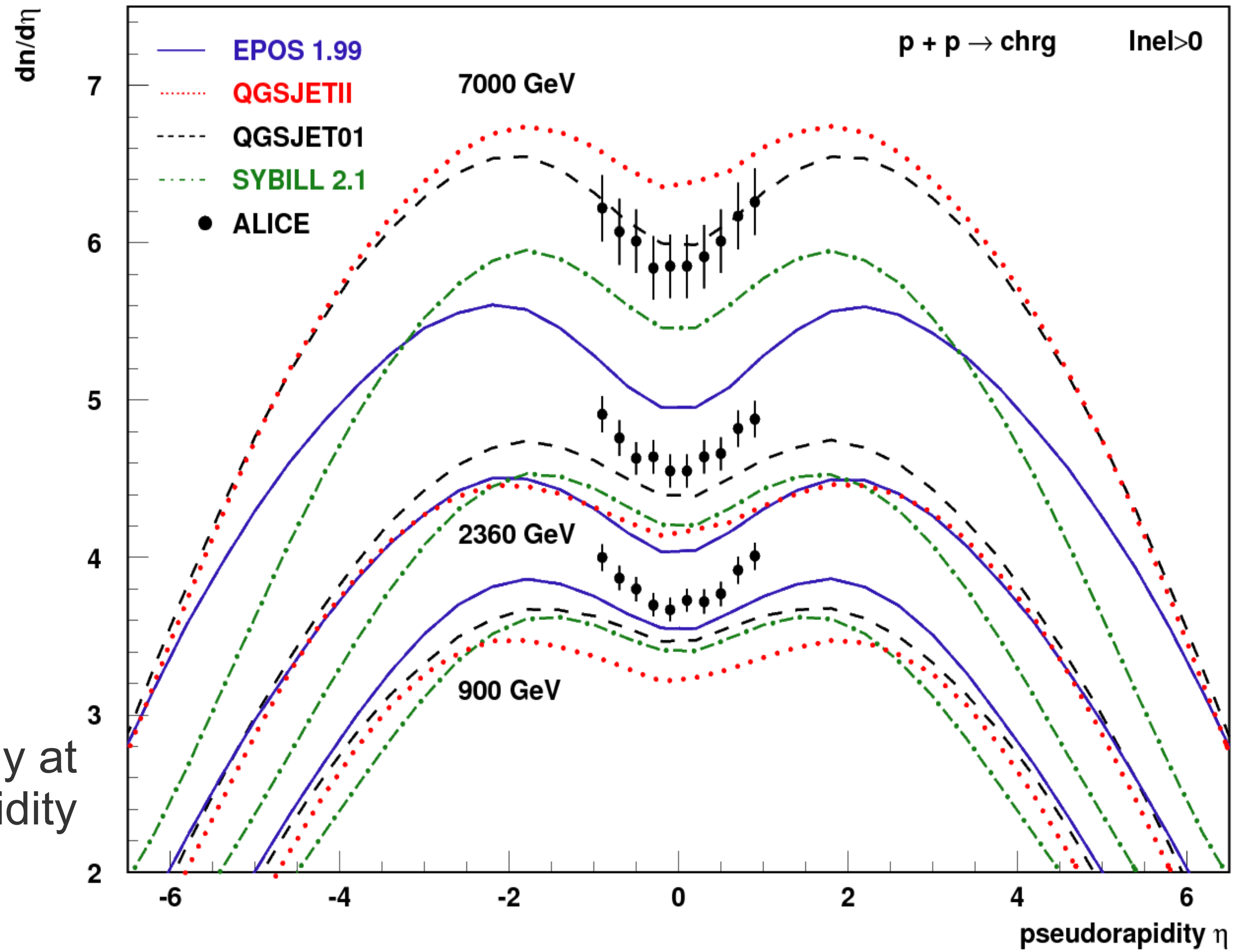




Pseudorapidity NSD CMS



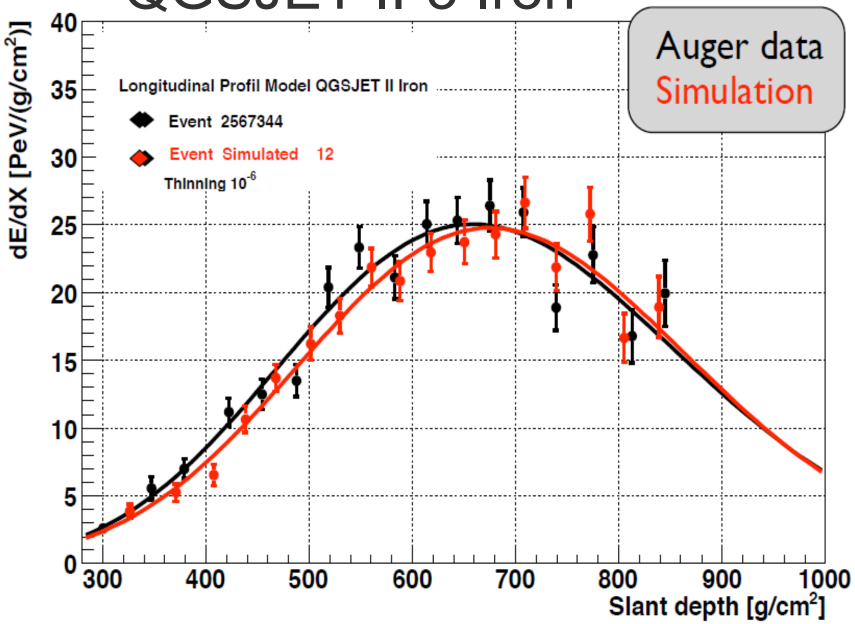
Pseudorapidity ALICE Inel>0

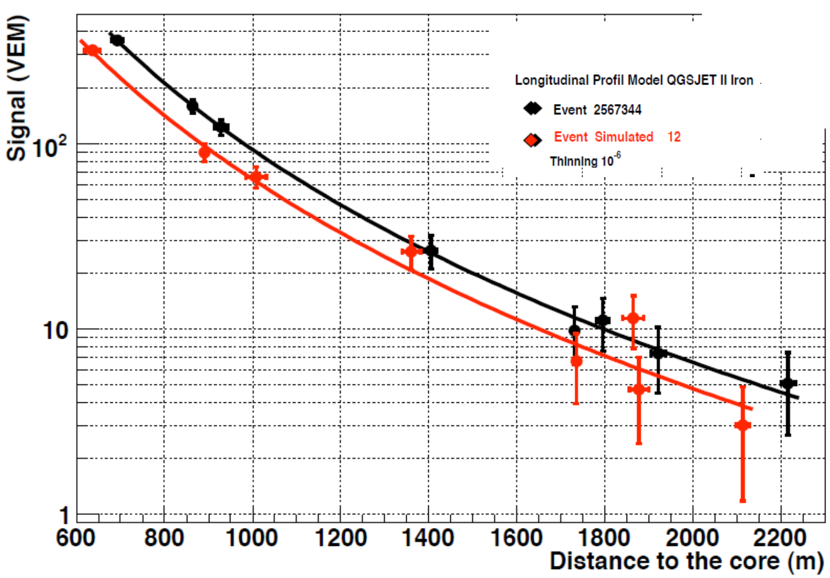


deficit only at midrapidity

FD and SD mismatch

QGSJET II-3 Iron





AUGER

- ➔ Comparison event-by-event
  - Fix simulated FD profile with data
  - Compare measured SD signal with simulated one

SD systematically lower in simulation : ~25 % shift in energy scale + ~50 % deficit in muon number (for QGSJETII-03)

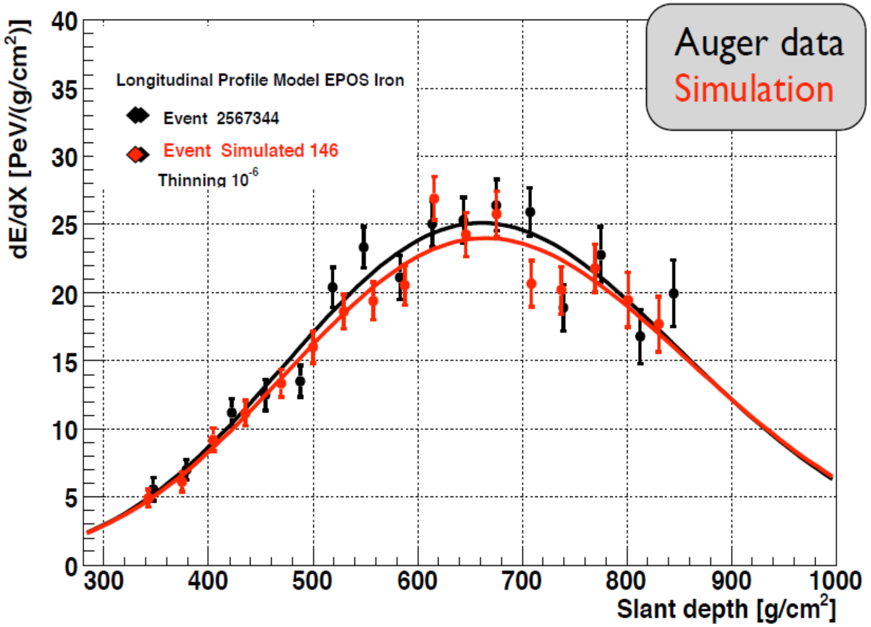
TA

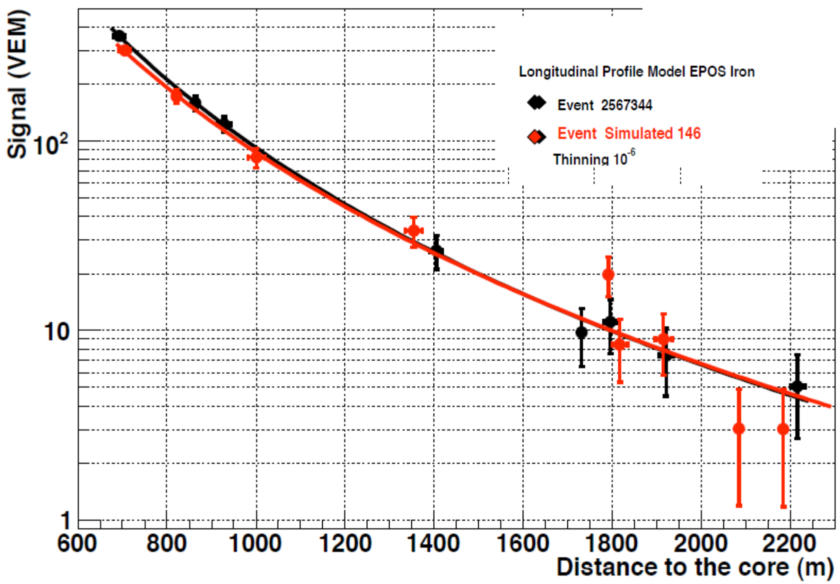
- ➔ Spectrum reconstruction
  - Spectrum using QGSJETII-03 for energy reconstruction
  - Renormalize energy using event seen by FD and SD using FD energy as reference

27 % shift in energy scale needed

FD and SD mismatch

EPOS 1.6 Iron





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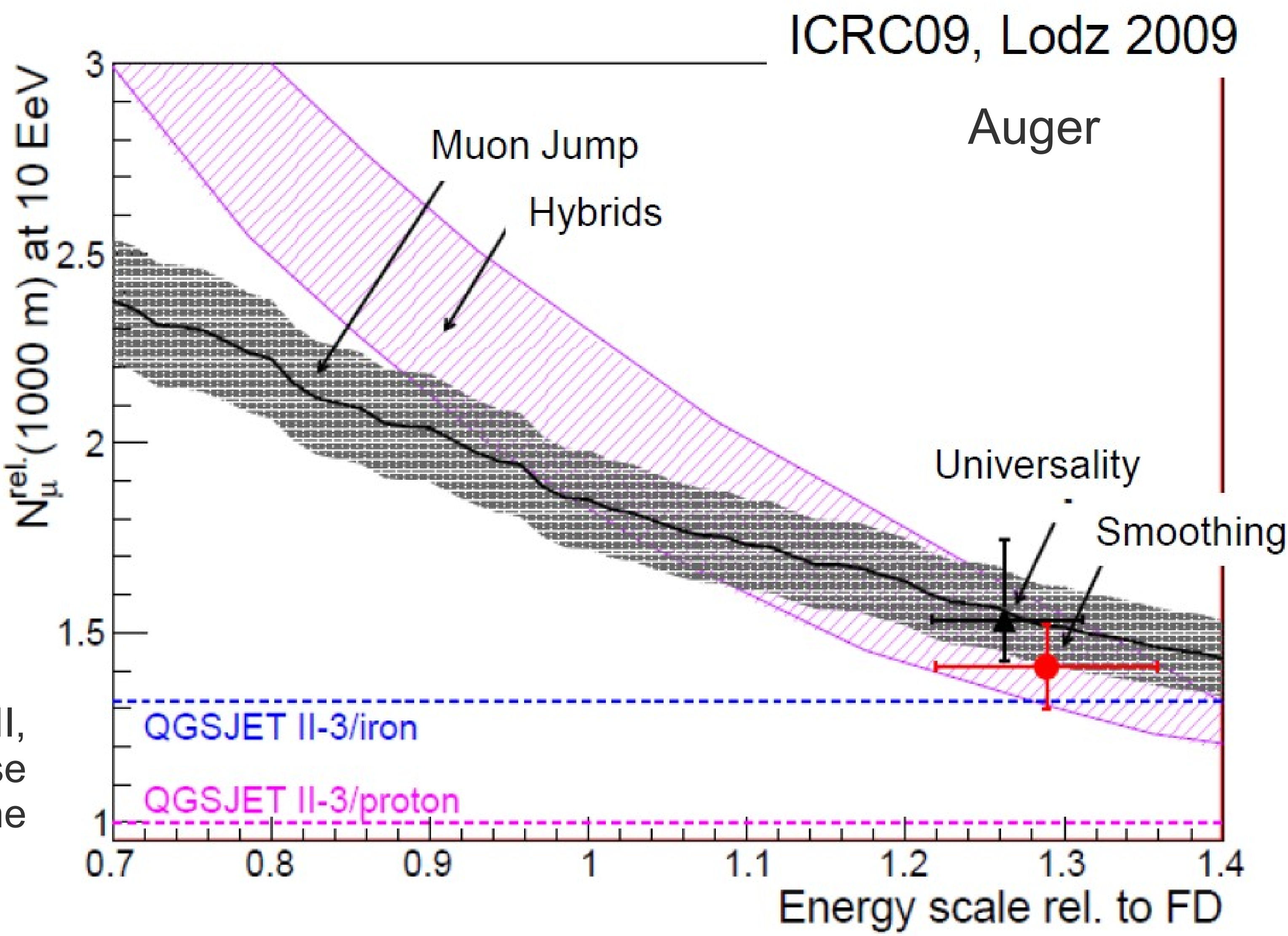
27 % shift in energy scale needed

Muons in Data

Is the problem seen using QGSJETII-3 with muons general ?



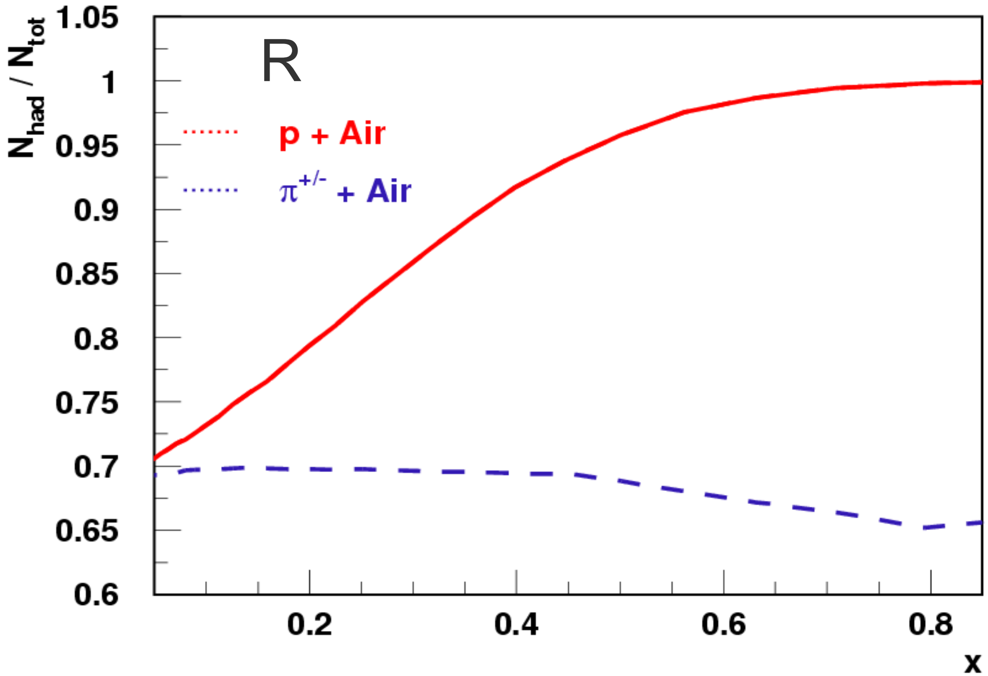
For QGSJETII, <Xmax> close to proton line

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 ...)



$$\alpha = \frac{\ln(N_{had})}{\ln(N_{tot})} = 1 + \frac{\ln(R)}{\ln(N_{tot})}$$

$$R = \frac{N_{had}}{N_{tot}} \approx \frac{N_{\pi^{ch}} + N_B}{N_{\pi^{ch}} + N_B + N_{\pi^0}}$$

Very important :

in (anti)Baryon-Air interactions, no leading neutral pion !

R~1

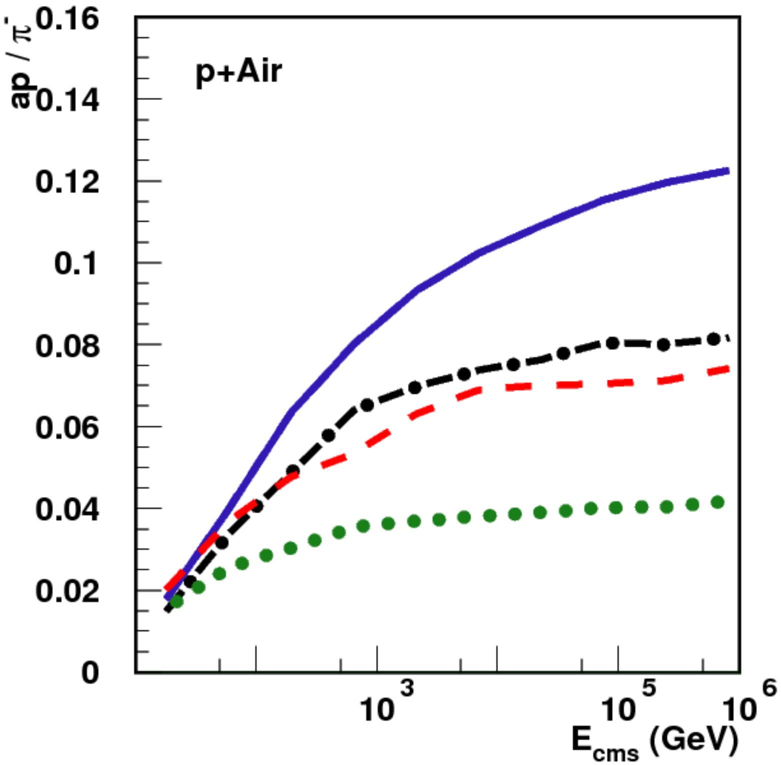
R depends on the number of (anti)B in p- or π-Air interactions

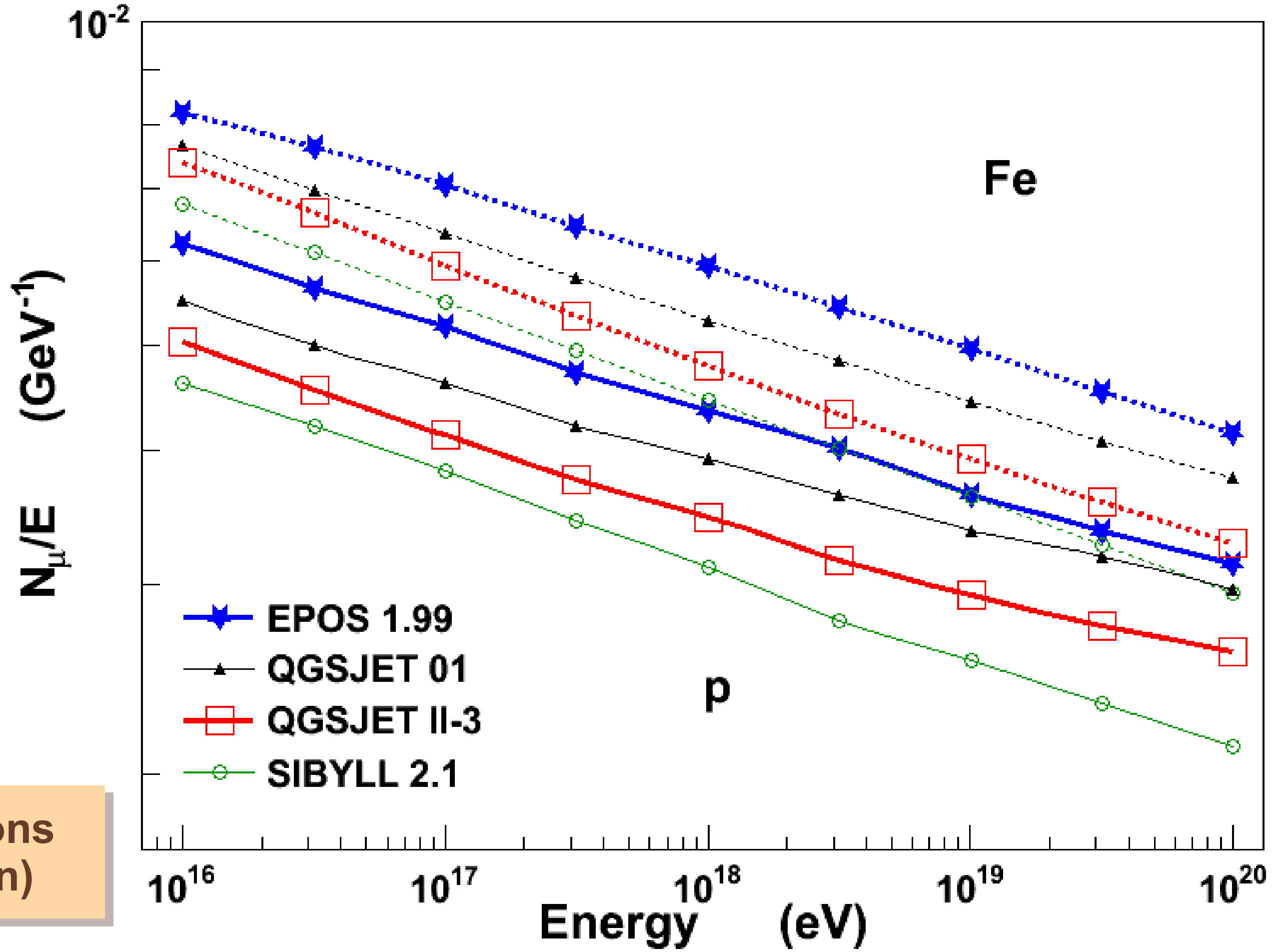
More fast (anti)baryons = $\alpha \rightarrow 1$ = more muons

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

Total Number of Muons

Discrepancy (baryon and pion spectra) between models
Much more muons in EPOS



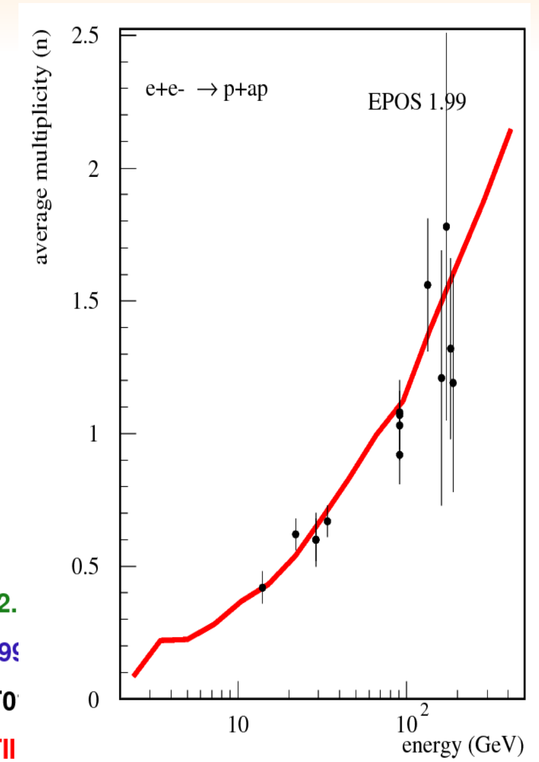


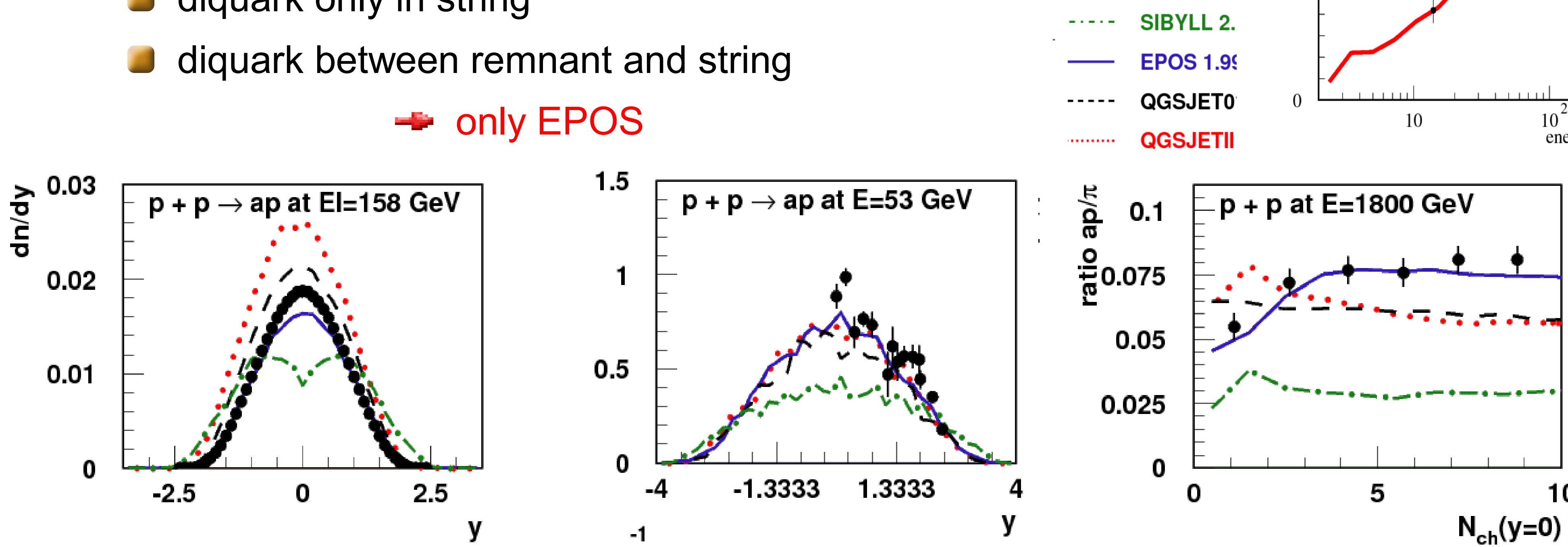
3 times less baryons = 40 % less muons (~difference between proton and iron)

Baryon Production

Baryon production at different level

- diquark pair during string fragmentation
  - tested in e+e-
  - do not reproduce energy evolution observed in pp
    - different string tension for gluon jet in EPOS
- diquark pair as string end
  - diquark only in string
  - diquark between remnant and string
    - only EPOS

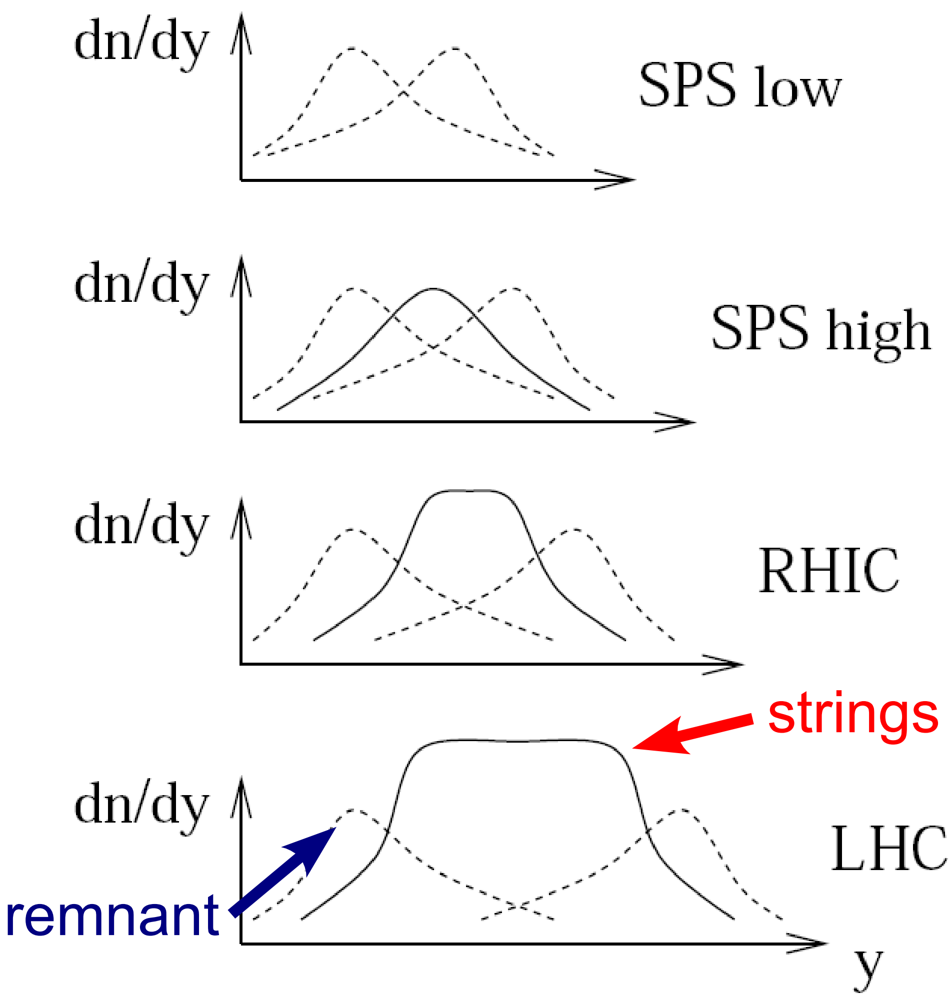




more baryons at high energy in EPOS

Forward Spectra

Forward particles mainly from projectile remnant



The inelasticity is closely related to diffraction and forward spectra

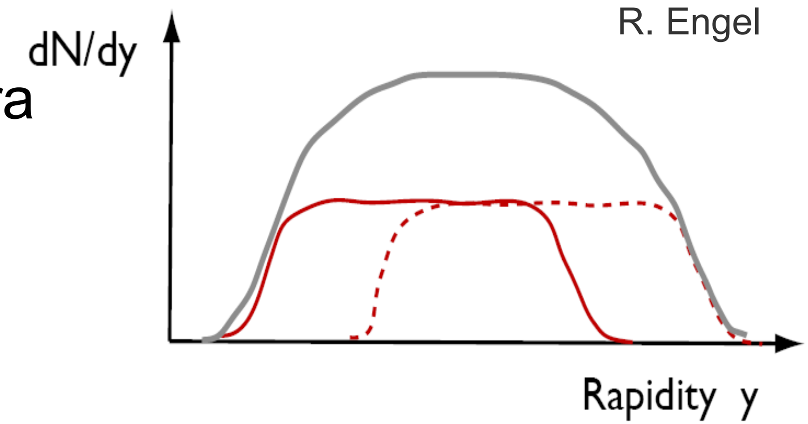
- SIBYLL
  - No remnant except for diffraction
  - Leading particle from string ends
- QGSJET
  - Low mass remnants
  - Leading particle similar to proj.
- EPOS
  - Low and high mass remnants
  - Any type of leading particle
    - from resonance
    - from string
    - from statistical decay

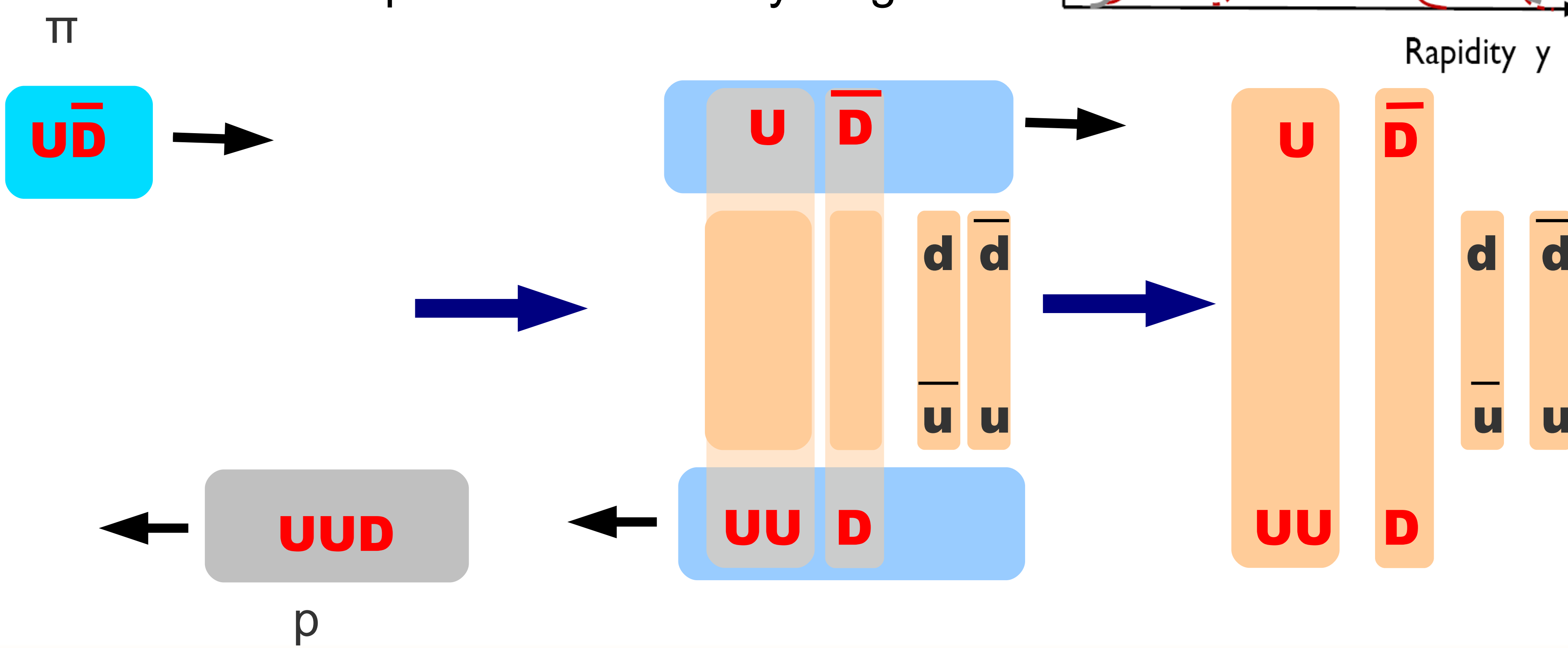
Remnants in SIBYLL

In SIBYLL : valence quarks attached to main string

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

R. Engel

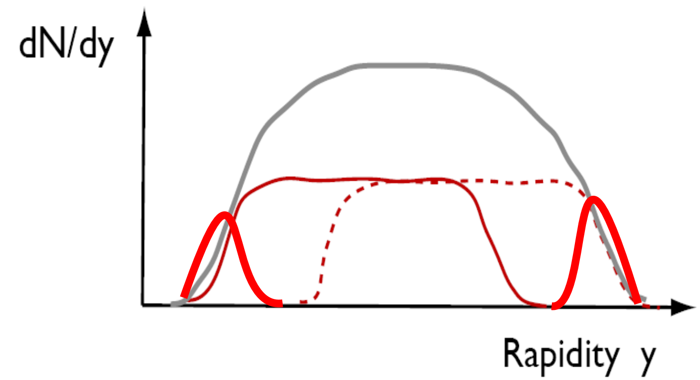


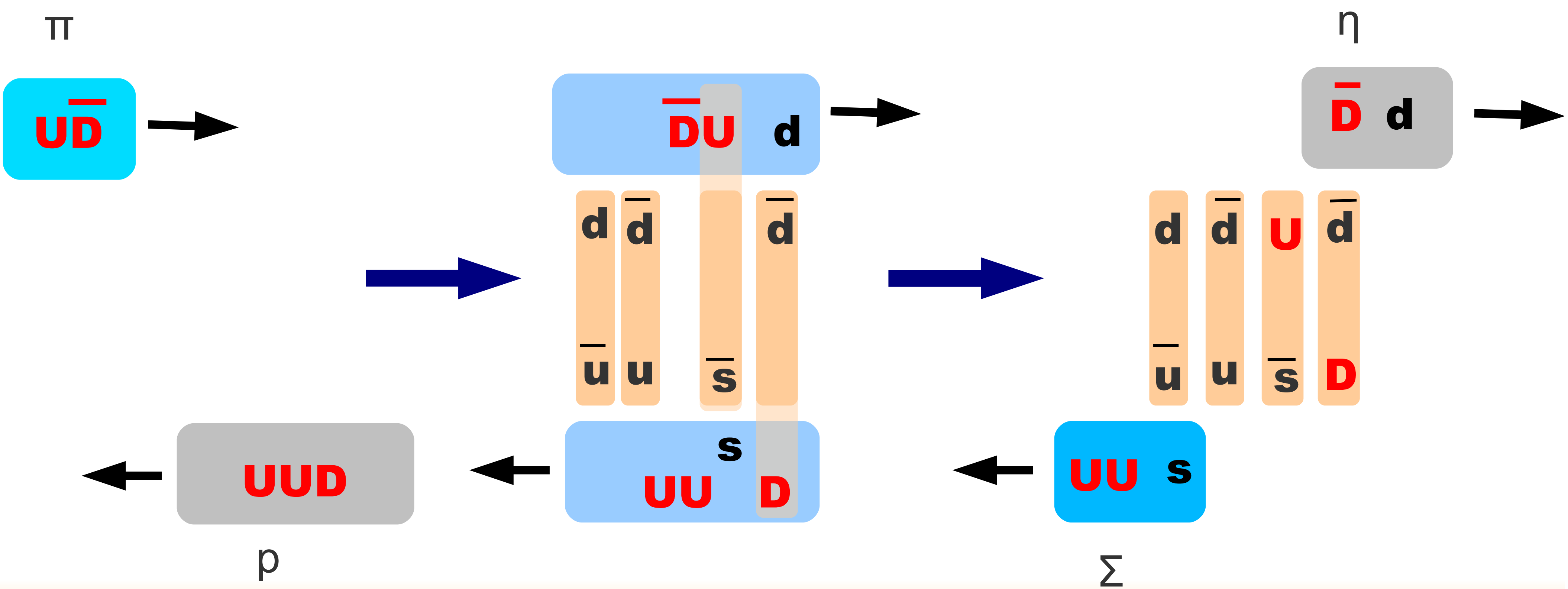


Remnants in QGSJET

In QGSJET : One quark exchange and leading remnant

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

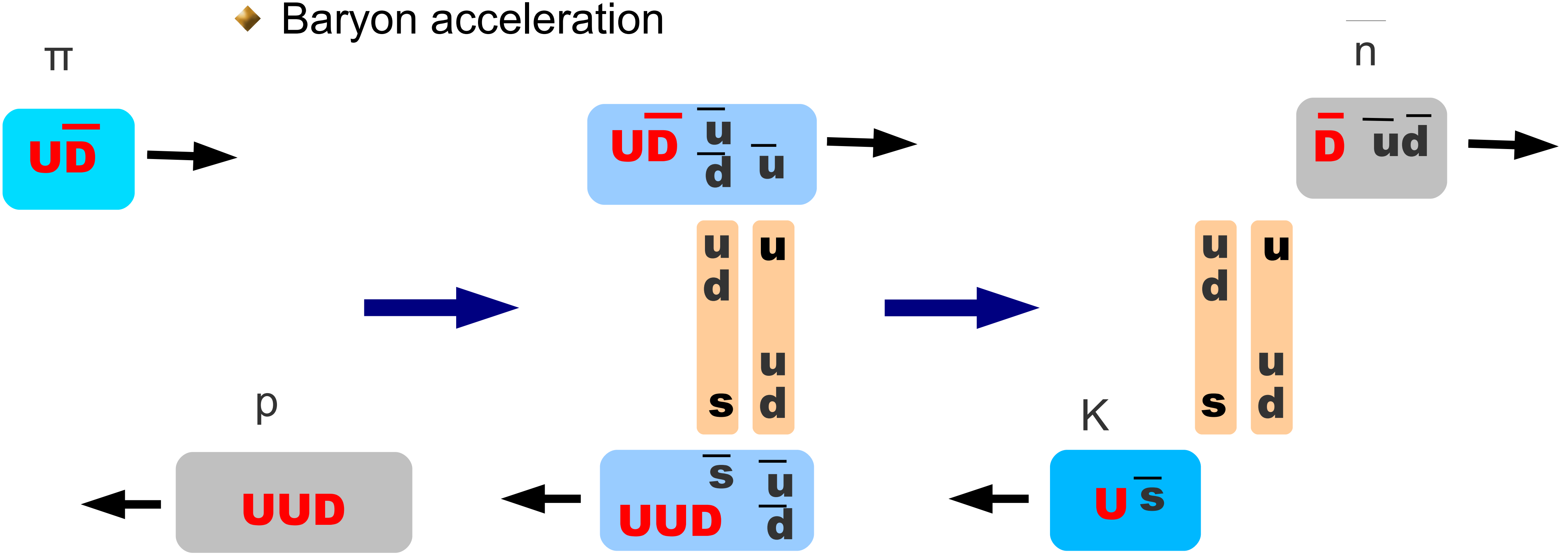




Remnants in EPOS

In EPOS : any possible quark/diquark transfer

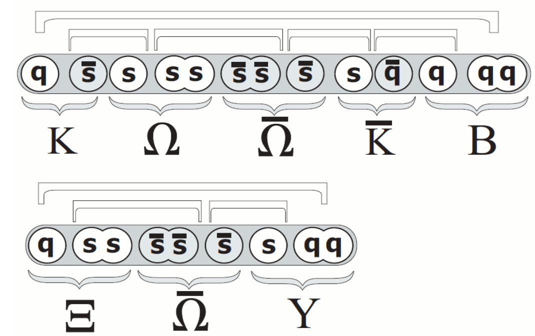
- Diquark transfer between string ends and remnants
- Baryon number can be removed from nucleon remnant :
  - Baryon stopping
- Baryon number can be added to pion/kaon remnant :
  - Baryon acceleration



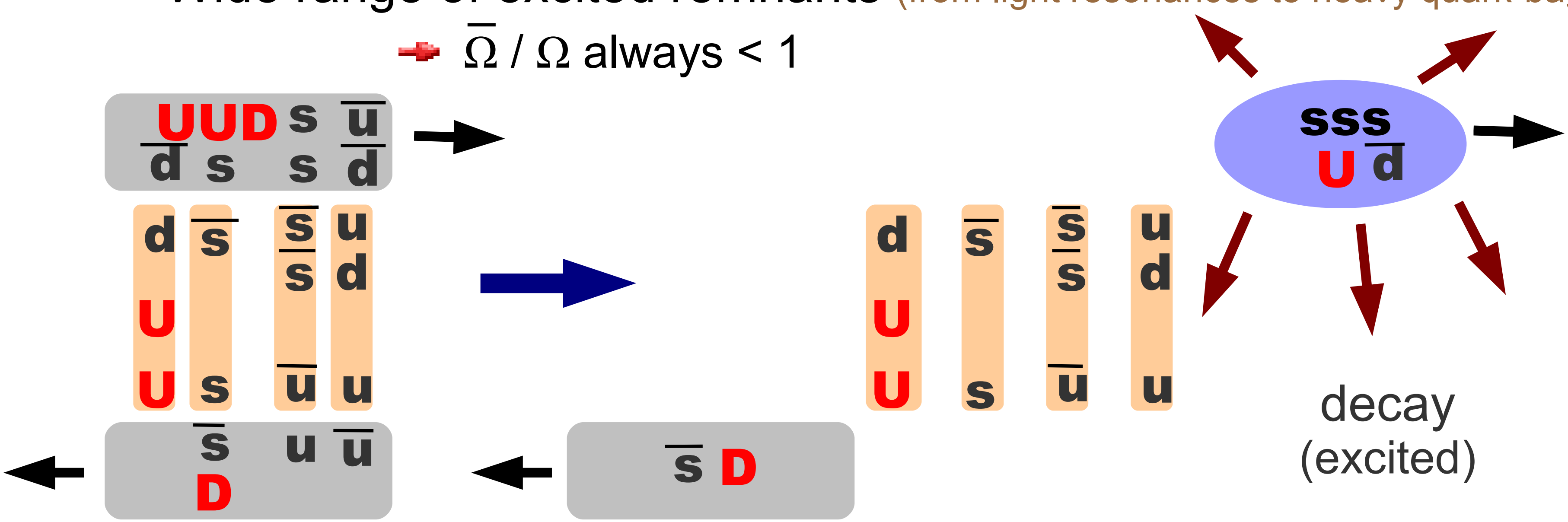
Baryons and Remnants

Parton ladder string ends :

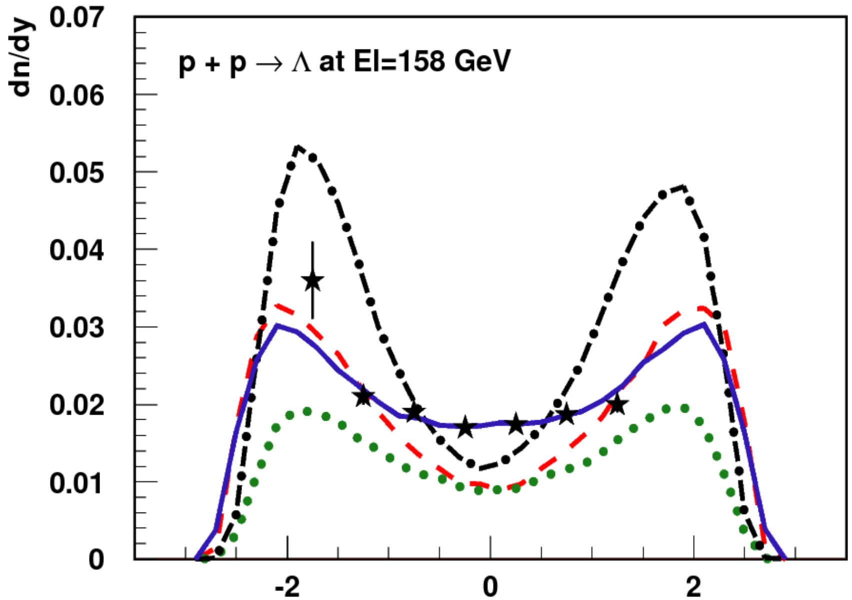
- Problem of multi-strange baryons at low energy (Bleicher et al., Phys.Rev.Lett.88:202501,2002)
  - 2 strings approach :
    - $\bar{\Omega} / \Omega$ always > 1
    - But data < 1 (Na49)



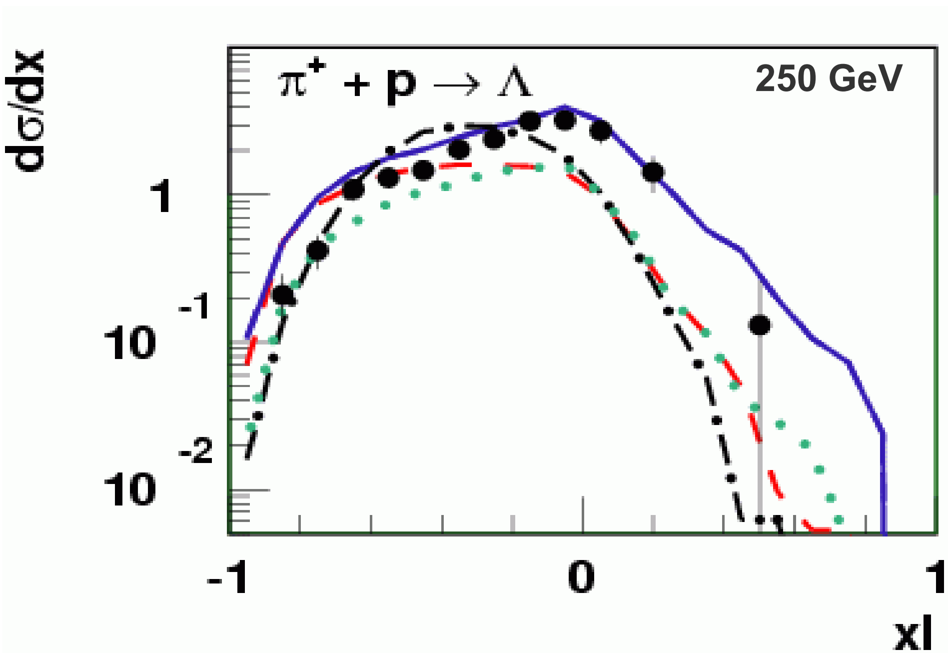
- EPOS
  - No “first string” with valence quarks : all strings equivalent
  - Wide range of excited remnants (from light resonances to heavy quark-bag)
    - $\bar{\Omega} / \Omega$ always < 1

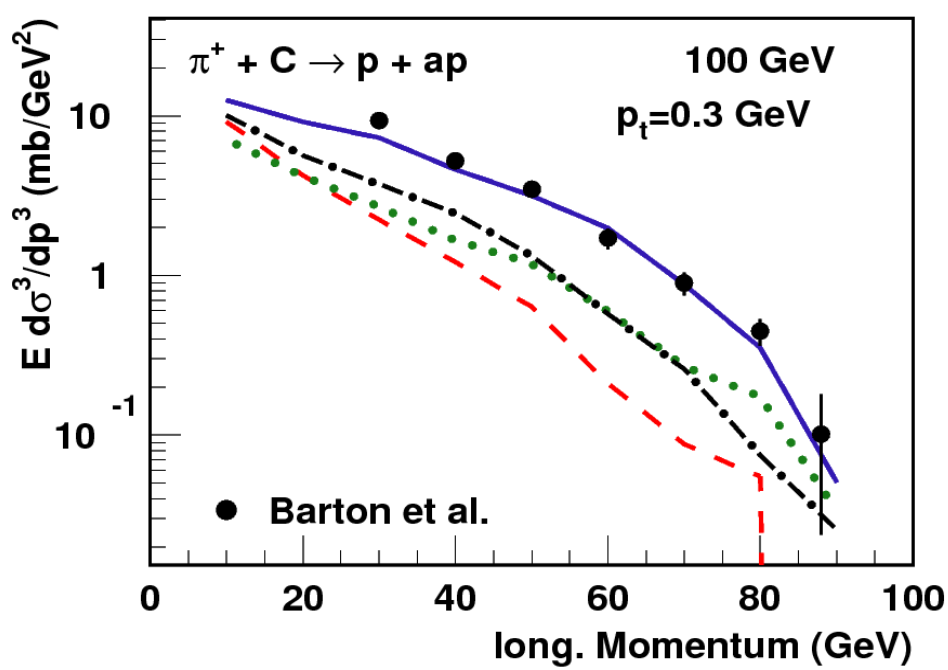


Baryon Forward Spectra



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

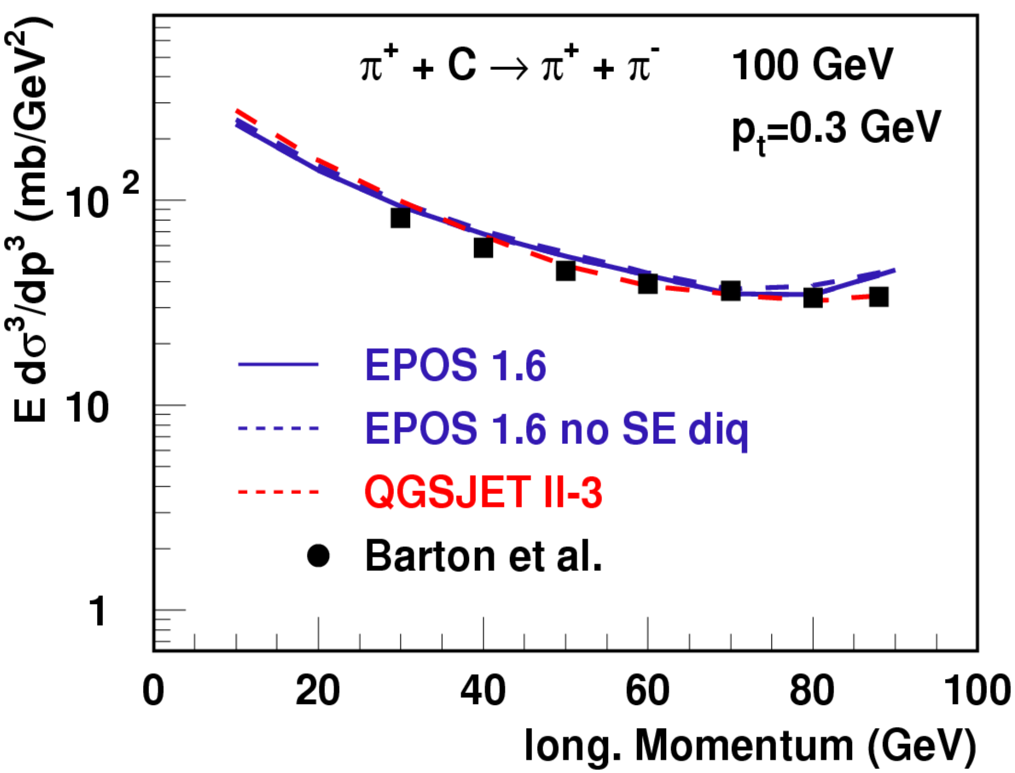


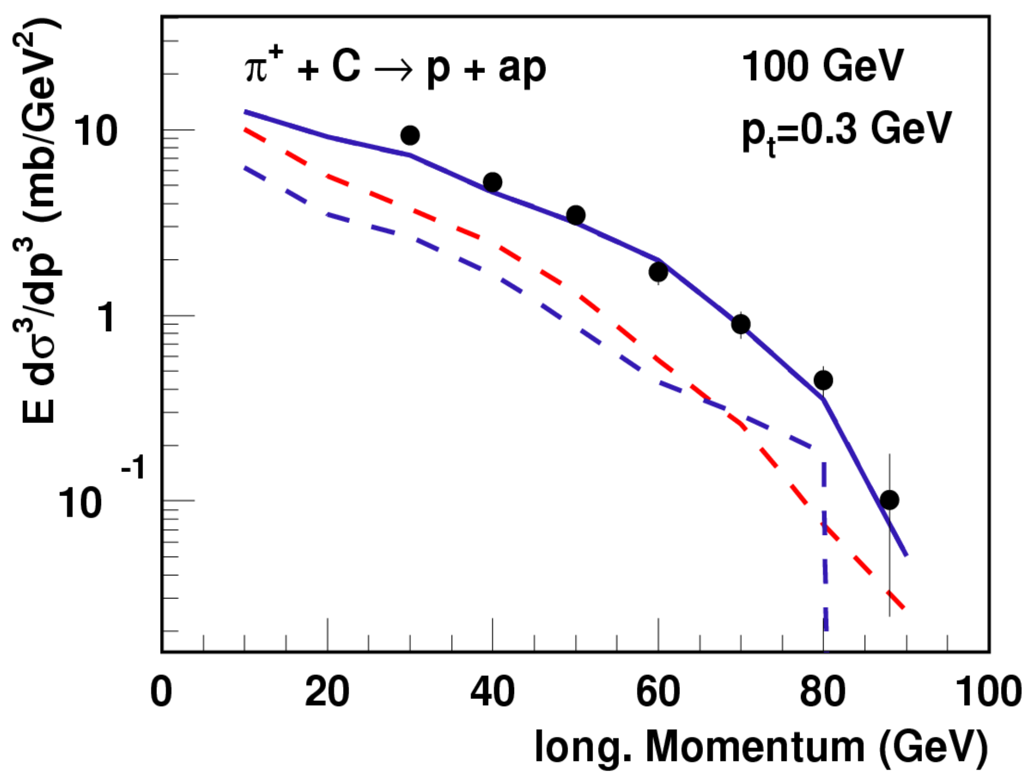


Baryons in Pion-Carbon

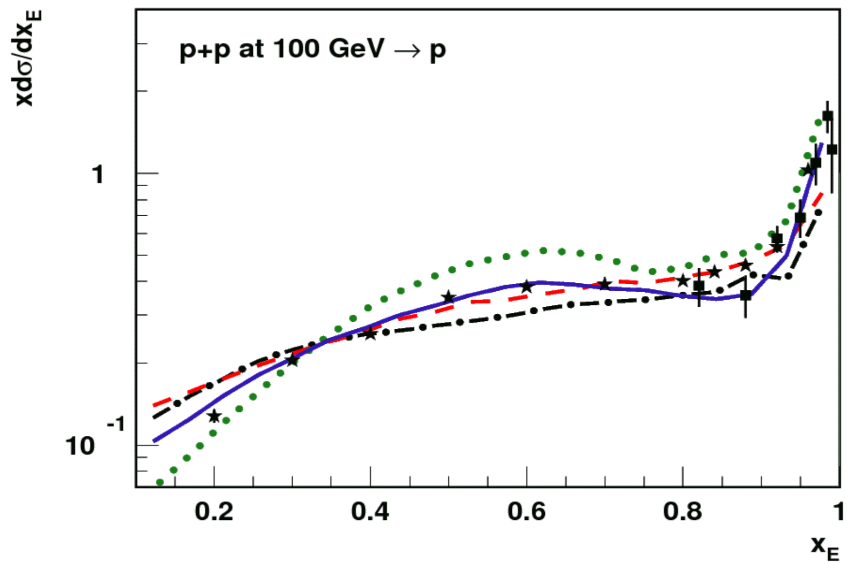
Very few data for baryon production from meson projectile, but for all :

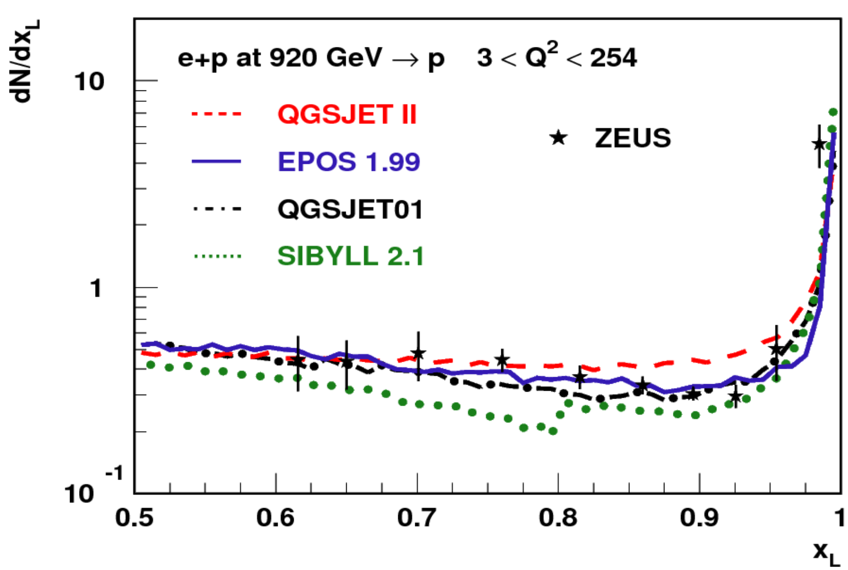
- strong baryon acceleration (probability ~20% per string end)
- proton/antiproton asymmetry (valence quark effect)
- target mass dependence



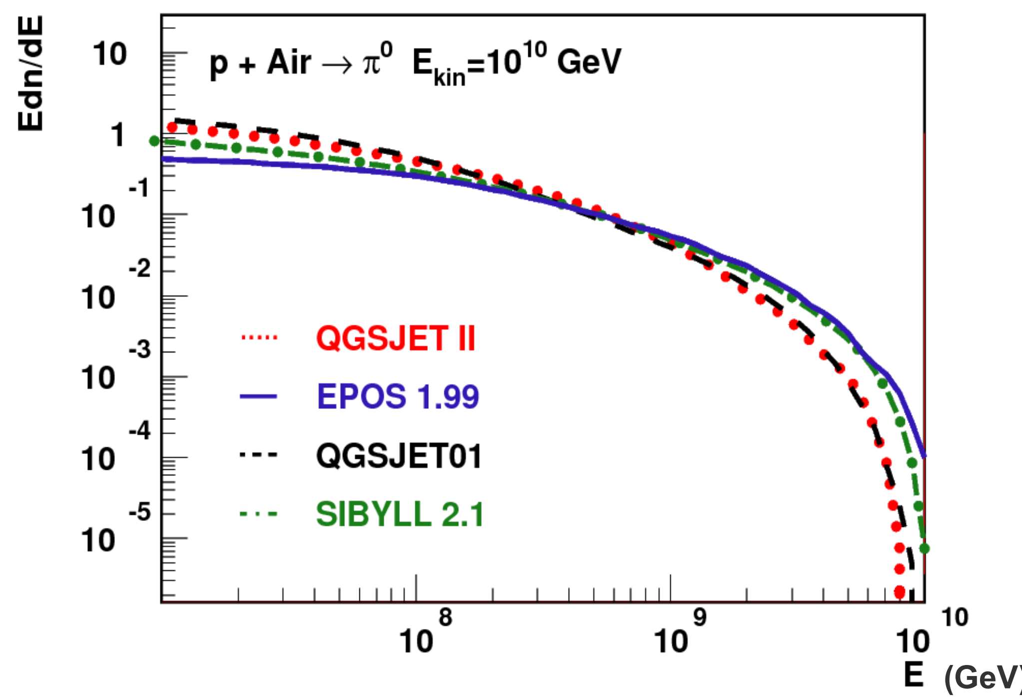


Diffraction and x Distributions



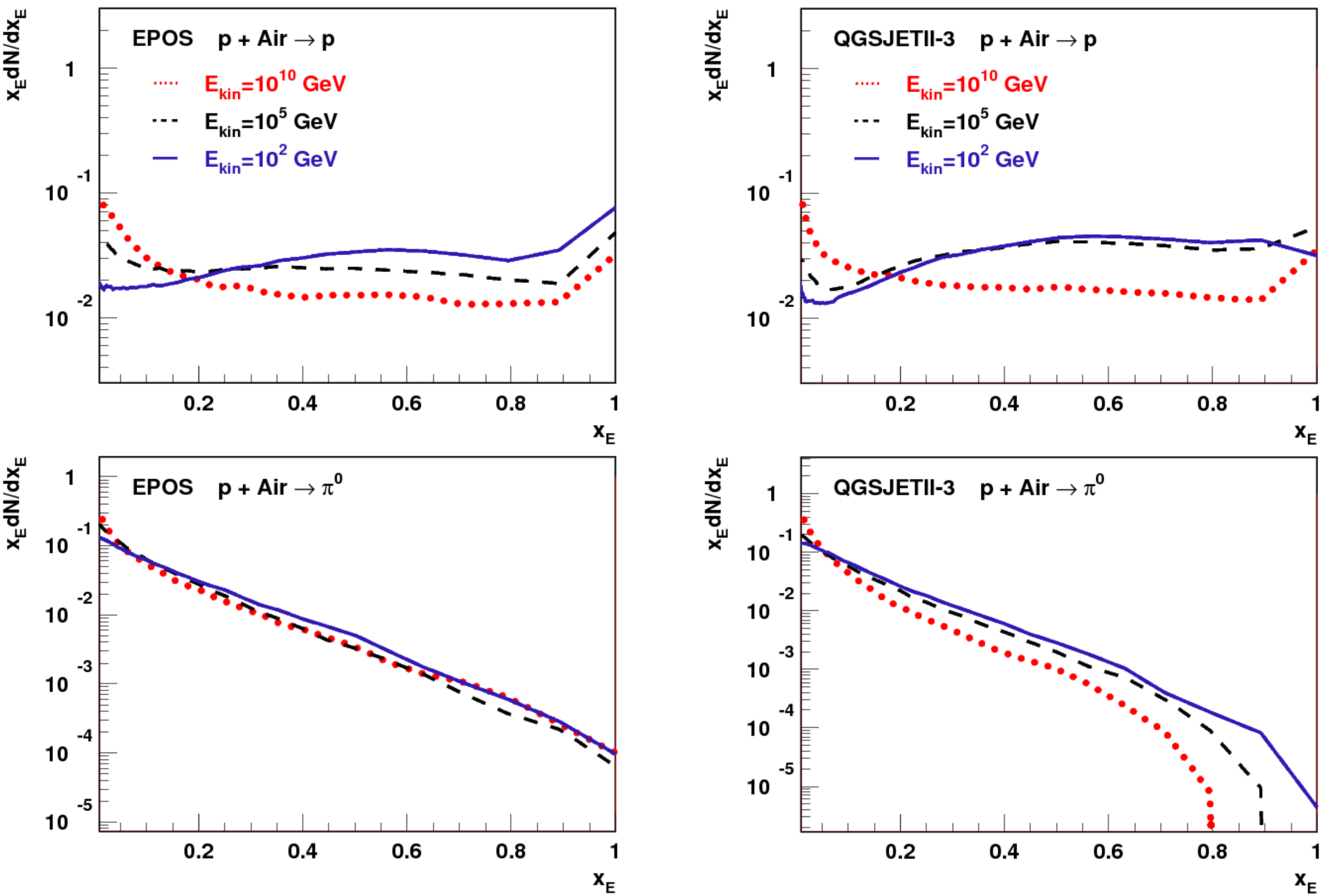


- most of the data at low energy (fixed target experiment)
- extrapolation tested with HERA data
- But large differences at CR energies



LHCf results very important

Scaling with Energy

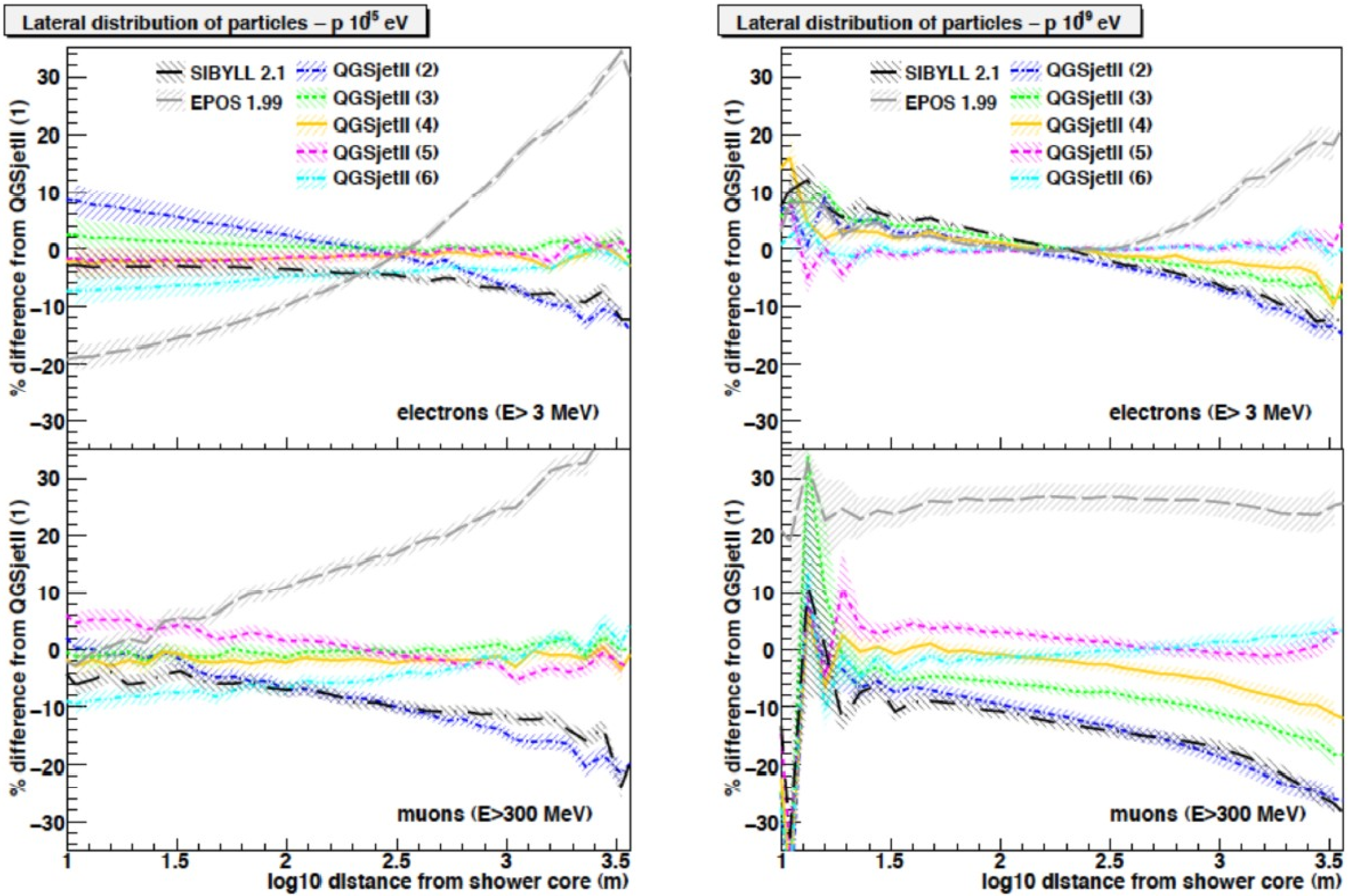


Lateral Distribution Function and Pt

- **Electromagnetic particles and muons detected far from the core produced by pions with low longitudinal momentum**
  - ➔ Transverse momentum (Pt) important
    - Detailed treatment in EPOS
  - ➔ <Pt> of baryons larger than the one from pions
    - More baryons in EPOS : <Pt> larger
    - Effect increase by collective effect

EPOS have flatter LDF due to the baryons and their <Pt>

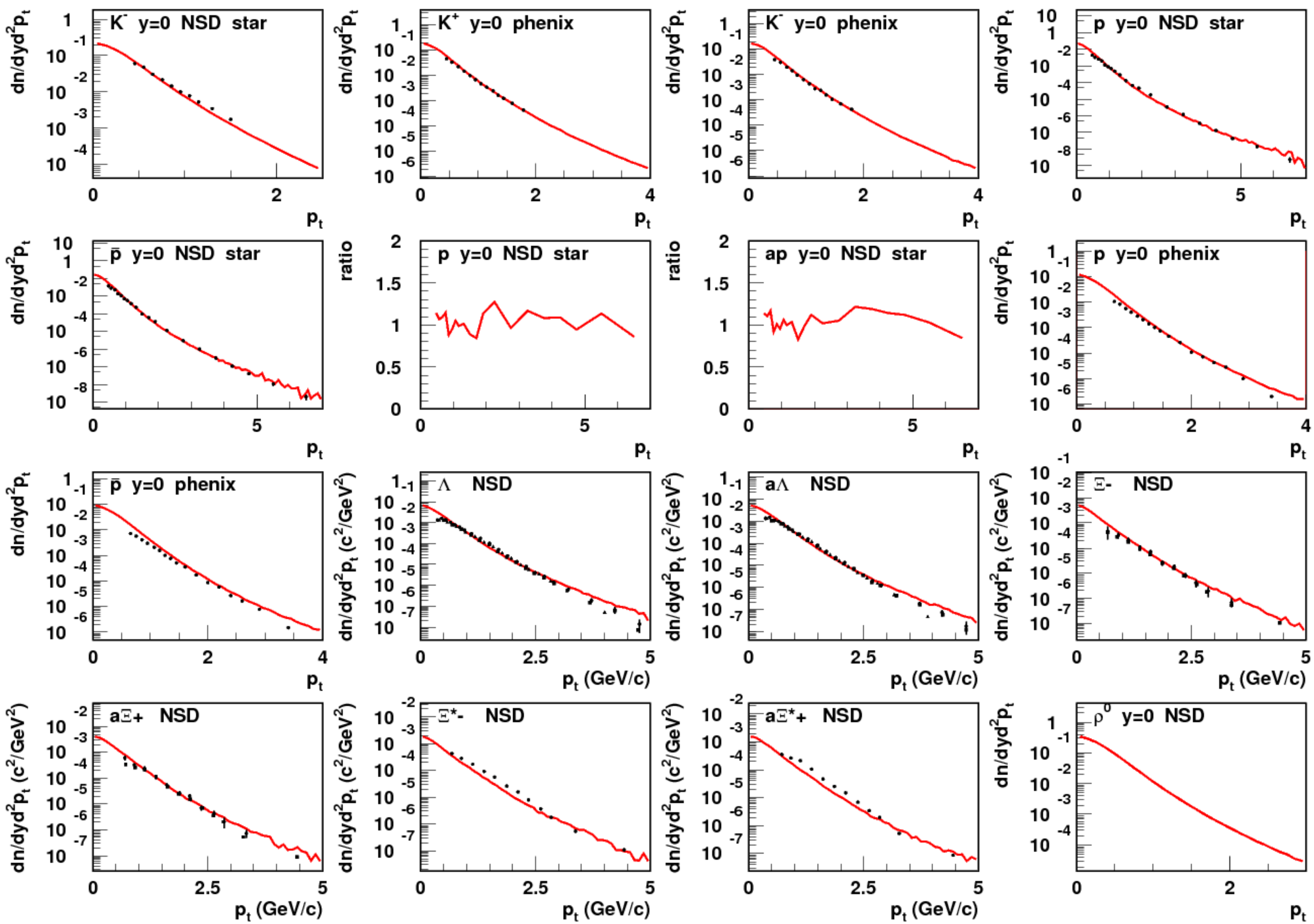
LDF



cf. J. Knapp talk this morning

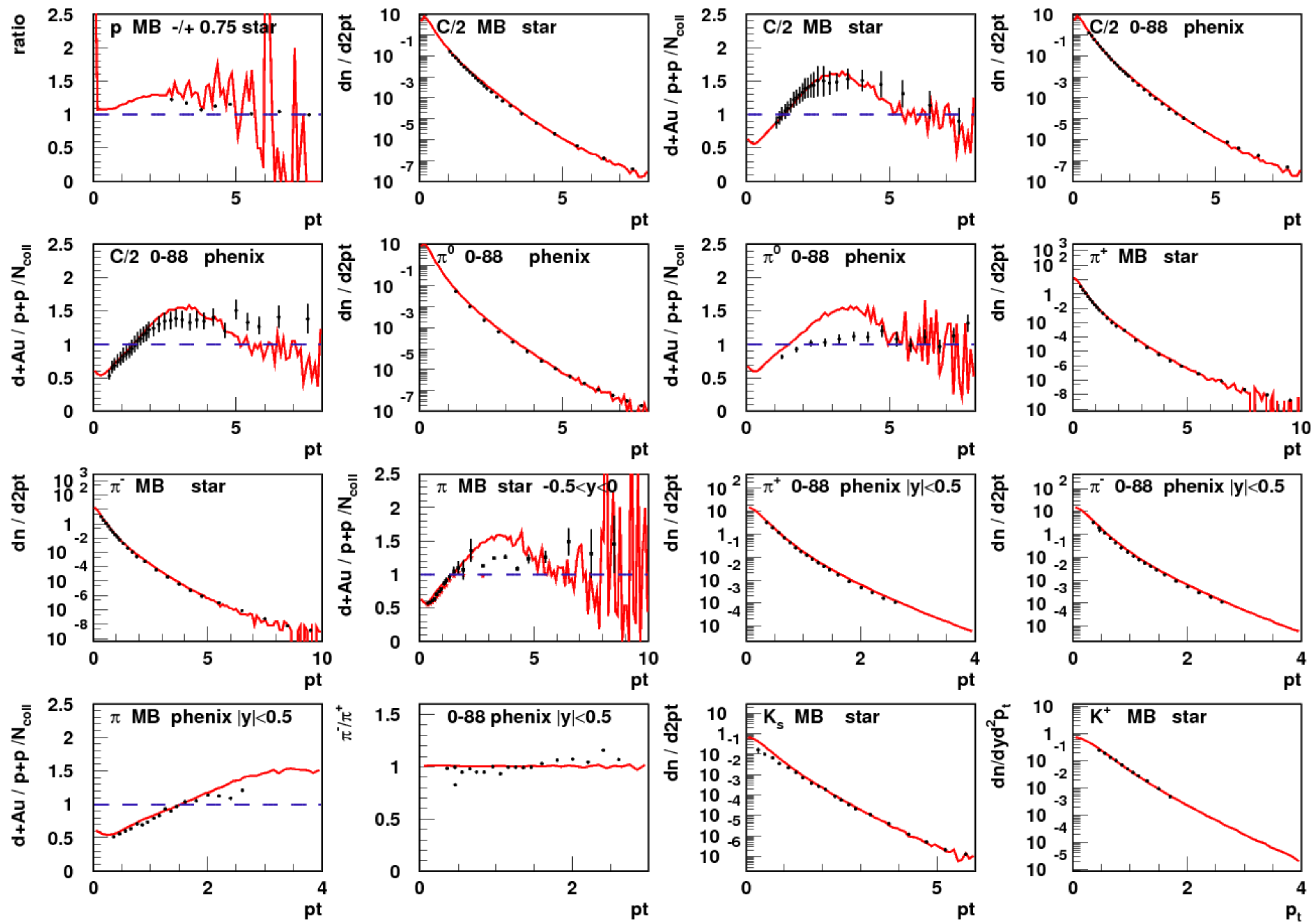
pp @ 200 GeV

EPOS reference spectra for RHIC



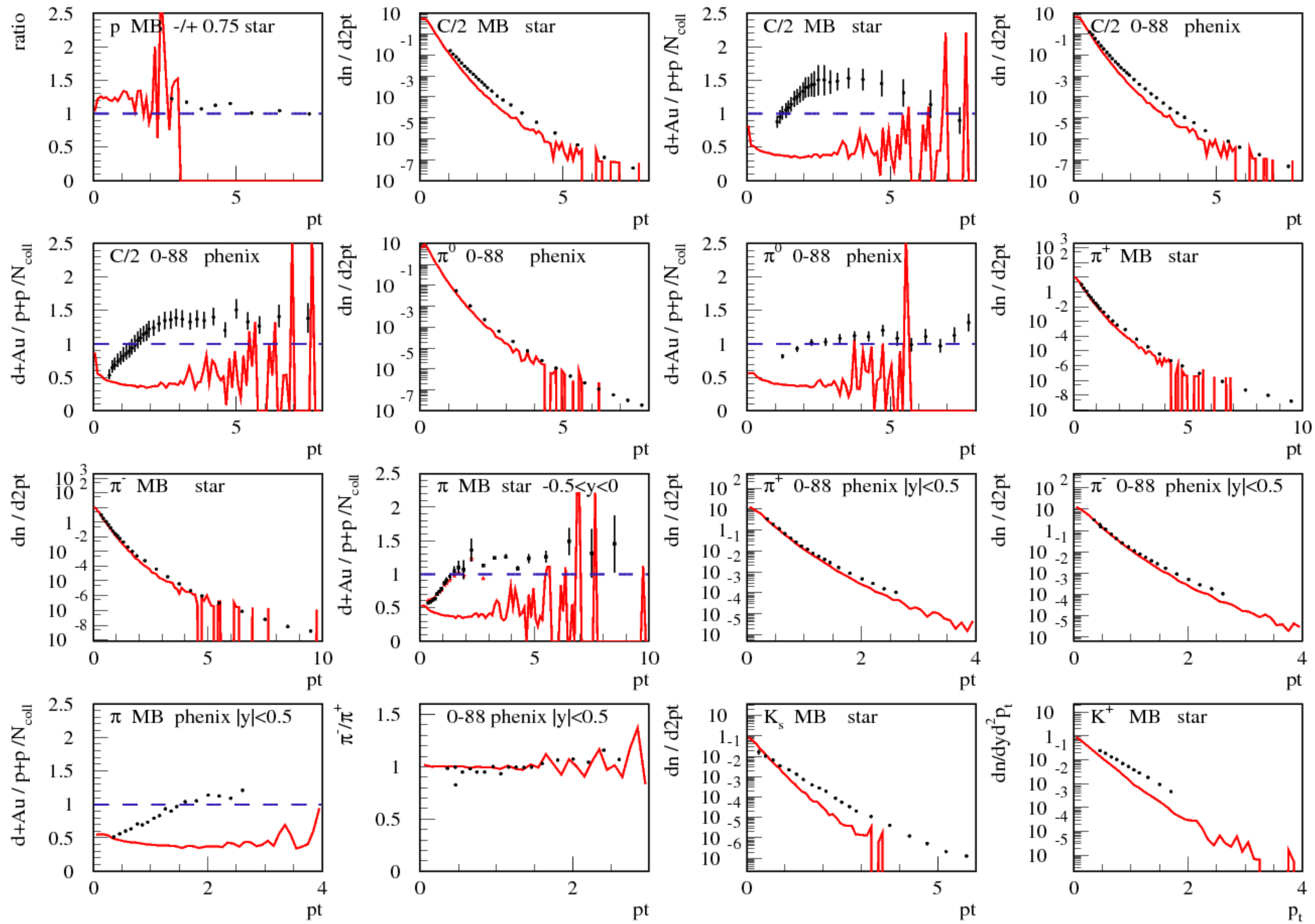
dAu @ 200 GeV

- **EPOS tested at RHIC**



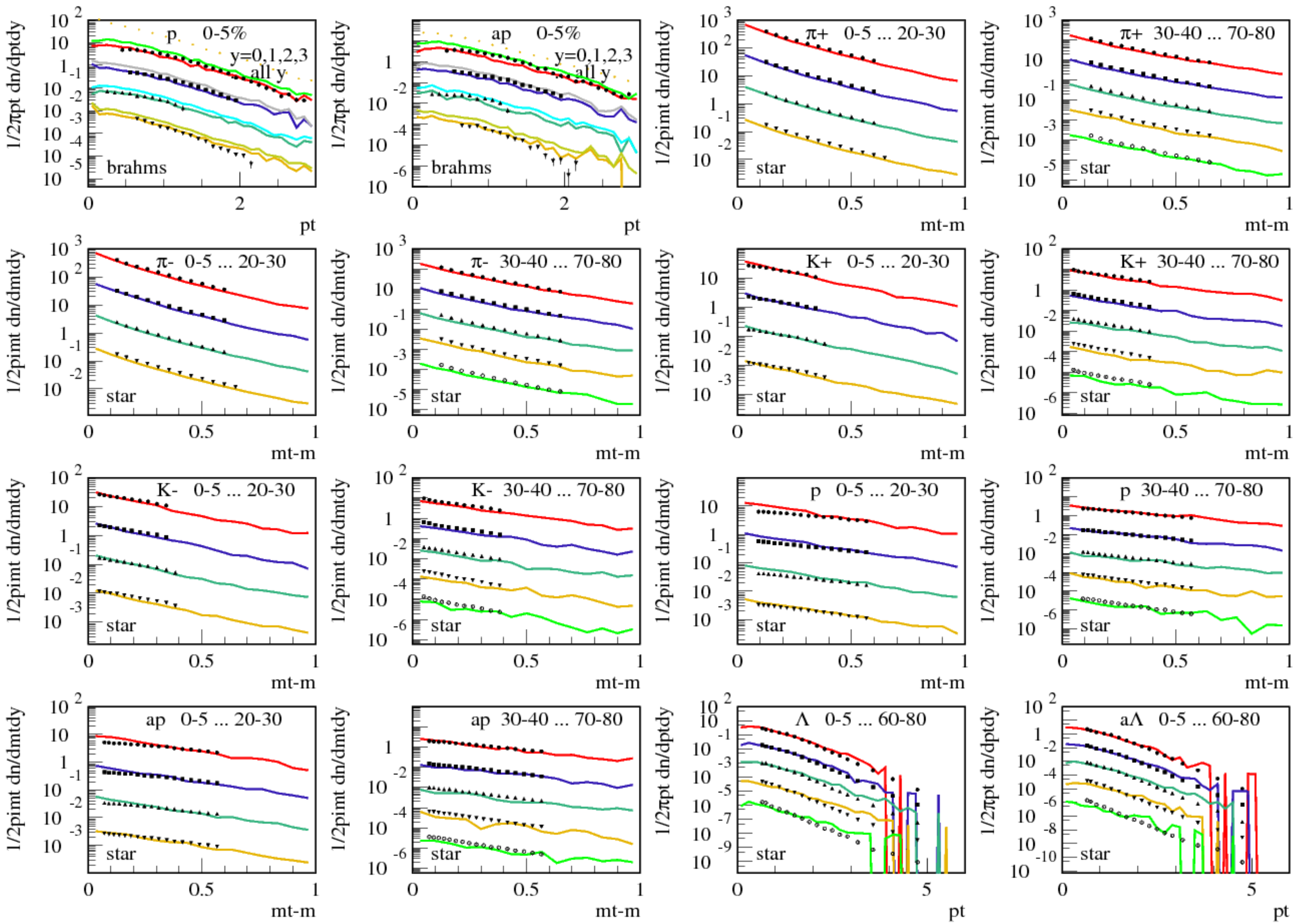
dAu @ 200 GeV

- **QGSJETII results : not trivial**

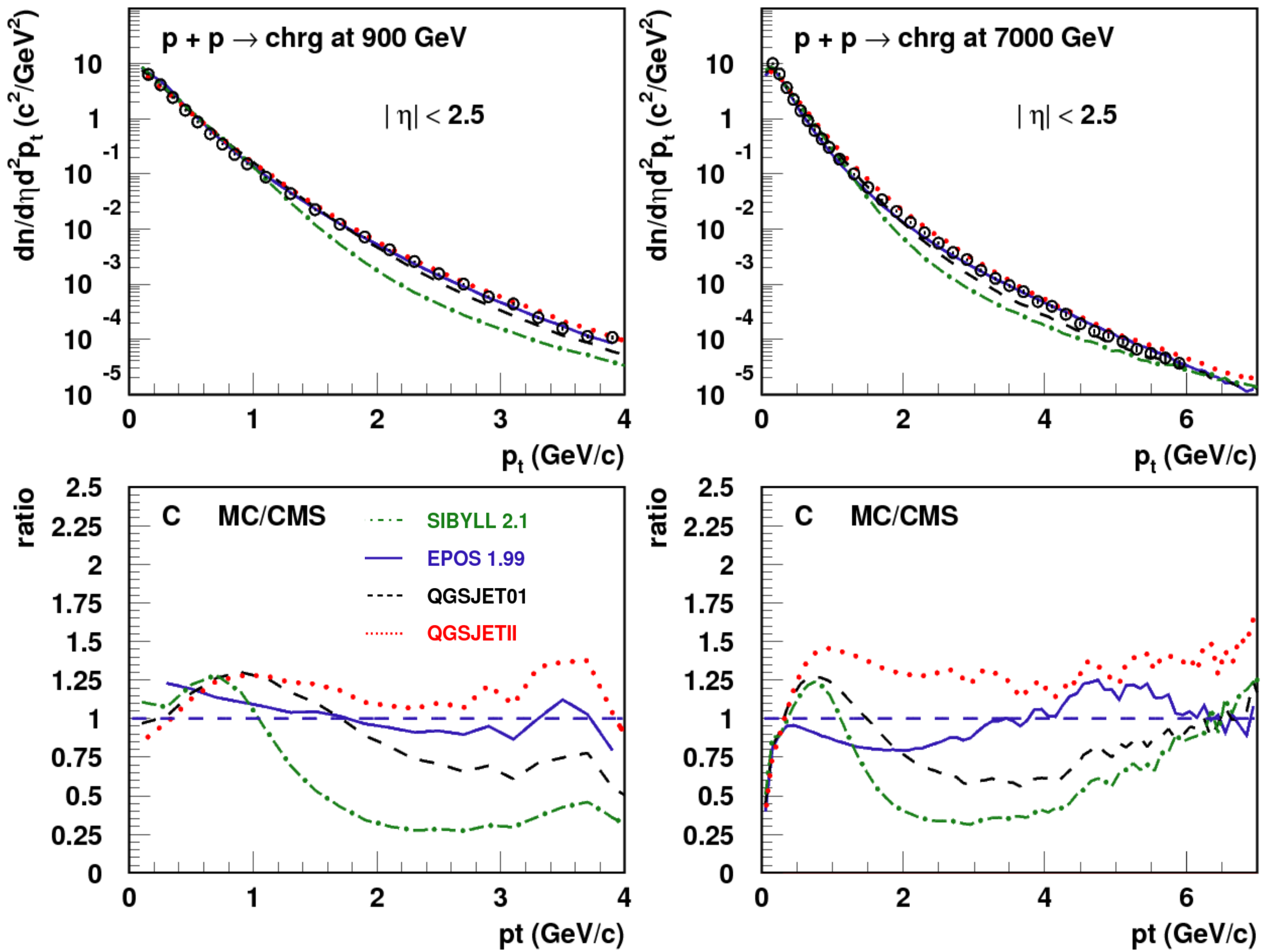


AuAu @ 200 GeV

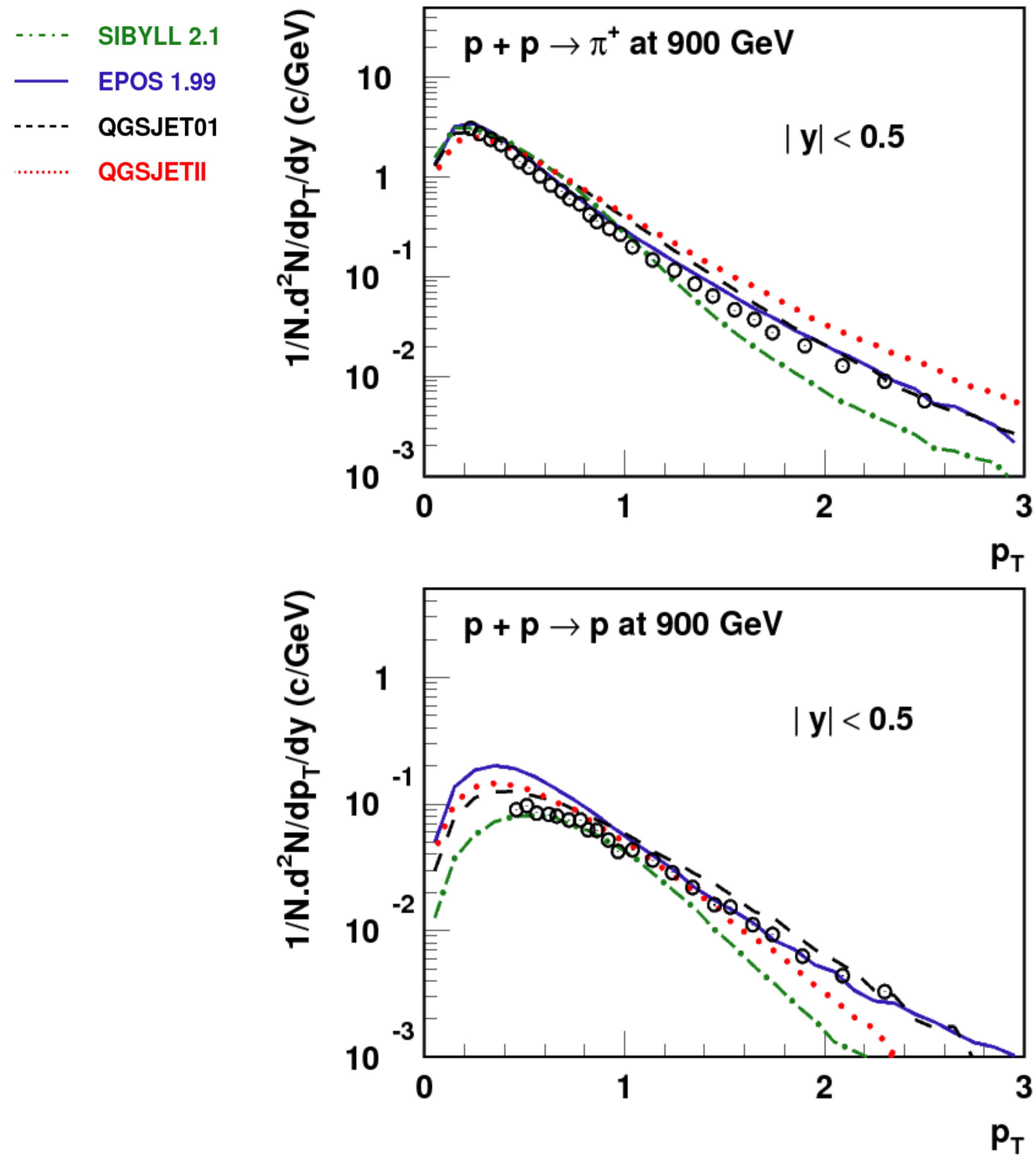
- **EPOS used for heavy ion collisions**

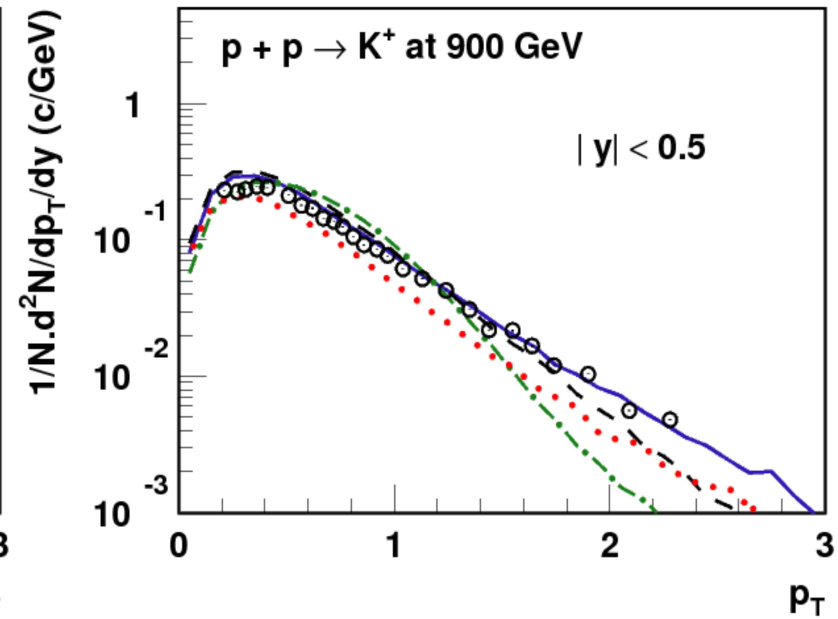


CMS Transverse Momentum p_T



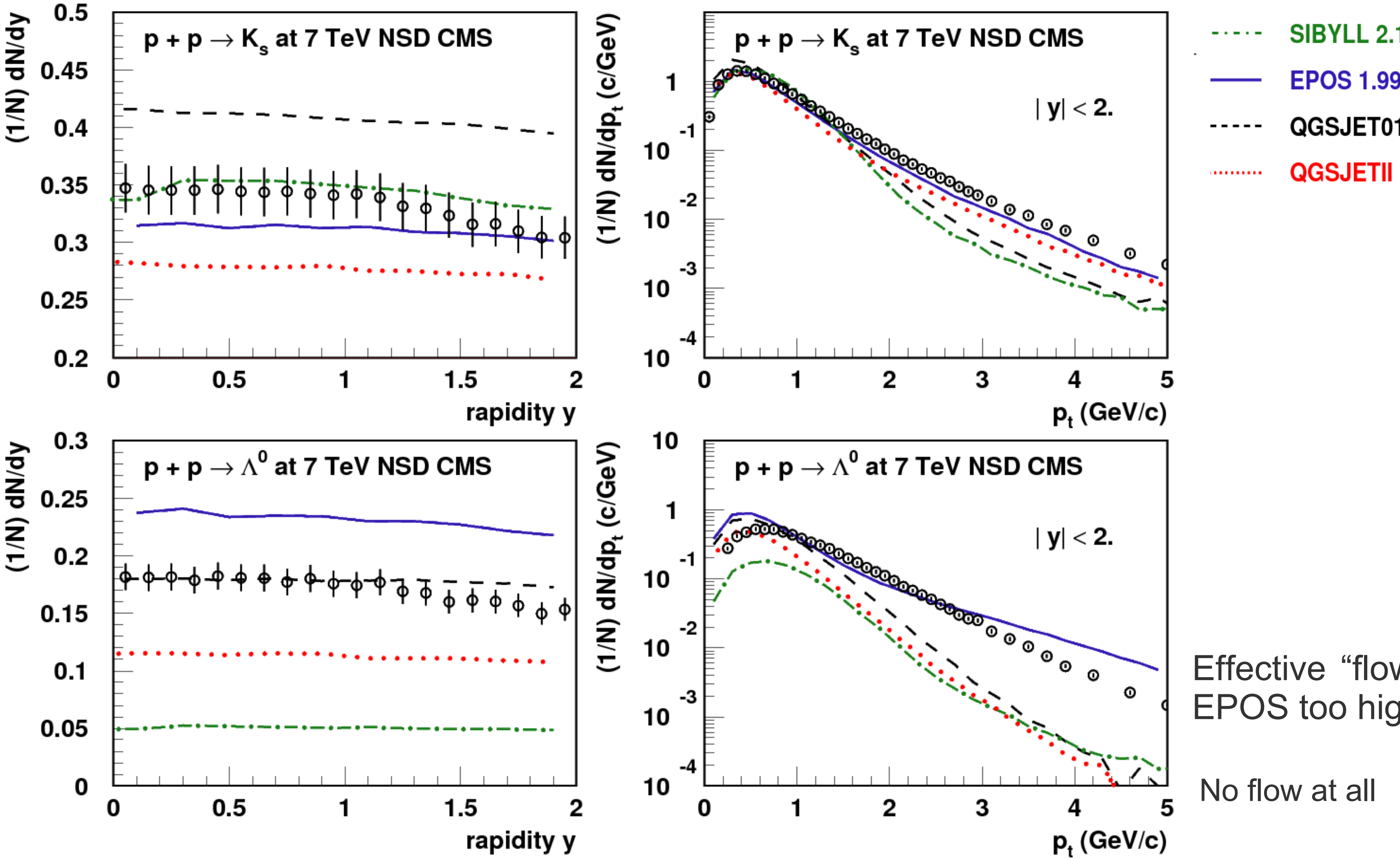
ALICE Identified Spectra 900 GeV





- **Individual particles**
  - EPOS OK (proton ?)
  - QGSJET01 OK !
  - QGSJETII Pion mean p_T too large

CMS Strangeness 7 TeV



Effective "flow" in EPOS too high

No flow at all

Summary

- **EPOS = hadronic interaction model constructed to understand accelerator data and used for CR**
  - Multiple scattering done on a solid theoretical basis
  - Treats nonlinear effects (=>dAu@RHIC)
  - Collective effects
  - Carefully tested (hh, hA, AA)
  - “Mini-plasma” in pp at LHC (900 GeV) and higher energy
- **EAS with EPOS**
  - deeper shower
  - more muons because of baryons
  - now compatible with all cosmic ray experiment (KASCADE, KASCADE-Grande, CASA-MIA, Yakutsk, Auger, …)
    - consistent but not the same primary mass than QGSJET !

Outlook

- **EPOS 2 :**
  - Improved screening and diffractive treatment to multiple scattering in better agreement with LHC
  - Complete 3D hydrodynamical calculation
- **Hydro on event-by-event basis :**
  - for AuAu@RHIC, explains naturally nontrivial features as “ridge” correlations, elliptical flow
  - Explains some nontrivial pp results (ridge, BE correlations)
- **On-going developments :**
  - Test all Min Bias LHC data
  - Improvement of hard events (jets) in MB
  - Selection of hard processes (specific born Pt)
  - Both at the same time : underlaying events