

# Hard-soft correlations in the EPOS event generator

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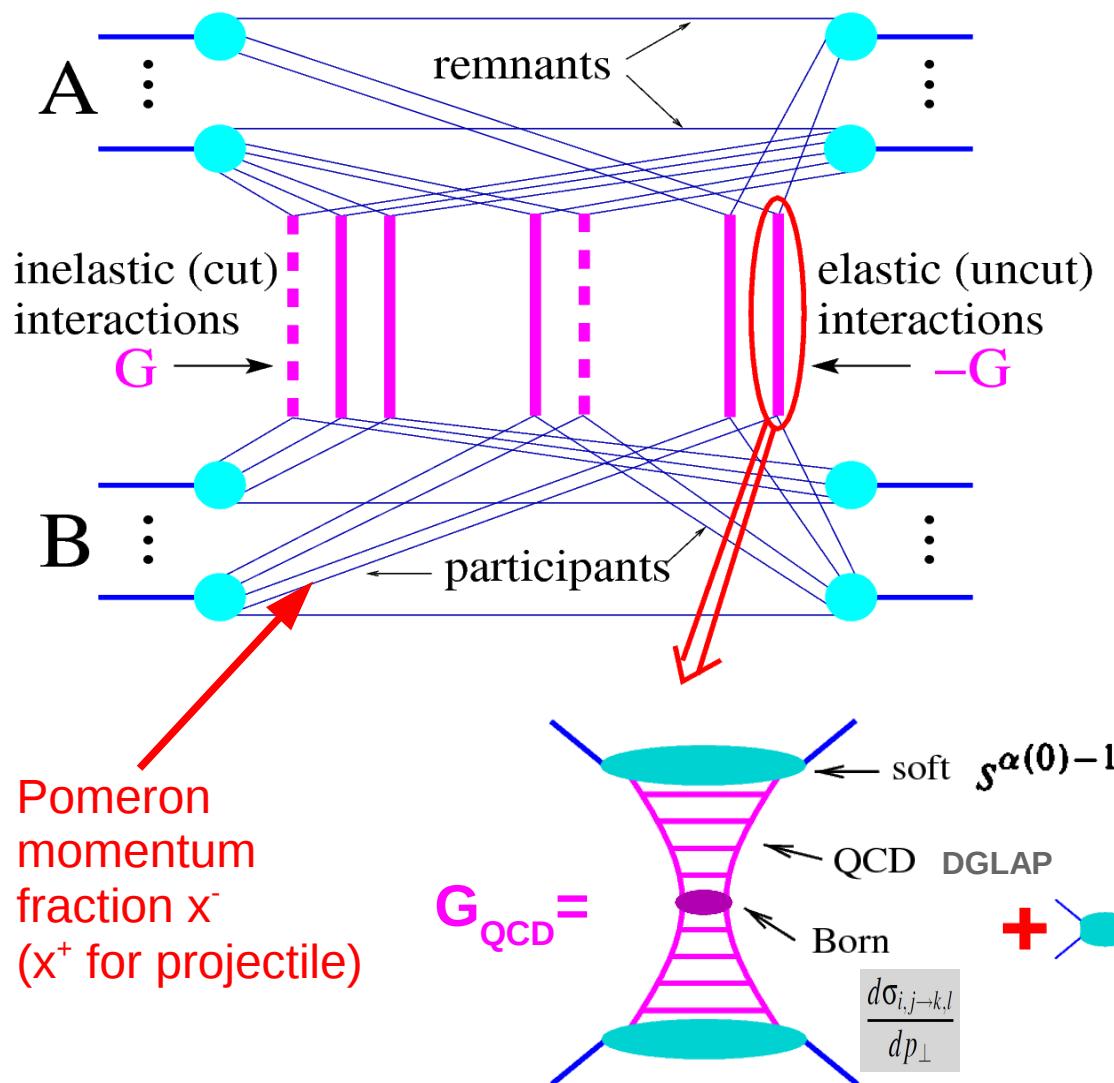


**Workshop GDR QCD, Clermont-Ferrand, France**  
**July the 23<sup>rd</sup> 2018**

# Outline

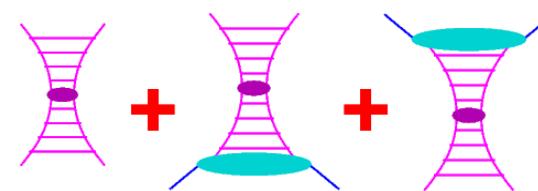
- EPOS Basic principles
- Non-perturbative scale  $Q_0^2$  ?
  - which dependence ?
- Preliminary results
  - transverse momentum for multiplicity classes
  - charm production
  - underlying events
  - $R_{pA}$
- Summary

# Parton-Based Gribov-Regge Theory



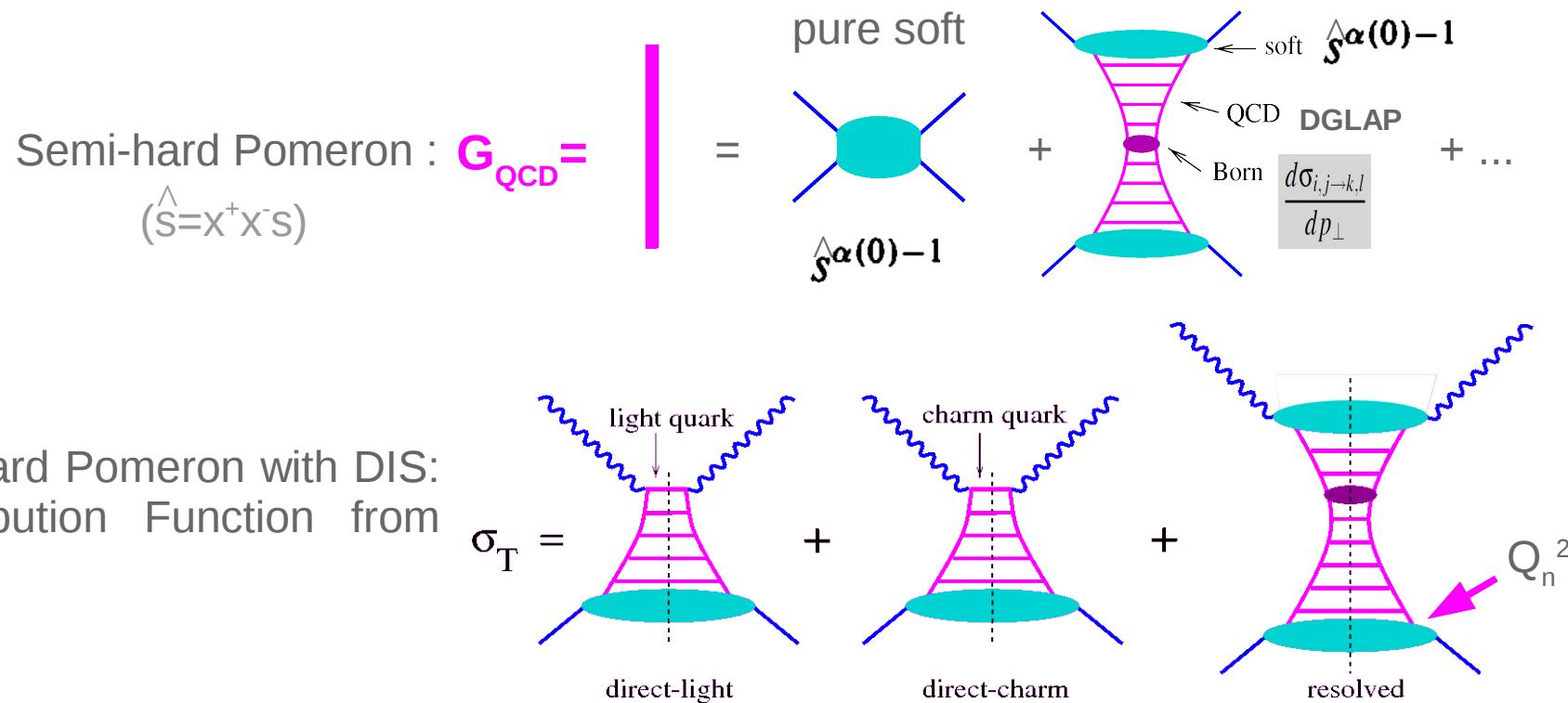
## Energy sharing at the cross section level

- Energy shared between cut and uncut diagrams (Pomeron)
- Reduced number of elementary interactions
- Generalization to (h)A-B
- Particle production from momentum fraction matrix (Markov chain metropolis)
- Theory based Pomeron definition



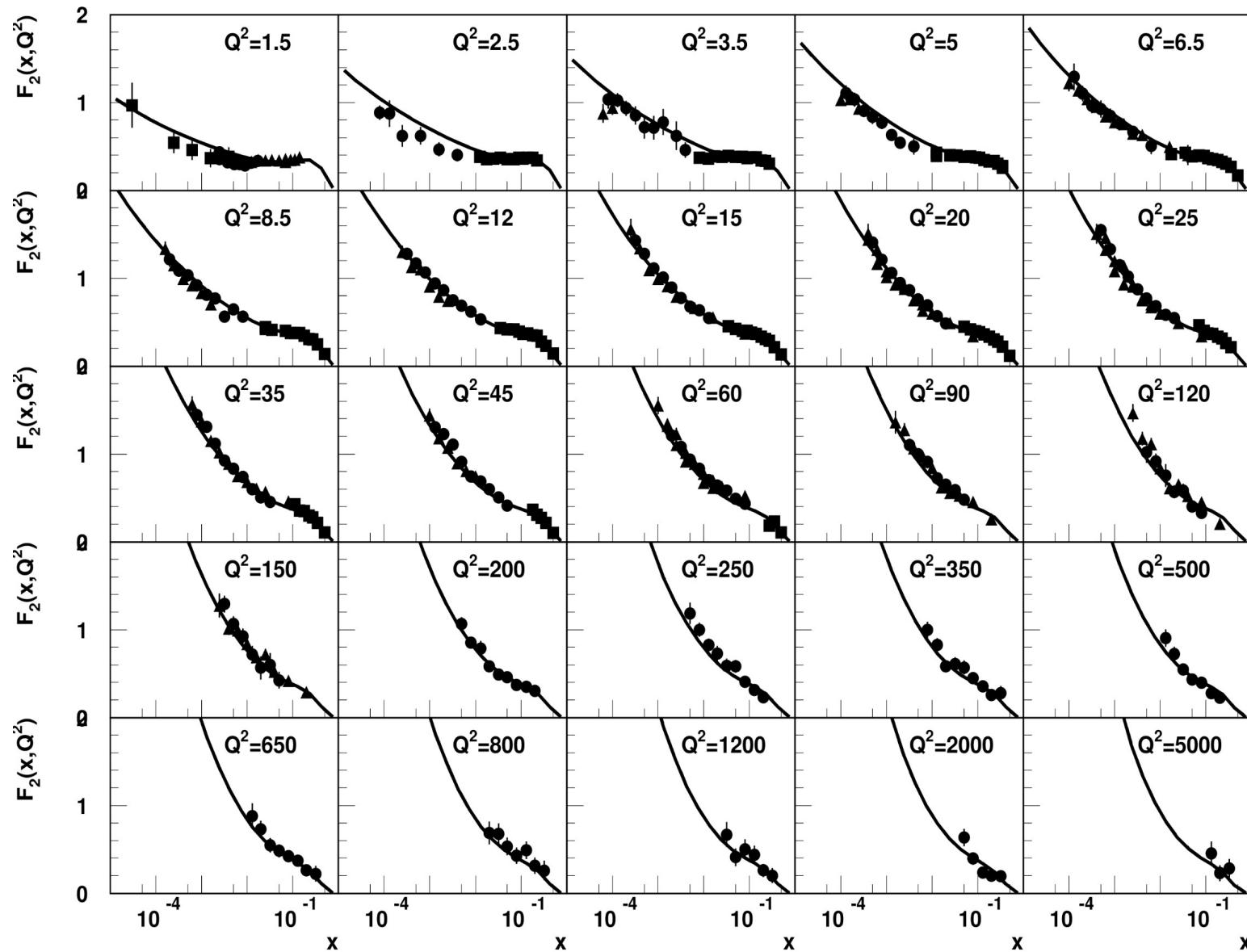
**Parton-based Gribov-Regge Theory**, H. J. Drescher, M. Hladik, S. Ostapchenko, T. Pierog, and K. Werner, Phys. Rept. 350 (2001) 93-289;

# EPOS : Pomeron Definition

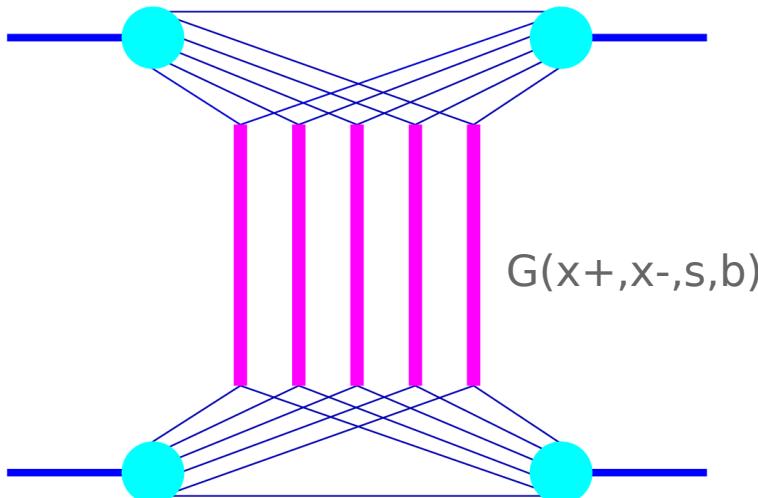


- Theory based Pomeron definition
- pQCD based (DGLAP and Born)
  - ✚ large increase at small  $x$  (without saturation)
- External pdf only for valence quark
- Minimum non-perturbative scale  $Q_n^2 = 2 \text{ GeV}^2$  with soft pre-evolution  $s^{\alpha(0)-1}$
- $F_2$  from HERA used to fix parameters for sea quarks and gluons below  $Q_n^2$

# EPOS Parton Distribution Function $Q_n^2=2 \text{ GeV}^2$



# Cross Section Calculation : EPOS



- Gribov-Regge but with energy sharing at parton level (Parton Based Gribov Regge Theory)
- amplitude parameters fixed from QCD and pp cross section (semi-hard Pomeron)
- cross section calculation take into account interference term

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

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

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

# EPOS – non-linear effects

Well known problem with pQCD based Pomerons

→ total cross-section too high : MPI required

→ in EPOS <Pomerons> fixed by b-dep of Pomeron amplitude (slope)

→ effective coupling introduced to mimic effect of enhanced diagrams and reduce cross-section (screening effect) to get cross-section AND multiplicity right in p-p, p-A and AA

→ Amplitude  $G_{\text{eff}}$  no longer fit to  $G_{\text{QCD}}$

No effective coupling

$$G_{\text{QCD}} \sim (x_1 x_2)^\beta$$

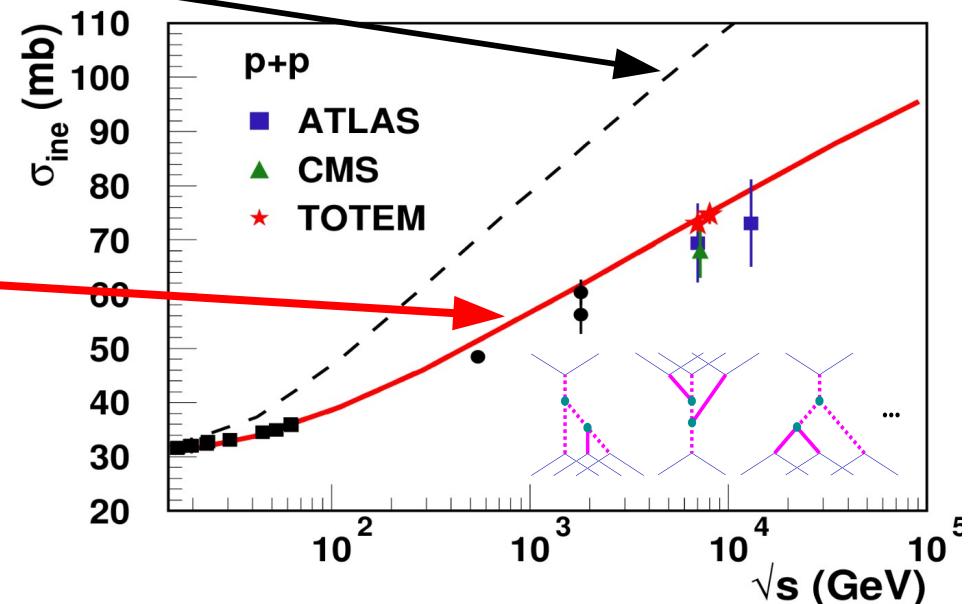
With effective coupling

$$G_{\text{eff}} \sim x_1^\beta x_2^{\beta-\varepsilon}$$

Parametrization

$$\varepsilon_S = a_S \beta_S Z(s, b, A)$$

$$\varepsilon_H = a_H \beta_H Z(s, b, A)$$



# Particle Production in EPOS

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

→ m cut Pomerons from :

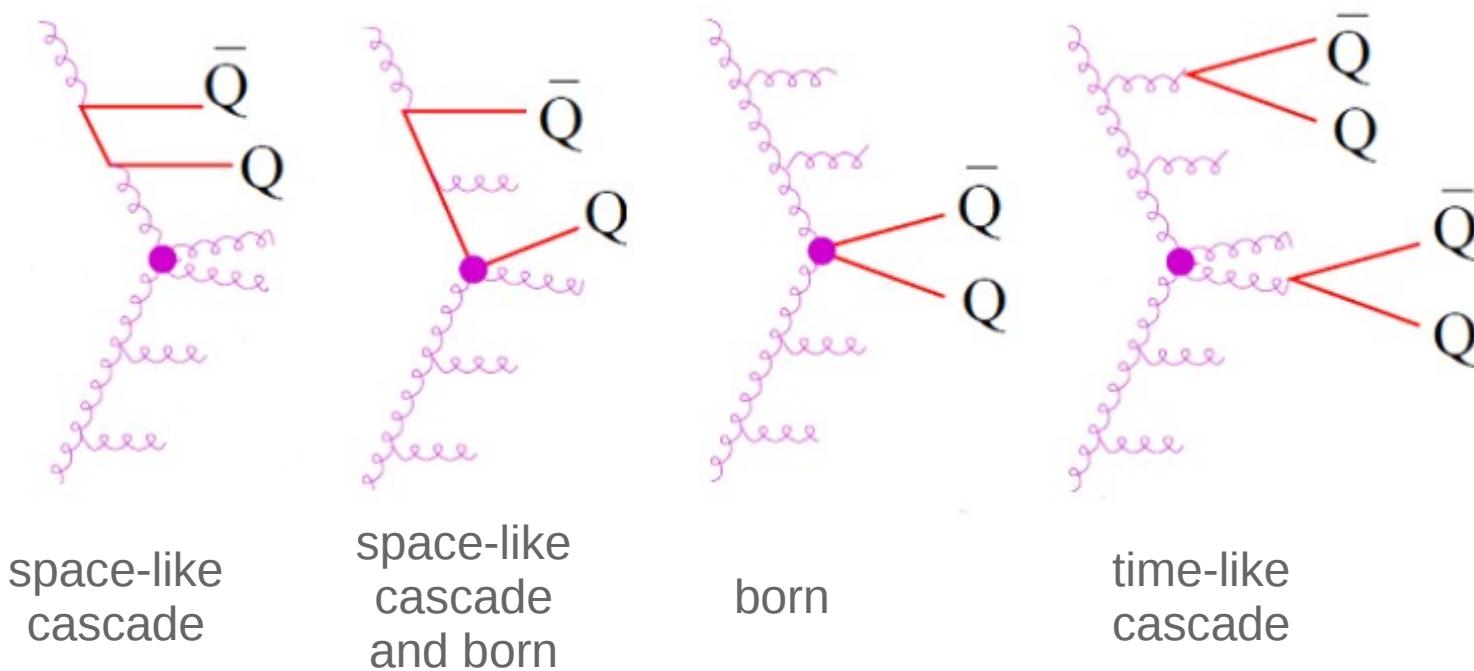
$$\Omega_{AB}^{(s,b)}(m, X^+, X^-) = \prod_{k=1}^{AB} \left\{ \frac{1}{m_k!} \prod_{\mu=1}^{m_k} G(x_{k,\mu}^+, x_{k,\mu}^-, s, b_k) \right\} \Phi_{AB}(x^{\text{proj}}, x^{\text{targ}}, s, b)$$

- m and X fixed together by a complex Metropolis (Markov chain)
- 2m “kinky” 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

Consistent treatment of cross section and particle production:  
number AND distribution of cut Pomerons depend on cross section

# Heavy Flavor Production

Heavy flavor production included in perturbative ( $Q^2 > Q_n^2$ ) calculation in EPOS 3

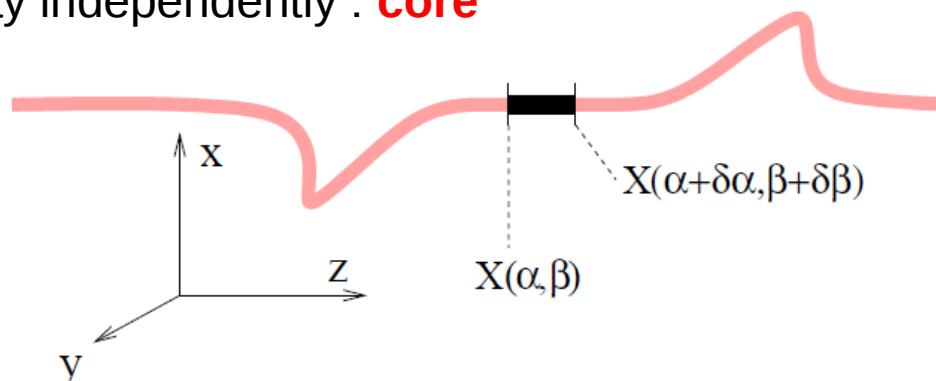
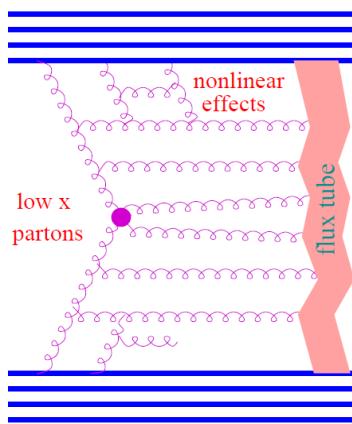


- “parameter free” : good test of hard Pomeron
- Heavy quarks ( $Q$ ) taken as string-end for the hadronization

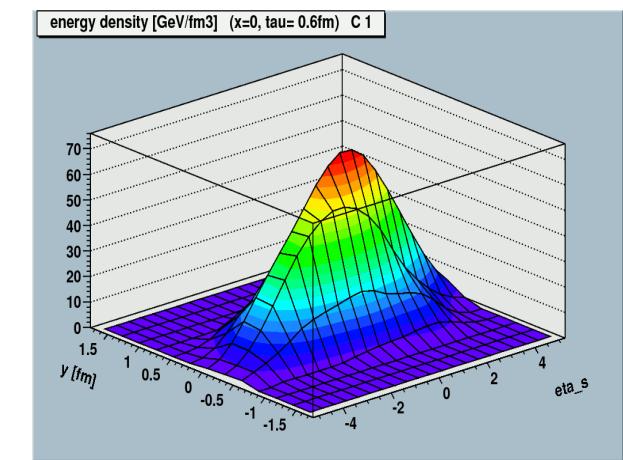
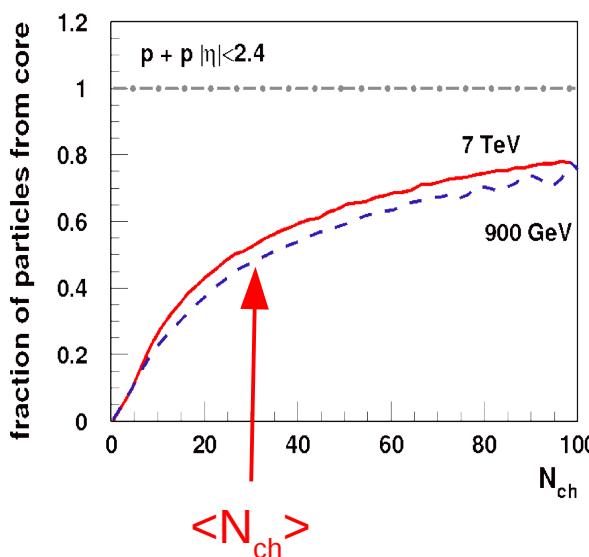
# High Density Core Formation

## Heavy ion collisions or high energy proton-proton scattering:

- the usual procedure has to be modified, since the density of strings will be so high that they cannot possibly decay independently : **core**

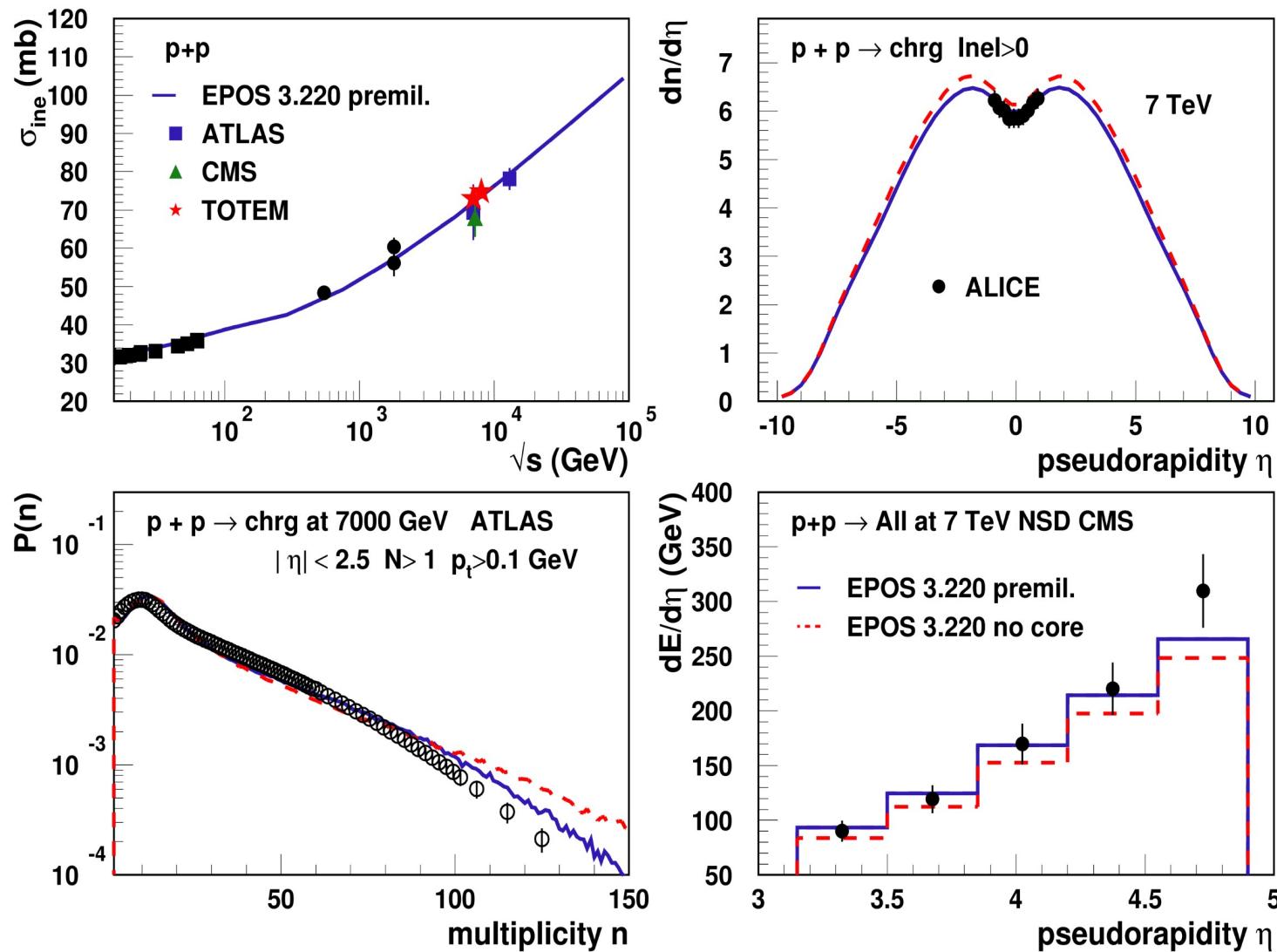


- Each string split into a sequence of string segments, corresponding to widths  $\delta\alpha$  and  $\delta\beta$  in the string parameter space
- If energy density from segments high enough
  - ◆ segments fused into core
    - full 3D+1 hydro evolution
    - lattice QCD EoS
- If low density (corona)
  - ◆ segments remain hadrons
    - string fragmentation



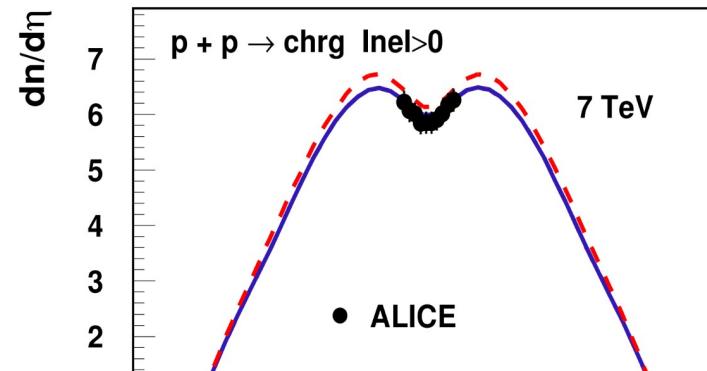
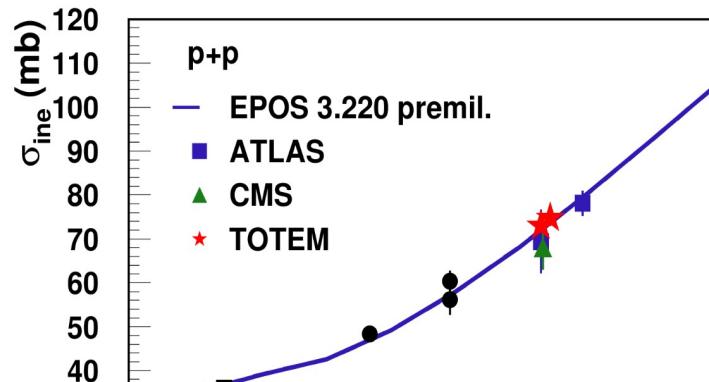
# Preliminary Results : With/out Core

Excellent results for minimum bias soft physics

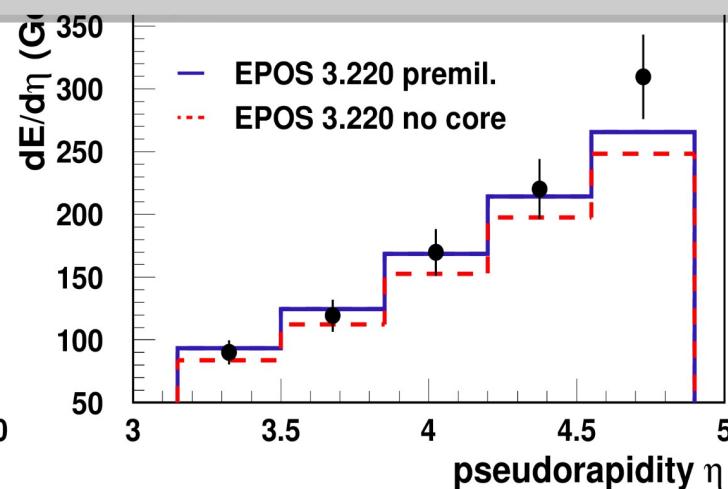
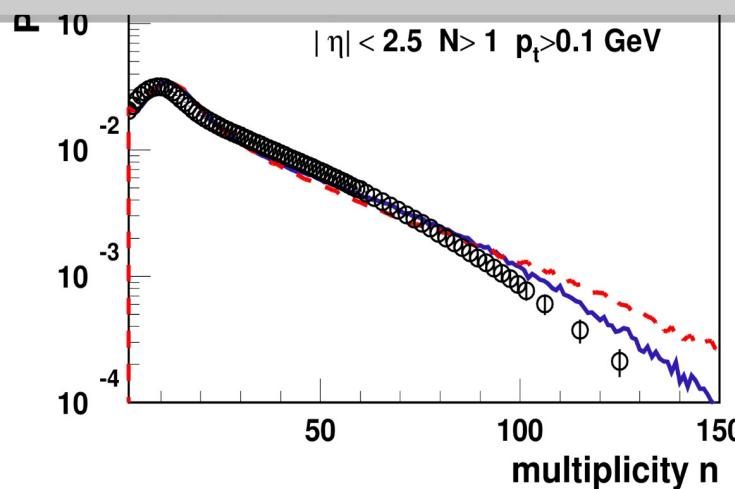


# Preliminary Results : With/out Core

Excellent results for minimum bias soft physics



Nice but what to do with harder scales ? Jets, UE, etc ...  
Can we recover  $G_{\text{QCD}}$  ?



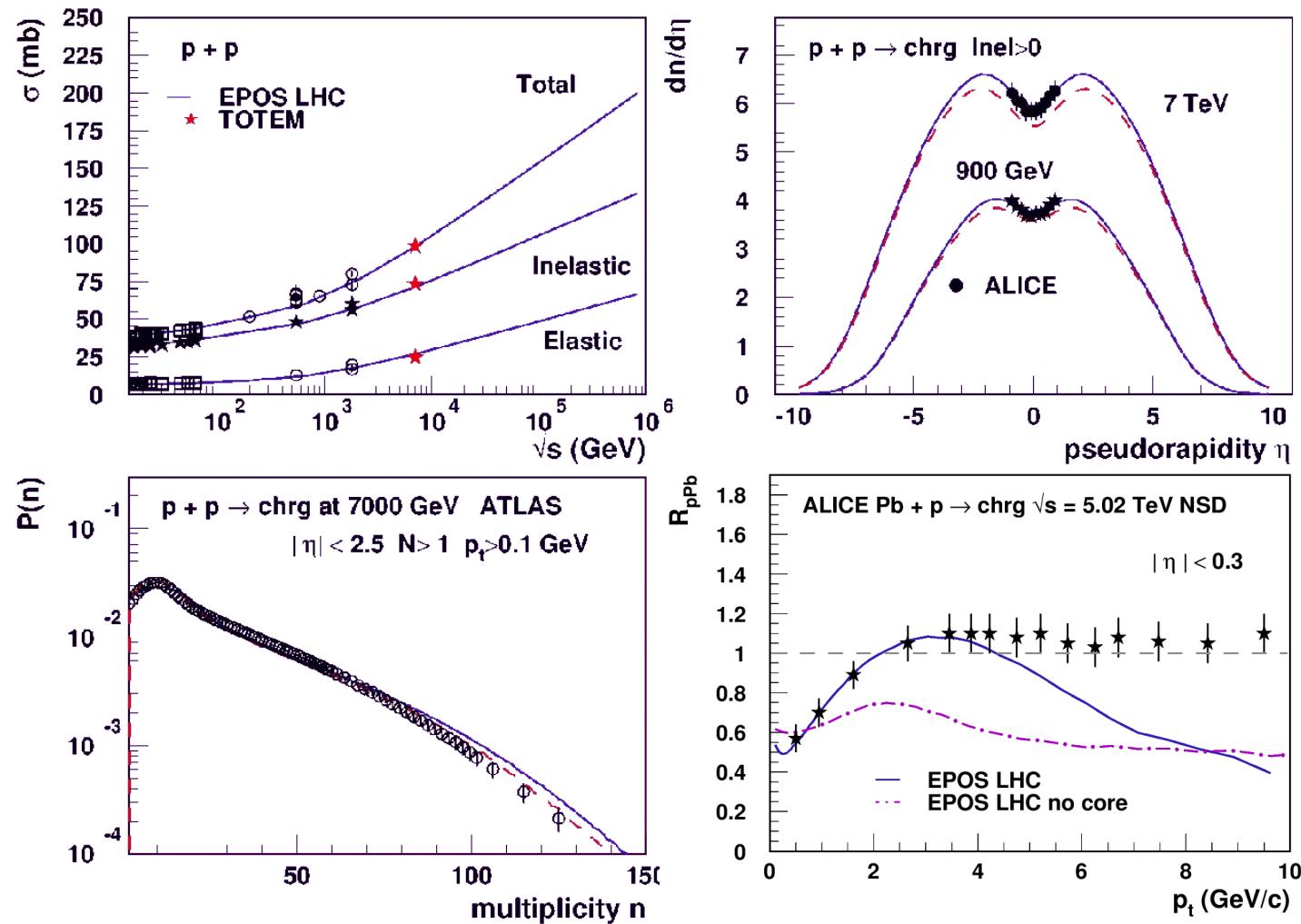
# EPOS LHC : Fixed $Q_0^2$ (old)

- Excellent results for soft physics
  - cross-section, multiplicity, etc ...

- Problem for hard processes

- lack of high  $p_t$
- no binary scaling for pA or AB

Since  $Q_0^2$  is fixed both low and high  $p_t$  are suppressed: in contradiction with data.



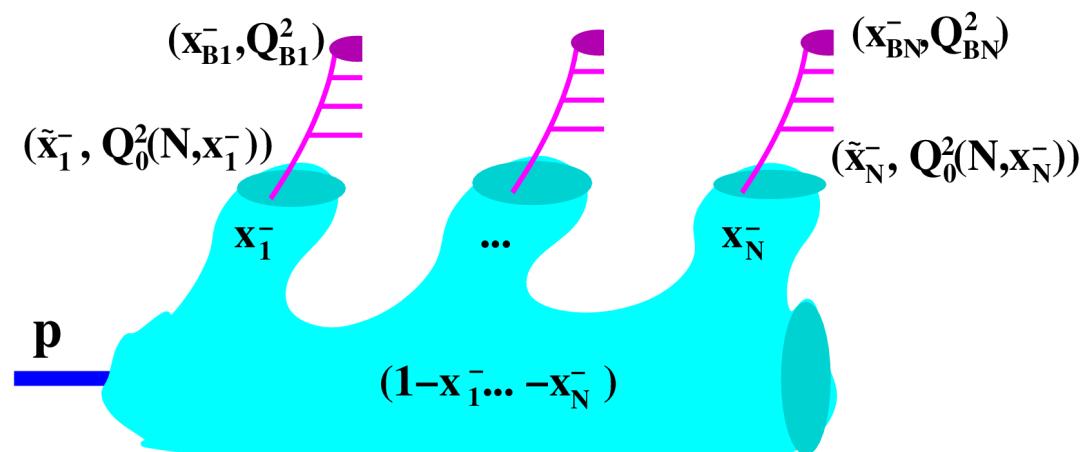
# Jet Production in EPOS

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

→ m cut Pomerons from :

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

- m(=N) and  $X=\{x_1, \dots, x_N\}$  fixed together by a complex Metropolis (Markov chain)
- if  $G_{\text{eff}} = G_{\text{QCD}}$  then each hard elementary interaction will be a minijet



**EPOS as an N-pdf generator (event-by-event) if  $Q_0^2(N, x)$  could be determined !**

# Non-perturbative Scale $Q_0^2$

- Model property : AGK cancellation

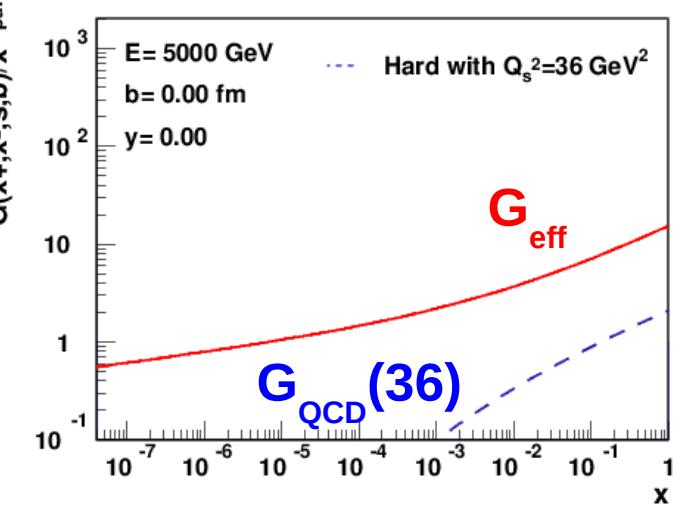
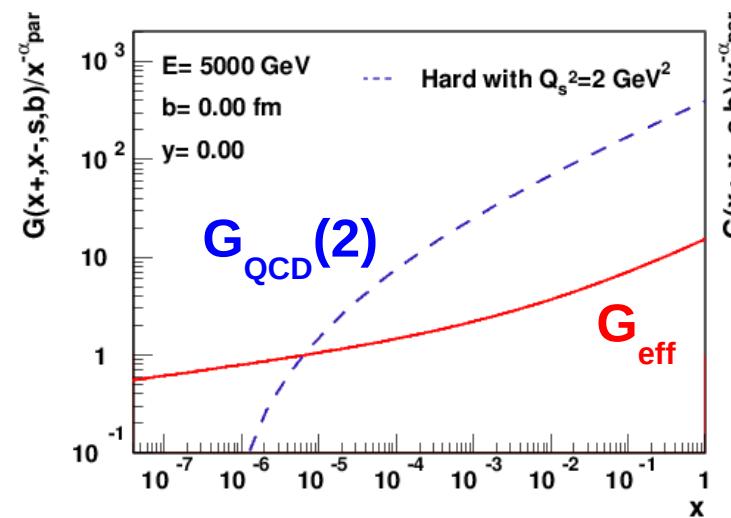
$$\begin{aligned} \frac{dn_{\text{Pom}}^{h_1 h_2}}{dx^+ dx^-}(x^+, x^-, s, b) &= \frac{dn_{\text{Pom}}^{(1) h_1 h_2}}{dx^+ dx^-}(x^+, x^-, s, b) \\ &= G_{\text{eff}}(x^+, x^-, s, b) F_{\text{remn}}^{h_1}(1 - x^+) F_{\text{remn}}^{h_2}(1 - x^-) \end{aligned}$$

- Assumption : factorization should be satisfied at large  $Q^2$

- satisfied if:  $\langle N_{\text{hard}} \rangle G_{\text{QCD}}(x, b, Q_0^2) = G_{\text{eff}}(s, x, b, A)$
- different non-perturbative scale event-by-event and even Pomeron-by-Pomeron depending on momentum fraction x

- Matching amplitude

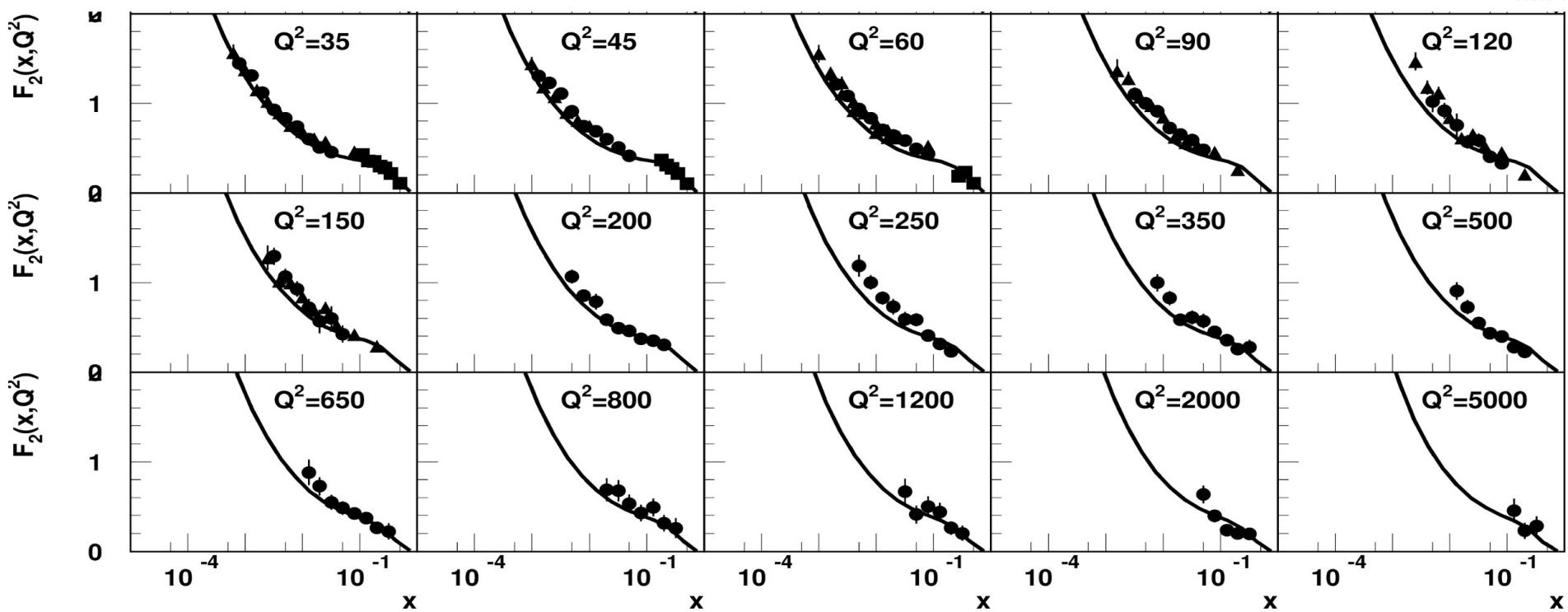
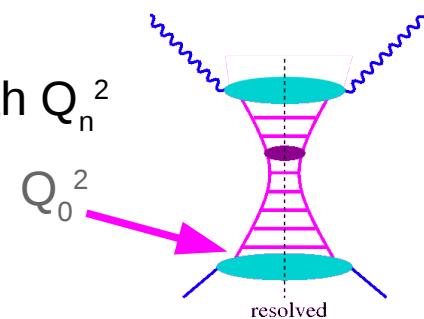
- $G_{\text{eff}} \leq G_{\text{QCD}}(Q_0^2 = Q_n^2)$
- increase  $Q_0^2$  until  $G_{\text{eff}} = \langle N_{\text{hard}} \rangle G_{\text{QCD}}(Q_0^2)$  for each parton scattering
- for  $Q^2 \gg Q_0^2(x, b)$  factorization holds



# EPOS Parton Distribution Function $Q_0^2=30 \text{ GeV}^2$

- Larger  $Q_0^2$

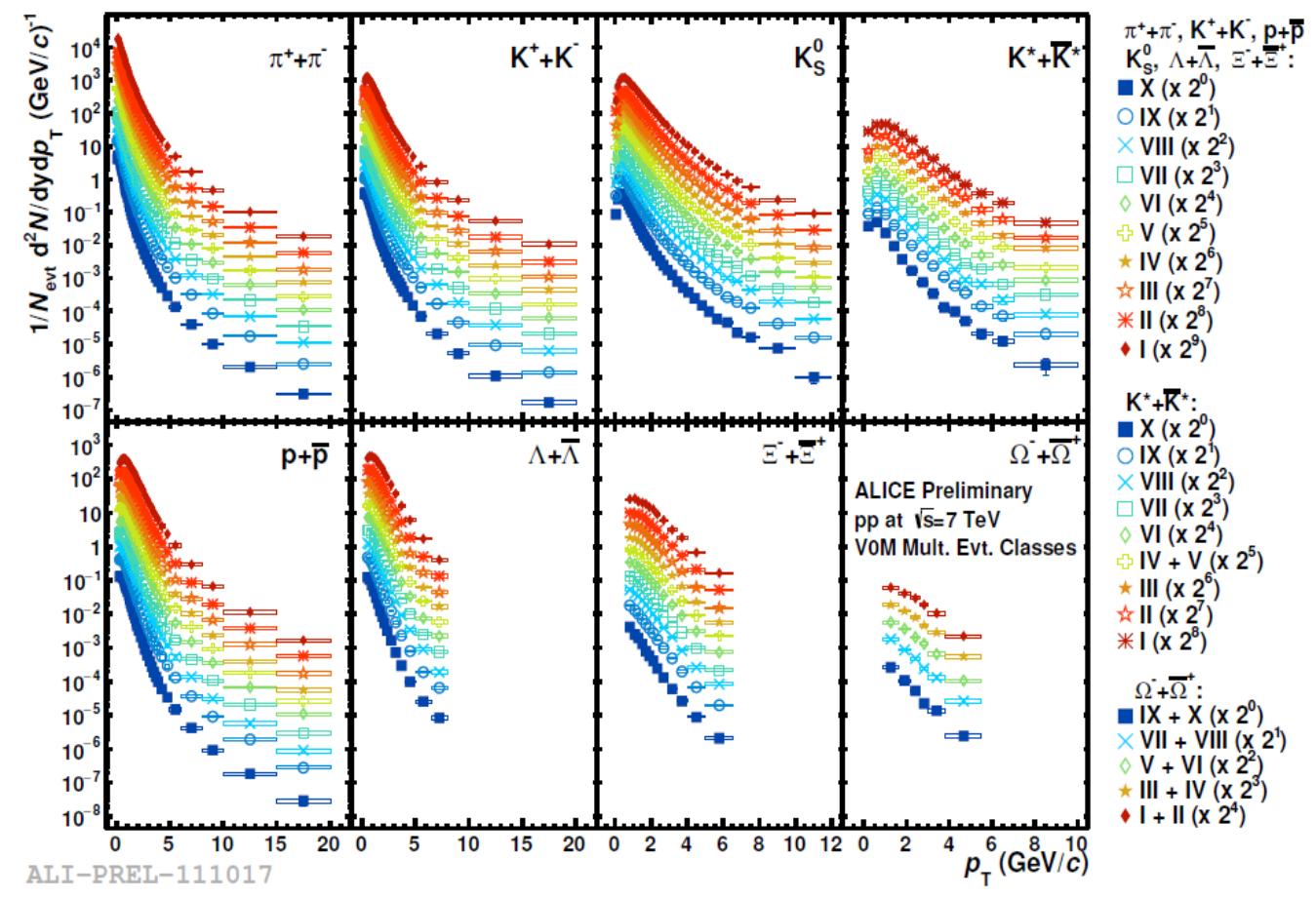
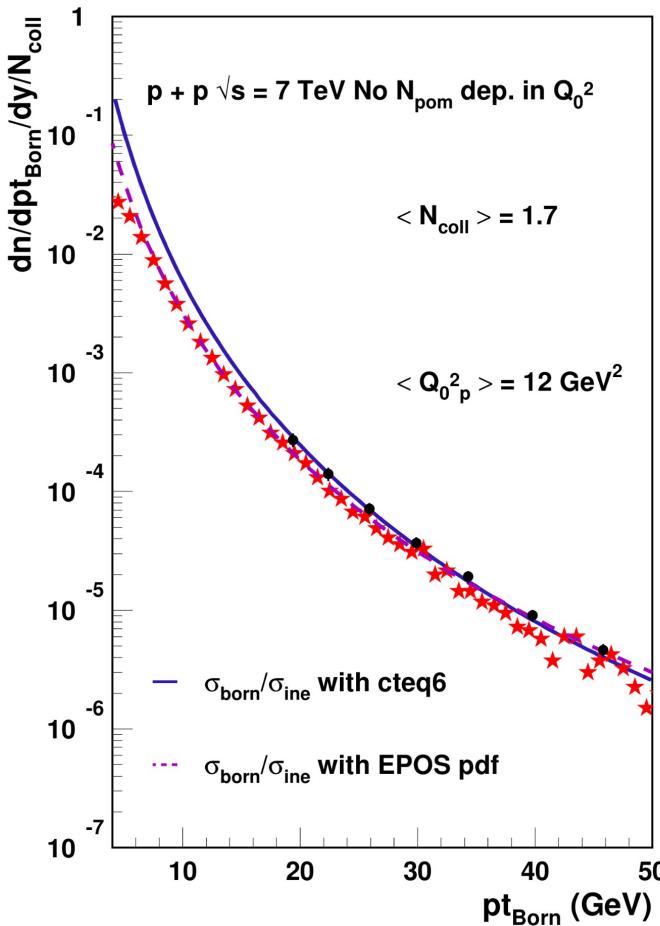
- partons which can be treated perturbatively (DGLAP evolution) and independently have already a large virtuality
- soft preevolution changed to get the same parton distribution than with  $Q_n^2$
- PDF for  $Q^2 > Q_0^2$  independent of  $Q_0^2$



# Jet and $p_t$

## Check with pp data at 7 TeV

- inclusive jet cross section: OK
- transverse momentum for different centrality bins

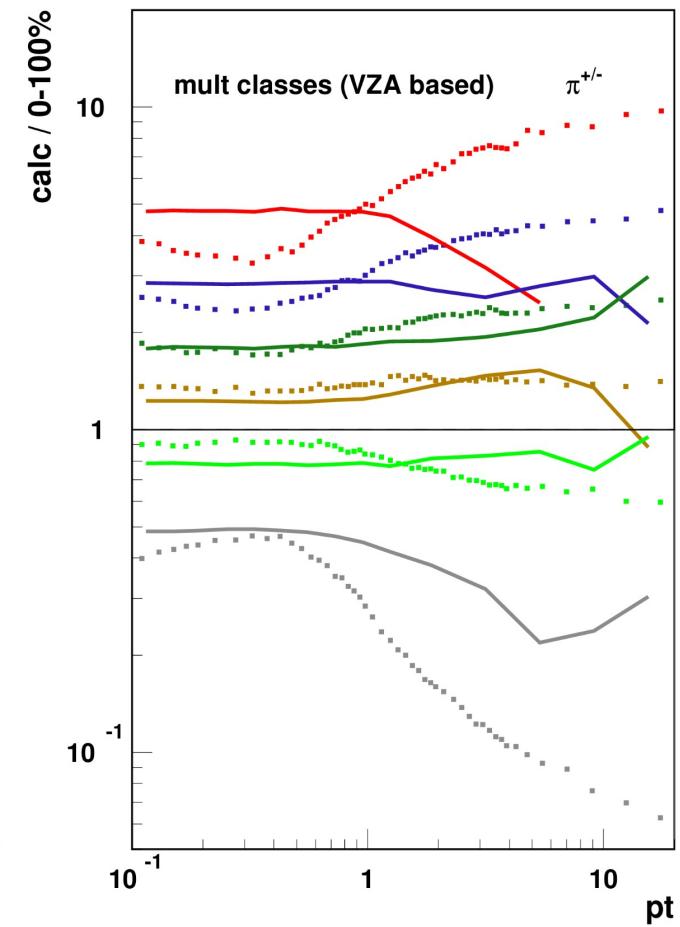
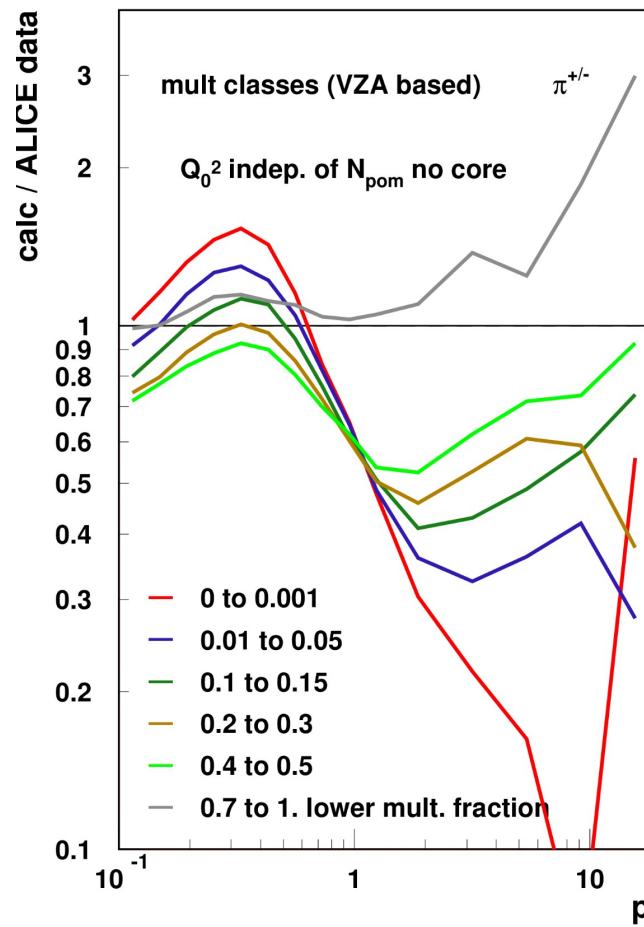
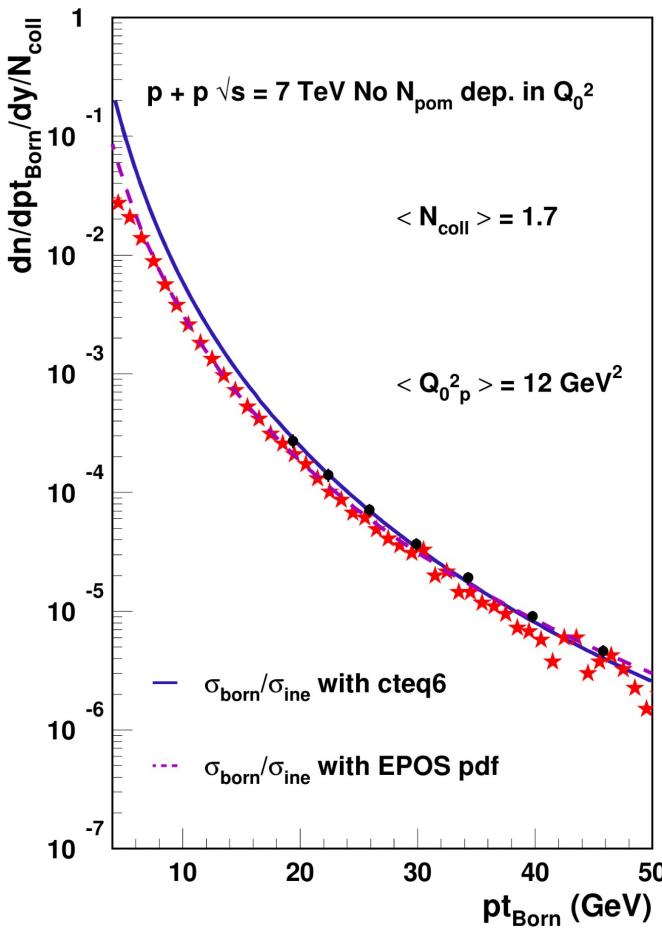


# Jet and $p_t$

## Check with pp data at 7 TeV

- inclusive jet cross section: **OK**
- transverse momentum for different centrality bins: **NO**

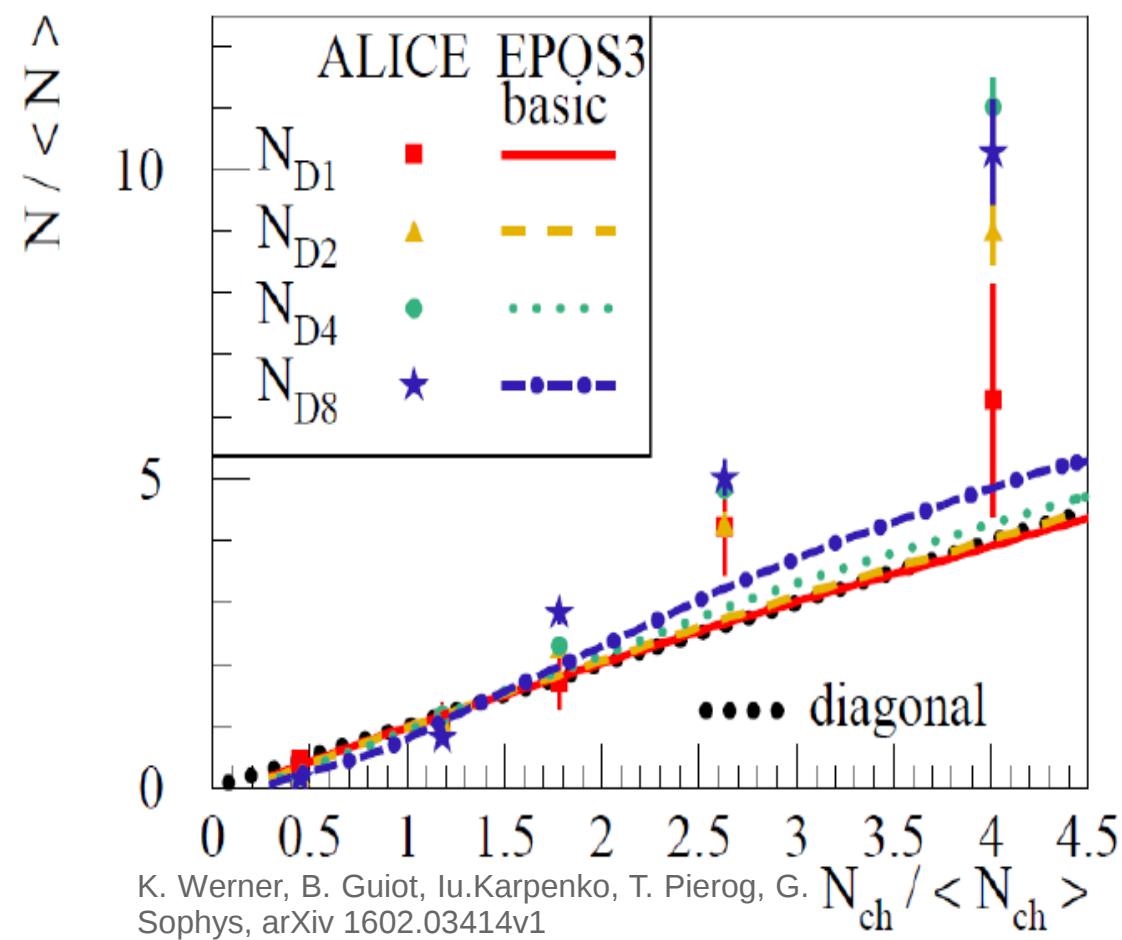
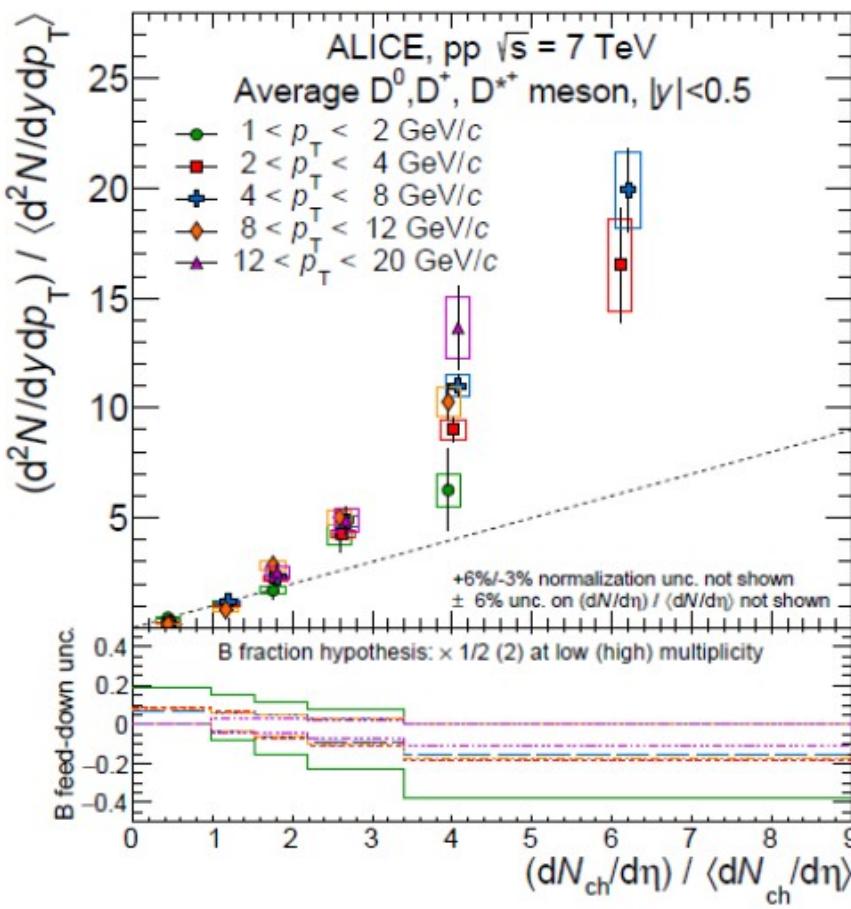
**Same slope for all multiplicities while data not flat**



# Charm Production

Similar behavior observed in D meson but presented in a different way

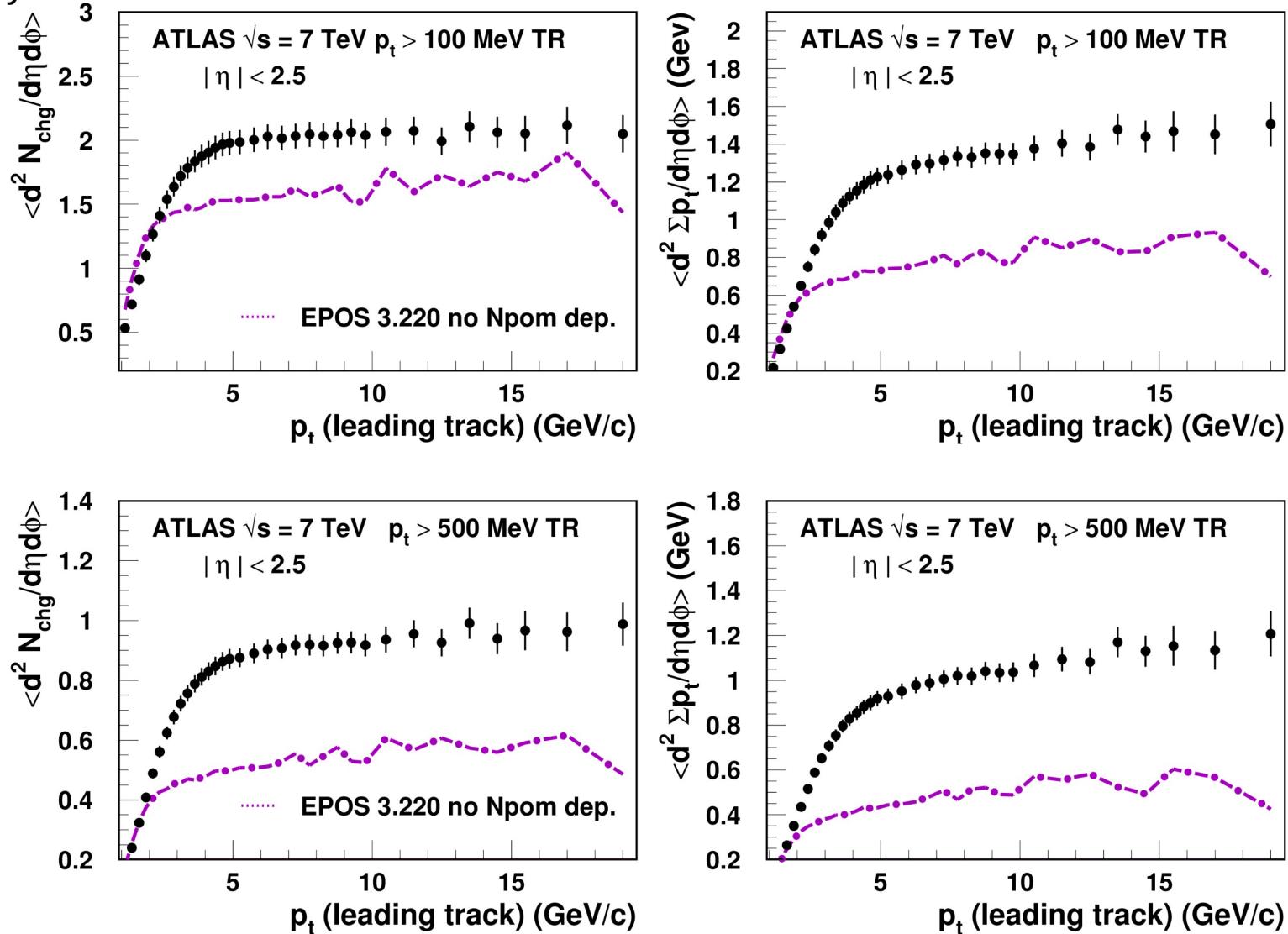
- more than linear increase of charm production and larger in higher pt bin = hardening of pt spectra with particle multiplicity
- small increase due to fluctuations observed in EPOS 3 but not sufficient to reproduce data



# Underlying Events

Check with pp data at 7 TeV

→ activity too low

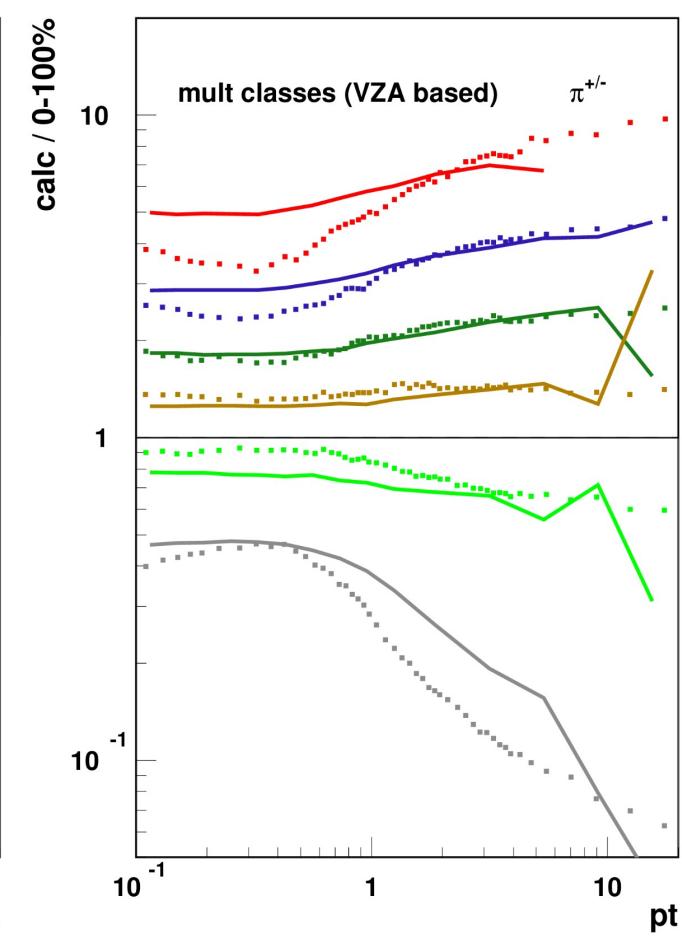
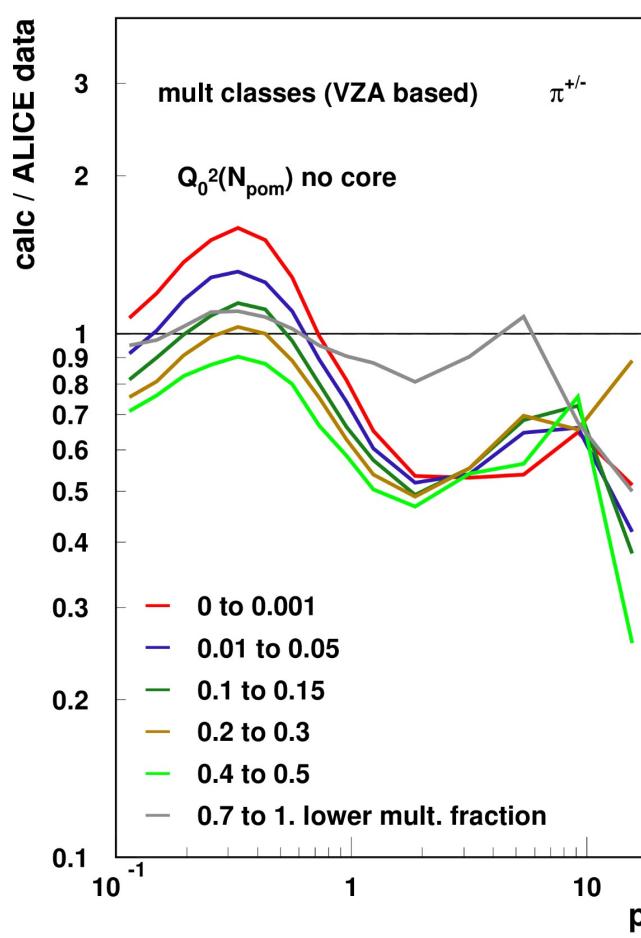
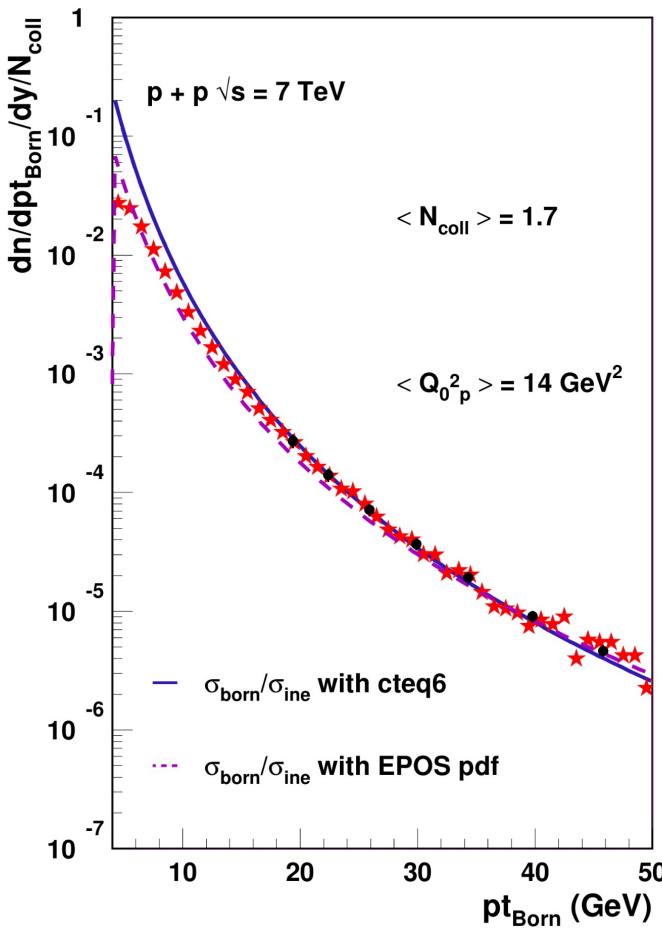


# Effect of MPI on $Q_0^2$

Is it possible to introduce the number of parton scattering  $N_{\text{hard}}$  in  $Q_0^2$  ?

→  $\langle N_{\text{hard}} \rangle G_{\text{QCD}}(x, b, Q_0^2) = G_{\text{eff}}(s, x, b, A)$  on average but for each event we can define :

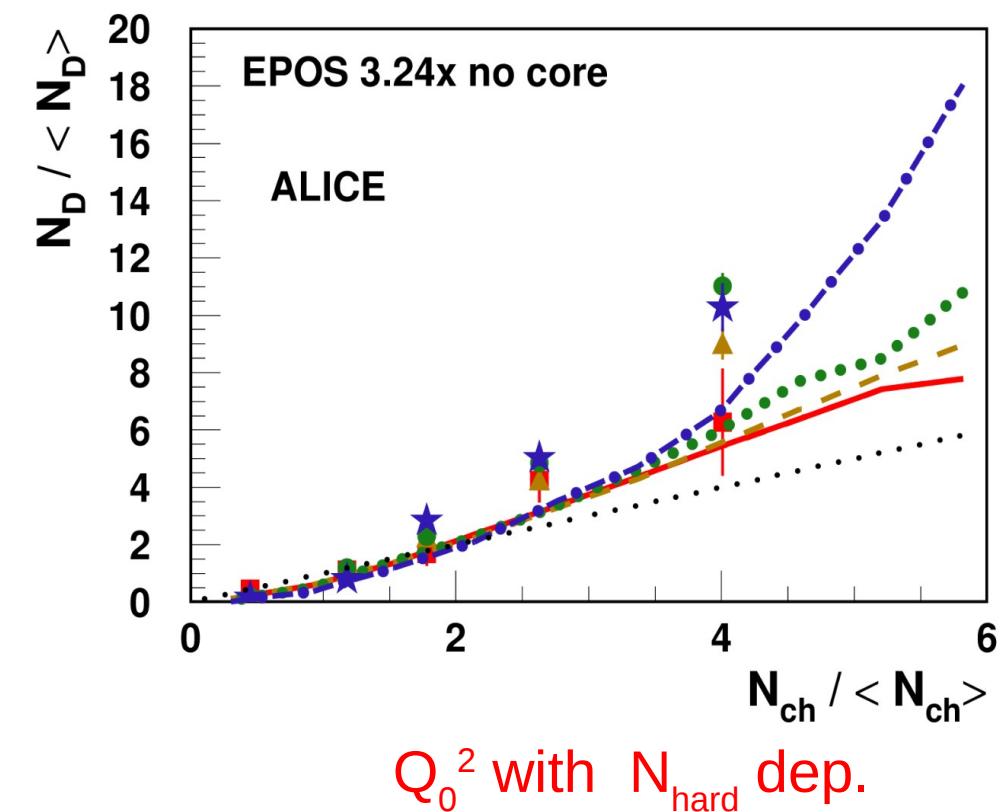
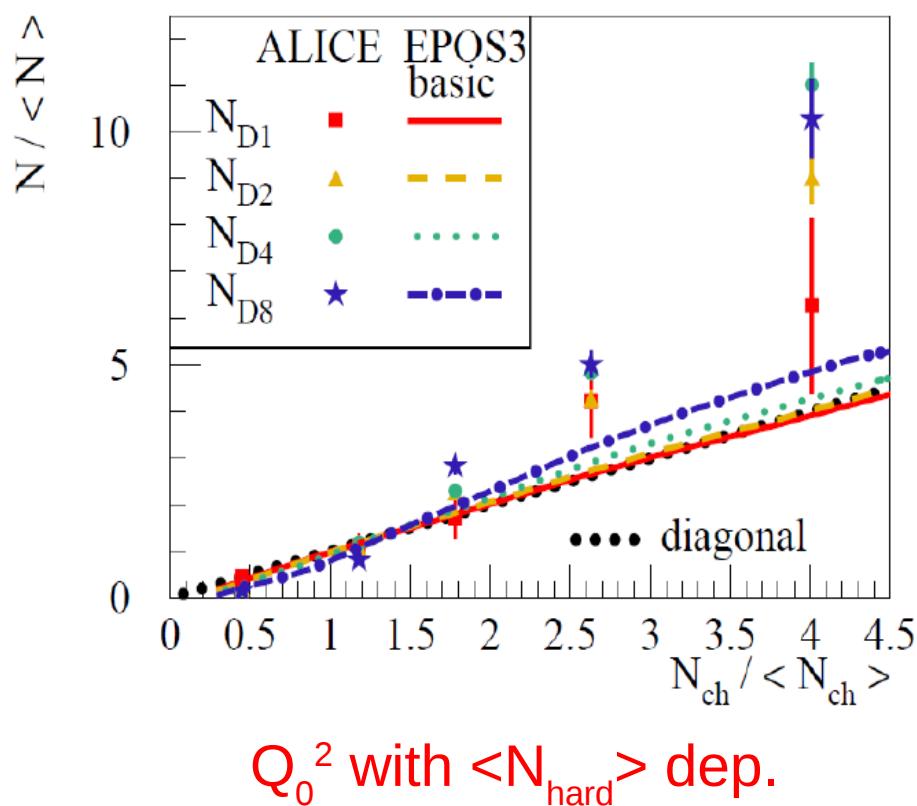
$$\textcolor{red}{\rightarrow} N_{\text{hard}} G_{\text{QCD}}(x, b, Q_0^2) = G_{\text{eff}}(s, x, b, A)$$



# Effect on Heavy Flavor Production

Similar behavior observed in D meson but presented in a different way

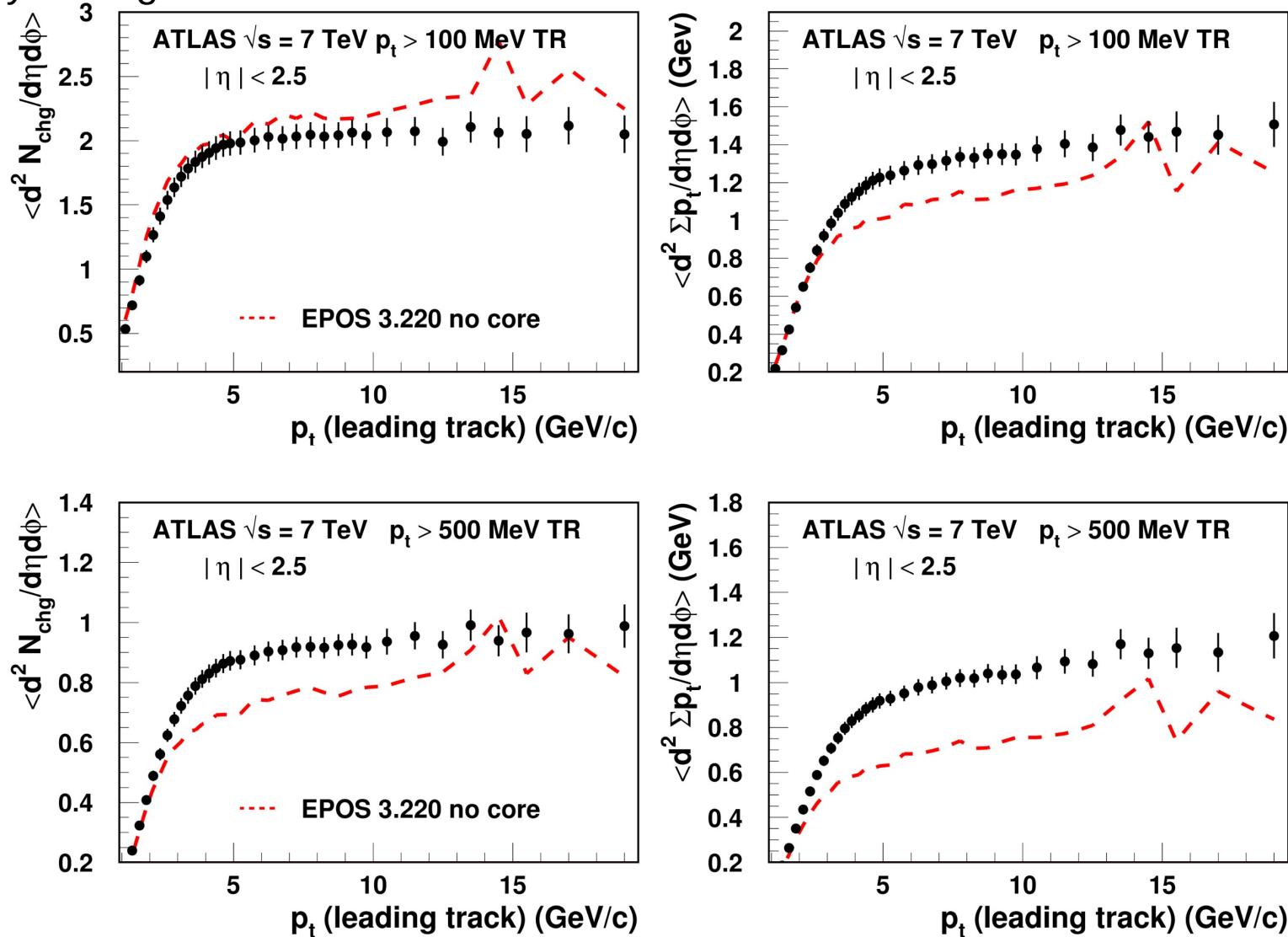
- increase of  $Q_0^2$  with multiplicity imply a non linear increase of charm production as function of multiplicity
- strong effect but still not enough compared to data
  - ➡ room for reduction of multiplicity due to collective effect (core)



# Underlying Events

Check with pp data at 7 TeV

→ activity too high ?



# Nuclear Interactions

- Factorization holds independently of centrality

- Once normalized by the number of binary collisions and inelastic cross-section, hard parton production (large  $Q^2$ ) similar in pp or nuclear collisions.

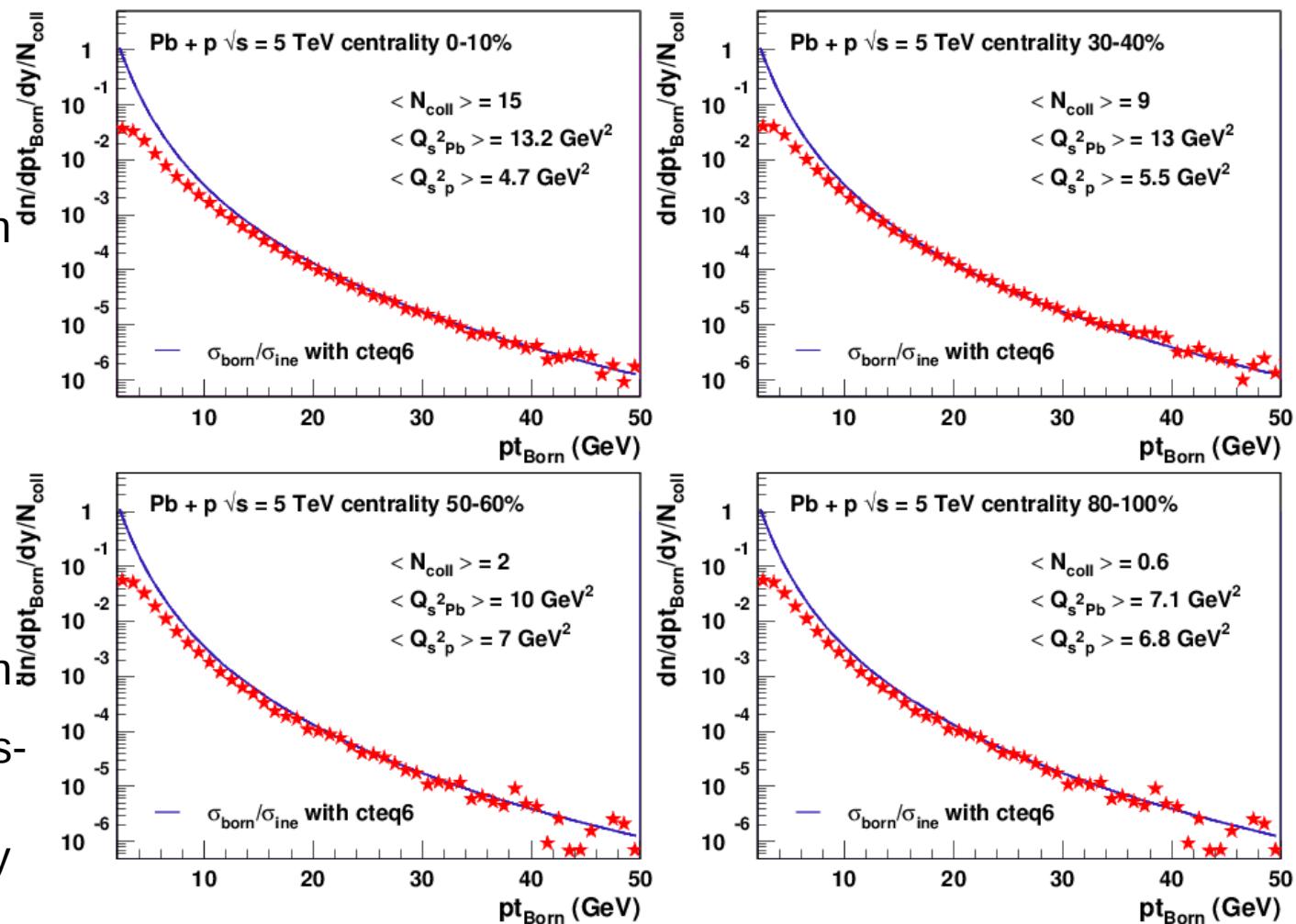
- EPOS 3

- extend  $N_{\text{hard}}$  to take into account connections with other nucleons ( $\sim N_{\text{bin}}$ )
- Define  $Q_0^2$  such that

$$(\sum N_{\text{hard}}) G_{\text{QCD}}(x, b, Q_0^2) = G_{\text{eff}}(s, x, b, A)$$

to produce ISR and born process in hard Pomeron

- Scaling of inclusive cross-section if  $N_{\text{hard}}$  and  $N_{\text{soft}}$  ( $N_{\text{pom}} = N_{\text{hard}} + N_{\text{soft}}$ ) properly determined



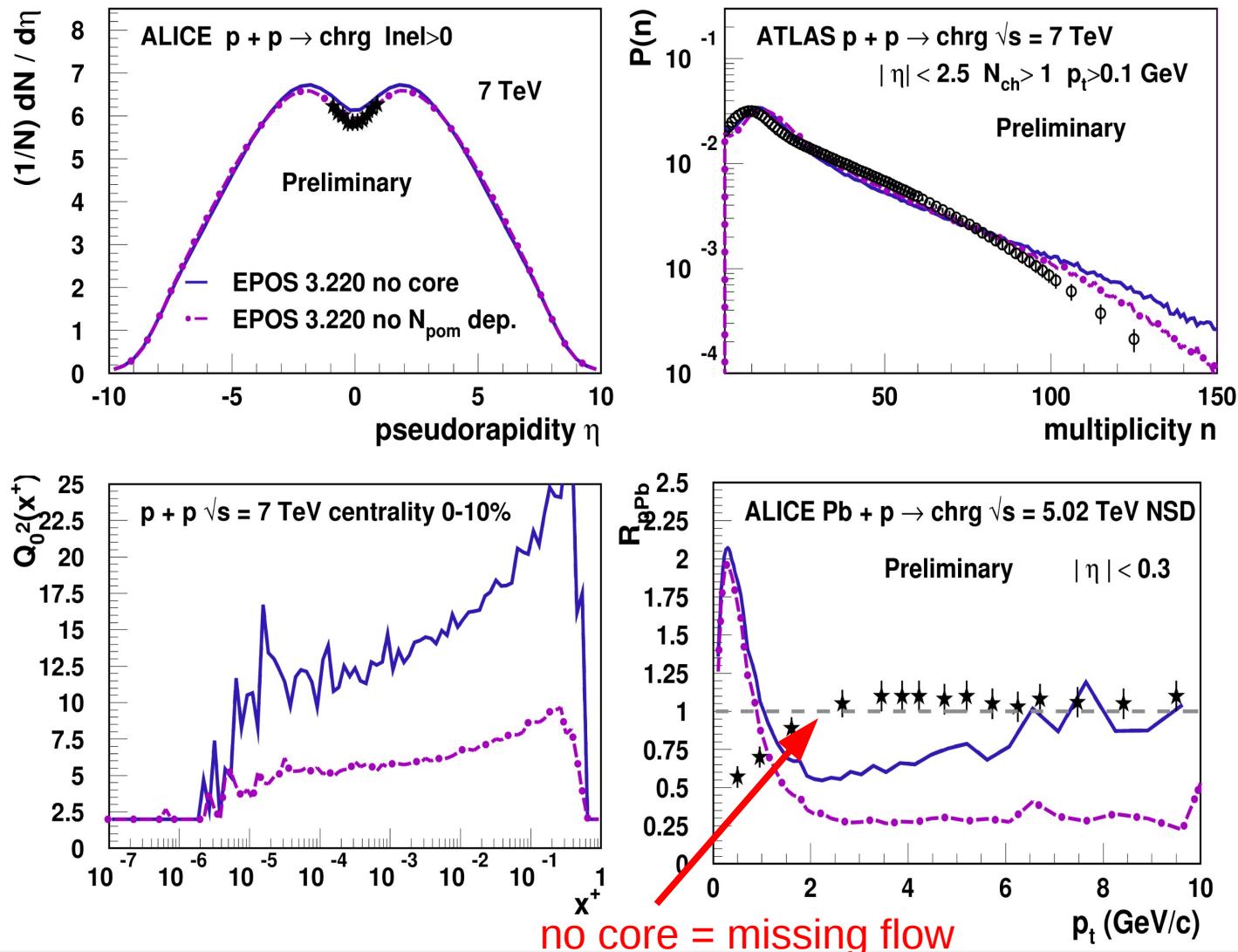
# Preliminary Results : Without Core

- Overestimate multiplicity to take into account the effect of hydro
  - change in multiplicity by changing  $Q_0^2$  definition only in the tail (as expected)

- Problem solved for hard processes

- complete factorization
- binary scaling for nuclear scattering simply by adding collision from all nucleons in  $N_{\text{pom}}$

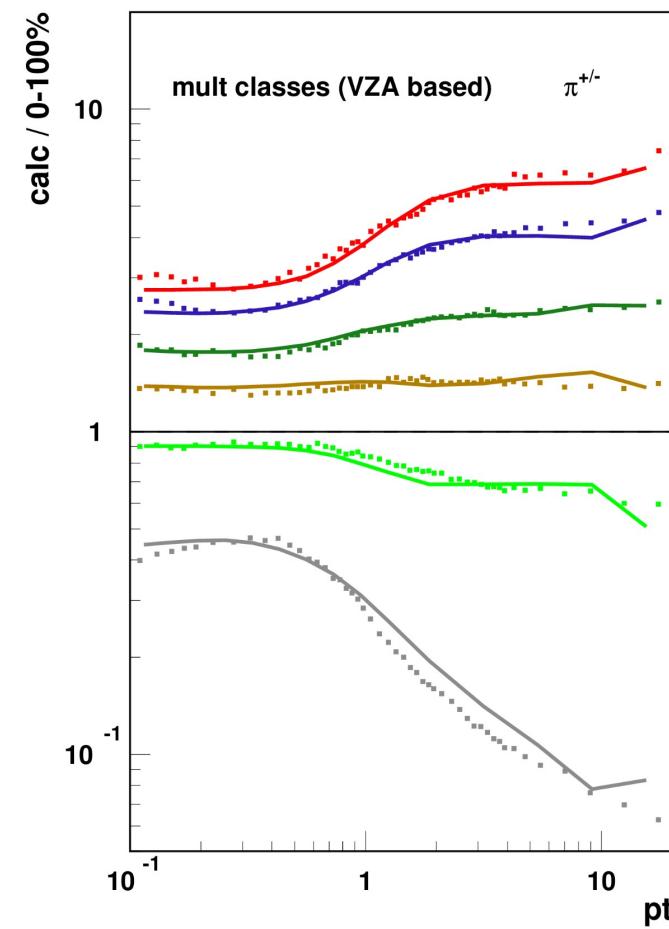
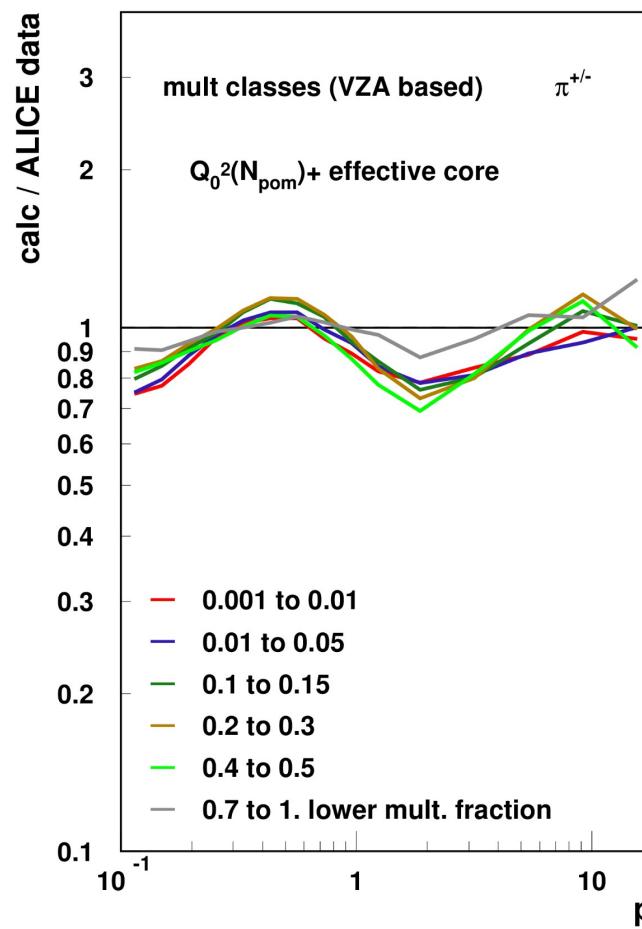
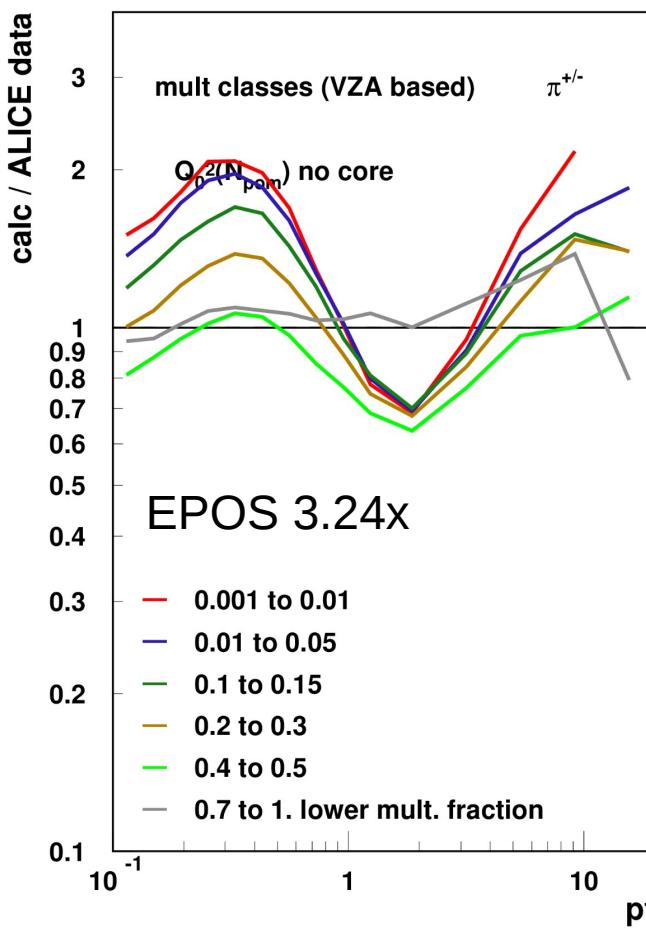
Same process to scale  $Q_0^2$  in pp, pA and AA gives factorization and binary scaling.



# Core Effect vs Centrality

**Flow change the shape of transverse momentum distribution**

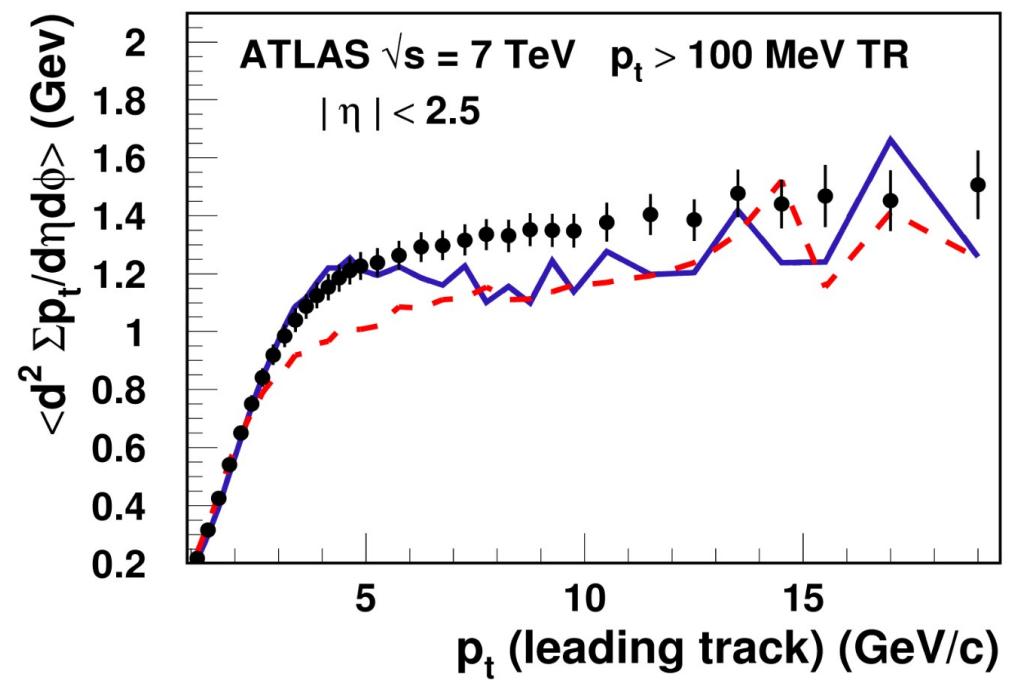
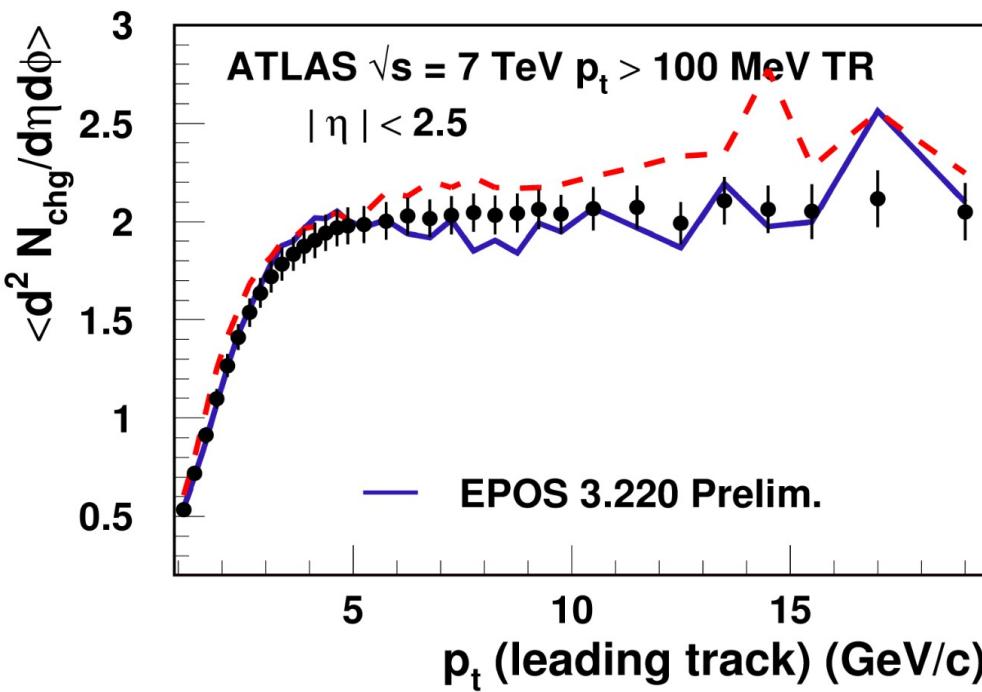
- effect on high pt due to parton energy loss (same as in HI) ... to be confirmed !
- test of real hydro vs CGC ?
- (tension between these data and ATLAS/CMS (absolute scale))



# Underlying Events: $p_t > 100 \text{ MeV}/c$

## $p_t > 100 \text{ MeV}/c$ particles in TRANS region

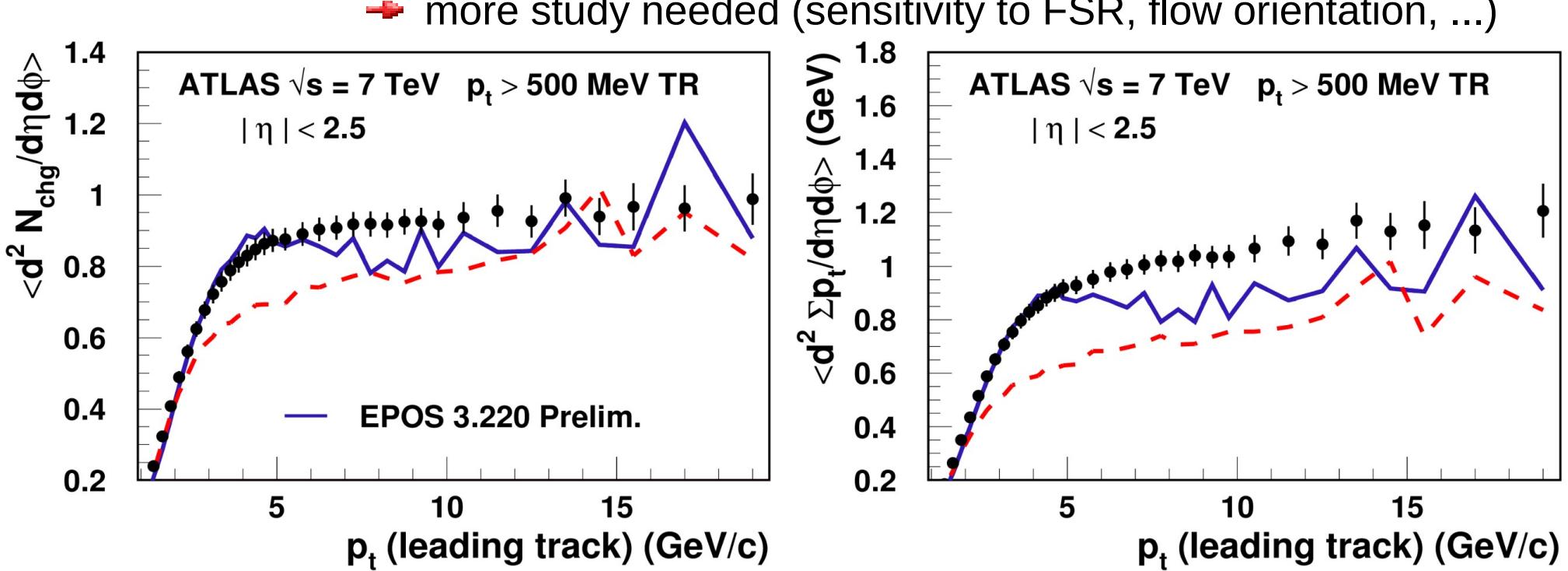
- without core  $N_{ch}$  is large like in MB but energy density is too low for  $p_t$  leading  $> 2 \text{ GeV}/c$
- with core the multiplicity is reduced and energy density at intermediate  $p_t$  is increased
- reasonable agreement with data
  - ◆ mean transverse energy still a bit low for high  $p_t$  leading track



# Underlying Events: $p_t > 500 \text{ MeV}/c$

## $p_t > 500 \text{ MeV}/c$ particles in TRANS region

- without core  $N_{\text{ch}}$  is too low and energy density is too low
- with core here both multiplicity and energy density are increased at intermediate  $p_t$
- reasonable agreement with data
  - ◆ mean transverse energy still a bit low for high  $p_t$  leading track
    - ➡ more study needed (sensitivity to FSR, flow orientation, ...)



# Underlying Events: Strangeness

## Lambda production in UE

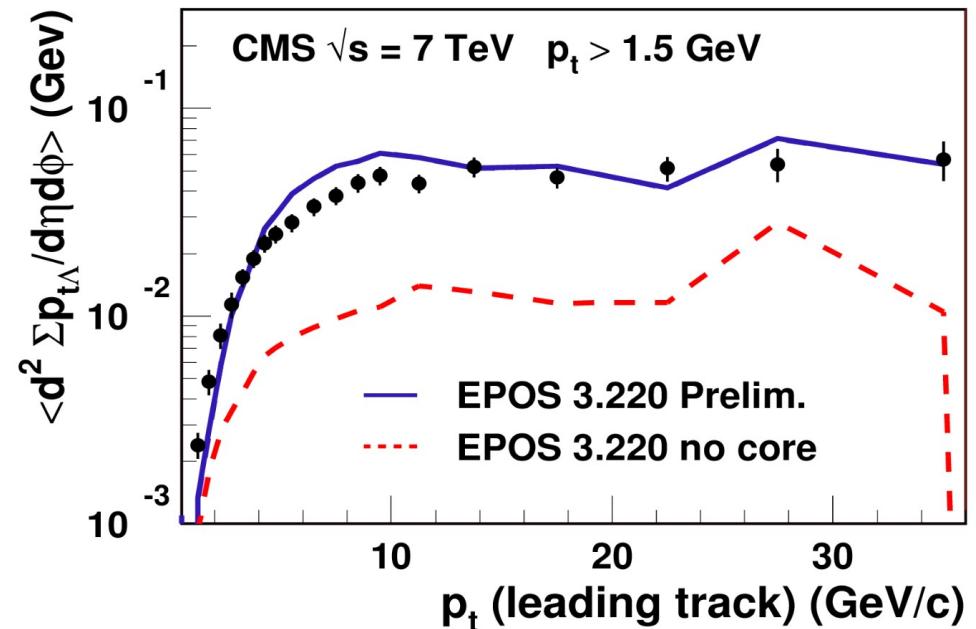
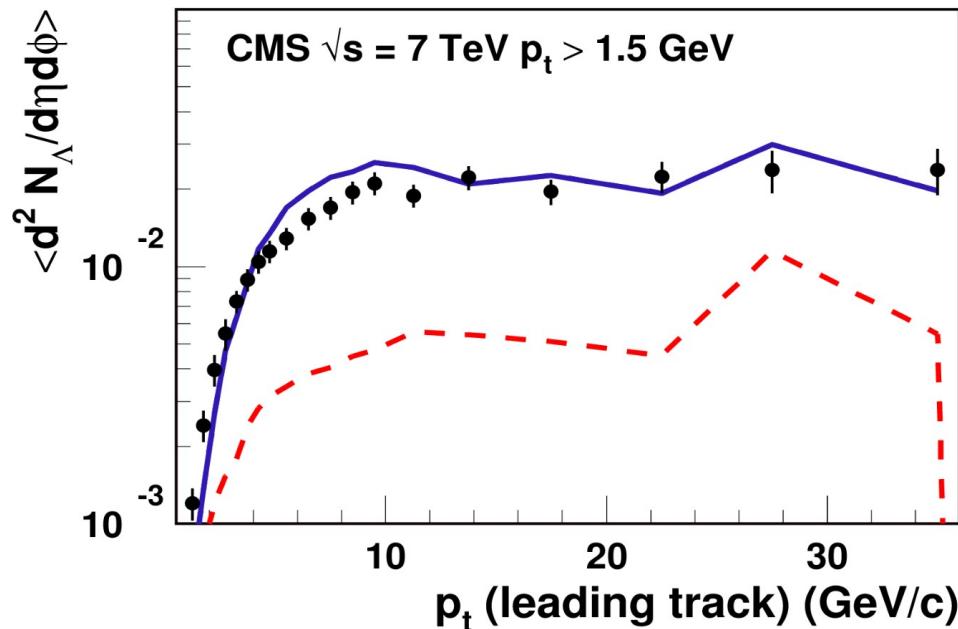
→ Without core, very low lambda production like for other HEP models

→ With core (and so hydro), much higher strangeness production

- statistical hadronization

- flow effect on transverse energy

→ very strong effect of collective hadronization in UE for strange baryon production



# Summary

## Difficult to describe min bias and hard scale events at the same time

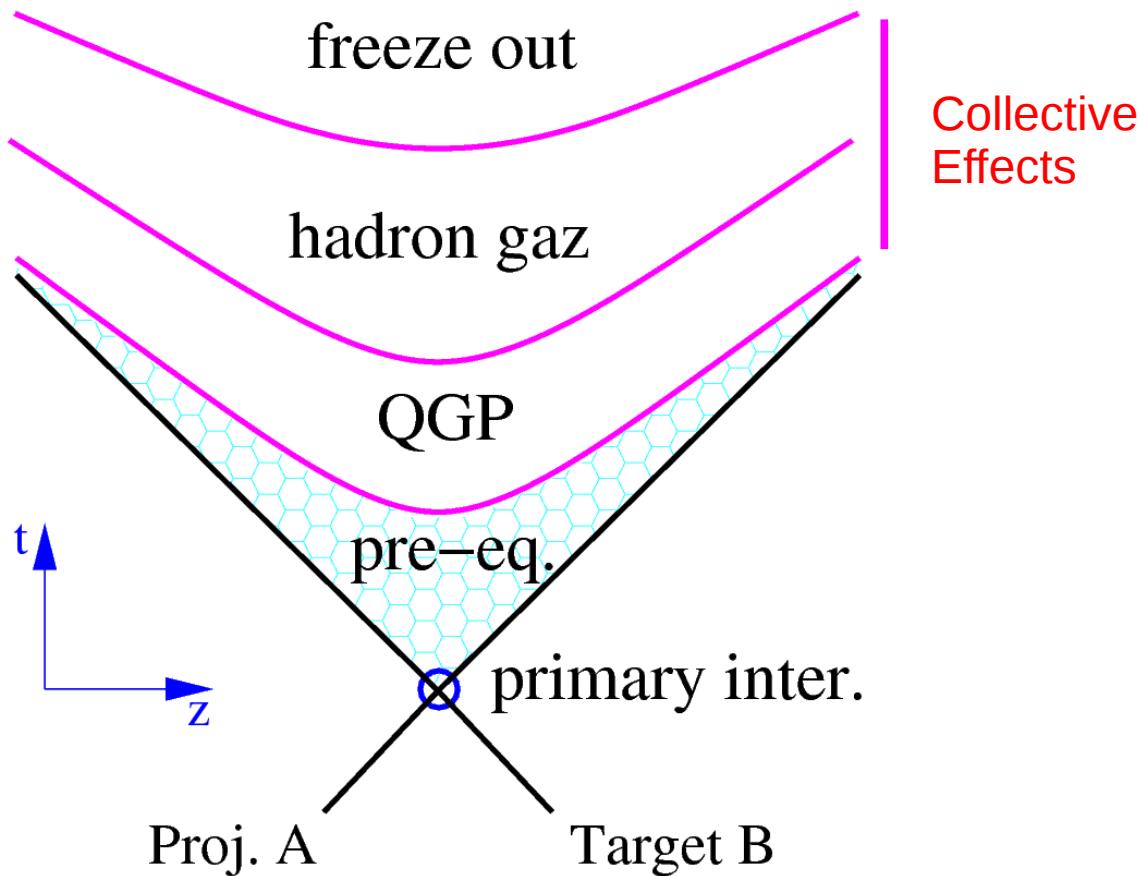
- UE and heavy flavor require large multiplicity
- transverse momentum distributions depend on event multiplicity even at high  $p_t$  (to high for flow effect)

## EPOS 3

- introduce non-perturbative scale  $Q_0^2$  **GENERATED** Pomeron-by-Pomeron and dependent on the number of MPI event-by-event.
- non perturbative N-pdf generation coupled with N independent DGLAP evolutions to get N hard partons event-by-event
- recover factorization and binary scaling for inclusive hard processes above  $Q_0^2$
- hydro expansion require higher MPI than imposed by multiplicity that reflects on UE and other variables like charm production.
- improve underlying event description in p-p but real hydro still to be tried for final results

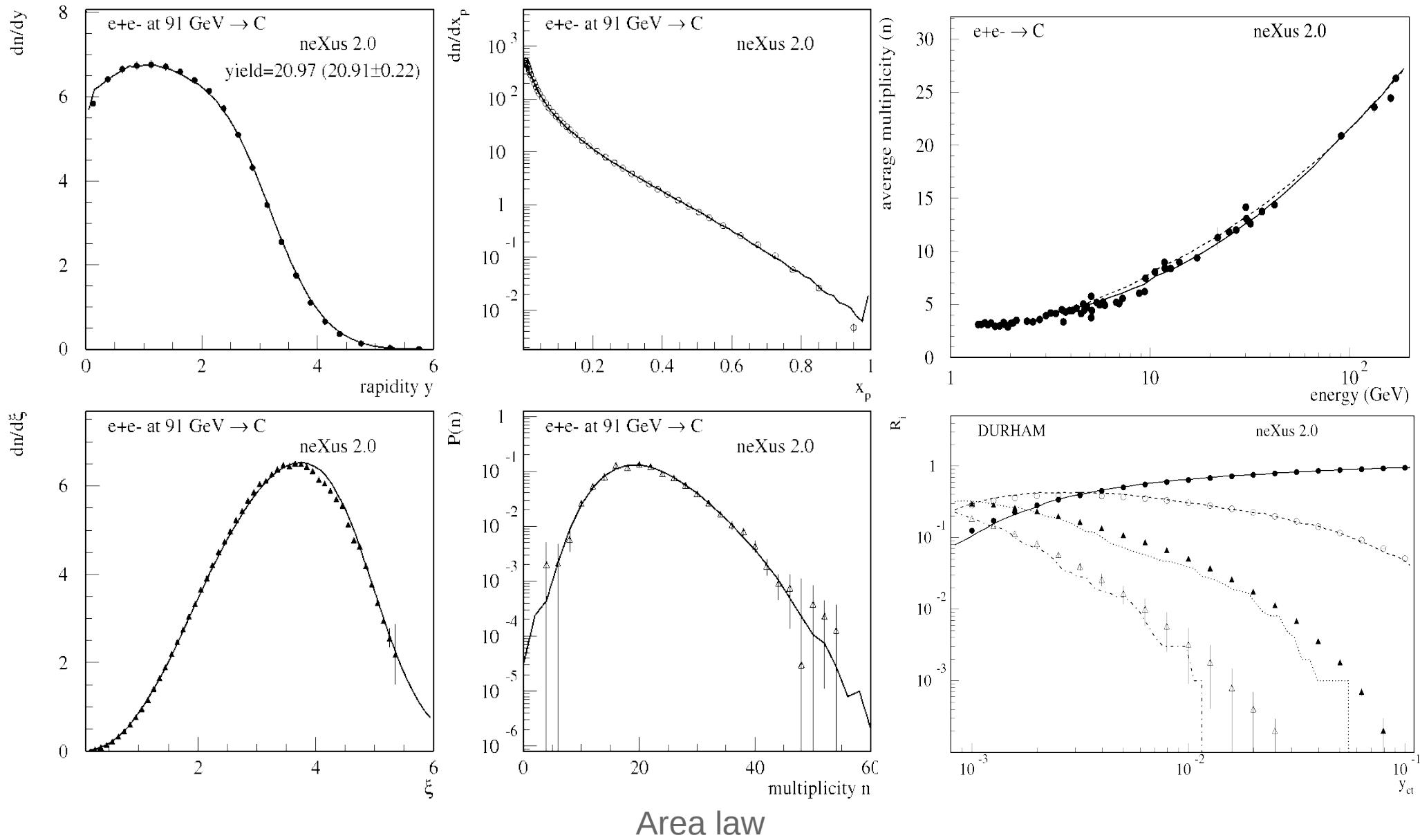
To reconcile minimum bias (MB) and underlying events (UE) in pp, we need both collective effects and variable non-pertub. scale.

# High Energy Hadronic Interactions



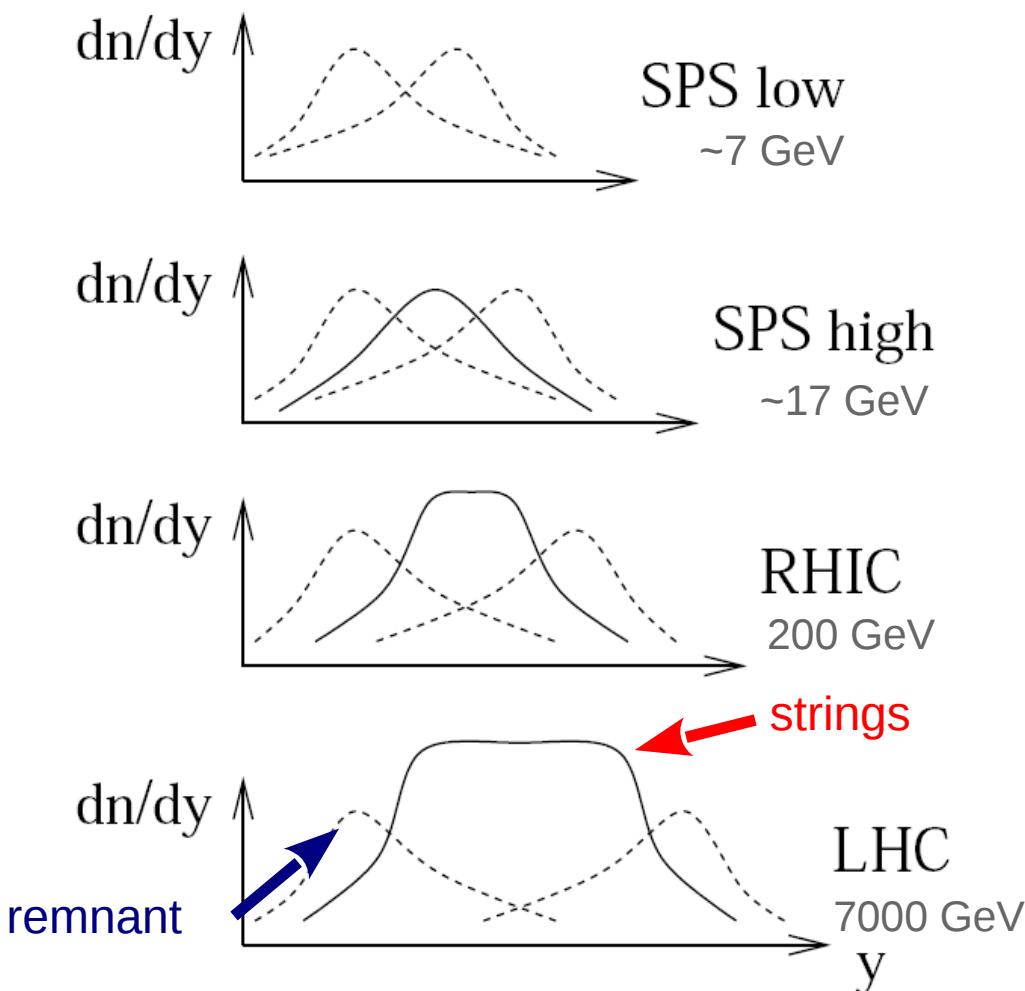
To reconcile minimum bias (MB) and underlying events (UE) in pp, we need both collective effects and variable non-pertub. scale.

# Test of string fragmentation with LEP data



# Remnants

**Forward particles mainly from projectile remnant**



**Forward hadronization from remnant :**

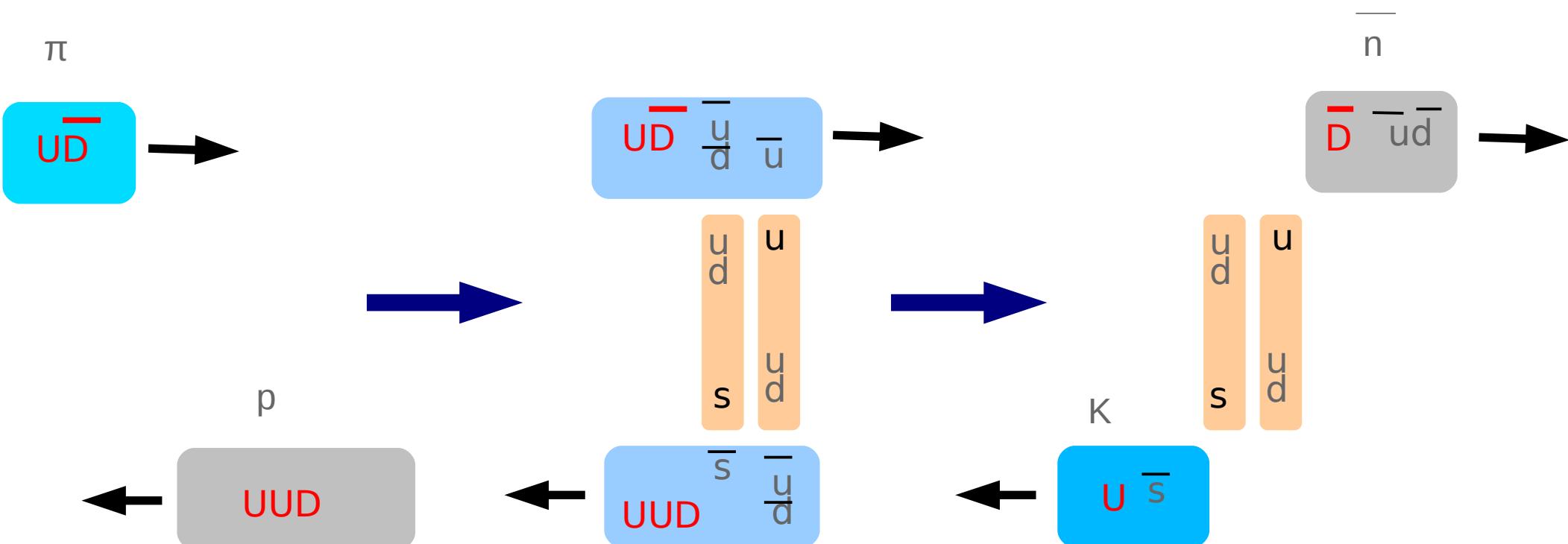
- ➔ At very low energy only particles from remnants
- ➔ At low energy (fixed target experiments) (SPS) strong mixing
- ➔ At intermediate energy (RHIC) mainly string contribution at mid-rapidity with tail of remnants.
- ➔ At high energy (LHC) only strings at mid-rapidity (baryon free)

**Remnant considered as universal object : same behavior at low or high energy**

# 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

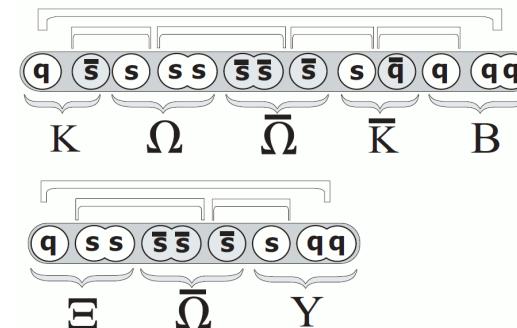
## Parton ladder string ends :

→ 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)

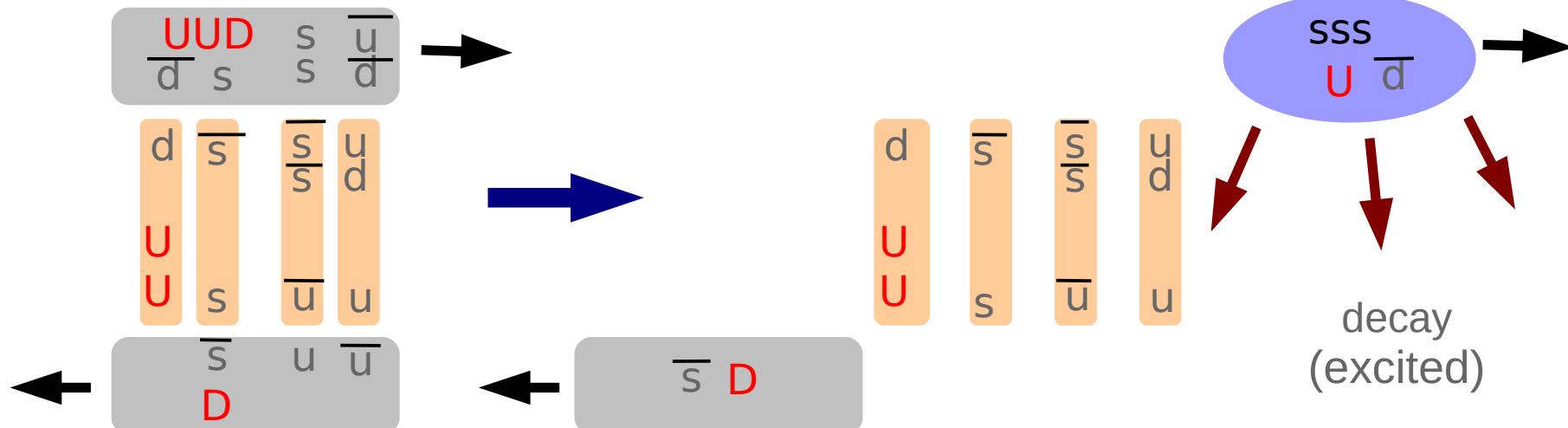


→ EPOS

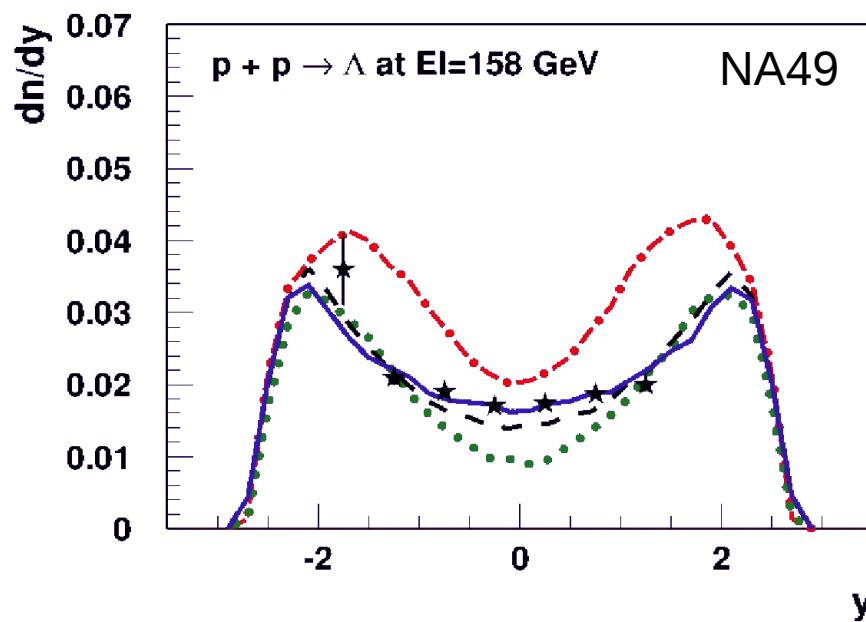
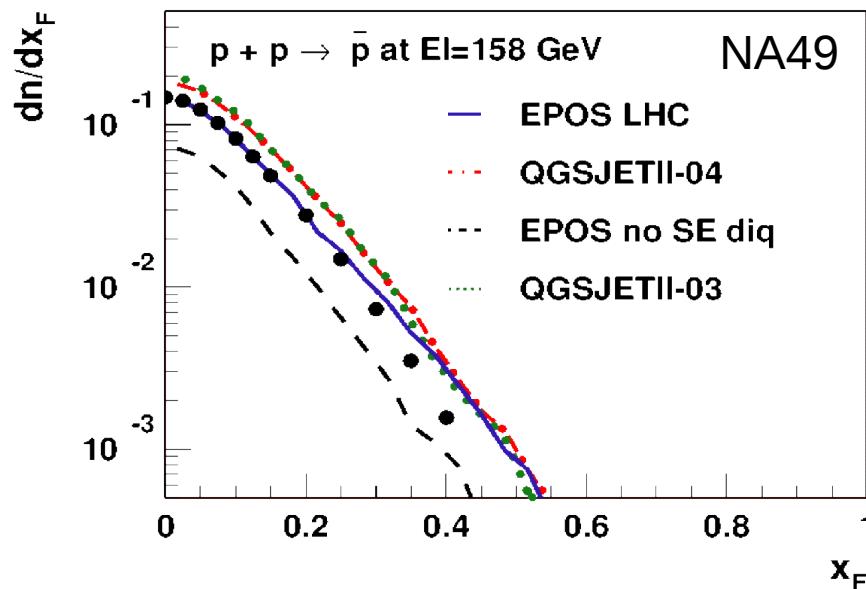
- ◆ No “first string” with valence quarks : all strings equivalent

- ◆ Wide range of excited remnants (hadronization via light resonance decay, string fragmentation or heavy quark-bag statistical decay)

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

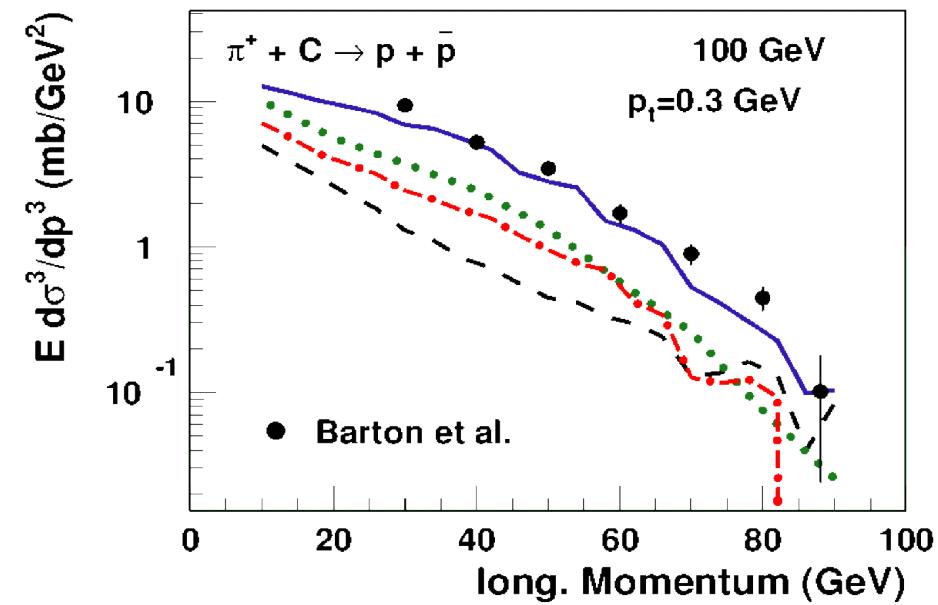


# Forward Baryons (low energy)



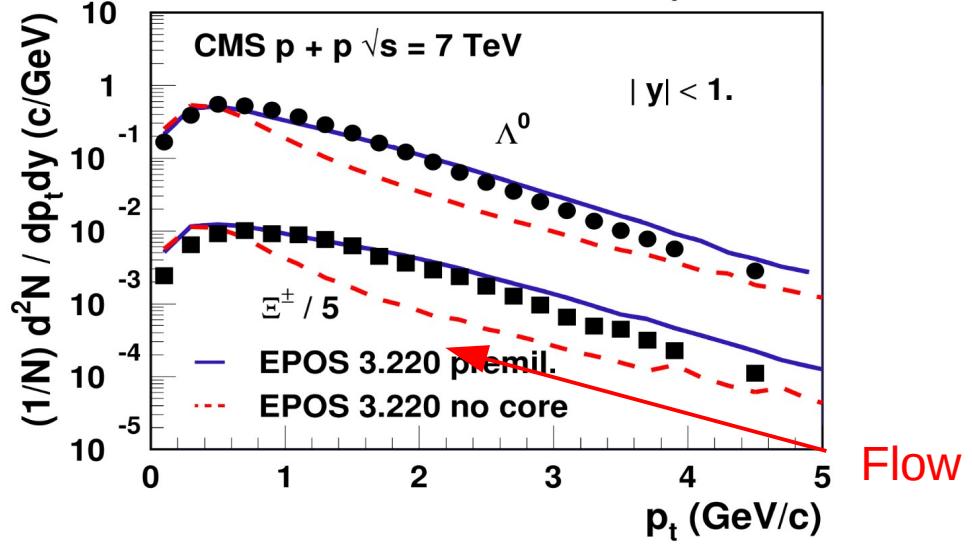
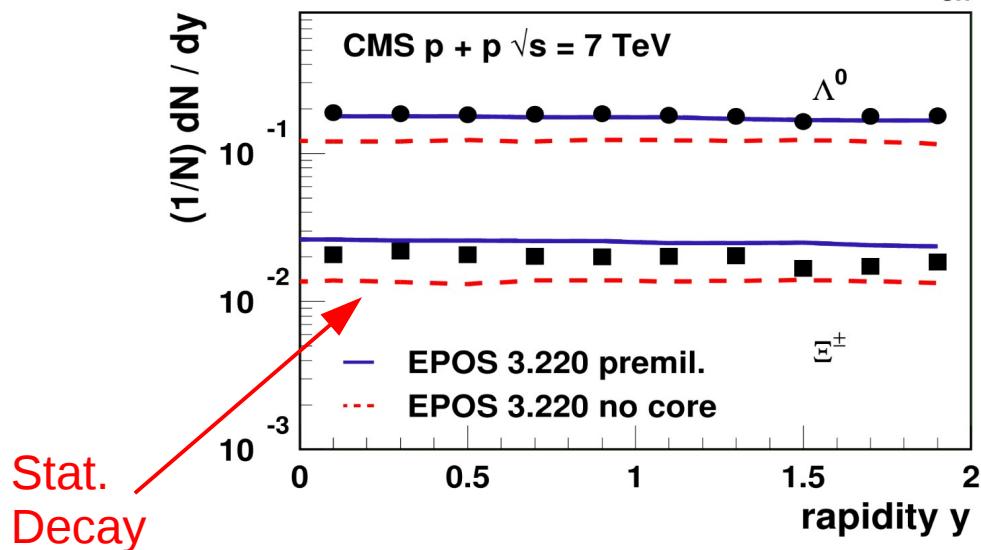
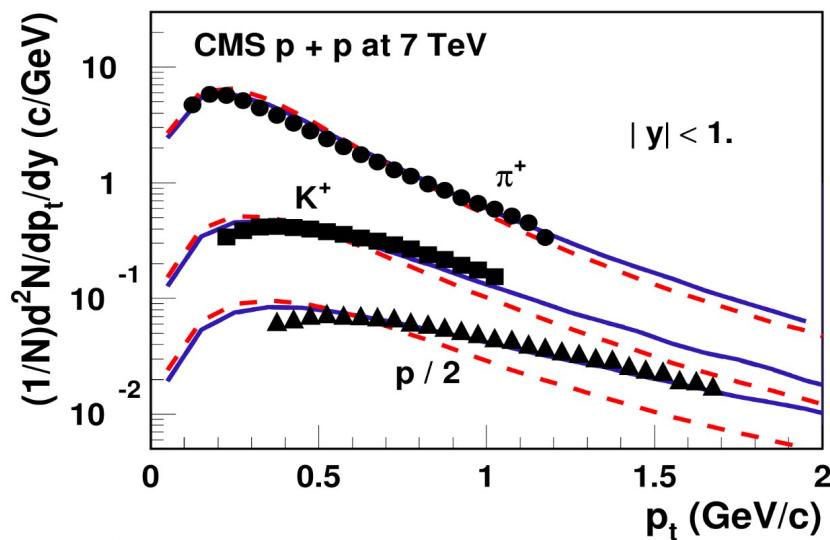
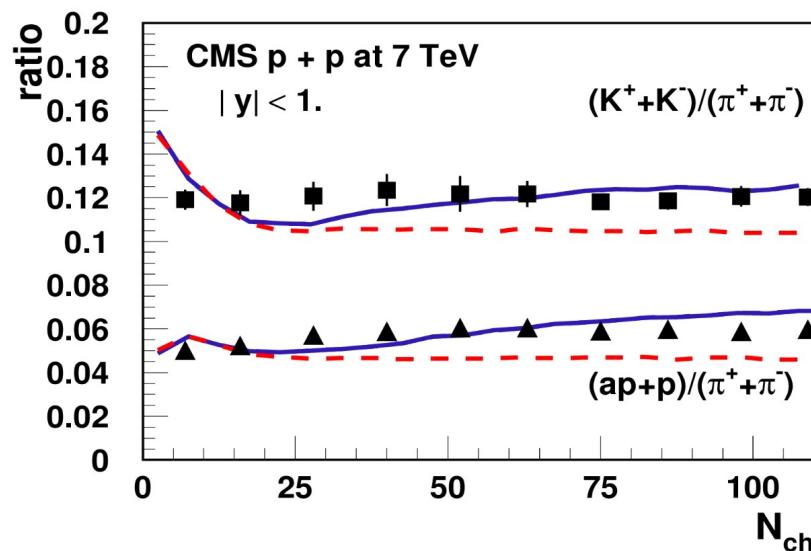
- ➔ Large differences between models
- ➔ Need a new remnant approach for a complete description (EPOS)
- ➔ Problems even at low energy
- ➔ No measurement at high energy !

Without remnant, string fragmentation has to be changed for baryon production



# Core Effect on Particle Yield

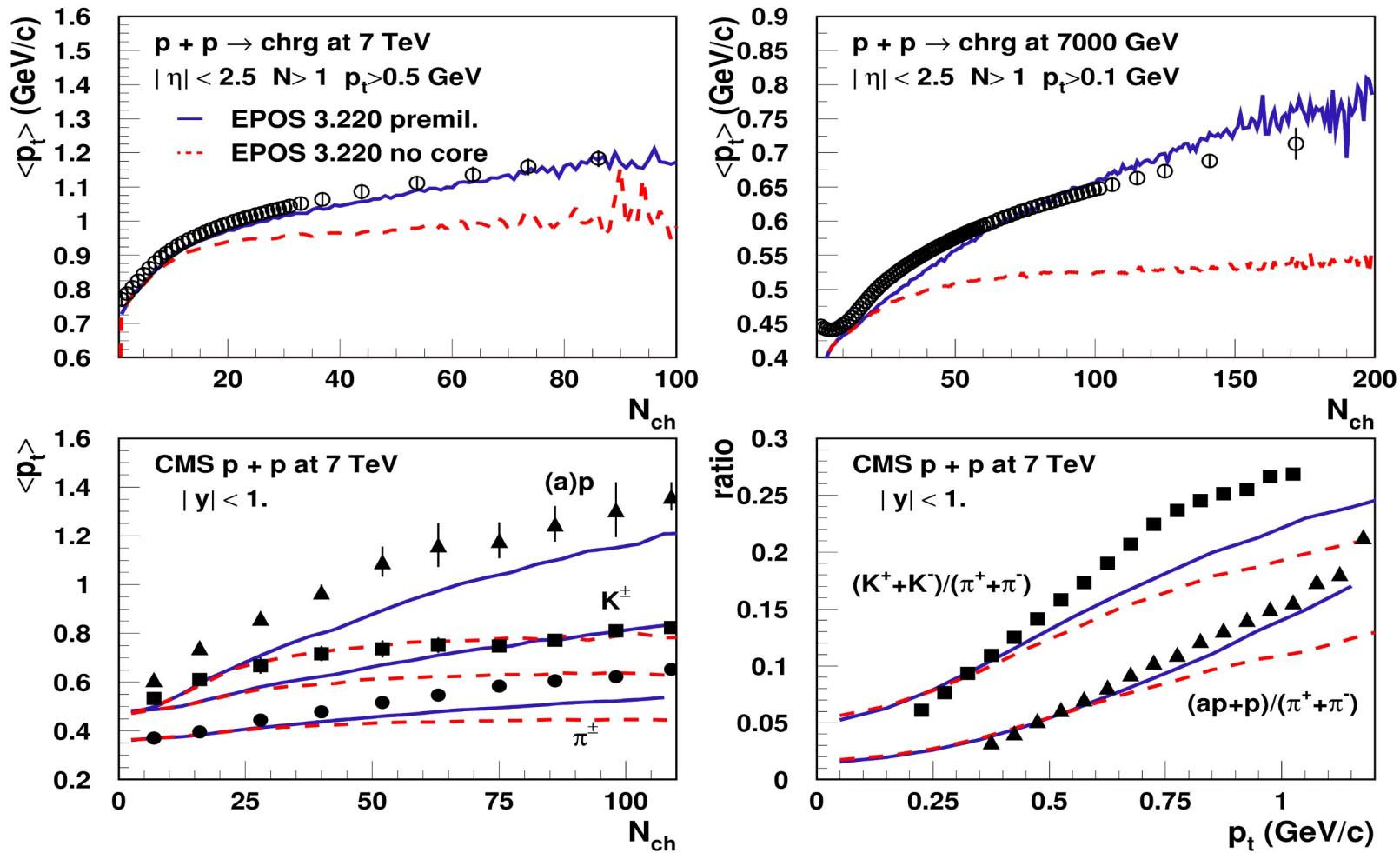
- Core hadronization change particle ratio
  - easier to produce strange baryons



# EPOS 3.216

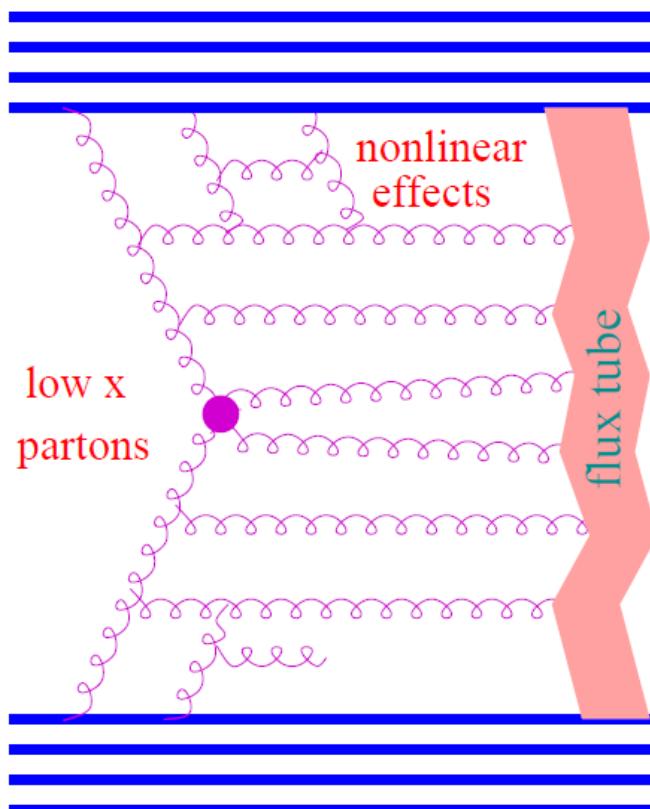
- Detailed description can be achieved

- identified spectra
- $p_t$  behavior driven by collective effects (flow)



# Elementary scatterings - flux tubes

- same energy sharing between the parallel scatterings is taken into account for cross section and particle production
  - MPI fixed by total cross-section
- many elementary collisions happening in parallel
- elementary scattering = “parton ladder” + soft component



- Parton evolutions from the projectile and the target side towards the center (small  $x$ )
- Evolution equation
  - DGLAP
- Parton ladder = quasilongitudinal color field (“flux tube”)
  - relativistic string
- Intermediate gluons
  - kink singularities in relativistic strings
- Fragmentation : production of quark-antiquark pairs
  - fragments – identified with hadrons

**Parton-based Gribov-Regge Theory**, H. J. Drescher, M. Hladík, S. Ostapchenko, T. Pierog, and K. Werner, Phys. Rept. 350 (2001) 93-289;