Heavy-quark Production and Further Recent Developments in EPOS

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Heavy Quark Hadroproduction from Collider to Astroparticle Physics, MITP, Mainz, Germany

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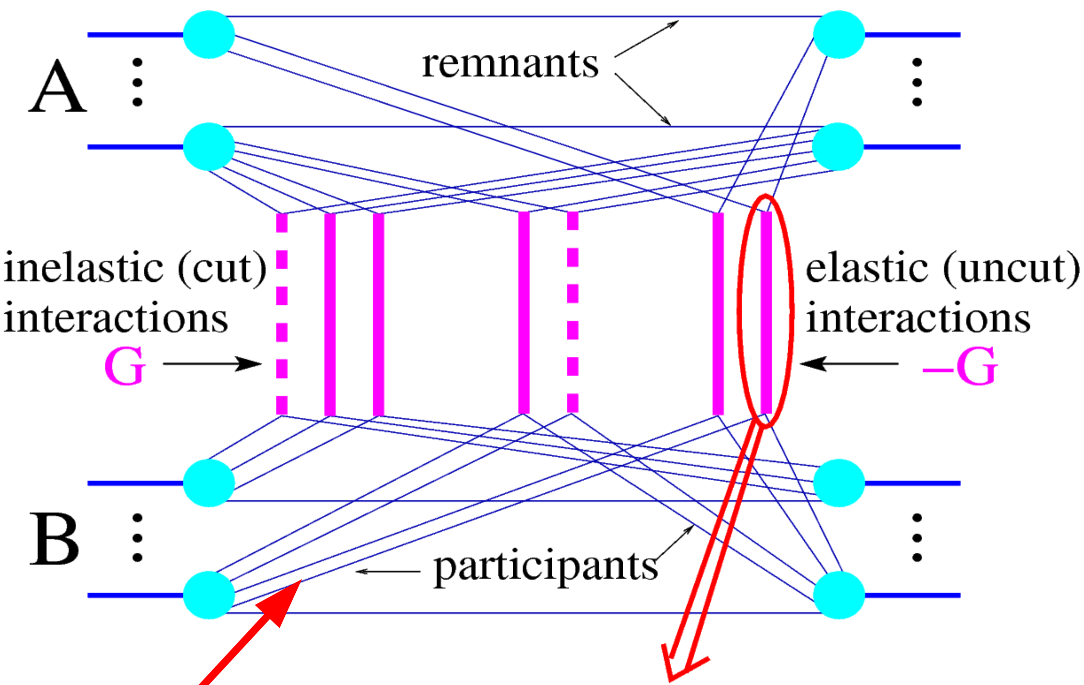
Outline

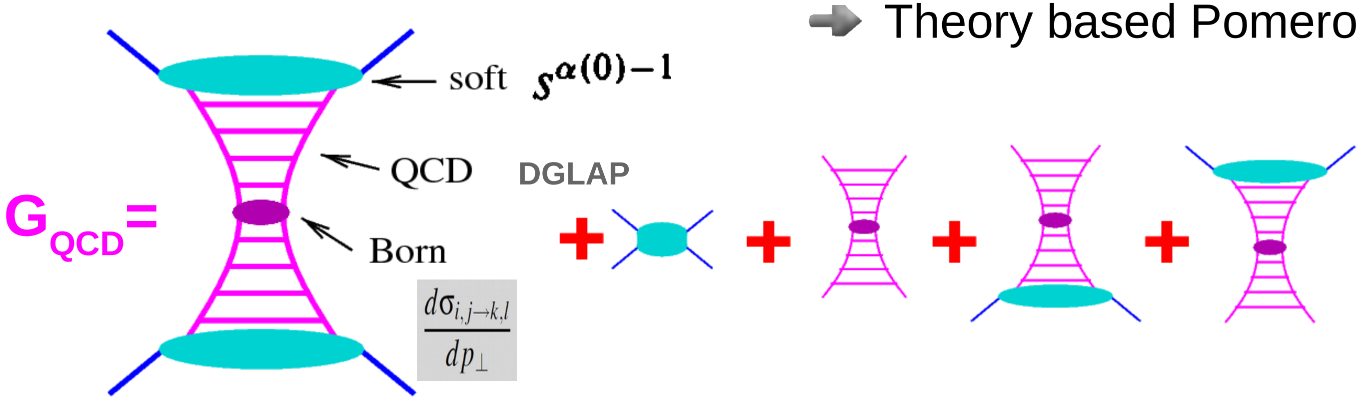
- **EPOS Basic principles**
  - For EPOS LHC and EPOS 3
- **Heavy Quark (HQ or Q) production**
  - Soft and perturbative production (EPOS 3)
- **Non-linear perturbative scale**
  - Evolution of particle production with multiplicity (EPOS 3)
- **Summary**

To reconcile soft and hard observables, EPOS 3 will have both collective effects and variable non-linear perturbative scale : impact on HQ production.

Parton-Based Gribov-Regge Theory



Pomeron momentum fraction x^- (x^+ for projectile)



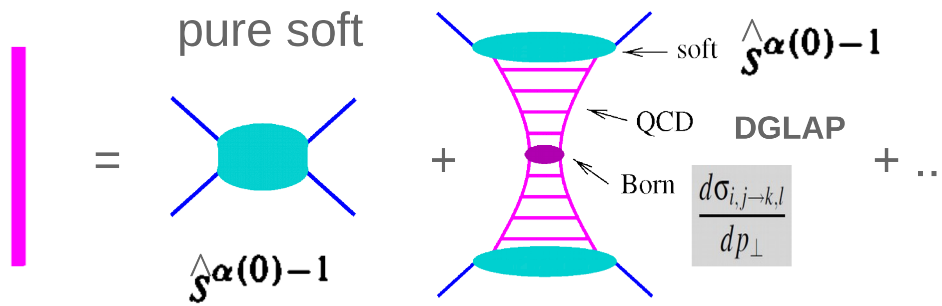
Energy sharing at the cross section level

- 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

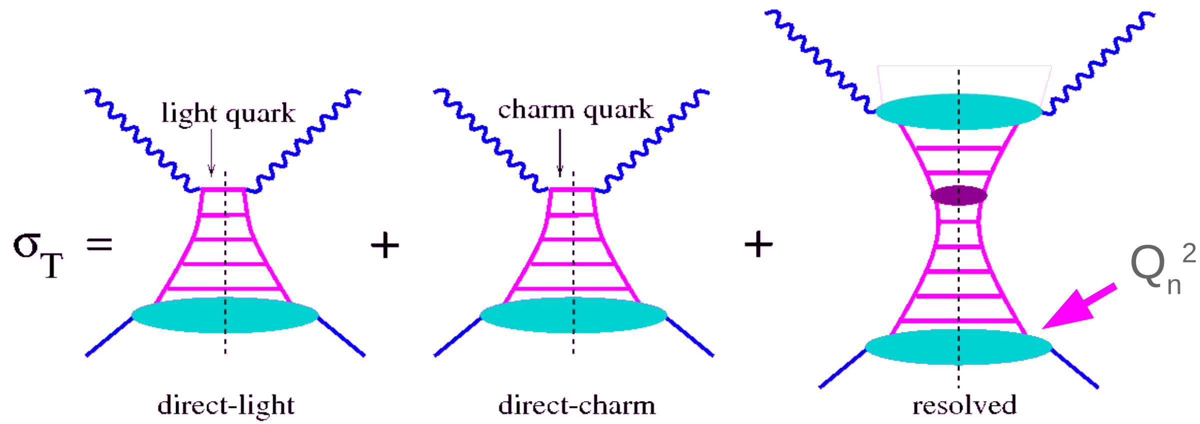
Parton-based Gribov-Regge Theory, H. J. Drescher, M. Hladik, S. Ostapchenko, T.Pierog, and K. Werner, Phys. Rept. 350 (2001) 93-289;

EPOS : Pomeron Definition

Semi-hard Pomeron : G_{QCD}=
($\hat{s}=x^+x^-s$)

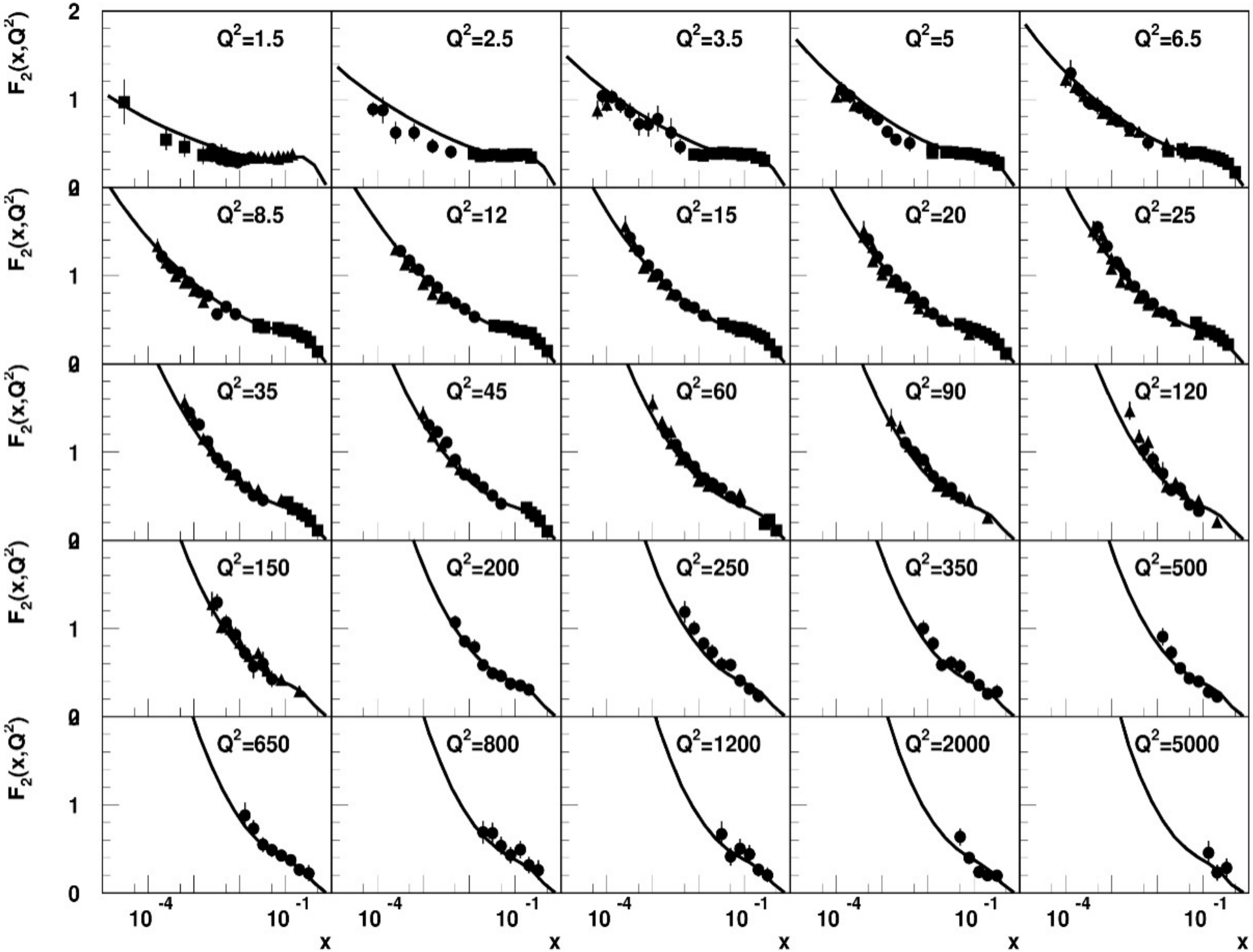


Test of semi-hard Pomeron with DIS: (Parton Distribution Function from HERA)

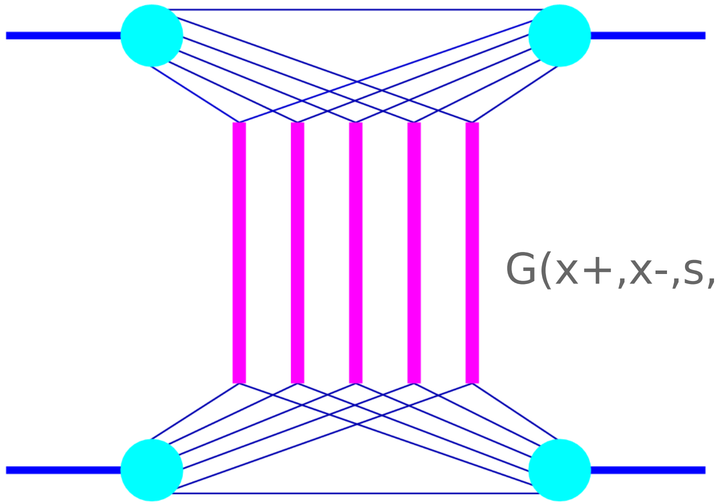


- Theory based Pomeron definion
  - pQCD based (DGLAP and Born)
    - large increase at small x (without saturation)
  - External pdf only for valence quark
  - Minimum non-perturbative scale Q_n^2=2 GeV^2 with soft pre-evolution $s^{\alpha(0)-1}$
  - F2 from HERA used to fix parameters for sea quarks and gluons below Q_n^2

EPOS Parton Distribution Function Q_n^2=2 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

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

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

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

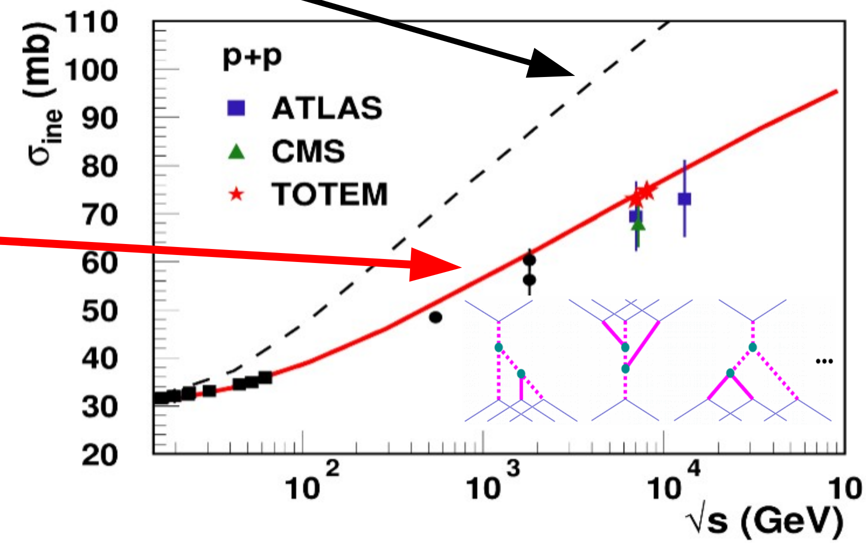
- total cross-section too high : MPI required
  - in EPOS <Pomerons> fixed by b-dep of Pomeron amplitude (slope)
- effective coupling introduced to mimic effect of enhanced diagrams and reduce cross-section (screening effect) to get cross-section AND multiplicity right in p-p, p-A and AA
  - Amplitude G_{eff} no longer fit to G_{QCD}

No effective coupling

$$\mathbf{G}_{\mathbf{QCD}} \sim (x_1 x_2)^{\beta}$$

With effective coupling

$$\mathbf{G}_{\mathbf{eff}} \sim x_1^{\beta} x_2^{\beta-\varepsilon}$$



Parametrization

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

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

Particle Production in EPOS

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

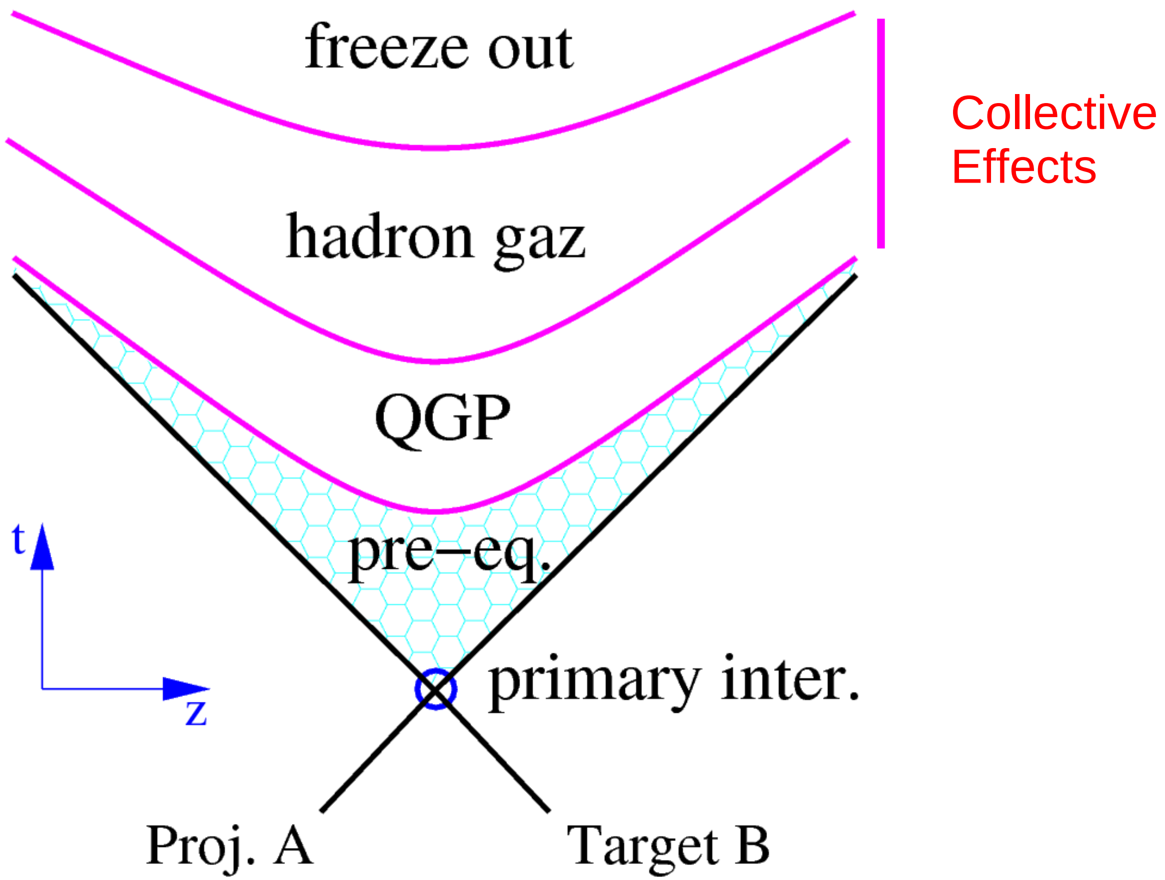
- m cut Pomerons from :

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

  - 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

To reconcile minimum bias (MB) and underlying events (UE) in pp, we need both collective effects and variable non-linear perturbative scale : impact on HQ production.

High Energy Hadronic Interactions

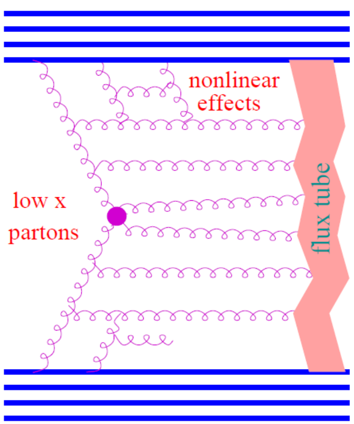


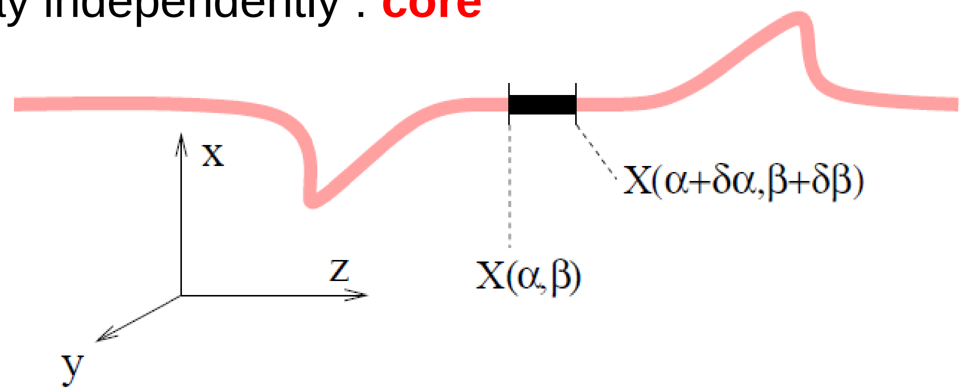
For a complete description of LHC pp data (from minimum-bias to high multiplicity), same process chain as for heavy ion needed.

High Density Core Formation

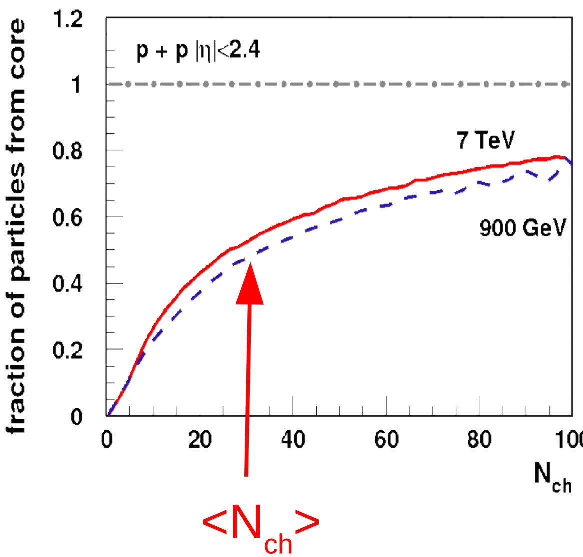
Heavy ion collisions or high energy proton-proton scattering:

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

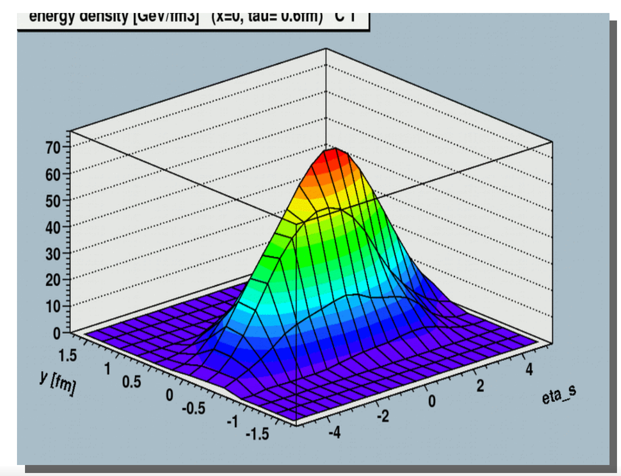




- Each string split into a sequence of string segments, corresponding to widths δα and δβ in the string parameter space



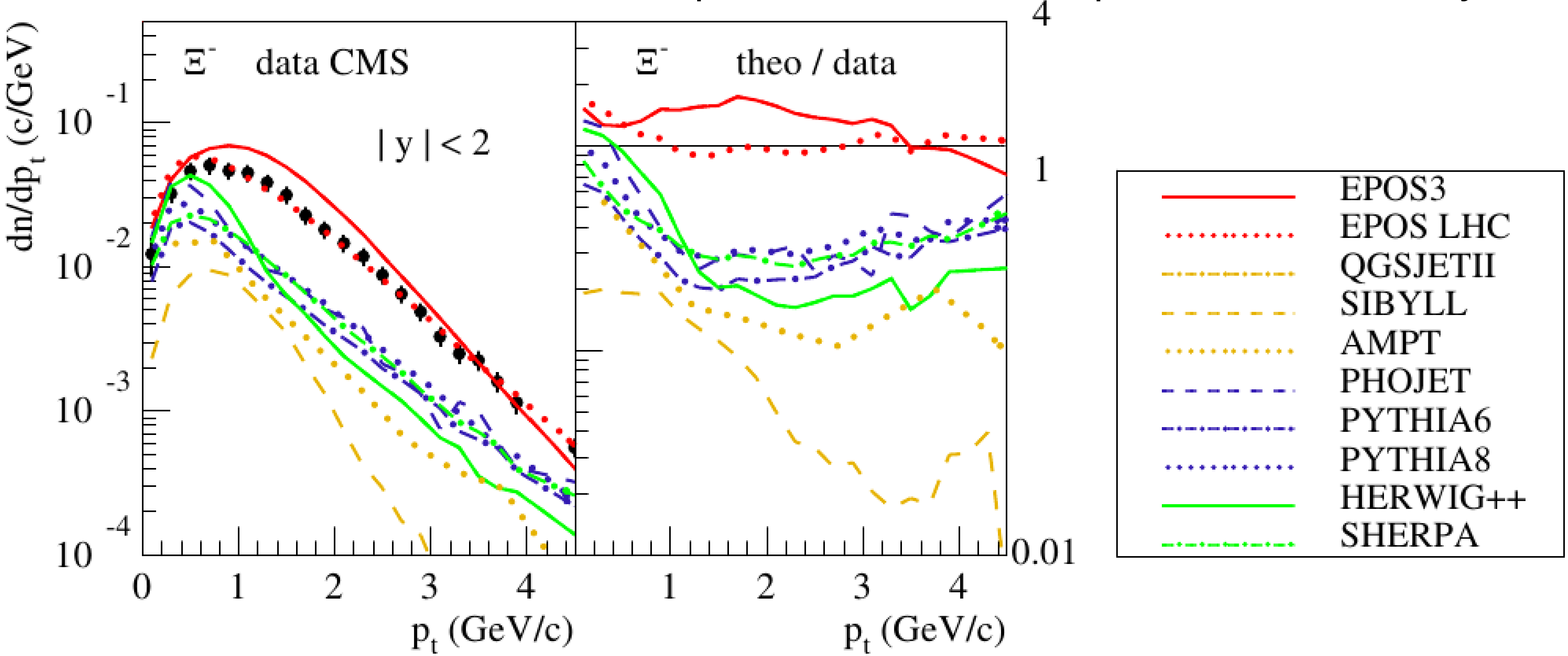
- If energy density from segments high enough
  - segments fused into core
    - full 3D+1 hydro evolution
    - lattice QCD EoS
- If low density (corona)
  - segments remain hadrons
    - string fragmentation



EPOS LHC

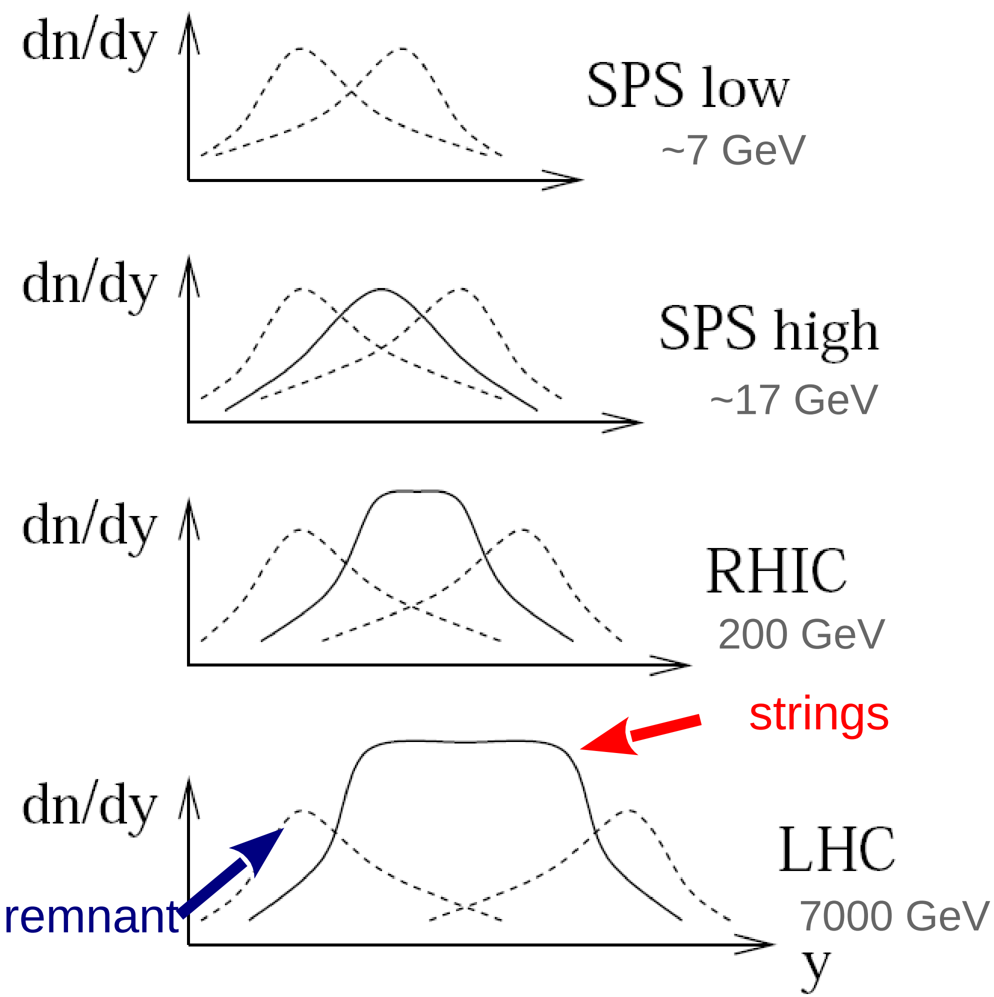
Detailed description can be achieved

- identified spectra
- p_t behavior driven by collective effects (statistical hadronization + flow)
  - large effect for multi-strange baryons (yield AND $<p_t>$)
  - flow effect possible on charmed particles but not on yield ?



Remnants

Forward particles mainly from projectile remnant



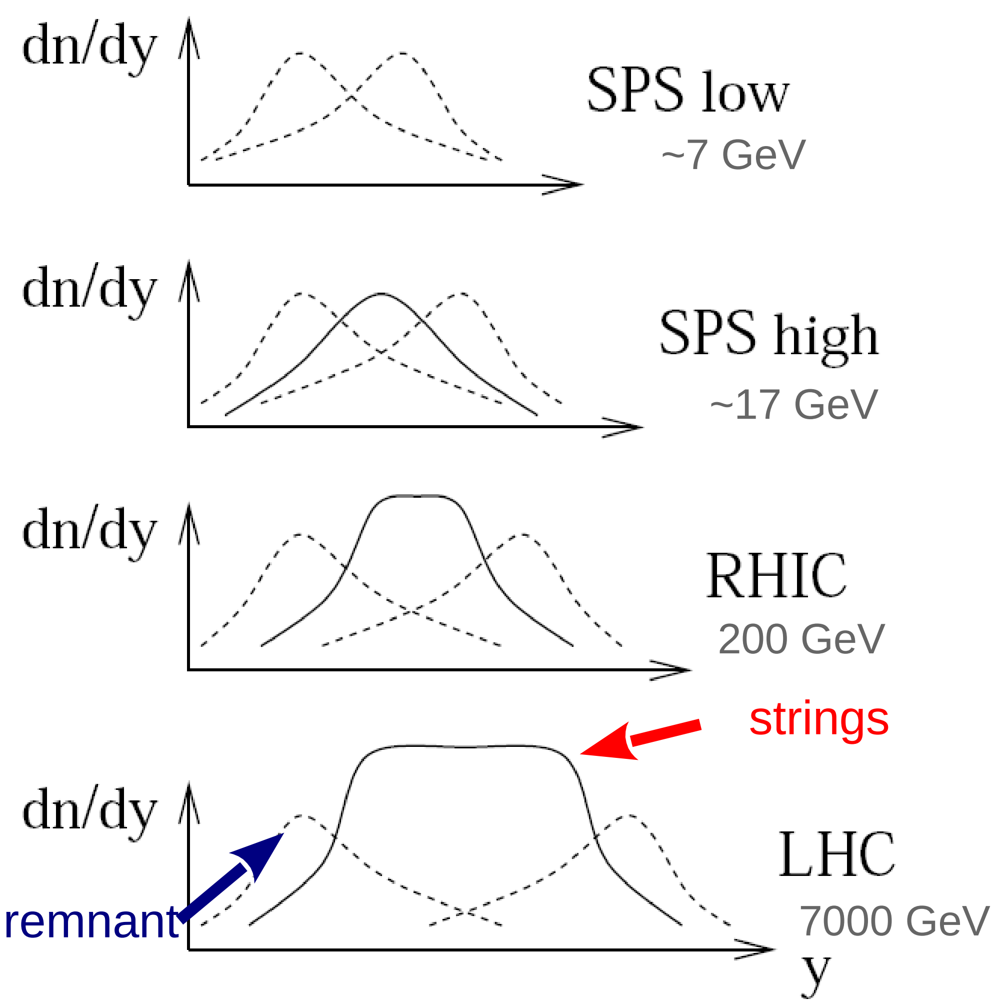
Forward hadronization from remnant :

- 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

Forward particles mainly from projectile remnant

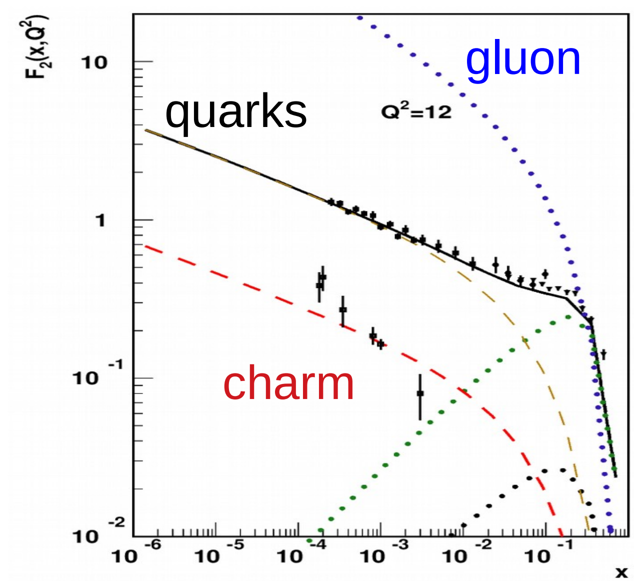


Forward hadronization from remnant :

- Place for forward charm
  - Soft intrinsic charm ?
  - Coalescence ?

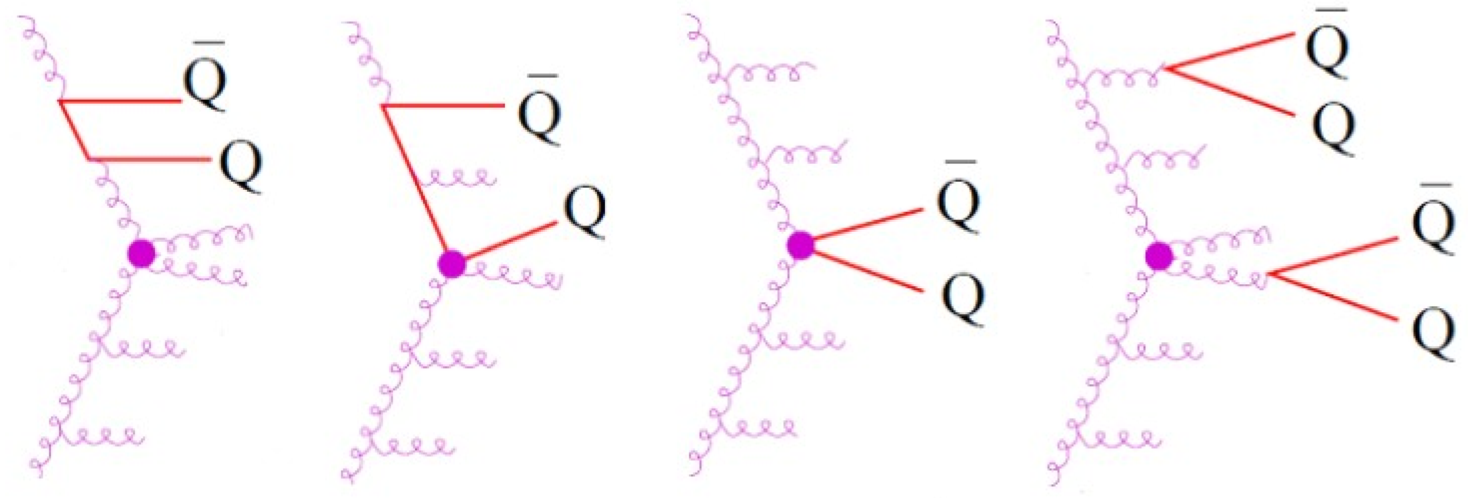
  Not yet implemented
  test with low energy data

- But charm in PDF to start parton cascade



Heavy Flavor Production

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



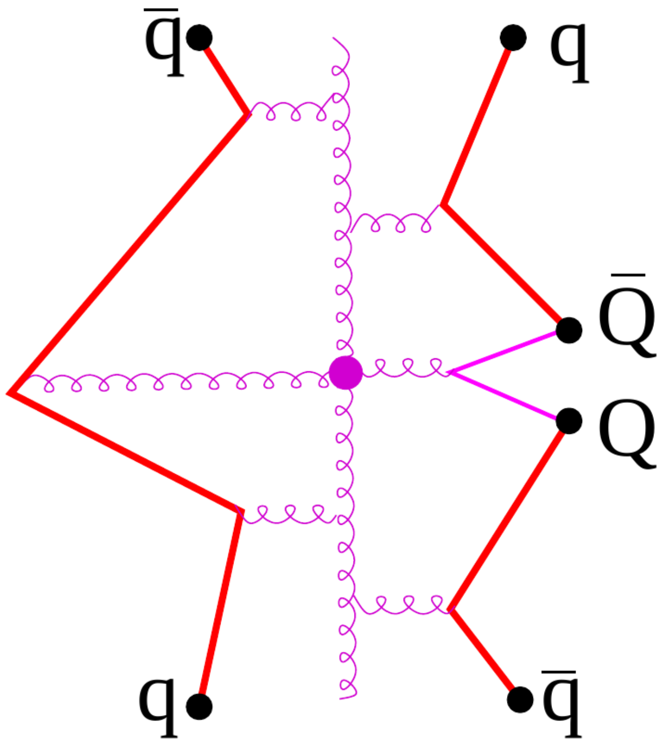
space-like cascade | space-like cascade and born | born | time-like cascade

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

Hadronization

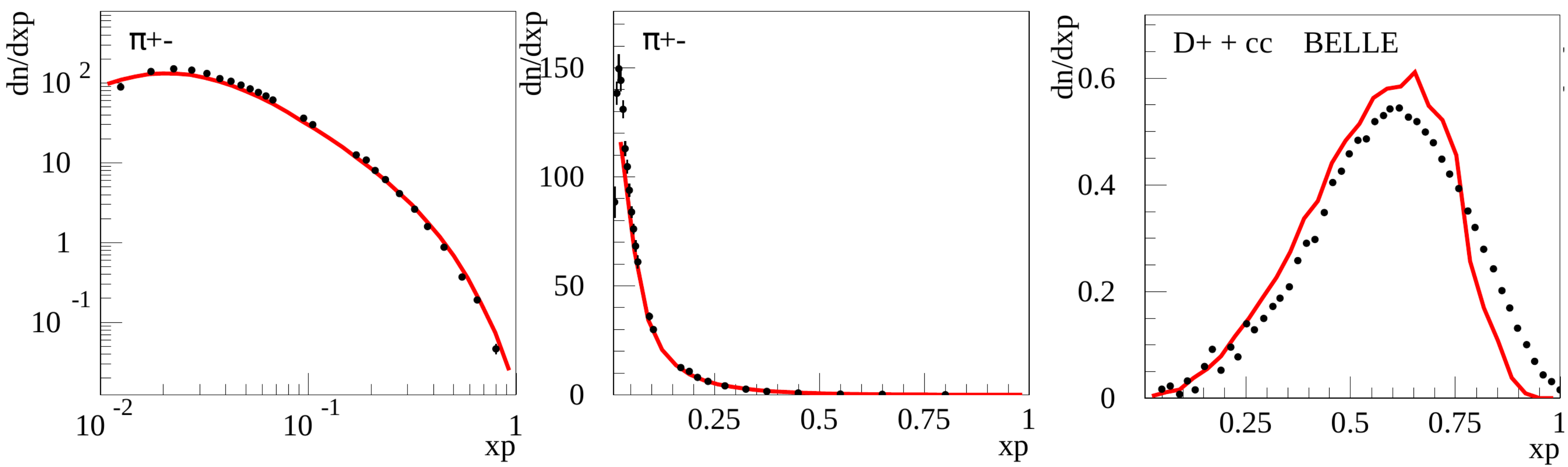
Heavy Quark String

- 2 “kinky” strings from one Pomeron (=parton ladder)
- HQ always used as string ends
- Hadronization tested with e+e- data



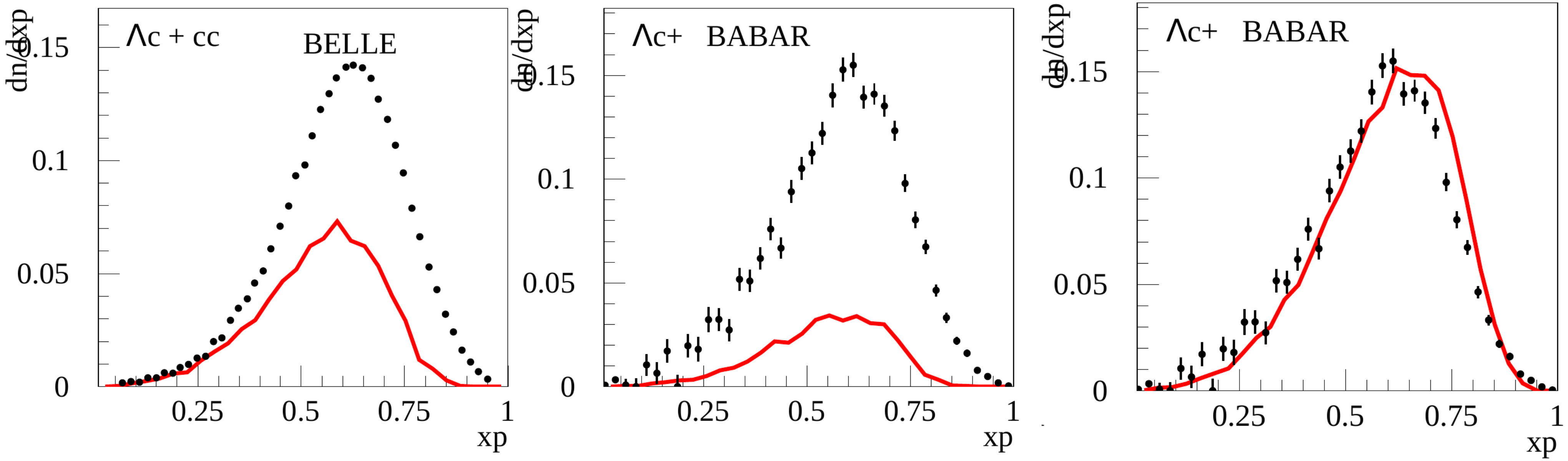
Test of Hadronization with e+e- Data : Mesons

- LEP data used to fix light hadron hadronization (area law used for string fragmentation, not Lund model)
  - Free parameters = effective mass of quarks and diquarks
  - String tension
- $x_p = E/E_{max}$ distribution much harder for charmed meson : HQ from string ends only (not produced during fragmentation : only 3 (light) flavors)



Test of Hadronization with e+e- Data : Baryons

- LEP data used to fix light hadron hadronization (area law used for string fragmentation, not Lund model)
  - Free parameters = effective mass of quarks and diquarks
  - String tension
- $x_p = E/E_{max}$ distribution much harder for charmed meson : HQ from string ends only (not produced during fragmentation : only 3 (light) flavors)
- Charmed baryon production underestimated using diquark mass suppression
  - Correct description of data if diquark mass is not used in diquark break probability (~ x10 compared to light quarks only)



Test of Hadronization with e+e- Data : Baryons

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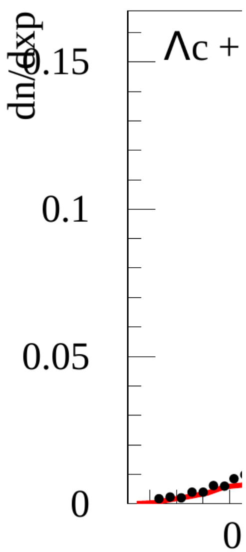
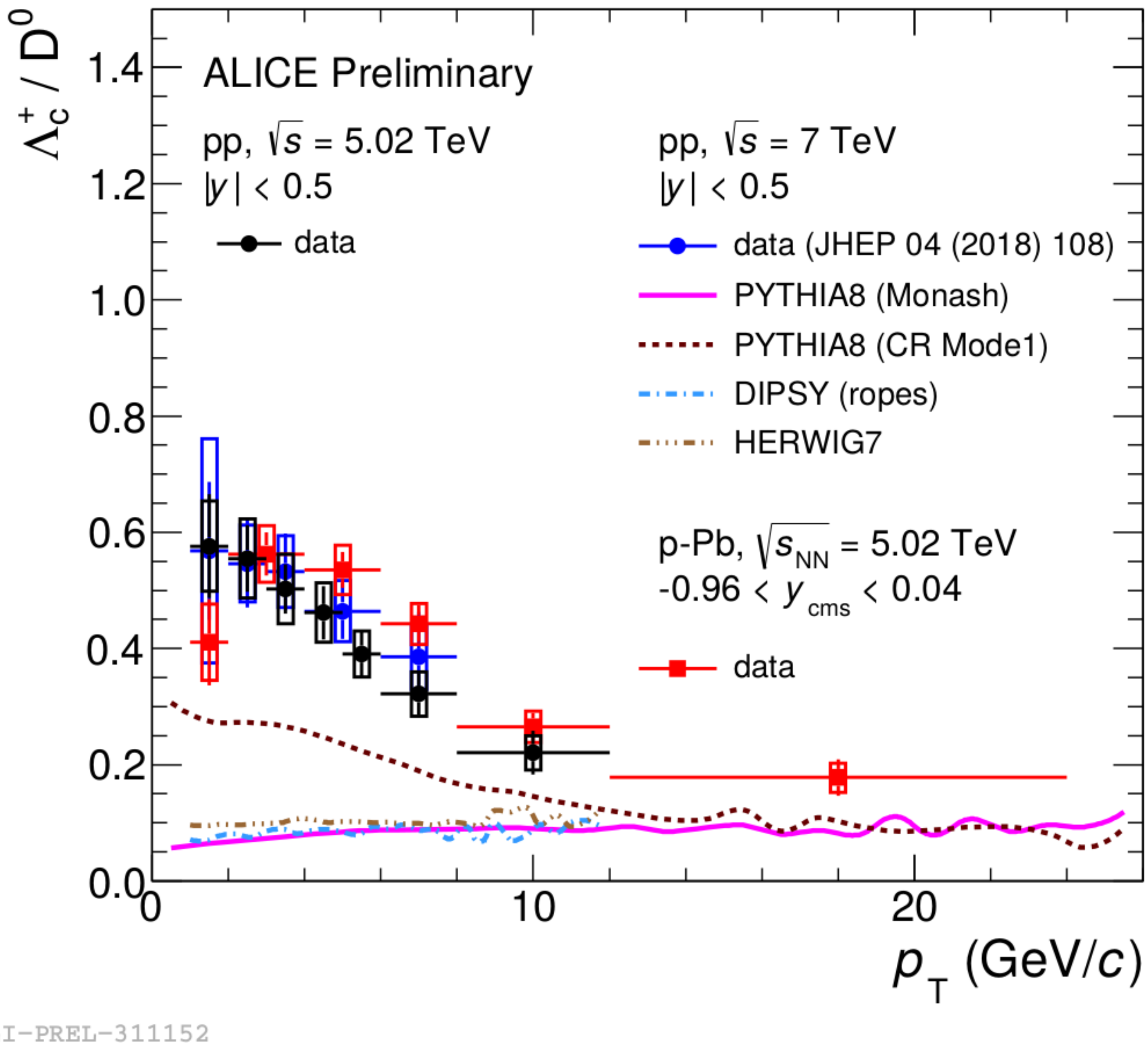
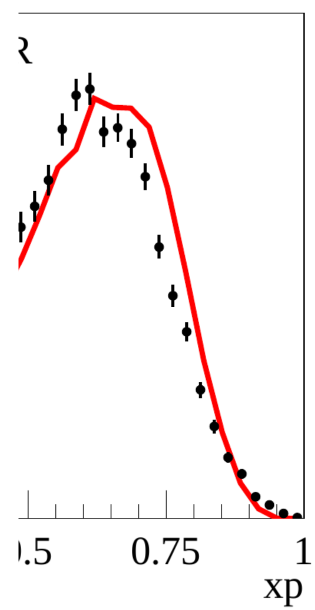
g ends only

ression

eak







Hadronization

Heavy Quark String

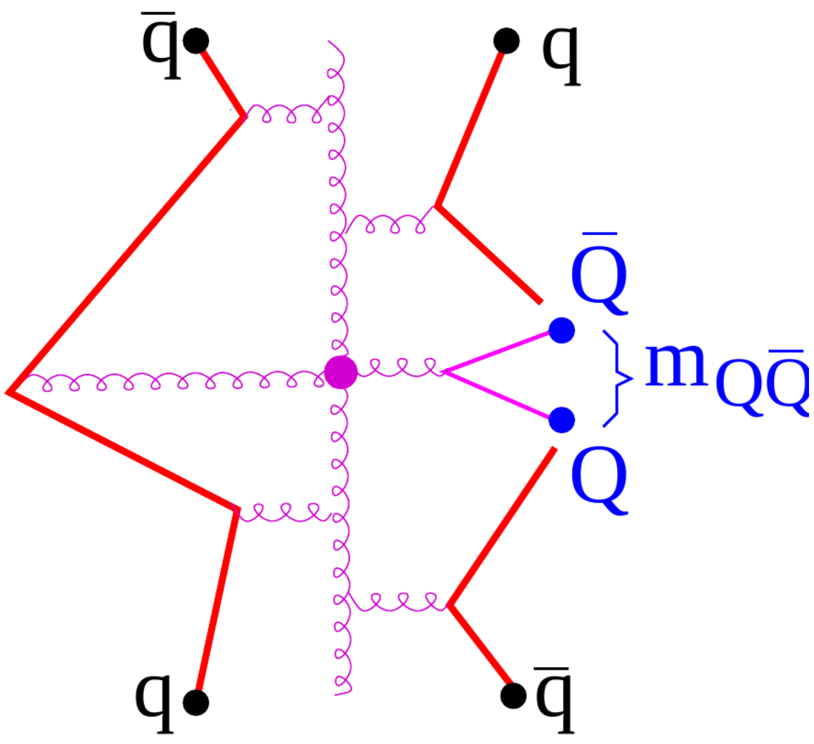
- 2 “kinky” strings from one Pomeron (=parton ladder)
- HQ always used as string ends
- Hadronization tested with e+e- data

- Quarkonium produced in born or TLC by pair production
  - Compute mass of the Q-$\bar{Q}$ system
  - If $2m_Q < m_{Q\bar{Q}} < 2m_{D(B)}$

    then $Q\bar{Q}$=quarkonium

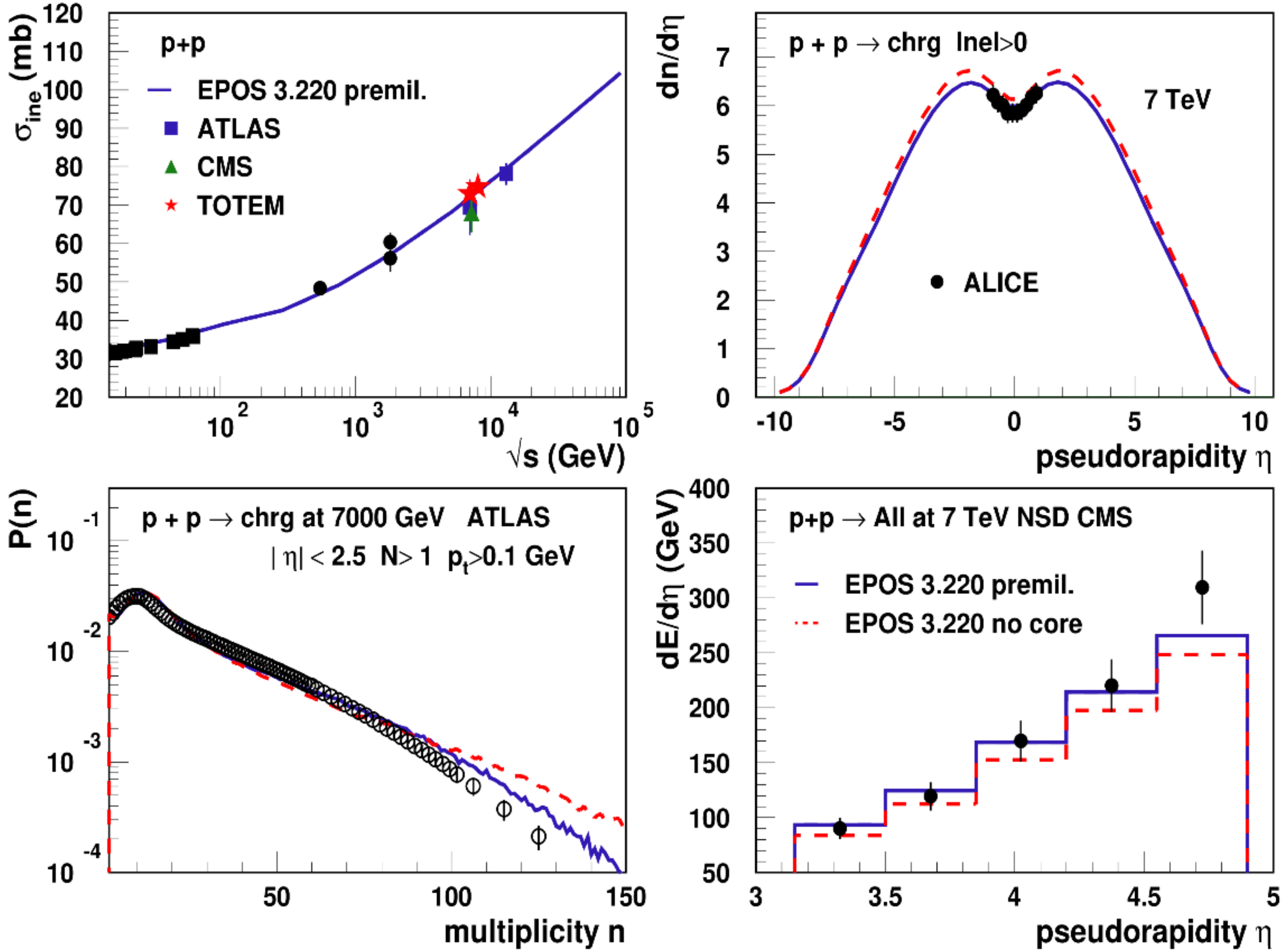
    with probability $w_{Q\bar{Q}\to J/\Psi(\Upsilon)}$

    (color evaporation model)



Preliminary Results : With/out Core

Excellent results for minimum bias soft physics



Preliminary Results : With/out Core

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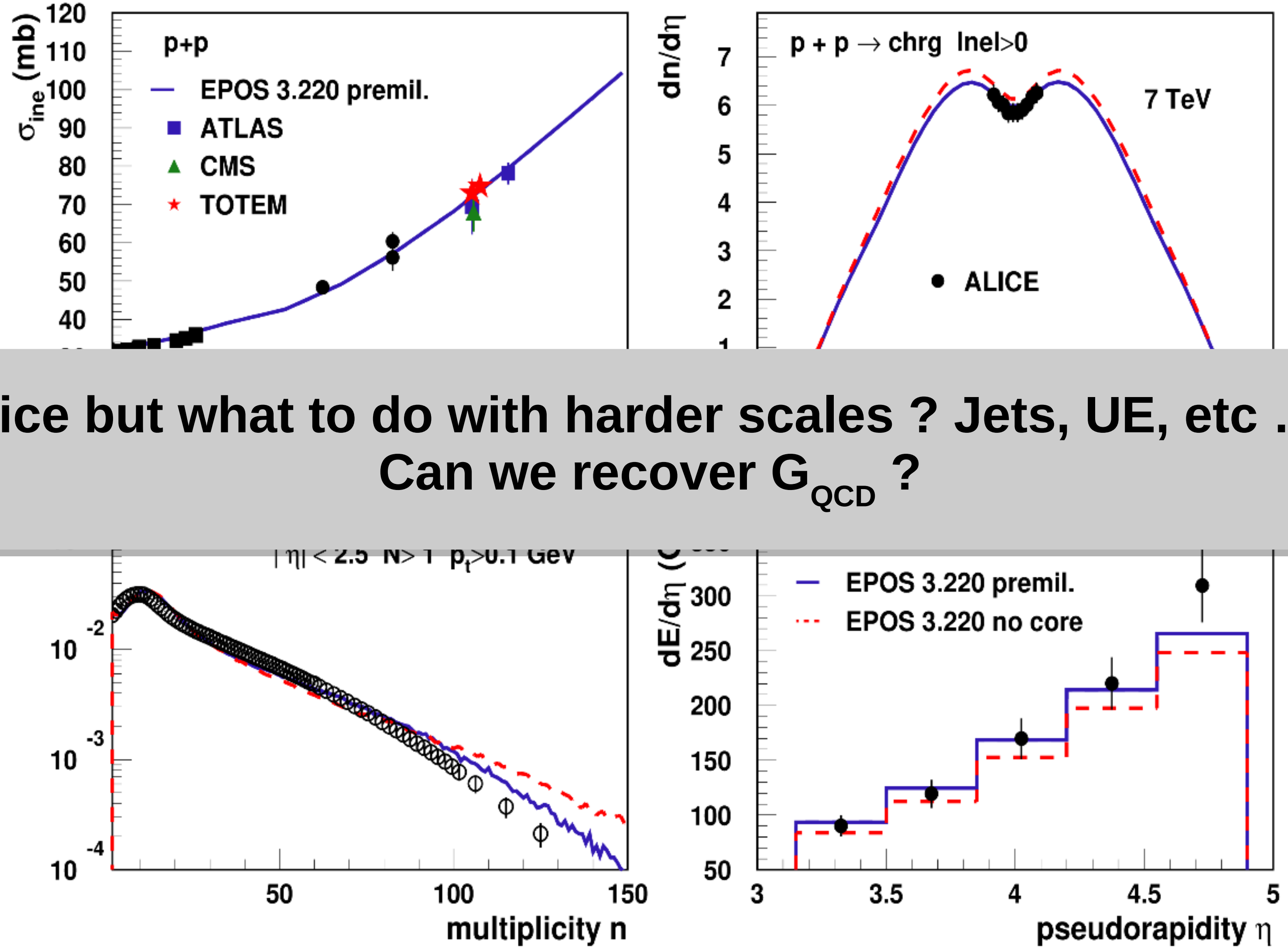


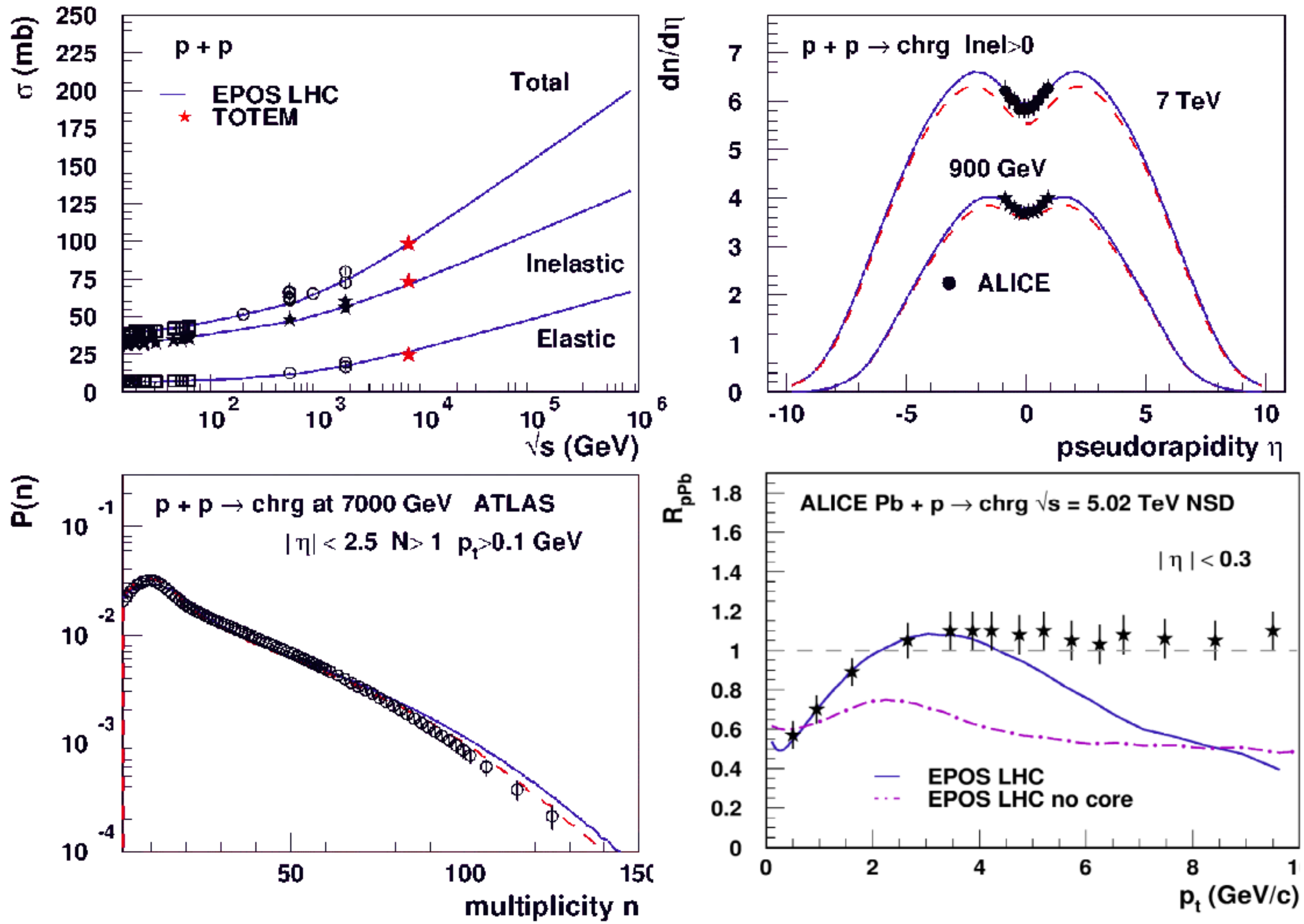
Nice but what to do with harder scales ? Jets, UE, etc …
Can we recover G_{QCD} ?

EPOS LHC : Fixed $Q_0^2 = Q_n^2$ (old)

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

- **Problem for hard processes**
  - ➡ Minimum scale for DGLAP = $Q_0^2 = Q_n^2$
  - ➡ lack of high pt
  - ➡ 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

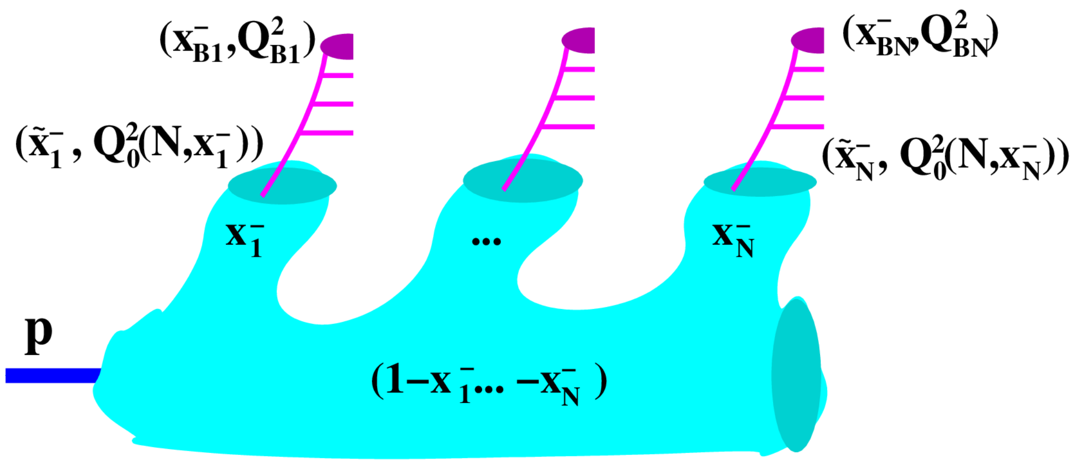
m number of exchanged elementary interaction per event fixed from elastic amplitude taking into account energy sharing :

- m cut Pomerons from :

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

  - m(=N) and X={x_1,...,x_N} fixed together by a complex Metropolis (Markov chain)

- if G_{eff}=G_{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 !

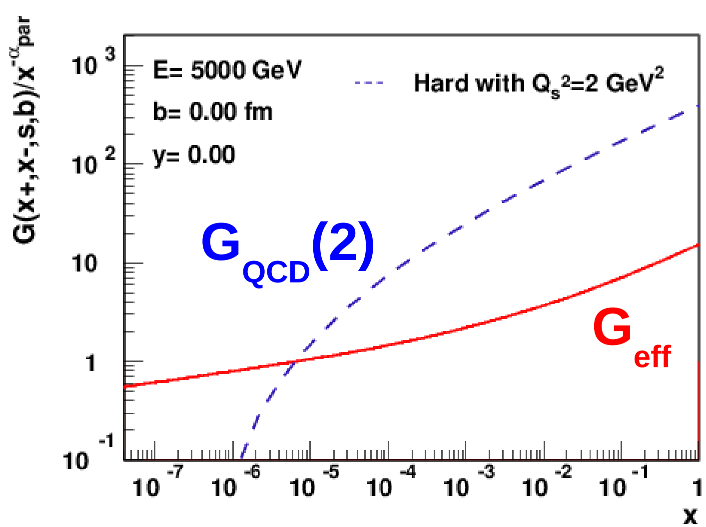
Non-linear Perturbative Scale Q_0^2

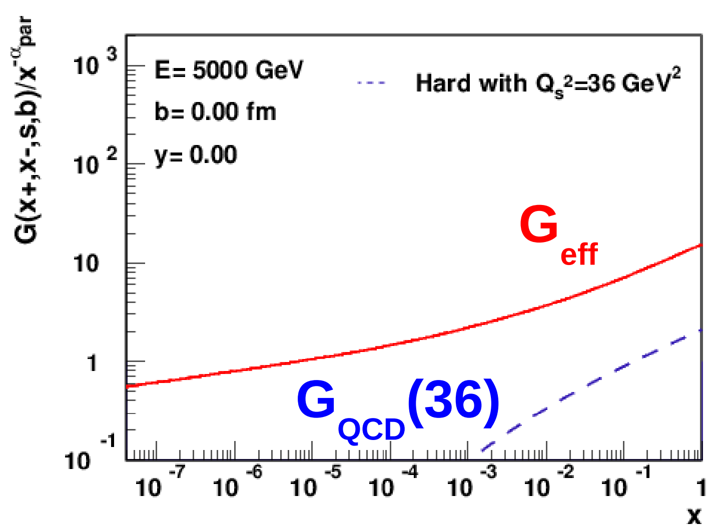
- **Model property : AGK cancellation**

$$\frac{dn^{h_1h_2}_{\text{Pom}}}{dx^+dx^-}(x^+,x^-,s,b) = \frac{dn^{(1)h_1h_2}_{\text{Pom}}}{dx^+dx^-}(x^+,x^-,s,b)$$
$$= G_{eff}(x^+,x^-,s,b)F^{h_1}_{\text{remn}}(1-x^+)F^{h_2}_{\text{remn}}(1-x^-)$$

- **Assumption : factorization should be satisfied at large Q^2**
  - ➜ satisfied if: $\langle N_{hard}\rangle\, G_{QCD}(x,b,Q_0^2)=G_{eff}(s,x,b,A)$
  - ➜ different non-linear pertubative scale event-by-event and even Pomeron-by-Pomeron depending on momentum fraction x

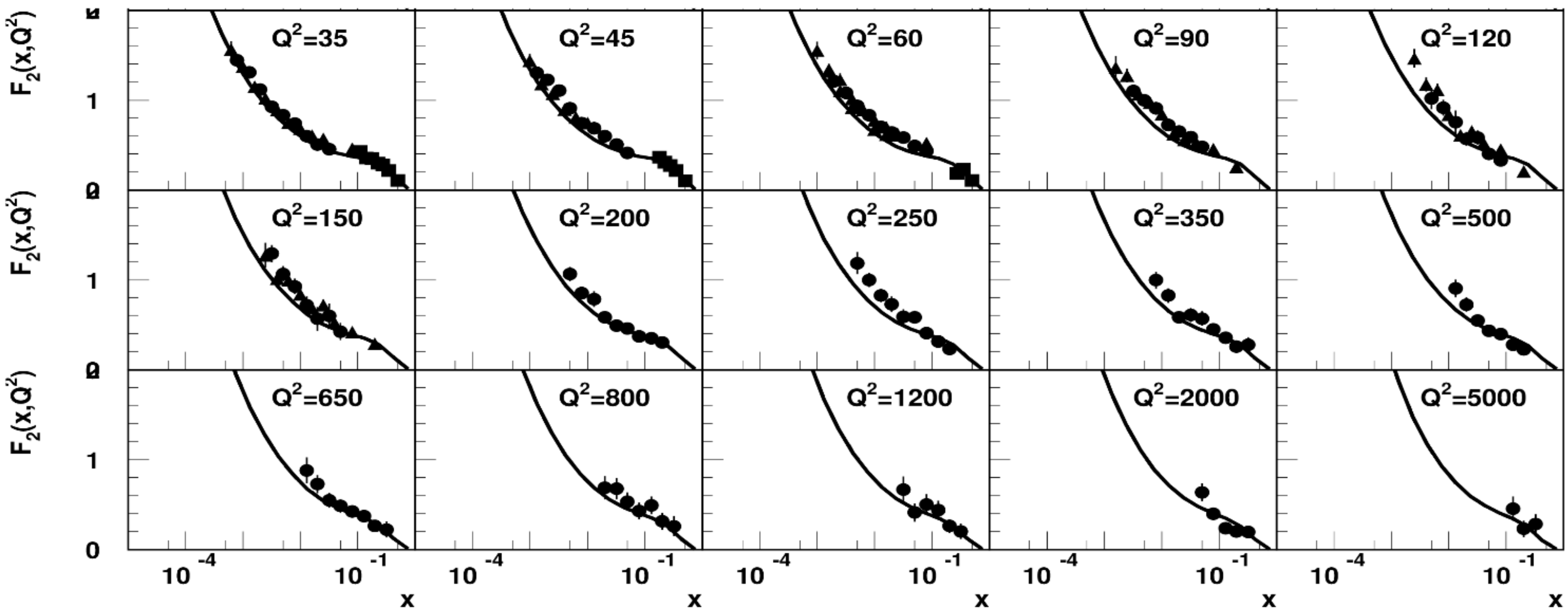
- **Matching amplitude**
  - ➜ $G_{eff} \leqslant G_{QCD}(Q_0^2=Q_n^2)$
  - ➜ increase Q_0^2 until $G_{eff}=\langle N_{hard}\rangle G_{QCD}(Q_0^2)$ for each parton scattering
  - ➜ for $Q^2 \gg Q_0^2(x,b)$ factorization holds





EPOS Parton Distribution Function Q_0^2=30 GeV^2

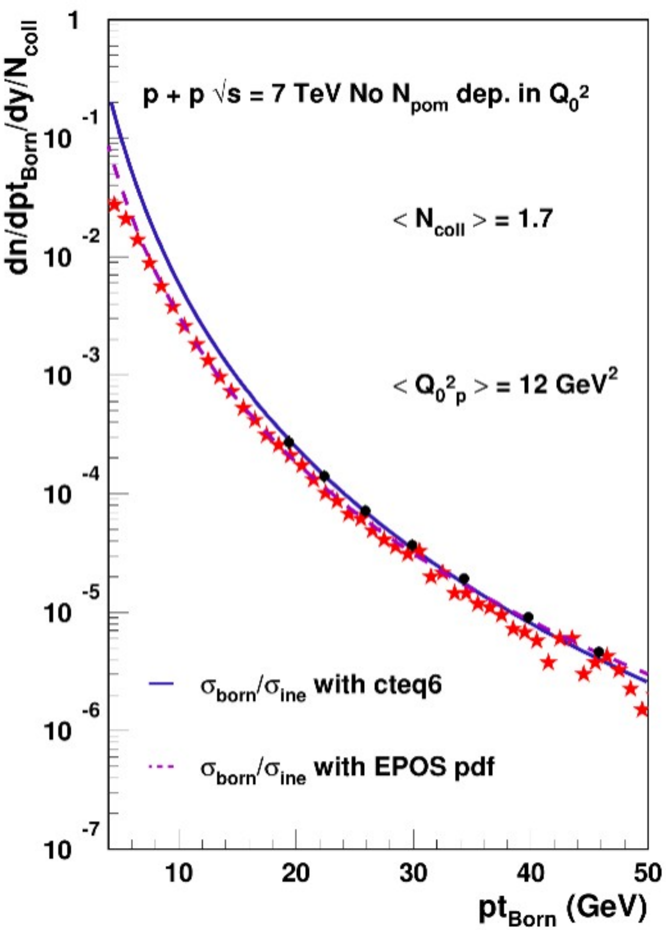
- **Larger Q_0^2**
  - partons which can be treated pertubatively (linear DGLAP evolution) and independently have already a large virtuality
  - soft preevolution changed to get the same parton distribution than with Q_n^2 (perturbative but non-linear evolution)
  - PDF for $Q^2 > Q_0^2$ independent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

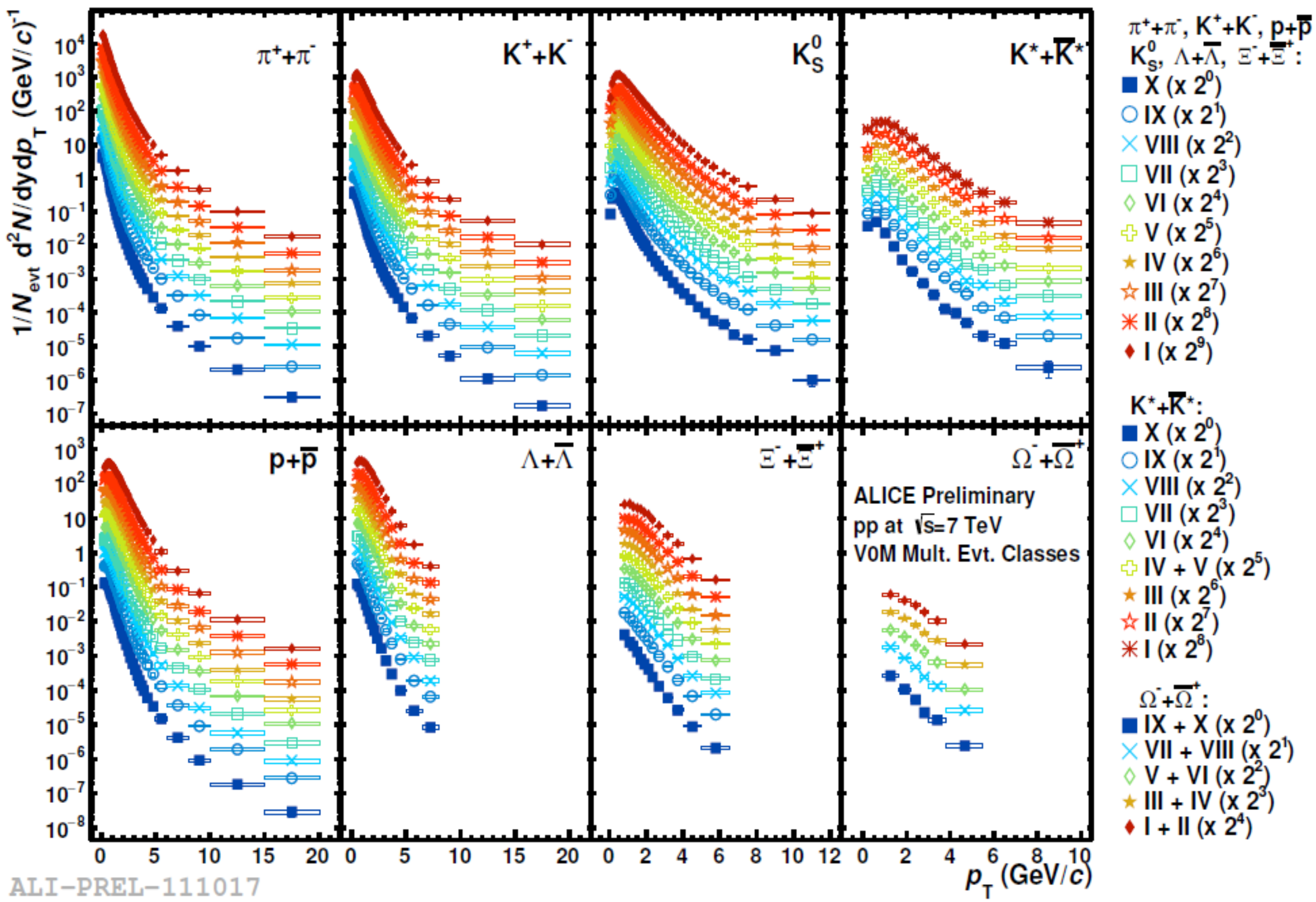


Jet and p_t

Check with pp data at 7 TeV

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





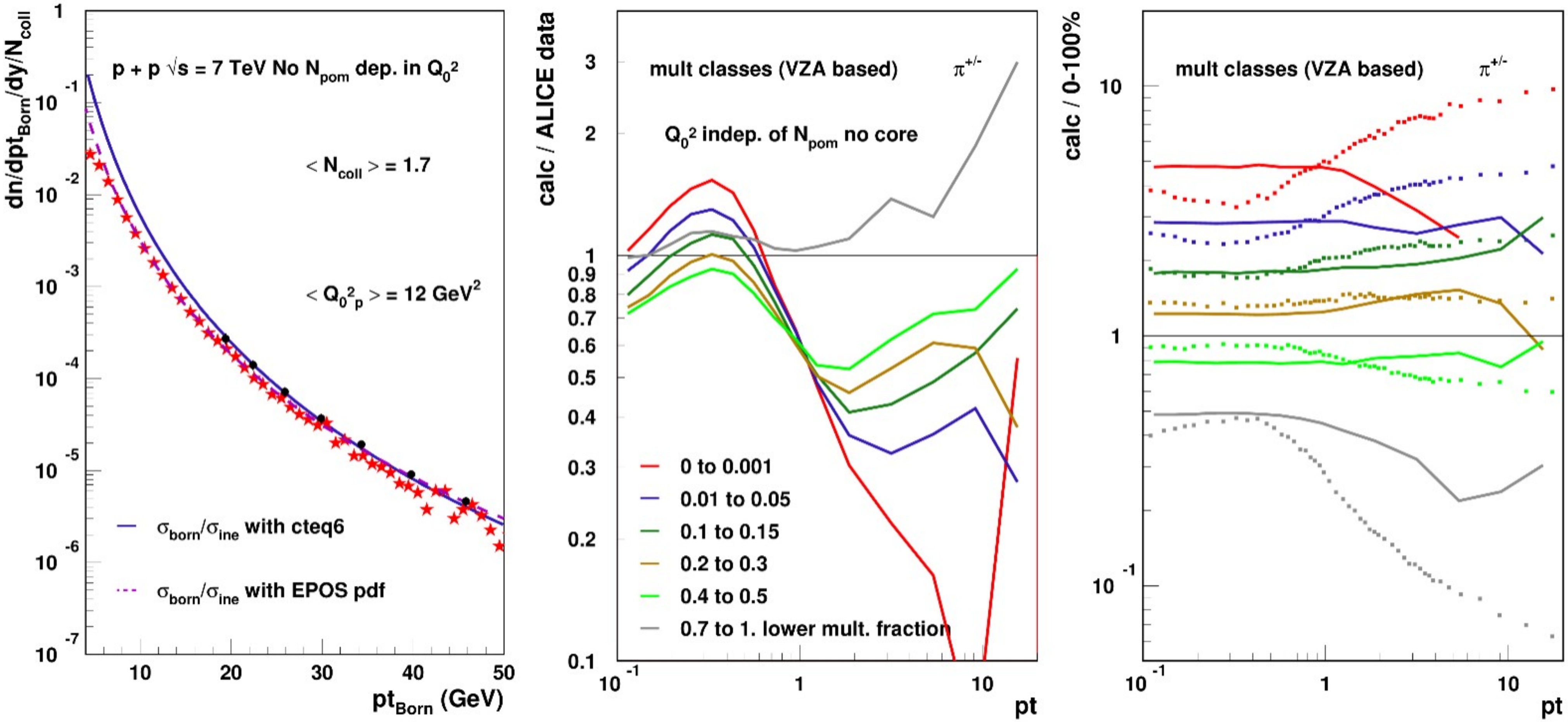
J.Phys.Conf.Ser. 779 (2017) no.1, 012071

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



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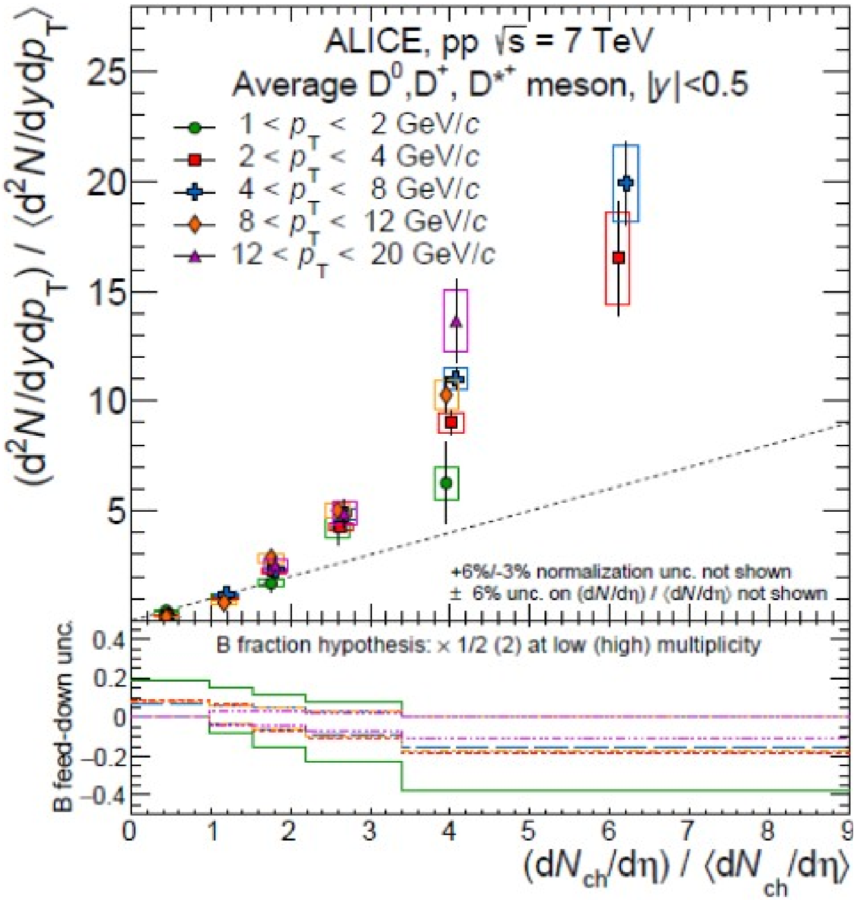
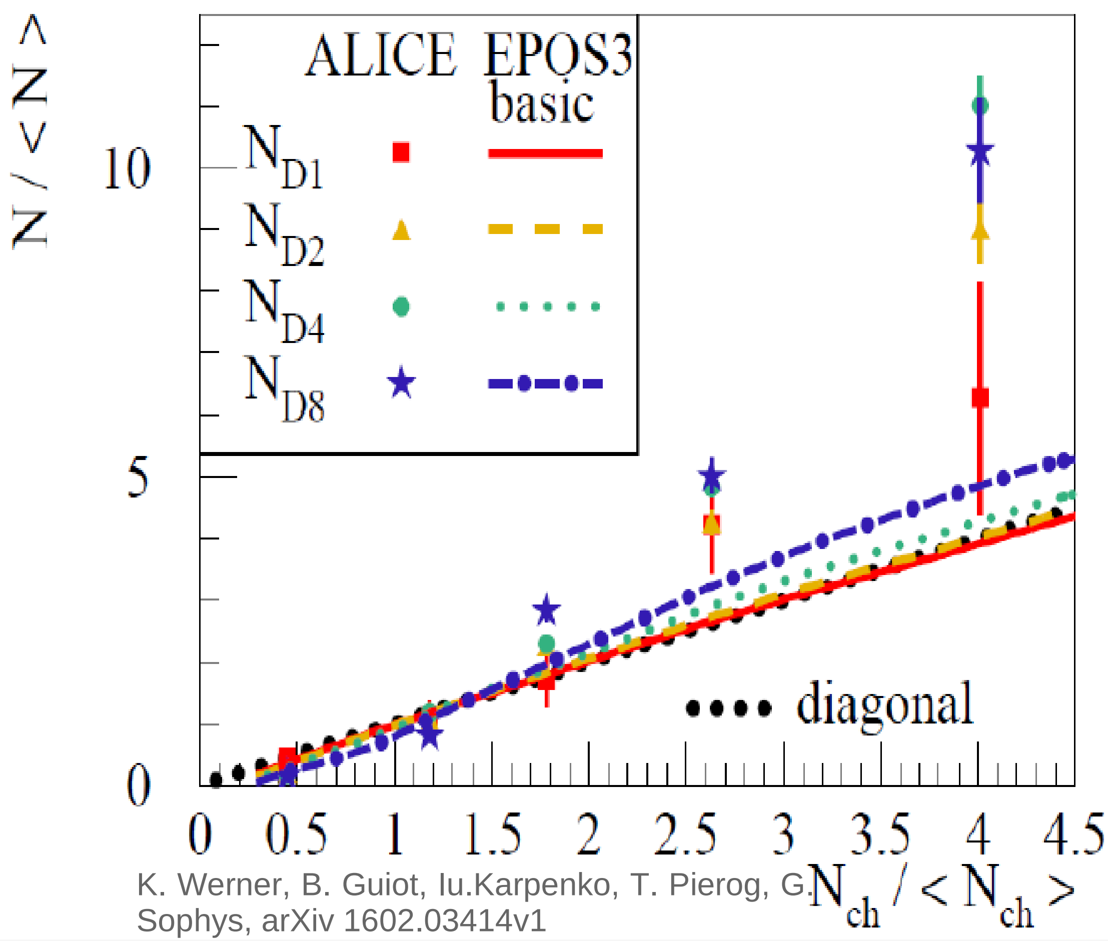
Charm Production

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



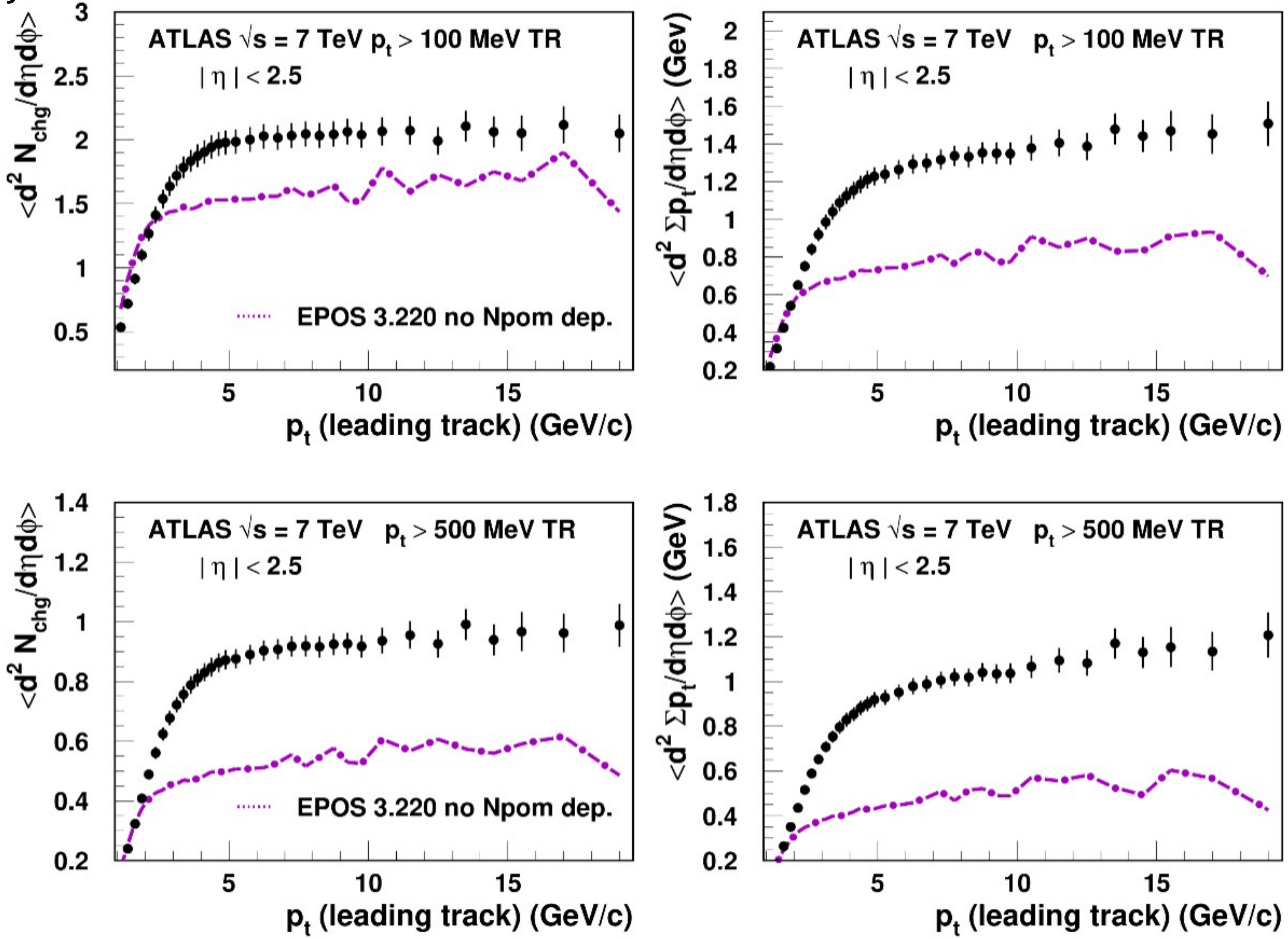


K. Werner, B. Guiot, Iu.Karpenko, T. Pierog, G. Sophys, arXiv 1602.03414v1

Underlying Events

Check with pp data at 7 TeV

➡ activity too low

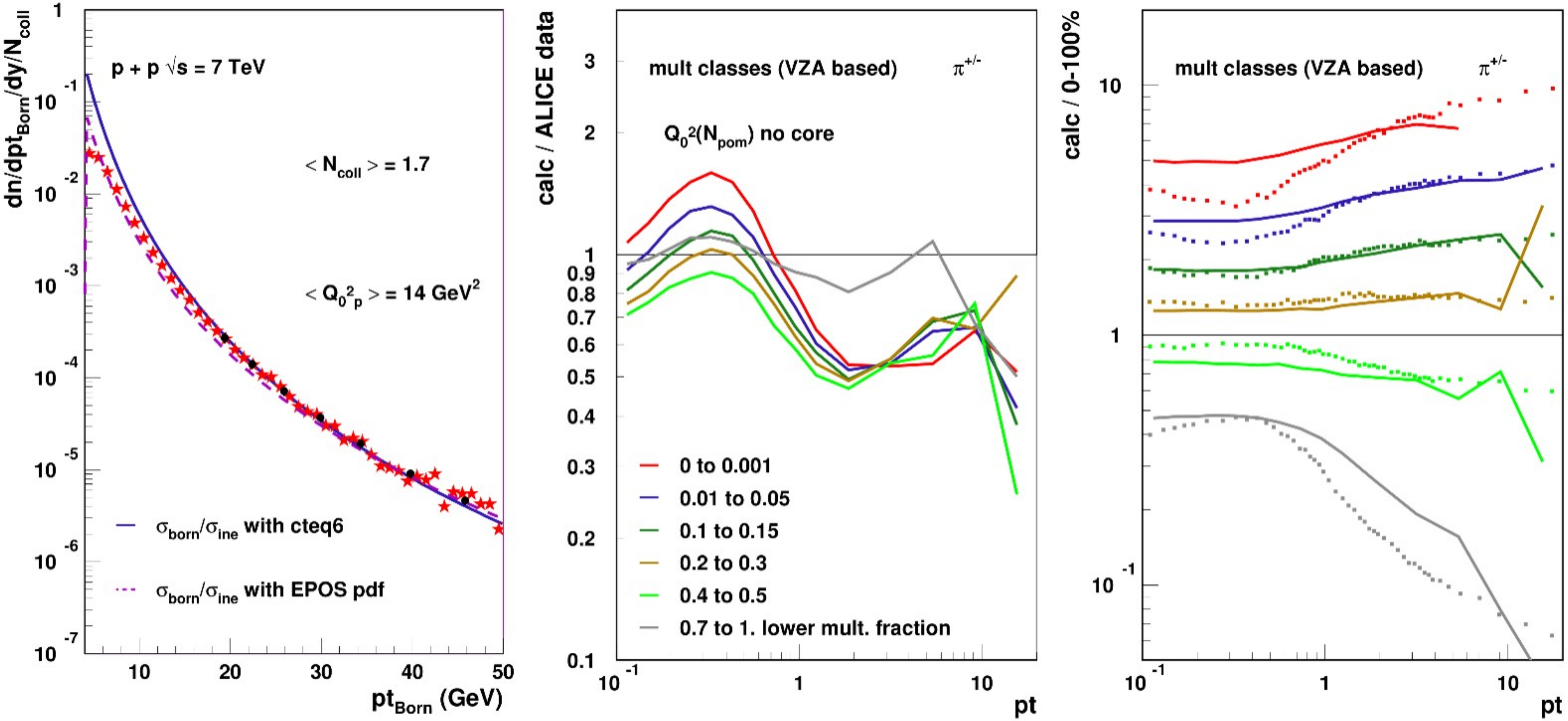


Effect of MPI on Q_0^2

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

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

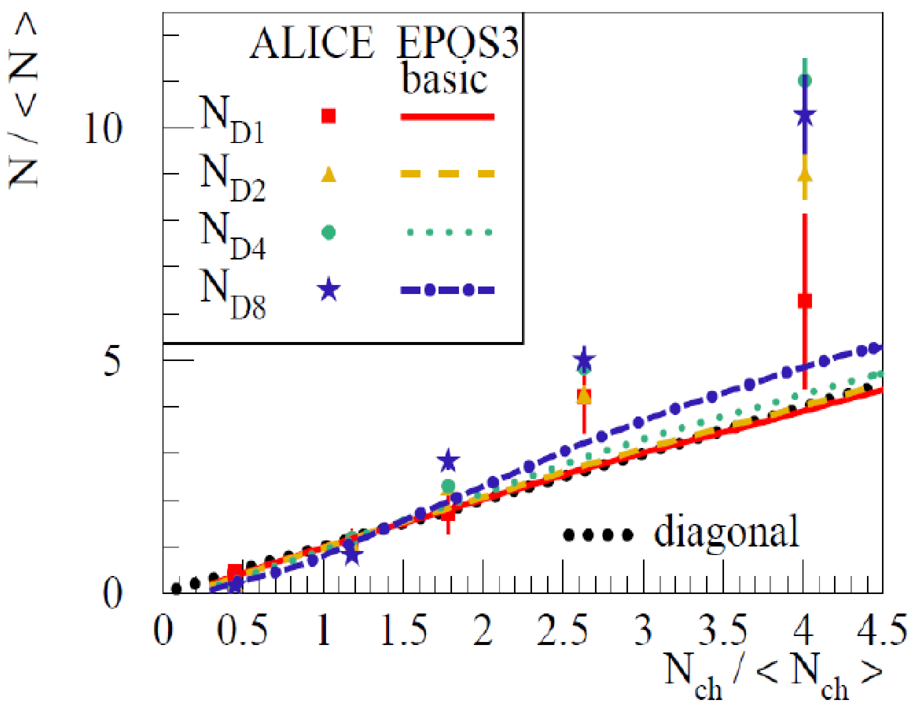
➜ $N_{hard}\ G_{QCD}(x,b,Q_0^2)=G_{eff}(s,x,b,A)$



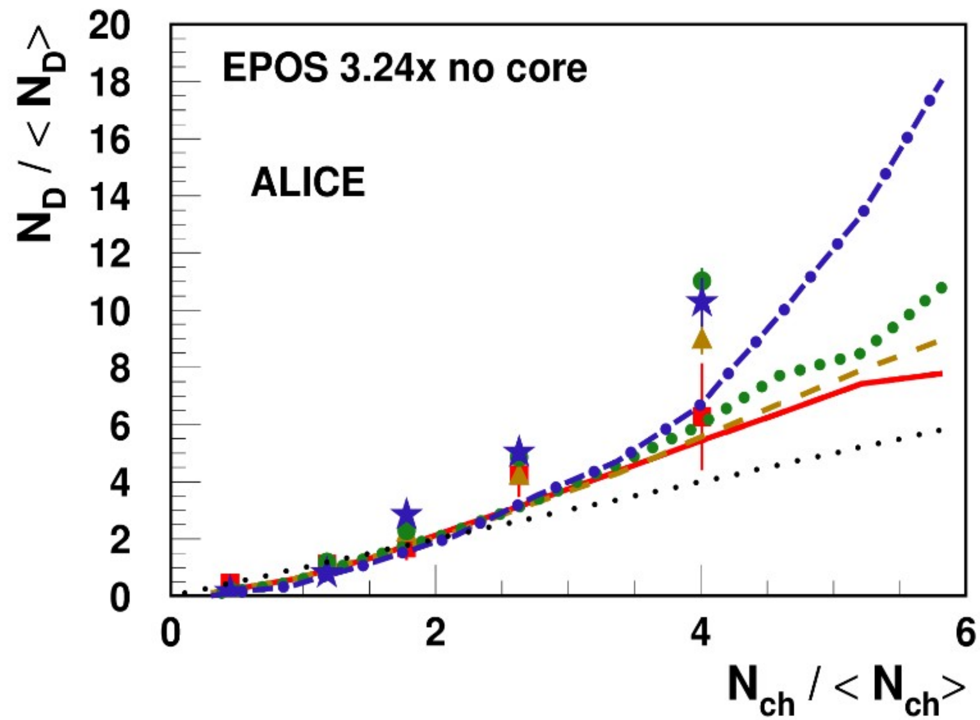
Effect on Heavy Flavor Production

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)



Q_0^2 with $<N_{hard}>$ dep.

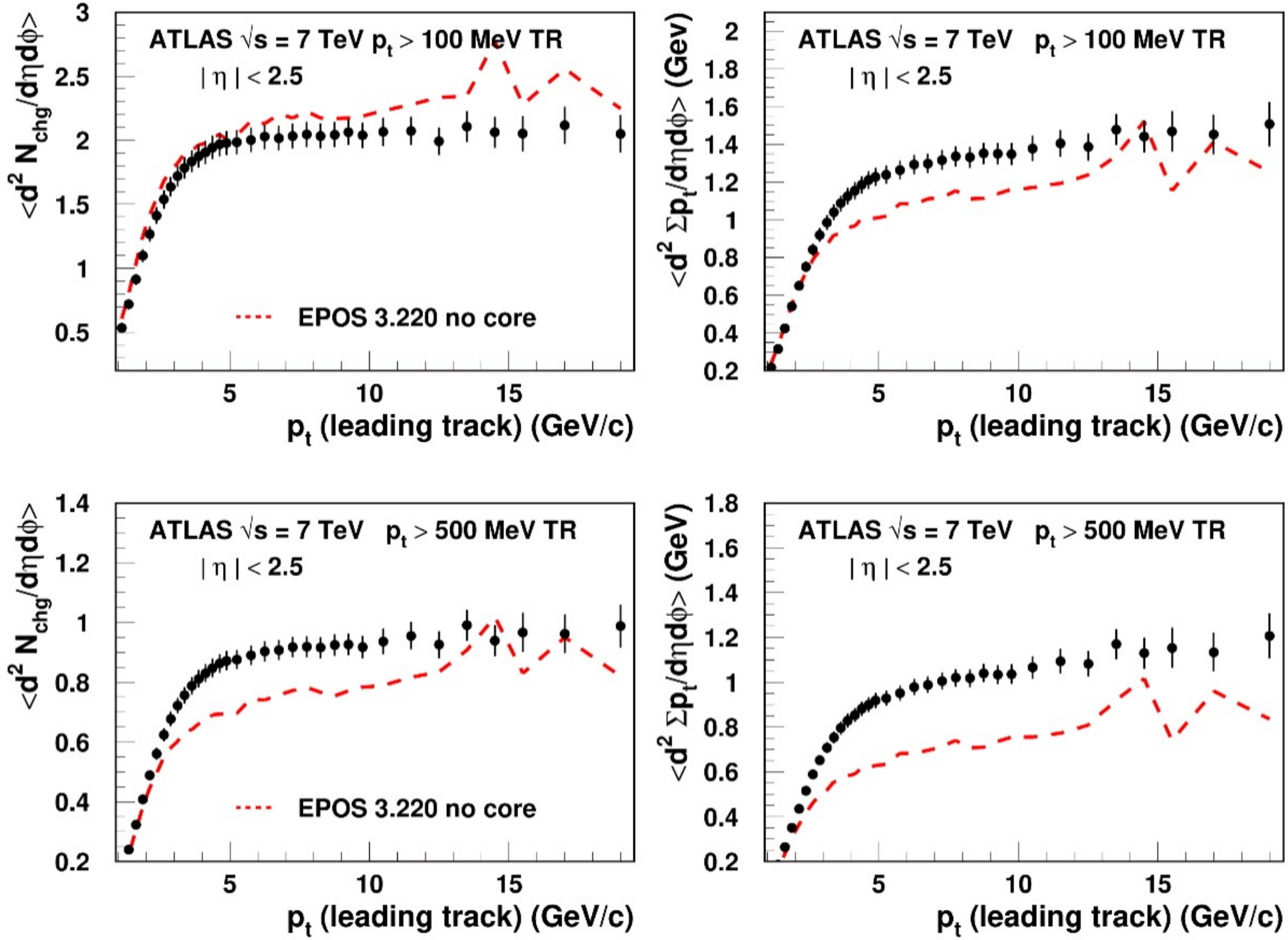


Q_0^2 with N_{hard} dep.

Underlying Events

Check with pp data at 7 TeV

➡ activity too high ?



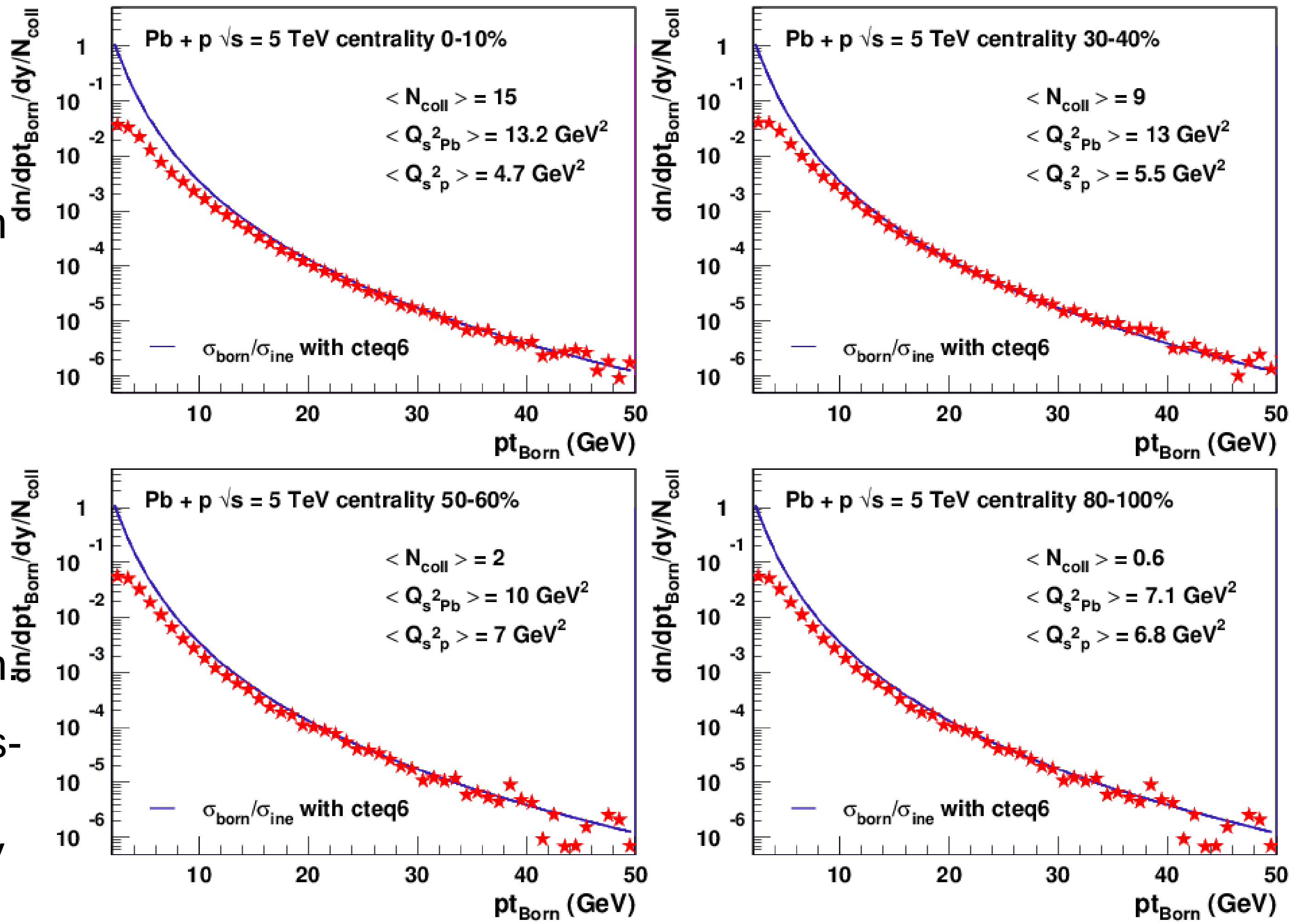
Nuclear Interactions

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

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

  to produce ISR and born process in hard Pomeron
  - Scaling of inclusive cross-section if N_{hard} and N_{soft} ($N_{pom}=N_{hard}+N_{soft}$) properly determined

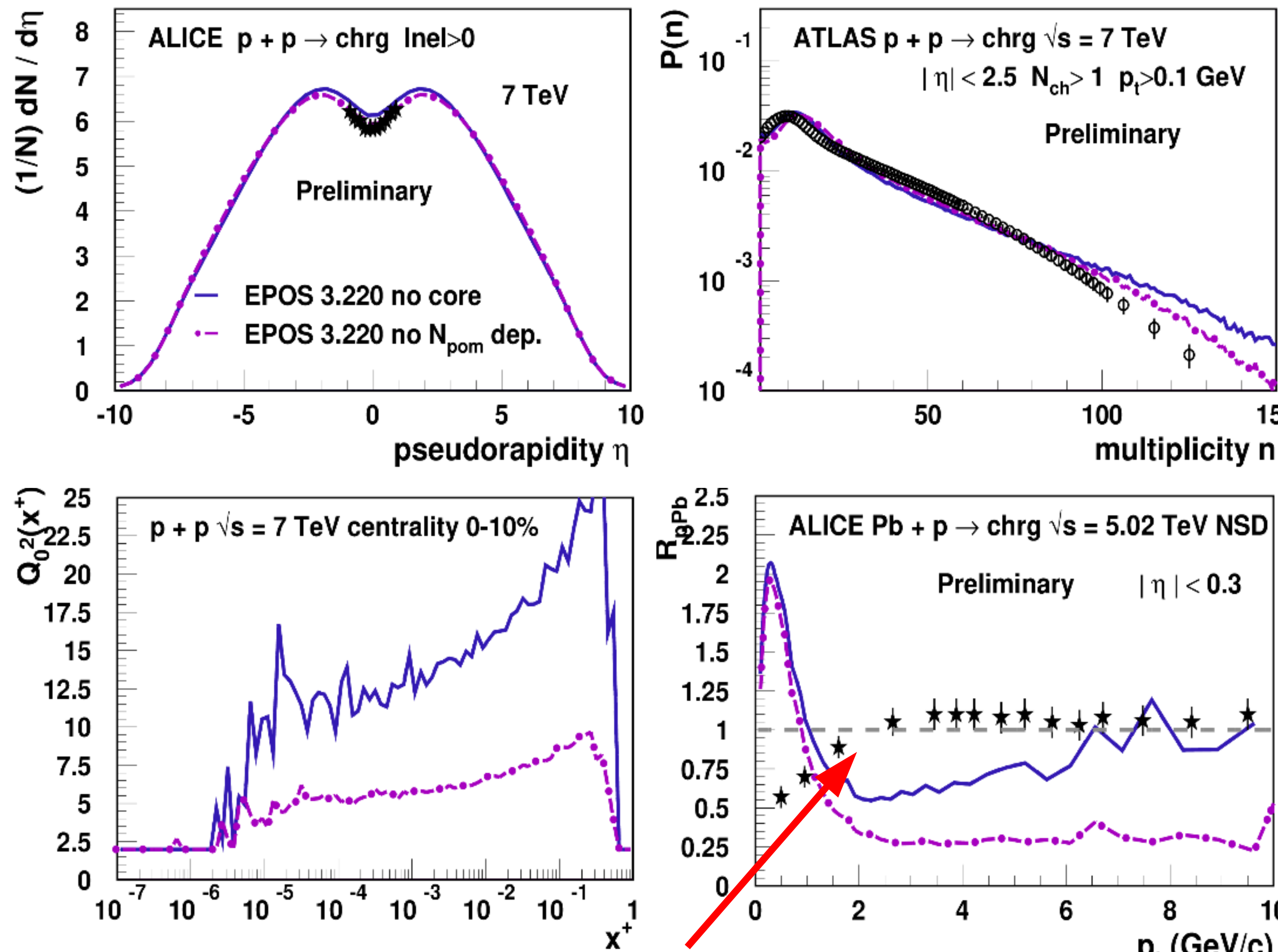


Preliminary Results : Without Core

- **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_{pom}

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

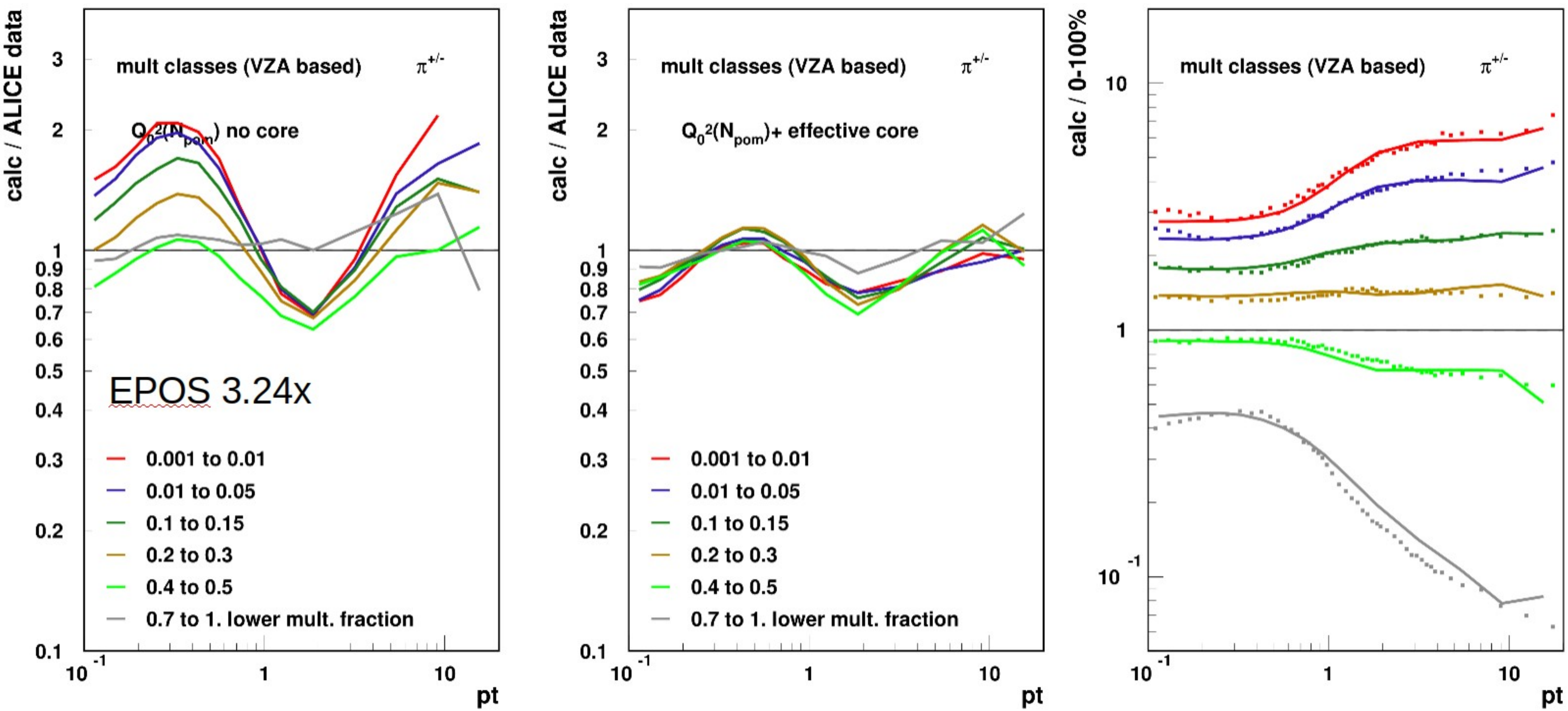


no core = missing flow

Core Effect vs Centrality

Flow change the shape of transverse momentum distribution

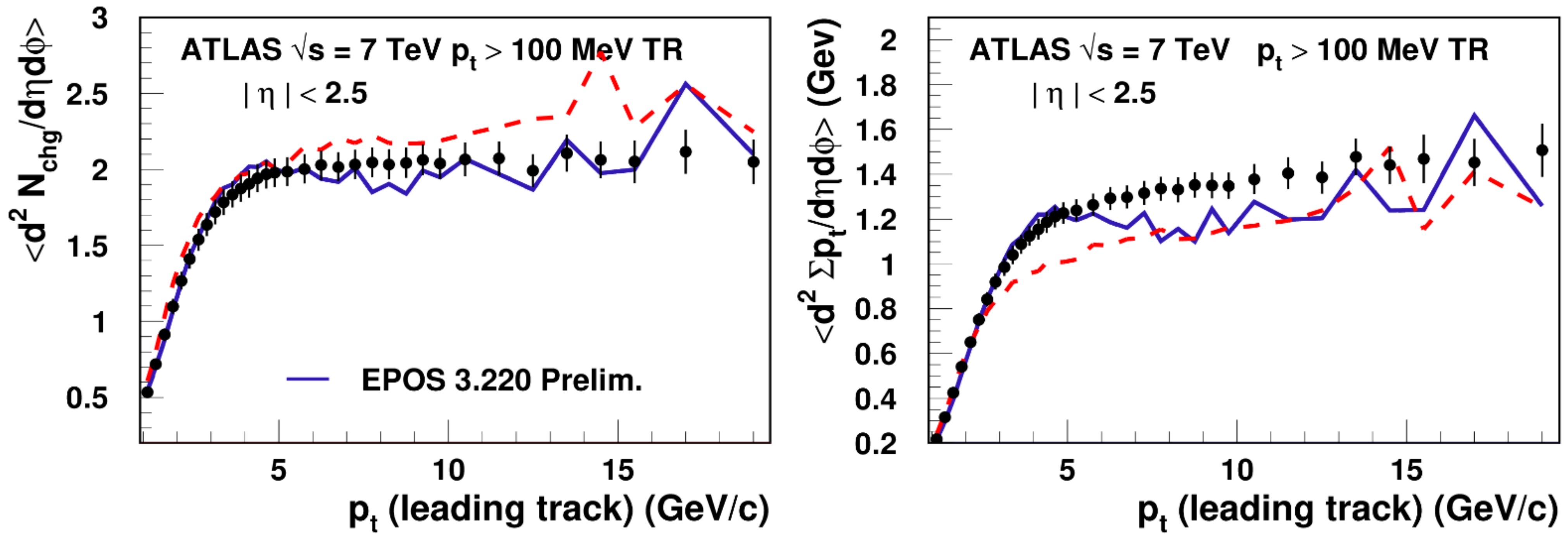
- effect on high p_t due to parton energy loss (same as in HI) … to be confirmed !
- test of real hydro vs CGC ?
- (tension between these data and ATLAS/CMS (absolute scale))



Underlying Events: p_t > 100 MeV/c

p_t > 100 MeV/c particles in TRANS region

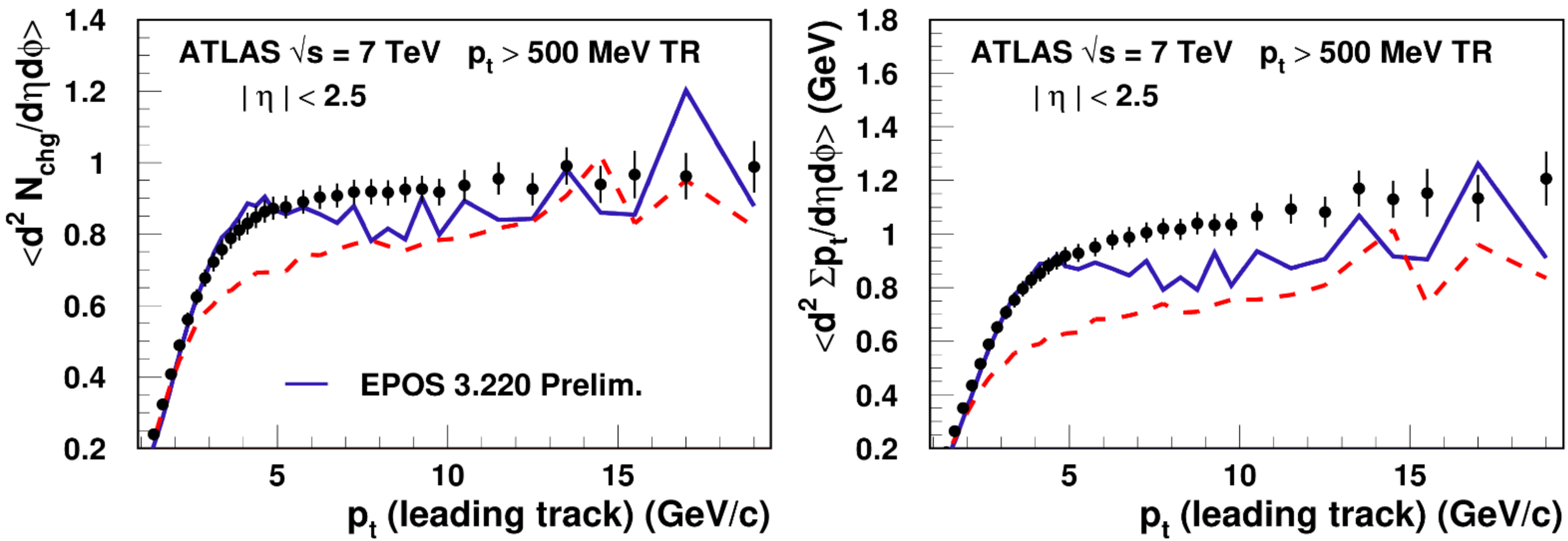
- without core N_{ch} is large like in MB but energy density is too low for p_t leading >2 GeV/c
- with core the multiplicity is reduced and energy density at intermediate p_t is increased
- reasonable agreement with data
  - mean transverse energy still a bit low for high p_t leading track



Underlying Events: p_t > 500 MeV/c

p_t > 500 MeV/c particles in TRANS region

- without core N_{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, ...)

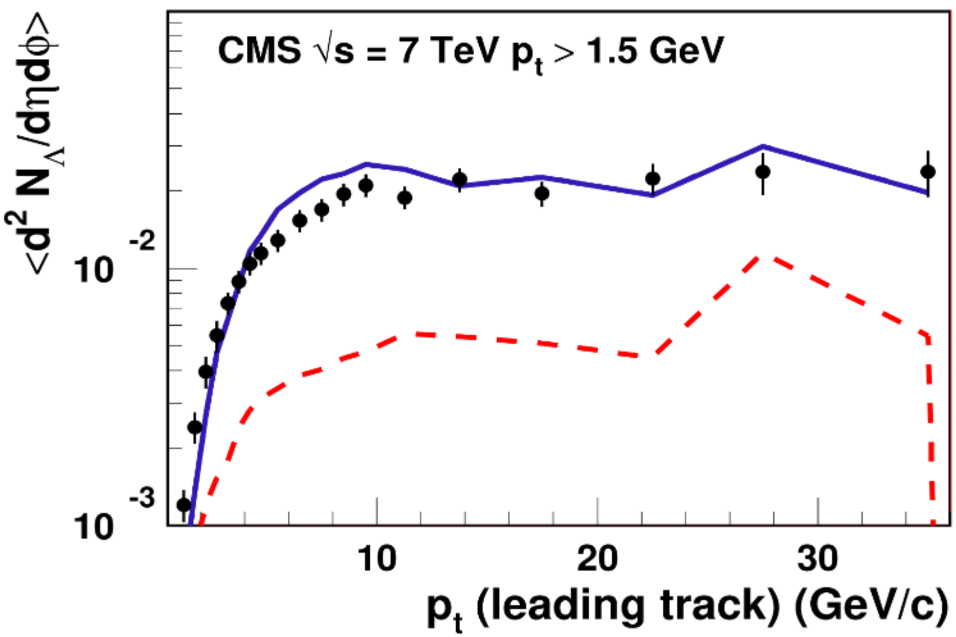


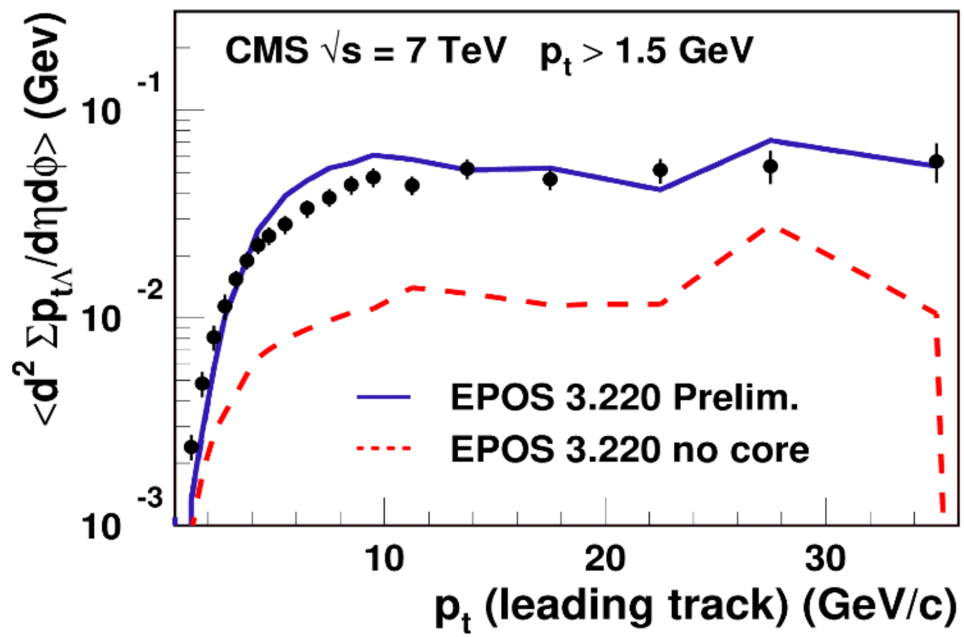
Underlying Events: Strangeness

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

To reconcile soft and hard observables, EPOS 3 will have both collective effects and variable non-linear perturbative scale : impact on HQ production.

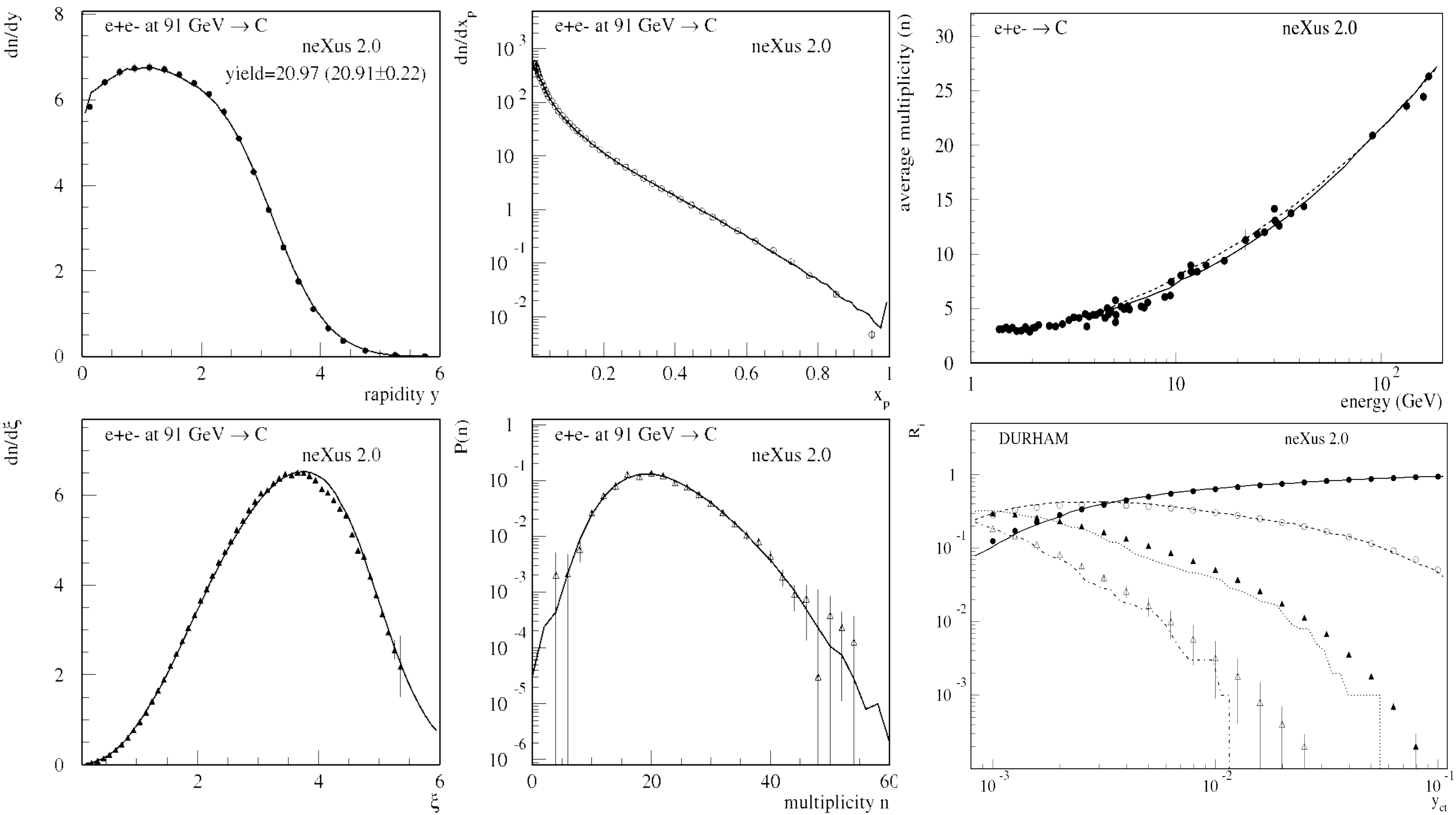
Difficult to describe min bias and hard scale events at the same time

- 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-)linear perturbative scale Q_0^2 GENERATED Pomeron-by-Pomeron and dependent on the number of MPI event-by-event.
- non-linear 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

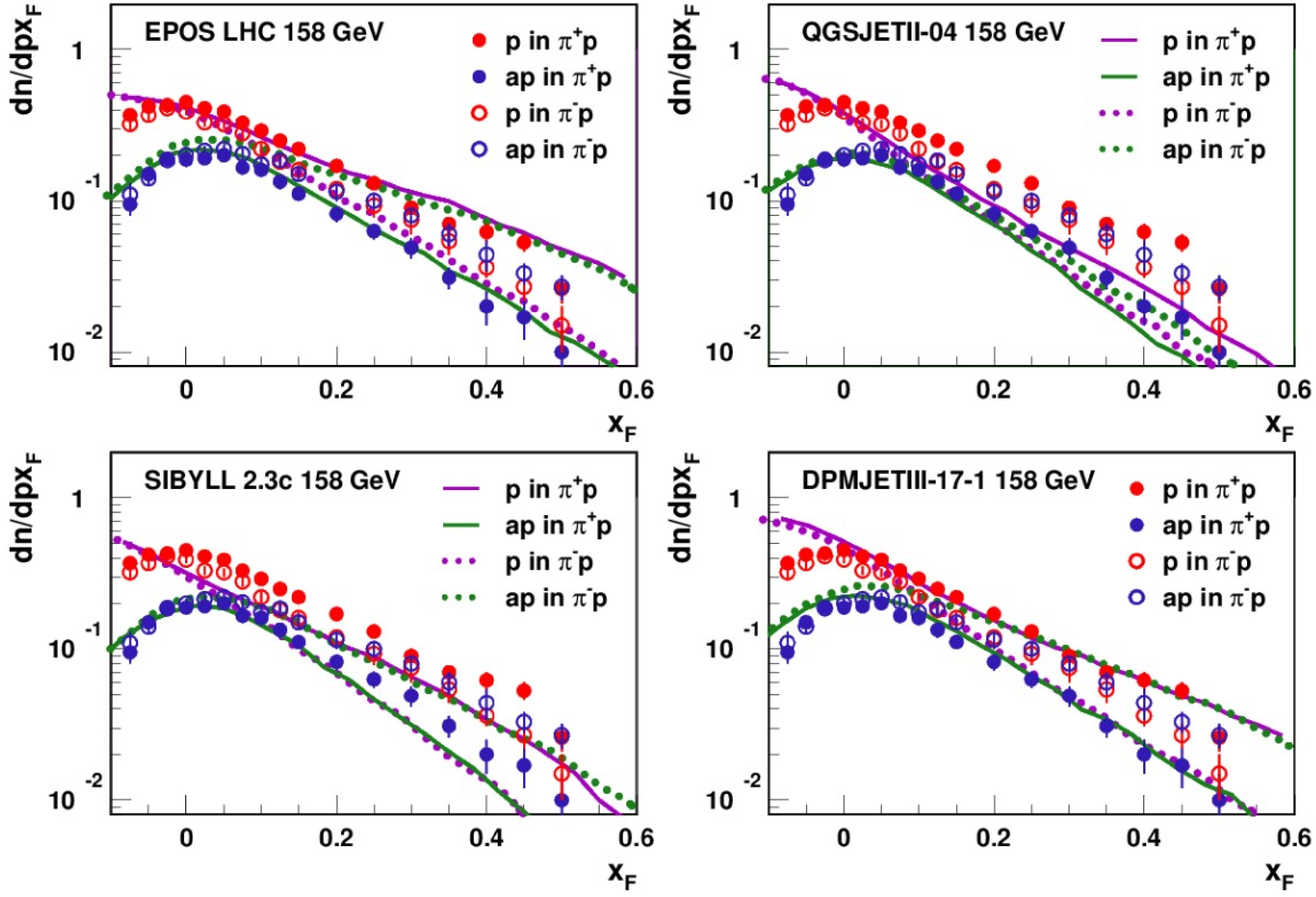
Test of string fragmentation with LEP data



Area law

Baryons in Pion Interactions

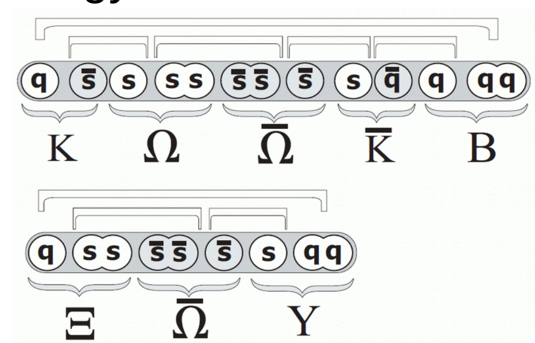
Data from NA49 (Gabor Veres PhD) : full picture



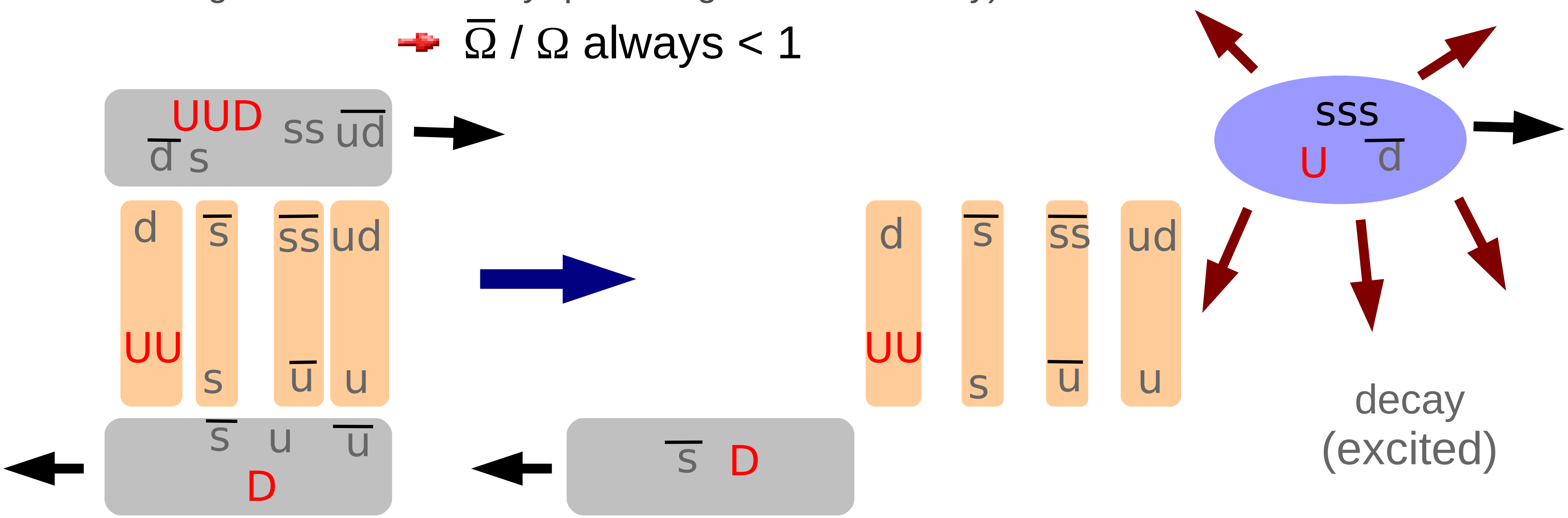
Baryons and Remnants

Parton ladder string ends :

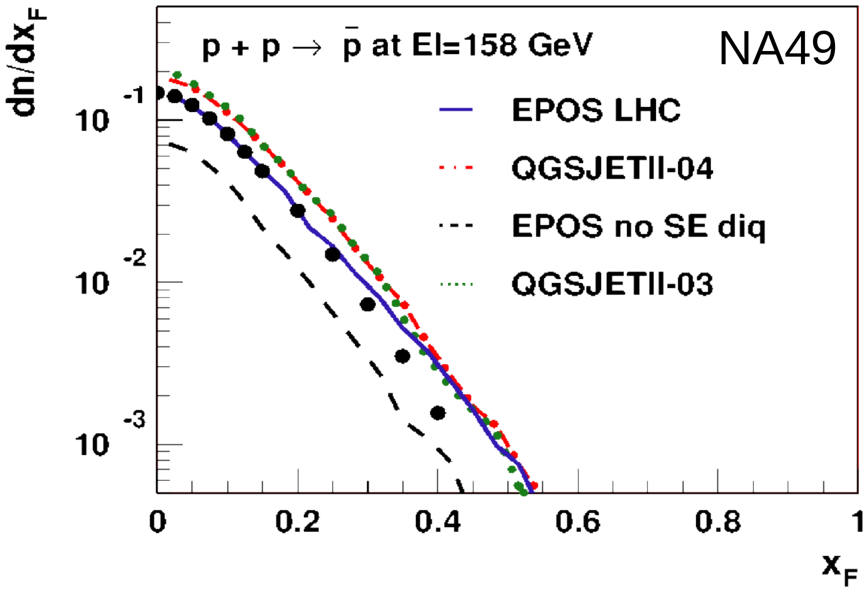
- Problem of multi-strange baryons at low energy (Bleicher et al., Phys.Rev.Lett.88:202501,2002)
  - 2 strings approach :
    - $\bar{\Omega}$ / Ω always > 1
    - But data < 1 (Na49)



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

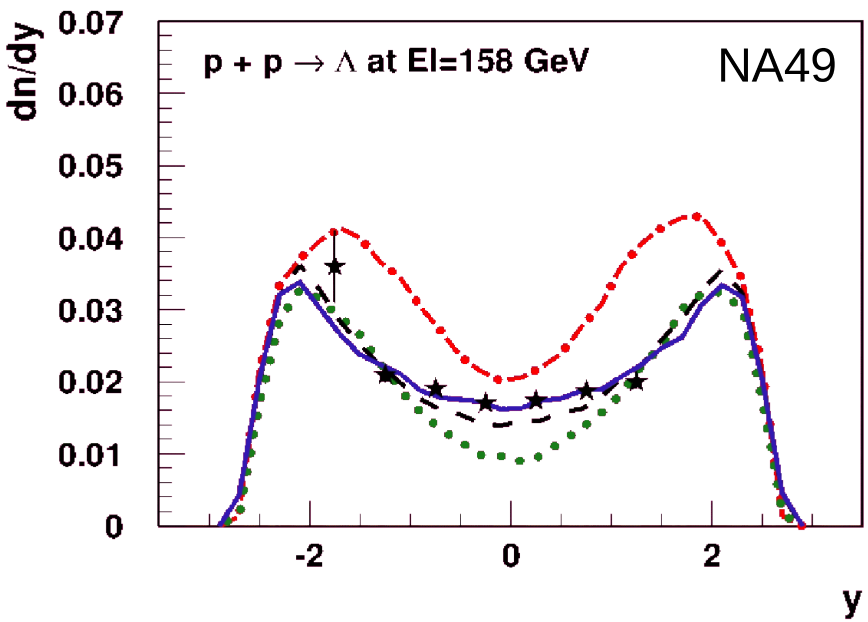


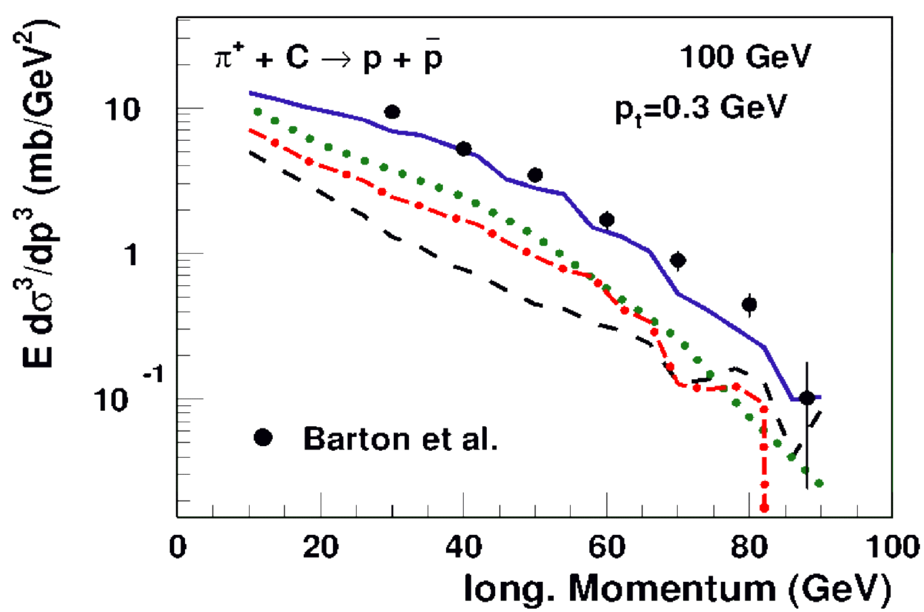
Forward Baryons (low energy)



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

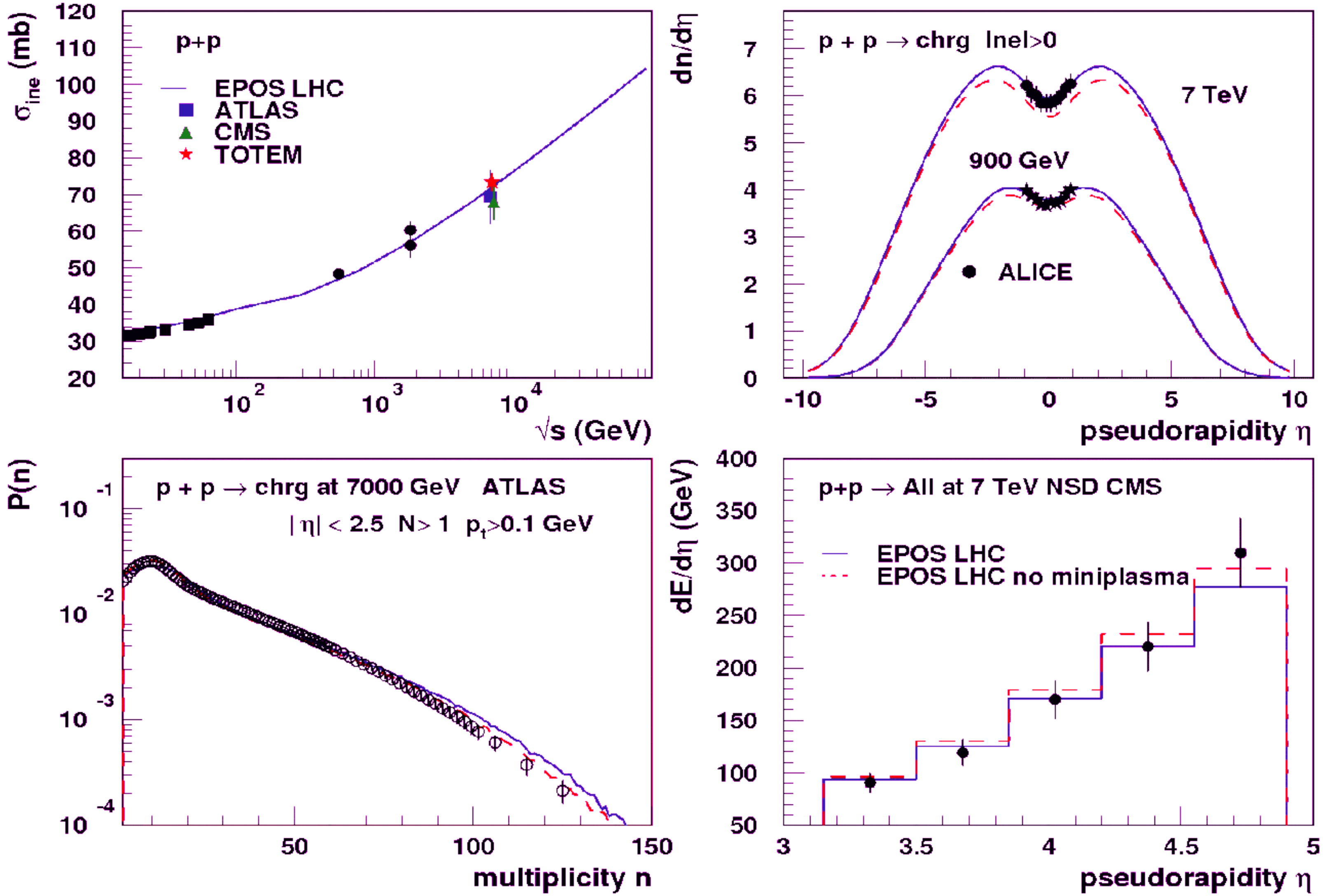
Without remnant, string fragmentation has to be changed for baryon production





EPOS LHC

Effective flow treatment



EPOS LHC

Detailed description can be achieved

- identified spectra
- p_t behavior driven by collective effects (statistical hadronization + flow)