EPOS 3

Tanguy Pierog

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

K. Werner, Iu. Karpenko, G. Sophys, Subatech, Nantes, France
B. Guiot, FSMT University, Valparaiso, Chile
M. Stefaniak, Warsaw University of Technology, Warsaw, Poland

Karlsruhe Institute of Technology

UHECR 2018, Paris, France

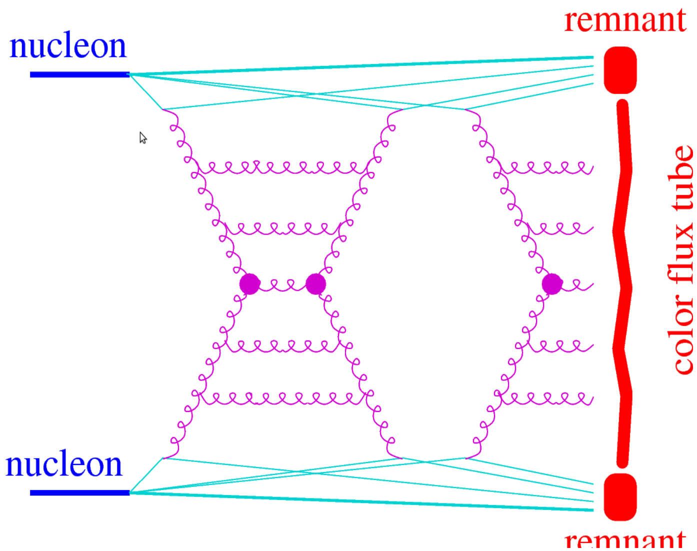
October the 11th 2018

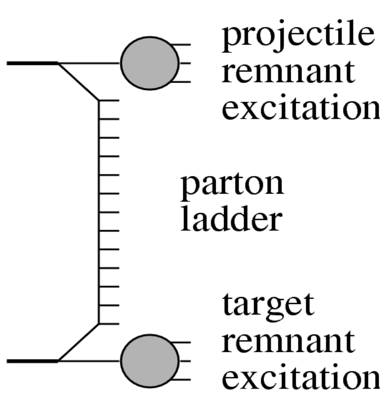
Outline

- **EPOS Basic principles**
- **Heavy ion (HI) Physics**
  - Variable linear pertubative scale
  - Flow measurement and hadronization
- **Air Shower (EAS) Physics**
  - diffraction and pion exchange
  - baryon stopping
- **Summary**

EPOS 3 will have major improvements : motivation = full set of LHC and SPS data. Significant impact on muon production expected.

The EPOS Model





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

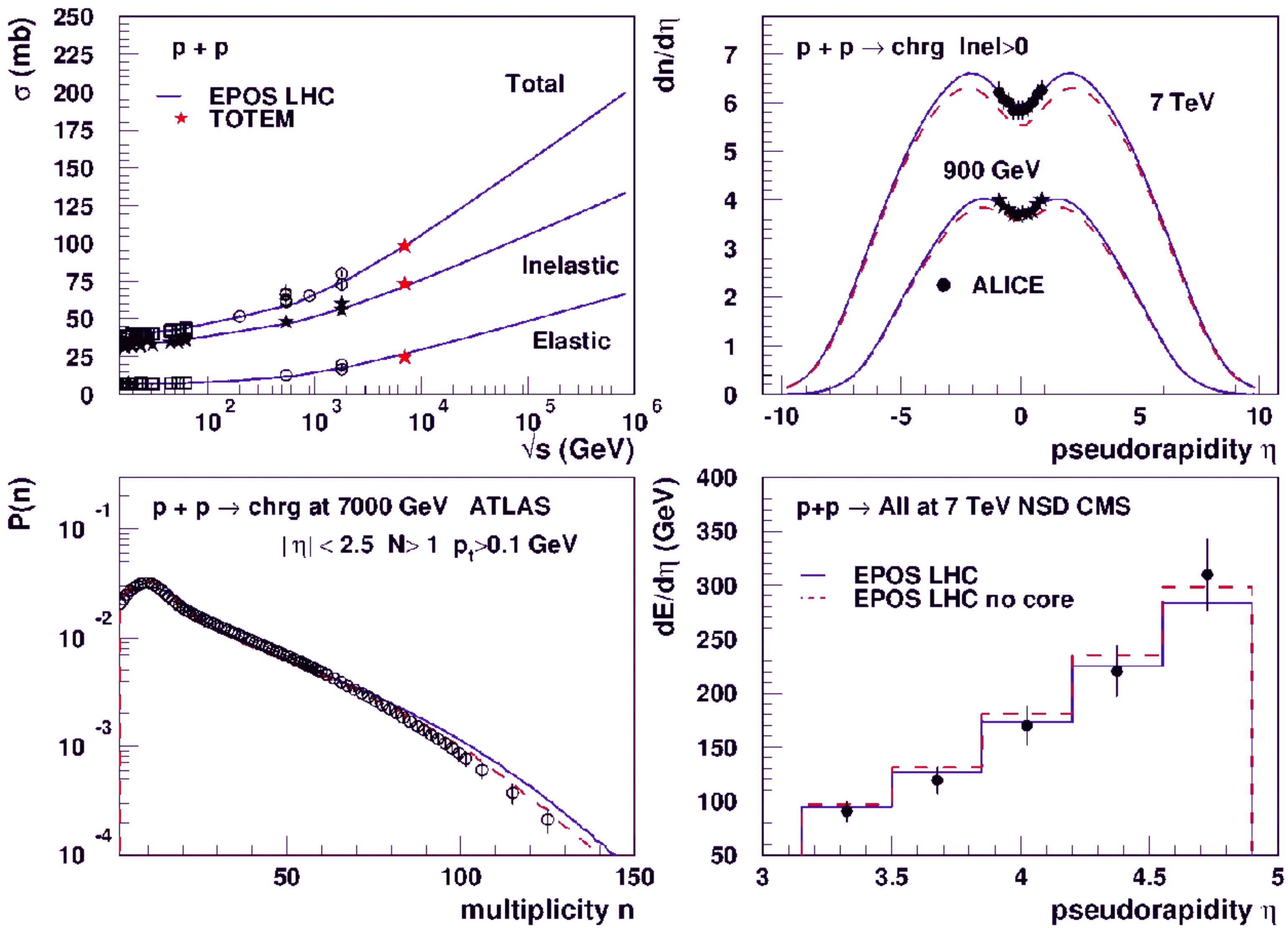
- Energy-sharing : for cross section calculation AND particle production
- Parton Multiple scattering
- Outshell remnants
- Screening and shadowing via unitarization and splitting
- Collective effects for dense systems (core+corona)

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) for pp or Heavy Ion

EPOS LHC ✔

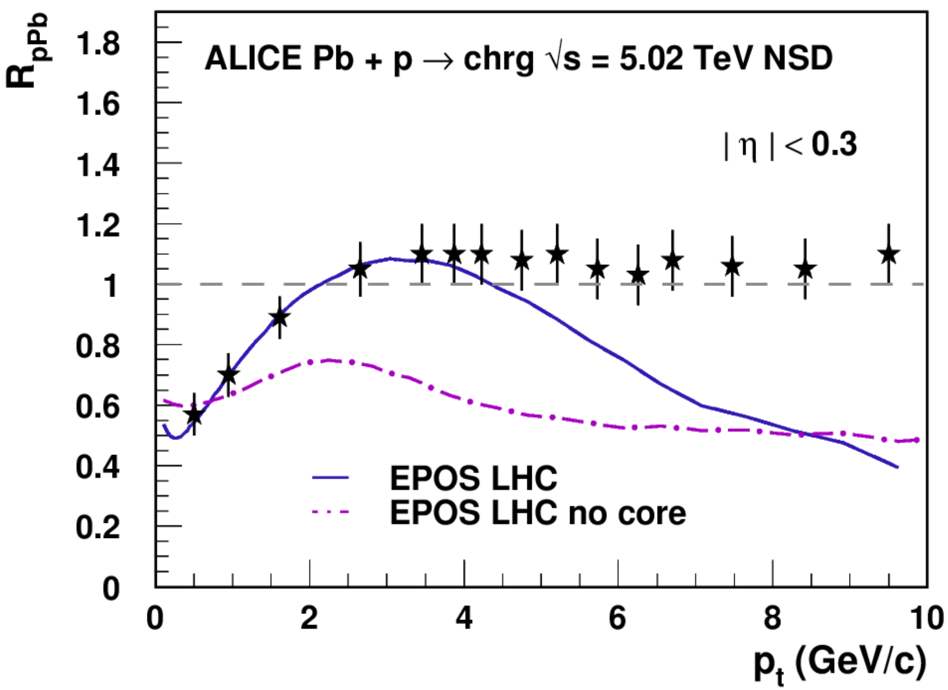
Excellent results for soft physics ...

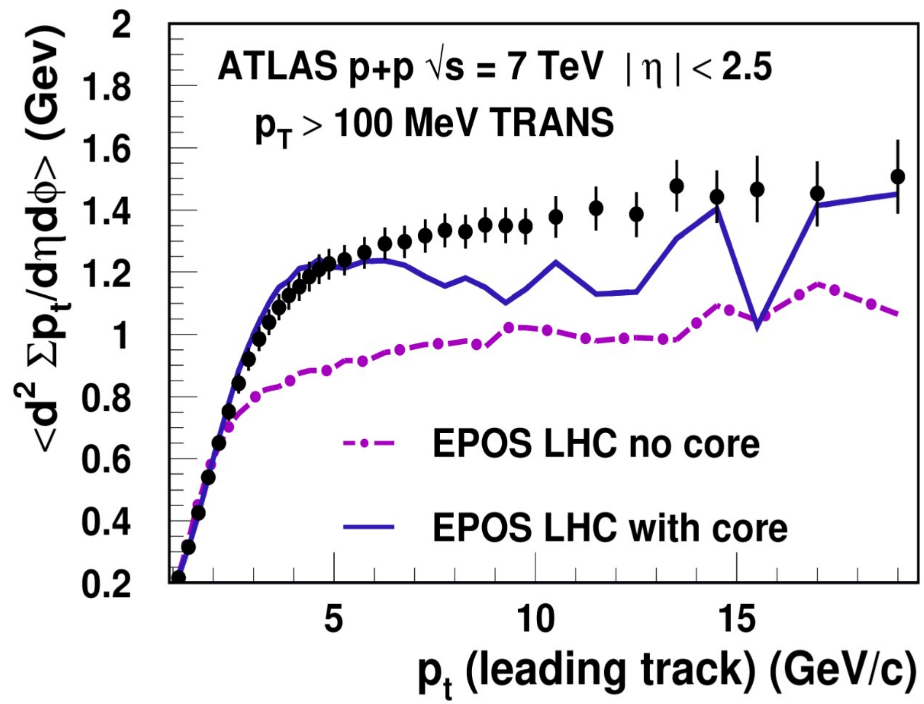


EPOS LHC ✗

But problems for hard physics …

- no heavy flavors
- no binary scaling
- problem with underlying activity

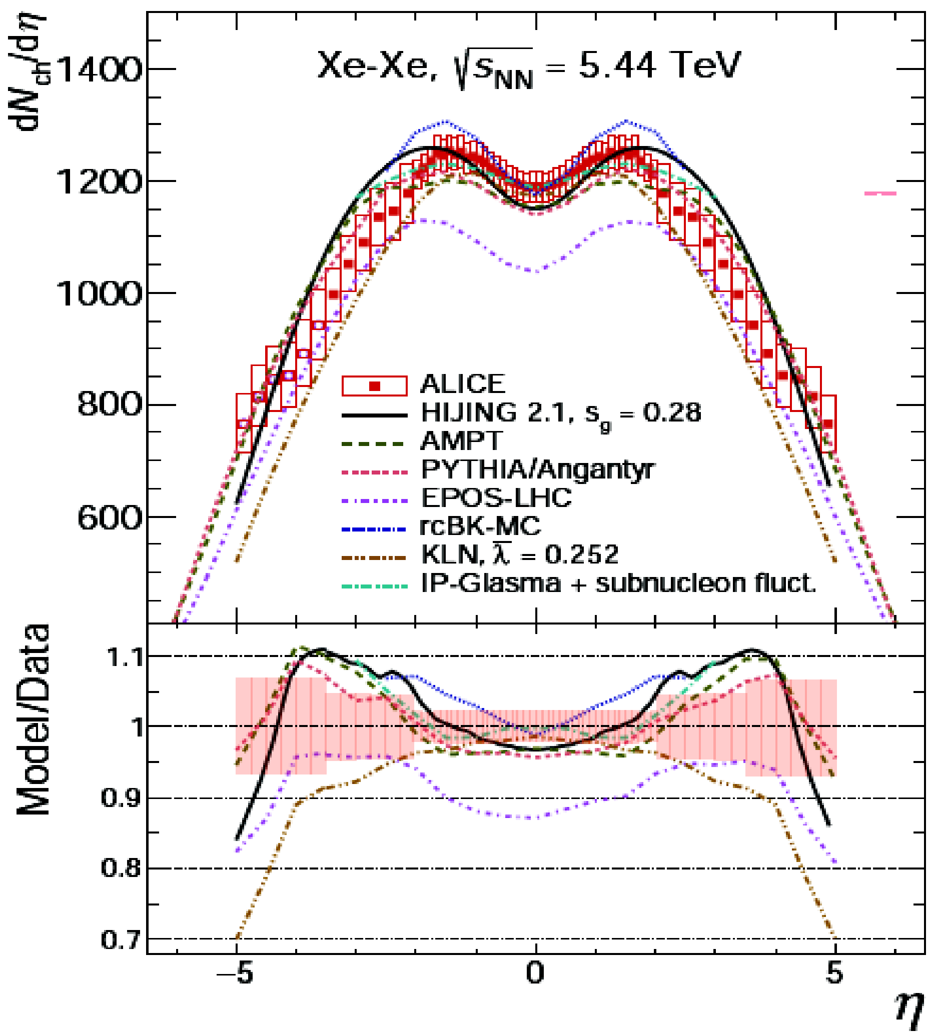


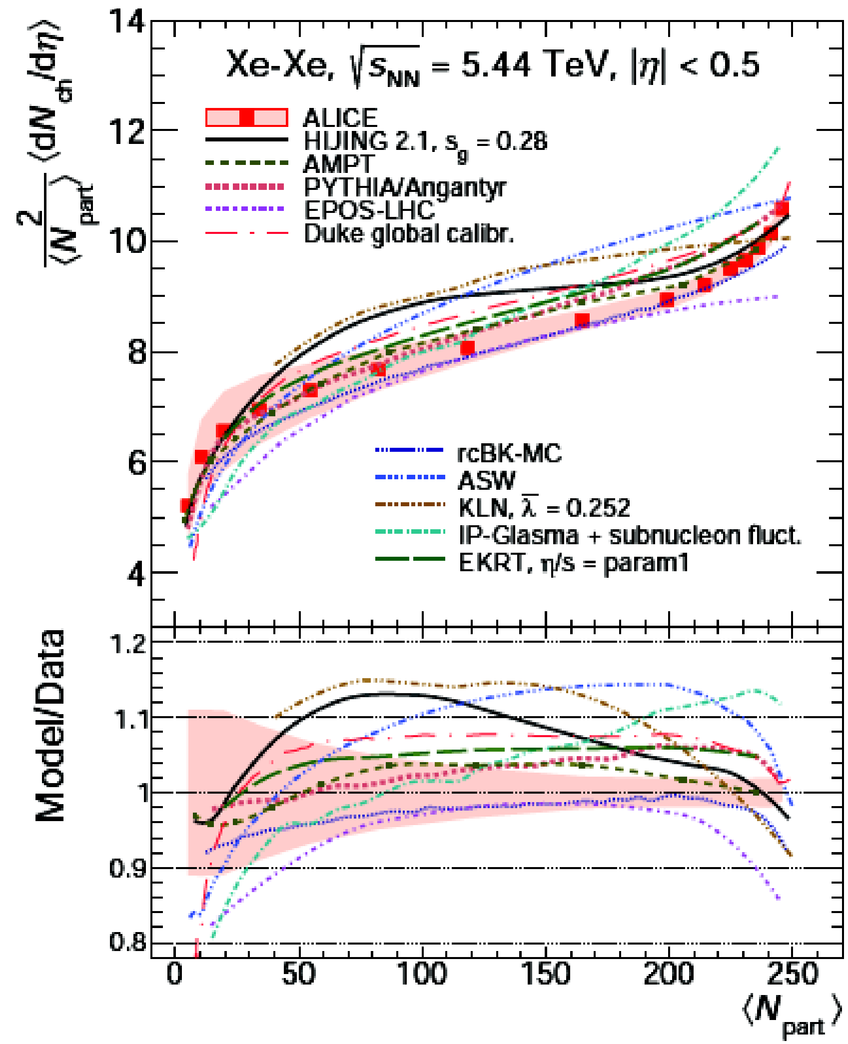


EPOS LHC ✗

But problems for hard physics … and heaven some soft physics !

➡ new data with non-linear behavior

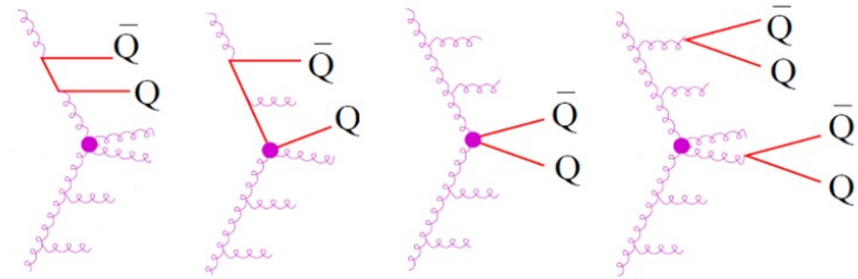


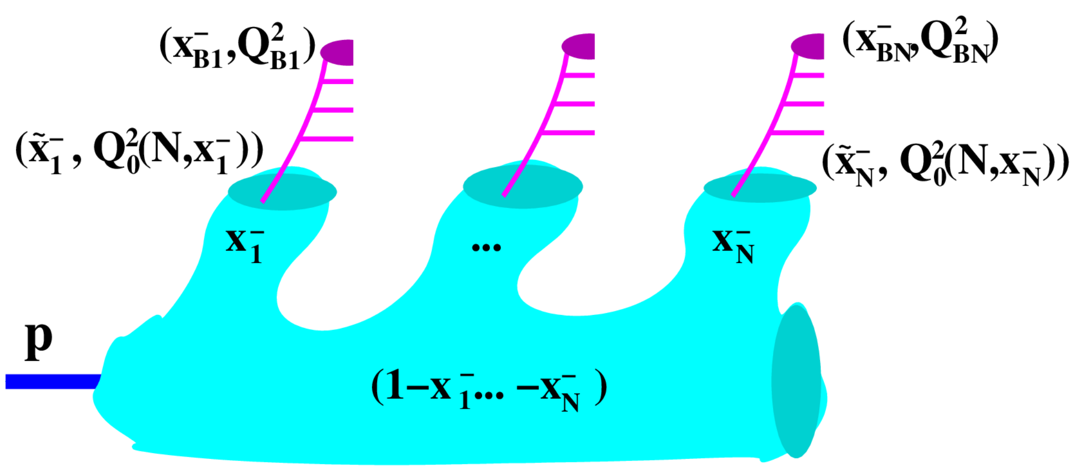


EPOS 3

Main motivation : complete description of HI interactions at LHC

- Full hydrodynamical simulation and parton energy loss in Quark Gluon Plasma
- include heavy quark production in pQCD calculations
- recover binary scaling at high p_t
  - factorization holds independently of centrality or number of multiple scattering : variable factorization scale

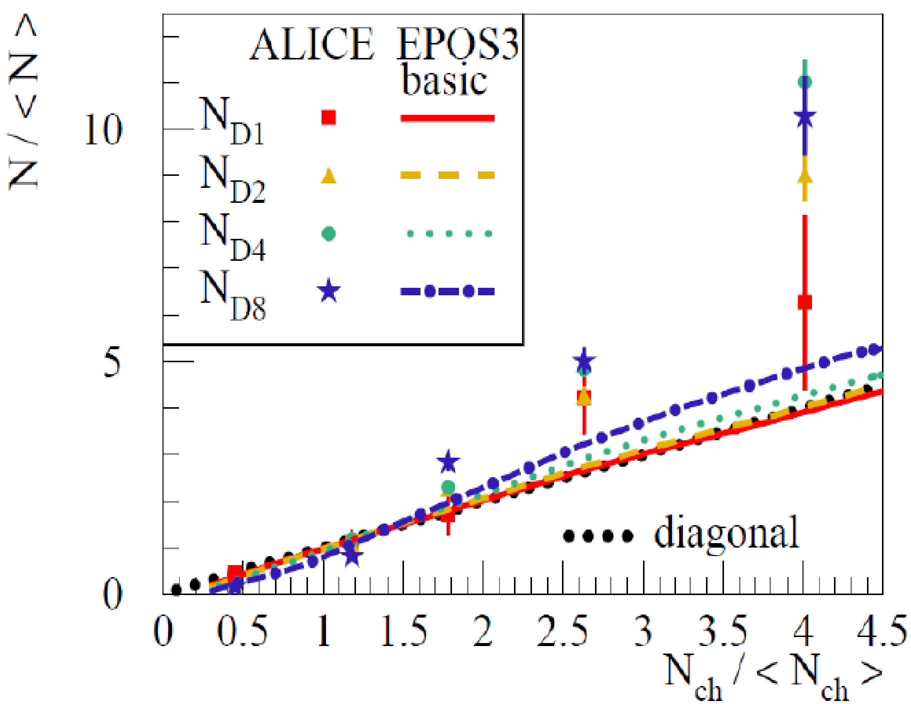




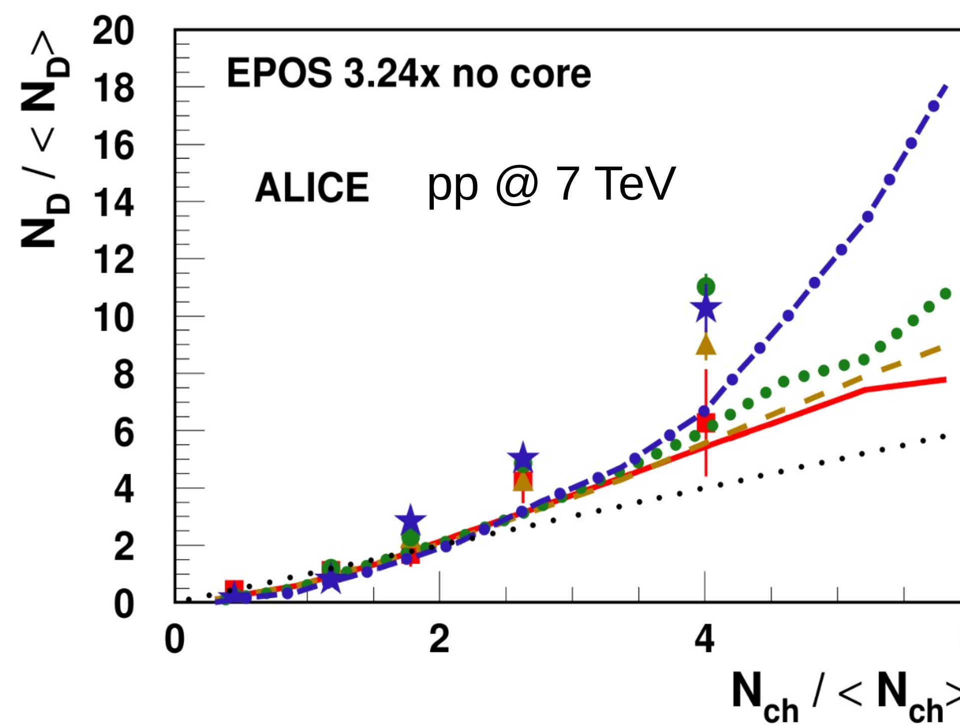
EPOS as an N-pdf generator (event-by-event) with $Q_0{}^2(N,x)$!

Non-linear increase of Charm Production

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



fixed Q_0^2

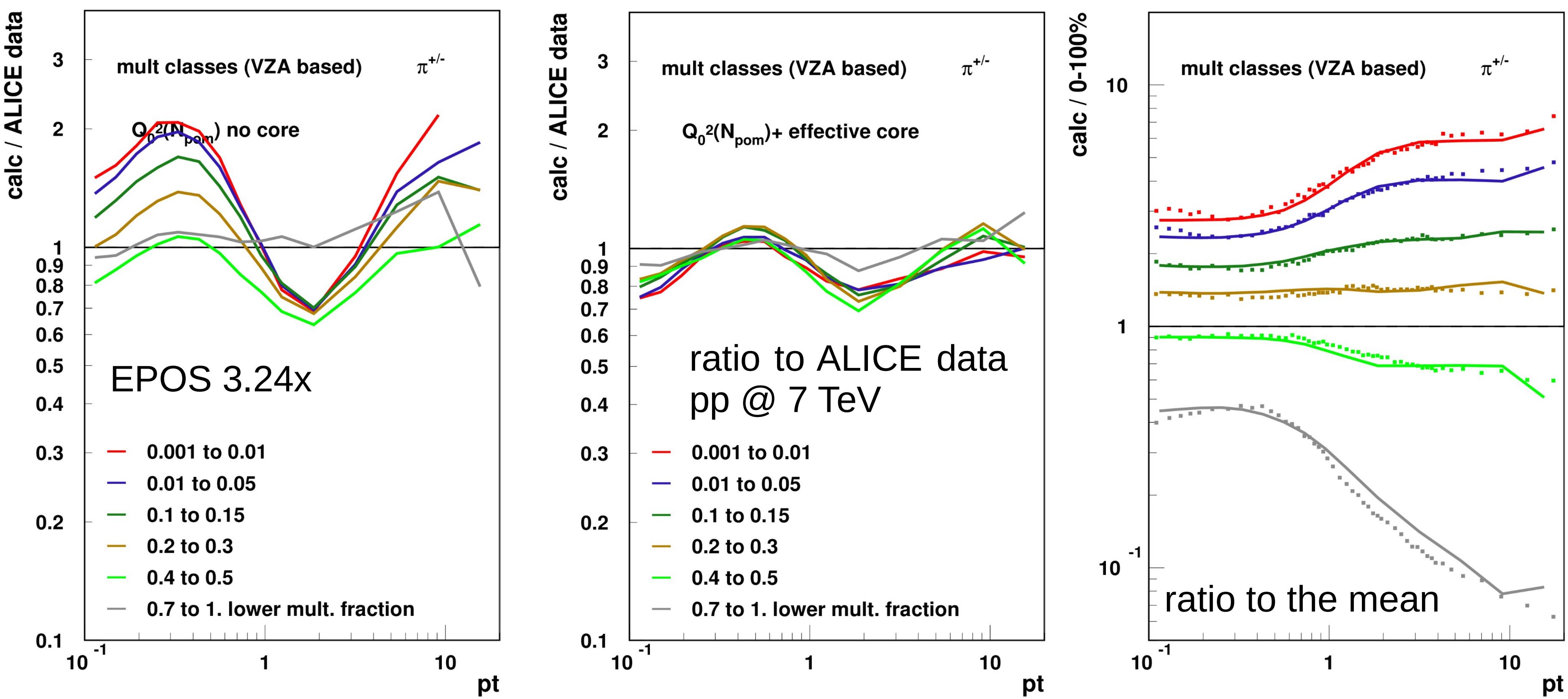


variable Q_0^2

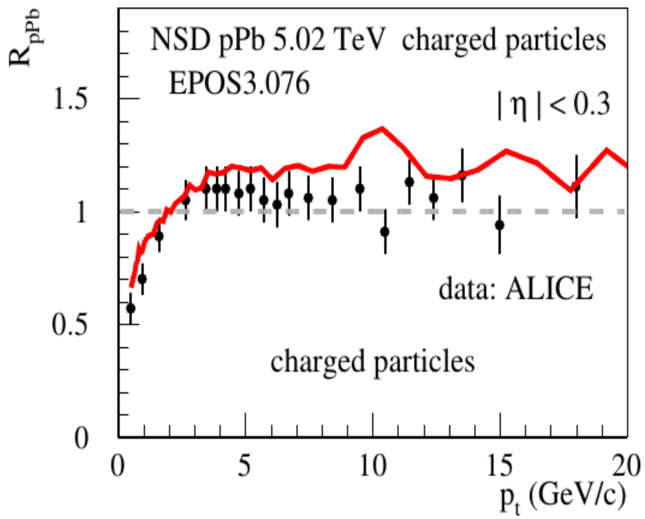
Evolution of p_t with Multiplicity

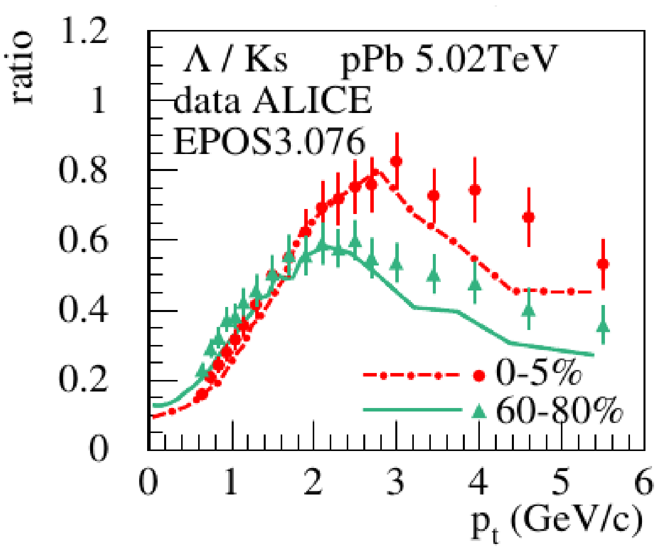
Core and Q_0^2 change the shape of transverse momentum distribution

- harder spectra for high multiplicity
- flow acting differently for different particles
- effect on high p_t due to parton energy loss (same as in HI) … to be confirmed !

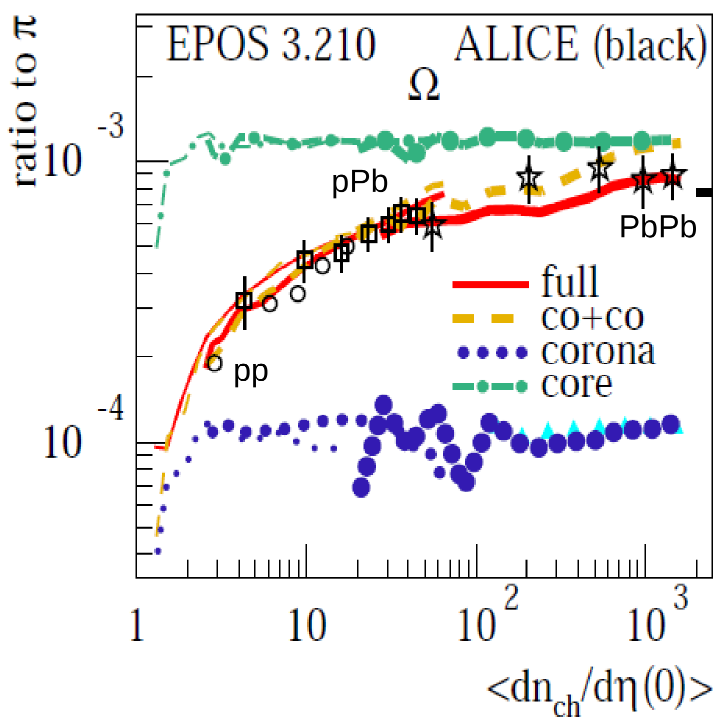


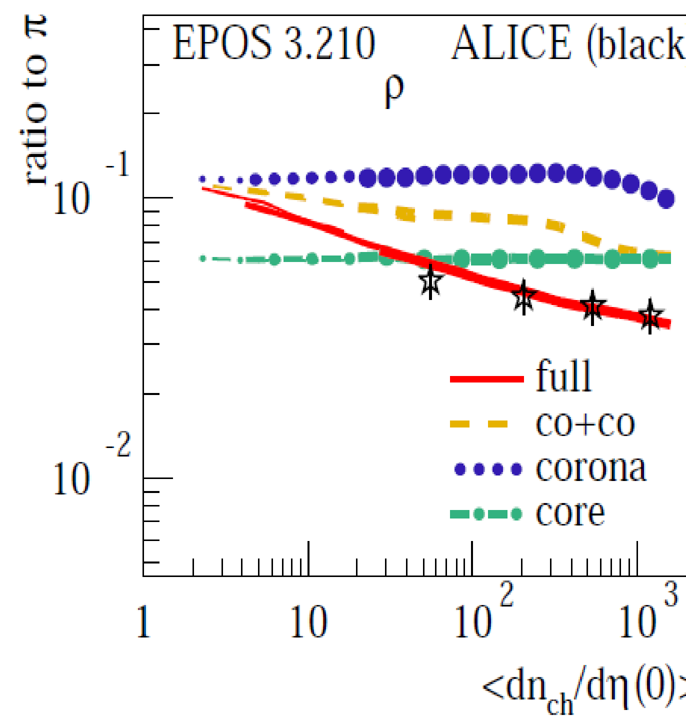
Full Picture for Heavy Ions





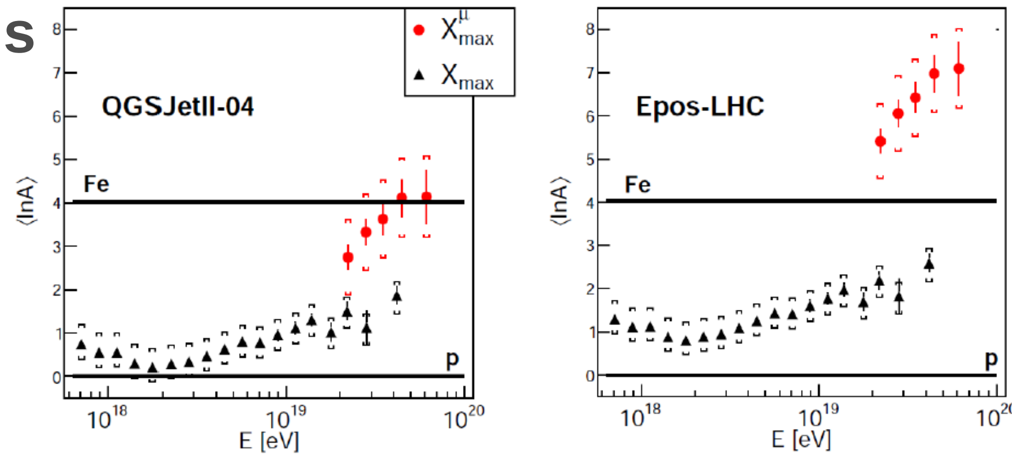
- flow and factorization
- Depending on the particle type (formation and life time), the different phase do not have the same consequences
  - increase of strangeness
  - suppression of resonances

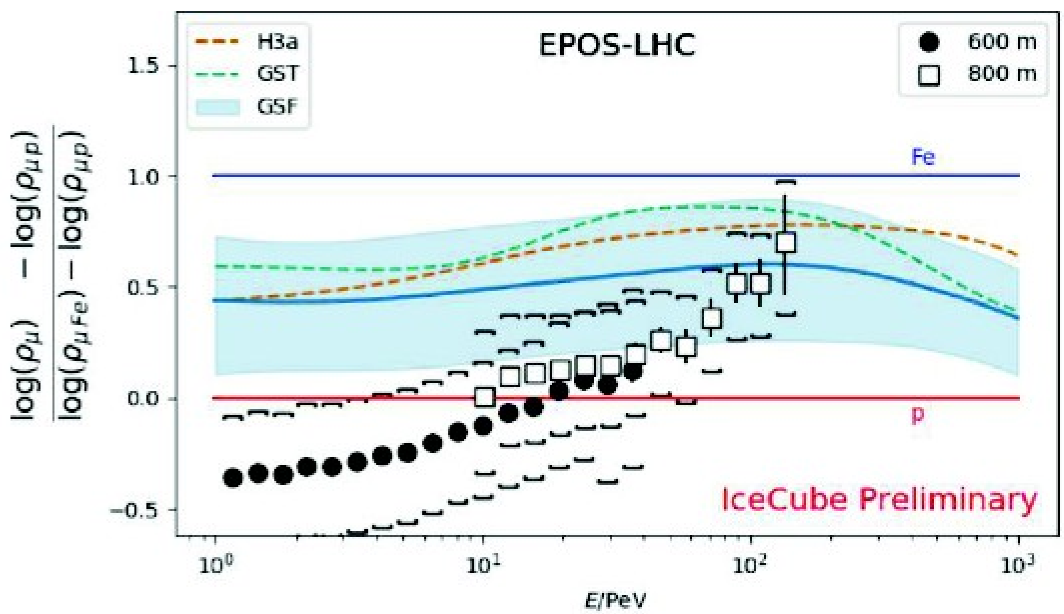




Muon Production in EPOS

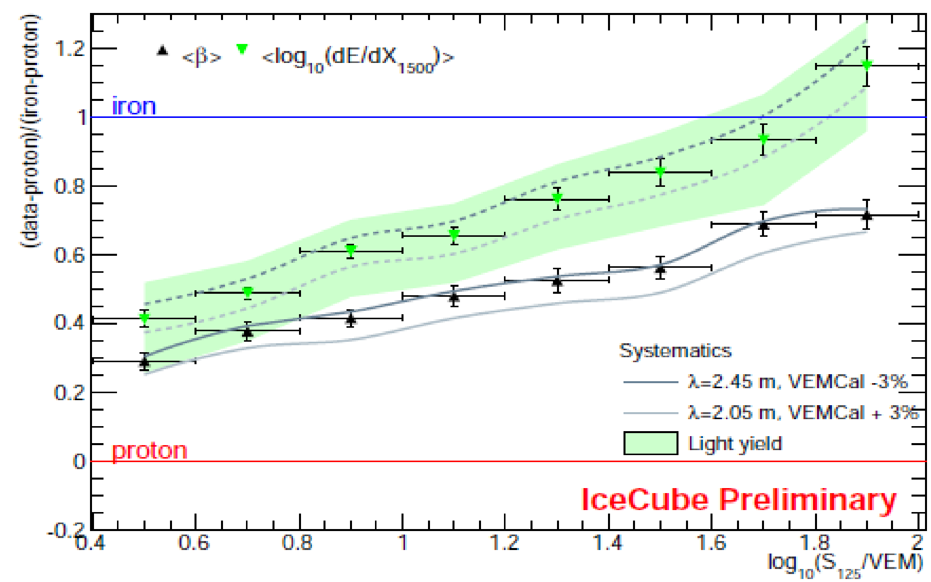
- **Large production of forward baryons**
  - ➡ late production of muons
  - ➡ large number of low energy muons
- **Open issues**
  - ➡ not enough muons far from the core
  - ➡ too strong attenuation vs zenith angle





effect increased by energy scale :
see H. Dembinski's talks.

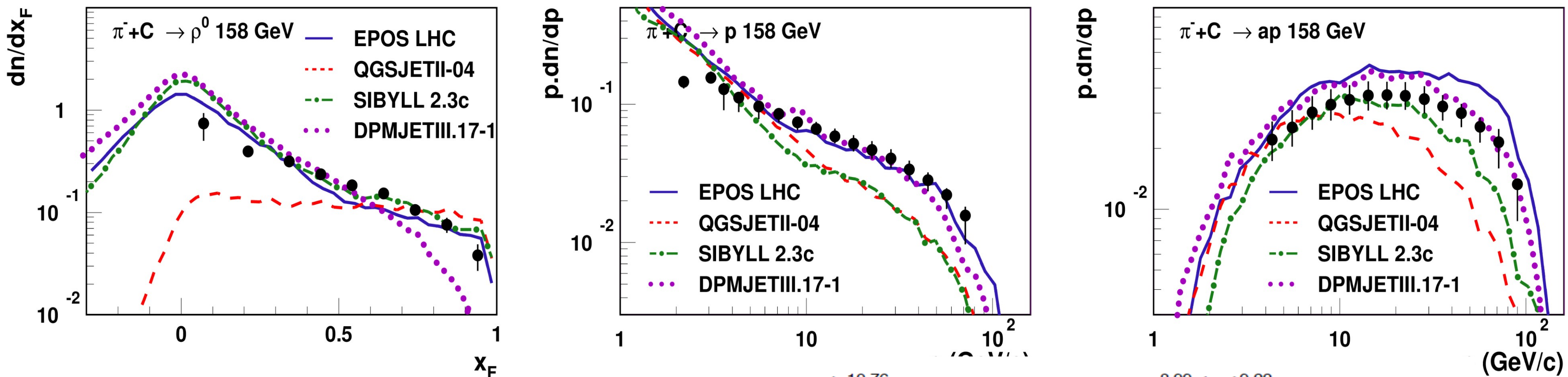
EPOS-LHC



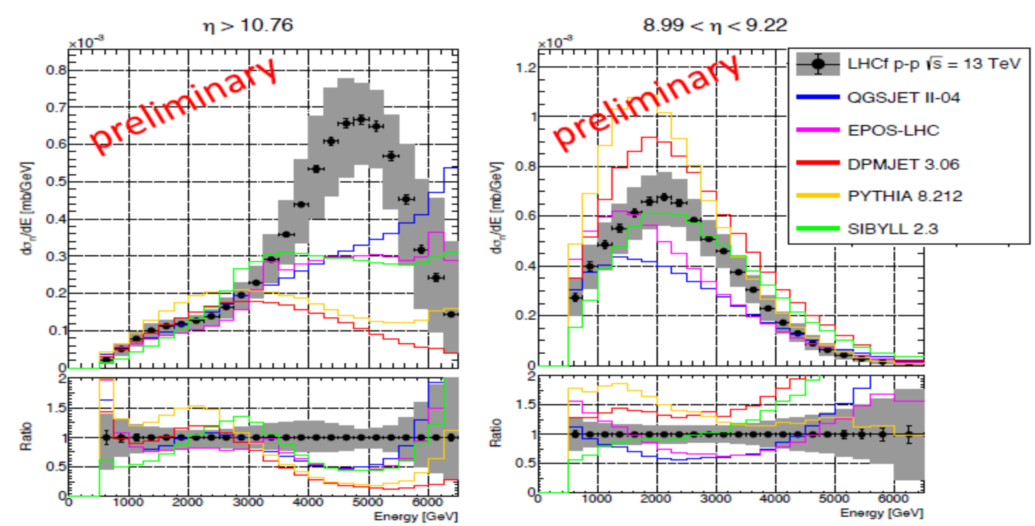
too many low energy muons
compared to high energy muons

Missing Process in EPOS LHC

- **New data from NA61 : wrong old data interpretation**
  - ➡ over production of anti-baryons in EPOS LHC : linked to problem in air showers
  - ➡ deficit of ρ^0 linked to missing process : pion exchange



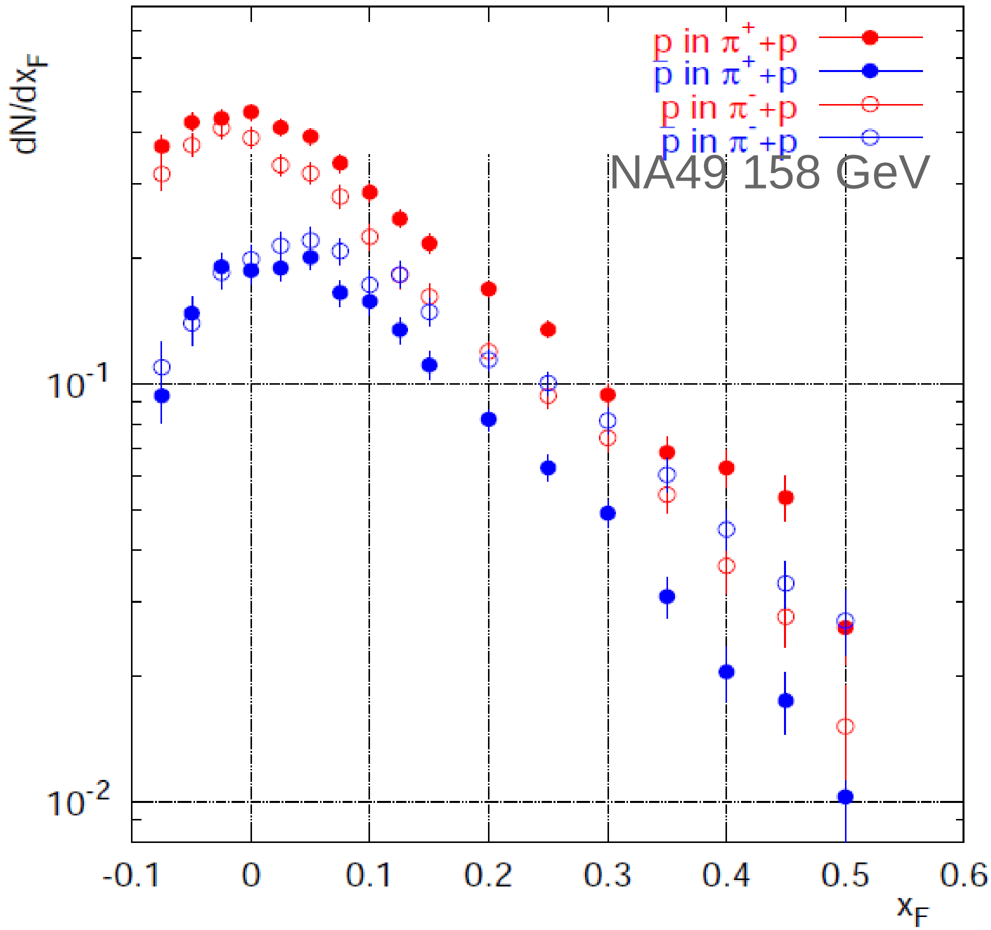
- **same problem for forward neutron production at LHC :**
  - ➡ missing pion exchange
- **problem with diffractive events at LHC :**
  - ➡ missing multiple scattering in high mass diffractive events

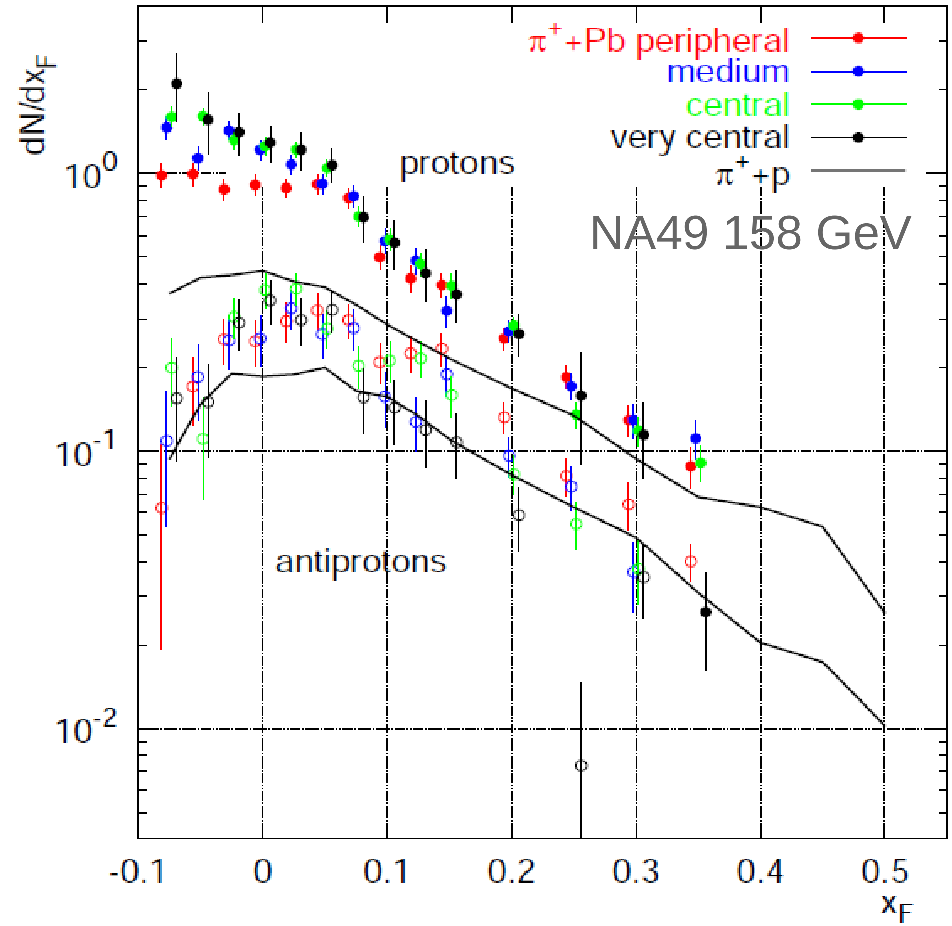


Baryons in Pion Interactions

Data from NA49 (Gabor Veres PhD) : full picture

- valence quark effect visible
- large part (half ?) of forward baryon production coming from the target !
- possible new source of low energy muons with small effect on MPD and effect on attenuation ?

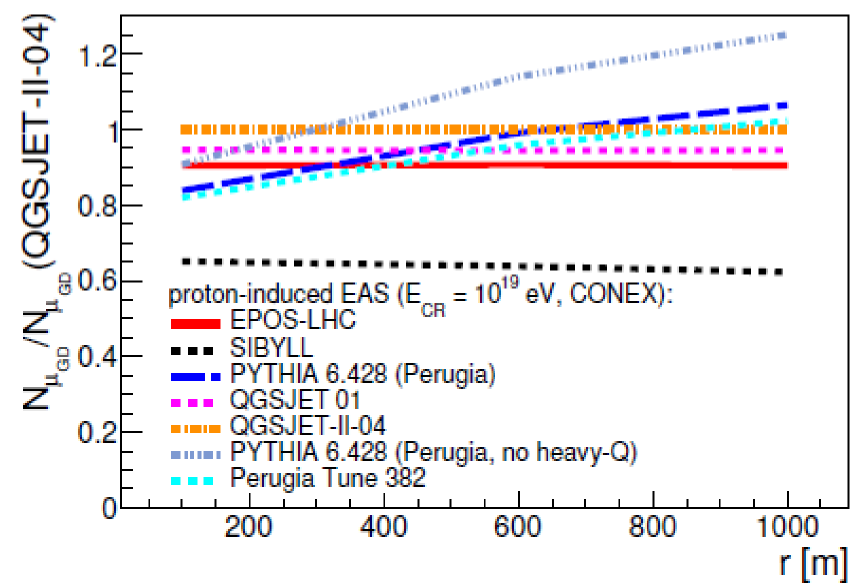




Impact of Heavy Ions on Air-Shower Physics

- **hard scale corrections**
  - impact on lateral distribution

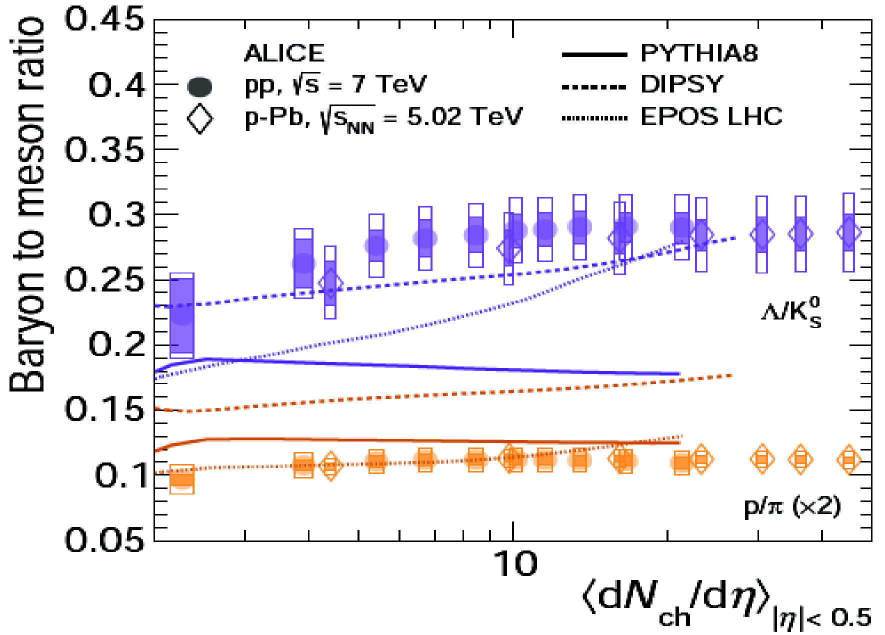
    (tests with Pythia: D'Enterria et al. arXive)



- **heavy quarks (both c and b)**
  - reliable predictions for prompt muon/neutrino contribution

- **hadronchemistery**
  - change in strangeness and electromagnetic energy fraction
  - change at lower multiplicity than in EPOS LHC :

    larger impact on EAS ?



Summary

EPOS LHC: very successful to describe soft particle production both for accelerator and air shower physics but ...

- hard scales not well reproduced in HI collisions
- still problems with muon production in EAS

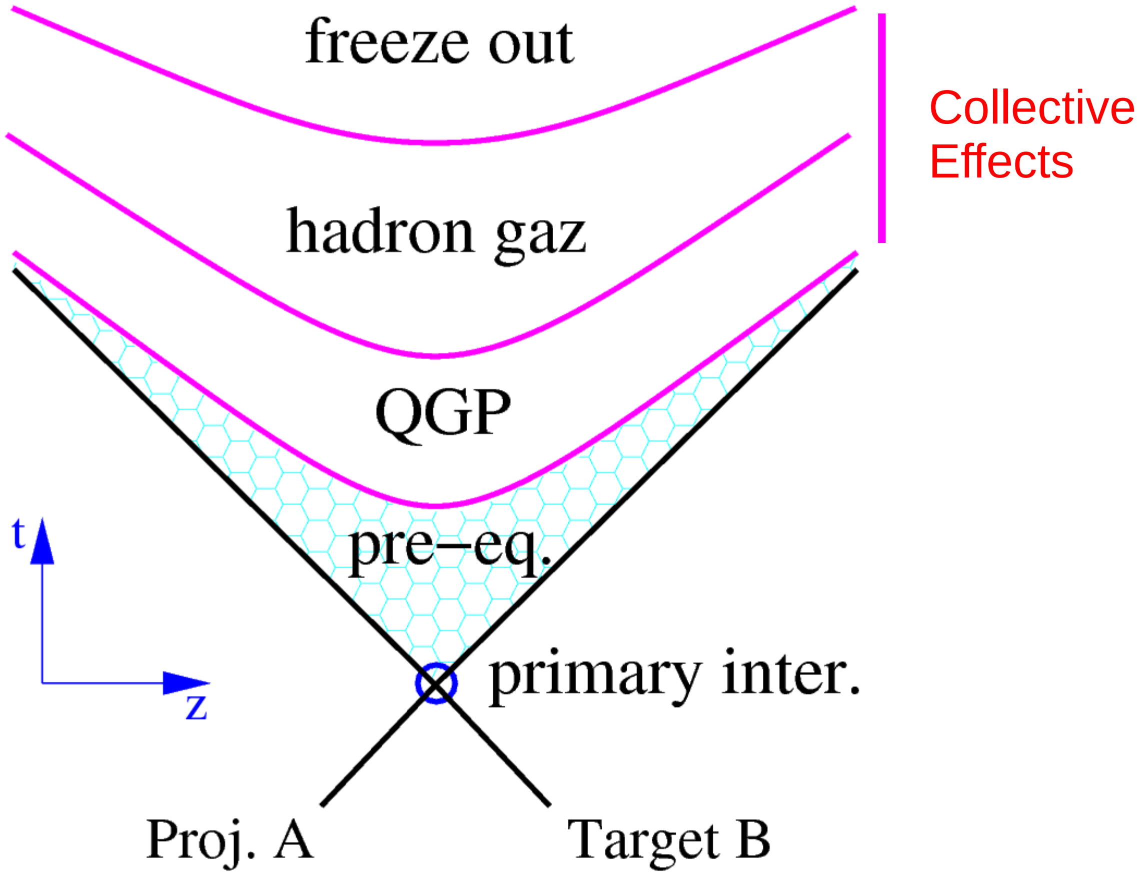
EPOS 3: try to correct all known problems

- introduce variable non-perturbative scale Q_0^2 to recover factorization and binary scaling for inclusive hard processes above Q_0^2
- real hydro expansion and fast effective one with the same hadronization
- heavy flavors production (true pQCD based calculation)
- new diffraction including multiple scattering and new channel for “real” pion exchange
- new baryon stopping, new nuclear fragmentation, extension to low energy ...

Disclaimer : These effects are NEW and NOT present in other MC used for EAS !

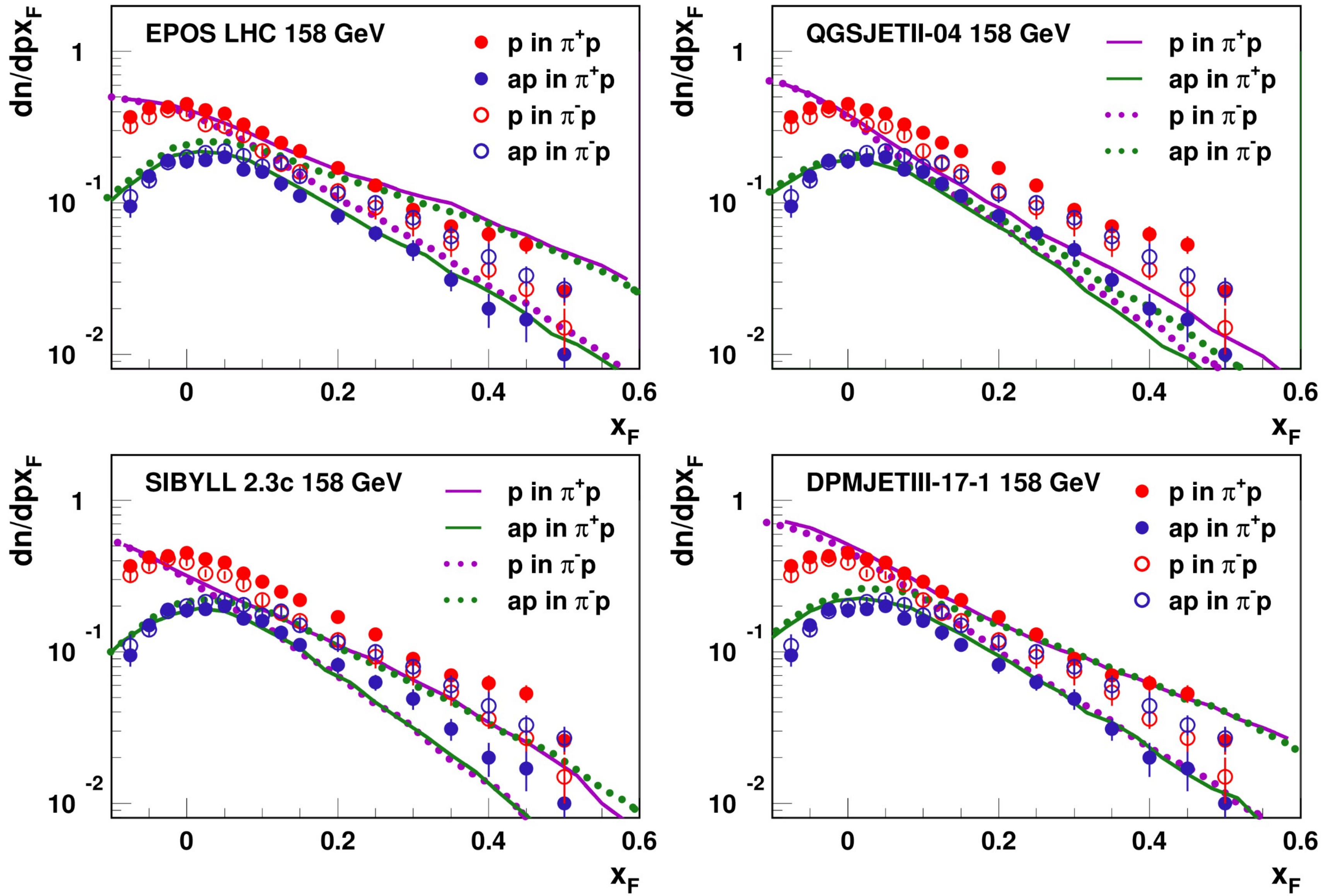
EPOS 3 will have major improvements : motivation = full set of LHC and SPS data. Significant impact on muon production expected.

High Energy Hadronic Interactions



Baryons in Pion Interactions

Data from NA49 (Gabor Veres PhD) : full picture



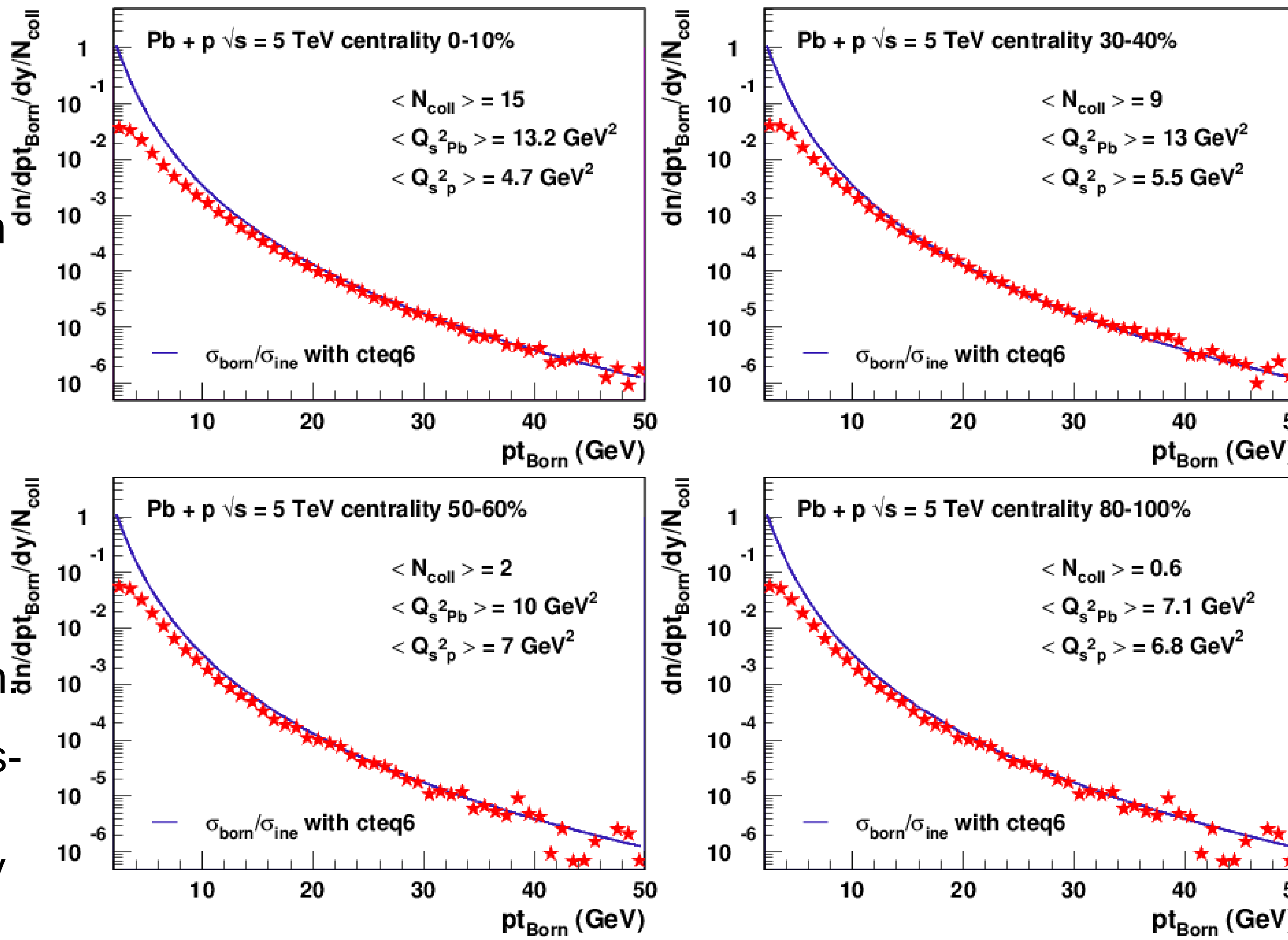
Nuclear Interactions

- **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

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

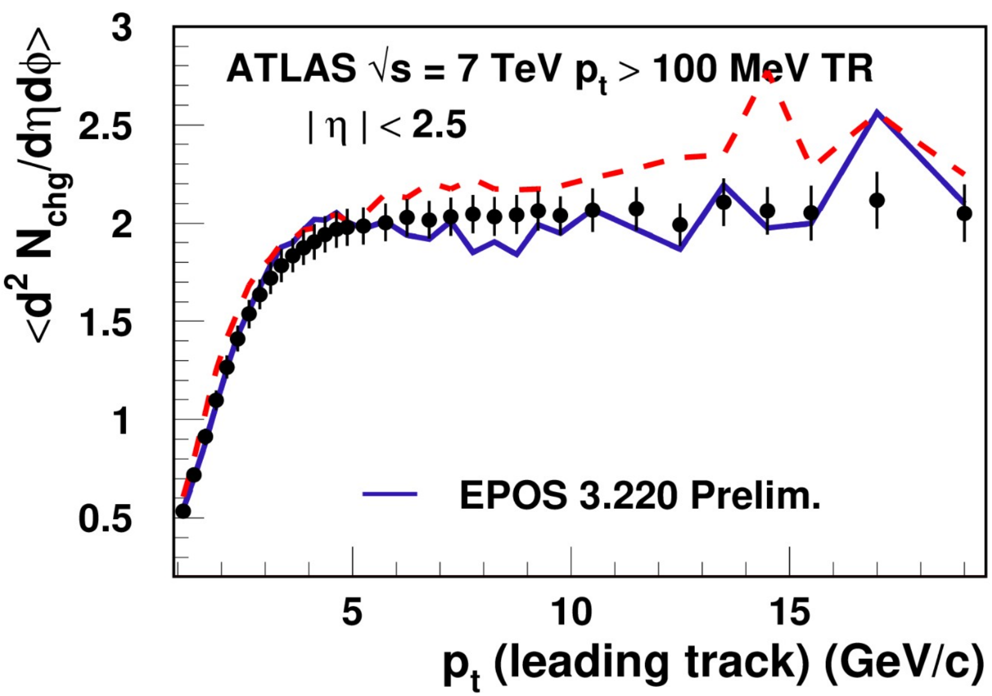
  to produce ISR and born process in hard Pomeron
  - Scaling of inclusive cross-section if N_{hard} and N_{soft} ($N_{pom}=N_{hard}+N_{soft}$) properly determined

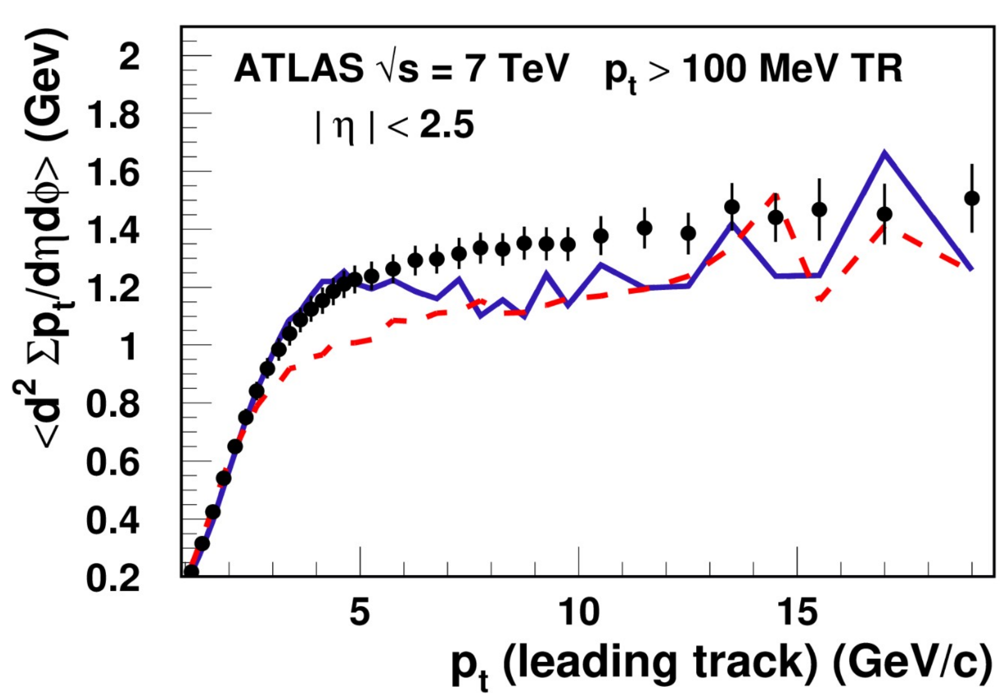


Underlying Events: p_t > 100 MeV/c

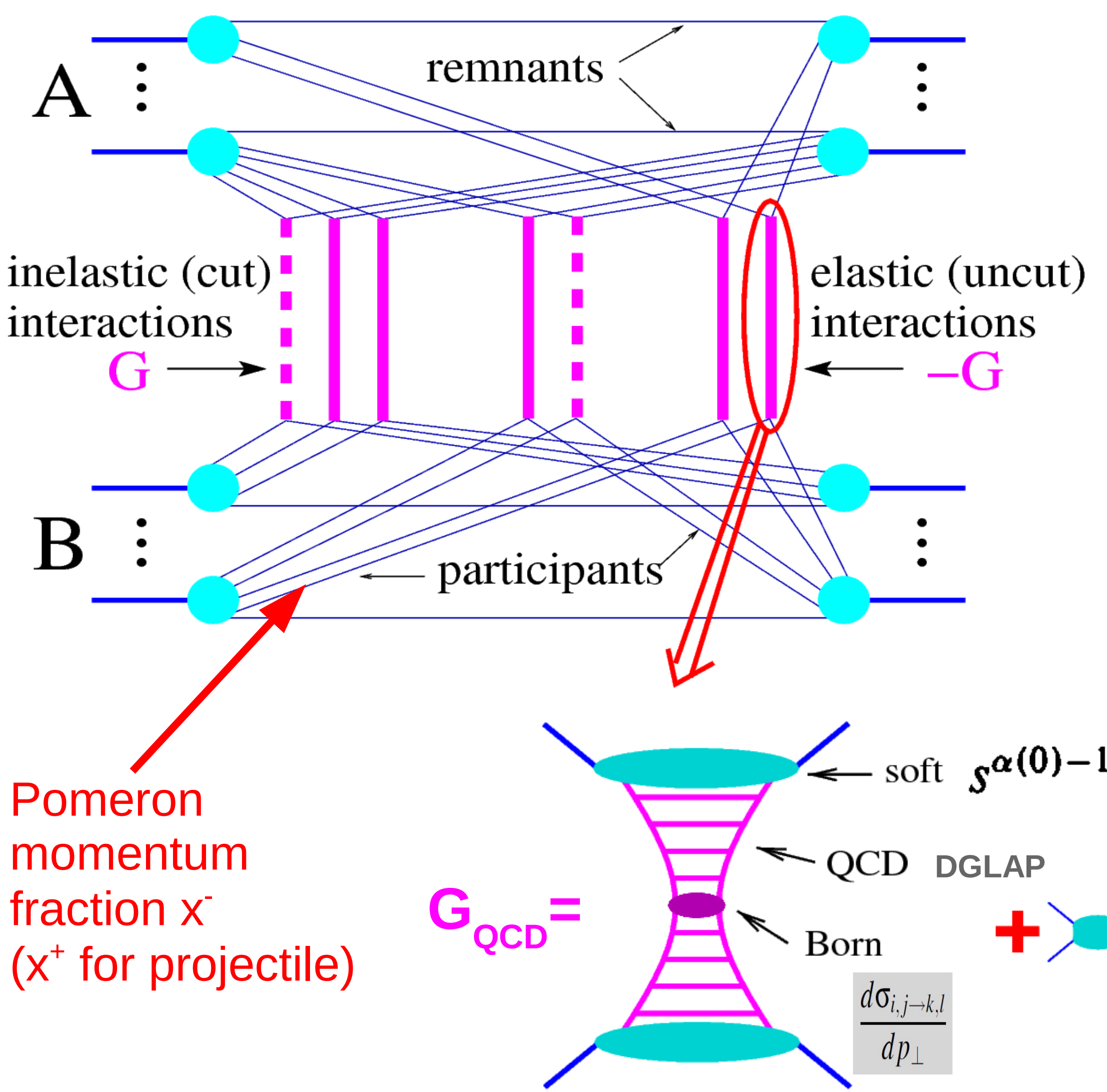
p_t > 100 MeV/c particles in TRANS region

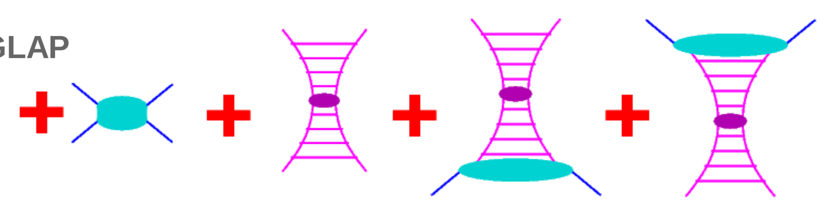
- without core N_{ch} is large like in MB but energy density is too low for p_t leading >2 GeV/c
- with core the multiplicity is reduced and energy density at intermediate p_t is increased
- reasonable agreement with data
  - mean transverse energy still a bit low for high p_t leading track





Parton-Based Gribov-Regge Theory





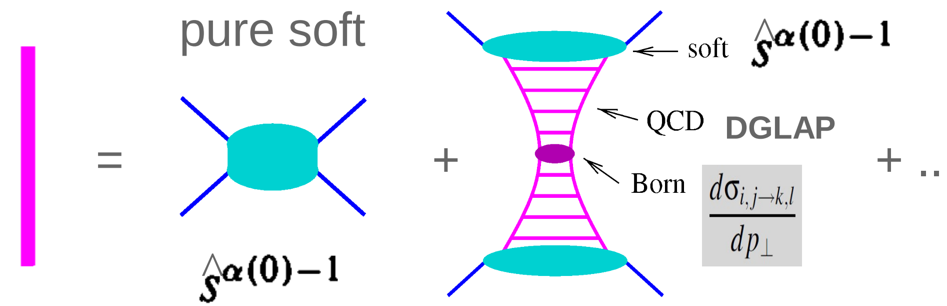
Energy sharing at the cross section level

- 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

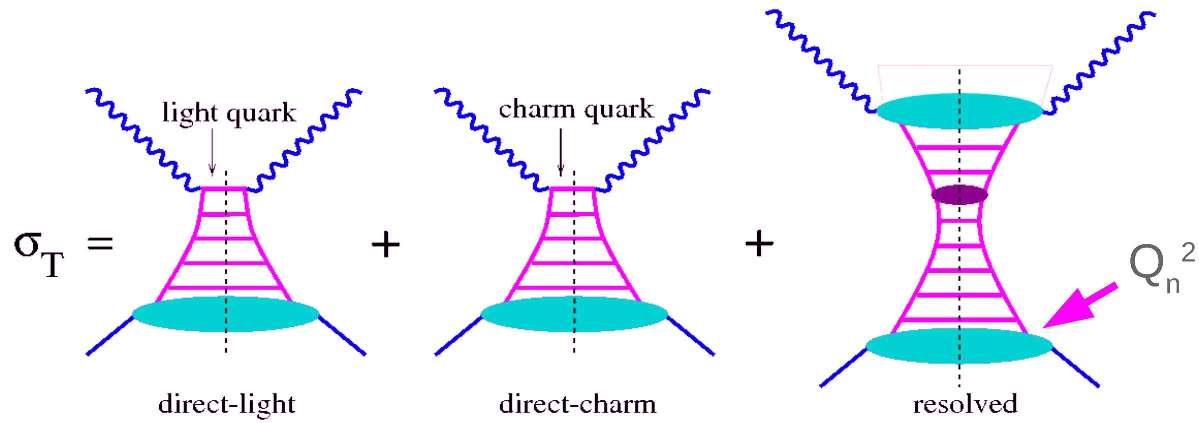
Parton-based Gribov-Regge Theory, H. J. Drescher, M. Hladik, S. Ostapchenko, T.Pierog, and K. Werner, Phys. Rept. 350 (2001) 93-289;

EPOS : Pomeron Definition

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

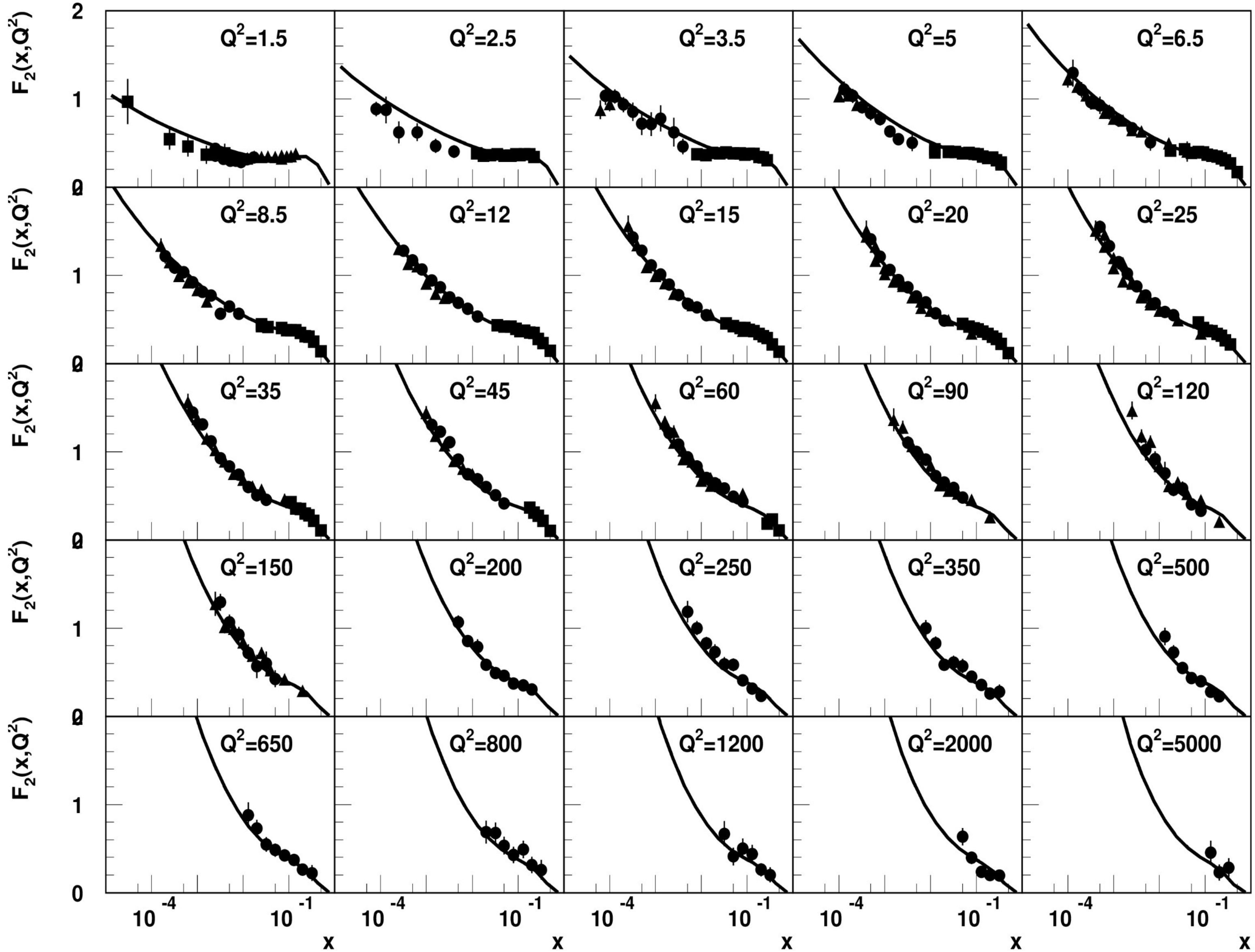


Test of semi-hard Pomeron with DIS: (Parton Distribution Function from HERA)

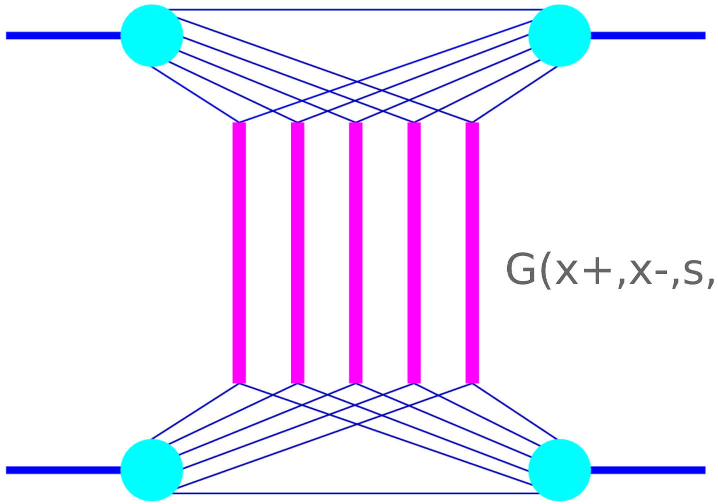


- Theory based Pomeron definion
  - pQCD based (DGLAP and Born)
    - large increase at small x (without saturation)
  - External pdf only for valence quark
  - Minimum non-perturbative scale Q_n^2=2 GeV^2 with soft pre-evolution $s^{\alpha(0)-1}$
  - F2 from HERA used to fix parameters for sea quarks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

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

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

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)

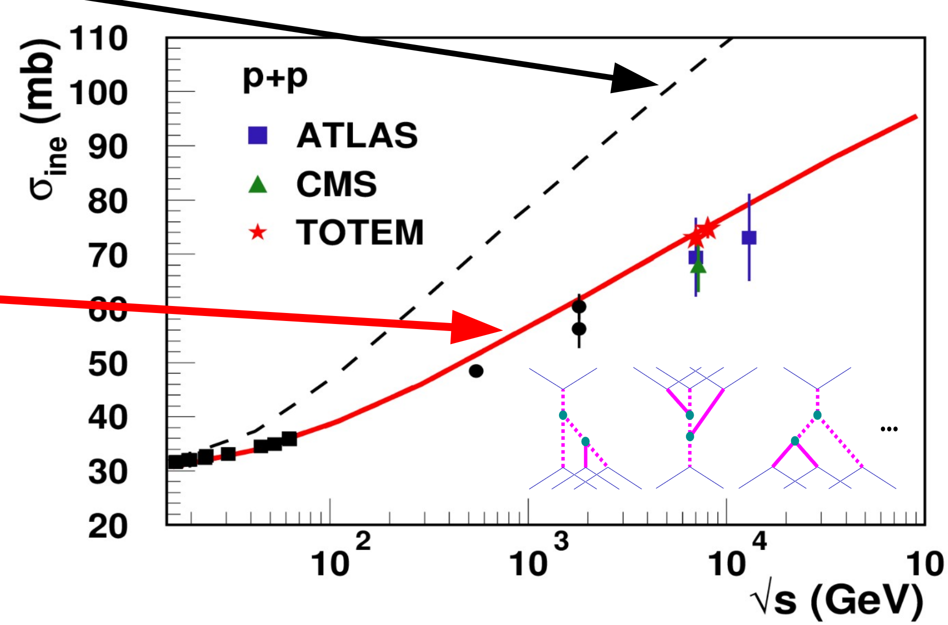
- effective coupling introduced to mimic effect of enhanced diagrams and reduce cross-section (screening effect) to get cross-section AND multiplicity right in p-p, p-A and AA
  - Amplitude G_{eff} no longer fit to G_{QCD}

No effective coupling

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

With effective coupling

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



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 :

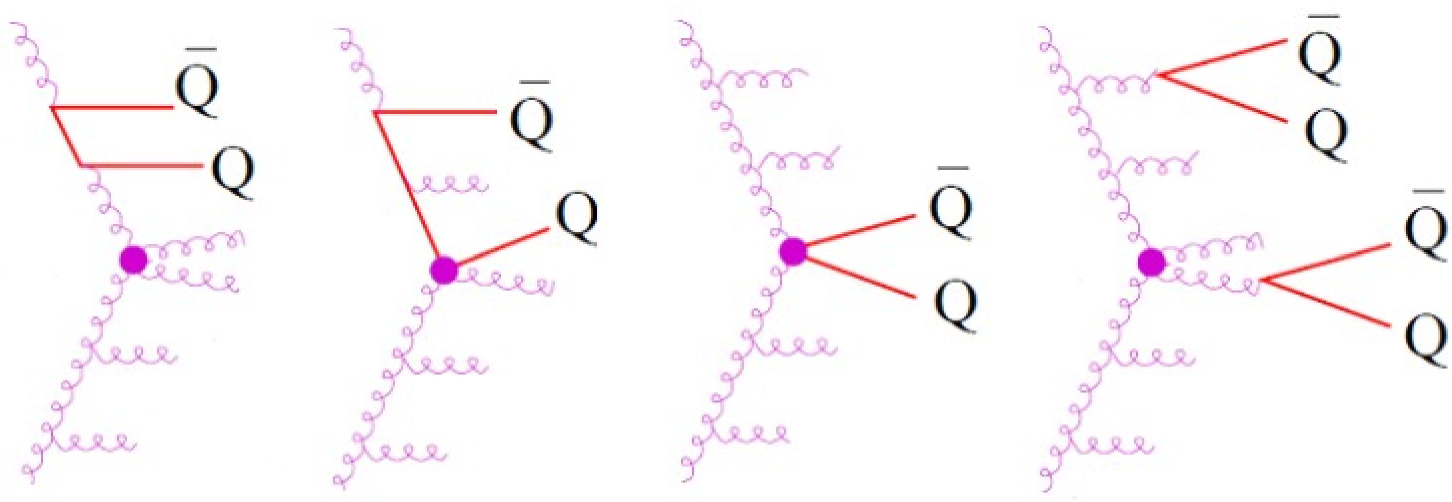
$$\Omega_{AB}^{(s,b)}(m, X^+, X^-) = \prod_{k=1}^{AB} \left\{ \frac{1}{m_k!} \prod_{\mu=1}^{m_k} G(x^+_{k,\mu}, x^-_{k,\mu}, s, b_k) \right\} \Phi_{AB}\left(x^{\text{proj}}, x^{\text{targ}}, s, b\right)$$

  - 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

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



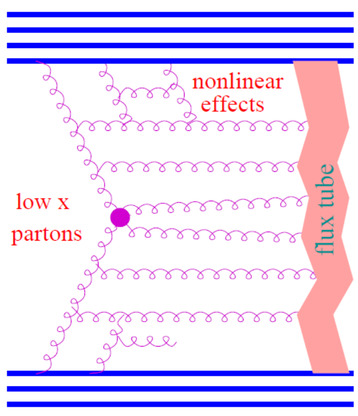
space-like cascade | space-like cascade and born | born | time-like cascade

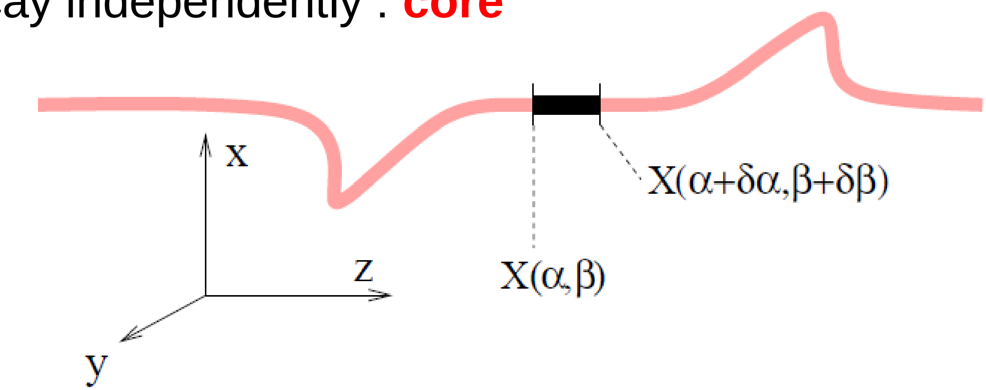
- "parameter free" : good test of hard Pomeron
- Heavy quarks (Q) taken as string-end for the hadronization

High Density Core Formation

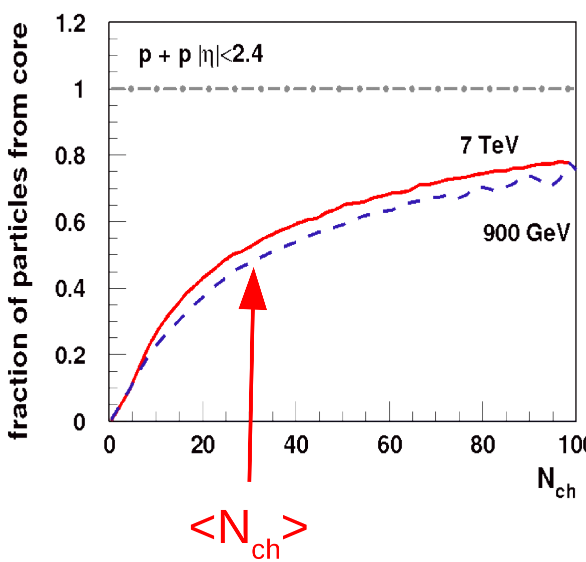
Heavy ion collisions or high energy proton-proton scattering:

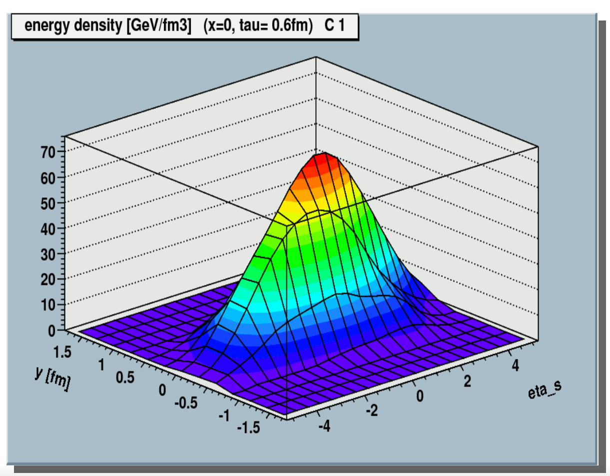
- the usual procedure has to be modified, since the density of strings will be so high that they cannot possibly decay independently : **core**





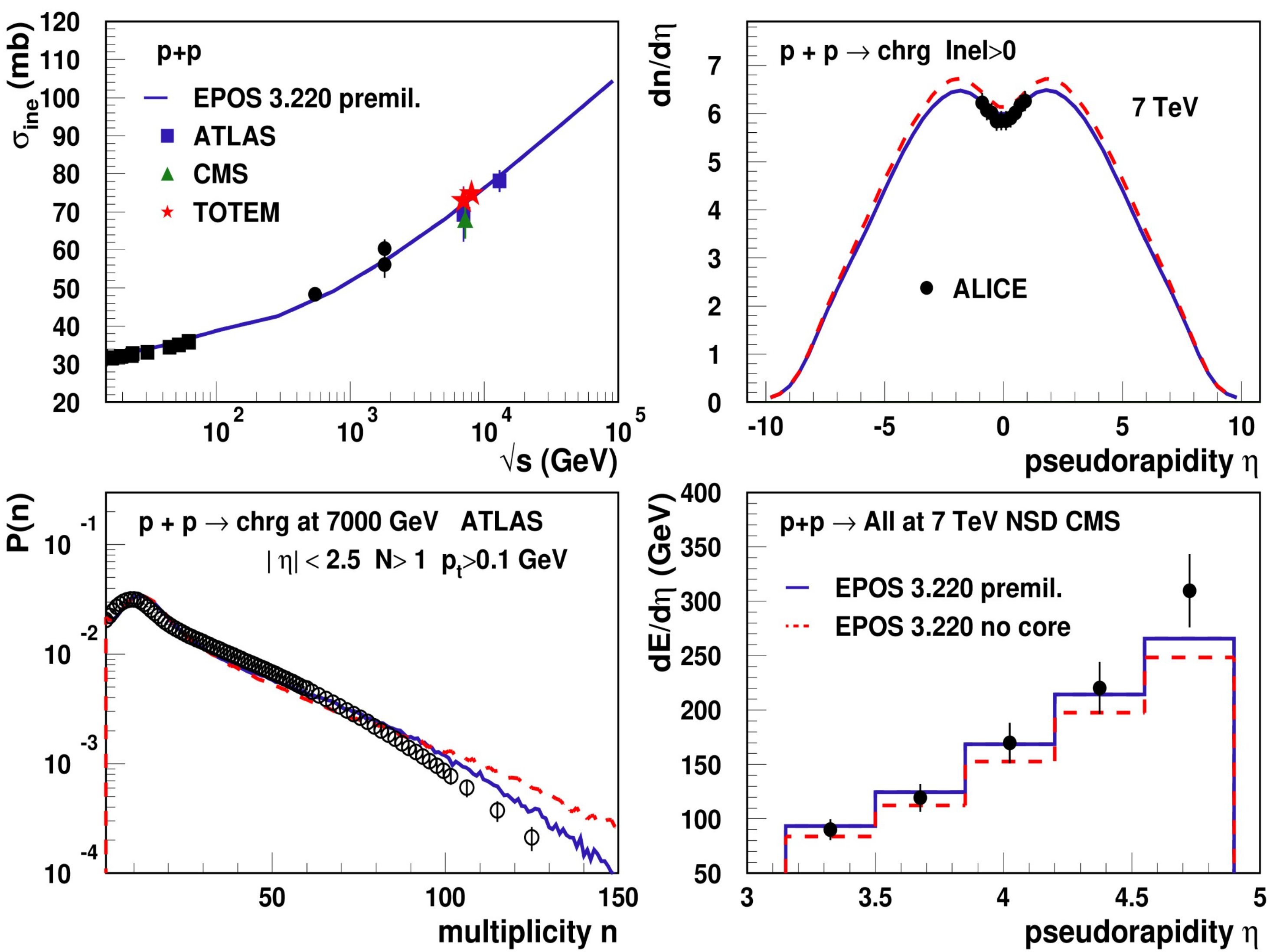
- Each string split into a sequence of string segments, corresponding to widths δα and δβ in the string parameter space
- If energy density from segments high enough
  - segments fused into core
    - full 3D+1 hydro evolution
    - lattice QCD EoS
- If low density (corona)
  - segments remain hadrons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





Preliminary Results : With/out Core

Excellent results for minimum bias soft physics

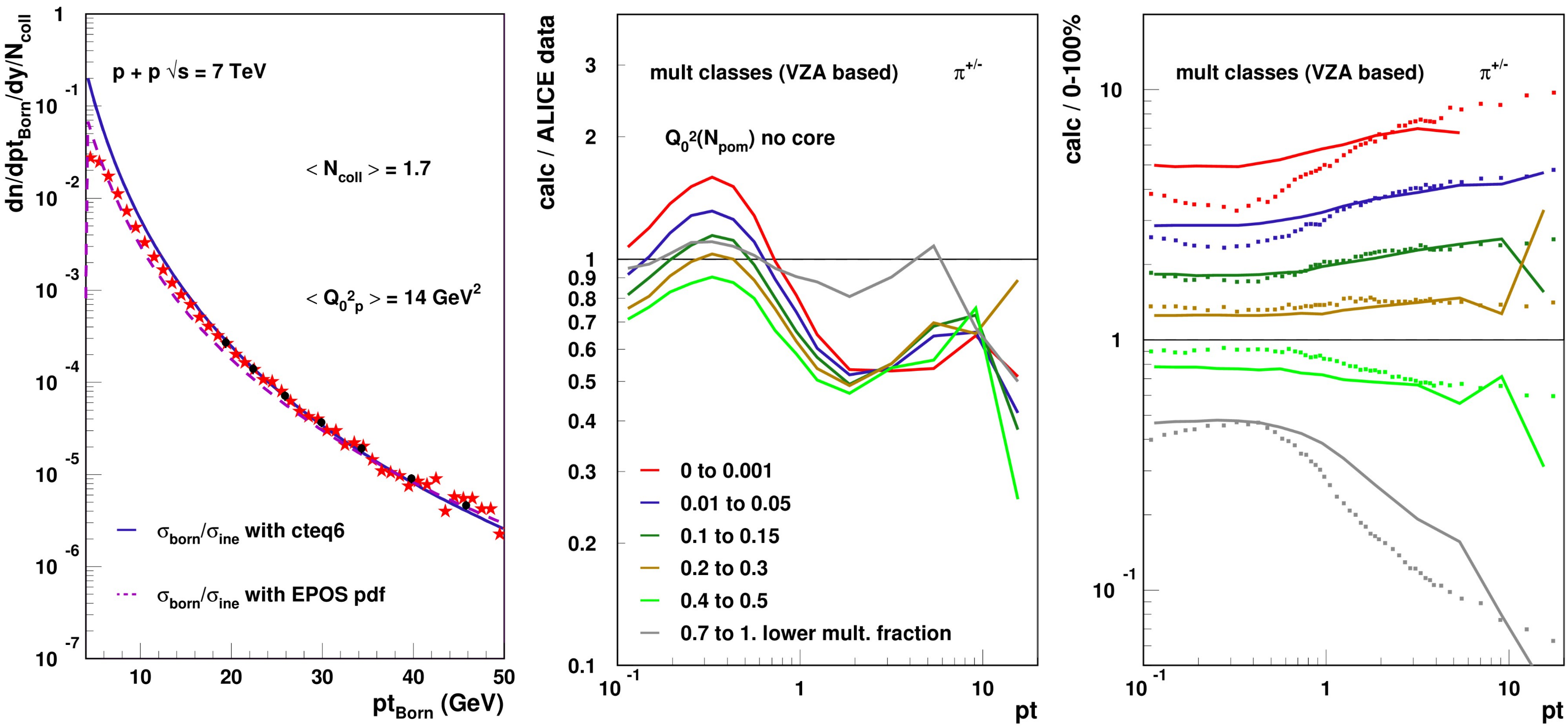


Effect of MPI on Q_0^2

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 :

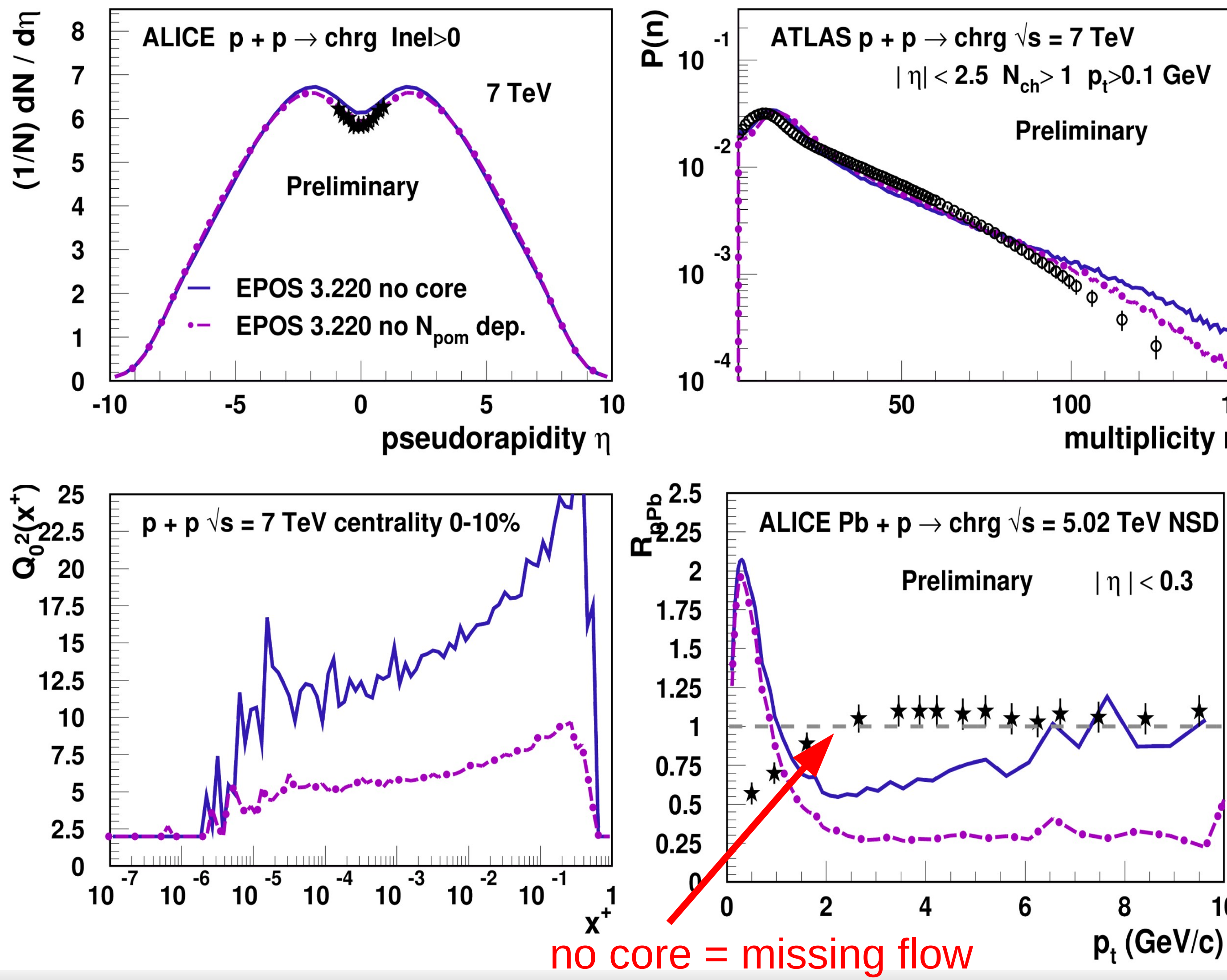
➡ $N_{hard}\ G_{QCD}(x,b,Q_0^2)=G_{eff}(s,x,b,A)$



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.



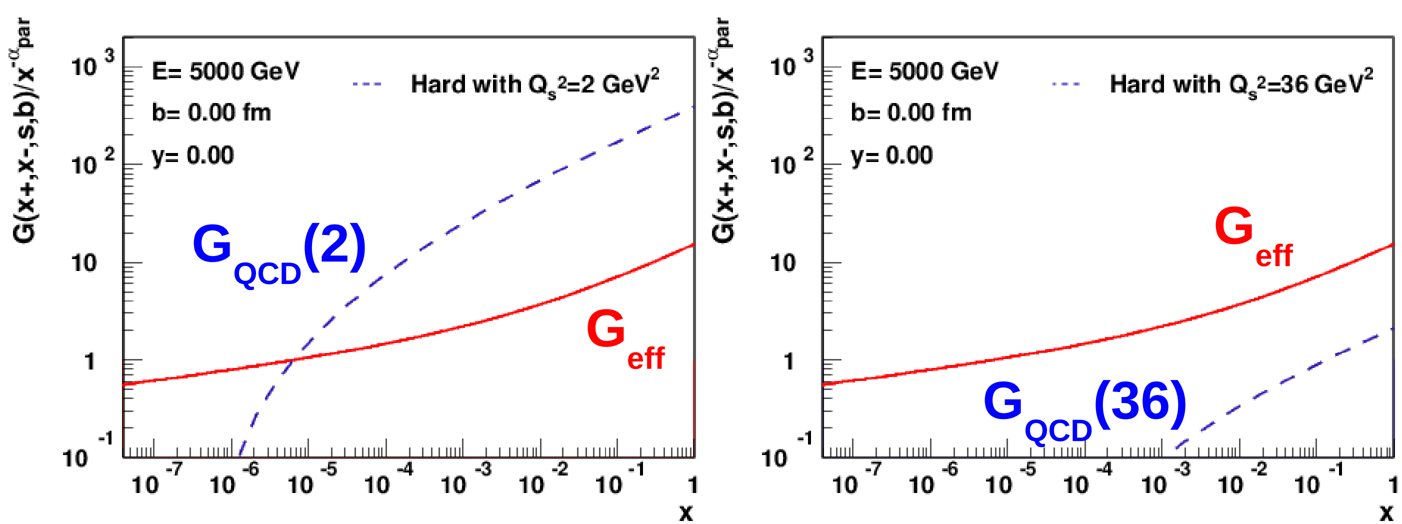
Non-perturbative Scale Q_0^2

- **Model property : AGK cancellation**

$$\frac{dn^{h_1 h_2}_{\mathrm{Pom}}}{dx^+ dx^-}(x^+, x^-, s, b) = \frac{dn^{(1)h_1 h_2}_{\mathrm{Pom}}}{dx^+ dx^-}(x^+, x^-, s, b)$$

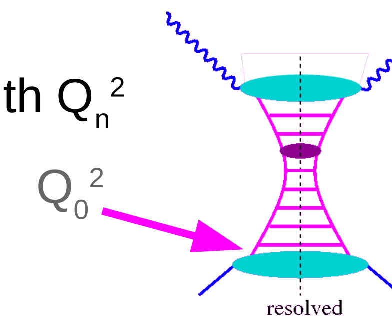
$$= G_{eff}(x^+, x^-, s, b) F^{h_1}_{\mathrm{remn}}(1 - x^+) F^{h_2}_{\mathrm{remn}}(1 - x^-)$$

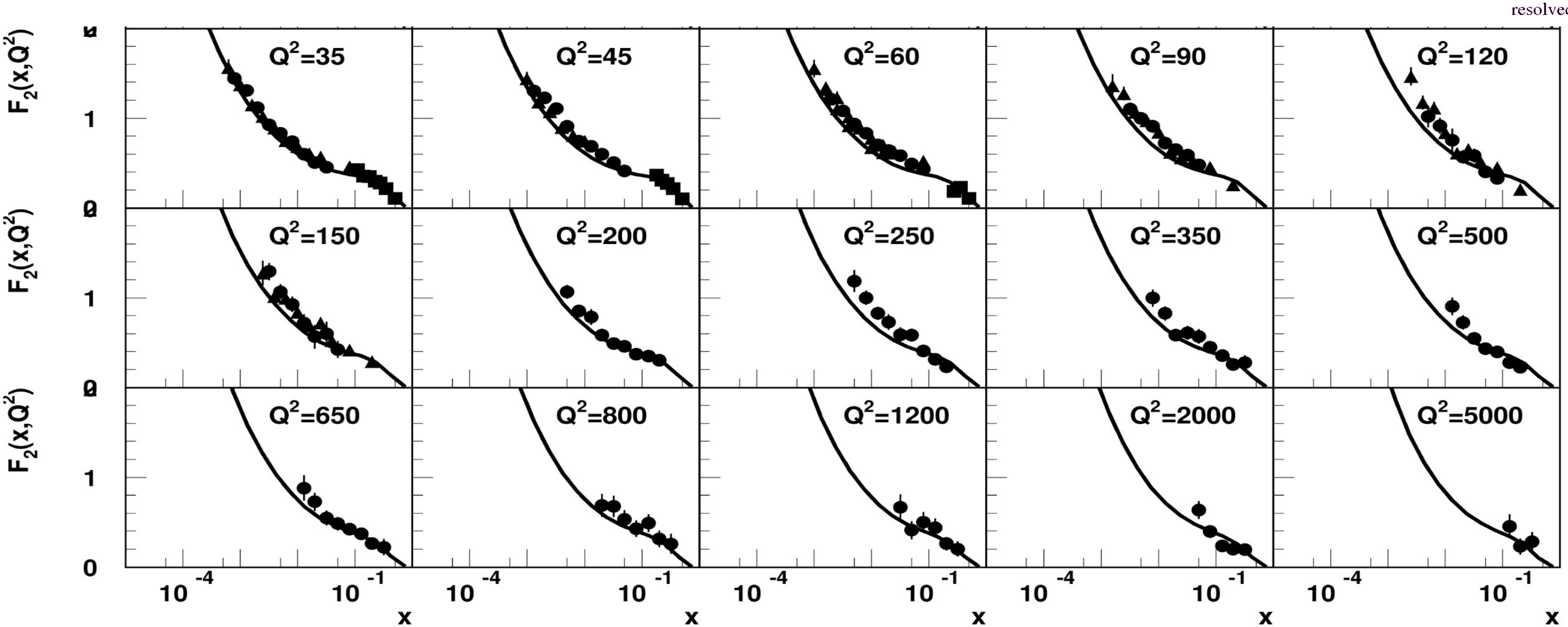
- **Assumption : factorization should be satisfied at large Q^2**
  - satisfied if: $<N_{hard}> G_{QCD}(x,b,Q_0^2) = G_{eff}(s,x,b,A)$
  - different non-pertubative scale event-by-event and even Pomeron-by-Pomeron depending on momentum fraction x
- **Matching amplitude**
  - $G_{eff} \leqslant G_{QCD}(Q_0^2 = Q_n^2)$
  - increase Q_0^2 until $G_{eff} = <N_{hard}> G_{QCD}(Q_0^2)$ for each parton scattering
  - for $Q^2 >> Q_0^2(x,b)$ factorization holds



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

- **Larger Q_0^2**
  - partons which can be treated pertubatively (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

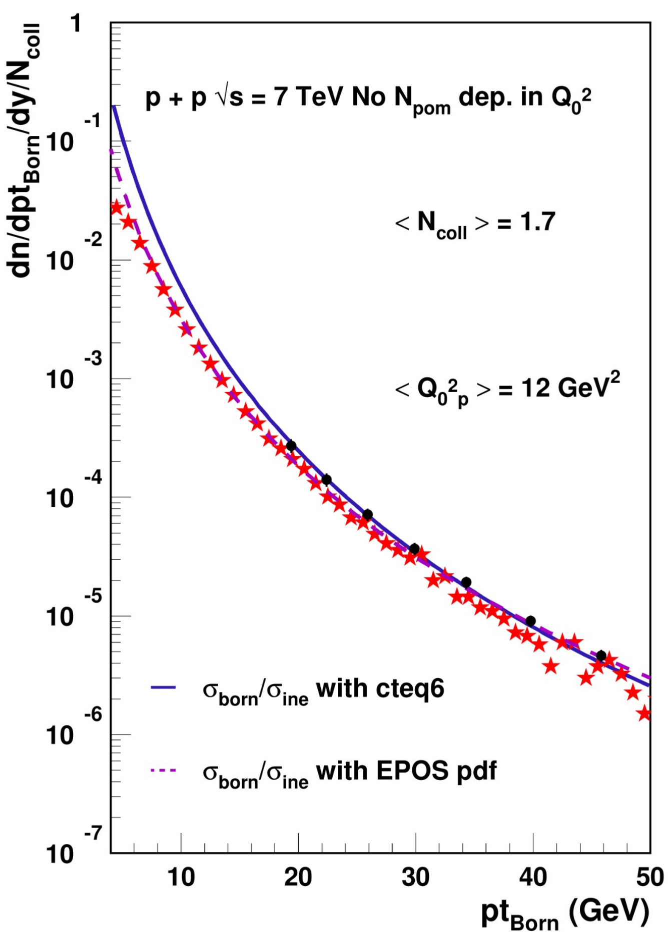


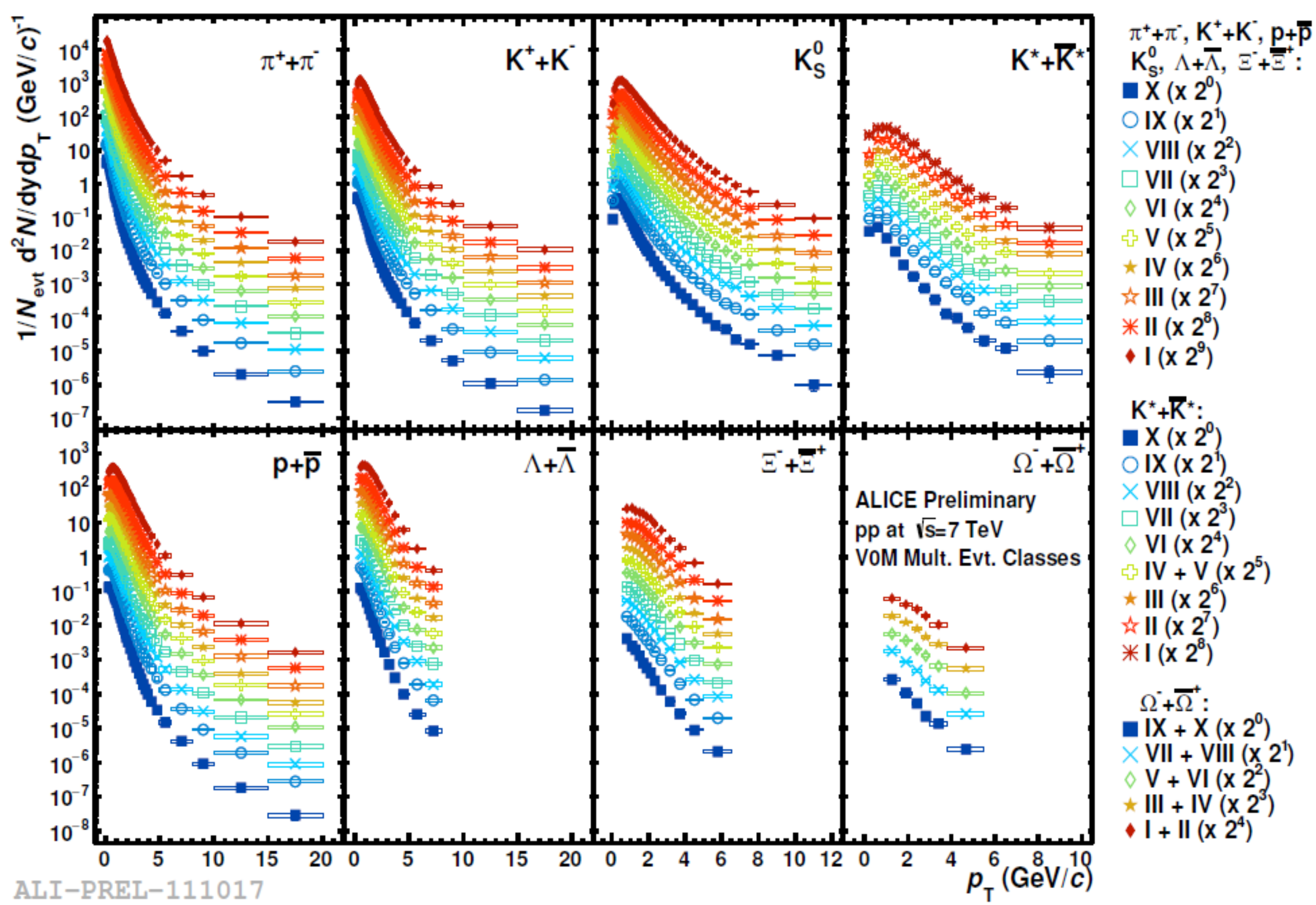


Jet and p_t

Check with pp data at 7 TeV

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





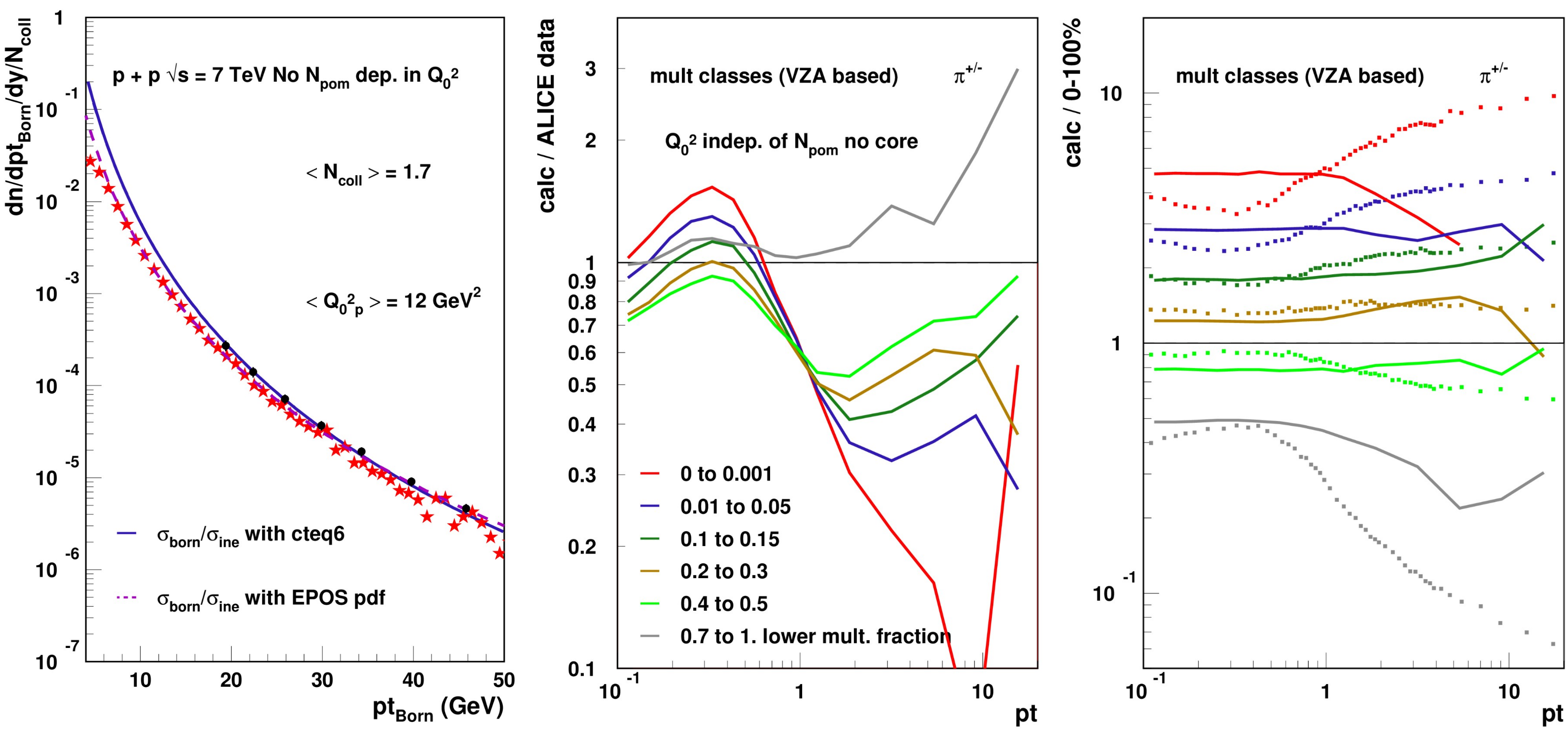
J.Phys.Conf.Ser. 779 (2017) no.1, 012071

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

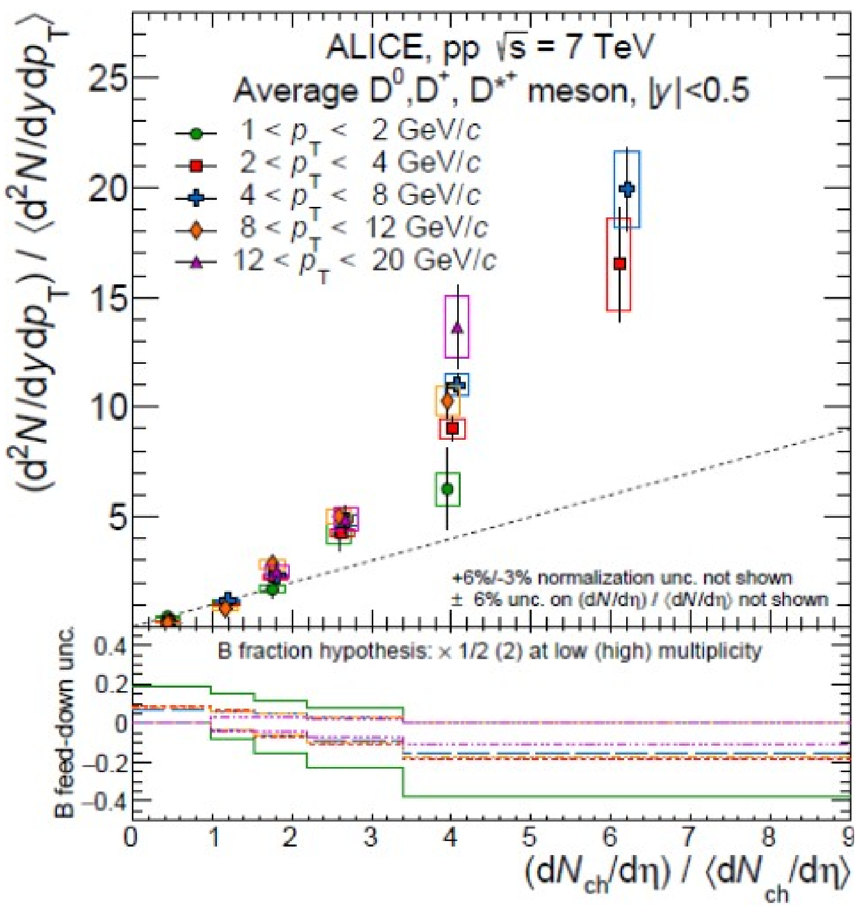


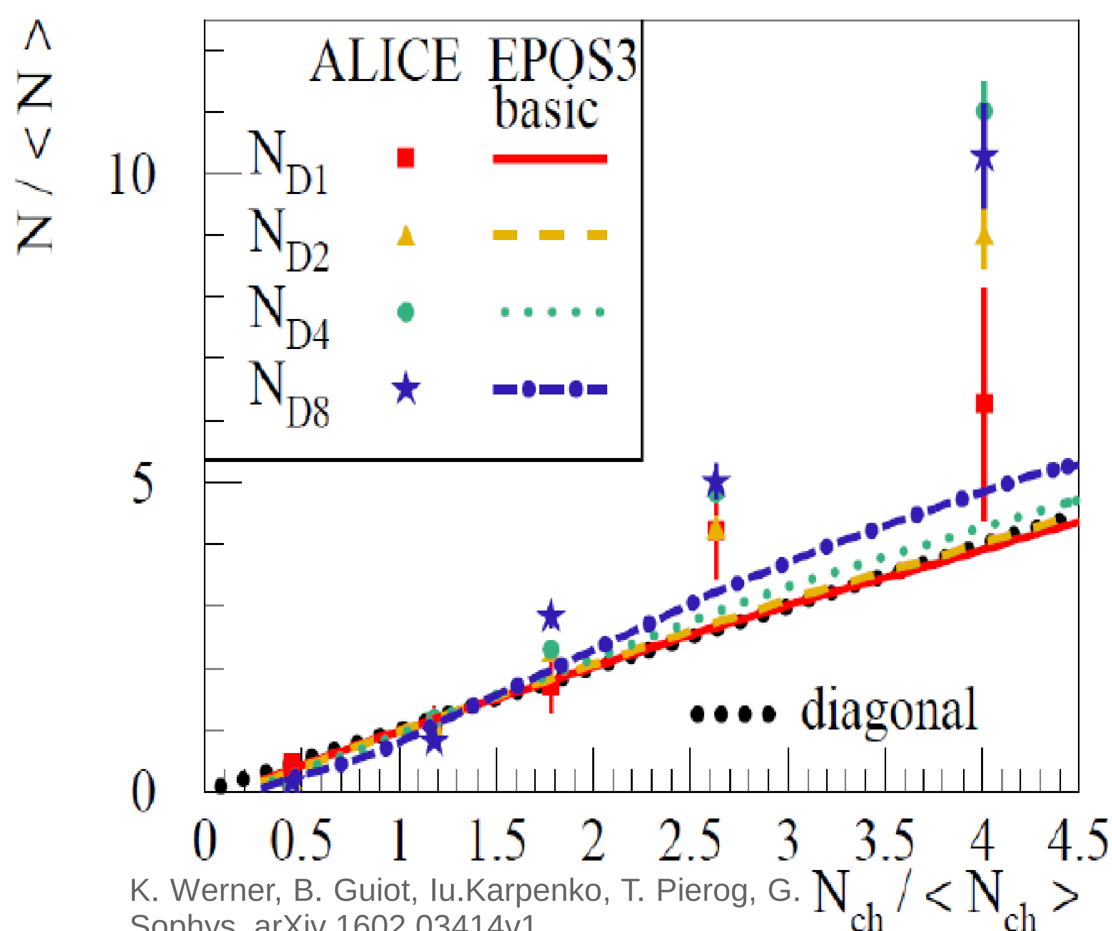
J.Phys.Conf.Ser. 779 (2017) no.1, 012071

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





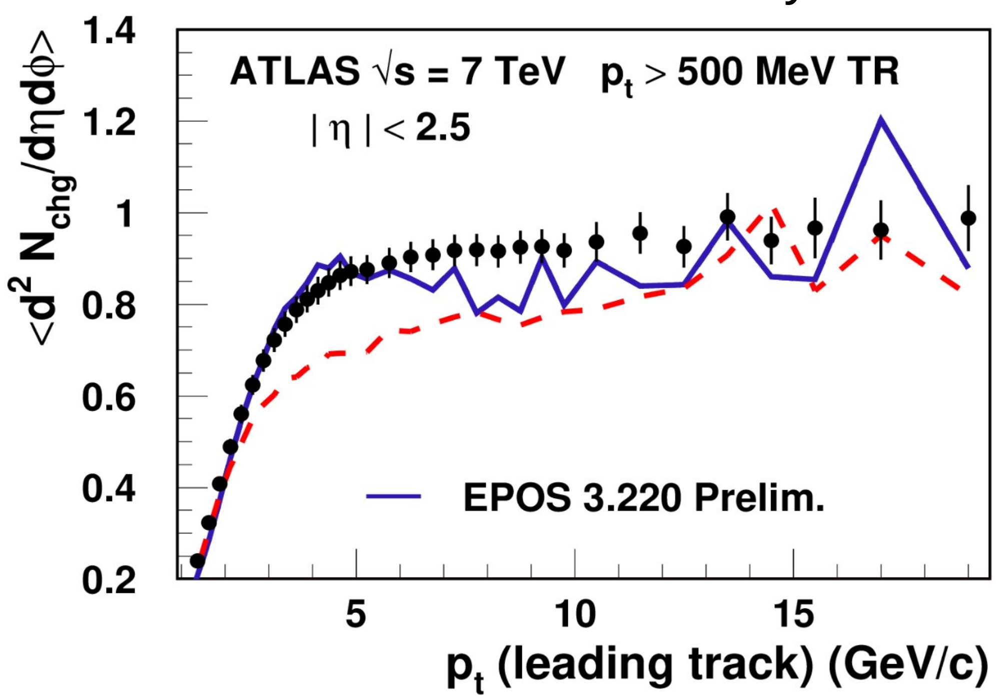
K. Werner, B. Guiot, Iu.Karpenko, T. Pierog, G. Sophys, arXiv 1602.03414v1

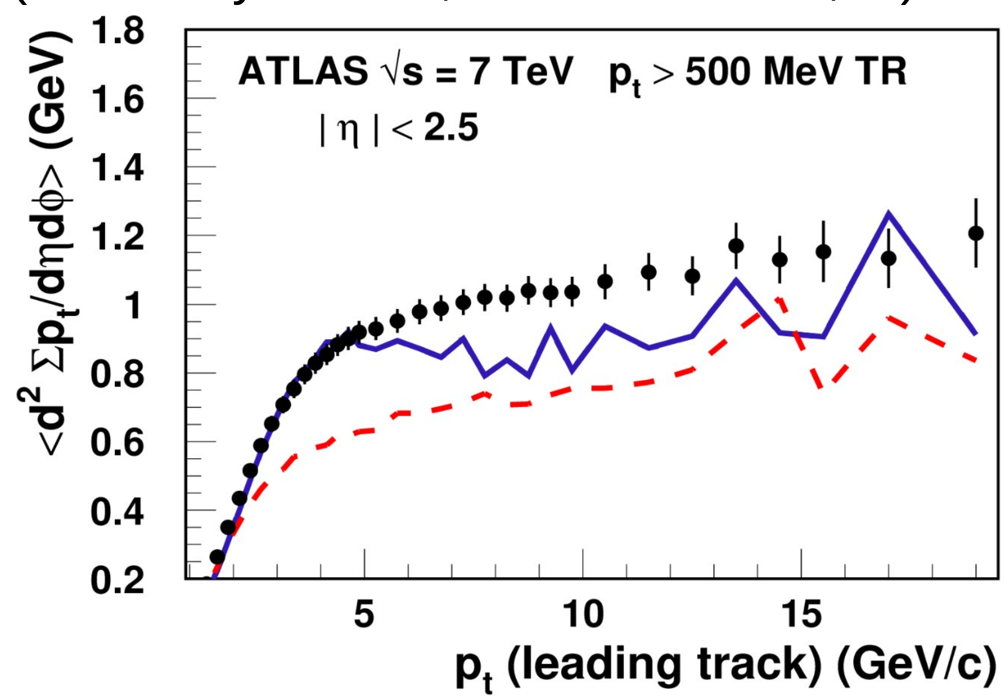
Underlying Events: p_t > 500 MeV/c

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, ...)



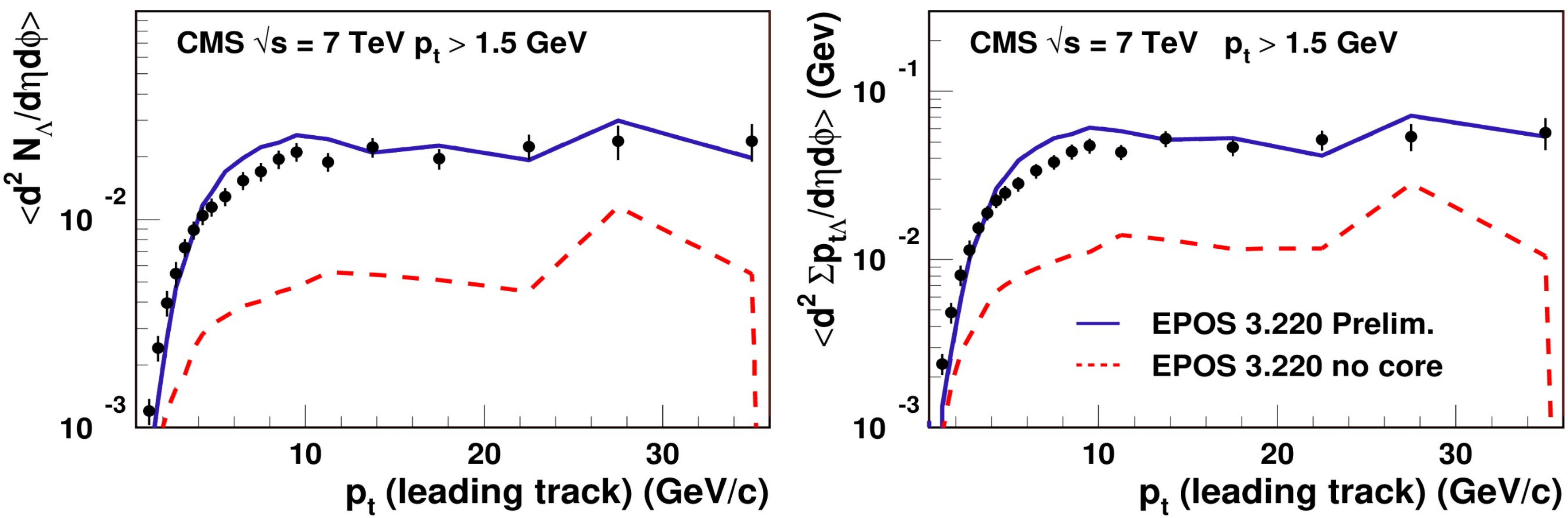


Underlying Events: Strangeness

Lambda production in UE

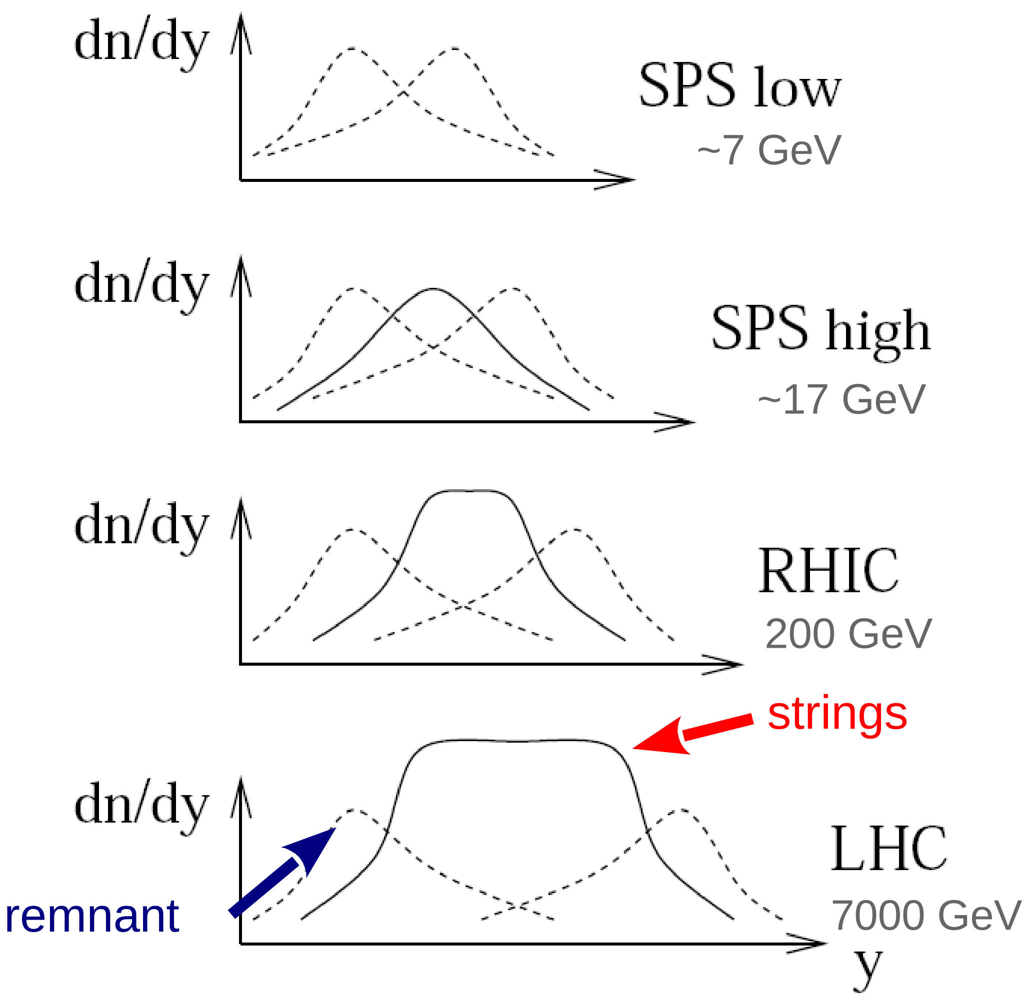
- Without core, very low lambda production like for other HEP models
- With core (and so hydro), much higher strangeness production
  - statistical hadronization
  - flow effect on transverse energy

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



Remnants

Forward particles mainly from projectile remnant



Forward hadronization from remnant :

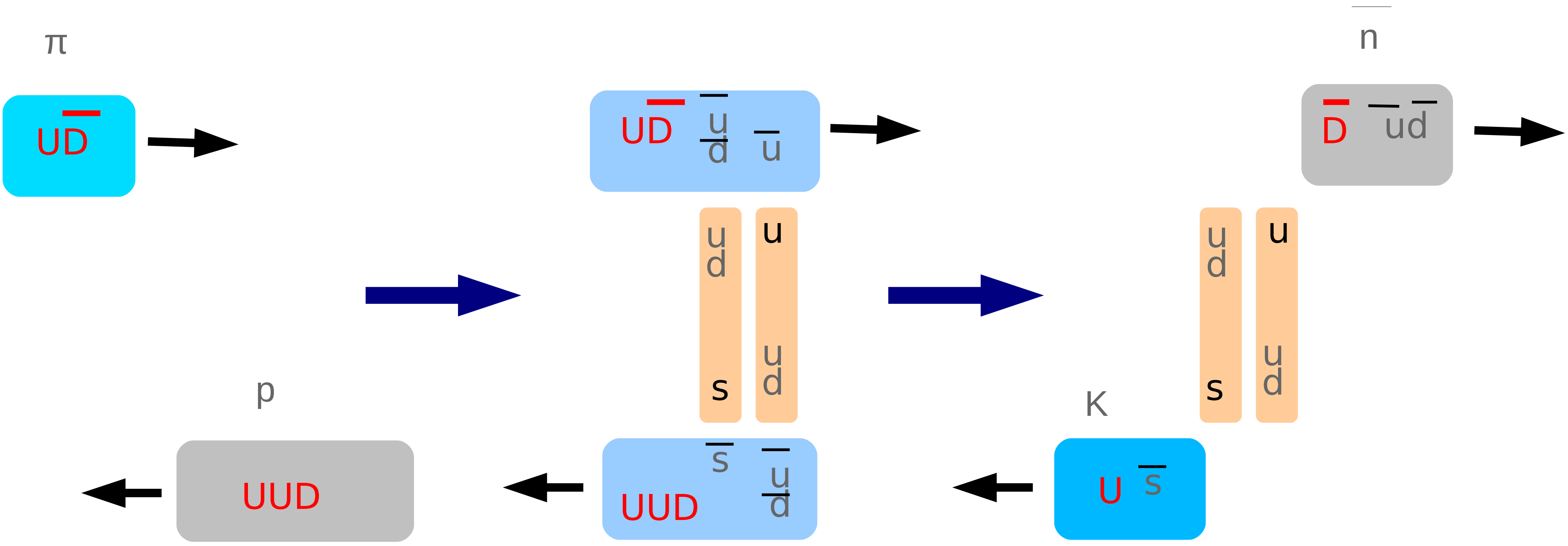
- At very low energy only particles from remnants
- At low energy (fixed target experiments) (SPS) strong mixing
- At intermediate energy (RHIC) mainly string contribution at mid-rapidity with tail of remnants.
- At high energy (LHC) only strings at mid-rapidity (baryon free)

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

Remnants in EPOS

In EPOS : any possible quark/diquark transfer

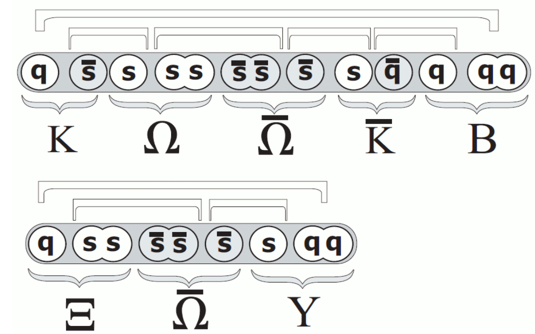
- Diquark transfer between string ends and remnants
- Baryon number can be removed from nucleon remnant :
  - Baryon stopping
- Baryon number can be added to pion/kaon remnant :
  - Baryon acceleration



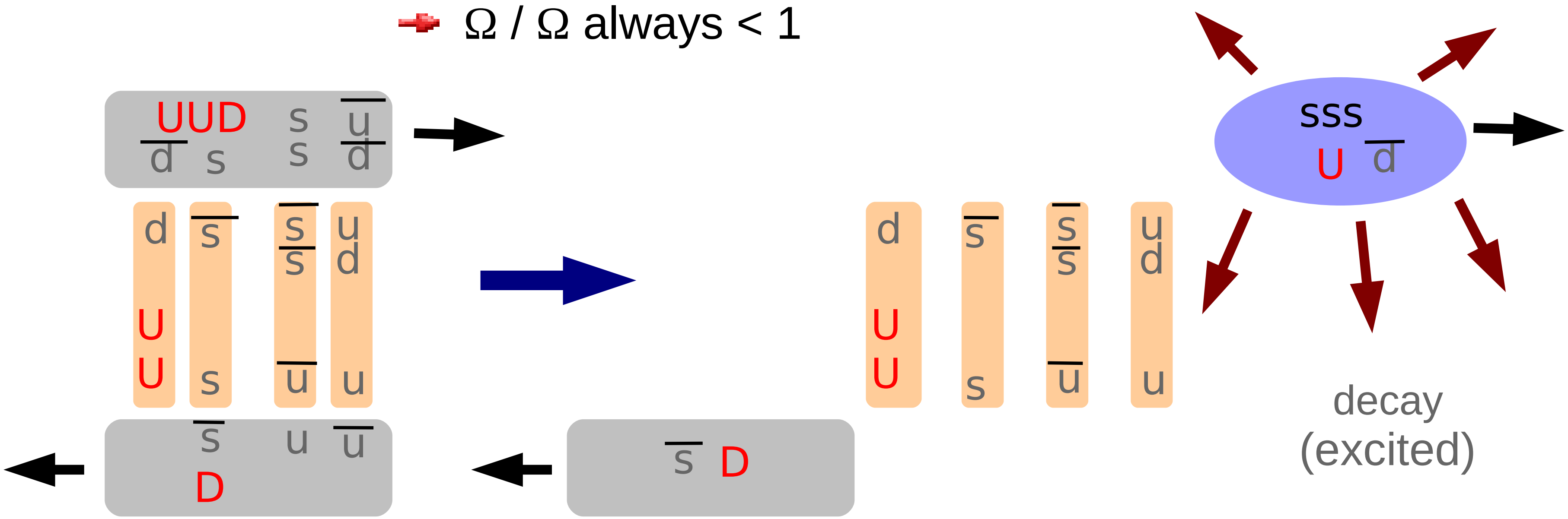
Baryons and Remnants

Parton ladder string ends :

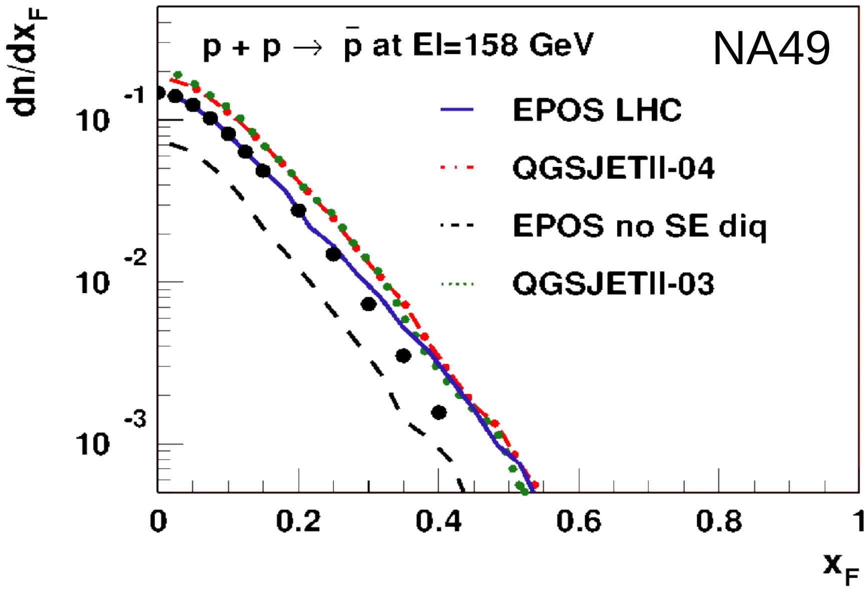
- Problem of multi-strange baryons at low energy (Bleicher et al., Phys.Rev.Lett.88:202501,2002)
  - 2 strings approach :
    - $\bar{\Omega}$ / Ω always > 1
    - But data < 1 (Na49)



- 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

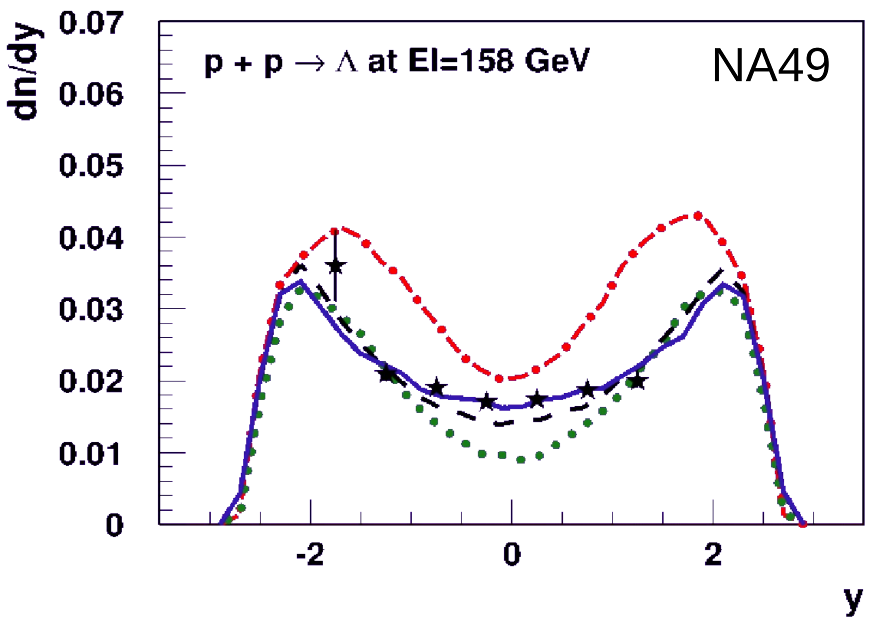


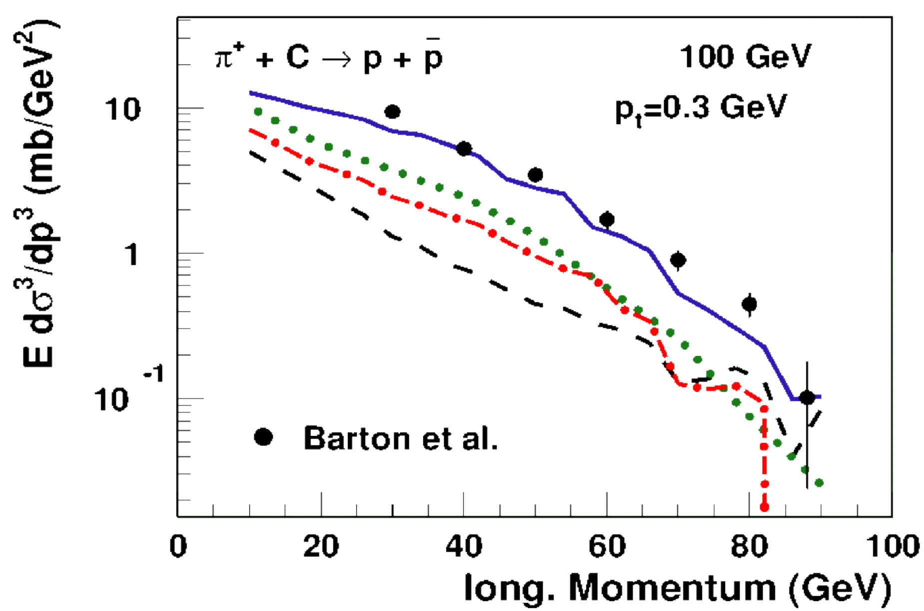
Forward Baryons (low energy)



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

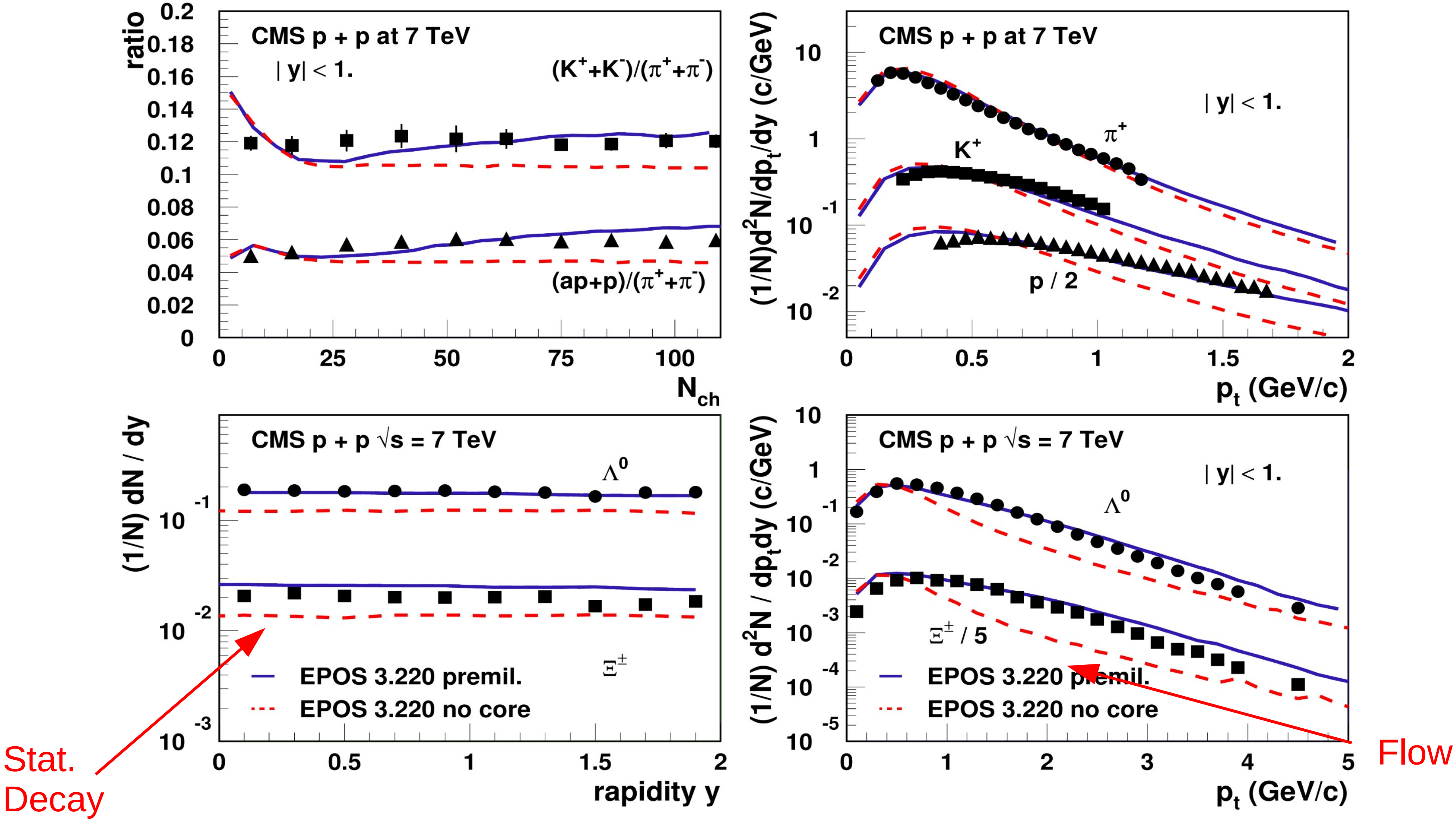
Without remnant, string fragmentation has to be changed for baryon production





Core Effect on Particle Yield

- **Core hadronization change particle ratio**
  - ➔ heasier to produce strange baryons



EPOS 3.216

- **Detailed description can be achieved**
  - identified spectra
  - p_t behavior driven by collective effects (flow)