Saturation in EPOS 3.1xx

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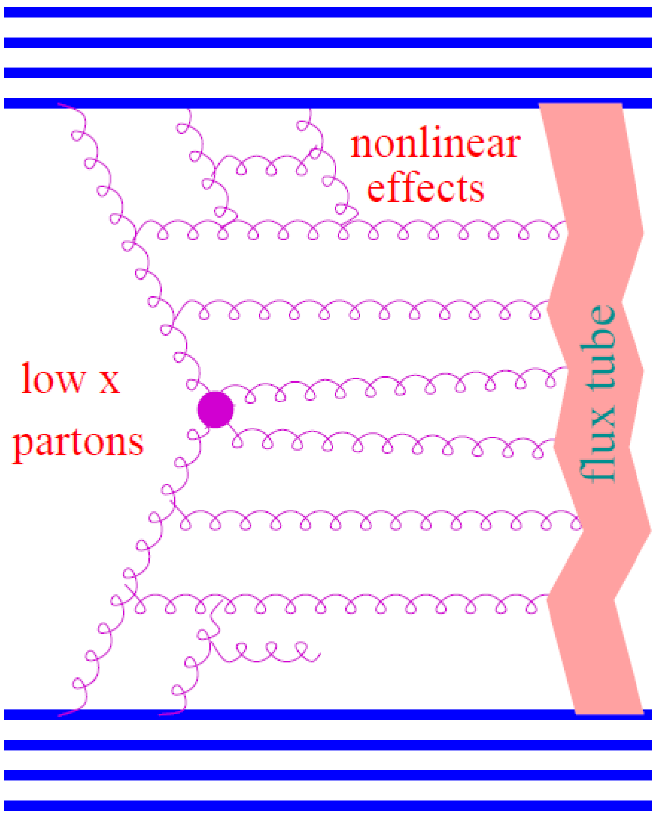
Outline

- **EPOS Basic principles**
- **Saturation in EPOS**
  - fixed Q_0^2
  - new saturation scale Q_s^2
- **Preliminary results**
- **Summary**

Elementary scatterings - flux tubes

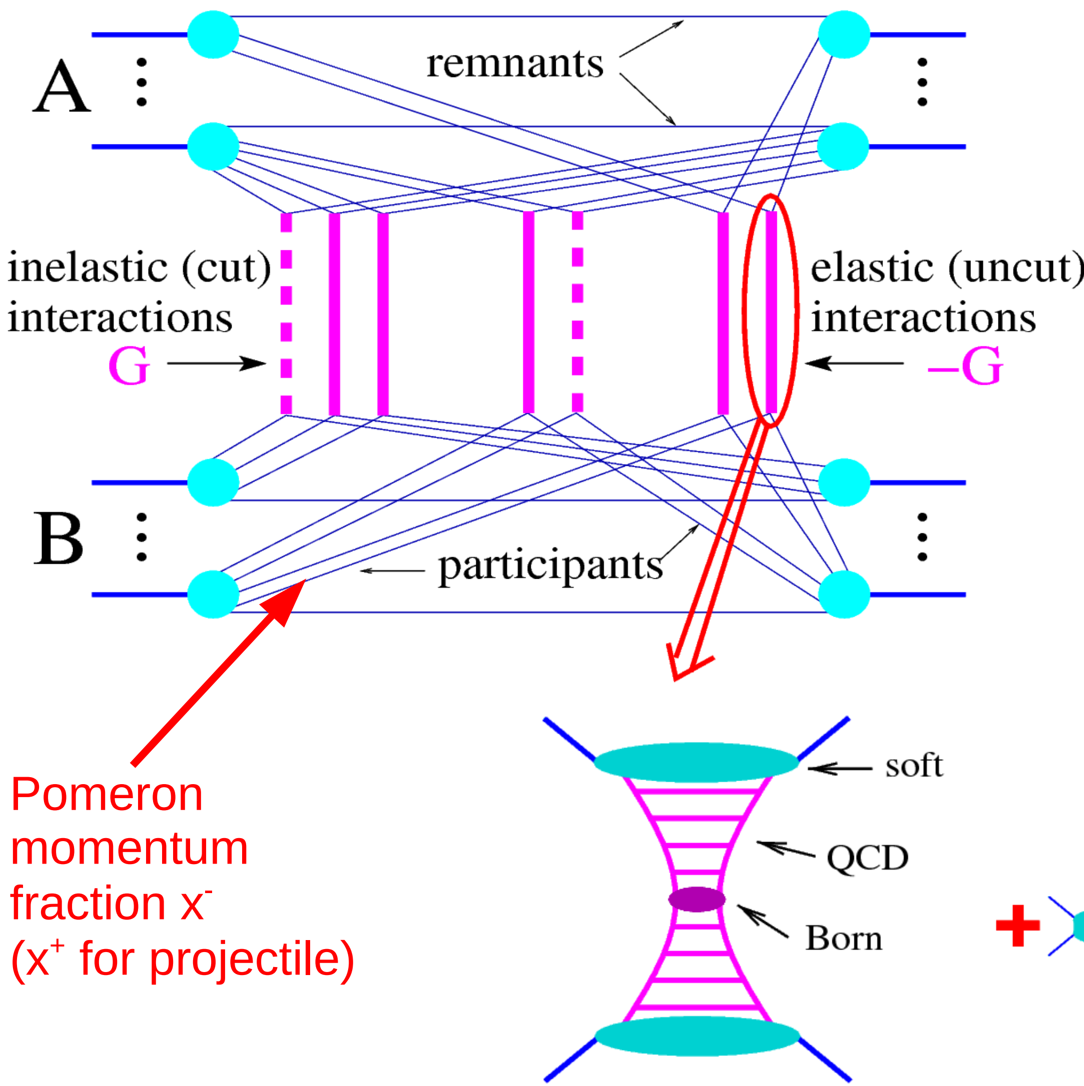
- same energy sharing between the parallel scatterings is taken into account for cross section and particle production
  - MPI fixed by total cross-section
- many elementary collisions happening in parallel
- elementary scattering = “parton ladder” + soft component



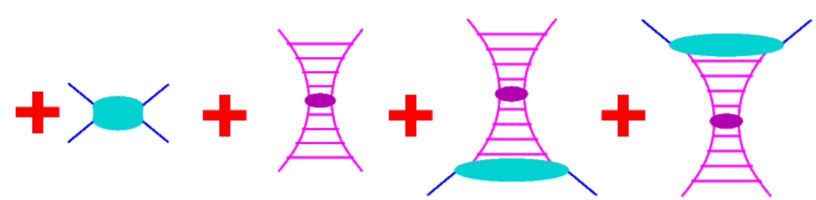
- Parton evolutions from the projectile and the target side towards the center (small x)
- Evolution equation
  - DGLAP
- Parton ladder = quasilongitudinal color field (“flux tube”)
  - relativistic string
- Intermediate gluons
  - kink singularities in relativistic strings
- Fragmentation : production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

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

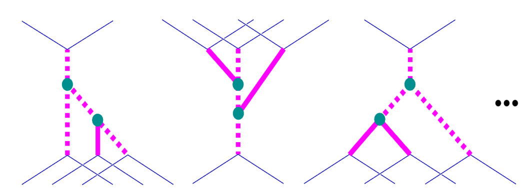
Parton-Based Gribov-Regge Theory



- **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)

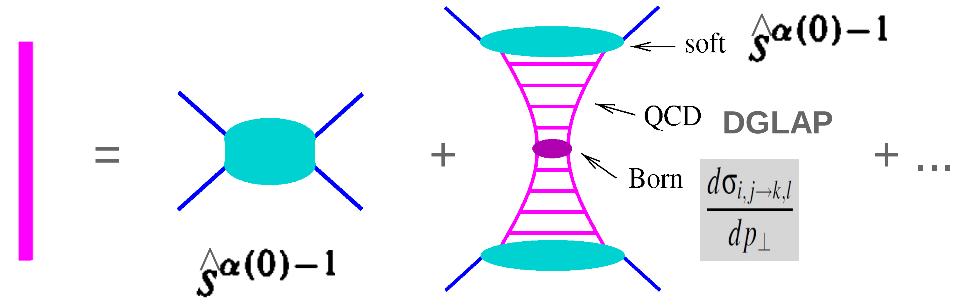


Non-linear effect (saturation) absorbed in modified vertex functions

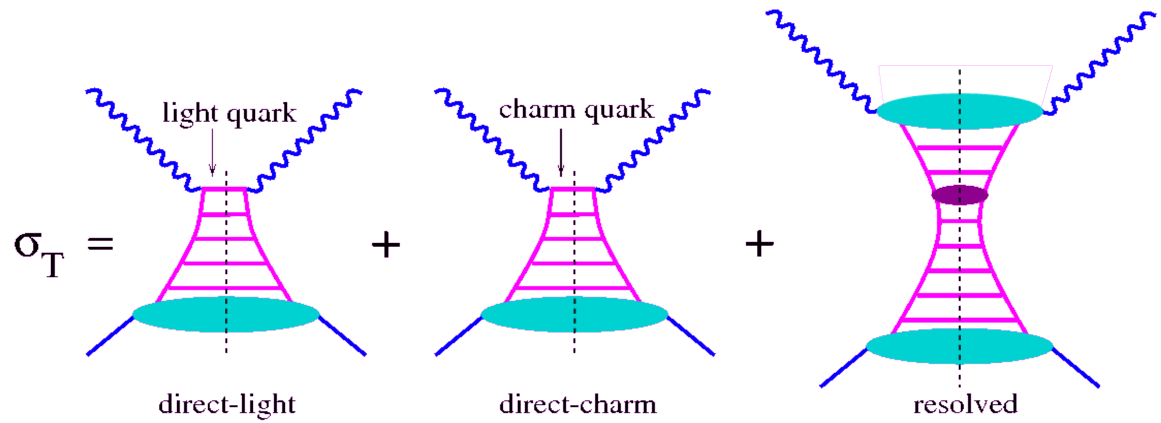


EPOS : Pomeron definition

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

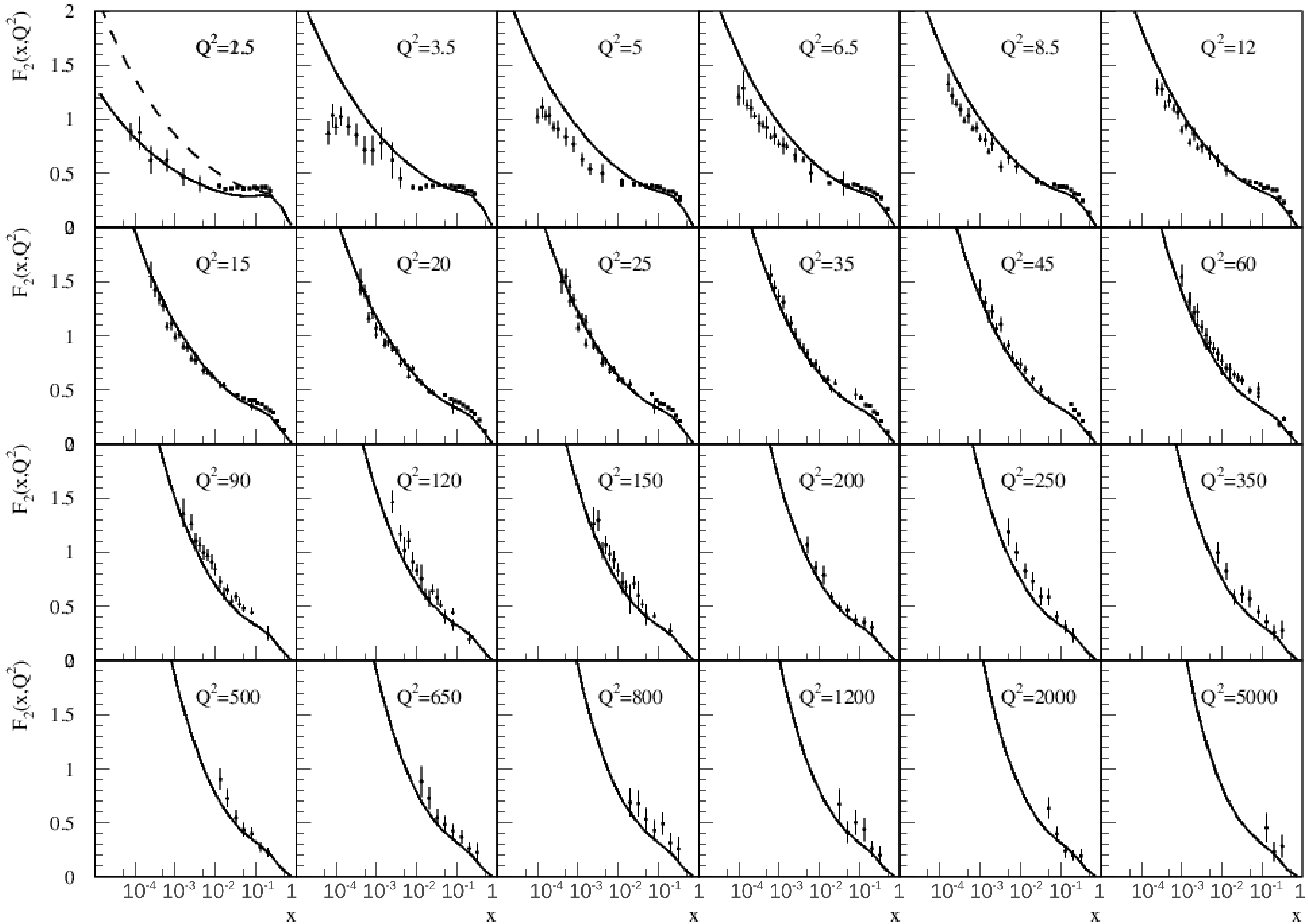


Test of semi-hard Pomeron with DIS: (Parton Distribution Function from HERA)

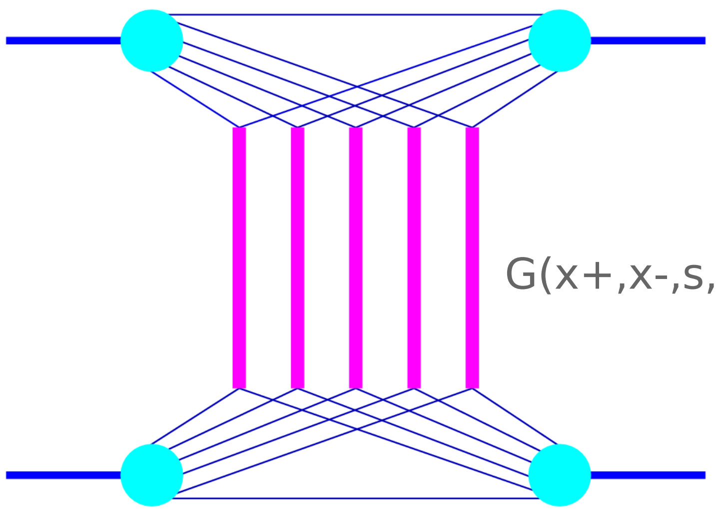


- Theory based Pomeron definion
  - pQCD based (DGLAP and Born)
    - large increase at small x (without saturation)
  - External pdf only for valence quark
  - F2 from HERA used to fix parameters for sea quarks and gluons

EPOS Parton Distribution Function



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

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

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

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

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 :

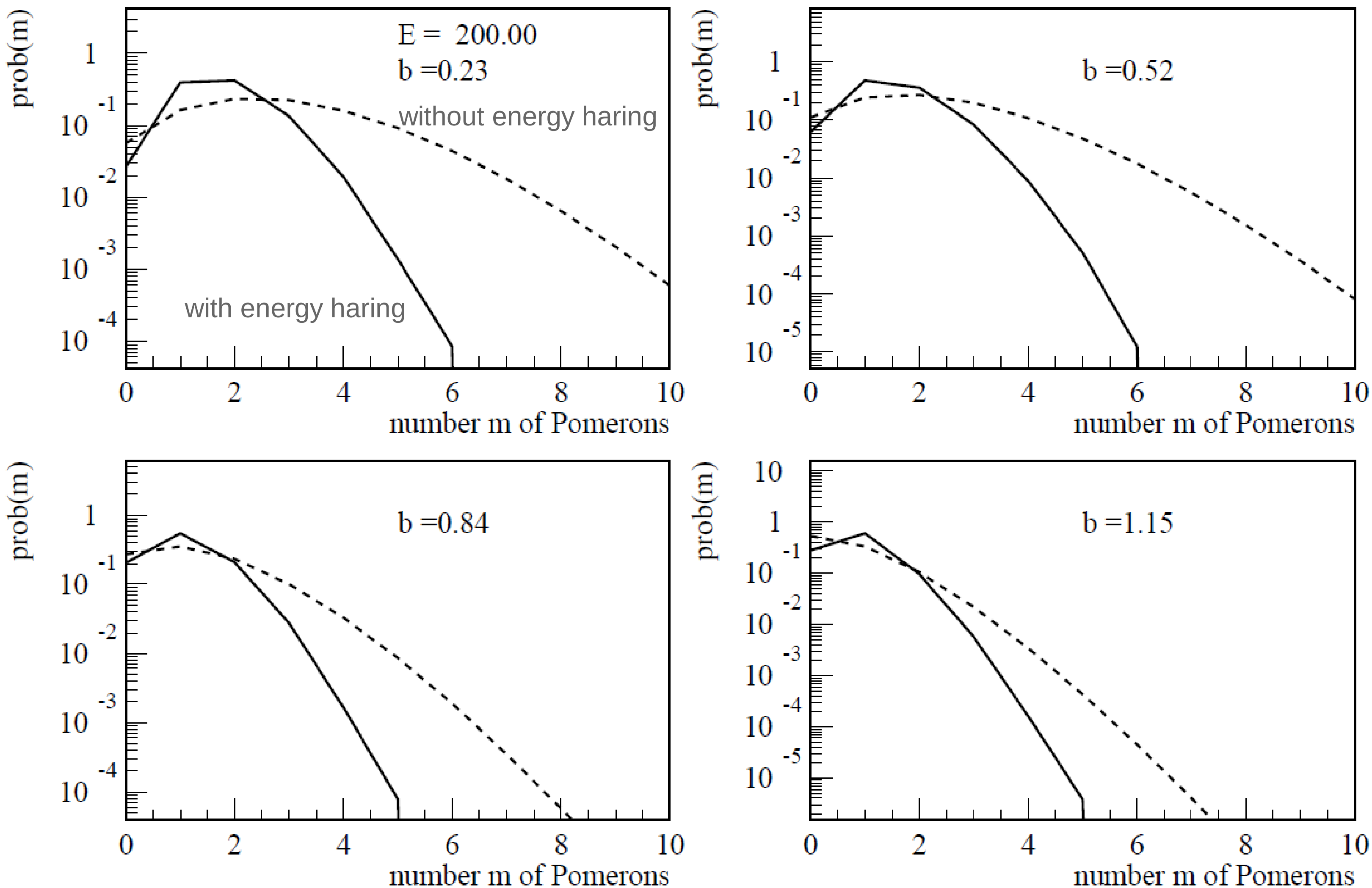
$$\Omega^{(s,b)}_{AB}(m,X^+,X^-)=\prod_{k=1}^{AB}\left\{\frac{1}{m_k!}\prod_{\mu=1}^{m_k}G(x^+_{k,\mu},x^-_{k,\mu},s,b_k)\right\}\Phi_{AB}\left(x^{\mathrm{proj}},x^{\mathrm{targ}},s,b\right)$$

  - m and X fixed together by a complex Metropolis (Markov chain)
- 2m strings formed from the m elementary interactions
  - energy conservation : energy fraction of the 2m strings given by X
- consistent scheme : energy sharing reduce the probability to have large m

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

Number of cut Pomerons

Fluctuations reduced by energy sharing (mean can be changed by parameters)



EPOS – non-linear effects

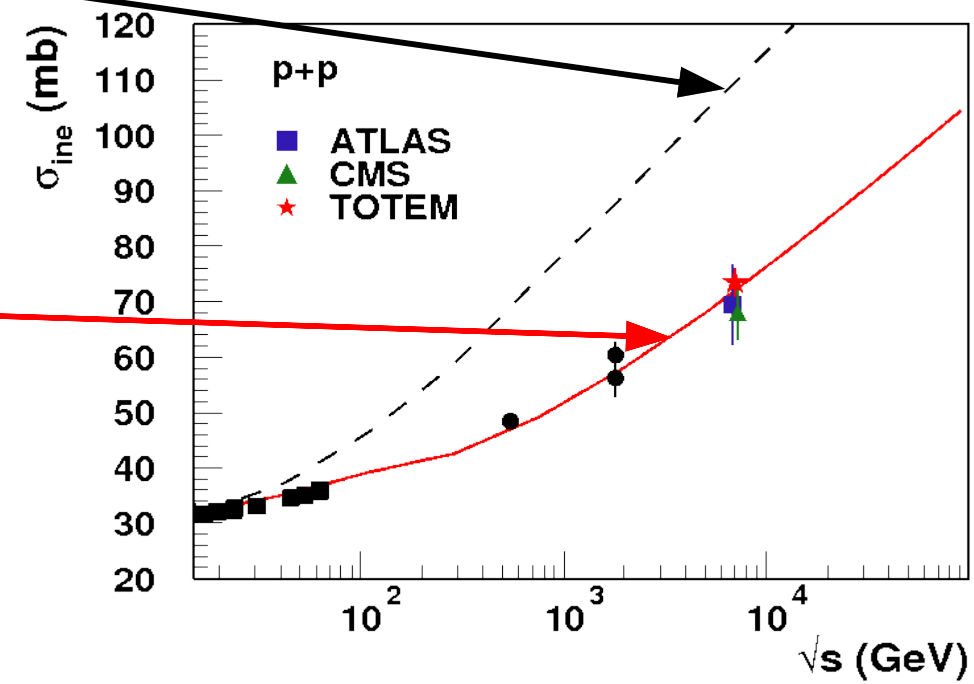
- **Well known problem with pQCD based Pomerons**
  - total cross-section too high : MPI required
    - in EPOS <Pomerons> fixed by b-dep of Pomeron amplitude (slope)
  - for historical reason Q_0^2 was free but fixed (no energy or b dependence)
  - effective coupling introduced to mimic effect of enhanced diagrams and reduce cross-section (screening effect) to get cross-section AND multiplicity right in p-p, p-A and AA.

No effective coupling

$$A_{pom} \sim (x_1 x_2)^{\beta}$$

With effective coupling

$$A_{pom} \sim x_1^{\beta} x_2^{\beta-\varepsilon}$$



Parametrization

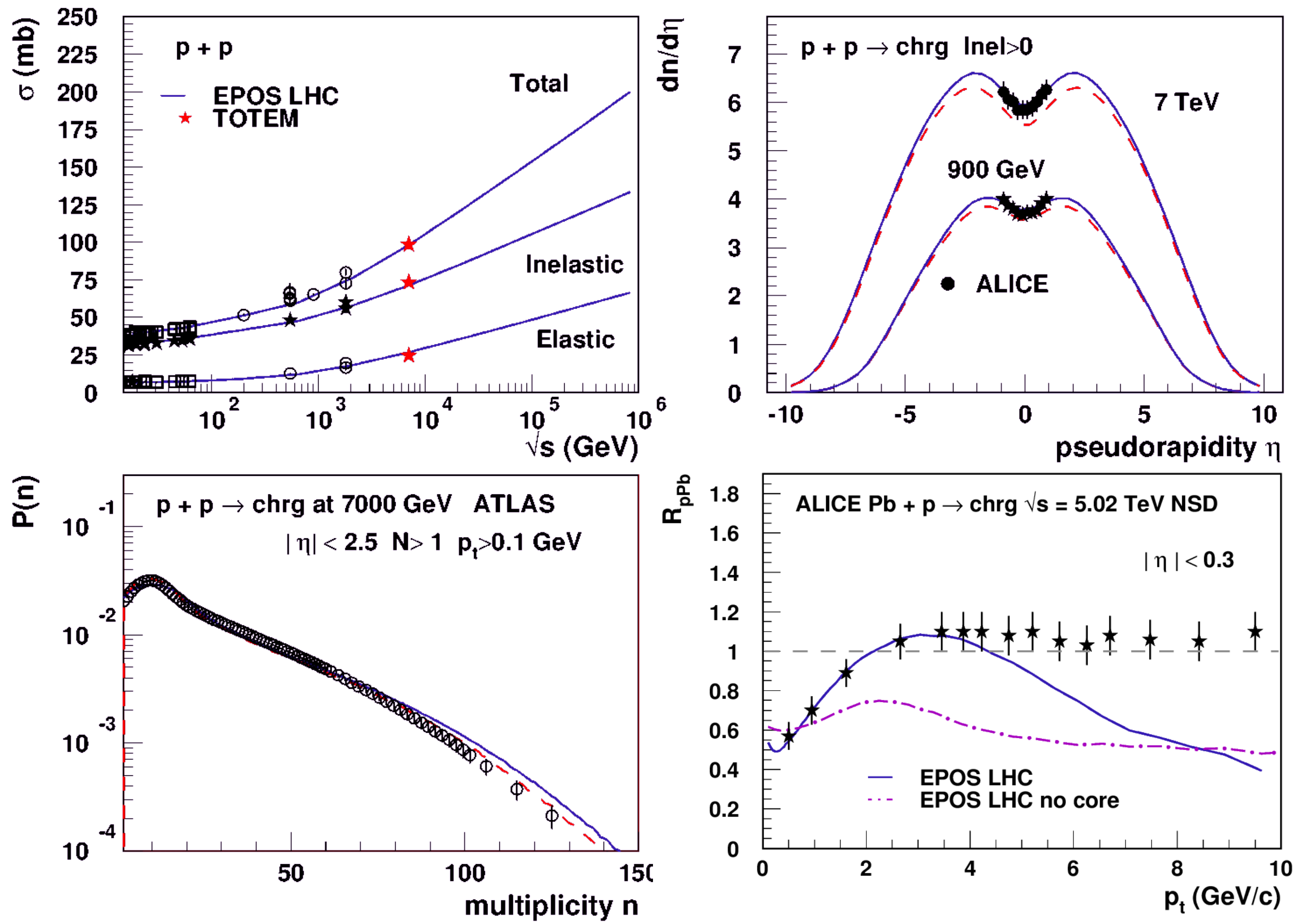
$$\varepsilon_S = a_S \, \beta_S \, Z(\mathrm{s,b,A})$$

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

Fixed Q_0^2 (old)

- **Excellent results for soft physics**
  - cross-section, multiplicity, etc ...
- **Problem for hard processes**
  - lack of high pt
  - no binary scaling for pA or AB

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



Variable $Q_s^2(s,x,b,A)$ (new)

- **Inspired by CGC**
  - different saturation scale event-by-event and even Pomeron-by-Pomeron depending on momentum fraction x, impact parameter b, squared energy s or number of participants.

- **EPOS 3.0xx**
  - define :

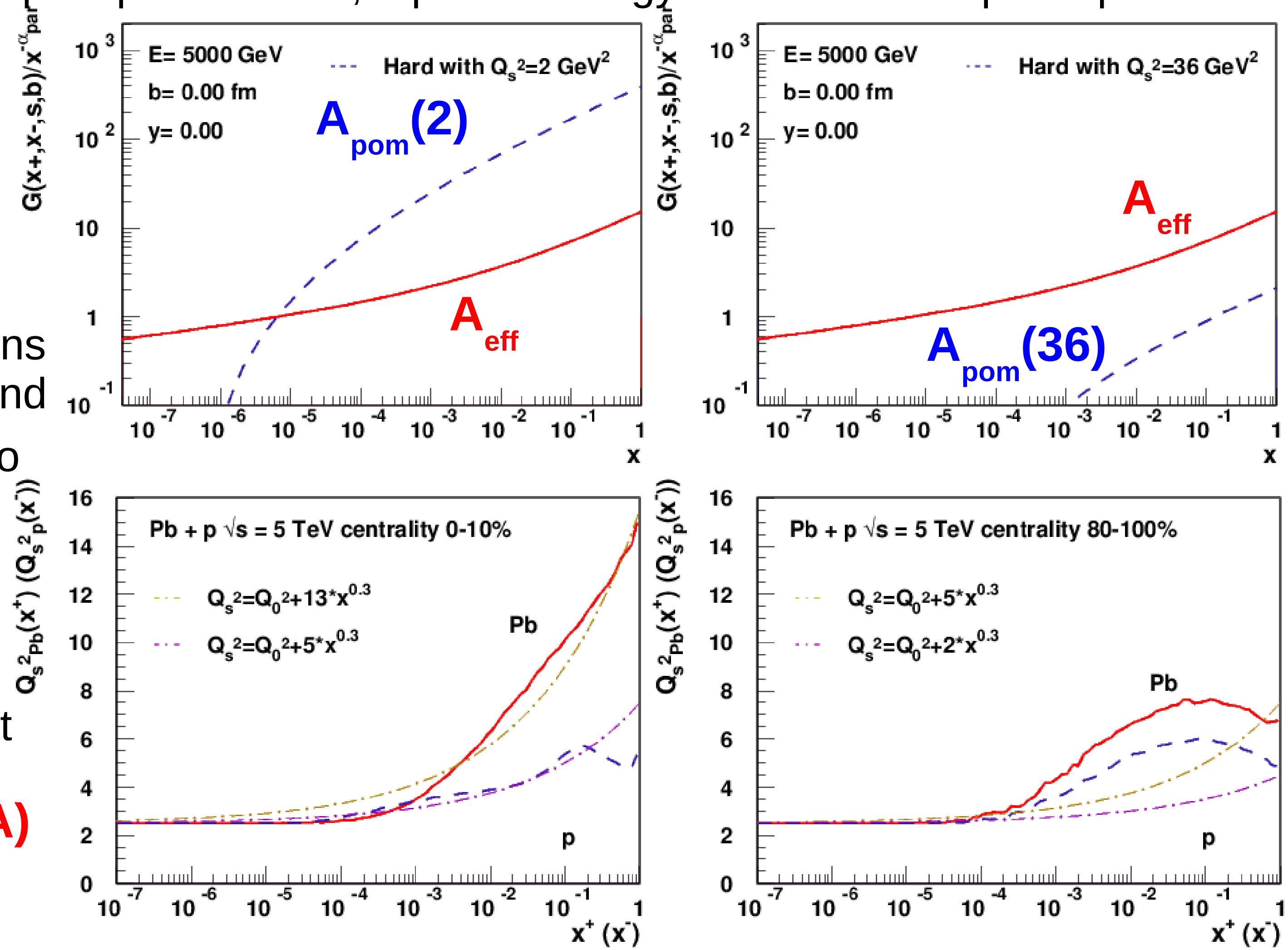
    $Q_s^2(s,x,b,A) \sim \hat{s}^{\lambda} N_{part}(b,A)$

    OK but lot of assumptions on unknown $N_{part}(b,A)$ and technically very heavy to use $A_{pom}(Q_s^2)$ in MC.

- **EPOS 3.1xx**
  - Use effective coupling and define Q_s^2 such that

$$N_{bin} A_{pom}(Q_s^2) = N_{col} A_{eff}(s,x,b,A)$$

after MC.



Predicted $Q_s^2(s,x,b,A)$

- **Inspired by CGC**
  - different saturation scale event-by-event and even Pomeron-by-Pomeron depending on momentum fraction x, impact parameter b, squared energy s or number of participants.

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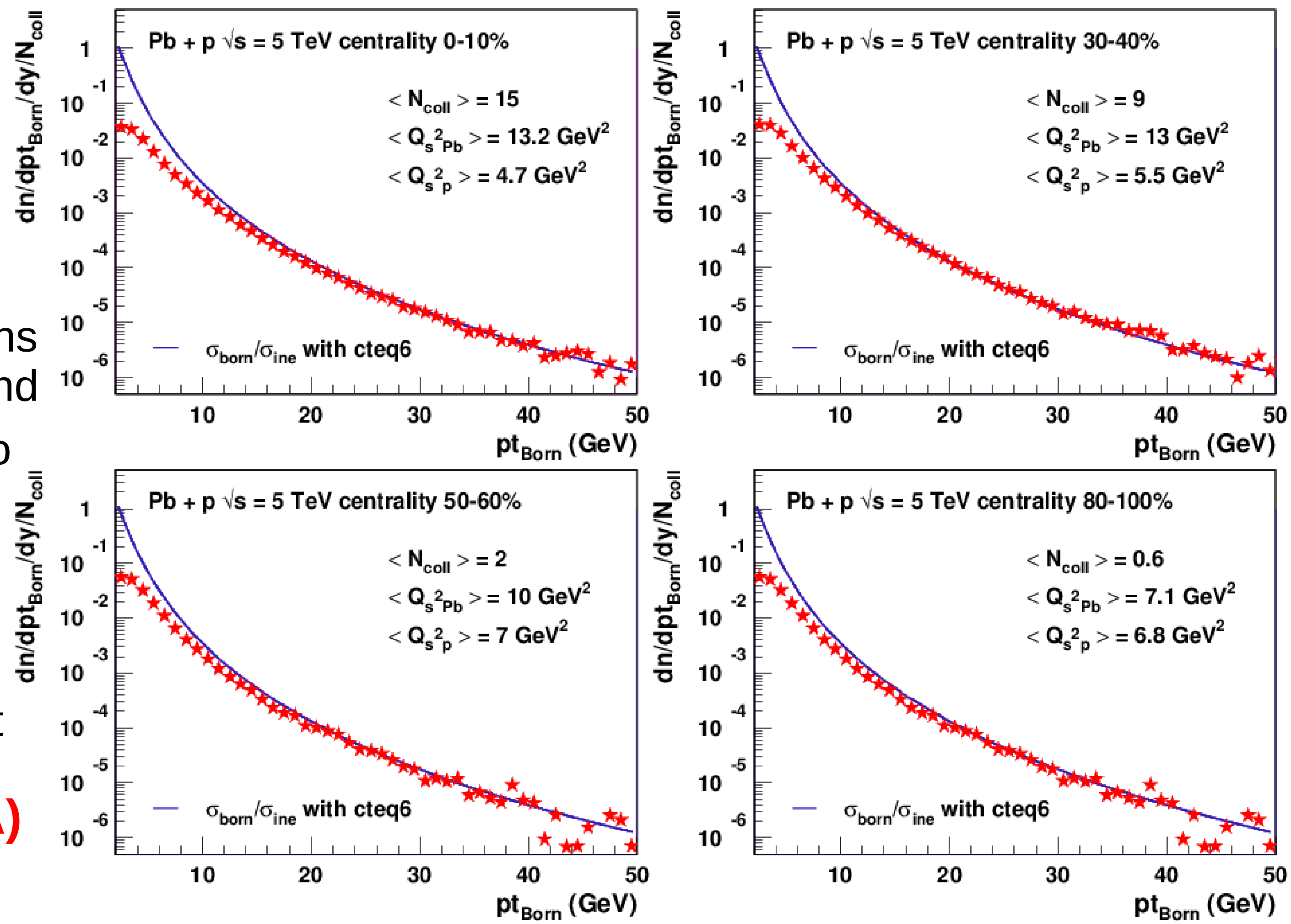
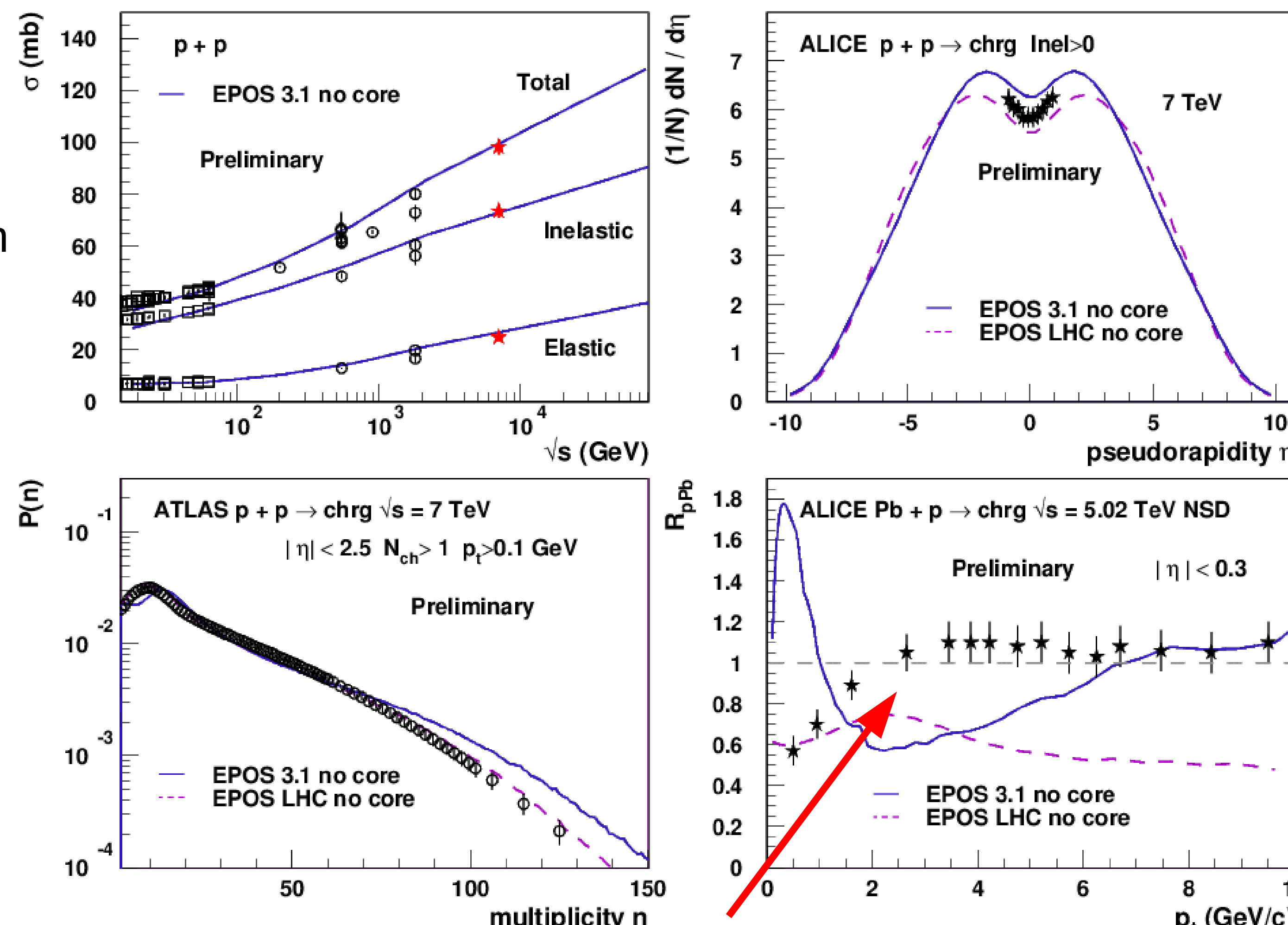


New Preliminary Results

- **Same excellent results for soft physics**
  - ➔ cross-section, multiplicity, etc ...

- **Problem solved for hard processes**
  - ➔ complete factorization
  - ➔ binary scaling by construction (strong assumption)

Since Q_s^2 is adapted to get the needed amplitude only low pt are suppressed. No change above Q_s^2.



no core = missing flow

Summary

Many observables difficult to describe by HEP MC described by EPOS

- consistent cross-section & particle production calculation :
  - MPI (fluctuations) and diffraction well described
- partial statistical hadronization boosted by a flow
- remnant picture
- full coherent scheme allows universal string fragmentation parameters
- Since Q_0^2 was fixed and focus given on soft Physics, hard component was suppressed in particular with nuclei.

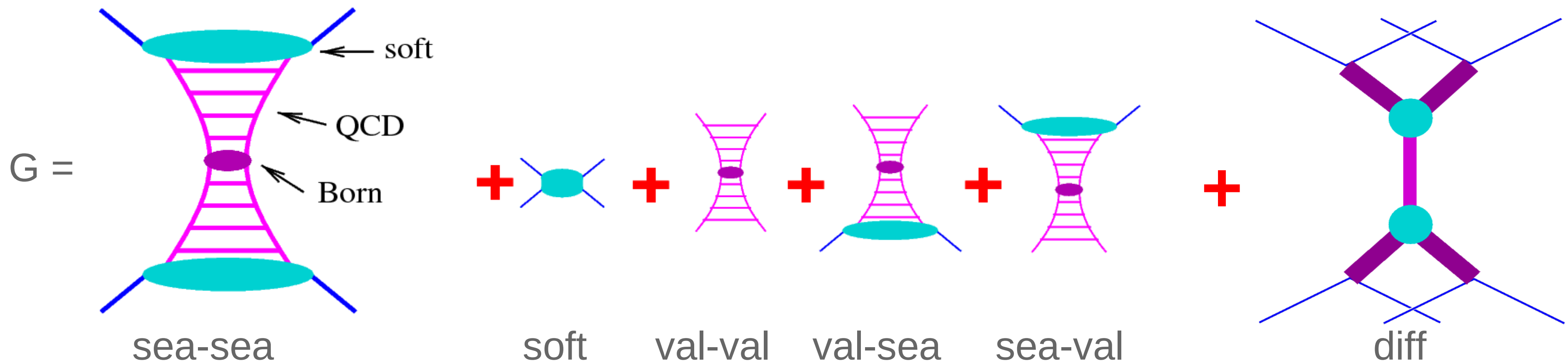
EPOS 3

- introduce saturation scale Q_s^2 COMPUTED Pomeron-by-Pomeron.
- impose factorization and binary scaling for hard processes above Q_s^2
- conserve full coherent scheme for cross-section and particle production + 3D+1 hydro

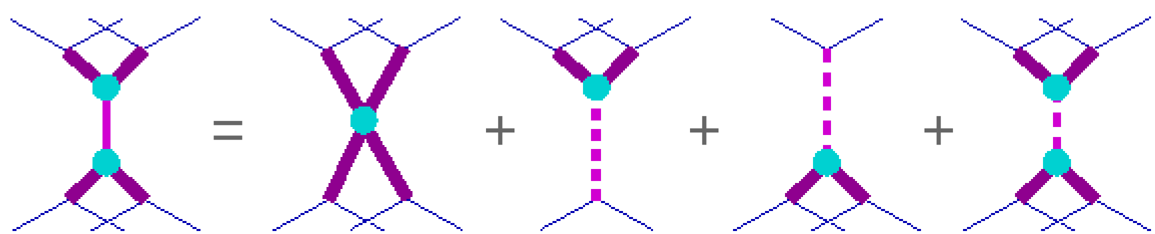
Variable Q_s^2 allows simultaneous description of soft and hard scales. CGC picture recovered for central nuclear collisions.

Diffraction in PBGRT

- **Using the same formalism**
  - ➡ Diffraction from an additional diagram

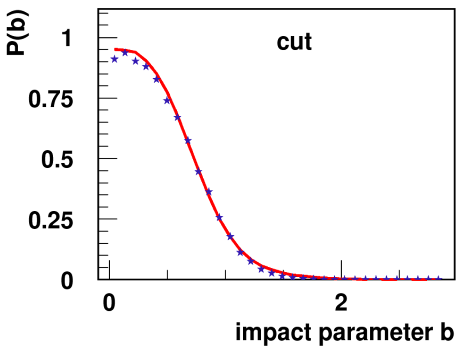


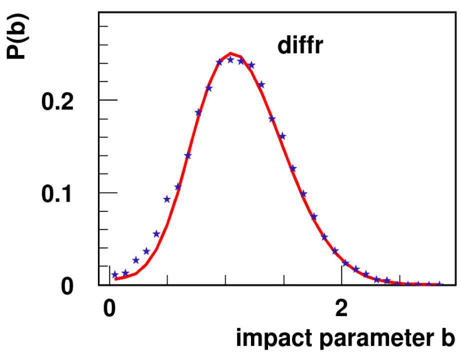
  - ➡ Same form as soft (Regge pole) but with different amplitude and width
  - ➡ Low mass and high mass diffraction from the same diagram



  - ➡ Parameters extracted from single diffractive (SD) cross-section
  - ➡ Events with only “diff” type diagrams are diffractive

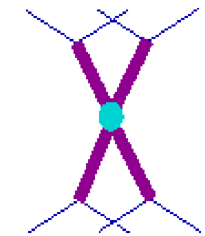
Low Mass Diffraction





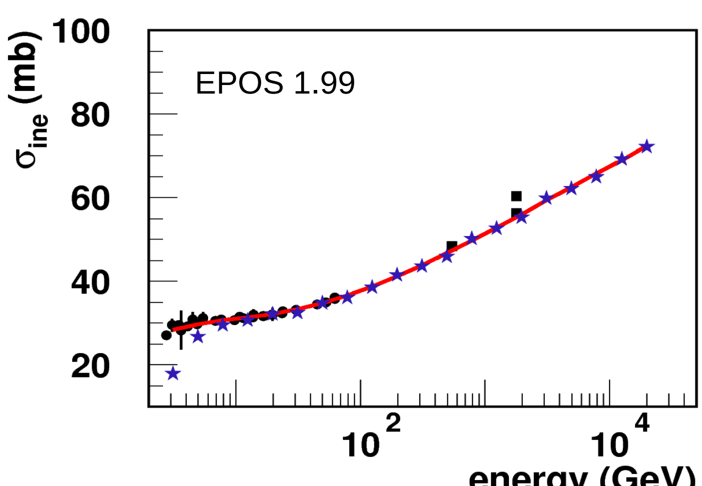
Diffractive event = event with only cut diff. diagrams

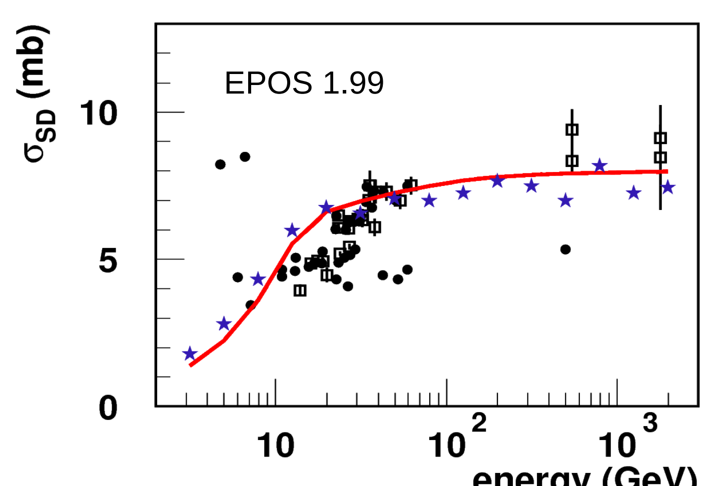
- Multiple cut-diff diagrams possible
- Remnant mass given by momentum fraction transfer
- No particle production directly from diagram
- Reggeon (single string or resonance) possible
- cut-diff diagrams used for remnant mass in non-diffractive events too (cut Pomeron)



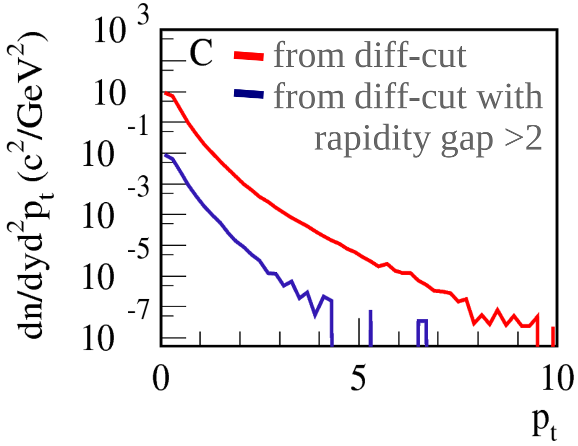
Theory

MC

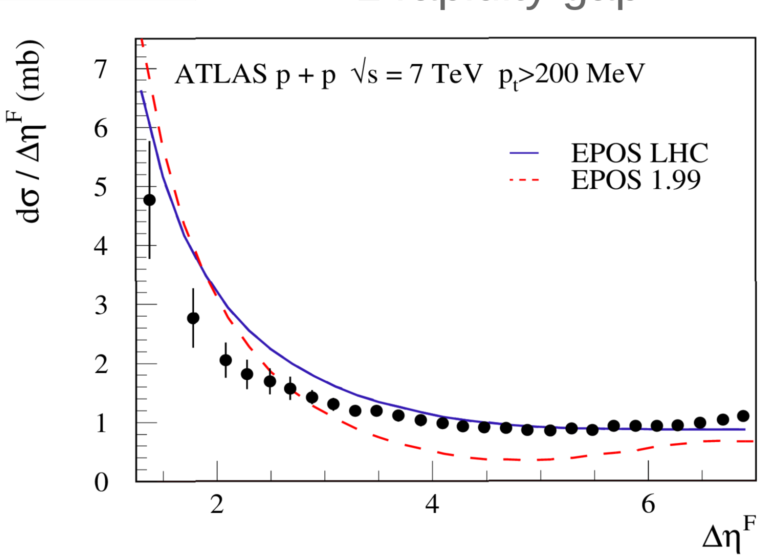




High Mass and Central Diffraction



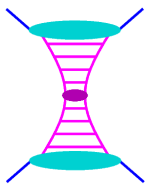
Projectile not excited :
1 rapidity gap



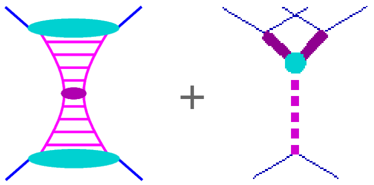
Same scheme but with particle production

- Do not change cross-section
- If only non-diffractive Pomeron are present, no mass given to remnant.
- 0, 1 or 2 rapidity gap depending on diagram exchange

Projectile and target not excited :
2 rapidity gaps

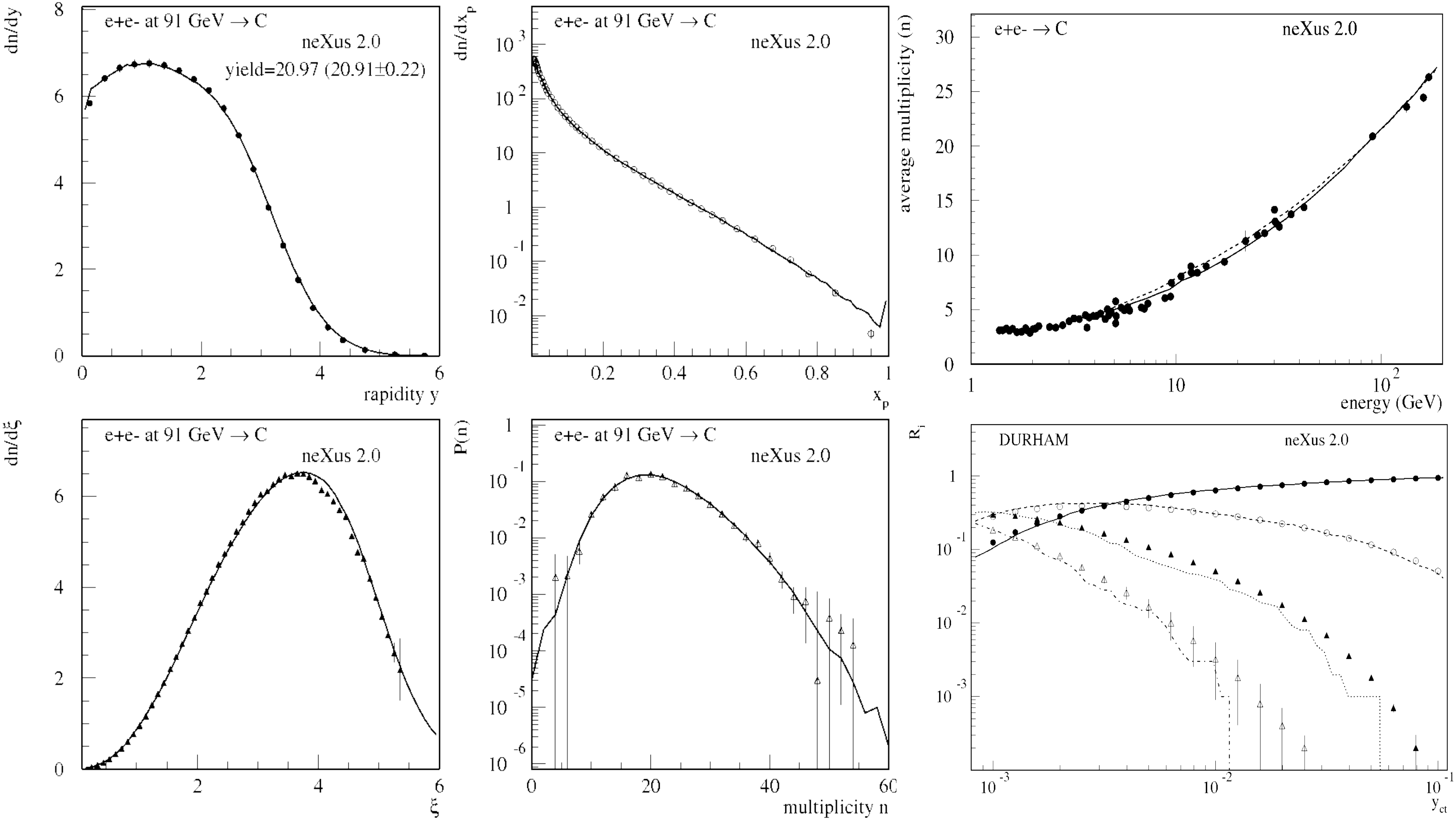


Only projectile not excited :
1 rapidity gaps



- Additional multiplicity contribution in ND events
- Work in progress

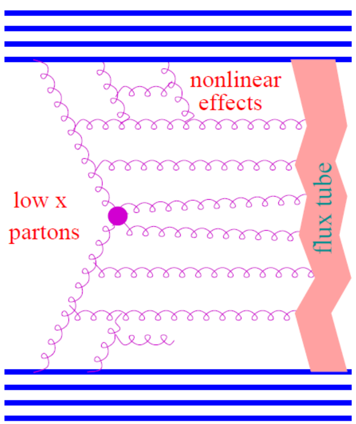
Test of string fragmentation with LEP data

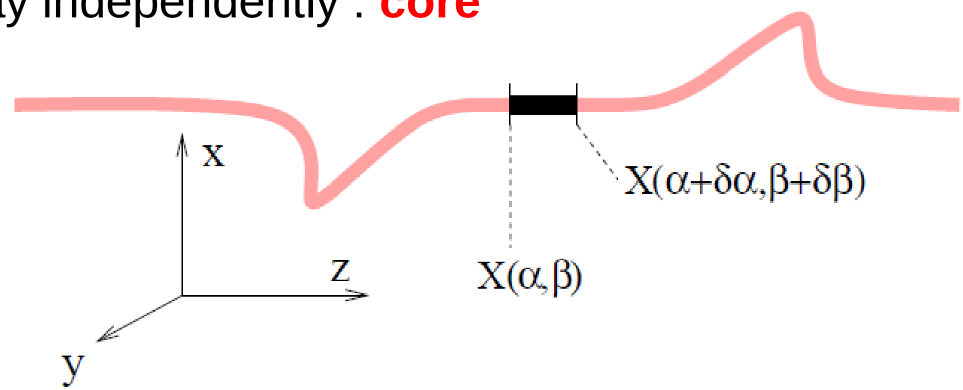


Area law

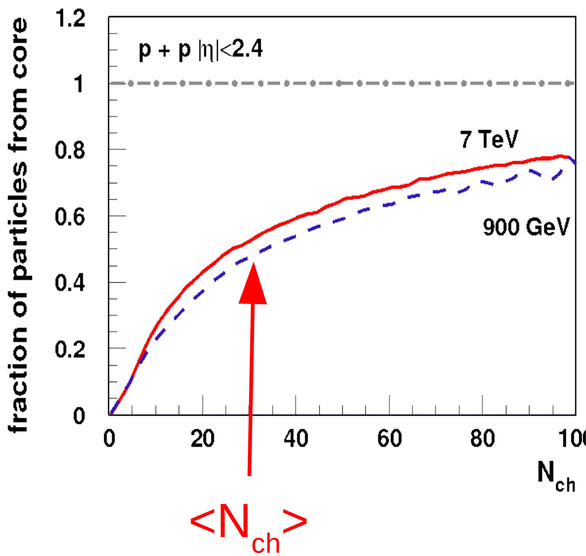
High Density Core Formation

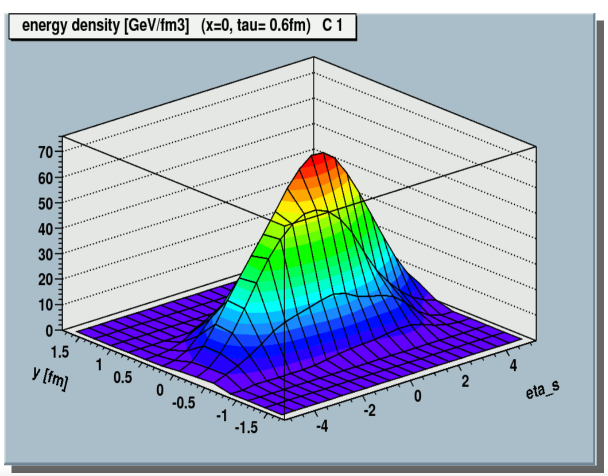
- **Heavy ion collisions or high energy proton-proton scattering:**
  - ➔ the usual procedure has to be modified, since the density of strings will be so high that they cannot possibly decay independently : **core**





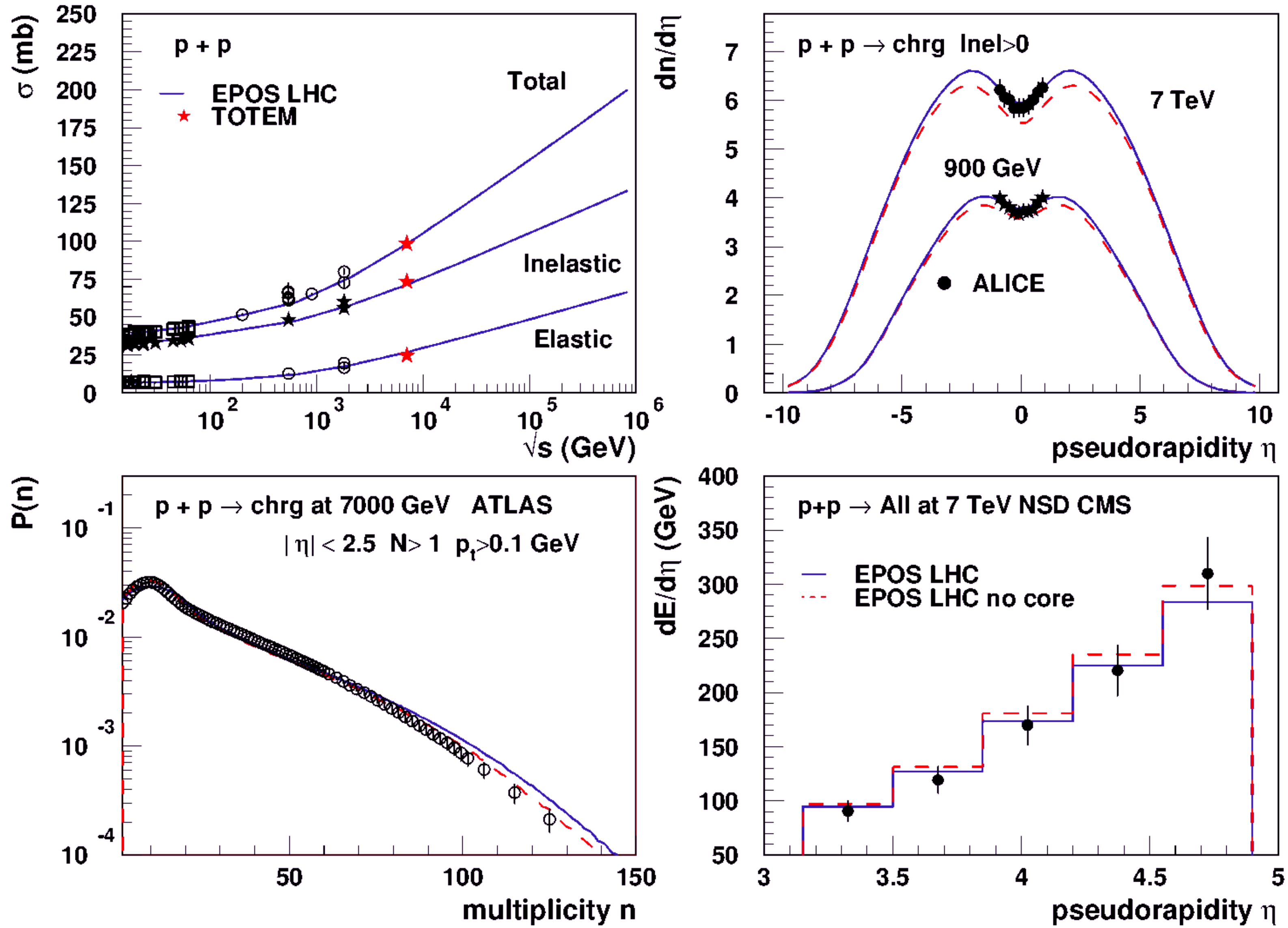
- ➔ Each string splitted into a sequence of string segments, corresponding to widths δα and δβ in the string parameter space
- ➔ If energy density from segments high enough
  - segments fused into core
    - statistical decay
    - flow from expansion
- ➔ If low density (corona)
  - segments remain hadrons
    - string fragmentation





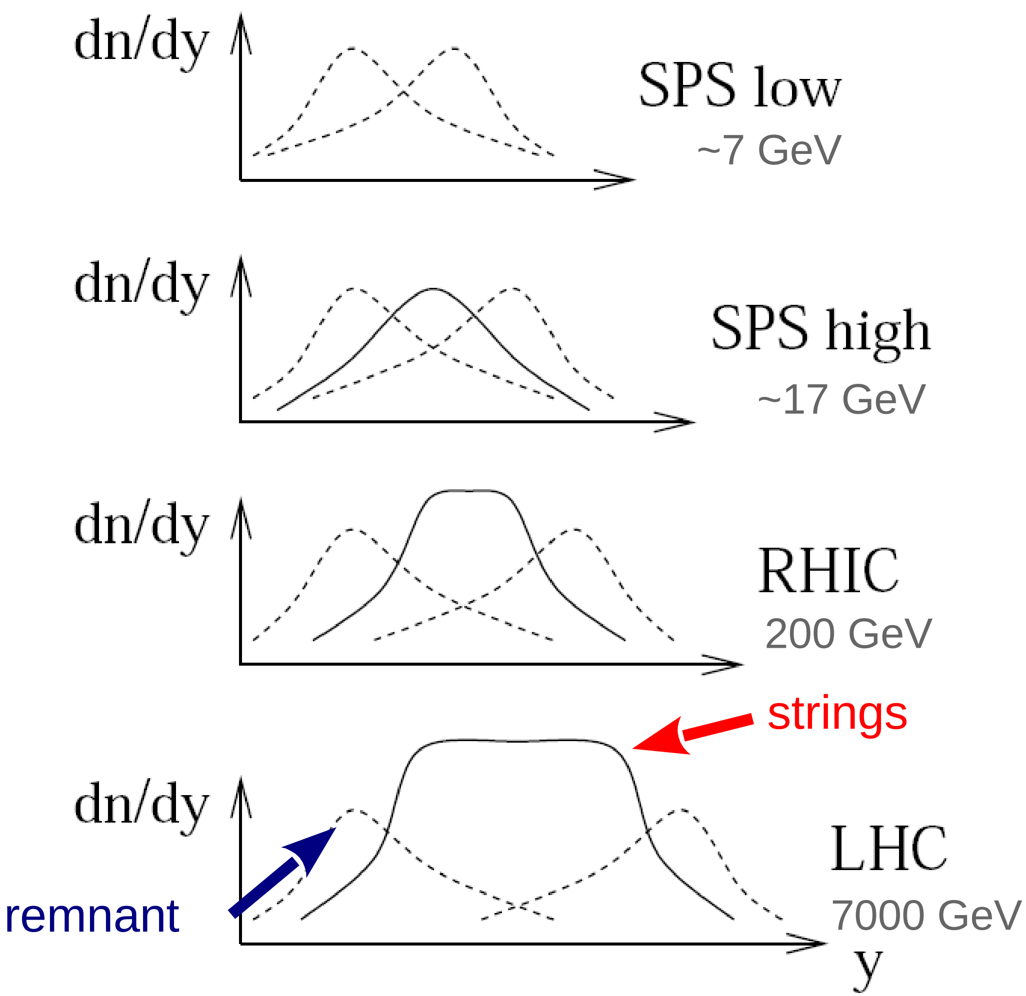
Core Effect on Total Multiplicity

- **Core hadronization doesn't change general event description.**



Remnants

Forward particles mainly from projectile remnant



Forward hadronization from remnant :

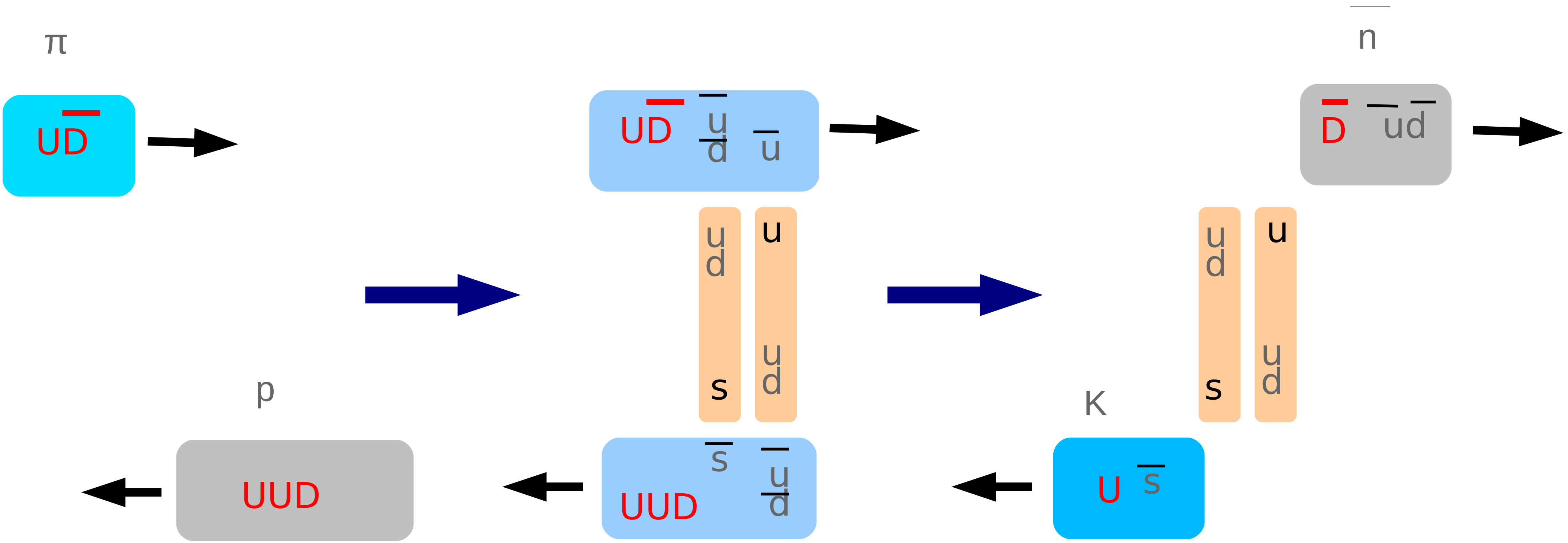
- At very low energy only particles from remnants
- At low energy (fixed target experiments) (SPS) strong mixing
- At intermediate energy (RHIC) mainly string contribution at mid-rapidity with tail of remnants.
- At high energy (LHC) only strings at mid-rapidity (baryon free)

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

Remnants in EPOS

In EPOS : any possible quark/diquark transfer

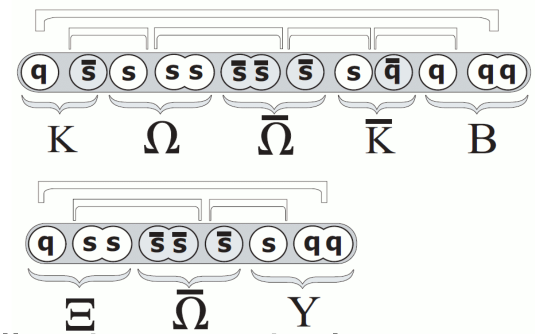
- Diquark transfer between string ends and remnants
- Baryon number can be removed from nucleon remnant :
  - Baryon stopping
- Baryon number can be added to pion/kaon remnant :
  - Baryon acceleration



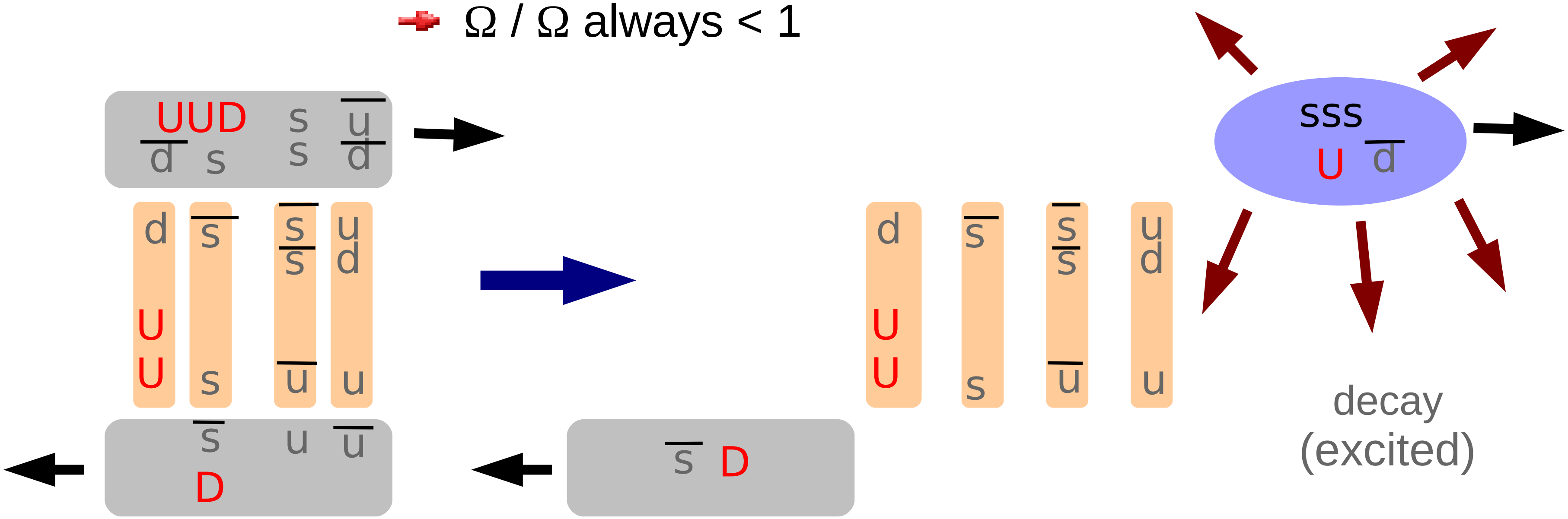
Baryons and Remnants

Parton ladder string ends :

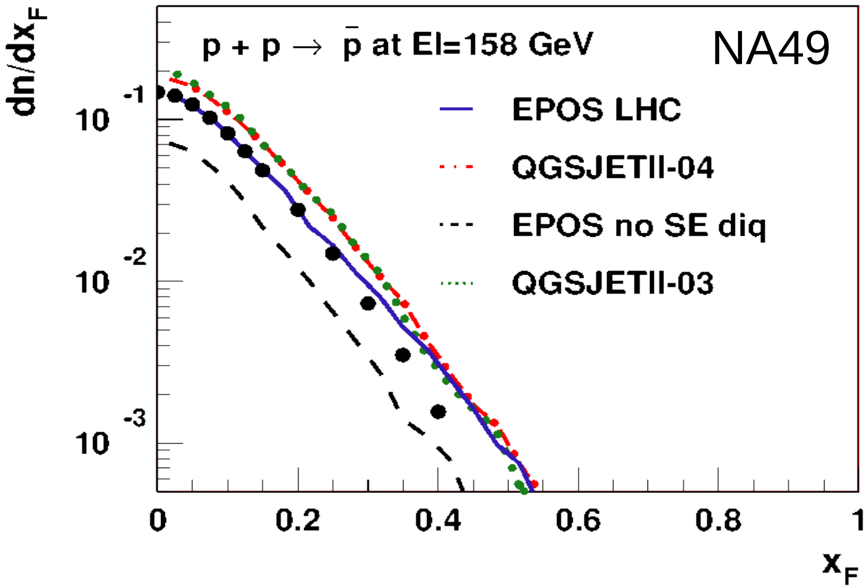
- Problem of multi-strange baryons at low energy (Bleicher et al., Phys.Rev.Lett.88:202501,2002)
  - 2 strings approach :
    - $\bar{\Omega}$ / Ω always > 1
    - But data < 1 (Na49)



- 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

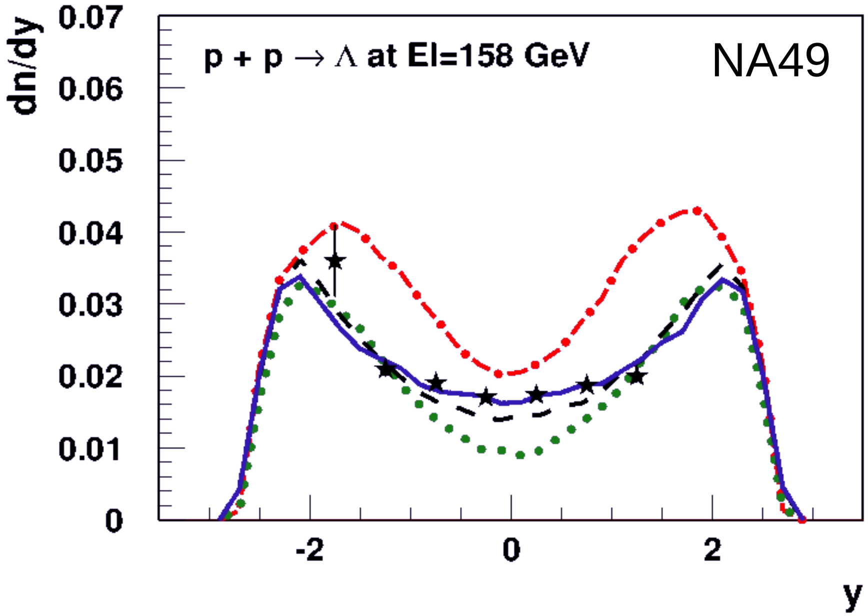


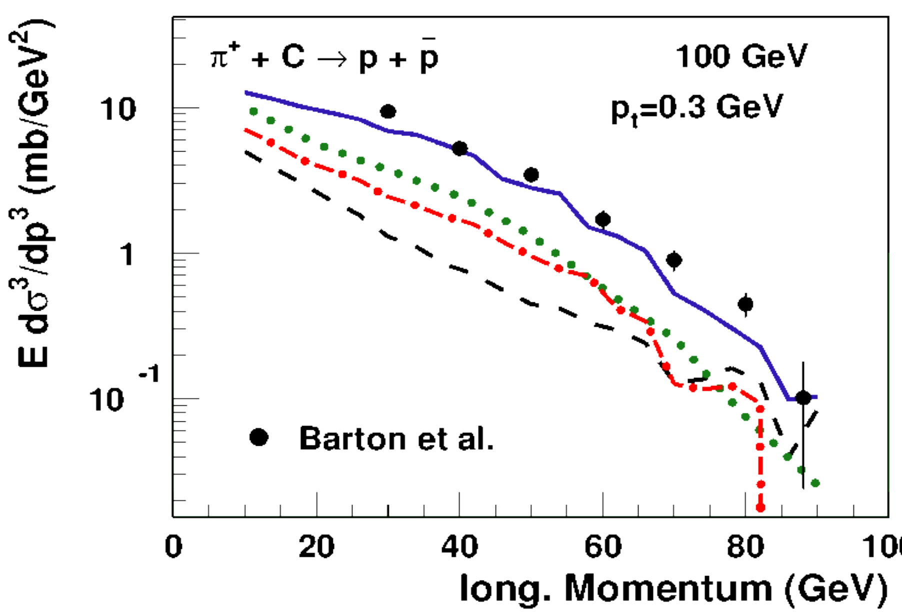
Forward Baryons (low energy)



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

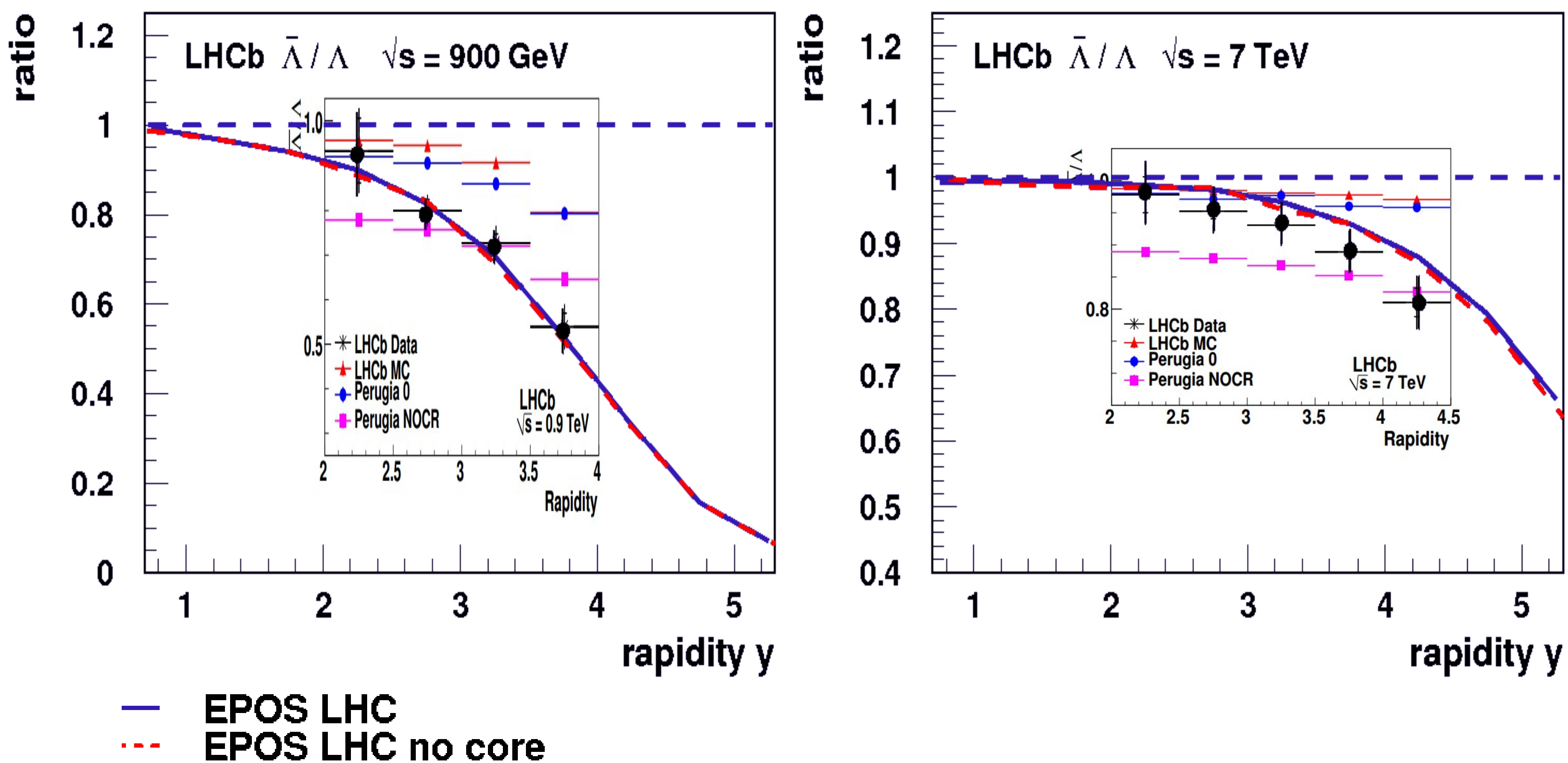
Without remnant, string fragmentation has to be changed for baryon production





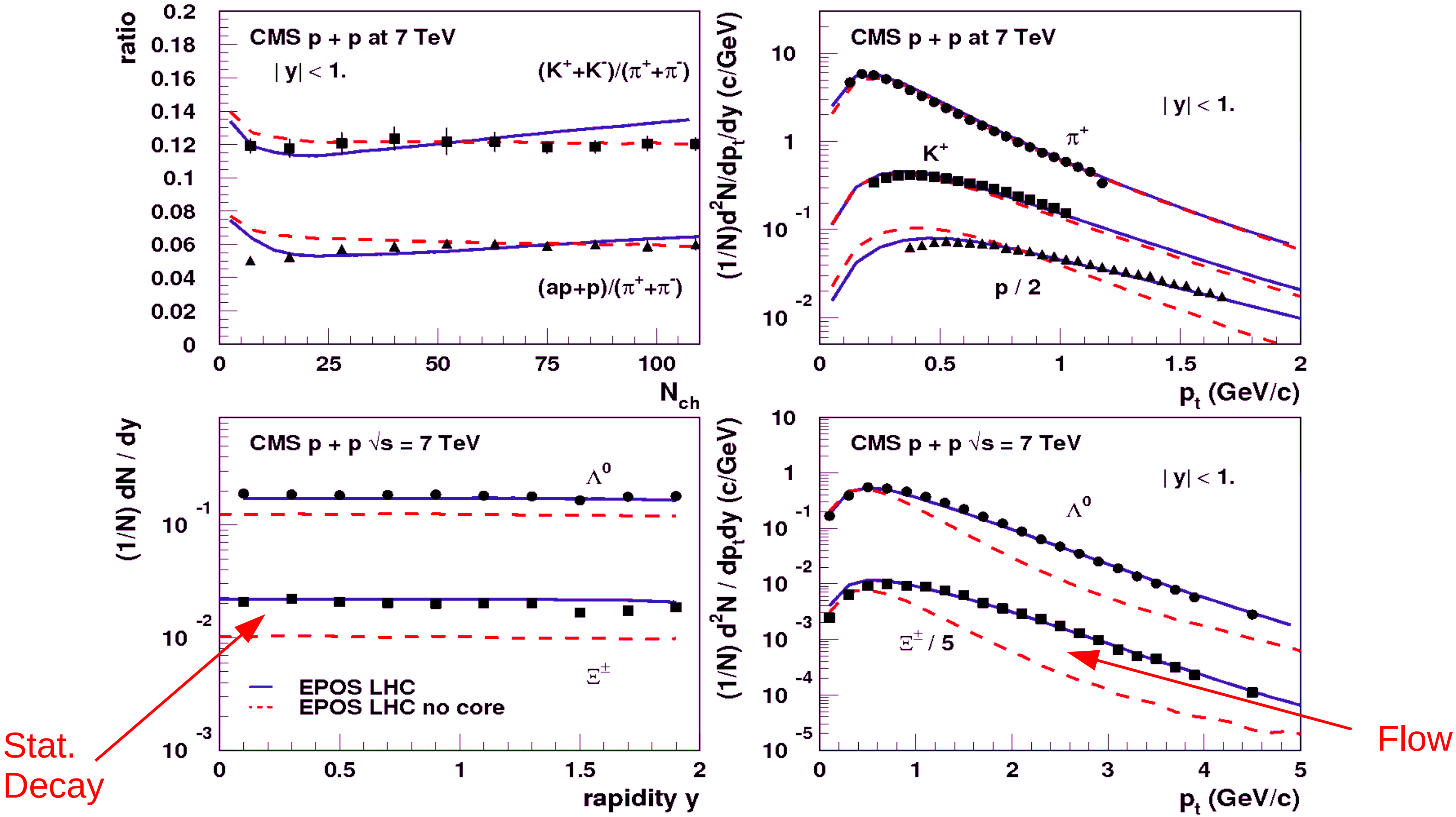
Forward Baryons (high energy)

- **Core hadronization doesn't change baryon transport.**
  - ➜ Remnant effect for baryon transport



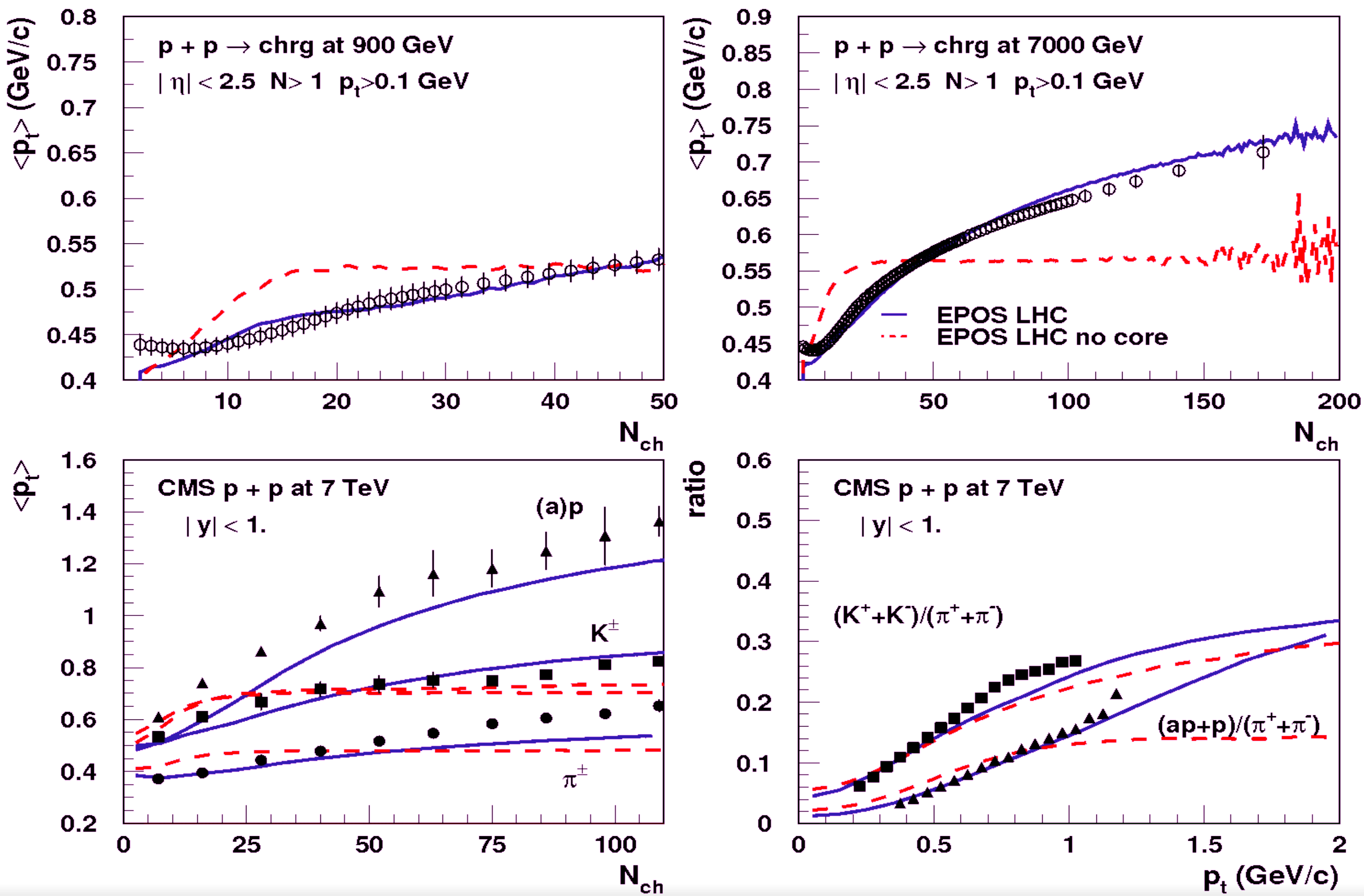
Core Effect on Particle Yield

- Core hadronization change particle ratio
  - ➜ heasier to produce strange baryons



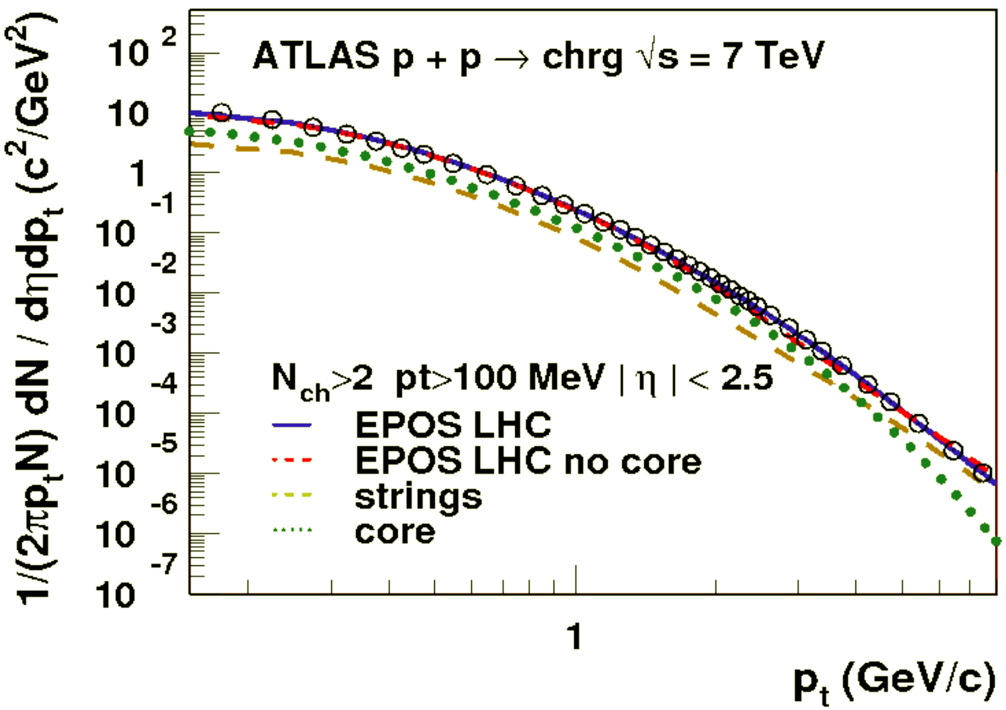
EPOS LHC

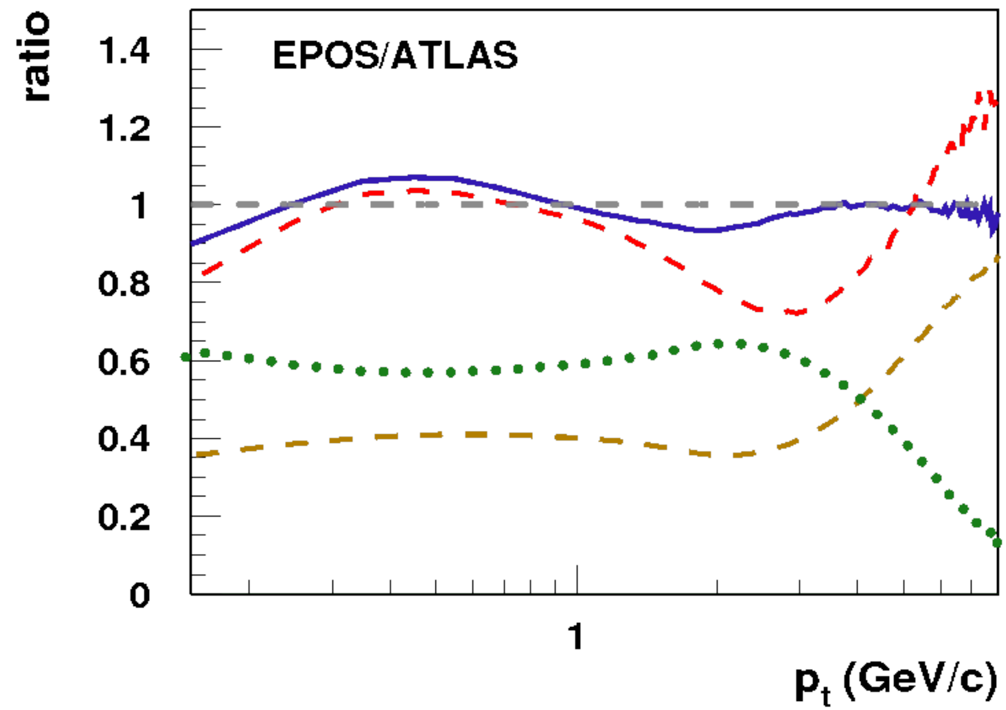
- **Detailed description can be achieved**
  - identified spectra
  - p_t behavior driven by collective effects (flow)



EPOS LHC

- **Detailed description can be achieved**
  - p_t behavior driven by collective effects (flow)
    - particles with $p_t \sim 0.5$ GeV/c boosted up to p_t=2-3 GeV/c
    - high p_t particles ($p_t \sim 10$ GeV/c) suppressed by energy loss in fluid
  - spectrum dominated by string (jet) particles only for $p_t > 5$ GeV/c



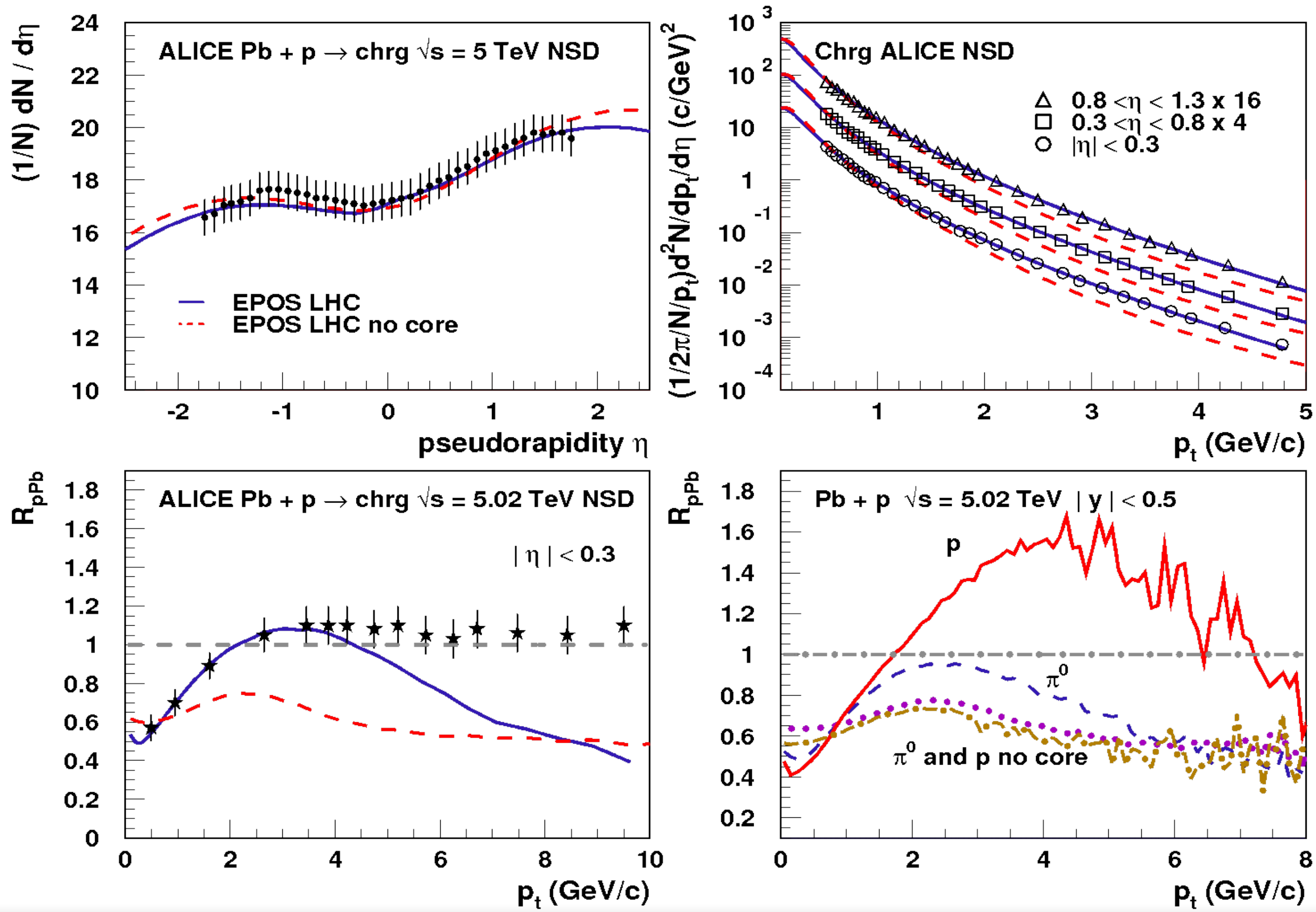


p-Pb : Increased Effects

- **Flow depends on N_{ch}**
  - large N_{ch} more often in pPb than in pp but same strength for same N_{ch}
  - R_{pPb} mass dependent (like in dAu @ RHIC) : for p_t < 6 GeV/c, R_{ppb}=1 by chance ?

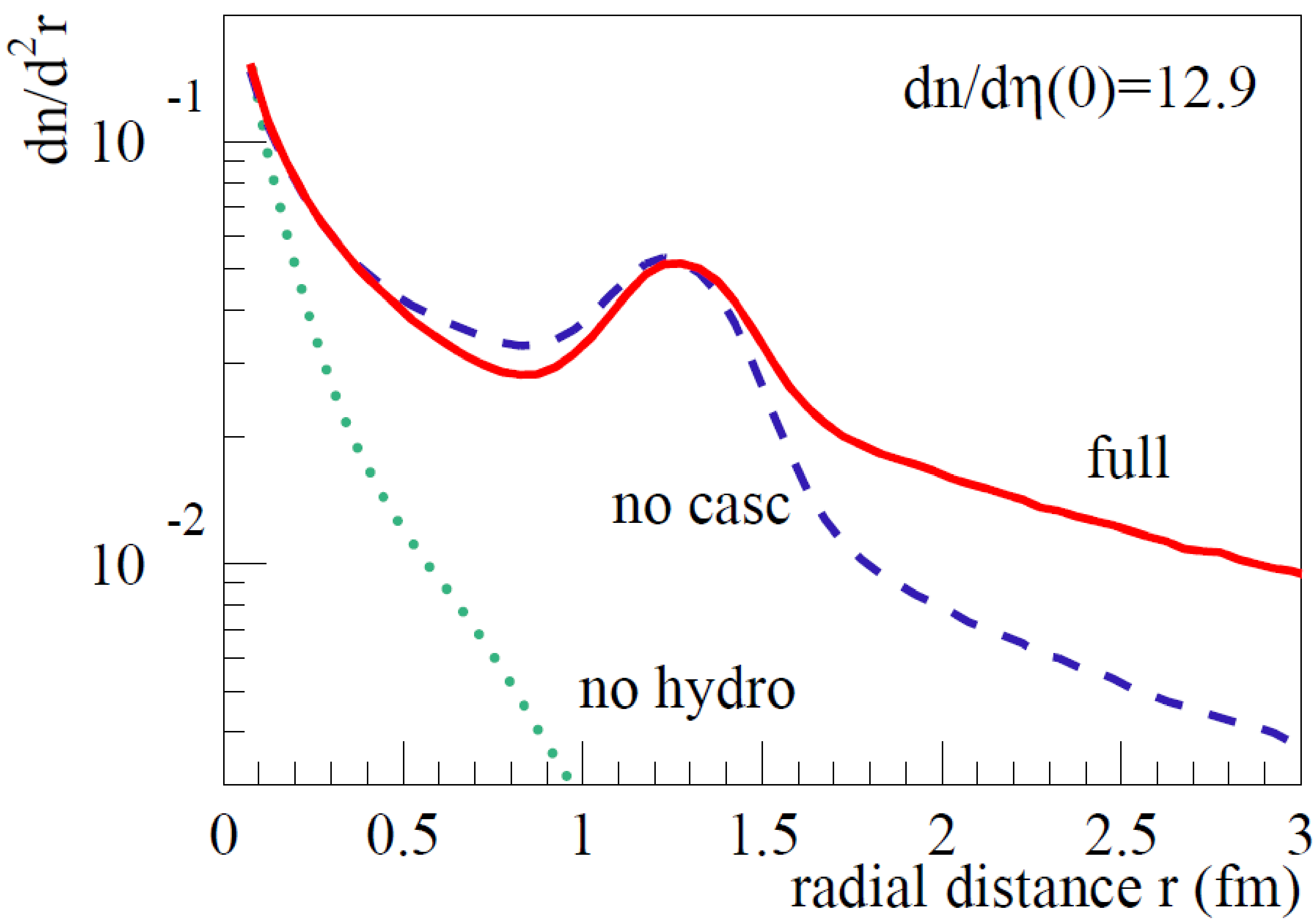
MPI reduction correct for low p_t : mutliplicity well reproduced (no tuning).

Initial state suppression artificially too strong at high p_t



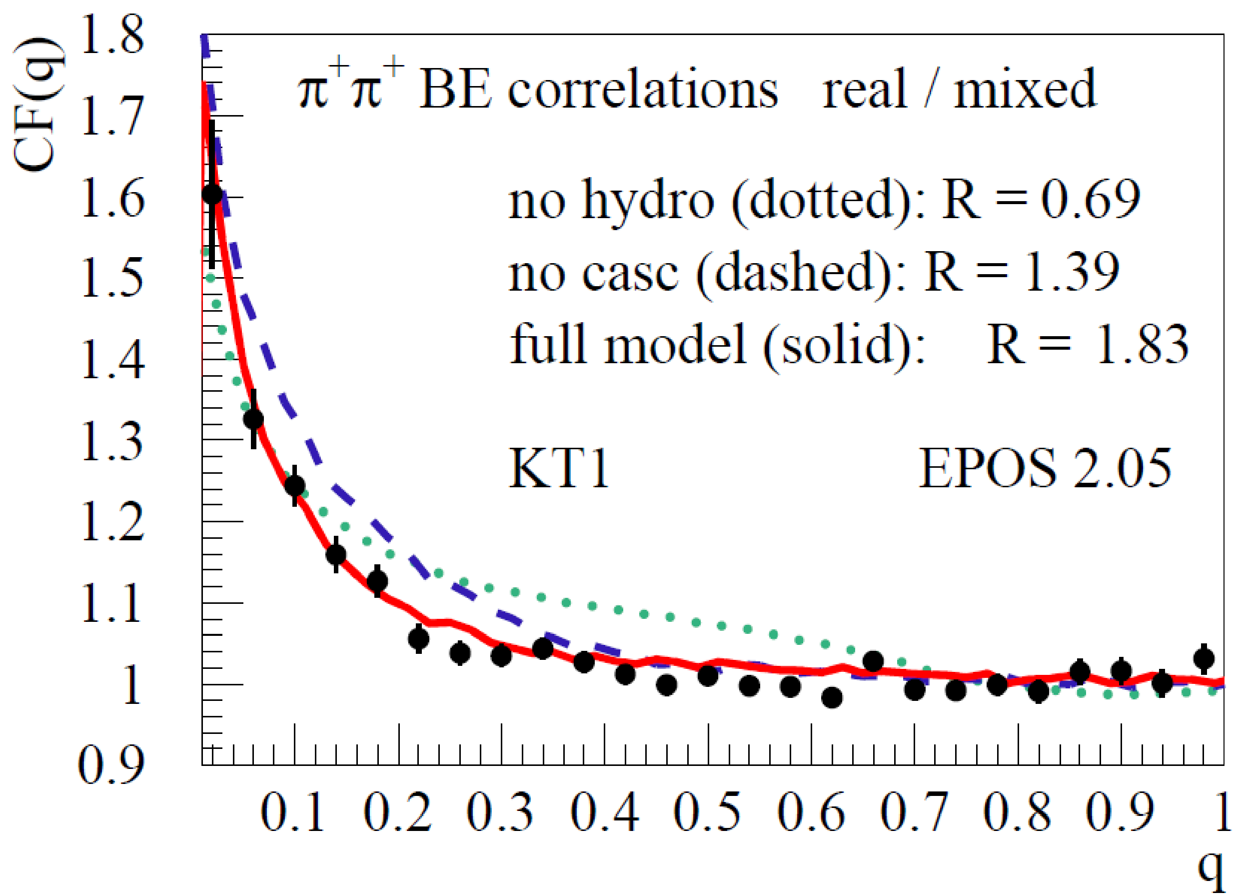
Radius of Particle Emission

- Space-time structure strongly affected (here 900 GeV)



Bose-Einstein Correlations

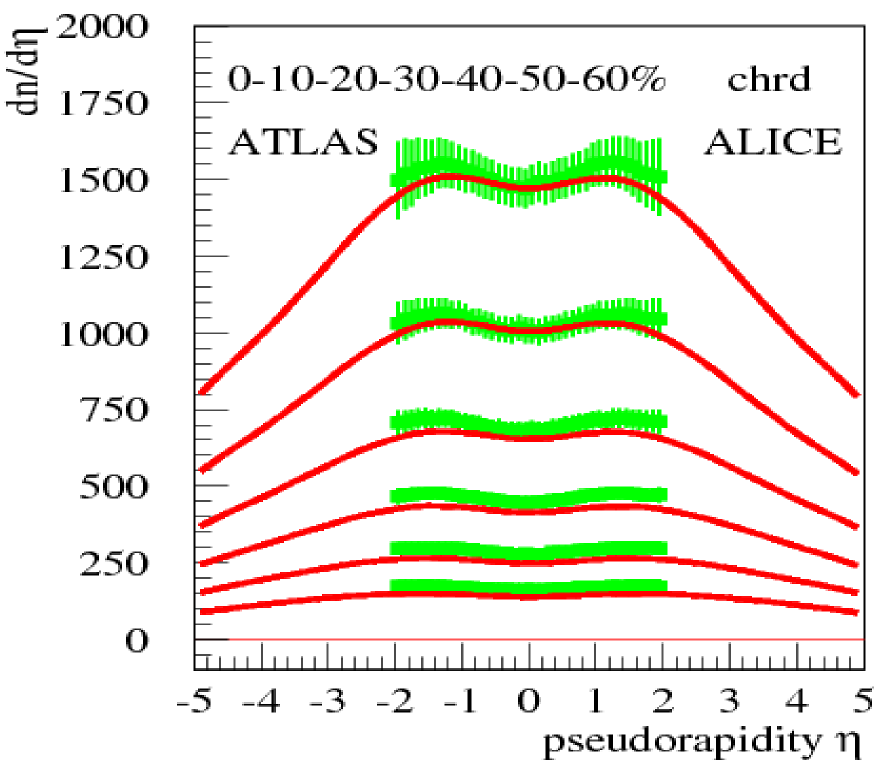
- Consequences for Bose-Einstein correlations

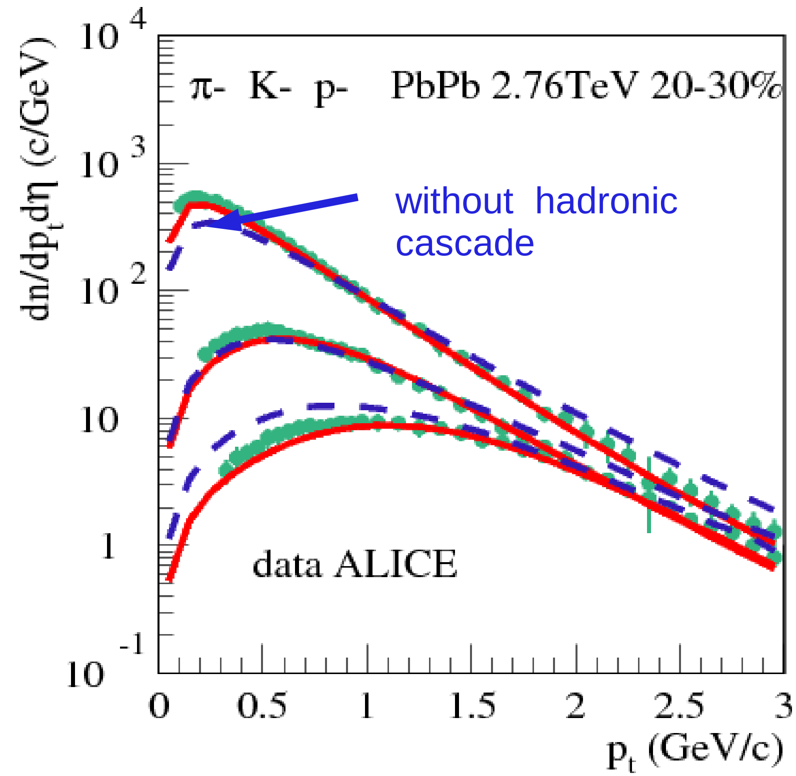


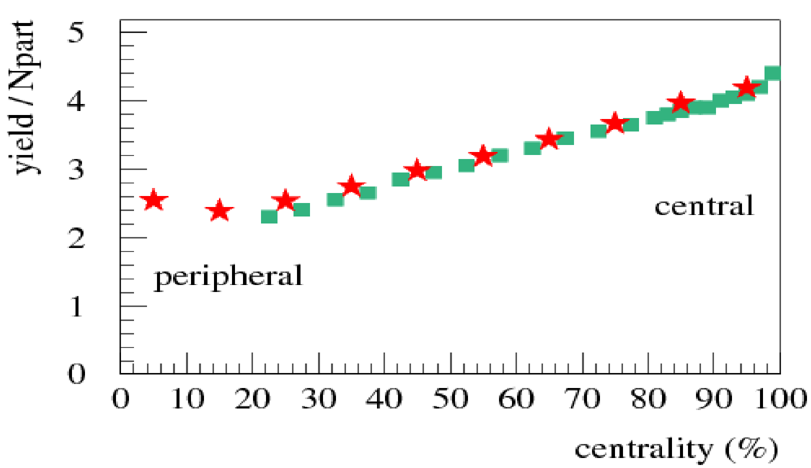
ALICE data.

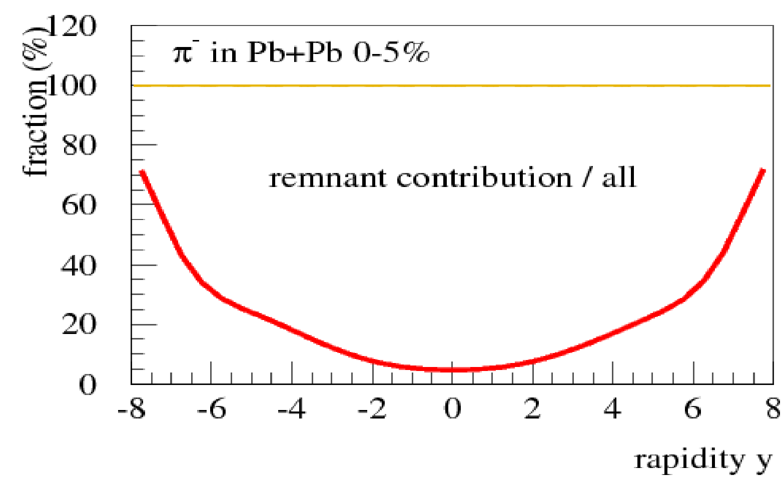
Radii R from exponential fit.
KT1= [100, 250], KT3= [400, 550], KT5= [700, 1000]

PbPb @ LHC

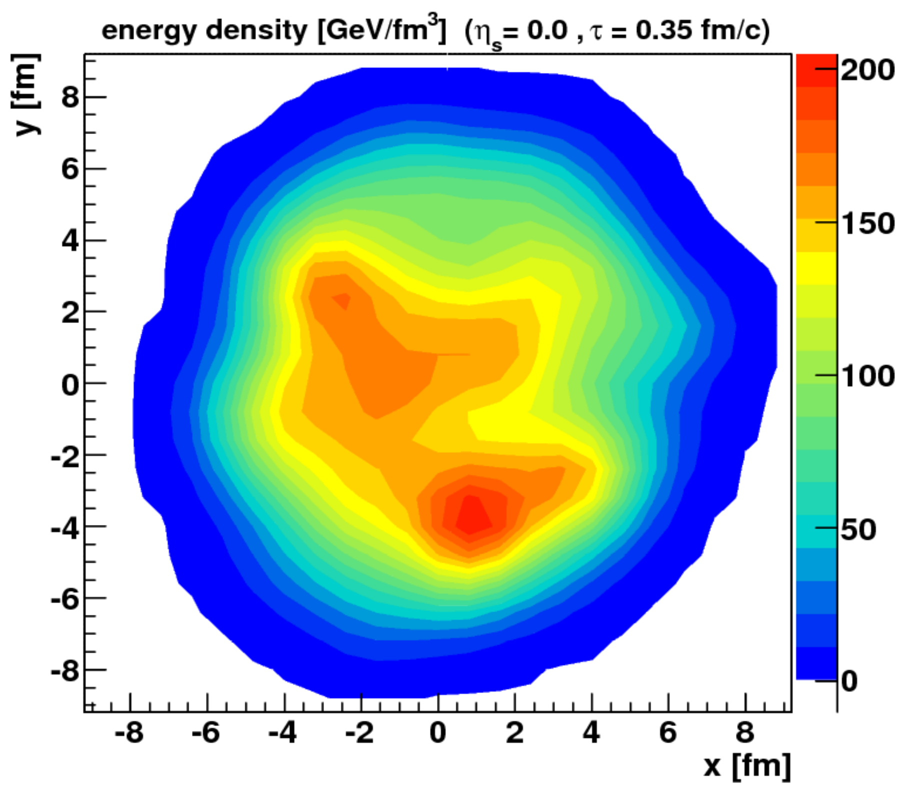

dn/dη
0-10-20-30-40-50-60%
chrd
ATLAS
ALICE
2000
1750
1500
1250
1000
750
500
250
0
-5 -4 -3 -2 -1 0 1 2 3 4 5
pseudorapidity η

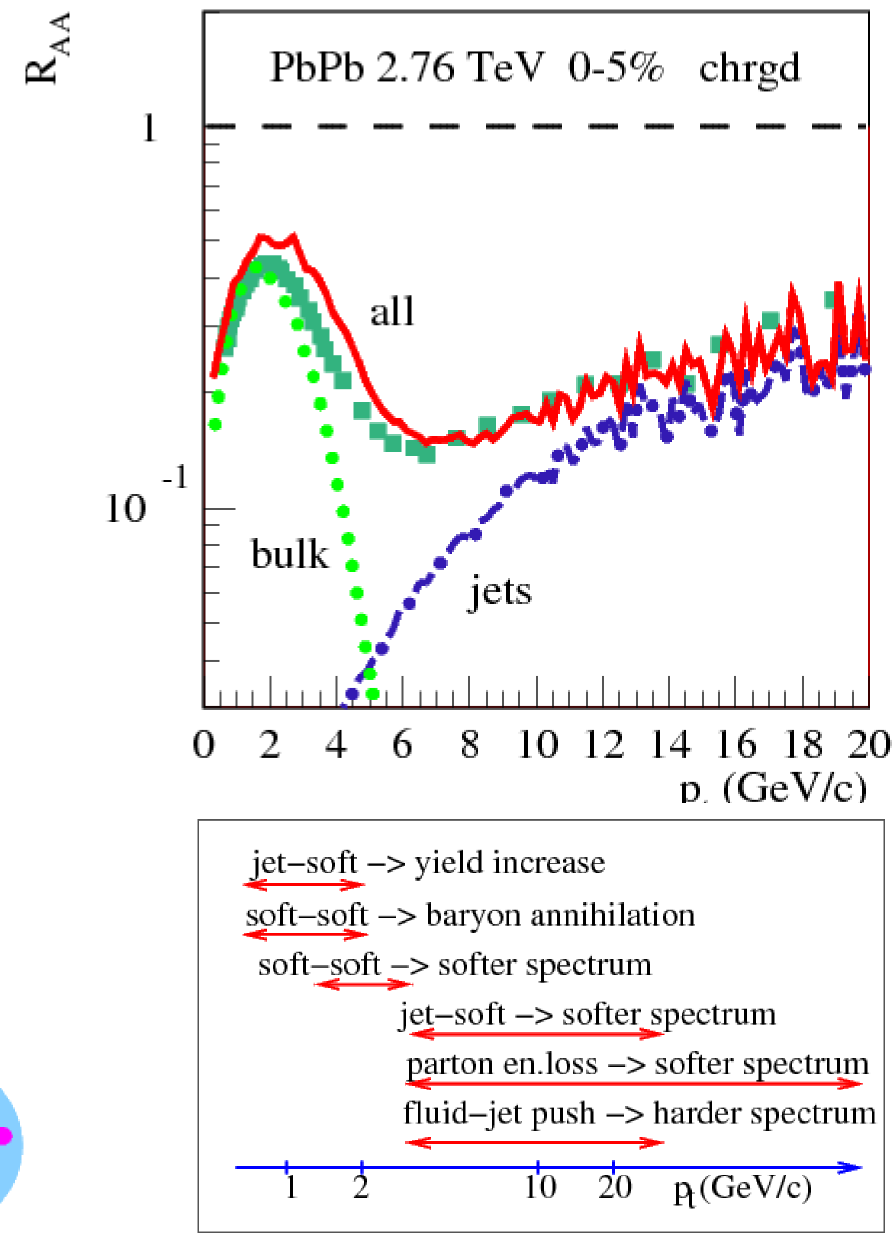

$dn/dp_t d\eta$ (c/GeV)
π- K- p-
PbPb 2.76TeV 20-30%
without hadronic cascade
data ALICE
10^4
10^3
10^2
10
1
10^{-1}
0 0.5 1 1.5 2 2.5 3
p_t (GeV/c)


yield / Npart
5
4
3
2
1
0
central
peripheral
0 10 20 30 40 50 60 70 80 90 100
centrality (%)

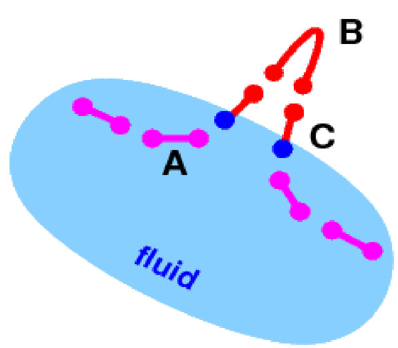

fraction (%)
π^- in Pb+Pb 0-5%
remnant contribution / all
120
100
80
60
40
20
0
-8 -6 -4 -2 0 2 4 6 8
rapidity y

jets in PbPb @ LHC

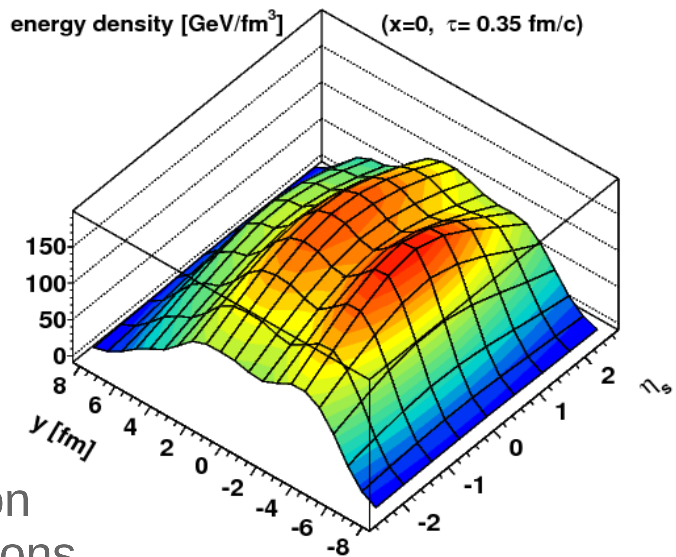




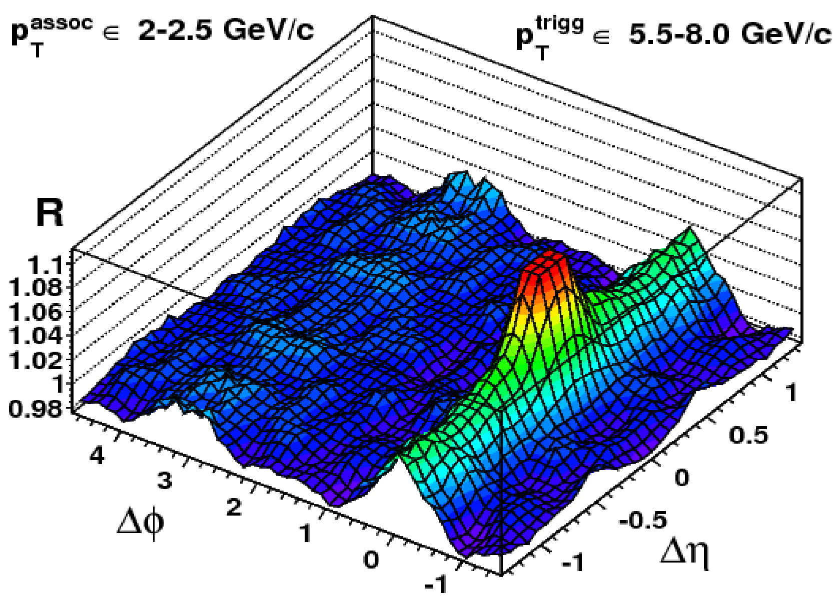
- **Jet interacts in bulk of matter**
  - ➡ parton energy loss
  - ➡ boost at the surface



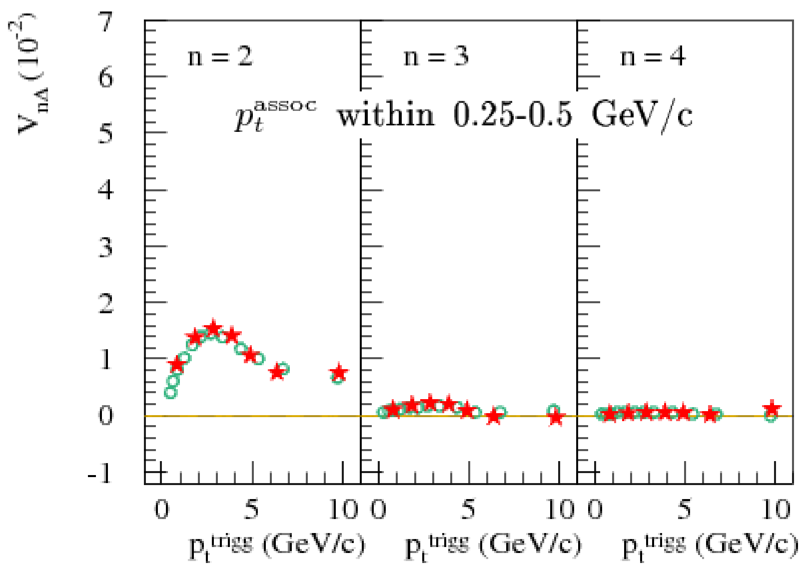
Correlations in PbPb@LHC

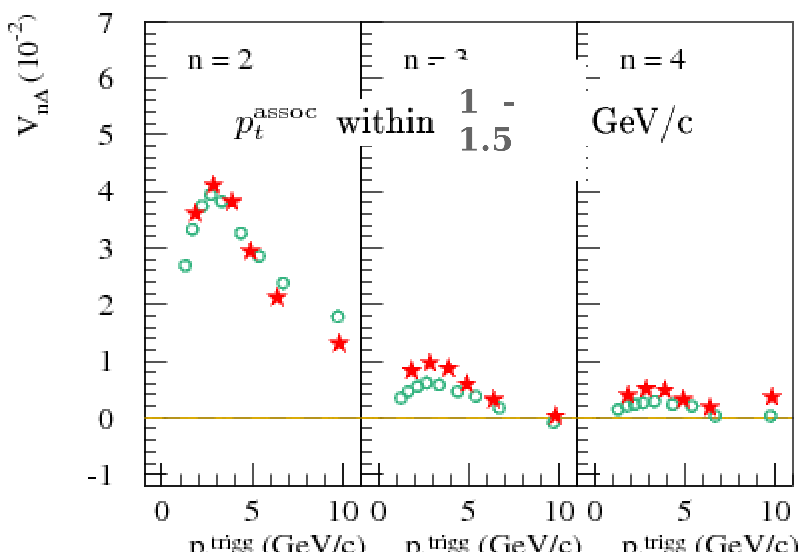


di-hadron correlations

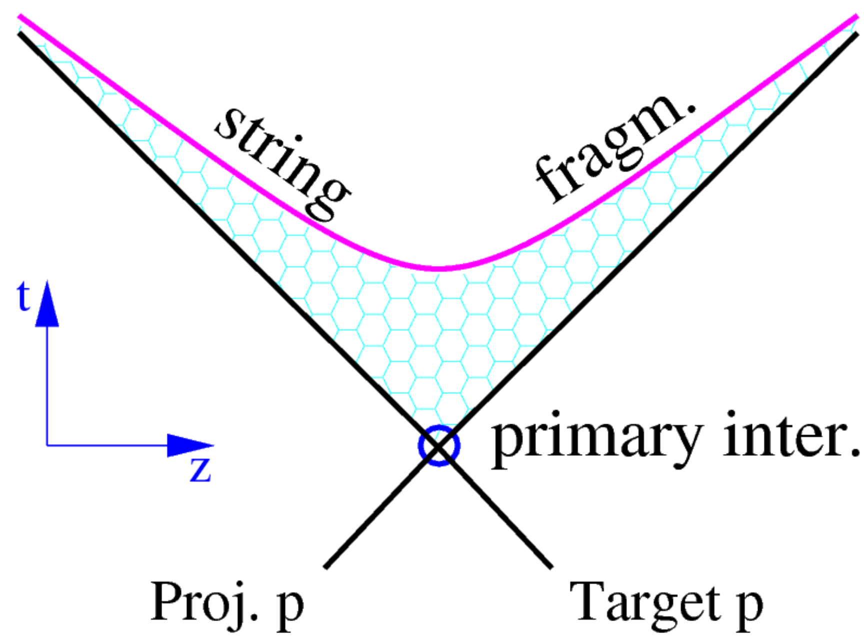


Fourier coefficient for most central events





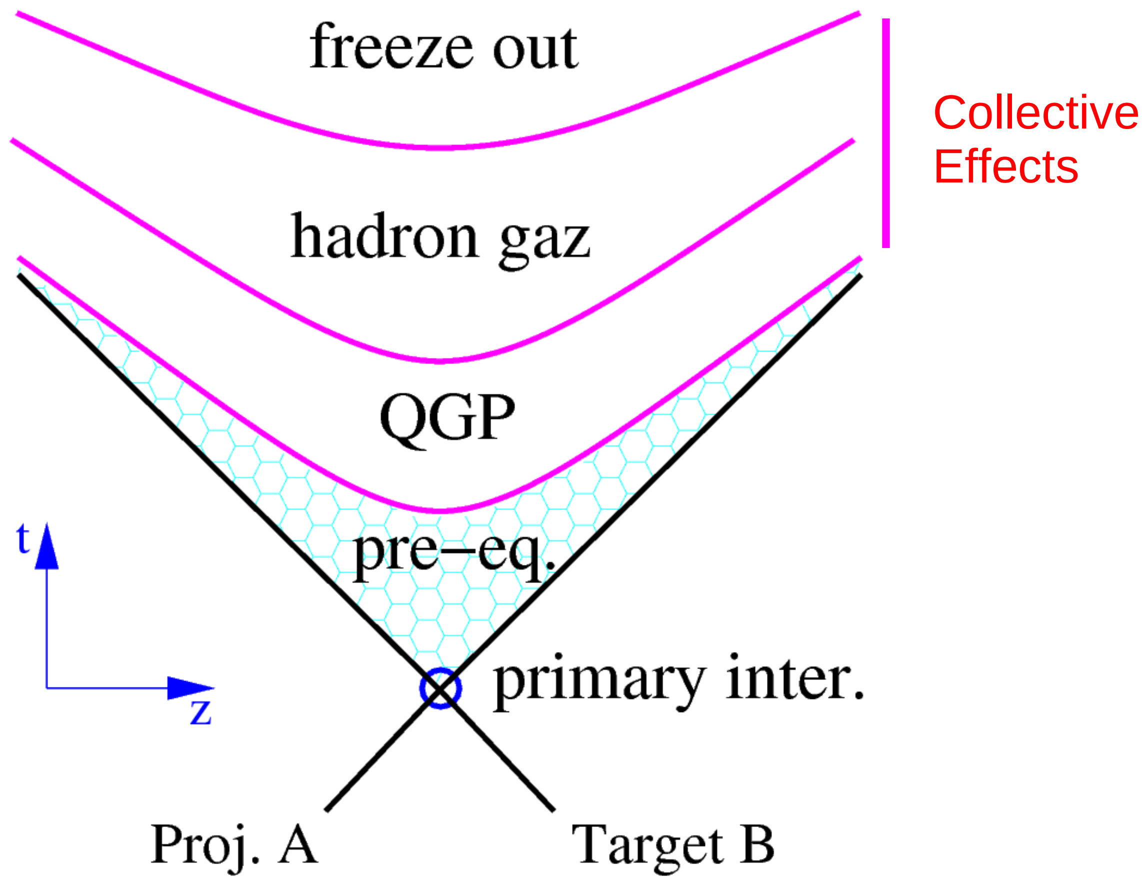
High Energy Hadronic Interactions : HEP view



MPI

Problem with some observables (UE, <pt>, ratios ...)

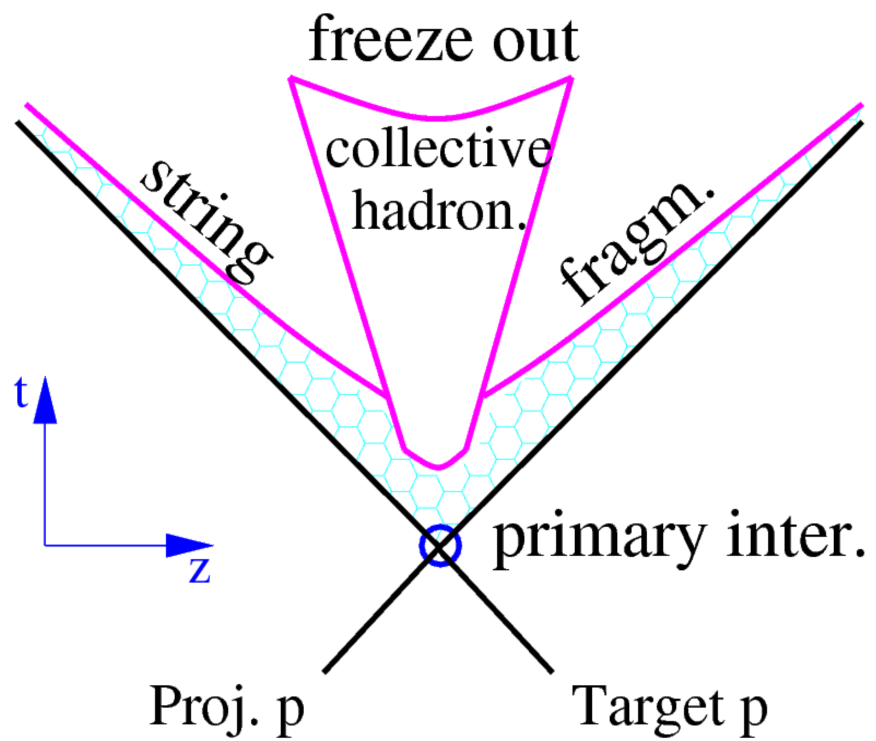
High Energy Hadronic Interactions : Heavy Ion view



General case : valid for pp if enough particles are produced !

High Energy Hadronic Interactions : EPOS LHC

- **Local high energy densities have different hadronization :**
  - Microcanonical decay
  - flow



General case : valid for pp if enough particles are produced !