Underlying Events and Hydro in EPOS 3

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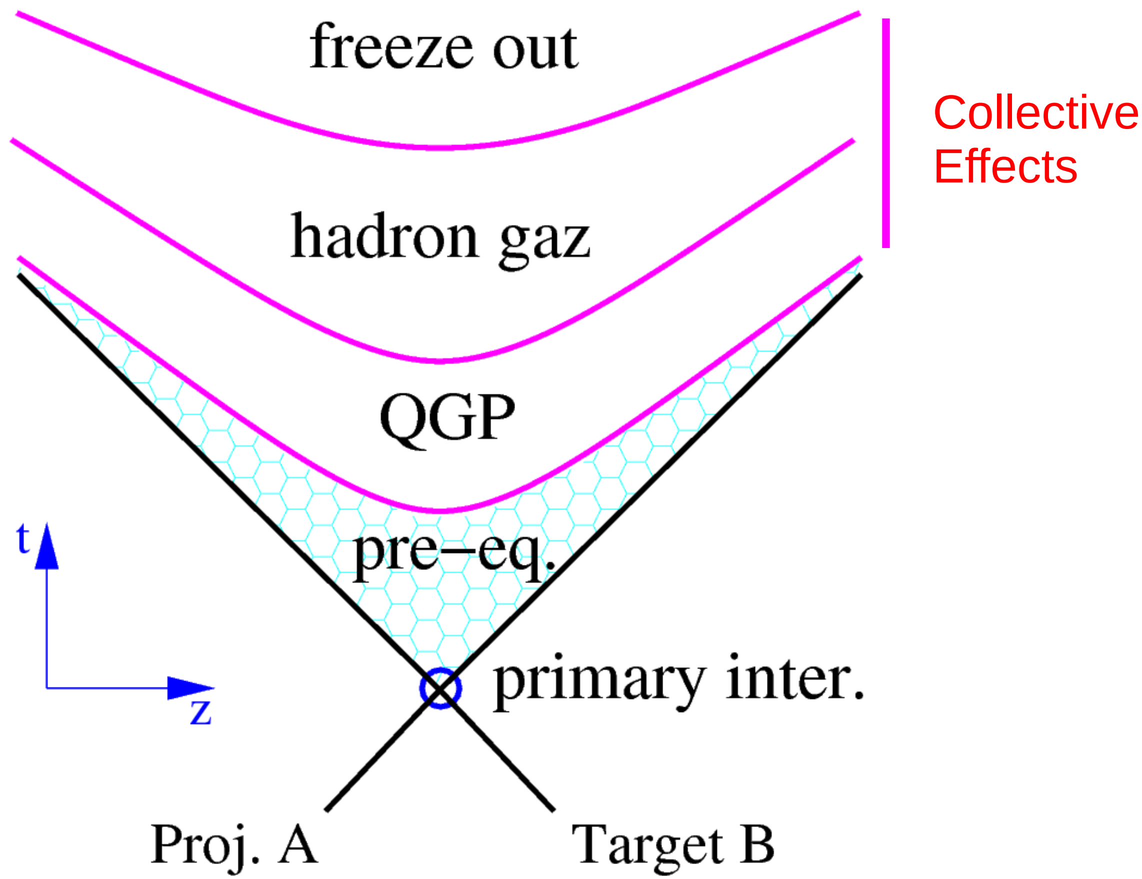
High Energy Hadronic Interactions



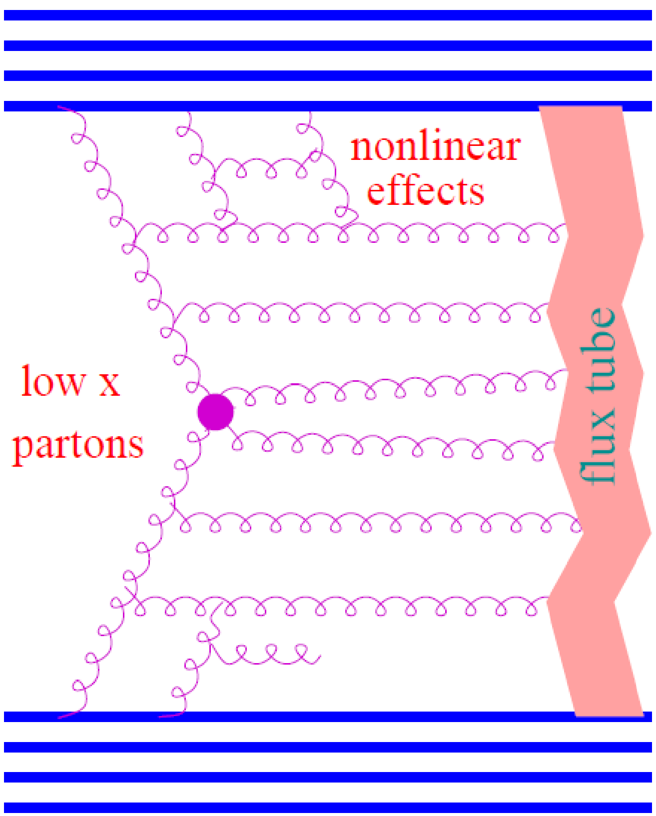
Effect of hydro visible in underlying events: strangeness production and higher MPI needed by hydro improve UE activity.

Outline

- **EPOS Basic principles**
- **EPOS 3**
  - new saturation scale Q_s^2
- **Preliminary results**
  - underlying events with/out hydro
- **Summary**

Elementary scatterings - flux tubes

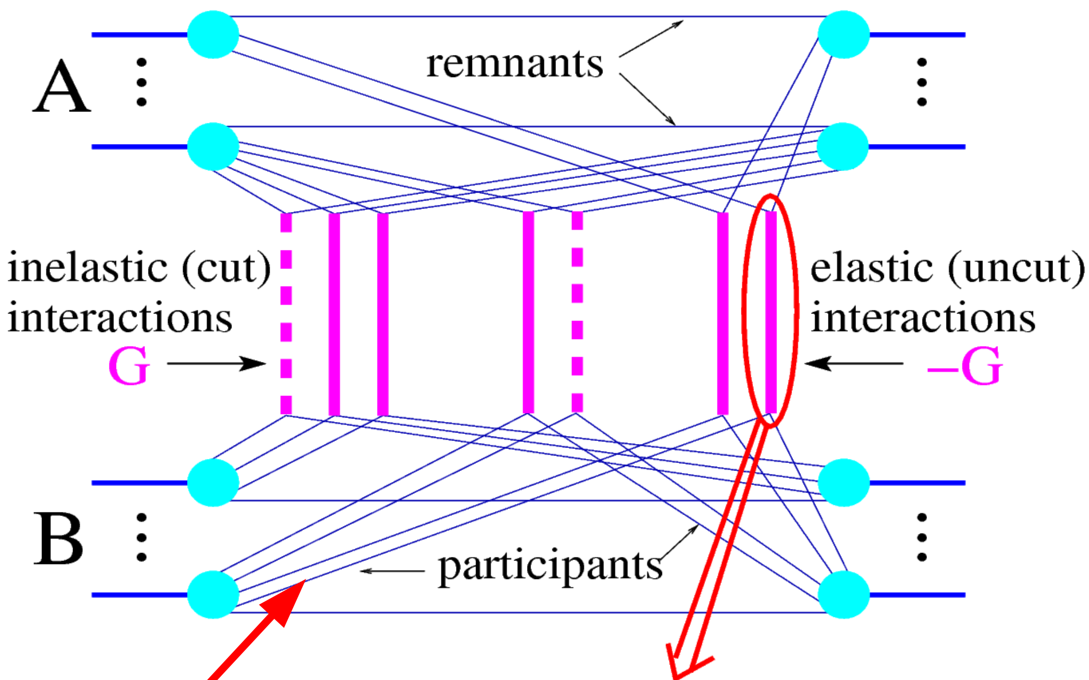
- same energy sharing between the parallel scatterings is taken into account for cross section and particle production
  - MPI fixed by total cross-section
- many elementary collisions happening in parallel
- elementary scattering = “parton ladder” + soft component



- 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

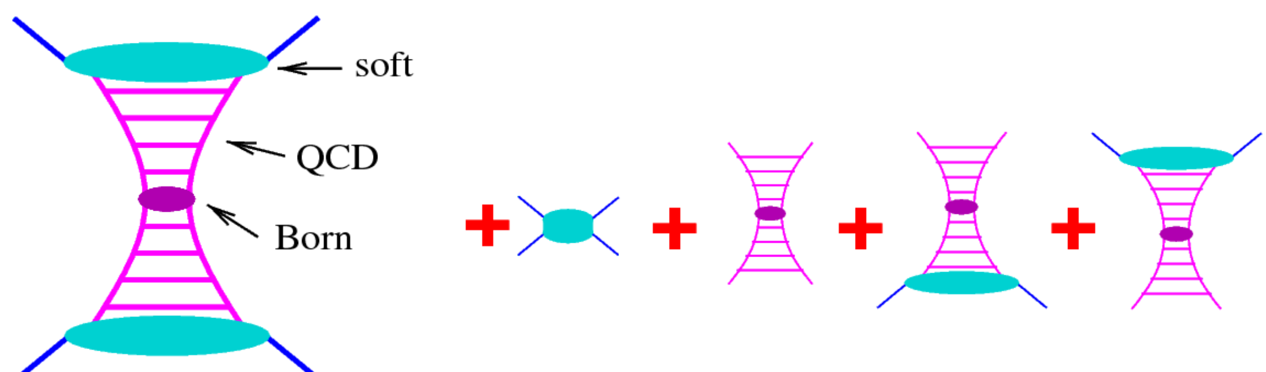
Parton-based Gribov-Regge Theory, H. J. Drescher, M. Hladik, S. Ostapchenko, T.Pierog, and K. Werner, Phys. Rept. 350 (2001) 93-289;

Parton-Based Gribov-Regge Theory

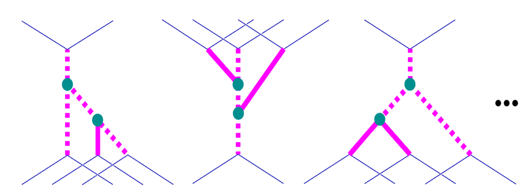


Pomeron momentum fraction x^- (x^+ for projectile)

- **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)

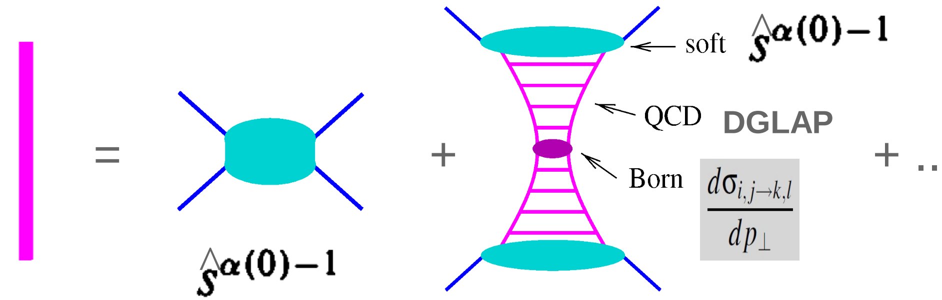


Non-linear effect (saturation) absorbed in modified vertex functions

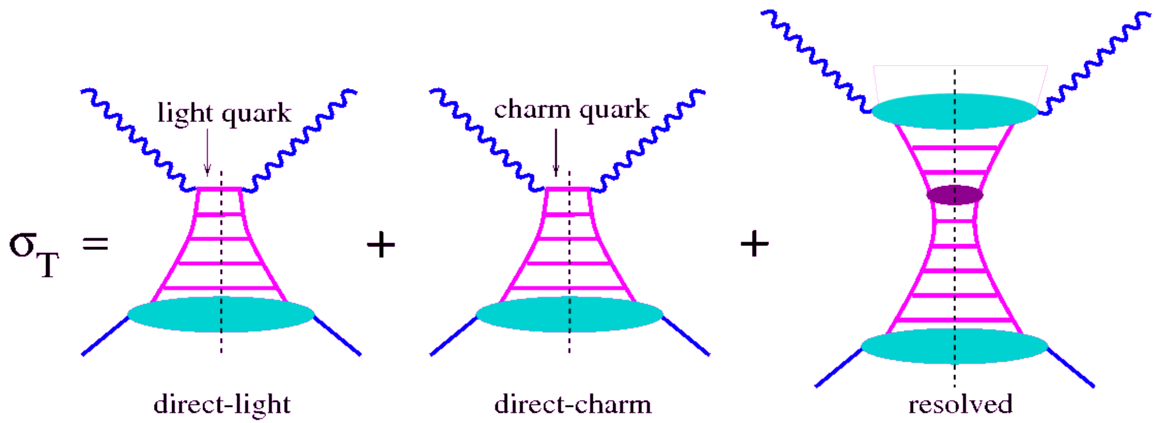


EPOS : Pomeron definition

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

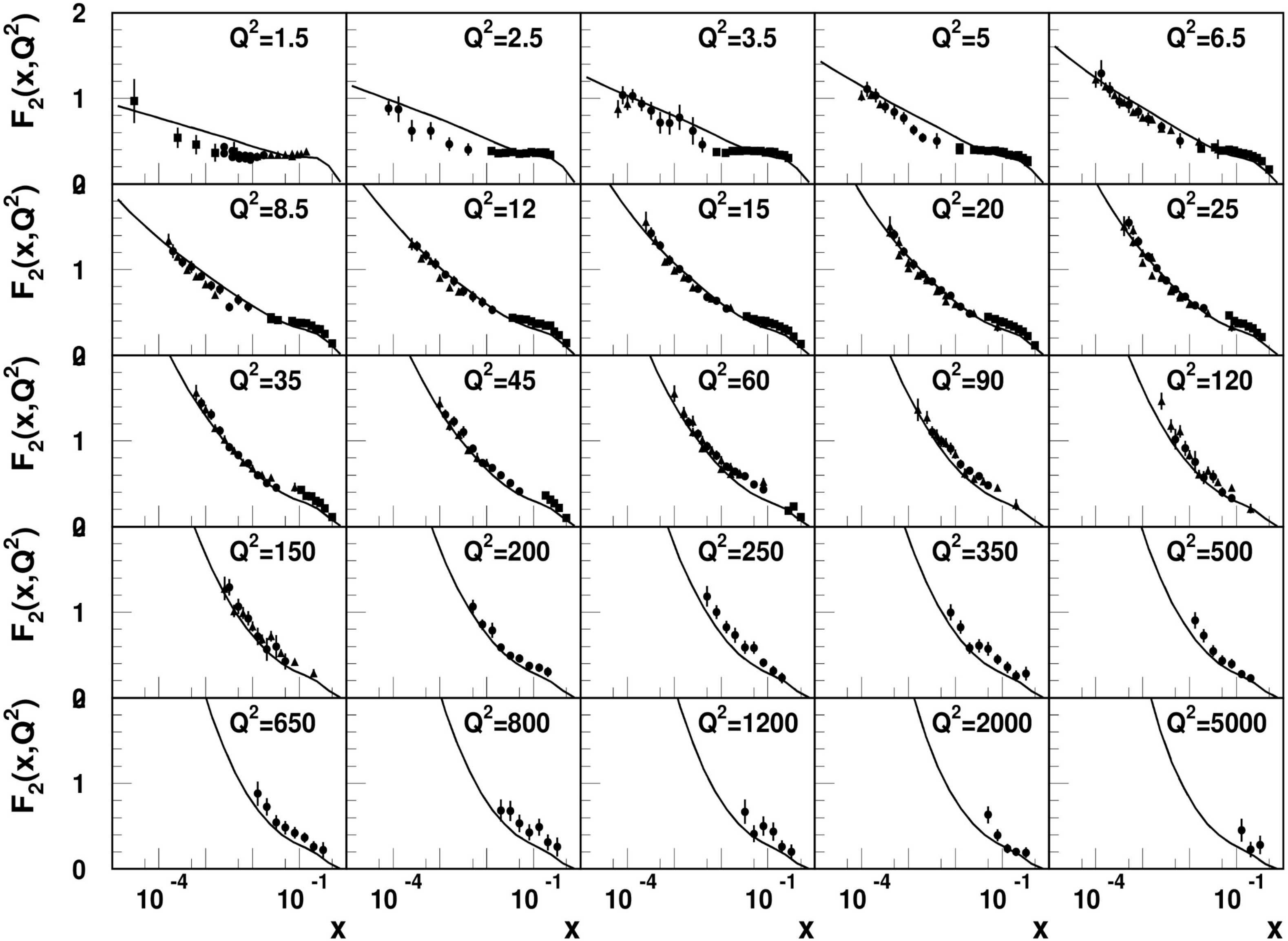


Test of semi-hard Pomeron with DIS: (Parton Distribution Function from HERA)

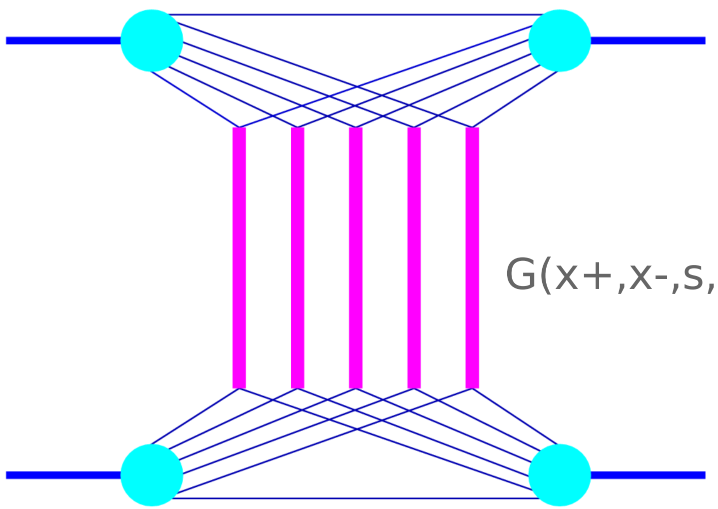


- Theory based Pomeron definion
  - pQCD based (DGLAP and Born)
    - large increase at small x (without saturation)
  - External pdf only for valence quark
  - F2 from HERA used to fix parameters for sea quarks and gluons

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

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

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

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 :

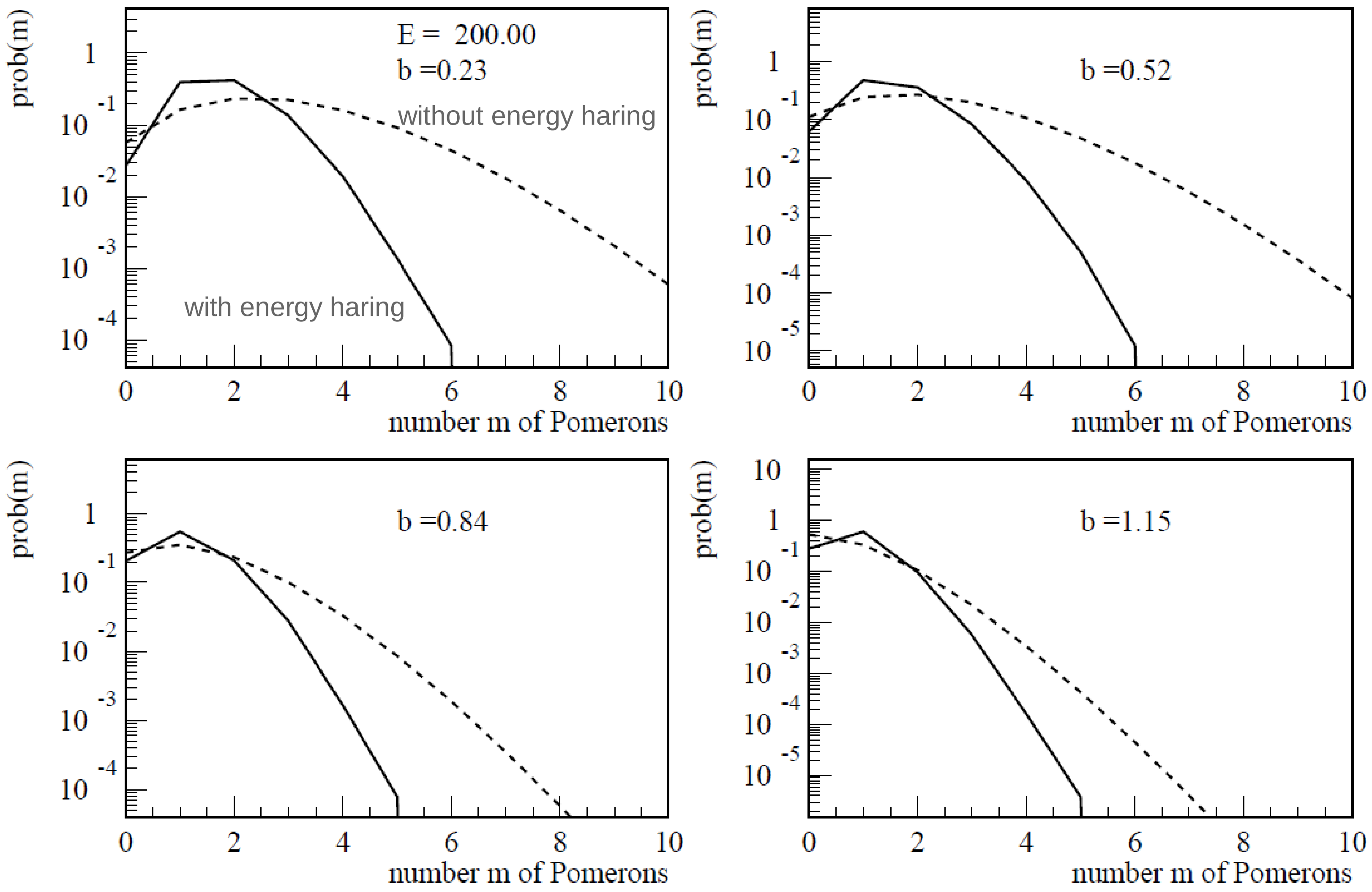
$$\Omega_{AB}^{(s,b)}(m, X^+, X^-) = \prod_{k=1}^{AB} \left\{ \frac{1}{m_k!} \prod_{\mu=1}^{m_k} G(x_{k,\mu}^+, x_{k,\mu}^-, s, b_k) \right\} \Phi_{AB}\left(x^{\text{proj}}, x^{\text{targ}}, s, b\right)$$

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

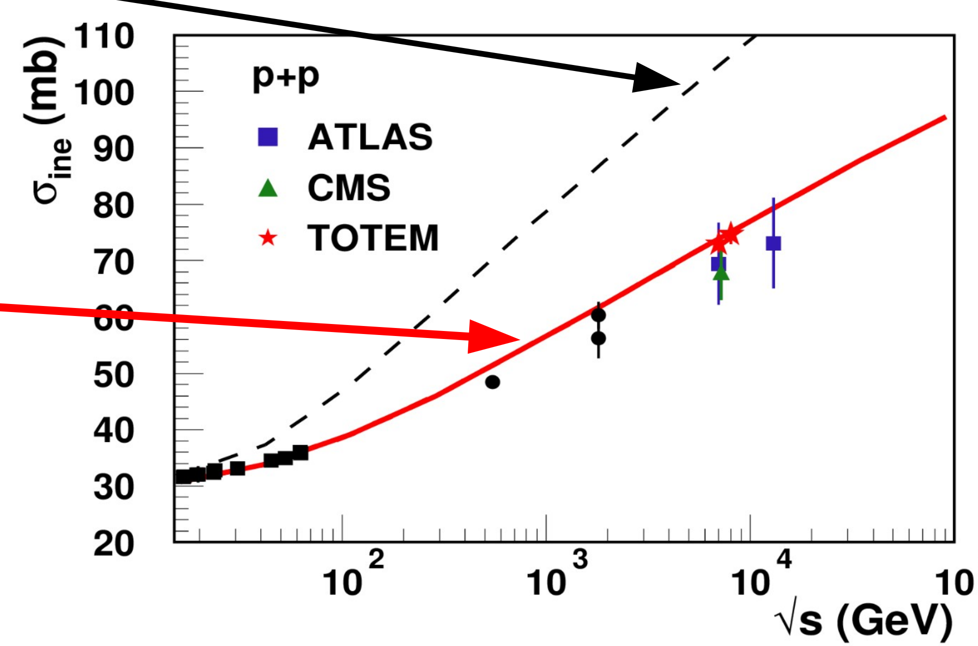
- **Well known problem with pQCD based Pomerons**
  - total cross-section too high : MPI required
    - in EPOS <Pomerons> fixed by b-dep of Pomeron amplitude (slope)
  - effective coupling introduced to mimic effect of enhanced diagrams and reduce cross-section (screening effect) to get cross-section AND multiplicity right in p-p, p-A and AA.

No effective coupling

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

With effective coupling

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



Parametrization

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

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

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.

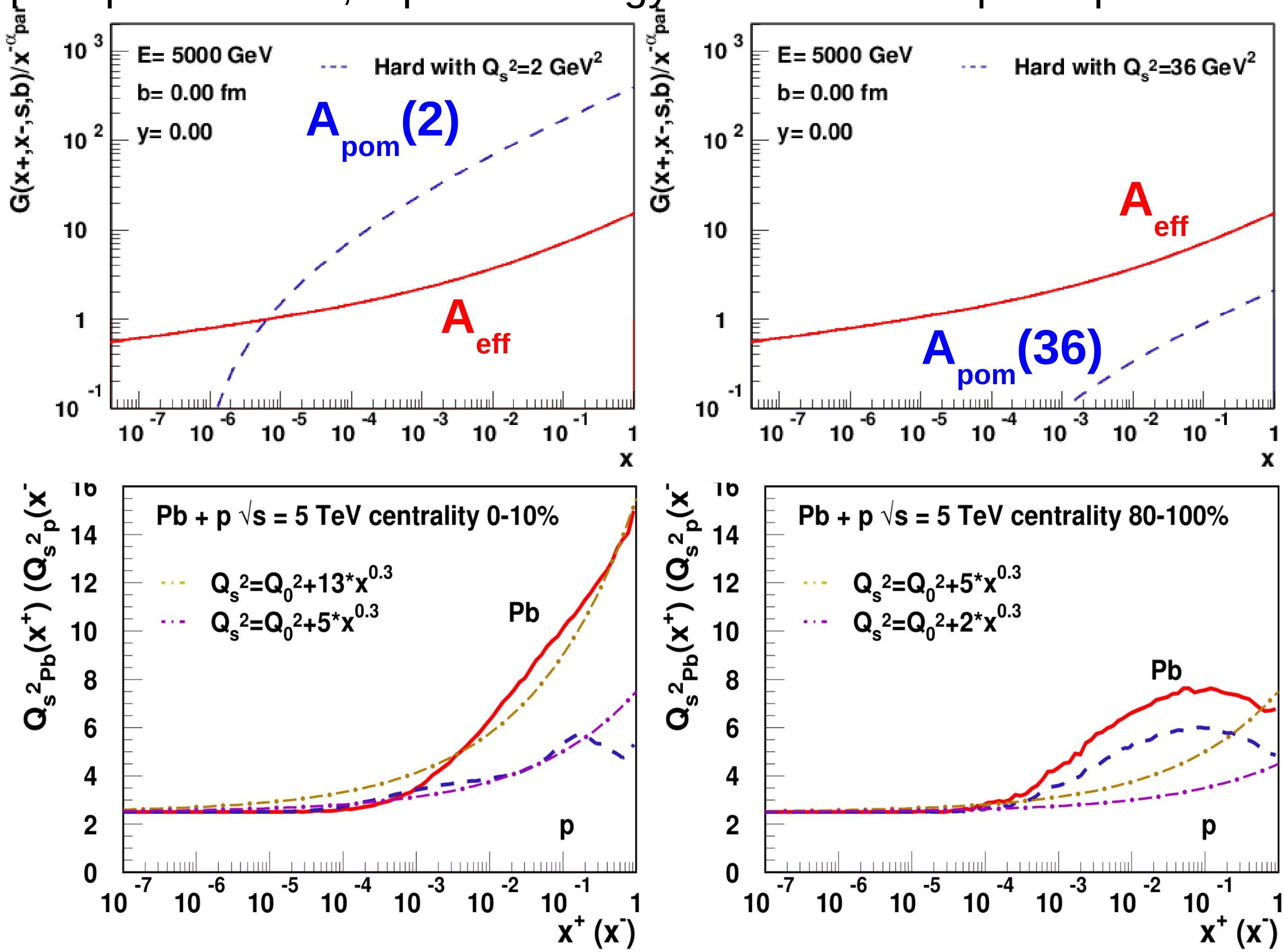
- **EPOS 3.2**
  - A_{eff} tuned to reproduce cross-sections and used in MC to produce Pomeron distributions
  - Define Q_s^2 such that

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

to get binary scaling in pA or AB

N_{bin}=glauber # of bin coll.

N_{col}=real # of bin coll.



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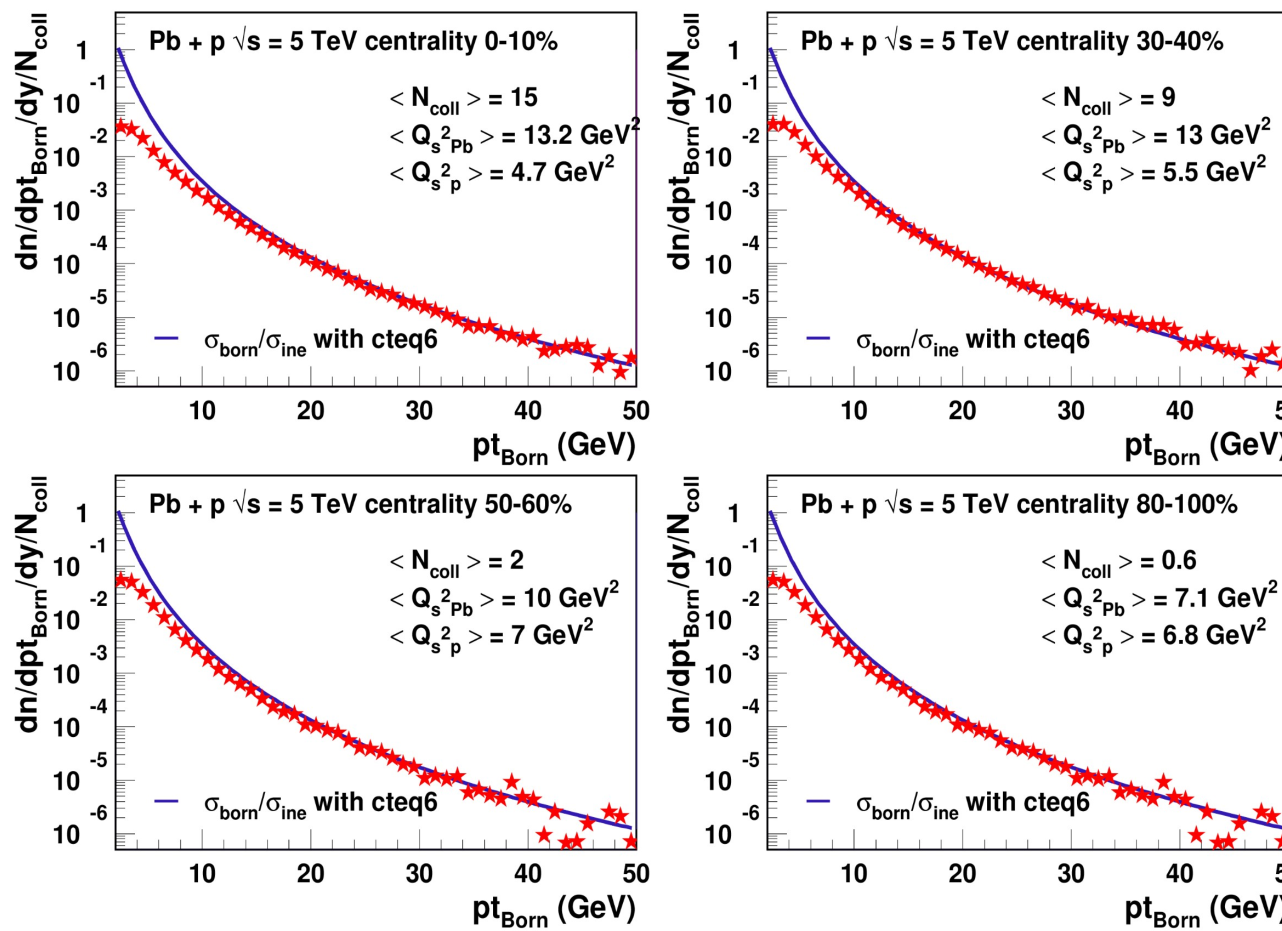
  - Scaling of inclusive cross-section by construction

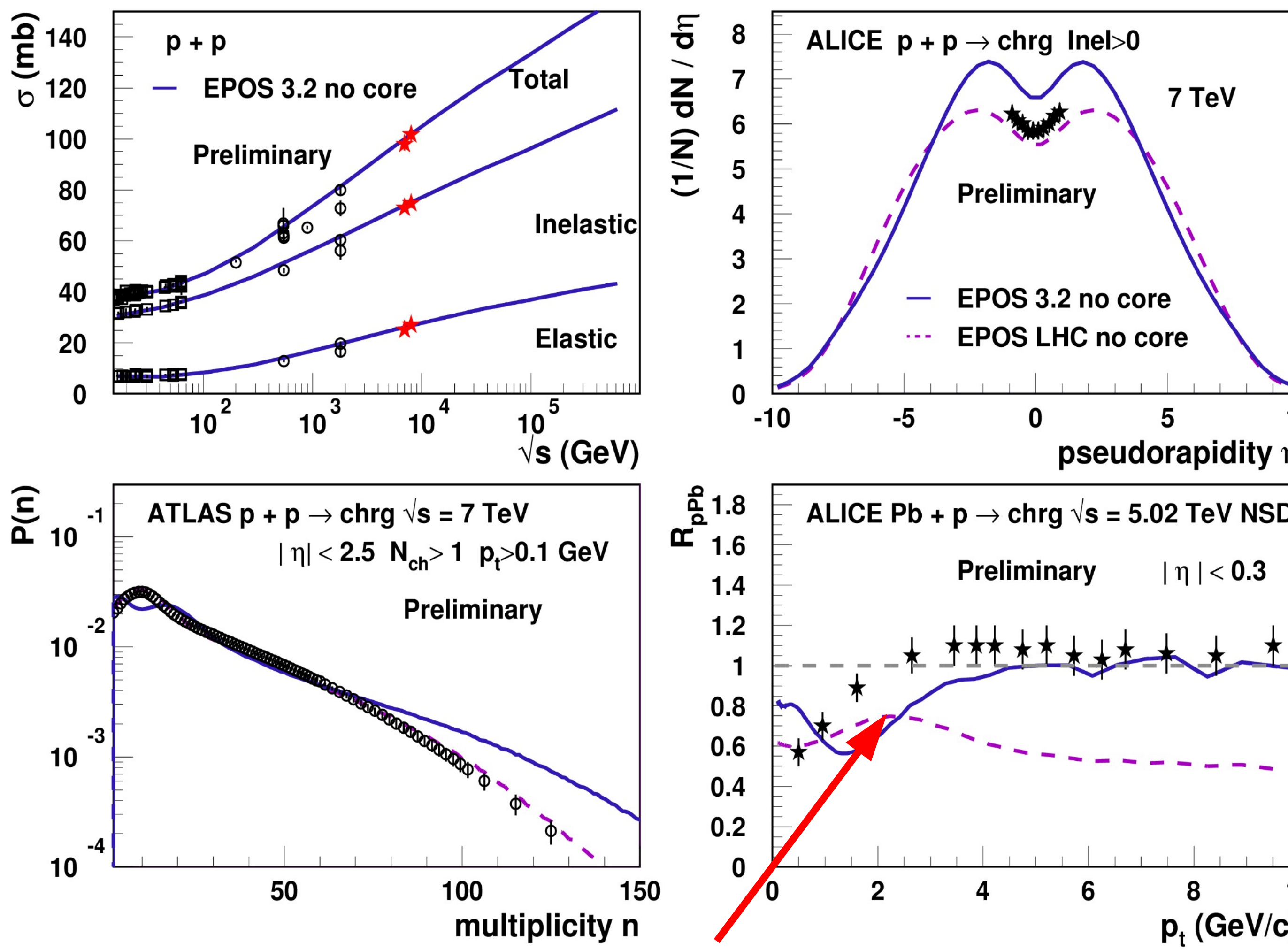


Preliminary Results : Without Core

- **Overestimate multiplicity to take into account the effect of hydro**
  - ➡ hydro reduce multiplicity to transfer energy to fluid expansion (flow)

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

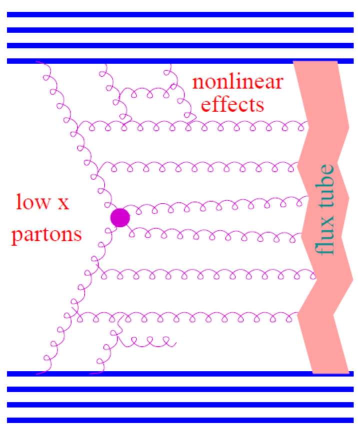
Since Q_s^2 is adapted to get the needed amplitude only low pt are suppressed. No change above Q_s^2.

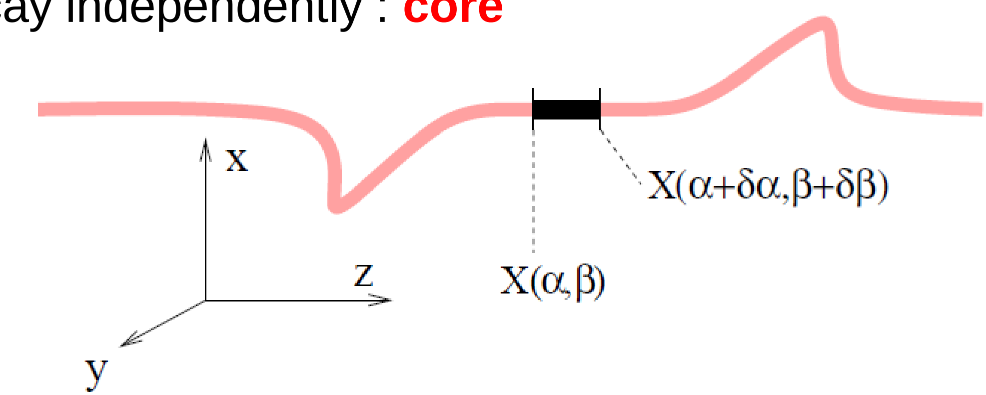


no core = missing flow

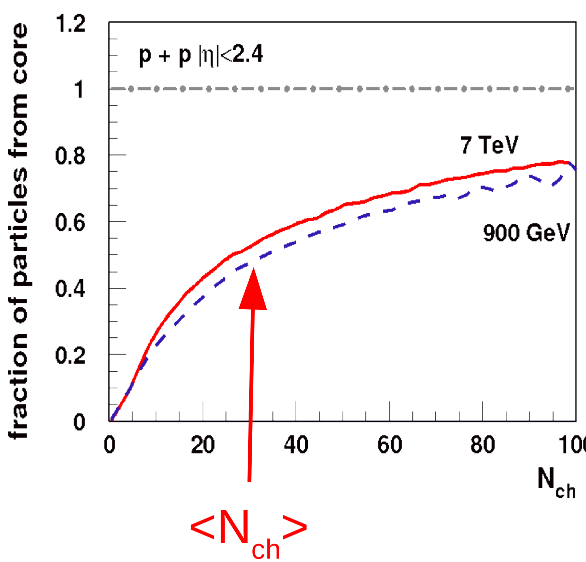
High Density Core Formation

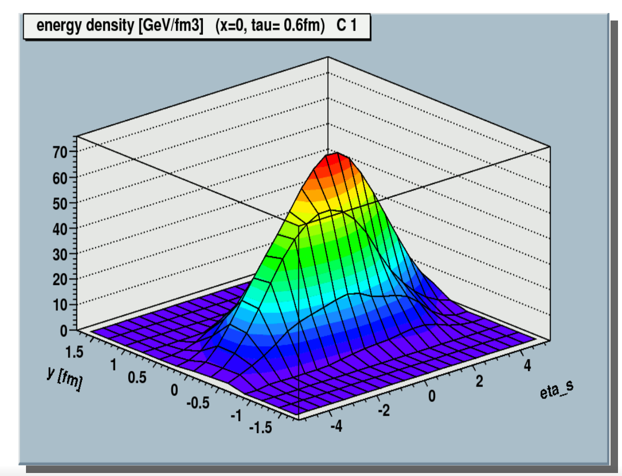
- **Heavy ion collisions or high energy proton-proton scattering:**
  - the usual procedure has to be modified, since the density of strings will be so high that they cannot possibly decay independently : **core**





- 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
    - full 3D+1 hydro evolution
    - lattice QCD EoS
- If low density (corona)
  - segments remain hadrons
    - string fragmentation





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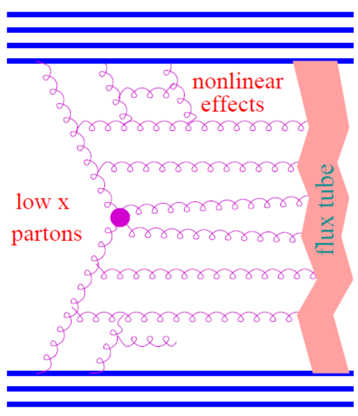
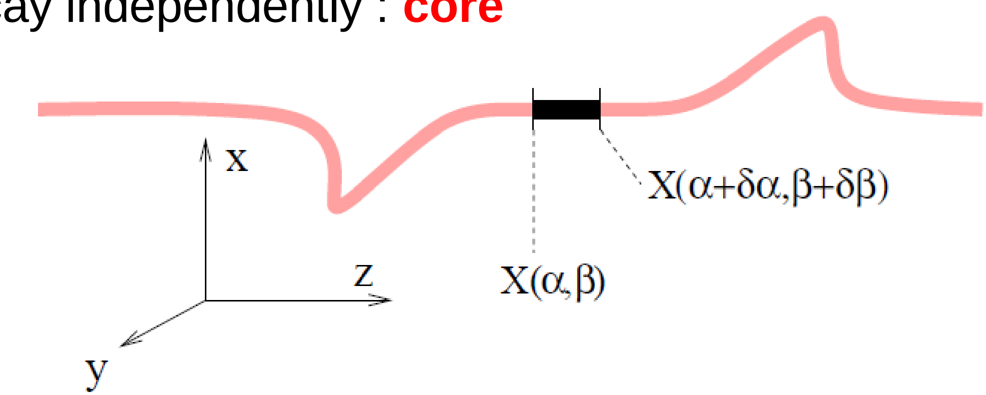
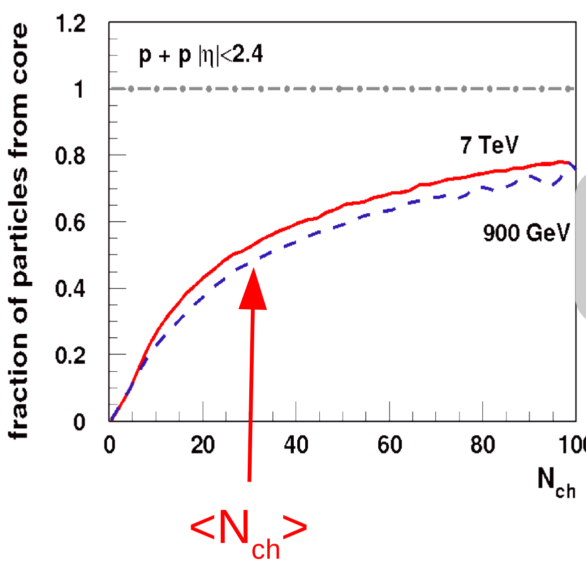


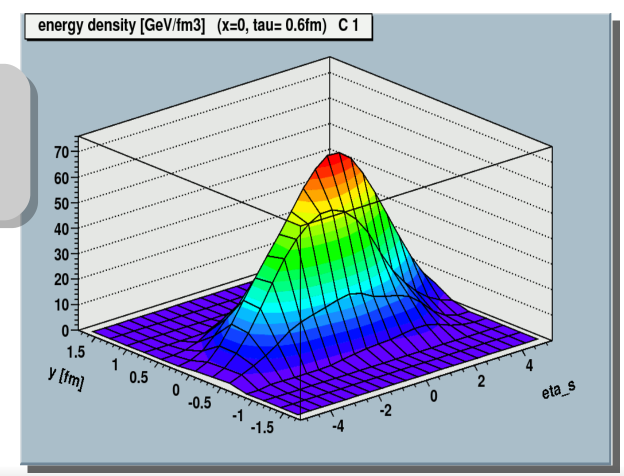


- Each string splitted into a sequence of string segments, corresponding to widths δα and δβ in the string parameter space
- If energy density from segments high enough
  - segments fused into core

Statistical decay and effective flow here like in EPOS LHC

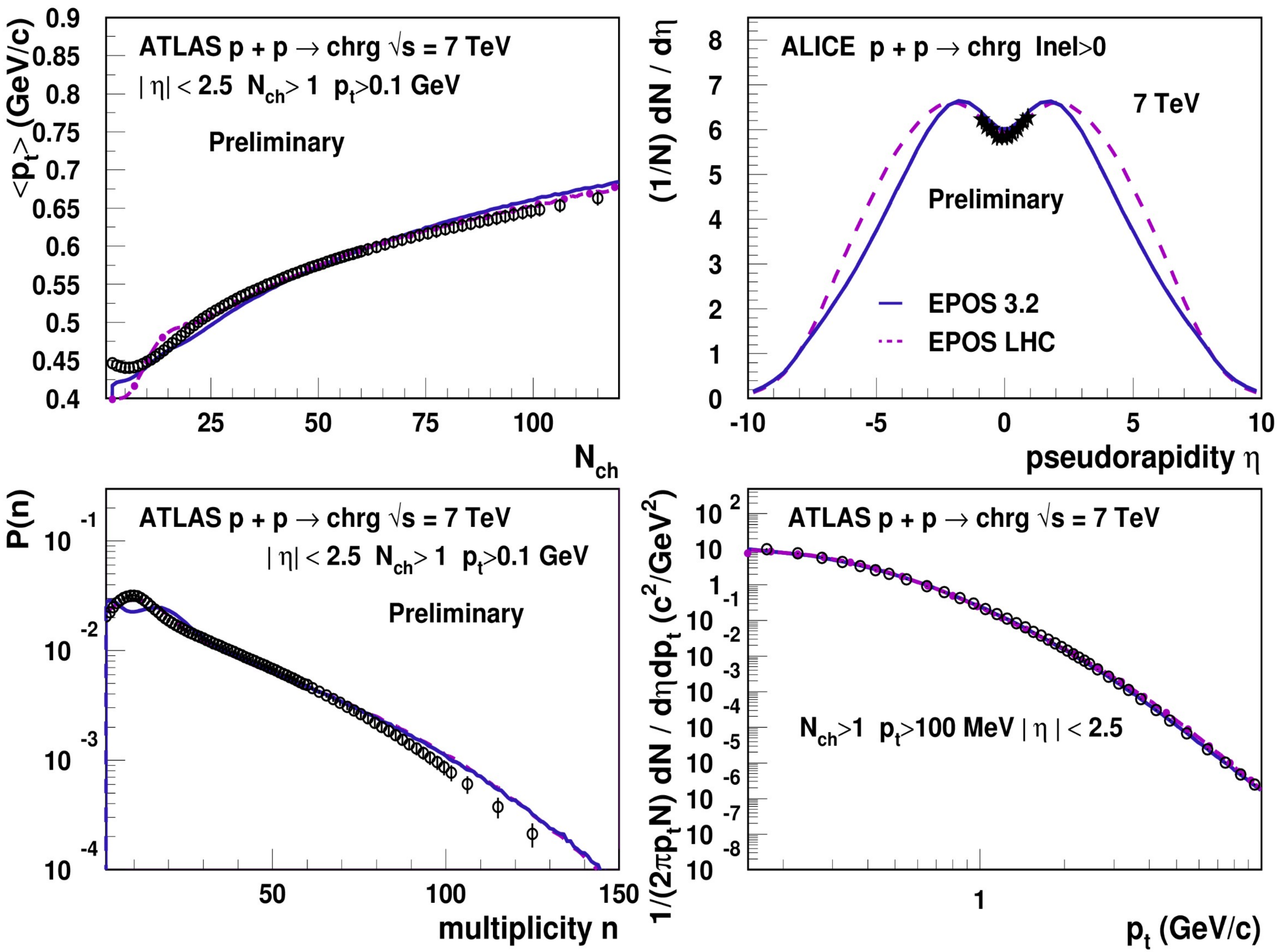
- If low density (corona)
  - segments remain hadrons
    - string fragmentation





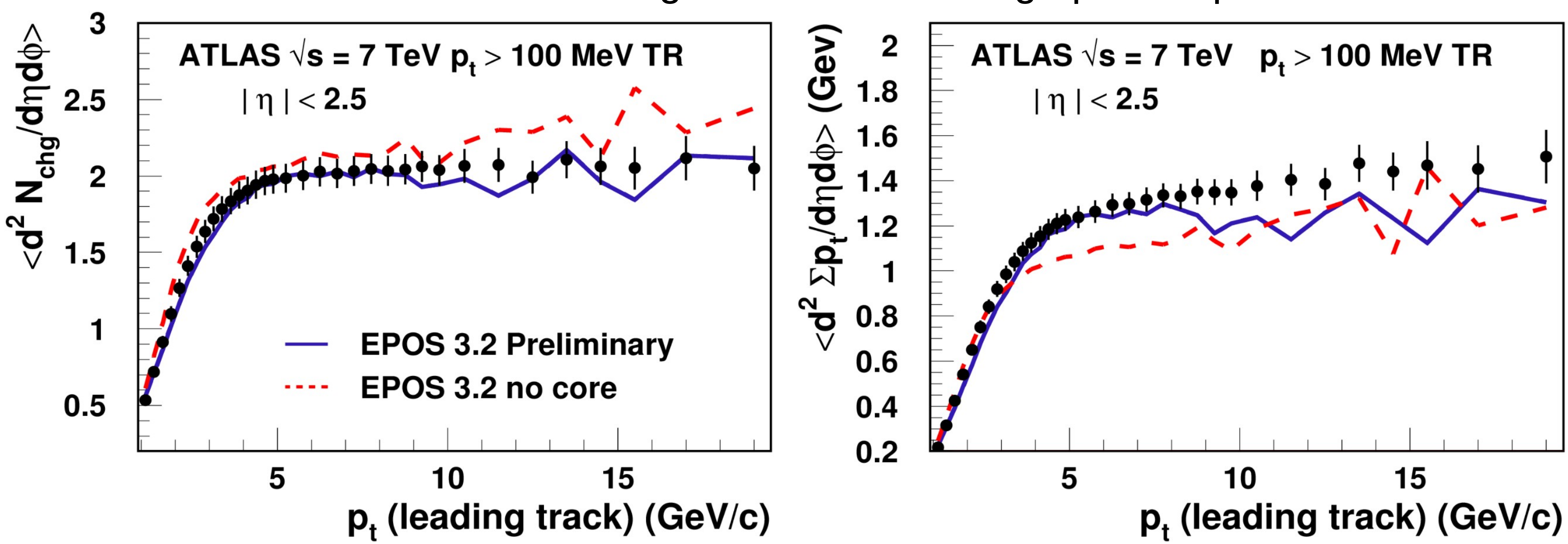
Preliminary Results : With Core

- Excellent results again for minimum bias soft physics



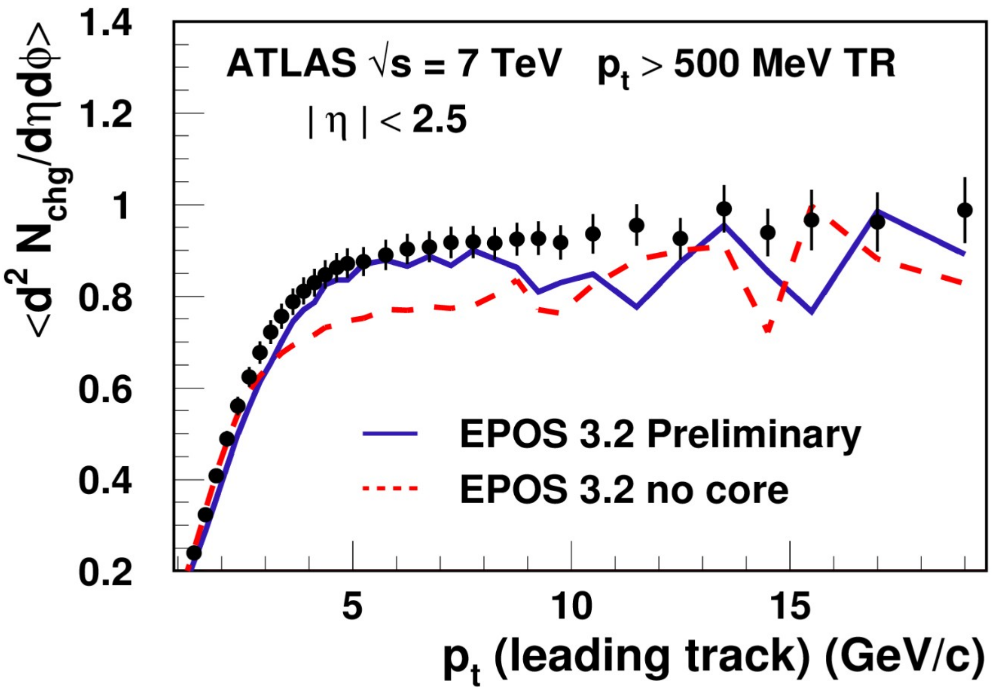
Underlying Events: p_t > 100 MeV/c

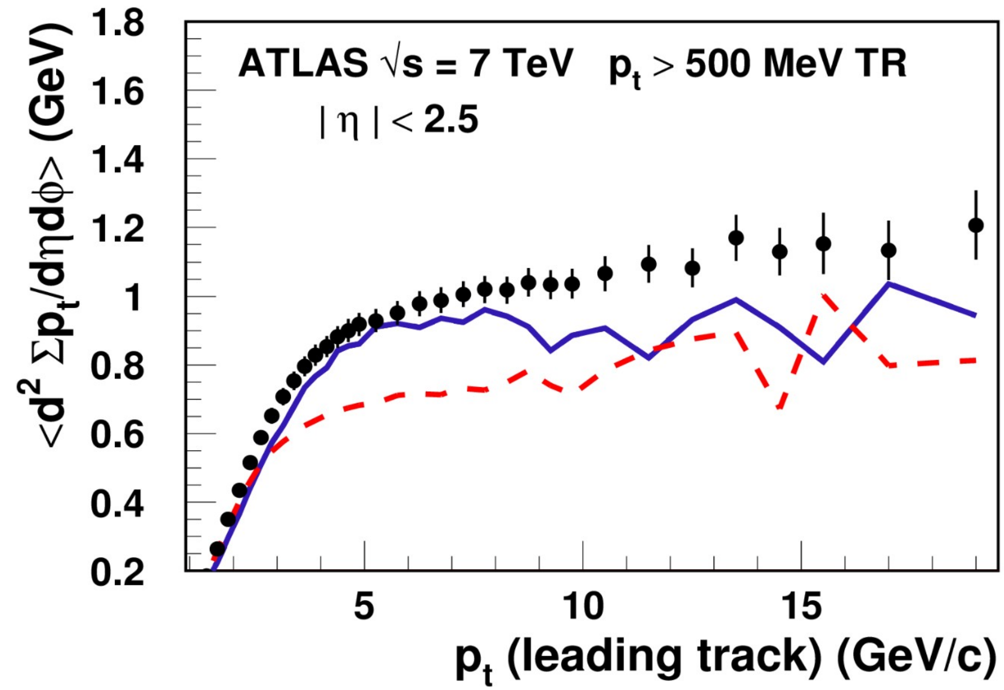
- p_t > 100 MeV/c particles in TRANS region
  - without core N_{ch} is large like in MB but energy density is too low for p_t leading ~7 GeV/c
  - with core multiplicity is reduced and energy density at intermediate p_t is increased
  - reasonable agreement with data
    - mean transverse energy still a bit low for high p_t leading track
      - still not enough MPI or lack of high pt from parton shower



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 for all p_t leading
  - with core multiplicity is increased 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
      - still not enough MPI or lack of high pt from parton shower

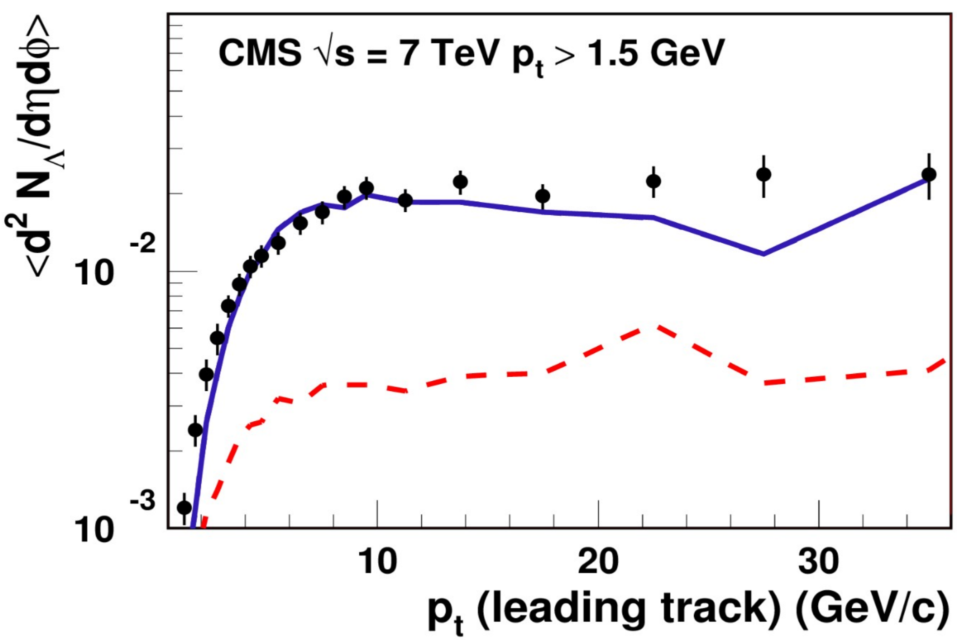


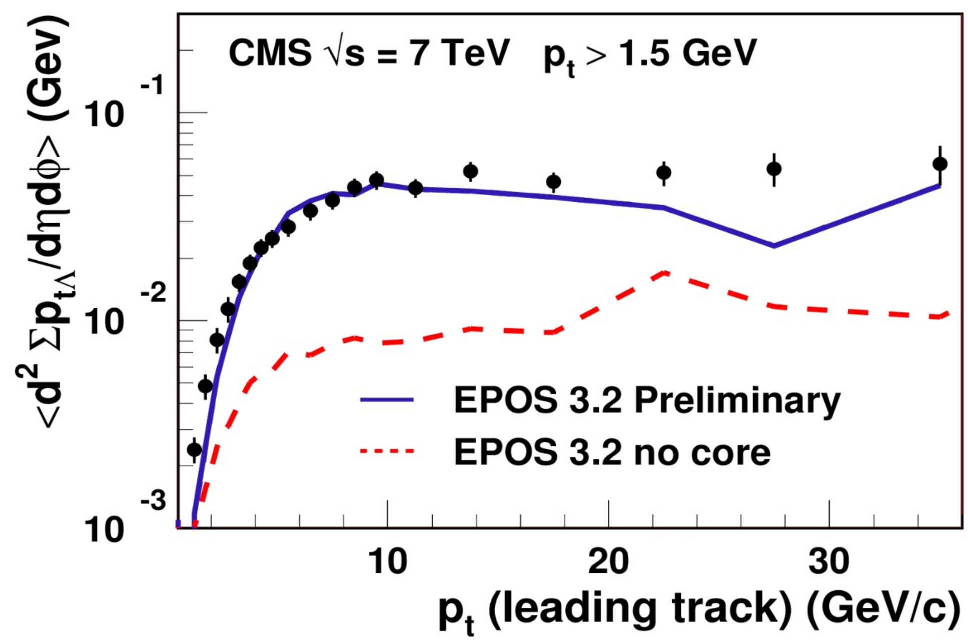


Underlying Events: Strangeness

- **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

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

EPOS 3

- introduce saturation scale Q_s^2 COMPUTED Pomeron-by-Pomeron.
- impose factorization and binary scaling for hard processes above Q_s^2
- hydro expansion require higher MPI than imposed by multiplicity that reflect on UE and other variables (like charm production see K. Werner's talk on Thursday)
- improve underlying event description in p-p but real hydro still to be tried for UE

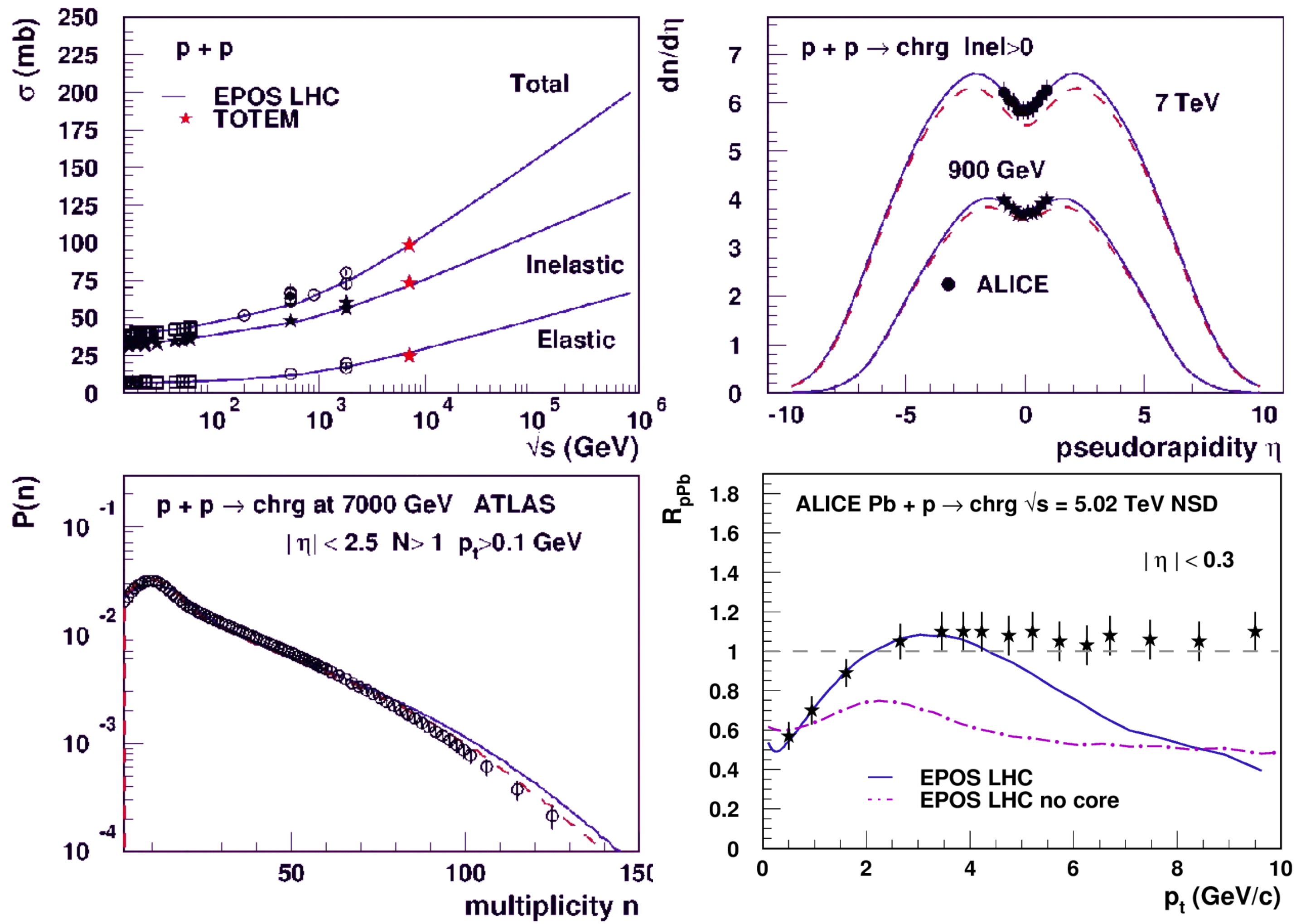
Effect of hydro visible in underlying events: strangeness production and higher MPI needed by hydro improve UE activity.

Fixed Q_0^2 (old)

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

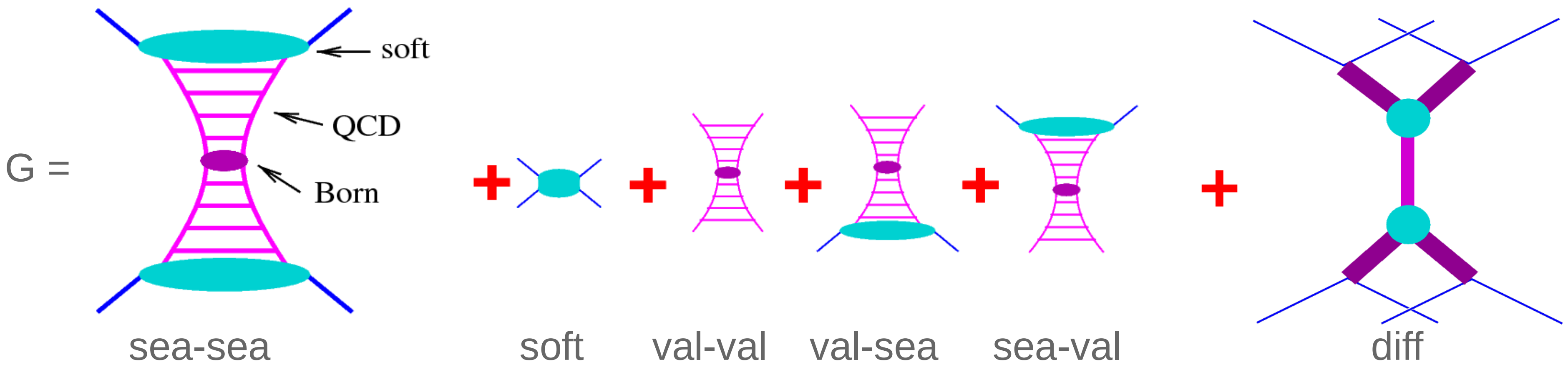
- **Problem for hard processes**
  - ➜ lack of high pt
  - ➜ no binary scaling for pA or AB

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

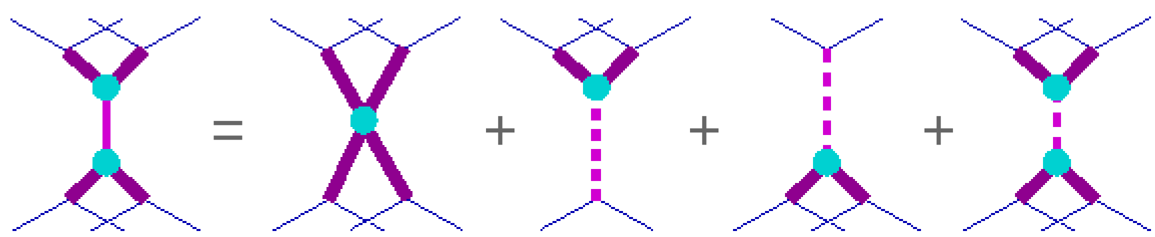


Diffraction in PBGRT

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

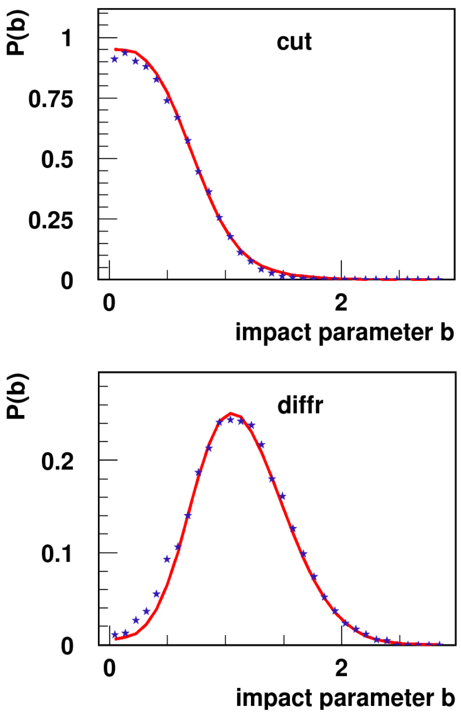


  - Same form as soft (Regge pole) but with different amplitude and width
  - Low mass and high mass diffraction from the same diagram



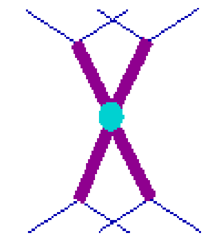
  - Parameters extracted from single diffractive (SD) cross-section
  - Events with only "diff" type diagrams are diffractive

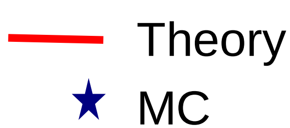
Low Mass Diffraction

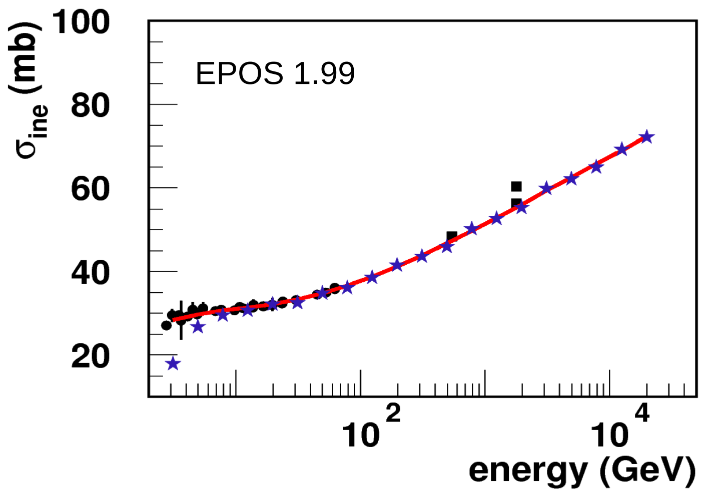


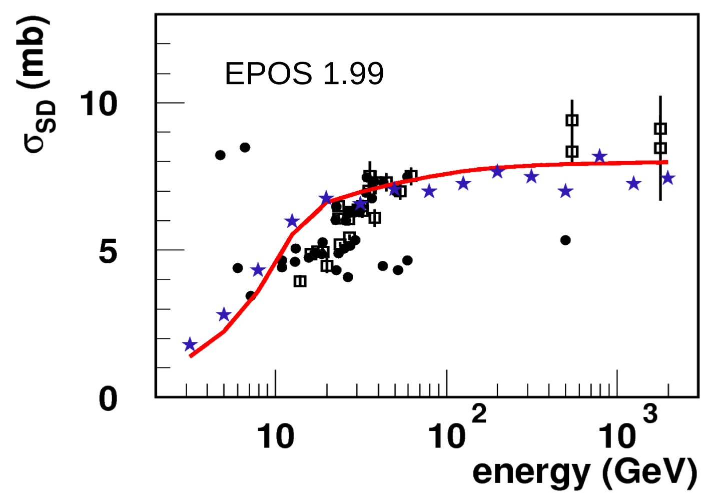
Diffractive event = event with only cut diff. diagrams

- 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)

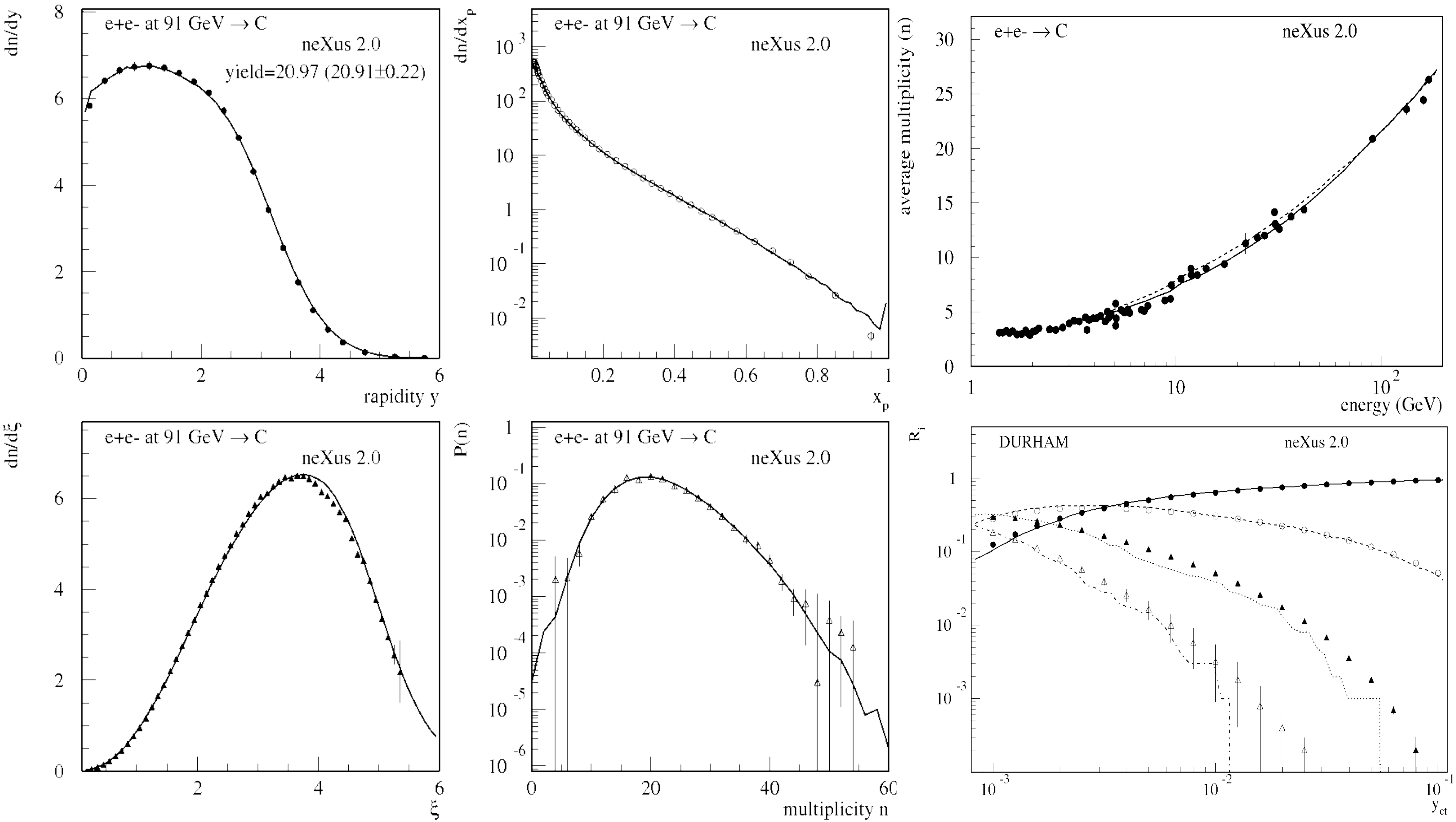








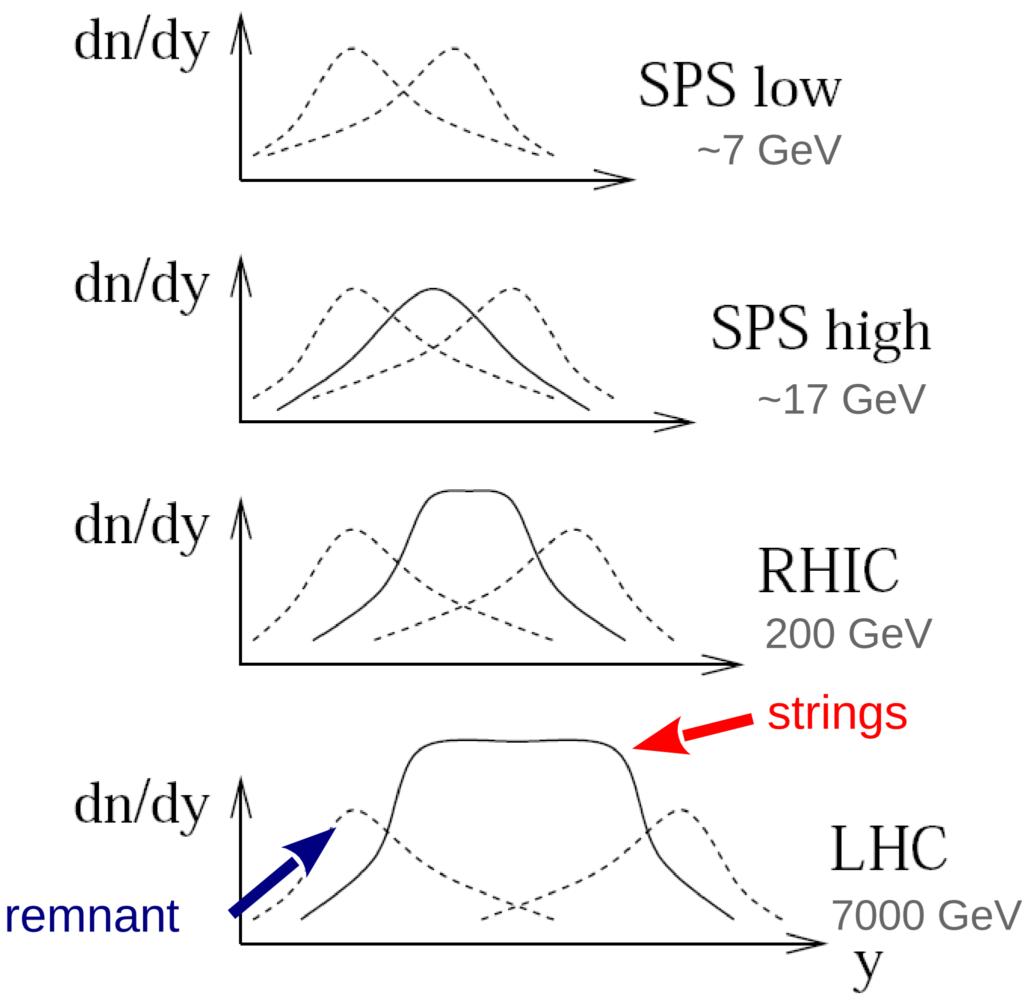
Test of string fragmentation with LEP data



Area law

Remnants

Forward particles mainly from projectile remnant



Forward hadronization from remnant :

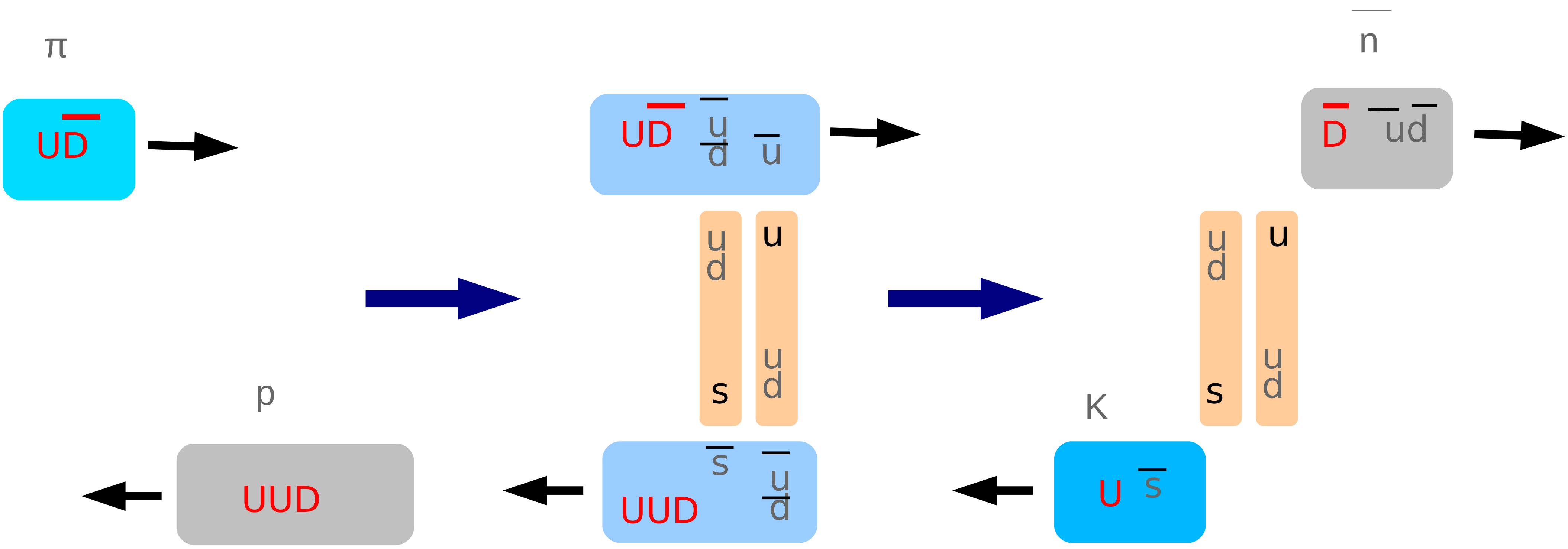
- At very low energy only particles from remnants
- At low energy (fixed target experiments) (SPS) strong mixing
- At intermediate energy (RHIC) mainly string contribution at mid-rapidity with tail of remnants.
- At high energy (LHC) only strings at mid-rapidity (baryon free)

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

Remnants in EPOS

In EPOS : any possible quark/diquark transfer

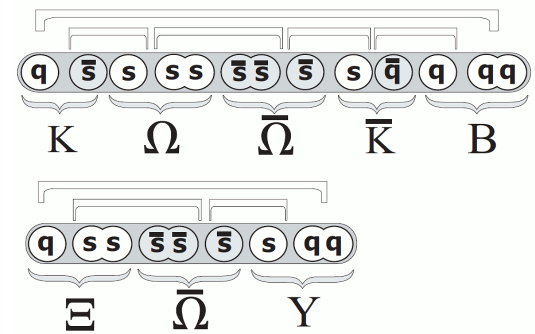
- Diquark transfer between string ends and remnants
- Baryon number can be removed from nucleon remnant :
  - Baryon stopping
- Baryon number can be added to pion/kaon remnant :
  - Baryon acceleration



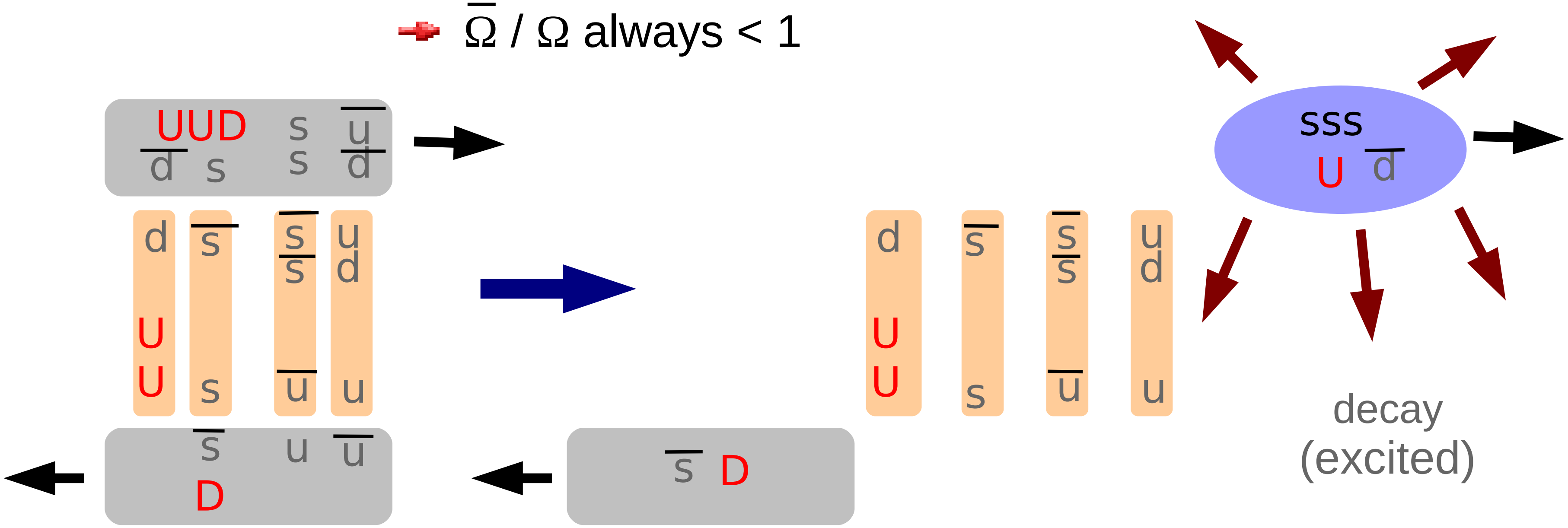
Baryons and Remnants

Parton ladder string ends :

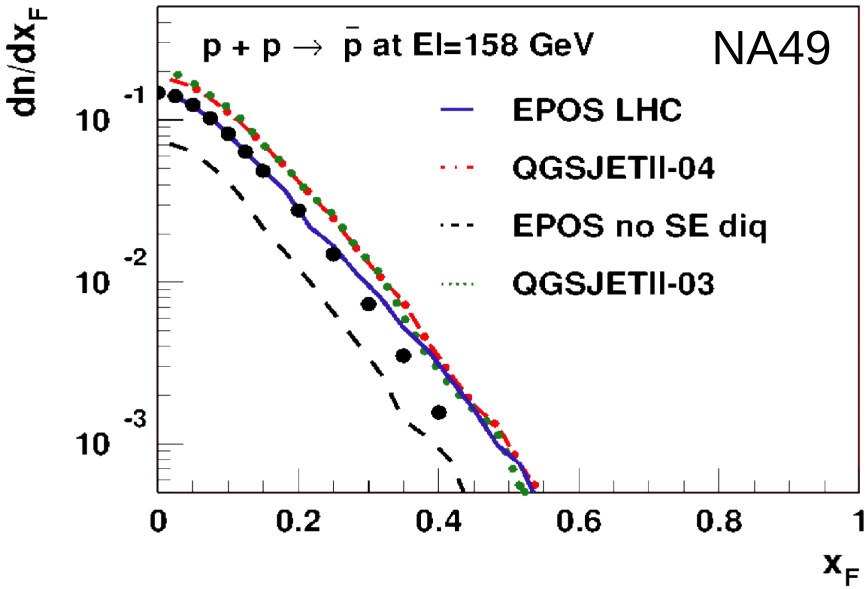
- Problem of multi-strange baryons at low energy (Bleicher et al., Phys.Rev.Lett.88:202501,2002)
  - 2 strings approach :
    - $\bar{\Omega}$ / Ω always > 1
    - But data < 1 (Na49)



- 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

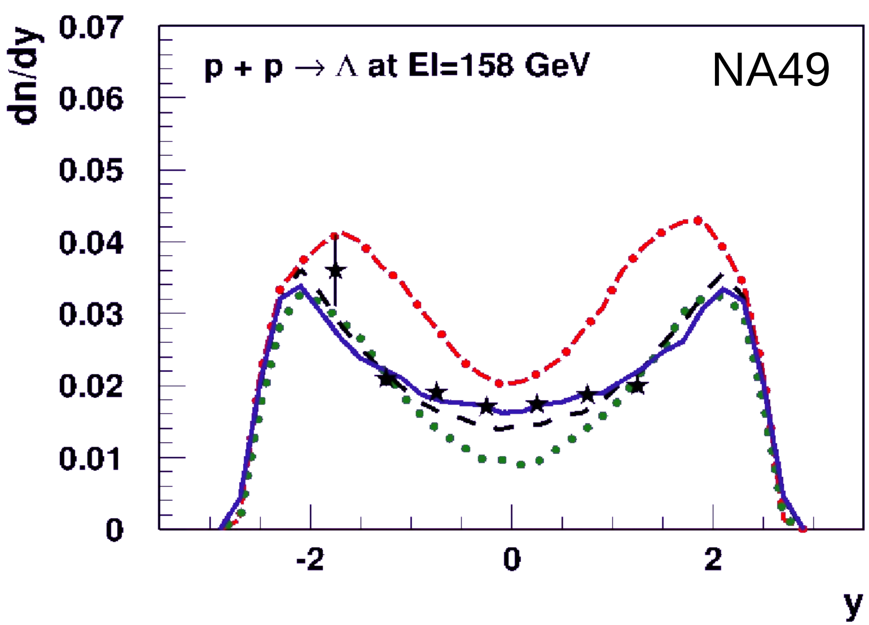


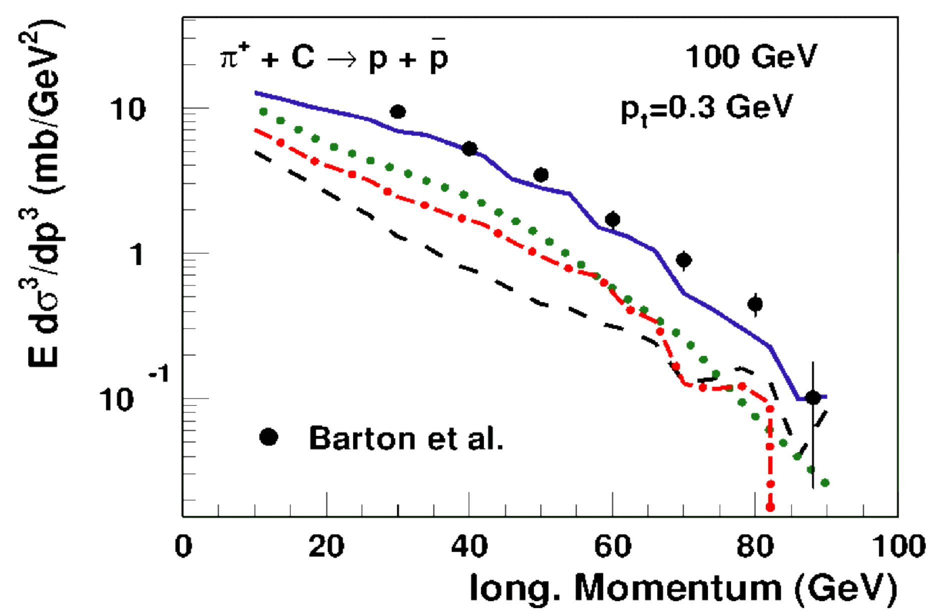
Forward Baryons (low energy)



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

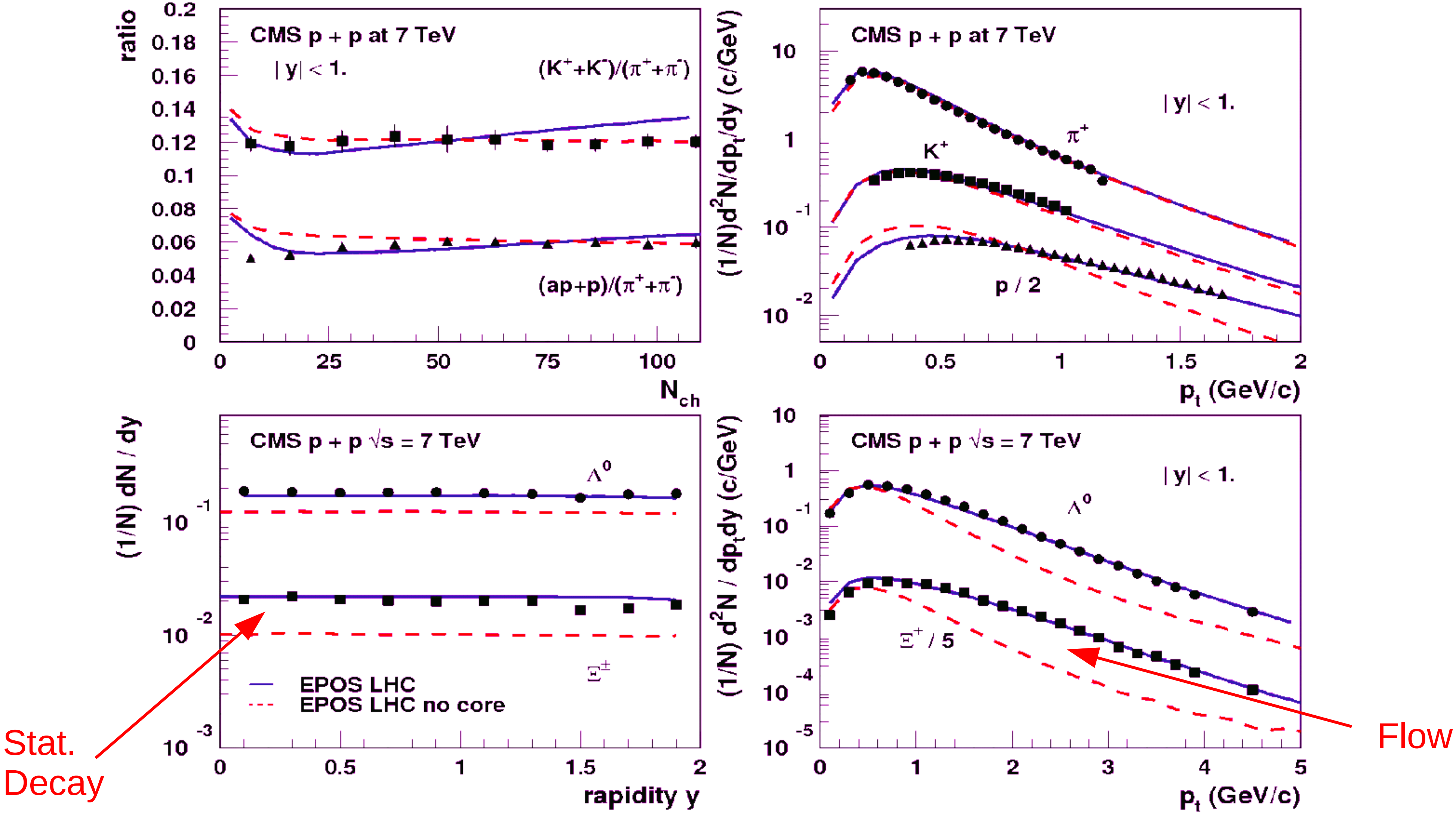
Without remnant, string fragmentation has to be changed for baryon production





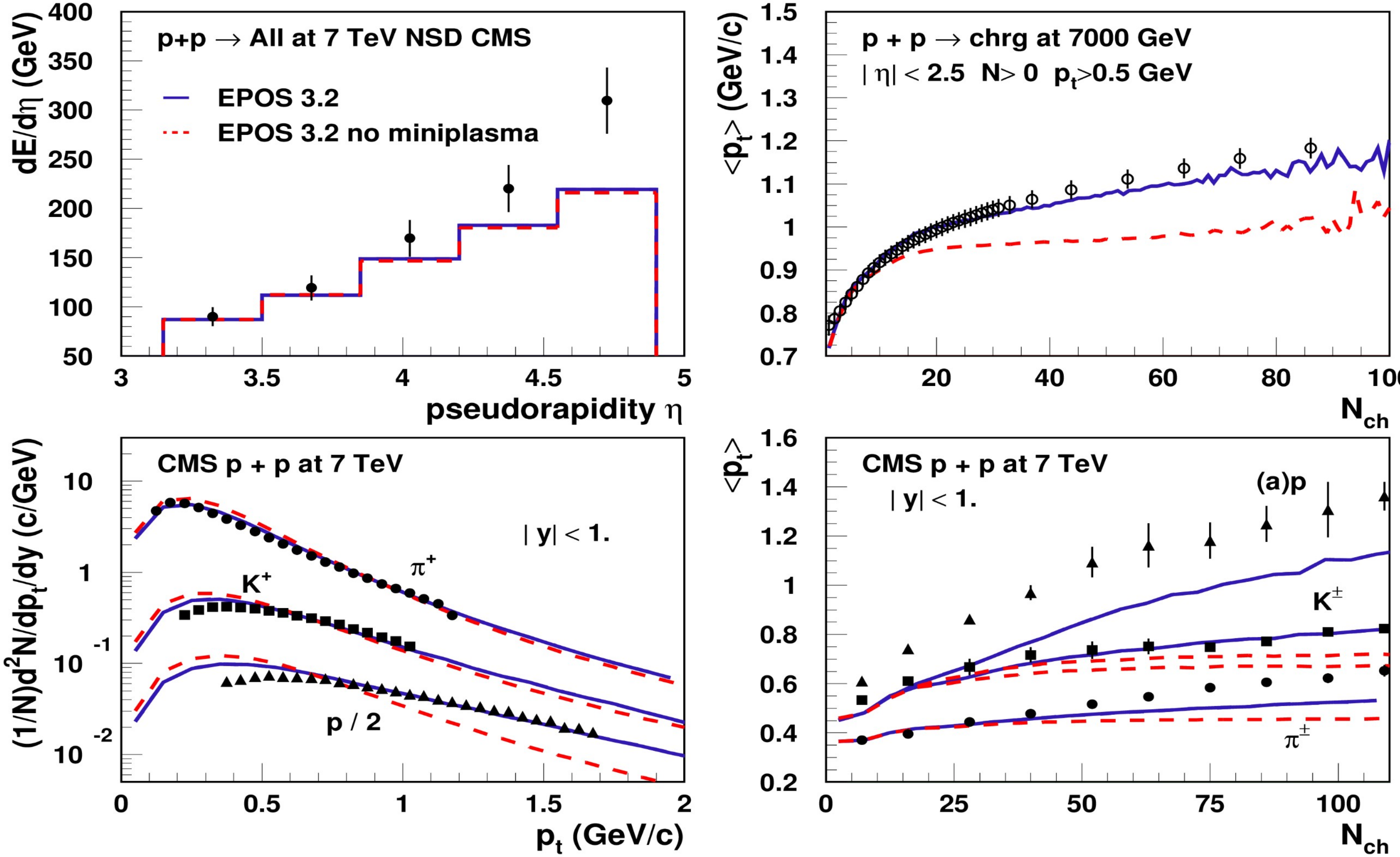
Core Effect on Particle Yield

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



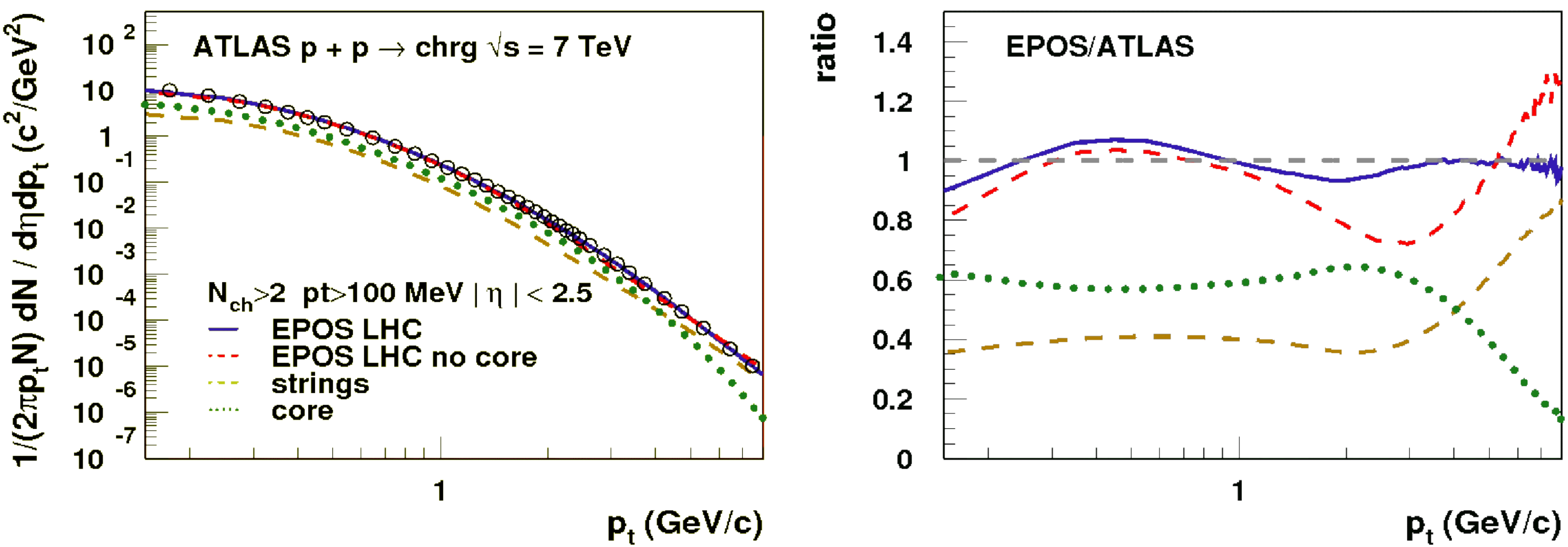
EPOS 3.2

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



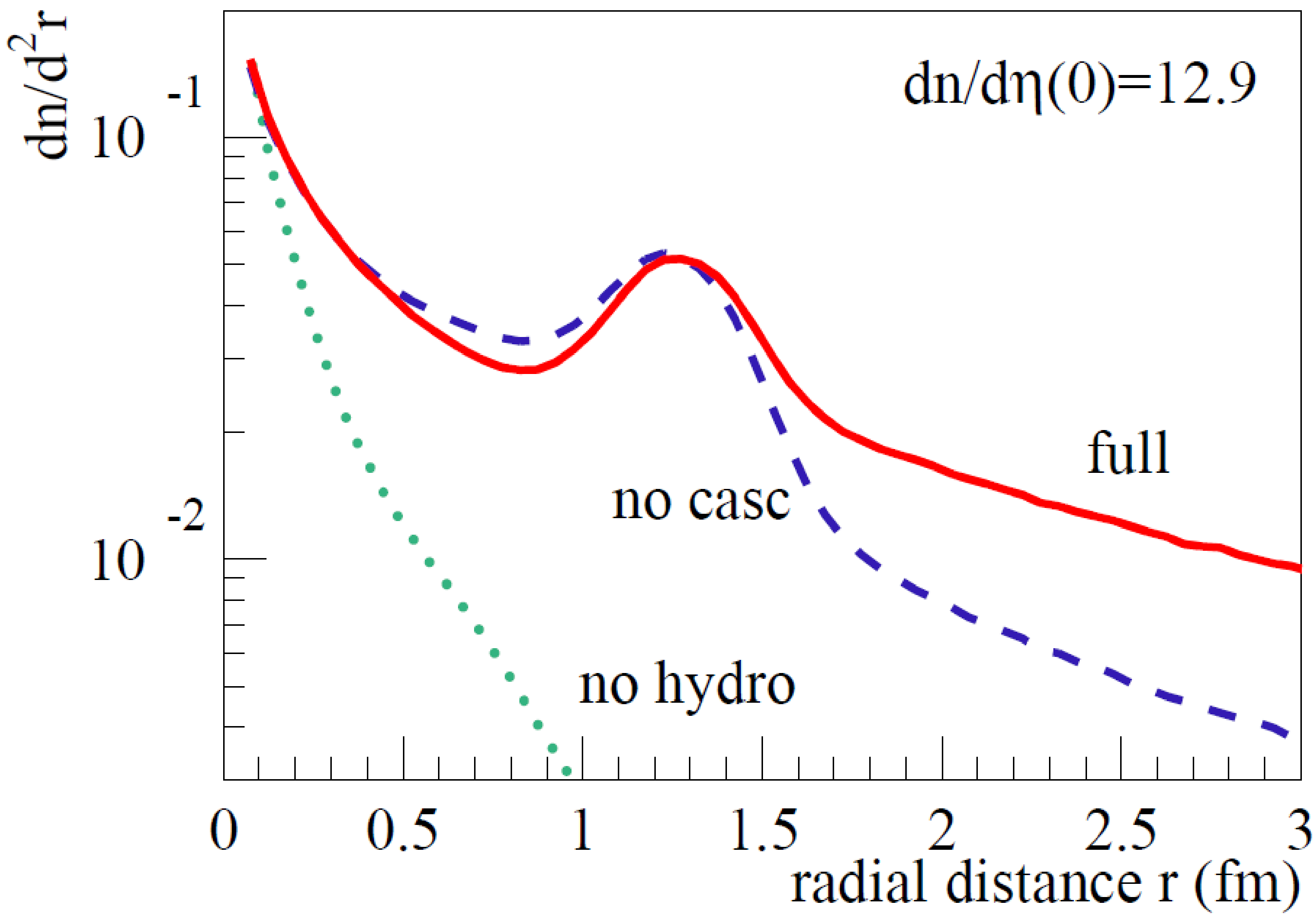
EPOS LHC

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



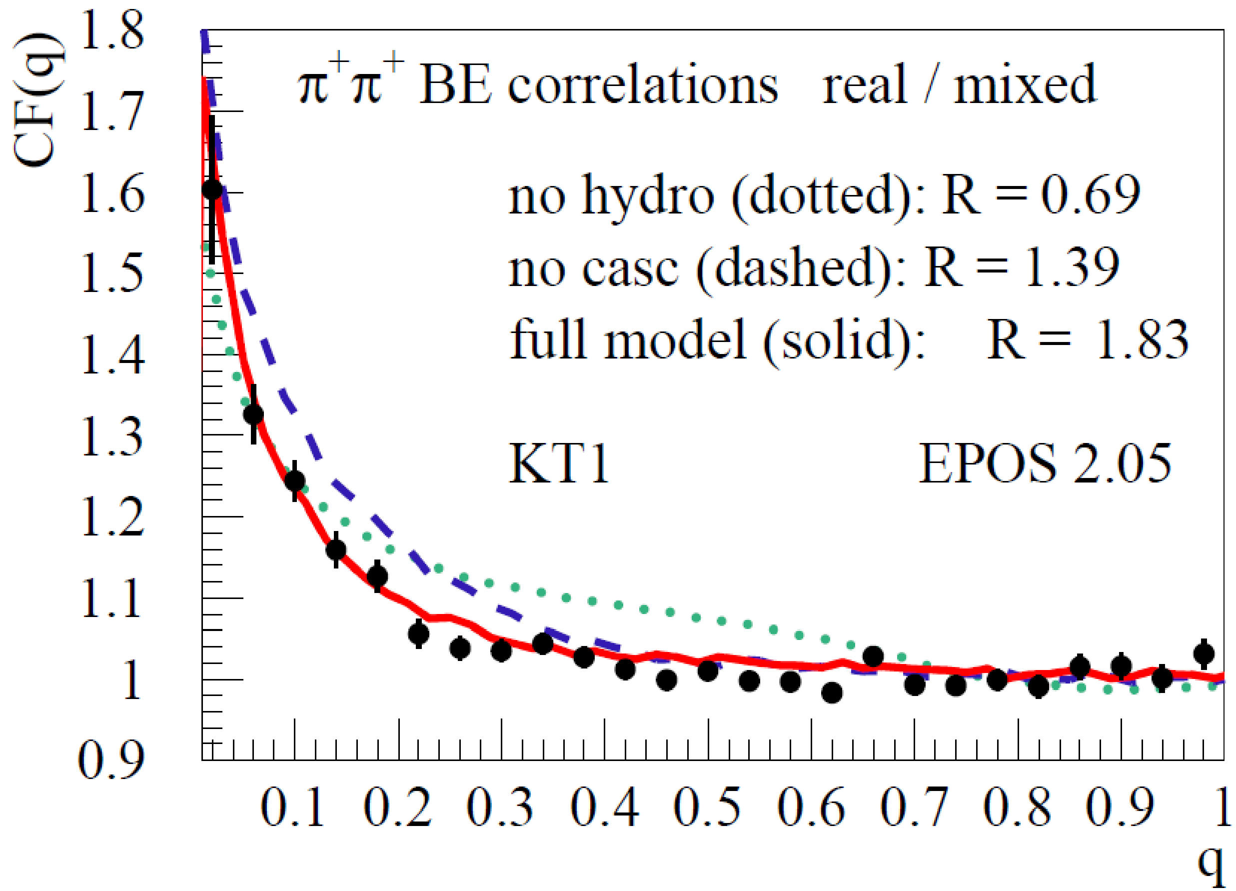
Radius of Particle Emission

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



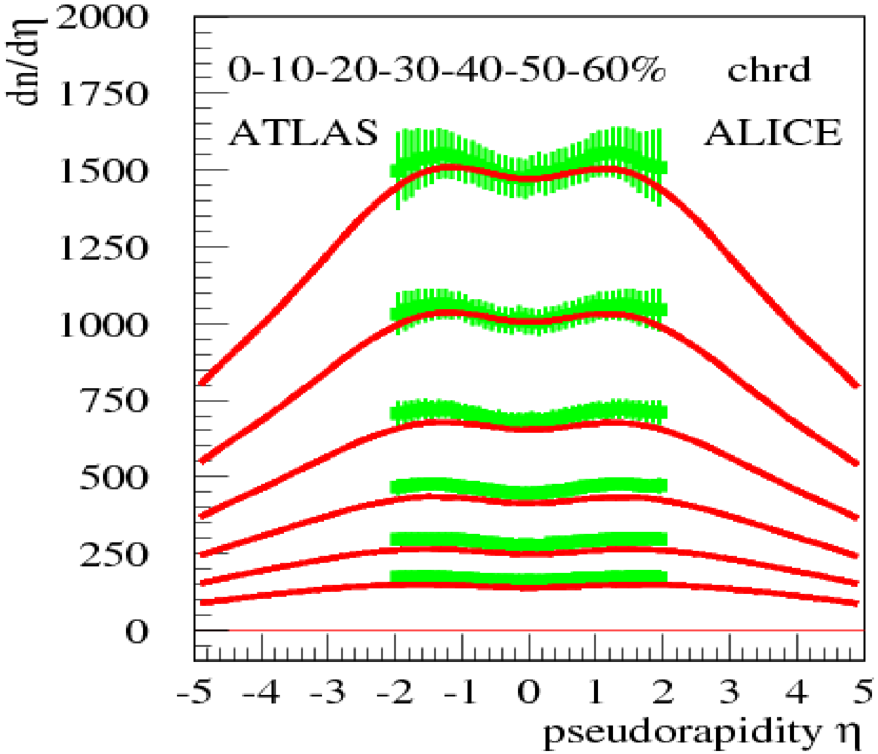
Bose-Einstein Correlations

➡ Consequences for Bose-Einstein correlations

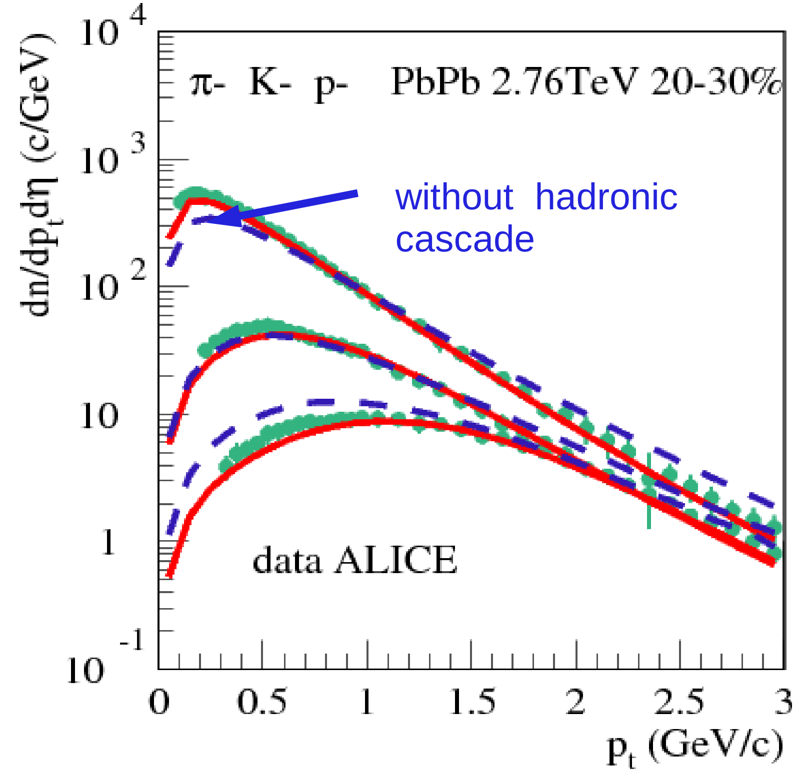


ALICE data. Radii R from exponential fit.
KT1= [100, 250], KT3= [400, 550], KT5= [700, 1000]

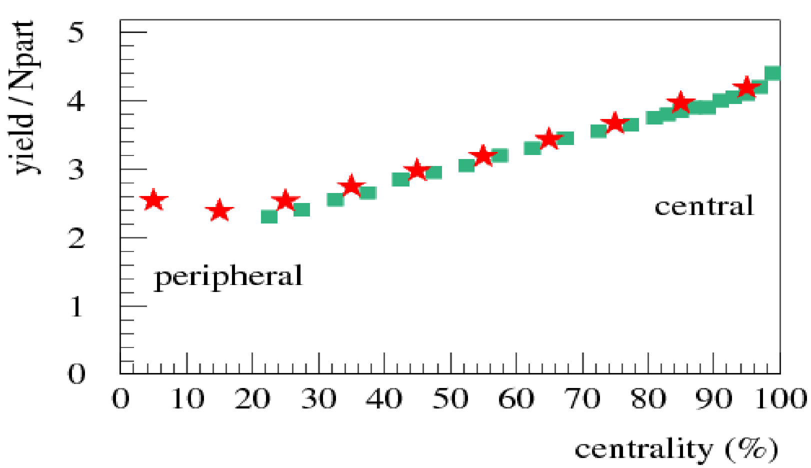
PbPb @ LHC



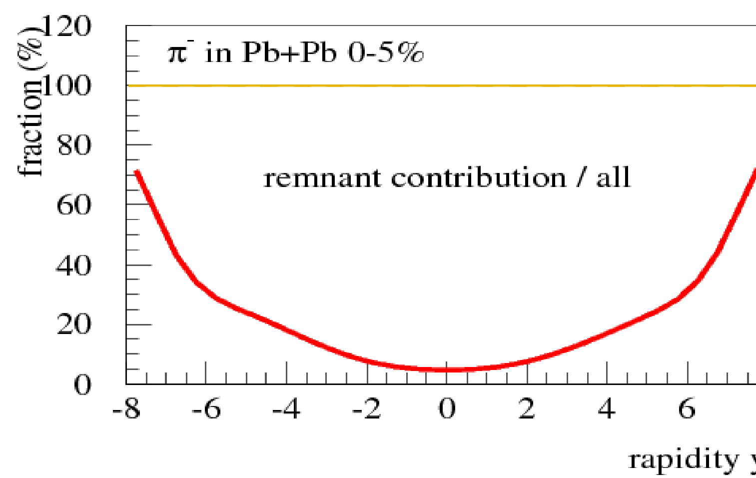
dn/dη
2000
1750
1500
1250
1000
750
500
250
0
0-10-20-30-40-50-60% chrd
ATLAS
ALICE
-5 -4 -3 -2 -1 0 1 2 3 4 5
pseudorapidity η



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

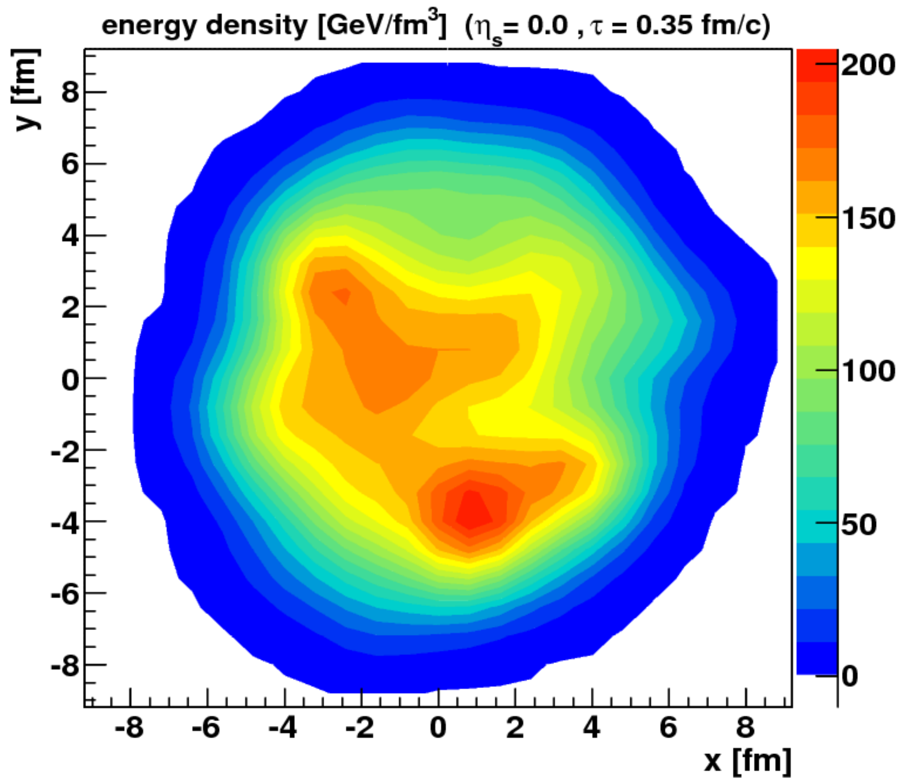


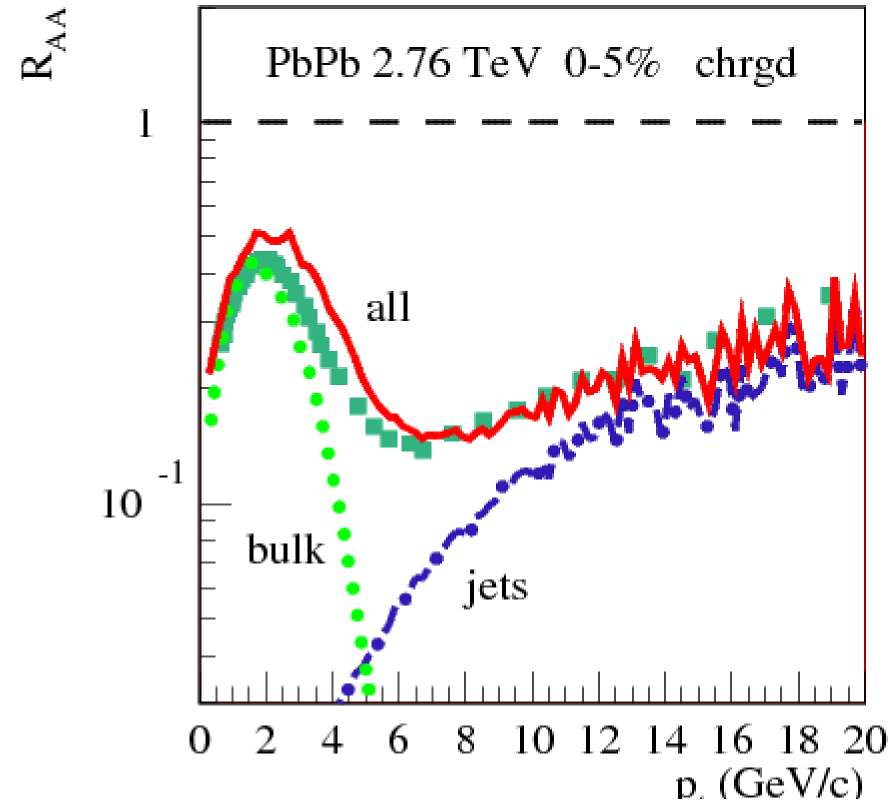
yield / Npart
5
4
3
2
1
0
central
peripheral
0 10 20 30 40 50 60 70 80 90 100
centrality (%)

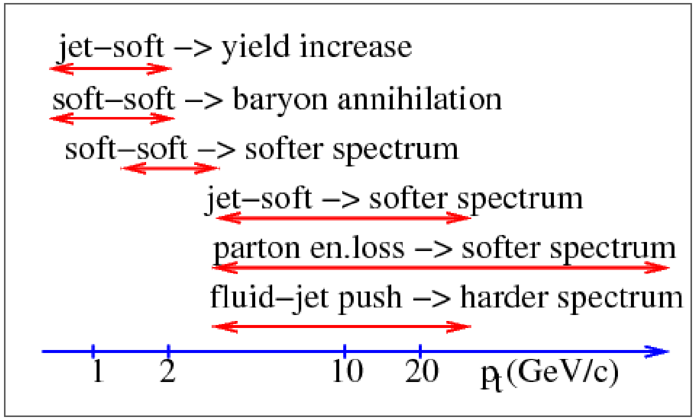


fraction (%)
120
100
80
60
40
20
0
π$^-$ in Pb+Pb 0-5%
remnant contribution / all
-8 -6 -4 -2 0 2 4 6 8
rapidity y

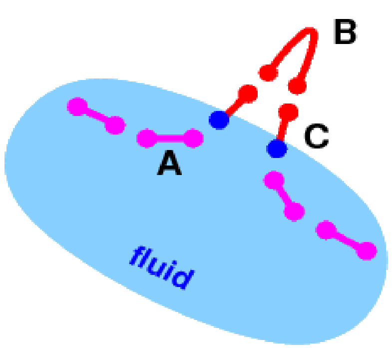
jets in PbPb @ LHC



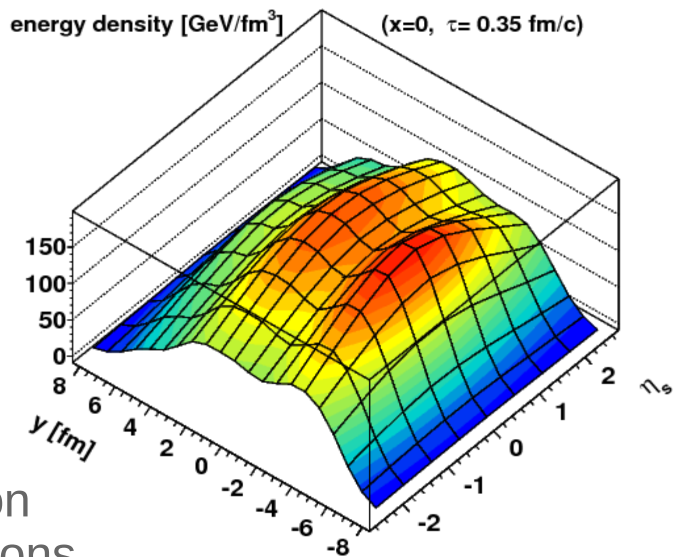




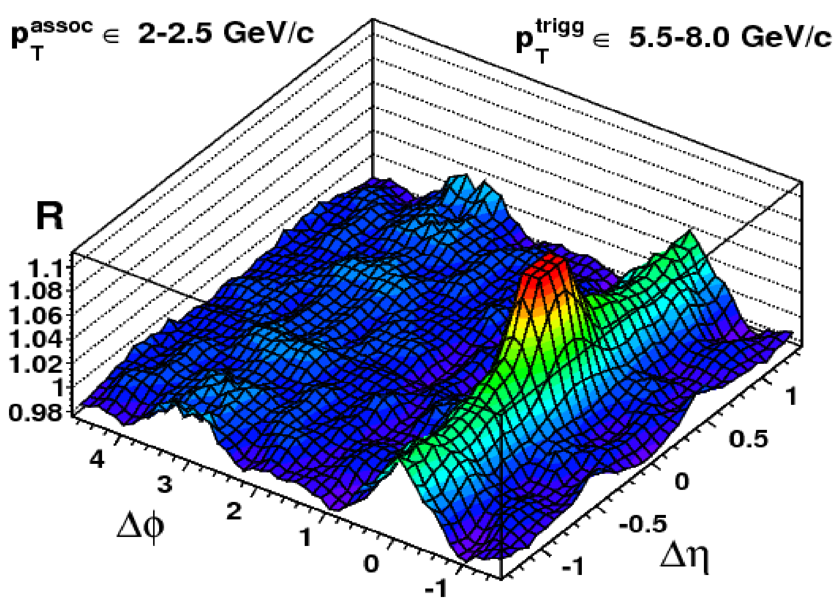
- **Jet interacts in bulk of matter**
  - ➡ parton energy loss
  - ➡ boost at the surface



Correlations in PbPb@LHC



di-hadron correlations



Fourier coefficient for most central events