MPI in EPOS and LHC tune

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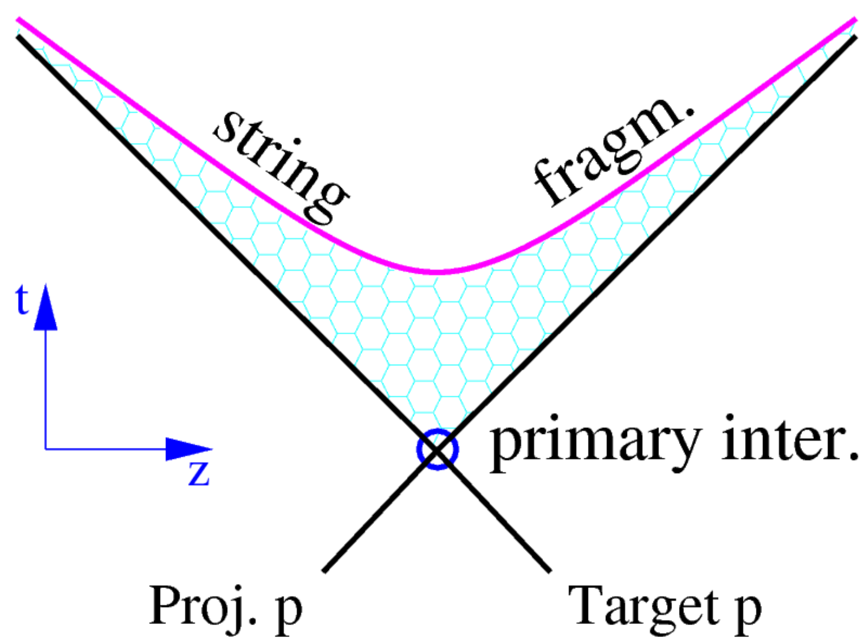
- **Two developments:**
  - Full EPOS (2) : try to understand all pp and AA data above few 100 GeV, do things the best way possible :
    - CPU time is no issue!!
    - See K. Werner's talk on Thursday
  - EPOS LHC (public): simplified version, which is fast, but grasps the essential features of Full EPOS
- **This talk:**
  - EPOS LHC based on EPOS 1.99 used for Cosmic Rays.

Outline

- **Introduction**
- **MPI in EPOS**
- **Collective effects**
  - Particle Production
  - Transverse Momentum
  - Correlations
- **Summary**

High Energy Hadronic Interactions : HEP view

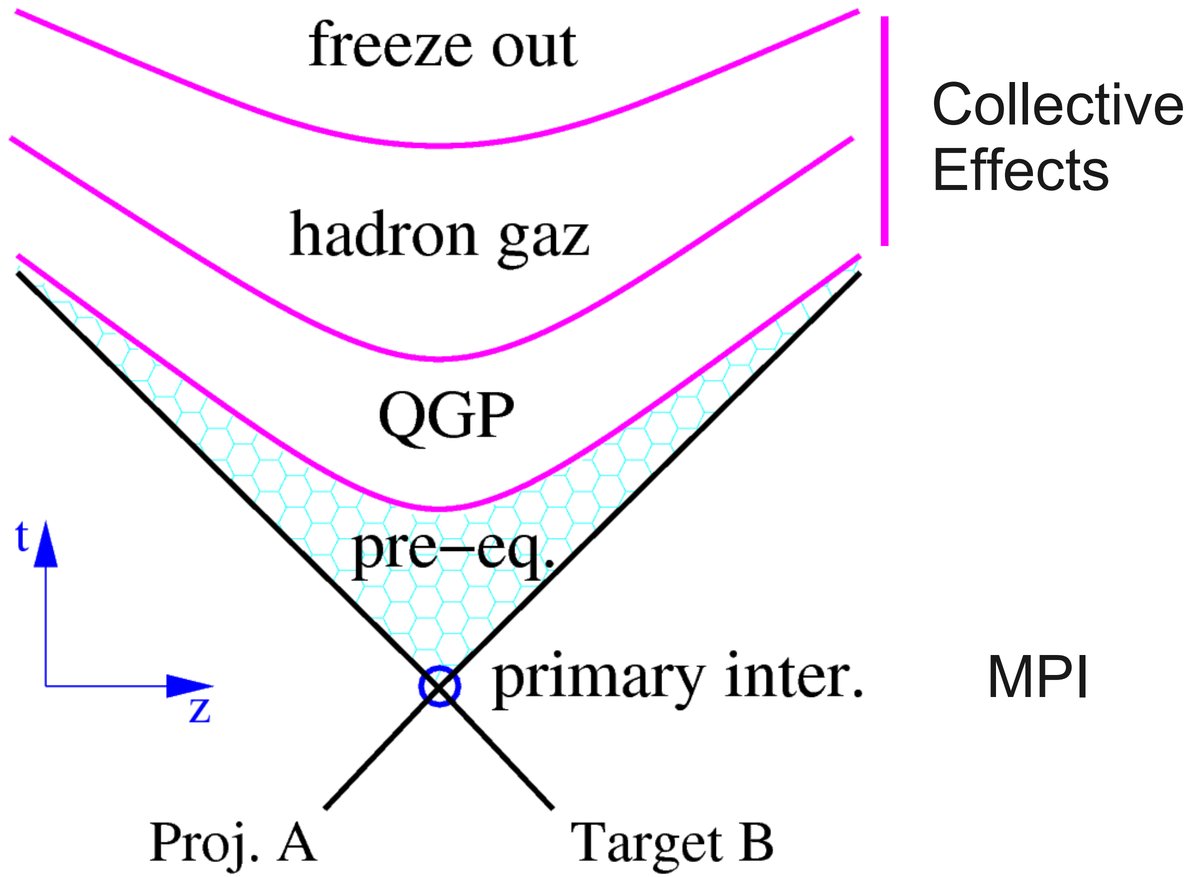


MPI

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

High Energy Hadronic Interactions : Heavy Ion view

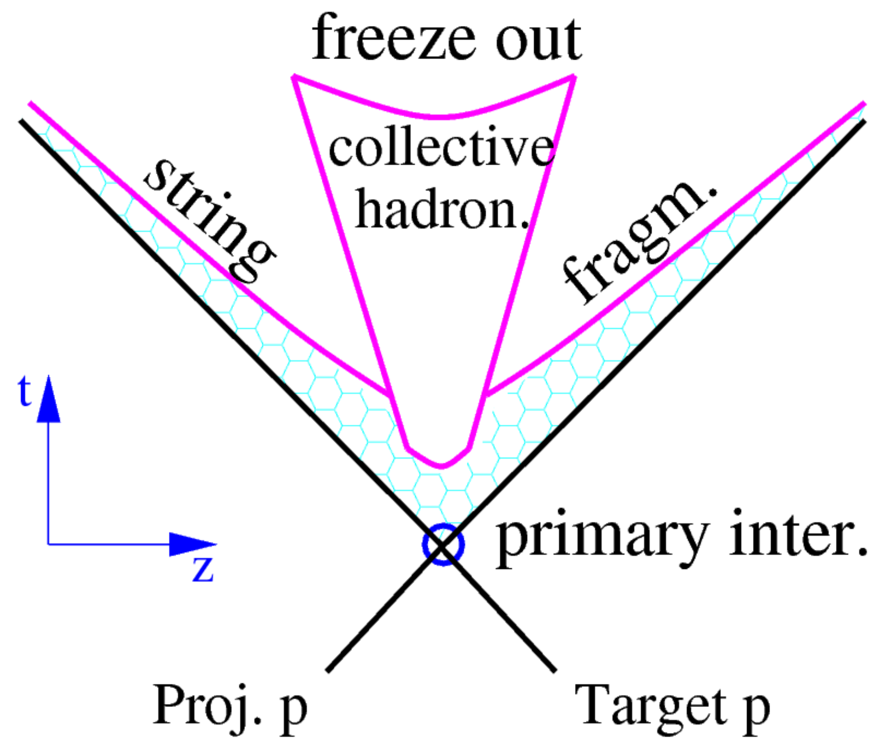
FULL Picture :
see Klaus' talk !



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

High Energy Hadronic Interactions : EPOS LHC

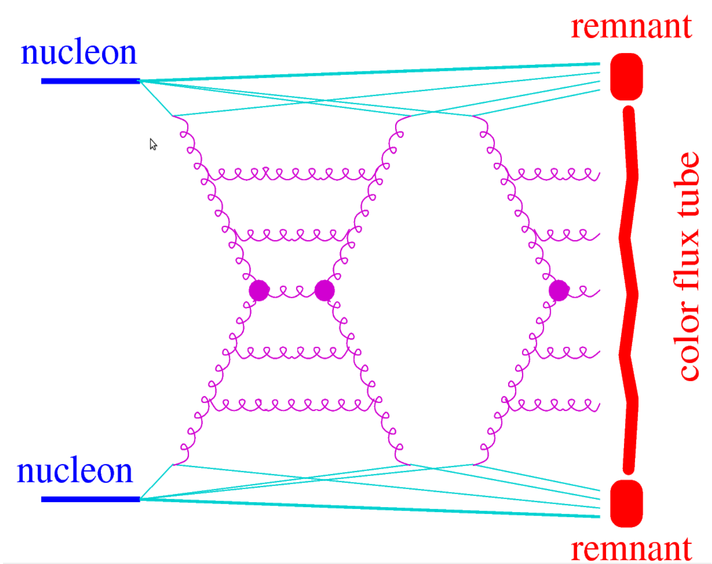
- **Local high energy densities have different hadronization :**
  - Microcanonical decay
  - flow

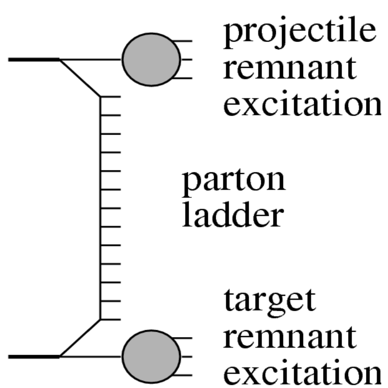


MPI

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

The EPOS Model





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

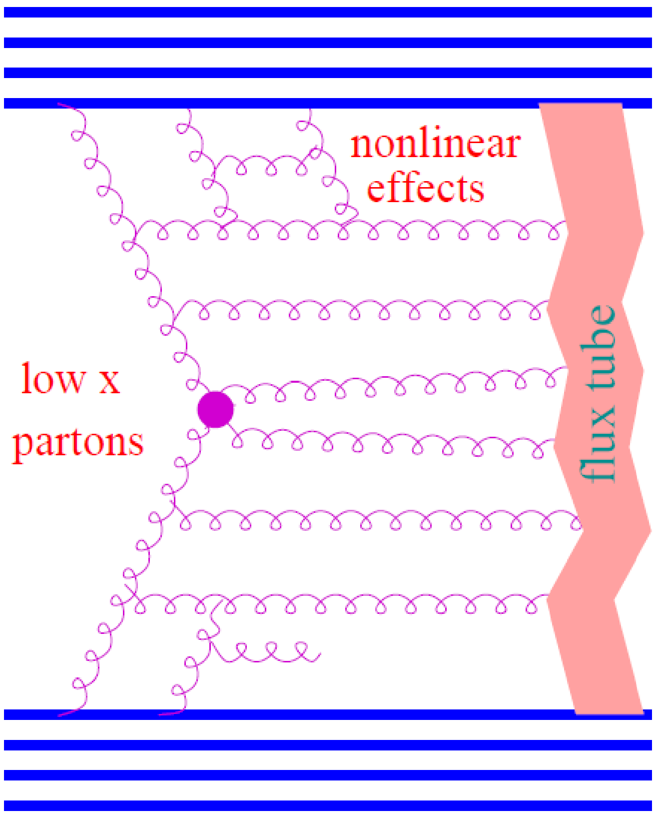
- Energy-sharing : for cross section calculation AND particle production
- Parton Multiple scattering
- Outshell remnants
- Screening and shadowing via unitarization and splitting
- Collective effects for dense systems

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)

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

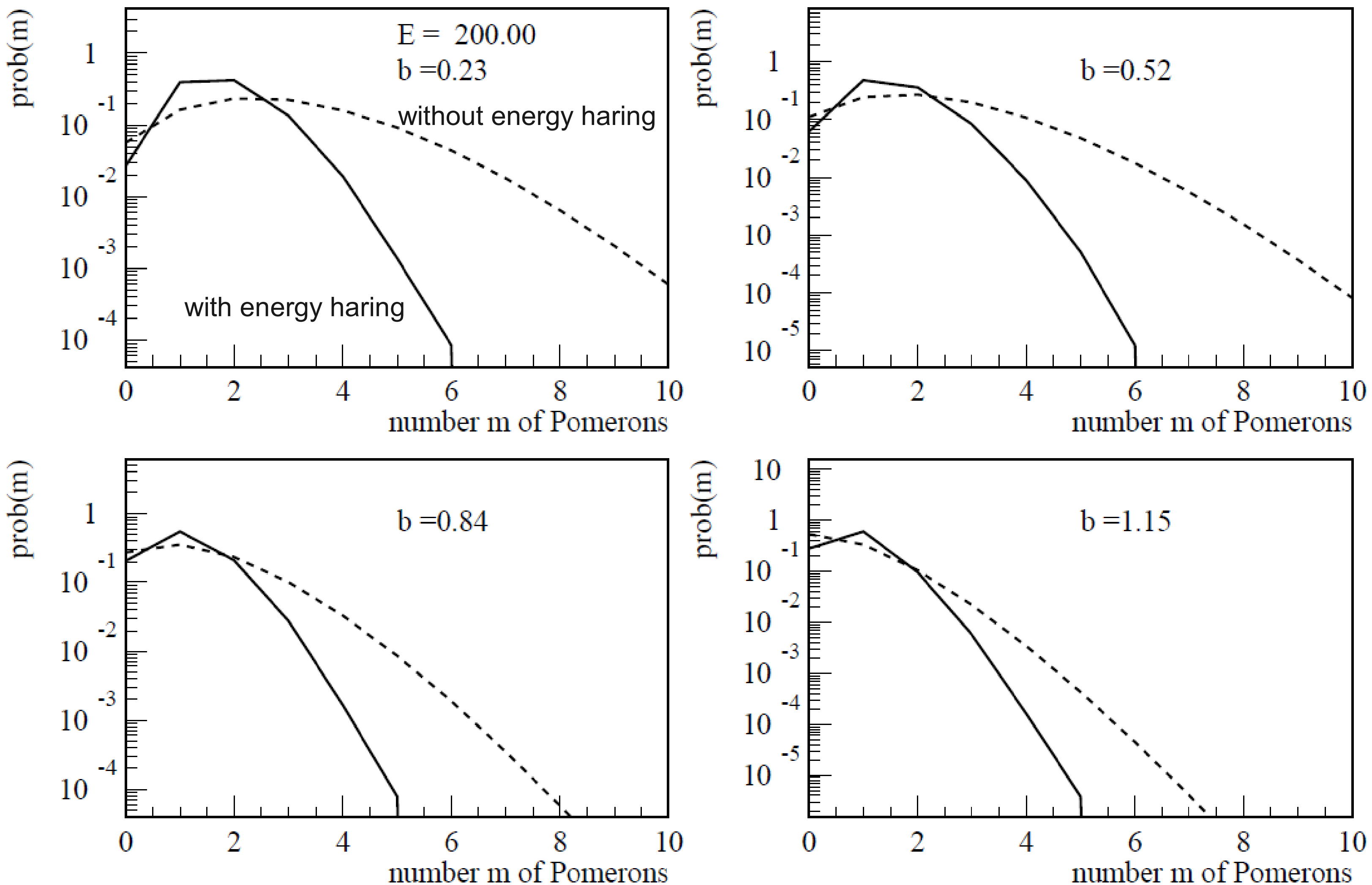


- Parton evolutions from the projectile and the target side towards the center (small x)
- Evolution equation
  - DGLAP
- Parton ladder = quasilongitudinal color field (“flux tube”)
  - relativistic string
- Intermediate gluons
  - kink singularities in relativistic strings
- Fragmentation : production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

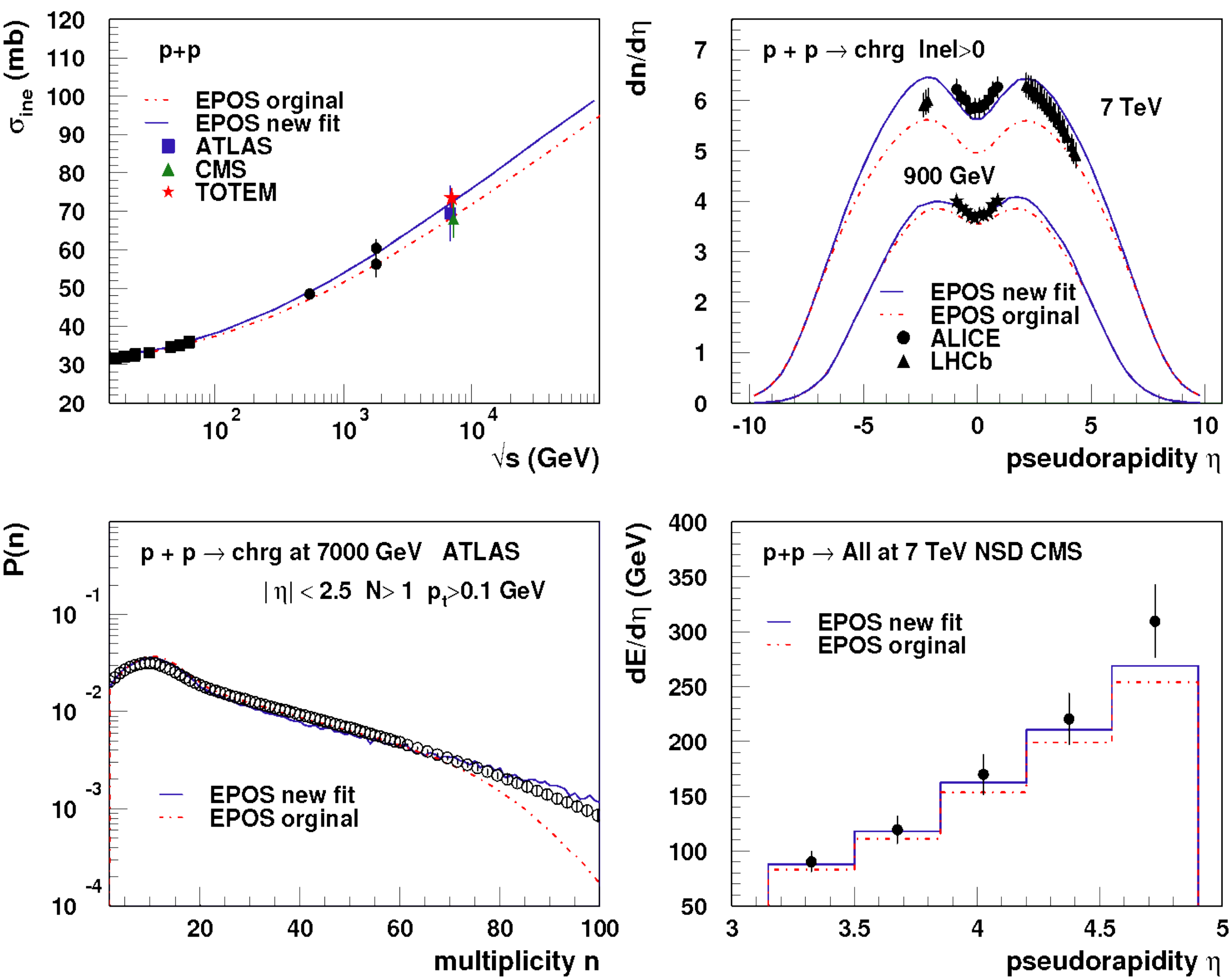
Parton-based Gribov-Regge Theory, H. J. Drescher, M. Hladik, S. Ostapchenko, T.Pierog, and K. Werner, Phys. Rept. 350 (2001) 93-289;

Number of Pomerons (flux tube and MPI)

- Fluctuations reduced by energy sharing (mean can be changed by parameters) : not Poissonian



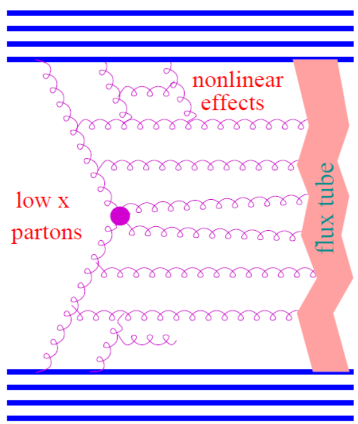
Cross-section and MPI

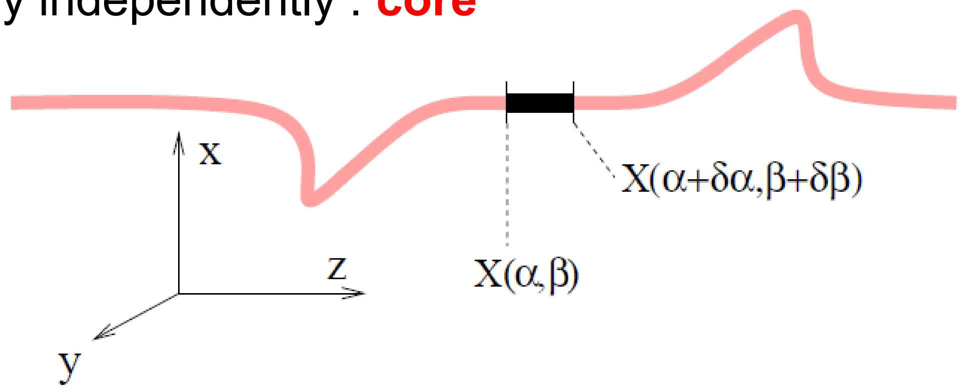


- **With TOTEM cross section:**
  - new xsection fit
  - only 1 parameter changed (max screening (saturation) lowered by 10%)
    - Multiplicity OK
    - Energy flow OK
  - link between cross-section and MPI OK

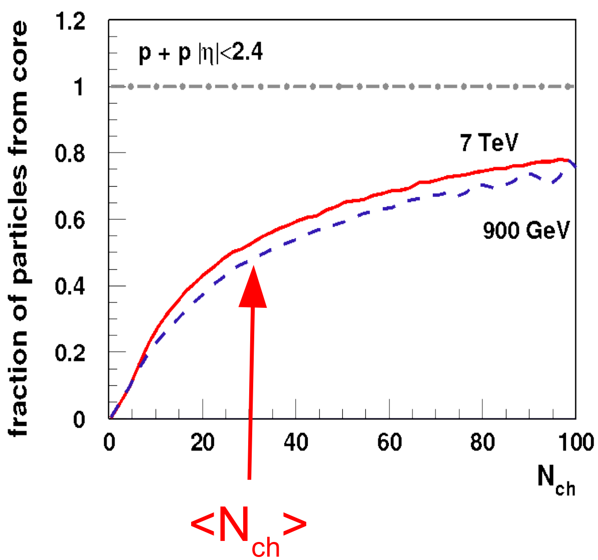
High Density Core Formation

- **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**

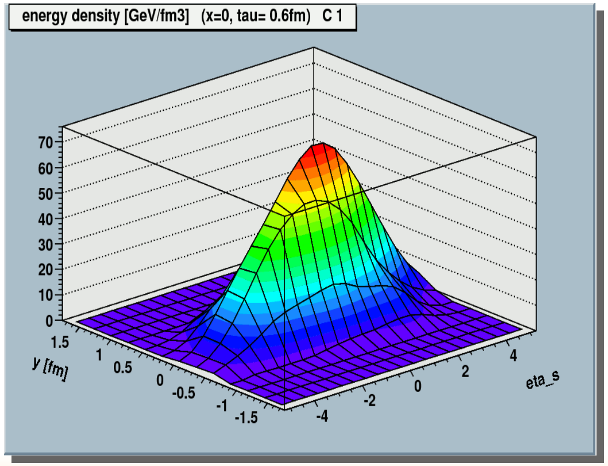




- Each string splitted into a sequence of string segments, corresponding to widths δα and δβ in the string parameter space

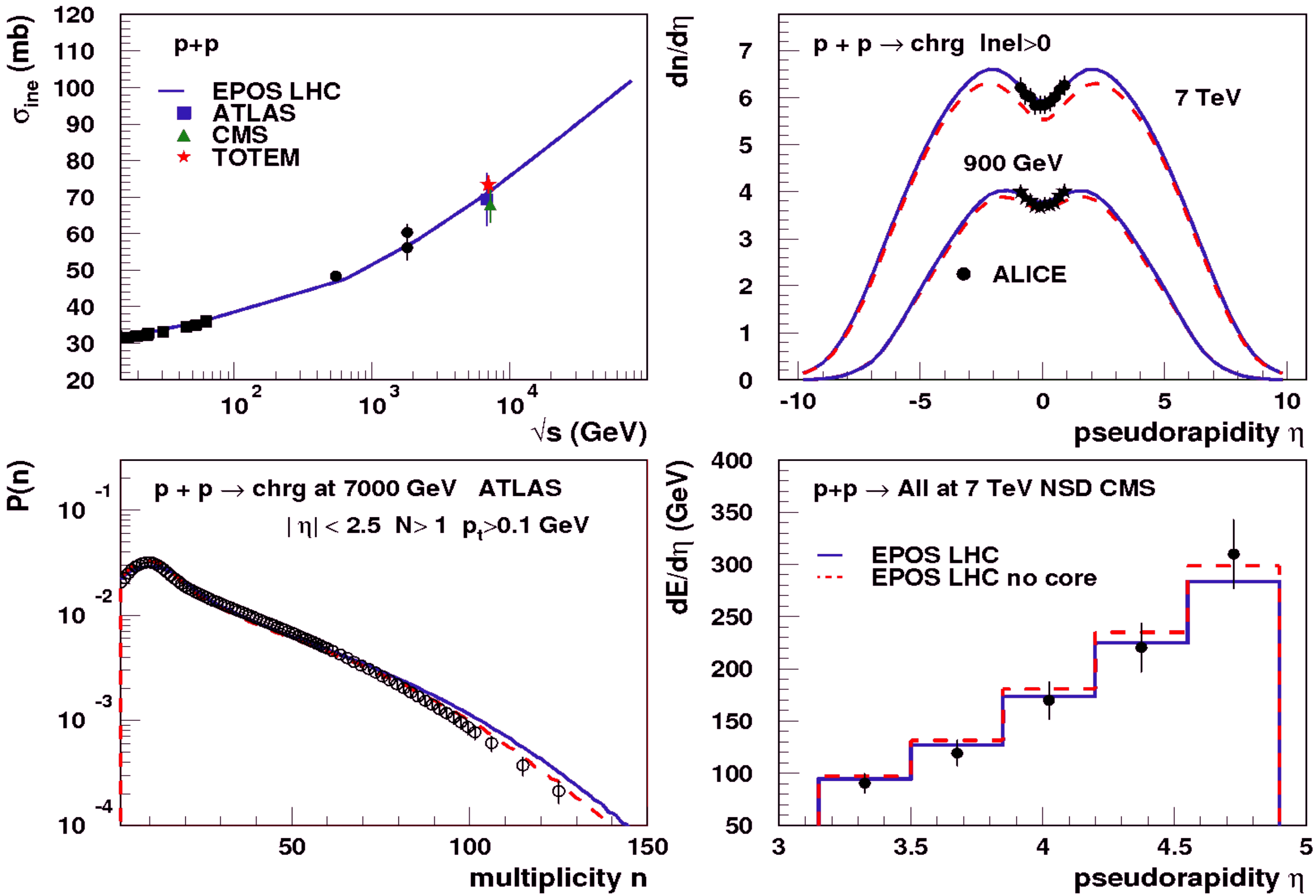


- If energy density from segments high enough
  - segments fused into core
    - statistical decay
    - flow from expansion
- If low density (corona)
  - segments remain hadrons
    - string fragmentation



Core Effect on Total Multiplicity

- Core hadronization doesn't change general event description.



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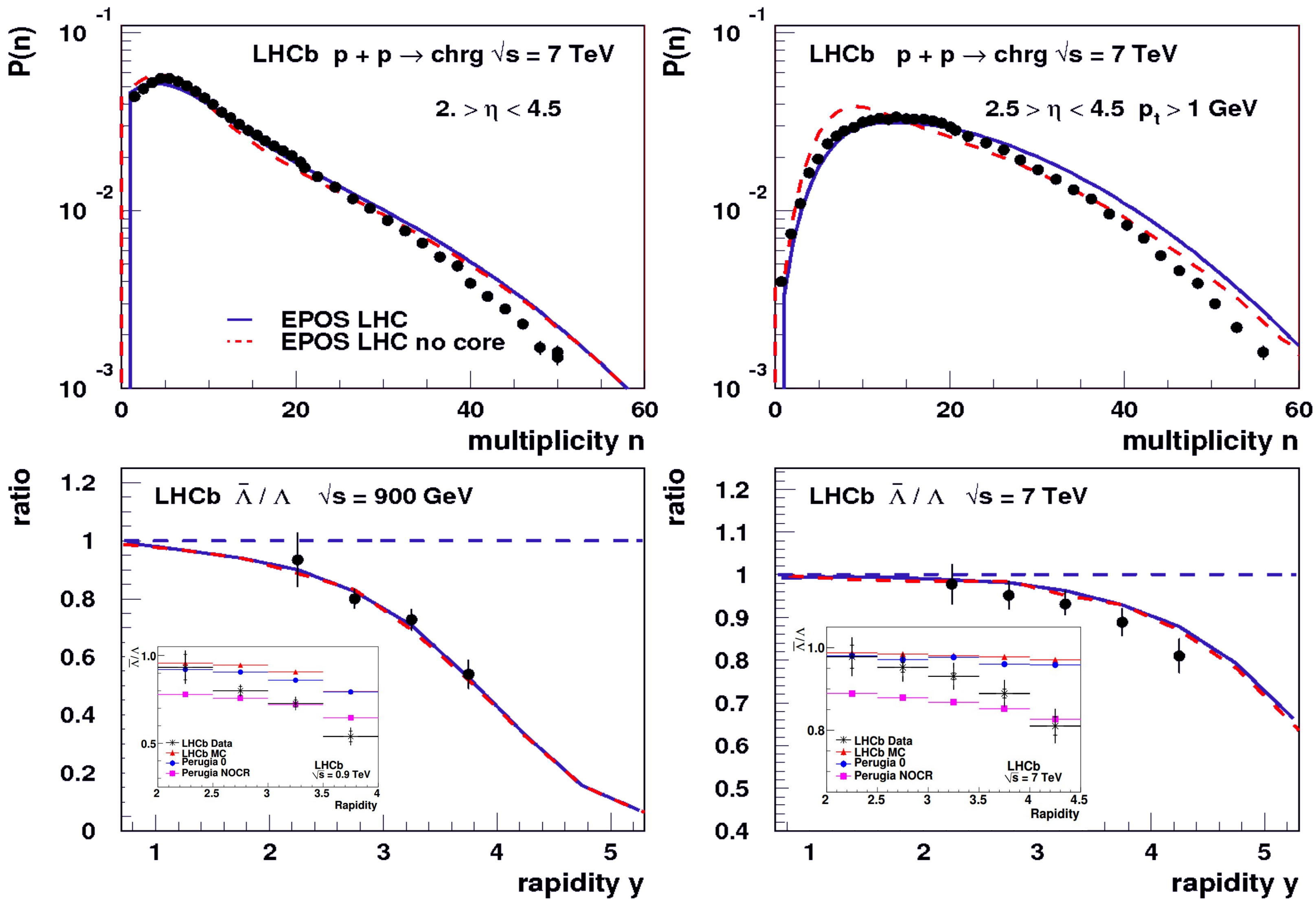
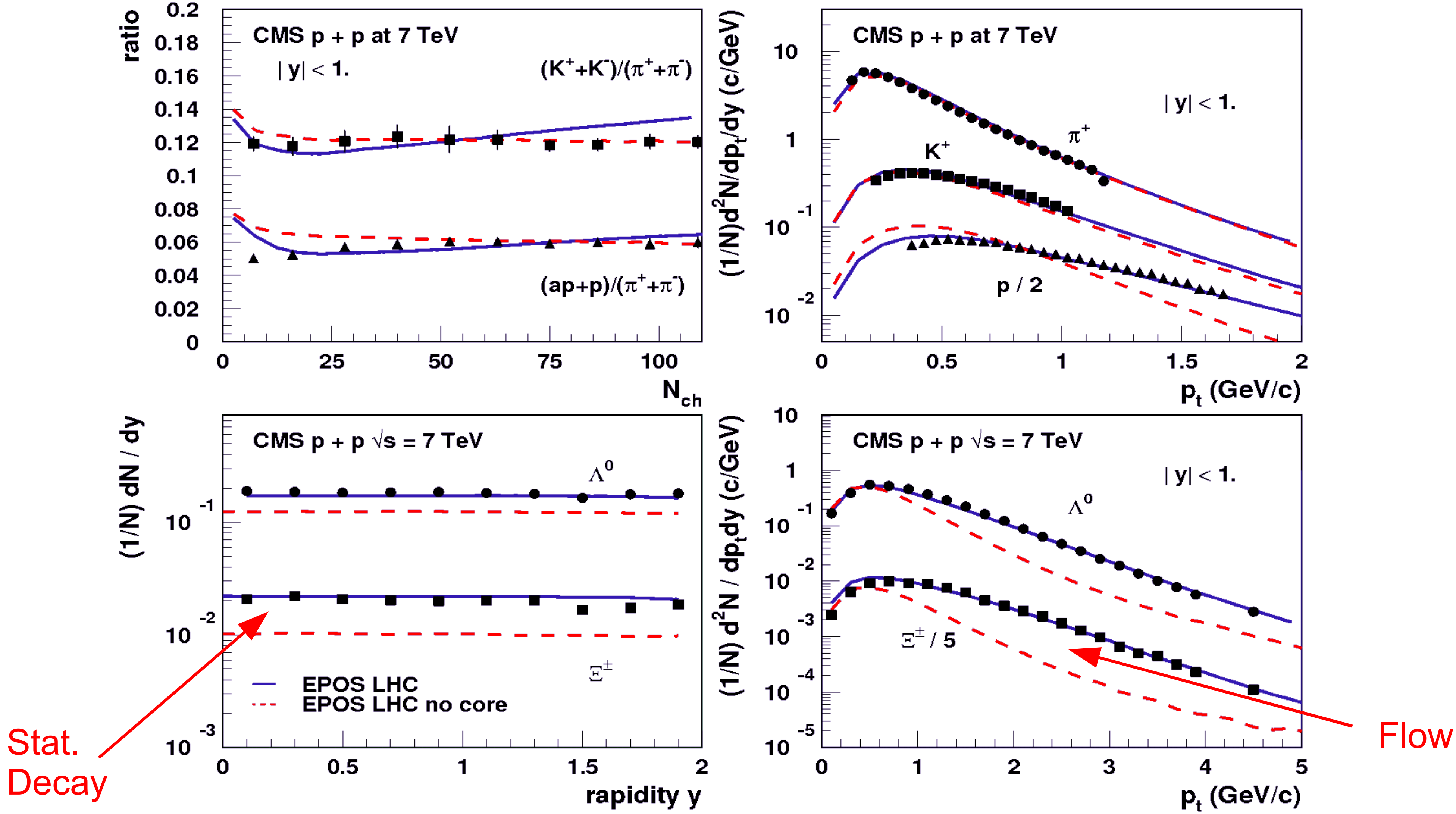


Remnant effect for baryon transport

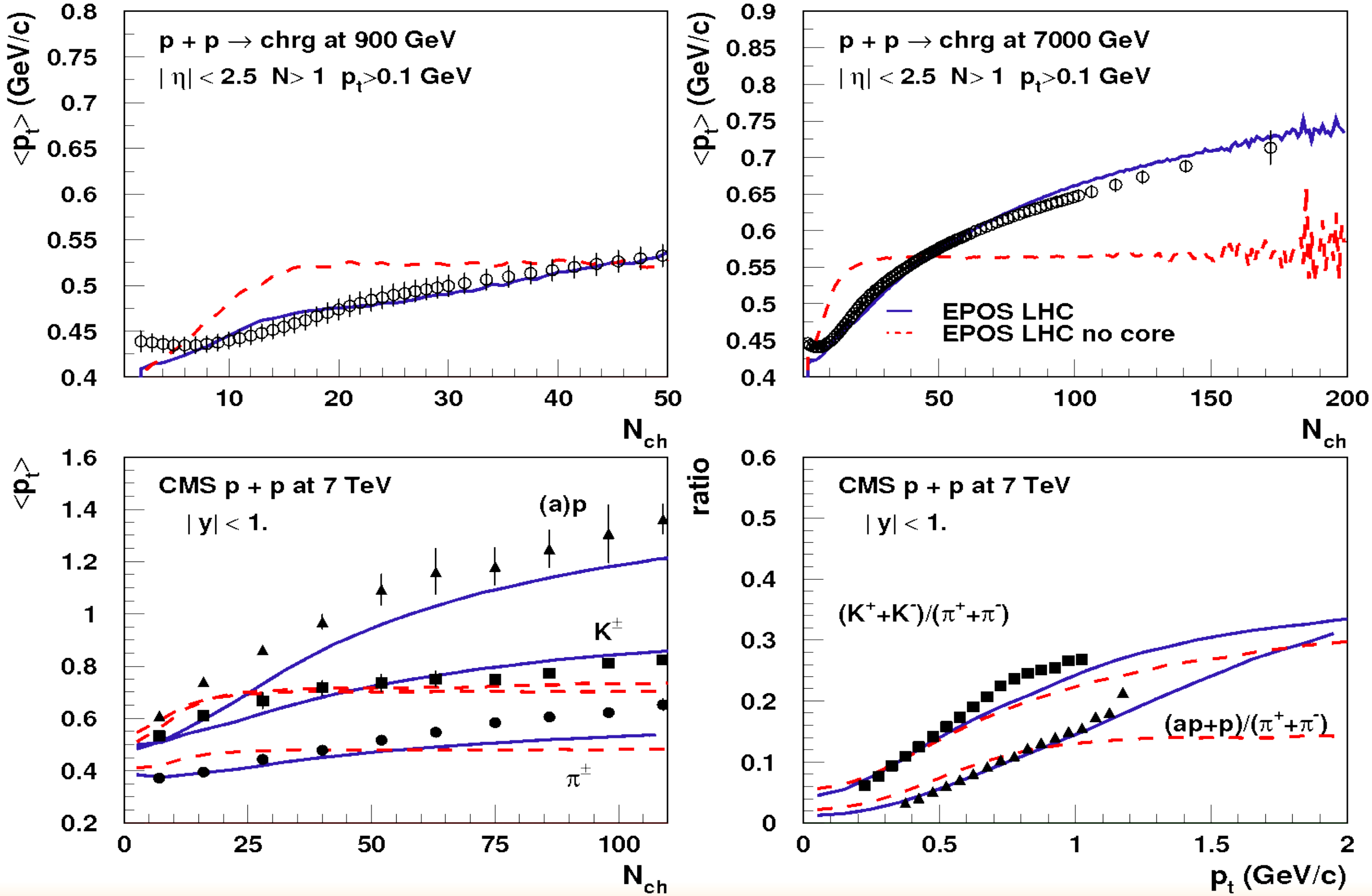
Core Effect on Particle Yield

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



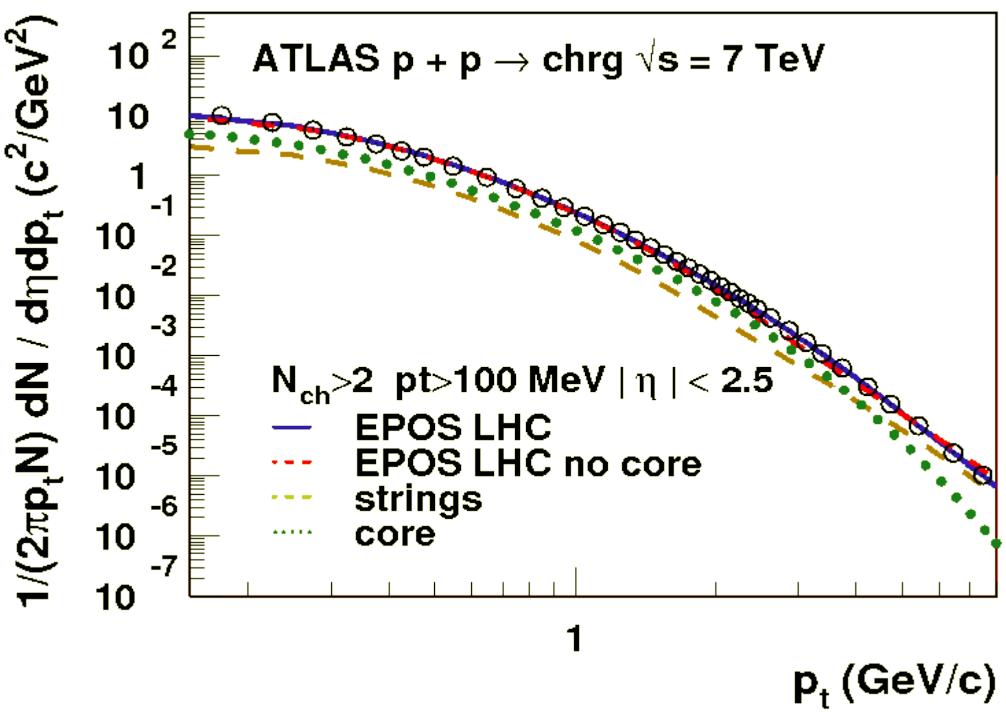
EPOS LHC

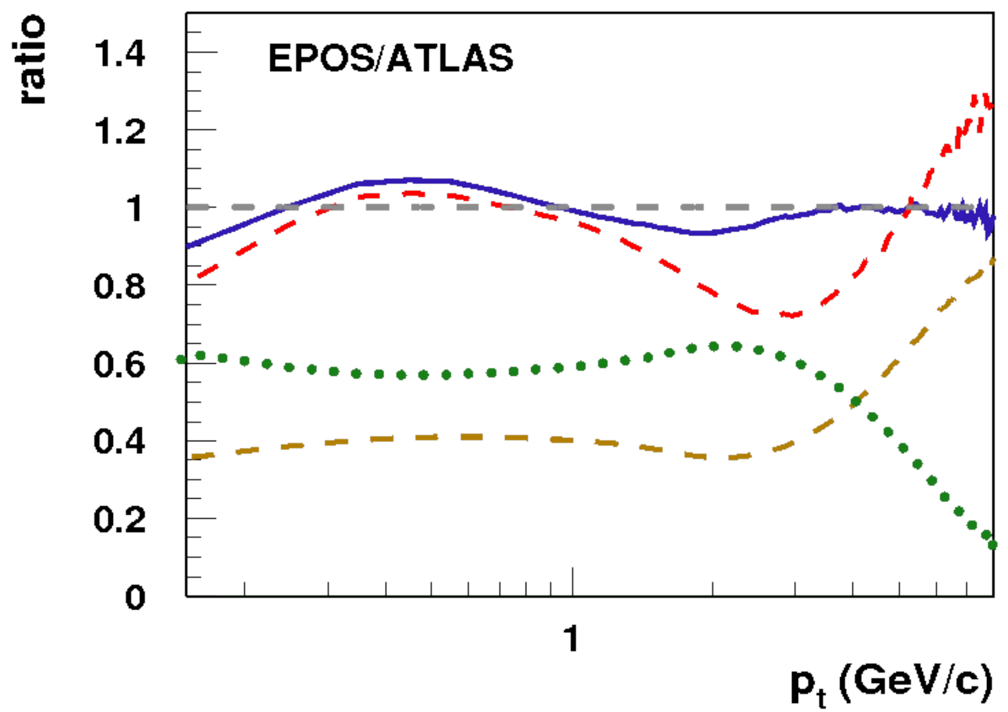
- **Detailed description can be achieved**
  - identified spectra
  - p_t behavior driven by collective effects (flow)



EPOS LHC

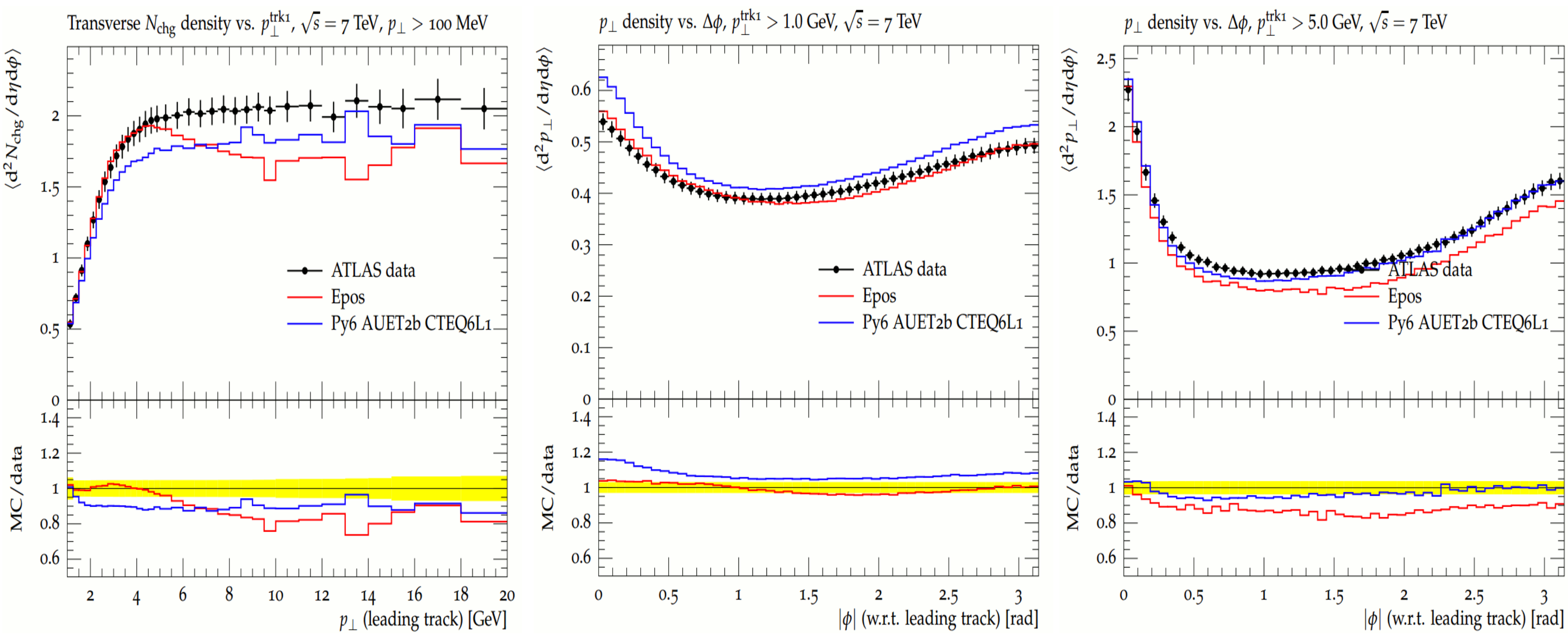
- **Detailed description can be achieved**
  - p_t behavior driven by collective effects (flow)
    - particles with $p_t \sim 0.5$ GeV/c boosted up to p_t=2-3 GeV/c
    - high p_t particles ($p_t \sim 10$ GeV/c) suppressed by energy loss in fluid
  - spectrum dominated by string (jet) particles only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





Underlying Events

- **EPOS fails to describe correlation with high p_t track**
  - but often better for low p_t track
- **Problem with hard scales**
  - same saturation applied to all Q^2 : good for soft but not for hard !



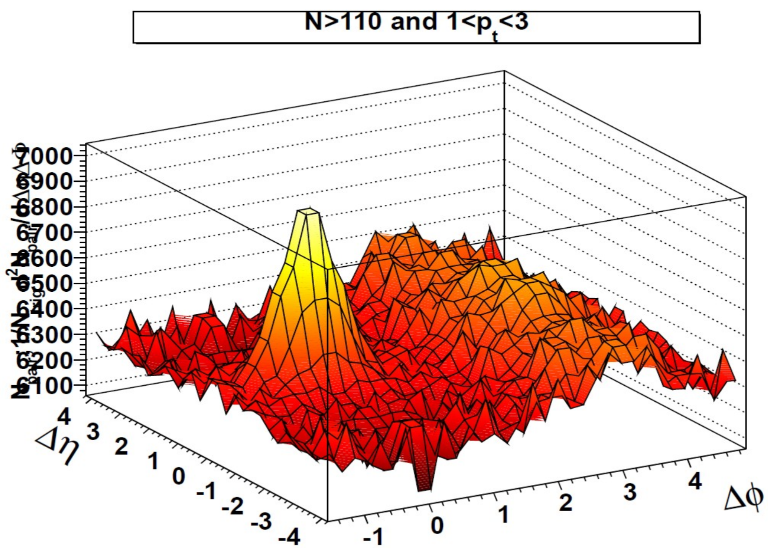
plots by Elena Yatsenko

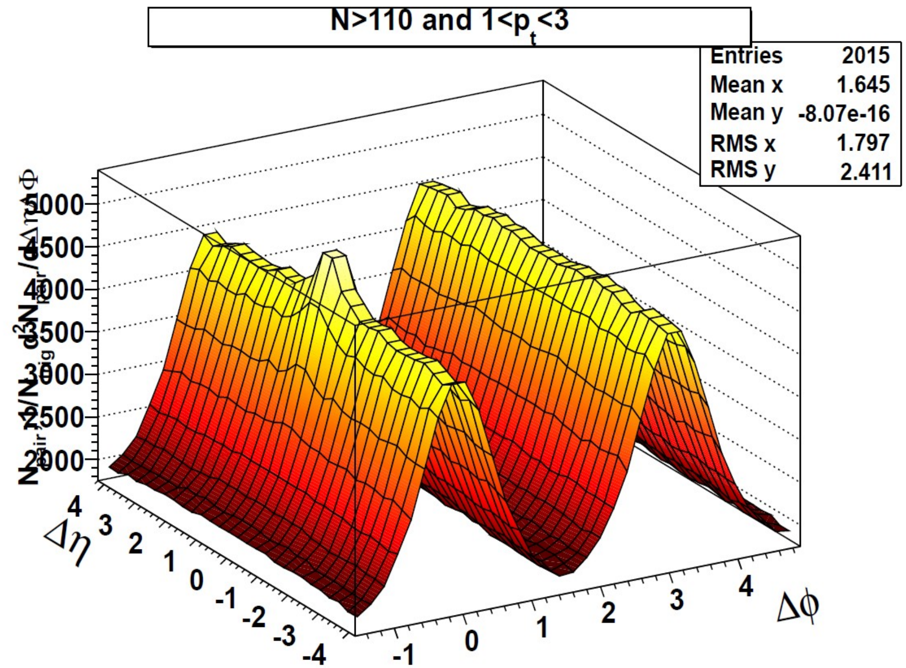
Di-hadron Correlation

- **High density core treated in pseudorapidity slides**
  - conserve local asymmetries
  - asymmetries are coming from strings : invariant in pseudorapitity
  - formation of a "ridge"

p-Pb

no core





with core

- **Correlations better treated in EPOS 2 :**
  - Bose Einstein correlations, ridge, etc ...
  - see K. Werner's talk

plots by Colin Baus

Summary

Many observables difficult to describe by HEP MC

- can be understood with a partial statistical hadronization boosted by a flow:
  - particle ratios
  - $<p_t>$ vs Nch vs particle mass
  - correlations (ridge, Bose-Einstein...)
- could be implemented in any MC after string fragmentation (even after color reconnection (transition at low N_{ch}))

EPOS LHC

- with TOTEM cross section, multiplicity well described (incl. LHCb) : MPI under control
- antibaryon-baryon ratio well described at all energies : good remnant treatment
- using a corrected flow, tune of p_t and $<p_t>$ possible for all particles species
- available in CMS, ATLAS and LHCf software frameworks

On-going developments :

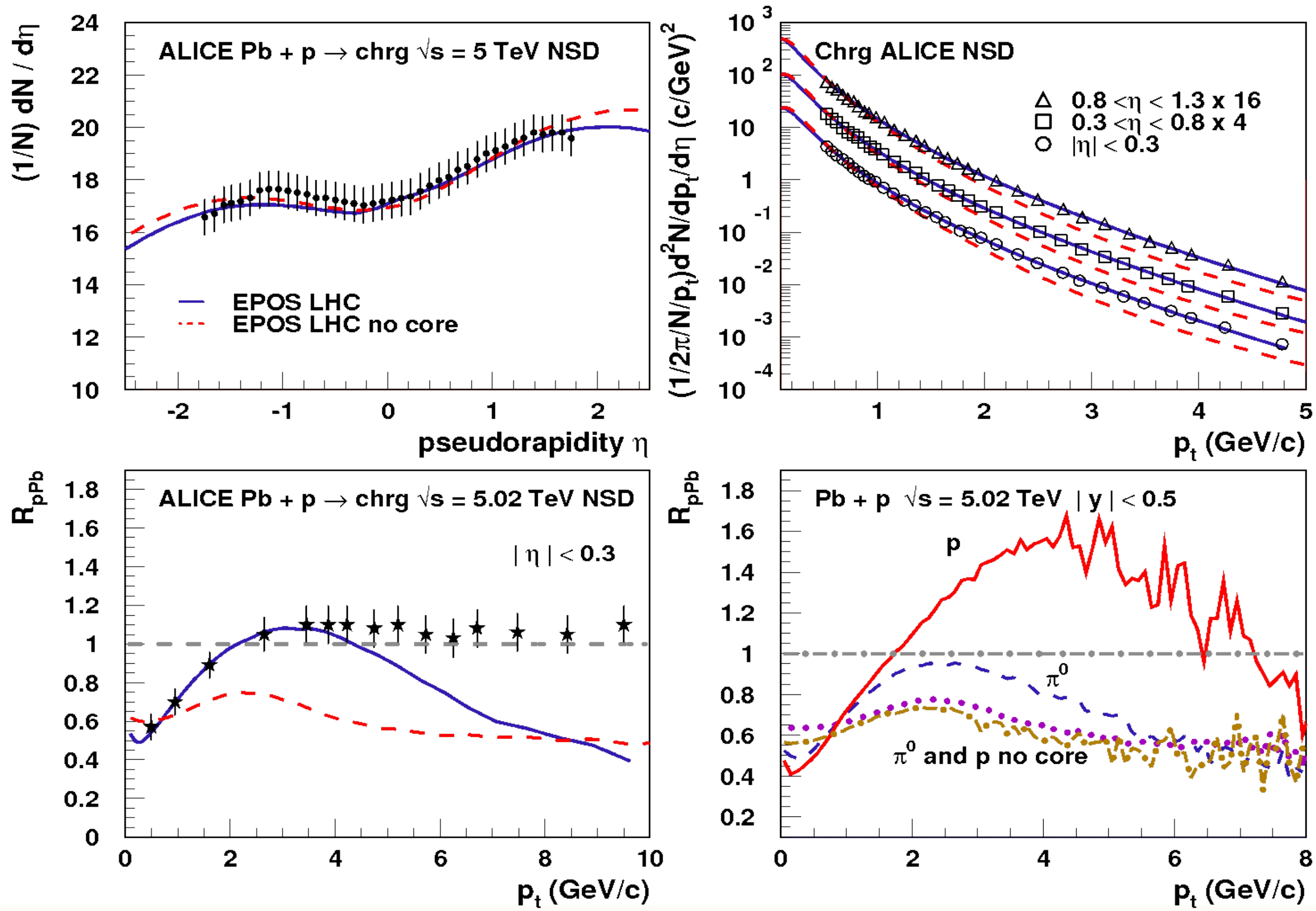
- Test all Min Bias LHC data
- Improvement of hard events (jets) in MB

p-Pb : Increased Effects

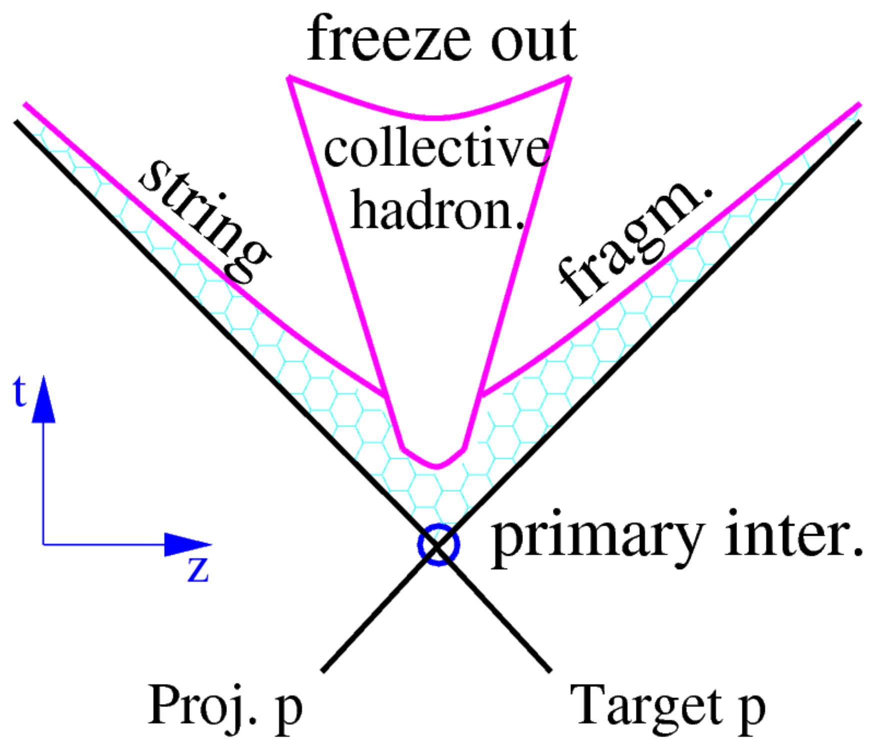
- **Flow depends on N_{ch}**
  - large N_{ch} more often in pPb than in pp but same strength for same N_{ch}
  - R_{pPb} mass dependent (like in dAu @ RHIC) : for p_t < 6 GeV/c, R_{ppb}=1 by chance ?

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

Initial state suppression artificially too strong at high p_t : same problem than for UE.

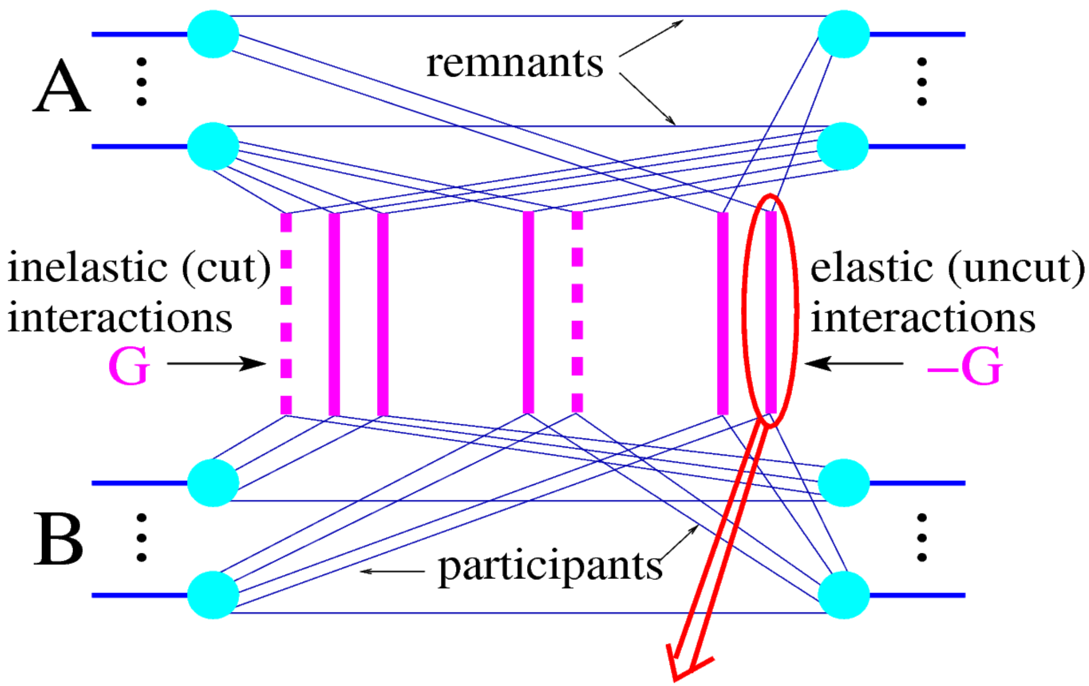


Thank You !

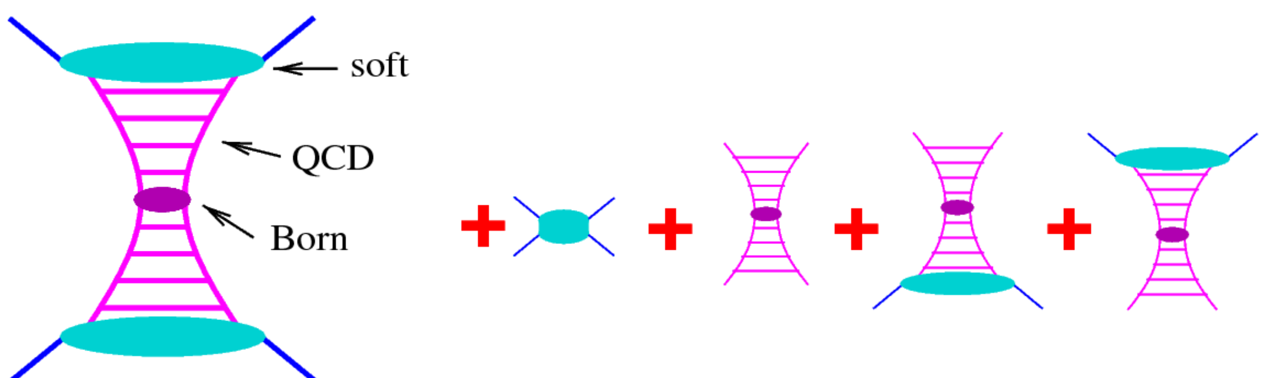


freeze out
collective
hadron.
string
fragm.
t
z
primary inter.
Proj. p
Target p

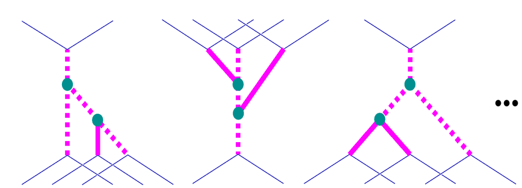
Parton-Based Gribov-Regge Theory



- **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)

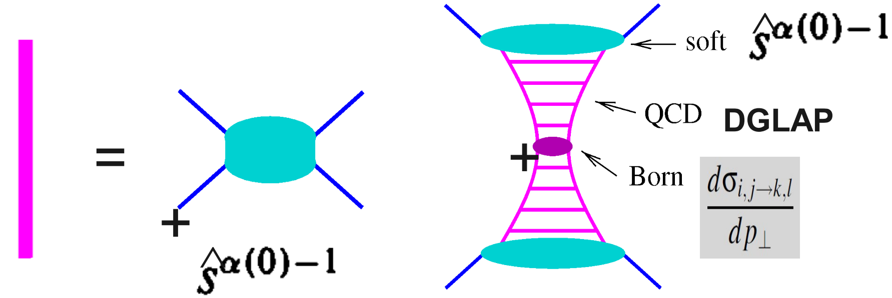


Non-linear effect (screening) absorbed in modified vertex functions

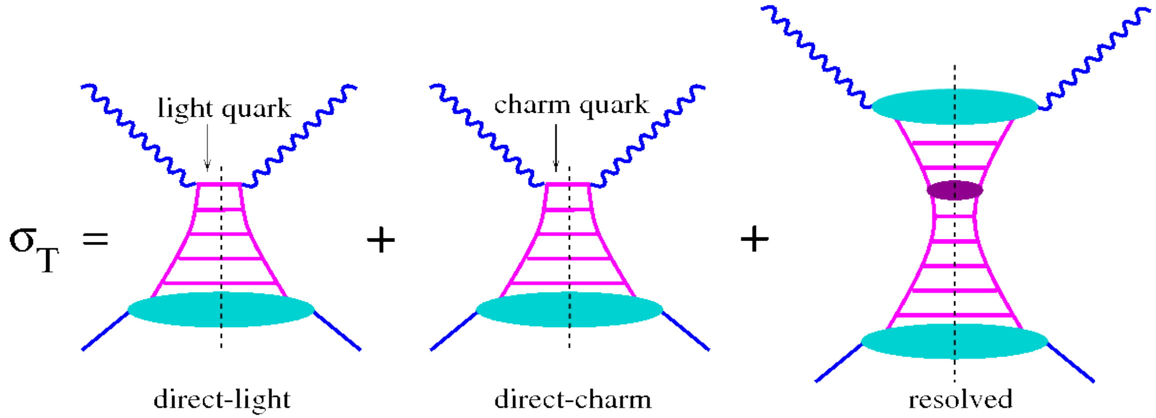


EPOS : Pomeron definition

Semi-hard Pomeron :



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

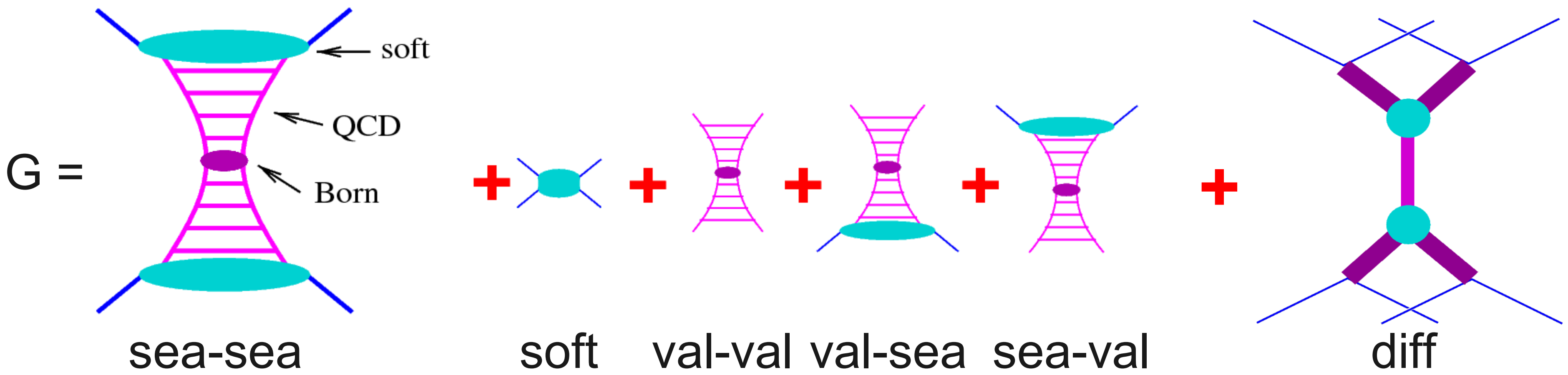


- Theory based Pomeron definion
  - pQCD based so large increase at small x (no saturation)
  - produce too high cross section
  - corrections needed using enhanced diagrams (triple Pomeron vertex)
    - effective coupling vertex

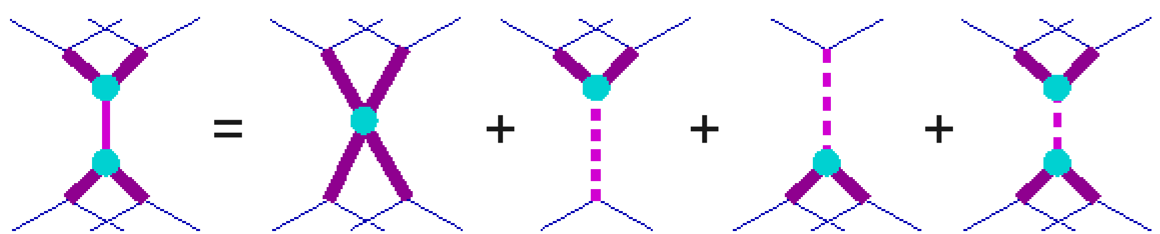
Diffraction in PBGRT

Using the same formalism

- Diffraction from an additional diagram

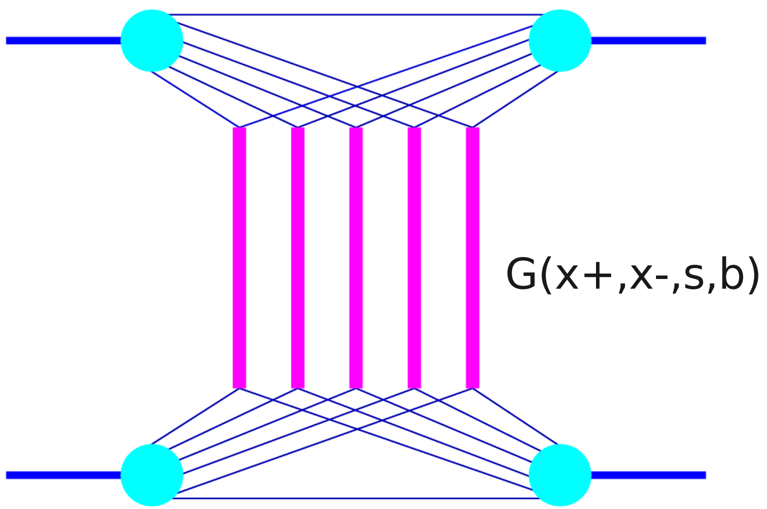


- Same form as soft (Regge pole) but with different amplitude and width
- Low mass and high mass diffraction from the same diagram



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

Cross Section Calculation : EPOS



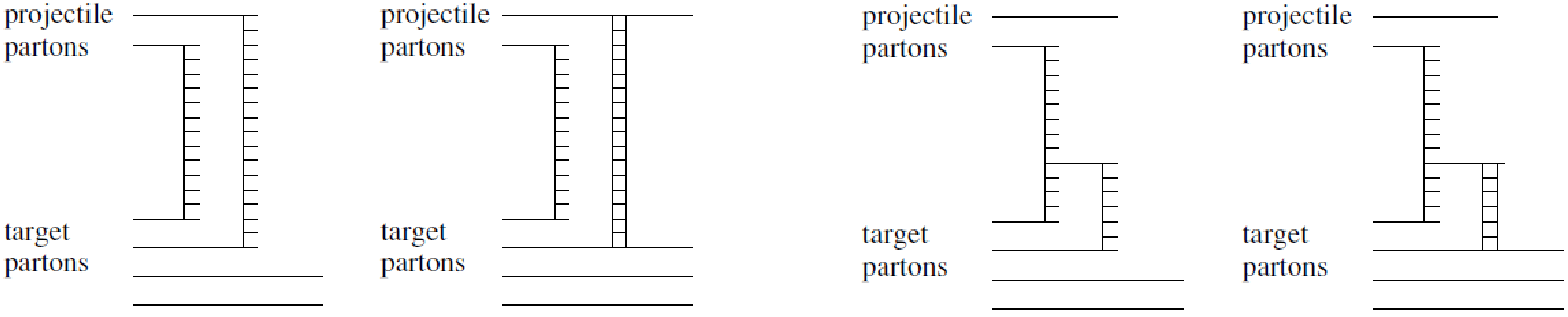
- PBGRT : Gribov-Regge but with energy sharing at parton level
- amplitude parameters fixed from QCD and pp cross section (semi-hard Pomeron)
- cross section calculation take into account interference term

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

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

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

EPOS – high parton density effects

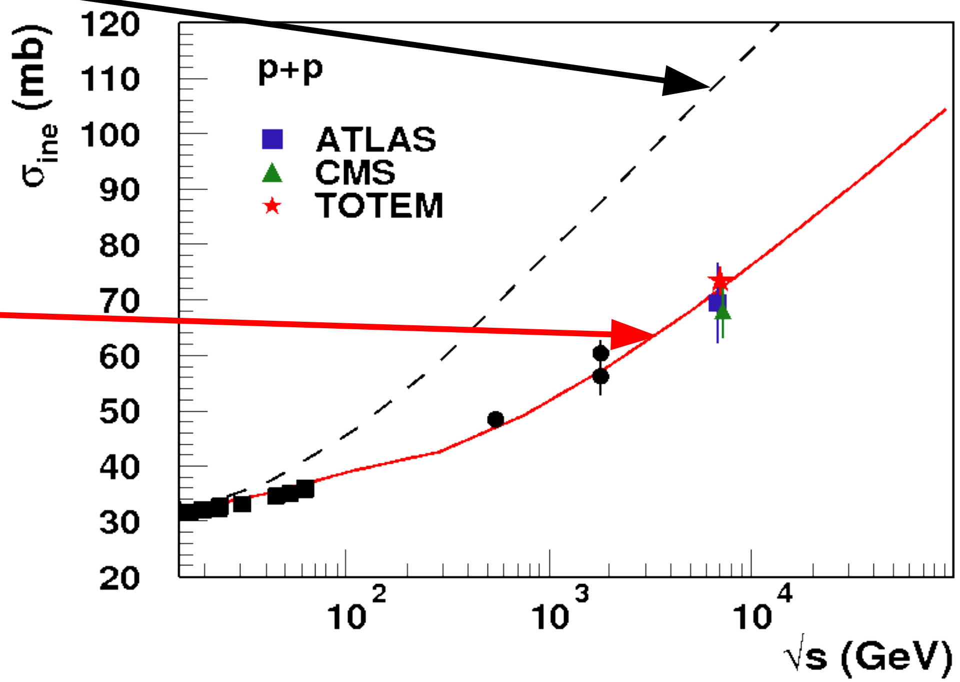


No effective coupling

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

With effective coupling

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



Parametrization

$$\varepsilon_S = a_S\, \beta_S\, Z(\mathrm{s,b})$$
$$\varepsilon_H = a_H\, \beta_H\, Z(\mathrm{s,b})$$

Particle Production in EPOS

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

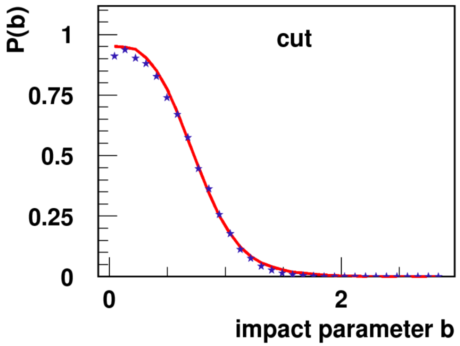
- m cut Pomerons from :

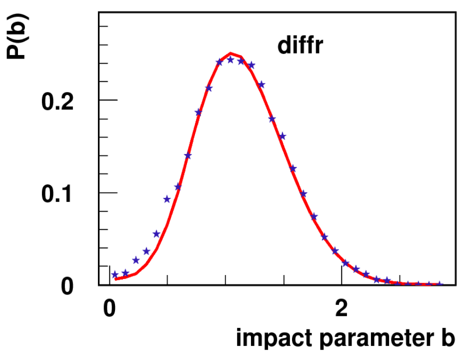
$$\Omega_{AB}^{(s,b)}(m,X^+,X^-) = \prod_{k=1}^{AB}\left\{\frac{1}{m_k!}\prod_{\mu=1}^{m_k} G(x_{k,\mu}^+,x_{k,\mu}^-,s,b_k)\right\}\ \Phi_{AB}\left(x^{\text{proj}},x^{\text{targ}},s,b\right)$$

  - 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

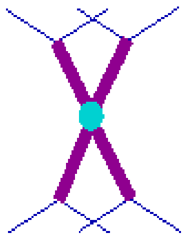
Low Mass Diffraction



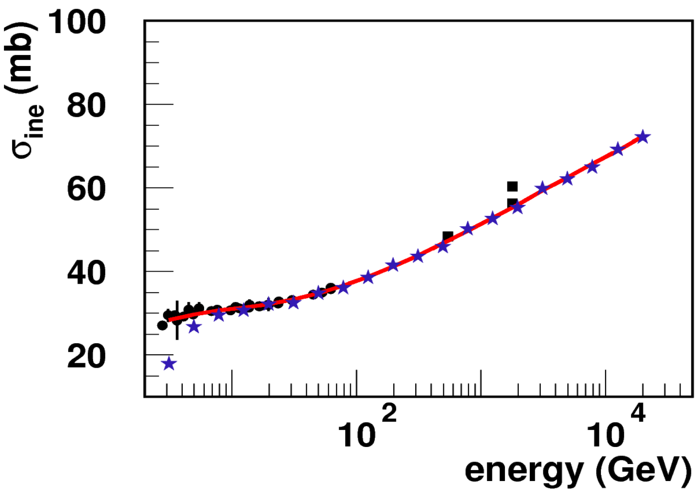


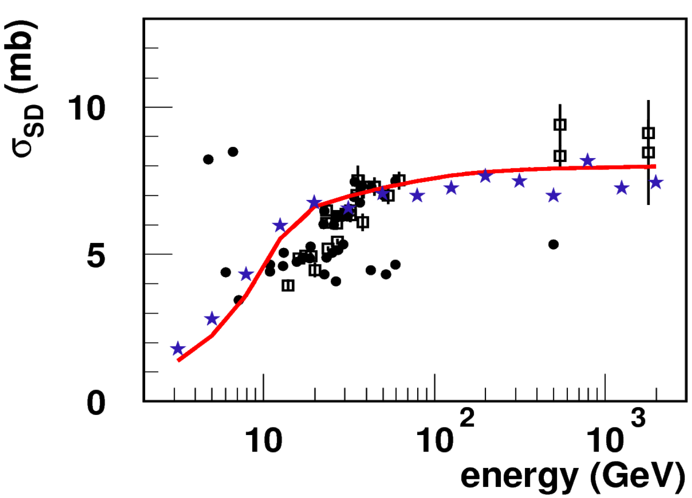
Diffractive event = event with only cut diff. diagrams

- Multiple cut-diff diagrams possible
- For each cut-diff diagram probability P_{dif} not to excite remnant
  - More cut-diff = more excitation : $(1-P_{dif}^{\ n})$
  - Important in pA
- No particle production directly from diagram
- P_{dif} (~0.25) fixes SD, DD (or elastic) probability.

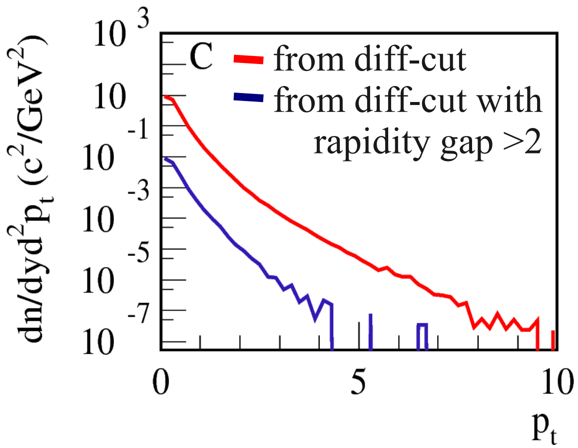


Theory
★ MC



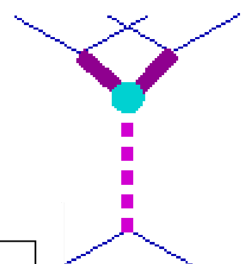


High Mass Diffraction

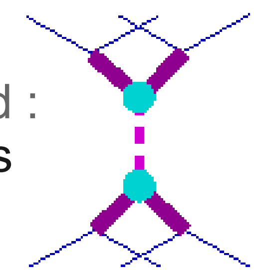


Same scheme but with particle production

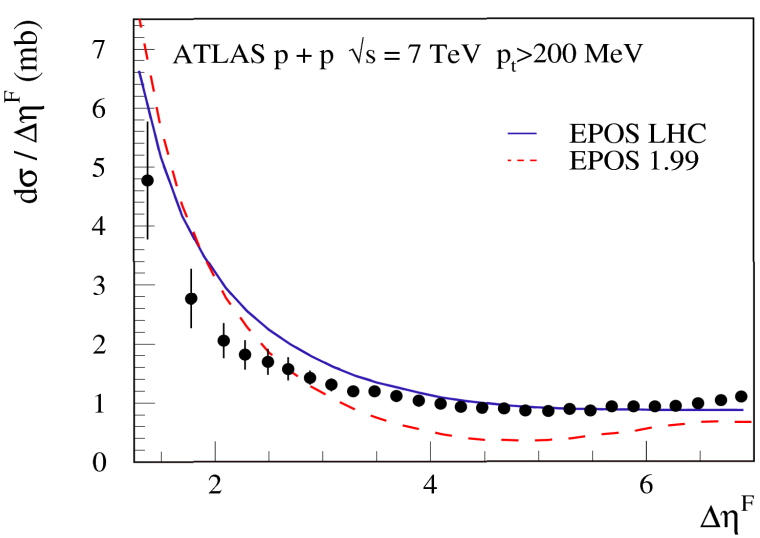
- Do not change cross-section
- For each cut-diff probability P_{HM}(mass,b,...) to remain as real (soft or semi-hard) cut diagram
- 0, 1 or 2 rapidity gap depending on P_{dif}



Projectile not excited :
1 rapidity gap

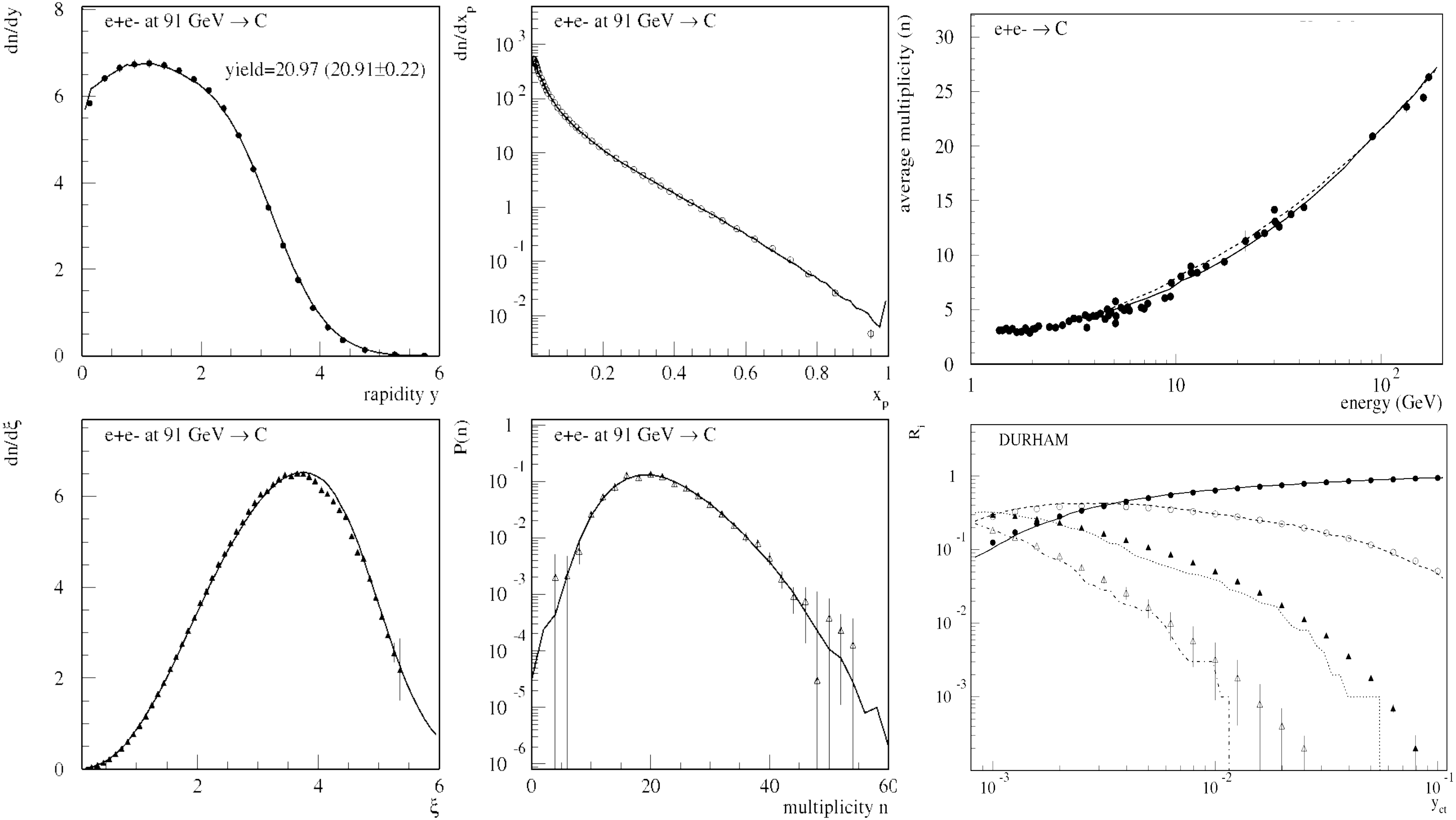


Projectile and target not excited :
2 rapidity gaps



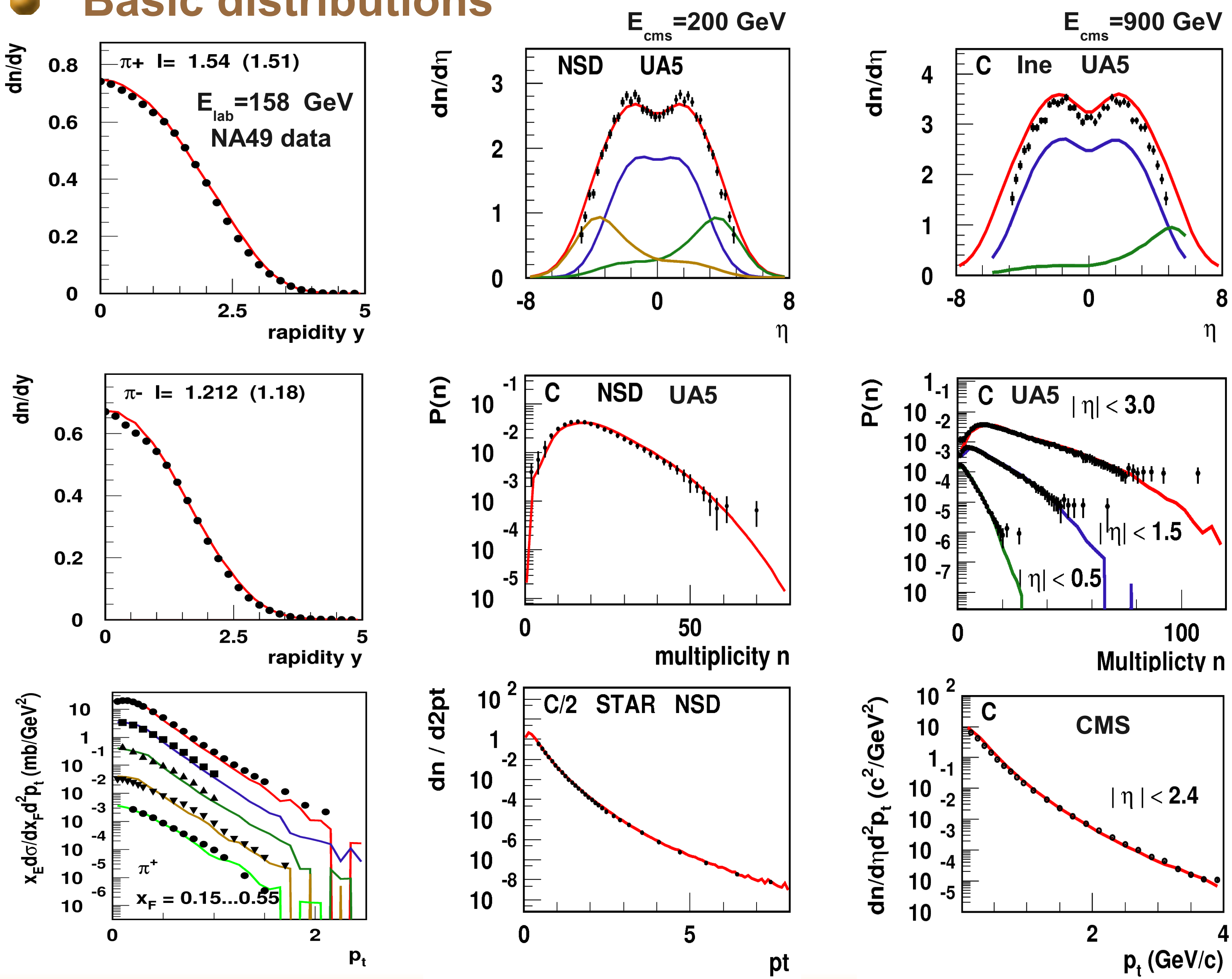
- Additional multiplicity contribution in ND events
- Work in progress

Test at LEP : area law

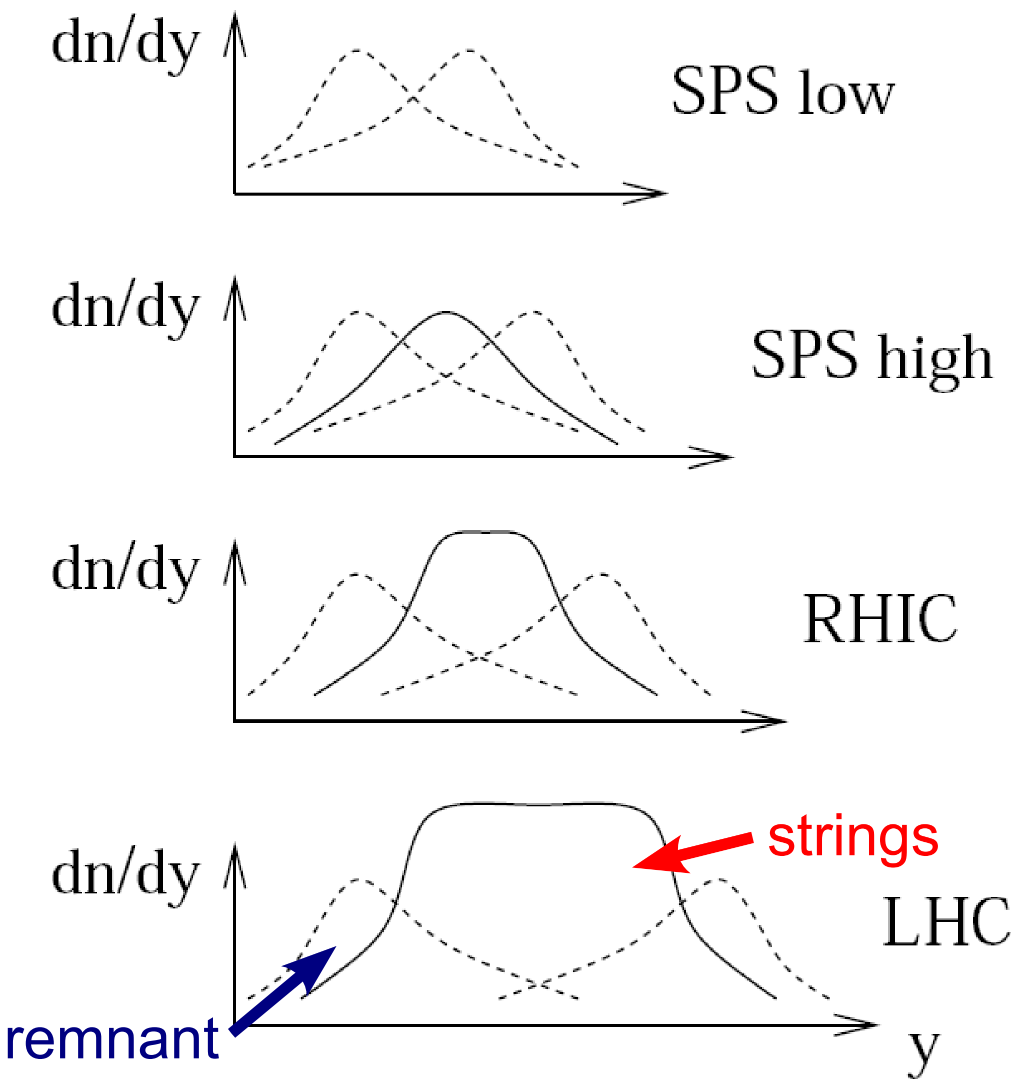


Basic Distributions

Basic distributions

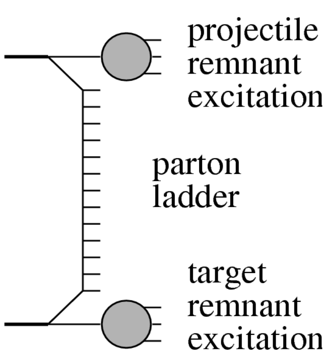


Remnants



Free remnants in EPOS:

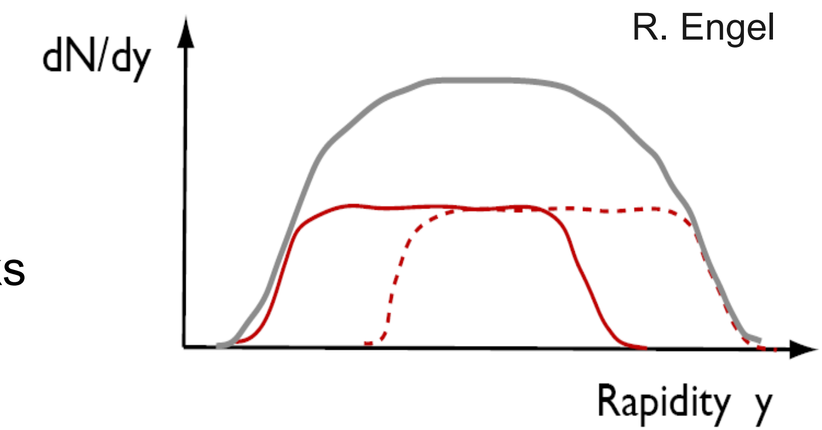
- from both diffractive or inelastic scattering
- excited state with $P(M) \sim 1/(M^2)^\alpha$
- very large contribution at low energy
- forward region at high energy
- depending on quark content and mass (excitation):
  - resonance
  - string
  - droplet (if #q>3)
  - string+droplet

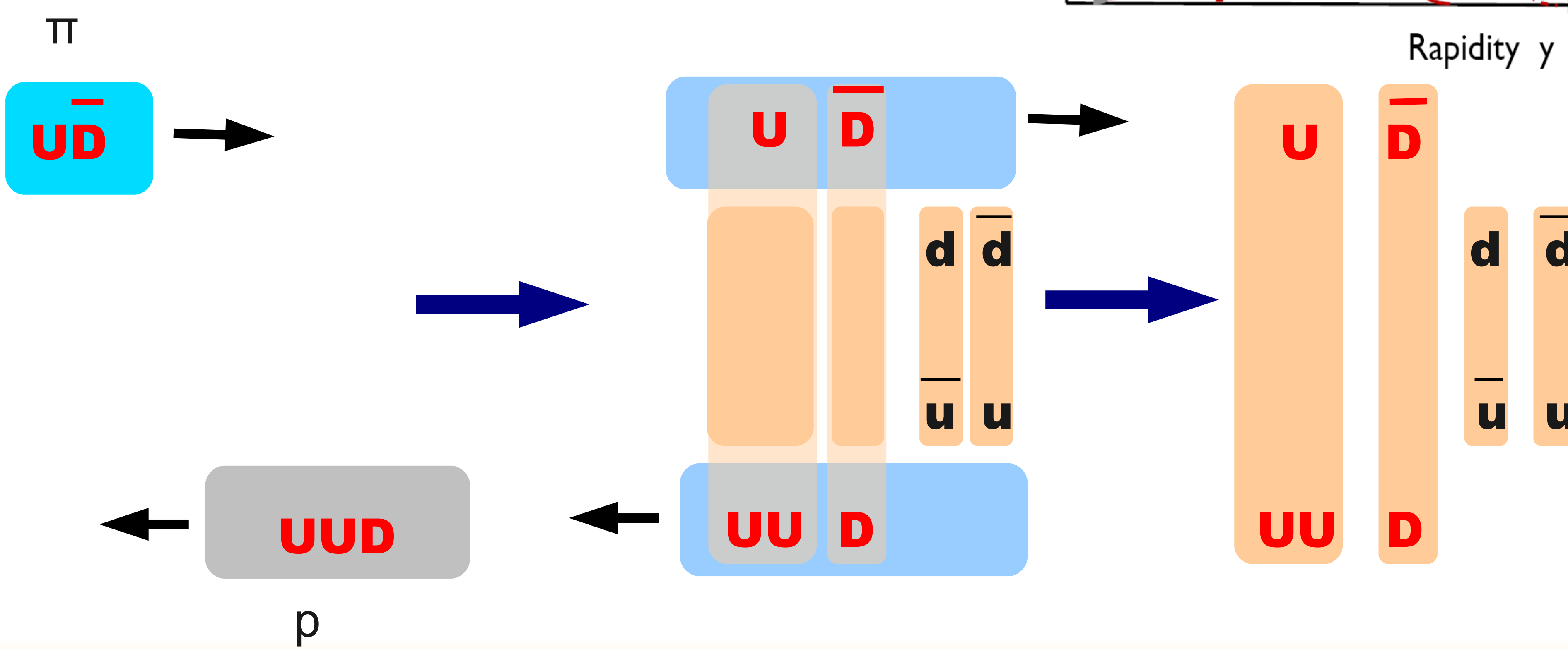


Remnants in PYTHIA

In PYTHIA : valence quarks attached to main string

- limited quark exchange
- very hard baryon and meson spectra
- string fragmentation
  - forward particle limited by valence quarks

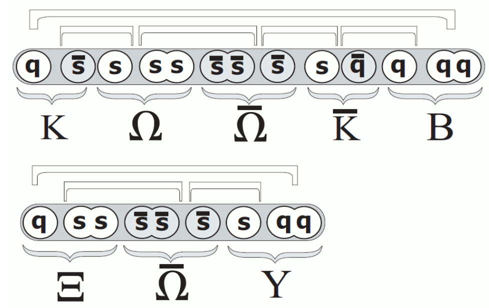




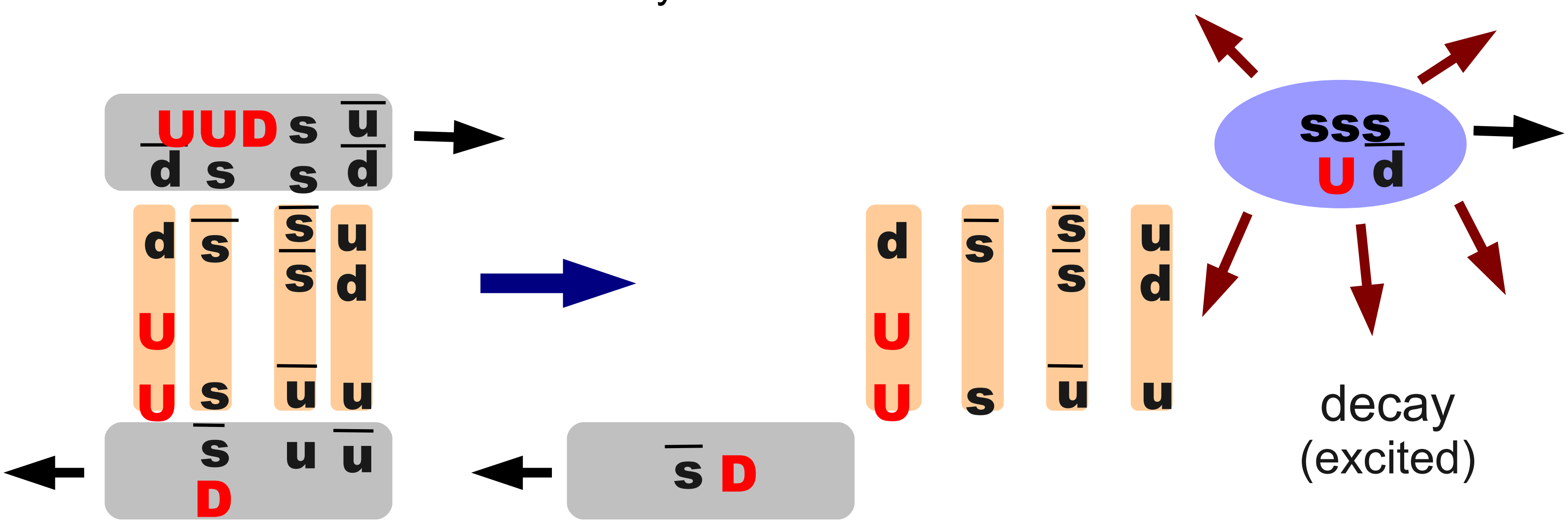
Baryons and Remnants

Parton ladder string ends :

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

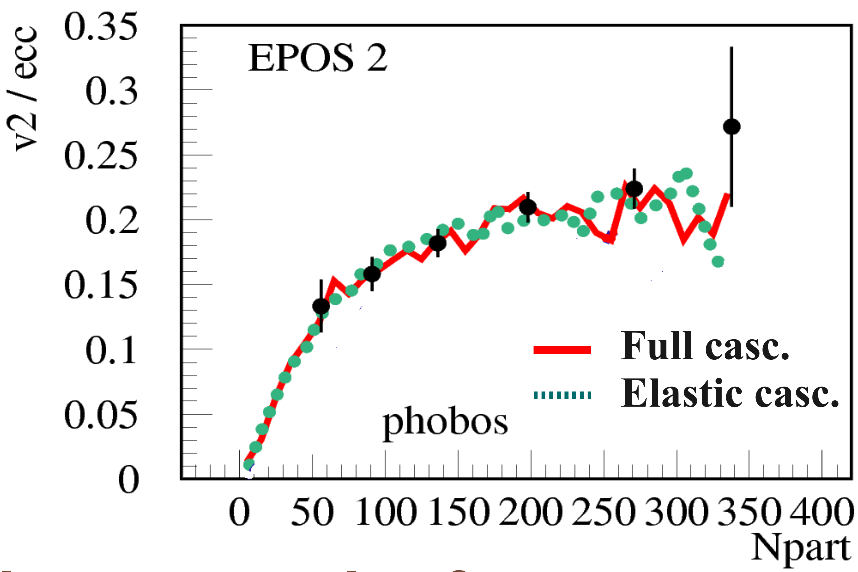


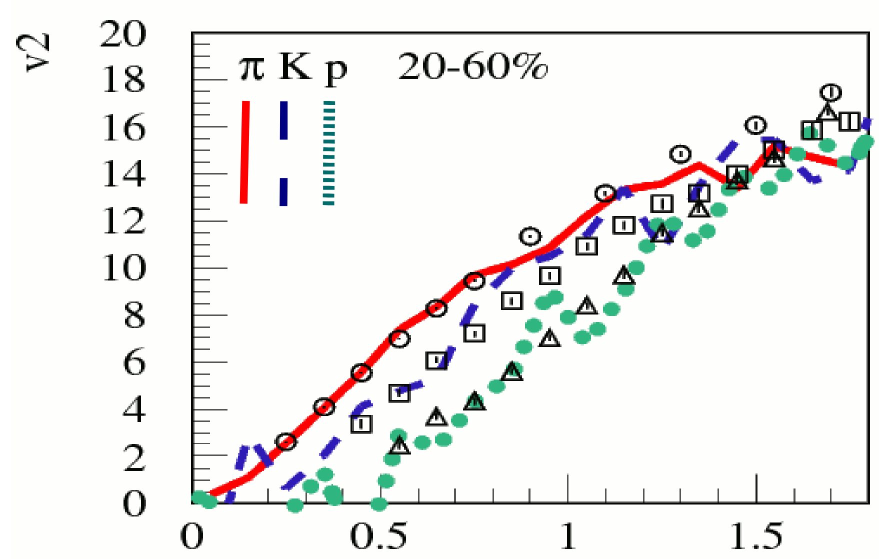
- EPOS
  - No “first string” with valence quarks : all strings equivalent
  - Wide range of excited remnants (from light resonances to heavy quark-bag)
    - $\overline{\Omega}$ / Ω always < 1



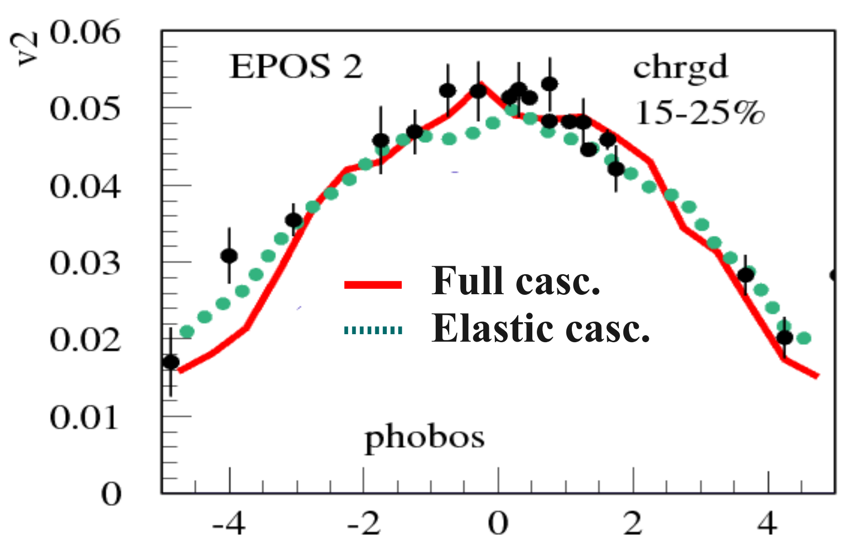
Check with Heavy Ions : AuAu@RHIC

➡ Early freeze-out (166MeV) + hadr. cascade





Important role of core-corona effect (K. Werner et al. J.Phys.G36:064030,2009)

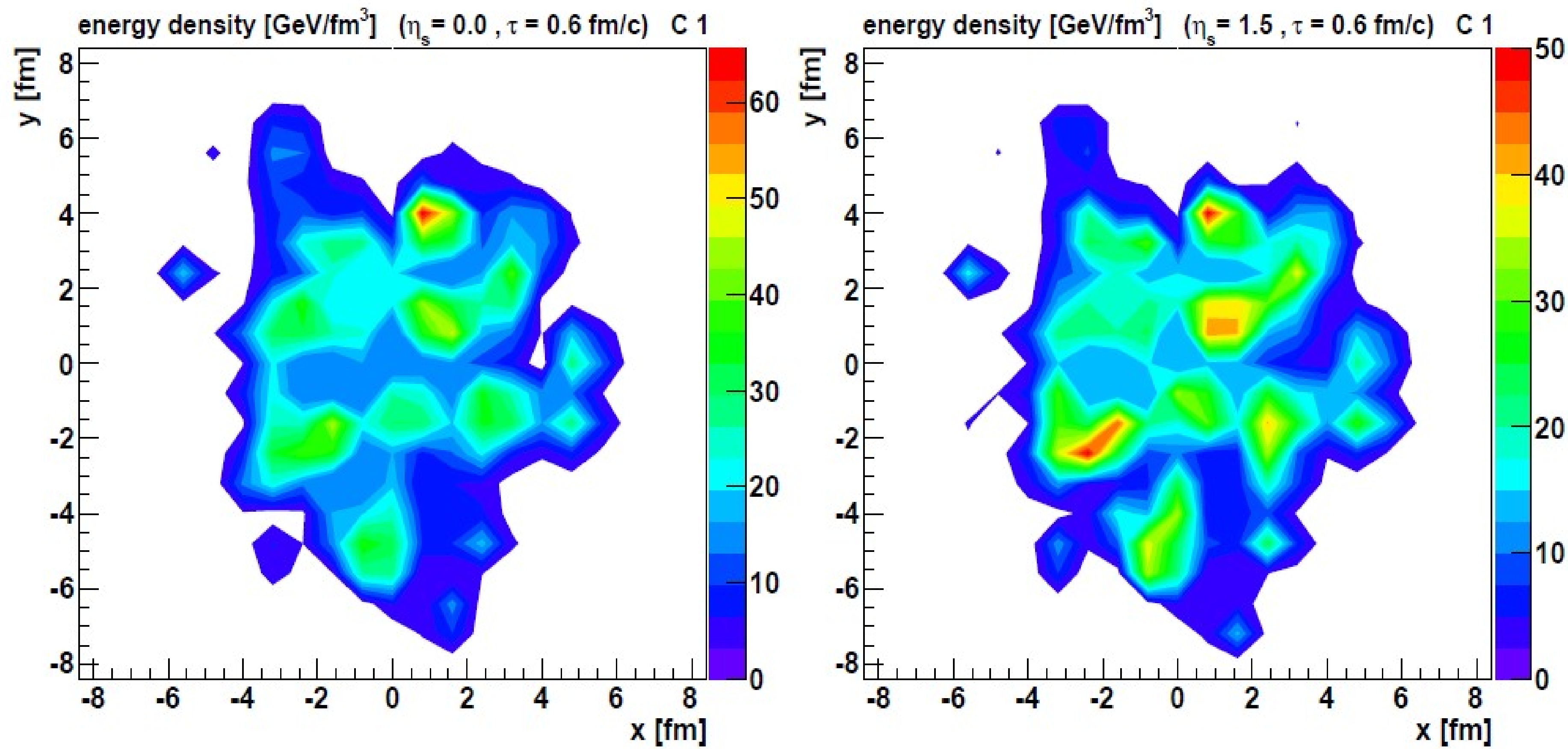


- **After checking successfully hundreds of particle spectra in AuAu**

➡ Event-by-event analysis

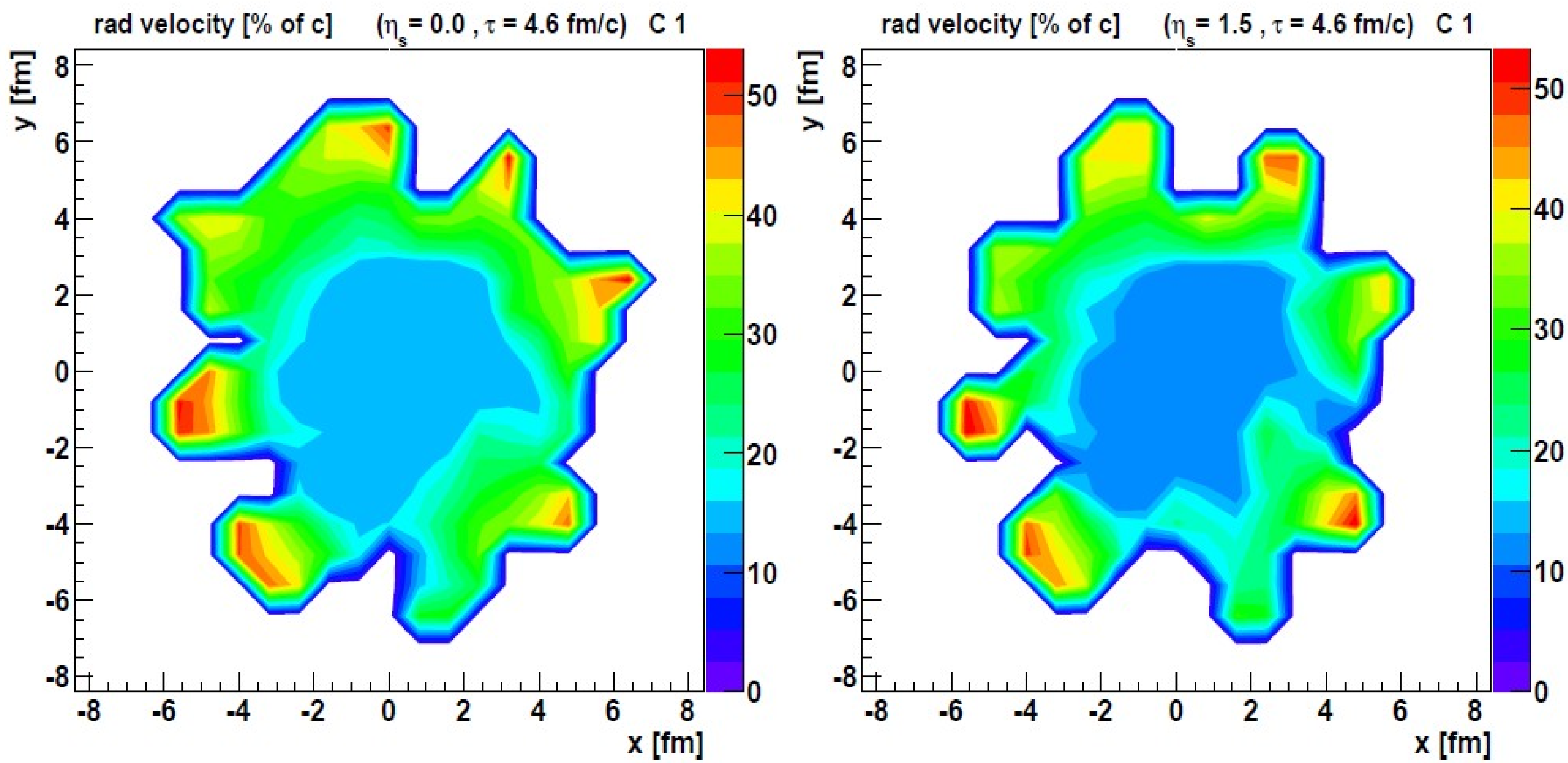
Event-by-Event Energy Density : AuAu

- Bumpy structure of energy density in transverse plane, but translational invariance
  - pseudorapidity extension of flux tubes



Event-by-Event Radial Flow : AuAu

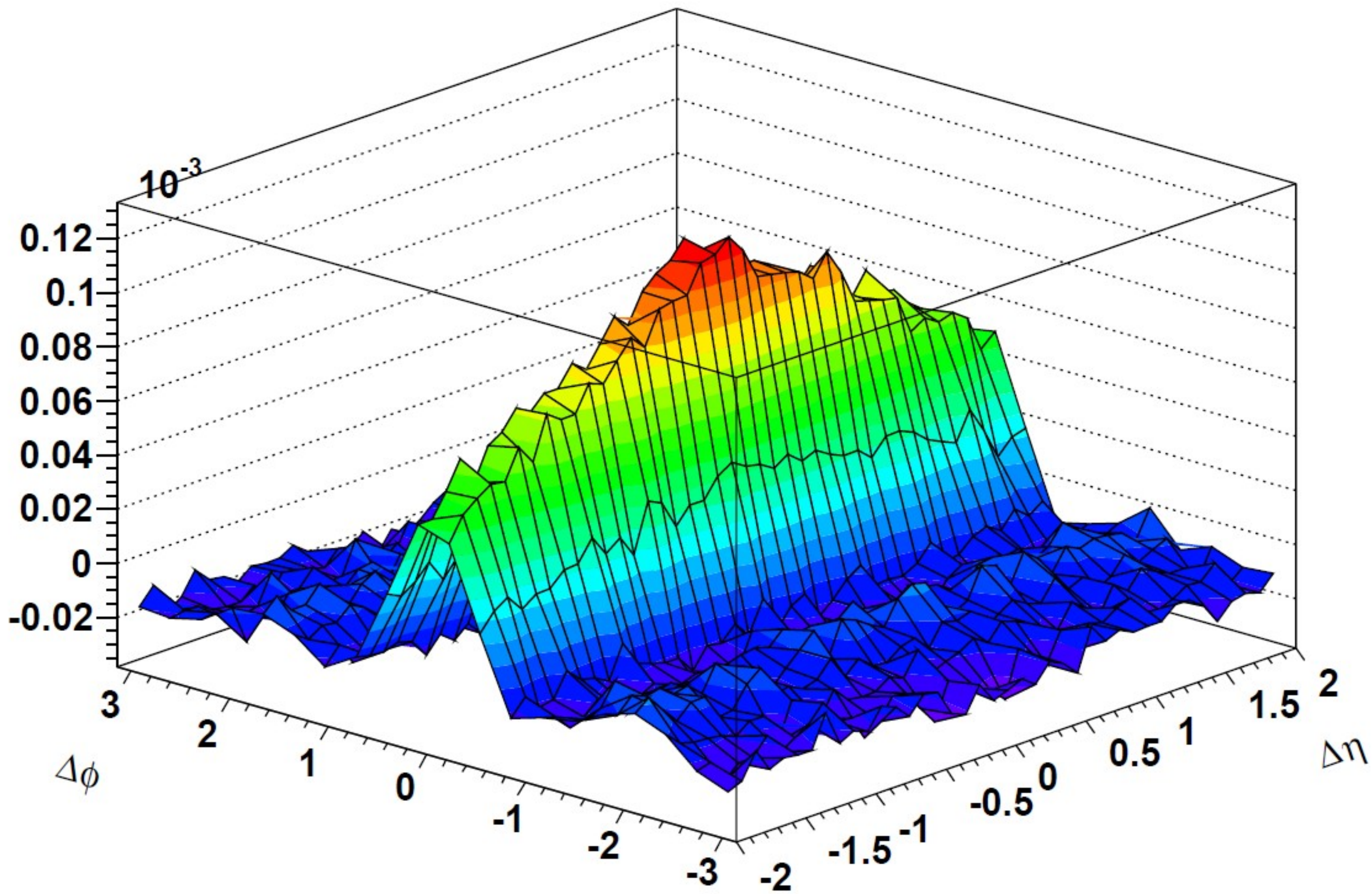
- **Leads to translational invariance of transverse flows**



➡ give the same collective push to particles produced at different values of η_s at the same azimuthal angle

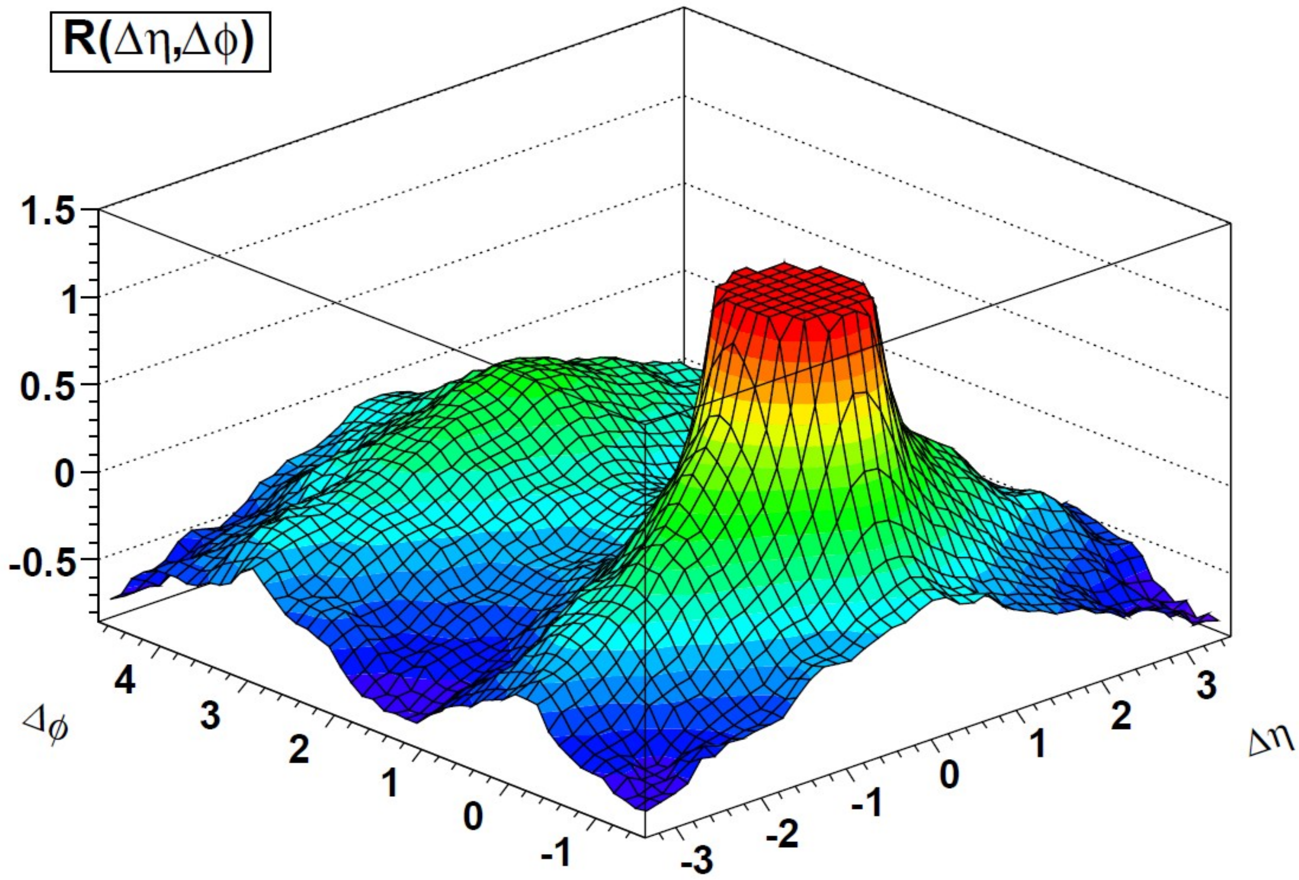
AuAu : Di-hadron correlation

- ridge-structure in the dihadron correlation dN/dΔηdΔφ for free



pp@7 TeV : Di-hadron correlation

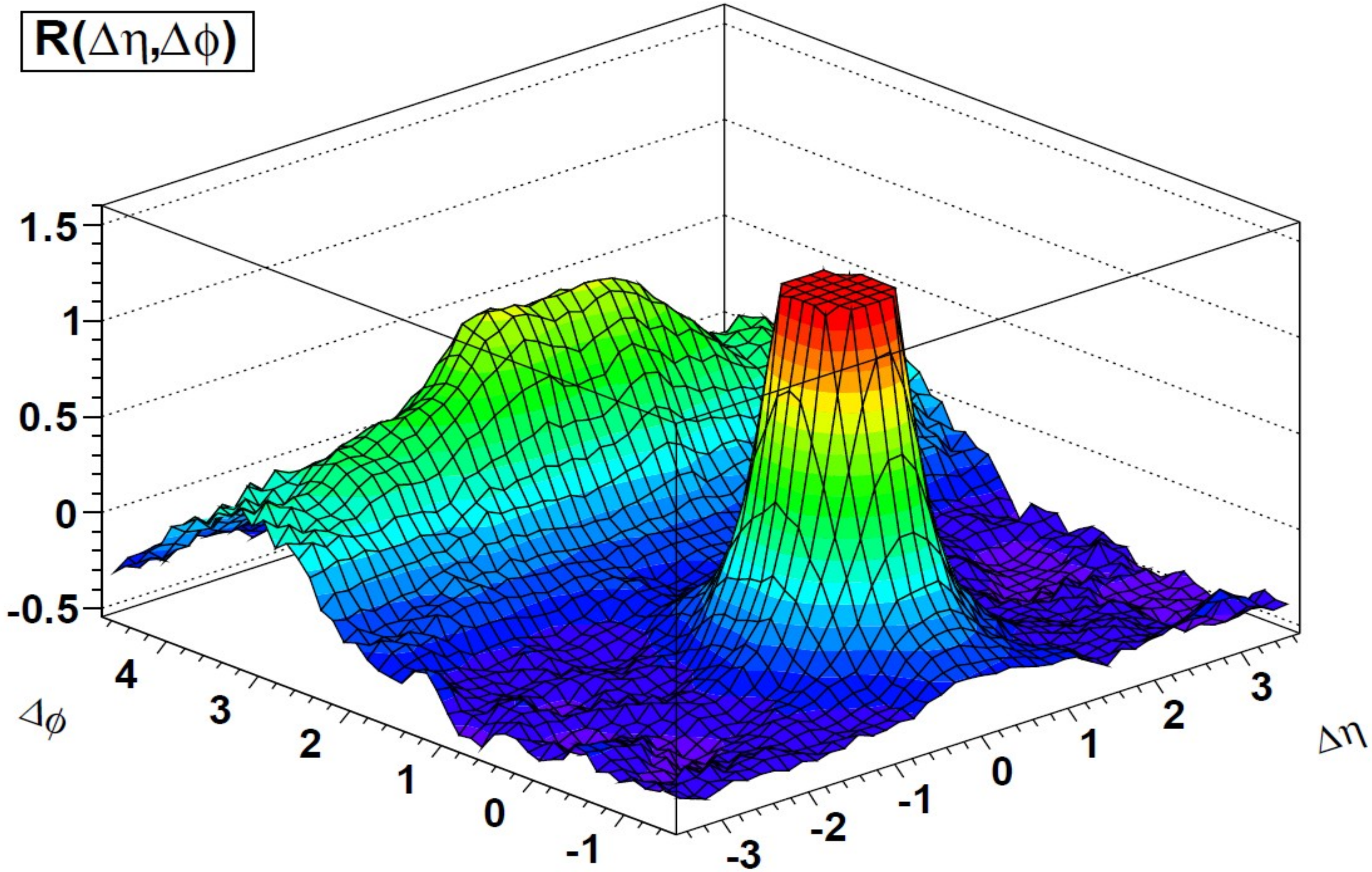
- Our calculation provides a similar ridge structure in pp@LHC using particles with 1 < pt < 3GeV/c, for high multiplicity events



close in form and magnitude compared to the CMS result (5.3 times mean multipl., compared to 7 in CMS)

pp@7 TeV : no Hydro

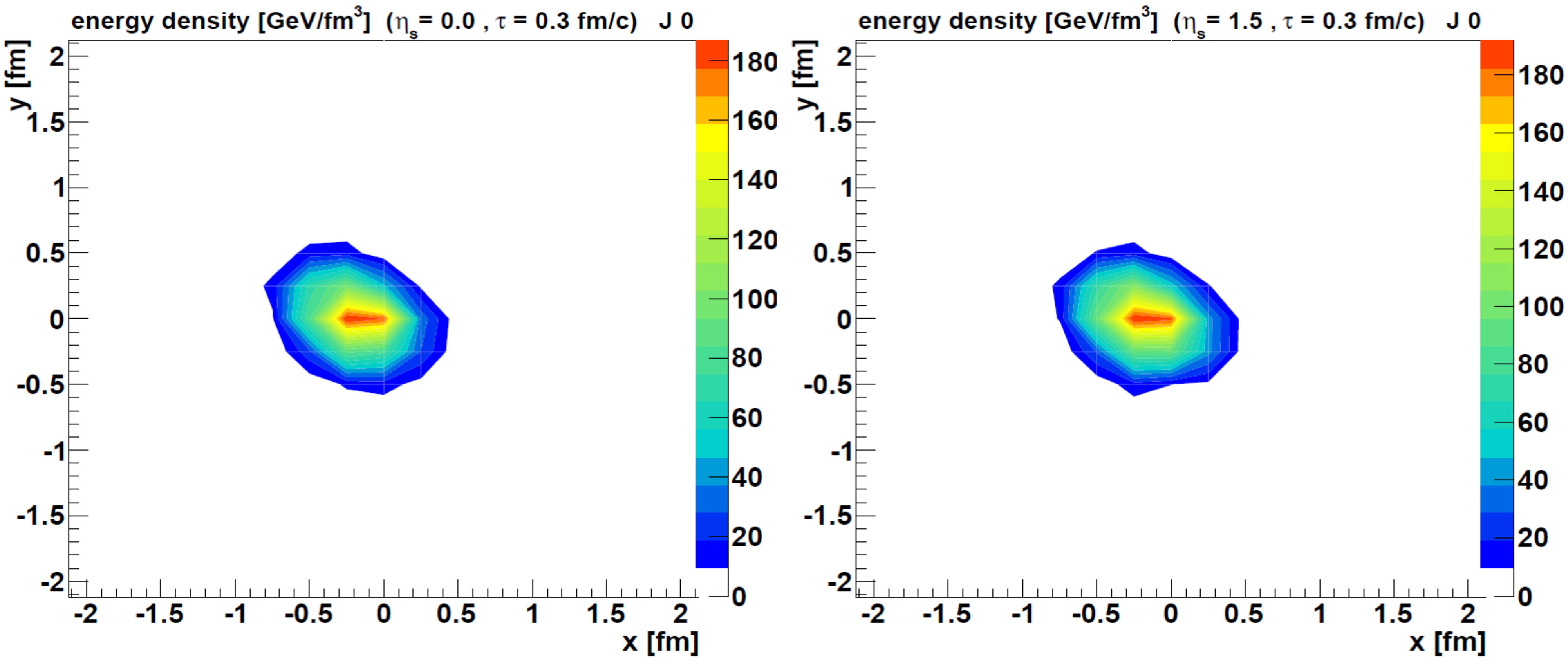
- Calculation without hydro => NO RIDGE



hydrodynamical evolution “makes” the effect! HOW?

Event-by-Event Energy Density : pp

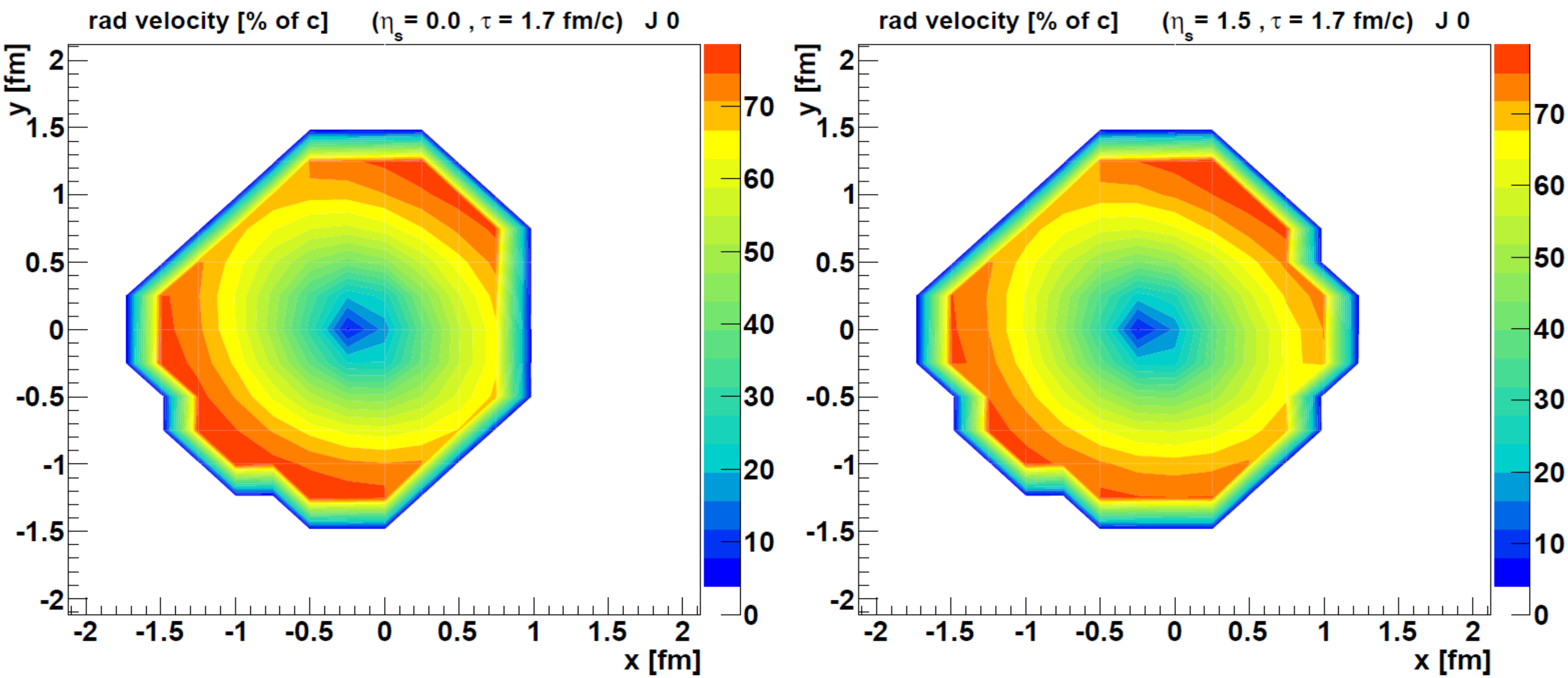
- Random azimuthal asymmetries of initial energy density but translationally invariant
  - pseudorapidity extension of flux tubes



Initial energy density in the transverse plane for two different η_s

Event-by-Event Radial Flow : pp

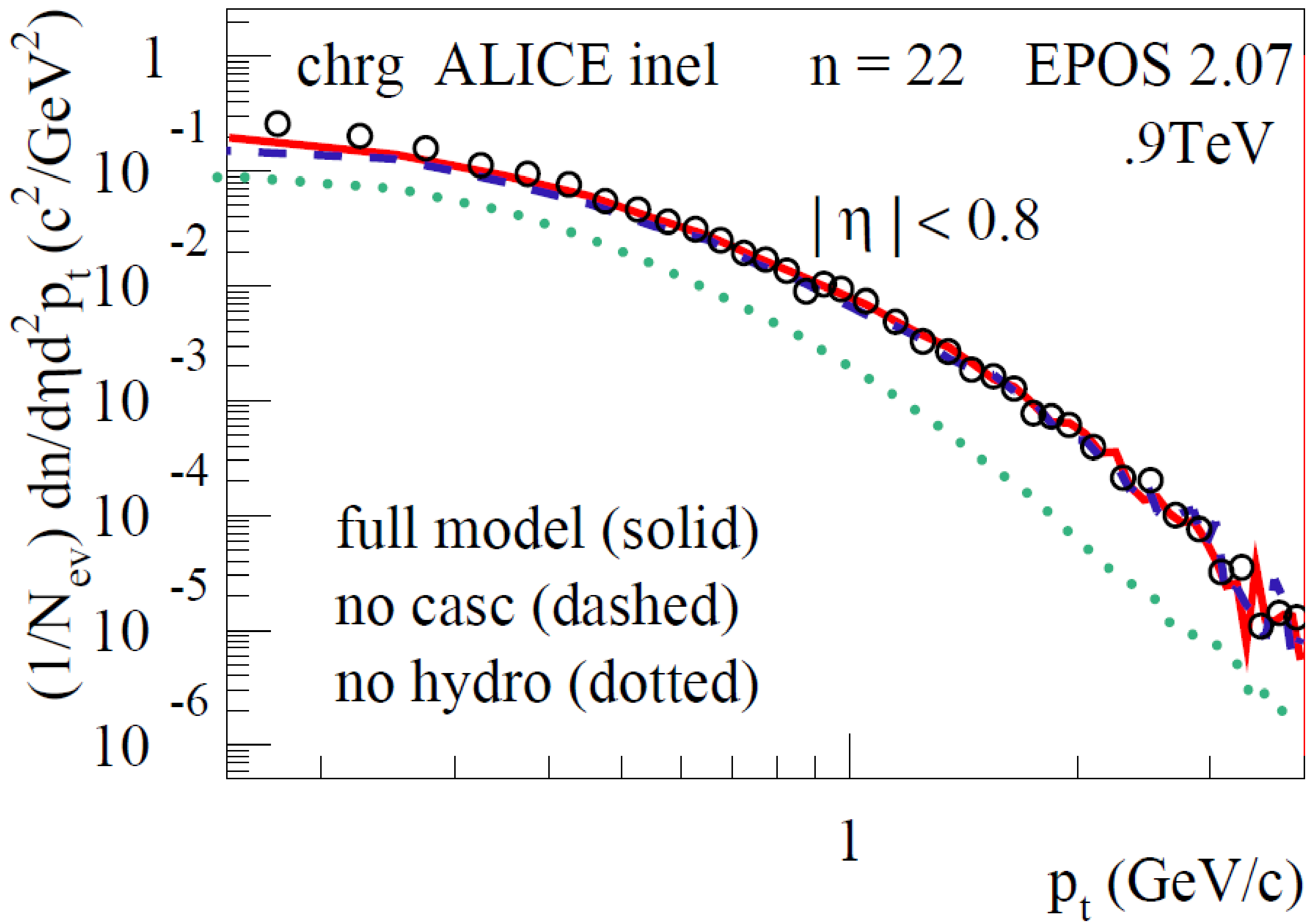
- Elliptical initial shapes leads to asymmetric flows as well translationally invariant (in η_s)



Radial flow velocity at a later time in the transverse plane

Pt Distribution

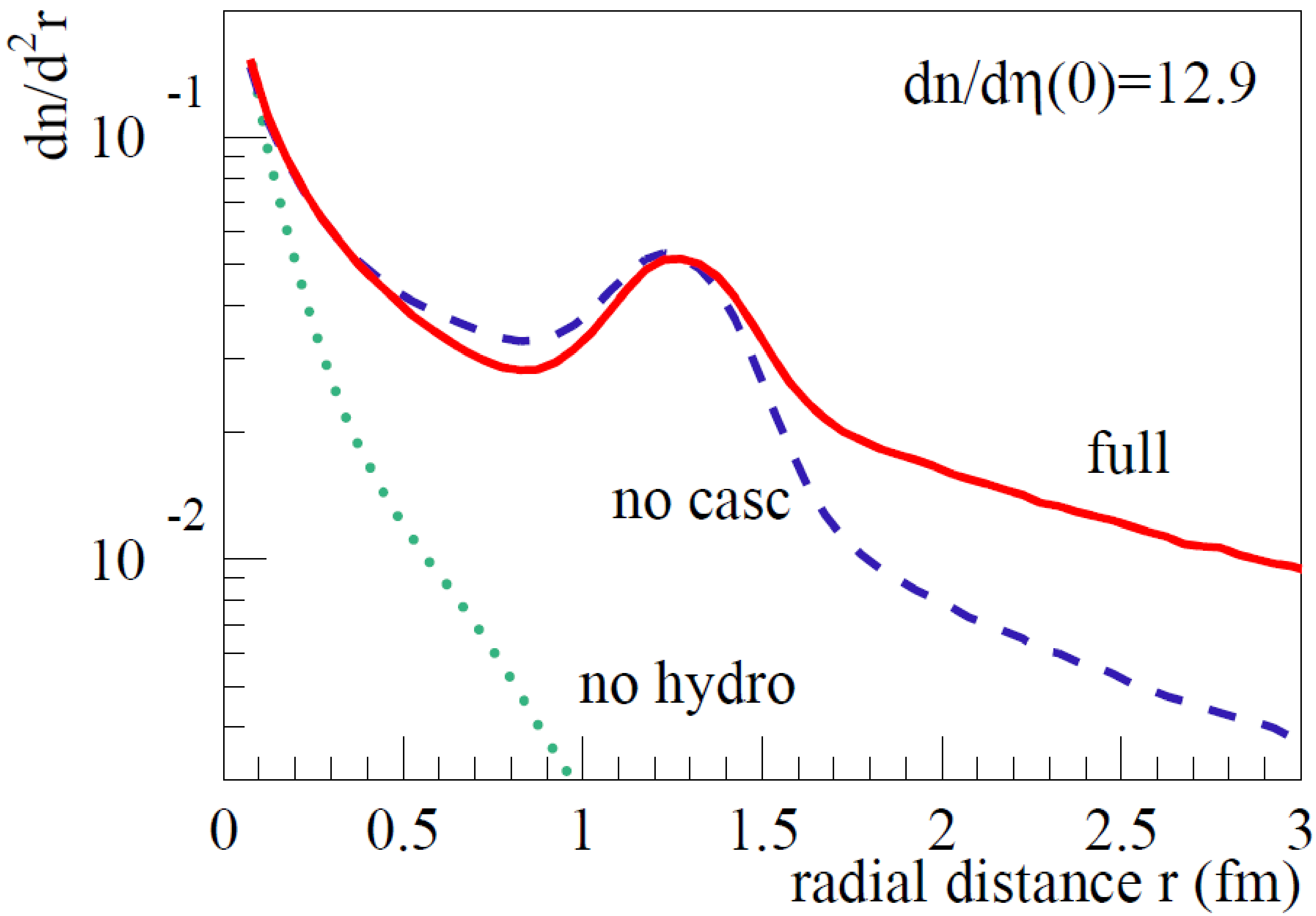
- Big effect for Pt distributions for high multiplicity events (here 900 GeV)



Flow !

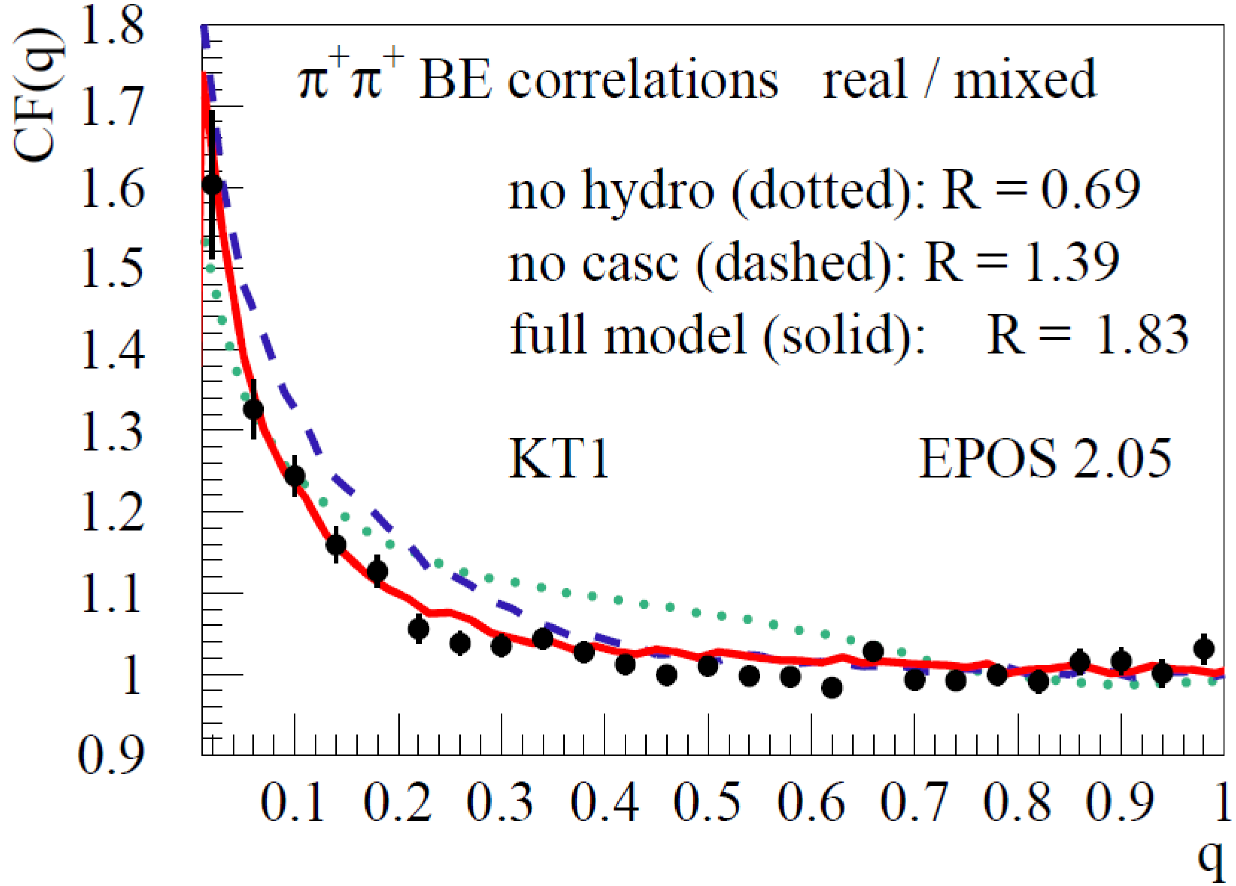
Radius of Particle Emission

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



Bose-Einstein Correlations

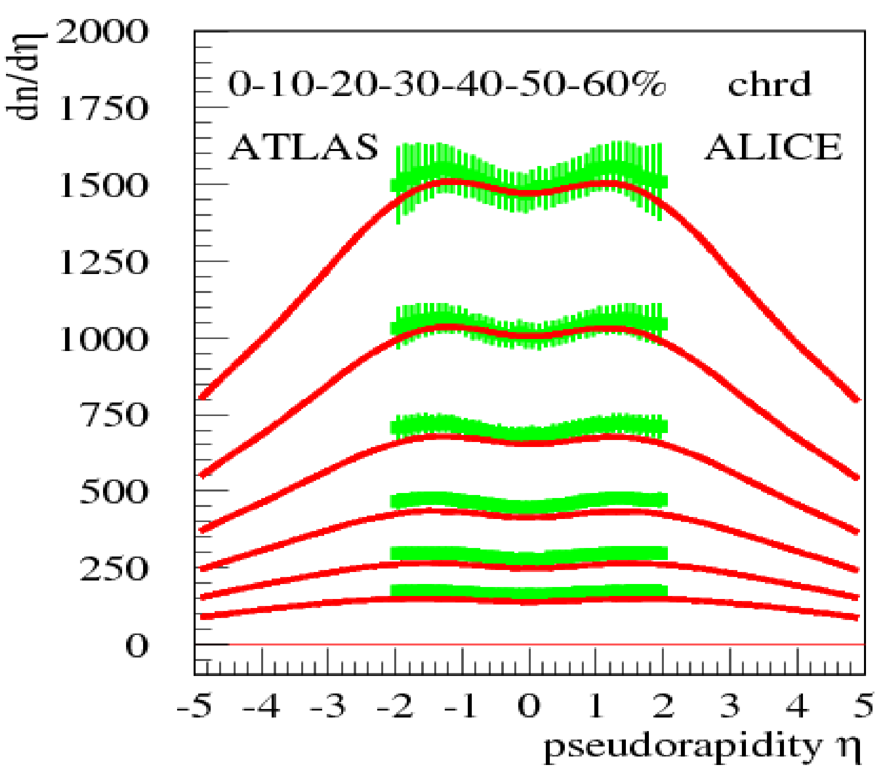
- Consequences for Bose-Einstein correlations

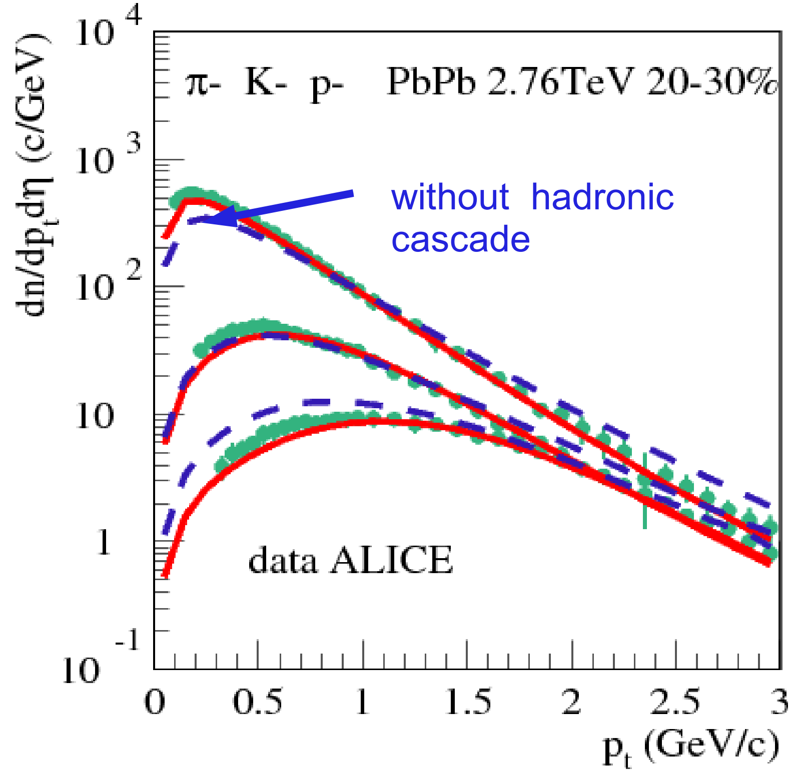


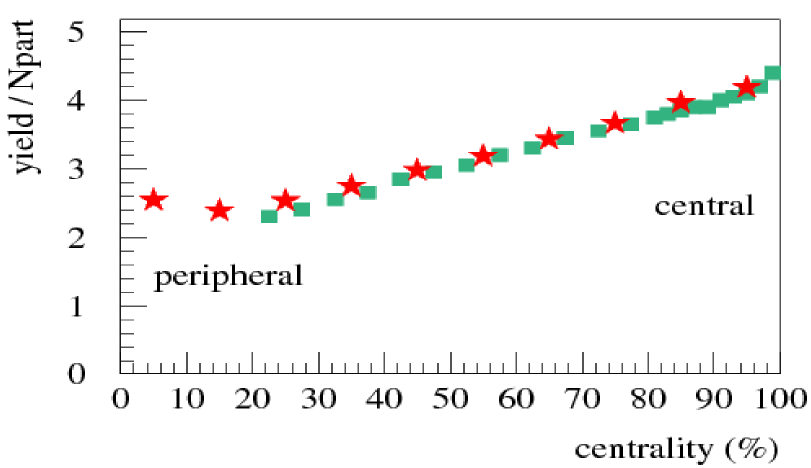
ALICE data.

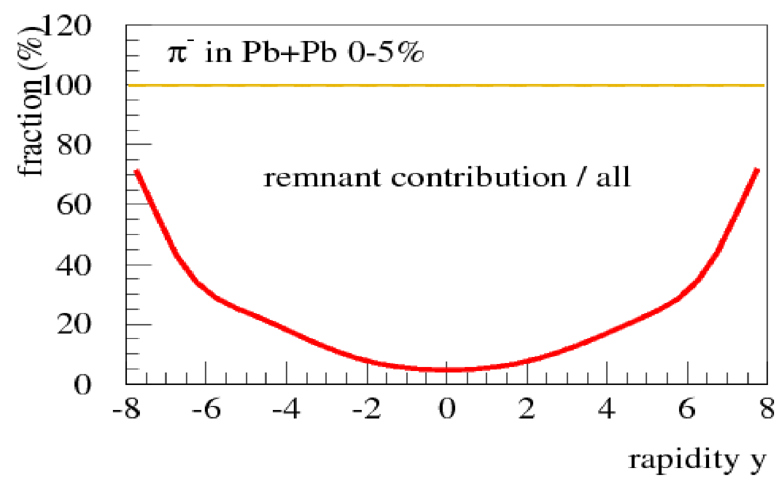
Radii R from exponential fit.
KT1= [100, 250], KT3= [400, 550], KT5= [700, 1000]

PbPb @ LHC

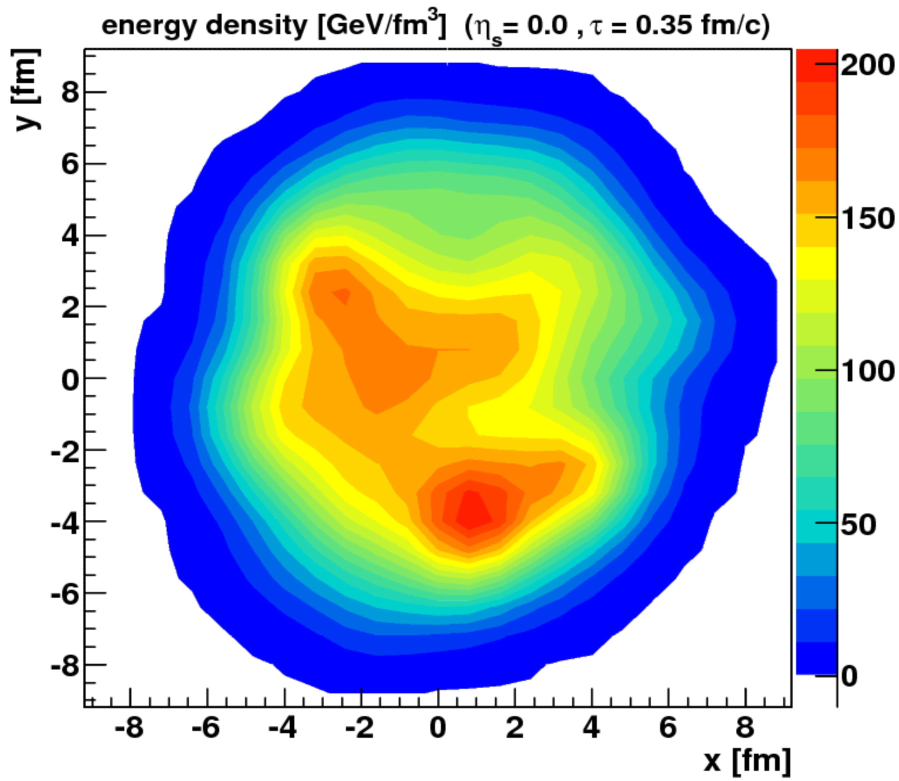

dn/dη
0-10-20-30-40-50-60%
chrd
ATLAS
ALICE
pseudorapidity η

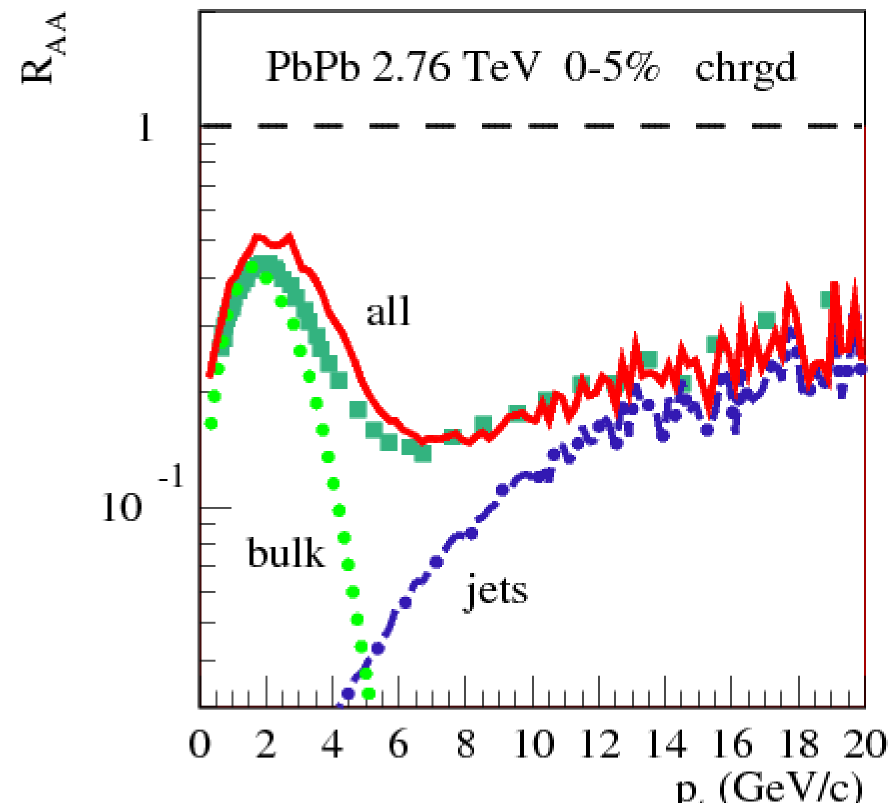

dn/dp$_t$dη (c/GeV)
π- K- p- PbPb 2.76TeV 20-30%
without hadronic cascade
data ALICE
p$_t$ (GeV/c)

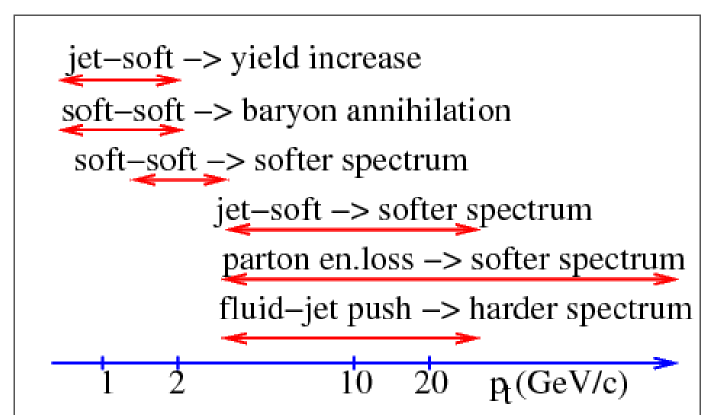

yield / Npart
central
peripheral
centrality (%)


fraction (%)
π$^-$ in Pb+Pb 0-5%
remnant contribution / all
rapidity y

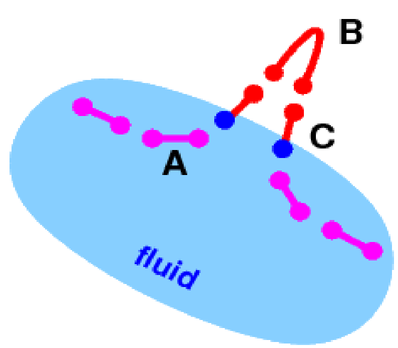
jets in PbPb @ LHC



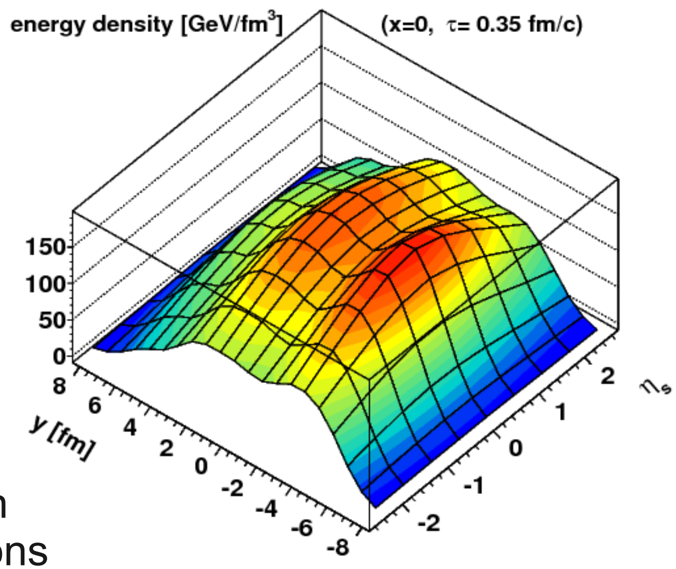




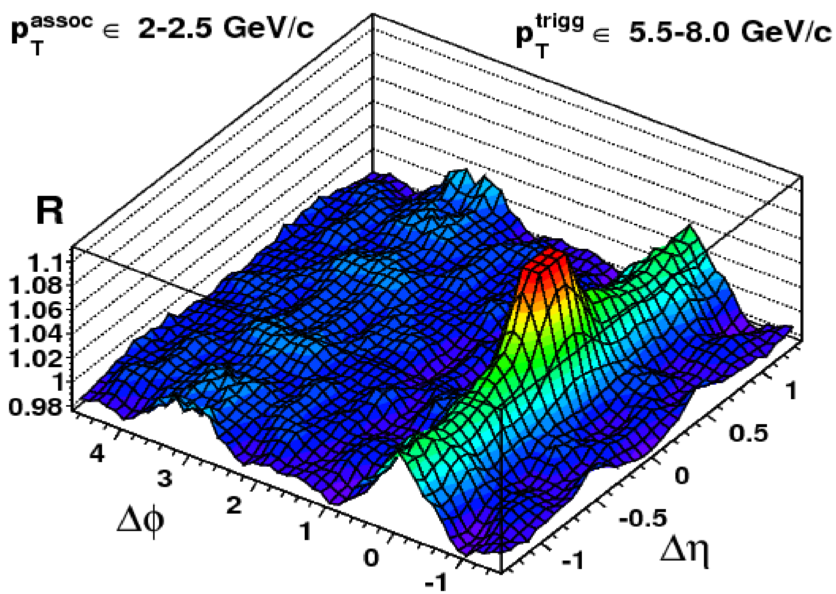
- **Jet interacts in bulk of matter**
  - parton energy loss
  - boost at the surface



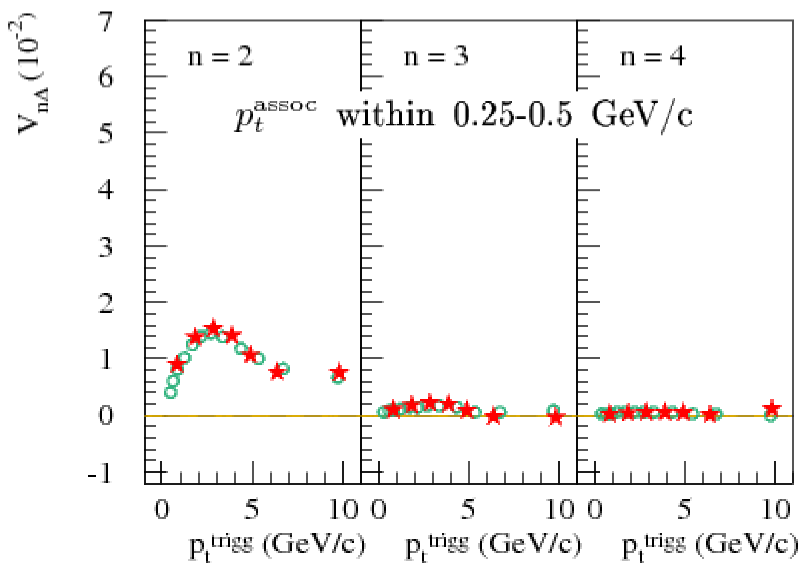
Correlations in PbPb@LHC

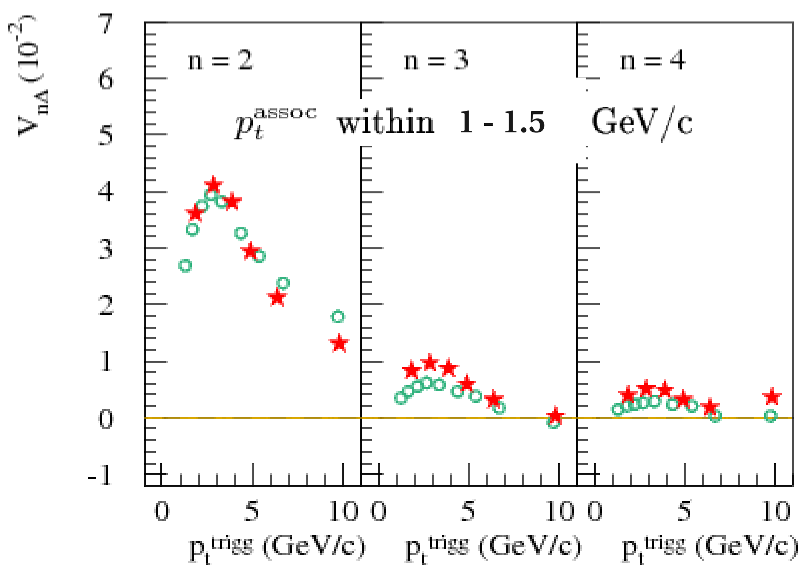


di-hadron correlations

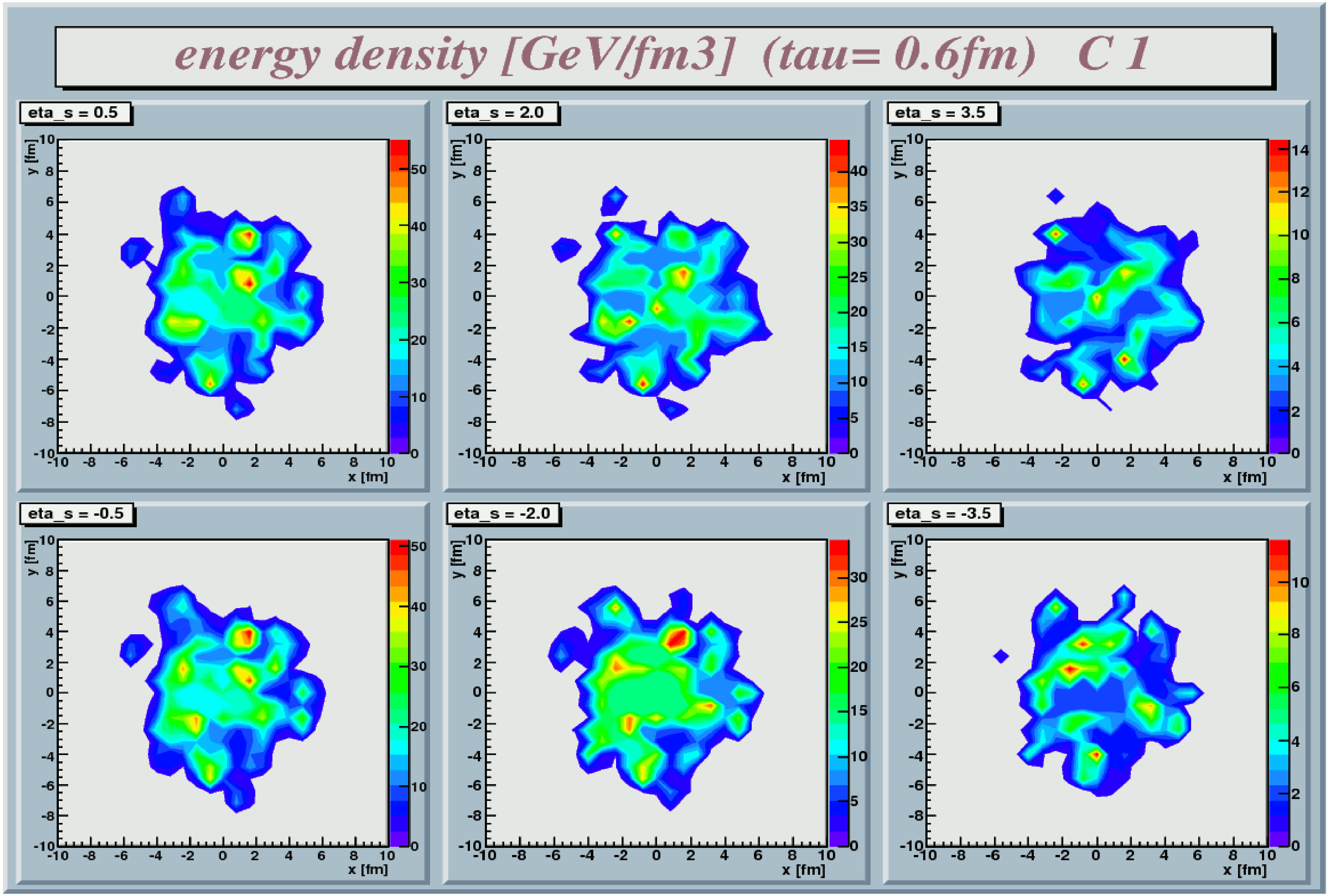


Fourier coefficient for most central events

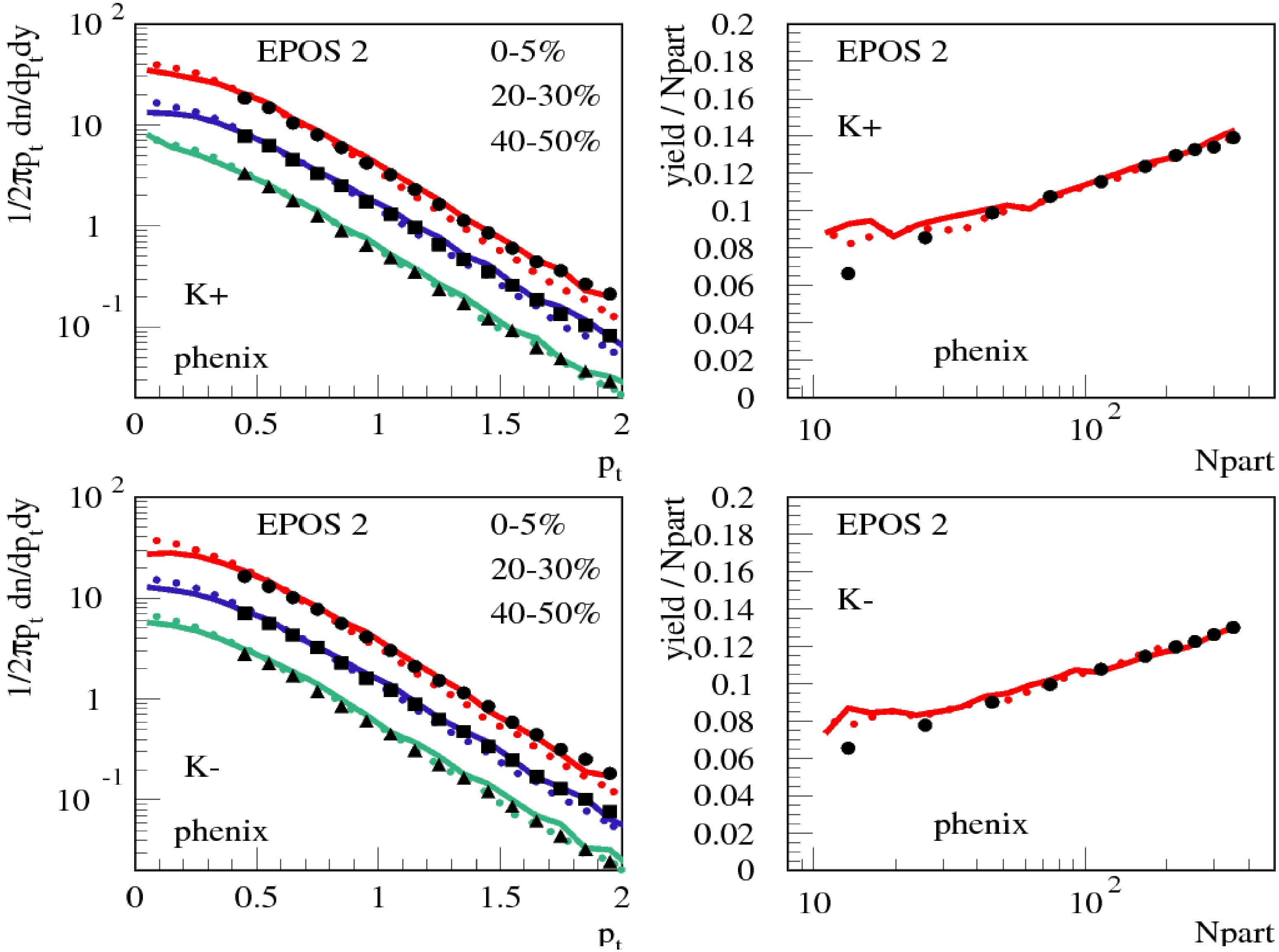




Initial Conditions AuAu@RHIC



AuAu : Kaon



solid lines: with hadronic cascade

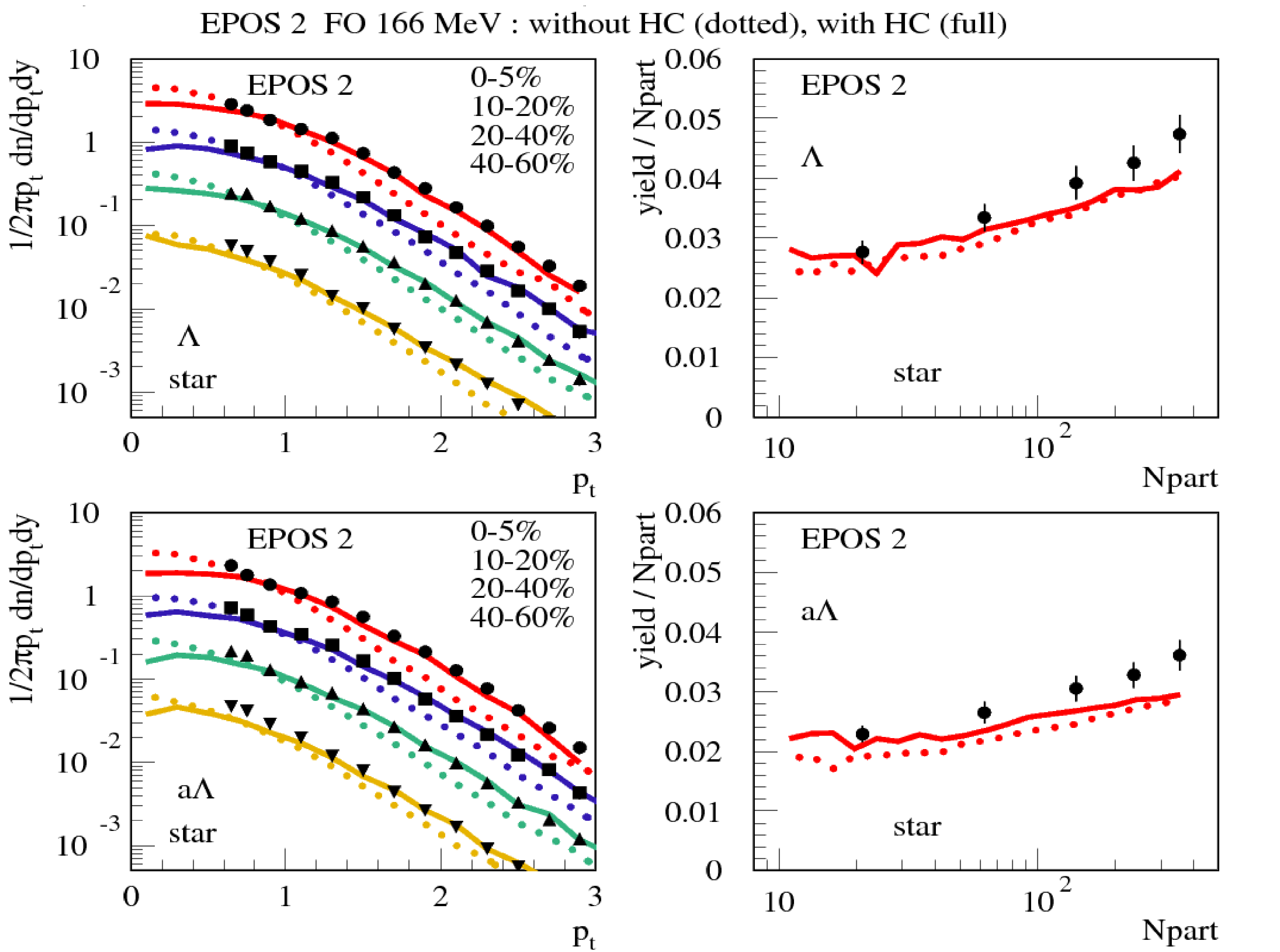
dotted lines: w/o cascade

AuAu : Lambda

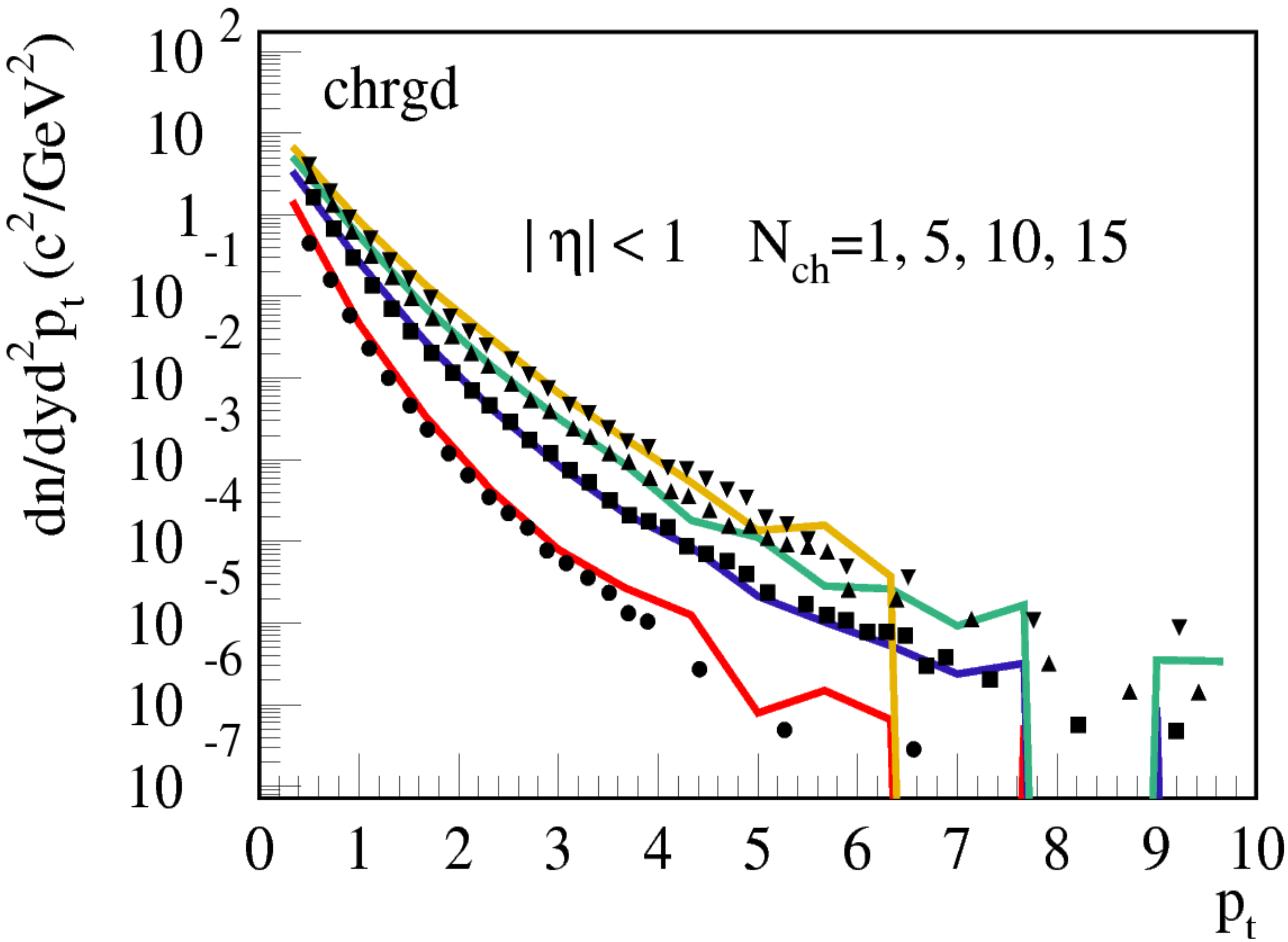
for better visibility:

pt spectra scaled by

1/2 (10-20%)
1/4 (20-40%)
1/8 (40-60%)



Pt distribution CDF ap-p@1.8 TeV with Hydro



Pt distribution CDF ap-p@1.8 TeV without Hydro