CGS vs EPOS : theory vs data ?

Tanguy Pierog

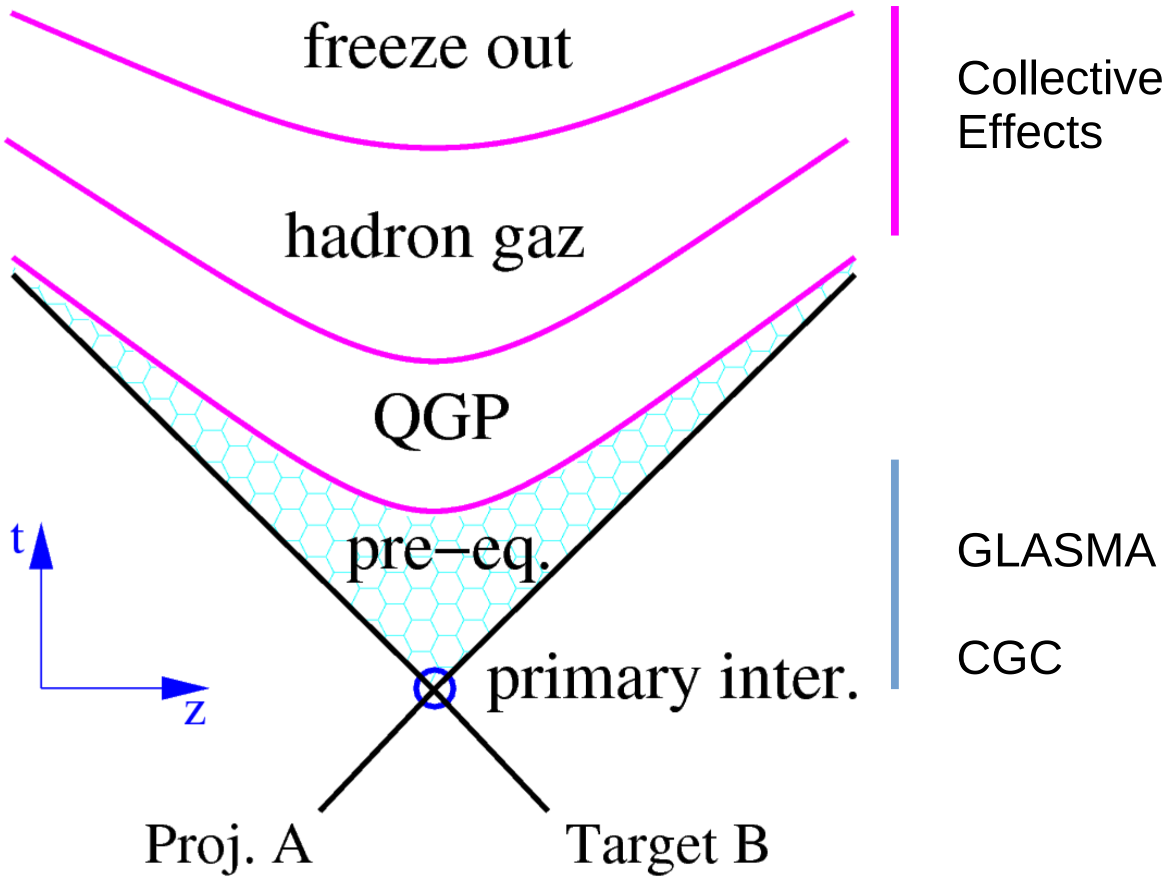
Karlsruhe Institute of Technology, Institut für Kernphysik,
Karlsruhe, Germany

CLASH workshop, Helsingborg, Sweden

June 26th - 29th 2023

High Energy Hadronic Interactions

Are CGC calculation in phase with what we can extract from data with a global approach like EPOS ?



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

From K. Werner

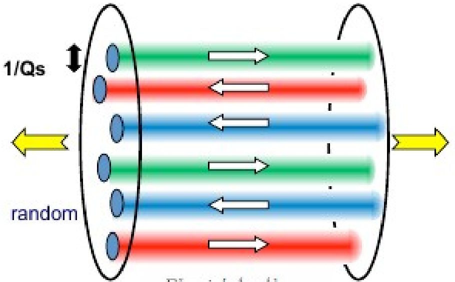
https://klaus.pages.in2p3.fr/epos4/

accomodate simultaneously

Energy conservation + **P**arallel scattering + fact**O**rization + **S**aturation

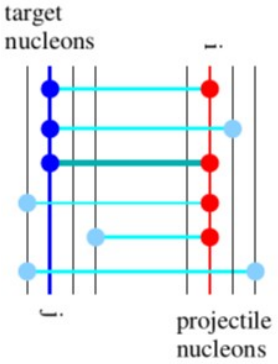
representing **4** crucial concepts of HE scattering

note: S-matrix theory is a useful tool!



$$E^z = ig[\alpha_1^i, \alpha_2^i]$$
$$B^z = ig\epsilon^{ij}[\alpha_1^i, \alpha_2^j].$$

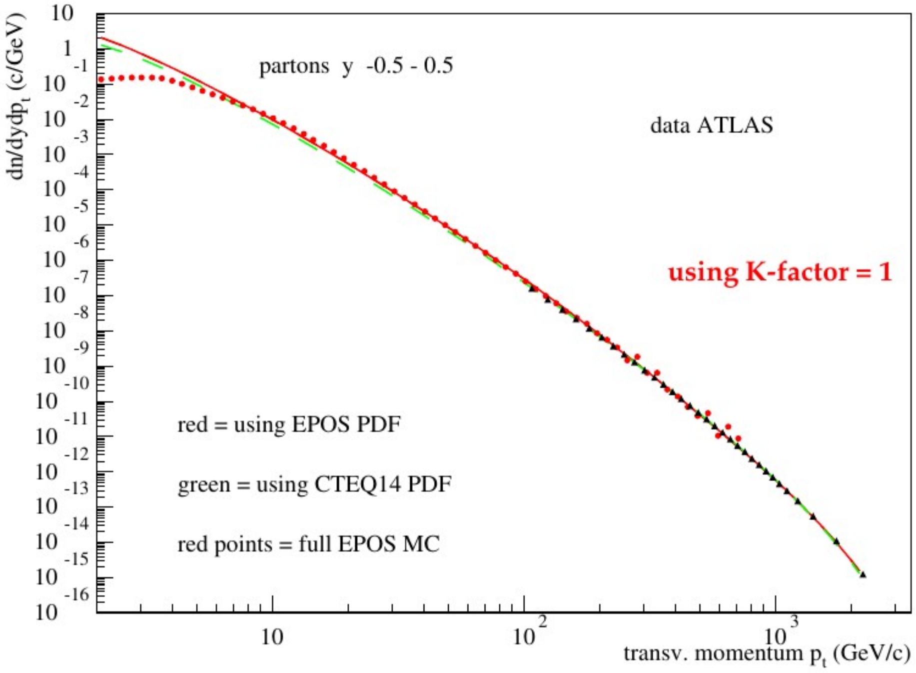
Typical configuration of a single event
just after the collision



- **EPOS in practice :**
  - Colored flux tube as in GLASMA
  - Saturation as in CGC
  - Factorization and binary scaling
  - Core-corona with hydro
- **Outcome**
  - Saturation scale, core fraction, etc … from DATA (best global fit)

What value for the saturation scale ?

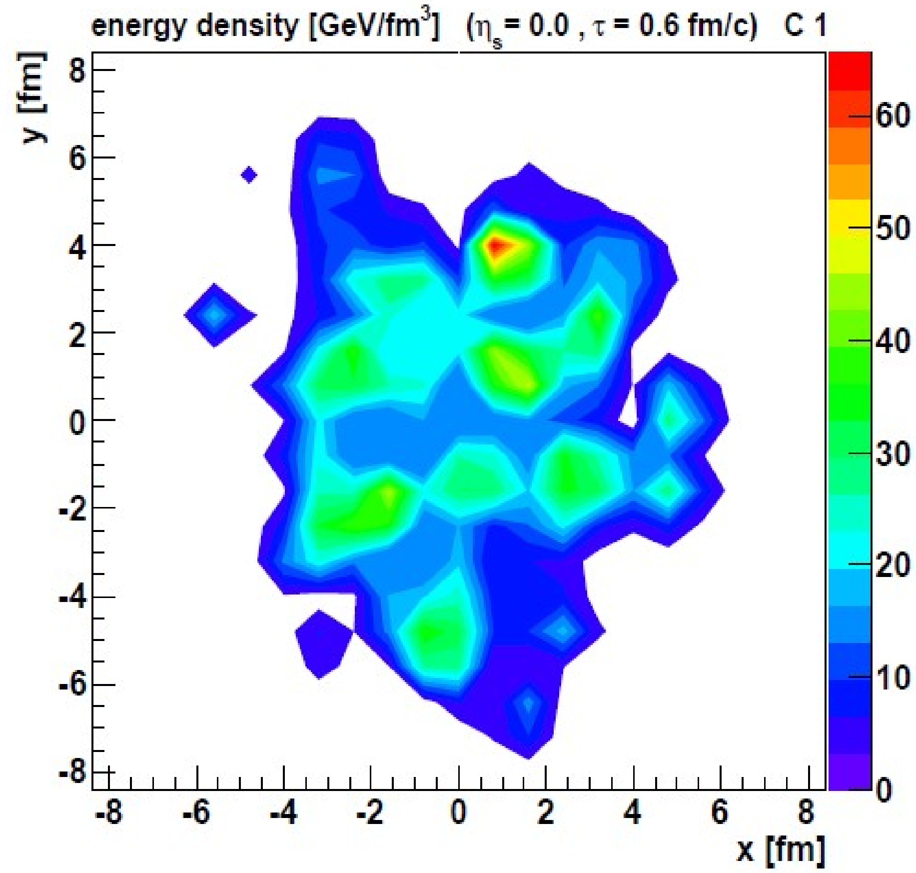
- **Tried CGC inspired numerical values in EPOS**
  - ➔ Failed to reproduce data
- **New approached based on factorisation + S-matrix**
  - ➔ Match pQCD amplitude with one compatible with cross-section and multiplicity (taking into account the fact that multiplicity is reduced by hydo (mass → flow))
  - ➔ Different saturation scale for each mini-jet with large variation event by event and for all systems

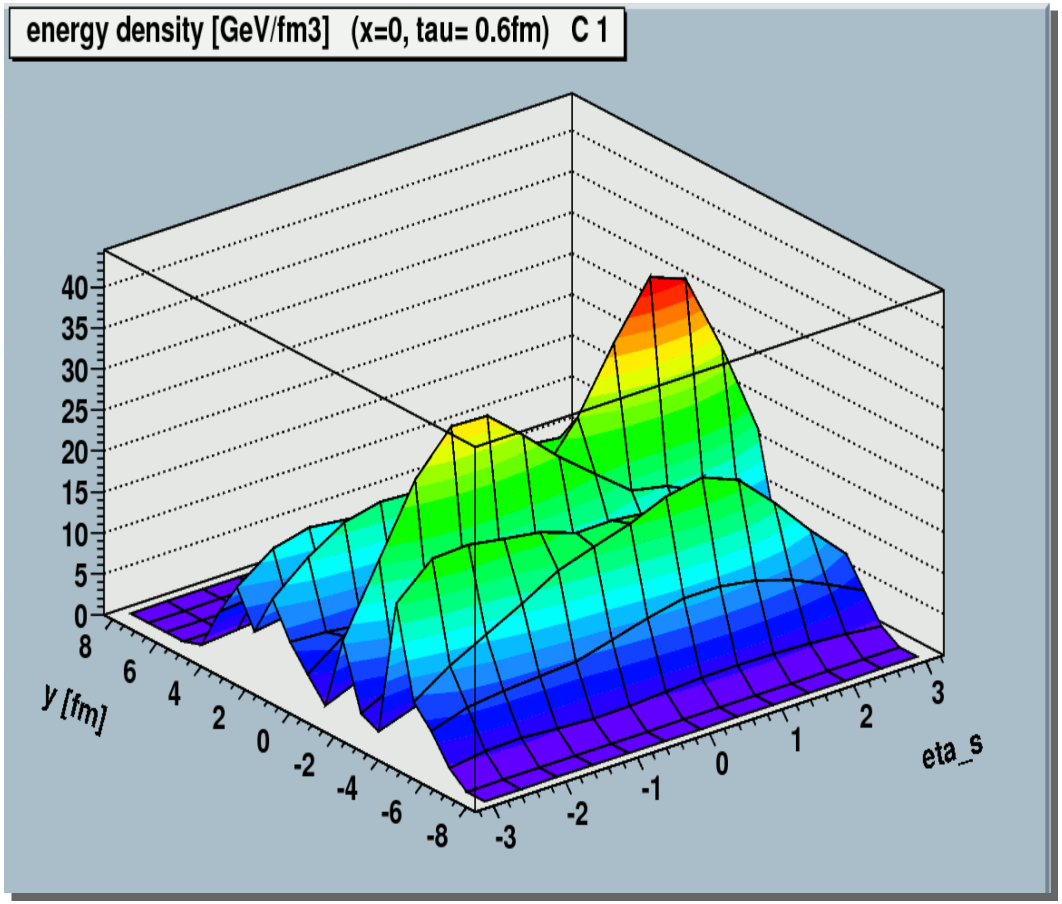


- ➔ “Saturation” below pt of 10 GeV @ LHC in average
- ➔ Extremely large difference from low to high multiplicity event
- ➔ Is it compatible with predictions from CGC ?
- ➔ If not ?
  - Not the same saturation ?
  - Calculation to simplified ?
  - How to account for the fluctuations ?

Event-by-Event Energy Density : AuAu

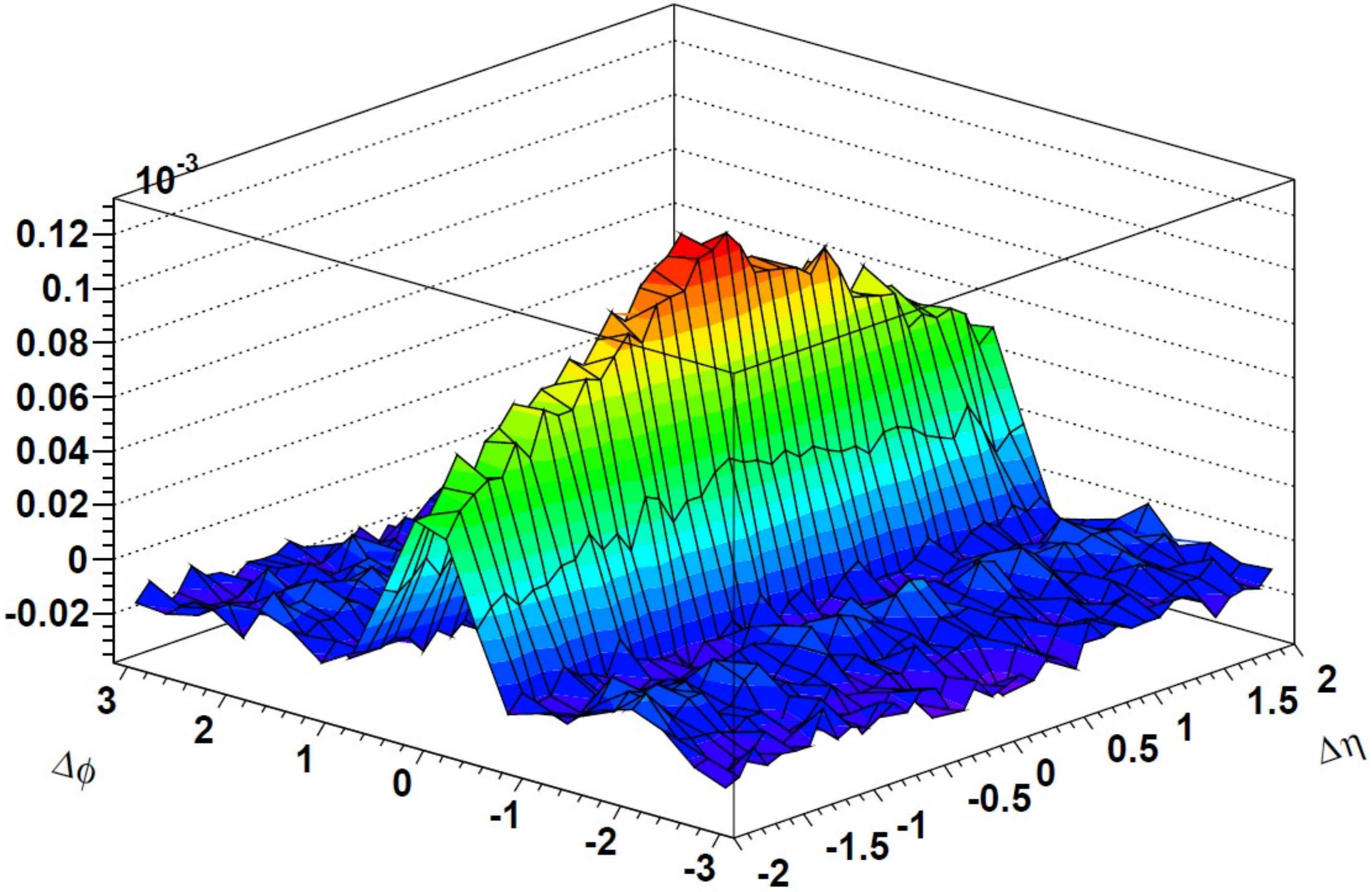
- Bumpy structure of energy density in transverse plane, but translational invariance
  - pseudorapidity extension of flux tubes





AuAu : Di-hadron correlation

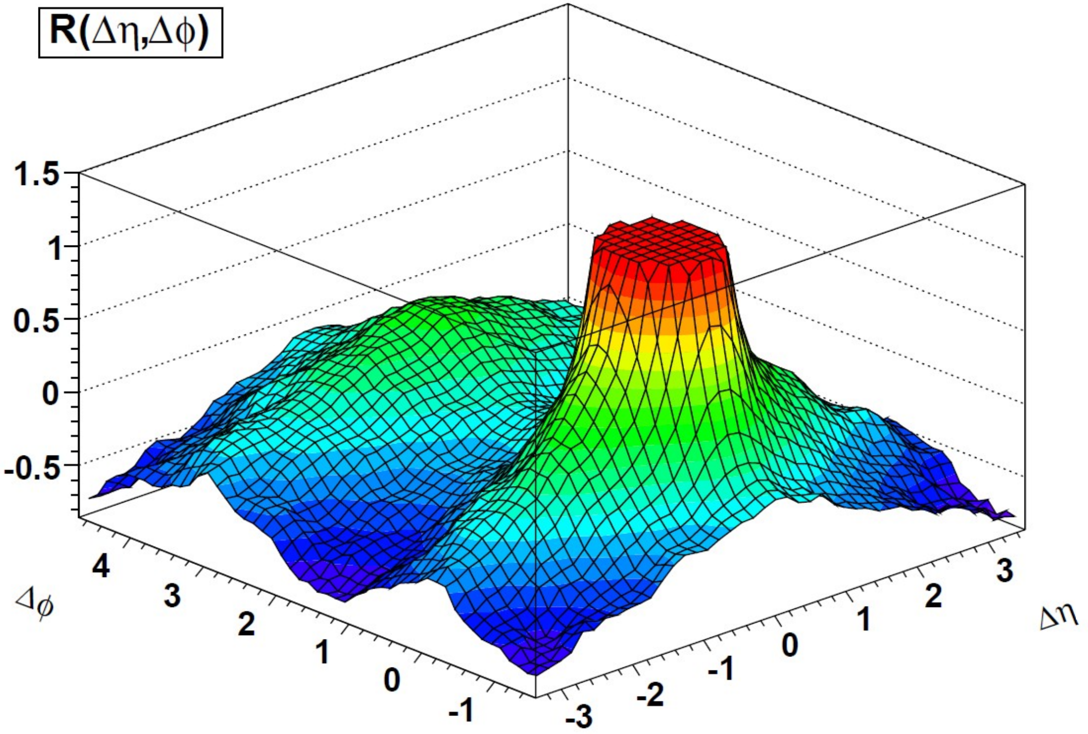
- ridge-structure in the dihadron correlation dN/dΔηdΔφ for free



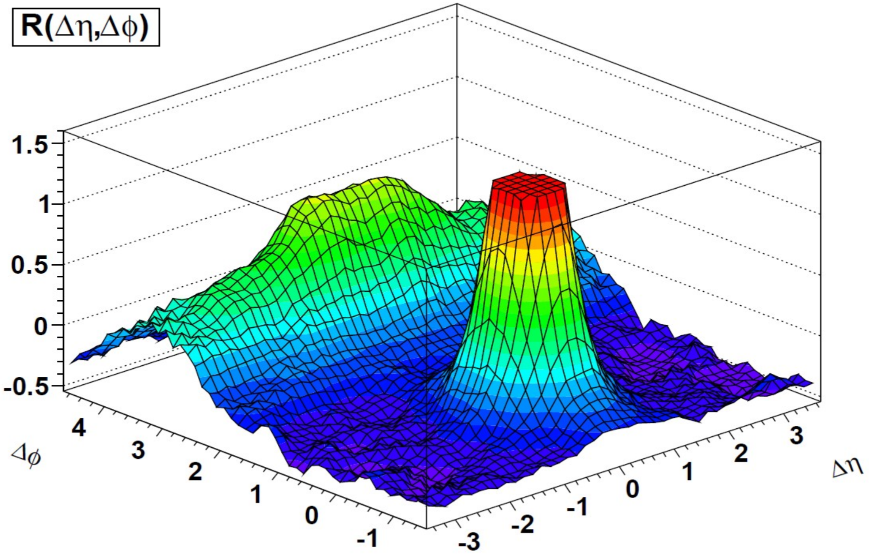
AuAu 0-10%, $3 < p_t^{\text{trig}} < 4\,\text{GeV/c}$ $2 < p_t^{\text{assoc}} < p_t^{\text{trig}}$

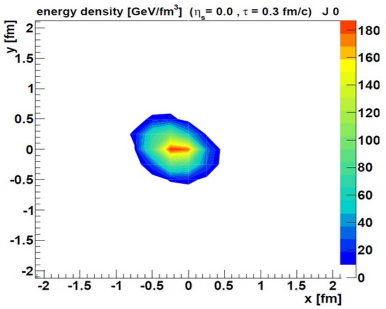
pp@7 TeV : Di-hadron correlation

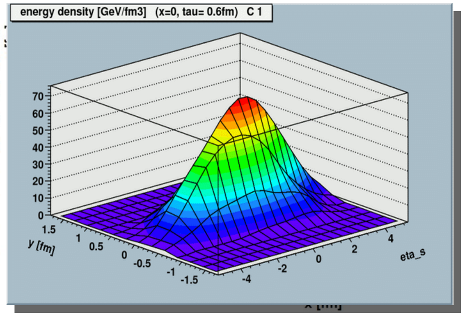
- Our calculation provides a similar ridge structure in pp@LHC using particles with 1 < pt < 3GeV/c, for high multiplicity events



without flow



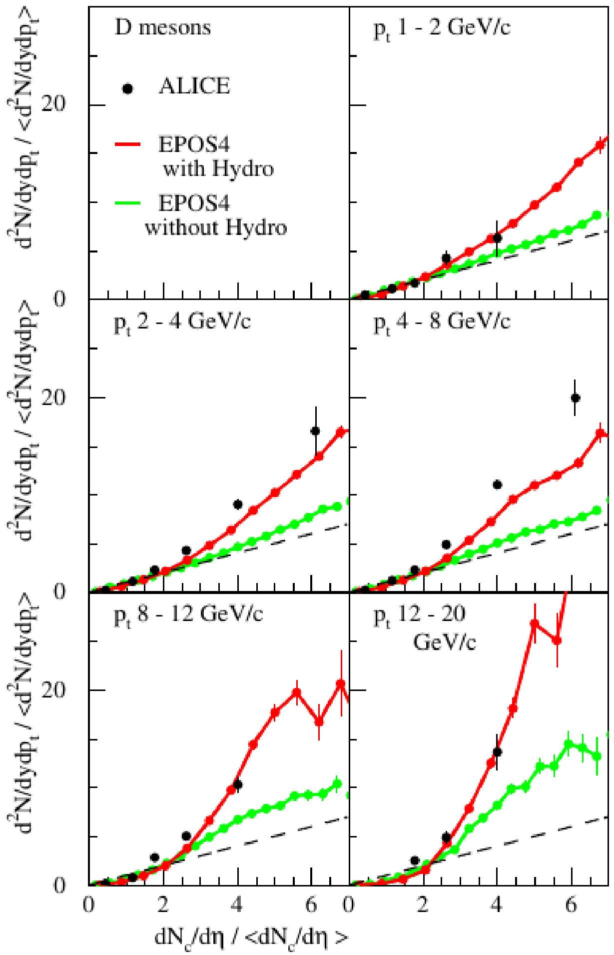




- Flow parameters in pp from geometry and strong constrain from other data
- Quantitatively describe ridge data

Any room for something else ?

How could CGC alone (and even with Pythia) reproduce data ?

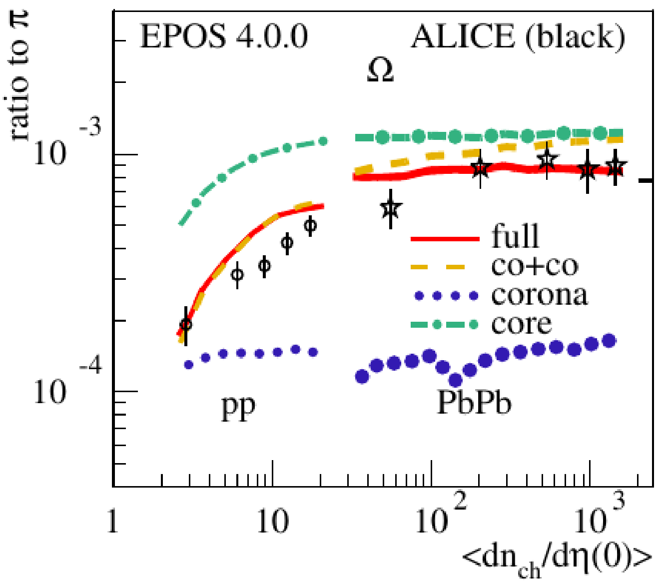


- Saturation : no linear <pt> charm increase
- Hydro : decrease final multiplicity for a given MPI

What we learn from a global approach

- Extremely complex interplay between all components
- Impossible to reproduce one observable with one component of the model only

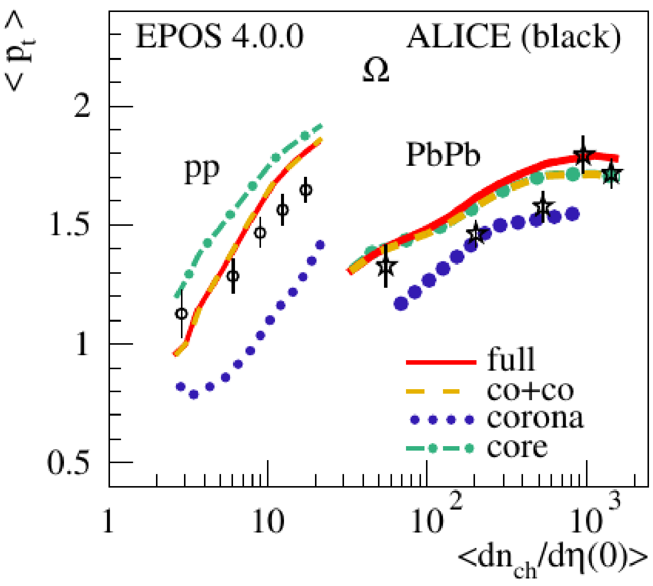
continuous curve



core-corona effect

+ microcanonical effect

jump



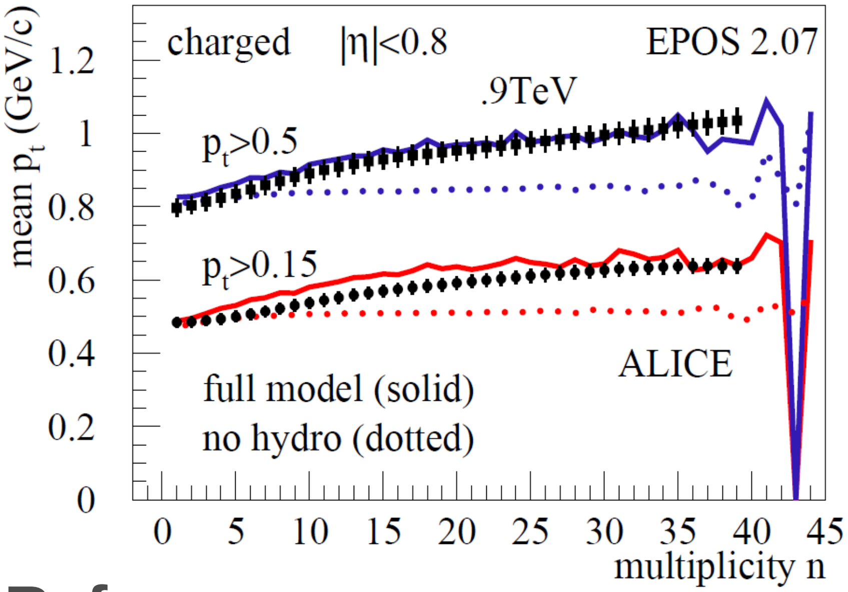
core-corona effect

saturation effect

+ flow effect

Be aware … data are not limited to one distribution !

- Summarized in <Pt> versus multiplicity (here 900 GeV)



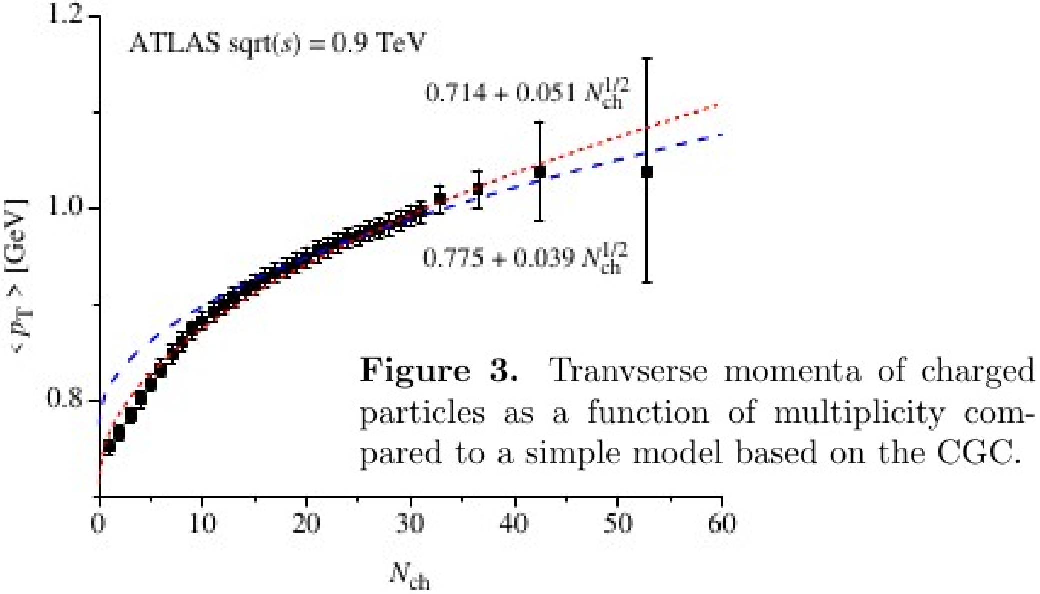
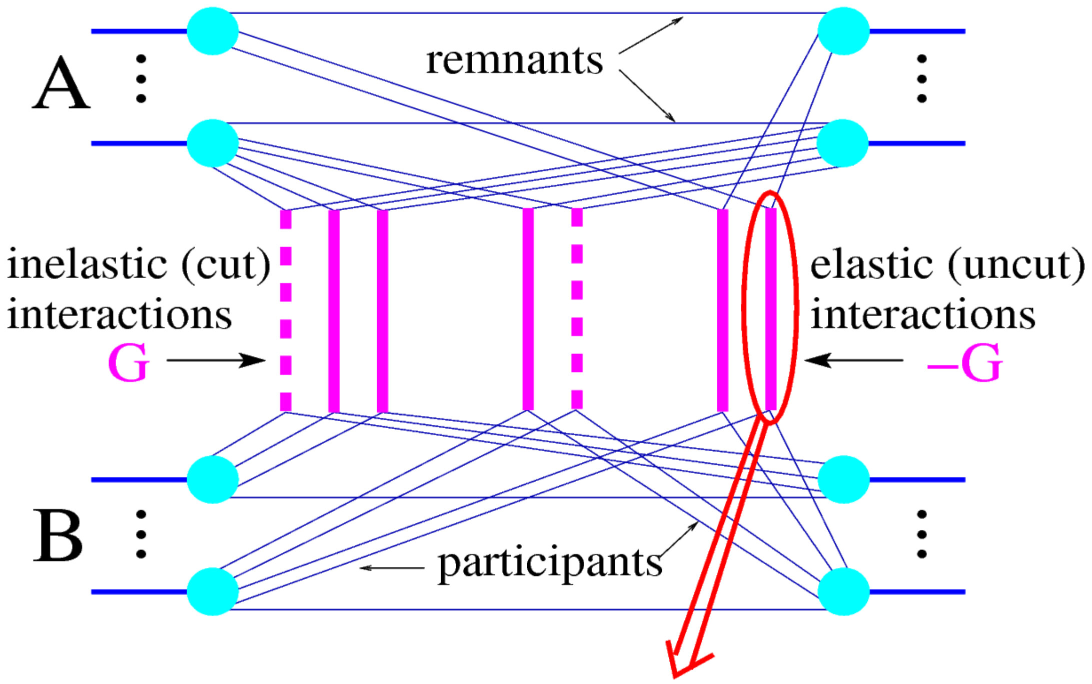


Figure 3. Tranvserse momenta of charged particles as a function of multiplicity compared to a simple model based on the CGC.

References

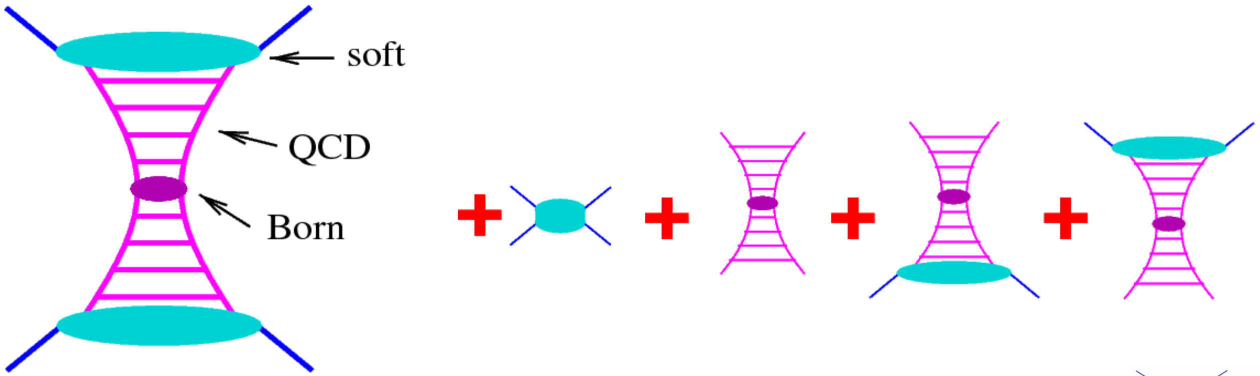
- *The Color Glass Condensate, Glasma and the Quark Gluon Plasma in the Context of Recent pPb Results from LHC.* **Larry McLerran** doi:10.1088/1742-6596/458/1/012024
- On a deep connection between factorization and saturationnew insight into modeling high-energy proton-proton and nucleus-nucleus scattering in the EPOS4 framework. **K. Werner.** 2301.12517 [hep-ph]
- *Perturbative QCD concerning light and heavy flavor in the EPOS4 Framework.* **K. Werner and B. Guiot.** 2306.02396 [hep-ph]
- *Core-corona procedure and microcanonical hadronization to understand strangeness enhancement in proton-proton and heavy ion collisions in the EPOS4 framework* **K. Werner.** 2306.10277 [hep-ph]

Parton-Based Gribov-Regge Theory

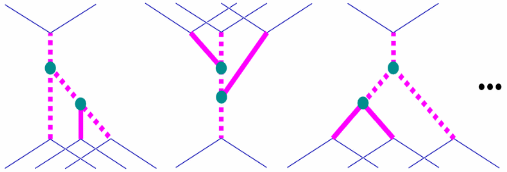


Energy sharing at the cross section level

- 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)

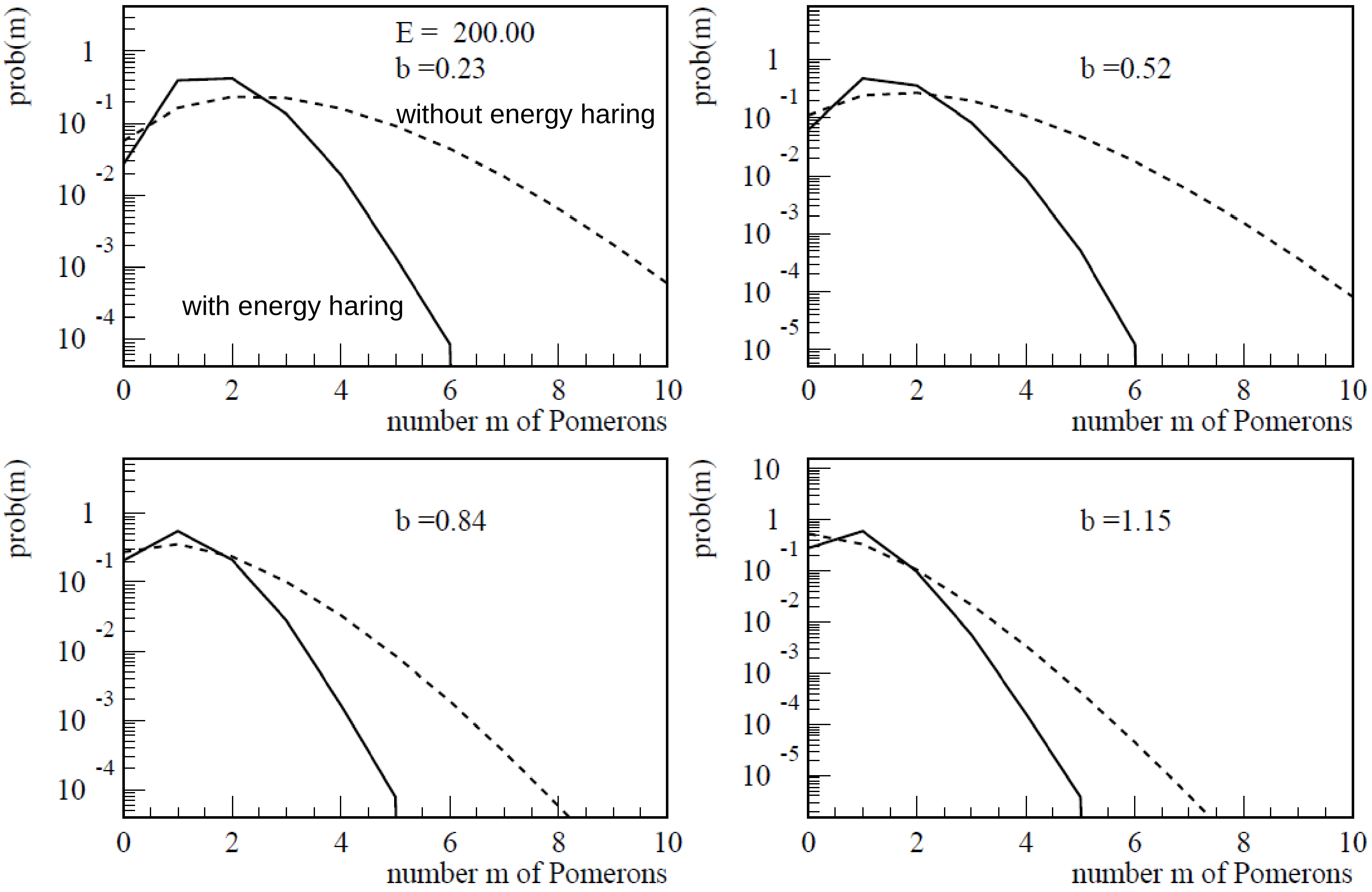


Non-linear effect (screening) absorbed in modified vertex functions



Number of cut Pomerons

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

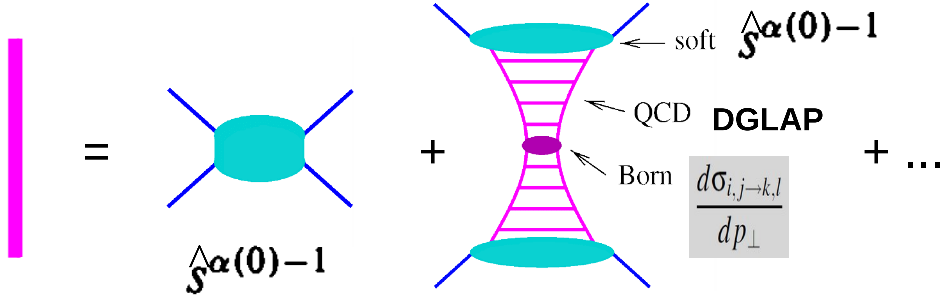


without energy haring

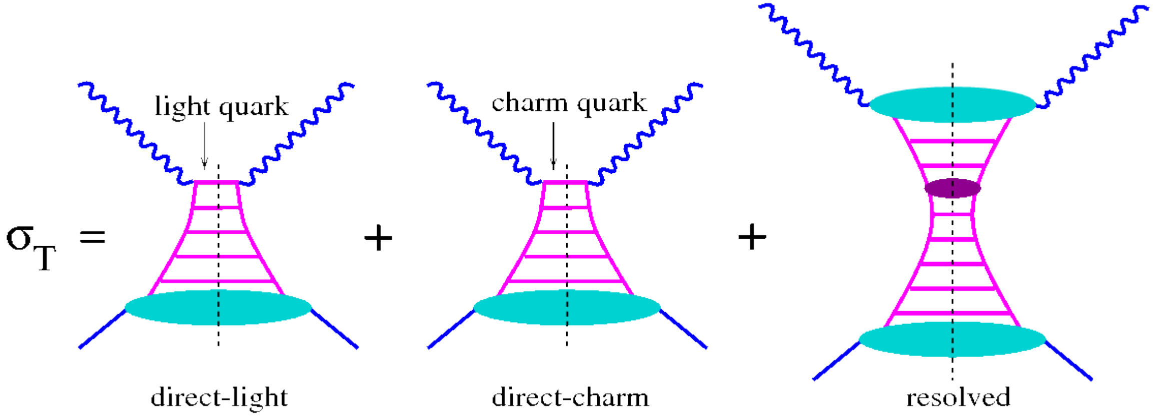
with energy haring

EPOS : Pomeron definition

Semi-hard Pomeron :

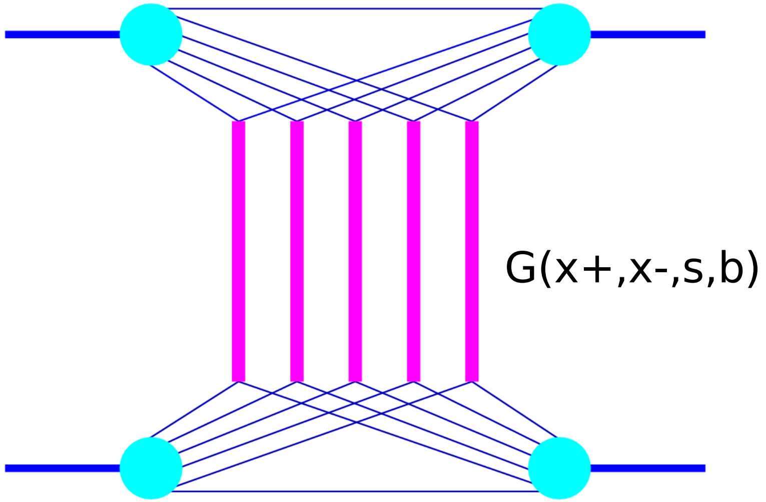


Test of semi-hard Pomeron with DIS: (Parton Distribution Function from HERA)



- 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

Cross Section Calculation : EPOS



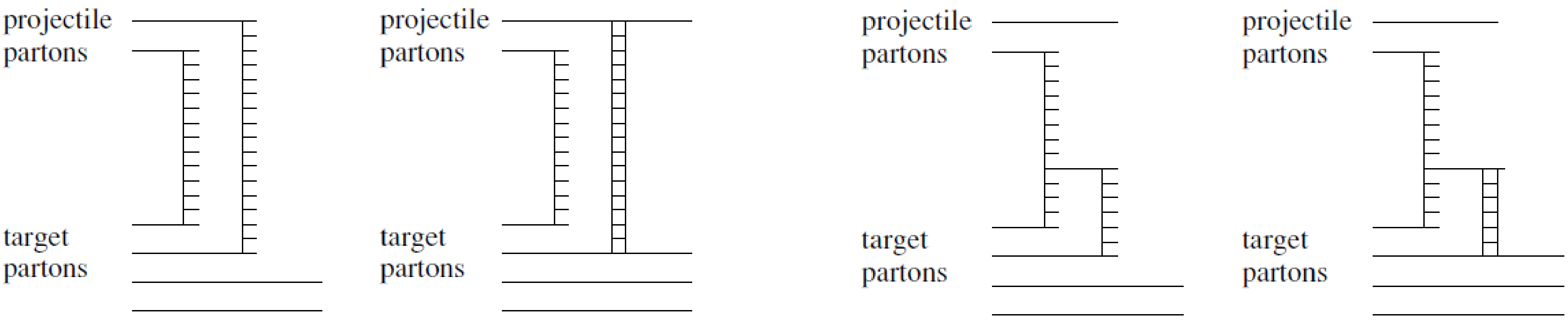
- PBGRT : Gribov-Regge but with energy sharing at parton level
- amplitude parameters fixed from QCD and pp cross section (semi-hard Pomeron)
- cross section calculation take into account interference term

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

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

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

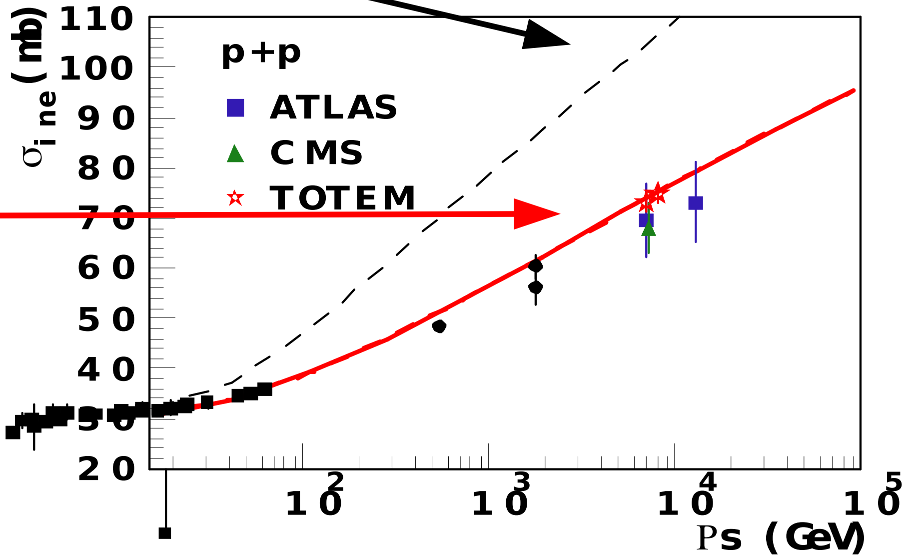


No effective coupling

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

With effective coupling

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



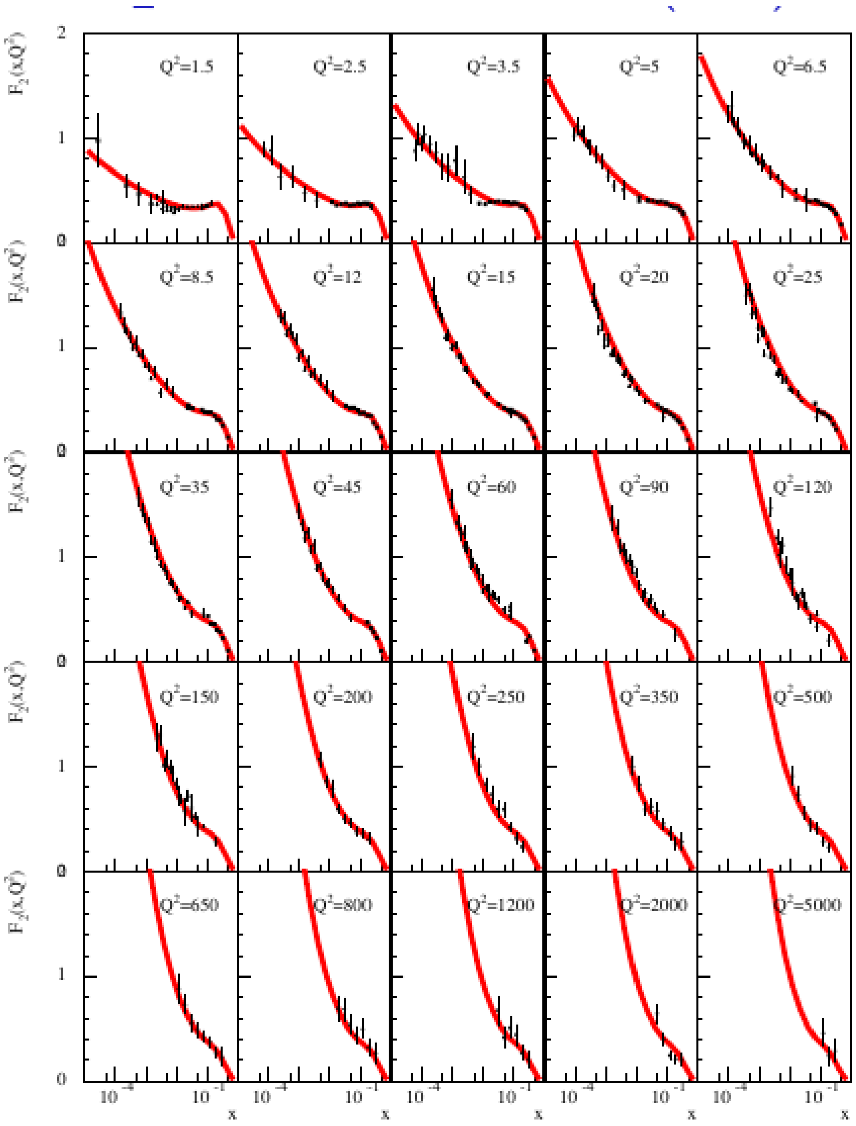
Parametrization

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

Parton Distribution Function

PDF based and DGLAP and initial soft parametrization with saturation

EPOS 4 (Klaus Werner)



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 :

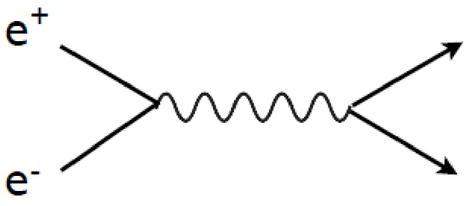
$$\Omega_{AB}^{(s,b)}(m,X^+,X^-)=\prod_{k=1}^{AB}\left\{\frac{1}{m_k!}\prod_{\mu=1}^{m_k}G(x_{k,\mu}^+,x_{k,\mu}^-,s,b_k)\right\}\ \Phi_{AB}\left(x^{\text{proj}},x^{\text{targ}},s,b\right)$$

  - 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

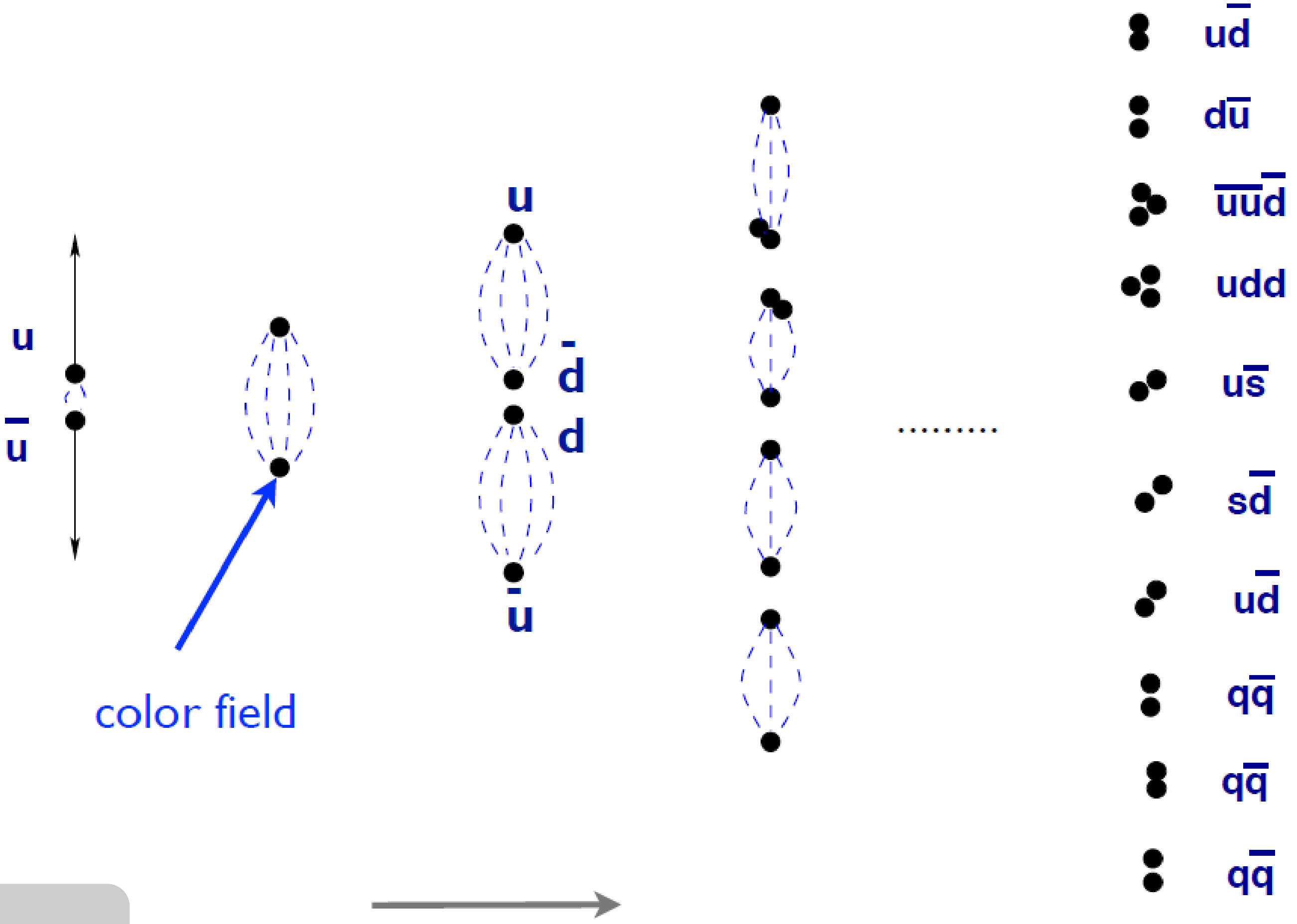
Consistent treatment of cross section and particle production:
number AND distribution of cut Pomerons depend on cross section

Simplest case: e^+e^- annihilation into quarks

Annihilation at high energy



Quarks together are color-neutral system



color field

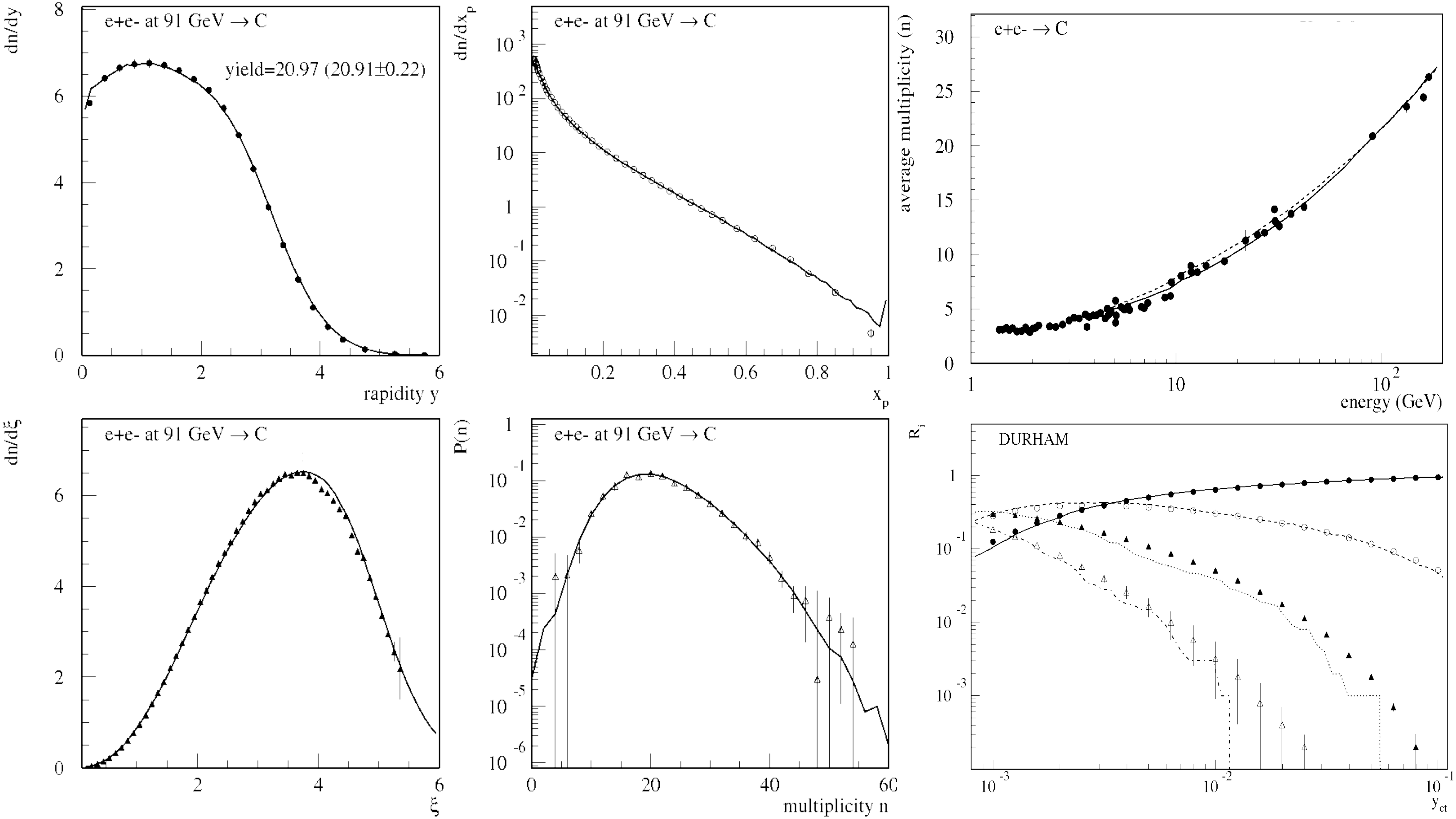
time

Area law used in EPOS (not Lund)

String fragmentation

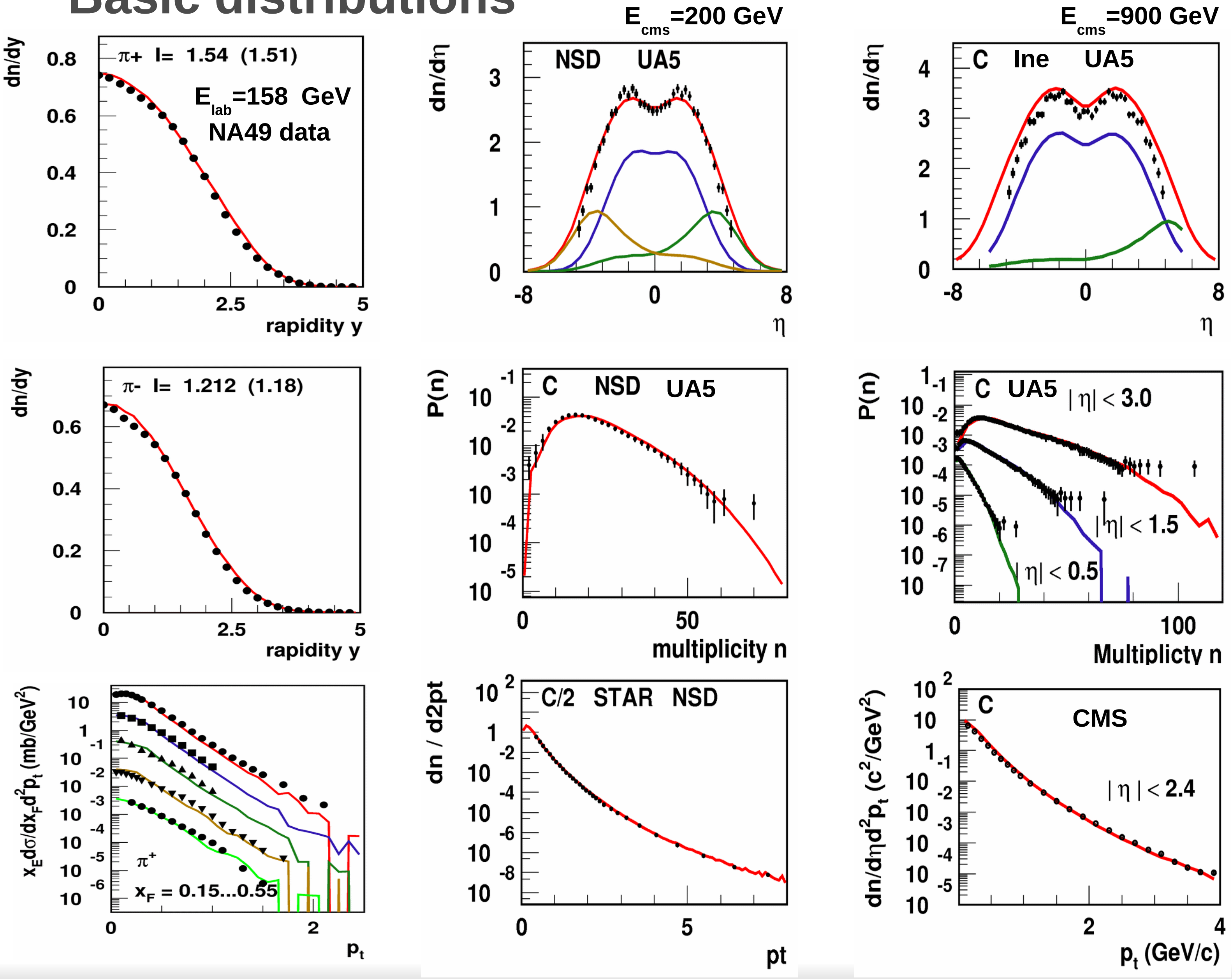
Chain of hadrons

Test at LEP


dn/dy
e+e- at 91 GeV → C
yield=20.97 (20.91±0.22)
rapidity y
0 2 4 6 8
dn/dx_p
e+e- at 91 GeV → C
x_p
0.2 0.4 0.6 0.8 1
10^{-2} 10^{-1} 1 10 10^2 10^3
average multiplicity (n)
e+e- → C
energy (GeV)
1 10 10^2
0 5 10 15 20 25 30
dn/dξ
e+e- at 91 GeV → C
ξ
2 4 6
P(n)
e+e- at 91 GeV → C
multiplicity n
0 20 40 60
10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1
R_j
DURHAM
y_{ct}
10^{-3} 10^{-2} 10^{-1} 1

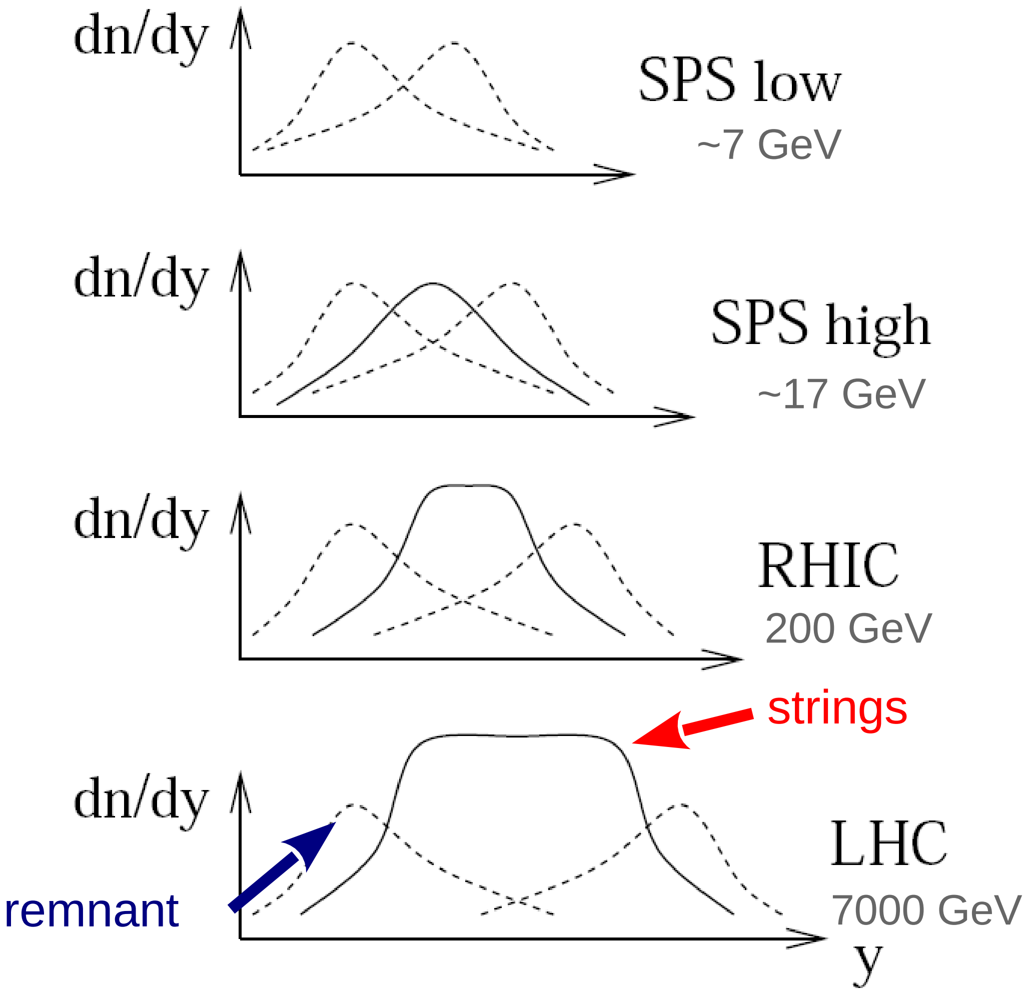
Basic Distributions

Basic distributions



Remnants

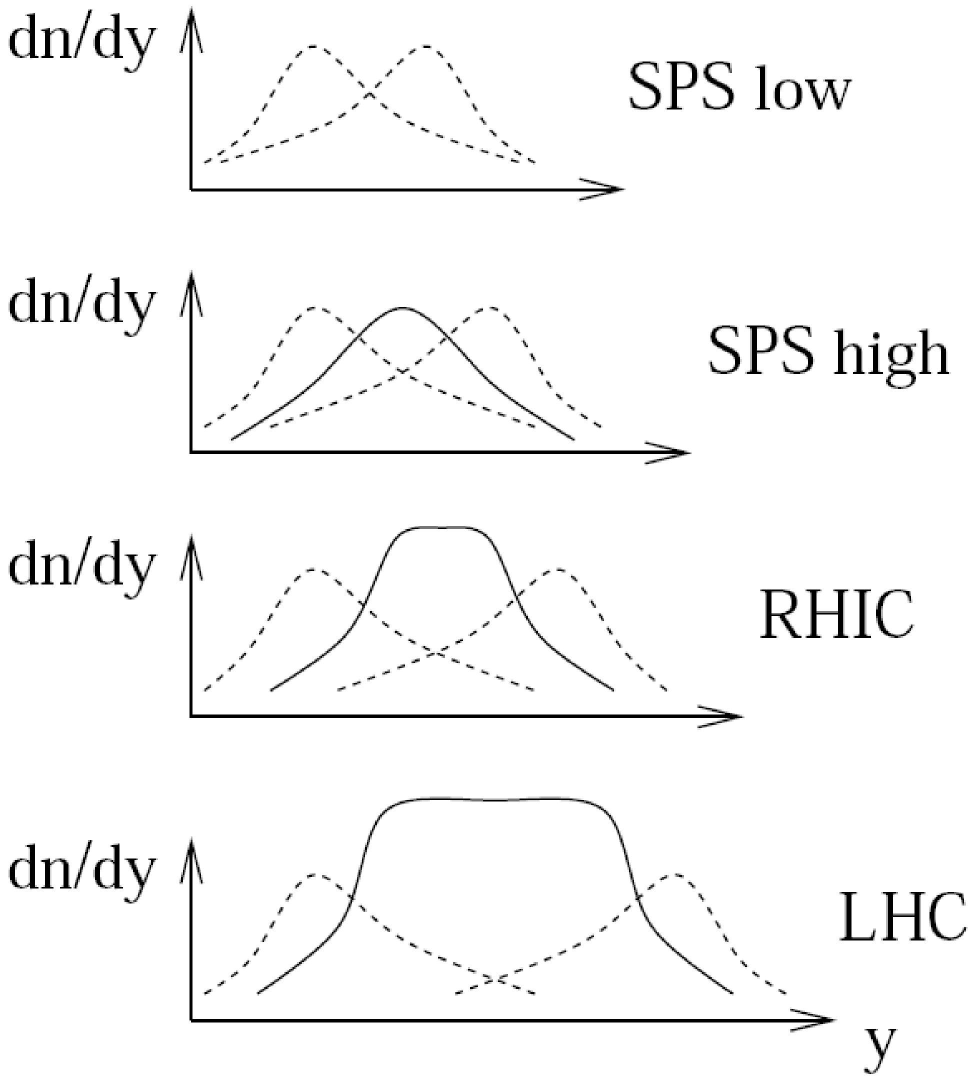
Forward particles mainly from projectile remnant



- 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)

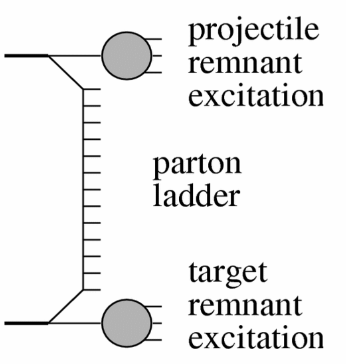
Different contributions of particle production at different energies or rapidities

Remnants



Free remnants in EPOS:

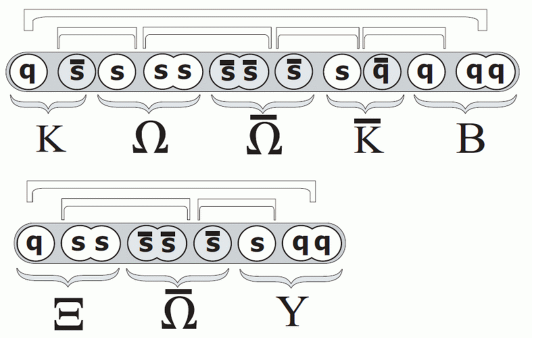
- from both diffractive or inelastic scattering
- excited state with P(M)~1/(M^2)$^\alpha$
- dominant contribution at low energy
- forward region at high energy
- depending on quark content and mass (excitation):
  - resonance
  - string
  - droplet (if #q>3)
  - string+droplet



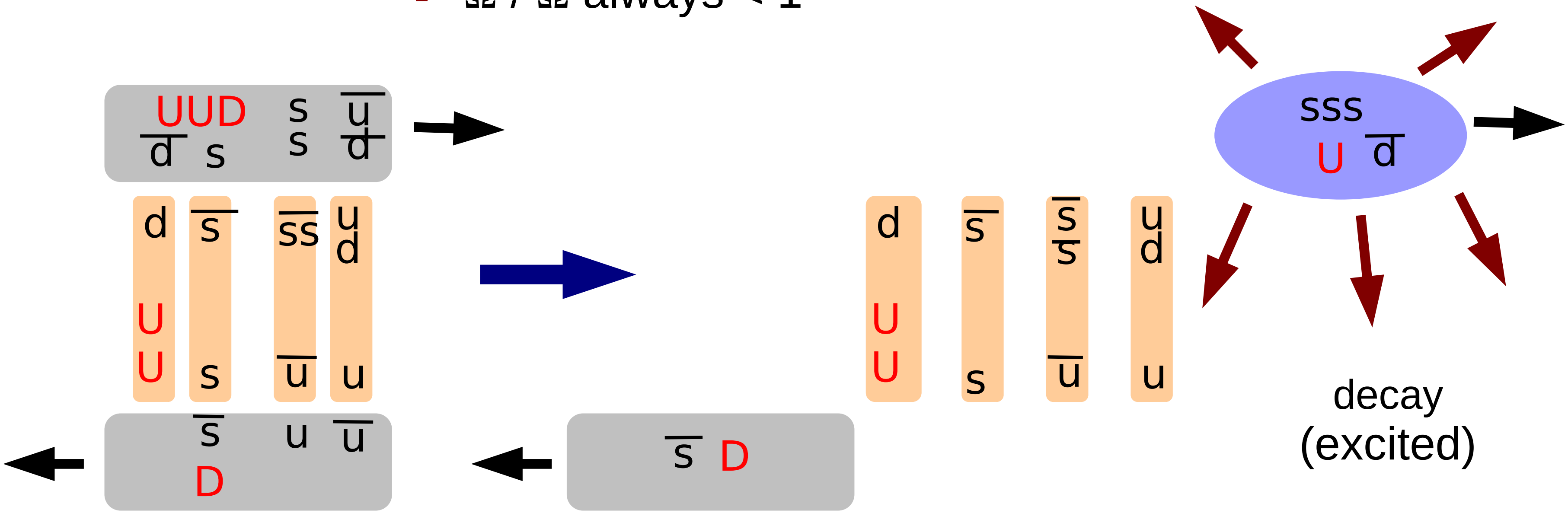
Baryons and Remnants

Parton ladder string ends :

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



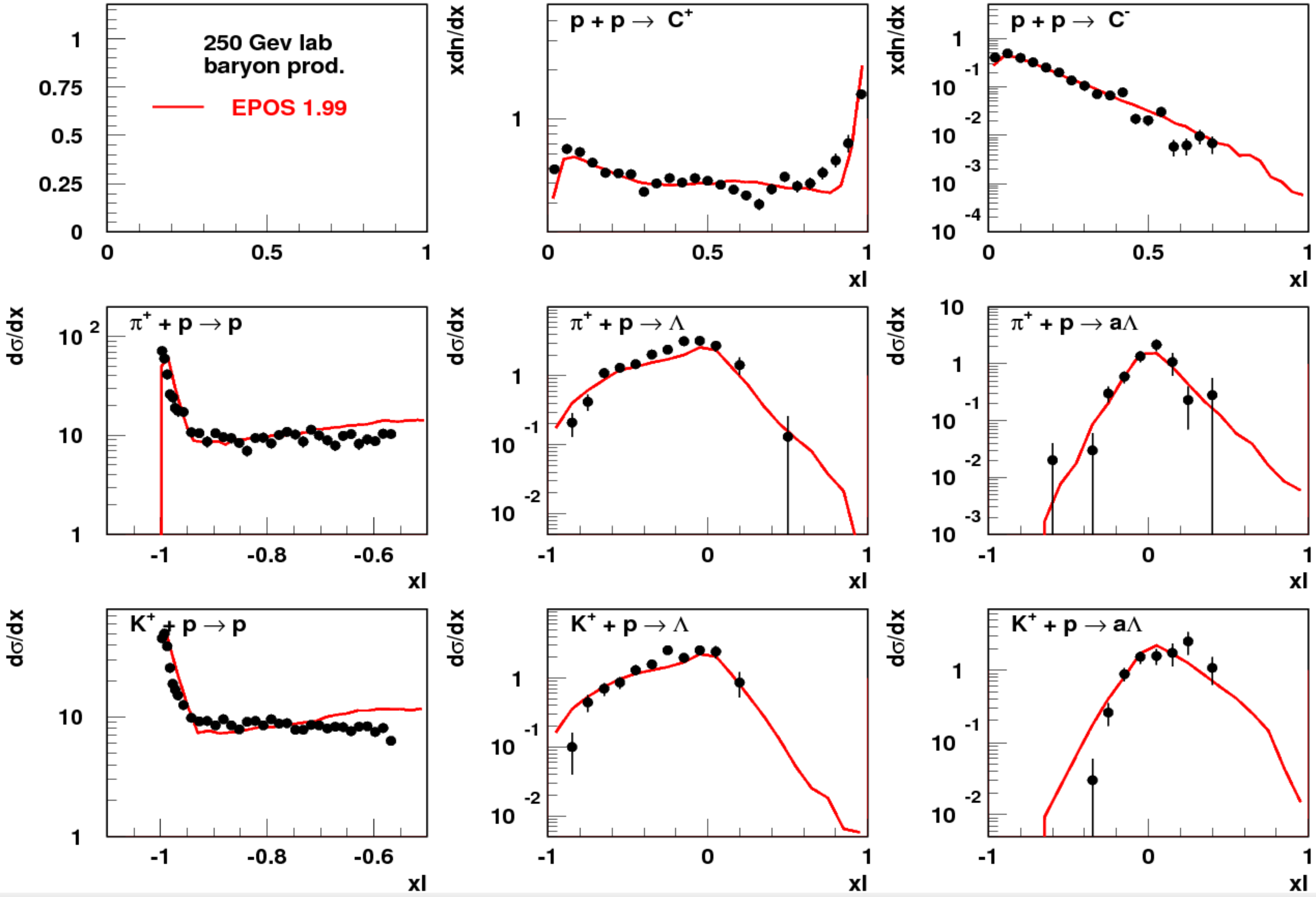
- EPOS
  - No “first string” with valence quarks : all strings equivalent
  - Wide range of excited remnants (from light resonances to heavy quark-bag)
    - $\bar{\Omega} / \Omega$ always < 1



decay
(excited)

Baryon Production

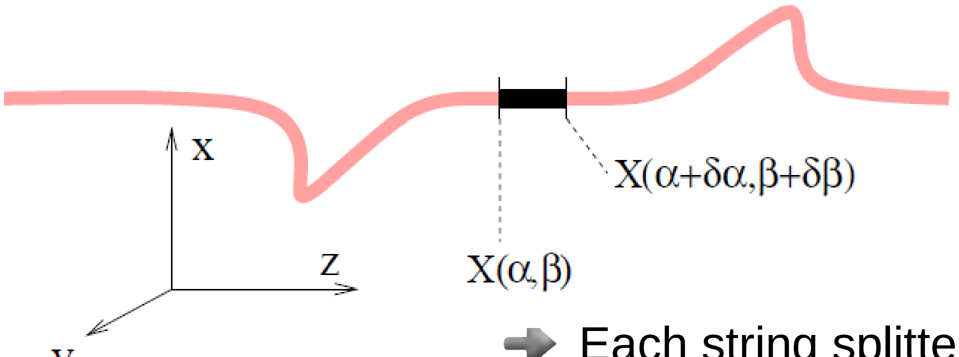
Baryon production for fixed target exp.

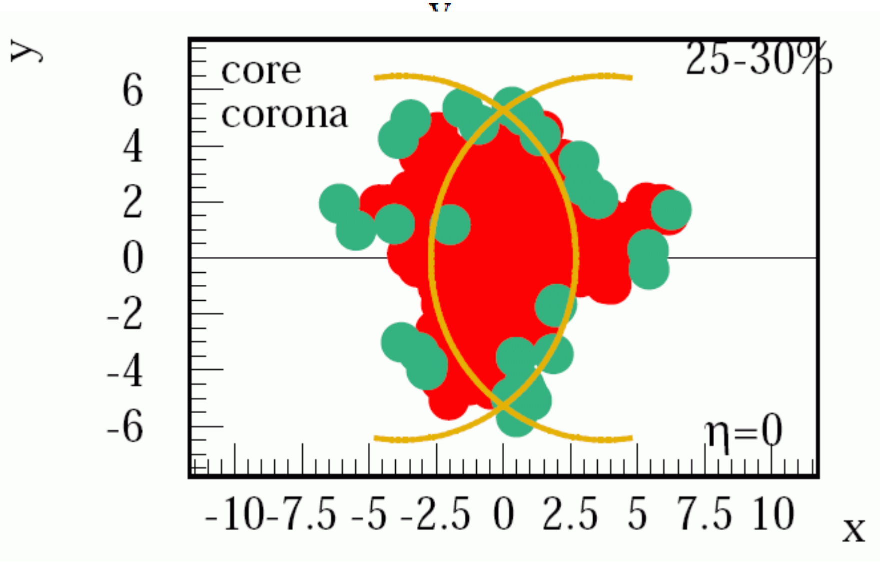


High Density Core Formation

Heavy ion collisions or very 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**





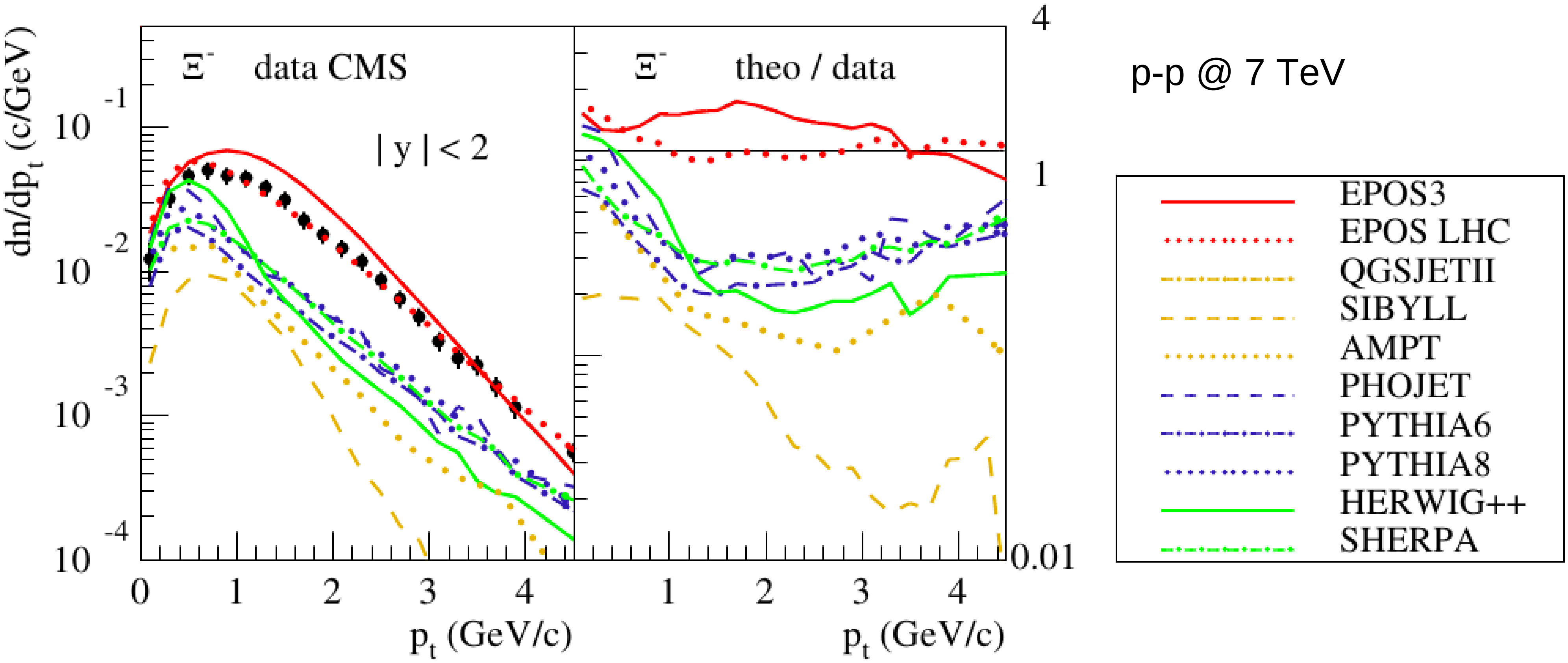
- Each string splitted into a sequence of string segments, corresponding to widths δα and δβ in the string parameter space
- If energy density from segments high enough
  - segments fused into core
    - flow from hydro-evolution
    - statistical hadronization
- If low density (corona)
  - segments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

Core in p-p

Detailed description can be achieved with core in pp

- identified spectra: different strangeness between string (low) and stat. decay (high)
- p_t behavior driven by collective effects (statistical hadronization + flow)

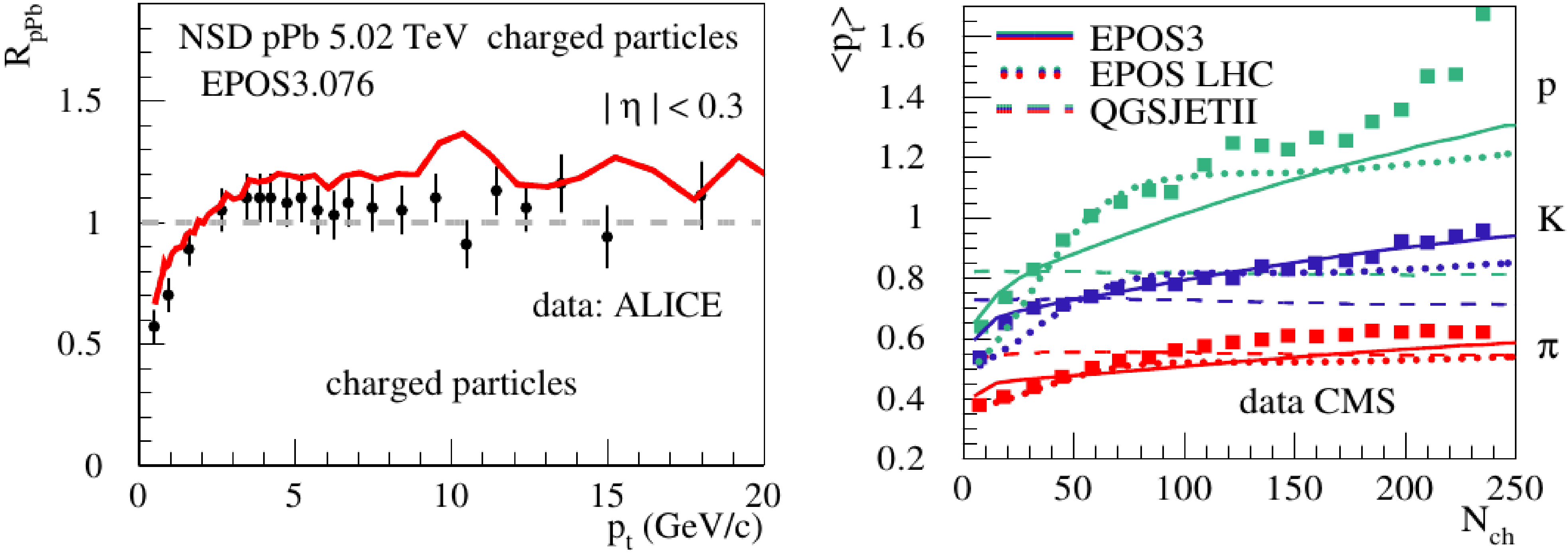
  - larger effect for multi-strange baryons (yield AND $<p_t>$)



EPOS 3

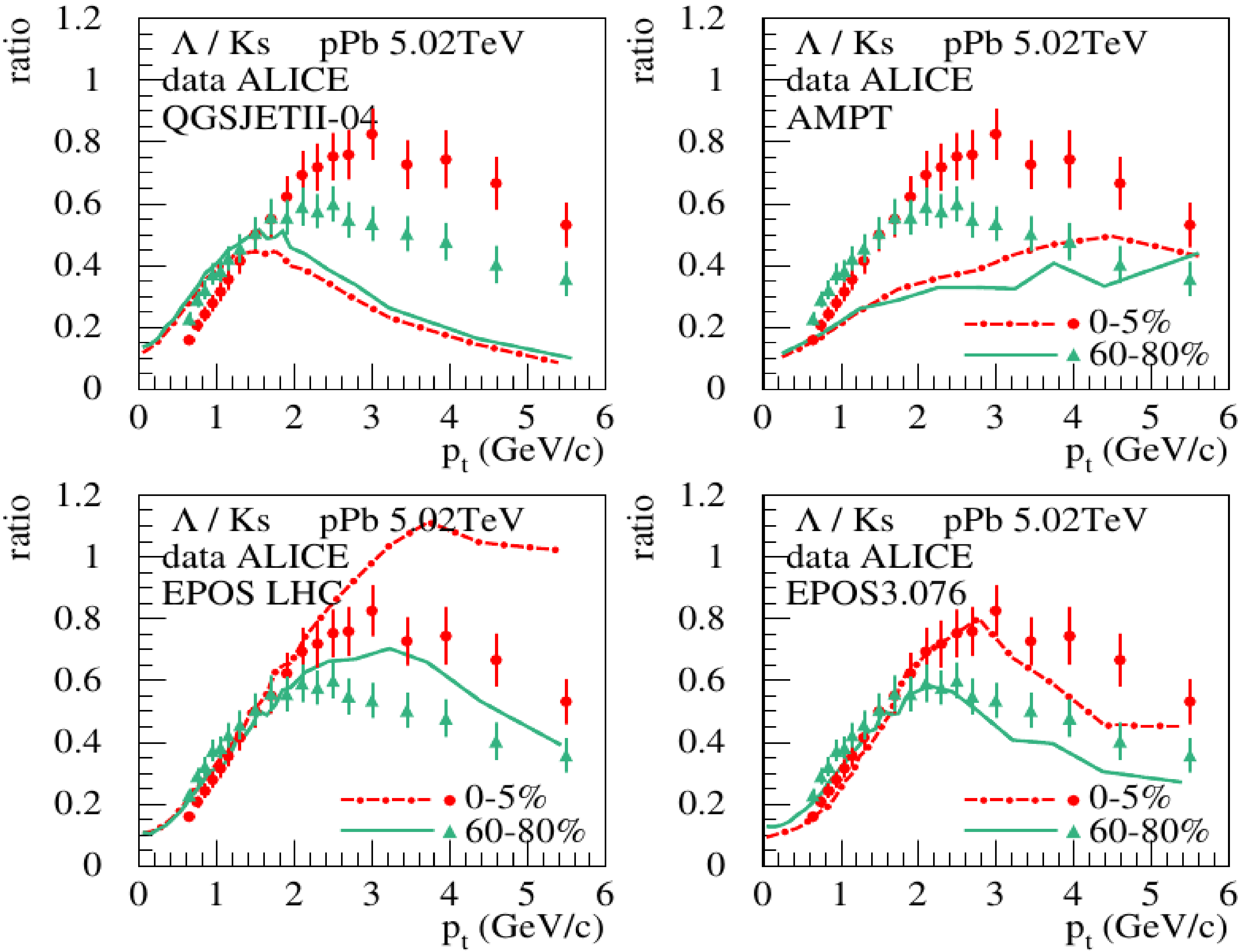
Use saturation scale to have a Q^2 dependent screening

- restore binary scaling for high p_t
- intermediate p_t due to flow based on real hydro simulations
  - mass splitting

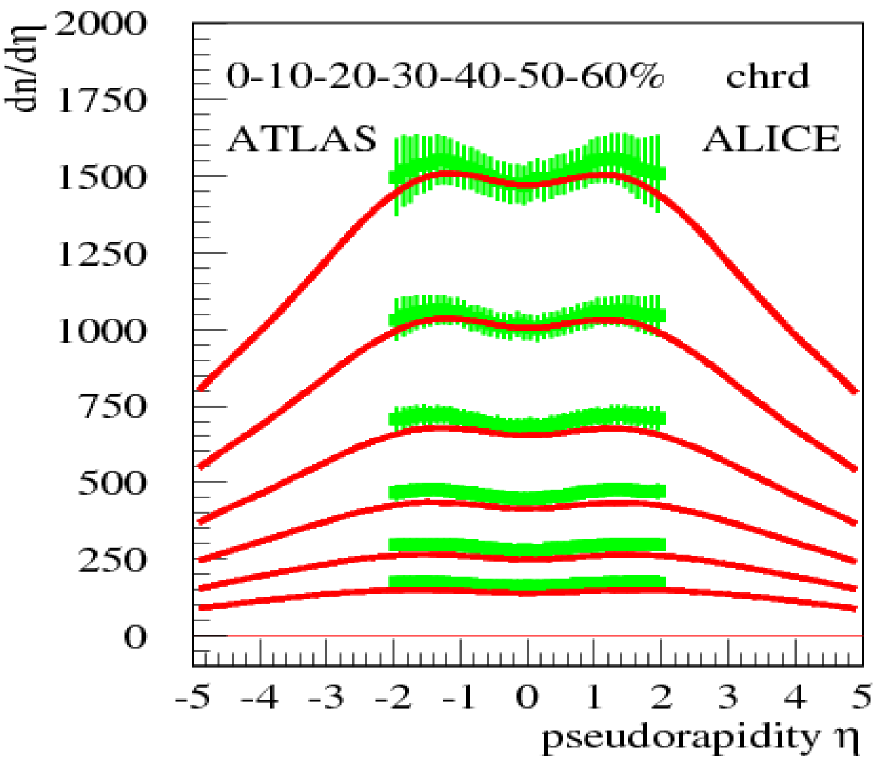


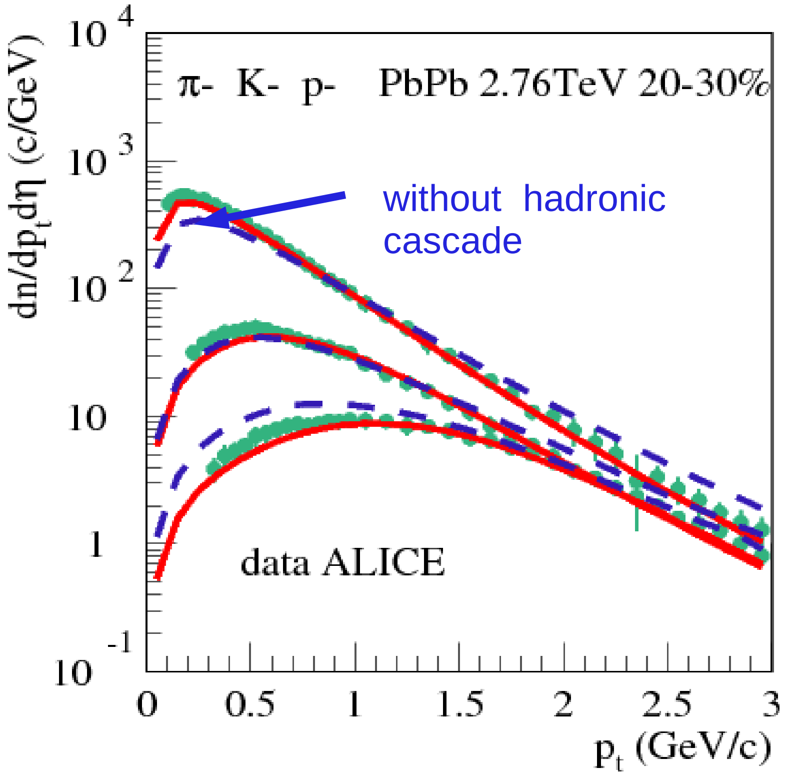
Real 3D Hydro

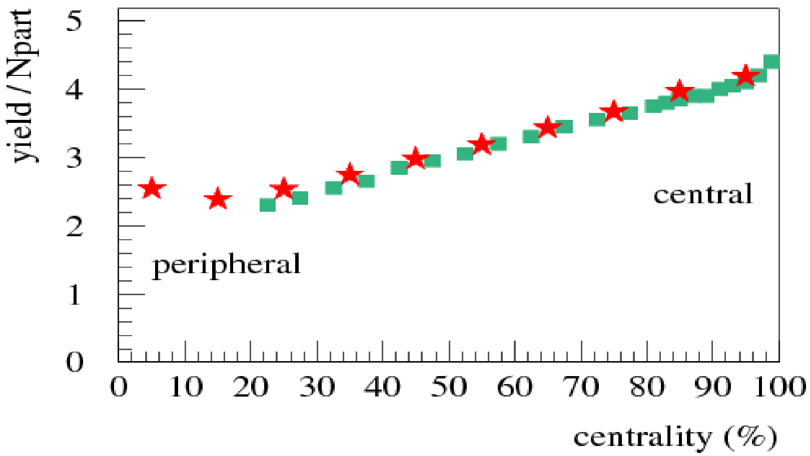
Particle ratio characteristic of collective flow effect.

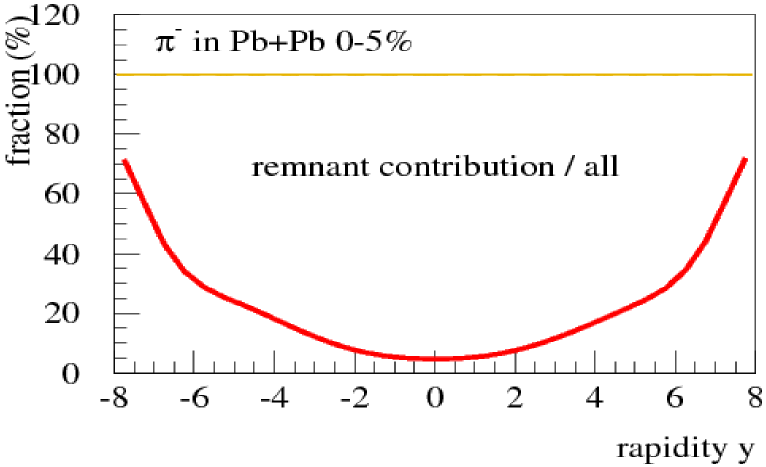


PbPb @ LHC

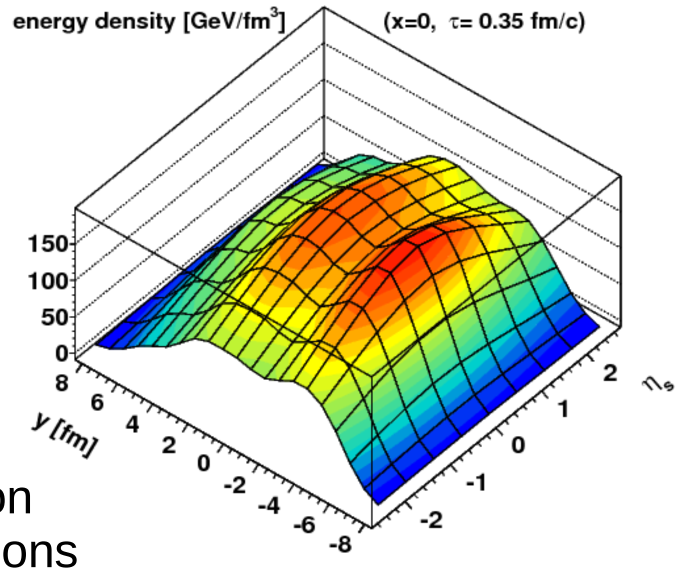



without hadronic cascade

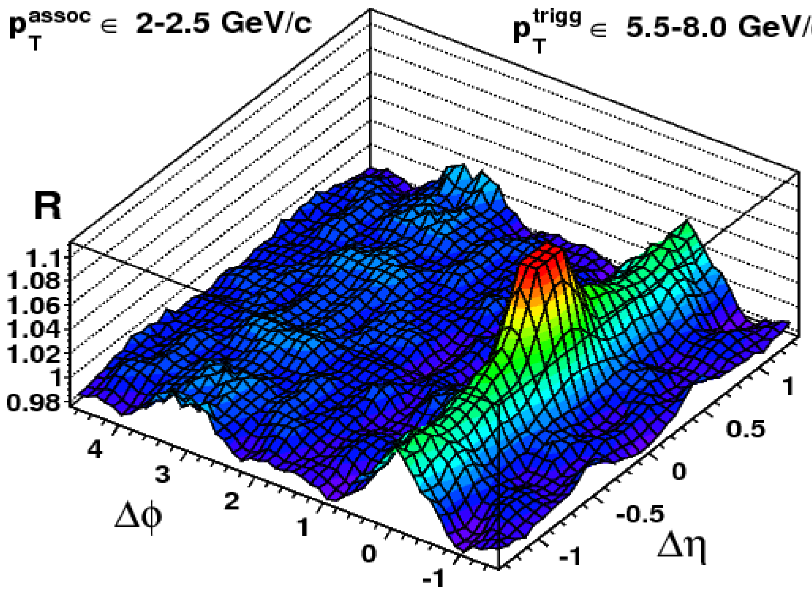




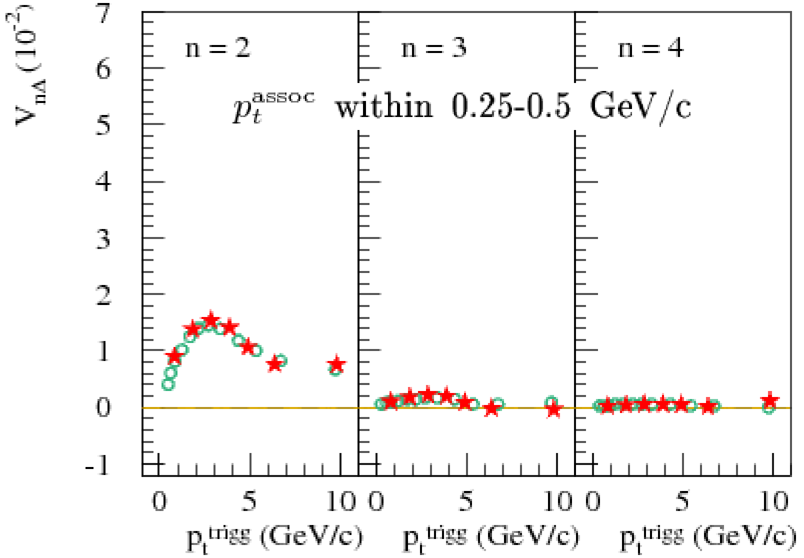
Correlations in PbPb@LHC

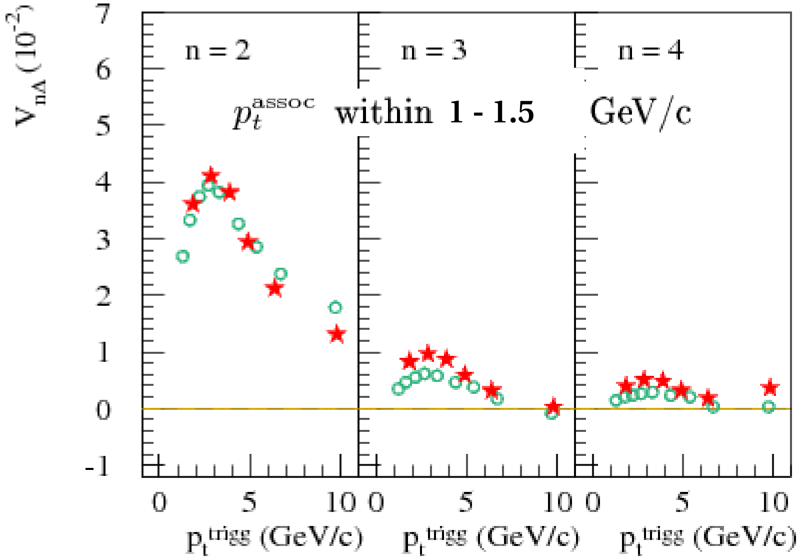


di-hadron correlations



Fourier coefficient for most central events





Collective effects

- One decade of RHIC experiments (heavy ion, pp, and dAu scattering,up to 200 GeV)

heavy ion collisions produce matter which expands as an almost ideal fluid

- mainly because azimuthal anisotropies can be explained on the basis of ideal hydrodynamics (mass splitting etc)

LHC pp results: first signs for collective behavior as well ...

Approach (1)

- **pp@LHC treated as Heavy Ion:**
  - Multiple scattering approach EPOS (marriage of pQCD and Gribov-Regge) :
    - initial condition for a hydrodynamic evolution if the energy density is high enough
  - event-by-event procedure
    - taking into the account the irregular space structure of single events :
      - ridge structures in two-particle correlations
  - core-corona separation :
    - only a part of the matter thermalizes;
  - 3+1 D hydro evolution
    - conservation of baryon number, strangeness, and electric charge

Approach (2)

- **pp@LHC treated as Heavy Ion:**
  - parton-hadron transition
    - realistic equation-of-state, compatible with lattice gauge results
    - cross-over transition from the hadronic to the plasma phase
  - hadronization,
    - Cooper-Frye, using complete hadron table
    - at an early stage (166 MeV, in the transition region)
    - with subsequent hadronic cascade procedure (UrQMD)

- **details see:**
  - arXiv:1004.0805, arXiv:1010.0400, arXiv:1011.0375 (ridge in pp)

    arXiv:1203.5704 (jet-bulk interaction)

Energy Density

- **Initial conditions at proper time $\tau=\tau_0$**
  - Energy tensor :

$$T^{\mu\nu}(x) \;=\; \sum_i \frac{\delta p_i^\mu \delta p_i^\nu}{\delta p_i^0} g(x-x_i), \quad \delta p = \left\{ \frac{\partial X(\alpha,\beta)}{\partial\beta}\delta\alpha + \frac{\partial X(\alpha,\beta)}{\partial\alpha}\delta\beta \right\}$$

  - Flavor flow :

$$N_q^\mu(x) \;=\; \sum_i \frac{\delta p_i^\mu}{\delta p_i^0}\, q_i\, g(x-x_i), \quad q \in \{u,d,s\}$$

- **Evolution according to the equations of ideal hydrodynamics:**

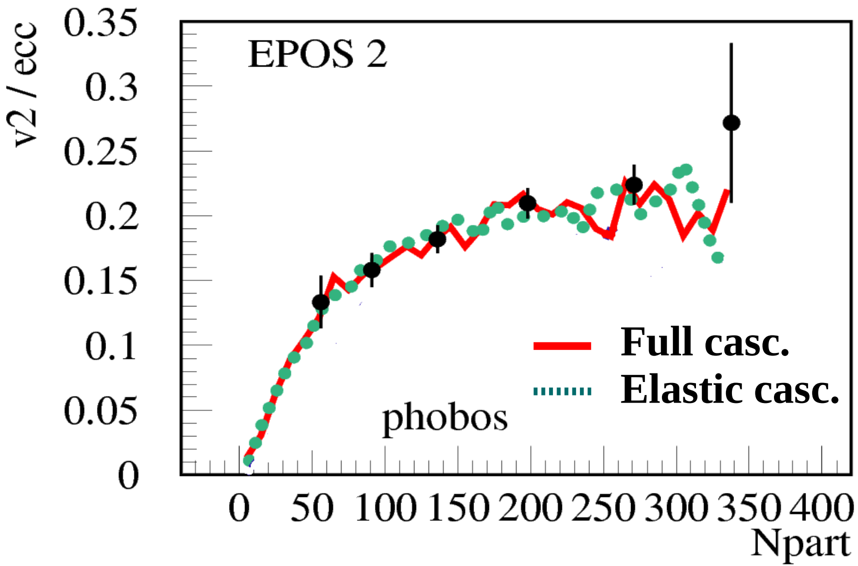
$$\partial_\mu T^{\mu\nu} = 0, \quad \text{using } T^{\mu\nu} = (\epsilon + p)\, u^\mu u^\nu - p\, g^{\mu\nu}$$

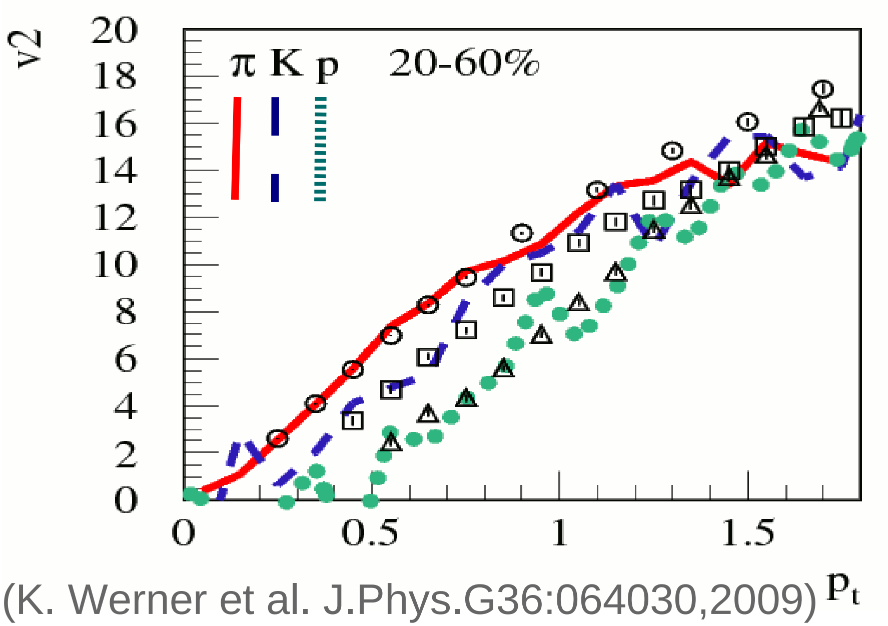
$$\partial N_k^\mu = 0, \quad N_k^\mu = n_k u^\mu,$$

with $k = B, S, Q$ referring to respectively baryon number, strangeness, and electric charge.

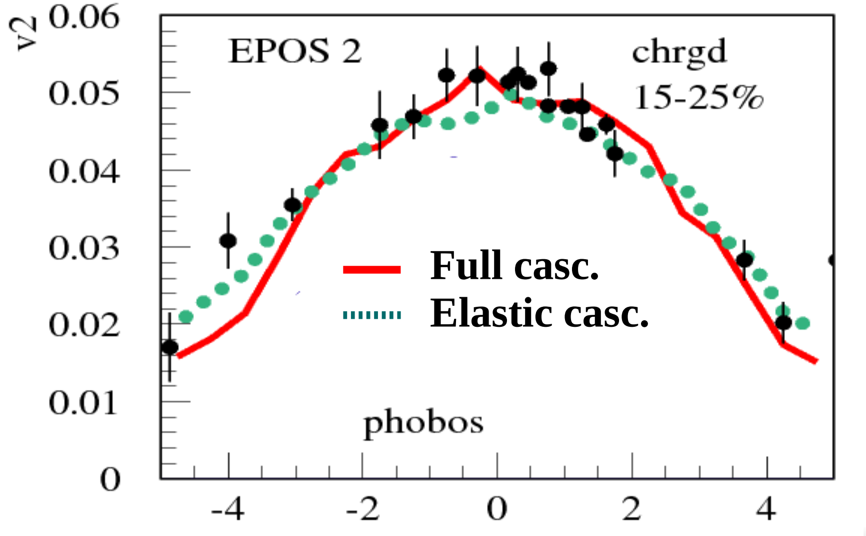
Check with Heavy Ions : AuAu@RHIC

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





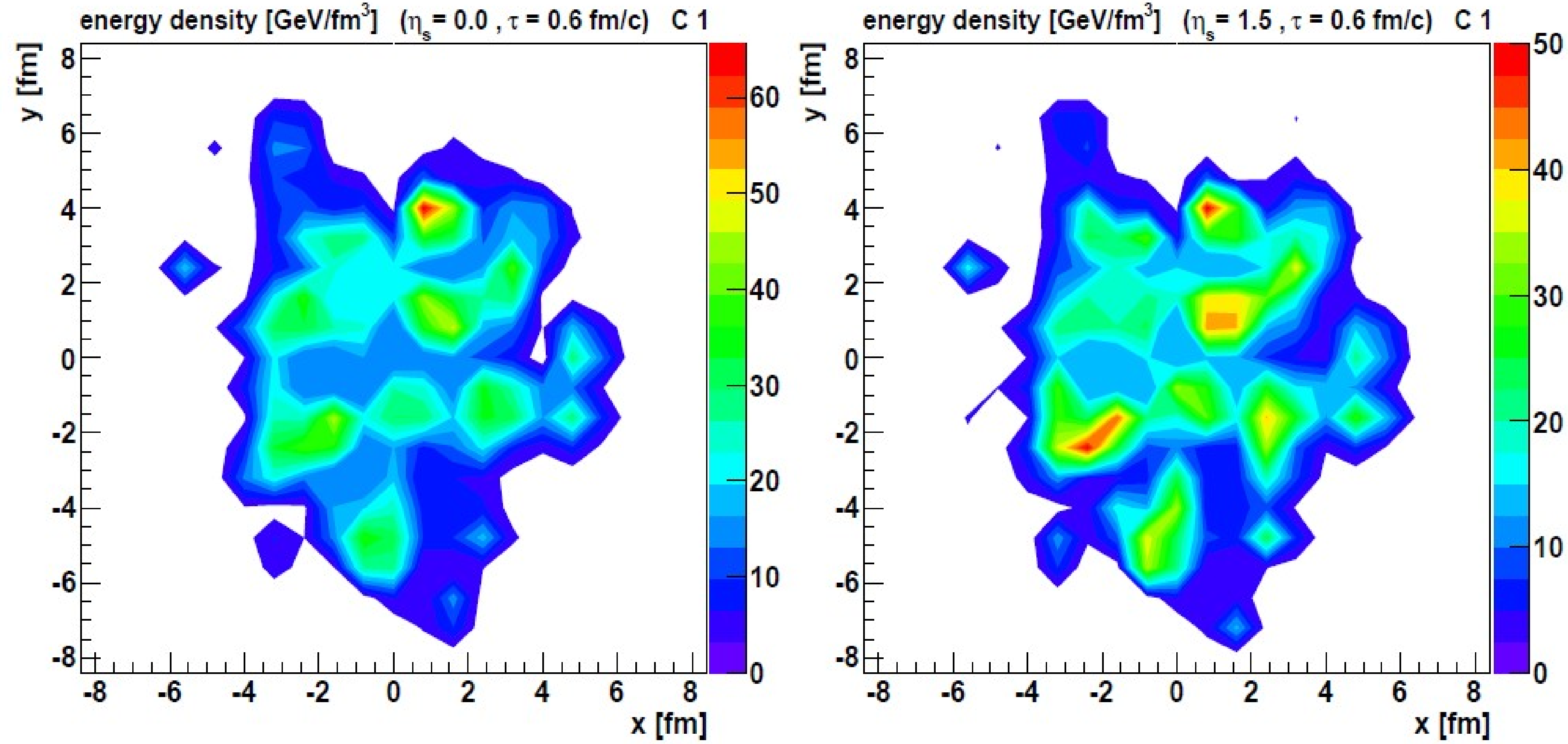
Important role of core-corona effect (K. Werner et al. J.Phys.G36:064030,2009)



- **After checking successfully hundreds of particle spectra in AuAu**
  - Event-by-event analysis

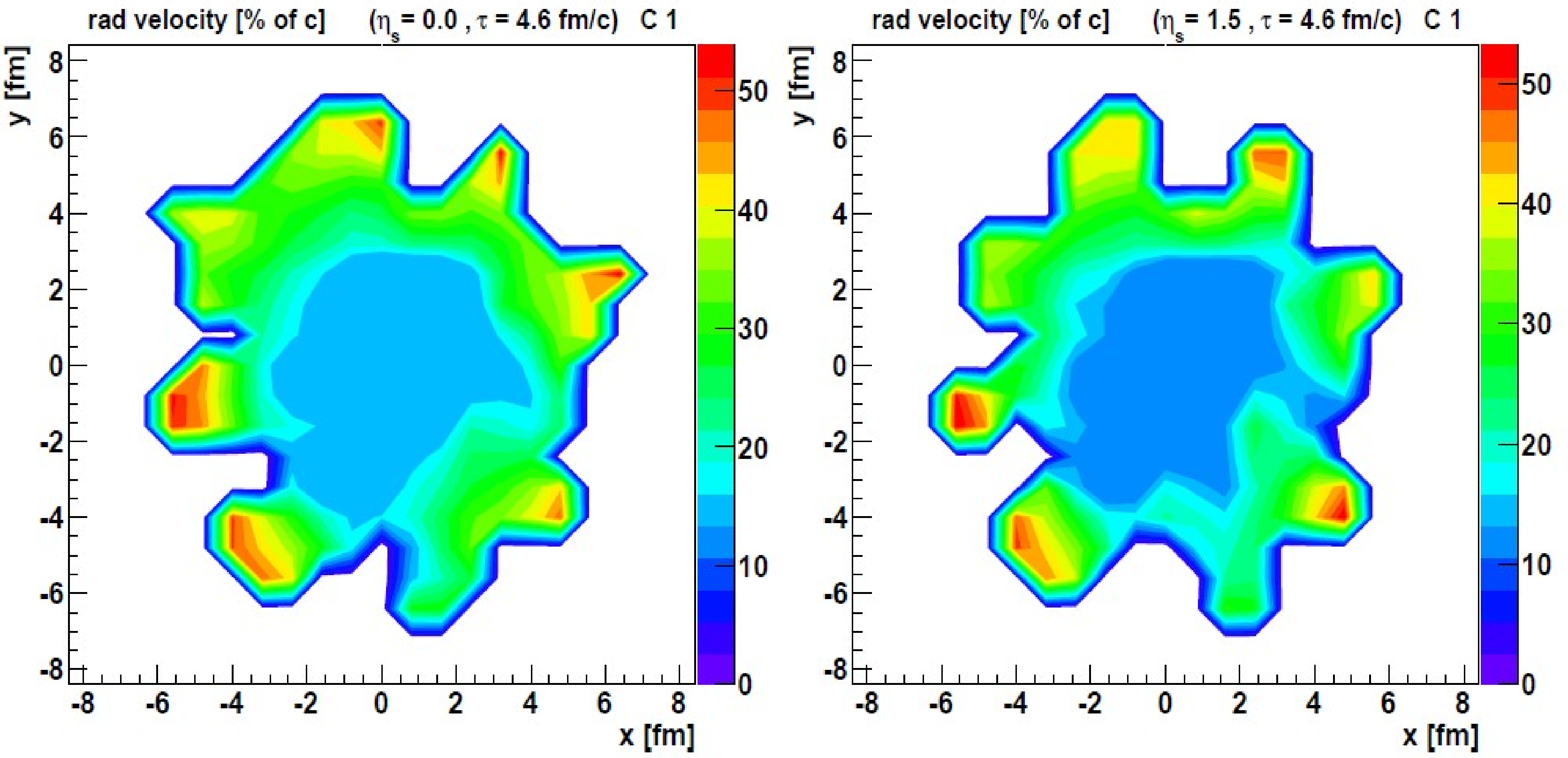
Event-by-Event Energy Density : AuAu

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



Event-by-Event Radial Flow : AuAu

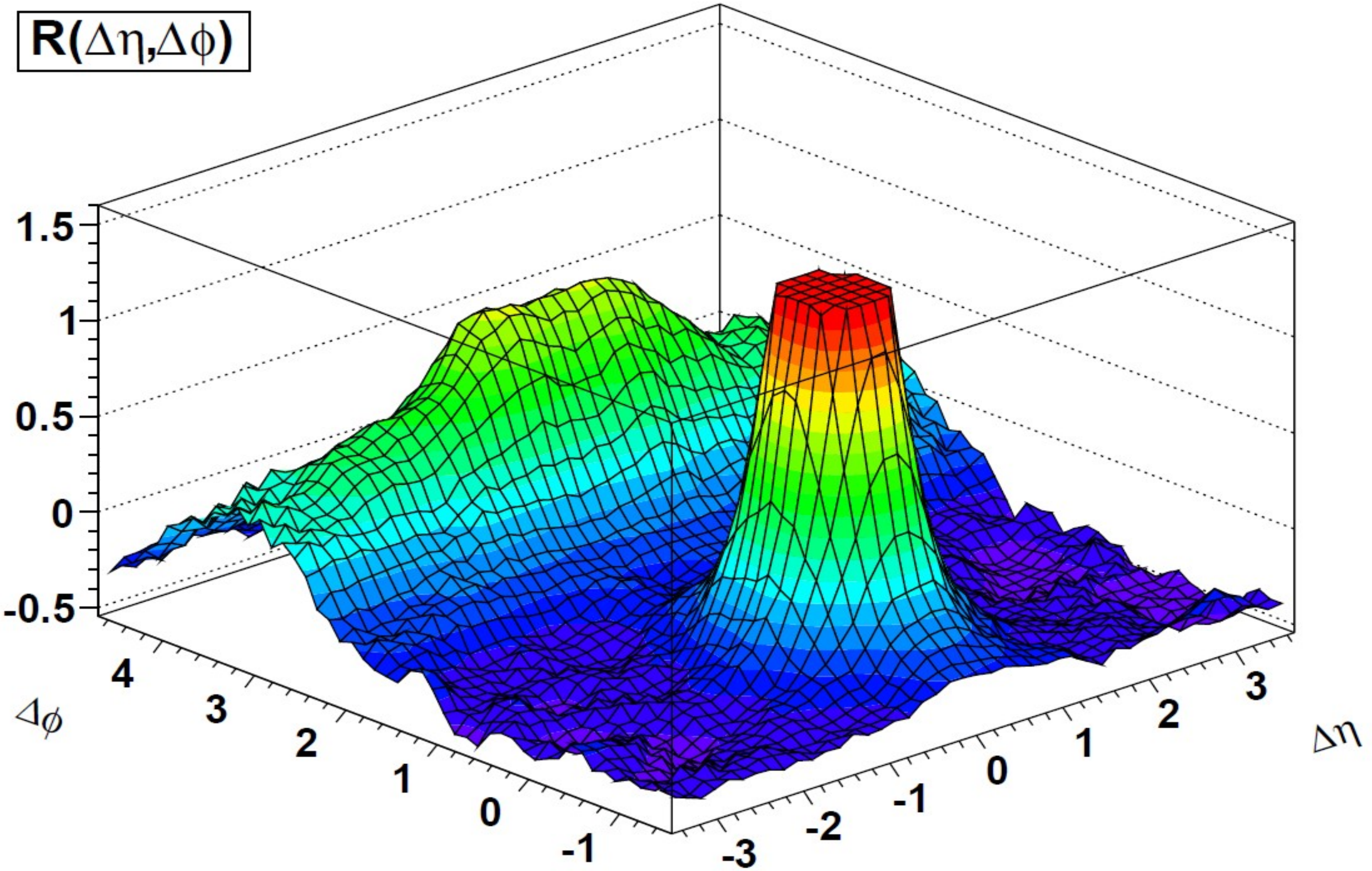
- **Leads to translational invariance of transverse flows**



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

pp@7 TeV : no Hydro

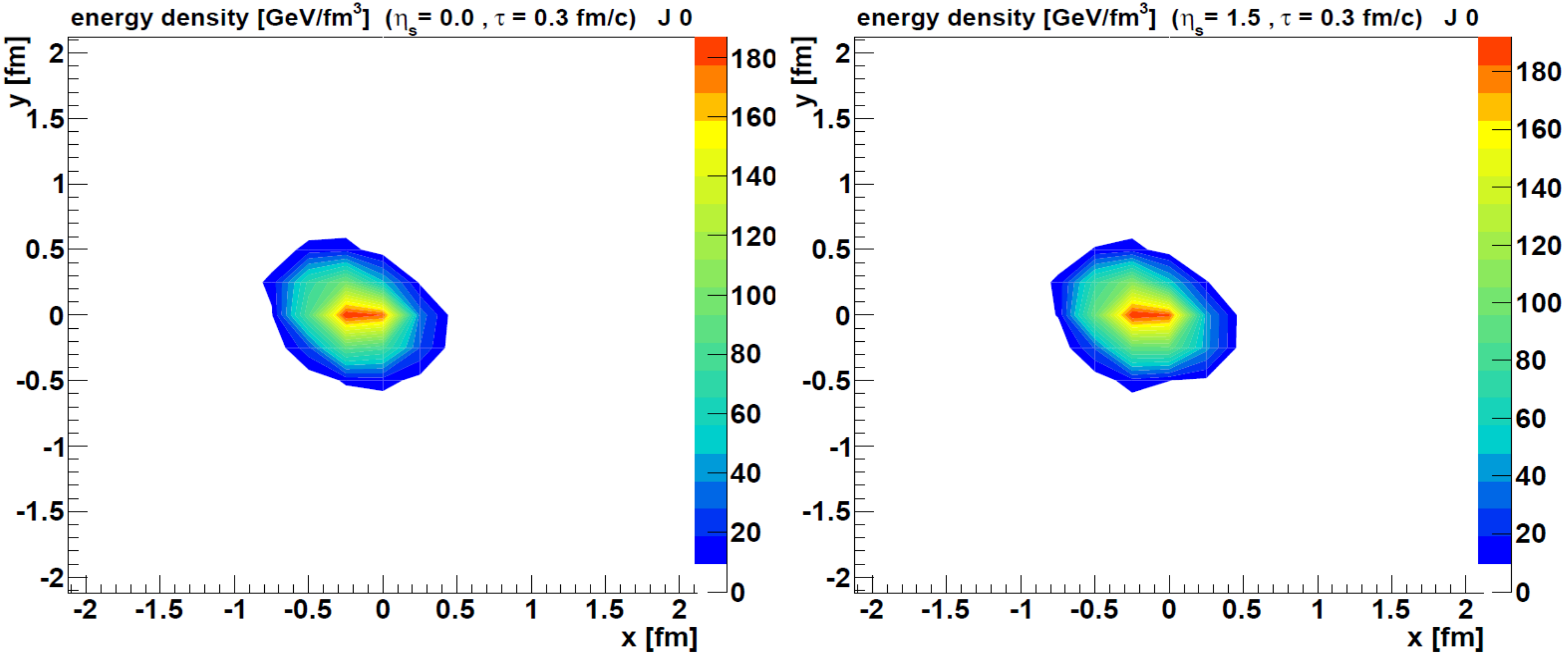
- Calculation without hydro => NO RIDGE



hydrodynamical evolution “makes” the effect! HOW?

Event-by-Event Energy Density : pp

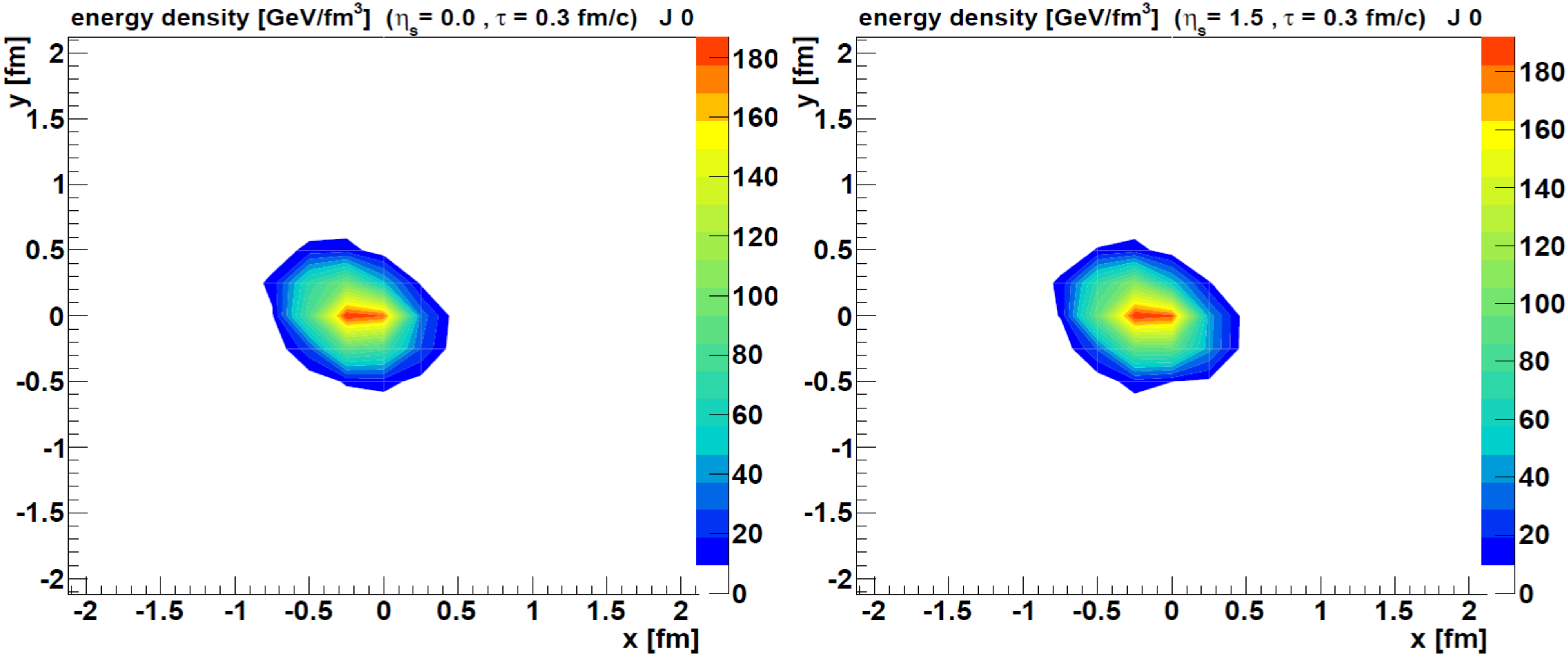
- Random azimuthal asymmetries of initial energy density but translationally invariant
  - pseudorapidity extension of flux tubes



Initial energy density in the transverse plane for two different η_s

Event-by-Event Energy Density : pp

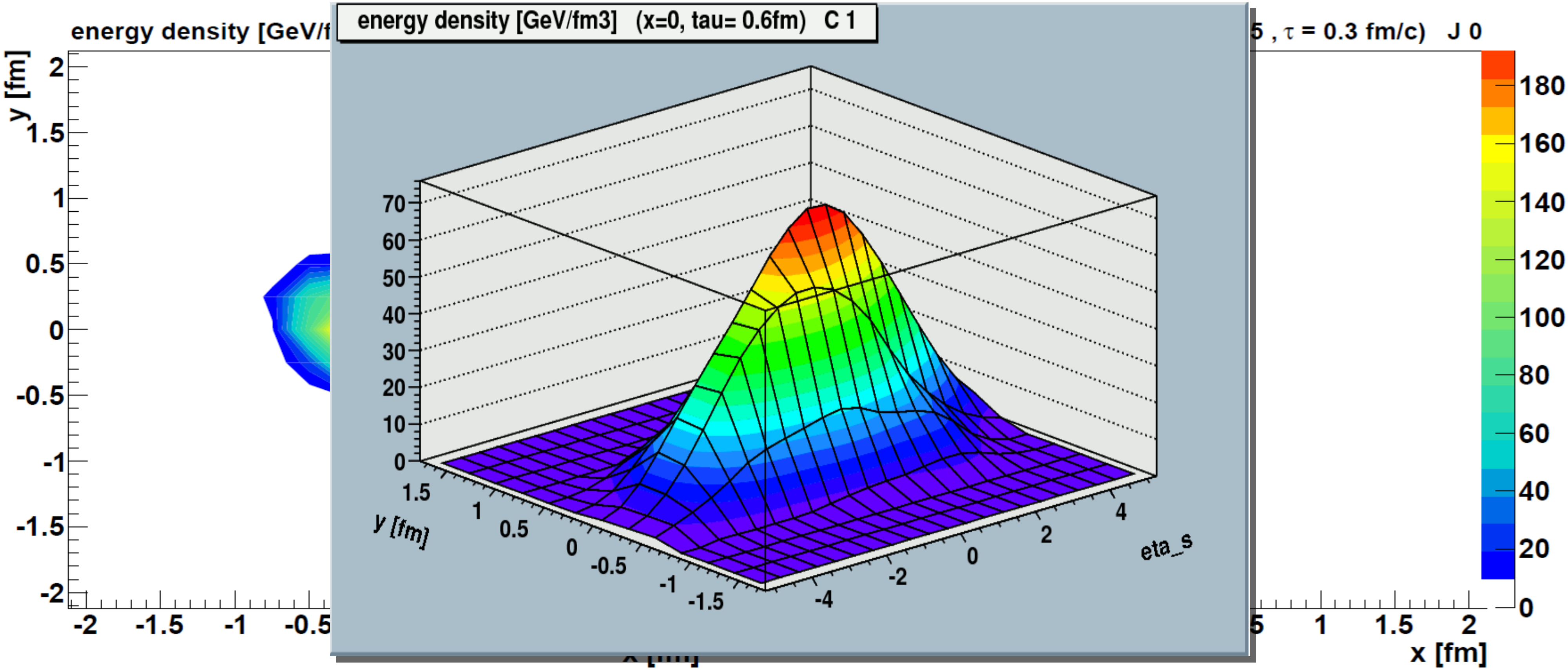
- Random azimuthal asymmetries of initial energy density but translationally invariant
  - pseudorapidity extension of flux tubes



Initial energy density in the transverse plane for two different η_s

Event-by-Event Energy Density : pp

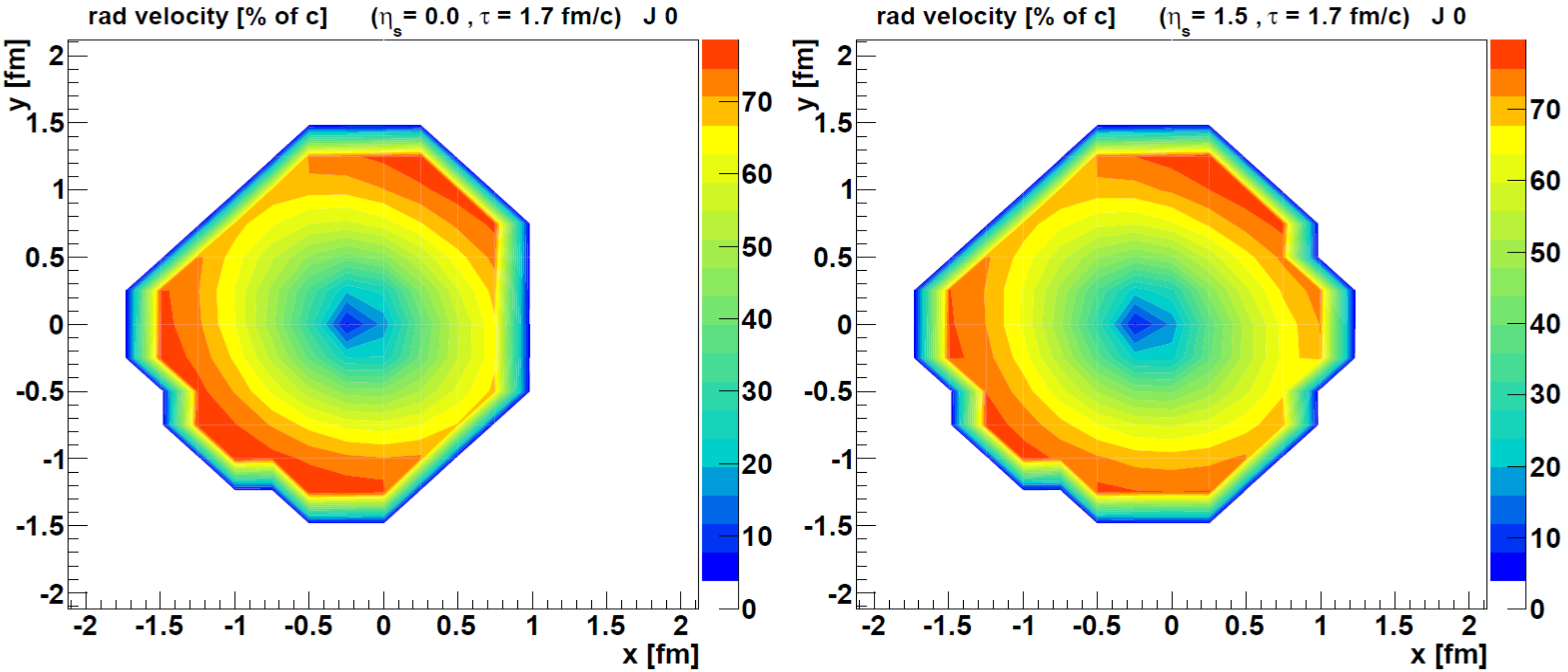
- Random azimuthal asymmetries of initial energy density but translationally invariant
  - pseudorapidity extension of flux tubes



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

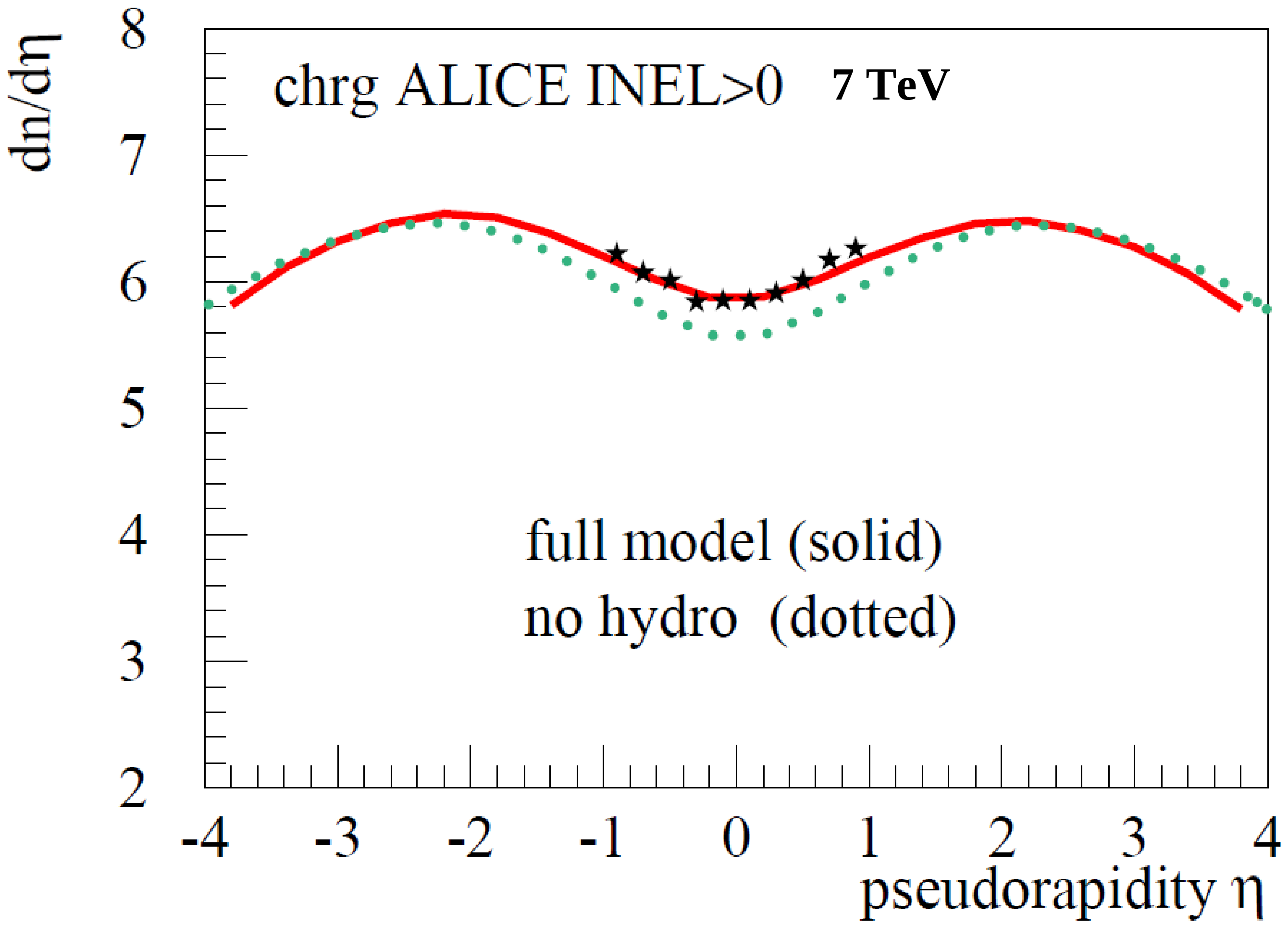
Summary Ridge in pp

- **Translational invariance of the flow asymmetry means:**
  - ➡ The system gives an increased collective push
  - ➡ to particles produced at different values of ηs
  - ➡ at the same azimuthal angle corresponding to a flow maximum

➡ ΔηΔφ correlation

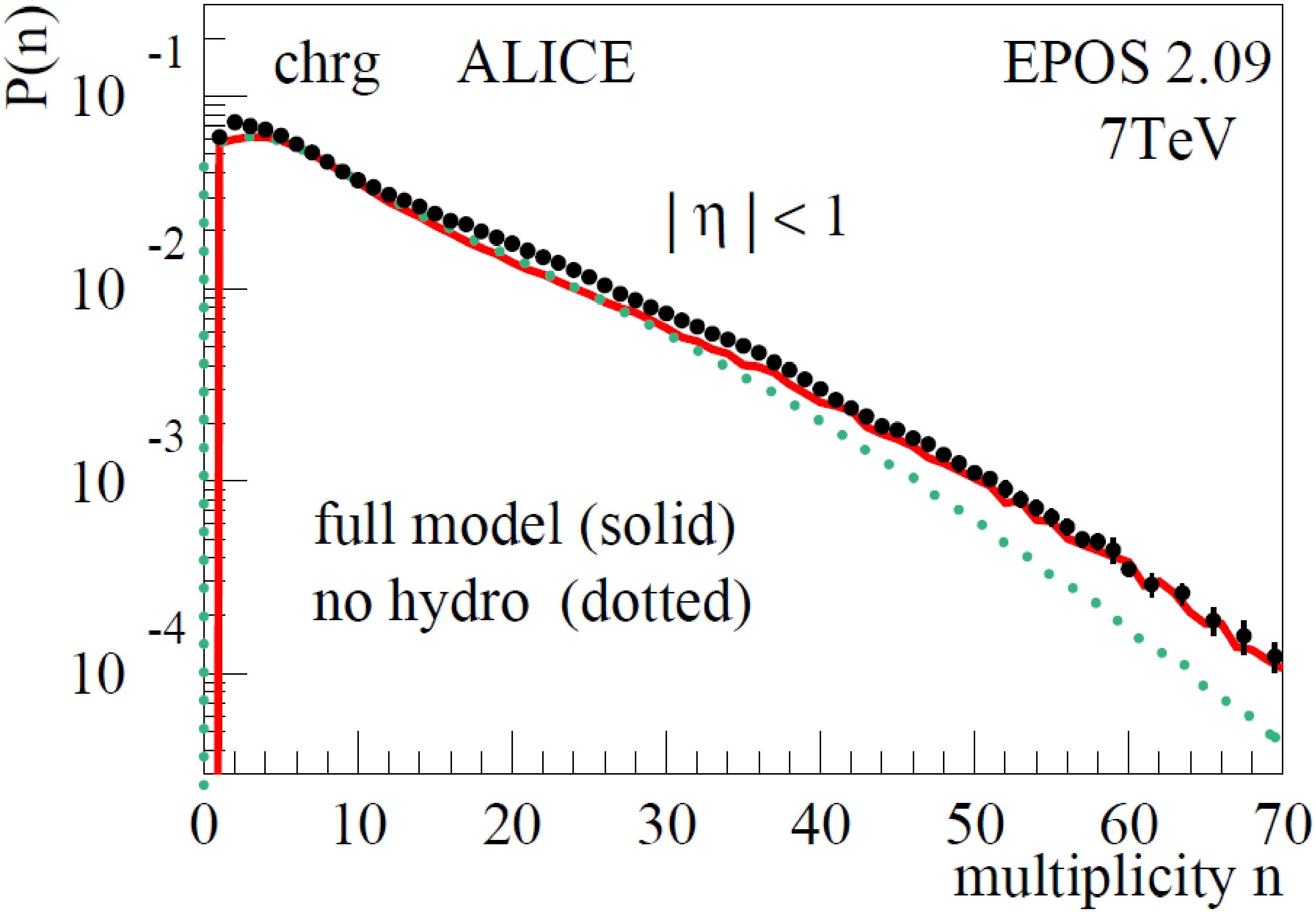
Pseudorapidity Distribution

- Little effect of hydro in MinBias dn/deta



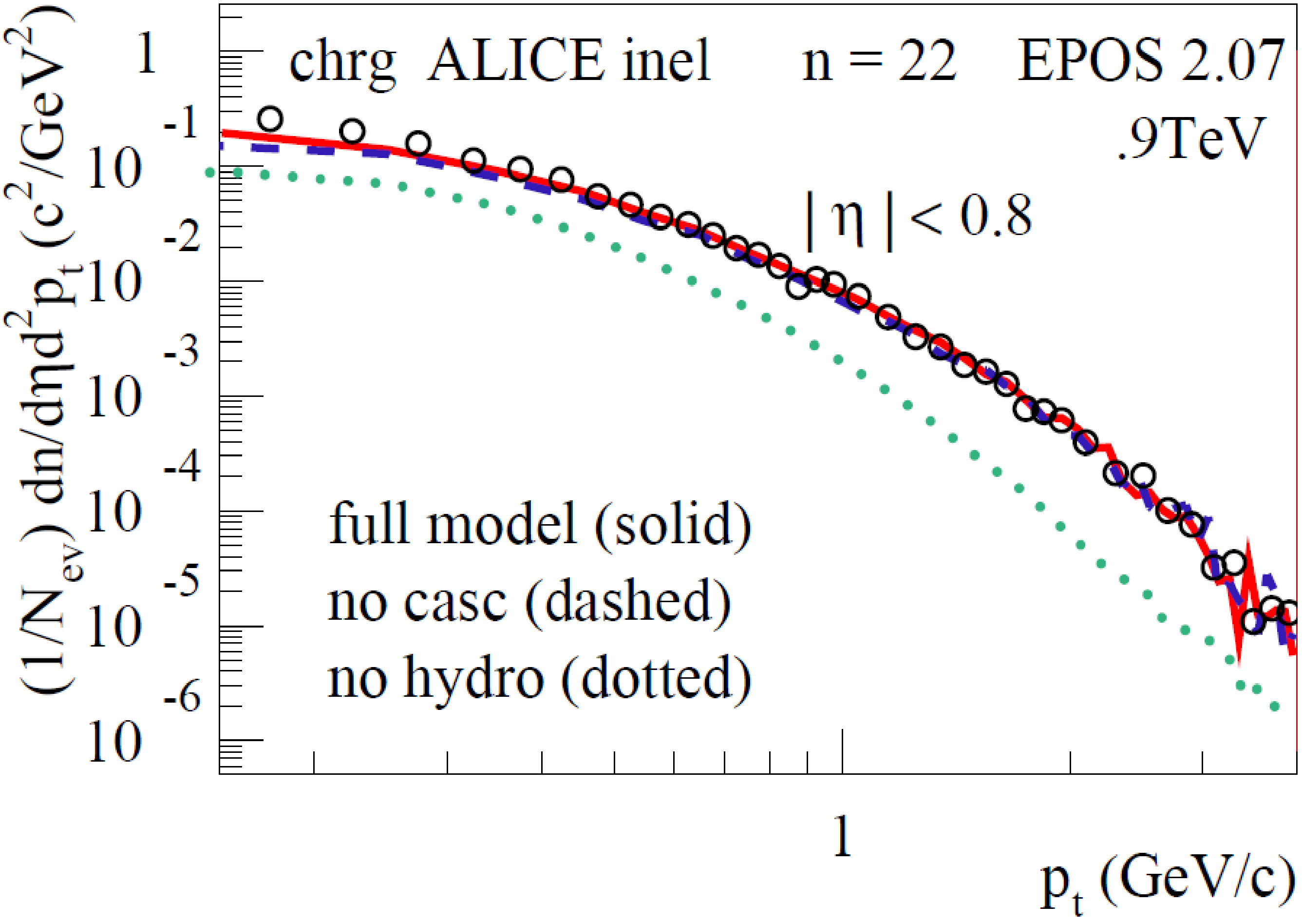
Multiplicity Distribution

- Little effect of hydro in MinBias dn/deta



Pt Distribution

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

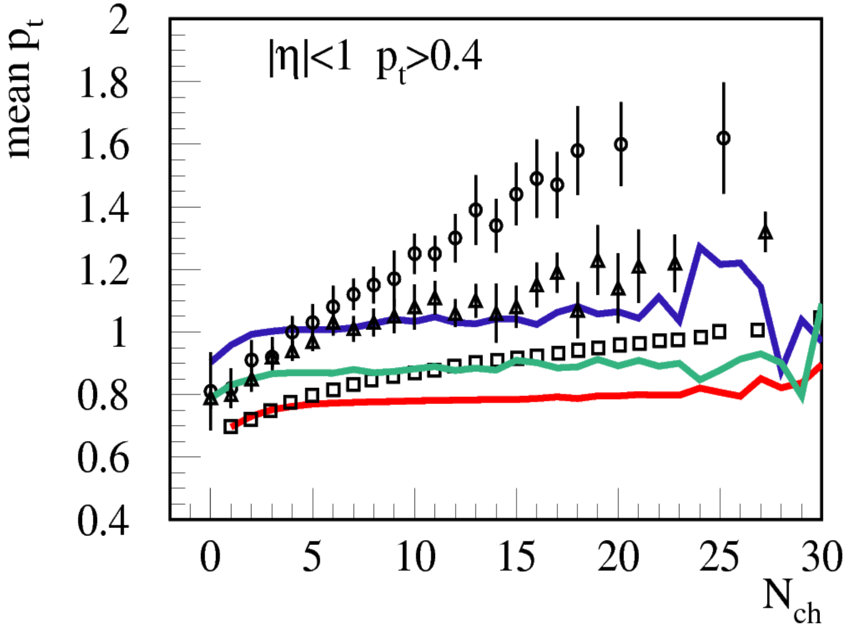


Flow !

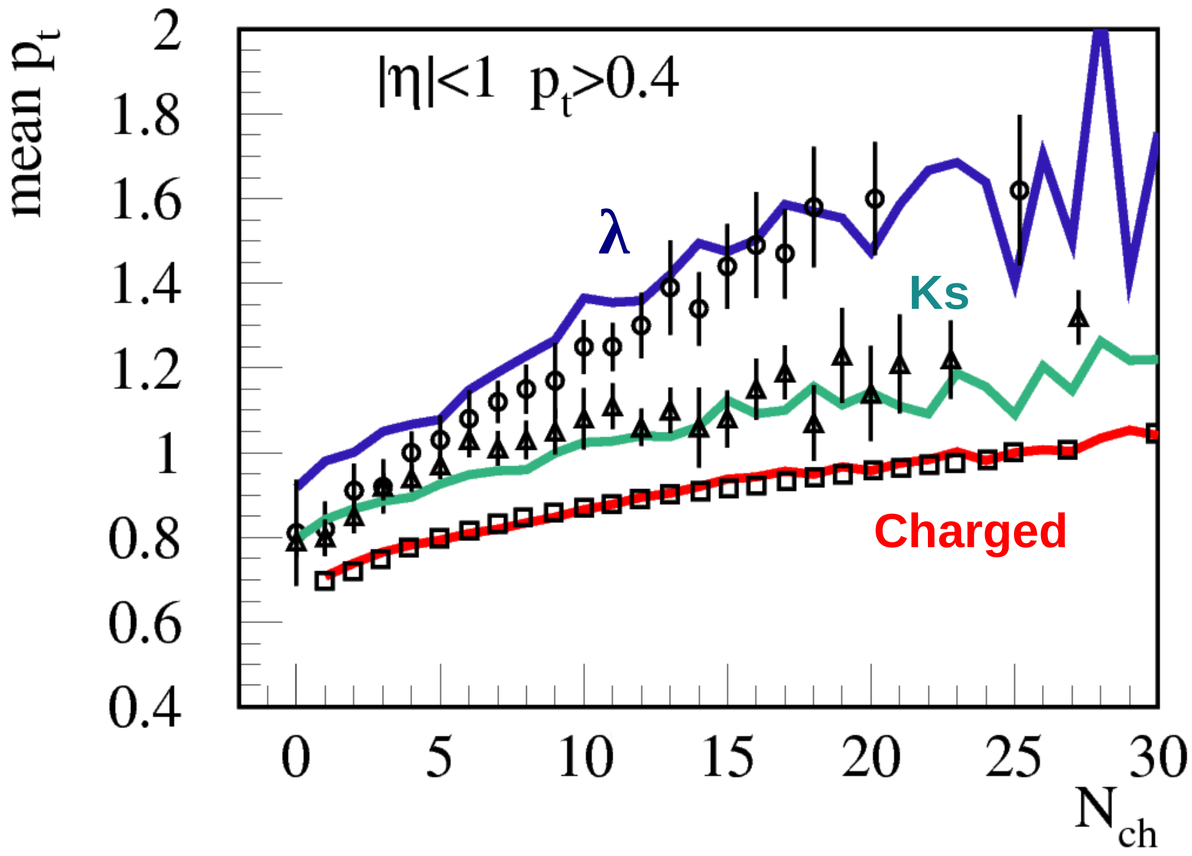
$\langle p_t \rangle$ vs multiplicity ap-p@1.8 TeV : EPOS 2

- **Using small flux tube size**
  - Very good description of CDF data
  - No additional parameter
  - Hadron mass dependence

No collective effects

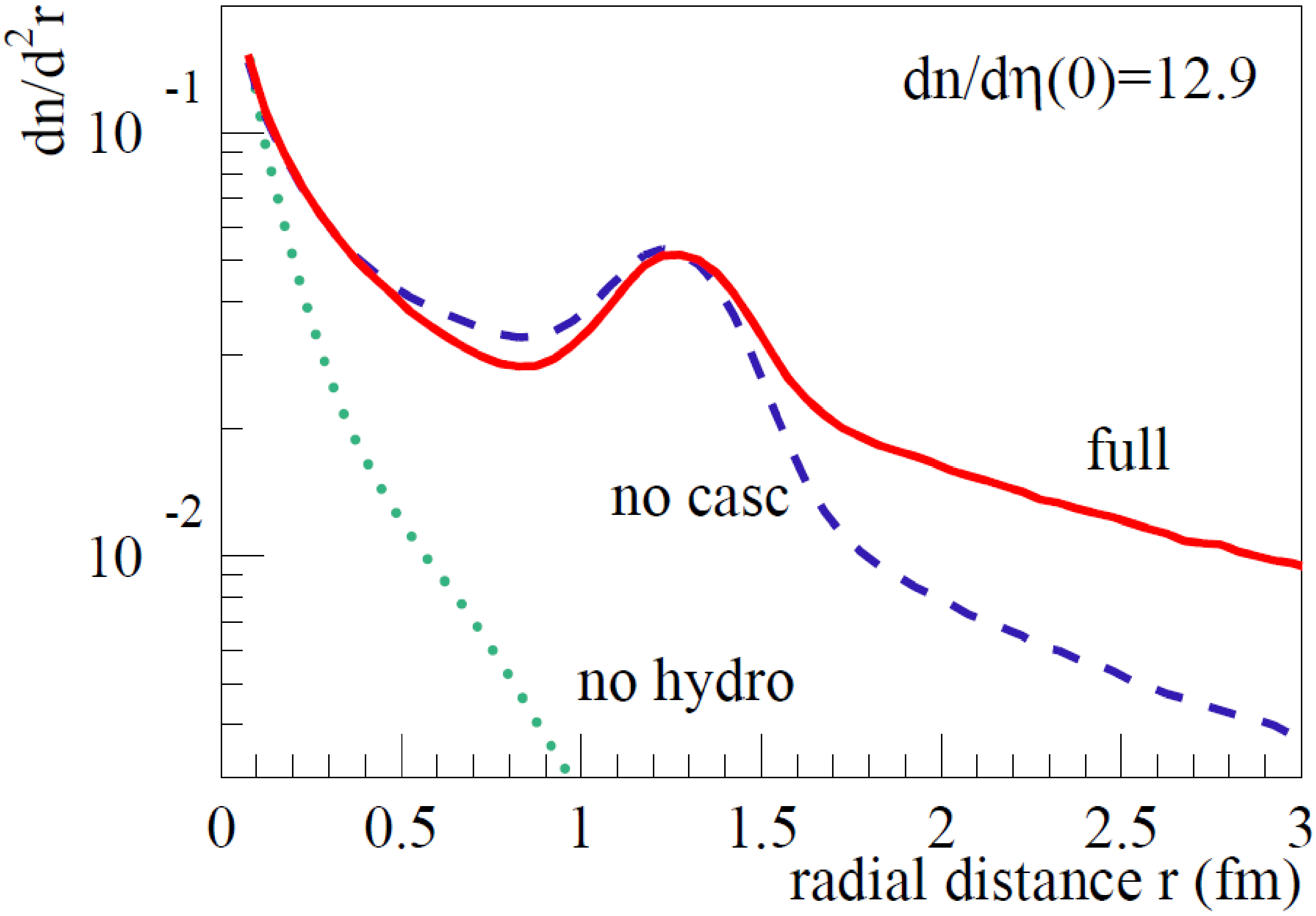


hydro+hadronic cascade



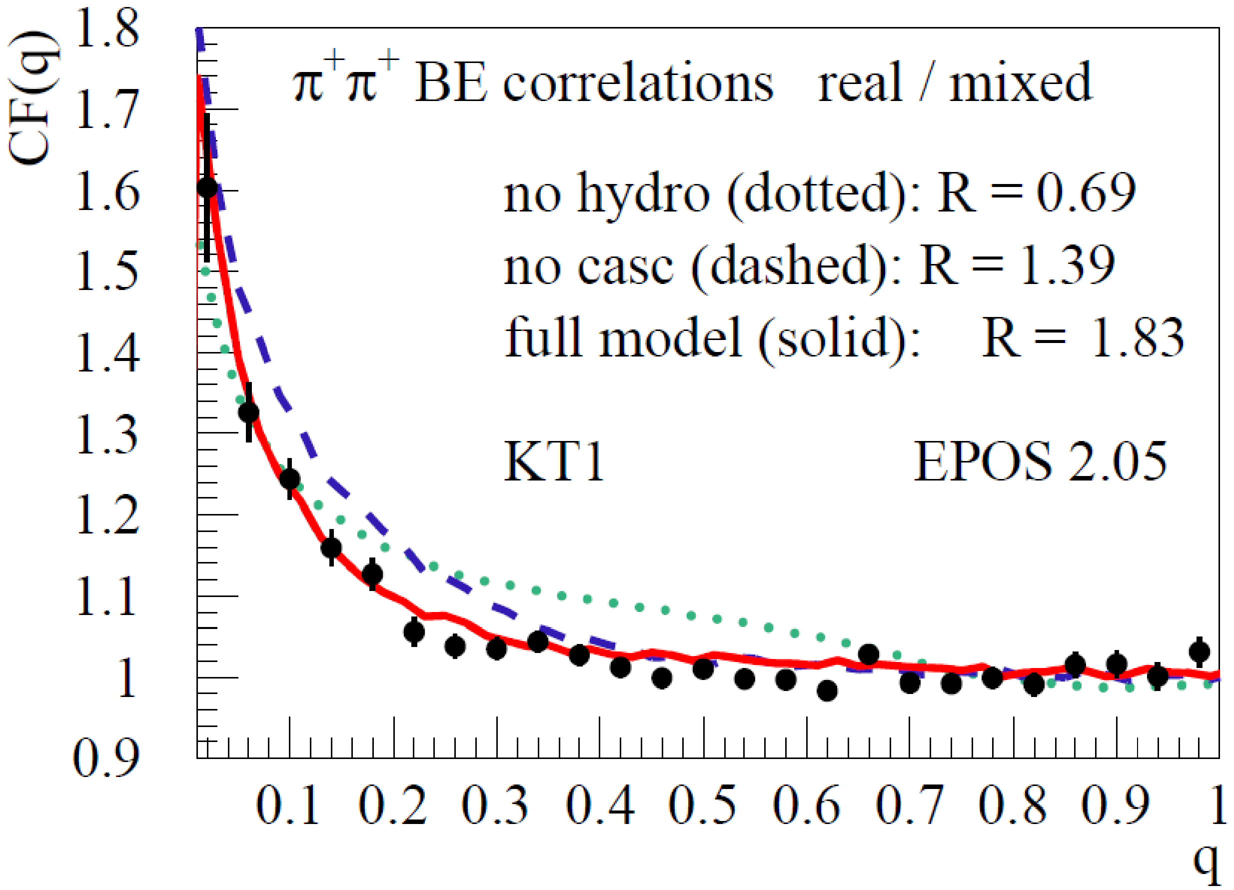
Radius of Particle Emission

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



Bose-Einstein Correlations

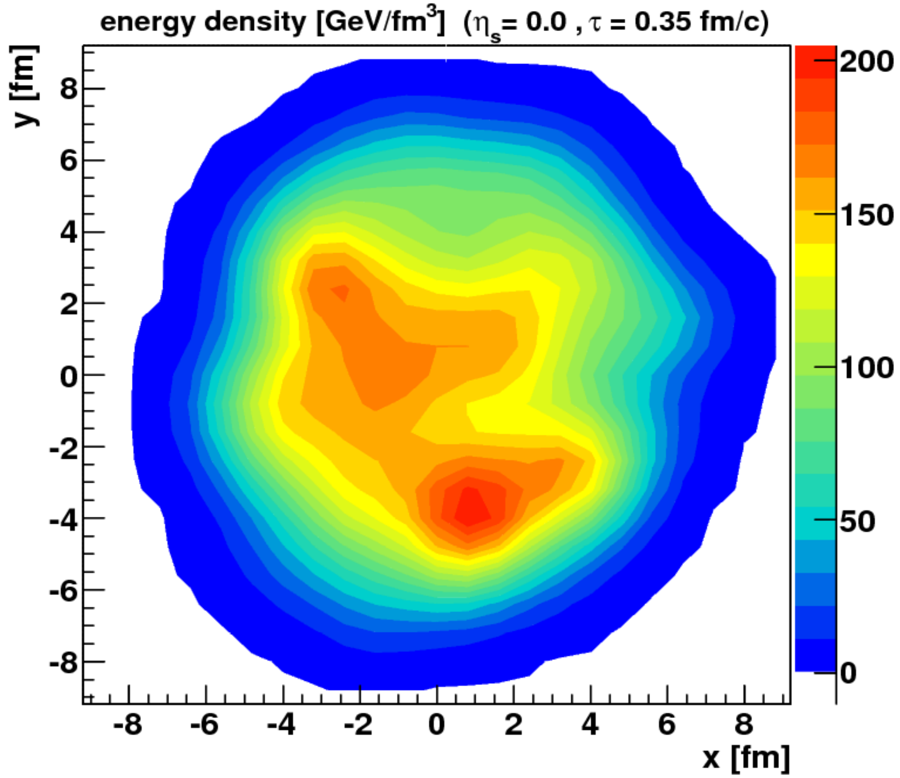
- Consequences for Bose-Einstein correlations

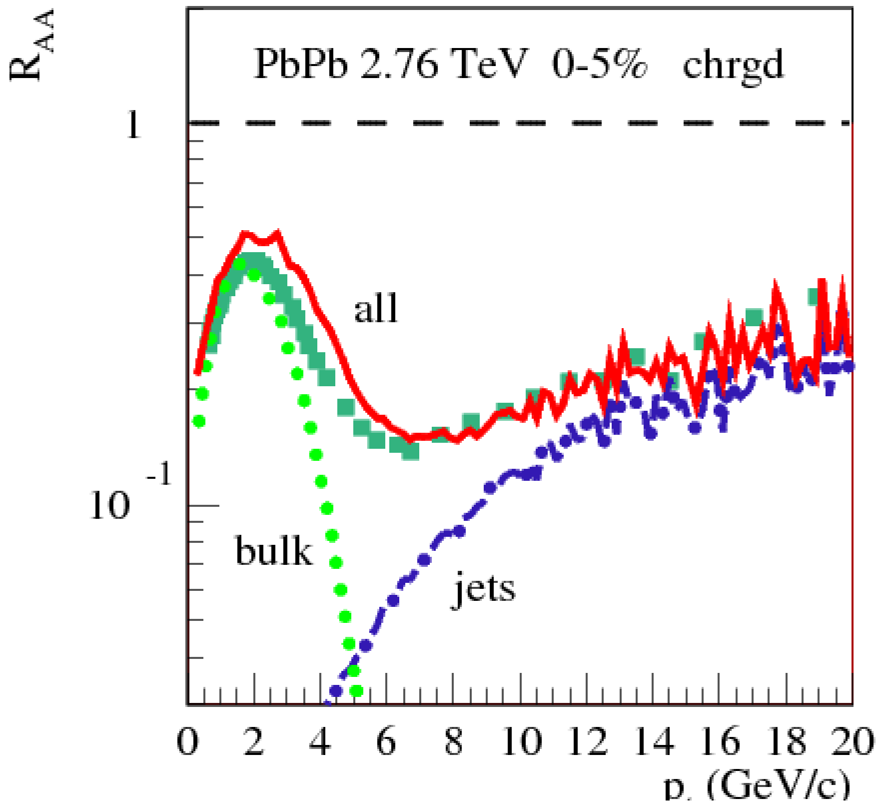


ALICE data.

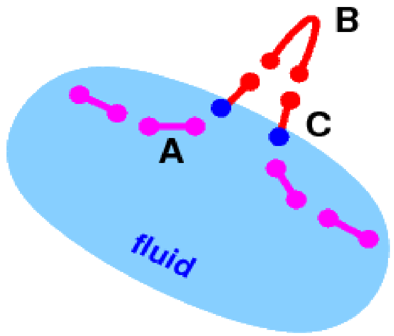
Radii R from exponential fit.
KT1= [100, 250], KT3= [400, 550], KT5= [700, 1000]

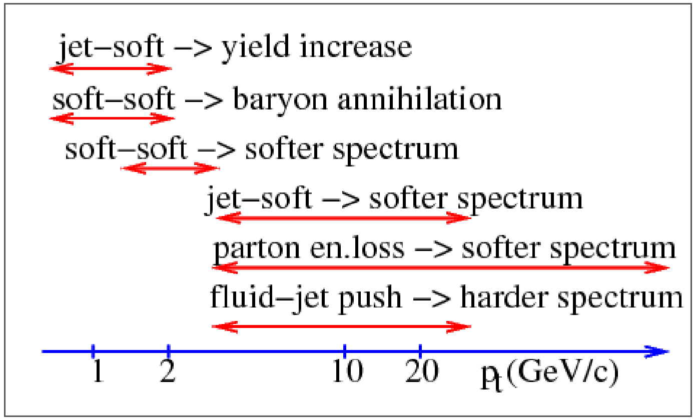
jets in PbPb @ LHC





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




jet–soft –> yield increase

soft–soft –> baryon annihilation

soft–soft –> softer spectrum

jet–soft –> softer spectrum

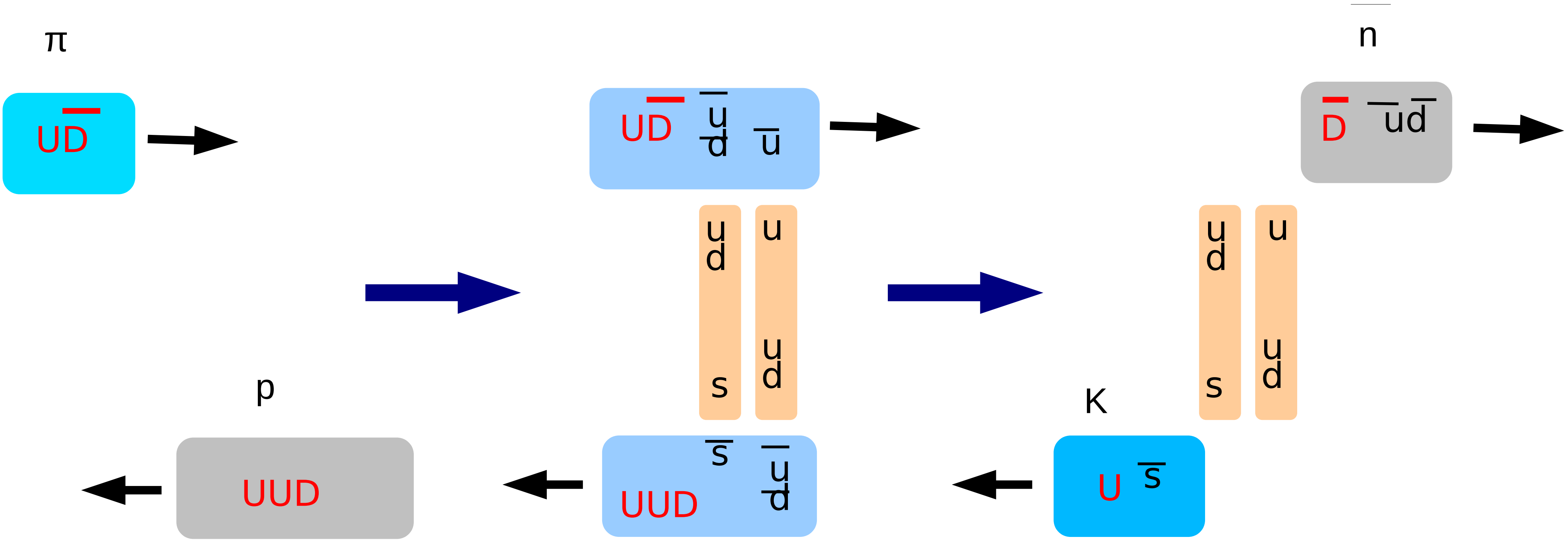
parton en.loss –> softer spectrum

fluid–jet push –> harder spectrum

Remnants in EPOS

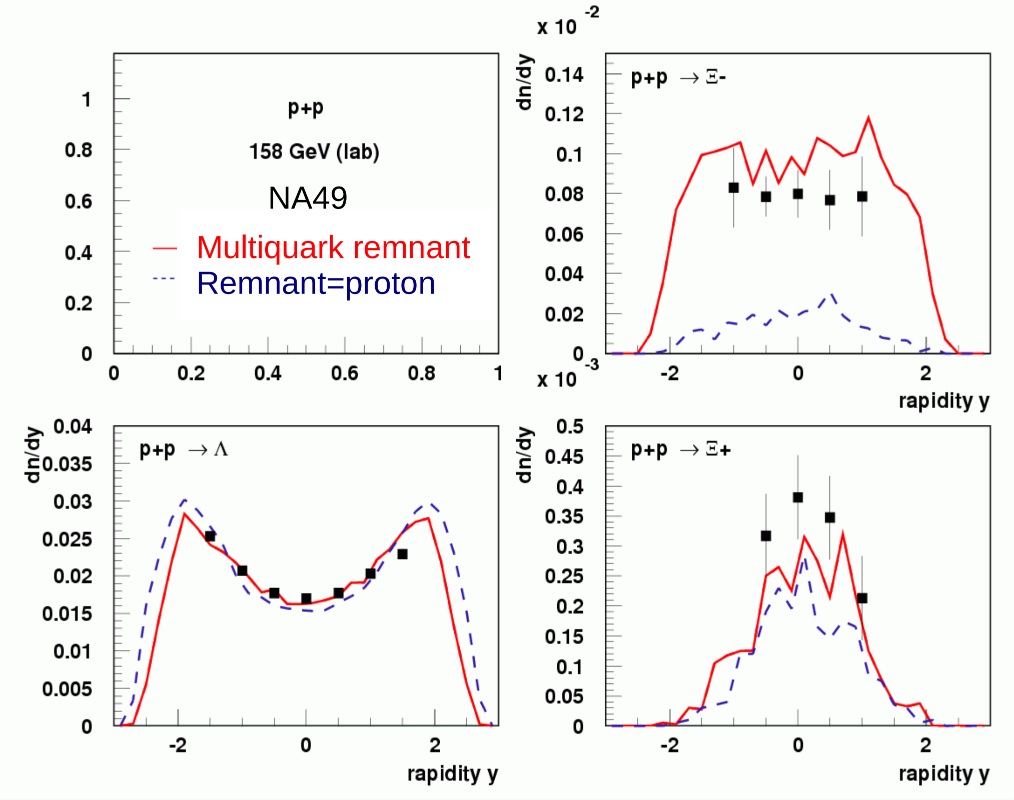
In EPOS : any possible quark/diquark transfer

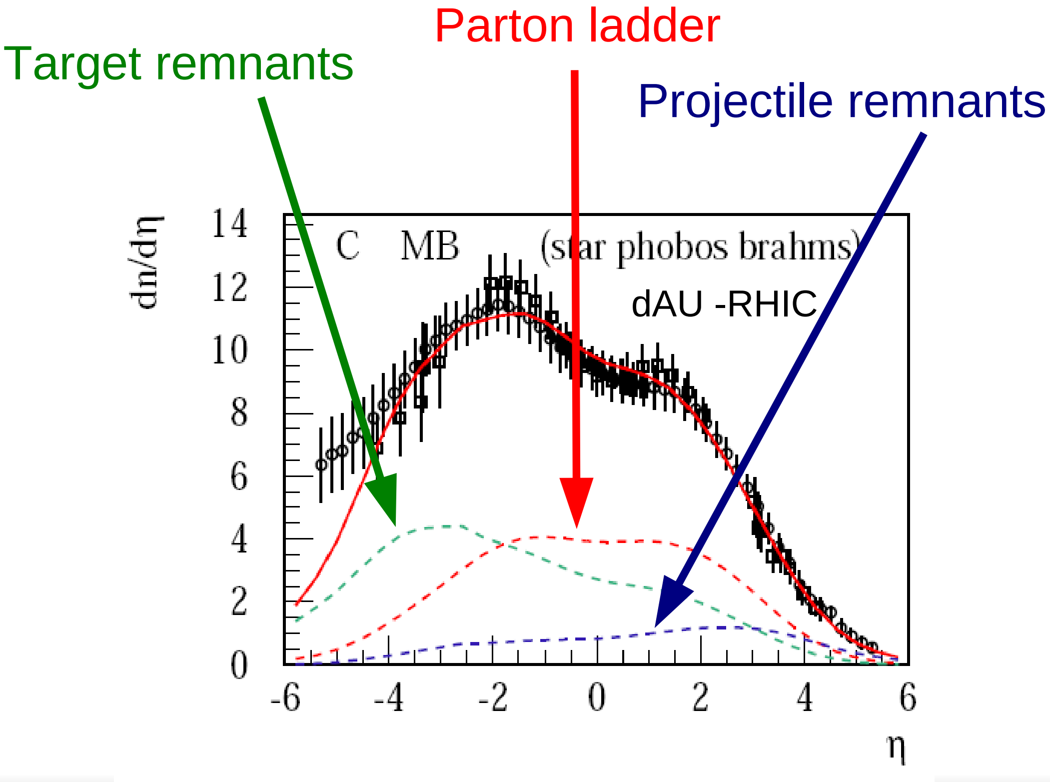
- Diquark transfer between string ends and remnants
- Baryon number can be removed from nucleon remnant :
  - Baryon stopping
- Baryon number can be added to pion/kaon remnant :
  - Baryon acceleration



Properties of Free Remnants

- **Valence quark not necessarily connected to parton ladder :**
  - Necessary to have aΩ/Ω < 1 (NA49 data)
  - Very broad remnant distribution
  - Can be used to describe effective enhanced diagrams (higher mass)
  - Very important for Cosmic Ray (leading particle)





Target remnants

Parton ladder

Projectile remnants