EPOS

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Two developments:

Full EPOS: try to understand
ALL pp and AA data above few 100 GeV,
do things the best way possible,
CPU time is no issue!!

EPOS for CRs: simplified version, which is fast, but
grasps the essential features of Full EPOS

This talk: Full EPOS, in particular
“collective effects in pp@LHC”

After one decade of RHIC experiments (heavy ion, pp, and dAu scattering, up to 200 GeV) it seems that

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 ...

We treat pp@LHC as AuAu@RHIC:

Multiple scattering approach EPOS (marriage of pQCD and Gribov-Regge)
used as 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,
leading to so-called ridge structures in two-particle correlations;

core-corona separation,
considering the fact that only a part of the matter thermalizes;

3+1 D hydro evolution,
including the conservation of baryon number, strangeness, and electric charge;

parton-hadron transition

- realistic equation-of-state,
  compatible with lattice gauge results,
- with a cross-over transition from the hadronic to the plasma phase;

hadronization,

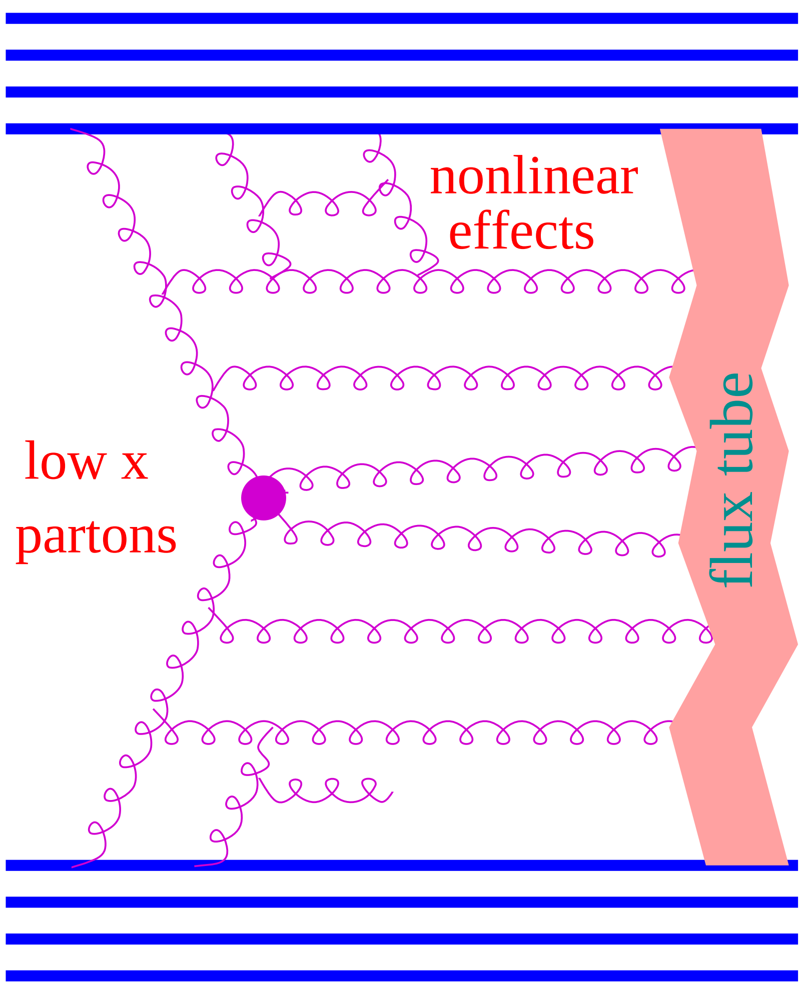
- here: Cooper-Frye, using complete hadron table,
- at an early stage (166 MeV, in the transition region),
- with subsequent hadronic cascade procedure (UrQMD)

details see:

arXiv:1004.0805, arXiv:1010.0400, arXiv:1011.0375 (ridge in pp)

Elementary scatterings - flux tubes

AA - even pp: **many elementary collisions happening in parallel**
elementary scattering = "parton ladder"



- ☐ Parton evolutions from the projectile and the target side towards the center (small x)
- ☐ Evolution is governed by an evolution equation, in the simplest case according to DGLAP.
- ☐ Parton ladder may be considered as a quasi-longitudinal color field, a so-called "flux tube", conveniently treated as a relativistic string.
- ☐ The intermediate gluons are treated as kink singularities in the language of relativistic strings, providing a transversely moving portion of the object.
- ☐ This flux tube decays via the production of quark-antiquark pairs, creating in this way fragments – which are identified with hadrons

Quantum mechanical treatment of multiple scattering is quite involved!

(when the energy sharing between the parallel scatterings is taken into account)

Details:

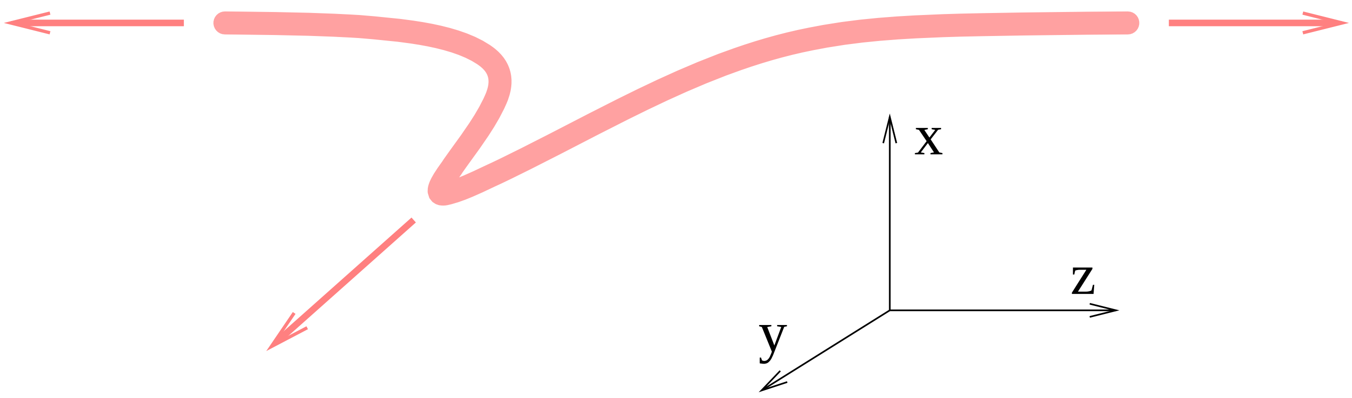
Parton-based Gribov-Regge Theory, H. J. Drescher, M. Hladik, S. Ostapchenko, T.Pierog, and K. Werner, Phys. Rept. 350 (2001) 93-289;

- Based on cutting rule techniques,
  one obtains partial cross sections for exclusive event classes,
- which are then simulated with the help of Markov chain techniques.

Parton ladder -> flux tube -> kinky string:

mainly longitudinal object (here parallel to the z-axis)

but due to the kinks there are string pieces moving transversely (in y-direction in the picture).

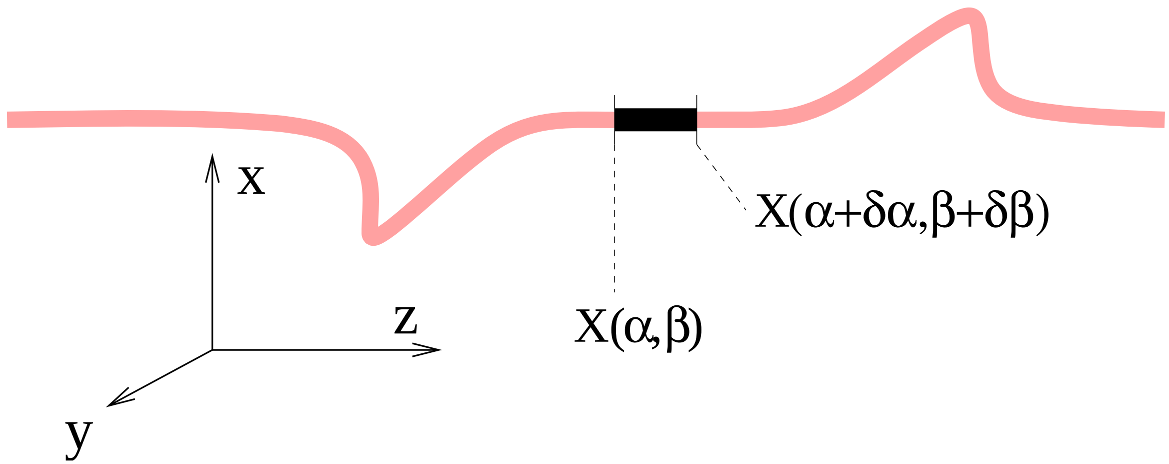


But despite these kinks, most of the string carries only little transverse momentum!

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

We split each string into a sequence of string segments, corresponding to widths $\delta\alpha$ and $\delta\beta$ in the string parameter space



For core part, $T^{\mu\nu}$ and the flavor flow at initial proper time $\tau = \tau_0$:

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

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

Evolution according to the equations of ideal hydrodynamics:

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

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

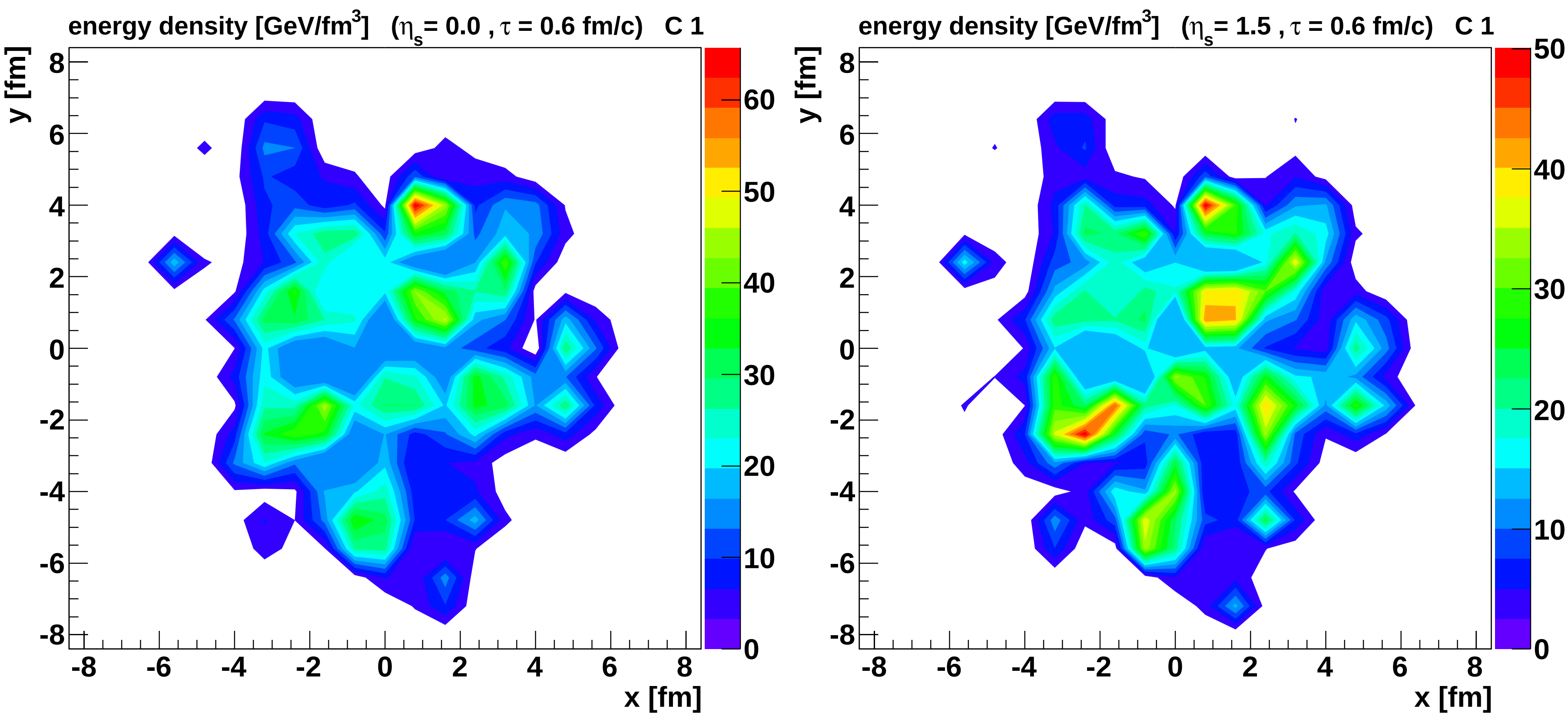
with $k = B$, S, Q referring to respectively baryon number, strangeness, and electric charge.

After checking successfully hundreds of particle spectra in AuAu, we study

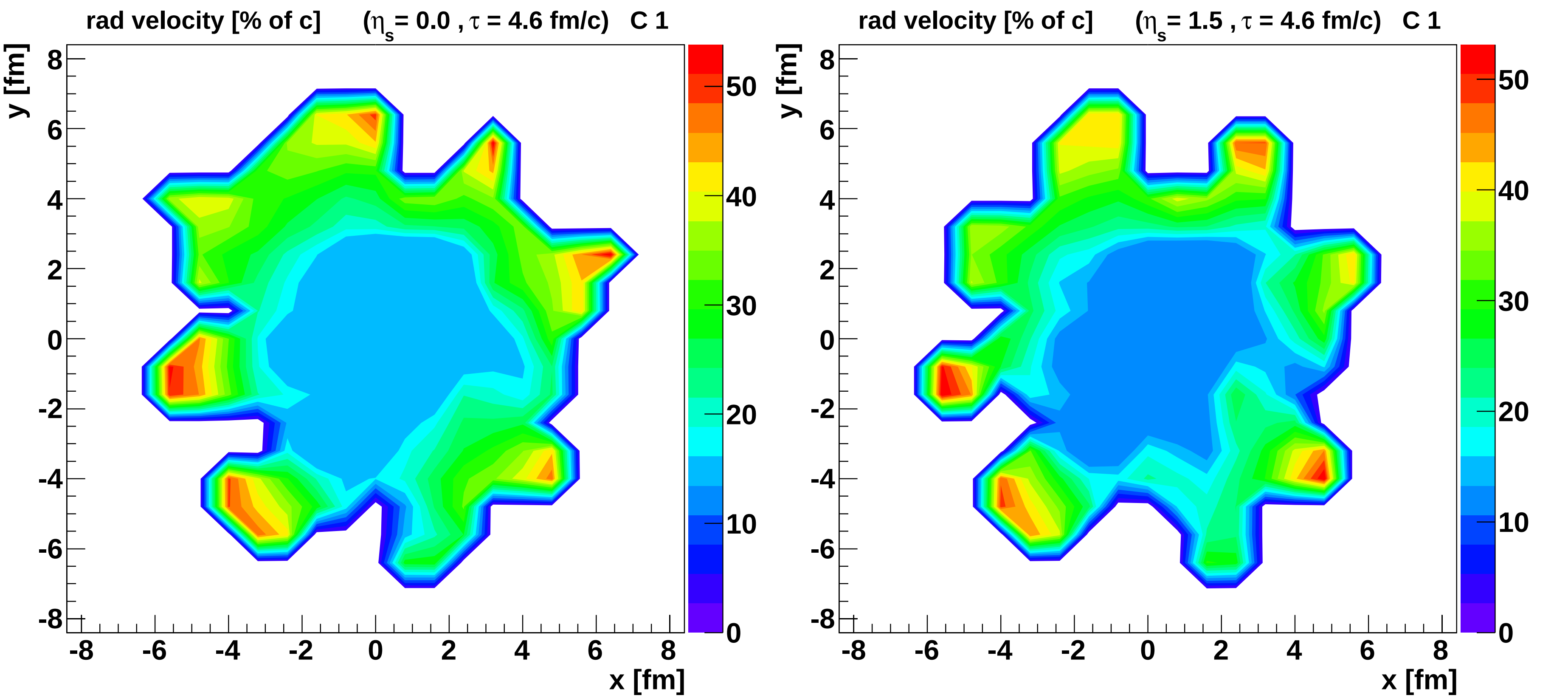
Interesting EbE features:

Bumpy structure of energy density in transverse plane,

but **translational invariance**

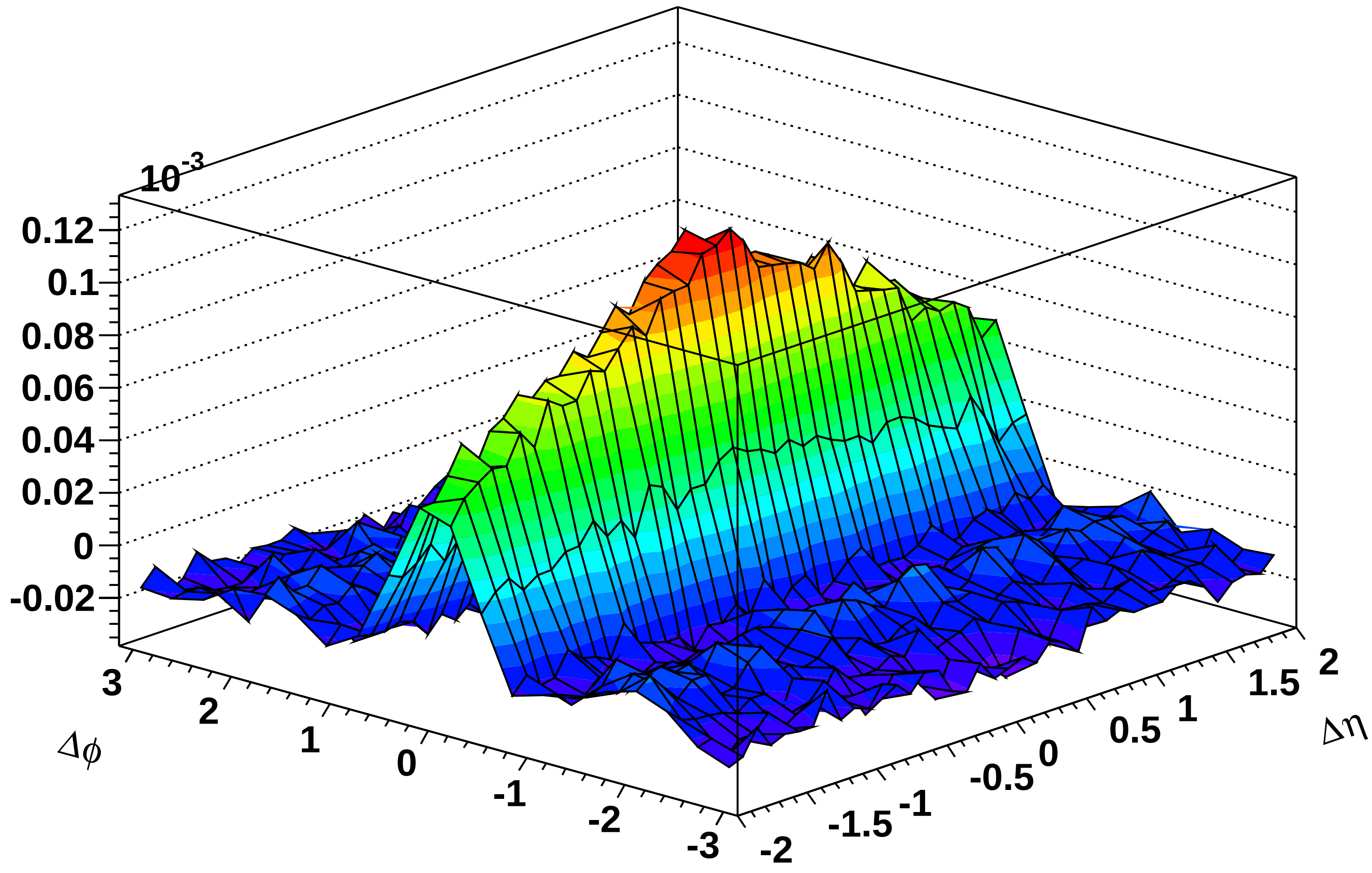


Leads to **translational invariance of transverse flows**



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

=> ridge-structure in the dihadron correlation $dN/d\Delta\eta\, d\Delta\phi$ **for free**

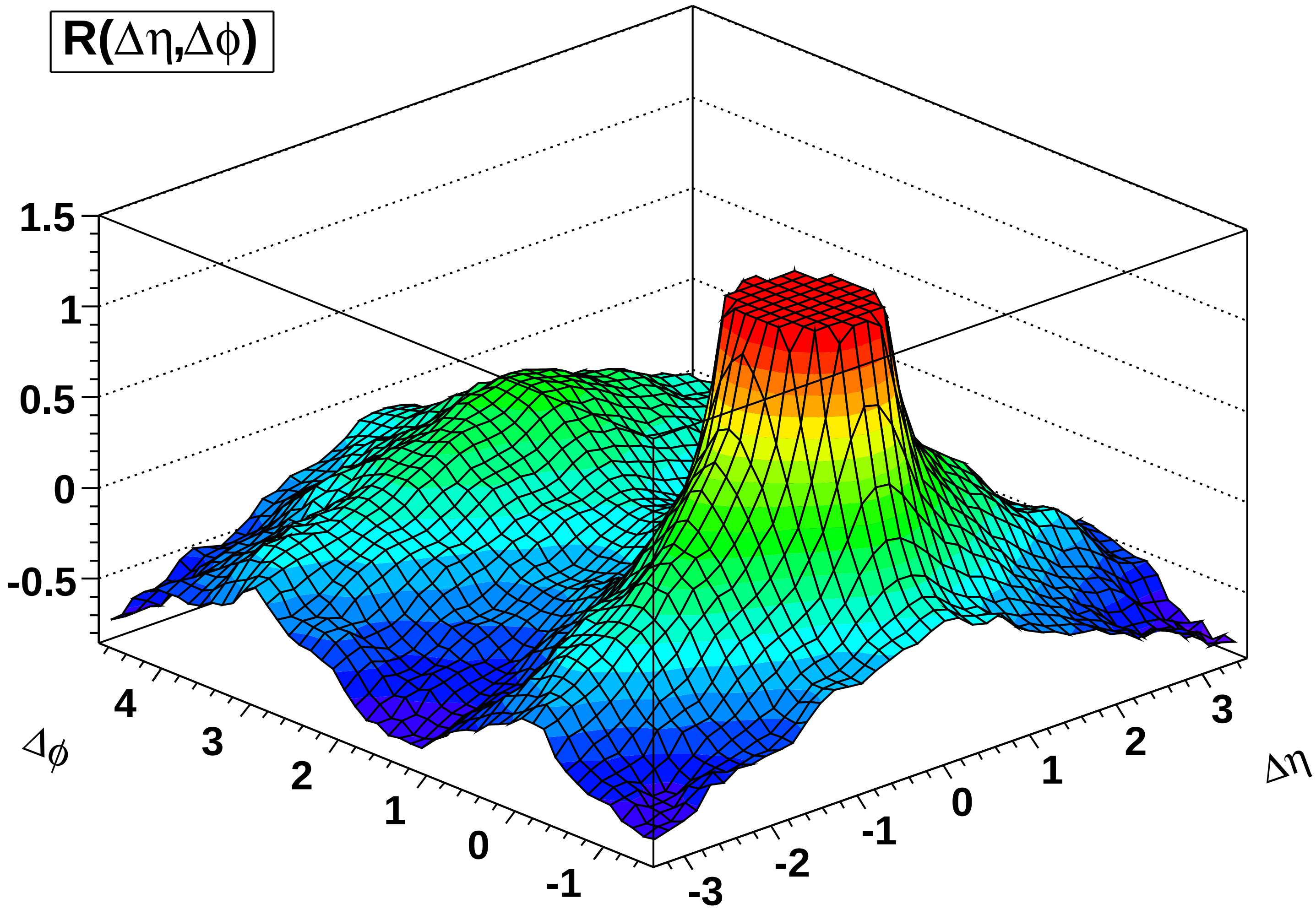


trigger particles with transverse momenta between 3 and 4 GeV/c, assoc particles with transverse momenta between 2 GeV/c and p_t of the trigger, in central Au-Au collisions at 200 GeV

pp@LHC

Our calculation provides a similar ridge structure in pp@7TeV

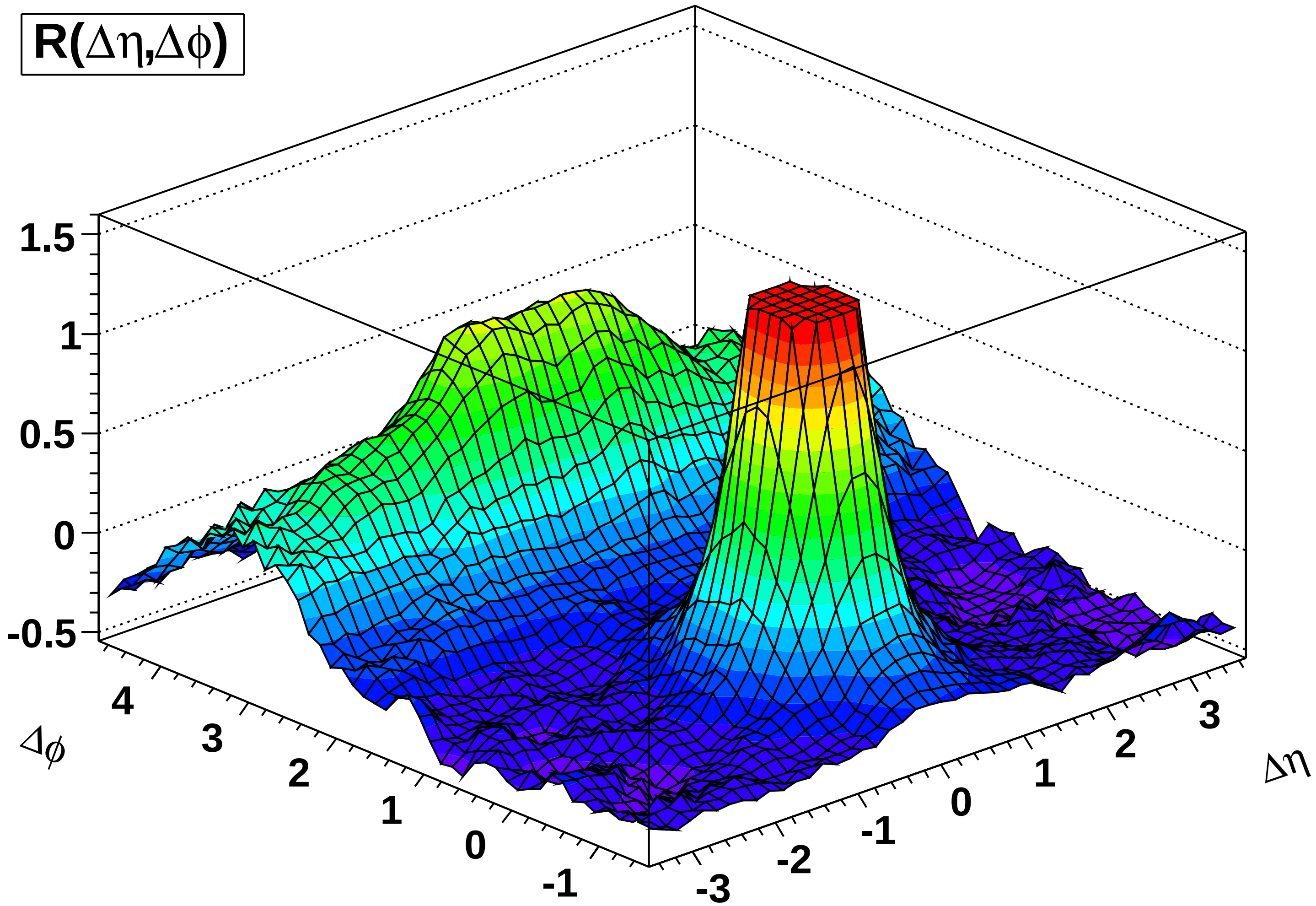
using particles with $1 < p_t < 3$GeV/c, for high multiplicity events



close in form and magnitude compared to the CMS result

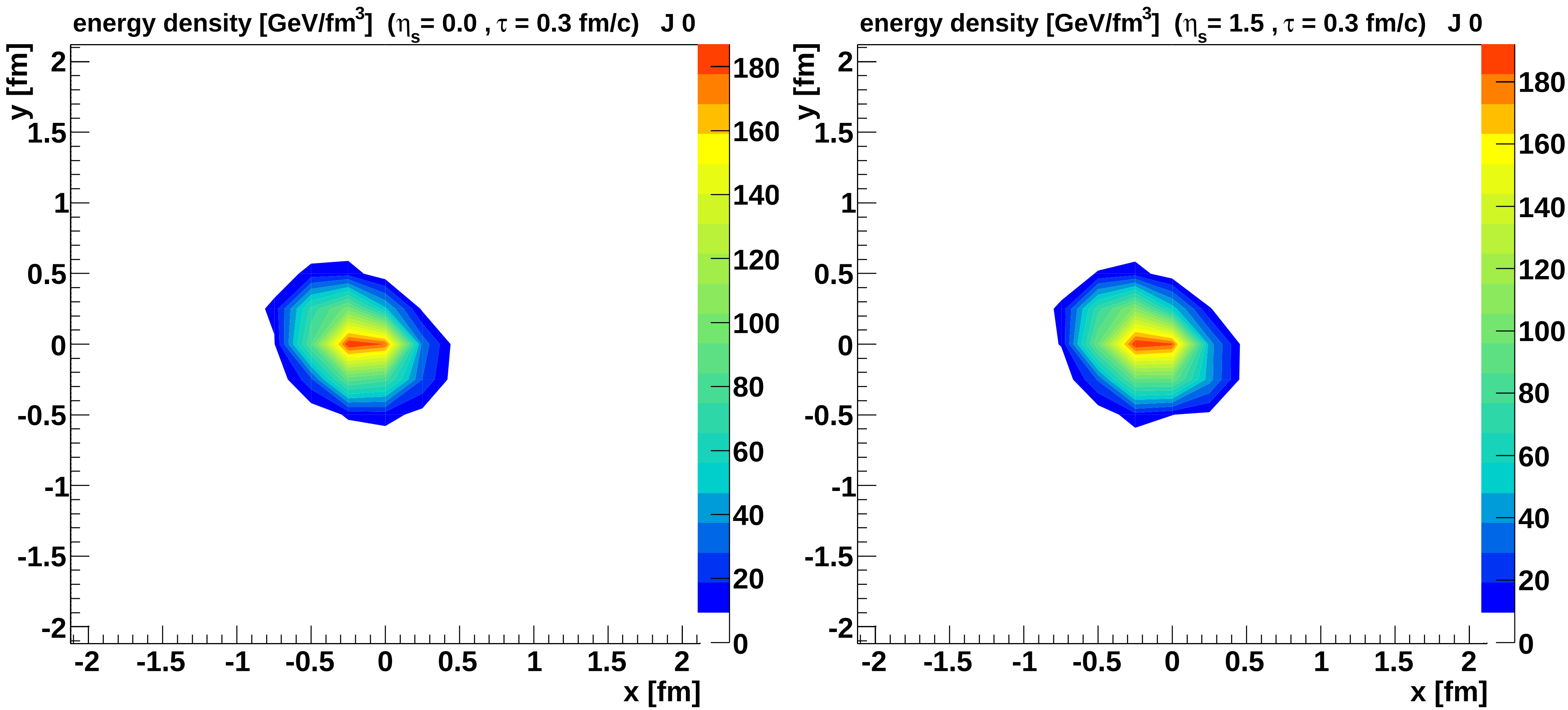
(5.3 times mean multipl., compared to 7 in CMS)

Calculation without hydro => NO RIDGE



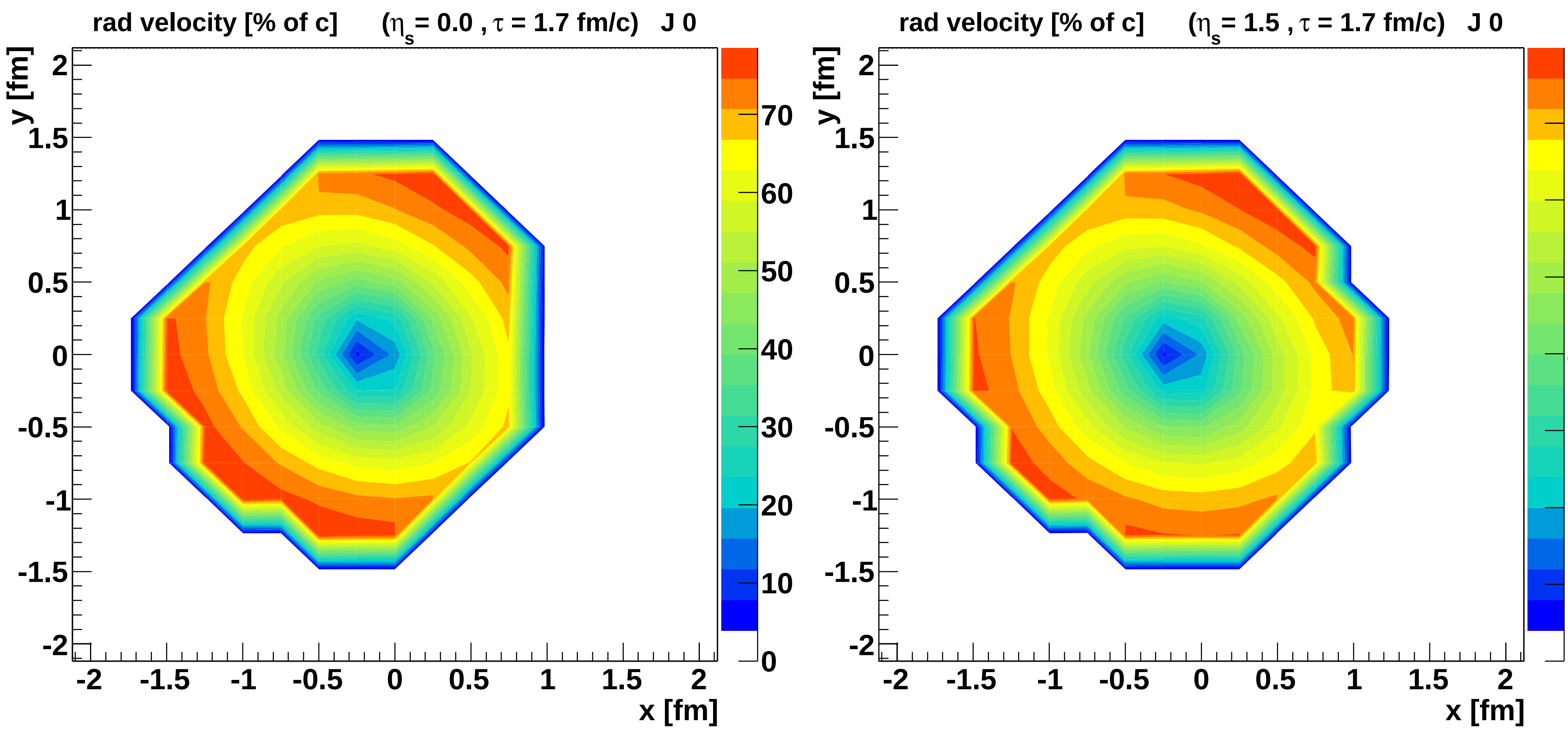
hydrodynamical evolution “makes” the effect! HOW?

Random azimuthal asymmetries of initial energy density
but translationally invariant



Initial energy density in the transverse plane for two different η_s

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



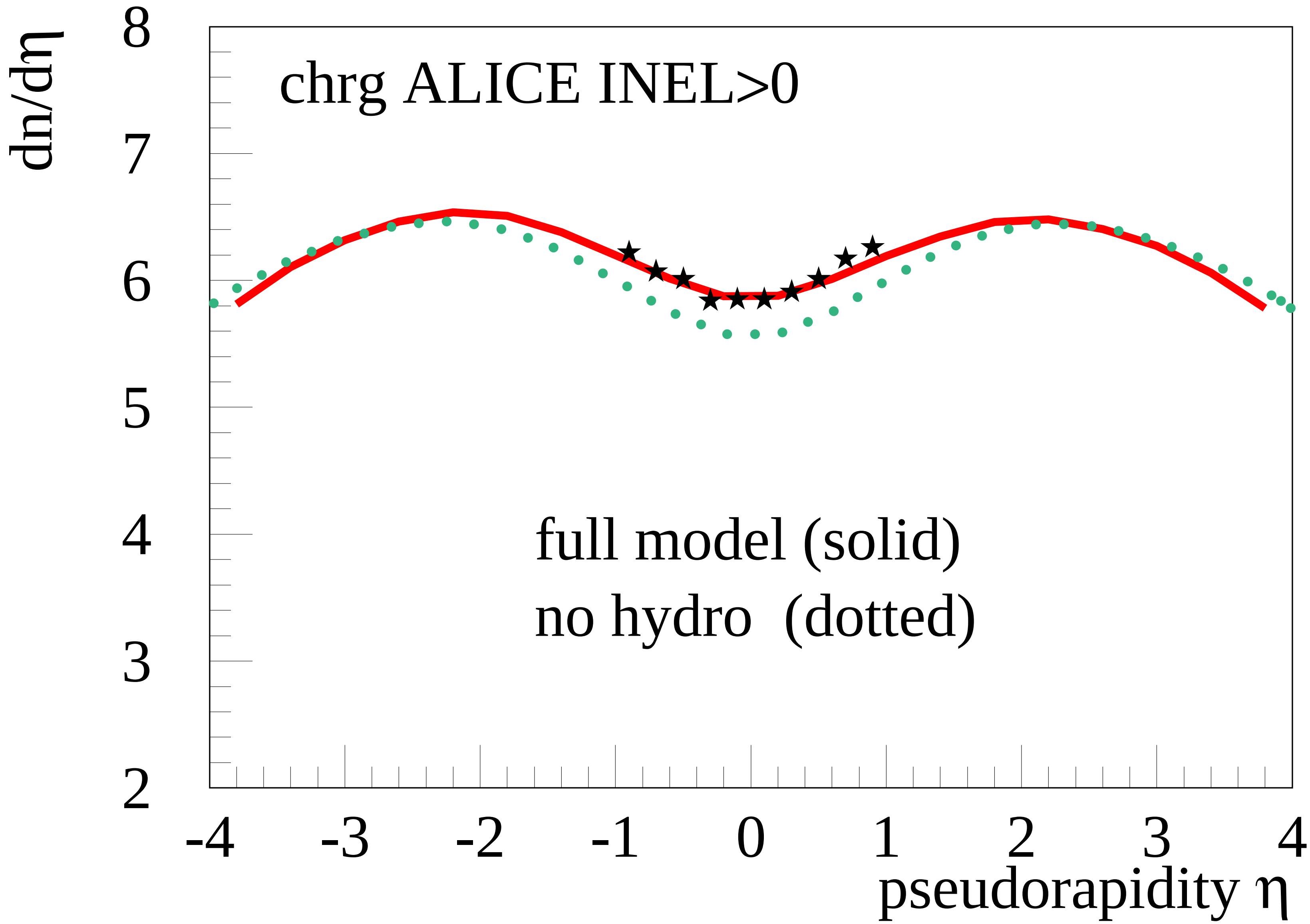
Radial flow velocity at a later time in the transverse plane

Translational invariance of the flow asymmetry means:

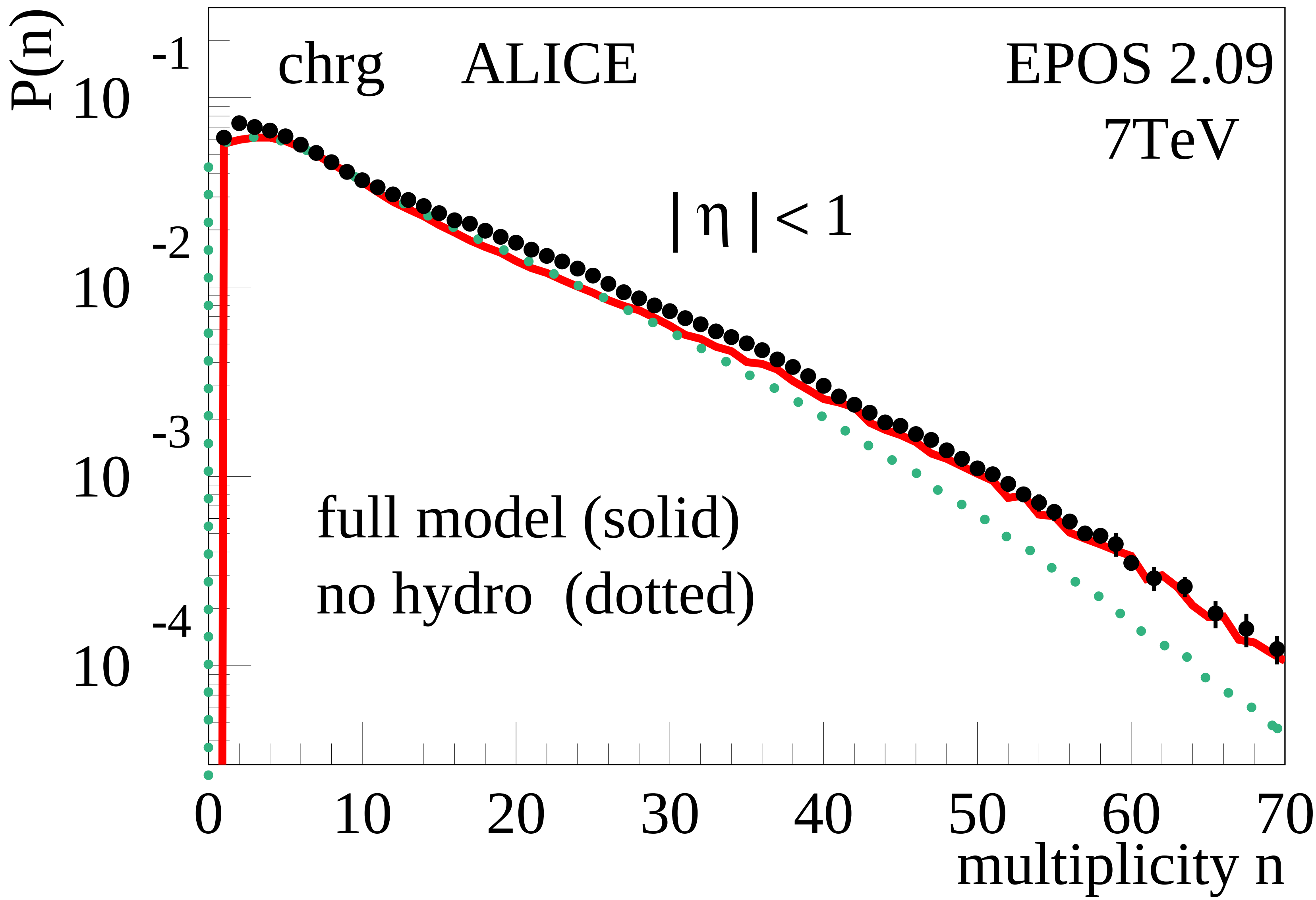
- **The system gives an increased collective push**
- **to particles produced at different values of η_s**
- **at the same azimuthal angle corresponding to a flow maximum**

=> $\Delta\eta\Delta\phi$ correlation

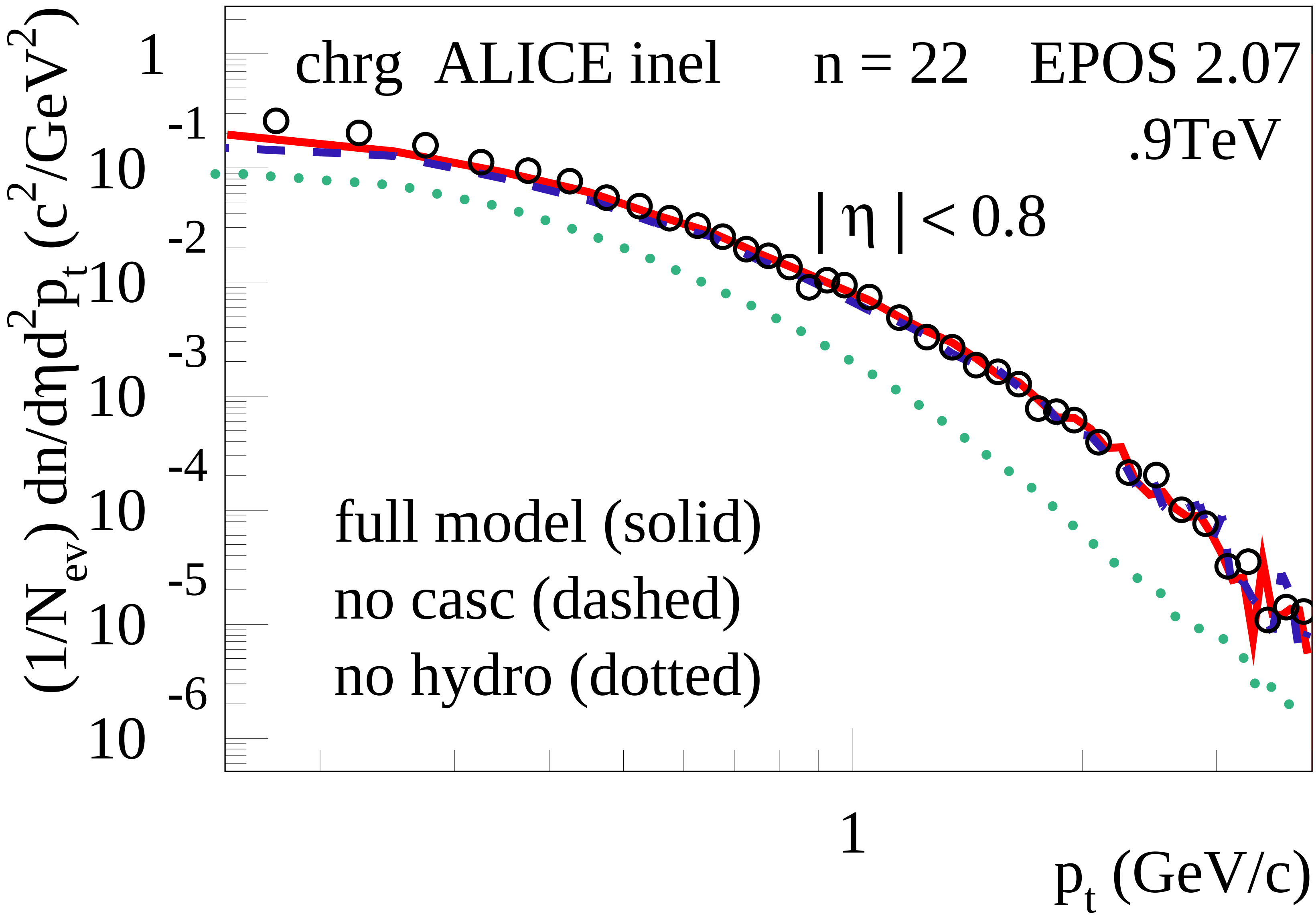
Particle spectra: Little effect of hydro in MB dn/deta



Same observation for multiplicity distribution

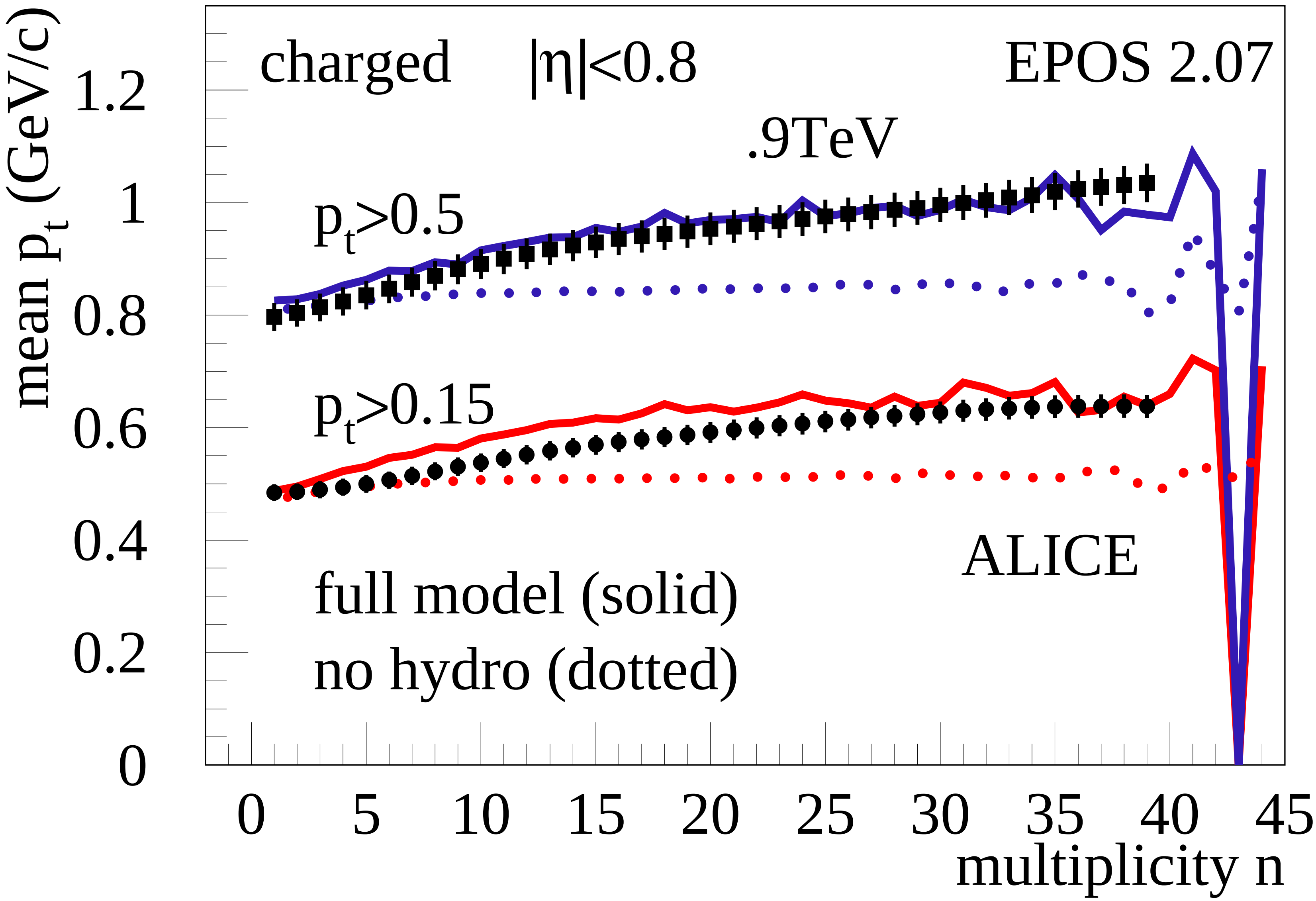


Big effect for pt distributions for high multiplicity events

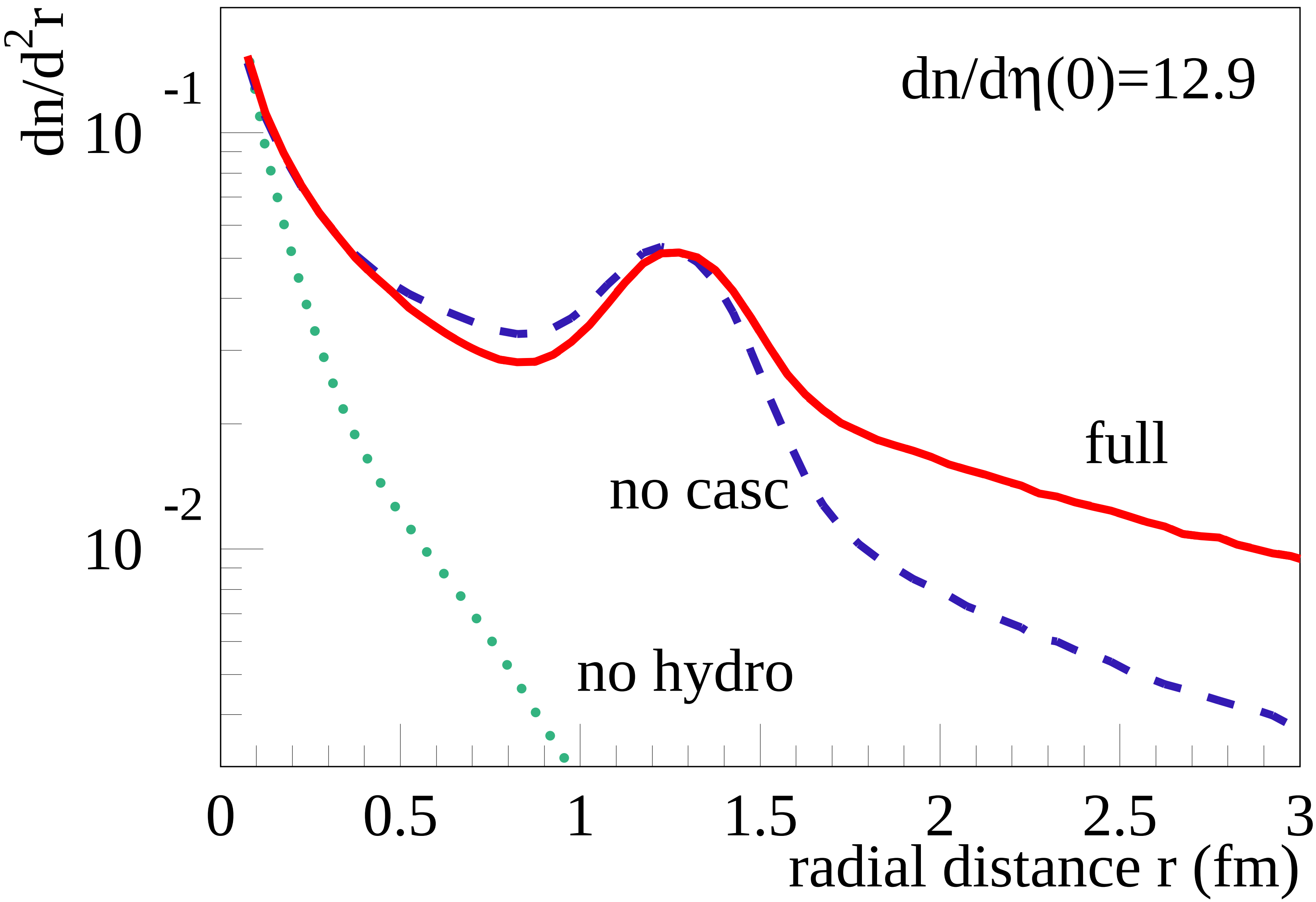


flow!!!

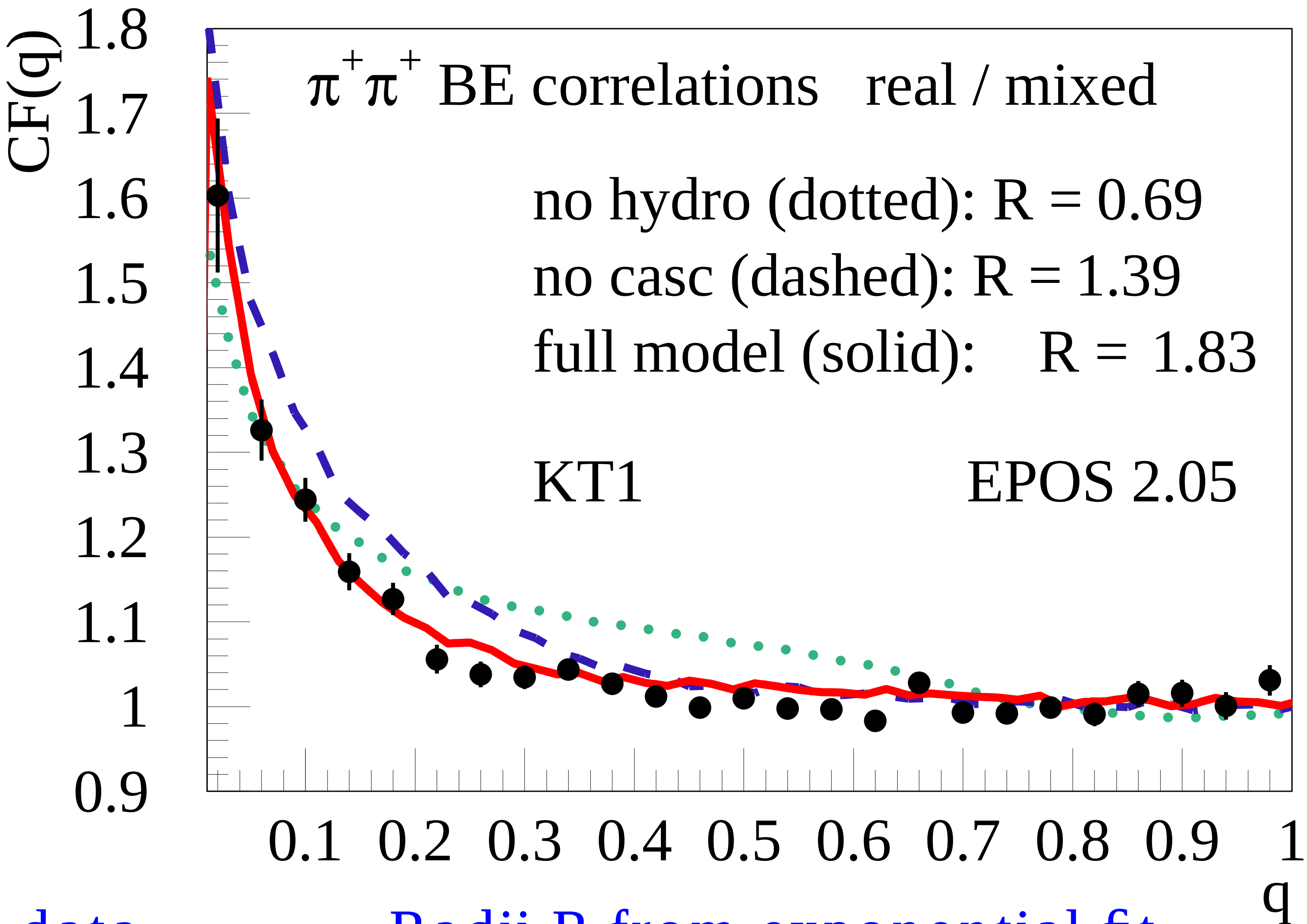
summarized in <pt> versus multiplicity



Space-time structure strongly affected (here 900 GeV)



Consequences for Bose-Einstein correlations



ALICE data. Radii R from exponential fit.

KT1$=[100, 250]$, KT3$=[400, 550]$, KT5$=[700, 1000]$

Summary

Multiple scattering approach & hydro works very well

- **for AuAu@RHIC, explains naturally nontrivial features as “ridge” correlations, elliptical flow**

- **and explains some nontrivial pp results (ridge, BE correlations)**

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Thank you !!