Quark-Gluon Plasma in Proton-Proton Scattering at the LHC?

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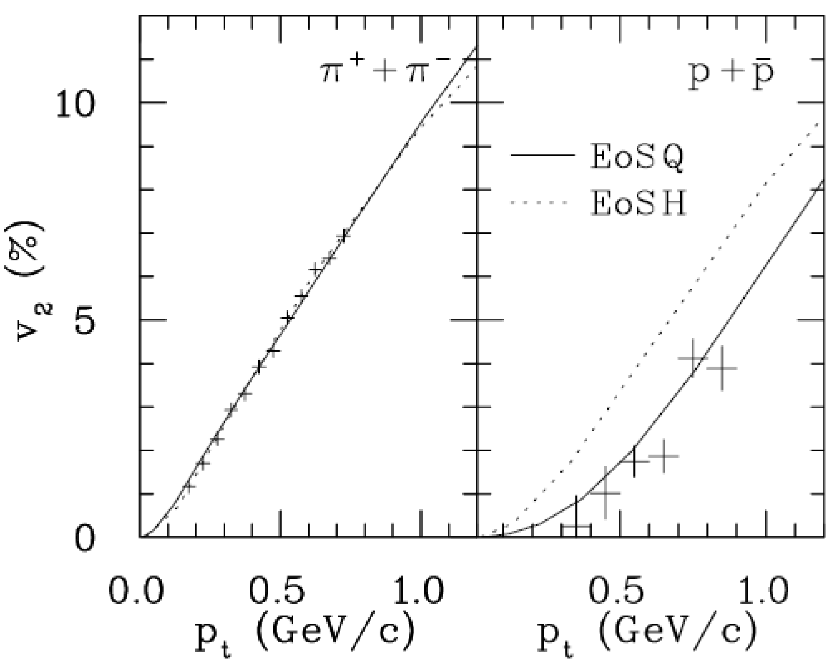
UR heavy ion collisions seem to produce matter which expands as an almost ideal fluid (of quark matter)

Houvinen et al, 2001



Many nontrivial observations
can be explained
on the basis of hydrodynamics

like azimuthal anisotropies
expressed via $v_2 = < \cos 2\phi >$

in hydro, space asymmetry translates into momentum asymmetry via flow

Also known (from RHIC):

No drastic change when considering smaller systems

- smaller nuclei
- and/or semi-peripheral collisions

What about proton-proton scatterings?

First LHC results:

signs for collective “fluid-like” behavior
in high multiplicty pp events as well ...

We employ a hydrodynamical scenario for pp@LHC (same procedure as for heavy ion collisions):

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 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 ideal hydro evolution,
including the conservation of baryon number, strangeness, and electric charge;

parton-hadron transition

* realistic equation-of-state with a cross-over transition for $\mu_B = 0$, compatible with latest lattice gauge results

  (S. Borsanyi et al , arXiv:1007.2580
  or M. Chenget al., arXiv:0911.2215)

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:

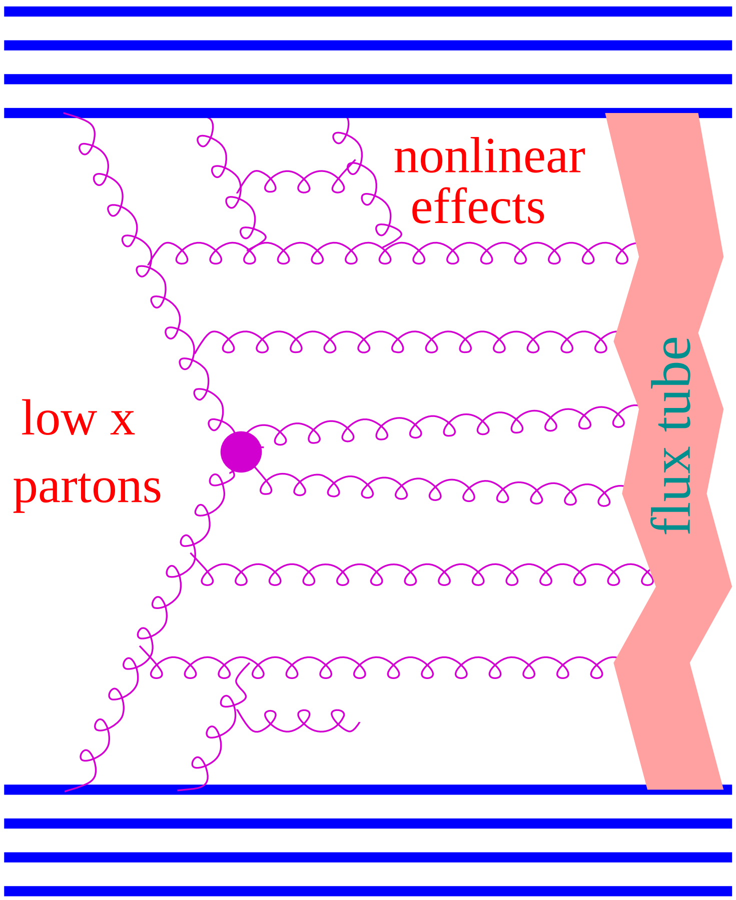
arXiv:1004.0805 (Ridges + many other things at RHIC), PRC 82,044904
arXiv:1010.0400 (Hydrodyn. evolution in pp@LHC), PRC 83, 044915
arXiv:1011.0375 (Ridges in pp@7TeV), PRL 106:122004,2011
arXiv:1104.2405 (BoseEinstein correlations in pp@7TeV)

Elementary scatterings - flux tubes

AA - even pp: **many elementary collisions happening in parallel.**

Not just rescattering of hard partons!

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

... in particular when the energy sharing between the parallel scatterings is taken into account

Details:

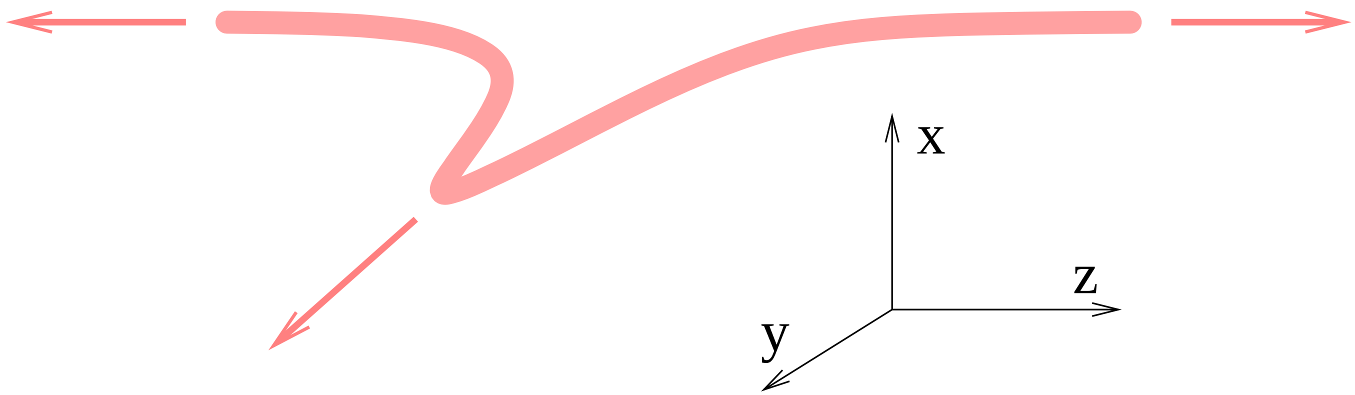
Parton-based Gribov-Regge Theory, H. J. Drescher, M. Hladik, S. Ostapchenko, T.Pierog, and K. Werner, Phys. Rept. 350 (2001) 93-289

- 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:

At LHC, almost all scatterings are hard, nevertheless
flux tubes are mainly longitudinal objects (here parallel to the z-axis)

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

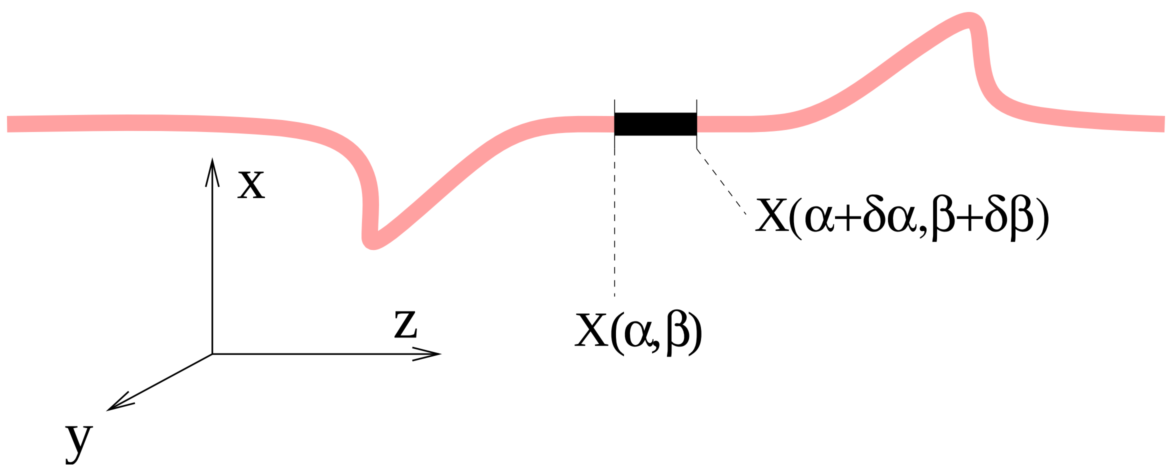


But despite these kinks, most of the string carries only little transverse momentum!

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.

Interesting observable:

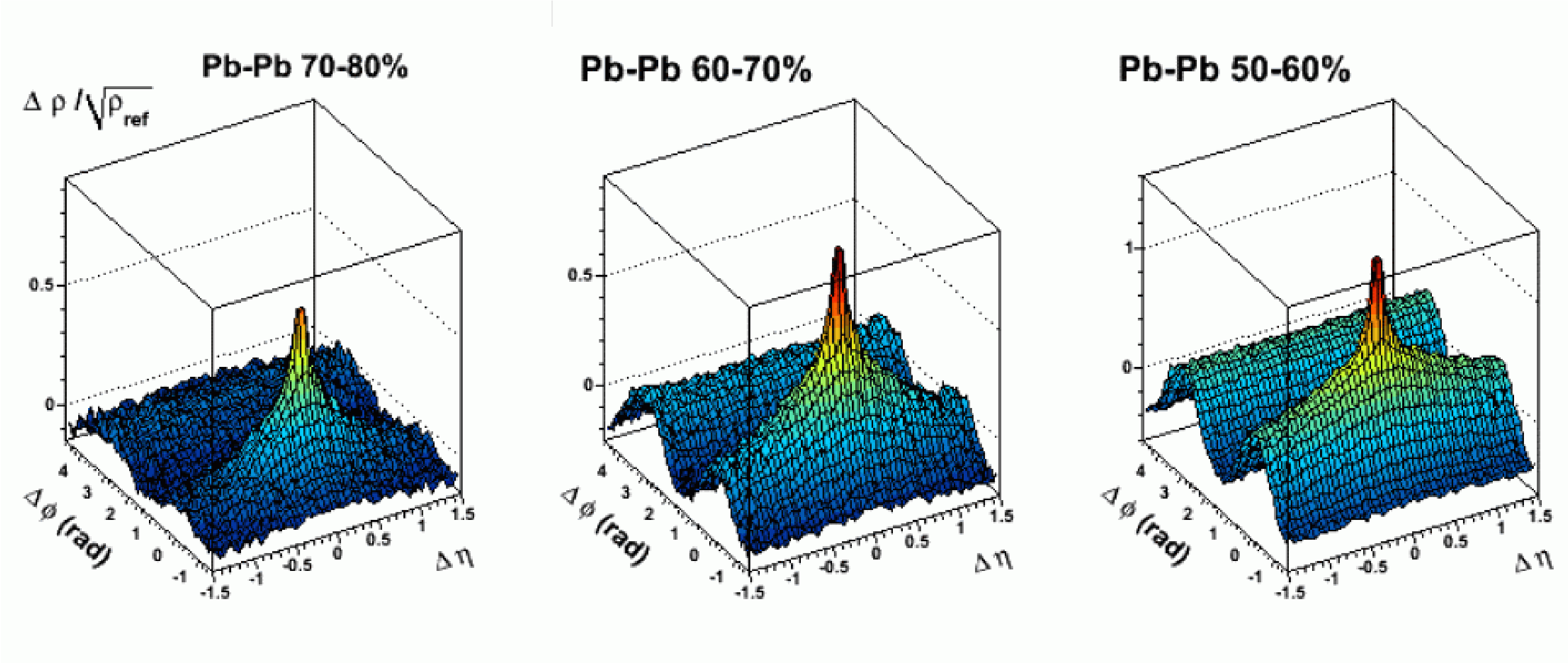
dihadron correlation function R($\Delta\eta$,$\Delta\phi$)

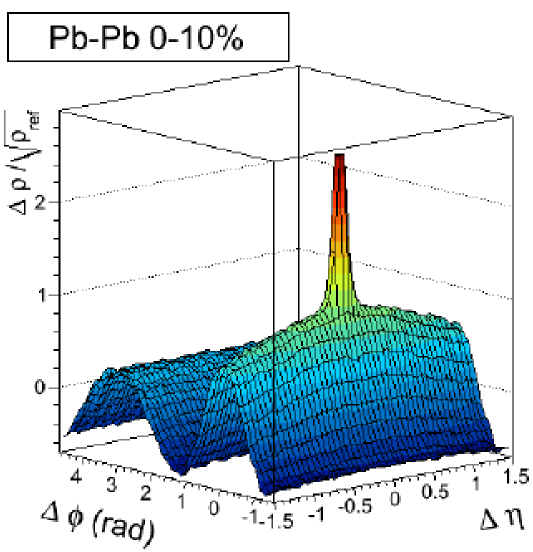
(triggered or untriggered)

First PbPb@2.76 TeV

then pp@7TeV

PbPb@2.76TeV (from A. Timmins, ALICE, QM11)

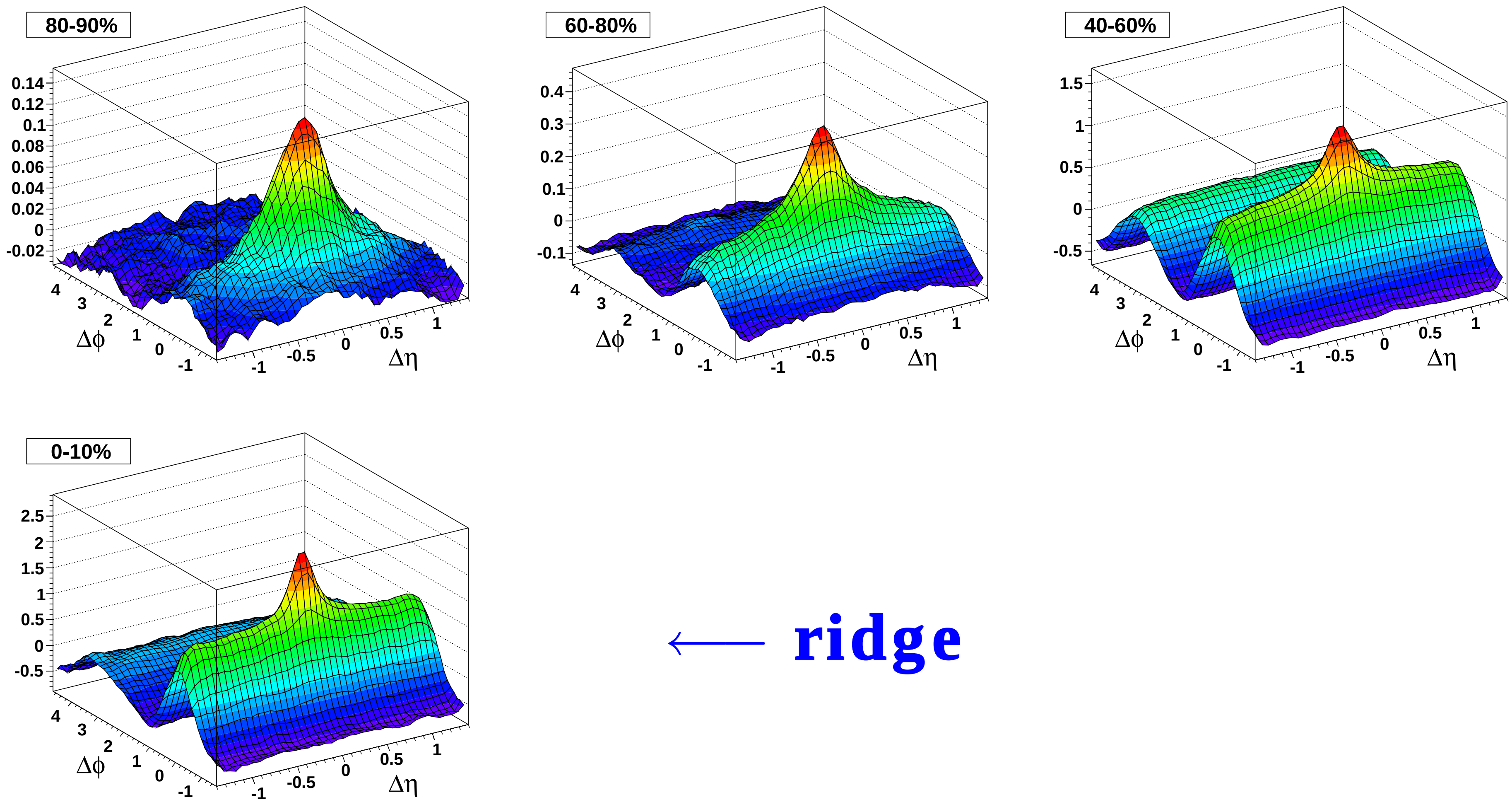




From peripheral to central

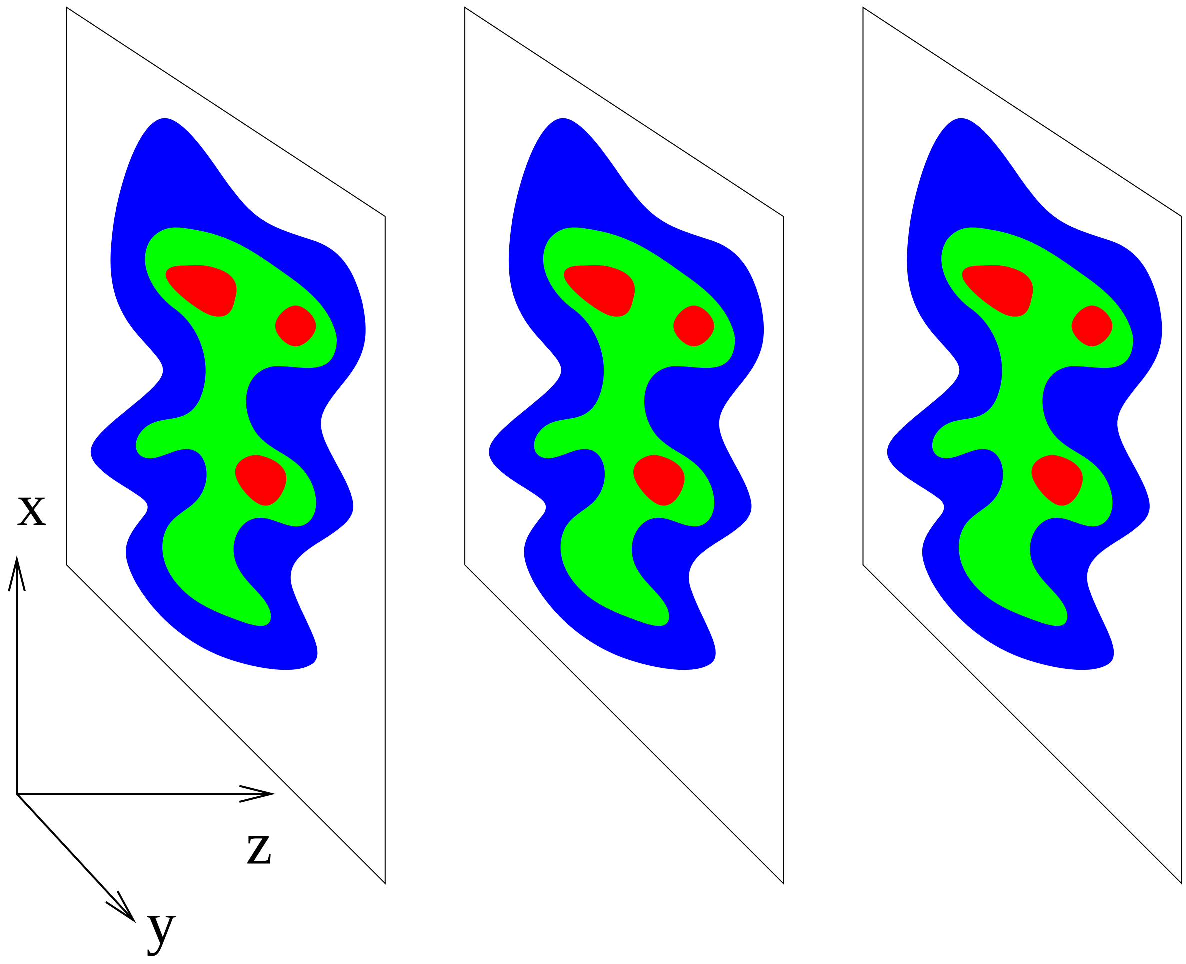
- ☐ jets
- ☐ elliptical flow
- ☐ Ridge

Our results (untriggered corr functions):

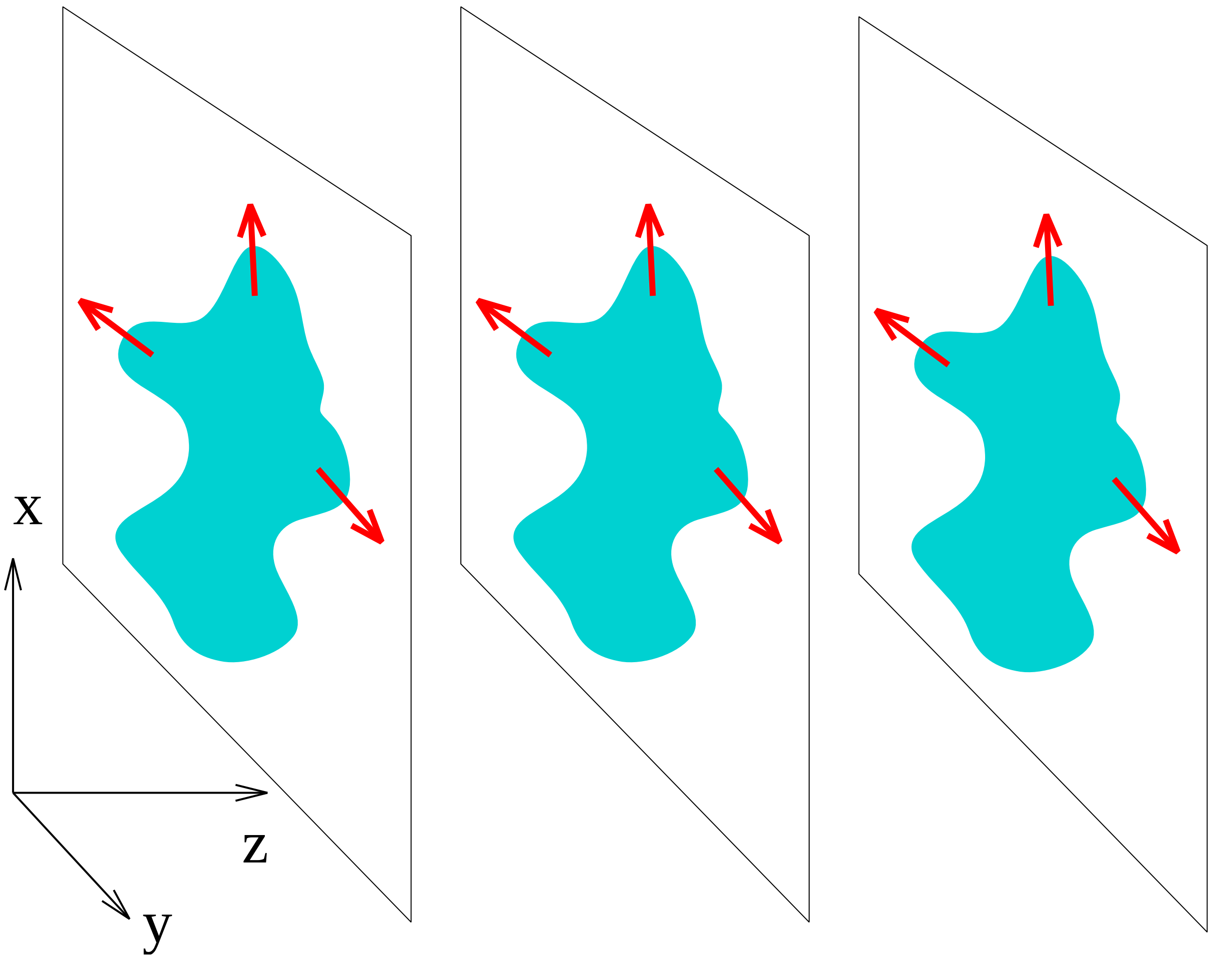


⟵ **ridge**

translational invariance of initial energy density



leads to **translational invariance of transverse flows later**

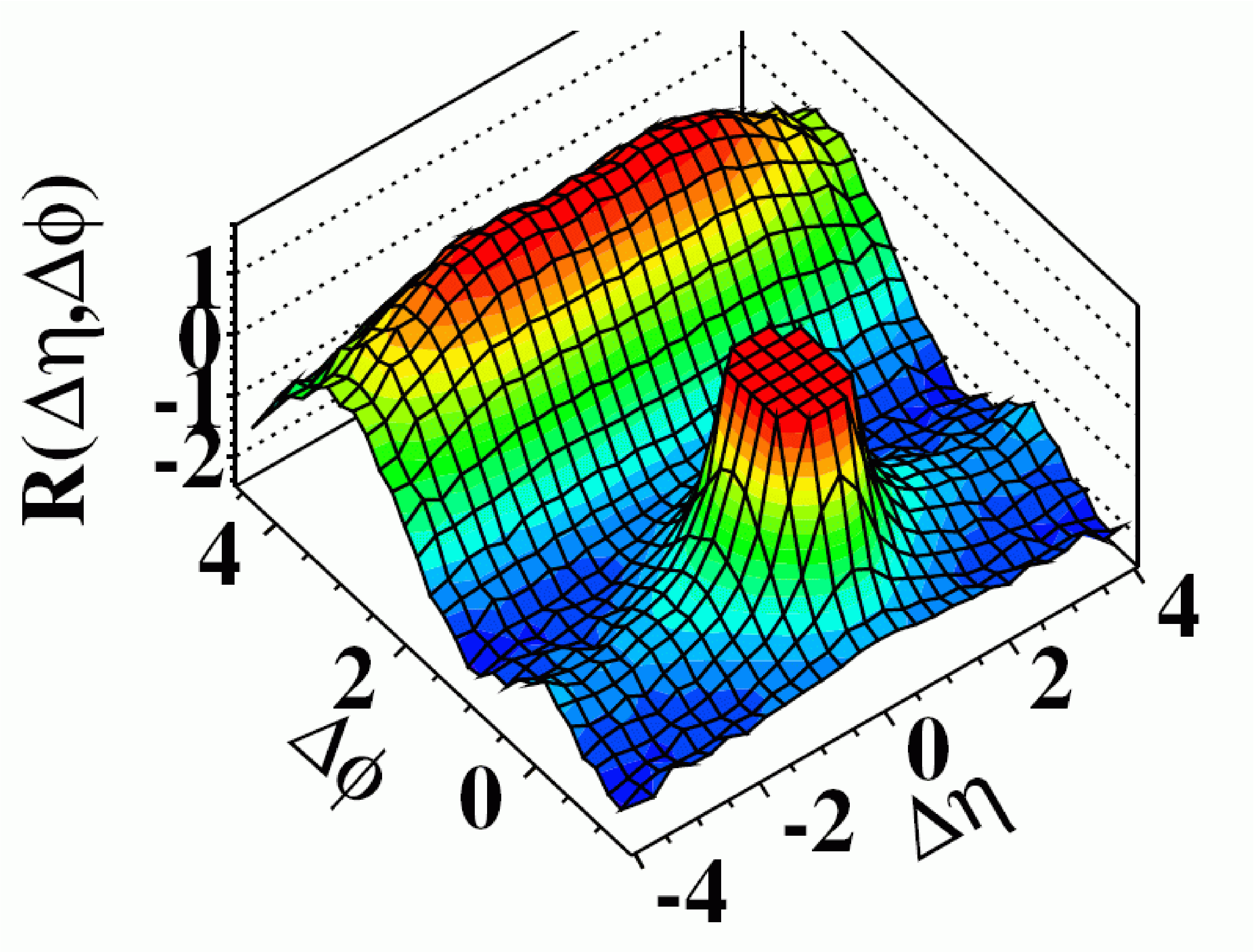


give the same collective push

to particles produced at different values of η_s

at the same azimuthal angle

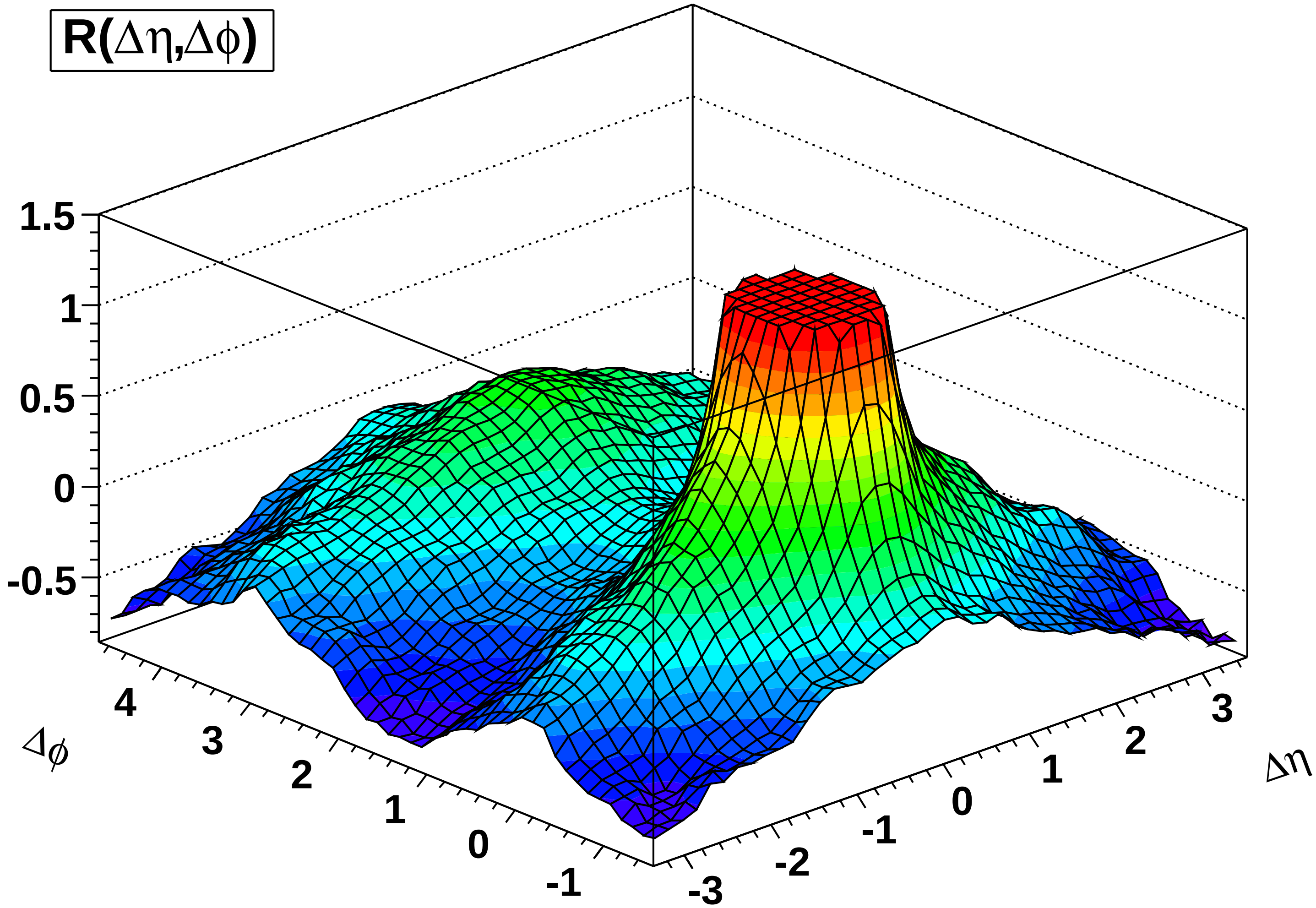
In pp@7TeV:
spectacular “ridge” discovery from CMS:



using particles with $1 < p_t < 3\text{GeV/c}$, for **high multiplicity events**

Our calculation provides a similar ridge structure

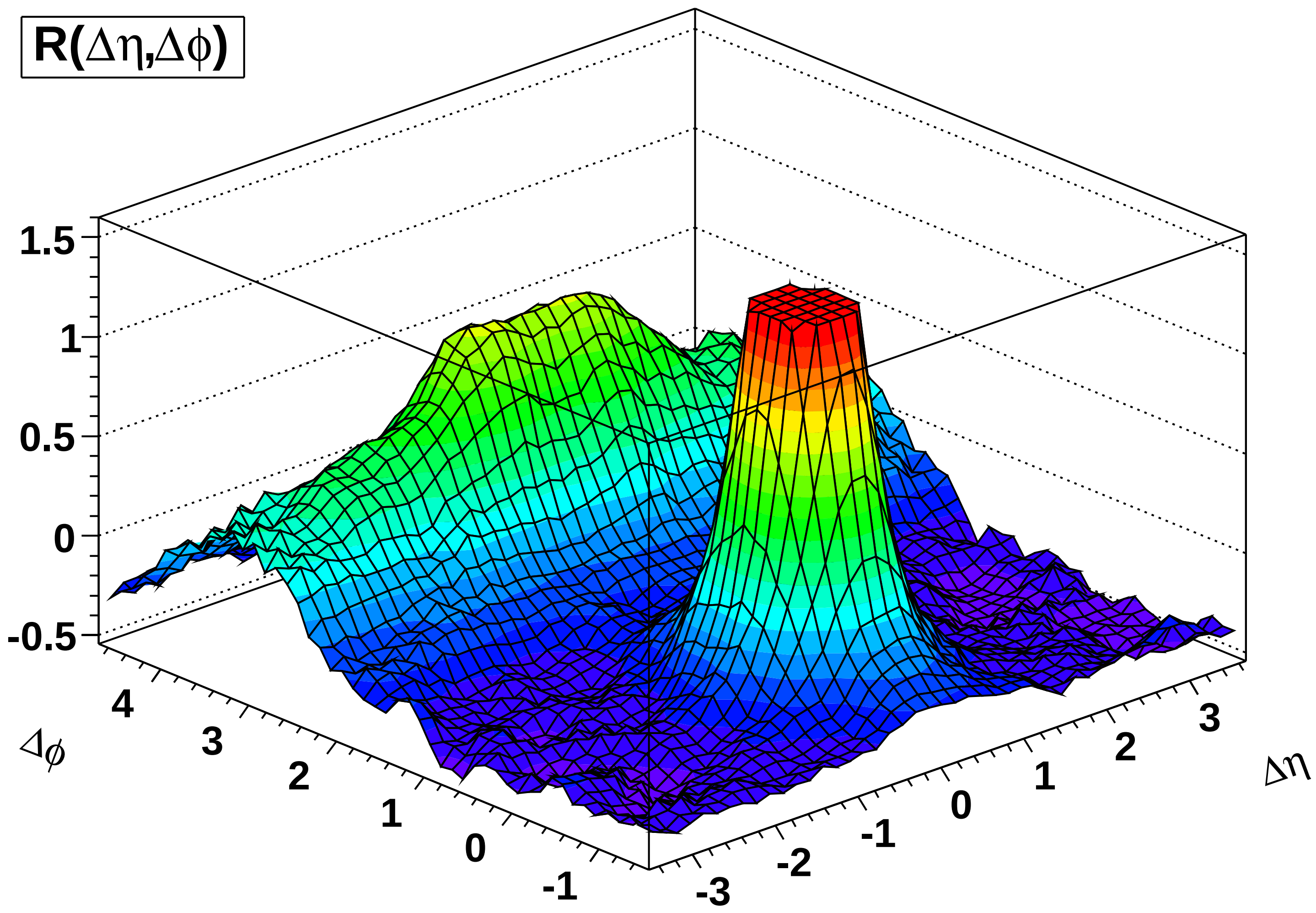
using also particles with $1 < p_t < 3$GeV/c, for **high multiplicity events**



close in form and magnitude compared to the CMS result

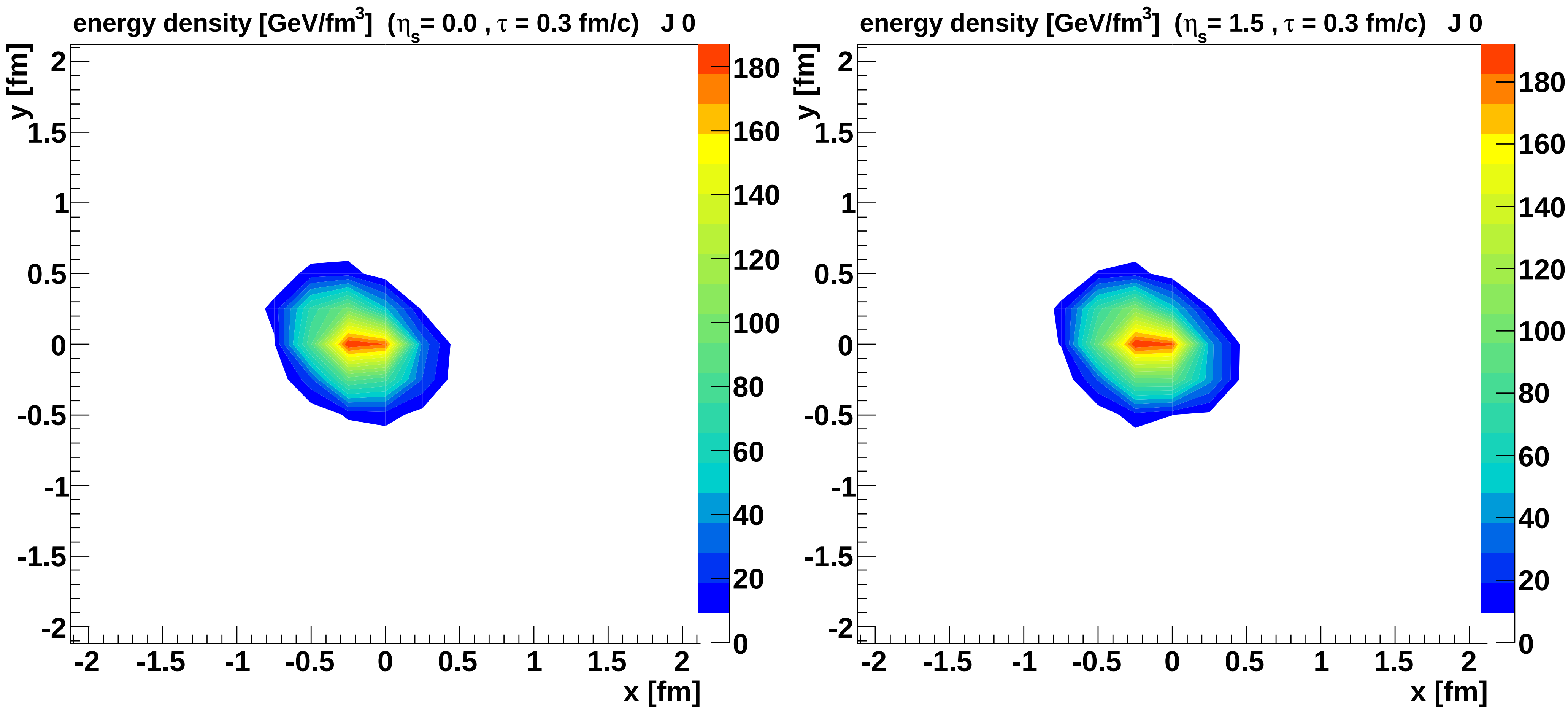
(5.3 times mean multipl., compared to 7 in CMS)

Calculation without hydro => NO RIDGE



hydrodynamical evolution “makes” the effect! HOW?

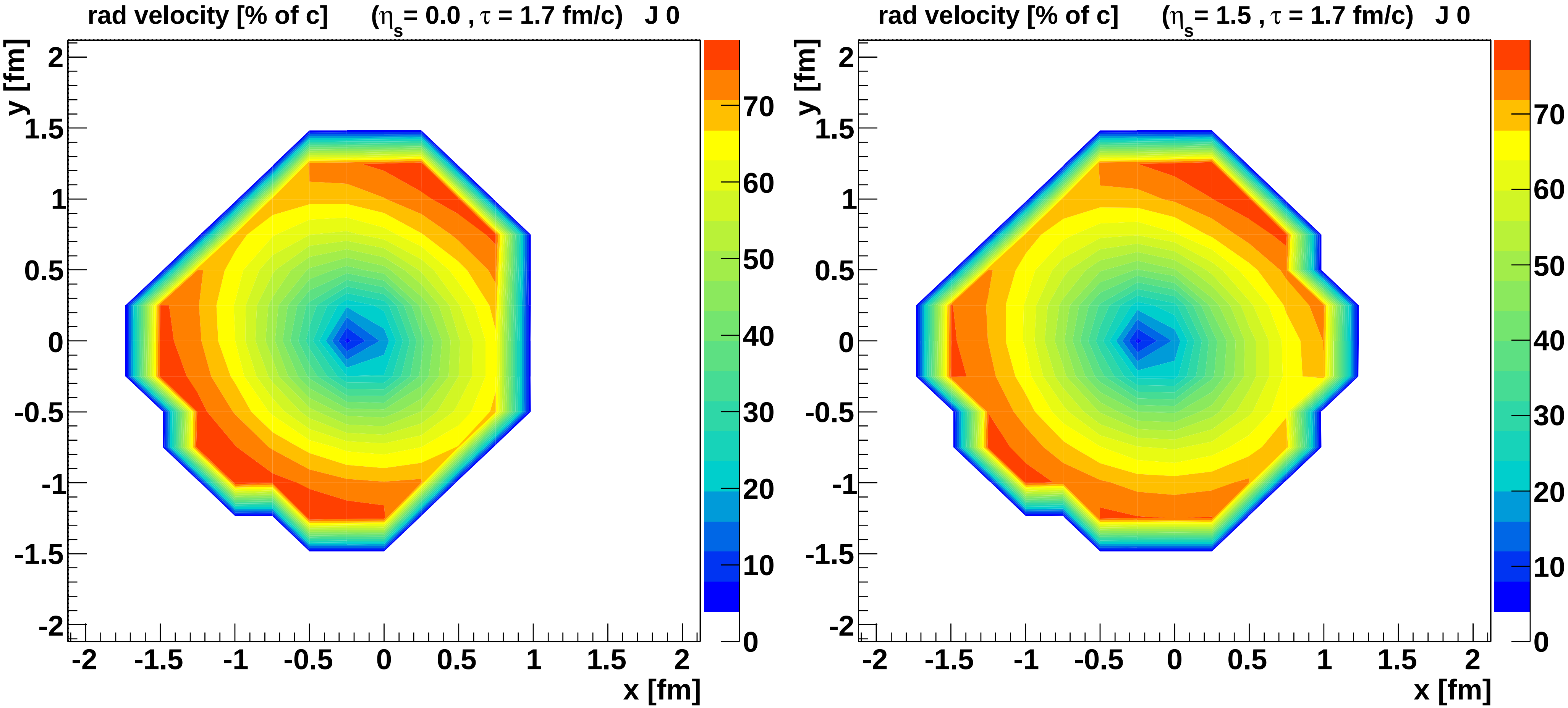
Random azimuthal asymmetries of initial energy density
but translationally invariant



Initial energy density in the transverse plane for two different η_s

Elliptical initial shapes leads to asymmetric flows

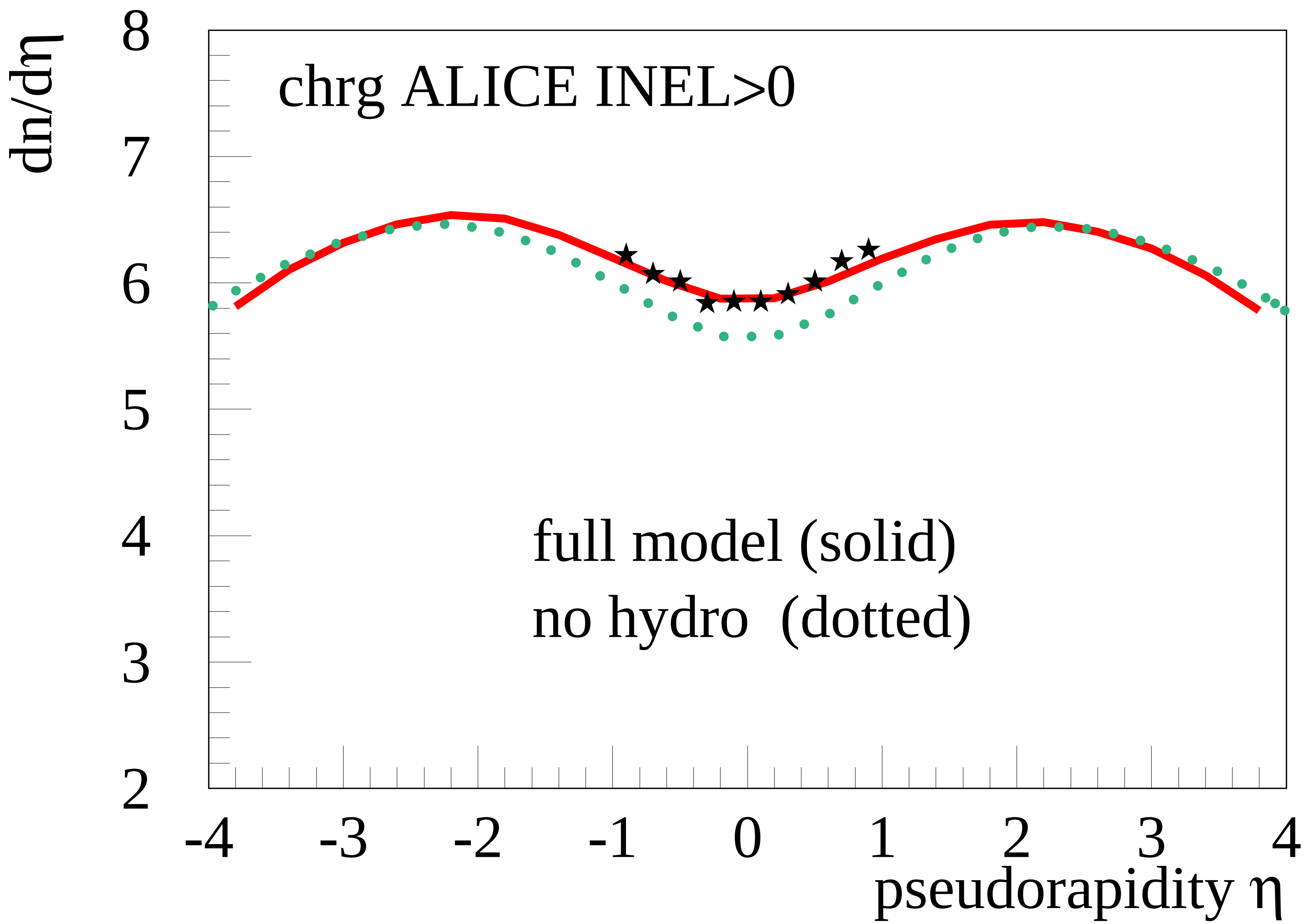
as well translationally invariant (in η_s)



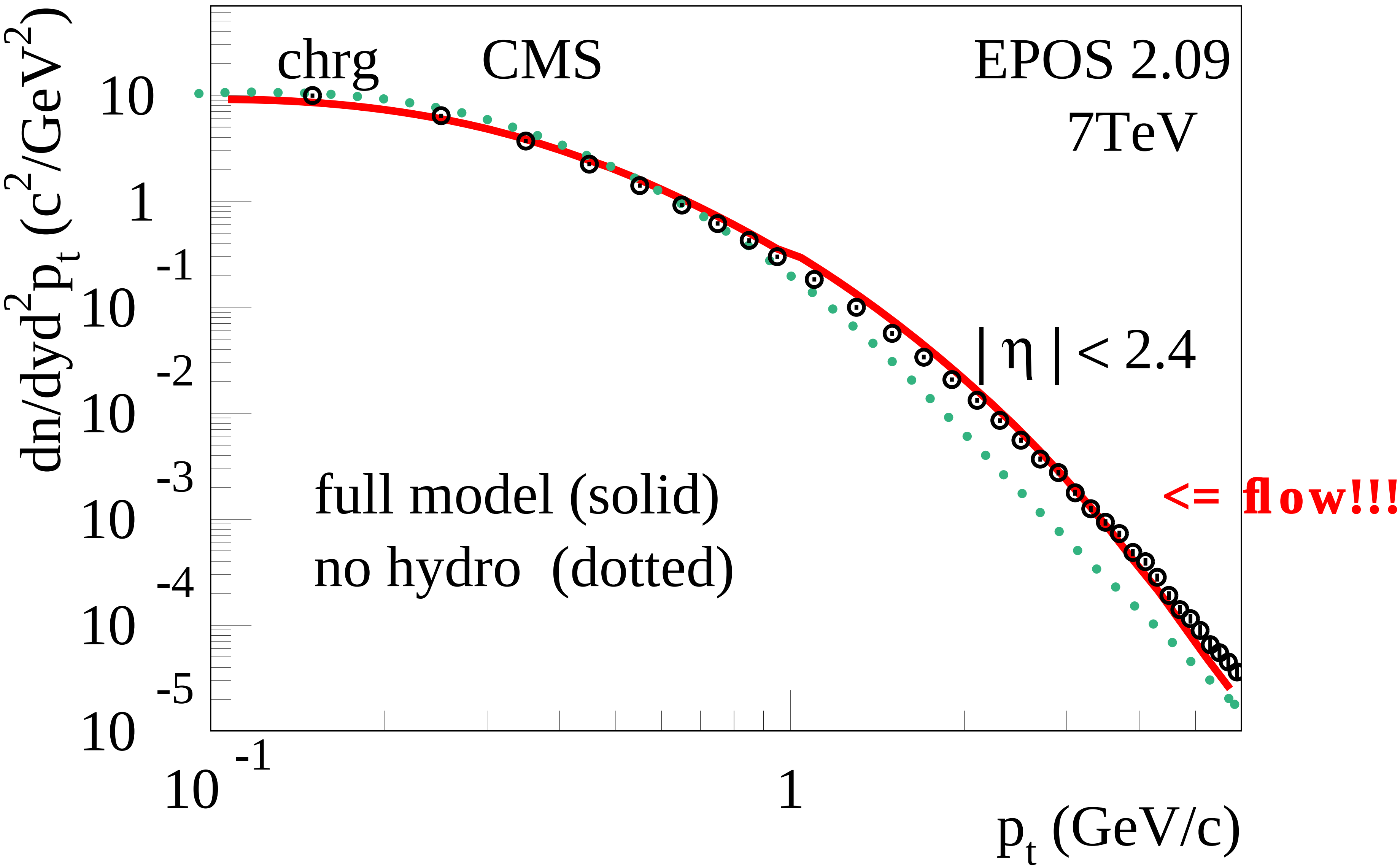
give the same collective push
to particles produced at different values of η_s
at the same azimuthal angle

Other observables

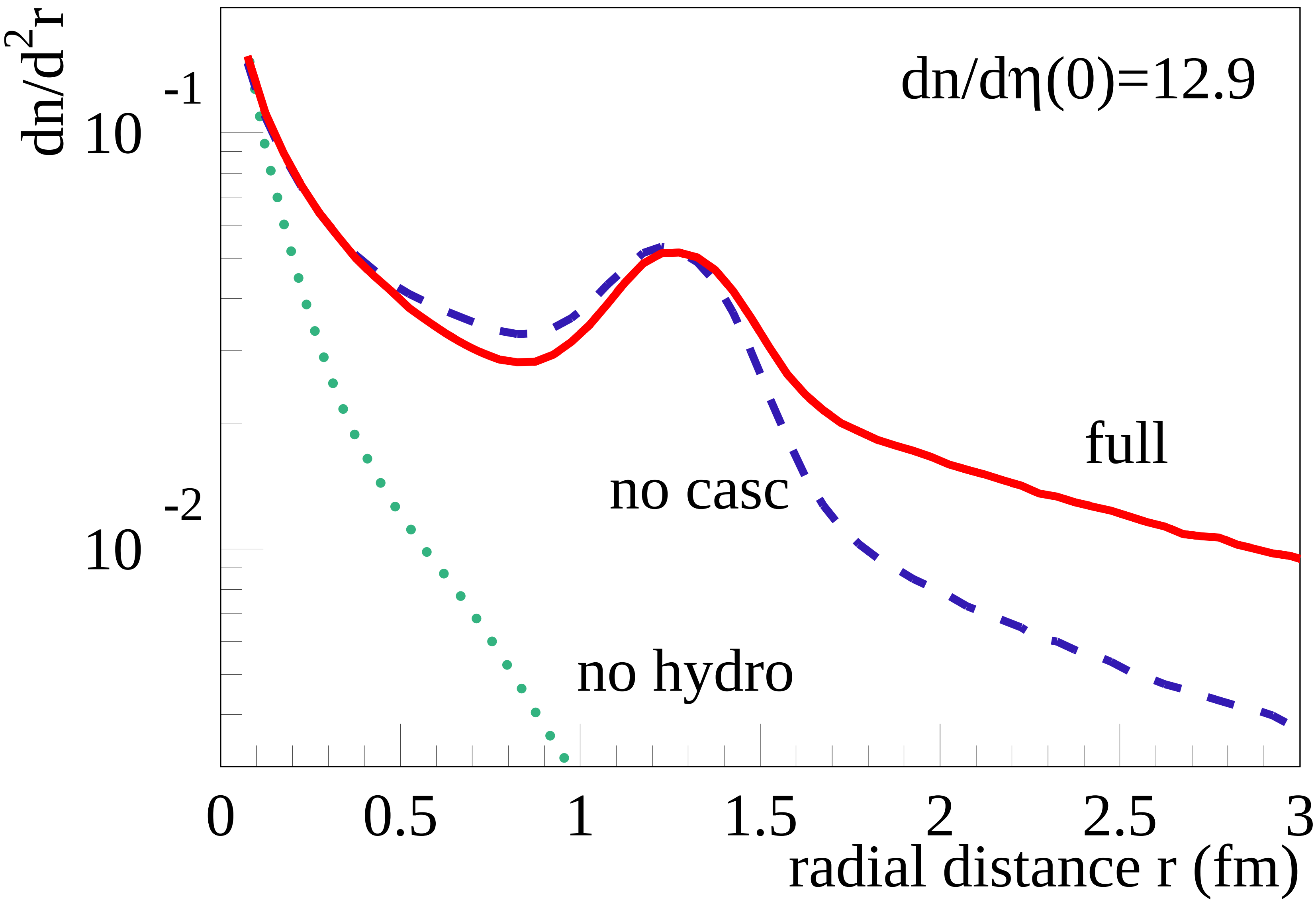
Particle spectra: Little effect of hydro in MB dn/deta



But: big effect for intermediate pt (even for MB)



Space-time structure strongly affected (here 900 GeV)



Consequences for Bose-Einstein correlations

Experiments measure:

Two-particle correlation functions $C(\mathbf{P}, \mathbf{q})$, with

- $\mathbf{P}$ = total momentum vector,
- $\mathbf{q}$ = relative momentum vector.

In case of identical mesons (like $\pi^+\pi^+$):

- BoseEinstein correlations,
  related to the space-time structure of particle production

Under “certain assumptions” the two-particle correlation function $C(\mathbf{P},\mathbf{q})$ is given as

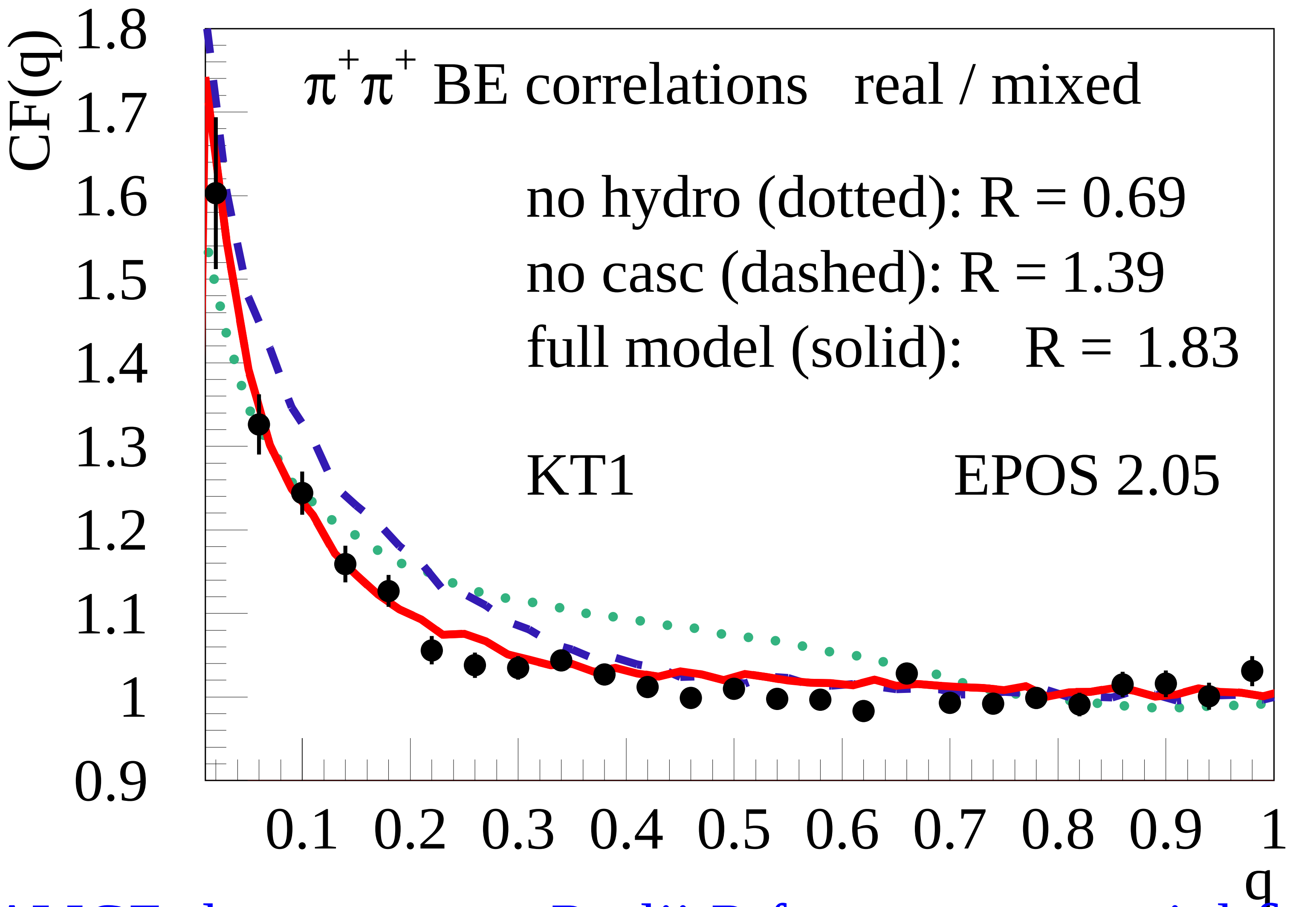
$$C(\mathbf{P},\mathbf{q}) = \int d^3r'\, S(\mathbf{P},\mathbf{r}')\, |\Psi(\mathbf{q}',\mathbf{r}')|^2$$

- $S(\mathbf{P},\mathbf{r}')$ = source function = probability of emitting a pair of hadrons with total momentum $\mathbf{P}$ and relative distance $\mathbf{r}'$
- Ψ outgoing two-particle wave function,
- $\mathbf{q}'$, $\mathbf{r}'$ relative momentum and distance in the pair center-of-mass system.

Here: source function S obtained from our simulations
parameters entirely determined from yields, spectra ..

Pair wave function:
we follow R. Lednicky, Physics of Particles and Nuclei 40 (2009) 307

Results for high multipl pp@900 GeV (here $q = \sqrt{\mathbf{q^2}}$,)



ALICE data. Radii R from exponential fit.

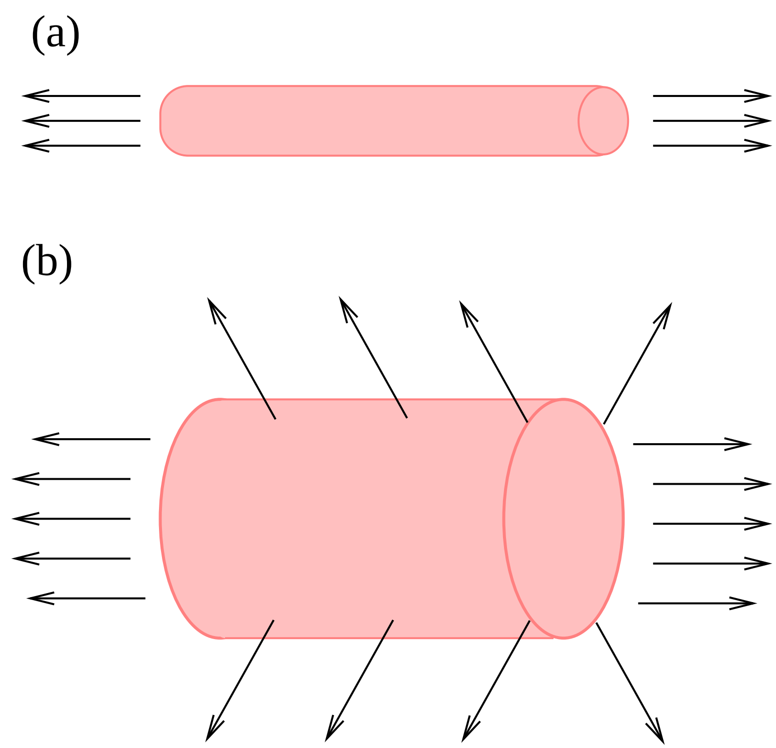
KT1= $[100, 250]$, KT3= $[400, 550]$, KT5= $[700, 1000]$ (KT=$\mathbf{P}_\perp/\mathbf{2}$)

pp@7TeV

Consider several multiplicity classes,
mult 1, ..., *mult 8*, as in arXiv:1101.3665 (ALICE)

mult 1: less than minimum bias
=> string decay (a)

mult 8: five time minimum bias
=> plasma decay (b)



"Classical" three dimensional analysis:

Correlation function parametrized as

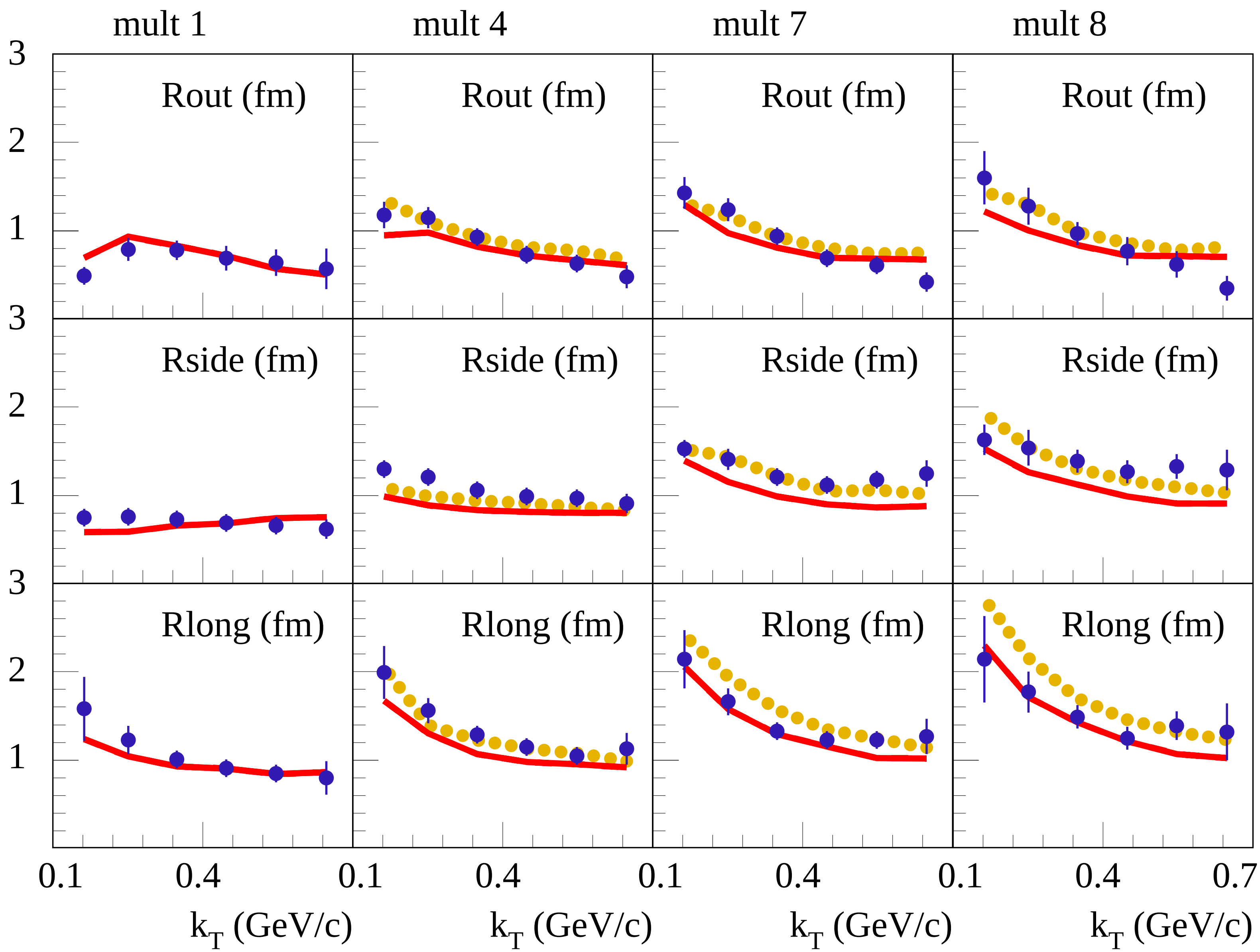
$$C(\mathbf{P},\mathbf{q}) = 1 + \lambda \exp\left(-R_{\mathrm{out}}^2\, q_{\mathrm{out}}^2 - R_{\mathrm{side}}^2\, q_{\mathrm{side}}^2 - R_{\mathrm{long}}^2\, q_{\mathrm{long}}^2\right)$$

long: beam direction

out: parallel to projection of **P** perpendicular to the beam

Fit parameters λ, R_{out}, R_{side}, and R_{long} are determined for different centrality classes and for different k_T , with

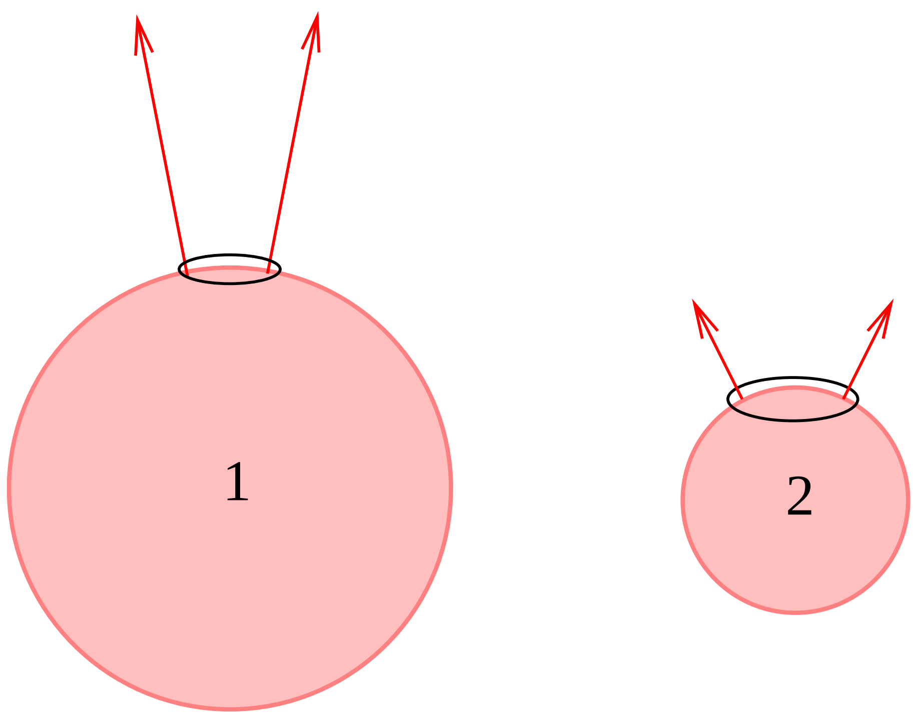
$$k_T = \frac{1}{2}\left(|\vec{p}_T(\mathrm{hadron}\,1) + \vec{p}_T(\mathrm{hadron}\,2)|\right).$$


mult 1
mult 4
mult 7
mult 8
Rout (fm)
Rside (fm)
Rlong (fm)
3
2
1
0.1
0.4
0.7
k_T (GeV/c)

Decreasing radii with k_T: flow effect

Pairs of radial flow vectors
on sufaces with different radii
(assuming lenths $\propto r$)
with constant difference,
for two different radii

two vectors in 2 more
distant compared to 1



Summary

Multiple scattering approach => multiple flux tubes, used as initial conditions for hydrodynamical evolution, realized in an event-by-event mode, in pp and AA

- □ **explains naturally nontrivial features as “ridge” correlations in HI collisions**

- □ **explains also some nontrivial pp phenomena (ridge, BE correlations)**

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Thank you !!