Femtoscopy within a Hydrodynamic Approach based on Flux Tube Initial Conditions

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in collaboration with

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1 Hydrodynamic evolution

Big activity on viscosity in hydrodynamics

BUT

there are many other “features” which are at least equally important

“Realistic” treatment of the hydrodynamic evolution

initial conditions here obtained from a flux tube approach (EPOS),
compatible with the string model used since many years (e^+e^-, pp),
and the color glass condensate picture;

possible initial flow (which helps but is not crucial here);

event-by-event procedure,
taking into the account
the highly 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;

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

complete hadron table, making the calculations compatible
with the results from statistical models;

hadronic cascade procedure,
after hadronization from the thermal system,
here at an early stage (166 MeV, in the transition region).

These features are not new!

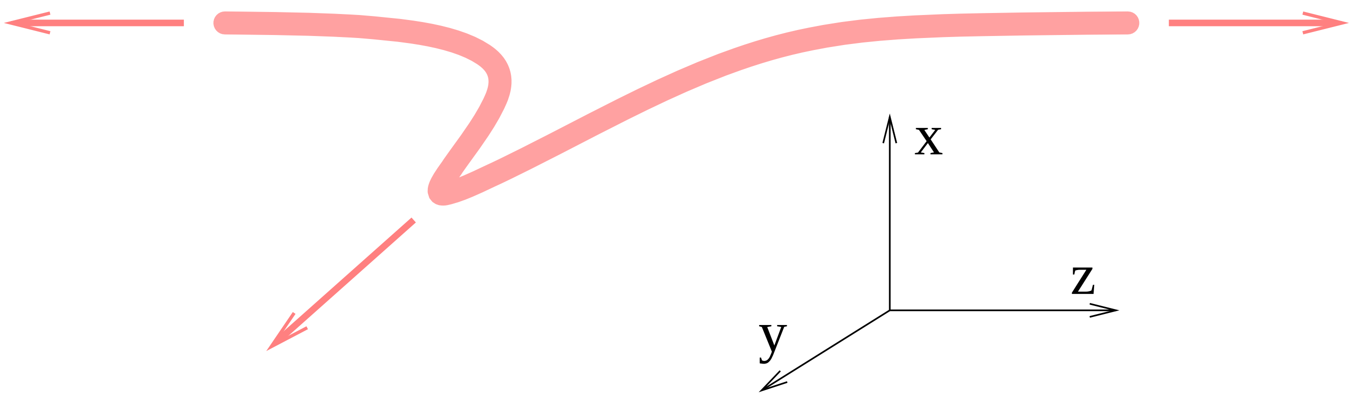
New is the attempt to put all these elements into a single approach, bringing together topics which are often discussed independently like statistical hadronization, flow features, saturation, the string model, ... => **EPOS 2**

details see: http://arxiv.org/abs/1004.0805

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).

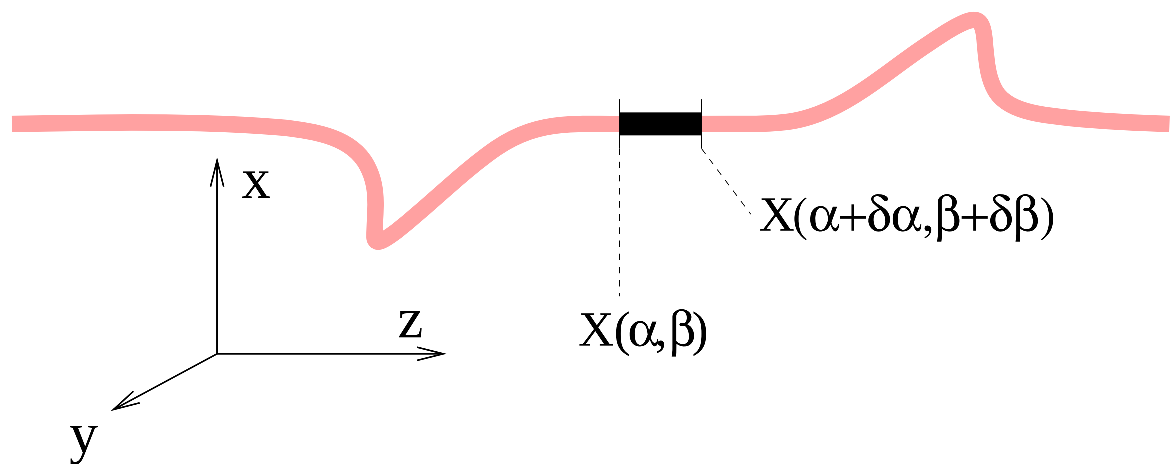


But despite these kinks, most of the string carries only little transverse momentum!

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:

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

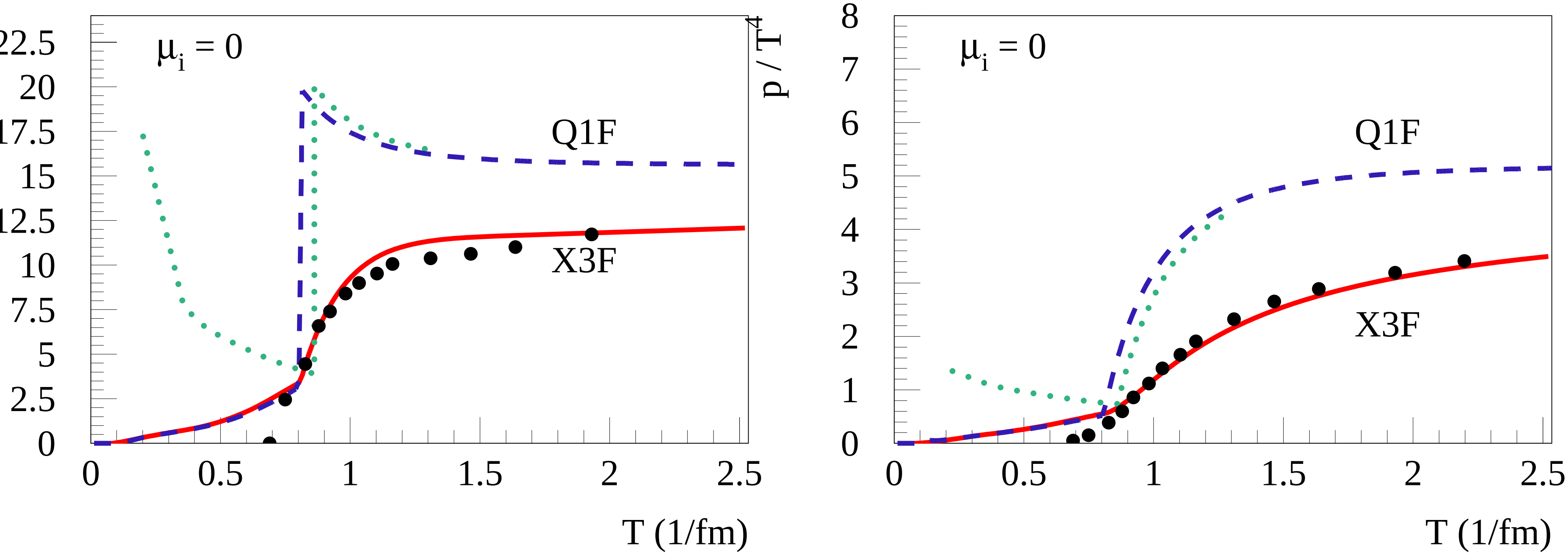
$$\partial N_k^\mu = 0, \quad N_k^\mu = n_k u^\mu,$$

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

EoS X3F:

$$p = p_Q + \left\{ \exp\left(-\frac{T - T_c}{\delta} \right) \Theta(T - T_c) + \Theta(T_c - T) \right\} (p_H - p_Q),$$

$$S = \frac{\partial p}{\partial T},\ n^i = \frac{\partial p}{\partial \mu^i},\ \varepsilon = TS + \sum_i \mu^i n^i - p,$$



The symbol X3F stands for “cross-over” and “3 flavor conservation”
Q1F: simple first order equation-of-state, with B conservation
dotted lines: EoS used by Hirano et al

- **Check basic "soft physics" RHIC data (only AuAu ≥ 200 distributions)**
  - **Particle yields and eta distributions**
    - STAR and PHENIX
      average yields and mean pt of pions, kaons, protons, lambdas, xis vs centrality
    - BRAHMS
      eta distr for different centralities 0-5% 5-10% 10-20% 20-30% 30-40% 40-50%
      rapidity distr of pions, kaons, protons(central)
      mean pt vs rapidity of pions, kaons (central)
  - **pt spectra**
    - PHOBOS: pt distributions of charged particles at centralities 0-6%, 6-15%, ..., 45-50%
    - BRAHMS: pt distributions of pions, kaons, protons at given rapidity (central)
    - PHENIX: pt distributions of pions, kaons, protons for different centralities:
      0-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70%, 70-80%, 80-92%
    - STAR: mt distributions of pions, kaons, protons for different centralities
      0-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70%, 70-80 %
    - STAR pt distributions of strange baryons for different centralities:
      0-5%, 10-20%, 20-40%, 40-60%, 60-80%
  - **v2:**
    - PHOBOS: v2 vs eta for different centralities: MB, 3-15, 15-25, 25-50, 0-40
      v2 vs centrality v2 vs pt of charged particles, 0-50
    - STAR v2 vs pt of pi, K, prt for different centralities
      MB, 0-5, 20-30, 40-50; Λ and K_s 10-40, 40-80
    - PHENIX v2 vs pt of π, K, p for 0-60, 20-60

http://arxiv.org/abs/1004.0805

2 Femtoscopy in AuAu at RHIC

Wanted: source function $S(\mathbf{P}, \mathbf{r}')$

probability of emitting a pair of hadrons
with total momentum $\mathbf{P}$ and relative distance $\mathbf{r}'$

Under "certain assumptions", S is related to the measurable two-particle correlation function $C(\mathbf{P}, \mathbf{q})$ as

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

$\mathbf{q}$ relative momentum,

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, v2
- pair wave function:
  we follow R. Lednicky, Physics of Particles and Nuclei 40 (2009) 307

Correlation function parametrized as

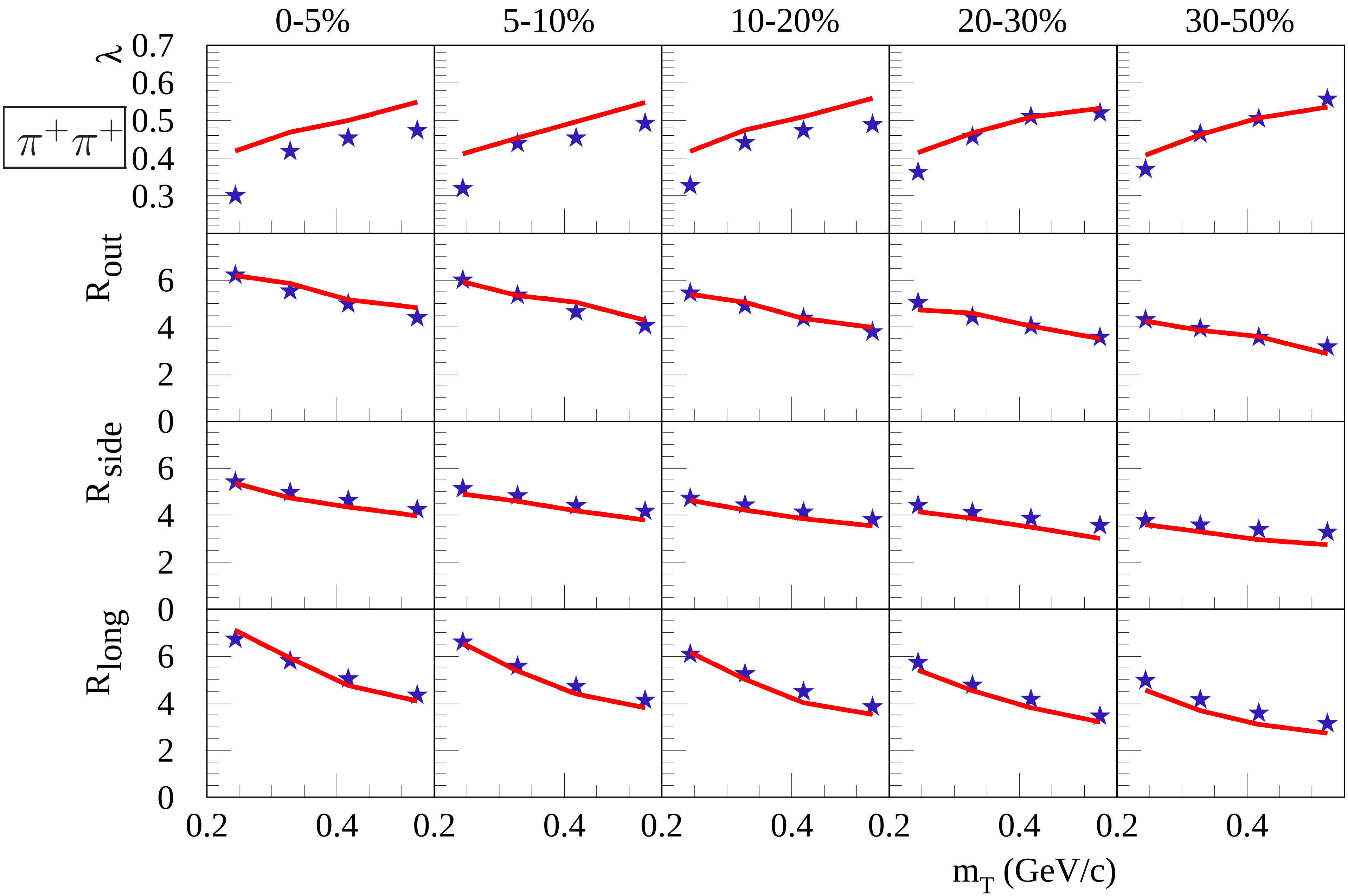
$$C(\mathbf{P},\mathbf{q}) = 1 + \lambda \exp\left(-R_{\mathrm{out}}^2\, q_{\mathrm{out}}^2 - R_{\mathrm{side}}^2\, q_{\mathrm{side}}^2 - R_{\mathrm{long}}^2\, q_{\mathrm{long}}^2\right)$$

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 m_T , with

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



radii decrease with increasing m_T, (x-p correlation)

radii decrease with decreasing centrality

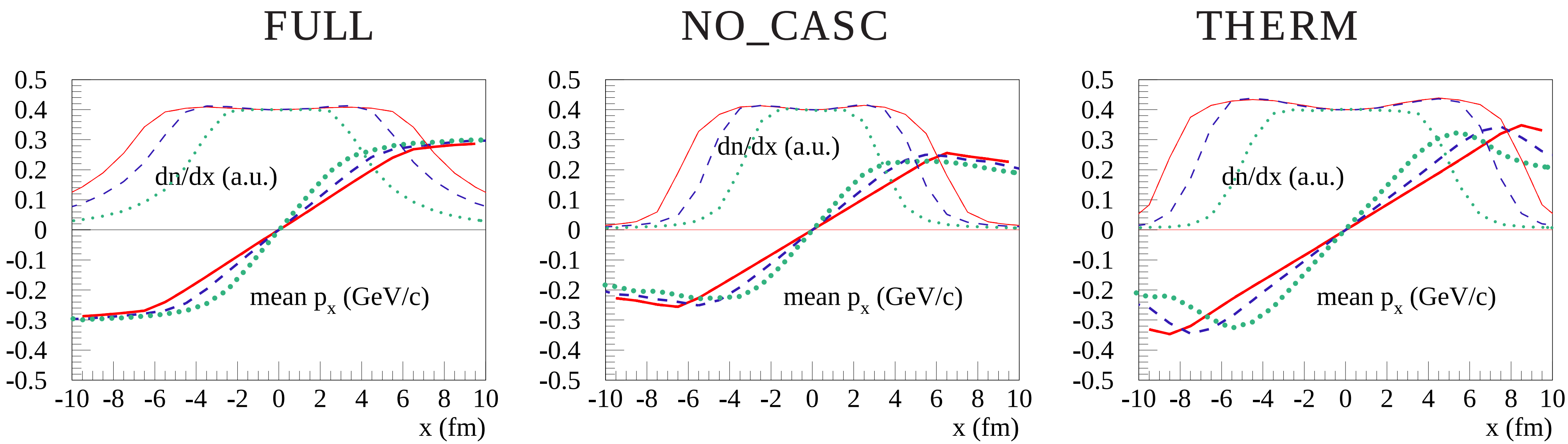
So far:

- full scenario
  Flux tube + hydro + hadronic cascade => FULL

Two other scenarios (for comparison):

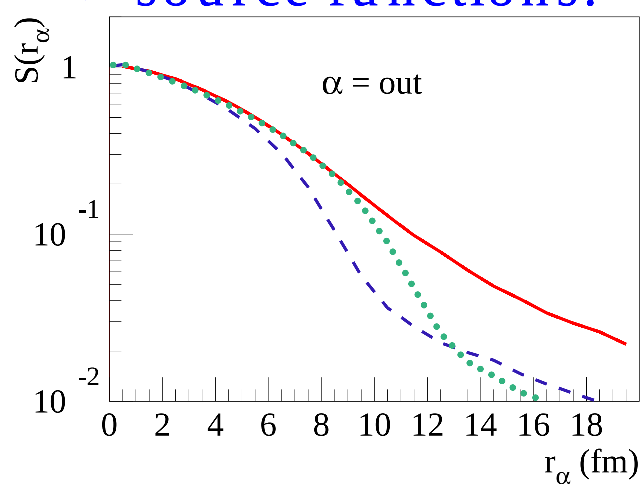
- calculation without hadronic cascade
  with final freeze out at 166 MeV => NO_CASC

- fully thermal scenario
  hydrodynamical evolution till a late freeze-out at 130 MeV
  and no cascade afterwards => THERM



In all cases: momentum-space correlations!

=> source functions:

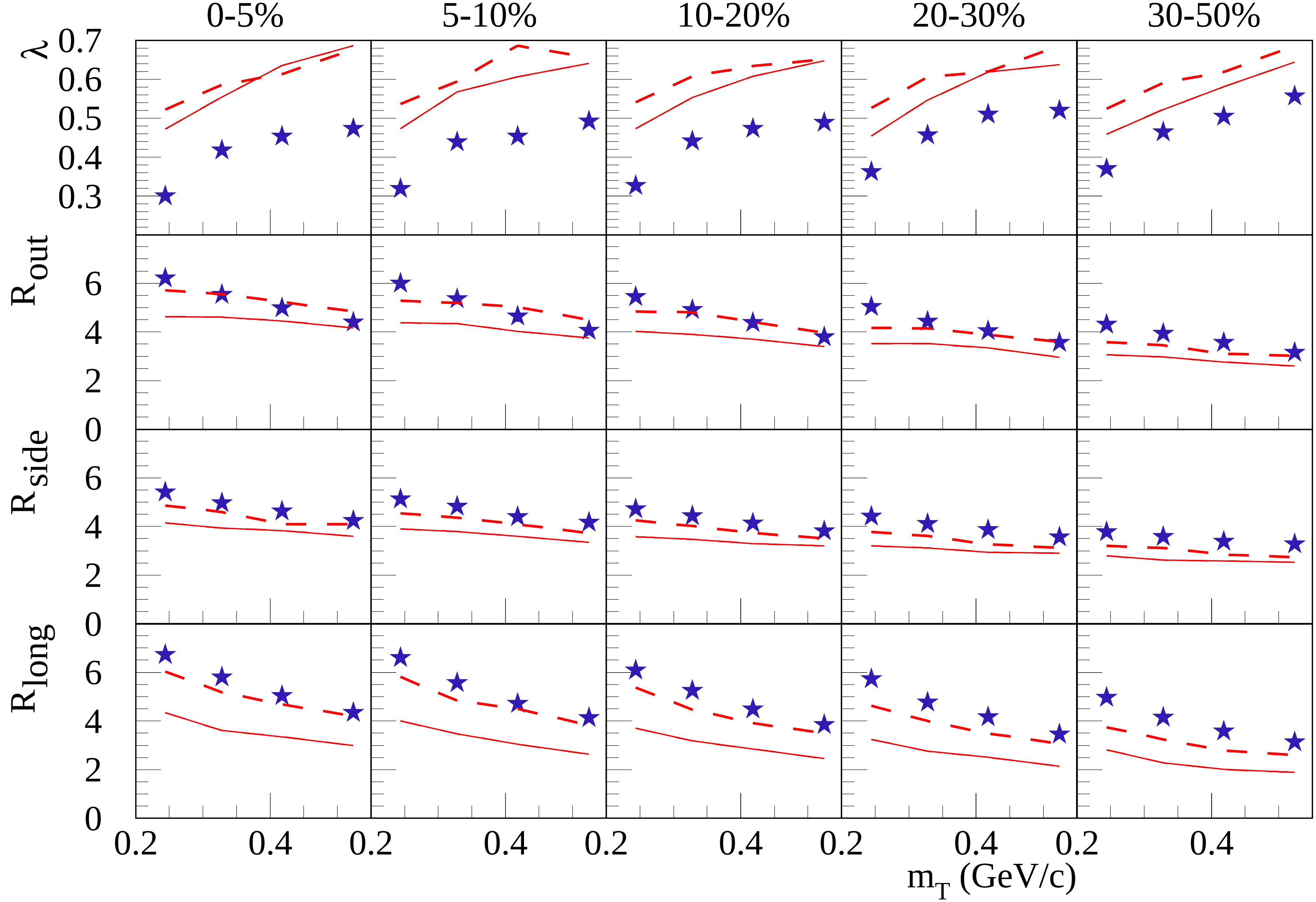


Differences compared to FULL:

- ☐ dn/dx for NO_CASC narrower
- ☐ dn/dx for THERM equally broad, but sharper edge

FULL = full line, NO_CASC = dashed, THERM = dotted

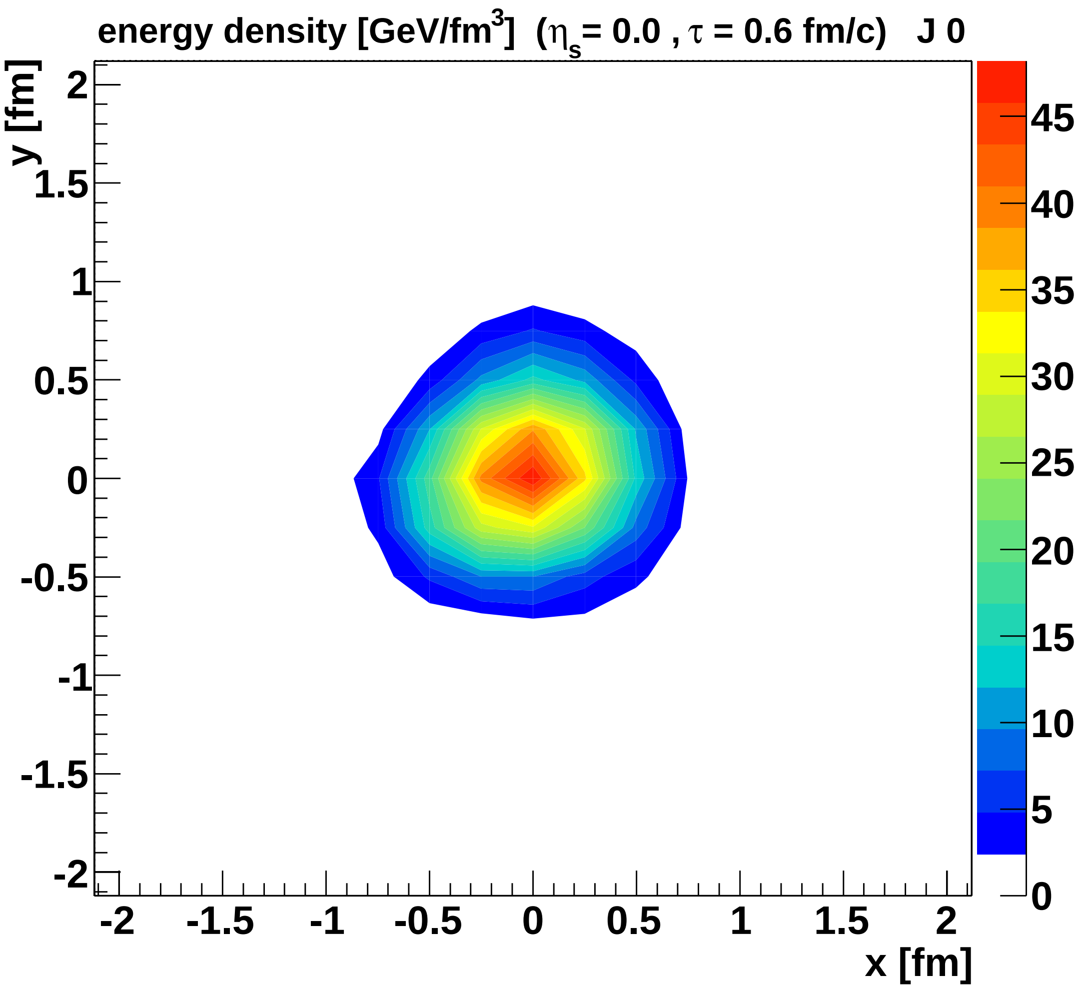
NO_CASC = full line THERM = dashed



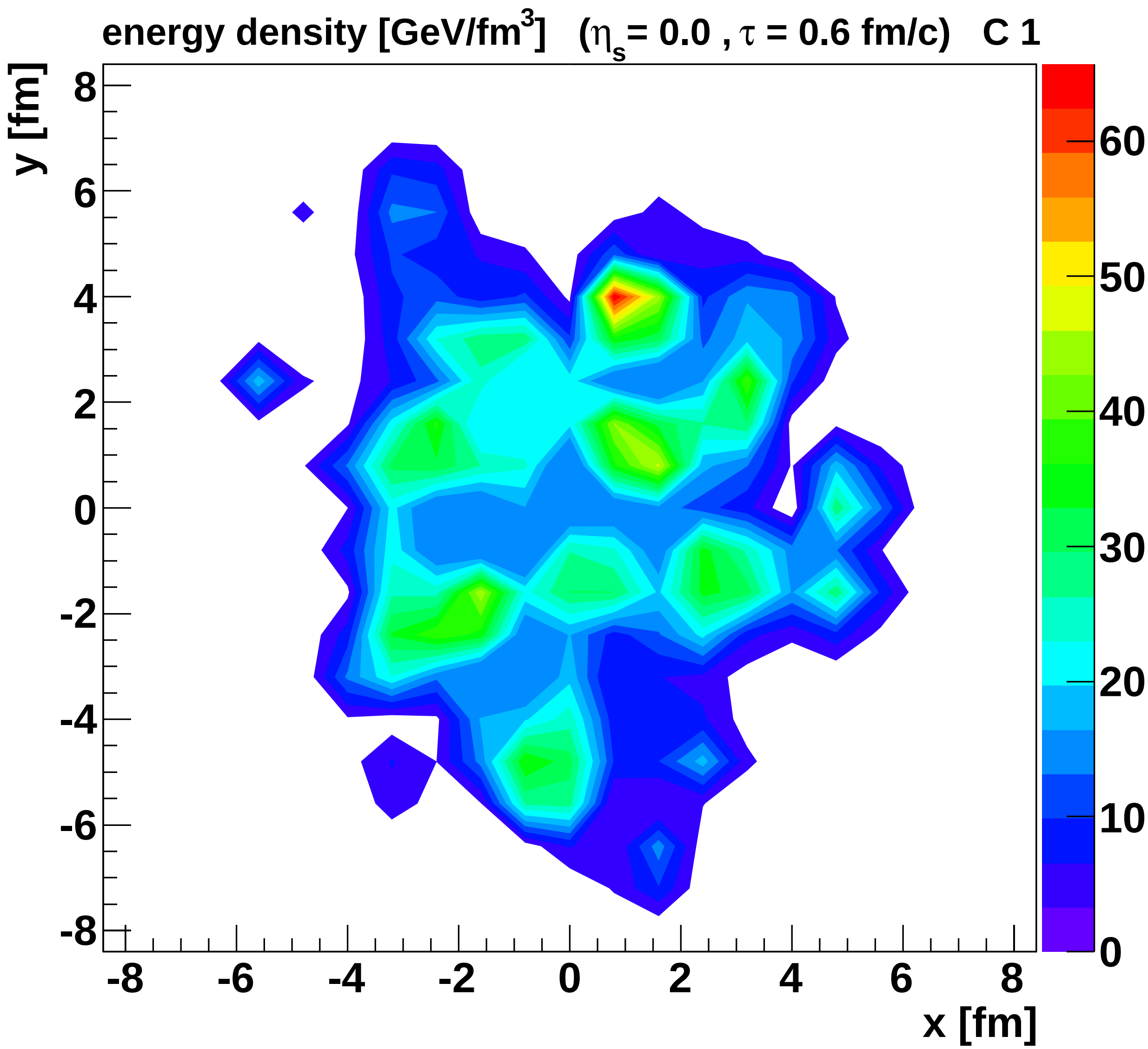
3 pp@LHC

high multiplicity pp **at 900 GeV** $(dn/d\eta(0) = 12.9)$

multiple scattering → many flux tubes → high densities



$AuAu$ at 200 GeV, central event

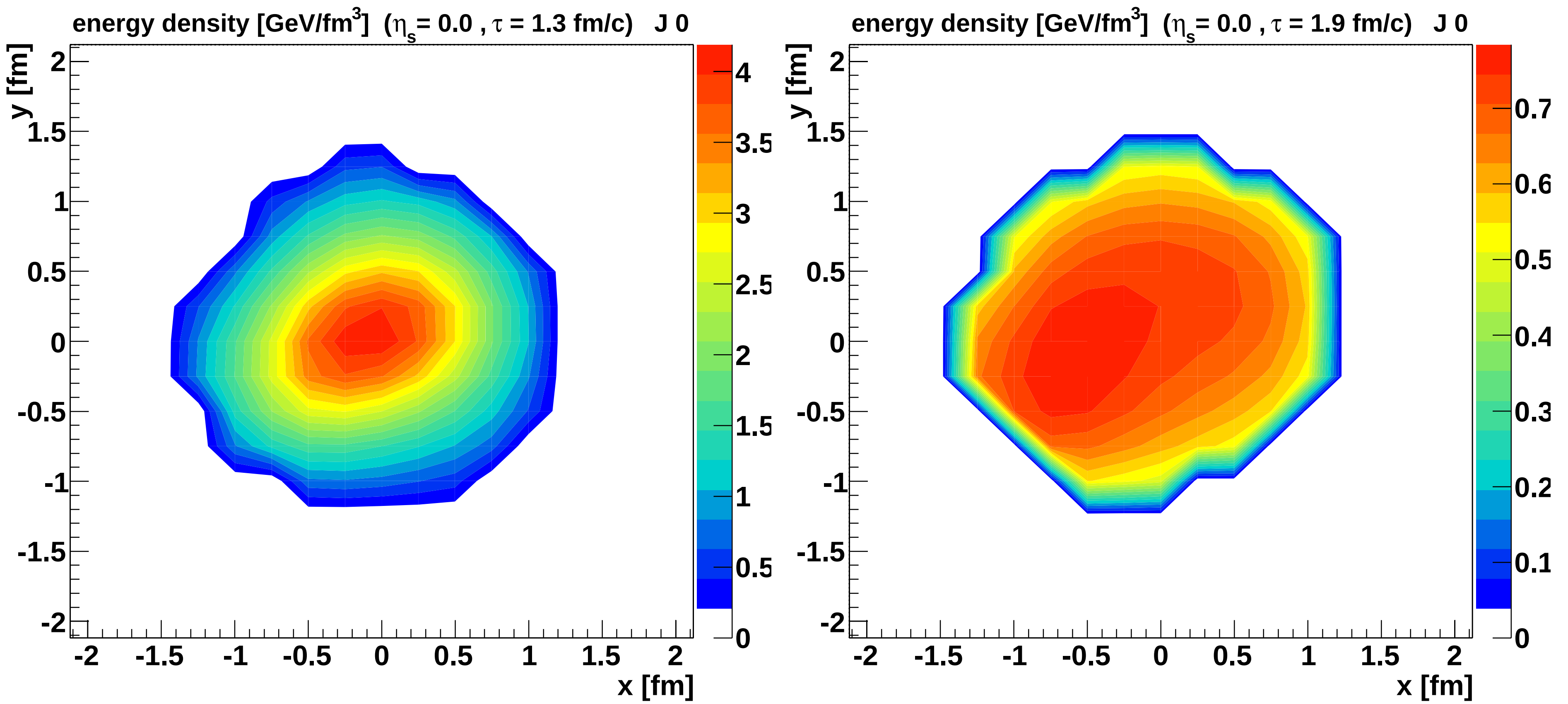


Size of the fluctuations in AuAu small, similar to sizes in pp@LHC

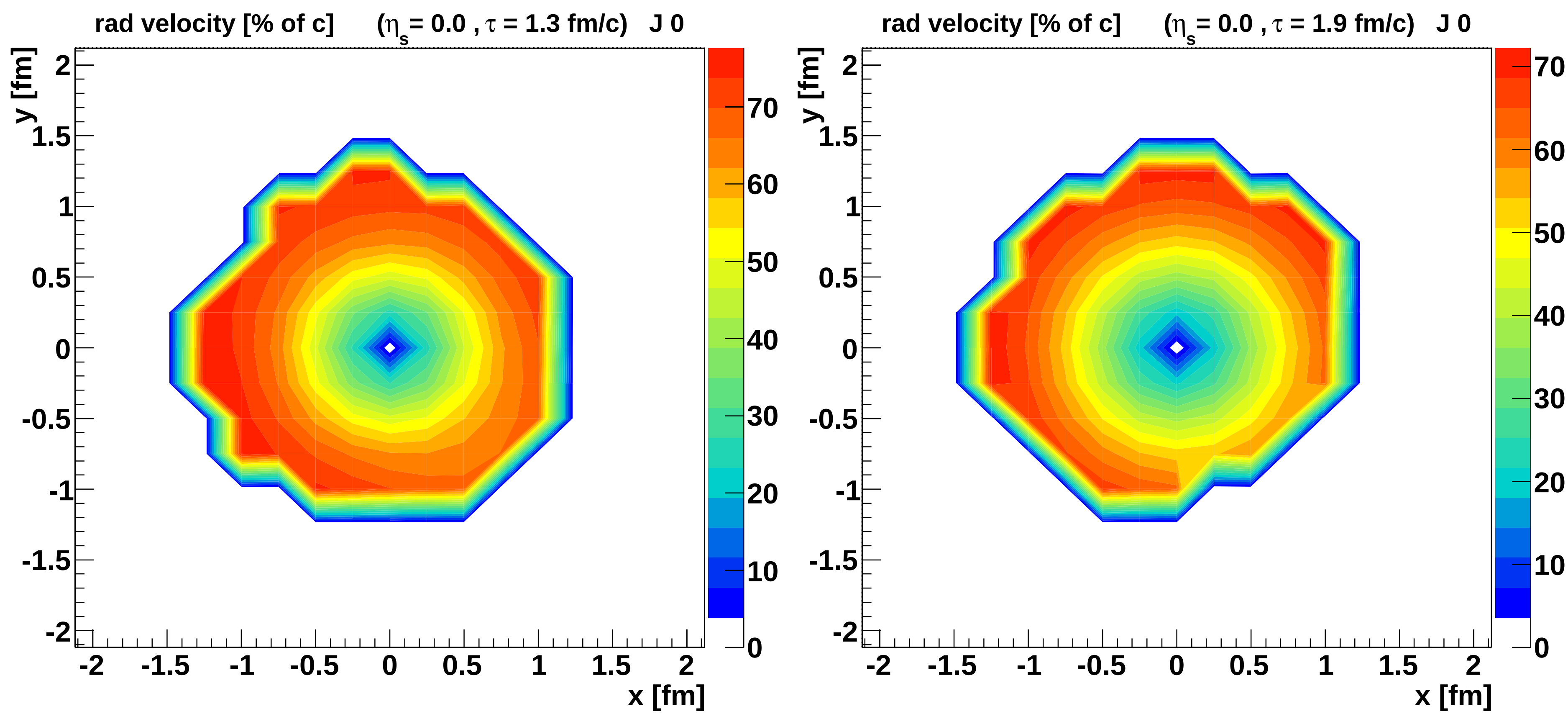
If hydro is applicable for AuAu@RHIC, it should be so for pp@LHC ...

so:
let's do hydro for pp

Time evolution of the energy density

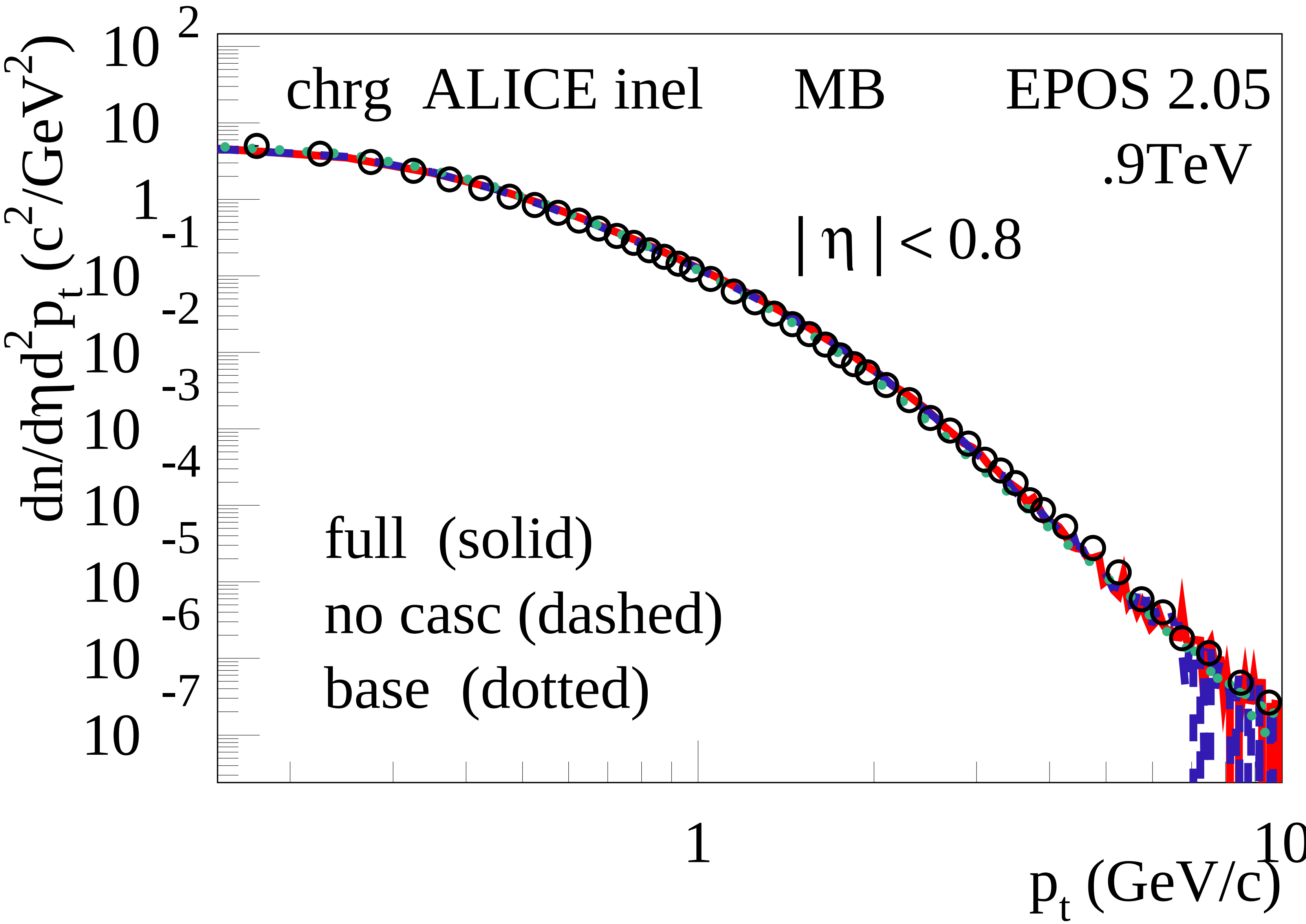


Time evolution of the radial flow



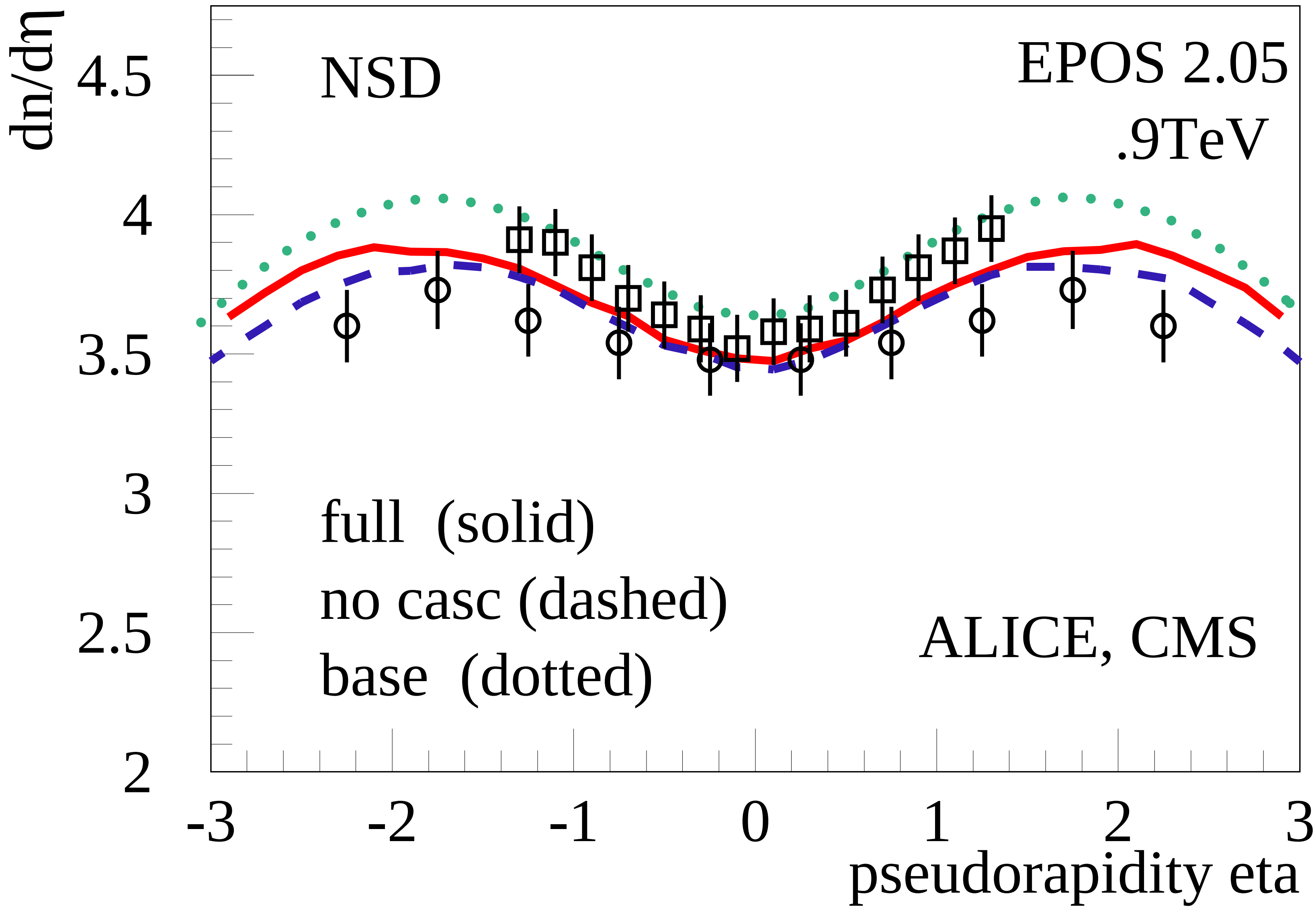
visible consequences ?

Little effect in MB charged ptl pt distributions



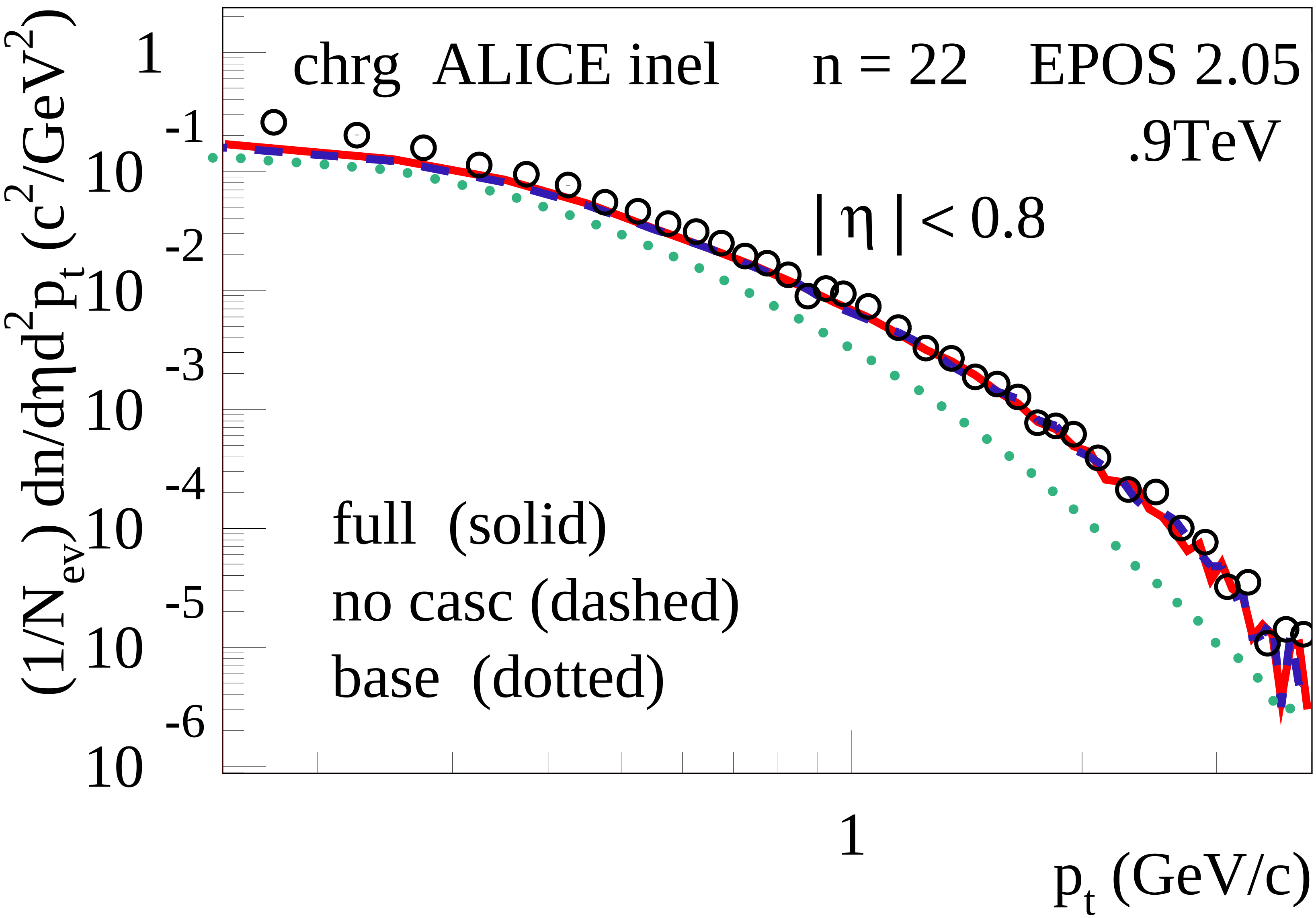
but...

but visible...

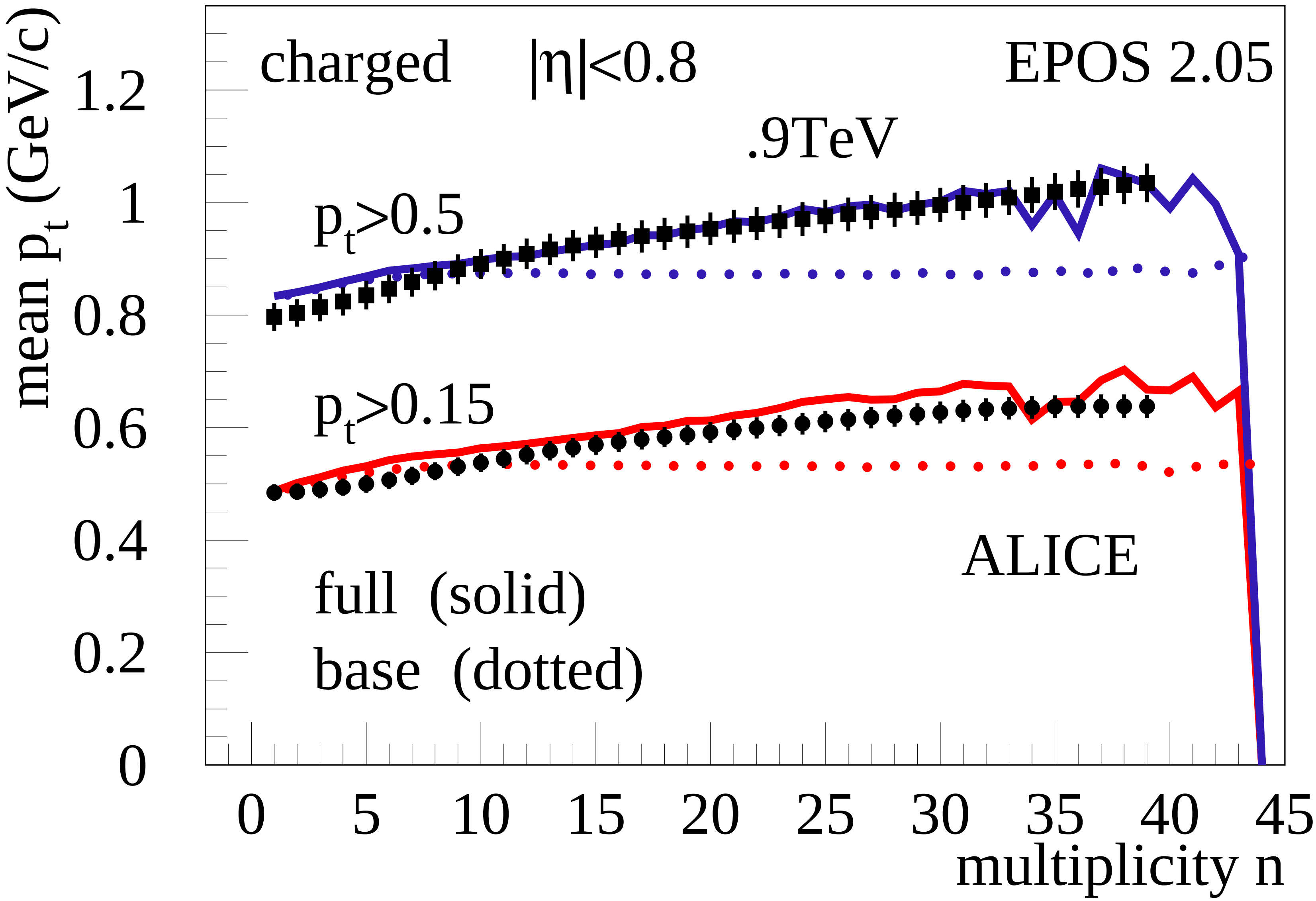


but...

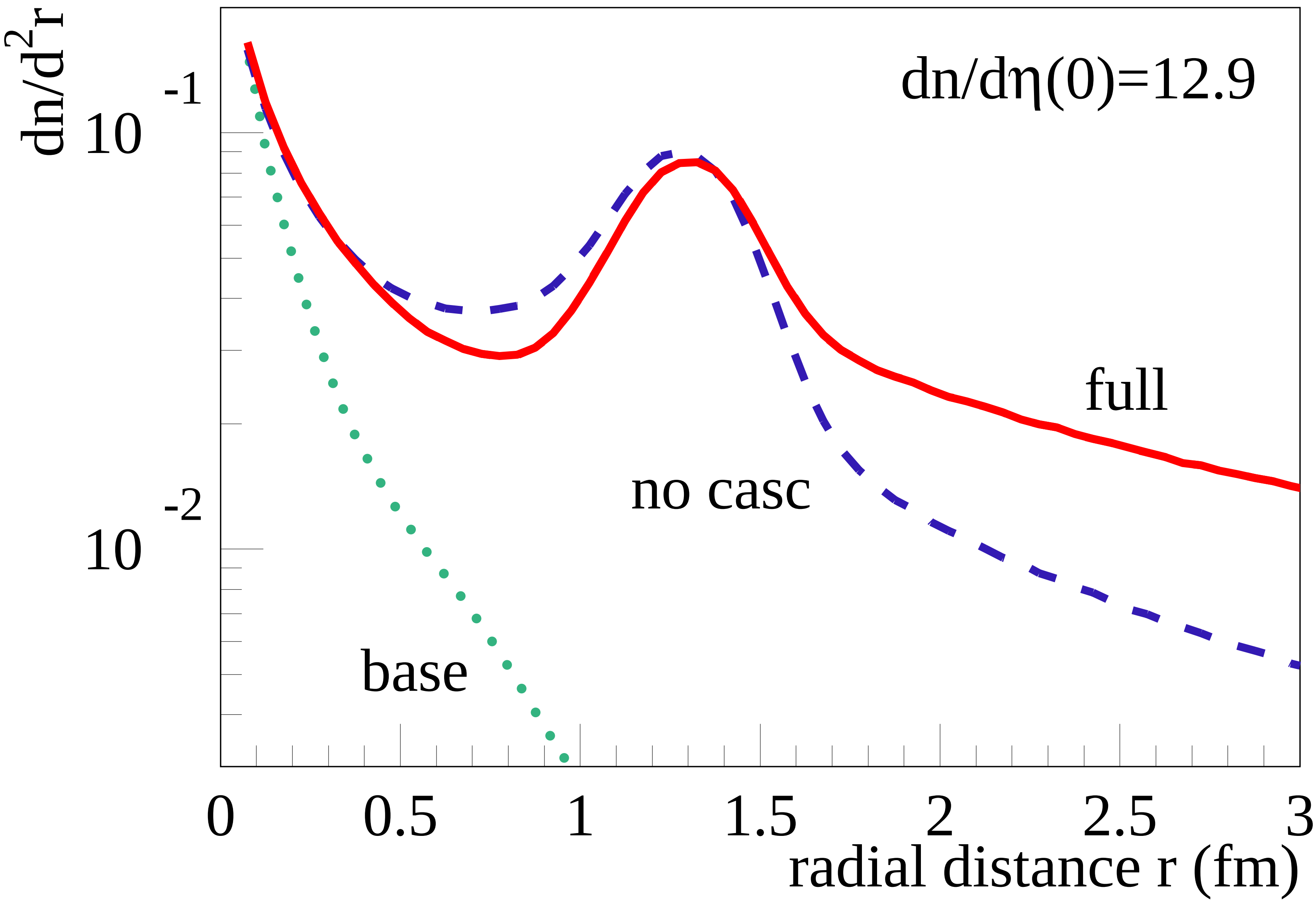
Pt distribution for high multiplicity events



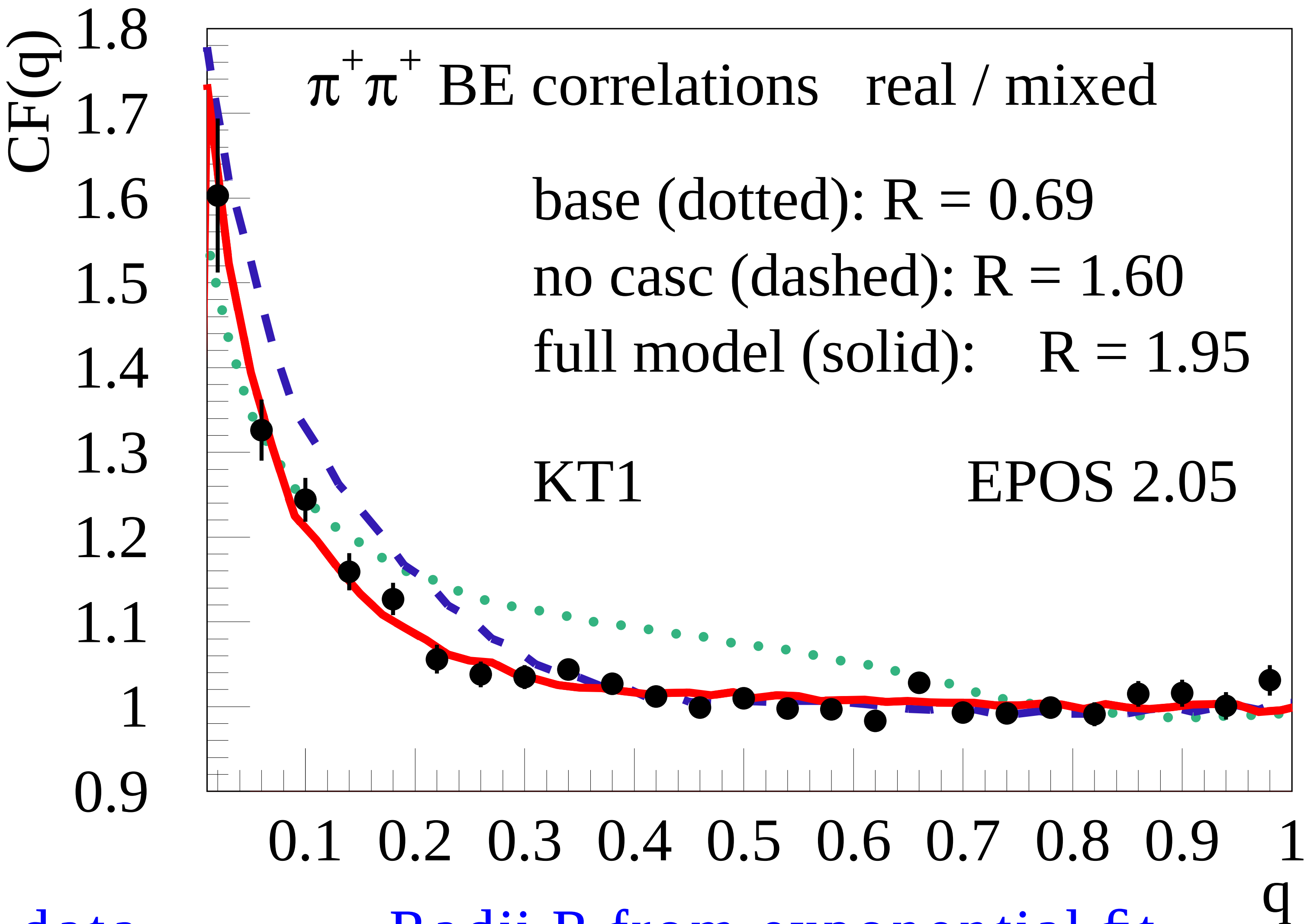
summarized in <pt> versus multiplicity



Space-time structure strongly affected



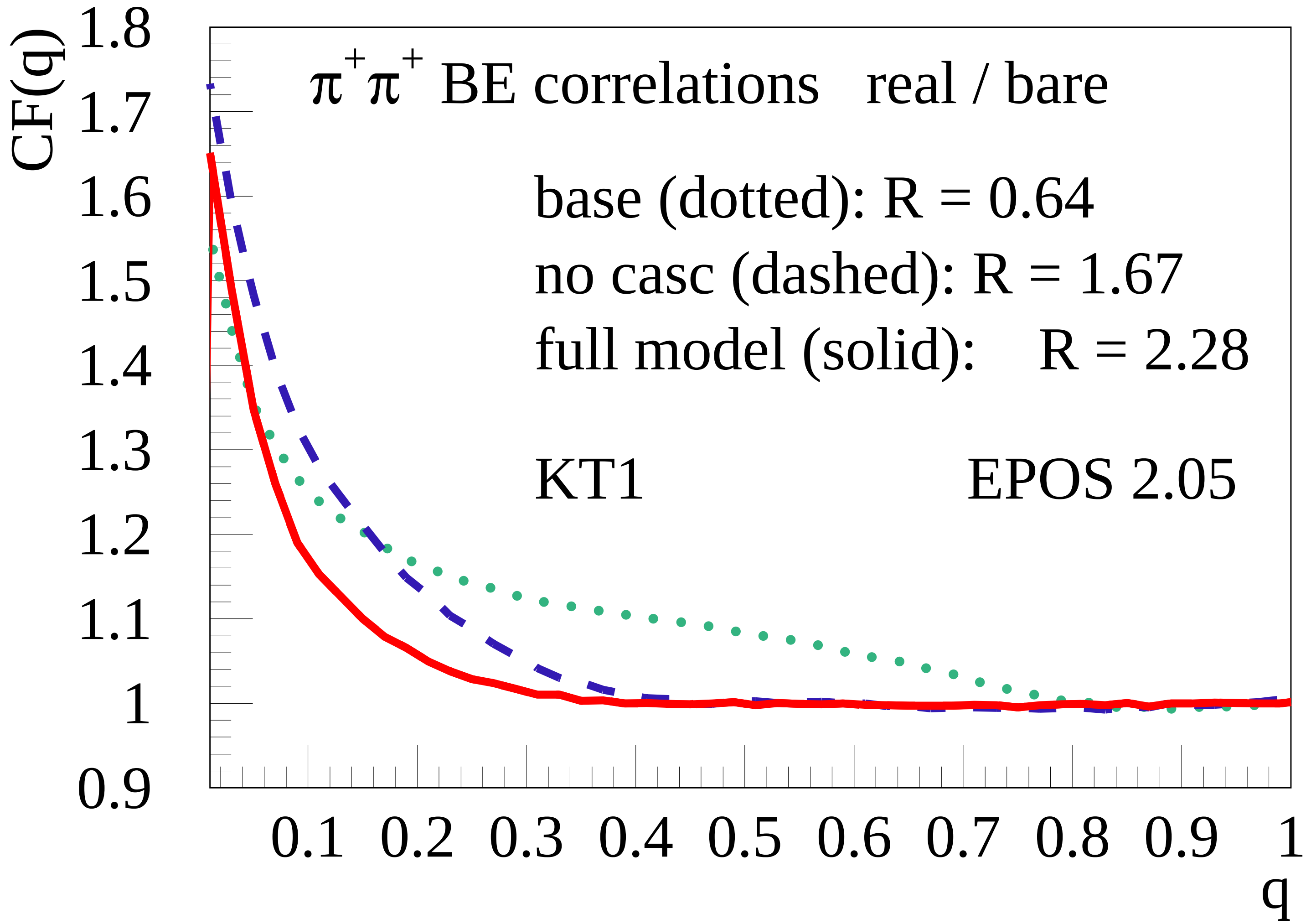
Consequences for Bose-Einstein correlations



ALICE data. Radii R from exponential fit.

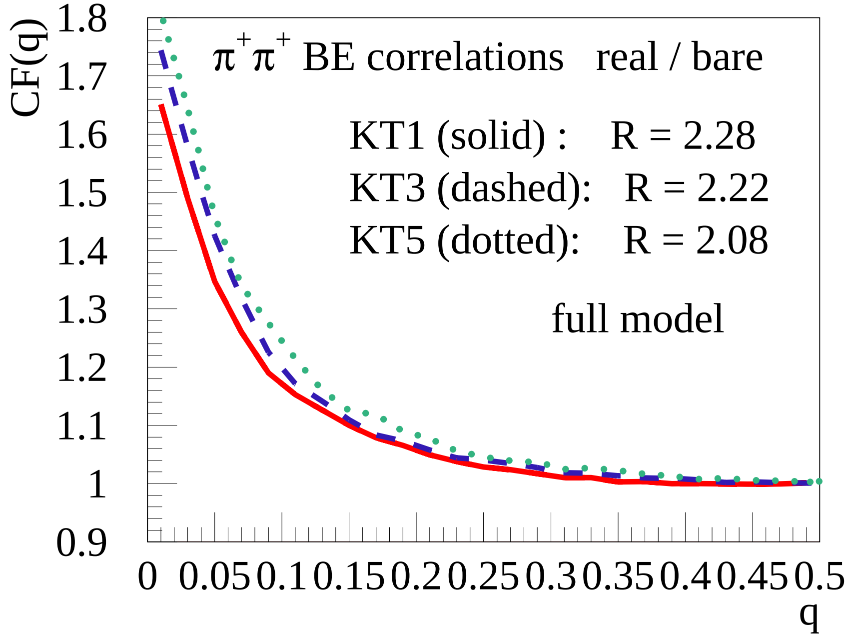
KT1$=[100,250]$, KT3$=[400,550]$, KT5$=[700,1000]$

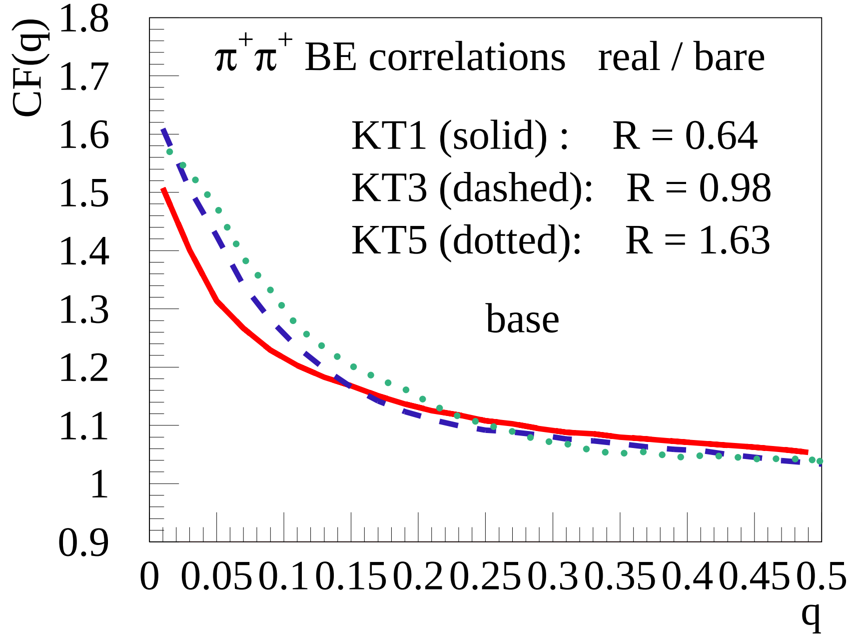
Better: normalize via “bare” case (simulation without BE)



flat for large q

kT dependence (pair transv momentum)





full case: Little kT dependence, base model: increasing radii

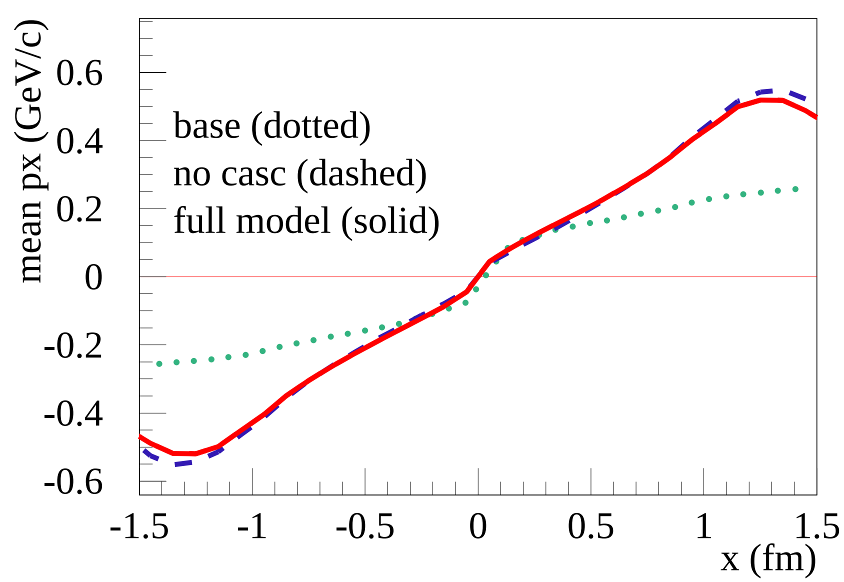
because the distribution of formation positions is broader for high p_t particles (high p_t resonances live longer)

Effect is in principle also present in AuAu scattering, but much more visible for the small pp system.

In pp two competing effects:

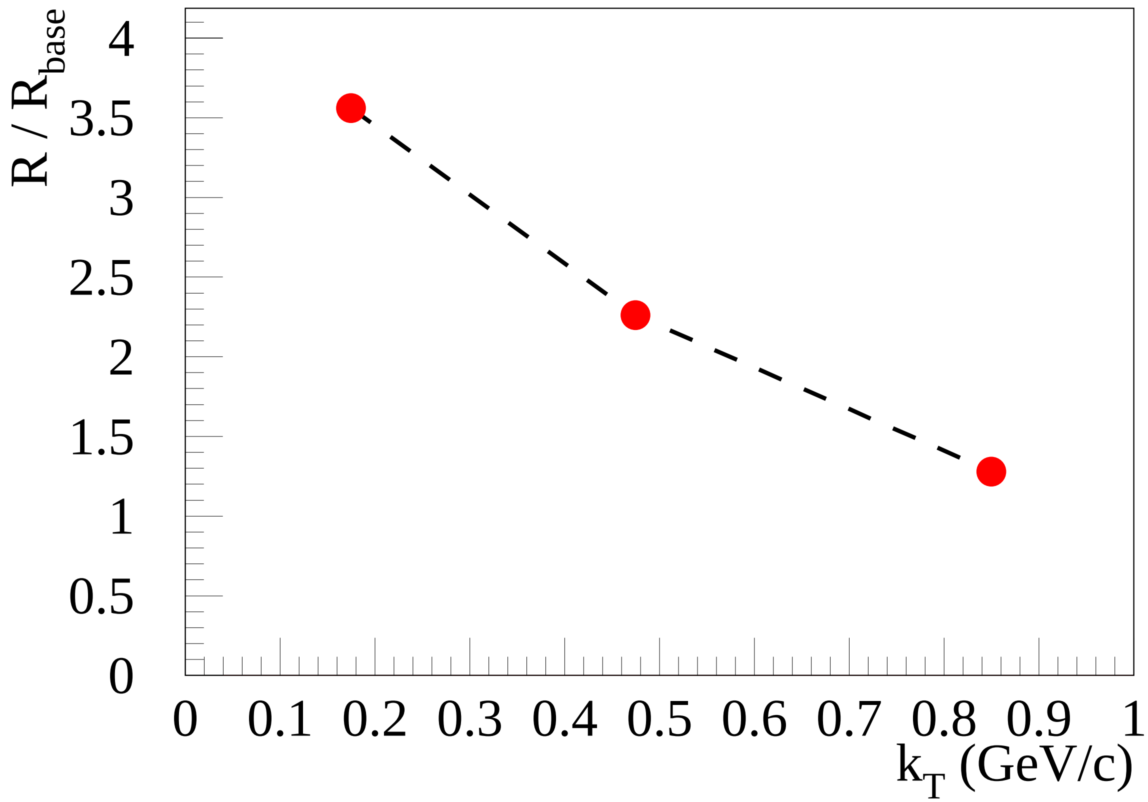
- ☐ radii increase with k_T, due to the bigger size of the source of the high p_t particles compared to the low p_t ones,
- ☐ radii decrease with k_T, as in AuAu, due to the p-x correlation.

$p - x$ correlation exists indeed for the case of hydrodynamic evolutions, and is much smaller in the basic scenario.



In this sense, the flatness of R is a manifestation of the $p - x$ correlation (and of flow)

otherwise the radii would increase

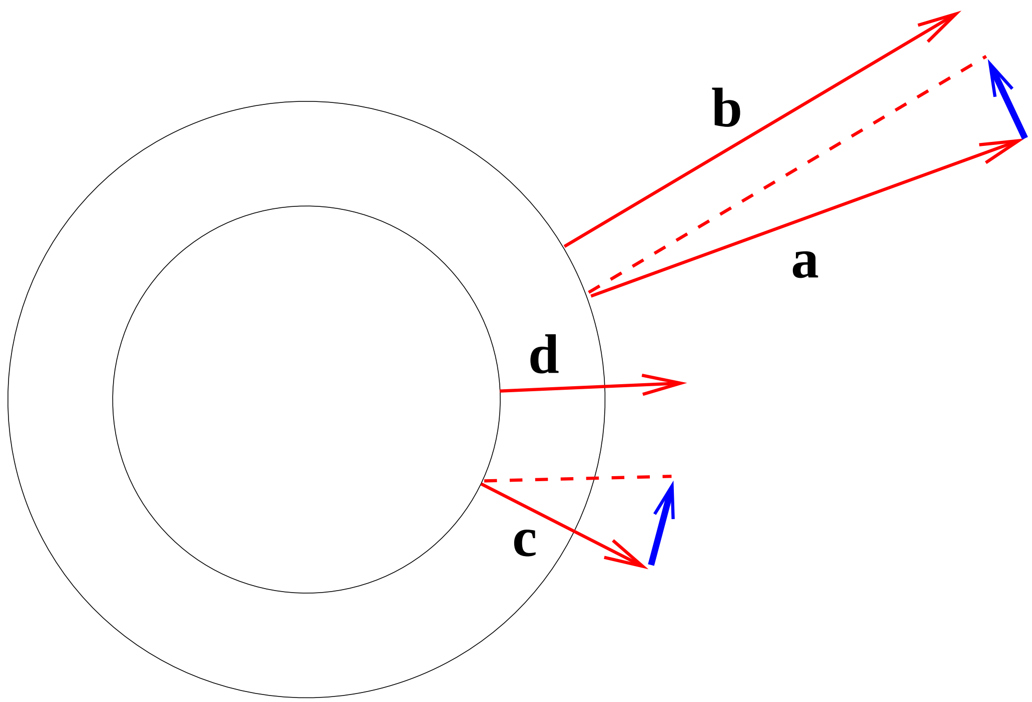


better plot ratio

$R_{\text{full model}}$ **/** R_{base}

Thank you !!

Radial flow effect on m_T dependence of femtoscopic radii:



distances get smaller outwards for fixed momentum differences