Collective Effects in Proton Proton and Heavy Ion Scattering, and the “Ridge” at RHIC

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Abstract. We discuss why the hydrodynamic description should not only be applicable to heavy ion collisions at RHIC, but also for proton proton scattering at the LHC. A new realistic treatment of the hydrodynamic evolution is tested by comparing to AuAu data at RHIC, in particular concerning the “ridge” phenomenon. We apply our new approach to obtain first results for pp at LHC energies.

1. Introduction
Let us consider the energy density at an early time in a Au-Au scattering at RHIC, as obtained from an EPOS simulation [1]. In fig. 1, we plot the energy density at different values of space-time rapidity $\eta$, as a function of the transverse coordinates $x$ and $y$. We observe a very bumpy structure concerning the $x-y$-dependence, whereas the variation with $\eta$ is small. There are in particular peaks in the $x-y$-plane, which show up at the same position at different values of $\eta$. So we have sub-flux-tubes which exhibit a long range structure in the longitudinal variable $\eta$.

In fig. 1, we clearly identify several sub-flux-tubes, with a typical width of the order of a fermi. This is exactly the width we obtain if we compute the initial energy density in proton scattering at the LHC. This means, if a hydrodynamic treatment is justified for Au-Au collisions at RHIC, it is equally justified for pp scattering at the LHC, provided the energy densities are high enough. This latter condition can easily be satisfied, since in proton-proton scattering on has the possibility to trigger on high multiplicity events, with ten or twenty times the multiplicity compared to an average event.

We are going to employ a new tool for treating the hydrodynamic evolution, based on the following features (see [1]):

- initial conditions obtained from a flux tube approach (EPOS), compatible with the string model used since many years for elementary collisions (electron-positron, proton proton), and the color glass condensate picture;
- consideration of the possibility to have a (moderate) initial collective transverse flow;
- event-by-event procedure, taking into the account the highly irregular space structure of single events, being experimentally visible via so-called ridge structures in two-particle correlations;
- core-corona separation, considering the fact that only a part of the matter thermalizes;
use of an efficient code for solving the hydrodynamic equations in 3+1 dimensions, including the conservation of baryon number, strangeness, and electric charge;

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

use of a complete hadron resonance table, making our calculations compatible with the results from statistical models;

hadronic cascade procedure after hadronization from the thermal system at an early stage.

In [1], we test the approach by investigating all soft observables of heavy ion physics, in case of AuAu scattering at 200 GeV. Here, we are going to discuss some selected (and interesting) topics.

2. Test case: the “ridge” at RHIC
A remarkable feature of an event-by-event treatment of the hydrodynamical evolution based on random flux tube initial conditions is the appearance of a so-called ridge-structure, found in Spherio calculations based on Nexus initial conditions [2, 3]. We expect to observe a similar structure doing an event-by-event hydrodynamical evolution based on flux-tube initial conditions from EPOS. The result is shown in fig. 2, where we plot the dihadron correlation $dN/d\Delta \eta d\Delta \phi$, with $\Delta \eta$ and $\Delta \phi$ being respectively the difference in pseudorapidity and azimuthal angle of a pair of particles. Here, we consider trigger particles with transverse momenta between 3 and 4 GeV/c, and associated particles with transverse momenta between 2 GeV/c and the $p_t$ of the trigger, in central Au-Au collisions at 200 GeV. Our ridge is very similar to the structure observed by the STAR collaboration [4].

In the following we will discuss a particular event, which can, however, be considered as a typical example, with similar observations being true for randomly chosen events. Important for understanding the strong $\Delta \eta - \Delta \phi$ correlation is the observation, that the initial energy density has a very bumpy structure as a function of the transverse coordinates $x$ and $y$. However, this irregular structure is the same at different longitudinal positions. This can be clearly seen in fig. 1, where we show for a given event the energy density distributions in the transverse planes at different space-time rapidities, namely $\eta_s = 0$ and $\eta_s = 1.5$: we observe almost the same structure. For different events, the details of the bumpy structures change, but we always find an approximate “translation invariance”: the distributions of energy density in the
Figure 2. Dihadron $\Delta \eta - \Delta \phi$ correlation in a central Au-Au collision at 200 GeV, as obtained from an event-by-event treatment of the hydrodynamical evolution based on random flux tube initial conditions. Trigger particles have transverse momenta between 3 and 4 GeV/c, and associated particles have transverse momenta between 2 GeV/c and the $p_t$ of the trigger.

Figure 3. Energy density at a proper time $\tau = 2.6\text{fm}/c$, at a space-time rapidities $\eta_s = 0$ and $\eta_s = 1.5$. 
transverse planes vary only little with the longitudinal variable \( \eta_s \). It should be noted that the colored areas represent only the interior of the hadronization surface, the outside regions are white. Hadronization is meant to be an intermediate step, before the hadronic cascade. An approximate translational invariance is also observed when we go to larger values of \( \eta_s \), so for example when we compare the energy density at \( \eta_s = 1.5 \) with the one at \( \eta_s = 3.0 \): the form of the energy distributions is similar, however, the magnitude at large \( \eta_s \) is smaller.

Considering later times, we see in figs. 3 and 4, that the approximate translational invariance is conserved, for both energy densities and radial flow velocities. It is remarkable (and again true in general, for arbitrary events) that the energy distribution in the transverse plane is much smoother than initially, the distribution looks more homogeneous. Very important for the following discussion is the flow pattern, seen in fig. 4, for \( \eta_s = 0 \) and \( \eta_s = 1.5 \): the radial flow is as expected largest in the outer regions. Closer inspection of the outside ring of large radial flows reveals an irregular atoll-like structure: there are well pronounced peaks of large flow over the

\[ \text{Figure 4.} \] Radial flow velocity at a proper time \( \tau = 2.6 \text{ fm}/c \), at a space-time rapidities \( \eta_s = 0 \) and \( \eta_s = 1.5 \).

\[ \text{Figure 5.} \] Energy density at a proper time \( \tau = 4.6 \text{ fm}/c \), at a space-time rapidities \( \eta_s = 0 \) and \( \eta_s = 1.5 \).
Figure 6. Radial flow velocity at a proper time $\tau = 4.6 \text{ fm/c}$, at a space-time rapidities $\eta_s = 0$ and $\eta_s = 1.5$.

background ring. At even later times, as seen in figs. 5 and 6, the outer surfaces get irregular, due to the irregular flows discussed above, again with well identified peaks of large radial flows.

The well isolated peaks of the radial flow velocities have two important properties: they sit close to the hadronization surface, and they sit at the same azimuthal angle, when comparing different longitudinal positions $\eta_s$. As a consequence, particles emitted from different longitudinal positions get the same transverse boost, when their emission points correspond to the azimuthal angle of a common flow peak position. And since longitudinal coordinate and (pseudo)rapidity are correlated, one obtains finally a strong $\Delta \eta - \Delta \phi$ correlation.

To summarize the above discussion: the flux tube initial conditions provide a bumpy structure of the energy density in the transverse plane, which shows, however, an approximate translational invariance (similar behavior at different longitudinal coordinates). Solving the hydrodynamic equations preserves this invariance, leading in the further evolution to an invariance of the transverse flow velocities. These identical flow patterns at different longitudinal positions lead to the fact that particles produced at different values of $\eta_s$ profit from the same collective push, when they are emitted at an azimuthal angle corresponding to a flow maximum.

Finally we have to address the question, why we have an irregular transverse structure with an approximate translational invariance. The basic structure of EPOS is such that each individual nucleon-nucleon collision results in a projectile and target remnant, and two or more elementary flux tubes (strings). The higher the energy the bigger the number of strings. Most of the energy of the reaction is carried by the remnants, the flux tubes cover only a limited range in rapidity, but their “lengths” (in rapidity) vary enormously. Nevertheless we obtain a very smooth variation of the energy density with the longitudinal coordinate $\eta_s$. This is due to the fact that the transverse positions of a string is given by the position of the nucleon pair, who’s interaction gave rise the the formation of the flux tube. These “pair positions” fluctuate considerably, event-by-event, and one obtains typically a situation where there are areas with a high density of interaction points, and areas which are less populated. These transverse positions of interacting pairs define also the corresponding positions of the flux tubes associated to the pairs. The flux tubes have variable longitudinal lengths, they do not cover the full possible length between projectile and target, but only a portion. But even then, the transverse structure (minima and maxima of the energy density) is to a large extent determined by the density of nucleon-nucleon pairs.
We just discussed one interesting observable, namely $\Delta \eta - \Delta \phi$ correlations. Many more exist, like azimuthal asymmetries, particle spectra, and yields. All these have been carefully studied to thoroughly test our approach.

3. Hydrodynamic evolution in proton proton scattering

Having tested our tool against heavy ion data at RHIC, we now proceed to proton-proton scattering at the LHC. This is work in progress, so for the moment we only show some very preliminary results concerning the hydrodynamic evolution in “central” pp scattering at 7 TeV. The word “central” has here a somewhat different meaning than in heavy ion scattering. The impact parameter plays also a role in proton proton scattering, but collisions with large $b$ lead to low multiplicity events. All interesting cases correspond to small impact parameters, because only then we have a considerable probability of a large number of elementary scatterings, corresponding to a high multiplicity of produced particles. Only these events exhibit large energy densities, and allow us to observe similar collective effects as in heavy ion collisions at RHIC.

In the following, we investigate proton proton collisions at 7 TeV, considering a case with eight elementary scatterings. We show a single event, however, a typical one for this “centrality” class. In fig. 7, we plot the energy density at $\tau = 0.6$ fm/c and at $\tau = 1.3$ fm/c, at a space-time rapidity $\eta_s = 0$. Indeed the initial energy density is high – up to 50 GeV/fm$^3$, comparable to what one reaches in central AuAu collisions at RHIC. The expansion is fast, at $\tau = 1.3$ fm/c the maximum energy density has already dropped to about 3 GeV/fm$^3$. Remarkable is the very large collective flow which develops very quickly. At $\tau = 1.3$ fm/c we observe already a maximum of 80% of the velocity of light, at (relatively) large distances from the center, see fig. 8. Having these large radial flows close to the hadronization surface, we expect big effect concerning particle spectra.

As already said, this is work in progress, full calculations with comparison to LHC data will come soon.

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Figure 8. Radial flow velocity at a proper time $\tau = 1.3\, \text{fm}/c$, at a space-time rapidity $\eta_s = 0$, in a “central” pp scattering.

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