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HYDRODYNAMICAL EVOLUTION IN HEAVY ION COLLISIONS AND pp SCATTERINGS AT THE LHC — RIDGES IN AA AND pp SCATTERING*

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We discuss recent developments in the EPOS approach, concerning an event-by-event treatment of the hydrodynamical evolution in heavy ion collisions and also in high multiplicity pp scatterings at the LHC. The initial conditions are flux-tubes, which are formed following elementary (multiple) scatterings. We show that this picture leads in a natural way to the so-called ridge structures, observed in heavy ion and proton–proton collisions.

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EPOS is a multiple scattering model in the spirit of the Gribov–Regge approach [1]. Here, one does not mean simply multiple hard scatterings, the elementary processes correspond to complete parton ladders, which means hard scatterings plus initial state radiation. In this case, this elementary process carries an important fraction of the available energy, and therefore we treat very carefully the question of energy sharing in the multiple scattering process. Open and closed ladders have to be considered in order to have a consistent quantum mechanical treatment. The corresponding graphs are

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squared, and we employ cutting rule techniques and Markov chains to obtain finally partial cross-sections. The cut parton ladders are identified with longitudinal color fields or flux tubes, treated via relativistic string theory.

In the case of very high energy pp collisions (at the LHC) or heavy ion scatterings already at RHIC, many flux tubes overlap and produce high energy densities. 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 η_s, 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 η_s is small. There are in particular peaks in the x–y plane, which show up at the same position at different values of η_s. So we have sub-flux-tubes which exhibit a long range structure in the longitudinal variable η_s. 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–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, which seems to be the case.

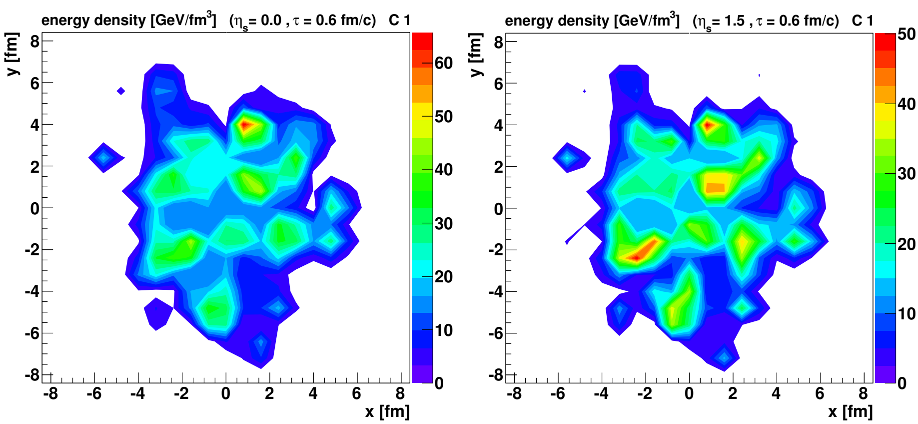

Fig. 1. Energy density in central Au–Au scattering at 200 GeV.

We therefore employ a sophisticated hydrodynamical scenario (for details see [1]), for both heavy ions and proton–proton scatterings at the LHC, with 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 [2]. The equation-of-state is compatible with lattice gauge results of Ref. [3]. We use a hadronic cascade procedure after hadronization from the thermal system at an early stage [4, 5].

In Ref. [1], we test the approach by investigating all soft observables of heavy ion physics, in the case of Au–Au scattering at 200 GeV. Here, we are going to discuss some selected (and interesting) topics. In Fig. 1, we see a complicated structure of the initial energy density in the transverse plane, but this structure is longitudinally translational invariant (same structure at different values of η_s). The equations of hydrodynamics preserve this translational invariance, and transport it to different quantities, as the radial flow, see Fig. 2. As a consequence, particles emitted from different

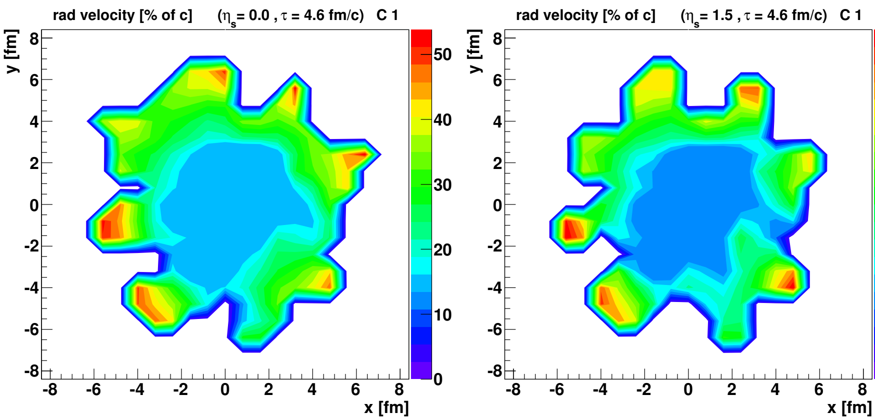

Fig. 2. Radial flow velocity at a proper time $\tau = 4.6$ fm/c, at a space-time rapidities $\eta_s = 0$ and $\eta_s = 1.5$.

longitudinal positions get the same transverse boost, when their emission points correspond to the azimuthal angle of a common flow peak position. Since longitudinal coordinate and (pseudo)rapidity are correlated, one obtains finally a strong $\Delta\eta$–$\Delta\phi$ correlation, as seen in Fig. 3, 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 $p_{\rm t}$ of the trigger, in central Au–Au collisions at 200 GeV. Our ridge is very similar to the structure observed by the STAR Collaboration [6].

The CMS Collaboration published recently results [7] on two particle correlations in $\Delta\eta$ and $\Delta\phi$, in *pp* scattering at 7 TeV. Most remarkable is the discovery of a ridge-like structure around $\Delta\phi = 0$, extended over many units in $\Delta\eta$, referred to as "the ridge", in high multiplicity *pp* events. A similar structure has been observed in heavy ion collisions at RHIC, as discussed earlier, and there is little doubt that the phenomenon is related to the hydrodynamical evolution of matter. This "fluid dynamical behavior" is actually considered to be the major discovery at RHIC.

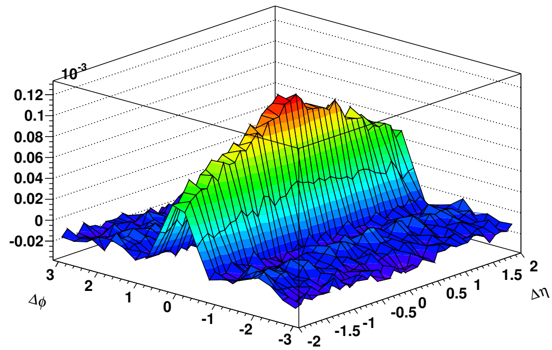

Fig. 3. Dihadron $\Delta\eta$–$\Delta\phi$ correlation in a central Au–Au collision at 200 GeV.

So does *pp* scattering provide as well a liquid, just ten times smaller than a heavy ion collision? It seems so! We showed recently [8] that if we take exactly the same hydrodynamic approach which has been so successful for heavy ion collisions at RHIC [1], and apply it to *pp* scattering, we obtain already very encouraging results compared to *pp* data at 0.9 TeV. In this paper, we apply this fluid approach, always the same procedure, to understand the 7 TeV results. In Fig. 4, we show that our hydrodynamic picture indeed leads to a near-side ridge, around $\Delta\phi = 0$, extended over many units in $\Delta\eta$. One should note that the correlation functions are defined and normalized as in the CMS publication, so we can say that our "ridge" is quite close in shape and in magnitude compared to the experimental result. The experimental high multiplicity bin corresponds to about 7 times average, whereas in our calculation (extremely demanding concerning CPU power) "high multiplicity" refers to 5.3 times average (we actually trigger on events with 10 elementary scatterings). We cannot go beyond, at the moment.

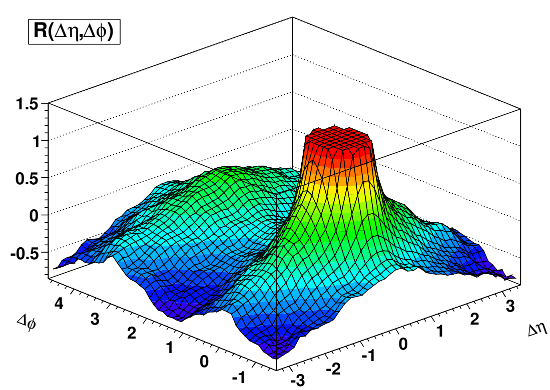

Fig. 4. Two particle correlation function R *versus* $\Delta\eta$ and $\Delta\phi$ for high multiplicity events in *pp* collisions at 7 TeV.

It is easy to understand the origin of the ridge, in a hydrodynamical approach based on flux tube initial conditions. Imagine many (say 20) flux tubes of small transverse size (radius ≈ 0.2 fm), but very long (many units of space-time rapidity η_s). For a given event, their transverse positions are randomly distributed within the overlap area of the two protons. Even for zero impact parameter (which dominated for high multiplicity events), this randomness produces azimuthal asymmetries, as shown in Fig. 5, upper panel. The energy density obtained from the overlapping flux tubes (details will be discussed later) shows an elliptical shape. And since the flux tubes are long, and only the transverse positions are random, we observe the same asymmetry at different longitudinal positions ($\eta = 0$ and $\eta = 1.5$ in the figure). So we observe a translational invariant azimuthal asymmetry!

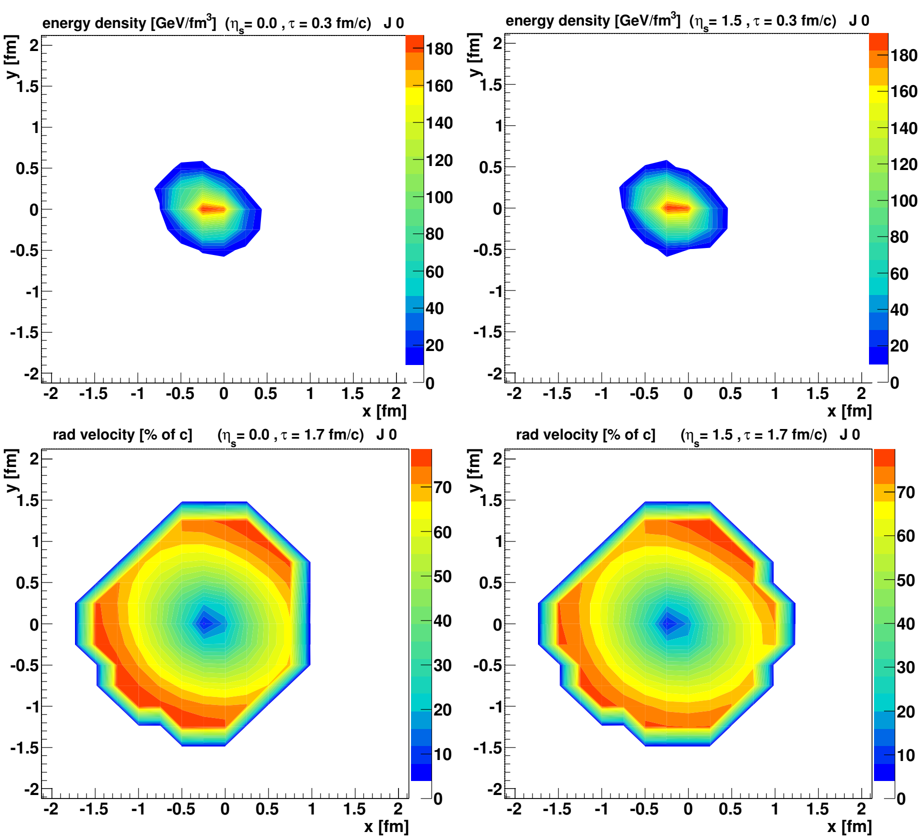

Fig. 5. Initial energy density (upper panel) and radial flow velocity at a later time (lower panel) for a high multiplicity *pp* collision at 7 TeV at a space-time rapidity $\eta_s = 0$ (left) and $\eta_s = 1.5$ (right).

If one takes this asymmetric but translational invariant energy density as initial condition for a hydrodynamical evolution, the translational invariance is conserved, and in particular translated into other quantities, like the flow. In Fig. 5, lower panel, we show the radial flow velocity at a later time again at the two space-time rapidities $\eta_s = 0$ (left) and $\eta_s = 1.5$ (right). In both cases, the flow is more developed along the direction perpendicular to the principal axis of the initial energy density ellipse. This is a very typical fluid dynamical phenomenon, referred to as elliptical flow.

Finally, particles are produced from the flowing liquid, with a preference in the direction of large flow. This preferred direction is therefore the same at different values of η_{s}. And since η_{s} and pseudorapidity η are highly correlated, one observes a $\Delta\eta\Delta\phi$ correlation, around $\Delta\eta = 0$, extended over many units in $\Delta\eta$: a particle emitted at some pseudorapidity η has a large chance to see a second particle at any pseudorapidity to be emitted in the same azimuthal direction.

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