The "Ridge" in Proton-Proton Scattering at 7 TeV

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We show that a hydrodynamical expansion leads in a natural way to the observed "ridge" structure in the two particle correlation function versus the pseudorapidity difference $\Delta\eta$ and the azimuthal angle difference $\Delta\phi$, around $\Delta\eta = 0$, extended over many units in $\Delta\eta$. Such a structure has been observed for high multiplicity events in *pp* scattering at 7 TeV. The reason for this phenomenon is the fact that in high multiplicity proton-proton events many elementary flux tubes are produced, which represent an energy density which by accident usually deviates from an ideal cylindrical symmetry. We have rather an elliptical shape in the transverse plane, however, this asymmetry is exactly the same at different longitudinal positions. This translational invariant asymmetry of the energy density, taken as an initial condition of a hydrodynamical evolution, will lead to a corresponding translational invariance of the collective flow, which will then produce this long range $\Delta\eta\Delta\phi$ correlation. It seems that quark-gluon matter is a perfect fluid even on length scales of 0.1 fm.

The CMS collaboration published recently results [1] 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 $\Delta\eta = 0$, 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, 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.

So does *pp* scattering provide as well a liquid, just ten times smaller than a heavy ion collision? It seems so! We showed recently [2] that if we take exactly the same hydrodynamic approach which has been so successful for heavy ion collisions at RHIC [3], 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. Before discussion the details of the approach, we present the most important results of this work, namely the correlation function. In fig. 1, we show that our hydrodynamic picture indeed leads to a near-side ridge, around $\Delta\eta = 0$, extended over many units in $\Delta\eta$. In fig. 2, we show in the corresponding result for the pure basic string model, without hydro evolution. There is no ridge any more! This shows that the hydro-

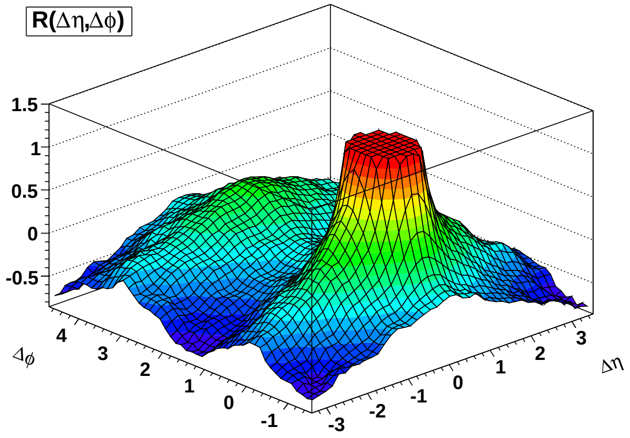

Figure 1: (Color online) Two particle correlation function R versus $\Delta\eta$ and $\Delta\phi$ for high multiplicity events in *pp* collisions at 7 TeV, as obtained from a hydrodynamical evolution based on flux tube initial conditions. We consider particles with p_t between 1 and 3 GeV/c.

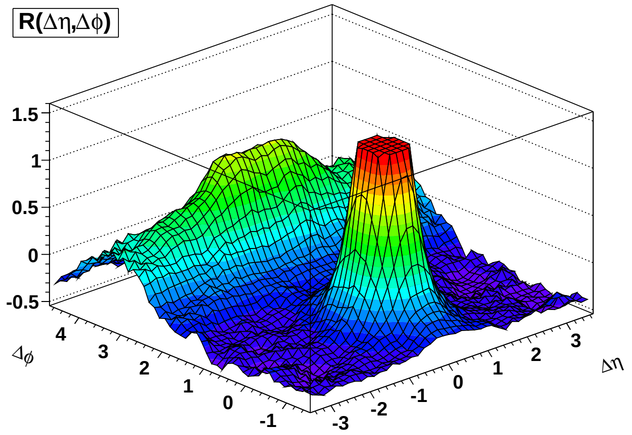

Figure 2: (Color online) Same as figure 1, but calculation without hydro evolution .i.e. particle production directly from string (flux tube) decay.

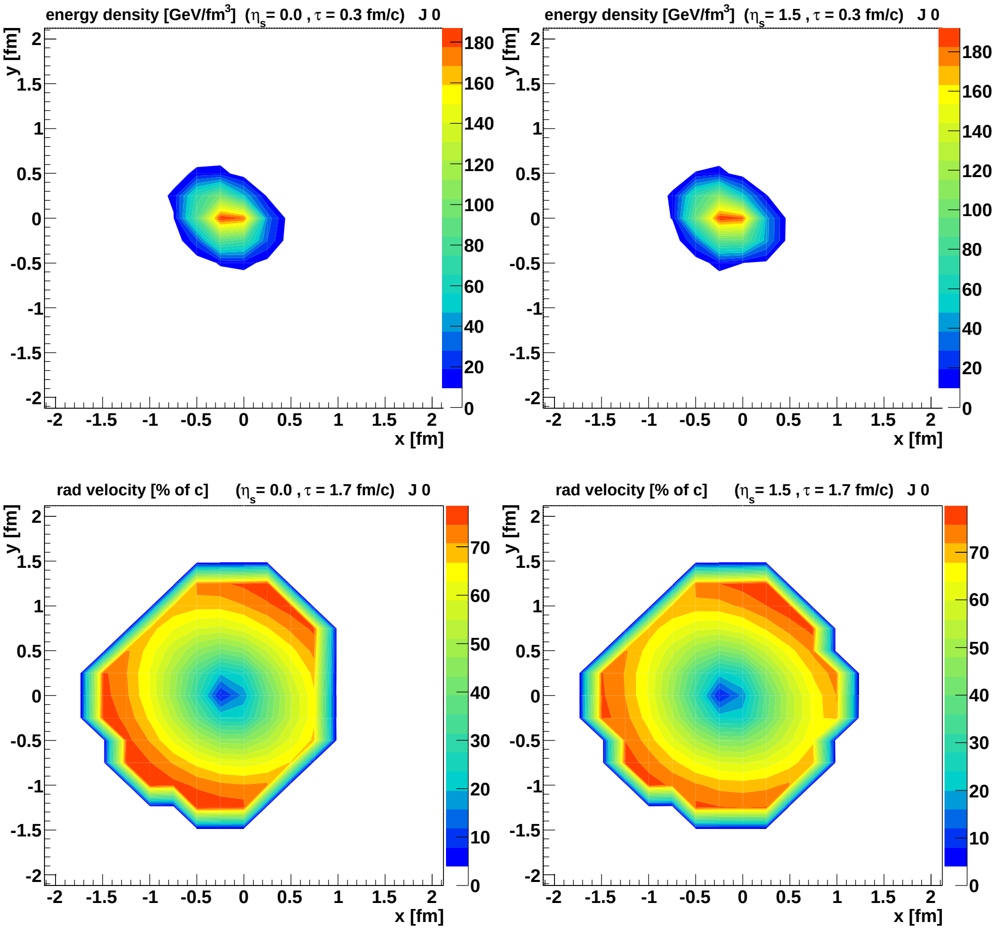

Figure **3**: (Color online) Initial energy density (upper panel) and radial flow velocity at a later time (lower panel) for a high multiplicity *pp* collision at 7 TeV at a space-time rapidity $\eta_s = 0$ (left) and $\eta_s = 1.5$ (right).

dynamical evolution "makes" the effect. 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 the experimental result. The experimental high multiplicity bin corresponds to about 7 times average, wheras in our calculation (extremely demanding concernig 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.

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. 3, 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!

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. 3, 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. Important for this discussion: the asymmetry of the flow is again translational invariant,

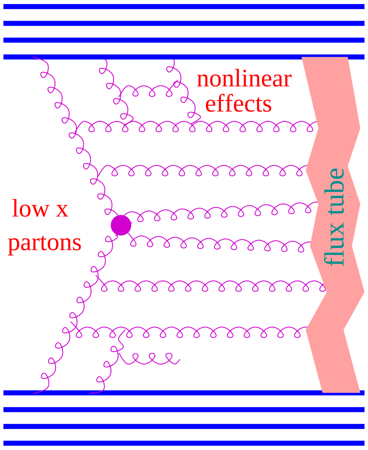

Figure **4**: (Color online) Elementary interaction in the EPOS model.

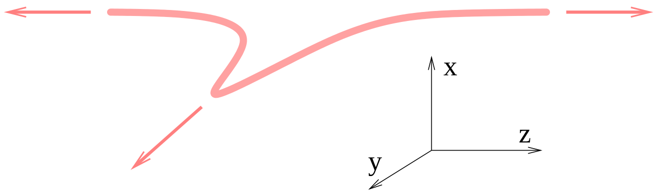

Figure **5**: (Color online) Flux tube with transverse kink in $\mathbb{R}^3$ space. The kink leads to transversely moving string regions (transverse arrow).

the same for different values of η_s.

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 a some pseudorapidity η has a large chance to see a second particle at any pseudorapidity to be emitted in the same azimuthal direction.

Our "flux tube + hydro" approach has been extensively discussed in [2, 3]; in this article, we will only sketch the main features. Crucial is an event-by-event treatment of the hydrodynamic evolution (3D treatment, realistic equation of state), where the initial condition for each event is obtained from an EPOS 2 calculation. This is a multiple scattering approach, formulated in Gribov-Regge fashion using cutting rule techniques in order to obtain partial cross sections [4]. The elementary scattering object is a semihard Pomerons, realized as a "parton ladder", see fig. 4, representing parton evolutions from the projectile and the target side towards the center (small x). The evolution is governed by an evolution equation, in the simplest case according to DGLAP. We will identify parton ladders with elementary flux tubes [5], the latter ones treated as classical strings. We use the simplest possible string: a two-dimensional surfaces $X(\alpha,\beta)$ in 3+1 dimensional space-time, with piecewise constant initial conditions, referred to as kinky strings. In fig. 5(a), we sketch the space components of this object: the string in $\mathbb{R}^3$ space is a mainly longitudinal object (here parallel to the z-axis) but due to the kinks (associated to transversely moving gluons) 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!

In case of very high energy proton-proton scattering, the density of strings will be so high that they cannot possibly decay independently. For technical reasons, we split each string into a sequence of string segments, at a given proper-time τ_0. One distinguishes between string segments in dense areas (more than some critical density ρ_0 of segments per unit volume), from those in low density areas. The high density areas are referred to as core, the low density areas as corona. String segments with transverse momentum larger than some p_t^{cut} (close to a kink) are excluded from the core. Based on the four-momenta of infinitesimal string segments, one computes the energy density $\varepsilon(\tau_0,\vec{x})$ (see fig. 3) and the flow velocity $\vec{v}(\tau_0,\vec{x})$, which serve as initial conditions for the subsequent hydrodynamic evolution, which lets the system expand and cool down till freeze out at some T_H according to the Cooper-Frye prescription.

Our above-mentioned results concerning the ridge are only meaningful if the model can reproduce elementary distributions. In the following we will compare two different scenarios: the full calculations, including hydro

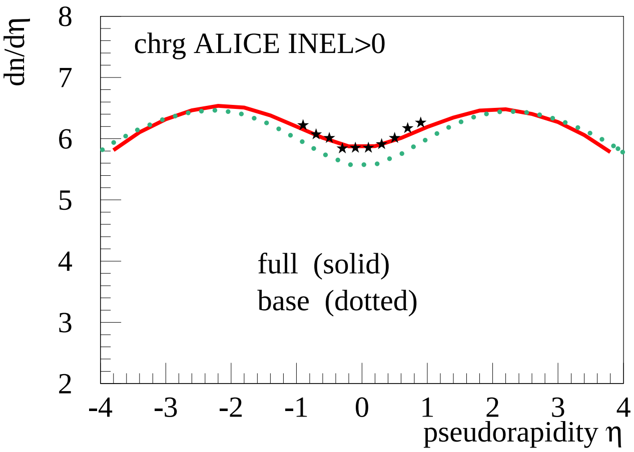

Figure **6**: (Color online) Pseudorapidity distribution in pp scattering at 7 TeV (INEL>0 trigger), compared to data (points).We show the full calculation (solid line), and a calculation without hydrodynamic evolution (dotted).

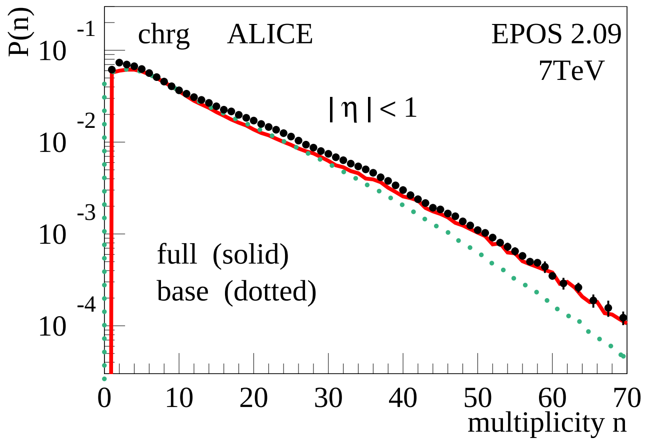

Figure **7**: (Color online) Multiplicity distribution in *pp* scattering at 7 TeV, compared to data (points). We show the full calculation (solid line), and a calculation without hydrodynamical evolution (dotted).

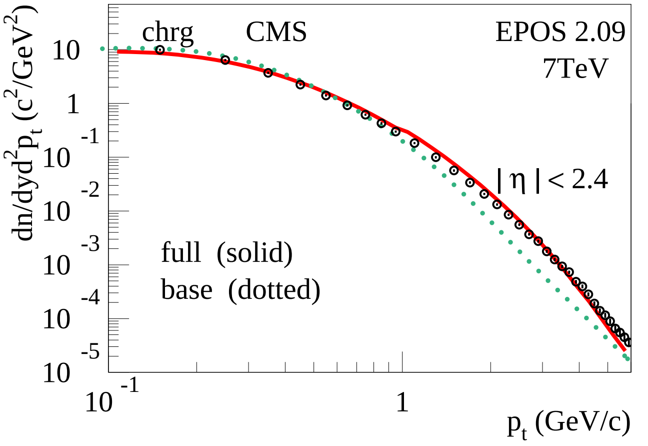

Figure **8**: (Color online) Transverse momentum distributions in *pp* scattering at 7 TeV, compared to data (points).We show the full calculation (solid line), and a calculation without hydrodynamical evolution (dotted).

evolution (full), and a calculation without hydrodynamical evolution (base). In fig. 6, we show pseudorapidity distributions of charged particles, compared to data from ALICE [6] . The two scenarios do not differ very much, and agree roughly with the data. Also the multiplicity distribution agrees reasonably well with data, see fig. 7. We then investigate transverse momentum distributions. Here the base calculation (without hydro) underestimates the data at intermediate p_t by a large factor, whereas the full calculation gets close to the data. This is a very typical behavior of collective flow: the distributions get harder at intermediate values of p_t (around 1-5 GeV/c).

To summarize: our hydrodynamic approach based on flux tube initial conditions, which has already been applied to explain very sucessfully hundreds of of spectra in AuAu collisions at RHIC, and which excellently describes the so-far published LHC spectra and Bose-Einstein correlation functions, provides in a natural fashion a so-called near-side ridge correlation in $\Delta\eta$ and $\Delta\phi$. This structure appears as a consequence of a longitunial invariant asymmetry of the energy density from overlapping flux tubes, which translates into longitudinal invariant elliptical flow.

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