OBSERVATION OF THE COLLECTIVE FLOW IN PROTON–PROTON COLLISIONS

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The scenario of a collective expansion of matter created in proton–proton (p–p) collisions at the CERN Large Hadron Collider (LHC) is discussed. Assuming a small transverse size and a formation time of 0.1 fm$/c$ of the source we observe the build up of a substantial transverse flow in relativistic hydrodynamic simulations. In order to demonstrate the collectivity in p–p collisions we propose to look at the multiplicity dependence of the elliptic flow coefficient. If high multiplicity events originate from azimuthally asymmetric events containing two flux tubes, an observable signal above the statistical fluctuations in the measured elliptic flow could appear.

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Particles emitted from the fireball created in relativistic nuclear collisions exhibit both thermal statistical emission and collective transverse flow. A strong indication of collectivity is seen in the azimuthally asymmetric flow. The asymmetry in momentum space is a consequence of the collective expansion of an azimuthally asymmetric source. Because the size of the system in p–p collisions is much smaller, the applicability of a strongly interacting fluid picture for the description of the fireball is less justified. Some signatures of statistical emission of particles are visible in elementary collisions [1], but they could be explained by phase space dominance effects. An interesting similarity in the spectra from p–p and Au–Au collisions has been noticed if energy and momentum conservation effects are taken into account [2]. Generally, from the observation of transverse momentum spectra alone it

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is difficult to demonstrate the presence of a collective flow, since qualitatively similar distributions could originate from statistical emission or some underlying individual particle production processes. The observation of the elliptic flow in p–p collisions would represent a clear signature of collectivity. Two important questions arise when addressing this problem. First, for multiplicities expected in p–p collisions at LHC (or even more at the BNL Relativistic Heavy Ion Collider (RHIC) if the picture is applicable at these energies) statistical fluctuations in the distribution of particles would generate non-zero asymmetry. The second one is the unknown mechanism that could lead to the asymmetry in the initial mini-fireball created in a p–p collision.

The small fireball in p–p collisions has been treated in a similar way as in heavy-ion collisions [3,4], with an azimuthally asymmetric fireball created in non-central collisions; another approach is proposed in Ref. [5]. All scenarios predict a small elliptic flow in proton–proton collisions. In heavy-ion collisions many individual nucleons participate, and the resulting initial density can be approximated as a continuous distribution, *e.g.* in the Glauber Model. In p–p collisions there are only a few constituent partons [6, 7], and the description based on the overlap of two densities in the colliding protons has no direct microscopic justification.

We follow a different approach. According to the constituent quark model, one, two or rarely more independent sources are excited in a p–p collision. The source is assumed to produce particles in wide range of rapidities as in the string model or in bremsstrahlung emission. In a string picture of particle production particle are emitted in an azimuthally symmetric way [8]. At LHC energies the string decay is fast and the created matter is dense. A collective expansion stage could appear afterwards, but one should not expect a significant geometrical asymmetry of the density in the transverse plane. We show that the collective expansion of such dense matter created from the decay of a single string-like object generates collective transverse flow, but without azimuthal asymmetry. The accumulated transverse flow affects the observed spectra and the Hanbury Brown–Twiss (HBT) correlation radii [9]. We propose another signature of the collectivity in p–p collisions. It is the presence of the azimuthal asymmetry in the emission of particles in events containing two strings (flux tubes). The rapid decay of two flux tubes in the same event leads to an azimuthally asymmetric fireball where elliptic flow could be generated in the expansion. The signal should be visible in high multiplicity events (Fig. 1).

Let us first estimate how much of the transverse flow can be generated in the expansion of the small fireball corresponding to the system formed in p–p collisions at LHC energies. We use ideal fluid relativistic hydrodynamics to describe the dynamics of the fireball [10]. We assume a Bjorken scaling flow

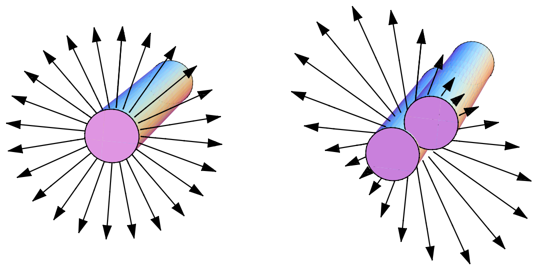

Fig. 1. Sketch of the one and two flux tubes configurations considered. On the left a single flux tube elongated in space-time rapidity generates azimuthally symmetric flow. On the right a configuration with two strings leads to an azimuthally asymmetric flow in the transverse plane.

in the longitudinal direction and a Gaussian profile of the energy density

$$\varepsilon_{\rm FT}(x,y) = \varepsilon_0 \exp\left(-\frac{x^2+y^2}{2\sigma^2}\right) \tag{1}$$

in the transverse plane, $\sigma = 0.5\,{\rm fm}$. The initial time for the expansion is $\tau_0 = 0.1\,{\rm fm}/c$ and the freeze-out temperature 140 MeV. The emission at freeze-out and the resonance decays are taken into account by the statistical emission code THERMINATOR [11] and a realistic equation of state of the plasma and hadronic phase is used [12]. The extrapolation of the charged particle multiplicity from RHIC to LHC energies gives $dN/d\eta|_{\eta=0} \simeq 5$ [13]. To reproduce this number we adjust the value of $\varepsilon_0 = 63\,{\rm GeV/fm}^3$, which corresponds to a temperature of 450 MeV at the center of the fireball.

In Fig. 2 is shown the freeze-out hypersurface. The lifetime of the fireball from the hydrodynamic evolution is of about $2{\rm fm}/c$. A finite time spent in the expansion of the system is a necessary condition for the build up of the

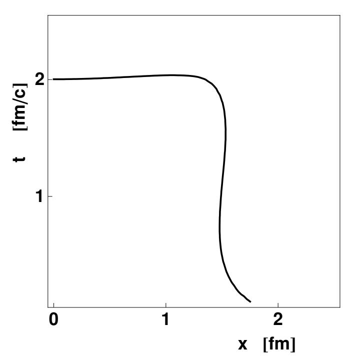

Fig. 2. Freeze-out hypersurface in the symmetric fireball corresponding to a p–p collision.

collective flow, since the transverse flow requires a minimal time of the order of $\sigma/c_{\rm s}$ to be generated, where $c_{\rm s} \simeq \sqrt{3}$ is the sound velocity. In Fig. 3 is shown the average transverse velocity in the system as function of time. The calculation shows that it is possible for the matter to acquire collective velocities of about $0.5\,c$ during the short rapid expansion of the p–p collision fireball. The presence of this collective velocity influences particle spectra, but its extraction from this observable is not unambiguous.

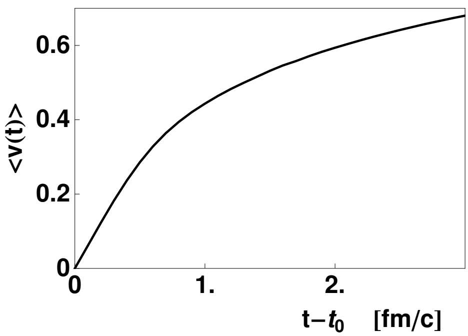

Fig. 3. Time dependence of the average transverse velocity in the fireball.

Constituent quark models predict that in some of the collisions several constituents take part, in string models of particle production it corresponds to the excitation of two or more strings. The energy density distribution in an event with two strings is the sum of two individual profiles (1)

$$\varepsilon_{\rm FT}\left(x, y-\frac{d}{2}\right)+\varepsilon_{\rm FT}\left(x, y+\frac{d}{2}\right), \tag{2}$$

where d is the separation between the two flux tubes. Depending on the distance $d = 0.7$–0.9 fm the energy distribution exhibits an eccentricity

$$e=\frac{\langle y^2-x^2\rangle}{\langle x^2+y^2\rangle} \tag{3}$$

of 0.2–0.29. The proportion of events with two strings can be estimated in constituent quark models [6, 7]. The result is reduced if constituent quarks are correlated as in the quark–diquark models [14] and increased if see quarks participate at higher energies. For the numerical estimate we take 20% of events with two strings. The final result depends weakly on this number because the one and two-string events are separated in the total particle multiplicity (for large enough rapidity intervals and neglecting possible strong multiplicity fluctuations). The multiplicity in the events with two strings is on average almost double.

The elliptic flow coefficient of charged particles is calculated in the pseudorapidity range $|\eta| < 4$

$$v_2 = \frac{1}{N}\sum_{i=1}^{N}\cos\left(2\left(\phi_i - \Psi\right)\right) \tag{4}$$

in each event. The *apparent* reaction plane angle Ψ is constructed in each event from the measured angular distribution to maximize v_2. This means that the elliptic flow is always positive due to the finite number of particles. A simple model of azimuthally symmetric, independent emission of particles [16] gives

$$v_2 = \frac{\sqrt{\pi}}{2\sqrt{N}} \simeq \frac{0.866}{\sqrt{N}}\,. \tag{5}$$

This dependence on the total multiplicity N is very different from the one expected for a collective expansion of an asymmetric source. We plot the quantity $\sqrt{N}v_2$ in Fig. 4. For one string events (dashed line) we obtain $\sqrt{N}v_2 \simeq 0.95$. It is more than expected for independent particles. This is due to correlations induced by resonance decays. The elliptic flow calculated from primordial particles (solid line with squares) follows the formula (5).

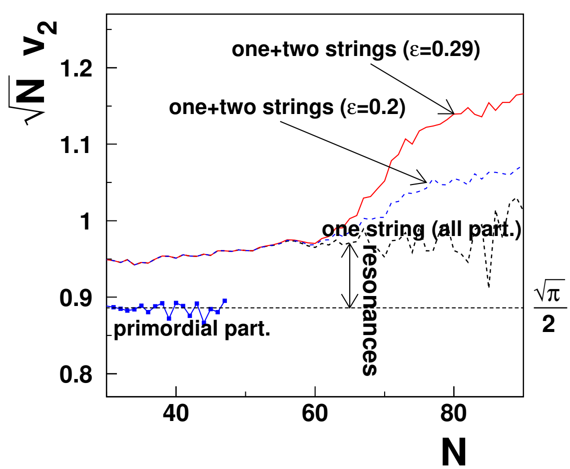

Fig. 4. Charged particle elliptic flow as function of the total charge multiplicity in the pseudorapidity interval $|\eta| < 4$. The solid and dash-doted lines represent the results for a mix of one and two-string events for two different initial separations of the two flux tubes (two different initial eccentricities e). The dashed line is the result when taking only one-string events, and the solid line with squares corresponds to primordial particles only in one-string events. The results for primordial particles follow the prediction (5) denoted by the dotted line.

The multiplicity of charged particles in one-string events is 45 ± 7. For higher multiplicities we have mainly two-string events. The hydrodynamic expansion of the asymmetric energy density (2) leads to a larger value of the elliptic flow (solid and dash-dotted lines in Fig. 4). The elliptic flow saturates at high multiplicities instead of decreasing as $1/\sqrt{N}$. At very high multiplicities more than two strings could be excited and the elliptic flow would decrease again. Using the reaction plane method, the trivial fluctuations from finite multiplicity (Eq. 5) can be easily subtracted. Let us note that the contribution to the elliptic flow from statistical fluctuations and resonances can be estimated and subtracted from the signal, also for other experimental estimators of the elliptic flow coefficient using higher cummulants.

We calculate the HBT radii from a Gaussian fit to the correlation functions from the hydrodynamic model of the p–p collision [17]. The finite lifetime of the fireball leads to an increase of the interferometry radii (Fig. 5)

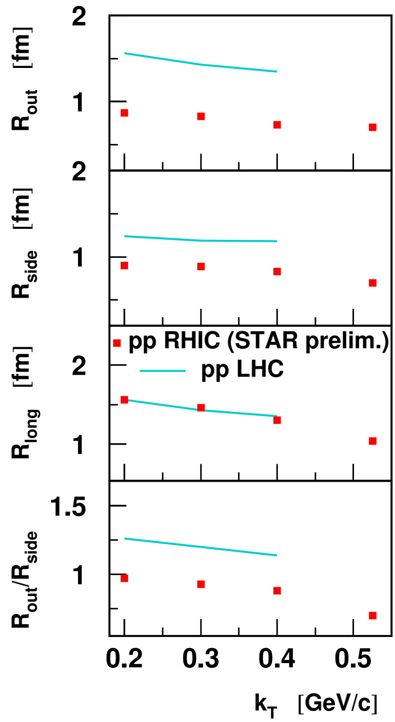

Fig. 5. Interferometry radii of pions as function of the transverse momentum of the pair from the hydrodynamic simulation of p–p collisions at LHC energies. The points represent preliminary data of the STAR Collaboration at RHIC $\sqrt{s} = 200\,\text{GeV}$ [15].

to about 1.5 fm. These values are larger than the measured values of R_{out} and R_{side} at RHIC for *p*–*p* collisions. Similar, larger values of the radii have been predicted in a rescattering model [9]. We confirm this observation in the hydrodynamic model of the expansion of the fireball. For pairs with the highest momentum a Gaussian fit cannot be obtained.

In summary, we use a hydrodynamic model of the dynamics of the small fireball created in *p*–*p* collisions at LHC energies. We conclude that during the lifetime of 2 fm/c significant transverse flow builds up. This has as a consequence the increase of HBT radii. We suggest to identify the elliptic flow in events with non-zero initial eccentricity. Such events could occur due to the excitation of two flux tubes. The elliptic flow of charged particles measured in a wide pseudorapidity range would show a departure from the one resulting from statistical fluctuations only. This would happen at higher multiplicities where two-string events dominate.

After the competition of this paper, Ref. [18] appeared. The authors discuss a similar idea for the eccentricity fluctuations in the initial state, but with possibly many small string-like objects excited in the interaction region of a proton–proton collision.

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