Eccentricity and elliptic flow in *pp* collisions at the LHC

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Abstract. High-multiplicity proton–proton collisions at the LHC may exhibit collective phenomena such as elliptic flow. We study this issue using DIPSY, a brand–new Monte Carlo event generator which features almost–NLO BFKL dynamics and describes the transverse shape of the proton including all fluctuations. We predict the eccentricity of the collision as a function of the multiplicity and estimate the magnitude of elliptic flow. We suggest that flow can be signaled by a sign change in the four–particle azimuthal correlation.

The observation of high–multiplicity events in *pp* collisions at the LHC opens up an interesting possibility that the collective flow, usually discussed in the context of nucleus collisions, may be realized in the final state of *pp* collisions [1]. Indeed, highest multiplicity events in the 7 TeV *pp* run have $dN_{ch}/d\eta \sim 40$ which is comparable to semi–central Cu–Cu collisions at RHIC, and flow has been observed in the latter. In this contribution we study some key questions about the possibility to observe elliptic flow [2] in *pp* using DIPSY—a recently released Monte Carlo event generator [3]. More details can be found in [4]. For related works, see, [5, 6, 7].

Firstly, one should bear in mind that high–multiplicity *pp* collisions and nucleus collisions with the same multiplicity are vastly different. In particular, the former are *rare fluctuations* in the broad N_{ch} distribution while the latter refer to average events at fixed centrality. There are several sources of multiplicity fluctuations in *pp*: (i) Impact parameter fluctuation—Unlike in nucleus collisions, in *pp* collisions it is not possible to determine the impact parameter for each event. High multiplicity events mostly come from collisions with small impact parameter. (ii) Intrinsic fluctuation of the proton's wavefunction—Protons at the LHC undergo the QCD evolution to become a dense system of small–x gluons. Since the QCD evolution is stochastic, there are large event–by–event fluctuations in the gluon number. High multiplicity events arise from protons with an unusually large occupation number of gluons. (iii) Fluctuation in the collision process—In a single high–multiplicity *pp* event, there are many (more than 10) gluon–gluon scatterings. The number of subcollisions fluctuates due to the probabilistic nature of collisions (partonic cross section). (iv) Fluctuation in the final state parton showering—High multiplicity events typically contain several jets, and the fragmentation of jets is a stochastic process.

At first, point (i) seems to be a fatal blow to any hope of observing elliptic flow v_2 in *pp*. Naively, in central collisions the eccentricity would be very small, hence small, unobservable v_2. However, this may be solved by point (ii). The QCD evolution generates fluctuations not only in the gluon number, but also in the transverse distribution of gluons because the gluon splitting probability depends on the transverse coordinates.‡ This makes it possible to have a sizable *participant eccentricity* even in central collisions

$$\epsilon_{\rm part} \equiv \frac{\sqrt{(\sigma_y^2-\sigma_x^2)^2+4\sigma_{xy}^2}}{\sigma_y^2+\sigma_x^2}\,, \tag{1}$$

where $\sigma_{x,y}$ are the variances of x and y coordinates of liberated gluons. [By 'liberated gluons' we mean gluons which actually interacted as well as those in the underlying events.] We have computed (1) using DIPSY [3, 8], a new event generator which takes into account all the points (i)–(iv) above. It is based on the QCD dipole model [9] which is the coordinate space formulation of the BFKL evolution, and therefore captures the correct transverse dynamics of small–x gluons. In addition to the leading–order BFKL, DIPSY features a dominant part of the next–to–leading corrections, energy conservation, and saturation effects. Thanks to this, the energy dependence of observables is a prediction in DIPSY. Once the parameters have been fixed at one value of energy, there is no ad hoc re-tuning of parameters at different energies.

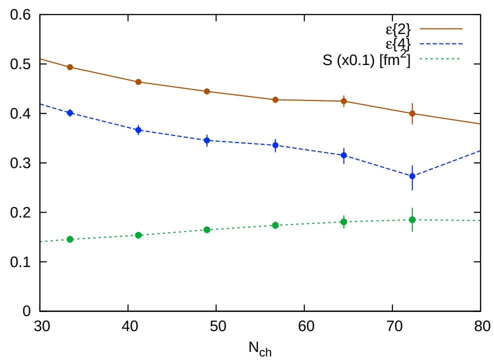
The result for the eccentricity $\epsilon\{2\} \equiv \sqrt{\langle\epsilon_{\rm part}^2\rangle}$ and $\epsilon\{4\} \equiv (2\langle\epsilon_{\rm part}^2\rangle^2-\langle\epsilon_{\rm part}^4\rangle)^{1/4}$ as well as the interaction area $\langle S\rangle$ at 7 TeV is plotted in Fig. 1 (left) as a function of N_{ch} within the ALICE acceptance $|\eta|<0.9$. [$\langle ...\rangle$ denotes event–by–event averaging in a given multiplicity bin.] We see that the eccentricity is about 30–40% in the highest multiplicity region. This is similar to the value in semi-central nucleus collisions at RHIC and the LHC.

Next we give an estimate v_2. In nucleus collisions, v_2 and ϵ are roughly proportional

$$v_2\{2\} = \epsilon\{2\}\left(\frac{v_2}{\epsilon}\right)_{\rm hydro}\frac{1}{1+\frac{\lambda}{K_0}\frac{\langle S\rangle}{\left\langle\frac{dN}{d\eta}\right\rangle}}\,, \tag{2}$$

where λ/K_0 is a certain parameter fitted to experimental data [10]. This empirical formula works both at RHIC and at the LHC, and both for Au–Au and Cu–Cu at

‡ Previous works considered the fluctuation of 'hot spots' [6] and 'flux tubes' [7]. There the transverse distribution of these objects was assumed to be random. In our case the transverse distribution of gluons is not random, but governed by the QCD evolution.



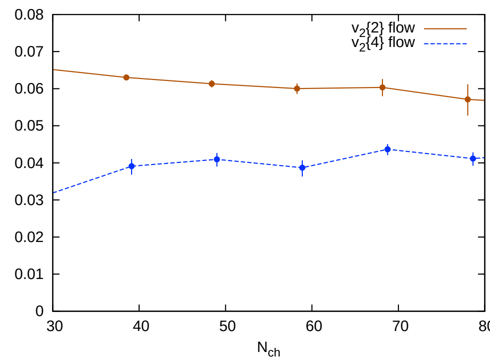


Figure 1. Predictions for the eccentricity and the interaction area $S\,(\times 0.1)[\mathrm{fm}^2]$ (left) and elliptic flow (right) versus the charged multiplicity in the interval $|\eta| < 0.9$ at $\sqrt{s} = 7$ TeV.

RHIC although they differ in size by a factor of two. The latter supports the general argument that the applicability of hydrodynamics is controlled by the dimensionless parameter $\alpha \equiv \frac{\lambda}{K_0}\frac{S}{dN/d\eta}$ rather than the system size. In high–multiplicity *pp* events, the necessary condition $\alpha < 1$ is well satisfied even after allowing for some uncertainty in the parameter λ/K_0. On the other hand, it is hard to imagine hydrodynamic behaviors in systems smaller than $S \sim 1\,\mathrm{fm}^2$ which sets the border between the hadronic and nuclear scales. We thus expect that (2) can be marginally applied for $S > 1\,\mathrm{fm}^2$, and this condition is better satisfied in high–multiplicity events (see Fig. 1).

In practice, we propose the following improvement of (2)

$$(v_2\{2\})^2 = \left(\frac{v_2}{\epsilon}\right)^2_{\mathrm{hydro}} \left\langle \frac{\epsilon^2_{\mathrm{part}}}{(1+\frac{\lambda}{K_0}\frac{S}{dN/d\eta})^2} \right\rangle , \tag{3}$$

and similarly,

$$(v_2\{4\})^4 = \left(\frac{v_2}{\epsilon}\right)^4_{\mathrm{hydro}} \left\{ 2\left\langle \frac{\epsilon^2_{\mathrm{part}}}{(1+\frac{\lambda}{K_0}\frac{S}{dN/d\eta})^2} \right\rangle^2 - \left\langle \frac{\epsilon^4_{\mathrm{part}}}{(1+\frac{\lambda}{K_0}\frac{S}{dN/d\eta})^4} \right\rangle \right\}. \tag{4}$$

The reason is that in *pp* collisions the eccentricity ϵ and the area S fluctuate widely even at fixed $dN/d\eta$. The above formulas nicely capture this event–by–event correlation of ϵ and S. Note that it is the squared value $(v_2\{2\})^2$ (and also $(v_2\{4\})^4$) that directly comes out of the experimental measurement of flow via multiparticle correlations

$$(v_2\{2\})^2 = \langle\{\cos 2(\phi_i - \phi_j)\}\rangle\,, \tag{5}$$

$$(v_2\{4\})^4 = 2(v_2\{2\})^4 - \langle\{\cos 2(\phi_i + \phi_j - \phi_k - \phi_l)\}\rangle, \tag{6}$$

where ϕ_i is the azimuthal angle of the i-th outgoing particle. The result for (3) and (4) are plotted in Fig. 1 (right). Elliptic flow is about 6%, comparable to the value found at the LHC.

Is it possible to observe the flow contribution $v_2 \sim 6\%$? The experimentally measured $v_2\{2\}$ and $v_2\{4\}$ differ from the genuine v_2 by the so–called nonflow contribution $(v_2\{n\})^n = v_2^n + \delta_n$ where δ_n is the n–particle correlations not associated with flow. In nucleus–nucleus collisions, they are relatively innocuous because they scale with the multiplicity as $\delta_n \sim \frac{c}{N_{ch}^{n-1}}$. In *pp* collisions, we expect that the parametric dependence on N_{ch} is unchanged, but there is a significant enhancement in the coefficient c due to various initial and final state effects. Indeed, the ALICE collaboration found $v_2\{2\} \approx 0.13$ in the highest multiplicity *pp* events [11] which is twice as large as the flow contribution, implying that the two–particle correlation is dominated by nonflow effects.

This peculiar situation in *pp* collisions necessitates us to turn to higher order cumulants $v_2\{n\}$ with $n \geq 4$ which are by definition insensitive to two–particle nonflow correlations. Actually, the ALICE collaboration has also measured $v_2\{4\}$ [11]. It turns out that the magnitude of $v_2\{4\}$ in the data is still larger than our flow prediction, but very interestingly, it has the 'wrong' sign—the rhs of (6) is negative! The same phenomena can be seen in Pythia and DIPSY (without flow). On the other hand, in the flow scenario the rhs of (4) is positive. We thus propose to look for this sign change in experiment as a possible signature of flow: If there is flow in the large N_{ch} region, then the fourth order cumulant (6), which is negative in the absence of flow, will decrease in magnitude as $\sim 1/N_{ch}^3$ and eventually turn positive.

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