Can we observe the elliptic flow in \( pp \) collisions at LHC?

Gyulnara Eyyubova
for the ALICE collaboration
Department of Physics, University of Oslo, Norway
E-mail: gyulnare@student.matnat.uio.no

Abstract. The azimuthal anisotropy of charged particles in heavy ion collisions is an important probe of quark-gluon plasma evolution at early stages of reaction. Now, with the start of Large Hadron Collider (LHC), the collective effects in proton-proton collisions are also of great interest. In this work we analyze the ability of different methods to extract elliptic flow in \( pp \) collisions at LHC. The analysis is based on Monte Carlo simulations of proton-proton collisions with PYTHIA, PHOJET and EPOS event generators at energies \( \sqrt{s} = 900 \text{ GeV} \) and \( 7 \text{ TeV} \).

1. Introduction

In non-central nucleus-nucleus collisions an initial overlap geometry is anisotropic. Unequal pressure gradients then produce an anisotropic momentum distribution of particles with respect to the event-by-event reaction plane. The observed particle yield versus azimuthal angle gives information on the early collision dynamics and is described by means of Fourier series:

\[
\frac{dN}{d\phi} = \frac{N_0}{2\pi} \left[ 1 + 2 \sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_R)) \right],
\]

where \( \Psi_R \) is the reaction plane angle. The second harmonic \( v_2 \) in Eq.(1) is called the elliptic flow. The measurements of \( v_2 \) at RHIC are commonly interpreted in terms of hydrodynamic expansion of a thermalized relativistic fluid. The STAR experiment at RHIC has measured azimuthal correlations in proton-proton collisions as a reference for nucleus-nucleus collisions in order to understand systematic errors of \( v_2 \) calculation, resulting from non-flow effect, such as resonance decays and inter- and intra-jet correlations [1]. It was assumed that there are no correlations due to elliptic flow in \( pp \) collisions.

At LHC energy, the expected large energy densities suggest the possibility of collective behavior even in \( pp \) collisions. Here the multiplicity tail contains more than 100 charged particles in central pseudorapidity region \( |\eta| < 1 \) at \( \sqrt{s} = 7 \text{ TeV} \)[2]. Assuming that the matter formed in \( pp \) collisions has the same properties as in \( A + A \) collisions, one also expects the formation of elliptic flow in \( pp \) collisions. There exist various attempts to apply hydrodynamical calculation to the \( pp \) collision system (see, e.g., [3, 4, 5]). Besides hydrodynamics, the mechanism of asymmetry can also arise due to initial conditions in Regge field theory [6] and in string interaction models [7]. The predicted values of the \( v_2 \) vary from 0.03 till 0.15 in different models. The aim of the
present work is to study the possibility of extraction of elliptic flow in $pp$ collisions at energies between $\sqrt{s} = 900$ GeV and 7 TeV using various MC event generators.

2. Elliptic flow analysis

Methods for the flow extraction. The main obstacle for $v_2$ determination is that it cannot be extracted directly as a Fourier coefficient in Eq. (1) and should be calculated via particle correlations since a position of the reaction plane $\Psi_R$ is unknown. Apart from the collective correlations w.r.t. the reaction plane, there exist the so-called non-flow correlations. Systematic uncertainties resulting from the non-flow correlations are much affected by multiplicity. Several anisotropic flow reconstruction methods, with their own advantages and limitations, are usually employed for the analysis of data, e.g., the Reaction Plane method, the Scalar Product, and the 2nd order cumulant method [8, 9]. These methods exhibit different sensitivity to two- or more-particle azimuthal correlations. Due to non-flow correlations, $v_2$ can be reliably extracted in two-particle correlation methods if $v_2 > 1/\sqrt{M}$ [10], where $M$ is the event multiplicity. There are also higher order correlation methods based on cumulants and many-particle correlation methods, such as Lee-Yang Zeros method [10]. They allow for measurements of azimuthal anisotropies down to values of order of $1/M^{3/4}$ for 4-particle correlation methods and $1/M$ for genuine multiparticle methods. The multiplicity and the number of events are relevant to multiparticle correlation methods as well. Unfortunately, these methods can hardly be employed with the currently available number of recorded $pp$ interactions of ALICE at the LHC.

Monte Carlo event generators at our disposal. None of available microscopic Monte Carlo (MC) models describes the development of anisotropic flow in elementary hadron–hadron interactions yet. Three popular MC event generators, namely, PYTHIA6.4 [11], PHOJET [12] and EPOS [13], were applied in these proceedings.

PYTHIA treats each hadron as a set of partons characterized by parton distributions. Initial parton shower is started by a parton from each set. One parton from each of the initial showers participates in a hard collision, where a number of outgoing partons is produced. Other partons from the showers may experience semihard interactions. The fragmentation process into the colorless hadrons takes place via the string fragmentation (so-called Lund model is used), cluster decays and decays of unstable particles and resonances. Both PHOJET and EPOS event generators belong to the family of microscopic models based on dual topological unitarization and utilized the color-exchange mechanism of string excitation. Here the hadronic interactions are treated in terms of Reggeon and Pomeron exchanges. In PHOJET the Pomeron exchange is subdivided into soft processes with small momentum transfer and at least one hard process with
large momentum transfer. In EPOS the complete picture of hadron-hadron collision consists of the three colorless objects, namely, the two off-shell remnants of the target and projectile, and the parton ladders between the two active partons on either side. As one can see below, jets in EPOS are playing a minor role compared to jets in PYTHIA or in PHOJET.

Results. The present analysis is based on the minimum bias pp events at $\sqrt{s} = 900 \text{ GeV}$ and 7 TeV with the mean multiplicity for MC models in the region $|\eta| < 1$ about 6 and 10 respectively. The $v_2$-coefficient was reconstructed by the Scalar Product Method $v_2\{SP\}$, and by the cumulants of the second order with Generating function $v_2\{2, \text{GF}\}$ and with Q-vector $v_2\{2, QC\}$ [14]. Fig.1 shows the $p_T$-integrated flow extracted for PHOJET- and EPOS-simulated pp collisions. Analysis of PHOJET data favors increase of the $v_2$ with rising energy, whereas for EPOS no strong energy dependence is observed. The $p_T$ dependencies of obtained coefficients for $v_2\{2, QC\}$ method are presented in Fig.2. Note that these coefficients are below 10% at $p_t \leq 0.5 \text{ GeV/c}$, but quickly rise up to 40% (EPOS) or even 90% (PYTHIA) at $p_T \approx 3 \text{ GeV/c}$. Since the intrinsic elliptic flow in the MC models is essentially zero, the reconstructed $v_2$ values are solely due to non-flow correlations. The integrated $v_2$ values also differ by a factor of 1.5 ($v_2^{\text{PYTHIA}}/v_2^{\text{PHOJET}} \approx 0.16$ versus $v_2^{\text{EPOS}} \approx 0.096$). As the multiplicities are practically the same, the stronger non-flow correlations in PYTHIA and PHOJET are attributed to jet contributions. It is worth noting that the presence of real flow can diminish the non-flow effects, as seen in Fig.3. Here the EPOS events are modified to carry certain amount of $v_2\{2\}$. The contribution of non-flow decreases with increasing true $v_2$. However, for the methods used, even for the input $v_2 = 15\%$ at the particle level, the non-flow contribution to the extracted $v_2$ coefficient is about 20%.

How can we disentangle flow and non-flow terms? If the correlation is dominated by elliptic flow, it should be approximately constant as a function of pseudorapidity. Flow correlates particles at all $\Delta \eta$, while non-flow effects from jets dominates short range correlations (small $\Delta \eta$) and can be reduced by the $\eta$-gap technique [15]. The $\eta$-gap analysis was performed within the Scalar Product method [9]. The general formula of the method is:

$$\langle\langle v_2(\eta, p_T)\rangle\rangle = \left\langle\left\langle \frac{Q u_i(\eta, p_T)}{M^q} \right\rangle\right\rangle \sqrt{\frac{Q^a Q^b}{M^a M^b}},$$

(2)

where $u_i = e^{i2\phi_i}$ is a unit vector associated with the $i$-th particle and $Q = \sum u_i$ is the event flow vector. Subevents a and b were separated by $\Delta \eta$. Fig.4 shows the dependence of calculated elliptic flow coefficient on $\Delta \eta$ in PYTHIA-simulated pp data at $\sqrt{s} = 7 \text{ TeV}$. The observed correlations decrease with increase of $\Delta \eta$. Still the obtained non-flow value of the $v_2$ is quite large even for $\Delta \eta \geq 0.9$. Larger $\Delta \eta$ can further reduce the correlations. Another way of non-flow
proton-proton collisions simulated by PYTHIA, PHOJET, and EPOS at $\sqrt{s} = 900$ and 7000 GeV are analyzed by two-particle correlation methods. The $p_T$-integrated $v_2$ coefficients reconstructed by the methods are found to vary from 10% to 15%. These values are attributed solely to the non-flow correlations.

To weaken the non-flow correlations $\eta$-gap separation of two subevents is applied. This reduces non-flow value for the PYTHIA events by a factor 1/3. Using an even larger $\Delta \eta$ will allow for a further reduction of the non-flow contributions.

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Figure 3. $v_2$-coefficient with the two-particle correlation methods for the EPOS-simulated $pp$ collisions with different values of input flow.

Figure 4. $\eta$-gap dependence of the azimuthal correlations restored from PYTHIA-simulated $pp$ collisions.