CALCULATIONS OF AZIMUTHAL FLOWS IN COLLISIONS OF HEAVY IONS USING THE REACTION PLANE AND TWO-PARTICLE CUMULANT METHODS AT THE HYDJET++ FOR LHC ENERGIES

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Monte Carlo models are widely used to study relativistic heavy-ion collisions, that is matter under extreme conditions through the analysis of azimuthal distributions of secondary particles. HYDJET++ is one such model. While initially relying on the true reaction plane method for azimuthal flow calculations, this approach is impractical for experimental comparisons. We enhanced HYDJET++ by implementing additional methods used in experiments, including reaction plane and cumulant techniques. Using this updated model, we simulated Pb–Pb and Xe–Xe collisions at $\sqrt{s_{NN}} = 5.02$ TeV and $\sqrt{s_{NN}} = 5.44$ TeV per nucleon pair in c.m.s respectively, calculating v_2 and v_3 flows via three methods and comparing them with each other and CMS data. These improvements refine the generator's applicability, highlight areas requiring further optimization, and expand its potential for future research.

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Introduction

Studying matter at extreme conditions remains a key area in high-energy physics. Such states are studied both by experiments, such as the CMS collaboration at the LHC [1], and by theoretical modeling using Monte Carlo generators such as HYDJET++ [2]. CMS provides highly accurate data on the azimuthal anisotropy, multiplicity, and non-flow correlations inherent in the experiment [3], which serve as a benchmark for checking and adjusting the models. In turn, HYDJET++ can model heavy-ion collisions in fairly wide ranges of various parameters. In addition, the generator includes important physical concepts – a hydrodynamic model and jet quenching. Comparison of these approaches expands our understanding of the dynamics of nuclear matter and the process of its evolution.

In our previous work, we simulated xenon and lead collisions at LHC energies and compared the results with experimental data [4]. It was shown that the standard true reaction plane method describes semi-central collisions well but performs poorly for central and peripheral ones. A comparison of

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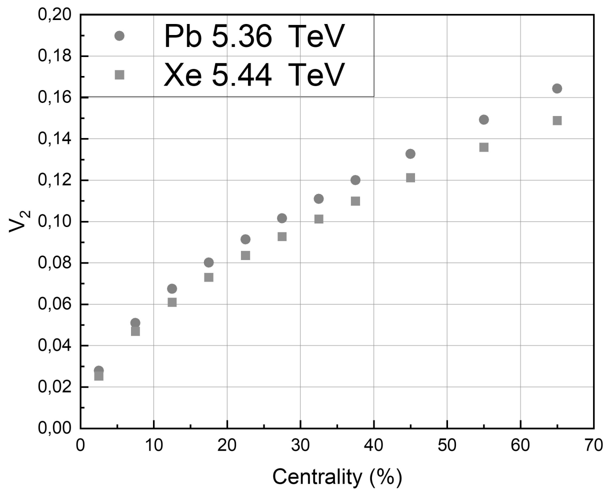

Fig. 1. Integral v_2 for 11 centralities for Pb–Pb collisions at 5.36 TeV and Xe—Xe collisions at 5.44 TeV per nucleon pair in c.m.s. in HYDJET++ generator

the ratios of azimuthal flows confirmed good agreement in the semi-central region [5].

To improve agreement with the experimental results, we proposed modifying the method for calculating azimuthal flows. In the standard approach, the reaction plane angle Φ_R is known, allowing the azimuthal distribution of charged particles to be expanded in a Fourier series, as shown in (1):

$$\frac{2\pi}{N}\frac{dN}{d\phi} = 1 + \sum_{i=1}^{\infty} 2v_n \cos\left[n(\phi - \Phi_R)\right], \tag{1}$$

Where N is the total number of particles, ϕ is the azimuthal angle, and v_n represents the n-th harmonic. Azimuthal distributions obtained with HYDJET++ are discussed in [4].

The distributions for the integral flow values obtained using default LHC tune in generator are in good agreement with the experiment (here the integral flow stands for the average flow value over a given centrality region in the tranversal momentum p_T interval from 0.5 to 3 GeV/c). A detailed comparison of the integral elliptical flows calculated in HYDJET++ and in the CMS experiment will be performed in the future, when Run3 data become available. For now, we present the dependence in Fig. 1 as a prediction. For further development, we focused on the reaction plane method and the two-particle cumulant method due to their frequent use in experiments.

Calculation methods

The methods for calculating azimuthal flows used in this work include the reaction plane method [6]. Unlike the standard generator approach, this method involves determining the reaction plane angle based on the beam direction and the impact parameter vector. The event plane can be calculated separately for each harmonic of the anisotropic flow, with the event flow vector Q_n and the event plane angle Ψ_n defined as follows (2):

$$\Psi_n = \left(\tan^{-1}\frac{Q_n \cos(n\Psi_n)}{Q_n \sin(n\Psi_n)}\right)/n = \left(\tan^{-1}\frac{\sum_i \omega_i \sin(n\phi_i)}{\sum_i \omega_i \cos(n\phi_i)}\right)/n \tag{2}$$

Here, the summation is performed over particles contributing to the event plane, with ω_i representing their weights. To ensure independence, particle groups are selected separately for plane determination and flow calculation. In our case, particles were divided by pseudorapidity into two hemispheres – positive and negative.

The two-particle cumulant method is a widely used approach for calculating anisotropic flow which helps suppress non-flow effects [7,8]. This method relies on the azimuthal correlations of particle pairs to determine the flow coefficients.

The two-particle azimuthal correlation for the n-th harmonic is defined as:

$$\langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle = \langle e^{in(\phi_1-\phi_2)}\rangle - |\langle e^{in\phi}\rangle|^2, \tag{3}$$

where ϕ_1 and ϕ_2 are the azimuthal angles of two particles, and the double angular brackets indicate an average over all particle pairs in an event and then over all events. This eliminates contributions from nonflow correlations, such as resonance decays or jets, when $\langle e^{in\phi}\rangle$ is small.

The flow coefficient v_n is then extracted as:

$$v_n\{2\} = \sqrt{\langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle}, \tag{4}$$

where $v_n\{2\}$ represents the flow calculated from two-particle cumulants.

This method can be extended to higher-order cumulants, which include correlations among more particles, such as the four-particle cumulants [7].

Results

The authors simulated relativistic lead and xenon ion collisions at 5.02 and 5.44 TeV per nucleon pair, respectively, in HYDJET++ generator to calculate elliptical flows using the reaction plane method. These energies were chosen to compare model calculations with CMS experimental data [3]. Simulations covered three centrality ranges of interest: central (5–10%), semi-central (20–25%), and peripheral (40–50%) collisions, with approximately 1 million events generated for each range.

The results shown in Fig 2 showed minimal differences between the new method and the true reaction plane approach. Ratios of elliptical flows in xenon to lead collisions were nearly identical to those obtained by the previous method, and both agreed satisfactorily with experimental data only in the semi-central range.

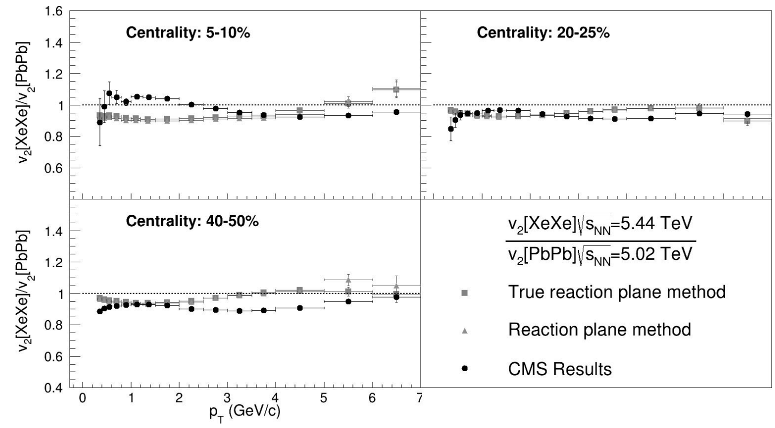

Fig. 2. Flows relations $v_2[XeXe]/v_2[PbPb]$ at $\sqrt{s_{NN}} = 5.44$ TeV and 5.02 TeV per nucleon pair in c.m.s respectively in HYDJET++ and CMS experiment

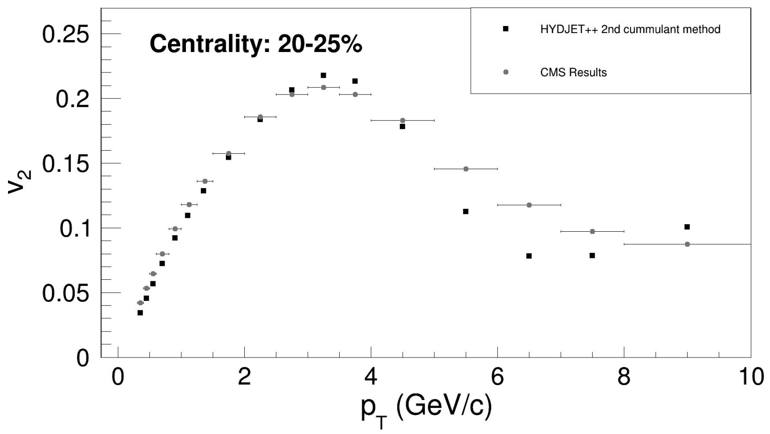

Fig. 3. Calculations for v_2 in Pb—Pb collisions at the $\sqrt{s_{NN}} = 5.02$ TeV in c.m.s. using 2nd order cummulant method in HYDJET++ and CMS experiment (statistic error bars for v_2 are smaller than the points)

The calculation of elliptical flow using the second-order cumulant method produced encouraging results. In the semi-central collision region, the generator with standard settings accurately reproduces the harmonic distribution as a function of transverse momentum. Fig. 3 compares this dependence with CMS experimental data from Run 2, showing excellent agreement up to moderate transverse momentum values (4 GeV/c). Note, that errors bars are smaller than the marker size due to the outstanding accuracy of the method. Minor deviations appear at higher p_T, highlighting an area of interest for future investigations.

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Conflict of interest

The authors declare that they have no conflicts of interest.

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