



## Letter

## Collision energy dependence of elliptic flow of identified hadrons in heavy-ion collisions using the PHSD model

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## ABSTRACT

We report the first predictions of elliptic flow ( $v_2$ ) of identified hadrons at mid-rapidity ( $|y| < 1.0$ ) in Au+Au collisions at  $E_{lab} = 6.7, 8, 11,$  and  $25$  A GeV using the Parton Hadron String Dynamics (PHSD) model. The transverse momentum ( $p_T$ ) dependence of identified hadron  $v_2$  in different centrality intervals (0-10%, 10-40%, and 40-80%) is shown. A clear centrality dependence of  $v_2(p_T)$  is observed for particles at  $E_{lab} = 6.7, 8, 11,$  and  $25$  A GeV. Within the PHSD model, the number of constituent quark (NCQ) scaling of  $v_2$  approximately follows in Au+Au collisions at all beam energies. A collision energy ( $\sqrt{s_{NN}}$ ) dependence of  $\pi, K,$  and  $p$   $v_2$  is studied in comparison with available published experimental data in the beam energy range of 6-25 A GeV. These predictions will help in interpreting the data from the forthcoming Compressed Baryonic Matter (CBM) experiment at the Facility for Antiproton and Ion Research (FAIR) and Multi-Purpose Detector (MPD) at the Nuclotron-based Ion Collider facility (NICA).

## 1. Introduction

In relativistic heavy-ion collisions, a unique form of matter known as Quark Gluon Plasma (QGP), characterized by de-confined quarks and gluons, is formed [1]. The study of QGP provides valuable insights into the properties of matter in extreme temperature and density conditions, resembling those of the early universe. QGP has been extensively investigated through experiments at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC), focusing on high temperatures ( $T$ ) and low net-baryon densities ( $\mu_B$ ) [2–6]. Current research in heavy-ion collision experiments is centered on the phase transition from hadronic matter to QGP and the Quantum Chromodynamics (QCD) [7] phase diagram at finite net-baryon density. An experimental approach to understand the phase structure of nuclear matter in a moderate baryon density region involves varying collision energies and studying observables as a function of collision centrality, transverse momentum ( $p_T$ ), and rapidity ( $y$ ).

One of the most widely studied observable in heavy-ion collisions is the azimuthal anisotropy of the produced particles. It provides valuable insight into the expansion dynamics and properties of the matter produced in heavy-ion collisions [8,9]. Azimuthal anisotropies result from

irregularities in the initial overlapping region and fluctuations in nucleon positions during non-central heavy-ion collisions, leading to asymmetries in particle production relative to the reaction plane [10,11]. The distribution of produced particles with respect to the angle of the reaction plane ( $\Psi_{RP}$ ) is commonly described using a Fourier series [12,13]:

$$E \frac{d^3 N}{dp^3} = \frac{d^2 N}{2\pi p_T dp_T dy} \left[ 1 + 2 \sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_{RP})) \right], \quad (1)$$

where  $\phi$  represents the azimuthal angle of the particle. The coefficients  $v_n$ , known as flow coefficients, are used to quantify the level of azimuthal anisotropy in particle production. Of these coefficients,  $v_2$ , the second-order coefficient, is specifically referred to as the elliptic flow.

At high energies, when the colliding nuclei transit time is shorter than the typical particle production time, the elliptic flow is mainly influenced by the collective expansion of the initial partonic density distribution [14]. This conclusion is based on the observed NCQ scaling of identified hadron  $v_2$  in the intermediate  $p_T$  range of 2 to 5 GeV/c [15,16]. The quark number scaling at top RHIC energy has been studied within the PHSD model [17]. Conversely, at low energies, the observed elliptic flow is significantly affected by the initial state baryon stopping and the nuclear mean-field effects [18–21]. In this case, a devi-

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