Effects of Non-Flow Contributions on Elliptic Flow in d-Au Collisions in the AMPT Model

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Date: 2025-03-10T00:00:00+00:00

Abstract

This study employs the A Multi-PhaseTransport (AMPT) model to analyze the elliptic flow (v2) distribution characteristics of charged hadrons produced in d-Au collisions at 200 GeV collision energy, focusing on investigating the influence of non-flow sources (such as jet fragments and resonance decays, etc.) on v2 in this small collision system. Utilizing the non-flow contribution subtraction method—subtracting charged hadron yields from d-Au peripheral collisions (centrality 60-100% or 80-100%) or pp collisions at the same collision energy from those of d-Au central collisions (centrality 0-5%) to eliminate non-flow effects—we systematically investigate the impact of non-flow effects on charged hadron v2 and the dependence of v2 on different subtraction schemes. The findings indicate that theoretical calculations after non-flow contribution subtraction better describe existing experimental data, with theoretical predictions from different subtraction schemes being similar. This research theoretically demonstrates that in the non-flow contribution subtraction method, subtracting peripheral collision or pp collision results has minimal influence on final theoretical predictions, providing a theoretical basis for researchers to remove non-flow contributions in small collision system experiments; the relevant theoretical calculations also offer theoretical references for subsequent experimental measurements.

Full Text

Preamble

Vol. 41, No. 00

March 2025

Nuclear Physics Review Vol. 41, No. 00, March 2025
Article ID: 1007-4627(2025)00-0080-07

Study on the Influence of Non-Flow Contribution on Elliptic Flow in d-Au Collisions Using the AMPT Model

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Abstract

This study employs the A Multi-Phase Transport (AMPT) model to analyze the elliptic flow (v_2) distribution characteristics of charged hadrons produced in d-Au collisions at a collision energy of 200 GeV, with particular emphasis on investigating the influence of non-flow sources (such as jet fragments and resonance decays) on v_2 in this small collision system. We utilize a non-flow contribution subtraction method that eliminates non-flow effects by subtracting the charged hadron yield from peripheral d-Au collisions (centrality 60–100% or 80–100%) or from pp collisions at the same energy from the yield in central d-Au collisions (centrality 0–5%). This approach allows us to systematically study both the impact of non-flow effects on charged hadron v_2 and the dependence of v_2 on different subtraction schemes. Our findings demonstrate that theoretical calculations after non-flow subtraction provide a better description of existing experimental data, and that different subtraction schemes yield similar theoretical predictions. This work theoretically proves that in the non-flow subtraction method, whether one subtracts peripheral collision results or pp collision results has minimal impact on the final theoretical predictions. This provides a theoretical basis for researchers to remove non-flow contributions in small collision system experiments, and the associated theoretical calculations offer valuable reference for future experimental measurements.

Keywords: A Multi-Phase Transport model (AMPT); Non-flow contribution subtraction; d-Au collisions; Elliptic flow (v_2)

Classification: O571.53
DOI: 10.11804/NuclPhysRev.41.01.80
Document code: A

Introduction

A primary objective of ultrarelativistic heavy-ion collision experiments is to explore new forms of strongly interacting matter—quark-gluon plasma (QGP)

—under extreme conditions of high temperature or high net baryon density [1-2]. This state of matter is widely believed to have existed in the early universe microseconds after the Big Bang and may currently form in the interiors of dense neutron stars. The concept of heavy-ion collisions was first proposed by Tsung-Dao Lee in 1970, who envisioned achieving extreme conditions by accelerating heavy nuclei to near-light speeds to produce numerous new particles. This idea was later validated by researchers, opening a new field of using relativistic heavy-ion collisions to study QGP. In-depth investigation of QGP not only helps reveal the evolution of the early universe but also provides crucial theoretical insights into the fundamental structure of matter and the nature of strong interactions.

In relativistic heavy-ion collision research, a key observable is the azimuthal anisotropy flow of particles in the final state [3-4], which provides information about the equation of state characteristics and collective motion features of QGP. By performing a Fourier expansion of the particle azimuthal distribution in transverse momentum space, one can obtain the second-order coefficient known as elliptic flow (v_2). As a critical observable for studying QGP collective motion, v_2 offers important insights into the collective behavior and properties of QGP. Therefore, investigating the azimuthal anisotropy flow of final-state particles in heavy-ion collisions is not only central to high-energy heavy-ion experiments but also an essential pathway to deepen our understanding of QGP and its characteristics.

To comprehensively understand the influence of cold nuclear matter on heavy-ion collision measurements, researchers have conducted systematic studies of small collision systems such as p(d)+A collisions. These investigations focus on several key aspects of cold nuclear matter effects in small systems, including modifications to parton distribution functions [5], broadening of intrinsic parton transverse momentum [6], and energy loss in cold nuclear matter [7]. Notably, in small collision systems, the ALICE, ATLAS, and CMS collaborations have observed positive v_2 values for hadrons in p+A collisions at a center-of-mass energy of $\sqrt{s_{NN}} = 200$ GeV in the central rapidity region [8-12], and the LHCb collaboration has made similar observations in the forward rapidity region [13]. Additionally, at lower beam energies, the PHENIX and STAR collaborations at RHIC have observed long-range correlation results for hadrons in d-Au [14-17] and ^{3}He-Au collisions [18].

During relativistic heavy-ion collisions, the charged hadron distribution exhibits anisotropy, which is primarily caused by hydrodynamic expansion of the medium in the early stage, manifesting as collective motion of the system. However, besides this dominant hydrodynamic mechanism, other non-flow dynamical effects can also influence the anisotropy measure v_2 [19-20]. These non-flow effects include jet fragments, resonance decays, and other processes that originate from local dynamical mechanisms rather than system-wide collective motion [21-22]. Since these non-flow effects can artificially inflate v_2 values [22-23], their precise quantification has become a critical topic in both theoretical research and experimental observation in high-energy physics.

To quantitatively analyze the contributions from non-flow effects, researchers in the relativistic heavy-ion collision field have developed various methods to eliminate correlations unrelated to v_2 in final-state charged hadrons (including pions, kaons, and protons) that arise from sources such as jet fragments and resonance decays [24]. In small collision system experiments, a common practice is to subtract correlations measured in peripheral collisions [9,25] or proton-proton (pp) collisions [17,26] to remove these non-flow contributions. Researchers then use fitting equations [27] to fit the subtracted two-particle azimuthal yield distributions and extract the resulting v_2 values.

In this study, we employ the AMPT model [28-31] to calculate two-particle correlation yields of charged hadrons in d-Au collisions at 200 GeV. Our aim is to investigate non-flow contribution subtraction methods using both peripheral d-Au collisions and pp collisions, compare the v_2 results obtained through these two approaches, and examine how the specific choice of peripheral collision centrality affects the differences between the two subtraction methods. This provides theoretical guidance for researchers seeking to remove non-flow contributions in small collision system experiments.

1.1 The A Multi-Phase Transport (AMPT) Model

The AMPT model [28-31] is a transport model that considers multiple stages of matter evolution in nucleus-nucleus collisions and can be used to study the v_2 of final-state charged hadrons in heavy-ion collisions. The model consists of four components: initial conditions, parton cascade, hadronization, and hadronic interactions. (1) The initial conditions are generated by the Heavy-Ion Jet INteraction Generator (HIJING) [32], which first produces minijets and soft excitation strings. These partons then undergo Lund string fragmentation to generate initial hadrons. The Lund string fragmentation model is a key component of AMPT for describing the hadronization process, with the fragmentation function determined by HIJING parameters a and b as: $f(z) \propto z^{-1}(1-z)^a \exp(-bm_\perp^2/z)$, where z is the light-cone momentum fraction of the produced hadron and $m_\perp$ is its transverse mass. (2) Under the string melting mechanism, these initial hadrons are dissociated into partons according to their flavor and spin structure, which then enter the subsequent parton cascade (Zhang' s Parton Cascade, ZPC) process [33]. The ZPC model calculates parton-parton scattering cross sections based on the Debye screening mass μ and strong coupling constant α_s: $\sigma_{gg} \approx 9\pi\alpha_s^2/\mu^2$. (3) After parton-parton scattering is complete, the partons enter the hadronization stage, where one (or two) partons closest in coordinate space combine to form hadrons. (4) The formed hadrons then undergo hadronic rescattering, which is handled by the A Relativistic Transport (ART) model [34] with scattering cross sections for baryon-baryon, baryon-meson, and meson-meson interaction channels.

In this study, we employ the AMPT model with string melting mechanism to simulate approximately 5 million events each for d-Au collisions at $\sqrt{s_{NN}} =$ 200 GeV and pp collisions at $\sqrt{s} = 200$ GeV. The collision centrality in d-Au collisions is determined by the impact parameter b in the AMPT simulations. To maintain consistency with experimental measurements used in this study and based on previous research and common classification standards in the literature [11], we define central collision event samples as 0–5% centrality events and peripheral collision event samples as 60–100% and 80–100% centrality events.

1.2 Definition of Anisotropic Flow

The magnitude of azimuthal anisotropy flow is quantified through the Fourier expansion of the particle azimuthal distribution, expressed as: $dN/d\varphi \propto 1 + 2\sum_n v_n(p_T)\cos[n(\varphi - \Psi_n)]$, where φ is the particle azimuthal angle, p_T is the particle transverse momentum, and Ψ_n is the reaction plane azimuthal angle in the laboratory frame. The anisotropic flow of produced particles is defined by the Fourier coefficients v_n. The first two coefficients of the Fourier expansion are directed flow v_1 and elliptic flow v_2. The second Fourier coefficient v_2 provides the dominant contribution to collision asymmetry [3,35-36] and encodes information about how the initial spatial anisotropy of the ellipsoidal (or almond-shaped) collision region is transferred to momentum space during QGP evolution, thereby affecting the particle azimuthal distribution. The observation of significant $v_2 > 0$ for final-state particles in high-energy heavy-ion collision experiments serves as an important signature for QGP formation.

2 Non-Flow Contribution Subtraction Method

The method of using two-particle correlations to extract azimuthal anisotropy flow has been extensively discussed in references [8-13,37-40]. This approach involves designating two correlated charged particles (denoted as h-h) as a trigger particle and an associated particle, with their correlation calculated in terms of relative azimuthal angle $\Delta\phi$ and pseudorapidity difference $\Delta\eta$.

Our analysis follows the methodology used in RHIC energy region experiments [14], employing AMPT-simulated events containing final-state charged hadrons with $0.5 < p_T < 3.5$ GeV/c, where each hadron pair includes at least one low-p_T particle ($0.5 < p_T < 0.75$ GeV/c). For each particle pair, the pseudorapidity difference in the center-of-mass frame is defined as $\Delta\eta = \eta_{\text{trig}} - \eta_{\text{assoc}}$, where η_{trig} and η_{assoc} are the pseudorapidities of the trigger and associated particles, respectively. The pseudorapidity difference range is set to $0.48 < |\Delta\eta| < 0.7$. The correlation is expressed as Y, defined as the associated yield per trigger particle: $Y = (1/N_{\text{trig}})dN_{\text{assoc}}/d\Delta\phi$, where N_{trig} is the total number of trigger particles and N_{assoc} is the total number of associated particles. We employ the zero-yield-at-minimum (ZYAM) method [41-42], which assumes that the two-particle correlation function reaches zero at its minimum.

The associated yields $Y_{0-5\%}$ in equation (2) are taken from 0–5% central d-Au collision events, $Y_{60-100\%}$ and $Y_{80-100\%}$ from 60-100% and 80-100% peripheral d-Au collision events respectively, and Y_{pp} from pp collision events. We define $\Delta Y_{\text{central-peripheral}}$ as the difference between central and peripheral d-Au collision yields, and $\Delta Y_{\text{central-pp}}$ as the difference between central d-Au and pp collision yields: $\Delta Y_{\text{central-peripheral}} = Y_{0-5\%} - Y_{\text{peripheral}}$ and $\Delta Y_{\text{central-pp}} = Y_{0-5\%} - Y_{pp}$. Both subtractions remove non-flow contributions, including jet fragments and resonance decays. We fit the non-flow-subtracted charged hadron yield distributions using equation (3), which exhibits two peaks centered at specific values $\Delta\phi = 0$ and $\Delta\phi = \pi$, to extract v_2:

$$\Delta Y = a_0 + 2\sum_n a_n \cos(n\Delta\phi)$$

We define c_n as the n-th order anisotropy coefficient: $c_n \equiv a_n/(b_{\text{ZYAM}} + a_0)$. Using the two-particle correlation method, the $v_n\{2PC\}$ coefficient for charged hadron h is defined as [11]:

$$v_n\{2PC\} = \sqrt{c_{h-h}}$$

3 Results and Discussion

Based on the particle correlation yield definition given by equation (2), Figure 1 [Figure 1: see original paper] presents the azimuthal distribution yields of final-state charged hadrons for 0–5% central d-Au collisions (green circles, $Y_{0-5\%}$) and pp collisions (blue squares, Y_{pp}) at pseudorapidity difference $0.48 < |\Delta\eta| < 0.7$ in the center-of-mass frame. Figure 1(a) shows both particles in the transverse momentum range $0.5 < p_T < 0.75$ GeV/c, while Figure 1(b) displays trigger particles with $0.5 < p_{T,\text{trig}} < 0.75$ GeV/c and associated particles with $1.25 < p_{T,\text{assoc}} < 1.5$ GeV/c. The black triangular markers show the difference $\Delta Y_{\text{central-pp}} = Y_{0-5\%} - Y_{pp}$, representing the modified yield of central d-Au collisions relative to pp collisions. To quantify this difference, we fit $\Delta Y_{\text{central-pp}}$ with the function $a_0 + 2a_2\cos(2\Delta\phi)$, shown as the red solid line.

Figure 2 [Figure 2: see original paper] compares the azimuthal distribution yields of final-state charged hadrons for 0–5% central d-Au collisions (green circles, $Y_{0-5\%}$) and 60–100% peripheral d-Au collisions (blue squares, $Y_{60-100\%}$) within the pseudorapidity difference range $0.48 < |\Delta\eta| < 0.7$. The black triangular markers show the difference $\Delta Y_{\text{central-peripheral}} = Y_{0-5\%} - Y_{60-100\%}$, representing the modified yield of central d-Au collisions relative to peripheral collisions. We quantify this difference using the same fitting function $a_0 + 2a_2\cos(2\Delta\phi)$, shown as the red solid line.

Analogous to Figure 2, Figure 3 [Figure 3: see original paper] presents the comparison of final-state charged hadron azimuthal distribution yields before and after non-flow effect removal for 80–100% peripheral d-Au collisions.

The results from Figures 1 through 3 clearly show that $Y_{0-5\%}$ is significantly larger than both $\Delta Y_{\text{central-peripheral}}$ and $\Delta Y_{\text{central-pp}}$ near relative azimuthal angles $\Delta\phi \approx 0$ and π, indicating substantial non-flow contributions in d-Au collisions at these angular separations. The statistical errors near $\Delta\phi = 0$ and π are relatively small, approximately 3%.

Based on equation (4), Figure 4 [Figure 4: see original paper] displays the second-order anisotropy coefficient c_2 for charged hadrons in 0–5% central d-Au collisions as a function of transverse momentum p_T. The red solid line represents the result for 0–5% central d-Au collisions without non-flow subtraction. The blue dashed, green dash-dotted, and pink long-dashed lines show the results after removing non-flow effects by subtracting yield distributions from pp collisions, 60–100% peripheral d-Au collisions, and 80–100% peripheral d-Au collisions, respectively.

In the $p_T > 1$ GeV/c region, the red solid line (with non-flow effects) lies above the blue dashed, green dash-dotted, and pink long-dashed lines (without non-flow effects), demonstrating that non-flow contributions have a noticeable impact on v_2 in d-Au collisions. After subtracting the per-trigger yields from either of the two different peripheral d-Au collision centralities (green dash-dotted and pink long-dashed lines) or from pp collisions (blue dashed line)—thereby removing non-flow effects from 0–5% central d-Au collisions—we find that all three results show nearly identical trends with p_T, indicating that the c_2 values are not significantly affected by the choice of subtraction method.

Using equation (5), Figure 5(a) [Figure 5: see original paper] presents the elliptic flow v_2 of charged hadrons in 0–5% central d-Au collisions as a function of p_T. The red solid line shows the v_2 distribution with non-flow effects for 0–5% central d-Au collisions. The elimination of non-flow effects is achieved by subtracting final-state charged hadron yield distributions from either peripheral d-Au or pp collisions, with the resulting v_2 distributions shown as blue dashed, green dash-dotted, and pink long-dashed lines. The black circular markers represent the v_2 measurements from PHENIX for 0–5% central d-Au collisions [15]. The charged hadron v_2 values increase with p_T, as particles in higher p_T regions are more susceptible to the influence of initial collision geometry anisotropy. The red solid line (including non-flow effects) is higher than the non-flow-subtracted results, theoretically confirming that non-flow effects influence elliptic flow v_2. The blue dashed, green dash-dotted, and pink long-dashed lines are very close to each other, indicating that in 0–5% central d-Au collisions, the impact of non-flow effects (such as jet correlations or resonance decays) on v_2 does not significantly depend on the subtraction method. Both approaches—subtracting yield distributions from peripheral d-Au collisions or from pp collisions—produce similar results. Comparing the charged hadron v_2 from AMPT calculations with that from PHENIX experimental data, we find that both show increasing v_2 with p_T, with small deviations between them, and that theoretical calculations after non-flow subtraction better describe the experimental data.

Figure 5(b) [Figure 5: see original paper] shows the v_2 ratio as a function of p_T from the AMPT model. The black dashed and red dash-dotted lines represent the ratios of v_2 obtained by subtracting 60–100% and 80–100% peripheral d-Au collision yields, respectively, from central d-Au collision yields, relative to

v_2 obtained by subtracting pp collision yields. The results show that, theoretically, the differences between the two non-flow removal methods are less than 2% and 1.4% across p_T up to 3.5 GeV/c when using 60–100% and 80–100% centrality peripheral collisions, respectively. This indicates that different subtraction schemes produce similar theoretical predictions. Additionally, the blue long-dashed line shows the ratio of v_2 from subtracting peripheral d-Au collision yields to v_2 without any subtraction, with a maximum deviation from unity of less than 6%, demonstrating that non-flow effects have a certain influence on elliptic flow in d-Au collisions. Notably, the blue long-dashed line shows slightly lower ratio values at higher p_T compared to lower p_T, with deviations from unity being somewhat larger at high p_T, suggesting that non-flow contributions may vary with p_T distribution due to different physical mechanisms contributing to particle production in different p_T ranges.

This study first provides a brief introduction to the AMPT model, then elaborates on the methodology and procedures for non-flow contribution subtraction. Finally, we present our research results and conduct an in-depth discussion and summary to provide a more comprehensive perspective on understanding non-flow contributions. In this work, the AMPT model is used to investigate the elliptic flow v_2 behavior in d-Au collisions at $\sqrt{s_{NN}} = 200$ GeV. We calculate two-particle relative azimuthal correlations for charged hadrons in 200 GeV d-Au collisions, finding that $Y_{0-5\%}$ is significantly larger than both $\Delta Y_{\text{central-peripheral}}$ and $\Delta Y_{\text{central-pp}}$ when the relative azimuthal angle $\Delta\phi$ approaches 0 and π. From these correlations, we extract the second-order coefficient v_2 as a function of p_T. Non-flow effects in central d-Au collisions are removed by subtracting final-state charged hadron yield distributions from peripheral d-Au collisions at 60–100% and 80–100% centrality or from pp collisions at $\sqrt{s} = 200$ GeV. Both non-flow removal methods yield nearly identical results, indicating that the impact of non-flow effects on v_2 does not significantly depend on whether one subtracts peripheral d-Au or pp collision yields. Furthermore, considering peripheral collisions at 60–100% and 80–100% centrality separately, we find that the two non-flow subtraction methods produce similar theoretical predictions.

Comparing charged hadron v_2 from AMPT calculations with PHENIX experimental data reveals that v_2 values increase with transverse momentum p_T, indicating that particles in higher p_T regions are more influenced by the initial collision geometry anisotropy. Analyzing the non-flow contribution ratio as a function of p_T provides deeper insight into the physics of particle production in heavy-ion collisions, as different physical mechanisms dominate in different p_T ranges. At low p_T, resonance decays may dominate, while at high p_T, jet-like correlations likely become the primary contribution.

This study, based on the AMPT model, simultaneously considers two non-flow subtraction methods in d-Au collisions and compares the effects of two different peripheral collision centralities on the results, theoretically demonstrating that subtracting either peripheral collisions or pp collisions yields similar results. Currently, this work only considers the influence of non-flow contributions on elliptic flow v_2 in d-Au collisions within the AMPT model. However, non-flow contributions also affect higher-order flow coefficients such as v_3. Extending the present methodology to systematically study the impact of non-flow contributions on v_3 in d-Au collisions within the AMPT model could provide additional theoretical references for researchers investigating non-flow subtraction methods in small collision systems.

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Note: Figure translations are in progress. See original paper for figures.