Study of Constituent Quark Scaling of Elliptic Flow in Proton-Lead Collisions Based on a Multi-Phase Transport Model

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Abstract

The elliptic flow constituent quark scaling phenomenon for final-state identified particles in high-energy heavy-ion collisions is regarded as one of the important signals revealing partonic anisotropic degrees of freedom. This study systematically investigates the elliptic flow v_2 of final-state light-flavor hadrons and their constituent quark scaling behavior in proton-lead collisions at a center-of-mass energy of 5.02 TeV using the A Multi-Phase Transport (AMPT) model. Based on the latest non-flow subtraction method, the AMPT model calculations well reproduce the experimental data. The results demonstrate that the parton cascade and quark recombination mechanism jointly dominate the constituent quark scaling phenomenon exhibited by final-state hadrons in the intermediate transverse momentum region. Furthermore, this study also examines the influence of the hadron rescattering mechanism and non-flow subtraction effects on the constituent quark scaling property in small-system collisions. These findings will provide further insights into the origin of collective behavior of final-state particles in small-system collisions.

Full Text

Preamble

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CNPC2023+ Study of the NCQ Scaling of Elliptic Flow in p–Pb Collisions with a Multiphase Transport Model

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Abstract

The number of constituent quark (NCQ) scaling of elliptic flow for identified particles in high-energy heavy-ion collisions is considered one of the important signals revealing partonic anisotropic degrees of freedom. In this study, we systematically investigate the elliptic flow v_2 of light-flavor hadrons and its NCQ scaling behavior in proton-lead collisions at a center-of-mass energy of 5.02 TeV using a multiphase transport model (AMPT). Based on the latest nonflow subtraction method, the AMPT model calculations reproduce experimental data well. The results demonstrate that the combination of parton cascade and quark recombination mechanisms dominates the NCQ scaling phenomenon exhibited by final-state hadrons in the intermediate transverse momentum region. Additionally, this work examines the effects of hadronic rescattering mechanisms and nonflow subtraction on NCQ scaling in small collision systems. These findings provide further insights into the origin of collective behavior of final-state particles in small systems.

Keywords: azimuthal anisotropy; small collision systems; transport model; nonflow effect
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Introduction

One of the primary goals of ultrarelativistic heavy-ion collision experiments is to investigate the existence and evolution of deconfined matter under extreme temperature or high net baryon density conditions [1-2], known as the quark-gluon plasma (QGP). The QGP is widely believed to have existed in the early universe a few microseconds after the Big Bang and to currently exist in the interior of dense neutron stars. Therefore, studying the QGP not only helps us understand the evolution history of the early universe but also reveals the fundamental composition of matter in the present world.

Among the many final-state observables in high-energy heavy-ion collision experiments, anisotropic flow [3-4] has been a focal point of research as an important probe reflecting the equation of state properties of quark matter and its hydrodynamic evolution characteristics. Influenced by the initial nuclear environment of incoming nucleons, event-by-event fluctuations, and pressure gradient anisotropy caused by collision geometry asymmetry, final-state particles produced in experiments exhibit azimuthal anisotropy. The azimuthal distribution of final-state particles can be expanded in a Fourier series [5-6]:

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_n v_n \cos[n(\varphi - \Psi_n)]$$

where φ is the azimuthal angle of final-state particles, Ψ_n is the n-th order event plane angle [7-8], and the expansion coefficients v_n are called anisotropic flow parameters. The second-order coefficient, v_2, known as the elliptic flow parameter, characterizes the magnitude of anisotropy in the azimuthal distribution in momentum space transferred from the initial spatial anisotropy of the almond-shaped collision region during QGP evolution. The magnitude of elliptic flow is highly sensitive to the fundamental transport properties of the QGP fireball, such as the temperature-dependent equation of state and the viscosity of quark matter [9-10]. Consequently, observing significant $v_2 > 0$ for final-state particles in high-energy heavy-ion collisions serves as one of the important criteria for QGP formation.

Over the past several decades, heavy-ion collision experiments at the Relativistic Heavy Ion Collider (RHIC) [11-13] and the Large Hadron Collider (LHC) [14-17] have conducted extensive measurements of elliptic flow, establishing a comprehensive paradigm for studying strongly coupled quark-gluon plasma. By extracting the ratio of shear viscosity to entropy density (η/s) and comparing it with hydrodynamic calculations, the quark-gluon plasma has been found to exhibit nearly perfect fluid behavior. Furthermore, measurements of identified particle elliptic flow in different transverse momentum (p_T) regions [18-19] reflect different physical mechanisms. In the low p_T region, elliptic flow exhibits a clear mass ordering effect: heavier particles (such as baryons) have smaller elliptic flow than lighter particles (such as mesons) at the same p_T. This effect is attributed to radial expansion of the QGP and is well explained by hydrodynamic calculations. In the intermediate transverse momentum region, particle elliptic flow shows different grouping phenomena according to hadron type (meson or baryon), which is typically interpreted as a signature of quark recombination or coalescence theory. These theories suggest that the elliptic flow v_2 of different hadrons, when scaled by the number of constituent quarks (NCQ or n_q) [20-21], exhibits approximately universal behavior:

$$\frac{v_2^B(p_T/3)}{3} = \frac{v_2^M(p_T/2)}{2}$$

where the superscript B (M) denotes baryons (mesons) composed of 3 (2) constituent quarks. This NCQ scaling remains valid when studying the dependence of v_2 on transverse kinetic energy $k_{ET} = m_T - m_0$.

Compared to heavy-ion collisions, proton-proton and proton-nucleus collision systems are generally considered not to produce QGP matter due to their smaller collision scales. However, in recent years, flow-like phenomena have also been observed in small system collisions at RHIC and LHC. The CMS, ATLAS, and ALICE experiments first observed long-range ridge structures in high-multiplicity proton-proton and proton-lead collisions, accompanied by significant nonflow elliptic flow v_2 [22-25]. In the intermediate transverse momentum region, the v_2 of identified particles exhibits NCQ scaling similar to that in heavy-ion collisions, but the underlying dominant mechanism remains unclear. Some studies based on final-state effects have extended hydrodynamic calculations from large to small systems, successfully describing the v_2 of final-state hadrons [26-28], but these theories rely on the strong assumption that sufficient scattering exists among constituents in small systems. On the other hand, the Color Glass Condensate (CGC) model and IP-Glasma model [29-30], which consider initial-state momentum correlations, can quantitatively describe certain collective behaviors of final-state particles in proton-lead collisions, but their dependence on collision system and rapidity remains inconclusive. Additionally, recent studies on parton escape mechanisms indicate that even few scattering events can generate sufficient azimuthal anisotropy, and this mechanism has been well validated in the AMPT model [31-32]. AMPT model calculations can quantitatively describe the v_2 of light-flavor hadrons in proton-lead collisions, with the nonequilibrium anisotropic parton escape mechanism making significant contributions [32].

This study employs the AMPT model to extend, for the first time, the calculation of v_2 for identified particles ($\pi^{\pm}$, $K^{\pm}$, $p(\bar{p})$) in $\sqrt{s_{NN}} = 5.02$ TeV proton-lead collisions up to a transverse momentum region of 8 GeV/c, and systematically investigates their NCQ scaling behavior. Additionally, this work explores the effects of key mechanisms in the AMPT model, such as quark cascade and hadronic rescattering, on elliptic flow and NCQ scaling in small collision systems. Furthermore, the impact of nonflow subtraction methods on the calculation results is also discussed in this work.

2.1 Multiphase Transport Model

This study employs the AMPT model with string melting mechanism (version v2.26t9b) [31,33] to calculate v_2 of final-state particles in 5.02 TeV proton-lead collisions. The AMPT model consists of four main processes: initial conditions, parton cascade, hadronization, and hadronic interactions. The initial conditions are generated by the Heavy Ion Jet INteraction Generator (HIJING) [34-35]. HIJING first produces minijets and soft excitation strings, which then generate initial hadrons through Lund string fragmentation. Under the string melting mechanism, these initial hadrons are "melted" into partons according to their flavor and spin structures, entering the subsequent parton cascade model [36] (Zhang's parton cascade, ZPC). The current parton cascade model only considers two-body elastic scattering processes, with the scattering cross-section given by:

$$\sigma_{gg} \approx \frac{9\pi\alpha_s^2}{2\mu^2}$$

In this work, the strong coupling constant α_s is set to 0.33, and the Debye screening mass μ is set to 2.2814 fm^{-1}, resulting in a total scattering cross-section σ of approximately 3 mb. As the Debye screening mass μ increases, the scattering cross-section σ gradually decreases and approaches 0. Therefore, this work also attempts to set μ to an extremely large value (such as 1×10^5) to make $\sigma \sim 0$, thereby investigating the effect of parton scattering processes on final-state collective flow.

After the scattering processes are completed, partons enter the hadronization stage [31], where they combine with the nearest one (or two) parton(s) to form mesons (or baryons). These hadrons formed through hadronization then enter the subsequent hadronic rescattering stage, which is described by a relativistic transport (ART) model containing baryon-baryon, baryon-meson, and meson-meson interactions. The hadron scattering time is set to $t_{\max} = 30$ fm/c by default. Additionally, this work also tests the case with $t_{\max} = 0.4$ fm/c to study the effect of hadronic scattering processes on particle collective behavior. In this configuration, hadrons essentially do not scatter, but resonance decay processes are still retained in the model [37].

2.2 Two-Particle Correlation Function and Nonflow Subtraction

The two-particle correlation function (2PC) is one of the commonly used methods for calculating elliptic flow signals, and it has been widely applied in small-system collision measurements due to its good performance in subtracting nonflow backgrounds [38]. Similar to Eq. (1), the observed two-particle correlation function $C(\Delta\varphi)$ can be expressed as a function of the number of particle pairs (N_{pairs}) varying with the azimuthal angle difference $\Delta\varphi = \varphi_a - \varphi_b$ between two particles (denoted as particles a and b), and can be expanded in a Fourier series:

$$C(\Delta\varphi) = \frac{dN_{\text{pair}}}{d\Delta\varphi} \propto 1 + 2\sum_n V_n^{\Delta}(p_T^a, p_T^b)\cos(n\Delta\varphi)$$

where $V_n^{\Delta}(p_T^a, p_T^b)$ represents the two-particle n-th order harmonic. Since particle emissions are independent in the absence of nonflow contributions, according to the factorization theorem, $V_n^{\Delta}(p_T^a, p_T^b)$ can be expressed as the product of single-particle flows $v_n(p_T^a)$ and $v_n(p_T^b)$:

$$V_n^{\Delta}(p_T^a, p_T^b) = v_n(p_T^a)v_n(p_T^b)$$

Therefore, the flow v_n of single particle a can be calculated using the 3×2PC method proposed by the PHENIX experiment [39], which constructs three mutually correlated particle groups (denoted as a, b, c) and extracts flow coefficients through their combinations:

$$v_n(p_T^a) = \frac{V_n^{\Delta}(p_T^a, p_T^b)V_n^{\Delta}(p_T^a, p_T^c)}{V_n^{\Delta}(p_T^b, p_T^c)}$$

In small collision systems, the main sources of nonflow are jet correlations and resonance decays. Short-range jet correlations and resonance decays can be removed by introducing sufficiently large rapidity gaps in the 3×2PC method, while the contribution of long-range jet correlations needs to be estimated using peripheral collision events [40]. In this work, we adopt the Template Fit method developed by the ATLAS experiment [41] to remove nonflow contributions. In this method, the correlation function distribution obtained in high-multiplicity events, $C_{\mathrm{HM}}(\Delta\varphi)$, is generally assumed to be fitted by scaling the correlation function from low-multiplicity events by a factor F and superimposing it with $\cos(n\Delta\varphi)$ $(n > 1)$:

$$C(\Delta\varphi) = F \cdot C_{\mathrm{LM}}(\Delta\varphi) + G(1 + 2V_n^{\Delta}\cos(n\Delta\varphi))$$

where G is a normalization factor to ensure that the integral of $C(\Delta\varphi)$ equals that of $C_{\mathrm{HM}}(\Delta\varphi)$.

To directly compare with ALICE experimental data, this work studies particles in the central pseudorapidity region $-0.8 < \eta < 0.8$, which matches the coverage of the Time Projection Chamber (TPC) in the ALICE experiment. Based on the 3×2PC method, this study constructs three long-range correlations between particles in the forward region ($-4 < \eta < -2.5$), backward region ($2.5 < \eta < 4$), and central region ($-0.8 < \eta < 0.8$): central-forward correlation (CF, $-4.8 < \Delta\eta < -1.7$), central-backward correlation (CB, $1.7 < \Delta\eta < 4.8$), and forward-backward correlation (FB, $-8 < \eta < -5$). From these, $V_2^{\Delta}(\mathrm{CF})$, $V_2^{\Delta}(\mathrm{CB})$, and $V_2^{\Delta}(\mathrm{FB})$ are calculated. Therefore, the final-state particle v_2 in a given p_T interval is calculated as:

$$v_2(p_T^a) = \sqrt{\frac{V_2^{\Delta}(\mathrm{CF})V_2^{\Delta}(\mathrm{CB})}{V_2^{\Delta}(\mathrm{FB})}}$$

Additionally, the collision centrality in this study is defined by counting the number of particles within the pseudorapidity acceptance of the ALICE V0A detector [42] ($2.8 < \eta < 5.1$).

3 Results and Discussion

Figure 1 [Figure 1: see original paper] shows the AMPT model calculations of v_2 as a function of transverse momentum p_T for charged hadrons $h^{\pm}$, $K^{\pm}$ mesons, $\pi^{\pm}$ mesons, and protons $P(\bar{P})$ in high-multiplicity (centrality 0–20%) proton-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results compare two cases: with nonflow subtraction (Template Fit) and without nonflow subtraction (Direct Fourier). It can be seen that the Template Fit method effectively suppresses contributions from nonflow signals such as long-range jets, with this contribution increasing with transverse momentum. After subtracting nonflow contributions, the AMPT model still yields significantly non-zero v_2 for $K^{\pm}$, $\pi^{\pm}$, and $P(\bar{P})$ over a wide transverse momentum range ($0 < p_T < 8$ GeV/c). In the low p_T region ($0 < p_T < 2$ GeV/c), the AMPT model successfully reproduces the mass ordering effect [43], where $v_2(K^{\pm}) \approx v_2(\pi^{\pm}) > v_2(P(\bar{P}))$, indicating that non-hydrodynamic mechanisms (such as the parton escape mechanism) in the AMPT model can also produce radial flow-like signals. In the intermediate p_T region ($2 < p_T < 5$ GeV/c), the v_2 of baryons and mesons shows clear separation, with $v_2(P(\bar{P})) > v_2(K^{\pm}) \approx v_2(\pi^{\pm})$, demonstrating that the baryon-meson grouping phenomenon is also reproduced in the AMPT model. At higher p_T ($p_T > 5$ GeV/c), the v_2 of various final-state particles tends to converge, suggesting that the physical mechanism dominating v_2 for high-p_T particles in small systems may be independent of particle species.

Figure 2 [Figure 2: see original paper] compares the AMPT model calculations with ALICE experimental measurements for v_2 of $h^{\pm}$, $K^{\pm}$, $\pi^{\pm}$, and $P(\bar{P})$ in high-multiplicity (centrality 0–20%) proton-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV. After nonflow background subtraction, the AMPT model results provide a good description of the experimentally observed v_2 for $h^{\pm}$, $K^{\pm}$, and $\pi^{\pm}$. However, for $P(\bar{P})$, the theoretical calculations are slightly higher than experimental results in the $p_T < 2$ GeV/c region, possibly due to limitations in the hadronization mechanism of the current AMPT version. The present hadronization mechanism tends to first combine nearby quarks into mesons before forming baryons from remaining quarks, which may cause deviations in both baryon yields and collective flow compared to experimental data. Nevertheless, the overall trend of the AMPT model calculations still agrees with experimental measurements, indicating that the AMPT model and parameter configuration used in this work can qualitatively reproduce experimental results.

Figure 3 [Figure 3: see original paper] presents the AMPT model results for v_2 of $K^{\pm}$ mesons, $\pi^{\pm}$ mesons, and protons $P(\bar{P})$ scaled by the number of constituent quarks (n_q) as a function of k_{ET}/n_q in high-multiplicity (centrality 0–20%) proton-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV, where $n_q = 3$ for baryons and $n_q = 2$ for mesons. After NCQ scaling, all particles show similar v_2 values in the range $k_{ET}/n_q < 1$ GeV, confirming the existence of quark degrees of freedom in the fluid-like matter within the transport model framework. However, the NCQ scaling behavior breaks down when $k_{ET}/n_q > 1$ GeV. This may be partly because in the current AMPT version, baryon formation through quark recombination only occurs after meson formation [44], and partly because the elliptic flow generation mechanism for high-p_T particles is completely different from that at low and intermediate p_T. Future upgrades to the AMPT model will help clarify this issue.

To further quantify the degree of NCQ scaling and study the underlying mechanisms affecting this behavior, this work introduces the following quantity based on previous studies [37]:

$$\chi = \frac{v_2^K/n_K^q - v_2^\pi/n_\pi^q}{v_2^\pi/n_\pi^q} - \frac{v_2^P/n_P^q - v_2^\pi/n_\pi^q}{v_2^\pi/n_\pi^q}$$

where v_2 represents the integrated flow in the range $0.4 < k_{ET} < 1$ GeV. Smaller χ values indicate better agreement with NCQ scaling, while larger values indicate more severe violation of NCQ scaling. Figure 4 [Figure 4: see original paper] shows the centrality dependence of χ calculated with AMPT models with and without hadronic rescattering in 5.02 TeV proton-lead collisions. The χ value gradually decreases from central to peripheral collisions, indicating better NCQ scaling in more peripheral collisions, consistent with previous findings in heavy-ion collision systems [37]. After nonflow subtraction, the χ value becomes closer to 0, demonstrating that nonflow contributions are a source of NCQ scaling violation. On the other hand, when hadronic rescattering effects are included in the AMPT model, the calculated χ is larger than that obtained without hadronic rescattering, indicating that hadronic rescattering processes in small collision systems also increase the degree of NCQ scaling violation, consistent with previous studies in heavy-ion collision systems [37].

To further investigate the physical mechanisms dominating final-state particle elliptic anisotropy in small collision systems, we examine the effect of parton scattering processes on V_2^{Δ} (see Eq. 8) in the AMPT model. Figure 5 [Figure 5: see original paper] shows the AMPT model calculations of V_2^{Δ}(CF) and V_2^{Δ}(CB) for charged hadrons as a function of p_T in $\sqrt{s_{NN}} = 5.02$ TeV proton-lead collisions, with and without parton scattering processes. When parton scattering is turned off ($\sigma \sim 0$), the V_2^{Δ} of charged particles becomes nearly zero. This demonstrates that in high-multiplicity small collision systems, the elliptic anisotropy of final-state particles primarily originates from parton scattering. These studies show that even with few parton scattering events in small collision systems, significant elliptic anisotropy can be generated through escape mechanisms [32].

Conclusion

This work systematically studies the elliptic flow v_2 of identified particles ($K^{\pm}$ mesons, $\pi^{\pm}$ mesons, protons $P(\bar{P})$) in $\sqrt{s_{NN}} = 5.02$ TeV proton-lead collisions using the AMPT model. Based on the latest nonflow subtraction method, we extend, for the first time in AMPT model calculations, the identified particle v_2 in high-multiplicity proton-lead collisions up to a transverse momentum region of 8 GeV/c, and successfully reproduce NCQ scaling. The study reveals that NCQ scaling in small collision systems depends on both nonflow effects and hadronic rescattering processes, while parton scattering processes constitute the primary source of elliptic anisotropy in final-state particles. Overall, this work provides new insights and perspectives for understanding the origin of partonic collectivity in small collision systems.

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