Mean Transverse Momentum of Identified Particles in Relativistic Heavy-Ion Collisions

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Abstract

In relativistic nucleus-nucleus (A+A) collisions, the average transverse momentum p_T of particles constitutes an important experimental observable, reflecting the characteristics of soft hadrons and the properties of hot nuclear matter. Systematic investigations of this quantity facilitate the acquisition of evolution information regarding the collision system. Utilizing experimental data for final-state particles in the mid-rapidity region of relativistic nucleus-nucleus collisions provided by the STAR experiment at the Relativistic Heavy Ion Collider (RHIC) in Long Island, USA, and the ALICE experiment at the Large Hadron Collider (LHC) in Geneva, Europe—including gold-gold (Au+Au), copper-copper (Cu+Cu), uranium-uranium (U+U), and lead-lead (Pb+Pb) collisions—phenomenological formulas are employed to fit the dependence of final-state particle average transverse momentum on collision centrality, particle mass, and collision energy, thereby satisfactorily describing the existing experimental data. Systematic studies confirm that the linear relationship between the average transverse momentum of identified final-state particles and collision centrality exhibits universality, establishing collision centrality as a preferred physical quantity for investigating particle average transverse momentum. Furthermore, the fitting parameters of the phenomenological functional formula describing particle average transverse momentum as a function of collision centrality also display universality in their adherence to a power-law relationship with collision energy. At identical collision energies and within the same system, the average transverse momentum of identified particles qualitatively satisfies a linear relationship with particle mass, although data for a small number of particles deviate from this linear relationship, potentially attributable to details of the particle production mechanism. Additionally, under identical collision centrality conditions, the dependence of identified particle average transverse momentum on the logarithm of collision energy follows a power-law relationship characterized by universality.

Full Text

Average Transverse Momenta of Identified Particles in Relativistic Nucleus-Nucleus Collisions

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Abstract
The average transverse momentum of identified particles is a crucial experimental observable in relativistic nucleus-nucleus (A+A) collisions, reflecting both the properties of soft hadrons and the characteristics of hot nuclear matter. Systematic investigation of this quantity provides valuable insights into the evolution of the collision system. Using publicly available experimental data from the STAR experiment at the Relativistic Heavy Ion Collider (RHIC) on Long Island, USA, and the ALICE experiment at the Large Hadron Collider (LHC) in Geneva, Europe, we have analyzed relativistic nucleus-nucleus collisions including Au+Au, Cu+Cu, U+U, and Pb+Pb systems. By applying phenomenological formulas to fit the dependence of final-state particle average transverse momentum on collision centrality, particle mass, and collision energy, we achieve excellent descriptions of the existing experimental data. Our systematic study confirms the universal linear relationship between the average transverse momentum of identified particles and collision centrality, establishing centrality as a preferred physical quantity for studying particle transverse momentum. Furthermore, the fitting parameters of the phenomenological function for average transverse momentum versus centrality exhibit a universal power-law relationship with collision energy. For a given collision energy and system, the average transverse momentum of identified particles shows a qualitative linear dependence on particle mass, though some particle species deviate from this trend, likely reflecting details of their production mechanisms. Additionally, at fixed centrality, the average transverse momentum of identified particles follows a universal power-law dependence on the logarithm of collision energy.

Keywords: A+A collisions, Average transverse momentum, Identified particle, Midrapidity

Chinese Classification: TL99

Quantum chromodynamics predicts that under extreme conditions of high temperature and density, quarks and gluons within nucleons become deconfined, forming a new state of matter called the Quark-Gluon Plasma (QGP) [1,2]. This novel matter state may have existed in the early universe microseconds after the Big Bang, and its study provides crucial insights into cosmic origins and evolution. The primary physics goals of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) and the Large Hadron Collider (LHC) at CERN include creating QGP through relativistic nucleus-nucleus collisions and investigating its properties [3–7]. To date, the RHIC-STAR experiment has completed two beam energy scan (BES) programs for Au+Au, U+U, and Cu+Cu collisions [5,6,8–16], while the LHC-ALICE experiment has conducted Pb+Pb and Xe+Xe collisions at center-of-mass energies per nucleon pair of 2.76, 5.02, and 5.44 TeV [7,17–25].

Experiments accelerate atomic nuclei to near-light speeds and collide them to create the extreme temperature and density conditions required for quark-gluon deconfinement and QGP formation [5,7,15,26,27]. By accelerating different projectile-target combinations and varying the center-of-mass collision energy, researchers can explore diverse QGP environments. Collision events are categorized by centrality for systematic study. Numerous experimental signatures now indirectly indicate QGP production in relativistic nucleus-nucleus collisions, including constituent quark number scaling of hadronic elliptic flow [28–31], jet quenching [32–34], baryon temperature scaling behavior [35,36], and hyperon polarization effects [37,38]. Since QGP cannot be directly detected due to color confinement, experimentalists measure and analyze final-state particle information, combining theoretical calculations or computer simulations to investigate QGP properties. Physicists construct various models to simulate relativistic nucleus-nucleus collision processes, comparing results with experimental measurements to explore collision system dynamics, properties, and particle production mechanisms [39–51]. Additionally, phenomenological description of experimental observables and identification of underlying patterns constitute important approaches in high-energy nuclear collision physics, yielding significant achievements [52–63]. Machine learning and artificial intelligence are emerging as powerful tools for scientific research, promising new opportunities for phenomenological studies in relativistic nucleus-nucleus collisions [64–70].

The average transverse momentum represents a key observable in relativistic nucleus-nucleus collision physics. Van Hove first introduced this concept [71,72], emphasizing that the relationship between mean transverse momentum and hadron multiplicity in high-energy proton-antiproton collisions could reveal phase transition characteristics. In reference [73], the average transverse momentum of charged particles was used to study the speed of sound in QGP produced in peripheral relativistic nucleus-nucleus collisions. After years of successful operation, RHIC and LHC have accumulated rich experimental datasets [5–25], enabling systematic studies of particle transverse momentum dependencies on collision energy, particle species, and other relevant quantities. This provides an experimental foundation for investigating the state, properties, and dynamical evolution characteristics of quark-gluon plasma matter under extreme conditions [6,8,19,20,40,52,64,65,74].

Olimov and collaborators discovered through phenomenological studies [75,76] that the average transverse momentum of particles produced in relativistic nucleus-nucleus collisions follows power-law relationships with charged particle pseudorapidity density, total average number of collisions, and total average number of participating nucleons. However, these physical quantities lack normalization, preventing direct comparison across different collision systems. In our previous work [77], we investigated the relationship between identified particle average transverse momentum (π^-, K^-, and antiprotons) and normalized quantities including collision centrality, average number of collisions per nucleon pair, average charged particle pseudorapidity density per nucleon pair, and average charged particle pseudorapidity density per collision. The results demonstrated linear dependence on collision centrality and power-law relationships with the other normalized quantities. Given that the fitting parameters for the phenomenological formulas describing average transverse momentum versus centrality and versus average collisions per nucleon pair exhibit excellent power-law behavior with collision energy, this phenomenological approach gains predictive capability. Consequently, we concluded that these two normalized quantities are preferred variables for studying particle transverse momentum. In practice, calculating the average number of collisions per nucleon pair requires knowledge of both the average number of participating nucleons and the average number of collisions, making centrality the more practical choice.

This paper examines all available identified particle average transverse momentum data from RHIC-STAR and LHC-ALICE across different collision systems to investigate the universality of the linear relationship between particle transverse momentum and collision centrality. We also test whether the power-law relationship between fitting parameters and collision energy is universal. At fixed collision energy and centrality, we analyze correlations between particle transverse momentum and mass to verify the qualitative mass-ordering relationship. Finally, at given centrality, we explore the energy dependence of identified particle transverse momentum to establish systematic patterns. The paper is organized as follows: Section 1 presents the experimental data sources and phenomenological formulas; Section 2 provides fitting results for identified particle transverse momentum versus centrality, mass, and collision energy, along with discussions; Section 3 summarizes our work and conclusions.

1. Experimental Data and Fitting Formulas

All data used in this analysis are publicly available from the STAR experiment at RHIC and the ALICE experiment at LHC, covering Au+Au collisions at 7.7-200 GeV, Cu+Cu collisions at 62.4 and 200 GeV, U+U collisions at 193 GeV, and Pb+Pb collisions at 2.76 and 5.02 TeV [5-24]. The identified particle average transverse momentum $\langle p_T \rangle$ is an experimentally measured quantity, while collision centrality C (Centrality $\times$ 100) is calculated by experimental groups using Monte Carlo Glauber model simulations of charged particle multiplicity distributions.

Our selection principle for phenomenological formulas prioritizes minimal free parameters (two per formula) and adopts forms widely used in high-energy physics phenomenology. To study $\langle p_T \rangle$ for final-state identified particles in A+A collisions across different energies and centralities, we employ a linear function:

$$\langle p_T \rangle = a_1 \cdot C + b_1 \tag{1}$$

At fixed collision system, energy, and centrality, a linear function describes the dependence on particle mass M:

$$\langle p_T \rangle = a_2 \cdot M + b_2 \tag{2}$$

After specifying particle type and centrality, an exponential function describes the collision energy dependence:

$$\langle p_T \rangle = a_3 \cdot \ln(s) + b_3 \tag{3}$$

where s is the center-of-mass collision energy per nucleon pair in GeV, and $\ln(s)$ is dimensionless. In equations (1)-(3), a_i and b_i (for $i = 1, 2, 3$) are free fitting parameters. Under given conditions, these formulas describe the relationship between $\langle p_T \rangle$ and centrality C, particle mass M, and collision energy s, respectively. Throughout all studied relativistic nucleus-nucleus collisions, particle and antiparticle average transverse momenta are nearly identical, so we consider only particles or antiparticles in our analysis.

2. Results and Discussion

2.1 Average Transverse Momentum and Centrality

In relativistic nucleus-nucleus collisions, centrality characterizes the collision geometry and overlap region, serving as an advantageous variable for studying the evolution and interactions of produced matter. Using equation (1), we fit the centrality dependence of midrapidity identified particle transverse momentum for Au+Au collisions at 7.7-200 GeV, Cu+Cu collisions at 62.4 and 200 GeV, and Pb+Pb collisions at 2.76 and 5.02 TeV. Figures 1 [Figure 1: see original paper] and 2 [Figure 2: see original paper] display experimental data points and fitting curves from equation (1), showing representative results for selected collision systems and energies (unshown results are similar). Corresponding fitting parameters and χ^2/ndf values are listed in Appendix Table A1.

The results demonstrate a universal linear relationship between identified particle average transverse momentum and collision centrality, independent of collision energy and system, confirming our previous conclusion [77] that centrality is a preferred physical quantity for studying $\langle p_T \rangle$. All slope parameters are negative, indicating anticorrelation between $\langle p_T \rangle$ and centrality. This reflects decreasing energy density, temperature, and average collisions per nucleon pair as centrality increases from central to peripheral collisions. The slope magnitude $|a_1|$ represents the rate of $\langle p_T \rangle$ change with centrality; values closer to zero indicate weaker dependence. A clear mass-ordering emerges in the centrality dependence: lighter particles show weaker centrality dependence than heavier particles, consistent with our earlier findings [77]. Different production times for particles of different masses explain this trend—heavy particles form early due to energy conservation, while light particles can be produced throughout the collision evolution. Section 2.2 revisits the mass dependence at fixed energy and centrality.

Due to limited systematic data availability, Figure 3 [Figure 3: see original paper] only shows the collision energy dependence of fitting parameters (slope magnitude $|a_1|$ and intercept b_1) for π^-, K^-, p, ϕ, and d. The points represent fitted parameters, while curves show power-law function $f(s) = a \cdot s^b$ fits. Excellent power-law relationships exist between fitting parameters and collision energy, endowing equation (1) with predictive power for identified particle $\langle p_T \rangle$ in relativistic nucleus-nucleus collisions. This confirms the universality of power-law parameter-energy relationships [77]. At fixed collision energy, both $|a_1|$ and b_1 exhibit mass ordering, increasing with collision energy.

2.2 Average Transverse Momentum and Particle Mass

Previous observations from π^-, K^-, and antiproton data reveal significant mass ordering in identified particle average transverse momentum [6,8-10,12,16,18,19,23,24,26,75-77]. Our earlier work [77] attributed this to production time differences—heavy particles emerge early due to energy conservation, while light particles form throughout the system evolution. To further validate this interpretation, we systematically analyze the mass dependence of identified particle $\langle p_T \rangle$.

Figure 4 [Figure 4: see original paper] presents linear fits using equation (2) for identified particle $\langle p_T \rangle$ versus mass M at fixed centrality in Au+Au collisions (7.7-200 GeV) and Pb+Pb collisions (2.76 and 5.02 TeV. Particles shown separately in subpanels have slightly different centrality ranges. Data points represent experimental measurements, while curves show equation (2) fits. Only representative results for most central collisions at selected energies are displayed (other energies and centralities yield similar patterns). Corresponding fitting parameters and χ^2/ndf values appear in Appendix Table A2.

The results show that $\langle p_T \rangle$ qualitatively follows a linear relationship with particle mass. Positive slope parameters a_2 indicate increasing $\langle p_T \rangle$ with mass. Some particles exhibit slight deviations from the linear trend, possibly related to details of their production mechanisms. Notably, experimental results at 13 TeV inelastic p+p collisions show separate classifications for meson and baryon average transverse momenta [78], a phenomenon not observed in relativistic nucleus-nucleus collisions. This may reflect nuclear medium effects in nucleus-nucleus collisions and warrants further comparative analysis in future work.

Figure 5 [Figure 5: see original paper] displays the collision energy dependence of fitting parameters (slope a_2 and intercept b_2) for $\langle p_T \rangle$ versus mass at centrality 0–5%. Both parameters increase with collision energy, following power-law relationships. Parameter a_2 reflects the growth rate of $\langle p_T \rangle$ with mass, which increases with collision energy. Parameter b_2 shows weak centrality dependence but also follows a power-law with collision energy, though slight deviations appear at 130 GeV and 200 GeV. This indicates that overall $\langle p_T \rangle$ increases with collision energy, discussed further in Section 2.3.

2.3 Average Transverse Momentum and Collision Energy

Center-of-mass collision energy is a critical degree of freedom in relativistic nucleus-nucleus collisions. Varying the collision energy helps explore QGP phase transitions, particle production mechanisms, and collision system dynamics. Limited by available experimental data, our analysis of $\langle p_T \rangle$ energy dependence focuses on five particle species: π^-, K^-, $\bar{p}$, K^{*0}, and d. Using equation (3), we fit the energy dependence of midrapidity $\langle p_T \rangle$ for collision energies from 7.7 to 5020 GeV at fixed centrality. Collision energy is plotted logarithmically to better visualize the relationship. Figure 6 [Figure 6: see original paper] shows experimental data and equation (3) fits, with fitting parameters and χ^2/ndf values in Appendix Table A3.

The exponential function provides excellent fits, demonstrating universal behavior for identified particle $\langle p_T \rangle$ versus collision energy. Figure 7 [Figure 7: see original paper] presents the centrality dependence of fitting parameters (coefficient a_3 and base b_3) for π^-, K^-, $\bar{p}$, and d. Parameter a_3 decreases linearly with centrality, consistent with the observation that $\langle p_T \rangle$ decreases with increasing centrality (Section 2.1). Parameter b_3 remains approximately constant across centralities, indicating that the energy dependence pattern is consistent for a given particle species regardless of centrality.

3. Conclusions

Using linear functions (1) and (2), exponential function (3), and identified particle average transverse momentum data from RHIC-STAR and LHC-ALICE, we have analyzed the dependence of midrapidity identified particle $\langle p_T \rangle$ on collision centrality C, particle mass M, and collision energy s under specified conditions. The results demonstrate universal linearity between identified particle $\langle p_T \rangle$ and collision centrality, establishing centrality as a preferred variable. The universal power-law relationship between fitting parameters of equation (1) and collision energy endows the formula with predictive capability.

At fixed collision energy and centrality, identified particle $\langle p_T \rangle$ shows qualitative linear dependence on particle mass (equation (2)), with minor deviations for some particles possibly related to production mechanism details. The mass dependence can be explained by different production timescales for particles of different masses in the collision system. At fixed centrality and particle species, the energy dependence follows the universal exponential relationship of equation (3), with positive correlation between $\langle p_T \rangle$ and collision energy. The coefficient a_3 decreases linearly with centrality, consistent with the centrality dependence of $\langle p_T \rangle$, while parameter b_3 shows weak centrality dependence, remaining approximately constant and indicating consistent energy evolution patterns across centralities. The universal patterns revealed for final-state identified particle $\langle p_T \rangle$ in relativistic nucleus-nucleus collisions provide new perspectives for understanding QGP evolution and properties.

Author Contributions: XIE Zhen collected data, performed analysis, and wrote the manuscript; ZHENG Hua supervised the analysis and revised the manuscript; ZHANG Wenchao, ZHU Lilin, LIU Xingquan, TAN Zhiguang, ZHOU Daimei, and Bonasera Aldo reviewed and edited the manuscript.

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Appendix A: Fitting Parameter Tables

Table A1 Fitting parameters from Eq. (1) for $\langle p_T \rangle$ versus centrality C and corresponding χ^2/ndf

Collision System, Energy	Particle	Slope a_1 (GeV/c^{-1})	Intercept b_1 (GeV/c^{-1})	χ^2/ndf
Au+Au, 7.7 GeV	π^-	$-2.66 \times 10^{-3} \pm 1.25 \times 10^{-3}$	0.776 ± 0.072	0.514/3
Au+Au, 7.7 GeV	K^-	$-6.94 \times 10^{-3} \pm 1.39 \times 10^{-3}$	1.317 ± 0.065	0.189/3
Au+Au, 7.7 GeV	$\bar{p}$	$-2.64 \times 10^{-3} \pm 1.24 \times 10^{-3}$	0.799 ± 0.055	0.382/4
...	...	...	...	...

Table A2 Fitting parameters from Eq. (2) for $\langle p_T \rangle$ versus particle mass M and corresponding χ^2/ndf

Collision System, Energy	Centrality	Slope a_2	Intercept b_2 (GeV/c^{-1})	χ^2/ndf
Au+Au, 7.7 GeV	5-10%	0.497 ± 0.040	0.302 ± 0.020	0.392/3
Au+Au, 7.7 GeV	10-20%	0.495 ± 0.040	0.298 ± 0.020	0.505/3
...	...	...	...	...

Table A3 Fitting parameters from Eq. (3) for $\langle p_T \rangle$ versus collision energy and corresponding χ^2/ndf

Particle	Centrality	Coefficient a_3 (GeV/c^{-1})	Base b_3	χ^2/ndf
π^-	5-10%	0.325 ± 0.011	1.060 ± 0.007	4.209/8
π^-	10-20%	0.317 ± 0.010	1.067 ± 0.006	5.805/8
…	…	…	…	…

Note: Complete tables with all parameter values are available in the original publication.

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