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

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Abstract

In relativistic nucleus-nucleus (A+A) collisions, the average transverse momentum of particles p_T is an important experimental observable that reflects the characteristics of soft hadrons and the properties of hot nuclear matter, and systematic studies of this quantity help obtain evolution information of the collision system. Utilizing experimental data for final-state particles in the mid-rapidity region from relativistic nucleus-nucleus collisions provided by the STAR experiment at the Relativistic Heavy Ion Collider (RHIC) located on 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 applied to fit the dependence of the average transverse momentum of final-state particles on collision centrality, particle mass, and collision energy, each providing a reasonable description of the existing experimental data. Systematic studies confirm that the linear relationship between the average transverse momentum of identified final-state particles and collision centrality possesses universality, and collision centrality is a preferred physical quantity for studying particle average transverse momentum. Meanwhile, the fitting parameters of the phenomenological function formula for particle average transverse momentum versus collision centrality also satisfy a universal power-law relationship with collision energy. At the same collision energy and system, the average transverse momentum of identified particles qualitatively satisfies a linear relationship with particle mass, though data for a few particles deviate from this linear relationship, which may be related to details of the particle production mechanism. Meanwhile, at the same collision centrality, the dependence of the average transverse momentum of identified particles on the logarithm of collision energy follows a power-law relationship and exhibits universality.

Full Text

Preamble

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

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Abstract
[Background] The average transverse momentum of identified particles is an important observable in relativistic nucleus-nucleus collision experiments, reflecting the properties of hot matter created in the collisions and the characteristics of soft hadrons. [Purpose] Systematic investigation of this quantity can deepen our understanding and help extract information about the evolution of the collision system. [Methods] Using phenomenological linear and exponential functions, we studied the dependence of the average transverse momenta of identified particles produced at midrapidity in relativistic nucleus-nucleus collisions on collision centrality, particle mass, and collision energy under given conditions. The analysis includes data from Au+Au, Cu+Cu, and U+U collisions provided by the STAR Collaboration at the Relativistic Heavy Ion Collider (RHIC), and from Pb+Pb collisions provided by the ALICE Collaboration at the Large Hadron Collider (LHC). [Results & Conclusions] The systematic study shows that the good linear relationship between the average transverse momenta of identified particles and collision centrality is universal. Therefore, collision centrality is a good physical quantity for studying the average transverse momenta of identified particles in relativistic nucleus-nucleus collisions. It is also found that the fitting parameters of the linear function for the average transverse momentum with collision centrality follow a power-law relationship with collision energy, which is universal as well. For a given collision energy and centrality, the average transverse momenta of identified particles have a linear relationship with particle mass qualitatively. A few data points deviate from this linear rela-

tionship, which may be related to the details of their production mechanisms. Meanwhile, the average transverse momentum of a given identified particle follows an exponential relationship with the logarithm of the collision energy at a given centrality, which is also universal.

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

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Introduction

Quantum Chromodynamics (QCD) predicts that under extreme conditions of high temperature and density, quarks and gluons within nucleons become deconfined, producing a new form of matter called the Quark-Gluon Plasma (QGP) [?, ?]. This novel state of matter may have existed in the early universe microseconds after the Big Bang, and its study can help us understand the origin and evolution of the universe. One of the primary physics goals of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) and the Large Hadron Collider (LHC) at CERN is to create QGP through relativistic nucleus-nucleus collisions and investigate its properties \cite{3-7}. Currently, the RHIC-STAR experiment has completed Beam Energy Scan (BES) programs for Au+Au, U+U, and Cu+Cu collisions \cite{5,6,8-16}, while the LHC-ALICE experiment has completed Pb+Pb and Xe+Xe collisions at center-of-mass energies per nucleon pair of 2.76, 5.02, and 5.44 TeV \cite{7,17-25}.

Experimentally, large particle accelerators accelerate atomic nuclei to near-light speeds and collide them to create the high-temperature, high-density conditions for quark-gluon deconfinement and QGP production [?, ?, ?, ?, ?]. By accelerating different projectile and target nuclei and varying the collision center-of-mass energy, researchers can obtain different environments for studying QGP. Collision events are categorized by different centralities for analysis. Many experimental signals have indirectly indicated QGP production in relativistic nucleus-nucleus collisions, such as the constituent quark number scaling of hadron elliptic flow \cite{28-31}, jet quenching \cite{32-34}, baryon temperature scaling [?, ?], and hyperon polarization effects [?, ?]. Since QGP cannot be directly detected due to color confinement, experiments measure and analyze final-state particle information, combined with theoretical calculations or computer simulations, to study QGP properties [?, ?]. Physicists construct different models to simulate relativistic nucleus-nucleus collision processes and compare results with experimental measurements to explore the dynamical evolution, properties, and particle production mechanisms of collision systems \cite{41-55}. Additionally, phenomenological description of experimental observables and searching for their underlying patterns constitute an important method for studying high-energy nuclear collisions, and physicists have achieved significant results in this area \cite{55-68}. Machine learning and artificial intelligence applications are becoming powerful tools for scientific research, which will bring new opportunities for phenomenological studies of relativistic nucleus-nucleus collision physics \cite{69-75}.

The average transverse momentum $\langle p_T \rangle$ is an important observable in relativistic nucleus-nucleus collision physics. Van Hove first proposed this concept [?, ?], emphasizing that the relationship between particle production average transverse momentum and hadron multiplicity in high-energy proton-antiproton collisions could reveal phase transition characteristics. In reference [?], the average transverse momentum of charged particles was used to study the speed of sound in QGP in peripheral relativistic nucleus-nucleus collisions. After years of successful operation, RHIC and LHC have accumulated rich experimental data \cite{5-25}, providing conditions for systematic studies of particle average transverse momentum dependence on collision energy, particle species, and other related physical quantities. This also provides experimental basis for physicists to study the state, properties, and dynamical evolution characteristics of quark-gluon plasma matter under extreme conditions [?, ?, ?, ?, ?, ?, ?, ?, ?].

Olimov and collaborators found through phenomenological studies [?, ?] that the average transverse momentum of particles produced in relativistic nucleus-nucleus collisions follows power-law relationships with charged particle multiplicity pseudorapidity density, total average number of collisions, and total average number of participating nucleons. However, since these physical quantities are not normalized, horizontal comparisons between different collision systems cannot be made. In our work [?], we studied the relationship between identified particle (π mesons, K mesons, and antiprotons) average transverse momentum and normalized quantities such as collision centrality, average number of collisions per nucleon pair, average charged particle multiplicity pseudorapidity density per nucleon pair, and average charged particle multiplicity pseudorapidity density per collision. The results showed that identified particle average transverse momentum has a linear relationship with collision centrality, and power-law relationships with the average number of collisions per nucleon pair, charged particle multiplicity per nucleon pair, and charged particle multiplicity per collision. Given that the fitting parameters of the phenomenological formula for identified particle average transverse momentum versus collision centrality and average number of collisions per nucleon pair follow good power-law relationships with collision energy, this phenomenological study gains predictive power, leading to the conclusion that these two normalized physical quantities are preferred for studying particle average transverse momentum. In fact, 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 in the system, making collision centrality the better choice for studying particle average transverse momentum.

This paper investigates whether the linear relationship between particle average transverse momentum and collision centrality is universal using all identified particle average transverse momentum data from different collision systems published by RHIC-STAR and LHC-ALICE. It also examines whether the power-law relationship between fitting parameters and collision energy is universal. Under the same collision energy and centrality, the correlation between particle average transverse momentum and particle mass is analyzed to test the qualitative mass-ordering relationship. Finally, the dependence of identified particle average transverse momentum on collision energy at given centralities is explored to provide the evolution pattern of identified particle average transverse momentum with collision energy in relativistic nucleus-nucleus collisions.

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1 Experimental Data and Fitting Formulas

All data used in this paper are from publicly available results of the STAR experiment at RHIC and the ALICE experiment at LHC, including 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, all at different centralities \cite{5-24}. The identified particle average transverse momentum $\langle p_T \rangle$ is an experimental measurement, while collision centrality C (Centrality = 100) is calculated by experimental groups using the Monte Carlo Glauber model on charged particle multiplicity distributions.

The principle for selecting phenomenological formulas in this paper is to minimize free parameters (all have only two free parameters) while using forms widely applied in phenomenological studies of high-energy physics data. When studying identified particle average transverse momentum $\langle p_T \rangle$ produced in A+A collisions at different collision energies and centralities, a linear function is adopted to describe the relationship between identified particle average transverse momentum $\langle p_T \rangle$ and collision centrality C:

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

At given collision system, energy, and centrality, a linear function describes the relationship between identified particle average transverse momentum $\langle p_T \rangle$ and particle mass M:

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

After specifying collision centrality and particle species, an exponential function describes the relationship between identified particle average transverse momentum $\langle p_T \rangle$ and collision energy:

$$\langle p_T \rangle = a_3 \cdot b_3^{\ln(\sqrt{s_{NN}}/\sqrt{s_0})} \tag{3}$$

where $\sqrt{s_{NN}}$ is the center-of-mass collision energy per nucleon pair in GeV, and $\sqrt{s_0} = 1$ GeV is a dimensionless normalization factor. In equations (1)-(3), a_i and b_i (i = 1, 2, 3) are free fitting parameters. Under given conditions, the relationship between identified particle average transverse momentum $\langle p_T \rangle$ and collision centrality C, particle mass M, and collision energy $\sqrt{s_{NN}}$ can be obtained through fitting. For all final-state particles studied in relativistic nucleus-nucleus collisions, the average transverse momentum data for particles and their corresponding antiparticles are nearly identical, so only particles or antiparticles are considered in this study.

2.1 Average Transverse Momentum and Centrality

In relativistic nucleus-nucleus collisions, collision centrality describes the geometric characteristics of the collision, representing the overlap degree of the collision region, making it a very useful physical quantity for studying and understanding the evolution and interactions of the produced matter. Using the linear function formula (1), we fit the relationship between average transverse momentum $\langle p_T \rangle$ of final-state identified particles such as π, K, p, ϕ, $\Lambda(1520)$, and deuterons d produced in Au+Au collisions at energies of 7.7-200 GeV, Cu+Cu collisions at 62.4 and 200 GeV, Pb+Pb collisions at 2.76 and 5.02 TeV, and U+U collisions at 193 GeV, as functions of collision centrality. As shown in [Figure 1: see original paper] and [Figure 2: see original paper], the symbols represent experimental data while the lines are fits using equation (1). Only partial results for certain collision systems and energies are displayed in these figures; unshown results are similar. The corresponding fitting parameters and χ^2/ndf values are listed in Appendix Table A1.

The figures demonstrate that the linear relationship between final-state identified particle average transverse momentum and collision centrality in relativistic nucleus-nucleus collisions is universal, independent of collision energy and system. This further confirms our previous conclusion [?] that collision centrality is a preferred physical quantity for studying identified particle average transverse momentum. The slope parameters a_1 are all negative, indicating that identified particle average transverse momentum is negatively correlated with collision centrality. This reflects that as centrality increases (from central to peripheral collisions), both the energy density and temperature of the collision region gradually decrease, and the average number of collisions per nucleon pair decreases.

The slope parameter a_1 represents how rapidly the average transverse momentum $\langle p_T \rangle$ changes with centrality C; the closer its absolute value is to zero, the slower the change. The dependence of particle average transverse momentum on centrality shows clear mass ordering: lighter particles have weaker centrality dependence while heavier particles show stronger dependence. This is consistent with our previous results [**?**], where different mass particles have different production processes. Due to energy conservation, heavy particles are produced early in the collision, while light particles can be produced throughout the entire collision process. In Section 2.2, we will discuss again the relationship between final-state identified particle average transverse momentum and particle mass at given collision energy and centrality.

Limited by the systematic availability of experimental data, [Figure 3: see original paper] only shows the collision energy dependence of the absolute slope values $|a_1|$ and intercepts b_1 from fitting π, K, and deuteron average transverse momentum versus centrality. The points represent fitting parameters while the lines are power-law function fits. The fitting parameters show excellent power-law relationships with collision energy, giving equation (1) predictive power for identified particle average transverse momentum in relativistic nucleus-nucleus collisions. This also confirms the universality of the power-law relationship for fitting parameters of the linear relationship between identified particle average transverse momentum and collision centrality [**?**]. At given collision energy, both the absolute slope parameter $|a_1|$ and intercept parameter b_1 follow the same mass ordering, showing increasing trends with collision energy.

2.2 Average Transverse Momentum and Particle Mass

From data on π, K, and $\bar{p}$ average transverse momentum in relativistic nucleus-nucleus collisions, clear mass ordering of identified particle average transverse momentum has been observed \cite{6,8-10,12,16,18,19,23,24,26,80–82}. Our previous work [**?**] explained this phenomenon as being related to particle production time. Due to energy conservation, heavy particles are produced early in the collision while light particles can be produced throughout the collision system evolution. To further confirm this explanation, we now systematically analyze the relationship between identified particle average transverse momentum and mass in relativistic nucleus-nucleus collisions.

At given collision centrality, [Figure 4: see original paper] shows the dependence of final-state identified particle average transverse momentum $\langle p_T \rangle$ on particle mass M fitted using the linear function formula (2) for Au+Au collisions at 7.7-200 GeV and Pb+Pb collisions at 2.76 and 5.02 TeV. Particles listed separately in subplots have centralities that differ slightly from most other particles. Symbols represent experimental data while lines are fits using equation (2). Only partial results for most central collisions at certain energies are displayed; fits for other centralities and energies are similar. Corresponding fitting parameters and χ^2/ndf values are in Appendix Table A2.

The results show that identified particle average transverse momentum $\langle p_T \rangle$ qualitatively satisfies a linear relationship with particle mass M. The slope parameters a_2 are all positive, indicating that identified particle average transverse momentum increases with particle mass. Some identified particles show slight upward or downward deviations from the fit curves, possibly related to details of their production mechanisms. Notably, experimental results in reference [?] show that meson and baryon average transverse momenta in inelastic p+p collisions at 13 TeV exhibit classification behavior, but this phenomenon is not observed in relativistic nucleus-nucleus collisions. This may reflect nuclear medium effects in nucleus-nucleus collisions and requires further comparative analysis, representing the focus of our next research work.

[Figure 5: see original paper] shows the collision energy dependence of fitting parameters a_2 (slope) and b_2 (intercept) for the relationship between identified particle average transverse momentum and particle mass at centralities of 0–5%, 20–40%, and 60–80%. The points are fitting parameters while lines are power-law function fits. Both slope and intercept parameters show qualitative trends of increasing with collision energy. The power-law relationship of fitting parameters with collision energy reflects that the growth rate of identified particle average transverse momentum with particle mass increases with collision energy. Parameter b_2 shows weak centrality dependence and also follows a power-law relationship with collision energy, though the 130 GeV and 200 GeV points show some deviation. This reflects that identified particle average transverse momentum overall increases with collision energy, which will be discussed in more detail in Section 2.3.

2.3 Average Transverse Momentum and Collision Energy

In relativistic nucleus-nucleus collisions, center-of-mass collision energy is a crucial degree of freedom for studying nuclear collision physics. Varying the collision energy helps investigate QGP phase transitions, analyze final-state particle production mechanisms and physical processes, and understand the dynamical evolution of collision systems. Limited by available experimental data, the current analysis of identified particle average transverse momentum versus collision energy includes five particles: π mesons, K mesons, antiprotons $\bar{p}$, ϕ mesons, and deuterons d.

Using the exponential function formula (3), we fit the dependence of midrapidity average transverse momentum $\langle p_T \rangle$ on collision energy for these particles at the same centrality across energies from 7.7–5020 GeV. To better observe the relationship, collision energy is plotted on a logarithmic scale. As shown in

[Figure 6: see original paper], symbols represent experimental data while lines are fits using equation (3). Corresponding fitting parameters and χ^2/ndf values are in Appendix Table A3.

[Figure 6: see original paper] shows the relationship between average transverse momentum and collision energy for π, K, $\bar{p}$, ϕ, and d, demonstrating that the exponential function fits experimental data well. The exponential relationship between identified particle average transverse momentum and collision energy is universal.

[Figure 7: see original paper] presents the fitting parameters—coefficient a_3 and base b_3—for π, K, $\bar{p}$, and d as functions of collision centrality. The points are fitting parameters. The results show that fitting parameters decrease linearly with collision centrality, consistent with the fact that identified particle average transverse momentum decreases with increasing centrality (see Section 2.1). The fitting parameter b_3 is approximately constant with collision energy, indicating that for a given particle species, the way average transverse momentum changes with collision energy is consistent across different centralities.

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3 Conclusions

Using linear function formulas (1) and (2), exponential function formula (3), and identified particle average transverse momentum data from RHIC-STAR and LHC-ALICE experiments, this paper analyzed the variation patterns of midrapidity identified particle average transverse momentum $\langle p_T \rangle$ with collision centrality C, particle mass M, and collision energy $\sqrt{s_{NN}}$ under given conditions. The results demonstrate that the linear relationship between identified particle average transverse momentum and collision centrality is universal, making collision centrality a preferred physical quantity for studying identified particle average transverse momentum. Additionally, the power-law relationship between fitting parameters of equation (1) for given identified particles and collision energy is also universal, giving equation (1) predictive capability for identified particle average transverse momentum.

At given collision energy and centrality, identified particle average transverse momentum $\langle p_T \rangle$ qualitatively satisfies a linear relationship with particle mass (equation (2)), with a few identified particle data points showing deviations that may be related to details of their production mechanisms. The relationship between identified particle average transverse momentum and particle mass can be explained by different production times for particles of different masses in the collision system. At given relativistic nucleus-nucleus collision centrality and for given identified particle species, the relationship between particle average transverse momentum $\langle p_T \rangle$ and collision energy satisfies the exponential function formula (3) and is universal. Identified particle average transverse momentum is positively correlated with collision energy. The coefficient a_3 of the exponential formula (3) decreases linearly with collision centrality, consistent with the relationship between identified particle average transverse momentum and collision centrality. Parameter b_3 shows weak centrality dependence and is approximately constant, indicating that the way identified particle average transverse momentum changes with collision energy is consistent across different centralities. The universality of the patterns revealed in this paper for final-state identified particle average transverse momentum in relativistic nucleus-nucleus collisions provides new perspectives for understanding QGP evolution and properties.

Author Contributions: XIE Zhen was responsible for data collection, analysis, and manuscript writing; ZHENG Hua supervised the data analysis and manuscript revision; ZHANG Wenchao, ZHU Lilin, LIU Xingquan, TAN Zhiguang, ZHOU Daimei, and Bonasera Aldo reviewed and revised the manuscript.

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Appendix A Fitting Parameter Tables

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

Collision system, energy	Particle	Slope a_1 (GeV/c)	Intercept b_1 (GeV/c)	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, 11.5 GeV	π	$-6.94 \times 10^{-3} \pm 1.39 \times 10^{-3}$	0.799 ± 0.055	0.189/3
Au+Au, 14.5 GeV	π	$-2.64 \times 10^{-3} \pm 1.24 \times 10^{-3}$	0.814 ± 0.053	0.382/4
Au+Au, 19.6 GeV	π	$-6.40 \times 10^{-3} \pm 1.36 \times 10^{-3}$	0.859 ± 0.048	0.123/3

Collision system, energy	Particle	Slope a_1 (GeV/c)	Intercept b_1 (GeV/c)	χ^2/ndf
Au+Au, 27 GeV	π	$-2.24 \times 10^{-3} \pm 1.21 \times 10^{-3}$	0.836 ± 0.047	0.675/4
Au+Au, 39 GeV	π	$-6.22 \times 10^{-3} \pm 1.37 \times 10^{-3}$	0.872 ± 0.049	0.296/3
Au+Au, 62.4 GeV	π	$-3.04 \times 10^{-3} \pm 1.12 \times 10^{-3}$	0.696 ± 0.024	0.063/4
Cu+Cu, 62.4 GeV	π	$-6.80 \times 10^{-3} \pm 1.40 \times 10^{-3}$	0.939 ± 0.100	0.141/3
U+U, 193 GeV	π	$-2.17 \times 10^{-3} \pm 1.11 \times 10^{-3}$	0.948 ± 0.067	0.320/4
Au+Au, 200 GeV	π	$-6.93 \times 10^{-3} \pm 1.45 \times 10^{-3}$	0.923 ± 0.028	0.166/3
Cu+Cu, 200 GeV	π	$-2.57 \times 10^{-3} \pm 1.13 \times 10^{-3}$	1.149 ± 0.039	0.279/4
Pb+Pb, 2.76 TeV	π	$-7.04 \times 10^{-3} \pm 1.44 \times 10^{-3}$	1.481 ± 0.071	0.178/3
Pb+Pb, 5.02 TeV	π	$-1.26 \times 10^{-3} \pm 8.12 \times 10^{-3}$	0.957 ± 0.093	0.166/5
Au+Au, 7.7 GeV	K	$-2.54 \times 10^{-3} \pm 2.05 \times 10^{-3}$	0.896 ± 0.050	0.481/2
Au+Au, 11.5 GeV	K	$-1.56 \times 10^{-3} \pm 1.62 \times 10^{-3}$	0.450 ± 0.022	0.122/2
Au+Au, 14.5 GeV	K	$-1.95 \times 10^{-3} \pm 8.27 \times 10^{-3}$	0.694 ± 0.038	0.394/5
Au+Au, 19.6 GeV	K	$-3.52 \times 10^{-3} \pm 1.08 \times 10^{-3}$	1.028 ± 0.053	1.184/4
Au+Au, 27 GeV	K	$-7.35 \times 10^{-3} \pm 1.47 \times 10^{-3}$	1.108 ± 0.112	0.402/3
Au+Au, 39 GeV	K	$-2.71 \times 10^{-3} \pm 2.65 \times 10^{-3}$	1.019 ± 0.039	0.078/1
Au+Au, 62.4 GeV	K	$-2.17 \times 10^{-3} \pm 1.41 \times 10^{-3}$	1.627 ± 0.076	0.114/4
Cu+Cu, 62.4 GeV	K	$-8.03 \times 10^{-4} \pm 4.68 \times 10^{-4}$	1.021 ± 0.107	0.030/7
U+U, 193 GeV	K	$-9.90 \times 10^{-4} \pm 8.28 \times 10^{-4}$	0.935 ± 0.050	0.070/7
Au+Au, 200 GeV	K	$-4.15 \times 10^{-3} \pm 9.92 \times 10^{-4}$	1.216 ± 0.089	0.488/7
Cu+Cu, 200 GeV	K	$-1.01 \times 10^{-3} \pm 2.79 \times 10^{-3}$	1.346 ± 0.038	0.104/2
Pb+Pb, 2.76 TeV	K	$-1.63 \times 10^{-3} \pm 9.14 \times 10^{-3}$	1.360 ± 0.032	2.120/8

Collision system, energy	Particle	Slope a_1 (GeV/c)	Intercept b_1 (GeV/c)	χ^2/ndf
Pb+Pb, 5.02 TeV	K	$-8.03 \times 10^{-3} \pm 1.59 \times 10^{-3}$	1.947 ± 0.158	0.504/3
Au+Au, 7.7 GeV	$\bar{p}$	$-1.32 \times 10^{-3} \pm 2.87 \times 10^{-3}$	2.230 ± 0.077	0.048/1
Au+Au, 11.5 GeV	$\bar{p}$	$-1.51 \times 10^{-3} \pm 1.42 \times 10^{-3}$	1.486 ± 0.039	0.050/4
Au+Au, 14.5 GeV	$\bar{p}$	$-1.76 \times 10^{-3} \pm 1.86 \times 10^{-3}$	1.451 ± 0.018	0.069/2
Au+Au, 19.6 GeV	$\bar{p}$	$-3.09 \times 10^{-3} \pm 1.10 \times 10^{-3}$	1.690 ± 0.102	4.160/6
Au+Au, 27 GeV	$\bar{p}$	$-2.99 \times 10^{-3} \pm 6.72 \times 10^{-4}$	1.317 ± 0.065	0.983/8
Au+Au, 39 GeV	$\bar{p}$	$-6.69 \times 10^{-3} \pm 3.39 \times 10^{-3}$	1.331 ± 0.064	0.156/1
Au+Au, 62.4 GeV	$\bar{p}$	$-1.23 \times 10^{-2} \pm 2.09 \times 10^{-3}$	1.322 ± 0.064	0.980/3
Cu+Cu, 62.4 GeV	$\bar{p}$	$-4.29 \times 10^{-3} \pm 7.73 \times 10^{-4}$	1.369 ± 0.066	0.757/6
U+U, 193 GeV	$\bar{p}$	$-3.22 \times 10^{-3} \pm 4.31 \times 10^{-4}$	1.400 ± 0.067	6.768/6
Au+Au, 200 GeV	$\bar{p}$	$-2.07 \times 10^{-3} \pm 2.12 \times 10^{-3}$	1.43 ± 0.070	0.113/1
Cu+Cu, 200 GeV	$\bar{p}$	$-6.69 \times 10^{-3} \pm 3.39 \times 10^{-3}$	0.957 ± 0.093	0.504/3
Pb+Pb, 2.76 TeV	$\bar{p}$	$-1.23 \times 10^{-2} \pm 2.09 \times 10^{-3}$	1.481 ± 0.071	0.048/1
Pb+Pb, 5.02 TeV	$\bar{p}$	$-4.29 \times 10^{-3} \pm 7.73 \times 10^{-4}$	1.627 ± 0.076	0.050/4

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

Collision system, energy	Centrality	Slope a_2	Intercept b_2 (GeV/c)	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
Au+Au, 7.7 GeV	20-30%	0.466 ± 0.038	0.301 ± 0.020	0.755/3
Au+Au, 7.7 GeV	30-40%	0.428 ± 0.037	0.303 ± 0.020	0.378/3

Collision system, energy	Centrality	Slope a_2	Intercept b_2 (GeV/c)	χ^2/ndf
Au+Au, 7.7 GeV	40-50%	0.417 ± 0.037	0.299 ± 0.020	1.216/3
Au+Au, 7.7 GeV	50-60%	0.352 ± 0.034	0.302 ± 0.019	1.410/3
Au+Au, 7.7 GeV	60-70%	0.346 ± 0.033	0.292 ± 0.018	3.218/3
Au+Au, 7.7 GeV	70-80%	0.277 ± 0.030	0.298 ± 0.017	0.465/3
Au+Au, 11.5 GeV	5-10%	0.511 ± 0.041	0.309 ± 0.021	3.320/3
Au+Au, 11.5 GeV	10-20%	0.507 ± 0.041	0.307 ± 0.021	0.120/3
Au+Au, 11.5 GeV	20-30%	0.492 ± 0.042	0.308 ± 0.021	0.136/3
Au+Au, 11.5 GeV	30-40%	0.446 ± 0.038	0.316 ± 0.021	0.499/3
Au+Au, 11.5 GeV	40-50%	0.433 ± 0.038	0.313 ± 0.020	0.150/3
Au+Au, 11.5 GeV	50-60%	0.372 ± 0.035	0.317 ± 0.020	0.454/3
Au+Au, 11.5 GeV	60-70%	0.364 ± 0.034	0.308 ± 0.019	0.420/3
Au+Au, 11.5 GeV	70-80%	0.300 ± 0.031	0.313 ± 0.018	1.967/3
Au+Au, 14.5 GeV	5-10%	0.505 ± 0.042	0.319 ± 0.023	1.113/3
Au+Au, 14.5 GeV	10-20%	0.501 ± 0.042	0.318 ± 0.023	2.100/3
Au+Au, 14.5 GeV	20-30%	0.485 ± 0.040	0.318 ± 0.022	0.160/3
Au+Au, 14.5 GeV	30-40%	0.466 ± 0.040	0.319 ± 0.022	0.134/3
Au+Au, 14.5 GeV	40-50%	0.452 ± 0.039	0.315 ± 0.021	0.060/3
Au+Au, 14.5 GeV	50-60%	0.377 ± 0.036	0.325 ± 0.021	1.217/3
Au+Au, 14.5 GeV	60-70%	0.374 ± 0.035	0.314 ± 0.020	0.171/3
Au+Au, 14.5 GeV	70-80%	0.315 ± 0.032	0.315 ± 0.020	0.646/3
Au+Au, 19.6 GeV	5-10%	0.533 ± 0.045	0.316 ± 0.025	1.045/3

Collision system, energy	Centrality	Slope a_2	Intercept b_2 (GeV/c)	χ^2/ndf
Au+Au, 19.6 GeV	10-20%	0.540 ± 0.045	0.312 ± 0.025	1.084/3
Au+Au, 19.6 GeV	20-30%	0.508 ± 0.044	0.319 ± 0.025	1.570/3
Au+Au, 19.6 GeV	30-40%	0.468 ± 0.041	0.321 ± 0.024	0.135/3
Au+Au, 19.6 GeV	40-50%	0.462 ± 0.041	0.317 ± 0.024	0.786/3
Au+Au, 19.6 GeV	50-60%	0.390 ± 0.037	0.327 ± 0.024	0.475/3
Au+Au, 19.6 GeV	60-70%	0.385 ± 0.037	0.318 ± 0.023	0.413/3
Au+Au, 19.6 GeV	70-80%	0.308 ± 0.033	0.327 ± 0.022	0.294/3
Au+Au, 27 GeV	5-10%	0.541 ± 0.045	0.328 ± 0.026	0.616/3
Au+Au, 27 GeV	10-20%	0.543 ± 0.045	0.323 ± 0.026	1.235/3
Au+Au, 27 GeV	20-30%	0.512 ± 0.045	0.324 ± 0.026	0.691/3
Au+Au, 27 GeV	30-40%	0.478 ± 0.041	0.328 ± 0.025	1.206/3
Au+Au, 27 GeV	40-50%	0.469 ± 0.041	0.326 ± 0.025	0.229/3
Au+Au, 27 GeV	50-60%	0.402 ± 0.038	0.334 ± 0.024	0.323/3
Au+Au, 27 GeV	60-70%	0.404 ± 0.037	0.325 ± 0.024	0.111/3
Au+Au, 27 GeV	70-80%	0.327 ± 0.036	0.331 ± 0.023	0.173/3
Au+Au, 39 GeV	5-10%	0.558 ± 0.048	0.335 ± 0.027	0.698/3
Au+Au, 39 GeV	10-20%	0.555 ± 0.048	0.331 ± 0.026	1.113/3
Au+Au, 39 GeV	20-30%	0.539 ± 0.046	0.333 ± 0.026	1.384/3
Au+Au, 39 GeV	30-40%	0.499 ± 0.042	0.339 ± 0.026	1.416/3
Au+Au, 39 GeV	40-50%	0.490 ± 0.042	0.336 ± 0.025	1.891/3
Au+Au, 39 GeV	50-60%	0.416 ± 0.038	0.344 ± 0.024	0.016/3

Collision system, energy	Centrality	Slope a_2	Intercept b_2 (GeV/c)	χ^2/ndf
Au+Au, 39 GeV	60-70%	0.415 ± 0.038	0.335 ± 0.024	0.058/3
Au+Au, 39 GeV	70-80%	0.335 ± 0.034	0.344 ± 0.023	0.057/3
Au+Au, 62.4 GeV	5-10%	0.592 ± 0.026	0.327 ± 0.013	0.552/3
Au+Au, 62.4 GeV	10-20%	0.607 ± 0.025	0.325 ± 0.012	9.345/7
Au+Au, 62.4 GeV	20-30%	0.587 ± 0.025	0.332 ± 0.015	12.017/7
Au+Au, 62.4 GeV	30-40%	0.554 ± 0.025	0.332 ± 0.013	11.888/7
Au+Au, 62.4 GeV	40-50%	0.542 ± 0.026	0.329 ± 0.016	8.547/7
Au+Au, 62.4 GeV	50-60%	0.472 ± 0.025	0.337 ± 0.017	7.938/7
Au+Au, 62.4 GeV	60-70%	0.468 ± 0.026	0.328 ± 0.018	8.648/7
Au+Au, 62.4 GeV	70-80%	0.390 ± 0.027	0.341 ± 0.018	7.307/7
Au+Au, 130 GeV	6-11%	0.628 ± 0.041	0.322 ± 0.016	9.174/7
Au+Au, 130 GeV	11-18%	0.721 ± 0.069	0.289 ± 0.017	8.773/7
Au+Au, 130 GeV	18-26%	0.711 ± 0.082	0.293 ± 0.030	5.397/5
Au+Au, 130 GeV	26-45%	0.707 ± 0.073	0.288 ± 0.026	0.152/2
Au+Au, 130 GeV	34-45%	0.689 ± 0.073	0.286 ± 0.026	0.056/2
Au+Au, 130 GeV	45-58%	0.632 ± 0.060	0.287 ± 0.018	0.050/2
Au+Au, 130 GeV	58-85%	0.565 ± 0.064	0.289 ± 0.025	0.057/2
Au+Au, 200 GeV	5-10%	0.625 ± 0.035	0.363 ± 0.023	0.366/2
Au+Au, 200 GeV	10-20%	0.572 ± 0.020	0.351 ± 0.022	0.123/2
Au+Au, 200 GeV	20-30%	0.677 ± 0.044	0.328 ± 0.024	0.988/1
Au+Au, 200 GeV	30-40%	0.649 ± 0.042	0.328 ± 0.023	16.078/10

Collision system, energy	Centrality	Slope a_2	Intercept b_2 (GeV/c)	χ^2/ndf
Au+Au, 200 GeV	40-50%	0.641 ± 0.040	0.320 ± 0.023	10.825/5
Au+Au, 200 GeV	50-60%	0.564 ± 0.037	0.328 ± 0.022	2.935/4
Au+Au, 200 GeV	60-70%	0.558 ± 0.037	0.322 ± 0.022	5.220/4
Au+Au, 200 GeV	70-80%	0.465 ± 0.034	0.329 ± 0.020	4.240/4
Pb+Pb, 2.76 TeV	5-10%	0.982 ± 0.033	0.388 ± 0.020	8.141/4
Pb+Pb, 2.76 TeV	10-20%	0.974 ± 0.032	0.389 ± 0.019	7.598/4
Pb+Pb, 2.76 TeV	20-30%	0.969 ± 0.032	0.391 ± 0.019	14.661/4
Pb+Pb, 2.76 TeV	30-40%	0.868 ± 0.025	0.414 ± 0.018	9.717/4
Pb+Pb, 2.76 TeV	40-50%	0.888 ± 0.032	0.389 ± 0.019	5.171/6
Pb+Pb, 2.76 TeV	50-60%	0.812 ± 0.031	0.400 ± 0.020	3.353/6
Pb+Pb, 2.76 TeV	60-70%	0.766 ± 0.030	0.388 ± 0.018	6.117/6
Pb+Pb, 2.76 TeV	70-80%	0.724 ± 0.034	0.380 ± 0.018	15.467/7
Pb+Pb, 5.02 TeV	5-10%	1.038 ± 0.035	0.414 ± 0.025	6.139/6
Pb+Pb, 5.02 TeV	10-20%	1.025 ± 0.028	0.424 ± 0.018	17.921/6
Pb+Pb, 5.02 TeV	20-30%	0.994 ± 0.028	0.432 ± 0.018	12.138/6
Pb+Pb, 5.02 TeV	30-40%	1.001 ± 0.029	0.416 ± 0.018	16.118/6
Pb+Pb, 5.02 TeV	40-50%	0.929 ± 0.027	0.432 ± 0.018	18.001/5
Pb+Pb, 5.02 TeV	50-60%	0.901 ± 0.027	0.421 ± 0.019	14.565/4
Pb+Pb, 5.02 TeV	60-70%	0.825 ± 0.028	0.421 ± 0.020	12.406/4
Pb+Pb, 5.02 TeV	70-80%	0.777 ± 0.029	0.417 ± 0.020	16.845/5

Table A3 Fitting parameters of the $\langle p_T \rangle$ versus collision energy $\sqrt{s_{NN}}$ for the identified particles from Eq. (3) and the corresponding χ^2/ndf

Particle	Centrality	Coefficient a_3 (GeV/c)	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
π	20-30%	0.318 ± 0.011	1.067 ± 0.006	5.521/8
π	30-40%	0.316 ± 0.010	1.065 ± 0.006	5.462/8
π	40-50%	0.316 ± 0.011	1.063 ± 0.006	5.187/8
π	50-60%	0.310 ± 0.011	1.062 ± 0.007	4.892/8
π	60-70%	0.307 ± 0.011	1.060 ± 0.007	3.617/8
π	70-80%	0.299 ± 0.011	1.060 ± 0.007	4.091/8
K	5-10%	0.293 ± 0.010	1.058 ± 0.007	5.221/8
K	10-20%	0.451 ± 0.013	1.087 ± 0.004	0.433/8
K	20-30%	0.444 ± 0.013	1.089 ± 0.004	0.637/8
K	30-40%	0.434 ± 0.013	1.092 ± 0.004	0.461/8
K	40-50%	0.425 ± 0.012	1.093 ± 0.004	0.861/8
K	50-60%	0.417 ± 0.012	1.093 ± 0.004	0.804/8
K	60-70%	0.396 ± 0.011	1.096 ± 0.004	1.105/8
K	70-80%	0.386 ± 0.012	1.094 ± 0.005	0.818/8
$\bar{p}$	5-10%	0.369 ± 0.010	1.097 ± 0.005	1.433/8
$\bar{p}$	10-20%	0.357 ± 0.011	1.097 ± 0.005	1.460/8
$\bar{p}$	20-30%	0.628 ± 0.030	1.103 ± 0.007	0.692/8
$\bar{p}$	30-40%	0.620 ± 0.027	1.103 ± 0.006	0.854/8
$\bar{p}$	40-50%	0.596 ± 0.024	1.106 ± 0.006	0.853/8

Particle	Centrality	Coefficient a_3 (GeV/c)	Base b_3	χ^2/ndf
$\bar{p}$	50-60%	0.566 ± 0.026	1.110 ± 0.007	0.855/8
$\bar{p}$	60-70%	0.535 ± 0.024	1.112 ± 0.006	0.855/8
$\bar{p}$	70-80%	0.501 ± 0.023	1.114 ± 0.007	0.791/8
ϕ	0-10%	0.471 ± 0.021	1.114 ± 0.006	1.043/8
ϕ	0-10%	0.456 ± 0.018	1.109 ± 0.006	2.194/8
d	10-20%	0.419 ± 0.019	1.111 ± 0.007	3.316/8
d	20-40%	0.594 ± 0.035	1.108 ± 0.010	1.246/8
d	40-60%	0.993 ± 0.049	1.098 ± 0.011	1.828/7
d	60-80%	0.959 ± 0.049	1.098 ± 0.012	1.567/7
d	60-80%	0.908 ± 0.048	1.096 ± 0.013	0.916/7
d	60-80%	0.799 ± 0.041	1.092 ± 0.013	0.558/7
d	60-80%	0.719 ± 0.049	1.074 ± 0.019	0.273/7