Production and ratio of $\pi$, $K$, $p$ and $\Lambda$ in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

S. Zhang, L. X. Han, Y. G. Ma*, J. H. Chen, and C. Zhong

Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China

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The particle production and their ratios for $\pi$, $K$, $p$, and $\Lambda$ are studied in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV based on a blast-wave model with thermal equilibrium mechanism. The transverse momentum spectra of the above mentioned particles at the kinetic freeze-out stage are discussed. The modification of the inverse slope of pion transverse momentum spectrum due to resonance decay has also been investigated. In addition, we found that the anti-particles to particles ratio as well as kaons to pions ratio agree with the data by the LHC-ALICE Collaboration reasonably well, while the $p/\pi$ ratio is overestimated by a factor of 1.5, similar to those from other thermal model calculations. It is found that the ratios of $p/\pi$ and $K/\pi$ are dominated by the radial flow but slightly affected by the baryon chemical potential. Our study thus constrains the parameters at the chemical and kinetic freeze-out stages within the framework of thermal model in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, and will help better understand the properties of the dense and hot matter created in high-energy heavy-ion collisions at freeze-out stage.

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I. INTRODUCTION

Ultra-relativistic heavy-ion collisions opens a window for studying the properties of the Quark-Gluon Plasma (QGP) which was predicted by quantum chromodynamics (QCD) [1]. This exotic matter is believed to be produced in the early stage of central Au + Au collisions at the top energy in the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory [2]. The sufficient experimental evidences [3] support that the new hot and dense QCD matter is not an ideal gas but instead a strongly interacting dense partonic matter named sQGP under extreme temperature and energy density. The collective properties of the exotic matter created at RHIC can be investigated through transverse momentum ($p_T$) distribution and elliptic flow of identified particles, and so far people have found that this matter behaves as a nearly ideal fluid [2]. Recently, experimental results in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in the Large Hadron Collider (LHC) are also reported by the ALICE Collaboration [4,5,6]. This provides another opportunity to investigate the bulk properties of the exotic QCD matter as an expanding fireball created in heavy-ion collisions at a higher energy, such as its baryon chemical potential $\mu_B$, chemical freeze-out temperature $T_{ch}$, and kinetic freeze-out temperature $T_{kin}$ as well as radial expansion velocity $\langle \beta_T \rangle$, etc.

Relativistic hydrodynamics and thermal models are very successful in describing particle productions at the freeze-out stage. The viscous hydrodynamic model VISH2+1 [9] has successfully described the transverse momentum distributions of $\pi$ and $K$. Similar model named HKM [11] coupling with UrQMD for the hadronic scattering stage can also reproduce the yields and distributions of particles such as $\pi$, $K$, and $p$. The EPOS model [11] aims at describing complete transverse momentum distributions of particles within the same dynamical picture. A multiphase transport (AMPT) model has been reconfigured to reproduce the $p_T$ distribution of charged particles as well as their elliptic flow in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [12]. Besides the studies from hydrodynamics or transport models mentioned about, the thermal model has also successfully described the production of particles in heavy-ion collisions with a few parameters such as the chemical freeze-out temperature, the baryon chemical potential, and the fireball volume [13]. From particle ratios, the thermal model [14] can be used to obtain the chemical freeze-out properties, such as the chemical freeze-out temperature $T_{ch}$ as well as the baryon $\langle \mu_B \rangle$ and the strangeness $\langle \mu_S \rangle$ chemical potential. By fitting the transverse momentum distribution, the blast-wave model [15] has often been used to extract the kinetic freeze-out properties such as the kinetic freeze-out temperature $T_{kin}$ and the radial flow velocity $\langle \beta_T \rangle$. These thermal models have also been applied in experimental analysis [8, 10] to study the chemical and kinetic freeze-out properties. Retie`ere and Lisa [17] have explored in detail an analytic parametrization of the freeze-out configuration and investigated the spectra, the collective flow, and the HBT correlation of hadrons produced in head-on collisions at top RHIC energy. In addition, the DRAGON model [18] and the THERMINATOR2 [19] model have also been developed to study the phase-space distribution of produced hadrons at freeze-out stage.

Due to the complicated initial condition and dynamical evolution in heavy-ion collisions, it is very likely that the particle production can be explained with different parameter sets of temperature, chemical potential, and radial flow. The values of these parameters give the acceptable range of the system properties at freeze-out
stage. The results in this paper come from the fitting based on the blast-wave model with thermal equilibrium mechanism. Transverse momentum ($p_T$) distributions of charged hadrons ($\pi, K, \text{and} p$) and $Λ$ hyperon in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are presented. The effect from resonance decay to the $p_T$ spectrum of pions will also be discussed. The inverse slope parameter of the $p_T$ spectrum is extracted for each particle species at various centralities. The multiplicities of anti-particles and particles become similar by tuning baryon chemical potential to about 0.1 MeV at LHC energy. The inclusive yields of charged hadrons and hyperons normalized to the pion yield in 0 – 5% centrality are compared with the experimental results. From the transverse momentum dependence of mixed ratios of $p/π$ and $K/π$, the radial flow effect on the mass ordering of $p_T$ distribution is investigated. The calculated results agree pretty well with the experimental measurements by the LHC-ALICE Collaboration, and a reasonable range of parameters at the chemical and kinetic freeze-out stages is discussed for the thermalized system at LHC energy.

II. BLAST-WAVE MODEL WITH THERMAL EQUILIBRIUM MECHANISM

As discussed above, thermal model can describe particle yield by adjusting parameters such as the chemical freeze-out temperature $T_{ch}$, the baryon chemical potential $\mu_B$, the strangeness chemical potential $\mu_S$, and the system volume $V$. On the other hand, one can extract these quantities at chemical freeze-out stage through particle ratios. The particle density of species $i$ can be expressed as

$$n_i(T_{ch}, \mu_B, \mu_S) = g_i \int \frac{d^3p}{(2\pi)^3} \left[ \exp \left( \frac{\sqrt{p^2 + m_i^2} - (\mu_B B_i + \mu_S S_i)}{T_{ch}} \right) \mp 1 \right]^{-1}$$

$$= I \left( g_i, m_i / T_{ch} \right) \sum_{n=1}^{\infty} (-1)^{n+1} \exp \left( \frac{n (\mu_B B_i + \mu_S S_i)}{T_{ch}} \right),$$

$$I \left( g_i, m_i / T_{ch} \right) = g_i \int \frac{d^3p}{(2\pi)^3} \left[ \sum_{n=1}^{\infty} (-1)^{n+1} \exp \left( -n \frac{\sqrt{p^2 + m_i^2}}{T_{ch}} \right) \right] , \quad (1)$$

with the upper (lower) sign for bosons (fermions) and $g_i$ being the degeneracy factor. Assuming that the chemical equilibrium condition is satisfied, Eq. (1) essentially determines the fraction of particle species $i$. Within the framework of the blast-wave model, the fireball created in high-energy heavy-ion collisions is assumed to be in local thermal equilibrium and expands at a four-component velocity $u_\mu$. The phase-space distribution of hadrons emitted from the expanding fireball can be expressed as a Wigner function [17–19]

$$S(x, p)d^4x = \frac{2s + 1}{(2\pi)^3} m_t \cosh(y - \eta) \exp \left( -\frac{p^\mu u_\mu}{T_{kin}} \right) \Theta(1 - \bar{r}(r, \phi)) H(\delta(\tau - \tau_0)d\tau d\eta dr d\phi, \quad (2)$$

where $s, y,$ and $m_t$ are respectively the spin, rapidity, and transverse mass of the hadron, and $p_\mu$ is the four-component momentum. Equation (2) is formulated in a Lorentz covariant way, $r$ and $\phi$ are the polar coordinates, and $\eta$ and $\tau$ are the pseudorapidity and the proper time, respectively. $\bar{r}$ is defined as

$$\bar{r} = \sqrt{\frac{(x^1)^2}{R^2} + \frac{(x^2)^2}{R^2}}, \quad (3)$$

with $(x^1, x^2)$ standing for the coordinates in the transverse plane and $R$ being the average transverse radius.

The kinetic freeze-out temperature $T_{kin}$ and the radial flow parameter $\rho_0$ are important in determining the transverse momentum spectrum, with the latter affecting the four-component velocity field. Since we are only interested in the $p_T$ spectrum at mid-rapidity, the pseudorapidity distribution $H(\eta)$ is not important. The $p_T$ spectrum can then be written as

$$dN \frac{d^2p_T}{2\pi p_T dp_T} = \int S(x, p)d^4x, \quad (4)$$
and the fraction of particle species and its phase-space distribution can be calculated from Eqs. (1) and (4).

III. TRANSVERSE MOMENTUM SPECTRA

The collective properties of the hot and dense matter created in ultra-relativistic heavy-ion collisions at freeze-out stage can be studied through transverse momentum \( p_T \) distributions of identified particles. Figure 4 shows the \( p_T \) distributions of \( \pi, K, p, \) and \( \Lambda \) in central and peripheral Pb + Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV by using the blast-wave model with thermal equilibrium mechanism. The parameters of kinetic temperature \( T_{\text{kin}} \) and radial flow parameter \( (\rho_0) \) used in the calculation are also shown in Fig. 4. The spectra become stiffer with increasing \( \rho_0 \) and \( T_{\text{kin}} \), and the results imply that the transverse momentum distribution is more sensitive to the radial flow parameter than to the kinetic freeze-out temperature. The ranges of the chemical and kinetic temperature \( (T_{\text{ch}} \text{ and } T_{\text{kin}}) \) as well as the chemical potential \( (\mu_B \text{ and } \mu_S) \) are consistent with those from other model calculations [9, 13] and the experimentally estimated values [8, 20]. The radial flow

\[
\langle \beta_T \rangle = \int \arctanh \left( \rho_0 \frac{r}{T_0} \right) r dr / \int r dr \tag{5}
\]

is related to the maximum flow rapidity

\[
\rho = \tilde{r} \left[ \rho_0 + \rho_a \cos(2\phi) \right]. \tag{6}
\]

The results are independent of \( \rho_a \) as after integration the \( \phi \) dependence is averaged out. The parameter \( \rho_0 \) from our analysis is comparable to that extracted from the experimental data [7, 8, 20, 21] except for \( \Lambda \) in central collisions \((0 - 10\%)\). In addition, we can see that the effect from the radial flow parameter \( \rho_0 \) on the spectra is more significant than the kinetic freeze-out temperature \( T_{\text{kin}} \). The results show that the inverse slopes \( T_{\text{loc}} \) increase with \( \rho_0 \) in the range of \( \rho_0 \) from 0.9 to 1.1, which is consistent with the previous calculation using the blast-wave model [17].

The properties of a thermalized system can be extracted from the spectra of identified particles. A rough description of spectra shape can be obtained by an exponential or a power-law fit. From Fig. 4 we can see that the spectra of identified particles become stiffer from peripheral collisions to central collisions. Experimental data have demonstrated that there is no obvious onset of the power-law tail at high \( p_T \) as observed in pp collisions [24], but in central collisions the spectra keep an almost exponential shape in a wide \( p_T \) range. The transverse momentum dependence of the slope parameters can display more clearly the trend of the spectra changing from the exponential pattern to the power-law one. Figure 3 shows the local inverse slope \( T_{\text{loc}} \) of the spectra as a function of \( p_T \), which is calculated by fitting the spectra with the following function [8]

\[
\frac{1}{p_T} \frac{dN}{d p_T} \propto e^{-p_T/T_{\text{loc}}}, \tag{7}
\]

It is seen that the inverse slopes of identified particles \( p_T \) spectra have a similar trend of \( p_T \) dependence to the experimental results [8]. The inverse slopes of the \( p_T \) spectra for \( K, p, \) and \( \Lambda \) decrease with the increasing transverse momentum, and this is more obvious for central collisions. In addition, they don’t change with increasing \( p_T \) above a certain value of the transverse momentum, which is about 1 GeV/c for \( K \) and 2 GeV/c for \( p \) and \( \Lambda \). It is also seen that \( T_{\text{loc}} \) for protons and kaons converges to a similar value of 0.45 GeV/c at high \( p_T \). In peripheral collisions from the ALICE [8] data, a modest increase of \( T_{\text{loc}} \) is seen at the highest \( p_T \), showing the onset of a power-law behavior. The above experimental results thus indicate that the system becomes more thermalized with sufficient particle interaction in central collisions in comparison with peripheral collisions.

For pions, however, the inverse slopes increase with \( p_T \) in both central and peripheral collisions, opposite to the trend observed for protons and kaons. At high \( p_T \), the power-law rise is more suppressed in central collisions in comparison with peripheral ones. The calculated results are consistent with the experimental ones except at high \( p_T \) \((p_T > 1.5 \text{ GeV}/c)\) in peripheral collisions. The pions from resonances decay contribute to the distribution at low transverse momenta, and this might be the reason why a different trend of pion spectrum compared to protons and kaons is observed [11, 12, 14]. The contribution of resonance decay to the total pion yield is estimated in this calculation by distinguishing directly produced pions from the fireball and pions from resonance decay, and they are compared in Fig. 9. In central collisions (left top), the yield of pions from resonance decay is higher than those from direct production, and this is more pronounced in the top of the right figures, i.e., the fraction of the contribution from resonance decay in the total yield grows with increasing \( p_T \) from 60% to 80%. In peripheral collisions (left and right bottom), however, this fraction decreases with increasing \( p_T \) from 60% to 40%, and the directly produced pion is dominant above \( p_T \sim 2 \text{ GeV}/c \). This implies that the contribution of the resonance decay is dominant in central collisions but only important at low \( p_T \) in peripheral collisions.

IV. PARTICLE RATIO ANALYSIS

The estimate of the baryon chemical potential \( \mu_B \) gives the value of about zero from the similar multiplicity of anti-particles and particles measured by the ALICE Collaboration [8]. The anti-particles to particles ratio can be approximately deduced from Eq. (1) by neglecting the
second- and higher-order terms, i.e.,

\[
\frac{\bar{n}_i}{n_i} \approx \exp \left( \frac{\mu_B (\bar{B}_i - B_i) + \mu_S (\bar{S}_i - S_i)}{T_{ch}} \right)
\]

\[
= \exp \left( \frac{-2 \mu_B |B_i| + \mu_S |S_i|}{T_{ch}} \right). \tag{8}
\]

From Eq. (8), it can be seen that the multiplicity ratio of anti-particle to particle is affected by the chemical properties of the bulk matter such as $T_{ch}$, $\mu_B$, and $\mu_S$. Table I gives the multiplicity ratios of anti-particles to particles from different parameter sets used in the calculation. It is seen that there is minor effect from the chemical freeze-out temperature $T_{ch}$ and the strangeness chemical potential $\mu_S$ on the ratio. However, the baryon chemical potential $\mu_B$ dominates the ratio of anti-baryon to baryon ($\bar{p}/p$ and $\bar{\Lambda}/\Lambda$). It is obviously seen that the ratios are compatible with unit for centralities of $0-5\%$ and $70-80\%$ with the chemical potential $\mu_B$ and $\mu_S$ close to zero, consistent with the experimental observation [8]. This means that the experimental results can be well de-
FIG. 2: (Color online) Local slopes of the $p_T$ distributions for $\pi$, $K$, $p$, and $\Lambda$ including their anti-particles as a function of $p_T$ in central and peripheral collisions. Lines: model calculations with $\mu_B = 0.1$ MeV, $\mu_S = 0.001$ MeV, and $T_{ch} = 150$ MeV for central collisions and $T_{ch} = 160$ MeV for peripheral collisions; Shadow: the ALICE data [8] for collision centrality 0−5% (left column) and 70−80% (right column). $T_{kin}$ is in MeV and $\rho_0$ is dimensionless.

scribed by thermal equilibrium mechanism, and this implies that the hot and dense matter created at LHC energy has nearly equal amount of matter and anti-matter with the chemical potential close to zero.

The accurate ratio of inclusive yields of particles to those of $\pi^+$ can be deduced from Eq. (1) as done in Eq. (8)

$$\frac{n_i}{n_{\pi^+}} = \frac{I(g_i,m_i/T_{ch})}{I(g_{\pi^+},m_{\pi^+}/T_{ch})} \exp\left(\frac{\mu_B B_i + \mu_S S_i}{T_{ch}}\right). \quad (9)$$

The ratio of inclusive particle yields to that of $\pi^+$ is thus determined by $T_{ch}$, $\mu_B$, and $\mu_S$ in addition to the intrinsic parameters of mass $m_i$ and the degeneracy factor $g_i$.

Figure 4 shows particle yield ratios of hadrons to $\pi^+$ in $0−5%$ centrality and they are compared with the experimental results [21, 26]. Within the range of the chemical freeze-out temperature $T_{ch}$ and the chemical potentials $\mu_B$ and $\mu_S$ as shown in Fig. 4, particle yield ratios of most hadrons to $\pi^+$ in this calculation are consistent with those in Ref. [13]. However, the thermal model cannot
FIG. 3: (Color online) Comparing the pion $p_T$ spectrum from direct production and resonance decay from model calculations with $(T_{ch}, \mu_B, \mu_S, T_{kin}, \rho_0) = (160, 0.1, 0.001, 99, 1)$ (all in MeV except that $\rho_0$ is dimensionless) for central collisions and $(T_{ch}, \mu_B, \mu_S, T_{kin}, \rho_0) = (150, 0.1, 0.001, 140, 0.78)$ for peripheral collisions. Left: Pions spectra from direct production and total yield in central and peripheral collisions; Right: The ratios of pions from resonance decay and direct production to the total yield as a function of $p_T$ in central and peripheral collisions.

TABLE I: Ratios of anti-particles to particles for $\pi$, $K$, $p$, and $\Lambda$ in central and peripheral collisions. Results from model calculations with $T_{kin} = 99$ MeV and $\rho_0 = 1$ for central collisions and $T_{kin} = 140$ MeV and $\rho_0 = 0.78$ for peripheral collisions are compared with the ALICE data [8] for collision centrality 0−5% and 70−80%.

| $(T_{ch}, \mu_B, \mu_S)$ (MeV) | $\pi^-/\pi^+$ | $K^-/K^+$ | $\bar{p}/p$ | $\Lambda/\Lambda$ |
|-------------------------------|----------------|-------------|--------------|-----------------|
| Centrality (0-5%), ALICE     | 0.998          | 1.00        | 0.971        | -               |
| (160, 0.1, 0.001)             | 0.99           | 0.99        | 1.00         | 0.99            |
| (150, 0.1, 0.001)             | 0.99           | 0.99        | 1.00         | 0.98            |
| (170, 0.1, 0.001)             | 0.99           | 0.99        | 1.00         | 1.00            |
| (160, 0.1, 0.1)               | 0.99           | 0.99        | 1.00         | 0.99            |
| (160, 10, 0.001)              | 0.99           | 0.99        | 0.88         | 0.88            |
| Centrality (70-80%), ALICE   | 0.994          | 1.00        | 1.033        | -               |
| (150, 0.1, 0.001)             | 0.997          | 0.995       | 1.003        | 0.997           |
| (140, 0.1, 0.001)             | 1.000          | 0.998       | 1.006        | 1.018           |
| (160, 0.1, 0.001)             | 0.995          | 0.993       | 0.994        | 0.994           |
| (150, 0.1, 0.1)               | 0.997          | 0.992       | 0.992        | 0.997           |
| (150, 10, 0.001)              | 0.998          | 0.994       | 0.879        | 0.877           |

reproduce the yield of protons ($T_{ch} = 150$ MeV) and $\Lambda$ hyperons ($T_{ch} = 160$ MeV) with the same parameters, and it calls for more theoretical works for particle production mechanism, which is beyond what we have in the present paper.

The transverse momentum dependence of mixed ratio of $p/\pi$ (stands for $(p + \bar{p})/\pi^+\pi^-$) and $K/\pi$ (stands for $(K^+ + K^-)/(\pi^+ + \pi^-)$) will be affected by both chemical freeze-out properties and kinetic freeze-out properties. From the above discussion, it is known that the slope of particle spectra and their ratios are mainly determined by the radial flow parameter $\rho_0$ and the baryon chemical potential $\mu_B$, respectively. It will be interesting to investigate these ratios in different ranges of $\rho_0$ and
FIG. 4: (Color online) Ratio of inclusive yields of particles to $\pi^+$ compared with the LHC-ALICE data for central (0 – 5\%) collisions $^{[21,26]}$. $T_{ch}$, $\mu_B$, and $\mu_S$ are all in MeV.

$^{[8]}$ $^{[8]}$ $^{[8]}$ $^{[8]}$

FIG. 5: (Color online) Ratios of $p/\pi$ (stands for $(p + \overline{p})/(\pi^+ + \pi^-)$) and $K/\pi$ (stands for $(K^+ + K^-)/(\pi^+ + \pi^-)$) as a function of $p_T$ in central and peripheral collisions. Lines: model calculations with $\mu_S = 0.001$ MeV, $T_{ch} = 160$ MeV and $T_{kin} = 99$ MeV for central collisions, and $T_{ch} = 150$ MeV and $T_{kin} = 140$ MeV for peripheral collisions; Shadow: the ALICE data $^{[8]}$ for collision centrality 0 – 5\% (left column) and 70 – 80\% (right column). $\rho_0$ is dimensionless and $\mu_B$ is in MeV.

$^{[8]}$ $^{[8]}$ $^{[8]}$ $^{[8]}$

$\mu_B$ used above. The ratios of $p/\pi$ and $K/\pi$ as a function of $p_T$ are shown in Fig. 5. It is seen that there is no significant effect from $\mu_B$ on the particle ratio, while a large radial flow parameter $\rho_0$ will reduce the ratios, especially for $p/\pi$. The effect from $\rho_0$ as well as the increasing trend of the ratios with transverse momentum are intrinsic features of hydrodynamical models, where heavier particles are pushed to higher $p_T$ by the collective motion of radial flow. The increasing trend of both ratios with $p_T$ is more pronounced in central collisions and this is consistent with the LHC-ALICE results $^{[8]}$. However, the ratios from our calculations are higher than the experimental results, except for $K/\pi$ in central collisions. For the $p/\pi$ ratio, the result from our calculations and those by other models $^{[10,25]}$ overestimate the value measured by the LHC-ALICE Collaboration $^{[8]}$. 
The particle yield and their ratios of $\pi$, $K$, $p$, and $\Lambda$ in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV have been investigated based on the blast-wave model with thermal equilibrium mechanism. A reasonable range of the parameters at chemical and kinetic freeze-out stages in our calculation is selected to study the thermalized system at LHC energy. The transverse momentum spectra demonstrate some thermal and dynamical properties of the system, such as the radial flow, the chemical and kinetic temperatures, and the baryon (strangeness) chemical potential. Similar to the early findings, the slope of spectra is dominated by the radial flow parameter $\rho_0$, while the anti-particles to particles ratio is essentially controlled by the baryon chemical potential, and the transverse momentum dependence of mixed ratios of $p/\pi$ and $K/\pi$ are only affected by $\rho_0$. It is found that the slopes of $K$ and $p$ spectra becomes independent of $p_T$, which is about 0.4 GeV/c for $K$ and 0.5 GeV/c for $p$, when the transverse momentum is above a certain value, which is about 1 GeV/c for $K$ and 2 GeV/c for $p$, and this indicates an exponential shape of the $p_T$ spectra at high $p_T$. The modification of the inverse slope of transverse momentum spectra for pions due to resonance decay has also been investigated. The anti-particles to particles ratios are compatible with unity in central and peripheral collisions, which is consistent with the LHC results. This implies that the baryon chemical potential is almost zero at LHC energy. The inclusive yields of particles normalized to $\pi^+$ are comparable to those measured by the LHC-ALICE Collaboration but the $p/\pi$ ratio is overestimated by a factor of 1.5 even though it is similar to those from other thermal model calculations. The ratios of $p/\pi$ and $K/\pi$ as a function of $p_T$ are consistent with the results from hydrodynamical models, i.e., the radial flow can push heavier particles to higher $p_T$. Our detailed study helps better understand the chemical and kinetic properties of the hot and dense QCD matter created in heavy-ion collisions at LHC energy.

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V. SUMMARY

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