NLO Productions of $\omega$ and $K_S^0$ with a Global Extraction of the Jet Transport Parameter in Heavy Ion collisions

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Abstract. In this work, we pave the way to calculate the productions of $\omega$ and $K_S^0$ mesons at large $p_T$ in p+p and A+A collisions at the RHIC and the LHC. The $\omega$ meson fragmentation functions (FFs) in vacuum at next-to-leading order (NLO) are obtained by evolving NLO DGLAP evolution equations with rescaled $\omega$ FFs at initial scale $Q_0^2 = 1.5$ GeV$^2$ from a broken SU(3) model, and the $K_S^0$ FFs in vacuum are taken from AKK08 parametrization directly. Within the framework of the NLO pQCD improved parton model, we make good descriptions of the experimental data on $\omega$ and $K_S^0$ in p+p both at the RHIC and the LHC. With the higher-twist approach to take into account the jet quenching effect by medium modified FFs, the nuclear modification factors for $\omega$ meson and $K_S^0$ meson at the RHIC and the LHC are presented with different sets of jet transport coefficient $q_0$. Then we make a global extraction of $q_0$ at the RHIC and the LHC by confronting our model calculations with all available data on 6 identified mesons: $\pi^0$, $\eta$, $\rho^0$, $\phi$, $\omega$, and $K_S^0$. The minimum value of the total $\chi^2$ for productions of these mesons gives the best value of $q_0 = 0.5$ GeV$^2$/fm for Au+Au collisions with $\sqrt{s_{NN}} = 200$ GeV at the RHIC, and $q_0 = 1.2$ GeV$^2$/fm for Pb+Pb collisions with $\sqrt{s_{NN}} = 2.76$ TeV at the LHC respectively, with the QGP spacetime evolution given by an event-by-event viscous hydrodynamics model IEBE-VISHNU. With these global extracted values of $q_0$, the nuclear modification factors of $\pi^0$, $\eta$, $\rho^0$, $\phi$, $\omega$, and $K_S^0$ in A+A collisions are presented, and predictions of yield ratios such as $\omega/\pi^0$ and $K_S^0/\pi^0$ at large $p_T$ in heavy-ion collisions at the RHIC and the LHC are provided.

PACS. 12.38.Mh Quark-gluon plasma – 25.75.-q Relativistic heavy-ion collisions – 13.85.Ni Inclusive production with identified hadrons

1 Introduction

Jet quenching effect describes the energy dissipation of an energetic parton when it traverses through the hot and dense QCD medium, which is produced shortly after the high energy nuclear collisions [1]. The single hadron production suppression at high $p_T$ region when compared to scaled p+p data is one of the primary perturbative probes to study the properties of this de-coupled quark and gluon QCD matter [2]. $\pi^0$ as the most well measured final state hadron, its nuclear modification factor $R_{AA}$ as a function of transverse momentum $p_T$ is interpreted as the consequence of jet quenching effect and it did help us to constrain the strength of the jet-medium interaction and also the properties of the QCD medium [3]. In 2013, Jet collaboration summarized different jet quenching theoretical frameworks and compared the jet transport parameters extracted by different energy loss models using the same hydro description of the QCD medium [4]. Meanwhile, the $R_{AA}$ for different final state identified hadrons have been measured, and their production suppressions as well as patterns of their yield ratios have been observed [5,6,7,8,9,10,11,12,13,14,15]. It is of interest and challenge to describe the cross sections of leading hadron of different types and their yield ratios with each other in heavy-ion collisions (HIC) at the RHIC and the LHC with a unified model of jet quenching, which should shed light on flavor dependence of parton energy loss and the intrinsic properties of identified hadron productions in p+p and A+A reactions [16,17,18,19,20,21,22,23].

Previous efforts on the leading hadron productions in A+A collisions mainly focused on the production suppression of pions. However we have achieved more understanding of the suppression patterns of different mesons by conducting calculations and analysis of the $R_{AA}$ and particle ratios for other identified hadron productions [21,22,23]. In a previous study [24] we have firstly calculated the $\eta$ production in A+A collisions both at the RHIC and the LHC, theoretically explained the coincidence of the $\eta/\pi^0$
ratios in p+p and Au+Au collision at larger \( p_T \) region, and further predict the similar overlapping of \( \eta/\pi^0 \) ratios in p+p and Pb+Pb with respect to \( p_T \) at the LHC, which has been very recently confirmed by ALICE measurement on \( \pi \) and \( \eta \) mesons at the LHC [15]. This theoretical approach has later been extended to include the productions of \( \rho^0 \) meson and \( \phi \) meson at large \( p_T \) in heavy-ion collisions [25][26], and shows that \( \rho^0/\pi^0 \) ratios in A+A should approach to that in p+p at larger \( p_T \) region, whereas the coincidence of yield ratios \( \phi/\pi^0 \) in the p+p and A+A particle will not show up over a wide region of \( p_T \) [29]. We emphasize that inclusive leading hadron yields in heavy-ion collisions should be determined by three factors: the initial hard parton spectrum, the parton energy loss mechanism, and the specific shape of parton fragmentation functions in vacuum; and the yield ratios of identified hadrons at large \( p_T \) are the combined effects of these three factors, not determined solely by one factor [24].

In this article, we investigate the production of other two mesons \( \omega \) and \( K_S^0 \) at large \( p_T \) in A+A collisions, which has never been computed so far, to the best of our knowledge. The \( \omega \) meson is constituted of similar valence quark of \( \pi^0 \) with larger mass 782.65 MeV and spin 1. Kaons are a group of lightest mesons, carrying strangeness components, \( K_S^0(z+1/3) \) is one type of the Kaons, which is consisted by s–quark, d–quark and their corresponding antiquarks. The productions of these two mesons have been measured in p+p and A+A collisions at the RHIC and also at the LHC, but lacking the theoretical description. Within the NLO pQCD improved parton model, we calculate \( \omega \) and \( K_S^0 \) yields at large \( p_T \) in heavy-ion collisions, by employing the medium-modification fragmentation functions (FFs) due to gluon radiation in the hot/dense QCD in the higher-twist approach of jet quenching [21][22][27][28][29], the same approach as in the calculations on productions of \( \eta, \rho^0 \) and \( \phi \) mesons in HIC [21][25][26].

It is noted in the previous studies, for the consistency, we implemented Hirano hydro description [30][31] to describe the space-time evolution of the QGP fireball. In this work, we may utilize a state-of-art, event-by-event (2+1)-D viscous hydrodynamics model (IEBE-VISHNU) [32] to give the space-time evolution information of the hot and dense medium. Due to the change of the medium description, the strength of the jet-medium interaction characterized by the jet transport parameter \( q_0 \) should be re-extracted. Taking the advantage of the systematical study of the nuclear modification factors with respect to \( p_T \) and a large amount of experimental data of \( \eta/\pi^0, \rho^0/\pi^0 \) and \( \phi/\pi^0 \) both at the RHIC and the LHC, with two more mesons \( \omega \) and \( K_S^0 \) calculated in this article, we can make a global extraction of the jet transport parameter \( q_0 \) with all the available experimental data of these 6 identified mesons \( R_{AA} \).

The article is organized as follows. We firstly present the theoretical framework of computing single hadron cross sections in p+p collision in Sec. 2, and give the p+p baseline in investigating the in-medium modification of these productions. In Sec. 3, we discuss the inclusive hadron production in A+A collisions with the medium-modified FFs, basing on the higher-twist approach of parton energy loss, and present the nuclear modification factors \( R_{AA} \) for \( \omega \) and \( K_S^0 \) at the RHIC and the LHC. Sec. 4 shows a global extraction of jet transport coefficient \( q_0 \) at the RHIC and the LHC by confronting our model calculations with all available data on 6 identified mesons: \( \omega^0, \eta, \rho^0, \phi, \omega, \) and \( K_S^0 \). In Sec.5, we make predictions on the identified hadron yield ratios \( \omega/\pi^0 \) and \( K_S^0/\pi^0 \) in p+p and A+A collisions, and compare them with experimental data if applicable. We give a brief summary in Sec. 6.

2 Large \( p_T \) yield of \( \omega \) and \( K_S^0 \) meson in p+p

We start with the productions of \( \omega \) and \( K_S^0 \) mesons at NLO in p+p collisions. In the framework of the pQCD improved parton model, the inclusive hadron production
in p+p collision can be given by the convolution of three parts, parton distribution functions (PDFs) in a proton, hard partonic scattering cross section denoted as $d\sigma/dl$ (up to the order of $\alpha_s$), and the parton fragmentation functions (FFs) to the final state hadron $D_{g(\omega)\to h}(z_h, Q^2)$. One may convolute PDFs and partonic cross section $d\sigma/dl$ into the initial hard (parton-) jet spectrum $F_{g,\omega}(p_T)$, and we have:

$$
\frac{1}{p_T} \frac{d\sigma_{\omega,K_0^0}}{dp_T} = \int F_q(p_T) \cdot D_{q\to \omega,K_0^0}(z_h, p_T) \frac{dz_h}{z_h} + \int F_g(p_T) \cdot D_{g\to \omega,K_0^0}(z_h, p_T) \frac{dz_h}{z_h}.$$

Fig. 3. The theoretical results of the $\omega$ meson production in p+p collisions at $\sqrt{s} = 200$ GeV confronted with the PHENIX data [14] and confronted with the ALICE data [39] at $\sqrt{s} = 7$ TeV.

Fig. 4. The theoretical results of the $K_0^0$ meson production in p+p collisions at $\sqrt{s} = 200$ GeV RHIC compared with STAR data [41] and at $\sqrt{s} = 2.76$ TeV LHC compared with ALICE data [15].

in which the quark and gluon fragmenting contributions are written separately to facilitate future discussions. A next-to-leading order (NLO) Monte Carlo code has been employed to calculate leading hadron productions in p+p collision [35], and the CT14 parametrization of PDFs for free proton [36] has been implemented. In the framework, as long as the parametrization of the specific final state hadron FFs in vacuum is available, one can predict its production yield at large $p_T$ in elementary p+p collision in principle.

In order to make the NLO calculation of $\omega$ and $K_0^0$ mesons in p+p, the NLO parton FFs of these two mesons are needed. The parton FFs of $K_0^0$ meson at NLO can be found in AKK08 parametrization [37], while there is not such kind of global parametrization for $\omega$ FFs in vacuum. So we have to rely on theoretical models and utilize $\omega$ parton FFs at a starting scale $Q_0^2 = 1.5$ GeV$^2$ provided by a broken SU(3) model [35,39]. And we note that our preceding investigations on leading $p_T$ and $\phi$ production [25,26] have benefited from this broken SU(3) model. In this model, the independent parton FFs of different flavor are reduced into 3 independent functions named as valence $V(x, Q_0^2)$, sea $\gamma(x, Q_0^2)$ and gluon $D_g(x, Q_0^2)$ by considering the SU(3) flavor symmetry with a symmetry breaking parameter also the isospin and charge conjugation invariance of the vector mesons. We can write these functions into a standard polynomial at the starting low energy scale of $Q_0^2 = 1.5$ GeV$^2$ as:

$$F_i(x) = Ka x^{b_i}(1 - x)^{c_i} (1 + d_i x + e_i x^2)$$

Where the full set of parameters defined in $V, \gamma, D_g$ and a few additional parameters defined for each vector meson such as strangeness suppression factor $\lambda$, vector mixing angle $\theta$, sea suppression factor $f^\omega_{\omega\omega}, f^\omega_{\gamma\omega}$ and $f^\omega_{\gamma\omega}$ have been determined in the broken SU(3) model in Ref. [38,39], and $K$ is a rescaling factor to make the best fit to leading hadron $p_T$ spectrum in p+p at the RHIC, and we fix $K = 3$ for $\omega$ meson in our NLO numerical simulations. To obtain a NLO parton FFs for $\omega$ at any energy scale $Q$, we employ a numerical NLO DGLAP evolution program provided in Ref. [40] with the initial parton FFs starting scale $Q_0^2 = 1.5$ GeV$^2$ as input.

We demonstrate in Fig. [1] the NLO DGLAP evolved FFs of $\omega$ meson as functions of $z_h$ at fixed $Q^2 = 1.5$ GeV$^2$ and $Q^2 = 100$ GeV$^2$ on the left and as functions of $Q$ at fixed $z_h = 0.4$ and $z_h = 0.6$ on the right. We find in the typical fraction region $z_h = 0.4 \rightarrow 0.7$ $D_\omega^\omega > D_\gamma^\omega$ $D_\gamma^\gamma$ $D_\mu^\mu$ $D_\mu^\mu$, unlike the case $D_\omega^\omega > D_\gamma^\omega$ $D_\mu^\mu$ $D_\mu^\mu$ in the $\phi$ FFs [26].

Due to the fact that in parton FFs, gluon exceeds quark contribution, an overwhelming advantage of gluon fragmenting contribution of the final state $\omega$ production in p+p collision is expected in the competition with quark fragmenting contribution. In Fig. [2] we plot the NLO FFs of $K_0^0$ from AKK08 parametrization in the same manner as $\omega$ meson in Fig. [1]. We find the strange quark FF $D_{g,k}^{K_0^0} > D_{g,k}^\omega$ in the typical $z_h = 0.4 \rightarrow 0.7$ region, therefore a competition of the gluon and quark fragmenting contributions is expected in the $K_0^0$ production in p+p...
Fig. 5. Left: Comparison between the PHENIX Data [14] of ω nuclear modification factor in Au + Au collisions at 200 GeV and numerical simulations at NLO. Right: The numerical prediction of ω nuclear modification factor in Pb + Pb collisions at 2760 GeV at NLO.

Fig. 6. Left: Comparison between the STAR Data [5] of K\(^0\) meson production factor in Au + Au collisions at 200 GeV and numerical simulations at NLO. Right: Comparison between the ALICE Data [15] of K\(^0\) meson modification factor in Pb + Pb collisions at 2760 GeV and numerical simulations at NLO.

collision based on the pattern discovered in the previous study on π\(^0\), η, ρ\(^0\) and φ meson.

With the NLO FFs in vacuum of both ω and K\(^0\) mesons, we are able to confront the numerical results of the ω and K\(^0\) meson productions in p+p collisions up to the NLO with the available experimental data both at the RHIC and at the LHC shown in Fig. 3 and Fig. 4. Note that in our simulations, the hard scales such as factorization scale, renormalization scale and fragmentation scale are chosen to be the same and proportional to the p\(_T\) of the final state hadron. We see the numerical results can match well with the experimental data on ω meson spectra both at the RHIC √s\(_{NN}\) = 200 GeV and the LHC √s\(_{NN}\) = 7 TeV with the rescaling factor K = 3 and the hard scales \(μ = 0.5\) p\(_T\), as shown in Fig. 3. We also demonstrate in Fig. 4 the good agreements of the theoretical calculations of leading K\(^0\) meson, with the STAR data and the ALICE data, where the hard scales are fixed to be \(μ = 1.0\) p\(_T\) to give the best fit.

3 Large p\(_T\) yield of ω and K\(^0\) Meson in A+A

To calculate the ω and K\(^0\) productions in A+A collisions, jet quenching effect should be included. In the article we utilize the higher-twist approach of parton energy loss, which relates parton energy loss due to its multiple scattering in QCD medium and medium-induced gluon radiation to twist-four processes, and shows that these processes may give rise to additional terms in QCD evolution equations and lead to the effectively medium-modified fragmentation functions; thus the partonic energy loss effect can be taken into account by replacing the FFs in vacuum with the effectively medium modified FFs [27,28,29,31,32]. By assuming a thermal ensemble of quasi-particle states in the hot/dense medium and also neglecting the multiple particle correlations inside the medium, the effective medium modified FFs are given as [21,22,24,25,26]:

\[
\tilde{D}_q^h(z_h,Q^2) = D^h_q(z_h,Q^2) + \frac{α_s(Q^2)}{2\pi} \int_0^{Q^2} \frac{d^2q^2}{q^2} P_{q\to qg}(z_h,Q^2) dz_h \tilde{D}_g^h(z_h,Q^2) + \Delta\gamma_{q\to qg}(z_h,Q^2) \]

The contribution of the medium-induced gluon radiation is attributed to the medium modified splitting functions represented by \(\Delta\gamma_{q\to qg}\) and \(\Delta\gamma_{g\to qg}\). In this formula, we assume the energy loss of the jet propagating through the medium is totally carried away by the radiative gluons, then the convolution of these energy loss kernels \(\Delta\gamma_{q\to qg}\) (\(\Delta\gamma_{g\to qg}\)) with the (DGLAP) evolved vacuum FFs at any scale \(D^h_q(z_h,Q^2)\) implies the assumption that the fast parton first loses its energy in the medium and then fragments into final state hadrons in vacuum.

The medium modified splitting functions depend on the properties of the local medium which can not be determined directly by the theoretical calculation itself. The jet transport parameter \(\hat{q}\) which defined as the average squared transverse momentum broadening per unit length is therefore introduced to profile the dependency of the local medium properties in these energy loss kernels [9].

The jet transport parameter \(\hat{q}\) can be phenomenologically assumed to be proportional to the local parton density in the hot/dense medium to adopt further medium description:

\[
\hat{q}(τ,r) = \hat{q}_0 \rho_{med}(τ,0) \frac{p^\mu u_\mu}{p^0},
\]

where \(\rho_{med}\) is the parton (quarks and gluon) density in the medium at a given temperature, \(q_0\) is the initial jet transport parameter at the center of the bulk medium at the initial time \(τ_0\), \(p^\mu\) is the four-momentum of the jet and \(u^\mu\) is the four flow velocity of the probed local medium in the collision frame. In this article we employ the state-of-art, event-by-event viscous hydrodynamics description IEBE-VISHNU [22] to give the space-time evolution information of the hot/dense medium such as temperature, parton density, four velocity of the local medium at any evolution time and position, as well as the formation time of the QGP \(τ_0 = 0.6\) fm. Therefore the only undetermined parameter is the calculation is \(q_0\) representing the strength of the jet-medium interaction, which may be fixed by fitting the data of leading hadrons (usually π meson) suppression in A+A collisions [9,21,24,25,26].

When averaging the medium modified FFs over the initial production position and jet propagation direction,
we are able to directly replace the vacuum FFs in the \( p+p \) formalism with these averaged medium modified FFs \( \langle \hat{D}_b^h(z_b, Q^2, E, b) \rangle \), therefore the formalism of the calculated cross section of the single hadron productions in HIC would take the form as:

\[
\frac{1}{N_{\text{coll}}(b)} \frac{d\sigma^{h}_{AB}}{dy dt_{\text{PT}}} = \sum_{abcd} \int dx_a dx_b f_{a/A}(x_a, \mu^2)f_{b/B}(x_b, \mu^2)
\times \frac{d\sigma}{dt}(ab \rightarrow cd) (\hat{D}_b^h(z_b, Q^2, E, b)) + \mathcal{O}(\alpha_s^3).
\]

in which \( \langle N_{\text{coll}}(b) \rangle = \int d^2r_A(r) t_B(|b - r|) \) is the number of binary nucleon-nucleon collisions at certain impact parameter \( b \) in \( A+B \) collisions and it can be calculated by using Glauber Model. \( f_{a/A}(x_a, \mu^2) \) represents the effective PDFs inside a nucleus. In our calculations, we employed EPPS16 NLO nuclear PDFs to include initial-state cold nuclear matter effects on single hadron productions.

Fig. 7. Theoretical calculation results of nuclear modification factors \( R_{AA} \) as functions of \( p_T \) at \( \hat{q}_0 = 0.4 - 0.7 \) GeV\(^2\)/fm confronted with the RHIC experimental data of \( \pi^0 \) [12], \( \eta \) [13], \( \phi \) [14], \( K_0^0 \) [15], \( \rho^0 \) and \( \omega \).

The nuclear modification factor \( R_{AA} \) as a function of \( p_T \) is calculated as cross sections in \( A + A \) collisions divided by the ones in \( p+p \) collision, scaled by the averaged number of binary nucleon-nucleon collisions with a chosen impact parameter \( b \): [3]

\[
R_{\text{AB}}^{h}(p_T, \eta) = \frac{\frac{d\sigma^{h}_{AB}}{dy dt_{\text{PT}}}}{\langle N_{\text{coll}}(b) \rangle \frac{d\sigma^{h}_{pp}}{dy dt_{\text{PT}}}}.
\]

The theoretical results of \( R_{AA} \) at various values of \( \hat{q}_0 = 0.4 - 0.7 \) GeV\(^2\)/fm for both \( \omega \) and \( K_0^0 \) mesons have been presented in Fig. [3] and Fig. [0].

Fig. 8. Theoretical calculation results of nuclear modification factors \( R_{AA} \) as functions of \( \hat{q}_0 = 1.0 - 3.0 \) GeV\(^2\)/fm confronted with the LHC experimental data of \( \pi^0 \) [12], \( \eta \) [13], \( \phi \) [14], \( K_0^0 \) [15], \( \rho^0 \) and \( \omega \).

When obtaining suitable value of \( \hat{q}_0 \) by comparing the theoretical calculations of \( R_{AA} \) for \( \omega \) and \( K_0^0 \) with the corresponding data, there exist two cautions. Firstly, since the data of \( \omega \) and \( K_0^0 \) meson at large \( p_T \) in \( A+A \) collisions are rather limited and with large uncertainty, it is difficult to make a good constrain on \( \hat{q}_0 \) with these data. Secondly, because we employ the IEBE-VISHNU hydrodynamics model to describe the space-time evolution of the fireball, which may give different information of physics quantities such as temperature and density from those provided by other hydro models such as Hirano hydro description. Therefore, we could not take advantage of the extracted value of \( \hat{q}_0 \) in Ref. [0], where Hirano hydro description has been utilized.

With these two cautions in mind, and realizing that with our model we are now ready to make a systematic study of 6 types of identified mesons such as \( \pi^0, \eta, \rho^0, \phi, \omega, \) and \( K_0^0 \) in heavy-ion collisions, it will be of great interest to make a global extraction of jet transport coefficient \( \hat{q}_0 \) at the RHIC and the LHC by confronting our model calculations (with the IEBE-VISHNU hydro model) against all available data on 6 identified mesons: \( \pi^0, \eta, \rho^0, \phi, \omega, \) and \( K_0^0 \), and then make precise calculations on nuclear modification modification factors of these mesons including \( \omega \), and \( K_0^0 \) as well as yield ratios of these 6 mesons in HIC.

4 Global Extraction of \( \hat{q}_0 \) with \( R_{AA} \) for Six Identified Mesons

We perform a systematic calculation of the \( R_{AA} \) of 6 identified mesons \( (\pi^0, \rho^0, \eta, \phi, \omega, K_0^0) \) to compare with all their
available experimental data at the RHIC and the LHC in Fig. 7 and Fig. 8.

In order to extract the best value of the initial jet transport parameter $\hat{q}_0$, we perform a $\chi^2$ fit to compare the theoretical results with different $\hat{q}_0$ and the available experimental data of all the different final hadrons.

$$\chi^2(a) = \sum_i \frac{|D_i - T_i(a)|^2}{\sigma_i^2} \quad (7)$$

In the above equations, $D_i$ represents the experimental grids and $T_i$ is our theoretical prediction at input parameter $a$. $\sigma_i^2$ means the $i$-th systematic and statistical experimental errors. We show in the top panel of Fig. 9 the derived $\chi^2$ averaged by the number of the compared data points for different final state mesons at various $\hat{q}_0 = 0.4 - 0.7$ GeV$^2$/fm at the RHIC with $\sqrt{s_{NN}} = 200$ GeV. In the bottom panel of Fig. 9, we plot the curve $\chi^2$/d.o.f as a function of $\hat{q}_0$ at the RHIC and the LHC, where the minimum of the curve $\chi^2$/d.o.f with respect to $\hat{q}_0$ presents the best fit of theory with data. We then observe that at the RHIC the minimum point of $\chi^2$/d.o.f of all 6 identified mesons gives the best value of $\hat{q}_0 = 0.5$ GeV$^2$/fm. It is noted that the production of $\pi^0$ will carry the largest weight due to its more abundant data with relatively smaller error bars. We also derive the best value of $\hat{q}_0$ in the Pb+Pb collisions at the LHC $\sqrt{s_{NN}} = 2.76$ TeV to be $\hat{q}_0 = 1.2$ GeV$^2$/fm, though the curve $\chi^2$/d.o.f at the LHC is much flatter that that at the RHIC. So theoretical results with $\hat{q}_0 = 1.1 - 1.4$ GeV$^2$/fm should all give decent descriptions on data at the LHC.

It is noted that in our current model the extracted values of jet transport coefficient $\hat{q}_0$ at the RHIC and the LHC are smaller than that by JET Collaboration in Ref. [9] as well as the ones in our preceding calculations [21, 25, 26]. These differences come mainly from the different hydro models utilized in the studies. We have checked [20] that if we employ Hirano hydro description in the calculation, the extracted values of $\hat{q}_0$ from our global fitting will be consistent with those in Ref. [9, 21, 25, 26], though the model in this article has the potential to give more precise extraction of jet transport coefficients when more data of identified hadrons in A+A collisions become available in the near future.

5 Particle Ratios of $\omega/\pi^0$ and $K^0_s/\pi^0$ in A+A

With the global extracted value of $\hat{q}_0$ discussed in Sec. 4 we are able to further investigate the particle ratio of $\omega$ and $K^0_s$ both at the RHIC and the LHC. We first calculate $\omega/\pi^0$ ratio as a function of $p_T$ and show the results in p+p and Au+Au at the RHIC in the left panel of Fig. 10 where the PHENIX experimental data on $\omega/\pi^0$ ratio in p+p are also illustrated. An enhancement of the ratio of $\omega$ to $\pi^0$ relative to that in p+p is found in small $p_T$ region, whereas a small suppression in large $p_T$ region. We also predict the $\omega/\pi^0$ ratio as a function of $p_T$ in p+p and Pb+Pb collisions with $\sqrt{s_{NN}} = 2.76$ TeV at the LHC. In Fig. 10 we don’t see the overlapping of the curves $\omega/\pi^0$ in p+p and A+A at large $p_T$, as we have observed for the ratios $\eta/\pi^0$ [23] and $\rho^0/\pi^0$ [23] in p+p and A+A.

To understand this feature deeper, we plot the gluon and quark (fragmentation) contribution fractions to $\omega$ (and $\pi^0$) in p+p and Au+Au at the RHIC in Fig. 11. One see in the p+p collision at the RHIC, the production of $\omega$ is dominated by gluon fragmentation. In the A+A collisions, the gluon suffers more energy loss than the light quark due to its larger color factor, which decreases the gluon contribution fraction and increase the light quark contribution fraction, but the dominant gluon contribution fraction of $\omega \sim 60\%$ is still observed up to $p_T = 20$ GeV in Au+Au at the RHIC. On the other hand, $\pi^0$ meson production is light quark fragmentation dominant in p+p, and jet quenching effect further enhance this dominance of light quark fragmentation to $\pi^0$ in A+A. Therefore, we see the yield ratio of $\omega/\pi^0$ in A+A should be suppressed relative to that in p+p due to energy loss effect, and it separates with the one in p+p even at very high $p_T$.

We also compute the $K^0_s/\pi^0$ ratio as a function of $p_T$ both at the RHIC and the LHC in Fig. 12. We find the curves in A+A and in p+p are approaching to each other with $p_T$ increasing, and an obvious coincidence of these two curves is seen at the LHC. We show the gluon
Fig. 10. Left: the yield ratios of $\omega/\pi^0$ as functions of $p_T$ in p+p and Au+Au collisions with 200 GeV at the RHIC, and PHENIX data in p+p [14]; Right: predictions of the yield ratios of $\omega/\pi^0$ as functions of $p_T$ in p+p and Pb+Pb collisions with 2.76 TeV at the LHC.

Fig. 11. Gluon and quark contribution fractions of the total yields of $\omega$ and $\pi^0$ mesons in p+p and Au+Au collisions with $\sqrt{s_{NN}} = 200$ GeV at the RHIC.

Fig. 12. Left: the production ratios of $K_S^0/\pi^0$ as functions of $p_T$ in p+p and Au+Au collisions with 200 GeV at the RHIC; Right: predictions of the production ratios of $K_S^0/\pi^0$ as functions of $p_T$ in p+p and Pb+Pb collisions with 2.76 TeV at the LHC.
and quark contribution fractions to $K_0^0$ ( and $\pi^0$ meson) as functions of $p_T$ in Fig. 13. We find in p+p collision, the productions of both $K_0^0$ and $\pi^0$ at very large $p_T$ are dominated by quark fragmentation. In A+A collisions, the gluon contribution may be further suppressed because gluon generally loses more energy. Thus, both in p+p and A+A collisions, the ratio $K_0^0/\pi^0$ should be largely determined by the ratio of quark FFs for $K_0^0$ ($D_q^{K_0^0}(z_h, Q^2)$) to quark FFs for $\pi^0$ ($D_q^{\pi^0}(z_h, Q^2)$) at very high $p_T$, where these FFs vary slowly with the momentum fraction $z_h$, very similar to the case of $\eta/\pi^0$ at high $p_T$. Even though in A+A collisions, jet quenching effect may shift $z_h$ of quark FFs, if quark FFs have a rather weak dependence on $z_h$ and $p_T$, we may see at very high $p_T$ the curves $K_0^0/\pi^0$ in A+A and p+p curves may come close to each other, and even coincide at the LHC.

6 Summary

In summary, we obtain the NLO FFs of $\omega$ meson in vacuum by evolving the rescaled $\omega$ FFs from a broken SU(3) model at a starting scale $Q_0^2 = 1.5$ GeV$^2$, and directly employ NLO $K_0^0$ FFs in vacuum from the AKK08 parameterizations, the numerical simulation of productions of both $\omega$ and $K_0^0$ matches well with the experimental data in p+p reactions. With the IEBE-VISHNU hydro profile of the QCD medium, we calculate the nuclear modification factors of $\omega$ and $K_0^0$ meson as well as $\pi^0$, $\eta$, $\phi$, $\rho^0$ in A+A collisions at the RHIC and the LHC, including jet quenching effect in higher-twist approach. The global extraction of jet transport parameter $\bar{q}_0$ are made, with comparison of the theoretical calculation and the experimental data of all six identified mesons: $\pi^0$, $\rho^0$, $\eta$, $\phi$, $\omega$, $K_0^0$. Furthermore, we predict the yield ratios of $\omega/\pi^0$ both at the RHIC and the LHC, and a fairly good agreement of the theoretical results and experimental data is found at the RHIC. Theoretical predictions of $K_0^0/\pi^0$ ratios as functions of $p_T$ at the RHIC and the LHC are presented as well.

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