Towards a qualitative hadron-parton correspondence in the nuclear modification factor

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In this work, we propose a method to show the correspondence between hadron and its quark component nuclear modification factors. A parton and hadron cascade model PACIAE based on the PYTHIA6.4 is employed to calculate the hadron and its quark component nuclear modification factors in the 0-5% most central Pb+Pb collisions at √sNN=2.76 TeV. It turns out that the hadron nuclear modification factor is usually smaller than that of its quark component. On the other hand, it is shown in our study that the “dead cone effect” is more likely to be identified with the quarks and mesons but not with the baryon states obviously.

I. INTRODUCTION

Jet quenching (energy loss) and particle azimuthal asymmetries (elliptic flow etc.) are the essential probes investigating the quark-gluon plasma (QGP) in the ultra-relativistic nucleus-nucleus collisions at RHIC [1–4] and LHC [5–7] energies. Nuclear modification factor is an important measurement exploring the jet quenching effect [8, 9]. The parton nuclear modification factor is responsible for the energy loss in partonic stages of initial state and parton rescattering stage. And the hadron nuclear modification factor in final hadronic state is one measure of the jet quenching in the hadronic stages of hadronization and hadronic rescattering. It is speculated that a connection can be built with the measurable final state hadron nuclear modification factor and the underlying quark energy loss.

The hadron transverse momentum dependent nuclear modification factor in final hadronic state of the nucleus-nucleus (A+A) collision is usually defined as [10]

\[ R_{AA}^h(p_T) = \frac{[dY(h)/dp_T]_{AA}}{N_{bin}[dY(h)/dp_T]_{pp}}, \]  

where \( Y(h) \) stands for the hadron (h) yield and \( N_{bin} \) refers to the binary collision number usually obtained within the optical Glauber model and/or Monte Carlo Glauber model [11–17]. It is sensitive to the relative variation of the particle transverse momentum distribution in the nucleus-nucleus and proton-proton collisions. However, the transverse momentum dependent nuclear modification factor is dominated by the energy loss (jet quenching). A substantial suppression of \( R_{AA}^h(p_T) < 1 \) in the intermediate to high \( p_T \) region is anticipated as the signal of the partonic energy loss in Quark Gluon Matter (QGM) [18]. The behavior of nuclear modification factor as a function of \( p_T \) is not monotonous. In general, a peak appears at \( p_T \sim 2 \) GeV/c, which the valley follows at the \( p_T \sim 6 \) GeV/c, then the function increases monotonously toward the unity [10]. Thus the model simulation is hard to reproduce the \( R_{AA}^h(p_T) \) calculated with experimentally measured transverse momentum distributions in \( p-p \) and nucleus-nucleus collisions, over full \( p_T \) region especially.

Similarly, the quark transverse momentum dependent nuclear modification factor in the deconfined QGM reads

\[ R_{AA}^q(p_T) = \frac{[dY(q)/dp_T]_{AA}}{N_{bin}[dY(q)/dp_T]_{pp}}. \]  

Taken \( \Lambda^0(uds) \) hadron as an example, it is consisted of the constituent quarks \( u, d, \) and \( s \). Identifying the correspondence between the hadron and its quark component nuclear modification factors would be worthwhile to study the effects of jet quenching. The recombination (coalescence) model [19–21] is hard in constructing this correspondence due to the complication in dealing with the flavor composition of constituent quarks. The spirit of “correspondence principle” [22–24] has been inspiring us to construct the correspondence between hadron and its quark component nuclear modification factors based on physical deductions. Consequently, a parton and hadron cascade model of PACIAE is employed calculating the hadron nuclear modification factor in final hadronic state (FHS) and its quark component nuclear modification factor in partonic state after parton-parton rescattering (PSw/R).

II. PHYSICAL DEDUCTIONS

The hadron (h) normalized transverse momentum distribution

\[ \frac{1}{N(h)}dY(h)/dp_T \]
corresponds to its quark component normalized transverse momentum distribution as

\[ N_{cq} \left( \sum_{q} \frac{1}{N(q)} dY(q)/dp_T \right). \]

In the above expressions the \( N(h) \) \( (N(q)) \) is total multiplicity of the hadron \( h \) (quark \( q \)). \( N_{cq} \) denotes the number of constituent quarks, and the sum is taken over all the constituent quarks. If both are multiplied by \( N(h) \), one can get the resulting hadron \( h \) unnormalized transverse momentum distribution

\[ dY(h)/dp_T, \]

which appears in the Eq. \( 1 \) and is corresponding to

\[ \sum_{q} \frac{N(h)}{N(q)} dY(q)/dp_T. \]

Then we have the hadron nuclear modification factor of Eq. \( 1 \) corresponding to its quark component nuclear modification factor of

\[ R_{AA}^{h(qc)}(p_T) = \frac{\left[ \sum_{q} w_q dY(q)/dp_T \right]_{AA}}{N_{bin} \sum_{q} w_q dY(q)/dp_T|_{pp}}. \]  

(3)

where the superscript \( h(qc) \) denotes the quark component of hadron \( h \) and \( w_q = \frac{N(h)}{N(q)} \).

The quark energy loss is supposed to follow the so called “dead cone effect” and the size of dead cone is proportional to the mass of the QED and/or QCD emitter. Quark with smaller mass will lose more energy during the propagation through the dense medium. Therefore, one may expect the flavor ordering of the energy loss and of nuclear modification at the parton level:

\[ \Delta E(g) > \Delta E(u) > \Delta E(s) > \Delta E(c) > \Delta E(b) > \Delta E(t) \]

and

\[ R_{AA}^{g} < R_{AA}^{u} < R_{AA}^{s} < R_{AA}^{c} < R_{AA}^{b} < R_{AA}^{t}. \]  

(4)

We also investigate the “dead cone effect” in the partonic state after parton-parton rescattering and in final hadronic state in the 0-5% centrality \( Pb + Pb \) collisions at \( \sqrt{s_{NN}}=2.76 \) TeV in this paper.

FIG. 1: The left panel shows \( \pi^+ + \pi^- \) transverse momentum distributions in FHS of 0-5% most central \( Pb + Pb \) and \( p + p \) collisions at \( \sqrt{s_{NN}}= 2.76 \) TeV (ALICE data are taken from [31]). The right panel is \( R_{AA}^{\pi^+\pi^-} (p_T) \).
III. PACIAE MODEL

The parton and hadron cascade model PACIAE [27] based on PYTHIA6.4 [28], is employed to calculate the hadron and its quark component nuclear modification factors in the 0-5% most central Pb + Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV. In PACIAE model the nucleon initial position in a nucleus-nucleus collision is distributed randomly according to the Woods-Saxon distribution and the number of participant (spectator) nucleons determined by the Glauber model [11–17]. Together with the initial momentum setup of $p_x = p_y = 0$ and $p_z = p_{beam}$, the initial nucleon list is constructed for a colliding nucleus-nucleus system. Collision happens between a pair of two nucleons if their relative transverse distance is less than or equal to the minimum approaching distance: $D \leq \sqrt{\sigma_{NN}/\pi}$. The collision time is calculated with the assumption of straight-line trajectories. All such nucleon pairs compose the nucleon-nucleon ($NN$) collision (time) list. A $NN$ collision with least collision time is selected.
from the collision list and executed by PYTHIA6.4 (subroutine PYEVNW) with the string hadronization temporarily turned-off and the strings as well as diquarks broken-up. The nucleon list and NN collision list are then updated. A new NN collision with least collision time is selected from the updated NN collision list and executed by PYTHIA6.4. Such a routine is repeated until the NN collision list is empty. The initial partonic state (IPS) of a nucleus-nucleus collision is reached.

The above initial partonic state is then proceeding to a partonic rescattering where the LO-pQCD parton-parton cross section \(29, 30\) are employed. The state, after partonic rescattering is referred to as partonic state after rescattering (PSw/R).

After string recovering, the Lund string fragmentation regime is employed to hadronize the strings resulting an intermediate hadronic state. This intermediate hadronic state proceeds with the hadronic rescattering. A final hadronic state (FHS) is reached for a nucleus-nucleus collision eventually.

IV. RESULTS AND CONCLUSIONS

In the PYTHIA model a \(K\) factor is introduced multiplying the hard scattering cross section. Together with the Lund string fragmentation parameters of \(\alpha\) and \(\beta\) as well as the Gaussian width (\(\omega\)) of primary hadron transverse momentum distribution are adjusted fitting globally the ALICE data \(31\) of \(\pi^+ + \pi^- p_T\) distributions in the 0-5% most central \(Pb + Pb\) and \(p + p\) collisions at \(\sqrt{s_{NN}} = 2.76\) TeV. The fitted parameters: \(K = 2.7, \alpha = 1.3, \beta = 0.09, \omega = 0.575\) for \(Pb + Pb\) (\(K = 0.7, \alpha = 0.3, \beta = 0.58, \omega = 0.36\) for \(p + p\)) are used in the later calculations, where the full \(\eta\) phase space is assumed. The hadron \(p_T\) distribution in heavy-ion collisions is observed to transit from exponential like at low transverse momenta to power law like at the high transverse momenta \(31\). It is approximately assumed by multiplying the exponentially simulated primary hadron \(p_T\) with a factor of 1.8 if \(p_T\) is larger than 2.5 GeV/c in the PYTHIA model (subroutine PYPTDI) for \(Pb + Pb\) collisions.

We see in the left panel of Fig.\(1\) that the fitted \(\pi^+ + \pi^- p_T\) distributions in the 0-5% most central \(Pb + Pb\) (black open triangles-up) and \(p + p\) (red open triangles-up) collisions at \(\sqrt{s_{NN}} = 2.76\) TeV are well consistent with the ALICE data (black full circles for \(Pb + Pb\) and red full circles for \(p + p\)) \(31\), respectively. The theoretical \(R^{\pi^+ + \pi^-}_{AA}(p_T)\) (red open squares, calculated with the fitted \(p_T\) distributions) is also found to agree with the experimental one (black full circles, calculated with the ALICE \(p_T\) distribution data) within error bars.

The calculated mesons \(R_{AA}(p_T)\) in full pseudorapidity phase space in FHS (black solid circles) are compared with their quark components ones in PSw/R (red open circles) in the upper panels of Fig.\(2\): left panel for \(\pi^+\), middle for \(K^+\), and right for \(\phi\), respectively. The lower panels are the same as upper ones, but showing baryon sectors of \(p\) (lower-left panel), \(\Lambda^0\) (lower-middle), and \(\Xi^-\) (lower-right), respectively. One can observe in the upper (lower) panel that, in \(p_T\) region above \(p_T \sim 2\) GeV/c the meson (baryon) \(R_{AA}\) is generally less than its quark component one. It can be understood as the hadron objects suffer more energy loss than their quark components. In other words, there is follow-up relation between hadron and its quark component energy loss. This observation offers a possibility to distinguish the partonic and hadronic energy losses as well as a reference for the reliable evaluation of the hadron nuclear modification factor.

A special feature seen in Fig.\(2\) is that the hadron \(R_{AA}\) calculated with single differential \(p_T\) distribution in full pseudorapidity phase space is not increasing toward unity at high \(p_T\) region as usually observed in finite
FIG. 4: The nuclear modification factor of quarks (left, in PSw/R), mesons (middle, in FHS), and baryons (right, in FHS) in 0-5% most central Pb + Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV.

pseudorapidity phase space (cf. ALICE in $|\eta| < 0.8$ [32] and CMS in $|\eta| < 1$ [6]). To understand this feature we draw $\pi^+$ single differential $p_T$ distribution in full pseudorapidity phase space in the 0-5% most central Pb + Pb and $p + p$ collisions at $\sqrt{s_{NN}}=2.76$ TeV in Fig.(4). One sees here that the high ($P_T$) suppression in $Pb + Pb$ collision is stronger with $p_T$ increasing, which is responsible for the $\pi^+$ $R_{AA}$ behavior at high $p_T$ region in the full pseudorapidity phase space as shown in upper-left panel of Fig.2.

In the Fig.(4) we compare the calculated nuclear modification factor for quarks ($u$, $s$, and $c$ in PSw/R, left panel), mesons ($\pi^+$, $K^+$, and $\phi$ in FHS, middle panel), and baryons ($p$, $\Lambda^0$, and $\Xi^-$ in FHS, right panel) in the 0-5% most central Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. This figure shows that in $p_T$ region above $p_T \sim 2$ GeV/c the “dead cone effect” is globally held for the sector of quark (in PSw/R) and meson (FHS), but not showing obviously for baryons (FHS) which has to be studied further. The nearly flat $R_{AA}(p_T)$ (cf. left panel) is because of the $c$ quark is produced in the hard scattering processes. Thus the $c$ quark $p_T$ distribution in Pb + Pb collision is nearly parallel to the one in $p + p$ collision at the same energy.

In summary, we introduce a correspondence between hadron nuclear modification factor and its quark component one based on the spirit of correspondence principle. Both of the hadron and its quark component nuclear
Modification factors are then calculated separately with the parton and hadron cascade model PACIAE based on PYTHIA 6.4 in the 0-5% most central \( p_b + p_b \) collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV. Because of the follow-up relation the hadron suffers more energy loss than its quark component, the hadron \( R_{AA} \) is less than its quark component one in the \( p_T \) region above \( p_T \sim 2 \) GeV/c. A comparison between the two serves a reference for the reliable evaluation of hadron nuclear modification factor and a possibility to distinguish the partonic and hadronic energy losses. Additionally, it turns out that the mass hierarchy of \( R_{AA} \) out of “dead cone effect”, can be found for the section of quarks and mesons but not obviously for baryons. This has to be studied further.

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