The impact of the medium and the jet-medium coupling on jet measurements at RHIC and LHC

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We compare a perturbative QCD-based jet-energy loss model to the measured data of the pion nuclear modification factor and the high-$p_T$ elliptic flow at RHIC and LHC energies. This jet-energy loss model (BBMG) is currently coupled to state-of-the-art hydrodynamic descriptions. We report on a model extension to medium backgrounds generated by the parton cascade BAMPS. In addition, we study the impact of realistic medium transverse flow fields and a jet-medium coupling which includes the effects of the jet energy, the temperature of the bulk medium, and non-equilibrium effects close to the phase transition. By contrasting the two different background models, we point out that the description of the high-$p_T$ elliptic flow for a non-fluctuating medium requires to include such a jet-medium coupling and the transverse flow fields. While the results for both medium backgrounds show a remarkable similarity, there is an impact of the background medium and the background flow on the high-$p_T$ elliptic flow.

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I. INTRODUCTION

One of the open challenges in heavy-ion physics is to gain a precise understanding of the jet-medium dynamics, the jet-medium interactions, and the jet-energy loss formalism. In this letter, we study the impact of the medium and the details of the jet-medium coupling on the pion nuclear modification factor ($R_{AA}$) and the high-$p_T$ elliptic flow ($v_2$) measured at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) [1–4].

We find that both the background medium and the details of the jet-medium coupling play an important role for the simultaneous description of the $R_{AA}$ and the high-$p_T$ $v_2$. This simultaneous description reveals the so-called high-$p_T$ $v_2$-problem [5, 6]. For various theoretical models [1, 7, 8], the high-$p_T$ elliptic flow below $p_T \sim 20$ GeV is about a factor of two below the measured data [1–4]. This effect has been discussed in literature [7, 8]. Recently, it has been shown by CUJET3.0 [9] that a jet-medium coupling $\kappa = \kappa(E^2, T)$ can solve the high-$p_T$ $v_2$-problem for non-fluctuating initial conditions. This jet-medium coupling depends on the energy of the jet $E$, the temperature of the medium $T$, and non-equilibrium effects around the phase transition of $T_c \sim 160$ MeV.

In this letter, we contrast results obtained for a background medium determined via the viscous hydrodynamic approach VISH2+1 [10] with the parton cascade BAMPS [11, 12] and study the impact of the jet-medium coupling $\kappa = \kappa(E^2, T)$ derived by CUJET3.0 [9].

We show that both medium backgrounds lead to surprisingly similar results. However, the background flow fields need to be included in both scenarios to enhance the high-$p_T$ elliptic flow which is otherwise too small. Applying the jet-medium coupling $\kappa = \kappa(E^2, T)$ finally leads to a reproduction of the high-$p_T$ $v_2$-data within measured error bars.

With this, we contrast two completely different background models and demonstrate the importance of the background flow fields and the jet-medium coupling for the correct description of the measured jet observables.

II. THE JET-ENERGY LOSS MODEL BBMG

The jet-energy loss model used in this letter (for convenience referred to as BBMG model) is based on the generic ansatz [5, 6]

$$\frac{dE}{d\tau} = -\kappa E^a(\tau) \tau^2 \exp((2z-\alpha)/4) \zeta_q \Gamma_f,$$  \hspace{1cm} (1)

with the jet-energy $E$, the path-length $\tau$, and the energy density of the background medium $\epsilon$.

In case of a radiative perturbative QCD (pQCD) energy-loss description used here, the explicit form of Eq. (1) is [5, 6]

$$\frac{dE}{d\tau} = -\kappa E^0(\tau) \tau^3 \exp(3/4) \zeta_q \Gamma_f.$$

Jet-energy loss fluctuations are included via the distribution $f_q(z_q) = \frac{(1+q)^2}{q^2} \left[ q + 2 - z_q \right]^9$ which allows for an easy interpolation between non-fluctuating ($\zeta_q=1$) distributions and those ones increasingly skewed towards small $\zeta_q<1$. Unless mentioned otherwise, the jet-energy loss fluctuations are included with $q=0$ [5].

The background flow fields are incorporated via the flow factor $\Gamma_f = \gamma_f [1 - v_f \cos(\phi_{jet} - \phi_{flow})]$ with the background flow velocities $v_f$ given by VISH2+1 [10] or BAMPS [11] and the $\gamma$-factor $\gamma_f = 1/\sqrt{1 - v_f^2}$ [13–15]. $\phi_{jet}$ is the jet angle w.r.t. the reaction plane and...
\[ \phi_{\text{flow}} = \phi_{\text{flow}}(\vec{x}, t) \] is the corresponding local azimuthal angle of the background flow fields.

Initially, the jets are distributed according to a transverse initial profile given by the bulk flow fields of \textsc{VISH2+1} and \textsc{BAMPS} [10, 11].

Besides the two background media, we also contrast a jet-medium coupling \( \kappa \) that depends only on the collision energy \( \kappa = \kappa(\sqrt{s_{NN}}) \) with the \textsc{CUIJET3.0} jet-medium coupling \( \kappa = \kappa(E^2, T) \) which depends on the jet energy, the local temperature, and includes possible non-perturbative effects around the phase transition as in Ref. [9]. The DQLV [17] jet-medium coupling was generalized in Ref. [9] to be of the form

\[
\kappa(E^2, T) = \alpha_S(E^2)\chi_T \left( f_E^2 + f_M^2 + f_E^2 f_M^2 / E^2 \right) \\
- (1 - \chi_T)(f_E^2 + f_M^2 + f_E^2 f_M^2 / E^2). \tag{3}
\]

Please note that Eq. (3) is qualitatively similar to \textsc{CUIJET3.0} as the running coupling constant there a function of momentum transfer \( \alpha(Q^2) \) while we assume that \( Q^2 = E^2 \). The above expression includes

(1) a running coupling effect via \( \alpha_S(E^2) = 1/[c + 9/4\pi \log(E^2/T_c^2)] \) with \( c = 1.05 \),

(2) the Polyakov-loop suppression of the color-electric scattering [18] via \( \chi_T = c_L + c_g L^2 \) with the pre-factors \( c_g = (10.5 N_f) / (10.5 N_f + 16) \) for quarks and \( c_g = 16 / (10.5 N_f + 16) \) for gluons. Here, we consider \( N_f = 3 \). \( L(T) = \left[ 1 + 4T \tanh(7.69(T - 0.0726)) \right]^{10} \) is a fit to lattice QCD [19, 20], as in Ref. [9],

(3) a model of near-critical \( T_c \) enhancement of scattering due to emergent magnetic monopoles. The functions \( f_E(T) \) and \( f_M(T) \) are also fits to lattice QCD [21]. The electric and magnetic screening masses are given by \( \mu_{E,M}(T) = f_{E,M}(T) \mu(T) \) with the Debye screening mass \( \mu^2(T) = \sqrt{4\pi\alpha_s(\mu^2)T} \sqrt{1 + N_f/6} \). The functions \( f_{E,M}(T) \) can be re-written to \( f_E(T) = \sqrt{\chi_T} \) and \( f_M(T) = 0.3\mu(T)/(T\sqrt{1 + N_f/6}) \) [3].

This jet-medium coupling decreases with the temperature of the background medium and thus shows an effective running with collision energy.

### III. RESULTS AND DISCUSSION

Fig. 1 shows the pion nuclear modification factor (\( R_{AA} \)) for central (left panel) and mid-central (middle panel) collisions at RHIC (black) and LHC (red) as well as the high-\( p_T \) pion elliptic flow (\( \nu_2 \)) for mid-central events (right panel). The measured data [1–4] are compared to a pQCD-based energy loss \( dE/d\tau = \kappa(\sqrt{s_{NN}})E^0 \tau^3 e^{3/4}\zeta_0 \) that includes jet-energy loss fluctuations (\( \zeta_0 \)). The jet-medium coupling depends on the collision energy \( |\kappa = \kappa(\sqrt{s_{NN}})| \) and the medium background is either described applying the hydrodynamic code \textsc{VISH2+1} [10] (solid lines) or the parton cascade \textsc{BAMPS} [11] (dashed-dotted lines). The background flow \( \Gamma_f \) is not included here.

Within the present error bars, both the central and the mid-central pion nuclear modification factor can be described using this pQCD ansatz without the background flow fields. However, the high-\( p_T \) \( \nu_2 \)-problem [2, 6] becomes obvious. The right panel of Fig. 1 shows that the high-\( p_T \) elliptic flow is below the measured data.

Including the background flow fields via \( \Gamma_f \) in Fig. 2 leads to a significant increase of the high-\( p_T \) elliptic flow while the pion nuclear modification factor is only affected marginally.

Fig. 2 reveals the strong influence of the background flow fields on the high-\( p_T \) elliptic flow.

Besides this, Figs. 1 and 2 demonstrate a surprising similarity between the results based on a medium described by viscous hydrodynamics [10] and the parton cascade \textsc{BAMPS} [11]. This similarity cannot be
expected a priori as the two background media are quite different: While the hydrodynamic description of VISH2+1 assumes an equilibrated system, the parton cascade BAMPS also includes non-equilibrium effects in the bulk medium evolution. However, since those effects are small, a temperature can be defined after a very short initial time $t_0$. In this work, we use $t_0 = 0.3$ fm at RHIC and $t_0 = 0.2$ fm at LHC energies.

In a third step, we include the jet-medium coupling $\kappa = \kappa(E^2, T)$ given by Eq. (3) in our jet-energy loss approach. The result is shown in Fig. 3 again for the hydrodynamic background VISH2+1 (solid lines) and a medium determined via the parton cascade BAMPS (dashed-dotted lines). As in Figs. 1 and 2 the pion nuclear modification factor is well described both at RHIC and LHC. However, the high-$p_T$ elliptic flow increases significantly below $p_T \sim 20$ GeV, especially for the BAMPS background which already includes non-equilibrium effects through microscopic, non-equilibrium transport calculations [11, 12].

Fig. 3 demonstrates that the jet-medium coupling $\kappa = \kappa(E^2, T)$ suggested by CUJET3.0 can solve the high-$p_T$ $v_2$-problem. However, the background medium considered does play an important role for the description of the high-$p_T$ elliptic flow. Please note that the initial conditions studied here are non-fluctuating, i.e. neglect event-by-event short-scale inhomogeneities. The effect of event-by-event fluctuations will be studied elsewhere.

To further investigate the influence of the parton cascade medium, we varied the jet-energy loss fluctuations. The results are shown in Fig. 3. As one can see, the slope of both the $R_{AA}$ and the high-$p_T$ $v_2$ at LHC energies changes when considering non-fluctuating ($\zeta = -1 = 1$) jet-energy loss distributions. To be more precise, the results get closer to the slope of the measured data. This is in contrast to results previously obtained with the pQCD-based jet-energy loss ansatz for the VISH2+1 background [10]. In Ref. [5] the slope of both the $R_{AA}$ and the high-$p_T$ $v_2$ did not change significantly when changing the jet-energy loss fluctuations. In particular, the results of Ref. [5] for the elliptic flow at $p_T > 20$ GeV coincided for various fluctuation distributions.

This result strengthens the observation that the background medium considered plays an important role for the correct description of the jet observables. However, while the nuclear modification factor is less influenced by the background medium, the impact of the background medium and background flow on the high-$p_T$ elliptic flow is quite significant.

### IV. Conclusions

We compared the measured data on the nuclear modification factor and the high-$p_T$ elliptic flow at RHIC and LHC energies to results obtained by the pQCD-based jet-energy loss model BBMG. We contrasted results obtained via a hydrodynamic background (VISH2+1) with results based on the parton cascade BAMPS [11, 12]. We showed that the results for both medium backgrounds exhibit a remarkable similarity, especially for the pion nuclear modification factor. We demonstrated that the background medium and background flow strongly influence the high-$p_T$ $v_2$. We found that for event-averaged or non-fluctuating initial conditions, studied here, the simultaneous description of the pion nuclear modification factor and high-$p_T$ elliptic flow requires to consider both the background flow fields and a jet-medium coupling that depends on the energy of the jet, the temperature of the medium, and non-equilibrium effects around the phase transition.
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