PROCEEDINGS OF SCIENCE

Exploring jet transport coefficients in the strongly interacting quark-gluon plasma

Ilia Grishmanovskii,^{a,*} **Taesoo Song,**^{b} **Olga Soloveva,**^{a,c} **Carsten Greiner**^{a,c} **and Elena Bratkovskaya**^{a,b,c}

[a] *Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität,Max-von-Laue-Str. 1, D-60438 Frankfurt am Main, Germany*

[b] *GSI Helmholtzzentrum für Schwerionenforschung GmbH,Planckstrasse 1, D-64291 Darmstadt, Germany*

[c] *Helmholtz Research Academy Hesse for FAIR (HFHF), GSI Helmholtz Center for Heavy Ion Physics, Campus Frankfurt, 60438 Frankfurt, Germany*

E-mail: `grishm@itp.uni-frankfurt.de`

We study the interaction of leading jet partons in a strongly interacting quark-gluon plasma (sQGP) medium based on the effective dynamical quasiparticle model (DQPM). The DQPM describes the non-perturbative nature of the sQGP at finite temperature T and baryon chemical potential μ_B based on a propagator representation of massive off-shell partons (quarks and gluons) whose properties (characterized by spectral functions with T, μ_B dependent masses and widths) are adjusted to reproduce the lattice Quantum Chromodynamics (lQCD) EoS for the QGP in thermodynamic equilibrium. We present the results for the jet transport coefficients, i.e. the transverse momentum transfer squared per unit length $\hat{q}$ in the QGP and investigate their dependence on the medium temperature T and jet parton energy.

FAIR next generation scientists - 7th Edition Workshop (FAIRness2022)
23-27 May 2022
Paralia (Pieria, Greece)

PoS(FAIRness2022)018

---

[*] Speaker

© Copyright owned by the author(s) under the terms of the Creative Commons
Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0).

PoS(FAIRness2022)018

Ultra-relativistic heavy-ion collisions performed at the Super Proton Synchrotron (SPS), the Relativistic Heavy-Ion Collider (RHIC) and the Large Hadron Collider (LHC) at CERN provide an access to a new hot and dense phase of matter, the quark-gluon plasma (QGP). An understanding of the properties of the QGP is one of the main goals of current research in heavy-ion physics.

Jet quenching appeared to be an effective tool for studying the degrees of freedom of the QGP matter. Produced in the early stage of the heavy-ion collisions, jets get high transverse momentum and traverse the QGP interacting with the medium through collisional and radiative processes. Starting from the pioneering work by Bjorken in 1982 [1] a substantial progress in the understanding of the jet energy loss has been made in the last decades. Theoretical studies [2] showed that the parton energy loss can be described by a series of jet transport coefficients such as the jet quenching parameter $\hat{q}$ which denotes the transverse momentum transfer squared per unit length (or time) of the propagating hard parton to the QGP medium.

Recently in Ref. [3] we have evaluated the jet transport coefficients – the transverse momentum transfer squared per unit length $\hat{q}$ as well as the energy loss per unit length $\Delta E = dE/dx$, using an effective field-theoretical model – the dynamical quasiparticle model (DQPM) [4–8]. In this study we concentrate on the energy loss of jet partons due to elastic scattering, which is expected to be the dominant contribution at low and intermediate jet momenta. In this contribution we recall the main findings from Ref. [3] related to the $\hat{q}$ coefficient.

1. Transport coefficients in DQPM

The DQPM [4–8] is an effective approach which describes the QGP in terms of strongly interacting quarks and gluons. Their properties are fitted to reproduce lattice QCD calculations in thermal equilibrium and at vanishing quark chemical potential. In the DQPM the quasiparticles are characterized by dressed propagators with complex self-energies, where the real part of the self-energies is related to dynamically generated thermal masses, while the imaginary part provides information about the lifetime and reaction rates of the partons. The off-shell partonic interaction cross sections have been evaluated based on the leading order scattering diagrams and depend on T, μ_B, the invariant energy of the colliding partons $\sqrt{s}$ as well as the scattering angle [8].

The general expression for a transport coefficient in kinetic theory in case of off-shell medium partons has the following form:

$$\langle O\rangle^{\rm off} = \frac{1}{2E_i}\sum_{j=q,\bar{q},g}\int\frac{d^4p_j}{(2\pi)^4}d_j f_j\tilde{\rho}(\omega_j,\mathbf{p}_j)\theta(\omega_j)\int\frac{d^3p_1}{(2\pi)^3 2E_1}\int\frac{d^4p_2}{(2\pi)^4}\tilde{\rho}(\omega_2,\mathbf{p}_2)\theta(\omega_2) \times (1\pm f_1)(1\pm f_2)\, O\, |\bar{\mathcal{M}}|^2\, (2\pi)^4\delta^{(4)}(p_i+p_j-p_1-p_2). \tag{1}$$

where d_j is the degeneracy factor for spin and color; $\tilde{\rho}(\omega_i)$ are renormalized spectral functions; f_j are the Fermi (Bose) distribution functions for quarks (gluons). The Pauli-blocking (-) and Bose-enhancement (+) factors account for the available density of final states. The notation $\sum_{j=q,\bar{q},g}$ includes the contribution from all possible partons which in our case are the gluons and the (anti-) quarks of three different flavors (u, d, s). In this study we consider

$$O = |\mathbf{p_T} - \mathbf{p'_T}|^2, \tag{2}$$

where p_T denotes transverse momentum. Such form of O corresponds to the jet transport coefficient $\hat{q}$.

2. Results

In Fig. 1 we show the temperature dependence of the scaled $\hat{q}/T^3$ transport coefficient for $\mu_B = 0$ for different approaches. The DQPM results are obtained by full off-shell calculations.

We mention that in general, there are four effects that lead to the DQPM results different from the pure pQCD calculation:

- Strong coupling is dominantly responsible for the sensitivity to the transport properties of the QCD medium since it enters the definitions of thermal masses/widths and scattering amplitudes. The strong temperature dependence of the coupling leads to a strong temperature dependence of the transport coefficients.
- Finite masses of the intermediate parton propagators play the same role as the Debye screening mass in HTL calculations providing the cut-off effect and a general suppression for the differential cross sections.
- Finite masses of the medium partons have three effects on the total value of the transport coefficients. Firstly, they enter the expression for the scattering amplitude and have a large effect for small scattering energies. For high energies (which is the case for jet partons), however, the

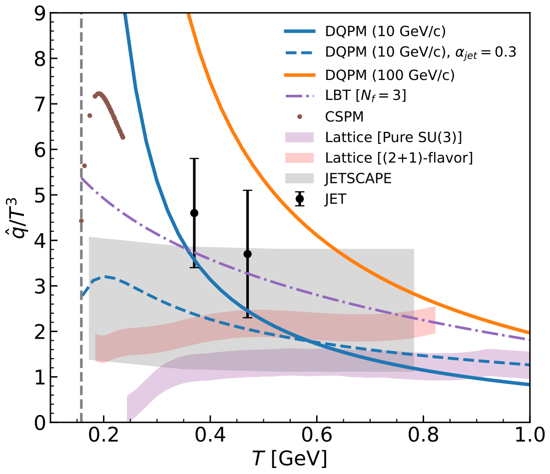

Figure 1: Temperature dependence of the scaled jet transport coefficient $\hat{q}/T^3$. The off-shell DQPM results are represented for a quark jet with mass $M = 0.01$ GeV and momentum 10 GeV/c (blue line) and 100 GeV/c (orange line). The blue dashed line shows the DQPM result with $\alpha_S^{jet} = 0.3$ at the jet parton vertices. The purple dash-dotted line represents the LBT results for $N_f = 3$ and $p = 10$ GeV/c [9], while the red and purple areas represent lQCD estimates [10] for pure SU(3) gauge theory and (2+1) flavour QCD, respectively, in the limit of an infinitely hard jet parton. The gray area corresponds to the results from the JETSCAPE Collaboration ($p = 100$ GeV/c) [11]. The black dots represent the phenomenological extraction by the JET Collaboration presented for $p = 10$ GeV/c [12], while the brown dots show the results from the color string percolation model (CSPM) [13]. The vertical gray dashed line indicates the critical temperature $T_C = 0.158$ GeV. The figure is taken from Ref. [3].

PoS(FAIRness2022)018

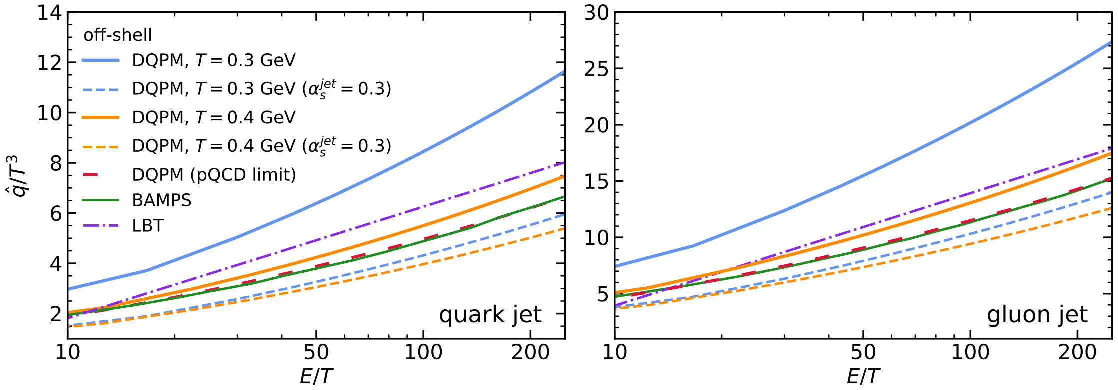

Figure 2: The scaled $\hat{q}/T^3$ coefficients as a function of E/T for a quark jet (left) and a gluon jet (right) for different medium temperatures. The blue solid (upper) and orange solid (middle) lines represent the off-shell DQPM result for $T = 0.3$ and 0.4 GeV, respectively. The dashed lines of the same color represent DQPM results with $\alpha_{jet} = 0.3$ at jet parton vertices for $T = 0.3$ and 0.4 GeV, respectively. The red long-dashed line represents the DQPM result in the pQCD limit. The green solid line represents BAMPS results [14] and the purple dash-dotted line stands for the LBT model results [9]. All calculations include only elastic energy loss. The figure is taken from Ref. [3].

effect of finite masses becomes negligible. Secondly, parton masses enter the definition of transport coefficients, which leads to an increase of $\hat{q}$. Thirdly, parton masses enter the distribution function of thermal partons $f(E, T, \mu_B)$ leading to a strong suppression of the transport coefficients, i.e. fewer scattering centers. This effect is dominant.

- The finite widths of partons also have a small effect on the scattering amplitudes, but are important for the off-shell calculations as they define the shape of the spectral function.

Thus, eventually a large sensitivity of the jet energy loss to the properties of the QCD medium comes not only from the strong coupling but from all aspects of the DQPM model.

As follows from Fig. 1 there are large model uncertainties in the determination of $\hat{q}$ from both theoretical and phenomenological sides.

Figure 2 shows the scaled $\hat{q}/T^3$ coefficients for a quark (left) and a gluon (right) jet for elastic scattering with off-shell medium partons (from Eq. (1)) as a function of the ratio of the jet energy over temperature E/T. For all temperatures, the $\hat{q}/T^3$ coefficient logarithmically increases with the increasing momentum p of the jet. This momentum dependence is in agreement with the asymptotic behavior of $\hat{q}$ for pQCD.

In order to elucidate the systematic differences between the DQPM, LBT and BAMPS evaluations, we consider the pQCD limit for the DQPM (red dashed lines in Figure 2):

- all partons are on-shell, i.e. widths are neglected;
- the exchange parton has a Debye mass in case of gluon $(\mu_D^g)^2 = \dfrac{8\alpha_S}{\pi}(N_c + N_f)T^2$ or quark $(M_D^q)^2 = \dfrac{2\alpha_S}{\pi}C_F T^2$, while the scattered partons are assumed to be massless;
- the DQPM coupling is fixed to $\alpha_S = 0.3$ as in the LBT and BAMPS models;
- the classical (Maxwell-Boltzmann) statistics is employed.

In the high energy limit $E/T \gg 1$ with $\alpha_s = 0.3$, there is a logarithmic scaling of $\hat{q}/T^3 =$

PoS(FAIRness2022)018

$const\ \ln\left(\frac{q_{max}^2}{4\mu_D^2}\right) = const\ \ln\left(\frac{E}{T}\right)$ with $q_{max} = 2.6E_{jet}T$. A similar asymptotic behavior can be seen for the energy loss as well. Due to the different Debye masses for the LBT and BAMPS models, the results for $\hat{q}/T^3$ differ at high E/T.

As seen from Fig. 2 for a quark jet (left plot) at low T the DQPM shows a substantially larger $\hat{q}/T^3$ than the pQCD results of BAMPS and LBT models due to the rise of α_S near T_C, while at high T the DQPM results approach the pQCD predictions. However, when replacing $\alpha_S \to \alpha_{jet} = 0.3$ at the jet parton vertices, the DQPM result decreases for low T and becomes even smaller than the pQCD models BAMPS and LBT. Moreover, the DQPM result in the pQCD limit (discussed above) is identical to the result of the BAMPS model (since the same Debye mass has been used in our calculations) for all E/T models at low T, too. For the gluon jet (right plot) the DQPM shows again a reasonable agreement with pQCD models - BAMPS and LBT - for $\alpha_{jet} = 0.3$ and for the pQCD limit cases.

3. Summary

We have studied the energy loss of fast jet partons by elastic scattering with off-shell quarks and gluons during the propagation through the strongly interacting quark-gluon plasma. The non-perturbative properties of the sQGP are described within the effective dynamical quasiparticle model (DQPM), which interprets the lQCD results on the QGP thermodynamics in terms of thermodynamics of off-shell quasiparticles with (T, μ_B)-dependent masses and widths and broad spectral functions.

We obtained a strong increase of $\hat{q}/T^3$ when approaching T_C which is attributed to the rise of the strong coupling $\alpha_S(T, \mu_B)$ at $T \to T_C$. When replacing $\alpha_S \to 0.3$ at the jet parton vertex the temperature dependence of $\hat{q}/T^3$ is getting weaker, which is even more visible in the pQCD limit. Moreover, $\hat{q}$ strongly increases with the momentum of jets.

The comparison of our results with pQCD models [14] shows that the energy loss of a jet parton in the non-perturbative QCD medium (as characterized by the DQPM) occurs stronger [3] than by scattering with massless pQCD partons. Furthermore, at large T our results for $\hat{q}$ are in qualitative agreement with pQCD results, with lattice results (pure SU(3) and (2+1)-flavor) as well as with phenomenological estimates by the JET and JETSCAPE collaborations and the Color String Percolation Model. However, we note that for a quantitative comparison with phenomenologically extracted $\hat{q}$ from a fit of jet observables measured in heavy-ion experiments, we need to account for the radiative energy loss, too, which is a subject of an upcoming study.

Thus, our study of jet transport coefficients shows a large sensitivity of the jet energy loss to the properties of the QCD medium: weakly interacting pQCD versus the strongly interacting non-perturbative QGP.

Acknowledgments

We acknowledge support by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) through the grant CRC-TR 211 "Strong-interaction matter under extreme conditions" - project number 315477589 - TRR 211. I.G. also acknowledges support from the "Helmholtz Graduate School for Heavy Ion research".

PoS(FAIRness2022)018

References

[1] J.D. Bjorken, *Energy loss of energetic partons in quark-gluon plasma : possible extinction of high p_T jets in hadron-hadron collisions*, *FERMILAB-PUB-82-59-THY* (1982) 20.

[2] M.H. Thoma and M. Gyulassy, *Quark Damping and Energy Loss in the High Temperature QCD*, *Nucl. Phys. B* **351** (1991) 491.

[3] I. Grishmanovskii, T. Song, O. Soloveva, C. Greiner and E. Bratkovskaya, *Exploring jet transport coefficients by elastic scattering in the strongly interacting quark-gluon plasma*, *Phys. Rev. C* **106** (2022) 014903 [`2204.01561`].

[4] A. Peshier and W. Cassing, *The Hot non-perturbative gluon plasma is an almost ideal colored liquid*, *Phys. Rev. Lett.* **94** (2005) 172301 [`hep-ph/0502138`].

[5] W. Cassing, *Dynamical quasiparticles properties and effective interactions in the sQGP*, *Nucl. Phys. A* **795** (2007) 70 [`0707.3033`].

[6] W. Cassing, *QCD thermodynamics and confinement from a dynamical quasiparticle point of view*, *Nucl. Phys. A* **791** (2007) 365 [`0704.1410`].

[7] H. Berrehrah, E. Bratkovskaya, T. Steinert and W. Cassing, *A dynamical quasiparticle approach for the QGP bulk and transport properties*, *Int. J. Mod. Phys. E* **25** (2016) 1642003 [`1605.02371`].

[8] P. Moreau, O. Soloveva, L. Oliva, T. Song, W. Cassing and E. Bratkovskaya, *Exploring the partonic phase at finite chemical potential within an extended off-shell transport approach*, *Phys. Rev. C* **100** (2019) 014911 [`1903.10257`].

[9] Y. He, T. Luo, X.-N. Wang and Y. Zhu, *Linear Boltzmann Transport for Jet Propagation in the Quark-Gluon Plasma: Elastic Processes and Medium Recoil*, *Phys. Rev. C* **91** (2015) 054908 [`1503.03313`].

[10] A. Kumar, A. Majumder and J.H. Weber, *Jet transport coefficient $\hat{q}$ in (2+1)-flavor lattice qcd*, 2020.

[11] JETSCAPE collaboration, *Determining the jet transport coefficient $\hat{q}$ from inclusive hadron suppression measurements using Bayesian parameter estimation*, *Phys. Rev. C* **104** (2021) 024905 [`2102.11337`].

[12] JET collaboration, *Extracting the jet transport coefficient from jet quenching in high-energy heavy-ion collisions*, *Phys. Rev. C* **90** (2014) 014909 [`1312.5003`].

[13] A.N. Mishra, D. Sahu and R. Sahoo, *Jet Transport Coefficient at the Large Hadron Collider Energies in a Color String Percolation Approach*, *Physics* **4** (2022) 315 [`2104.02328`].

[14] F. Senzel, *The Landau-Pomeranchuk-Migdal effect within a partonic transport approach*, Ph.D. thesis, Goethe U., Frankfurt (main), https://inspirehep.net/literature/1816215, 2020.

PoS(FAIRness2022)018