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

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HIC in the QCD phase diagram | June 27 - July 7, 2022

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Outline

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- Dynamical QuasiParticle Model (DQPM)
- Transport coefficients in kinetic theory
- Results:
  - q-hat coefficient
  - energy loss
- Summary

Dynamical QuasiParticle Model (DQPM)

- DQPM – effective model for the description of non-perturbative (strongly interacting) QCD based on lQCD EoS

- The QGP phase is described in terms of interacting quasiparticles - massive quarks and gluons - with Lorentzian spectral functions:

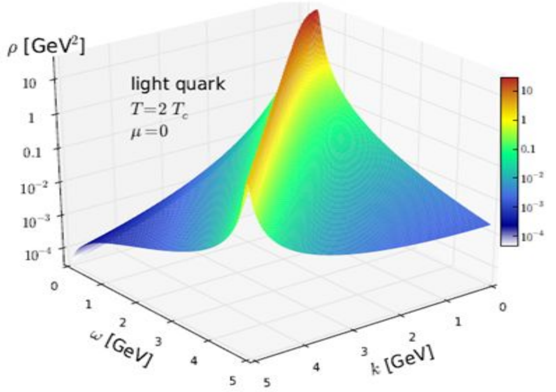
$$\rho_j(\omega, \mathbf{p}) = \frac{4\omega\gamma_j}{\left(\omega^2 - \mathbf{p}^2 - M_j^2\right)^2 + 4\gamma_j^2\omega^2}$$

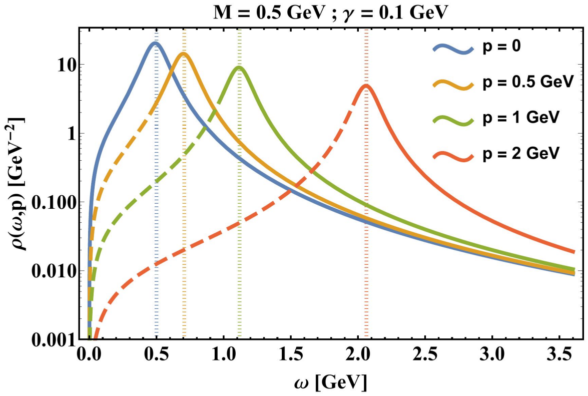
- Field quanta are described in terms of dressed propagators with complex self-energies:

gluon propagator: $\Delta^{-1} = P^2 - \Pi$; quark propagator: $S_q^{-1} = P^2 - \Sigma_q$

gluon self-energy: $\Pi = M_g^2 - 2i\gamma_g\omega$; quark self-energy: $\Sigma_q = M_q^2 - 2i\gamma\omega$

- Real part of the self-energy - thermal masses
- Imaginary part of the self-energy - interaction widths of partons

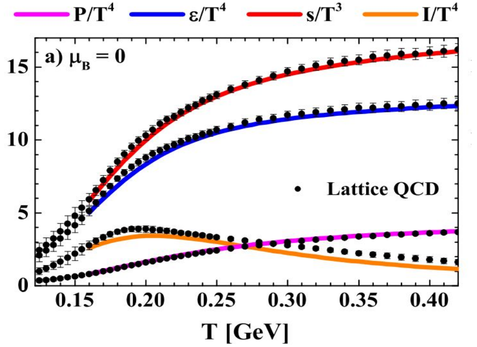




P. Moreau et al., PRC 100, 014911 (2019)

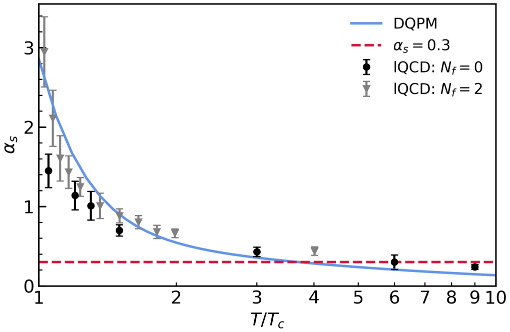
DQPM ingredients

Input: entropy density vs T for μ_B=0

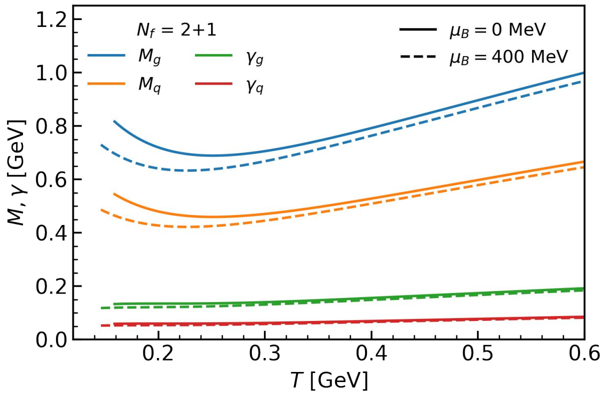


$$g^2(s/s_{SB}) = d((s/s_{SB})^e - 1)^f$$

$$s_{SB}^{QCD} = 19/9\pi^2 T^3$$



Masses and widths of quasiparticles depend on the temperature of the medium and μ_B



$$M^2_{q(\bar{q})}(T,\mu_q) = \frac{N_c^2-1}{8N_c} g^2(T,\mu_q)\left(T^2 + \frac{\mu_q^2}{\pi^2}\right)$$

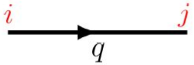
$$M^2_g(T,\mu_q) = \frac{g^2(T,\mu_q)}{6}\left(\left(N_c + \frac{1}{2}N_f\right)T^2 + \frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$$

$$\gamma_{q(\bar{q})}(T,\mu_q) = \frac{1}{3}\frac{N_c^2-1}{2N_c}\frac{g^2(T,\mu_q)T}{8\pi}\ln\left(\frac{2c}{g^2(T,\mu_q)}+1\right)$$

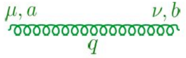
$$\gamma_g(T,\mu_q) = \frac{1}{3}N_c\frac{g^2(T,\mu_q)T}{8\pi}\ln\left(\frac{2c}{g^2(T,\mu_q)}+1\right)$$

Partonic interactions in DQPM

DQPM partonic interactions are described in terms of leading order diagrams:

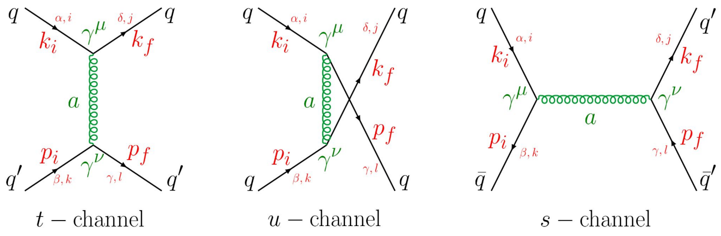
quark propagator: 

$$= i\delta_{ij}\frac{\not{q} + M_q}{q^2 - M_q^2 + 2i\gamma_q q_0}$$

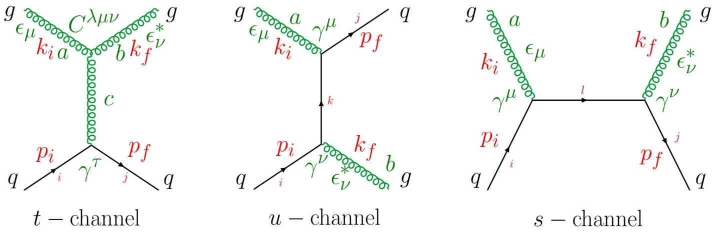
gluon propagator: 

$$= -i\delta_{ab}\frac{g^{\mu\nu} - q^\mu q^\nu / M_g^2}{q^2 - M_g^2 + 2i\gamma_g q_0}$$

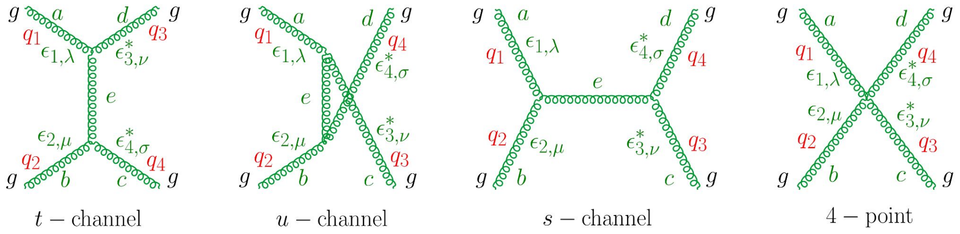
qq’ → qq’ scattering



qg → qg scattering

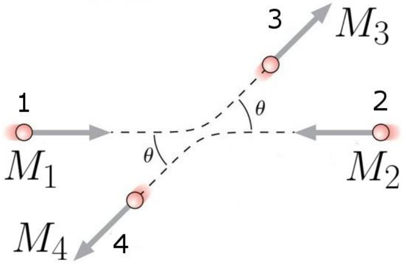


gg → gg scattering

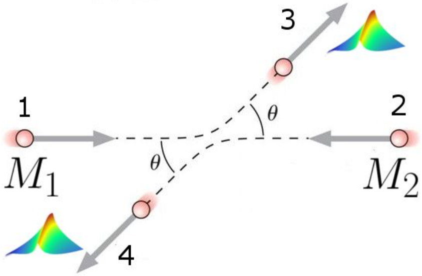


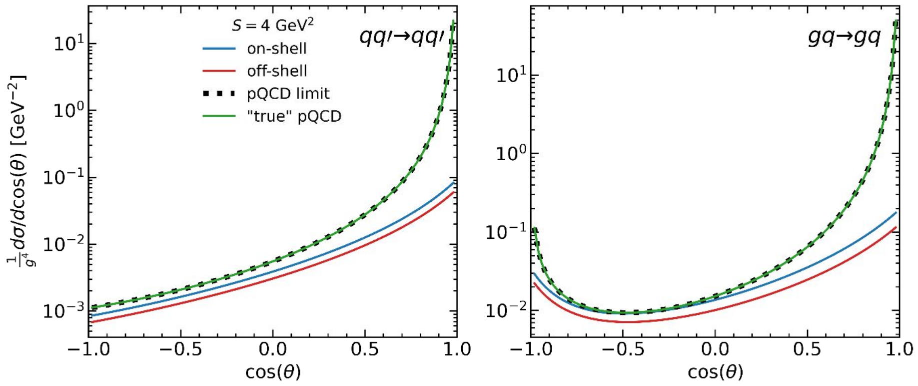
DQPM partonic cross sections

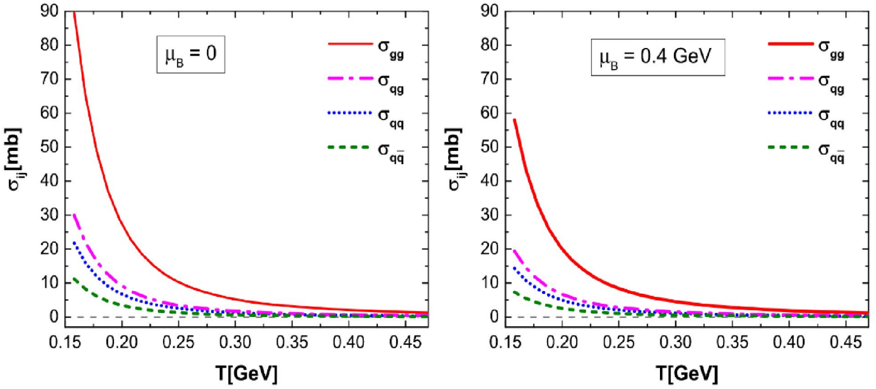
On-shell: final masses = pole masses



Off-shell: integration over final masses







➔ can reproduce pQCD cross sections

➔ strong T dependence

➔ weak μ_B dependence

DQPM: summary

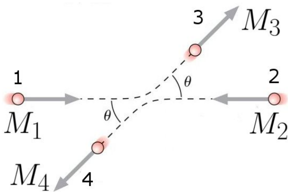
There are four effects that make the DQPM different from the pure pQCD:

1. non-perturbative origin of the strong coupling which depends on T, μ_B
2. finite masses of the intermediate parton propagators (screening masses)
3. finite masses of the medium partons
4. finite widths of partons

Transport coefficients in kinetic theory

On-shell:

- integration over momentums
- masses = pole masses

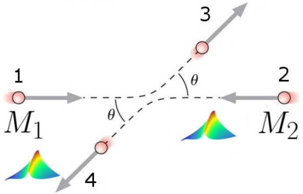


$$E^2 = m^2 + p^2$$

$$\langle \mathcal{O} \rangle^{\text{on}} = \frac{1}{2E_i} \sum_{j=q,\bar{q},g} d_j f_j \int \frac{d^3 p_j}{(2\pi)^3 2E_j} \times \int \frac{d^3 p_1}{(2\pi)^3 2E_1} \int \frac{d^3 p_2}{(2\pi)^3 2E_2} \times (1 \pm f_1)(1 \pm f_2) \mathcal{O} |\overline{\mathcal{M}}|^2 (2\pi)^4 \delta^{(4)}(p_i + p_j - p_1 - p_2)$$

Off-shell:

- integration over momentums
- + two additional integrations over medium partons energy



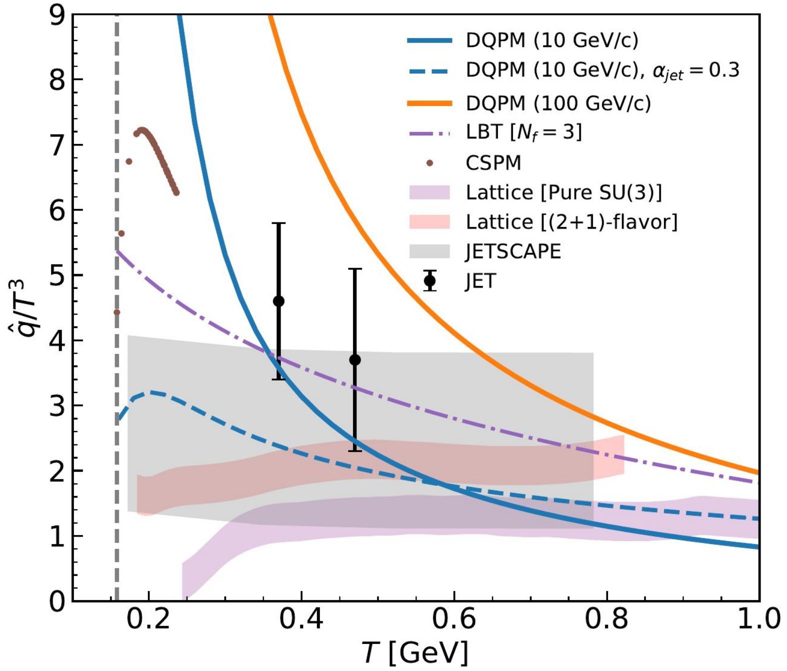
$$\frac{1}{2E} \rightarrow \int \frac{d\omega}{(2\pi)} \rho(\omega, \mathbf{p}) \theta(\omega)$$

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

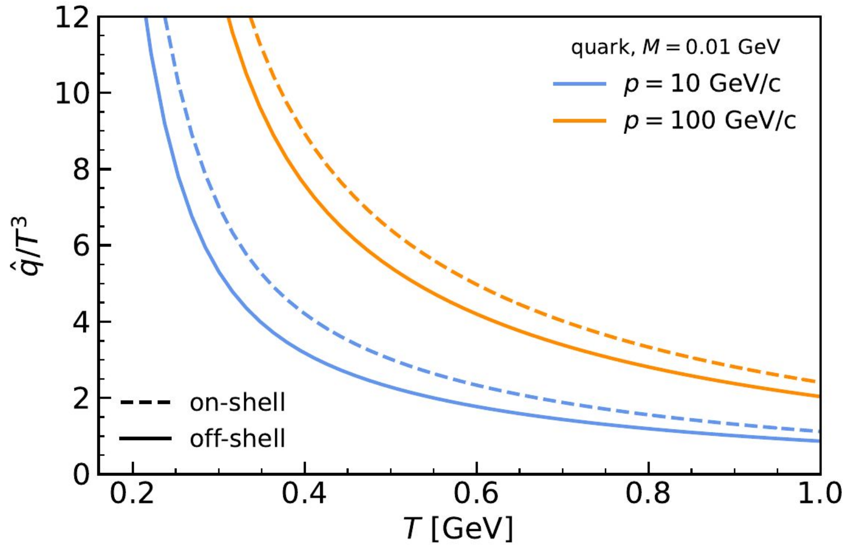
$$\langle \mathcal{O} \rangle = \begin{cases} \mathcal{A}, & \mathcal{O} = (\mathbf{p} - \mathbf{p}') \\ dE/d\tau, & \mathcal{O} = (E - E') \\ \hat{q}, & \mathcal{O} = (p_t^2 - p_t'^2) \end{cases}$$

Results: q-hat

The DQPM q-hat(T) for elastic scattering of a jet quark vs other models



On-shell vs off-shell

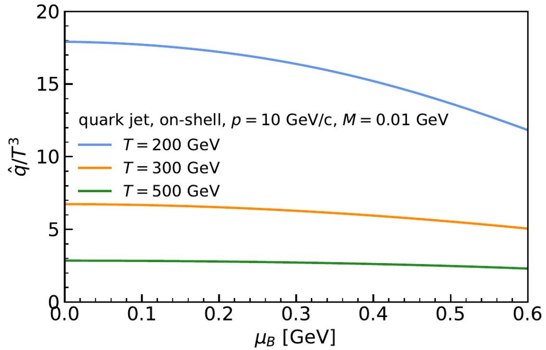


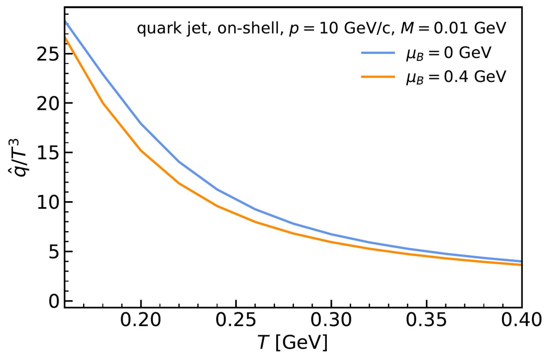
➔ Off-shell < on-shell

JET: K. M. Burke et al., *PRC 90, 014909 (2014);* **lQCD:** A. Kumar et al., *arxiv:2010.14463;* **LBT:** Y. He et al., *PRC 91 (2015);*
JETSCAPE: S. Cao *et al. PRC 104, 024905 (2021);* **CSPM:** A.Mishra et al., *Physics 4, 315 (2022)*

Results: q-hat

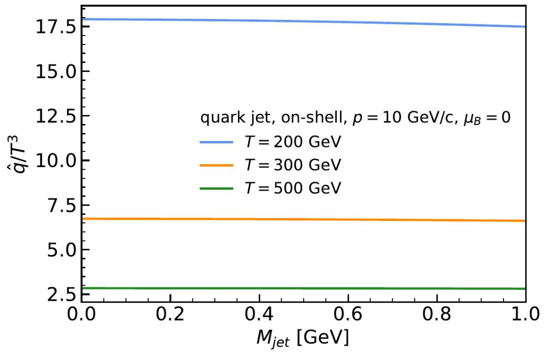
μ_B dependence

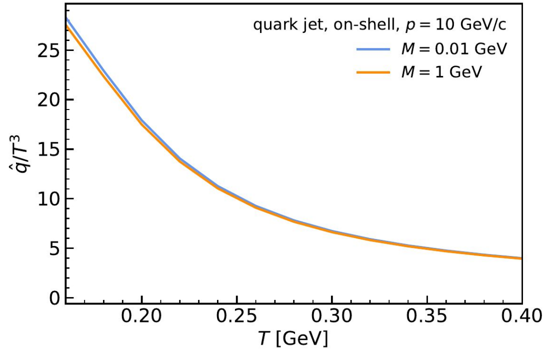




➔ Decreases with μ_B

Mass dependence

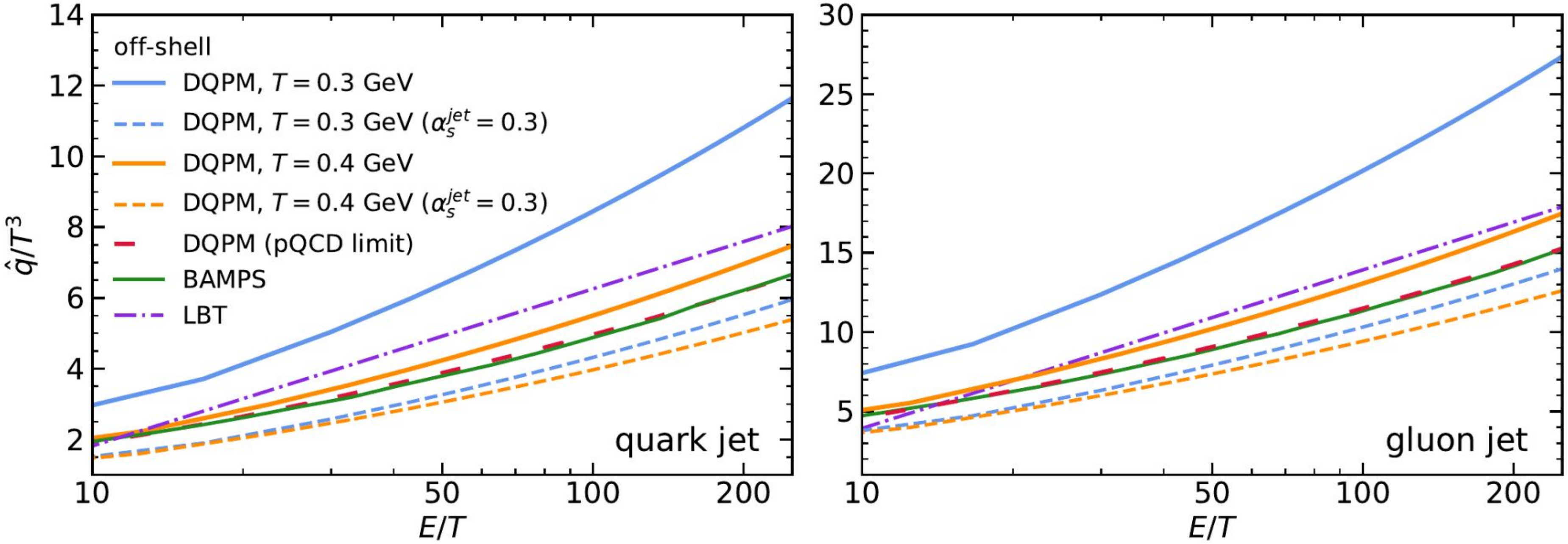




➔ Decreases with M, but dependence is negligible

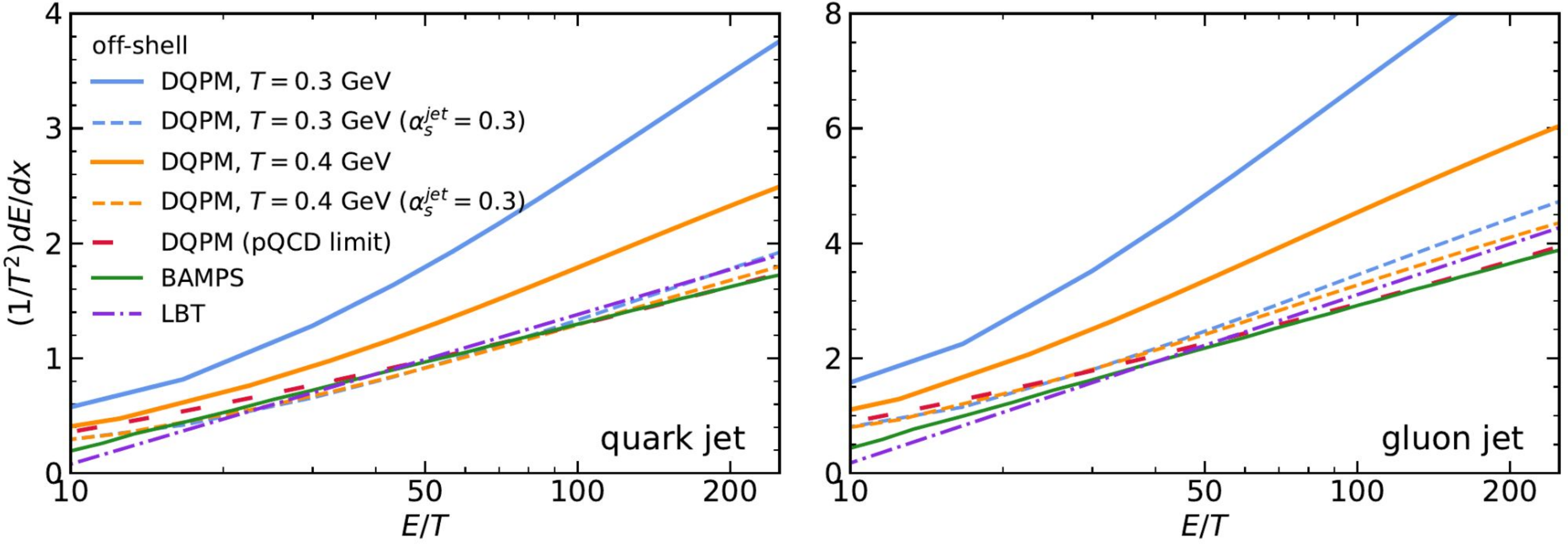
Results: q-hat

Energy dependence of the scaled q-hat



Results: energy loss

Energy dependence of the scaled energy loss dE/dx



Summary and outlook

Summary:

- Transport coefficients q-hat and dE/dx are evaluated for the the propagation of the jet parton (quark and gluon) through the strongly interacting QGP based on the DQPM
  - q-hat coefficient is calculated as a function of medium *temperature*, jet *momentum*, jet mass, chemical *potential*
  - dE/dx is calculated as a function of jet *momentum*
- DQPM predicts stronger energy loss than pQCD models due to the elastic interaction of jet parton with non-perturbative QGP
- DQPM reproduces the pQCD limits for zero masses and widths of medium partons

Future:

- Investigate radiative processes
- Implement jets into full transport simulation