# Exploring jet transport coefficients by elastic and radiative scatterings in the strongly interacting quark-gluon plasma

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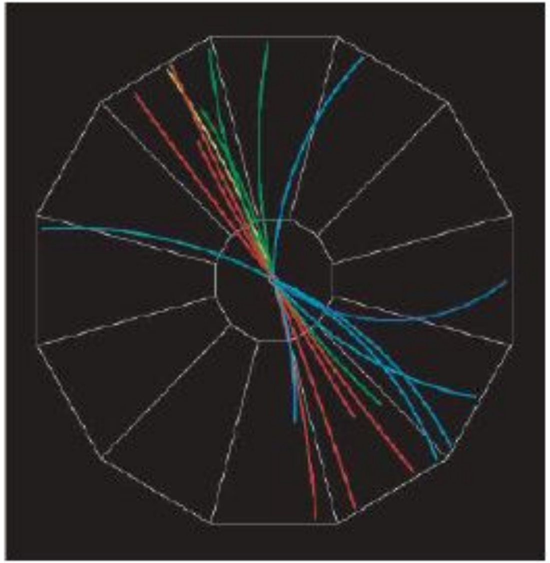
# Outline

- Introduction: jets
- Dynamical QuasiParticle Model (DQPM)
- Elastic and inelastic cross sections
- Transport coefficients in kinetic theory
- Summary

## What is jet?

A jet is a collimated spray of hadrons generated via successive parton branchings, starting with a highly energetic and highly virtual parton (quark or gluon) produced by the collision

p+p @ $\sqrt{s}$ = 200 GeV



## Why do we study jets?

- Early formation time
- Not thermalized in the medium
- Contain the information on the QGP properties

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

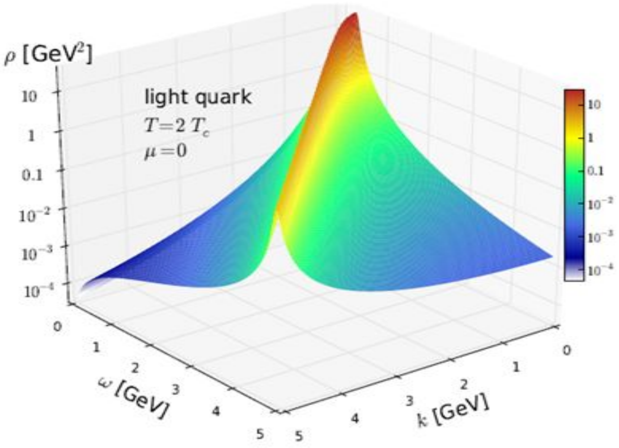
- The QGP phase is described in terms of interacting quasiparticles - massive quarks and gluons - with Lorentzian spectral functions:

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

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

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

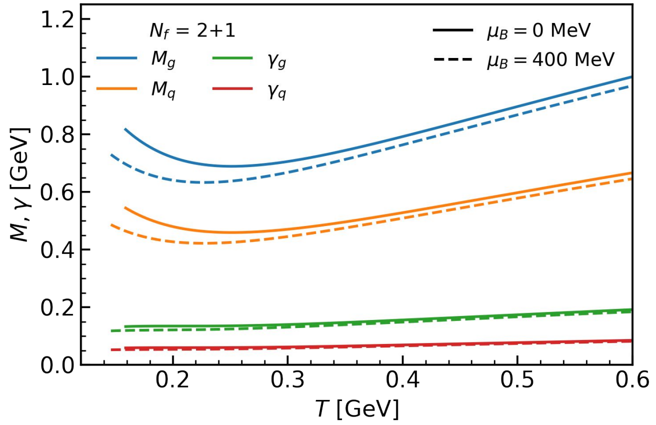
$$\text{gluon self-energy: } \Pi = M_g^2 - 2i\gamma_g\omega; \qquad \text{quark self-energy: } \Sigma_q = M_q^2 - 2i\gamma\omega$$




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

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

Masses and widths of quasiparticles depend on the temperature of the medium and $\mu_B$

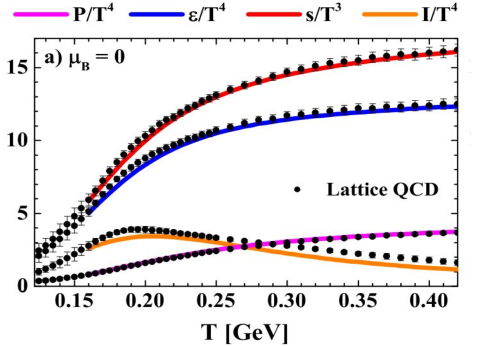



$$m_g^2(T,\mu_B) = C_g \frac{g^2(T,\mu_B)}{6} T^2 \left(1 + \frac{N_f}{2N_c} + \frac{1}{2}\frac{\sum_q \mu_q^2}{T^2\pi^2}\right)$$

$$m_{q(\bar{q})}^2(T,\mu_B) = C_q \frac{g^2(T,\mu_B)}{4} T^2 \left(1 + \frac{\mu_q^2}{T^2\pi^2}\right)$$

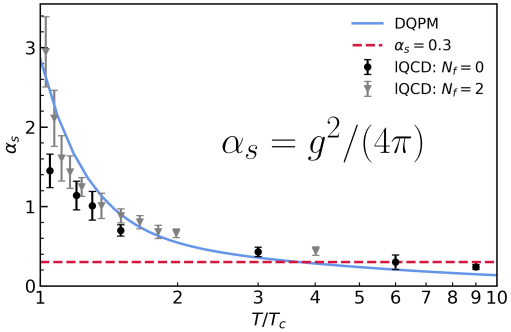
$$\gamma_j(T,\mu_B) = \frac{1}{3} C_j \frac{g^2(T,\mu_B) T}{8\pi} \ln\left(\frac{2c_m}{g^2(T,\mu_B)} + 1\right)$$

Input: entropy density vs T for $\mu_B$=0




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

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




O. Kaczmarek, F. Zantow, Phys. Rev. D 71, 114510

# DQPM: summary

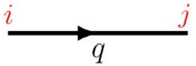


There are four effects that make the DQPM different from the "pure" pQCD:

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

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

quark propagator:

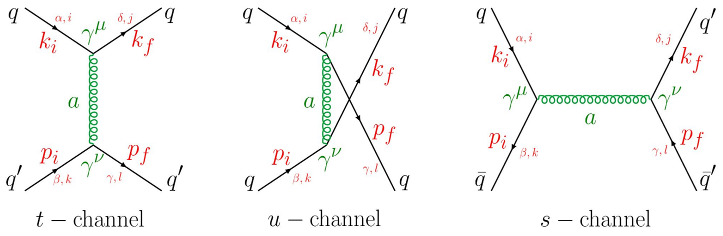


$$= i\delta_{ij} \frac{\not{q} + M_q}{q^2 - M_q^2 + 2i\gamma_q q_0}$$

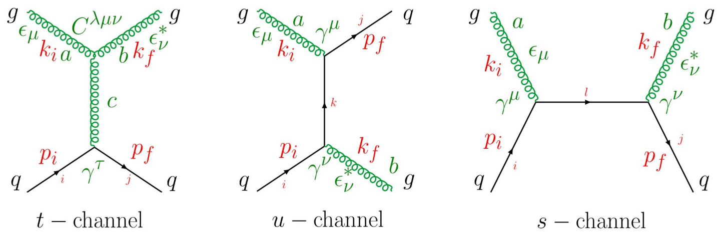
gluon propagator:

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

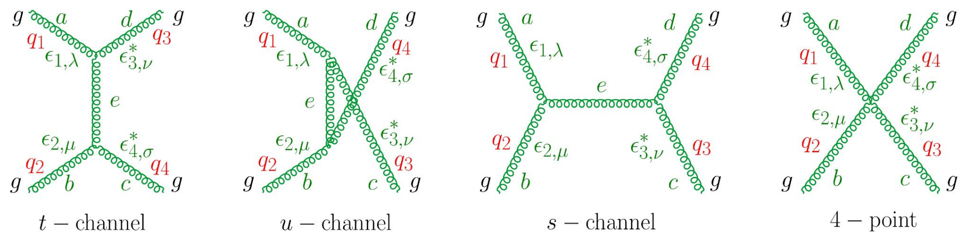
## qq' → qq' scattering




## qg → qg scattering



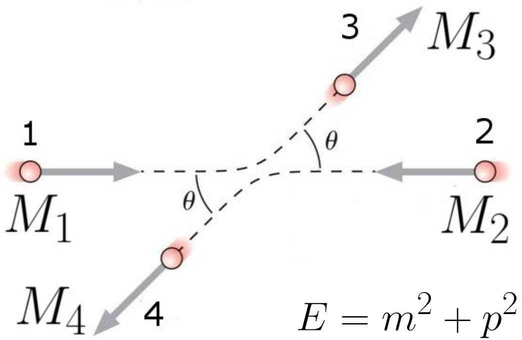

## gg → gg scattering



# DQPM partonic cross sections

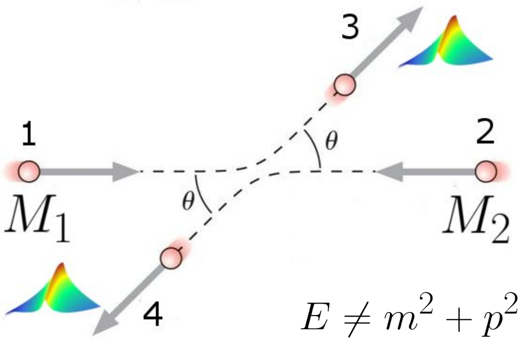


**On-shell:** final masses = pole masses




$$d\sigma^{\text{on}} = \frac{d^3p_3}{(2\pi)^3 2E_3} \frac{d^3p_4}{(2\pi)^3 2E_4} (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - p_4) \frac{|\bar{\mathcal{M}}|^2}{F}$$

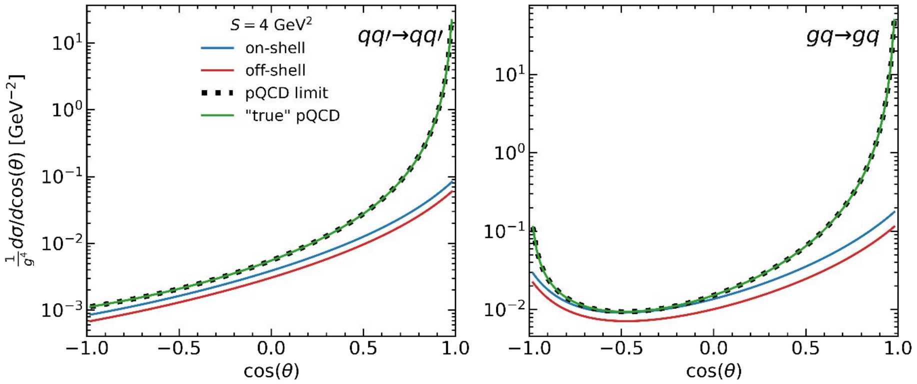
**Off-shell:** integration over final masses




$$F d\sigma^{\text{off}} = \frac{d^4p_3}{(2\pi)^4} \frac{d^4p_4}{(2\pi)^4} \tilde{\rho}_3(\omega_3, \mathbf{p}_3)\, \theta(\omega_3)\, \tilde{\rho}_4(\omega_4, \mathbf{p}_4)\, \theta(\omega_4)$$

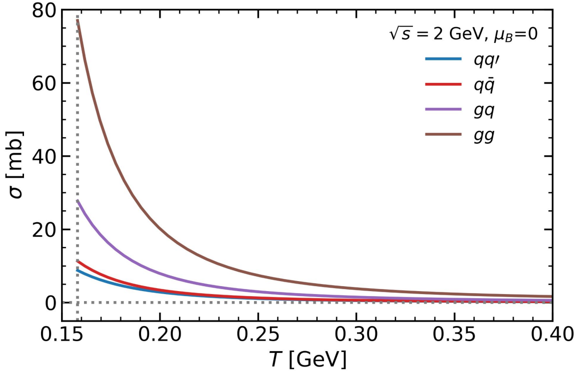
$$\times (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - p_4) |\bar{\mathcal{M}}|^2$$

DQPM angular dependence for differential cross sections (scaled by $g^4$) for different reactions (CMS)




- ➔ DQPM reproduces pQCD cross sections for masses and widths $\to 0$
- ➔ DQPM angular distribution is more "isotropic" then pQCD
- ➔ the off-shell effects are small for energetic partons and for high T

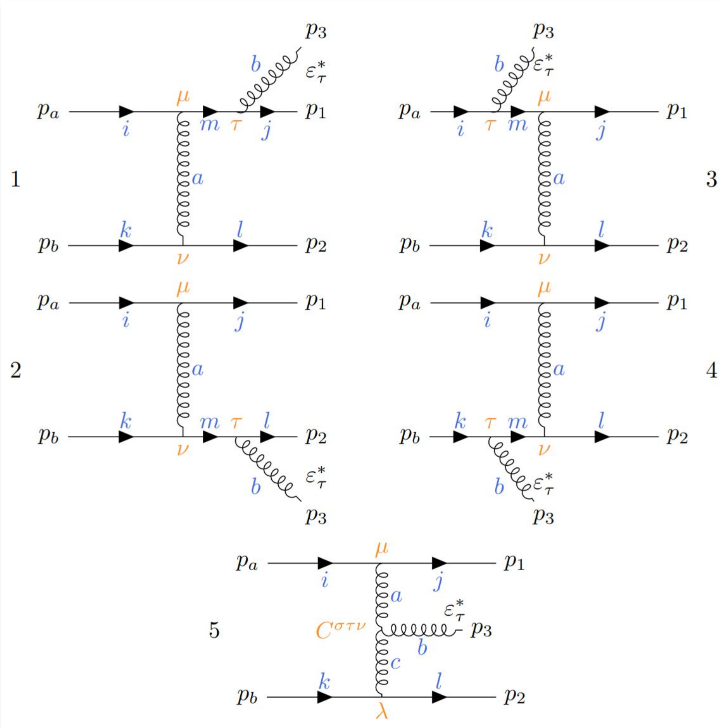
Total cross section




- ➔ strong $T$ dependence

**pQCD result**: F. A. Berends et al., Phys. Lett., B103, 124 (1981)

***t*-channel**




$$\Pi_{\mu\nu}(k) = \left[-i\frac{g_{\mu\nu} - (k_\mu k_\nu)/M_g^2}{k^2 - M_g^2 + 2i\gamma_g\omega_k}\right] \quad \text{(gluon propagator)},$$

$$\Lambda(k) = \left[i\frac{\not{k} + M_q}{k^2 - M_q^2 + 2i\gamma_q\omega_k}\right] \quad \text{(quark propagator)},$$

$$V_{ik}^{\nu,a} = (-ig\gamma^\nu T_{ik}^a) \quad \text{(vertex)},$$

$$i\mathcal{M}_1 = \bar{u}^l(p_2)V_{lk}^{\nu,a}u^k(p_b)\Pi_{\mu\nu}(p_b - p_2)\bar{u}^j(p_1)\varepsilon_\tau^*(p_3)V_{jm}^{\tau,b}\Lambda(p_1 + p_3)V_{mi}^{\mu,a}u^i(p_a)$$

$$i\mathcal{M}_2 = \bar{u}^j(p_1)V_{ji}^{\mu,a}u^i(p_a)\Pi_{\mu\nu}(p_a - p_1)\bar{u}^l(p_2)\varepsilon_\tau^*(p_3)V_{lm}^{\tau,b}\Lambda(p_2 + p_3)V_{mk}^{\nu,a}u^k(p_b)$$

$$i\mathcal{M}_3 = \bar{u}^l(p_2)V_{lk}^{\nu,a}u^k(p_b)\Pi_{\mu\nu}(p_b - p_2)\bar{u}^j(p_1)V_{jm}^{\mu,a}\Lambda(p_a - p_3)\varepsilon_\tau^*(p_3)V_{mi}^{\tau,b}u^i(p_a)$$

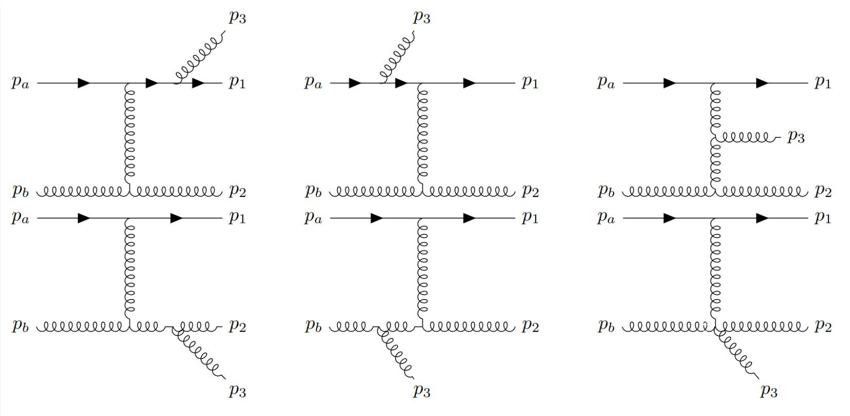
$$i\mathcal{M}_4 = \bar{u}^j(p_1)V_{ji}^{\mu,a}u^i(p_a)\Pi_{\mu\nu}(p_a - p_1)\bar{u}^l(p_2)V_{lm}^{\nu,a}\Lambda(p_b - p_3)\varepsilon_\tau^*(p_3)V_{mk}^{\tau,b}u^k(p_b)$$

$$i\mathcal{M}_5 = \bar{u}^j(p_1)V_{ji}^{\mu,a}u^i(p_a)\ \bar{u}^l(p_2)V_{lk}^{\lambda,c}u^k(p_b)\Pi_{\mu\nu}(p_a - p_1) \times \Pi_{\lambda\sigma}(p_b - p_2)\varepsilon_\tau^*(p_3)\left(-gf^{abc}C^{\sigma\tau\nu}(p_b - p_2, -p_3, p_2 - p_b + p_3)\right)$$

➔ emitted gluon is massive!

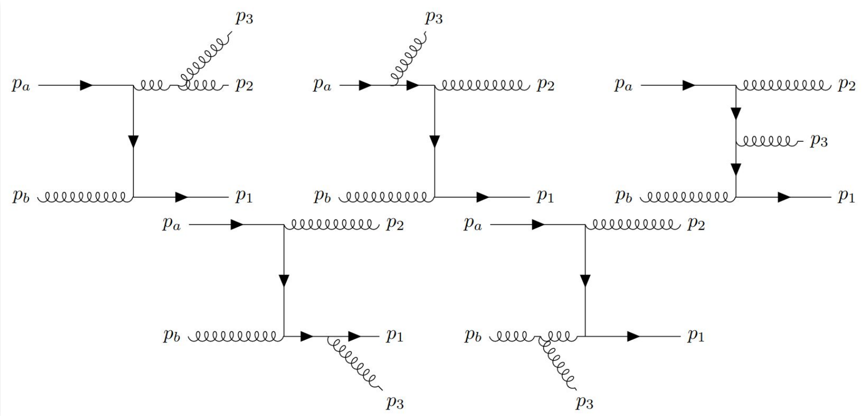
# Partonic inelastic interactions: q+g → q+g+g

***t*-channel**

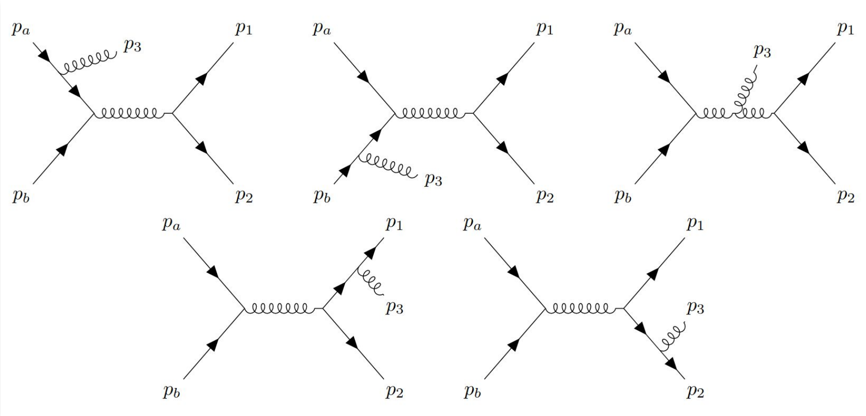



→ most dominant

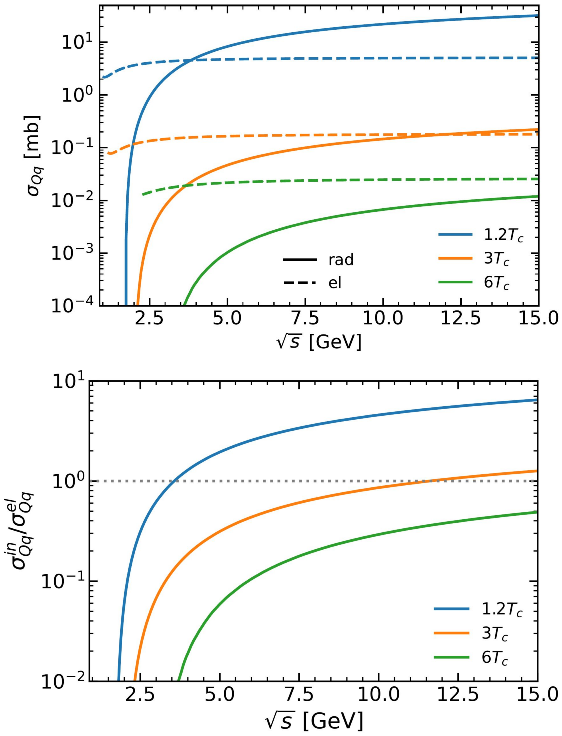
***u*-channel**




***s*-channel**

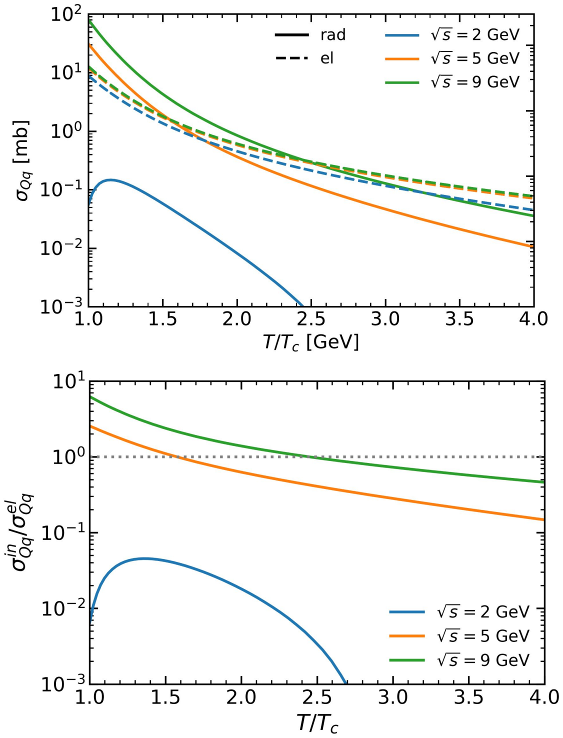


## Energy dependence



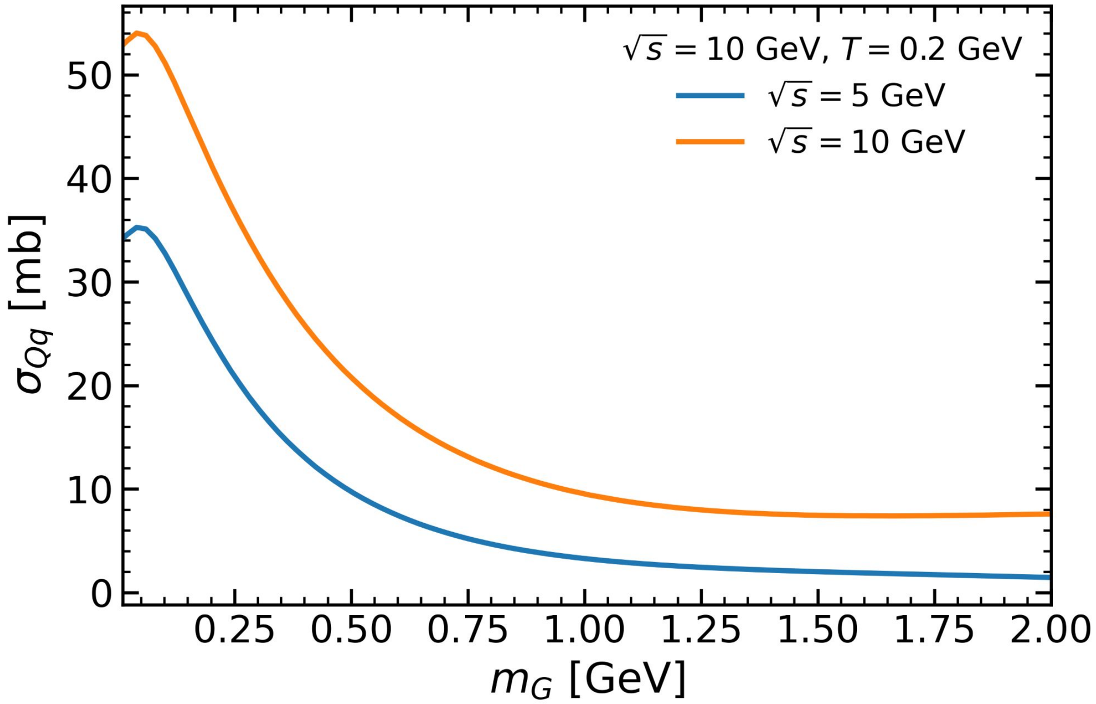

➔ suppression of radiative cross section for small energies

## Temperature dependence




➔ enhancement of radiative cross section for small temperatures

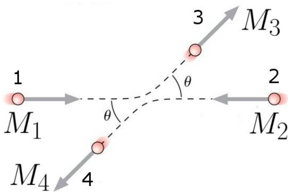
# Dependence on the mass of the emitted gluon



# Transport coefficients in kinetic theory

## On-shell:

- integration over momentums
- masses = pole masses

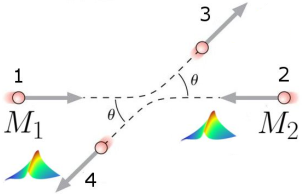



$$E^2 = m^2 + p^2$$

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

## Off-shell:

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



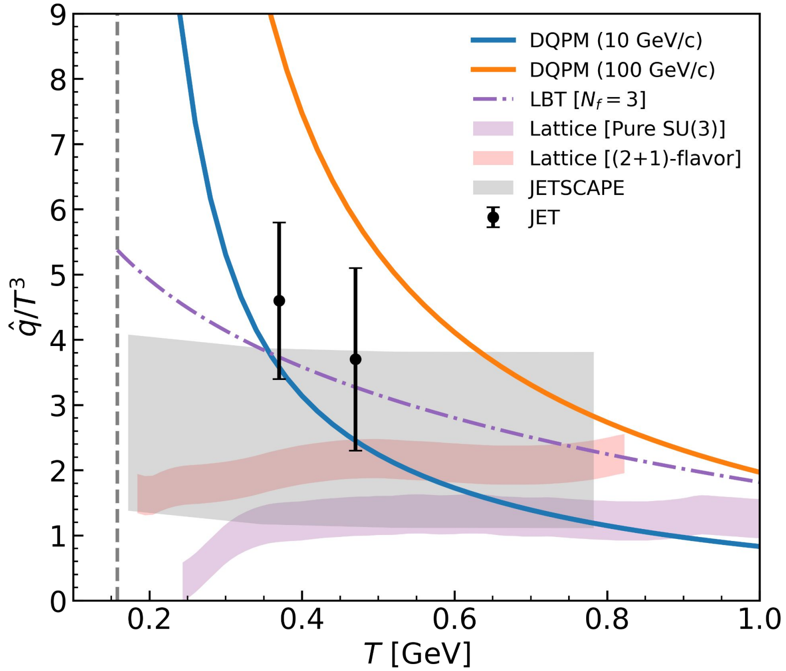

$$\frac{1}{2E} \to \int \frac{d\omega}{(2\pi)} \rho(\omega, \mathbf{p}) \theta(\omega)$$

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

$$\mathcal{O} = |\vec{p_T} - \vec{p_T}'|^2 \to \langle O \rangle = \hat{q}$$

$$\mathcal{O} = (E - E') \to \langle O \rangle = dE/dx$$

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




**JET:** K. M. Burke et al., *PRC 90, 014909 (2014)*

**lQCD:** A. Kumar et al., PRD.106.034505

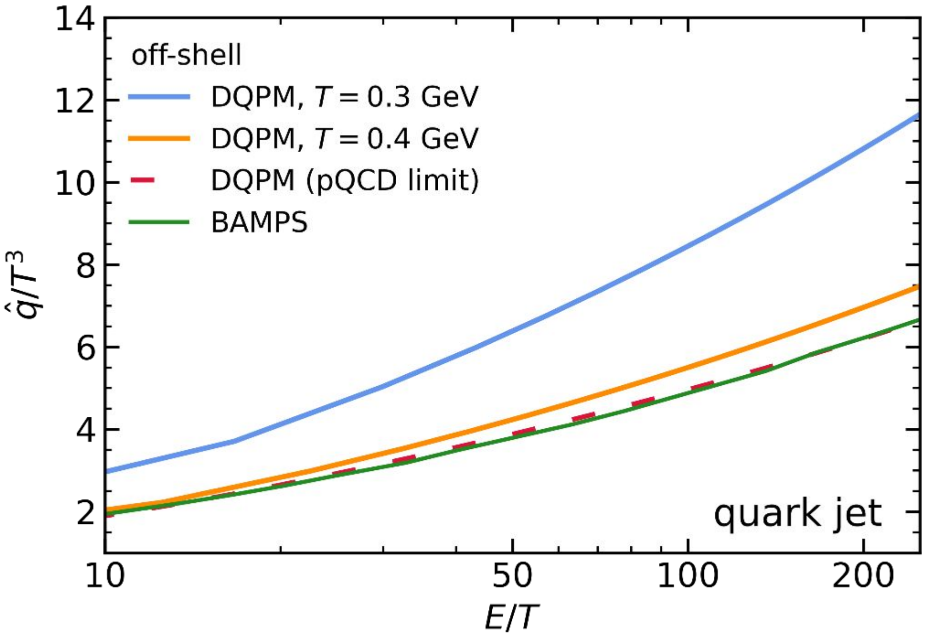
**LBT:** Y. He et al., *PRC 91 (2015)*

**JETSCAPE:** S. Cao *et al. PRC 104, 024905 (2021)*

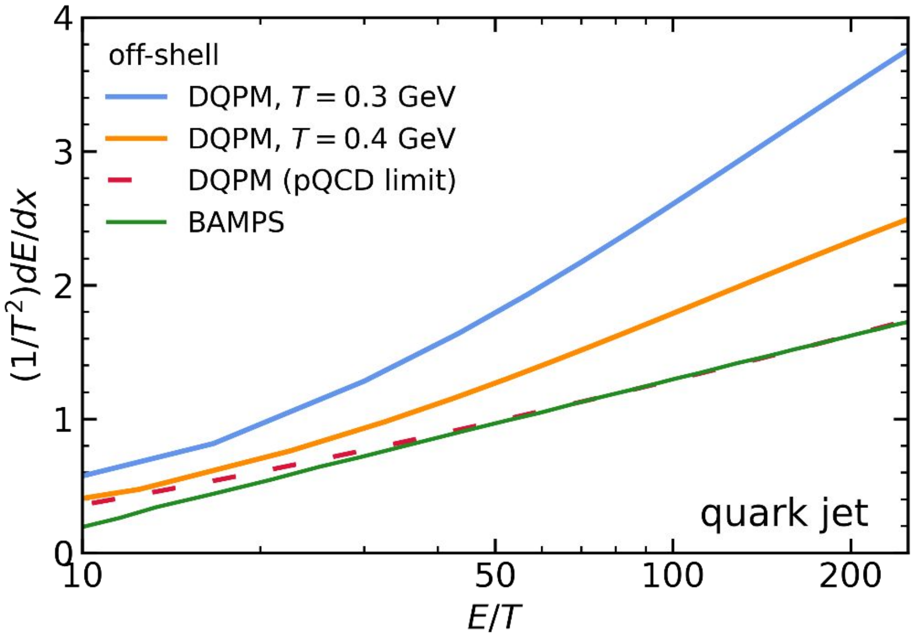
I.Grishmanovskii, T.Song, O.Soloveva, C.Greiner, E.Bratkovskaya, *Phys. Rev. C 106, 014903*

# Results: q-hat and energy loss

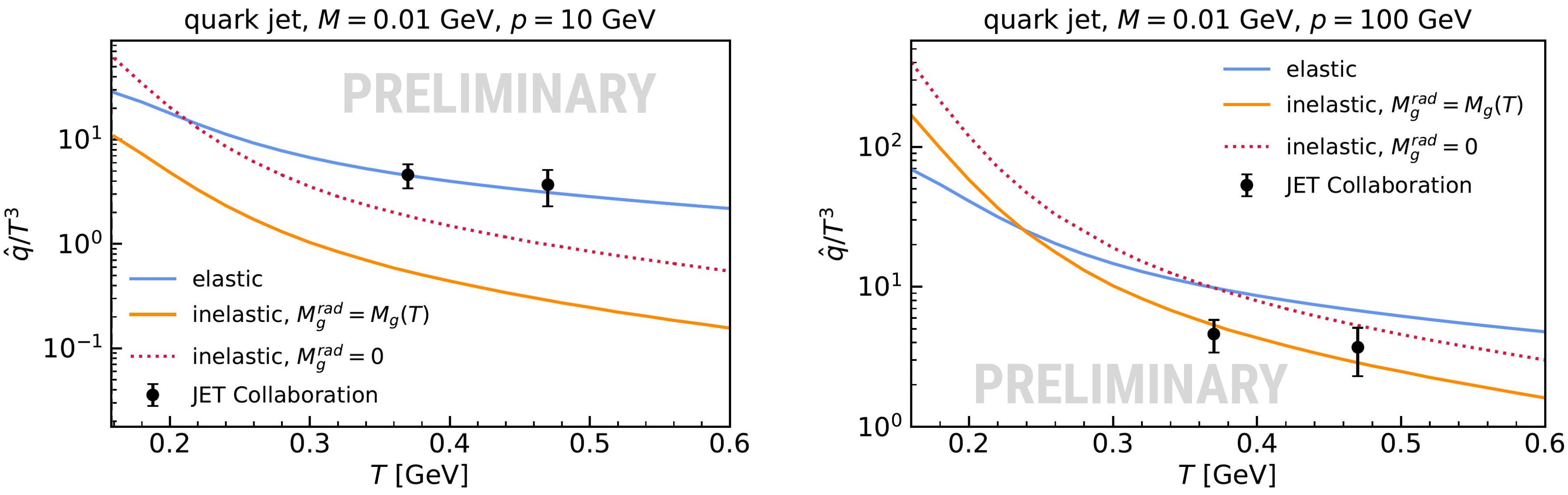
Energy dependence of the scaled q-hat




Energy dependence of the scaled energy loss dE/dx




➔ All models predict logarithmic growth of q-hat and dE/dx with jet energy (momentum)




- ➔ inelastic q-hat is suppressed for low jet momentum, but can be significant for high momentum
- ➔ emitted gluon mass is important

# Outlook



## Summary:

- Elastic and inelastic cross sections are calculated within DQPM
- Transport coefficients (q-hat and dE/dx) are evaluated for the propagation of the jet parton through the strongly interacting QGP based on the DQPM
- DQPM predicts stronger energy loss than pQCD models
- DQPM reproduces the pQCD limits for zero masses and widths of medium partons

## Future:

- Implementing cross sections into full transport simulation (PHSD)