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

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**arXiv:2204.01561**

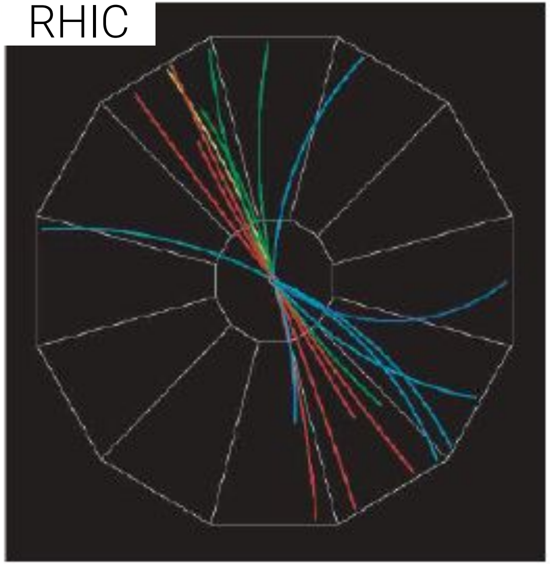
# Outline

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

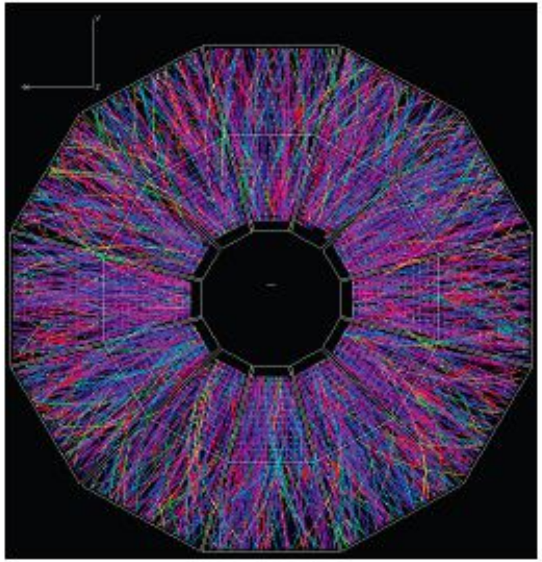
# What is jet?

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.

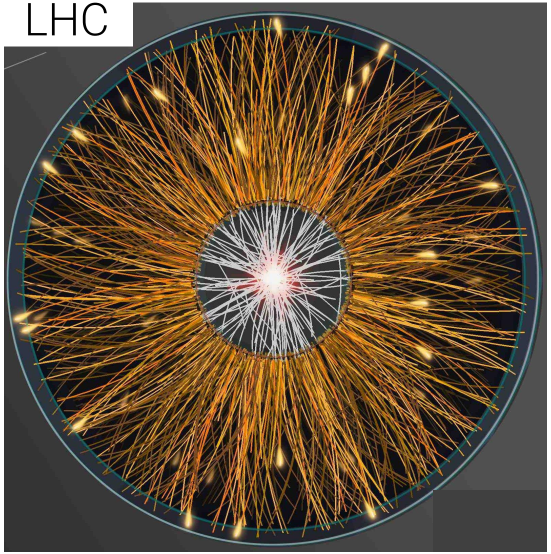
p+p @ $\sqrt{s}$ = 200 GeV



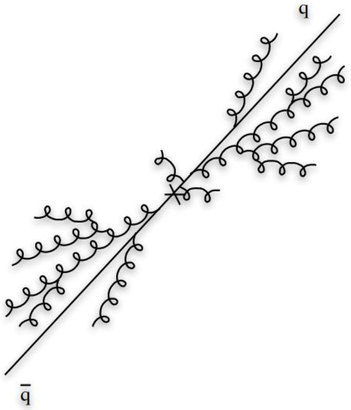

Au+Au @ $\sqrt{s_{NN}}$ = 200 GeV

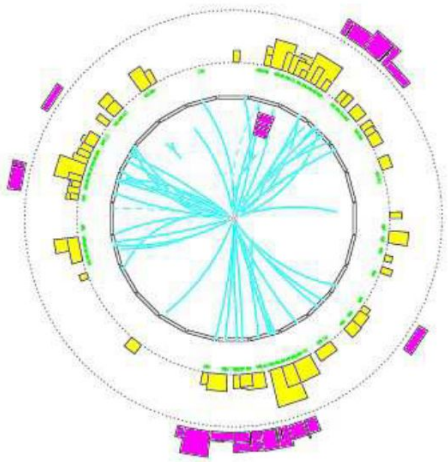


Pb+Pb @ $\sqrt{s_{NN}}$=2.76



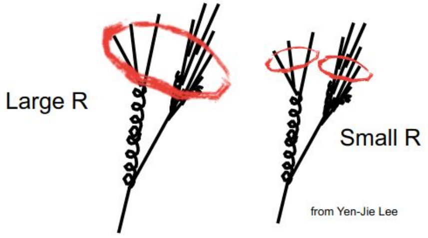
# Jet definition



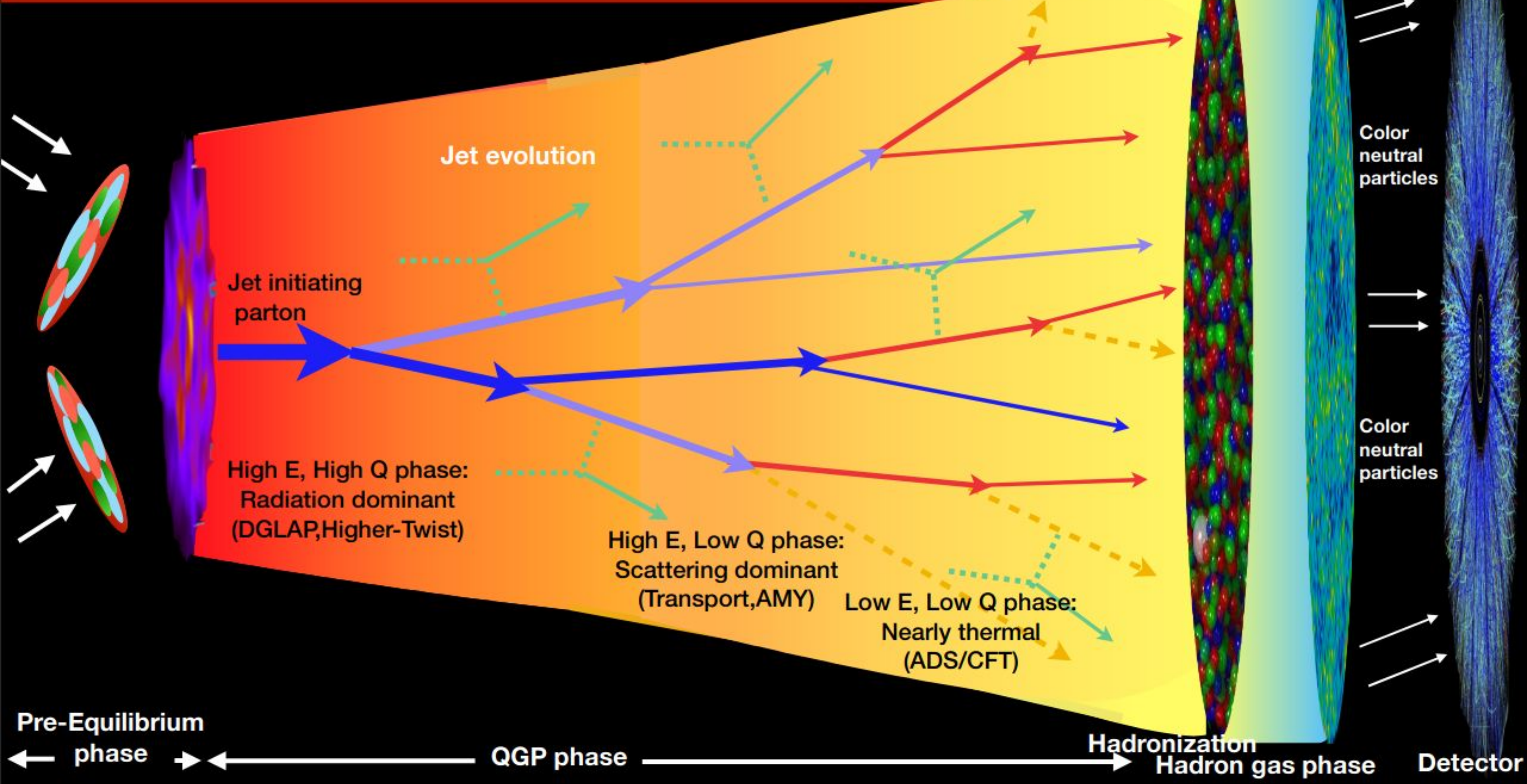
- Jets are obvious structures when one looks at an event display;

- However, one must introduce a prescription for defining what exactly one means by the jet ⟶ specify a jet definition




Which jets are found depends on resolution parameter

# Jet evolution in QGP a multi-scale phenomenon



# Why jets?

## Why do we study jets?

- Early formation time → can probe entire evolution of system
- Formed by hard partonic scattering → cross section calculable in pQCD
- Modification of jet observables resulting from interactions with the QGP medium can offer insight into medium properties

## What can we learn from jets?

- What is the origin of the partonic energy loss in the medium?
- Where does the lost energy of the jet go?
- How is the jet fragmentation modified when traversing the medium?
- Is there a flavor dependence of the energy loss?
- ...

## How do we study jet interaction with the QGP medium?

- Transport coefficients
- ...

# How do we study jets?

Nonperturbative approaches:

- Lattice QCD *(talk by Paolo Parotto)*
- Functional methods *(talk by Philipp Isserstedt)*
- **Effective models**
- ...

# 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:

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

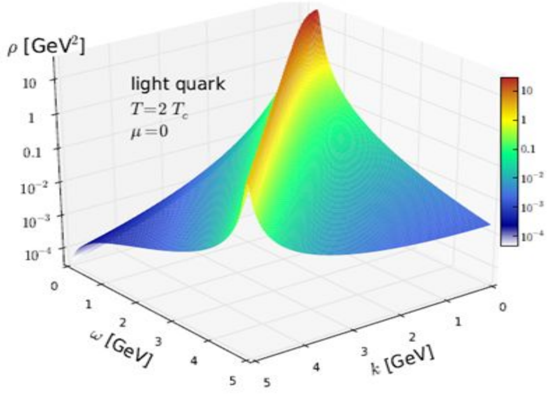
- Field quanta are described in terms of dressed propagators with complex self-energies:

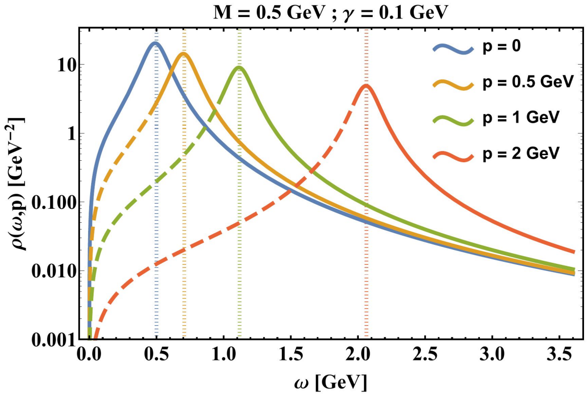
gluon propagator: $\Delta^{-1} = P^2 - \Pi;$
gluon self-energy: $\Pi = M_g^2 - 2i\gamma_g\omega;$

quark propagator: $S_q^{-1} = P^2 - \Sigma_q$
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

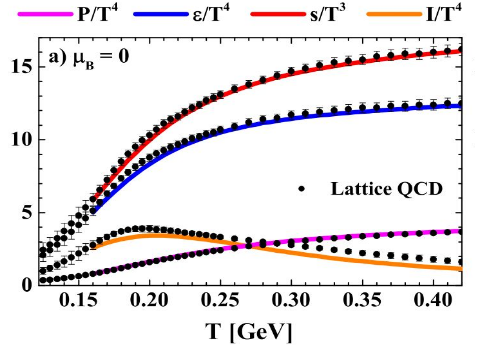
P. Moreau et al., PRC 100, 014911 (2019)



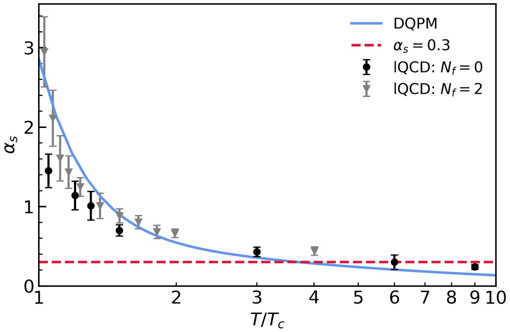
# DQPM ingredients

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

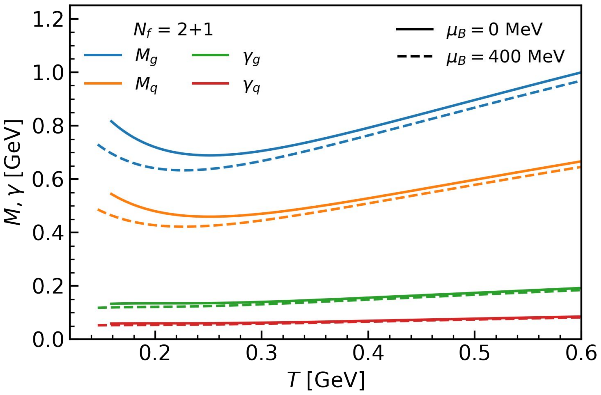



$$g^2(s/s_{SB}) = d((s/s_{SB})^e - 1)^f$$

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




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




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

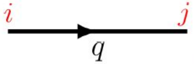
$$M^2_g(T,\mu_q) = \frac{g^2(T,\mu_q)}{6}\left(\left(N_c + \frac{1}{2}N_f\right)T^2 + \frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$$

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

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

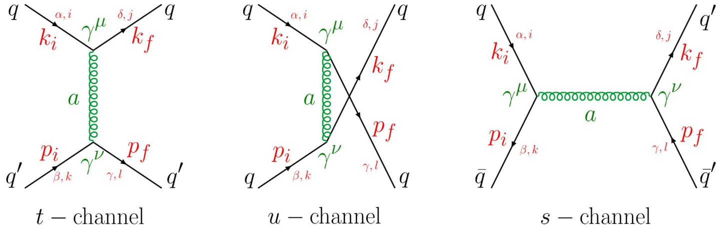
# Partonic interactions in DQPM

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

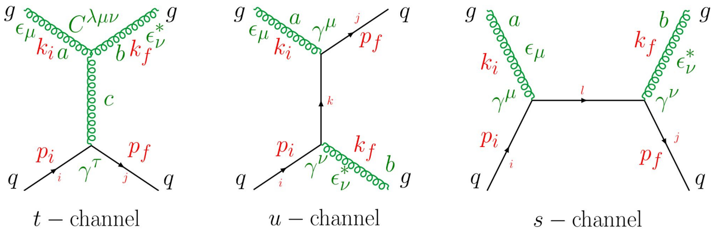
quark propagator:  $= i\delta_{ij}\dfrac{\not{q} + M_q}{q^2 - M_q^2 + 2i\gamma_q q_0}$

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

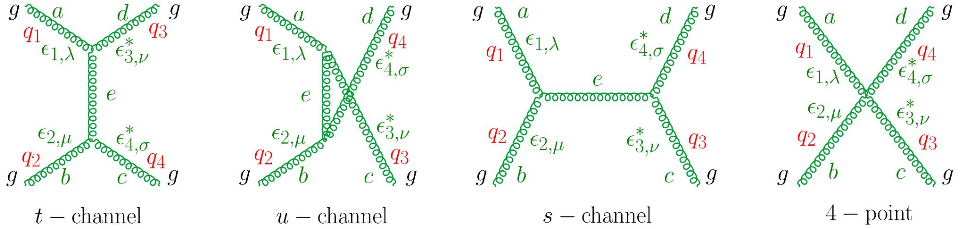
## qq’ → qq’ scattering




## qg → qg scattering

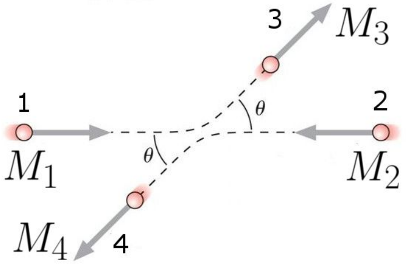



## gg → gg scattering

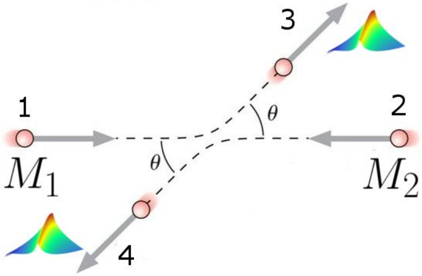


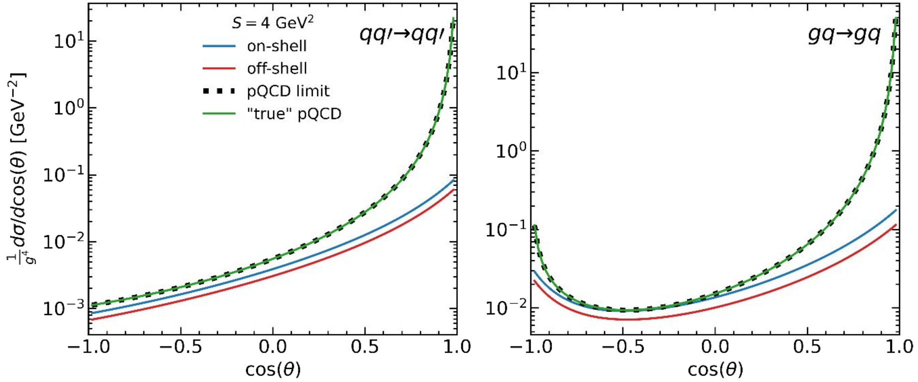
# DQPM cross sections

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

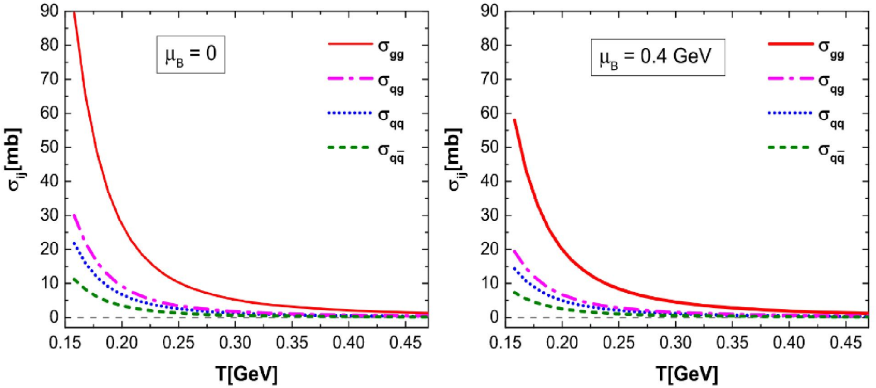



**Off-shell:** integration over final masses




- can reproduce pQCD cross sections




- strong $T$ dependence
- weak $\mu_B$ dependence

# DQPM: summary

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

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

# Transport coefficients

The most interesting coefficient connected to the jet is the averaged transverse momentum broadening squared per unit length of propagation

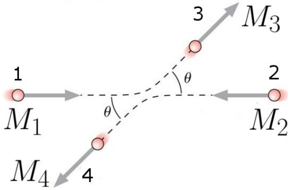
$$\hat{q}_a = \sum_{b,(cd)} \int dq_\perp^2 \frac{d\sigma_{ab\to cd}}{dq_\perp^2} \rho_b q_\perp^2$$

- characterizes both the local gluon number density and the strength of jet-medium interaction

# Transport coefficients in kinetic theory

## On-shell:

- integration over momentums
- final mass = pole (thermal) mass

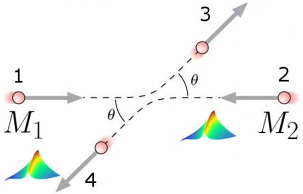



$$E^2 = m^2 + p^2$$

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

## Off-shell:

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



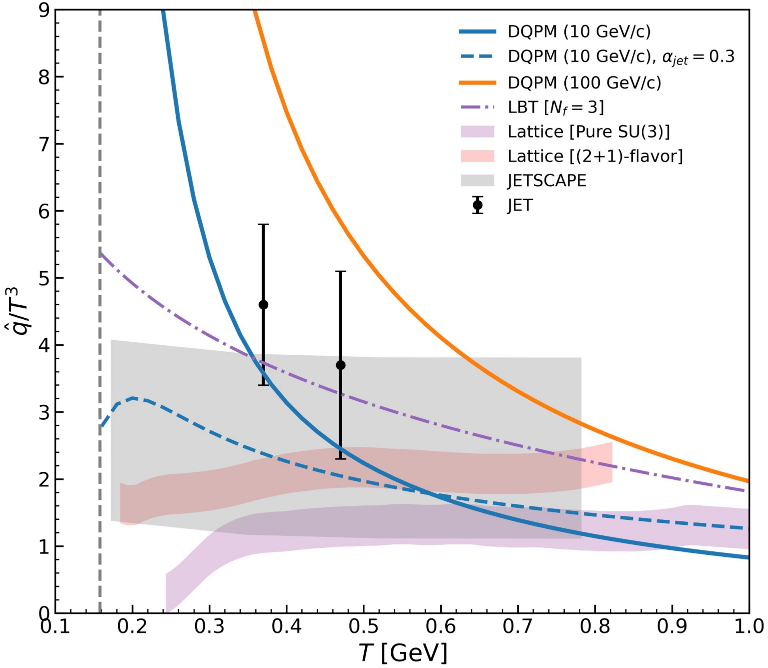

$$\frac{1}{2E} \to \int \frac{d\omega}{(2\pi)} \rho(\omega, \mathbf{p}) \theta(\omega)$$

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

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

# Results: q-hat

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

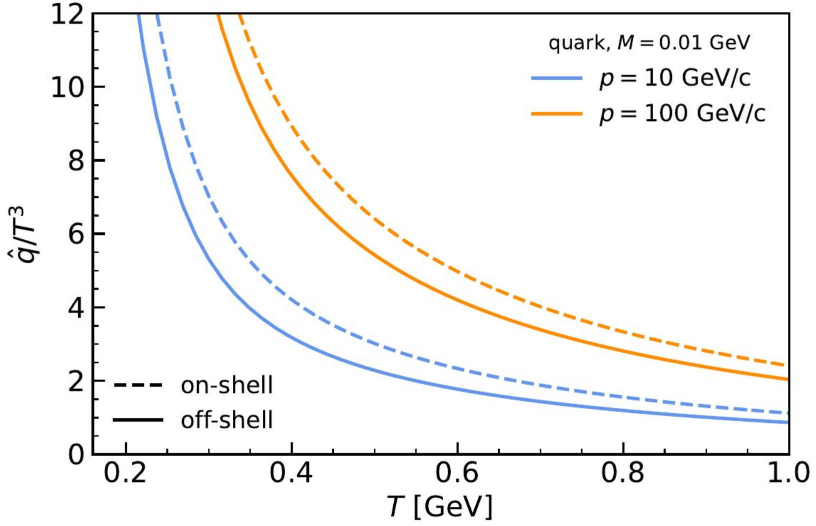



**JET:** K. M. Burke et al., *PRC 90, 014909 (2014);* **lQCD:** A. Kumar et al., *arxiv:2010.14463;* **LBT:** Y. He et al., *PRC 91 (2015);*

**JETSCAPE:** S. Cao *et al. PRC 104, 024905 (2021);* **CSPM:** A.Mishra et al., *Physics 4, 315 (2022)*

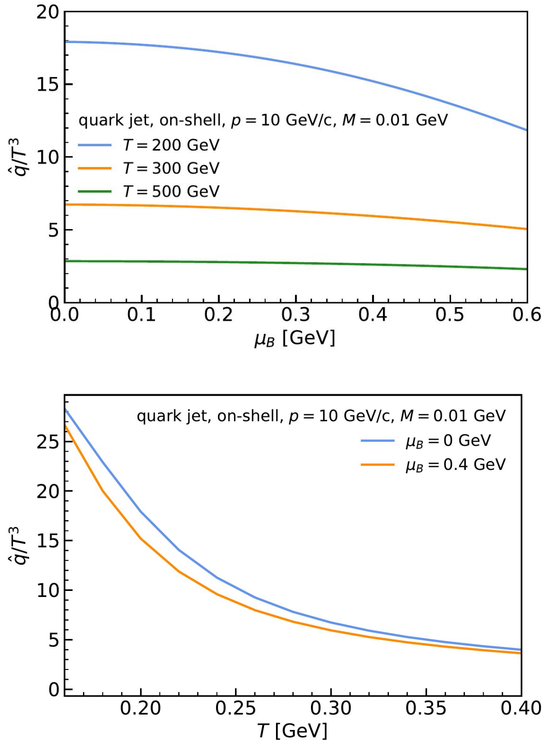
# Results: q-hat

On-shell vs off-shell



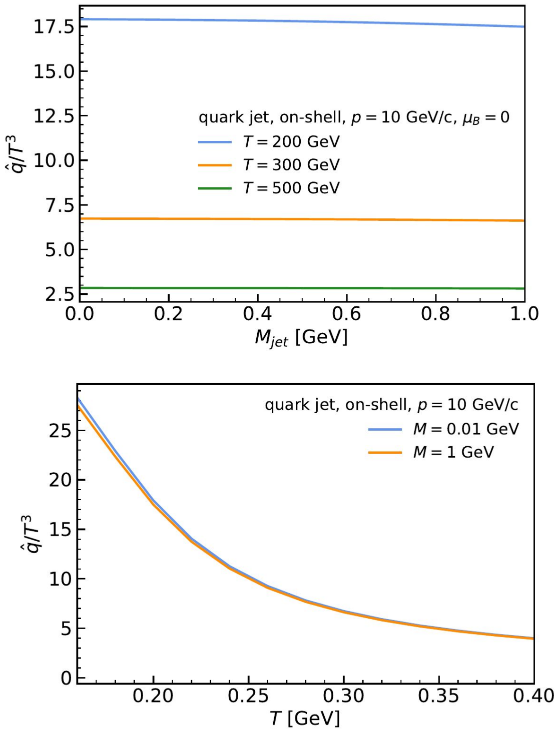
# Results: q-hat

## $\mu_B$ dependence




- Decreases with $\mu_B$

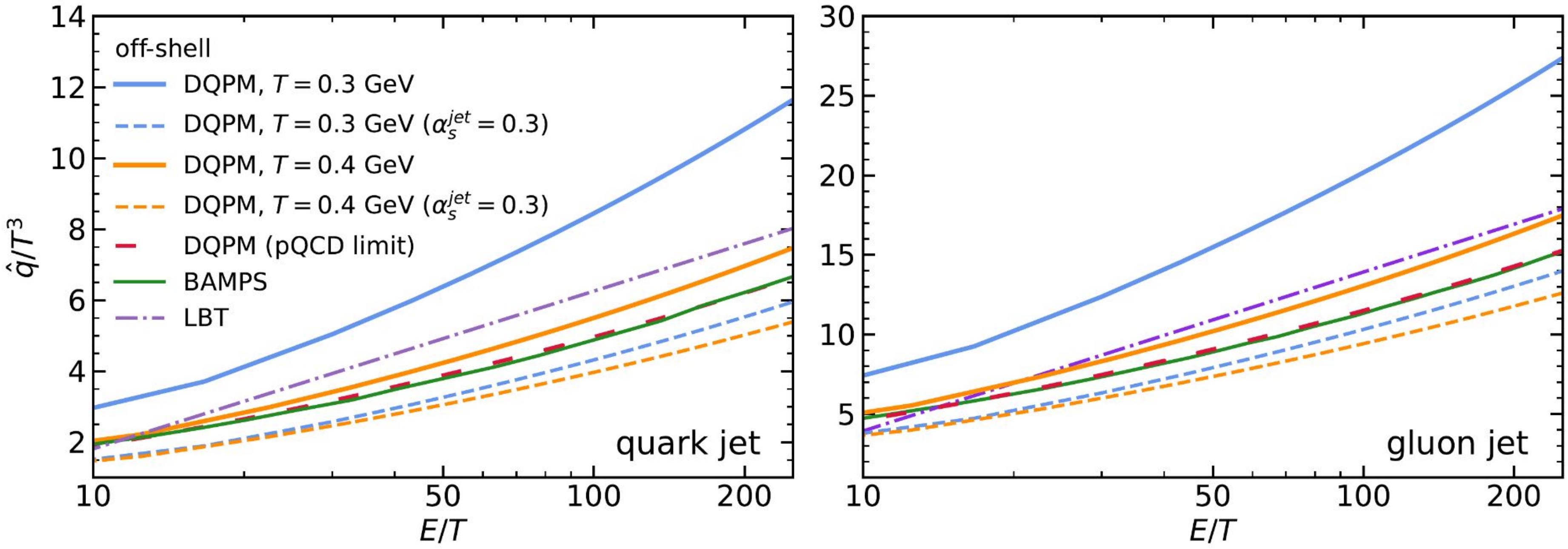
## Mass dependence




- Decreases with M, but dependence is negligible

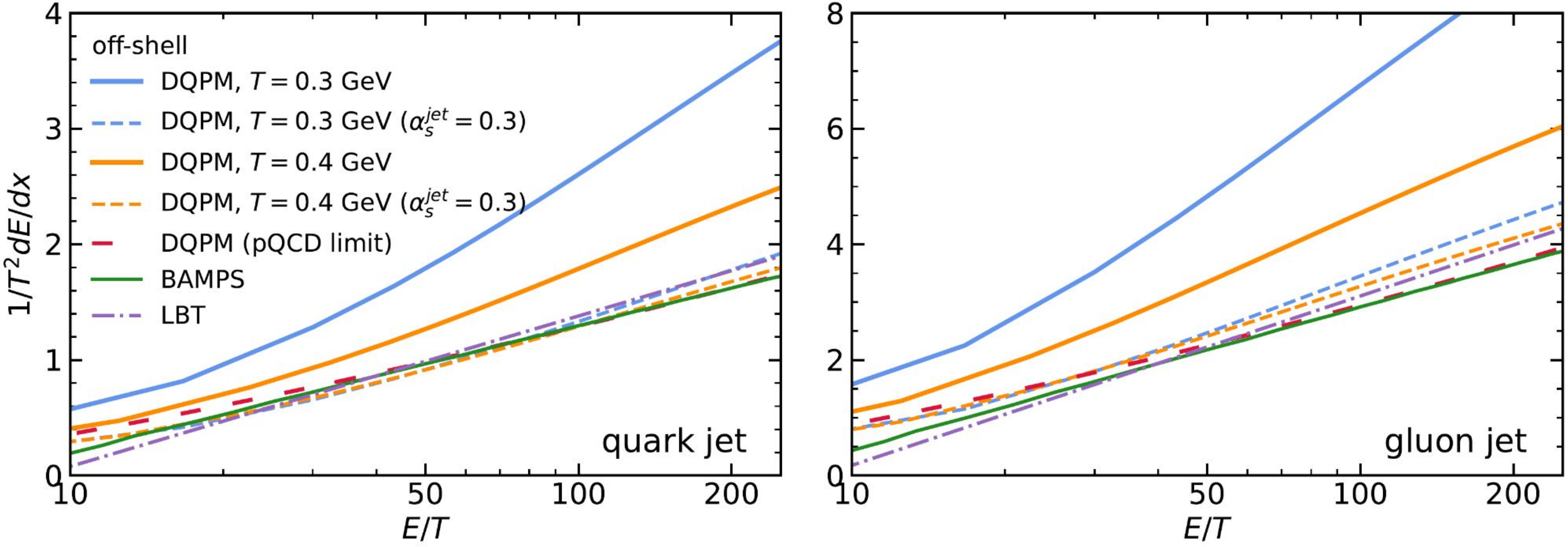
# Results: q-hat

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