

TRANSPORT PROPERTIES OF THE STRONGLY INTERACTING QUARK-GLUON PLASMA

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in collaboration with

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MOTIVATION

- QGP appears to be a **strongly interacting system** of partons
 - pQCD methods are **not applicable** for the thermal QGP
 - one should rely on **non-perturbative methods**
- Effective **quasiparticles models** (QPMs) describe the **partonic degrees of freedom** and their interactions
- QPMs allow us to dynamically investigate
 - the evolution (thermalization) of the QGP
 - strangeness production
 - jet/charm attenuation
 - etc.

DYNAMICAL QUASIPARTICLE MODEL (DQPM)

DQPM INGREDIENTS

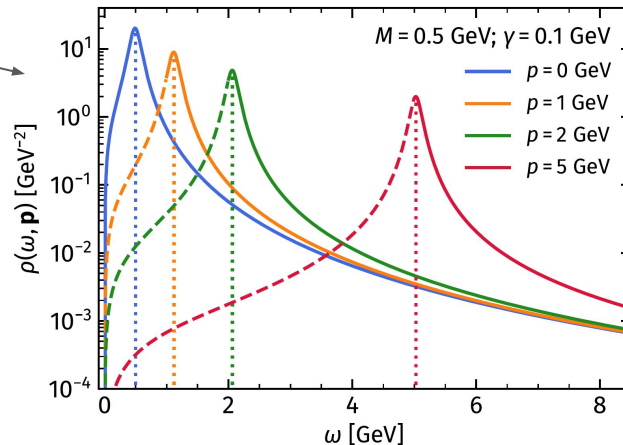
- DQPM – effective model for the description of **non-perturbative** QCD based on **lattice QCD EoS**
- The QGP phase is described in terms of strongly interacting off-shell **partons** with Lorentzian spectral functions:

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

- Theoretical basis: **“resummed”** single-particle Green’s functions
→ quark/gluon **propagators** with **complex self-energies**

$$\Delta_i(\omega, \mathbf{p}) = \frac{1}{\omega^2 - \mathbf{p}^2 - \Pi_i}, \quad \Pi_i = m_i^2 - 2i\gamma_i\omega$$

- **Real part** of the self-energy → **thermal mass**
- **Imaginary part** of the self-energy → **interaction width**



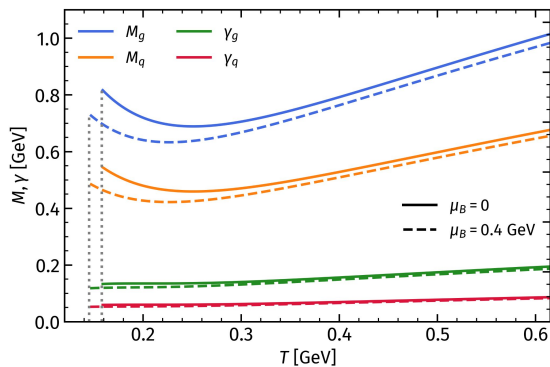
DQPM INGREDIENTS

- Masses** and **widths** of quasiparticles depend on T and μ_B

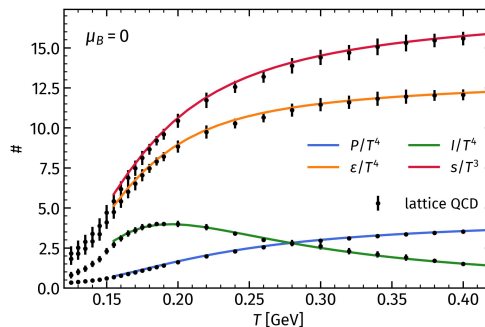
$$m_g^2(T, \mu_B) = C_g \frac{g^2(T, \mu_B)}{6} T^2 \left(1 + \frac{N_f}{2N_c} + \frac{1}{2} \frac{\sum_q \mu_q^2}{T^2 \pi^2} \right)$$

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

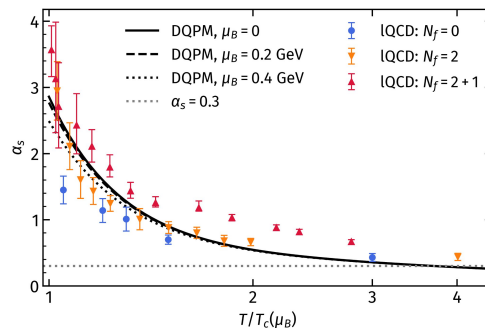
$$\gamma_j(T, \mu_B) = \frac{1}{3} C_j \frac{g^2(T, \mu_B) T}{8\pi} \ln \left(\frac{2c_m}{g^2(T, \mu_B)} + 1 \right)$$



- Strong coupling** (g) is defined from **IQCD entropy density** at $\mu_B=0$



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



$$\alpha_s = g^2(T, \mu_B)/(4\pi)$$

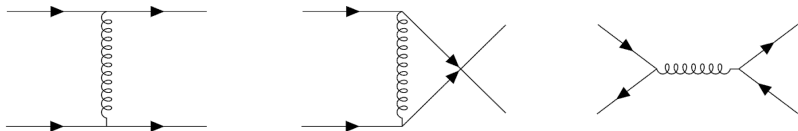
→ DQPM allows to explore QCD in the **non-perturbative regime** of the (T, μ_B) **phase diagram**

PARTONIC INTERACTIONS

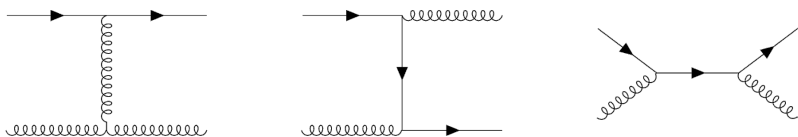
PARTONIC INTERACTIONS

- DQPM partonic interactions are described in terms of **elastic** ($2 \rightarrow 2$) and **inelastic** ($2 \rightarrow 3$) scatterings

quark + quark \rightarrow quark + quark



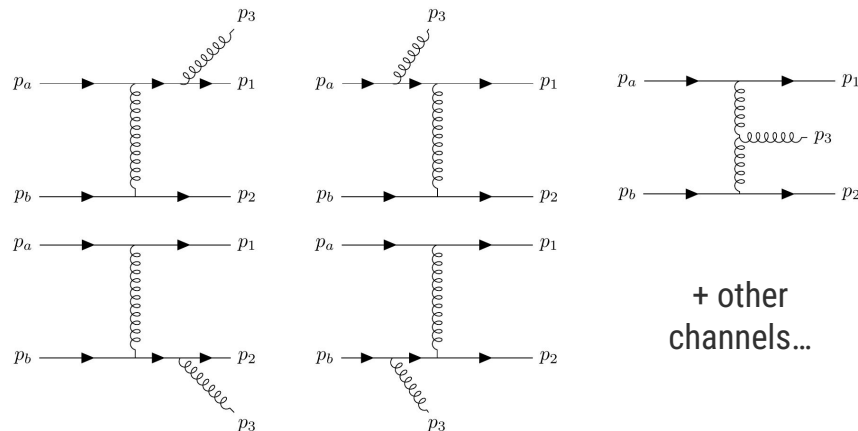
quark + gluon \rightarrow quark + gluon



gluon + gluon \rightarrow gluon + gluon



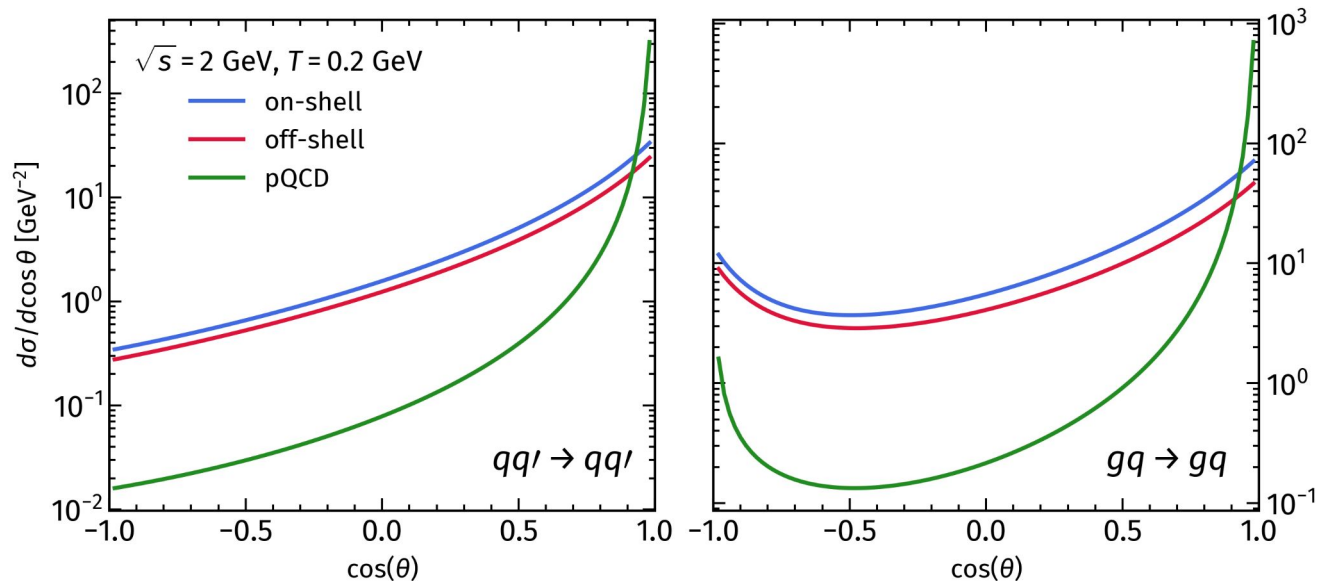
quark + quark \rightarrow quark + quark + gluon (t-channel)



+ other channels...

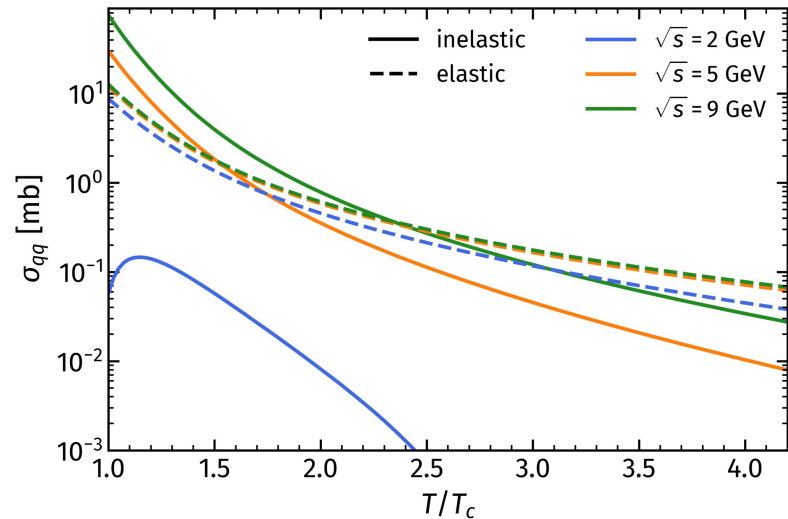
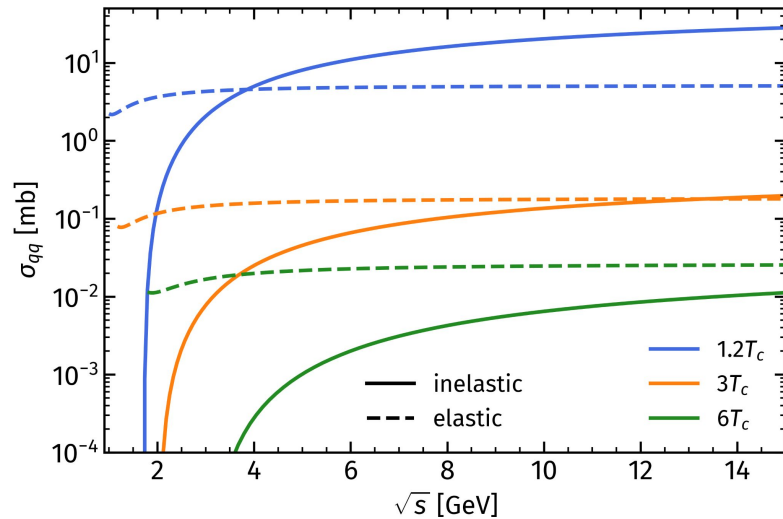
- No approximations** applied
- All interference terms** included
- Emitted gluon is **massive**
- Reproduces** the pQCD propagators for **zero masses** and **widths**

ELASTIC DIFFERENTIAL CROSS SECTIONS



- DQPM interactions are **stronger**
- DQPM **angular distributions** are more **"isotropic"**
- The off-shell effects are small for energetic partons and for high temperatures

PARTONIC TOTAL CROSS SECTIONS

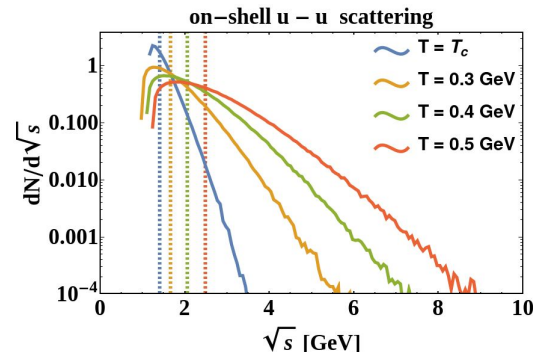
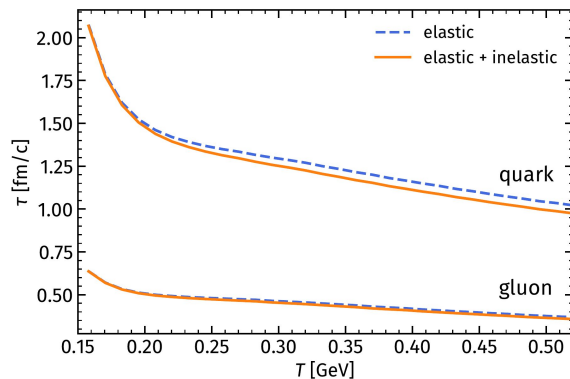
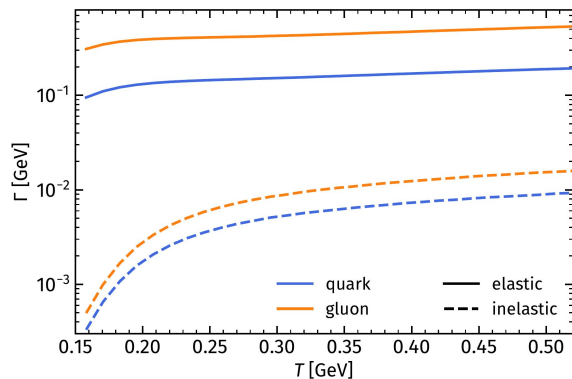


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- **Elastic** cross sections dominate at **low** energies and **high** temperatures
 - **Inelastic** cross sections dominate at **high** energies and **low** temperatures
 - **Temperature** dependence is stronger for the inelastic reactions and is mainly driven by the DQPM **strong coupling**
- $\left. \begin{array}{l} |\overline{\mathcal{M}}_{2 \rightarrow 2}|^2 \propto \alpha_s^2 \\ |\overline{\mathcal{M}}_{2 \rightarrow 3}|^2 \propto \alpha_s^3 \end{array} \right\}$

PARTONIC INTERACTION RATE

- **Interaction rate** (Γ) describes the **frequency** at which partons **interact** with each other within a medium
- **Relaxation time** ($\tau \sim 1/\Gamma$) defines the **time** it takes for a system to **return to equilibrium** after a change or disturbance



→ **Low** energies are **avored**

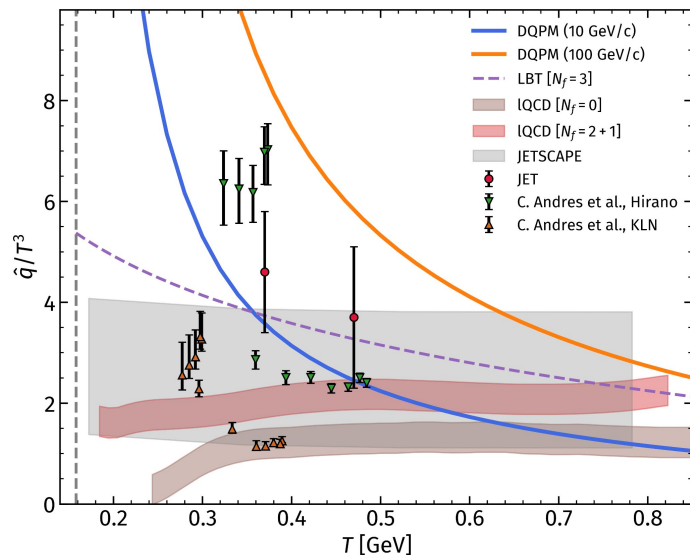
I. Grishmanovskii et al., PRC 109, 024911 (2024)

- The partonic **interaction rates** and **relaxation time** are primarily governed by **elastic** scattering
- **Inelastic processes** – with massive gluon emission – are **suppressed** in the **thermalized** QCD medium

JET/CHARM TRANSPORT COEFFICIENTS

\hat{q} FROM ONLY ELASTIC REACTIONS

- Transport coefficients are **material properties** that characterize the **response of a system** to external forces
- **q-hat** (\hat{q}) defines the **transverse momentum transfer squared** per unit length: $\hat{q} = \langle q_{\perp}^2 / \lambda \rangle$
- **Energy loss** (dE/dx) quantifies the **rate** at which a high-energy parton **loses its energy** while propagating

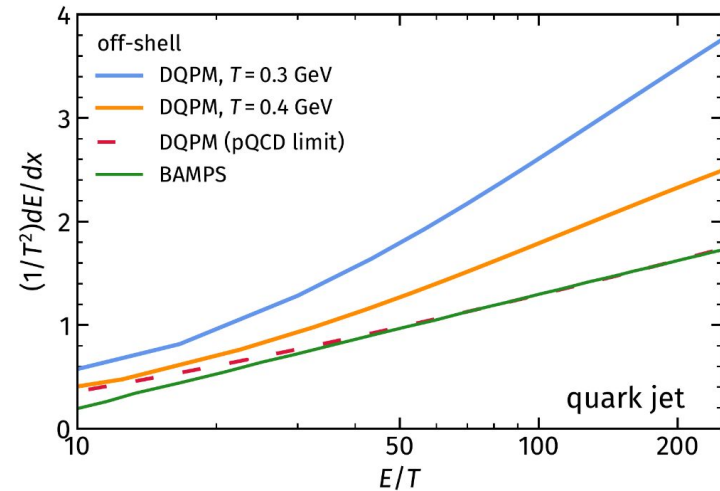
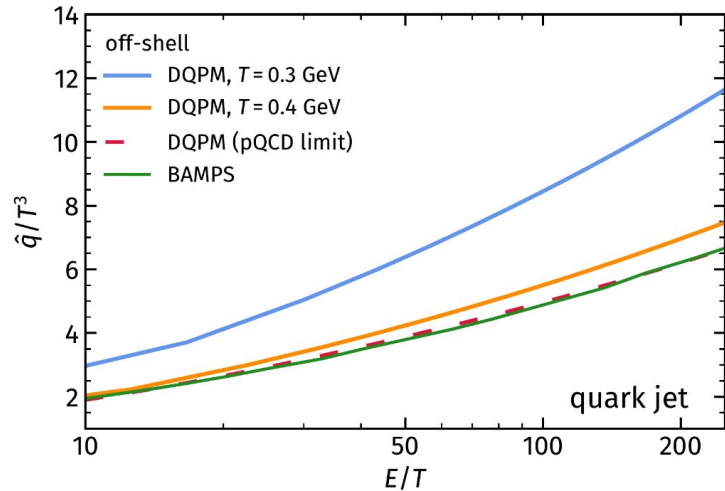


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→ **Agreement** with the other models at **low jet energy**

→ Rapid **rise** with **decreasing** medium **temperature**

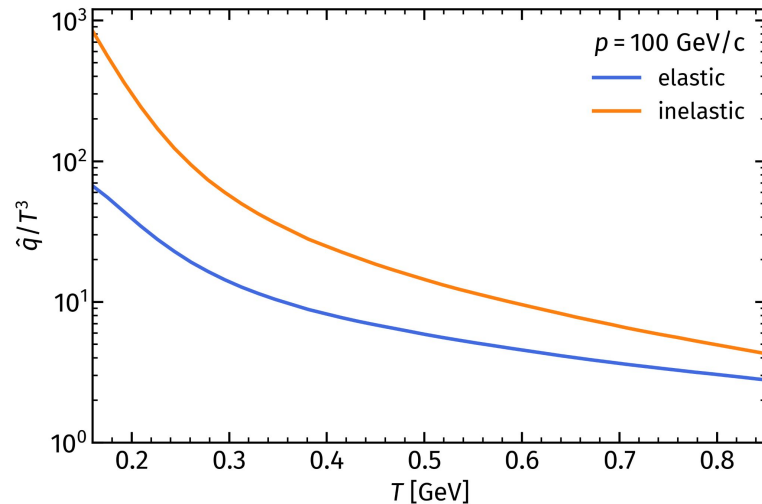
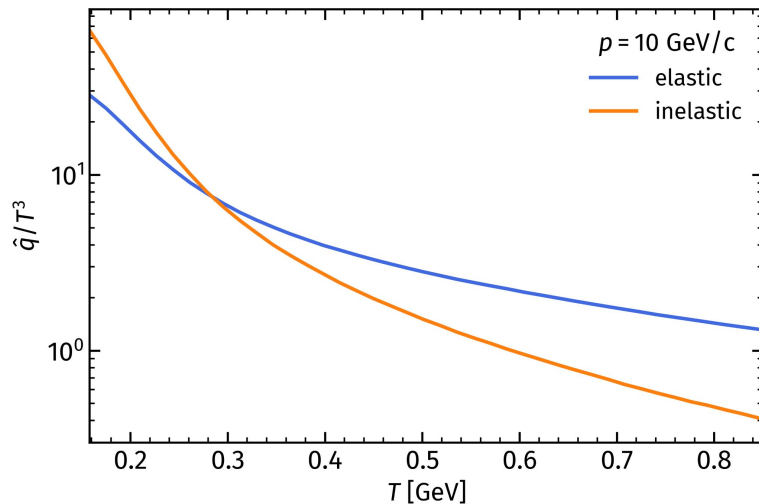
\hat{q} AND dE/dx FROM ELASTIC REACTIONS



I. Grishmanovskii et al., PRC 106, 014903 (2022)

- **Logarithmic growth** of \hat{q} -hat and dE/dx with **jet energy**
- DQPM predicts **stronger suppression**
- **Aligning** with **pQCD-based** calculations in the **pQCD-limit**

\hat{q} FROM ELASTIC AND INELASTIC REACTIONS



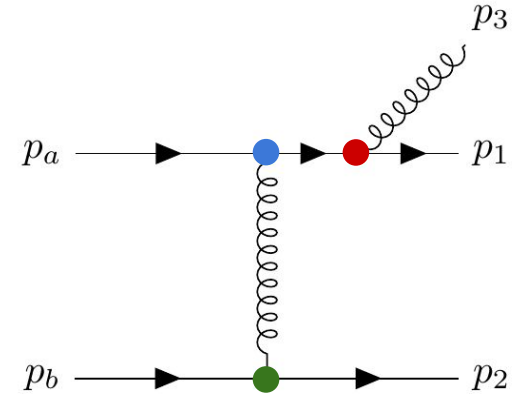
I. Grishmanovskii et al., PRC 110, 014908 (2024)

- Temperature and momentum **dependence** is stronger for **inelastic** reactions
- **Stronger energy loss** at large energies and small temperatures
→ **questionable suppression** of jets in heavy-ion collisions

DIFFERENT “SCENARIOS” FOR STRONG COUPLING

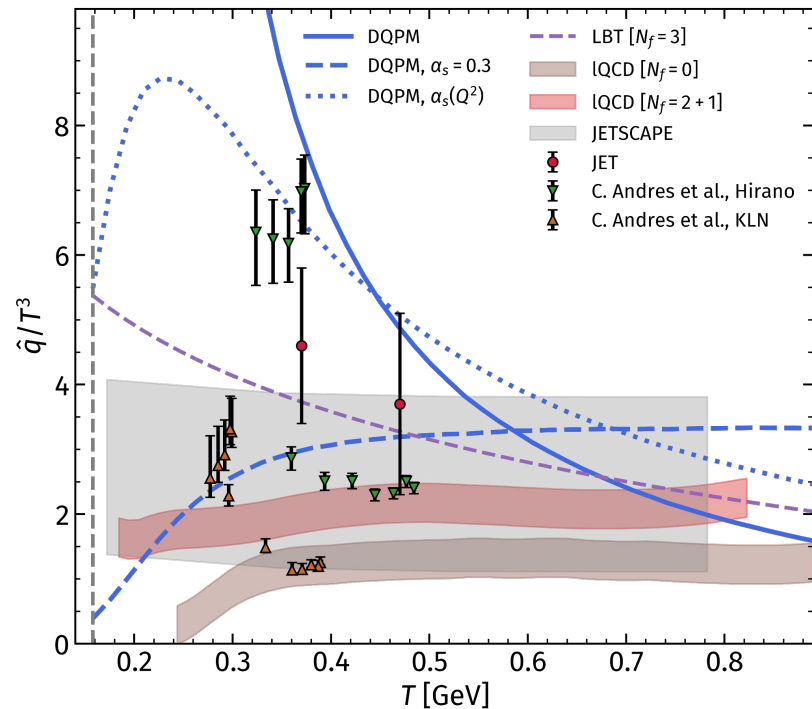
- Jet is **not a part** of the QGP medium \rightarrow strong coupling is **not thermal**
 \rightarrow consider different strong couplings in *thermal* (●), *jet* (●), and *radiative* (●) vertices

	Vertex		
Model	● thermal	● jet	● emitted gluon
DQPM	$\alpha_s(T)$		
DQPM, $\alpha_s = 0.3$	$\alpha_s = 0.3$		
DQPM, $\alpha_s(Q^2)$	$\alpha_s(T)$	$\alpha_s(Q^2)$	$\alpha_s(k_t^2)$



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\hat{q} FOR DIFFERENT “SCENARIOS”

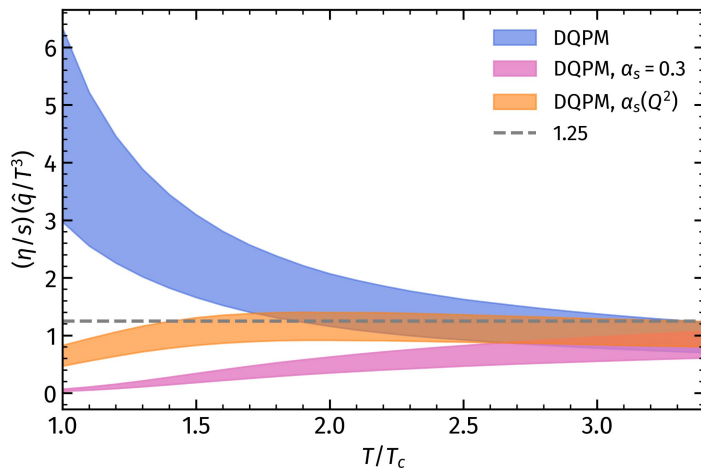


- High sensitivity to the choice of the strong couplings
- The “default” DQPM with the thermal couplings produces the highest values

I. Grishmanovskii et al., PRC 110, 014908 (2024)

RELATION BETWEEN η/s AND \hat{q}

- **Shear viscosity** η describes **resistance** to sheared flow
- Both \hat{q} and η serve as a **measure** of the parton **coupling strength** within the medium
- In the **weakly coupled limit**: $\eta/s \approx 1.25 \frac{T^3}{\hat{q}}$

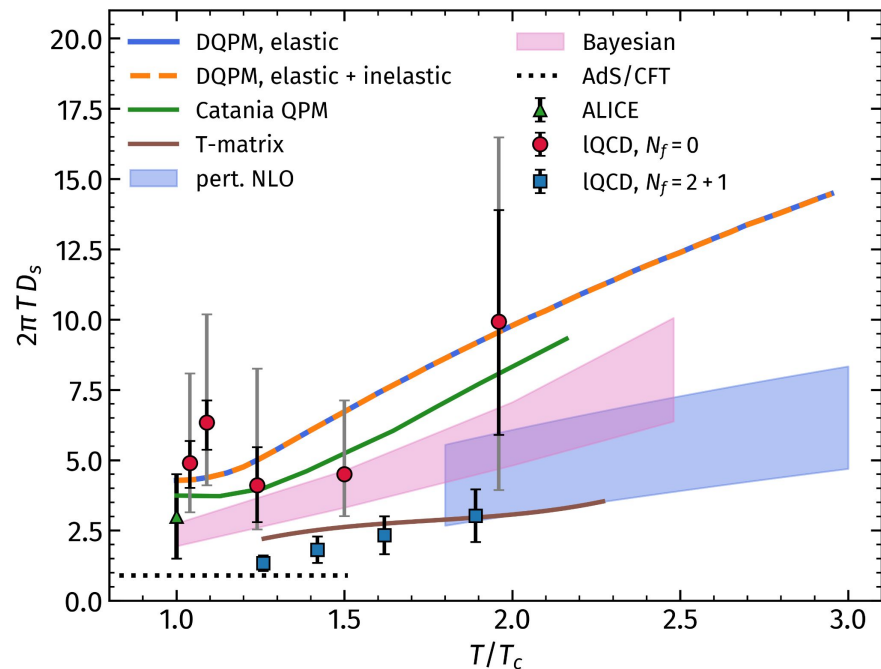


- **Sensitive** to the choice of the **strong coupling**
- **Valid** in the **weak coupling regime** (at high temperatures)
- **Violated** in the **strong coupling regime** (at low temperatures)

B. Müller, PRD 104, L071501 (2021)

I. Grishmanovskii et al., PRC 110, 014908 (2024)

CHARM DIFFUSION COEFFICIENT



- Diffusion coefficient: $D_s = \lim_{p_c \rightarrow 0} \frac{T}{(\mathcal{A}/p)M_c}$

→ **Inelastic** contribution to the diffusion coefficient is **negligible**

SUMMARY

- DQPM provides a **self-consistent approach** to study **partonic interactions** and **transport properties** of the QGP
- **Inelastic** interactions are **suppressed** in a thermalized QGP medium, but are **crucial** in the context of **jet attenuation**
- **Jet energy loss** of hard jet partons is **larger** within the DQPM compared to the pQCD-based calculations
- **Transport coefficients** are highly **sensitive** to the choice of the **strong coupling**
- The **inelastic** reactions play a **minor role** in the determination of the **spatial diffusion coefficient**