TRANSPORT PROPERTIES OF THE STRONGLY INTERACTING QUARK-GLUON PLASMA

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in collaboration with

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CRC–TR 211
Strong-interaction matter under extreme conditions

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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

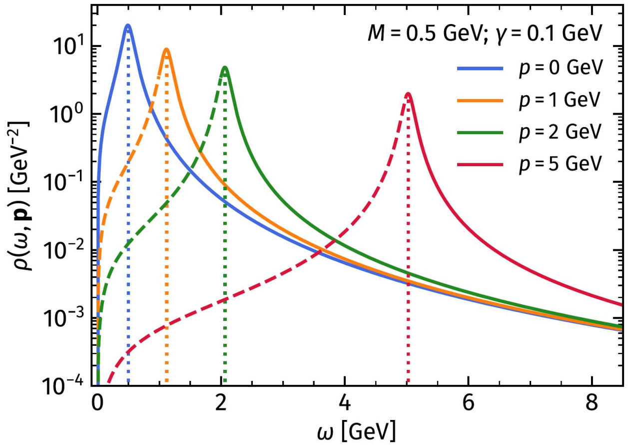
- Effective quasiparticles models describe the partonic degrees of freedom and their interactions, making it possible to dynamically investigate
  - the evolution (thermalization) of the QGP
  - strangeness production
  - jet/charm attenuation
  - etc.

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 quasiparticles – massive quarks and gluons – with Lorentzian spectral functions:

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



- Theoretical basis: "resummed" single-particle Green's functions → quark/gluon propagators with complex self-energies

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

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

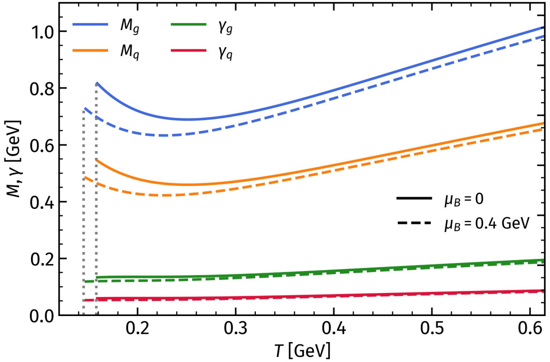
DQPM INGREDIENTS

- Masses and widths of quasiparticles depend on T and μ_B

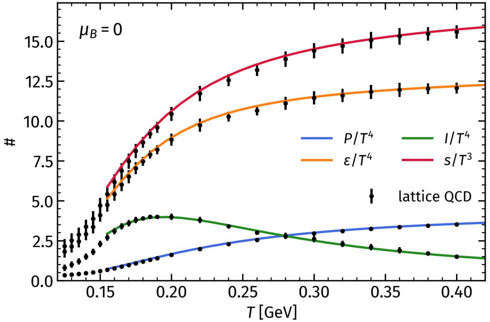
$$m_g^2(T,\mu_\mathrm{B}) = C_g \frac{g^2(T,\mu_\mathrm{B})}{6} T^2 \left(1 + \frac{N_f}{2N_c} + \frac{1}{2}\frac{\sum_q \mu_q^2}{T^2\pi^2}\right)$$

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

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

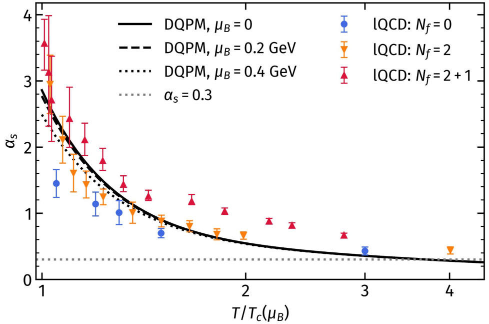


- Strong coupling (g) is defined from lQCD entropy density at μ_B=0



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

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



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

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

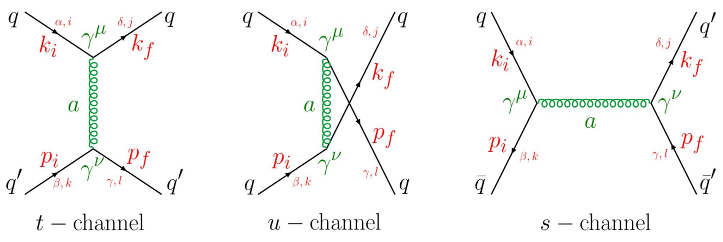
PARTONIC INTERACTIONS

PARTONIC ELASTIC INTERACTIONS

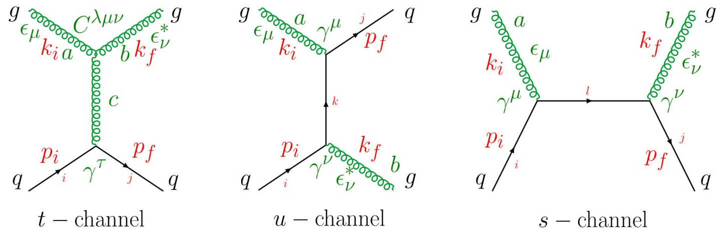
- DQPM partonic interactions are described in terms of elastic (2→2) and inelastic (2→3) scatterings

- No approximations applied
- All interference terms included
- Reproduces the pQCD propagators for zero masses and widths

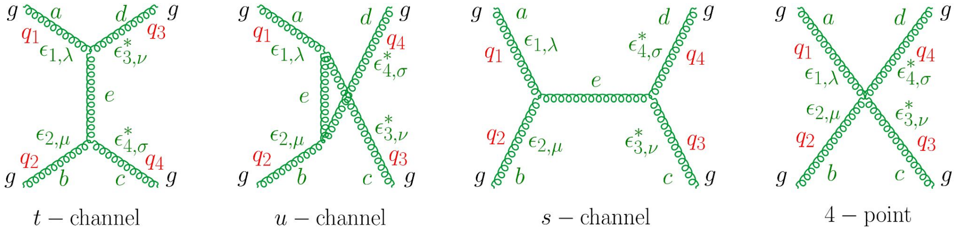
quark + quark



quark + gluon

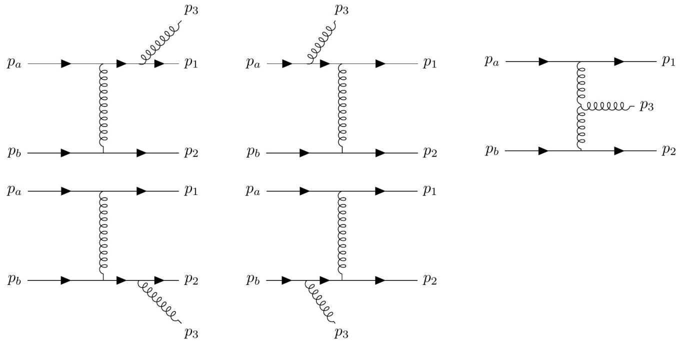


gluon + gluon

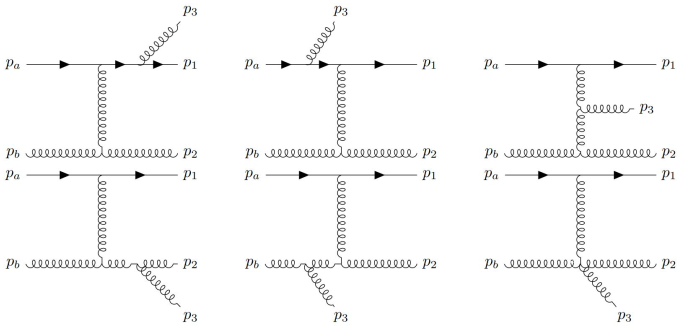


PARTONIC INELASTIC INTERACTIONS

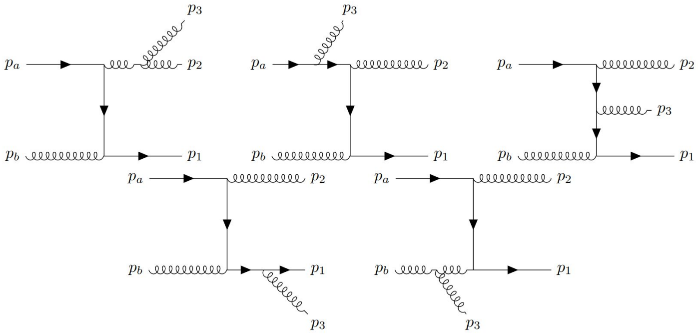
quark + quark (*t*-channel)



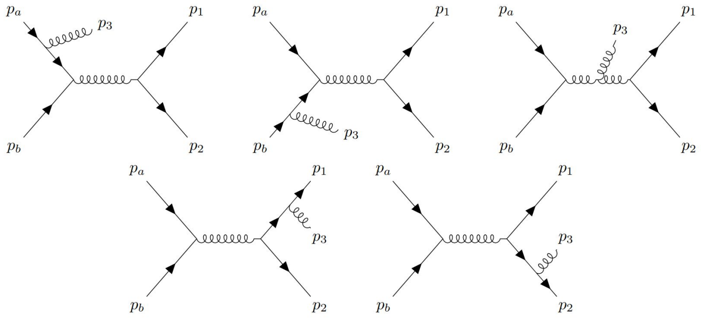
quark + gluon (*t*-channel)



quark + gluon (*u*-channel)

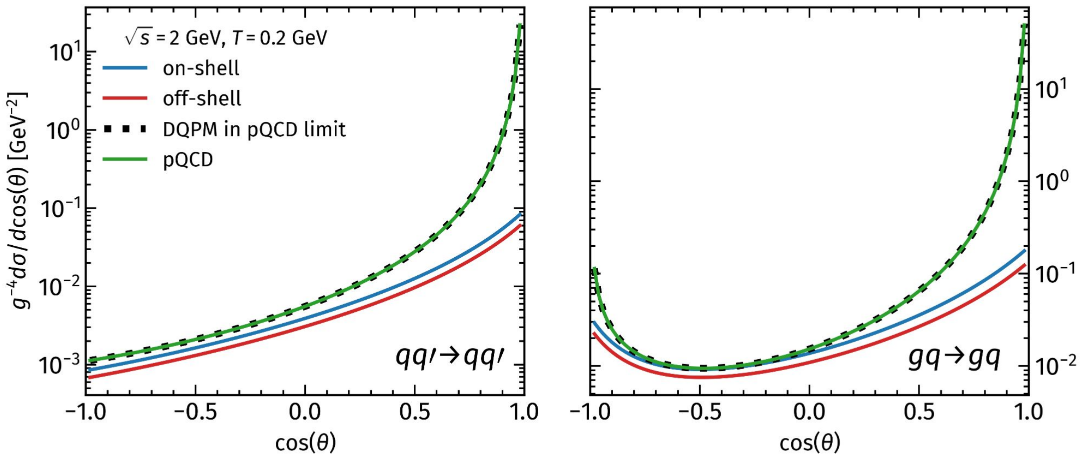


quark + gluon (*s*-channel)



- **No approximations** applied
- **All interference terms** included
- Emitted gluon is **massive**

DQPM ELASTIC DIFFERENTIAL CROSS SECTIONS

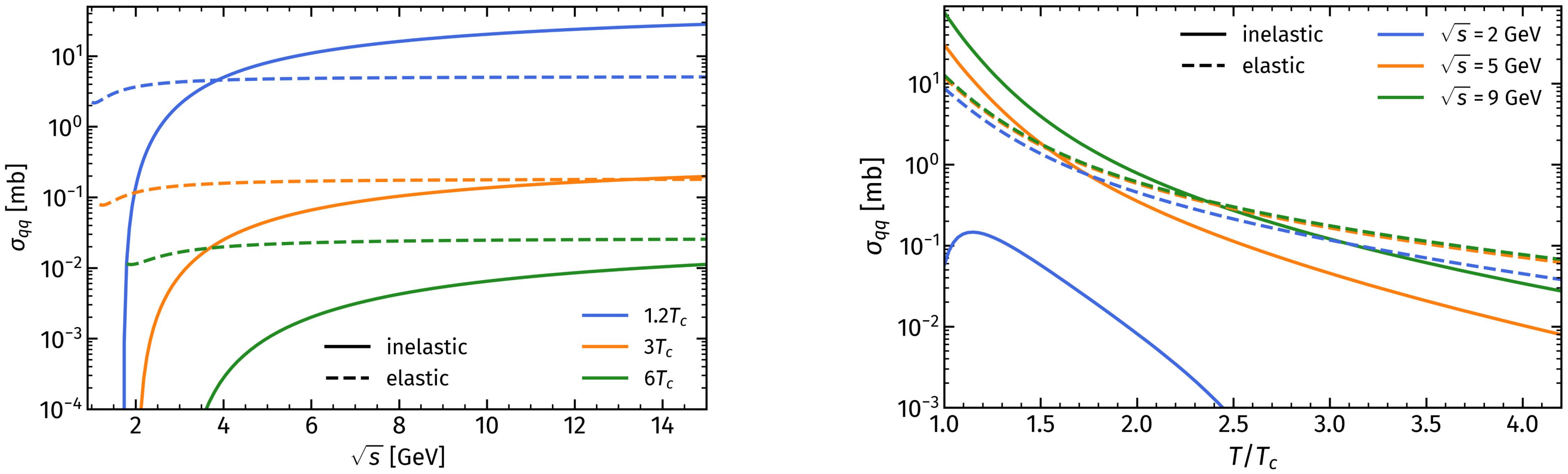


➔ DQPM **angular distributions** are more **"isotropic"**

➔ DQPM **reproduces** pQCD cross sections for **zero** masses and widths (pQCD limit)

➔ The **off-shell** effects are **small** for energetic partons and for high temperatures

PARTONIC CROSS SECTIONS: ELASTIC VS INELASTIC



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

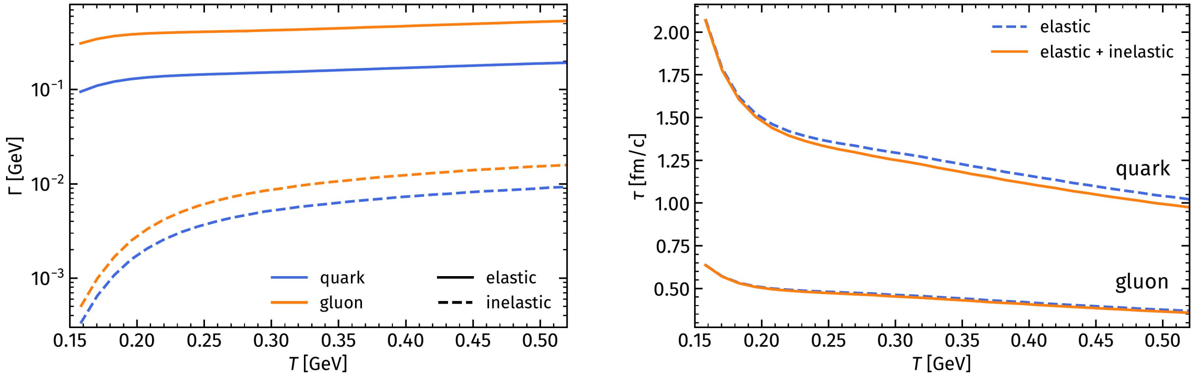
- ➔ **Elastic** cross sections dominate at **low** energies and **high** temperatures
- ➔ **Inelastic** cross sections dominate at **high** energies and **low** temperatures

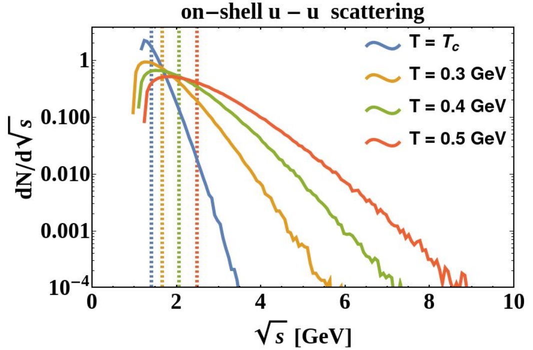
$$|\overline{\mathcal{M}}_{2\to 2}|^2 \propto \alpha_s^2$$
$$|\overline{\mathcal{M}}_{2\to 3}|^2 \propto \alpha_s^3$$

- ➔ **Temperature** dependence is stronger for the inelastic reactions and is mainly driven by the DQPM **strong coupling**

PARTONIC INTERACTION RATE

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





➔ Low energies are favored

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

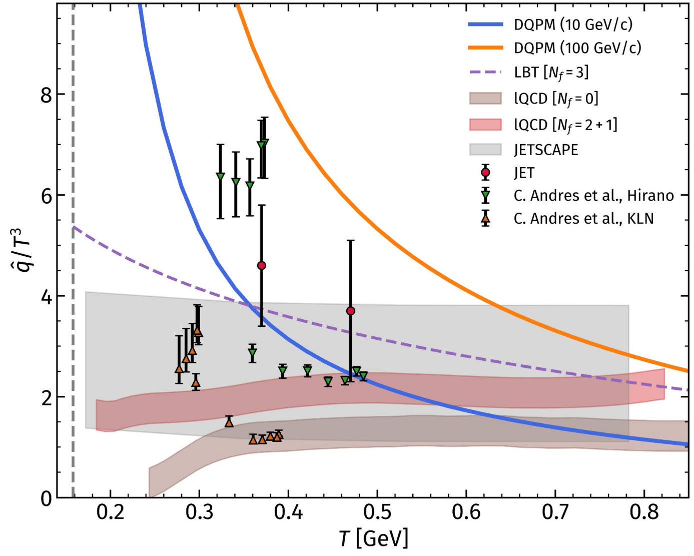
➔ The partonic interaction rates and relaxation time are primarily governed by elastic scattering

➔ Inelastic processes – with massive gluon emission – are suppressed in the thermalized QCD medium

JET TRANSPORT COEFFICIENTS

q̂ FROM ELASTIC REACTIONS

- Transport coefficients are **material properties** that characterize the **response of a system** to external forces
- **q-hat** (q̂) 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

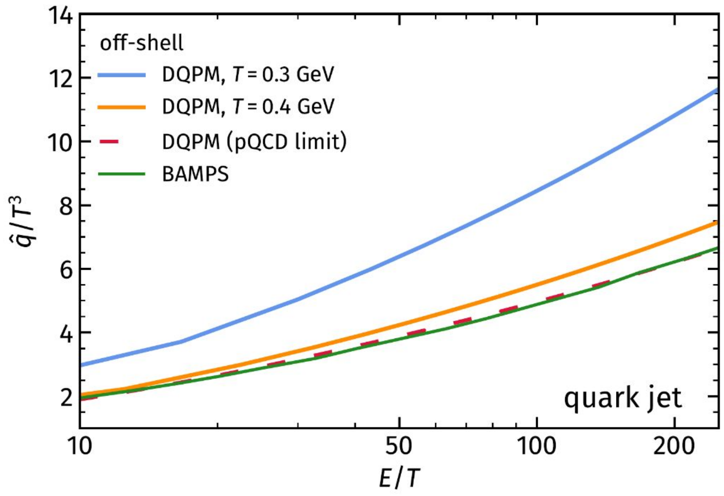


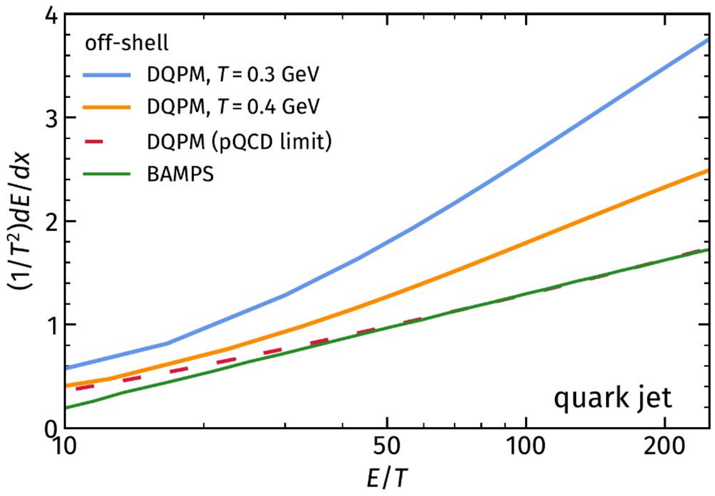
I. Grishmanovskii et al., PRC 109, 024911

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

➔ Rapid **rise** with **decreasing** medium **temperature**

q̂ AND dE/dx FROM ELASTIC REACTIONS





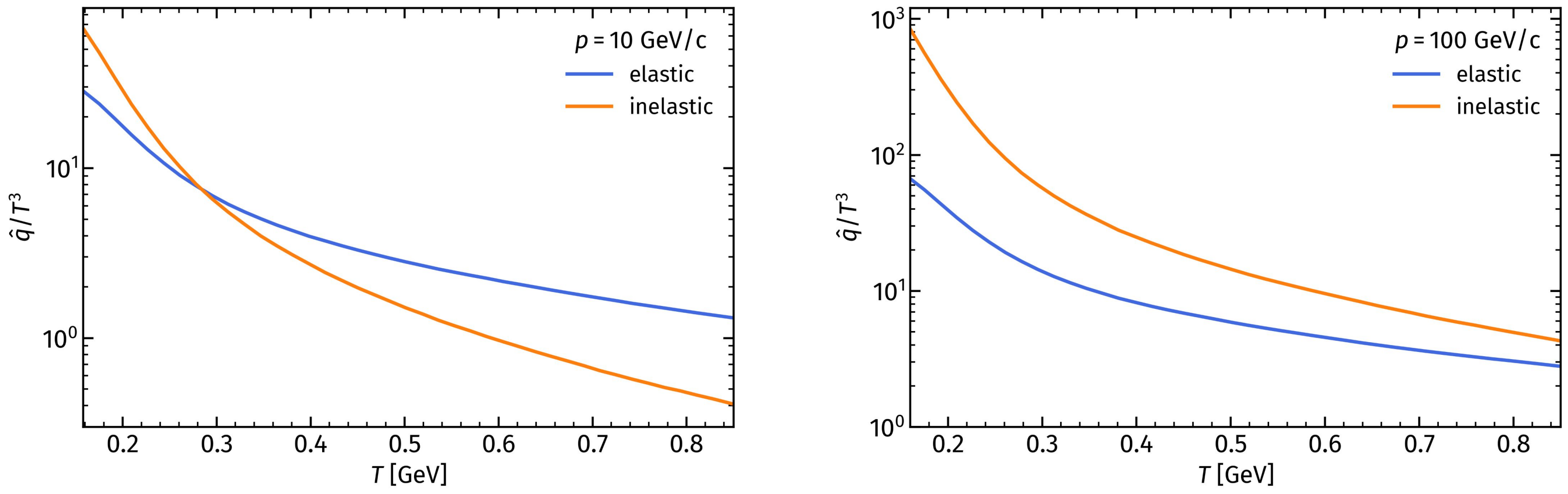
I. Grishmanovskii et al., PRC 106, 014903 (2022)

➔ Logarithmic growth of q-hat and dE/dx with jet energy

➔ DQPM predicts stronger suppression

➔ Aligning with pQCD-based calculations in the pQCD-limit

q̂ FROM ELASTIC AND INELASTIC REACTIONS



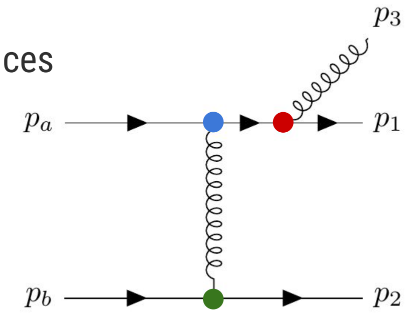
I. Grishmanovskii et al., PRC 110, 014908 (2024)

- ➔ 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 → strong coupling is not thermal

  → consider different strong couplings in *thermal* (●), *jet* (●), and *radiative* (●) vertices



	Vertex		
Model	• medium parton	• jet parton	• emitted gluon
Scenario 0	$g^{\mathrm{DQPM}}(T)$		
Scenario I	$g = \sqrt{4\pi \times 0.3}$		
Scenario II	$g^{\mathrm{DQPM}}(T)$	$g(Q^2)$	$g(k_t^2)$
Scenario III	$g^{\mathrm{DQPM}}(T)$	$g(E)$	$g(E)$
Scenario IV	$g^{\mathrm{DQPM}}(T)$	$g(ET)$	$g(Q^2)$

Scenario 0 → "default" DQPM (thermal coupling)

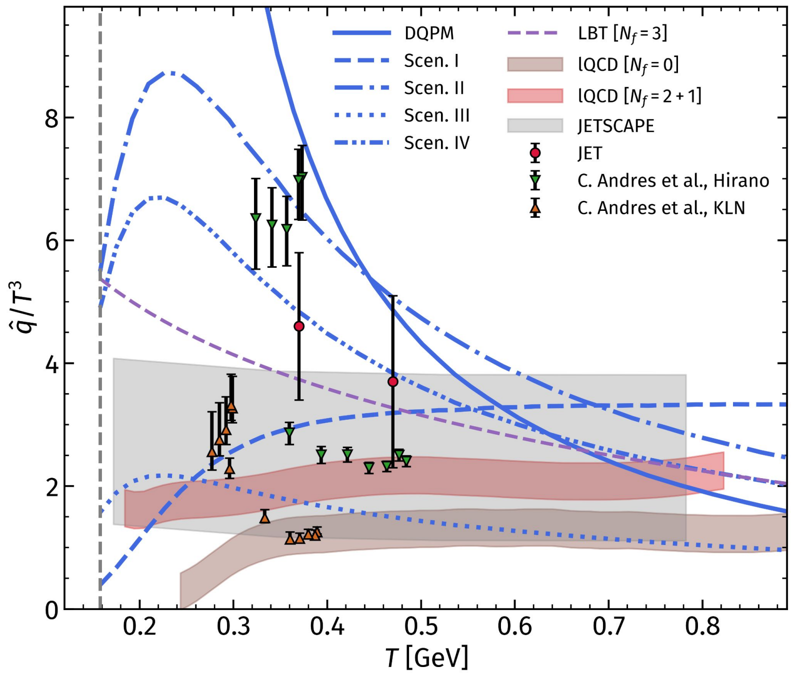
Scenario I → constant strong coupling

Scenarios II–IV:

$$g^2(t) = \frac{48\pi^2}{(11N_c - 2N_f)} \frac{1}{\ln\left(\frac{t}{\Lambda^2}\right)}$$

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

$\hat{q}$ FOR DIFFERENT "SCENARIOS"



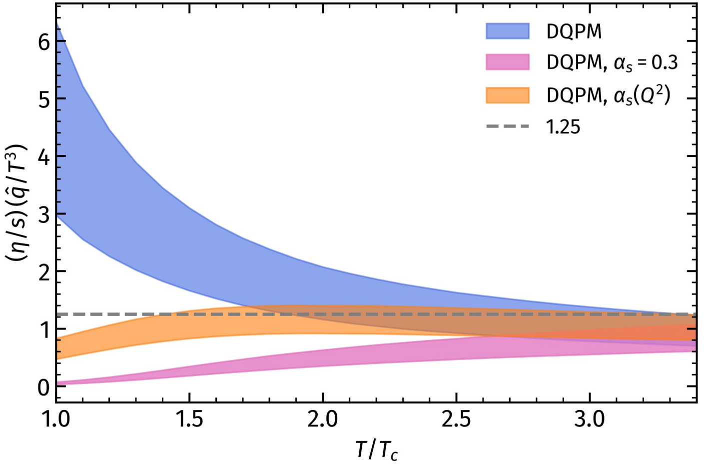
➔ High sensitivity to the choice of the strong couplings

➔ The "default" DQPM with the thermal couplings produces the highest values of the transport coefficients

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

RELATION BETWEEN η/s AND q̂

- **Shear viscosity** η describes **resistance** to sheared flow
- Both q̂ 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)

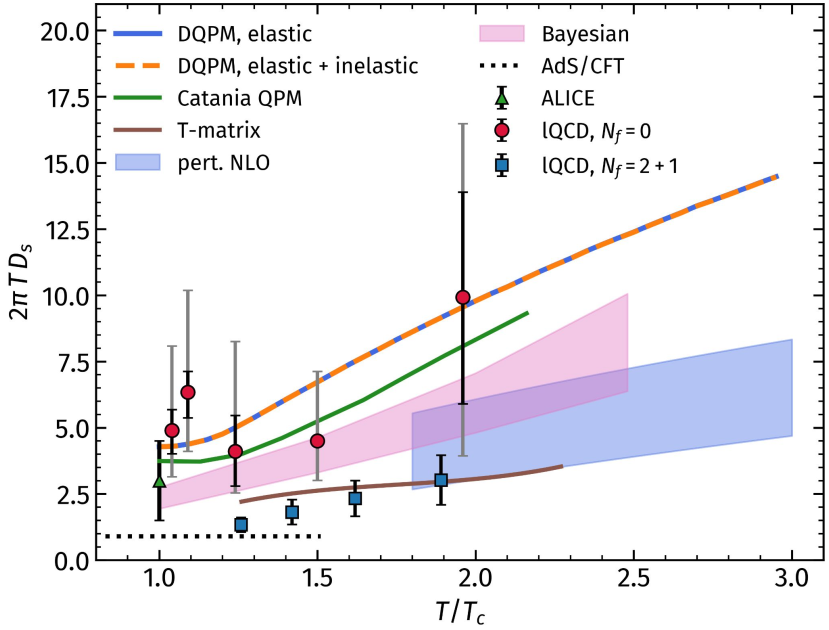
➔ **Violated** in the **strong coupling regime** (at low temperatures)

B. Müller, PRD 104, L071501 (2021)

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

CHARM DIFFUSION COEFFICIENT

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



➔ 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**