Probing the properties of strongly interacting QGP by jet partons

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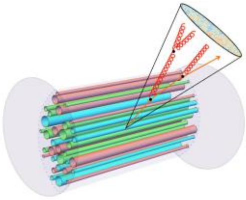
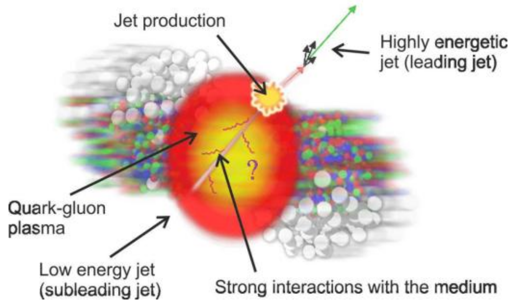
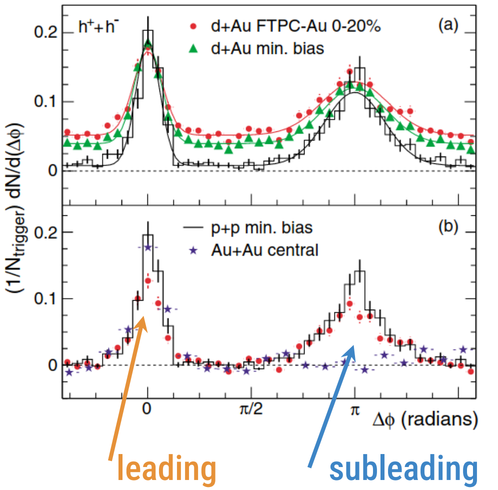


Why to study jets?

Jets provide a **powerful tool** for studying the properties of the QGP:

1. Early formation time → follow the entire evolution of the system
2. Not thermalized in the medium
   → can serve as an "external" probe
3. Formed by hard partonic scattering
   → cross section calculable in pQCD





The goal:

➔ to study the attenuation of jet partons in the strongly interacting non-perturbative QGP (sQGP in HIC) with a focus on the medium response

➔ effective models of QGP

Dynamical QuasiParticle Model (DQPM)

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

Degrees-of-freedom: strongly interacting dynamical quasiparticles - quarks and gluons

Theoretical basis :

- ‚resummed' single-particle Green's functions → quark (gluon) propagator (2PI) :

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

gluon self-energy: $\Pi = M_g^2 - i2\gamma_g\omega$ & quark self-energy: $\Sigma_q = M_q^2 - i2\gamma_q\omega$

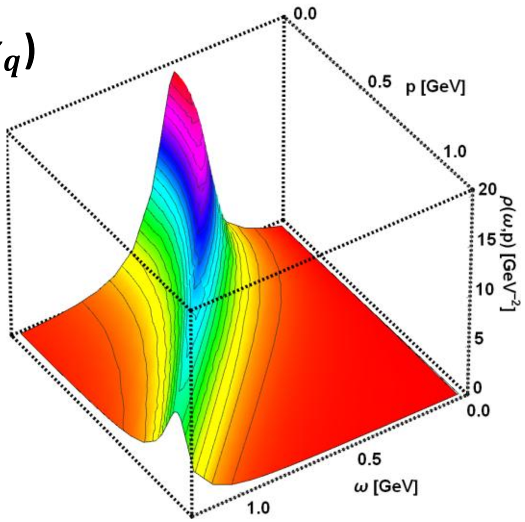
Properties of the quasiparticles are specified by scalar complex self-energies:

$Re\Sigma_q$: thermal masses (M_g, M_q); $Im\Sigma_q$: interaction widths (γ_g, γ_q)

→ spectral functions $\rho_q = -2ImS_q$ → Lorentzian form:

$$\rho_j(\omega,\mathbf{p}) = \frac{\gamma_j}{\tilde{E}_j}\left(\frac{1}{(\omega-\tilde{E}_j)^2+\gamma_j^2} - \frac{1}{(\omega+\tilde{E}_j)^2+\gamma_j^2}\right)$$

$$\equiv \frac{4\omega\gamma_j}{\left(\omega^2-\mathbf{p}^2-M_j^2\right)^2+4\gamma_j^2\omega^2} \qquad \tilde{E}_j^2(\mathbf{p}) = \mathbf{p}^2 + M_j^2 - \gamma_j^2$$



A. Peshier, W. Cassing, PRL 94 (2005) 172301; W. Cassing, NPA 791 (2007) 365: NPA 793 (2007), H. Berrehrah et al, Int.J.Mod.Phys. E25 (2016) 1642003; P. Moreau et al., PRC100 (2019) 014911; O. Soloveva et al., PRC101 (2020) 045203

DQPM: parton properties

Realization concept:

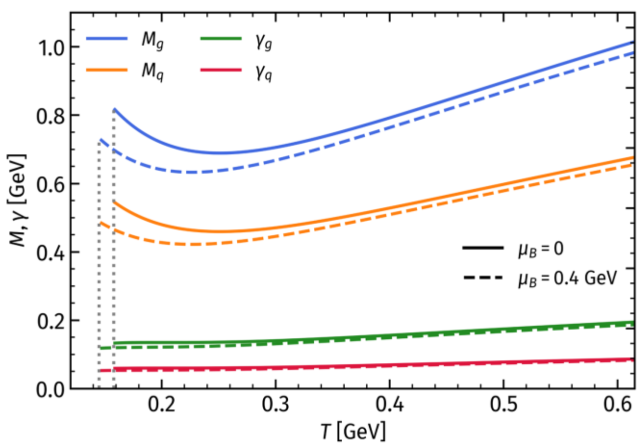
- ❑ introduce an ansatz (HTL; with few parameters) for the (T, μ_B) dependence of masses/widths
- ❑ evaluate the QGP thermodynamics in equilibrium using the Kadanoff-Baym theory
- ❑ fix DQPM parameters by comparison of the DQPM entropy density to lQCD at μ_B=0

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

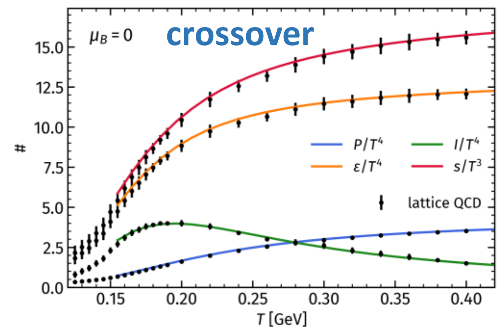
$$m_g^2(T,\mu_B) = C_g \frac{g^2(T,\mu_B)}{6} T^2 \left(1 + \frac{N_f}{2N_c} + \frac{1}{2}\frac{\sum_q \mu_q^2}{T^2\pi^2}\right)$$

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

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

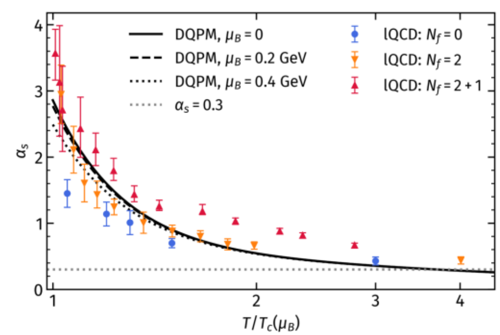


- **Strong coupling** (g) is defined from lQCD entropy density at μ_B=0, using $\frac{\partial}{\partial T}\left(\frac{s_{DQPM}}{T^3}\right) = 0$



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

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



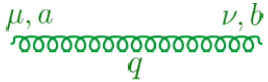
$$\alpha_s = g^2(T,\mu_B)/(4\pi)$$

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

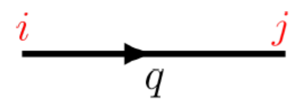
Partonic interactions: matrix elements

DQPM partonic cross sections → leading order diagrams

- **Propagators for massive bosons and fermions:**



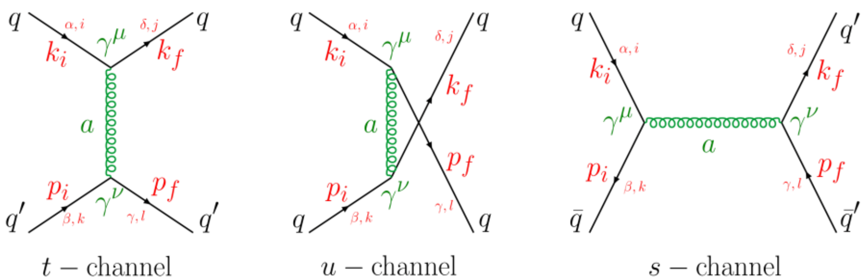
$$= -i\delta_{ab}\frac{g^{\mu\nu} - q^{\mu}q^{\nu}/M_g^2}{q^2 - M_g^2 + 2i\gamma_g q_0}$$



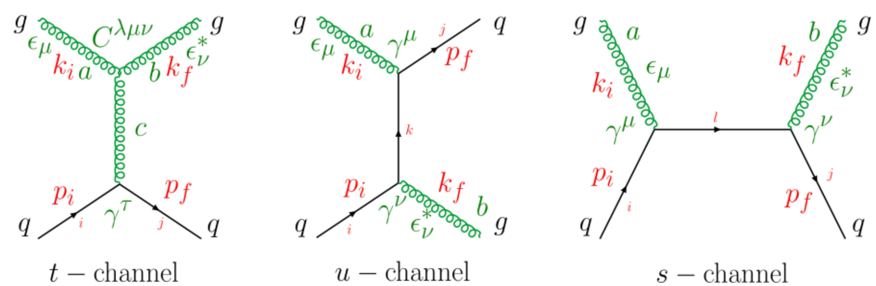
$$= i\delta_{ij}\frac{\not{q} + M_q}{q^2 - M_q^2 + 2i\gamma_q q_0}$$

- **(Quasi-) elastic channels:**

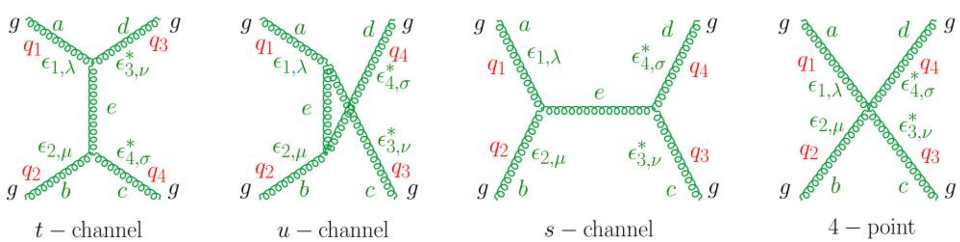
qq’ → qq’ scattering



gq → gq scattering



gg→ gg scattering



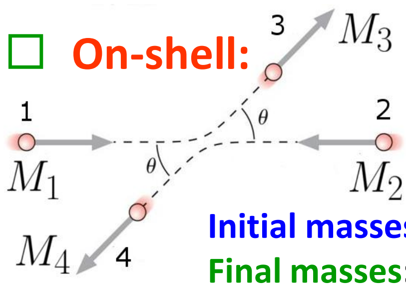
- **Inelastic channels:**

$$\mathrm{q} + \bar{\mathrm{q}} \to \mathrm{g}$$
$$\mathrm{g} \to \mathrm{q} + \bar{\mathrm{q}}$$

H. Berrehrah et al, PRC 93 (2016) 044914, Int.J.Mod.Phys. E25 (2016) 1642003, → **P. Moreau et al., PRC100 (2019) 014911**

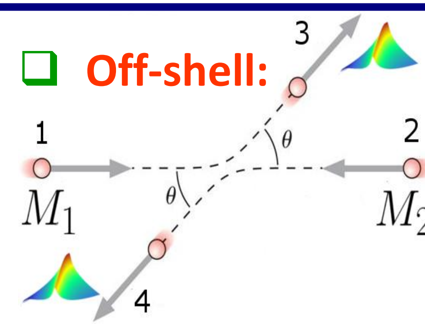
Differential cross sections

❑ **On-shell:**

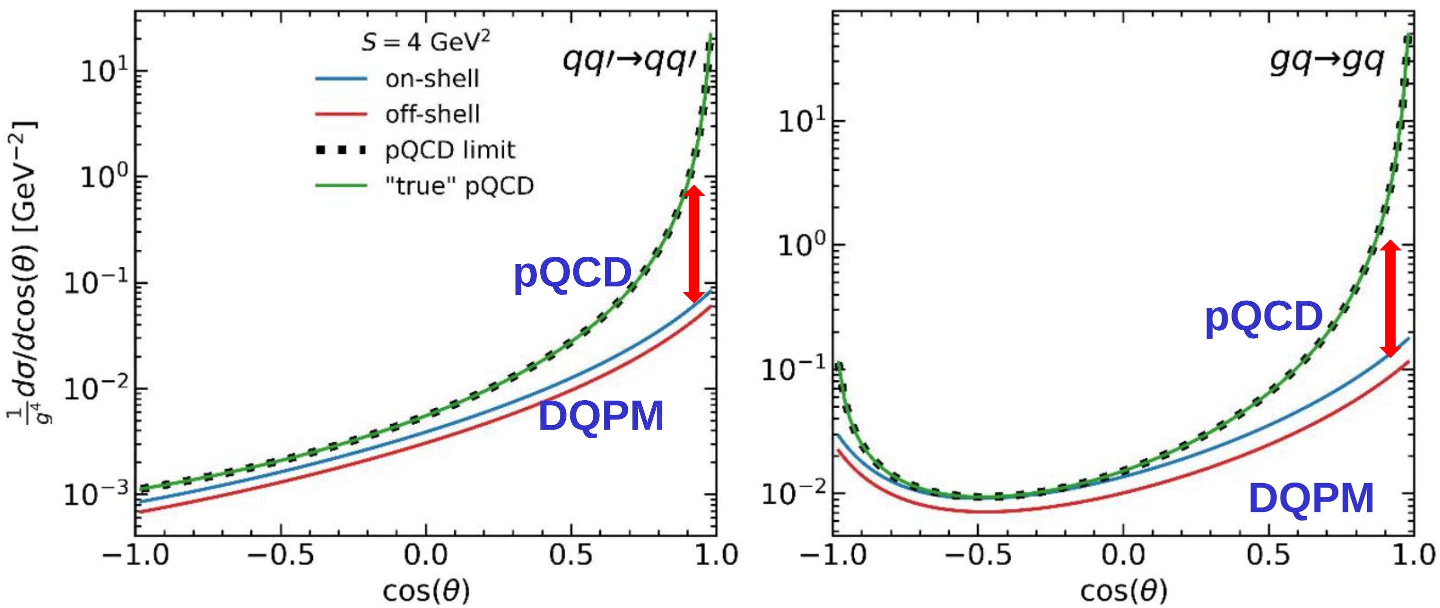


Initial masses: pole masses
Final masses: pole masses

❑ **Off-shell:**



Initial masses: pole masses
Final masses: integration over spectral functions

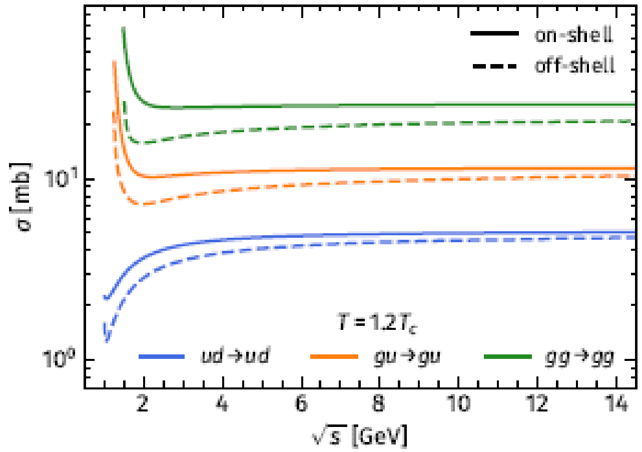


Plot by Ilia Grishmanovskii

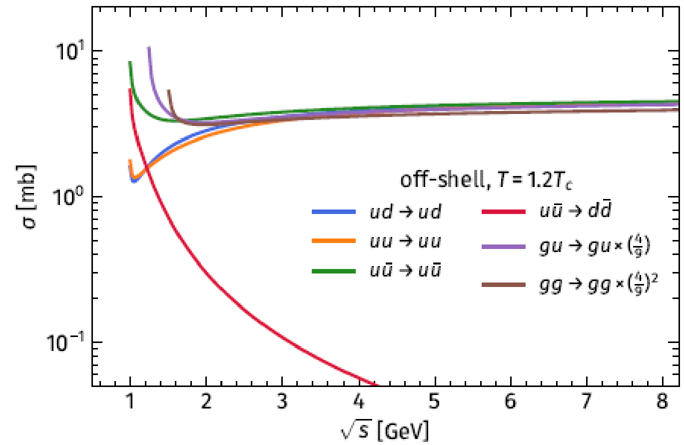
- ❑ **DQPM: M→0, γ→0 ➔ reproduces pQCD limits**
- ❑ **Differences between DQPM and pQCD : less forward peaked angular distribution leads to more efficient momentum transfer**

P. Moreau et al., PRC100 (2019) 014911

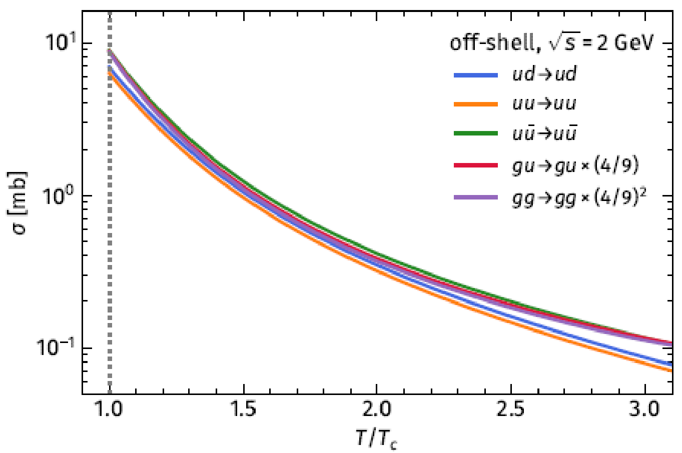
Total elastic cross sections



- ❑ **off-shell effects are stronger at low $s^{1/2}$**

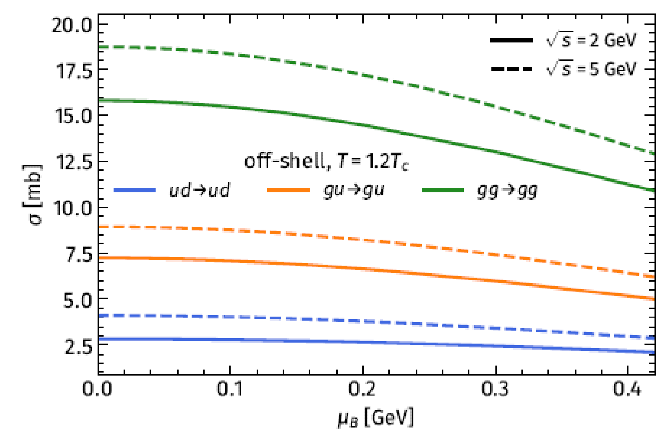


- ❑ **strong channel dependence at low $s^{1/2}$**



- ❑ **strong *T* dependence**
- ❑ **~ scaling with color ratio**

$$|\overline{\mathcal{M}}_{gg}|^2 \approx \frac{C_g}{C_q}|\overline{\mathcal{M}}_{gq}|^2 \approx \left(\frac{C_g}{C_q}\right)^2 |\overline{\mathcal{M}}_{qq}|^2$$



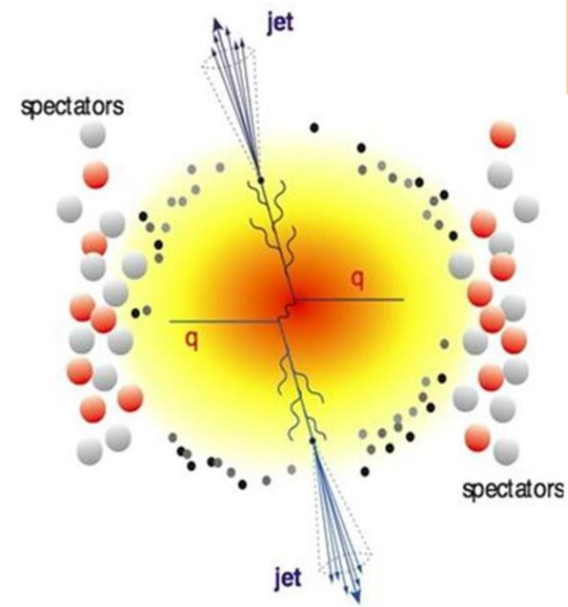
- ❑ **weak μ_B dependence**

I. Grishmanovskii et al., PRC 110, 014908 (2024), plots from PhD Thesis

Probing the properties of the sQGP with jet partons

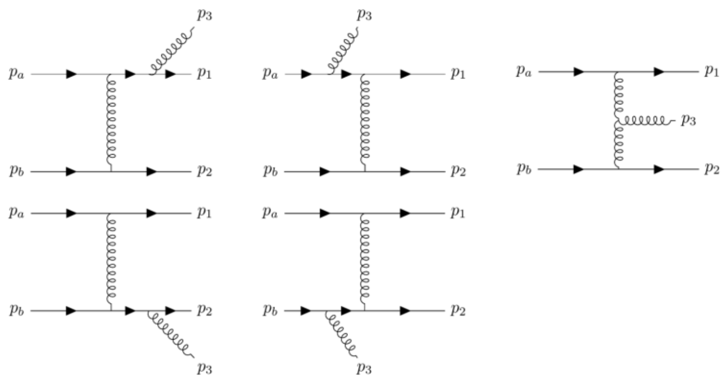
Extension of DQPM (T, μ_q)

elastic (2→2) + inelastic (2→3) scattering

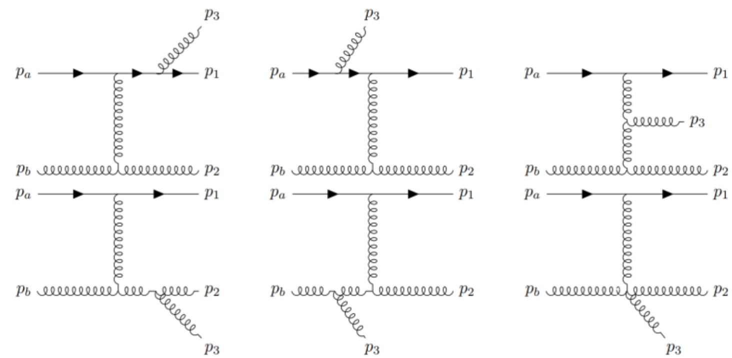


Partonic inelastic 2→3 interactions

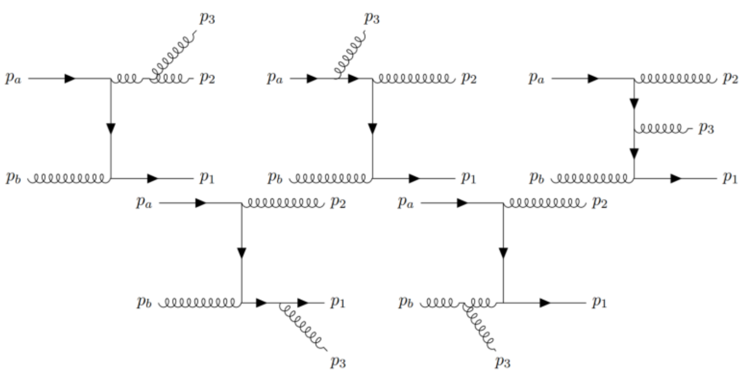
quark + quark



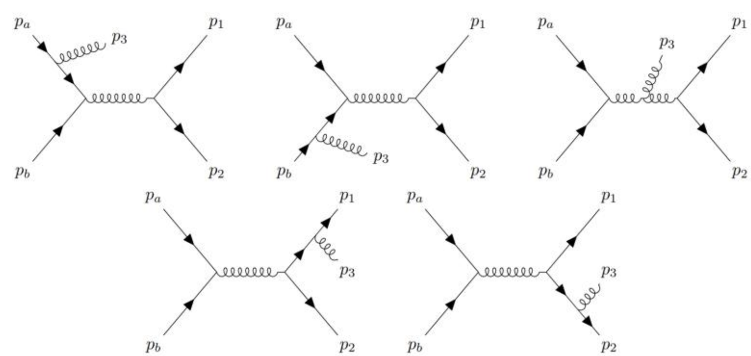
quark + gluon (t-channel)



quark + gluon (u-channel)



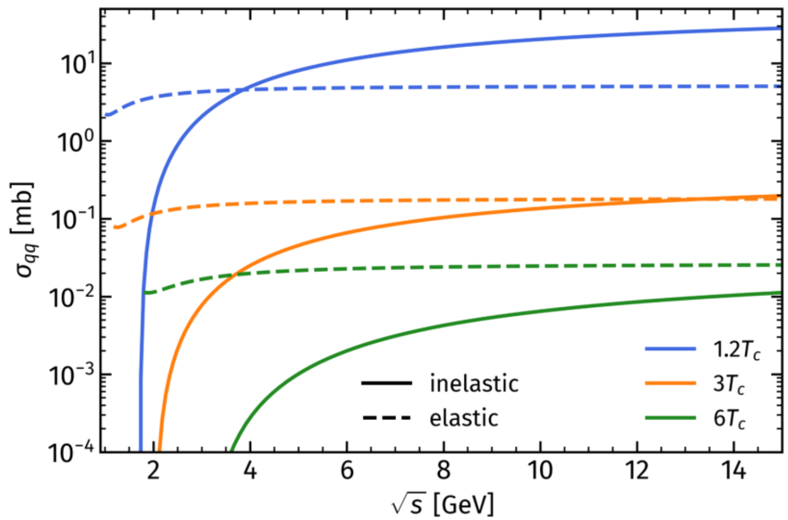
quark + gluon (s-channel)



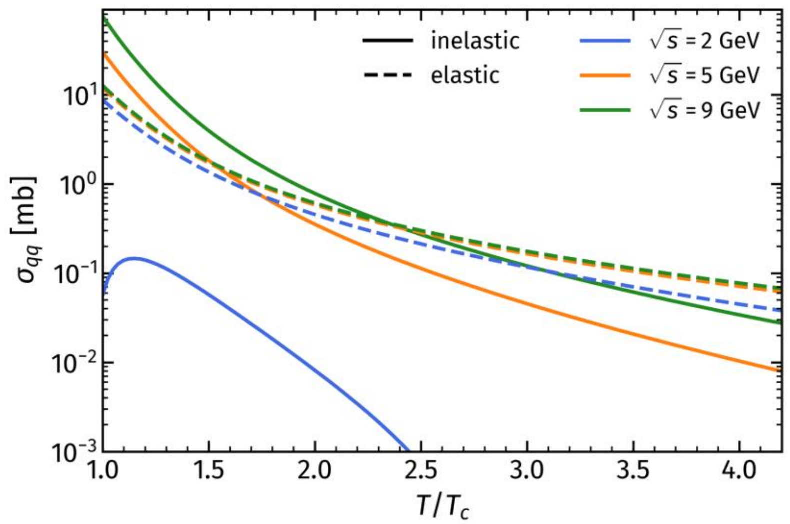
- **No approximations applied**
- **All interference terms included**
- **Emitted gluon is massive in DQPM**

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

Partonic cross sections: elastic vs. inelastic



$$|\overline{\mathcal{M}}_{2\to2}|^2 \propto \alpha_s^2$$



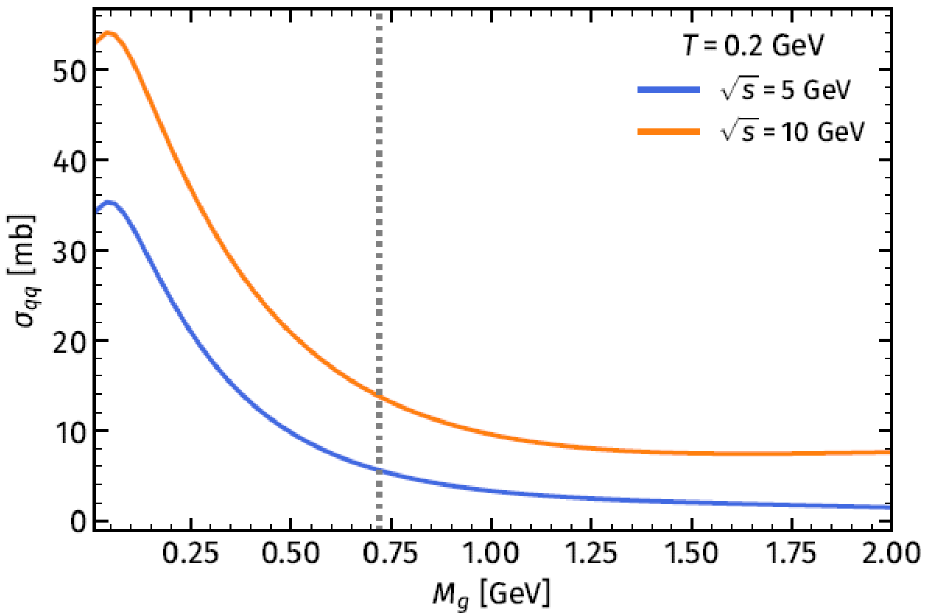
$$|\overline{\mathcal{M}}_{2\to3}|^2 \propto \alpha_s^3$$

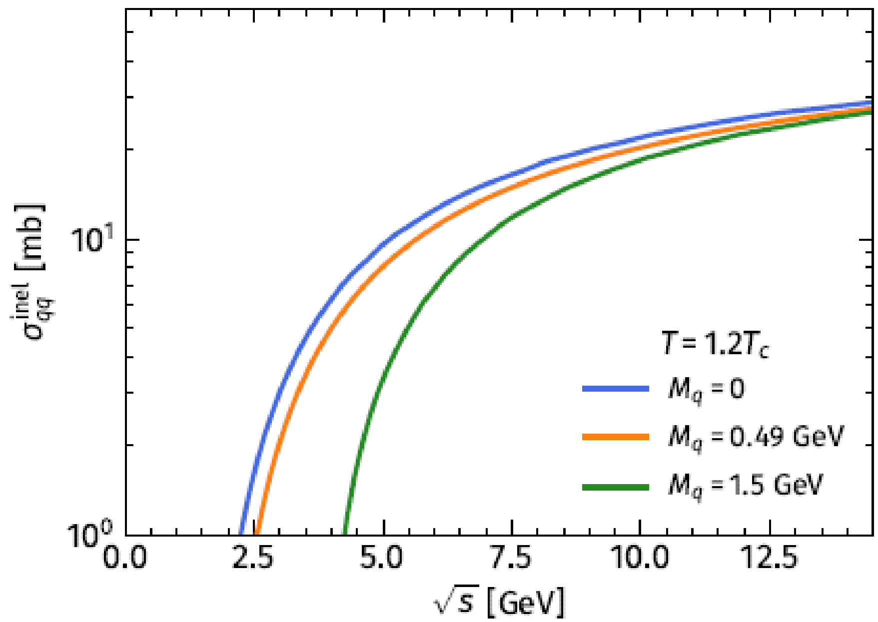
- ➔ **Elastic (2→2) cross sections dominate at low energies and high temperatures**
- ➔ **Inelastic (2→3) cross sections dominate at high energies and low temperatures**
- ➔ **Temperature dependence is stronger for the inelastic reactions and is mainly driven by the DQPM strong coupling**

*** In calculations - emitted gluon has a thermal pole mass $m_g^0(T)$**

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

Inelastic cross sections: emitted gluon m_g





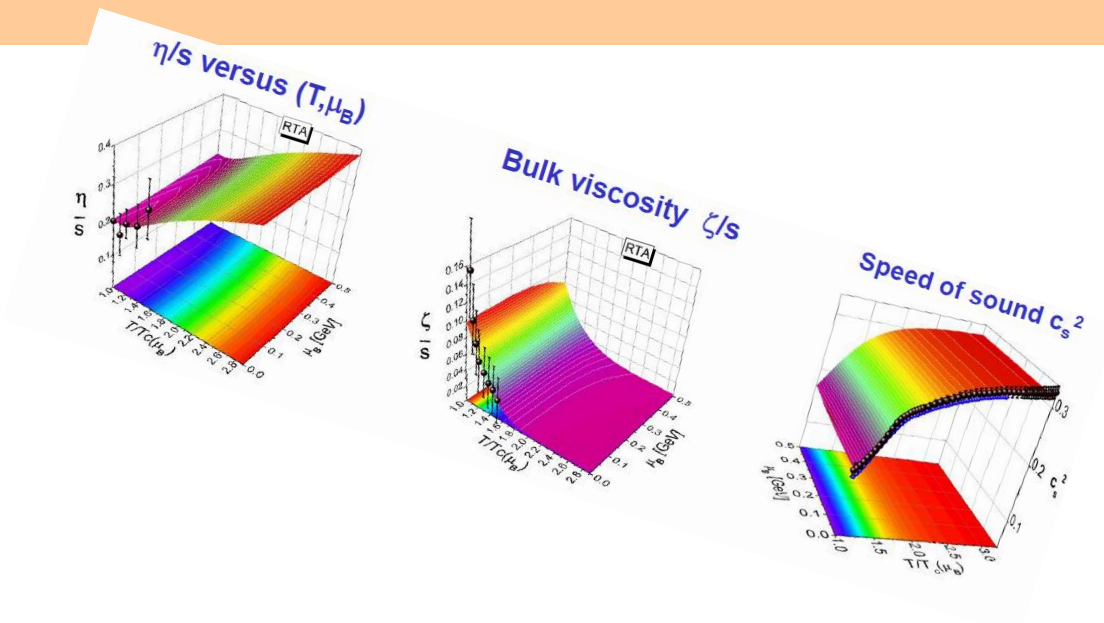
- **Strong dependence of inelastic total cross section on the mass of emitted gluon m_g**

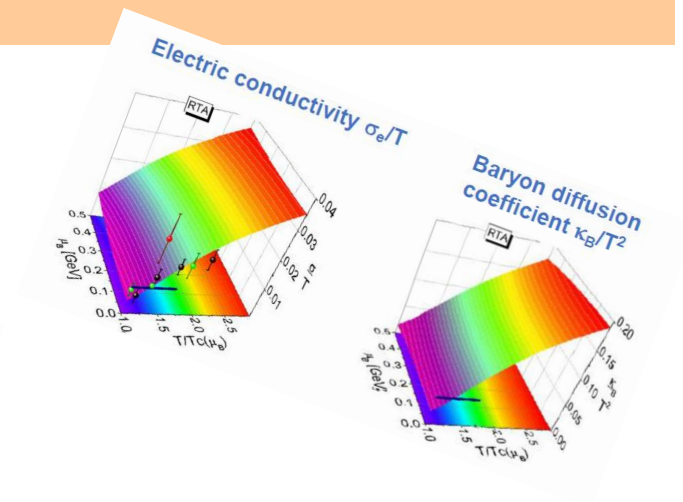
- **Shift of the threshold of inelastic σ_{qq} with increasing mass of colliding quarks M_q**

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

DQPM (T, μ_q) :

transport coefficients of sQGP at finite (T, μ_q) including elastic and inelastic scattering



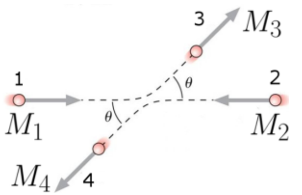


→ *cf. talk by Olga Soloveva on Thursday*

Jet transport coefficients

On-shell:

- **integration over momenta**
- **masses = pole masses**

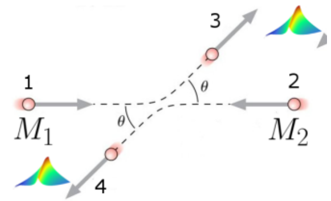


$$E^2 = m^2 + p^2$$

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

Off-shell:

- **integration over momenta**
- **+ two additional integrations over medium parton energies**



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

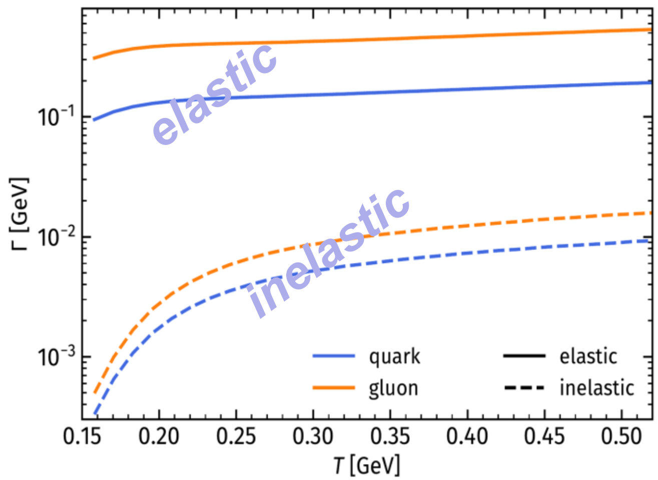
$$\begin{aligned}\langle \mathcal{O}\rangle^{\rm off} =& \frac{1}{2E_i}\sum_{j=q,\bar{q},g} d_j f_j \int \frac{d^4p_j}{(2\pi)^4}\rho(\omega_j,\mathbf{p}_j)\theta(\omega_j)\\ &\times \int \frac{d^3p_1}{(2\pi)^3 2E_1}\int \frac{d^4p_2}{(2\pi)^4}\rho(\omega_2,\mathbf{p}_2)\theta(\omega_2)\\ &\times (1\pm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

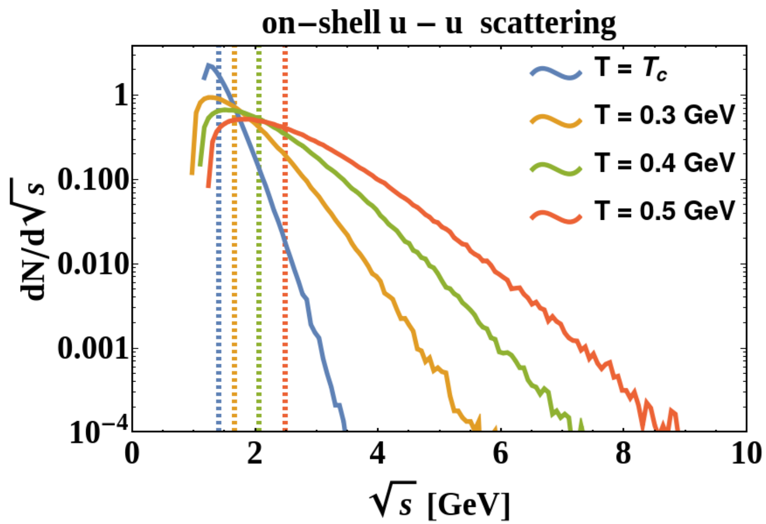
$$\langle \mathcal{O}\rangle_u = \sum_q \langle \mathcal{O}\rangle_{uq} + \sum_{\bar{q}}\langle \mathcal{O}\rangle_{u\bar{q}} + \langle \mathcal{O}\rangle_{ug} = \langle \mathcal{O}\rangle_{uu\to uu} + \langle \mathcal{O}\rangle_{ud\to ud} + \langle \mathcal{O}\rangle_{us\to us} + \langle \mathcal{O}\rangle_{u\bar{u}\to u\bar{u}} + \langle \mathcal{O}\rangle_{u\bar{d}\to u\bar{d}} + \langle \mathcal{O}\rangle_{u\bar{s}\to u\bar{s}} + \langle \mathcal{O}\rangle_{ug\to ug}$$

- ❑ **Scattering rate Γ :** $\mathcal{O} = 1$
- ❑ **Transverse momentum transfer squared per unit length $\hat{q}$:** $\mathcal{O} = |\vec{p_T} - \vec{p_T}'|^2 \rightarrow \langle O\rangle = \hat{q}$
- ❑ **Energy loss per unit length dE/dx:** $\mathcal{O} = (E - E') \rightarrow \langle O\rangle = dE/dx$
- ❑ **Drag coefficient A:** $\mathcal{O} = p_L - p_L'$

Partonic interaction rates in equilibrated sQGP

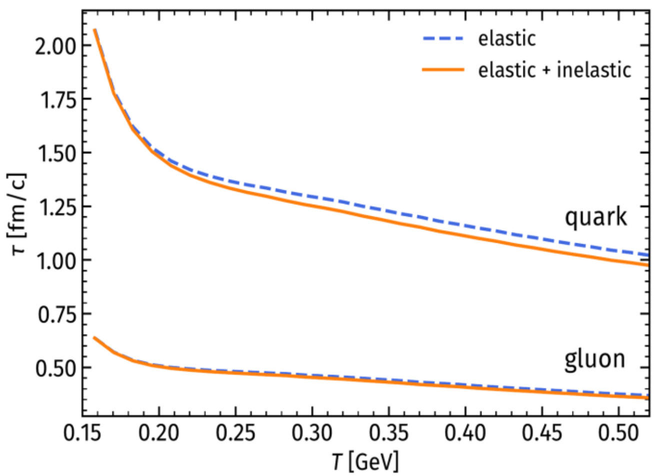
Interaction rate





In thermalized QGP low energies are favored where the elastic scatterings dominate

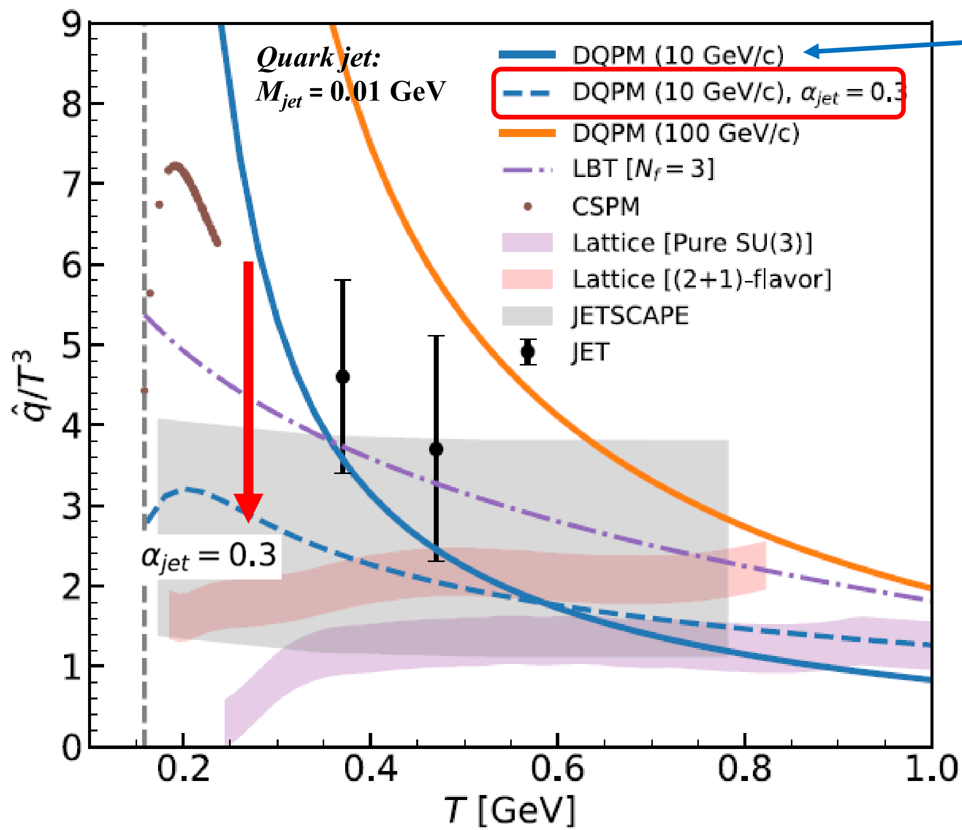
Relaxation time (τ ~ 1/Γ)

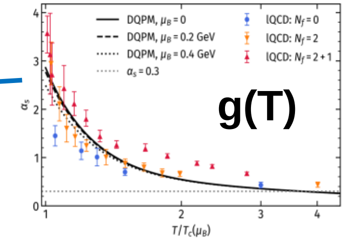


- ➔ **The partonic interaction rate and relaxation time are primarily governed by elastic scattering**
- ➔ **Inelastic processes – with massive gluon emission – are suppressed in the thermalized QCD medium**

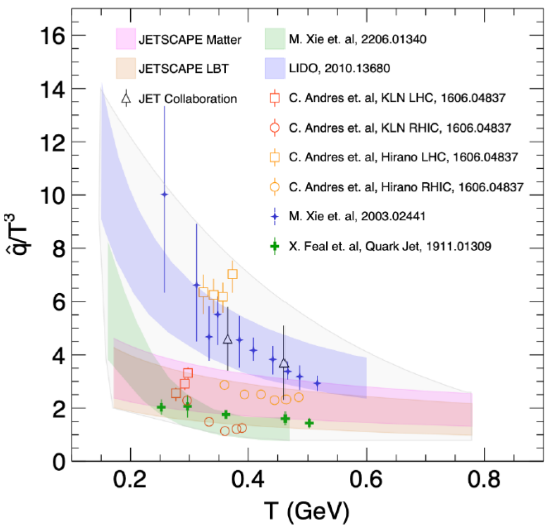
I. Grishmanovskii et al., PRC 109, 024911 (2024)

$\hat{q}$ from elastic scattering





LA, Lee, Winn, Prog.Part.Nucl.Phys. 127 (2022) 103990]

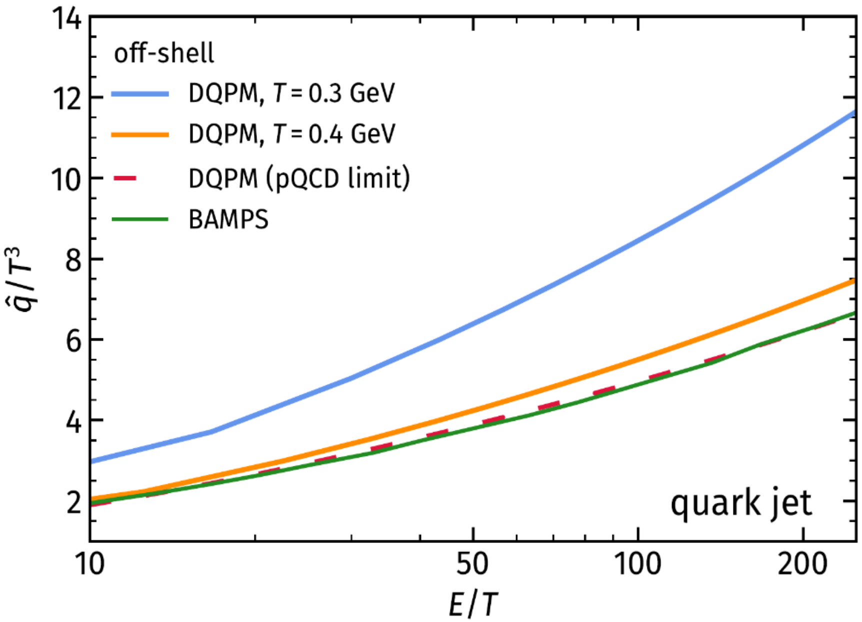


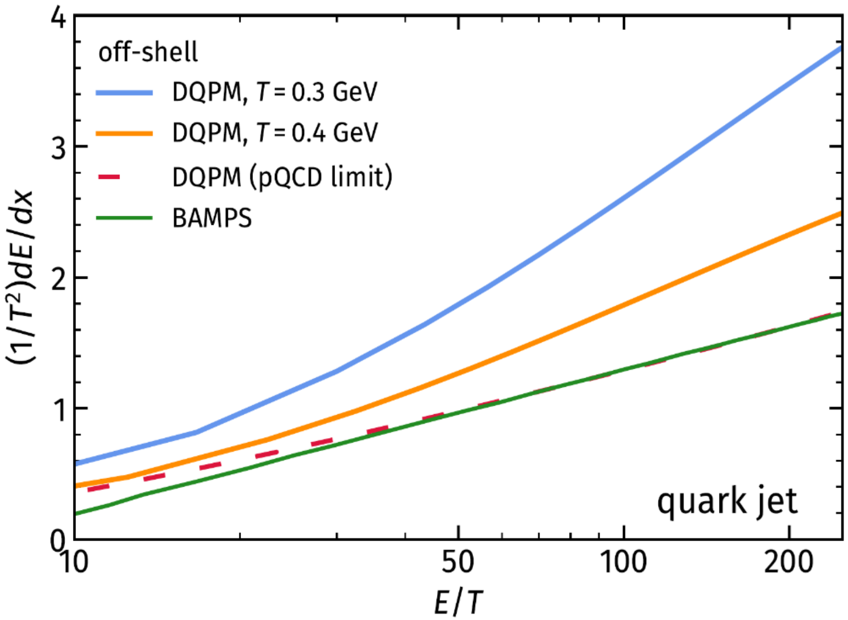
➔ **Agreement with the other models at low jet energy**

➔ **Rapid rise with decreasing medium temperature due to strong increase of g(T)**

I. Grishmanovskii et al., Phys. Rev. C 106, 014903 (2022)

$\hat{q}$ and dE/dx from elastic scattering vs jet energy





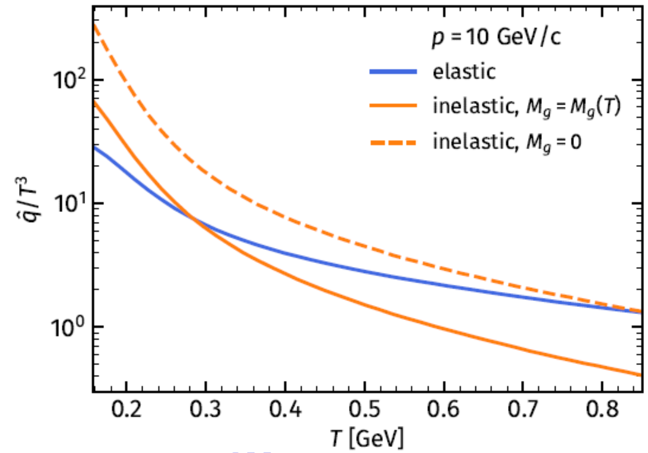
➔ **Logarithmic growth of q-hat and energy loss dE/dx with jet energy E**

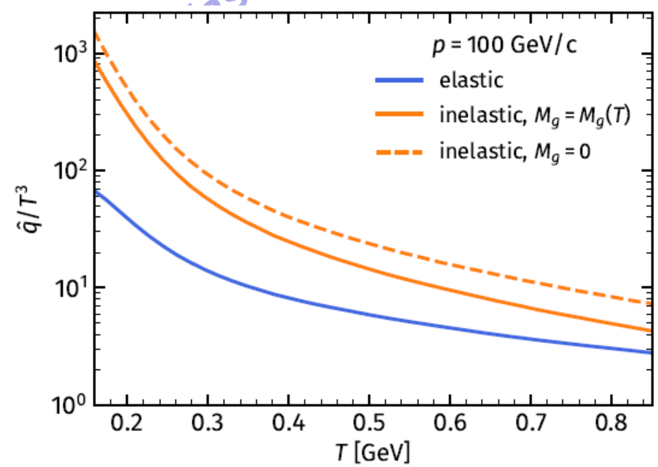
➔ **DQPM predicts stronger suppression than pQCD**

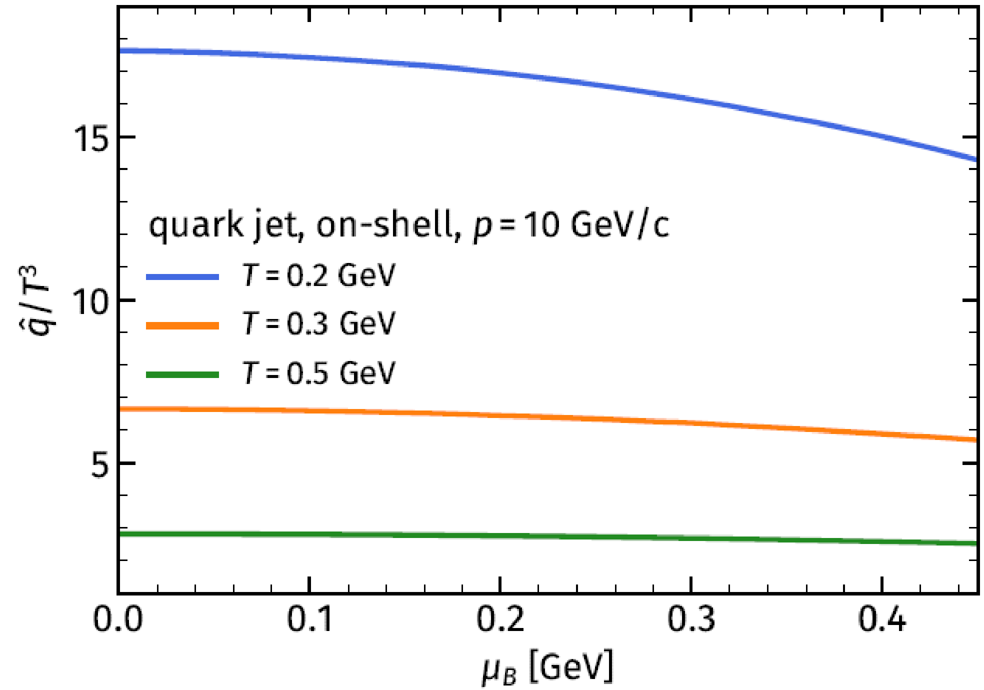
➔ **Aligning with pQCD-based calculations in the pQCD-limit ($m_{q,g}$=0, $\gamma_{q,g}$=0)**

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

$\hat{q}$ from elastic (2→2) vs. inelastic (2→3) scattering







→ **Weak dependence of $\hat{q}$ on μ_B**

→ **Temperature and momentum dependence is stronger for inelastic reactions**

→ **Stronger energy loss at large jet energies and small temperatures**

→ **Emission rate decreases with increasing gluon mass**

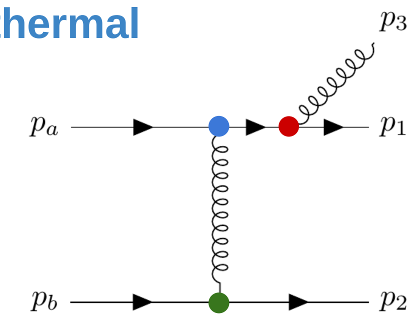
I. Grishmanovskii et al., PRC 110, 014908 (2024)

Different scenarios for strong couplings

- Jet is not a part of the QGP medium → strong coupling is not thermal

  → consider different strong couplings

  in *thermal* (●), *jet* (●), and *radiative* (●) vertices



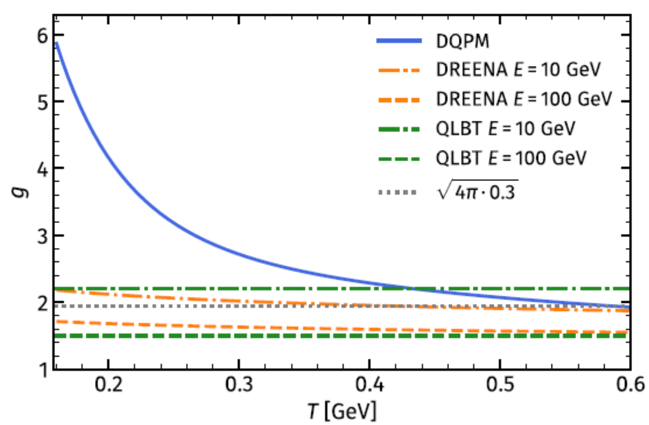
		Vertex		
	Model	● medium parton	● jet parton	● emitted gluon
	Scenario 0	$g^{\mathrm{DQPM}}(T)$		
	Scenario I	$g = \sqrt{4\pi \times 0.3}$		
Zakharov model	Scenario II	$g^{\mathrm{DQPM}}(T)$	$g(Q^2)$	$g(k_t^2)$
QLBT model	Scenario III	$g^{\mathrm{DQPM}}(T)$	$g(E)$	$g(E)$
DREENA framework	Scenario IV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

Scenario 0 → "default" DQPM (thermal coupling)

Scenario I → constant strong coupling

Scenarios II–IV:

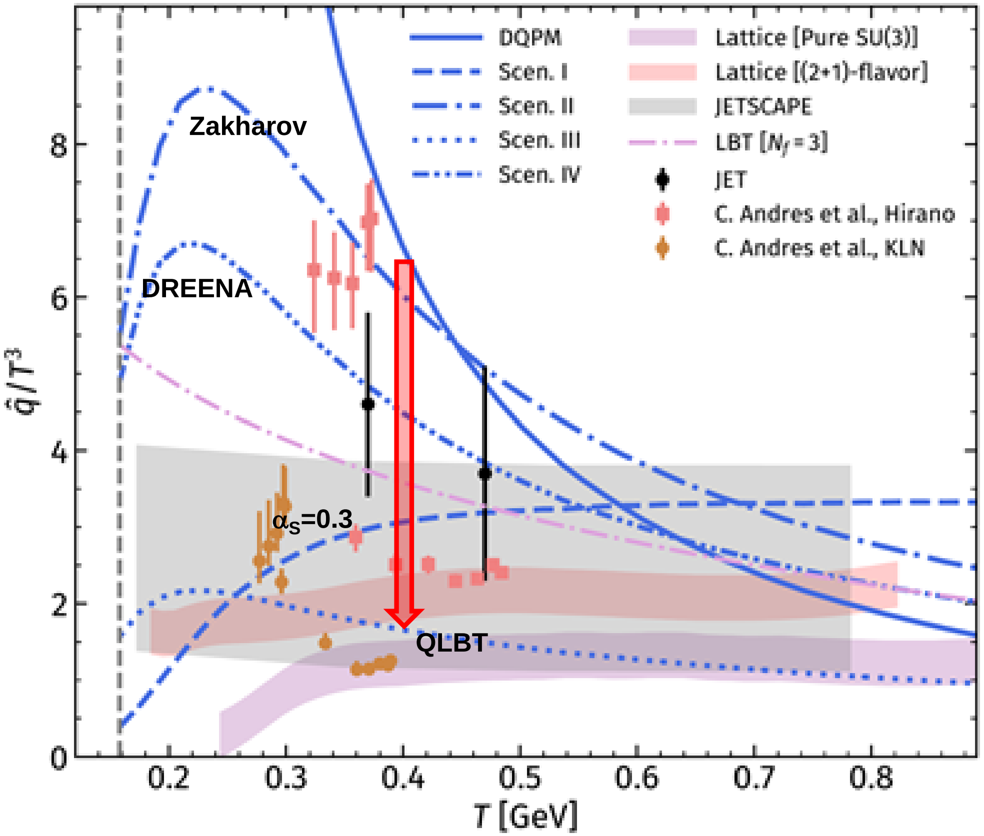
$$g^2(t) = \frac{48\pi^2}{(11N_c - 2N_f)} \frac{1}{\ln\left(\frac{t}{\Lambda^2}\right)}$$

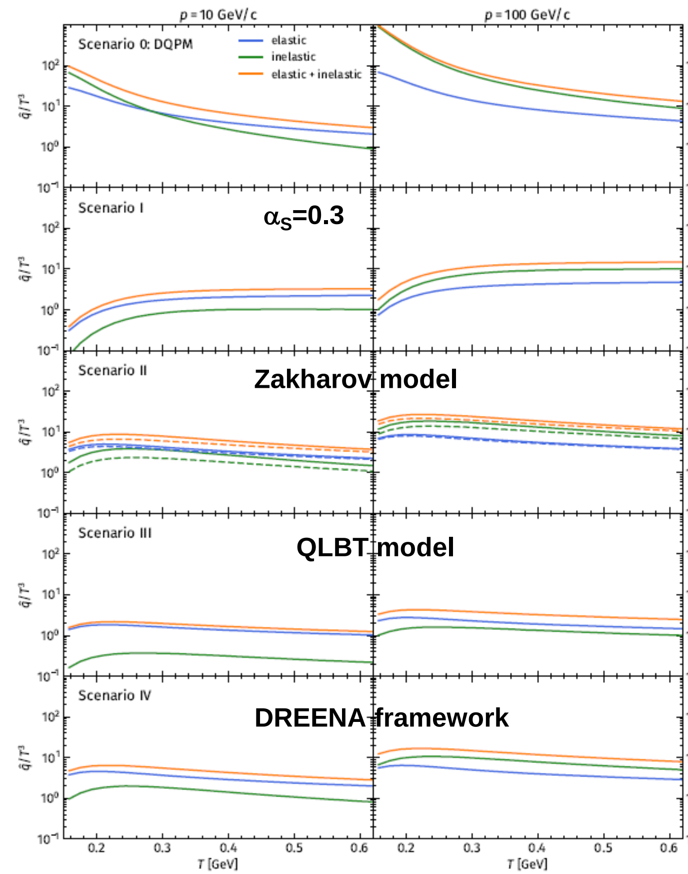


[II] B. G. Zakharov, JETP Lett. 112, 681 (2020).
[III] F.-L. Liu et al., Eur. Phys. J. C 82, 350 (2022).
[IV] D. Zigic et al, Front. Phys. 10, 957019 (2022).

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

$\hat{q}$ from elastic + inelastic scattering



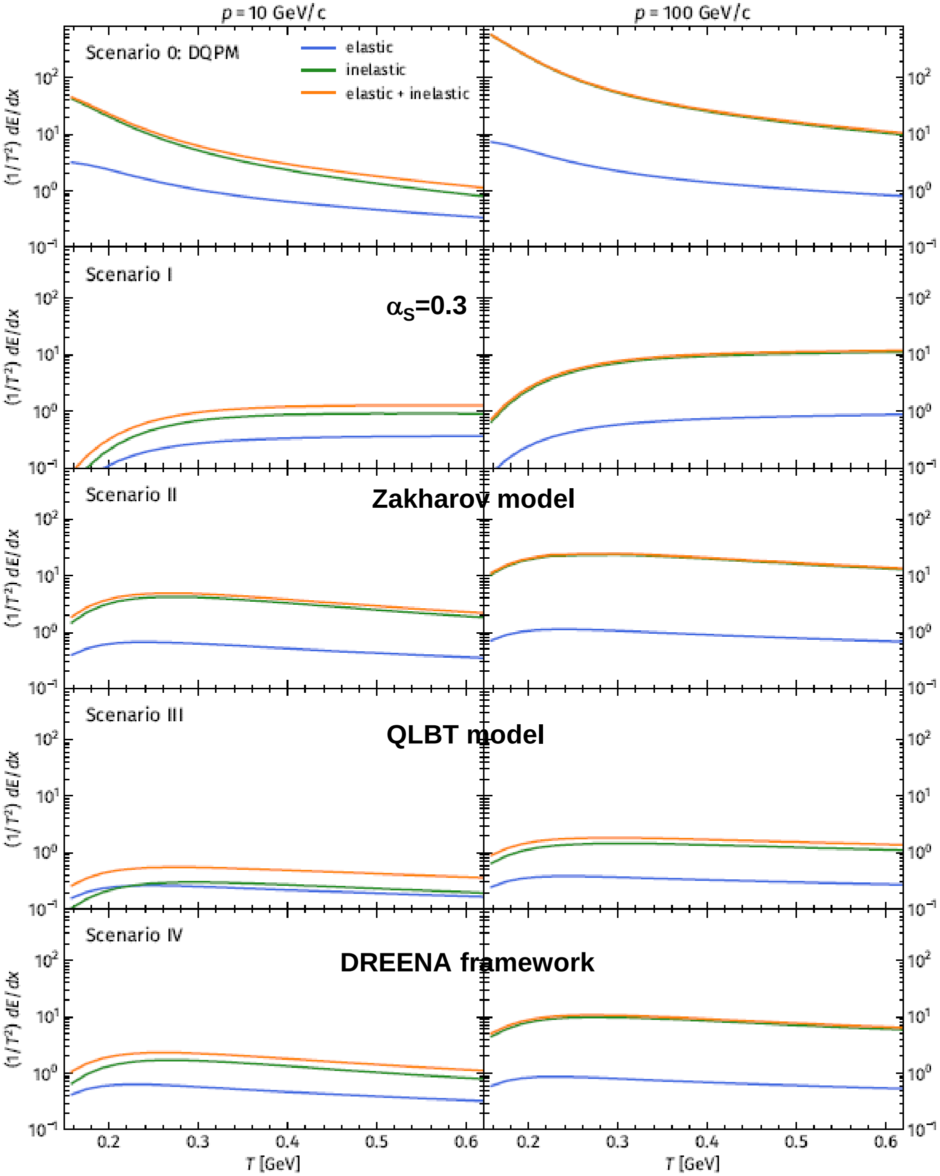


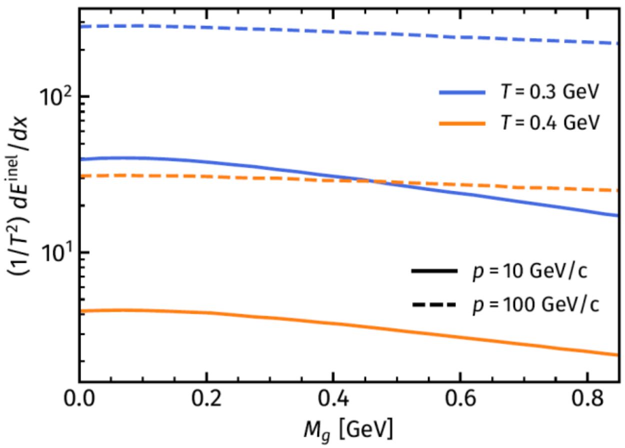
➔ **High sensitivity to the choice of the strong coupling ("scenario")**

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

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

dE/dx from elastic + inelastic scattering





➔ **High sensitivity to the choice of the strong coupling ("scenario")**

➔ **The "default" DQPM with the thermal couplings produces the highest energy loss**

➔ **Energy loss is decreasing with increasing m_g**

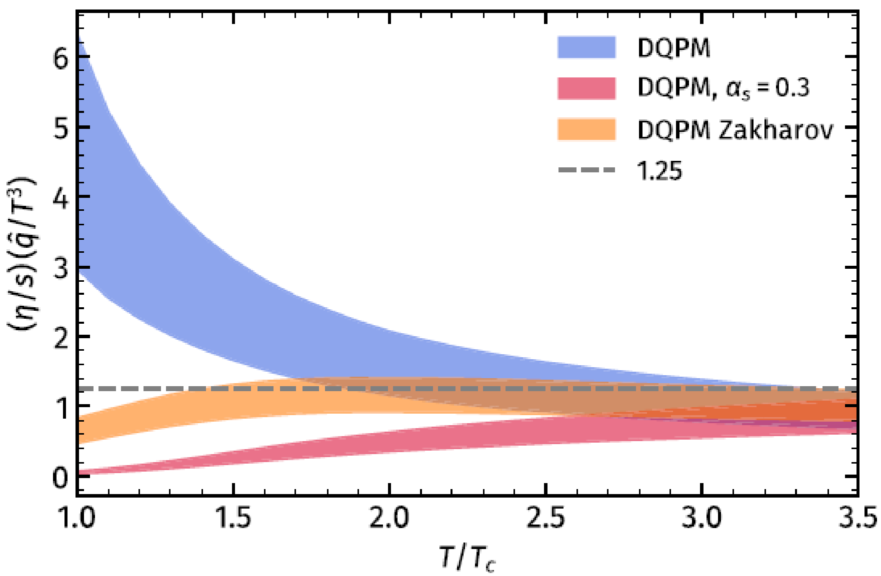
I. Grishmanovskii et al., PRC 110, 014908 (2024)

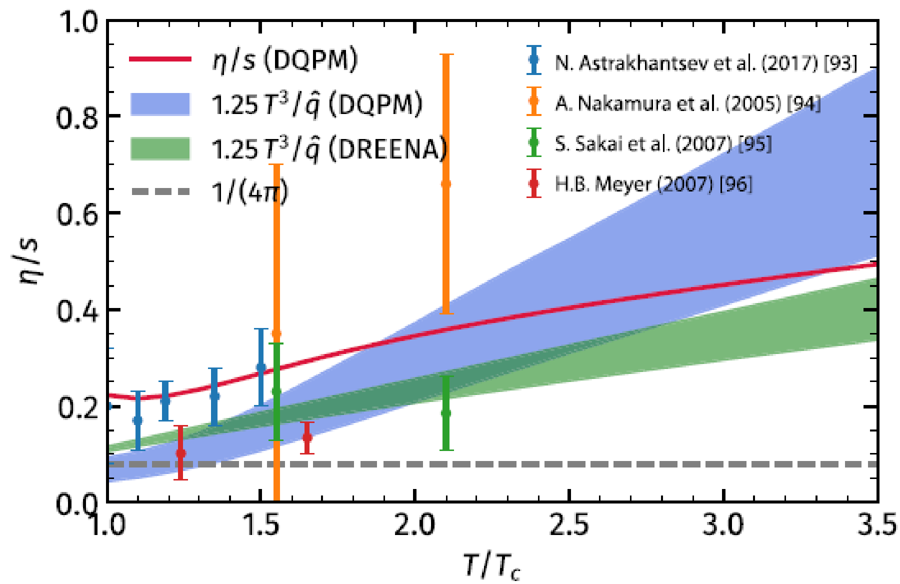
Relation between η/s and $\hat{q}$

In the weak coupling limit:

B. Müller, PRD 104, L071501 (2021)

$$\eta/s \approx 1.25 \frac{T^3}{\hat{q}}$$





- ➔ **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)**

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

Summary

- DQPM provides a **self-consistent approach** to study **partonic interactions** and **transport properties** of the sQGP
- **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
- **Jet transport coefficients** are highly **sensitive** to the choice of the **strong coupling**

Outlook:

- Study the full jet evolution within microscopic transport approach PHSD*
- Implement the LPM effect

→ *cf. talk by Olga Soloveva on Thursday*

Thank you for your attention!

Thanks to Organisers!