ICHEP 2024 PRAGUE

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42nd International Conference on High Energy Physics

18-24 July · 2024 · Prague · Czech Republic

TRANSPORT PROPERTIES OF THE STRONGLY INTERACTING QUARK-GLUON PLASMA

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Phys.Rev.C 109 (2024), 024911
Phys.Rev.C 110 (2024), 014908

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

CRC-TR 211 Strong-interaction matter under extreme conditions

GSI

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MOTIVATION

- QGP appears to be a strongly interacting system of partons → pQCD methods are not fully applicable for the QGP → one should rely on nonperturbative methods

- Effective QCD models focus on the most relevant degrees of freedom and interactions, making it possible to dynamically investigate
  - the evolution of the QGP,
  - jet attenuation in the QGP medium,
  - …

DYNAMICAL QUASIPARTICLE MODEL (DQPM)

DQPM INGREDIENTS

- DQPM – effective model for the description of nonperturbative QCD based on lQCD EoS
- The QGP phase is described in terms of strongly interacting off-shell quasiparticles – massive quarks and gluons – with Lorentzian spectral functions:

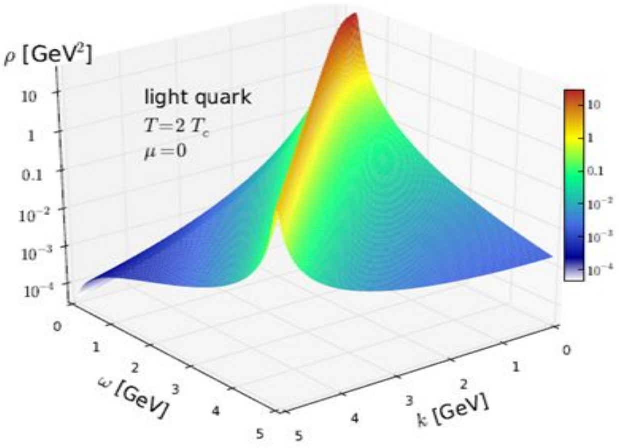
$$\rho_j(\omega, \mathbf{p}) = \frac{4\omega\gamma_j}{\left(\omega^2 - \mathbf{p}^2 - M_j^2\right)^2 + 4\gamma_j^2\omega^2}$$

- Theoretical basis: “resummed” single-particle Green’s functions $\longrightarrow$ quark (gluon) propagator (2PI) 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)

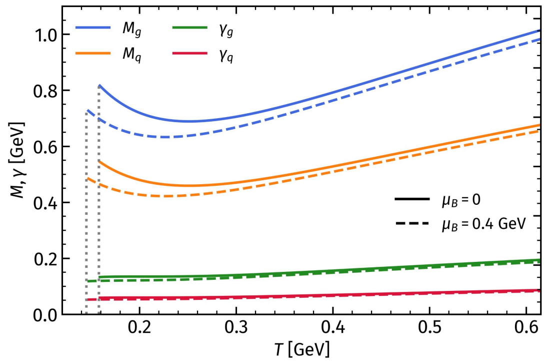
DQPM INGREDIENTS

- Masses and widths of quasiparticles depend on T and μ_B

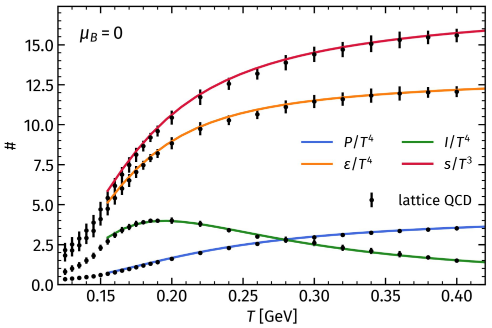
$$m_g^2(T,\mu_B) = C_g \frac{g^2(T,\mu_B)}{6} T^2 \left(1 + \frac{N_f}{2N_c} + \frac{1}{2}\frac{\sum_q \mu_q^2}{T^2\pi^2}\right)$$

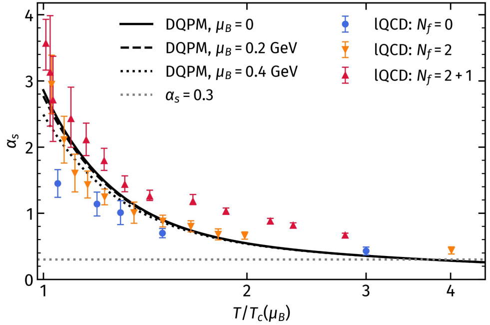
$$m_{q(\bar{q})}^2(T,\mu_B) = C_q \frac{g^2(T,\mu_B)}{4} T^2 \left(1 + \frac{\mu_q^2}{T^2\pi^2}\right)$$

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



- Input: entropy density vs T for μ_B=0 → fix DQPM parameters by comparison of the DQPM entropy density to lQCD at μ_B =0





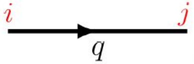
$$g^2(s/s_{SB}) = d((s/s_{SB})^e - 1)^f$$

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

PARTONIC INTERACTIONS

PARTONIC ELASTIC INTERACTIONS

- DQPM partonic interactions are described in terms of leading order diagrams
- DQPM reproduces the pQCD propagators for zero masses and widths of partons

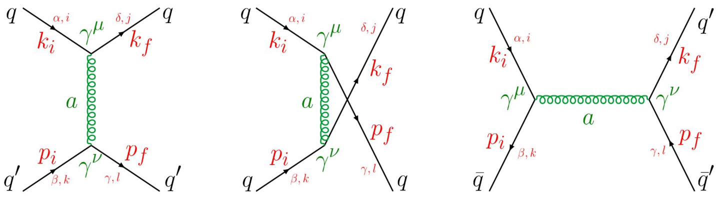
quark propagator: 

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

gluon propagator: 

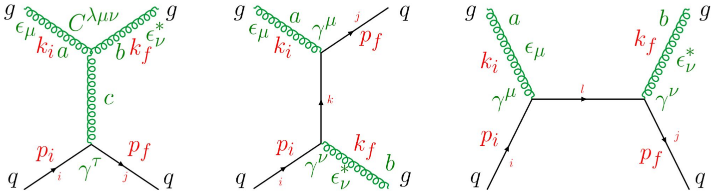
$$= -i\delta_{ab}\frac{g^{\mu\nu} - q^\mu q^\nu / M_g^2}{q^2 - M_g^2 + 2i\gamma_g q_0}$$

qq → qq scattering



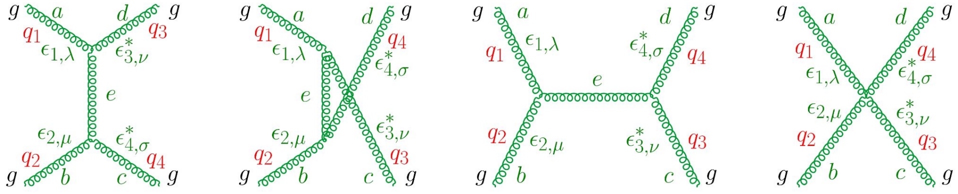
t − channel | u − channel | s − channel

qg → qg scattering



t − channel | u − channel | s − channel

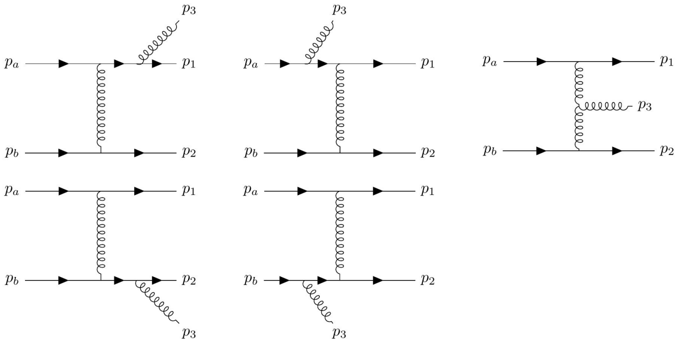
gg → gg scattering



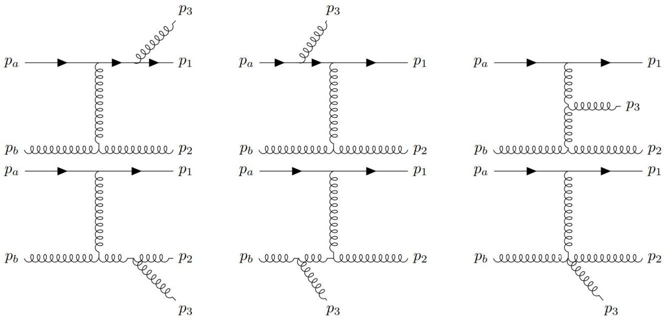
t − channel | u − channel | s − channel | 4 − point

PARTONIC INELASTIC INTERACTIONS

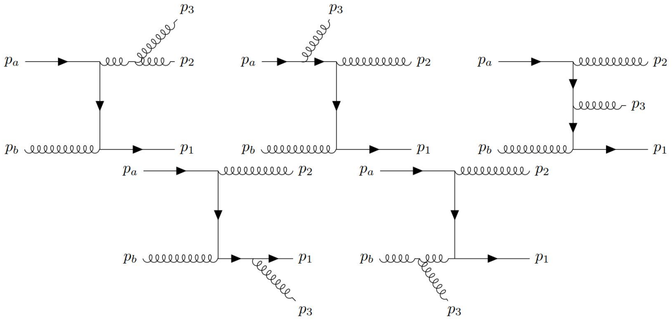
qq’ → qq’g



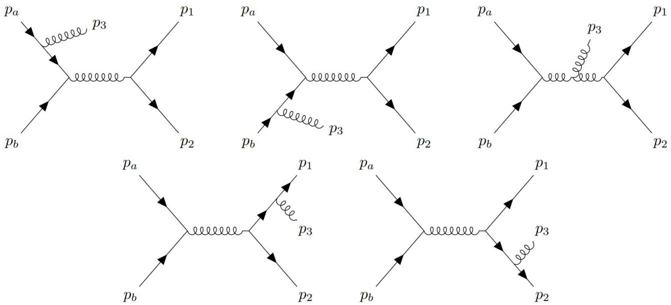
qg → qgg (t-channel)



qg → qgg (u-channel)

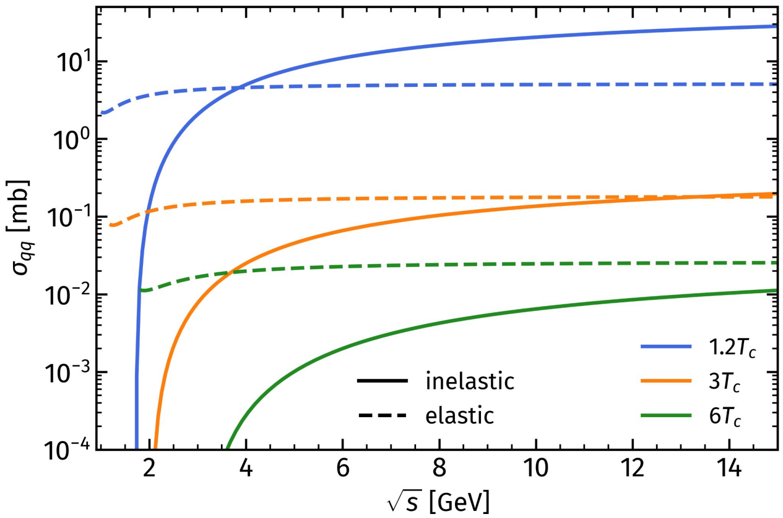


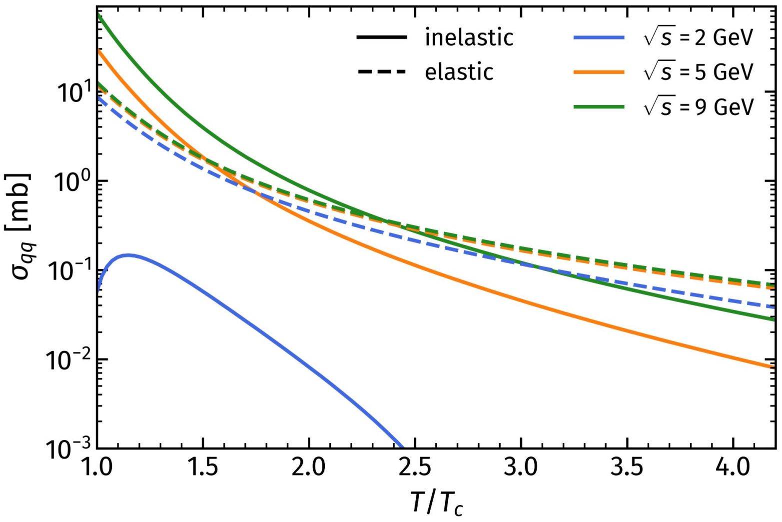
qg → qgg (s-channel)



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

PARTONIC CROSS SECTIONS: ELASTIC VS INELASTIC





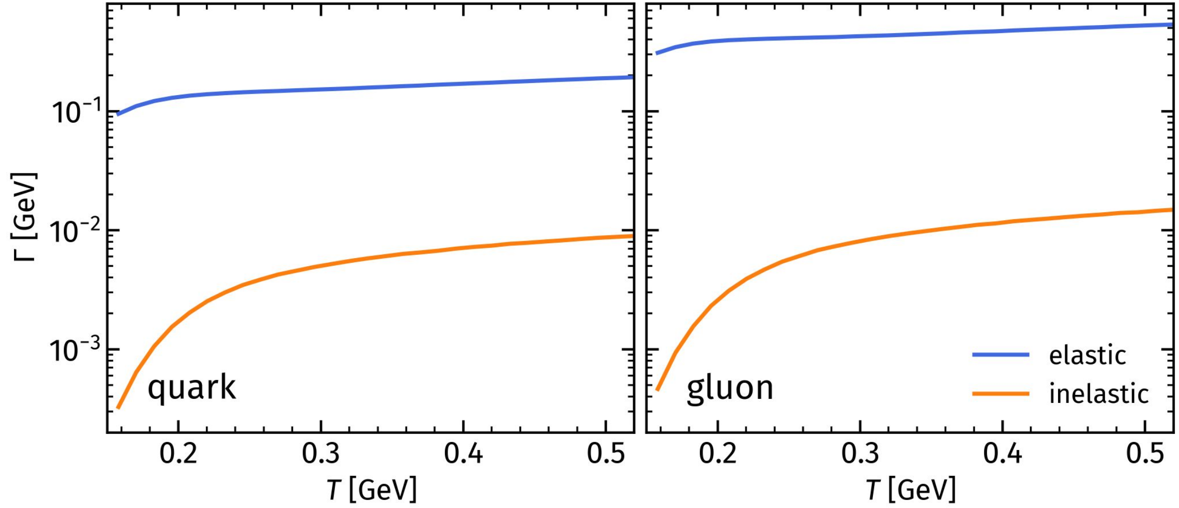
➔ Suppression of inelastic cross section for small energies

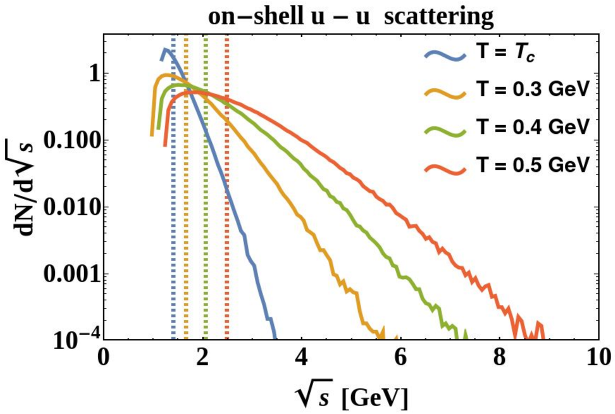
➔ Enhancement of inelastic cross section for small temperatures

➔ Temperature dependence is driven by the DQPM strong coupling

PARTONIC INTERACTION RATE

- Interaction rate describes the frequency at which partons interact with each other within QGP medium

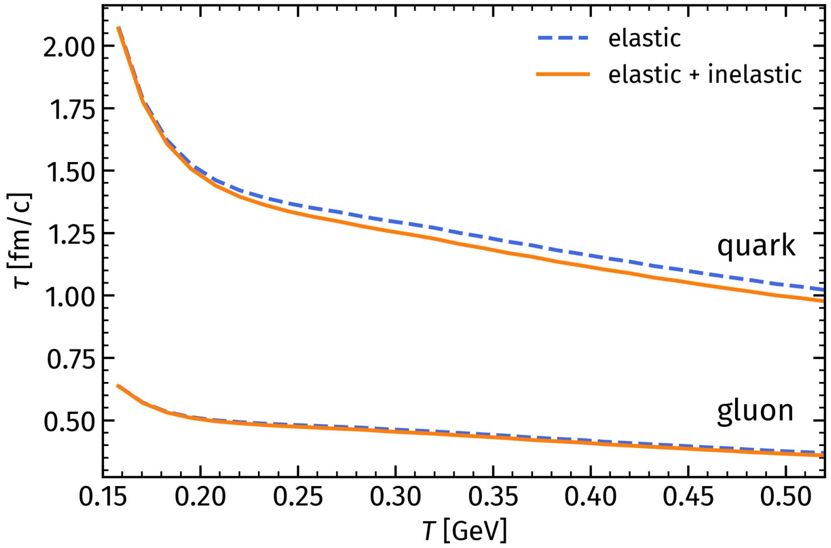




➔ Inelastic interaction rates of thermal light quarks and gluons are strongly suppressed at all temperatures due to the suppression of high-energetic collisions

RELAXATION TIME

- Relaxation time defines the time it takes for a system to return to equilibrium after a change or disturbance



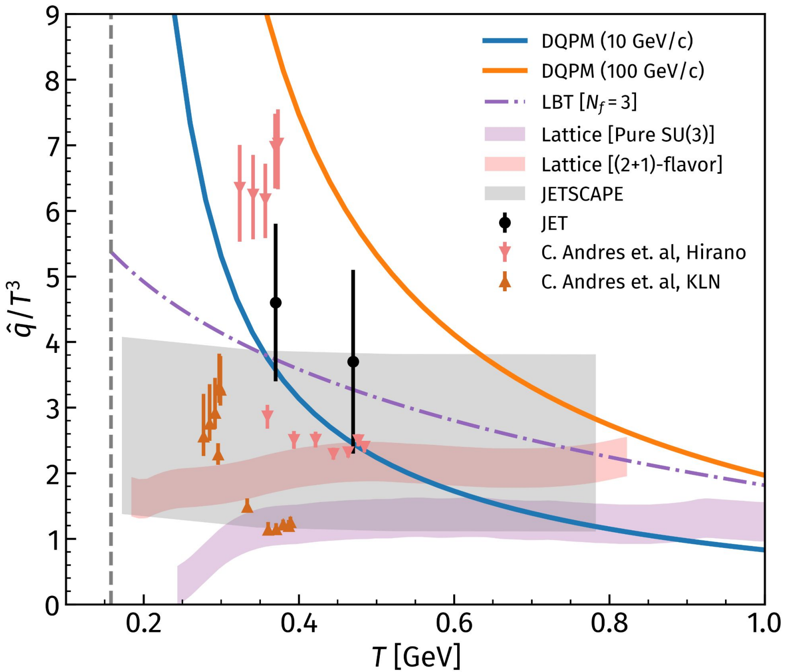
$$\tau\left(T,\mu_B\right) \propto \frac{1}{\Gamma(T,\mu_B)}$$

➔ Accounting for inelastic processes only slightly shortens the relaxation time of thermal sQGP

JET TRANSPORT COEFFICIENTS

Q-HAT FROM ELASTIC REACTIONS

- $\hat{q}$ defines the transverse momentum transfer squared per unit length: $\hat{q} = \langle q_\perp^2/\lambda \rangle$
- Can be calculated by using kinetic theory



DQPM: I.Grishmanovskii at al., Phys.Rev.C 109 (2024), 024911

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

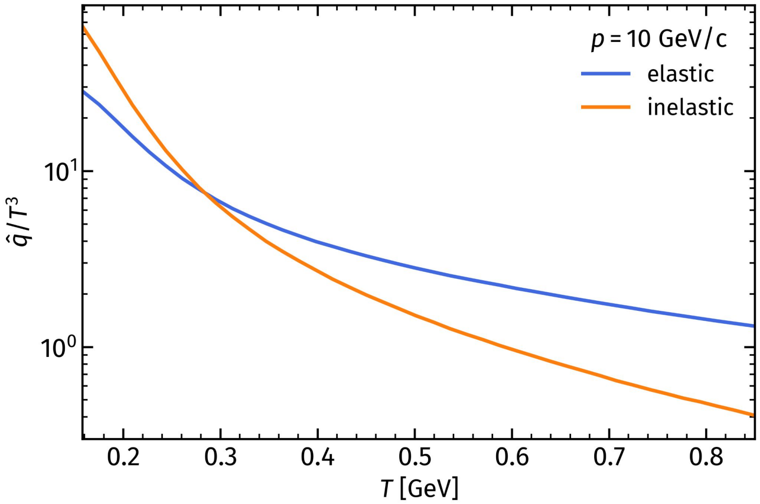
lQCD: A. Kumar et al., PRD.106.034505

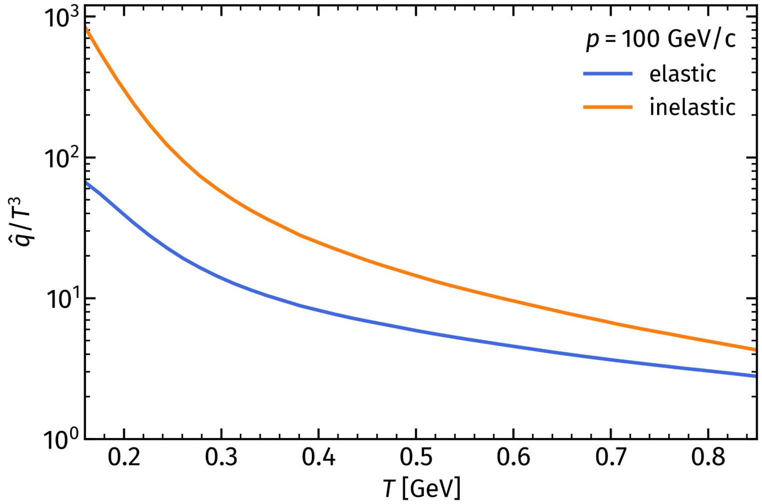
LBT: Y. He et al., *PRC 91 (2015)*

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

BDMPS: C.Andres *et al., Eur.Phys.J.C 76 (2016) 9, 475*

Q-HAT FROM ELASTIC AND INELASTIC REACTIONS





➔ Inelastic q-hat is suppressed for low jet momentum, but is significant for high momentum

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	$g^{\text{DQPM}}(T)$		
Scenario I	$g = \sqrt{4\pi \times 0.3}$		
Scenario II	$g^{\text{DQPM}}(T)$	$g(Q^2)$	$g(k_t^2)$
Scenario III	$g^{\text{DQPM}}(T)$	$g(E)$	$g(E)$
Scenario IV	$g^{\text{DQPM}}(T)$	$g(ET)$	$g(Q^2)$

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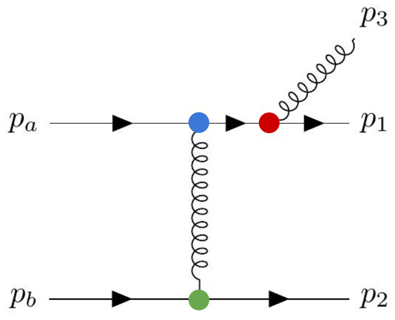
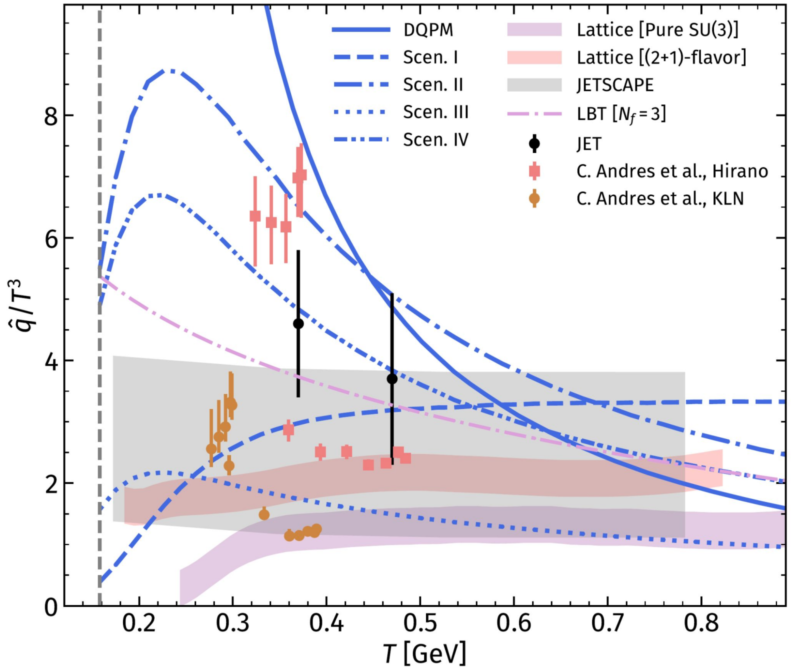


$$g^2(E) = \frac{48\pi^2}{(11N_c - 2N_f)\ln[(AE/T_c + B)^2]}$$

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

Q-HAT FOR DIFFERENT "SCENARIOS"



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- ➔ High sensitivity to the choice of the strong couplings
- ➔ The "default" DQPM with the thermal couplings produces the highest values of the transport coefficients

OUTLOOK

In this study we employed the Dynamical QuasiParticle Model – which describes the QGP medium in terms of strongly interacting massive off-shell quarks and gluons, whose properties are fitted to reproduce the lattice QCD thermodynamics at zero baryon chemical potential – to explore the properties of the sQGP, in particular:

- Partonic cross sections
- Partonic interaction rates
- Relaxation time
- Jet transport coefficients (q-hat)

Perspectives:

- Implement inelastic 2→3 cross sections into full transport simulation (PHSD)
- Study the full jet evolution within transport simulations
- Implement the LPM effect