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Attenuation of jet partons and heavy quarks in strongly interacting QGP

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&

Ilya Grishmanovskii, Taesoo Song,

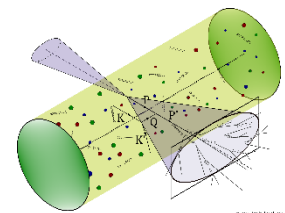
Olga Soloveva, Carsten Greiner



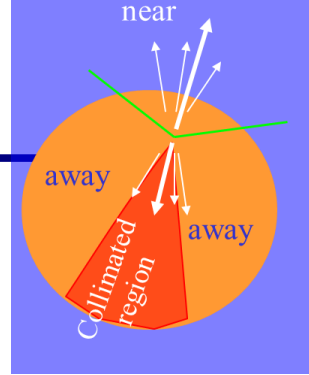
Workshop “High energy probes of the initial stages“

March 31, 2025 to April 4, 2025

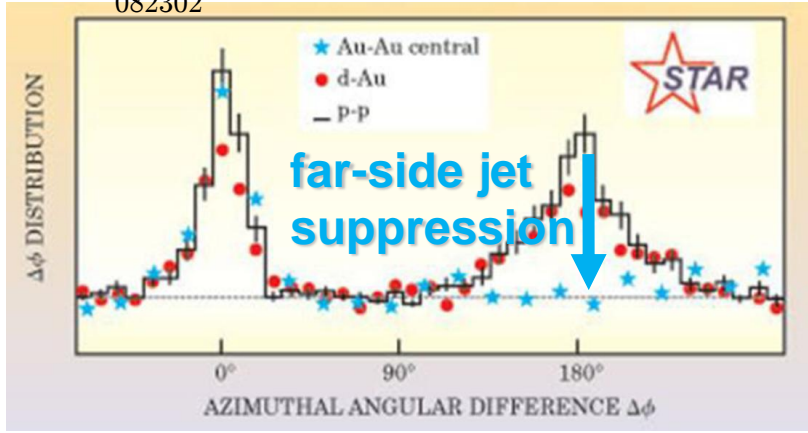
CERN



Jet suppression



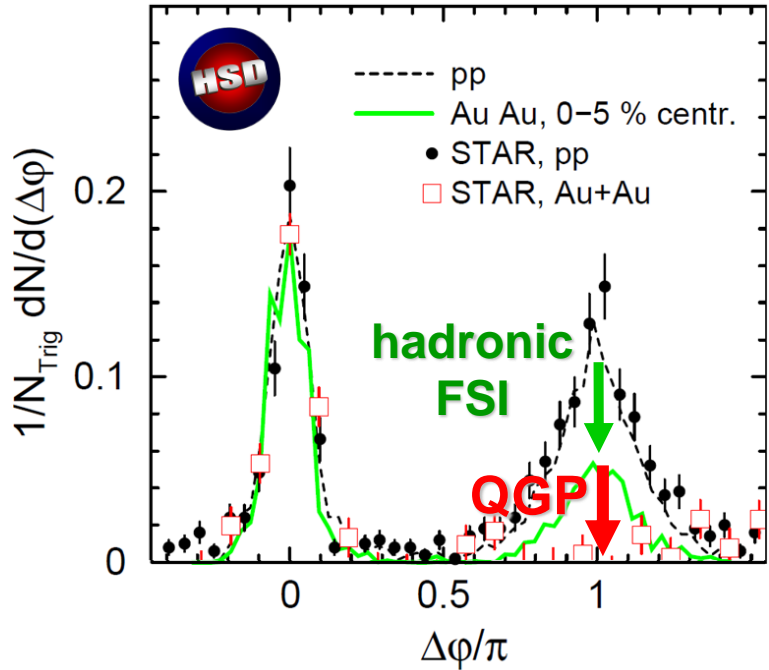
C. Adler et al. [STAR], Phys. Rev. Lett. 90 (2003) 082302



STAR (2003):
Discovery of **“Jet Quenching”**:
strong suppression of far-side jet in A+A vs p+p and d+A

HSD (Hadron-String Dynamics)
microscopic transport approach (2004):

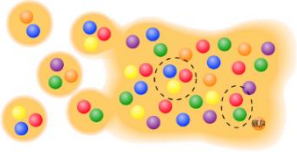
W. Cassing, K. Gallmeister, C. Greiner,
J.Phys.G30 (2004) S801; NPA 748 (2005) 41



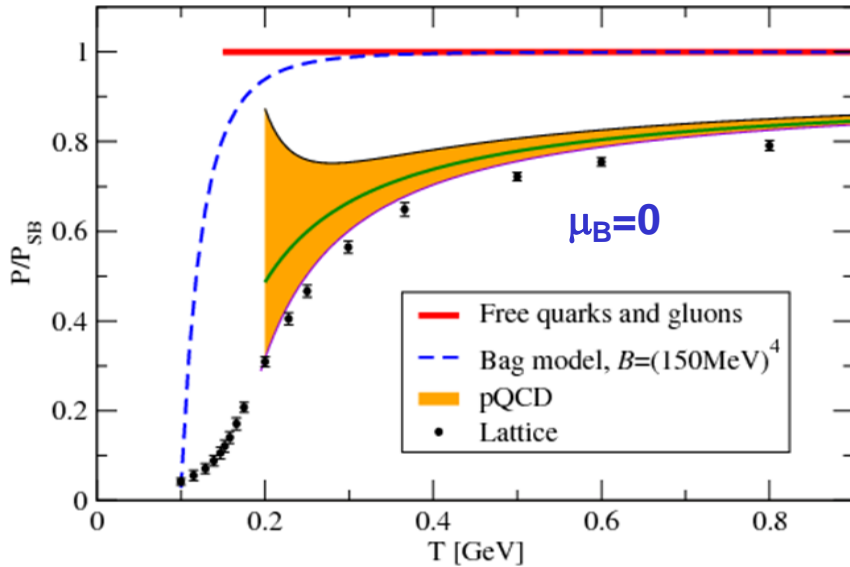
- good description of jet quenching in p+p, d+A and near-side jet angular correlation for central Au+Au
 - strong underestimation of suppression of the far-side jet due to hadronic interaction
- ➔ indication for **strong jet suppression in QGP**

➔ **Modeling of interaction of jet partons with sQGP**

Degrees-of-freedom of QGP



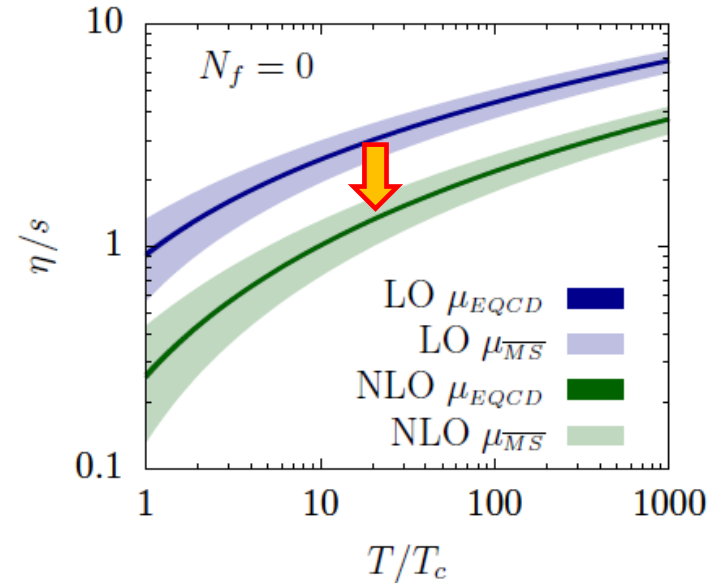
IQCD: QGP EoS at finite μ_B



Non-perturbative QCD ← pQCD

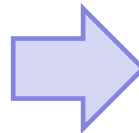
pQCD: (Yang-Mills) shear viscosity η

J. Ghiglieri, G.D. Moore, D. Teaney, JHEP 1803 (2018) 179



pQCD:

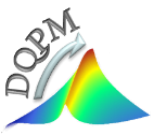
- weakly interacting system
- massless quarks and gluons



Thermal (non-perturbative) QCD:

- strongly interacting system
- massive quarks and gluons

→ Quasiparticles = effective degrees-of-freedom



Dynamical QuasiParticle Model (DQPM)

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

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

Theoretical basis :

□ ,resummed‘ single-particle Green‘s functions → quark (gluon) propagator (2PI) :

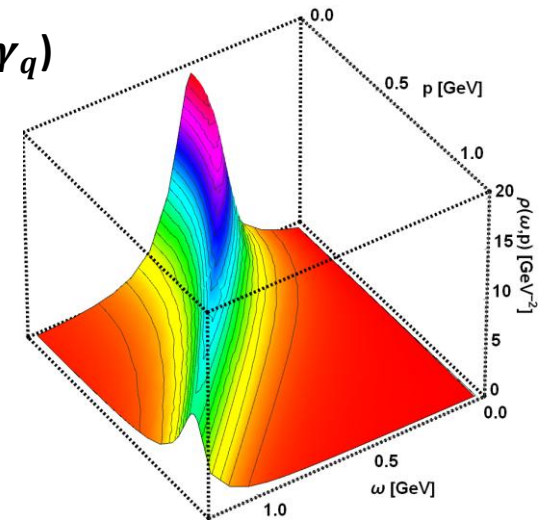
$$\begin{aligned}
 &\text{gluon propagator: } \Delta^{-1} = P^2 - \Pi \quad \& \quad \text{quark propagator } S_q^{-1} = P^2 - \Sigma_q \\
 &\text{gluon self-energy: } \Pi = M_g^2 - i2\gamma_g\omega \quad \& \quad \text{quark self-energy: } \Sigma_q = M_q^2 - i2\gamma_q\omega
 \end{aligned}$$

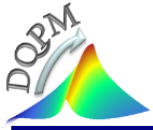
Properties of the quasiparticles are specified by scalar **complex self-energies:**

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

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

$$\begin{aligned}
 \rho_j(\omega, \mathbf{p}) &= \frac{\gamma_j}{\tilde{E}_j} \left(\frac{1}{(\omega - \tilde{E}_j)^2 + \gamma_j^2} - \frac{1}{(\omega + \tilde{E}_j)^2 + \gamma_j^2} \right) \\
 &\equiv \frac{4\omega\gamma_j}{(\omega^2 - \mathbf{p}^2 - M_j^2)^2 + 4\gamma_j^2\omega^2} \quad \tilde{E}_j^2(\mathbf{p}) = \mathbf{p}^2 + M_j^2 - \gamma_j^2
 \end{aligned}$$





DQPM: parton properties

Realization concept:

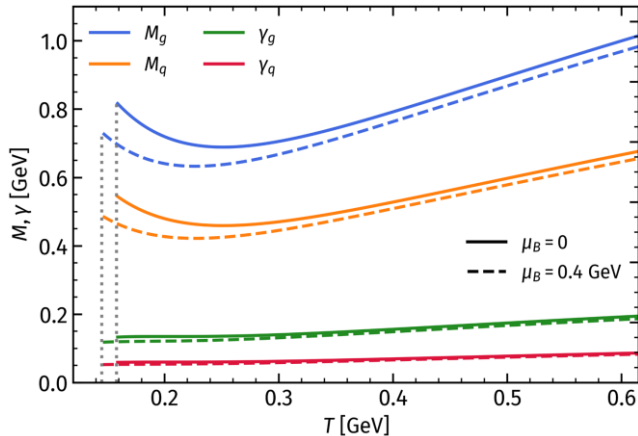
- introduce an **ansatz** (HTL; with few parameters) for the (T, μ_B) dependence of masses/widths
- evaluate the **QGP thermodynamics** in equilibrium using the Kadanoff-Baym theory
- fix DQPM parameters by comparison of the DQPM entropy density to **IQCD** at $\mu_B=0$

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

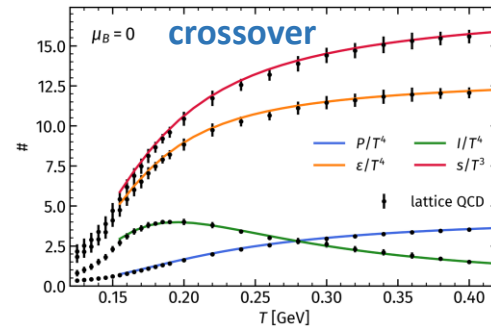
$$m_g^2(T, \mu_B) = C_g \frac{g^2(T, \mu_B)}{6} T^2 \left(1 + \frac{N_f}{2N_c} + \frac{1}{2} \frac{\sum_q \mu_q^2}{T^2 \pi^2} \right)$$

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

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

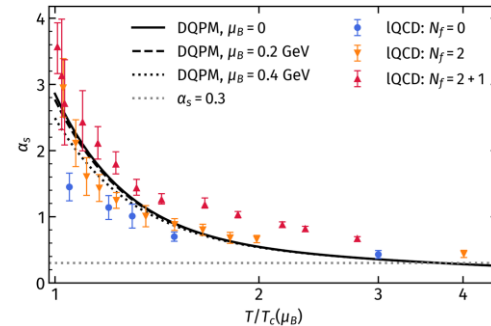


- Strong coupling (g)** is defined from **IQCD entropy density** at $\mu_B=0$, using $\frac{\partial}{\partial T} \left(\frac{S_{DQPM}}{T^3} \right) = 0$



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

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



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

→ 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 \rightarrow **leading order diagrams**

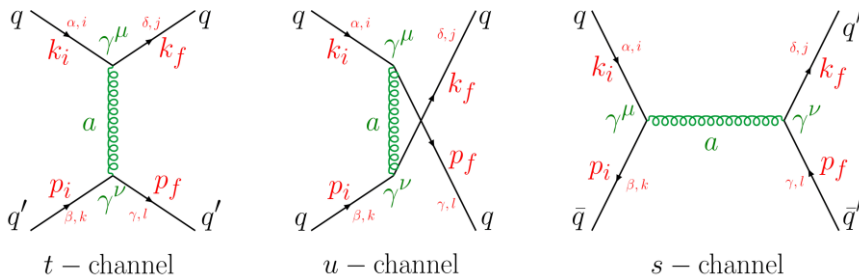
Propagators for massive bosons and fermions:

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

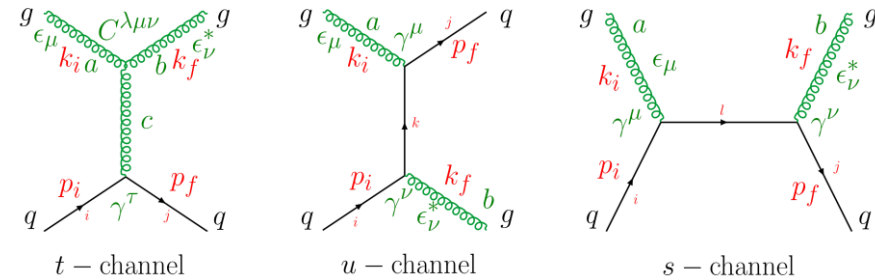
(Quasi-) elastic channels:

$$\begin{array}{c} i \\ \longrightarrow \\ q \end{array} \begin{array}{c} j \\ \longrightarrow \\ q \end{array} = i\delta_{ij} \frac{q + M_q}{q^2 - M_q^2 + 2i\gamma_q q_0}$$

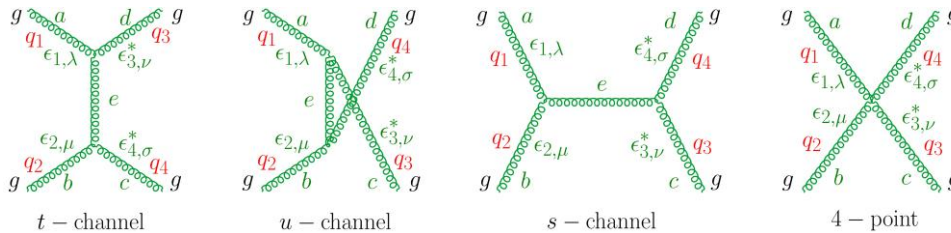
qq' \rightarrow qq' scattering



gq \rightarrow gq scattering



gg \rightarrow gg scattering



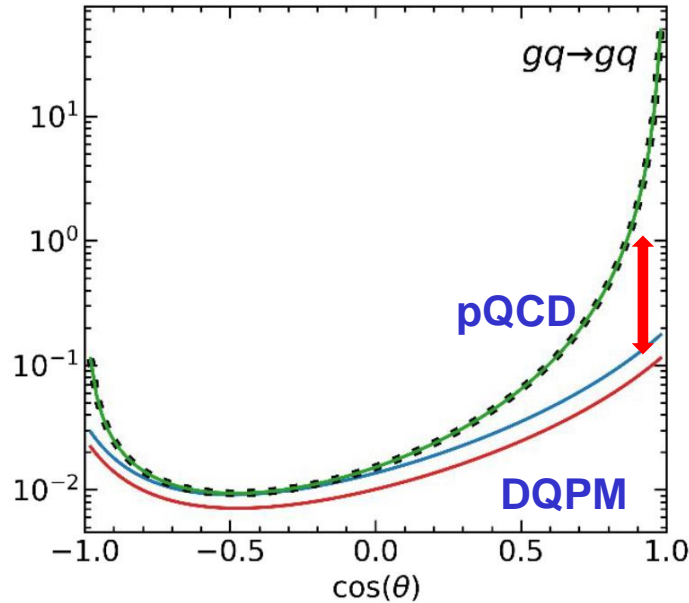
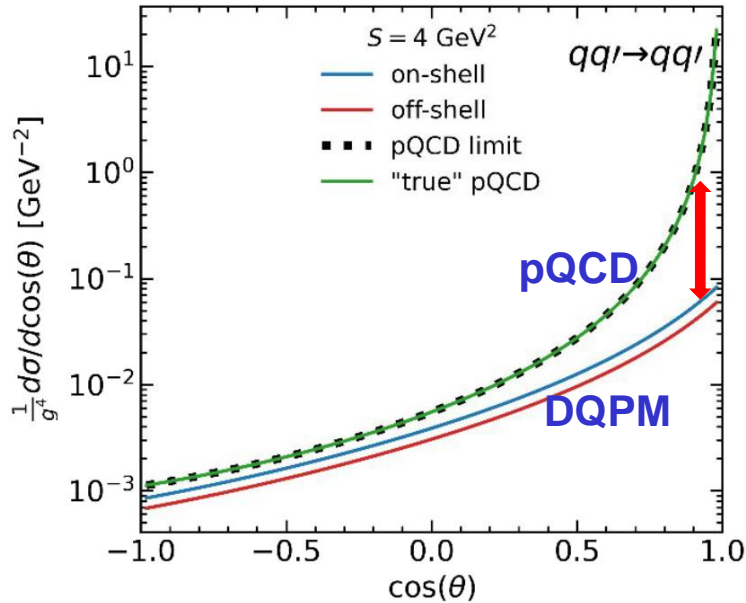
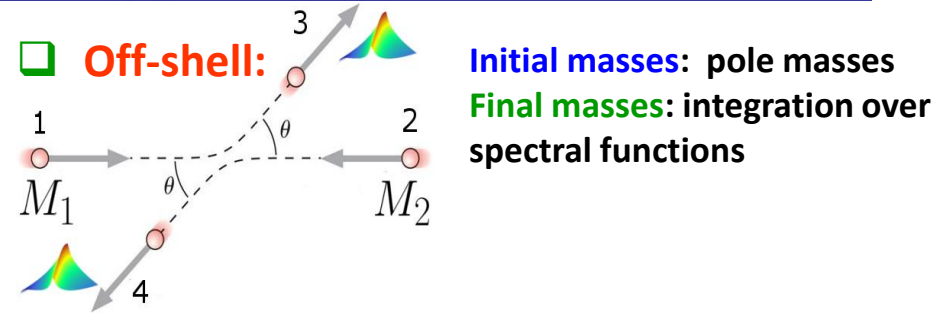
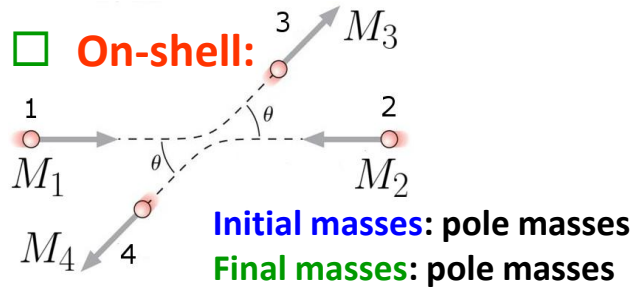
Inelastic channels:

$$q + \bar{q} \rightarrow g$$

$$g \rightarrow q + \bar{q}$$

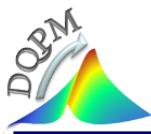


Differential cross sections

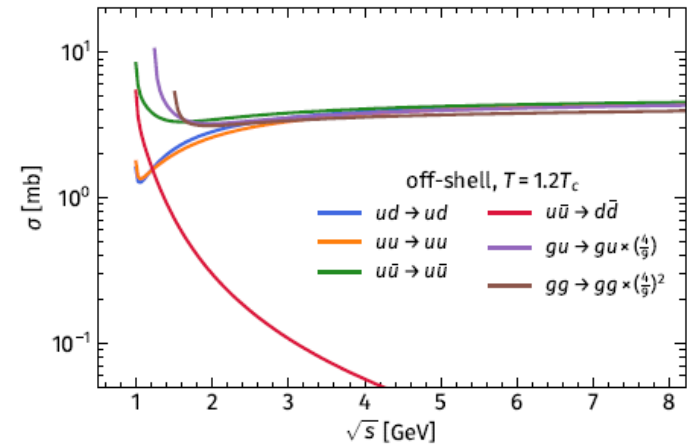
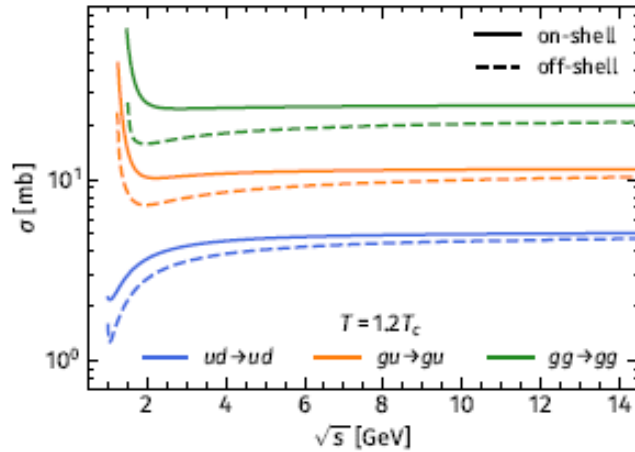


Plot by Ilia Grishmanovskii

- DQPM: $M \rightarrow 0, \gamma \rightarrow 0 \rightarrow$ reproduces pQCD limits
- Differences between DQPM and pQCD : less forward peaked angular distribution leads to more efficient momentum transfer

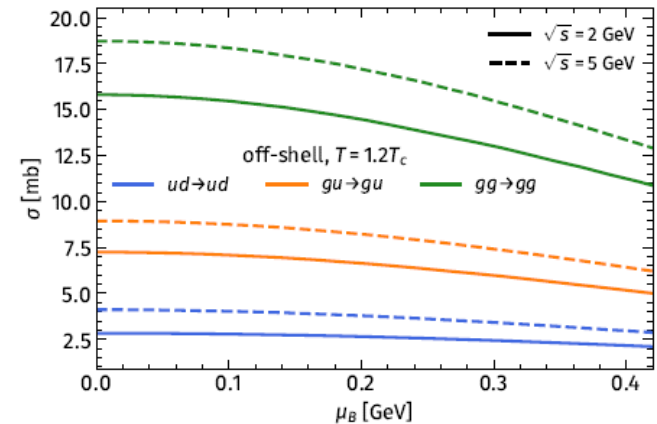
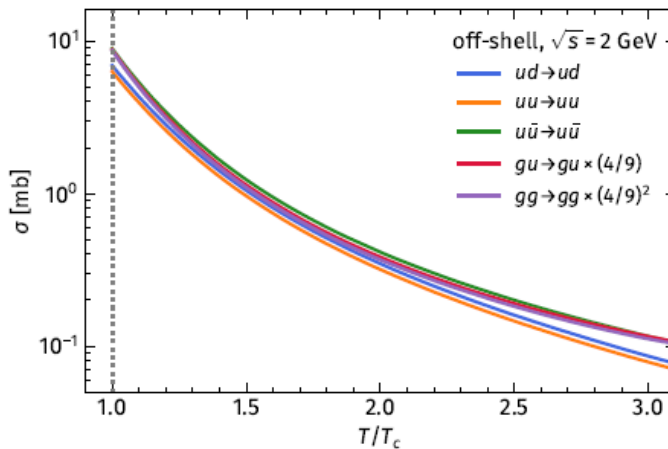


Total elastic cross sections



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

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



strong T dependence
 \sim scaling with color ratio

weak μ_B dependence

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

DQPM: Mean-field potential for quasiparticles

Space-like part of energy-momentum tensor $T_{\mu\nu}$ defines the **potential energy density**:

$$V_p(T, \mu_q) = T_{g-}^{00}(T, \mu_q) + T_{q-}^{00}(T, \mu_q) + T_{\bar{q}-}^{00}(T, \mu_q)$$

space-like gluons + space-like quarks+antiquarks

$$\tilde{T}_{r_g^\pm} \dots = d_g \int \frac{d\omega}{2\pi} \frac{d^3p}{(2\pi)^3} 2\omega \rho_g(\omega) \Theta(\omega) n_B(\omega/T) \Theta(\pm P^2) \dots$$

$$\tilde{T}_{r_q^\pm} \dots = d_q \int \frac{d\omega}{2\pi} \frac{d^3p}{(2\pi)^3} 2\omega \rho_q(\omega) \Theta(\omega) n_F((\omega - \mu_q)/T) \Theta(\pm P^2) \dots$$

$$\tilde{T}_{r_{\bar{q}}^\pm} \dots = d_{\bar{q}} \int \frac{d\omega}{2\pi} \frac{d^3p}{(2\pi)^3} 2\omega \rho_{\bar{q}}(\omega) \Theta(\omega) n_F((\omega + \mu_q)/T) \Theta(\pm P^2) \dots$$

→ **Mean-field scalar potential (1PI)** for quarks and gluons (U_q, U_g) vs **parton scalar density ρ_s** :

$$U_s(\rho_s) = \frac{dV_p(\rho_s)}{d\rho_s} \quad \rho_s = N_g^+ + N_q^+ + N_{\bar{q}}^+$$

$$U_q = U_s, \quad U_g \sim 2U_s$$

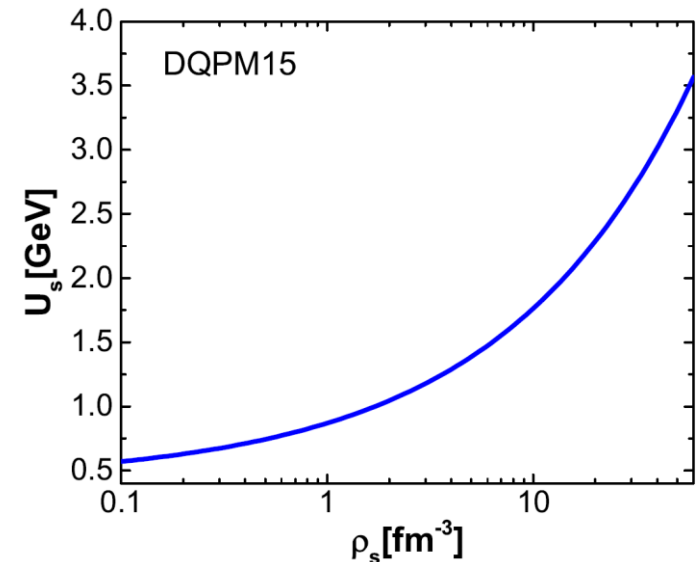
Quasiparticle **potentials** (U_q, U_g) are **repulsive** !

PHSD: → **the force** acting on a quasiparticle j :

$$F \sim M_j/E_j \nabla U_s(x) = M_j/E_j dU_s/d\rho_s \nabla \rho_s(x)$$

$$j = g, q, \bar{q}$$

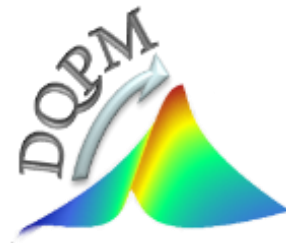
→ **accelerates** particles

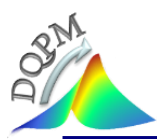


QGP near equilibrium

DQPM (T, μ_q):

transport properties at finite (T, μ_q)





Transport coefficients: shear viscosity η at finite (T, μ_q)

Relaxation-Time Approximation (RTA)

(+ cross-check with Kubo formalism):

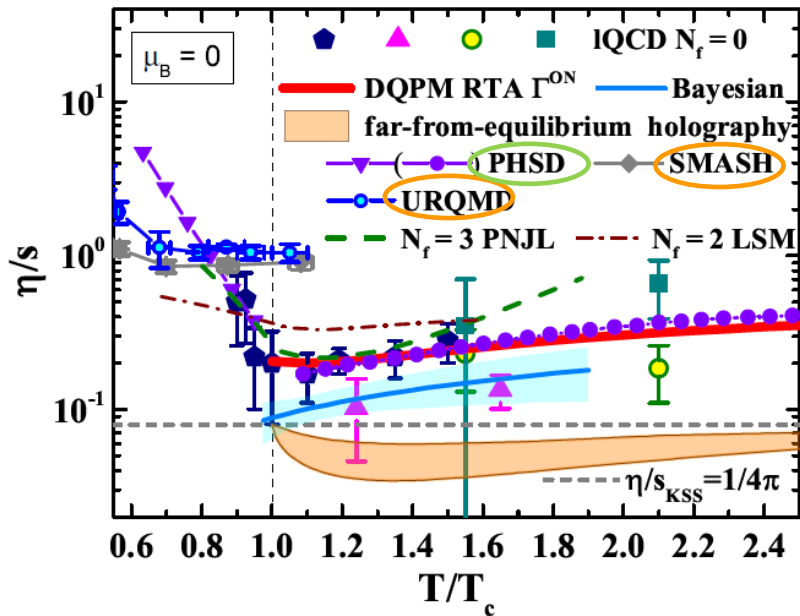
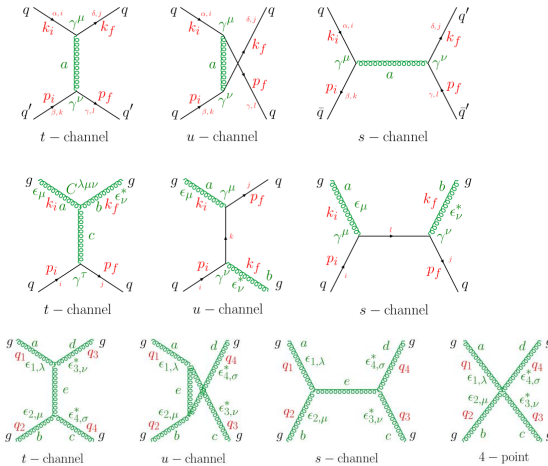
$$\eta^{\text{RTA}}(T, \mu_B) = \frac{1}{15T} \sum_{i=q, \bar{q}, g} \int \frac{d^3p}{(2\pi)^3} \frac{p^4}{E_i^2} \tau_i(\mathbf{p}, T, \mu_B) d_i (1 \pm f_i) f_i$$

$$\tau_i(\mathbf{p}, T, \mu_B) = \frac{1}{\Gamma_i(\mathbf{p}, T, \mu_B)}$$

Parton interaction

$$\Gamma_i \propto \sum_j d_j f_j \sigma_{ij}$$

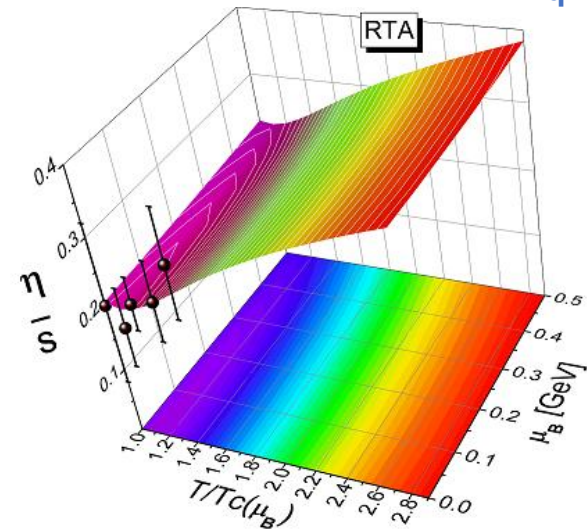
$\sigma_{ij} \rightarrow$ 'leading order' diagrams

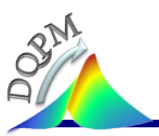


η/s from DQPM = η/s from PHSD in a box

- Good agreement with IQCD
- Light increase of shear viscosity with μ_B

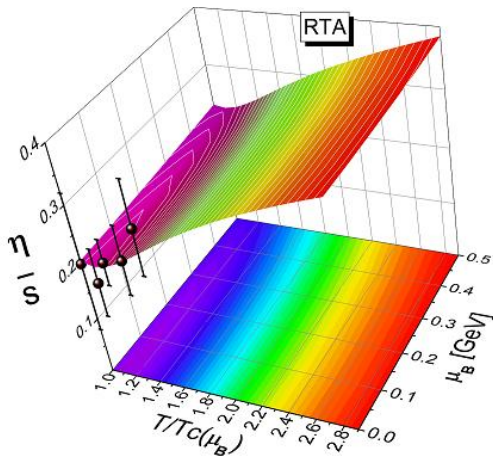
Shear viscosity $\eta/s(T, \mu_q)$



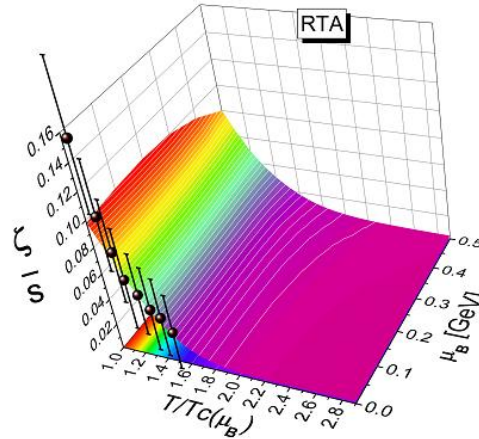


Transport coefficients

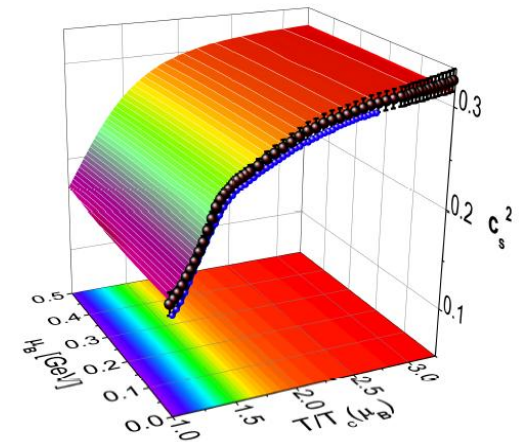
η/s versus (T, μ_B)



Bulk viscosity ζ/s

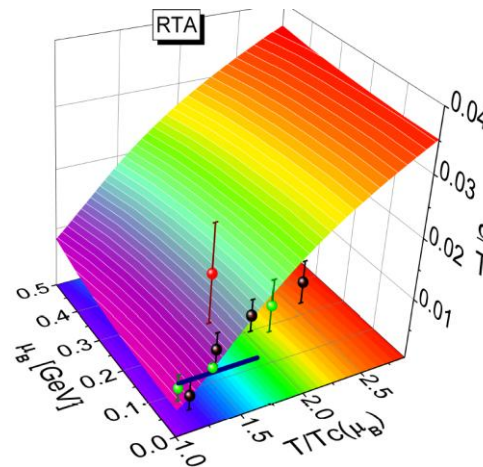


Speed of sound c_s^2

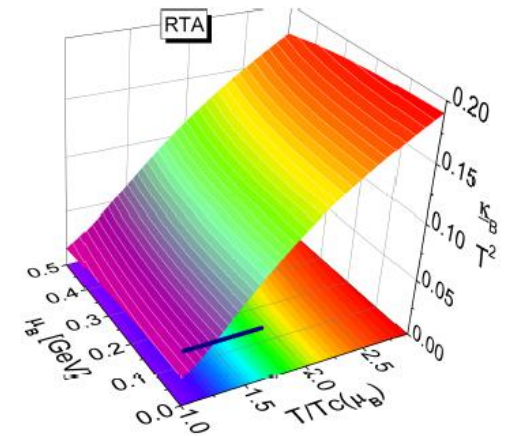


P. Moreau et al., PRC100 (2019) 014911;
O. Soloveva et al., PRC110 (2020) 045203

Electric conductivity σ_e/T



Baryon diffusion coefficient κ_B/T^2



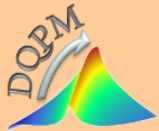
Full diffusion coefficient matrix:

$$\begin{pmatrix} j_B^\mu \\ j_Q^\mu \\ j_S^\mu \end{pmatrix} = \begin{pmatrix} \kappa_{BB} & \kappa_{BQ} & \kappa_{BS} \\ \kappa_{QB} & \kappa_{QQ} & \kappa_{QS} \\ \kappa_{SB} & \kappa_{SQ} & \kappa_{SS} \end{pmatrix} \cdot \begin{pmatrix} \nabla^\mu \alpha_B \\ \nabla^\mu \alpha_Q \\ \nabla^\mu \alpha_S \end{pmatrix}$$

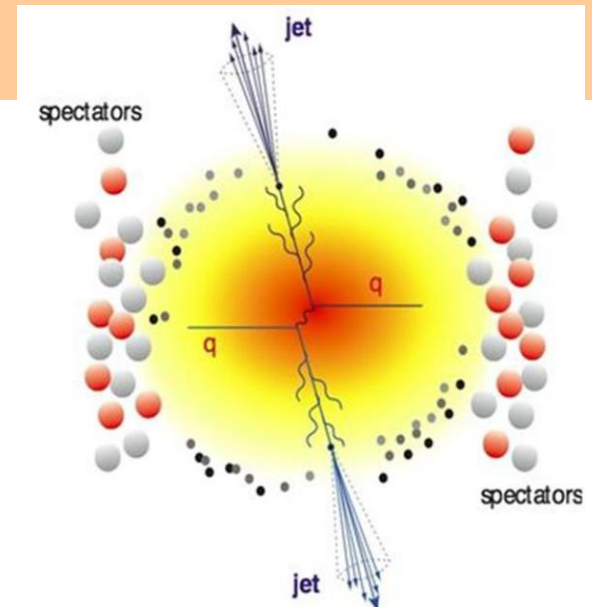
J. A. Fotakis et al., PRD 104 (2021) , 034014

➔ Weak dependence of transport coefficients on μ_B

Probing the properties of the sQGP with jet partons

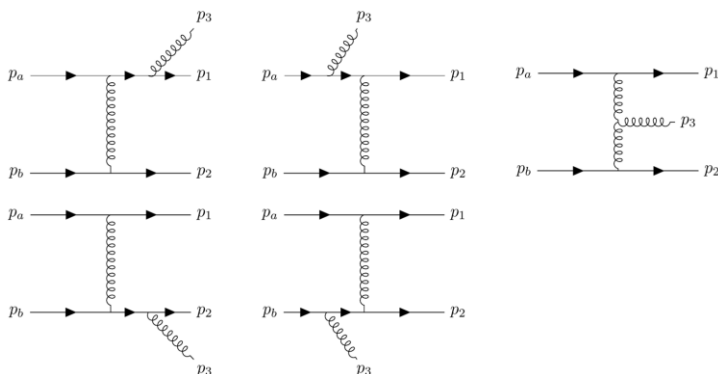


Extension of DQPM (T, μ_q)
elastic ($2 \rightarrow 2$) + inelastic ($2 \rightarrow 3$)
scattering

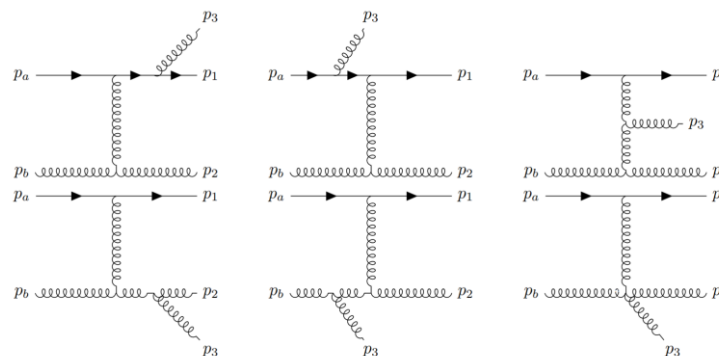


Partonic inelastic 2→3 interactions

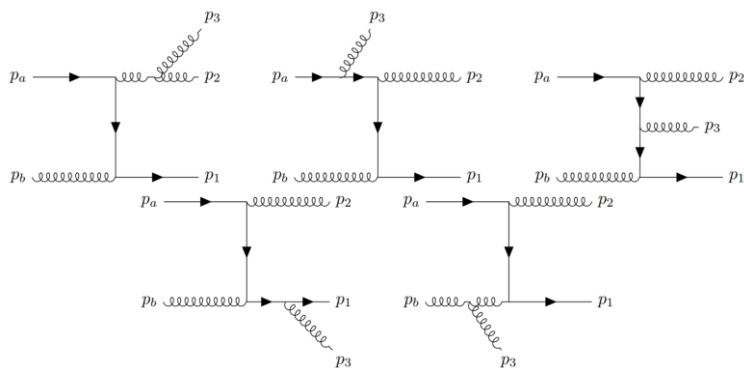
quark + quark



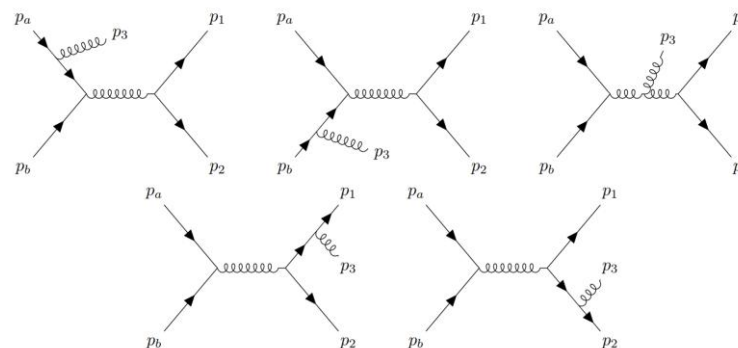
quark + gluon (t-channel)



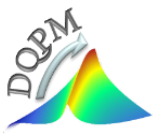
quark + gluon (u-channel)



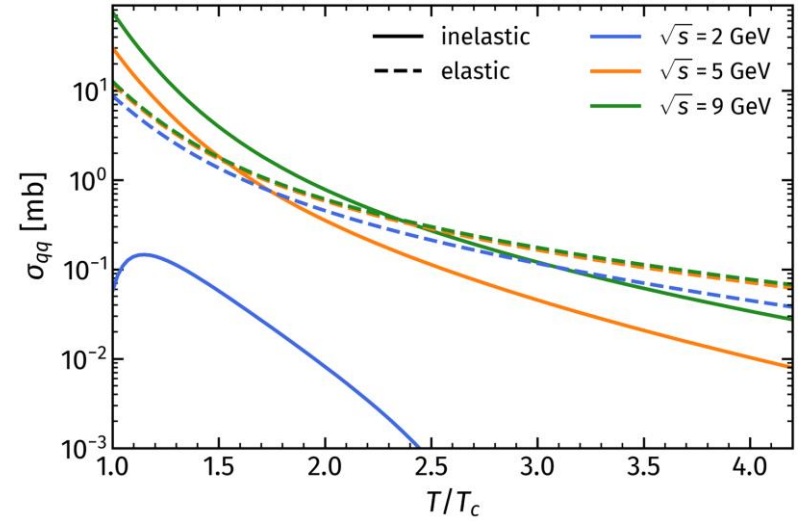
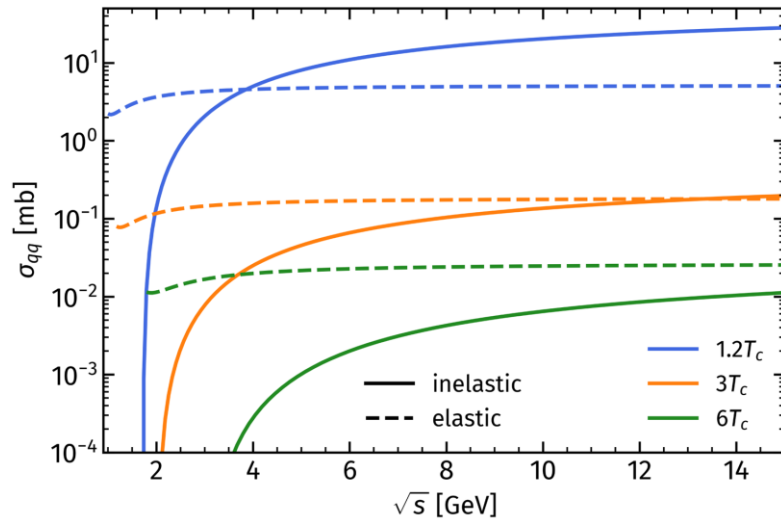
quark + gluon (s-channel)



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



Partonic cross sections: elastic vs. inelastic

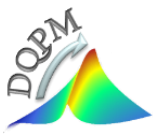


$$|\overline{\mathcal{M}}_{2 \rightarrow 2}|^2 \propto \alpha_s^2$$

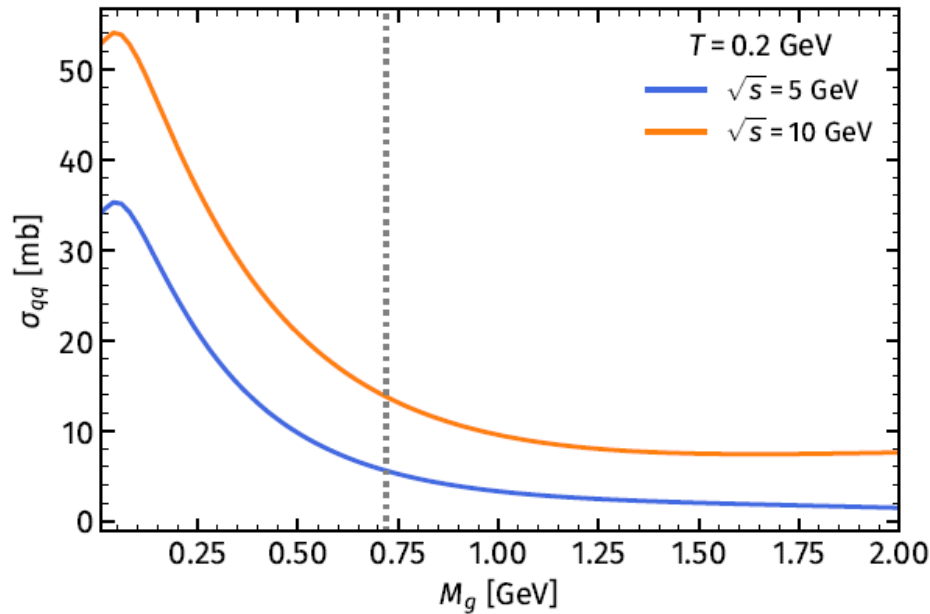
$$|\overline{\mathcal{M}}_{2 \rightarrow 3}|^2 \propto \alpha_s^3$$

- **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**

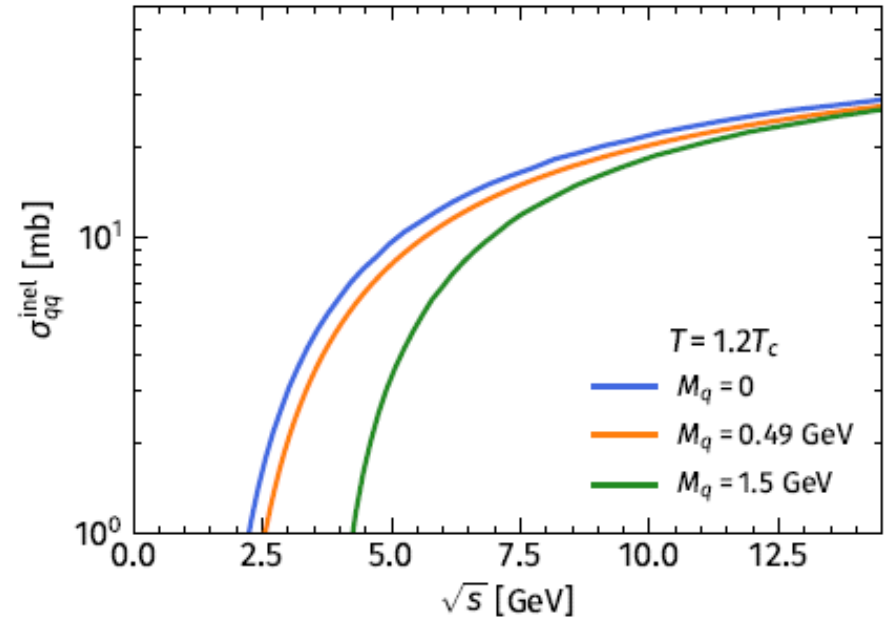
* In calculations - emitted gluon has a thermal pole mass $m_g^0(T)$



Inelastic cross sections: emitted gluon m_g



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

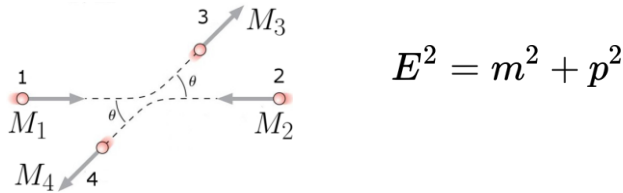


- Shift of the threshold of inelastic σ_{qq} with increasing mass of colliding quarks M_q

Jet transport coefficients from elastic scattering

On-shell:

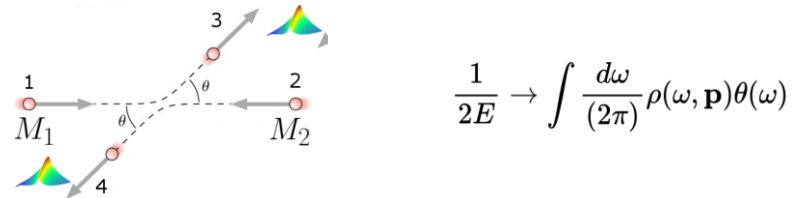
- integration over momenta
- masses = pole masses



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

Off-shell:

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



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

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

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

□ Scattering rate Γ :

$$\mathcal{O} = 1$$

□ Transverse momentum transfer squared per unit length \hat{q} :

$$\mathcal{O} = |\vec{p}_T - \vec{p}'_T|^2 \rightarrow \langle \mathcal{O} \rangle = \hat{q}$$

□ Energy loss per unit length dE/dx :

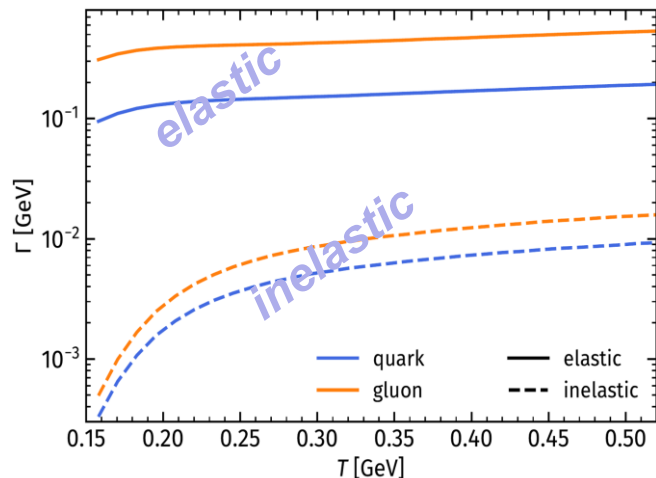
$$\mathcal{O} = (E - E') \rightarrow \langle \mathcal{O} \rangle = dE/dx$$

□ Drag coefficient A :

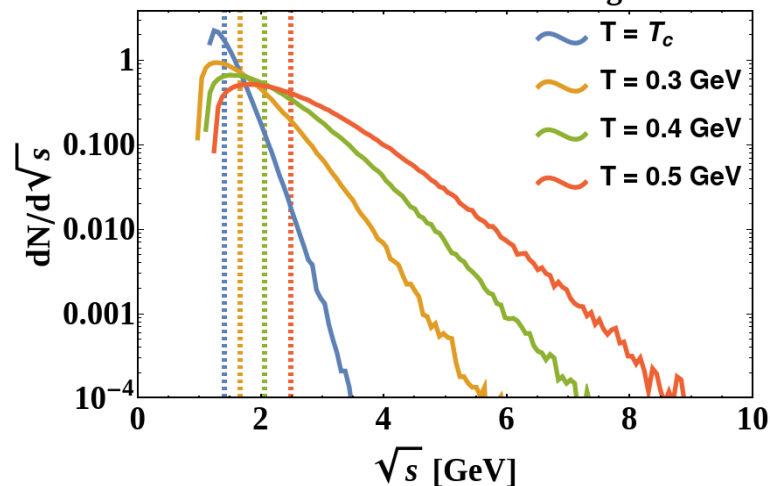
$$\mathcal{O} = p_L - p'_L$$

Partonic interaction rates in equilibrated sQGP

Interaction rate



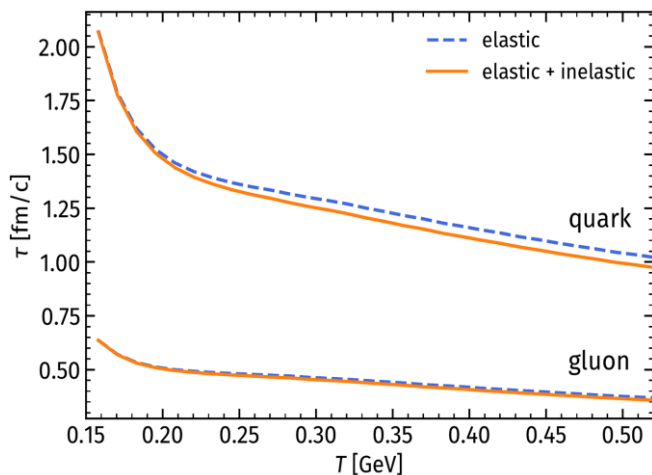
on-shell u - u scattering



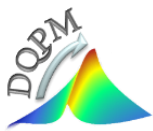
In thermalized QGP **low** energies are **avored** where the elastic scatterings dominate



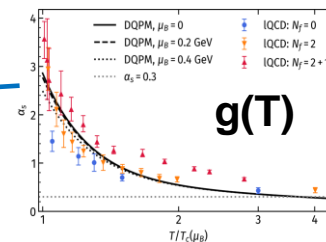
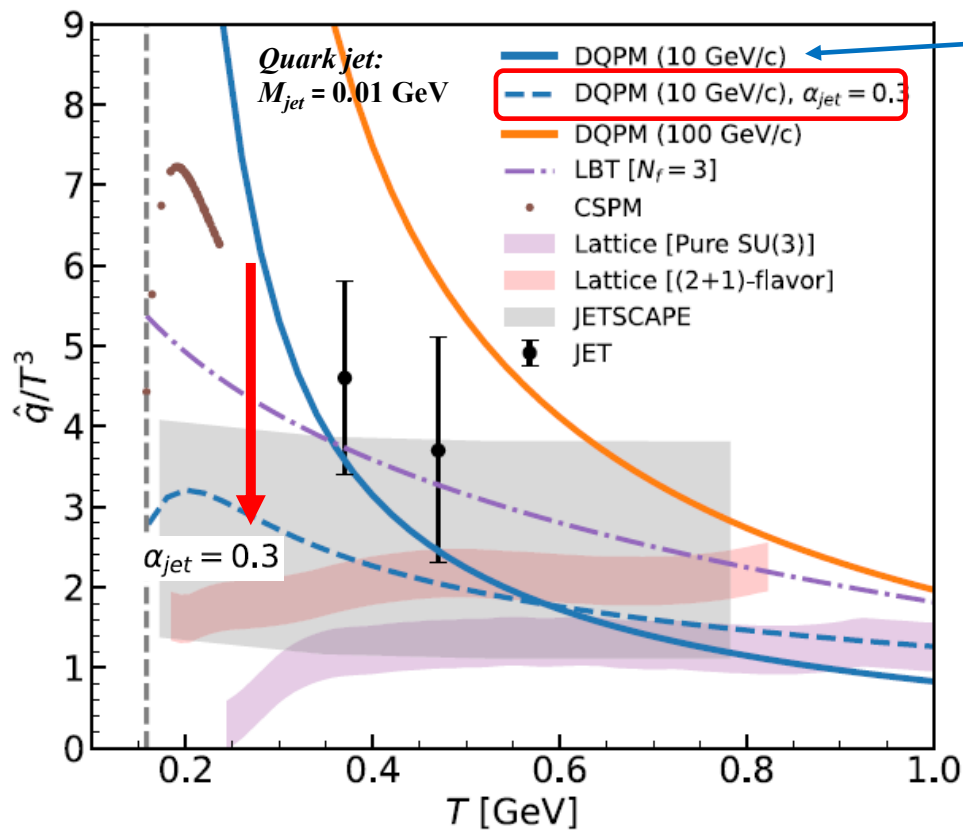
Relaxation time ($\tau \sim 1/\Gamma$)



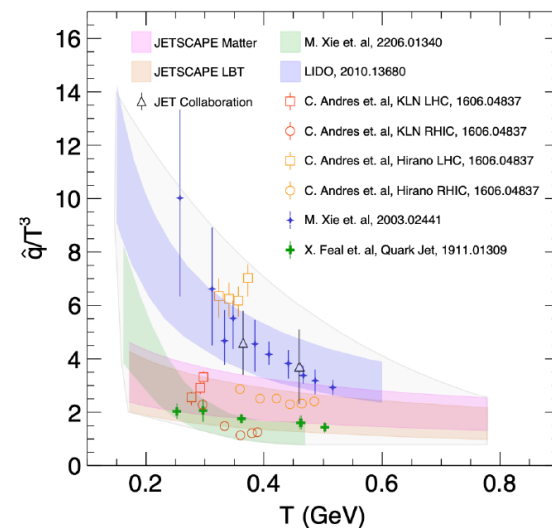
- The partonic **interaction rate** and **relaxation time** are primarily governed by **elastic** scattering
- **Inelastic processes** – with massive gluon emission – are **suppressed** in the **thermalized** QCD medium



\hat{q} from elastic scattering



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

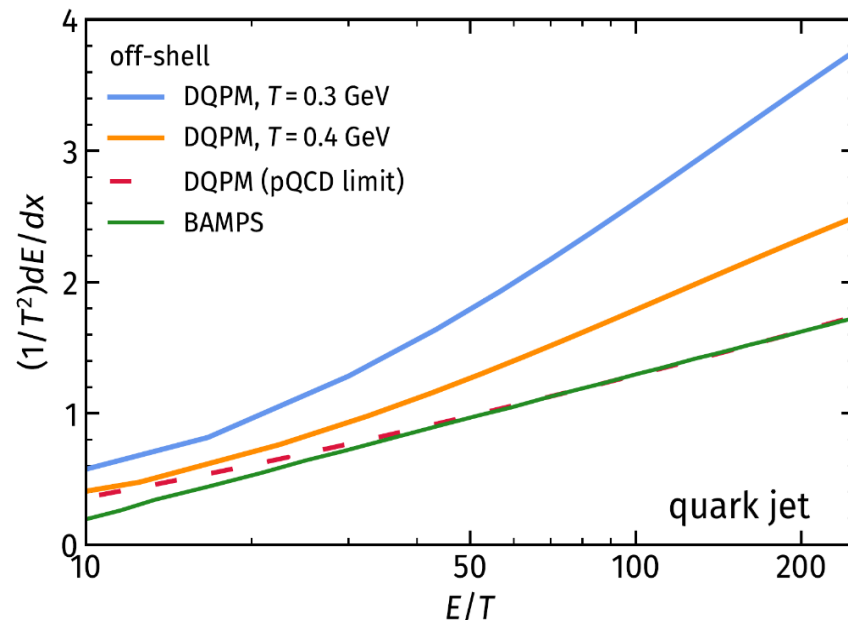
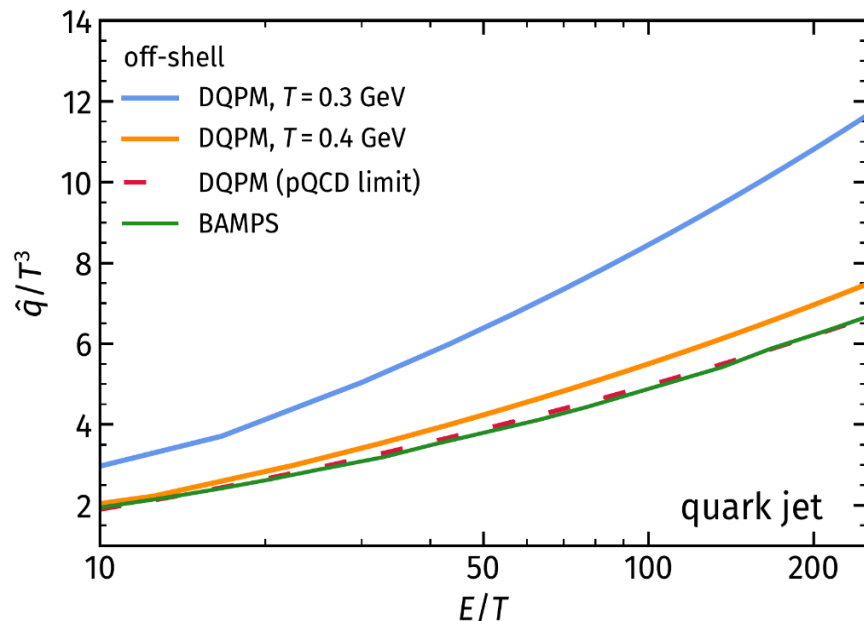


Cf. talk by Liliana Apolinario

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

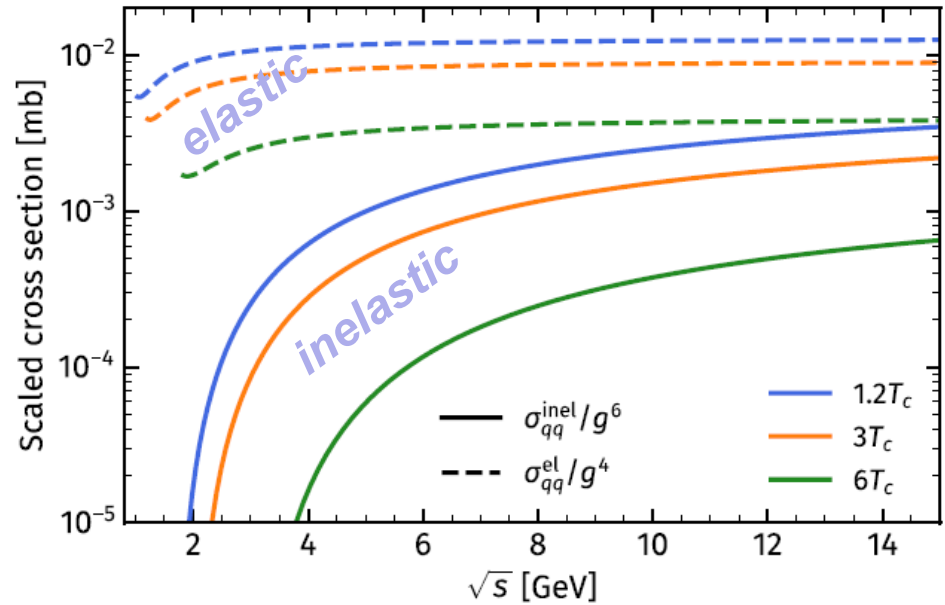
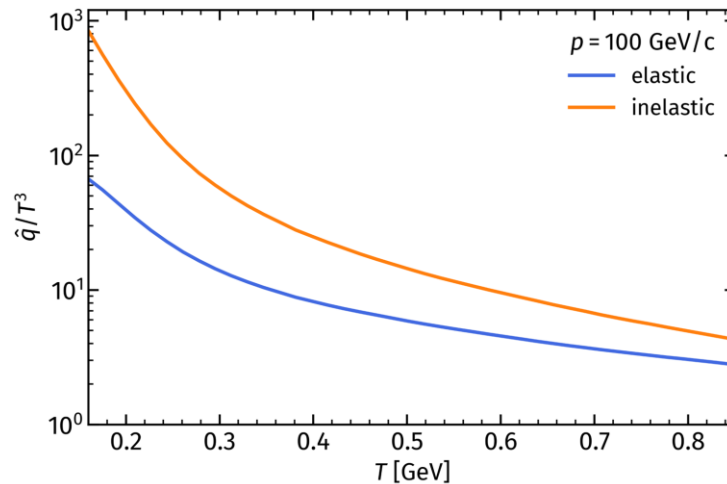
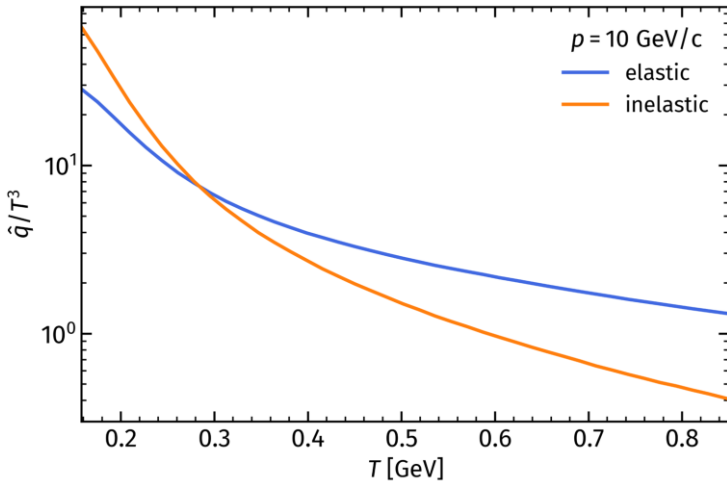
→ Rapid **rise** with **decreasing** medium **temperature** due to strong increase of $g(T)$

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



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

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



→ Strong **dependence** of **elastic** ($\sim g^4$) and **inelastic** ($\sim g^6$) cross sections on **strong coupling g**

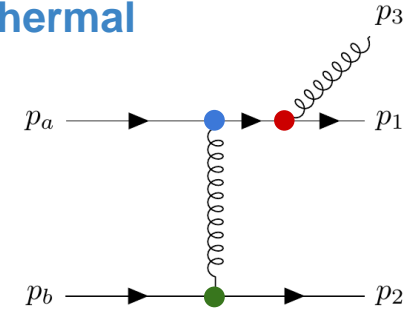
- Temperature and momentum **dependence** is stronger for **inelastic** reactions
- **Stronger energy loss** at large jet energies and small temperatures
- ? **'questionable'** **suppression** of jets in heavy-ion collisions

Different scenarios for strong couplings

- 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



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

\rightarrow “default” DQPM (thermal coupling)

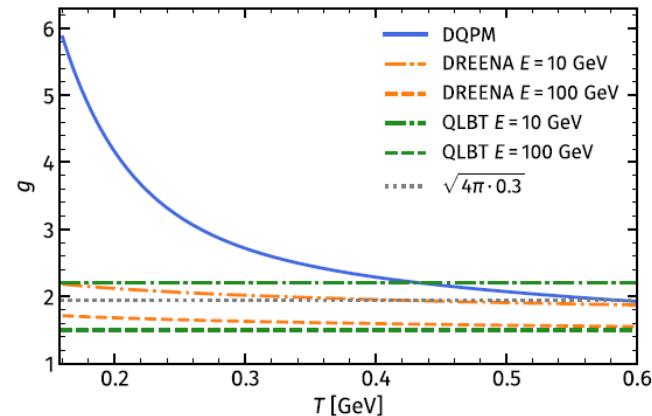
\rightarrow constant strong coupling

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

Zakharov model

QLBT model

DREENA framework

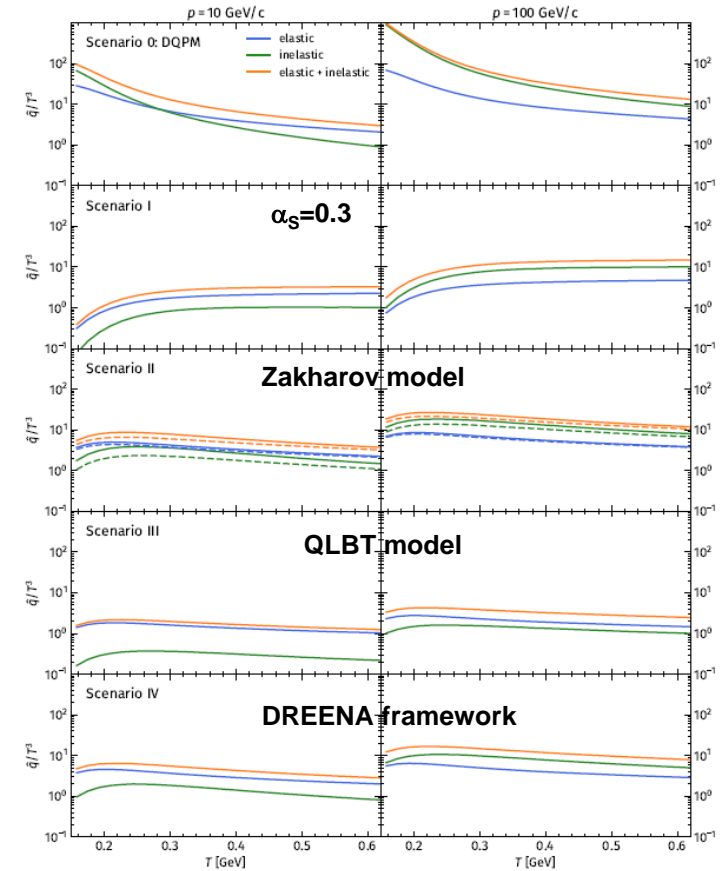
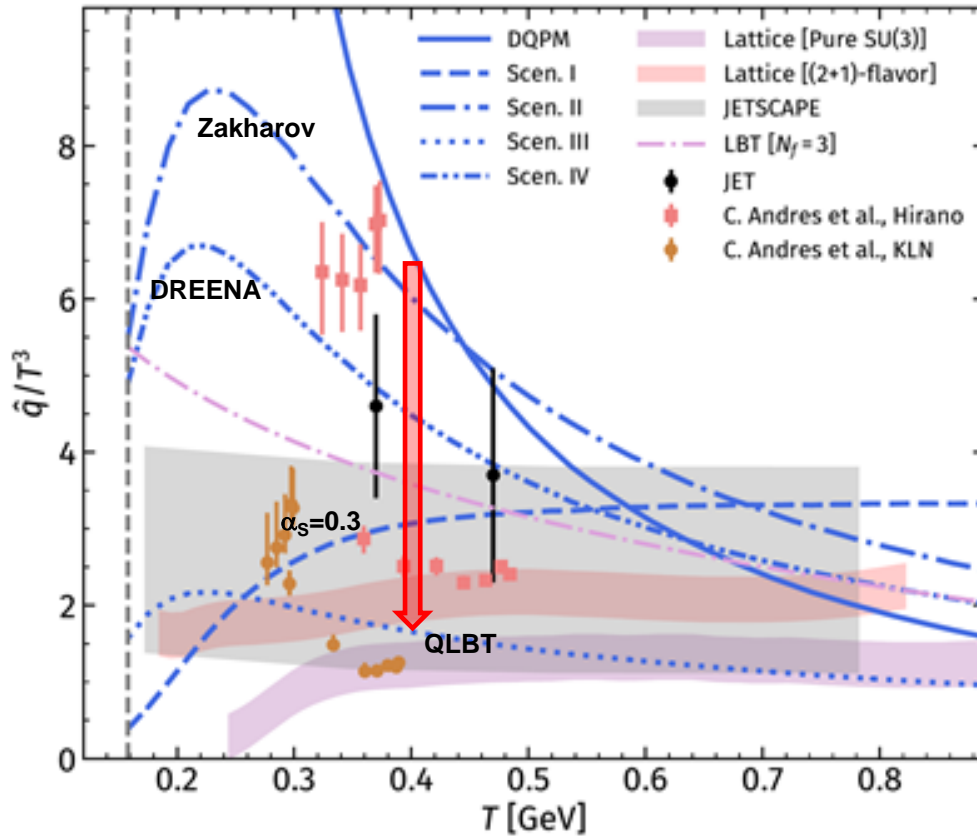


[II] B. G. Zakharov, JETP Lett. 112, 681 (2020).

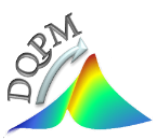
[III] F.-L. Liu et al., Eur. Phys. J. C 82, 350 (2022).

[IV] D. Zigic et al., Front. Phys. 10, 957019 (2022).

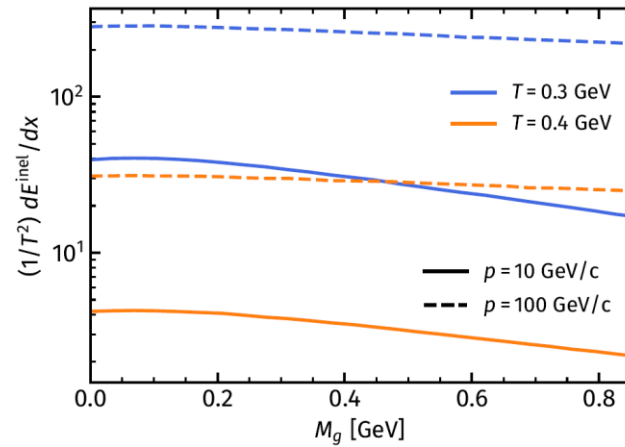
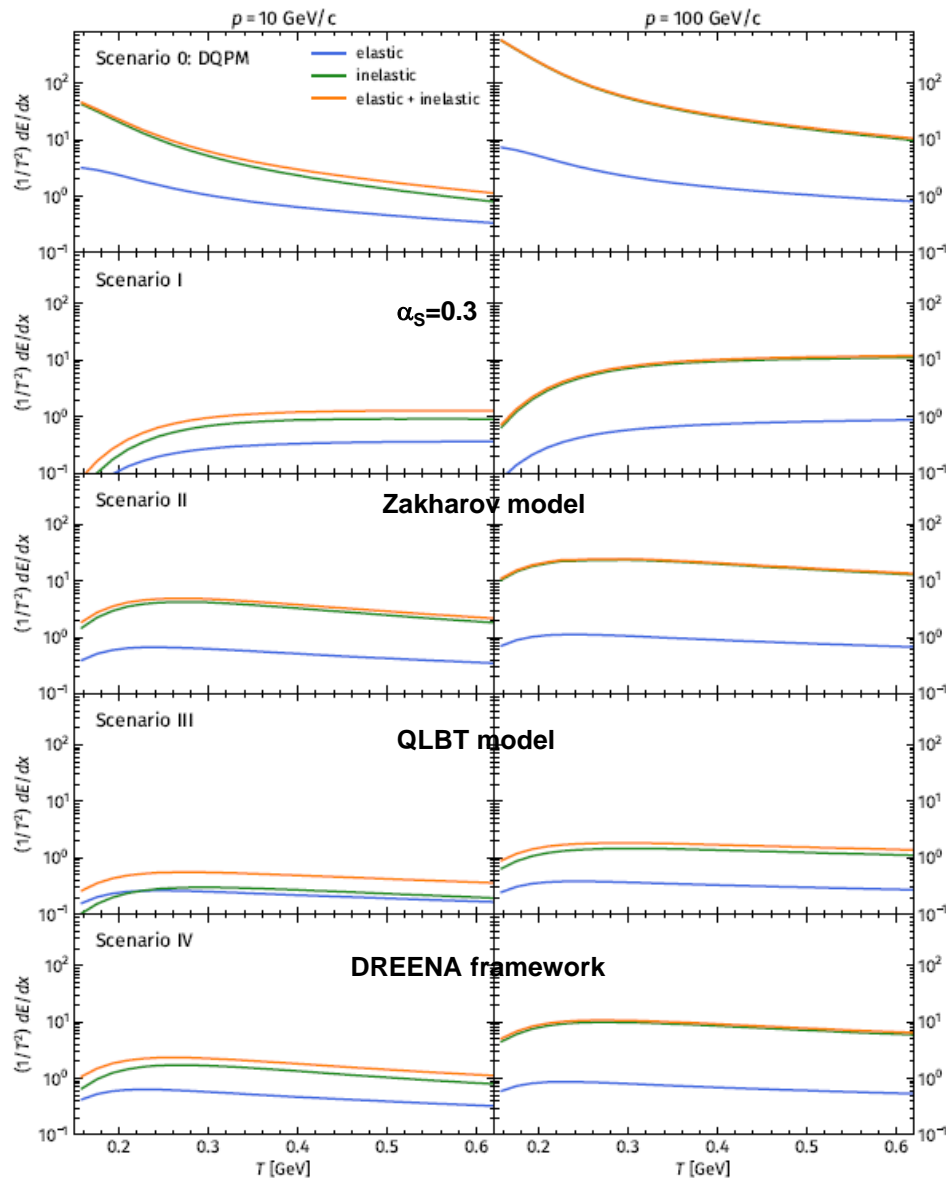
\hat{q} from elastic + inelastic scattering



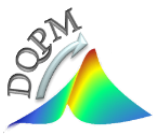
- **High sensitivity** to the **choice of the strong coupling** (“scenario”)
- The **“default” DQPM** with the thermal couplings produces the **highest values** of the transport coefficients



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

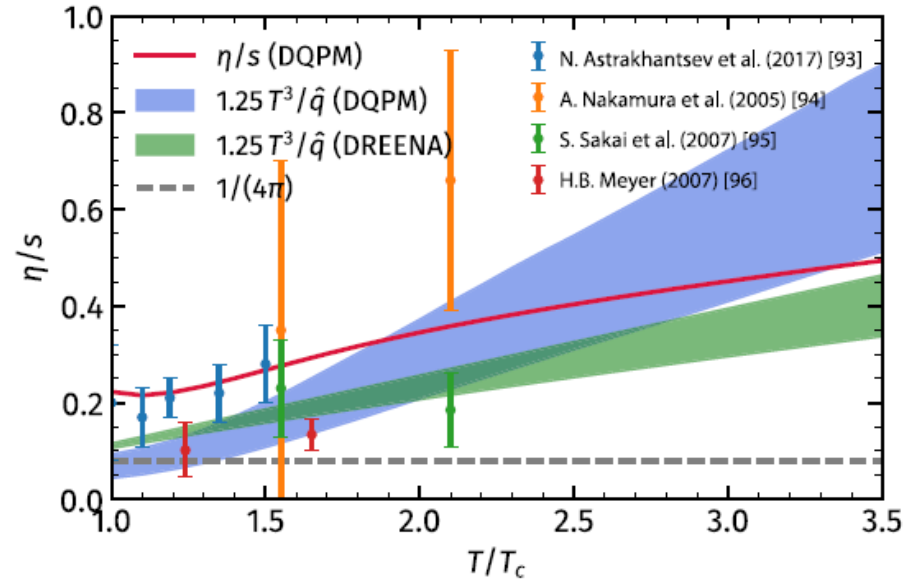
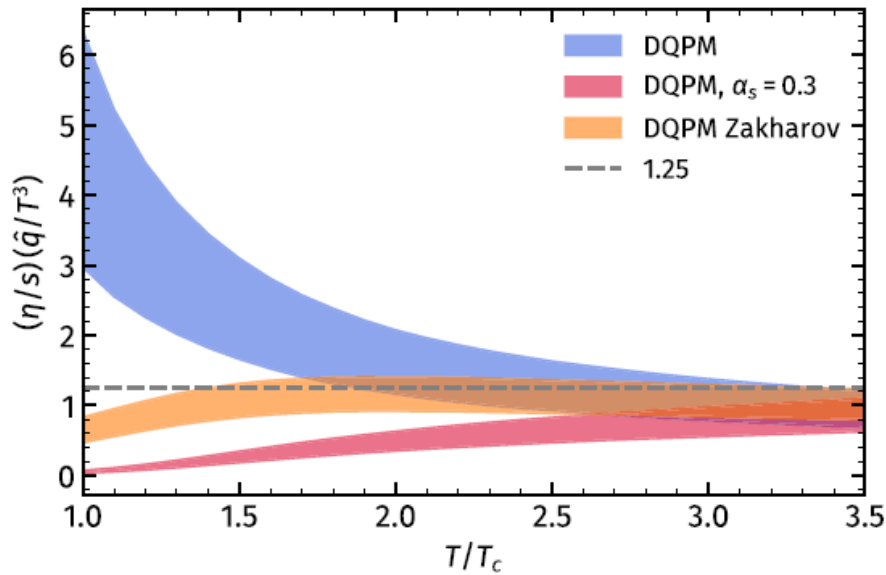


Relation between η/s and \hat{q}

In the **weak coupling limit**:

B. Müller, PRD 104, L071501 (2021)

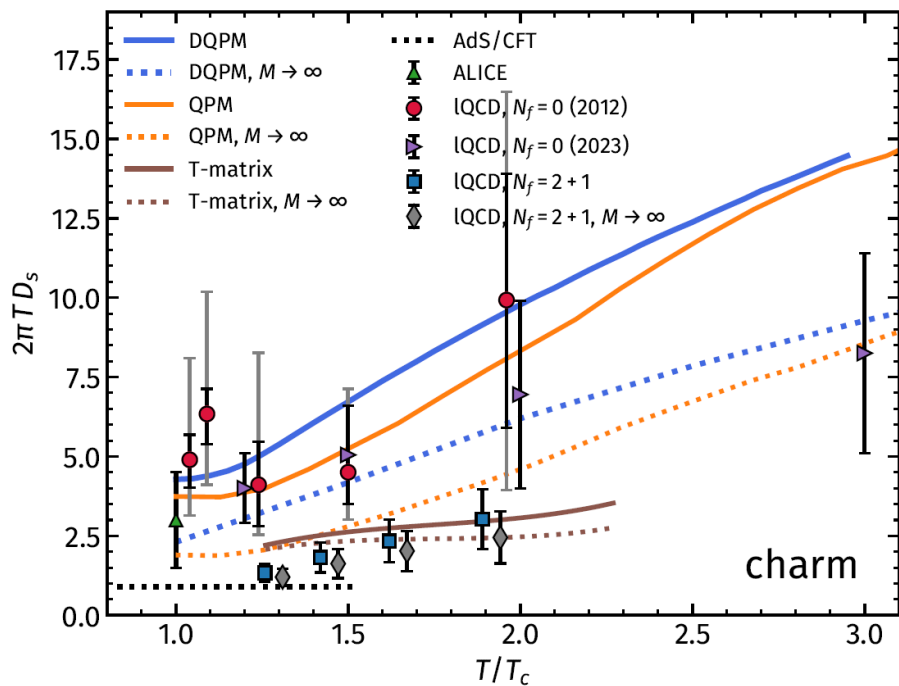
$$\eta/s \approx 1.25 \frac{T^3}{\hat{q}}$$



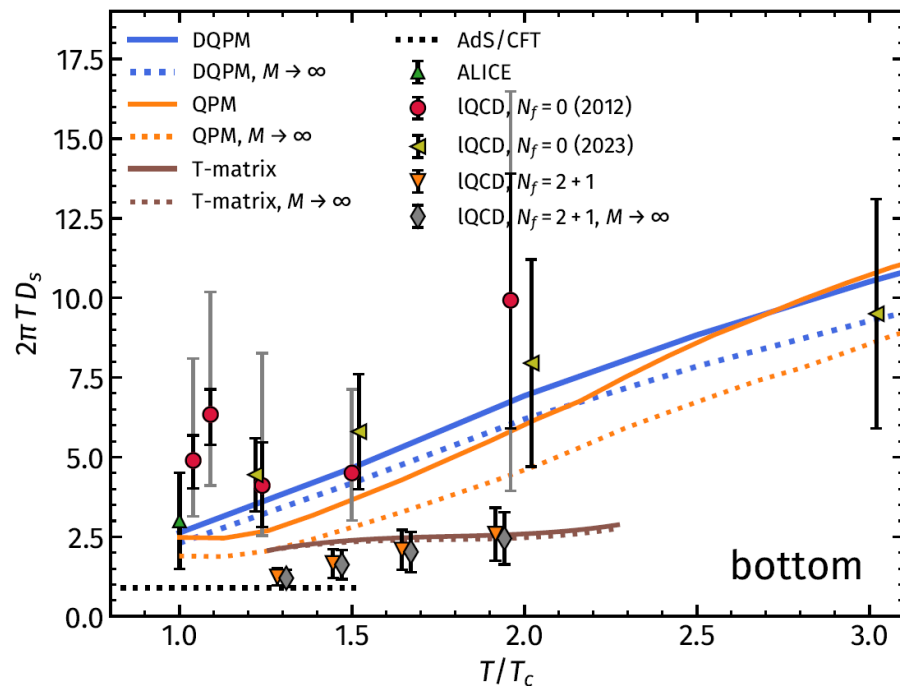
- **Sensitive** to the choice of the **strong coupling**
- **Valid** in the **weak coupling regime** (at high temperatures)
- **Violated** in the **strong coupling regime** (at low temperatures)

Spatial diffusion coefficient $D_s(T)$ for heavy quarks

Charm quark



Bottom quark



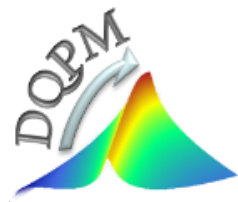
→ **Inelastic reactions play a minor role** (vs. elastic reactions) in the determination of D_s which is obtained for $p \rightarrow 0$ limit

$$D_s = \lim_{p \rightarrow 0} \frac{T}{(\mathcal{A}/p)M}$$

→ **D_s decreases with increasing mass** of the heavy quark

QGP: in-equilibrium \rightarrow off-equilibrium

Microscopic transport theory



- Baryons
- Antibaryons
- Mesons
- Quarks
- Gluons

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



b = 2.2 fm - Section view





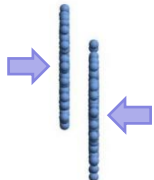
Parton-Hadron-String-Dynamics (PHSD)



PHSD is a **non-equilibrium microscopic transport approach** for the description of **strongly-interacting hadronic and partonic matter** created in heavy-ion collisions

Dynamics: based on the solution of **generalized off-shell Cassing-Juchem transport equations** for time-like particles derived from Kadanoff-Baym many-body theory

Initial A+A collision



Initial A+A collisions :

$N+N \rightarrow$ **string formation** \rightarrow decay to pre-hadrons + leading hadrons

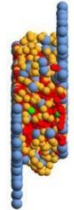
Formation of QGP stage if local $\varepsilon > \varepsilon_{\text{critical}}$:

dissolution of **pre-hadrons** \rightarrow partons

Partonic phase - QGP:

QGP is described by the **Dynamical QuasiParticle Model (DQPM)** matched to reproduce **lattice QCD EoS** for finite T and μ_B (crossover)

Partonic phase



- **Degrees-of-freedom:** strongly interacting quasiparticles:

massive quarks and gluons (g, q, q_{bar}) with sizeable collisional widths in a self-generated mean-field potential

- **Interactions:** (quasi-)elastic and inelastic collisions of partons

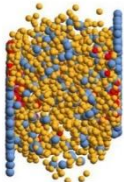
Hadronization to colorless **off-shell mesons and baryons:**

Strict 4-momentum and quantum number conservation

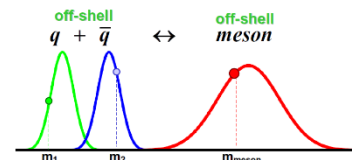
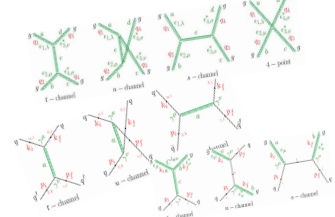
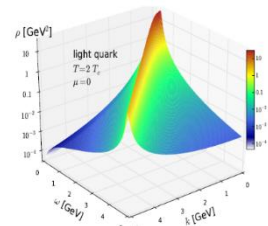
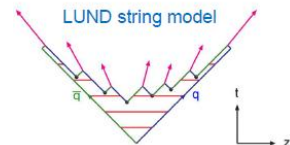
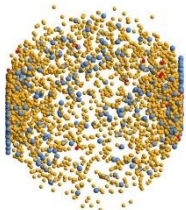
Hadronic phase: hadron-hadron interactions – **off-shell HSD**

including $n \leftrightarrow m$ selected reactions (for strangeness, anti-baryons, deuteron production)

Hadronization

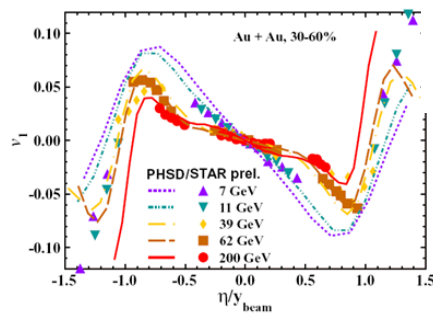
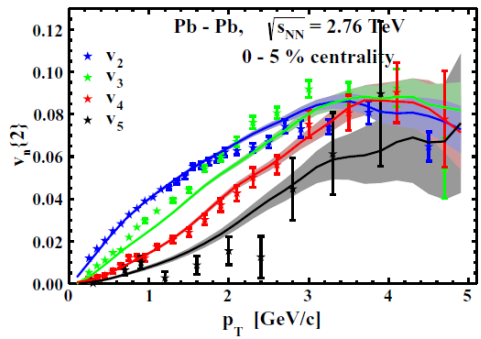
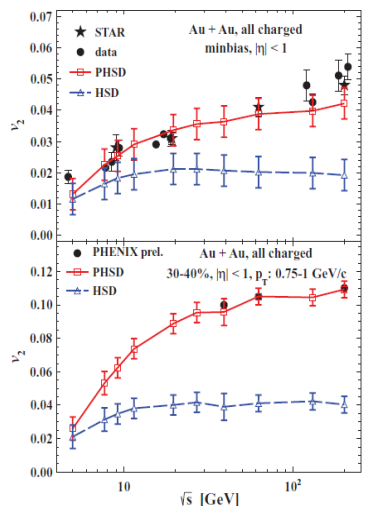
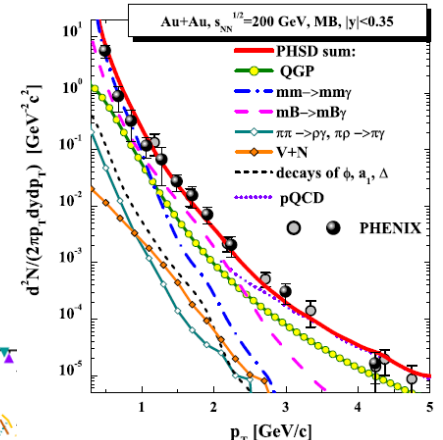
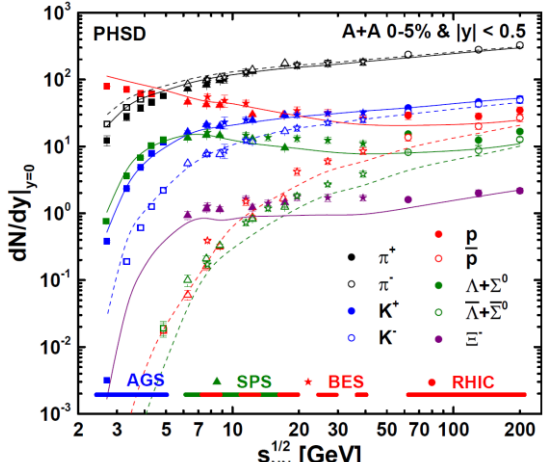
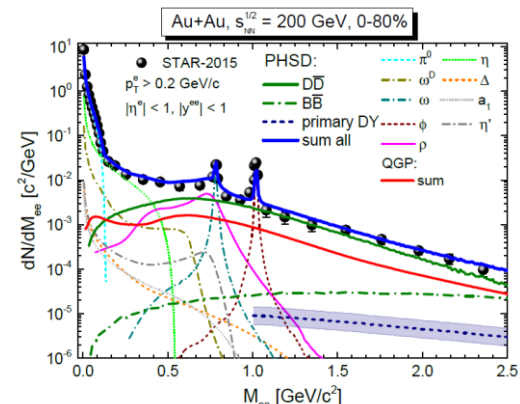
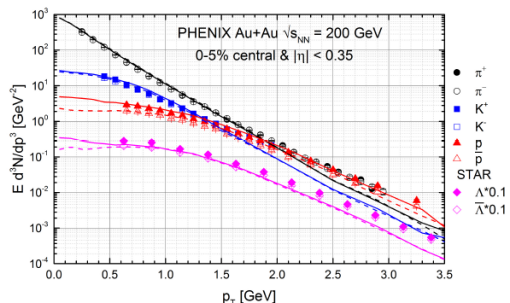
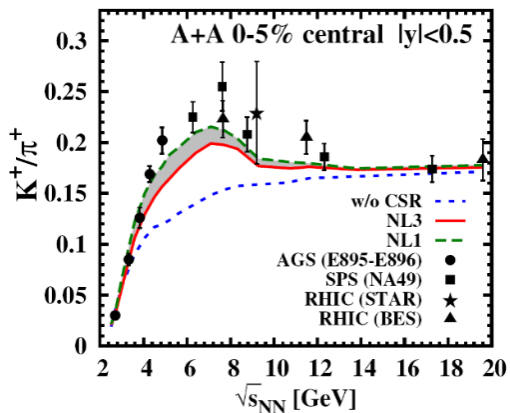


Hadronic phase

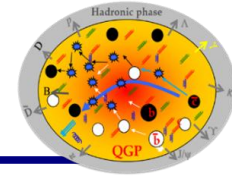




Description of A+A with PHSD (highlights)

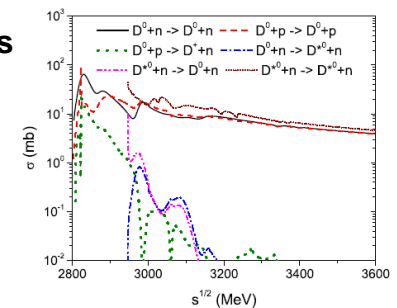
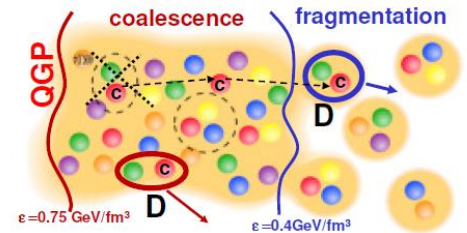
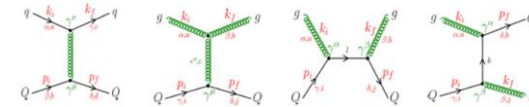
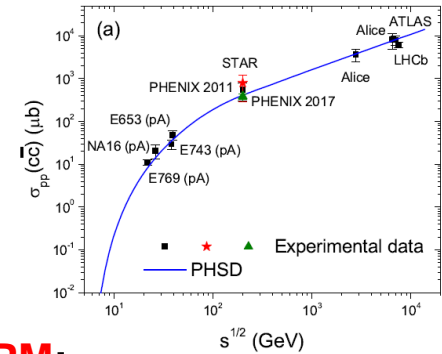


PHSD provides a good description of 'bulk' and electromagnetic observables (y -, p_T -distributions, flow coefficients v_n , ...) from SIS to LHC



Dynamics of heavy quarks in A+A :

- Production** of heavy (charm and bottom) quarks in initial binary collisions ($\sigma_{CC}(s)$, p_T : PYTHIA & FONLL) + shadowing and Cronin effects
- Interactions in the non-perturbative QGP – according to the DQPM:** elastic scattering with off-shell massive partons $Q+q \rightarrow Q+q$
 $\sigma_{Qq}(T, \mu_B, s, \cos\theta, m_Q, m_q)$, \rightarrow collisional energy loss
- Hadronization:** c/cbar quarks $\rightarrow D(D^*)$ -mesons:
 Dynamical hadronization scenario for heavy quarks :
 coalescence with $\langle r \rangle = 0.9$ fm & fragmentation
 $0.4 < \varepsilon < 0.75$ GeV/fm³ $\varepsilon < 0.4$ GeV/fm³
- Hadronic interactions:**
 D+baryons; D+mesons based on G-matrix and effective chiral Lagrangian approach with heavy-quark spin symmetry (>200 channels)
 (Juan Torres-Rincon, Laura Tolos)



* PHSD references on charm dynamics:

Taesoo Song et al., PRC 92 (2015) 014910, PRC 93 (2016) 034906, PRC 96 (2017) 014905

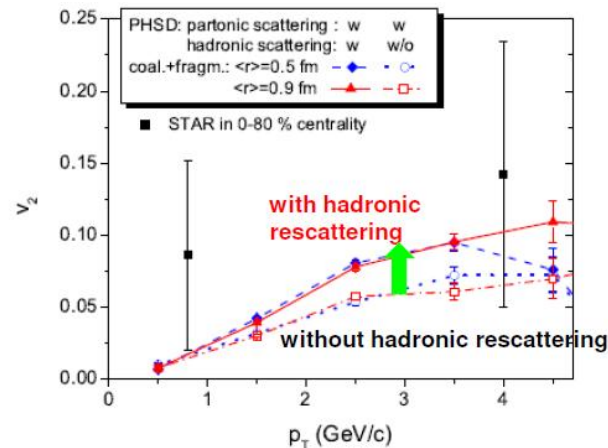
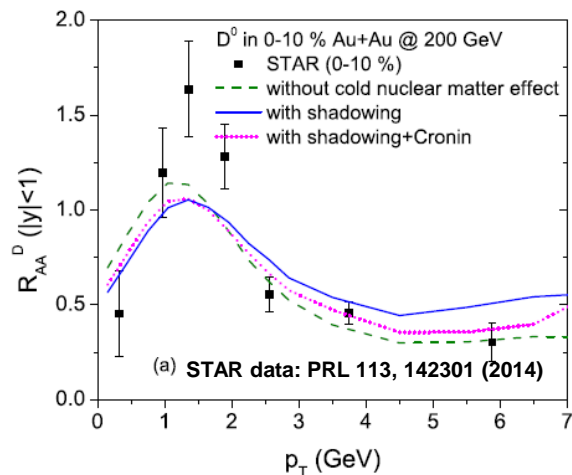
PRC 97 (2018) 064907; PRC 101 (2020) 044901; PRC 101 (2020) 044903



PHSD vs charm observables at RHIC

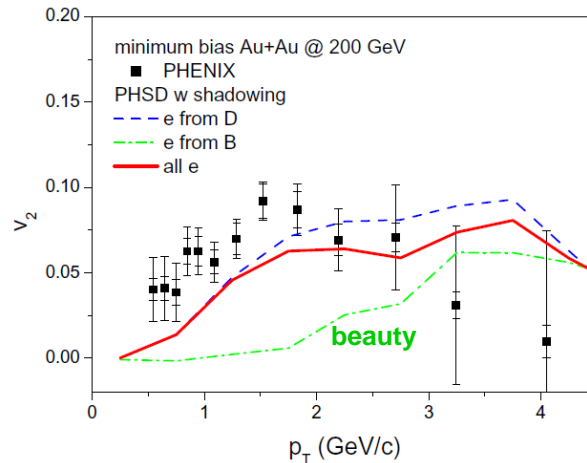
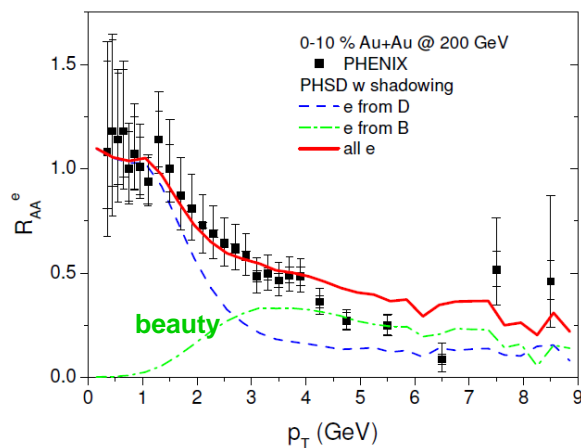
STAR

R_{AA} and v_2 vs p_T
from D^0 -mesons
in Au+Au @ 200 GeV →



PHENIX

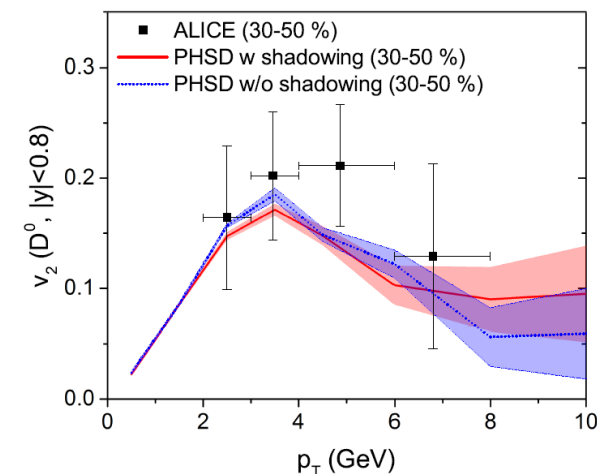
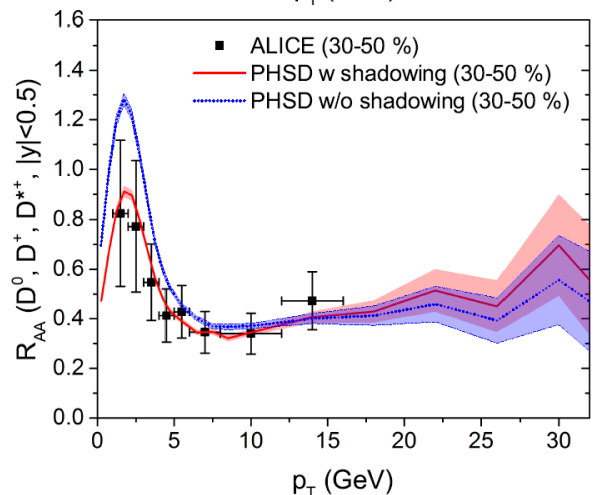
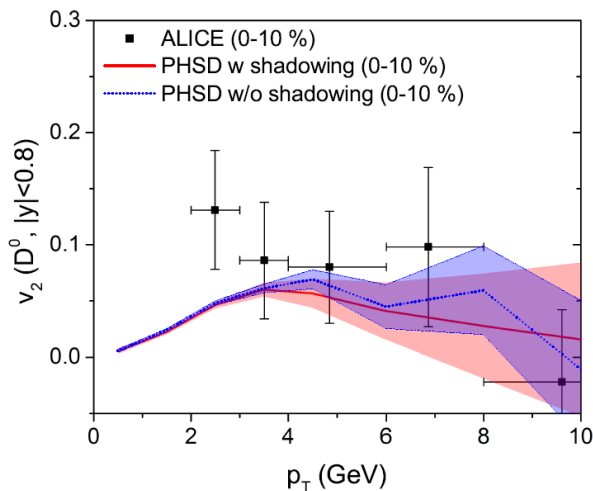
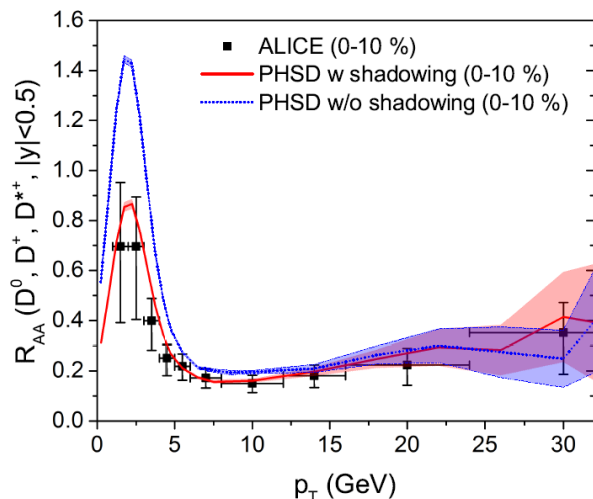
R_{AA} and v_2 vs p_T
from **single electrons**
in Au+Au @ 200 GeV →



- The exp. data for the R_{AA} and v_2 are described in the PHSD by **QGP collisional energy loss** due to elastic scattering of charm quarks with massive quarks and gluons in the QGP
- + by the **dynamical hadronization scenario** „coalescence & fragmentation“
- + by **strong hadronic interactions** due to resonant elastic scattering of D, D^* with mesons and baryons
- **Feed back from beauty** contribution becomes dominant for single electrons R_{AA} and v_2 at $p_T > 3$ GeV



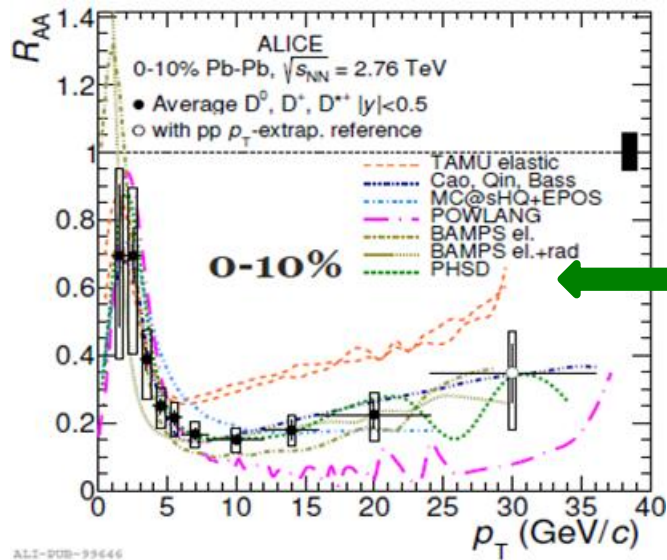
Charm R_{AA} at LHC: PHSD vs ALICE



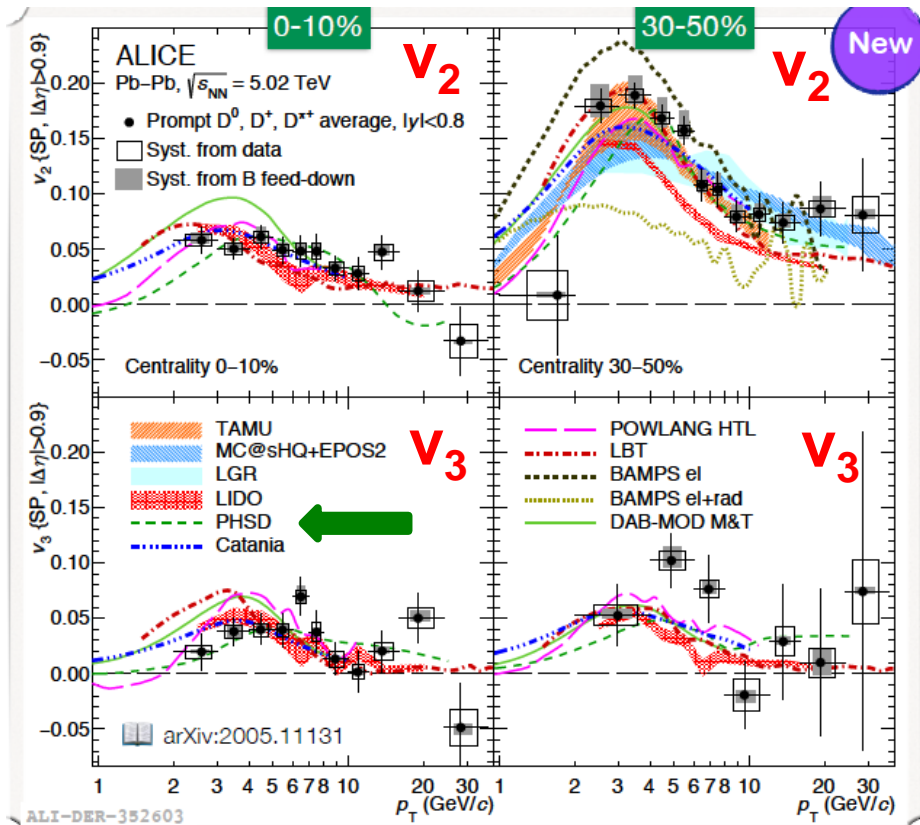
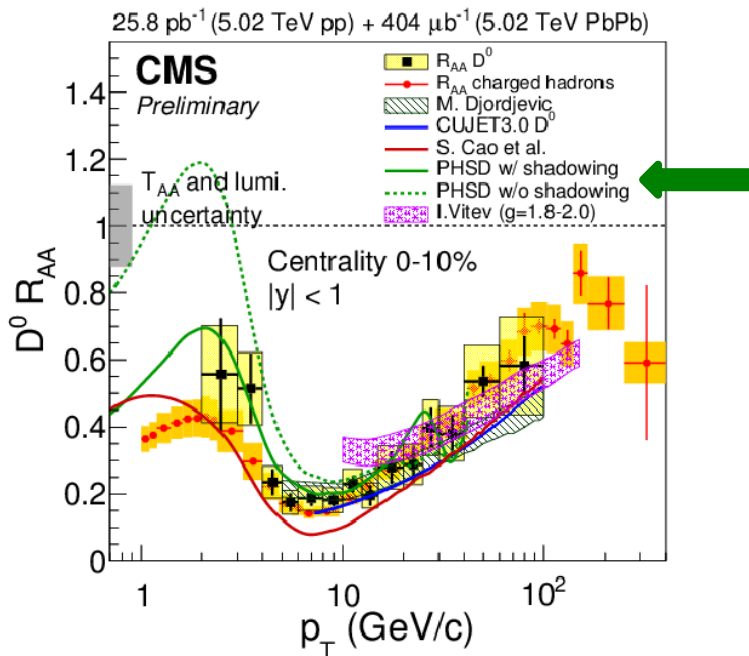
- in PHSD the energy loss of D-mesons at high p_T can be dominantly attributed to partonic scattering
- Shadowing effect suppresses the low p_T and slightly enhances the high p_T part of R_{AA}
- Hadronic rescattering moves R_{AA} peak to higher p_T ; increases v_2



PHSD vs charm observables at LHC (predictions)



ALI-DOB-39646



ALI-DER-352603

- ❑ 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
- ❑ **Transport coefficients** are highly **sensitive** to the choice of the **strong coupling**
- ❑ $D_s(T)$ for heavy quarks is not sensitive to inelastic reactions
- ❑ **PHSD** provides a **microscopic description** of non-equilibrium **charm dynamics** in the partonic and hadronic phases

Outlook:

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

The background is a vibrant blue gradient with numerous colorful bokeh lights in shades of orange, yellow, green, and purple. A string of lights with small, glowing bulbs is visible at the top, and some light trails or streaks are scattered throughout the scene.

**Thank you for your
attention!**

Thanks to Organisers!