Heavy quark transport properties from LHC to CBM energies

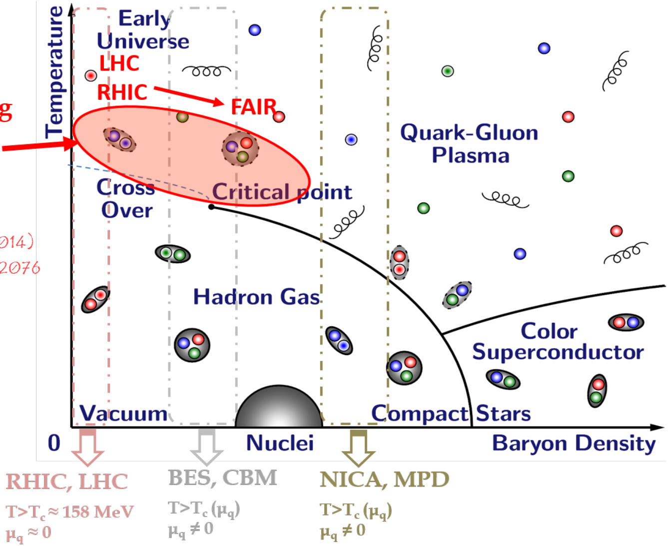
Hamza Berrehrah

Collaborators : E. Bratkovskaya, W. Cassing, P.B. Gossiaux & J. Aichelin

NeD-TURIC, June 10, 2014

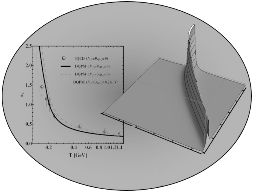
Global Project : HQ dynamics and transport properties at finite (T,μ)

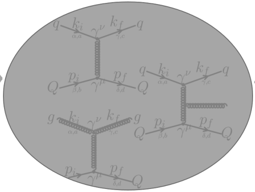
HQ scattering on (q, g) at finite (T, μ_q)

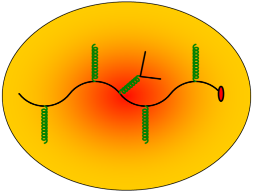


Phys.Rev. C89, 054901 (2014)
J. Phys. : Conf.Ser. 509 012076
arXiv :1405.3243

HQ scattering and quenching in a finite temperature and chemical potential QCD medium







1. DQPM at finite (T, μ)
   - Fundamental ingredients : α_s, IR
   - q,g,Q masses, widths, spectral functions

   [Eur. Phys. J. Spec. Top. 168, 3 (2009) PRL 94 (2005) 172301]

2. HQ scattering at finite (T, μ)
   - Elastic cross section : qQ, gQ
   - Inelastic cross section : qQg, gQg, . . .

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   - Dynamical energy loss
   - $\parallel$ & $\perp$ Momentum loss (Drag, $\hat{q}$, Diffusion . . .)

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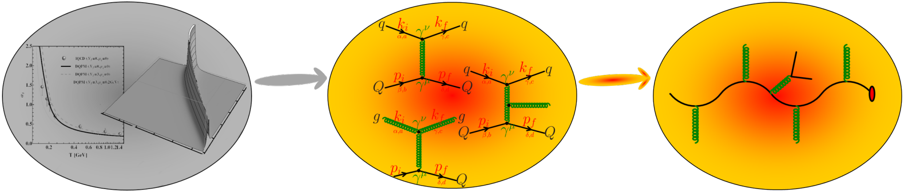

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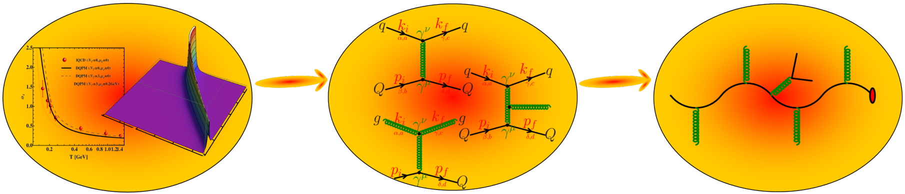

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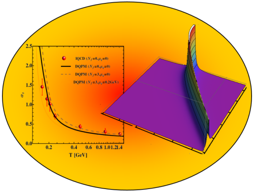

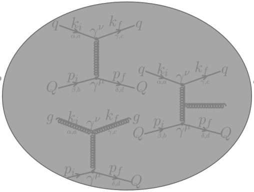

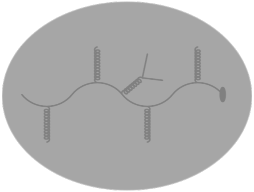

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Dynamical quasi-particle model (DQPM) at finite T

1 DQPM entropy density

$$s_i^{DQP} = -\int \frac{d\omega}{2\pi}\frac{d^3p}{(2\pi)^3}\frac{\partial n_i}{\partial T}\left(\Im \ln(-\Delta^{-1}) + \Im\Pi \times \Re\Delta\right)$$

Peshier, Cassing, PRL 94 (2005) 172301
Cassing, NPA 791 (2007) 365; NPA 793 (2007)
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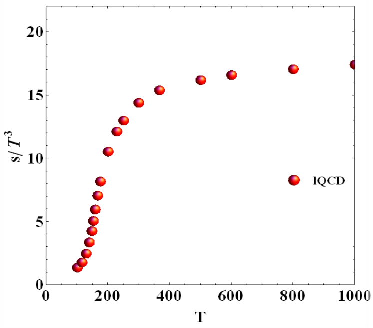

2 DQPM Masses and Widths

$$m_g^2 = \frac{g^2}{6}\left(N_c + \frac{1}{2}N_f\right)T^2, \qquad m_q^2 = g^2\frac{N_c^2-1}{8N_c}T^2$$

$$\gamma_g = \frac{1}{3}N_c\frac{g^2T}{8\pi}\ln\left(\frac{2c}{g^2}+1\right), \quad \gamma_q = \frac{1}{3}\frac{N_c^2-1}{2N_c}\frac{g^2T}{8\pi}\ln\left(\frac{2c}{g^2}+1\right)$$

3 DQPM Coupling Constant

$$g^2(T) = \frac{48\pi^2}{(11N_c - 2N_f)\ln\left(\lambda^2(T/T_c - T_s/T_c)^2\right)}$$

4 DQPM Parameters $T_s,\ \lambda,\ c$

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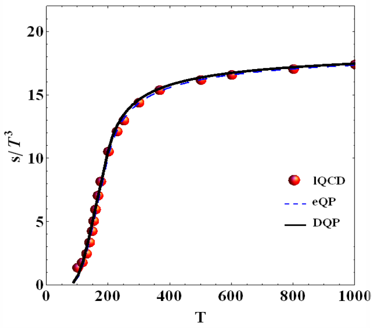

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$$T_c = 0.158\ \text{GeV},\ T_s = 0.56\,T_c$$
$$\lambda = 2.42,\ c = 14.4$$

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Dynamical quasi-particle model (DQPM) at finite T

1. DQPM α_s, m and γ

DQPM gives a good description of lQCD results

Peshier, Cassing, PRL 94 (2005) 172301
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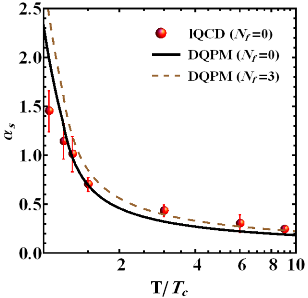

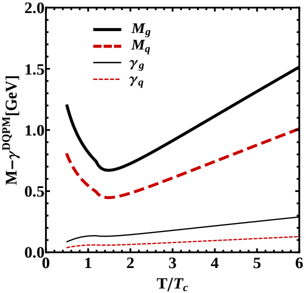

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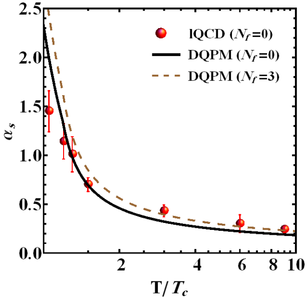
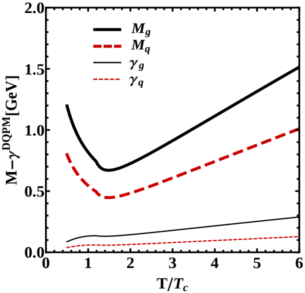
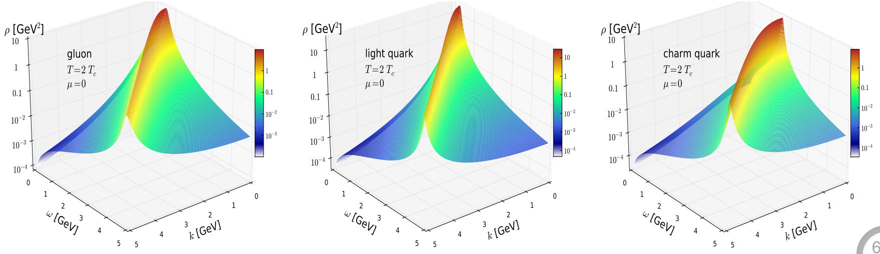




2. DQPM $\rho(\omega, p, T)$



Dynamical quasi-particle model (DQPM) at finite (T,μ)

1 Scaling hypothesis

$$M_g^2(T) = \frac{g^2(T/T_c)}{6}\left((N_c + \frac{1}{2}N_f)T^2 + \frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$$

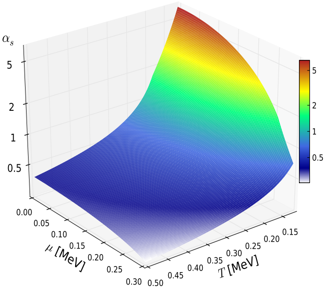
$$M_q^2(T) = \frac{N_c^2-1}{8N_c} g^2(T/T_c)\left(T^2 + \frac{\mu_q^2}{\pi^2}\right)$$

$$\Downarrow$$

$$T^{*2} = T^2 + \frac{\mu^2}{\pi^2}$$

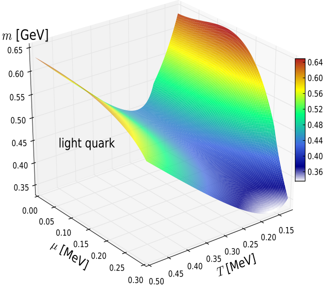
$$g(T/T_c(\mu=0)) \longrightarrow g(T^\star/T_c(\mu))$$

$$T_c(\mu) = T_c(\mu=0)\times\sqrt{1-8.79\mu^2}$$



2 α_s, masses at finite (T,μ)

- $\mu_q \nearrow \rightarrow$ decrease of α_s, $m_{q,g,Q}$
- $\mu_q \nearrow \rightarrow$ shift of the BW spectral function to small m, but same amplitude



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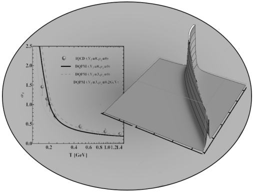

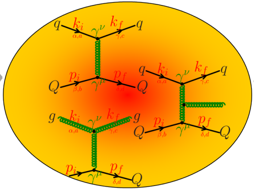

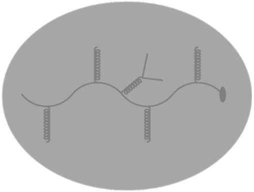

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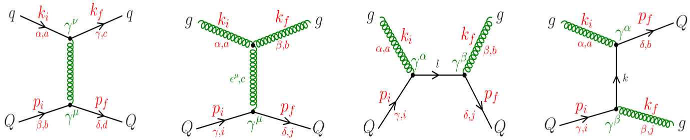
[arXiv :1405.3243]

HQ elastic scattering at finite (T, μ_q) :

On- vs Off-shell non-pQCD based approaches



- DpQCD (Dressed pQCD) : On-shell non-pQCD
  - $\alpha_s^{DQPM}(T)$, IR, m : from DQPM (DQPM pole mass for g, q, Q)
  - $G^{\mu\nu}(q, m_g) = -i \dfrac{g_{\mu\nu} - q_\mu q_\nu / m_g^2}{q_0^2 - \boldsymbol{q}^2 - m_g^2}$
- IEHTL (Infrared Enhanced HTL) : Off-shell non-pQCD
  - $\alpha^{DQPM}(T)$, IR, m, ρ^{BW} from DQPM (finite mass and width)
  - Off-shell kinematical limits
  - $G^{\mu\nu}(q, m_g) = -i \dfrac{g_{\mu\nu} - q_\mu q_\nu / m_g^2}{q_0^2 - \boldsymbol{q}^2 - m_g^2 + i 2 \gamma_g q_0}$
  - $\sigma^{IEHTL}(s, T) = \int \Pi dm^{(i)} \; \sigma^{q,g-Q} \; (s, m^{(1)}, m^{(2)}, m^{(3)}, m^{(4)}) \; \rho_{(1)}(m^{(1)}) \; \rho_{(2)}(m^{(2)}) \; \rho_{(3)}(m^{(3)}) \; \rho_{(4)}(m^{(4)})$

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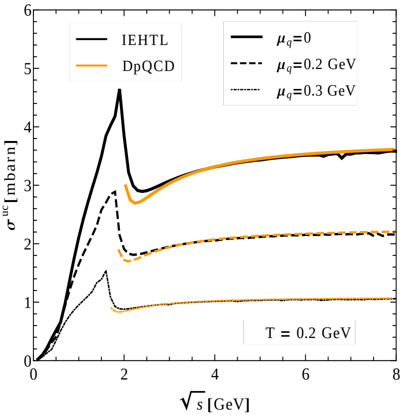

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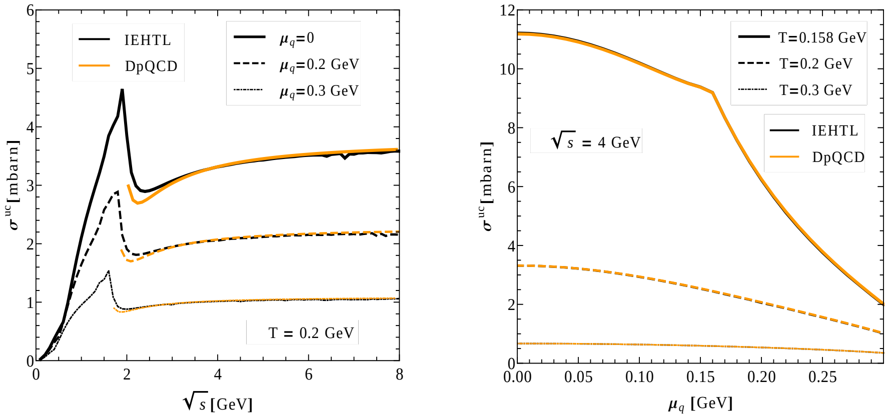

- Effect of $\rho^{BW}(m)$ is negligible (small parton width), except reducing the kinematic threshold
- $(T, \mu_q) \nearrow \rightarrow m_g(T, \mu_q) \searrow$, but $\alpha_s \searrow$: decease of σ^{qQ}, with large effect for (small T, large μ_q)
- Large enhancement of σ^{qQ} for T close to $T_c(\mu_q) \rightarrow$ infrared enhanced of $\alpha_s(T)$

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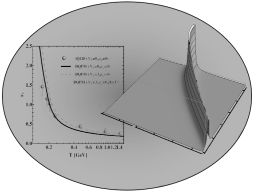

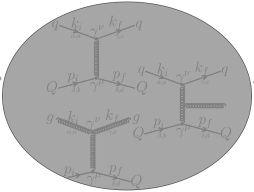

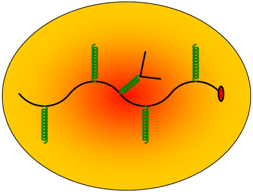

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HQ Transport properties at finite (T,μ_q)

$$\frac{d<\mathcal{X}>}{dt} = \frac{1}{(2\pi)^5 2E_p}\int \frac{d^3q}{2E_q} f(\vec{q}) \int \frac{d^3q'}{2E_{q'}} \int \frac{d^3p'}{2E_{p'}} \delta^{(4)}(P_{in}-P_{fin})\, \mathcal{X} \sum |\mathcal{M}_{2,2}|$$

- $\mathcal{X} = 1 \mapsto$ Interaction rate : $\mathcal{R}(p_Q, T, \mu_q) = \frac{dN_{coll}}{dt}$
- $\mathcal{X} = (E-E') \mapsto$ Energy Loss : $\frac{dE}{dt}(p_Q, T, \mu_q)$
- $\mathcal{X} = (\vec{p}-\vec{p}') \mapsto$ Drag coefficient : $\mathcal{A}(p_Q, T, \mu_q)$
- $\mathcal{X} = (p^i - p'^i)(p^j - p'^j) \mapsto$ Diffusion coefficient : $B^{ij}(p_Q, T)$

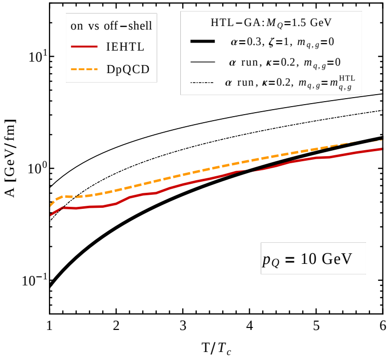
1. On-Shell case

$$Tr^{\rm on}_{(i)} = \int \frac{d^3p_i}{(2\pi)^3 2E_i}, \qquad \sum|\mathcal{M}_{2,2}| \equiv \sum|\mathcal{M}^{HTL-GA}_{2,2}|, \ \ \sum|\mathcal{M}^{DpQCD}_{2,2}|$$

2. Off-Shell case

$$Tr^{\rm on}_{(i)} \to Tr^{\rm off}_{(i)} = \int \frac{d^4p_i}{(2\pi)^4}\rho_i(p_i)\Theta(\omega_i), \qquad \frac{1}{2E_p} \to \int \frac{d\omega}{2\pi}\rho_p(\omega)\theta(\omega), \qquad \sum|\mathcal{M}_{2,2}| \equiv \sum|\mathcal{M}^{IEHTL}_{2,2}|$$

HQ energy and longitudinal momentum losses at finite T



Perturbative approaches

- HTL-GA
  - $\alpha_s(Q^2)$, massless q, g/massive $m_{q,g} = m^{HTL}_{q,g}$
  - $G^{\mu\nu}(q, m_g) = -i\, \dfrac{g_{\mu\nu}}{q^2 - \kappa \tilde{m}_D^2}$, $\kappa \approx 0.2$
- Naive-pQCD
  - $\alpha_s = 0.3$, $G^{\mu\nu}(q, m_g) = -i\, \dfrac{g_{\mu\nu}}{q^2 - m_D^2}$, $m_D = gT$

Gossiaux et al, Prog.Theor.Phys.Suppl. 193 (2012) 110-116
Phys.Rev. C78 (2008) 014904, C79 (2009) 044906,

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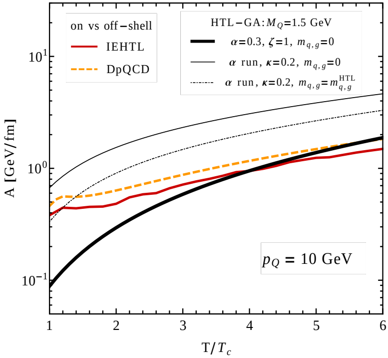

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- On- $\rightarrow$ off-shell : noticeable difference in A, dE/dx (propagators + asymmetry of $\rho^{BW}(m)$)
- pQCD $\rightarrow$ non-pQCD based models : reduction of A, dE/dx
- Finite $m_{q,g}$ $\rightarrow$ reduction of the drag coefficient, dE/dx in the HTL-GA approach
- pQCD α_s cst $\rightarrow$ α_s running : large effect in A, dE/dx temperature dependence
- Enhancement of DpQCD/IEHTL at low temperatures $\rightarrow$ strong increase of α_s (infrared enhancement)

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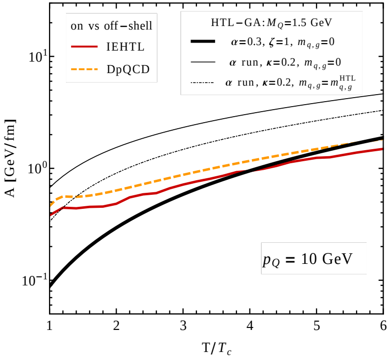
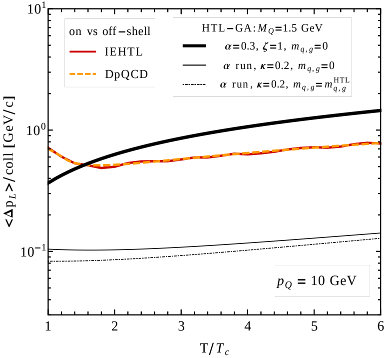
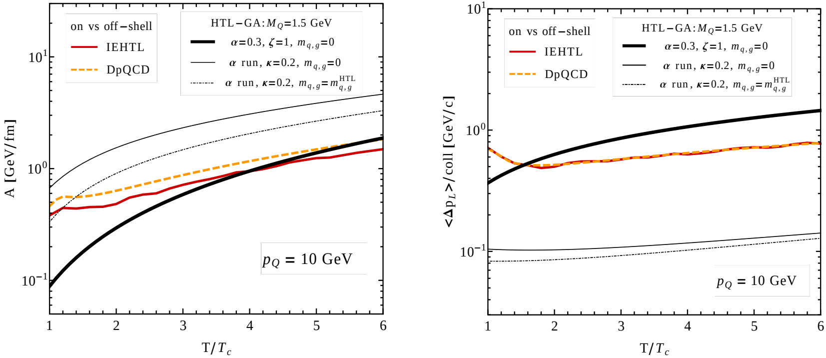




- On- $\rightarrow$ off-shell : noticeable difference in A, dE/dx (propagators + asymmetry of $\rho^{BW}(m)$)
- pQCD $\rightarrow$ non-pQCD based models : reduction of A, dE/dx but enhancement of $\langle \Delta p_L \rangle$
- Finite $m_{q,g}$ $\rightarrow$ reduction of the drag coefficient, dE/dx and $\langle \Delta p_L \rangle$ in the HTL-GA approach
- pQCD α_s cst $\rightarrow$ α_s running : large effect in A, dE/dx and $\langle \Delta p_L \rangle$ temperature dependence
- Enhancement of DpQCD/IEHTL at low temperatures $\rightarrow$ strong increase of α_s (infrared enhancement)
- A, dE/dx and $< \Delta p_L >$ depend on : i) our description of $\sigma^{q,g-Q}$, ii) nature of the QGP

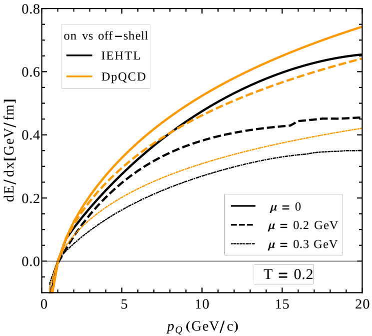
HQ energy and longitudinal momentum losses at finite T



- On- → off-shell : noticeable difference in A, dE/dx (propagators + asymmetry of $\rho^{BW}(m)$)
- pQCD → non-pQCD based models : reduction of A, dE/dx but enhancement of $\langle \Delta p_L \rangle$
- Finite $m_{q,g}$ → reduction of the drag coefficient, dE/dx and $\langle \Delta p_L \rangle$ in the HTL-GA approach
- pQCD α_s cst → α_s running : large effect in A, dE/dx and $\langle \Delta p_L \rangle$ temperature dependence

A, dE/dx, $\langle \Delta p_L \rangle$, ...vary substantially due to different assumptions/ingredients → Systematic study of the models on the level of : i) microscopic/mesoscopic ingredients, ii) macroscopic observables v_2, R_{AA}

HQ energy and longitudinal momentum losses at finite (T, μ_q)



- On- $\rightarrow$ off-shell : noticeable difference in dE/dx, A but uniform as $\mu_q \nearrow$
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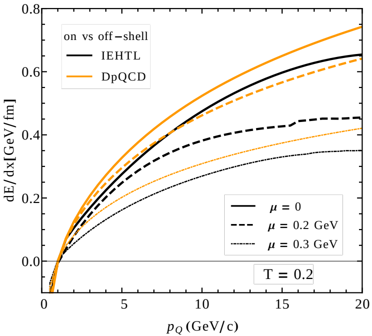

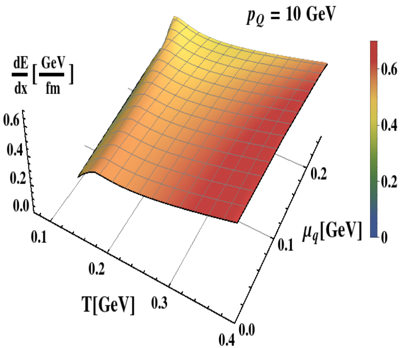

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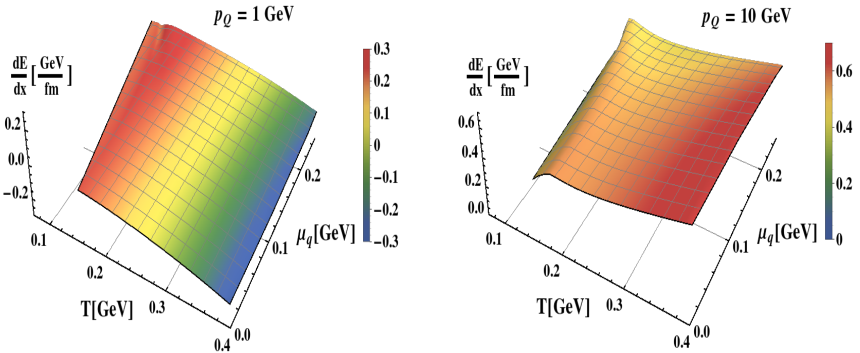

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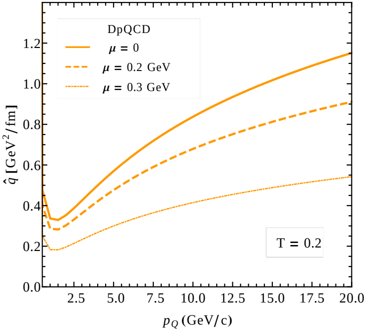
- $\mu_q = 0 \to$ finite μ_q : smooth dependence on both variables T and μ
- $\mu_q = 0$: for low p_Q, HQ gains energy to approach thermal equilibrium ($dE/dx < 0$)
- $\mu_q \neq 0$: for low p_Q, HQ losses energy even at small T

HQ might loss considerable energy not only in a HOT but also in a DENSE medium

HQ transverse momentum loss at finite (T,μ_q)



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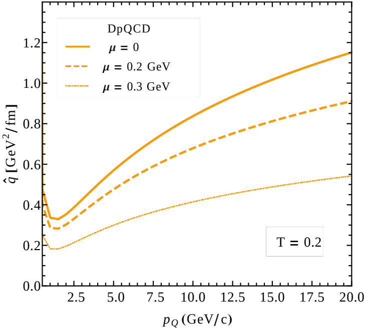
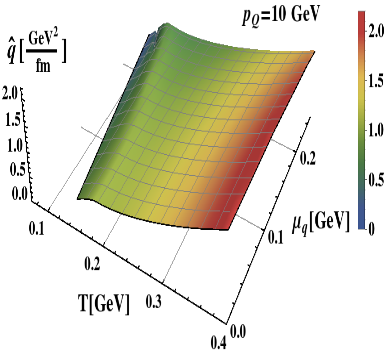
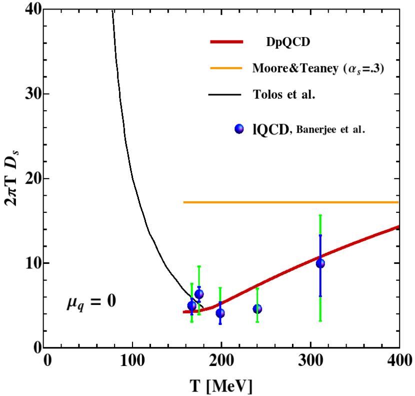




- $\mu_q = 0 \rightarrow$ finite μ_q : decrease of $\hat{q}$ but at $T = 0.2$ GeV $\Rightarrow$ varying (T, μ_q) ? ?
- $\mu_q = 0 \rightarrow$ finite μ_q : decrease of $\hat{q}$, $\forall$ T, $\forall$ p_Q

HQ transverse momentum loss is more remarkable in a HOT medium. The DENSE medium has little influence on $\frac{\Delta < p_T^2 >}{\Delta x}$.

HQ spatial diffusion coefficient in HOT and DENSE medium



$\Longrightarrow$ $\mu \neq 0$

- $D_s = T/(M_Q \eta_D) = 2T^2/\kappa$; $\kappa = d < (\vec{p} - \vec{p}')^2 > /3d\tau$, Nice agreement around the cross over T_c at $\mu = 0$
- Minimum at T_c for FAIR energies ? ?

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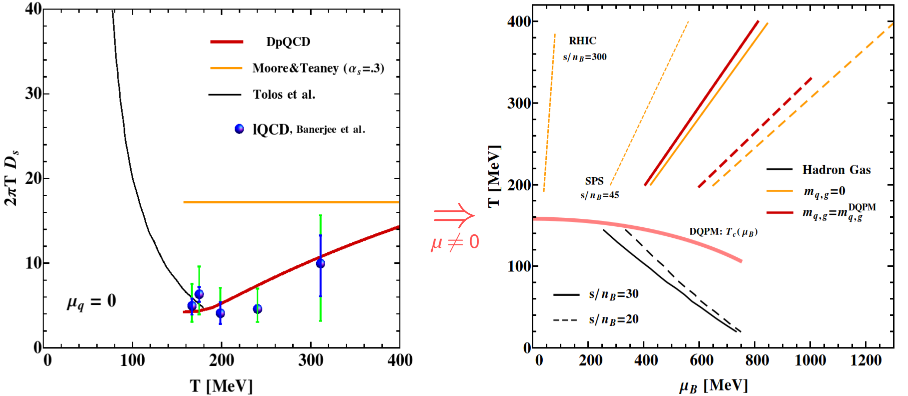

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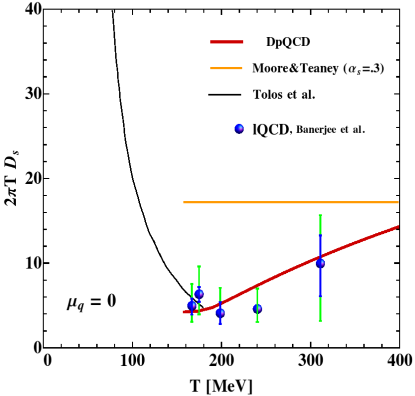

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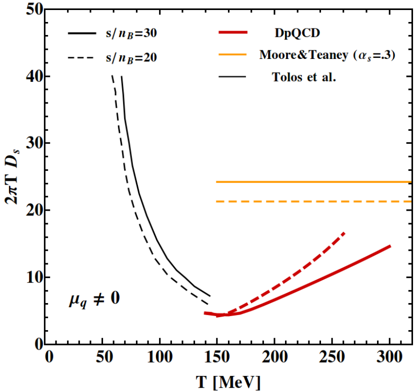

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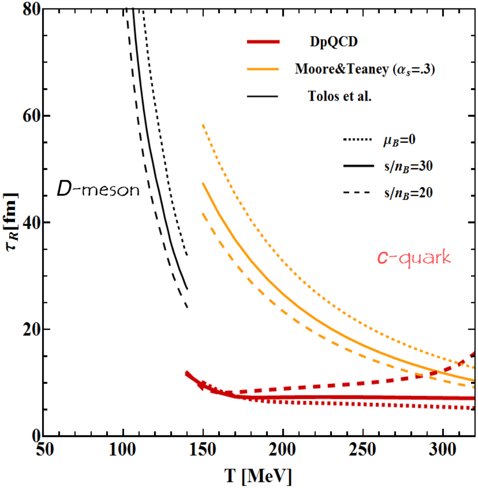
- Adiabatic FAIR trajectories (with $S/N_B = 20 - 30$) following . . .
- Continuous transition → No 1st order transition → Consistent with our model assumptions
- HQ physics : Both partonic and hadronic worlds contribute ? → quantitative studies

HQ relaxation time in HOT and DENSE medium



- Almost good matching between c-quark and D-meson relaxation times
- Perturbative models → large c-quark relaxation time around T_c
- Non-perturbative treatment of c-quark interactions with q,g → necessary around T_c
- $\mu_q = 0 \rightarrow \mu_q$ finite : small enhancement of τ_R, due to a decrease of the q,g-Q interaction strength

Moore and Teaney, PRC 71, 064904 (2005)
Tolos et al, PRD 88, 074019 (2013)

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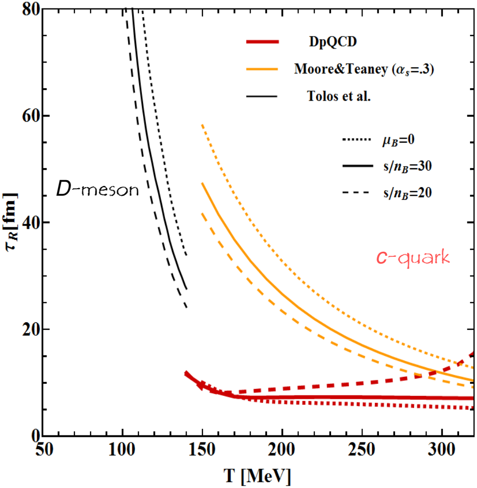

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Strong indication that close to the phase transition the effective degrees-of-freedom are dynamically dressed massive quasi-particles and not massless quarks and gluons.

Moore and Teaney, PRC 71, 064904 (2005)
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3 Perspectives : HQ dynamics in the QGP at finite (T,μ)

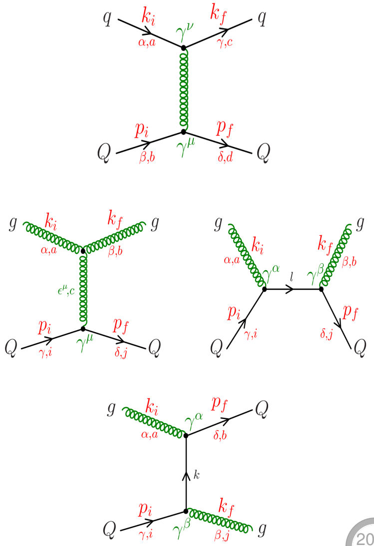
- Extend our model to include 1st order transition
- Implement the HQ partonic processes into the PHSD transport approach to study HQ dynamics at CBM, SPS, RHIC and LHC

Back up

Cross Sections at finite temperature

1 Problems

- Coupling constant α_s (qqg, ggg and $gggg$ vertices)
- Regularization cut-off $\frac{1}{t-\mu}$
- Quark and gluon propagators at finite temperature and chemical potential
- q,Q,g masses at finite temperature and chemical potential
- Gauge invariance of the amplitudes



Dynamical quasi-particle model (DQPM) at finite T

1 DQPM entropy density

$$s_i^{DQP} = -\int \frac{d\omega}{2\pi}\frac{d^3p}{(2\pi)^3}\frac{\partial n_i}{\partial T}\left(\Im \ln(-\Delta^{-1}) + \Im\Pi \times \Re\Delta\right)$$

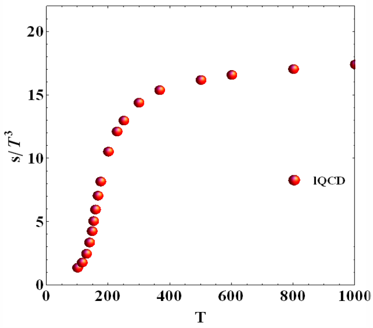
Peshier, Cassing, PRL 94 (2005) 172301
Cassing, NPA 791 (2007) 365 ; NPA 793 (2007)
lQCD : WB JHEP. 09 (2010) 073 ; 11 (2010) 077

$$s^{DQP} = s^{(0),DQP} + \Delta s^{DQP},$$

$$s^{(0),DQP} = \frac{1}{T}\int\frac{d^3p}{(2\pi)^3}\left(-T\ln(1-e^{-\omega/T}) + \omega\, n_B(\omega)\right)$$

$$\Delta s^{DQP} = \int\frac{d\omega}{2\pi}\frac{d^3p}{(2\pi)^3}\frac{dn_B}{dT}\left(\arctan\lambda - \frac{\lambda}{1+\lambda^2}\right),$$

with : $\lambda = \Im\Delta/\Re\Delta$



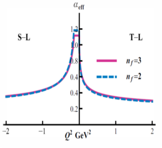
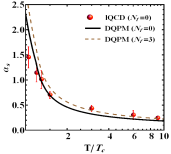
$$\Delta(p_0,\boldsymbol{p}) = \int_{-\infty}^{+\infty}\frac{d\omega}{2\pi}\frac{A(\omega,\boldsymbol{p})}{p_0-\omega}$$

$$\Updownarrow$$

$$A(\omega,\boldsymbol{p}) = \frac{\gamma}{E}\left(\frac{1}{(\omega-E)^2+\gamma^2} - \frac{1}{(\omega+E)^2+\gamma^2}\right)$$

$T_c = 0.158$ GeV, $T_s = 0.56\,T_c$
$\lambda = 2.42$, $c = 14.4$

On- vs Off-shell; pQCD vs non-pQCD based approaches

	Naive pQCD	HTL-GA	DpQCD	IEHTL
α_s	Constant $\alpha_s = 0.3$			
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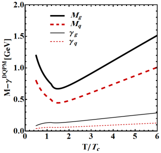
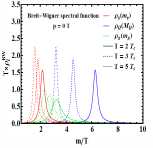
Masses	$M_c = 1.5$ GeV, $m_q = m_g = 0$			

On- vs Off-shell ; pQCD vs non-pQCD based approaches

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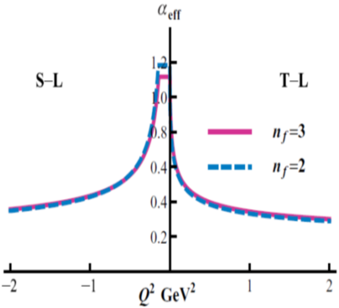
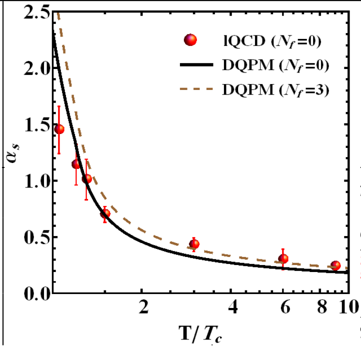
α_s				
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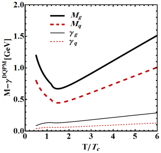
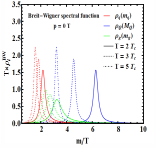
Masses	$M_c = 1.5$ GeV, $m_q = m_g = 0$			

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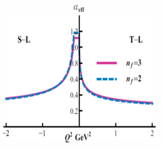
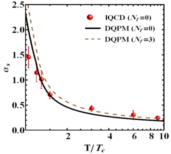
α_s	Constant $\alpha_s = 0.3$			
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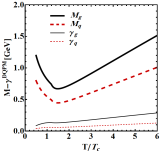
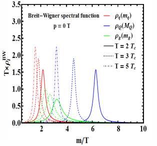
Masses	$M_c = 1.5$ GeV, $m_q = m_g = 0$			

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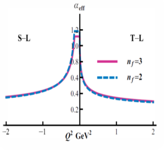

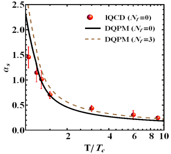

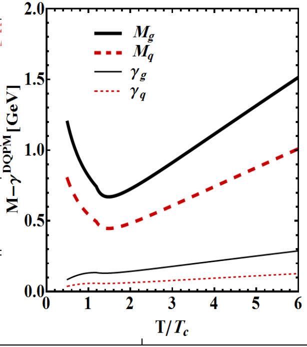

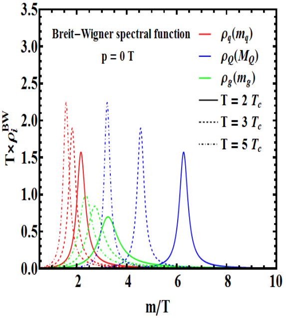

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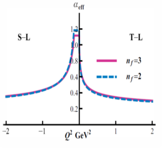
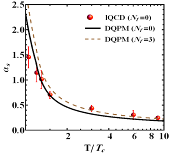
α_s	Constant $\alpha_s = 0.3$			
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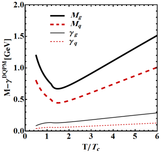
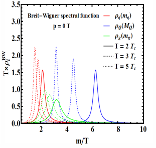
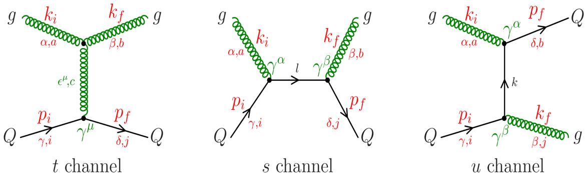
Masses	$M_c = 1.5$ GeV, $m_q = m_g = 0$			

Heavy Quark Elastic Scattering

1 gQ Elastic Scattering

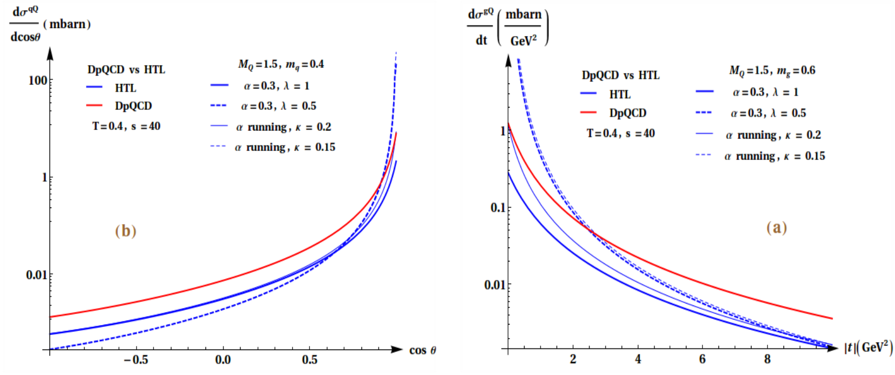
Additional Problems : 3 gluon vertex, gauge invariance



- **pQCD (massless g, q)**
  Transverse gauge :
  $$\sum_{spins} \varepsilon_i^{\mu} \varepsilon_i^{\star\mu'} = -g^{\mu\mu'} + \frac{2}{s}(p_i^{\mu} k_i^{\mu'} + p_i^{\mu'} k_i^{\mu})$$
- **HTL (Hard Thermal Loop)**
  Transverse gauge
  $$G_F^{\mu\nu}(q, m_g) = -i \, \frac{g_{\mu\nu}}{q^2 - \kappa m_D^2}$$
- **DpQCD (Dressed pQCD)**
  Lorentz Covariance : $\sum_{pol,i} \varepsilon_{i,\alpha}\varepsilon_{i,\lambda} = g_{\alpha\lambda} - \frac{k_{i,\alpha}\, k_{i,\lambda}}{(m_g^i)^2}$,
  $$G_F^{\mu\nu}(q, m_g) = -i \, \frac{g_{\mu\nu} - q_\mu q_\nu / m_g^2}{q^2 - m_g^2}, \quad S_F(p, M_Q) = \frac{\not{p} + M_Q}{p^2 - M_Q^2}$$
- **IEHTL (Infrared Enhanced HTL)**
  Lorentz Covariance, $G_F^{\mu\nu}(q, m_g) = -i \, \frac{g_{\mu\nu} - q_\mu q_\nu / m_g^2}{q_0^2 - \mathbf{q}^2 - m_g^2 + i2\gamma_g q_0}$
  $$S_F(p, M_Q) = \frac{\not{p} + M_Q}{p_0^2 - \mathbf{p}^2 - M_Q^2 + i2\gamma_Q p_0}$$

Heavy Quark Elastic Scattering

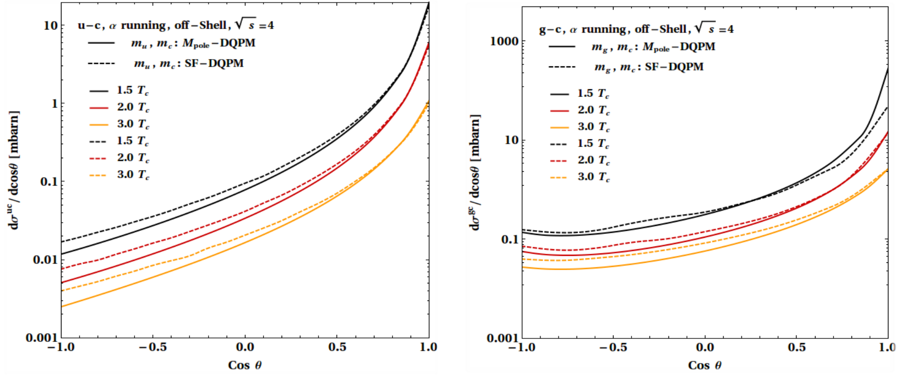
❶ σ_{qQ}, σ_{gQ} : HTL vs DpQCD



- HTL/DpQCD : Different behaviours for small/large "t"
- σ_{qQ} higher value for running + $\kappa = 0.2$ (differences related to $m_g^{excganged}$)
- σ_{qQ}/σ_{gQ} : Same conclusions with larger values for σ_{gQ} ● $\sigma(T \nearrow) < \sigma(T \searrow)$

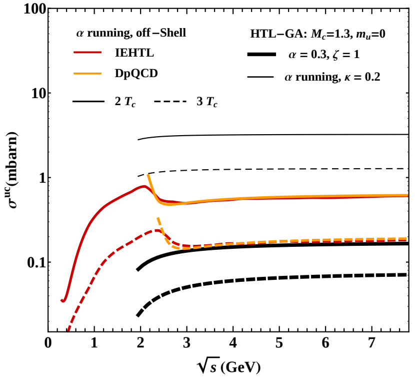
Heavy Quark Elastic Scattering

1 σ_{qQ}, σ_{gQ} : DpQCD (On-Shell) vs IEHTL (Off-Shell)



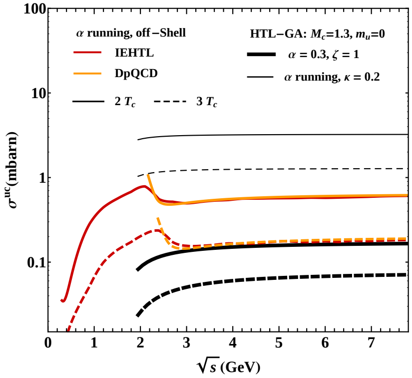
- Deviation of off-shell curves compared to on-shell ones for large angles θ
- Effect of $A(m,T)$ on σ_{qQ} is negligible (small DQPM parton width)
- $\sigma_{qQ}(T \nearrow) < \sigma_{qQ}(T \searrow)$

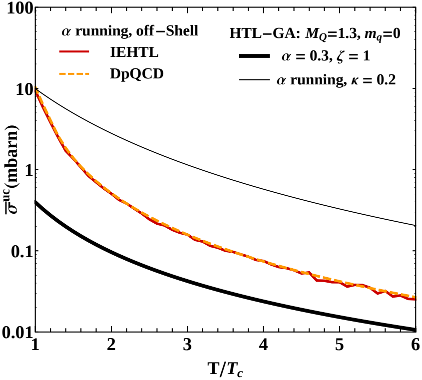
HQ elastic scattering at finite T : HTL-GA vs DpQCD vs IEHTL



- Different behaviours between HTL-GA and DpQCD/IEHTL for small/large "t"
- σ^{qQ} larger value for HTL-GA with α running + $\kappa = 0.2$ (differences related to $m_g^{\text{exchanged}}$)
- Effect of $\rho^{BW}(m)$ is negligible (small parton width), except reducing the kinematic threshold
- Same conclusions as σ^{qQ} can be drawn with larger values for σ^{gQ} ($9/4$: color Casimir operators)

HQ elastic scattering at finite T : HTL-GA vs DpQCD vs IEHTL





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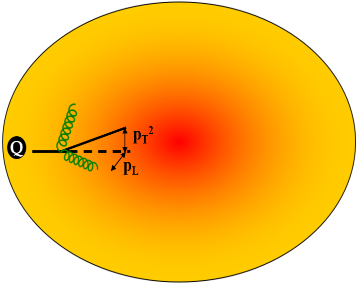
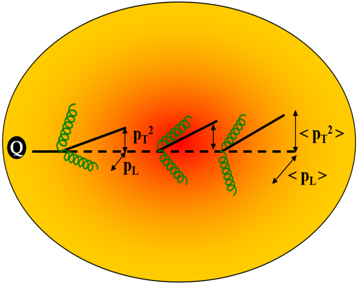
- $\bar{\sigma}^{qQ}$: diff power laws in T, i.e. $\bar{\sigma}^{qQ} \sim T^{-\beta}$ (diff β) → sizeable effect on the transport

HQ Transport properties



1. Single collision
   - $< p_L >$: average longitudinal transfer momentum
   - $< p_T^2 >$: average transverse transfer momentum squared

HQ Transport properties



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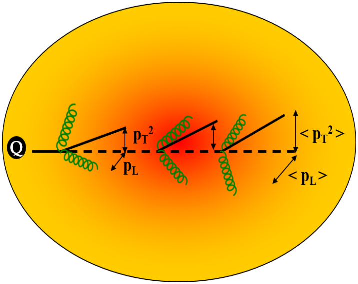
2. **Average over number of collisions**
   - Drag : $A = < p_L > \times \frac{N_{coll}}{fm}$
   - $\hat{q}$: $\hat{q} = \frac{d < p_T^2 >}{dx} = \frac{< p_T^2 >_{\text{single coll}}}{\ell} = \frac{2}{\nu}\, b_T$
   - $B^{ij}(\vec{p}) = b_L(p)\, \hat{p}^i \hat{p}^j + b_T(p)\, (\delta^{ij} - \hat{p}^i \hat{p}^j)$,
     with : $b_L(p) = \frac{< \Delta p_L^2 >}{\Delta t}$; $\quad b_T = \frac{1}{2} \frac{< \Delta p_T^2 >}{\Delta t}$
   - Collisional energy loss : $\frac{d < E >}{dx}$
   - relaxation time τ/mean free path

HQ Transport properties



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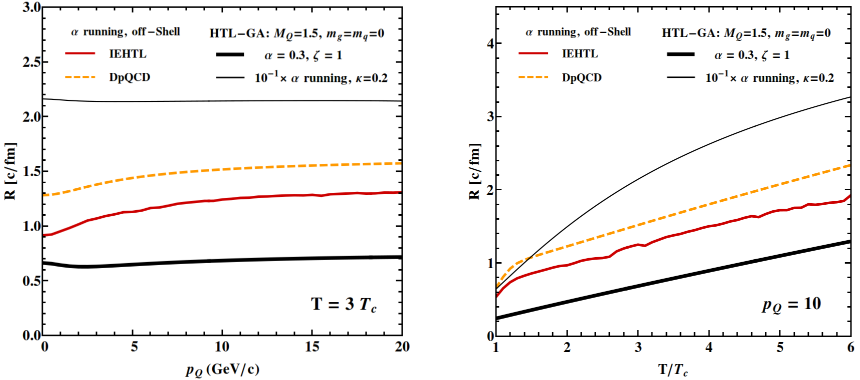
$\mathcal{R}$: Interaction rate



- $\mathcal{R}$ is larger when $\sigma^{q,g-Q}$ is described by HTL-GA with running α_s as compared to the DpQCD/IEHTL models. $\mathcal{R}$ (α_s running) > $\mathcal{R}$ (α_s cst).
- Effect of $\rho(m, T)$ on $\mathcal{R}$ is noticeable (shift of the off-shell threshold)
- $\mathcal{R}$ depends on : i) our description of $\sigma^{q,g-Q}$, ii) nature of the QGP constituents

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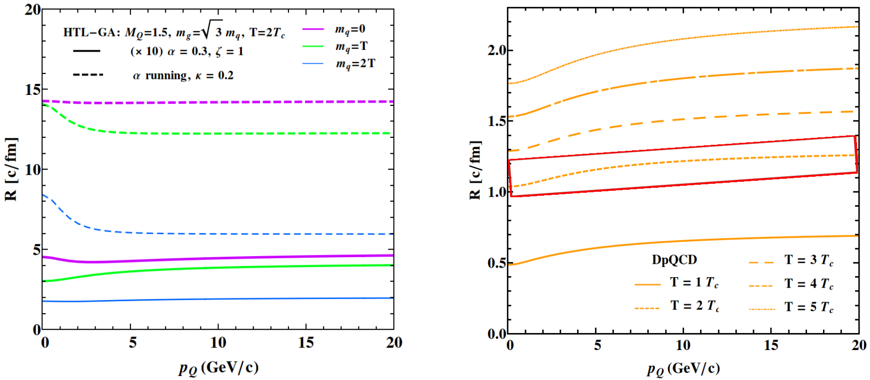

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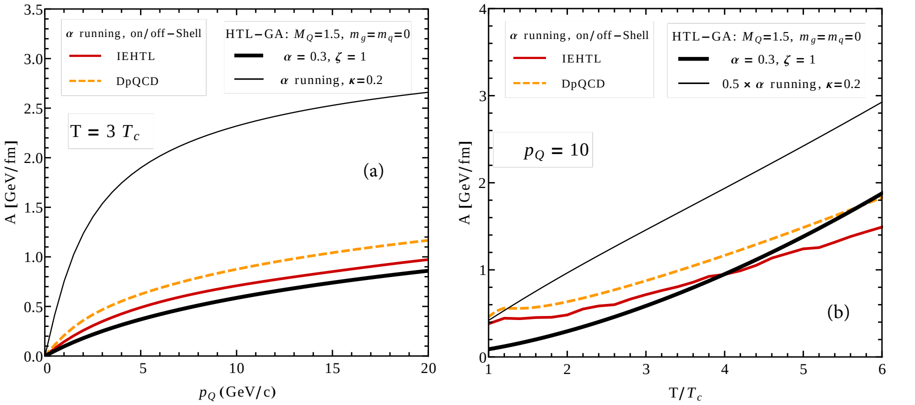
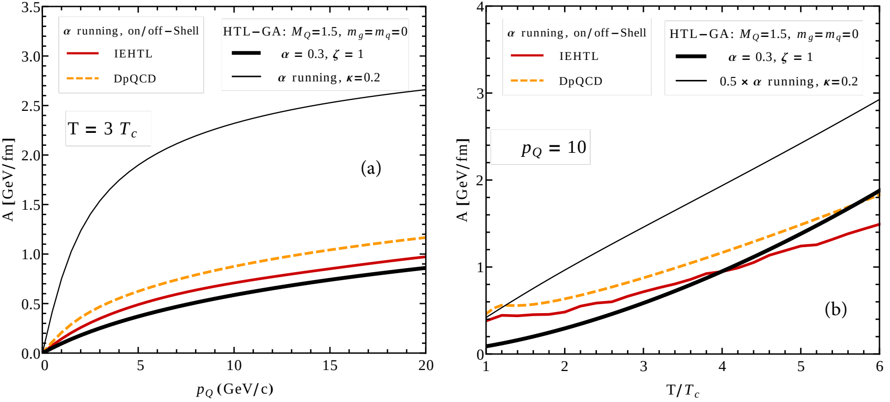
$\mathcal{A}$: Drag force and coefficient



- On-shell → off-shell : noticeable difference in $\mathcal{A}$ (shift of the off-shell threshold)
- pQCD → non-pQCD based models : reduction of $\mathcal{A}$.
- $\mathcal{A}$ is larger for HTL-GA with running α_s as compared to the DpQCD/IEHTL models.

$\mathcal{A}$: Drag force and coefficient



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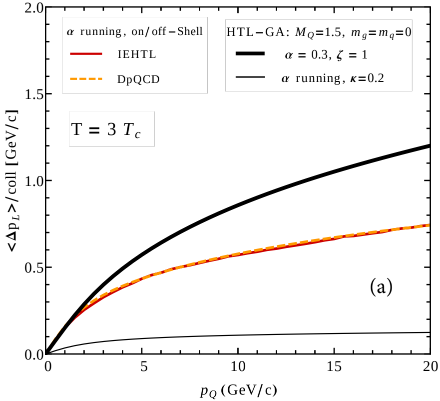
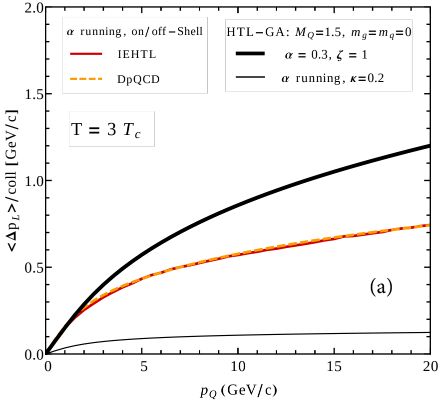
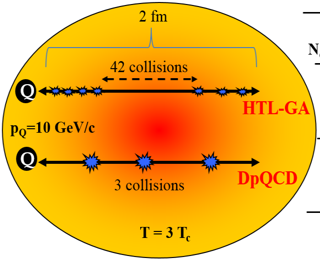
$<\Delta p_L> = \mathcal{A}/\mathcal{R}ate$: average longitudinal momentum loss



- Opposite trends are observed for the momentum transfer per collision $<\Delta p_L>$ 🙂
- $\rightarrow$ finite parton mass leads to an increase of the momentum transfer per collision

$<\Delta p_L>= \mathcal{A}/\mathcal{R}ate$: average longitudinal momentum loss

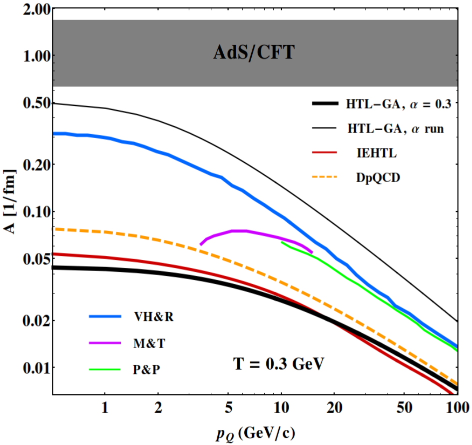




R N_{coll}/fm	A GeV/fm	$<\Delta p_L>$ GeV
~ 21	~ 2.5	~ 0.12
~ 1.5	~ 0.85	~ 0.57

- Opposite trends are observed for the momentum transfer per collision $<\Delta p_L>$ ☺
- → finite parton mass leads to an increase of the momentum transfer per collision
- Q undergoes more kicks from massless medium partons than the massive ones but nevertheless transfer less energy → finite $m_{q,g}$ + (α_s, IR regulator)

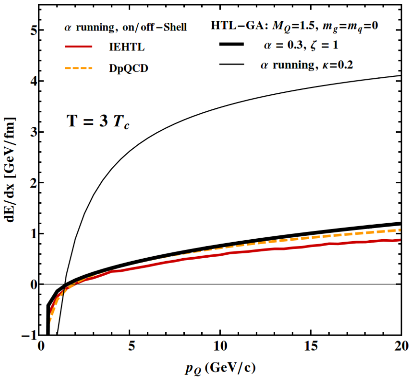
Drag coefficient : extended models comparison

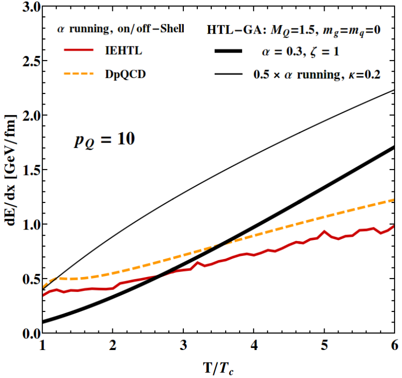


- $\mathcal{A}$ is momentum independent in AdS/CFT approach. All pQCD and non-pQCD based drag coefficients ↘ with ↗ p_Q.
- $\mathcal{A}$ vary substantially due to different assumptions/ ingredients
- → Systematic study between the models on the level of
  i) microscopic/mesoscopic ingredients,
  ii) macroscopic observabes v_2, R_{AA}

P.B. Gossiaux & J. Aichelin 2009 J. Phys. G : Nucl. Part. Phys. 36 064028

dE/dx : Energy loss





- Conclusions for $\mathcal{A}$ remain valid for dE/dx → reduction of dE/dx for finite $m_{q,g}$
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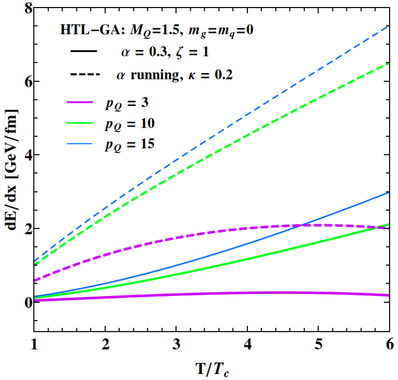
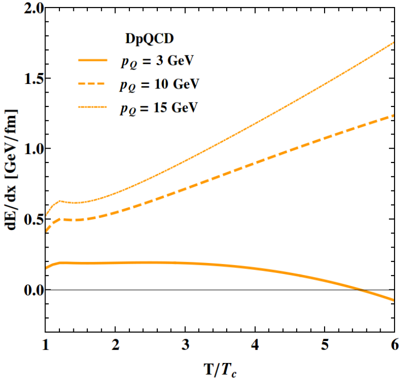
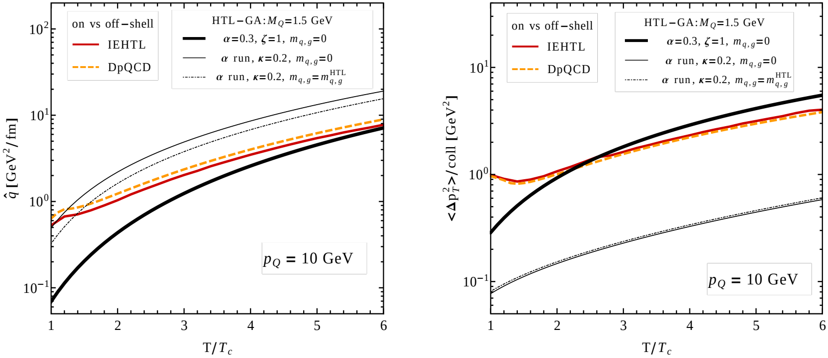
dE/dx : Energy loss





- Conclusions for $\mathcal{A}$ remain valid for dE/dx → reduction of dE/dx for finite $m_{q,g}$
- Q undergoes more kicks from massless medium partons than the massive ones but nevertheless transfer less energy
- For large T the low p_Q HQ starts to gain energy to approach thermal equilibrium

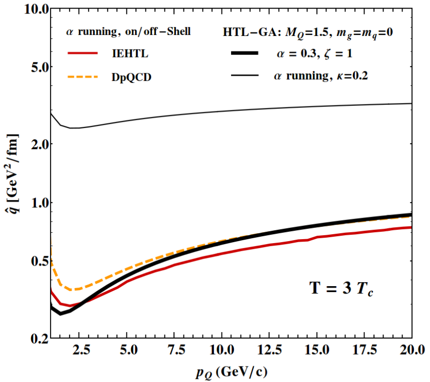
HQ transverse momentum loss at finite T

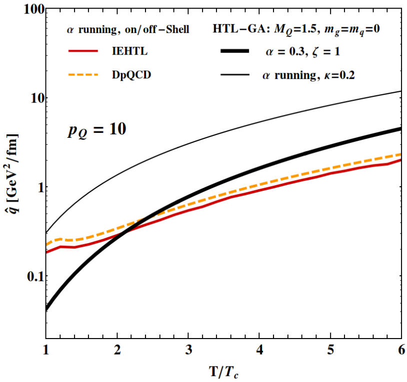


- $\hat{q} = \frac{\Delta <p_T^2>}{\Delta x} = \frac{4E}{p}\, B_T$, $\langle \Delta p_T^2 \rangle \propto \hat{q}/R \propto \langle |t| \rangle$, $\langle \Delta p_L \rangle \propto A/R \propto \frac{\langle |t| \rangle}{mq}$, with : $\langle |t| \rangle = [\langle \sigma |t| \rangle (q = \frac{m_Q p}{M_Q})]/\sigma_{as}$
- Finite $m_{q,g}$ $\rightarrow$ increase of the transverse Q momentum loss per collision in the HTL-GA
- More kicks in HTL-GA but less energy/momentum transfer per collision than in DpQCD/IEHTL
- $\sim$ temperature independence of $\langle \Delta p_L \rangle$, but large increase of $\langle \Delta p_T^2 \rangle$ with T $\nearrow$

A, dE/dx, $\langle \Delta p_L \rangle$, $\hat{q}$, ...vary substantially due to different assumptions/ingredients $\rightarrow$ Systematic study of the models on the level of : i) microscopic/mesoscopic ingredients, ii) macroscopic observables v_2, R_{AA}

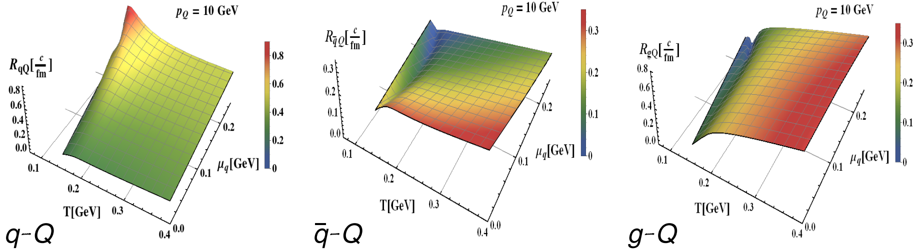
$\hat{q} = \frac{d<p_T^2>}{dx}$: average transverse momentum loss





- Q transverse momentum loss : Massless HQ in HTL-GA (α_s running) $\gg$ massive on-shell case (DpQCD) and off-shell (IEHTL) → finite $m_{q,g}$ + (α_s, IR regulator)
- Collisions with massless q, g have a shorter mean free path than with massive q, g
- $T \nearrow \rightarrow$ huge variation in the transverse Q momentum (HTL-GA, DpQCD/IEHTL)

HQ interaction rates and energy/momentum losses at finite (T, μ_q)



DENSE matter : HQ interacts mores with q than $\bar{q}, g$, due to the excess of q.

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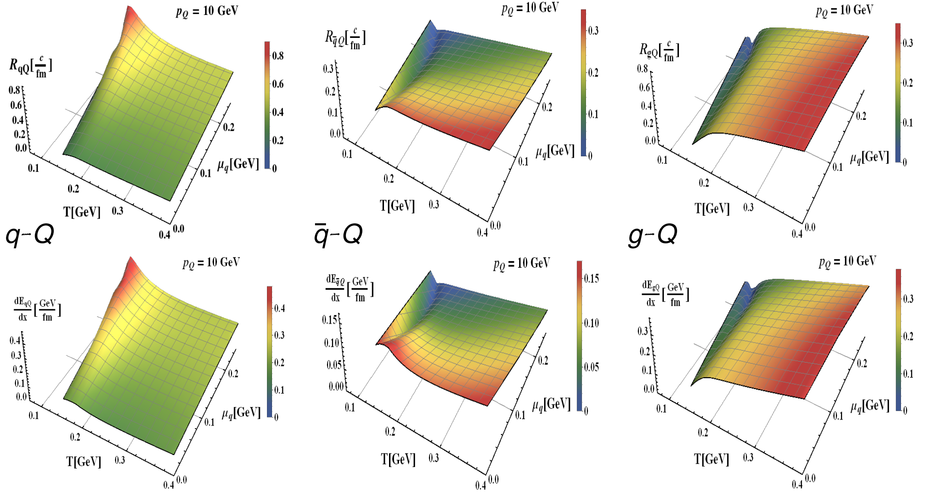

DENSE matter : HQ interacts mores with q than $\bar{q}, g$, due to the excess of q.

HQ energy/momentum losses scales with the interaction rates $\rightarrow dE_{qQ}/dx > dE_{\bar{q}Q}/dx$