Interplay Between Quantum and Classical Corrections to $\hat{q}$

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INT Workshop: Probing QCD at High Energy and Density with Jets

Outline

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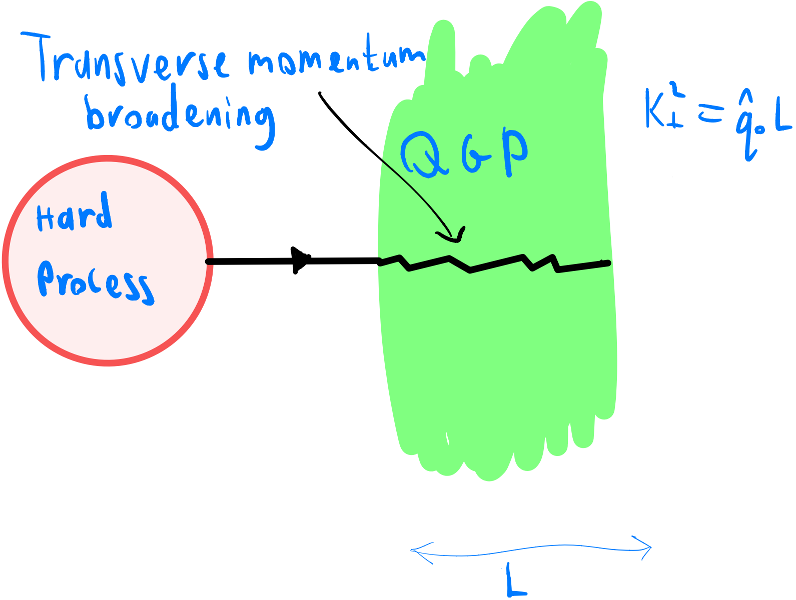
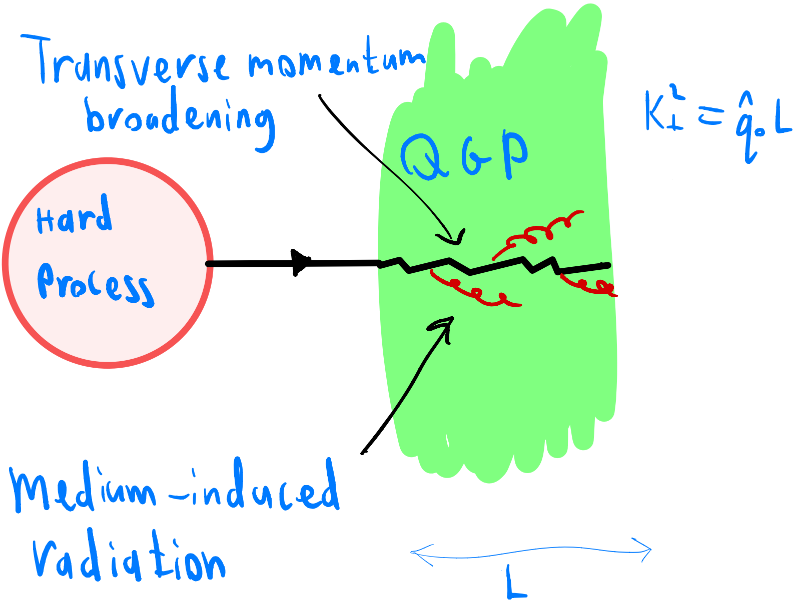
Jet Energy Loss




Transverse momentum
broadening
QGP
$k_\perp^2 \simeq \hat{q}_0 L$
Hard
Process
Medium-induced
radiation
L

BACKGROUND

- $\hat{q}$ has been extracted from:
  - Experimental data [Burke et al., 2014, Han et al., 2022]
  - Bayesian analysis [Cao et al., 2021, Xie et al., 2023]

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- Plays role of transport coefficient in kinetic description

- Controls in-medium shower in multiple scattering regime

- Can be related to the transverse scattering rate, $\mathcal{C}(k_\perp)$

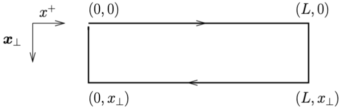
$$\hat{q}(\mu) = \int^{\mu} \frac{d^2 k_\perp}{(2\pi)^2} k_\perp^2 \mathcal{C}(k_\perp)$$

$$\lim_{L\to\infty} \langle W(x_\perp) \rangle = \exp(-\mathcal{C}(x_\perp)L)$$

- $W(x_\perp)$ is a Wilson loop defined in the $(x^+, x_\perp)$ plane

  [Casalderrey-Solana and Teaney, 2007, D'Eramo et al., 2011, Benzke et al., 2013]

- Can compute perturbatively for the case of a **weakly coupled QGP**



[Ghiglieri and Teaney, 2015]

Thermal Scales in a Weakly Coupled QGP

- T, hard scale associated with energy of individual particles
  $\Rightarrow$ hard-hard interactions can be described perturbatively

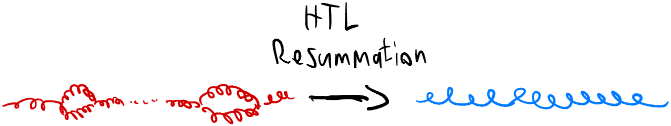
- gT, soft scale associated with energy of collective excitations
  $\Rightarrow$ soft-soft interactions can also be described perturbatively

- g^2T, ultrasoft scale is associated with nonperturbative physics
  $\Rightarrow$ loops can be added at no extra cost (Linde problem)
  $\Rightarrow$ cannot use perturbation theory

HTL Effective Theory

- For hard-soft interactions, we are not so lucky either... Turns out that one can add loops for free $\implies$ perturbative expansion breaks down

- Hard Thermal Loop (HTL) effective theory comes to the rescue, allowing us to resum these loops



Summary of Perturbative Expansion

At leading order, $\hat{q}_0 \sim g^4 T^3$:

- Contribution from hard scale [Arnold and Xiao, 2008]
- Contribution from soft scale [Aurenche et al., 2002]

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At $\mathcal{O}(g)$: contribution from soft scale [Caron-Huot, 2009]

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- soft scale
- ultrasoft scale
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Summary of Perturbative Expansion

At leading order, $\hat{q}_0 \sim g^4T^3$:

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At $\mathcal{O}(g^2)$, receives contributions from:

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- ultrasoft scale
- Logarithmically enhanced **quantum corrections**

Outline

Classical Corrections – Background

- Corrections coming from exchange of gluons between medium and parton that are $\lesssim gT$

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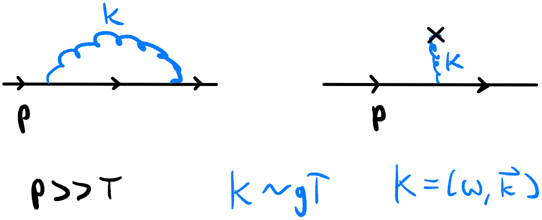
$$\implies \quad n_B(\omega) \equiv \frac{1}{\exp\left(\frac{\omega}{T}\right) - 1} \gg 1$$

$\implies$ corrections are enhanced!



Mapping onto EQCD

- Can compute some of these classical corrections using **Hard Thermal Loop** (HTL) effective theory, but analytically difficult in practice

- Thanks to observation from [Caron-Huot, 2009], these classical corrections can be computed in **Electrostatic QCD** (EQCD)

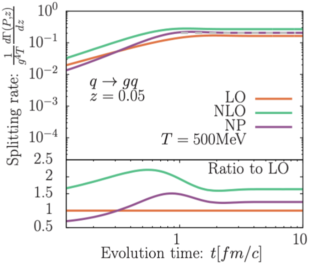
- EQCD is a 3 dimensional theory of static modes

  $\Rightarrow$ Can be studied on the **lattice**!

  $\Rightarrow$ Paved way for **non-perturbative** (NP) determination of classical corrections to $\mathcal{C}(k_\perp)$!

- Series of papers [Panero et al., 2014, Moore et al., 2021, Schlichting and Soudi, 2021], culminated with NP determination of in-medium splitting rate for medium of finite size

- Difference between rate from LO kernel and NP kernel can be up to 50%!



Outline

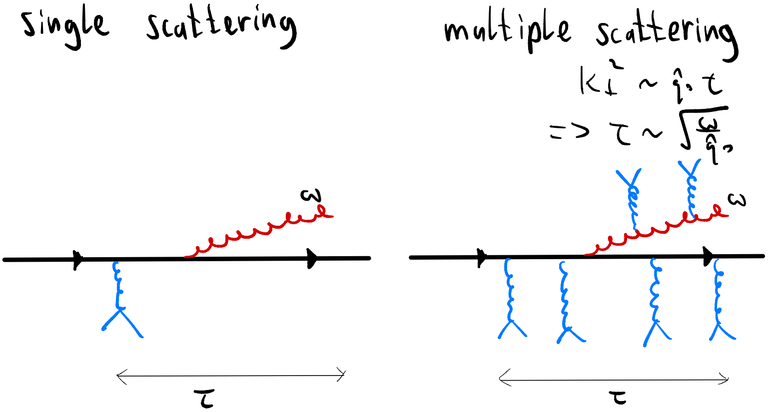
Quantum Corrections – Background

- $\mathcal{O}(g^2)$ corrections found to have double logarithmic $\sim \ln^2(L/\tau_{\text{min}})$ and single logarithmic enhancements by [Liou et al., 2013](LMW) and separately by [Blaizot et al., 2014](BDIM) for a medium with **static scattering centers**

- These are **radiative, quantum corrections**, coming from keeping track of the recoil during the medium-induced emission of a gluon

Physical Picture

- LMW and BDIM argued that these **quantum corrections** come from the single-scattering regime
- formation time $\tau = \omega / k_\perp^2$



Quantum Corrections – Background

- Resummation of double logs performed recently
  [Caucal and Mehtar-Tani, 2022]
  $\Rightarrow$ effectively renormalising $\hat{q}(\mu)$
- Same double logs found in calculation of double gluon emission with overlapping formation times [Arnold et al., 2021]
  $\Rightarrow$ Universality

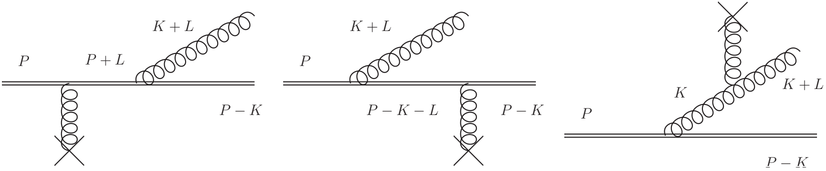
- Both LMW and BDIM calculations used the **Harmonic Oscillator Approximation (HOA)**, which is more well-suited to multiple scattering regime

- Both calculations also assume medium to be composed of **static scattering centers**
  $\rightarrow$ Not clear how phase spaces of classical $\mathcal{O}(g)$ and quantum $\mathcal{O}(g^2)$ corrections are connected

Which is larger: $K\mathcal{O}(g)$ or $\ln^2(\#)\mathcal{O}(g^2)$?

Hard to say... But can definitely make a start by revisiting computation of quantum corrections

Double Logs from the literature



$N = 1$ term in opacity expansion emerges from dipole picture

$$\delta\mathcal{C}(k_\perp,\rho)_{\text{LMW}} = 4\alpha_s C_R \int \frac{d\omega}{\omega} \int^{\rho} \frac{d^2 l_\perp}{(2\pi)^2} \mathcal{C}_0(l_\perp) \frac{l_\perp^2}{k_\perp^2 (\mathbf{k}_\perp + \mathbf{l}_\perp)^2} \tag{1}$$

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Double Logs from the literature

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$\downarrow$ $|\mathbf{k}_\perp+\mathbf{l}_\perp| \gg l_\perp \Rightarrow$ Single Scattering

$$\delta\mathcal{C}(k_\perp,\rho)_{\text{LMW}} = 4\alpha_s C_R \int \frac{d\omega}{\omega}\int^\rho \frac{d^2 l_\perp}{(2\pi)^2}\mathcal{C}_0(l_\perp)\frac{l_\perp^2}{k_\perp^4}$$

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$\hat{q}_0(\rho) \to \hat{q}_0 \Rightarrow$ HOA

$$\delta\mathcal{C}(k_\perp)_{\rm LMW} = 4\alpha_s C_R \hat{q}_0 \frac{1}{k_\perp^4}\int \frac{d\omega}{\omega}$$

Reminder: $\hat{q}(\mu) = \int^\mu \frac{d^2 k_\perp}{(2\pi)^2} k_\perp^2 \mathcal{C}(k_\perp)$

Double Logs from the literature

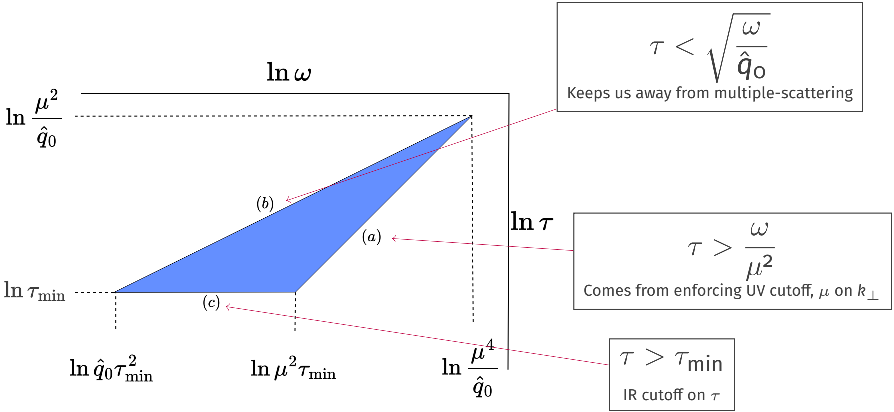
Convenient to work instead with formation time, $\tau = \frac{\omega}{k_\perp^2}$

$$\delta\hat{q}_{\mathrm{LMW}}(\mu) = 4\alpha_s C_R \hat{q}_0 \int^{\mu} \frac{d^2 k_\perp}{(2\pi)^2 k_\perp^2} \int \frac{d\omega}{\omega} = \frac{\alpha_s C_R}{\pi} \hat{q}_0 \int^{f(\mu)} \frac{d\tau}{\tau} \int \frac{d\omega}{\omega}$$

But what should limits be???

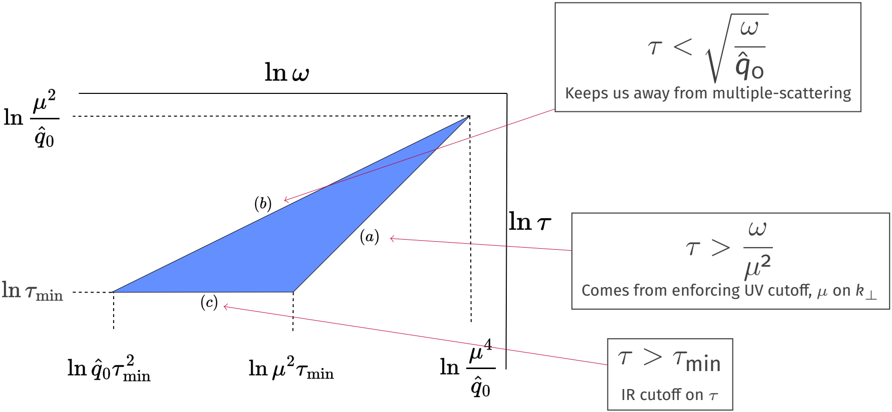
Will of course dictate size of logs!

Double Logs from the literature



$$\delta\hat{q}_{\mathrm{LMW}}(\mu) = \frac{\alpha_s C_R}{\pi}\hat{q}_0 \int_{\tau_{\min}}^{\mu^2/\hat{q}_0} \frac{d\tau}{\tau} \int_{\hat{q}_0\tau^2}^{\mu^2\tau} \frac{d\omega}{\omega} = \frac{\alpha_s C_R}{2\pi}\hat{q}_0 \ln^2 \frac{\mu^2}{\hat{q}_0\tau_{\min}}$$

Double Logs from the literature



$$\delta \hat{q}_{\mathrm{LMW}}(\mu) = \frac{\alpha_s C_R}{\pi} \hat{q}_0 \int_{\tau_{\min}}^{\mu^2/\hat{q}_0} \frac{d\tau}{\tau} \int_{\hat{q}_0 \tau^2}^{\mu^2 \tau} \frac{d\omega}{\omega} \overset{\mu^2 = \hat{q}_0 L}{=} \frac{\alpha_s C_R}{2\pi} \hat{q}_0 \ln^2 \frac{L}{\tau_{\min}}$$

Outline

From Static Scattering to a Weakly Coupled QGP

How to adapt BDIM/LMW result to weakly coupled QGP?

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$$\downarrow$$

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$$\Longrightarrow\; n_B(\omega) \equiv \frac{1}{e^{\frac{\omega}{T}}-1} \text{ can be ignored iff } \omega_{\rm min} = \hat{q}_0\tau_{\rm min}^2 \gg T$$

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↓

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$\implies n_B(\omega) \equiv \frac{1}{e^{\frac{\omega}{T}}-1}$ can be ignored iff $\omega_{\rm min} = \hat{q}_0\tau_{\rm min}^2 \gg T$

But is this consistent with single scattering?

From Static Scattering to a Weakly Coupled QGP

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$$\boxed{\hat{q}_0 \sim g^4 T^3}$$

Need to demand $g^4 T^3 \tau_{\min}^2 \gg T$

$$\Rightarrow \tau_{\min} \text{ should be } \gg \frac{1}{g^2 T}$$

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$\boxed{\hat{q}_0 \sim g^4 T^3}$

Need to demand $g^4 T^3 \tau_{\min}^2 \gg T$

$\Rightarrow \tau_{\min}$ should be $\gg \dfrac{1}{g^2 T}$

But $\dfrac{1}{g^2 T}$ is the mean free time between multiple scatterings!

$\Rightarrow$ Would lead us away from single scattering regime!

$\Longrightarrow$ In order to stay away from multiple scattering regime, must account for thermal effects

$$\delta\hat{q}_{\mathrm{LMW}}(\mu) = \frac{\alpha_s C_R}{\pi}\hat{q}_0 \int_{\tau_{\min}}^{\mu^2/\hat{q}_0} \frac{d\tau}{\tau} \int_{\hat{q}_0\tau^2}^{\mu^2\tau} \frac{d\omega}{\omega}$$

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Introduce intermediate regulator
$\tau_{\mathrm{int}} \ll 1/g^2 T$

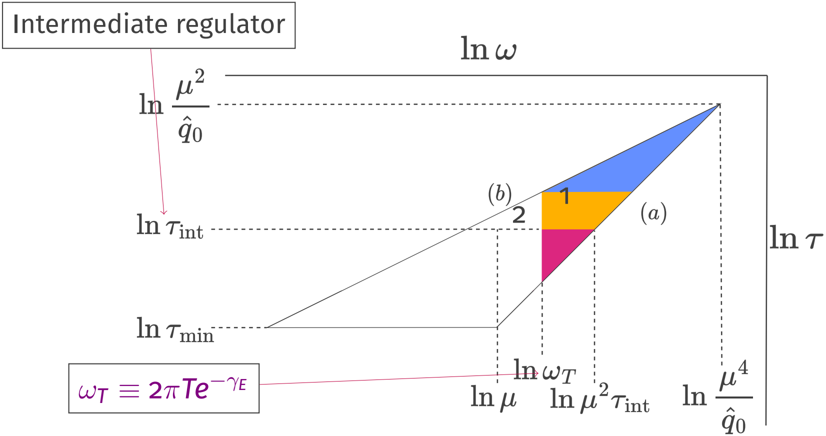
$$\delta\hat{q}_{1+2}(\mu) = \frac{\alpha_s C_R}{\pi}\hat{q}_0 \int_{\tau_{\mathrm{int}}}^{\mu^2/\hat{q}_0} \frac{d\tau}{\tau} \int_{\hat{q}_0\tau^2}^{\mu^2\tau} \frac{d\omega}{\omega}(1 + 2n_B(\omega))$$

$$= \frac{\alpha_s C_R}{2\pi}\hat{q}_0 \left\{ \ln^2 \frac{\mu^2}{\hat{q}_0\tau_{\mathrm{int}}} - \frac{1}{2}\ln^2 \frac{\omega_T}{\hat{q}_0\tau_{\mathrm{int}}^2} \right\}$$

$\omega_T \equiv 2\pi T e^{-\gamma_E}$

$2n_B(\omega)$ accounts for stimulated emission and absorption of thermal gluons

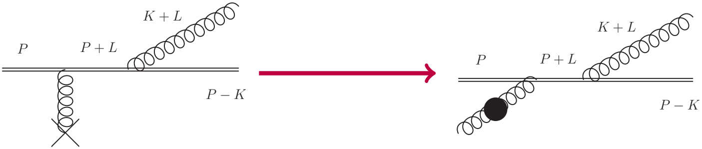
Double Logs in a Weakly Coupled QGP



$$\delta\hat{q}_{1+2}(\mu) = \frac{\alpha_s C_R}{2\pi}\hat{q}_0\left\{ \ln^2\frac{\mu^2}{\hat{q}_0\tau_{\rm int}} - \frac{1}{2}\ln^2\frac{\omega_T}{\hat{q}_0\tau_{\rm int}^2}\right\}$$

Strict Single Scattering

- Investigate which logs are produced by *soft, collinear* modes through a *semi-collinear* process associated with formation time $\tau_{\text{semi}} \sim 1/gT$ [Ghiglieri et al., 2013, Ghiglieri et al., 2016]

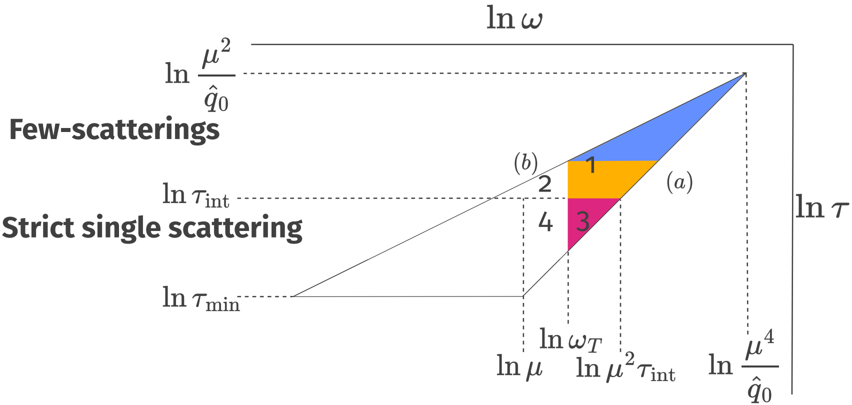


Only spacelike interactions with medium

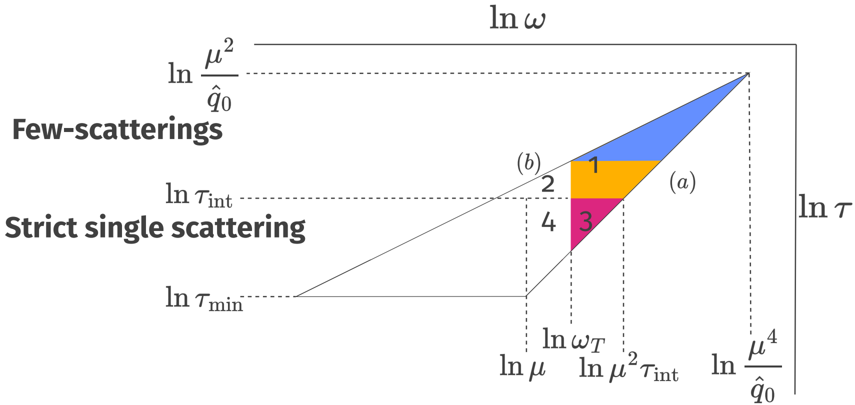
Now timelike interactions are allowed too

$\Rightarrow$ Going beyond instantaneous approximation!

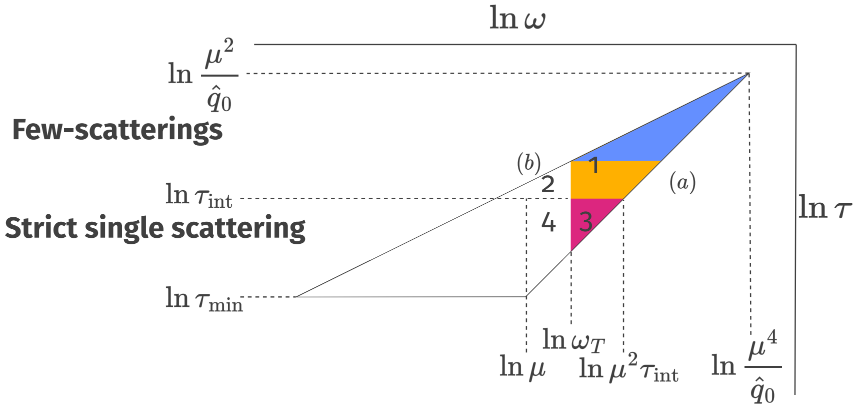
Double Log with Single Scattering



$$\delta \hat{q}_{3+4}(\mu) = \frac{\alpha_s C_R}{2\pi} \hat{q}_0 \ln^2 \frac{\mu^2 \tau_{\rm int}}{\omega_T} + \text{subleading logs}$$



$$\delta\hat{q}_{\rm GW}(\mu) = \delta\hat{q}_{1+2}(\mu) + \delta\hat{q}_{3+4}(\mu) = \frac{\alpha_s C_R}{4\pi}\hat{q}_0 \ln^2\frac{\mu^4}{\hat{q}_0\omega_T}$$



Why is it that region 2 and 4 do not contribute to the double Logs?

First, note that

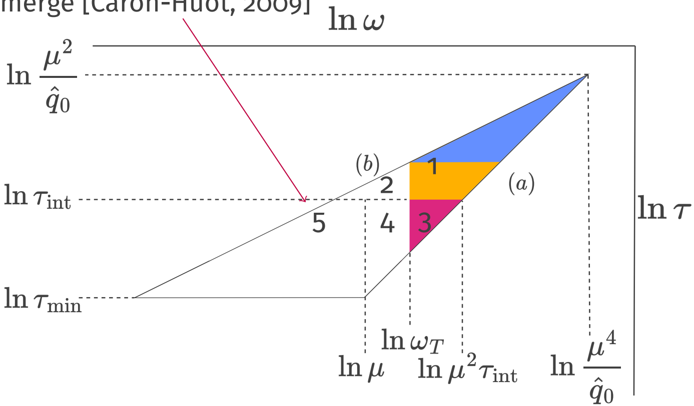
$$\lim_{\frac{\omega}{T}->0}\Big(1+2n_B(\omega)\Big)=1+\frac{2T}{\omega}-1 \tag{2}$$

The absence of the IR scale in any logarithms can then be seen by looking at the following integral, with $\nu_{IR} \ll T \ll \nu_{UV}$

$$\begin{aligned}\int_{\nu_{IR}}^{\nu_{UV}}\frac{d\omega}{\omega}\Big(\underbrace{1}_{\text{vacuum}}+\underbrace{2n_B(\omega)}_{\text{thermal}}\Big) &= \underbrace{\ln\frac{\nu_{UV}}{\nu_{IR}}}_{\text{vacuum}}+\underbrace{\frac{2T}{\nu_{IR}}-\ln\frac{2\pi T}{\nu_{IR}e^{\gamma_E}}+\ldots}_{\text{thermal}} \\ &= \frac{2T}{\nu_{IR}}+\ln\frac{\nu_{UV}e^{\gamma_E}}{2\pi T}+\ldots\end{aligned} \tag{3}$$

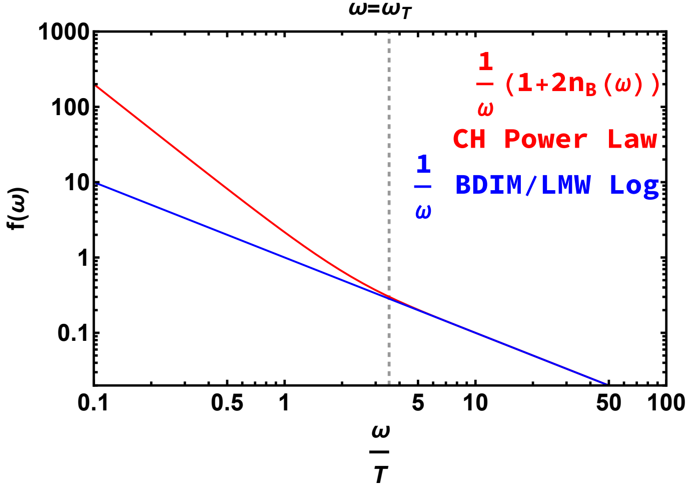
Relation to Classical Corrections

Region of phase space from which classical $\mathcal{O}(g)$ corrections emerge [Caron-Huot, 2009]



How can we understand the transition to power law enhancement in regions 2 and 4?

Can understand transition by looking at ω integrand, $f(\omega)$



$$\omega_T \equiv 2\pi T e^{-\gamma_E}$$

$$n_B(\omega) \equiv \frac{1}{e^{\frac{\omega}{T}} - 1}$$

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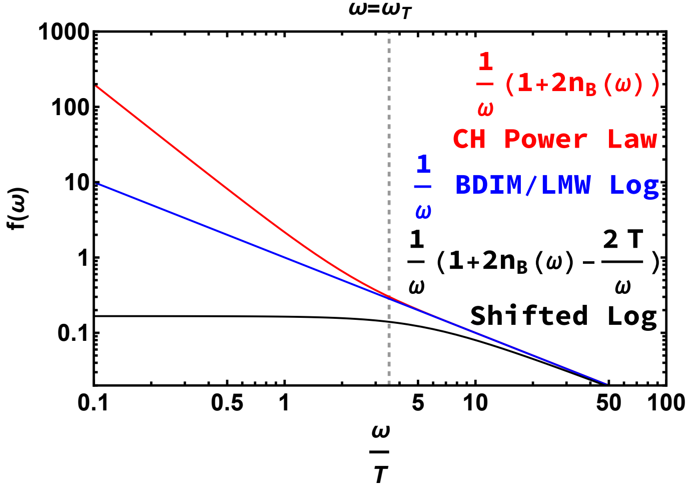
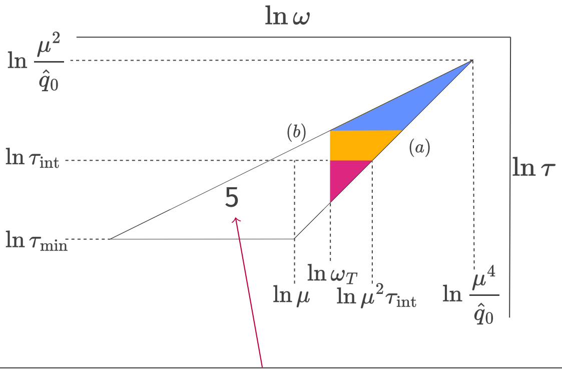


$\omega_T \equiv 2\pi T e^{-\gamma_E}$

$$n_B(\omega) \equiv \frac{1}{e^{\frac{\omega}{T}} - 1}$$

Relation to Classical Corrections

Our results include power law corrections depending on our IR cutoff



They cancel against cutoff-dependent corrections computed from [Caron-Huot, 2009]$\Rightarrow$ Non-trivial check!

Going Beyond Harmonic Oscillator Approximation

HOA not well-suited to single-scattering

Going Beyond Harmonic Oscillator Approximation

HOA not well-suited to single-scattering
So how can we go beyond it?

$$\delta\hat{q}_{\mathrm{GW}}(\mu) = \frac{\alpha_s C_R}{4\pi}\hat{q}_0 \ln^2 \frac{\mu^4}{\hat{q}_0\omega_T} \longrightarrow \frac{\alpha_s C_R}{4\pi}\hat{q}(\rho)\ln^2 \frac{\#}{\omega_T}$$

where $\hat{q}(\rho) \propto \ln \frac{\rho^2}{m_D^2}$

ρ separates us from neighbouring region
with simultaneously single-scattering and multiple scatterings

Appearance of $\hat{q}_0$ in double log signifies lack of understanding of transition between single scattering and multiple scattering regimes

Going Beyond Harmonic Oscillator Approximation

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where $\hat{q}(\rho) \propto \ln \frac{\rho^2}{m_D^2}$

Need to solve transverse momentum-dependent LPM equation without **HOA** [Ghiglieri and Weitz, 2022] in order to shed light on how these issues could be addressed

SUMMARY/OUTLOOK

- Have computed double logarithmic corrections to $\hat{q}$, showing how they are connected to classical corrections
  $\Rightarrow$ Still need to go beyond **HOA** to quantitatively determine argument of logs
- Try to better understand transition from single scattering to multiple scattering using Improved Opacity expansion
  [Barata et al., 2021]
- Would similar calculation of logs in calculation of double gluon emission [Arnold et al., 2021] alter conclusion?
- Incorporate our findings for $\omega \sim T$ and smaller τ regions into resummation equations [Caucal and Mehtar-Tani, 2022]

Thanks for listening!

References I

[Arnold et al., 2021] Arnold, P., Gorda, T., and Iqbal, S. (2021).
The LPM effect in sequential bremsstrahlung: analytic results for sub-leading (single) logarithms.

[Arnold and Xiao, 2008] Arnold, P. B. and Xiao, W. (2008).
High-energy jet quenching in weakly-coupled quark-gluon plasmas.
Phys.Rev., D78:125008.

[Aurenche et al., 2002] Aurenche, P., Gelis, F., and Zaraket, H. (2002).
A Simple sum rule for the thermal gluon spectral function and applications.
JHEP, 0205:043.

[Barata et al., 2021] Barata, J. a., Mehtar-Tani, Y., Soto-Ontoso, A., and Tywoniuk, K. (2021).
Medium-induced radiative kernel with the Improved Opacity Expansion.
JHEP, 09:153.

References II

[Benzke et al., 2013] Benzke, M., Brambilla, N., Escobedo, M. A., and Vairo, A. (2013).
Gauge invariant definition of the jet quenching parameter.
JHEP, 1302:129.

[Blaizot et al., 2014] Blaizot, J.-P., Dominguez, F., Iancu, E., and Mehtar-Tani, Y. (2014).
Probabilistic picture for medium-induced jet evolution.
JHEP, 1406:075.

[Burke et al., 2014] Burke, K. M. et al. (2014).
Extracting the jet transport coefficient from jet quenching in high-energy heavy-ion collisions.
Phys.Rev., C90(1):014909.

[Cao et al., 2021] Cao, S. et al. (2021).
Determining the jet transport coefficient $\hat{q}$ from inclusive hadron suppression measurements using Bayesian parameter estimation.
Phys. Rev. C, 104(2):024905.

References III

[Caron-Huot, 2009] Caron-Huot, S. (2009).
O(g) plasma effects in jet quenching.
Phys.Rev., D79:065039.

[Casalderrey-Solana and Teaney, 2007] Casalderrey-Solana, J. and Teaney, D. (2007).
Transverse Momentum Broadening of a Fast Quark in a N=4 Yang Mills Plasma.
JHEP, 04:039.

[Caucal and Mehtar-Tani, 2022] Caucal, P. and Mehtar-Tani, Y. (2022).
Universality aspects of quantum corrections to transverse momentum broadening in QCD media.

[D'Eramo et al., 2011] D'Eramo, F., Liu, H., and Rajagopal, K. (2011).
Transverse Momentum Broadening and the Jet Quenching Parameter, Redux.
Phys.Rev., D84:065015.

References IV

[Ghiglieri et al., 2013] Ghiglieri, J., Hong, J., Kurkela, A., Lu, E., Moore, G. D., and Teaney, D. (2013).
Next-to-leading order thermal photon production in a weakly coupled quark-gluon plasma.
JHEP, 1305:010.

[Ghiglieri et al., 2016] Ghiglieri, J., Moore, G. D., and Teaney, D. (2016).
Jet-Medium Interactions at NLO in a Weakly-Coupled Quark-Gluon Plasma.
JHEP, 03:095.

[Ghiglieri and Teaney, 2015] Ghiglieri, J. and Teaney, D. (2015).
Parton energy loss and momentum broadening at NLO in high temperature QCD plasmas.
Int. J. Mod. Phys., E24(11):1530013.
To appear in QGP5, ed. X-N. Wang.

References V

[Ghiglieri and Weitz, 2022] Ghiglieri, J. and Weitz, E. (2022).
Classical vs quantum corrections to jet broadening in a weakly-coupled Quark-Gluon Plasma.
JHEP, 11:068.

[Han et al., 2022] Han, Q.-F., Xie, M., and Zhang, H.-Z. (2022).
Extracting the jet transport coefficient from hadron suppressions by confronting current NLO parton fragmentation functions.

[Liou et al., 2013] Liou, T., Mueller, A., and Wu, B. (2013).
Radiative $p_\perp$-broadening of high-energy quarks and gluons in QCD matter.
Nucl.Phys., A916:102–125.

[Moore et al., 2021] Moore, G. D., Schlichting, S., Schlusser, N., and Soudi, I. (2021).
Non-perturbative determination of collisional broadening and medium induced radiation in QCD plasmas.
JHEP, 10:059.

[Panero et al., 2014] Panero, M., Rummukainen, K., and Schäfer, A. (2014).
A lattice study of the jet quenching parameter.
Phys.Rev.Lett., 112:162001.

[Schlichting and Soudi, 2021] Schlichting, S. and Soudi, I. (2021).
Splitting rates in QCD plasmas from a non-perturbative determination of the momentum broadening kernel $C(q_\perp)$.

[Xie et al., 2023] Xie, M., Ke, W., Zhang, H., and Wang, X.-N. (2023).
Information-field-based global Bayesian inference of the jet transport coefficient.
Phys. Rev. C, 108(1):L011901.

What is EQCD?

- Integrate out hard scale, T from QCD

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- Arrive at **3 dimensional gluon effective field theory** for momenta, $gT \sim m_D$, inverse screening length for chromoelectric fields
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$$\mathcal{L}_{\text{EQCD}} = \frac{1}{2g_{\text{3d}}^2} \operatorname{Tr} F_{ij}F_{ij} + \operatorname{Tr} D_i\Phi D_i\Phi + m_D^2 \operatorname{Tr}\Phi^2 + \lambda \left(\operatorname{Tr}\Phi^2\right)^2$$

where Φ is adjoint scalar, $i, j = 1, 2, 3$

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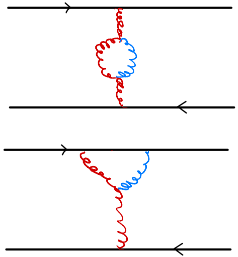
- $\Rightarrow$ **"Dimensional Reduction"**

Contributing diagrams

- Can think of sticking together amplitude and conjugate amplitude to get diagrams on the right
- **Black lines** represent hard parton in the amplitude and conjugate amplitude
- Red gluons are bremsstrahlung, represented by thermal propagators
- Blue gluons are those that are exchanged with the medium and are represented by HTL propagators



Where do these diagrams come from?