Modeling coherence effects of parton energy loss: heavy quark

Weiyao Ke, Yingru Xu, Wenkai Fan, and Steffen Bass

Duke University

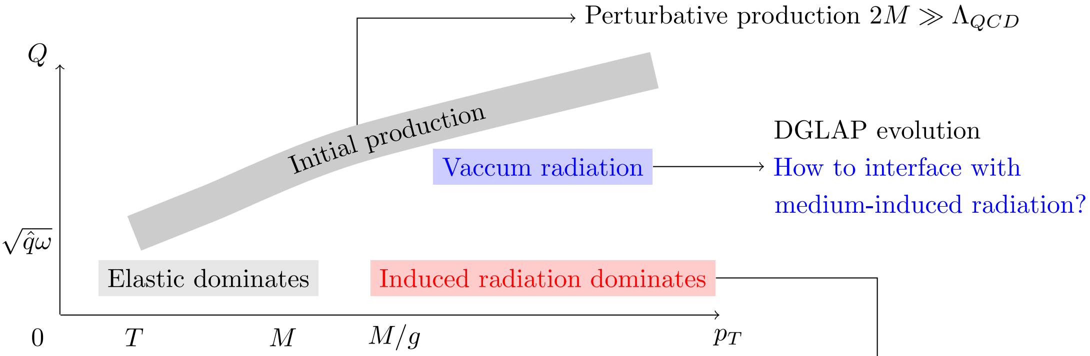
JetScape Workshop
Texas A&M University
January 11, 2019

This work is supported by US Department of Energy Grant no. DE-FG02-05ER41367, and National Science Foundation Grant no. ACI-1550225.

Theory

1. Transport of heavy quark
2. Coherence of medium-induced radiation
3. Interfacing vacuum-like and medium-induced radiation
4. Summary & work in progress

Transport of heavy quark (at least perturbatively)



q-transfer to medium

$q \gg m_D$: few body vac process

$q \sim m_D$: many body, diffusion model

Medium-induced radiation:

1. Dead cone effect: $\omega/k_\perp^2 \to \omega/(k_\perp^2 + x^2M^2)$
2. LPM effect: coherent / incoherent?

See Tianyu Dai's talk Sunday

Coherence of medium-induced radiation

- Radiation is coherent within $\tau_f \sim 2\omega/k_\perp^2$, where interactions adds up coherently.

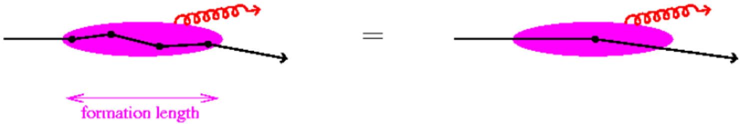


Figure by P. Arnold

- The LPM effect: N coherent scatterings $\approx$ 1 scattering, $dI^{\rm coh} \sim dI^{\rm incoh}/N \sim dI^{\rm incoh}\frac{\lambda}{\tau_f}$.

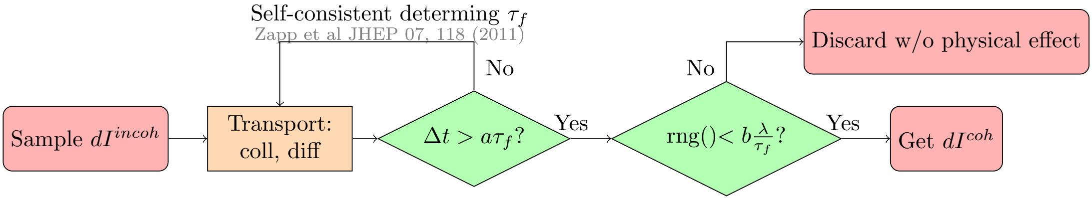
Table: τ_f compared to other length scales

Mean free path	$\lambda \sim m_D^2/\hat{q} \lesssim 1$ fm	$\lambda \ll \tau_f$.
Bjorken expansion time scale	$T^3 d\tau/dT^3 = \tau$	comparable to τ_f
Path length in QGP fireball	a few fermi	comparable to τ_f.

A “non-local” problem for Boltzmann equation

- Interpret τ_f as lifetime for a virtual state “$q + g$ (preformed gluon)” to decay.
  Energy $\gg$ scattering rate $\gg$ width.

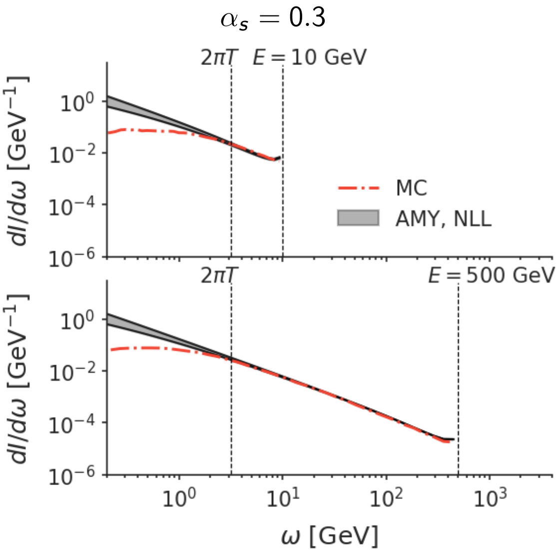
- Treat them as “quasi-particles” in the Boltzmann transport with
  - x^μ and p^μ of the original quark.
  - Cross-section / diffusion coefficient with color charge resembling a gluon.
  - “Decay” probability λ/τ_f after $\Delta t = \tau_f$.



How accurate is this method? Tune a, b to match semi-analytic calculation in idealized cases!

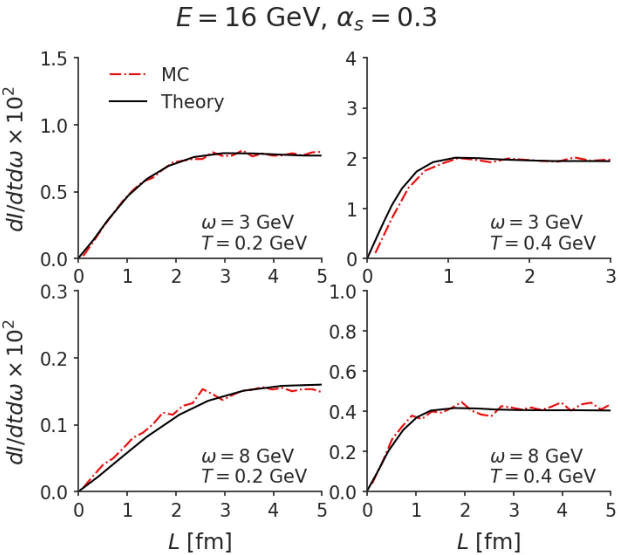
Ke, Xu, and Bass, arXiv:1810.08177.

Validate the implementation: infinite medium limit



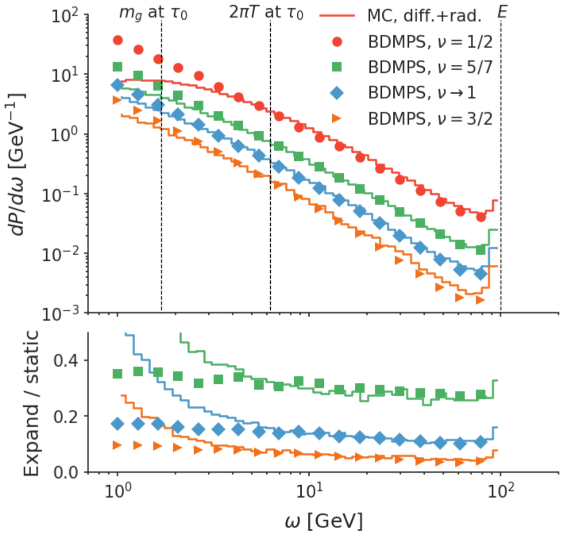
- $a \sim 1.0$ and $b \sim 1.4$.
- Theoretical spectra $dI/d\omega$ from AMY calculation to NLL order Arnold and Dogan, PRD 78 065008.
- $\omega < 2\pi T$, goes back to incoherent simulation (blue lines)
- $\omega > 2\pi T$, agree with theoretical results within $\pm 10\%$

Validate the implementation: finite medium



- Path-length (L) dependent differential rate $dI/d\omega$ Caron-Huot and Gale, PRC 82 064902.
- Achieve similar level of accuracy as the previous case.

Validate the implementation: expanding medium



- Differential spectra $dI/d\omega$ have been calculated in an expanding medium Baier et al, PRC 58 1706.

$$T^3 = T_0^3 \left(\frac{\tau_0}{\tau}\right)^{2-\frac{1}{\nu}}$$

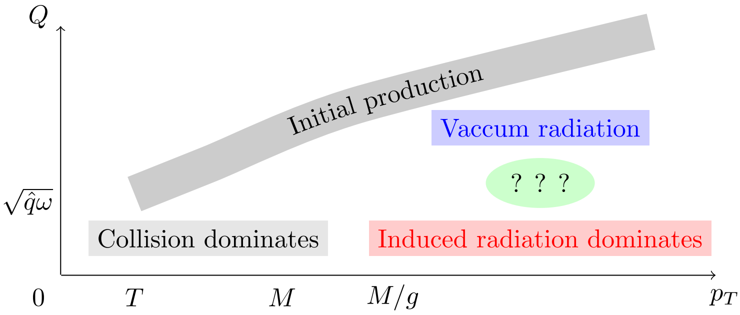
Static: $\nu = 1/2$. Bjorken: $\nu = 1$.

- Expansion time scale $\frac{T^3 d\tau}{dT^3} = \frac{\tau}{2-1/\nu}$.
- Compare to MC (diffusion + radiation) with $\hat{q}_0 = C_A m_D^2 T$, $\alpha_s = 0.3$.
- Good agreement in the LPM region from static limit to fast expansion.

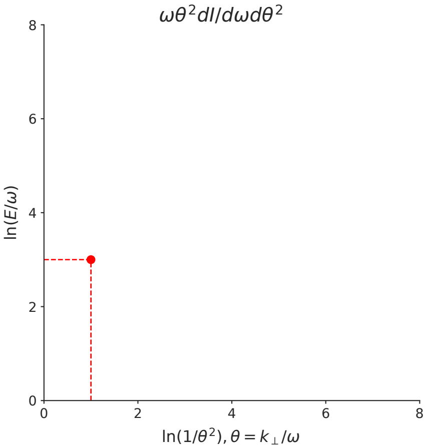
Interfacing Vacuum-radiation and medium-induced radiation

To include virtuality effect:

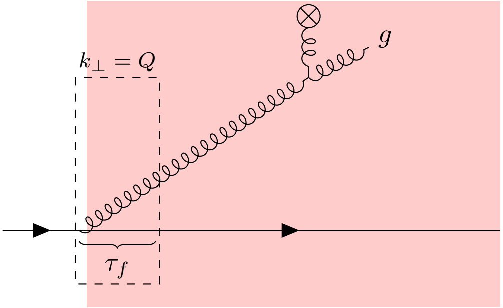
- DGLAP evolution without a "medium", N_{vac} .
- Medium-induced calculation, N_{med} .
- Where do they meet?



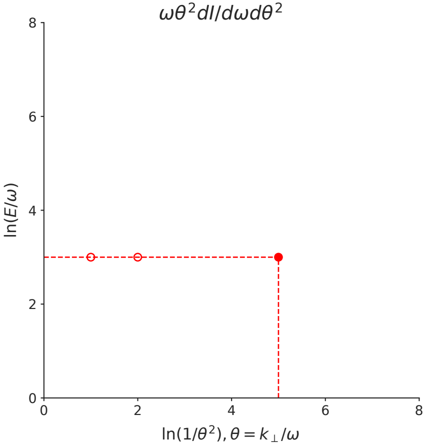
Vacuum-like and medium-induced radiation PRL 120 232001 P. Caucal et al



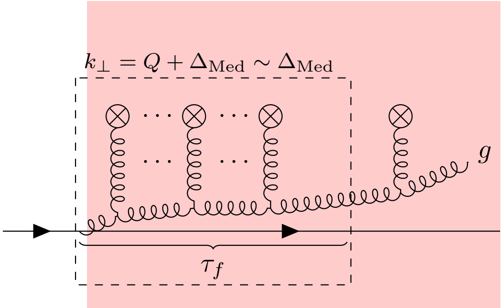
- Vacuum branching w/ large Q.
- Very short formation time ω/Q^2.
- Formed before it scatters with medium.
- Vacuum matrix-element works.



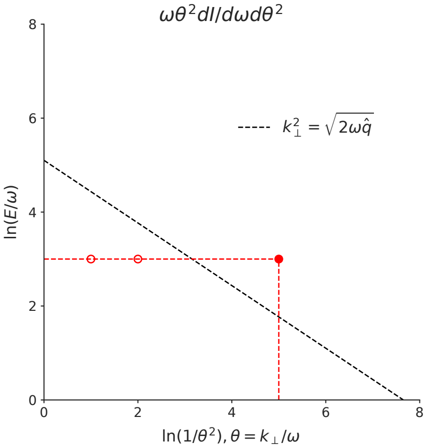
Vacuum-like and medium-induced radiation PRL 120 232001 P. Caucal et al



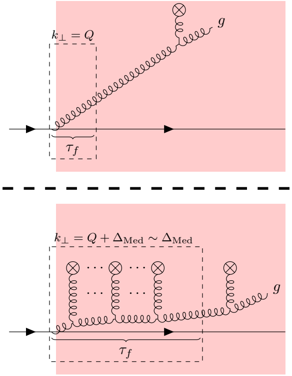
- A branching start with small Q, large τ_f.
- Many medium interactions contribute within τ_f.
- $\Delta_{\mathrm{Med}} \gg Q$, effectively an on-shell particle.
- This is a medium-induced branching.



Vacuum-like and medium-induced radiation PRL 120 232001 P. Caucal et al



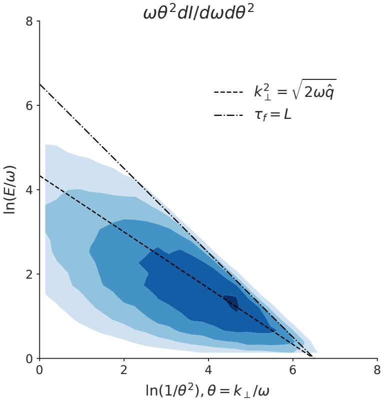
- Draw a line where $Q \sim \Delta_{\rm Med}$.
- $N \approx N_{\rm vac}(\text{stops at } Q^2 \sim \sqrt{\omega\hat{q}}) + N_{\rm med}$

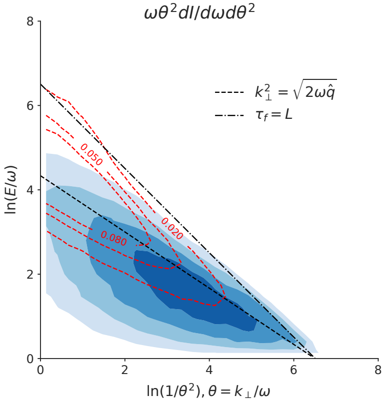


Separate at $Q^2 \sim \sqrt{\omega\hat{q}}$

Since we only care about the heavy flavor for now.

1. In Pythia final state radiation: find all gluons radiated by the heavy quark.
2. Treat these gluons as "performed", adding their k^μ back to the heavy quark.
3. Do transport until $\Delta t = \tau_f(\Delta t)$.
4. Look at how much $k_\perp$ it gains from medium Δk_T^2, reject this radiation.
   If $k_\perp^2(t = \tau_f) > R \times \Delta k_T^2$: redo this branching. Else: remove this branching.

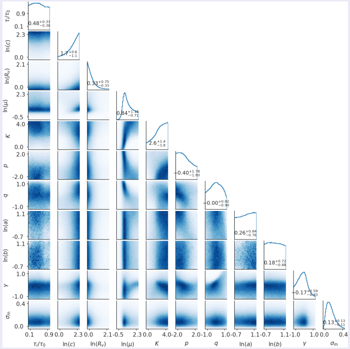


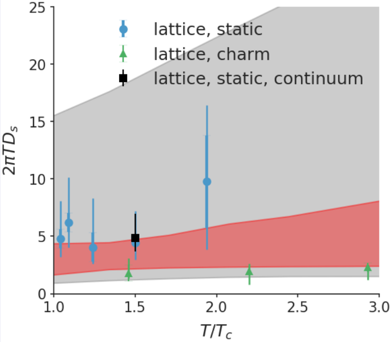


Summary

- Improving LPM implementation. Quantitative agreement with theoretical calculations.
- Interfacing vacuum-like and medium-induced radiation.
- Improvements are implemented in the LIDO model.

An updated Bayesian analysis is in progress (Preliminary!)



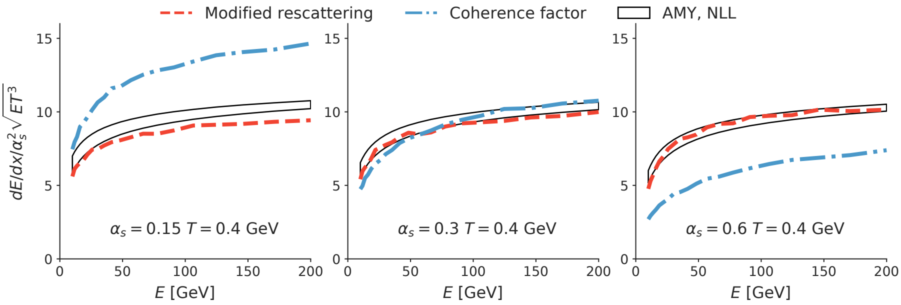


These improvements should help increase the fidelity of such an extraction.

Backup: Compare to the old approach

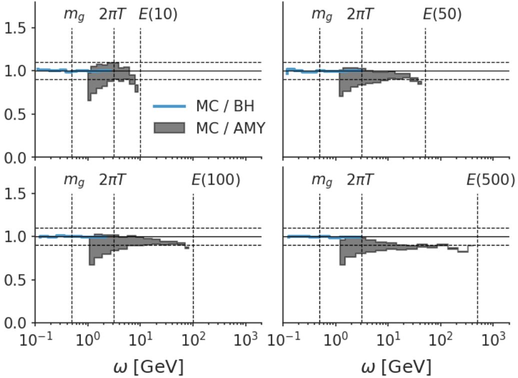
In our old approach, LPM effect is introduced as a coherence factor in the $2 \to 3$ matrix-element, without multiple scatterings.

$$\int \frac{d\sigma_{23}}{d\hat{t}dk^3} d\hat{t} \frac{dk^3}{2k} \to \int \frac{d\sigma_{23}}{d\hat{t}dk^3} 2\left[1 - \cos\left(\frac{\Delta t}{\tau_f}\right)\right] d\hat{t} \frac{dk^3}{2k}, \tau_f \sim \frac{2k}{k_\perp^2}$$

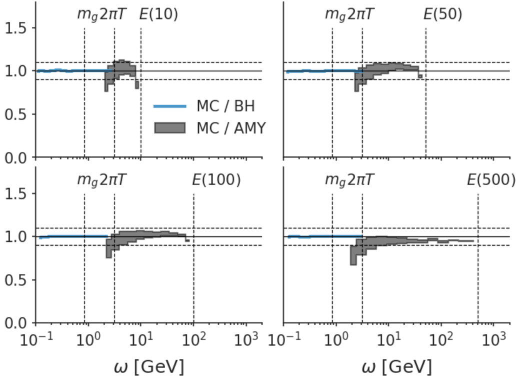


Backup: Ratio to AMY-NLL

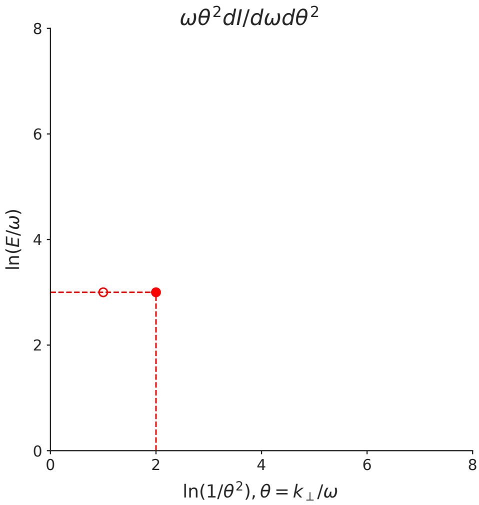
$\alpha_s = 0.1$



$\alpha_s = 0.3$



Backup: a few interactions



- Vacuum branching w/ moderate Q.
- O(1) interaction with medium within τ_f.
- Option: use MATTER when $\Delta_{\rm Med} \ll Q$.