Far forward

The physics of the fragmentation region in heavy-ion collisions

Isobel Kolbé, Mawande Lushozi
Institute for Nuclear Theory, University of Washington, Seattle, Washington, USA
ikolbe@uw.edu

Motivation

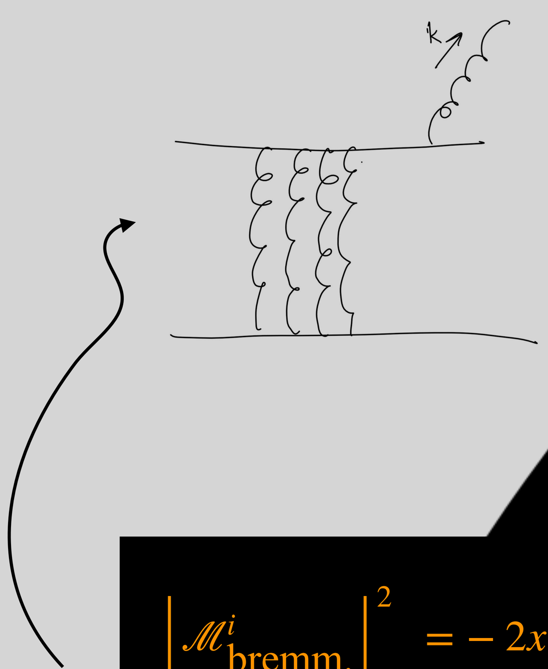
- The fragmentation region is interesting:
  - Access to densities $\gtrsim 2$ * nuclear saturation density ~ neutron star core density.
  - Give insight into cosmic-ray physics.
  - Not well studied - new frontiers!
  - The authors have previously studied [4] matter in the fragmentation region, but were forced to use a flat momentum spectrum for the gluon radiation. A more rigorous spectrum is needed i.o.t. fully model the behavior of fluids in this region.
- Technically interesting challenge:
  - The fragmentation region is dominated by soft (small-x) gluons, so we are dealing with the physics of the color-glass condensate (CGC).
  - But relativistic collisions necessarily also involve perturbative QCD physics.
  - How does one bridge the gap?

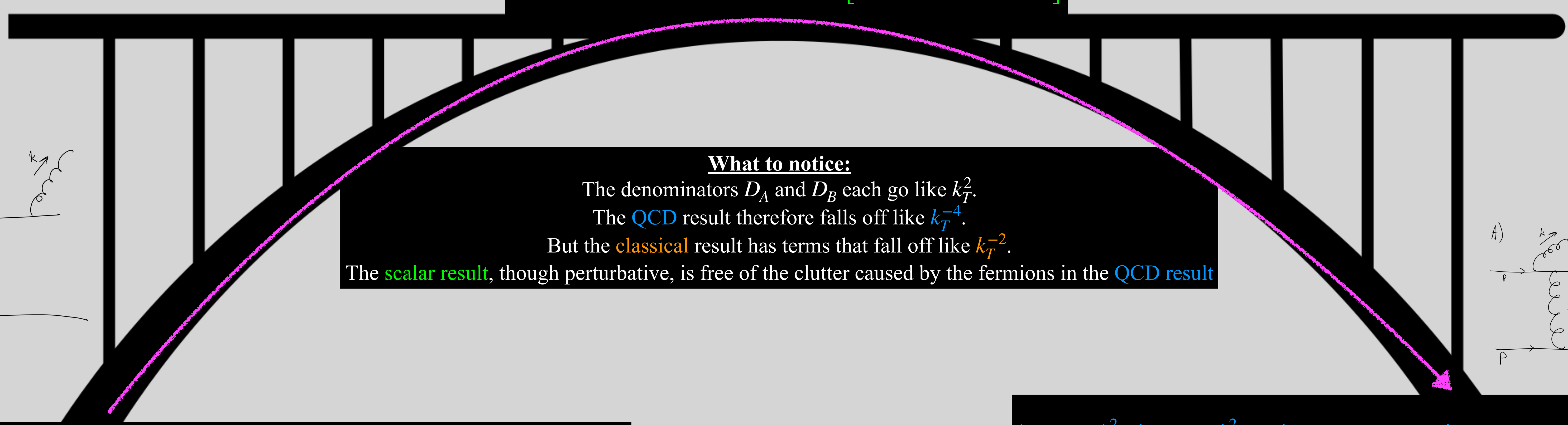
The Basic Problem

- We will motivate an ansatz for gluon bremsstrahlung in the fragmentation region that properly connects the non-perturbative region (hereinafter the "classical result" [1] with the perturbative QCD region (hereinafter the "QCD" result) [2].
- The problem with the classical result: The high-k_T (momentum of the radiated gluon) limit of the classical result does not have the same fall-off as the QCD result (which must be correct at high-k_T).
- The problem with the QCD result: It does not take into account the spectrum of transferred momentum $q_\perp$, which depends on the non-perturbative physics of the gluons in the nucleus (as an internal momentum, $q_\perp$ is integrated out, but there should be a distribution of $q_\perp$ in the non-perturbative limit, resulting from the multiple gluon interactions).
- We perform a perturbative calculation of bremsstrahlung for a scalar field which carries *classical* color charge (hereinafter the "scalar result") which offers a bridge between the fully classical calculation and the fully fermionic QCD calculation.
- The scalar result suggests a modification of the classical result which leads to the correct high-k_T fall-off but still includes the non-perturbative physics of the CGC

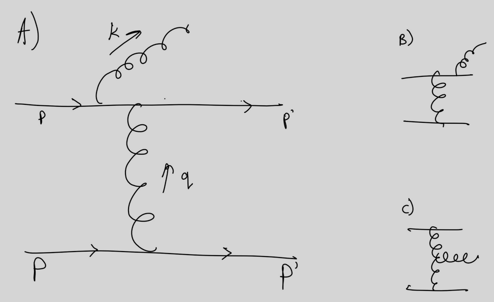
- In order to fully understand the fragmentation region, we need to know the momentum spectrum of gluon bremmstrahlung.
- Hard because of competing effects:
  - The non-perturbative physics of colliding ultra-relativistic nuclei (gluons dominate, $\therefore \exists$ multiple gluon interactions)
  - Perturbative physics of high-frequency (high-momentum) radiation.
- Already known: non-perturbative limit [1,2], as well as the perturbative limit [3].
- The non-perturbative limit (called the "classical result" here) does not give the correct high-momentum behaviour.
- We present a scalar version of the full pQCD result that also uses a classical color charge to motivate a modification of the classical result.
- Having modified the classical result, we present an ansatz for gluon bremsstrahlung in the fragmentation region.
- This ansatz may now be used to model the behavior of fluids in the fragmentation region.

$$\left|\mathscr{M}_{Sc.}\right|^2 = \frac{32m^2P^2g^6}{q_\perp^4}C(R)C_2^2(R)d_R x^2(1-x)^2\left[m^2\left(\frac{1}{D_A}-\frac{1}{D_B}\right)^2 - \frac{q_\perp^2}{D_A D_B}\right]$$





What to notice:
The denominators D_A and D_B each go like k_T^2.
The QCD result therefore falls off like k_T^{-4}.
But the classical result has terms that fall off like k_T^{-2}.
The scalar result, though perturbative, is free of the clutter caused by the fermions in the QCD result



$$\left|\mathscr{M}^i_{\text{bremm.}}\right|^2_{Cl.} = -2x^2M^2\left(\frac{1}{D_A}+\frac{1-x}{D_B}\right)^2 + \frac{x}{D_A} - \frac{x(1-x)}{D_B} + x^2(1-x)\frac{q_\perp^2}{D_A D_B}$$ [1,2]

[3]
$$\left|\mathscr{M}_A^{\text{QCD}}\right|^2 + \left|\mathscr{M}_B^{\text{QCD}}\right|^2 + 2\left|\mathscr{M}_A^{\text{QCD}}\mathscr{M}_B^{\text{QCD},*}\right| = \frac{4K}{d_R}C_R^2C(R)\left[4x^2(x-1)M^2\left(\frac{1}{D_A}-\frac{1}{D_B}\right)^2 + \frac{x^2(x^2-2x+2)}{D_A D_B}q_\perp^2\right]$$

Using the scalar result to justify a perturbative modification of the classical result:

Start with a change of notation to match the original classical result in [1,2], given there as:

$$\left.\frac{dN}{dyd^2k_T}\right|_{Class.} = \frac{g^2C_F}{8\pi^3}\int\frac{d^2h}{(2\pi)^2}\tilde{S}(\mathbf{k}-\mathbf{h})\left[\frac{h^i}{h_T^2+2(k^-)^2} - \frac{k^i-\xi p'^i}{|\mathbf{k}-\xi\mathbf{p}'|^2+\xi^2m^2}\right]^2.$$

In this notation, the scalar result has the form

$$\left.\frac{dN}{dyd^2k_T}\right|_{Sc.} = \frac{g^2C_R}{16\pi^3}\frac{1}{1-\xi}\left[\frac{k^i}{k_T^2+2(k^-)^2} - (1+\xi)\frac{k^i-\xi p'^i}{|\mathbf{k}-\xi\mathbf{p}'|^2+\xi^2m^2}\right]^2.$$

The $\tilde{S}(\mathbf{k}-\mathbf{h})$ contains the non-perturbative physics of the CGC (more precisely, it is the two-point correlation of Wilson lines).

In the McLerran-Venugopalan model, $\tilde{S}(\mathbf{k}-\mathbf{h})$ is Gaussian.

In the high-energy limit (that is, in the limit where we expect the classical result to resemble the scalar result), $\tilde{S}(\mathbf{k}-\mathbf{h})$ is a delta function, the integral over which sets $\mathbf{h}\to\mathbf{k}$. In this limit then, the classical result gives precisely the scalar result, except for the overall factor of $(1-\xi)^{-1}$ and the factor of $(1+\xi)$ in front of the second term.

We therefore posit a modification of the classical result, yielding an ansatz for gluon bremsstrahlung in the fragmentation region, as follows

$$\left.\frac{dN}{dyd^2k_T}\right|_{Ansatz} = \frac{g^2C_F}{8\pi^3}\int\frac{d^2h}{(2\pi)^2}\tilde{S}(\mathbf{k}-\mathbf{h})\boxed{\frac{1}{1-\xi}}\left[\frac{h^i}{h_T^2+2(k^-)^2} - \boxed{(1+\xi)}\frac{k^i-\xi p'^i}{|\mathbf{k}-\xi\mathbf{p}'|^2+\xi^2m^2}\right]^2.$$

Our Ansatz may now be used to model the momentum spectrum of bremsstrahlung in the fragmentation region.

The Ansatz has the following properties:

- In the small-x limit ($\xi \to 1$), the ansatz reduces to the classical result
- In the high energy limit ($\tilde{S}(\mathbf{k}-\mathbf{h}) \to \delta(\mathbf{h}-\mathbf{k})$), the ansatz reduces to the perturbative (scalar result).

[1] K. Kajantie, Larry D. McLerran, and Risto Paatelainen. Gluon Radiation from a classical point particle II: dense gluon fields. *Phys. Rev. D*, 101(5):054012, 2020.
[2] Keijo Kajantie, Larry D. McLerran, and Risto Paatelainen. Gluon Radiation from a Classical Point Particle. *Phys. Rev. D*, 100(5):054011, 2019.
[3] Mawande Lushozi, Larry D. McLerran, Micha l Praszalowicz, and Gongming Yu. Gluon Bremsstrahlung in Relativistic Heavy Ion Collisions. *Phys. Rev. C*, 102(3):034908, 2020.
[4] Isobel Kolb ́e, Mawande Lushozi, Larry D. McLerran, and Gongming Yu. Distribution of Nuclear Matter and Radiation in the Fragmentation Region. *Phys. Rev. C*, 103(4):044908, 2021.