Photon radiation induced by rescattering in strong-interacting medium with a magnetic field

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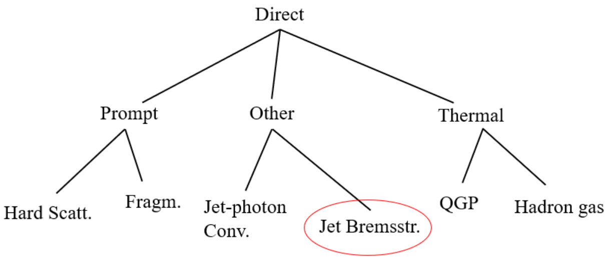
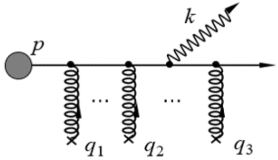
November 27, 2025

[Yue Zhang and Han-Zhong Zhang, arXiv:2510.17597]

Overview

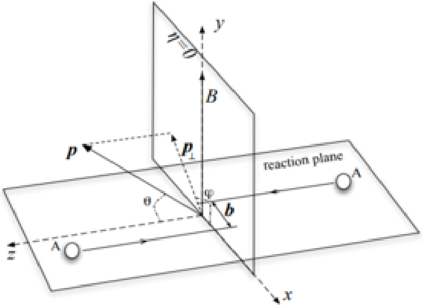
Introduction

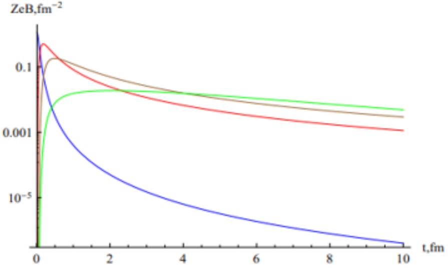




- Medium-induced photon bremsstrahlung serves as both a key source of direct photons and a probe for investigating the electromagnetic energy loss of jet.
- The jet will interact strongly with the medium when it passes through the QGP medium, and the multiple scattering will induce gluon (photon) radiation.

Introduction





- The relative motion of the two beams of high-energy charged particles will form a magnetic field. The strength of this field is estimated to reach strengths of approximately $eB \sim 5m_\pi^2 \sim 10^9\mathrm{G}$ at RHIC and $eB \sim 50m_\pi^2 \sim 10^{10}\mathrm{G}$ at LHC.
- The finite electrical conductivity of the QGP significantly delays the decay of magnetic field.

[K. Tuchin, AHEP 2013, 490495 (2013)]

GLV energy loss formalism

In the GW model, the interactions between the quark jet and the target parton can be modeled by the static color-screened Yukawa potential:

$$\begin{aligned} V_n &= V(q_n)e^{iq_n \cdot x_n} \\ &= 2\pi\delta(q^0)v(\boldsymbol{q}_n)e^{-i\boldsymbol{q}_n \cdot \boldsymbol{x}_n} T_{a_n}(j) \otimes T_{a_n}(n), \end{aligned}$$

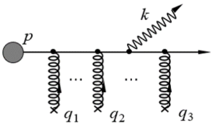
and

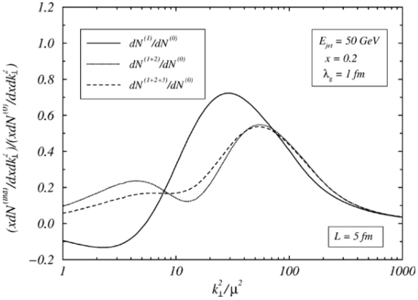
$$v(\boldsymbol{q}_n) = \frac{4\pi\alpha_s}{\boldsymbol{q}_n^2 + \mu^2} = \frac{4\pi\alpha_s}{q_{nz}^2 + \mu_n^2},$$

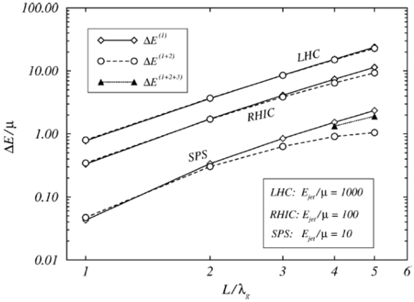
where x_n are the coordinates of parton n, q_n the momentum transfer from a target parton n, μ the Debye thermal mass of gluon in the hot medium. $T_{a_n}(j)$ and $T_{a_n}(n)$ represent the color matrices for jet and target partons, respectively.

[M. Gyulassy and X.-N. Wang, NPB 420, 583 (1994)]

GLV energy loss formalism







- GLV argued that the medium-induced radiation spectrum and the corresponding energy loss can be expanded in terms of opacity $\bar{n} = L/\lambda$.
- They have demonstrated that the opacity expansion may converge rapidly and that the main contribution is dominated by the first order in opacity.

[M. Gyulassy, P. Levai, and I. Vitev, NPB 594, 371 (2001)]

Charged scalar propagator in a magnetic field

By choosing a symmetric gauge $A_\mu = (0, 0, Bx, 0)$, the propagator can be represented in the form of summation over the Landau levels

$$i\Delta(p) = 2i \sum_{l=0}^{\infty} \frac{(-1)^l L_l\left(\frac{2p_\perp^2}{|qB|}\right) e^{-\frac{p_\perp^2}{|qB|}}}{p_\parallel^2 - (2l+1)|qB| - m^2 + i\epsilon},$$

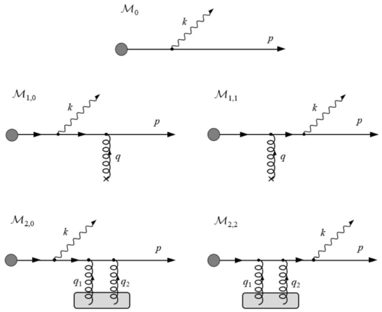
with $(a \cdot b)_\parallel = a^0 b^0 - a^3 b^3$ and $(a \cdot b)_\perp = a^1 b^1 + a^2 b^2$.
For massive hard jet in AA collisions, we can simplify and expand the propagator to the quadratic term of qB as

$$\begin{aligned} i\Delta(p) &= 2i \frac{e^{-\frac{p_\perp^2}{|qB|}}}{p_\parallel^2 - m^2} \sum_{l=0}^{\infty} \frac{(-1)^l L_l\left(\frac{2p_\perp^2}{|qB|}\right)}{1 - (2l+1)|qB|/(p_\parallel^2 - m^2)} \\ &\approx \frac{i}{p^2 - m^2}\left[1 - \frac{(qB)^2}{(p^2 - m^2)^2} - \frac{2(qB)^2 p_\perp^2}{(p^2 - m^2)^3}\right]. \end{aligned}$$

[A. Ayala, A. Sanchez, G. Piccinelli, and S. Sahu, PRD 71, 023004 (2005)]

Photon radiation and jet electromagnetic energy loss

The scattering amplitudes for the first three orders, namely self-quenching, single rescattering and double Born rescattering are denoted as $\mathcal{M}_0$, $\mathcal{M}_1$ and $\mathcal{M}_2$, respectively.



$$
\begin{aligned}
|\mathcal{M}|^2 &= |\mathcal{M}_0 + \mathcal{M}_1 + \mathcal{M}_2 + \cdots|^2 \\
&= |\mathcal{M}_0|^2 + |\mathcal{M}_1|^2 + 2\mathrm{Re}(\mathcal{M}_1\mathcal{M}_0^*) \\
&\quad + 2\mathrm{Re}(\mathcal{M}_2\mathcal{M}_0^*) + \cdots \,.
\end{aligned}
$$

Notice that the term about $\mathrm{Re}(\mathcal{M}_1\mathcal{M}_0^*)$ does not contribute to the result due to $\mathrm{Tr}\, T_a(j) = 0$.

[H.-Z. Zhang, Z.-B. Kang, B.-W. Zhang, and E. Wang, EPJC 67, 445 (2010)]

Photon radiation and jet electromagnetic energy loss

The initial and final jet momenta, as well as the momentum and polarization vector of the emitted photon, can then be written in terms of light-cone components as follows:

$$
\begin{aligned}
p_i &= \left[p^+, p^-, \mathbf{0}_\perp\right], \\
p_f &= \left[(1-x)\,p^+, \frac{(\boldsymbol{q}_\perp - \boldsymbol{k}_\perp)^2 + m^2}{(1-x)\,p^+}, \boldsymbol{q}_\perp - \boldsymbol{k}_\perp\right], \\
k &= \left[xp^+, \frac{\boldsymbol{k}_\perp^2}{xp^+}, \boldsymbol{k}_\perp\right], \\
\epsilon &= \left[0, \frac{2\boldsymbol{\epsilon}_\perp \cdot \boldsymbol{k}_\perp}{xp^+}, \boldsymbol{\epsilon}_\perp\right],
\end{aligned}
$$

where x is the momentum fraction of the jet parton that transferred to the photon. We only consider a kinematic configuration in central rapidity region where the quark propagates parallel to the magnetic field, then the calculation can be further simplified.

Photon radiation and jet electromagnetic energy loss

According to Feynman's rule of GW model, the scattering amplitude of self-quenching diagram can be written directly

$$\mathcal{M}_0 = -iJ(p+k)e^{i(p+k)\cdot x_0}\mathcal{R}_0,$$

where we have factored out the part associated with the emitted photon and denoted it as radiation amplitude $\mathcal{R}_0$, and

$$\begin{aligned}\mathcal{R}_0 &= -ig_e\epsilon\cdot(2p+k)i\Delta(p+k)\\ &= 2g_e(1-x)\frac{\boldsymbol{\epsilon}_\perp\cdot\boldsymbol{k}_\perp}{\boldsymbol{k}_\perp^2+x^2m^2}\left[1-\frac{(qB)^2x^2(1-x)^2}{(\boldsymbol{k}_\perp^2+x^2m^2)^2}\right]\\ &= 2g_e(1-x)\boldsymbol{\epsilon}_\perp\cdot\left[\boldsymbol{H}-x^2(1-x)^2\boldsymbol{H}^B\right].\end{aligned}$$

Here we define the following quantities for follow the convention of relevant references,

$$\boldsymbol{H} = \frac{\boldsymbol{k}_\perp}{\boldsymbol{k}_\perp^2+x^2m^2},\quad \boldsymbol{H}^B = \frac{(qB)^2\boldsymbol{k}_\perp}{(\boldsymbol{k}_\perp^2+x^2m^2)^3}.$$

Photon radiation and jet electromagnetic energy loss

Then radiation spectrum can be written as

$$\frac{d^2 N_\gamma^{(0)}}{d|\boldsymbol{k}_\perp|^2 dx} = \frac{1}{4(2\pi)^2}\frac{1}{x}|\mathcal{R}_0|^2.$$

The scattering amplitude corresponding to the first single rescattering diagram is

$$\begin{aligned}
\mathcal{M}_{1,0} = &\int \frac{d^4 q_1}{(2\pi)^4} iJ(p+k-q_1)e^{i(p+k-q_1)\cdot x_0} i\Delta(p+k-q_1) ig_e \epsilon\cdot(2p+k-2q_1) \\
&\times i\Delta(p-q_1)(-i)(2p-q_1)^0 V(q_1)e^{iq_1\cdot x_1} \\
\approx\, & J(p+k)e^{i(p+k)\cdot x_0}(-i)g_e 2(E-\omega)\frac{2\boldsymbol{\epsilon}_\perp\cdot\boldsymbol{k}_\perp}{x}\int\frac{d^2\boldsymbol{q}_{1\perp}}{(2\pi)^2}e^{-i\boldsymbol{q}_{1\perp}\cdot\boldsymbol{b}_{1\perp}} \\
&\times\int\frac{dq_{1z}}{2\pi} v(q_{1z},\boldsymbol{q}_{1\perp})\Delta(p+k-q_1)\Delta(p-q_1)e^{-iq_{1z}(z_1-z_0)}a_1 T_{a_1},
\end{aligned}$$

where $\boldsymbol{b}_{1\perp} = \boldsymbol{x}_{1\perp} - \boldsymbol{x}_{0\perp}$.

Photon radiation and jet electromagnetic energy loss

Therefore,

$$\mathcal{M}_{1,0} = -iJ(p+k)e^{i(p+k)\cdot x_0} \int \frac{d^2\boldsymbol{q}_{1\perp}}{(2\pi)^2} v(0, \boldsymbol{q}_{1\perp}) e^{-i\boldsymbol{q}_{1\perp}\cdot\boldsymbol{b}_{1\perp}} a_1 T_{a_1} \mathcal{R}_{1,0},$$

we have factored out the radiation part $\mathcal{R}_{1,0}$ from the scattering amplitude here.

$$\mathcal{R}_{1,0} = -2ig_e(1-x)\frac{\boldsymbol{\epsilon}_\perp \cdot \boldsymbol{k}_\perp}{\boldsymbol{k}_\perp^2 + x^2m^2} \times \left[1 + \frac{(qB)^2x^2}{(\boldsymbol{k}_\perp^2 + x^2m^2)^2} + \frac{(qB)^2x^2(1-x)^2}{(\boldsymbol{k}_\perp^2 + x^2m^2)^2}\right]\left[1 - e^{i\omega_0(z_1-z_0)}\right],$$

where we define

$$\omega_0 = \frac{\boldsymbol{k}_\perp^2 + x^2m^2}{2\omega(1-x)}.$$

Photon radiation and jet electromagnetic energy loss

By doing a similar calculation, we can also obtain the radiation amplitude $\mathcal{R}_{1,1}$ of second single scattering diagram,

$$\mathcal{R}_{1,1} = -2ig_e(1-x)\frac{\boldsymbol{\epsilon}_\perp \cdot (\boldsymbol{k}_\perp - x\boldsymbol{q}_{1\perp})}{(\boldsymbol{k}_\perp - x\boldsymbol{q}_{1\perp})^2 + x^2m^2} \times \left\{1 - \frac{(qB)^2x^2(1-x)^2}{[(\boldsymbol{k}_\perp - x\boldsymbol{q}_{1\perp})^2 + x^2m^2]^2}\right\} e^{i\omega_0(z_1-z_0)}.$$

Add the two together to obtain the single scattering radiation amplitude $\mathcal{R}_1$,

$$\begin{aligned}\mathcal{R}_1 &= \mathcal{R}_{1,0} + \mathcal{R}_{1,1} \\ &= -2ig_e(1-x)\boldsymbol{\epsilon}_\perp \cdot \left\{\left[\boldsymbol{H} + x^2\boldsymbol{H}^B + x^2(1-x)^2\boldsymbol{H}^B\right]\left[1 - e^{i\omega_0(z_1-z_0)}\right]\right. \\ &\quad \left. + \left[\boldsymbol{C}_1 - x^2(1-x)^2\boldsymbol{C}_1^B\right]e^{i\omega_0(z_1-z_0)}\right\},\end{aligned}$$

where

$$\boldsymbol{C}_1 = \frac{\boldsymbol{k}_\perp - x\boldsymbol{q}_{1\perp}}{(\boldsymbol{k}_\perp - x\boldsymbol{q}_{1\perp})^2 + x^2m^2}, \quad \boldsymbol{C}_1^B = \frac{(qB)^2(\boldsymbol{k}_\perp - x\boldsymbol{q}_{1\perp})}{[(\boldsymbol{k}_\perp - x\boldsymbol{q}_{1\perp})^2 + x^2m^2]^3}.$$

Photon radiation and jet electromagnetic energy loss

The expression of $\mathcal{R}_{2,0}$ and $\mathcal{R}_{2,2}$ are given by

$$\mathcal{R}_{2,0} = -g_e(1-x)\boldsymbol{\epsilon}_\perp \cdot \left[\boldsymbol{H} + x^2\boldsymbol{H}^B + x^2(1-x)^2\boldsymbol{H}^B\right]\left[1 - e^{i\omega_0(z_j - z_0)}\right],$$

$$\mathcal{R}_{2,2} = -g_e(1-x)\boldsymbol{\epsilon}_\perp \cdot \left[\boldsymbol{C}_2 - x^2(1-x)^2\boldsymbol{C}_2^B\right] e^{i\omega_0(z_j - z_0)},$$

where

$$\boldsymbol{C}_2 = \frac{\boldsymbol{k}_\perp - x\boldsymbol{q}_{1\perp} - x\boldsymbol{q}_{2\perp}}{(\boldsymbol{k}_\perp - x\boldsymbol{q}_{1\perp} - x\boldsymbol{q}_{2\perp})^2 + x^2m^2}, \quad \boldsymbol{C}_2^B = \frac{(qB)^2(\boldsymbol{k}_\perp - x\boldsymbol{q}_{1\perp} - x\boldsymbol{q}_{2\perp})}{[(\boldsymbol{k}_\perp - x\boldsymbol{q}_{1\perp} - x\boldsymbol{q}_{2\perp})^2 + x^2m^2]^3}.$$

Add the two together to obtain the double Born scattering radiation amplitude $\mathcal{R}_2$,

$$\begin{aligned}\mathcal{R}_2 &= \mathcal{R}_{2,0} + \mathcal{R}_{2,2} \\ &= -g_e(1-x)\boldsymbol{\epsilon}_\perp \cdot \left\{\left[\boldsymbol{H} + x^2\boldsymbol{H}^B + x^2(1-x)^2\boldsymbol{H}^B\right]\left[1 - e^{i\omega_0(z_j - z_0)}\right]\right. \\ &\qquad \left. + \left[\boldsymbol{C}_2 - x^2(1-x)^2\boldsymbol{C}_2^B\right] e^{i\omega_0(z_j - z_0)}\right\}.\end{aligned}$$

[H.-Z. Zhang, Z.-B. Kang, B.-W. Zhang, and E. Wang, EPJC 67, 445 (2010)]

Photon radiation and jet electromagnetic energy loss

The ensemble average over the scattering center location can be expressed as the combination of the impact parameter average and the longitudinal locations average, as follows

$$\langle \cdots \rangle = \frac{1}{A_\perp} \int d^2 \boldsymbol{b}_{j\perp} dz_0 dz_j \rho(z_0, z_j) \cdots .$$

Define L as the target size. Longitudinally, the distribution of the initial location of jet and the location of scattering center is defined by

$$\rho(z_0, z) = \frac{\theta(L-z)}{L/2} \exp\left(- \frac{L-z}{L/2} \right) \frac{\theta(z-z_0)}{L/2} \exp\left(- \frac{z-z_0}{L/2} \right).$$

Photon radiation and jet electromagnetic energy loss

Making the following rewriting,

$$\frac{N}{A_\perp}\int d^2\boldsymbol{q}_\perp \frac{d^2\sigma_{\rm el}}{d^2\boldsymbol{q}_\perp} = \frac{N\sigma_{\rm el}}{A_\perp}\int d^2\boldsymbol{q}_\perp \frac{1}{\sigma_{\rm el}}\frac{d^2\sigma_{\rm el}}{d^2\boldsymbol{q}_\perp},$$

we can find

$$\frac{N\sigma_{\rm el}}{A_\perp} = \frac{L}{\lambda} \equiv \bar{n},$$

where $\bar{n}$ is called the opacity, which represents the mean number of rescatterings.

$$\begin{aligned}
\mathrm{Tr}\left\langle |\mathcal{M}_1|^2 + 2\mathrm{Re}(\mathcal{M}_2\mathcal{M}_0^*)\right\rangle = {} & d_R d_T |J(p)|^2 \frac{L}{\lambda}\int \frac{\mu^2 d^2\boldsymbol{q}_\perp}{\pi(\boldsymbol{q}_\perp^2+\mu^2)^2} \\
& \times \int dz_0 dz \rho(z_0, z)\left[|\mathcal{R}_1|^2 + 2\mathrm{Re}(\mathcal{R}_2\mathcal{R}_0^*)\right].
\end{aligned}$$

Photon radiation and jet electromagnetic energy loss

The first order in opacity photon emission rate can be computed from formula

$$d^3N_J d^3N_\gamma^{(1)} = \frac{1}{d_T}\mathrm{Tr}\left\langle |\mathcal{M}_1|^2 + 2\mathrm{Re}(\mathcal{M}_2\mathcal{M}_0^*)\right\rangle \frac{d^3\boldsymbol{p}}{(2\pi)^3 2E}\frac{d^3\boldsymbol{k}}{(2\pi)^3 2\omega},$$

with $d_T = 8$ is the dimension of the target color representation for a pure gluon plasma. Then the photon radiation spectrum now is

$$\frac{d^2N_\gamma^{(1)}}{d|\boldsymbol{k}_\perp|^2 dx} = \frac{1}{4(2\pi)^2}\frac{1}{x}\frac{L}{\lambda}\int d^2\boldsymbol{q}_\perp |\bar{v}(0,\boldsymbol{q}_\perp)|^2 \int dz_0 dz \rho(z_0, z)\left[|\mathcal{R}_1|^2 + 2\mathrm{Re}(\mathcal{R}_2\mathcal{R}_0^*)\right].$$

Define several dimensionless quantities

$$u = \frac{|\boldsymbol{q}_\perp|^2}{\mu^2}, \quad y = \frac{|\boldsymbol{k}_\perp|^2}{\mu^2}, \quad w = \frac{m^2}{\mu^2}, \quad v = \frac{qB}{\mu^2}.$$

Photon radiation and jet electromagnetic energy loss

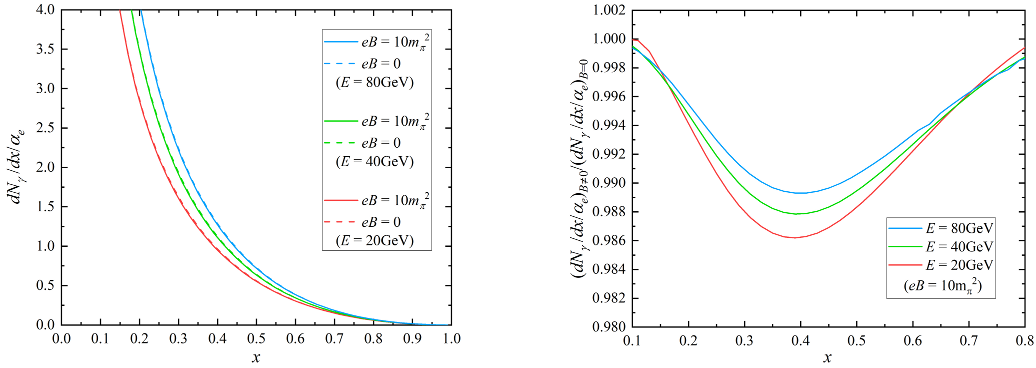
$$\frac{d^2N_\gamma^{(0)}}{dxdy} = \frac{4\alpha_e}{9\pi}\frac{(1-x)^2}{x}\left[\frac{y}{(y+x^2w)^2} - 2x^2(1-x)^2\frac{v^2y}{(y+x^2w)^4}\right],$$

$$\begin{aligned}\frac{d^2N_\gamma^{(1)}}{dxdy} = {}& \frac{4\alpha_e}{9\pi}\frac{(1-x)^2}{x}\frac{L}{\lambda}\int\frac{d\theta}{2\pi}\int du\frac{\mu^2}{(1+u)^2}\left\{\frac{y}{(y+x^2w)^2} - 2\frac{y-x\sqrt{yu}\cos\theta}{(y+x^2w)(y+x^2u-2x\sqrt{yu}\cos\theta+x^2w)}\right. \\ & + \frac{y+x^2u-2x\sqrt{yu}\cos\theta}{(y+x^2u-2x\sqrt{yu}\cos\theta+x^2w)^2} + x^2(3+4(1-x)^2)\frac{v^2y}{(y+x^2w)^4} \\ & + 2x^2(1-x)^2\frac{v^2(y-x\sqrt{yu}\cos\theta)}{(y+x^2w)(y+x^2u-2x\sqrt{yu}\cos\theta+x^2w)^3} - 2x^2(1-x)^2\frac{v^2(y+x^2u-2x\sqrt{yu}\cos\theta)}{(y+x^2u-2x\sqrt{yu}\cos\theta+x^2w)^4} \\ & - 2x^2(1+(1-x)^2)\frac{v^2(y-x\sqrt{yu}\cos\theta)}{(y+x^2w)^3(y+x^2u-2x\sqrt{yu}\cos\theta+x^2w)} \\ & - I(\omega_0,L)\left[2\frac{y}{(y+x^2w)^2} - 2\frac{y-x\sqrt{yu}\cos\theta}{(y+x^2w)(y+x^2u-2x\sqrt{yu}\cos\theta+x^2w)} + x^2(3+2(1-x)^2)\frac{v^2y}{(y+x^2w)^4}\right. \\ & + 2x^2(1-x)^2\frac{v^2(y-x\sqrt{yu}\cos\theta)}{(y+x^2w)(y+x^2u-2x\sqrt{yu}\cos\theta+x^2w)^3} \\ & \left.\left. - 2x^2(1+(1-x)^2)\frac{v^2(y-x\sqrt{yu}\cos\theta)}{(y+x^2w)^3(y+x^2u-2x\sqrt{yu}\cos\theta+x^2w)}\right]\right\}.\end{aligned}$$

LPM effect

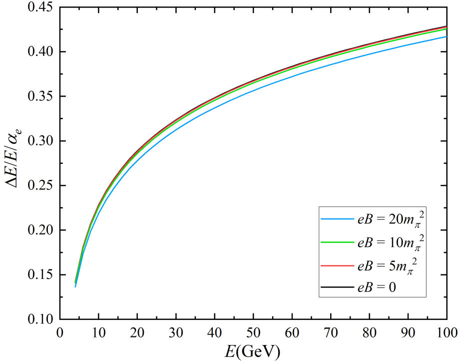
[Yue Zhang and Han-Zhong Zhang, arXiv:2510.17597]

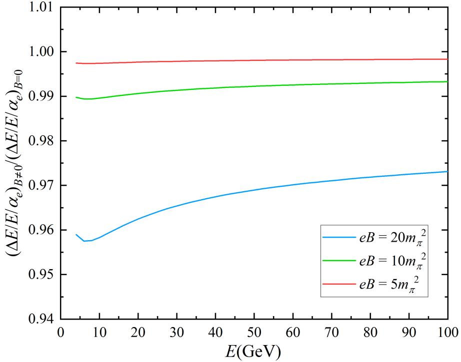
Numerical analysis



- The higher the jet energy, the greater the number of emitted photons.
- A slight suppression of the overall photon radiation over a broad range of jet energies.

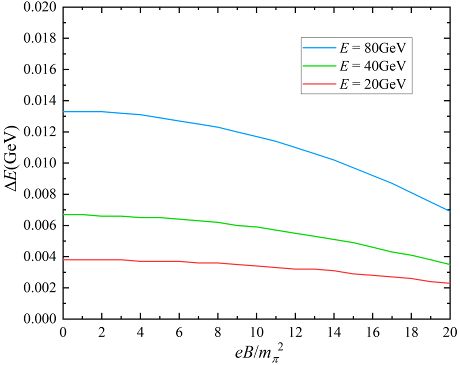
Numerical analysis





- The jet fractional energy loss due to electromagnetic radiation increases with the jet initial energy rises.
- The reduction in photon yield consequently leads to a moderate decrease in the electromagnetic energy loss of the jet.

Numerical analysis



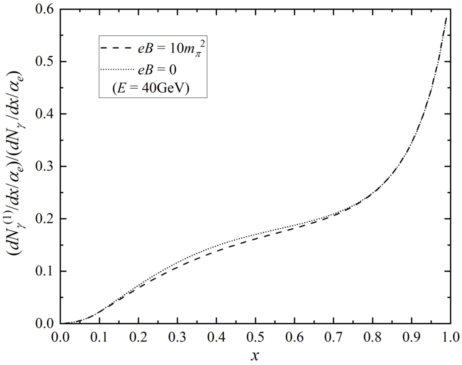
- The total energy loss for three different jet initial energies is plotted as the function of the background magnetic field strength.
- The corrections introduced by magnetic field modified the LPM effect associated with multiple scattering and enhanced the destructive interference.

Summary

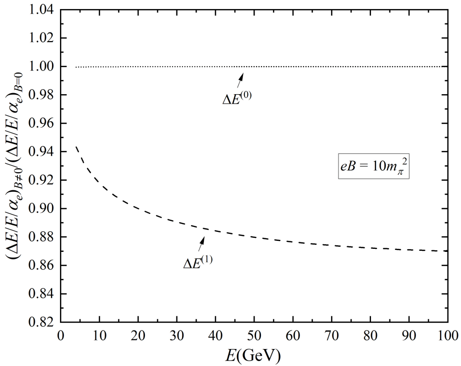
- We derived the photon bremsstrahlung in GLV formalism and weak field expansion approximation, for a quark jet propagating a QGP along a direction parallel to a background magnetic field.
- Our numerical results indicate that the presence of a magnetic field leads to a slight overall suppression of medium-induced photon production and corresponding electromagnetic radiative energy loss of jet.
- One can produce two QGP media that differ primarily in the strength of the internal magnetic field, thereby enabling a direct investigation of its influence on photon production and jet quenching.

Thank you for your attention!

Backup



$eB = 10m_\pi^2$
$eB = 0$
$(E = 40\text{GeV})$
$(dN_\gamma^{(1)}/dx/\alpha_e)/(dN_\gamma/dx/\alpha_e)$
x
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0



$\Delta E^{(0)}$
$\Delta E^{(1)}$
$eB = 10m_\pi^2$
$(\Delta E/E/\alpha_e)_{B\neq 0}/(\Delta E/E/\alpha_e)_{B=0}$
E(GeV)
0.82
0.84
0.86
0.88
0.90
0.92
0.94
0.96
0.98
1.00
1.02
1.04
0
10
20
30
40
50
60
70
80
90
100