The photon production and the collective flows from magnetic induced process in glasma

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We present an event-by-event study of photon production in the early stage of high energy nuclear collisions, where the system is dominated by highly occupied of gluons. The photons are produced through the gluon scattering and splitting processes when strong magnetic field is included. We study the spectra and collective flows of the photons and show their dependence on transverse momentum $q_T$. It is found that the photons from the boost invariant evolving glasma provide visible enhancement on spectrum and obvious contribution on $v_2$ of total the direct photons in large $q_T$ region. The results, by weighting on top of parton-hadron-string dynamics (PHSD) model, agree even better with experiment measurements in Au-Au 20%-40% centrality collisions at $\sqrt{s_{NN}} = 200\text{GeV}$.

I. INTRODUCTION

As is known, photons are important probes in heavy-ion collisions, which provide fruitful signals to investigate the pre-equilibrium stage of the collisions, the quark-gluon plasma (QGP), and the hadronic phase. Experiments at Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) have confirmed that elliptic flow of direct photons is large and can be compared to that of hadrons [1–5]. These measurements have triggered a large amount of theoretical work on modeling and interpreting the phenomenon [6–23]. Beside all the achievements made by the physicists, theoretical calculations still underestimate the measurements so far. This is the so called “direct photon puzzle”.

Event-by-event hydrodynamic model provide a time-dependent environment for photon generations, the state-of-the-art computation has found a reasonable agreement for low $q_T$ photon, see [10], the computation shows a significant contribution from late stage photon emission as well as a sizable $v_2$. Partonic channels also constitute the part of observed direct photons. The parton-hadron-string dynamics (PHSD) model copes the full evolution of a relativistic heavy-ion collisions, the photon emitting from different QGP stage is systematically studied in [8, 11, 12]. The PHSD model has greatly achieved in explaining photons from medium, especially, the computation results agree pretty well on $v_2$ and $v_3$ measurement for $q_T < 2\text{GeV}$ region. Meanwhile, to have a full understanding on the photons, other efforts have also been made on modeling the problem, for example other transport models developed in [9, 21, 23] for early stage, and so on.

Up to now, $v_2$ in $q_T > 3\text{GeV}$ regime is still not yet well described. As is noticed, strong magnetic field is produced through non-central collisions in early stage of Relativistic Heavy Ion Collisions [24–29]. Thus, all known sources of photon emission experience such magnetic environment. The magnetic field breaks translation invariance, photon emitting from magnetized medium becomes possible candidate for solving the direct photon $v_2$ problem. Models have been developed in various circumstances recently, for example, method through gauge/gravity duality [30]; photon from conformal anomaly [31] as well as chiral anomaly [32]; the photon production by quark splitting and annihilation in strong magnetic field [33].

Noteworthily, in pre-equilibrium stage of heavy ion collisions, where the large-$x$ partons act as static sources of the small-$x$ modes that constitute the Color-Glass Condensate (CGC) fields inside the two Lorentz-contracted colliding nuclei [34–38]. By interacting of CGC fields, the chromoelectric and chromomagnetic fields are formed. This is the glasma [39] and the initial stage is gluon-dominated. Thus in such strong magnetized gluonic system, photon can emit through gluon scattering and splitting processes, see [40, 41]. In this paper, we present an event by event study on photon emission from a boost invariant evolving glasma: to avoid the difficulty of a full description on evolution of initial electromagnetic (EM) fields, we introduce an ansatz of temporal profile to mimic the time evolution of EM fields and focus on the overlap region of two colliding nuclei. Ultimately, we weight our results on top of PHSD model and make comparisons with Au-Au collision measurements at 20%-40% centrality in RHIC energy.

We organize the article as follow: In Sec. II we briefly review that how to describe the evolving glasma through CYMs; In Sec. III we recall the photon production in presence of a strong magnetic field through gluon scatterings and splittings. And we deform the problem in a 2+1D boost invariant glasma. In Sec. IV we do event by event calculation and show our results of the spectra and collective flows. We summarize our results and make some outlooks on future efforts in Sec. IV.
II. THE EVOLVING GLASMA

The dynamics of the central rapidity region is determined by the small Bjorken $x$ gluons before the collision where saturation takes place [34–36, 42], thus classical Effective Field Theories (EFTs) become useful tools [43–47]. The glasma serves as the initial condition for evolution of the classical gluon field. In early stage, the evolution can be studied by the Classical Yang-Mills (CYM) equations [48–53] up to formation of the quark-gluon plasma. In this paper, the gauge fields have been rescaled by the QCD coupling $A_\mu \rightarrow A_\mu/g$, therefore $g$ does not appear explicitly in the equations.

In the MV model the color charge densities $\rho^a$ act as static sources of the transverse CGC fields in the two colliding nuclei: they are assumed to be random variables that, for each nucleus, are normally distributed with zero average and with variance specified by the equation

$$\langle \rho^a(x_T,\eta_1)\rho^b(y_T,\eta_2) \rangle = (g^2\mu)^2\delta^{ab}\delta(x_T-y_T)\delta(\eta_1-\eta_2),$$

where $a$ and $b$ denote the adjoint color indices, $x_T$ and $y_T$ denote transverse plane coordinates. $g^2\mu$ above is the only energy scale in the model which is related to the saturation momentum $Q_s$ [54]; we refer to the estimation that $Q_s/g^2\mu \approx 1.15$. To specify the initial condition, it is convenient to work in Bjorken coordinates $(\tau, \eta)$, where

$$t = \tau \cosh \eta,$$

$$z = \tau \sinh \eta,$$

and in the radial gauge, where $A_\tau = 0$. In order to compute the glasma fields we firstly solve the Poisson equations, namely

$$-\nabla \cdot \alpha^{(A)}(x_T) = \rho^{(A)}(x_T),$$

$$-\nabla \cdot \alpha^{(B)}(x_T) = \rho^{(B)}(x_T),$$

with $A$ and $B$ denoting the two colliding nuclei. The solutions of these equations are

$$\alpha^{(A)}_i(x_T) = iU^{(A)}(x_T)\partial x_T\alpha^{(A)}_i(x_T),$$

$$\alpha^{(B)}_i(x_T) = iU^{(B)}(x_T)\partial x_T\alpha^{(B)}_i(x_T),$$

where the Wilson line is defined as $U(x_T) \equiv \mathcal{P}\exp(-i \int dx_T^a\alpha_a(z(x_T)))$, with $\mathcal{P}$ being the path order operator and $z(x_T)$ is trajectory. In terms of these fields, the glasma gauge potential at $\tau \to 0^+$ can be written as

$$A_i = \alpha^{(A)}_i + \alpha^{(B)}_i, i = x, y,$$

$$A_\eta = 0.$$

Solving the Yang-Mills equations near the light cone, one finds that the transverse color electric and color magnetic fields vanish as $\tau \to 0$, but the longitudinal electric and magnetic fields are non-vanishing [57]:

$$E_\eta = i\sum_i[\alpha^{(A)}_i, \alpha^{(B)}_i],$$

$$B_\eta = i(\{[\alpha^{(A)}_x, \alpha^{(B)}_y] + [\alpha^{(A)}_y, \alpha^{(B)}_x]).$$

In all the discussion above we have neglected the possibility of fluctuations that, among other things, would break the longitudinal boost invariance. We also assume that $g^2\mu$ has no dependence on the transverse plane coordinates. To mimic the energy density profile that would be produced in realistic collisions [51, 52], we will remove this assumption in future work.

After preparing the initial condition of CYM equations, within the gauge $A_\tau = 0$ the Lagrangian density reads

$$\mathcal{L} = \text{Tr}[-\frac{1}{\tau}(\partial_\tau A_\eta)^2 - \tau(\partial_\tau A_i)^2 + \frac{1}{\tau}F^2_{\eta i} + \frac{\tau}{2}F^2_{ij}],$$

and the canonical momenta are defined by

$$E_i = \tau \partial_\tau A_i, \quad E_\eta = \frac{1}{\tau} \partial_\tau A_\eta.$$

As a consequence, the Hamiltonian density at mid-rapidity is

$$\mathcal{H} = \text{Tr}[-\frac{1}{\tau}E_i^2 + \tau E_\eta^2 + \frac{1}{\tau}F^2_{\eta i} + \frac{\tau}{2}F^2_{ij}].$$

Thus we can identify Hamiltonian by:

$$H(\tau) = \int dx_T^2\mathcal{H}(x_T, \tau) = \int \frac{d^2p_T}{(2\pi)^2}w(p_T)\rho(\tau, p_T),$$

where $\omega_p = |p_T|$ is the free dispersion relation of gluons at initial stage, and $\rho(\tau, p_T)$ is their occupation number. We use the equation above to estimate the occupation number in evolving glasma and the relation is as follow:

$$n(p_T, \tau) = \frac{1}{|p_T|}\text{tr}\left(\frac{1}{\tau}E_{\eta}(p_T, \tau)E_{\eta}(-p_T, \tau)\right) + \tau E_{\eta}(p_T, \tau)E_{\eta}(-p_T, \tau) + \frac{1}{\tau}F_{\eta i}(p_T, \tau)F_{\eta i}(-p_T, \tau) + \frac{\tau}{2}F_{ij}(p_T, \tau)F_{ij}(-p_T, \tau).$$

Due to the large occupation number of gluon, we can use classical equation of motion to describe evolution of the system. Then CYM equations in Bjorken coordinates are:

$$\partial_\tau E_i = \frac{1}{\tau}D_\eta F_{\eta i} + \tau D_j F_{ji},$$

$$\partial_\tau E_\eta = \frac{1}{\tau}D_\eta F_{\eta i},$$

with $D_\mu = \partial_\mu + iA_\mu$ is the covariant derivative.

III. PHOTON EMITTING FROM MAGNETIZED GLUONIC SYSTEM

As mentioned in Sec. I, the early stage dynamics immediately after the collision can be described by highly occupied gluon system. In non-central collisions, magnetic field is produced intensively at early stage. Hence, in
this scenario, photon can be produced by gluon scattering and splitting in a magnetized medium. The fermion propagator in present of a constant magnetic field, which can be read as in [58]:

\[
S(x, y) = \phi(x, y) \int \frac{d^4p}{(2\pi)^4} e^{-i(x-y)p} \tilde{S}(p)
\]  

(19)

in which \(\tilde{S}(p)\) is the translational invariant part in momentum space. The total propagator carry a Schwinger phase \(\phi(x, y) = e^{i\epsilon_f \int s^2 d\tau(s)(A_\mu(x) + F_{\mu\nu}(z(s) - z(s1))^{\nu})}\), where the condition \(z(s_1) = x, z(s_2) = y\) is satisfied.

In Landau level representation, the translation invariant part of the fermion propagator is also defined as follow [59]:

\[
\tilde{S}(p) = e^{-\frac{x^2}{\nu^2}} \sum_{n=0}^{\infty} \frac{(-1)^n D_n(p)}{p_0 + i\epsilon - m^2 - p_3^2 - 2n|e_fB|}
\]

(20)

where \(D_n(p)\) is:

\[
D_n(p) = \frac{2(\gamma p \cdot p p + m)(P^+ L_n(2p_T^2 |e_fB|)) - P^- L_{n-1}(2p_T^2 |e_fB|)}{+ 4(\gamma p \cdot p t) L_{n-1}(2p_T^2 |e_fB|)}
\]  

(21)

with \(P^\pm = \frac{1 \pm i\gamma^1\gamma^2\text{sign}(e_fB)}{2}\) is the projection operator, and \(L_n(x)\) is the general Laguerre polynomials. Transverse and parallel components are projected by metric with respect to the direction of magnetic field. To investigate lowest order contribution of photon emitting from gluons, one need the propagator in lowest landau level(LLL) and first landau level(1LL). This can be understood via the properties of the Dirac matrices. The perturbative analysis based on Feynman diagram, see Fig.1, results in the amplitude:

\[
M_{gg\to\gamma} = \int d^4x \int d^4y \int d^4z \int d^3s \int d^4t \int d^3r \int D^4(p)
\]

\[
e^{-i\epsilon(p-t-r)} e^{-i\epsilon(\tau-\kappa-\sigma)} e^{-i\epsilon(x+y-z)} \phi(x, y) \phi(y, z) \phi(z, x) \times \text{tr} [i\epsilon \gamma^\mu iS_{AB}(s)iS^\mu_{CD}(r)iS^\mu_{DE}iS(t) + c.c] \times \epsilon_\alpha(q) \epsilon_\mu(p) \epsilon_\nu(k),
\]

(22)

while \(t_{AB}^\mu\) is the generator in adjoint presentation, and \(\gamma^\mu, \epsilon_\mu(p)\) are Dirac matrix and polarization vector respectively. Meanwhile, each vertex carries a Schwinger phase factor. It is similar to process of splittings, \(M_{gg\to\gamma}+g\gamma\). To compute the amplitude of soft photon, one can assume that all the loop momenta are far less than that of magnetic field, i.e. \(|eB| \gg r^2, s^2, t^2\). By using this approximation, one can get the averaged amplitude square as in [40, 41]:

\[
\sum_p |M|^2 = \sum_p |M_{g\to\gamma}|^2 = \sum_p |M_{g\to\gamma'}|^2 = \sum_p \frac{2\alpha_\epsilon \alpha_s^2}{N_c \pi} \sum_f e_f^2 \left(2\omega_k^2 + \omega_k - 2\omega_k\right) \times \frac{q_f^2}{\omega_q^2} \exp \left[-\frac{q_f^2}{\omega_q^2|e_fB|} (\omega_p^2 + \omega_k^2 + 2\omega_k\omega_p)\right],
\]

(23)

while it is averaged over polarization. Here, \(\alpha_\epsilon\) is the fine structure constant, \(\alpha_s\) is the strong coupling and \(N_c\) is number of colors and \(e_f\) the electric charge number of flavors. Notice that scattering and splitting processes have the same contribution on squared transition amplitude \(|M|^2\). The differential multiplicity, when including both
the two effects, is computed as follow:
\[
\omega_g \frac{dN_g}{d^3p} = \frac{1}{2(2\pi)^3} \int \frac{d\alpha}{2} \int d\Pi_p \int d\Pi_k (2\pi)^4 \\
\times \left( \delta^{(4)}(q - p - k) n(\omega_p) n(\omega_k) \\
+ \delta^{(4)}(p - k - q) n(\omega_p)(1 + n(\omega_k)) \right) \\
\times \sum_p |\mathcal{M}|^2
\]
(24)
where \(d\Pi_p = \frac{d^3p}{(2\pi)^3 2\omega_p}\) is the Lorentz invariant measure in momentum space.

The amplitude \(\mathcal{M}\) is transverse to the plane formed by magnetic field and the propagation direction, \([40]\). In boost invariant computation, we project the problem on the transverse plane of the colliding system: we choose magnetic field lies in \(y\) direction and neglect the expansion of the system on transverse plane, thus, we can factor out \(S_T = \int d^2x_T\) as transverse overlap area of two colliding nuclei. By considering the energy-momentum conservation on light cone, the polarization direction of the produced photon is paralleled to \(q_x\). One thing need to mention is that, \(q_x\) is the only possible polarization direction, thus, \(q_x = 0\) indicates that no such photon yields, and \(\omega_q = 0\) meets the IR singularity in our calculation. In the next section, we introduce a soft cut off to remove the IR singularity and carry out an event-by-event calculation on \(q + g \to \gamma\) as well as \(g \to g' + \gamma\) processes within intensive magnetic field. Especially, we explain the collective flow behavior qualitatively by considering the introduced regulator, and show the improvements on PHSD results when compare to experimental measures. We leave the more rigorous treatment on IR singularity in the system for our future studies.

IV. NUMERICAL RESULTS

In this section we present our numerical results. Firstly, we consider a simplification on magnetic fields generated at initial stage. Then, we study the photon spectra and collective flows in \(\text{Au-Au}\) collision at RHIC energy.

A. An ansatz of electromagnetic field at initial stage

Currently, we focus on overlap region of colliding nuclei, the homogeneously distributed EM fields can be a good approximation. Moreover, we can simplify the EM fields according to the dominant component by
\[
\vec{B} \approx B_y, \quad \vec{E} \approx 0.
\]
(25)
To avoid the complexity of initial EM evolution, we introduce a decay function in time for the magnetic field. With the simplifications above, it becomes \(\vec{B}(\tau) = (0, B_0 f(\tau), 0)\). The decay function is defined by:
\[
f(\tau) = \frac{1}{1 + \tau^2/\tau_B^2},
\]
(26)
where \(\tau_B\) is the lifetime of magnetic field and acts as a parameter in this work. Here, \(B_0 = |\langle B_y \rangle|\), it’s the absolute averaged value in overlap region of two colliding nuclei at \(\tau = 0\). The average is done as follow: we reproduce the initial fields by using the Liénard-Wiechert Potentials:
\[
e\vec{E}(t, x) = \alpha e \sum_n \frac{1 - v^2}{R^3(1 - [\vec{R} \times \vec{v}]^2/R^2)^{3/2}} \frac{\vec{R}}{R},
\]
\[
e\vec{B}(t, x) = \alpha e \sum_n \frac{1 - v^2}{R^3(1 - [\vec{R} \times \vec{v}]^2/R^2)^{3/2}} \vec{v} \times \vec{R}.
\]
(27)
while protons are randomly located according to Woods-Saxon distribution
\[
\rho(r) = \rho_0 (1 + \omega r^2/\rho_0^2)^{(1 + e^{-\omega r})^{-1}}.
\]
(28)
All parameters in Eq.(28) can be found in [60]; then we do average on events as well as on transverse plane. This is in agreement with the result from [27, 28], while the difference comes from that we also do average on transverse plane. The averaged amplitude of magnetic field at different impact parameters are plotted in Fig.2.
B. Differential multiplicity of the photons from evolving glasma

In the event by event study, we define event average of $\mathcal{O}$ by:

$$\langle \mathcal{O} \rangle = \frac{1}{N_{\text{event}}} \sum_{\text{event}} \mathcal{O}_{\text{event}}$$  \hspace{1cm} (29)$$

For each event, photon from gluon scattering and splitting is computed as follow:

$$\frac{dN_\gamma}{d^3q} = \frac{S_T \alpha_s \alpha_s^2}{2(2\pi)^5 N_c} \sum_f e_f^2 \int_0^\tau \tau d\tau f \int d\omega_k \frac{\omega_p}{\omega_k}$$

$$\times \left( n(\omega_p, \tau) n(\omega_k, \tau) \delta(\omega_q - \omega_k - \omega_p) + n(\omega_p, \tau) \right)$$

$$\times \left( 1 + n(\omega_k, \tau) \right) \delta(\omega_p - \omega_k - \omega_q)$$

$$\times \frac{q_T^2}{\omega_q^2} \exp \left[ - \frac{q_T^2}{\omega_q^2} \sum_{\gamma^*} \frac{\omega_\gamma^* + \omega_k^* + \omega_p^*}{|\gamma^*|} \right],$$

with $S_T$ is the transverse area at different impact parameters, we set $N_c = 3$ and $e_f^2 = \{4/9, 1/9, 1/9\}$ for three flavors of light quarks. There is an IR singularity above in the integral over gluon energy, and it is removed by a soft cutoff, $\Lambda_{QCD} = 200\text{MeV}$, which equivalently by dressing the gluons with a small mass. The corresponding event average is written as:

$$\left\langle \frac{dN_\gamma}{d^3q} \right\rangle = \frac{S_T \alpha_s \alpha_s^2}{2(2\pi)^5 N_c} \sum_f e_f^2 \left( \int_0^\tau \tau d\tau f_{g\rightarrow g+\gamma} \right)$$

$$+ \left( \int_0^\tau \tau d\tau f_{g+g\rightarrow g+\gamma} \right),$$

(31)

with $f_{g\rightarrow g+\gamma}$ and $f_{g+g\rightarrow g+\gamma}$ are momentum space integral part for scattering and splitting in Eq.(30) respectively.

In each event, gluon occupation number $n(\omega_p, \tau)$ is computed by Eq.(16). After integrating over momentum space as well as time, we plot the differential multiplicity of the photons in Fig.3. We use result at different impact parameters to denote spectrum from different centrality classes. Immediately, we can study from Eq.(30) that stronger magnetic field can activate higher energy gluons, thus the photon production prefers stronger magnetic field; But increase the strength of magnetic field will not lead to a persistent enhancement of the spectrum, since higher energy gluons have lower occupation numbers. Moreover, increasing the impact parameter results in reducing the effective transverse overlap area of two colliding nuclei, thus less participants lead to less number of photons emitting from the medium. Therefore, the photon yield is sensitive to the centrality classes, depend on two competition effects between the magnetic field and the number of participants. The interplay of these competition effects lead to nonmonotonic behavior of the differential multiplicity of the photons with respect to the impact parameters shown in Fig.3.

To make a comparison with results from PHSD model and the experiment measurement, we also plot Fig.4 with $r_T = 0.05\text{fm}/c$, where we use result at impact parameter $b = 8\text{fm}$ as an approximation to denote the 20% - 40% central collision. It shows that, in $q_T < 3\text{GeV}$ region, the gluon induced photon spectrum becomes lower as $q_T$ goes to zero when compare to PHSD result; while in $q_T > 3\text{GeV}$, the spectrum becomes comparable to PHSD result as well as experimental measurements. We also weight the yields on top of PHSD calculation and find only in larger $q_T$ part, contribution on total photon spectrum becomes visible. The improvement on PHSD result is still agreed to the measurements and becomes more visualized in $q_T > 3\text{GeV}$ region. In next subsection, we will show that these photons provide obvious contribution on the total elliptic flows of direct photon, and they improve previous PHSD results magnificently.

C. Collective flows of the photon

Expanding the differential multiplicity in Fourier modes:

$$\frac{dN_\gamma}{dq^2} = \frac{1}{2\pi} \frac{dN}{q_T dq_T dy} \left( 1 + 2 \sum_{n=-\infty}^\infty n \cos[n(\phi - \psi_{RP})] \right),$$

(32)

with $y$ the momentum rapidity, $\phi$ is azimuthal angle, $\psi_{RP}$ is the reaction plane angle (here, we set $\psi_{RP} = 0$). To calculate the coefficient, we can use orthogonality of the trigonometric basis. The event average over $v_n$ is com-
The anisotropy part in Eq. (30) can be factored out as: 

\[
\langle v_i(q_T) \rangle = \int_0^\tau \tau d\tau \left\langle \frac{\int_0^{2\pi} d\phi \cos n\phi (f_{g+g\to\gamma} + f_{g\to g+\gamma})}{2 \int_0^{2\pi} d\phi (f_{g+g\to\gamma} + f_{g\to g+\gamma})} \right\rangle
\]  

(33)

while \( f_{g+g\to\gamma} \) and \( f_{g\to g+\gamma} \) have \( \phi \) dependence implicitly in equation above. In order to estimate the contribution of these photons on total collective flows, we weight our result on top of PHSD model [12], and then, compare it to experiment measurements in [2]. The weighted average is defined below:

\[
v_i = \frac{dN^{PHSD}_{q_T\text{dep}}}{dq_T\text{dep}dy} \langle v_i \rangle^{PHSD} + \left( \frac{dN^{PHSD+\text{Gluon induced}}_{q_T\text{dep}}}{dq_T\text{dep}dy} \langle v_i \rangle \right) \]

(34)

here \( v_i \) is the corresponding weighted Fourier coefficient, and we compute the cases with \( i = 2, 3 \).

Before showing the fully numerical results, we can have a qualitatively analysis on behavior of collective flows. The anisotropy part in Eq. (30) can be factored out as:

\[
\cos^2 \phi e^{-\cos^2 \phi A} = \frac{\omega_0^2}{\omega_k^2} e^{-\frac{\omega_0^2 + \omega_k^4 + \omega_0 \omega_k}{\omega_k^4 e^{\phi B}}}
\]

(35)

while other parts do not carry anisotropy after event average. Using the free dispersion relation, \( \omega_0 = |q_T| \), we can identify \( q_z/\omega_1 \) to \( \cos \phi \). When considering the IR singularity, the angular integral in Eq. (33) does not result in exact modified Bessel functions. Here, we name \( A = (\omega_0^2 + \omega_k^4 + \omega_0 \omega_k)/|e_f B| \), for both cases in scattering and splitting process.

In weak field limit (with respect to high \( q_T \) gluons), where \( (\omega_0^2 + \omega_k^4 + \omega_0 \omega_k) \gg |e_f B| \), the \( \cos^2 \phi \) in exponential is highly smeared by the factor \( A \). Thus the dominant term contributing to collective flow becomes \( \cos^2 \phi \), and this leads to: \( v_2 \approx 1/2 \) and \( v_{n \neq 2} \approx 0 \). We comment that this is the case on light cone with a specify oriented magnetic field.
For strong field limit, where \((\omega_f^2 + \omega_k^2 + \omega_A \omega_k) \ll |e_f B|\), we can do Taylor expansion on \(\cos^2 \phi e^{-\cos^2 \phi A}\) with respect to \(A\). This expansion gives infinite terms carrying none zero Fourier modes. The linear term of \(A\) carries coefficient \(\cos^4 \phi\), and this provides the first nonzero \(\cos 3\phi\) term. Consequently, it is the main finite \(v_3\) source in our computation.

The fully numerical result agrees with our qualitatively interpretations. To figure out the contribution on total collective flows, we weight our results on top of PHSD model by means of Eq.(34), and make comparisons with experiment measurements. The weighted results are plotted in Fig.5 and Fig.6. In Fig.5, we find that for \(q_T < 1.5\text{GeV}\) region, our result do not destroy PHSD computation. That’s because for very soft part, the spectrum of photon from gluons is much lower than PHSD estimations. But in \(q_T > 1.5\text{GeV}\) region, the photon generated by gluons becomes sizable, and the weighted result agrees even better to the experiment measurement on \(v_2\) in 1.5GeV < \(q_T\) < 3GeV region. Meanwhile in Fig.6, \(v_3\) of the photon does not affect PHSD result at all. We also attach our result in 3GeV < \(q_T\) < 4GeV, where PHSD computation is missing, and the colored band stands for the upper and lower boundary of damping \(v_3(q_T)\). It is interesting to find that our computation provide the right tendency when compare to the measurement, and this phenomenon has not been shown anywhere else.

V. CONCLUSION AND OUTLOOK

In this paper we present an event based study on the photons emitted through gluon scattering and splitting in strong magnetic field in an evolving glasma. The initial condition is generated by MV model and the system is evolved by CYMs. We use the boost invariant assumption to dress the highly anisotropic property of initial stage, and introduce the temporal profile to mimic the evolution of the short lived strong magnetic field. The spectra of the photons are studied in different scenarios, and we find the yield of the photon is sensitive to the central classes as well as the evolution of magnetic field. We use the result at \(b = 8\text{fm/c}\) as an approximation of 20% - 40% central class collisions.

The result from Fig.4 agrees with the measurements very well. Besides, we find that in low \(q_T\) region the contribution from gluon induced processes can be ignored, but the enhancement becomes sizable in larger \(q_T\) part: by means of about 20% enhancement on spectrum at \(q_T = 3\text{GeV}\), and even higher in larger \(q_T\) region.

To remove the IR singularity in our calculation, a soft cut off is introduced, and this results in the non-trivial behavior of the collective flows of the photons. Even the photons only have limited enhancement on total spectrum, but the contribution on total \(v_2\) is large. We weight our results on top of PHSD model, and find that when including the photon produced in magnetized glasma, the result agrees the experiment measure even better, e.g. from 0.0356 (only PHSD model [12]) to 0.1251 (weighted result) when comparing to measurement 0.1412±0.04 in [2] at \(q_T = 3\text{GeV}\). Besides, \(v_3\) from our computation does not affect PHSD result and we also provide the right tendency in \(q_T > 3\text{GeV}\) region.

Through the calculation presented in this paper, we systematically studied photons from gluon scattering and splitting in strong magnetic field at initial stage, and showed their importance to total collective flows of direct photon. Even though, the real system do not have exact boost invariant which plays important role in early stage, our results are meaningful up to a cutoff as long as it is not seriously broken in mid-rapidity regime. One key motivation to break boost invariance will be aiming to know the exact configuration and evolution of initial magnetic field. To this end, it is possibly achieved in a 3+1D calculation with a colored-particle-in-cell (CPIC) model developed in [61, 62], and we leave this for our future efforts.

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