

PHENOMENOLOGICAL ANALYSIS OF DIPHOTON PRODUCTION WITH MEDIUM-MODIFIED QUARK MASSES

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*Received 28 December 2025, accepted 11 September 2026,
published online 19 October 2026*

In this paper, the properties of Quark–Gluon Plasma (QGP) are investigated by studying the production rate of diphotons as a function of their invariant mass. Since diphotons are non-interactive constituents and carry information from initial phase to final phase, they are treated as a special probe. The current work is an extension of Kumar *et al.* [*Phys. Scr.* **96**, 124060 (2021)], in which thermal quark mass is utilized. Considering parton’s thermal interactions, we use a phenomenological quasi-particle approach which combines a thermally generated mass, the current mass, and a term connecting the two, which is used as effective quark mass. The effective quark mass replaces the role of the thermal quark mass, and the resulting diphoton production rate spectra are in good agreement with those obtained in previous theoretical studies. The model results serve as a benchmark for evaluating diphoton yields across different quasi-particle treatments. Therefore, the modified quasi-particle model does not invalidate the calculation of the diphoton production rate and helps us better understand the evolution of the QGP through its electromagnetic signals by providing a framework for studying experimental data from heavy-ion collisions at RHIC and the LHC.

DOI:10.5506/APhysPolB.57.11-A4

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1. Introduction

The forces between quarks mediated by gluon exchange are well described by the strong interaction theory referred to as Quantum Chromo-Dynamics (QCD) [1, 2]. One of the fundamental predictions of QCD is the transformation of hadronic matter at very high temperatures and/or densities. During this transition, quarks and gluons are released from hadrons and form a new state of matter known as Quark–Gluon Plasma (QGP) [3]. Several significant facets of QCD govern this transition:

- (I) Color Confinement: When the strong coupling constant increases over large distances (low momentum transfer), quarks and gluons confine within hadrons [4].
- (II) Asymptotic Freedom: When the coupling constant decreases at very small distances (high momentum transfer), quarks and gluons behave as almost free particles within the QGP.
- (III) Chiral Symmetry Breaking: The dynamic generation of quark masses within hadrons [5].

These special features make the QGP’s study a fascinating area of particle physics research. This exotic state of matter is created by nucleus–nucleus collisions facilities at RHIC at BNL and the LHC at CERN. Its incredibly short lifetime of about 3 fm/c makes direct observation extremely difficult, necessitating the use of indirect probes [6, 7]. Several such signals have been developed to study this deconfined matter, including photon and lepton production [8–10], droplet formation [11–13], strangeness enhancement [14], J/ψ suppression [15], the equation of state [16], and elliptical flow [17, 18].

This work focuses on electromagnetic signatures, which are considered particularly clean probes. Because photons and leptons do not interact via the strong force, they have a long mean free path and can exit the plasma with minimal interaction. Therefore, unlike hadrons, they carry largely undisturbed information from their point of creation to the detector. This property makes them highly effective for studying the properties of both the hadronic and QGP phases [19], and one of the best tools for the detection and characterization of the QGP [20]. This study is confined to the production of paired particles such as diphotons and dileptons because their invariant mass can be reconstructed from the final-state products. It is important to note that diphoton production is a purely electromagnetic process of order α^2 , while single photon production at leading order proceeds via an $\alpha\alpha_s$ process.

The production mechanisms for diphotons and dileptons from quark–antiquark annihilation are quite similar; however, the pairs are distinguished by their production cross sections and the influence of their thermal masses within the medium [21, 22]. Although both probes are useful for measuring the kinematics and temperature of the QGP, dilepton spectra can be complicated by contributions from hadronic resonance decays, making diphotons a cleaner channel for certain spectroscopic studies. For these reasons, electromagnetic probes in heavy-ion collisions are considered effective thermometers of the QGP. This work aims to calculate the production rate and emission spectra of thermal diphotons as a function of their invariant mass, produced during the hydrodynamical expansion of the plasma.

However, a significant challenge in using electromagnetic signatures is the large background contribution from various hadronic processes. The thermal photons from the QGP phase constitute only a small fraction of the total photon spectrum measured in experiments. Isolating the desired signal requires careful and effective subtraction of the substantial background noise. The total photon spectrum is composed of signals from different sources, which dominate distinct kinematic regions. At high transverse momentum κ_T , the yield is primarily from prompt photons produced in initial hard scatterings, while at low κ_T , photons from hadronic decays are the main contributors [23]. The thermal photon signal from the QGP is expected to be most significant in the intermediate range of $\kappa_T \approx 3\text{--}7$ GeV, providing an observational window for its study [24].

A central task for researchers is to isolate the thermal signal from the large backgrounds. Although various techniques have been developed to mitigate the background [25], the complete removal of the noise is an ongoing challenge that requires the development of new methods [26]. This study considers the thermal production of photon pairs from the QGP. We focus on the lowest-order channel, quark–antiquark annihilation $q\bar{q} \rightarrow \gamma\gamma$, as it is a dominant process for thermal diphoton emission due to its high production yield. In both the hadronic and gluonic phases, other higher-order channels such as quark–gluon scattering $qg \rightarrow \gamma\gamma$ and gluon–gluon fusion $gg \rightarrow \gamma\gamma$ are also important generators of diphotons. These processes can be described using more advanced methods, such as soft-gluon re-summation approaches [27].

In this paper, we use lowest-order process, $q\bar{q} \rightarrow \gamma\gamma$, using a quasi-particle approach [28–30]. The finite, temperature-dependent mass of the quarks is a crucial part of the model since it directly affects the production rate of diphotons. The thermal quark mass is useful as it removes infrared divergences in the production rate at temperatures over the critical point [29–35]. Furthermore, a logarithmic term including the thermal mass contains the strong coupling constant. It regulates the emission rate of diphotons [36].

The quasi-particle model used in Refs. [29, 30] is significantly revised in this work. The thermal quark mass is replaced by an effective quark mass m_{eq} that incorporates the quark's current masses [37] and quark's thermal mass. Further, we compute the diphoton production rate via the lowest-order channel at three QGP relevant temperatures: 200 MeV, 300 MeV, and 400 MeV. Finally, this work aims to provide a deeper understanding of the unusual form of matter through the study of diphoton emission rate. These theoretical rates are crucial inputs for hydrodynamic models of QGP evolution.

2. A brief phenomenological model approach

A thermalized state of matter called Quark–Gluon Plasma (QGP) is created under extremely high temperatures and densities. Indirect signatures are needed to investigate this medium, and electromagnetic waves are thought to be some of the best probes. To calculate the diphoton production rate, this work employs a phenomenological quasi-particle model [10, 29, 30, 38, 39]. The quasi-particle model, as described in [40], effectively captures the non-ideal properties of the plasma near the transition temperature $T \approx 200$ MeV. Around this temperature, thermal excitations of quarks and gluons lead to the formation of these quasi-particles. A key aspect of our work is the use of an effective quark mass [37, 40], as opposed to a purely dynamical one, which also allows the model to predict the transition temperature from the hadronic to the plasma phase. The effective mass of these quasi-particles m_{eq}^2 can be extracted from thermal Hamiltonian [12] defined as

$$H(\kappa, T) = \sqrt{\kappa^2 + m_{\text{eq}}^2}. \quad (1)$$

For large momenta κ , the Hamiltonian can be approximated as $\kappa + \frac{m_{\text{eq}}^2}{2\kappa}$. The effective mass m_{eq} replaces the usual thermal quark mass at high temperatures. This in-medium mass effectively captures thermal and collective effects and has been widely reported in several works [37, 40–43]

$$m_{\text{eq}}^2 = m_c^2 + \sqrt{2}m_cm_{\text{tf}} + m_{\text{tf}}^2. \quad (2)$$

The terms in this expression correspond to the squared current quark mass m_c^2 , a term that couples the current and thermal masses $\sqrt{2}m_cm_{\text{tf}}$, and the squared thermally-generated fermion mass m_{tf}^2 . These thermal effects arise from the strong interactions between quarks and gluons at high temperatures, which makes the quasi-particle mass strongly dependent on the medium [16, 38, 44, 45]. The thermal fermion mass m_{tf} is defined as [16, 46]

$$m_{\text{tf}}^2 = T^2(\gamma_q)g^2(\kappa). \quad (3)$$

In the above equation, T represents the temperature, and the factor γ_q is treated as a phenomenological flow parameter which gives the hydrodynamical aspects of hot QGP evolution. We used $\gamma_q = 1/6$ in our calculation as it significantly enhances the quark-flow dynamics [9–12, 46]. This confirms the hydrodynamical behaviour of the hot plasma, consistent with the modified quasi-particle framework. The term $g(\kappa)$ is the QCD coupling constant, which is related to α_s by the expression

$$g^2(\kappa) = 4\pi\alpha_s. \quad (4)$$

For the purposes of this work, the coupling is defined for two quark flavours $n_f = 2$ [12]. The relativistic momentum κ has been extensively discussed and reported by many authors, and references provided therein [29, 46]. It is given by

$$\kappa = \left[\frac{\gamma A_{\text{QCD}}^2 N^{\frac{1}{3}} T^2}{2} \right]^{\frac{1}{2}}. \quad (5)$$

Here, γ is a parameter analogous to the Reynolds number, which defines the flow properties of the QGP [38, 47, 48] and the factor A_{QCD} is a QCD parameter which separates the perturbative and non-perturbative region of QCD.

The current study on electromagnetic probes, specifically in the QGP sector, is evaluated within the modified quasi-particle framework incorporating effective quark masses. Recently, Sethy and co-workers [49, 50] have successfully applied these models to investigate electromagnetic radiation in QGP and hadronic sector. The quasi-particle treatment also confirms the thermodynamic variables consistency with lattice QCD results [51, 52]. This assures the existence and validity of the model. Since the results of the equation of state (EoS) show consistency with the experimental results, the emission characteristics also support the reliability of our approach. Therefore, the quasi-particle treatment with effective mass captures both the physical consistency of the QGP phase and the sensitivity of diphoton yields to medium parameters. With the validity of modified quasi-particle framework, the diphoton production rate in QGP medium is studied in the next section.

3. Diphoton production rate in the QGP

In heavy-ion collisions, diphotons are produced from both the initial QGP and the later hadronic phase through the interactions among quarks, gluons, and pions. The production yield in both phases is highly sensitive to the temperature of the medium. As the QGP expands and cools, it transitions into a hadron gas. Since photons do not interact with the strong

force, they travel undisturbed from their site of formation to the detector, making electromagnetic radiation an ideal probe for the entire process. This allows them to transmit direct information about the QGP properties.

The strong background signal from the hadronic phase is a major obstacle in these investigations. However, significant production rates have been detected by experiments at RHIC and the LHC, and methods to reduce the background are available. Building on previous research in this field [36], this work concentrates on the quark–antiquark annihilation mechanism, which is the major diphoton generation channel within the QGP

$$q + \bar{q} \rightarrow \gamma + \gamma. \quad (6)$$

The production rate is calculated within the framework of finite-temperature field theory. This approach incorporates medium-induced screening effects and uses re-summation techniques to account for contributions from hard and soft momentum scales within the plasma [33, 35, 36]. The resulting expression for the diphoton production rate as a function of invariant mass is given by

$$\frac{dR}{dM^2} = \frac{0.25}{\pi^3} \sum_f e_f^4 \alpha^2 N_c \sqrt{\frac{\pi M T^3}{2}} \ln \left(\frac{c M^2}{m_{\text{eq}}^2} \times \frac{2\pi}{3} \right) e^{-\frac{M}{T}}. \quad (7)$$

In this equation, M is the invariant mass of the photon pair, T is the temperature, and N_c is the number of colours. The parameter α is the fine-structure constant, and c is a constant with a value of approximately 0.042.

The production rate given by equation (7) is most applicable to diphotons with large invariant masses $M > T$, a regime accessible at temperatures above the critical temperature T_c . The deconfined phase of quarks and gluons exists for a very short period (approximately 10^{-23} s) before it cools and hadronizes into the final-state hadron gas. The following section presents the numerical results for the diphoton production rate, calculated using the effective quark mass model for the lowest-order annihilation process.

4. Results

This section presents the numerical results for the diphoton production rate determined with the help of modified quasi-particle model using the effective quark mass. The rate is calculated as a function of the diphoton invariant mass at several temperatures equal to or greater than the critical temperature. The results presented are exclusively for the QGP phase and do not include contributions from the hadron gas phase. For this, a simplest lowest-order quark–antiquark annihilation process is utilized to evaluate the diphoton production rate in the QGP medium which serves as a dominant

channel and has been widely used by researchers within the relevant mass range [29, 36]. Notably, our comparisons are limited to the theoretical assessments, focusing on elementary (quark–antiquark annihilation) processes within the QGP sector at finite temperature. A detailed comparison with lattice data results has not been included for the lowest order processes. It is because we have not incorporated higher-order correction terms in the strong coupling term, which arises from real and virtual gluon emission [27].

The analysis aims to achieve two goals. First, our results are compared with previous studies [29, 36] to benchmark the model. Second, we seek to validate the use of the effective quark mass by examining its specific impact on the diphoton mass spectrum in the QGP medium.

Figure 1 shows the diphoton production rate as a function of invariant mass at a fixed temperature of $T = 200$ MeV. The plot compares the results from the current work, which uses the effective quark mass m_{eff} , with our previous study based on a thermal quark mass m_{th} [29] and with the work of Haglin [36]. Compared to the results from Haglin, our model predicts a considerably enhanced diphoton yield in the low-mass region. Furthermore, the curve for the effective mass model is in very close agreement with the thermal mass model. This confirms that incorporating the effective quark mass provides a valid and consistent result for the diphoton rate calculation.

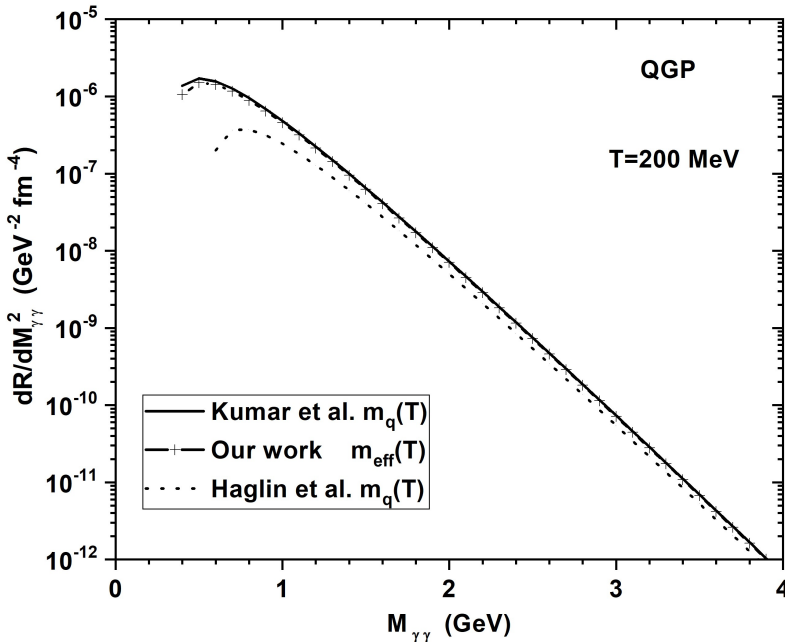


Fig. 1. Diphoton production rate as a function of invariant mass at $T = 200$ MeV compared with the works of Kumar *et al.* [29] and Haglin [36].

Figure 2 presents the diphoton mass spectrum at two temperatures, $T = 200$ MeV and $T = 300$ MeV, comparing the effective quark mass and thermal quark mass models. There are two important things to note. First, the yield at $T = 300$ MeV is much higher than the rate at $T = 200$ MeV, indicating that the production rate is quite sensitive to temperature. This is expected since greater temperatures accelerate the production rate by increasing the thermal interactions between quasi-particles. Second, at both temperatures, the effective quark mass model is in excellent agreement with the thermal quark mass model. This consistency further validates our approach, confirming that the effective mass model correctly describes the system and is a suitable framework for these calculations.

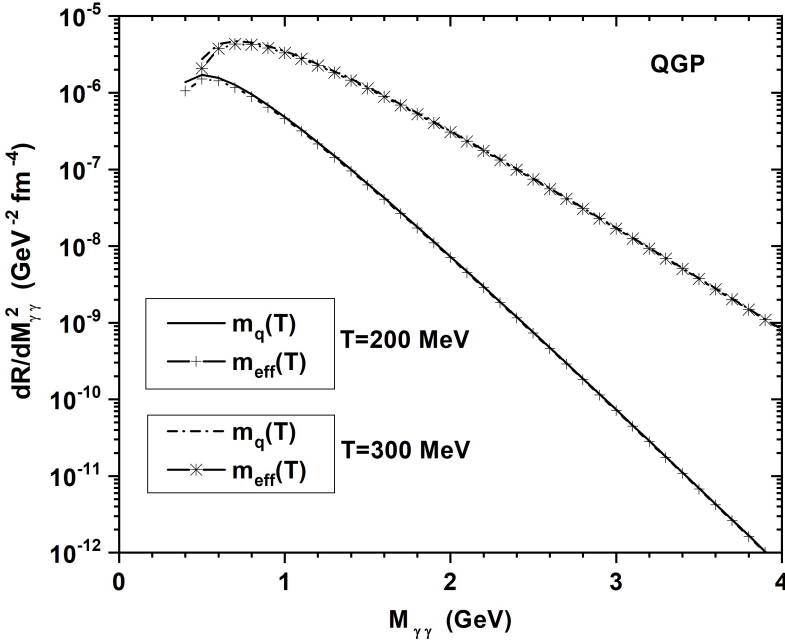


Fig. 2. Plot for the diphoton mass spectrum comparing our previous work (using thermal quark mass) [29] with our present work (using effective quark mass) at two sets of temperature *i.e.* $T = 200$ MeV and $T = 300$ MeV.

Figure 3 illustrates the production rate of diphotons calculated with the effective quark mass model for temperatures of $T = 200$ MeV, 300 MeV, and 400 MeV. The results show a significant enhancement in the diphoton yield as the temperature increases across this range. The strong temperature dependence is a key feature of thermal production from the QGP, as the increased density of interacting quarks and gluons at higher temperatures

naturally leads to a larger production rate. The sensitivity of the diphoton yield to temperature underscores its importance as a signature for detecting and studying the properties of the QGP in heavy-ion collisions.

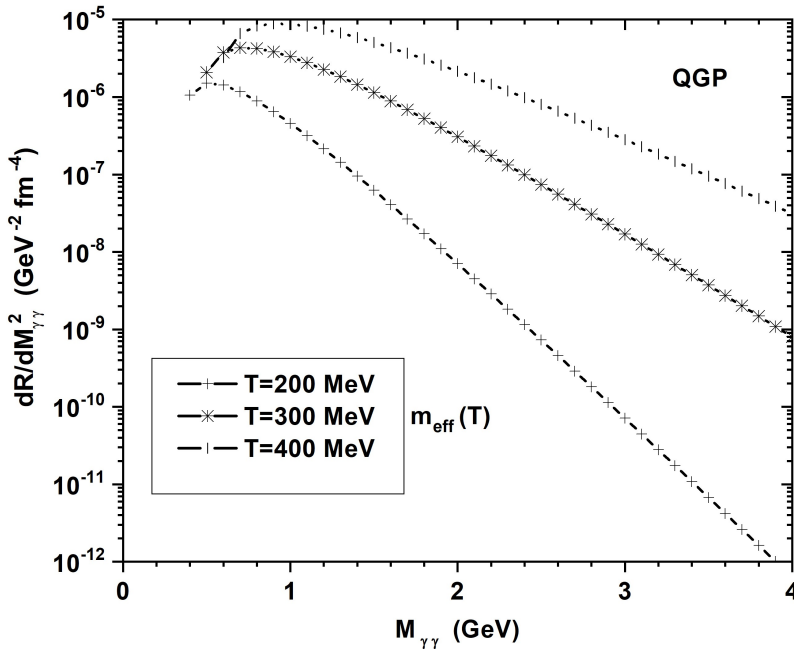


Fig. 3. Plot of the diphoton production rate as a function of photon pair mass at three different temperatures $T = 200$ MeV, $T = 300$ MeV, and $T = 400$ MeV.

We noticed that the earlier quasi-particle treatment used as a thermal quark mass was not enough and risks oversimplified manner. The consistency and robustness come from the coupling of current quark mass and thermal masses. Finally, we report that the modified quasi-particle approach, incorporating effective masses, provides a more reliable framework because it couples fundamental quark properties with medium-dependent effects. Therefore, the current model has a stronger theoretical justification for future experimental comparisons and offers the best platform for probing the QGP properties.

5. Conclusion

In this work, we investigated the properties of the QGP by calculating the diphoton production rate from the quark–antiquark annihilation channel. Our study employed a phenomenological quasi-particle model which utilizes an effective quark mass. Previous work included only the temperature-

dependent thermal mass term, which captures medium effects but ignores the intrinsic quark mass. In contrast, the current work uses effective masses based on a modified quasi-particle model that combines both the current quark mass (intrinsic) and the thermal mass (medium induced). This modification provides a more physical basis for looking deeper into the QGP. Although the current quark masses for light quarks (ud) are small compared to thermal masses, this is still a matter for precision from QGP investigations. Once the two-flavor dynamics are consistent with the effective masses of quark and do not alter the results of diphotons, additional flavors such as strange quark and heavier quarks may be systematically incorporated into the model. Therefore, these masses play a significant role in the investigation of electromagnetic probes in the QGP; however, their full impact remains a subject for further study.

The results confirm that the diphoton yield is highly sensitive to the temperature of the QGP, increasing significantly as the medium gets hotter. We demonstrated that the calculations using the effective quark mass are in excellent agreement with previous models based on a thermal quark mass, which validates the current approach. Furthermore, our model predicts an enhanced diphoton yield in the low-mass region when compared to the results of Haglin [36].

Large background signals from the hadronic phase make it difficult to get a complete view of the mass spectrum, even if this study highlights the significance of diphotons as a probe. A more precise understanding of the QGP properties will be made possible through future efforts to properly isolate the thermal signal.

We reported that the earlier work that employed only the thermal mass term is not sufficient to describe the properties of the QGP. The consistency and robustness arise from the current quark mass that comes from the first-principle inputs plus thermal quark mass that generates from the medium effects.

Finally, we conclude that the effective masses obtained within the modified quasi-particle approach provide a more reliable framework, as this approach couples fundamental quark properties with medium-dependent effects. The model results serve as a benchmark for evaluating diphoton yields across different versions of quasi-particle treatments. The dual inclusion makes it physically complete and consistent with the model calculation. Thus, it has a stronger theoretical justification for future experimental comparisons and offers a best platform for probing the QGP properties.

The authors wish to thank the Department of Physics at Hansraj College, University of Delhi for their support in pursuing this research in high-energy particle physics.

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