Study of Electromagnetic Radiation rate in hot magnetised QGP in the ambit of Effective model

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A talk presented in

EMERGENT TOPICS IN RELATIVISTIC HYDRODYNAMICS, CHIRALITY, VORTICITY AND MAGNETIC FIELD

Magnetized medium

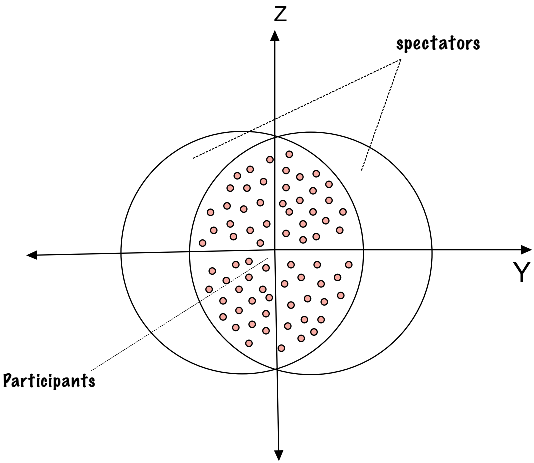


Figure: Non-central HIC

Formation of the Fireball

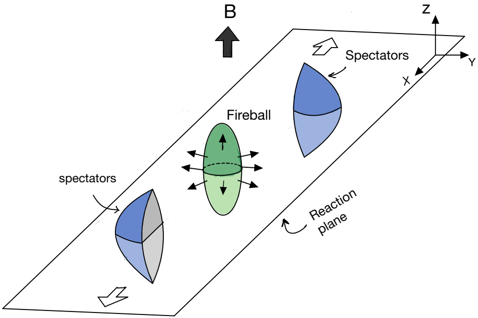


Figure: A cartoon diagram of non-central HIC. A strong magnetic field is generated inside the fireball (marked in green) in the z direction due to the spectator particles (marked in blue).

Why Studying the effects of magnetic field is so Interesting?

- It gives rise to a lot of novel phenomena like
  - Chiral magnetic effects (CME),
  - Chiral vortical effects(CVE),
  - Magnetic catalysis (MC),
  - Inverse magnetic catalysis (IMC),
  - Superconductivity of the vacuum

  and many more.

- Apart from HIC, a class of neutron stars called magnetar exhibits magnetic field ($B = 10^{14} - 10^{15}$ Gauss at the surface)

Time Dependence of the Magnetic Field

Initially, the magnetic field is very high ($|eB| \sim 15m_\pi^2$ at LHC and $|eB| \sim m_\pi^2$ at RHIC) just after the collision. But

- It decays with time on time-scale $\sim 2-3$ fm/c.
- Sovkov et. al. (Phys Rev Lett 110, 192301) suggested that the decay is very rapid and goes as inverse square with time whereas
- Tuchin (Phys Rev C 88, 024910) suggested although the decay is rapid, high electrical conductivity in the generated medium helps it to sustain a little bit longer in time.

Why Electromagnetic Probes are Considered as Efficient?

E.M. probes (Photons and di-leptons) are

1. produced in **every stage** after "little bang"
2. produced throughout the **entire volume** of the fireball
3. colorless and hence interact only **electromagnetically** with the medium and leave the medium without final state interactions due to its large mean free path

In this talk, I shall concentrate on di-leptons only

Lepton pair Production

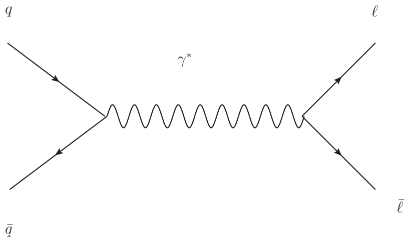


Figure: Virtual photon decays into di-lepton. ($q + \bar{q} \rightarrow \gamma^* \rightarrow \ell + \bar{\ell}$) Colorless and interact predominantly through the electromagnetic interaction $\rightarrow$ large mean free path. They carry least contaminated information of QGP state.

In this talk, I shall focus only on **thermal di-leptons**.

Lepton pair production in a Magnetized medium

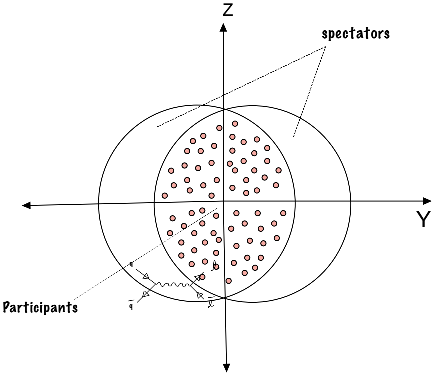


Figure: Lepton pair production in non-central HIC [1]

[1] Relevant works : ✍[Tuchin PRC 87,88 (2013)], ✍[Sadooghi and Taghinavaz, An.P 376 (2017)], ✍[Bandyopadhyay et al. PRD 94,95 (2016-17)], ✍[Ghosh et al. PRD 98,101 (2018-20)], ✍[Islam et al. PRD 99 (2019)], ✍[Wang and Shovkovy, arxiv:2205.00276 (2022)] etc..

Kinematics

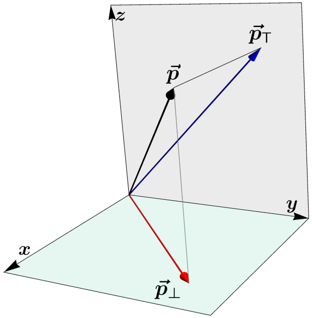
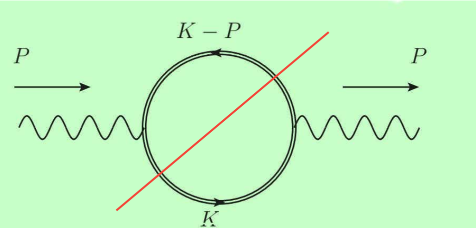


Figure: diagram depicting various momentum components of virtual photon momentum. p_T is the component of photon momentum **transverse to the direction of propagation of the two nuclei.** $p_\perp$ is the component **transverse to the direction of magnetic field.**

Dilepton rate (DR)

$$\frac{dN}{d^4Xd^4P} \equiv \frac{dR}{d^4P} = \frac{\alpha_{\rm EM}}{12\pi^3}\frac{1}{P^2}\frac{1}{e^{p_0/T}-1}\sum_{f=u,d}\frac{1}{\pi}\,\mathrm{Im}\,\Pi^{\mu}_{\mu,f}(P),$$



$$\Pi^{\mu}_{\mu,f}(P) = -iN_c q_f^2\int\frac{d^4K}{(2\pi)^4}\mathrm{Tr}\left[\gamma^{\mu}S_f^{(B)}(K)\gamma_{\mu}S_f^{(B)}(K-P)\right].$$

where $S_f^{(B)}$ is the Schwinger proper time propagator (for arbitrary external magnetic field) in the momentum space.

Processes

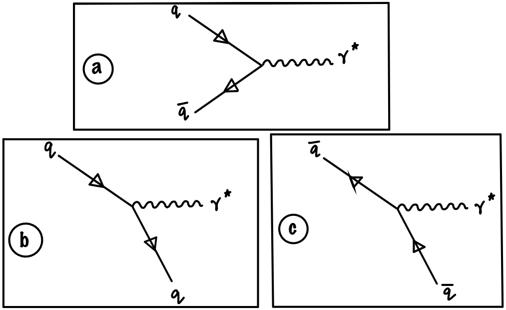


Figure: Fig. (a), (b), (c) shows quark-antiquark annihilation, quark decay and anti-quark decay processes, respectively. The quark and anti-quark decay process is absent in the absence of background field.

DR in a hot magnetized medium

✍[Das, Bandyopadhyay, Islam. Phys.Rev.D 106 (2022) 5, 056021]

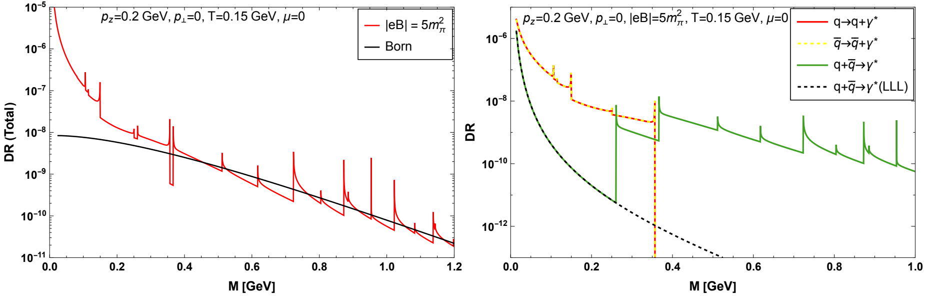


Figure: DR as a function of invariant mass for an arbitrary external magnetic field (left panel). Separate contributions coming from different processes along with the LLL approximated rate in the black dashed line (right panel).

DR in a hot magnetized medium

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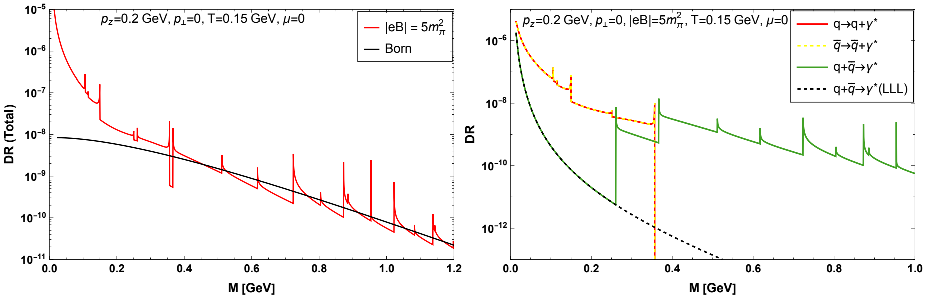

Figure: 1. Significant enhancement in the lower invariant mass regime due to contributions from the decay processes.
2. LLL approximated result exactly matches with the general result.

DR in a hot magnetized medium : effect of finite $p_\perp$

✍[Das, Bandyopadhyay, Islam. Phys.Rev.D 106 (2022) 5, 056021]

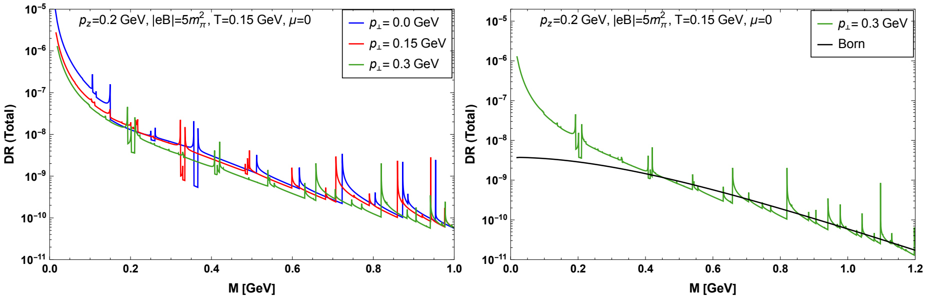

Figure: DR as a function of invariant mass for an arbitrary external magnetic field for different values of $p_\perp$ (left panel). Comparison with the Born rate for a higher value of $p_\perp$ (right panel).

DR in a hot magnetized medium : effect of finite $p_\perp$

✍[Das, Bandyopadhyay, Islam. Phys.Rev.D 106 (2022) 5, 056021]

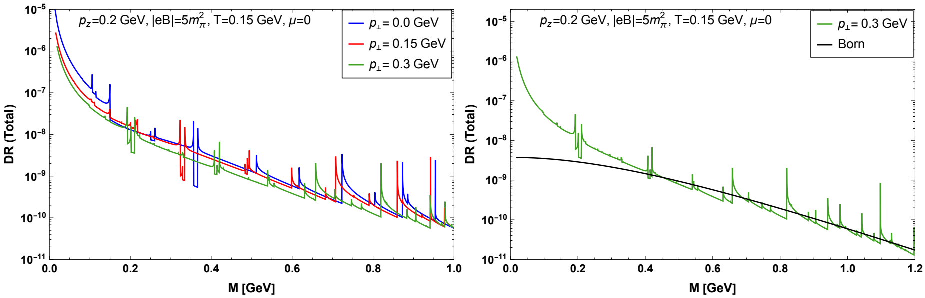

Figure: 1. With increasing values of $p_\perp$, DR gets suppressed.
2. In spite of the suppression, significant enhancement in the lower invariant mass regime is still there.

NJL Model

- NJL model (1961) : Developed in 1961 by Nambu and Jona Lasinio as a pre-QCD theory of nucleons.
- A model Lagrangian simpler to work with, constructed to have QCD symmetry structures.
- NJL Lagrangian in presence of an external EM field :

$$\mathcal{L}_{\rm NJL} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi}\left(i\not{D} - m\right)\psi + G_S\left[(\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma_5\vec{\tau}\psi)^2\right],$$

  where G_S is the scalar coupling constant, $D_\mu = \partial_\mu - iqA_\mu$.
- The effective mass within mean field approximation :

$$M_{\rm eff} = m - 2G_S \sum_{f=u,d} \langle\bar{\psi}_f\psi_f\rangle,$$

Magnetic Catalysis (MC) and Inverse MC (IMC)

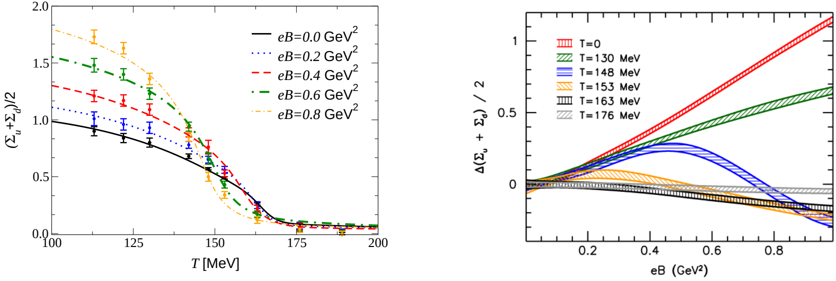

Figure: MC/IMC effects on the quark condensates. [2]

[2] ✍[Bali et al. PRD 86, JHEP 1202 (2012)]

See also : ✍**[Bruckmann et al. JHEP 1304 (2013)]**, ✍**[Mueller and Pawlowski, PRD 91 (2015)]**, ✍**[Andersen et al. JHEP 1502 (2015)]**, ✍**[Ayala et al. PRD 92 (2015)]**, ✍**[Braun et al. PLB 755 (2016)] etc..**

Recent interesting take : ✍**[D'Elia et al., PRD 105 (2022)]**

MC and IMC within NJL model

- ✍[Farias et. al. EPJA 53 (2017)]
  Effects of the IMC on the quasi particle effective/constituent mass $\mathcal{M}$ is incorporated by using a medium dependent scalar coupling $G_S(eB, T)$:

$$G_S(eB, T) = c(eB)\left[1 - \frac{1}{1 + e^{\beta(eB)[T_a(eB) - T]}}\right] + s(eB),$$

  where $c(eB)$, $\beta(eB)$, $T_a(eB)$ and $s(eB)$ depend only on the magnitude of B.

- Medium dependent effective mass $M_{\text{eff}}(eB, T)$ shows both the features of MC and IMC which we incorporate in our DR.

MC and IMC within NJL model

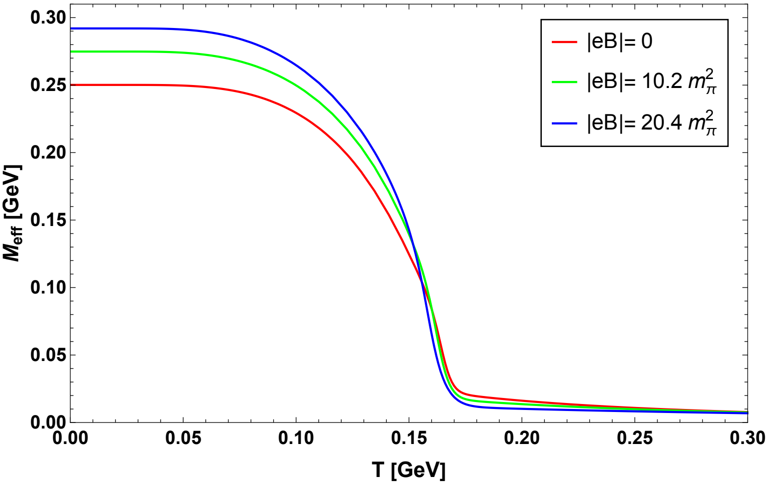

Figure: Medium dependent effective mass $M_{\rm eff}(eB, T)$ shows both the features of MC and IMC which we incorporate in our DR.

DR in a hot magnetized medium within NJL model : (I)

✍[Das, Bandyopadhyay, Islam. Phys.Rev.D 106 (2022) 5, 056021]

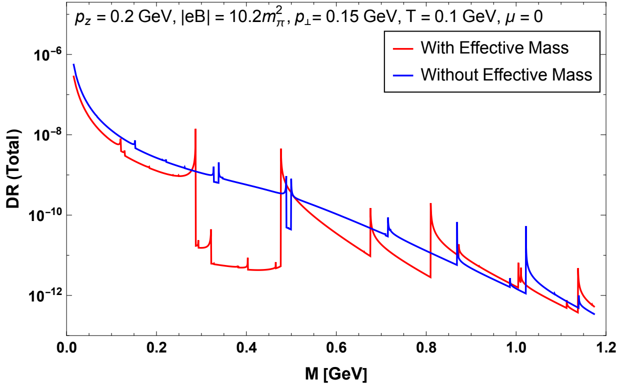

Figure: The comparison between the rates calculated using basic thermal field theory and in the ambit of effective model for the value of $eB = 10.2\ m_\pi^2$.

DR in a hot magnetized medium within NJL model : (I)

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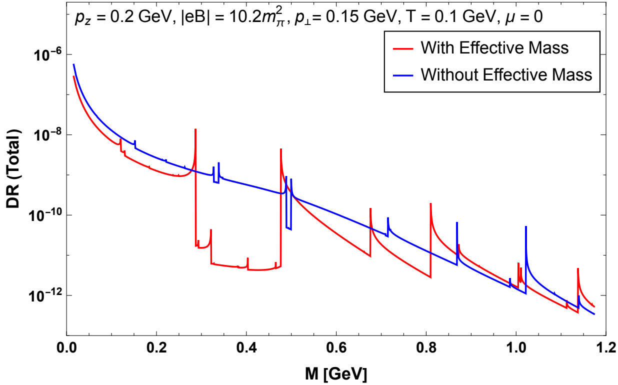

Figure: Appearance of a mass gap between decay and annihilation processes can be observed due to a larger threshold value because of the effective mass.

DR in a hot magnetized medium within NJL model : (II)

✍[Das, Bandyopadhyay, Islam. Phys.Rev.D 106 (2022) 5, 056021]

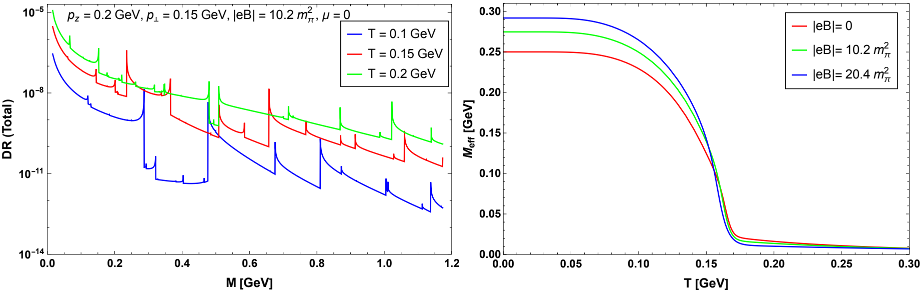

Figure: DR as a function of invariant mass for three different values of temperatures, in an effective model environment.

DR in a hot magnetized medium within NJL model : (II)

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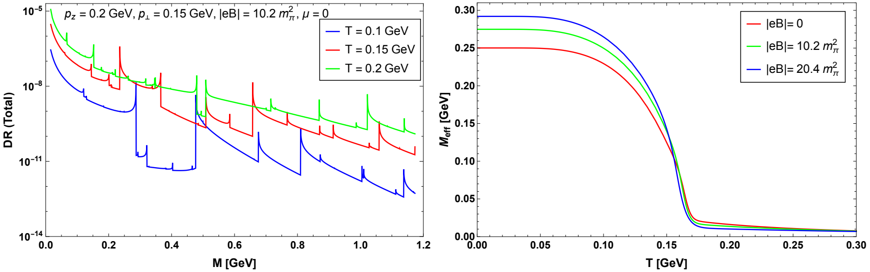

Figure: With increasing values of temperature :

1. The mass gap gets diminished because of lower values of effective mass.
2. Total DR gets increased.

DR in a hot magnetized medium within NJL model : (III)

✍[Das, Bandyopadhyay, Islam. Phys.Rev.D 106 (2022) 5, 056021]

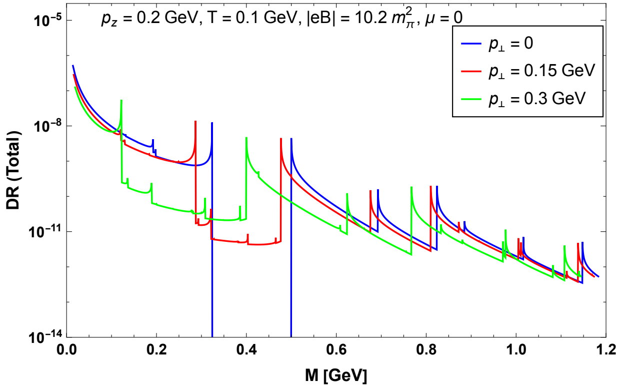

Figure: DR for three different values of $p_\perp$ for $T = 0.1$ GeV.

DR in a hot magnetized medium within NJL model : (III)

✍[Das, Bandyopadhyay, Islam. Phys.Rev.D 106 (2022) 5, 056021]

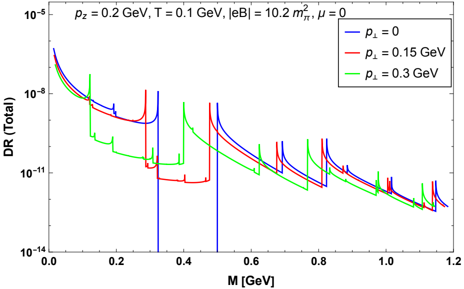

Figure: As $p_\perp$ is increased :

1. The connecting line between the gap starts increasing its strength and the gap widens.
2. The mass gap shifts toward left.
3. The suppression of the total DR is still there.

DR in a hot magnetized medium within NJL model : (IV)

✍[Das, Bandyopadhyay, Islam. Phys.Rev.D 106 (2022) 5, 056021]

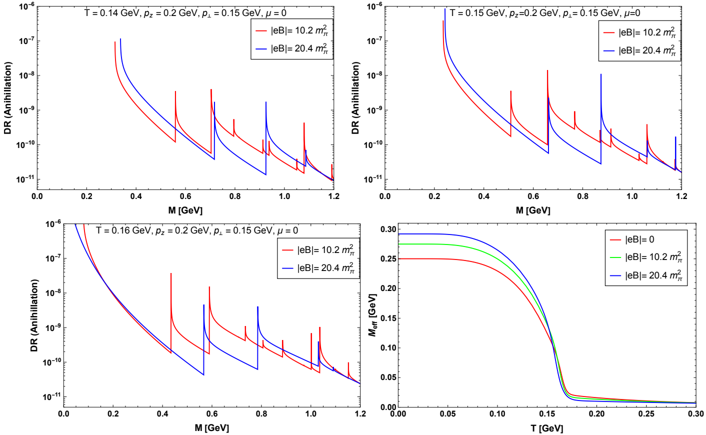

Figure: Comparison of the rates calculated in the effective model for two different values of eB and at three different regions of the QCD phase diagram.

DR in a hot magnetized medium within NJL model : (IV)

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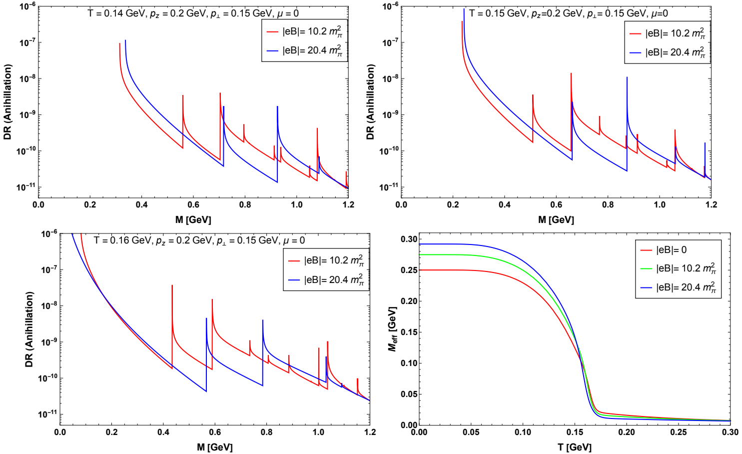

Figure: Clear reflection of IMC at the starting points of the annihilation rates.

To summarize

- DR from a hot dense magnetized medium for **nonzero values** of p_z and $p_\perp$ has been calculated and decomposed into different processes. We found **significant enhancement** compared to Born rate at the **lower regime** of invariant mass.
- We have incorporated **both the MC and IMC** effects through the effective quark mass and observed **its effect on the DR**.
- The subsequent **occurrence of a mass gap** between the decay and the annihilation processes for certain values of the temperature and the external magnetic field and its interesting behaviours have been discussed.
- We have also explicitly noticed the interesting effects of IMC on the rate, specifically on the annihilation rate, near the crossover temperature.

Future outlook

Dilepton spectra : Space-time evolution of the di-lepton production rate.

$$\frac{dN}{dM} = \int d^4X \frac{d^3p\ M}{p_0} \left(\frac{dN}{d^4X\ d^4P} \right)$$

with the natural framework of relativistic hydrodynamics.