Lepton pair production from a hot and dense QCD medium in presence of an arbitrary magnetic field

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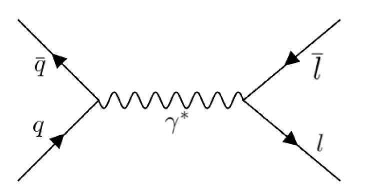
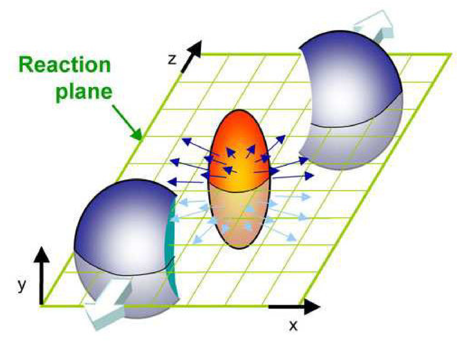
Motivation

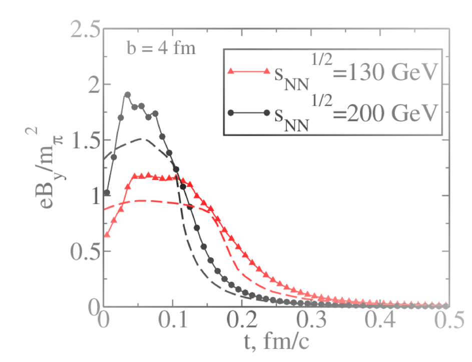
Production of lepton pair and its importance

- Leptons, being weakly interacting, have a large mean free path when produced in a strongly interacting medium. Thus they carry less contaminated information about the medium they are created in.
- They are used as a thermometer for the QGP medium.



Presence of magnetic field





- A very strong magnetic field ($eB \approx m_\pi^2$ at RHIC and $\approx 10\,m_\pi^2$ at LHC) is generated in the direction perpendicular to the reaction plane, due to the relative motion of the ions themselves. ($m_\pi^2 = 1.96 \times 10^{-2}$ GeV$^2 \approx 10^{18}$ Gauss)
- The very high initial magnitude of this magnetic field then decreases very fast, being inversely proportional to the square of time(?). [A. Bzdak and V. Skokov, PRL, 2013; K. Tuchin, PRC, 2013]
- The presence of an external field, in principle, can affect different observables related to the QCD medium created in heavy ion collisions.

Calculational novelty in our work

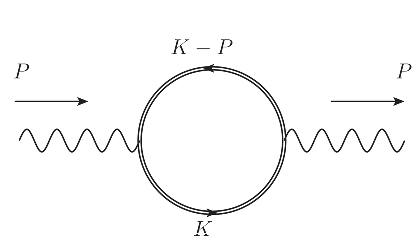
- So far dilepton rate from a magnetised medium has been calculated in different articles using different techniques. [Bandyopadhyay et al, Ghosh et al, Sadooghi et al, Wang et al].
- Many of the calculations used different approximations, particularly either strong or weak magnetic field approximations.
- In case of arbitrary magnetic field, either parallel (p_z) or perpendicular ($p_\perp$) components of the external momentum have been assumed to be zero for the ease of estimation.
- We, in this work which is easy to grasp, closely related with Wang et al (2022), try to estimate the rate for arbitrary strength of magnetic field in the most possible general scenario.
- We further subject the emission of lepton pair to an effective model scenario, which also encompasses the known IMC effect unlike all other previous efforts.

Methodology

- We can use the most general fermionic propagator in a magnetized medium to write down the one loop electromagnetic (EM) polarization tensor or the photon self-energy tensor (for a given flavour f) as

$$\Pi_f^{\mu\nu}(P) = -iN_c q_f^2 \int \frac{d^4K}{(2\pi)^4} \mathrm{Tr}\left[\gamma^\mu S_f^B(K)\gamma^\nu S_f^B(K-P)\right], \tag{1}$$

where, S_f^B is the Schwinger propagator for arbitrary eB.



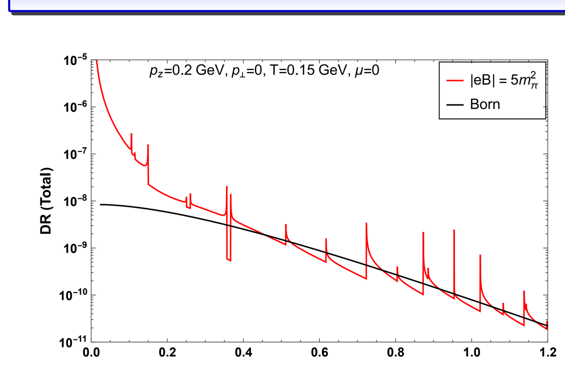
- This photon self-energy can be further related to the dilepton rate (DR) as

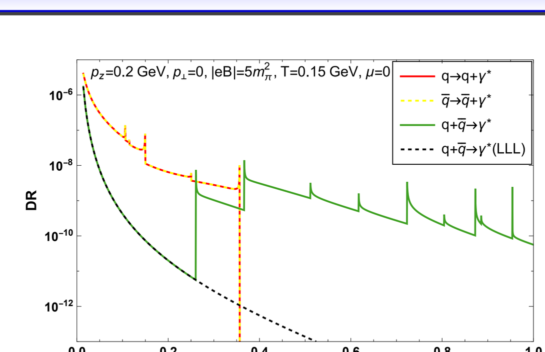
$$\frac{dN}{d^4Xd^4P} \equiv \frac{dR}{d^4P} = \frac{\alpha_{\mathsf{EM}}}{12\pi^3}\frac{1}{P^2}\frac{1}{e^{p_0/T}-1}\sum_{f=u,d}\frac{1}{\pi}\mathrm{Im}\,\Pi^{\mu}_{\mu,f}(P). \tag{2}$$

- This is our master equation that we use to estimate the rate of lepton pairs coming out of the magnetised medium.

Results

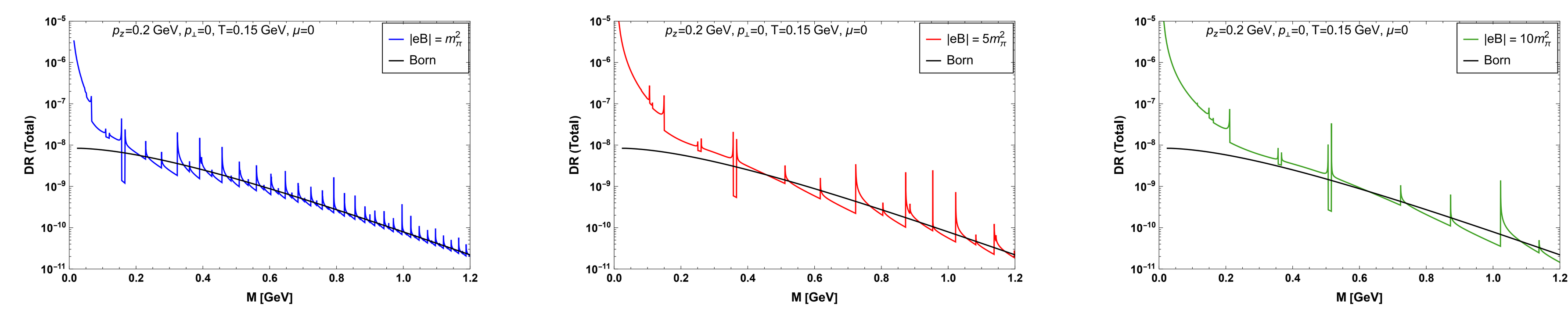
Effect of magnetic field on DR





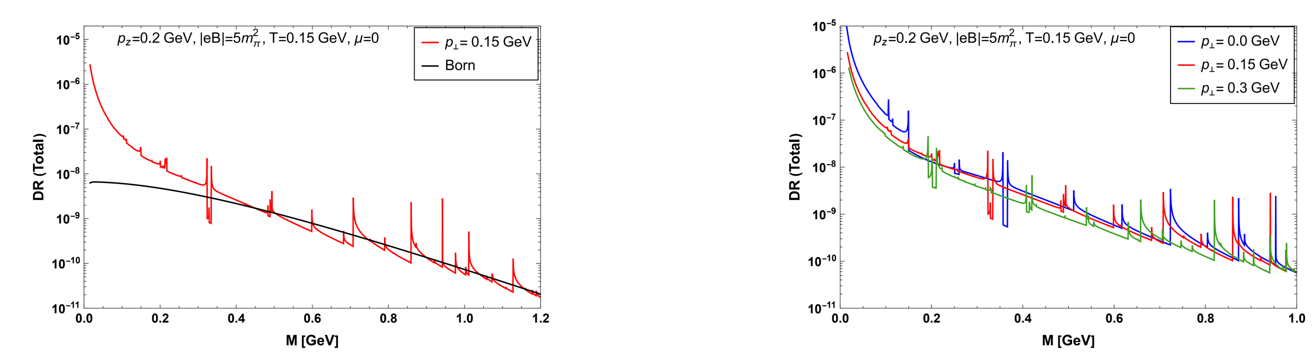
- In the left panel we have the plot of DR as a function of invariant mass for $eB = 5\,m_\pi^2$ with p_T being zero. In the right panel the contribution coming from different processes are shown separately along with the LLL approximated rate in the black dashed line.

With the increase in the magnetic field



- Plots of dilepton rate as a function of invariant mass for different values of magnetic field. Born rate is also shown for the comparison. The figures are obtained for zero values of $p_\perp$. The rate gets enhanced as the strength of the magnetic field is increased.

Effect of non-zero $p_\perp$ in the rate



- The top-left panel shows the dilepton rate estimated as a function of invariant mass for $p_\perp = 0.15$ GeV and given values of eB and T. It is also compared with the corresponding born rate. The right panel takes a closer view on the effect of $p_\perp$ in the total DR by comparing among three different $p_\perp$ values.

In the ambit of mean field model

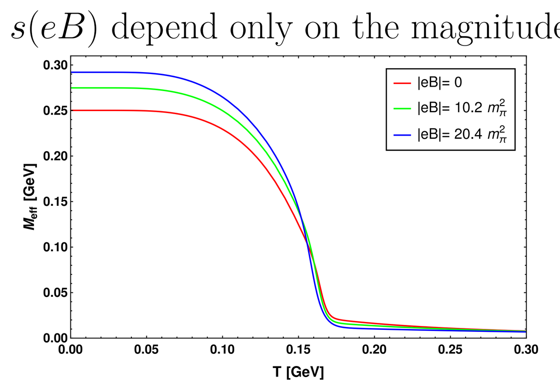
- Dynamical generation of quark mass in presence of background magnetic field is taken into account through effective mean field model like NJL one.[Nambu & Jona-Lasinio (1961)]

$$\mathcal{L}^B_{\mathrm{NJL}} = \bar{\psi}(i\not{D} - m_0)\psi + \frac{G_S}{2}[(\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma_5\vec{\tau}\psi)^2] - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}. \tag{3}$$

- We incorporate here the IMC effect by using a medium dependent coupling constant $G_S(eB,T)$ [Farias et. al. EPJA 53 (2017)]:

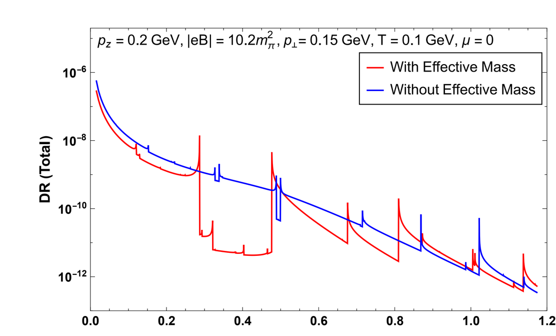
$$G_S(eB,T) = c(eB)\left[1 - \frac{1}{1+e^{\beta(eB)[T_a(eB)-T]}}\right] + s(eB), \tag{4}$$

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

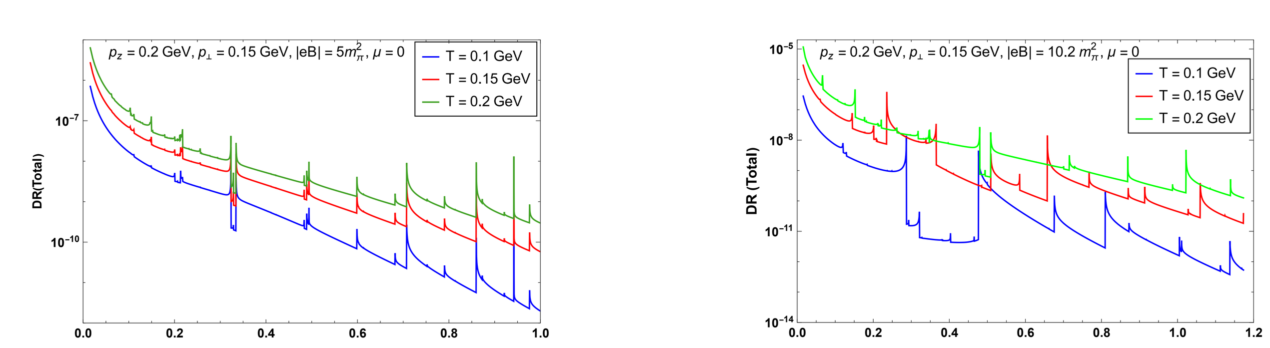


- The plot of medium dependent effective mass as a function of temperature for different values of eB.

The rate in the ambit of effective model



- The comparison between the rates calculated using basic thermal field theory and in the ambit of effective model for the value of $eB = 0.2$ GeV.



- Dilepton rate plotted as a function of invariant mass for three different values of temperatures: (left panel) in an ordinary scenario and (right panel) in an effective model environment.

Conclusion

- We have calculated the dilepton rate for arbitrary strength of magnetic field with both non-zero values of p_z and $p_\perp$.
- We could break down the rate into the contributions coming from different processes and showed that it gets enhanced as compared to the Born rate in presence of eB, particularly at the lower end of the invariant mass.
- In the ambit of effective model we have observed the occurrence of a mass gap between the decay and annihilation processes and the interesting interplay of temperature and magnetic field on its characteristics.
- As an outlook, it will be interesting to have an estimation of the dilepton spectrum. That will facilitate to have a direct experimental comparision.