Thermommagnetic effects in heavy-ion collisions

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Introduction and motivation

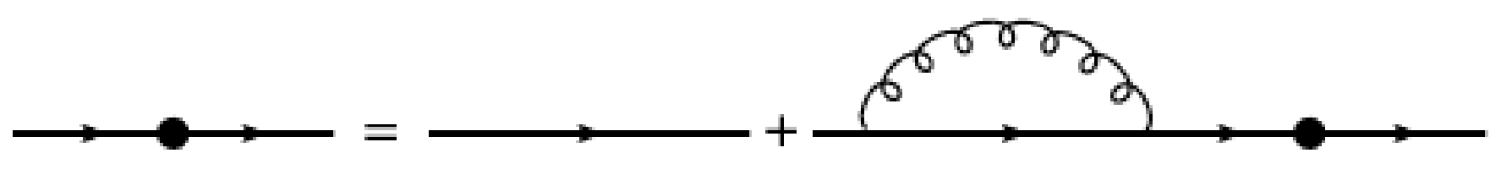
- In heavy-ion collisions, a very strong anisotropic magnetic field is generated due to the relative motion of the ions.
- Strength $\sim 15m_\pi^2$ for $\sqrt{s_{NN}} = 4.5TeV$.
- In a direction perpendicular to the reaction plane.
- Magnetic field decreases with time.
- Study of the properties of in-medium quarks and gluons in presence of the magnetic field is important.
- We have calculated magnetic field dependent quark and gluon propagator within HTL approximation and used those effective propagators to calculate Debye mass, thermodynamics in one loop level and to study the dilepton production rate.

Fermion propagators in magnetic field

- Fermion propagator in tree level in presence of magnetic field reads

$$\begin{aligned}S(K) &= \int d^4x e^{iK\cdot x}\mathcal{S}\left(x-x'\right)\\ &= -i\int_0^\infty ds\exp\left[is\left(K_\shortparallel^2-\frac{\tan\left(q_fBs\right)}{q_fBs}K_\perp^2-m_f^2\right)\right]\\ &\times\left[\left(1+\gamma_1\gamma_2\tan\left(q_fBs\right)\right)\left(\not{K}_\shortparallel+m_f\right)-\sec^2\left(q_fBs\right)\not{K}_\perp\right]\\ &= \exp\left(-\frac{K_\perp^2}{\left|q_fB\right|}\right)\sum_{l=0}^{\infty}(-1)^n\frac{D_n\left(q_fB,K\right)}{K_\shortparallel^2-m_f^2-2l\left|q_fB\right|}\end{aligned}$$

- Upto one loop level, the effective fermion propagator can be obtained as



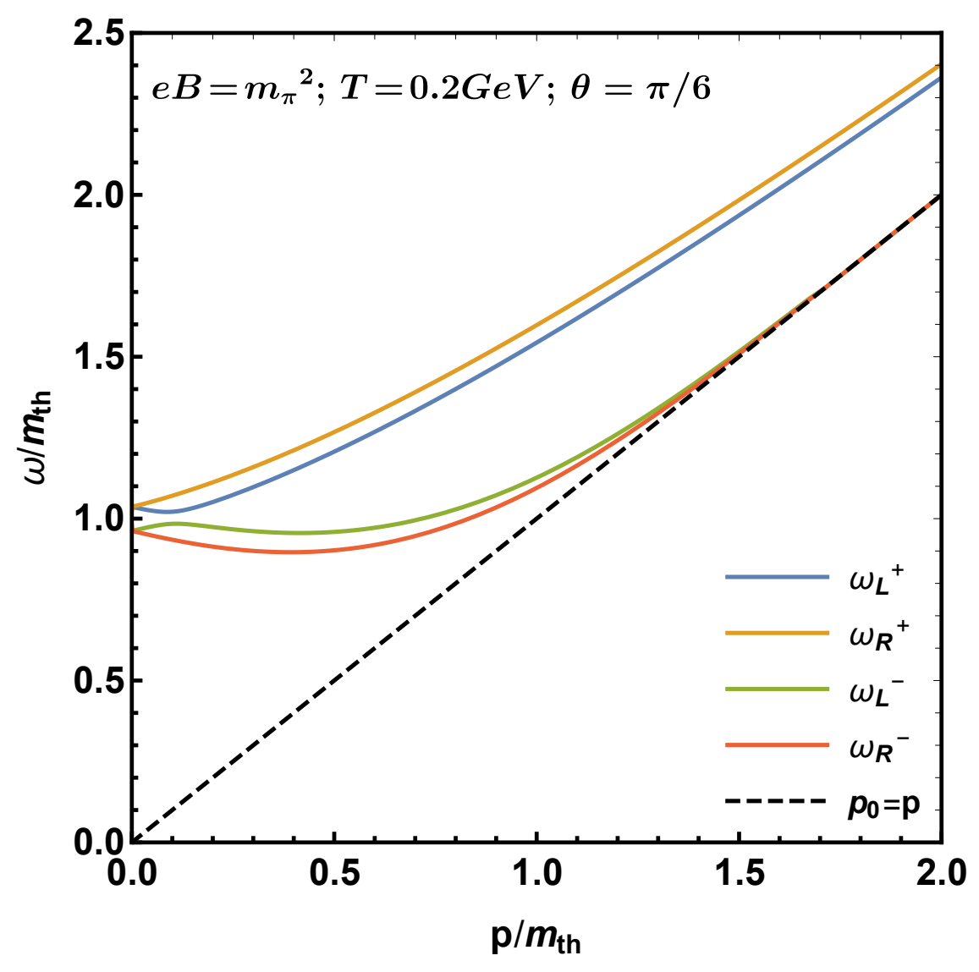
- The one-loop effective fermion propagator can be written from the Dyson-Schwinger equation as

$$\begin{aligned}S^{*-1}(P) &= S_0^{-1}(P)-\Sigma(P)\\ &= \mathcal{P}_+\not{L}\mathcal{P}_-+\mathcal{P}_-\not{R}\mathcal{P}_+\end{aligned}$$

where

$$\begin{aligned}L^\mu(p_0,p_\perp,p_z)&=\mathcal{A}(p_0,\boldsymbol{p})\,P^\mu+\mathcal{B}_+(p_0,p_\perp,p_z)\,u^\mu+c(p_0,\boldsymbol{p})\,n^\mu\\ R^\mu(p_0,p_\perp,p_z)&=\mathcal{A}(p_0,\boldsymbol{p})\,P^\mu+\mathcal{B}_-(p_0,p_\perp,p_z)\,u^\mu-c(p_0,\boldsymbol{p})\,n^\mu\\ \mathcal{P}_\pm &= \frac{1}{2}\left(\mathbb{1}\pm\gamma_5\right)\end{aligned}$$

- Quark dispersion plot in HTL approximation



- In presence of magnetic field, each dispersion modes is separated in two modes, namely, left chiral and right chiral.

General structure of gauge boson

- General structure of gluon self energy can be written as,

$$\Pi^{\mu v} = bB^{\mu v}+cR^{\mu v}+dQ^{\mu v}+aN^{\mu v}$$

where b, c, d, a are four Lorentz-invariant form factors associated with the four basis tensors as

$$\begin{aligned}A^{\mu\nu} &= \tilde{g}^{\mu\nu}-\frac{\tilde{P}^\mu\tilde{P}^\nu}{\tilde{P}^2}\\ B^{\mu\nu} &= \frac{1}{\bar{u}^2}\bar{u}^\mu\bar{u}^\nu\\ R^{\mu\nu} &= g_\perp^{\mu\nu}-\frac{P_\perp^\mu P_\perp^\nu}{P_\downarrow^2}\\ N^{\mu\nu} &= \frac{\bar{u}^\mu\bar{n}^\nu+\bar{u}^\nu\bar{n}^\mu}{\sqrt{\bar{u}^2}\sqrt{\bar{n}^2}}\\ Q^{\mu v} &= \frac{\bar{n}^\mu\bar{n}^v}{\bar{n}^2}\end{aligned}$$

where

$$\begin{aligned}\tilde{P}^\mu &= P^\mu-(P\cdot u)u^\mu = P^\mu-p_0u^\mu\\ \tilde{g}^{\mu v} &= g^{\mu v}-u^\mu u^v\\ \bar{u}^\mu &= u^\mu-\frac{p_0P^\mu}{P^2}\\ P_\perp^\mu &= P^\mu-p_0u^\mu+p^3n^\mu = P^\mu-P_\shortparallel^\mu\\ g_\perp^{\mu v} &= g^{\mu v}-u^\mu u^v+n^\mu n^v = g^{\mu v}-g_\shortparallel^{\mu v}\end{aligned}$$

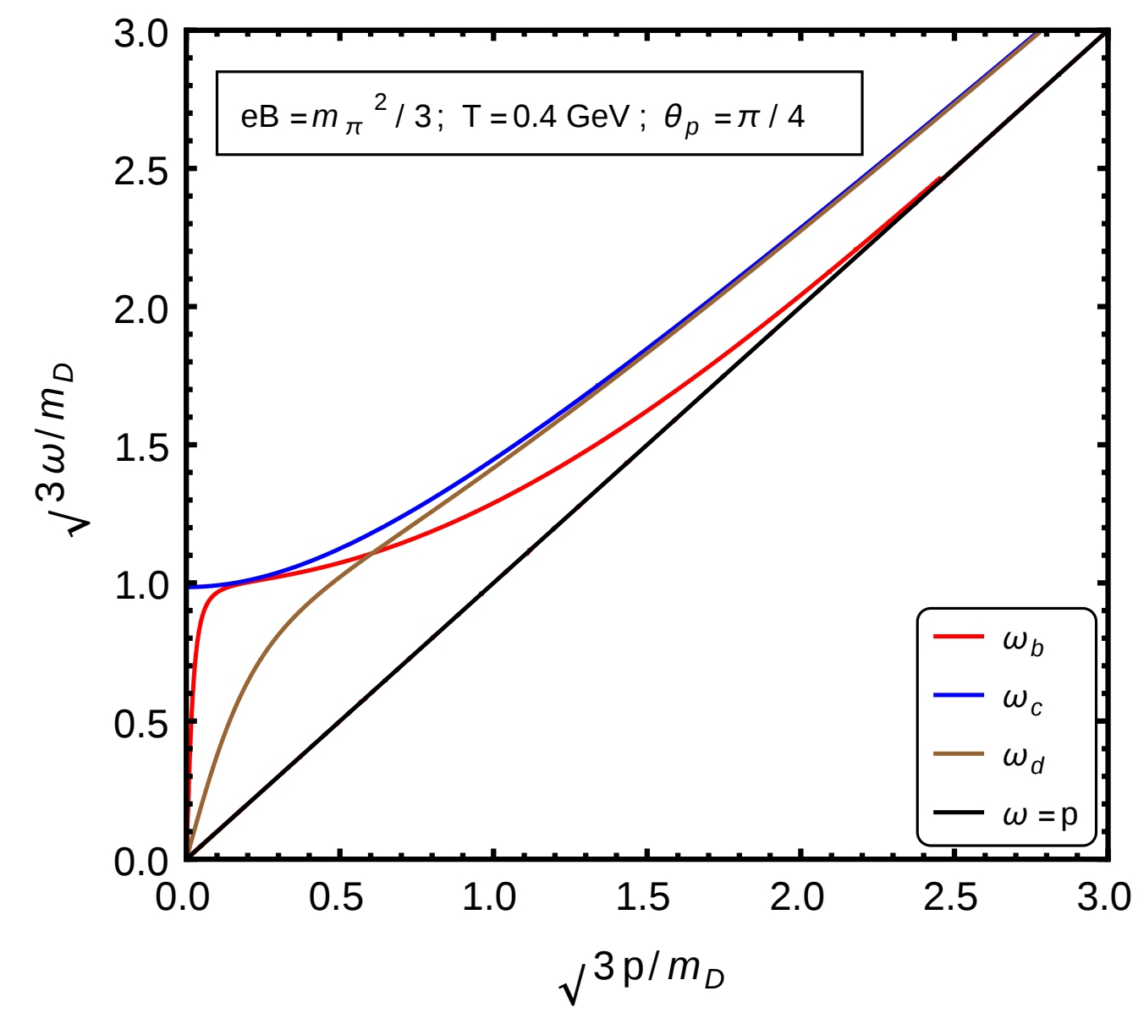
- Gluon propagator becomes

$$\begin{aligned}\mathcal{D}_{\mu\nu} &= \frac{\xi P_\mu P_\nu}{P^4}+\frac{\left(P^2-d\right)B_{\mu\nu}}{\left(P^2-b\right)\left(P^2-d\right)-a^2}+\frac{R_{\mu\nu}}{P^2-c}\\ &+\frac{\left(P^2-b\right)Q_{\mu\nu}}{\left(P^2-b\right)\left(P^2-d\right)-a^2}+\frac{aN_{\mu\nu}}{\left(P^2-b\right)\left(P^2-d\right)-a^2}\end{aligned}$$

- Quasi-particles poles can be found solving

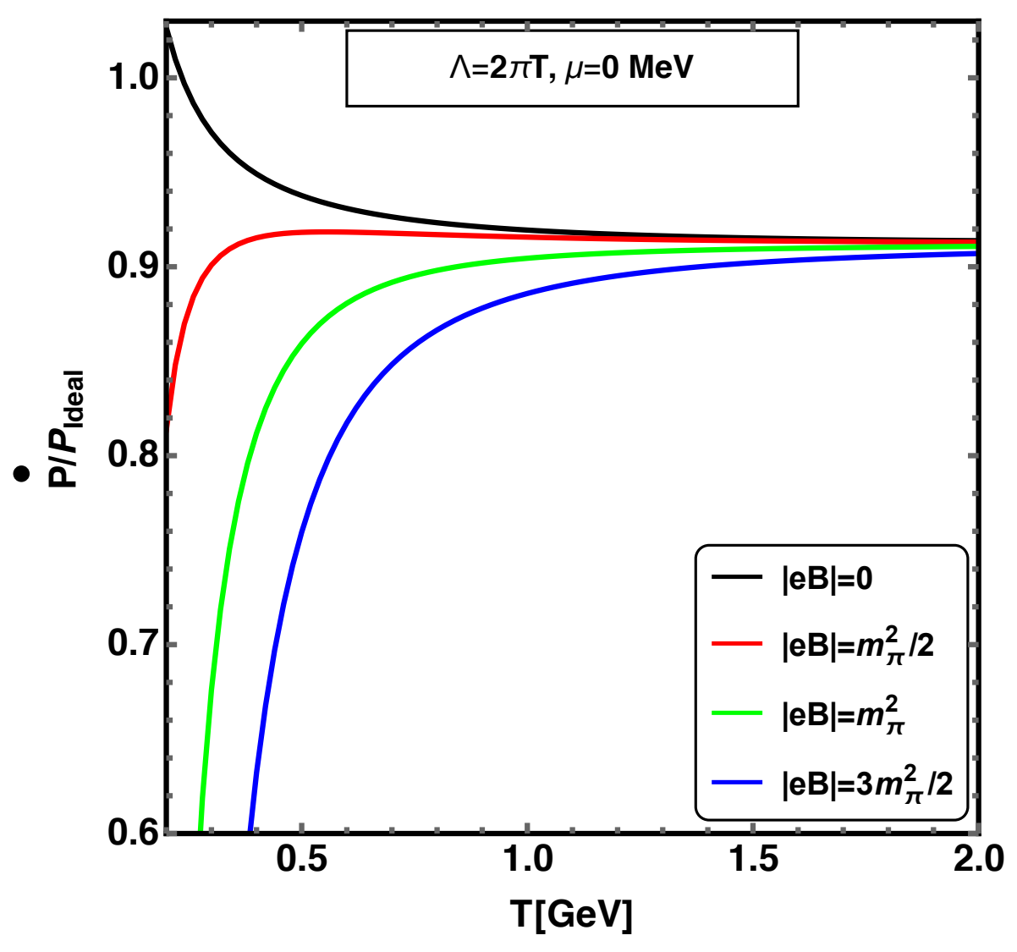
$$\begin{aligned}\left(P^2-b\right)\left(P^2-d\right)-a^2=0\\ P^2-c=0\end{aligned}$$

- Gluon dispersion plot in HTL approximation



- The plasma frequencies for the b and d mode are zero whereas for vanishing magnetic field, those are finite.
- This could be due the weak field approximation that we are using. At weak field approximation, magnetic field strength is the lowest scale in the theory. So, our result cannot describe the gluon propagation around very small external momentum.
- To understand the behavior of the quasiparticles mode near $p = 0$, we need to study the system at general values of the magnetic field without expanding the full propagator.

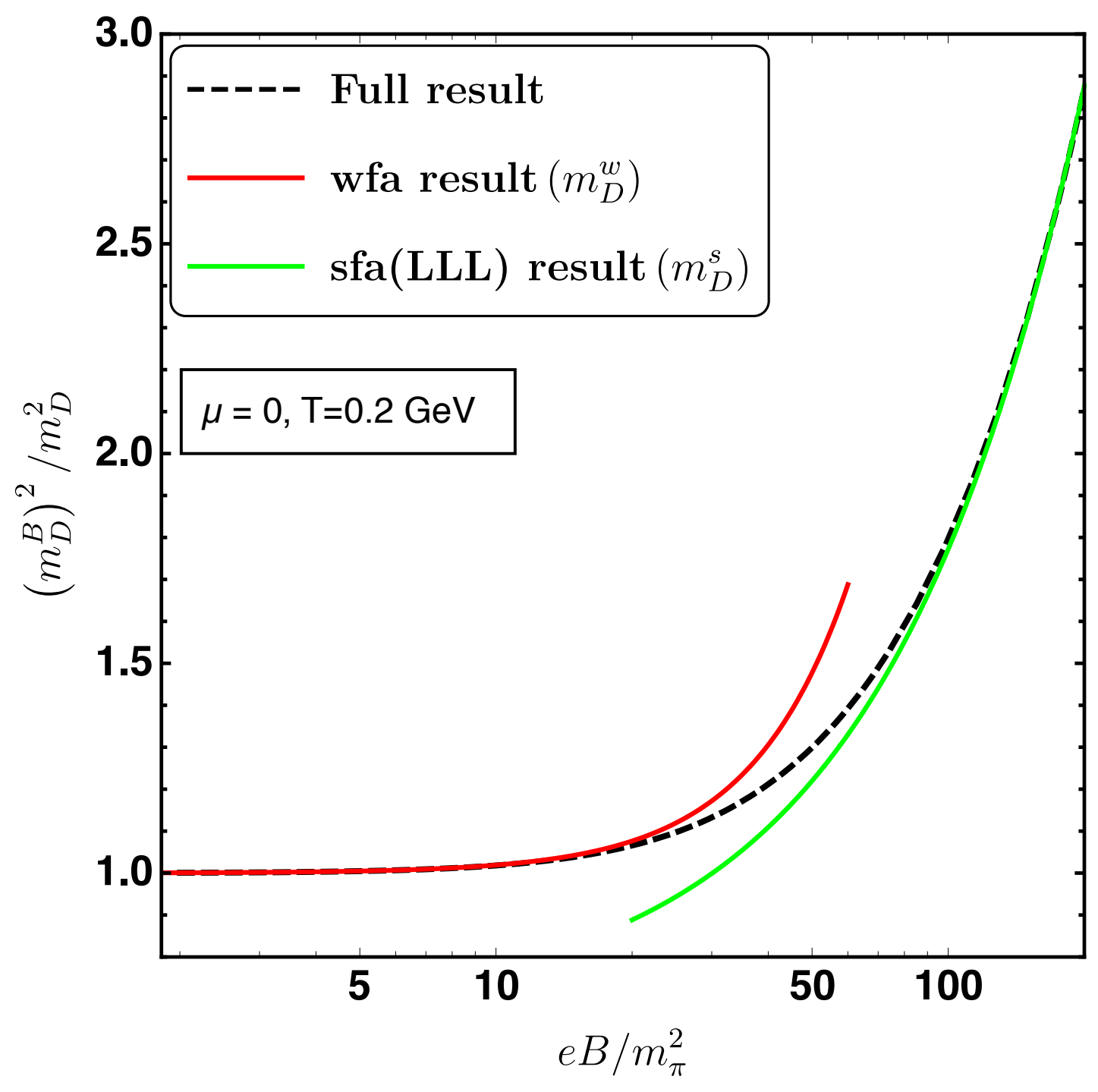
QCD pressure at weak magnetic field



- The weak field pressure is strongly affected at low $(T < 0.8\text{GeV})$ beyond which the HTL result takes over.
- Higher loop study of QCD pressure at general strength of magnetic field is necessary.

At general magnetic field

- At arbitrary strength of the magnetic field, it is possible to calculate QCD Debye mass.
- We have compared the Debye mass at the arbitrary strength with the weak and strong field results



- The study of quarks and gluons dispersion relation at general field strength is still ongoing.

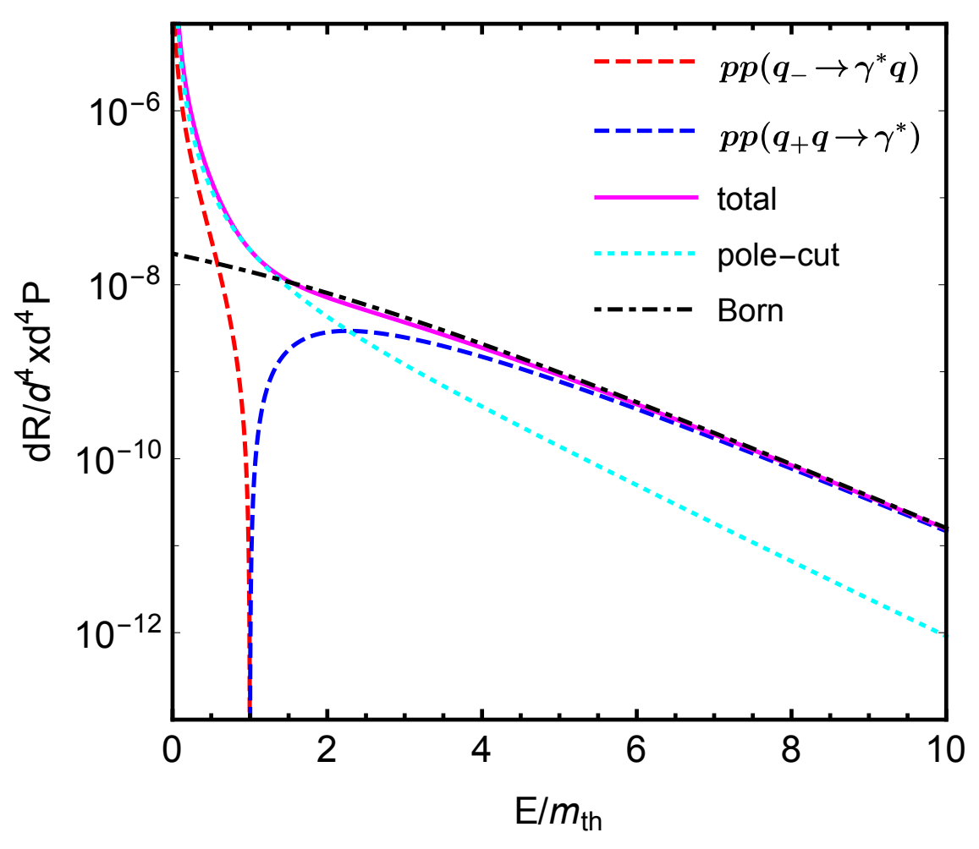
Dilepton production rate

- Photons and dileptons are being used to probe the properties of nuclear and quark- gluon matter as the mean free path for photons in hot and dense matter is very large, typically more than 10^2 to 10^4 fm. This is due to the relative smallness of the fine structure constant. It makes these good probes of the medium because they do not suffer final state interactions, and therefore convey information about the system directly to the detectors.
- The dilepton production rate can be derived from the imaginary part of the photon self-energy as

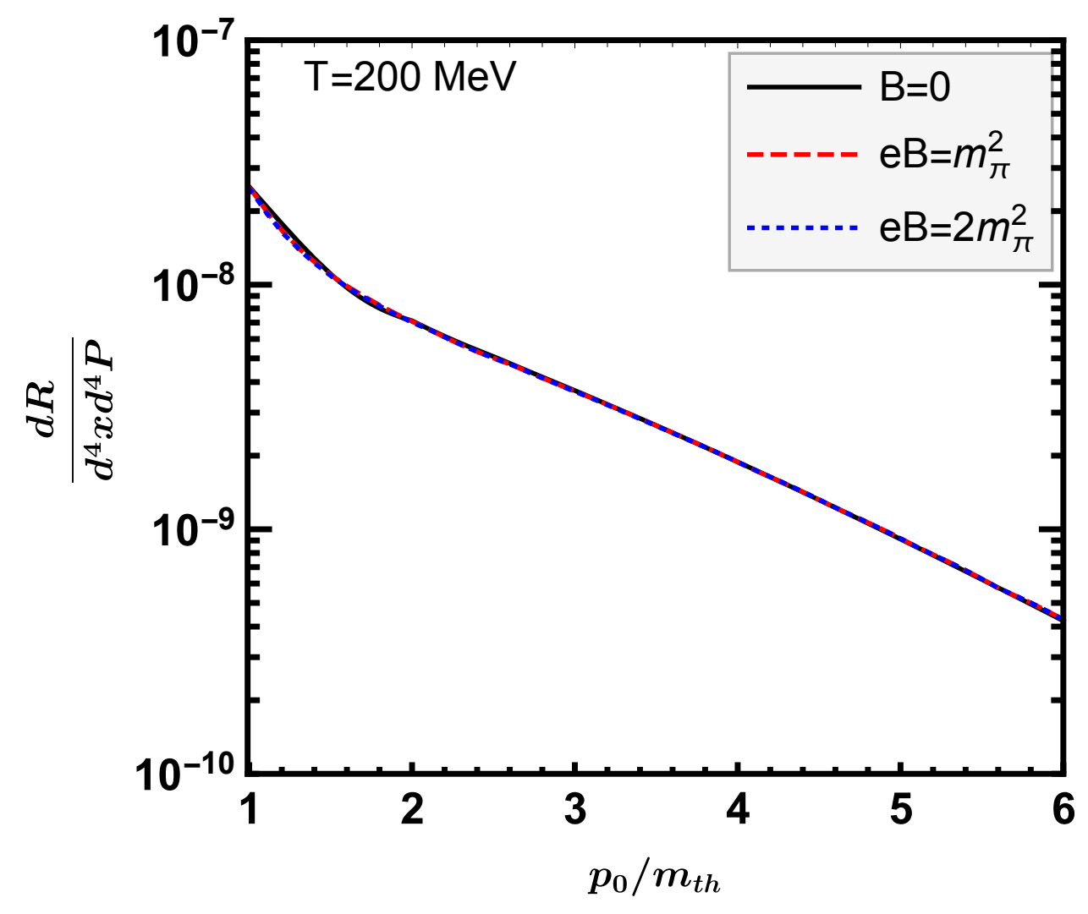
$$\frac{dR}{d^4xd^4P} = -\frac{\alpha}{12\pi^4}\frac{1}{e^{E/T}-1}\frac{\text{Im}\Pi_\mu^\mu(P)}{M^2}.$$

where $\alpha = e^2/4\pi$, P is the four-momentum of the virtual photon, E is its energy, and we use the notation $P \equiv (p_0 = E, \vec{p})$ and $p = |\vec{p}|$. The square of the invariant mass of dilepton pair is $M^2 = p_0^2 - p^2$.

- Dilepton rate at vanishing magnetic field



- Dilepton rate at finite magnetic field



- The effect of weak magnetic field on hard dilepton production rate is very nominal. The magnetic field field effect on low mass dilepton production rate will be interesting.
- To compute that within HTL resummation in presence of the magnetic field, one needs to take into account all the N-point function in vertex diagram as well as four point vertex diagram will also contributes.

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