Spectra and flow of magnetised lepton pairs

Chowdhury Aminul Islam

7th International Conference on Chirality, Vorticity and Magnetic Field

University of Chinese Academy of Sciences
Yanqi Lake Campus

19.07.2023

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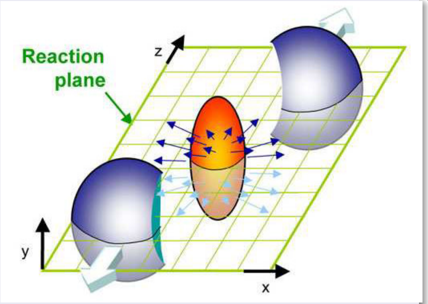
Noncentral Heavy Ion collisions:



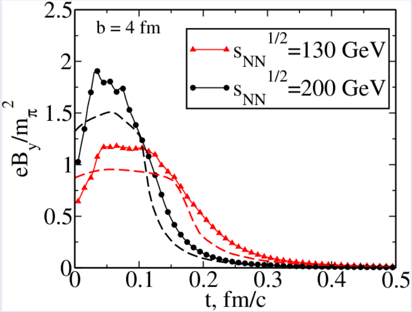
Pictorial representation of noncentral heavy ion collisions.

Production of a strong magnetic field in HICs

- A very strong magnetic field ($\approx m_\pi^2$ 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)

[V. Skokov et al, IJMP,2009]



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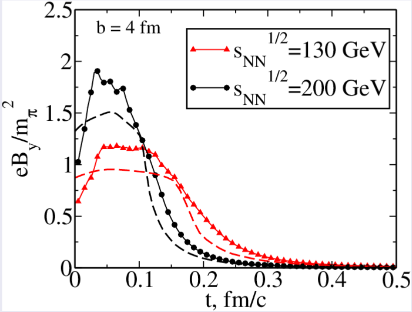
- A comparison with other terrestrial strengths: Earth $\approx 10^{-18}\ m_\pi^2$, usual laboratory $\approx 10^{-13}\ m_\pi^2$, max.

- A magnetar: $\approx 10^-5 - 10^-3\ m_\pi^2$.

[V. Skokov et al, IJMP,2009]



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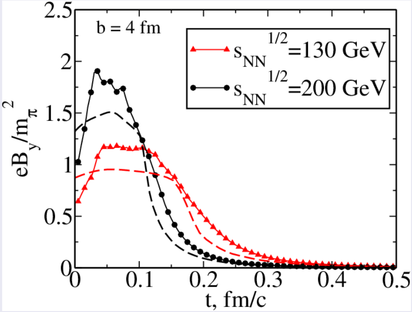

- The presence of an external field in the medium subsequently requires modification of the present theoretical tools.

EM probes, particularly leptons:

- Photons and leptons (virtual photons) can probe the interior of a QCD medium.
- They are produced from multiple stages.
- They can be used to extract information from the hot and dense matter.
- We are particularly interested in the thermal leptons.

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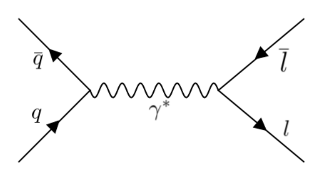
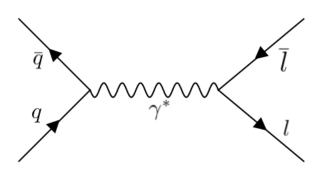
Lepton pair

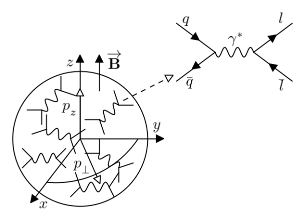


Lepton pair from the magnetised medium:

Lepton pair



A magnetised medium

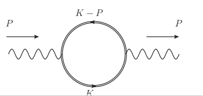


- A straightforward question is to ask whether the dilepton production will be affected by the magnetic field.

Methodology:

- This dilepton rate (DR) is given by [H. A. Weldon PRD 42, 2384].

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



- We can use the fermionic propagator, depending on the scenarios, to write down the one loop electromagnetic (EM) polarization tensor

$$\Pi^{\mu\nu}_f(P) = -iN_c q_f^2 \int \frac{d^4K}{(2\pi)^4}\mathsf{Tr}\left[\gamma^\mu S^B_f(K)\gamma^\nu S^B_f(K-P)\right]. \quad (2)$$

Fermionic propagator in presence of eB:

- Schwinger propagator in momentum space as

$$S_f^{(B)}(K) = \exp\left(-\frac{k_\perp^2}{|q_f B|}\right)\sum_{\ell=0}^{\infty}(-1)^\ell \frac{D_\ell(K, q_f B)}{k_{\shortparallel}^2 - 2\ell|q_f B| - m_f^2 + i\epsilon}\,, \qquad (3)$$

where

$$D_\ell(K, q_f B) = (\not{k}_{\shortparallel} + m_f)\left\{L_\ell\left(\frac{2k_\perp^2}{|q_f B|}\right)\left[\mathbb{1} - i\gamma^1\gamma^2 \mathsf{sgn}(q_f B)\right] - L_{\ell-1}\left(\frac{2k_\perp^2}{|q_f B|}\right)\left[\mathbb{1} + i\gamma^1\gamma^2 \mathsf{sgn}(q_f B)\right]\right\} + 4\not{k}_\perp L_{\ell-1}^1\left(\frac{2k_\perp^2}{|q_f B|}\right). \qquad (4)$$

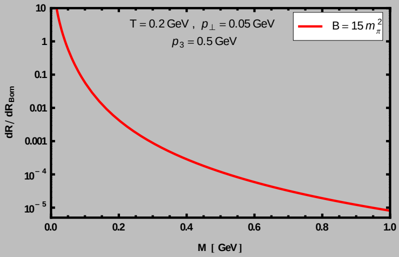
- m_f and q_f are the mass and charge of the fermion of flavor f, respectively; ℓ denotes the Landau level index.

Work done so far:

- So far dilepton rate from a magnetised medium has been calculated in different articles using different techniques. [A. Bandyopadhyay et al, Snigdha Ghosh et al, N. Sadooghi et al, X. Wang et al].
- Many of the calculations used different approximations, particularly either strong or weak magnetic field approximations.
- For arbitrary magnetic field, either parallel (p_z) or perpendicular ($p_\perp$) component taken to be zero.

One of the very fast:

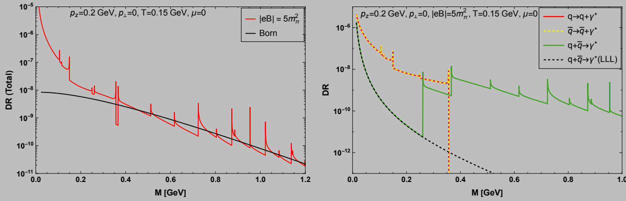
- The rate was estimated in the LLL approx (strong eB)[A. Bandyopadhyay, CAI, M. G. Mustafa, PRD, 2016].



Calculational novelty in the present effort:

- We have relaxed all approximations related to the field and external momentum.
- It is easy to grasp because of the simplicity in ITF.
- There are similar works which talk about the ellipticity of the lepton pairs as well. X. Wang and I. Shovkovy, 2022, 2023; ☞ Talk by X. Wang

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.

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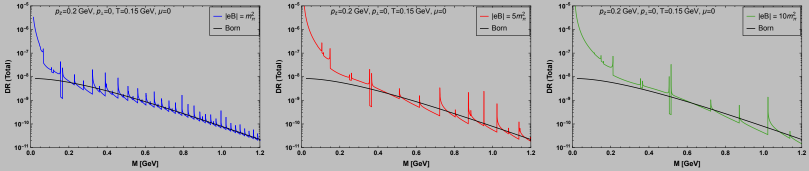

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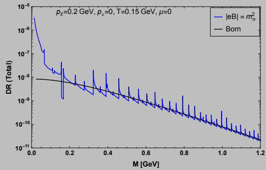

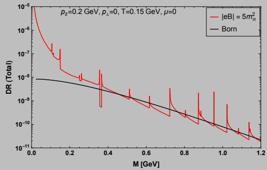

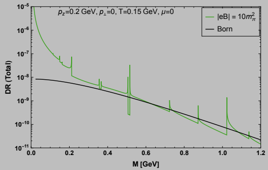

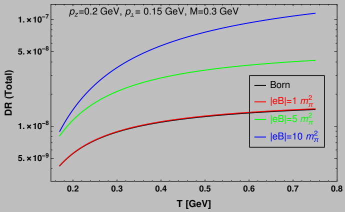

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Rate to spectrum:

- The expression of dilepton rate,

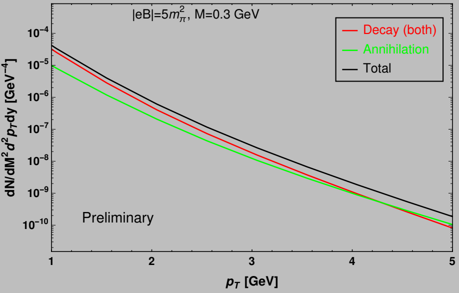
$$\frac{dN}{d^4X d^4P} \equiv \frac{dR}{d^4P} = \frac{\alpha_{\mathsf{EM}}}{12\pi^3}\frac{1}{P^2}\frac{1}{e^{p_0/T}-1}\sum_{f=u,d}\frac{1}{\pi}\,\mathsf{Im}\,\Pi^{\mu}_{\mu,f}(P). \quad (5)$$

- For convenience we make a variable transformation from $(p_0, p_x, p_y, p_z) \to (M, p_T, \phi, y)$

- The Born rate becomes,

$$\frac{dN}{d^4x M dM p_T dp_T dy d\phi} = \frac{5N_c\alpha^2_{\mathsf{EM}}}{108\pi^4}\frac{1}{\sqrt{M_T^2\sinh^2 y + p_T^2}}\frac{T}{e^{\frac{M_T\cosh y}{T}}-1}\left(1+\frac{2m_f^2}{M^2}\right)$$
$$\times \log\left(\frac{\left[\exp\left(-\frac{M_T\cosh y+\mu}{T}\right)+e^{-\omega_-/T}\right]\left[e^{-\mu/T}+e^{-\omega_+/T}\right]}{\left[\exp\left(-\frac{M_T\cosh y+\mu}{T}\right)+e^{-\omega_+/T}\right]\left[e^{-\mu/T}+e^{-\omega_-/T}\right]}\right), \quad (6)$$

Dilepton spectrum



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Summary:

- We have been able to calculate the dilepton rate for arbitrary strength of magnetic field for the most general case.
- 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.
- We are trying to obtain the spectrum in presence of eB.
- We expect that the enhancement in the rate will be as well reflected in the spectrum and in turn could affect the corresponding flow.

Thank You

A few words on the lifetime of the field

- The very high initial magnitude of this magnetic field then decreases very fast, being inversely proportional to the square of time(?).

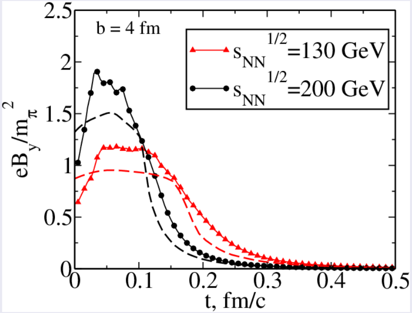
  [A. Bzdak et al, PRL, 2013;

  K. Tuchin, PRC, 2013]

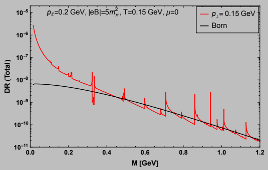
  [Z. Wang et al, PRC, 2022;

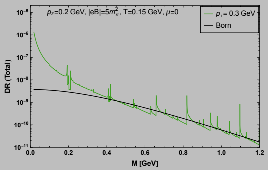
  STAR, PRC, 2022]

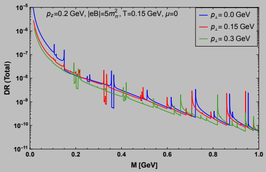
[V. Skokov et al, IJMP,2009]



Effect of the transverse momentum:







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