Characteristics of QCD medium in extreme conditions

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Outline:

- Electromagnetic probes, particularly dilepton (lepton pair).
- Generation of a strong magnetic field (eB) in heavy-ion collisions (HIC):

  a) Dilepton production

  b) Topological susceptibility
- Creation of a robust angular momentum (J) in HICs and emission of dilepton from a rotating QCD medium
- Conclusion

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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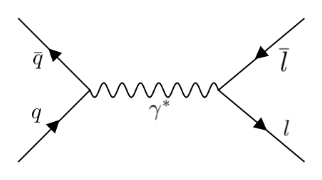
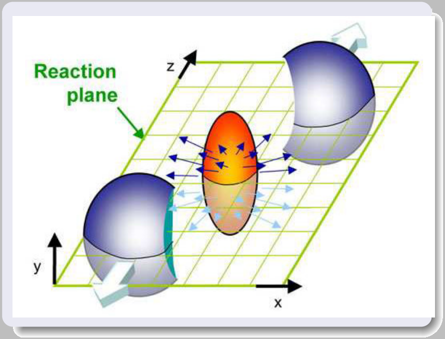
Lepton pair



Noncentral Heavy Ion collisions:



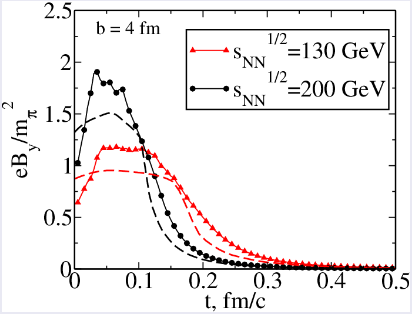
Pictorial representation of noncentral heavy ion collisions.

Production of a strong magnetic field in HICs

- A very strong magnetic field ($eB \approx m_\pi^2$ at RHIC & $eB \approx 15 m_\pi^2$ 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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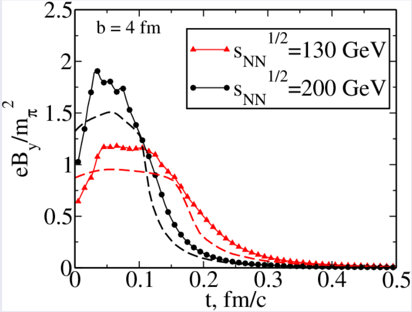
- A comparison with other terrestrial strengths: Earth $\approx 10^{-18}$ m_π^2, usual laboratory $\approx 10^{-13}$ m_π^2, max.

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

[V. Skokov et al, IJMP,2009]



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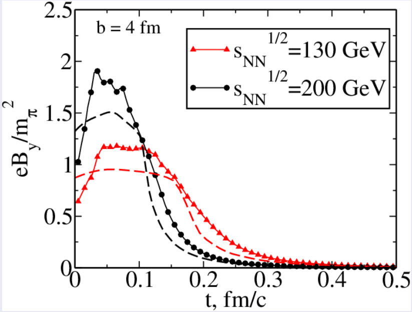
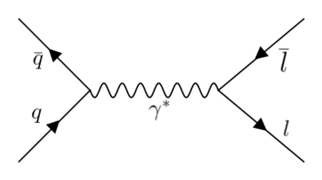
- The presence of an external field in the medium subsequently requires modification of the present theoretical tools.

[V. Skokov et al, IJMP,2009]

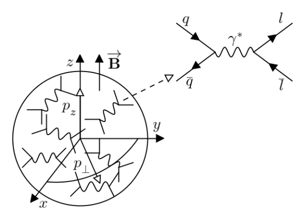


Lepton pair from the magnetised medium:

Lepton pair



A magnetised medium

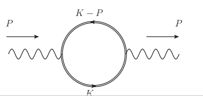


- A straightforward question is to ask whether the dilepton production will be affected by the magnetic field.

Methodology:

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

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



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

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

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:

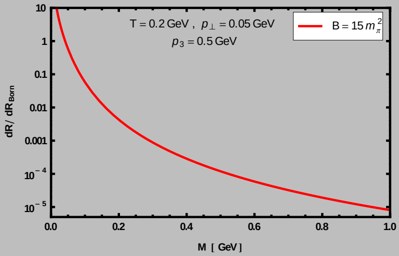
- So far dilepton rate from a magnetised medium has been calculated in different articles using different techniques. [A. Bandyopadhyay et al, Snigdha Ghosh et al, N. Sadooghi et al, X. Wang et al].

- 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:

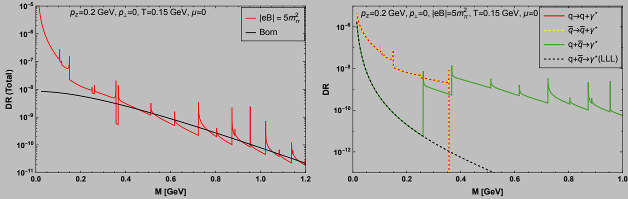
- The rate was estimated in the LLL approx (strong eB)[A. Bandyopadhyay, CAI, M. G. Mustafa, PRD, 2016].



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 is similar work done which talks about the ellipticity of the lepton pairs as well. X. Wang and I. Shovkovy, PRD, 2022

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.

A. Das, A. Bandyopadhyay, CAI, PRD 2022

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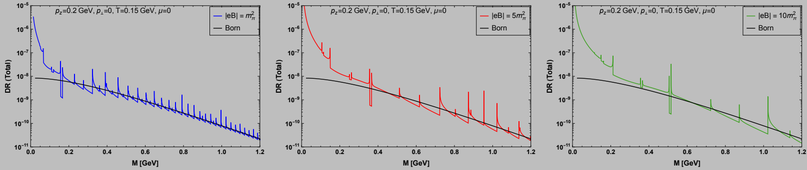

A. Das, A. Bandyopadhyay, CAI, PRD 2022

An effective model treatment, namely the NJL

- The NJL Lagrangian [M. Frank et al., Phys. Lett. B 562 (2003) 221-226]

$$\mathcal{L}_{\rm NJL} = \mathcal{L}_0 + \mathcal{L}_1 + \mathcal{L}_2$$

$$\mathcal{L}_0 = \bar{\psi}\left(i\partial\!\!\!/ - m\right)\psi$$

$$\mathcal{L}_1 = G_1\left\{(\bar{\psi}\psi)^2 + (\bar{\psi}\vec{\tau}\psi)^2 + (\bar{\psi}i\gamma_5\psi)^2 + (\bar{\psi}i\gamma_5\vec{\tau}\psi)^2\right\}$$

$$\mathcal{L}_2 = G_2\left\{(\bar{\psi}\psi)^2 - (\bar{\psi}\vec{\tau}\psi)^2 - (\bar{\psi}i\gamma_5\psi)^2 + (\bar{\psi}i\gamma_5\vec{\tau}\psi)^2\right\}$$

- $\mathcal{L}_2$ explicitly breaks $U(1)_A$.
- Symmetry only allows the $\langle\bar{\psi}\psi\rangle$ condensate, which depends on $(G_1 + G_2)$.
- With μ_I or magnetic field as the $SU(2)$ symmetry is broken one can have $\langle\bar{\psi}\tau_3\psi\rangle$ which has a $(G_1 - G_2)$ dependence.
- G_1 and G_2 can be parameterized as $G_1 = (1-c)G_0/2$ and $G_2 = cG_0/2$
- $c = 1/2$ corresponds to the standard NJL model.

NJL model in presence of a magnetic field

- The Lagrangian in presence of eB [D. P. Menezes et al., Phys. Rev. C 79, 035807 (2009)]

$$\mathcal{L}_{\rm NJL} = \bar{\psi}(i\gamma_\mu D^\mu - m_0)\psi + \mathcal{L}_1 + \mathcal{L}_2 - \frac{1}{4}F^{\mu\nu}F_{\mu\nu},$$

  with $D^\mu = \partial^\mu - iqA^\mu$ ($q_u = 2/3e$ and $q_d = -1/3e$) and $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$.

- Due to eB there are two important modifications.

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- I) The dispersion relation gets modified as,

$$E_f(B) = [M_f^2 + p_z^2 + 2k|q_f|B]^{1/2}$$

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- II) The integral over the three momenta gets modified as,

$$\int \frac{d^3p}{(2\pi)^3} \to \frac{|q_f|B}{2\pi} \sum_{k=0}^{\infty} \int_{-\infty}^{\infty} \frac{dp_z}{2\pi}$$

Topological susceptibility:

- The topological term $\frac{\theta g^2}{32\pi^2}\mathcal{F}\tilde{\mathcal{F}}$ breaks the CP symmetry of strong interaction.
- Topological susceptibility(χ_t) can be formally related to the mass of the axion field.[S. Weinberg, Phys. Rev. Lett. 40, 223 (1978)]
- As the dynamical axion is considered to be a possible solution to strong CP problem, θ can be related to the axion fields, $\theta = a/f_a$.
- With a chiral rotation of the quark fields

$$\mathcal{L}_2 \to \mathcal{L}_a = 2\,G_2\left\{e^{i\frac{a}{f_a}}\det\bar{\psi}(1+\gamma_5)\psi + e^{-i\frac{a}{f_a}}\det\bar{\psi}(1-\gamma_5)\psi\right\}. \quad (5)$$

- $\Omega(T, eB, \theta)$ being the free energy with these modification, the topological susceptibility is $\chi_t = \frac{d^2\Omega(T,eB,\theta)}{d\theta^2}|_{\theta=0}$.

Topological susceptibility:

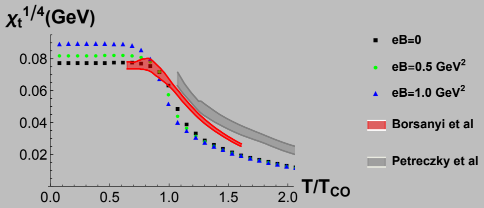


Figure: Top sus as a function of temperature and magnetic field.

[CAI et al., PRD 2021, S. Borsanyi et al., Nature 2016, Petreczky et al., PLB 2016]

Topological susceptibility:

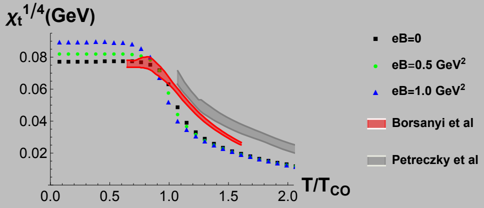


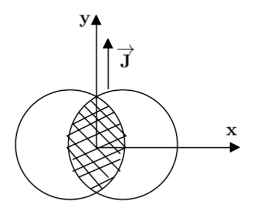
Figure: Top sus as a function of temperature and magnetic field.

[CAI et al., PRD 2021, S. Borsanyi et al., Nature 2016, Petreczky et al., PLB 2016]

- We have also investigated the role of $U(1)_A$ breaking in the pion mass difference.[CAI et al., J. Phys. G 2023]

Generation of a large ang mom in NC HICs

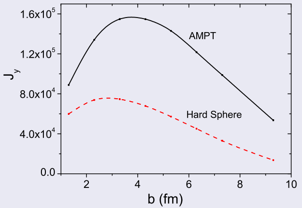
- In noncentral HICs, a strong ang mom is supposed to be created ($J \propto b\sqrt{S_{NN}}$) [F. Becattini et al, PRC, 2008; Y. Jiang et al PRC, 2016]



Generation of a large ang mom in NC HICs

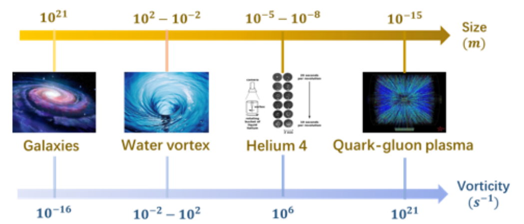
- The strength of ang mom is in the range of $10^4 - 10^5\ \hbar$, with the vorticity exceeding $0.5\ fm^{-1}$.

[Y. Jiang et al, PRC,2016]



Generation of a large ang mom in NC HICs

- It is huge as compared to other known events:



Taken from X. G. Huang's talk

Methodology:

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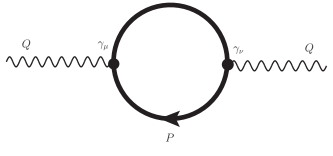
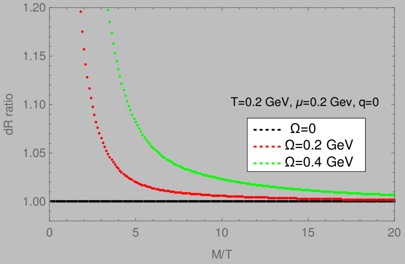
$$\frac{dN}{d^4xd^4q} = \frac{5\alpha^2}{27\pi^3}\frac{1}{M^2}\frac{1}{\exp(\frac{\omega}{T})-1}\mathrm{Im}\,\Pi^a_a(q). \qquad (6)$$



- In the same fashion, we can calculate the photon polarisation diagram as M. Wei, CAI, M. Huang PRD 2022; M. Wei et al 2020

$$\Pi^{ab}(q) = -iN_fN_c\int d^4\tilde{r}Tr_D[i\gamma^aS(0;\tilde{r})i\gamma^bS(\tilde{r};0)]e^{iq\cdot\tilde{r}}, \qquad (7)$$

Effect of rotation on DR:



- Ratios of dilepton rate as a function of temperature scaled invariant mass for different values of angular velocity, with nonzero T and μ.

M. Wei, CAI, M. Huang PRD 2022

Upshots:

- We could break down the dilepton 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.
- Below the crossover, the topological susceptibility gets enhanced by the magnetic field.
- In presence of rotation an enhancement in the rate has been observed. The very important boundary effects are further need to be considered.
- It will be interesting to have an estimation of the dilepton spectrum. That will facilitate to have a direct experimental comparision.

Thank You