Impact of the electromagnetic field on Z^0 leptonic invariant mass in ultrarelativistic heavy ion collisions

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Abstract. The extraordinary strong magnetic field generated in ultrarelativistic heavy ion collisions makes it possible to investigate many novel effects in the hot QCD matter, and a direct probe of it thus becomes an urgent task in the field. Here we report a new way to probe it, where the leptonic invariant mass distribution of Z^0 boson will be modified in the presence of the magnetic field due to the Lorentz force on the lepton pairs from the decay of Z^0 boson. It is found that the magnetic field can decrease the mean value of Z^0 leptonic invariant mass and increase its width, and both shifts approximately depend on the integral of the magnetic field over its time duration quadratically.

1 Introduction

The presence of a strong magnetic field in ultrarelativistic heavy ion collisions can induce many novel effects, such as the chiral magnetic effect (CME) which can probe the local parity (P) and charge conjugation parity (CP) violations of QCD [1, 2] and the magnetic field dependence of the chiral condensate [3]. However, there are quite a lot of disagreements in the calculation of the time evolution of the magnetic field due to the uncertainty of the electrical conductivity of QGP [4, 5] as well as the difficulty in numerically solving magnetohydrodynamics or transport approach coupled to the Maxwell equations. This inspired the studies to search for a direct probe of the strong electromagnetic (e.m.) fields, and it is proposed that the directed flow $v_1 = \langle p_x/p_T \rangle$ splitting between positively and negatively charged light hadrons [6, 7] as well as heavy meson pairs [8–13] can serve the purpose. Here we report a new and cleaner probe of the strong e.m. fields proposed in our recent manuscript [14] via the invariant mass distribution of Z^0 boson reconstructed from its decaying lepton pairs, since the momenta of these leptons should be modified by e.m. fields. It is significantly easier to measure the leptonic invariant mass distribution of Z^0 boson than the v_1 splitting, thus opening up a more accessible experimental probe.

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2 Z^0 boson in ultrarelativistic heavy ion collisions and the transport of leptons from the decay of Z^0 boson

The initial conditions of the lepton pairs decaying from Z^0 boson in heavy ion collisions inherit from the distribution of Z^0 boson in the 4-D momentum and coordinate spaces. In momentum space, the transverse momenta $\mathbf{p}_T$ and rapidity y_z dependences of Z^0 boson are given by fitting the experimental measurements on Z^0 boson in pp collisions at the same collision energies, and the energy of Z^0 boson is given by $E_p = \sqrt{M^2 + \mathbf{p}^2}$. Here the mass distribution of Z^0 is given by a Breit-Wigner form:

$$\rho(M) = \frac{1}{\pi}\frac{\Gamma/2}{(M - M_0)^2 + \Gamma^2/4}, \tag{1}$$

with $M_0 = 91.1876$ GeV and $\Gamma = 2.4952$ GeV[15]. In coordinate space, the transverse coordinate distribution of Z^0 boson is given by the profile of the binary nucleon-nucleon collisions, while the longitudinal coordinate and time are given by $z = \tau_{Z^0} \sinh y_z$ and $t = \tau_{Z^0} \cosh y_z$ with $\tau_{Z^0} = \hbar/m_{Z^0} = 0.0022$ fm$/c$. This indicates that the space-time rapidity η_S of Z^0 boson is assumed to be equal to its rapidity. Finally one can obtain the spacetime coordinate of lepton pairs from their mother Z^0 that moves in a straight line, where the decay time follows a distribution $\rho(\Delta t) \propto e^{-\frac{\Gamma \Delta t}{\gamma_v}}$, with γ_v being the Lorentz contraction factor.

The lepton pairs not only interact with e.m. fields after their production, but also interact with the charged quarks due to the lepton-quark scattering in the quark-gluon plasma (QGP) phase, though the effect of the latter one may be small. To consider both effects, the Langevin equations are employed:

$$d\mathbf{x} = \frac{\mathbf{p}}{E}dt, \tag{2}$$

$$d\mathbf{p} = -\gamma \mathbf{p} dt + \boldsymbol{\xi}\sqrt{2D_p dt} + q(\mathbf{E} + \mathbf{v} \times \mathbf{B}), \tag{3}$$

where the momentum diffusion coefficient D_p is related to the drag coefficient γ, energy of leptons E, and the local temperature T by $D_p = \gamma E T$, and each component of $\boldsymbol{\xi}$ is a real number randomly sampled from a normal distribution with $\langle \xi_i \rangle = 0$ and $\langle \xi_i \xi_j \rangle = \delta_{ij}$. The value of D_p can be calculated by the lepton-quark scattering, see details in Ref. [14].

For the space and time dependence of e.m. fields, a general parametrization of them used in several studies is adopted in this study, knowing the large uncertainty in calculating e.m. fields:

$$eB_y(x, y, \tau) = -eB(\tau)\rho_B(x, y), \rho_B(x, y) = \exp[-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}], eB(\tau) = eB_0/(1 + (\tau/\tau_B)^a), \tag{4}$$

where eB_0, σ_x and σ_y are usually given by the estimates of e.m. fields in the vacuum in AA collisions at $t = 0$ [16], and τ_B and a are the parameters that control the lifetime and the specific manner of decay of e.m. fields, respectively. The electric field eE_x is then determined by solving the Faraday's Law $\nabla \times \mathbf{E} = -\partial \mathbf{B}/\partial t$:

$$eE_x(t, x, y, \eta_S) = \rho_B(x, y) \int_0^{\eta_S} d\chi B' \left(\frac{t}{\cosh\chi}\right) \frac{t}{\cosh\chi}. \tag{5}$$

After the modification on the momenta by e.m. fields and lepton-quark scattering, the invariant mass of Z^0 boson is reconstructed from these lepton pairs.

The modification of Z^0 boson leptonic invariant mass is investigated primarily on systems of PbPb collisions at 5.02 TeV due to the large number of Z^0 production events. In this colliding system at centrality 20-30%, corresponding to impact parameter $b = 7.5$ fm, the

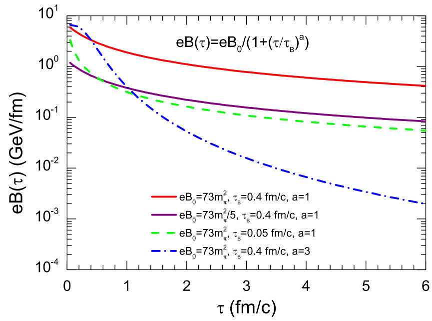

Figure 1. (Color online) The time dependence of $eB(\tau)$ with different parameter sets of eB_0, τ_B and a.

parameters in Eq. (4) are found to be $eB_0 = 73\, m_\pi^2$, $\sigma_x = 3$ fm and $\sigma_y = 4$ fm [11], where eB_0 is the magnitude of magnetic field estimated in the vacuum at $t = 0$. To have a general investigation eB_0 is varied by 5 times, τ_B is varied by 8 times and a is varied by 3 times in this study. In Fig.1 we show the time evolution of $eB(\tau)$ with four parameter sets of eB_0, τ_B and a,and it should be noted that the parameter set $eB_0 = 73\, m_\pi^2$, $\tau_B = 0.4$ fm$/c$ and $a = 1$ can reproduce the ALICE measurement on the v_1 splitting between (D^0,$\overline{D}^0$).

3 Numerical results

To the effect of the lepton-quark scattering in the QGP, the modification is found to be extremely small. To quantitatively characterize the modification of Z^0 leptonic invariant mass, we define its mean value shift $\Delta\langle M\rangle$ and width shift $\Delta\sigma$ as

$$\Delta\langle M\rangle = \langle M_f\rangle - \langle M_i\rangle, \Delta\sigma = \sigma_f - \sigma_i = \sqrt{\frac{\sum(M_f - \langle M_f\rangle)^2}{N-1}} - \sqrt{\frac{\sum(M_i - \langle M_i\rangle)^2}{N-1}}. \quad (6)$$

It is found that $\Delta\langle M\rangle$ is about -1.9 MeV due to the drag of QGP and $\Delta\sigma$ is about 0.2 MeV, though both shifts are beyond the experimental determination. On the other hand, as shown by the red solid lines in the left, middle and right panels of Fig.2, the parameter set $eB_0 = 73\, m_\pi^2$, $\tau_B = 0.4$ fm$/c$ and $a = 1$ can modify largely Z^0 leptonic invariant mass compared to the black solid lines, where $\langle M\rangle$ decreases by 246 MeV and σ increases by 305 MeV. Moreover, if one decreases the accumulation of e.m. fields by decreasing eB_0 or τ_B or by increasing a, the modification becomes smaller as shown in Fig. 2.

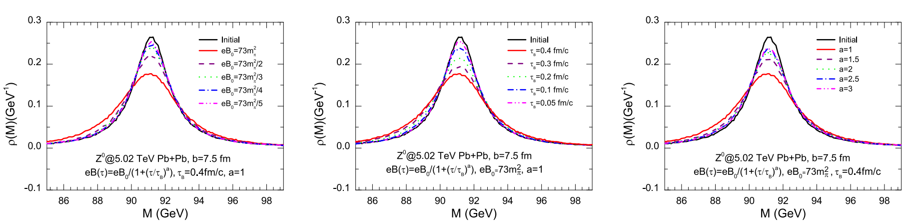

Figure 2. (Color online) The eB_0, τ_B and a dependences of Z^0 invariant mass distribution at midrapidity $|y_z| \le 0.5$ reconstructed by lepton pairs after interacting with e.m. fields. Left: eB_0 varies from $73\, m_\pi^2/5$ to $73\, m_\pi^2$; Middle: τ_B varies from 0.05 fm$/c$ to 0.4 fm$/c$; Right: a varies from 1 to 3.

Since the momenta change of leptons is directly related to the accumulation of e.m. fields $\chi_B = \int_{\tau_0}^{\tau_1} d\tau eB(\tau)$, where τ_0 and τ_1 are the formation time of leptons and the time when they leave e.m. fields, we further check the relation between $\Delta\langle M\rangle$ ($\Delta\sigma$) and χ_B. It is found [14] that $\Delta\sigma$ depends on χ_B quadratically no matter one varies eB_0, τ_B or a. Since the invariant mass is symmetric with charge conjugation, it should depend on the square of χ_B at leading order if one varies the electric and magnetic fields by the same factor. $\Delta\langle M\rangle$ thus should depend on χ_B quadratically when one varies eB_0, which is what is found in Ref. [14]. On the other hand, though $\Delta\langle M\rangle$ does not depend on the χ_B quadratically when one varies τ_B or a, it still depends on the power of it. The power is found to be 2.12 or 2.33, which is still close to 2.

4 Conclusion

The Z^0 leptonic invariant mass in ultrarelativistic heavy ion collisions is investigated with Langevin equations at LHC energy. It is found that lepton-quark scattering modifies Z^0 leptonic invariant mass extremely small while e.m. fields can modify both its mean value and width by few hundred MeV, thus providing a cleaner probe of e.m. fields in ultrarelativistic heavy ion collisions. With the current statistics on the Z^0 boson in PbPb collisions, it is possible to experimentally detect this modification of a few hundred MeV in the invariant mass of Z^0 boson. It is also found that both its mean value and width depend approximately on the integral of the magnetic field over its time duration quadratically, which makes a measurement on the modification of Z^0 leptonic invariant mass a direct probe of the time accumulation of magnetic field.

References

[1] D. Kharzeev, R. D. Pisarski and M. H. G. Tytgat, Phys. Rev. Lett. **81**, 512-515 (1998).
[2] D. E. Kharzeev, L. D. McLerran and H. J. Warringa, Nucl. Phys. A **803**, 227-253 (2008).
[3] H. T. Ding, S. T. Li, J. H. Liu, and X. D. Wang, Phys. Rev. D **105** (3), 034514 (2022).
[4] H. T. Ding, A. Francis, O. Kaczmarek, F. Karsch, E. Laermann and W. Soeldner, Phys. Rev. D **83**, 034504 (2011).
[5] A. Amato, G. Aarts, C. Allton, P. Giudice, S. Hands and J. I. Skullerud, Phys. Rev. Lett. **111** no.17, 172001 (2013).
[6] U. Gursoy, D. Kharzeev and K. Rajagopal, Phys. Rev. C **89** no.5, 054905 (2014).
[7] U. Gursoy, D. Kharzeev, E. Marcus, K. Rajagopal and C. Shen, Phys. Rev. C **98** no.5, 055201 (2018).
[8] S. K. Das, S. Plumari, S. Chatterjee, J. Alam, F. Scardina and V. Greco, Phys. Lett. B **768**, 260-264 (2017).
[9] S. Chatterjee and P. Bozek, Phys. Lett. B **798**, 134955 (2019).
[10] Lucia Oliva, S. Plumari, and V. Greco, JHEP **05**, 034 (2021).
[11] Y. Sun, S. Plumari and V. Greco, Phys. Lett. B **816**, 136271 (2021).
[12] Y. Sun, V. Greco and S. Plumari, Eur. Phys. J. Plus **136** no.7, 726 (2021).
[13] Z.F. Jiang, S.S. Cao, W.J. Xing, X.Y. Wu, C. B. Yang, and B.W. Zhang, Phys. Rev. C **105**, 054907 (2022).
[14] Y. Sun, V. Greco and X.N. Wang, Phys. Lett. B **827**, 136962 (2022).
[15] M. Tanabashi et al. [Particle Data Group], Phys. Rev. D **98** no.3, 030001 (2018).
[16] W. T. Deng and X. G. Huang, Phys. Rev. C **85**, 044907 (2012).