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Investigating charge dependent flow observables induced by electromagnetic fields in relativistic heavy ion collisions

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An extraordinary strong electromagnetic field is expected to be generated in off-central relativistic heavy ion collisions, resulting in a splitting in the directed flow v_1 of charged particles with opposite charge or $(D^0, \overline{D}^0)$ charmed mesons. Despite the complex dynamics of charged particles due to the strong interactions with QGP, it is possible at $p_T > m$ to directly correlate the splitting in the anisotropic flows v_n of charged particles with opposite charge to some main features of the magnetic field. In particular for the slope of the splitting $d\Delta v_1/dy_z|_{y_z=0}$ of positively and negatively charged particles at high p_T, it can be formulated as $d\Delta v_1/dy_z|_{y_z=0} = -\alpha \frac{\partial \ln f}{\partial p_T} + \frac{2\alpha-\beta}{p_T}$, where f is the p_T spectra of the charged particles and the constants α and β are constrained by the y component of magnetic fields and the sign of α is simply determined by the difference $\Delta[tB_y(t)]$ in the center of colliding systems at the formation time of particles and at the time when particles escape e.m. fields or freeze out. It supplies a useful guide to quantify the effect of different magnetic field configurations and provides an evidence of why the measurement of Δv_1 of heavy quarks and leptons decayed from Z^0 boson and their correlations are a powerful probe of the initial strong e.m. fields in relativistic collisions.

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1. Introduction

The strongest ever electromagnetic (e.m.) field is created in non-central relativistic heavy ion collisions, leading to many interesting phenomena including the well-known chiral magnetic effect (CME) [1–5], which probes the parity (P) and charge conjugation parity (CP) symmetry violation processes in quantum chromodynamics (QCD) that may happen in quark-gluon plasma (QGP). The strong e.m. field can lead to many other interesting phenomena such as the chiral magnetic wave (CMW) [6, 7] and the splitting in the spin polarization of hyperons [8, 9]. However, in the calculation of e.m. fields in heavy ion collisions, there are many uncertainties and numerical problems. To overcome these difficulties, people proposed to measure the charge dependent flows (v_n) of charged mesons and baryons [10] as well as neutral charged charmed mesons [11, 12] to probe the strong e.m. fields directly. These studies are very meaningful for the understanding of the effect of e.m. fields, however they lack a general description of charge dependent flows induced by e.m. fields that goes beyond the details of e.m. fields. Here we want to report our findings for the general behavior of charge dependent flow observables induced by e.m. fields found in Refs. [13, 14]. The purpose of these studies is not only trying to build the bridge between the spatial and temporal configurations of e.m. fields and final observables in the theoretical side, but also can be used to determine whether the Δv_n observed experimentally has an electromagnetic origin.

2. Charge dependent flow harmonics by electromagnetic fields

The modification on the momentum space of charged particles by e.m. fields can always be expressed in terms of a transition function $T(\Delta p_x, \Delta p_y, \Delta y_z, p_x, p_y, y_z)$ satisfying the conservation law $\int d^2\Delta p_T d\Delta y_z T(\Delta p_x, \Delta p_y, \Delta y_z, p_x, p_y, y_z) = 1$. The function T represents the distribution of the shifts in the transverse momenta $\mathbf{p}_T = (p_x, p_y)$ and rapidity y_z by e.m. fields. Starting from a boost-invariant spectra of charged particles $f(p_T)$, after the small modification by e.m. fields, the distribution $f^{'}(\mathbf{p}_T, y_z)$ shall be:

$$\begin{aligned} f^{'}(\mathbf{p}_T, y_z) &= \int d^2\Delta p_T d\Delta y_z f(\mathbf{p}_T - \Delta\mathbf{p}_T, y_z - \Delta y_z) \times T(\Delta\mathbf{p}_T, \Delta y_z, \mathbf{p}_T - \Delta\mathbf{p}_T, y_z - \Delta y_z) \\ &\approx \int d^2\Delta p_T d\Delta y_z [f(\mathbf{p}_T, y_z) T(\Delta\mathbf{p}_T, \Delta y_z, \mathbf{p}_T, y_z) - \frac{\partial fT}{\partial p_x}\Delta p_x - \frac{\partial fT}{\partial p_y}\Delta p_y - \frac{\partial fT}{\partial y_z}\Delta y_z] \\ &= f - (\frac{\partial f\overline{\Delta p}_x}{\partial p_x} + \frac{\partial f\overline{\Delta p}_y}{\partial p_y} + f\frac{\partial\overline{\Delta y}_z}{\partial y_z}), \end{aligned} \quad (1)$$

where the average shifts $\overline{\Delta p}_a$ with $a = x, y, z$ are defined as:

$$\overline{\Delta p}_a(\mathbf{p}_T, y_z) = \int d^2\Delta p_T d\Delta y_z\, T(\Delta\mathbf{p}_T, \Delta y_z, \mathbf{p}_T, y_z)\, \Delta p_a. \quad (2)$$

For rapidity, one can further express $\overline{\Delta y}_z$ in terms of $\overline{\Delta p}_x$, $\overline{\Delta p}_y$, $\overline{\Delta p}_z$ as:

$$\overline{\Delta y}_z = -\frac{p_T \tanh y_z}{m_T^2}(\cos\phi\overline{\Delta p}_x + \sin\phi\overline{\Delta p}_y) + \frac{\overline{\Delta p}_z}{m_T \cosh y_z}, \quad (3)$$

where $\phi = \tan^{-1}(p_x/p_y)$ is the azimuthal angle relative to the reaction plane in momentum space. Since the colliding systems are symmetric with $y \leftrightarrow -y$, in momentum space one should have $\overline{\Delta p}_x(p_T, \phi, y_z) = \overline{\Delta p}_x(p_T, 2\pi - \phi, y_z)$, $-\overline{\Delta p}_y(p_T, \phi, y_z) = \overline{\Delta p}_y(p_T, 2\pi - \phi, y_z)$ and $\overline{\Delta p}_z(p_T, \phi, y_z) = \overline{\Delta p}_z(p_T, 2\pi - \phi, y_z)$. Therefore, the Fourier decomposition with respect to the angle ϕ of the average shift can be expressed as:

$$\overline{\Delta p}_x = \sum 2a_n(p_T, y_z)\cos n\phi, \overline{\Delta p}_y = \sum 2b_n(p_T, y_z)\sin n\phi, \overline{\Delta p}_z = \sum 2c_n(p_T, y_z)\cos n\phi. \tag{4}$$

Since

$$\frac{\partial}{\partial p_x} = \cos\phi\frac{\partial}{\partial p_T} - \frac{\sin\phi}{p_T}\frac{\partial}{\partial\phi}, \frac{\partial}{\partial p_y} = \sin\phi\frac{\partial}{\partial p_T} + \frac{\cos\phi}{p_T}\frac{\partial}{\partial\phi}, \tag{5}$$

the distribution function $f'(\mathbf{p}_T, y_z)$ shall relate to the initial $f(\mathbf{p}_T, y_z)$ as:

$$\begin{aligned} f' &= f - \{\frac{\partial f(a_1+b_1)}{\partial p_T} + f(-\frac{p_T}{m_T^2}\frac{\partial(a_1+b_1)\tanh y_z}{\partial y_z} + \frac{a_1+b_1}{p_T} + \frac{2}{m_T}\frac{\partial c_0/\cosh y_z}{\partial y_z})\} \\ &- \{-f\frac{p_T}{m_T^2}\frac{\partial(a_0+b_0)\tanh y_z}{\partial y_z} + \frac{\partial(a_0+b_0)f}{\partial p_T}\}\cos\phi - \sum_{n=1}\{\frac{\partial f(a_{n+1}+b_{n+1}+a_{n-1}-b_{n-1})}{\partial p_T} \\ &+ f[\frac{(n+1)(a_{n+1}+b_{n+1})-(n-1)(a_{n-1}-b_{n-1})}{p_T} - \frac{p_T}{m_T^2}\frac{\partial\tanh y_z(a_{n+1}+b_{n+1}+a_{n-1}-b_{n-1})}{\partial y_z} \\ &+ \frac{2}{m_T}\frac{\partial c_n/\cosh y_z}{\partial y_z}]\}\cos n\phi. \end{aligned} \tag{6}$$

An interesting observation is that the Lorentz force in the longitudinal direction (c_n) leads also to non-zero charge dependent v_n that measures the anisotropy in transverse momenta according to Eq. (6).

If p_T is larger than the mass of charged particles, Lorentz force is not sensitive to p_T any more, because $p_T/m_T \approx 1$. Furthermore, the equations of motion do not depend on the p_T of the particle implying similar trajectories, which leads to:

$$\frac{\partial a_n}{\partial p_T} \simeq 0, \frac{\partial b_n}{\partial p_T} \simeq 0, \frac{\partial c_n}{\partial p_T} \simeq 0 (p_T \gg m). \tag{7}$$

This will lead to a simple form of Eq. (6) for the charge dependent spectra or flow harmonics without knowing the details of e.m. fields. For example, for the spectra and the slope of the directed flow splitting of charged particles modified by e.m. fields, they become [14]

$$f'|_{y_z=0} = f\left[1 - (a_1+b_1)\frac{\partial \ln f}{\partial p_T} - \frac{2}{p_T}\frac{\partial c_0}{\partial y_z}\right]|_{y_z=0}, \tag{8}$$

$$\frac{d\Delta v_1}{dy_z}|_{y_z=0} = -\alpha\frac{\partial \ln f}{\partial p_T} + \frac{2\alpha-\beta}{p_T}. \tag{9}$$

To show the validity of Eqs. (8) and (9), we take the leptons decayed from Z^0 boson at 5.02 TeV PbPb collisions as an example. These leptons are chosen because they can be separated from leptons from other sources easily and do not interact with QGP strongly. The spectra of leptons is generated by decaying Z^0 into lepton pairs, where the momentum distribution of Z^0 is obtained by fitting the experimental measurements [15, 16]. Because of the kinematics of decay, the spectra of these leptons has a peak at $p_T = m_{Z^0}/2 = 45$ GeV. This can be seen in the left panel of Fig. 1, where $-\frac{\partial \ln f}{\partial p_T}$ of leptons changes sign at p_T =45 GeV. According to Eq. (8), the sign change of $-\frac{\partial \ln f}{\partial p_T}$ will lead to a sign change of the ratio between the yields of positively and negatively leptons in the presence of e.m. fields. To see this, we adopt the method in Ref. [10] to calculate the spatial and temporal configurations of e.m. fields in non-central 5.02 TeV PbPb collisions at 20-30% centrality assuming the conductivity of QGP $\sigma_{el} = 0.046$ fm^{-1} that is within the LQCD estimates. After the modification of momenta due to Lorentz force, the spectra ratio is calculated and shown in the middle panel of Fig. 1, where a clear sign jump is seen but with a small magnitude. We also look at the $d\Delta v_1^l/dy_z|_{y_z=0}$ of leptons, which is shown in the right panel of Fig. 1. However, there is no jump with $\sigma_{el} = 0.046$ fm^{-1}. This is just because α is small. On the other hand, if we assume $\sigma_{el} = 0.023$ fm^{-1}, that is also within LQCD estimates, we do see a jump of $d\Delta v_1^l/dy_z|_{y_z=0}$ at same $p_T = 45$ GeV.

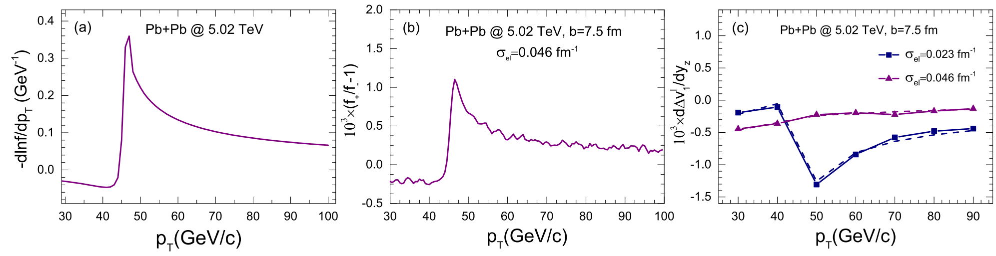

Figure 1: (Color online) (a)$-\frac{\partial \ln f}{\partial p_T}$ of leptons decayed from Z^0 boson. (b) The ratio between the yields of positively and negatively leptons decayed from Z^0 boson assuming medium conductivity $\sigma_{el} = 0.046$ fm^{-1}. (c) $d\Delta v_1^l/dy_z|_{y_z=0}$ of lepton pairs generated by e.m. fields with the medium conductivity $\sigma_{el} = 0.023$ and 0.46 fm^{-1}.

We also take heavy quarks to show the validity of Eq. (9), where charm and bottom quarks are generated using the spectra from the Fixed Order+Next-to-Leading Log (FONLL) QCD [17]. Because of the interaction with QGP, we adopt the standard Langevin equations including the drag and diffusion terms as well as the Lorentz force [11, 12] for the evolution of heavy quarks. At the end of the QGP phase, we utilize the Peterson fragmentation to generate the mesons. The spectra of charm and bottom quarks are shown in the left panel of Fig. 2, where it is seen that $-\frac{\partial \ln f}{\partial p_T}$ of charm quarks is larger than that of bottom quarks. Assuming $\sigma_{el} = 0.023$ fm^{-1}, we first show the rapidity dependence of Δv_1 of $(D^0, \overline{D}^0)$ mesons fragmented by charm quarks at $p_T = 3$ and 10 GeV$/c$ by solid lines in the middle panel of Fig. 2, where negative slopes are observed. By only changing the spectra of charm quark to that of bottom quarks while keeping others exactly the same, Δv_1 of $(D^0, \overline{D}^0)$ mesons is shown by the dashed line at the same p_T, where one can clearly see that the magnitude of the negative slopes becomes smaller, due to the smaller value of $-\frac{\partial \ln f}{\partial p_T}$. Eq. (9) also suggests that Δv_1 does not depend on the mass of charged particles significantly. Thus in the right panel of Fig. 2, we study the effect of the mass of heavy quarks on Δv_1. By varying the mass of them from that of charms m_c ~1.3 GeV to that of bottoms m_b ~4 GeV while keeping others, it is seen that the slope of Δv_1 vs y_z changes negligible, which proves our findings.

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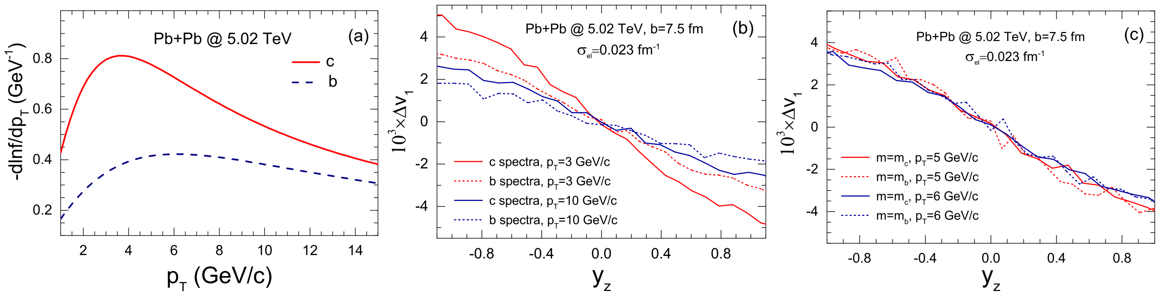

Figure 2: (Color online) (a)$-\frac{\partial \ln f}{\partial p_T}$ of charm and bottom quarks. (b) Δv_1 vs y_z of heavy mesons fragmented by heavy quarks with the initial spectra taken from that of charm quarks and that of bottom quarks at $p_T = 3$ and 10 GeV$/c$. (c) Δv_1 vs y_z of mesons fragmented by heavy quarks with the quark mass taken from that of charm quarks and that of bottom quarks at $p_T = 5$ and 6 GeV$/c$.

3. Charge dependent directed flow by electromagnetic fields

Another interesting finding is to the directed flow in Eq. (9), where we find α is simply related to the magnetic field in y direction [14]

$$\alpha = -|q|K\{\tau_1 B_y(\tau_1, 0) - \tau_0 B_y(\tau_0, 0)\}, \tag{10}$$

where K is a constant in the range of 0 to 1, and τ_1 and τ_0 are the escape time from the e.m. fields and the formation time of charged particles respectively. Using the same e.m. fields assuming $\sigma_{el} = 0.023$ fm^{-1} as Fig. 2, we study the formation time dependence of Δv_1, where the results are shown in the left panel of Fig. 3. By varying the formation time from that of charm quarks $t_c \sim 0.1$ fm$/c$ to that of bottom quarks $t_b \sim 0.033$ fm$/c$, we find a significant reduction of the magnitude of the slope of Δv_1 vs y_z, even though the formation time changes super small. In the right panel of Fig. 3, we show $-tB_y$ of the y component of the magnetic field in the center of fireball. It is seen that $-tB_y$ changes significantly in the first 0.2 fm$/c$, which then changes α significantly according to Eq. (10).

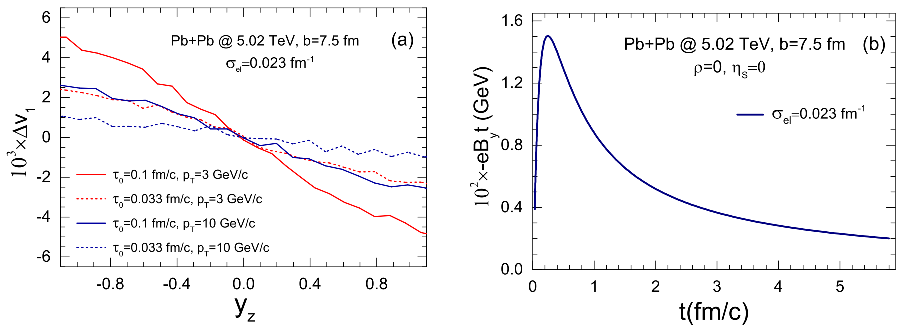

Figure 3: (Color online) (a) Δv_1 vs y_z of charmed mesons with the formation time taken from that of charm quarks and that of bottom quarks at $p_T = 3$ and 10 GeV$/c$. (b) $-tB_y$ of magnetic field in the center of overlapping region assuming $\sigma_{el} = 0.023$ fm^{-1}.

4. Conclusions

In this proceeding we report our findings on the general formula for the charge dependent spectra and flow observables generated by e.m. fields, which has a simple form at $p_T \gg m$. In particular, for the directed flow splitting of charged particles due to e.m. fields, it can be formulated as $d\Delta v_1/dy_z|_{y_z=0} = -\alpha\frac{\partial \ln f}{\partial p_T} + \frac{2\alpha-\beta}{p_T}$, where α is simply determined by the difference $\Delta[tB_y(t)]$ in the center of colliding systems at the formation time of particles and at the time when they escape e.m. fields or freeze out of the y component of magnetic fields. An experimental check of the p_T pattern predicted for the splitting of Δv_n and the spectra ratio of matter/anti-matter would provide a strong probe of e.m. fields. Moreover, because the formation times of charm quarks and lepton pairs decayed from Z^0 bosons are similar, the correlations between the charm meson directed flow splitting and the one of leptons from Z^0 decay (yet to be measured) will be another strong probe of e.m. fields.

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