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Modification of Z^0 leptonic invariant mass in ultrarelativistic heavy ion collisions as a measure of the electromagnetic field

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ABSTRACT

An extraordinary strong magnetic field, $eB_0 \approx 10^{18}$ Gauss, is expected to be generated in non-central ultrarelativistic heavy ion collisions and it is envisaged to induce several effects on hot QCD matter including the possibility of local parity and local charge conjugation and parity symmetry violations. A direct signature of such e.m. fields and a first quantitative measurement of its strength and lifetime are still missing. We point out that both the mean value of leptonic invariant mass of Z^0 boson, reconstructed by its decaying lepton pairs, and the relative width are modified in relativistic heavy ion collisions due to the presence of strong initial e.m. fields. We propose a measurement of the leptonic invariant mass of Z^0 as a novel probe of the strength of the B_y. Both shifts could be up to about few hundred MeV and are found to depend on the integral of B_y over the time duration quadratically (approximate). Hence it provides a novel and clear probe of electromagnetic fields, which can be tested experimentally.

1. Introduction

The ultrarelativistic heavy ion collisions (uRHICs) experiments conducted at both the BNL Relativistic Heavy Ion Collider (RHIC) [1, 2] and the CERN Large Hadron Collider (LHC) [3] have created a new state of matter with deconfined quarks and gluons, the quark-gluon plasma (QGP). The QGP is found to be the most perfect fluid created in nature [4–6]. Heavy ion collisions also provide the possibility to probe the local parity (P) as well as charge conjugation and parity (CP) symmetry violation processes in Quantum chromodynamics (QCD) that may be generated by the metastable local domains of gluon fields with a non-zero winding number [7–9]. The most promising way to probe the P and CP violations in QCD is to measure the chiral magnetic effect (CME) [10–16], where a strong magnetic field with a long lifetime is required in order to generate a signal large enough.

A huge electromagnetic field can be generated in non-central ultrarelativistic heavy ion collisions. However, there are a lot of inherent uncertainties in the calculation of the time evolution of the magnetic field in heavy ion collisions due to the uncertainty of the electrical conductivity of QGP [17–19], the poor knowledge of the properties of the initial non-equilibrium stage as well as the complexity of numerically solving magnetohydrodynamics (MHD). This inspired the search for a direct probe of the strong e.m. fields by measuring the directed flow $v_1 = \langle p_x/p_T \rangle$ splitting between positively and negatively charged hadrons [20,21], especially heavy meson pairs ($D^0, \overline{D}^0$) [22–24] or the leptons decayed from Z^0 boson [24]. Here we propose a new probe of electromagnetic fields via the leptonic invariant mass distribution of Z^0 boson reconstructed from its decaying lepton pairs, whose final momenta should be affected by the presence of e.m. fields. It should be significantly easier to measure the invariant mass distribution of Z^0 boson than the $v_1(p_T)$ splitting between its decaying leptons of opposite charge. Hence the measurement of the invariant mass distribution of Z^0 would open up a more accessible experimental probe that as we discuss in this Letter can be directly linked to the time integral of the magnetic field.

The paper is organized as follows: In Sec. 2 we discuss the parametrization of e.m. fields and a description of the coordinate and momentum distributions of both Z^0 boson and its decaying lepton pairs. In Sec. 3 we present several numerical results including the invariant mass distribution of Z^0 reconstructed by its decaying lepton pairs in the presence of e.m. fields and the dependence of the shifts of both the invariant mass of Z^0 and its width on the configuration of e.m. fields. Summary and conclusions are given in Sec. 4.

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2. Electromagnetic fields and leptons from Z^0

To study the effect of e.m. fields on the Z^0 invariant mass reconstructed by its decaying lepton pairs, we adopt a general parametrization of the configurations of e.m. fields used in several studies [13–15,25,26]:

$$eB_y(x, y, \tau) = -B(\tau)\rho_B(x, y) \tag{1}$$

$$\rho_B(x, y) = \exp[-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}] \tag{2}$$

$$B(\tau) = eB_0/(1 + (\tau/\tau_B)^a), \tag{3}$$

where B_0, σ_x and σ_y are usually given by the estimates of e.m. fields in the vacuum in AA collisions at $t = 0$ [27]. The above gives the transverse coordinate dependence and time evolution of B_y. The electric field eE_x is then determined by solving the Faraday's Law $\nabla \times \mathbf{E} = -\partial \mathbf{B}/\partial t$:

$$eE_x(t, x, y, \eta_S) = \rho_B(x, y) \int_0^{\eta_S} d\chi\, B'\left(\frac{t}{\cosh\chi}\right) \frac{t}{\cosh\chi} \tag{4}$$

where the invariant time τ and space-time rapidity η_S are related to t and z by $\tau = \sqrt{t^2 - z^2}$ and $\eta_S = \frac{1}{2}\ln(\frac{t+z}{t-z})$. We note that the above configurations of e.m. fields may not apply to space with a large magnitude of η_S and transverse coordinate $\rho = \sqrt{x^2 + y^2}$, where one should solve the full Maxwell equations with complex boundary conditions. However, we can safely adopt the above configurations of e.m. fields at small magnitude of η_S and ρ considering initial transverse coordinates of particles are mostly centered in the overlapping region making the detailed behavior of the e.m. fields at large ρ irrelevant.

We will focus on 5.02 TeV PbPb collisions at 20-30% centrality for the numerical calculations, which corresponds to impact parameter $b = 7.5$ fm. However, the conclusions should be general based on our physical arguments. The parameters in this colliding system are found to be $eB_0 = 73 m_\pi^2$, $\sigma_x = 3$ fm and $\sigma_y = 4$ fm [24], where eB_0 is the maximum initial value estimated in the vacuum.

The distribution of Z^0 boson in the transverse plane is given by the binary nucleon-nucleon collisions of colliding nuclei, while in the longitudinal axis $z = \tau_{Z^0} \sinh y_z$ and $t = \tau_{Z^0} \cosh y_z$ with $\tau_{Z^0} = \hbar/m_{Z^0} = 0.0022$ fm/c, where y_z is the rapidity of Z^0. The momentum distribution of Z^0 in 5.02 TeV Pb+Pb collisions is given by fitting the experimental measurements [28,29] with:

$$\frac{dN}{d^2 p_T dy_z} = f(\mathbf{p_T}, y_z) \propto 10^{-a p_T^n} e^{-\frac{y_z^2}{2\Delta_l^2}}, \tag{5}$$

where $a = 0.6896$, $n = 0.4283$ and $\Delta_l = 3.034$ are found to give quite a good description of p_T and y_z dependence of Z^0 boson, as reported in [24].

We use the Monte Carlo method to generate Z^0 boson, whose invariant mass distribution is given by a Breit-Wigner distribution:

$$\rho(M) = \frac{1}{\pi} \frac{\Gamma/2}{(M - M_0)^2 + \Gamma^2/4}, \tag{6}$$

with $M_0 = 91.1876$ GeV and $\Gamma = 2.4952$ GeV [30]. Finally the spacetime coordinate of produced lepton pairs is given by their mother Z^0 that moves in a straight line, with the decay time following a distribution $\rho(\Delta t) \propto e^{-\frac{\Gamma \Delta t}{\gamma_v}}$, with γ_v being the Lorentz contraction factor. After the interaction with e.m. fields, these lepton pairs are used to reconstruct the invariant mass of Z^0 boson.

3. Numerical results

3.1. The effect of lepton-quark scattering

Before discussing the effect of external e.m. fields on the Z^0 boson invariant mass distribution, it should be noted that this distribution can also be modified due to the lepton-quark scattering in QGP [31]. To consider this effect, we employ the standard Langevin equations:

$$dx_i = \frac{p_i}{E} dt, \tag{7}$$

$$dp_i = -\gamma p_i dt + \xi_i \sqrt{2 D_p dt}, \tag{8}$$

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 ξ_i is a real number randomly sampled from a normal distribution with $\langle \xi_i \rangle = 0$ and $\langle \xi_i \xi_j \rangle = \delta_{ij}$. D_p is related to the transverse momentum broadening rate $\hat{q}$ due to elastic collisions between leptons and the medium quarks by $D_p = \hat{q}/4$ [32]. Since the small angle scattering cross section for lepton-quark scattering is:

$$\frac{d\sigma}{dq_\perp^2} \approx e_q^2 \frac{2\pi \alpha_e^2}{q_\perp^4}, \tag{9}$$

$\hat{q}$ will be:

$$\begin{aligned} \hat{q} &= \sum_q \int_{\mu^2}^{s^*/4} dq_\perp^2 \rho_q e_q^2 \frac{d\sigma}{dq_\perp^2} q_\perp^2 \\ &= \frac{12\zeta(3)}{\pi} \alpha_e^2 T^3 \ln\frac{s^*}{4\mu^2}, \end{aligned} \tag{10}$$

where α_e is the fine structure constant in QED, $\zeta(3) \approx 1.202$, ρ_q is the number density of quarks of each flavor, $s^* \approx 5.6 E T$ is the average center of mass energy of lepton-quark scattering through one photon exchange, and $\mu^2 = \frac{1}{2}(3 + N_c \sum_q e_q^2) e^2 T^2 = 10\pi\alpha_e T^2$ is the Debye screening mass for the exchange photon from quark and lepton loops.

To quantitatively characterize the effect of lepton-quark scattering or the e.m. fields on the invariant mass of Z^0 boson, we define two quantities:

$$\Delta\langle M \rangle = \langle M_f \rangle - \langle M_i \rangle \tag{11}$$

$$\begin{aligned} \Delta\sigma &= \sigma_f - \sigma_i \\ &= \sqrt{\frac{\sum(M_f - \langle M_f \rangle)^2}{N-1}} - \sqrt{\frac{\sum(M_i - \langle M_i \rangle)^2}{N-1}}, \end{aligned} \tag{12}$$

where f and i stand for the invariant mass of Z^0 reconstructed by lepton pairs in vacuum and with the effect of lepton-quark scattering or the e.m. fields, and N is the number of Z^0 boson used in calculation.

After the evolution of leptons in QGP due to lepton-quark scattering described by Eq. (8), the results show $\Delta\langle M \rangle = -1.9$ MeV and $\Delta\sigma \leq 0.2$ MeV, which is a small number compared to the experimental uncertainty on M_0 and Γ and the modification due to e.m. fields as we will show below. We thus do not include this in the following discussions of the effects of e.m. fields. However, it should be noted that this effect is stronger in more central collision because the lifetime is longer and the temperature of QGP is higher, while the effect of e.m. fields should be smaller because the magnetic field decreases in more central collisions.

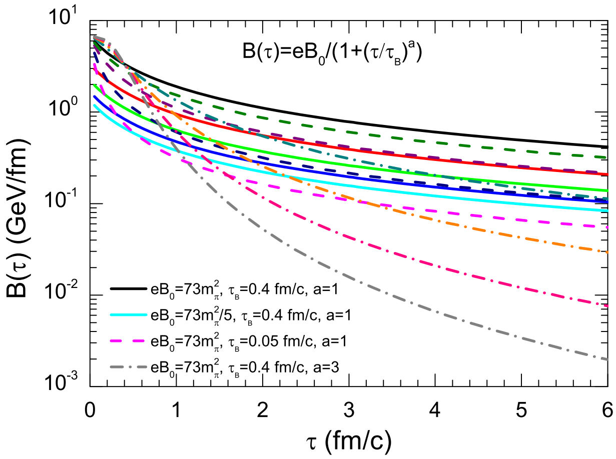

Fig. 1. Time evolution of $B(\tau)$ with different sets of eB_0, τ_B and a, where eB_0, τ_B and a increase from $73m_\pi^2/5$ to $73m_\pi^2$, from 0.05 fm/c to 0.4 fm/c and from 1 to 3, respectively.

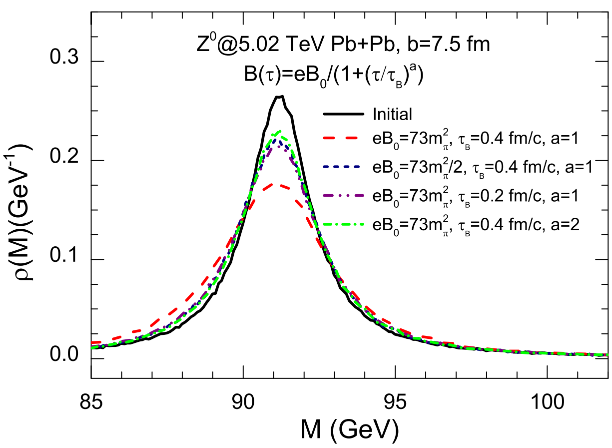

Fig. 2. The invariant mass distribution of Z^0 boson at midrapidity $|y_Z| \leq 0.5$ reconstructed by lepton pairs after interacting with e.m. fields.

3.2. Relating the leptonic invariant mass and width of Z^0 to e.m. fields strength

In Fig. 1 we show the time evolution of $B(\tau)$ with different sets of eB_0, τ_B and a, where one can see that a wide range of e.m. fields is explored. We do not show the time evolution of E_x, calculated by Eq. (4), which also varies according to different sets of eB_0, τ_B and a.

The results of the invariant mass distribution of Z^0 are shown in Fig. 2, where the solid black line shows the initial distribution of Z^0 invariant mass in vacuum, which has a Breit-Wigner form as in Eq. (6). The red line shows the distribution of the Z^0 invariant mass reconstructed from lepton pairs after interacting with e.m. fields with $eB_0 = 73m_\pi^2$, $\tau_B = 0.4$ fm/c and $a = 1$. This set of parameters is found to reproduce the directed flow splitting between D^0 and $\overline{D}^0$ with $d\Delta v_1/d\eta = 0.49 \pm 0.17(stat.) \pm 0.06(syst.)$ as measured by the ALICE experiment [33]. It is seen by the red dashed line that such an e.m. field would strongly increase the width σ_{Z^0} of the distribution of Z^0 invariant mass by about 300 MeV and decrease the mean value $\langle M_{Z^0}\rangle$ by about 250 MeV. We have varied eB_0, τ_B and a by a factor of two, respectively. The results are shown by the navy, purple and green lines in Fig. 2, where it is seen that the width increases as well but not as much as the red line. The large uncertainty of ALICE measurements on the v_1 splitting of D^0 does not allow a determination of the e.m. field.

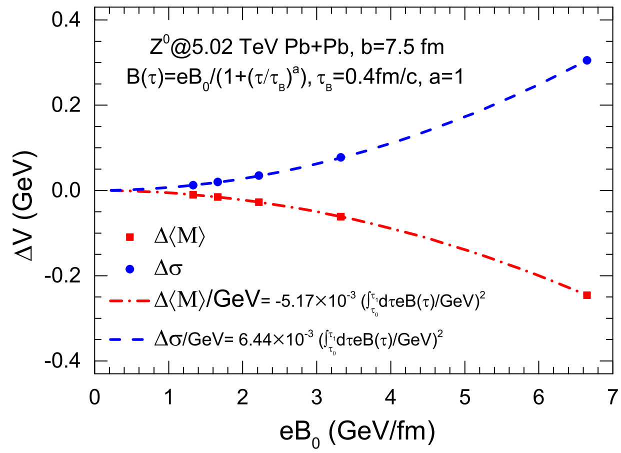

Fig. 3. The eB_0 dependence of p_T integrated $\Delta\langle M\rangle$ and $\Delta\sigma$ of midrapidity ($|y_z| \leq 0.5$) Z^0 boson induced by e.m. fields.

Currently it is still to be clarified whether Δv_1^D is determined only by the e.m. fields [24]. Therefore to have a comprehensive study of the effect of e.m. fields on the invariant mass of Z^0 reconstructed by lepton pairs, we vary eB_0, τ_B and a in $B(\tau)$ to find some general pattern relating $\Delta\langle M_{Z^0}\rangle$ and $\Delta\sigma_{Z^0}$ to the strength and time dependence of the magnetic field. We vary eB_0 by a factor of 5 and the life time τ_B by a factor of 8 and the power law parameter a by a factor of 3 respectively, while keeping other parameters unchanged.

In Fig. 3, we show how p_T integrated $\Delta\langle M\rangle$ and $\Delta\sigma$ of Z^0 boson in midrapidity ($|y_z| \leq 0.5$) changes with eB_0, keeping $\tau_B = 0.4$ fm/c and $a = 1$. It is seen by the red squares and blue circles that $\Delta\langle M\rangle$ changes from -9.9 MeV to -246 MeV, and $\Delta\sigma$ from 12.6 MeV to 305 MeV, with eB_0 increasing from $73m_\pi^2/5$ to $73m_\pi^2$.

Because the invariant mass of Z^0 boson is symmetric with charge conjugation, $\Delta\langle M\rangle$ should be proportional to $(eB_0)^2$ in the leading order. More specifically, supposing one Z^0 boson at rest with mass M decays into lepton pairs whose momenta $\boldsymbol{p}$ and $-\boldsymbol{p}$ change by $\Delta\boldsymbol{p}_1$ and $\Delta\boldsymbol{p}_2$ due to e.m. fields, then the invariant mass will change by:

$$\Delta M = M_f - M = \sqrt{(E(\boldsymbol{p}+\Delta\boldsymbol{p}_1)+E(-\boldsymbol{p}+\Delta\boldsymbol{p}_2))^2-(\Delta\boldsymbol{p}_1+\Delta\boldsymbol{p}_2)^2} - M \approx \frac{(\Delta\boldsymbol{p}_1-\Delta\boldsymbol{p}_2)^2+4\boldsymbol{p}\cdot(\Delta\boldsymbol{p}_1-\Delta\boldsymbol{p}_2)}{2M}, \quad (13)$$

with $E(\boldsymbol{p}) = \sqrt{m_l^2+\boldsymbol{p}^2}$. The negative value of $\Delta\langle M\rangle$ implies thus $\langle\boldsymbol{p}\cdot(\Delta\boldsymbol{p}_1-\Delta\boldsymbol{p}_2)\rangle < 0$, noting that in general $\Delta\boldsymbol{p}_1 \neq \Delta\boldsymbol{p}_2$.

The time integral $\int_{\tau_0}^{\tau_1} d\tau eB(\tau)$ should be a good quantity to qualify the effect of e.m. fields, where τ_0 is the production time of lepton pairs that is about 0.08 fm/c and τ_1 is the effective time when charged particles escape e.m. fields, which is about 6-8 fm/c in semi-peripheral collisions. We found that both $\Delta\langle M\rangle$ and $\Delta\sigma$ can be simply fitted as $k(\int_{\tau_0}^{\tau_1} d\tau eB(\tau))^2$ with $k_M = -5.17 \times 10^{-3}$ for the mass, shown as the red dash-dotted line in Fig. 3, and for the width $k_\sigma = 6.44 \times 10^{-3}$, as the blue dashed line.

In Fig. 4, we extend the study to τ_B dependence of the p_T integrated $\Delta\langle M\rangle$ and $\Delta\sigma$ of Z^0 boson in midrapidity, varying τ_B by a factor of 8 from 0.05 fm/c to 0.4 fm/c. Because it is not trivial that the effects of E_x and B_y change by the same factor if one changes τ_B, we fit $\Delta\langle M\rangle$ and $\Delta\sigma$ of Z^0 boson by $k(\int_{\tau_0}^{\tau_1} d\tau eB(\tau))^n$, where n is not fixed to 2. However, we found $\Delta\langle M\rangle$ is still nearly proportional to the square of the integral with the fit parameter $n_M = 2.122$ and $k_M = -4.08 \times 10^{-3}$, as shown by the red

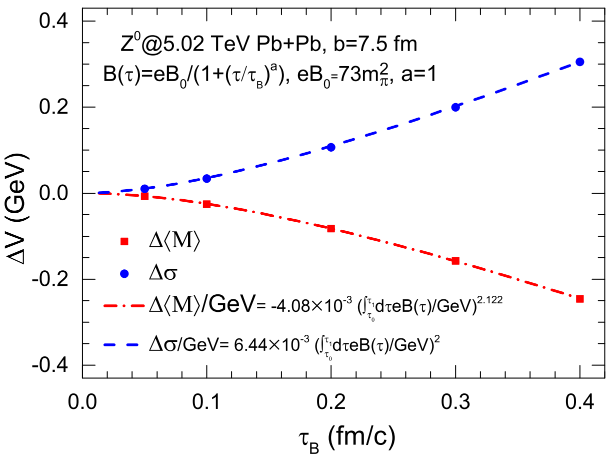

Fig. 4. The τ_B dependence of p_T integrated $\Delta\langle M\rangle$ and $\Delta\sigma$ of midrapidity ($|y_z| \leq 0.5$) Z^0 boson induced by e.m. fields.

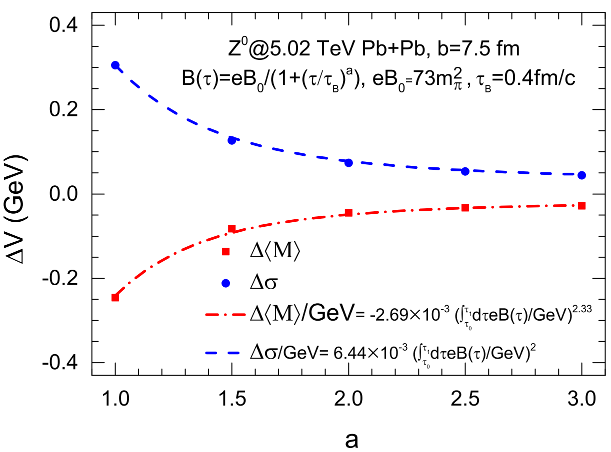

Fig. 5. The a dependence of p_T integrated $\Delta\langle M\rangle$ and $\Delta\sigma$ of midrapidity ($|y_z| \leq 0.5$) Z^0 boson induced by e.m. fields.

dash-dotted line. Instead $\Delta\sigma$ as a function of τ_B has the fitting parameters k_σ and $n_\sigma = 2$ that are the same as the previous case studied as a function of eB_0, see the blue dashed line. According to the red squares and blue circles, $\Delta\langle M\rangle$ changes from -7.46 MeV to -246 MeV, and $\Delta\sigma$ from 10.2 MeV to 305 MeV, with τ_B increasing from 0.05 fm/c to 0.4 fm/c.

Finally, we vary the power law decay parameter a in $B(\tau)$ by a factor of 3 which implies a very large change in the time dependence. The red squares and blue circles in Fig. 5 show that $\Delta\langle M\rangle$ changes from -246 MeV to -27.9 MeV, and $\Delta\sigma$ from 305 MeV to 44.1 MeV, with a increasing from 1 to 3. Moreover, as shown by the red dash-dotted and blue dashed lines in Fig. 5, $\Delta\langle M\rangle$ is fitted well with $k_M = -2.69 \times 10^{-3}$ and $n_M = 2.33$ which however stays still quite close to 2, while the parameters k_σ and n_σ used in fitting $\Delta\sigma$ as a function of a are found again and quite remarkably to be the same as the other two cases, hence the quadratic relation remains a solid general relation.

In principle one may think to correlate the shifts of the mass $\Delta\langle M\rangle$ and $\Delta\sigma$ of Z^0 with the splitting in the directed flow $d\Delta v_1^l/dy_z|_{y_z=0}$ of the leptons of opposite charge as has been studied in [24], however it has to be noticed that the latter depends only on the $d\Delta p_x/dy_z$, while the invariant mass distribution depends on all the vector components of the shift, according to Eq. (13). We have carried on a first study that finds a significant correlation, but only when $d\Delta v_1^l/dy_z|_{y_z=0} > 0.05$, i.e. the Δp_x remains dominant, but the correlations weaken when it has smaller

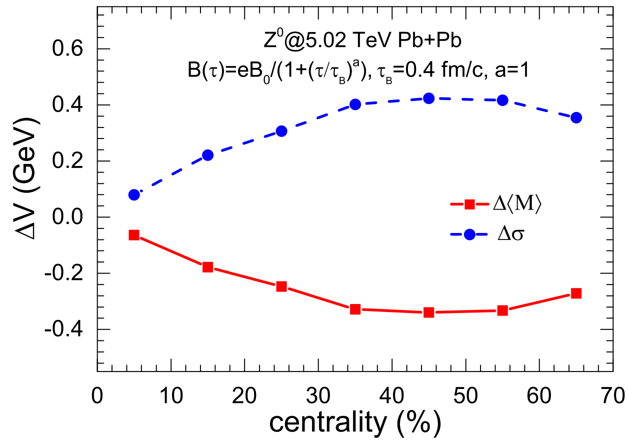

Fig. 6. The centrality dependence of p_T integrated $\Delta\langle M\rangle$ and $\Delta\sigma$ of midrapidity ($|y_z| \leq 0.5$) Z^0 boson induced by e.m. fields.

positive and negative values. A more detailed analysis about this aspect will be published later.

We also notice that $\langle\Delta \boldsymbol{p}_1 - \Delta \boldsymbol{p}_2\rangle$ should be zero due to P symmetry, but if one looks at the y_z dependence of $\langle\Delta \boldsymbol{p}_1 - \Delta \boldsymbol{p}_2\rangle$, it will be proportional to $y_z \boldsymbol{B}$ in the leading order. Eq. (13) implies thus that $\Delta\langle M\rangle$ should be proportional to $y_z^2\langle(d\Delta \boldsymbol{p}_1/dy_z - d\Delta \boldsymbol{p}_2/dy_z)^2\rangle$ at small $|y_z|$. Therefore we have also performed an initial study for the case $\tau_b = 0.4$ fm/c and $a = 1$ finding at small y_z an additional y_z^2 dependence of both the mass and the width of Z^0. However the increase of $\Delta\langle M\rangle$ is about one order of magnitude smaller than the one observed in at $y_z = 0$, while the $\Delta\sigma$ can acquire an additional increase that is comparable to the one found at zero rapidity. We will report about these further aspects in an upcoming longer paper.

3.3. The centrality dependence of the leptonic invariant mass and width of Z^0 in the presence of the e.m. fields

Finally we present the shifts of Z^0 leptonic invariant mass and its width induced by e.m. fields as a function of centrality. To do this one needs to calculate the space extension, the strength and the time evolution of the magnetic field. Given the evolution of the first two with centrality should follow from the initial geometry, while the time dependence of the magnetic field is the main quantity we aim to constraint, we consider the case where the time evolution is independent of centrality. This can serve as a baseline to interpret the future experimental results vs the centrality dependence.

On the centrality dependence of the strength and the space extension of the magnetic field, we estimate it using its value in the vacuum in AA collisions at $t = 0$ as well [27]. The results are shown in Fig. 6, where it is seen that both $\Delta\langle M\rangle$ and $\Delta\sigma$ increase monotonically from -64 MeV to -340 MeV and from 79 MeV to 423 MeV respectively, as the centrality increases from 5% to 45%. The pattern comes as a balance between the increase with the impact parameter of the maximum initial value of the magnetic field and the decrease of the space and time extension of the fireball and of the magnetic field as driven by the evolution of the geometry.

At centrality around 40% the two effects become of equal magnitude and the mass and width modifications are nearly independent of centrality. Therefore we estimate that this is the centrality where the effects should be maximal; if experimentally the maximum is reached at smaller centrality it would be a signature that the lifetime of the magnetic field decreases with centrality already at smaller centrality.

4. Conclusions and discussions

This Letter points out a new effect that should be observable in relativistic heavy ion collisions: the modification of both the mean value and the width of the Z^0 leptonic invariant mass due to the strong initial electromagnetic field, more specifically a decrease of the invariant mass of Z^0 that can be as large as few hundred MeV and the increase of the width by a similar magnitude. Using a wide range of reasonable parametrization for the electromagnetic field, and carrying out a comprehensive study of the modification of the invariant mass of Z^0, we find that the decrease of the invariant mass $\langle \Delta M_{Z^0} \rangle$ is proportional to $\left(\int_{\tau_0}^{\tau_1} d\tau eB(\tau)\right)^n$ with n that has a very weak dependence on the specific behavior of the $B_y(\tau)$ and has a range of $n_M = 2.16 \pm 0.16$. Even more remarkable is that the increase in the width $\Delta\sigma_{Z^0} = k_\sigma \left(\int_{\tau_0}^{\tau_1} d\tau eB(\tau)\right)^2$ with $k_\sigma = 6.44 \times 10^{-3}$ for all the configurations explored. Moreover, the shifts of both the invariant mass and the width of reconstructed Z^0 boson are expected to depend also on the rapidity of Z^0 quadratically and are expected to further increase the width of the invariant mass distribution. These modifications on the invariant mass distribution of reconstructed Z^0 boson due to electromagnetic fields provide a clear probe of electromagnetic fields, which can be tested by experiments at LHC. The main effect pointed out is novel and quite relevant in itself considering that a modification of the invariant mass of the Z^0 in AA collisions has never been pointed out before, it appears to be a powerful tool to have a measure of the time integral of the magnetic field produced in relativistic heavy ion collisions. In the future it could be also complemented by the recent suggestions to measure the splitting of the directed flow of D^0 and $\bar{D}^0$ and $l^\pm$ [22,24,34], that instead is found to be proportional to $\tau_0 B_y(\tau_0) - \tau_1 B_y(\tau_1)$. The scope of such studies is even more wide because a determination of the e.m. field can trigger a breakthrough in the ongoing search for the CME, CMW and CVE effects [10–16] as well as on the splitting of the Λ polarization [35–37].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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