

Effects of quark gluon plasma droplet evolution on charge separation in small collision systems within a multiphase transport model

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In relativistic high-energy heavy-ion collisions, the chiral magnetic effect (CME) could produce a charge separation in quark gluon plasma (QGP) and remain in the final hadron system during evolution, observed as the correlator $\Delta\gamma$. This physics procedure could also occur in small collision systems if the CME were to emerge in the QGP droplet. In this paper, we study the effects of QGP droplet evolution on charge separation in small collision systems, based on a multiphase transport model. Our calculations indicate that, with given initial charge separation, the effects of parton level evolution and hadron level evolution weaken the charge separation indeed, but there are still enough signals that could survive to the final hadron system. Furthermore, we found that, the contribution of background to $\Delta\gamma$ is negligible in small collision systems. So, we propose the small collision system is a good place to check the contribution of the CME.

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I. INTRODUCTION

In relativistic heavy-ion collisions, the extremely high temperature needed for quantum chromodynamics (QCD) phase transition is satisfied, and quarks and gluons are deconfined, forming a kind of new matter called quark gluon plasma (QGP). In off-center heavy-ion collisions, extremely strong transient electric and magnetic fields are also generated [1–8]. On the other hand, people have realized that there may be parity symmetry ($\mathcal{P}$) or charge conjugation and parity symmetry ($\mathcal{CP}$) violation effects due to quantum anomalous fluctuation of a QCD vacuum [9–14]. This effect could cause a charge separation in QGP due to the coupling of $\mathcal{CP}$ violation and strong magnetic fields, called the chiral magnetic effect (CME) [13,15–17].

As the local charge separation induced by the CME cannot be observed directly in experiment, the three-point azimuthal correlator is introduced [18] to measure the charge imbalance:

$$\gamma_{\alpha\beta} = \langle \cos(\Phi_\alpha + \Phi_\beta - 2\Phi_{RP}) \rangle, \quad (1)$$

where Φ_α and Φ_β are azimuthal angles of charged particles α and β , and Φ_{RP} is the azimuthal direction of the reaction plane. Also, in order to erase the charge-independent backgrounds like local momentum conservation, the difference of the correlator

$$\Delta\gamma = \gamma_{OS} - \gamma_{SS} \quad (2)$$

is introduced [13], where γ_{OS} represents the opposite charge particle pair and γ_{SS} represents the same charge particle pair. Besides the contribution from the CME to the charge correlator $\Delta\gamma$, there are other QCD background effects that can contribute to $\Delta\gamma$ too. These effects are related to the QGP flow v_2 [19–22]. So, the correlator observed in experiment include two contributions indeed

$$\Delta\gamma = \Delta\gamma_{CME} + \Delta\gamma_{background}. \quad (3)$$

The contribution of the CME to the correlator $\Delta\gamma$ is proportional to the angular difference between Φ_B and Φ_{RP} , expressed as [23]

$$\Delta\gamma_{CME} \propto B^2 \cos[2(\Phi_B - \Phi_{RP})], \quad (4)$$

where Φ_B is the azimuthal angle of the magnetic field. In order to confirm and clarify $\Delta\gamma_{CME}$, i.e. the contribution of the CME to $\Delta\gamma$, an isobaric collision is proposed [24]. While the experimental data [25] recently indicated that these background contributions $\Delta\gamma_{background}$ are quite large, it is still a difficult task to confirm the contribution from CME in heavy-ion collision experiments.

In our previous work, we proposed a new method to check and clarify the contribution of CME in small collision systems [26,27]. However, people used to think of there should be no charge separation caused by the CME effect in small collision systems for two reasons. The first one is people believed there was an absence of azimuthal correlation between Φ_B and Φ_2 [28,29], so the observation of $\Delta\gamma_{CME}$ could not continue after averaging over many events. The second reason is related to the small scale of time and space of QGP droplets in small collision systems. People thought the initial charge separation could not continue in the final hadron system after the whole evolution process in small collision systems.

With regard to the first reason, as already discussed in our previous work [26], we found that the orientation of the E - M

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field produced in $p + A$ has a nonvanishing correlation with Φ_{RP} . Furthermore, we found that in the small collision system $p^\uparrow + A$ evolved a transversely polarized proton as projectile, there are two specified colliding schemes in which the correlator $\Delta\gamma_{\text{CME}}$ has a significant dependence on the angle between the reaction plane and the polarization direction. So the initial charge separation could be produced by local strong violation in the small collision systems $p + A$ and $p^\uparrow + A$.

In this paper, we concentrate on the discussion about the second reason, i.e., the effects of evolution with a given initial charge separation in a small collision system. We calculate the surviving charge separation described as $\Delta\gamma$ after parton level evolution and hadron level evolution. The content of this article is as follows: In Sec. II, we introduce our calculation framework briefly. The results of calculations are given in Sec. III. Finally, in Sec. IV, we give a summation about our calculation.

II. CALCULATION FRAMEWORK

In this work, a multiphase transport (AMPT) model [30,31] is employed to perform the simulation of $p + \text{Au}$ collisions with the energies available at the BNL Relativistic Heavy Ion Collider with $\sqrt{s} = 200$ GeV.

In the AMPT model, an event of a heavy-ion collision ($A + A$ or $p + A$) is divided into four stages: the production of the initial condition of the parton level, the evolution of the parton level, the hadronization of partons into hadrons, and the evolution of the hadron level. In the first stage, the Heavy Ion Jet Interaction Generator (HIJING) [32,33] model is used to simulate heavy-ion collisions. The wounded nucleons and produced minijets are treated as excited strings attached by partons. Around stage two and stage three, there are two distinct versions of the AMPT model available: the default version, and the string-melting version. In the default version, these attached partons will suffer a parton level evolution described as the Zhang parton cascade (ZPC) process [34]. After that, the partons are recombined with excited strings. Then hadronization occurs through the Lund string fragmentation model [35–37] to generate hadrons. In the string-melting version, all excited strings are melted into partons. All of these partons suffer the ZPC parton cascade in the second stage. Then hadrons are produced through a quark recombination model [38,39] in the third stage. In stage four, after all partons are hadronized into hadrons, a relativistic transport (ART) [40] model is used to describe the hadron level evolution.

In our calculation, the string-melting version of the AMPT model is used to simulate the evolution of a QGP droplet which is produced in a high-energy $p + \text{Au}$ collision. The projectile is set as a proton flying with $E = 100$ GeV along the $+z$ direction, while the target is Au flying with $E = 100$ GeV per nucleon along the $-z$ direction. In order to concentrate on the effects of evolution on charge separation, we set the impact parameter vector b to lie on the x coordinate pointing from p to Au. So the azimuthal direction of the reaction plane Φ_{RP} is 0 in the following calculation, and the direction of the magnetic field is in the $-y$ direction on average. In the ZPC parton evolution step, a 10-mb parton cross section is set.

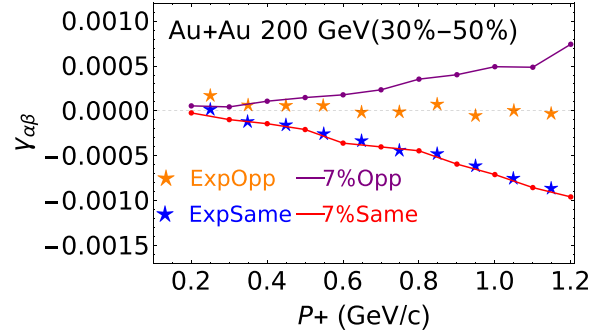


FIG. 1. $\gamma_{\alpha\beta}$ as a function of P_+ for Au + Au collisions with 30%–50% centrality. A percentage of 7% initial charge separation is set in the AMPT calculation to fit these data.

Since there is no CME mechanism in the current AMPT models, we put a new stage into the AMPT model after string melting to simulate the initial charge separation along magnetic fields induced by the CME. Following the method in Ref. [41], a few percentages of quarks are selected randomly, their y components of momentum are interchanged to form an initial charge separation. In detail, the p_y 's of upward-moving $\bar{u}$ and downward-moving u are interchanged, and the p_y 's of upward-moving d and downward-moving $\bar{d}$ are interchanged correspondingly. After this stage is accomplished, all partons enter the ZPC evolution stage to suffer the latter evolution.

To determine the reasonable percentage of interchanged quarks, we performed a simulation of Au + Au collisions to fit the observed experiment data of $\gamma_{\alpha\beta}$ [42,43]. Shown in Fig. 1 is the $\gamma_{\alpha\beta}$ of Au + Au collisions in a centrality bin of 30% to 50% as a function of P_+ , which is defined as

$$P_+ = \frac{P_{T,\alpha} + P_{T,\beta}}{2}, \quad (5)$$

where $P_{T,\alpha}$ and $P_{T,\beta}$ are the transverse momenta of particles α and β . After a global fitting, we found that the percentage of 7% for the initial charge separation can fit the data of γ_{SS} very well. At the same time, we can see the failure of fitting the data of γ_{OS} like in Ref. [41]. The asymmetry of γ_{SS} and γ_{OS} may be caused by some charge-independent background effects existing in heavy-ion collisions.

In our following calculation, this percentage of 7% is used for $p + \text{Au}$ collisions, since we have found that the value of the correlator $\Delta\gamma_{\text{CME}}$ in $p + \text{Au}$ collisions is of the same order as that in Au + Au collisions [26,27]. The main goal of this work is to study the effects of evolution on charge separation, to check how much initial charge separation could survive to the final hadron stage. So the percentage of 7% could be considered as a reasonable upper limit of the CME effect in $p + \text{Au}$ collisions.

III. RESULTS

In this section, we calculate the charge correlator $\gamma_{\alpha\beta}$ carefully in $p + \text{Au}$ collisions with an initial charge separation. We show the results as a function of the impact parameter b , kinetic variable P_+ , and $\Delta\eta$ respectively. On each data point in the following figures, the statistical error is shown

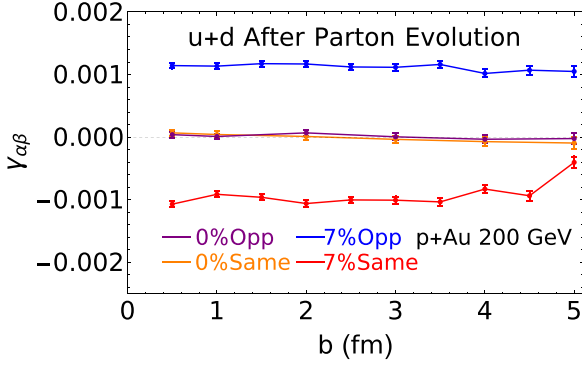


FIG. 2. $\gamma_{\alpha\beta}$ as a function of the impact parameter b for $p + \text{Au}$ collisions after ZPC parton level evolution. Results of 7% and 0% of initial charge separation are shown for comparison.

as an error bar. This error is defined as the standard deviation $\sigma = (\sqrt{\sum (s_i - \langle s \rangle)^2})/N$.

First, let us check the correlator $\gamma_{\alpha\beta}$ as a function of the impact parameter b .

The initial charge correlator $\gamma_{OS} \approx 1.59 \times 10^{-3}$ and $\gamma_{SS} \approx -1.38 \times 10^{-3}$ for the parton system after the quark interchange stage. Because we set the interchange percentage 7% as b independent, the initial value of $\gamma_{\alpha\beta}$ is also b independent. After parton evolution, the value of $\gamma_{\alpha\beta}$ should be weakened as we expected, since the azimuthal correlation between quarks would be disrupted by the cascade process. Shown in Fig. 2, the value of $\gamma_{\alpha\beta}$ decreases to about ± 0.001 . In this figure, we can see that γ_{OS} and γ_{SS} are almost symmetric in each impact parameter bin. This means that the effects of parton evolution on charge separation is charge independent and almost centrality independent. We can see from Fig. 2 that at large impact parameter $b > 4$ fm, the γ_{SS} shows a depression; this is only because the number of partons decreases in the off-central collisions, then the number of quarks interchanged may be much less than small and middle impact parameters even with the same percentage.

After hadronization and hadron level evolution, the correlator $\gamma_{\alpha\beta}$ should be weakened furthermore. In Fig. 3, we can see about 40% charge separation survived into the final hadron system as we expected. To compare the results of γ_{OS} and γ_{SS}

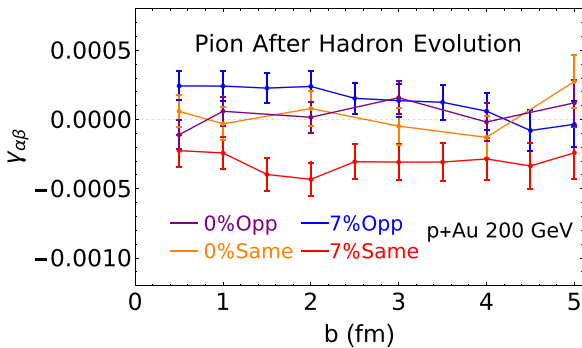


FIG. 3. $\gamma_{\alpha\beta}$ as a function of the impact parameter b for $p + \text{Au}$ collisions after hadron level evolution. Results of 7% and 0% of initial charge separation are shown for comparison.

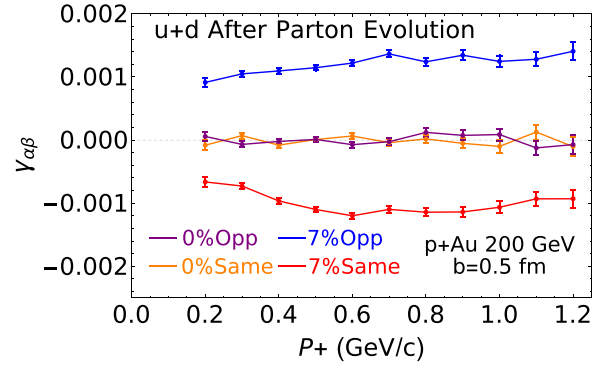


FIG. 4. $\gamma_{\alpha\beta}$ as a function of P_+ for $p + \text{Au}$ collisions after ZPC parton level evolution. Results 7% and 0% of initial charge separation are shown for comparison.

is interesting. We can see that the value of γ_{OS} is depressed more than that of γ_{SS} obviously, especially at middle and large impact parameters.

Furthermore, we give a comparison between results with interchange percentages of 7% and 0%. The latter one means there is no CME mechanism in our calculation. Figure 2 shows that the results with 0% after parton level evolution are still zero at each impact parameter. In Fig. 3, the zero results continue into the final hadron system within the statistical error bar. These results are quite different from what was observed in $\text{Au} + \text{Au}$ collisions in Ref. [41]. In a $\text{Au} + \text{Au}$ collision, a nonzero $\gamma_{\alpha\beta}$ is obtained after parton level evolution with 0% interchange percentage, and these nonzero results are expanded after hadron level evolution.

These zero results of the $p + \text{Au}$ collision tell us that

$$\Delta\gamma = \Delta\gamma_{\text{CME}} + \Delta\gamma_{\text{background}} = 0 \quad (6)$$

from Eq. (3). With the contribution of the CME being zero, as we set it, we can conclude that the background contribution $\Delta\gamma_{\text{background}}$ in $p + \text{Au}$ is negligible. A possible reason for these could be related to the strength of the QGP flow v_2 . Since the value of v_2 is observable in $\text{Au} + \text{Au}$, the background contribution $\Delta\gamma_{\text{background}}$ is quite large. But in the $p + \text{Au}$ collision, there is almost no flow in the QGP droplet, then $\Delta\gamma_{\text{background}}$ is almost zero. These results suggest to us that the observed significant correlator $\Delta\gamma$ in the CMS experiment [44] could come from the CME mainly.

Then, we checked the correlator $\gamma_{\alpha\beta}$ as a function of the kinematic variable P_+ for both the parton level and the hadron level. P_+ is defined as in Eq. (5), which means the average value of the transverse momentum of the pair particles. In this calculation, the impact parameter $b = 0.5$ fm is set.

In Fig. 4, the results of $\gamma_{\alpha\beta}$ with 7% initial charge separation after parton level evolution are shown. We can see their values are almost ± 0.001 again with a slight expanding with the increase of P_+ . The values of γ_{OS} and γ_{SS} are symmetric approximately in the whole range of P_+ . And in the range of $P_+ > 0.6$ GeV, the values of both γ_{OS} and γ_{SS} get a saturation to 0.0012. This phenomenon tell us the effects of parton evolution on charge separation have only a weak dependence on the kinematic variable within the AMPT model.

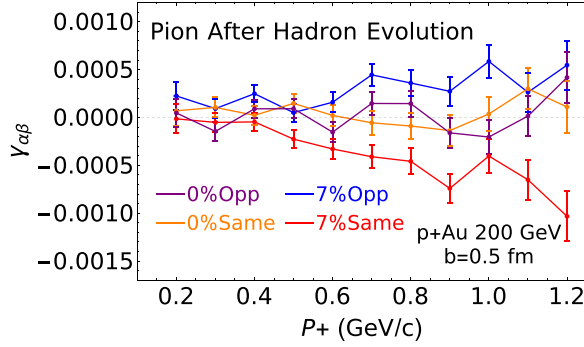


FIG. 5. $\gamma_{\alpha\beta}$ as a function of P_+ for $p + \text{Au}$ collisions after hadron level evolution. Results of 7% and 0% of initial charge separation are shown for comparison.

The results of $\gamma_{\alpha\beta}$ at the final hadron level as a function of P_+ are shown in Fig. 5. These results with 7% are similar to the experimental data of Au + Au shown in Fig. 1. Significant P_+ -dependent results for both γ_{OS} and γ_{SS} are seen. In the range of small p_+ , both of them are depressed very much. The reason for these depressions is that the number of hadrons with small p_T is much more than the number of hadrons with large p_T . So the hadrons with small p_T suffer much more cascade collision and lose azimuthal correlation much more.

However, the results clearly show a charge sign dependence. Only 30% values of γ_{OS} are observed, while about 50% to 90% values of γ_{SS} are transferred into the final hadron level in the range of $P_+ > 0.6$ GeV. The reason for this phenomenon is perhaps related to the local momentum conservation in the resonance decay process. In experiments, $\Delta\gamma$ is defined as in Eq. (2) to remove this effect.

Also, the results of 0% are shown in Figs. 4 and 5. As we expected, they are zero in the whole P_+ range. These results confirm that the parton evolution and the hadron evolution will not bring any additional charge separation caused by background effects in small collisions.

Finally, we check the correlator $\gamma_{\alpha\beta}$ as a function of another kinematic variable $\Delta\eta$ for both the parton level and the hadron level. $\Delta\eta$ is defined as $\Delta\eta = |\eta_\alpha - \eta_\beta|$ and is shown in Figs. 6

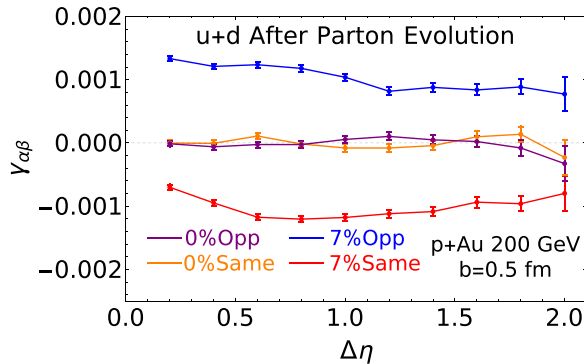


FIG. 6. $\gamma_{\alpha\beta}$ as a function of $\Delta\eta$ for $p + \text{Au}$ collisions after ZPC parton level evolution. Results of 7% and 0% of initial charge separation are shown for comparison.

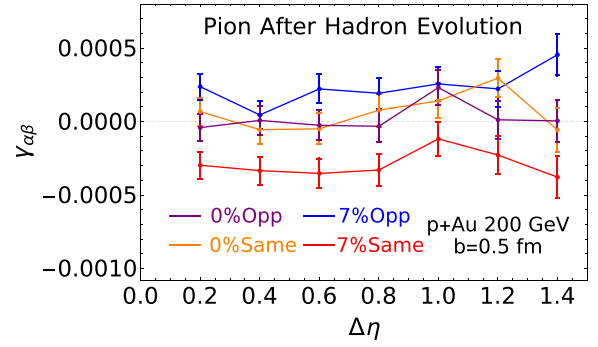


FIG. 7. $\gamma_{\alpha\beta}$ as a function of $\Delta\eta$ for $p + \text{Au}$ collisions after hadron level evolution. Results of 7% and 0% of initial charge separation are shown for comparison.

and 7. The impact parameter b is set as 0.5 fm in these calculations.

The results of $\gamma_{\alpha\beta}$ show us values of about ± 0.001 remain after parton level evolution, and hadron level evolution depressed γ_{OS} values more than γ_{SS} values as we have already seen before. In detail, only 15% of γ_{OS} survive after hadron level evolution, and this ratio for γ_{SS} is about 30%. Unlike the obvious dependence on P_+ shown in Fig. 5, the dependence of $\gamma_{\alpha\beta}$ on $\Delta\eta$ shown in Fig. 7 is negligible. This means a strong longitudinal correlation exists in the correlator $\gamma_{\alpha\beta}$. These results are quite different from what is observed in Au + Au in Ref. [41]. The results in that paper show a strong dependence on the $\Delta\eta$ even with 0% interchange percentage, indicating the strong bias of near-rapidity pairs of $\gamma_{\alpha\beta}$ in Au + Au. The difference between $p + \text{Au}$ and Au + Au could be explained as the longer lasting time of the QGP; therefore, stronger longitudinal correlation of string is broken in heavy-ion collisions.

The results above are all about the correlator $\gamma_{\alpha\beta}$, and our results of $\gamma_{\alpha\beta}$ have shown effects of backgrounds are negligible in $p + \text{Au}$ collisions. However, the correlator $\gamma_{\alpha\beta}$ is free of reaction-plane independent backgrounds. In order to check the effects of reaction-plane independent backgrounds in $p + \text{Au}$ collisions, we define a new correlator which is sensitive to

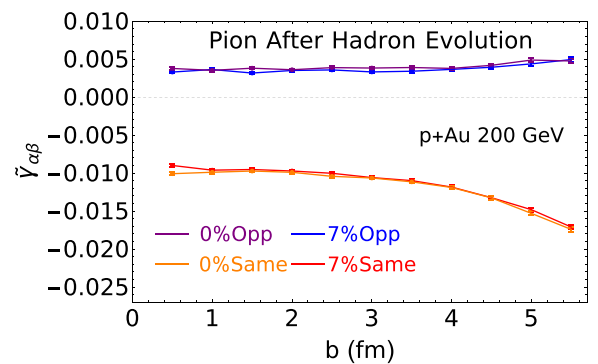


FIG. 8. $\tilde{\gamma}_{\alpha\beta}$ as a function of b for $p + \text{Au}$ collisions after hadron level evolution. Results of 7% and 0% of initial charge separation are shown for comparison.

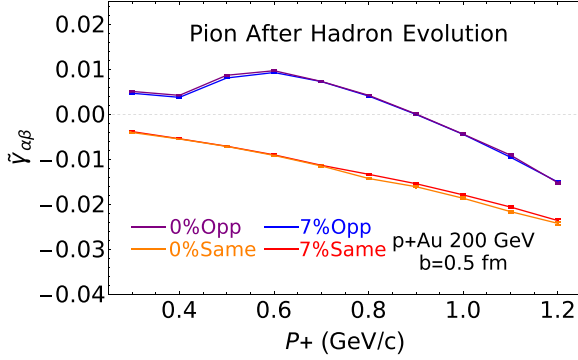


FIG. 9. $\tilde{\gamma}_{\alpha\beta}$ as a function of P_+ for $p + \text{Au}$ collisions after hadron level evolution. Results of 7% and 0% of initial charge separation are shown for comparison.

reaction-plane independent backgrounds [41]:

$$\tilde{\gamma}_{\alpha\beta} = \langle \cos(\Phi_\alpha - \Phi_\beta) \rangle. \quad (7)$$

Our results are shown in Fig. 8 as a function of the impact parameter b and in Fig. 9 as a function of P_+ . We can see from these two figures that the results with 7% and 0% are almost identical. These results prove that the value of $\tilde{\gamma}$ is dominated by reaction-plane independent backgrounds.

In order to check the CME signal in $\tilde{\gamma}_{\alpha\beta}$, we compare results of $\gamma_{\alpha\beta}$ with the difference of $\tilde{\gamma}_{\alpha\beta}$ with and without CME effects. This comparison is shown in Fig. 10 as a function of P_+ . The same order of them are seen. That means the contribution of the CME is nonvanishing indeed in $p + \text{Au}$ collisions.

IV. SUMMARY

In summary, we have studied the effects of parton level evolution and hadron level evolution on the charge separation in small system $p + \text{Au}$ collisions, by performing the AMPT model. With a given initial charge separation by interchange momentum of 7% quarks supposed to be induced by the CME, the effect of evolution can reduce charge separation

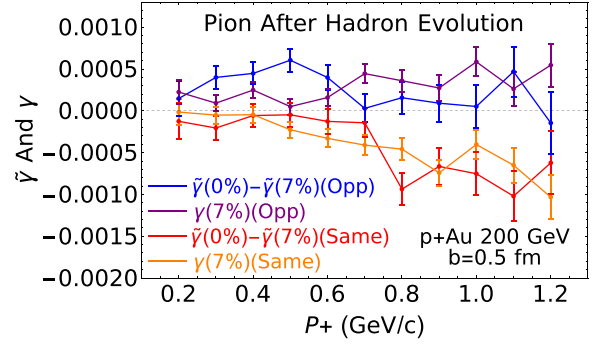


FIG. 10. The CME signals in $\gamma_{\alpha\beta}$ and in $\tilde{\gamma}_{\alpha\beta}$ are presented together as a function of P_+ . The blue and red curves come from the subtraction of the curves in Fig. 9, correspondingly, while the purple and orange curves come from Fig. 5.

significantly. However, there is still an amount of charge separation signals that survive into the final hadron system. The results of 0% are also presented as a comparison. Because there is no CME contribution in this calculation, the observed signal should come from the background contribution completely. So the zero result means the background has no contribution to the correlator $\Delta\gamma$ in $p + \text{Au}$ collisions. As a conclusion, even though the contribution of the CME in $p + \text{Au}$ could be a little smaller than that in $\text{Au} + \text{Au}$, a small collision is still a good place to check the CME as we proposed in Refs. [26,27].

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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