An Experimental Handle on Magnetic Field from Spectator Protons in A+A Collisions

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Abstract: The chiral magnetic effect (CME) and the chiral magnetic wave (CMW) have been predicted to arise from the coupling of domains with quark chirality imbalances in the quark-gluon plasma (QGP) and the strong magnetic field produced by energetic spectator protons. Searches for these quark chirality effects in nucleus-nucleus collisions have been performed at RHIC and the LHC as major scientific goals. For example, the RHIC 2018 run will be devoted to the isobaric collisions of ^{96}Ru+^{96}Ru and ^{96}Zr+^{96}Zr at $\sqrt{s_{NN}}$ = 200 GeV, where one may expect an up-to 20% difference in the experimental observables related to the magnetic-field-induced effects. Current data indicate that the experimental sensitivity to the chirality effects also depends on the beam energy and the colliding system size, presumably owing to variations in the magnetic field and/or the size of the QGP droplets. Therefore, another venue to enhance the experimental sensitivity could be Au+Au collisions at lower beam energies. We will demonstrate with the AMPT simulations that the number of net protons (N_{net-p}) at mid-rapidity is anti-correlated with the number of spectator protons, and hence provides an excellent handle on the magnetic field from spectator protons in Au+Au collisions at lower RHIC beam energies. Equipped with the event-shape-engineering technique [1], the search for chirality effects by varying N_{net-p} in Au+Au collisions at lower energies (with $\sqrt{s_{NN}}$ still higher than 10 GeV) will complement the isobaric collision data. The future RHIC Beam Energy Scan II program will facilitate the application of our method and discern the true contribution due to the quark chirality effects.

Chiral Anomaly in QCD and the Chiral Magnetic Effect

➢The strong interactions in general conserve parity but, as a consequence of the formation of topologically rare configurations of gluon fields, parity may be violated locally.

➢In ultra relativistic collisions of heavy nuclei (HIC), interaction of deconfined quarks with those non-trivial topological gauge fields may produce parity-violated metastable domains with imbalance in the number of left and right handed quarks.

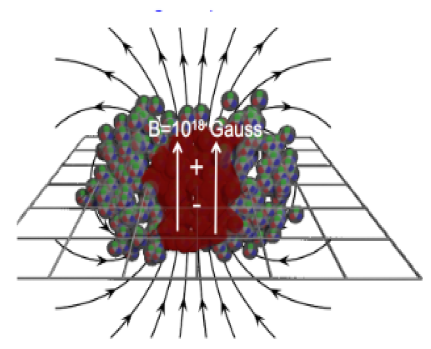


Fig.1

➢In non-central HIC, strong electric and magnetic field is produced mostly due to the fast moving spectator protons.

➢ The coupling of strong B-field with the chiral asymmetry in the microscopic domains induce an electric charge separation in the direction of B-field and hence an electric current. This phenomenon is known as Chiral Magnetic Effect or CME.

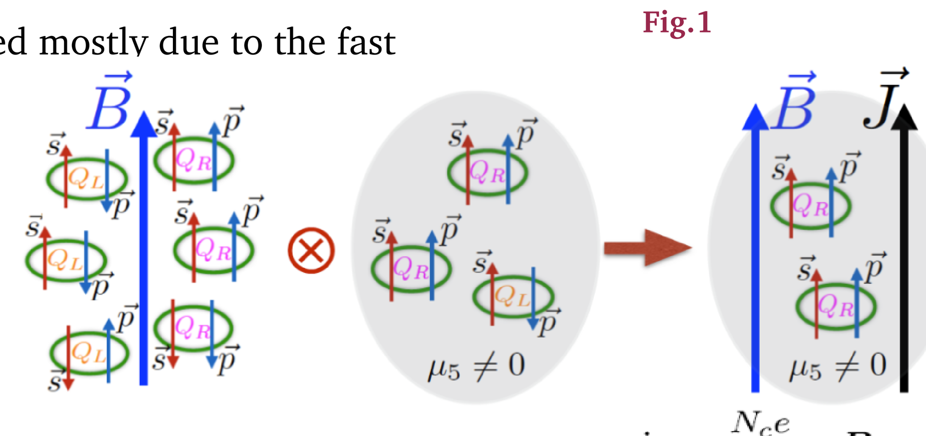


Fig.2

$$j_V = \frac{N_c e}{2\pi^2}\mu_A \boldsymbol{B}$$

Experimental measure of CME

➢ The CME induced charge separation is along the B-field or perpendicular to reaction plane.

➢ The charge-dependent 3-particle correlator (γ)[2] is one of the experimental measure of CME-driven charge separation.

➢ Although the measurements are qualitatively consistent with CME expectations but it still remains inconclusive mainly because of several known sources of background that may account for the observed signal partially or fully.

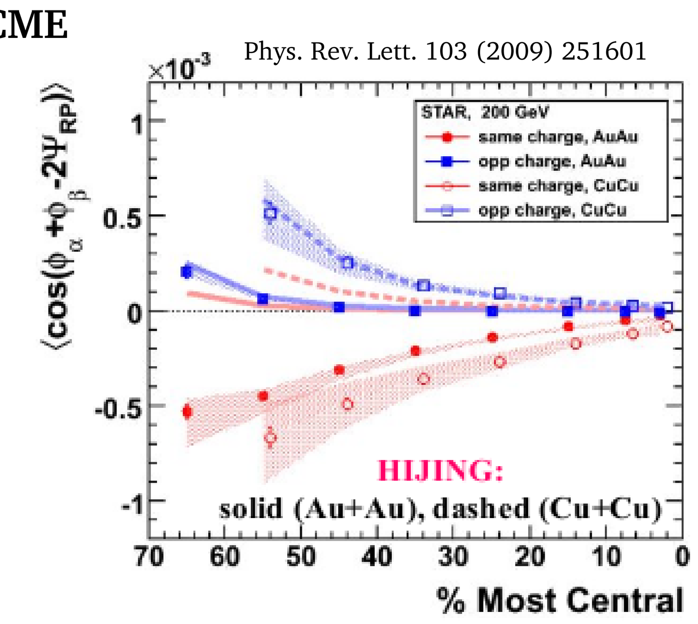


Fig.3

Challenges in measuring CME

➢Weak signal strength and large background.

➢No mean so far to measure magnetic fields in experiments.

➢ Here, we propose that net-protons could be an experimental handle on the magnetic fields generated by the spectator protons in HIC

Magnetic Fields in Heavy Ion Collisions

Fast moving colliding nuclei in off-central collisions can generate transient but strong magnetic fields.

In Au+Au collisions at top-RHIC it can reach up to as high as $eB \sim m_\pi^2 \sim 10^{18}$ Gauss.

➢ Using the Liénard-Wiechart potentials, magnetic fields due to spectator protons are calculated event-by-event [3].

➢Figure 4 shows the x and y components of event-averaged magnetic field at the center-of-mass of the collision zone (r = 0) for Au+Au collisions at 27 GeV centre-of-mass energy

Fig.4

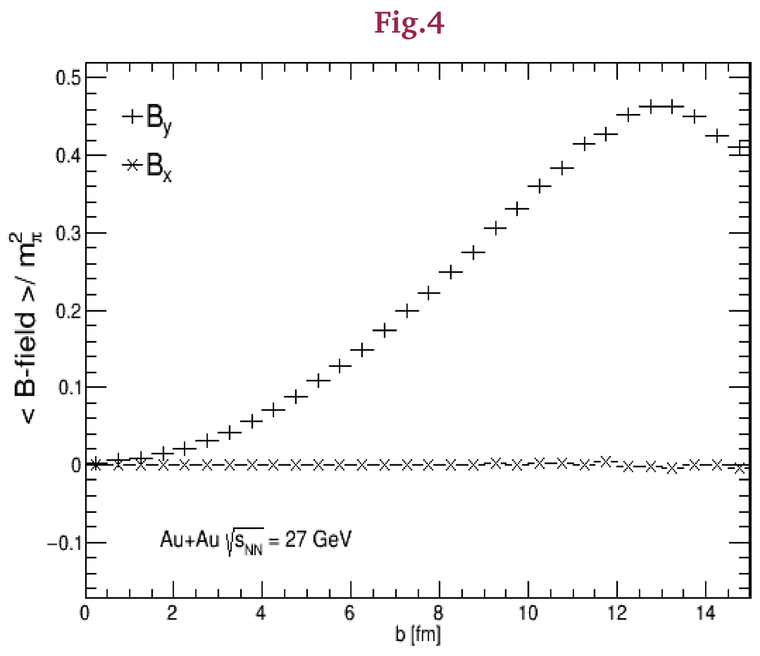
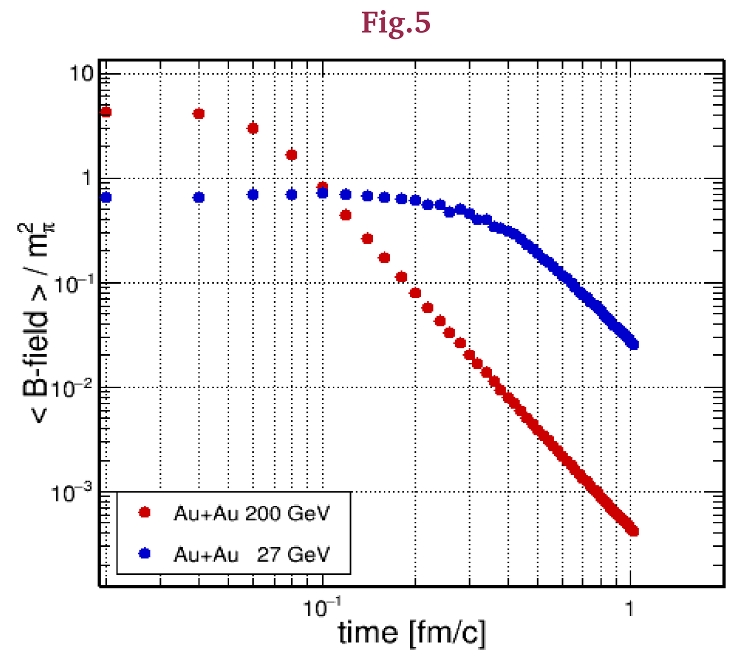


Fig.5



➢ Figure 5 shows the time evolution of magnetic field at r =0, in mid-central (b = 8 fm) Au+Au collisions at 200 GeV and 27 GeV centre-of-mass energy.

Magnetic field at 200 GeV drops more sharply than 27 GeV.
Long lived magnetic field at lower beam energy might enhance the signal due to CME-driven charge separation.

Reference

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[3] Wei-Tian Deng and Xu-Guang Huang.Phys, Rev. C 85, 044907 (2012).
[4] Xiaofeng Luo (for the STAR Collaboration), PoS (COPD2014) 019 [arXiv : 1501.03010].

Net-proton : An experimental handle on magnetic fields in A+A collisions

At low and intermediate collision energies at RHIC (say 7 to 27 GeV), owing to the baryon stopping, net-baryon density, hence the net-proton fluctuates around a large non-zero value.

➢In Figure 6 mean of the net-proton distributions as a function of average number of participant nucleons in Au+Au collisions at 27 GeV from AMPT and STAR data [4] are shown.

➢Trend is qualitatively consistent but model calculation underestimates the STAR data.

➢Further investigation is underway to tune model parameters for better quantitative reproducibility.

Fig.6

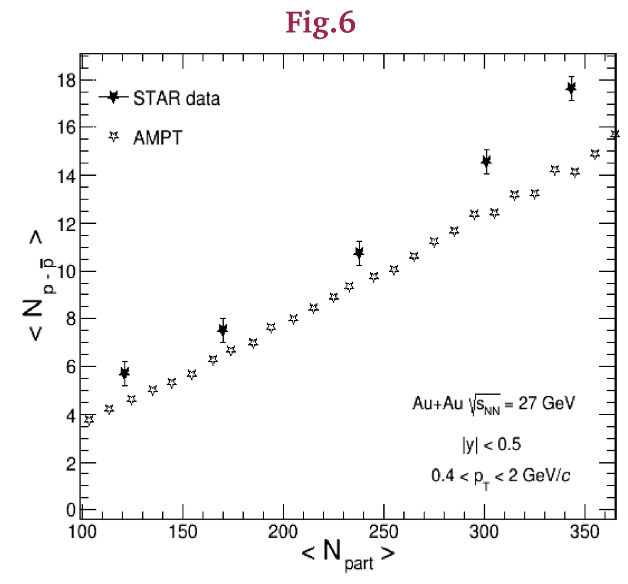
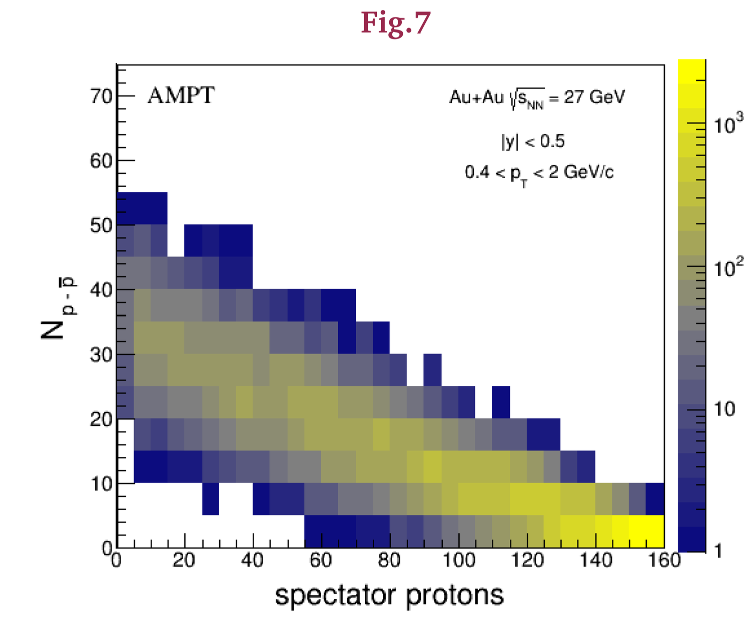


Fig.7



➢ In AMPT, as shown in Fig.7, net-protons ($N_{p-\bar{p}}$) and spectator protons exhibit an anti-correlation.

➢ Less net-protons implies higher spectator protons, hence larger magnetic field.

This anti-correlation can be exploited to classify events into varying strength of magnetic fields

Net-proton and magnetic field

control over magnetic fields in experiment

Figure 8 demonstrates the variation of magnetic field with net-proton. Increasing magnetic fields with decreasing net-protons is consistent with the assertion made earlier.

Fig.8

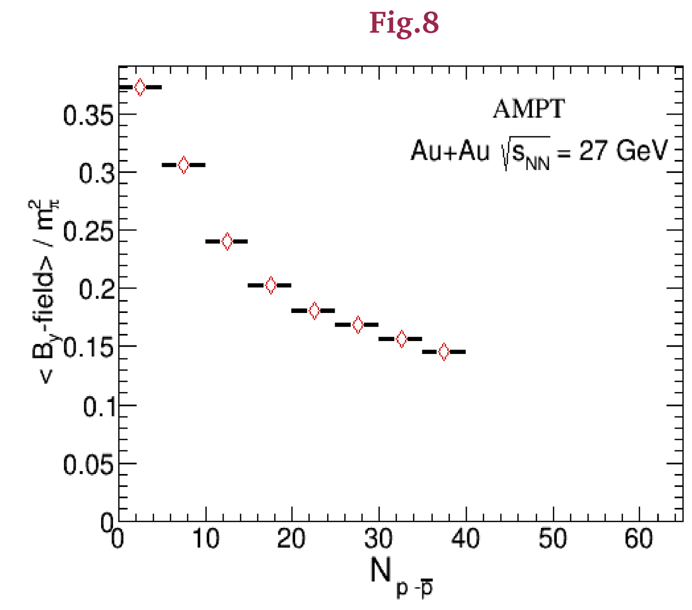
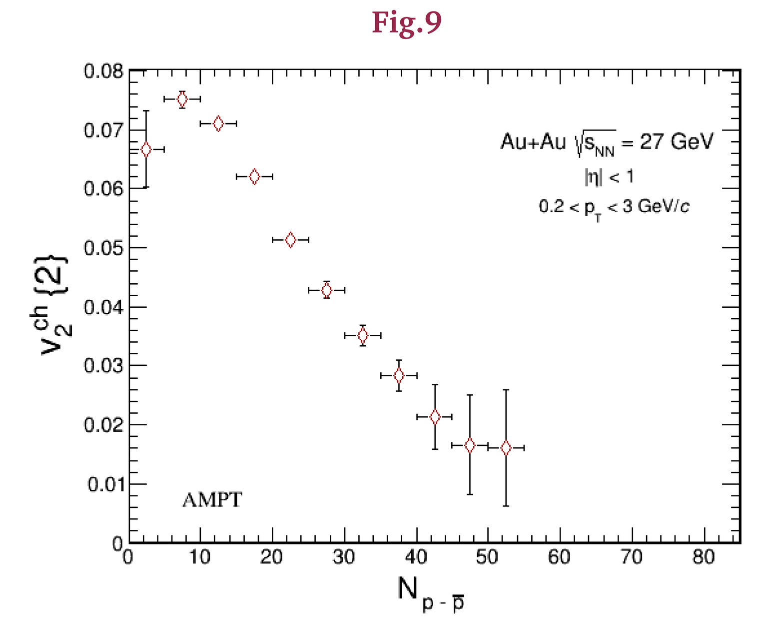


Fig.9



➢ Figure 9 shows the variation of elliptic flow (v_2) with net-proton. v_2 is the dominant contributor to the background in CME-related observables.

➢ Using the novel technique of event-shape-engineering (ESE), v_2 background can be mitigated significantly (see Gang Wang's poster #826)

Summary

➢ Based on the Monte-Carlo Glauber model, impact parameter dependence and time evolution of magnetic fields from spectator protons has been studied.

➢ Long-lived magnetic fields at lower energies may be conducive to the CME studies.

➢ Net-protons offer an experimental control on the strength of magnetic fields especially at low collision energies at RHIC.

➢ Coupled with ESE, search for chiral anomaly as a function of net-proton can be attributed to the varying magnitude of magnetic fields in A+A collisions.