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Experimental Status of the Chiral Magnetic Effect

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Abstract. Experimental searches for definitive evidence of the Chiral Magnetic Effect in heavy-ion collisions have become increasingly ingenious over the past decade, but a clear separation of any CME signal from flow-related backgrounds remains elusive. Although the isobar analysis by STAR does not appear to show a signal given the current preliminary background estimate, there is a tantalizing statistically significant signal in Au-Au at top RHIC energy using a spectator plane versus participant plane analysis. I discuss the status of these works in some detail, and discuss the possible advantage of an analysis that takes advantage of the expected correlation between the parity-odd event-by-event CME signal and other parity-odd measures such as the net hyperon helicity.

1 CME and Local Parity Violation

Within the rich field of heavy-ion physics, one of the exciting possibilities is that we may be able to observe the consequences of the creation of metastable regions in which parity and charge-parity symmetries are violated by the strong interaction [1]. This "Local Parity Violation" may manifest itself in various ways in heavy-ion collisions, but one of the most interesting is that this effect in the presence of the enormous magnetic fields generated by the colliding nuclei would cause a separation of electric charges along the direction of the magnetic field [2]-this is the "Chiral Magnetic Effect". If an observation of the CME could be clearly established in heavy-ion collisions, it would imply the existence of these $\mathcal{CP}$-violating regions, the restoration of approximate chiral symmetry in the Quark Gluon Plasma medium, and the action of an ultra-strong magnetic field on the collision region (see [3] for a review).

As illustrated in Figure 1 (taken from [4]), each parity-violating region can be characterized by an integer winding number Q_w which gives equal chirality imbalance (difference in left- and right-handed quarks) among every light quark flavor $N_L^f - N_L^f = 2Q_w$. The sign of Q_w is random region-to-region, with an equal chance of $Q_w > 0$ (for which negative electric charge flows in the direction of magnetic field) and $Q_w < 0$ (positive charge flows in the magnetic field direction). So the CME can be directly searched for only through correlation or fluctuation analyses, essentially comparing the behavior of charge flow along the B-field direction to charge flow perpendicular to that, as is done explicitly with the observable $\gamma \equiv \langle\cos[\varphi_\alpha + \varphi_\beta - 2\psi_2]\rangle$ [5]. Here, ϕ_α and ϕ_β are the azimuthal angles of charged particles in the event, ψ_2 is the second-order flow plane (which is roughly perpendicular to the magnetic field), and the average is taken over all particles in an event. γ quantifies the tendency of same- (or opposite-) charged particles to go in the same direction along the magnetic field as compared to perpendicular to the field. $\Delta\gamma \equiv \gamma^{OS} - \gamma^{SS}$ then makes a further comparison

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of opposite-signed correlations minus same-signed correlations. For a CME-like effect, we expect a positive value for $\Delta\gamma$, particularly in mid-central collisions where the magnetic field generated by spectator protons is large.

Another possible avenue for a search is to look for other parity odd effects. For example: *if* the strange quark can be treated as light in this context, it has the same chirality imbalance as both the up and down quarks. This means that regions with $Q_w > 0$, for example, give an excess of left-handed strange quarks, which would then be expected to cause a helicity imbalance among Λ hyperons. It has been suggested to look directly at fluctuations in Λ net helicity event-to-event [6, 7]; this may be quite challenging in practice because there are other potential sources of fluctuations, from physics and from detector effects, that are difficult to establish precisely. I suspect that a more promising avenue is to look for a correlation between this effect and the CME [8]-I'll come back to this!

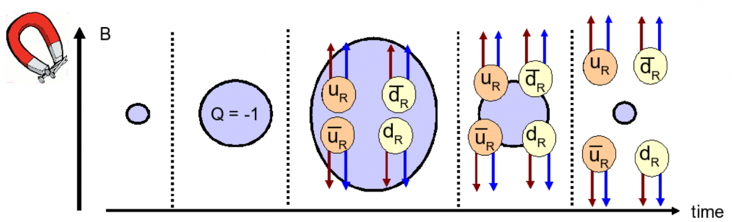

Figure 1: Cartoon representation (from [4]) of the CME effect with charge separation along the direction of the event magnetic field. A given winding number ($Q_w = -1$ in this example) has the same effect on all light quark flavors; up and down as pictured here, but potentially strange quarks as well! This would lead to charge separation along the magnetic field in addition to other parity-odd effects.

2 Isobars: blind analysis and subsequent work

Initial measurements of $\Delta\gamma$ at RHIC [9] and LHC [10] showed a signal qualitatively consistent with expectations from CME, but production of 2-particle opposite-signed clusters in which the clusters have a positive elliptic flow gives a signal in $\Delta\gamma$ (and every other CME-sensitive observable) that is very difficult to distinguish from a CME signal. Previous efforts to separate this flowing-cluster background, perhaps most notably using small-system and event-shape-engineering studies ([11] and [12] give nice overviews) indicate that the CME signal is at most a small fraction of the measured $\Delta\gamma$ signal. To be useful, then, efforts to identify CME need to be able to sort out a CME fraction (f_{CME}) of something like 10% of the measured $\Delta\gamma$.

A significant effort to increase the sensitivity for separating signal from background was undertaken with the RHIC isobar run, for which STAR analyzed approximately 2 billion events each of Zr^{96}_{40}+Zr^{96}_{40} and Ru^{96}_{44}+Ru^{96}_{44} collisions, the central idea being that with more protons, *Ru* collisions produce a higher magnetic field than *Zr* collisions (calculations [13] give a 15%-20% higher value for B^2, which is the quantity that the CME signal should scale with). To the extent that the nuclei are the same shape, the backgrounds should be the same (and to the extent they they have slight differences, those can be largely removed by scaling $\Delta\gamma$ by v_2). So the idea is straightforward: look for any excess in $\Delta\gamma/v_2$ in *Ru* compared to *Zr* and attribute that to CME. The results of the blind analysis[14] for the ratio $(\Delta\gamma/v_2)_{Ru}/(\Delta\gamma/v_2)_{Zr}$ are reproduced in Figure 2 along with some additions that are explained below. The blind analysis results clearly show no excess signal in *Ru*, and in fact even show a small excess in *Zr*, for all the varieties of the $\Delta\gamma/v_2$ measurements (i.e., the leftmost seven points of Figure 2).

An important caveat is that there is a multiplicity (N) difference between the two species at matching centrality, and the $\Delta\gamma$ observable has a trivial $1/N$ statistical dependence for the case where the signal comes dominantly from flowing 2-particle clusters (which is true here). A more informative first-order comparison, then, would be to compare these leftmost seven points not to unity, but instead to the ratio of N^{-1} for the two species (that is the point at the far right of Figure 2); using this baseline would indicate a small CME signal above background. However, there are important further considerations to that comparison; the first is a small non-flow correction to the 1/N scaling based on the numbers of observed same-sign and opposite-signed clusters in the two species, the second is the expected difference between the isobars in contributions to $\Delta\gamma$ from direct 3-particle correlations (e.g. jets). These relatively small corrections are now crucial for understanding whether there is any evidence for CME signal in isobar collisions. Preliminary work by STAR, reported at [15] and discussed at more length in [16], quantifies these two contributions through studies with data and the HIJING model (used to study the 3-particle contributions). This work gives the conclusion that the sum of these non-flow differences in the isobars would have the net effect of moving the comparison baseline for the $\Delta\gamma/v_2$ up from the 1/N line by a factor of 1.0125. Given the current uncertainty in these non-flow contributions, that baseline becomes the tan- and green-colored bands shown around the leftmost seven points in Figure 2. That these data points are consistent with these bands indicates that in the context of these *preliminary* calculations, there is no significant CME signal observed above background in these isobar collisions.

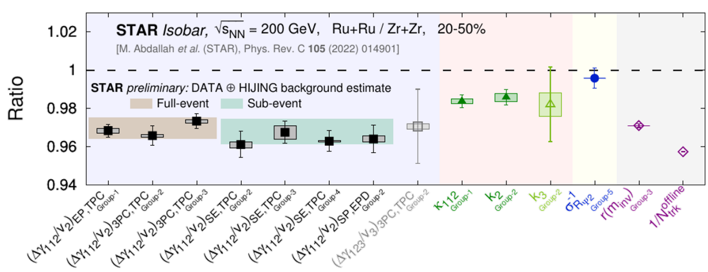

Figure 2: Results of the blind isobar analysis from STAR with some post-blinding additions. The left-most seven points are measurements of the Ru/Zr ratio of $\Delta\gamma/v_2$, four of which use sub-event analysis to suppress non-flow contributions. As discussed in the text, a good 1st-order baseline for those seven points is the ratio of inverse multiplicities at the far right, but a more complete *preliminary* baseline estimate is given by the tan and aqua bands that overlay those seven points. Other points in the plot are also discussed briefly in the text.

A couple more words about this figure: The green points represent a method of removing some of the v_2-related contributions to $\Delta\gamma$ by dividing it by the average reaction-plane independent two-particle correlations times the overall v_2. Although this first-order correction will not remove all backgrounds, it is interesting to note that these points do not lie above unity (which is their proper first-order baseline for comparison), so no CME signal is indicated by this method either.

An important study[17] was carried out to complement the isobar analysis, with the purpose of benchmarking the sensitivities of different observables using the analysis code from the isobar analysis to analyze simulated data. Of particular note, this study compared $\Delta\gamma$ to a measurement involving the width of the R correlator [18] and found these methods to have very similar sensitivities to a CME signal; this conclusion was bolstered by analytical work in [17] comparing these observables. I conclude that such additional observables are good tools to double-check the results from $\Delta\gamma$, but we should not expect any qualitatively different conclusions or better sensitivity to come from them. Results of the Ru/Zr ratio for the R correlator inverse width are shown as the blue point in Figure 2 - that this measured ratio is below 1 is consistent with the finding of no measurable CME signal; another useful result derived from [17] is that the first-order baseline for comparison of the R-correlator ratio when constructed independently from two subevents is not unity but rather the ratio of v_2 of the isobars (roughly 1.02 for this case, though non-flow will also contribute).

3 Recent Au+Au full energy results

In my view, the other big step forward for CME measurements in the last year is a recently published paper [19] by STAR using 2.4B events of 200 GeV $Au + Au$ data. The event plane can be determined using the azimuthal angles of spectator nucleons (the "spectator" plane) - that plane should be quite closely correlated with the direction of the event B-field which is mostly generated by the spectator protons, so measuring $\Delta\gamma$ relative to this plane should maximize the contribution from the CME. Alternatively, the event plane can be determined using produced particles near mid-rapidity (the "participant" plane). $\Delta\gamma$ measured with respect to this plane should maximize the contribution of flow-related background effects. Using $\Delta\gamma$ measurements from both of these planes, one can extract the fraction of the $\Delta\gamma$ that comes from CME under the assumption that the sole contributions are CME and v_2-related background. Results from this STAR measurement[19] are shown in Figure 3 - each column of the figure represents the CME fraction (f_{CME}) extracted from a slightly different version of the measurement, with each red point representing a result in mid-central collisions where we may expect the CME fraction to be maximized, and the blue points representing results in peripheral collisions for reference. A statistically significant f_{CME} of around 10% is extracted in mid-central collisions, but there are concerns that non-flow may still contribute. To reduce that effect, the two right-most columns use a sub-event method in which the participant plane is found using one-half of the TPC and the particles of interest for $\Delta\gamma$ from the other half. It is important to note that some non-flow effects can cause f_{CME} to appear *smaller* than its "true" value, so it is not obvious which direction non-flow will drive the f_{CME}. Still, it is crucial to continue to study these results to understand if this is truly a signal!

We should then ask: can we reconcile a possible 10% f_{CME} signal in $Au + Au$ with the apparent lack of signal from the isobar run? STAR met its sensitivity goal in the isobar run to achieve a sensitivity of 0.5% for the Ru/Zr ratio, which implies that a 10% f_{CME} signal would yield a 4σ signal in the isobar analysis-that signal is clearly not observed. So the question becomes: is it reasonable to expect a significantly smaller f_{CME} in the isobar systems than in $Au + Au$? There are simple arguments that make a reasonable case for "yes": the B-field should scale roughly as $A^{1/3}$, and the dominant "flowing clusters" background should roughly scale as multiplicity, or $1/A$, which together argue for a factor of ≈ 3 smaller f_{CME} in isobar than $Au + Au$. A calculation [20] using the AVFD model, reaches a similar conclusion, and while there are many assumptions involved, it does appear reasonable that these results can be consistent with one another.

4 Correlations of charge separation with other parity-odd effects

Looking to the future, one idea that I find very exciting is the possibility of correlating a *parity-odd* CME measurement, event by event, with other signals of Local Parity Violation (LPV). If the strange quark can be considered a light quark, then it will have the same net chirality in each event as the up and down quarks. Some of these strange quarks will go

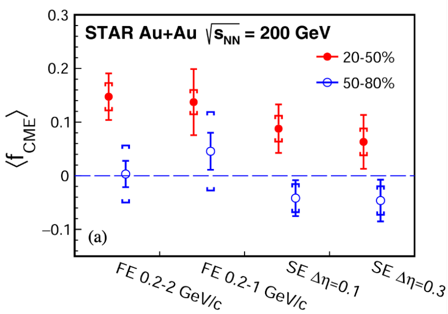

Figure 3: f_{CME}, the fraction of the $\Delta\gamma$ that is due to CME, as determined by an analysis that compares correlations with the participant plane to those with the spectator plane[19]. Subevent analyses are performed to reduce the contribution of non-flow, as discussed in the text

into the formation of Λ hyperons, which will then acquire a net helicity in each event caused by LPV. Importantly, the handedness of CME and the net lambda (and anti-lambda) helicity should be the same in every event, so that events in which positive charges flow in the direction of the magnetic field vector(i.e., Q_w is negative, as depicted in the Figure 1 cartoon) will have an excess of right-handed (helicity) Λs, and likewise an excess of *left-handed* Λs should be expected in events with positive charges flowing *opposite* to the B-field. To distinguish charge flow "along" the B-field from charge flow "opposite to" the B-field, the first-order event plane is needed for each event. Using ψ_1, the signed charge flow can be characterized by $\Delta a_1 =< \sin(\phi_+ - \psi_1) > - < \sin(\phi_- - \psi_1) >$. In the presence of LPV/CME, we expect a negative correlation between Δa_1 and $\Delta N_\Lambda = N_\Lambda^L - N_\Lambda^R$.

A *preliminary* measurement of the covariance between these two quantities has been made by STAR using about 400M events of 27 GeV $Au + Au$ data. This is shown in Figure 3 as a function of centrality. The signature for LPV would be a negative covariance in this plot for the "on-peak" signal. Nothing statistically significant is observed in this exploratory measurement, but this method will be repeated in larger full-energy data sets and has the advantage that the backgrounds to these two observables are largely (completely?) uncorrelated by background sources so that the expected negative covariance signal should be very resistant to false LPV/CME signals.

5 Summary and Acknowledgements

With the current preliminary background estimates by STAR, there is not a significant CME signal in the isobar data. There **is** a statistically significant signal that implies a CME fraction of around 10% from (in my opinion) the best current analysis of top energy $Au + Au$ data, using both spectator plane and participant plane information to disentangle the background. That signal could be consistent with a non-observation in the isobar data with justifiable assumptions about how the CME signal may scale with system size. The $Au+Au$ analysis is, however, still not free of non-flow backgrounds; more work to understand these backgrounds (both "2-particle + flow" and "direct 3-particle") in detail is still crucial to understanding whether a signal is present.

For the future, it is expected that full energy $Au+Au$ runs of RHIC in 2023 and 2025 will increase the available statistics by roughly an order of magnitude, which will allow a much more thorough study of non-flow backgrounds to pin down whether the spectator/partcipiant plane analysis is seeing a true signal. Other CME-only observables may provide some additional, but not radically different, information, but taking advantage of the parity-odd behavior

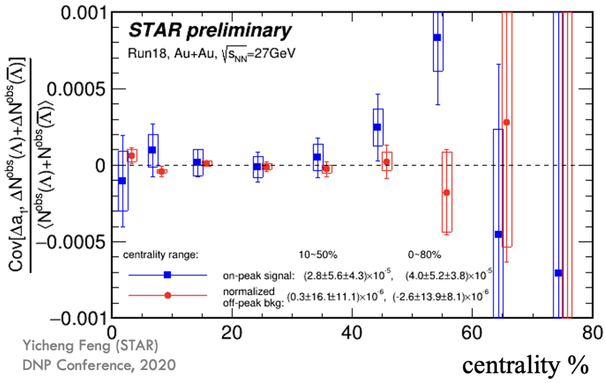

Figure 4: Event-by-event covariance between charge separation along the magnetic field (using first-order event plane information from the STAR EPD detector) and the net handedness of Λs + anti-Λs. A signal for LPV/CME would appear as a negative covariance for the blue points in mid-central collisions. No signal is seen in this 27 GeV data but the method can be used on forthcoming large top energy Au+Au datasets.

of the CME by correlating its signal event-by-event with other parity odd observables, such as net lambda helicity, opens up a qualitatively different way of searching that I consider quite exciting!

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