Estimate of a nonflow baseline for the chiral magnetic effect in isobar collisions at RHIC

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Abstract. Recently, STAR reported the isobar ($^{96}_{44}$Ru + $^{96}_{44}$Ru, $^{96}_{40}$Zr + $^{96}_{40}$Zr) results for the chiral magnetic effect (CME) search [1]. The Ru+Ru to Zr+Zr ratio of the CME-sensitive observable $\Delta\gamma$, normalized by elliptic anisotropy (v_2), is observed to be close to the inverse multiplicity (N) ratio. In other words, the ratio of the $N\Delta\gamma/v_2$ observable is close to the naive background baseline of unity. However, nonflow correlations are expected to cause the baseline to deviate from unity. To further understand the isobar results, we decompose the nonflow contributions to $N\Delta\gamma/v_2$ (isobar ratio) into three terms [2] and quantify each term by using the nonflow in v_2 measurement, published STAR data [1] and HIJNG simulations. From these estimates, we arrive at a nonflow baseline of the isobar ratio of $N\Delta\gamma/v_2$ for the CME. We report this nonflow baseline and discuss its implications.

1 Introduction

Quantum chromodynamics (QCD) predicts vacuum fluctuations, rendering nonzero topological charge in a local domain. As a result, there would be more particles with one certain chirality than the other, which is called the chirality anomaly. If meanwhile there is a strong magnetic field created by the spectator protons in heavy-ion collisions, the particles would have spins locked either parallel or anti-parallel to the magnetic field direction depending on their charges. Then, with the same chirality preference but opposite spins, the positive and negative charges would have opposite momenta. This charge separation phenomenon is called the chiral magnetic effect (CME).

To search for the CME, STAR conducted the isobar experiments in 2018, and recently published their isobar results [1]. The two isobar species, $^{96}_{44}$Ru and $^{96}_{40}$Zr, were expected to have similar background due to the same nucleon number, while Ru was expected to have larger CME signal due to more protons and therefore stronger magnetic field. If so, this CME observable $\Delta\gamma$ over elliptic flow v_2 would be measured larger in Ru+Ru than Zr+Zr. However, from the recent STAR isobar paper, the Ru+Ru/Zr+Zr ratio of this observable is below unity, which is on the contrary to the initial expectation. The main reason is the multiplicity difference between the two isobars. If we include the multiplicity scaling, namely $N\Delta\gamma/v_2$, then the background baseline would be naively unity. The isobar data are indeed above unity. In order to conclude whether this is evidence for CME, one needs to consider next level background contributions to $N\Delta\gamma/v_2$ from nonflow effects.

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2 $\Delta\gamma$ observable and its nonflow backgrounds

The CME-sensitive observable $\Delta\gamma \equiv C_3/v_2^*$ is defined by

$$C_{3,\mathrm{os}} = \langle \cos(\phi_\alpha^\pm + \phi_\beta^\mp - 2\phi_c) \rangle, \quad C_{3,\mathrm{ss}} = \langle \cos(\phi_\alpha^\pm + \phi_\beta^\pm - 2\phi_c) \rangle, \quad C_3 = C_{3,\mathrm{os}} - C_{3,\mathrm{ss}}, \tag{1}$$

where α, β indicate particles of interest (POI), and c is a reference particle as an estimate of the event plane whose resolution is equal to the elliptic flow v_2^*. The superscripts $+, -$ indicate the charge sign of particles. The subscripts OS, SS stand for opposite-sign and same-sign pairs, respectively. Their difference is taken to cancel charge-independent backgrounds. We have used an asterisk (*) on v_2 to indicate that it is the measured v_2 containing nonflow.

The v_2^* measurement contains flow and nonflow, respectively:

$$v_2^{*2} = v_2^2 + v_{2,\mathrm{nf}}^2, \quad \epsilon_{\mathrm{nf}} \equiv v_{2,\mathrm{nf}}^2 / v_2^2, \tag{2}$$

where ϵ_{nf} denotes their ratio. C_3 is composed of a flow-induced background (major), a 3-particle nonflow correlation (minor), and the possible CME signal [2]. Since we mainly focus on the backgrounds, the CME signal term is not written out:

$$C_3 = \frac{N_{2\mathrm{p}}}{N^2} C_{2\mathrm{p}} v_{2,2\mathrm{p}} v_2 + \frac{N_{3\mathrm{p}}}{2N^3} C_{3\mathrm{p}} = \frac{v_2^2 \epsilon_2}{N} + \frac{\epsilon_3}{N^2}. \tag{3}$$

$C_{2\mathrm{p}} \equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{2\mathrm{p}}) \rangle$ is the 2-particle (2p) nonflow correlations, such as resonance decay daughters with respect to their parent azimuthal angle ($\phi_{2\mathrm{p}}$). $C_{3\mathrm{p}} \equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle_{3\mathrm{p}}$ is the 3-particle (3p) nonflow correlations, such as jets where all the 3 particles are correlated. Thus,

$$\frac{N\Delta\gamma}{v_2^*} = \frac{NC_3}{v_2^{*2}} = \frac{\epsilon_2}{1+\epsilon_{\mathrm{nf}}} + \frac{\epsilon_3}{Nv_2^2(1+\epsilon_{\mathrm{nf}})} = \frac{\epsilon_2}{1+\epsilon_{\mathrm{nf}}} \left(1 + \frac{\epsilon_3/\epsilon_2}{Nv_2^2} \right), \tag{4}$$

where $\epsilon_2 \equiv \frac{N_{2\mathrm{p}} v_{2,2\mathrm{p}}}{N v_2} C_{2\mathrm{p}}$ and $\epsilon_3 \equiv \frac{N_{3\mathrm{p}}}{2N} C_{3\mathrm{p}}$ are short-hand notations. With approximations to leading order, we get the nonflow contributions to the isobar ratio:

$$\begin{aligned} \frac{(N\Delta\gamma/v_2^*)^{\mathrm{Ru}}}{(N\Delta\gamma/v_2^*)^{\mathrm{Zr}}} &\equiv \frac{(NC_3/v_2^{*2})^{\mathrm{Ru}}}{(NC_3/v_2^{*2})^{\mathrm{Zr}}} = \frac{\epsilon_2^{\mathrm{Ru}}}{\epsilon_2^{\mathrm{Zr}}} \cdot \frac{(1+\epsilon_{\mathrm{nf}})^{\mathrm{Zr}}}{(1+\epsilon_{\mathrm{nf}})^{\mathrm{Ru}}} \cdot \frac{\left[1 + \epsilon_3/\epsilon_2/(Nv_2^2)\right]^{\mathrm{Ru}}}{\left[1 + \epsilon_3/\epsilon_2/(Nv_2^2)\right]^{\mathrm{Zr}}} \\ &\approx 1 + \frac{\Delta\epsilon_2}{\epsilon_2} - \frac{\Delta\epsilon_{\mathrm{nf}}}{1+\epsilon_{\mathrm{nf}}} + \frac{\epsilon_3/\epsilon_2/(Nv_2^2)}{1+\epsilon_3/\epsilon_2/(Nv_2^2)} \left(\frac{\Delta\epsilon_3}{\epsilon_3} - \frac{\Delta\epsilon_2}{\epsilon_2} - \frac{\Delta N}{N} - \frac{\Delta v_2^2}{v_2^2} \right). \end{aligned} \tag{5}$$

In the above expression the quantities with Δ are the differences between Ru+Ru and Zr+Zr, while the others refer to those from Zr+Zr (or similarly Ru+Ru). We need those ϵ-terms for an improved background estimate.

3 Nonflow estimates

To get the nonflow in v_2^* measurement, ϵ_{nf}, we perform fit on the 2-particle ($\Delta\eta$, $\Delta\phi$) 2D distribution for ~~middle-central~~ mid-central collisions (Fig. 1). The fit function is given by:

$$\begin{aligned} f(\Delta\eta, \Delta\phi) =& A_1 G_{\mathrm{NS},W}(\Delta\eta) G_{\mathrm{NS},W}(\Delta\phi) + A_2 G_{\mathrm{NS},N}(\Delta\eta) G_{\mathrm{NS},N}(\Delta\phi) + A_3 G_{\mathrm{NS},D}(\Delta\eta) G_{\mathrm{NS},D}(\Delta\phi) \\ &+ \frac{B}{2-|\Delta\eta|} \mathrm{erf}\left(\frac{2-|\Delta\eta|}{\sqrt{2}\sigma_{\Delta\eta,\mathrm{AS}}} \right) G_{\mathrm{AS}}(\Delta\phi \pm \pi) + D G_{\mathrm{RG}}(\Delta\eta) \\ &+ C[1 + 2V_1 \cos(\Delta\phi) + 2V_2 \cos(2\Delta\phi) + 2V_3 \cos(3\Delta\phi)], \end{aligned} \tag{6}$$

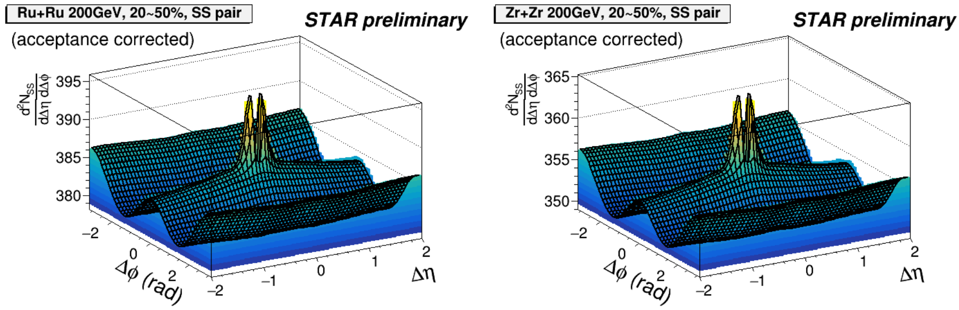

Figure 1. The two-particle $(\Delta\eta, \Delta\phi)$ distributions of SS pairs (left: Ru+Ru; right: Zr+Zr). The POI are from $0.2 < p_T < 2.0$ GeV/c, $|\eta| < 1$. The centrality range is 20–50%, which is defined by cutting on the POI multiplicity. The acceptance is corrected by mixed-event technique.

Table 1. Some of the fit parameters and nonflow calculations.

STAR preliminary		Ru+Ru	Zr+Zr
SS	fit parameter C	381.651 ± 0.011	351.988 ± 0.009
SS	fit parameter $V_2 = v_2^2$	0.0029716 ± 0.0000029	0.0028668 ± 0.0000025
SS	$\langle\cos(2\Delta\phi)\rangle_{ss}$ ($|\Delta\eta| > 0.05$)	0.0035968 ± 0.0000010	0.0034930 ± 0.0000010
inclusive	$\langle\cos(2\Delta\phi)\rangle = v_2^{*2}$ ($|\Delta\eta| > 0.05$)	0.0037161 ± 0.0000007	0.0036088 ± 0.0000007
inclusive	nonflow $U = \langle\cos(2\Delta\phi)\rangle - V_2$	0.0007446 ± 0.0000030	0.0007420 ± 0.0000026
inclusive	$\epsilon_{\rm nf} = U/V_2$	$(25.06 \pm 0.10)\%$	$(25.88 \pm 0.09)\%$

where $G(x)$ are Gaussian functions. The first line has three 2D Gaussians (A-terms) for the nearside (~~NS~~NS) correlations. The first term in the second line is for the awayside (~~AS~~AS) correlations (B-term), whose $\Delta\eta$ projection is an error function divided by a triangle, and whose $\Delta\phi$ projection is a Gaussian centering at $\pm\pi$. The second term in the second line (D-term) is a Gaussian centering at $\Delta\eta = 0$ and independent of $\Delta\phi$ (referred to as the ridge, ~~RG~~RG). The third line is the flow pedestal (C-term), where $V_n = v_n^2$ are the squared "true flows" assumed η-independent. Some of the fit results are listed in Table 1. By comparing the "true flow" from fit (V_2) with the inclusive measurement ($\langle\cos(2\Delta\phi)\rangle$ with a η-gap), we estimate $\epsilon_{\rm nf}$ to be approximately 25%. The dominant contribution is from the A_1-term; ~~taking half of it as systematic uncertainty, we~~ we take half of this term as the systematic uncertainty for $\epsilon_{\rm nf}$, and obtain $\Delta\epsilon_{\rm nf} = (-0.82 \pm 0.13 \mp 0.30)\%$, $-\Delta\epsilon_{\rm nf}/(1+\epsilon_{\rm nf}) = (0.65 \pm 0.11 \pm 0.22)\%$, $\Delta v_2^2/v_2^2 = \Delta V_2/V_2 = (3.7 \pm 0.1 \mp 0.3)\%$.

Due to the large η gap between TPC and ZDC, there is no 3p nonflow correlation between POI and ZDC event plane, so the ϵ_2 can be obtained from ZDC measurements [1]:

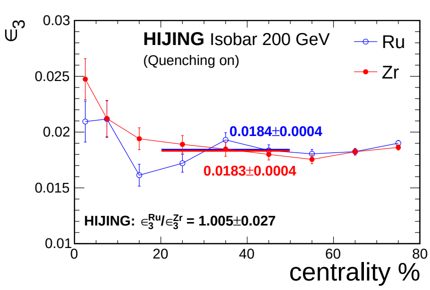

Figure 2. HIJING simulation estimates of ϵ_3.

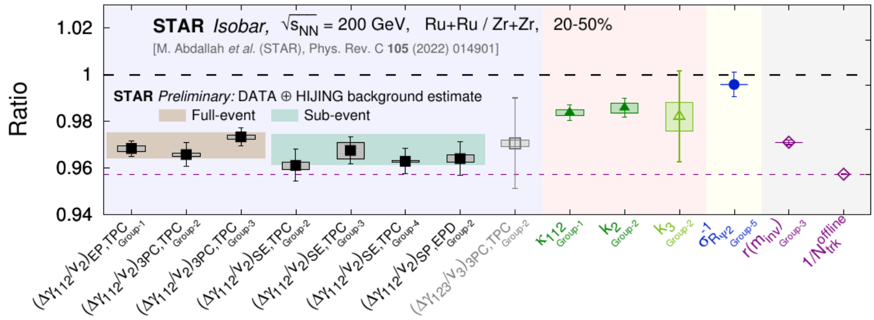

Figure 3. Background estimates with total uncertainties (bands) on the isobar ratio of $\Delta\gamma/v_2$ [1] .

$\epsilon_2 = \frac{N\Delta\gamma\{ZDC\}}{v_2\{ZDC\}} \approx 0.57 \pm 0.04 \pm 0.02$ (where the tracking efficiency efficiency is assumed to be ~80%). For the isobar difference, however, the ZDC precision is too poor: $\Delta\epsilon_2/\epsilon_2 \approx (2.3 \pm 9.2)\%$. If we assume two isobars have similar C_{2p}, then $\epsilon_2 \propto Nr$, where the pair multiplicity difference $r \equiv \frac{N_{os}-N_{ss}}{N_{os}}$ is precisely measured [1]. Thus, the isobar difference can be estimated $\Delta\epsilon_2/\epsilon_2 = \Delta r/r + \Delta N/N = (-2.95 \pm 0.08)\% + 4.4\% = (1.45 \pm 0.08)\%$, which has better precision.

The 3p nonflow ϵ_3 is hard to estimate from data, so we use HIJING model. HIJING does not have ~~flows~~flow, so the only term left should be just the 3p nonflow. From this simulation, we get $\epsilon_3 \approx (1.84 \pm 0.04 \pm 0.92)\%$, while the isobar difference is small (consistent with zero) $\Delta\epsilon_3/\epsilon_3 = (0.5 \pm 2.7)\%$ (Fig. 2). ~~For safety, we~~ We assumed 50% ~~systematical~~ systematic uncertainty for ϵ_3.

With all the estimates above, we finally get by using Eq. ~~5~~(5):

$$\begin{aligned}\frac{(N\Delta\gamma/v_2^*)^{\mathrm{Ru}}}{(N\Delta\gamma/v_2^*)^{\mathrm{Zr}}} &\approx 1+\frac{\Delta\epsilon_2}{\epsilon_2}-\frac{\Delta\epsilon_{\mathrm{nf}}}{1+\epsilon_{\mathrm{nf}}}+\frac{\epsilon_3/\epsilon_2/(Nv_2^2)}{1+\epsilon_3/\epsilon_2/(Nv_2^2)}\left(\frac{\Delta\epsilon_3}{\epsilon_3}-\frac{\Delta\epsilon_2}{\epsilon_2}-\frac{\Delta N}{N}-\frac{\Delta v_2^2}{v_2^2}\right)\\ &=1+(1.45 \pm 0.08)\% + (0.65 \pm 0.11 \pm 0.22)\%\\ &\quad + (0.094 \pm 0.007 \pm 0.048)[(0.5 \pm 2.7) - (1.45 \pm 0.08) - 4.4 - (3.7 \pm 0.1 \pm 0.3)]\%\\ &=1+(1.45 \pm 0.08)\%+(0.65 \pm 0.11 \pm 0.22)\%-(0.85 \pm 0.26 \pm 0.44)\%\\ &=1.013 \pm 0.003 \pm 0.005. \end{aligned} \tag{7}$$

All the above estimates are for the full-event method~~. The sub-event method can follow the same procedure ; we estimate (1.011 ± 0.005 ± 0.005) for the quantity~~ [1]. Following the above procedure for sub-events, we estimate the equivalent of Eq. (7) as (1.011 ± 0.005 ± 0.005). We can plot those nonflow background estimates together with the STAR isobar data in Fig. 3.

4 Summary

This study fits v_2 nonflow from $(\Delta\eta, \Delta\phi)$ distribution, and measures 2p nonflow in C_3 using STAR isobar data [1]. The 3p nonflow in C_3 is evaluated by HIJING simulations. ~~We~~ Using the above information, we obtain an improved ~~isobar background estimate~~ background estimate of isobar ratio $\frac{(N\Delta\gamma/v_2^*)^{\mathrm{Ru}}}{(N\Delta\gamma/v_2^*)^{\mathrm{Zr}}} \approx (1.013 \pm 0.003 \pm 0.005)$ for full-event, and $(1.011 \pm 0.005 \pm 0.005)$ for sub-event.

References

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