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

– a poster for 2022 RHIC/AGS users' meeting

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June 9, 2022

2022 RHIC/AGS ANNUAL USERS' MEETING
From RHIC to EIC
At the QCD Frontiers
This meeting will be held virtually.
June 7–10, 2022

PURDUE UNIVERSITY
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STAR

Abstract

We study nonflow contributions in CME observables from isobar collisions and arrive at a new background estimate for CME.

Supported in part by the U.S. DEPARTMENT OF ENERGY Office of Science

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0. Chiral Magnetic Effect (CME)

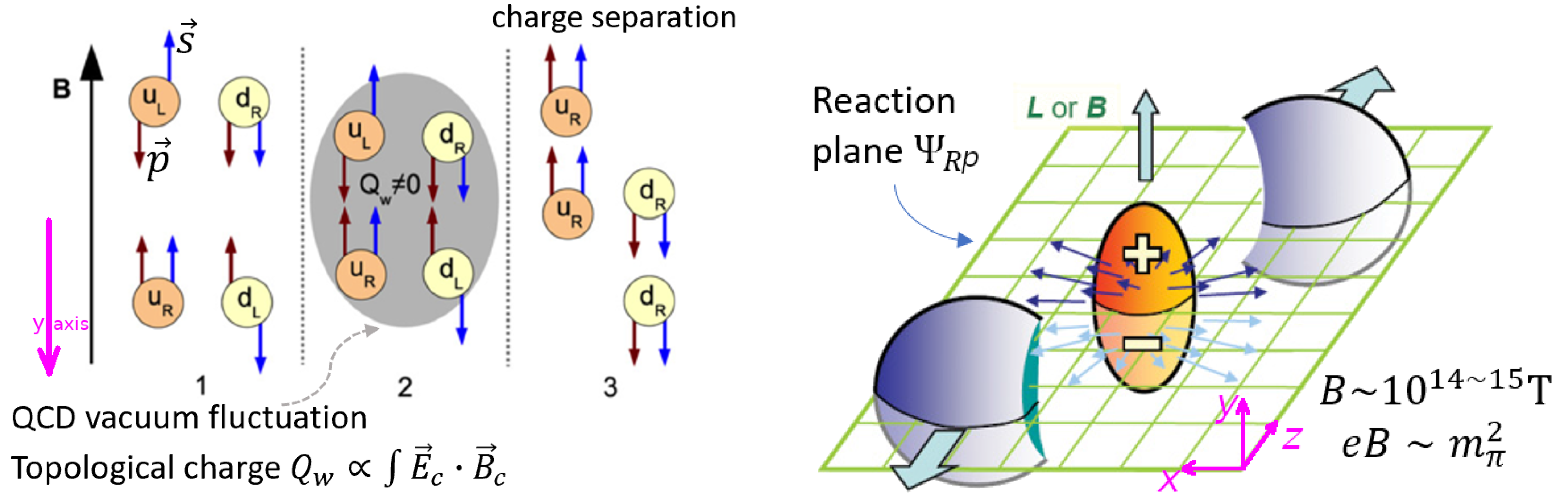

Figure 1: CME schematics. [Kharzeev, McLerran and Warringa, Nucl. Phys. A **803**, 227 (2008)]

QCD vacuum fluctuation → particles with same chirality preference → opposite momenta along $\vec{B}$ for +/− charges, charge separation, CME

noncentral heavy-ion collisions → magnetic field $\vec{B}$ → opposite spins along $\vec{B}$ for +/− charges → opposite momenta along $\vec{B}$ for +/− charges, charge separation, CME

1. $\Delta\gamma$ Observable

- The CME-sensitive observable $\Delta\gamma$ is widely used, $\Delta\gamma \equiv C_3/v_2^*$, where $C_{3,\mathrm{os}} = \langle\cos(\phi_\alpha^\pm + \phi_\beta^\mp - 2\phi_c)\rangle$, $\quad C_{3,\mathrm{ss}} = \langle\cos(\phi_\alpha^\pm + \phi_\beta^\pm - 2\phi_c)\rangle$, $\quad C_3 = C_{3,\mathrm{os}} - C_{3,\mathrm{ss}}$. The subscript OS stands for opposite-sign pair and SS for same-sign pair.
- The asterisk (*) on v_2 indicates it is the measured v_2 containing nonflow.
- $\Delta\gamma$ contains CME and a major background proportional to v_2 (true v_2 flow).

2. Isobar Results

- Isobar expectation: $\Delta\gamma/v_2$ in Ru+Ru is larger than in Zr+Zr.

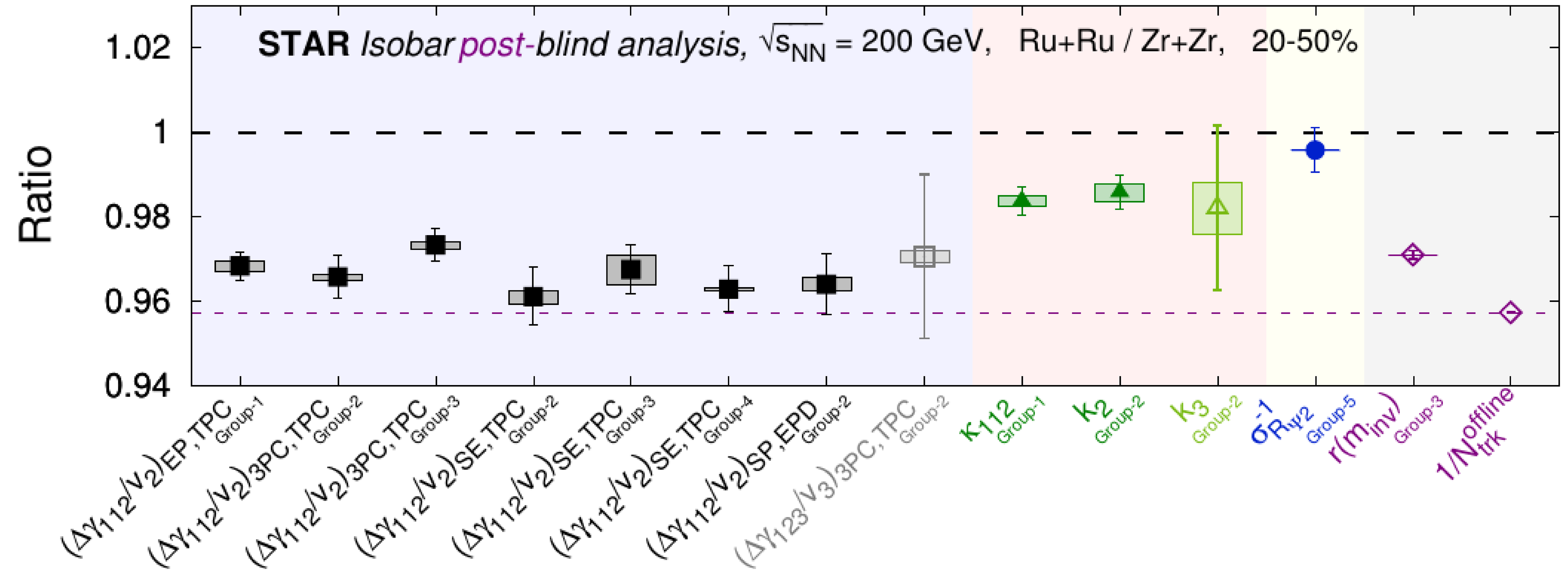

Figure 2: Post-blind results from STAR isobar analysis [STAR, Phys. Rev. C **105**, 014901 (2022)].

- The main reason that the isobar ratio of $\Delta\gamma/v_2$ is less than unity is because of the multiplicity difference.
- The better quantity is $N\Delta\gamma/v_2$. Its naive background baseline is unity.
- Isobar data are above this naive baseline.

3. Nonflow Contribution to Isobar Baseline

- The naive baseline of unity would be correct if there was no nonflow. Nonflow correlations will cause the baseline to deviate from unity.
- We use the letter "ϵ" to denote the nonflow components.
- Nonflow in v_2^*: $\quad v_2^{*2} = v_2^2 + v_{2,\mathrm{nf}}^2, \quad \epsilon_{\mathrm{nf}} \equiv v_{2,\mathrm{nf}}^2/v_2^2$.
- C_3 is composed of flow-induced background (major), 3p nonflow correlations (minor), and possible CME (not written out) [Y. Feng, J. Zhao, H. Li, H. j. Xu and F. Wang, Phys. Rev. C **105**, 024913 (2022)]:

$$C_3 = \frac{C_{2p}N_{2p}}{N^2} v_{2,2p} v_2 + \frac{C_{3p}N_{3p}}{2N^3} = \frac{v_2^2\epsilon_2}{N} + \frac{\epsilon_3}{N^2}, \tag{1}$$

- The CME-sensitive observable $\Delta\gamma$ is $\Delta\gamma = C_3/v_2^*$, and then

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

  - 2-particle (2p) nonflow (e.g., resonance, ...) $C_{2p} \equiv \langle\cos(\phi_\alpha + \phi_\beta - 2\phi_{2p})\rangle$.
  - 3-particle (3p) nonflow (e.g., jets, ...) $C_{3p} \equiv \langle\cos(\phi_\alpha + \phi_\beta - 2\phi_c)\rangle$.
  - $N \approx N_+ \approx N_-$ is POI multiplicity; $N_{2p,3p}$ is 2p (3p) nonflow pair (triplet) multiplicity. (POI stands for particle of interest.)
  - $\epsilon_2 \equiv C_{2p}N_{2p}v_{2,2p}/(Nv_2)$ is the 2p correlation w.r.t. the 2p cluster azimuth and coupled with 2p cluster elliptic flow.
  - $\epsilon_3 \equiv C_{3p}N_{3p}/(2N)$ is the 3p correlation within the correlated triplet.

- Isobar ratio: (where notation $\Delta X = X^{\mathrm{Ru}} - X^{\mathrm{Zr}}$)

$$\frac{(N\Delta\gamma/v_2^*)^{\mathrm{Ru}}}{(N\Delta\gamma/v_2^*)^{\mathrm{Zr}}} \equiv \frac{(NC_3/v_2^{*2})^{\mathrm{Ru}}}{(NC_3/v_2^{*2})^{\mathrm{Zr}}} \approx \frac{\epsilon_2^{\mathrm{Ru}}}{\epsilon_2^{\mathrm{Zr}}} \cdot \frac{(1+\epsilon_{\mathrm{nf}})^{\mathrm{Zr}}}{(1+\epsilon_{\mathrm{nf}})^{\mathrm{Ru}}} \cdot \frac{[1+\epsilon_3/\epsilon_2/(Nv_2^2)]^{\mathrm{Ru}}}{[1+\epsilon_3/\epsilon_2/(Nv_2^2)]^{\mathrm{Zr}}}$$
$$\approx 1 + \frac{\Delta\epsilon_2}{\epsilon_2} - \frac{\Delta\epsilon_{\mathrm{nf}}}{1+\epsilon_{\mathrm{nf}}} + \frac{\epsilon_3/\epsilon_2/(Nv_2^2)}{1+\epsilon_3/\epsilon_2/(Nv_2^2)}\left(\frac{\Delta\epsilon_3}{\epsilon_3} - \frac{\Delta\epsilon_2}{\epsilon_2} - \frac{\Delta N}{N} - \frac{\Delta v_2^2}{v_2^2}\right) \tag{3}$$

- Need ϵ_{nf}, ϵ_2, ϵ_3 for a new background estimate.

4. Nonflow Estimates

a) Nonflow to v_2^*–measurement of ϵ_{nf}

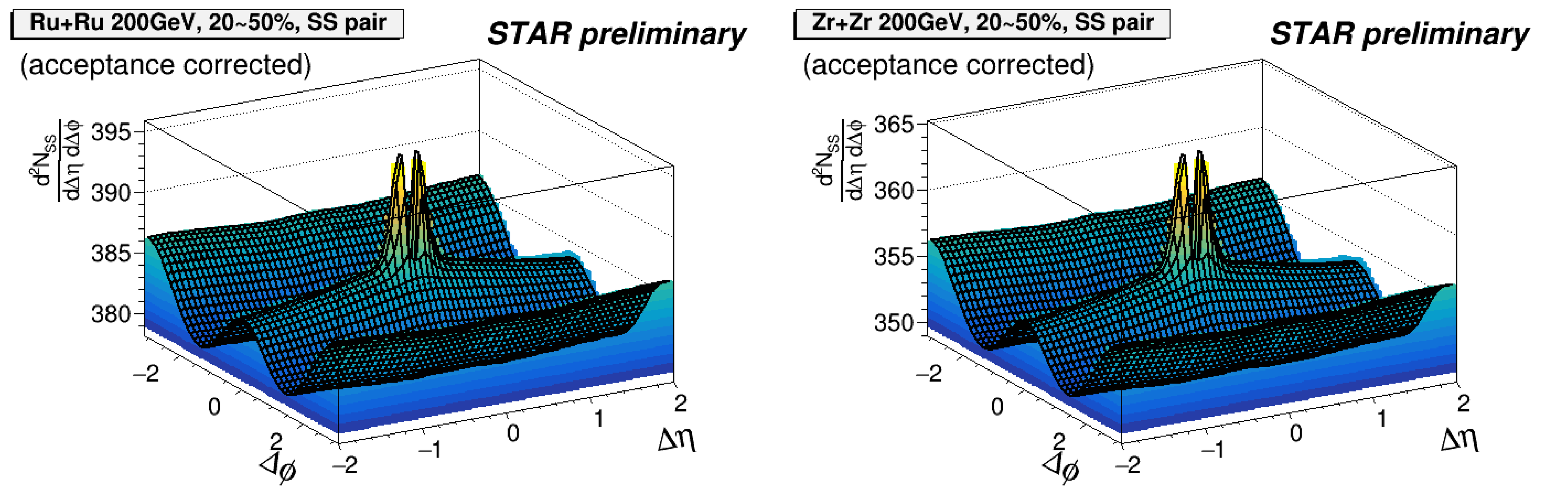

Figure 3: The two-particle $(\Delta\eta, \Delta\phi)$ distributions of SS pairs (left: Ru+Ru; right: Zr+Zr). The POI are from $0.2 < p_T < 2.0$ GeV/c, $|\eta| < 1$. The centrality range is $20 - 50\%$, which is defined by the POI multiplicity. The acceptance is corrected by mixed-event technique.

- Fit function $f(\Delta\eta, \Delta\phi)$

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

$G_s(x)$ Gaussian function, $V_n = v_n^2$ assumed η-independent.
NS–nearside, AS–awayside, RG–ridge; W–wide, N–narrow, D–dip.

	STAR preliminary	Ru+Ru	Zr+Zr
SS	fit parameter C	381.651 ± 0.011	351.988 ± 0.009
	fit parameter $V_2 = v_2^2$	0.002972 ± 0.000003	0.002867 ± 0.000003
	$\langle\cos(2\Delta\phi)\rangle_{\mathrm{SS}}$ $(|\Delta\eta| > 0.05)$	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
	nonflow $U = \langle\cos(2\Delta\phi)\rangle - V_2$	0.000745 ± 0.000003	0.000742 ± 0.000003
	$\epsilon_{\mathrm{nf}} = U/V_2$	$(25.06 \pm 0.10)\%$	$(25.88 \pm 0.09)\%$

- If the nearside wide Gaussian (A_1 term) is counted into "true" flow, $(v_2^2)^{\mathrm{Ru}} = 0.003489$, $(v_2^2)^{\mathrm{Zr}} = 0.003381$, $\epsilon_{\mathrm{nf}}^{\mathrm{Ru}} = 6.50\%$, $\epsilon_{\mathrm{nf}}^{\mathrm{Zr}} = 6.73\%$.
  Half of this difference from the default is counted as systematic uncertainty.
  $\Delta\epsilon_{\mathrm{nf}} = (-0.82 \pm 0.13 \mp 0.30)\%$, $-\Delta\epsilon_{\mathrm{nf}}/(1+\epsilon_{\mathrm{nf}}) = (0.65 \pm 0.11 \pm 0.22)\%$.
  $\Delta v_2^2/v_2^2 = \Delta V_2/V_2 = (3.7 \pm 0.1 \mp 0.3)\%$.

b) Estimate of $\Delta\epsilon_2/\epsilon_2$

- ϵ_2 can be obtained from ZDC measurement (no nonflow, assuming negligible CME) [STAR, Phys. Rev. C **105**, 014901 (2022)]
  $\epsilon_2 = \frac{N\Delta\gamma\{\mathrm{ZDC}\}}{v_2\{\mathrm{ZDC}\}} \approx 0.57 \pm 0.04 \pm 0.02$ (tracking efficiency $\sim 80\%$) and $\Delta\epsilon_2/\epsilon_2 \approx (2.3 \pm 9.2)\%$. The $\Delta\epsilon_2$ precision is too poor.
- AMPT simulation w.r.t. reaction plane gives $\Delta\epsilon_2/\epsilon_2 \approx (3.5 \pm 1.4)\%$.
- However, the pair multiplicity difference $r \equiv (N_{\mathrm{OS}} - N_{\mathrm{SS}})/N_{\mathrm{OS}}$ is relatively precisely measured [STAR, Phys. Rev. C **105**, 014901 (2022)].
  Assuming $C_{2p}^{\mathrm{Ru}} = C_{2p}^{\mathrm{Zr}}$, then $\epsilon_2 \propto Nr$, and
  $\Delta\epsilon_2/\epsilon_2 = \Delta r/r + \Delta N/N = (-2.95 \pm 0.08)\% + 4.4\% = (1.45 \pm 0.08)\%$.

c) Estimate of $\Delta\epsilon_3/\epsilon_3$

- We use HIJING simulation to obtain $\epsilon_3 \approx (1.84 \pm 0.04)\%$, and $\Delta\epsilon_3/\epsilon_3 = (0.5 \pm 2.7)\%$ ($\sim 8.6 \times 10^8$ events for each isobar).
- We assume 50% systematic uncertainty for ϵ_3 ($\pm 0.92\%$), and assume $\Delta\epsilon_3/\epsilon_3$ is presently dominated by statistics.
- HIJING without jet quenching gives $\epsilon_3 = (2.24 \pm 0.05)\%$, differing from the default by 22%, suggesting 50% systematics a safe guesstimate.

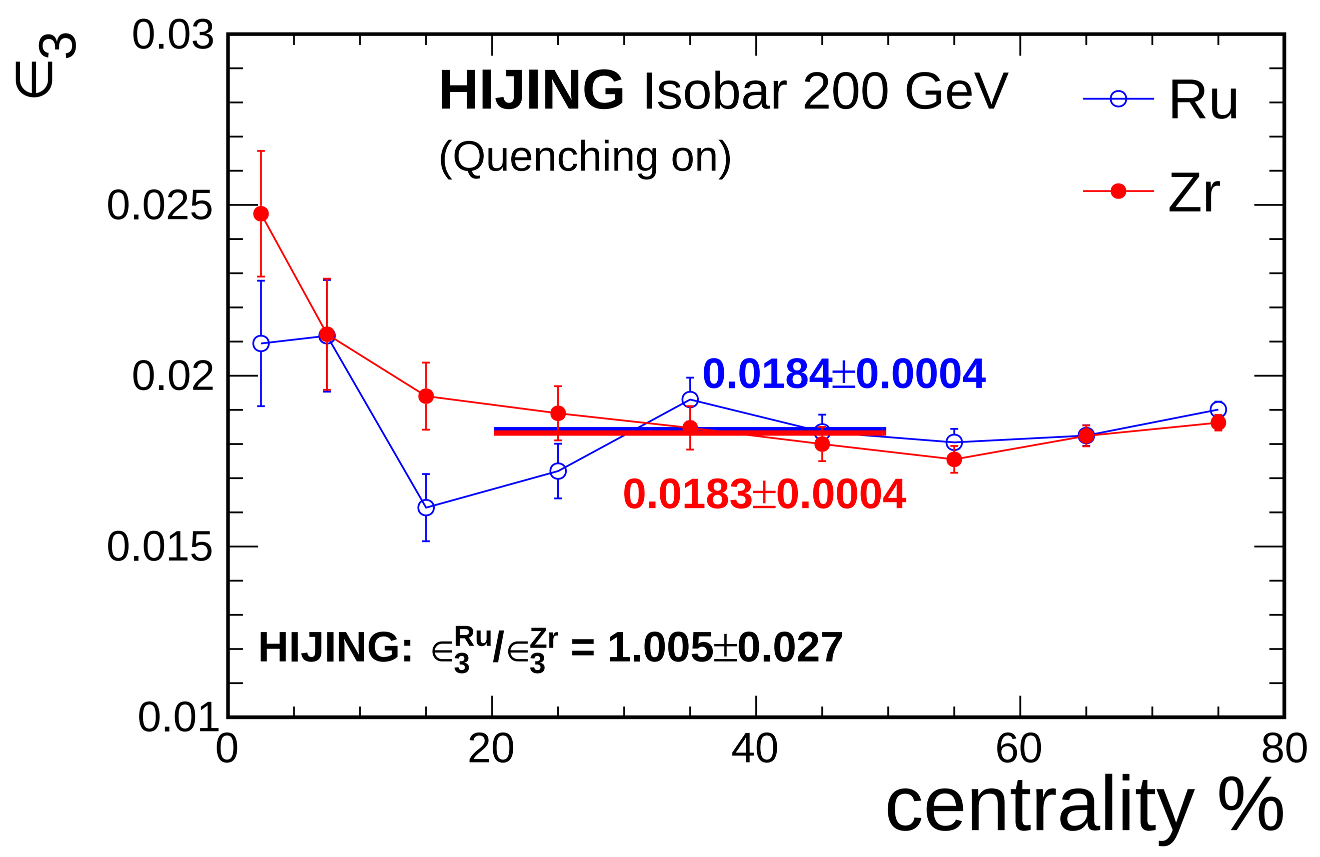

Figure 4: HIJING simulation estimates ϵ_3.

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5. Estimated Background Level For Isobar $N\Delta\gamma/v_2$ Ratio

* Except this column, all numbers on this poster refer to those for full-event.

Quantity		Method	Systematic uncertainty	Full-event value	Sub-event value*
Multiplicity $\Delta N/N$	Measured		Negligible	4.4%	4.4%
Flow $\Delta v_2^2/v_2^2$	Measured	Nonflow subtracted as per below	From nonflow syst.	$\Delta v_2^2/v_2^2 = (3.7 \pm 0.1 \pm 0.3)\%$	$\Delta v_2^2/v_2^2 = (3.7 \pm 0.1 \pm 0.3)\%$
v_2 nonflow	Measured	$(\Delta\eta, \Delta\phi)$ correlations, experimentally measured	Nonflow$\sim 25\%$ (full event), dominated by NS wide Gaus; consider $\pm 1/2$ WG as syst. uncertainty	$-\Delta\epsilon_{\text{nf}} = (0.82 \pm 0.13 \pm 0.30)\%$ $\frac{-\Delta\epsilon_{\text{nf}}}{1+\epsilon_{\text{nf}}} = (0.65 \pm 0.11 \pm 0.22)\%$	$-\Delta\epsilon_{\text{nf}} = (0.59 \pm 0.15 \pm 0.27)\%$ $\frac{-\Delta\epsilon_{\text{nf}}}{1+\epsilon_{\text{nf}}} = (0.48 \pm 0.12 \pm 0.22)\%$
v_2-induced bkgd: $\epsilon_2 = N\Delta\gamma/v_2$	Measured	Measured by ZDC (assume negligible CME)	Small	$\epsilon_2 = (0.57 \pm 0.04 \pm 0.02)\%$	$\epsilon_2 = (0.79 \pm 0.05 \pm 0.01)\%$
v_2-induced bkgd difference: $\frac{\Delta\epsilon_2}{\epsilon_2} \sim \frac{\Delta(N_{2\text{p}}/N)}{(N_{2\text{p}}/N)} = \frac{\Delta(rN)}{rN}$	Measured	$r = (N_{\text{OS}} - N_{\text{SS}})/N_{\text{OS}}$ experimentally measured	Negligible	$\frac{\Delta\epsilon_2}{\epsilon_2} = (1.45 \pm 0.08)\%$	$\frac{\Delta\epsilon_2}{\epsilon_2} = (1.45 \pm 0.08)\%$
3p contribution to C_3: $\epsilon_3 = C_{3\text{p}}N_{3\text{p}}/(2N)$	Model estimate	HIJING simulations quenching-on	Quenching-on and off difference$\sim 20\%$. Take $\pm 50\%$ as syst. uncertainty	$\epsilon_3 = (1.84 \pm 0.04 \pm 0.92)\%$	$\epsilon_3 = (1.91 \pm 0.09 \pm 0.95)\%$
3p contribution difference: $\Delta\epsilon_3/\epsilon_3$	Model estimate	HIJING simulation quenching-on	Assumed negligible relative to the large stat. uncertainty	$\frac{\Delta\epsilon_3}{\epsilon_3} = (0.5 \pm 2.7)\%$ $\frac{\epsilon_3/\epsilon_2}{Nv_2^2} = 0.104 \pm 0.008 \pm 0.053$	$\frac{\Delta\epsilon_3}{\epsilon_3} = (-1.8 \pm 6.3)\%$ $\frac{\epsilon_3/\epsilon_2}{Nv_2^2} = 0.079 \pm 0.006 \pm 0.040$
background estimate				$1.013 \pm 0.003 \pm 0.005$	$1.011 \pm 0.005 \pm 0.005$

- The numerical value of Eq. 3 (for full-event method as example) can thus be estimated as follows:

$$\frac{(N\Delta\gamma/v_2^*)^{\text{Ru}}}{(N\Delta\gamma/v_2^*)^{\text{Zr}}} \approx 1 + (1.45 \pm 0.08)\% + (0.65 \pm 0.11 \pm 0.22)\% + (0.094 \pm 0.007 \pm 0.048)[(0.5 \pm 2.7)\% - (1.45 \pm 0.08)\% - 4.4\% - (3.7 \pm 0.1 \pm 0.3)\%]$$
$$= 1 + (1.45 \pm 0.08)\% + (0.65 \pm 0.11 \pm 0.22)\% - (0.85 \pm 0.26 \pm 0.44)\% = 1.013 \pm 0.003 \pm 0.005 \quad (4)$$

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6. Summary and Outlook

- v_2 nonflow and 2p nonflow are measured. 3p nonflow is estimated by HIJING. Large degree of cancellation between 2p and 3p nonflow.
- New preliminary isobar background estimate $\frac{(N\Delta\gamma/v_2^*)^{\text{Ru}}}{(N\Delta\gamma/v_2^*)^{\text{Zr}}} \approx (1.013 \pm 0.003 \pm 0.005)$ for full-event, $(1.011 \pm 0.005 \pm 0.005)$ for sub-event.
- ϵ_3 estimate in a data-driven way in future?

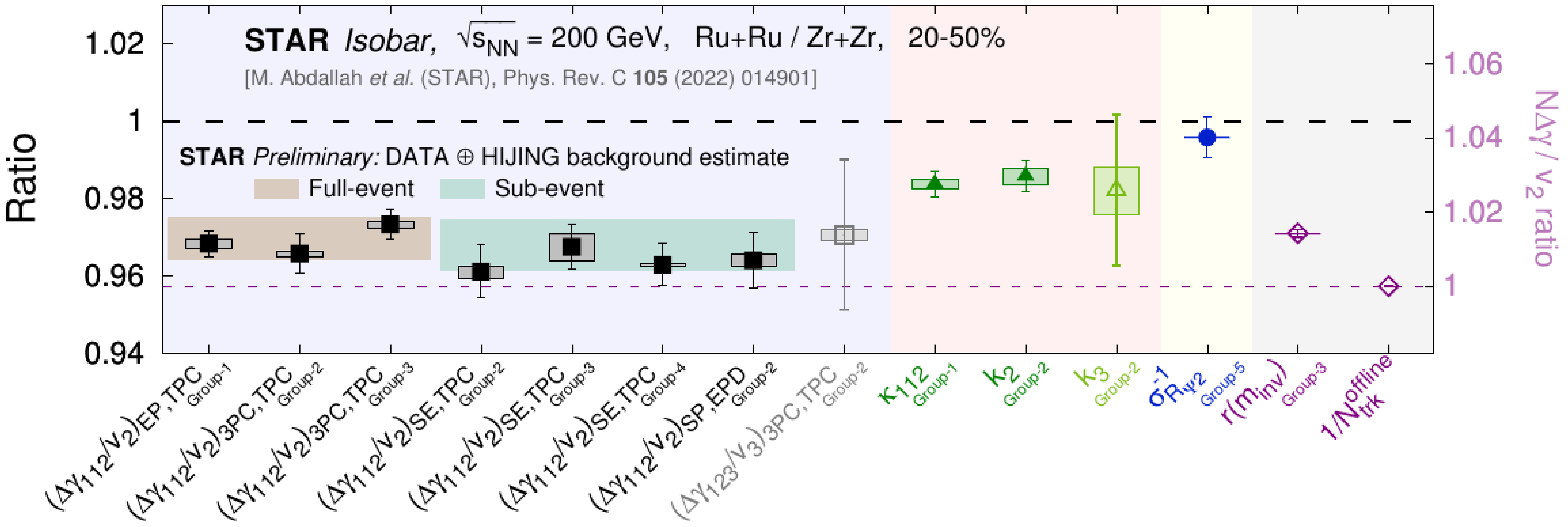

Figure 5: Background estimate in brown on the isobar Ru/Zr ratio of $\Delta\gamma/v_2$ from STAR isobar analysis [STAR, Phys. Rev. C **105**, 014901 (2022)].

The STAR Collaboration,
https://drupal.star.bnl.gov/STAR/presentations