STAR

# Experimental Investigations of Chiral Magnetic Effects


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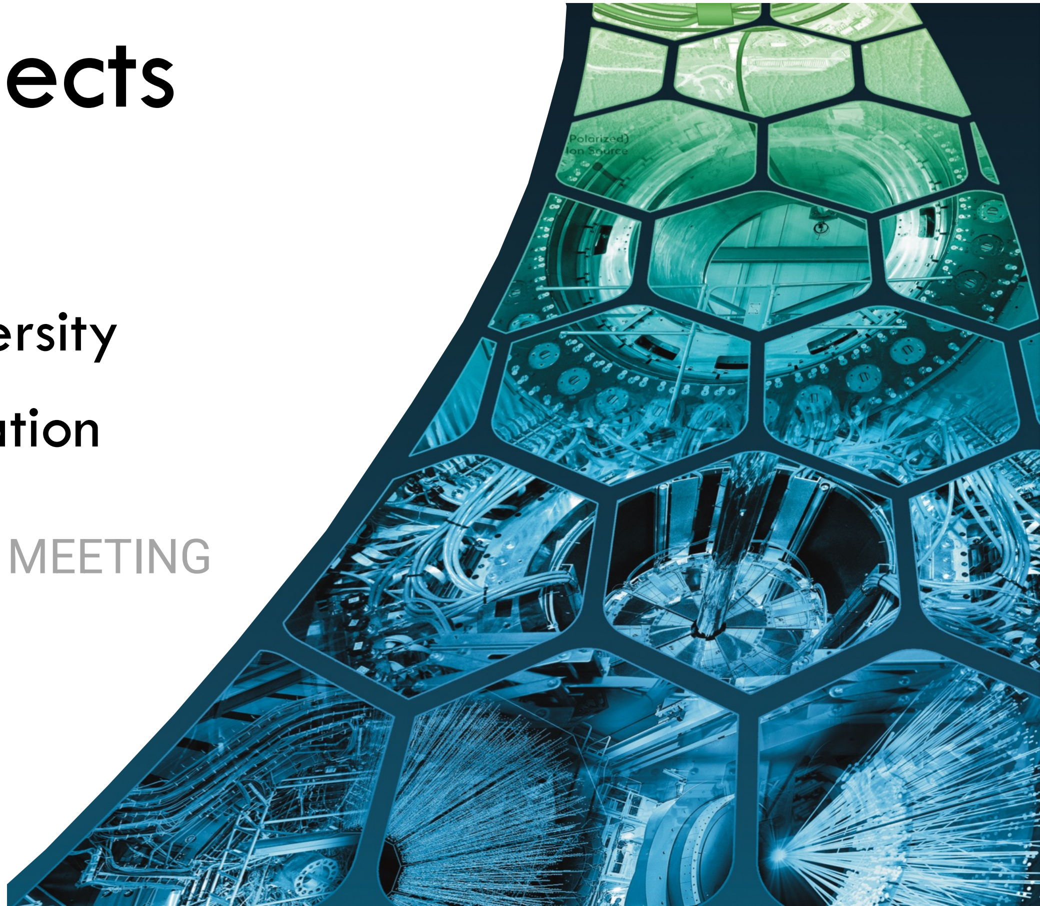
for the STAR Collaboration


2022 RHIC/AGS ANNUAL USERS' MEETING

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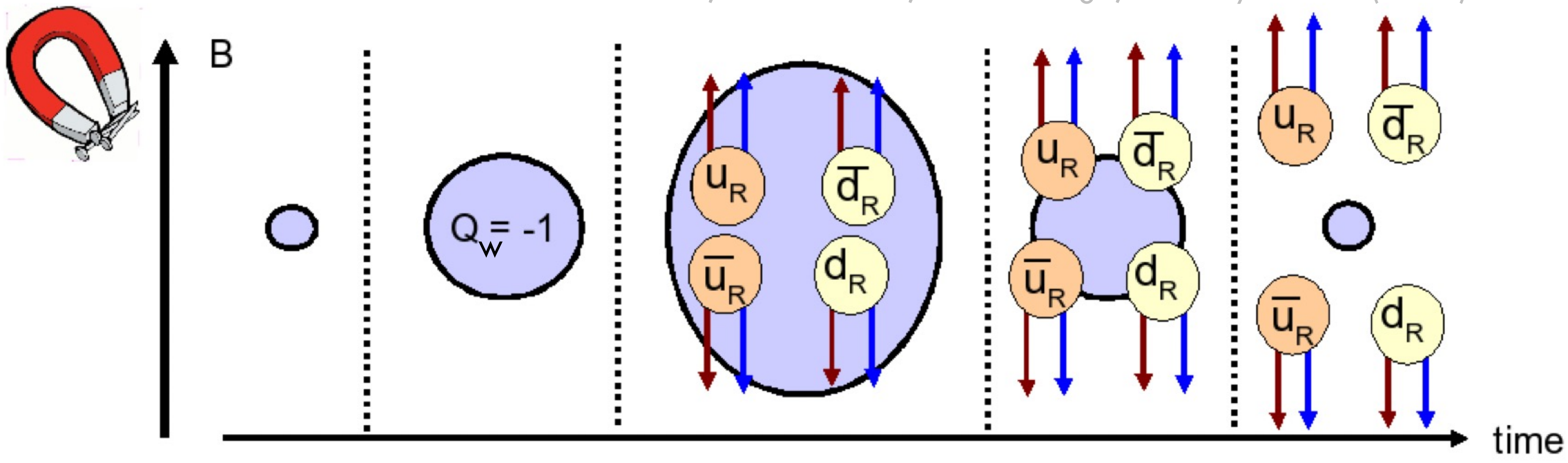
SCSU

# Chiral Magnetic Effect

D E Kharzeev, L D McLerran, H J Warringa, Nucl Phys A 803 (2008)

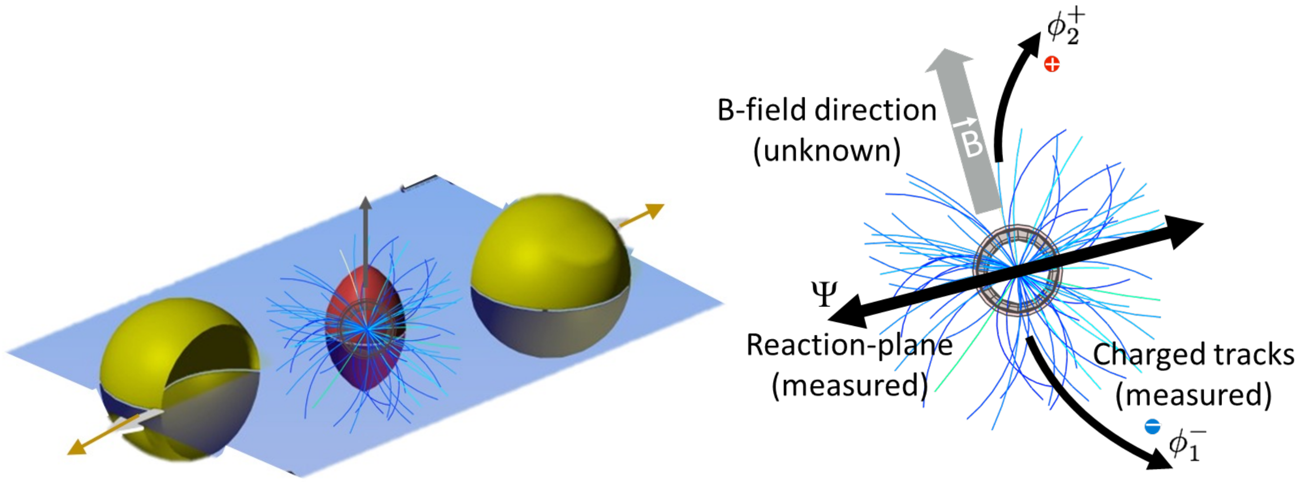



1) Chirality imbalance among all light quark flavor from topological fluctuations of gluon fields $(N_L^f - N_R^f) = 2Q_w$ i.e. "Local Parity Violation"

2) Large magnetic field, generated mostly by spectator protons

Combine to give the CME: net electric charge flow along (or opposite to, depending on sign of $Q_w$ in this event) the magnetic field direction

# CME Sensitive Observables : $\Delta\gamma$

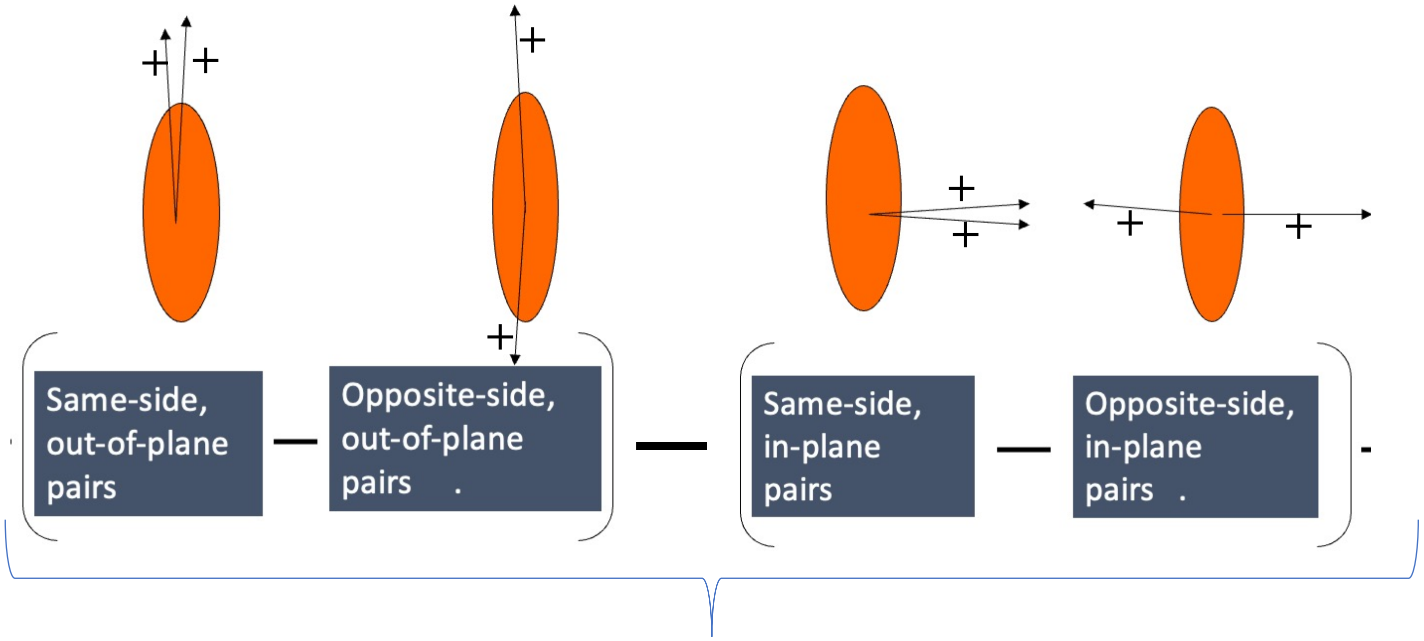



S. A. Voloshin, Phys. Rev. C 70, 057901 (2004)

$$\gamma^{\alpha,\beta} \equiv \langle cos(\phi^\alpha + \phi^\beta - 2\psi_2)\rangle$$

$$\Delta\gamma = \gamma^{OS} - \gamma^{SS}$$

2nd order event plane (1st order adds no more information here)!

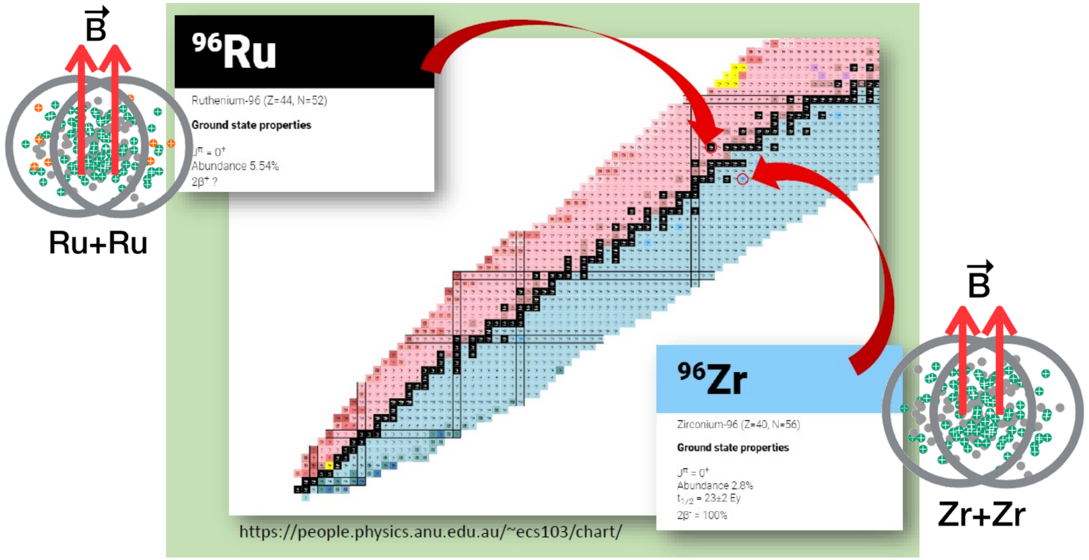



$\Delta\gamma$ : Same-sign pairs – Opposite-sign pairs

Key backgrounds:

- $v_2$+(clusters, local charge conservation)
- 3-particle correlations

# Experimental Search With Isobar Collisions




$$\Delta\gamma = \Delta\gamma^{CME} + k\frac{v_2}{N} + \Delta\gamma^{non-flow}$$

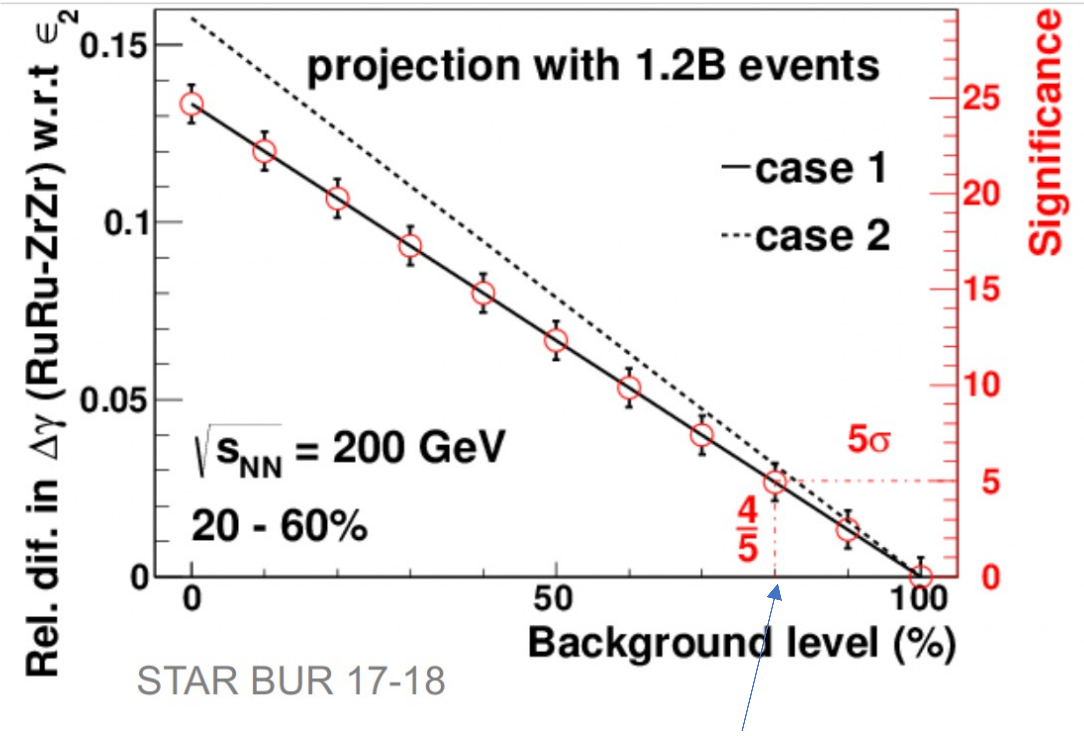
Measurement | Signal | "Flowing Clusters" Background | Smaller backgrounds

$$\Delta\gamma^{Ru+Ru} = \Delta\gamma^{CME} + k\frac{v_2}{N} + \Delta\gamma^{non-flow}$$

$$\neq \quad \approx \quad \approx$$

$$\Delta\gamma^{Zr+Zr} = \Delta\gamma^{CME} + k\frac{v_2}{N} + \Delta\gamma^{non-flow}$$

$B^2$ is ~15% different




$f_{CME}$=20%


S. A. Voloshin, Phys. Rev. C70 (2004) 057901; S. A. Voloshin, Phys. Rev. Lett. 105 (2010) 172301; W.-T. Deng, et al Phys. Rev. C94 (2016) 041901; Khachatryan Vet al.(CMS) Phys. Rev. Lett.118 (2017) 122301; Adam J et al.(STAR) Phys. Lett. B 798 (2019) 134975

# Details of Isobar Blind Analysis

J. Adam *et al.* (STAR) Nucl. Sci. Tech. 32 (2021) 48

**STEP-0**
**Mock Data challenge**
Test data structure
(Au+Au data)
~2 months

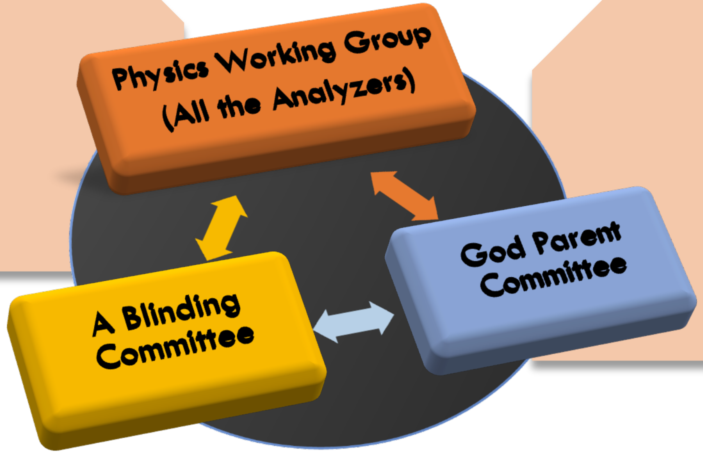
**STEP-1**
**Isobar Mixed Analysis**
Code freezing
(Each run is Ru+Ru & Zr+Zr)
~1 year

**STEP-2**
**Isobar Blind analysis**
QA with ~ 1% data
(Each run is Ru+Ru or Zr+Zr)
~1/2 year

**STEP-3**
**Isobar Unblind analysis**
Final analysis
(Ru+Ru & Zr+Zr separated)
~2-3 months

**Blind analyses (5 groups):**
- $\Delta\gamma, \Delta\delta$ *and* κ
- $\Delta\gamma, \Delta\delta, \Delta\gamma(\Delta\eta)$
- $\Delta\gamma$ *in* $\mathrm{PP/SP}$, $\Delta\gamma(M_{inv})$
- $\Delta\gamma$ *in* $\mathrm{PP/SP}$
- $R(\Delta S)$ Correlator.

Connections between the methods are studied



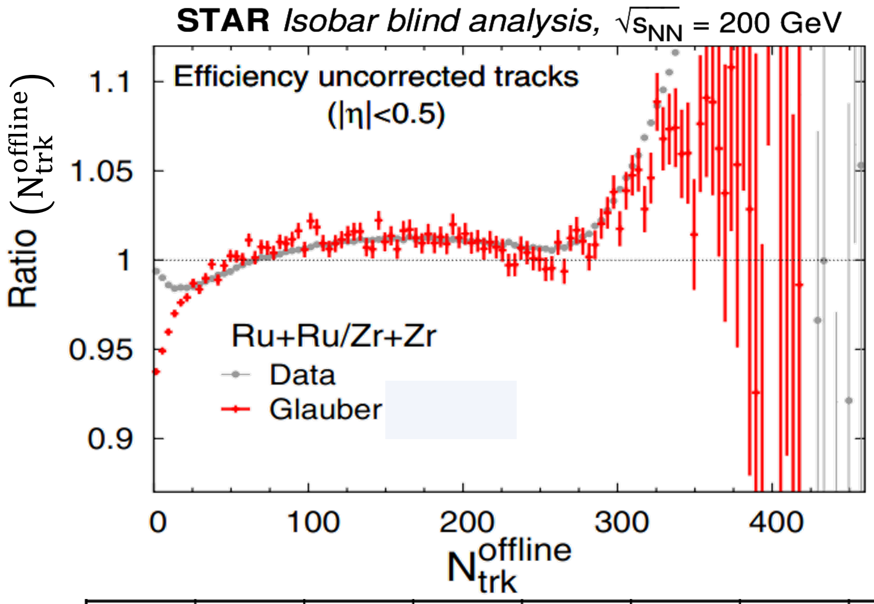

**Using the frozen code from STEP-1:**
- Sensitivity of observables tested using AVFD simulation
- Similar sensitivities are found in all observables

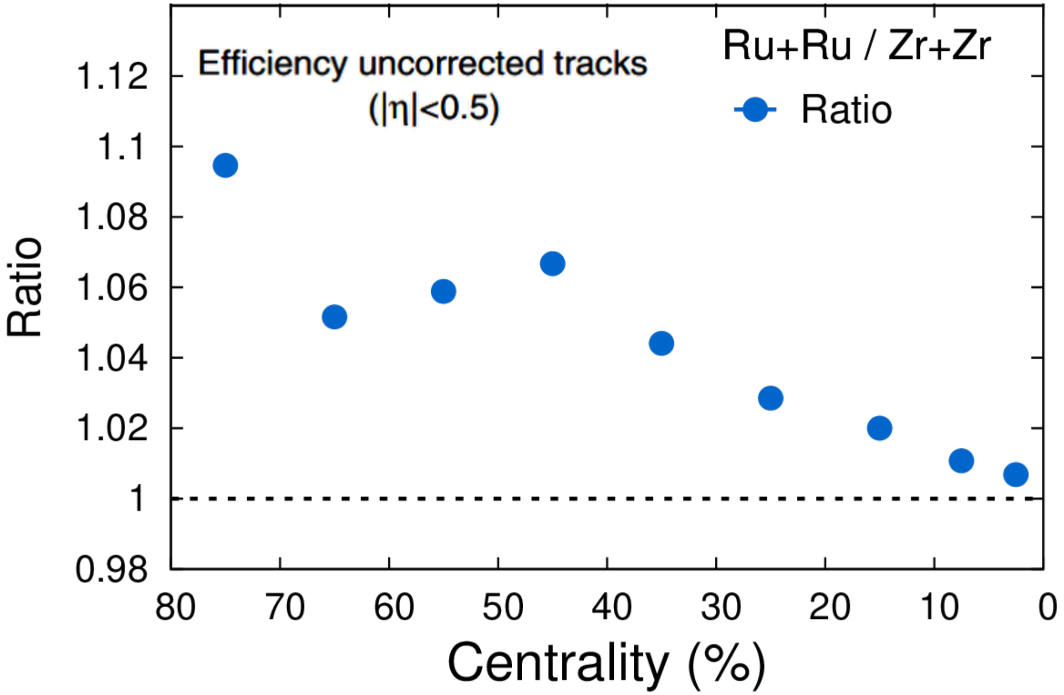
S. Choudhury *et al.* Chin. Phys. C, 46 (2022) 014101

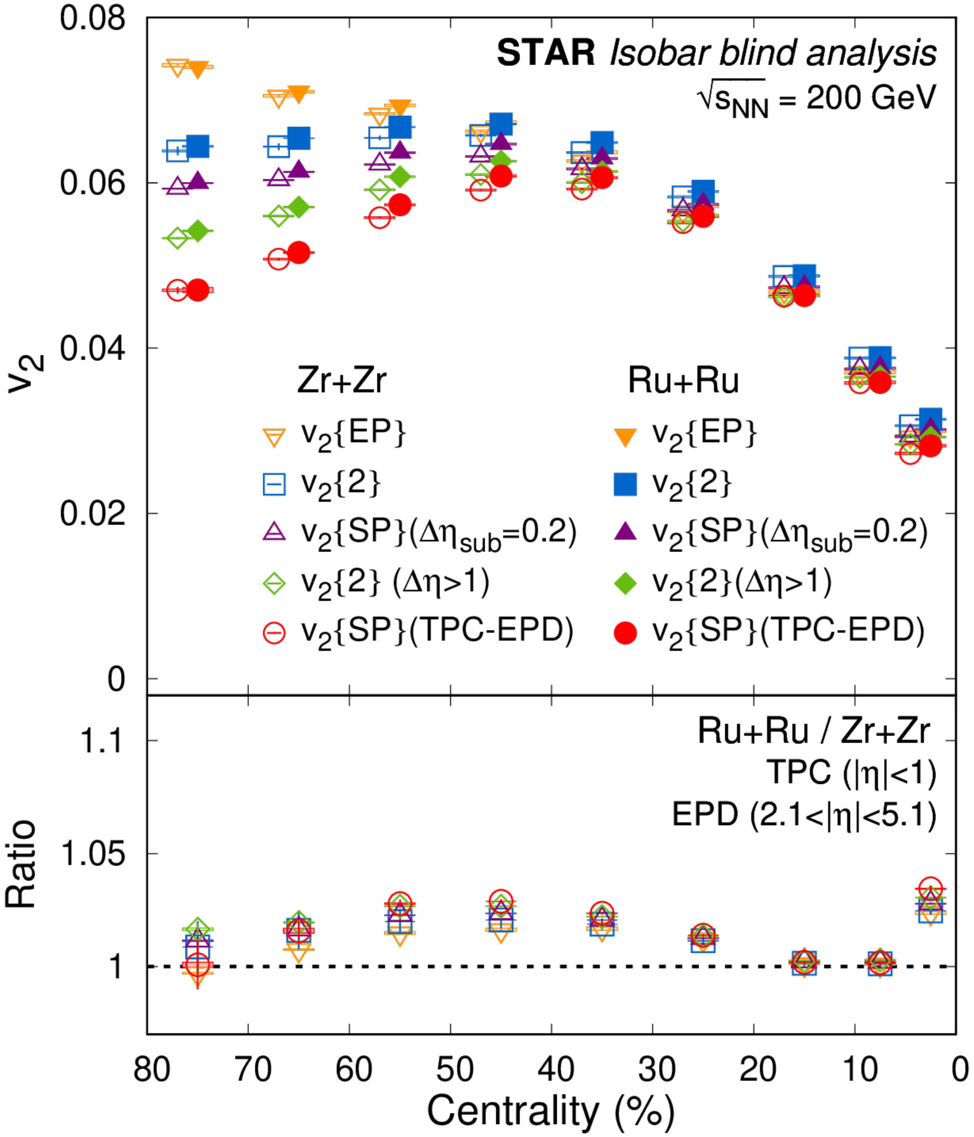
A large, collective effort

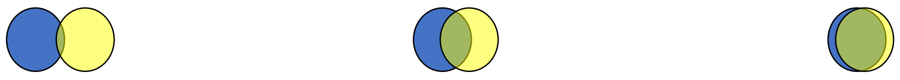
# Isobars: Multiplicity and $v_2$

M. S. Abdallah *et al.* (STAR) Phys. Rev. C, 105 (2022) 014901

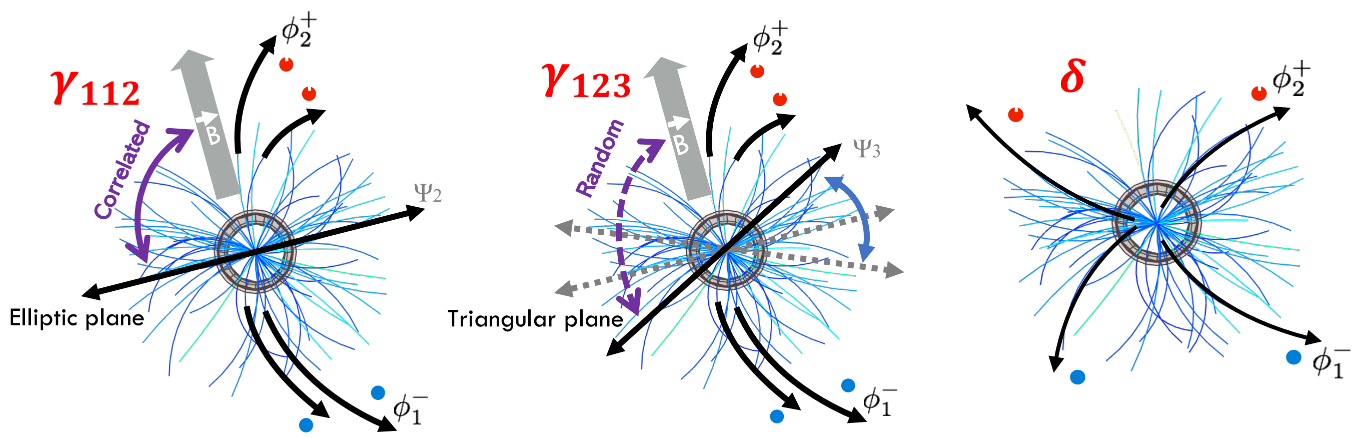


# Isobar: $\Delta\gamma$ Measurement Using Full TPC




$$\gamma_{112} \equiv \left\langle \cos\left(\Phi_1(\eta_1) + \Phi_2(\eta_2) - 2\psi_2^{|\eta|<1}\right)\right\rangle$$

$$\gamma_{123} \equiv \left\langle \cos\left(\Phi_1(\eta_1) + 2\Phi_2(\eta_2) - 3\psi_3^{|\eta|<1}\right)\right\rangle$$

$$\delta = \langle \cos(\Phi_1 - \Phi_2)\rangle$$

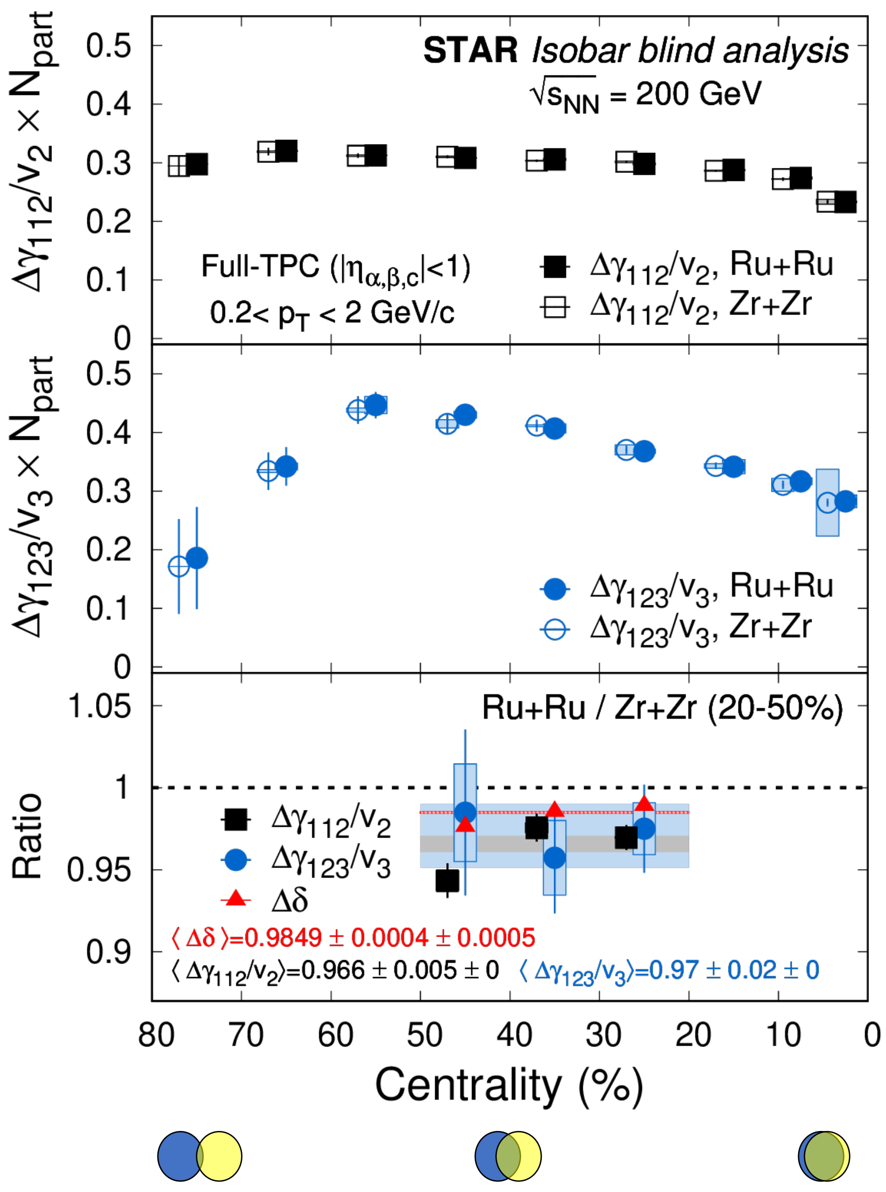
**Pre-defined CME criteria:**

$$\frac{(\Delta\gamma_{112}/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{112}/v_2)^{\mathrm{Zr+Zr}}} > 1$$

$$\frac{(\Delta\gamma_{112}/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{112}/v_2)^{\mathrm{Zr+Zr}}} > \frac{(\Delta\gamma_{123}/v_3)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{123}/v_3)^{\mathrm{Zr+Zr}}}$$

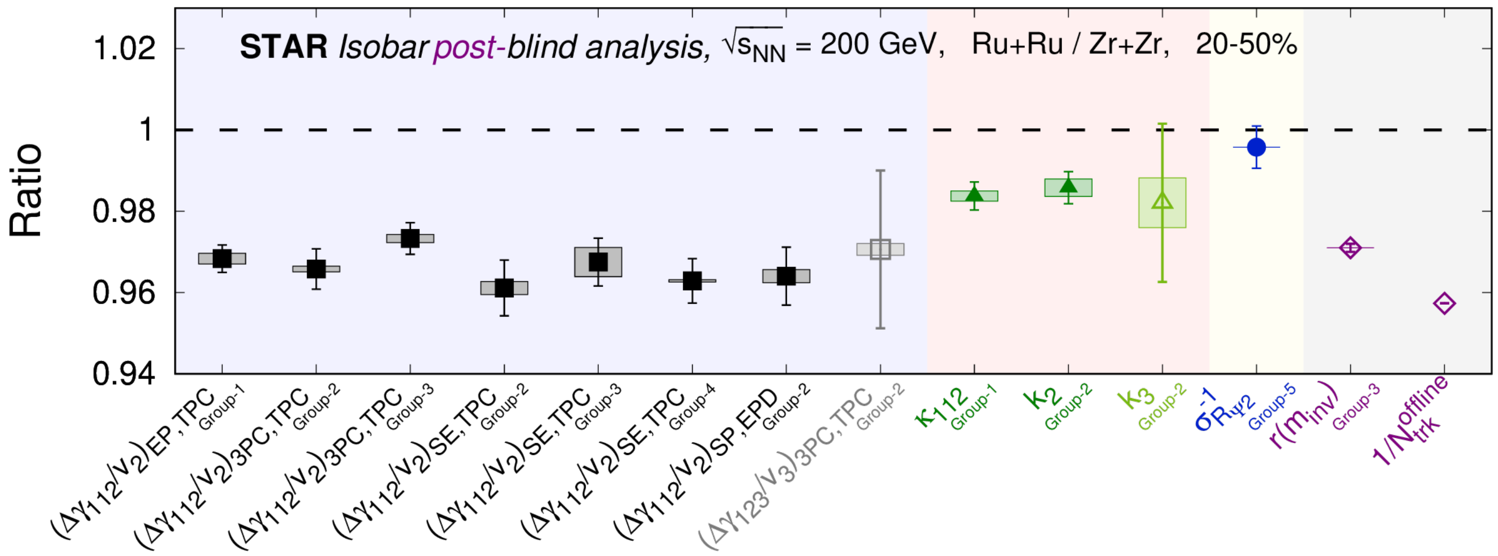
$$\frac{(\Delta\gamma_{112}/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{112}/v_2)^{\mathrm{Zr+Zr}}} > \frac{(\Delta\delta)^{\mathrm{Ru+Ru}}}{(\Delta\delta)^{\mathrm{Zr+Zr}}}$$

Data not consistent with pre-defined CME criteria



M. S. Abdallah *et al.* (STAR) Phys. Rev. C, 105 (2022) 014901

# Summary of the Isobar Blind Analysis




## From the blind analysis

- No pre-defined criterion is satisfied for the observation of CME
- Precision of 0.4% is reached in the ratio of observables between the two systems.
- $\Delta\gamma/v_2$ ratios are below unity - mainly driven by the multiplicity difference between the two isobars

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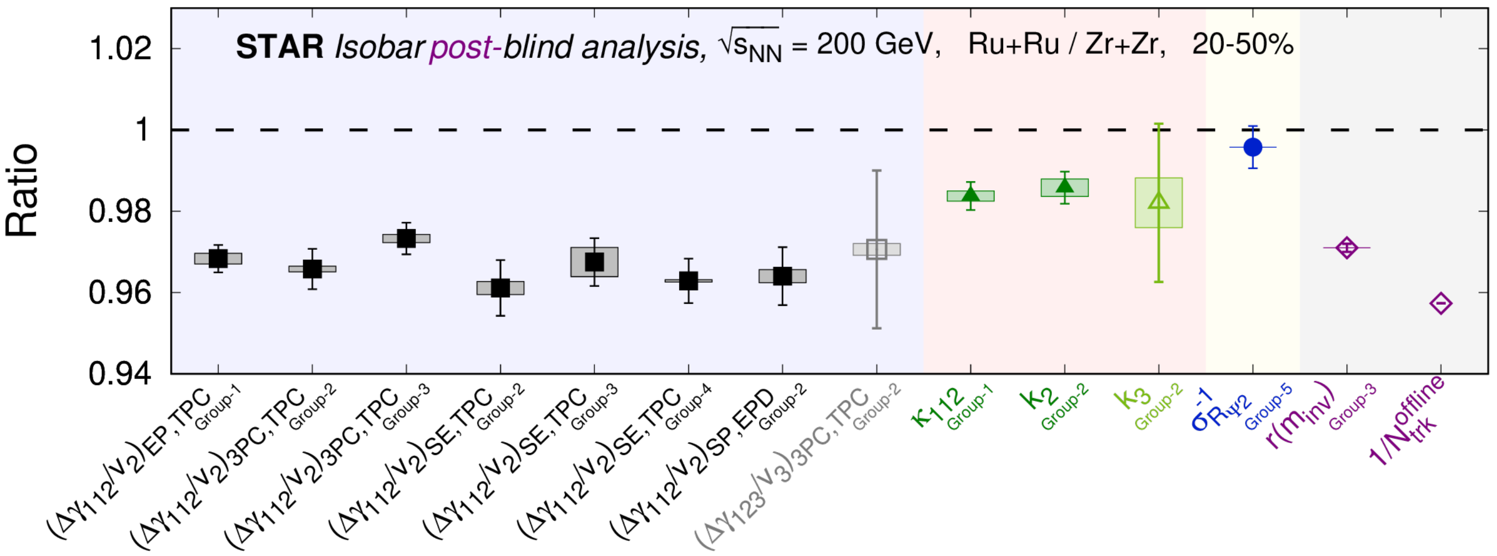
M. S. Abdallah *et al.* (STAR) Phys. Rev. C, 105 (2022) 014901

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**Important post-blinding points:**

If background comes from flowing clusters, we'd expect $\Delta\gamma/v_2$ to scale as 1/N (with some caveats…)

See STAR poster by Yicheng Feng

Additional Correction: (PRELIMINARY)

$$\frac{(N\Delta\gamma/v_2^*)^{Ru}}{(N\Delta\gamma/v_2^*)^{Zr}} \approx 1 + \frac{\Delta\epsilon_2}{\epsilon_2} - \frac{\Delta\epsilon_{nf}}{1+\epsilon_{nf}} + \frac{\epsilon_3/\epsilon_2/(Nv_2^2)}{1+\epsilon_3/\epsilon_2/(Nv_2^2)}\left(\frac{\Delta\epsilon_3}{\epsilon_3} - \frac{\Delta\epsilon_2}{\epsilon_2} - \frac{\Delta N}{N} - \frac{\Delta v_2^2}{v_2^2}\right)$$

$$\epsilon_2 = \langle\cos(\phi_a + \phi_b - 2\phi_{cluster})\rangle \frac{N_{2p} v_{2,2p}}{N v_2}$$

Flowing cluster background scales with $N_{2p}/N^2$

Estimated by measuring $N_{2p}$ directly in data

$$\frac{\Delta\epsilon_2}{\epsilon_2} = (1.45 \pm .08)\%$$

$$\epsilon_{nf} = v_{2,nf}^2 / v_{2,true}^2$$

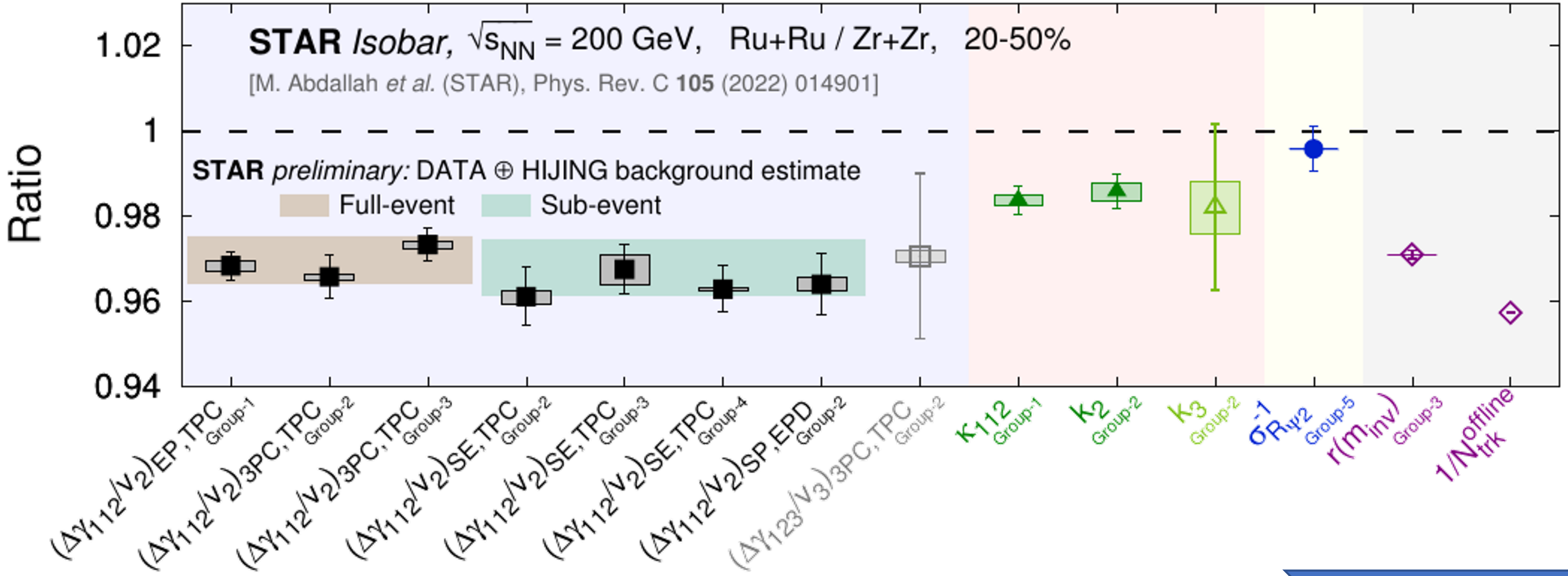
Estimation by 2-D decomposition of 2-particle correlations gives

$$\frac{-\Delta\epsilon_{nf}}{1+\epsilon_{nf}} = (0.65 \pm 0.11 \pm 0.22)\%.$$

Contribution of direct 3-particle correlations.

Estimation from HIJING gives $-(0.85 \pm 0.26 \pm 0.44)\%$

# Preliminary Isobar Background Estimate (Post-Blinding)




See STAR poster by Yicheng Feng

Isobar post-blinding: $\Delta\gamma$ results consistent with preliminary background estimate within current uncertainty.

# Isobar: Charge Separation Measurement with $\boldsymbol{R}_{\Psi_2}$

N. Magdy *et al.* Phys. Rev. C, 97 (2018) 061901

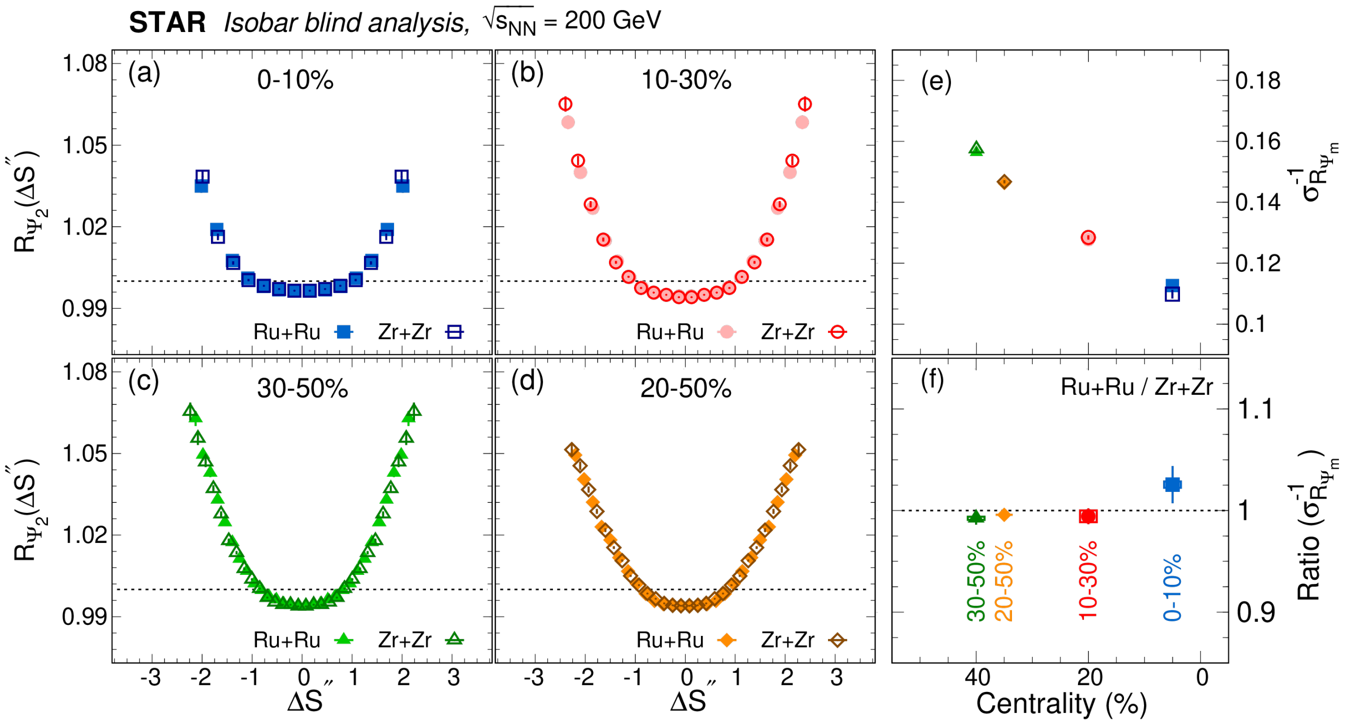
$$\boldsymbol{R}_{\Psi_2}(\Delta S) = \boldsymbol{C}_{\Psi_2}(\Delta S)/C^{\perp}_{\Psi_2}(\Delta S)$$

$$\boldsymbol{C}_{\Psi_2} = \frac{\boldsymbol{N}_{\mathbf{real}}(\Delta S)}{\boldsymbol{N}_{\mathbf{shuffled}}(\Delta S)}$$

$$\Delta S = \left\{ \frac{\sum_{i=1}^{n+} w_i^+ \sin(\phi_i - \psi_2)}{\sum_{i=1}^{n+} w_i^+} - \frac{\sum_{i=1}^{n-} w_i^- \sin(\phi_i - \psi_2)}{\sum_{i=1}^{n-} w_i^-} \right\}$$

$\sigma_{\Psi_2}$ is the Gaussian width of the respective $R(\Delta S'')$

Measurement of the in-plane and out-of-plane distributions of the dipole separation event-by-event




**Pre-defined CME criterion in blind analysis:**

$$1/\sigma_{\Psi_2}^{\mathrm{Ru+Ru}} > 1/\sigma_{\Psi_2}^{\mathrm{Zr+Zr}}$$

No significant difference is observed between two isobar systems

In studies with frozen code for blind analysis, $\boldsymbol{R}_{\Psi_2}$ and $\Delta\gamma$ have similar sensitivities to CME signal and background; $1/\sigma^2_{\boldsymbol{R}_{\Psi_2}} \approx N\Delta\gamma$

M. S. Abdallah *et al.* (STAR) Phys. Rev. C, 105 (2022) 014901

# Isobar: $\kappa_{112}$ Measurement with Full TPC

M. S. Abdallah *et al.* (STAR) Phys. Rev. C, 105 (2022) 014901

**Pre-defined CME criteria:**

$$\frac{(\Delta\gamma_{112}/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{112}/v_2)^{\mathrm{Zr+Zr}}} > \frac{(\Delta\delta)^{\mathrm{Ru+Ru}}}{(\Delta\delta)^{\mathrm{Zr+Zr}}}$$

The background contributions due to local charge conservation (LCC) and transverse momentum conservation (TMC) have a similar characteristic structure that involves the coupling between $v_2$ and $\delta$.

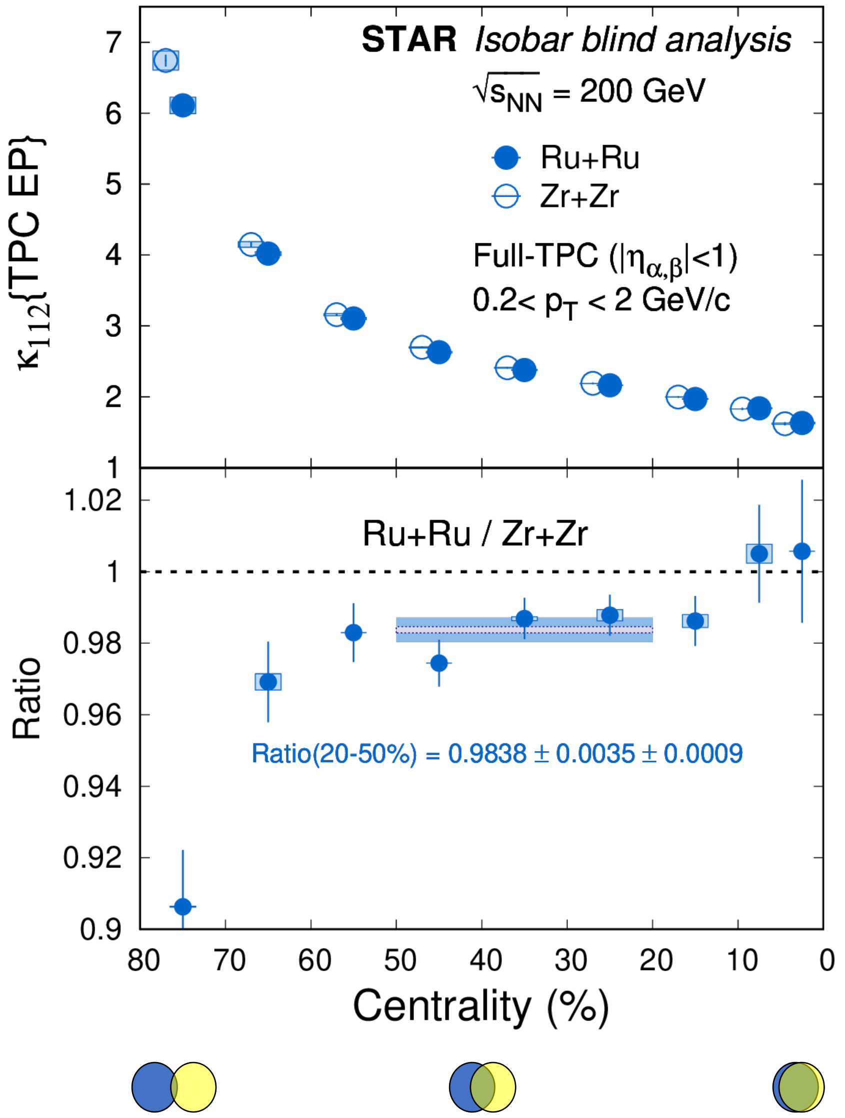
So, we studied the the normalized quantity:

$$\kappa_{112} \equiv \frac{\Delta\gamma_{112}}{v_2\Delta\delta}$$

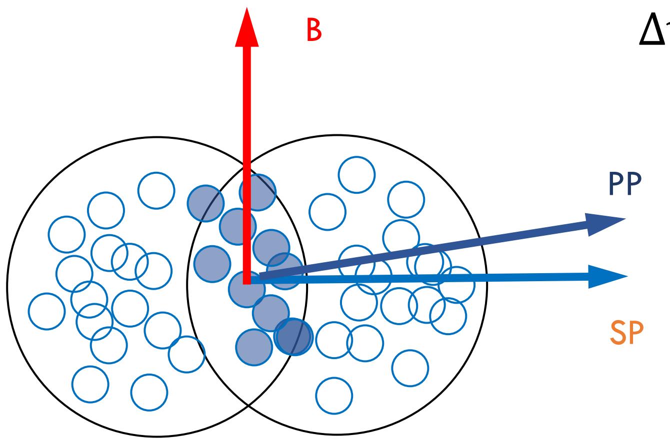
**Pre-defined CME criterion:**

$$\frac{(\kappa_{112})^{\mathrm{Ru+Ru}}}{(\kappa_{112})^{\mathrm{Zr+Zr}}} > 1$$

Data not compatible with pre-defined CME criterion



# 200 GeV Au-Au Data, Using Participant and Spectator Planes




PP(TPC) : maximum background
SP(ZDC-SMD) : maximum signal

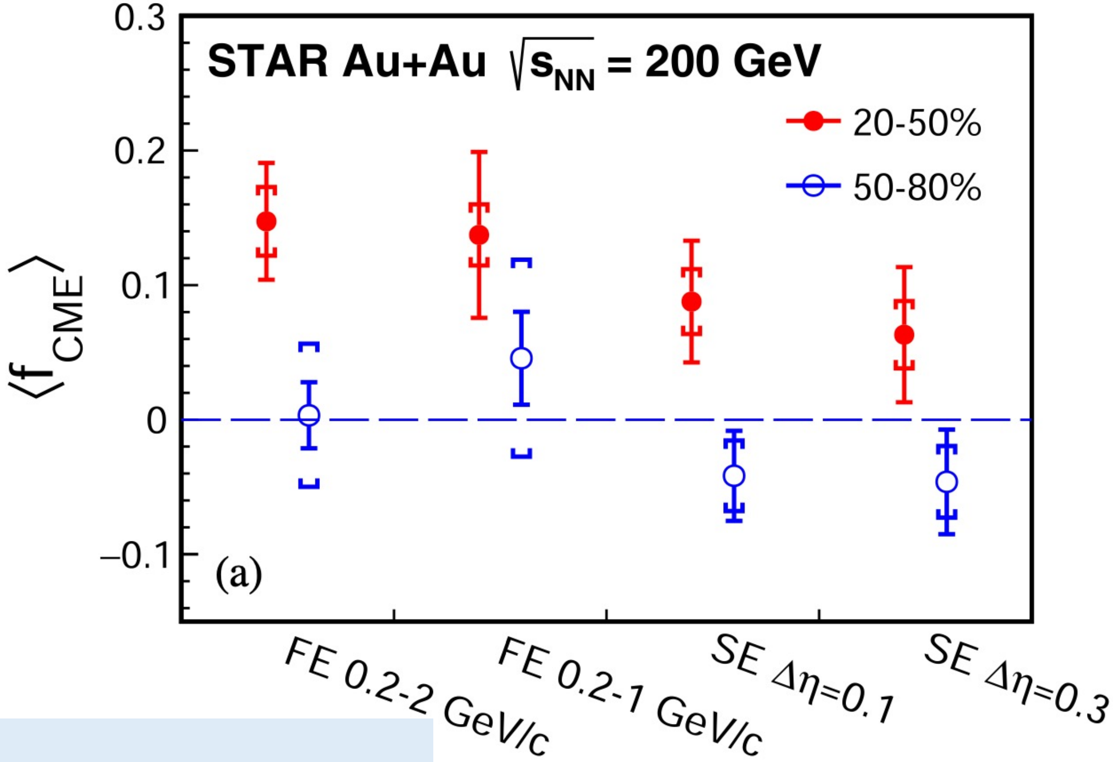
H-J. Xu, et al, CPC 42 (2018) 084103; S. A. Voloshin, Phys. Rev. C 98 (2018) 054911

$$\Delta\gamma\{PP\} = \Delta\gamma_{CME}\{PP\} + \Delta\gamma_{BKG}\{PP\}$$
$$\Delta\gamma\{SP\} = \Delta\gamma_{CME}\{PP\}/a + \Delta\gamma_{BKG}\{PP\}a$$

$$a = \langle\cos 2(\Psi_{PP} - \Psi_{SP})\rangle$$

$$f_{CME}^{PP} = \frac{\frac{\Delta\gamma\{SP\}}{\Delta\gamma\{PP\}}/a - 1}{1/a^2 - 1}$$

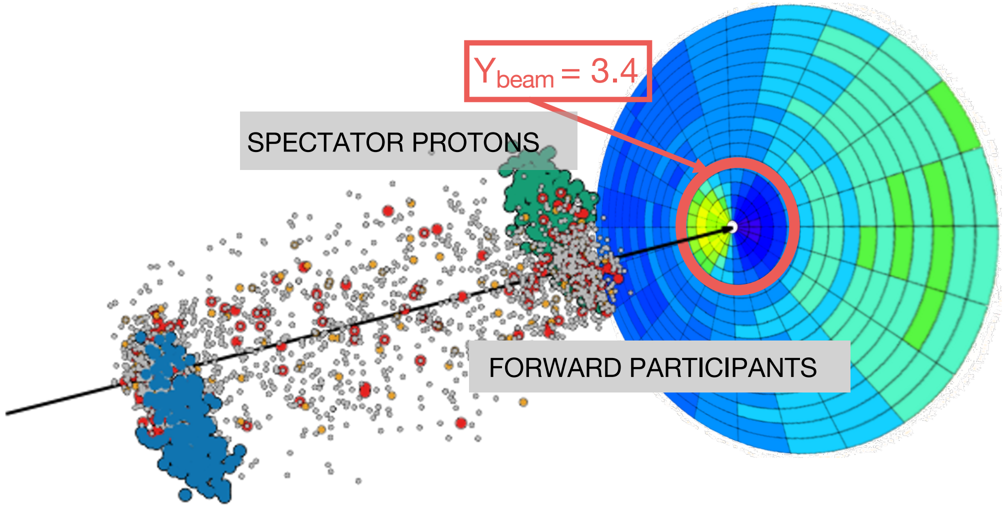
M. S. Abdallah *et al.* (STAR) Phys. Rev. Lett, 128 (2022) 092301



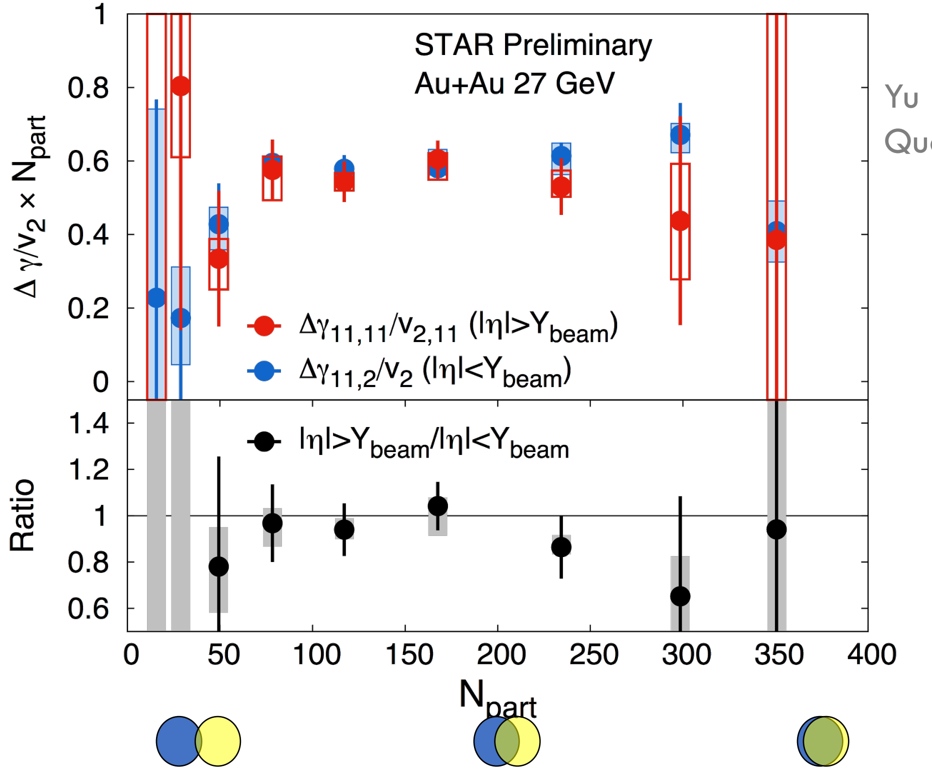

- Can we reconcile this $f_{CME}$ in Au-Au with isobar results? In isobar system, smaller B-field ($\sim A^{1/3}$), larger $\Delta\gamma$ "flowing clusters" background ( $\sim 1/A$) , would argue for a smaller $f_{CME}$ in isobar compared to Au-Au. Y. Feng et. al., Phys. Lett. B820 (2021) 136549

- STAR 2022 BUR: with 20B events from runs 23 and 25, we can achieve better than 5σ significance provided the possible CME signal fraction remains at 8%

# New Work: Measurement with STAR EPD @ 27 GeV




We measure the elliptic flow and the charge separation, using $\Delta\gamma$ w.r.t. **EPD-inner first harmonic plane** and the **EPD-outer second harmonic plane**.




Yu Hu (STAR)
Quark Matter 2022

$$\Delta\gamma = \Delta\gamma^{BG} + \Delta\gamma^{CME}$$

**If** $\Delta\gamma^{BG} = b\, v_2$

$$\left(\frac{\Delta\gamma}{v_2}\right) = \frac{\langle cos(\alpha+\beta-2\Psi)\rangle}{\langle cos(2a-2\Psi)\rangle}$$

*RP, PP, SP…*

Under a ‘pure background’ scenario, all these ratios are equal. If different measurements yield different ratios, this would indicate a CME signal.

The ratio of $\Delta\gamma/v_2$ between spectator-proton rich EPD $\Psi_1$ plane and participant-dominated $\Psi_2$ plane. CME-driven correlations will make this ratio >1.

S. A. Voloshin, Phys. Rev. C 98 (2018) 054911

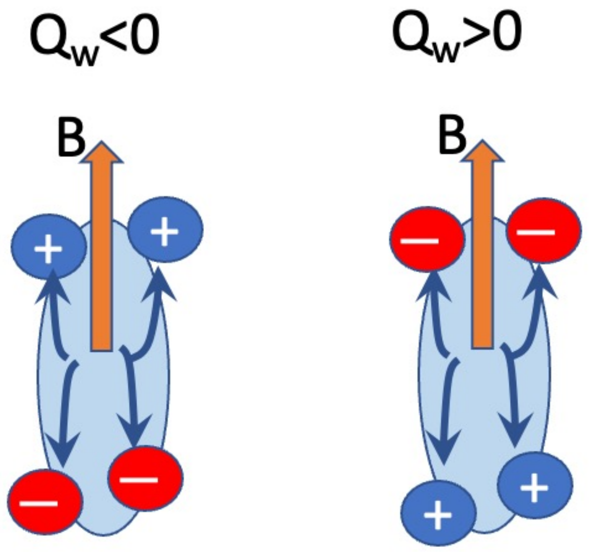
# New Work: Correlations with Other Parity-Odd Signals ($\Lambda$ helicity)

Another observable sensitive to Local Parity Violation is net helicity of $\Lambda s$ in each event.

F. Becattini *et al.* Phys.Lett.B 822 (2021) 136706
F. Du *et al.* Phys.Rev.C 78 (2008) 044908

In each event, sign of charge separation dipole and net helicity are both determined by same $Q_w$ ! $(N_L^f - N_R^f) = 2Q_{\rm w}$

→In events where positive charges flow in B-field direction, expect $N_L^\Lambda - N_R^\Lambda > 0$



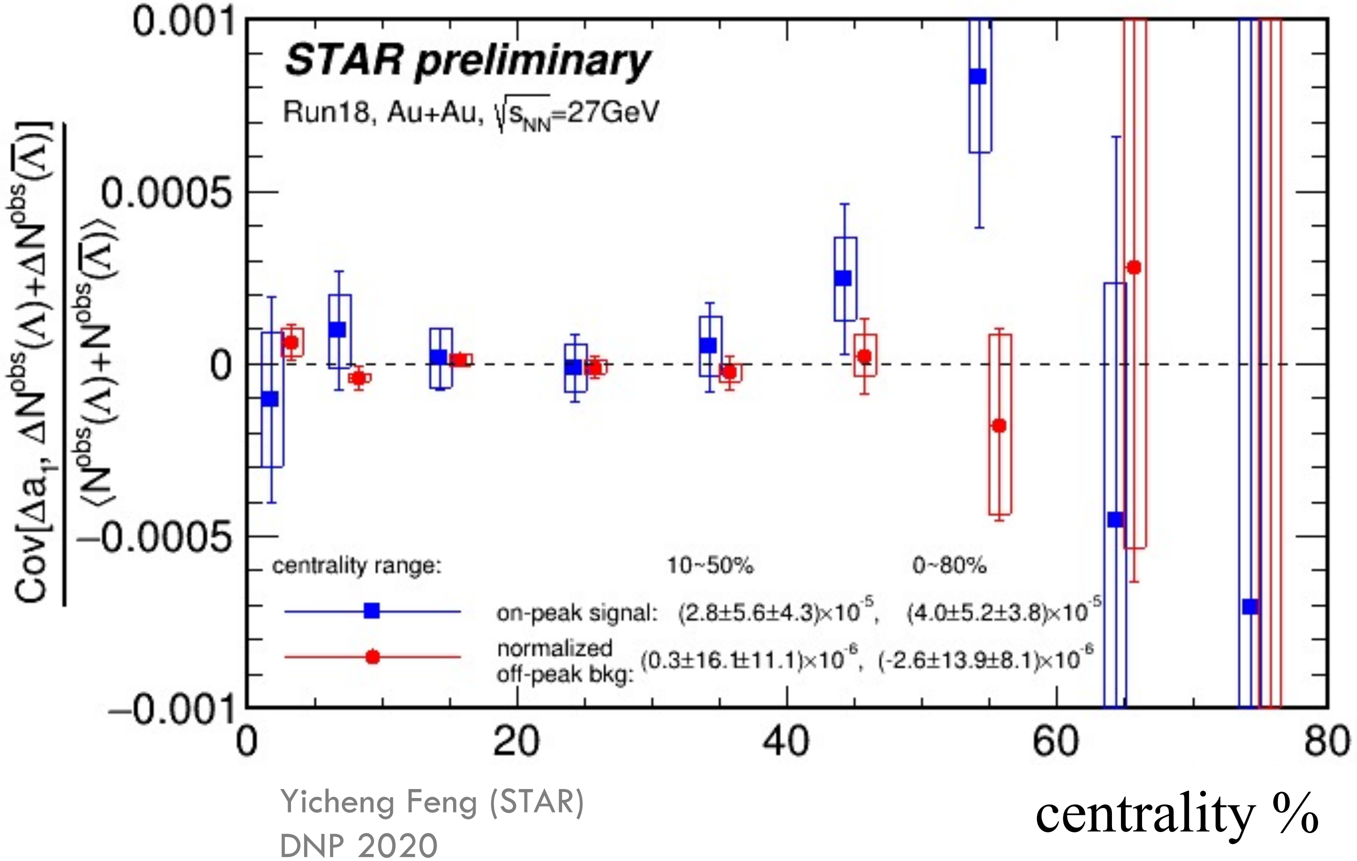

$N_L^\Lambda > N_R^\Lambda$ $N_R^\Lambda > N_L^\Lambda$

$N_L^{\bar{\Lambda}} > N_R^{\bar{\Lambda}}$ $N_R^{\bar{\Lambda}} > N_L^{\bar{\Lambda}}$

Can look for a correlation between sign of CME in each event and net handedness of $\Lambda$ in that event. Two parity-odd observables with very different background sources (can also observe $\bar{\Lambda}$ as further systematics check and/or to increase statistical power)

Need 1st order event plane (STAR EPD or ZDC/SMD)

# New Work: Correlations with Other Parity-Odd Signals ($\Lambda$ helicity)




Yicheng Feng (STAR)
DNP 2020

$$a_1^{\pm} = \langle \sin(\phi_{\pm} - \Psi_{\mathrm{RP}}) \rangle \qquad \Delta N = N_L^{\Lambda} > N_R^{\Lambda}$$

$$\Delta a_1 = \frac{N_+}{N_+ + N_-} a_1^+ - \frac{N_-}{N_+ + N_-} a_1^-$$

In 27GeV Au+Au data, we use EPD for $\psi_1$

Measure covariance between

$a_1^+ - a_1^-$ and $N_L^{\Lambda} > N_R^{\Lambda}$

"positive charge flow along B-field"

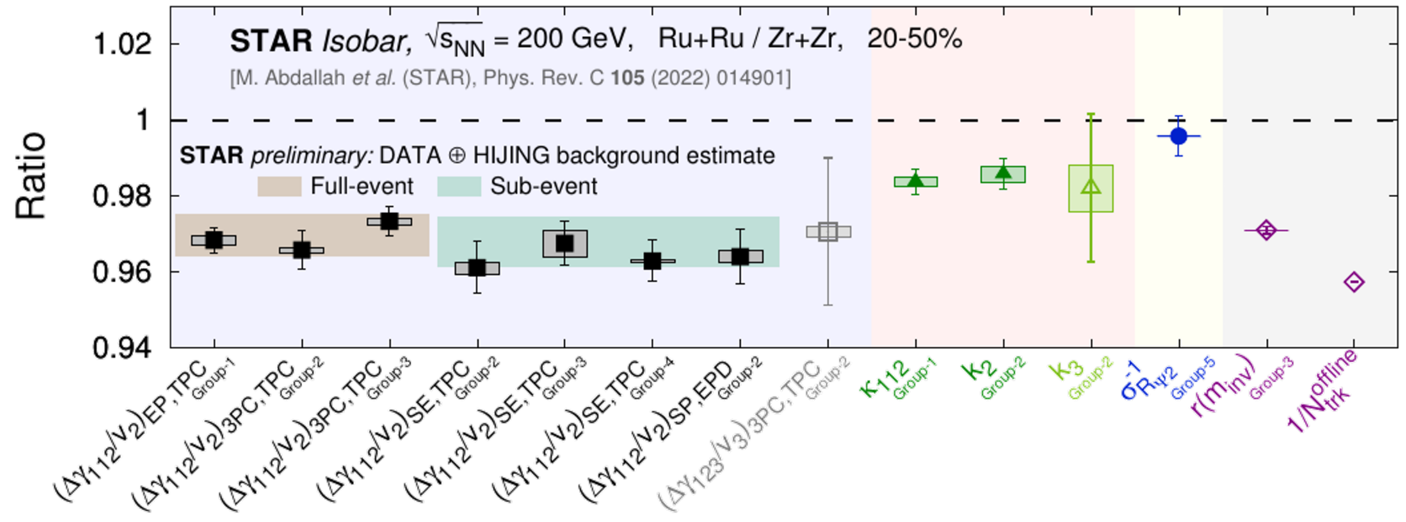
"Excess of left-helicity $\Lambda$"

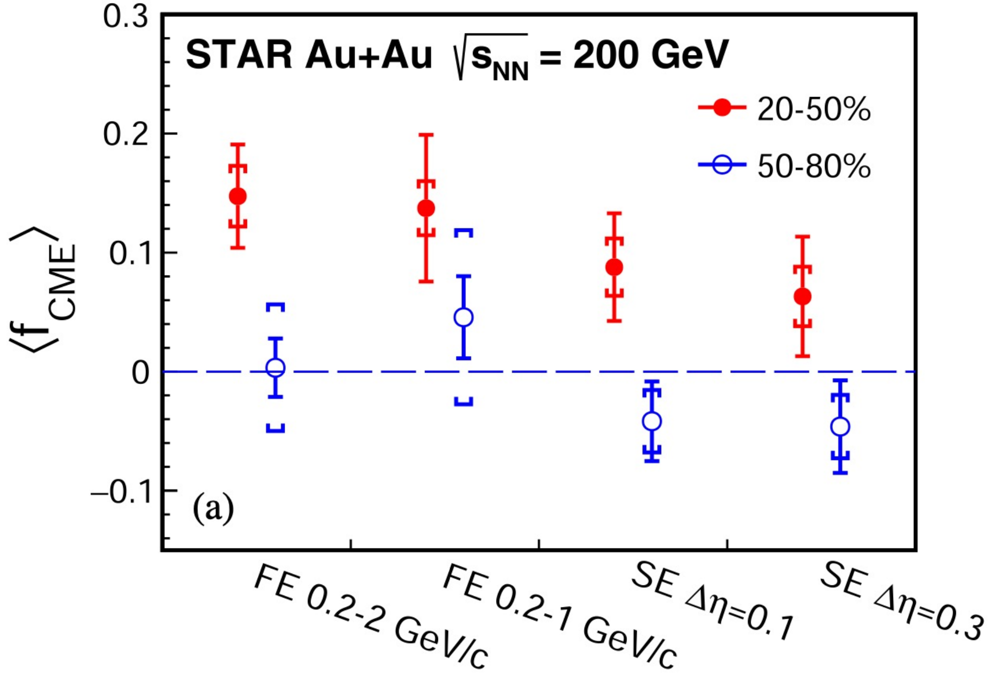
Positive covariance (blue points above zero, 20-60% centrality) would indicate presence of two parity-odd effects tied to local parity violation

In 27GeV run 18 data, signal consistent with zero within uncertainty

2022 STAR BUR: This method will be target for future high-statistics Au-Au runs.

# Summary: Current Experimental Status of CME in STAR




Isobar blind analysis: no method shows evidence for CME using pre-defined criteria.

Isobar post-blinding: $\Delta\gamma$ results consistent with preliminary background estimate within current uncertainty. We are working to reduce this uncertainty.

In 200GeV Au+Au data, spectator versus participant plane analysis shows signal 1-3$\sigma$ above zero; working to better understand possible remaining non-flow contributions.

More novel analyses underway, including using 1st-order plane to investigate correlations with another parity-odd observable ($\Lambda$ helicity)