Experimental Investigations of Chiral Magnetic Effects

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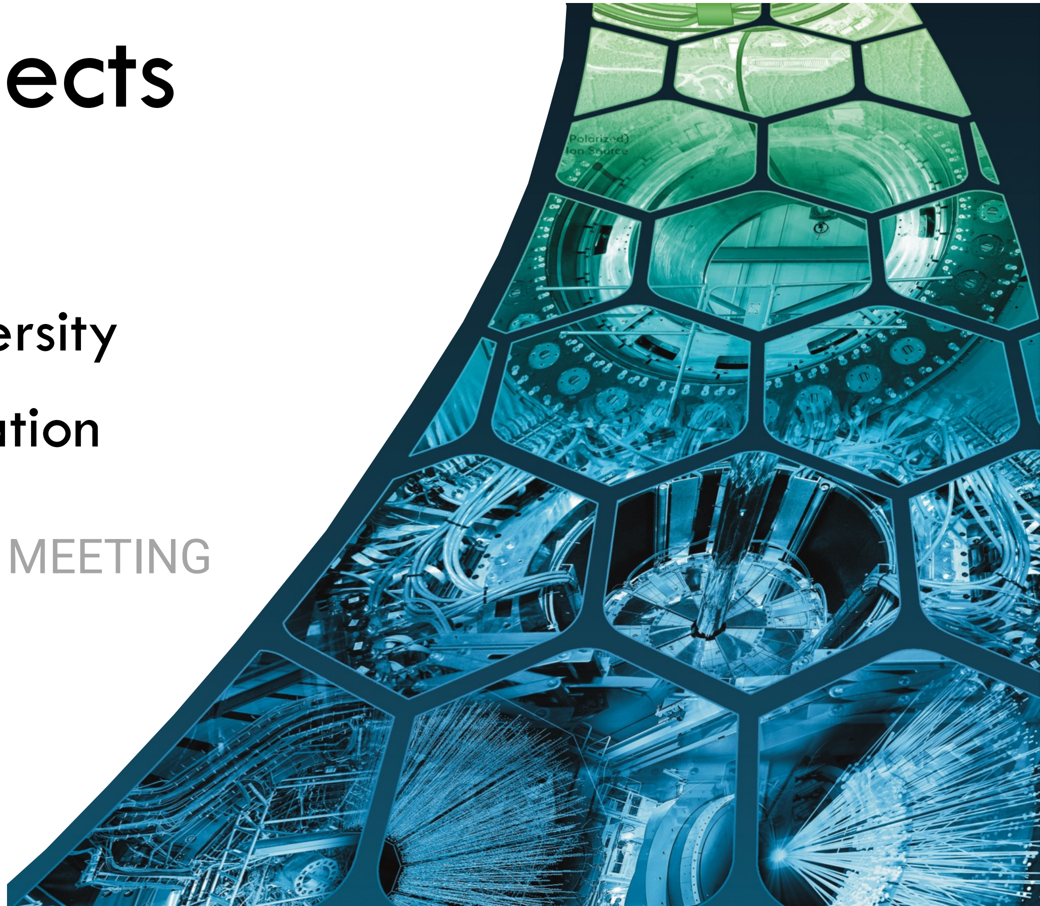
for the STAR Collaboration

2022 RHIC/AGS ANNUAL USERS' MEETING



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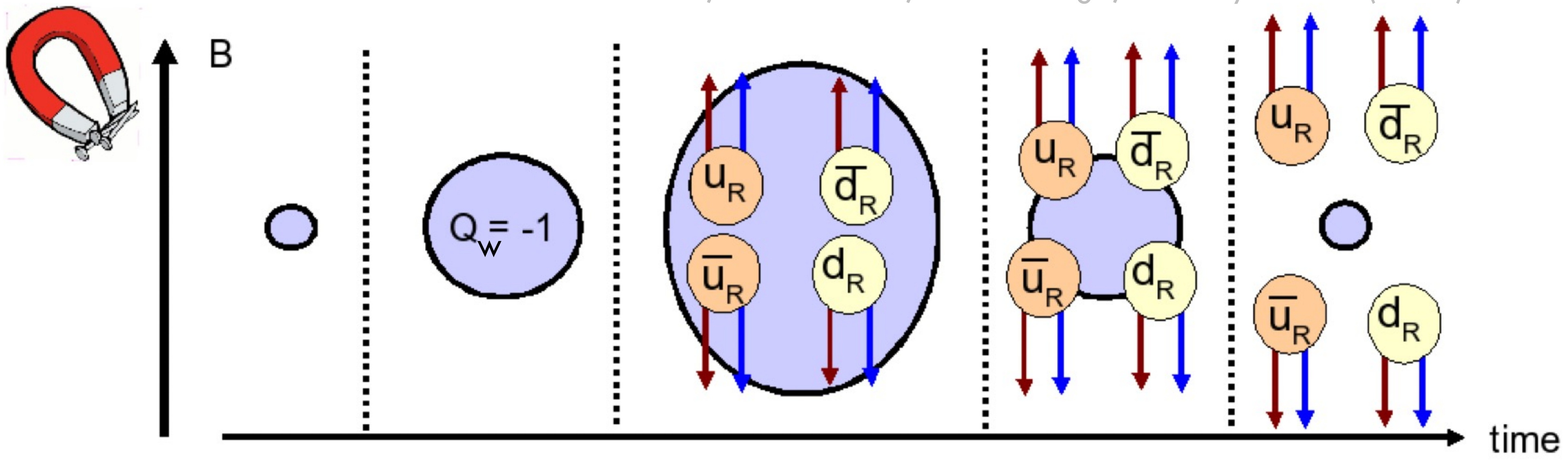
Chiral Magnetic Effect

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

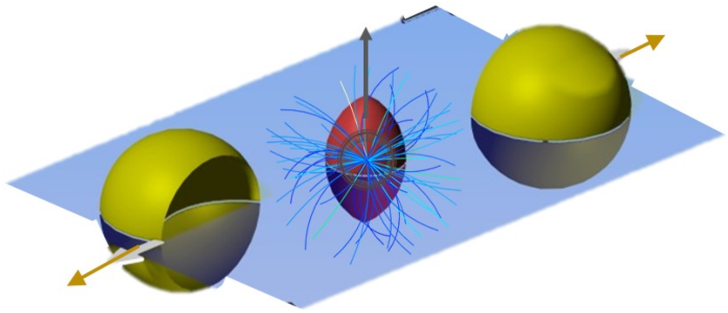


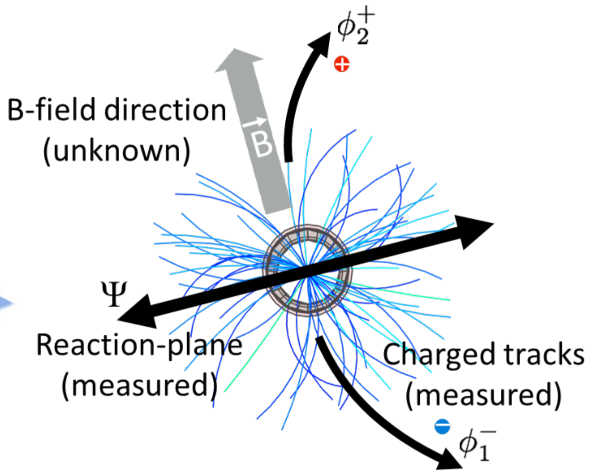
1) Chirality imbalance among all light quark flavor from topological fluctuations of gluon fields $(N_L^f - N_R^f) = 2Q_{\rm w}$ i.e. "Local Parity Violation"

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 : $\Delta\gamma$



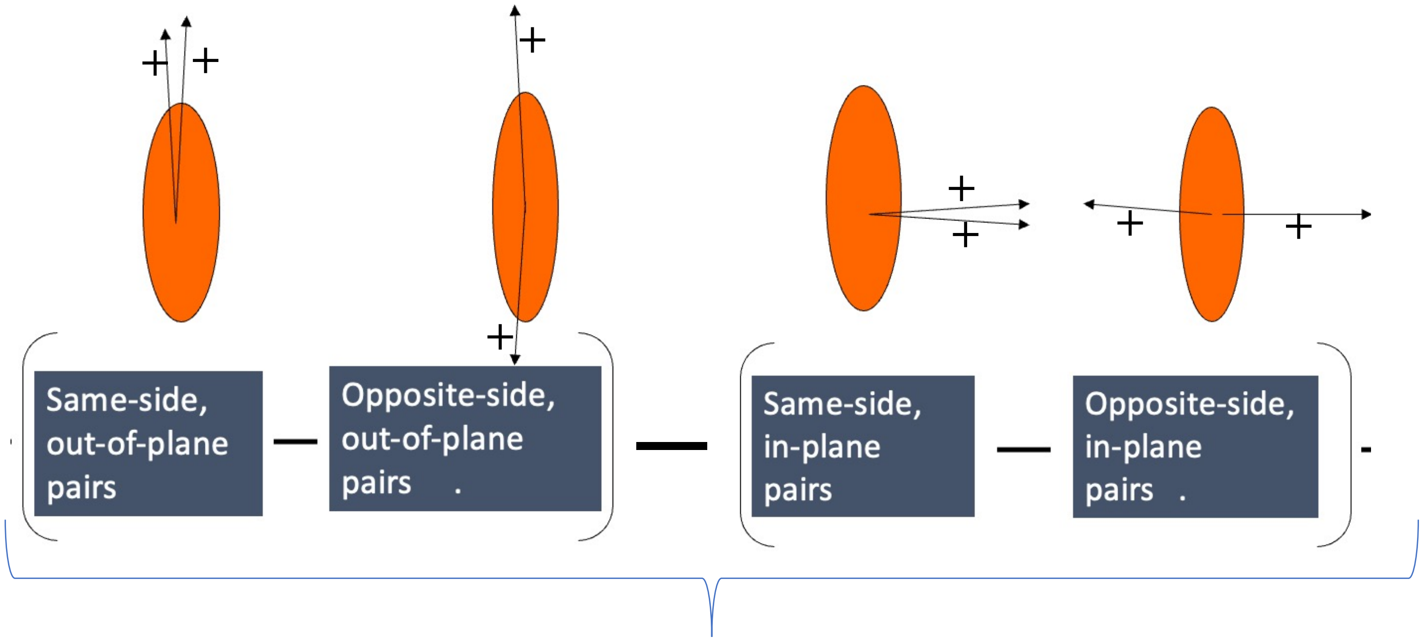


S. A. Voloshin, Phys. Rev. C 70, 057901 (2004)

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

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

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

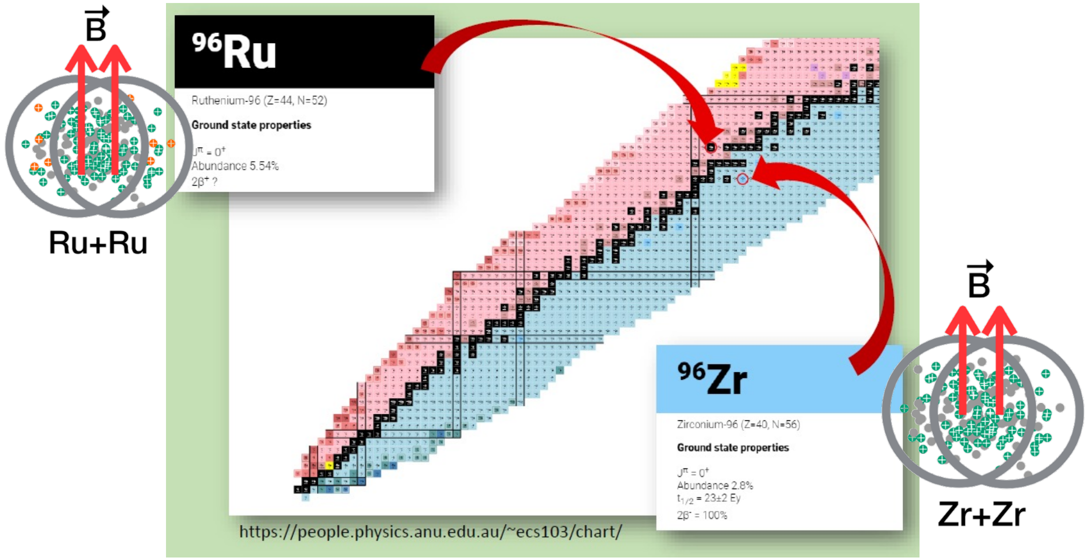


$\Delta\gamma$: Same-sign pairs – Opposite-sign pairs

Key backgrounds:

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

Experimental Search With Isobar Collisions



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

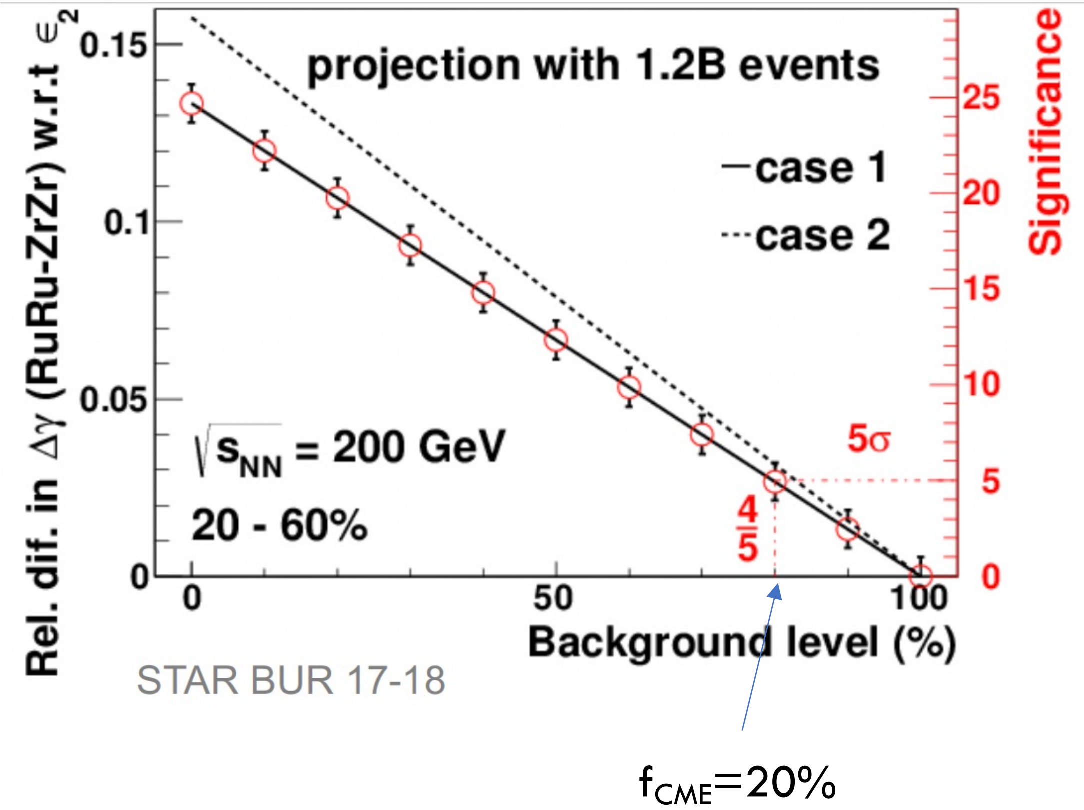
Measurement — Signal — "Flowing Clusters" Background — Smaller backgrounds

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

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

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

B^2 is ~15% different



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

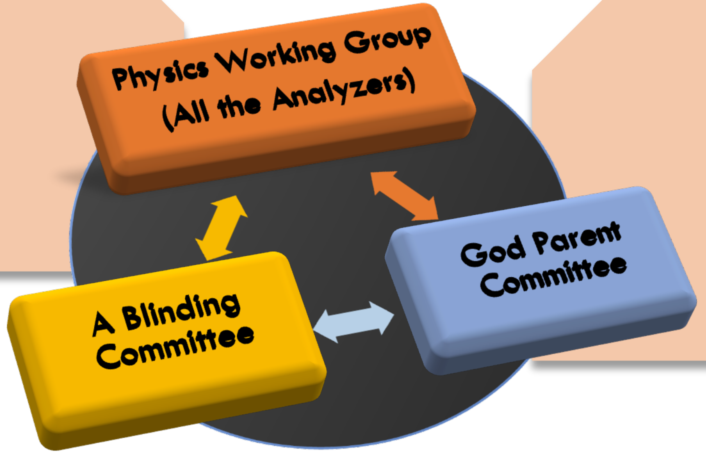
STEP-3
Isobar Unblind analysis
Final analysis
(Ru+Ru & Zr+Zr separated)
~2-3 months

Blind analyses (5 groups):

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

A large, collective effort

Connections between the methods are studied

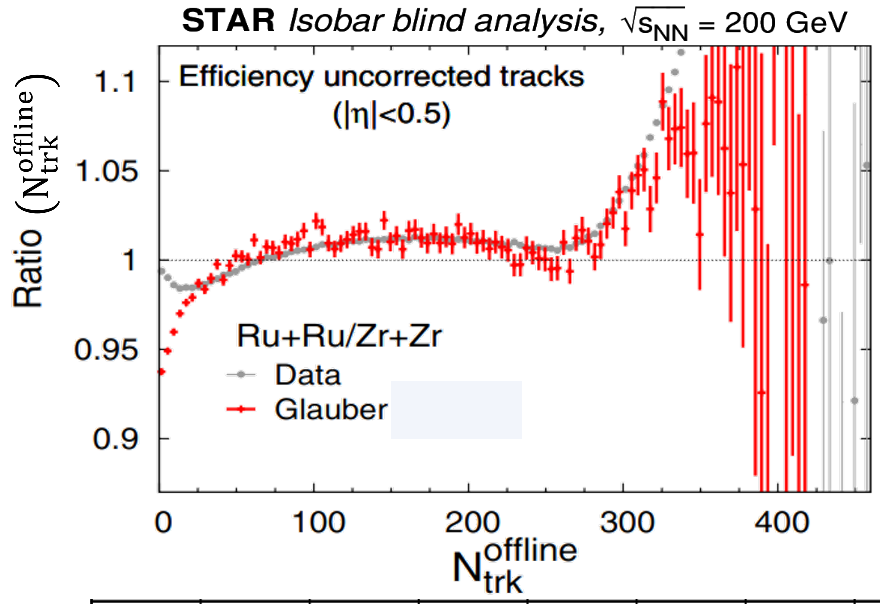


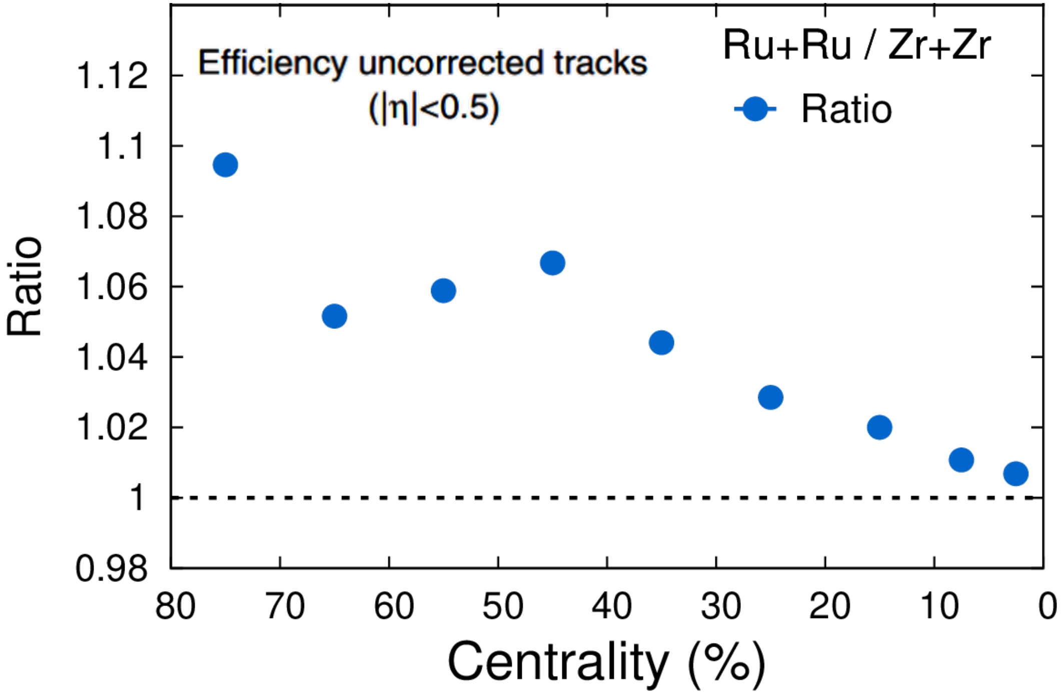
Using the frozen code from STEP-1:

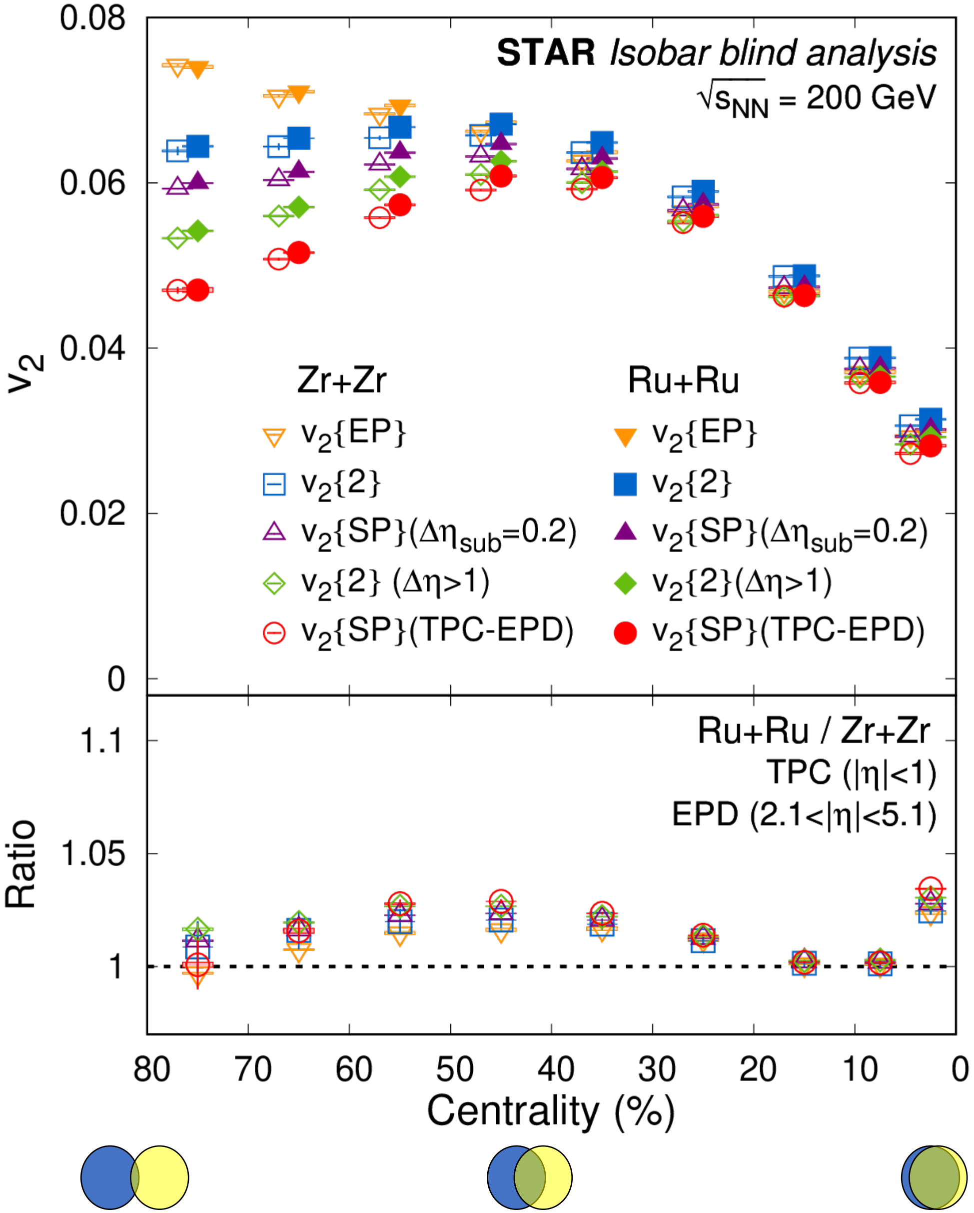
- Sensitivity of observables tested using AVFD simulation
- Similar sensitivities are found in all observables

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

Isobars: Multiplicity and v_2

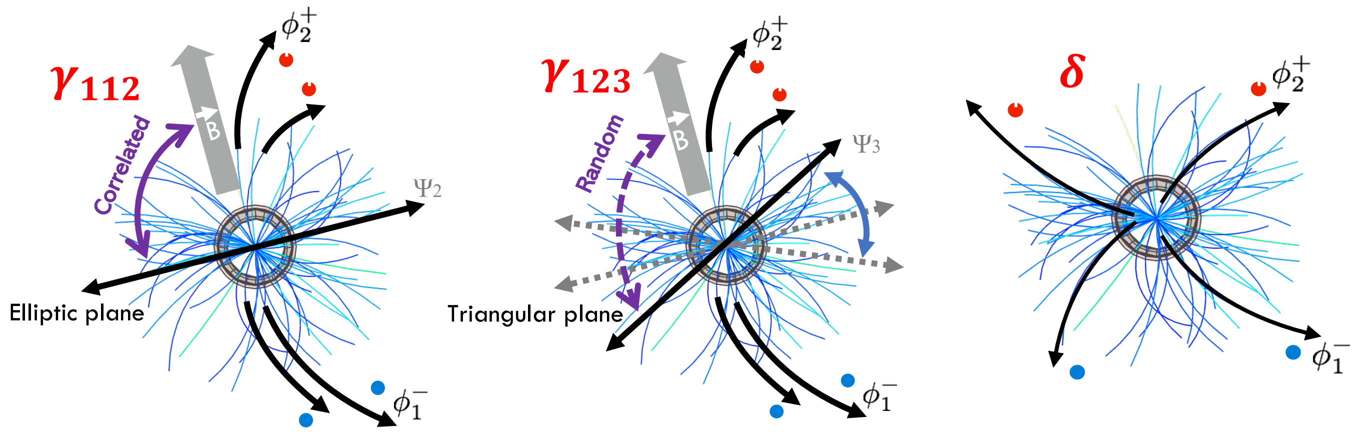






M. S. Abdallah et al. (STAR) Phys. Rev. C, 105 (2022) 014901

Isobar: Δγ Measurement Using Full TPC



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

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

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

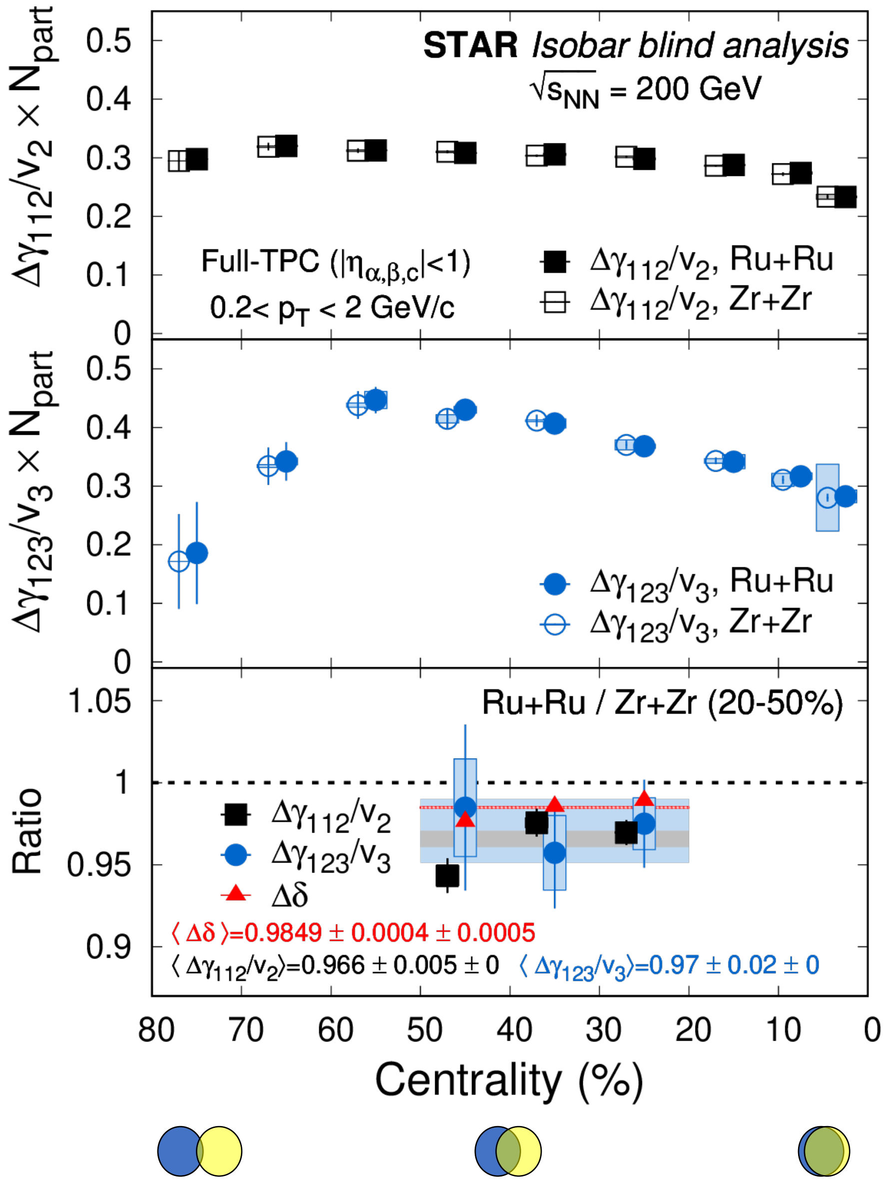
Pre-defined CME criteria:

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

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

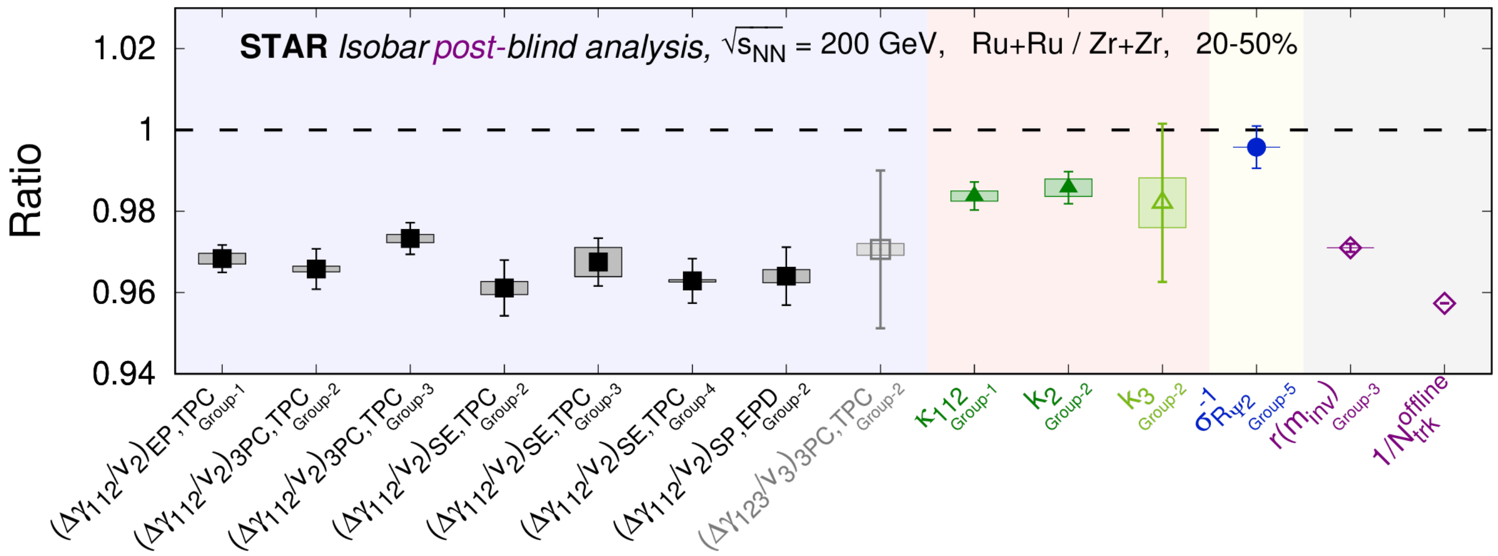
$$\frac{(\Delta\gamma_{112}/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{112}/v_2)^{\mathrm{Zr+Zr}}} > \frac{(\Delta\delta)^{\mathrm{Ru+Ru}}}{(\Delta\delta)^{\mathrm{Zr+Zr}}}$$

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

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

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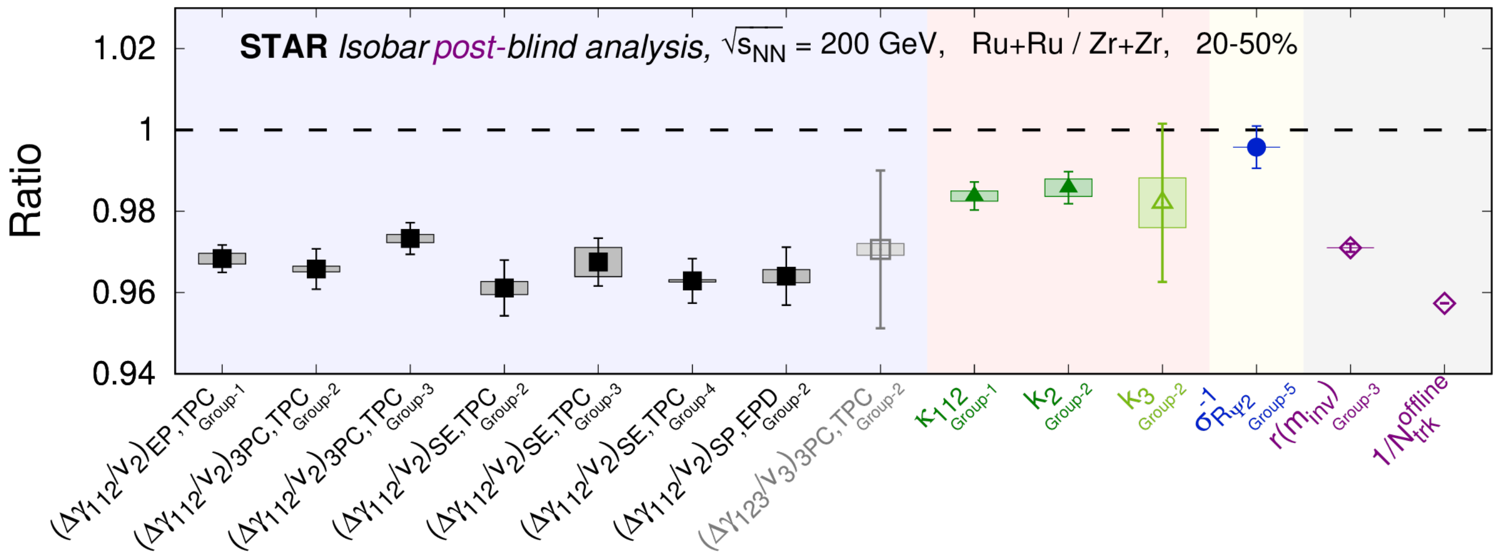

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Important post-blinding points:

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

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

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

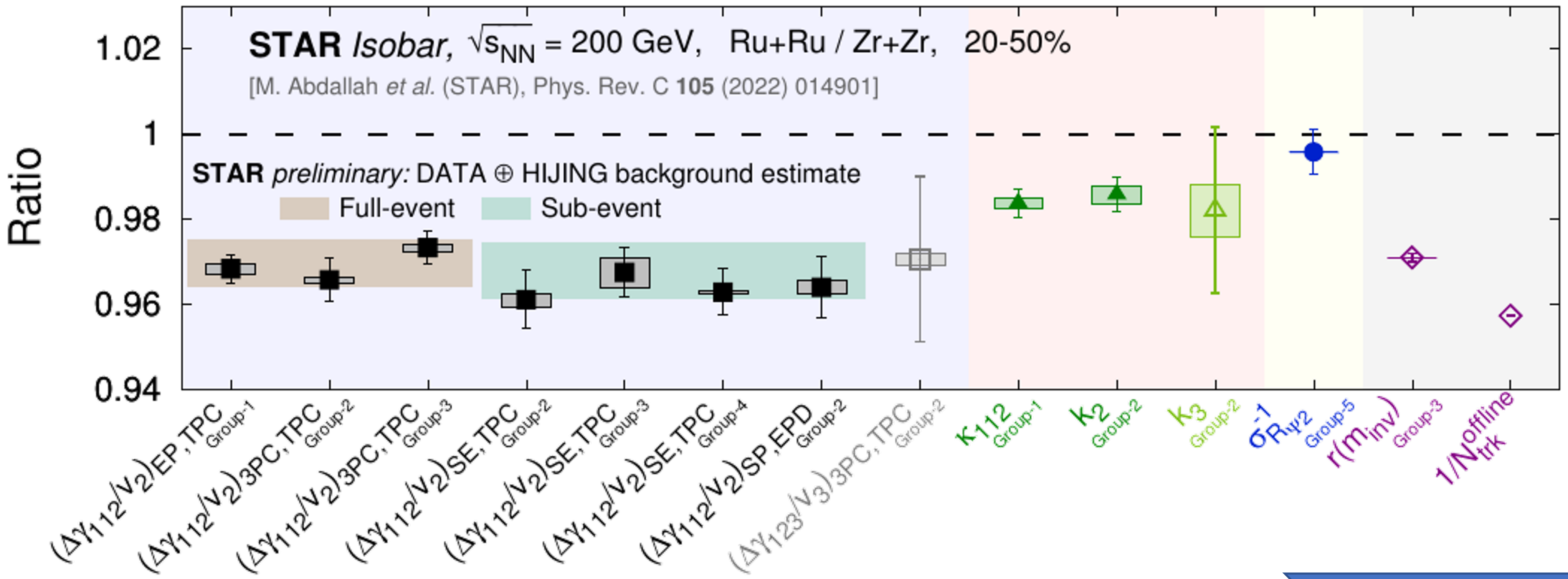
Estimation by 2-D decomposition of 2-particle correlations gives

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

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 R_{Ψ_2}

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

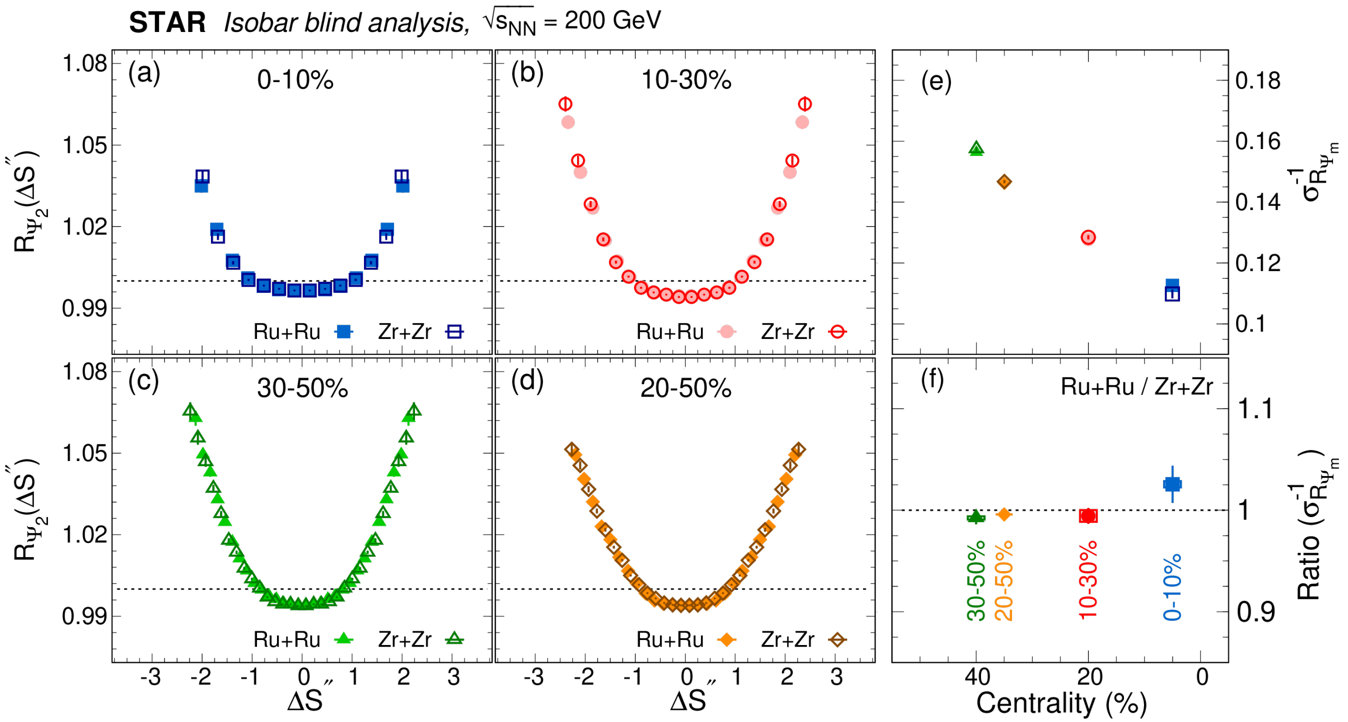
$$R_{\Psi_2}(\Delta S) = C_{\Psi_2}(\Delta S)/C^{\perp}_{\Psi_2}(\Delta S)$$

$$C_{\Psi_2} = \frac{N_{real}(\Delta S)}{N_{shuffled}(\Delta S)}$$

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

σ_{Ψ_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



No significant difference is observed between two isobar systems

Pre-defined CME criterion in blind analysis:

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

In studies with frozen code for blind analysis, R_{Ψ_2} and $\Delta\gamma$ have similar sensitivities to CME signal and background; $1/\sigma^2_{R_{\Psi_2}} \approx N\Delta\gamma$

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

Isobar: κ_{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 δ.

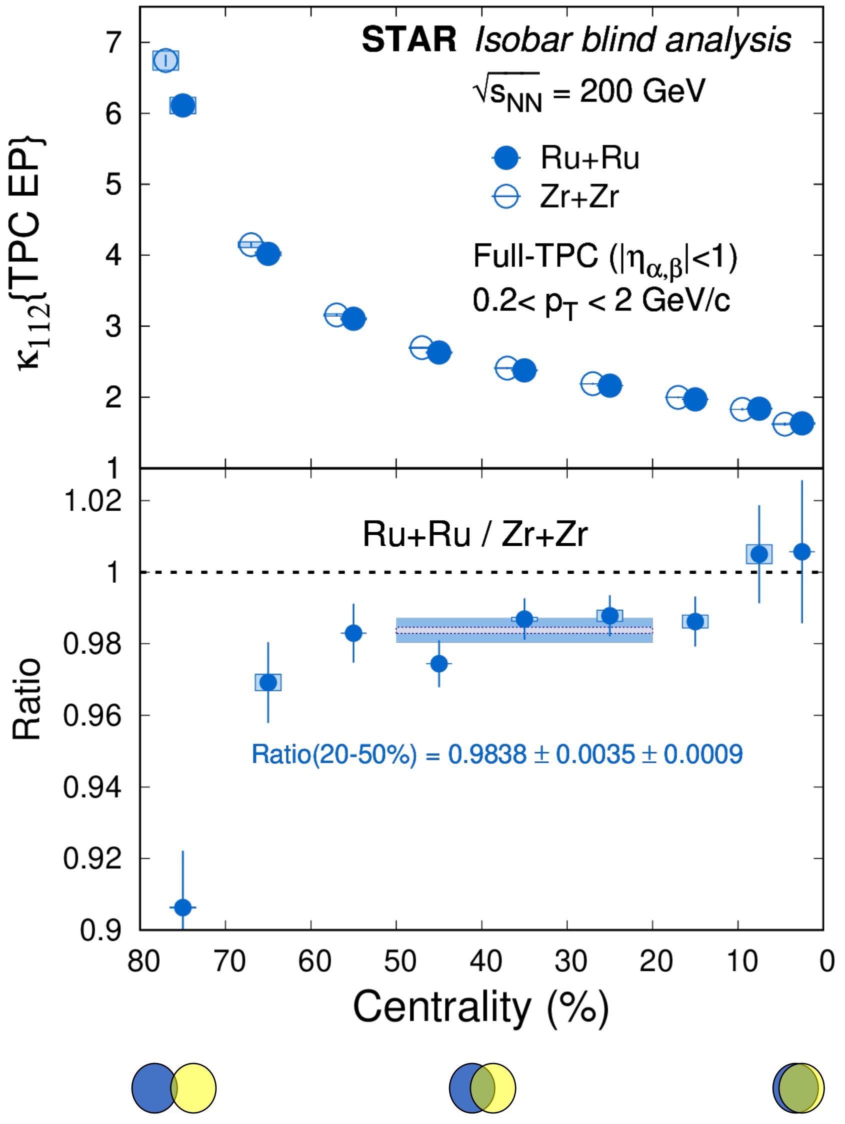
So, we studied the the normalized quantity:

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

Pre-defined CME criterion:

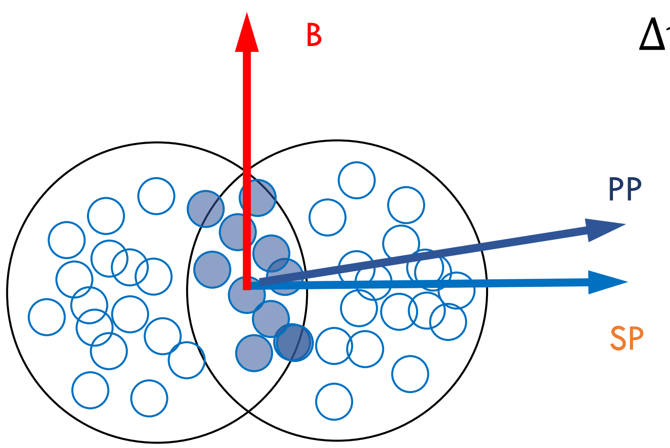
$$\frac{(\kappa_{112})^{\mathrm{Ru+Ru}}}{(\kappa_{112})^{\mathrm{Zr+Zr}}} > 1$$

Data not compatible with pre-defined CME criterion



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

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



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

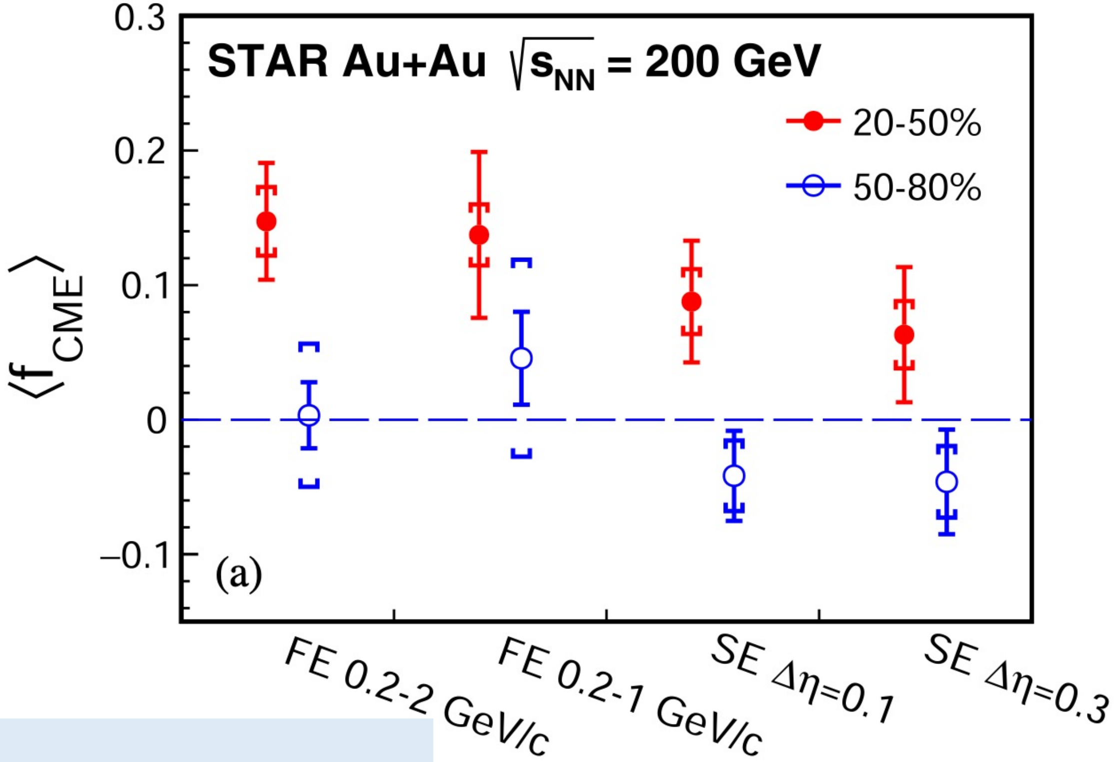
$$a = \langle\cos 2(\Psi_{PP} - \Psi_{SP})\rangle$$

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

PP(TPC) : maximum background

SP(ZDC-SMD) : maximum signal

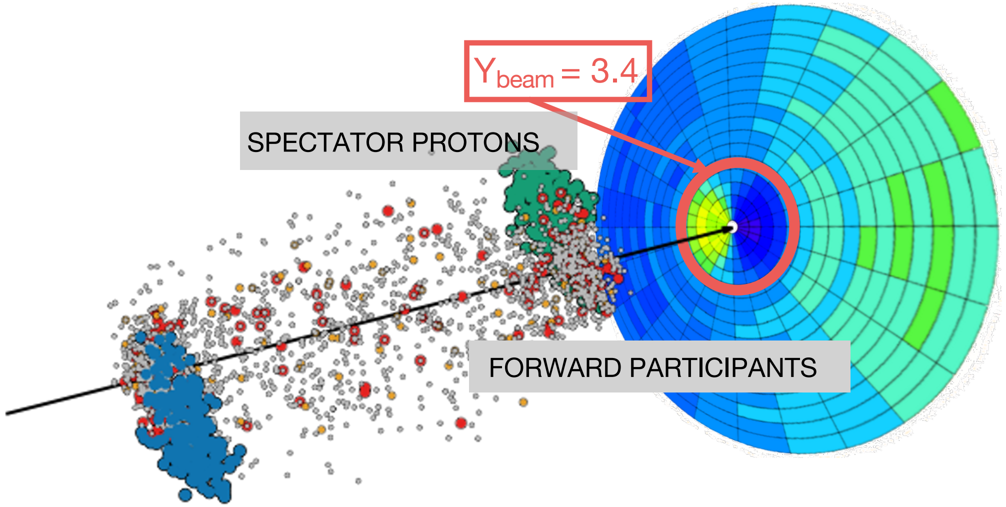
H-J. Xu, et al, CPC 42 (2018) 084103; S. A. Voloshin, Phys. Rev. C 98 (2018) 054911



- 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



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

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

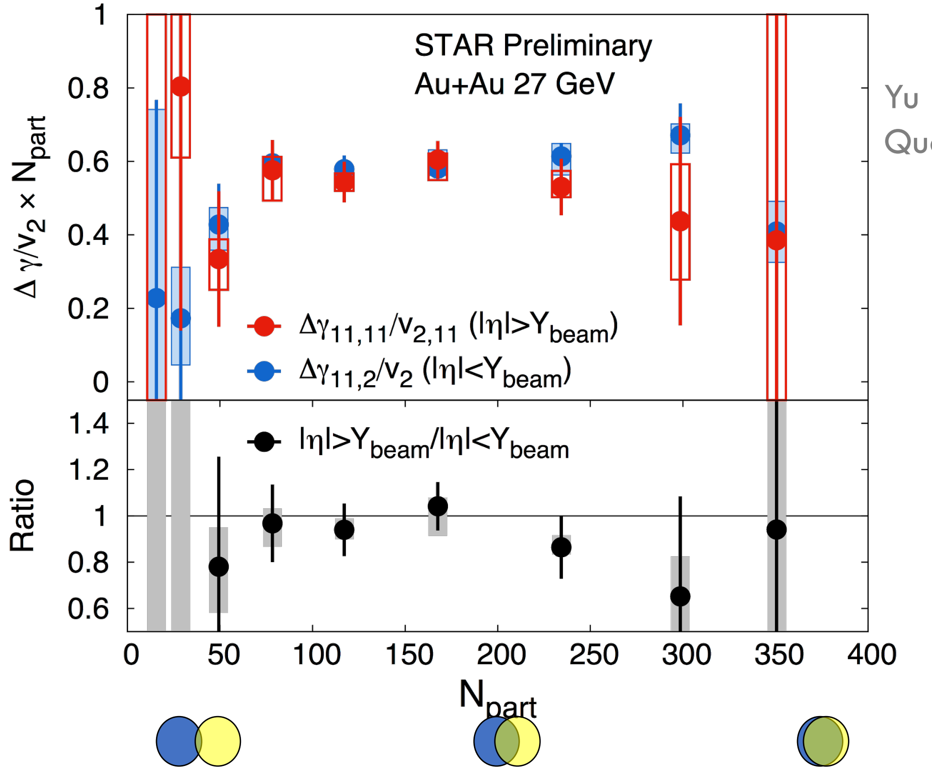
$$\left(\frac{\Delta\gamma}{v_2}\right) = \frac{\langle \cos(\alpha + \beta - 2\Psi)\rangle}{\langle \cos(2a - 2\Psi)\rangle}$$

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.

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

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

The ratio of $\Delta\gamma/v_2$ between spectator-proton rich EPD Ψ_1 plane and participant-dominated Ψ_2 plane. CME-driven correlations will make this ratio >1.

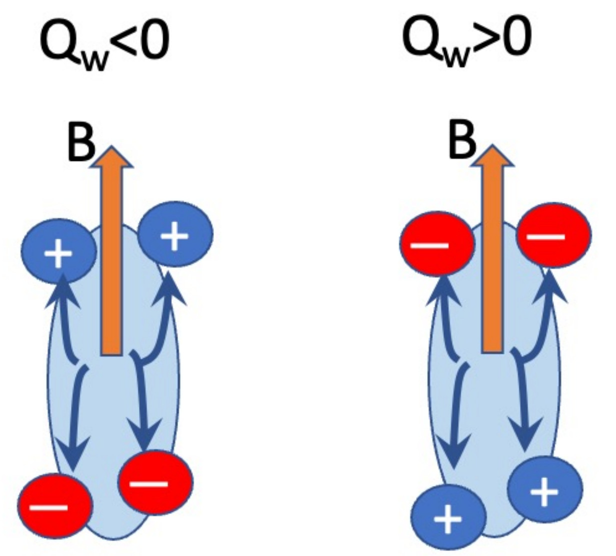
New Work: Correlations with Other Parity-Odd Signals (Λ helicity)

Another observable sensitive to Local Parity Violation is net helicity of Λs 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 ! $(N_L^f - N_R^f) = 2Q_w$

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



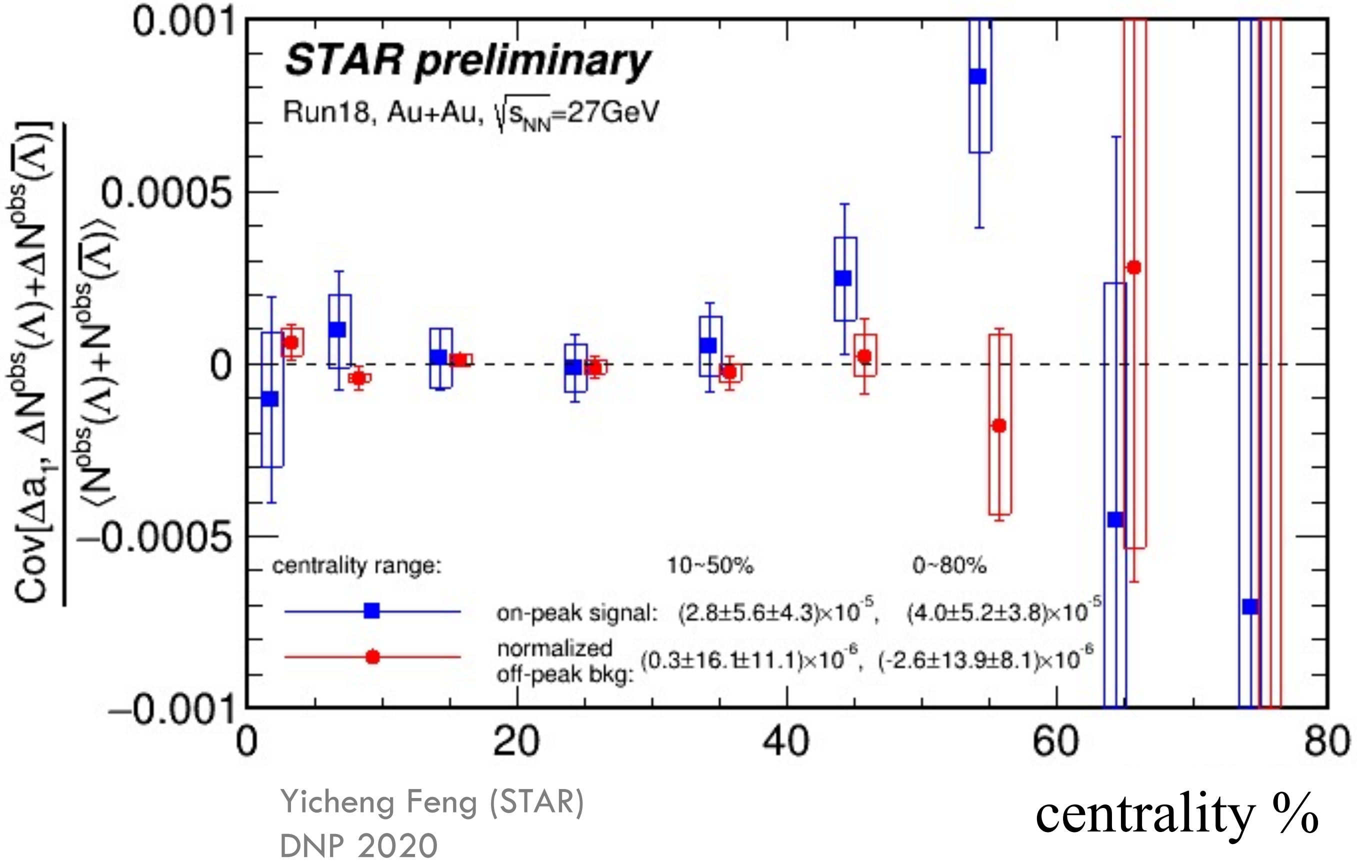
$N_L^\Lambda > N_R^\Lambda$ $N_R^\Lambda > N_L^\Lambda$

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

Can look for a correlation between sign of CME in each event and net handedness of Λ in that event. Two parity-odd observables with very different background sources (can also observe $\overline{\Lambda}$ 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 (Λ helicity)



Yicheng Feng (STAR)
DNP 2020

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

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

In 27GeV Au+Au data, we use EPD for ψ_1

Measure covariance between

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

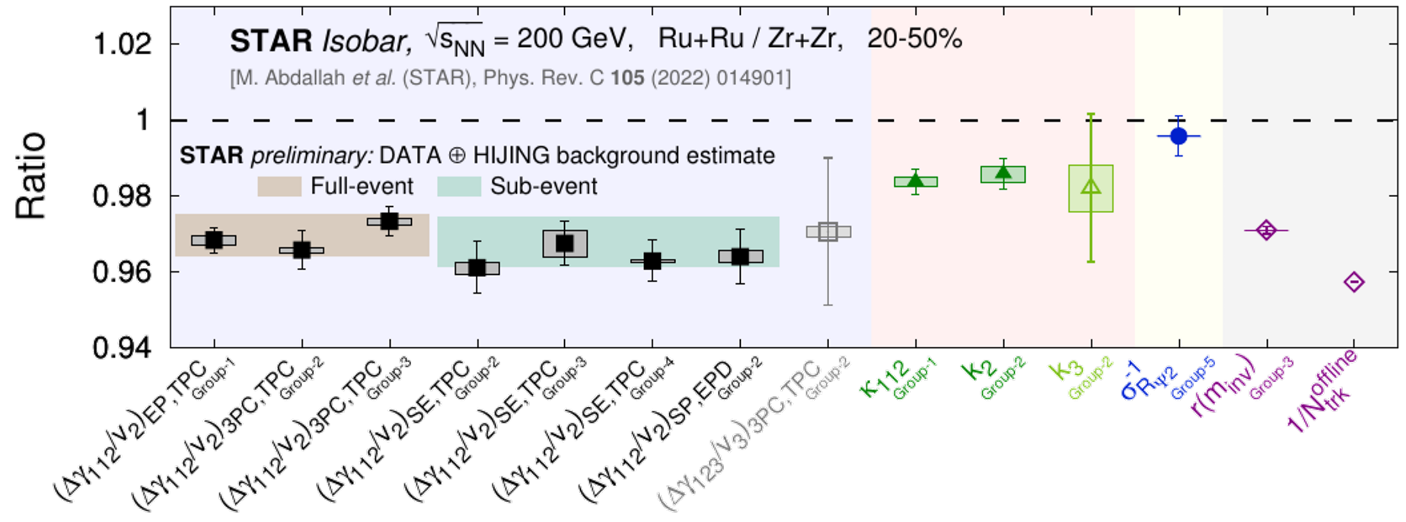
"positive charge flow along B-field" "Excess of left-helicity Λ"

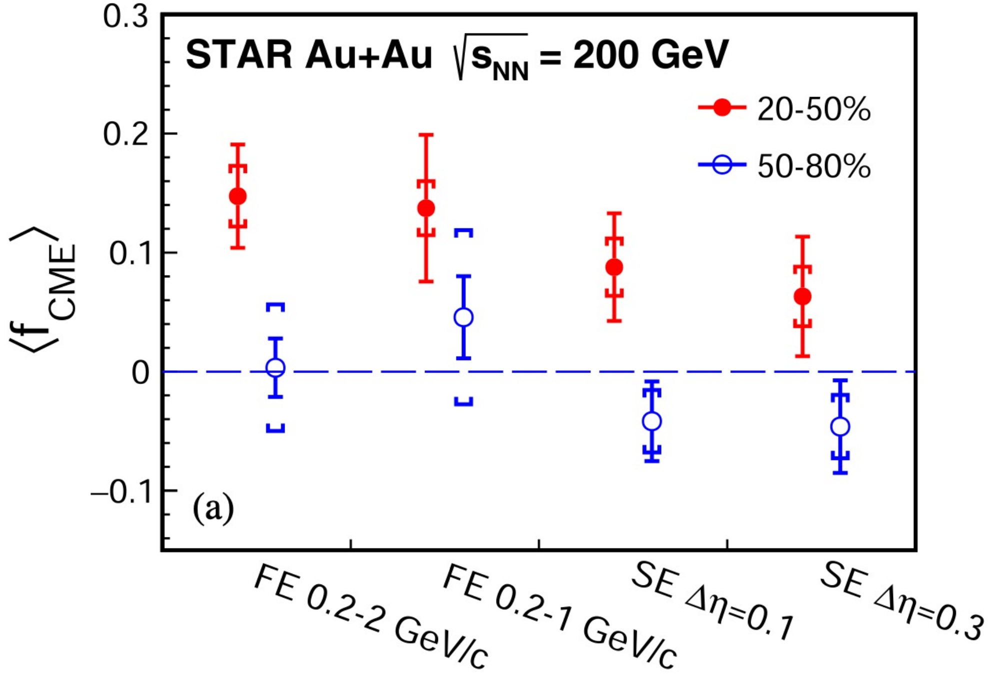
Positive covariance (blue points above zero, 20-60% centrality) would indicate presence of two parity-odd effects tied to local parity violation

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 1-3σ 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 (Λ helicity)

ADDITIONAL SLIDES

Isobar: Extraction of CME fraction: approach II

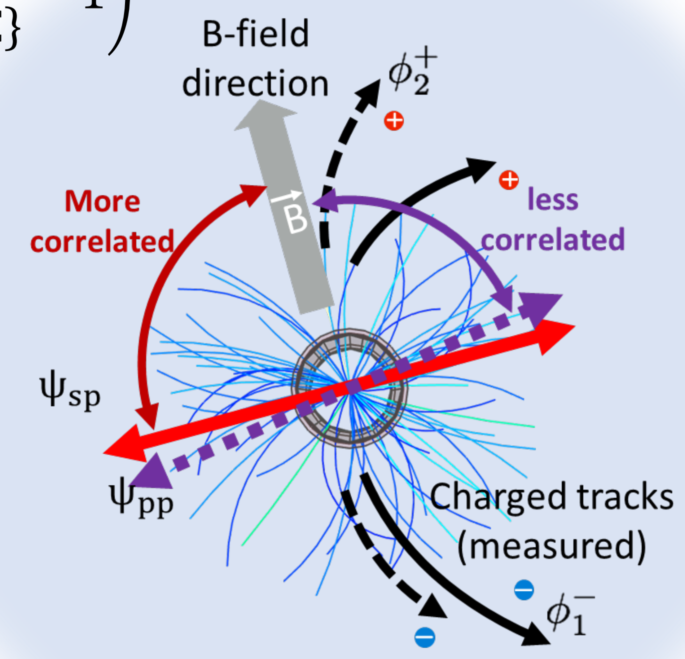
$$\frac{(\Delta\gamma/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma/v_2)^{\mathrm{Zr+Zr}}} = 1 + f_{\mathrm{CME}}^{\mathrm{Zr+Zr}}\left[\left(B^{\mathrm{Ru+Ru}}/B^{\mathrm{Zr+Zr}}\right)^2 - 1\right]$$

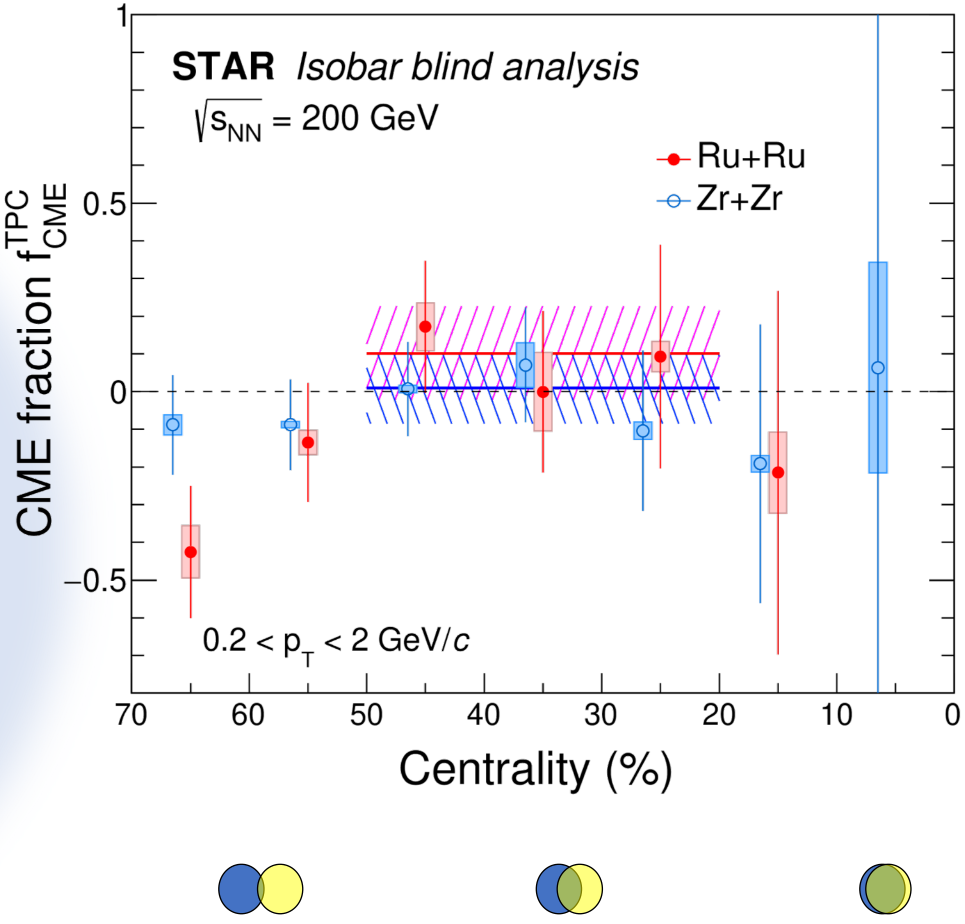
$$\frac{(\Delta\gamma/v_2)_{\mathrm{ZDC}}}{(\Delta\gamma/v_2)_{\mathrm{TPC}}} = 1 + f_{\mathrm{CME}}^{\mathrm{TPC}}\left(\frac{v_2^2\{\mathrm{TPC}\}}{v_2^2\{\mathrm{ZDC}\}} - 1\right)$$

Pre-defined CME criterion:

$$f_{\mathrm{CME}}^{\mathrm{TPC}} > 0$$

Differences in the method of estimating $v_2\{\mathrm{ZDC}\}$ and $v_2\{\mathrm{TPC}\}$ compared with the approach-I





Uncertainty dominated, no significant difference is observed between two isobar systems

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

Isobar Extraction of CME fraction: approach I

- TPC Ψ_{EP} → proxy of Ψ_{PP}
- ZDC Ψ_1 → proxy of Ψ_{RP}

$\Delta\gamma$ w.r.t. TPC Ψ_{EP} and ZDC Ψ_1 contain different fractions of CME and Bkg.

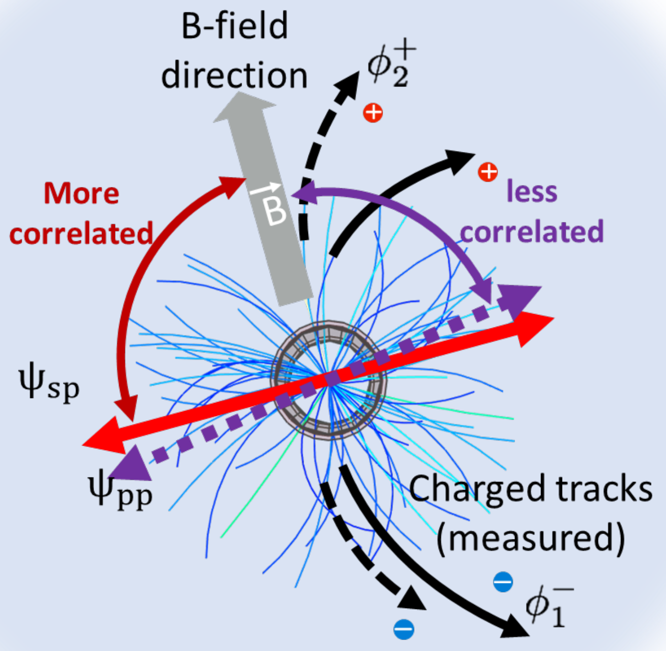
$$\Delta\gamma(\Psi_{TPC}) = \Delta\gamma^{BG}(\Psi_{TPC}) + \Delta\gamma^{CME}(\Psi_{TPC}) \quad ①$$

$$\Delta\gamma(\Psi_{ZDC}) = \Delta\gamma^{BG}(\Psi_{ZDC}) + \Delta\gamma^{CME}(\Psi_{ZDC}) \quad ②$$

$$\frac{\Delta\gamma^{BG}(\Psi_{TPC})}{\Delta\gamma^{BG}(\Psi_{ZDC})} = \frac{v_2(\Psi_{TPC})}{v_2(\Psi_{ZDC})} \quad ③$$

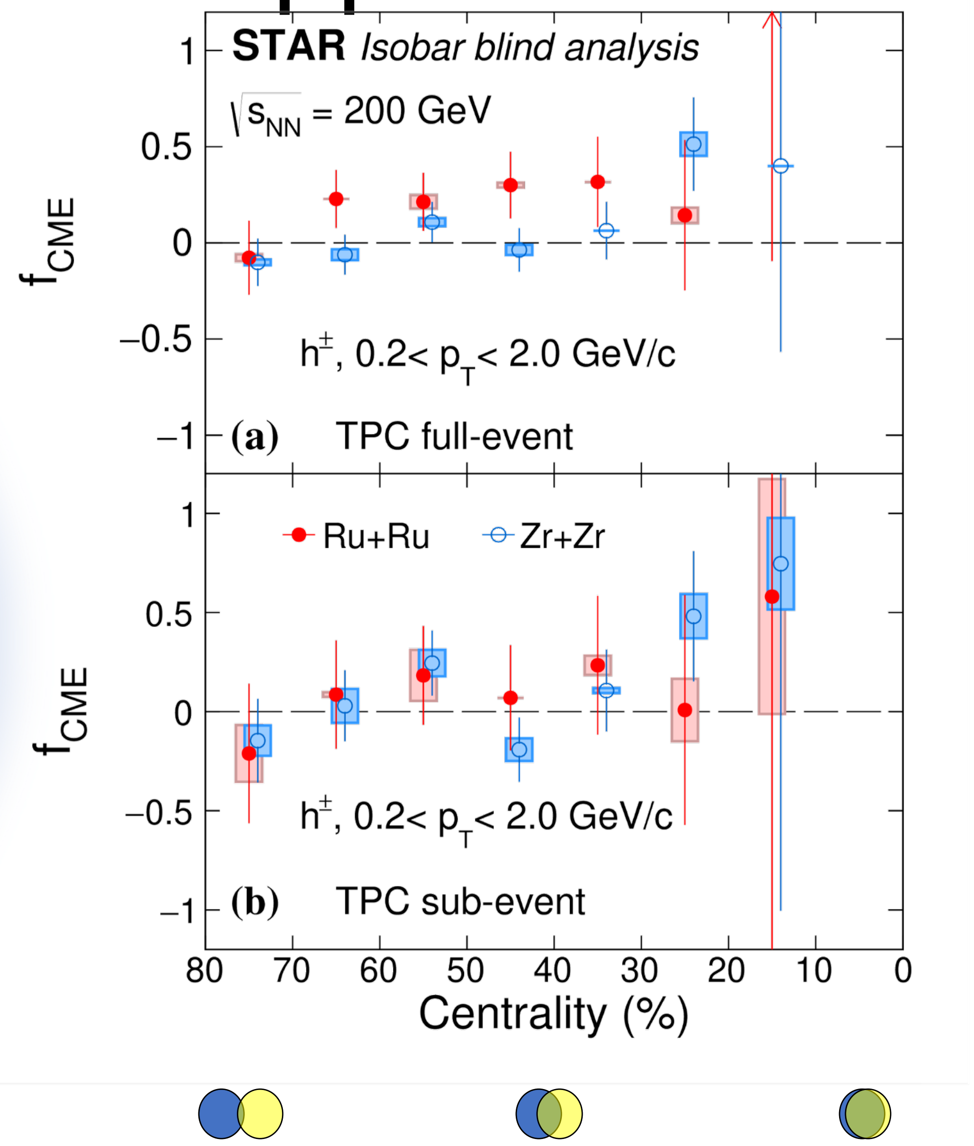
$$\frac{\Delta\gamma^{CME}(\Psi_{TPC})}{\Delta\gamma^{CME}(\Psi_{ZDC})} = \frac{v_2(\Psi_{ZDC})}{v_2(\Psi_{TPC})} \quad ④$$

$$f_{CME} = \frac{\Delta\gamma^{CME}(\Psi_{TPC})}{\Delta\gamma(\Psi_{TPC})} \quad ⑤$$



Pre-defined CME criterion:

$$f_{CME}^{Ru+Ru} > f_{CME}^{Zr+Zr} > 0$$



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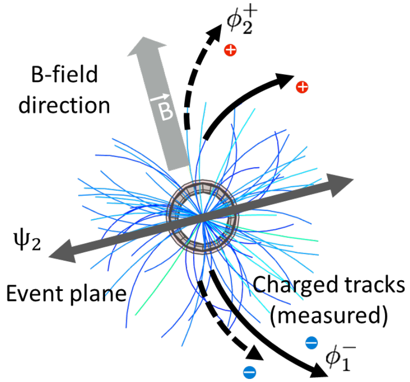
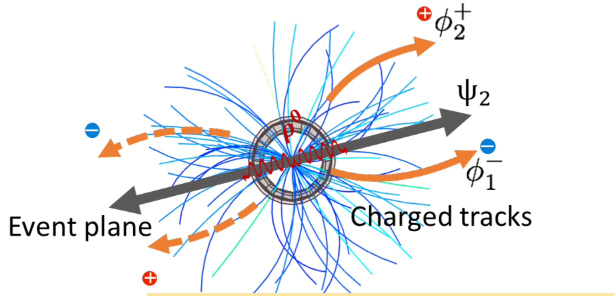
M. S. Abdallah *et al.* (STAR) Phys. Rev. C, 105 (2022) 014901
J. Adam *et al.* (STAR), (2020), arXiv:2006.05035

Isobar: $\Delta\gamma$ vs. invariant mass





resonance background

$$\Delta\gamma^{bkgd} \propto \langle\cos(\phi^\alpha + \phi^\beta - 2\phi^{\text{res}})\rangle v_2^{\text{res}}$$

resonance decay daughters | azimuthal angle of the resonance

Focus on contrasting two isobar systems. Assuming the background is proportional to v_2, then:

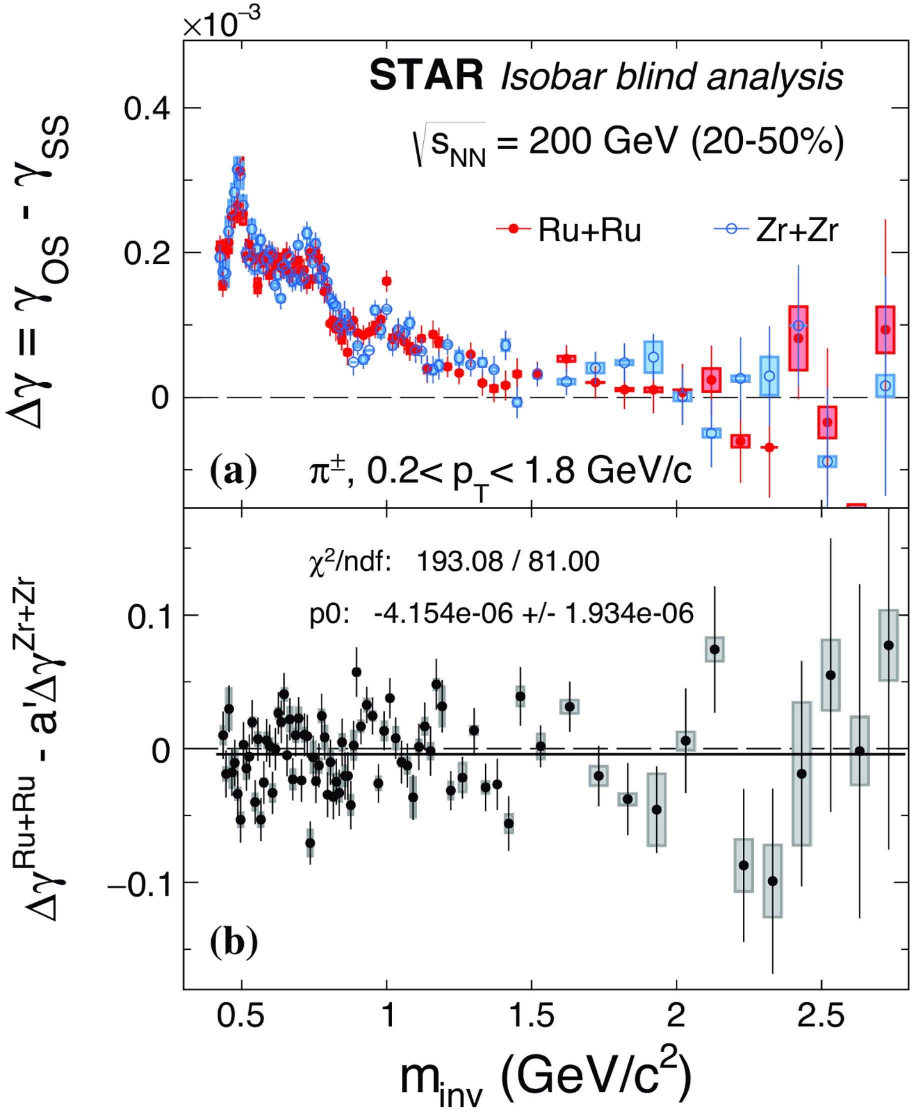
$$\Delta\gamma^{\text{Ru+Ru}} - a'\Delta\gamma^{\text{Zr+Zr}} = \Delta\gamma^{\text{Ru+Ru}}_{\text{CME}} - a'\Delta\gamma^{\text{Zr+Zr}}_{\text{CME}}$$

Where: $a' = v_2^{\text{Ru+Ru}}/v_2^{\text{Zr+Zr}}$

Pre-defined CME criterion in the differential measurement:

$$\Delta\gamma^{\text{Ru+Ru}} - a'\Delta\gamma^{\text{Zr+Zr}} > 0$$

Do not see a significant difference between systems



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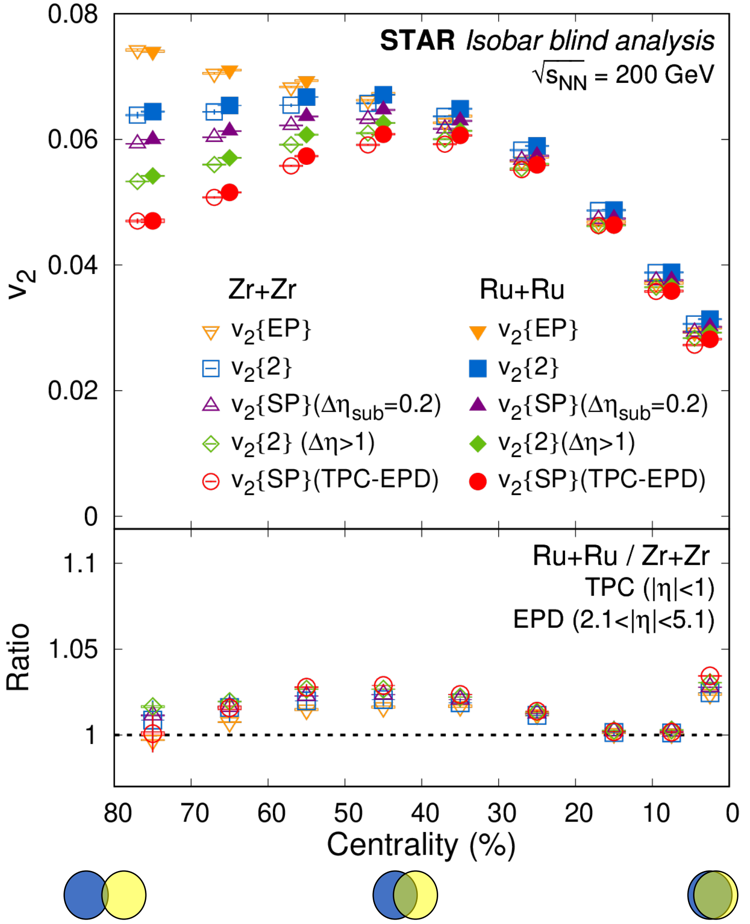
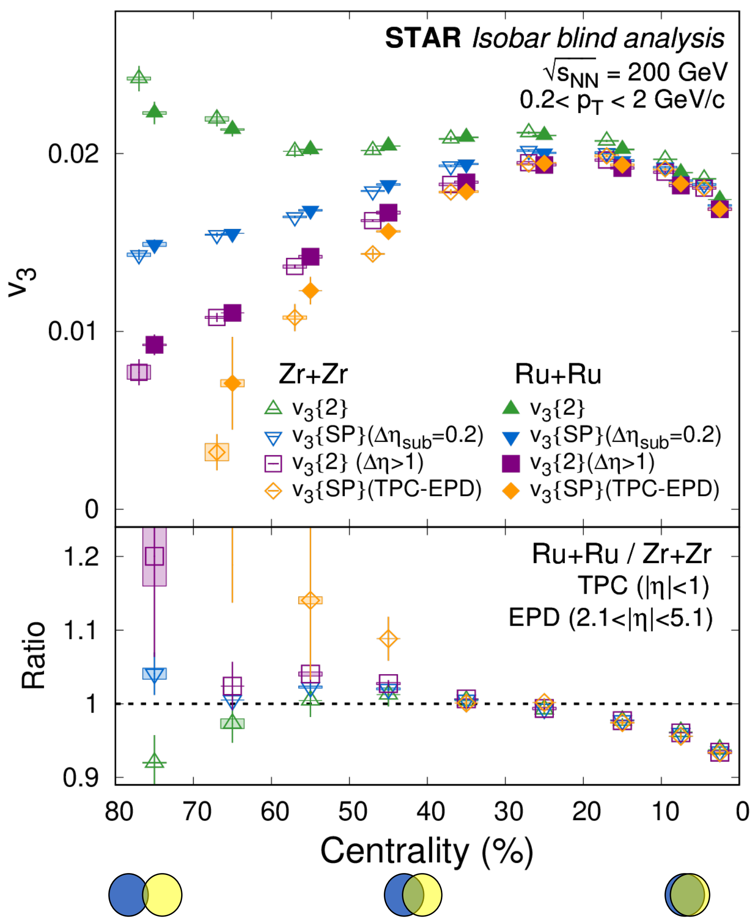
Isobar: Elliptic flow & triangular flow measurements





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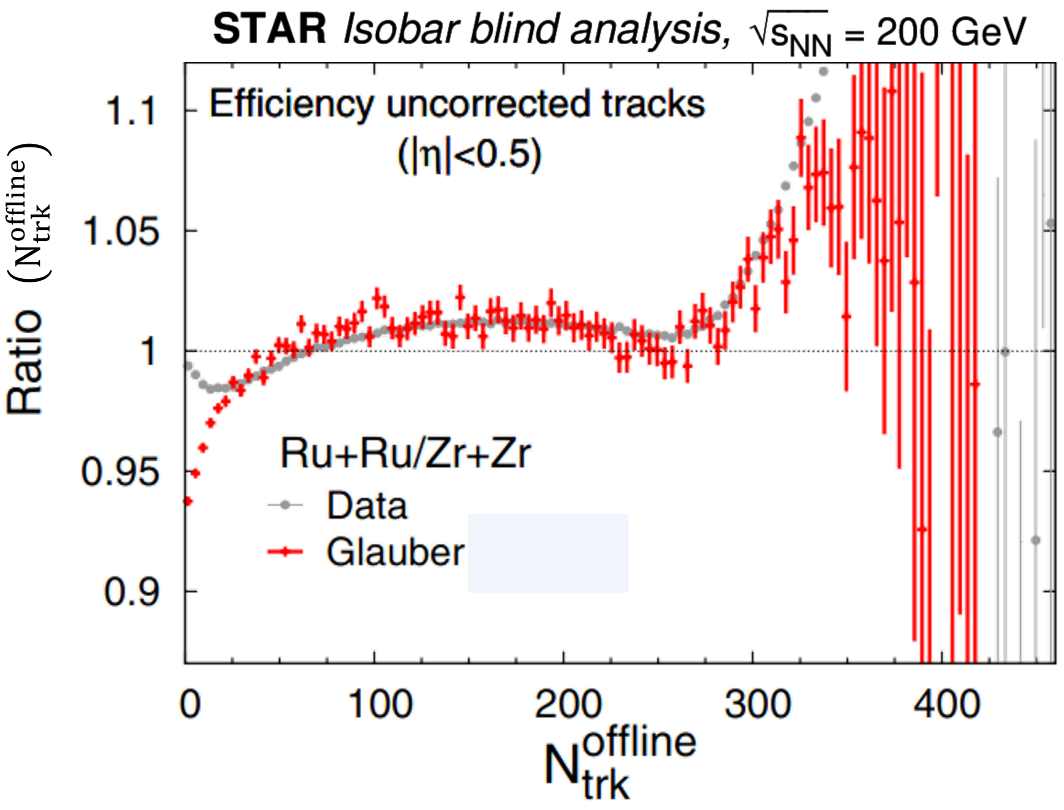
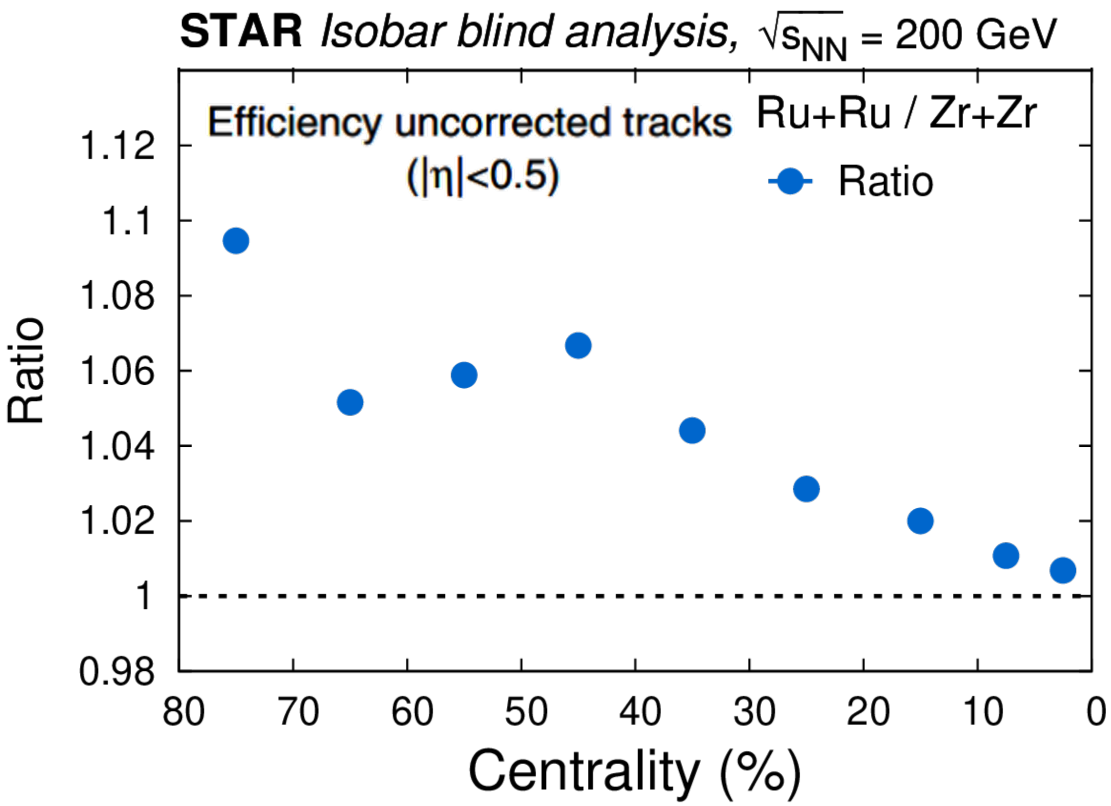
Isobar: Multiplicity and Centrality

	Glauber		
Nucleus	R (fm)	a (fm)	β_2
$^{96}_{44}$Ru	5.067	0.500	0
$^{96}_{40}$Zr	4.965	0.556	0



❖ Glauber model including larger size of Ru and smaller size of Zr provides a good fit to the multiplicity distribution.



❖ Mean raw multiplicity density in Ru+Ru is larger than in Zr+Zr at matching centrality

New Work: Measurement with EPD @ 27 GeV

$$\gamma_{\alpha\beta} = cos(\phi^{\alpha} + \phi^{\beta} - 2\Psi)$$

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

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.

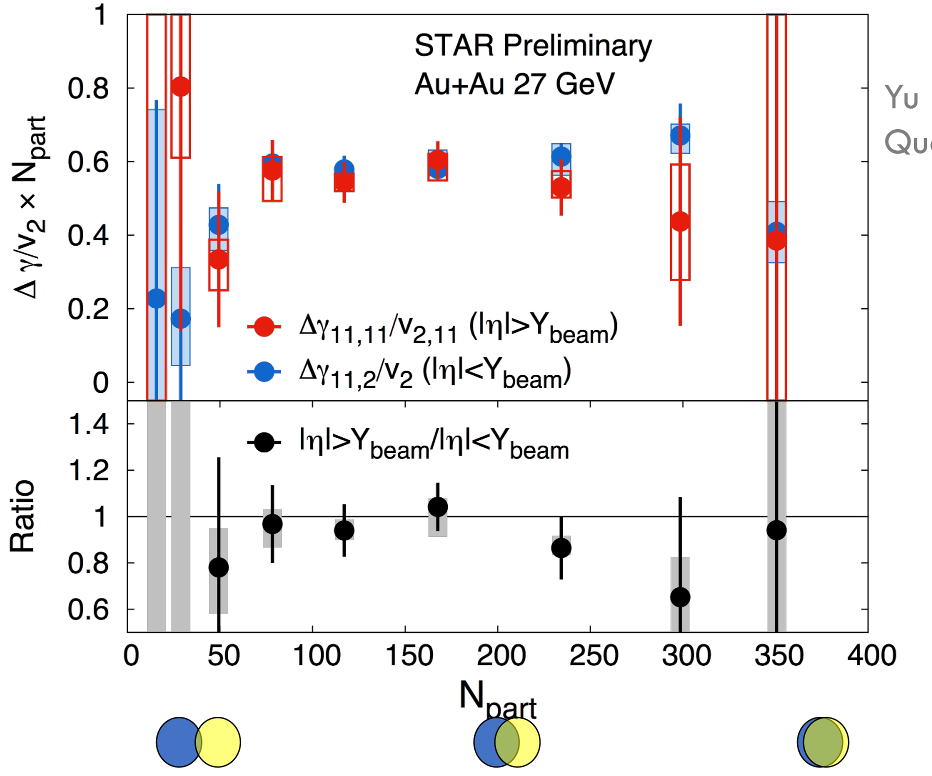
S. A. Voloshin, Phys. Rev. C 98 (2018) 054911

In a flow-driven background scenario, we expect

$$\frac{\Delta\gamma}{v_2}(\Psi_A) = \frac{\Delta\gamma}{v_2}(\Psi_B) = \frac{\Delta\gamma}{v_2}(\Psi_C) = \cdots$$

Where the Ψ_A, Ψ_B, Ψ_C… are different planes at same/similar rapidities

We measure the elliptic flow and the charge separation, using Δγ w.r.t. **TPC-EPD-inner first harmonic planes** and the **TPC-EPD-outer second harmonic plane**.



Yu Hu (STAR) Quark Matter 2022

The ratio of $\Delta\gamma/v_2$ between spectator proton rich EPD Ψ_1 plane and participant dominated Ψ_2 plane is presented — CME driven correlations will make this ratio >1.