The 9th International Conference on Quarks and Nuclear Physics
QNP 2022

Chiral Magnetic Effect search from isobar running at RHIC

Yu Hu[1,2](胡昱)

for the STAR collaboration

1. Lawrence Berkeley National Laboratory

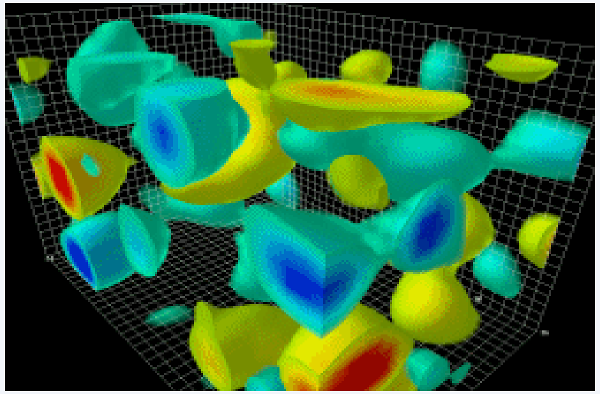
BERKELEY LAB

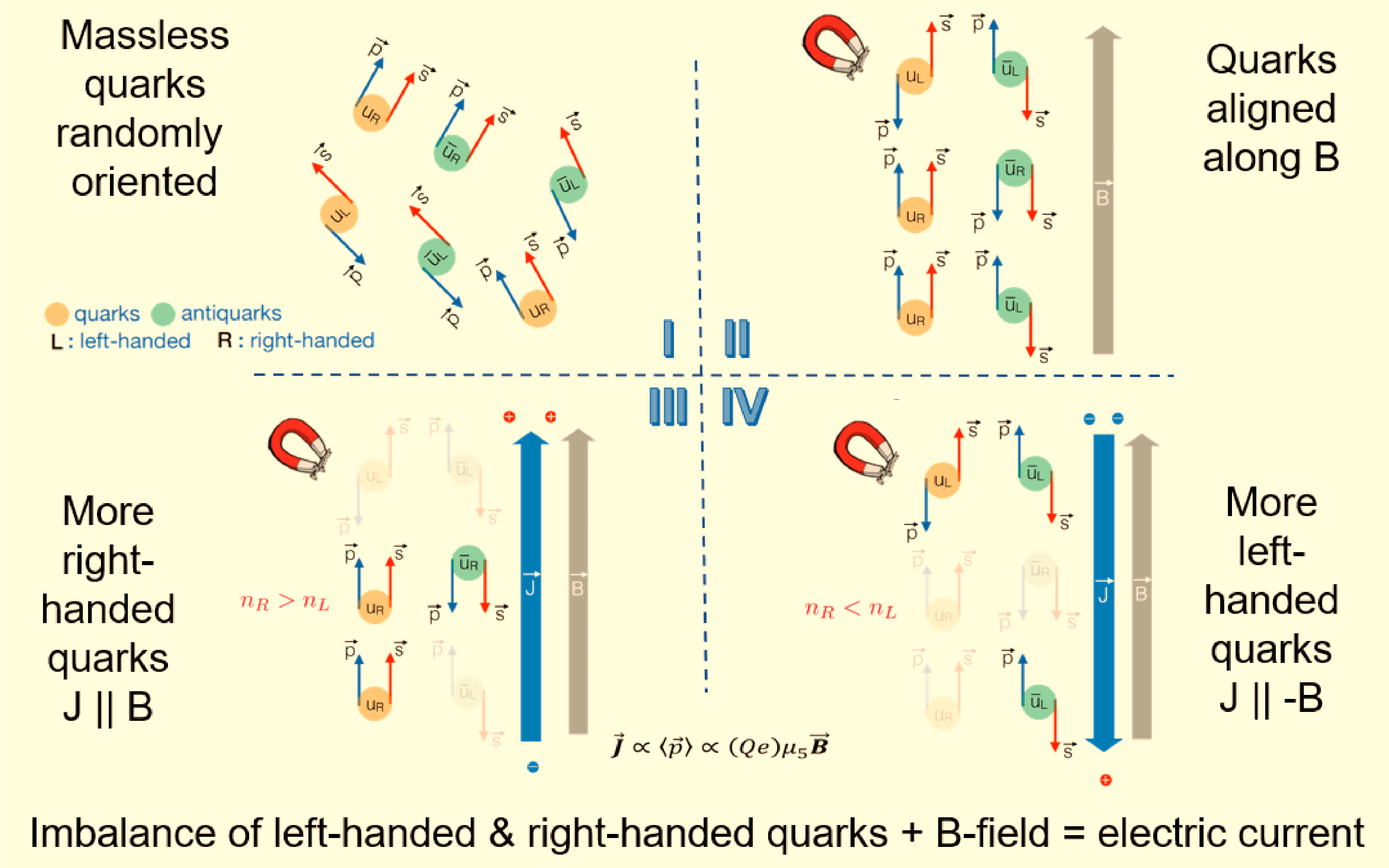
Supported by U.S. DEPARTMENT OF ENERGY Office of Science

2022.09.08

The Chiral Magnetic Effect (CME)

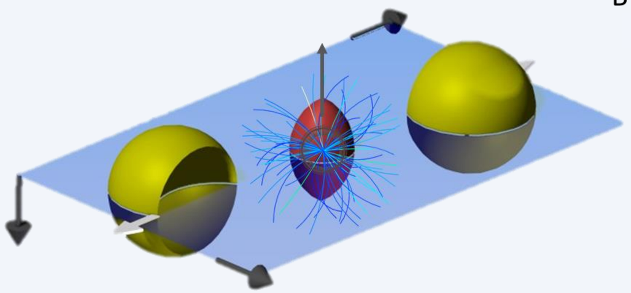
Derek B. Leinweber

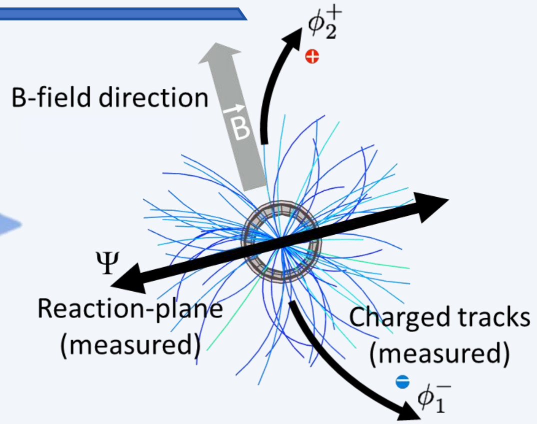




- Topological transitions in the QCD plasma are allowed to change the chirality of the quarks. The electric dipole can be used to observe such chirality-changing transitions
- With the strongest magnetic field that can be produced in experiment, **heavy ion collision**, the **chiral magnetic effect** is one of the most attractive phenomena

Experimental search with isobar collisions





Use $\Delta\gamma$ as an example:

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

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

Measurement — Signal — Background 1 — Background 2

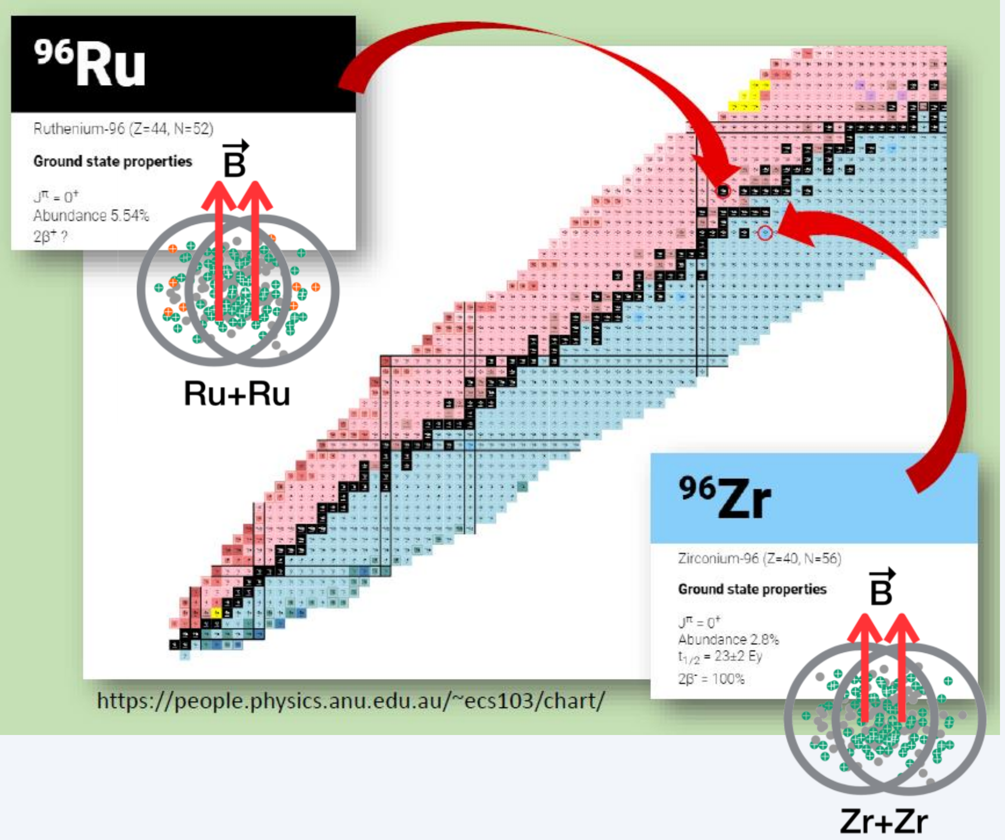
$$\Delta\gamma^{Ru+Ru} = \Delta\gamma^{CME} + k\frac{v_2}{N} + \Delta\gamma^{non-flow}$$

$\neq \quad \approx \quad =$

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

$\boldsymbol{B}^2$ is ~15% different

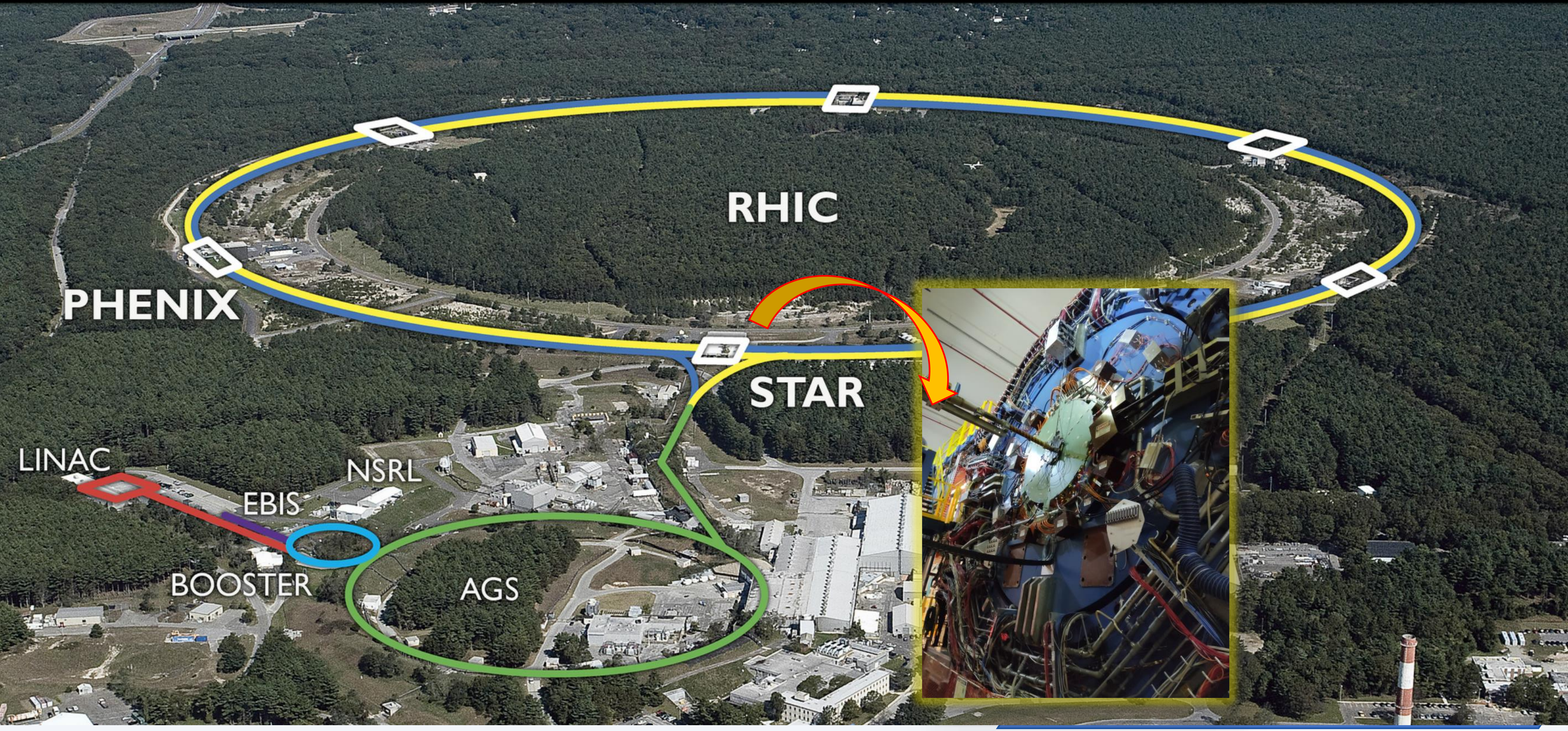
Within 4%



https://people.physics.anu.edu.au/~ecs103/chart/

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

The Solenoidal Tracker at RHIC (STAR):



Details of blind analysis

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

→

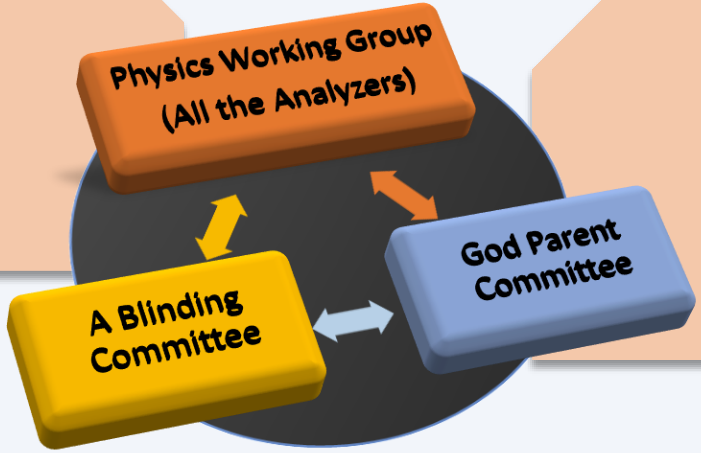
STEP-3
Isobar Unblind analysis
Final analysis (Ru+Ru & Zr+Zr separated)
~2-3 months

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.

A large, collective effort

Connections between the methods are studied



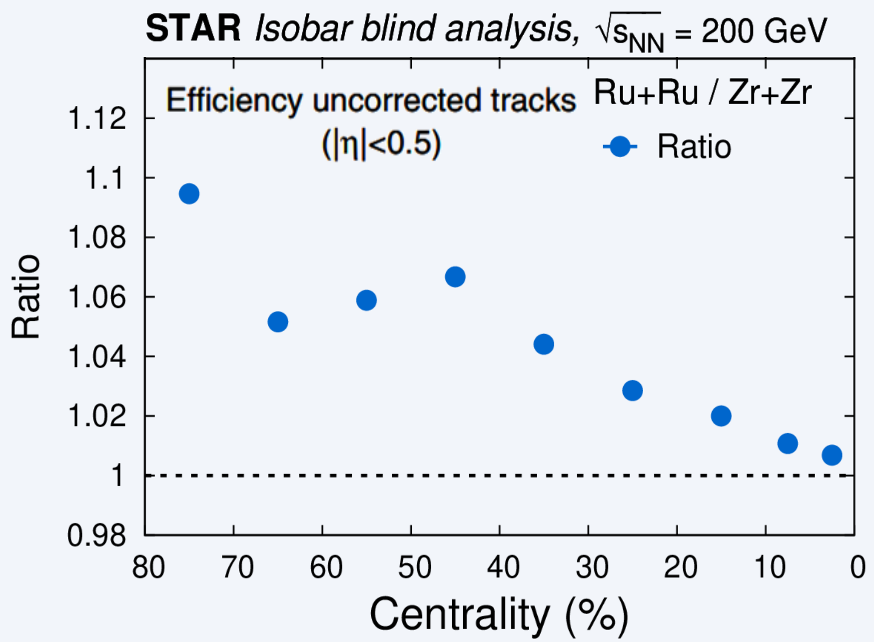
Using the frozen code from STEP-1:

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

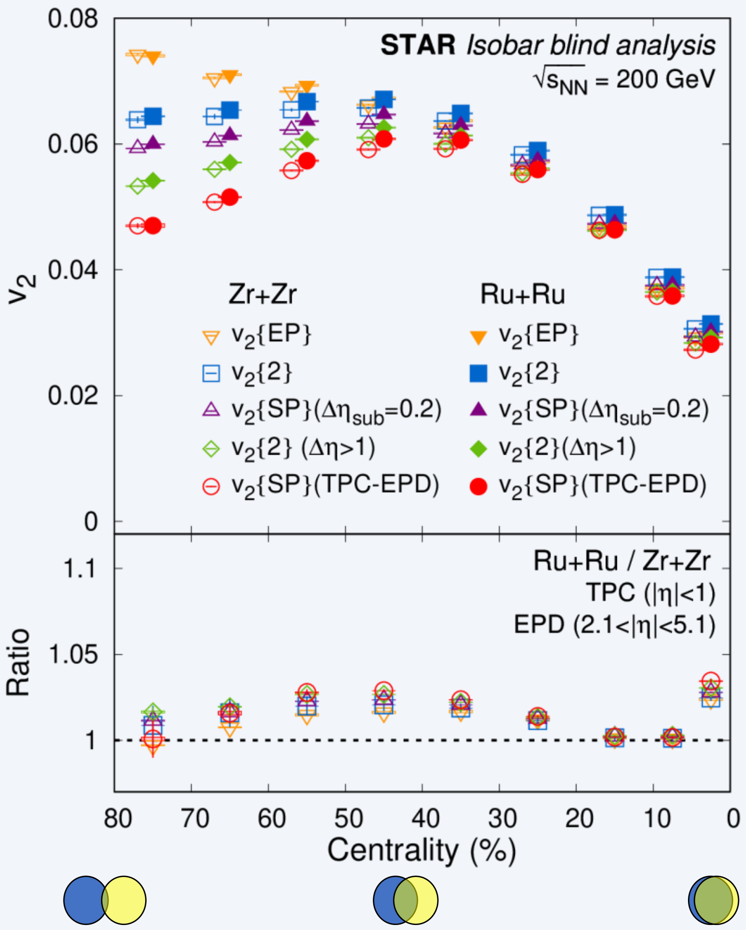
S. Choudhury *et al.* Chin. Phys. C, 46 (2022) 014101

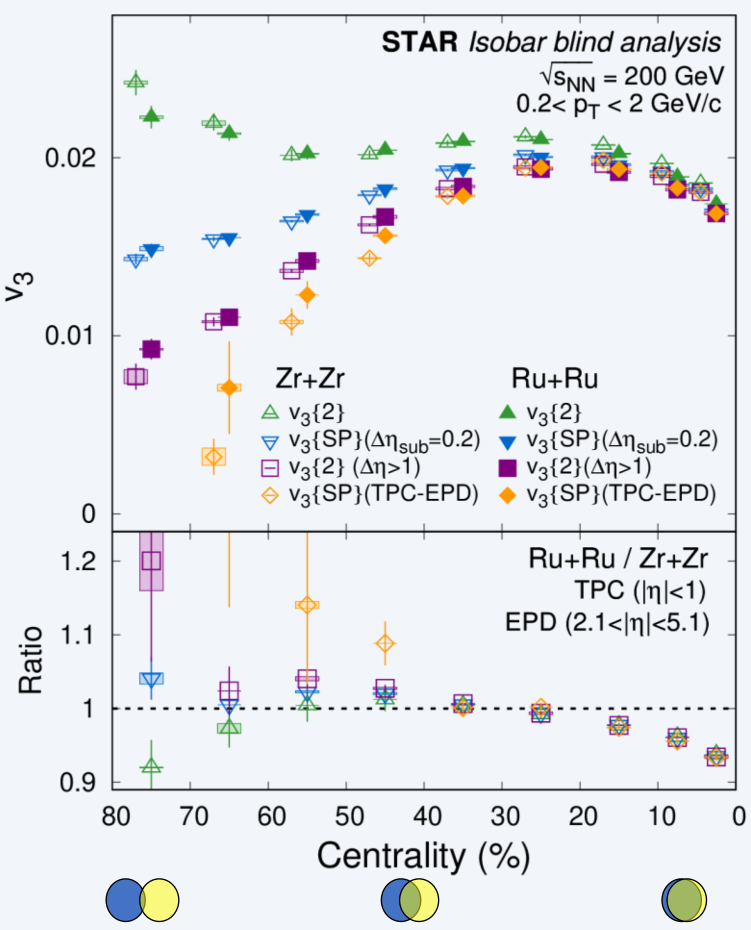
Flow measurements

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



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

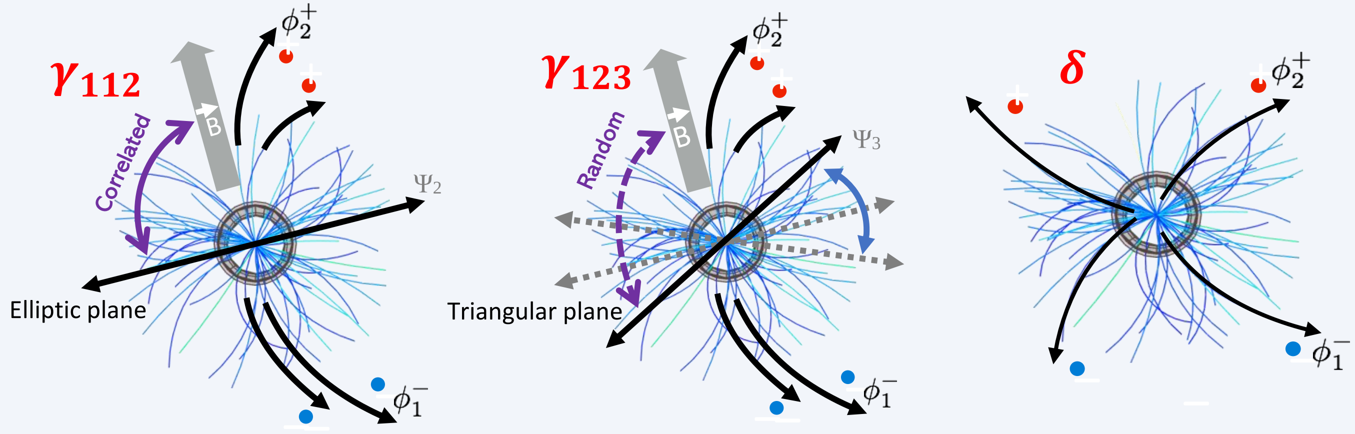




- v_n changes depending on the rapidity gap remind us of the non-flow effects in this analysis
- The v_n ratios deviate from unity indicating differences in the shape, nuclear structure between two isobars

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

1. γ measurement with full TPC ($|\eta| < 1$)



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

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

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

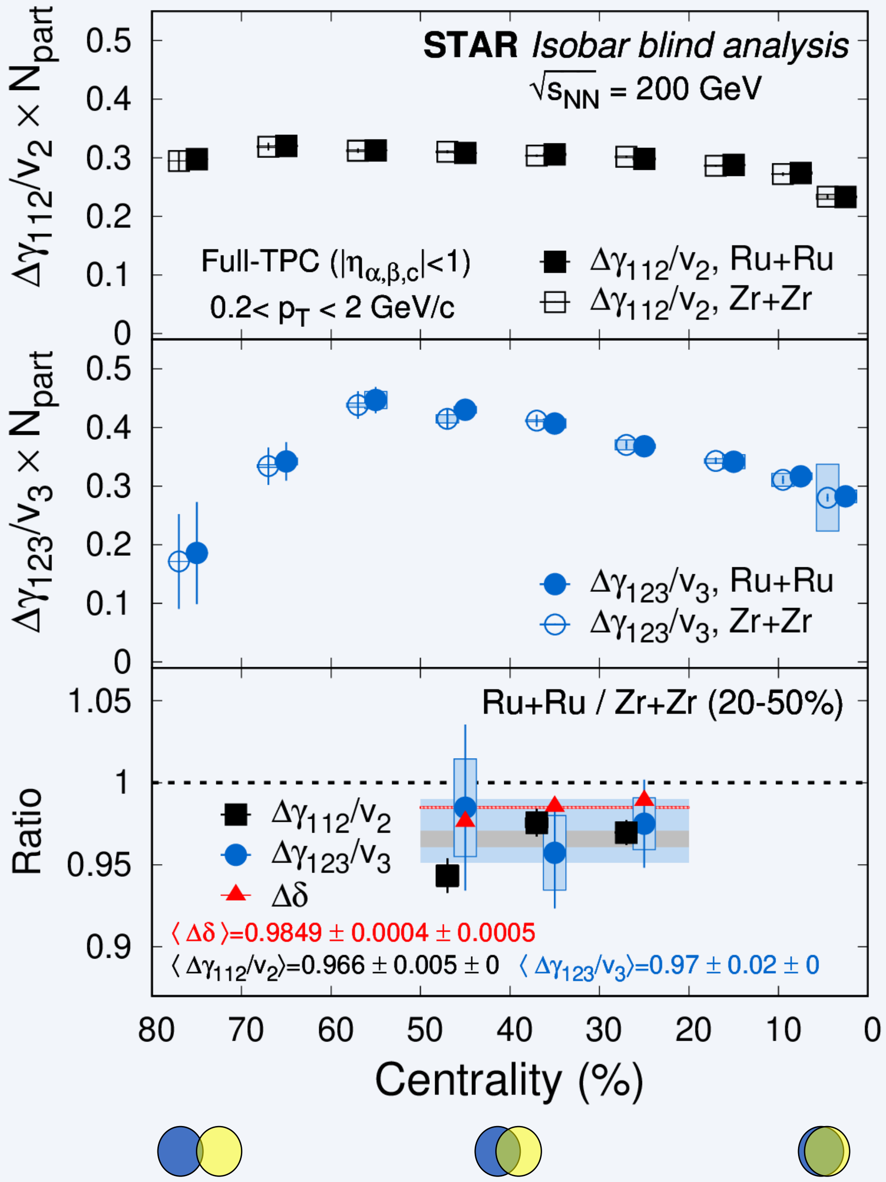
Pre-defined CME criteria:

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

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

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

Data not compatible with pre-defined CME criteria



2. κ_{112} measurement with full TPC ($|\eta| < 1$)

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

A.M. Sirunyan *et al.* (CMS) Phys. Rev. C, 97 (2018) 044912

Pre-defined CME criteria:

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

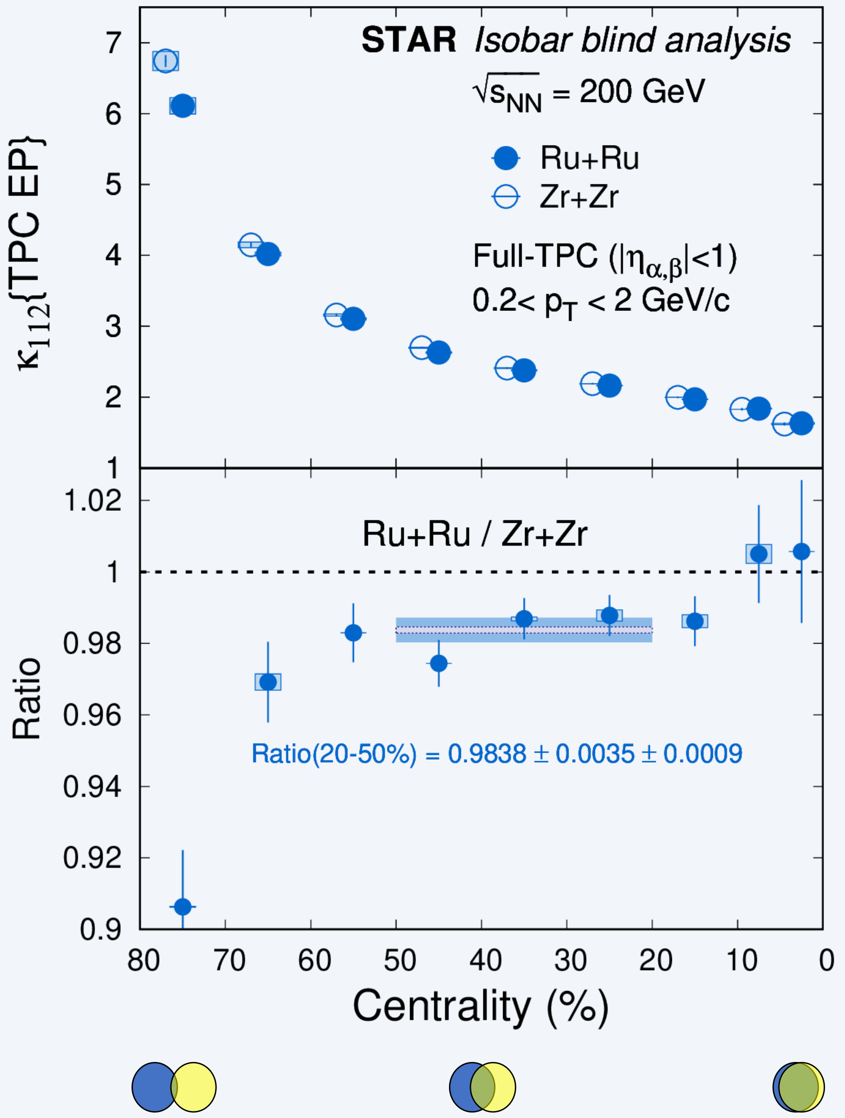
The background contributions due to the local charge conservation (LCC) and transverse momentum conservation (TMC) have a similar characteristic structure that involves the coupling between v_2 and δ. So, we studied the the normalized quantity:

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

Pre-defined CME criterion:

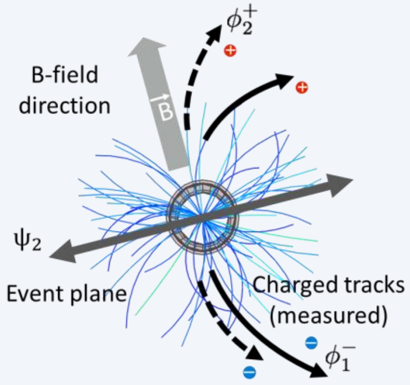
$$\frac{(\kappa_{112})^{\mathrm{Ru+Ru}}}{(\kappa_{112})^{\mathrm{Zr+Zr}}} > 1$$

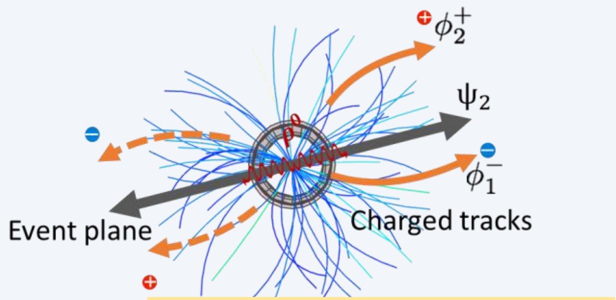
Data not compatible with pre-defined CME criterion



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

3. Differential measurement vs. invariant mass





resonance background

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

resonance decay daughters | azimuthal angle of the resonance

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

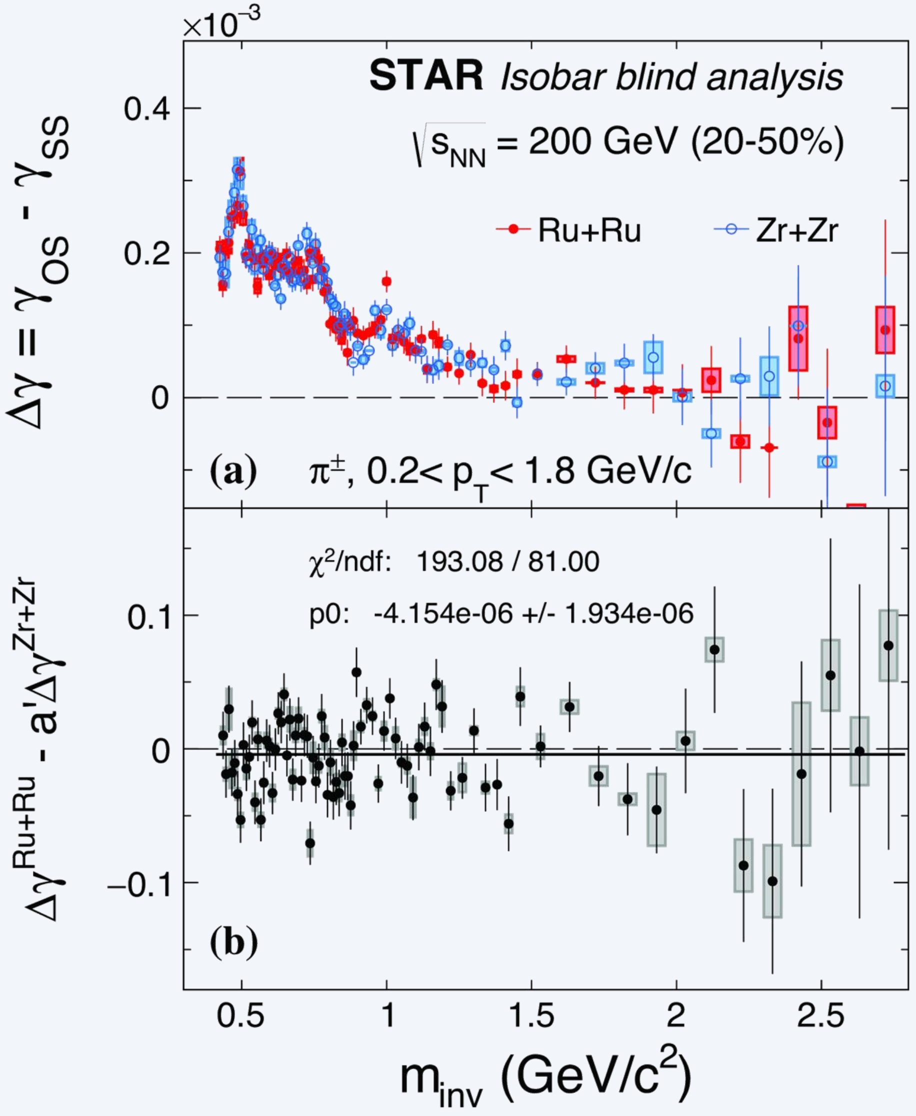
$$\Delta\gamma^{\mathrm{Ru+Ru}} - a'\Delta\gamma^{\mathrm{Zr+Zr}} = \Delta\gamma^{\mathrm{Ru+Ru}}_{\mathrm{CME}} - a'\Delta\gamma^{\mathrm{Zr+Zr}}_{\mathrm{CME}}$$

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

Pre-defined CME criterion in the differential measurement:

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

Do not see a significant difference between systems



4. 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.

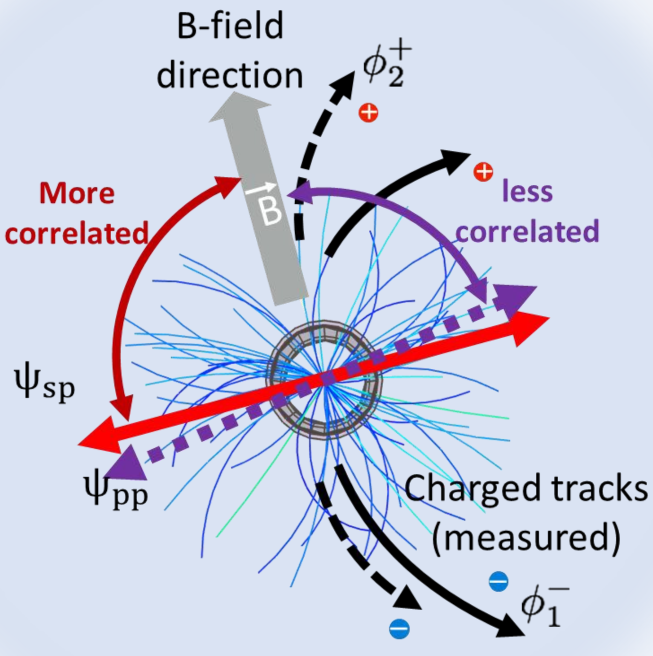
$$\Delta\gamma(\Psi_{TPC}) = \Delta\gamma^{BG}(\Psi_{TPC}) + \Delta\gamma^{CME}(\Psi_{TPC}) \quad ①$$

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

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

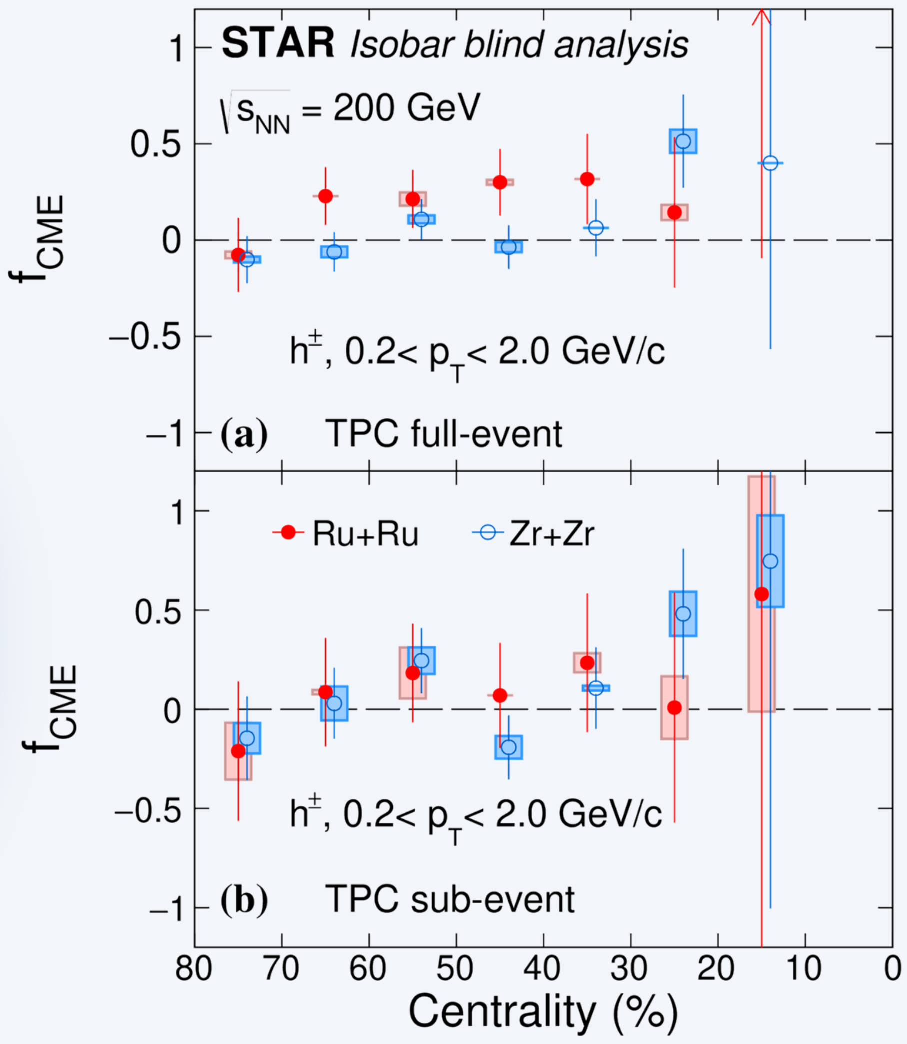
$$\frac{\Delta\gamma^{CME}(\Psi_{TPC})}{\Delta\gamma^{CME}(\Psi_{ZDC})} = \frac{v_2(\Psi_{ZDC})}{v_2(\Psi_{TPC})} \quad ④$$

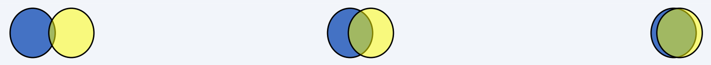
$$f_{CME} = \frac{\Delta\gamma^{CME}(\Psi_{TPC})}{\Delta\gamma(\Psi_{TPC})} \quad ⑤$$



Pre-defined CME criterion:

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





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

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

4. Extraction of CME fraction: approach II

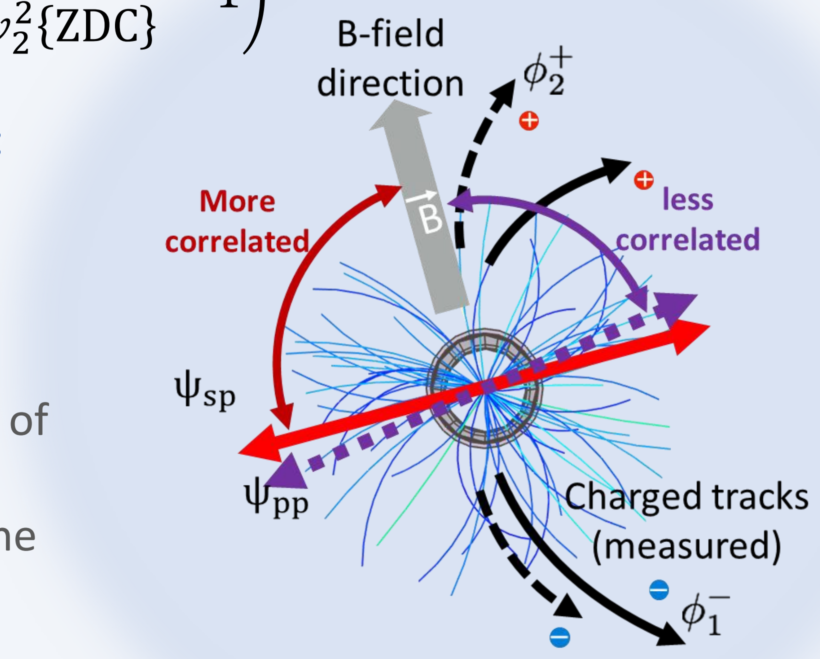
$$\frac{(\Delta\gamma/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma/v_2)^{\mathrm{Zr+Zr}}} = 1 + f_{\mathrm{CME}}^{\mathrm{Zr+Zr}}\left[\left(B^{\mathrm{Ru+Ru}}/B^{\mathrm{Zr+Zr}}\right)^2 - 1\right]$$

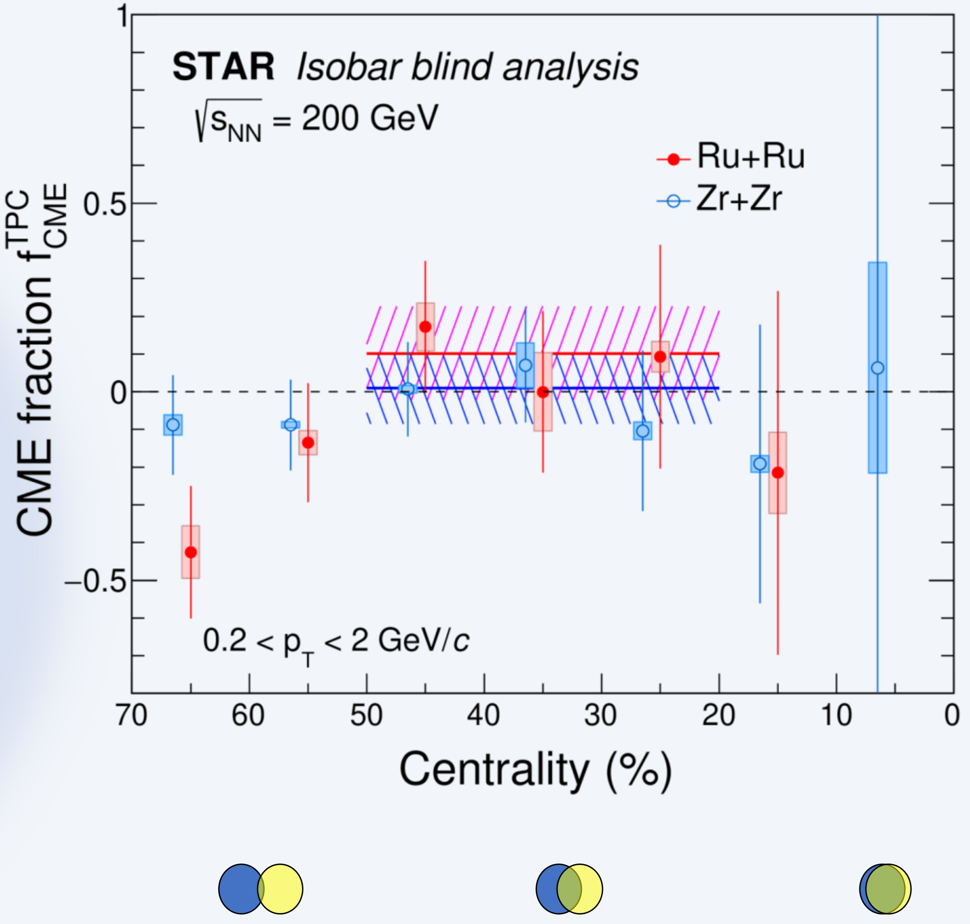
$$\frac{(\Delta\gamma/v_2)_{\mathrm{ZDC}}}{(\Delta\gamma/v_2)_{\mathrm{TPC}}} = 1 + f_{\mathrm{CME}}^{\mathrm{TPC}}\left(\frac{v_2^2\{\mathrm{TPC}\}}{v_2^2\{\mathrm{ZDC}\}} - 1\right)$$

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

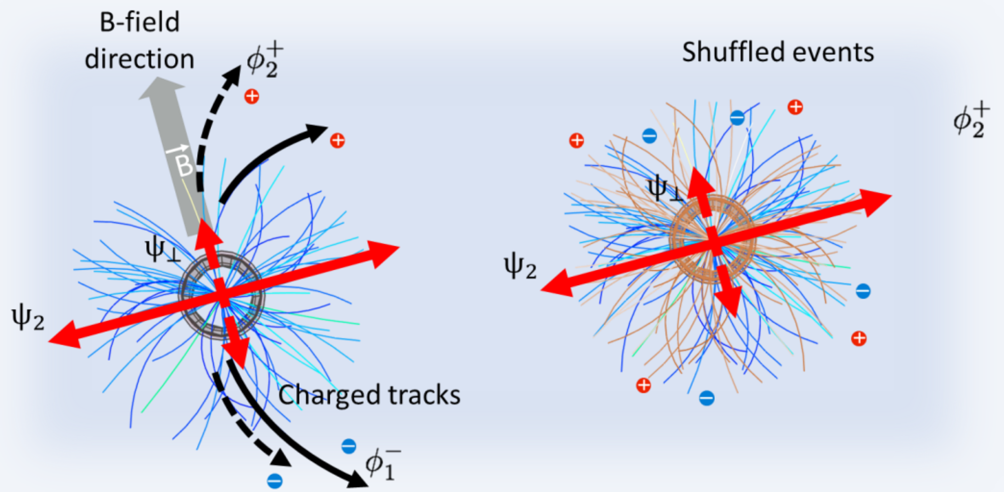




Uncertainty dominated, no significant difference is observed between two isobar systems

5. Charge separation measurement with R_{Ψ_2}

M. S. Abdallah *et al.* (STAR) Phys. Rev. C, 105 (2022) 014901
N. Magdy *et al.* Phys. Rev. C, 96 (2018) 061901
S. Choudhury *et al.* Chin. Phys. C, 46 (2022) 014101



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

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

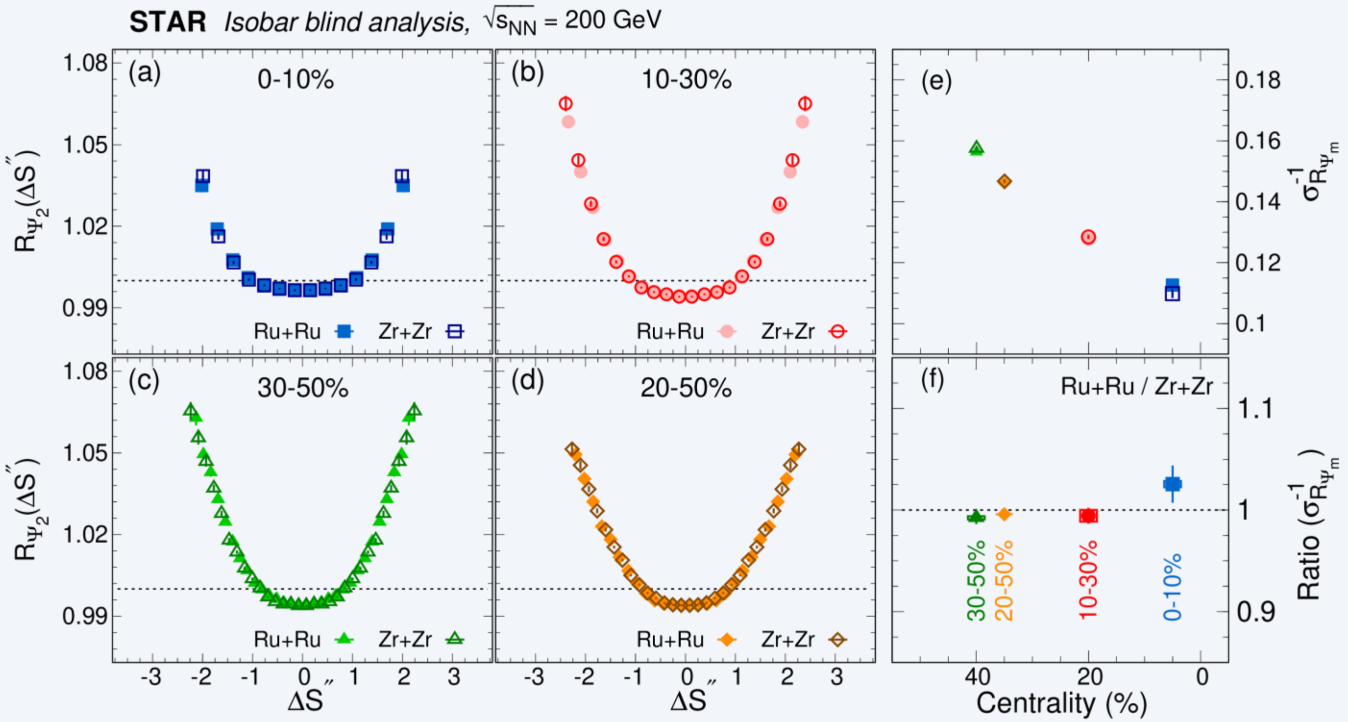
$$\Delta S = \frac{\sum_{i=1}^{n+} w_i^+ \sin(\Delta\phi_i - \Psi_2)}{\sum_{i=1}^{n+} w_i^+} - \frac{\sum_{i=1}^{n-} w_i^- \sin(\Delta\phi_i - \Psi_2)}{\sum_{i=1}^{n-} w_i^-}$$

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

Pre-defined CME criterion:

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



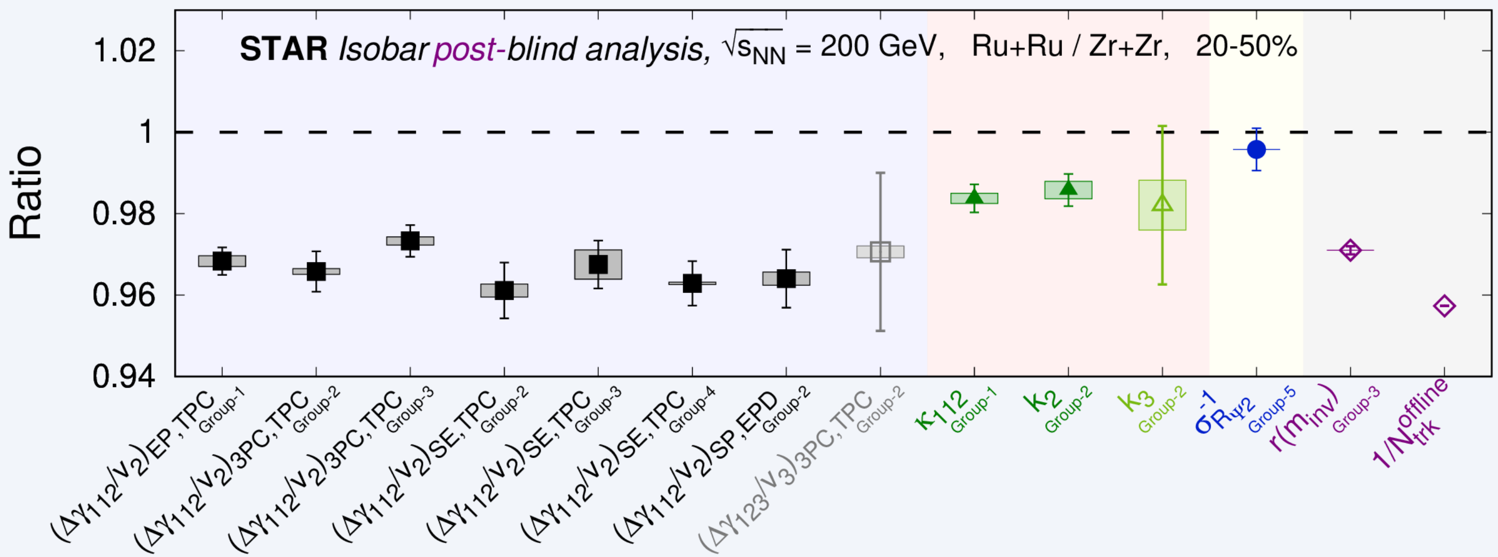
No significant difference is observed between two isobar systems

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

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

Summary on the isobar blind analysis

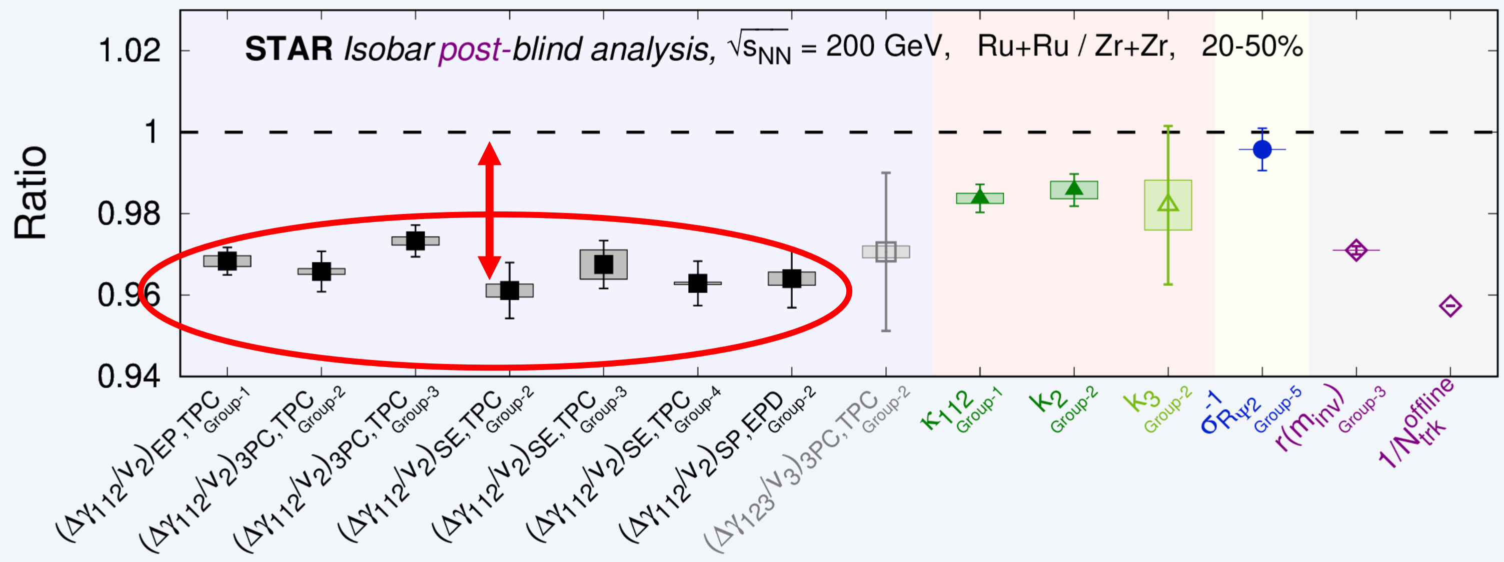


From the blind analysis

- No pre-defined criterion is satisfied for the observation of CME
- Precision of 0.4% is reached in the ratio of observables between 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

Summary on the isobar blind analysis



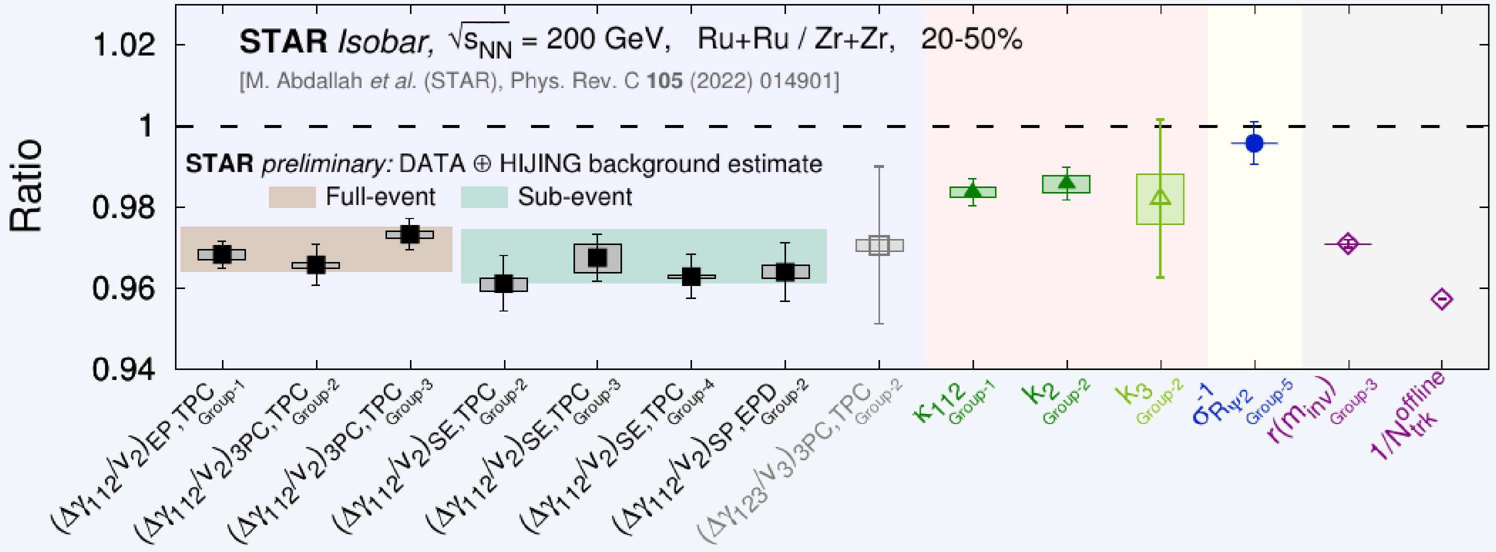
From the blind analysis

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

Non-flow studies (new since isobar paper)

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

Y. Feng (STAR). Poster in QM 2022



From the blind analysis

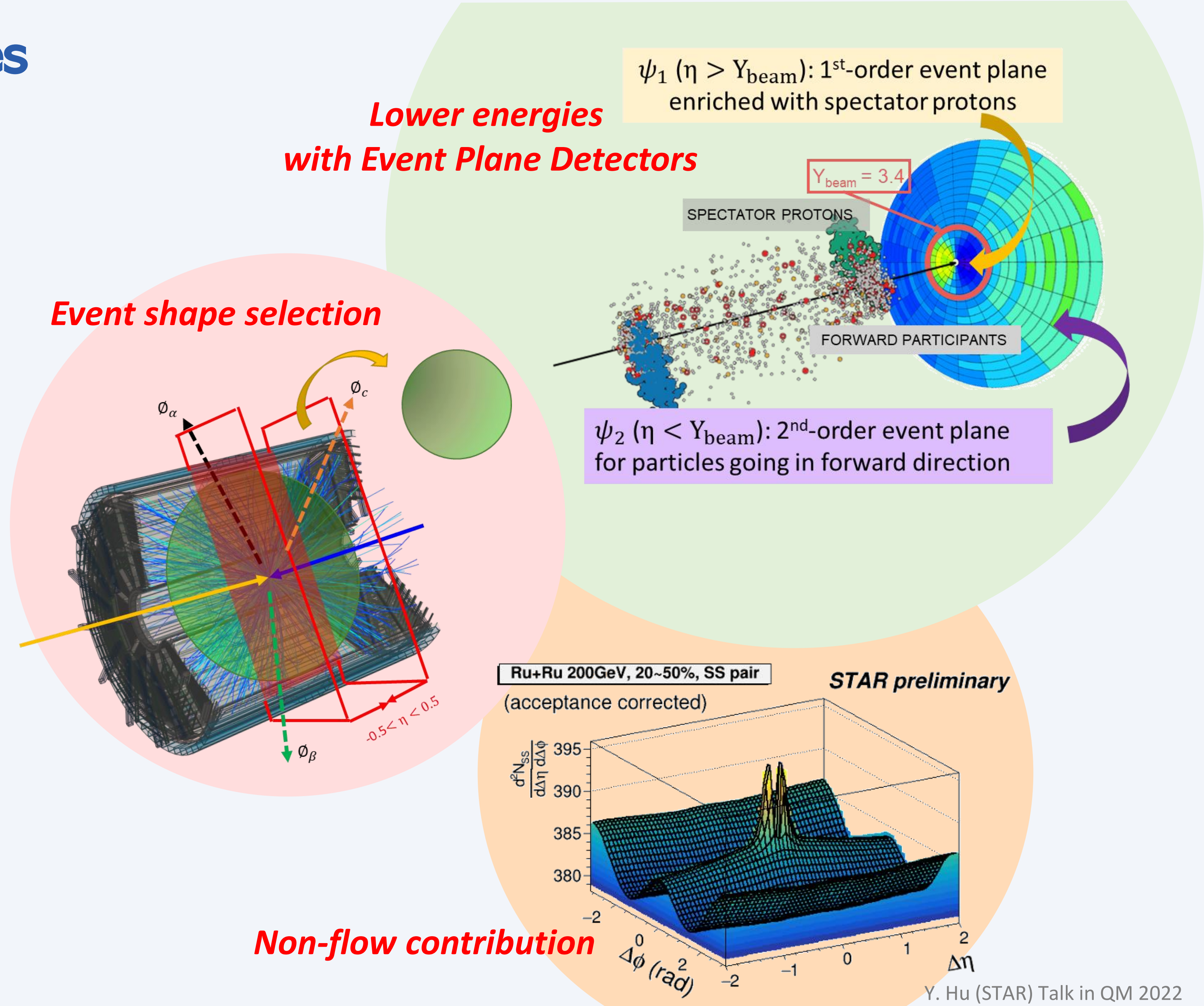
- No pre-defined criterion is satisfied for the observation of CME
- Precision of 0.4% is reached in the ratio of observables between two systems
- **$\Delta\gamma/v_2$ ratios are below unity - mainly driven by the multiplicity difference between the two isobars**

Non-flow study to understand $N\Delta\gamma/v_2$ measurements in isobar

- ❖ Non-flow contribution will cause extra deviations
- ❖ The deviation can be understood by non-flow in the measured v_2 (estimated with data) , the flow-induced CME background (estimated with data), and 3-particle non-flow contributions (estimated with HIJING)
- ❖ The isobar data are consistent with the current estimate of non-flow background within uncertainties

Summary and new oppotunities

- No pre-defined criterion is satisfied for the observation of CME
- Precision of 0.4% is reached in the ratio of observables between two systems
- The ongoing non-flow effect studies show the isobar data are consistent with the current estimate of non-flow background within the uncertainties



Y. Hu (STAR) Talk in QM 2022
Y. Feng (STAR). Poster in QM 2022

Thank you!

BERKELEY LAB

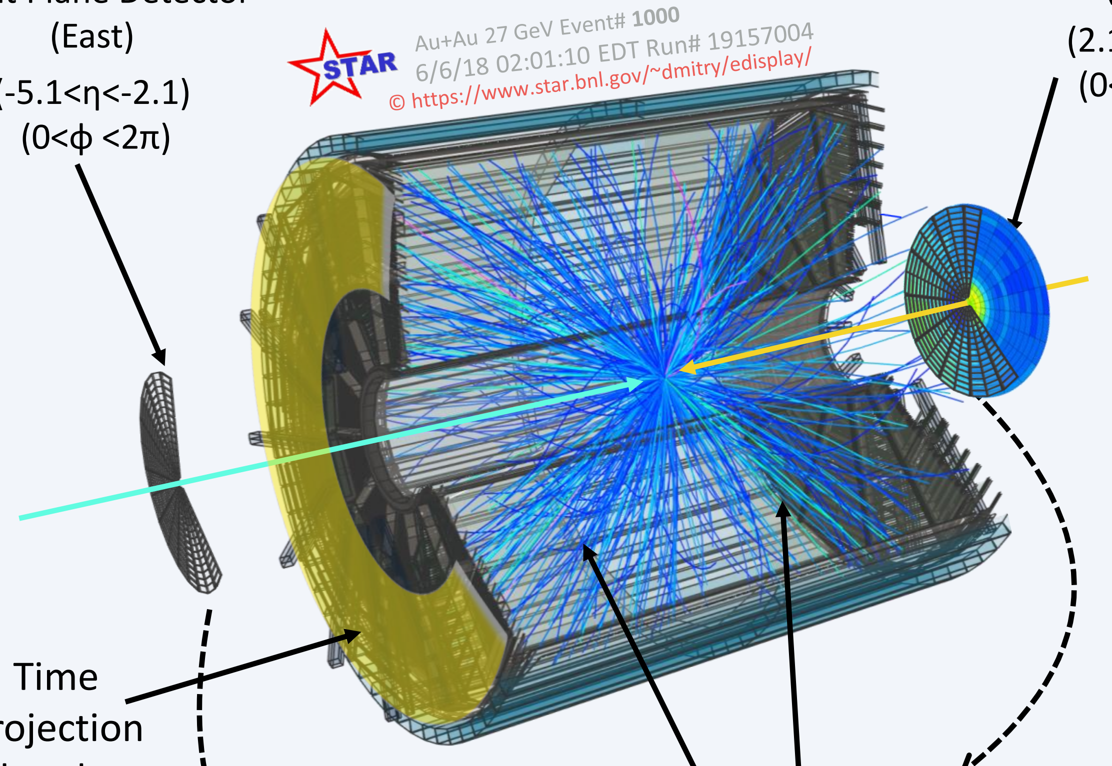
Supported by
U.S. DEPARTMENT OF
ENERGY

Backup

Approach-I: measurement with the Event Plane Detector (EPD)

Event Plane Detector (East)
(-5.1<η<-2.1)
(0<ϕ <2π)

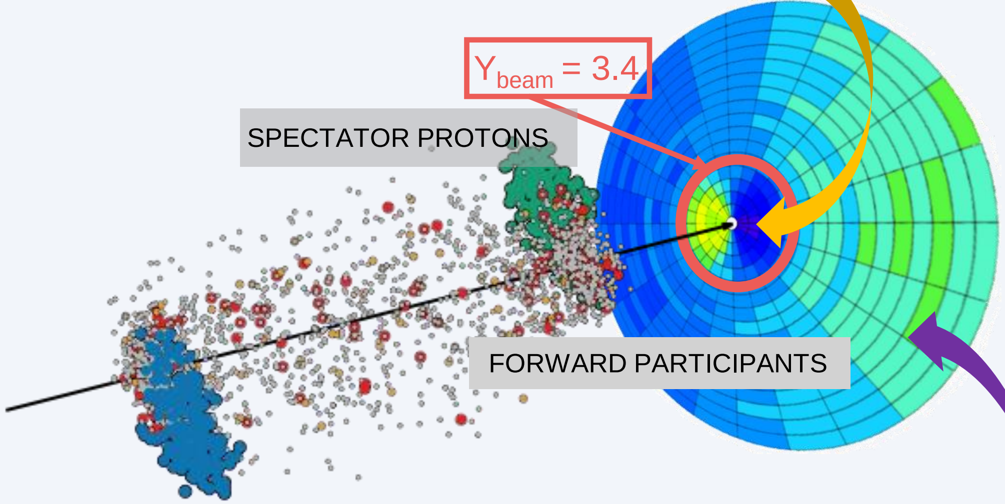
Event Plane Detector (West)
(2.1<η<5.1)
(0<ϕ <2π)



Time Projection Chamber
(-1<η<1)
(0<ϕ <2π)

$$\gamma^{\alpha,\beta} \equiv \left\langle \cos\left(\phi_a^\alpha + \phi_b^\beta - 2\psi_{RP}\right)\right\rangle$$

ψ_1 ($\eta > Y_{beam}$): 1st-order event plane enriched with spectator protons



The inner region of EPD detects spectator protons, whose directed flow signal has an opposite direction compared to the outer sectors that are dominated by the participants.

ψ_2 ($\eta < Y_{beam}$): 2nd-order event plane for particles going in forward direction

We measure charge-dependent azimuthal correlator using TPC and EPD

Approach-I: 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 the background scenario, all these ratios equal one to another. If two different measurements yield different ratios, this would indicate the CME signal.

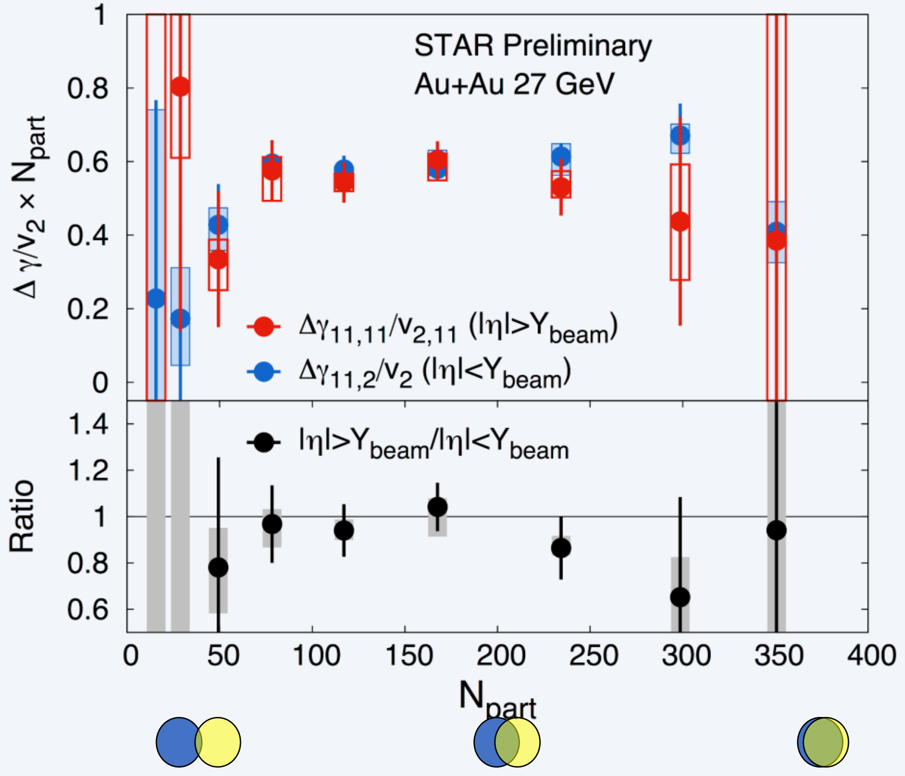
S. A. Voloshin, Phys. Rev. C 98 (2018) 054911

In a short word, under the flow driven background scenario, we should have:

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

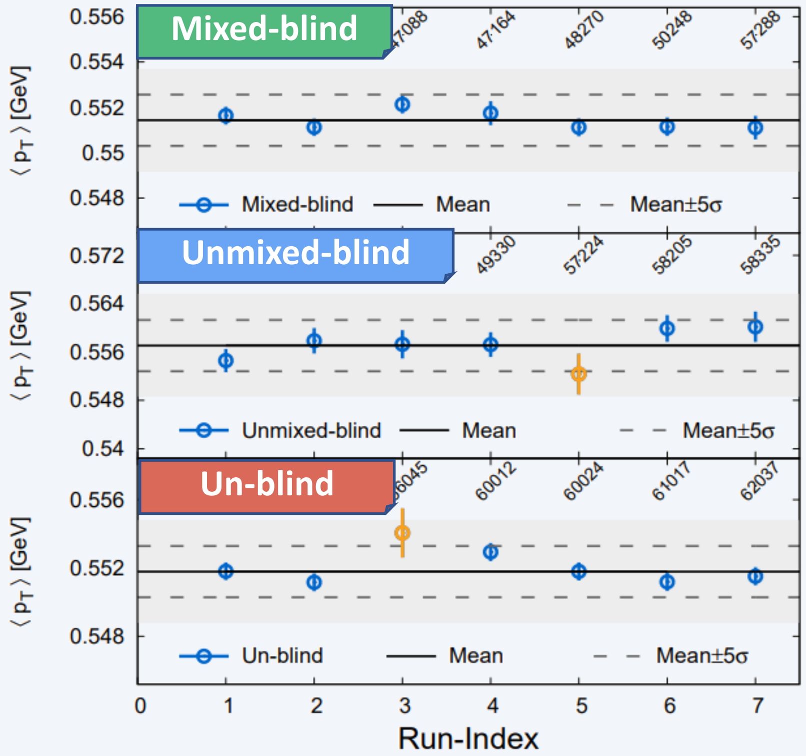
Where the Ψ_A, Ψ_B, Ψ_C… are different planes at same/similar rapidities

We measure the elliptic flow and the charge separation, using γ correlator (Δγ=γ(OS)-γ(SS)), w.r.t. **TPC-EPD-inner first harmonic planes** and the **TPC-EPD-outer second harmonic plane**.



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.

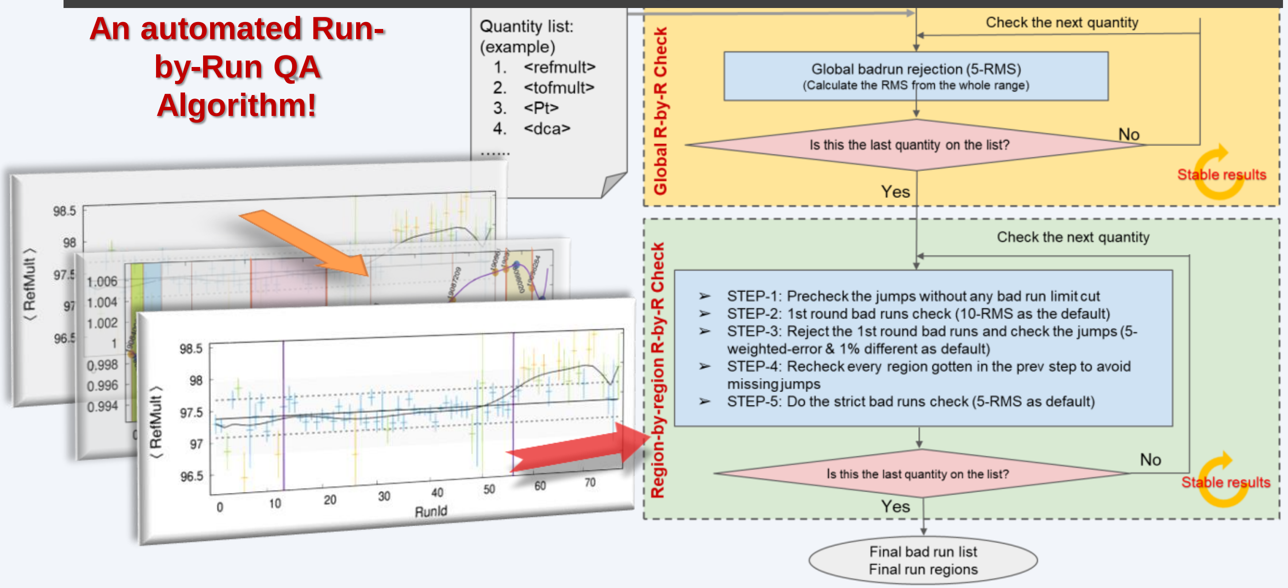
Details in the isobar blind analysis



Fully automated algorithm developed for blind QA

How do we define the stable run period before we have the data?

An automated Run-by-Run QA Algorithm!



Equations in the non-flow studies

$$\frac{(N\Delta\gamma/\mathrm{v}_2)^{\mathrm{Ru+Ru}}}{(N\Delta\gamma/\mathrm{v}_2)^{\mathrm{Ru+Ru}}} \equiv \frac{(NC_3/v_2)^{\mathrm{Ru+Ru}}}{(NC_3/v_2)^{\mathrm{Zr+Zr}}}$$

$$\approx \frac{\epsilon_2^{\mathrm{Ru+Ru}}}{\epsilon_2^{\mathrm{Zr+Zr}}} \frac{(1+\epsilon_{\mathrm{non-flow}})^{\mathrm{Ru+Ru}}}{(1+\epsilon_{\mathrm{non-flow}})^{\mathrm{Zr+Zr}}} \frac{\left[1+\frac{\epsilon_3}{\epsilon_2}/\left(Nv_{2-\mathrm{measured}}^2\right)\right]^{\mathrm{Ru+Ru}}}{\left[1+\frac{\epsilon_3}{\epsilon_2}/\left(Nv_{2-\mathrm{measured}}^2\right)\right]^{\mathrm{Zr+Zr}}}$$

$$\approx 1 + \frac{\Delta\epsilon_2}{\epsilon_2} - \frac{\Delta\epsilon_{non-flow}}{1+\epsilon_{non-flow}} + \frac{\frac{\epsilon_3}{\epsilon_2}/\left(Nv_{2-measured}^2\right)}{1+\frac{\epsilon_3}{\epsilon_2}/\left(Nv_{2-measured}^2\right)}[\ldots]$$