Search for the Chiral Effect using isobar collisions and BES-II data from STAR

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for the STAR collaboration

1. Fudan University; 2. Brookhaven National Laboratory

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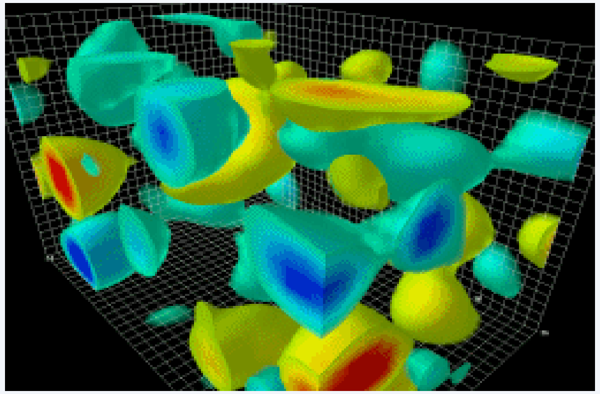
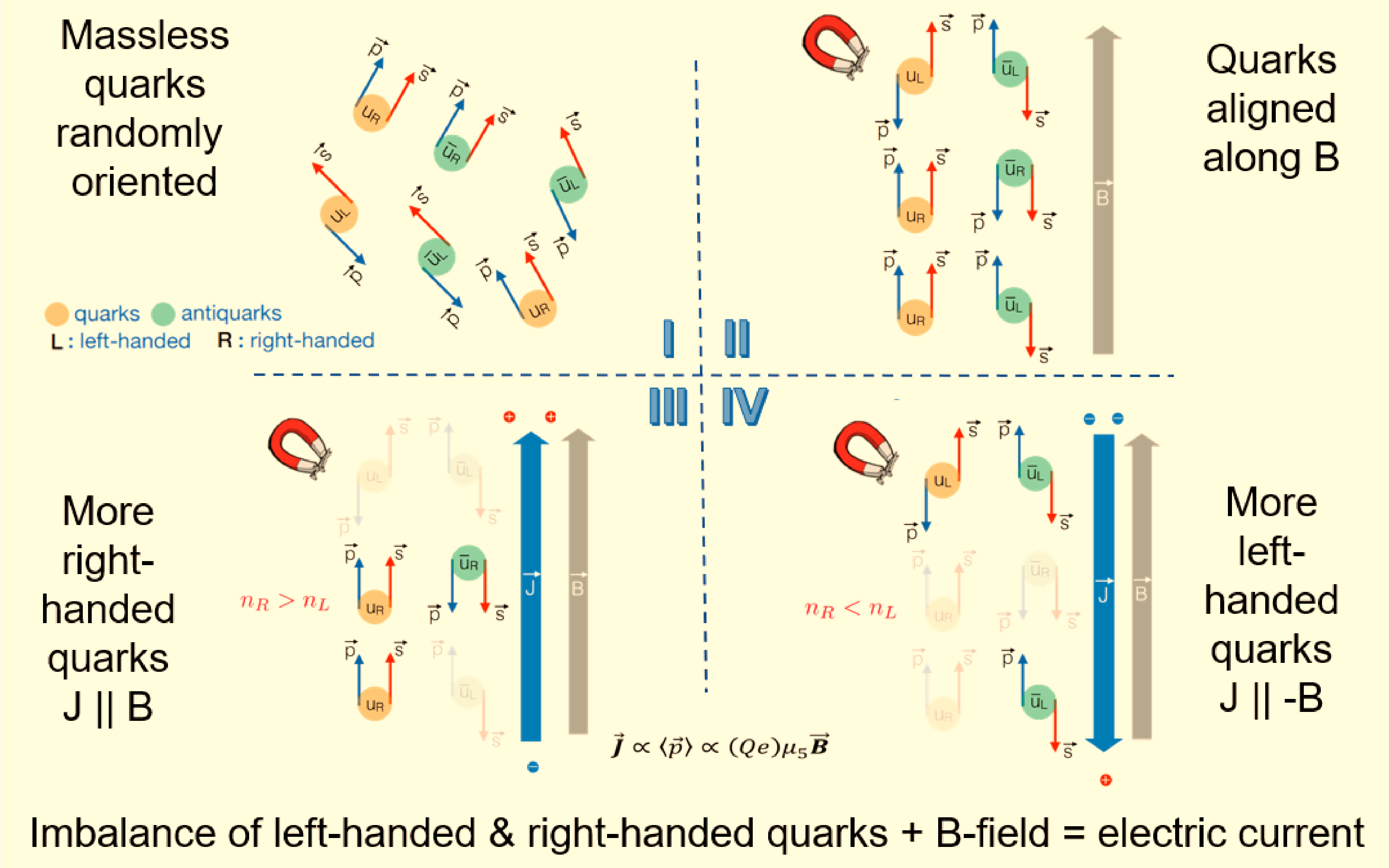
2022.04.07

The Chiral Magnetic Effect (CME)

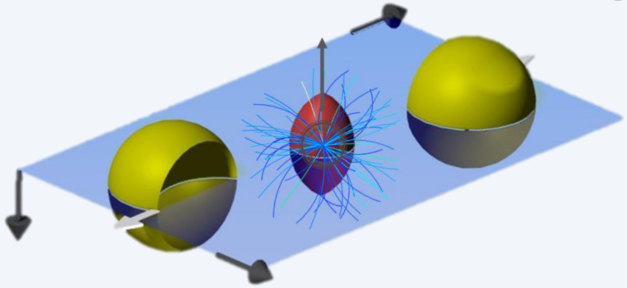
Derek B. Leinweber

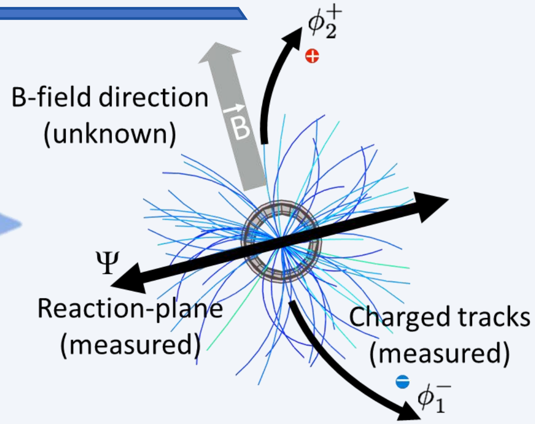




- Topological transitions in the QCD plasma are allowed to change the chirality of the quarks. The electric dipole can be used to observe such chirality-changing transitions
- With the strongest magnetic field that can be produced in experiment, **heavy ion collision**, the **chiral magnetic effect**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

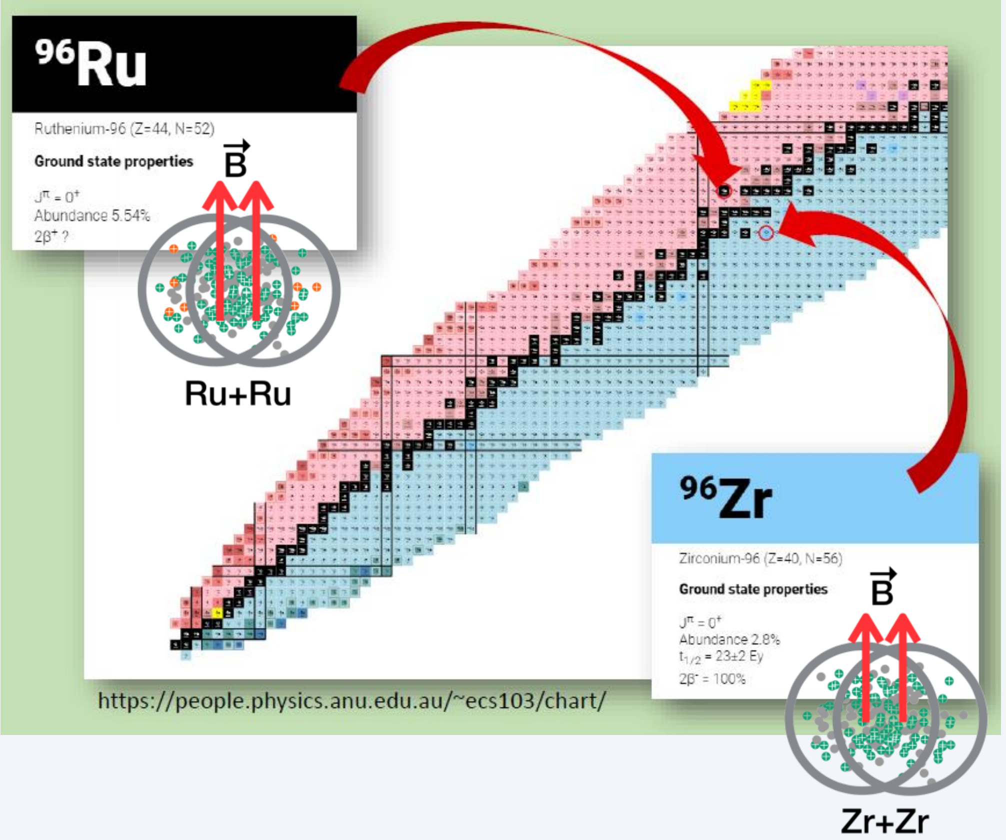
$$\Delta\gamma^{Ru+Ru} = \Delta\gamma^{CME} + k\frac{v_2}{N} + \Delta\gamma^{non-flow}$$

$$\neq \qquad \approx \qquad =$$

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

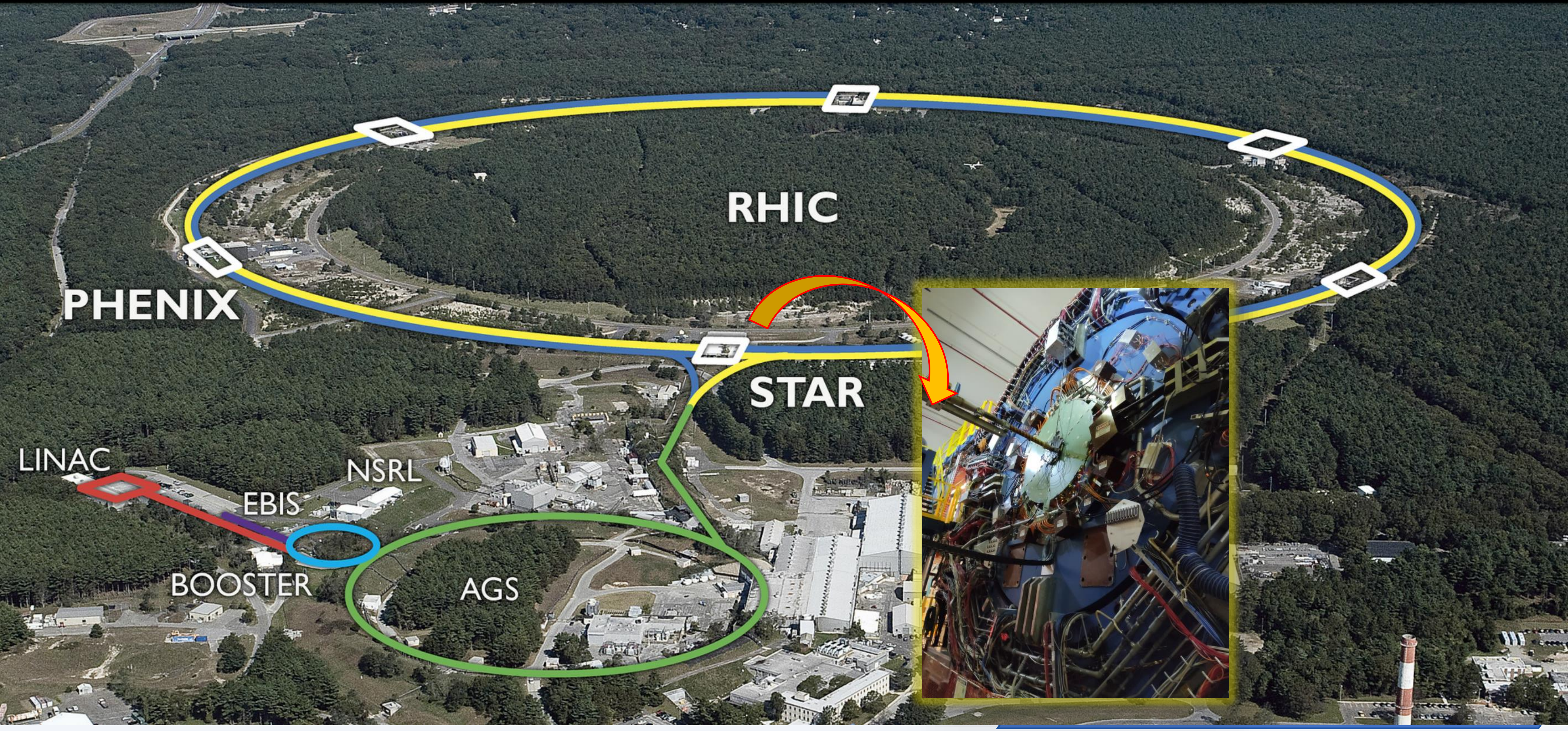
$\boldsymbol{B}^2$ are ~15% different

Within 4%



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

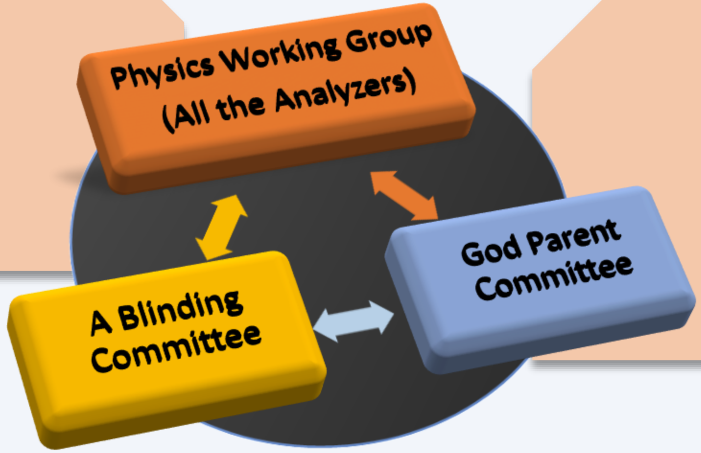
STEP-3
Isobar Unblind analysis
Final analysis
(Ru+Ru & Zr+Zr separated)
~2-3 months

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:

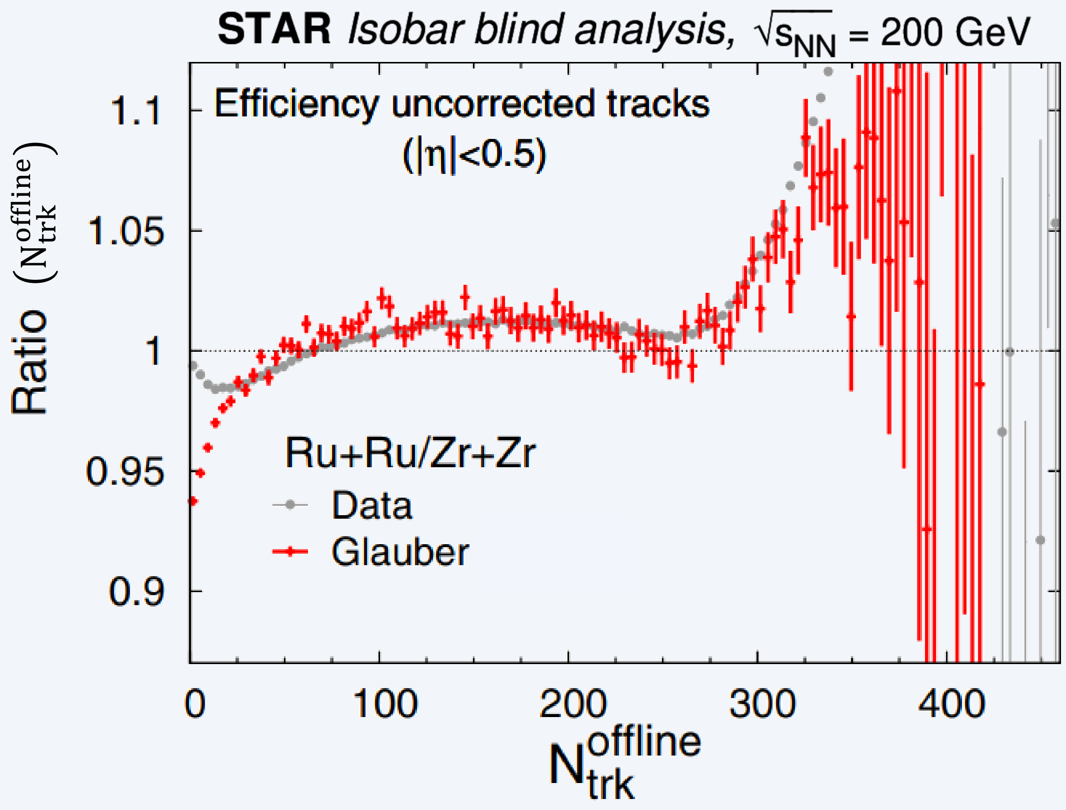
- Sensitivity of observables tested using AVFD simulation
- Similar sensitivities are found in all observables

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

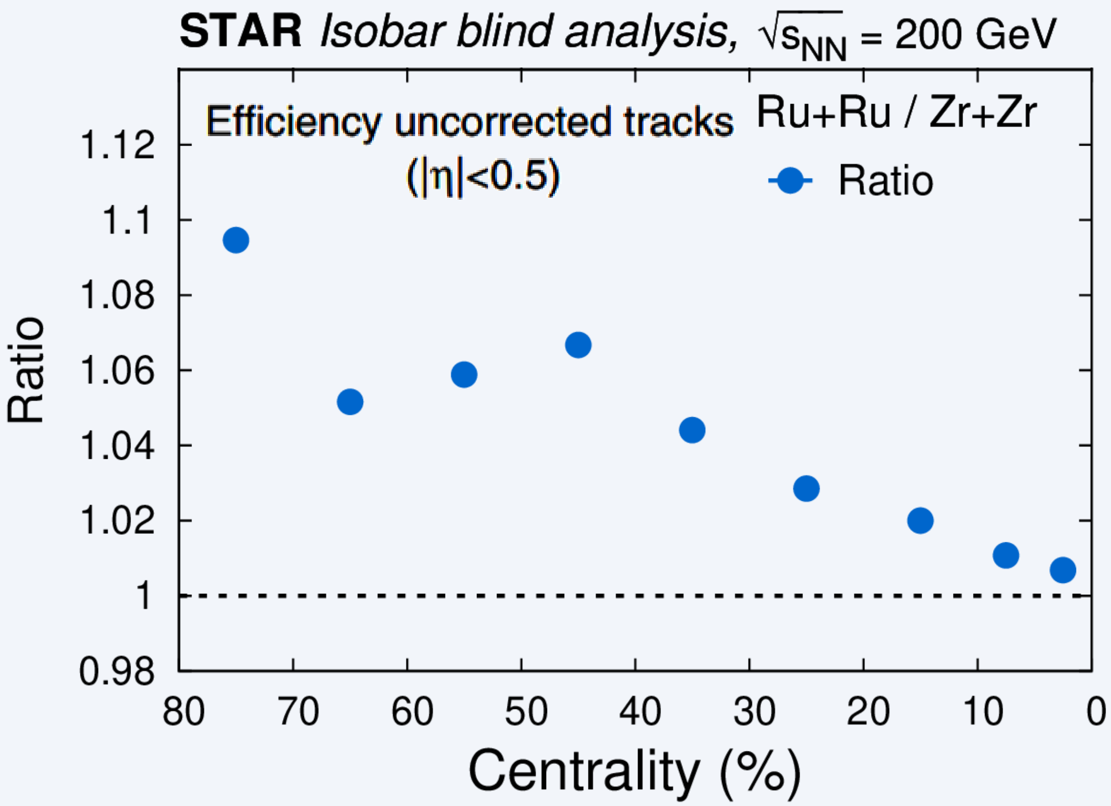
Multiplicity and centrality

M. S. Abdallah *et al.* (STAR) Phys. Rev. C, 105 (2022) 014901
Efficiency is the same between Ru+Ru and Zr+Zr

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



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



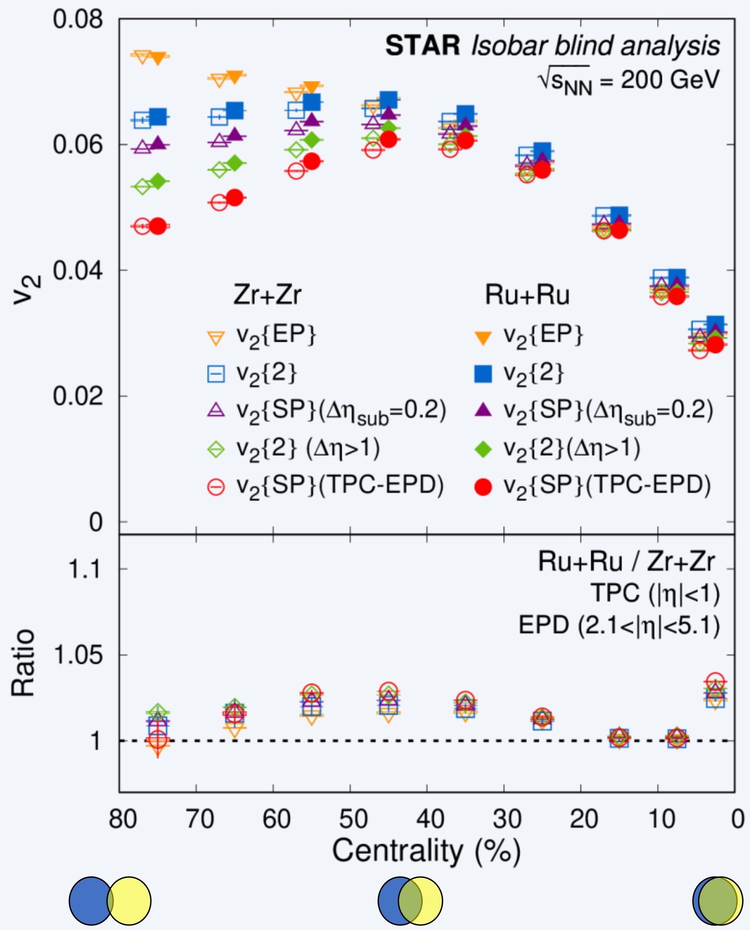
❖ Mean raw multiplicity density is larger in Ru+Ru than in Zr+Zr in matching centrality

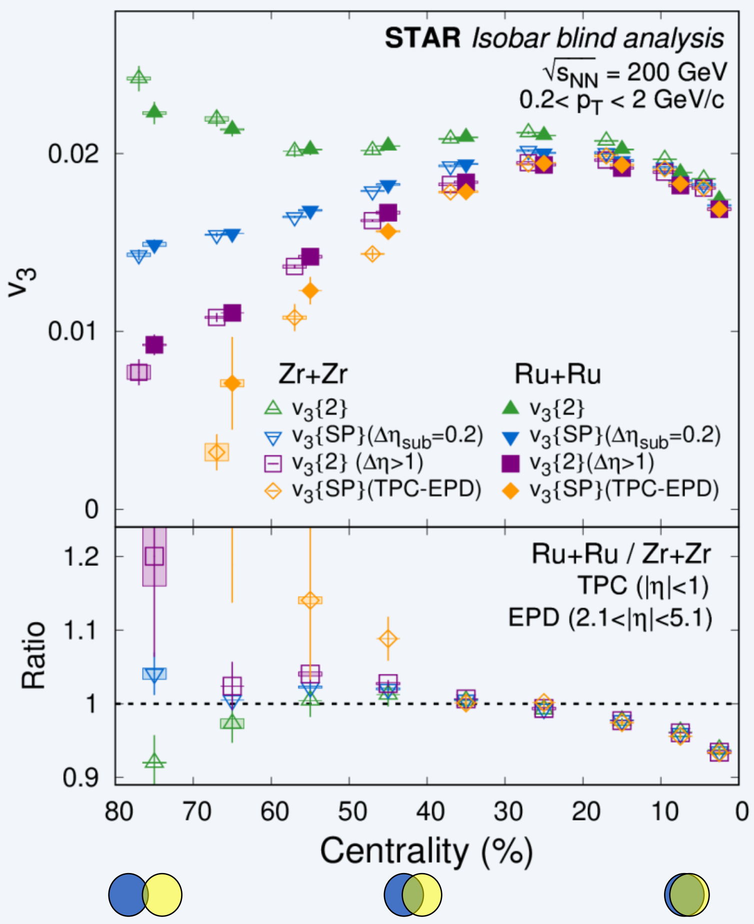
Parallel Session T01, Apr 6

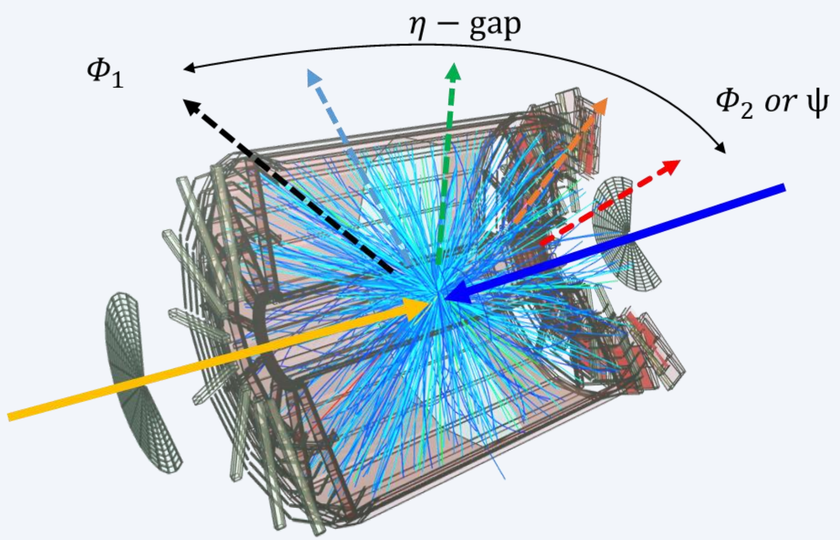
STAR talk by Haojie Xu

Elliptic flow & triangular flow measurements

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







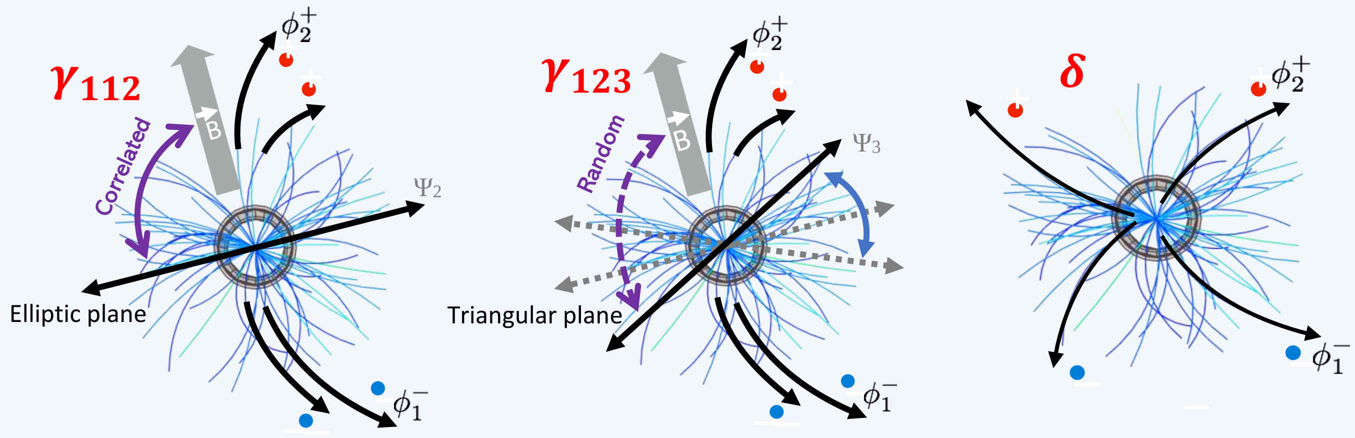
Poster Session 2 T01

STAR poster by Chunjian Zhang

- Deviations 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 ($|\eta| < 1$)



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

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

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

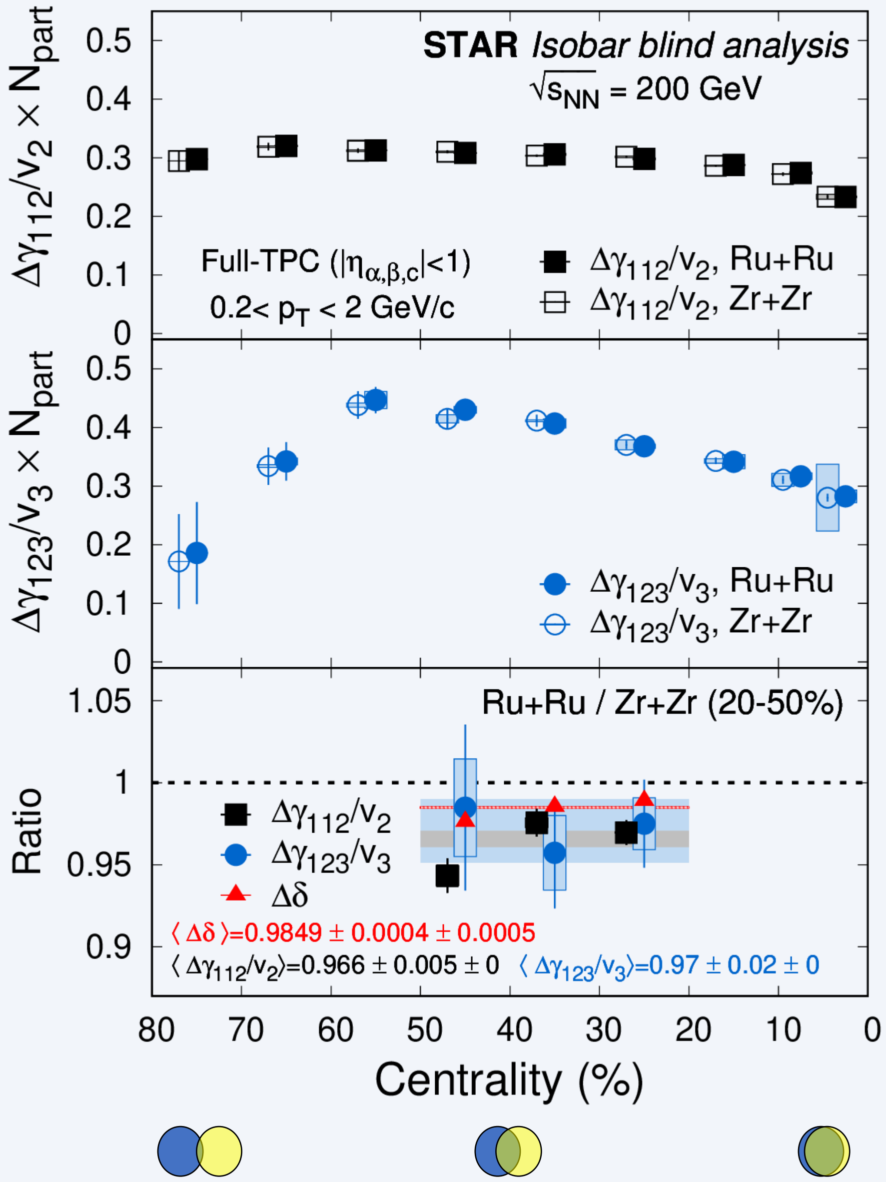
Pre-defined CME criteria:

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

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

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

Data not 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:

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

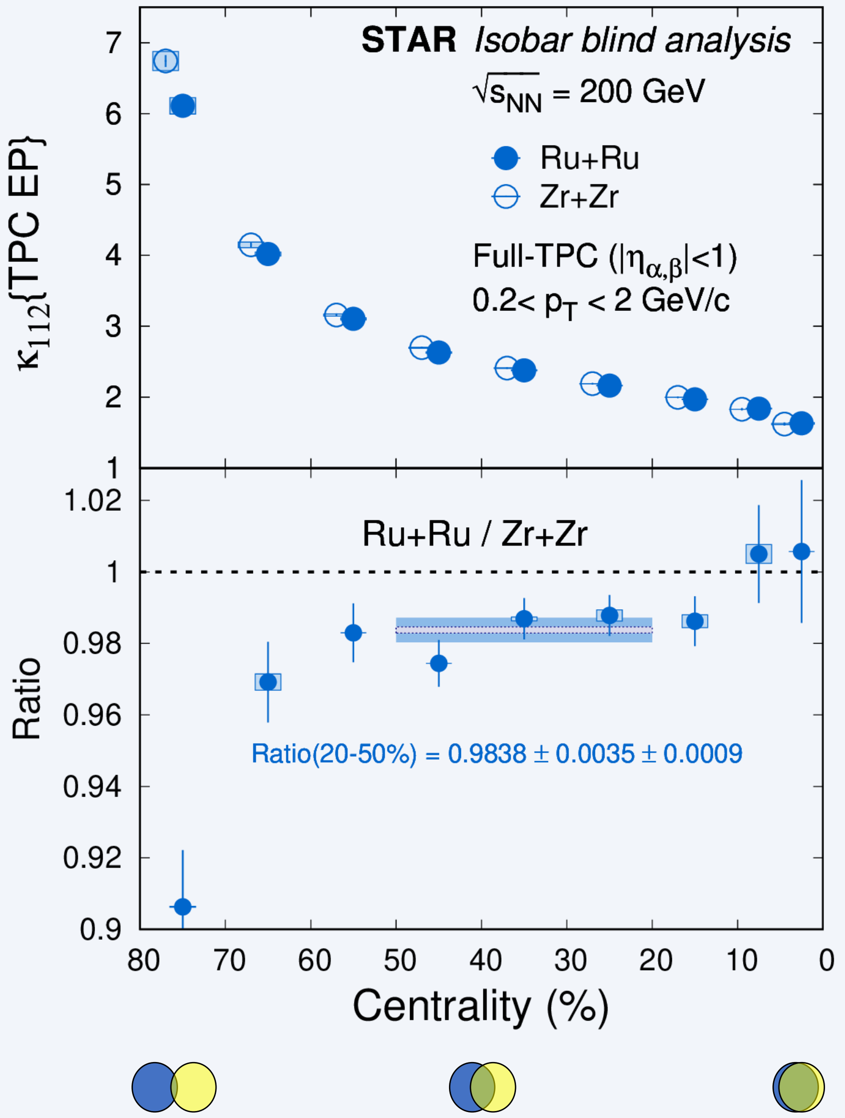
The background contributions due to the local charge conservation (LCC) and transverse momentum conservation (TMC) have a similar characteristic structure that involves the coupling between v_2 and δ. So, we studied the the normalized quantity:

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

Pre-defined CME criterion:

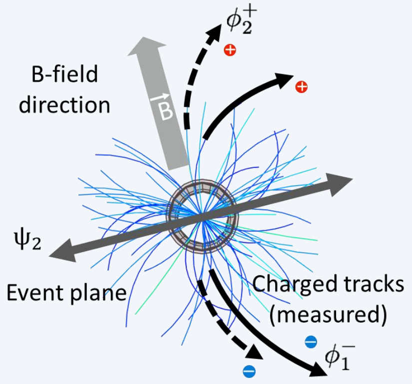
$$\frac{(\kappa_{112})^{\mathrm{Ru+Ru}}}{(\kappa_{112})^{\mathrm{Zr+Zr}}} > 1$$

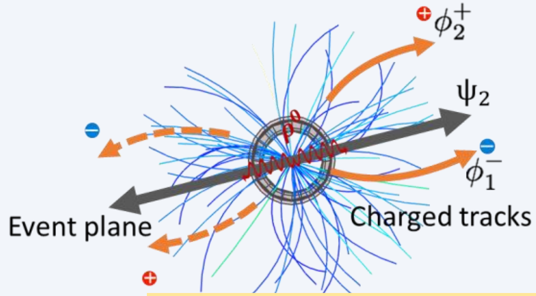
Data not compatible with pre-defined CME criterion



3. Differential measurement vs. invariant mass

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





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:

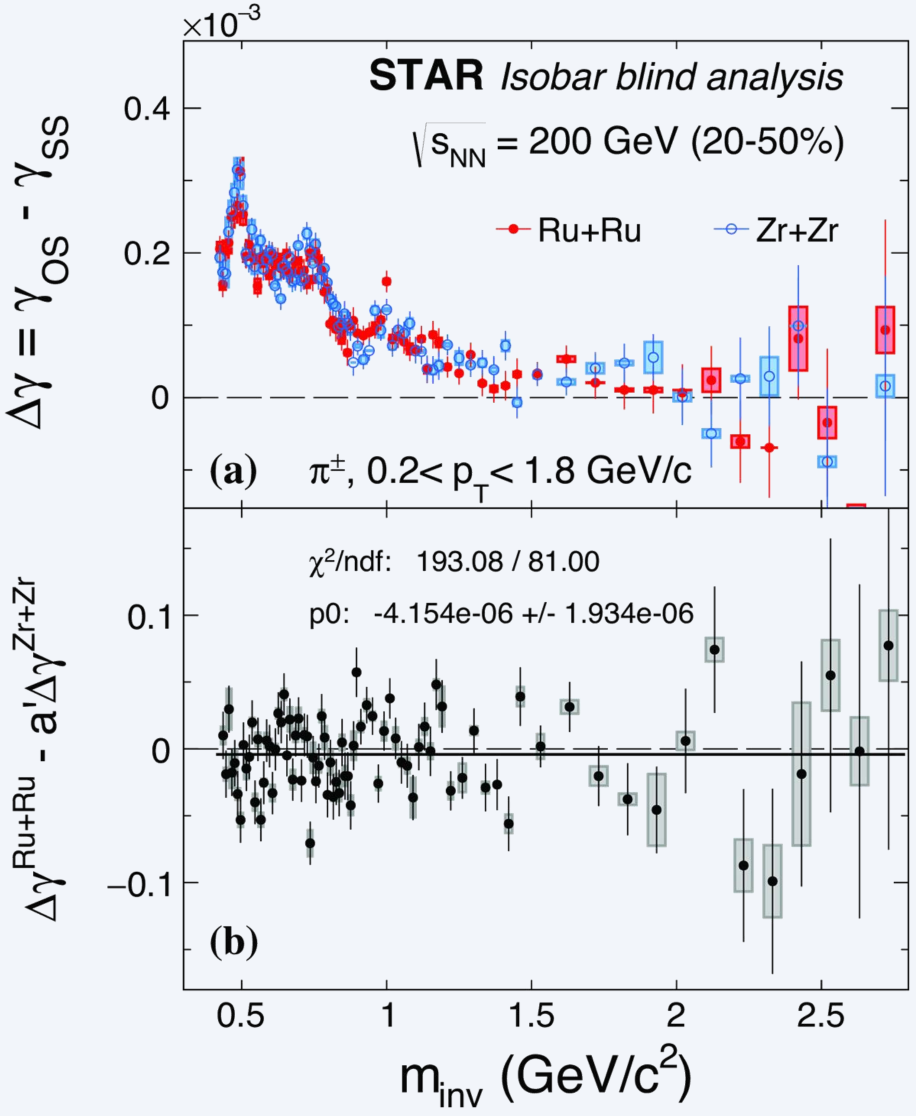
$$\Delta\gamma^{\mathrm{Ru+Ru}} - a'\Delta\gamma^{\mathrm{Zr+Zr}} = \Delta\gamma_{\mathrm{CME}}^{\mathrm{Ru+Ru}} - a'\Delta\gamma_{\mathrm{CME}}^{\mathrm{Zr+Zr}}$$

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.

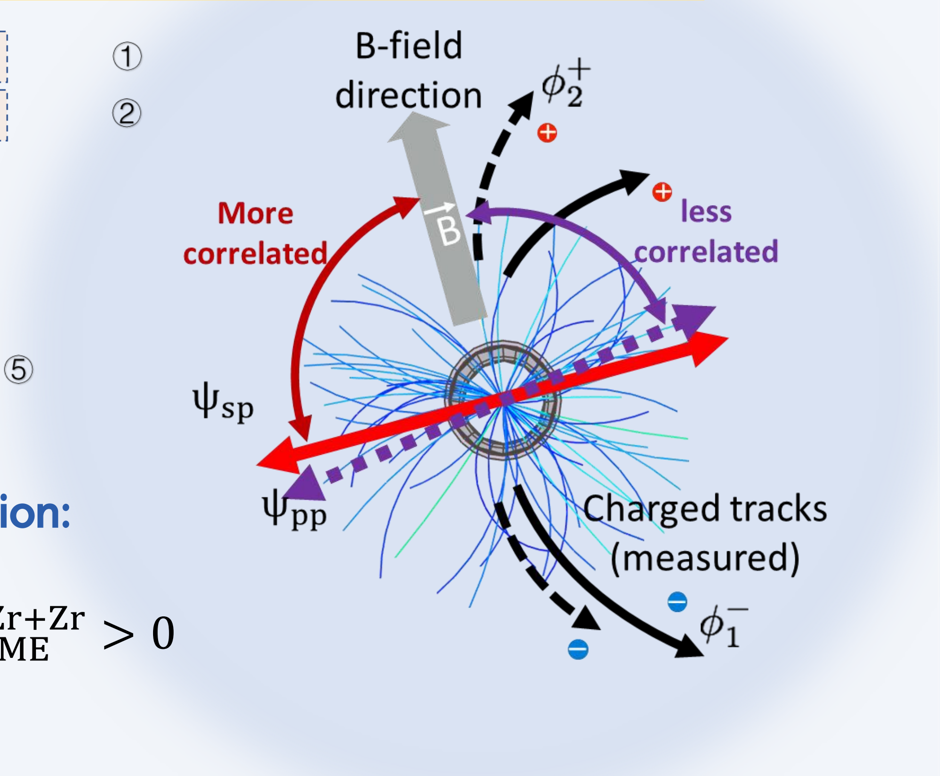
$$\Delta\gamma(\Psi_{TPC}) = \Delta\gamma^{BG}(\Psi_{TPC}) + \Delta\gamma^{CME}(\Psi_{TPC}) \quad ①$$

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

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

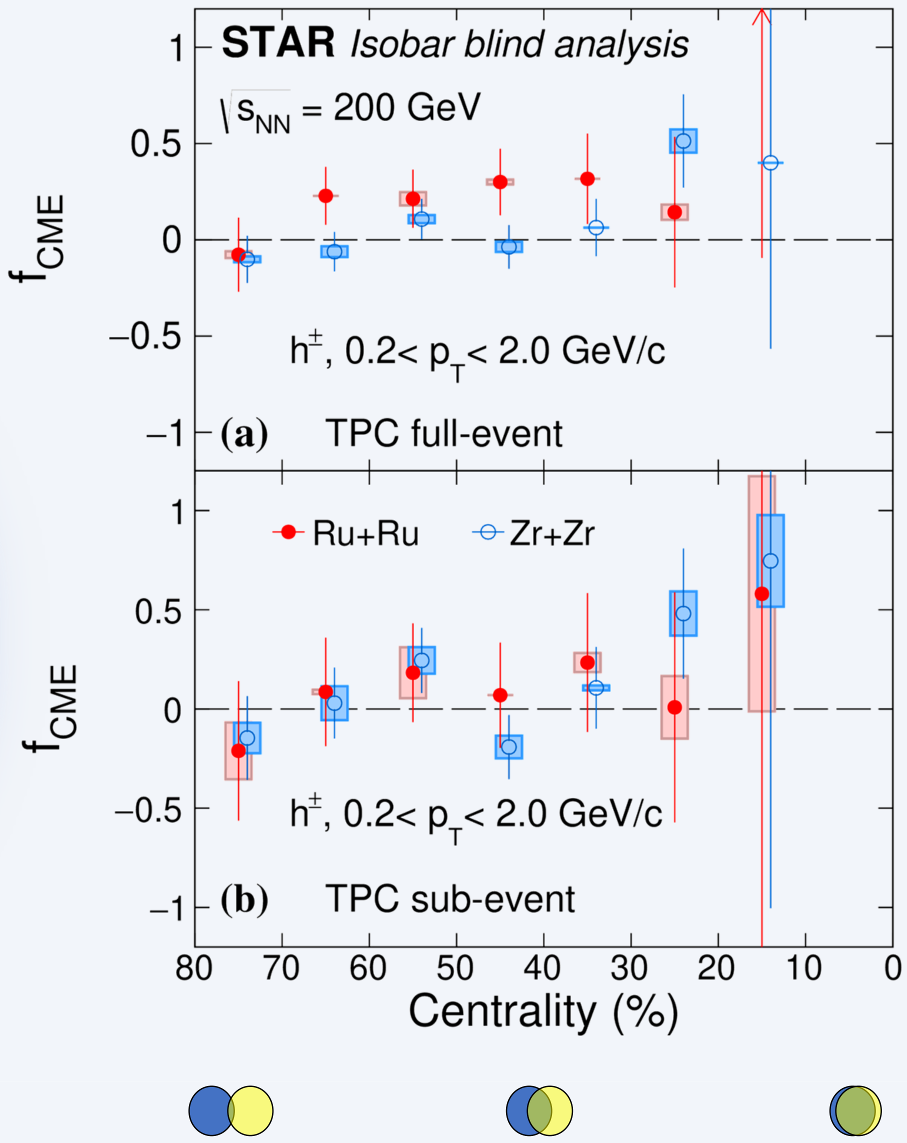
$$\frac{\Delta\gamma^{CME}(\Psi_{TPC})}{\Delta\gamma^{CME}(\Psi_{ZDC})} = \frac{v_2(\Psi_{ZDC})}{v_2(\Psi_{TPC})} \quad ④$$

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



Pre-defined CME criterion:

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



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

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

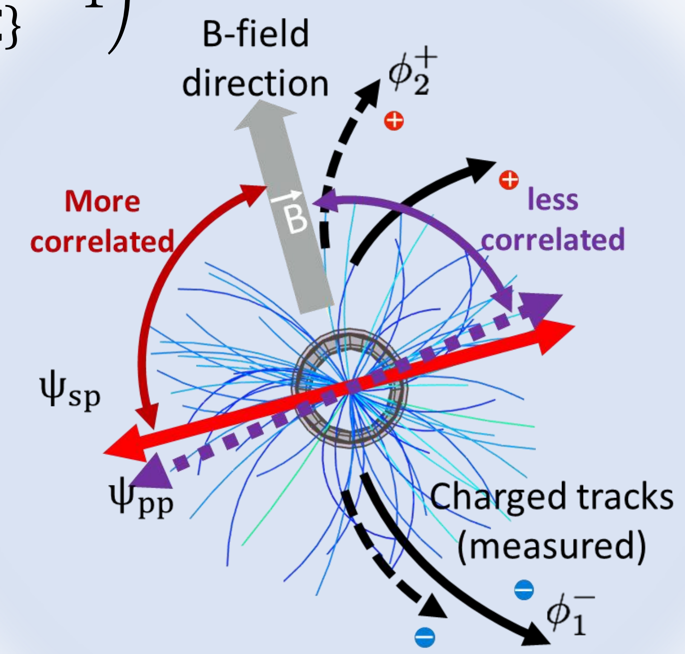
4. Extraction of CME fraction: approach II

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

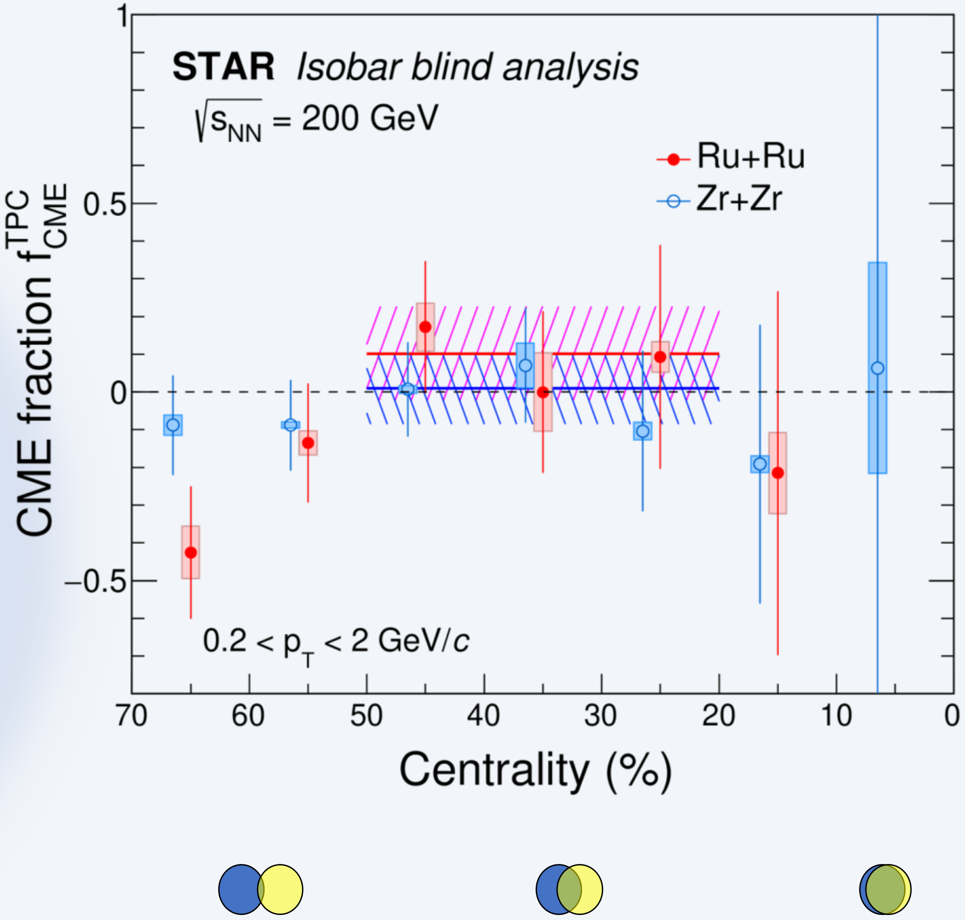
$$\frac{(\Delta\gamma/v_2)_{\mathrm{ZDC}}}{(\Delta\gamma/v_2)_{\mathrm{TPC}}} = 1 + f_{\mathrm{CME}}^{\mathrm{TPC}}\left(\frac{v_2^2\{\mathrm{TPC}\}}{v_2^2\{\mathrm{ZDC}\}} - 1\right)$$

Pre-defined CME criterion:

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



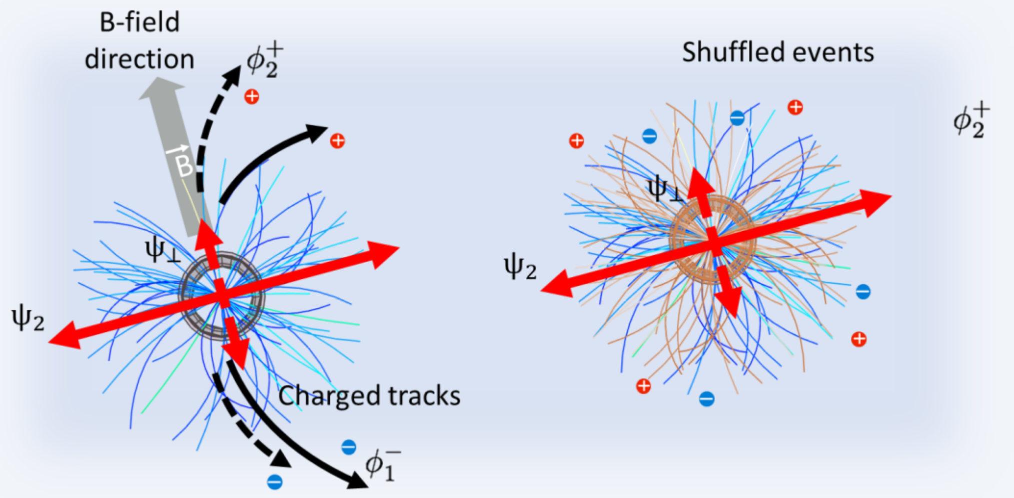
Differences in the method of estimating $v_2\{\mathrm{ZDC}\}$ and $v_2\{\mathrm{TPC}\}$ compared with the approach-I

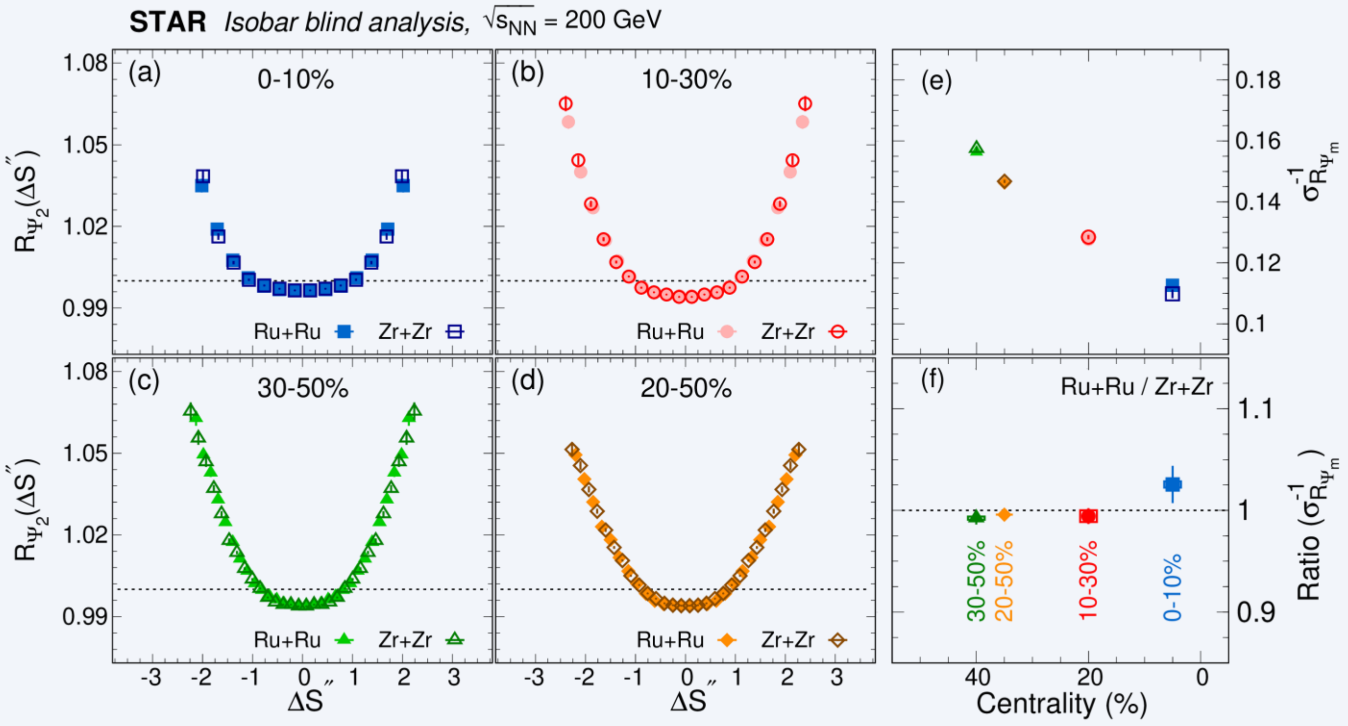


Uncertainty dominated, no significant difference is observed between two isobar systems

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 distribution of the dipole separation event-by-event

Pre-defined CME criterion:

$$1/\sigma_{\psi_2}^{\text{Ru+Ru}} > 1/\sigma_{\psi_2}^{\text{Zr+Zr}}$$

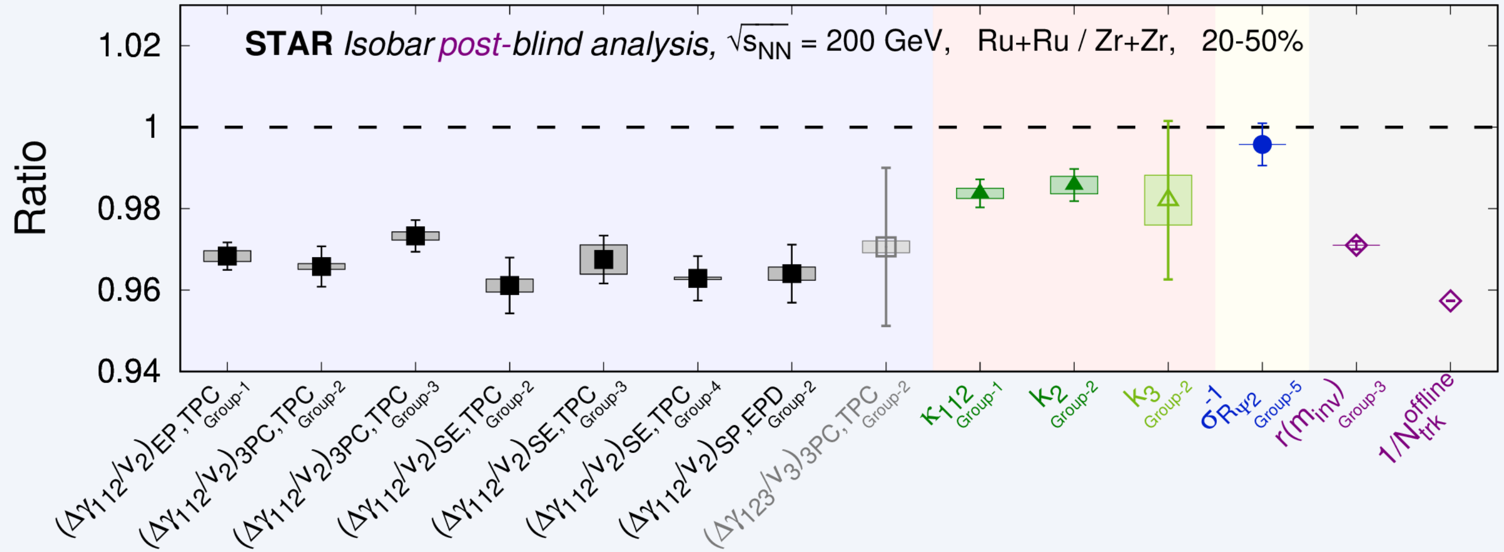
No significant difference is observed between two isobar systems

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

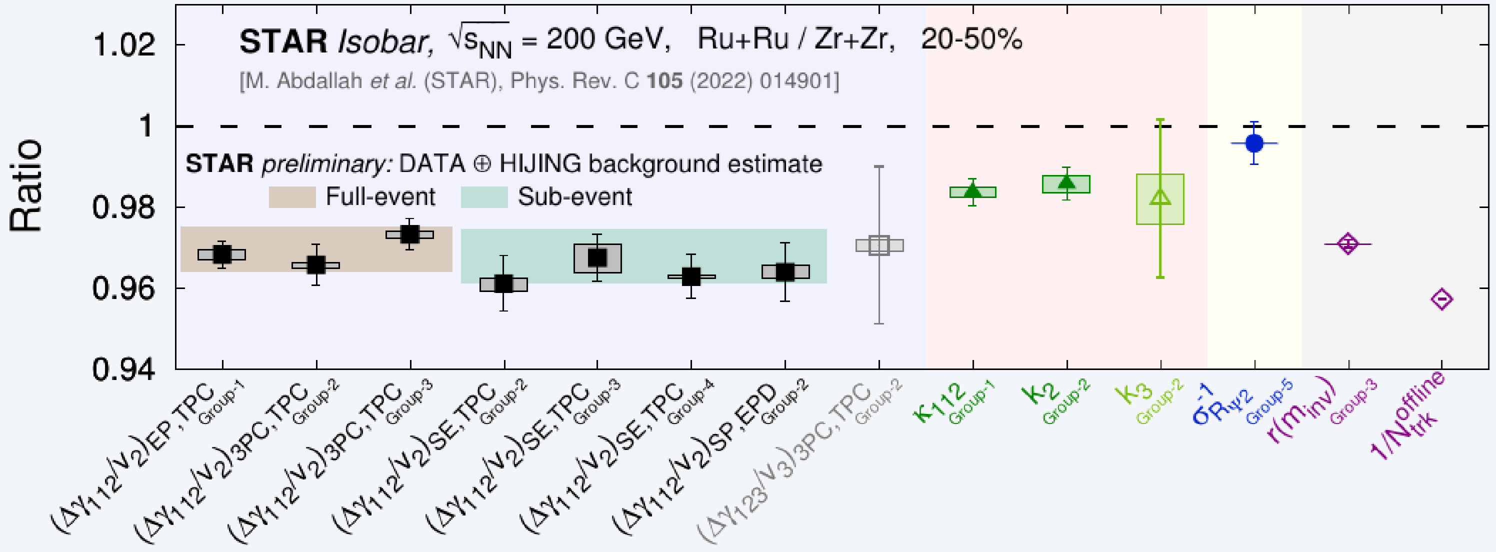
Summary on the isobar blind analysis



From the blind analysis

- No significant difference is observed for all the CME observables between two isobar 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)



From the blind analysis

- No significant difference is observed for all the CME observables between two isobar 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 error

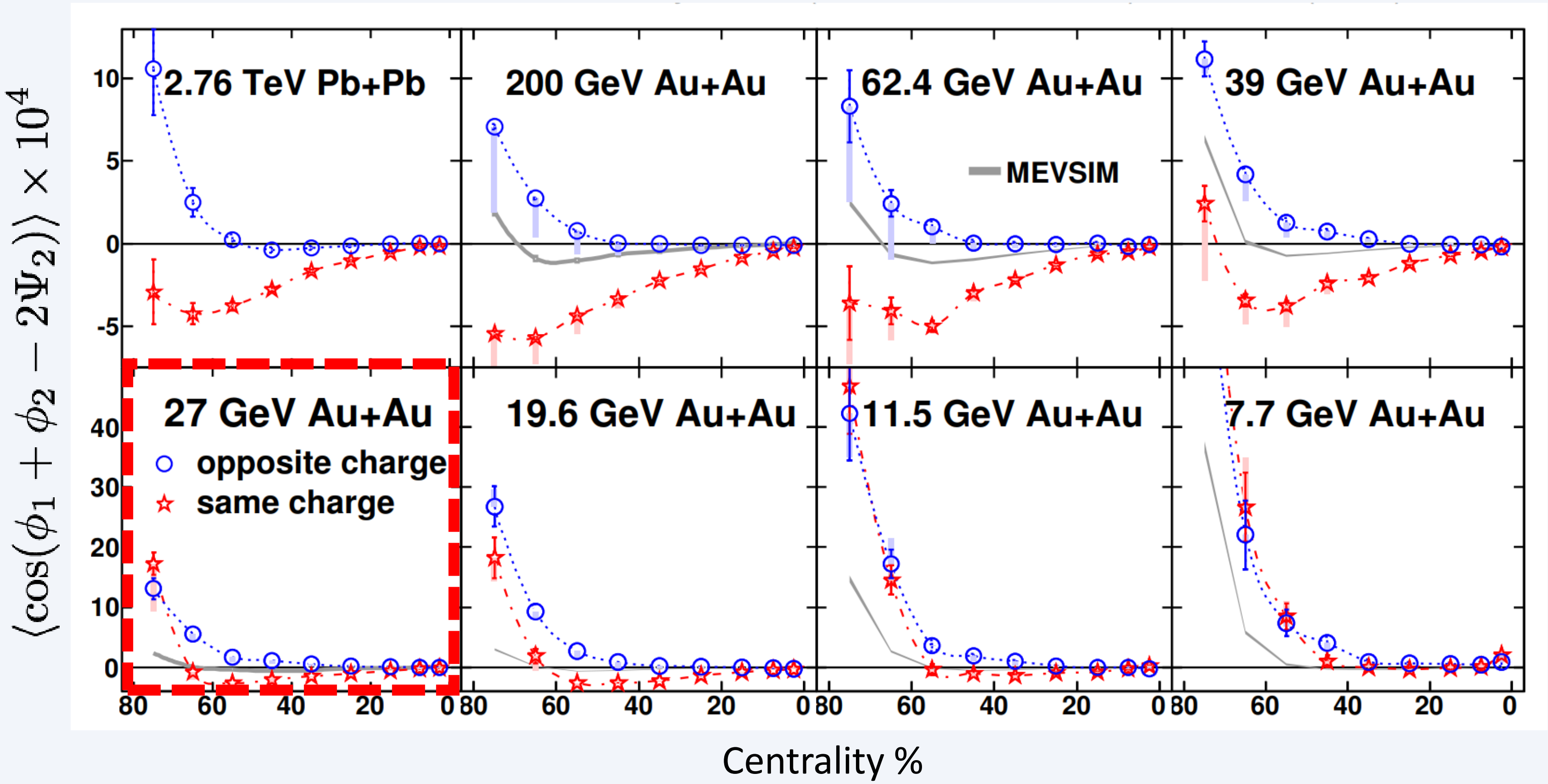
Poster Session 1 T02

STAR poster by Yicheng Feng

CME measurements at lower energies

The STAR collaboration has measured charge separation over a wide range of collision energies

L. Adamczyk *et al.* (STAR), Phys. Rev. Lett., 113 (2014) 052302
B. Abelev *et al.* (ALICE), Phys. Rev. Lett., 110 (2013) 012301



A more definitive result may be obtained in the future if we can increase the statistics by a factor of ten for the low energies...

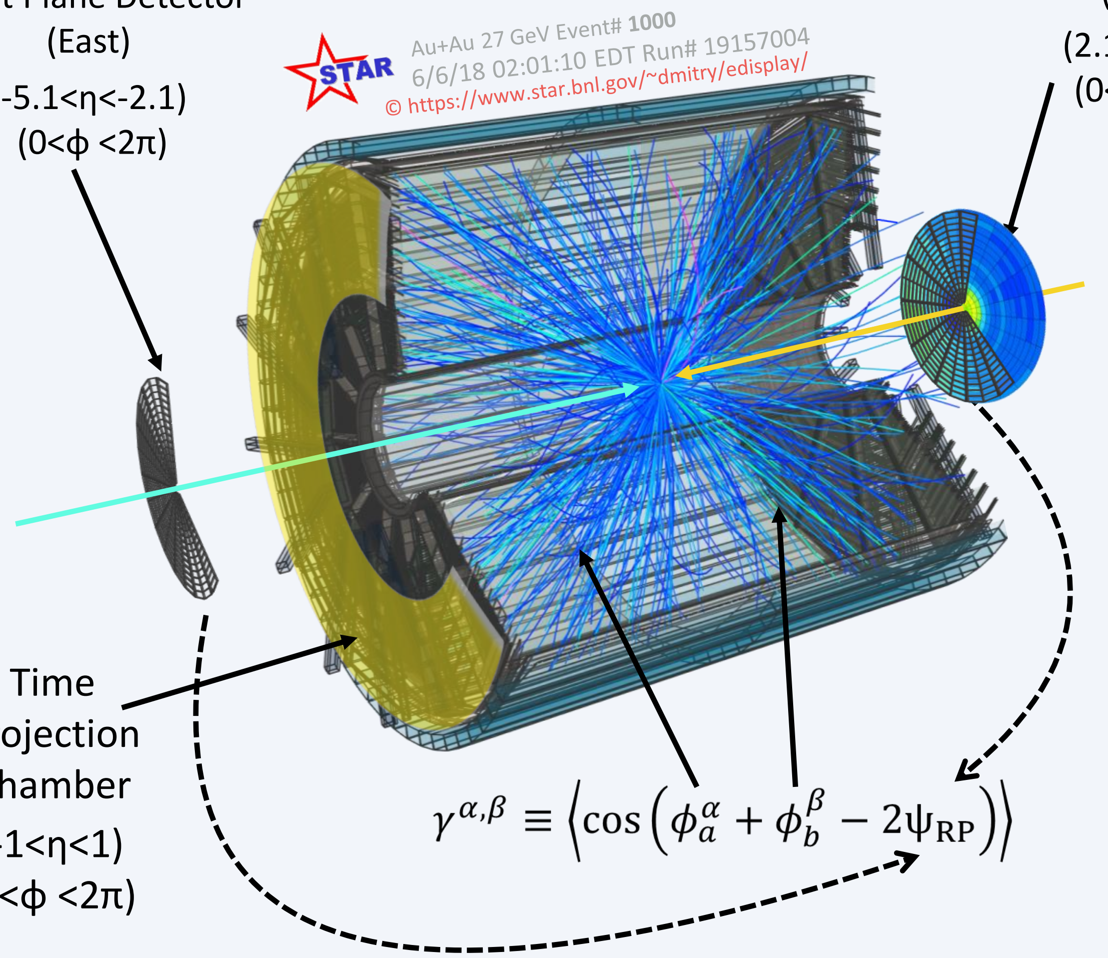
Adamczyk, L. (STAR), Phys. Rev. Lett., 113 (2014) 052302

With the BES-II data

❖ New capabilities
the new installed Event Plane Detectors

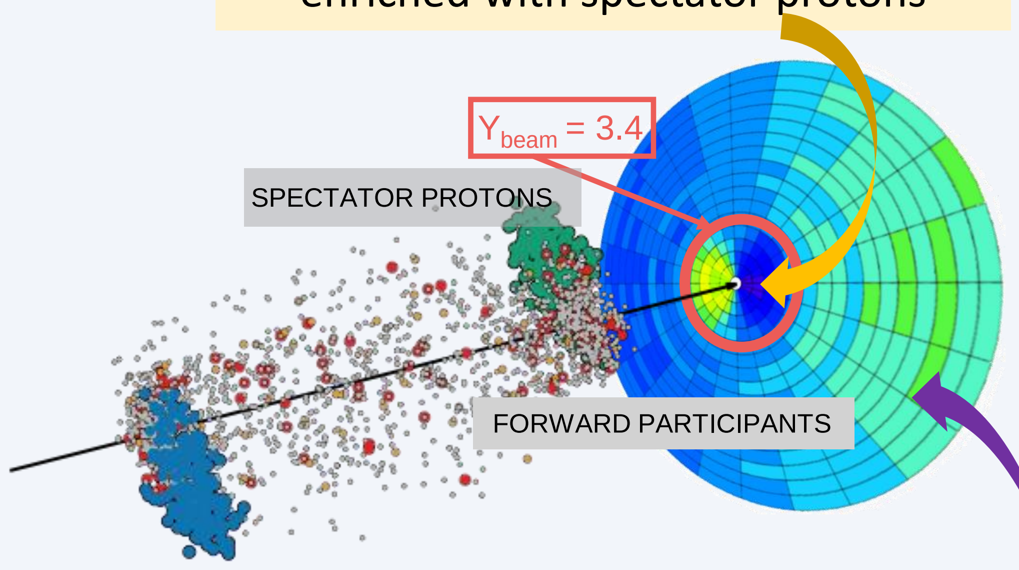
❖ ~10 times statistics
the Event Shape Engineering technique

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



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

ψ_1 ($\eta > Y_{\mathrm{beam}}$): 2nd-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 ($\eta < Y_{\mathrm{beam}}$): 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.

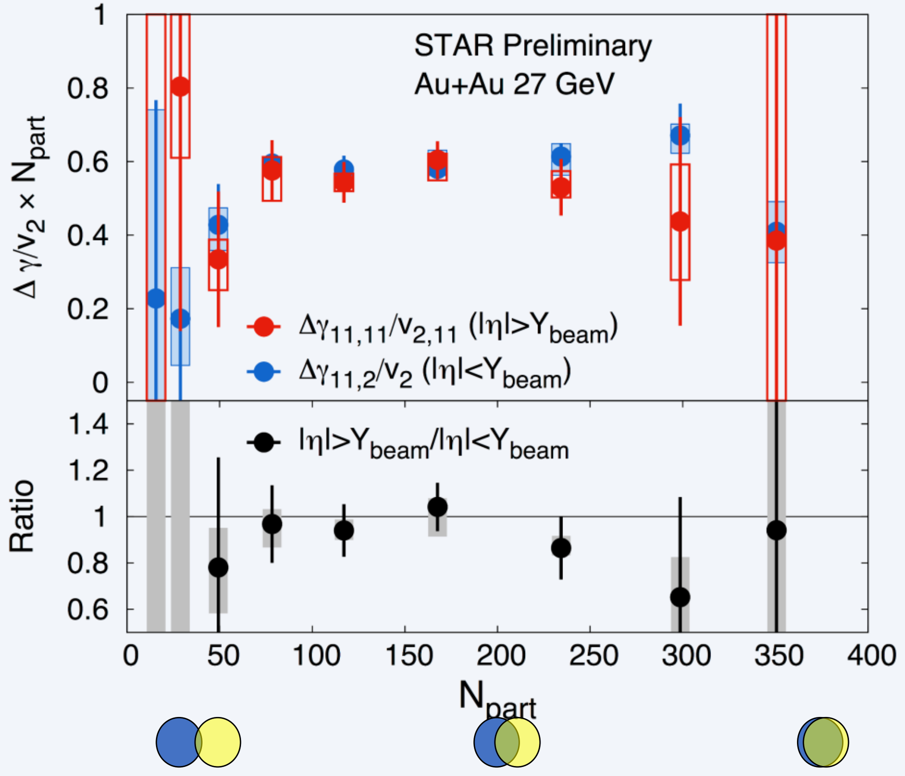
S. A. Voloshin, Phys. Rev. C 98 (2018) 054911

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**.



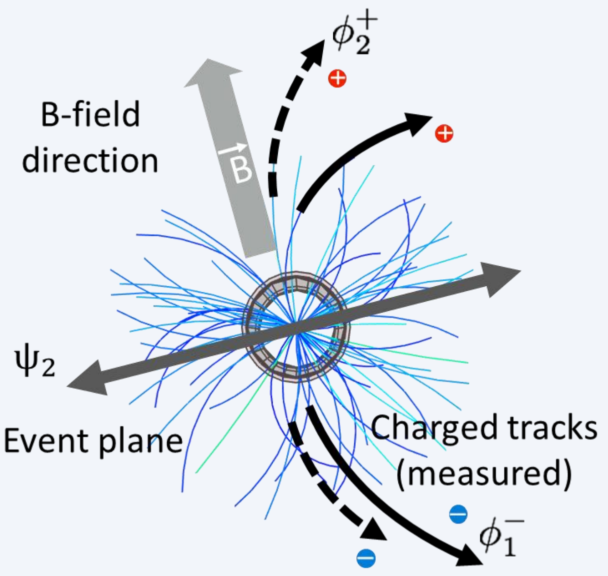
The ratio of $\Delta\gamma/v_2$ between spectator proton rich EPD Ψ_1 plane and participant dominated Ψ_2 plane is presented — CME driven correlations will make this ratio >1.

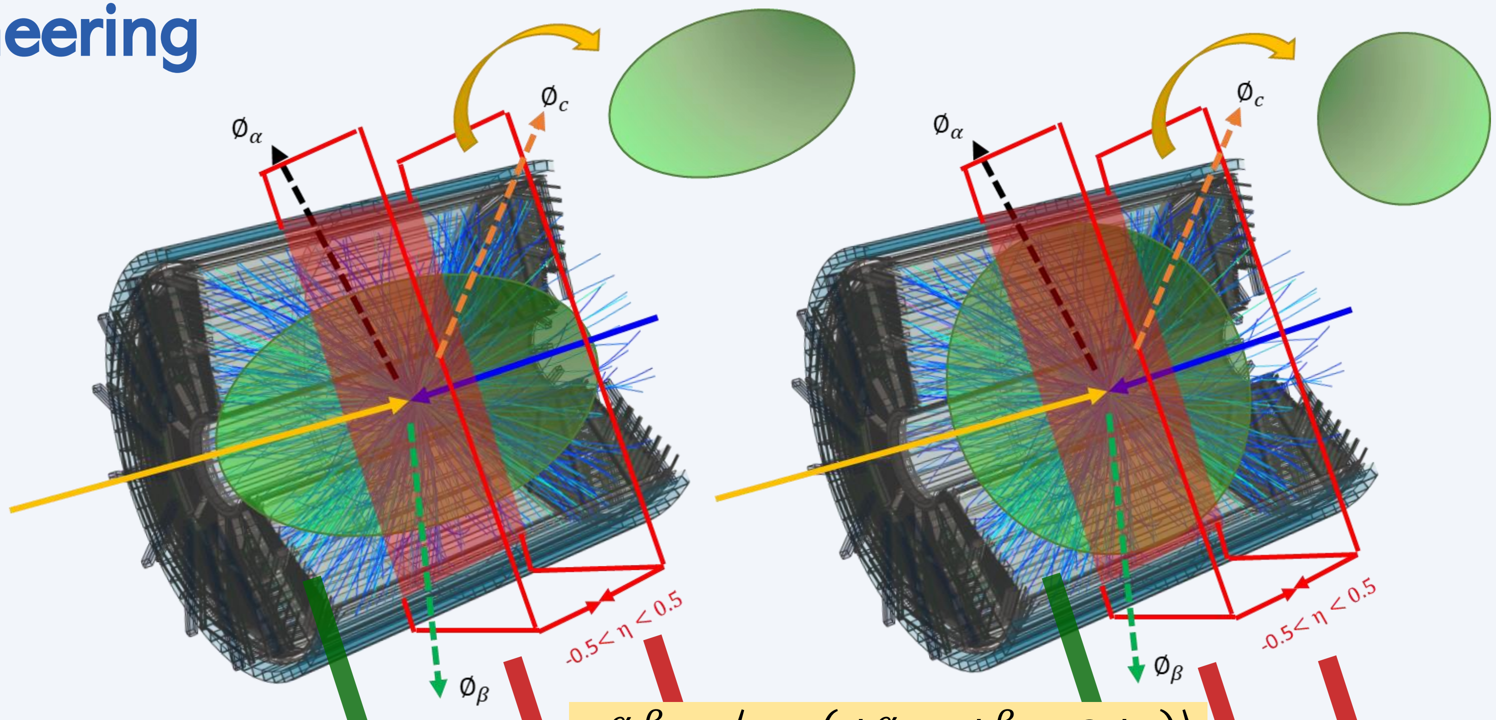
Approach-II: Event Shape Engineering

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

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

By looking at the events in different shapes with the flow vectors (corresponding to different v_2). Then try to estimate the $\Delta\gamma^{CME}$ level





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

We use $|\eta| < 0.5$ to select the event shape;
Use the flow vector to control the event shape;

We use $|\eta| < 0.5$ as ϕ^{α} and ϕ^{β} sources;

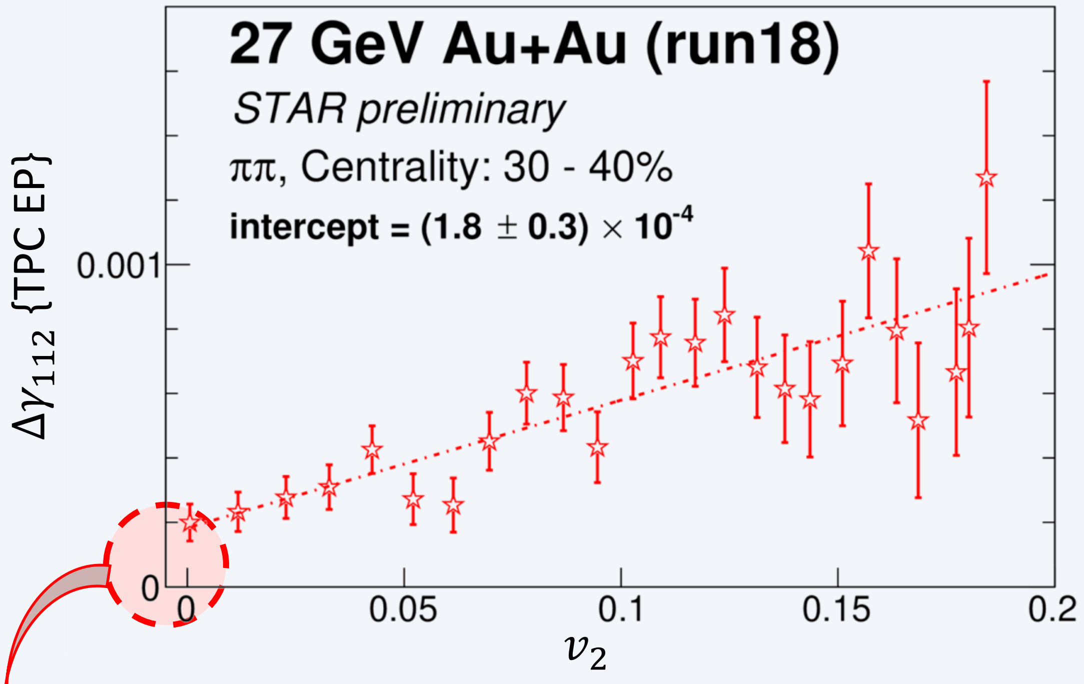
We use the $0.55 < \eta < 1$ and $-1 < \eta < -0.55$ to determine our event plane ψ_2;

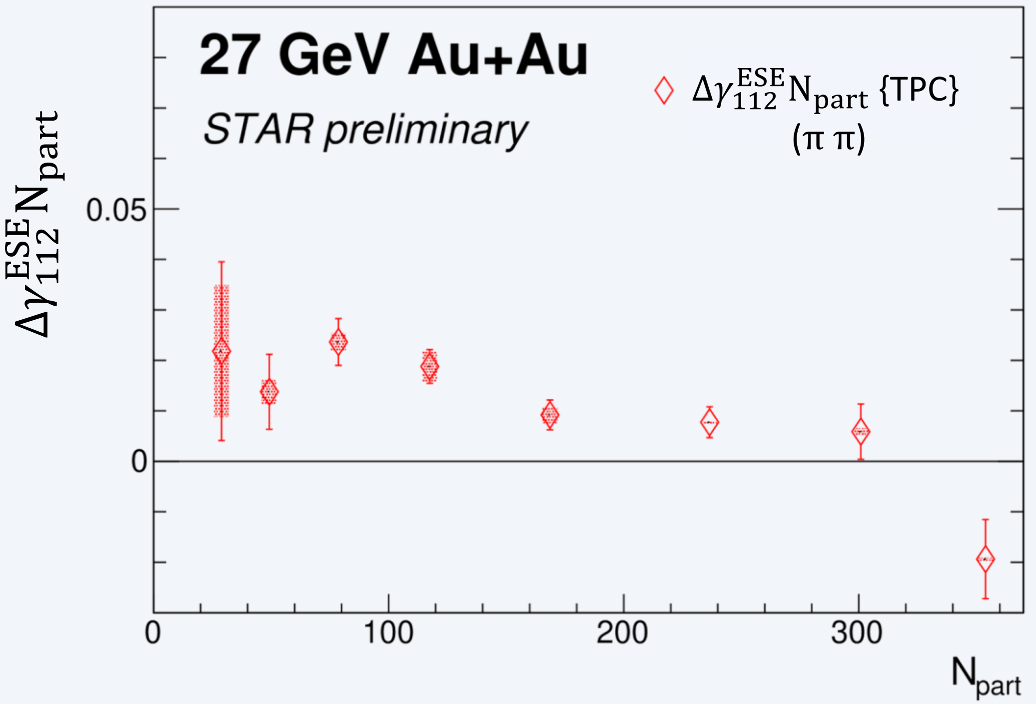
L. Adamczyk *et al.* (STAR), Phys. Rev. Lett., 113 (2014) 052302
R. Milton *et al.* Phys. Rev. C, 104 (2021) 064906

Approach-II: Event Shape Engineering technique @ 27 GeV

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

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





The measured $\Delta\gamma_{112}^{ESE}$ in different centralities scaled by N_{part}

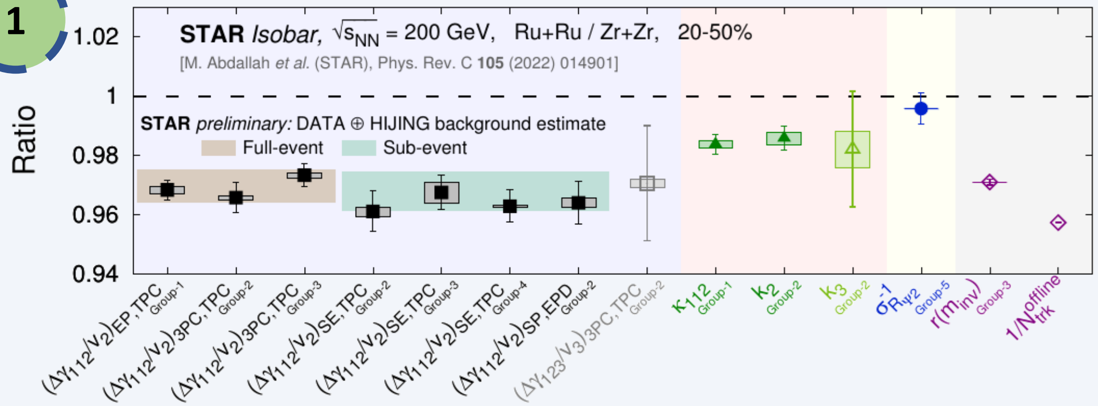
- The measured $\Delta\gamma_{112}$ decreases linearly with v_2
- The intercept ($\Delta\gamma_{112}^{ESE}$) maximized the possible CME signal fraction

- A promising approach towards the CME signal
- The background is significantly reduced with this approach
- $\Delta\gamma_{ESE}^{112}$ with finite numbers are observed in this approach. A quantitative investigation of the remaining background is needed for this measurement

L. Adamczyk *et al.* (STAR), Phys. Rev. Lett., 113 (2014) 052302
R. Milton *et al.* Phys. Rev. C, 104 (2021) 064906

Summary

1



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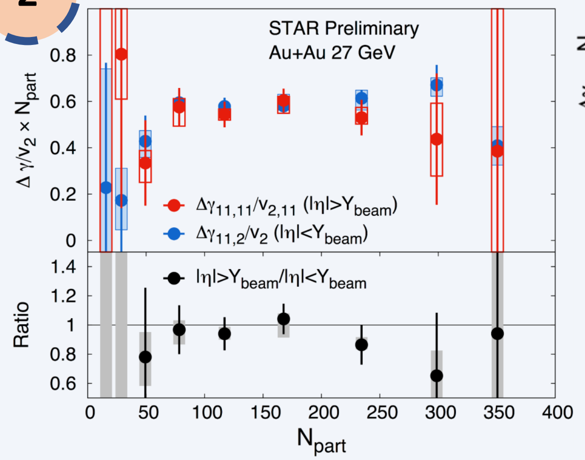

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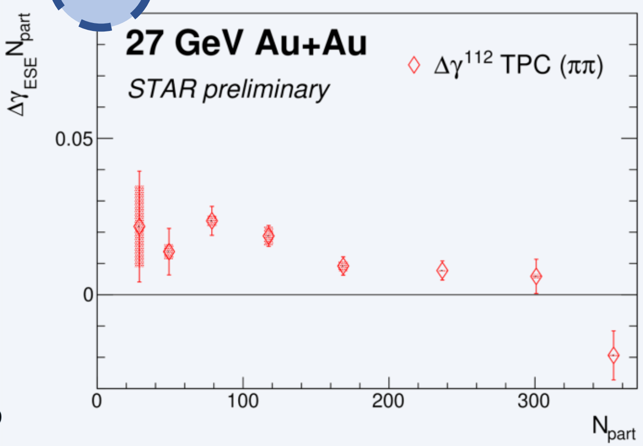


- ❖ Based on the assumption in the isobar blind analysis, a CME-related signal fraction which is larger than 20% is ruled out
- ❖ The going-on non-flow effects studies show the isobar data are consistent with the current estimate of non-flow background within the error
- ❖ Different techniques are used to search for the CME signal at 27 GeV. The BES-II data and EPDs bring a new opportunity for the CME search at lower energies in the future

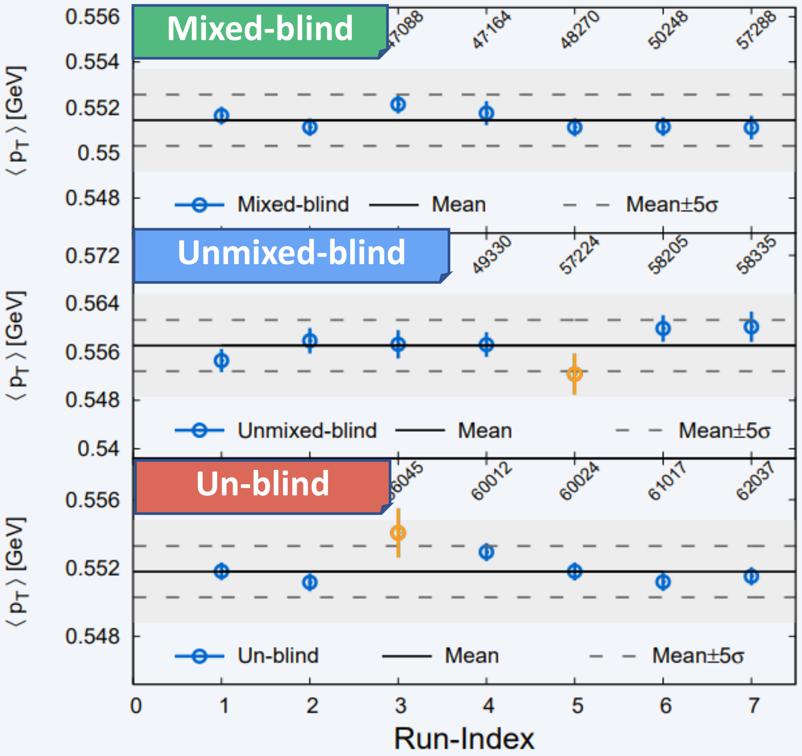
Thank you!

Supported in part by U.S. DEPARTMENT OF ENERGY

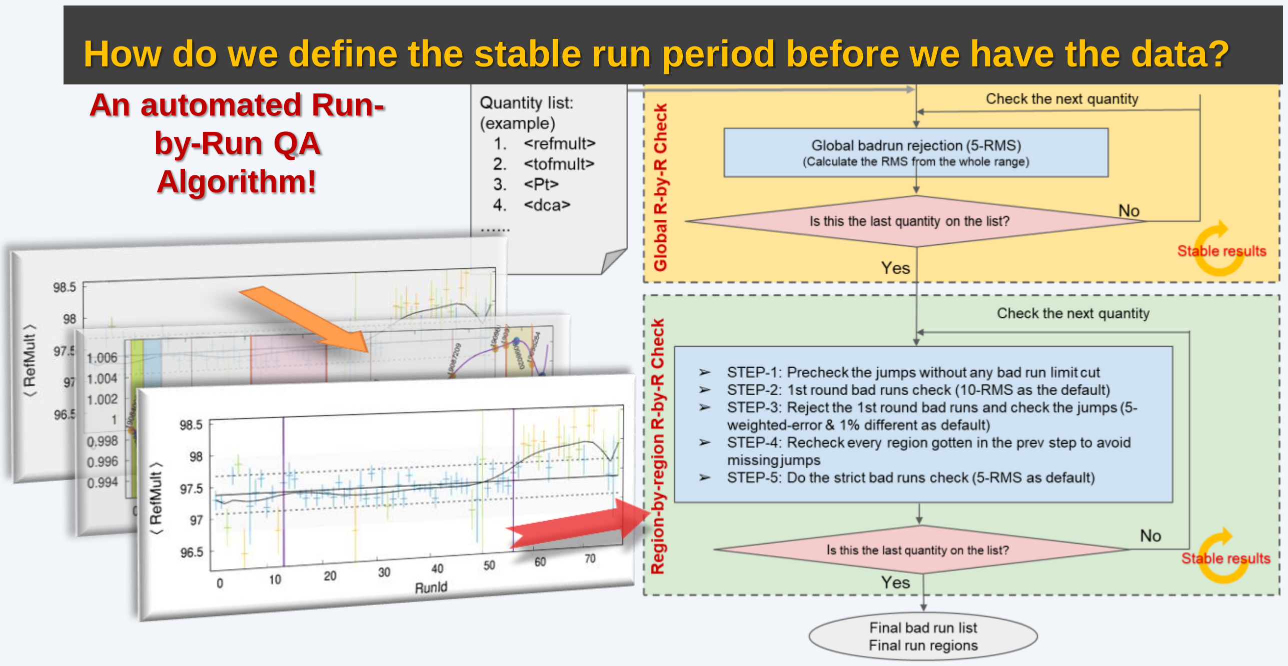
2022.04.07

Backup

Backup-1: details in the isobar blind analysis



Fully automated algorithm developed for blind QA



Backup-2: equations in the non-flow studies

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

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

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