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STAR

Searching the Chiral Magnetic Effect with the STAR Detector: An Overview

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https://drupal.star.bnl.gov/STAR/presentations

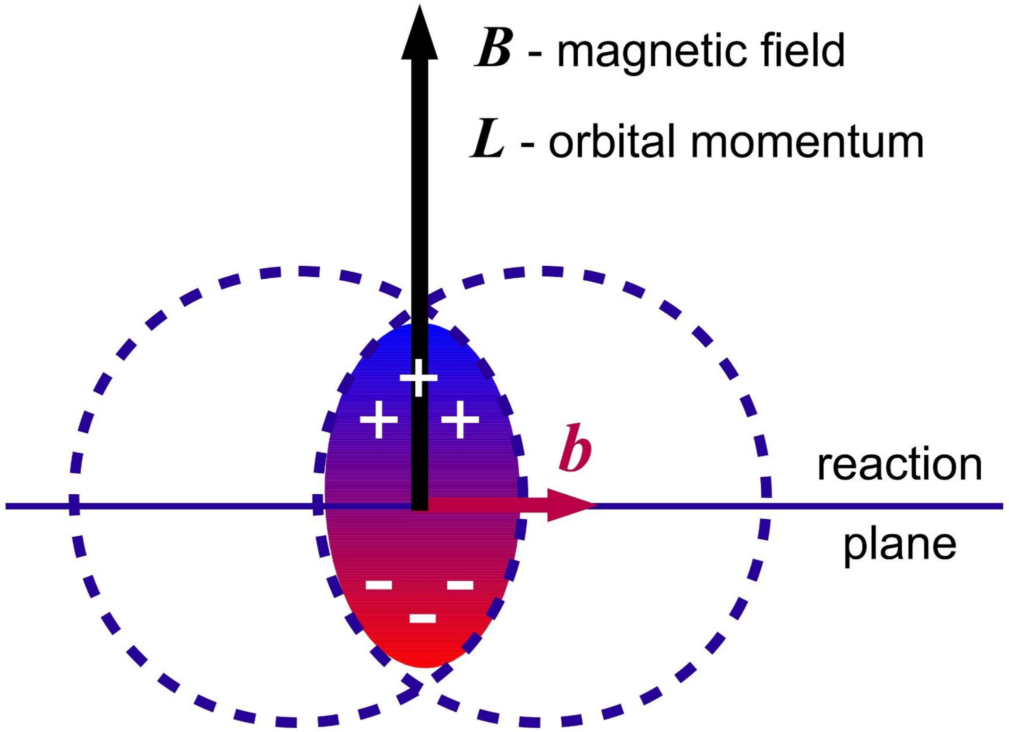
Outline

- Introduction to the Chiral Magnetic Effect
- CME-Sensitive Observables (γ)
- STAR Experiment: Previous measurements
- Recent experimental approaches from STAR
- Summary and Outlook

Introduction

Chiral Magnetic Effect in heavy Ion collisions?

- In non-central nuclear collisions, strong magnetic field is created by the fast-moving spectator protons and chirality imbalance causes the charge separation perpendicular to the reaction plane, known as the CME.

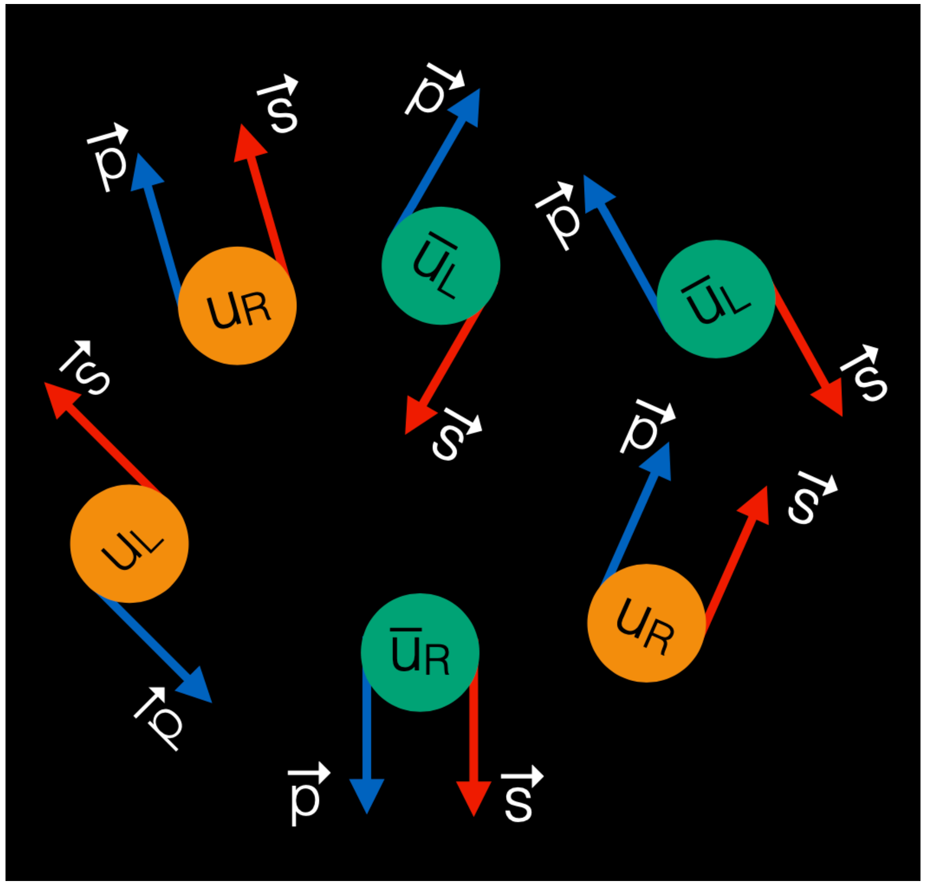


CME in hot QCD:

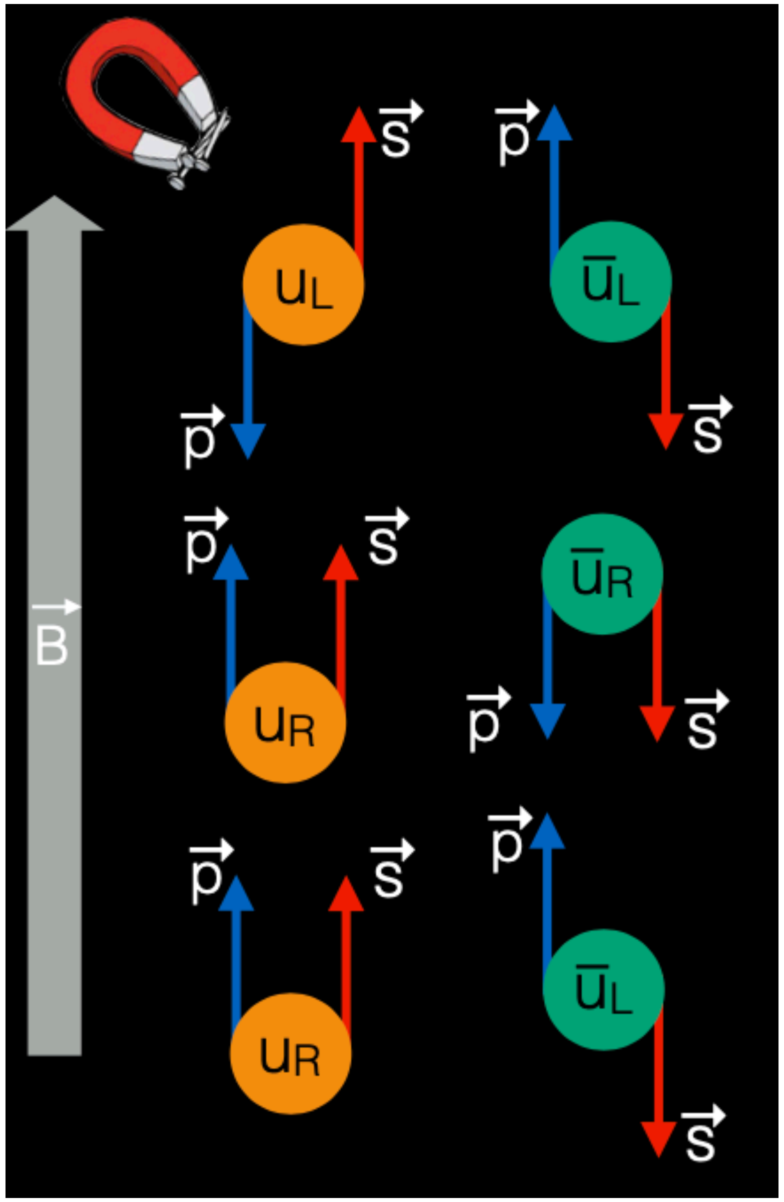
- Deconfined medium of massless quarks
- Presence of strong magnetic field
- Mechanism to create the imbalance of right and left handed quarks

K. Fukushima, D. E. Kharzeev and H. J. Warringa, Phys. Rev. D 78, 074033 (2008).
S. Voloshin, Phys. Rev. C 70, 057901 (2004).

Chiral Magnetic Effect



- *Imbalance of chirality*
- *Excess right/left-handed quarks*



Massless Quarks produced in the system will have random spin orientations

Strong B-field will align the spin of the quarks due to magnetic polarization

P. Tribedy, Free meson seminar, TIFR, Oct 7th, 2021

Experimental Observables for CME

- The STAR at RHIC and the ALICE at the LHC have studied the CME by measuring the three particle (γ)- correlator.
- Measure charge separation across Ψ_{RP}/Ψ_2 using the following correlator;

$$\gamma = \langle cos(\phi_a + \phi_b - 2\Psi_{RP}) \rangle$$

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

$$\gamma_{SS} \neq \gamma_{OS} \text{ and } \gamma_{OS} > 0\ ,\ \gamma_{SS} < 0$$

Quantity of interest:

$$\Delta\gamma\ (= \gamma_{OS} - \gamma_{SS}) > 0$$

- CME causes difference in opposite-sign (OS) and same-sign (SS) correlation
- The measured correlator gives CME signal and background.

$$\Delta\gamma \ = \Delta\gamma^{CME} + k\frac{v2}{N} + \Delta\gamma^{Non-flow}$$

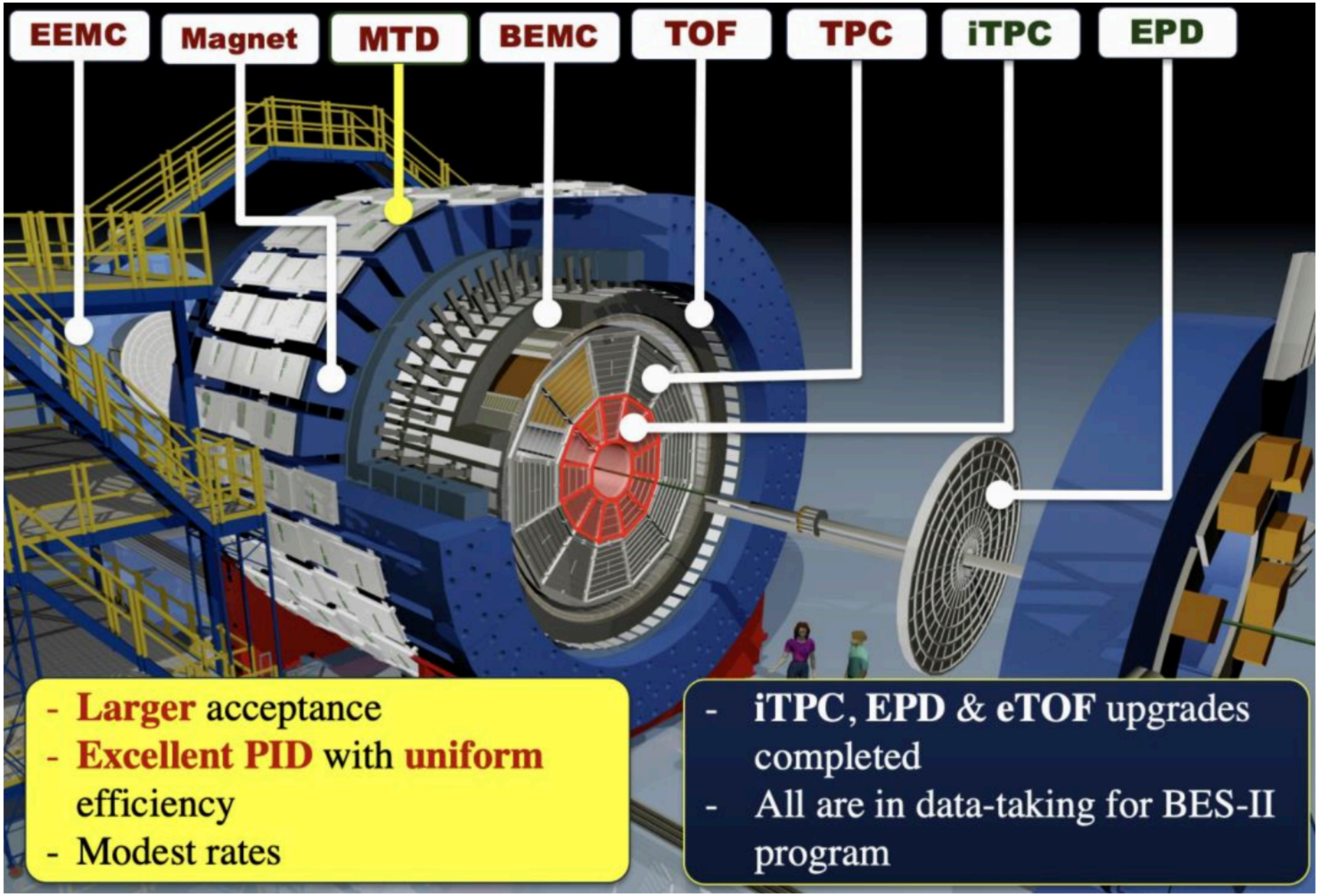
Measurement

Signal

Background-1

Background-2

STAR Experiment



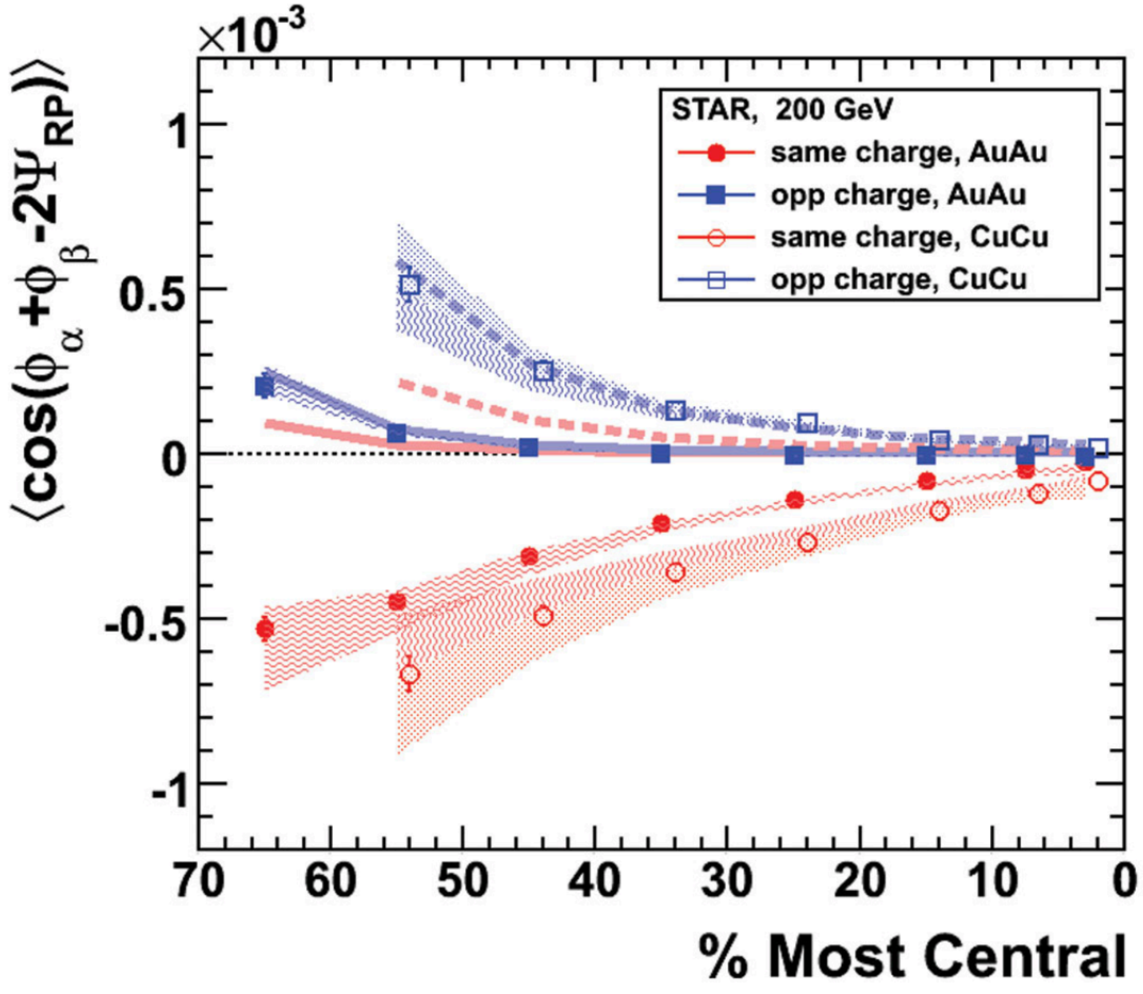
- **Larger** acceptance
- **Excellent PID** with **uniform** efficiency
- Modest rates

- **iTPC, EPD & eTOF** upgrades completed
- All are in data-taking for BES-II program

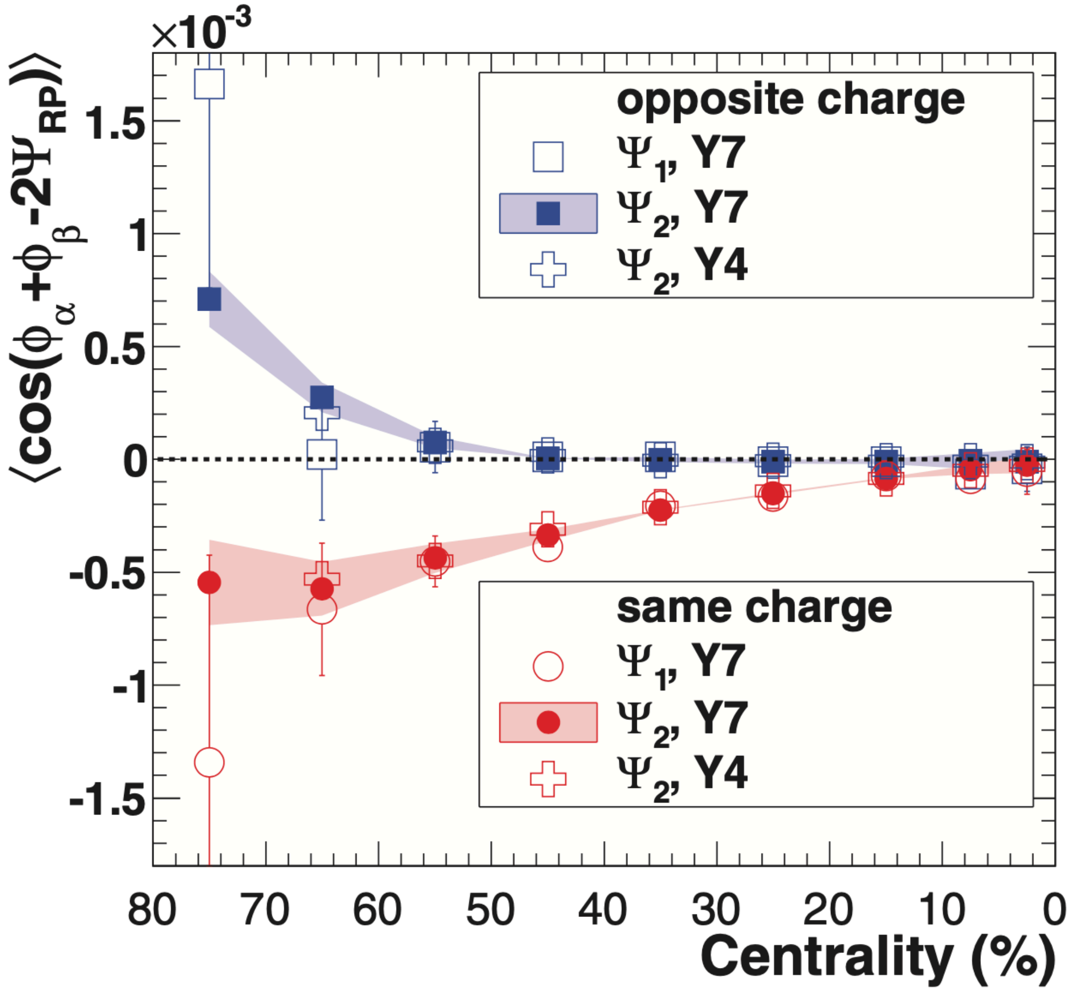
- Main characteristics of the STAR: Large coverage i.e., $\phi(0, 2\pi)$ and $\eta(-1, 1)$, Excellent particle identification at low p_T using TPC and at intermediate p_T using TOF
- Event Plane Detector (both sides) with $\eta(2.1, 5.1)$ and $\phi(0, 2\pi)$

Previous measurements from STAR

First Measurements



STAR, Phys. Rev. Lett. 103 (2019) 251601;
Phys. Rev. C 81, 054908 (2010)

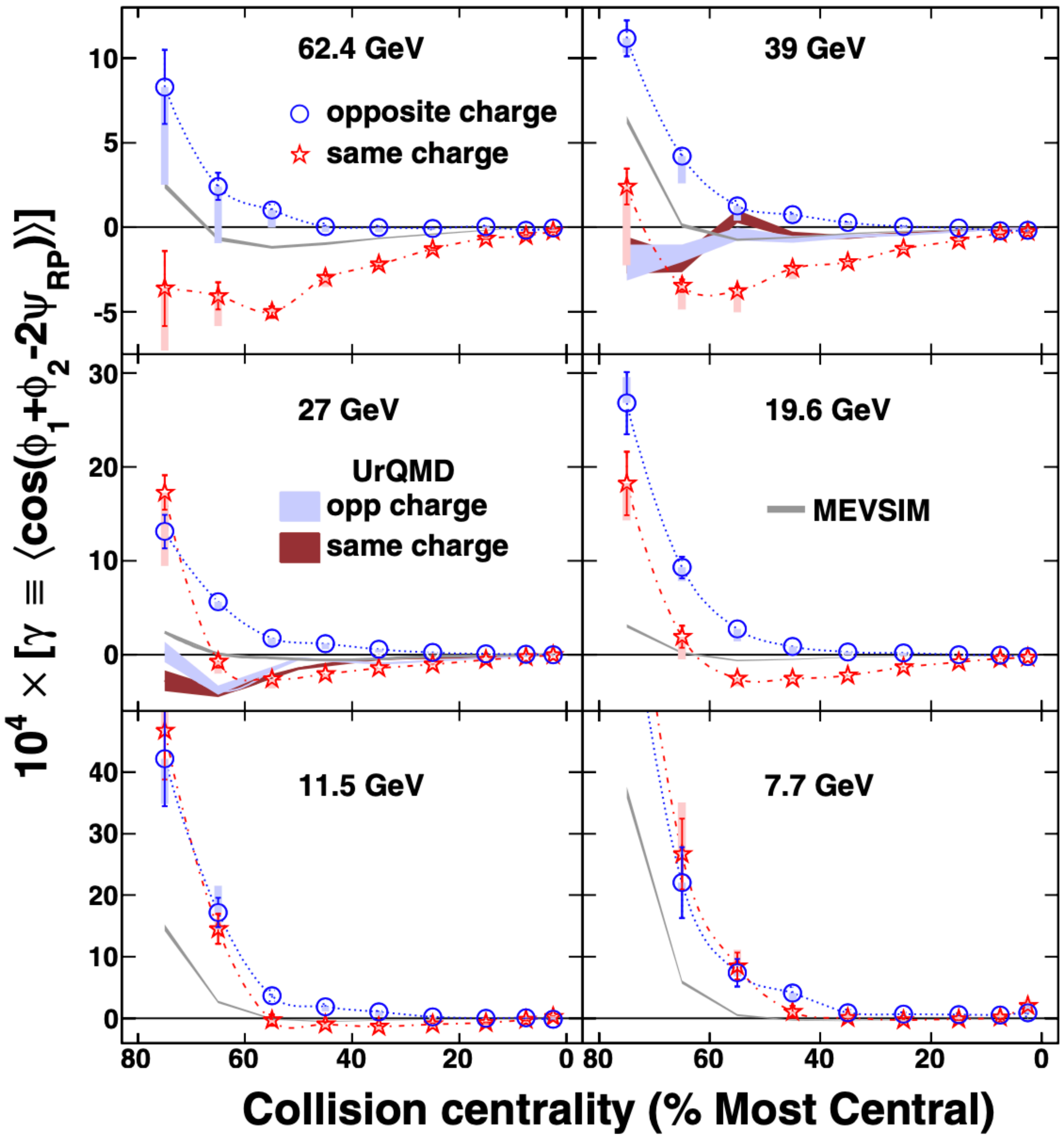


STAR, Phys. Rev. C 88 (2013) 064911

- First measurement; Large signal

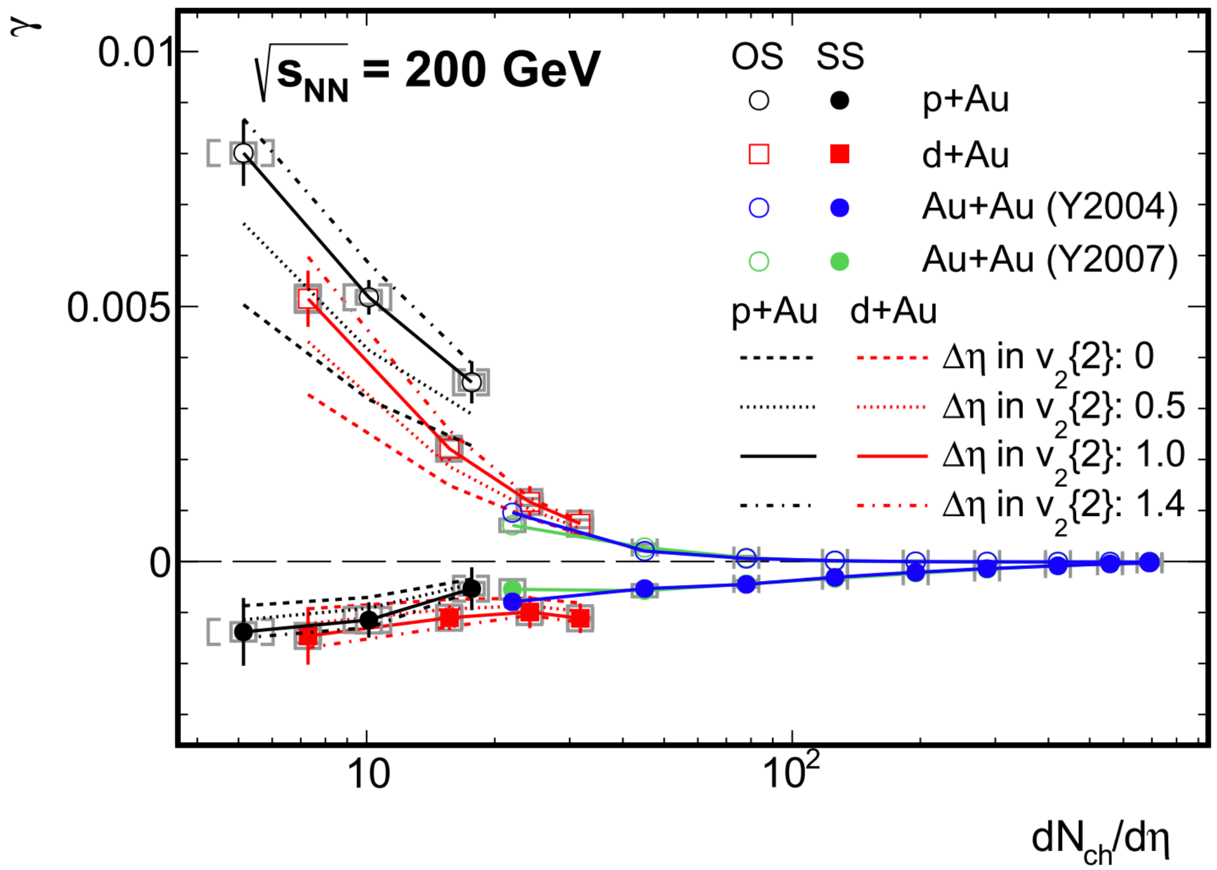
- Measurement wrt ZDC Ψ_1
- Similar result wrt TPC Ψ_2

First Measurements wrt BES and systems size



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

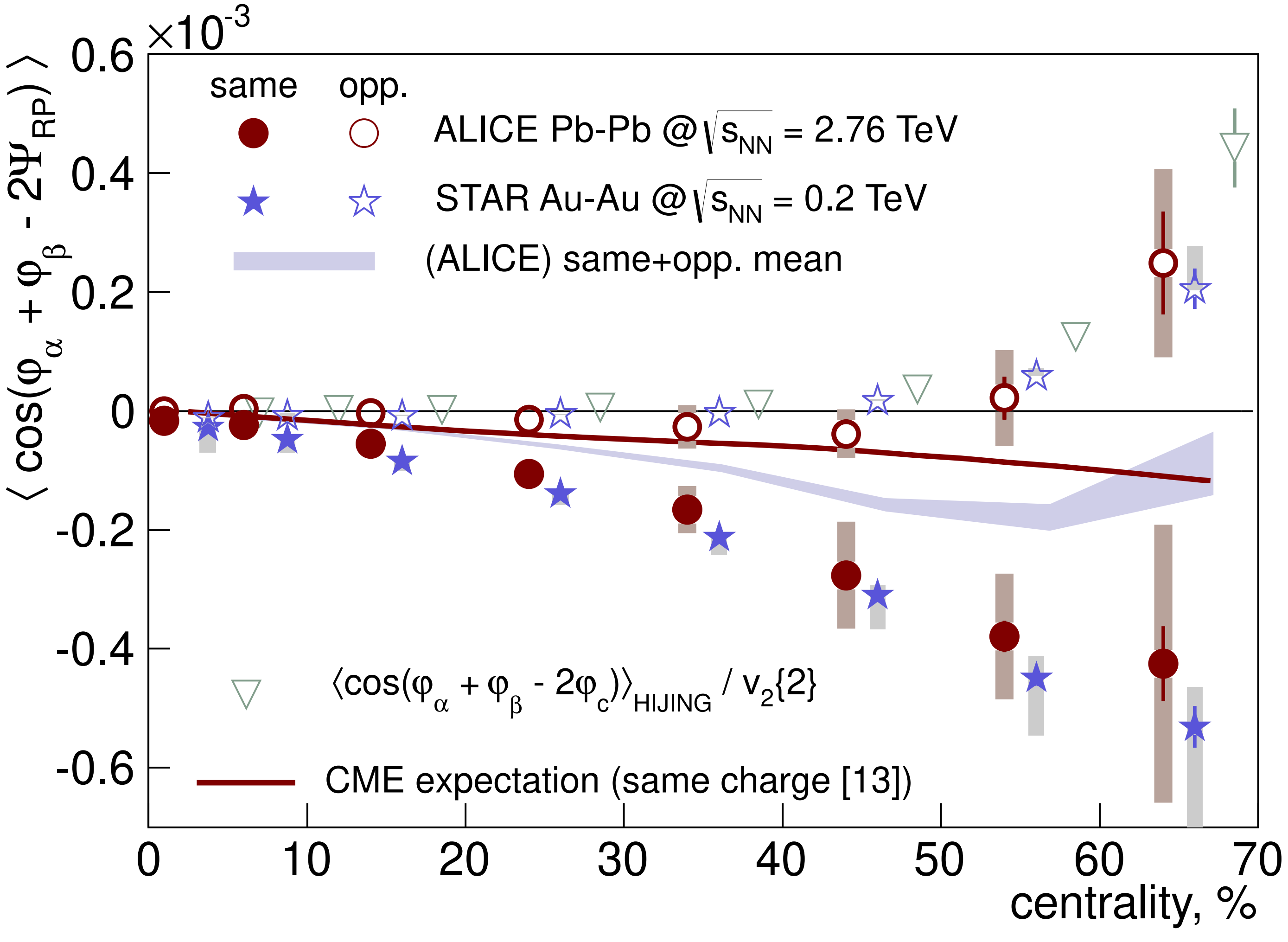
- Beam Energy Dependence from BES-I: Signal vanishes at low energy



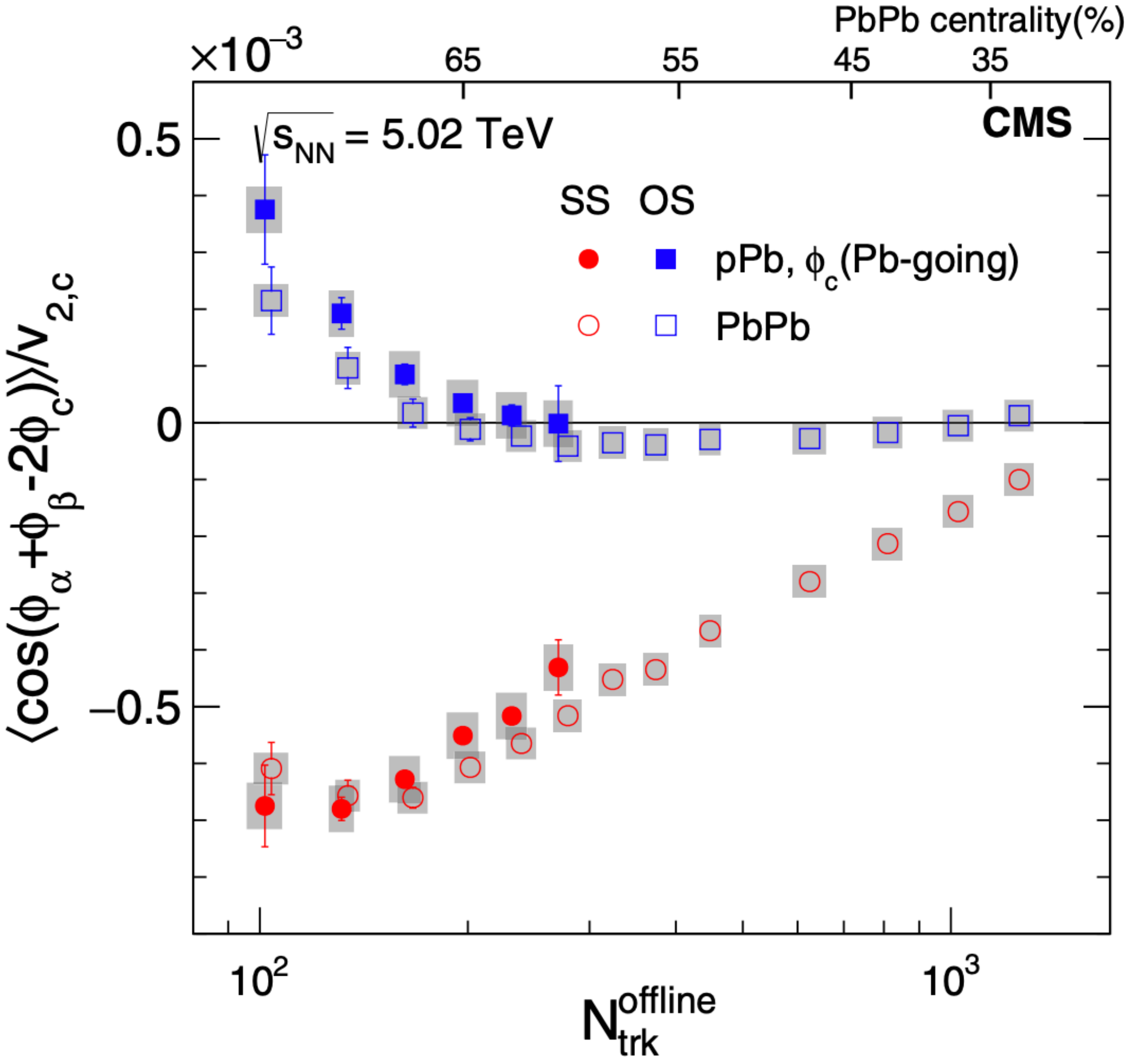
STAR, Phys. Lett. B 798 (2019) 134975

- Small system (p+Au, d+Au)
- Signal as large as heavy ion
- Large background contributions?

Similar measurement from LHC



ALICE Collaboration, Phys. Rev. Lett. 110, 012301 (2013)



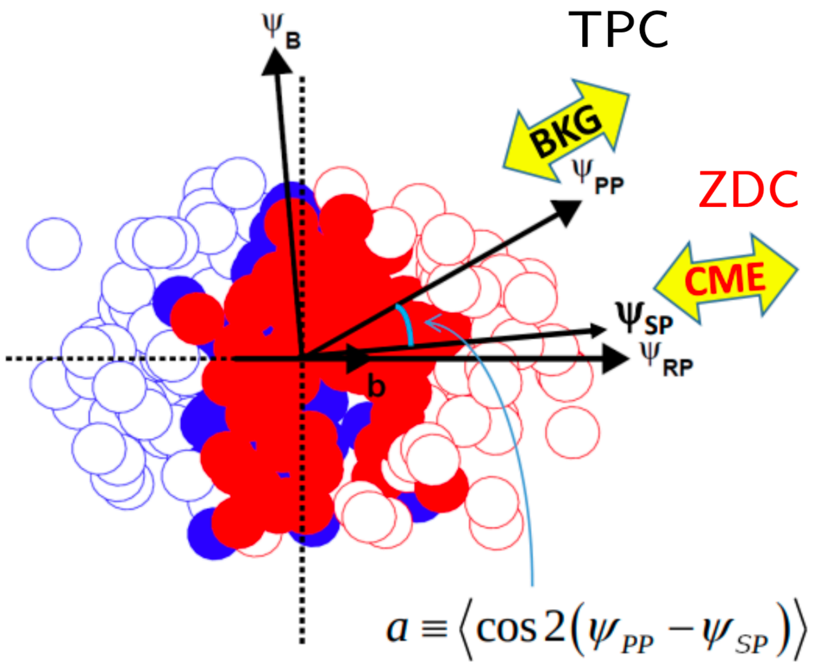
CMS Collaboration, Phys. Rev. Lett. 118, 122301 (2017)

- Similar results from LHC, though very different energy and species

Latest results from STAR

SP/PP comparison method

- Participant plane (PP) — nucleons collided — collision zone — flow — backgrounds w/flow
- Spectator plane (SP) — nucleons flying through — magnetic field — CME signal
- The signal and background (coupled with flow) respond to those two planes differently — SP, PP comparison — separate the signal and background (coupled with flow)

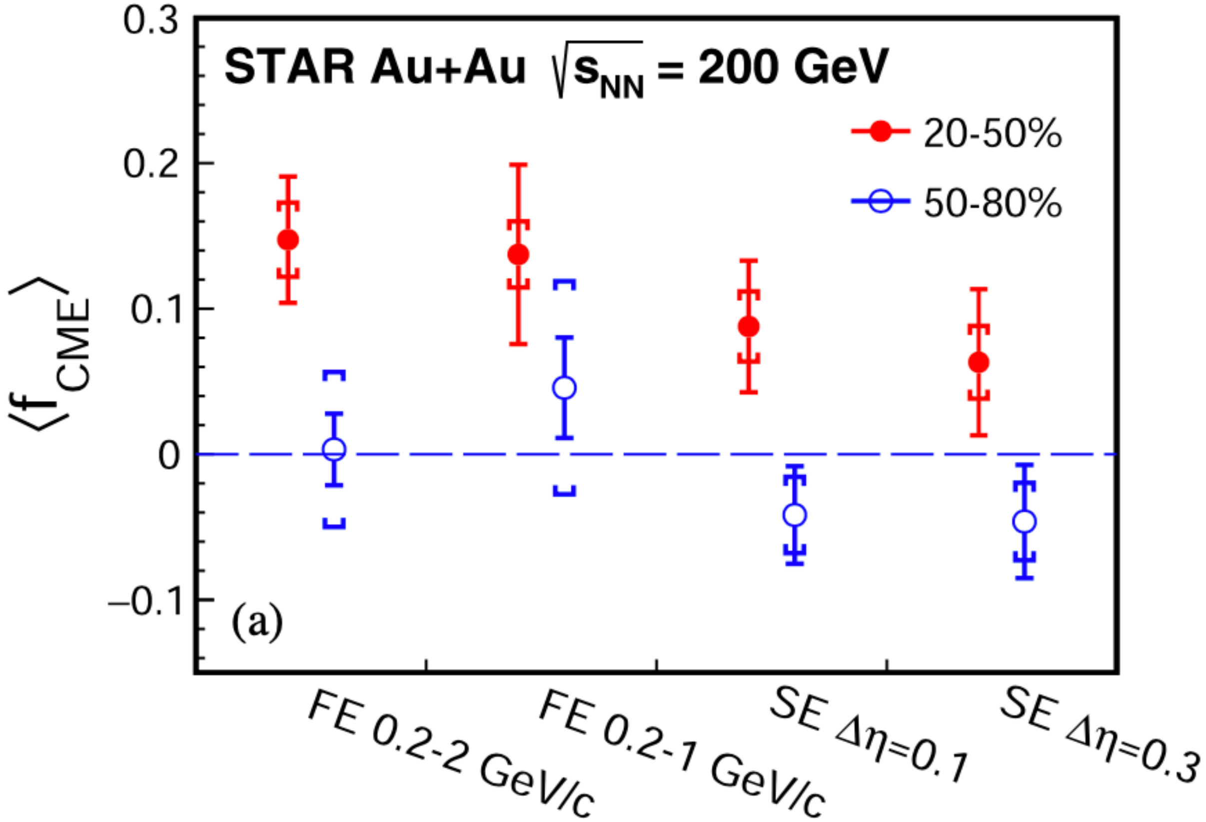


$$a \equiv \langle \cos 2(\psi_{PP} - \psi_{SP}) \rangle$$

$$a = v_2\{\mathrm{SP}\}/v_2\{\mathrm{PP}\}$$

$$A = \Delta\gamma\{\mathrm{SP}\}/\Delta\gamma\{\mathrm{PP}\}$$

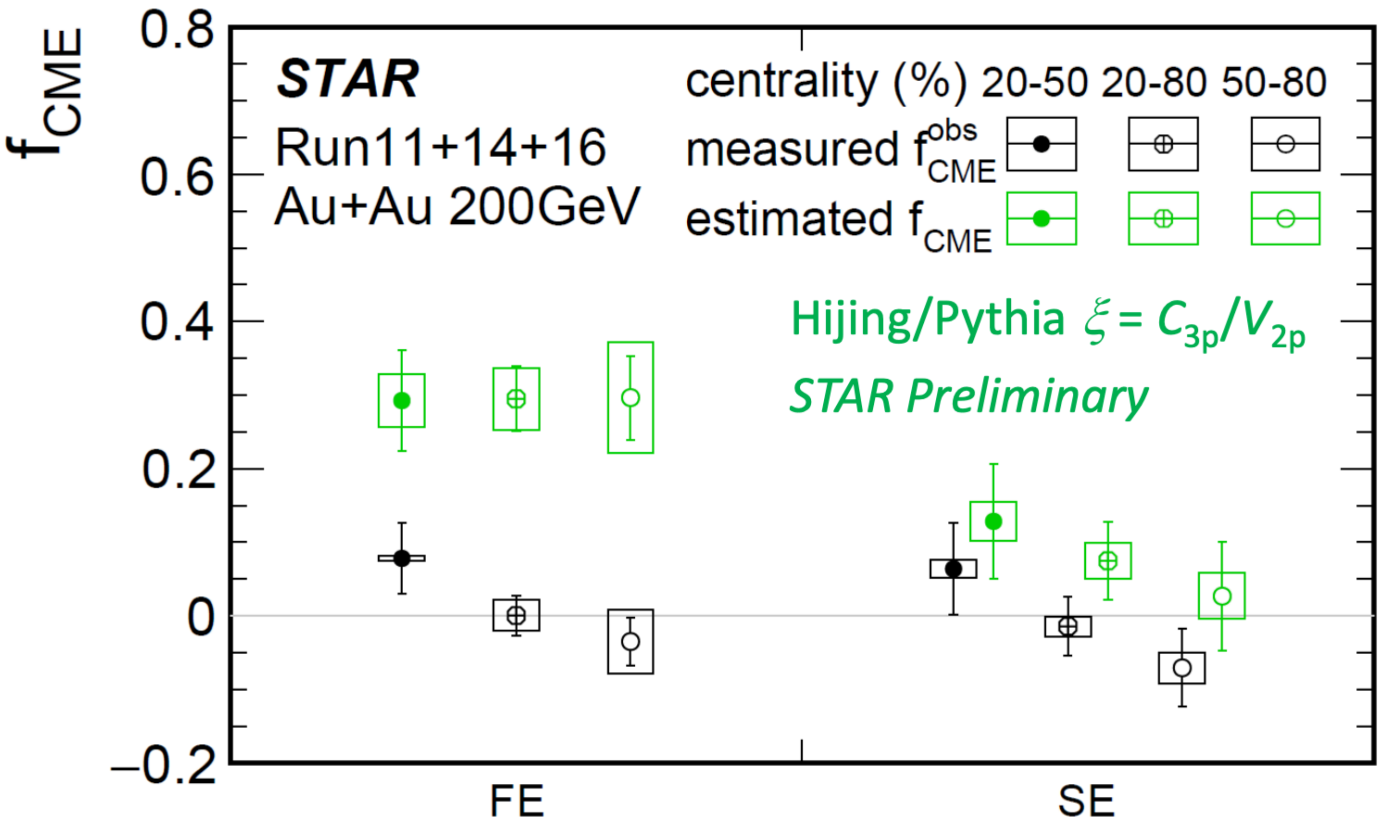
$$f_{\mathrm{CME}} = \frac{\Delta\gamma_{\mathrm{CME}}\{\mathrm{EP}\}}{\Delta\gamma\{\mathrm{EP}\}} = \frac{A/a - 1}{1/a^2 - 1}$$

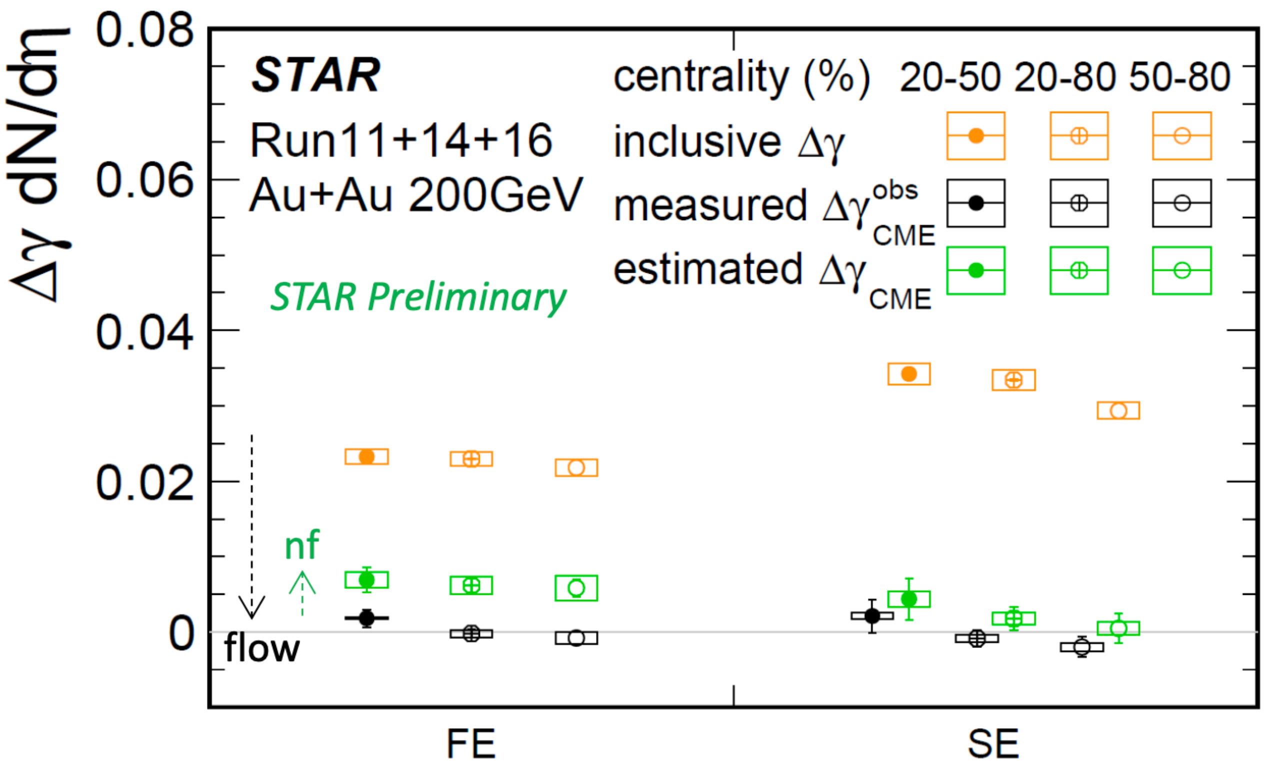


- Consistent-with-zero $\langle f_{CME} \rangle$ in peripheral 50-80% collisions with relatively large errors
- Indications of finite extracted $\langle f_{CME} \rangle$ in mid-central 20-50% collisions, with 1-3σ significance. Flow background is minimized by the SP/PP planes and non-flow contributions to $\langle f_{CME} \rangle$ are still under investigation.

STAR, Phys. Rev. Lett. 128, 092301 (2022)

SP/PP comparison method





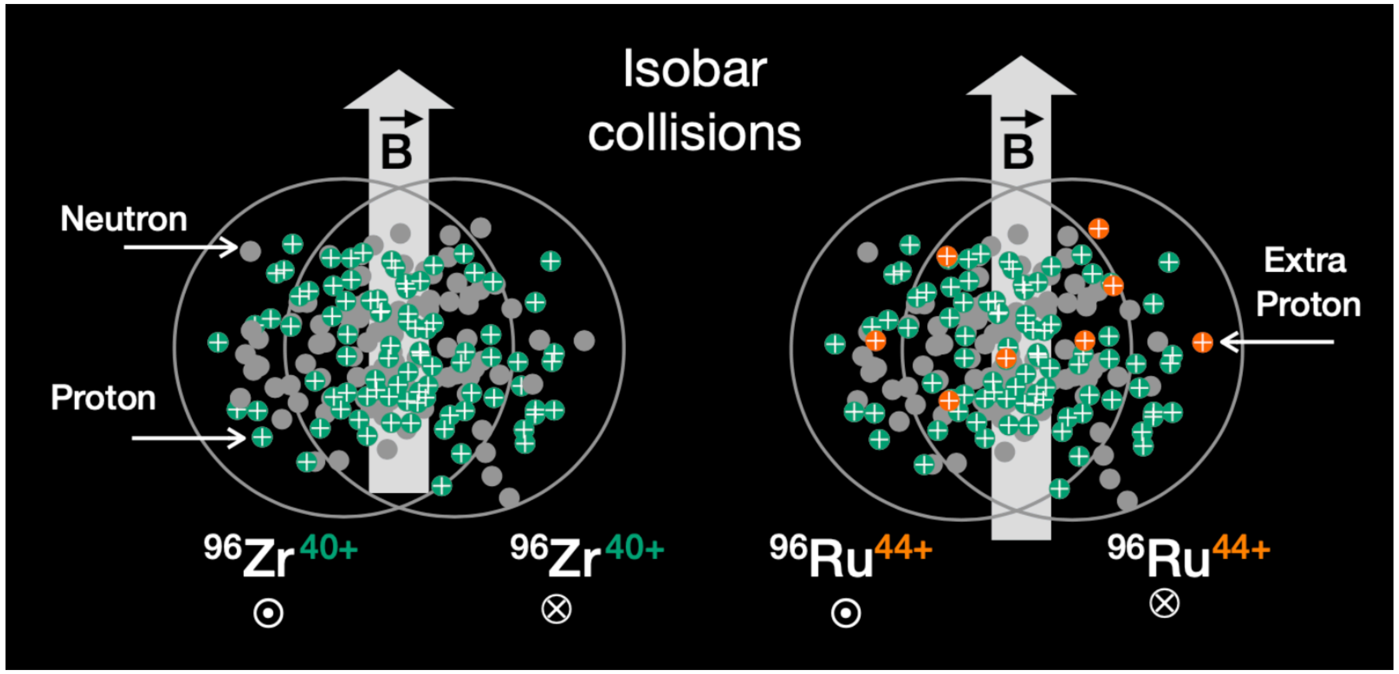
- f_{CME} after subtracting estimated non-flow contribution
- Preliminary results indicate a non-zero extracted f_{CME} in full-event analysis, with minimal centrality dependence. f_{CME} full-event > sub-event

F. Wang, 9th Conference on Chirality, Vorticity, and Magnetic Fields in Quantum Matter, July 2025
Feng et al., PLB 820 136549 (2021)
ALICE, PLB 856 138862 (2024)

Isobar Collisions

Isobar Collisions

- Initial expectation: ${}^{96}_{44}Ru +^{96}_{44} Ru$ and ${}^{96}_{40}Zr +^{96}_{40} Zr$: same A, different Z → same background → different signal
- Ru+Ru: proton number ↑ → magnetic field ↑ → CME signal ↑ → $\Delta\gamma/v_2$ ↑ → Ratio (Ru/Zr) > 1
- The magnetic field is ~10-18% larger in Ru+Ru collisions
- Expect enhanced CME effect in Ru+Ru collisions than Zr+Zr collisions.



P. Tribedy, Free meson seminar, TIFR, Oct 7th, 2021

STAR, Phys. Rev. C 105, 014901 (2022)

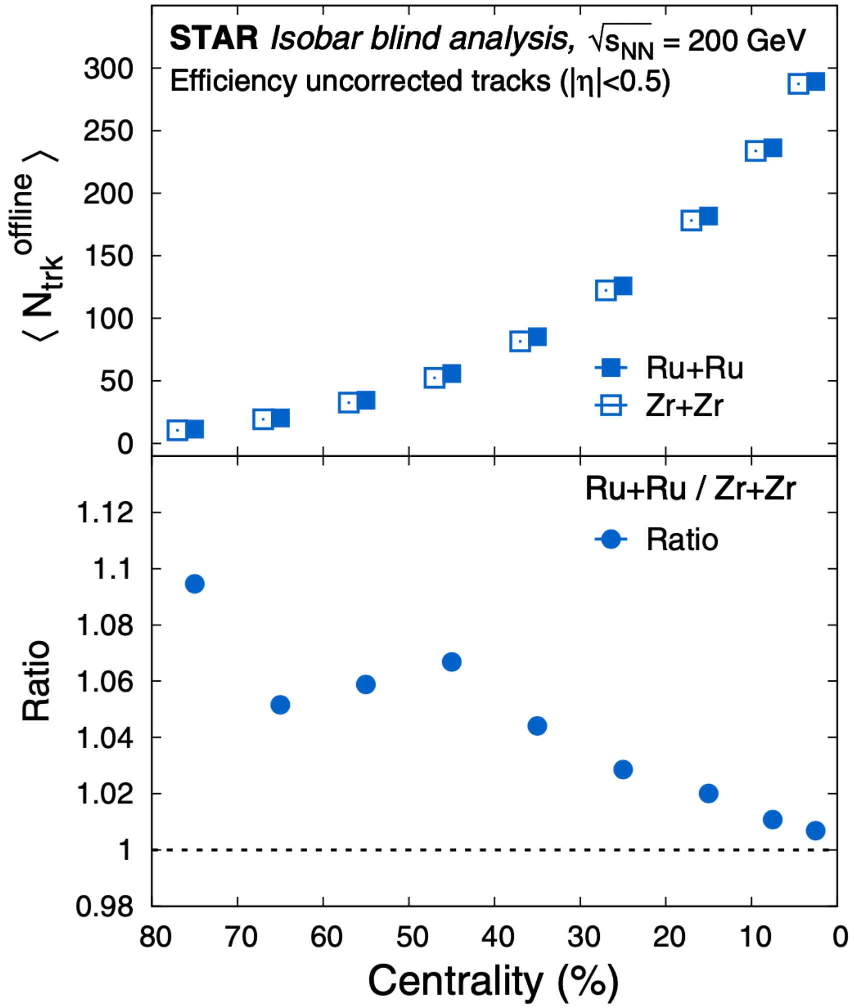
Isobar Collisions: Blind Analysis

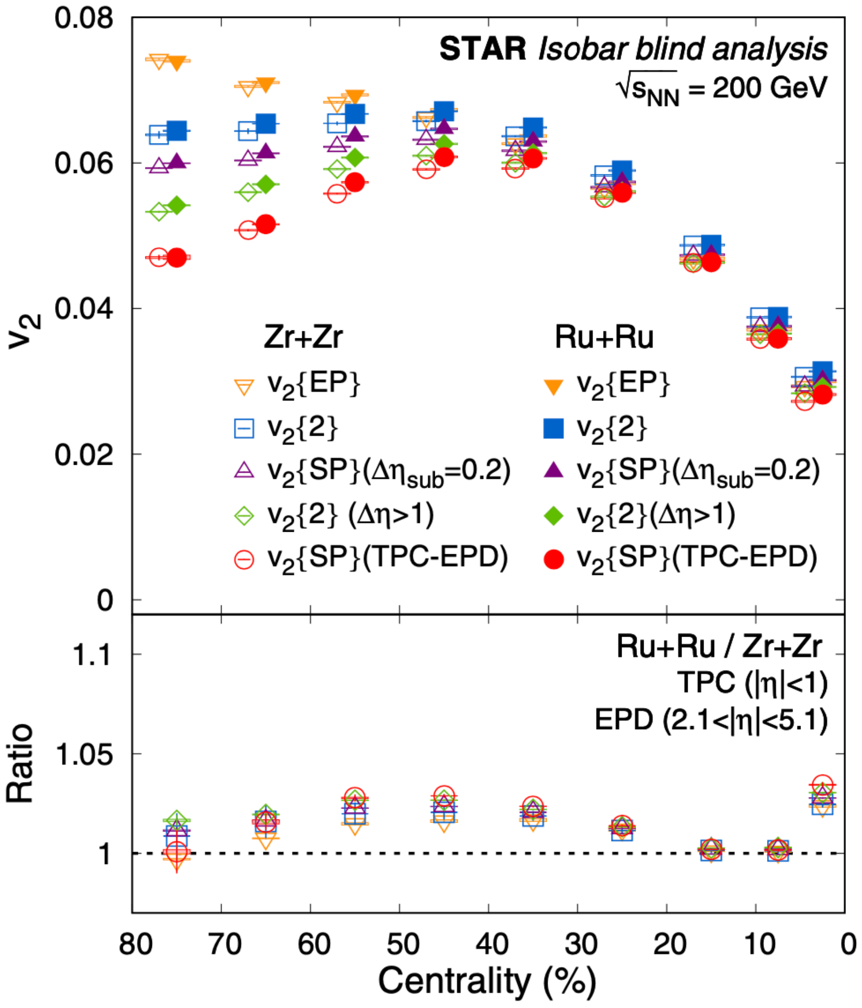
Step-0
Mock Data challenge
Test data structure (Au+Au data)

Step-1
Isobar Mixed analysis
Code freezing (Each run is Ru+Ru & Zr+Zr)

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

Step-3
Isobar Unblind analysis
Final analysis (Ru+Ru & Zr+Zr separated)

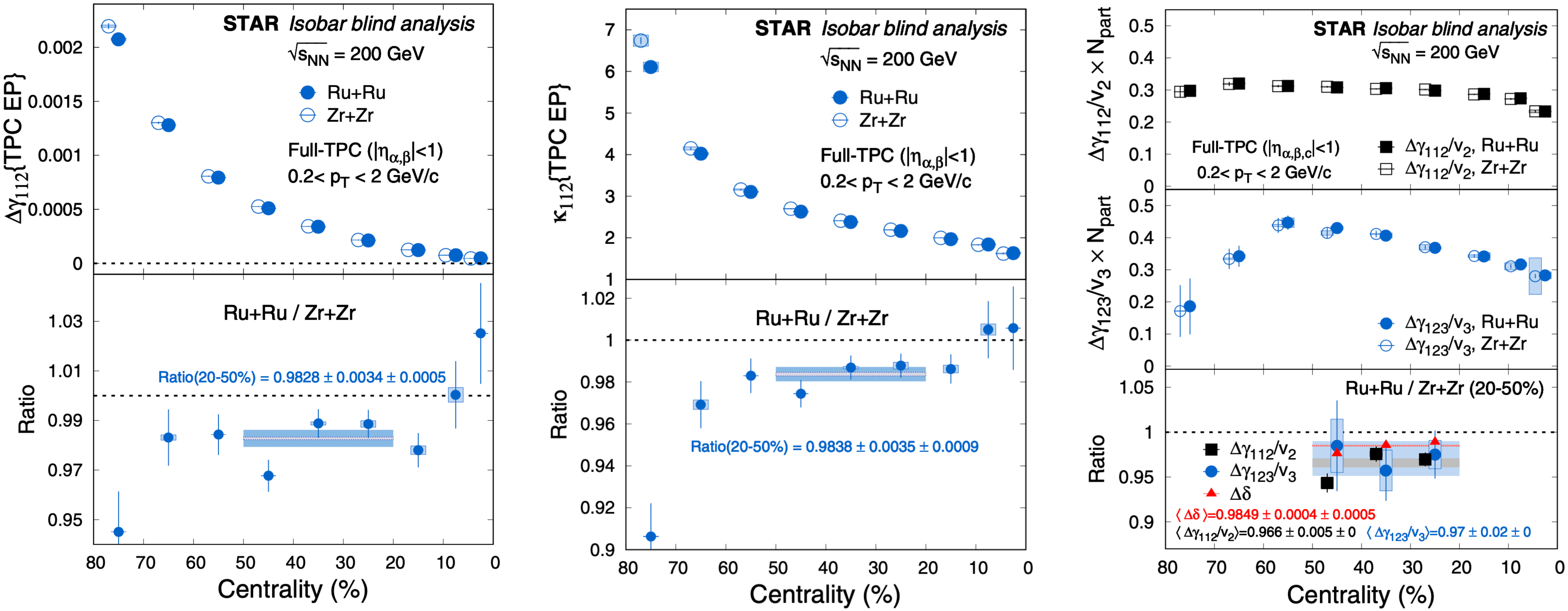




- The multiplicity for both isobars is different (~4% for mid-central)
- v_2 (main background for CME) is different in both isobars

STAR, Phys. Rev. C 105, 014901 (2022)

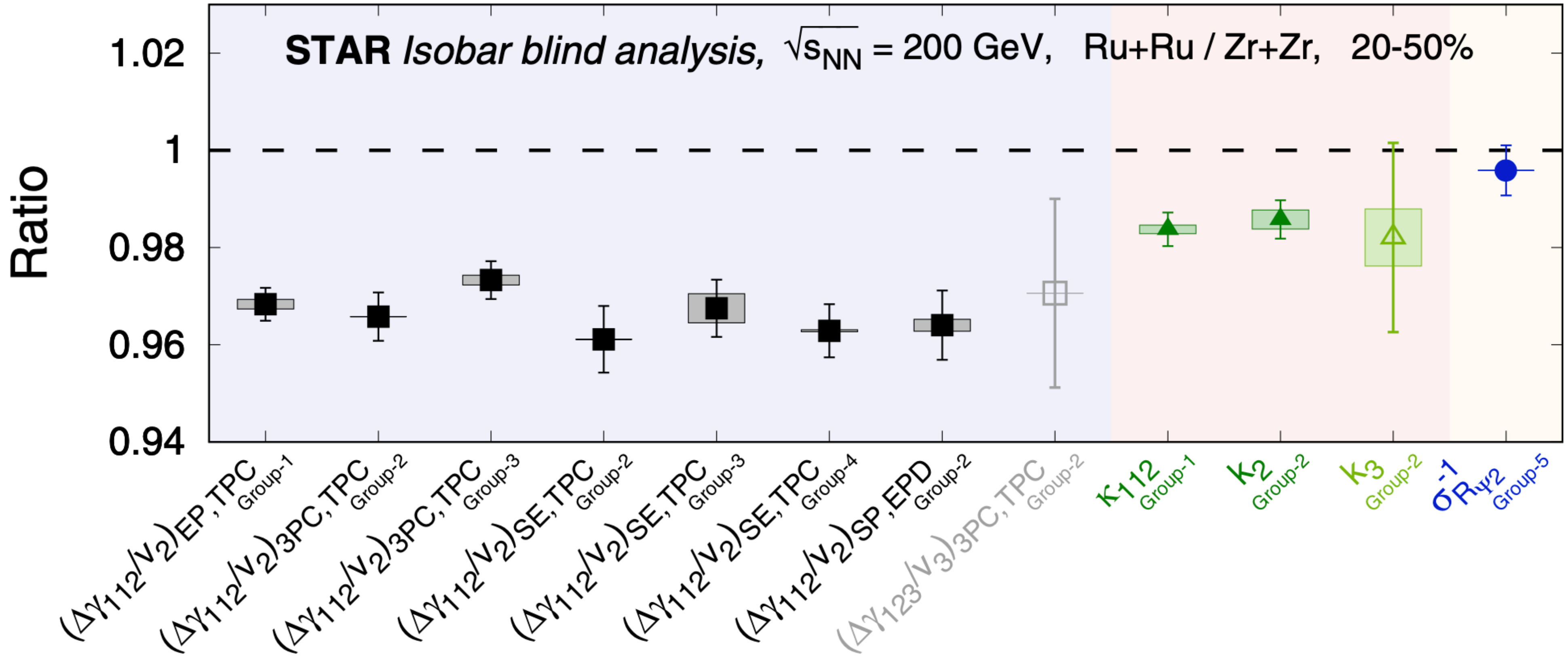
Isobar Collisions: $\Delta\gamma$, $\Delta\gamma/v_2$, *and* $k = \Delta\gamma/v_2\Delta\delta$



- Ru+Ru/Zr+Zr ratios all below unity, naively unexpected.
- The observed difference is primarily due to multiplicity differences between Ru+Ru and Zr+Zr; additionally, nuclear structure differences (e.g., deformation, neutron skin) impact the initial geometry and flow backgrounds.

STAR, Phys. Rev. C 105, 014901 (2022)

Isobar Collisions

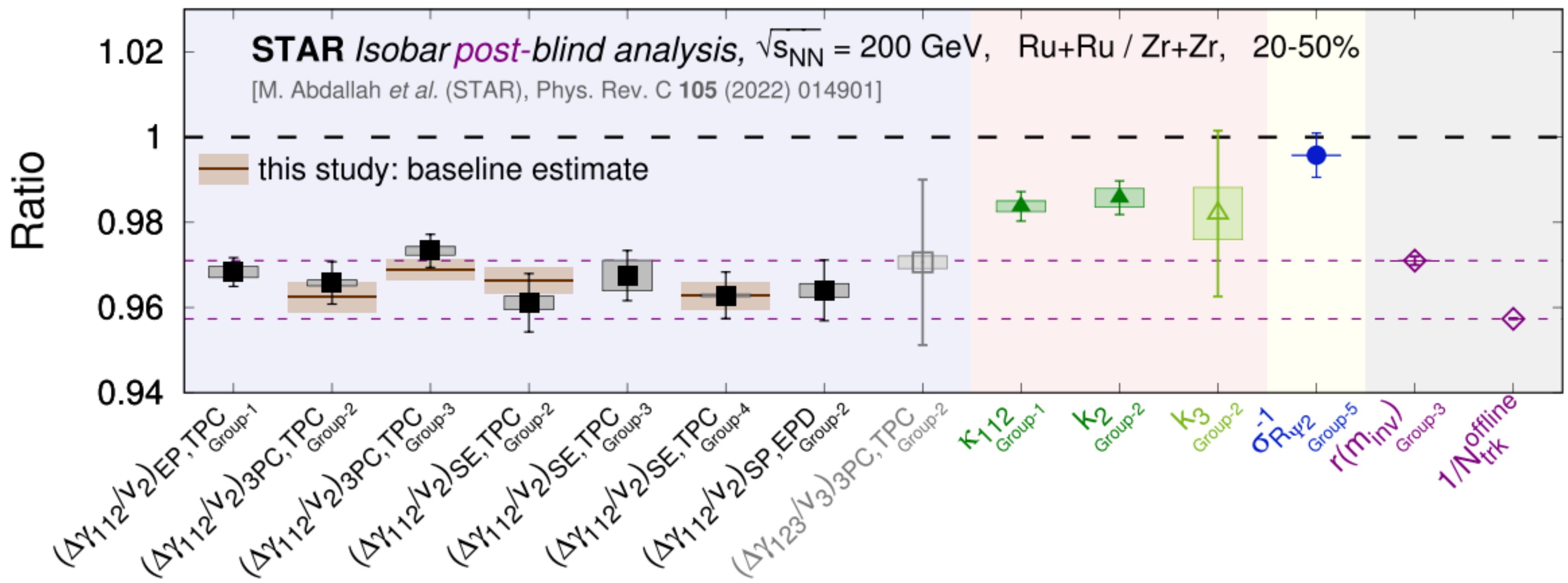


- STAR blind analysis: The observed ratio (Ru/Zr < 1) may reflect nuclear structure differences between Ru and Zr nuclei, in addition to multiplicity bias

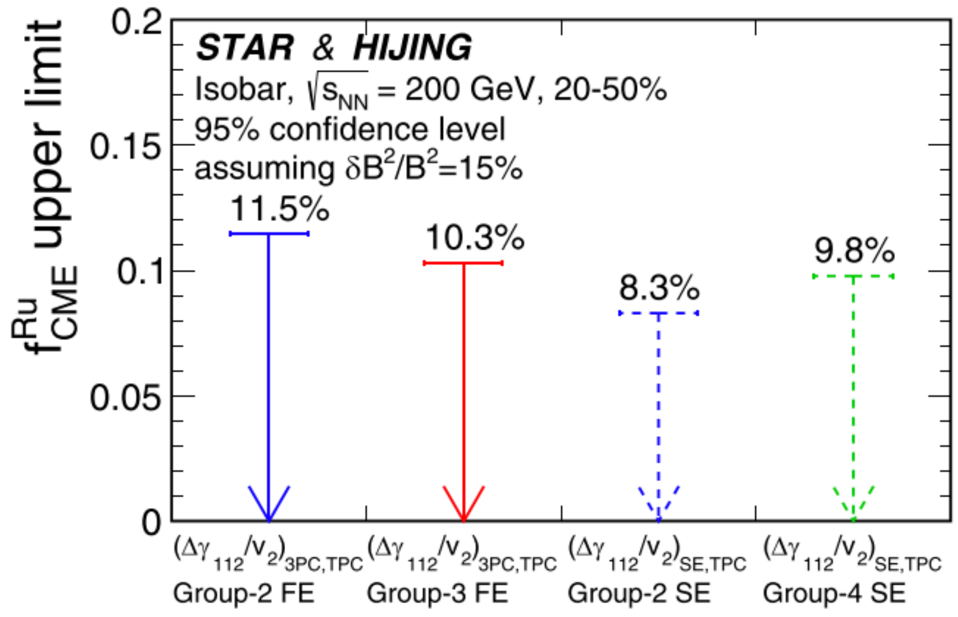
Xu et al., Phys. Rev. Lett. 121022301 (2018)

STAR, Phys. Rev. C 105, 014901 (2022)

Isobar Collisions

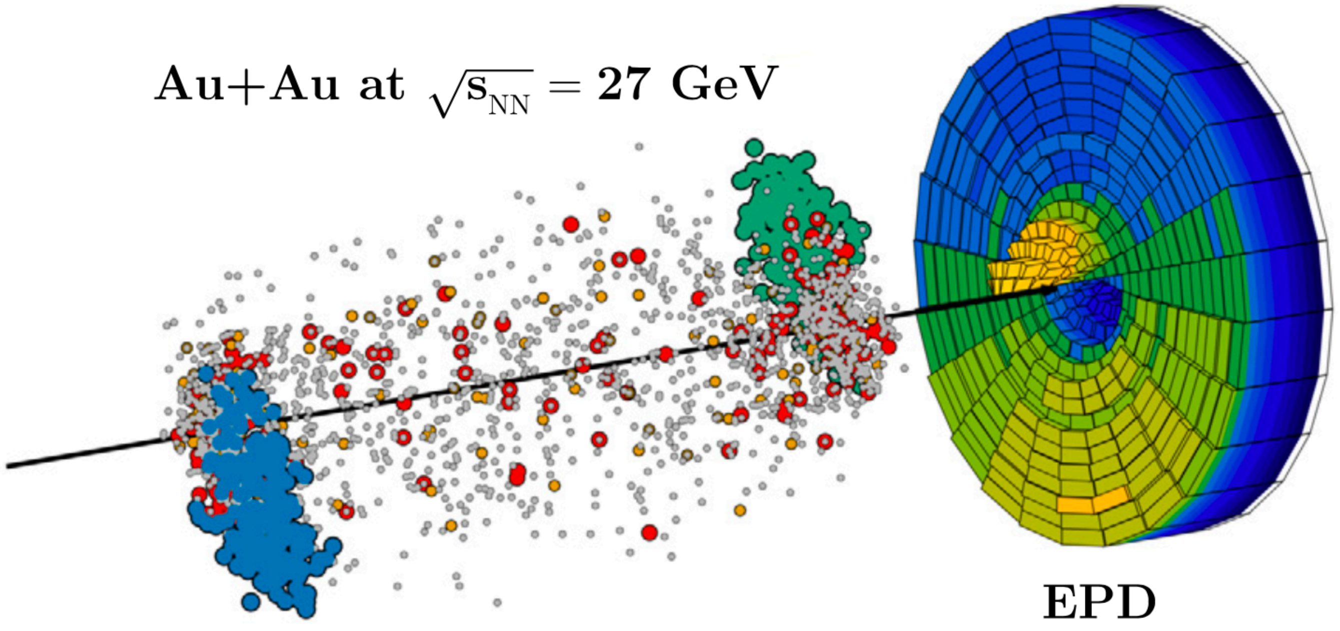


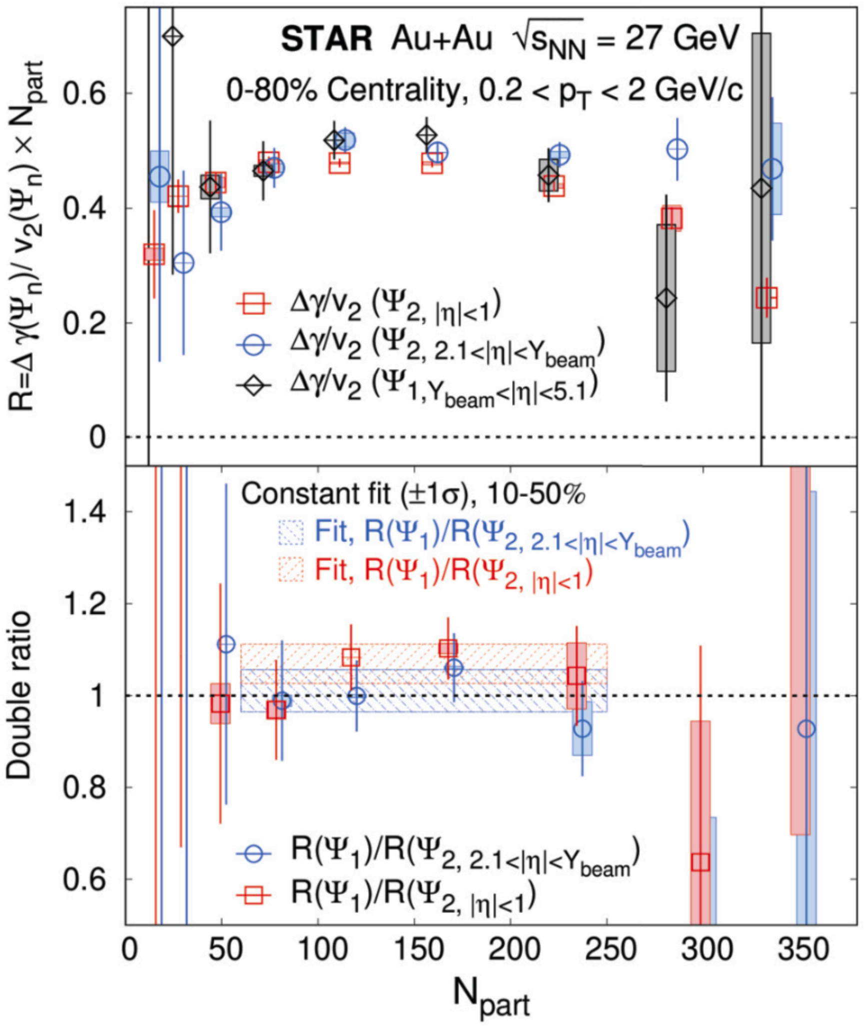
- A comprehensive post-blind analysis was performed after the initial isobar blind study.
- Multiple observables (Δγ, Δγ/⟨v_2⟩, k=Δγ/Δδ, R-correlator, SDM) analyzed using both full-event and sub-event methods.
- Estimated baseline taking into account non-flow contributions to the background consistent with measured values.
- Upper limit on CME signal contribution: <10% at 95% confidence level.

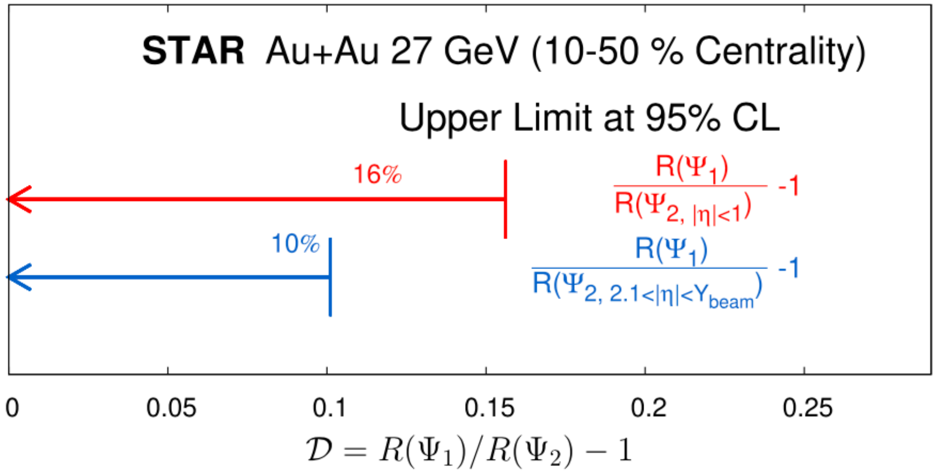


STAR, Phys. Rev Research 6, L032005 (2024)

LOW ENERGY (27 GeV) DATA



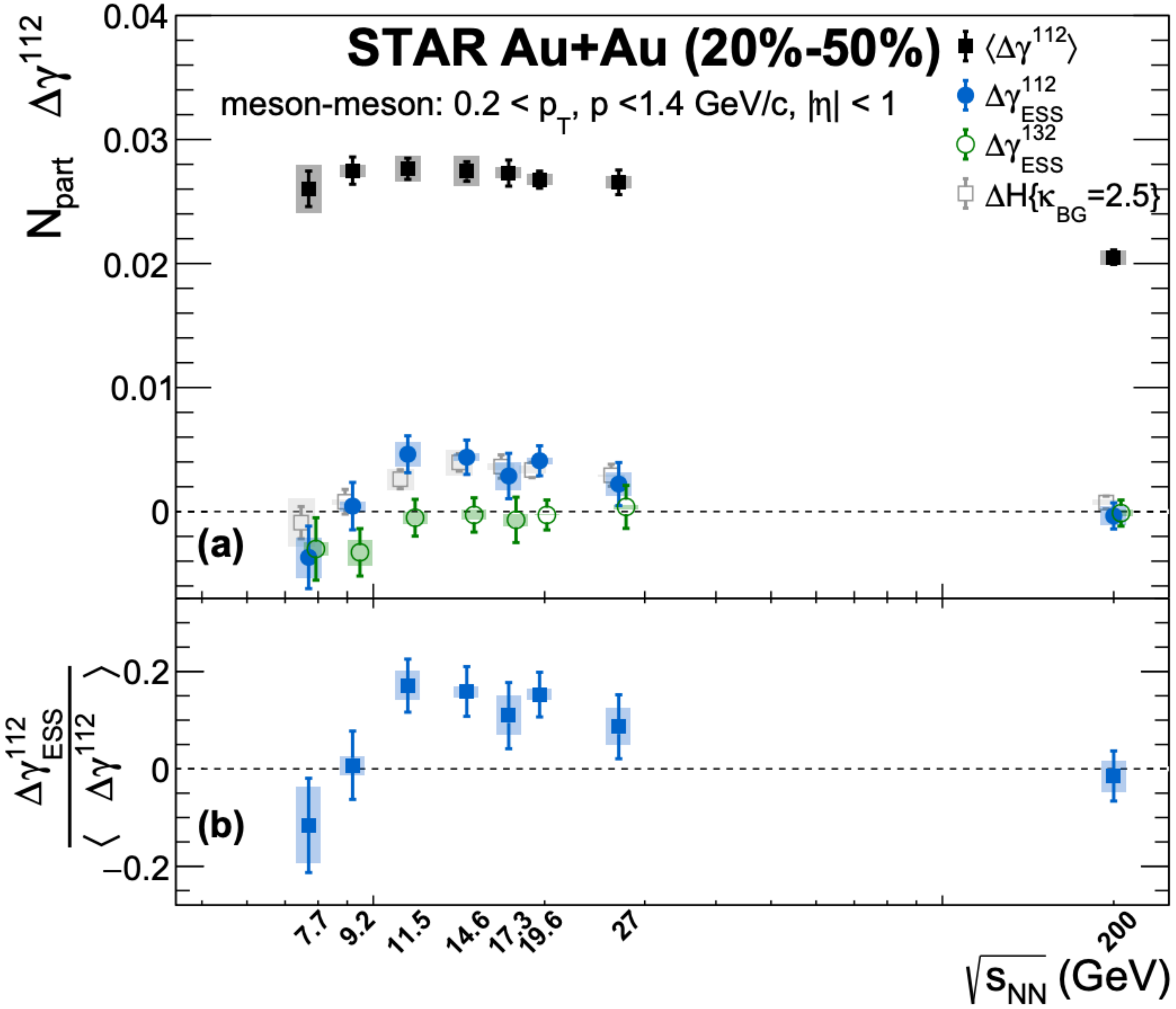


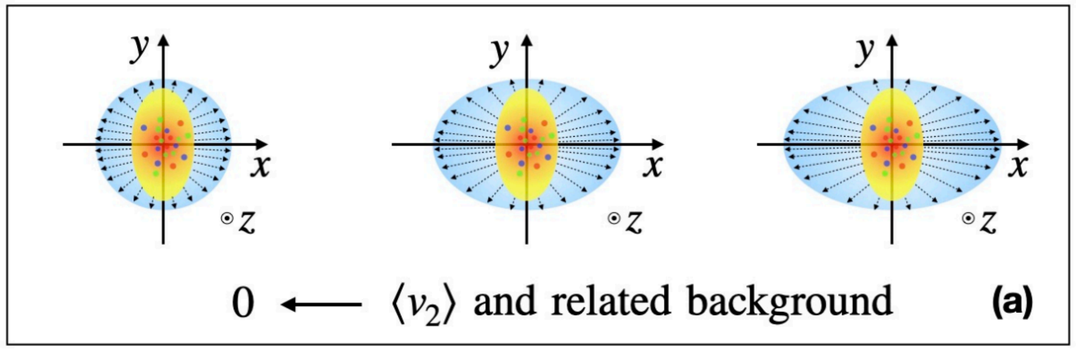


- Higher statistics, new detector (EPD) with 2.1 < |η| < 5.1
- New approach: Inner EPD - first-order harmonic plane; Outer EPD - second-order harmonic plane (Inner EPD 3.4 < |η| < 5.1 and outer EPD 2.1 < |η| < 3.4)
- Double Ratio (R_{Ψ_1}/R_{Ψ_2}) is consistent with unity
- Upper Limit at 10% and 16% at 95% CL

STAR, Phys. Lett. B 839, 137779 (2023)

Results from BES-II with Event Shape Selection (ESS) Analysis





$$\Delta\gamma_{ESS}^{112(132)} = (1 - v_2)^2 \Delta\gamma^{112(132)}\big|_{v_2=0}$$

$$\gamma_{112} = \frac{\langle\cos(\phi_\alpha + \phi_\beta - \Psi_f - \Psi_b)\rangle}{\langle\cos(\Psi_f - \Psi_b)\rangle} \qquad v_2 = \frac{\langle\cos(2\phi - \Psi_f - \Psi_b)\rangle}{\langle\cos(\Psi_f - \Psi_b)\rangle}$$

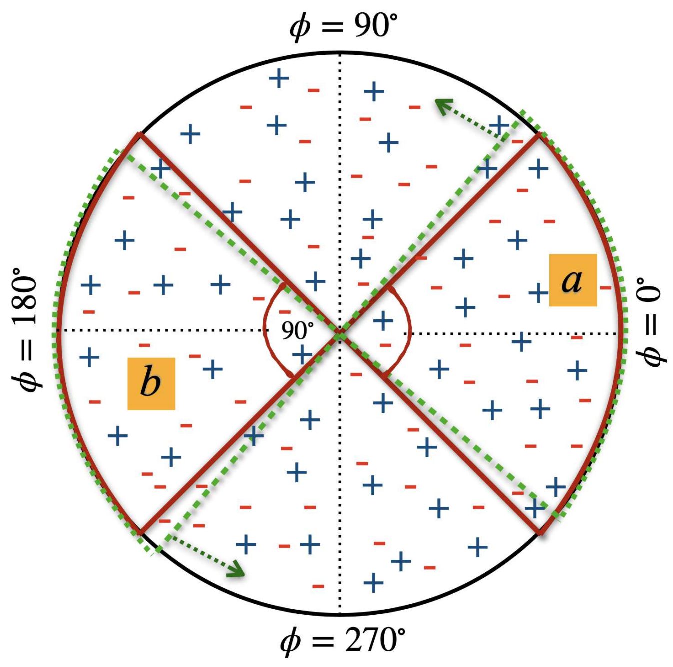
$\Psi_f(\Psi_b)$ are spectator plane at forward (backward) rapidities using the EPD for 7.7-27 GeV (ZDC-SMD for 200 GeV)

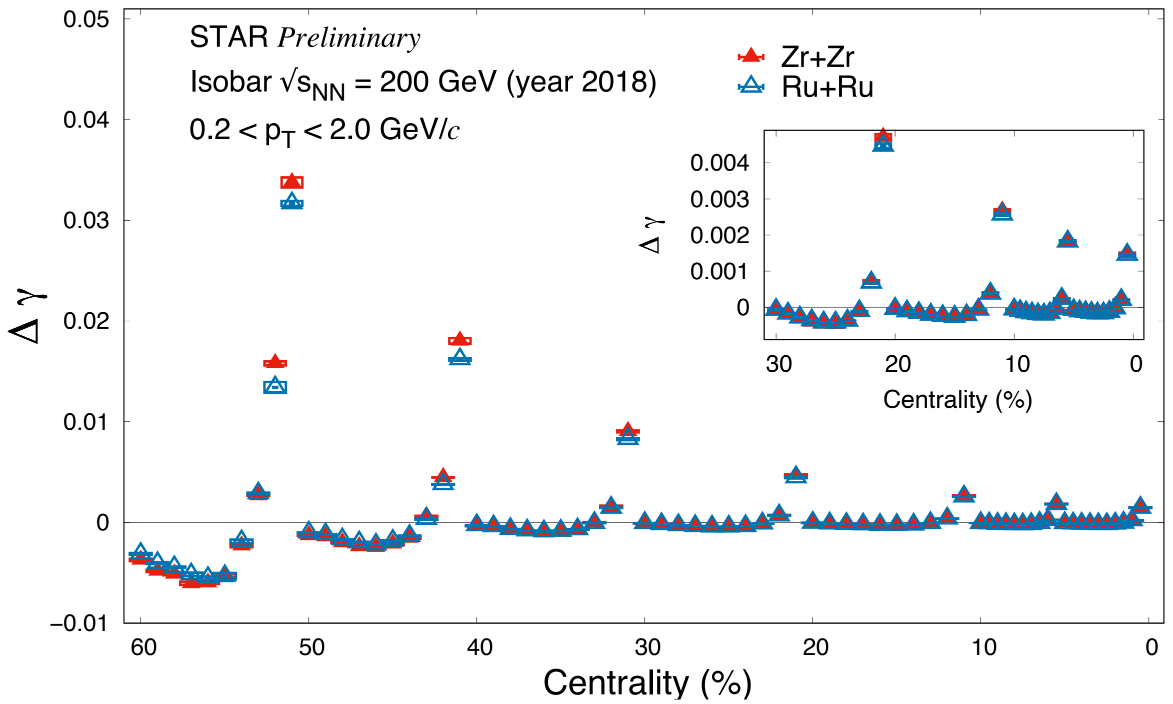
- ESS uses the event-by-event magnitude of q_2 to categorize events by elliptic flow shape
- ESS estimates the CME signal when the background contribution from v_2 is effectively zero
- $\Delta\gamma_{ESS}^{112}$ is non-zero at 11.5–19.6 GeV with significance above background
- The background indicator $\Delta\gamma_{ESS}^{132}$ is consistent with zero across all energies
- $\Delta\gamma_{ESS}^{112}$ consistent with zero at both 7.7 and 200 GeV

STAR, https://arxiv.org/pdf/2506.00275

New Approaches

Sliding Dumbbell Method

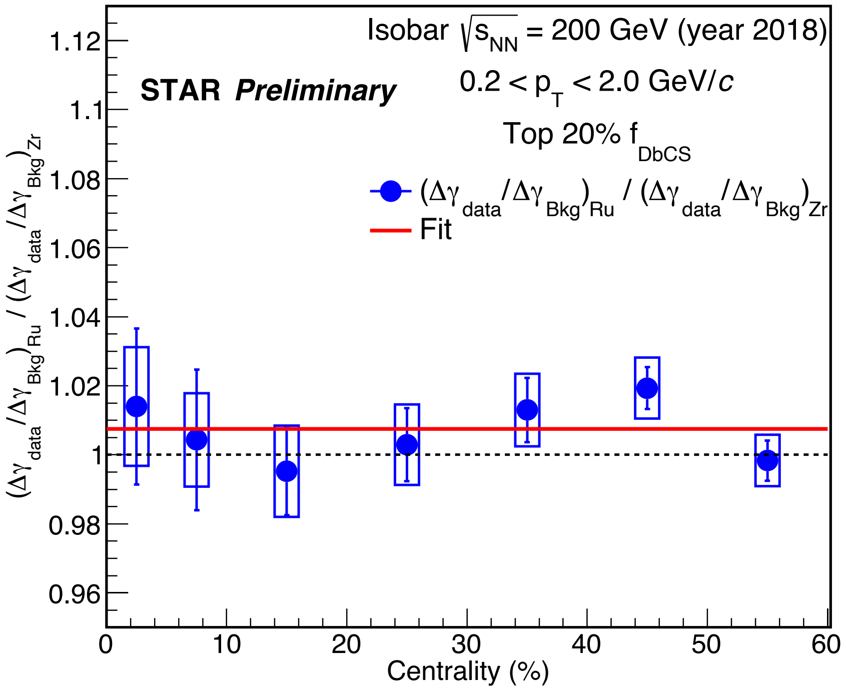




- The azimuthal plane in each event is scanned by sliding the dumbbell of $\Delta\phi = 90°$ in steps of $\delta\phi = 1°$ while calculating, Db_{+-} for each region to obtain maximum values of Db_{+-} (Db_{+-}^{max}) in each event with a condition that $Db_{asy} < 0.25$.

$$Db_{+-} = \frac{n_+^a}{(n_+^a + n_-^a)} + \frac{n_-^b}{(n_+^b + n_-^b)} \qquad f_{DbCS} = Db_{+-}^{max} - 1$$

- $\Delta\gamma$ is positive for the top 20% (30%) f_{DbCS} bins for 0-40% (40-60%) centralities.
- The double ratio is 1.007±0.003 (pol0 Fit) for 0-60% centralities showing no enhanced CME in Ru+Ru compared to Zr+Zr even in top 20% potential CME-like events



M.M. Aggarwal et al., Pramana - J Phys ***98****, 117 (2024)*
J. Singh (STAR), Springer Proc.Phys. 304, 464-468 (2024)
J. Singh (STAR), Quark Matter 2022, ICNFP-2024

Summary

- CME is very important physics. Significant efforts in theory and experiments.
- STAR has pioneered and played significant role in the CME search. Primary efforts in understanding and removing backgrounds.
- The possible CME is a small fraction of the measured $\Delta\gamma$ signal.
- STAR Au+Au collisions data indicate a finite extracted $\langle f_{CME} \rangle$with 1-3σ significance, however, non-flow contributions are still under investigation.
- In the Isobar blind analysis an anticipated precision down to 0.4% is achieved. No enhanced CME signal is observed in Ru+Ru compared to Zr+Zr collisions.

Outlook

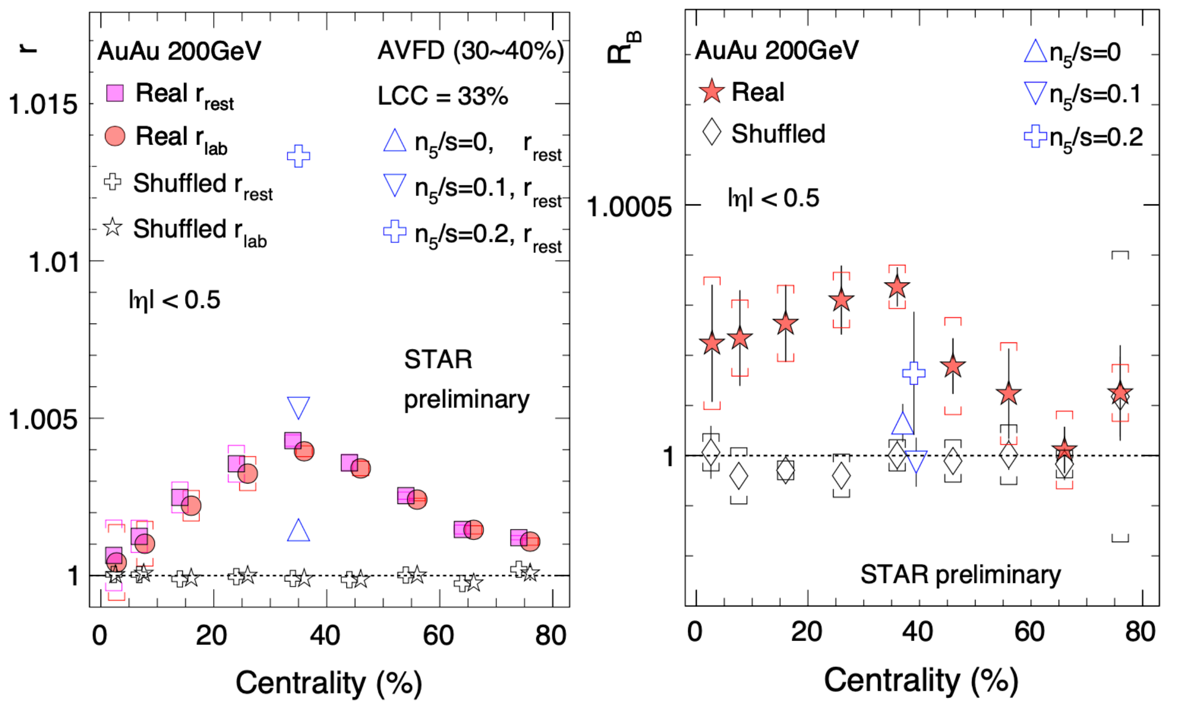
- High statistics Au+Au runs and new detector with wider acceptance will further improve sensitivity to CME-related observables.

Thank you

Back up

Other Observables

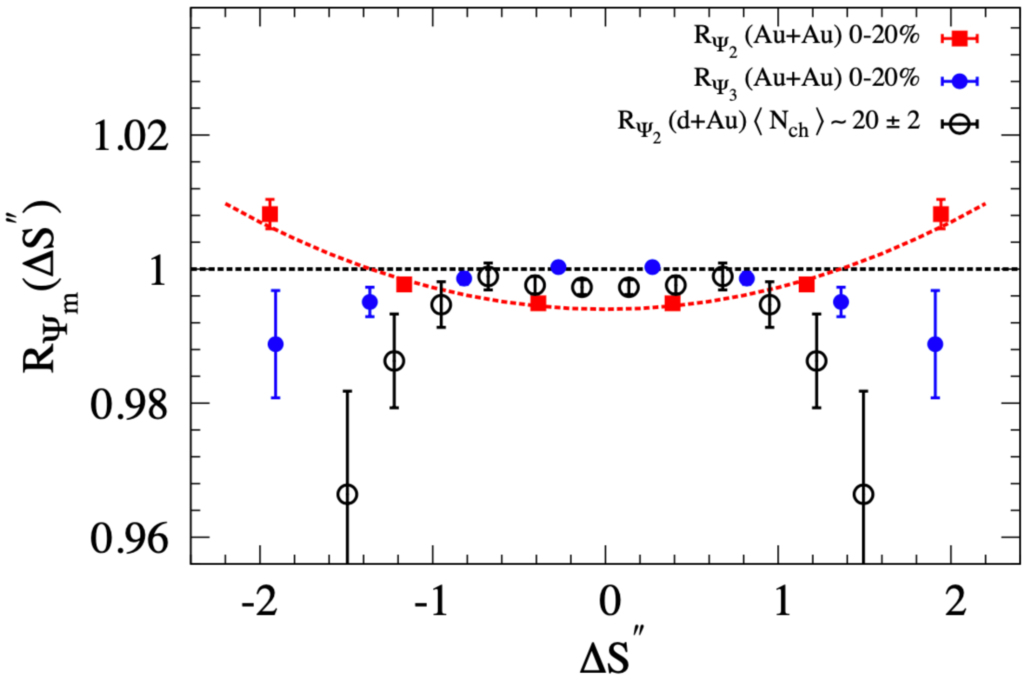
Signed Balance Function



- r is out-of-plane to in-plane ratio of the SBF momentum-ordering difference
- Both r_{rest} and $R_B = r_{rest}/r_{lab}$ are larger than unity, above model calculations without CME

Tang, CPC 44 (2020) 054101
Yufu Lin (STAR), NPA 1005 (2021) 121828, QM 2019

R correlator

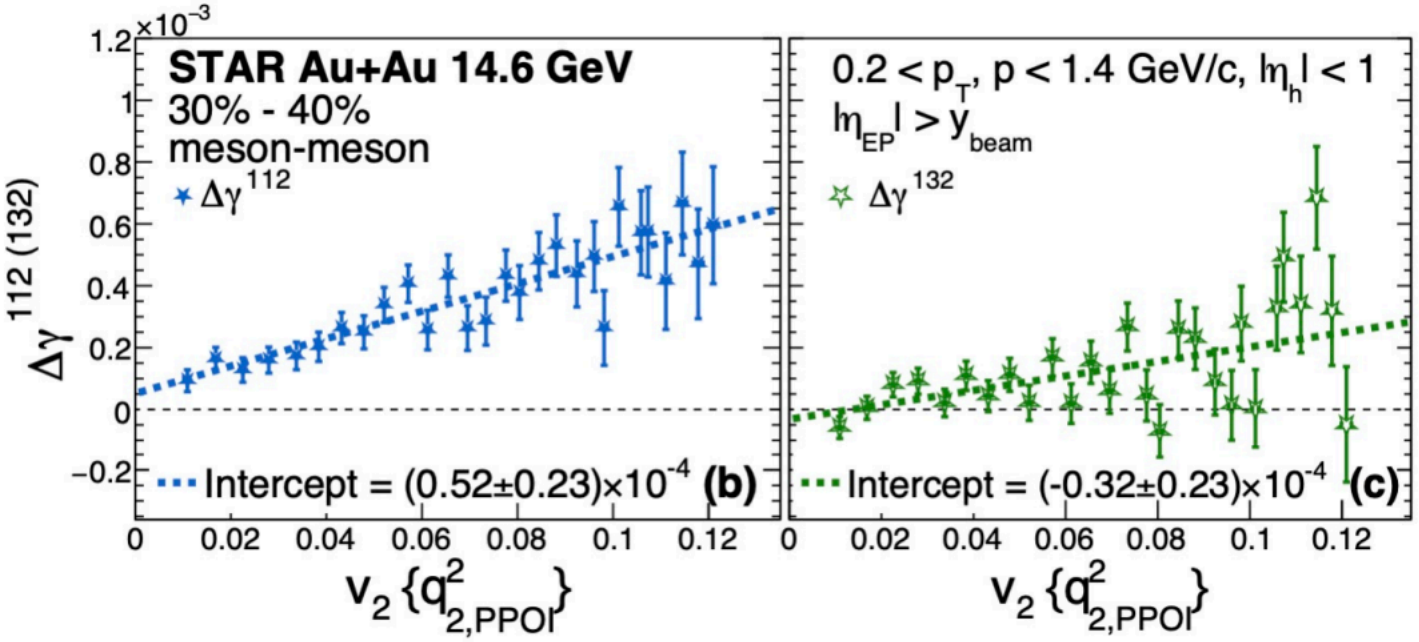


$$R_{\Psi_m}(\Delta S) = \frac{C_{\Psi_m}(\Delta S)}{C^{\perp}_{\Psi_m}(\Delta S)}, \quad m = 2, 3$$

- The $R_{\Psi_m}(\Delta S)$ correlator compares the charge separation signal along the event plane with that perpendicular to it.
- A CME signal would manifest as a deviation in R_{Ψ_2} that is not mirrored in R_{Ψ_3} (i.e., $R_{\Psi_2} \neq R_{\Psi_3}$).

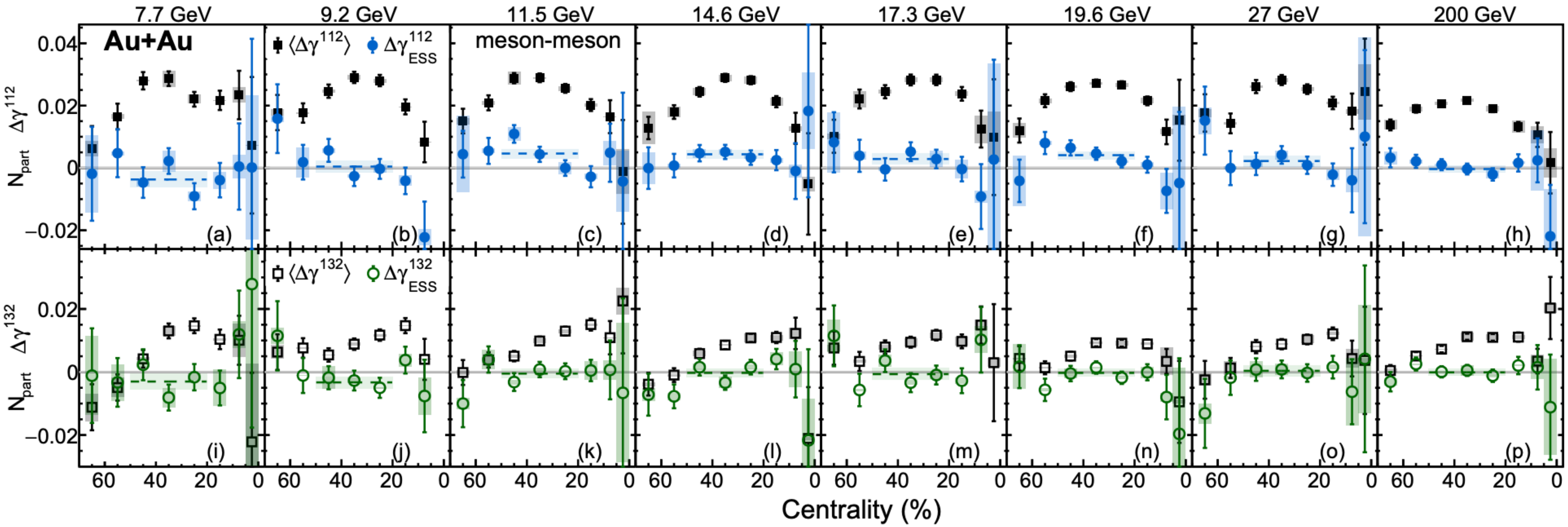
N. Magdy, Phys. Rev. C **97**, 061901(R), 2018
P. Tribedy, Journal of Physics, 1602 012002 (2020)

Results from BES-II with Event Shape Selection Analysis



$$q^2_{2,\mathrm{PPOI}} = \frac{\left(\sum_{i=1}^{N_{\mathrm{pair}}} \sin 2\varphi_i^{\mathrm{p}}\right)^2 + \left(\sum_{i=1}^{N_{\mathrm{pair}}} \cos 2\varphi_i^{\mathrm{p}}\right)^2}{N_{\mathrm{pair}}(1 + N_{\mathrm{pair}} v^2_{2,\mathrm{pair}})}$$

- Event shape selection uses $q^2_{2,PPOI}$, constructed from particle pairs of interest (PPOI), to avoid self-correlations with v_2.
- Better short-range fluctuations



- $\Delta\gamma^{132}_{ESS}$ is consistent with zero across all centralities, while $\Delta\gamma^{112}_{ESS}$ shows a finite signal in mid-central (20--50%) collisions between 10--20 GeV, significantly reduced compared to ensemble-averaged results.