

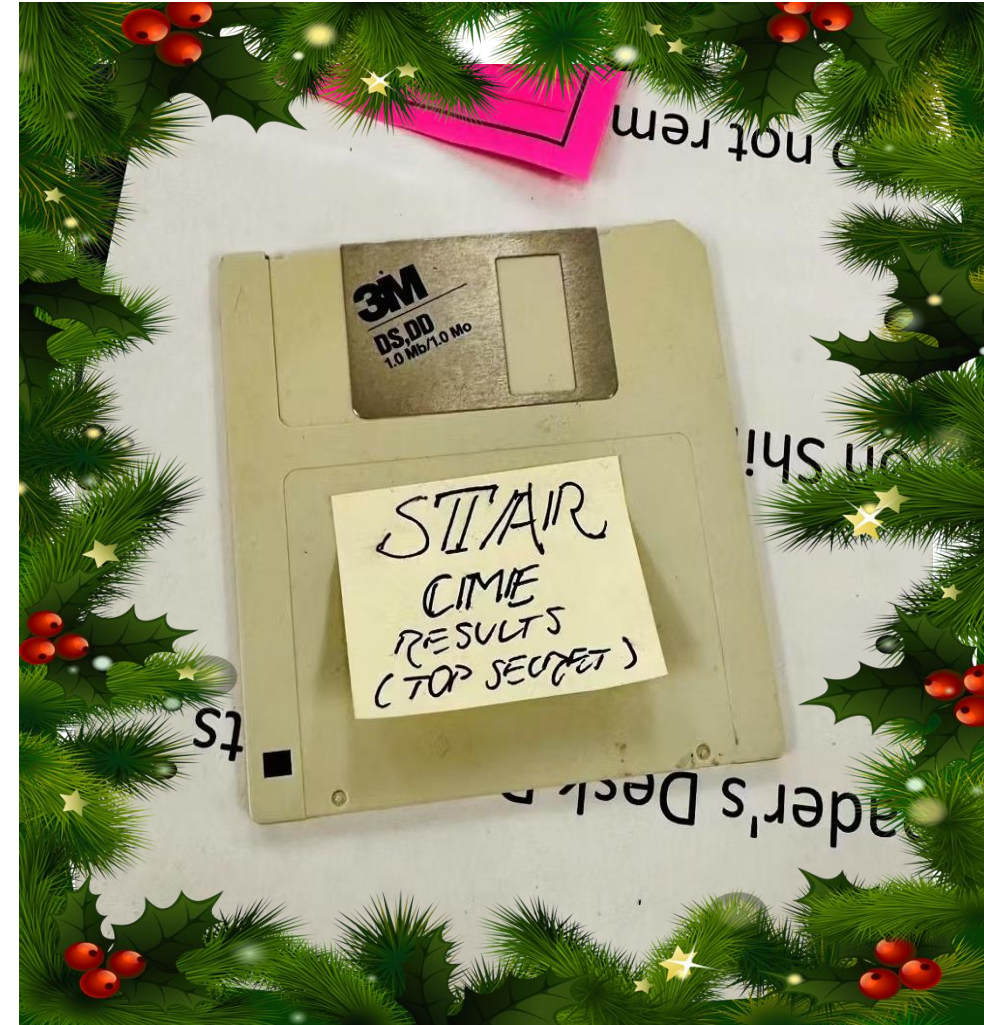
STAR 25-year Anniversary: Search for the CME

Zhiwan Xu (Argonne National Lab)

12/18/2025



U.S. DEPARTMENT
of ENERGY



Search for the CME: Two collaborative Decades

First theory paper

1998 2009 2010 2013 2014 2015 2019 2022 2023 2024 2025

Physical Review Letters

GO WORMLE + ACCESS BY ARXIV.ORG NATIONAL LABORATORY

Possibility of Spontaneous Parity Violation in Hot QCD

Dmitri Kharzeev¹, Robert D. Pisarski², and Michel H. G. Tytgat^{2,3}

Phys. Rev. Lett. **81**, 512 - Published 20 July, 1998

DOI: <https://doi.org/10.1103/PhysRevLett.81.512>

Citations 338

Physical Review C

GO WORMLE + ACCESS BY ARXIV.ORG NATIONAL LABORATORY

Observation of charge-dependent azimuthal correlations and possible local strong parity violation in heavy-ion collisions

B. I. Abelev¹, M. M. Appenauer^{2,3}, Z. Ahammed⁴, A. V. Alakhverdzia¹, B. D. Anderson¹, D. Arkhipkin⁵, G. S. Averchev¹, I. Balasov¹, O. Barannikova⁶ et al. (STAR Collaboration)

Phys. Rev. C **81**, 054908 - Published 28 May, 2010

DOI: <https://doi.org/10.1103/PhysRevC.81.054908>

Physical Review Letters

GO WORMLE + ACCESS BY ARXIV.ORG NATIONAL LABORATORY

Beam-Energy Dependence of Charge Separation along the Magnetic Field in Au + Au Collisions at RHIC

L. Adamczyk¹, J. K. Adkins², G. Agakishiev³, M. M. Appenauer⁴, Z. Ahammed⁵, I. Alekseev⁶, J. Alfaro⁷, C. D. Anson⁸, A. Aparin⁹ et al. (STAR Collaboration)

Phys. Rev. Lett. **113**, 052302 - Published 30 July, 2014

DOI: <https://doi.org/10.1103/PhysRevLett.113.052302>

Physical Review C

GO WORMLE + ACCESS BY ARXIV.ORG NATIONAL LABORATORY

Measurement of charge multiplicity asymmetry correlations in high-energy nucleus-nucleus collisions at $\sqrt{s_{NN}} = 200$ GeV

L. Adamczyk¹, J. K. Adkins², G. Agakishiev³, M. M. Appenauer⁴, Z. Ahammed⁵, I. Alekseev⁶, J. Alfaro⁷, C. D. Anson⁸ et al. (STAR Collaboration)

Phys. Rev. C **89**, 044908 - Published 23 April, 2014

DOI: <https://doi.org/10.1103/PhysRevC.89.044908>

Physical Review C

GO WORMLE + ACCESS BY ARXIV.ORG NATIONAL LABORATORY

Pair invariant mass to isolate background in the search for the chiral magnetic effect in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV

M. S. Abdallah¹, J. K. Adkins², L. Adamczyk³, J. R. Adams⁴, J. K. Adkins⁵, G. Agakishiev⁶, L. Appenauer⁷, M. M. Appenauer⁸, Z. Ahammed⁹ et al. (STAR Collaboration)

Phys. Rev. C **106**, 034908 - Published 16 September, 2022

DOI: <https://doi.org/10.1103/PhysRevC.106.034908>

Physical Review C

GO WORMLE + ACCESS BY ARXIV.ORG NATIONAL LABORATORY

Search for the chiral magnetic effect with isobar collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR Collaboration at the BNL Relativistic Heavy Ion Collider

M. S. Abdallah¹, B. E. Aboune², J. K. Adkins³, L. Adamczyk⁴, J. R. Adams⁵, J. K. Adkins⁶, G. Agakishiev⁷, L. Appenauer⁸, M. M. Appenauer⁹ et al. (STAR Collaboration)

Phys. Rev. C **105**, 014901 - Published 3 January, 2022

DOI: <https://doi.org/10.1103/PhysRevC.105.014901>

Physical Review C

GO WORMLE + ACCESS BY ARXIV.ORG NATIONAL LABORATORY

Search for the chiral magnetic wave using anisotropic flow of identified particles at energies available at the BNL Relativistic Heavy Ion Collider

M. I. Abdulhamid¹, B. E. Aboune², J. K. Adkins³, J. R. Adams⁴, G. Agakishiev⁵, L. Appenauer⁶, M. M. Appenauer⁷, Z. Ahammed⁸, A. Aitbaev⁹ et al. (STAR Collaboration)

Phys. Rev. C **108**, 014908 - Published 14 July, 2023

DOI: <https://doi.org/10.1103/PhysRevC.108.014908>

Physical Review Research

GO WORMLE + ACCESS BY ARXIV.ORG NATIONAL LABORATORY

Upper limit on the chiral magnetic effect in isobar collisions at the Relativistic Heavy-Ion Collider

M. I. Abdulhamid¹, B. E. Aboune², J. K. Adkins³, J. R. Adams⁴, G. Agakishiev⁵, L. Appenauer⁶, M. M. Appenauer⁷, Z. Ahammed⁸, A. Aitbaev⁹ et al. (STAR Collaboration)

Phys. Rev. Research **6**, 032205 - Published 9 July, 2024

DOI: <https://doi.org/10.1103/PhysRevResearch.6.032205>

Physical Review Letters

GO WORMLE + ACCESS BY ARXIV.ORG NATIONAL LABORATORY

Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

B. I. Abelev¹, M. M. Appenauer^{2,3}, Z. Ahammed⁴, A. V. Alakhverdzia¹, B. D. Anderson¹, D. Arkhipkin⁵, G. S. Averchev¹, I. Balasov¹, O. Barannikova⁶ et al. (STAR Collaboration)

Phys. Rev. Lett. **103**, 251601 - Published 14 December, 2009

DOI: <https://doi.org/10.1103/PhysRevLett.103.251601>

Citations 445

Physical Review C

GO WORMLE + ACCESS BY ARXIV.ORG NATIONAL LABORATORY

Fluctuations of charge separation perpendicular to the event plane and local parity violation in $\sqrt{s_{NN}} = 200$ GeV Au + Au collisions at the BNL Relativistic Heavy Ion Collider

L. Adamczyk¹, J. K. Adkins², G. Agakishiev³, M. M. Appenauer⁴, Z. Ahammed⁵, I. Alekseev⁶, J. Alfaro⁷, C. D. Anson⁸, A. Aparin⁹ et al. (STAR Collaboration)

Phys. Rev. C **88**, 064911 - Published 28 December, 2013

DOI: <https://doi.org/10.1103/PhysRevC.88.064911>

Physical Review Letters

GO WORMLE + ACCESS BY ARXIV.ORG NATIONAL LABORATORY

Observation of Charge Asymmetry Dependence of Pion Elliptic Flow and the Possible Chiral Magnetic Wave in Heavy-Ion Collisions

L. Adamczyk¹, J. K. Adkins², G. Agakishiev³, M. M. Appenauer⁴, Z. Ahammed⁵, I. Alekseev⁶, J. Alfaro⁷, C. D. Anson⁸, A. Aparin⁹ et al. (STAR Collaboration)

Phys. Rev. Lett. **114**, 252302 - Published 26 June, 2015

DOI: <https://doi.org/10.1103/PhysRevLett.114.252302>

Physical Review Letters

GO WORMLE + ACCESS BY ARXIV.ORG NATIONAL LABORATORY

Search for the Chiral Magnetic Effect via Charge-Dependent Azimuthal Correlations Relative to Spectator and Participant Planes in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

M. S. Abdallah¹, J. K. Adkins², L. Adamczyk³, J. R. Adams⁴, J. K. Adkins⁵, G. Agakishiev⁶, L. Appenauer⁷, M. M. Appenauer⁸, Z. Ahammed⁹ et al. (STAR Collaboration)

Phys. Rev. Lett. **128**, 092301 - Published 1 March, 2022

DOI: <https://doi.org/10.1103/PhysRevLett.128.092301>

Physics Letters B

Volume 794, 30 November 2020, 34475

Charge-dependent pair correlations relative to a third particle in p+Au and d+Au Au collisions at RHIC

STAR Collaboration

Abstract

Quark interactions with topological glass configurations can induce χ helicity imbalance and local parity violation in quantum chromodynamics. This can lead to electric charge "vorticity" along the strong magnetic field in relativistic heavy-ion collisions – the "chiral magnetic effect" (CME). We search for the CME in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV by measuring the charge-dependent pair correlations relative to a third particle in p+Au and d+Au collisions at RHIC.

Physics Letters B

Volume 819, 30 April 2020, 34475

Search for the chiral magnetic effect in Au+Au collisions at $\sqrt{s_{NN}} = 27$ GeV with the STAR forward event plane detectors

STAR Collaboration

Abstract

A decisive experimental test of the Chiral Magnetic Effect (CME) is considered one of the major scientific goals at the Relativistic Heavy-Ion Collider (RHIC) towards understanding "nontrivial topological fluctuations of the Quantum Chromodynamics vacuum. In Au+Au collisions at $\sqrt{s_{NN}} = 27$ GeV, we search for the CME by measuring the charge-dependent pair correlations relative to a third particle in p+Au and d+Au collisions at RHIC.

Physical Review C

GO WORMLE + ACCESS BY ARXIV.ORG NATIONAL LABORATORY

Event-by-event correlations between $\Lambda(\bar{\Lambda})$ hyperon global polarization and handedness with charged hadron azimuthal separation in Au + Au collisions at $\sqrt{s_{NN}} = 27$ GeV from STAR

M. I. Abdulhamid¹, B. E. Aboune², J. K. Adkins³, J. R. Adams⁴, G. Agakishiev⁵, L. Appenauer⁶, M. M. Appenauer⁷, Z. Ahammed⁸, A. Aitbaev⁹ et al. (STAR Collaboration)

Phys. Rev. C **108**, 014909 - Published 27 July, 2023

DOI: <https://doi.org/10.1103/PhysRevC.108.014909>

Physical Review C

GO WORMLE + ACCESS BY ARXIV.ORG NATIONAL LABORATORY

Estimate of background baseline and upper limit on the chiral magnetic effect in isobar collisions at $\sqrt{s_{NN}} = 200$ GeV at the BNL Relativistic Heavy Ion Collider

M. I. Abdulhamid¹, B. E. Aboune², J. K. Adkins³, J. R. Adams⁴, G. Agakishiev⁵, L. Appenauer⁶, M. M. Appenauer⁷, Z. Ahammed⁸, A. Aitbaev⁹ et al. (STAR Collaboration)

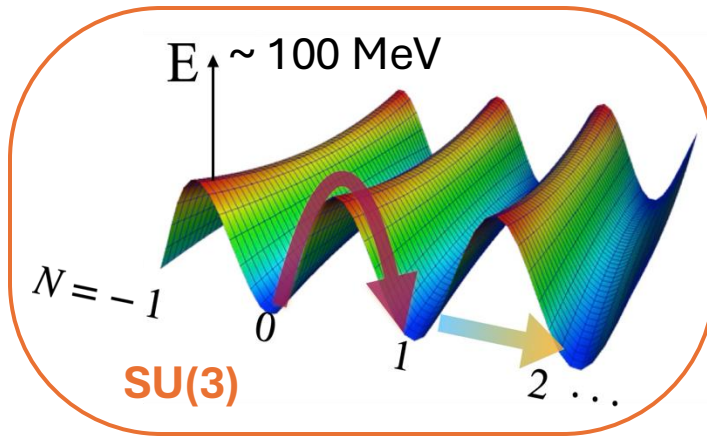
Phys. Rev. C **110**, 014905 - Published 9 July, 2024

DOI: <https://doi.org/10.1103/PhysRevC.110.014905>

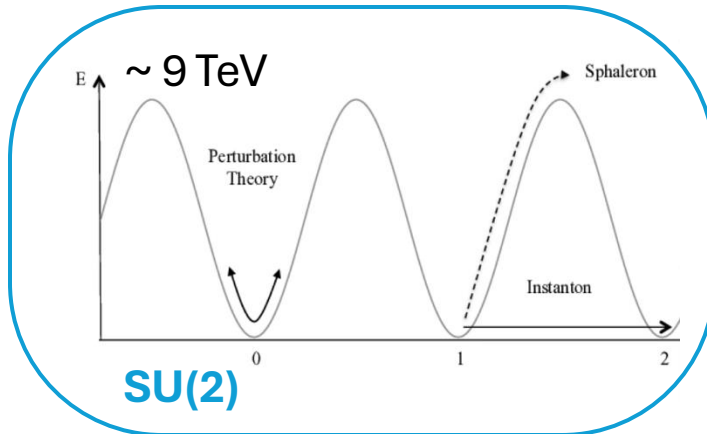


- 15 STAR papers: 4PRL, 8PRC, 2PLB, PRR...
- 4 ongoing paper committee
- 10+ PhD Thesis
- 50+ Conferences presences

What is Chiral Magnetic Effect (CME)?

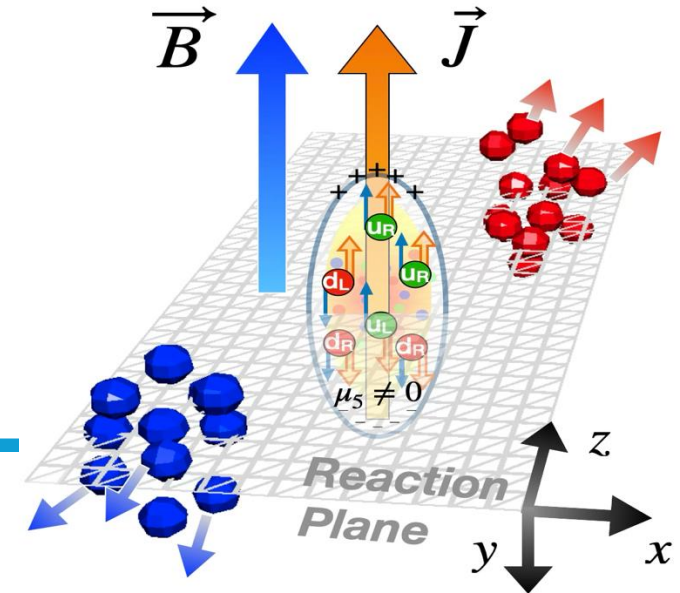


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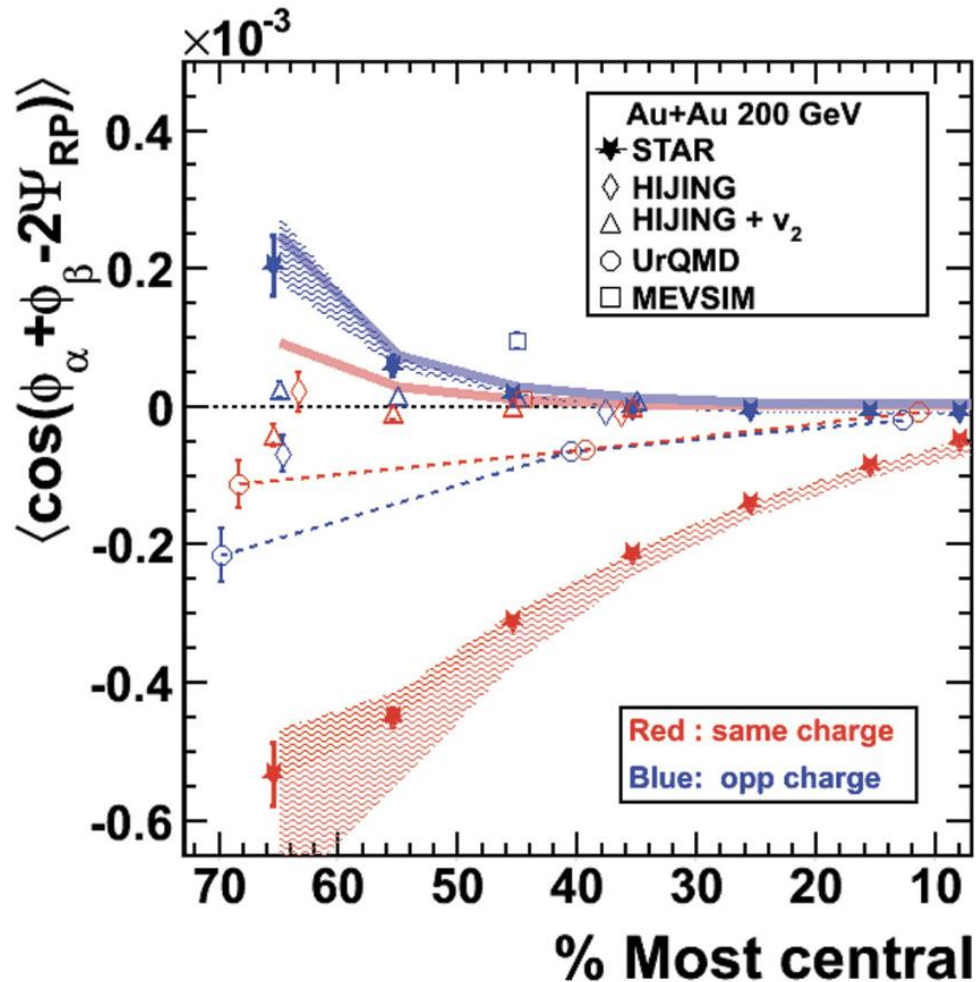
Charge separations (\vec{J}) induced by magnetic field (\vec{B}) for quarks at chirality imbalance (μ_5).

$$\vec{J} \propto \mu_5 \vec{B}$$



- It is about the fundamental QCD symmetry
- It may help explain baryogenesis from an experimental observation

First measurement: 2009



- CME observables:

$$\gamma^{112} = \langle \cos(\phi_1 + \phi_2 - 2\Psi_{RP}) \rangle$$

$$\Delta\gamma^{112} = \gamma^{OS} - \gamma^{SS}$$

- Also: R(ΔS) correlator,
signed balance functions.

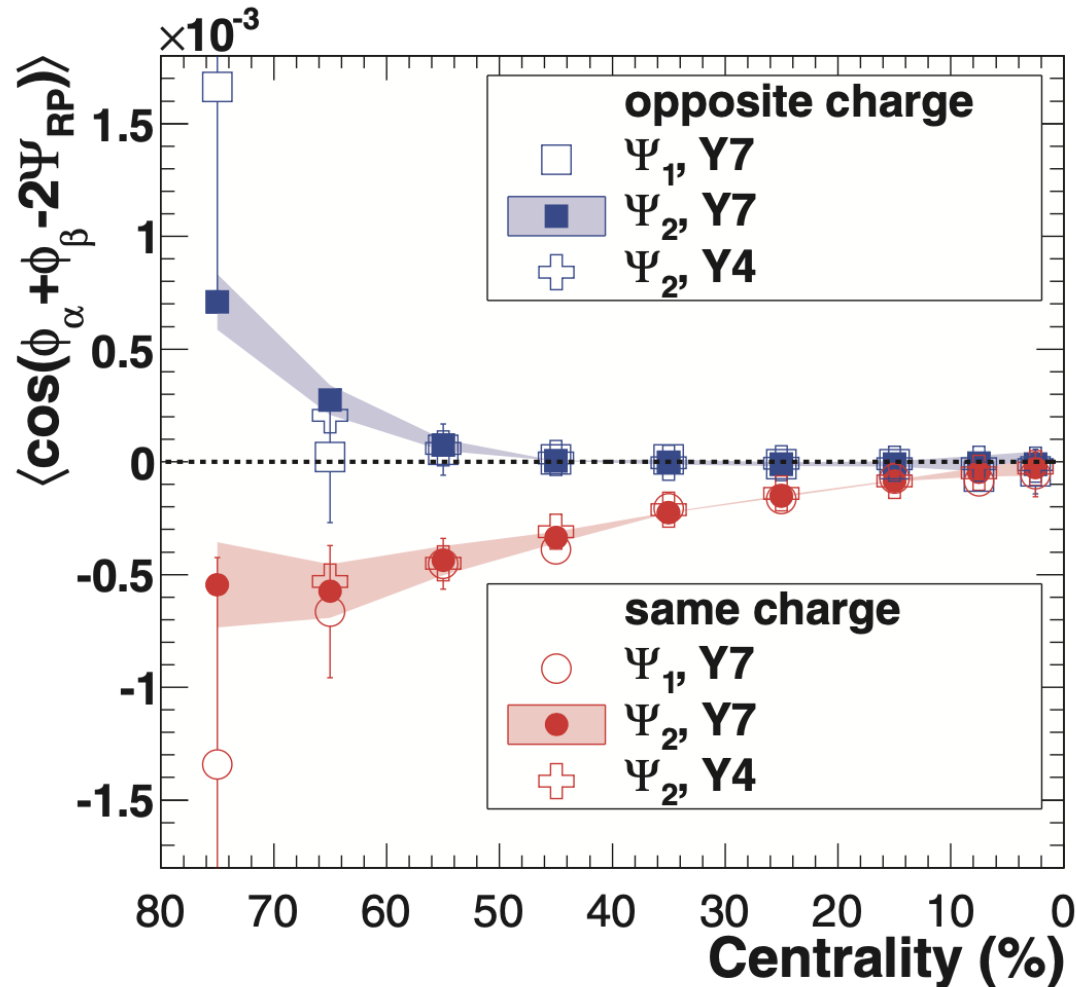
Voloshin, Phys. Rev. C 70, 057901 (2004)

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

Tang, Chin. Phys. C 44, 054101 (2020)

$\gamma_{OS} > \gamma_{SS}$, consistent with CME expectation.

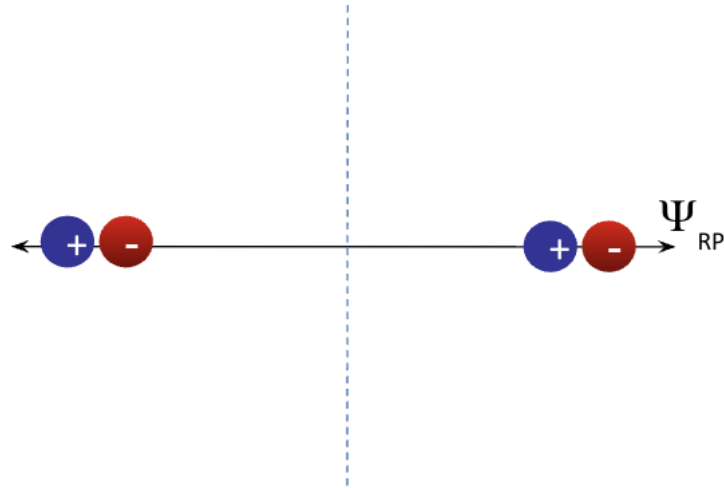
Confirming signal along B field (Ψ_1)?



- $\gamma_{os} > \gamma_{ss}$ with 1st-order EP (from spectator neutron v_1)
 → Possible parity violation?
- neutron Ψ_1 doesn't necessarily represent the B field direction, not as much as proton Ψ_1 .
- However, very soon the result is challenged by backgrounds...

Puzzle: What is the background?

Flow BKG



$$\gamma_{SS} = -1$$

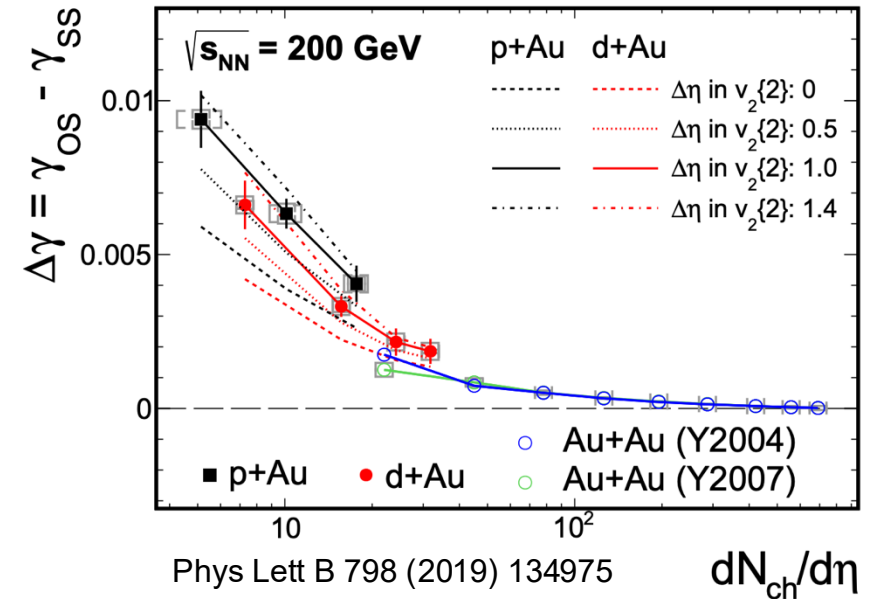
$$\delta_{SS} = -1$$

$$v_2 = 1$$

$$\gamma_{OS} = 0$$

$$\delta_{OS} = 0$$

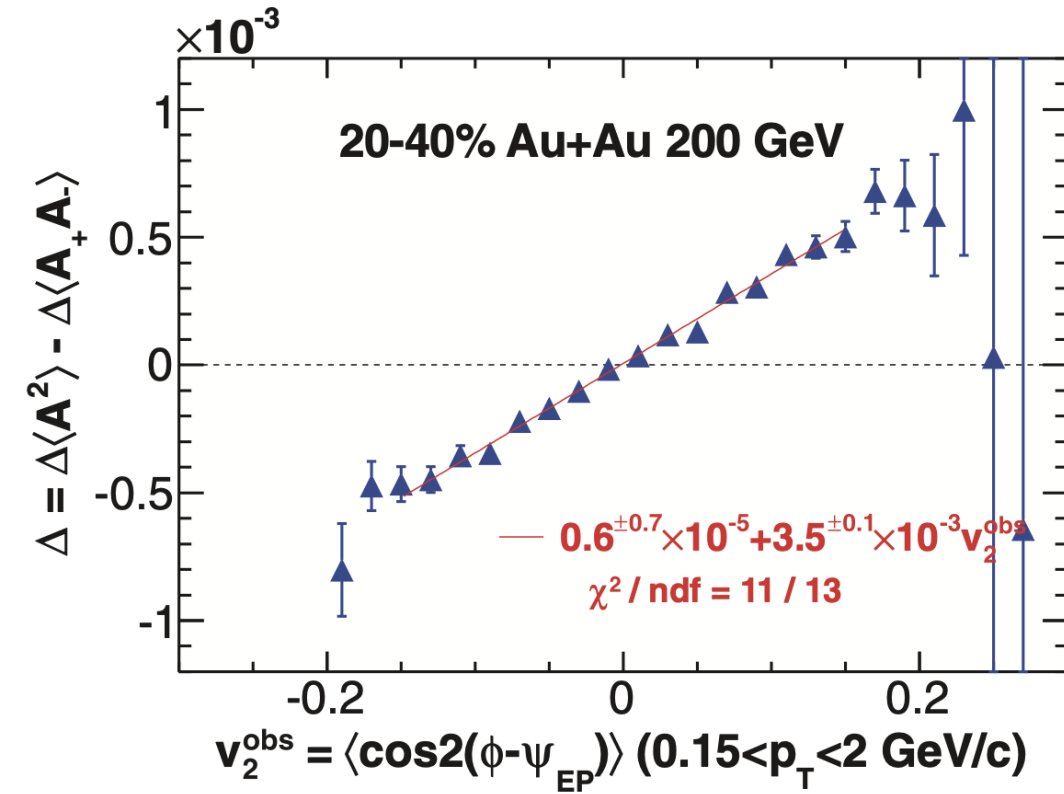
Nonflow BKG



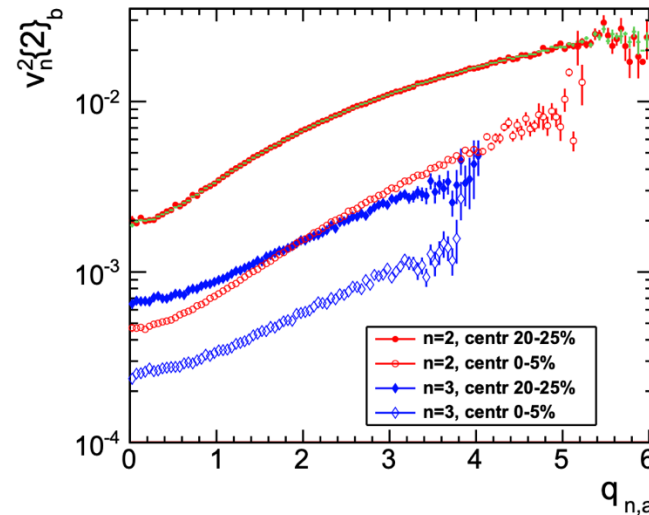
- Flow BKG: v_2 + resonance decay/LCC/TMC \rightarrow fake finite $\Delta\gamma$
- Nonflow BKG: larger $\Delta\gamma$ in p(d)+Au compared with Au+Au
- Measurement of CME is challenged by flow and non-flow background:

$$\Delta\gamma^{112} = \gamma^{OS} - \gamma^{SS} = \Delta\gamma^{CME} + \kappa v_2 \frac{1}{N} + \Delta\gamma^{nonflow}$$

Direct event-by-event “obs-v2” removal?

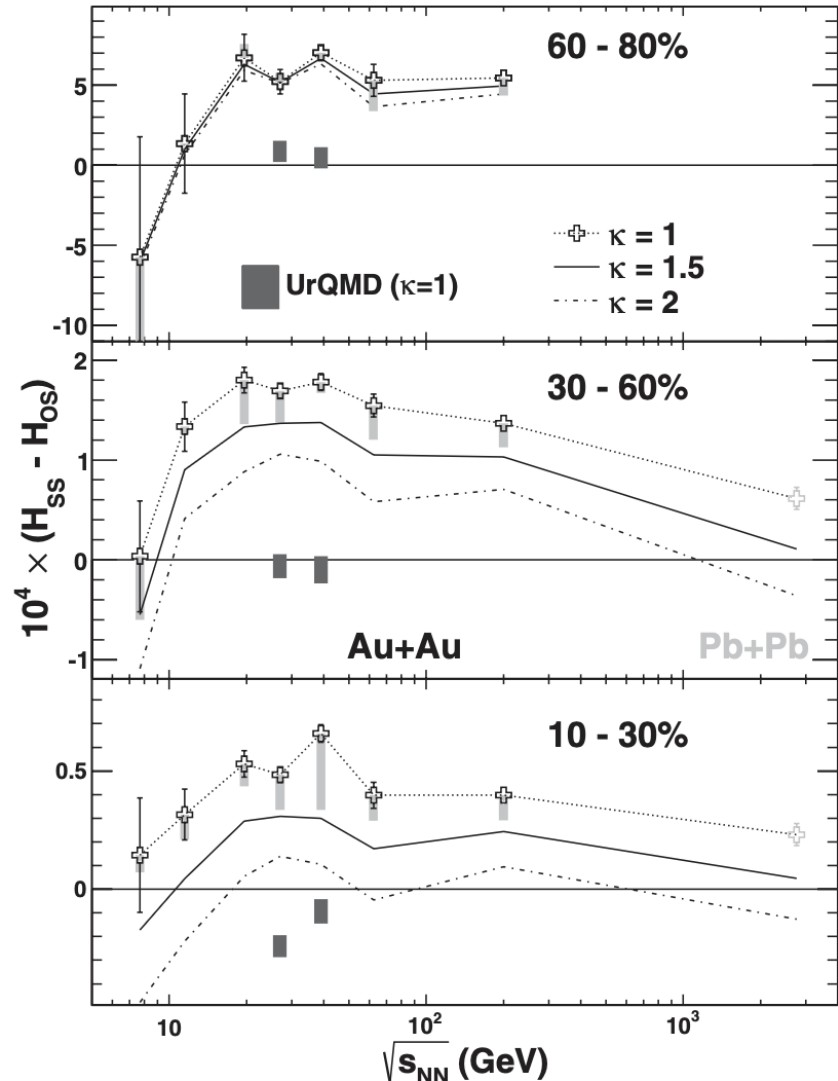


- A direct projection of CME observable to the event-by-event v_2^{obs} results intercept \sim zero.
- However, the selection could be biased, as the true v_2 is not zero.
- A proper way to do event shape is use q_n bin



$$q_n = \sqrt{\frac{\sum \cos(n\phi)^2 + \sum \sin(n\phi)^2}{N}}$$

Beam Energy Scan I – hint at low energy?



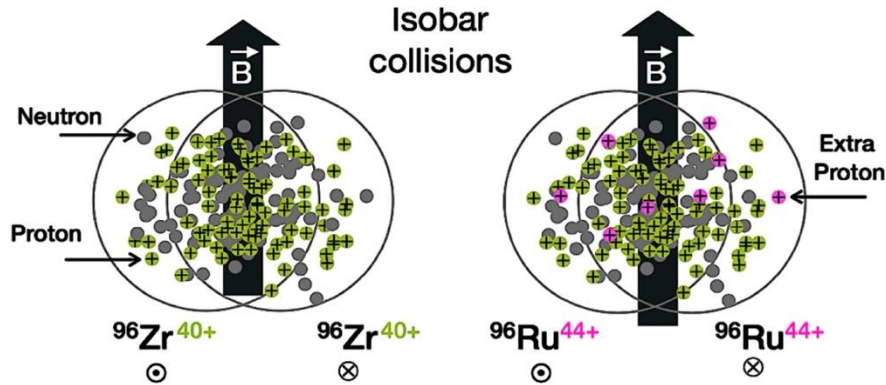
$$H^\kappa = (\kappa v_2 \delta - \gamma^{112}) / (1 + \kappa v_2)$$

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

Use H to remove event averaged v_2 -bkg from γ^{112} , assuming it is well quantified by $\kappa v_2 \delta$

- κ – prior
- CME signal (ΔH) decreased to zero at 7.7 and 2.76 GeV, and are finite in between near 20 GeV

Isobar collision – blind analysis

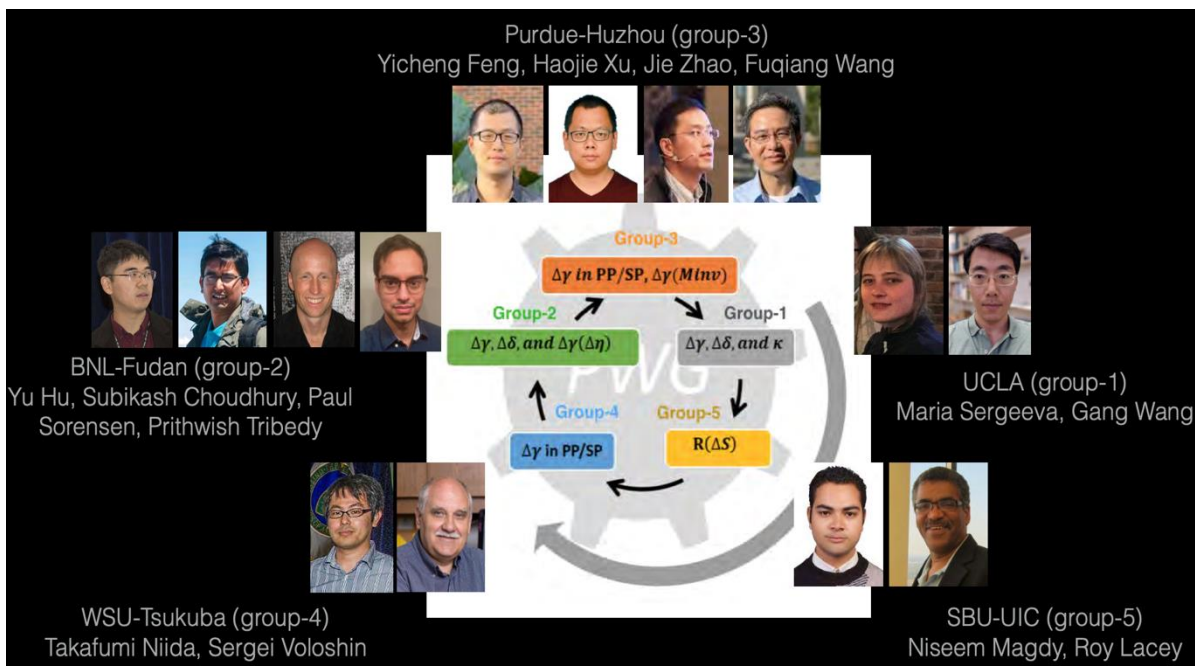


- $A=96 \rightarrow$ Similar backgrounds
- $Z = 40+4 \rightarrow$ Different B induced CME signal

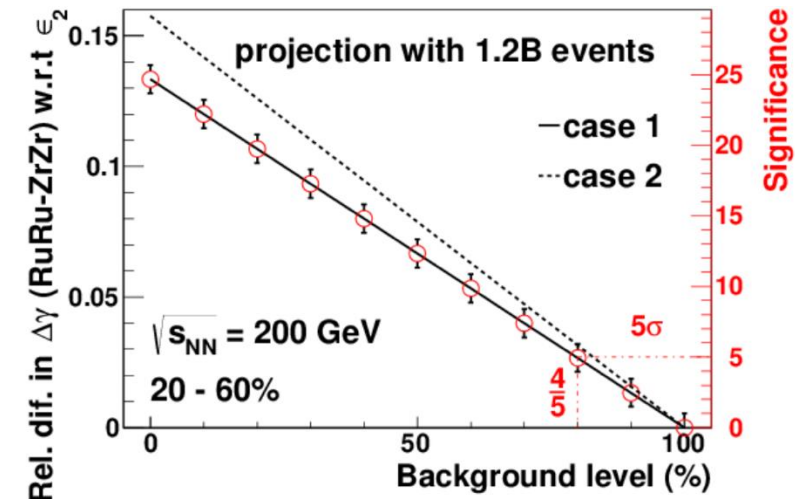
$$R = \frac{\Delta\gamma/v_2\{Ru+Ru\}}{\Delta\gamma/v_2\{Zr+Zr\}} \begin{cases} = 1 \text{ for BKG} \\ > 1 \text{ for CME} \end{cases}$$

Predefined CME signal

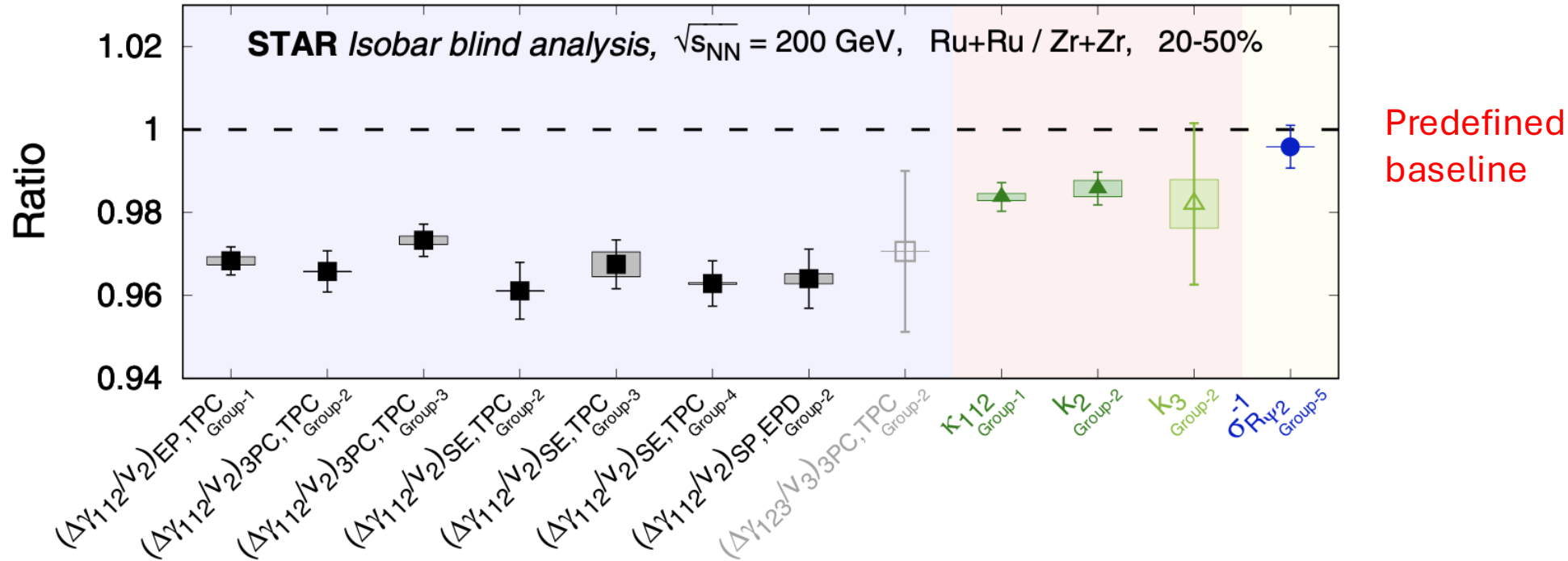
- Conducted by 5 independent groups



In courtesy of P. Tribedy



Isobar collision – blind analysis

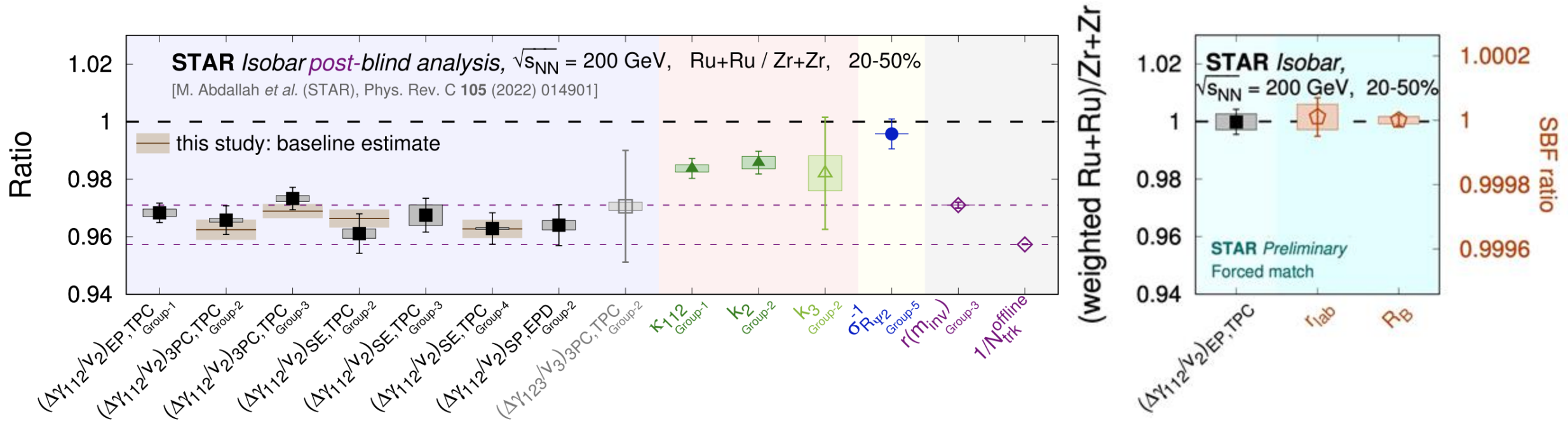


- No predefined CME signal is observed \rightarrow B field may decay too fast at 200 GeV.
- Backgrounds in two systems are different and dominates the measurement.

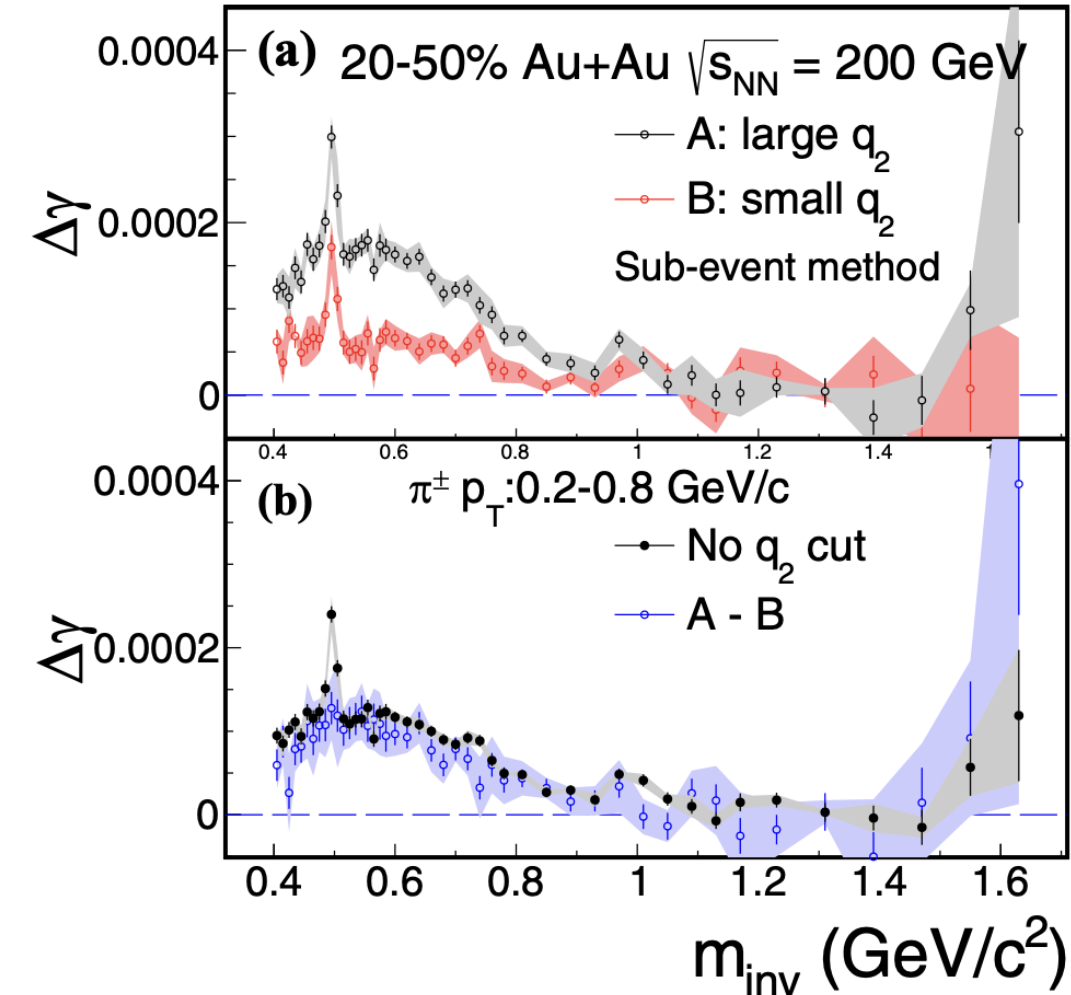
Isobar collision - post blind analysis

The ratio of Ru+Ru/Zr+Zr:

- consistent with the new baseline estimated from N^{mult} , v_2 and HIJING model
- consistent with unity by force matching two system (N^{mult} and v_2)

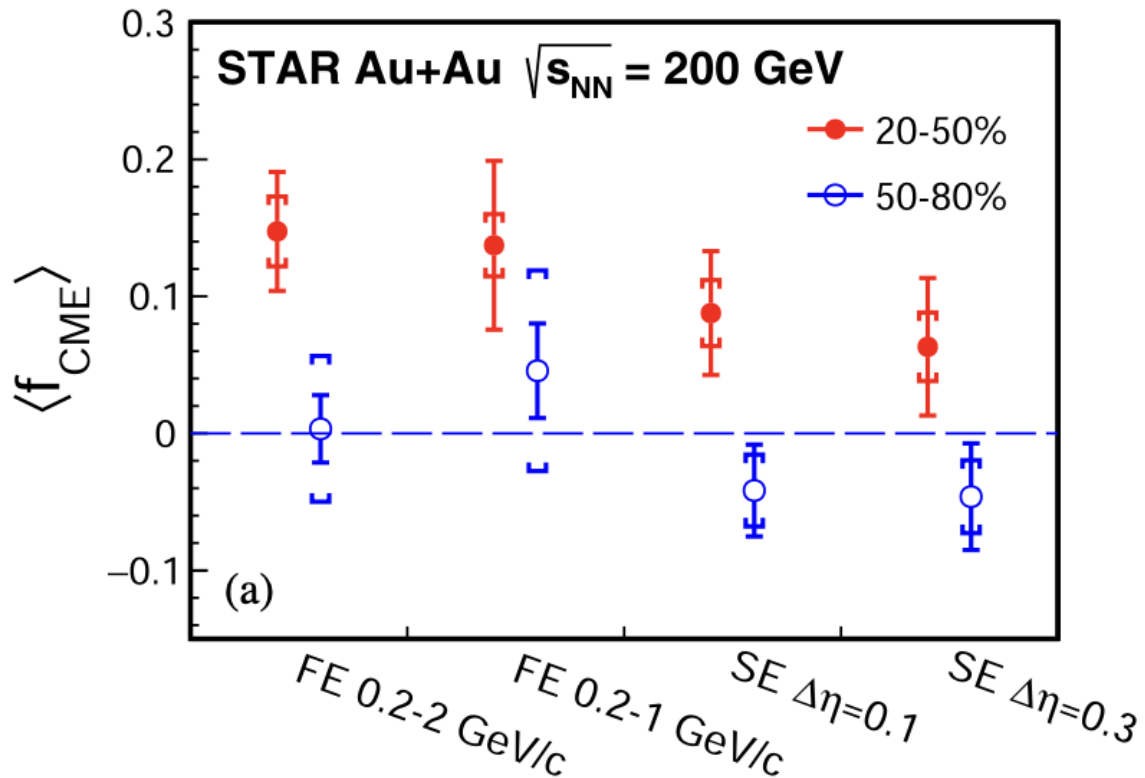


Background suppression – Pair Invariant mass



- Assume the large resonance decay background is reduced at large m_{inv} :
- $\Delta\gamma$ value is found to be significantly smaller, averaged to be $(2 \pm 4 \pm 5)\%$ of the inclusive
- Cutting on invariant mass may be equivalent to cutting on opening angle, which changed the $\Delta\gamma$ measurement.

Background suppression – Spectator/Participant Plane

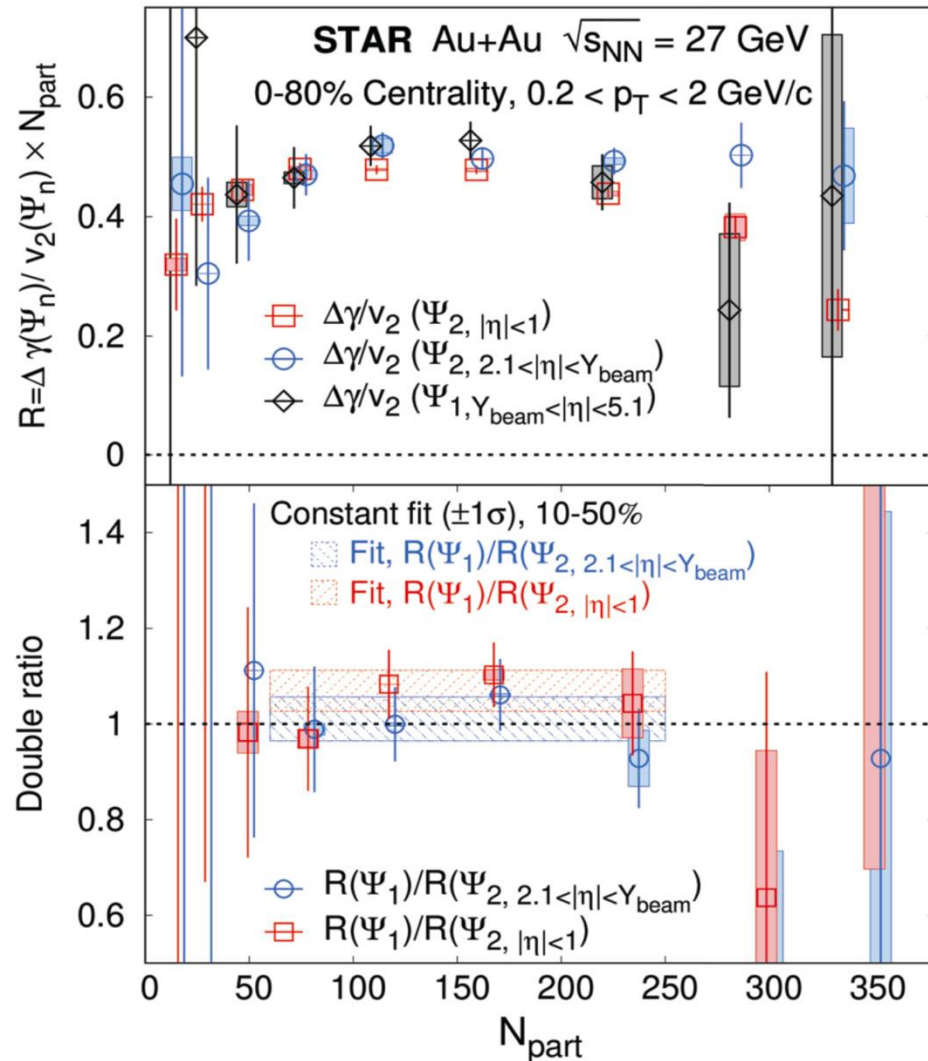


Assume Ψ_1 has minimal flow background and maximal B field signal, Ψ_2 has maximal flow background and minimal signal,

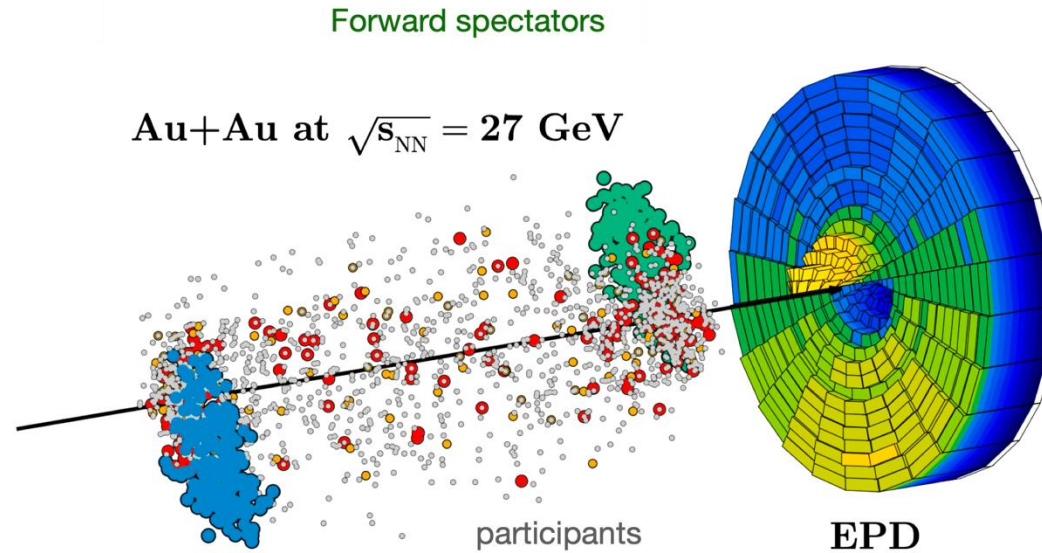
$$f_{CME} = \frac{\Delta\gamma_{CME}}{\Delta\gamma\{\psi_{PP}\}} = \frac{\Delta\gamma\{\psi_{SP}\}/\Delta\gamma\{\psi_{PP}\} - v_2\{\psi_{SP}\}/v_2\{\psi_{PP}\}}{1/(v_2\{\psi_{SP}\}/v_2\{\psi_{PP}\}) - v_2\{\psi_{SP}\}/v_2\{\psi_{PP}\}}$$

- consistent with zero at 50-80% but could be finite in 20-50%.
- Possible nonflow effects in P.P $\rightarrow f_{cme}$ decreasing when eta gap increases

Background suppression – Spectator/Participant Plane

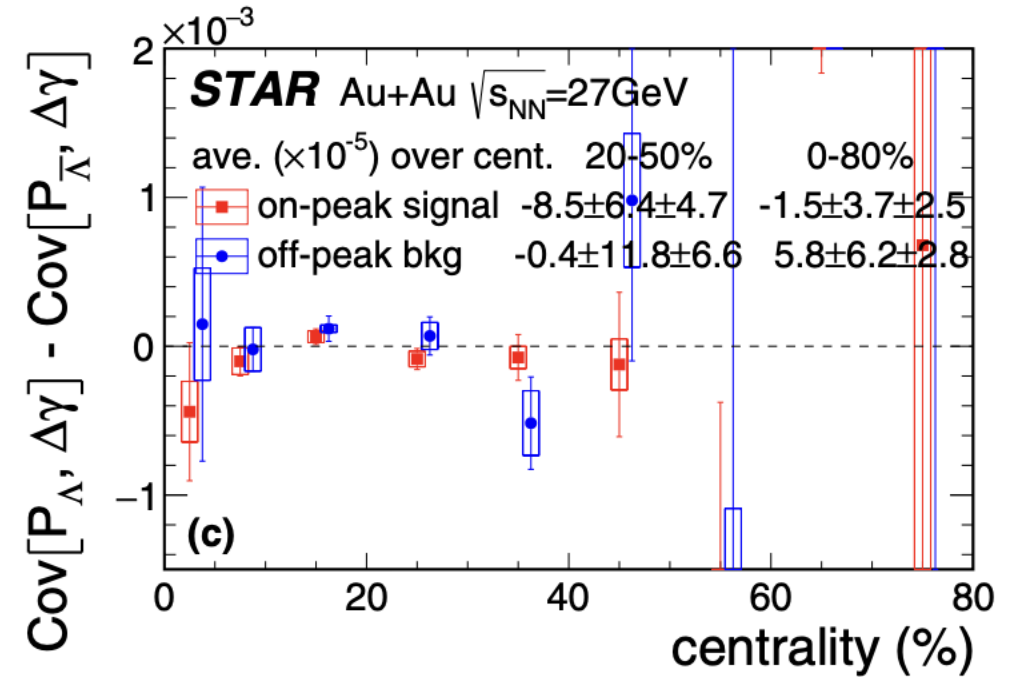
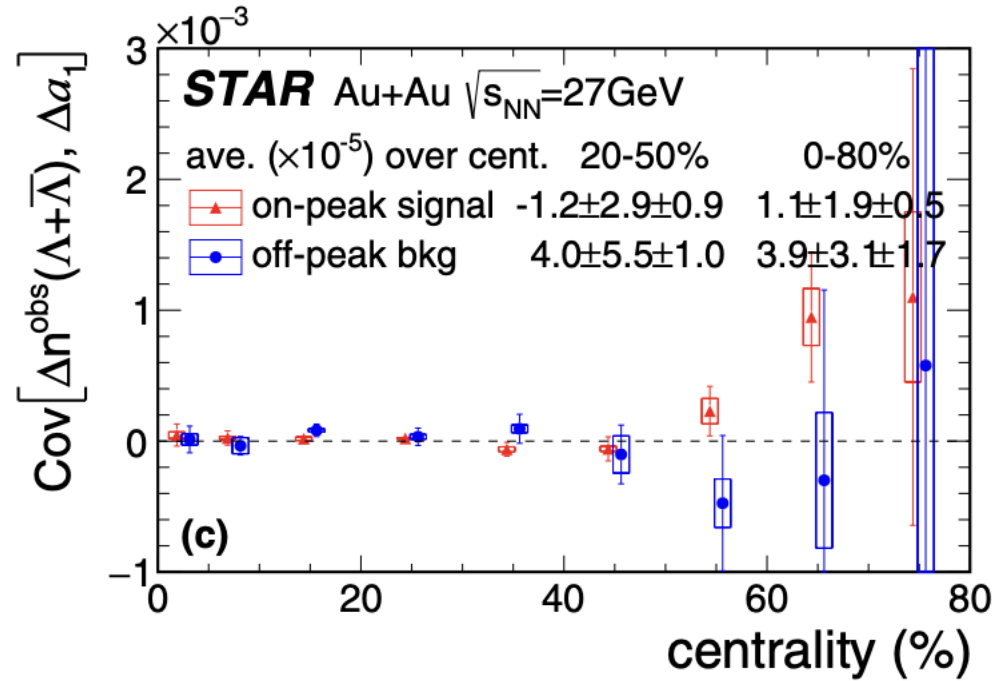


Phys Lett B 839 (2023) 137779



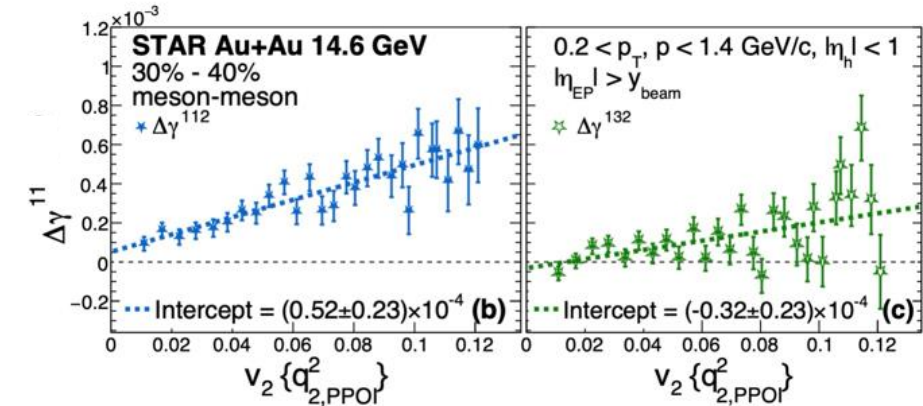
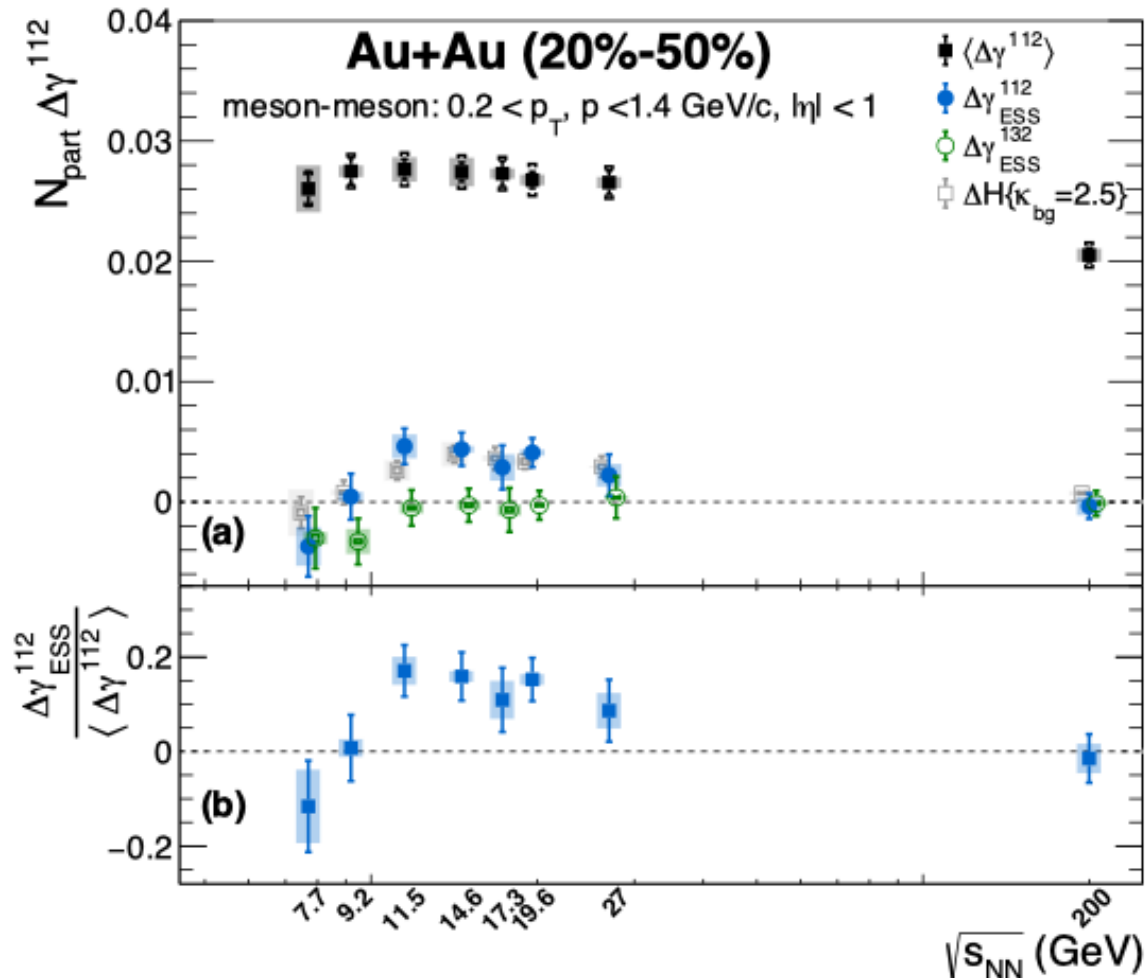
- With new EPD detector – low energy proton Ψ_1 reconstruction.
- Observed SP/PP ratio consistent with zero ($\sim 1.5\sigma$) at 27 GeV, limited by statistics

Chiro-polarization correlation



- CME and Λ polarization may share correlation from B field, expect Covariance > 0 .
 ΔN (L-R) and Δa_1 may share correlation, expect Cov > 0
- Observe $\text{Cov}[\Delta N, \Delta a_1]$ and $\text{Cov}[\Delta P, \Delta \gamma]$ consistent with zero, limited by statistics
- Λ is produced relatively later, while CME is early effect.

Event Shape at BES-II – low energy hint?



Use the Event Shape Selection to suppress the flow BKG, and EPD/ZDC detector to suppress nonflow BKG:

- **Finite charge separations** (2.5, 3, 3.2 σ) at 11.5, 14.6 and 19.6 GeV, combined $> 5\sigma$
- 1.1 σ at 27 and 1.3 σ at 17 GeV
- $\kappa_{bg} \sim 2.5$, well consistent with H-correlator
- Identified backgrounds $> 80\%$



As STAR turns 25th,
the experiment
successfully concludes,
and the physics
continues...

What to do next?

- A coherent picture across systems:
Zr+Zr/Ru+Ru/Cu+Cu/U+U/Au+Au
- A consistent beam-energy description
with more focus on BES-II and run24/25
- Link CME physics (or pre-conditions) to
other related physics