STAR 25-year Anniversary: Search for the CME

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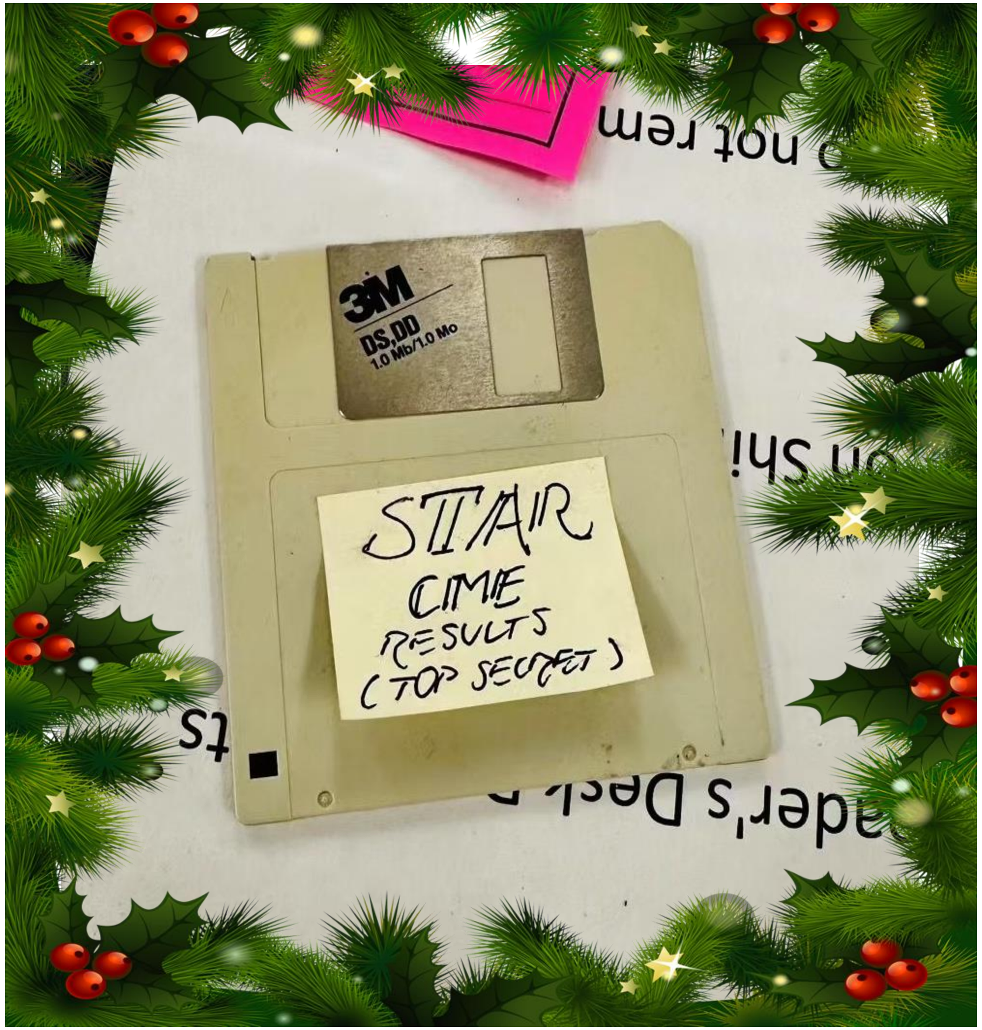
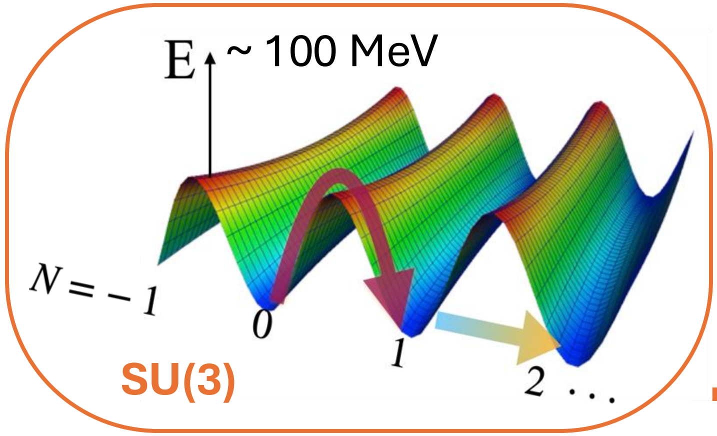
12/18/2025



Search for the CME: Two collaborative Decades

- 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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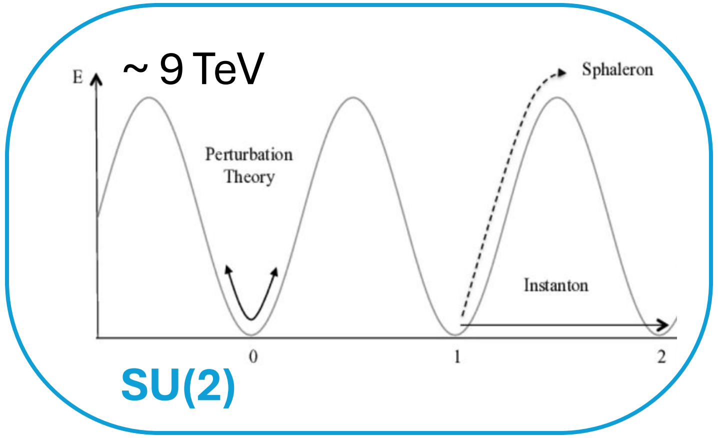
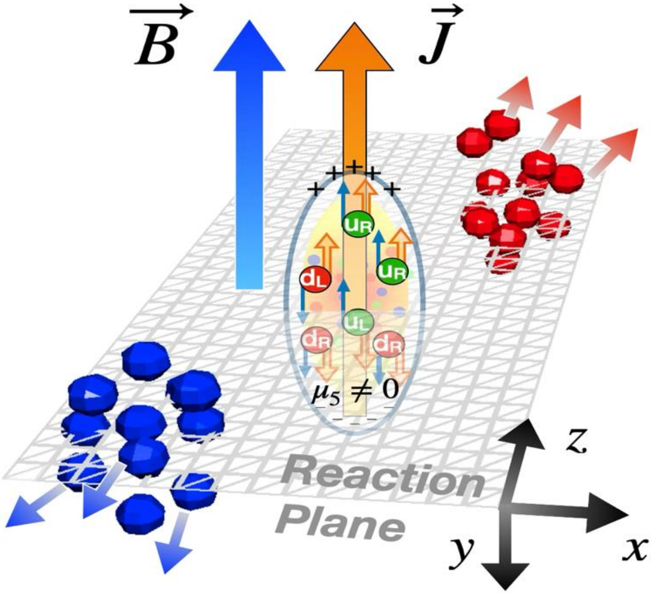


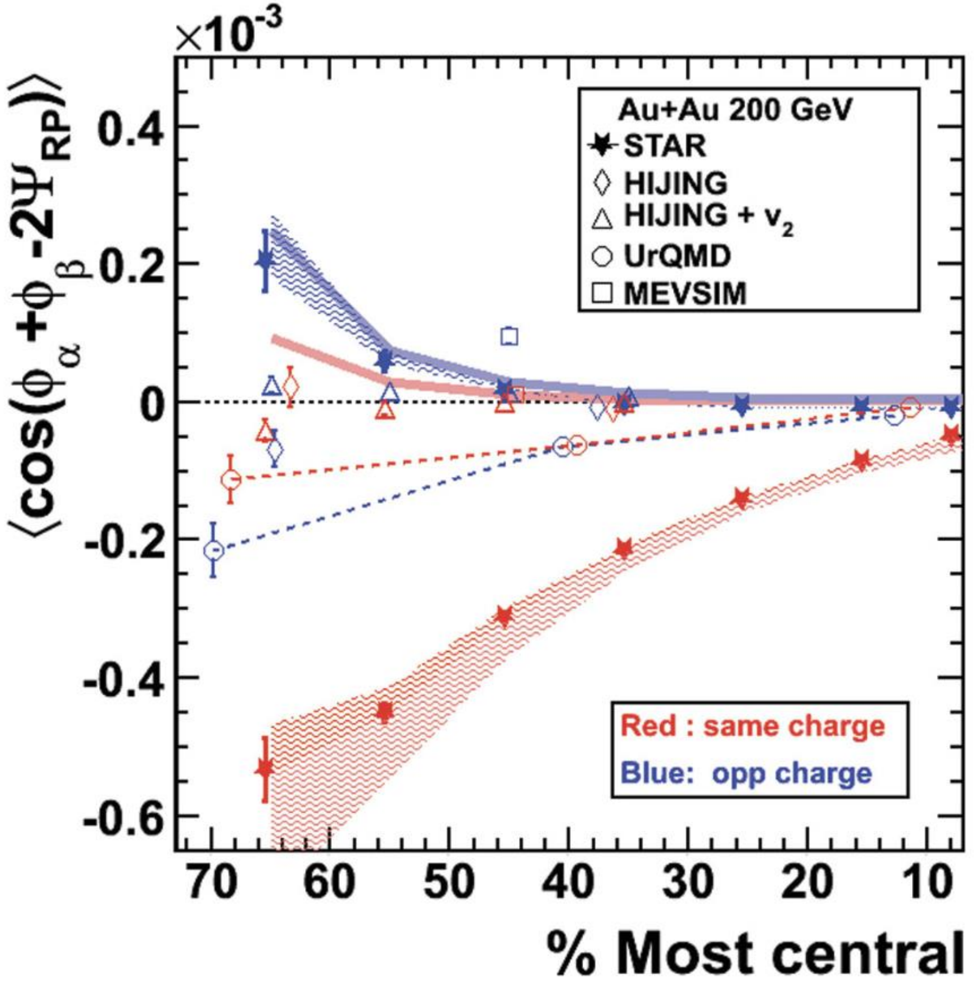
Charge separations (J) induced by magnetic field (B) for quarks at chirality imbalance (μ_5).

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



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

First measurement: 2009



- CME observables:

$$\gamma^{112} = \langle \cos(\varphi_1 + \varphi_2 - 2\Psi_{RP}) \rangle$$

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

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

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

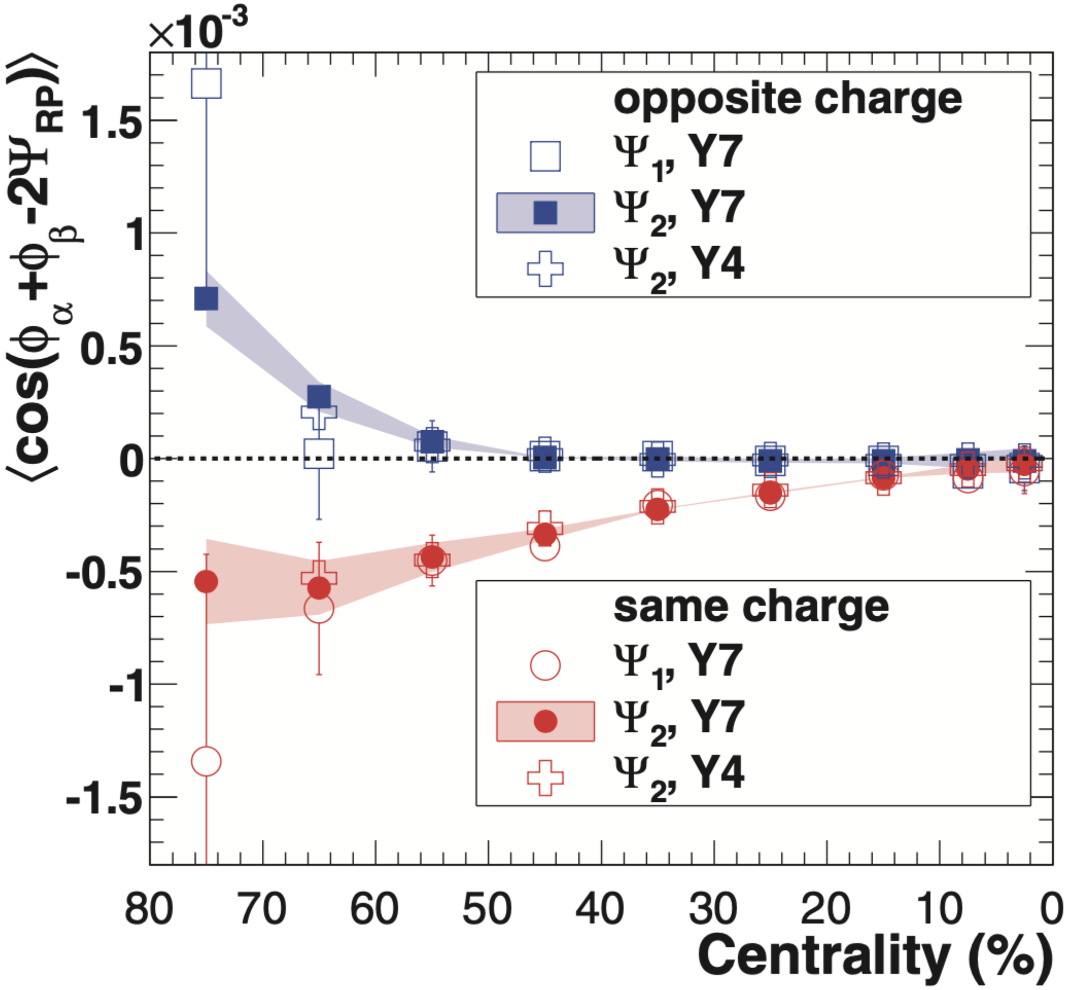
N. Magdy et al Phys. Rev. C 97, 061901 (2018)

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

$\gamma_{os} > \gamma_{ss}$, consistent with CME expectation.

PRL 103(2009)251601;PRC 81(2010)54908

Confirming signal along B field (Ψ_1)?



- $\gamma_{os} > \gamma_{ss}$ with 1st-order EP (from spectator neutron v_1)

  → Possible parity violation?

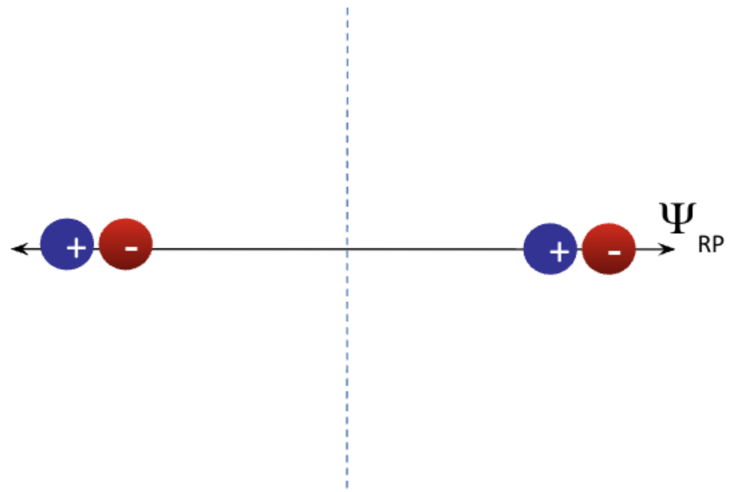
- neutron Ψ_1 doesn't necessarily represent the B field direction, not as much as proton Ψ_1.

- However, very soon the result is challenged by backgrounds...

PRC 88 (2013) 64911

Puzzle: What is the background?

Flow BKG

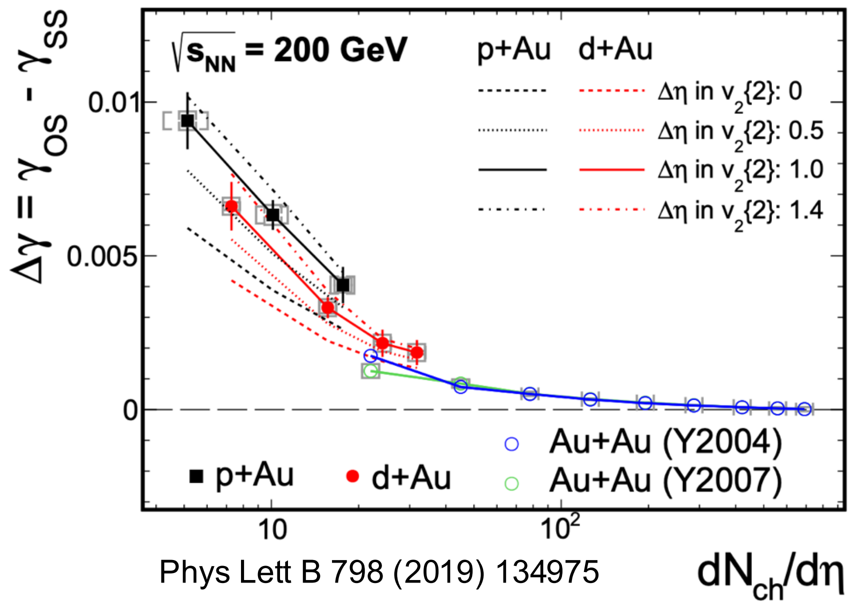


$\gamma_{SS} = -1$
$\delta_{SS} = -1$

$v_2 = 1$

$\gamma_{OS} = 0$
$\delta_{OS} = 0$

Nonflow BKG

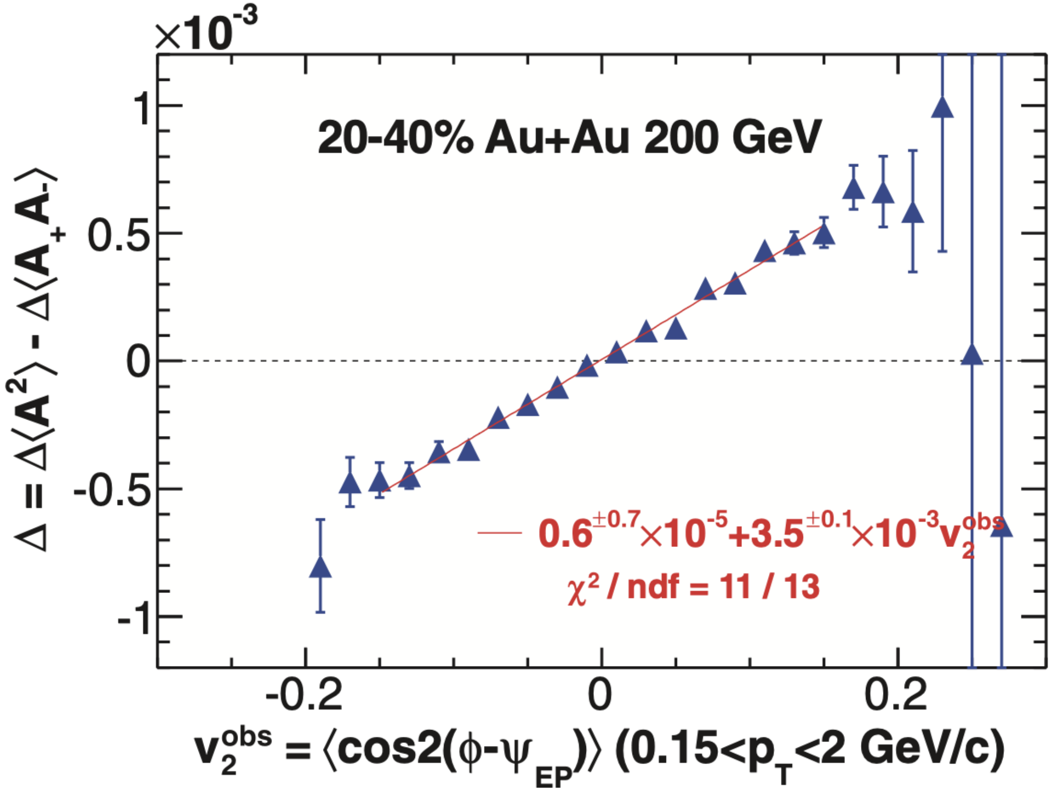


Phys Lett B 798 (2019) 134975

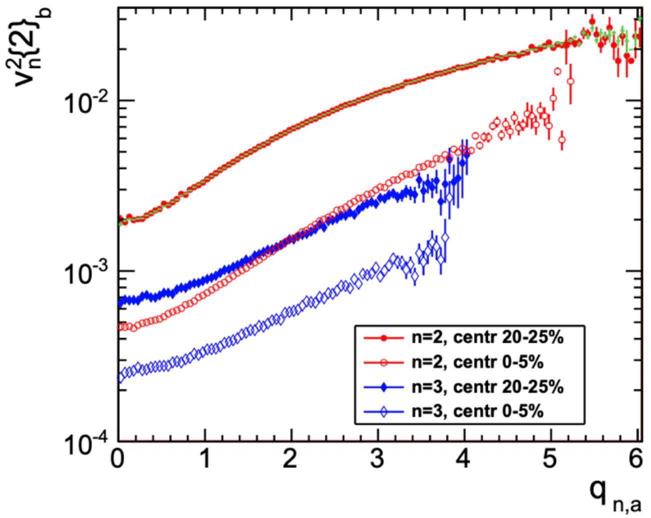
- Flow BKG: v_2+ resonance decay/LCC/TMC → fake finite $\Delta\gamma$
- Nonflow BKG: larger $\Delta\gamma$ in p(d)+Au compared with Au+Au
- Measurement of CME is challenged by flow and non-flow background:

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

Direct event-by-event "obs-v2" removal?



- A direct projection of CME observable to the event-by-event v_2^{obs} results intercept ~ 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

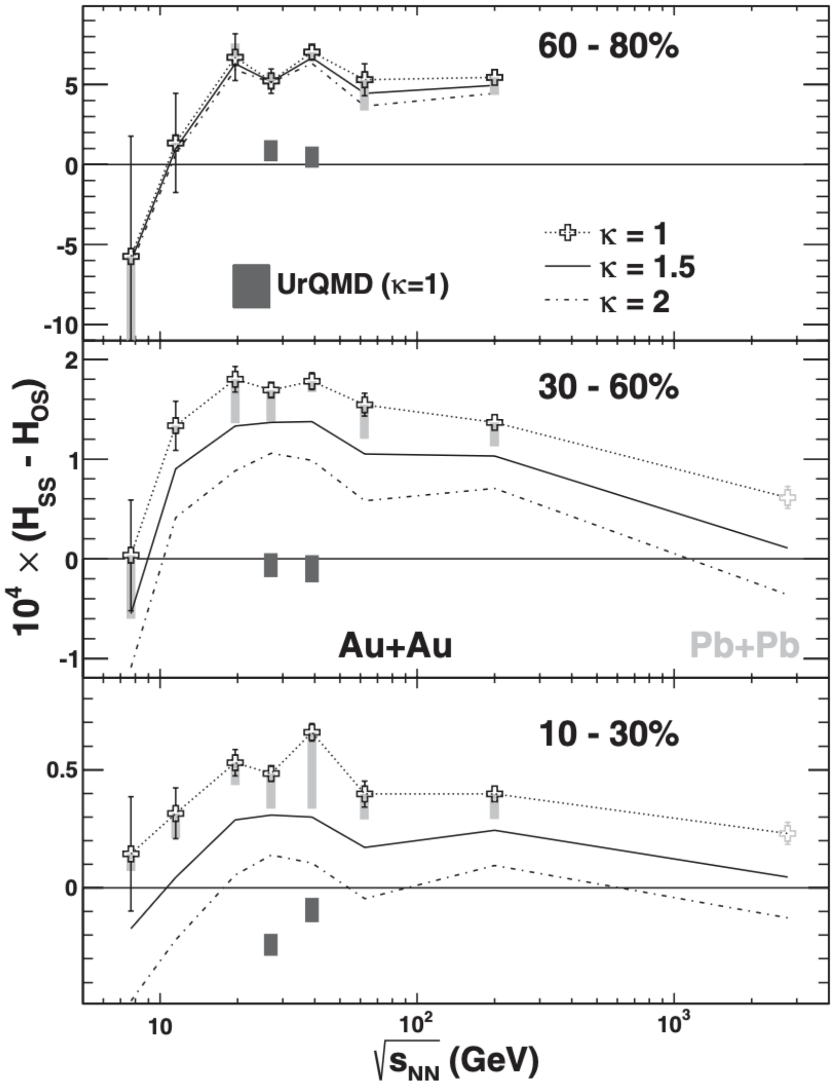


$$q_n = \sqrt{\frac{\sum \cos(n\varphi)^2 + \sum \sin(n\varphi)^2}{N}}$$

PhysRevC.89.044908 (2014)

Schukraft, Timmins, Voloshin, Phys. Lett. B 719, 394 (2013)

Beam Energy Scan I – hint at low energy?



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

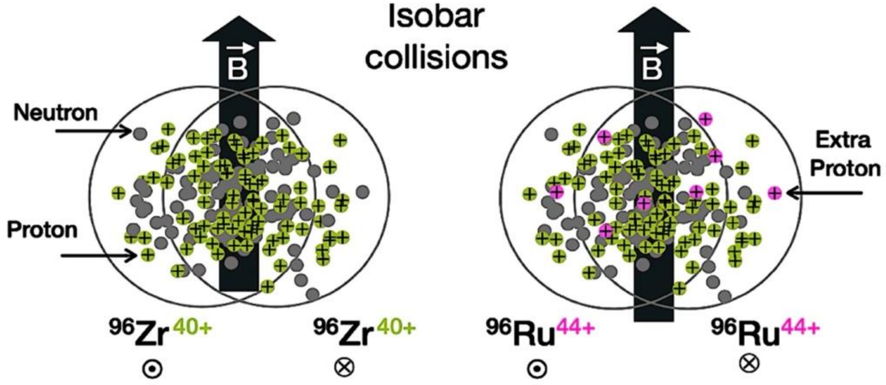
$$\Delta H = H^{OS} - H^{SS}$$

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

STAR, PRL 113 (2014) 052302

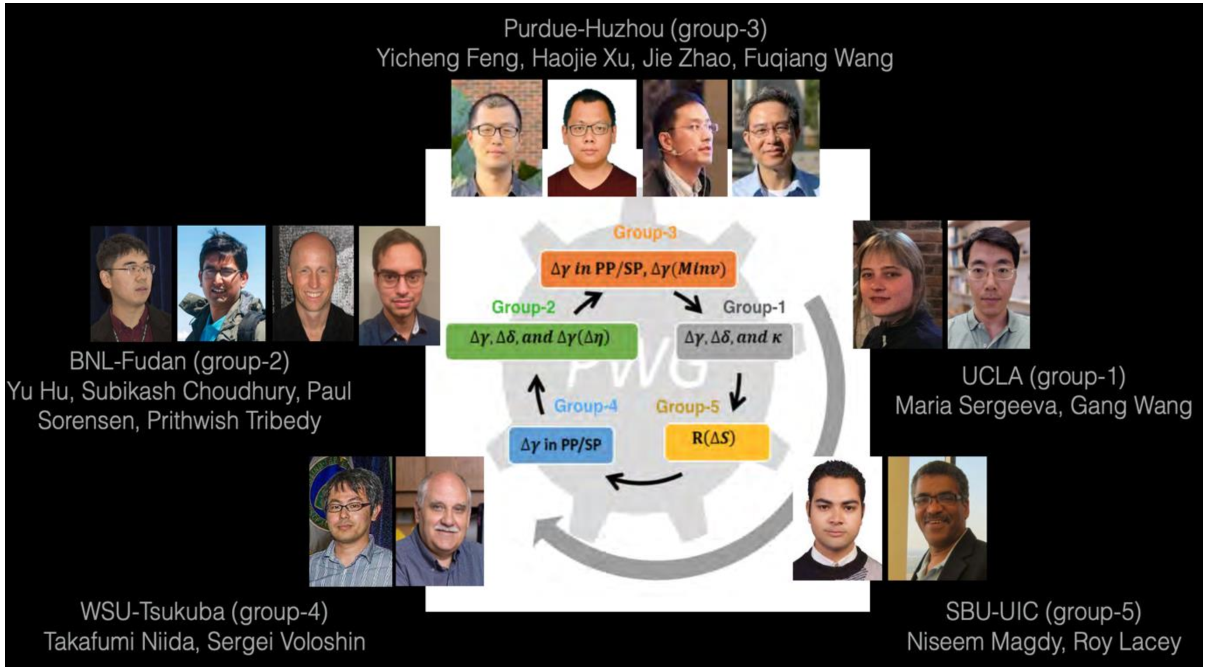
Isobar collision – blind analysis



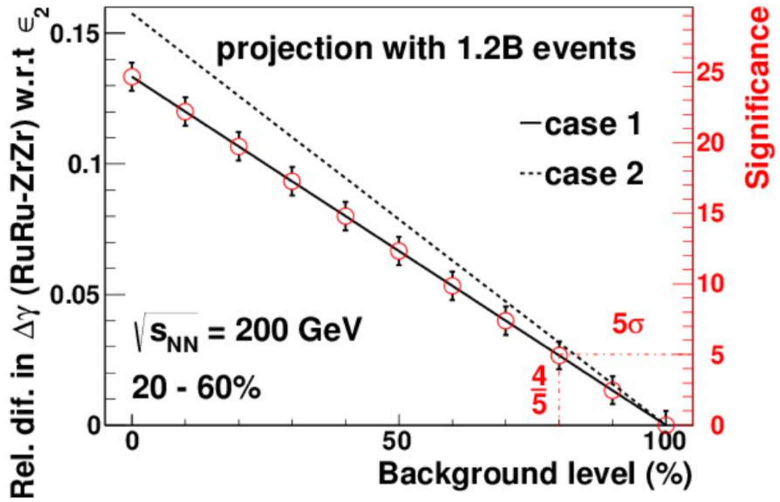
- A=96 → Similar backgrounds
- Z = 40+4 → Different B induced CME signal
- $R = \frac{\Delta\gamma/v_2\{Ru+Ru\}}{\Delta\gamma/v_2\{Zr+Zr\}} \begin{cases} = 1 \;\; for \;\; BKG \\ > 1 \;\; for \;\; CME \end{cases}$

Predefined CME signal

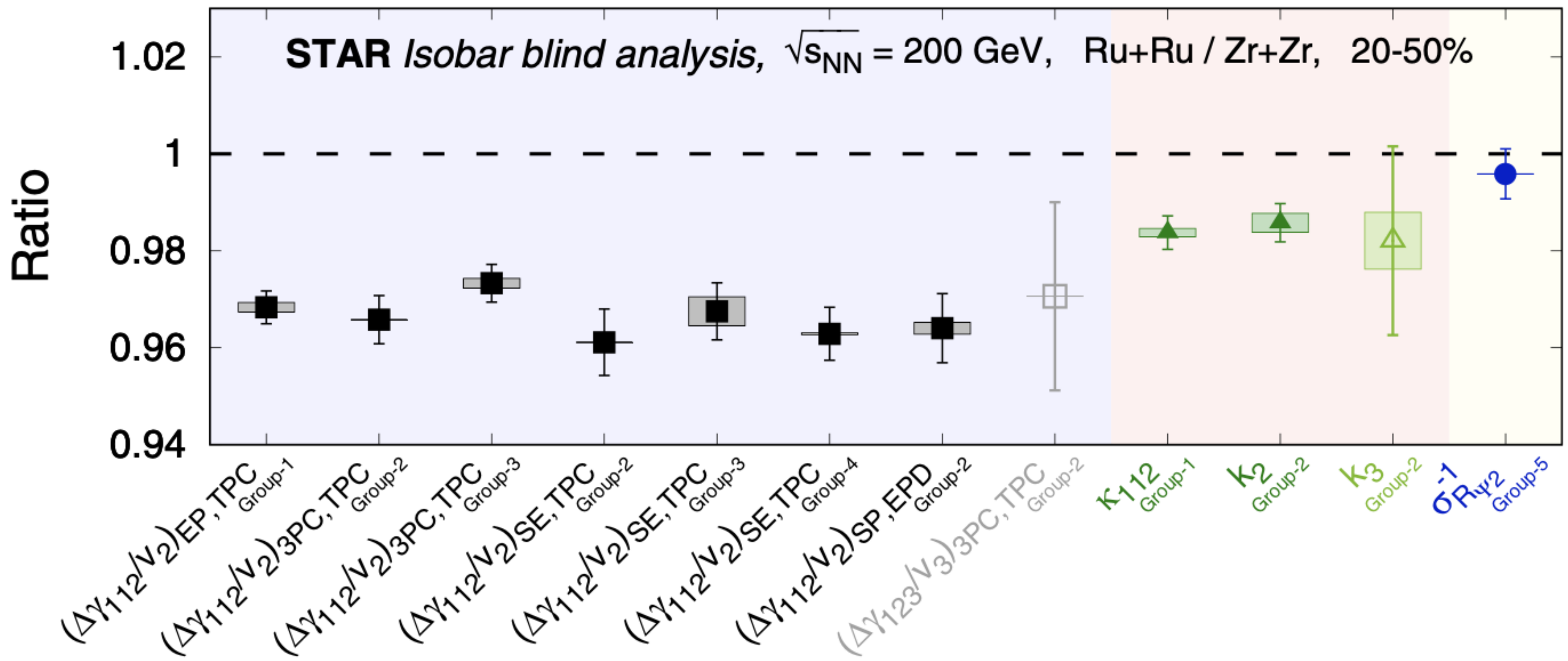
- Conducted by 5 independent groups



In courtesy of P. Tribedy



Isobar collision – blind analysis



Predefined baseline

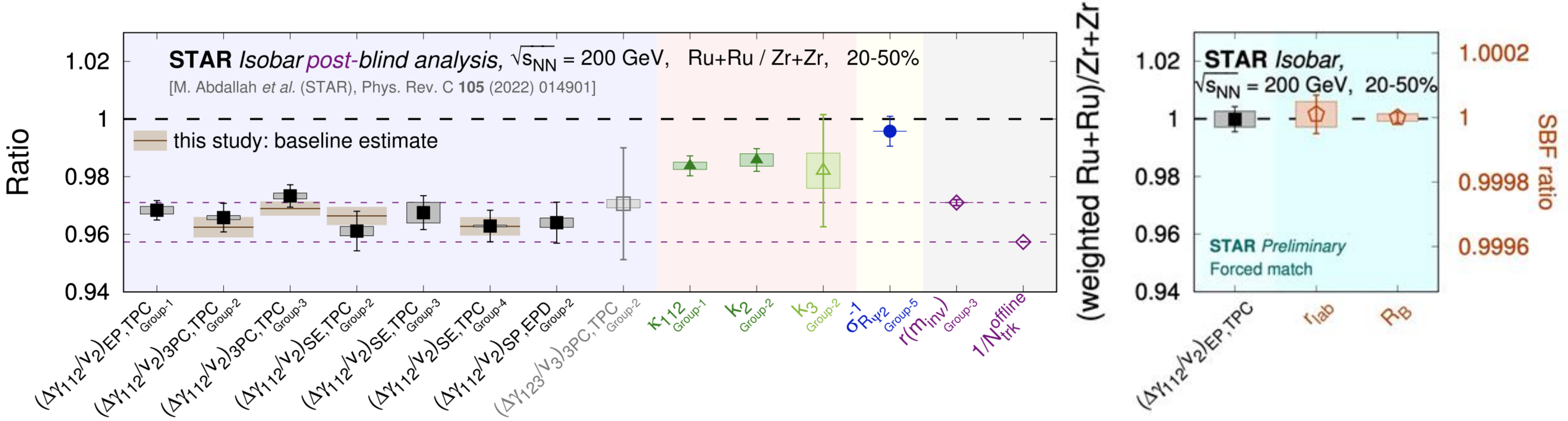
- No predefined CME signal is observed → B field may decay too fast at 200 GeV.
- Backgrounds in two systems are different and dominates the measurement.

PhysRevC.105.014901 (2022)

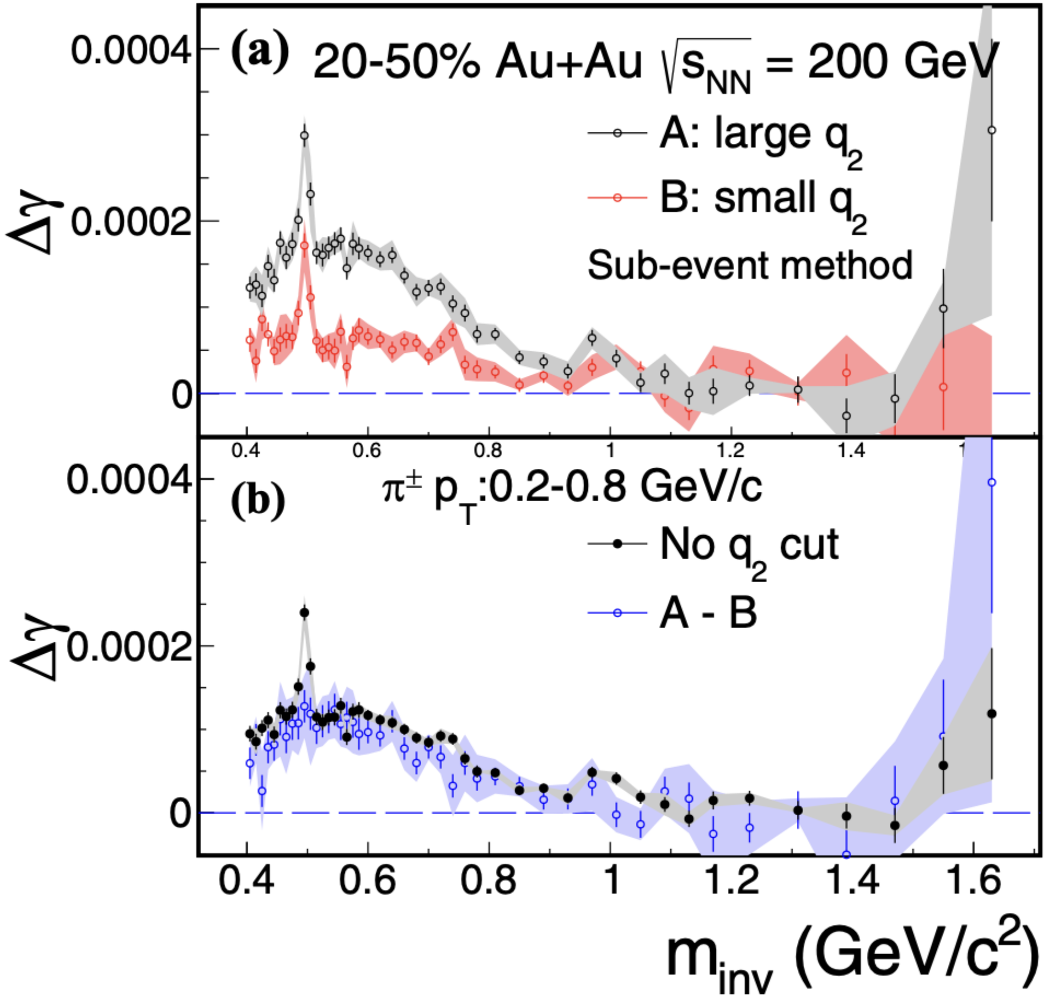
Isobar collision - post blind analysis

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

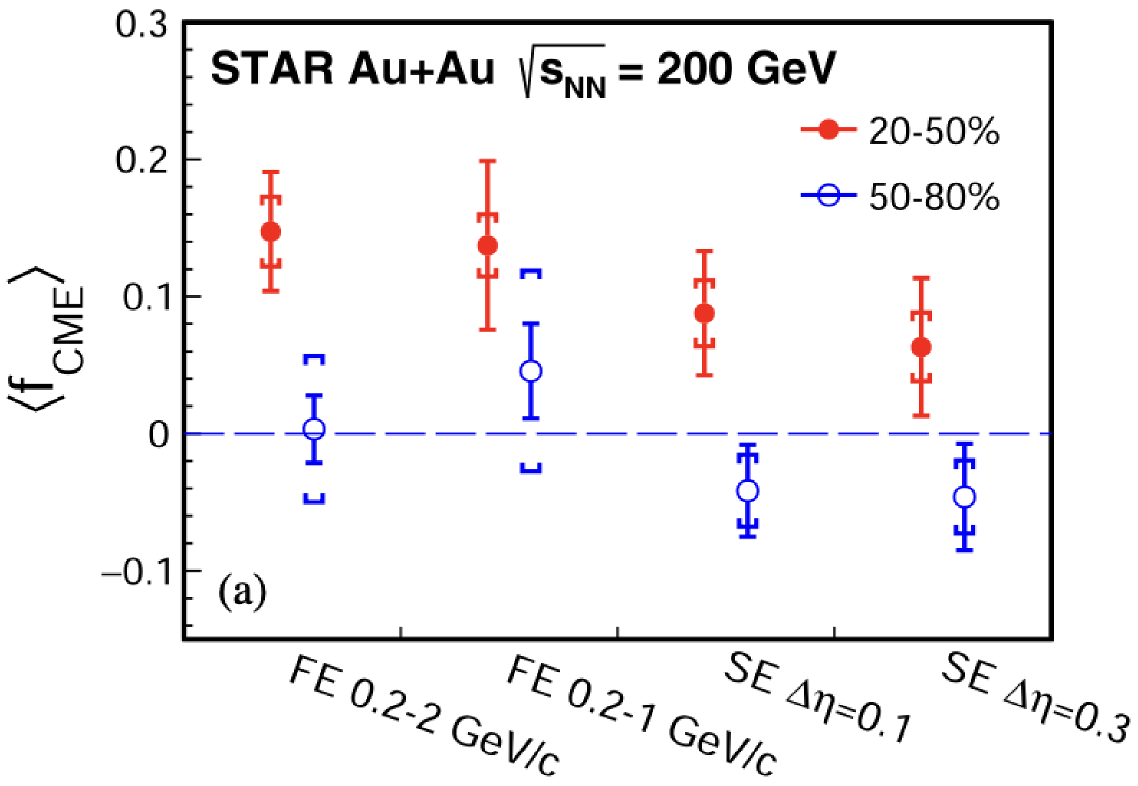


- Assume the large resonance decay background is reduced at large m_{inv} :
- Δγ value is found to be significantly smaller, averaged to be (2 ± 4 ± 5)% of the inclusive

- Cutting on invariant mass may be equivalent to cutting on opening angle, which changed the Δγ measurement.

PhysRevC.106.034908 (2022)

Background suppression – Spectator/Participant Plane



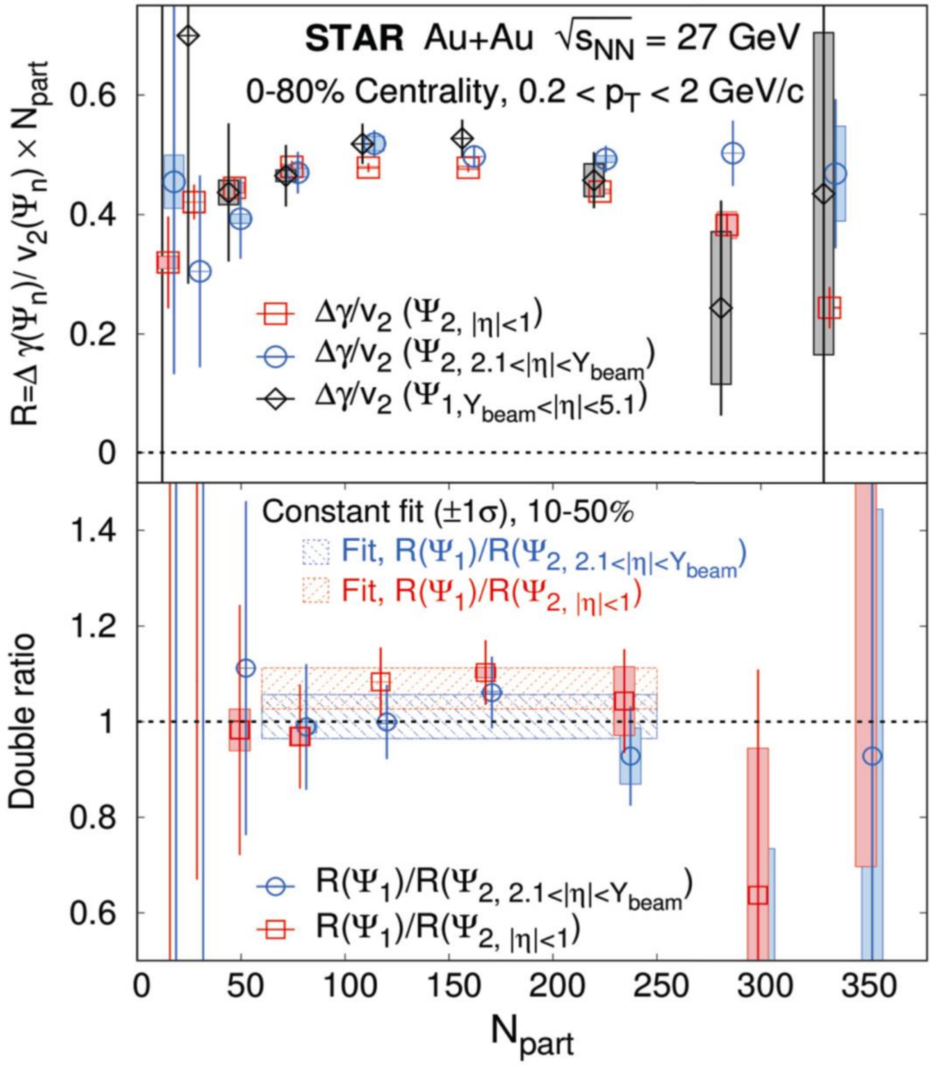
Assume Ψ_1 has minimal flow background and maximal B field signal, Ψ_2 has maximal flow background and minimal signal,

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

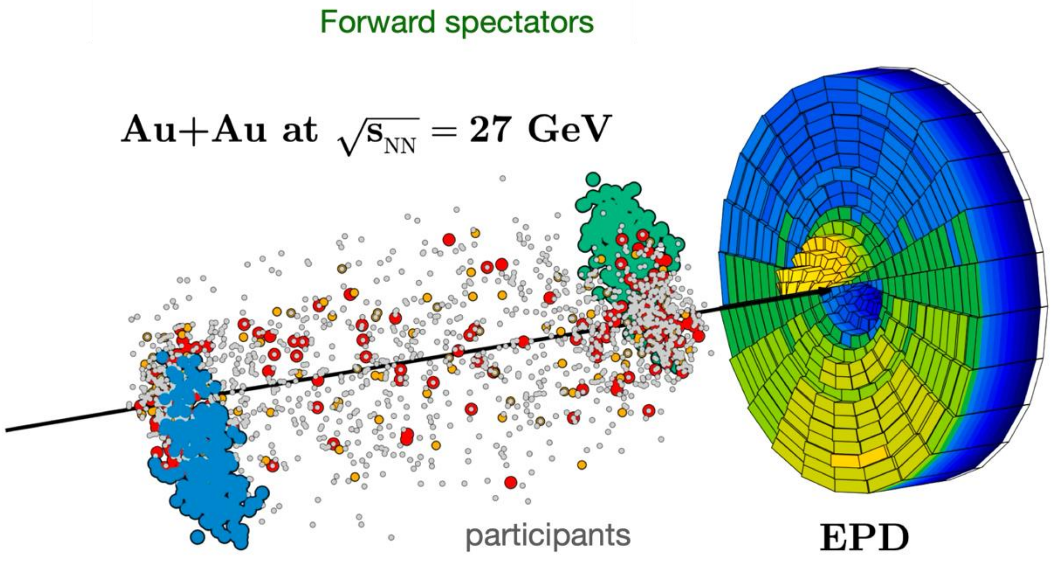
- consistent with zero at 50-80% but could be finite in 20-50%.
- Possible nonflow effects in P.P → f_{cme} decreasing when eta gap increases

PhysRevLett.128.092301 (2022)

Background suppression – Spectator/Participant Plane

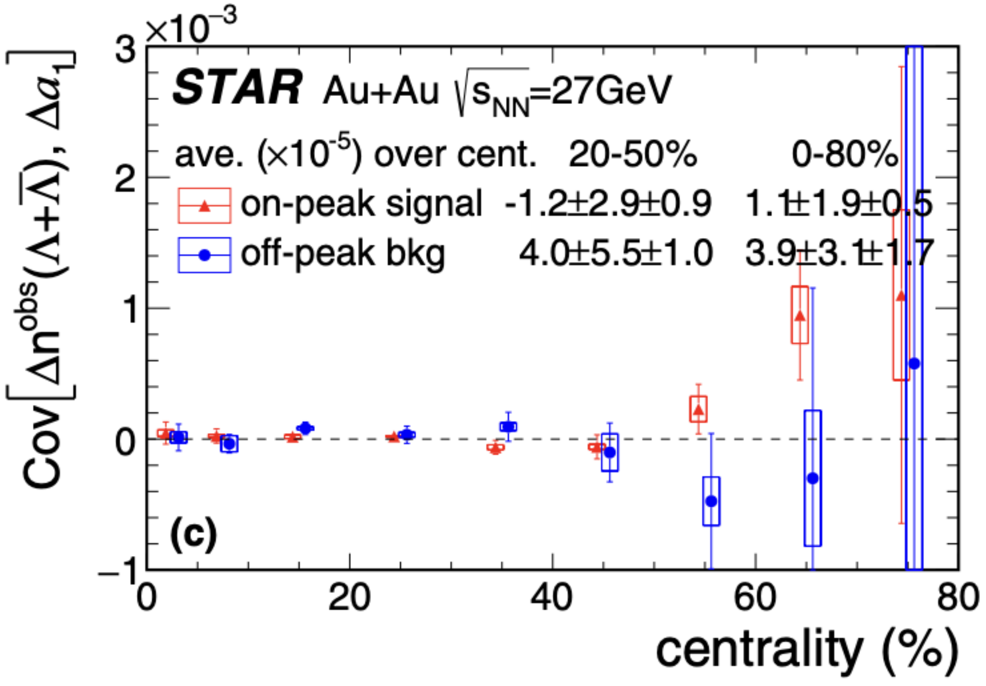


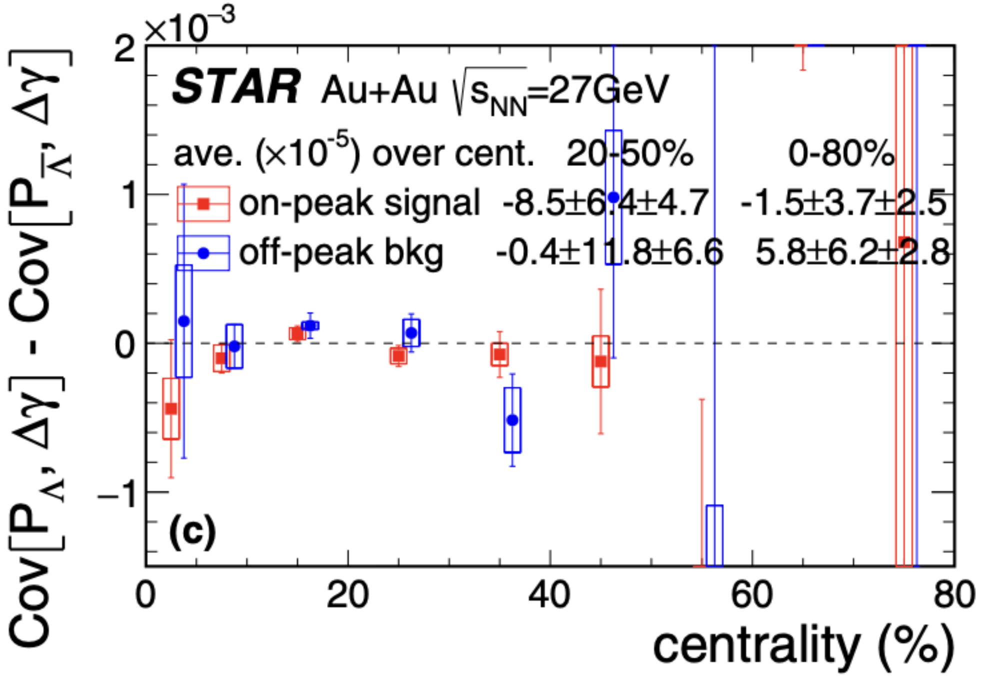
Phys Lett B 839 (2023) 137779



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

Chiro-polarization correlation

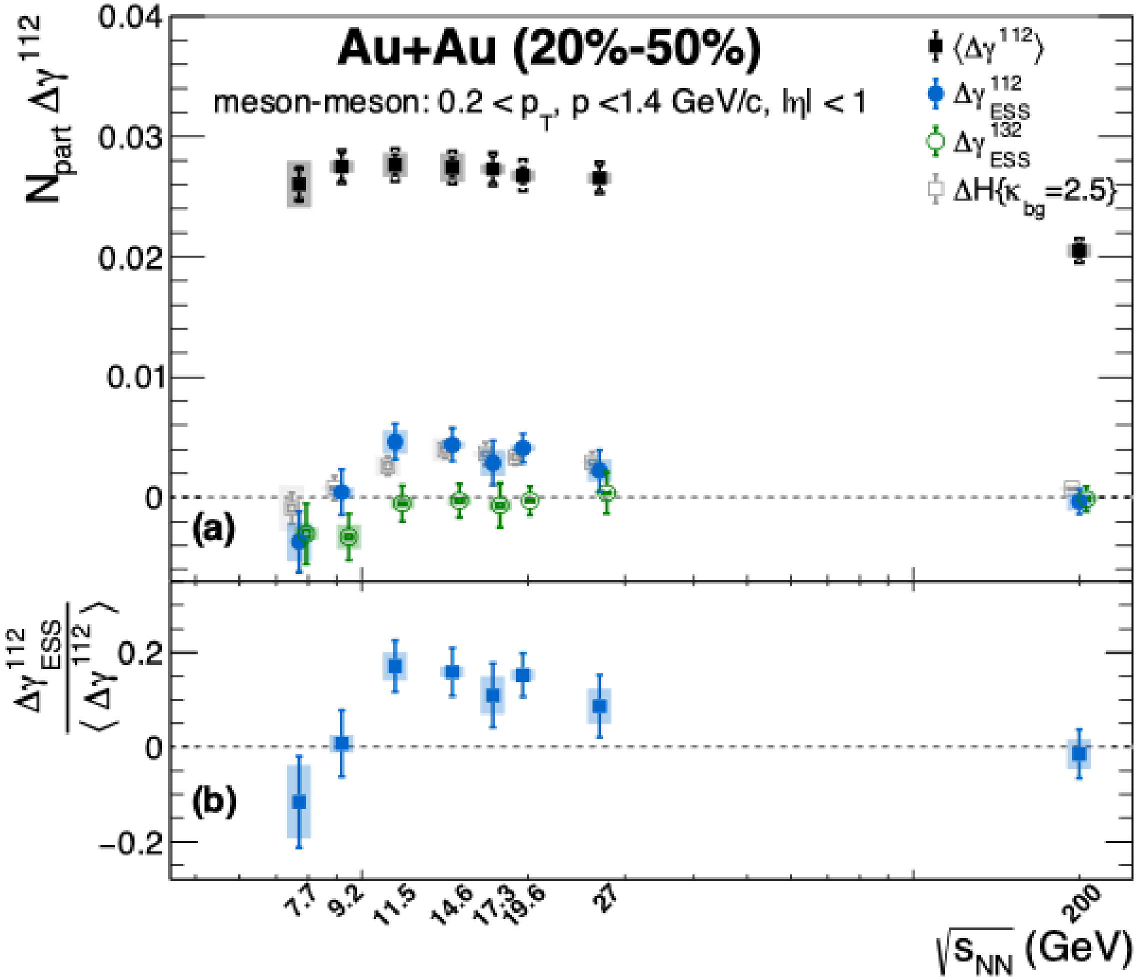


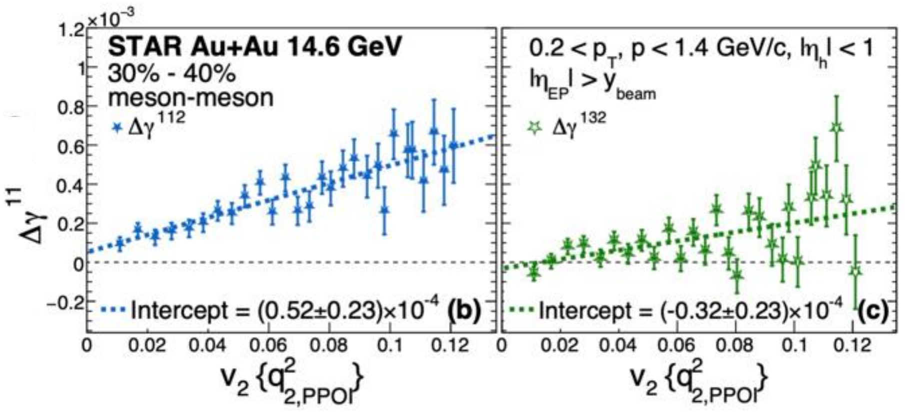


- CME and Λ polarization may share correlation from B field, expect Covariance > 0. ΔN (L-R) and Δa_1 may share correlation, expect Cov >0
- Observe Cov[ΔN, Δa_1] and Cov[ΔP, Δγ] consistent with zero, limited by statistics
- Λ is produced relatively later, while CME is early effect.

PhysRevC.108.014909

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, 3.2σ) at 11.5, 14.6 and 19.6 GeV, combined > 5σ
- 1.1σ at 27 and 1.3σ at 17 GeV
- κ_{bg}~ 2.5, well consistent with H-correlator
- Identified backgrounds > 80%

arXiv:2506.00275, arXiv:2506.00278

As STAR turns 25^{th}, 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