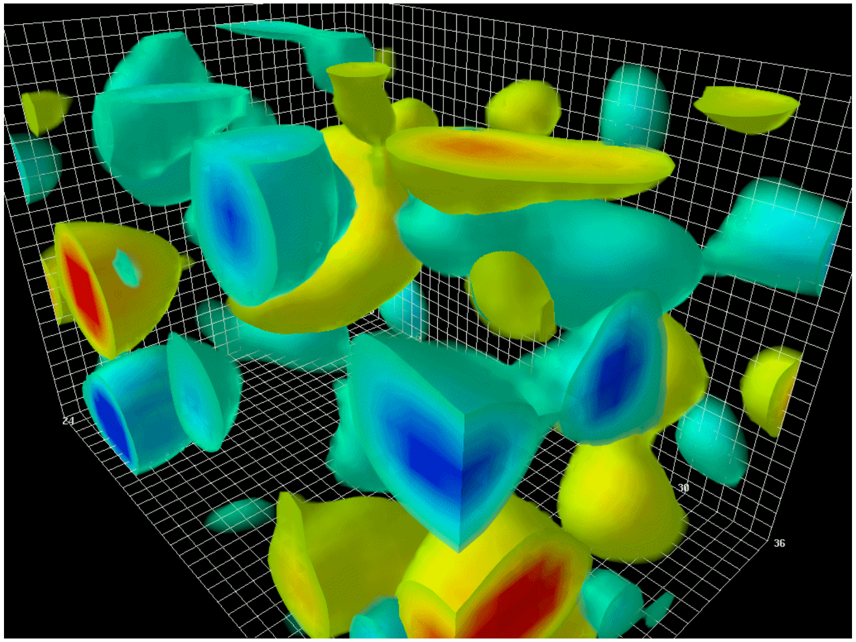
Experimental search for the Chiral Magnetic Effect

Jie Zhao

Apr. 25, 2026

QCD vacuum

fluctuations of topological charge



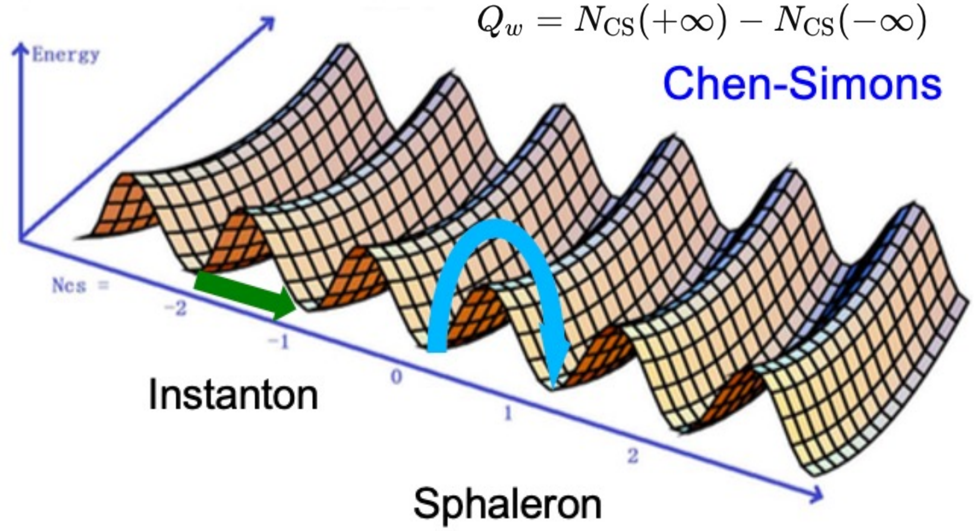
The volume of the box is 2.4 x 2.4 x 3.6 fm

Derek Leinweber

$$Q_w = \frac{g^2}{32\pi^2}\int d^4x F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a$$

$$Q_w = N_{CS}(+\infty) - N_{CS}(-\infty)$$

Chen-Simons



D. Kharzeev et al., PRL. 81, 512 (1998)

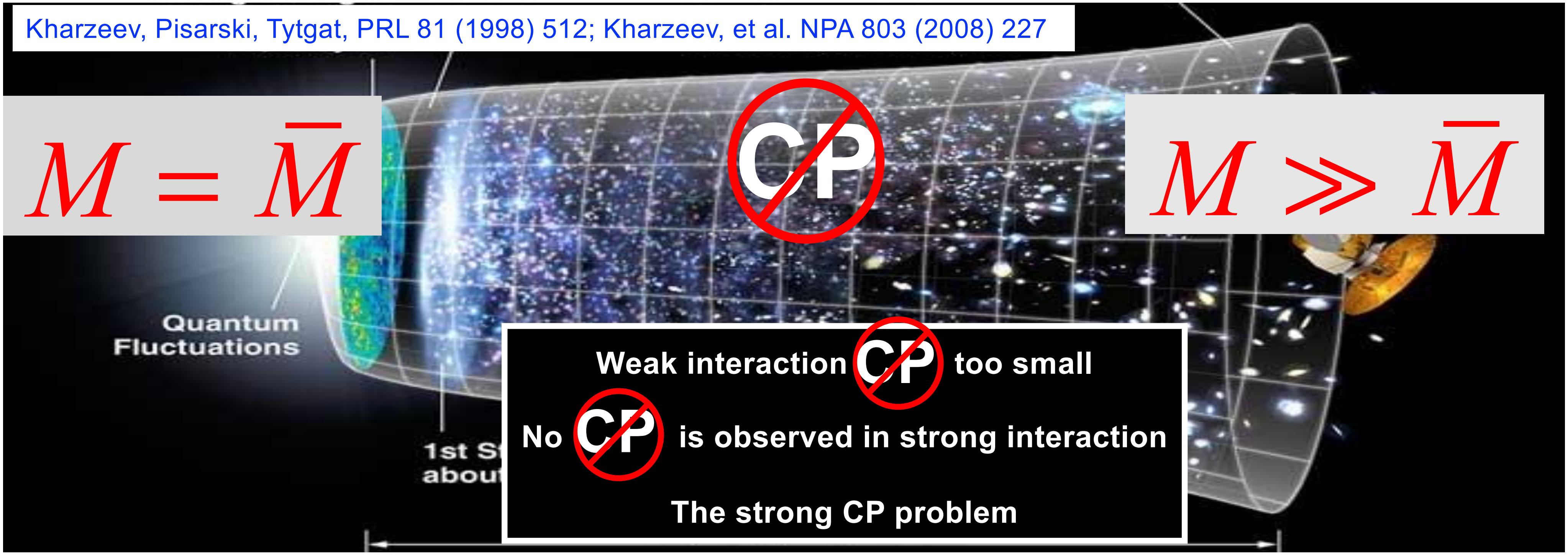
Dimitri Diakonov, PPNP, 51, 173-222, (2003)

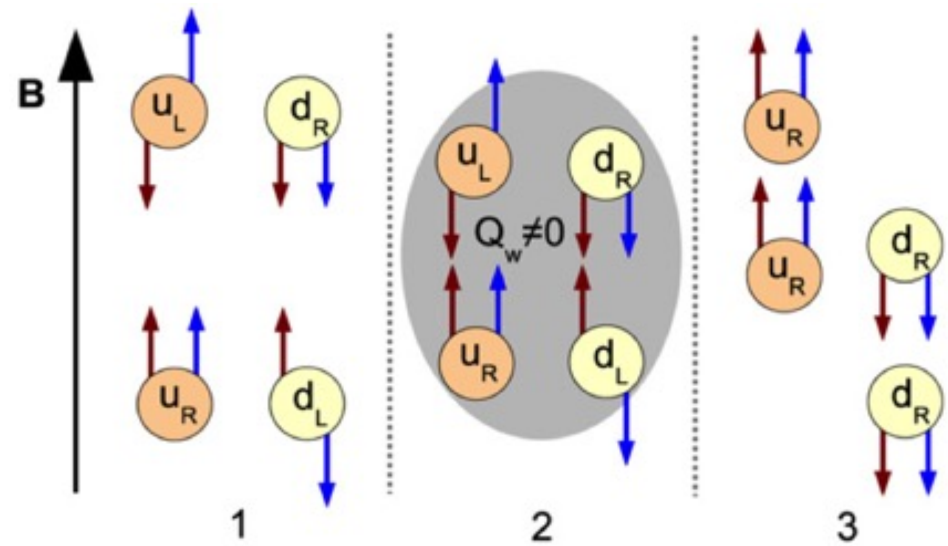
- Transition between QCD vacuum states by instanton/sphaleron mechanism.
- Topological 't Hooft θ-vacuum: (1) Axion (static), (2) CME (dynamical), …

$$|\theta\rangle = \sum_{n=-\infty}^{\infty} e^{in\theta}|n\rangle \qquad \mathcal{L}_\theta = \theta\,\frac{g^2}{32\pi^2}F^a_{\mu\nu}\tilde{F}^{a\mu\nu} \propto \theta\,\mathbf{E}^a\cdot\mathbf{B}^a \qquad n \to n + Q_w \qquad \mathcal{A} \propto e^{i\theta Q_w}$$

- Fluctuations of topological charge (Q_w~N_L-N_R) in QCD, "Winding number"
- Non-zero $Q_w \neq 0$ introduce chirality imbalance ($N_L \neq N_R$), local P/CP violation

The strong CP problem



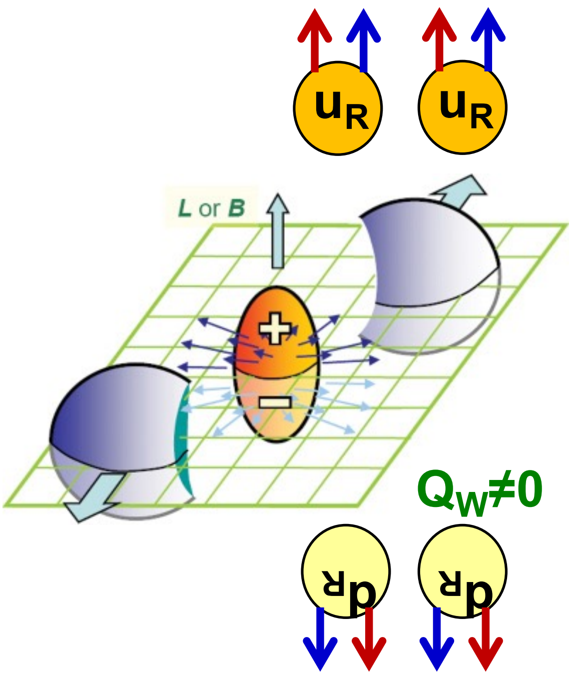


- **Strong magnetic field**
- **Quark degree of freedom, χ-symmetry**
- **QCD vacuum fluctuations,**

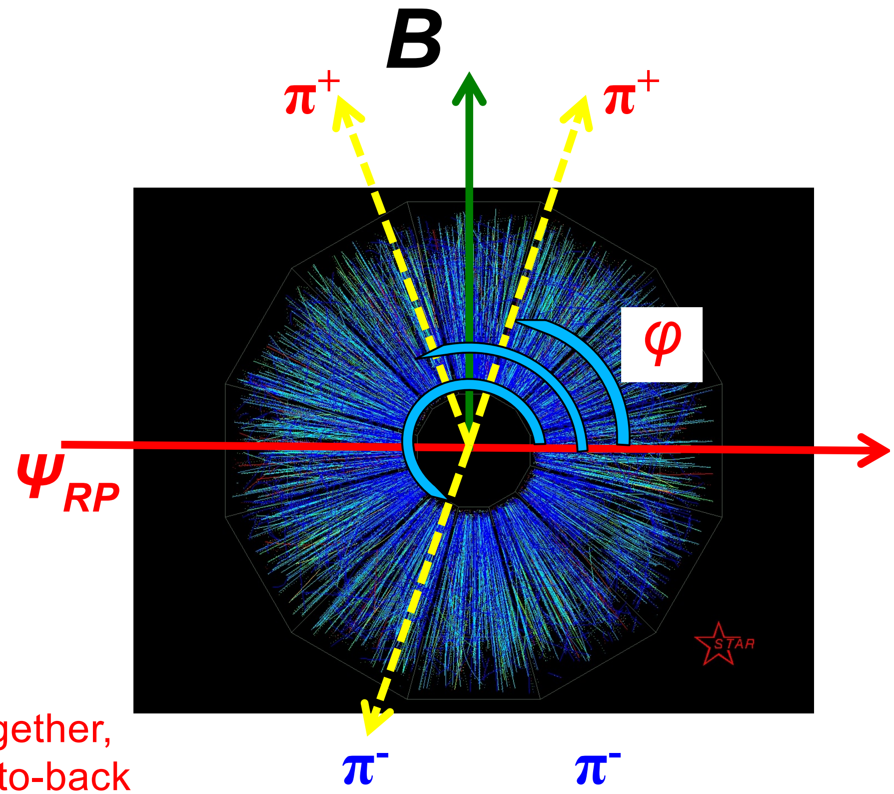
  Topological gluon field, $Q_w \neq 0$.
- **Local P, CP violations**

How to measure CME?

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



same-sign (++/--) pairs go together,
opps.-sign (+-/-+) pairs back-to-back



The sign of Q_w **can vary** event to event and domain to domain ➔ one has to measure correlations

$$\gamma = \langle \cos(\varphi_\alpha + \varphi_\beta - 2\psi_{RP}) \rangle$$

$$\gamma^{+-} = \cos(\pi^+ + \pi^- - 0) = \cos(360°) = +1$$

$$\gamma^{++} = \cos(\pi^+ + \pi^+ - 0) = \cos(180°) = -1$$

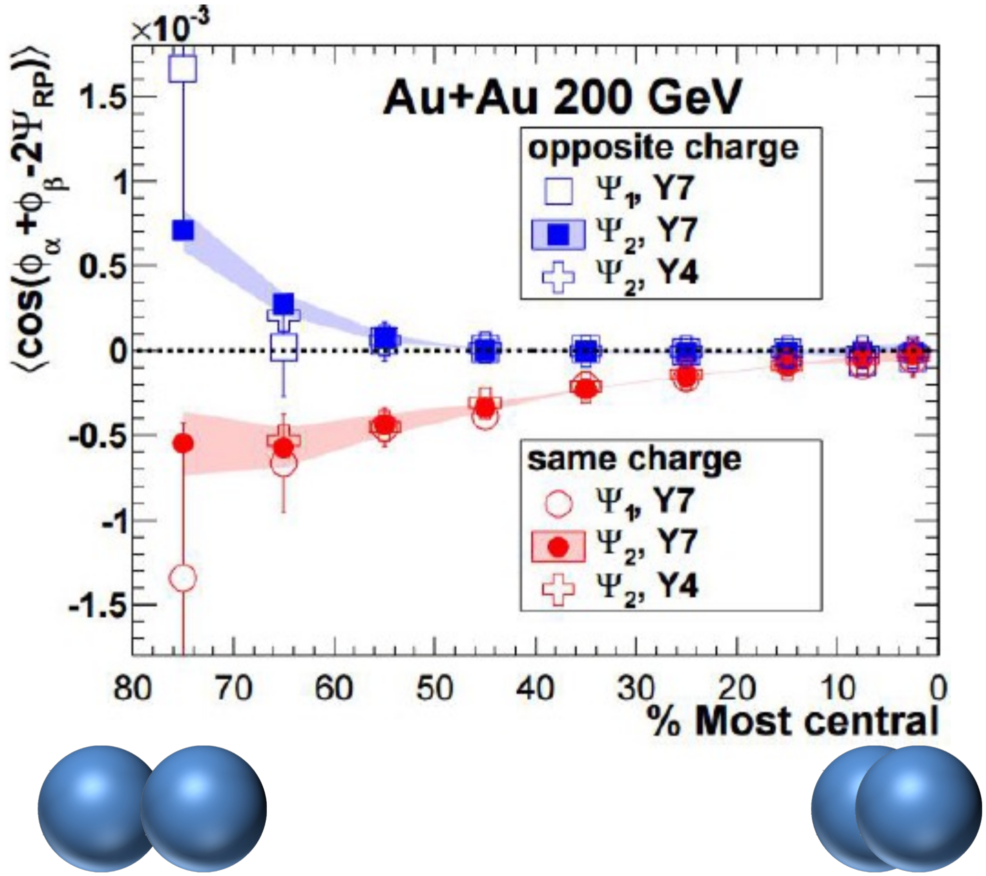
$$\Delta\gamma = \gamma^{+-} - \gamma^{++/--} = 2 > 0$$

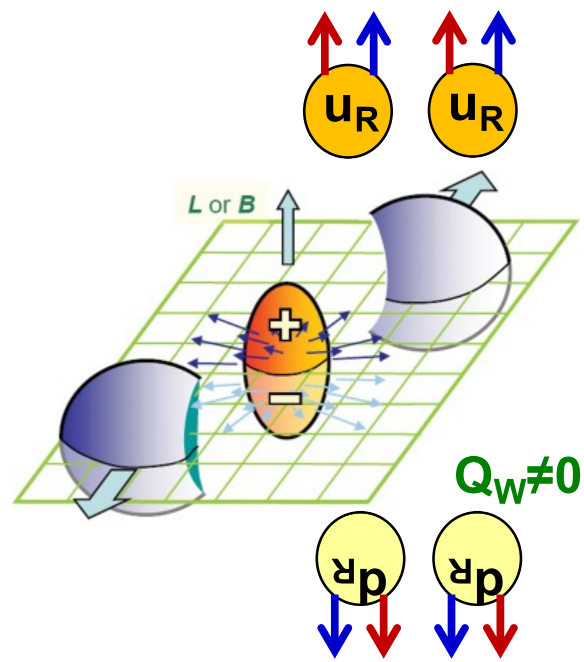
φ represents the azimuthal angle

α, β denote the charge of the particles, with combination of +-(-+), ++, --

Early measurements

STAR collaboration, PRL 103(2009)251601; PRC 81(2010)54908; PRC 88 (2013) 64911





++/-- pairs go together,
+-/-+ pairs back-to-back

➢ Qualitatively consistent with CME expectations

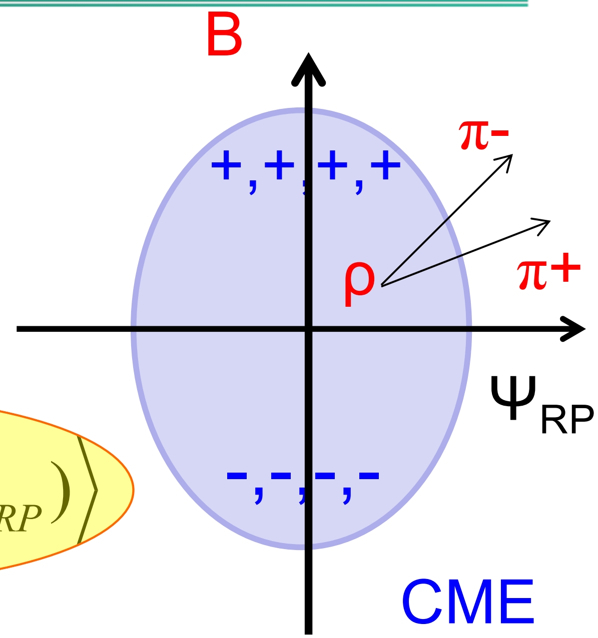
Background?

S. A. Voloshin, PRC 70, 057901 (2004)
F. Wang, PRC 81, 064902 (2010)
A. Bzdak, V. Koch and J. Liao, PRC 83, 014905 (2011)
S. Schlichting and S. Pratt, PRC 83, 014913 (2011)
F. Wang, J. Zhao, PRC 95,051901(R) (2017)

$$\gamma = \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\psi_{RP}) \right\rangle$$

$$= \frac{N_{cluster}}{N_\alpha N_\beta} \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{cluster}) \cos(2\varphi_{cluster} - 2\psi_{RP}) \right\rangle$$

two-particle correlation — v_2



$\gamma^{+-} = \cos(\pi^+ + \pi^- - 0) = \cos(360°) = +1$
$\Delta\gamma > 0$ CME

≈

$\gamma^{+-} = \cos(\pi^+ + \pi^- - 0) = \cos(0°) = +1$
$\Delta\gamma > 0$ Decay BKG.

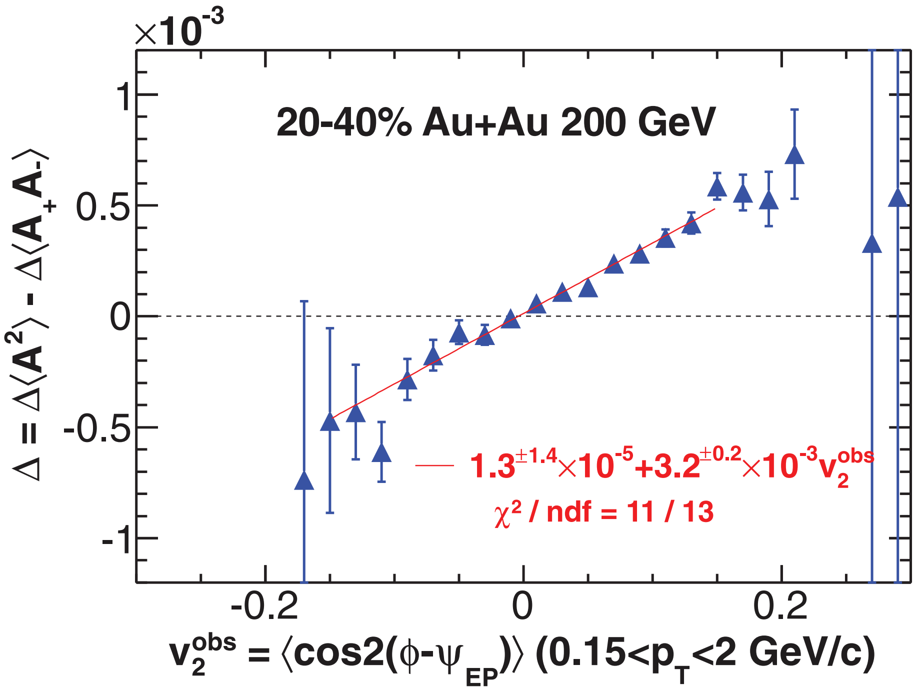
- Background from two-particle correlation coupled with v_2
- Remove background by selecting on v_2=0 (event shape)

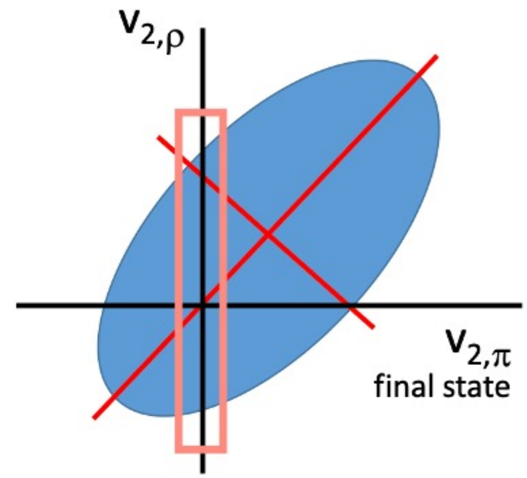
Background issue, event-by-event v_2

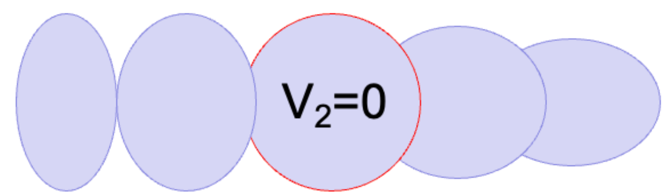
STAR, PRC 89,044908 (2014)

F. Wang, J. Zhao, PRC 95 (2017) 051901(R)

Δ similar to $\Delta\gamma$



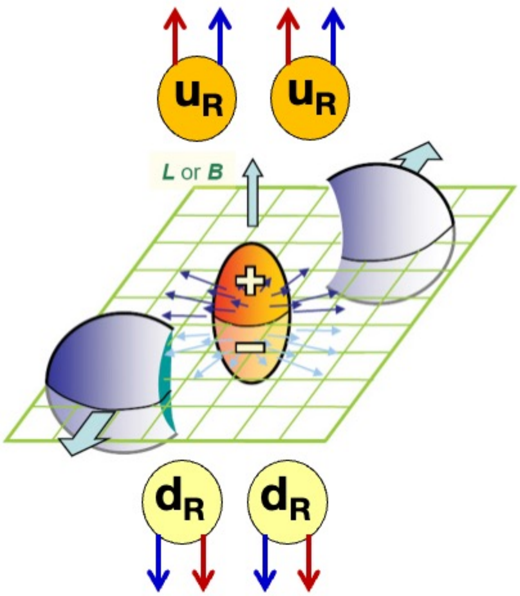




- Charge correlator linear as function of event-by-event v_2 (v_2^{obs} or $v_{2,ebye}$)
- suggests large v_2 background contributions
- By selecting the events with $v_2^{obs} = 0$, the correlator is largely reduced, but not totally eliminated, as background ~ $v_{2,\rho}$ not $v_{2,\pi}$

Search for the CME

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



$$\gamma = \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\psi_{RP}) \right\rangle$$

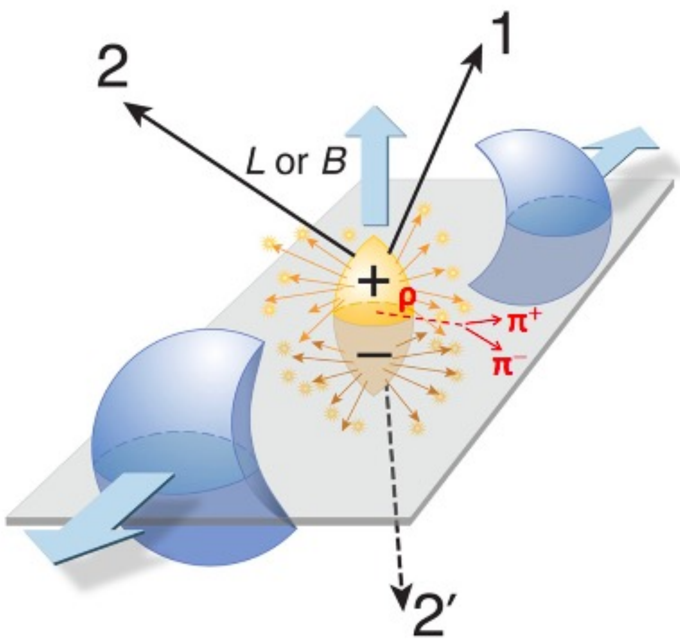
$$= \frac{N_{cluster}}{N_\alpha N_\beta} \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{cluster}) \cos(2\varphi_{cluster} - 2\psi_{RP}) \right\rangle$$

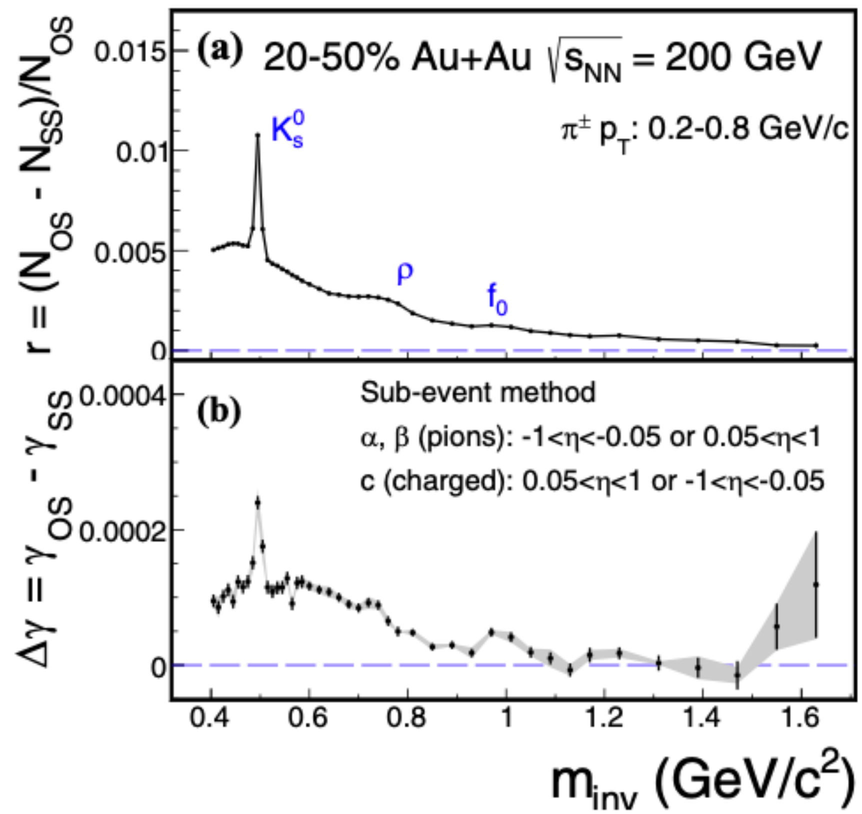
Resonance decay … v_2

- **Invariant mass method**
- **Δγ with respect to Ψ_{RP} (ZDC) and Ψ_{PP} (TPC)**
- **CME in isobar collisions**

Invariant mass method

STAR, Phys. Rev. C 106 (2022) 034908
J. Zhao, H. Li, F. Wang, EPJC (2019) 79:168





$$\gamma = \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\psi_{RP}) \right\rangle$$

$$= \frac{N_{cluster}}{N_\alpha N_\beta} \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{cluster}) \cos(2\varphi_{cluster} - 2\psi_{RP}) \right\rangle$$

Resonance decay … v_2

- Identify the background by invariant mass of α+β pairs
- Explicit demonstration of "resonance" background

Isolate the CME from background

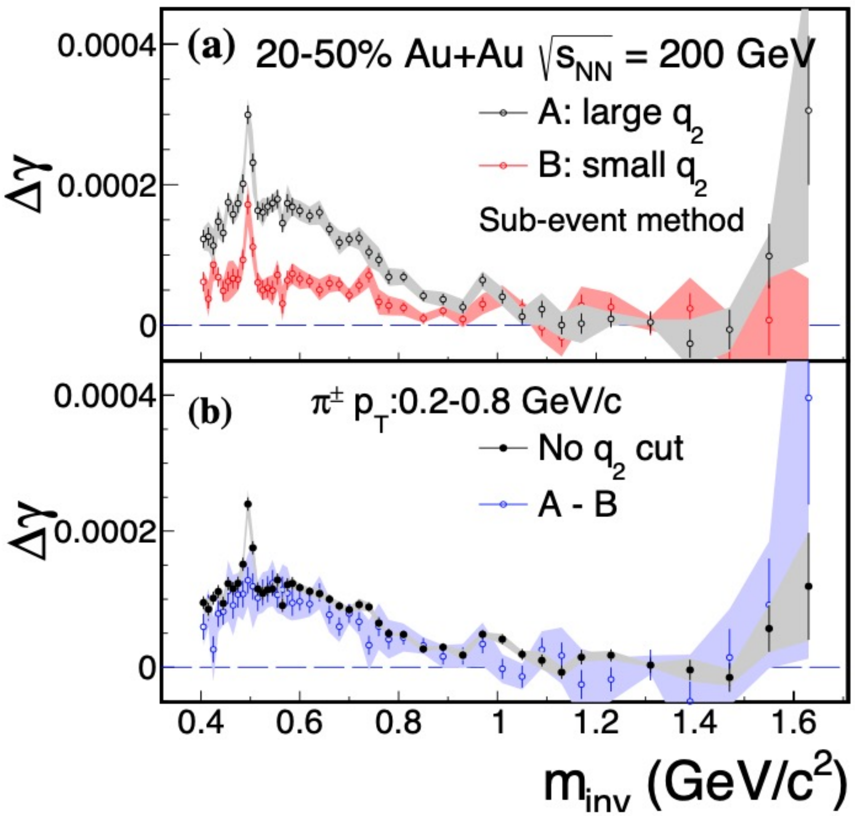
STAR, Phys. Rev. C 106 (2022) 034908

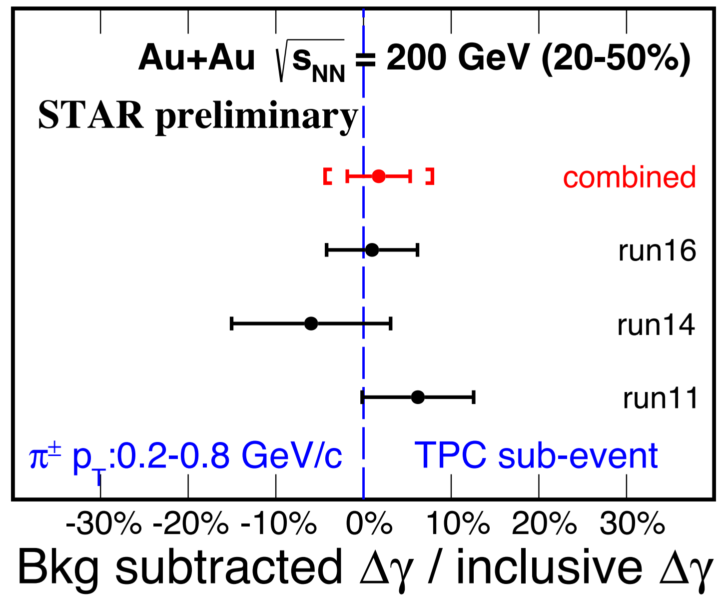
$\Delta\gamma(m) = r(m)*\cos(\alpha+\beta-2\phi_{reso.})*v_{2,reso.} + \text{CME}$

Background shape

Bkg. shape: $\Delta\gamma_A - \Delta\gamma_B$ (A,B select by q_2)

Fit $\Delta\gamma = k*(\Delta\gamma_A - \Delta\gamma_B) + \text{CME}$





$$\frac{N_{cluster}}{N_\alpha N_\beta}\langle\cos(\varphi_\alpha+\varphi_\beta-2\varphi_{cluster})\cos(2\varphi_{cluster}-2\psi_{RP})\rangle$$

vary v_2

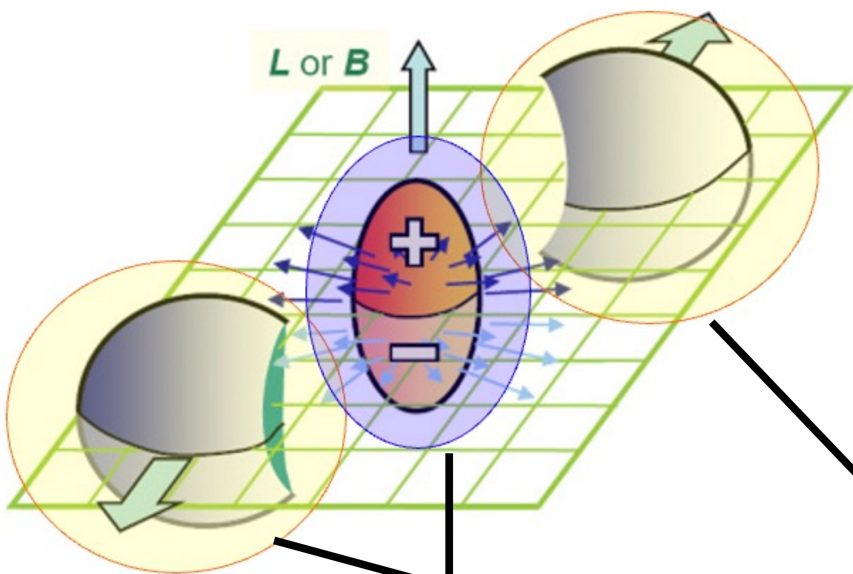
J. Zhao, H. Li, F. Wang, EPJC (2019) 79:168

➢ CME signal fraction is ~15% at 95% C.L.

Use Ψ_{PP} and Ψ_{RP} to solve Bkg and CME

H-J Xu, J. Zhao, X. Wang, H. Li, Z. Lin, C. Shen and F. Wang, CPC 42 (2018) 084103
H-J Xu, X. Wang, H. Li, J. Zhao, Z. Lin, C. Shen and F. Wang, PRL 121 (2018) 022301

B. Alver *et al.* (PHOBOS) , PRL **98**, 242302 (2007).

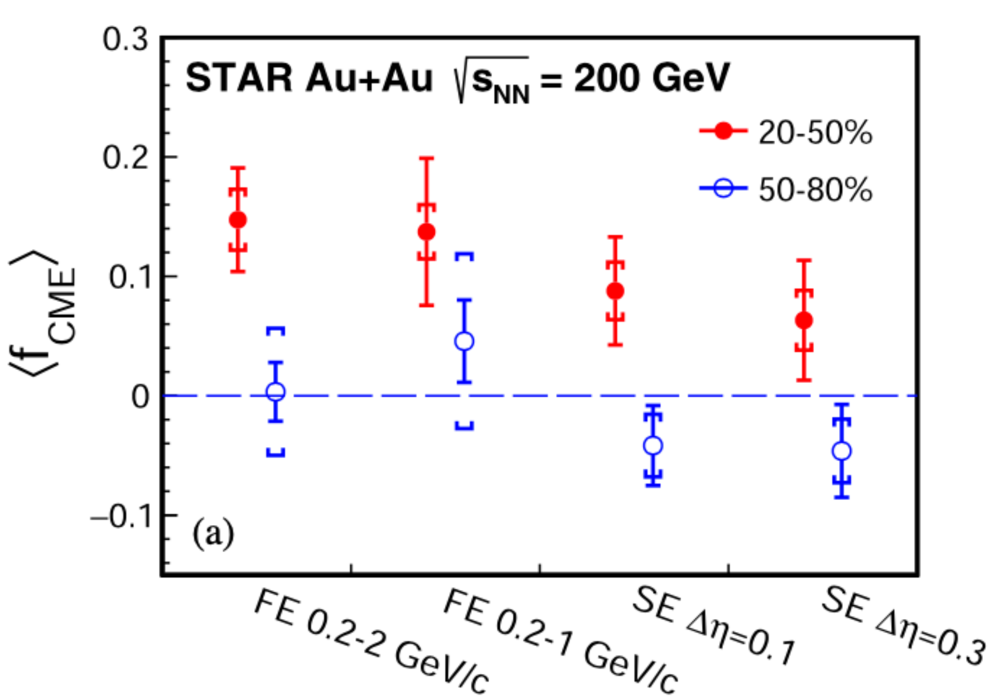


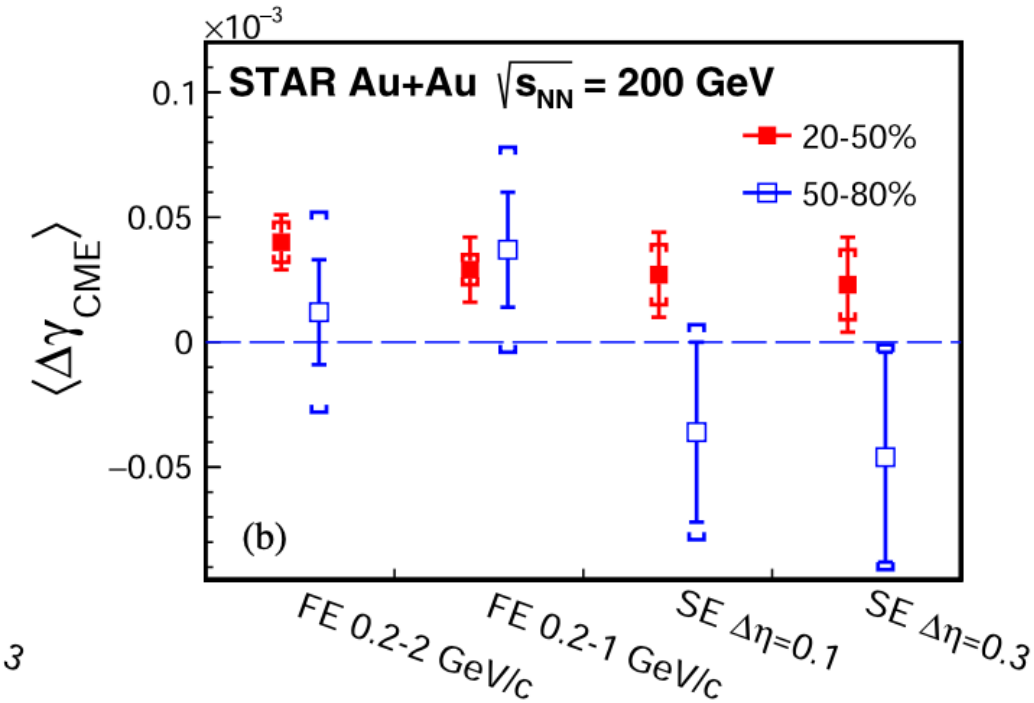
- Ψ_{PP} maximizes v_2,
  - ➔ v_2 background
- Ψ_{RP} maximizes the magnetic field (B),
  - ➔ CME signal
- Ψ_{PP} and Ψ_{RP} are correlated, but not identical due to geometry fluctuations

- $\Delta\gamma$ w.r.t. TPC Ψ_{EP} (proxy of Ψ_{PP}) and ZDC Ψ_1 (proxy of Ψ_{RP}) contain different fractions of CME and Bkg

Δγ with respect to Ψ_{PP} and Ψ_{RP}

STAR collaboration, PRL. 128, 092301 (2022)

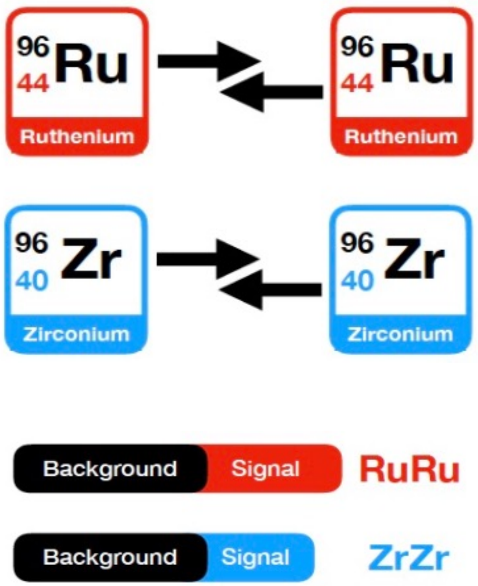


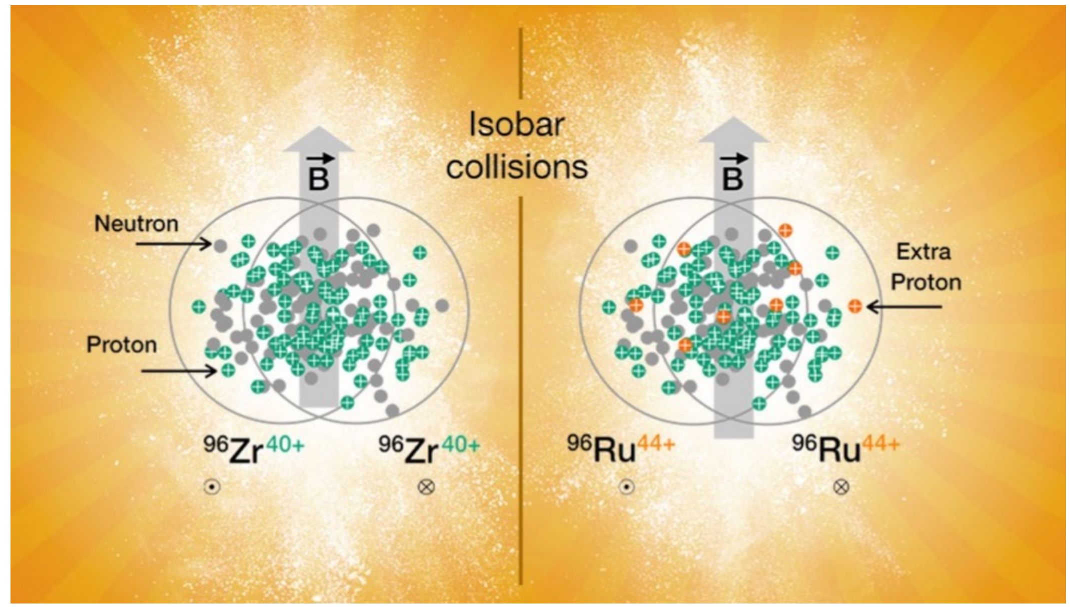


- possible CME signal is 5-10% of the early measurements, with1-3σ significance，may still have non-flow contributions
- rigorous non-flow study under investigation   Y. Feng
- Expect 20B from 2023+25 runs, more precise conclusion

CME in isobar collisions

STAR , Phys. Rev. C 105 (2022) 14901
S. A. Voloshin, Phys.Rev. Lett. 105, 172301 (2010)
W-T Deng, X-G Huang, G-L Ma, and G. Wang Phys. Rev. C 94, 041901(R) (2016)



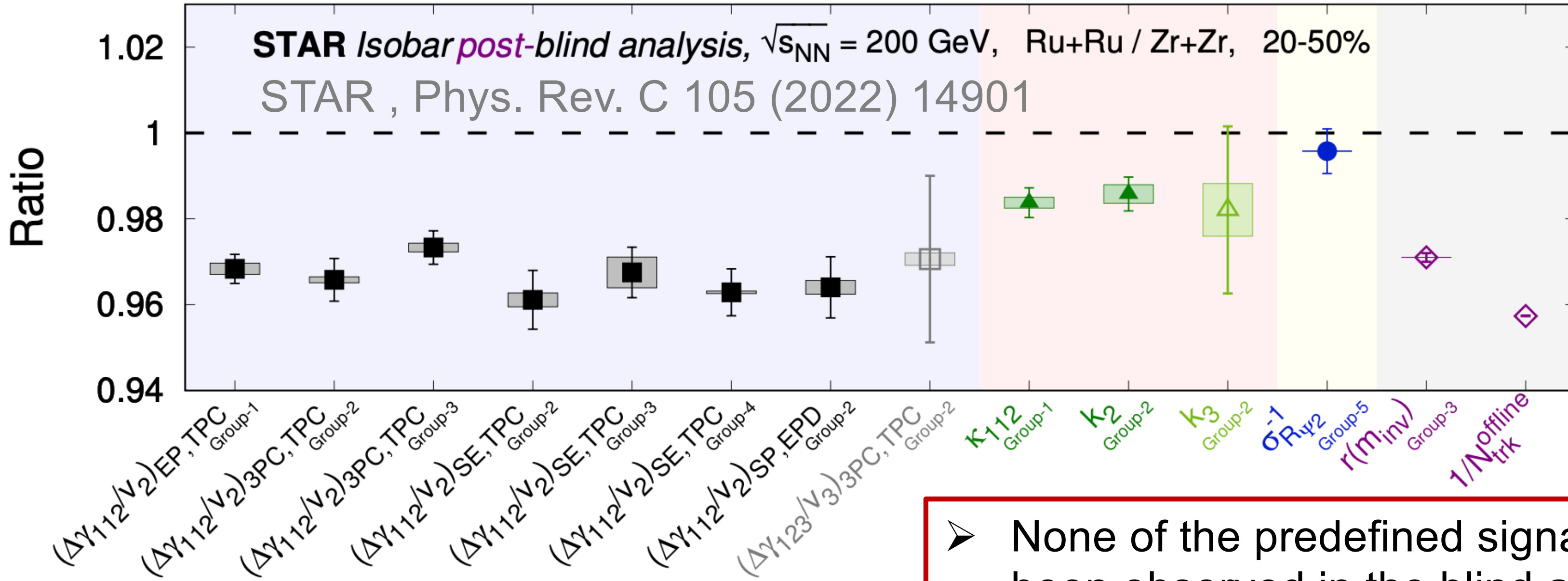


D. E. Kharzeev, J.F. Liao, Nature Rev.Phys. 3 (2021) 1, 55-63
S. Shi，H. Zhang, D. Hou, J.F. Liao, Phys. Rev. Lett. 125 (2020) 242301

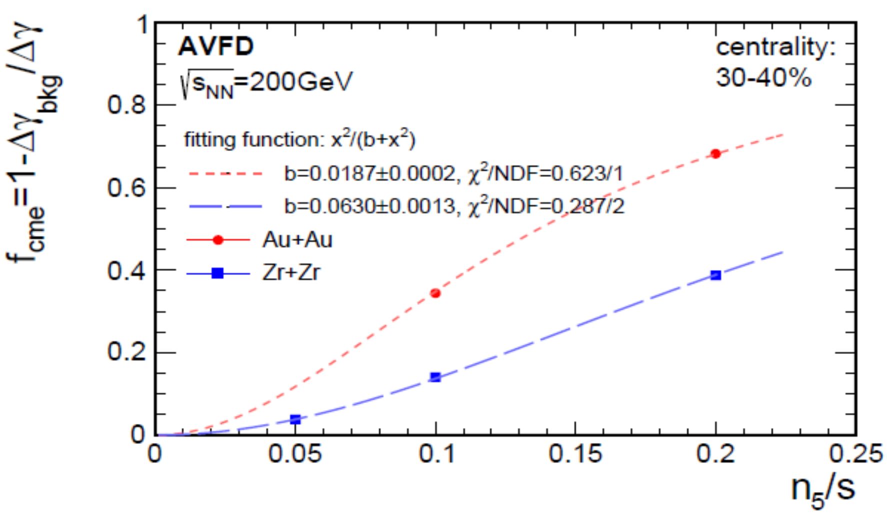
Isobars idea:

- ✓ **similar shape -> similar background,**
- ✓ **different Z -> different magnetic field -> change in CME signal**

CME in isobar collisions



- None of the predefined signatures have been observed in the blind analysis
- Blind analysis assumes background ~ v_2 only. Multiplicity, nonflow effect.



Y. Feng, F. Wang, etal., Phys. Lett. B 820, 136549 (2021)

Bkg. ~ 1/N ~ 1/A

$\Delta\gamma_{CME}$ ~ B^2 ~ $A^{2/3}$ (B. field ~ $A/A^{2/3}$ ~ $A^{1/3}$)

Background: isobar/AuAu ~ 2

Signal: AuAu/isobar ~ 1.5

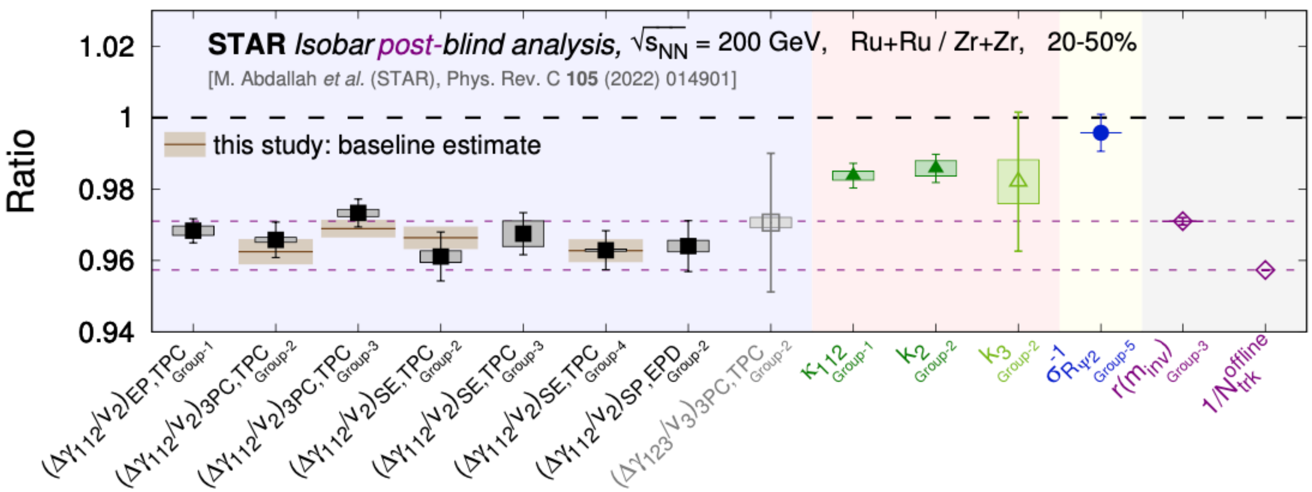
f_{cme} possibly a factor of ~3 reduction

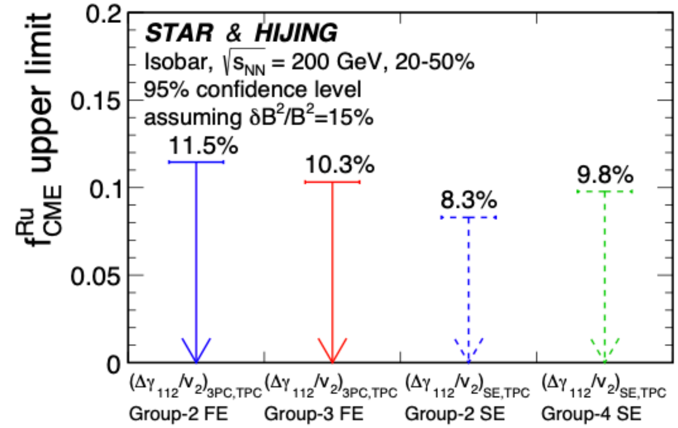
AVFD simulation: indicates smaller signal in isobar than Au+Au

Isobar background baseline

Y. Feng QM23

STAR, Phys. Rev. C 110, 014905 (2024)
STAR, Phys. Rev. R 6, L032005 (2024)





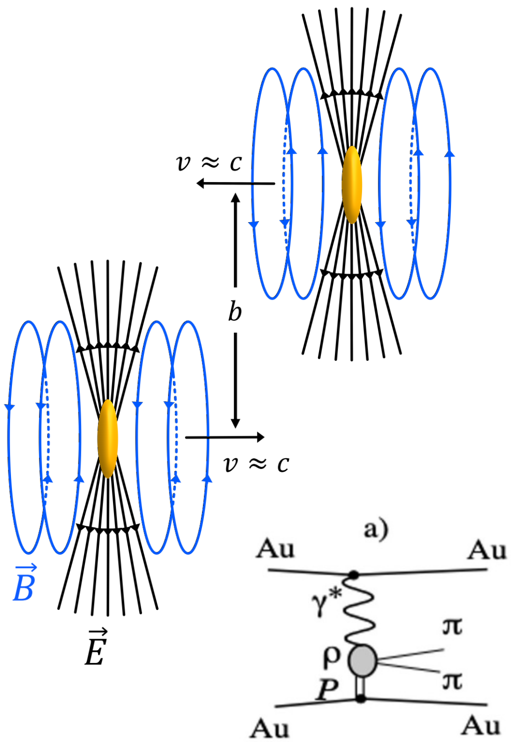
- Data are consistent with estimated baseline.
- CME fraction upper limit ~ 10% at 95% CL

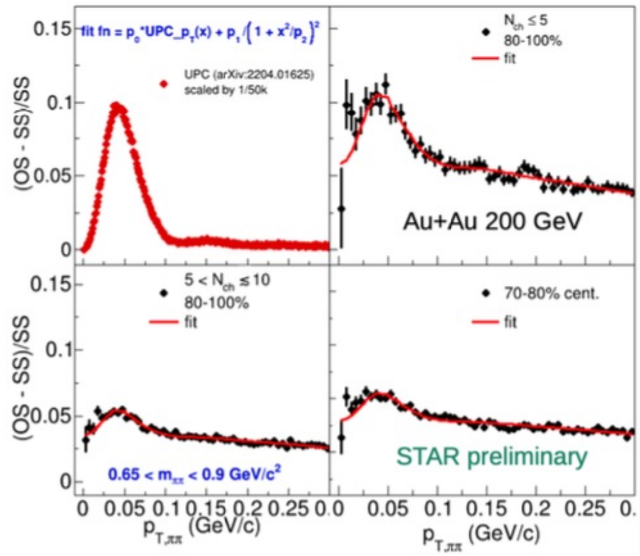
Rough estimate:
Data + baseline uncertainty ~ 0.7%
Assuming B_2 difference 15%
f_{cme} uncertainty ~ 0.7%/15% ~ 5% →
2σ upper limit ~ 10%

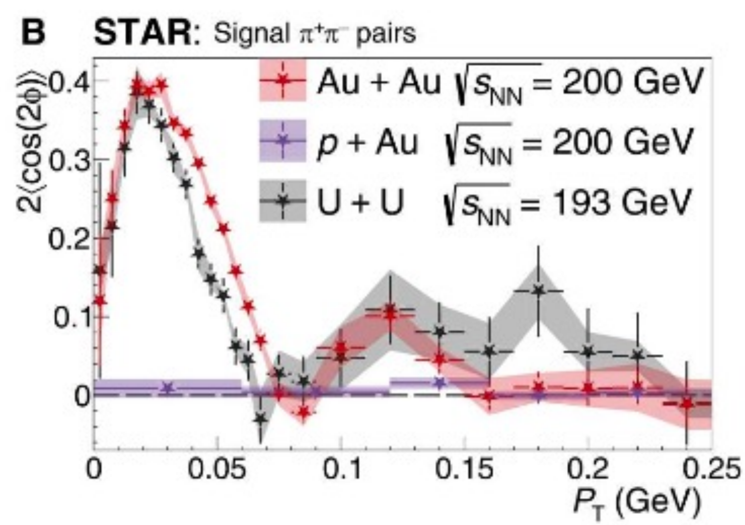
$$Y_{\rm bkgd} \equiv \frac{(\Delta\gamma_{\rm bkgd}/v_2^*)^{\rm Ru}}{(\Delta\gamma_{\rm bkgd}/v_2^*)^{\rm Zr}} \approx 1 + \frac{\delta(C_{\rm 2p}/N)}{C_{\rm 2p}/N} - \frac{\delta\epsilon_{\rm nf}}{1+\epsilon_{\rm nf}} + \frac{1}{1+\frac{Nv_2^2}{C_{\rm 3p}/C_{\rm 2p}}}\left(\frac{\delta C_{\rm 3p}}{C_{\rm 3p}} - \frac{\delta C_{\rm 2p}}{C_{\rm 2p}} - \frac{\delta N}{N} - \frac{\delta v_2^2}{v_2^2}\right)$$

photon-nuclear background

X. Wu, et al., Phys. Rev. Res. 4, L042048 (2022)







Isaac Upsal, DNP2022

STAR, Sci. Adv. 9, eabq3903 (2023) 4

Jing Gu, et al., Phys. Rev. C 113, 044914 (2026)

- photon-nuclear backgrounds ~ EM field, mimic CME
- different from the conventional flow background ~ v_2
- produce negative contribution to Δγ ~ - 0.2%
- distinct kinematic (nuclear size): p_T< 100 MeV, remove

Summary

- The Chiral Magnetic Effect (CME) is extremely important in QCD
- The possible CME signal ~5-10% of the early measurements, with 1-3σ significance, non-flow may still be present.
- RHIC 2023-2025, more Au+Au data