Overview of the Chiral Magnetic Effect (CME) and outlook to STAR high-statistical new data

– The 2^{nd} International Workshop on Physics at High Baryon Density (PHD2025)

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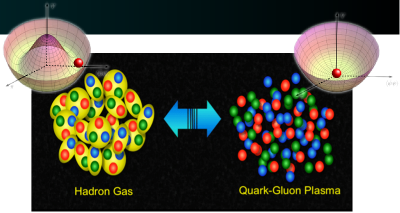
Y. Feng, S. A. Voloshin, and F. Wang, *Experimental search for the chiral magnetic effect in relativistic heavy-ion collisions: A perspective*, Phys. Rev. Res. **7**, no.3, 031001 (2025), arXiv:2502.09742 [nucl-ex]

Outline

Physics context



- QGP in heavy-ion collisions: quark mass negligible
  $\rightarrow$ **chiral symmetry restoration**
- **η-η' puzzle:** m_η(548 MeV) $< m_{\eta'}$(958 MeV) $\rightarrow$ not explainable with chiral symmetry. [Weinberg, *The U(1) problem*, PRD 11(1975)3583]
- **'t Hooft instanton mechanism** can resolve this puzzle
  ['t Hooft, PRL 37(1976)8], [Peccei, Lect. Notes Phys. 741(2008)3] $\rightarrow$ break the chiral symmetry, $\mathcal{P}$, and $\mathcal{CP}$.

$$\mathcal{L}_{\text{QCD}} = \sum_q \bar{\psi}_{q,a} \left(\underbrace{i\gamma^\mu \partial_\mu \delta_{ab} - m_q \delta_{ab}}_{\text{quark}} \underbrace{- g_s \gamma^\mu t^C_{ab} \mathcal{A}^C_\mu}_{\text{quark-gluon interaction}} \right) \psi_{q,b} \underbrace{- \frac{1}{4} G^A_{\mu\nu} G^{A,\mu\nu}}_{\text{gluon}} + \underbrace{\theta \frac{\alpha_s}{8\pi} G^A_{\mu\nu} \tilde{G}^{A,\mu\nu}}_{\text{'t Hooft vacuum}}$$

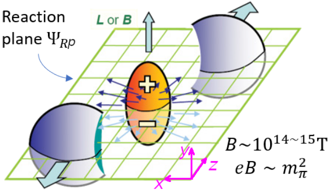
gluon: $\frac{1}{2}(E^2_A - B^2_A)$

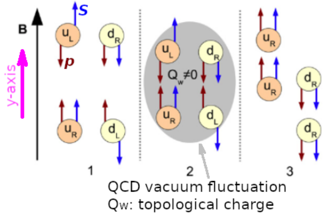
't Hooft vacuum: $-\theta \frac{\alpha_s}{2\pi} \vec{E}_A \cdot \vec{B}_A$

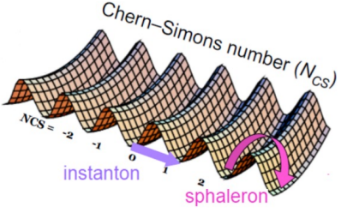
- low-energy experiments $\rightarrow$ θ upper limit $\sim 10^{-10}$
  [PDG, PTEP 083C01 (2022)], [Kim and Carosi, Rev.Mod.Phys.82(2010)557-602]
  $\rightarrow$ too small to explain the matter-antimatter asymmetry in the universe (**the strong $\mathcal{CP}$ problem**).

analogy to E&M field
$\vec{E}$: $\mathcal{C}$-odd, $\mathcal{P}$-odd, $\mathcal{T}$-even
$\vec{B}$: $\mathcal{C}$-odd, $\mathcal{P}$-even, $\mathcal{T}$-odd

- Is θ a constant? dependent on energy scale? larger value in early universe?
  Heavy-ion collisions approach the energy scale of early universe! $\rightarrow$ **check heavy-ion collisions!**







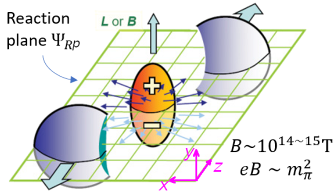
[Kharzeev *et al.*, PRL 81(1998)512; NPA 803(2008)227]

QCD vacuum fluctuation → nonzero topological charge → imbalanced chirality

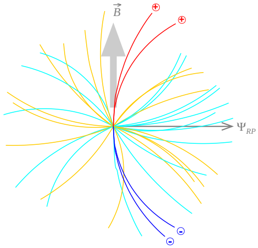
noncentral heavy-ion collisions → magnetic field $\vec{B}$ → opposite spins along $\vec{B}$ for $+/-$ charges

imbalanced chirality + opposite spins along $\vec{B}$ for $+/-$ charges → opposite momenta along $\vec{B}$ for $+/-$ charges, charge separation, CME azimuth Fourier series

$$\frac{\mathrm{d}N^{\pm}}{\mathrm{d}\phi^{\pm}} \propto 1 + 2a_1^{\pm}\sin(\phi^{\pm} - \Psi_{\mathrm{RP}}) + \sum_n 2v_n \cos n(\phi^{\pm} - \Psi_{\mathrm{RP}})$$



CME term $a_1^{\pm}$, in the same event $a_1 = a_1^{+} = -a_1^{-}$.
$\rightarrow$ random direction from event to event $\rightarrow$ $\langle a_1 \rangle$ vanishes



two particles α, β in the same event

$$\gamma_{\alpha\beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\mathrm{RP}}) \rangle,$$

Opposite-sign (OS) charged pair: γ_{OS}; same-sign (SS) γ_{SS}; their difference

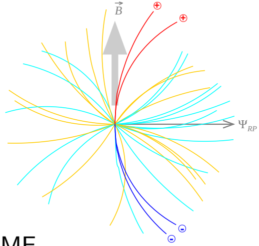
$$\Delta\gamma = \gamma_{\mathrm{OS}} - \gamma_{\mathrm{SS}}.$$

charge-independent backgrounds canceled (like momentum conservation)

[Voloshin, RPC 70(2004)057901]

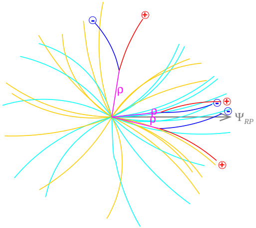
Signal and background in $\Delta\gamma$

signal

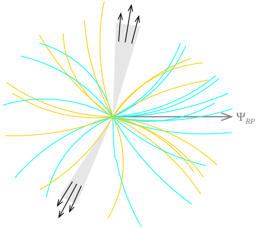


CME

backgrounds



resonance decay



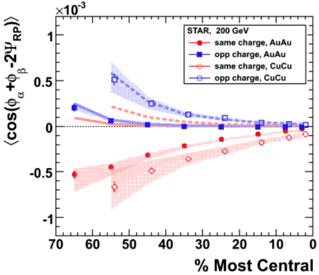
jets, di-jets

...

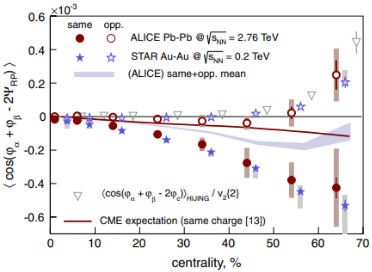
- 2-particle background like resonance decay (e.g., $\rho \to \pi^+\pi^-$), which is coupled with v_2.
  [Voloshin, RPC 70(2004)057901], [Wang, PRC 81(2010)064902], [Bzdak, Koch, Liao, PRC 81(2010)031901]
- In data analysis, RP is unknown, so the reconstructed event plane (EP) is used as a proxy.
  EP + 2 POIs $\to$ correlated triplets (jets, di-jets, ...) $\to$ background

Outline

The first measurements on $\Delta\gamma$



[STAR, PRL 103(2009)251601, PRC 81(2010)054908]



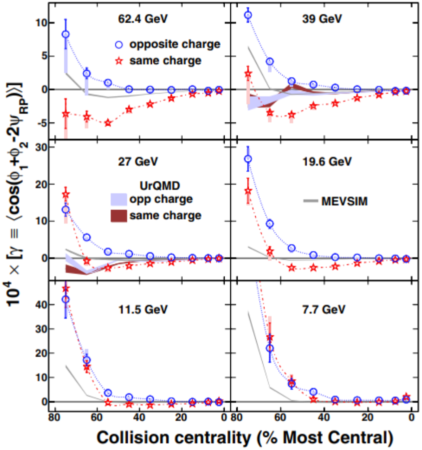
[ALICE, PRL 110(2013)012301]

← similar results, though very different energy, species

- $\gamma_{\rm OS} > 0, \gamma_{\rm SS} < 0 \to \Delta\gamma > 0$, qualitatively consistent with CME signal (?)
- background contribution not understood

  "Improved theoretical calculations of the expected signal and potential physics backgrounds ...are essential to understand whether or not the observed signal is due to [CME]." – [STAR, PRL 103(2009)251601]
- Follow-up calculations and simulations indicate that the backgrounds could be very significant

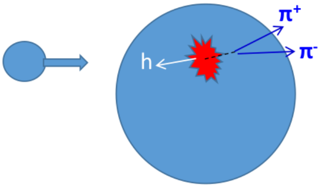
  [Wang, PRC 81(2010)064902] [Bzdak, Koch, Liao, PRC 81(2010)031901] [Schlichting, Pratt, PRC 83(2011)014913]

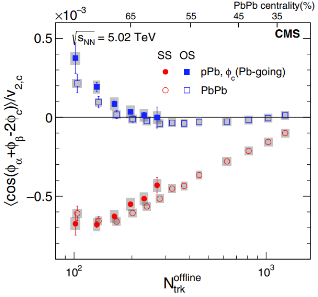


[STAR, PRL 113(2014)051302]

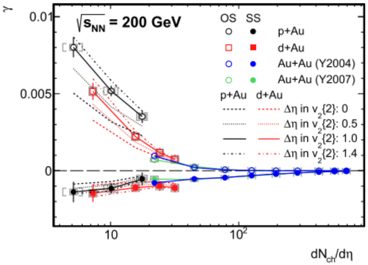
- STAR first beam energy scan (BES-I): Au+Au, $\sqrt{s_{\mathrm{NN}}} = 7.7 - 62.4$ GeV.
- *"weak energy dependence down to 19.6 GeV and then falls steeply at lower energies"* – [STAR, PRL 113(2014)051302]

Small system measurements





[CMS, PRL 118(2017)122301]

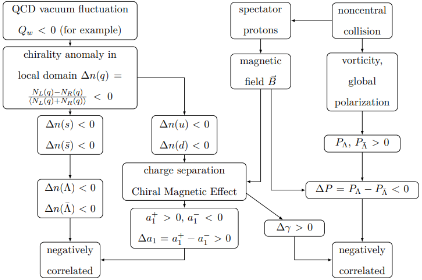


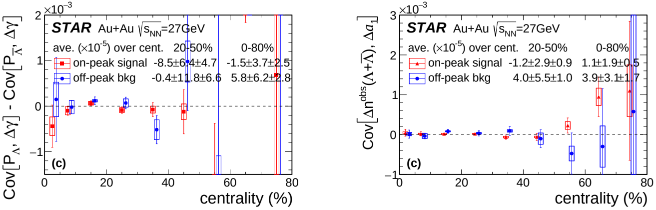
[STAR, PLB 798(2019)134975]

- Small system → random B and EP orientations → zero signal expected
- Similar results between small systems and A+A → large background

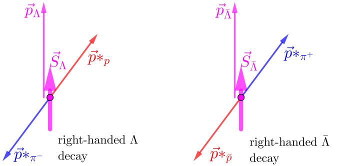
Outline

Correlation between CME observables with Λ measurements





[STAR, PRC 108(2023)014909] consistent with zero



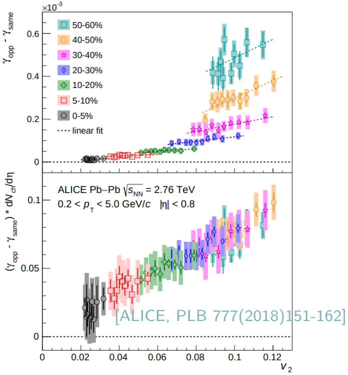
- magnetic field $\rightarrow \Lambda,\ \bar{\Lambda}$ polarization split $\rightarrow$ correlated with $\Delta\gamma$.
- topological charge fluctuation
  $\rightarrow$ CME sign (Δa_1) and Λ handedness $\rightarrow$ correlated
- The results are consistent with 0 within uncertainty.

Event shape methods

Event Shape Engineering (ESE):

q_2: different η ranges from $\Delta\gamma$, v_2

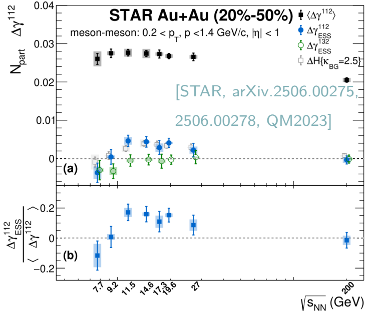
$$q_2^2 = \frac{(\sum \cos 2\phi)^2 + (\sum \sin 2\phi)^2}{N}$$



Event Shape Selection (ESS):

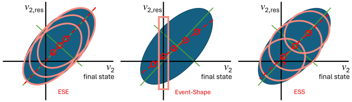
$q_{2,\text{pair}}$: same η range as $\Delta\gamma$, v_2

$$q_{2,\text{pair}}^2 = \frac{(\sum \cos 2\phi_{\text{pair}})^2 + (\sum \sin 2\phi_{\text{pair}})^2}{N_{\text{pair}}(1 + N_{\text{pair}}\langle v_2 \rangle)}$$



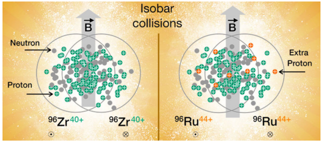
General idea:

- bin events by q_2 range
- calculate $\Delta\gamma$, v_2 for each bin
- map $\Delta\gamma$-v_2 $\rightarrow$ linear fit $\rightarrow$ intercept at $v_2 = 0$

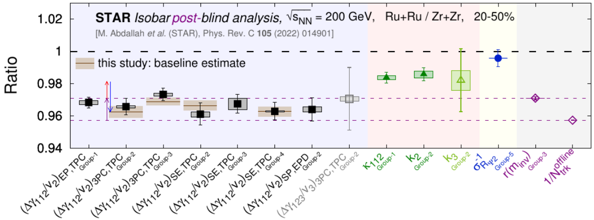


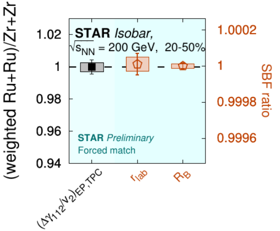
- STAR measurements w.r.t. SP (ZDC or inner EPD) can reduce nonflow backgrounds
- Event shape methods are designed to remove backgrounds coupled with flow.
- Underlying complications $\rightarrow$ better understanding needed [H. Li, *et al.*, arXiv.2407.14489, 2509.21297, QM2025]

The isobar experiment



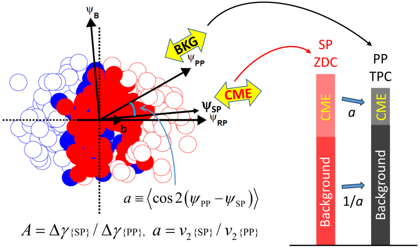
- **Initial expectation:** $^{96}_{44}$Ru, $^{96}_{40}$Zr: same A, different Z $\to$ same background, different signal
- Ru+Ru: proton number $\uparrow$ $\to$ magnetic field $\uparrow$ $\to$ CME signal $\uparrow$ $\to$ $\Delta\gamma/v_2$ $\uparrow$ $\to$ Ru/Zr > 1





- **STAR blind analysis** [STAR, PRC 105(2022)014901] $\to$ isobar ratios Ru/Zr < 1, opposite to the initial expectation $\leftarrow$ multiplicity diff. $\leftarrow$ nuclear structure [H. Xu *et al.*, PRL 121(2018)022301] .
- Nonflow background baseline estimate $\to$ CME upper limit 10% (95% CL) [STAR, PRC 110(2024)014905, PRR 6(2024)L032005, QM2023] . flow-induced backgrounds $\uparrow$ nonflow in v_2 $\uparrow$ 3-particle nonflow $\downarrow$
- Forced match method [STAR, QM2023] $\to$ consistent with unity
- Isobar signal/noise can be much smaller than Au+Au [Y. Feng, *et al.*, PLB 820(2021)136549]

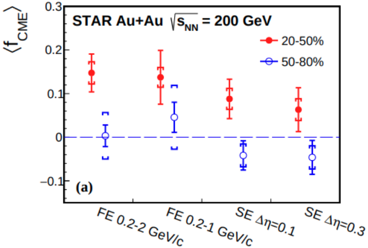
SP/PP comparison method → f_{CME}



$A = \Delta\gamma\{\mathrm{SP}\}/\Delta\gamma\{\mathrm{PP}\},\ a = v_2\{\mathrm{SP}\}/v_2\{\mathrm{PP}\}$

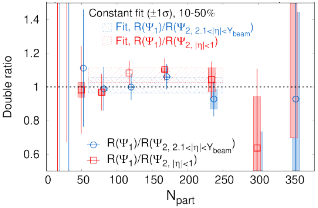
$f_{\mathrm{CME}}^{\mathrm{obs}} = \frac{\Delta\gamma_{\mathrm{CME}}\{\mathrm{PP}\}}{\Delta\gamma\{\mathrm{PP}\}} = \frac{A/a-1}{1/a^2-1}$

[H. Xu, *et al.*, CPC **42**(2018)084103]



Au+Au 200 GeV, TPC vs. ZDC, 2 ∼ 3σ

[STAR, PRL 128(2022)092301]



Au+Au 27 GeV, EPD, $< 1\sigma$

[STAR, PLB 839(2023)137779]

- 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)

f_{CME}: CME signal fraction in inclusive $\Delta\gamma$

residual background: nonflow

Nonflow contamination

[Y. Feng, *et al.*, PRC 105(2022)024913]

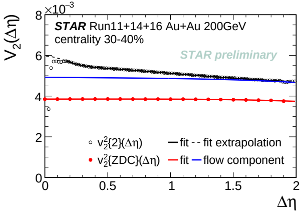
[New study in process]

$$f_{\rm CME} \equiv \frac{\Delta\gamma^{\rm PP}_{\rm CME}}{\Delta\gamma\{\rm TPC\}} = \frac{\sqrt{1+\epsilon_{\rm nf}}}{\frac{1}{a^2}-(1+\epsilon_{\rm nf})}\left[\left(\frac{A}{a}-1\right)+\epsilon_{\rm nf}\left(\frac{C_{\rm 3p}/V_{\rm 2p}}{(N_3C_3)/(N_2V_2)}-1\right)\right]$$

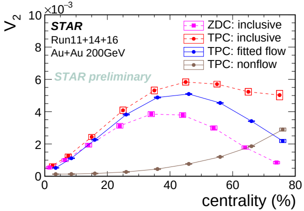
V_2 nonflow – estimated by a date-driven fit

- $v_2\{\textsc{zdc}\}(\eta)$ measurement $\rightarrow$ $V_2\{\textsc{zdc}\}(\Delta\eta)$ $\rightarrow$ fit flow shape
- Flow decorrelation $1-2F_2\Delta\eta$, $F_2 = 0.0115 \pm 50\%$ (syst.)
- Flow fluctuations effect: assumed constant over η
- Nonflow modelled by two Gaussians
- Fit flow + nonflow to $V_2(\Delta\eta)$ [Y. Feng, F. Wang, JPG 52(2025)013001]

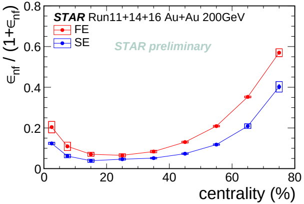
- measurement of v_2 w.r.t. TPC
  $V_2 \equiv \langle\cos 2(\phi_\alpha - \phi_\beta)\rangle = v_2^2\{2\}$
- nonflow fraction in V_2: $\frac{\epsilon_{\rm nf}}{1+\epsilon_{\rm nf}} \equiv \frac{V_2^{\rm nf}}{V_2}$
- measurements $a = v_2\{\textsc{zdc}\}/v_2\{2\}$,
  $A = \Delta\gamma\{\textsc{zdc}\}/\Delta\gamma\{\textsc{tpc}\}$



$V_2(\Delta\eta)$ fit



fitted flow and nonflow vs cent.



nonflow fraction in V_2

Nonflow contamination

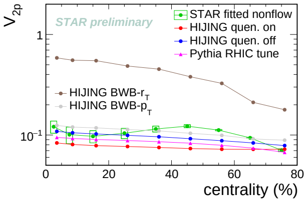
[Y. Feng, *et al.*, PRC 105(2022)024913]

[New study in process]

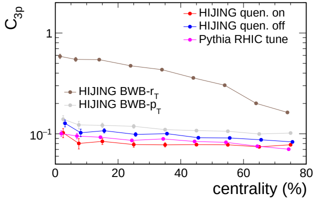
$$f_{\mathrm{CME}} \equiv \frac{\Delta\gamma^{\mathrm{PP}}_{\mathrm{CME}}}{\Delta\gamma\{\mathrm{TPC}\}} = \frac{\sqrt{1+\epsilon_{\mathrm{nf}}}}{\frac{1}{a^2}-(1+\epsilon_{\mathrm{nf}})}\left[\left(\frac{A}{a}-1\right)+\epsilon_{\mathrm{nf}}\left(\frac{C_{3\mathrm{p}}/V_{2\mathrm{p}}}{(N_3C_3)/(N_2V_2)}-1\right)\right]$$

RP-independent 3-particle correlations – model simulations

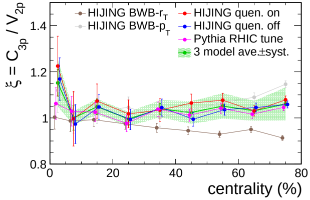
- 3-particle correlations primarily from (di-)jets
- for correlated triplets $C_{3\mathrm{p}} = \langle\cos(\phi_\alpha+\phi_\beta-2\phi_c)\rangle N_{3\mathrm{p}}/N$, for correlated pairs $V_{2\mathrm{p}} = \langle\cos 2(\phi_\alpha-\phi_\beta)\rangle N_{2\mathrm{p}}/N$
- Assume $\xi = C_{3\mathrm{p}}/V_{2\mathrm{p}}$ ratio in data = model. A ratio is more robust than individual 3p, 2p correlations.
- Various models (w/o flow) are consistent in terms of ξ:
  HIJING, HIJING w/o jet quenching, HIJING w/ blast wave boost along p_T, along r_T, Pythia 8
  $\rightarrow$ continuing to investigate systematics



nonflow in V_2



RP-ind. $C_{3\mathrm{p}}$ 3p nonflow



$\xi = C_{3\mathrm{p}}/V_{2\mathrm{p}}$

Nonflow contamination

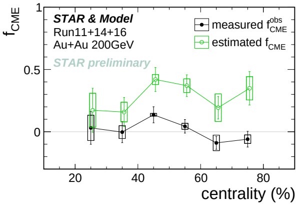
[Y. Feng, *et al.*, PRC 105(2022)024913]

[New study in process]

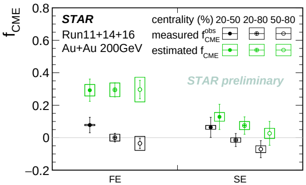
$$f_{\mathrm{CME}} \equiv \frac{\Delta\gamma^{\mathrm{PP}}_{\mathrm{CME}}}{\Delta\gamma\{\mathrm{TPC}\}} = \frac{\sqrt{1+\epsilon_{\mathrm{nf}}}}{\frac{1}{a^2}-(1+\epsilon_{\mathrm{nf}})}\left[\left(\frac{A}{a}-1\right)+\epsilon_{\mathrm{nf}}\left(\frac{C_{3\mathrm{p}}/V_{2\mathrm{p}}}{(N_3C_3)/(N_2V_2)}-1\right)\right]$$

f_{CME} after subtracting estimated nonflow

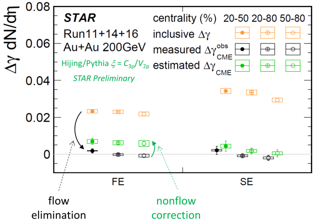
- Significant f_{CME} in full-event
- Weak centrality dependence
- f_{CME} full-event > sub-event; $\Delta\gamma_{\mathrm{CME}}$ (scaled by $\mathrm{d}N/\mathrm{d}\eta$) compatible in 20-50% centrality.



f_{CME} before/after correction



f_{CME} average values

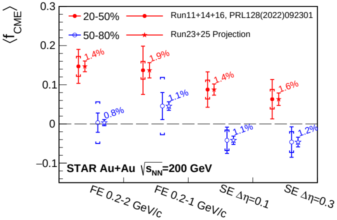


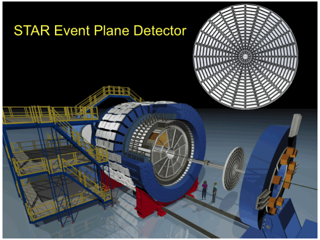
$\Delta\gamma_{\mathrm{CME}} = f_{\mathrm{CME}} * \Delta\gamma$

Outline

Outlook to STAR high-statistical new data

year	minimum bias [$\times 10^9$ events]
2014 2016	2
2023 2025	20





- STAR: $\times 10$ more statistics for Au+Au at 200 GeV in 2023-2025

$\rightarrow$ large reduce in statistical uncertainty

- newly-added detectors can help (e.g, EPD, iTPC, ...)

[STAR, *Beam Use Request for Run23-25*, tab 5]

Outline

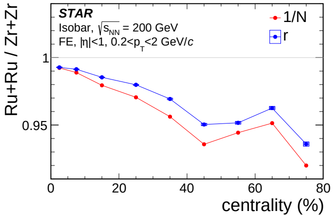
Summary

- CME – a fundamental physics in QCD
- Major background contamination
- Novel methods to extract CME
  - Isobar experiments
  - Event shape methods
  - Correlation measurement between CME and Λ polarization
  - SP/PP methods (TPC, ZDC, EPD)
  - Nonflow estimate [New study in process]
- STAR new data: Au+Au $\sqrt{s_{\mathrm{NN}}} = 200$ GeV $\rightarrow$ $\times 10$ more statistics new EPD, iTPC $\rightarrow$ with wider acceptance

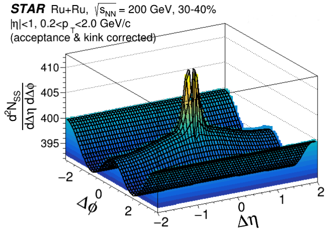
Backup

The isobar experiment – nonflow background baseline estimate

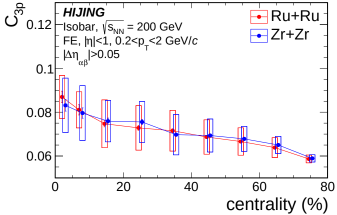
flow-induced backgrounds:
resonance decays → estimated by pair excess $r = \frac{N_{\rm OS} - N_{\rm SS}}{N_{\rm OS}}$

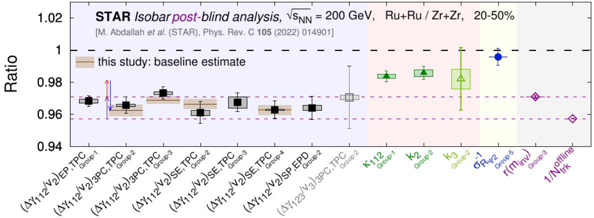


nonflow in v_2 measurement:
fit two-particle $(\Delta\eta, \Delta\phi)$ 2D distribution to decompose



3-particle nonflow:
HIJING model → no flow → solely 3p nonflow bkg

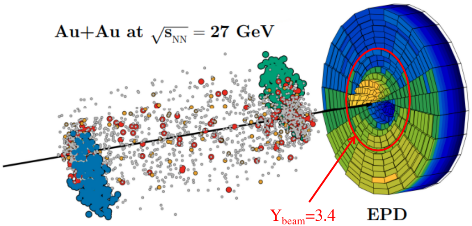




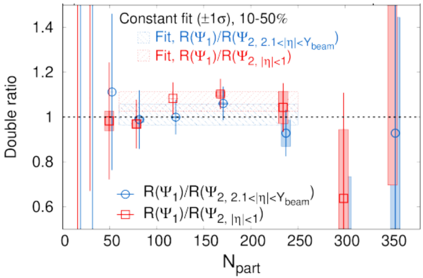
- **Post-blind:** nonflow background baseline estimate → CME upper limit 10% (95% CL)

  [STAR, PRC 110(2024)014905, PRR 6(2024)L032005]

SP/PP comparison method



[STAR, PLB 839(2023)137779]



← consistent with unity

- Notation $R(\Psi) = \Delta\gamma(\Psi)/v_2(\Psi)$
- low energy 27 GeV → beam rapidity $Y_{\text{beam}} = 3.4$ → EPD $(2.1 < |\eta| < 5.1)$ divided into 2 parts
  - inner EPD $3.4 < |\eta| < 5.1$ → estimate SP
  - outer EPD $2.1 < |\eta| < 3.4$ → estimate PP (blue markers)
- TPC $(|\eta| < 1)$ is also used for PP (red markers)