

Searches for the chiral magnetic effect at the STAR experiment

International Symposium on Spin Polarization in Relativistic Heavy Ion Collisions 2026, Hefei, China

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Introduction

Early experimental approaches

Recent experimental approaches

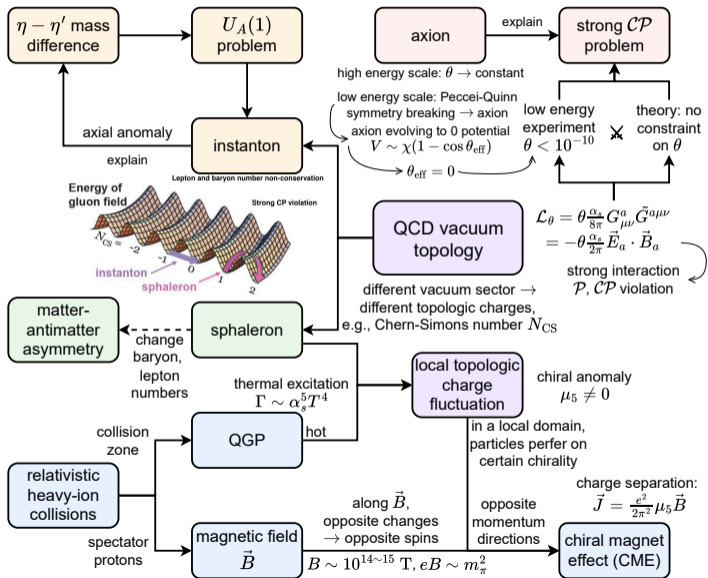
SP/PP comparison method and nonflow estimate

Outlook

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Physics context



$$m_\eta (548 \text{ MeV}) < m_{\eta'} (958 \text{ MeV}) \rightarrow U_A(1) \text{ problem}$$

[Weinberg, PRD 11(1975)3583]

't Hooft vacuum

[t Hooft, PRL 37(1976)8]

QCD vacuum topological sectors \leftrightarrow the topological charge N_{CS} transitions between them via:

- instanton: quantum tunneling
- sphaleron: thermal excitation

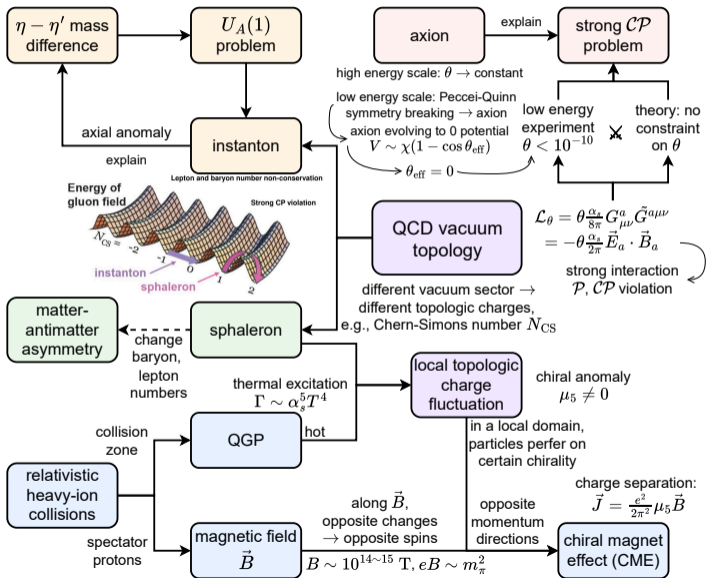
sphaleron

\rightarrow matter-antimatter asymmetry

Strong CP problem

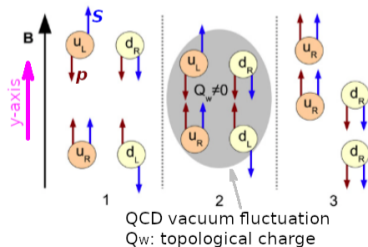
- Theory didn't constraint θ value.
- Neutron electric dipole moment (nEDM) measurement $\theta < 10^{-10}$

Physics context



CME, chiral magnetic effect
 vacuum topological fluctuations
 + external strong magnetic field
 \rightarrow charge separation observable

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



Commonly-used observable: azimuthal correlator $\Delta\gamma$

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

CME term a_1^\pm

- in the same event $a_1 = a_1^+ = -a_1^-$.
- fluctuation randomly from event to event $\rightarrow \langle a_1 \rangle$ vanishes

two particles α, β in the same event

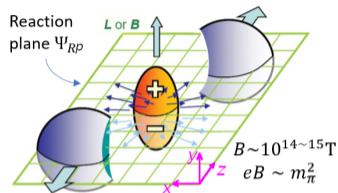
$$\gamma_{\alpha\beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle,$$

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

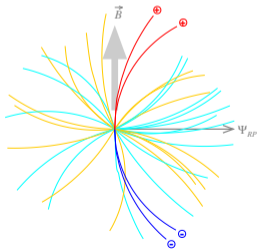
$$\Delta\gamma = \gamma_{OS} - \gamma_{SS}.$$

charge-independent backgrounds canceled
(like momentum conservation)

[Voloshin, RPC 70(2004)057901]

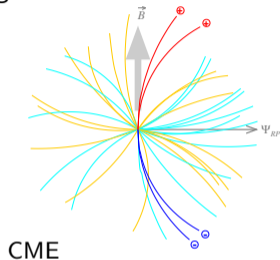


Ψ_{RP} reaction plane (RP)
direction
 v_n flow coefficient

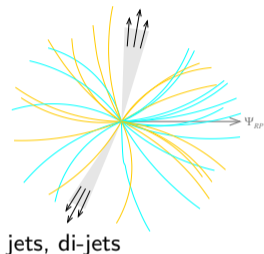
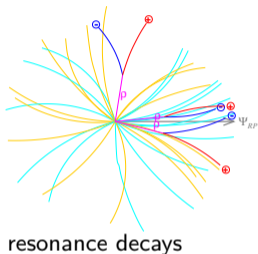


Signal and background in $\Delta\gamma$

Signal



Backgrounds



.....

- 2-particle background like resonance decay (e.g., $\rho \rightarrow \pi^+ \pi^-$), 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 \rightarrow correlated triplets (jets, di-jets, ...) \rightarrow background

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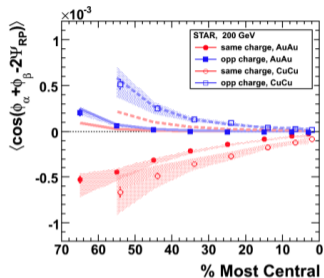
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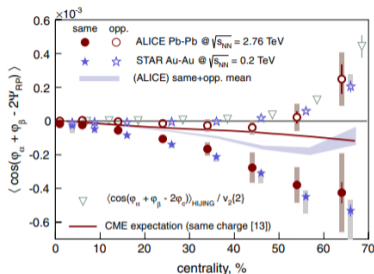
Summary



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

- $\gamma_{os} > 0, \gamma_{ss} < 0 \rightarrow \Delta\gamma > 0$, qualitatively consistent with CME signal (?)
- background contribution not understood

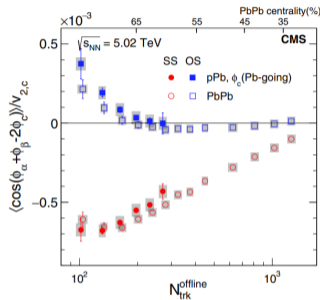
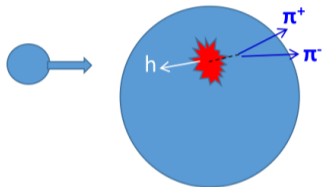
"Improved theoretical calculations of the expected signal and potential physics backgrounds ...are essential to understand whether or not the observed signal is due to [CME]."

– [STAR, PRL 103(2009)251601]

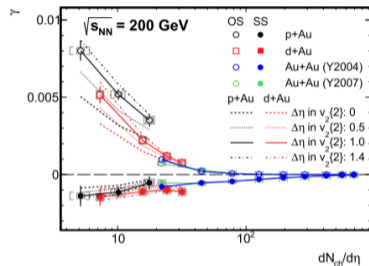
- Follow-up calculations and simulations indicate that the backgrounds could be very significant

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

Small system measurements



[CMS, PRL 118(2017)122301]



[STAR, PLB 798(2019)134975]

- Small system (p/d+Au/Pb, ...) \rightarrow random B and EP orientations \rightarrow zero signal expected
- Similar results between small systems and A+A \rightarrow large background

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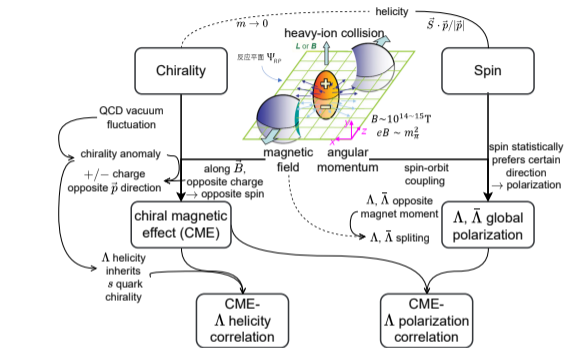
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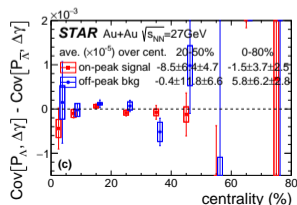
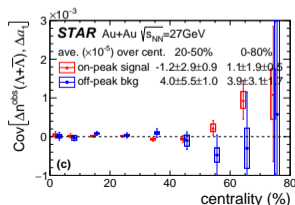
Summary



Correlation between CME and Λ polarizations



- magnetic field
→ Λ , $\bar{\Lambda}$ global polarization splitting
→ correlated to CME
- chiral anomaly → Λ helicity
→ correlated to CME
- STAR measurements consistent to 0 within uncertainties
(Run18 Au+Au $\sqrt{s_{NN}} = 27 \text{ GeV}$)



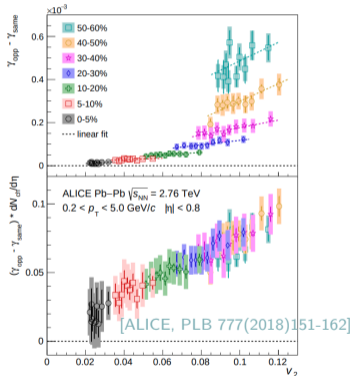
[STAR, PRC 108(2023)014909]

Event shape method

Event Shape Engineering (ESE):

q_2 (event shape): different η range from observables $\Delta\gamma$, v_2

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



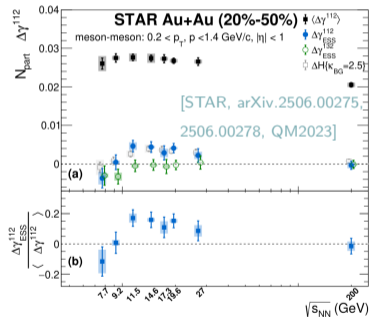
- Event shape method \rightarrow intercept at $v_2 = 0 \rightarrow$ reduce flow background
- Underlying complication \rightarrow needs further understanding

[H. Li, *et al.*, PRC 112(2025)054901, arXiv:2509.21297, QM2025]

Event Shape Selection (ESS):

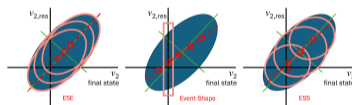
$q_{2,\text{pair}}$ (event shape): same η range as observables $\Delta\gamma$, v_2

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



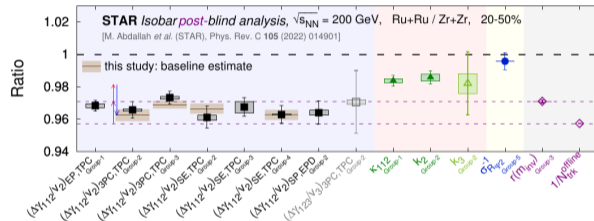
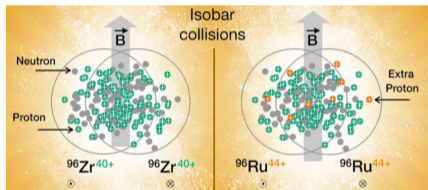
General idea:

- categorize events by event shape q_2 ($q_{2,\text{pair}}$) ranges
- in each category, calculate observables $\Delta\gamma$, v_2
- linear fit $\Delta\gamma$ - v_2
 \rightarrow intercept at $v_2 = 0$



Isobar experiment

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



- STAR blind analysis $\rightarrow \text{Ru/Zr} < 1 \leftarrow$ multiplicity difference \leftarrow nuclear structure
[STAR, PRC 105(2022)014901] [H. Xu et al., PRL 121(2018)022301]
- nonflow background baseline \rightarrow CME upper limit 10% (95% CL) [STAR, PRC 110(2024)014905, PRR 6(2024)L032005, QM2023]. flow background \uparrow nonflow in v_2 measurement \uparrow 3p nonflow \downarrow

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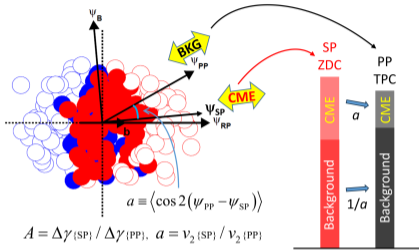
SP/PP comparison method and nonflow estimate

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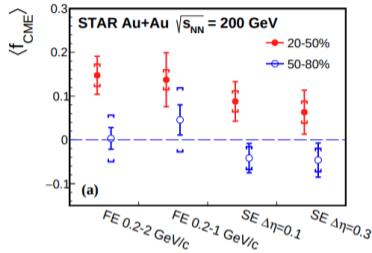
Spectator plane (SP), participant plane (PP) comparison $\rightarrow f_{\text{CME}}$



$$A = \Delta\gamma_{\text{SP}} / \Delta\gamma_{\text{PP}}, \quad a = v_2\{\text{SP}\} / v_2\{\text{PP}\}$$

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

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



Au+Au 200 GeV, TPC vs. ZDC, 2.9σ

[STAR, PRL 128(2022)092301]

$\Delta\gamma$ "signal fraction"

$$f_{\text{CME}}^{\text{obs}} = \frac{\Delta\gamma_{\text{CME}}\{\text{PP}\}}{\Delta\gamma\{\text{PP}\}} = \frac{(\Delta\gamma/v_2)_{\text{SP}} - 1}{\frac{v_2^2\{\text{PP}\}}{v_2^2\{\text{SP}\}} - 1}$$

SP/PP projection coeff.

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

- Participant plane (PP) ← collided nucleons → collective flow → flow background
- Spectator plane (SP) ← spectator protons → magnetic field → CME signal
- Signal and flow background respond two planes differently → comparing SP and PP → remove flow background

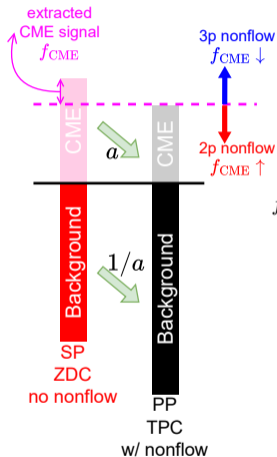
residue background: nonflow

Decomposition of nonflow backgrounds

[STAR, PRL 128(2022)092301]

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

[New study in process]



direct measurement

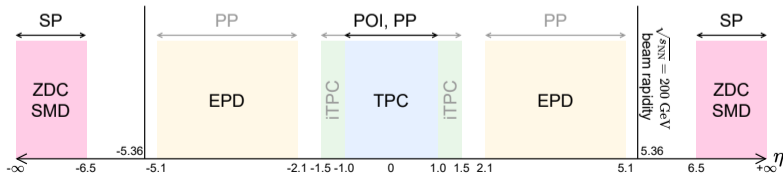
$$f_{CME}^{obs} = \frac{\Delta\gamma_{CME}\{TPC\}}{\Delta\gamma\{TPC\}} = \frac{(\Delta\gamma/v_2)_{ZDC} - 1}{\frac{v_2^2\{TPC\}}{v_2^2\{ZDC\}} - 1}$$

nonflow background

$$f_{CME} \equiv \frac{\Delta\gamma_{CME}\{PP\}}{\Delta\gamma\{PP\}} = \frac{\sqrt{1 + \epsilon_{nf}}}{\frac{v_2^2\{TPC\}}{v_2^2\{ZDC\}} - (1 + \epsilon_{nf})} \left[\frac{(\Delta\gamma/v_2)_{ZDC}}{(\Delta\gamma/v_2)_{TPC}} - 1 + \epsilon_{nf} \left(\frac{C_{3p}/V_{2p}}{(N_3 C_3)/(N_2 V_2)} - 1 \right) \right]$$

ZDC/TPC ratio

$N\Delta\gamma/v_2$ measurement

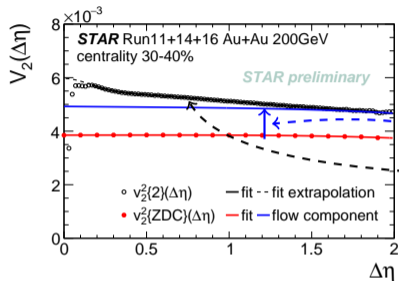


Nonflow in V_2 measurement (2p nonflow)

[STAR, PRL 128(2022)092301]

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

[New study in process]



• $v_2\{\text{ZDC}\}(\eta)$ measurement $\rightarrow V_2\{\text{ZDC}\}(\Delta\eta) \rightarrow$ fit flow shape

• event plane decorrelation $1 - 2F_2\Delta\eta$

• flow fluctuations, assumed independent from η

• double Gaussian fits to nonflow

• fit $V_2(\Delta\eta)$ to separate flow and nonflow

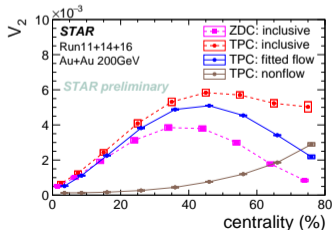
[Y. Feng, F. Wang, JPG 52(2025)013001]

• 2p correlation for TPC flow

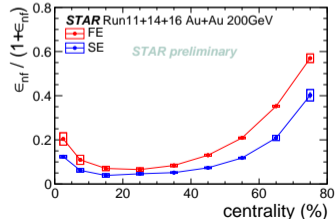
$$V_2 \equiv \langle \cos 2(\phi_\alpha - \phi_\beta) \rangle = v_2^2\{2\}$$

• nonflow fraction in V_2 measure

$$\frac{\epsilon_{\text{nf}}}{1 + \epsilon_{\text{nf}}} \equiv \frac{V_2^{\text{nf}}}{V_2}$$

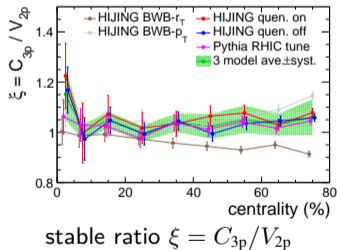
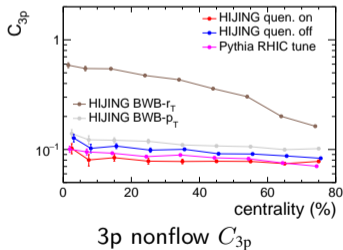
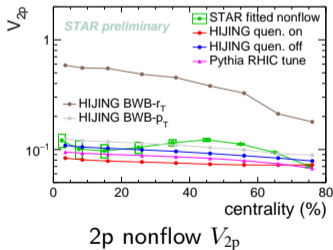


fit results in each centrality bin



nonflow fraction in V_2

- correlated triplets (jets, di-jets)
- models (no flow) \rightarrow 3p/2p nonflow ratio $\xi = C_{3p}/V_{2p}$ stable
HIJING, HIJING w/o jet quenching, HIJING w/ blast wave boost along p_T , along r_T , Pythia 8
- assume data also follow model $\xi \rightarrow$ estimate 3p nonflow in data

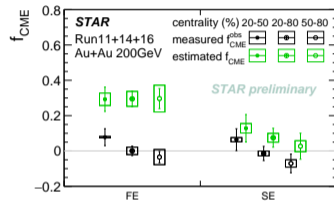
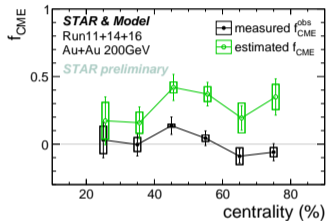
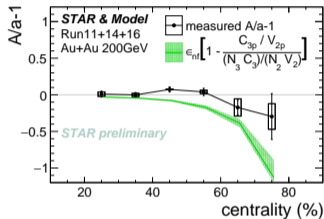


f_{CME} after subtracting estimated nonflow

[STAR, PRL 128(2022)092301]

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

[New study in process]



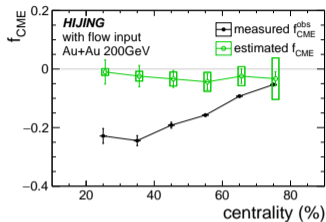
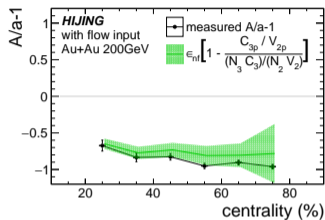
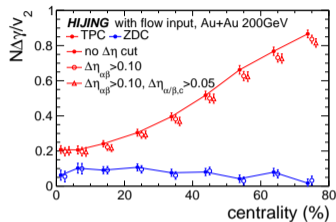
$$\frac{(\Delta\gamma/v_2)_{\text{ZDC}}}{(\Delta\gamma/v_2)_{\text{TPC}}} - 1 \text{ and bkg estimate}$$

f_{CME} after correction

f_{CME} centrality averages

- f_{CME} becomes larger after correction
- systematic uncertainty includes different variations: data cuts, fit function, model dependence

HIJING simulation to test this method



before correction $f_{CME}^{obs} < 0 \rightarrow$ negative bkg
 after correction $f_{CME} \sim 0 \rightarrow$ method valid

- No CME signal in model
- PP fluctuates around RP event by event, simulated using Gaussian distribution
- re-weight each track by elliptic flow $v_2 = 0.05p_T$ ($p_T < 2$ GeV/c), $v_2 = 0.1$ ($p_T \geq 2$ GeV/c)
- default HIJING (no flow) \rightarrow estimate nonflow

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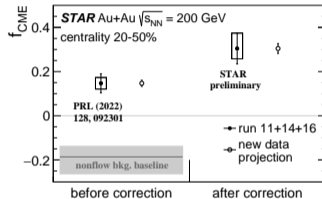


STAR high-statistics new data

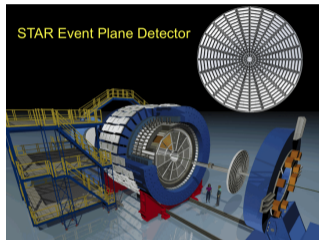
year	minimum bias [$\times 10^9$ events]
2014	2
2016	
2023	20
2025	

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

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



→ big reduce in statistical uncertainty



- new detectors improve acceptance, event plane resolution (e.g. EPD, iTPC, ...)

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- Background contamination is the major challenge in experimental searches for CME.
Many methods have been tried to mitigate background.
- Our recent study looked into backgrounds in Au+Au $\sqrt{s_{NN}} = 200$ GeV
 - **flow background** \leftarrow SP/PP comparison method
 - **2p nonflow** \leftarrow fit $\Delta\eta$ dependence, separate flow and nonflow in v_2 measurement
 - **3p nonflow** \leftarrow assumed proportional to 2p nonflow—weak dependence on models, radial flow, and centrality
- STAR new data: Au+Au $\sqrt{s_{NN}} = 200$ GeV \rightarrow $\times 10$ statistics; new detectors EPD, iTPC \rightarrow larger acceptance, resolution

