Isolating charge separation in Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV in search of the chiral magnetic effect via comprehensive background subtraction

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Outline

Introduction

Flow background: SP/PP comparison method

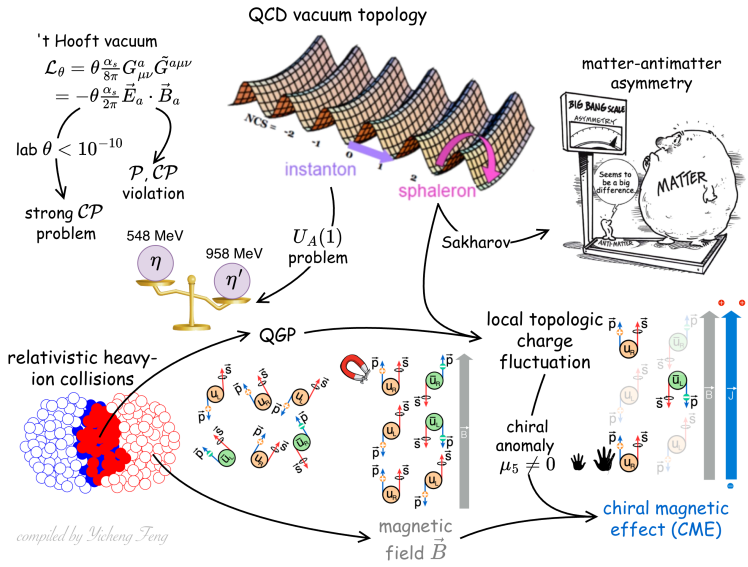
Nonflow background

- Fit decomposition (2p) + model estimation (3p)
- Small system scaling method
- Results and comparisons

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Physics context of the chiral magnetic effect (CME)



$m_\eta < m_{\eta'} \to U_A(1)$ **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}

Strong $\mathcal{CP}$ problem

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

CME, **chiral magnetic effect**

vacuum topological fluctuations + external strong magnetic field $\to$ charge separation observable

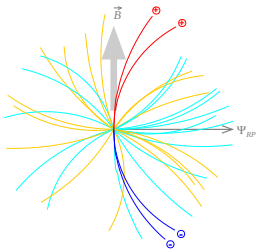
[Kharzeev *et al.*, PRL 81(1998)512; NPA 803(2008)227]

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

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

CME term $a_1^{\pm}$

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



two particles α, β in the same event

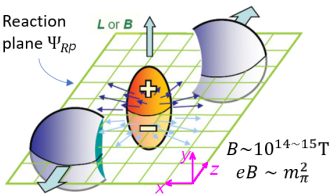
$$\gamma_{\alpha\beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\mathrm{RP}}) \rangle,$$

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)

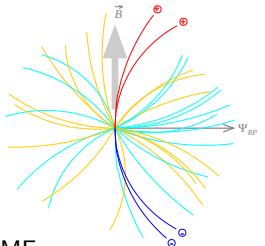
[Voloshin, PRC 70(2004)057901]



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

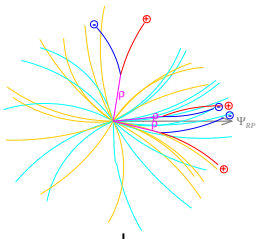
Signal and background in $\Delta\gamma$

Signal

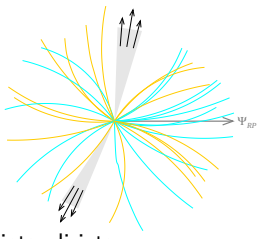


CME

Backgrounds



resonance decays



jets, di-jets

... ...

- 2-particle background like resonance decay (e.g., $\rho \to \pi^+\pi^-$), which is coupled with v_2.
  [Voloshin, PRC 70(2004)057901], [Wang, PRC 81(2010)064902], [Bzdak, Koch, Liao, PRC 81(2010)031901]
- In experiments, the RP cannot be measured $\to$ reconstructed event plane (EP) as a proxy.
  EP + 2 POIs $\to$ correlated triplets (jets, di-jets, ...) $\to$ background

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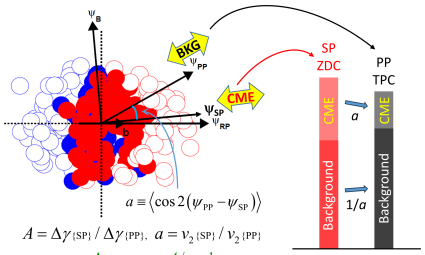
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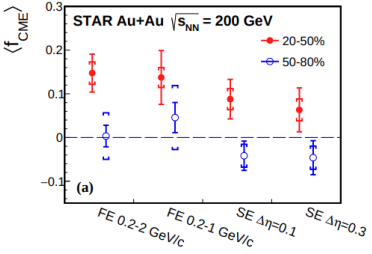
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Flow background removal—SP/PP comparison $\rightarrow f_{\rm CME}^{\rm obs}$



[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"

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

SP/PP projection coeff.

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

- Participant plane (PP) $\leftarrow$ collided nucleons $\rightarrow$ collective flow $\rightarrow$ flow background
- Spectator plane (SP) $\leftarrow$ spectator protons $\rightarrow$ magnetic field $\rightarrow$ CME signal
- The signal and flow background project differently onto the two planes $\rightarrow$ comparing SP and PP $\rightarrow$ remove flow background

residual background: nonflow

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Nonflow backgrounds in the TPC $\Delta\gamma$ measurement

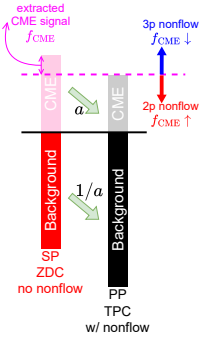
$(\Delta\gamma/v_2)_{\rm TPC} = \dfrac{\Delta C_3}{V_2} = \dfrac{\langle\cos(\phi_\alpha+\phi_\beta-2\phi_c)\rangle_{\rm OS-SS}}{v_2^2\{2\}}$ contains nonflow effects:

$$\frac{\Delta\gamma^{\rm PP}}{\sqrt{\langle(v_2^{\rm PP})^2\rangle}} = \frac{\Delta C_3 - \Delta C_3^{\rm nf}}{V_2 - V_2^{\rm nf}} = \frac{\Delta C_3}{V_2}\left(1-\frac{\Delta C_3^{\rm nf}}{\Delta C_3}\right)(1+\epsilon_{\rm nf})$$

nonflow in $v_2^2\{2\}$ measurement: $\left\langle\left(v_2^{\rm PP}\right)^2\right\rangle = V_2 - V_2^{\rm nf}, \quad \epsilon_{\rm nf} \equiv \dfrac{V_2^{\rm nf}}{V_2 - V_2^{\rm nf}}$

flow fluctuation $\left\langle v_2^{\rm PP}\right\rangle^2 \approx \dfrac{1}{2}\left(v_2^2\{2\} - V_2^{\rm nf} + v_2^2\{4\}\right)$

correlated triplets contributions: $\dfrac{\xi_{\rm nf}}{\xi_{\rm inc}} = \dfrac{\Delta C_3^{\rm nf}/V_2^{\rm nf}}{\Delta C_3/V_2}$

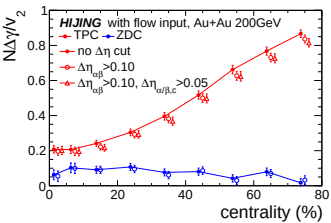


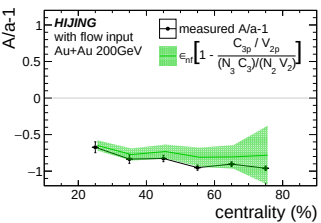
$$f_{\rm CME} = \frac{\left[\dfrac{(\Delta\gamma/v_2)_{\rm ZDC}}{(\Delta\gamma/v_2)_{\rm TPC}} - 1\right] + \epsilon_{\rm nf}\left(\dfrac{\xi_{\rm nf}}{\xi_{\rm inc}} - 1\right)}{\dfrac{v_2\{\rm TPC\}}{v_2^2\{\rm ZDC\}}\sqrt{\dfrac{1}{2}\left(\dfrac{v_2^2\{2\}}{1+\epsilon_{\rm nf}} + v_2^2\{4\}\right)} - \sqrt{1+\epsilon_{\rm nf}}}$$

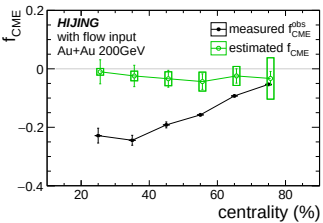
- direct measurements
- $\epsilon_{\rm nf}$: 2p nonflow in $v_2\{2\}$
- $\xi_{\rm nf}$: RP-independent 3p correlations

Then: how to get $\epsilon_{\rm nf}$ and $\xi_{\rm nf}$?

HIJING simulation to test this methodology







before correction $f_{\mathrm{CME}}^{\mathrm{obs}} < 0 \rightarrow$ negative bkg
after correction $f_{\mathrm{CME}} \sim 0 \rightarrow$ 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 $v_2 = 0.05 p_T$ ($p_T < 2$ GeV/c), $v_2 = 0.1$ ($p_T \geq 2$ GeV/c)
- default HIJING (no flow) $\rightarrow$ estimate nonflow

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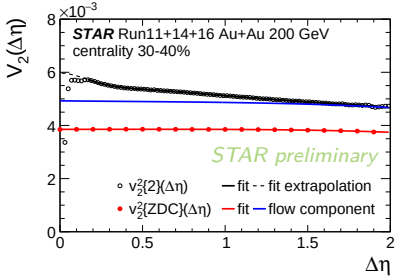
Summary

2p nonflow: fit decomposition of V_2 measurement

[STAR, PRL 128(2022)092301]

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

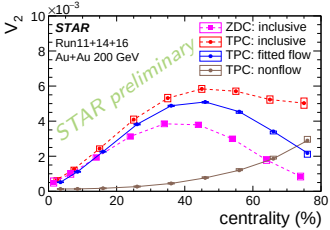
[this analysis]



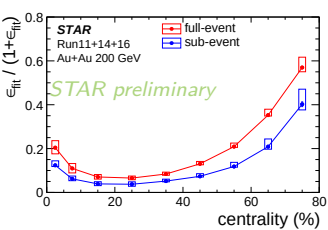
- $v_2\{\mathrm{ZDC}\}(\eta)$ measurement $\rightarrow V_2\{\mathrm{ZDC}\}(\Delta\eta) \rightarrow$ fit flow shape
- event plane decorrelation $1 - 2F_2\Delta\eta$
- flow fluctuations, assumed independent of η
- double Gaussian fits to nonflow
- fit $V_2(\Delta\eta)$ to separate flow and nonflow

  [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 the V_2 measurement $\frac{\epsilon_{\mathrm{nf}}}{1+\epsilon_{\mathrm{nf}}} \equiv \frac{V_2^{\mathrm{nf}}}{V_2}$



fit results in each centrality bin



nonflow fraction in V_2

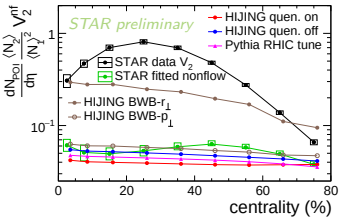
3p nonflow: model simulations for $\xi_{\rm nf}$

[STAR, PRL 128(2022)092301]

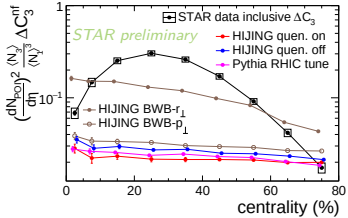
[Y. Feng, *et al.*, PRC 105(2022)024913]

[this analysis]

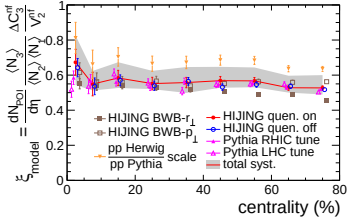
- correlated triplets (jets, di-jets) $\rightarrow$ RP-independent 3p correlations
- individual $V_2^{\rm nf}$, $\Delta C_3^{\rm nf}$ are model dependent,
  but their ratio $\xi_{\rm nf}$ is relatively stable across the tested models and tunes:
  HIJING quen. on, quen. off, + BWB radial flow, PYTHIA8 RHIC/LHC tunes, HERWIG
- assume data follow the model $\xi_{\rm nf}$ $\rightarrow$ estimate 3p nonflow in data



2p nonflow $V_2^{\rm nf}$



3p nonflow $\Delta C_3^{\rm nf}$



stable 3p/2p ratio across models

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Small-system scaling: the superimposition method

Assumption: an Au+Au collision is a superimposition of n_{sm} zero-bias small-system collisions,

$$n_{\text{sm}} = \frac{\langle N_1 \rangle_{\text{AA}}}{\langle N_1 \rangle_{\text{sm}}} = \frac{(\frac{\mathrm{d}N_{\text{POI}}}{\mathrm{d}\eta})_{\text{AA}}}{(\frac{\mathrm{d}N_{\text{POI}}}{\mathrm{d}\eta})_{\text{sm}}}$$

nonflow does not change shape or magnitude, and scales with multiplicity:

$$V_2^{\text{nf}} \propto \frac{(\frac{\mathrm{d}N_{\text{POI}}}{\mathrm{d}\eta})_{\text{sm}}}{(\frac{\mathrm{d}N_{\text{POI}}}{\mathrm{d}\eta})_{\text{AA}}} V_{2,\text{sm}} \,, \qquad \Delta C_3^{\text{nf}} \propto \frac{(\frac{\mathrm{d}N_{\text{POI}}}{\mathrm{d}\eta})^2_{\text{sm}}}{(\frac{\mathrm{d}N_{\text{POI}}}{\mathrm{d}\eta})^2_{\text{AA}}} \Delta C_{3,\text{sm}}$$

The scaling relations need to include multiplicity-fluctuation corrections

with the Au+Au V_2 and ΔC_3:

$$\varepsilon_{\text{sm}} = \frac{V_2^{\text{nf}}}{V_2 - V_2^{\text{nf}}}, \qquad \xi_{\text{sm}} = \left(\frac{\mathrm{d}N_{\text{POI}}}{\mathrm{d}\eta} \frac{\langle N_3 \rangle}{\langle N_1 \rangle^3} \frac{\Delta C_3}{V_2} \right)_{\text{sm}}$$

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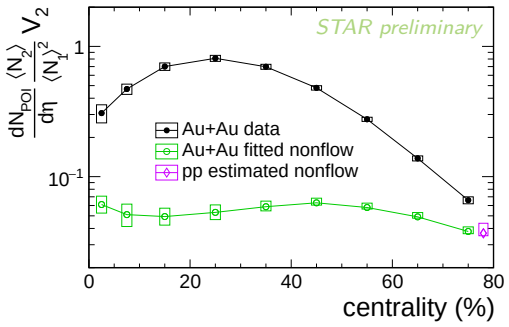
Nonflow background

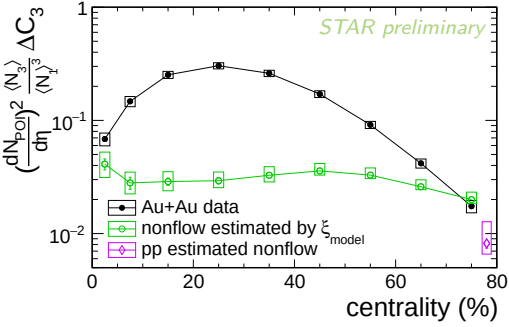
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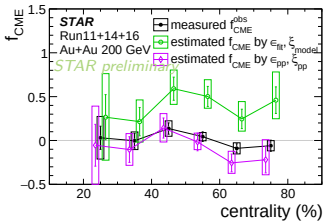
Comparing the two nonflow estimates

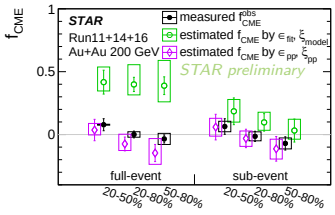


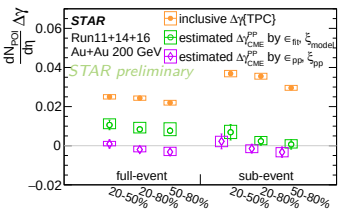


- pp-based V_2^{nf} $\approx$ fitted V_2^{nf} $<$ inclusive V_2
- pp-based ΔC_3^{nf} $<$ model-based ΔC_3^{nf} $<$ inclusive ΔC_3

f_{CME} after subtracting the estimated nonflow

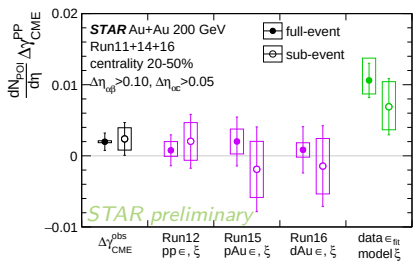


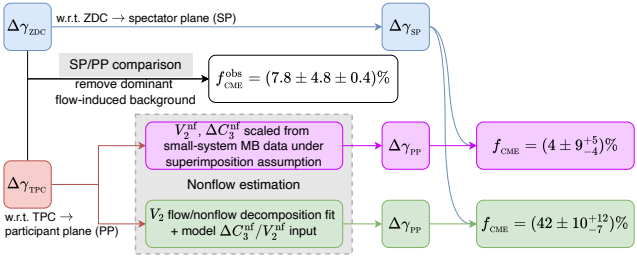




- full-event f_{CME} > sub-event f_{CME}: the sub-event has a smaller $\Delta\eta$ between POIs
- $\Delta\gamma_{\mathrm{CME}} = f_{\mathrm{CME}}\Delta\gamma$

Final result: centrality averages





Approach I: small-system scaling

- requires **zero-bias**, while data is MB which can be strongly biased in small systems
- **superimposition** assumption: nonflow does not change shape or magnitude, and multiplicity scaling.

Approach II: fit decomposition (2p) + model estimation (3p)

- ϵ_{nf} fit function assumption
- ξ_{nf} from models → **model dependence**

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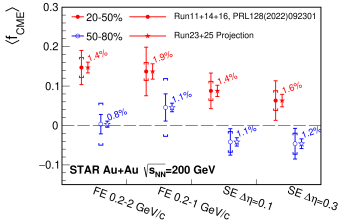
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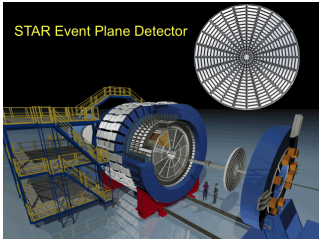
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New high-statistics STAR data

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





- STAR: collected 10× more statistics in 2023-2025 for Au+Au 200 GeV

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

→ large reduction of the statistical uncertainty

→ improved precision

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

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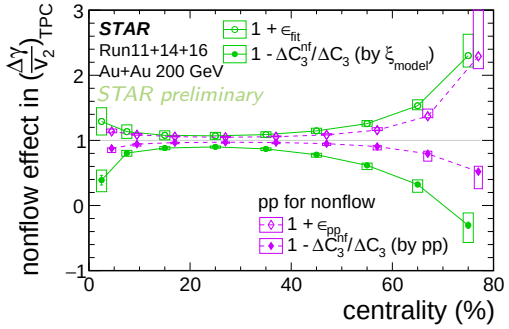
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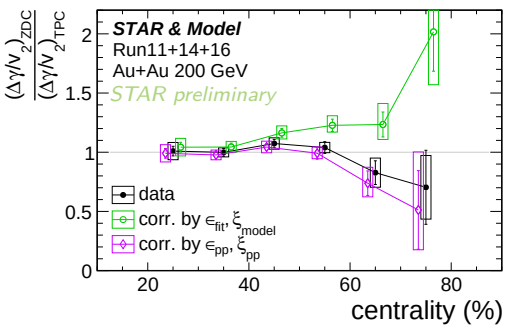
- Background is the major challenge in CME searches.
- Au+Au $\sqrt{s_{\rm NN}} = 200$ GeV: comprehensive background subtraction
  - **flow background** ← SP/PP comparison (ZDC vs. TPC)
  - **2p nonflow** ($\epsilon_{\rm nf}$) ← $V_2(\Delta\eta)$ fit decomposition, or small system scaling
  - **3p nonflow** ($\xi_{\rm nf}$) ← model ratio, or small-system scaling
- CME fractions estimated under two nonflow-background treatments:
  - small systems: $\langle f_{\rm CME}\rangle_{20-50\%} = (4 \pm 9^{+5}_{-4})\%$ ← not zero-bias, superimposition assumption
  - data fit + models: $\langle f_{\rm CME}\rangle_{20-50\%} = (42 \pm 10^{+12}_{-7})\%$ ← model dependence

  → interpretation sensitive to the background estimation methods
- STAR new data ($\times 10$, EPD/iTPC) will substantially improve sensitivity

Backup

The double ratio after subtracting the estimated nonflow

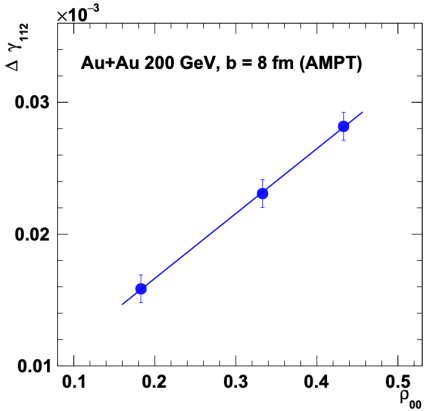




- the 2p correction is > 1 and the 3p correction is < 1 $\rightarrow$ they act in opposite directions
- with ε_{fit} and ξ_{model}: the double ratio > 1 $\rightarrow$ positive f_{CME}
- with ε_{sm} and ξ_{sm}: the double ratio ~ 1 $\rightarrow$ f_{CME} consistent with zero

Estimate effects from ρ spin alignment

- global spin alignment $\rightarrow$ charge separation
  e.g., $\rho^0 \rightarrow \pi^+\pi^-$ into $\gamma_{\rm os}$
- if along the magnetic field
  $\rightarrow$ mimic a CME contribution in this correlator.
- For a 2% spin alignment $(\rho_{00} - 1/3)$ in mid-central Au+Au collisions $\rightarrow \Delta\gamma \lesssim 10^{-6}$
  $\rightarrow$ smaller than the statistical uncertainty of the measured $\Delta\gamma$



[D. Shen, et al., *Phys. Lett. B* **839** (2023) 137777]