# Overview of experimental search for the chiral magnetic effect

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# OUTLINE

- Chiral magnetic effect (CME) and the $\Delta\gamma$ observable
- Flow and nonflow backgrounds
  1. Isobar collisions – vary signal
  2. Event shape engineering – vary background
  3. Au+Au collisions – vary both signal and background
- Summary

# CHIRAL MAGNETIC EFFECT (CME)

## The strong interaction

$$\mathcal{L}_{QCD} = \sum_q \left( \bar{\psi}_{qi} i\gamma^\mu \left[ \delta_{ij}\partial_\mu + ig\left(G^\alpha_\mu t_\alpha\right)_{ij} \right] \psi_{qj} - m_q \bar{\psi}_{qi}\psi_{qi} \right) - \frac{1}{4} G^\alpha_{\mu\nu} G^{\mu\nu}_\alpha$$

quarks — quark-gluon interactions — quarks — gluons

$$= \frac{1}{2}\left(E^2_\alpha - B^2_\alpha\right)$$

‘t Hooft vacuum

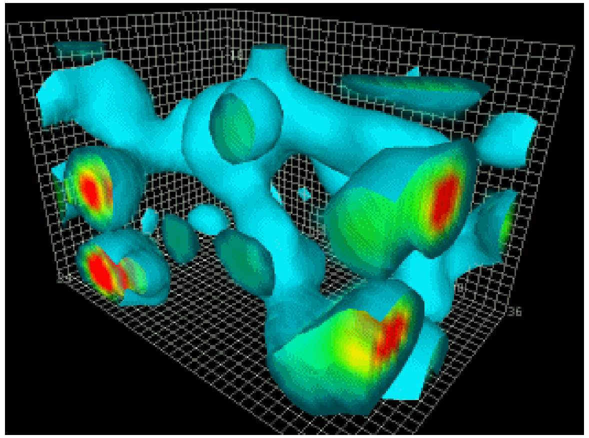
$$+\theta \frac{\alpha_s}{8\pi} G^\alpha_{\mu\nu} \tilde{G}^{\mu\nu}_\alpha = -\theta \frac{\alpha_s}{2\pi} \vec{E}_\alpha \cdot \vec{B}_\alpha$$

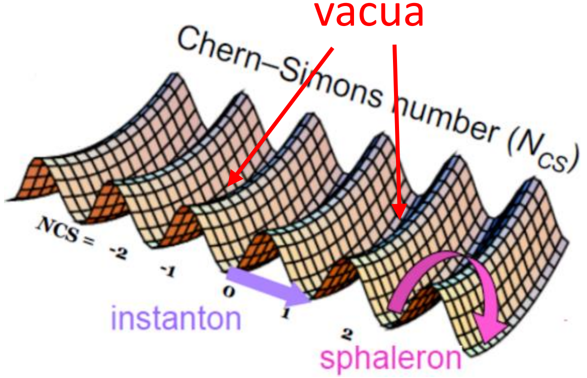
to solve the $U(1)_A$ problem (1976)

**E**: C-odd, P-odd, T-even
**B**: C-odd, P-even, T-odd

Explicitly breaks CP

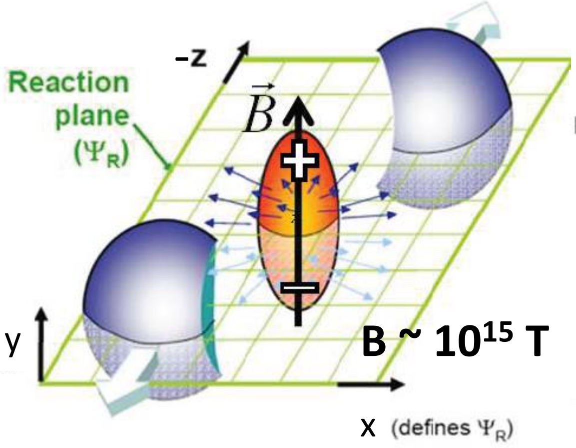
Early universe ultraviolet $\theta \approx 1$ ?? >> current infrared $\theta \approx 0$



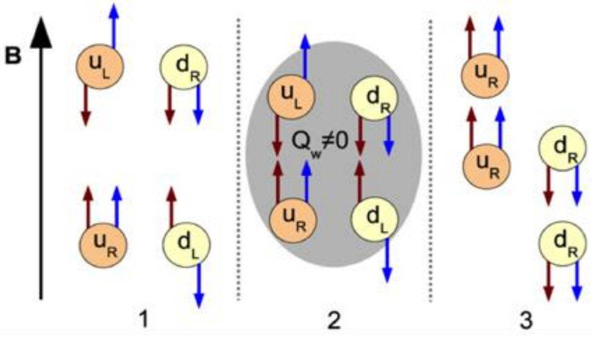



Kharzeev,Pisarski,Tytgat,PRL81(1998)512

QCD vacuum fluctuation, chiral anomaly, topological gluon field




Kharzeev, et al. NPA 803 (2008) 227



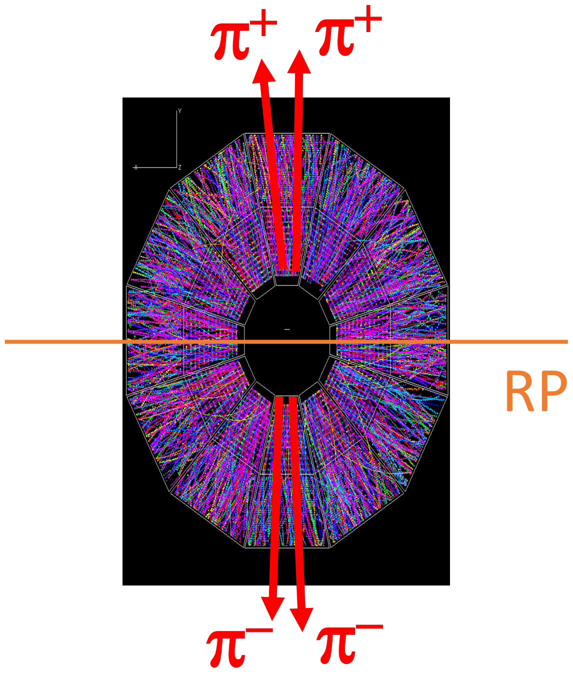

**Chiral Magnetic Effect (CME)**

Discovery of CME: Chiral symmetry restoration, Local P/CP violation (matter-antimatter asymmetry)

# Δγ CORRELATOR AND EARLY RESULTS

*Voloshin, PRC 2004*
*STAR, PRL 2009, PRC 2010*

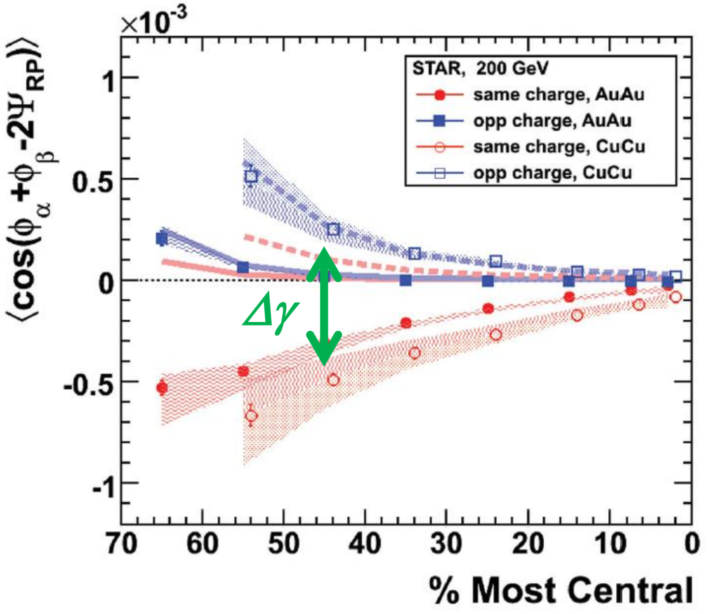
Look for charge separation




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

$$\gamma_{+-,-+} > 0, \quad \gamma_{++,--} < 0$$

$$\Delta\gamma = \gamma_{\text{opposite-sign}} - \gamma_{\text{same-sign}} > 0$$



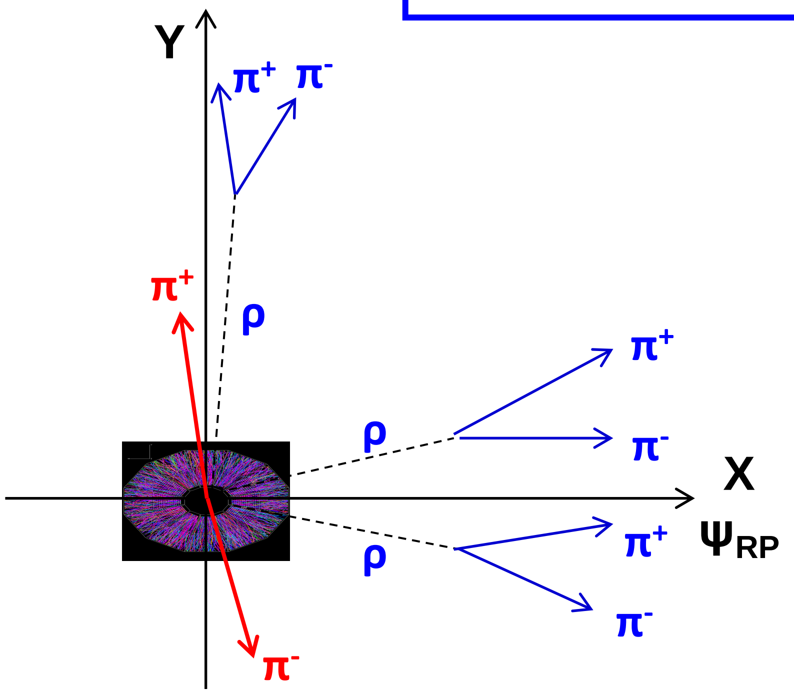

**Significant signal**
**$\Delta\gamma \sim 5 \times 10^{-4}$**
**A few % signal!**

# SIGNIFICANT FLOW-INDUCED BACKRGOUND

*Voloshin 2004*
*FW 2009*
*Bzdak, Koch, Liao 2010*
*Pratt, Schlichting 2010*

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

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




$$dN_\pm / d\varphi \propto 1 + 2v_1 \cos\varphi^\pm + 2a_\pm \cdot \sin\varphi^\pm + 2v_2 \cos 2\varphi^\pm + \ldots$$

$$\gamma_{\alpha\beta} = \left[ \left\langle \cos(\varphi_\alpha - \psi_{RP}) \cos(\varphi_\beta - \psi_{RP}) \right\rangle - \left\langle \sin(\varphi_\alpha - \psi_{RP}) \sin(\varphi_\beta - \psi_{RP}) \right\rangle \right]$$
$$+ \left[ \frac{N_{cluster}}{N_\alpha N_\beta} \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{cluster}) \cos(2\varphi_{cluster} - 2\varphi_{RP}) \right\rangle \right]$$
$$= \left[ \left\langle v_{1,\alpha} v_{1,\beta} \right\rangle - \left\langle a_\alpha a_\beta \right\rangle \right] + \frac{N_{cluster}}{N_\alpha N_\beta} \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{cluster}) \right\rangle v_{2,cluster}$$

$$\Delta\gamma = 2\left\langle a_1^2 \right\rangle + \frac{N_\rho}{N_\alpha N_\beta} \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_\rho) \right\rangle v_{2,\rho}$$

Flow-induced charge-dependent background:
nonflow coupled with flow

$$\Delta\gamma_{\mathrm{Bkg}} \propto v_2 / N$$

# THE NONFLOW BACKGROUND

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

- The flow-induced background is very-well understood

$$\Delta\gamma = 2\langle a_1^2\rangle + \frac{N_\rho}{N_\alpha N_\beta}\langle\cos(\varphi_\alpha + \varphi_\beta - 2\varphi_\rho)\rangle v_{2,\rho}$$

- Nonflow issues are the next/final hurdle

$$\Delta C_3 = 2\langle a_1^2\rangle v_{2,c\perp B} + \frac{N_{2\mathrm{p}}}{N_\alpha N_\beta}\langle\cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{2\mathrm{p}})\rangle v_{2,2\mathrm{p}} v_{2,c} + \frac{N_{3\mathrm{p}}}{N_\alpha N_\beta N_c}\langle\cos(\varphi_\alpha + \varphi_\beta - 2\varphi_c)\rangle$$

$$= 2\langle a_1^2\rangle v_{2,c\perp B} + \frac{C_{2\mathrm{p}} N_{2\mathrm{p}}}{N^2} v_{2,2\mathrm{p}} v_{2,c} + \frac{C_{3\mathrm{p}} N_{3\mathrm{p}}}{2N^3}$$

$$\Delta\gamma = 2\langle a_1^2\rangle \frac{v_{2,c\perp B}}{v_{2,c}^*} + \frac{C_{2\mathrm{p}} N_{2\mathrm{p}}}{N^2} \frac{v_{2,2\mathrm{p}} v_{2,c}}{v_{2,c}^*} + \frac{C_{3\mathrm{p}} N_{3\mathrm{p}}}{2N^3 v_{2,c}^*}$$

CME — 2p nonflow — flow — 3p nonflow

flow-induced bkgd

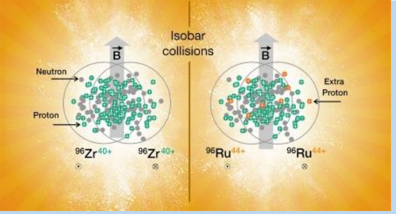
$$N \approx N_+ \approx N_-$$

$$C_{2\mathrm{p}} = \langle\cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{2\mathrm{p}})\rangle$$

$$C_{3\mathrm{p}} = \langle\cos(\varphi_\alpha + \varphi_\beta - 2\varphi_c)\rangle_{3\mathrm{p}}$$

$v_{2,c\perp B}$ : $v_2$ of $c$ particle wrt direction $\perp B$

$v_{2,c}^*$ : measured $v_2$ of $c$ particle containing nonflow

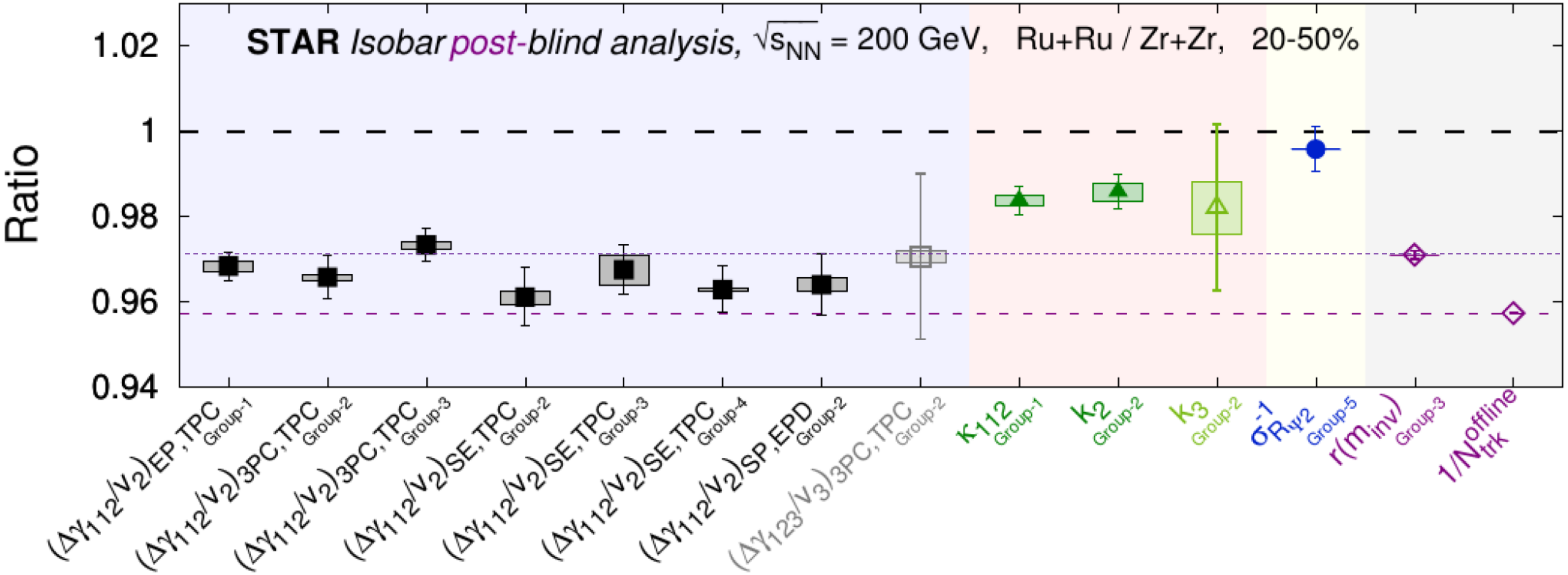



# ISOBAR COLLISIONS

*Voloshin, PRL 105 (2010) 172301*
*STAR, PRC 105 (2022) 014901*
*Haojie Xu et al. PRL 121 (2018) 022301*
*Hanlin Li et al. PRC 98 (2018) 054907*

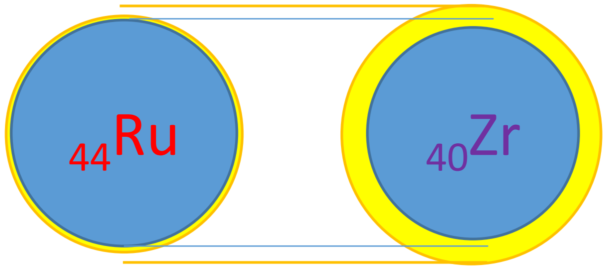
Same A -> Same background
Different Z -> different signal

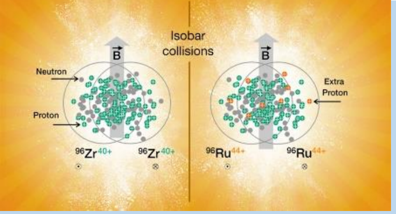
$\Delta\gamma/v_2$




0.4% precision is achieved!
But isobar ratios are below unity.

Primary reason is mult. difference
due to nuclear structure subtlety



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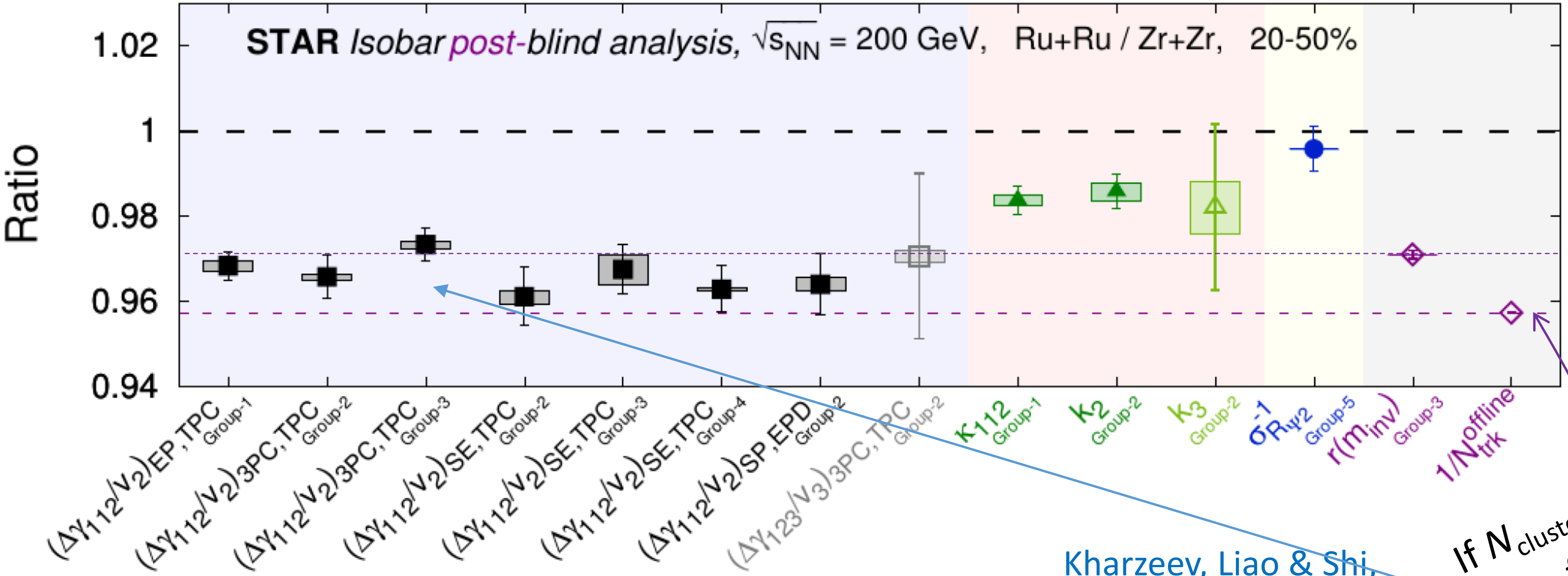


Only considering flow-induced background…

Kharzeev, Liao & Shi, *PRC* 106 (2022) L051903

If $N_{cluster} \propto N$
Then $f_{CME} = 6.8 \pm 2.6\%$

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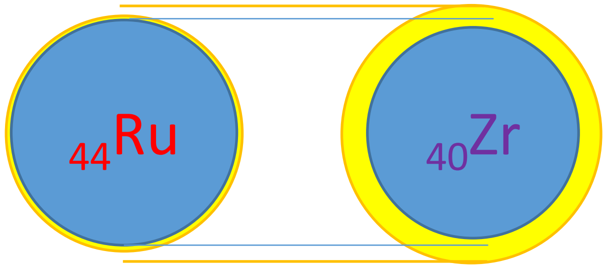
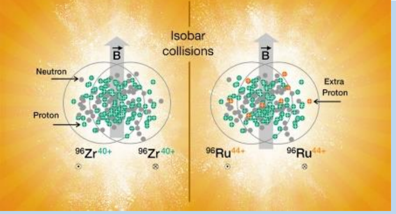



$$\Delta\gamma_{bkg} \propto N_{cluster} / N^2$$

$$\Delta\gamma_{bkg} = \frac{N_\rho}{N_\alpha N_\beta}\left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_\rho)\right\rangle v_{2,\rho}$$

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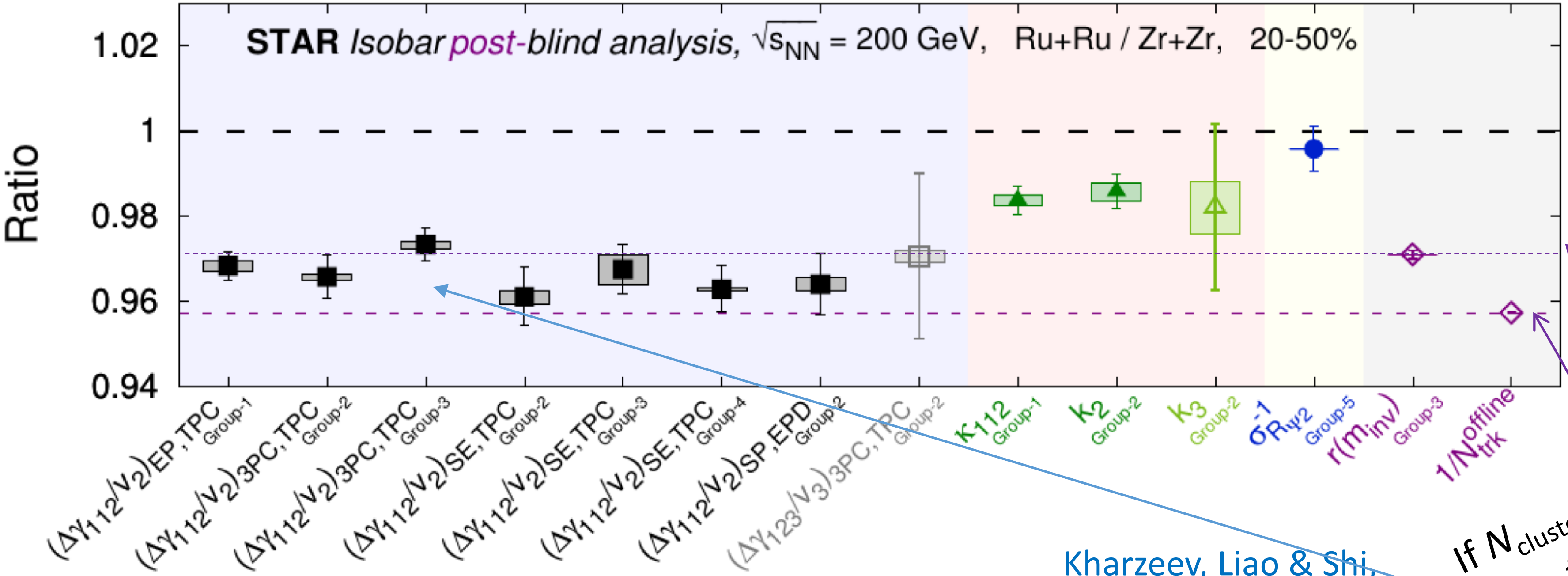


Only considering flow-induced background…

$$r = \frac{N_{OS} - N_{SS}}{N_{OS}}$$

If $N_{cluster} \propto N$
Then $f_{CME} = 6.8 \pm 2.6\%$

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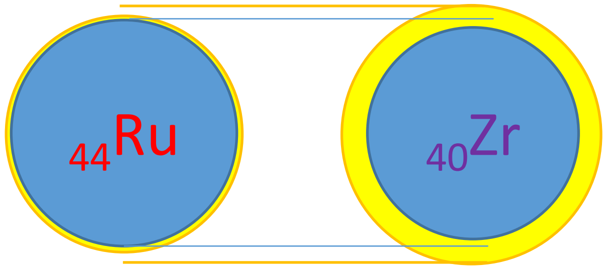


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# NONFLOW ESTIMATES IN ISOBAR

*Feng et al., PRC 105 (2022) 024913*
*FENG Yicheng (STAR): QM'2022, SQM'2022*
*to be released before QM23*

$$C_3 = \frac{C_{2p}N_{2p}}{N^2} v_{2,2p} v_2 + \frac{C_{3p}N_{3p}}{2N^3}; \quad C_{2p} \equiv \langle \cos(\alpha + \beta - 2\phi_{2p}) \rangle \quad C_{3p} \equiv \langle \cos(\alpha + \beta - 2c) \rangle_{3p}$$

$$\varepsilon_2 \equiv \frac{C_{2p}N_{2p}}{N} \cdot \frac{v_{2,2p}}{v_2} \quad ; \quad \varepsilon_3 \equiv \frac{C_{3p}N_{3p}}{2N}$$

$$v_2^{*2} = v_2^2 + v_{2,\mathrm{nf}}^2 \qquad \varepsilon_{\mathrm{nf}} \equiv v_{2,\mathrm{nf}}^2 / v_2^2$$

$$N \approx N_+ \approx N_- \qquad \Delta X \equiv X^{\mathrm{Ru}} - X^{\mathrm{Zr}}$$

$$\frac{\left(N\Delta\gamma / v_2^*\right)^{\mathrm{Ru}}}{\left(N\Delta\gamma / v_2^*\right)^{\mathrm{Zr}}} \equiv \frac{\left(NC_3 / v_2^{*2}\right)^{\mathrm{Ru}}}{\left(NC_3 / v_2^{*2}\right)^{\mathrm{Zr}}} \approx \frac{\varepsilon_2^{\mathrm{Ru}}}{\varepsilon_2^{\mathrm{Zr}}} \cdot \frac{\left(1+\varepsilon_{\mathrm{nf}}\right)^{\mathrm{Zr}}}{\left(1+\varepsilon_{\mathrm{nf}}\right)^{\mathrm{Ru}}} \cdot \frac{\left(1+\frac{\varepsilon_3/\varepsilon_2}{Nv_2^2}\right)^{\mathrm{Ru}}}{\left(1+\frac{\varepsilon_3/\varepsilon_2}{Nv_2^2}\right)^{\mathrm{Zr}}} \approx \frac{\varepsilon_2^{\mathrm{Ru}}}{\varepsilon_2^{\mathrm{Zr}}} - \frac{\Delta\varepsilon_{\mathrm{nf}}}{1+\varepsilon_{\mathrm{nf}}} + \frac{\frac{\varepsilon_3/\varepsilon_2}{Nv_2^2}}{1+\frac{\varepsilon_3/\varepsilon_2}{Nv_2^2}} \left( \frac{\Delta\varepsilon_3}{\varepsilon_3} - \frac{\Delta\varepsilon_2}{\varepsilon_2} - \frac{\Delta N}{N} - \frac{\Delta v_2^2}{v_2^2} \right)$$

# NONFLOW ESTIMATES IN ISOBAR

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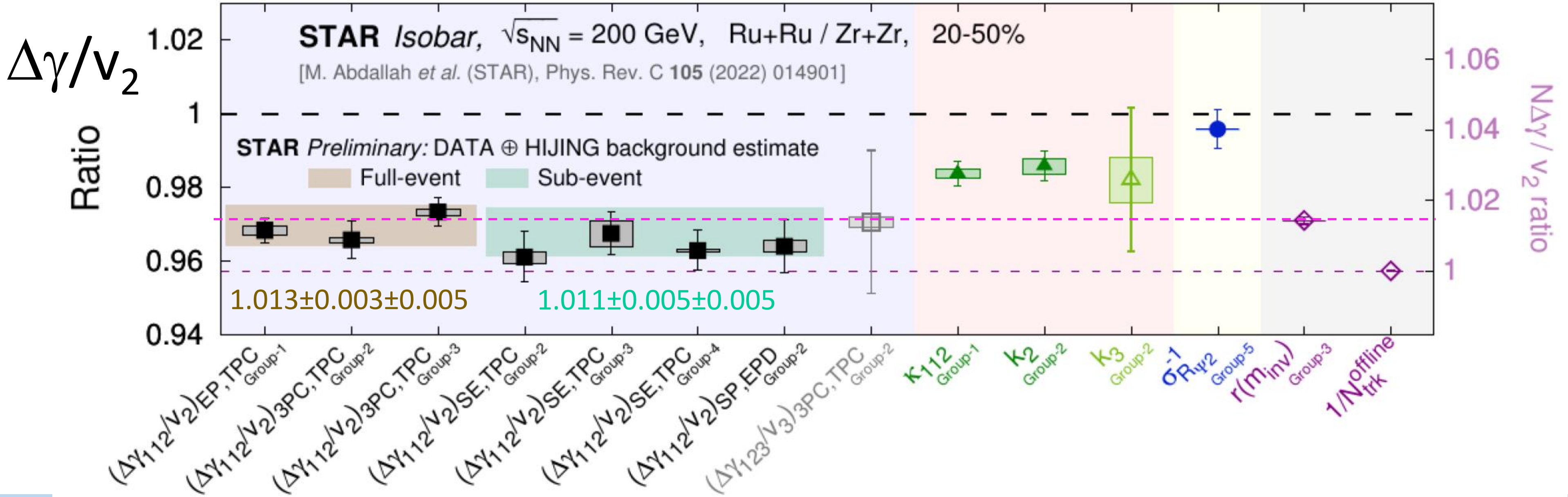
$$C_3 = \frac{C_{2\mathrm{p}} N_{2\mathrm{p}}}{N^2} v_{2,2\mathrm{p}} v_2 + \frac{C_{3\mathrm{p}} N_{3\mathrm{p}}}{2N^3}; \quad C_{2\mathrm{p}} \equiv \langle \cos(\alpha+\beta-2\phi_{2\mathrm{p}}) \rangle \quad C_{3\mathrm{p}} \equiv \langle \cos(\alpha+\beta-2c) \rangle_{3\mathrm{p}}$$

$$\varepsilon_2 \equiv \frac{C_{2\mathrm{p}} N_{2\mathrm{p}}}{N} \cdot \frac{v_{2,2\mathrm{p}}}{v_2} \; ; \; \varepsilon_3 \equiv \frac{C_{3\mathrm{p}} N_{3\mathrm{p}}}{2N}$$

$$v_2^{*2} = v_2^2 + v_{2,\mathrm{nf}}^2 \qquad \varepsilon_{\mathrm{nf}} \equiv v_{2,\mathrm{nf}}^2 / v_2^2$$

$$N \approx N_+ \approx N_- \qquad \Delta X \equiv X^{\mathrm{Ru}} - X^{\mathrm{Zr}}$$

$$\frac{\left(N\Delta\gamma / v_2^*\right)^{\mathrm{Ru}}}{\left(N\Delta\gamma / v_2^*\right)^{\mathrm{Zr}}} \equiv \frac{\left(NC_3 / v_2^{*2}\right)^{\mathrm{Ru}}}{\left(NC_3 / v_2^{*2}\right)^{\mathrm{Zr}}} \approx \frac{\varepsilon_2^{\mathrm{Ru}}}{\varepsilon_2^{\mathrm{Zr}}} \cdot \frac{\left(1+\varepsilon_{\mathrm{nf}}\right)^{\mathrm{Zr}}}{\left(1+\varepsilon_{\mathrm{nf}}\right)^{\mathrm{Ru}}} \cdot \frac{\left(1+\frac{\varepsilon_3/\varepsilon_2}{Nv_2^2}\right)^{\mathrm{Ru}}}{\left(1+\frac{\varepsilon_3/\varepsilon_2}{Nv_2^2}\right)^{\mathrm{Zr}}} \approx \frac{\varepsilon_2^{\mathrm{Ru}}}{\varepsilon_2^{\mathrm{Zr}}} - \frac{\Delta\varepsilon_{\mathrm{nf}}}{1+\varepsilon_{\mathrm{nf}}} + \frac{\frac{\varepsilon_3/\varepsilon_2}{Nv_2^2}}{1+\frac{\varepsilon_3/\varepsilon_2}{Nv_2^2}} \left( \frac{\Delta\varepsilon_3}{\varepsilon_3} - \frac{\Delta\varepsilon_2}{\varepsilon_2} - \frac{\Delta N}{N} - \frac{\Delta v_2^2}{v_2^2} \right)$$




Current total uncertainty:
0.4%⊕0.3%⊕0.5% = 0.7%

Assuming 15% $B^2$ diff:
$\delta f_{\mathrm{CME}}$ = 0.7%/15% = 5%

*My conservative estimate:*
$f_{\mathrm{CME}}$ < 10% at 98% CL

# CONCLUSION FROM ISOBAR DATA

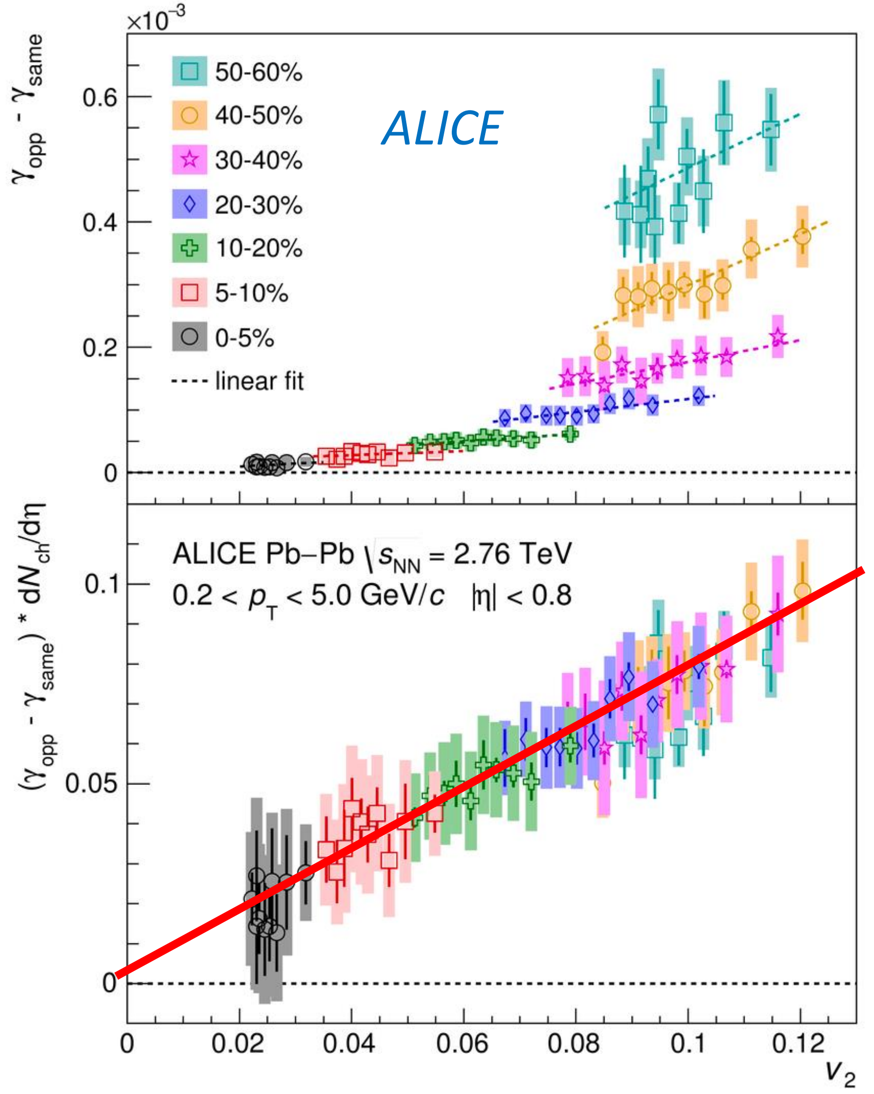
CME

UPPER LIMIT 10%

AT 95% CONFIDENCE LEVEL

# EVENT-SHAPE-ENGINEERING METHOD

*Schukraft, Timmins, Voloshin, PLB 719 (2013) 394*
*ALICE, PLB 777 (2018) 151*
*CMS, PRC 97 (2018) 044912*



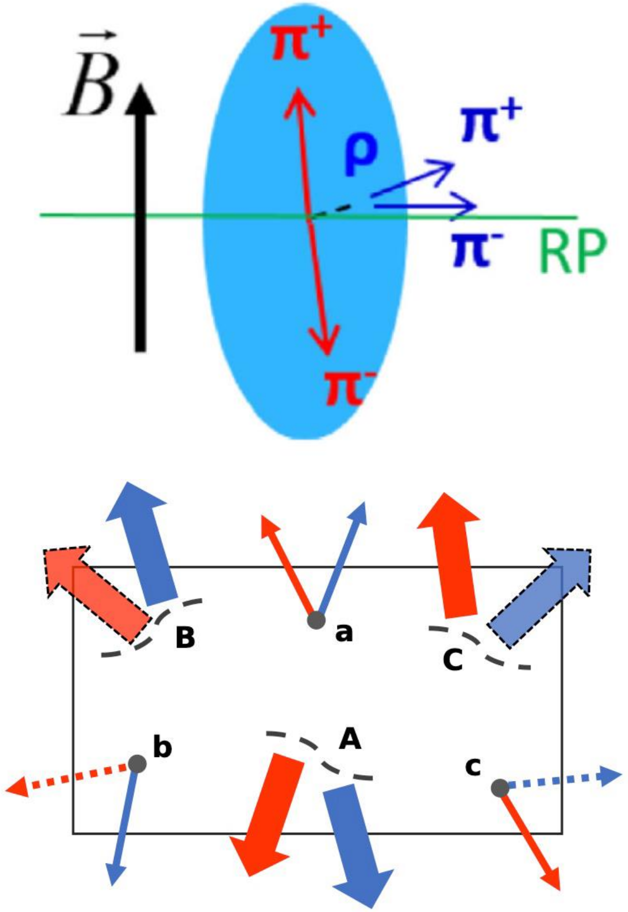

$$\Delta\gamma_{\mathrm{Bkg}} = \frac{N_\rho}{N_\alpha N_\beta}\left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_\rho)\right\rangle v_{2,\rho}$$

ALICE:
Model study of $v_2$-dependent reconstruction of B direction within a given centrality because different $q_2$ classes have different EP resolutions.

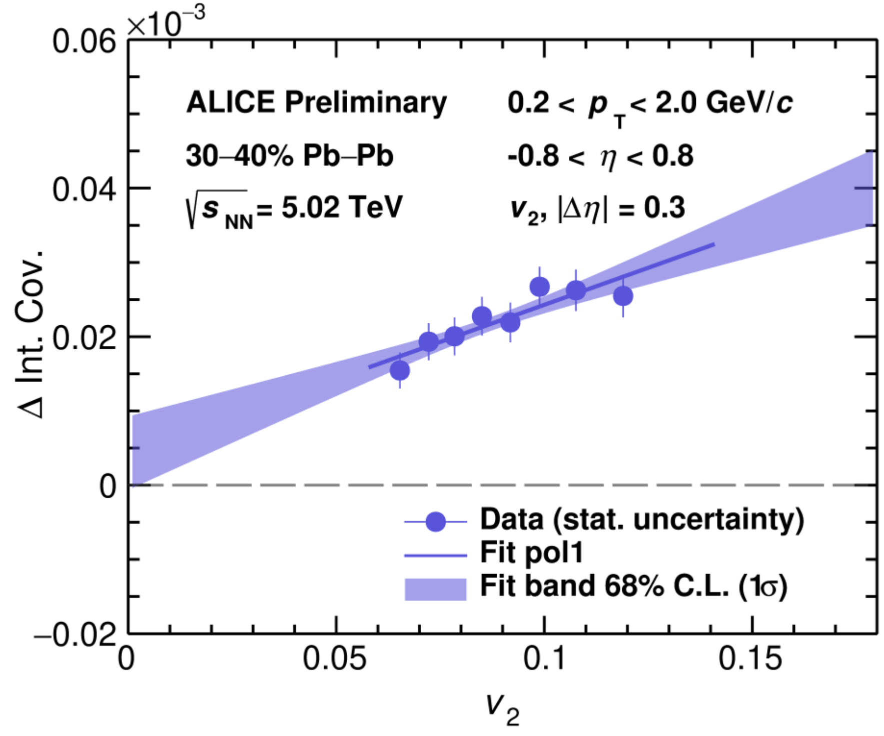
# CMW & CME: COMMON BKG SOURCE

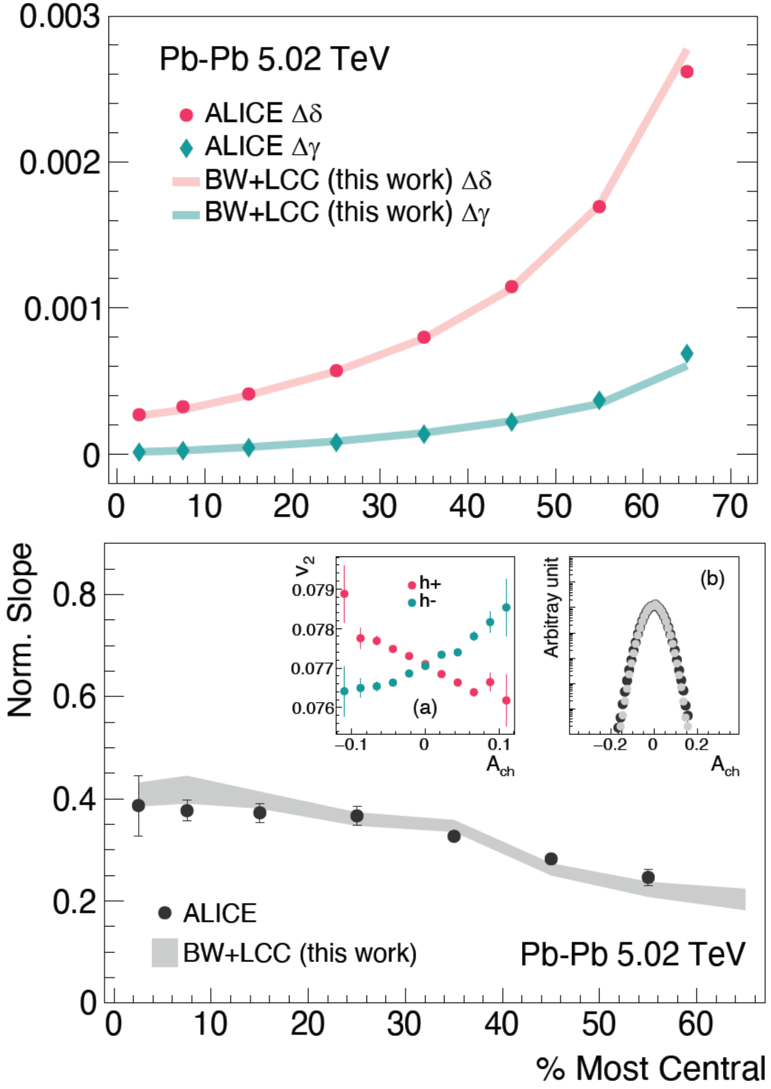
Wu, Shou, et al., PRC 107, L031902 (2023)
Wu (ALICE), SQM 2002, EPJ Web Conf. 276, 01001 (2023)

**LCC background**




Qiye Shou, Chirality Workshop 2023



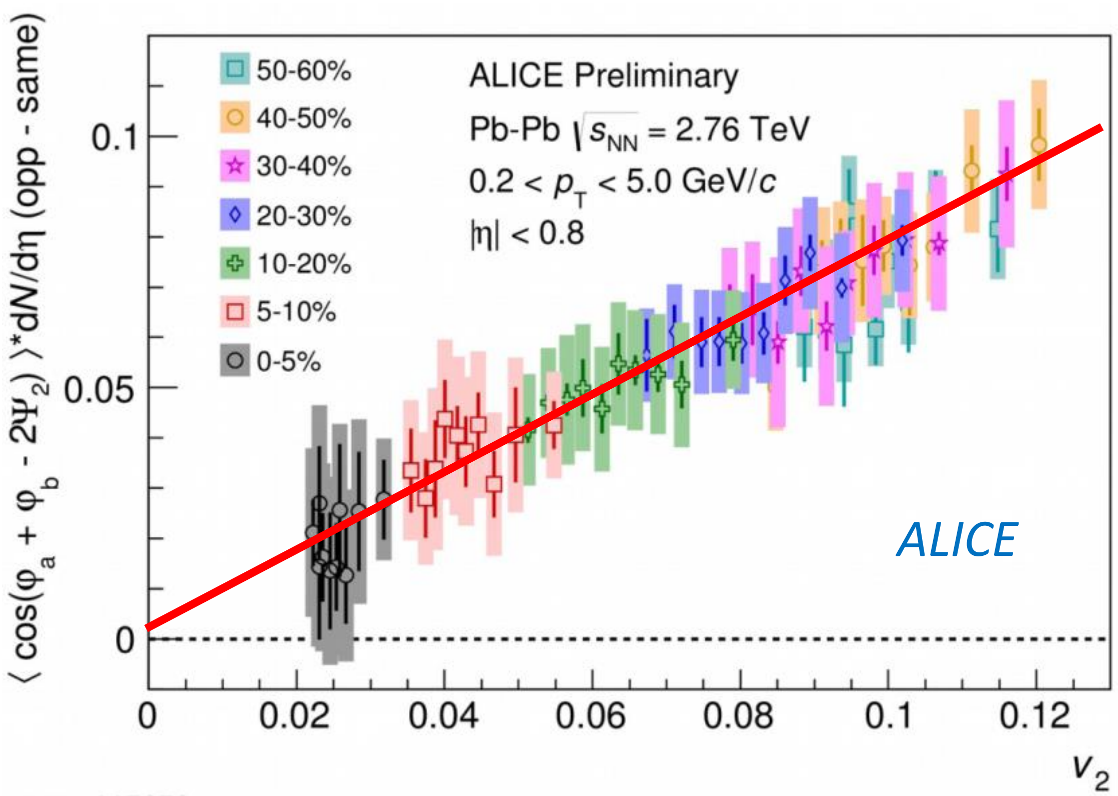



# HANDLE NONFLOW IN ESE

Schukraft, Timmins, Voloshin, PLB 719 (2013) 394
Feng et al., PRC 105 (2022) 024913

Contaminated by 3p nonflow

3p nonflow removal will bring down $\Delta\gamma$ magnitude




v2 contaminated by nonflow

$$\Delta\gamma_{\rm Bkg} = \frac{N_\rho}{N_\alpha N_\beta}\left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_\rho)\right\rangle v_{2,\rho}$$

Flow background is taken care of

- Remove v2 nonflow by $(\Delta\eta,\Delta\phi)$ analysis?
- Use $v_2\{4\}$ instead of $v_2\{2\}$ to minimize nonflow? (implicit assumption: fluct. ~ $v_2$)

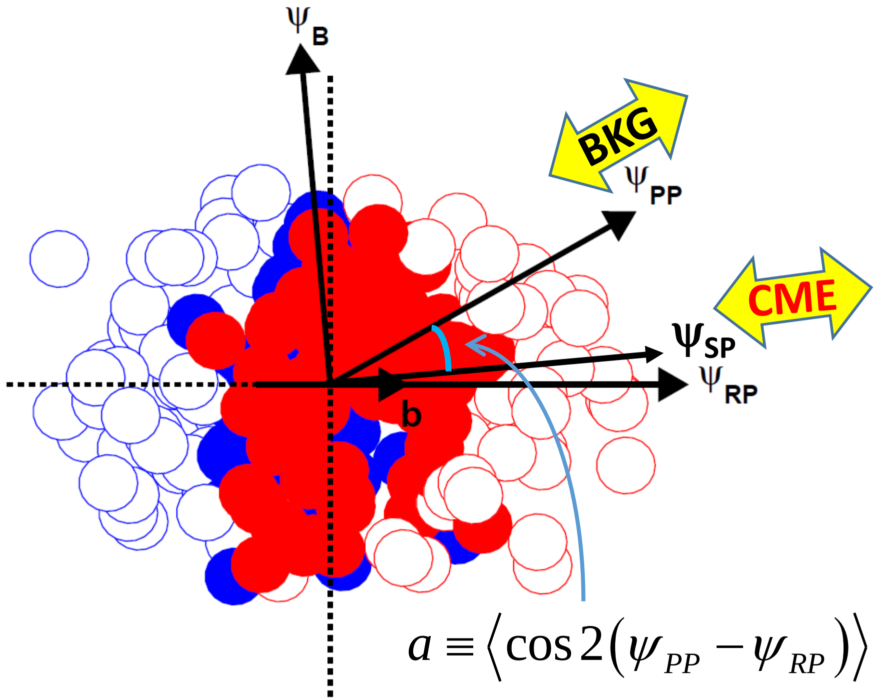
Once nonflow taken care of, ESE is a promising way to extract CME signal

Vary both signal and background:

Spectator/Participant Plane Method

# 200 GEV AU+AU COLLISIONS

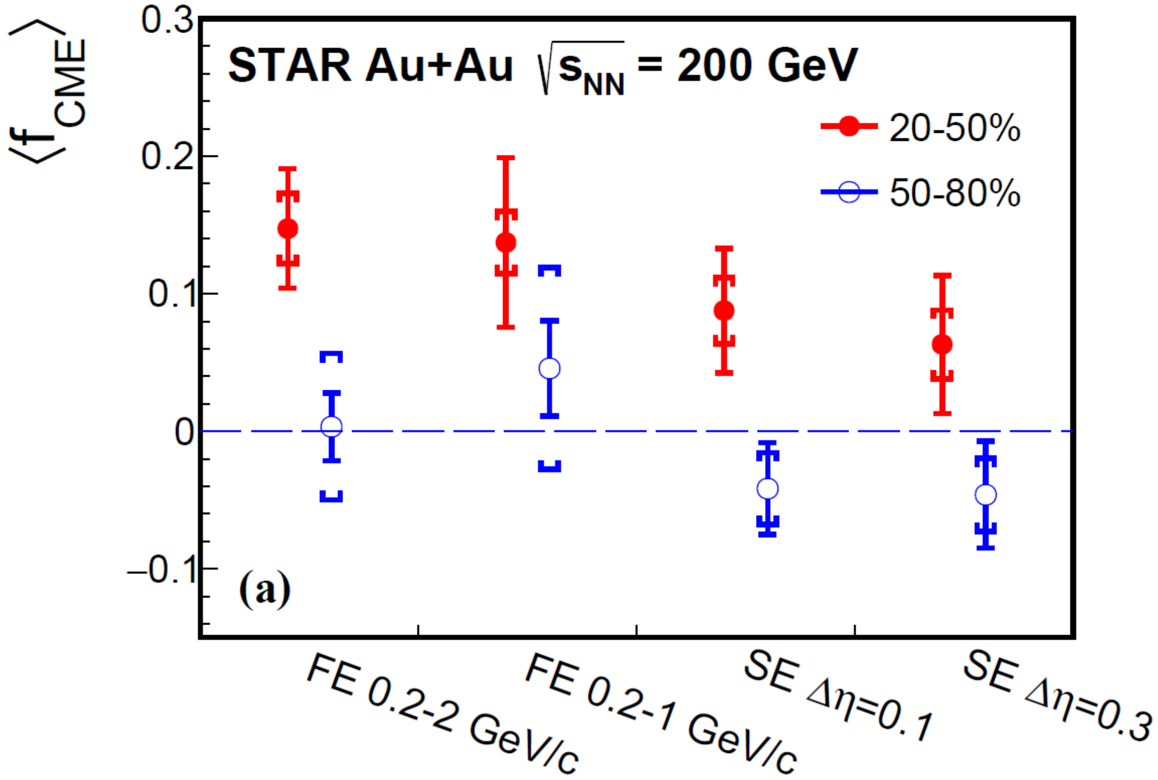
*H.-j. Xu, et al., CPC 42 (2018) 084103, arXiv:1710.07265*
*S.A. Voloshin, PRC 98 (2018) 054911, arXiv:1805.05300*
*STAR, PRL 128 (2022) 092301*




$$a \equiv \langle \cos 2(\psi_{PP} - \psi_{RP}) \rangle$$

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

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




- Peripheral 50-80%: consistent-with-zero signal
- Mid-central 20-50%: indication of finite CME, ~2σ significance

# NONFLOW IN AU+AU

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

$$\Delta C_3^{\mathrm{Ru}}\{\mathrm{EP}\} = \left(\frac{C_{2p}N_{2p}}{N^2} v_{2,2p}\{\mathrm{EP}\} v_{2,c}\{\mathrm{EP}\}\right)^{\mathrm{Ru}} + \left(\frac{C_{3p}N_{3p}}{2N^3}\right)^{\mathrm{Ru}}$$

$$\Delta C_3^{\mathrm{Zr}}\{\mathrm{EP}\} = \left(\frac{C_{2p}N_{2p}}{N^2} v_{2,2p}\{\mathrm{EP}\} v_{2,c}\{\mathrm{EP}\}\right)^{\mathrm{Zr}} + \left(\frac{C_{3p}N_{3p}}{2N^3}\right)^{\mathrm{Zr}}$$

| | |
|---|---|
| Au+Au | $\Delta C_3^{\mathrm{Bkg}}\{\mathrm{SP}\} = \frac{C_{2p}N_{2p}}{N^2} v_{2,2p}\{\mathrm{SP}\} v_{2,c}\{\mathrm{SP}\}$<br>$\Delta C_3^{\mathrm{Bkg}}\{\mathrm{EP}\} = \frac{C_{2p}N_{2p}}{N^2} v_{2,2p}\{\mathrm{EP}\} v_{2,c}\{\mathrm{EP}\} + \frac{C_{3p}N_{3p}}{2N^3}$ |

# NONFLOW IN AU+AU

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$$\Delta C_3^{\text{Ru}}\{\text{EP}\} = \left(\frac{C_{2\text{p}}N_{2\text{p}}}{N^2} v_{2,2\text{p}}\{\text{EP}\}v_{2,c}\{\text{EP}\}\right)^{\text{Ru}} + \left(\frac{C_{3\text{p}}N_{3\text{p}}}{2N^3}\right)^{\text{Ru}}$$

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| Au+Au | |
|---|---|
| | $\Delta C_3^{\text{Bkg}}\{\text{SP}\} = \frac{C_{2\text{p}}N_{2\text{p}}}{N^2} v_{2,2\text{p}}\{\text{SP}\}v_{2,c}\{\text{SP}\}$ <br> $\Delta C_3^{\text{Bkg}}\{\text{EP}\} = \frac{C_{2\text{p}}N_{2\text{p}}}{N^2} v_{2,2\text{p}}\{\text{EP}\}v_{2,c}\{\text{EP}\} + \frac{C_{3\text{p}}N_{3\text{p}}}{2N^3}$ |

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

$$\epsilon_{\text{nf}} \equiv v_{2,\text{nf}}^2 / v_2^2$$

$$\frac{A}{a} = \frac{\Delta\gamma\{\text{SP}\}/\Delta\gamma\{\text{PP}\}}{v_2\{\text{SP}\}/v_2^*\{\text{PP}\}} = \frac{C_3\{\text{SP}\}}{v_2^2\{\text{SP}\}} \cdot \frac{v_2^{*2}\{\text{PP}\}}{C_3\{\text{PP}\}} = \frac{1+\varepsilon_{\text{nf}}}{1+\dfrac{\varepsilon_3/\varepsilon_2}{Nv_2^2\{\text{PP}\}}}$$

$$\varepsilon_2 = \frac{C_{2\text{p}}N_{2\text{p}}}{N} \cdot \frac{v_{2,2\text{p}}}{v_2} \approx N\Delta\gamma / v_2 \qquad \varepsilon_3 = \frac{C_{3\text{p}}N_{3\text{p}}}{2N}$$

# NONFLOW IN AU+AU

Feng et al., PRC 105 (2022) 024913

$$\Delta C_3^{\mathrm{Ru}}\{\mathrm{EP}\} = \left(\frac{C_{2p}N_{2p}}{N^2} v_{2,2p}\{\mathrm{EP}\} v_{2,c}\{\mathrm{EP}\}\right)^{\mathrm{Ru}} + \left(\frac{C_{3p}N_{3p}}{2N^3}\right)^{\mathrm{Ru}}$$

$$\Delta C_3^{\mathrm{Zr}}\{\mathrm{EP}\} = \left(\frac{C_{2p}N_{2p}}{N^2} v_{2,2p}\{\mathrm{EP}\} v_{2,c}\{\mathrm{EP}\}\right)^{\mathrm{Zr}} + \left(\frac{C_{3p}N_{3p}}{2N^3}\right)^{\mathrm{Zr}}$$

| Au+Au | $\Delta C_3^{\mathrm{Bkg}}\{\mathrm{SP}\} = \frac{C_{2p}N_{2p}}{N^2} v_{2,2p}\{\mathrm{SP}\} v_{2,c}\{\mathrm{SP}\}$ <br> $\Delta C_3^{\mathrm{Bkg}}\{\mathrm{EP}\} = \frac{C_{2p}N_{2p}}{N^2} v_{2,2p}\{\mathrm{EP}\} v_{2,c}\{\mathrm{EP}\} + \frac{C_{3p}N_{3p}}{2N^3}$ |
|---|---|

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$v_2$ nonflow → makes TPC Δγ smaller → positive $f_{\mathrm{CME}}$

3p nonflow → makes TPC Δγ larger → negative $f_{\mathrm{CME}}$

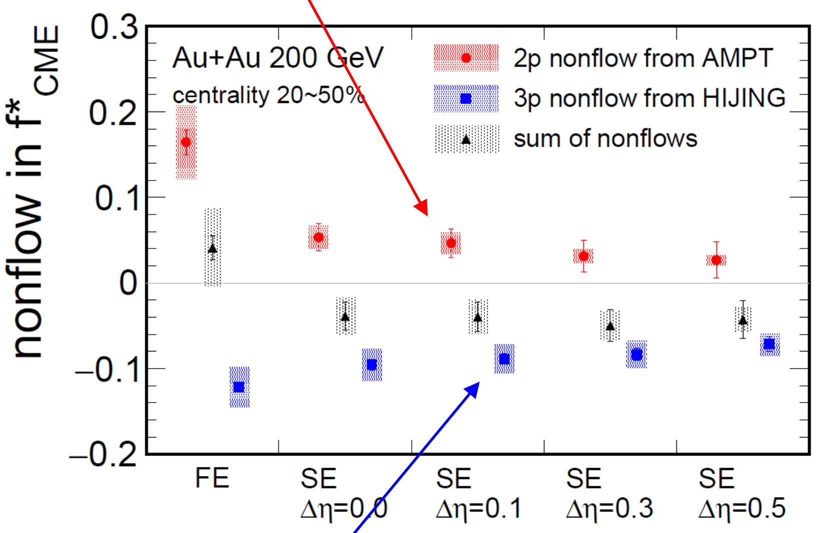
$$\varepsilon_2 = \frac{C_{2p}N_{2p}}{N} \cdot \frac{v_{2,2p}}{v_2} \approx N\Delta\gamma / v_2 \qquad \varepsilon_3 = \frac{C_{3p}N_{3p}}{2N}$$

$$f_{\mathrm{CME}}^* \approx \left(\varepsilon_{\mathrm{nf}} - \frac{\varepsilon_3/\varepsilon_2}{Nv_2^2\{\mathrm{PP}\}}\right) \Bigg/ \left(\frac{1+\varepsilon_{\mathrm{nf}}}{a^2} - 1\right)$$

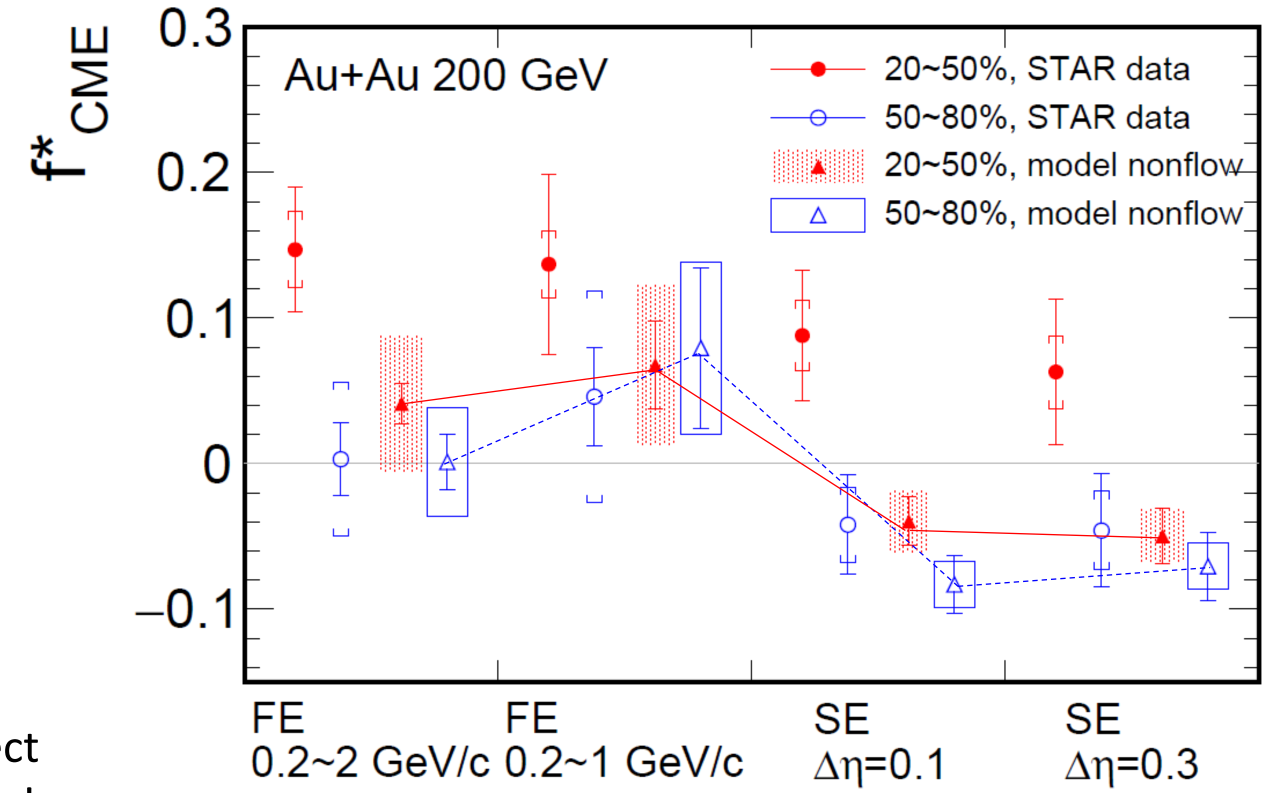
# NONFLOW SUBTRACTED SIGNAL

*STAR, PRL 128 (2022) 092301*
*Feng et al., PRC 105 (2022) 024913*

AMPT 2p estimates




HIJING 3p estimates




Net nonflow effect could be negative!

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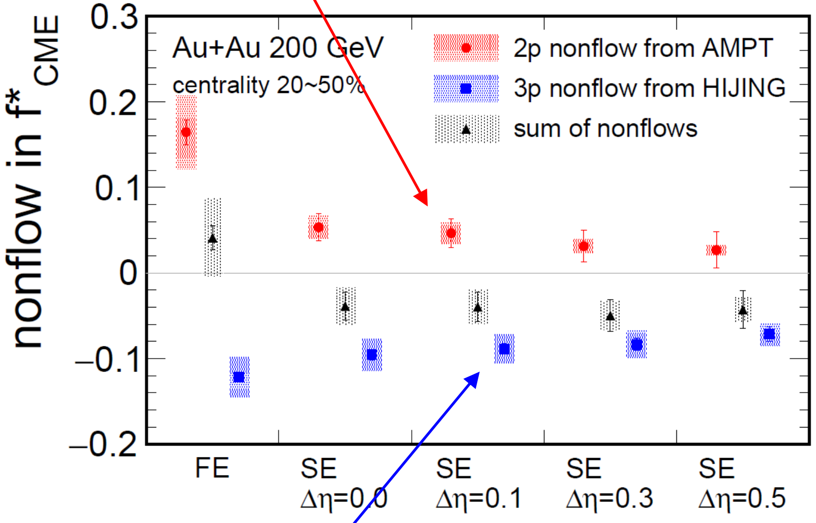


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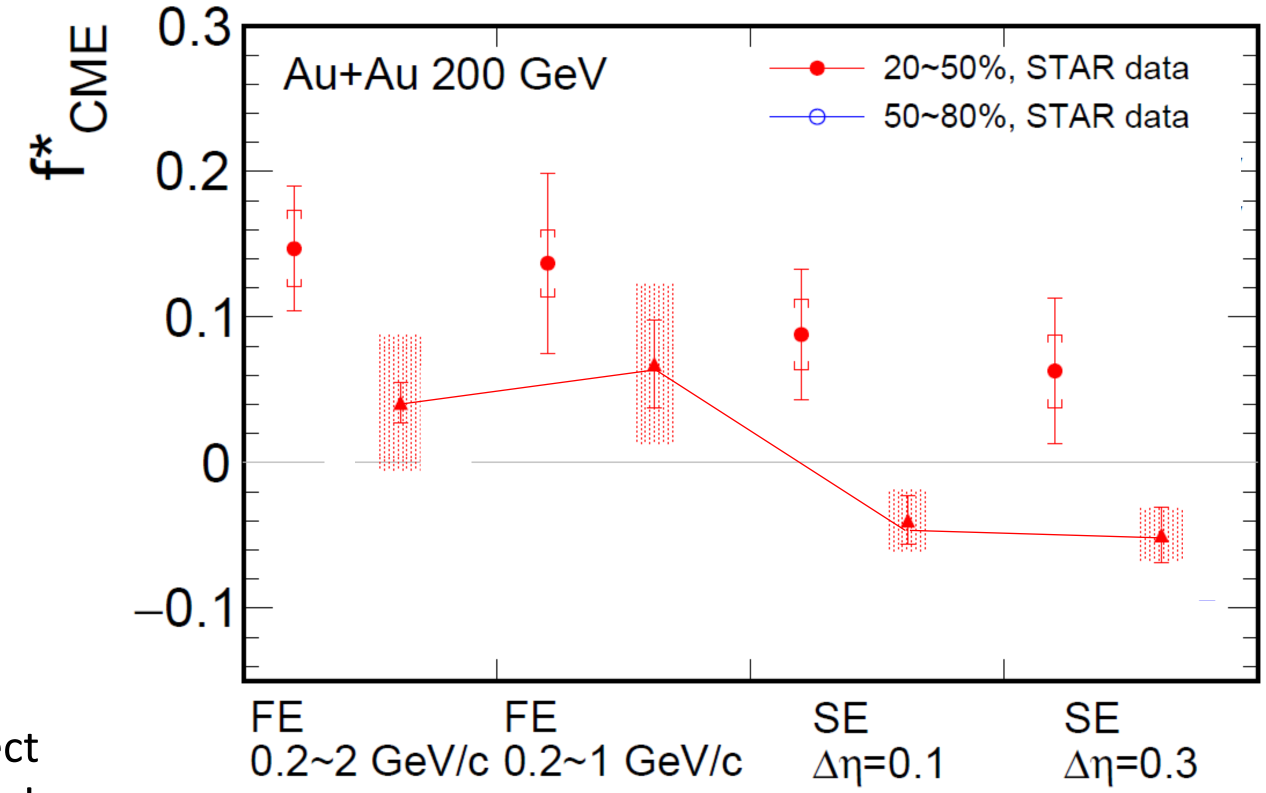

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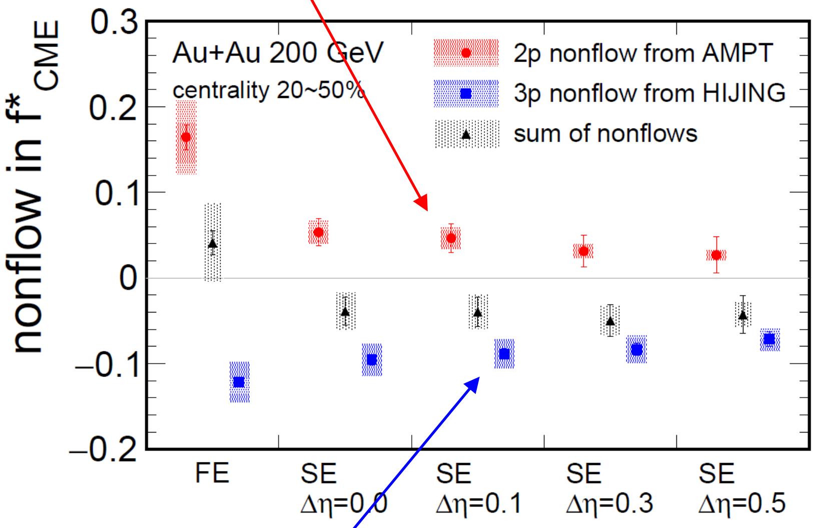
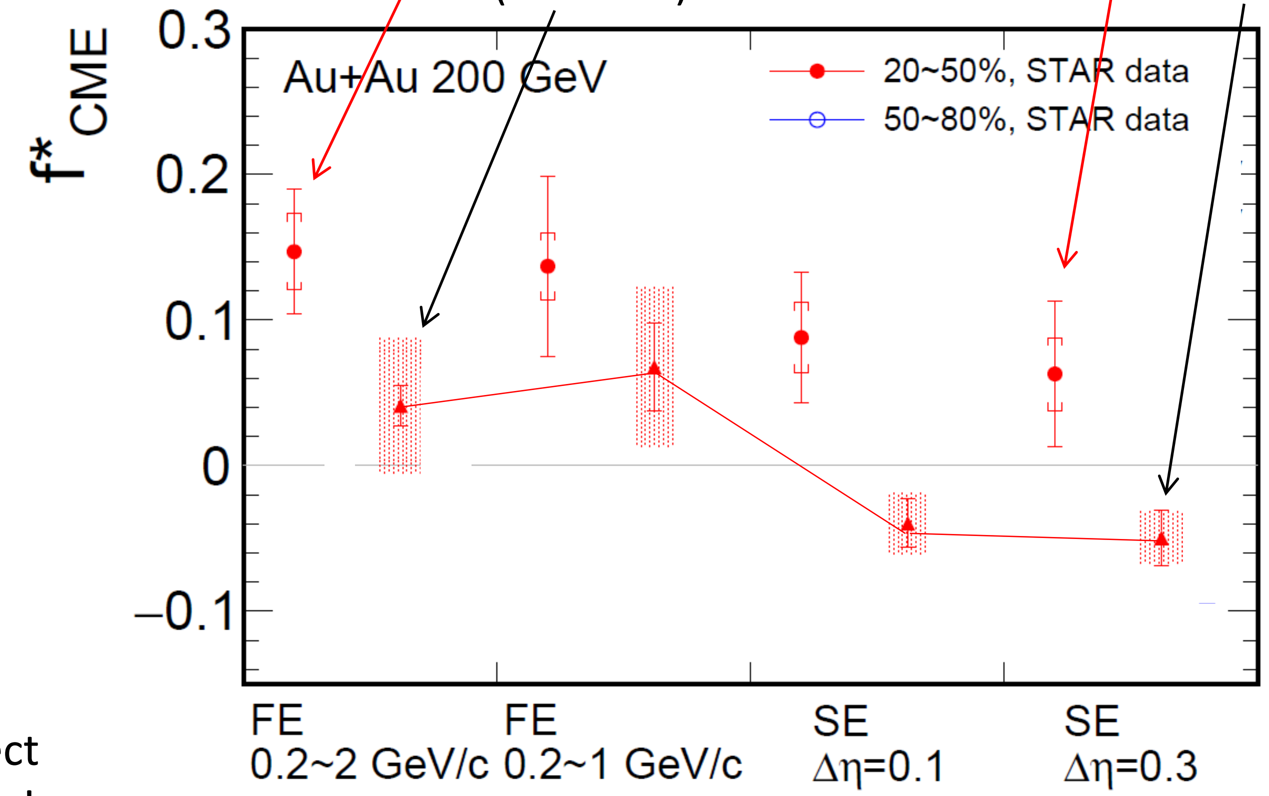



HIJING 3p estimates

Net nonflow effect could be negative!

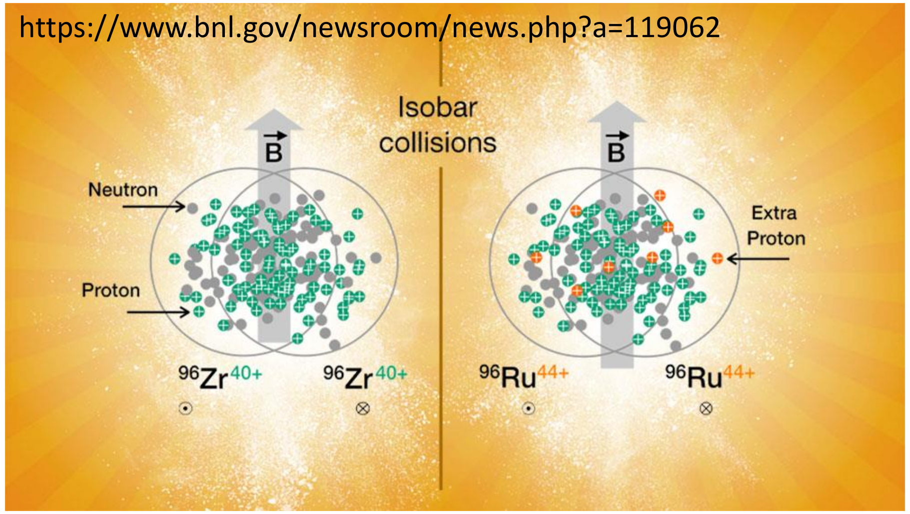
(14.7 ± 5.0)%
(4.1 ± 4.8)%
(6.3 ± 5.6)%
(–5.0 ± 2.6)%




There may indeed be hint of ~10% CME in Au+Au data!

# AU+AU AND ISOBAR ARE CONSISTENT

*Shi et al., Ann. Phys. 394 (2018) 50–72*
*Feng et al., PLB 820 (2021) 136549*




$\Delta\gamma \propto B^2$, differ by 15% between isobars

If CME signal in isobar ~ Au+Au ~ 10%,

Then isobar difference ~ 15%*10% = 1.5%.

With 0.4% uncertainty, ~4$\sigma$ effect

Background $\propto$ 1/N → isobar/AuAu ~ 2

Mag. field B ~ $A/A^{2/3}$ ~ $A^{1/3}$, $\Delta\gamma_{CME}$ ~ $B^2$ ~ $A^{2/3}$ → Signal: AuAu/isobar ~ 1.5

Could be x3 reduction in $f_{CME}$

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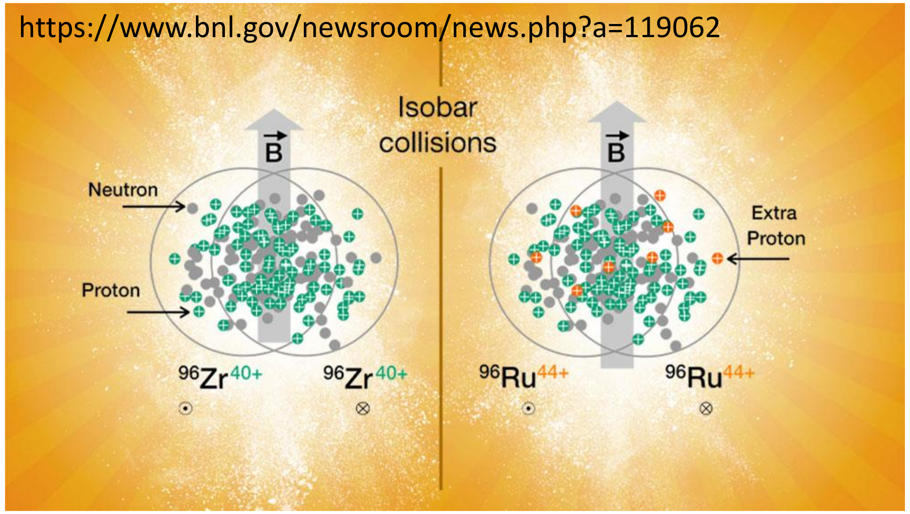


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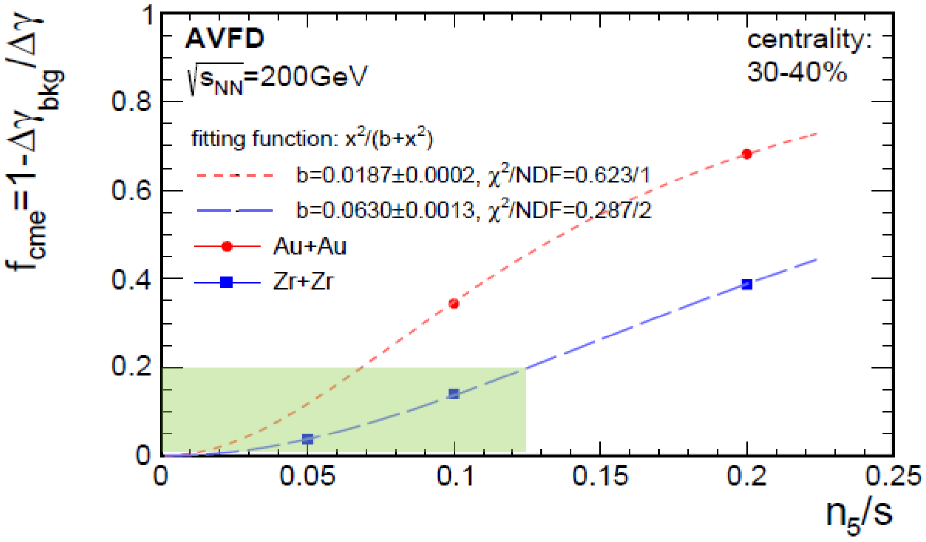



If AuAu $f_{CME}$=10%, then isobar 3% (1σ effect)

Ru/Zr = 1 + 15%*3% = 1.005 (±0.004)

# "LOOSE" CONCLUSION FROM AU+AU DATA

CME SIGNAL

10% ± 5%

# "LOOSE" CONCLUSION FROM AU+AU DATA

CME SIGNAL

10% ± 5%

To outlook:

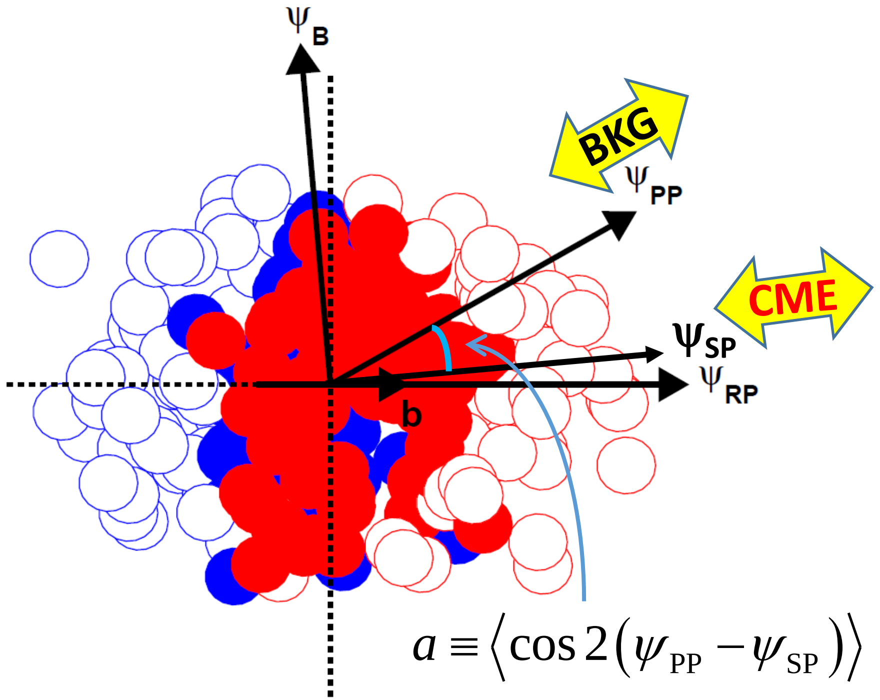
x10 more data, iTPC larger acceptance, EPD larger $\eta$ gap

Expect 1-1.5% total uncertainty

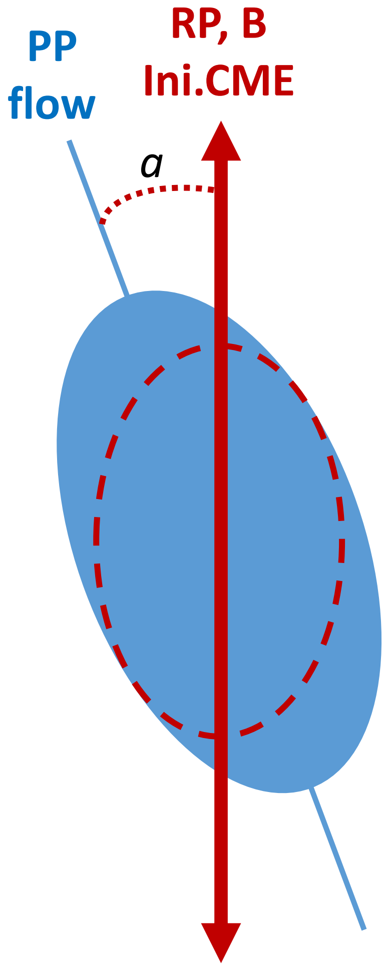
Any additional issues?

# FINAL-STATE EVOLUTION EFFECT?

*Choudhury et al., CPC 46 (2022) 014101*
*Shi et al., Ann. Phys. 394 (2018) 50–72*
*STAR, PRL 128 (2022) 092301*
*B-X Chen, X-L Zhao, G-L Ma, 2301.12076*




$$a \equiv \langle \cos 2(\psi_{\mathrm{PP}} - \psi_{\mathrm{SP}}) \rangle$$




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

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

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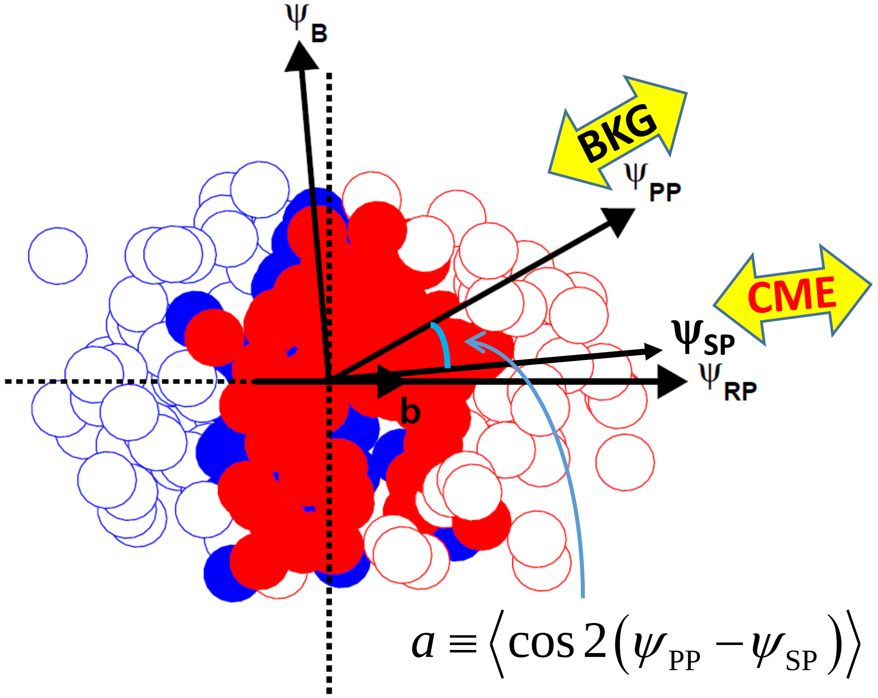
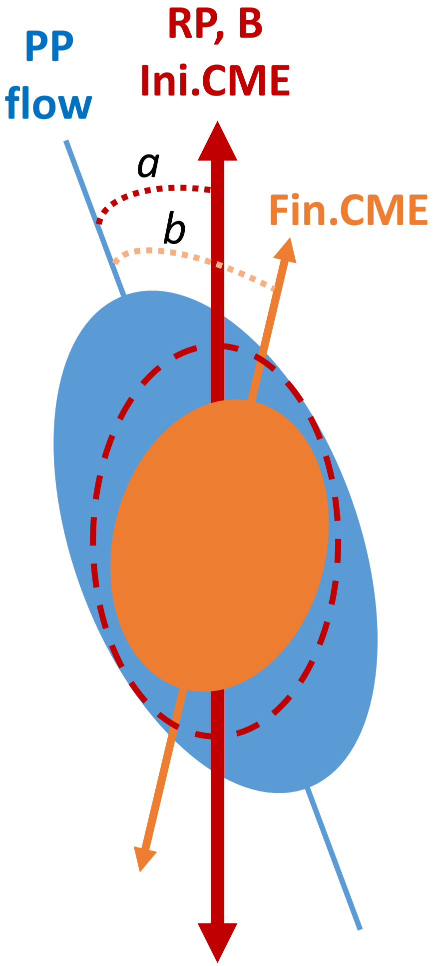



$$a \equiv \langle \cos 2(\psi_{PP} - \psi_{SP}) \rangle$$

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

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




CME along axis B (and PP) more suppressed, making "CME ellipse" tilt away from B (and PP), thus *b* < *a*.

However, final-state CME now needs to be projected onto not only PP but also RP.

$$\frac{\Delta\gamma_{CME}\{PP\}}{\Delta\gamma_{CME}\{SP\}} = \frac{\Delta\gamma_{CME} \langle \cos 2(\psi_{CME} - \psi_{PP}) \rangle}{\Delta\gamma_{CME} \langle \cos 2(\psi_{CME} - \psi_{SP}) \rangle} = \langle \cos 2(\psi_{PP} - \psi_{SP}) \rangle = a$$

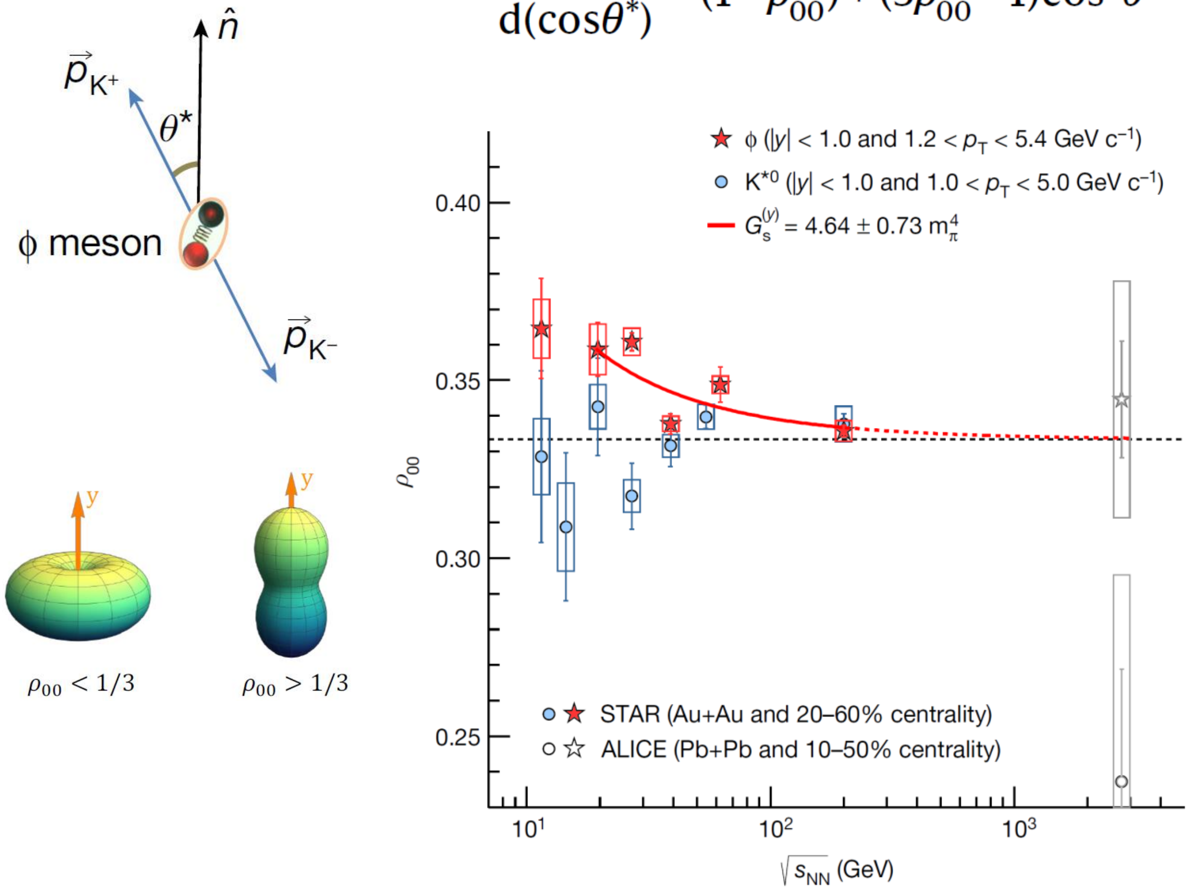
For measurements w.r.t. PP and RP, the $f_{CME}$ formula is still valid.

AMPT indicates otherwise; maybe the absorption effect is more complex.

# GLOBAL SPIN ALIGNMENT EFFECT?

*Z.-T. Liang, X.-N. Wang, PRL 94, 102301 (2005)*
*STAR, Nature 548, 62 (2017)*
*Diyu Shen et al., PLB 839 (2023) 137777*

$$\frac{dN}{d(\cos\theta^*)} \propto (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*$$




Conceivable that $\rho$ mesons can also have significant spin alignment.
A couple of % back-to-back preference along *L* can have a large contribution to Δγ.
Potential background to CME?

Probably not.

Because spin alignment is caused by orbit-spin interaction, and is therefore relative to the participant orbital angular momentum, so behaves just like participant flow background.

However, $v_2$ measurement is affected by $\rho$ spin alignment, and can be significant.

# SUMMARY

- CME has been one of the most active and challenging fields of research
- Theoretically well understood; Experimentally many innovative approaches

- Flow-induced background is well understood and under control
- Nonflow is the next (and hopefully final) issue

- All indications suggest a finite ~10% CME signal ($2\sigma$ significance)
- At least x10 more data to come, larger acceptance, new event-plane detector