

# CME Au+Au Results and Nonflow Issues

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# CHIRAL MAGNETIC EFFECT (CME)

Kharzeev, Pisarski, Tytgat, PRL 81 (1998) 512  
Kharzeev, et al. NPA 803 (2008) 227



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## Possibility of Spontaneous Parity Violation in Hot QCD

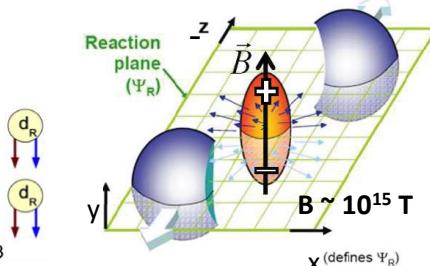
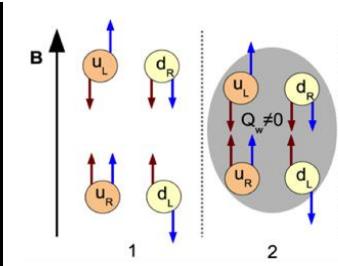
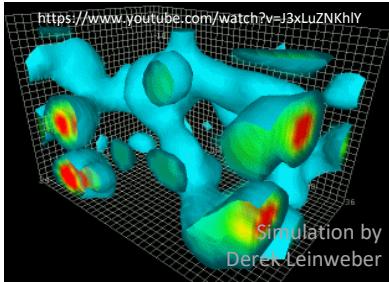
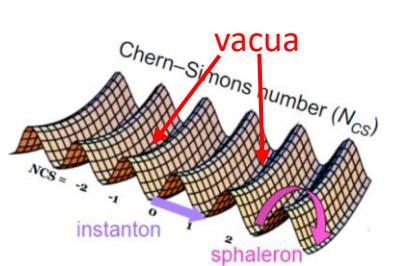
Dmitri Kharzeev,<sup>1</sup> Robert D. Pisarski,<sup>2</sup> and Michel H. G. Tytgat<sup>2,3</sup>

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(Received 3 April 1998)

We argue that for QCD in the limit of a large number of colors, the axial U(1) symmetry of massless quarks is effectively restored at the deconfining phase transition. If this transition is of second order, metastable states in which parity is spontaneously broken can appear in the hadronic phase. These metastable states have dramatic signatures, including enhanced production of  $\eta$  and  $\eta'$  mesons, which can decay through parity violating decay processes such as  $\eta \rightarrow \pi^0 \pi^0$ , and global parity odd asymmetries for charged pions. [S0031-9007(98)06613-7]



QCD vacuum fluct.  $\rightarrow$  Chiral anomaly  $\rightarrow$  Topological gluon field  $\rightarrow$  Chirality imbalance  $\rightarrow$  Charge separation  
Discovery of CME: Chiral symmetry restoration; Local P/CP violation (matter-antimatter asymmetry), etc.

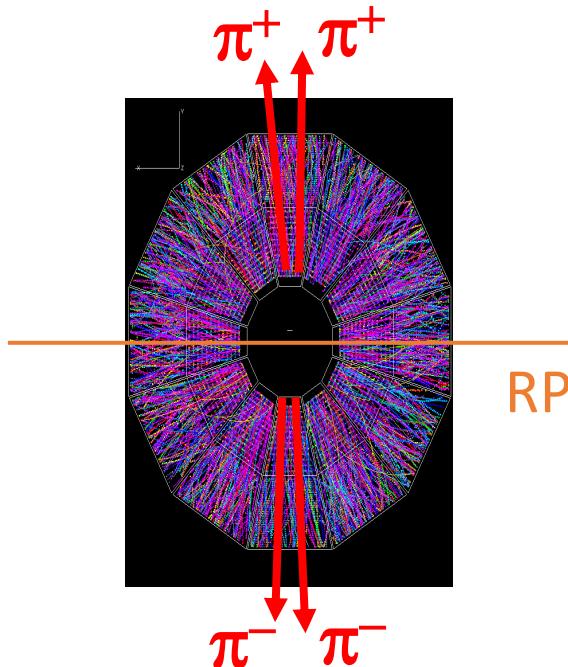
# OUTLINE

1. The  $\Delta\gamma$  observable
2. Flow-induced background
3. Nonflow backgrounds
4. Remarks on possible additional issues
5. Summary

# $\Delta\gamma$ CORRELATOR AND EARLY RESULTS

Voloshin, PRC 2004  
STAR, PRL 2009, PRC 2010

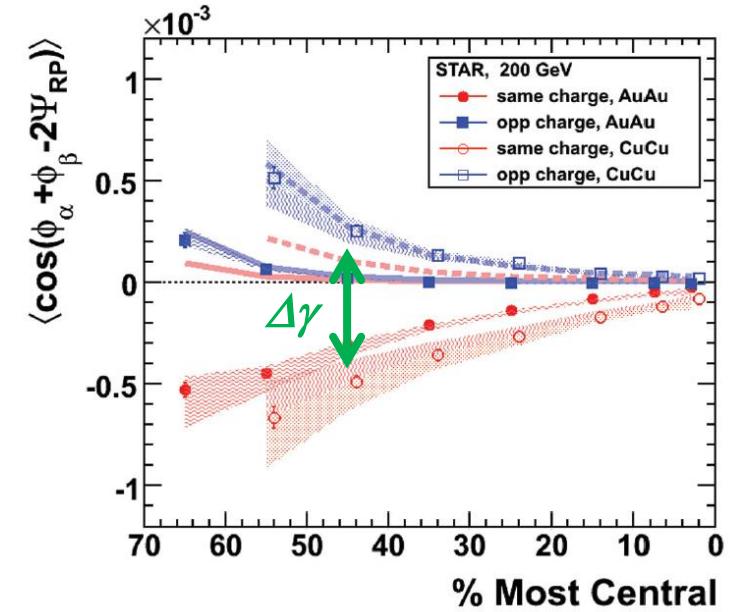
Look for charge separation



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

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

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



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

# SIGNIFICANT FLOW-INDUCED BACKGROUND

Voloshin 2004

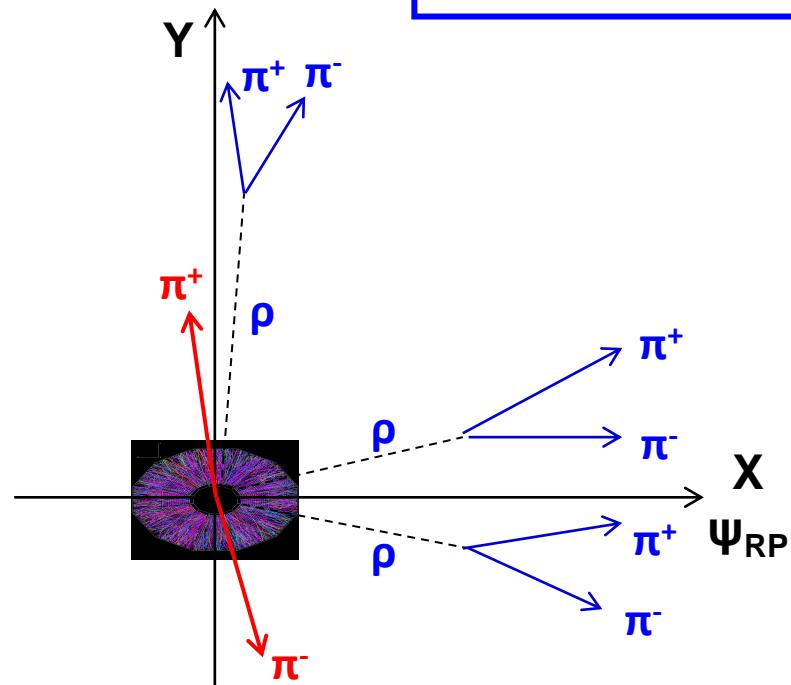
FW 2009

Bzdak, Koch, Liao 2010

Pratt, Schlichting 2010

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

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



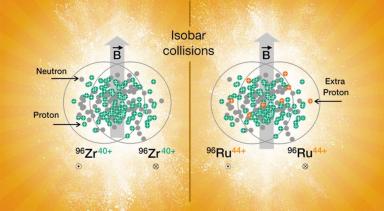
$$dN_\pm / d\varphi \propto 1 + 2v_1 \cos \varphi^\pm + 2a_\pm \cdot \sin \varphi^\pm + 2v_2 \cos 2\varphi^\pm + \dots$$

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

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

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

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



# ISOBAR COLLISIONS

Voloshin, PRL 105 (2010) 172301

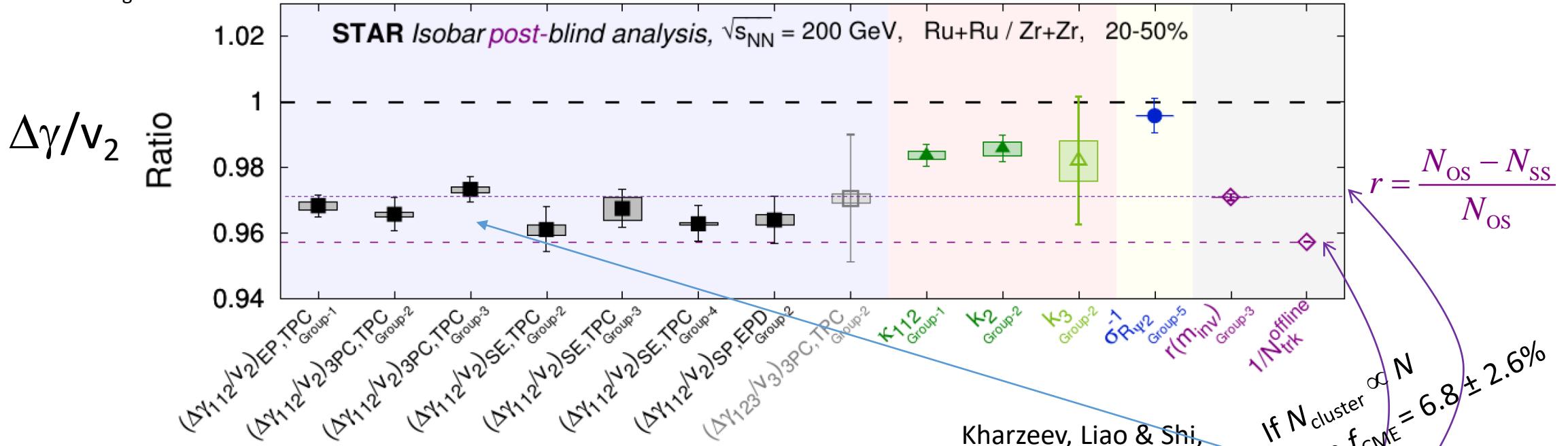
STAR, PRC 105 (2022) 014901

Haojie Xu et al. PRL 121 (2018) 022301

Hanlin Li et al. PRC 98 (2018) 054907

Same A  $\rightarrow$  Same background  
Different Z  $\rightarrow$  different signal

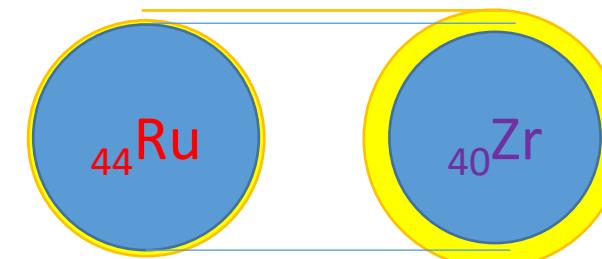
When background is large, we cannot rely on models. Have to use data!



0.4% precision is achieved!

But isobar ratios are below unity.

Primary reason is mult. difference  
due to nuclear structure subtlety

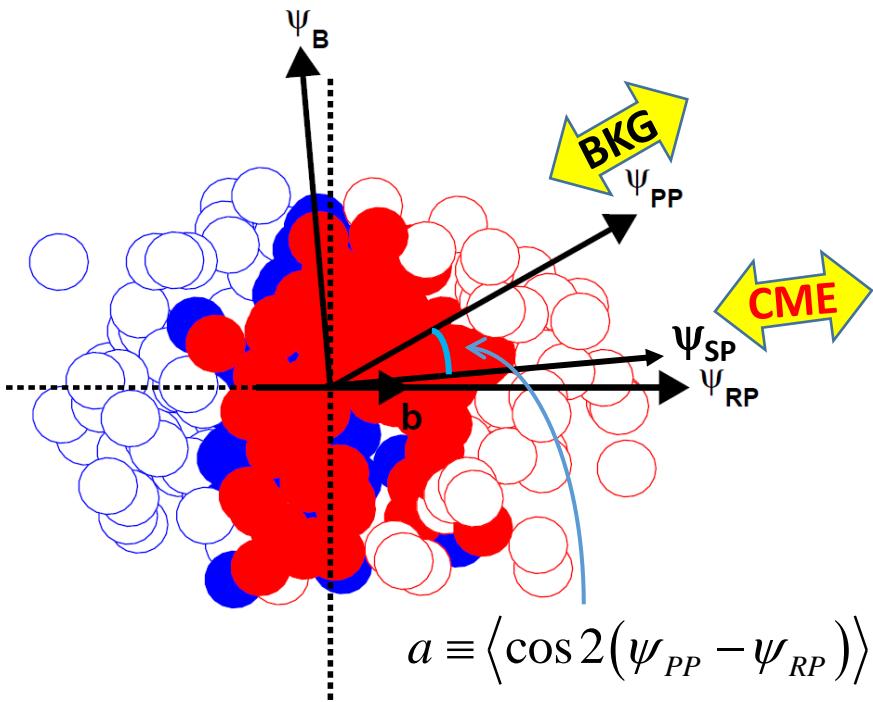


$$\Delta\gamma_{bkg} \propto N_{cluster} / N^2$$

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

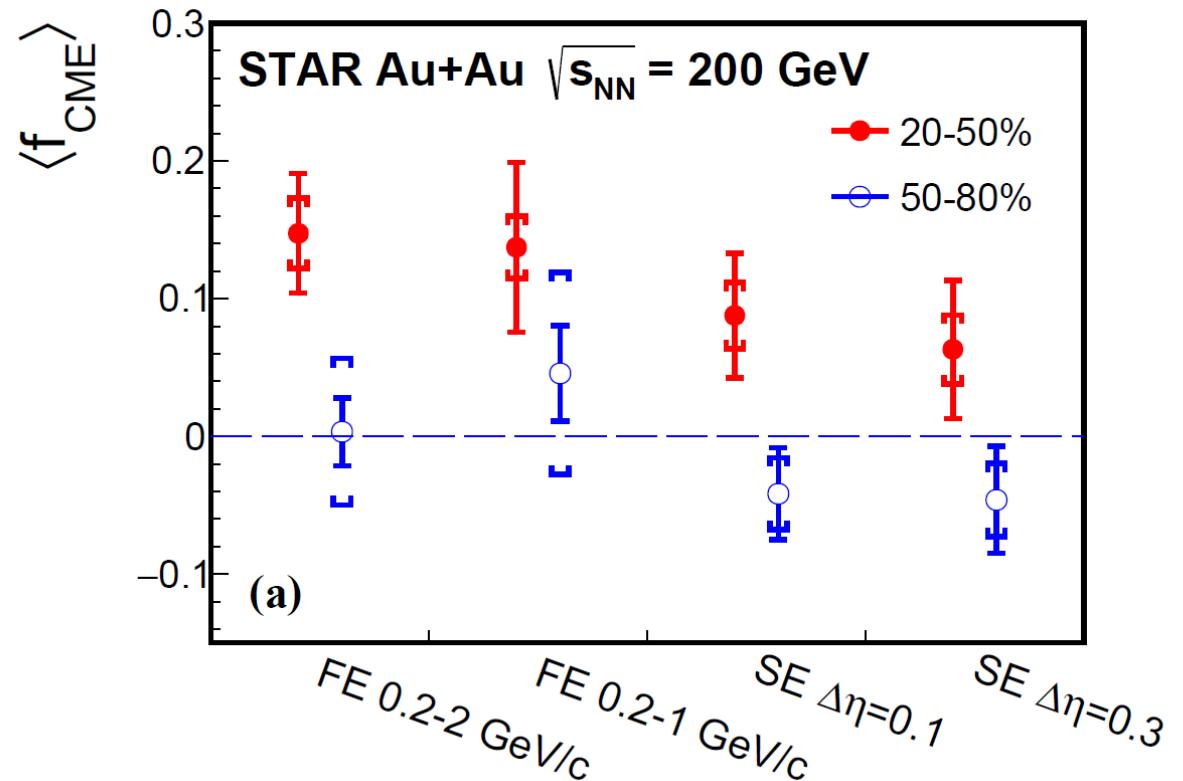
# 200 GEV AU+AU COLLISIONS

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



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

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



- Peripheral 50-80%: consistent-with-zero signal
- Mid-central 20-50%: indication of finite CME,  $\sim 2\sigma$  significance

# THE NONFLOW ISSUE

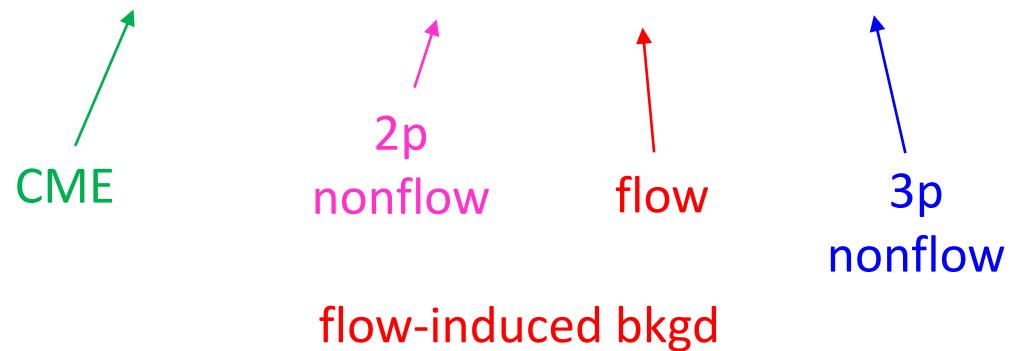
Feng et al., PRC 105 (2022) 024913

- The flow-induced background is very-well understood
- Nonflow issues are the next/final hurdle

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

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

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



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

$$\begin{aligned} N &\approx N_+ \approx N_- \\ C_{2p} &= \langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{2p}) \rangle \\ C_{3p} &= \langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_c) \rangle_{3p} \end{aligned}$$

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

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

# NONFLOW ESTIMATES IN ISOBAR

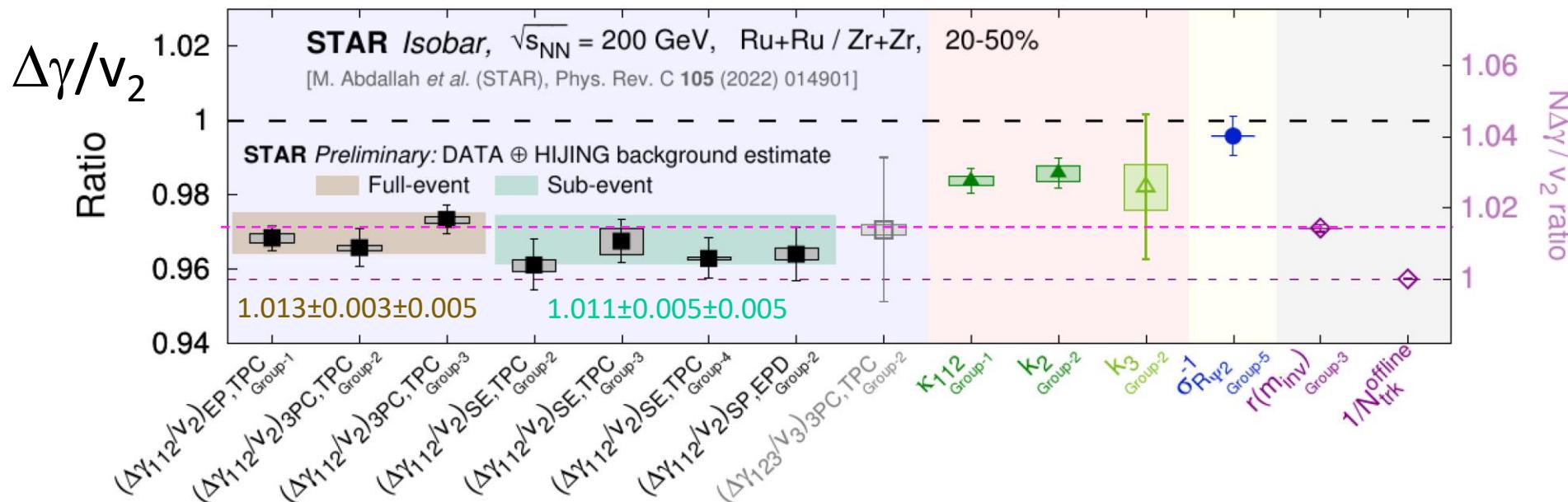
Feng et al., PRC 105 (2022) 024913  
 FENG Yicheng (STAR): QM'2022, SQM'2022  
 to be released before QM23

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

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

$$\begin{aligned} v_2^{*2} &= v_2^2 + v_{2,nf}^2 & N &\approx N_+ \approx N_- \\ \varepsilon_{nf} &\equiv v_{2,nf}^2 / v_2^2 & \Delta X &\equiv X^{\text{Ru}} - X^{\text{Zr}} \end{aligned}$$

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



Current total uncertainty:  
 $0.4\% \oplus 0.3\% \oplus 0.5\% = 0.7\%$

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

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

# NONFLOW IN AU+AU

Feng et al., PRC 105 (2022) 024913

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

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

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

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

$$\frac{A}{a} = \frac{\Delta\gamma\{\text{SP}\}/\Delta\gamma\{\text{PP}\}}{v_2\{\text{SP}\}/v_2^*\{\text{PP}\}} = \frac{C_3\{\text{SP}\}}{v_2^2\{\text{SP}\}} \cdot \frac{v_2^{*2}\{\text{PP}\}}{C_3\{\text{PP}\}} = \frac{1 + \epsilon_{\text{nf}}}{1 + \frac{\epsilon_3/\epsilon_2}{Nv_2^2\{\text{PP}\}}}$$

$$\epsilon_2 = \frac{C_{2p}N_{2p}}{N} \cdot \frac{v_{2,2p}}{v_2} \approx N\Delta\gamma/v_2 \quad \epsilon_3 = \frac{C_{3p}N_{3p}}{2N}$$

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

v<sub>2</sub> nonflow → makes TPC Δγ smaller  
→ positive f<sub>CME</sub>

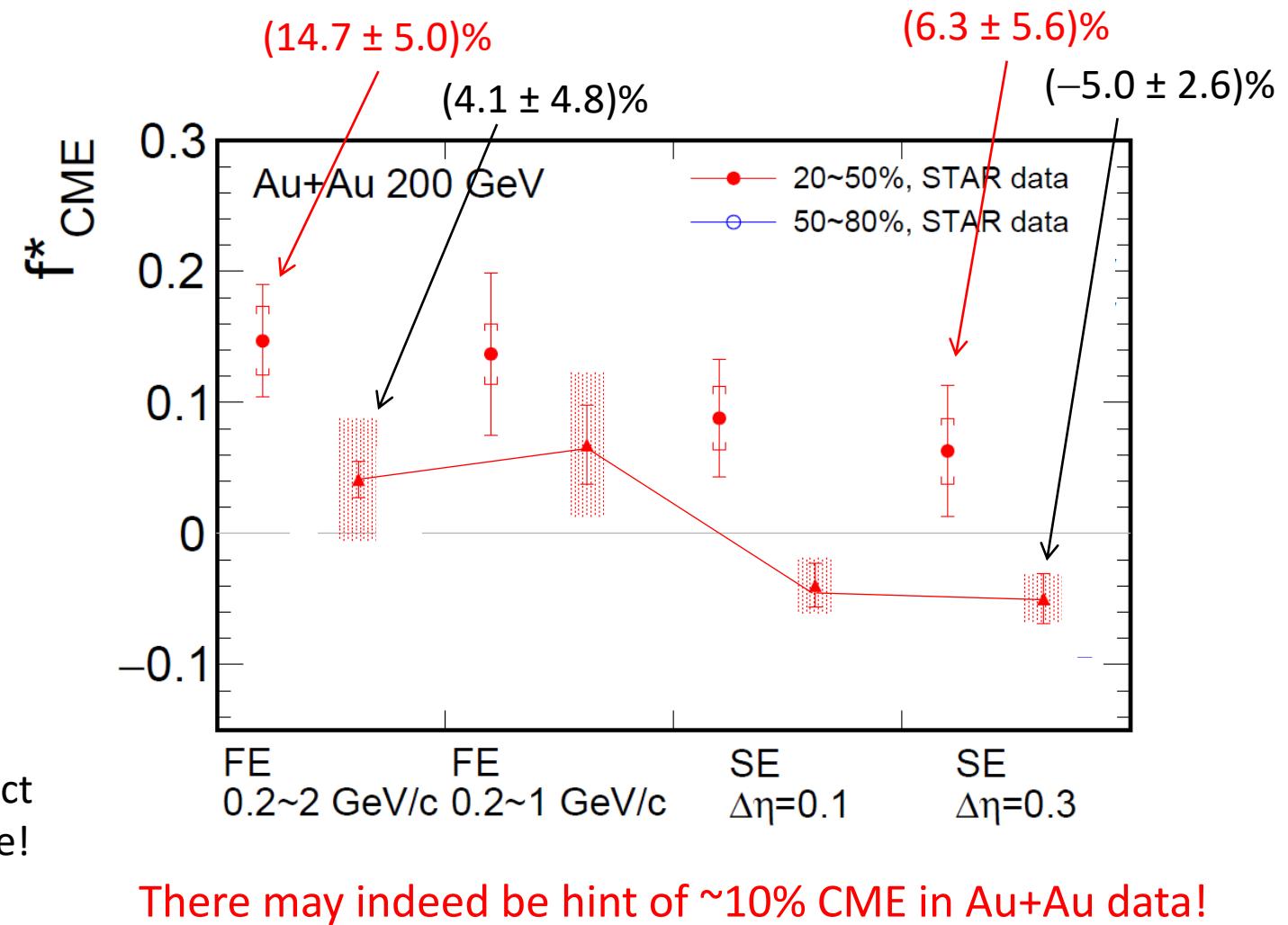
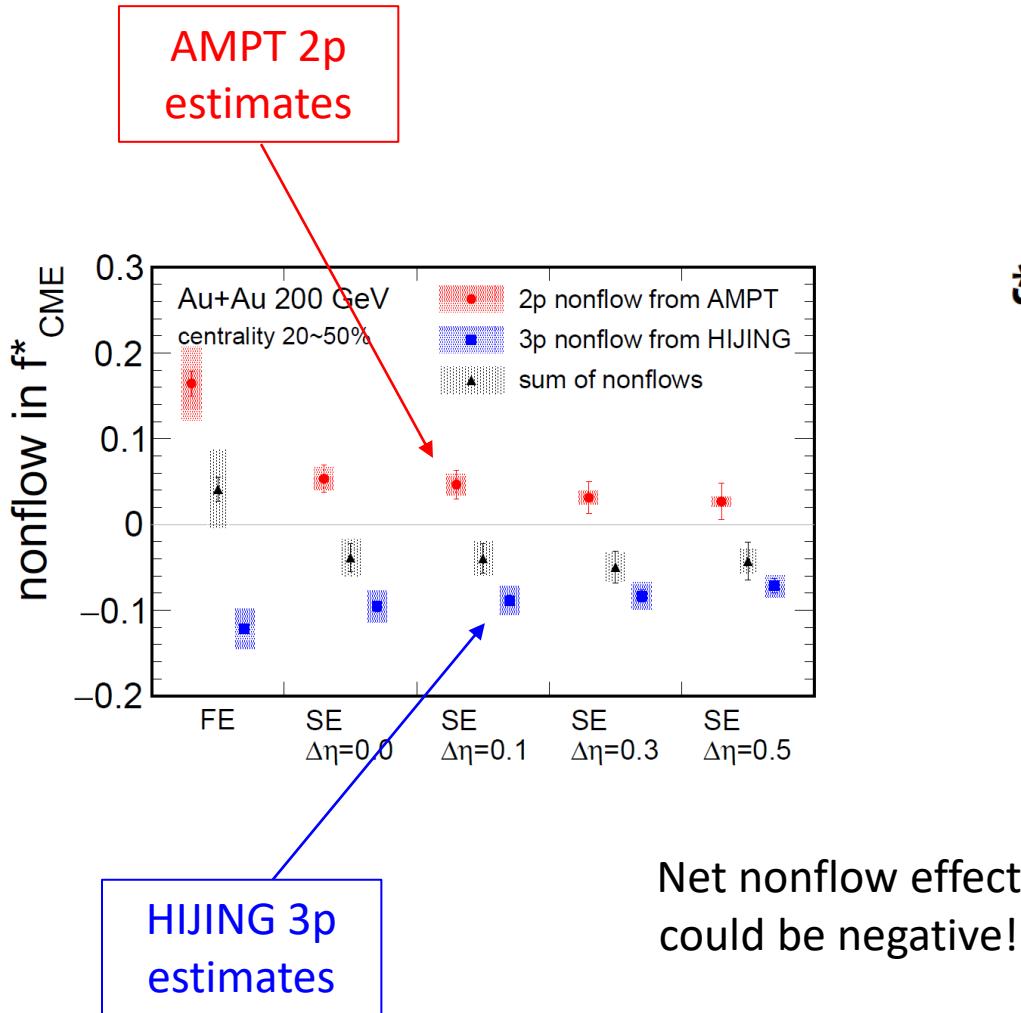
3p nonflow → makes TPC Δγ larger  
→ negative f<sub>CME</sub>

$$f_{\text{CME}}^* \approx \left( \epsilon_{\text{nf}} - \frac{\epsilon_3/\epsilon_2}{Nv_2^2\{\text{EP}\}} \right) \Bigg/ \left( \frac{1 + \epsilon_{\text{nf}}}{a^2} - 1 \right)$$

$$f_{\text{CME}}^* = \left( \frac{1 + \epsilon_{\text{nf}}}{1 + \frac{\epsilon_3/\epsilon_2}{Nv_2^2\{\text{EP}\}}} - 1 \right) \Bigg/ \left( \frac{1 + \epsilon_{\text{nf}}}{a^2} - 1 \right) = \left( \frac{1 + \epsilon_{\text{nf}}}{1 + \frac{(1 + \epsilon_{\text{nf}})\epsilon_3/\epsilon_2}{Nv_2^{*2}\{\text{EP}\}}} - 1 \right) \Bigg/ \left( \frac{1}{a^{*2}} - 1 \right)$$

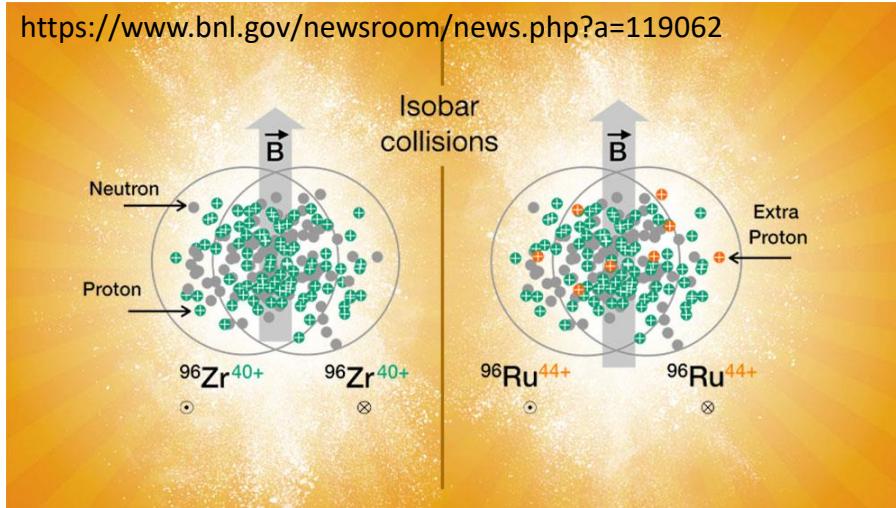
# NONFLOW SUBTRACTED SIGNAL

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



# 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  $\sim \text{Au+Au} \sim 10\%$ ,

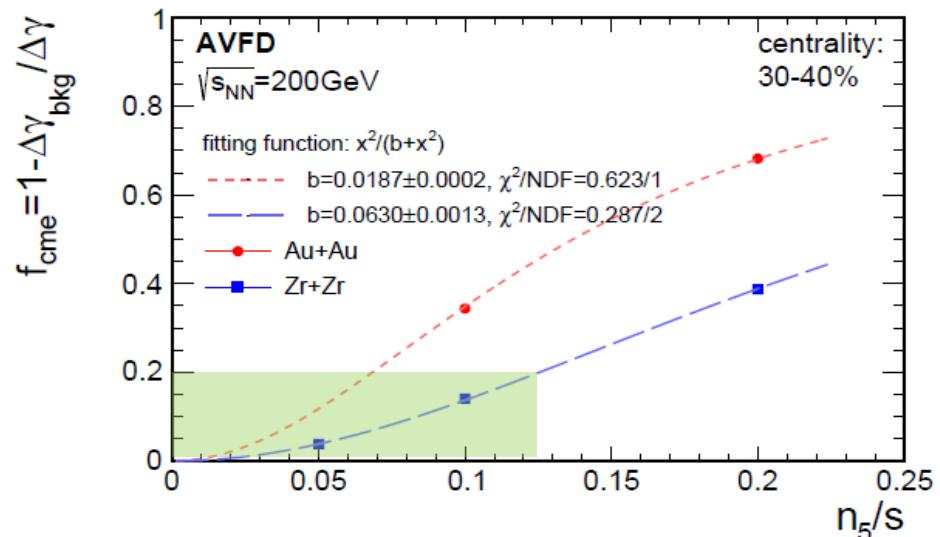
Then isobar difference  $\sim 15\% * 10\% = 1.5\%$ .

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

Background  $\propto 1/N \rightarrow \text{isobar/AuAu} \sim 2$

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

Could be x3 reduction in  $f_{\text{CME}}$



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

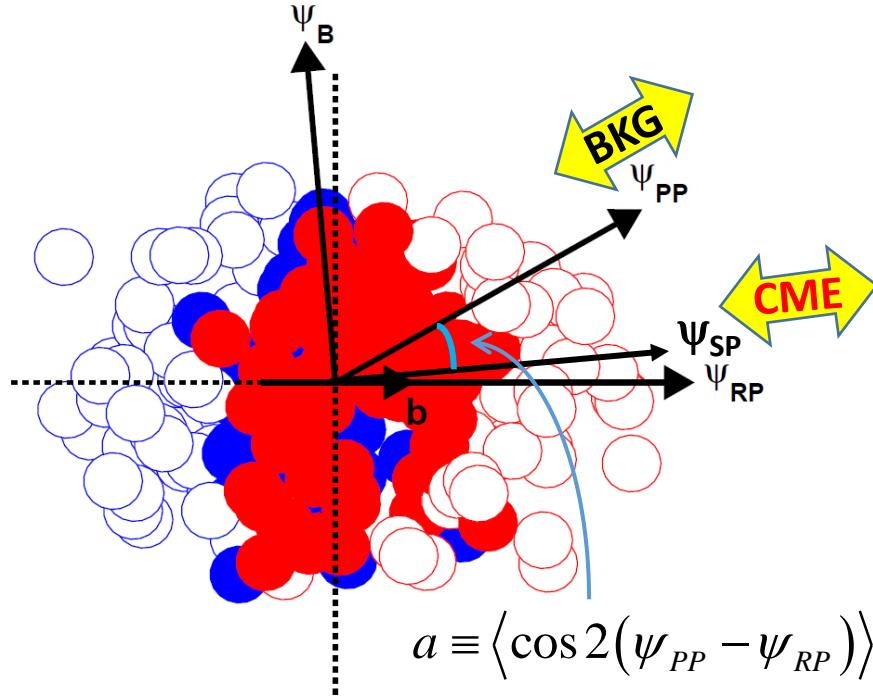
$$\text{Ru/Zr} = 1 + 15\% * 3\% = 1.005 (\pm 0.004)$$

Any additional issues?

A few remarks

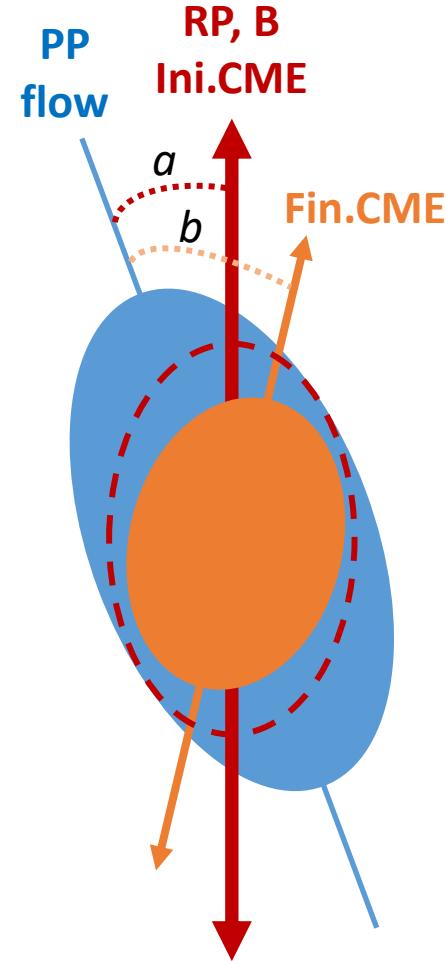
# FINAL-STATE EVOLUTION EFFECT?

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



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

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



fluctuations are independent from those of the  $\psi_{PP}$  [39]. It is possible, however, that the magnetic field projection factor is not strictly  $a$  because of final-state evolution effects on the charge separation [46]. A full study of this would require rigorous theoretical input and is beyond the

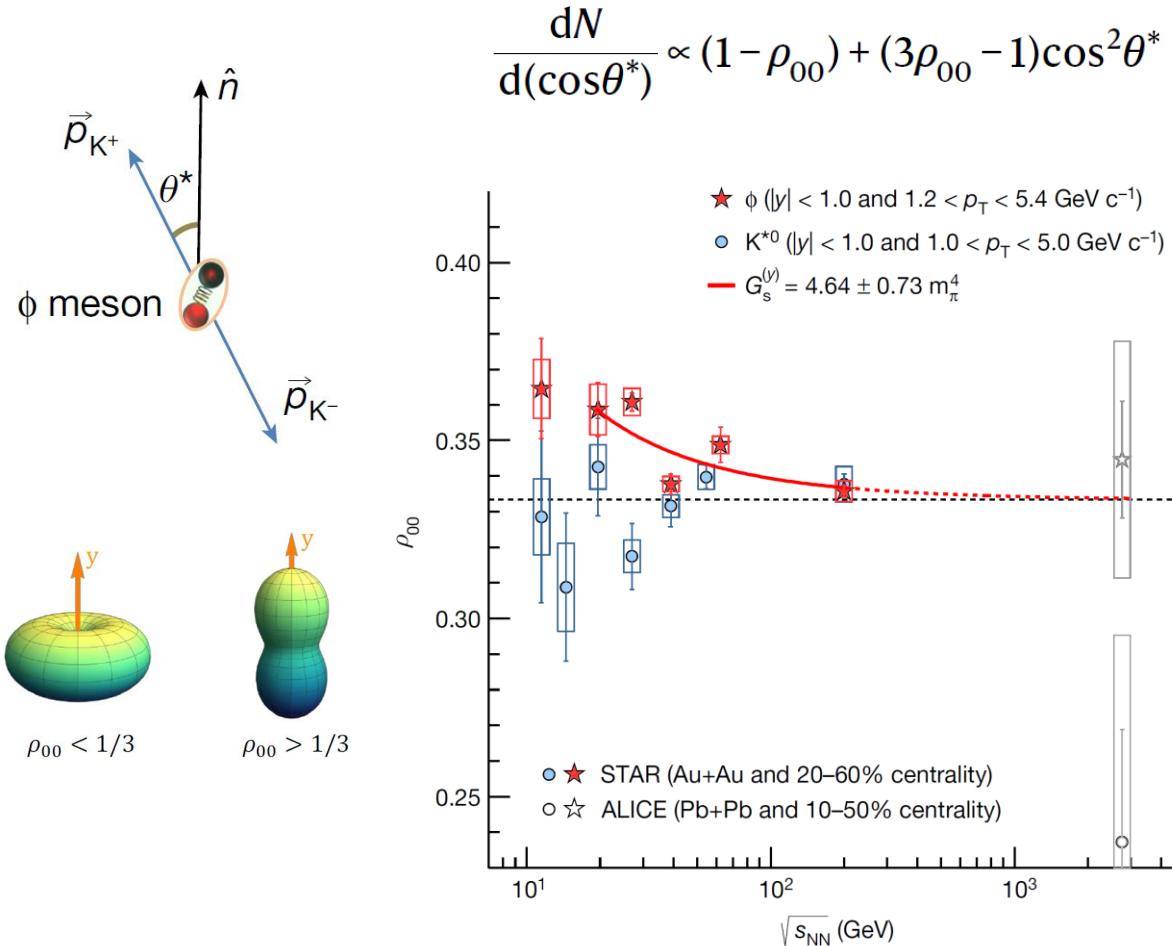
$$f_{\text{CME}}\{b\} = \frac{\Delta\gamma_{\text{CME}}\{\text{PP}\}}{\Delta\gamma\{\text{PP}\}} = \frac{A/a - 1}{1/a^2 - 1}$$

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

Taking  $b = a$  would overestimate the final-state CME fraction, but still an underestimate of the initial CME signal.

# 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



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  $\Delta\gamma$ .  
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 like participant flow background.

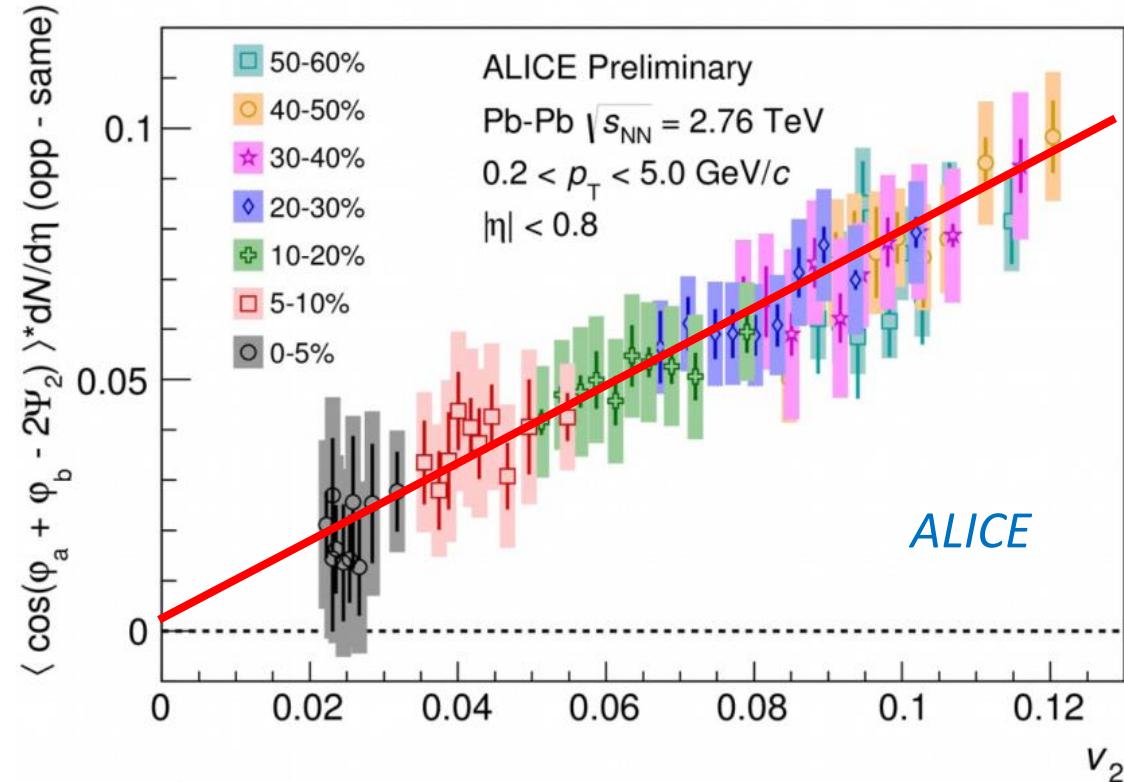
$v_2$  measurement is affected by  $\rho$  spin alignment, and can be significant.

# EVENT-SHAPE-ENGINEERING METHOD

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

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

3p nonflow  
brings down  
 $\Delta\gamma$  magnitude



Use  $v_2\{4\}$  to minimize nonflow?  
Implicit assumption: fluct.  $\sim v_2$

ALICE: sophisticated (model-dep.)  
assumption of B determination within  
a given centrality

Promising way to extract  
possible CME signal

Will need to assess  
nonflow effects as well

# SUMMARY

- CME has been one of the most active and challenging fields of research
- Theoretically well understood, although difficult for quantitative predictions
- Experimentally many innovative approaches, including a dedicated isobar run
- **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