Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions

UCLA Chirality Retreat

Perspectives on the STAR isobar and gold-gold data

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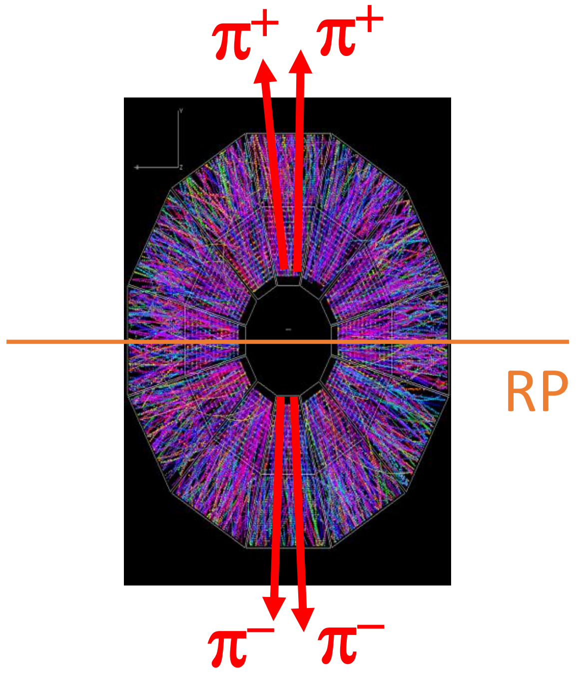
OUTLINE

1. Various methods to eliminate flow-induced backgrounds
2. Further background contamination from nonflow and genuine 3-particle correlations
3. Hint of CME in Au+Au, and upper limit in isobar
4. Summary & outlook

THE Δγ CORRELATOR

Voloshin, PRC 2004

Look for charge separation

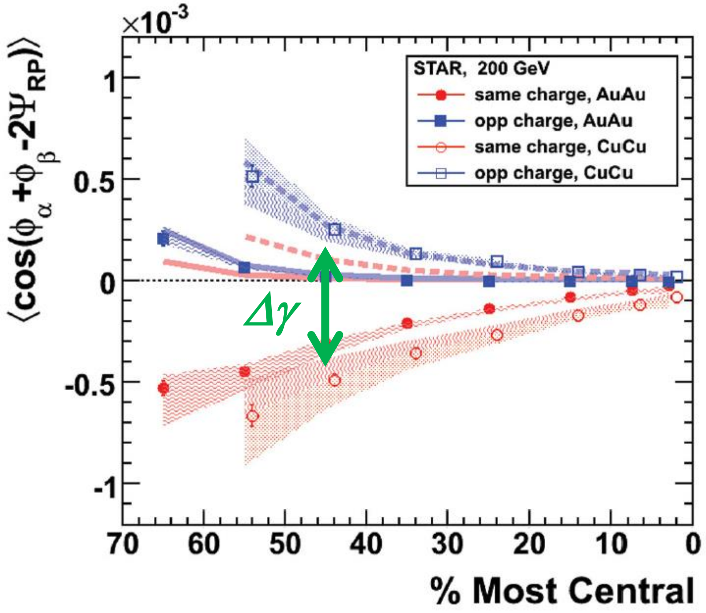


$$\gamma_{\alpha\beta} = \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{RP}) \right\rangle$$

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

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

STAR, PRL 2009, PRC 2010



Significant signal

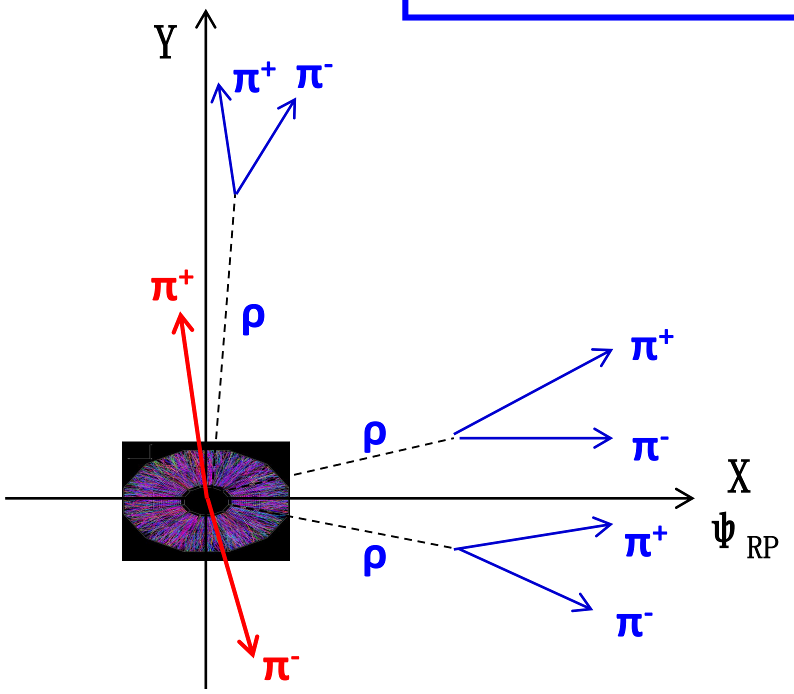
$\Delta\gamma \sim 5 \times 10^{-4}$

BACKGROUND IN $\Delta\gamma$ CORRELATOR

Voloshin 2004; FW 2009; Bzdak, Koch, Liao 2010; Pratt, Schlichting 2010; …

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

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



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

$$\gamma_{\alpha\beta} = \left[\left\langle \cos(\varphi_\alpha - \psi_{RP}) \cos(\varphi_\beta - \psi_{RP}) \right\rangle - \left\langle \sin(\varphi_\alpha - \psi_{RP}) \sin(\varphi_\beta - \psi_{RP}) \right\rangle \right]$$

$$+ \left[\frac{N_{cluster}}{N_\alpha N_\beta} \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{cluster}) \cos(2\varphi_{cluster} - 2\varphi_{RP}) \right\rangle \right]$$

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

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

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

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

SLIGHTLY MORE FORMALLY…

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

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

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

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

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

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

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

CME

2p nonflow

flow

3p nonflow

flow-induced bkgd

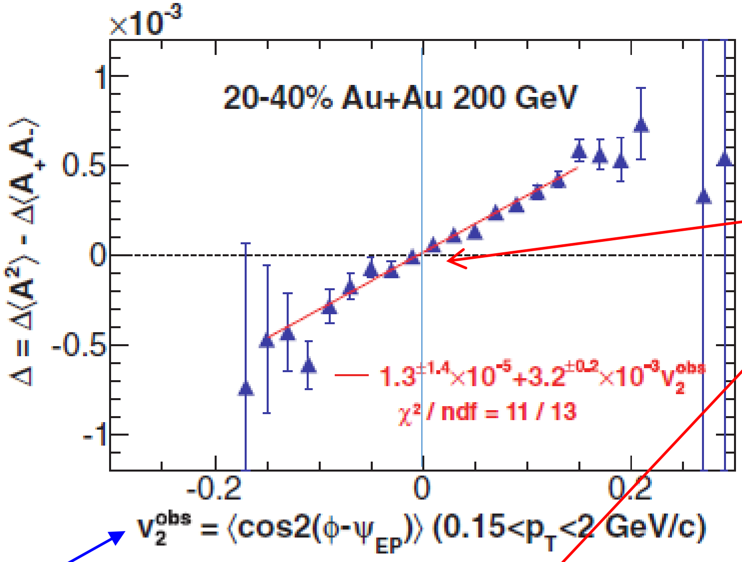
$v_{2,c\perp B}$: v_2 of c particle wrt direction $\perp B$

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

STATISITICAL EVENT-SHAPE-ENGINEERING

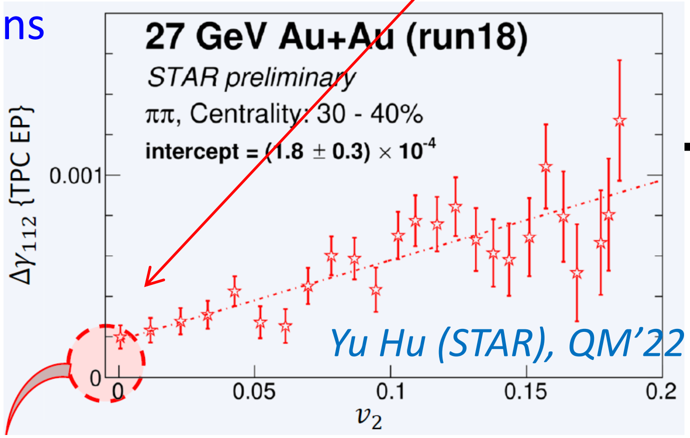
STAR, PRC 89 (2014) 044908

Here Δ is similar to $\cos(\alpha+\beta-2\psi)$ correlator



Primarily stat. fluctuations

Event-by-event v_2 technique

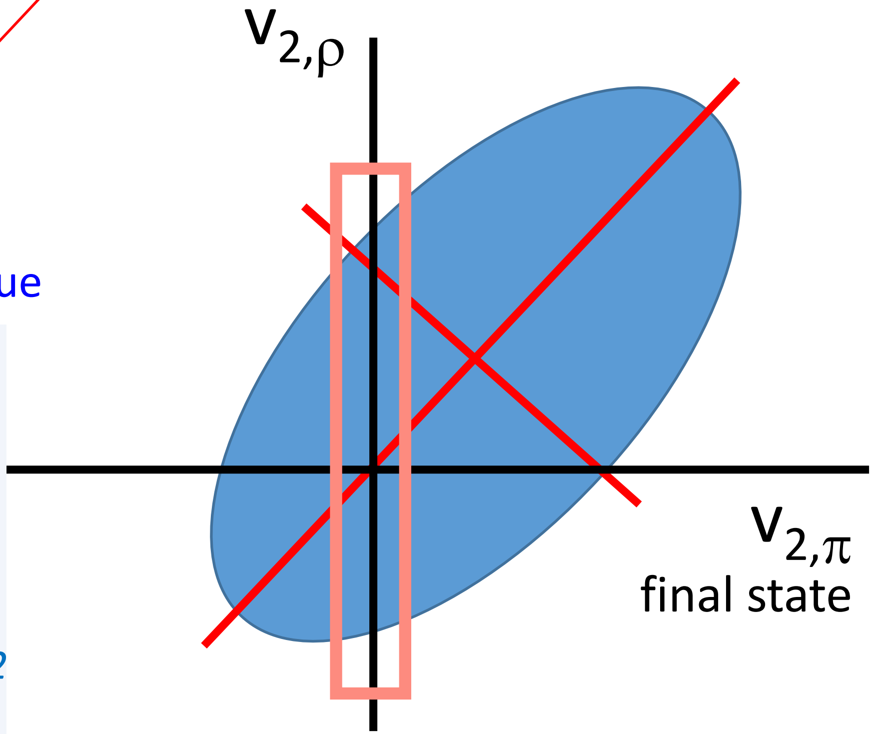


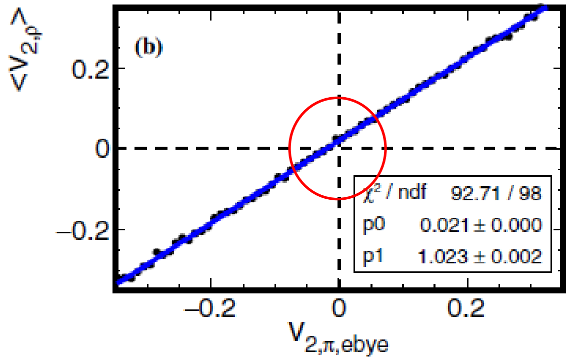
Yu Hu (STAR), QM'22

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

Still has residual background, because background ~ $v_{2,\rho}$ not $v_{2,\pi}$

FW, Jie Zhao, PRC 95 (2017) 051901(R)





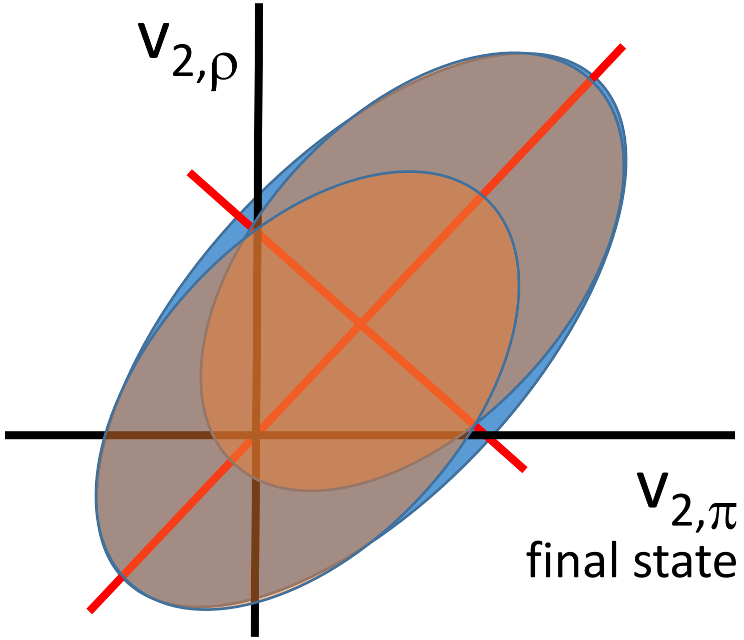
- Engineering on stat. fluctuations
- Background suppressed, but not totally eliminated
- LHC does not have this issue as v_2 selection in different phase space

DYNAMICAL EVENT-SHAPE-ENGINEERING

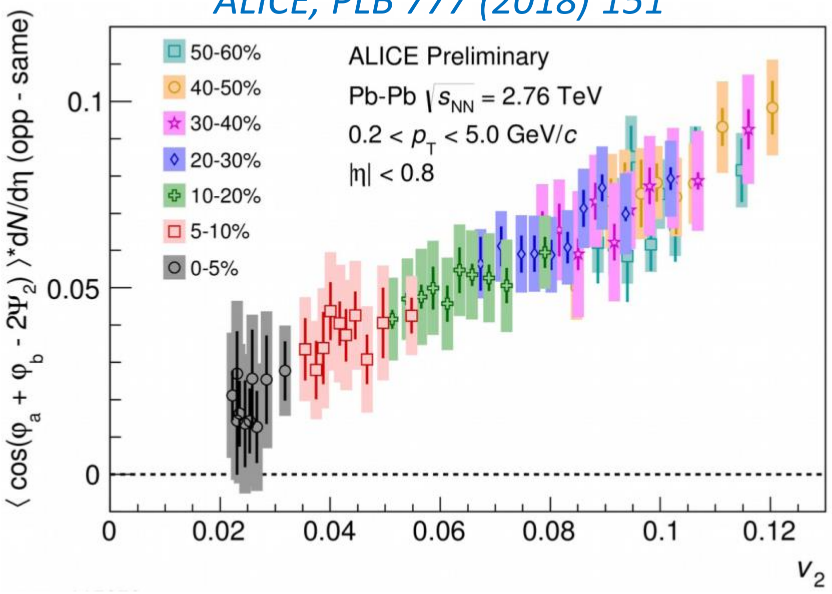
Schukraft, Timmins, Voloshin, PLB 719 (2013) 394

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

ESE displaced from
α, β phase space



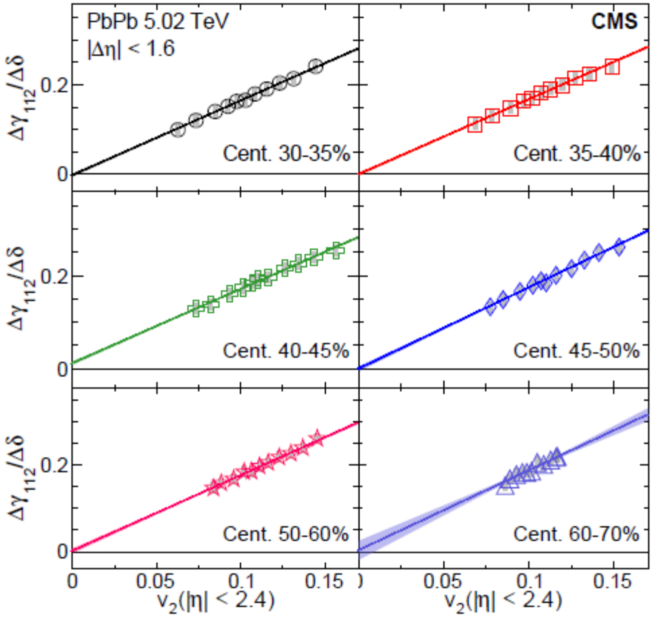
ALICE, PLB 777 (2018) 151



More sophisticated (model-dep.) assumption of B dependence on v2 within a given centrality

Upper limit 26%

CMS, PRC 97 (2018) 044912



Assume CME does not depend on v_2 within a given centrality

Upper limit 7%

Promising way to extract possible CME signal. Will need to assess nonflow effects

THE R OBSERVABLE

*Ajitanand, Lacey, et al., PRC **83** (2011) 011901*
*Magdy, Lacey, et al., PRC **97** (2018) 061901(R)*

$$\Delta S = \langle \sin(\varphi - \psi_2) \rangle_+ - \langle \sin(\varphi - \psi_2) \rangle_-$$

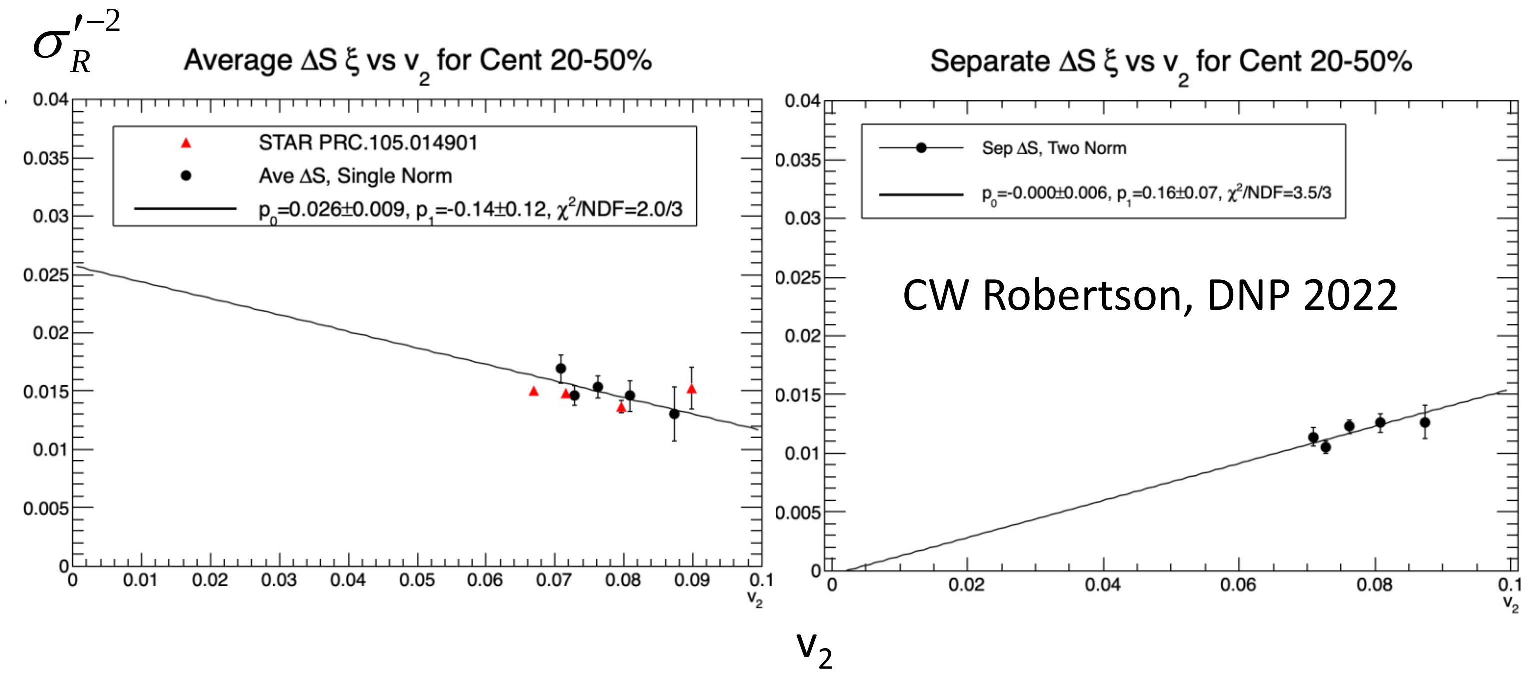
$$R(\Delta S) = \frac{N(\Delta S_{\text{real}})}{N(\Delta S_{\text{shuffled}})} \Big/ \frac{N(\Delta S^{\perp}_{\text{real}})}{N(\Delta S^{\perp}_{\text{shuffled}})}$$

Width of R(ΔS) distribution reduces to variance sin*sin, cos*cos → equivalently the $\Delta\gamma$ variable

Normalized by shuffled width: $\sigma_R'^{-2} = N\Delta\gamma \propto v_2$

Choudhury et al., CPC 46 (2022) 014101

Execution of R analysis: $\Delta S = \left(\Delta S^{\text{East-EP}}_{\text{West-POI}} + \Delta S^{\text{West-EP}}_{\text{East-POI}} \right) / 2$



Earlier claims of CME; many issues identified.
ESE studies indicate "v2-independence."
Latest claim by Lacey et al., arXiv:2203.10029:
Scale by N, so isobar R compatible with CME.
See *Comment* by FW, arXiv:2204.08450

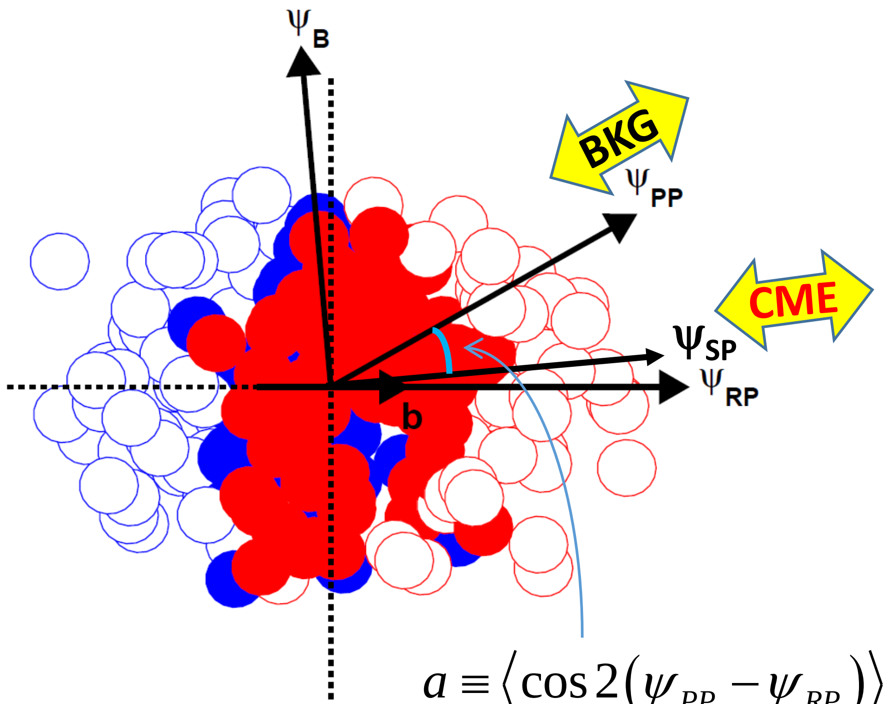
Issue identified: Reuse of data in average causes autocorrelation, yielding non-zero intercept. *Feng et al, PRC 103 (2021) 034912*

Positive intercept not present in analysis with separate ΔS

SPECTATOR & PARTICIPANT PLANES

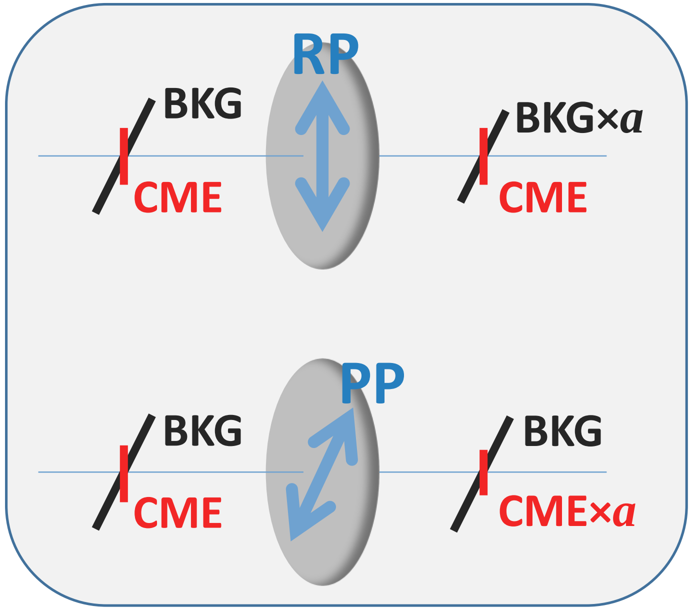
H.-j. Xu, FW, et al., CPC 42 (2018) 084103, arXiv:1710.07265
S.A. Voloshin, PRC 98 (2018) 054911, arXiv:1805.05300

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



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

INTRA-EVENT "CME-v_2 FILTER"



IN THE SAME EVENT

$$\Delta\gamma\{\text{SP}\} = \frac{\Delta\gamma_{\text{CME}}\{\text{PP}\}}{a} + a\Delta\gamma_{\text{Bkg}}\{\text{PP}\}$$

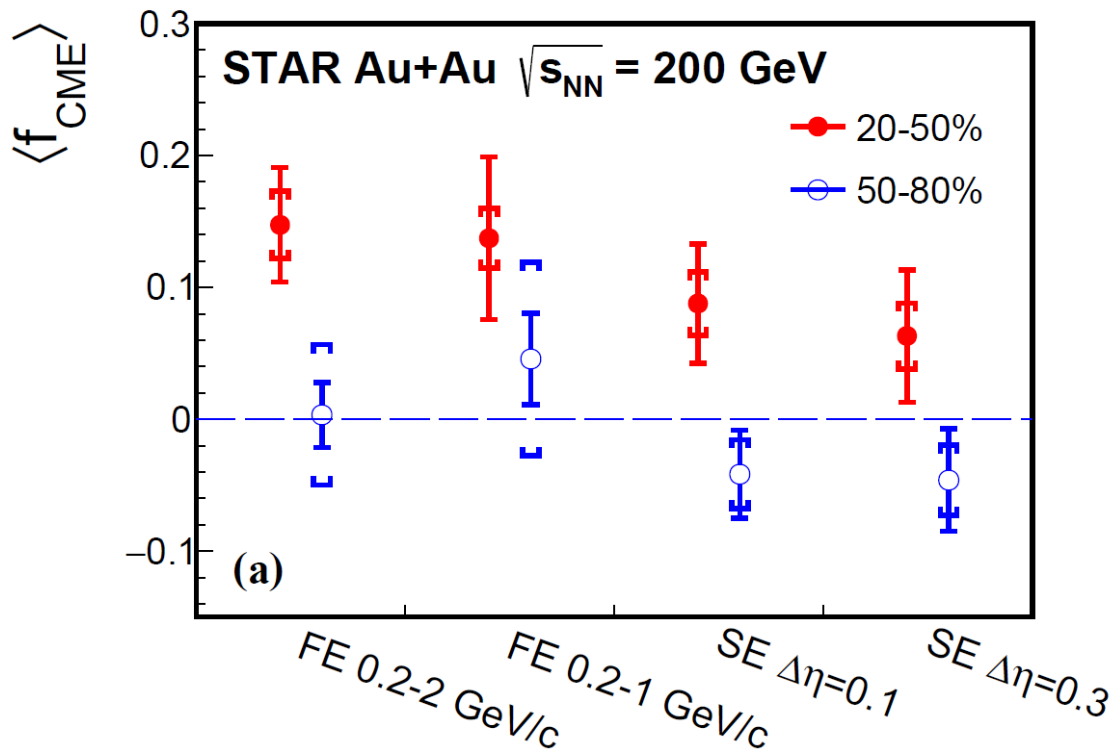
$$\Delta\gamma\{\text{PP}\} = \Delta\gamma_{\text{CME}}\{\text{PP}\} + \Delta\gamma_{\text{Bkg}}\{\text{PP}\}$$

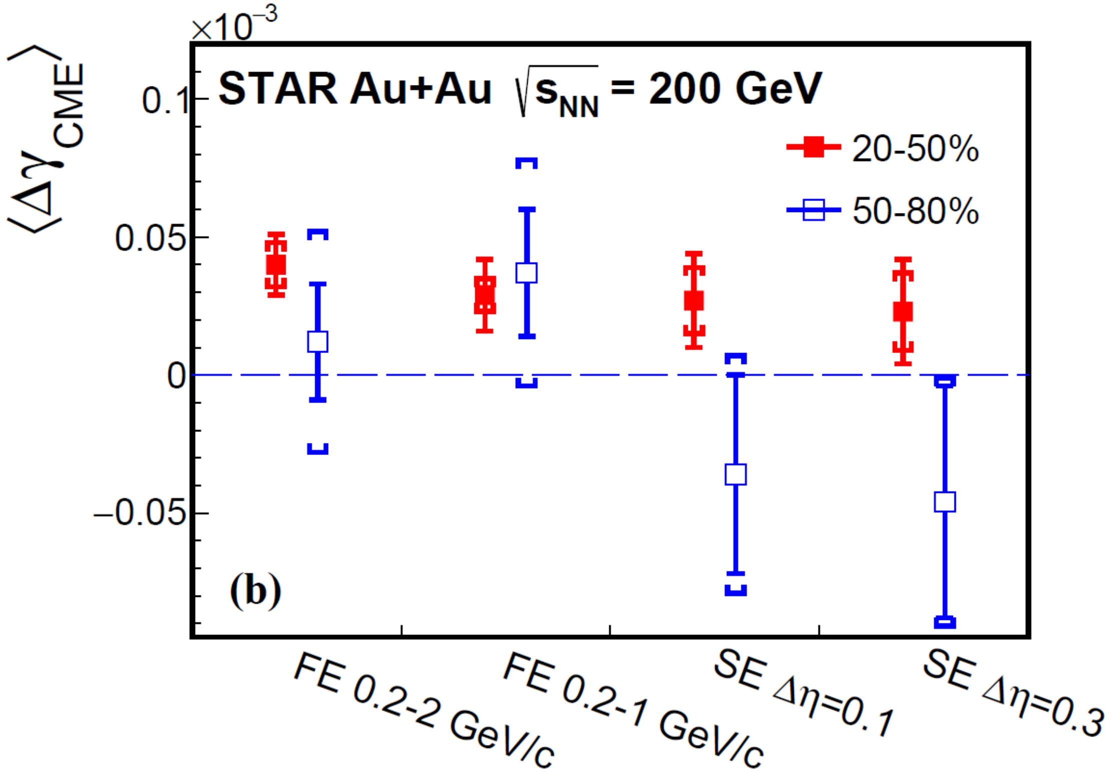
$$f_{\text{CME}} = \frac{\Delta\gamma_{\text{CME}}\{\text{PP}\}}{\Delta\gamma\{\text{PP}\}} = \frac{A/a-1}{1/a^2-1}$$

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

Au+Au Collisions at 200 GeV (2.4B MB)

STAR, PRL 128 (2022) 092301, arXiv:2106.09243





- Peripheral 50-80% collisions: consistent-with-zero signal with relatively large errors
- Mid-central 20-50% collisions: indication of finite CME signal with 1-3σ significance
- How much is there remaining nonflow contamination?

REMAINING NONFLOW EFFECTS

Feng, FW, et al., PRC 105 (2022) 024913, arXiv:2106.15595

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

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

$$\Delta C_3 = 2\langle a_1^2\rangle v_{2,c\perp B} + \frac{C_{\rm 2p}N_{\rm 2p}}{N^2} v_{2,\rm 2p} v_{2,c} + \frac{C_{\rm 3p}N_{\rm 3p}}{2N^3}$$

Nonflow in $\Delta\gamma$ → negative $f_{\rm CME}$

$$\Delta C_3^{\rm Bkg}\{\rm SP\} = \frac{C_{\rm 2p}N_{\rm 2p}}{N^2} v_{2,\rm 2p}\{\rm SP\} v_{2,c}\{\rm SP\}$$

$$\Delta C_3^{\rm Bkg}\{\rm EP\} = \frac{C_{\rm 2p}N_{\rm 2p}}{N^2} v_{2,\rm 2p}\{\rm EP\} v_{2,c}\{\rm EP\} + \frac{C_{\rm 3p}N_{\rm 3p}}{2N^3}$$

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

$$\varepsilon_3 = \frac{C_{\rm 3p}N_{\rm 3p}}{2N}$$

Nonflow in v_2 → positive $f_{\rm CME}$

$$v_2^*\{\rm PP\} = \sqrt{v_2^2\{\rm PP\} + v_{2,\rm nf}^2}$$

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

$$f^*_{\rm CME} \approx \left(\epsilon_{\rm nf} - \frac{\epsilon_3/\epsilon_2}{Nv_2^2\{\rm EP\}}\right) \Big/ \left(\frac{1+\epsilon_{\rm nf}}{a^2} - 1\right)$$

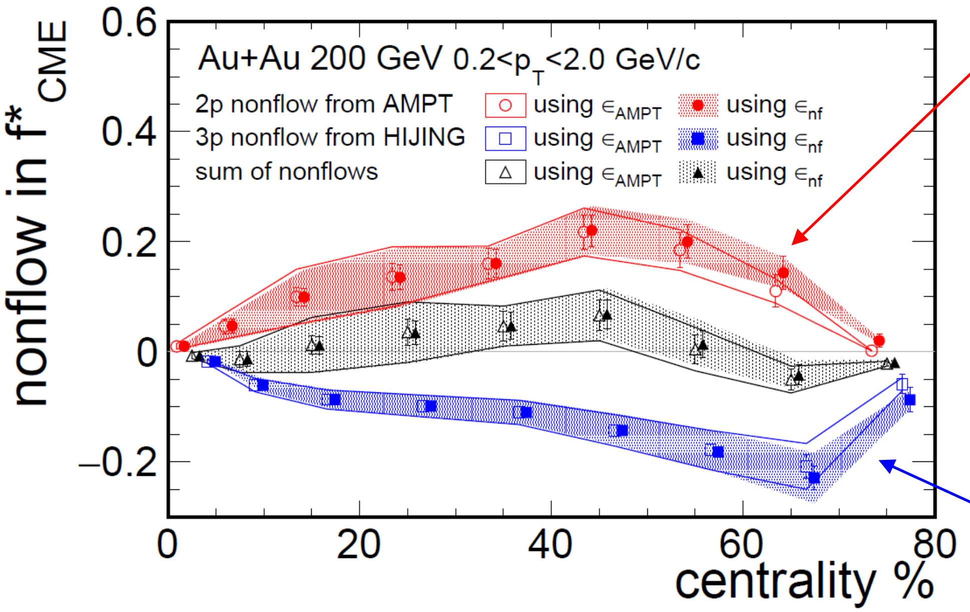
$$f^*_{\rm CME} = \left(\frac{1+\epsilon_{\rm nf}}{1+\frac{\epsilon_3/\epsilon_2}{Nv_2^2\{\rm EP\}}} - 1\right) \Big/ \left(\frac{1+\epsilon_{\rm nf}}{a^2} - 1\right) = \left(\frac{1+\epsilon_{\rm nf}}{1+\frac{(1+\epsilon_{\rm nf})\epsilon_3/\epsilon_2}{Nv_2^{*2}\{\rm EP\}}} - 1\right) \Big/ \left(\frac{1}{a^{*2}} - 1\right)$$

MODEL ESTIMATES OF NONFLOW

Feng, FW, et al., PRC 105 (2022) 024913, arXiv:2106.15595

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

$$f^*_{\mathrm{CME}} \approx \left(\epsilon_{\mathrm{nf}} - \frac{\epsilon_3/\epsilon_2}{Nv_2^2\{\mathrm{EP}\}}\right) \Big/ \left(\frac{1+\epsilon_{\mathrm{nf}}}{a^2} - 1\right)$$

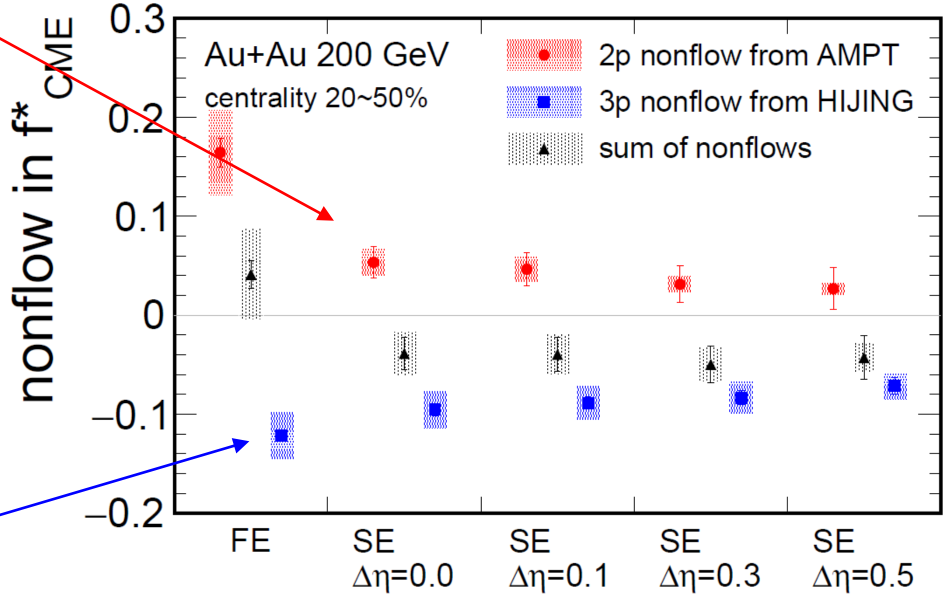


AMPT 2p estimates

v_2 nonflow data analysis ongoing

Limited-scope data comparison ongoing

HIJING 3p estimates

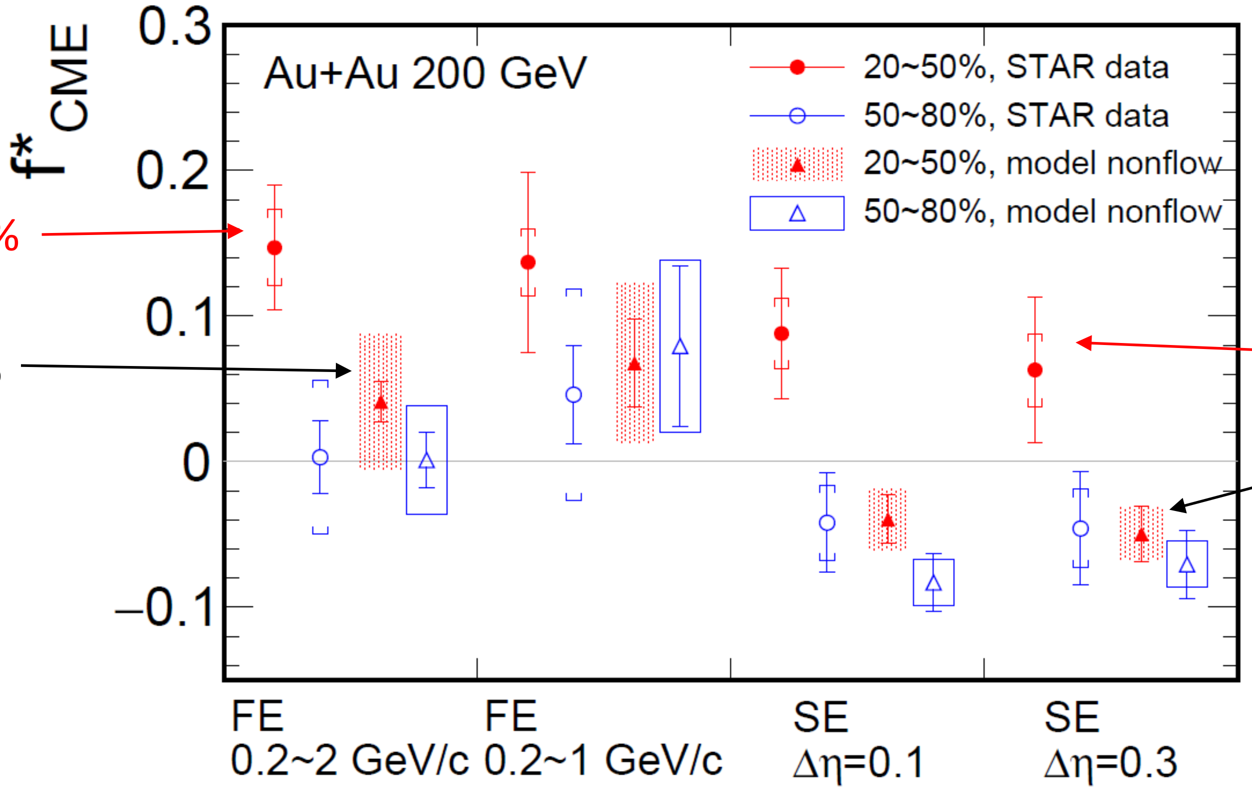


IMPLICATIONS TO Au+Au DATA

STAR, PRL 128 (2022) 092301, arXiv:2106.09243
Feng, FW, et al., PRC 105 (2022) 024913, arXiv:2106.15595

(14.7 ± 5.0)%

(4.1 ± 4.8)%



(6.3 ± 5.6)%

(−5.0 ± 2.6)%

Net nonflow effect could be negative

There may indeed be hint of CME in the Au+Au data

BACK TO ISOBAR DATA

$$\Delta C_3 = 2\left\langle a_1^2 \right\rangle v_{2,c\perp B} + \frac{C_{2\mathrm{p}} N_{2\mathrm{p}}}{N^2} v_{2,2\mathrm{p}} v_{2,c} + \frac{C_{3\mathrm{p}} N_{3\mathrm{p}}}{2N^3}$$

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

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

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

$$\frac{\left(N\Delta\gamma / v_2^*\right)^{\mathrm{Ru}}}{\left(N\Delta\gamma / v_2^*\right)^{\mathrm{Zr}}} = \frac{\left(NC_3 / v_2^{*2}\right)^{\mathrm{Ru}}}{\left(NC_3 / v_2^{*2}\right)^{\mathrm{Zr}}} = \frac{\left(C_{2\mathrm{p}} \frac{N_{2\mathrm{p}}}{N} \frac{v_{2,2\mathrm{p}}}{v_2}\right)^{\mathrm{Ru}}}{\left(C_{2\mathrm{p}} \frac{N_{2\mathrm{p}}}{N} \frac{v_{2,2\mathrm{p}}}{v_2}\right)^{\mathrm{Zr}}} \cdot \frac{\left(1+\varepsilon_{\mathrm{nf}}\right)^{\mathrm{Zr}}}{\left(1+\varepsilon_{\mathrm{nf}}\right)^{\mathrm{Ru}}} \cdot \frac{\left(1+\frac{\varepsilon_3/\varepsilon_2}{Nv_2^2}\right)^{\mathrm{Ru}}}{\left(1+\frac{\varepsilon_3/\varepsilon_2}{Nv_2^2}\right)^{\mathrm{Zr}}}$$

- Depending on the relative Ru+Ru/Zr+Zr difference of various nonflow effects, the baseline can be above, equal, or below unity
- Final isobar conclusion requires detailed nonflow studies

REMAINING NONFLOW EFFECTS

FENG, Yicheng (STAR): QM'2022, SQM'2022

Feng, FW, et al., PRC 105 (2022) 024913, arXiv:2106.15595

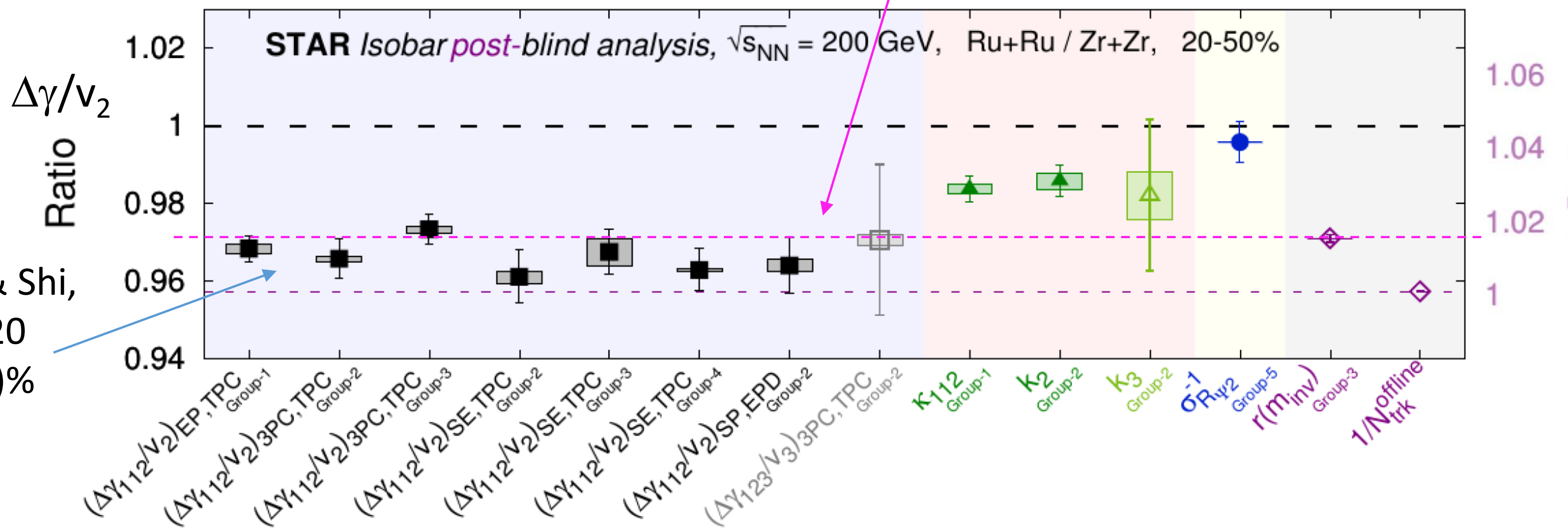
$$C_3 = \frac{C_{2p}N_{2p}}{N^2} v_{2,2p} v_2 + \frac{C_{3p}N_{3p}}{2N^3}; \quad C_{2p} \equiv \langle \cos(\alpha+\beta-2\phi_{2p}) \rangle, \quad C_{3p} \equiv \langle \cos(\alpha+\beta-2c) \rangle_{3p}$$

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

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

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

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



If $N_{2p} \propto N$:

Kharzeev, Liao & Shi, arXiv:2205.00120

f_{CME} = (6.8 ± 2.6)%

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

REMAINING NONFLOW EFFECTS

FENG, Yicheng (STAR): QM'2022, SQM'2022

Feng, FW, et al., PRC 105 (2022) 024913, arXiv:2106.15595

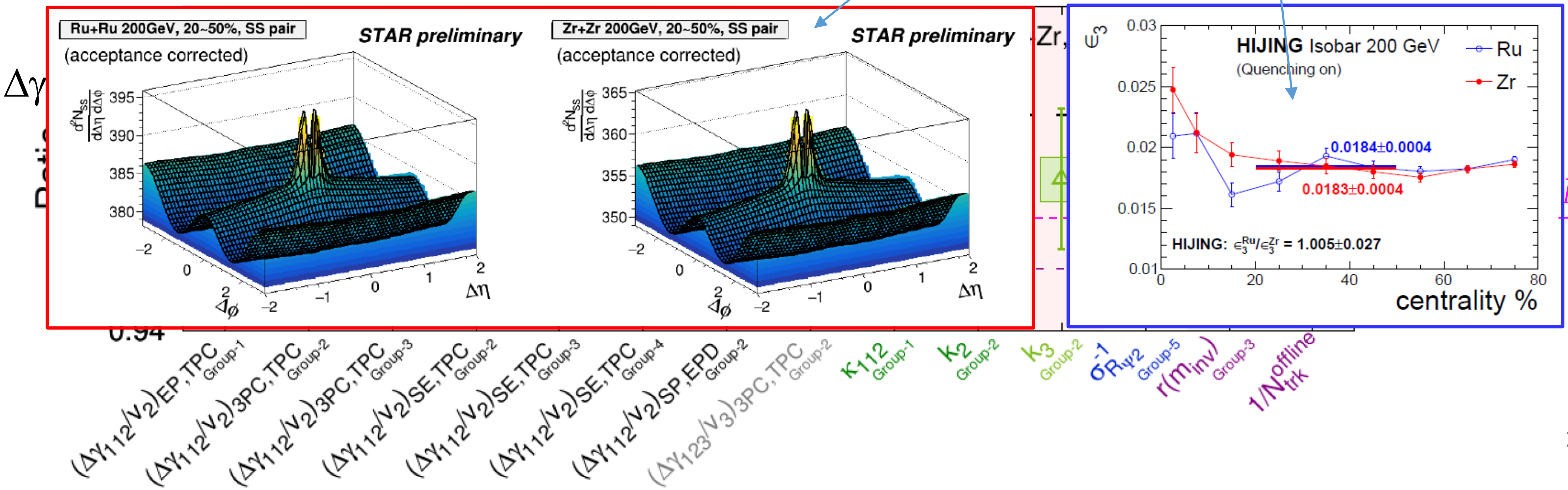
$$C_3 = \frac{C_{2p}N_{2p}}{N^2} v_{2,2p} v_2 + \frac{C_{3p}N_{3p}}{2N^3}; \quad C_{2p} \equiv \left\langle \cos(\alpha+\beta-2\phi_{2p}) \right\rangle, \quad C_{3p} \equiv \left\langle \cos(\alpha+\beta-2c) \right\rangle_{3p}$$

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

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

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

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



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

REMAINING NONFLOW EFFECTS

FENG, Yicheng (STAR): QM'2022, SQM'2022

Feng, FW, et al., PRC 105 (2022) 024913, arXiv:2106.15595

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

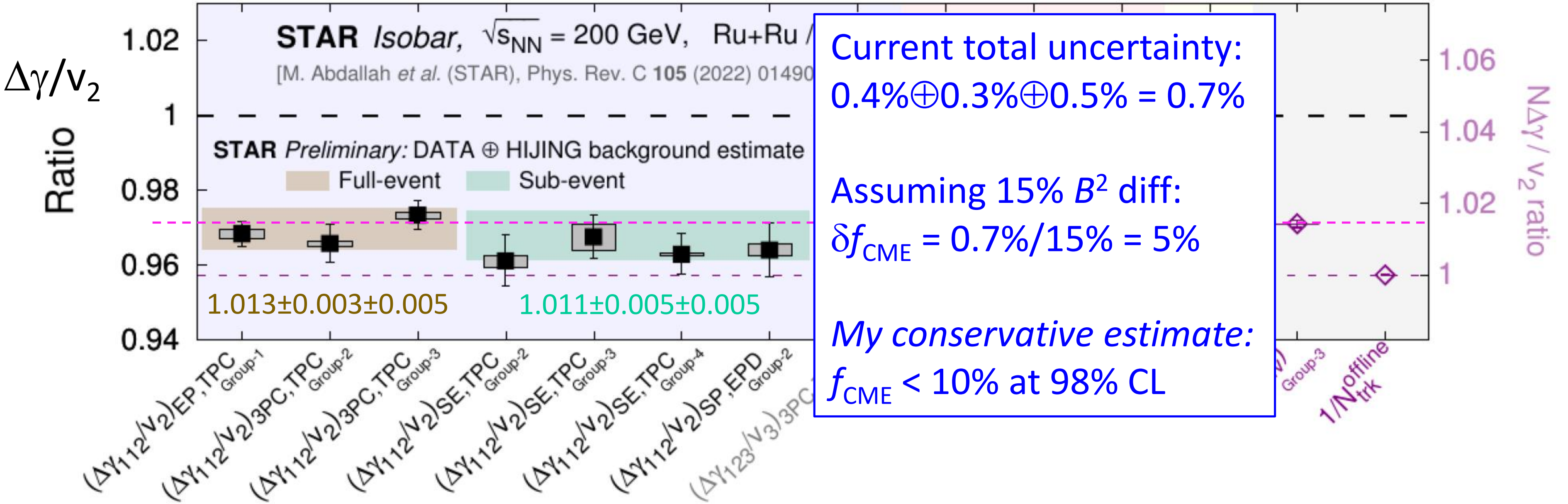
$$\varepsilon_2 \equiv \frac{C_{2p}N_{2p}}{N}\cdot\frac{v_{2,2p}}{v_2}, \quad \varepsilon_3 \equiv \frac{C_{3p}N_{3p}}{2N}$$

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

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

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

Good cancelation of v2 nonflow and 3p correlation



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

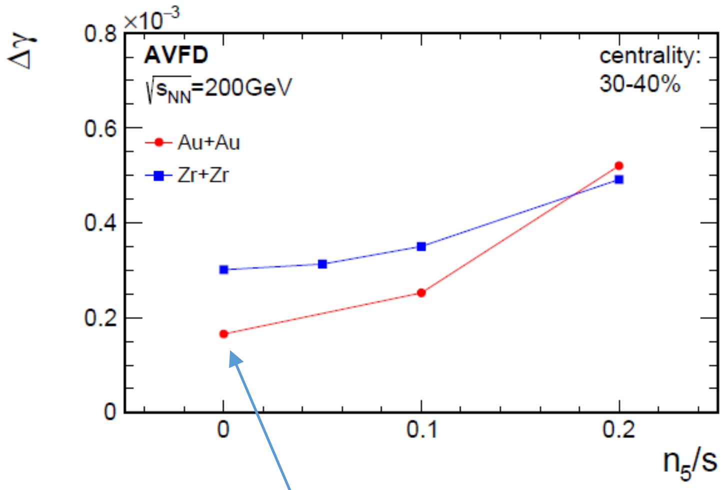
Assuming 15% B^2 diff:
δf_{CME} = 0.7%/15% = 5%

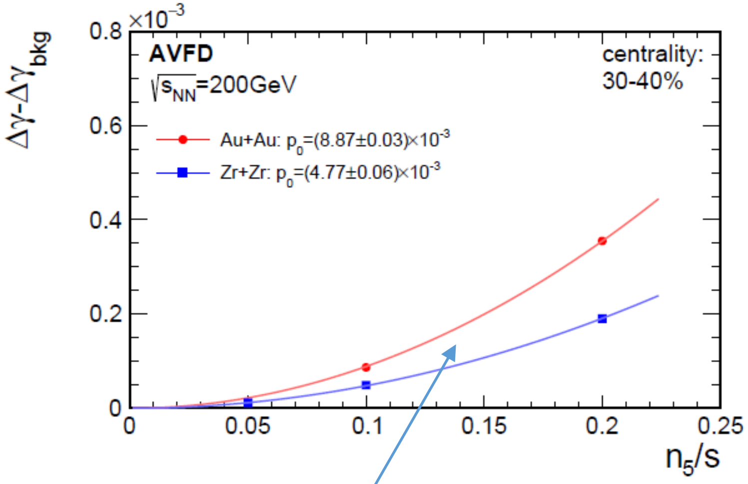
My conservative estimate:
f_{CME} < 10% at 98% CL

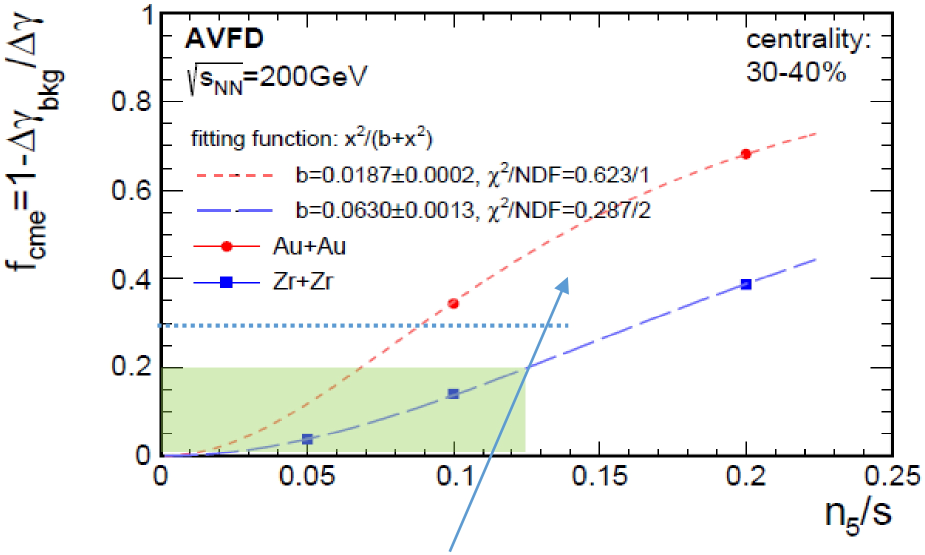
ISOBAR SIGNAL MAY BE SMALL

Feng, Lin, Zhao & FW, PLB 820 (2021) 136549, arXiv:2103.10378

AVFD simulations in preparation for isobar blind analysis







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} at the same n_5/s
If AuAu f_{CME}=10%, then isobar 3% (1σ effect)
Ru/Zr = 1 + 15%*3% = 1.005 (±0.004)

Caveats: Axial charge densities and sphaleron transition probabilities could be different between Au+Au and isobar, e.g. AVFD-glasma μ_5/s: isobar/AuAu ~ 1.5

SUMMARY, NEAR FUTURE, OUTLOOK

- CME is a very important physics. Large efforts to eliminate backgrounds.
  - Flow-induced background
  - **Nonflow contamination in v_2 measurements**
  - **Genuine 3-particle correlation background**
  - Invariant mass depndence
  - Event-shape engineering
  - Isobar collisions
  - **Spectator/participant plane comparison**

- Isobar signal consistent with zero (not contradictory to Au+Au);
  Stringent upper limit on the way.

- Au+Au data (2.4 B MB events) **hint at finite CME signal** with small significance;
  Rigorous nonflow data analysis on the way. Expect 20B Au+Au from 2023+25 runs.