

The 6th International Conference on Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions

~~May 11-15, 2020~~ November 1-5, 2021

Stony Brook University, Wang Center



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COLLABORATION

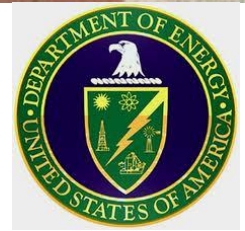


Search for CME in Au+Au collisions at STAR

Fuqiang Wang (Purdue University)

For the STAR Collaboration

Supported in part by



OUTLINE

- Physics motivation and observables
- Overview of STAR measurements in Au+Au collisions
 Emphasis on recent measurements
- Summary and outlook

CHIRAL MAGNETIC EFFECT (CME)

The strong interaction

$$\mathcal{L}_{QCD} = \sum_q \left(\bar{\psi}_{qi} i\gamma^\mu \left[\delta_{ij} \partial_\mu + ig \left(G_\mu^\alpha t_\alpha \right)_{ij} \right] \psi_{qj} - m_q \bar{\psi}_{qi} \psi_{qi} \right) - \frac{1}{4} G_{\mu\nu}^\alpha G_\alpha^{\mu\nu} = \frac{1}{2} (E_\alpha^2 - B_\alpha^2)$$

quarks
quark-gluon interactions
quarks
gluons

't Hooft vacuum

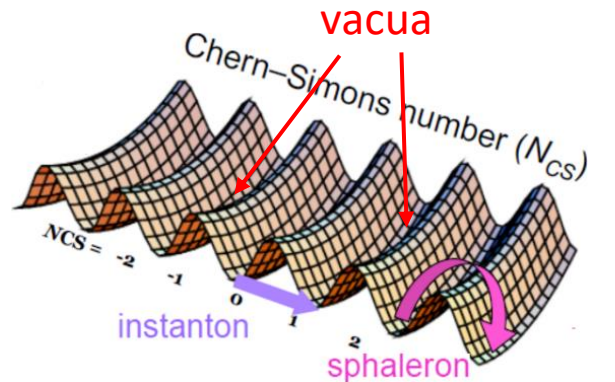
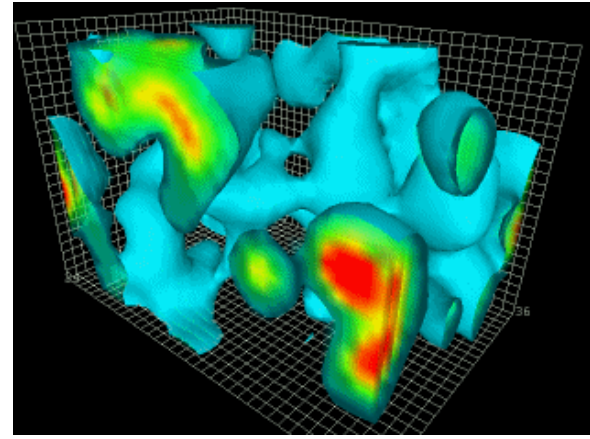
$$+ \theta \frac{\alpha_s}{8\pi} G_{\mu\nu}^\alpha \tilde{G}_\alpha^{\mu\nu} = -\theta \frac{\alpha_s}{2\pi} \vec{E}_\alpha \cdot \vec{B}_\alpha$$

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 $\theta \approx 1$?? \gg current infrared $\theta \approx 0$



Kharzeev, Pisarski, Tytgat, PRL81(1998)512

QCD vacuum fluctuation, chiral anomaly, topological gluon field

Reaction plane (Ψ_R)

\vec{B}

$B \sim 10^{15} \text{ T}$

X (defines Ψ_R)

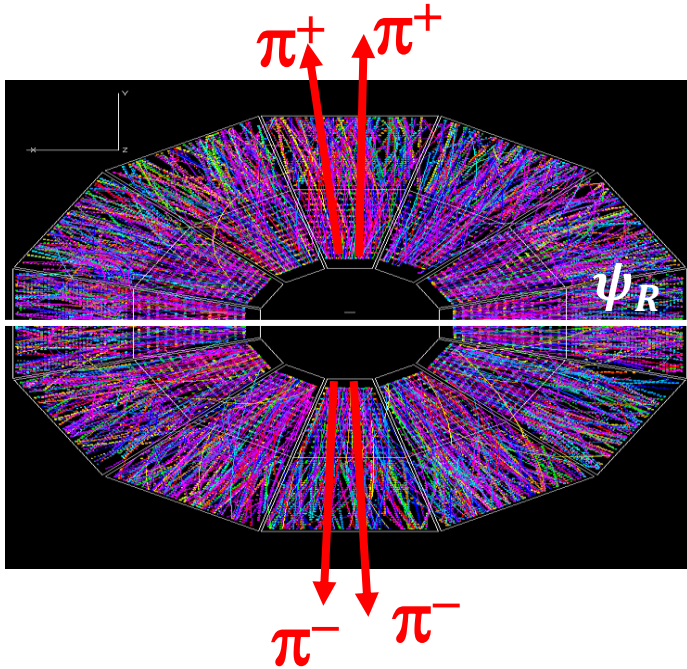
Kharzeev, et al. NPA 803 (2008) 227

Chiral Magnetic Effect (CME)

Discovery of the CME would imply: Chiral symmetry restoration (current-quark DOF & deconfinement);
Local P/CP violation that may solve the strong CP problem (matter-antimatter asymmetry)

THE COMMON γ VARIABLE

Voloshin, PRC 70 (2004) 057901

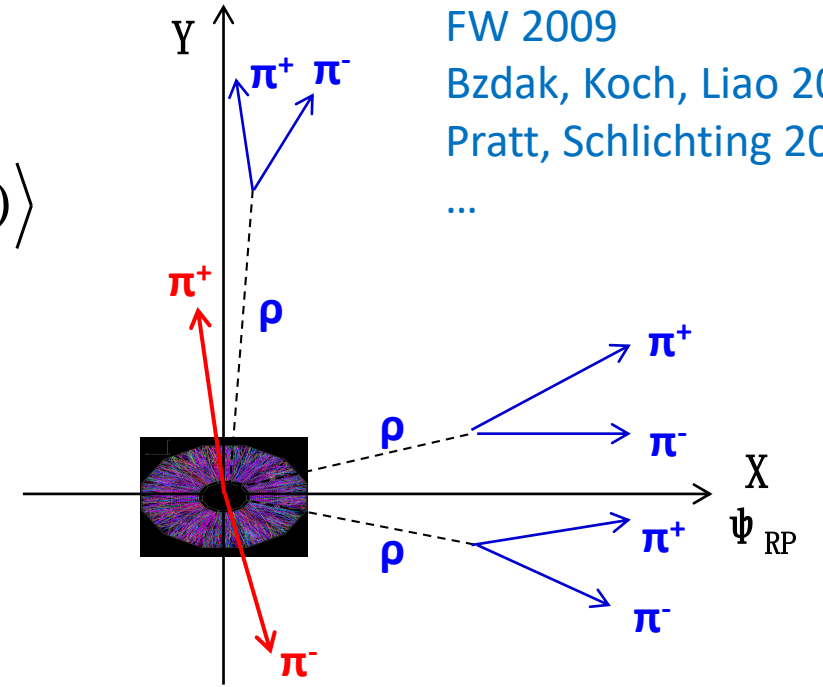


$$\gamma_{\alpha\beta} = \langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{RP}) \rangle$$

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

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

$$\Delta\gamma > 0$$



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

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

$$= \left[\langle v_{1,\alpha} v_{1,\beta} \rangle - \langle a_\alpha a_\beta \rangle \right] + [\text{charge-independent Bkg (e.g. mom. conservation)}] + \frac{N_{\text{cluster}}}{N_\alpha N_\beta} \langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{\text{cluster}}) \rangle v_{2,\text{cluster}}$$

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

THE R VARIABLE

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

Choudhury et al. arXiv:2105.06044 [nucl-ex],
 CPC in print.

$$\Delta S = \frac{\sum_1^p \sin\left(\frac{m}{2} \Delta\varphi_m\right)}{p} - \frac{\sum_1^n \sin\left(\frac{m}{2} \Delta\varphi_m\right)}{n}$$

$$R(\Delta S_m) \equiv \frac{N(\Delta S_{m,\text{real}})}{N(\Delta S_{m,\text{shuffled}})} / \frac{N(\Delta S_{m,\text{real}}^\perp)}{N(\Delta S_{m,\text{shuffled}}^\perp)}, \quad m = 2, 3, \dots,$$

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

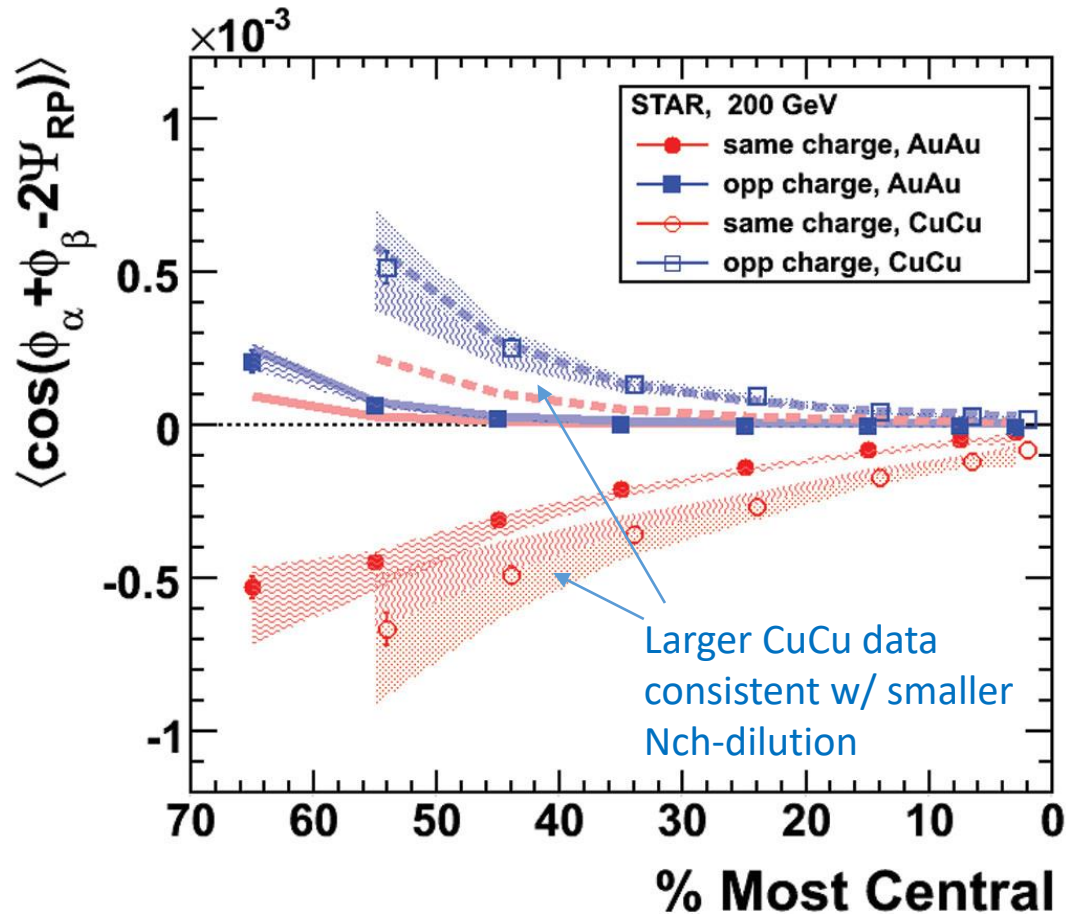
$$\frac{S_{\text{concavity}}}{\sigma_{R2}^2} \approx -\frac{M}{2}(M-1)\Delta\gamma_{112}$$

$$\frac{S_{\text{concavity}}}{\sigma_{R2'}^2} = \frac{S_{\text{concavity}}}{\sigma_{R2}^2} \langle (\Delta S_{2,\text{shuffled}})^2 \rangle \approx -\frac{M}{2}(M-1)\Delta\gamma_{112} \times \frac{2}{M} \approx -M\Delta\gamma_{112}$$

- Established analytical relationship between $\Delta\gamma$ and $R_{\Psi_2}(\Delta S)$
- “Equivalence” verified by MC simulations and the EBE-AVFD model
- $\Delta\gamma$ and $R_{\Psi_2}(\Delta S)$ have similar sensitivities to CME signal and background

THE FIRST MEASUREMENT BY STAR, 2009

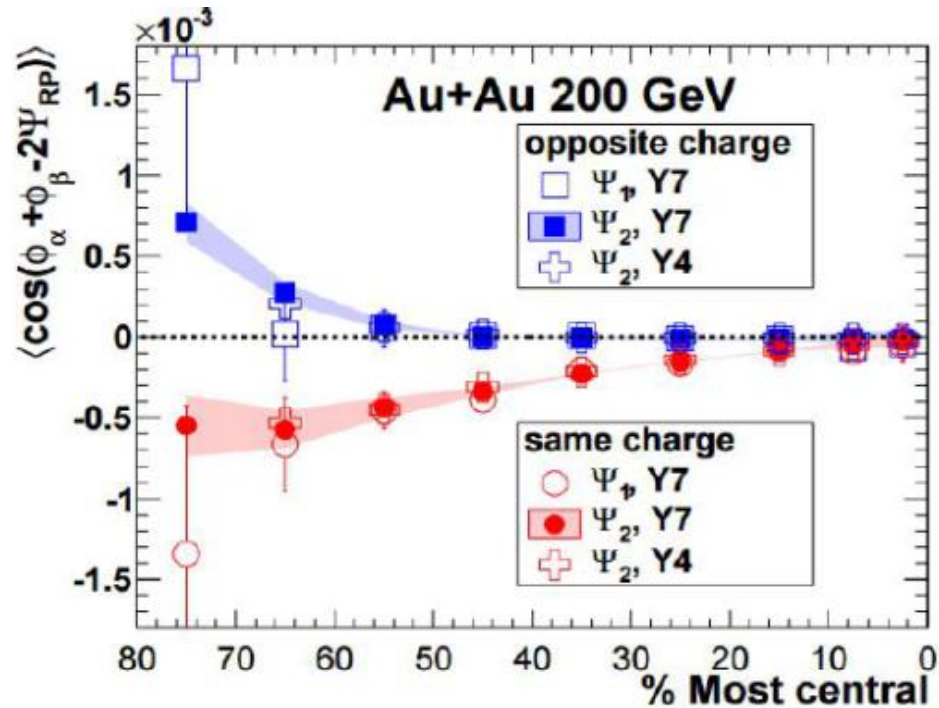
STAR, PRL 103, 251601 (2009); PRC 81, 054908 (2010)



- “Qualitatively the results agree with [CME]”
- “So far... we have not identified effects that would explain the observed [SS] correlations. The observed signal cannot be described by the background models that we have studied (HIJING, HIJING+v2, URQMD, MEVSIM)...”
- “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]”

W.R.T. SPECTATOR NEUTRONS, 2013

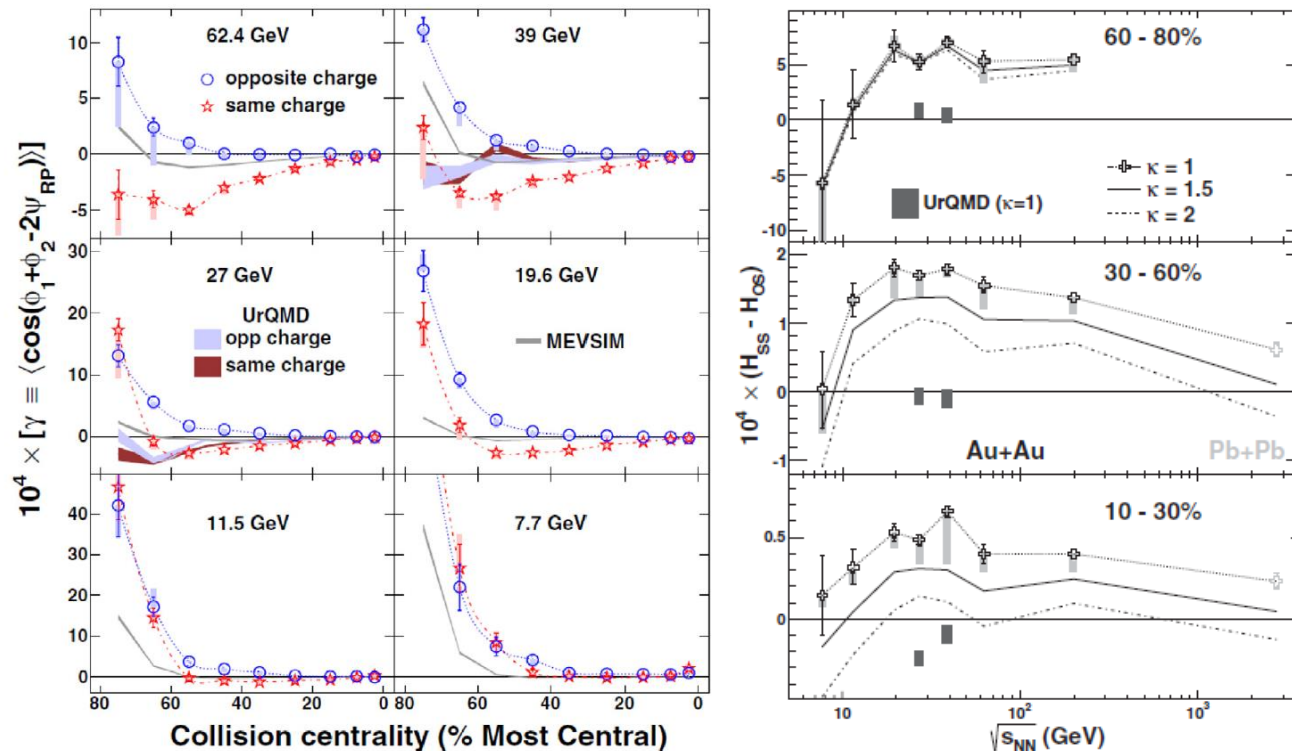
STAR, PRC 88 (2013) 064911



- $\Delta\gamma$ w.r.t. ZDC spectator neutron event plane Ψ_1
- $\Delta\gamma\{\text{ZDC}\} \approx \Delta\gamma\{\text{TPC}\}$ within large errors for the ZDC results
- ZDC and TPC results do not have to be the same

BES MEASUREMENTS, 2014

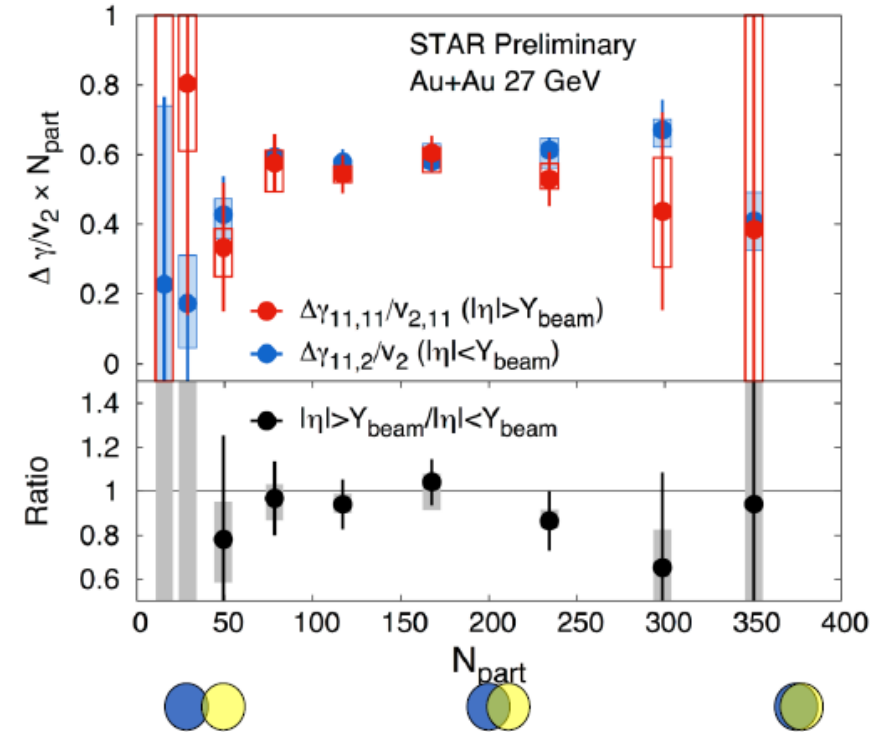
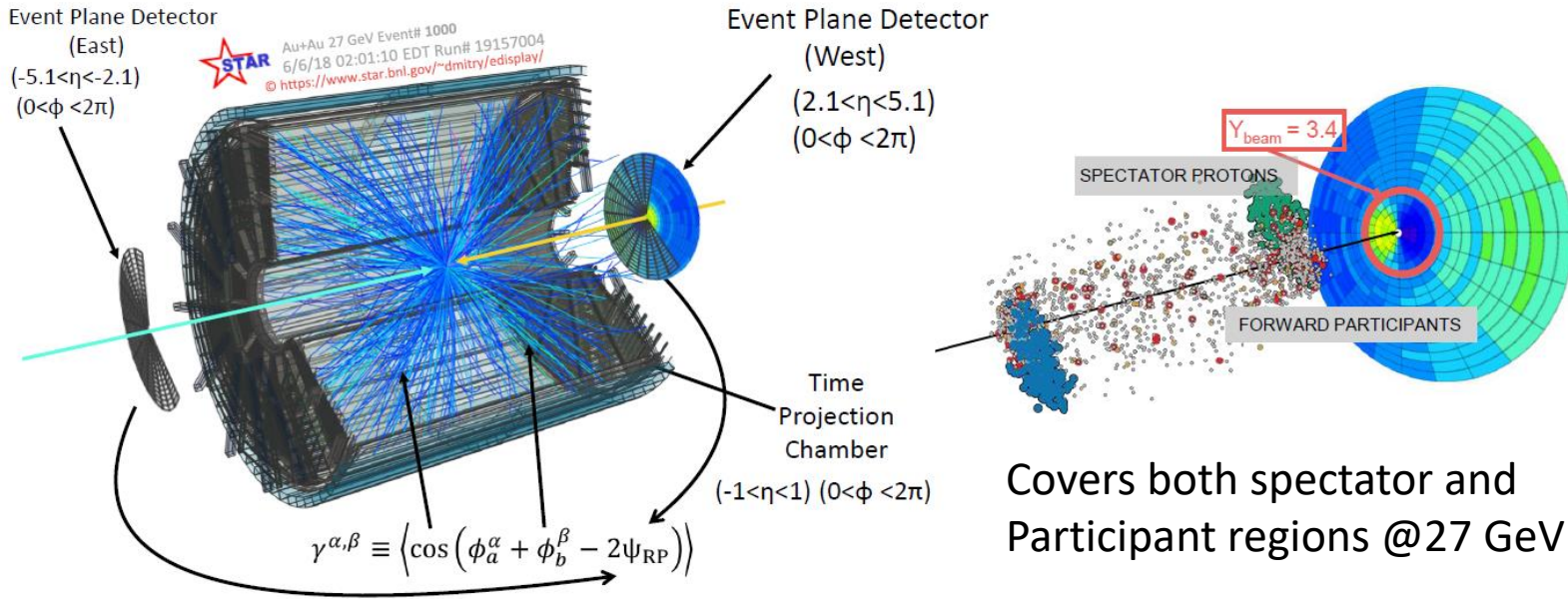
STAR, PRL 113 (2014) 052302



- Expect energy dependence in **B** and CME
- $\kappa \approx \Delta\gamma / (v_2\Delta\delta)$, where $\delta = \langle \cos(\phi_1 - \phi_2) \rangle$ as background estimator
- “indicates a large contribution from the P-even background...”
- This trend may be consistent with the [CME] because there should be a smaller probability for the CME at lower energies...”
- A more definitive result may be obtained ... if we can reduce the uncertainty associated with ... the value of κ .

MORE RECENT LOW ENERGY (27 GeV) DATA

Yu Hu (STAR), SQM 2021

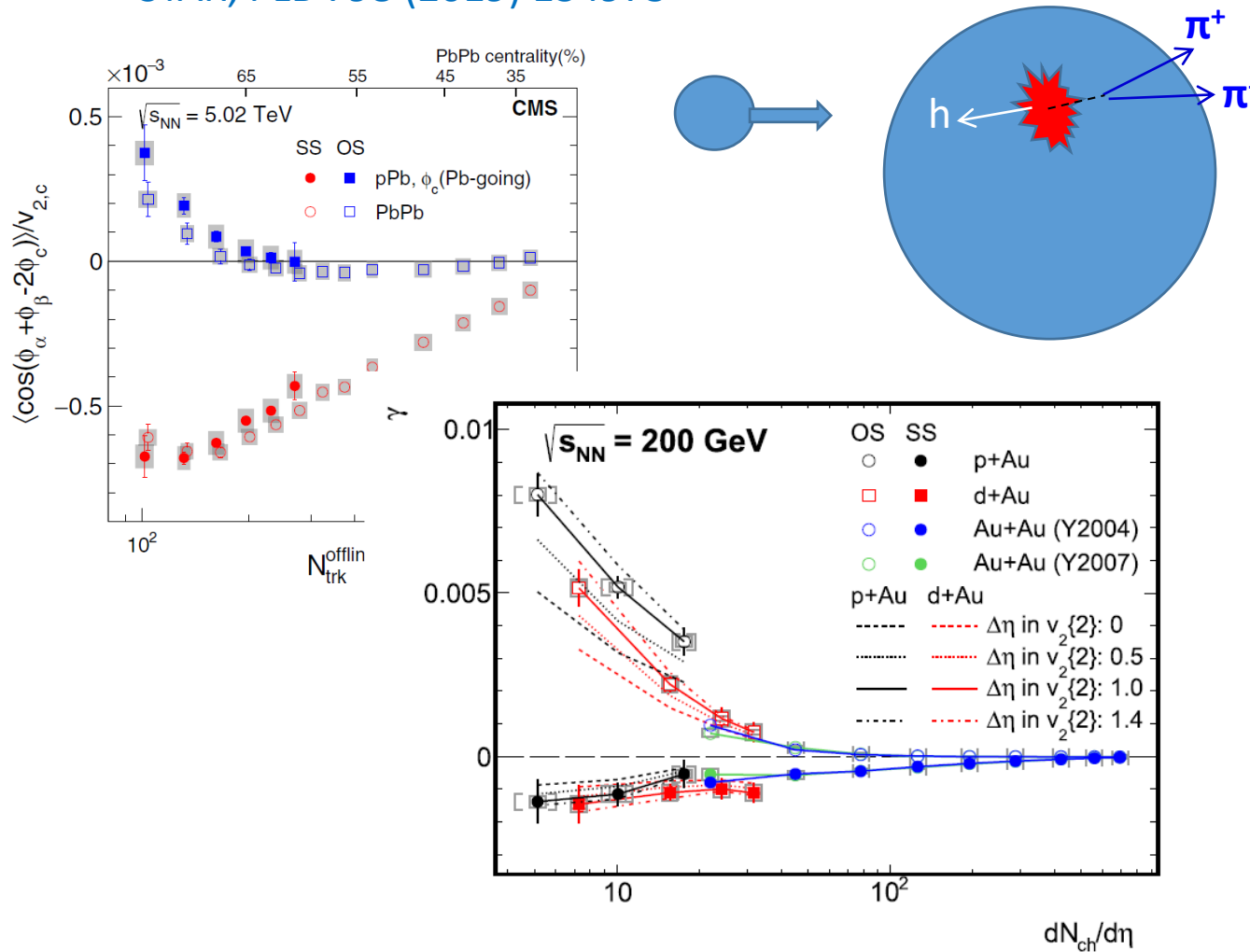


- Higher statistics, new detector (EPD)
- New approach: inner EPD -> first-order harmonic plane; Outer EPD -> second-order harmonic plane.
- Current data consistent with background contributions

SMALL SYSTEM MEASUREMENTS, 2019

CMS, PRL 118 (2017) 122301

STAR, PLB 798 (2019) 134975

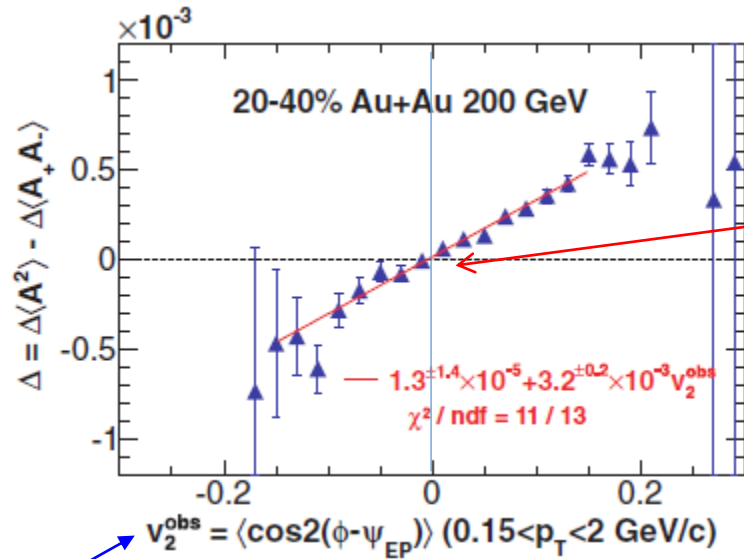


- Large $\Delta\gamma$ observed in small systems, similar to heavy ions.
- Zero signal is expected b/c random B and EP orientations
- Physics of background may differ between small systems (e.g. 3-particle nonflow) and heavy ions (flow), but raise warning for pro-CME interpretation of heavy ion data

“ESE” MEASUREMENTS, 2014

STAR, PRC 89 (2014) 044908

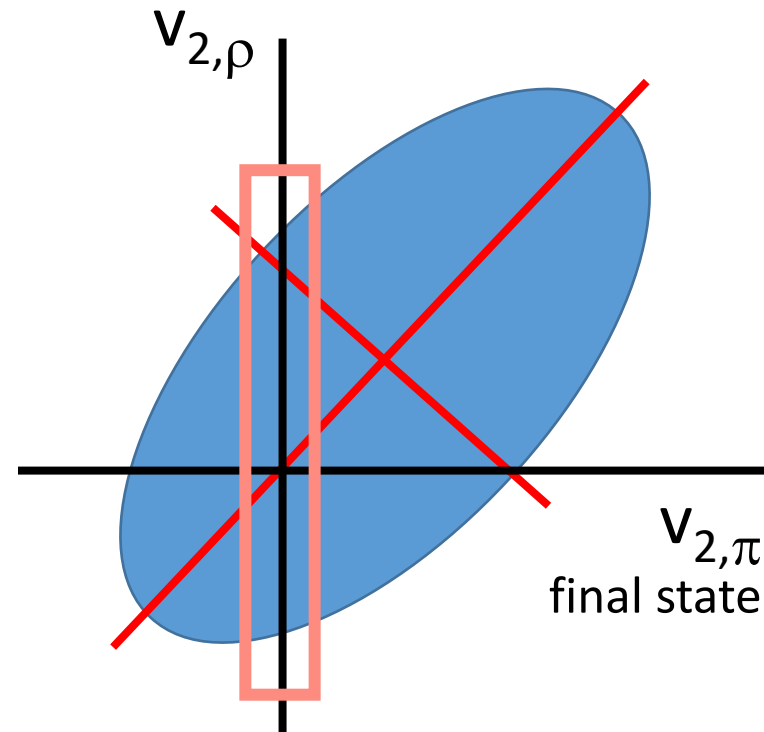
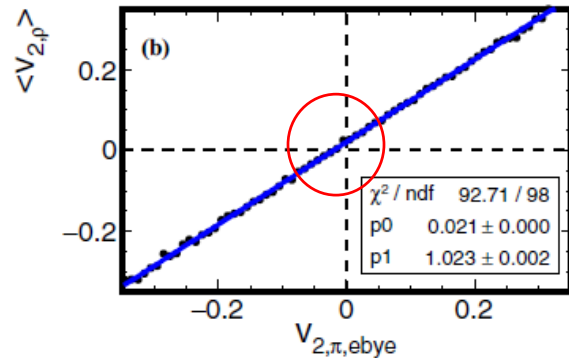
Here Δ is similar to $\cos(\alpha+\beta-2\psi)$ correlator



Still has residual background, because background $\sim v_{2,\rho}$ not $v_{2,\pi}$
FW, Jie Zhao, PRC 95 (2017) 051901(R)

Primarily stat. fluctuations

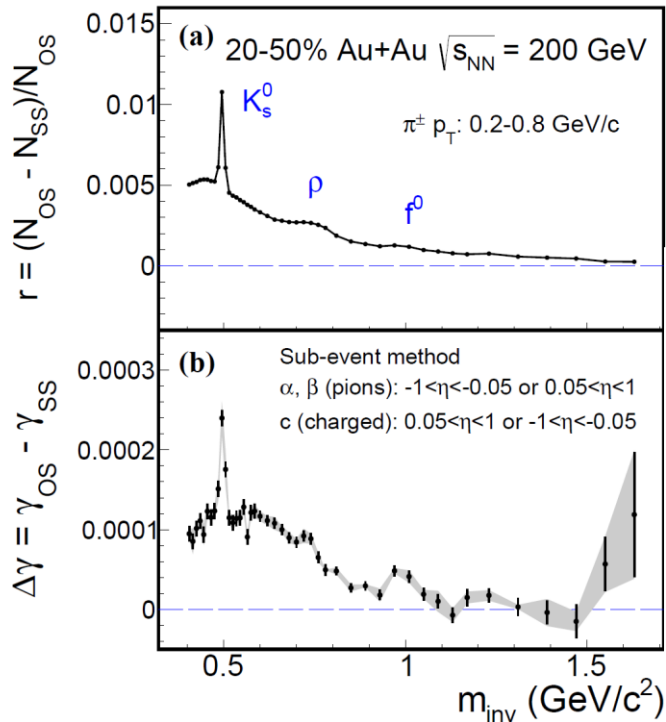
Event-by-event v_2 technique



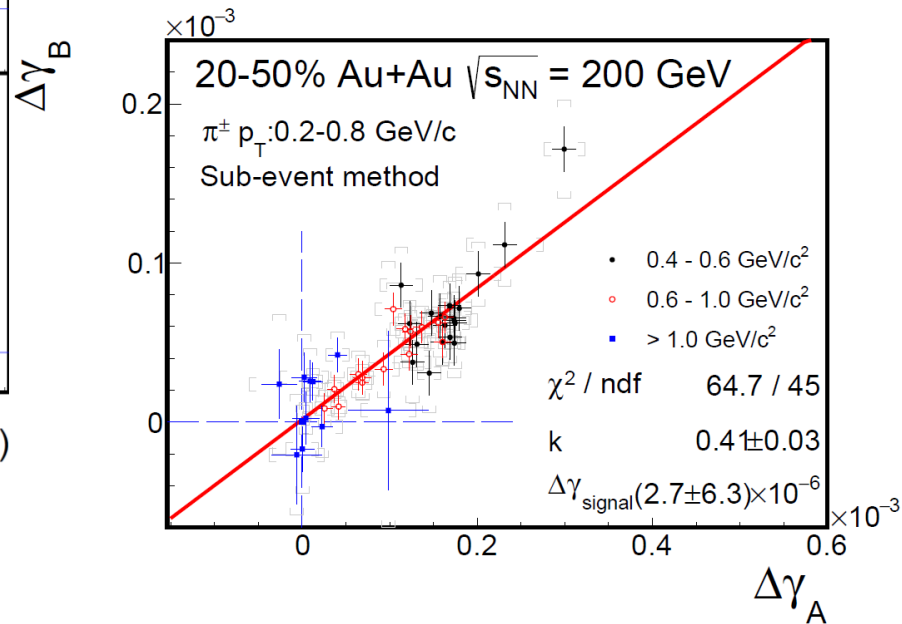
- Engineering on stat. fluctuations
- Background suppressed, but not totally eliminated
- LHC does not have this issue as v_2 selection in different phase space

MEASUREMENT IN INVARIANT MASS, 2020

Jie Zhao, Hanlin Li, FW, Eur.Phys.J.C 79 (2019) 168
 STAR, arXiv:2006.05035



$$\frac{N_\rho}{N_\alpha N_\beta} \langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{clus}) \rangle \times v_{2,clus}$$



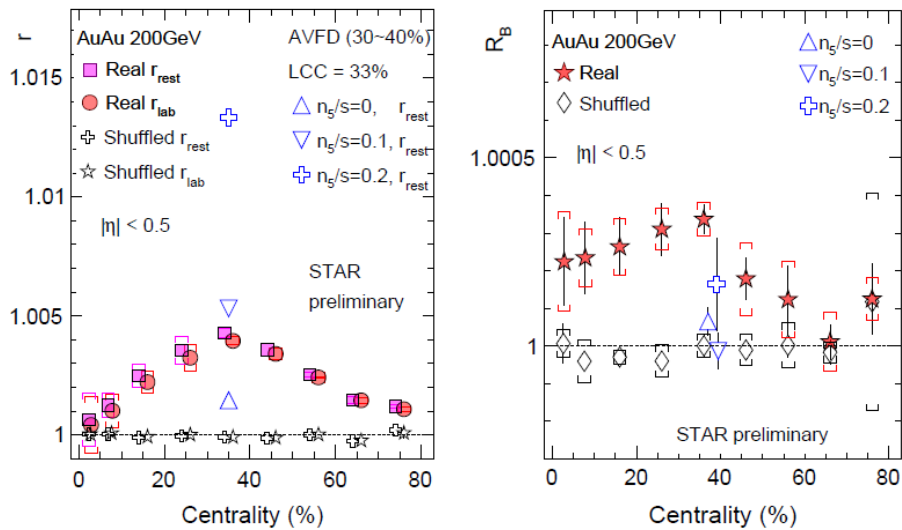
- Explicit demonstration of “resonance” background
- Exploit “ESE” to extract CME, assuming CME is mass independent
- Upper limit 15% at 95% CL

NEW OBSERVABLES/APPROACHES

Signed balance function (SBF)

Tang, CPC 44 (2020) 054101

Yufu Lin (STAR), NPA 1005 (2021) 121828



- r is out-of-plane to in-plane ratio of the SBF momentum-ordering difference
- Both r_{rest} and $R_B = r_{rest}/r_{lab}$ are larger than unity, above model calculations without CME.

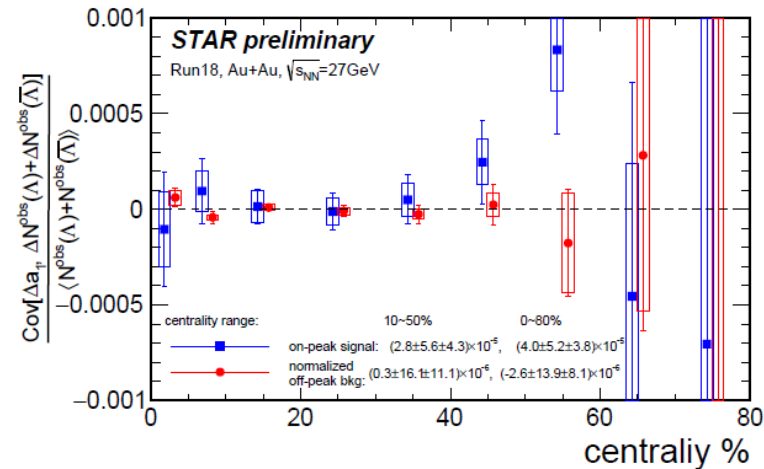
CME-helicity correlation

Du, Finch, Sandweiss, PRC 78 (2008) 044908

044908

Finch, Murray, PRC 96 (2017) 044911

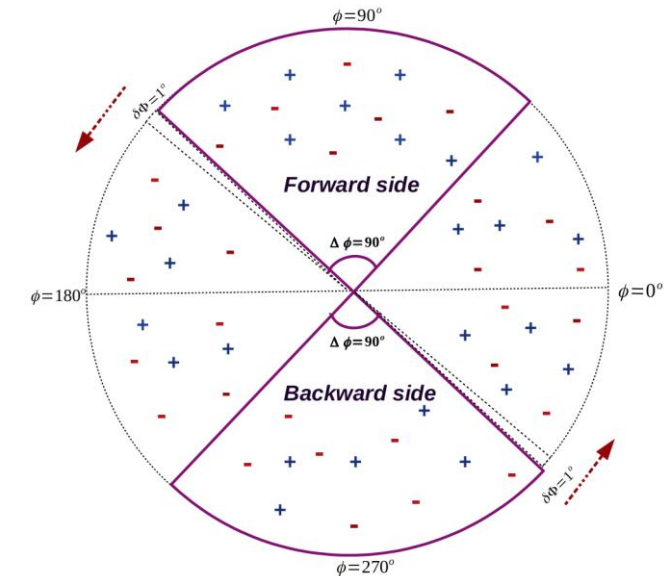
Yicheng Feng (STAR), DNP 2020



- Positive correlation btw CME Δa_1 and Λ net-helicity from chirality anomaly
- Current signal consistent with zero within uncertainties

Sliding Dumbbell

Jagbir Singh (STAR) QM 2019

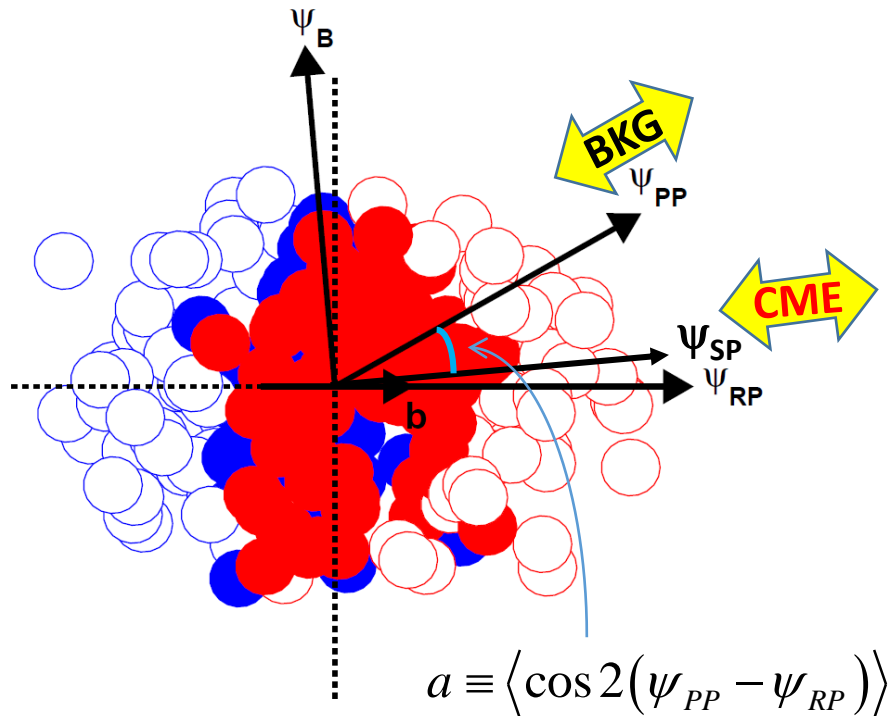


- Select CME enriched sample
- Perform $\Delta\gamma$ measurement with background subtraction in separate event classes

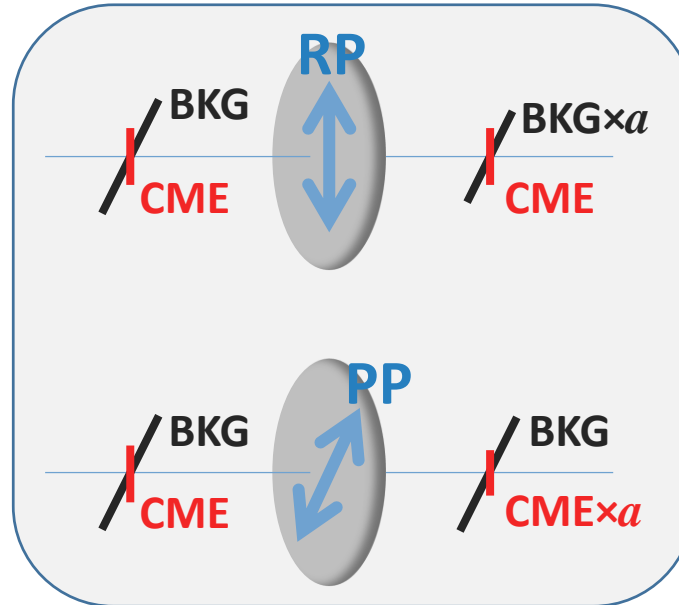
W.R.T. SPECTATOR & PARTICIPANT PLANES, 2021

Haojie Xu et al., CPC 42 (2018) 084103, arXiv:1710.07265

S.A. Voloshin, PRC 98 (2018) 054911, arXiv:1805.05300



INTRA-EVENT "CME- v_2 FILTER"



IN THE SAME EVENT

$$\Delta\gamma_{\{SP\}} = a\Delta\gamma_{Bkg\{PP\}} + \Delta\gamma_{CME\{PP\}} / a$$

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

$$A = \Delta\gamma_{\{SP\}} / \Delta\gamma_{\{PP\}}$$

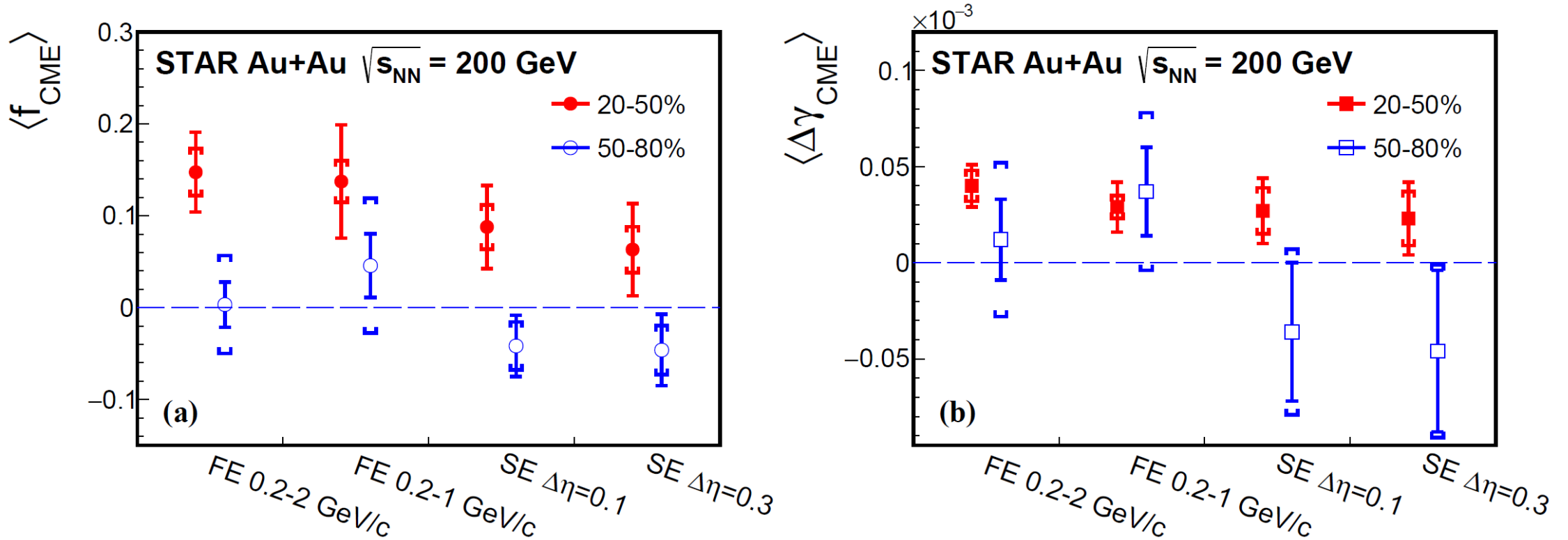
$$a = v_2\{SP\} / v_2\{PP\}$$

$$\Delta\gamma_{\{SP\}} / a - \Delta\gamma_{\{PP\}} = (1/a^2 - 1)\Delta\gamma_{CME\{PP\}}$$

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

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

STAR, arXiv:2106.09243



- Consistent-with-zero signal in peripheral 50-80% collisions with relatively large errors
- Indications of finite signal in mid-central 20-50% collisions, with 1-3 σ significance
- Possible remaining nonflow effects

REMAINING NONFLOW EFFECTS

Feng et al., arXiv:2106.15595

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

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

$$C_3\{\text{SP}\} = \frac{C_{2\text{p}}N_{2\text{p}}}{N^2} v_{2,2\text{p}}\{\text{SP}\}v_2\{\text{SP}\},$$

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

$$C_3^*\{\text{EP}\} = \frac{C_{2\text{p}}N_{2\text{p}}}{N^2} v_{2,2\text{p}}\{\text{EP}\}v_2\{\text{EP}\} + \frac{C_{3\text{p}}N_{3\text{p}}}{2N^3}.$$

$$\epsilon_2 \equiv \frac{C_{2\text{p}}N_{2\text{p}}v_{2,2\text{p}}}{Nv_2}$$

$$\epsilon_3 \equiv \frac{C_{3\text{p}}N_{3\text{p}}}{2N}$$

$$\Delta\gamma_{\text{bkgd}} = \frac{N_{2\text{p}}}{N^2} \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{2\text{p}}) \rangle v_{2,2\text{p}}$$

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

$$C_{3\text{p}} = \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle_{3\text{p}}$$

$$v_2^*\{\text{EP}\} = \sqrt{v_2^2\{\text{EP}\} + v_{2,\text{nf}}^2}$$

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

Nonflow in v_2
→ positive f_{CME}

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

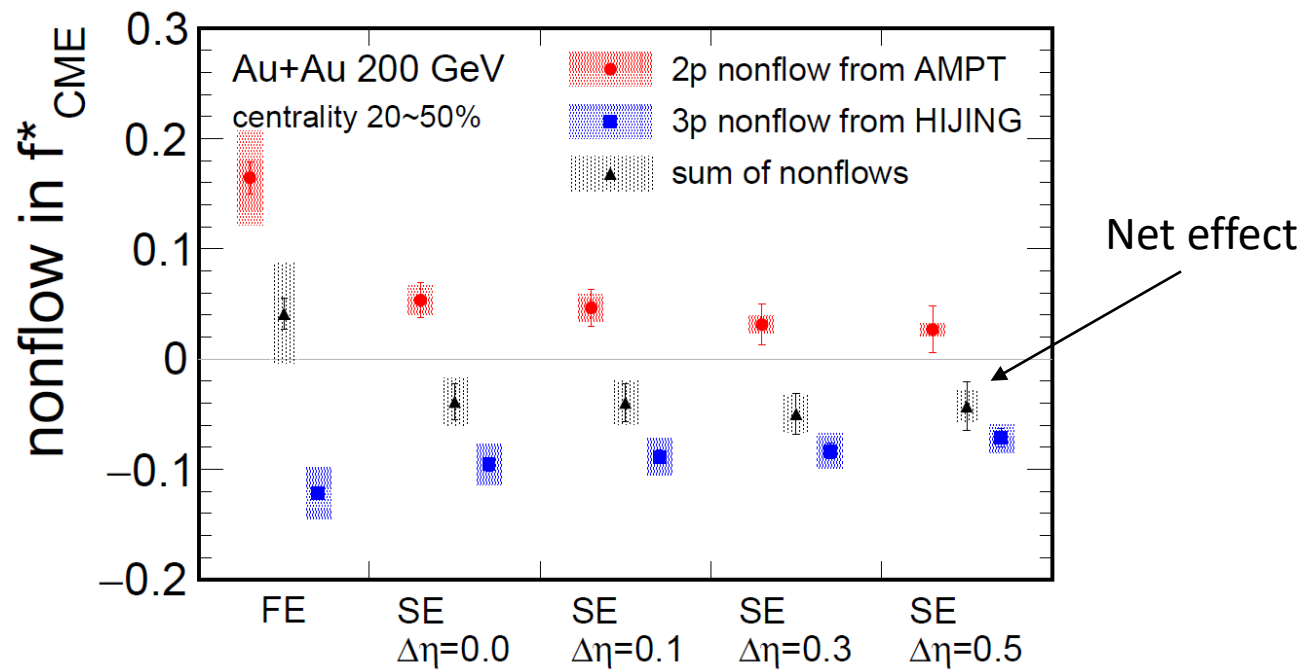
$$f_{\text{CME}}^* = \left(\frac{1 + \epsilon_{\text{nf}}}{1 + \frac{\epsilon_3 / \epsilon_2}{Nv_2^2\{\text{EP}\}}} - 1 \right) / \left(\frac{1 + \epsilon_{\text{nf}}}{a^2} - 1 \right)$$

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

MODEL ESTIMATES OF NONFLOW

Feng et al., arXiv:2106.15595

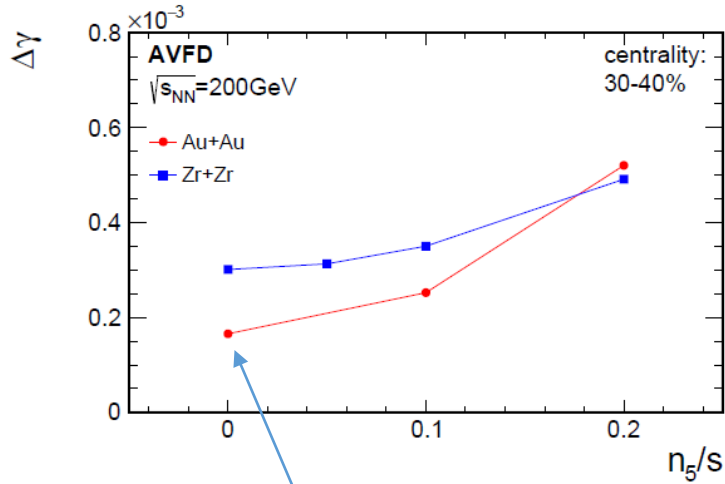
$$f_{\text{CME}}^* \approx \left(\epsilon_{\text{nf}} - \frac{\epsilon_3/\epsilon_2}{Nv_2^2\{\text{EP}\}} \right) / \left(\frac{1 + \epsilon_{\text{nf}}}{a^2} - 1 \right)$$



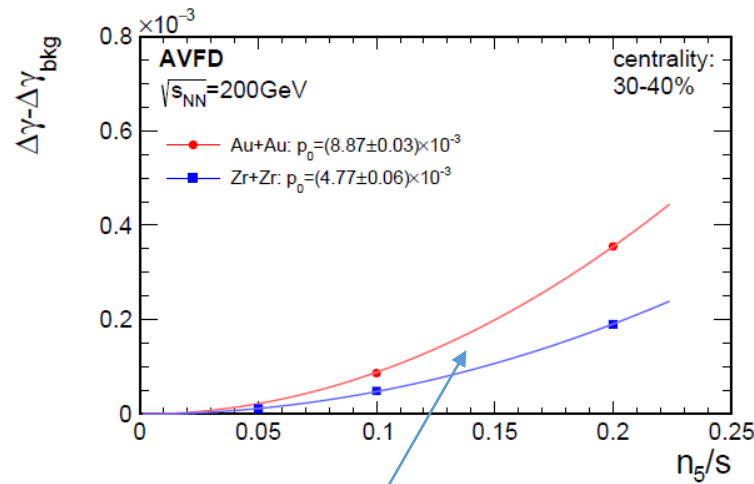
- 2-particle nonflow estimates from AMPT
- 3-particle nonflow estimates from HIJING
- Net effect on f_{CME}^* can possibly be negative (model dependent)
- Further, additional model studies

Au+Au DATA AND ISOBAR ARE CONSISTENT

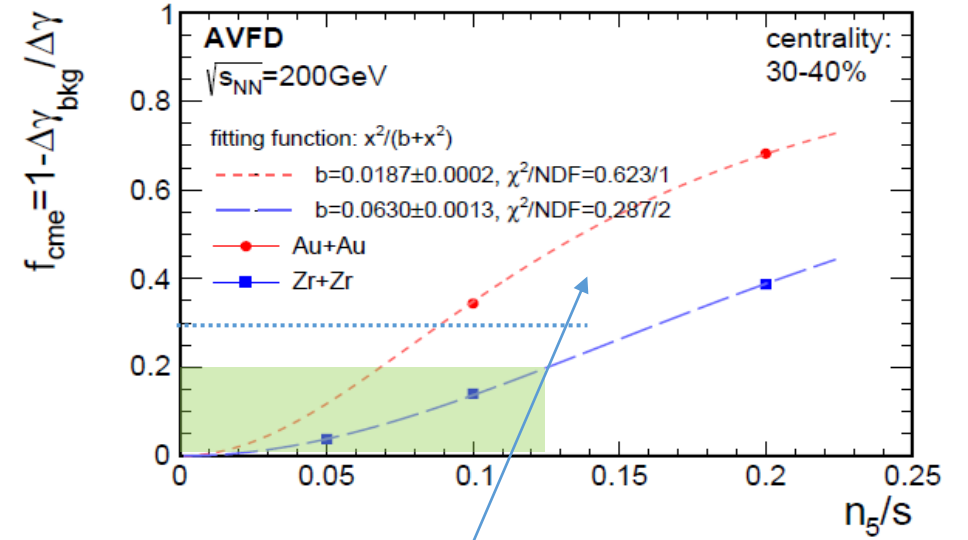
Yicheng Feng, Yufu Lin, Jie Zhao, FW, arXiv:2103.10378



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



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



Could be x3 reduction in f_{CME} at the same n_5/s
 If AuAu $f_{\text{CME}}=10\%$, then isobar 3% (1σ effect)
 $\text{Ru/Zr} = 1 + 15\% \cdot 3\% = 1.005 (\pm 0.004)$

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

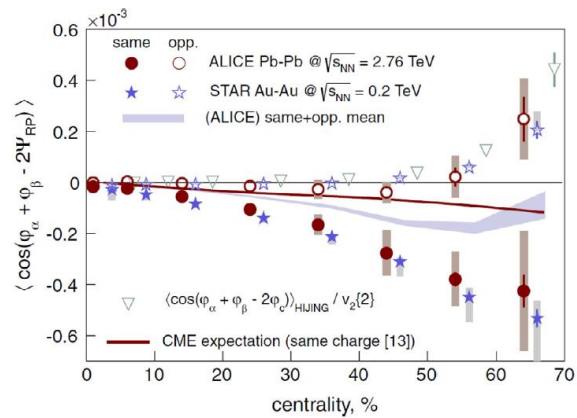
SUMMARY AND OUTLOOK

- CME is very important physics. Significant efforts in theory and experiments.
- STAR has pioneered and played significant role in the CME search.
Primary efforts in understanding and removing backgrounds.
- The possible CME is a small fraction of the measured $\Delta\gamma$ signal.
Most recent STAR data indicate **a finite CME signal with 1-3 σ significance**;
nonflow effects under investigation.
- **Current data 2.4B MB Au+Au events. Expect 20B from 2023+25 runs.**
And large BES-II data samples.

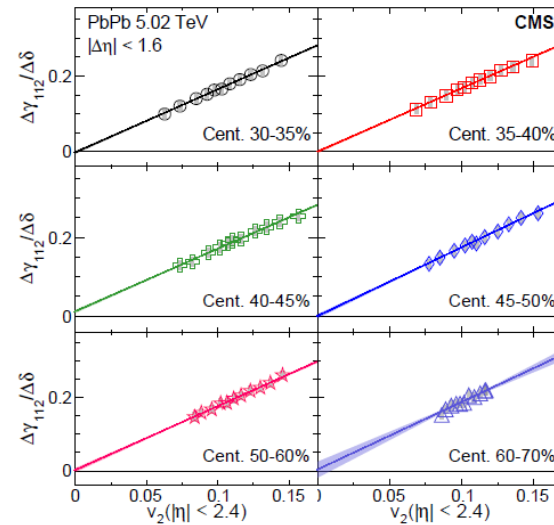
Backup slides

ESE AT LHC

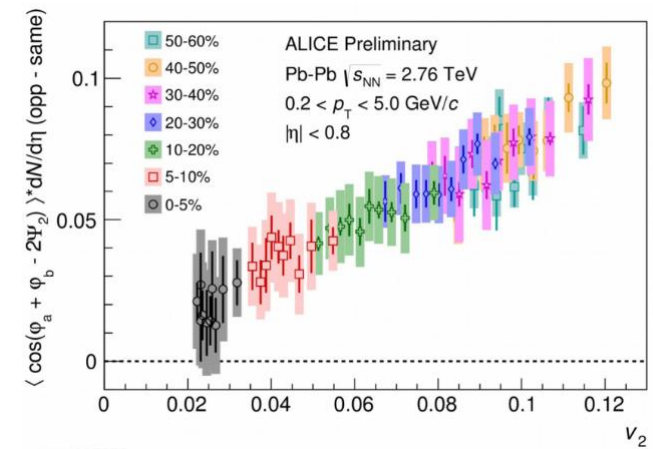
ALICE, PRL 110 (2013) 012301



CMS PRC97(2018)044912

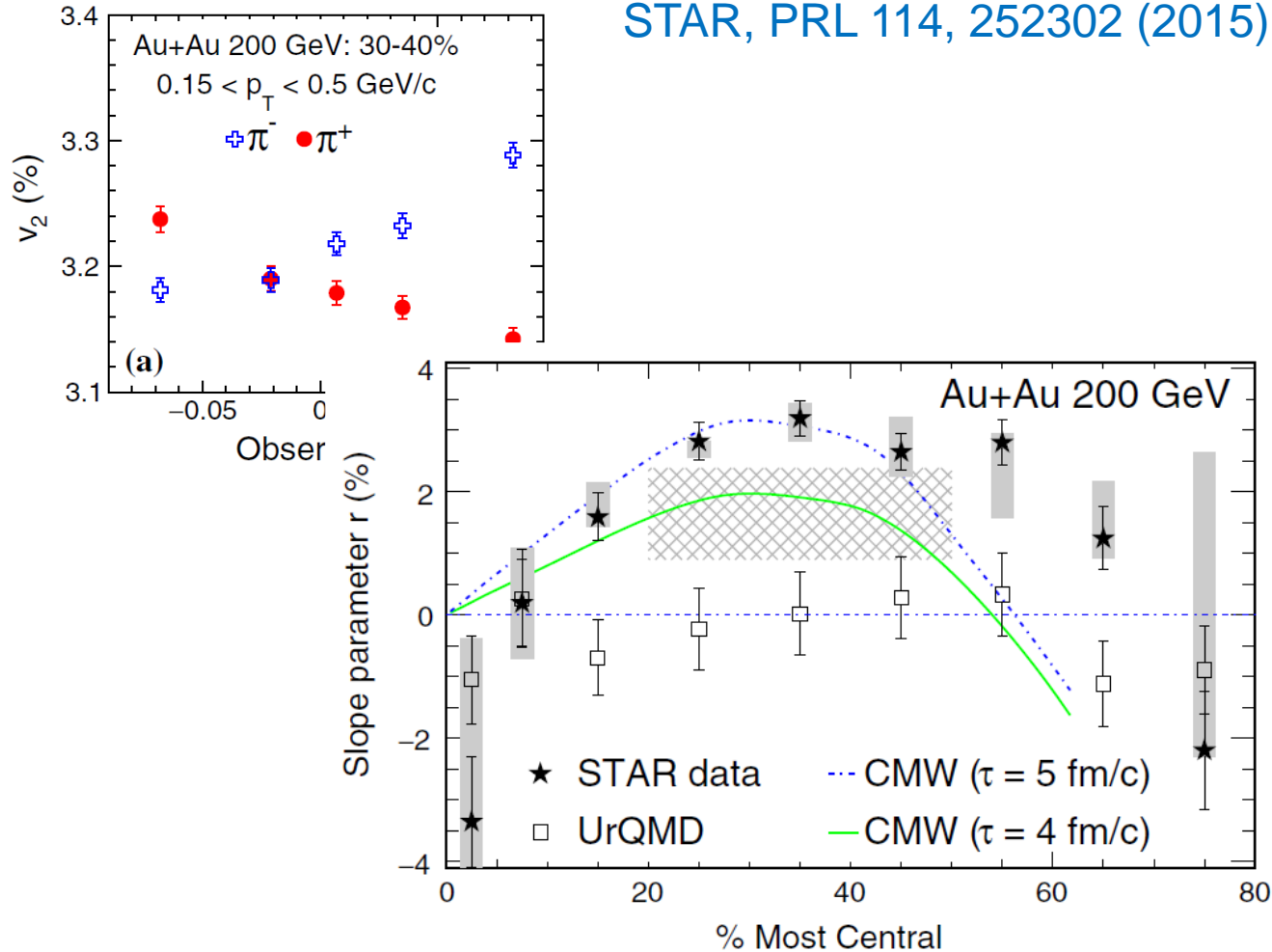


ALICE PLB777(2018)151



CMW RESULTS BY STAR, 2015

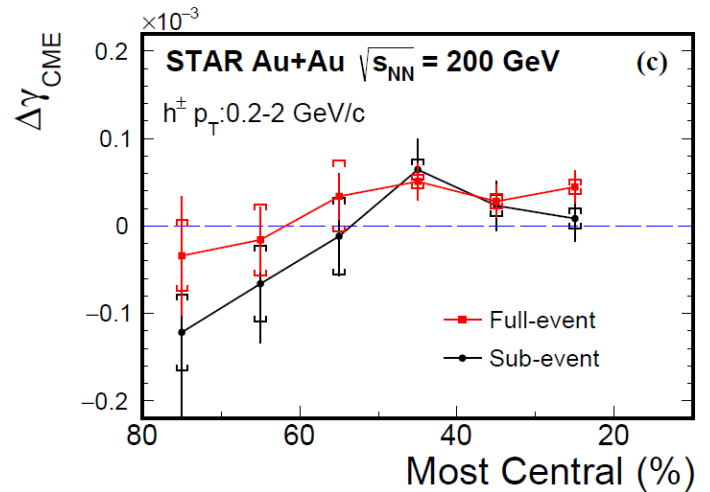
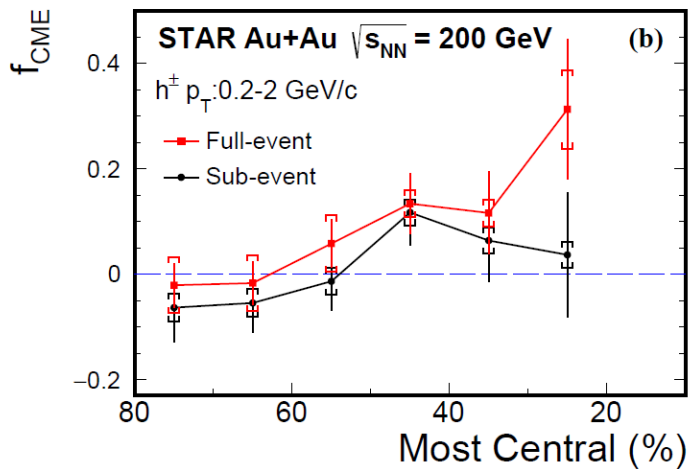
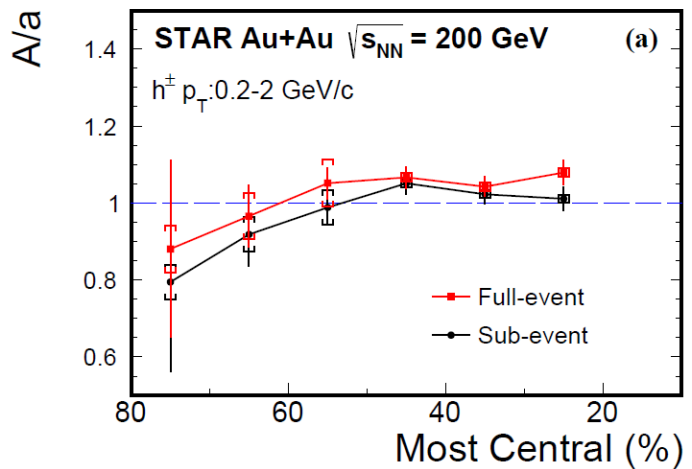
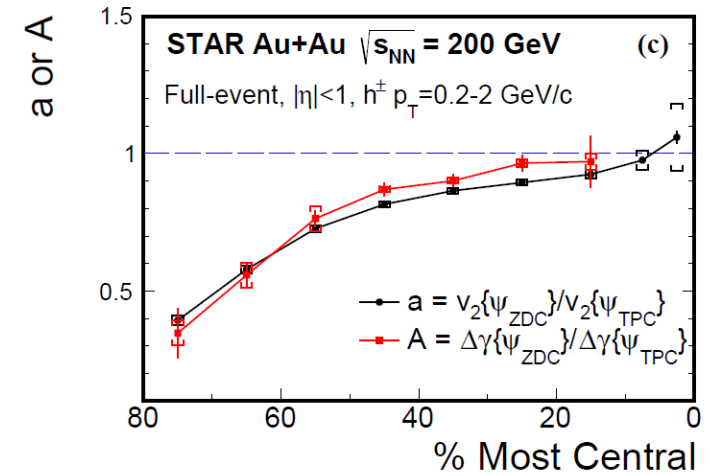
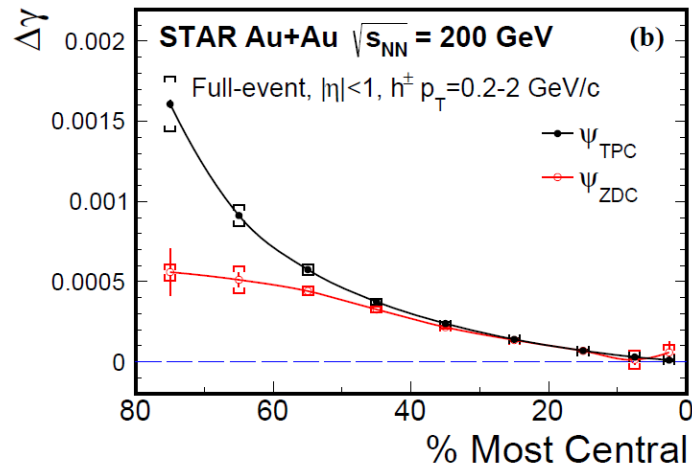
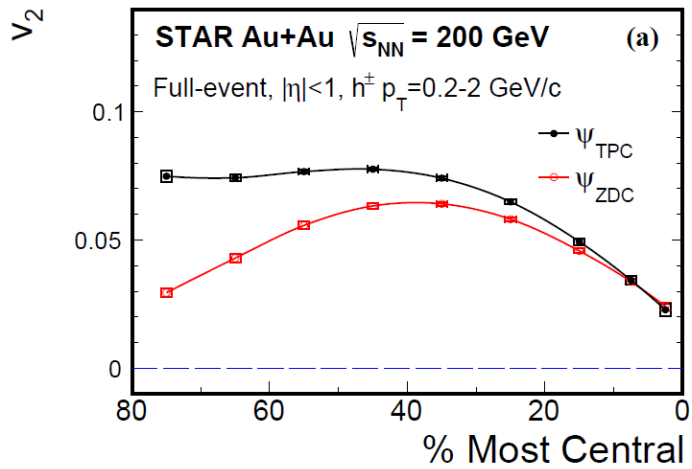
STAR, PRL 114, 252302 (2015)



- “...qualitatively reproducing the expectation from the CMW model.”
- “The slope parameter ... displays no obvious trend of the beam energy dependence ...”
- “None of the conventional models discussed, as currently implemented, can explain our observations.”
- Backgrounds less thoroughly studied for CMW than CME.

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

STAR, arXiv:2106.09243

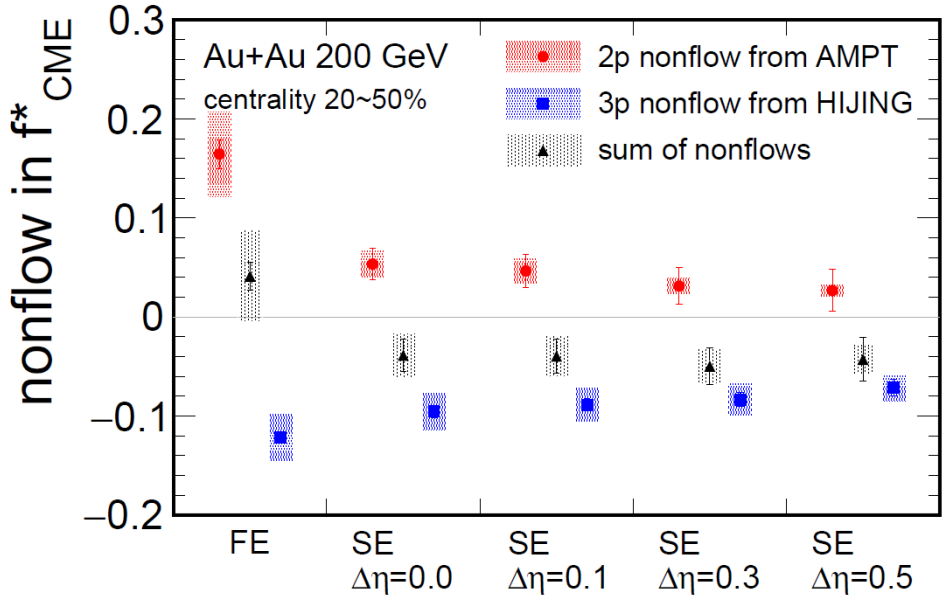
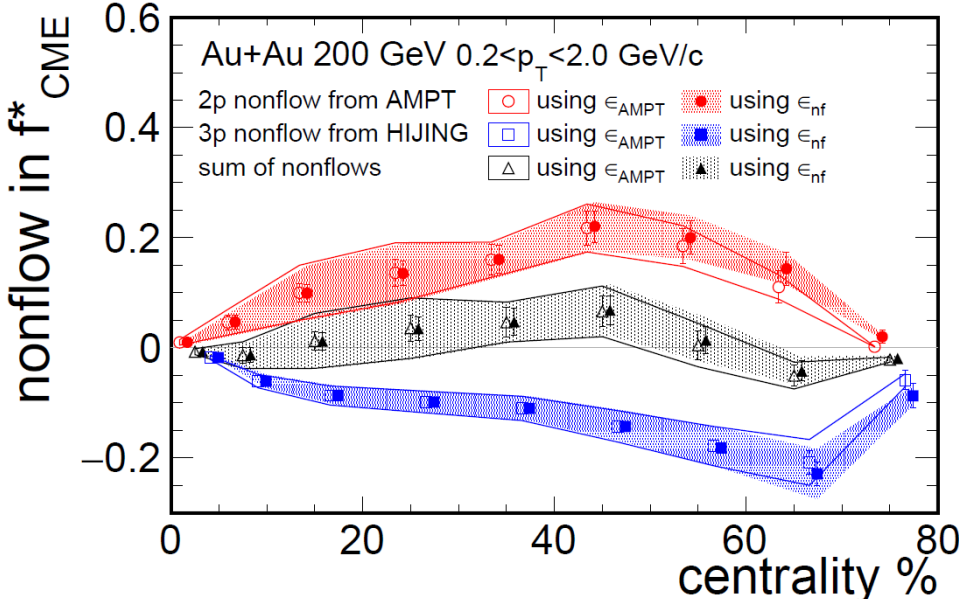


MODEL ESTIMATES OF NONFLOW

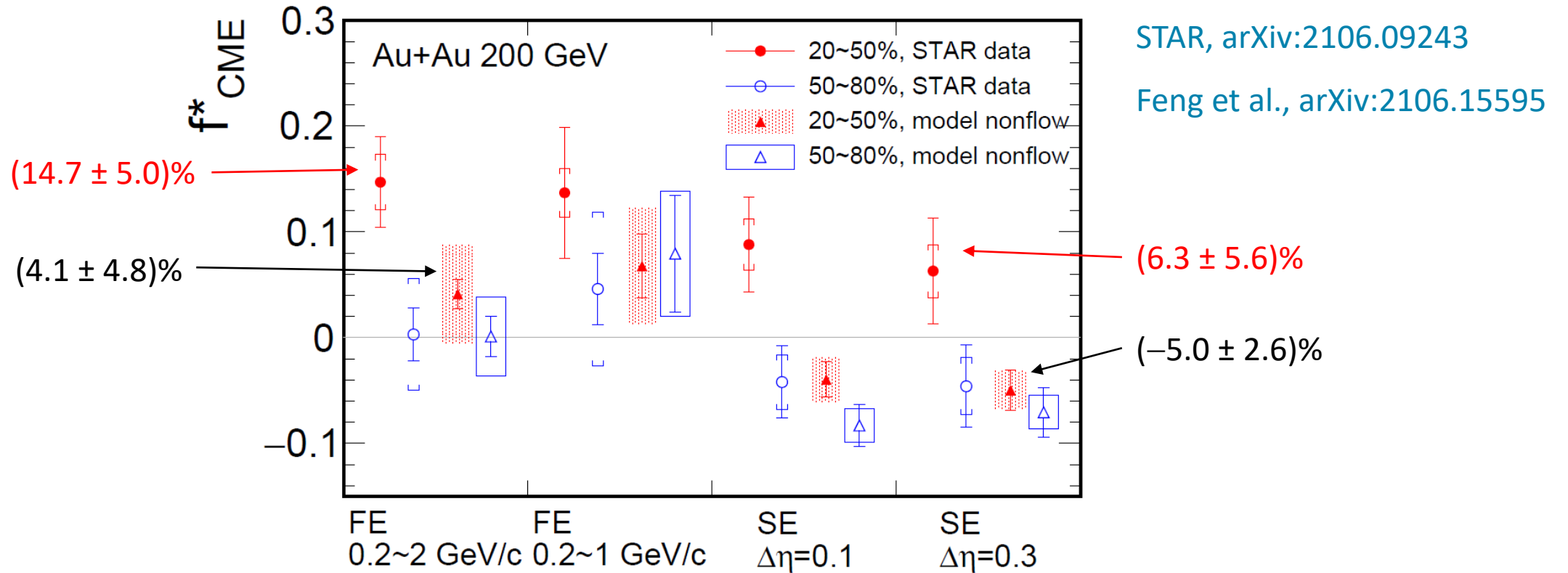
Feng et al., arXiv:2106.15595

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

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



NONFLOW EFFECTS IN f_{CME}^*



There may indeed be hint of CME in the data, $\sim 2\sigma$

REMAINING NONFLOW EFFECTS

Feng et al., arXiv:2106.15595

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

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

$$C_3\{\text{SP}\} = \frac{C_{2\text{p}}N_{2\text{p}}}{N^2} v_{2,2\text{p}}\{\text{SP}\}v_2\{\text{SP}\},$$

Nonflow in $\Delta\gamma$
 \rightarrow negative f_{CME}

$$v_2^*\{\text{EP}\} = \sqrt{v_2^2\{\text{EP}\} + v_{2,\text{nf}}^2}$$

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

$$C_3 = \frac{C_{2\text{p}}N_{2\text{p}}}{N^2} v_{2,2\text{p}}v_2 + \frac{C_{3\text{p}}N_{3\text{p}}}{2N^3}$$

$$\varepsilon_2 = \frac{C_{2\text{p}}N_{2\text{p}}}{N} \cdot \frac{v_{2,2\text{p}}}{v_2}$$

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

- 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 will require detailed nonflow studies**