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

~~May 11-14, 2020~~ November 1-5, 2021

Stony Brook University, Wang Center

Search for CME in Au+Au collisions at STAR

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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

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

quarks — quark-gluon interactions — quarks

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

gluons

't Hooft vacuum

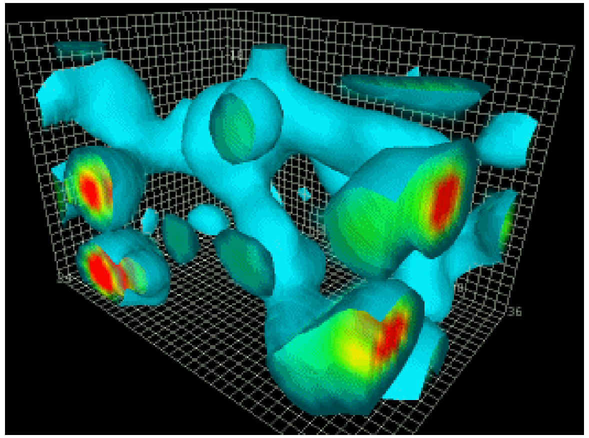
$$+\theta \frac{\alpha_s}{8\pi} G^\alpha_{\mu\nu} \tilde{G}^{\mu\nu}_\alpha = -\theta \frac{\alpha_s}{2\pi} \vec{E}_\alpha \cdot \vec{B}_\alpha$$

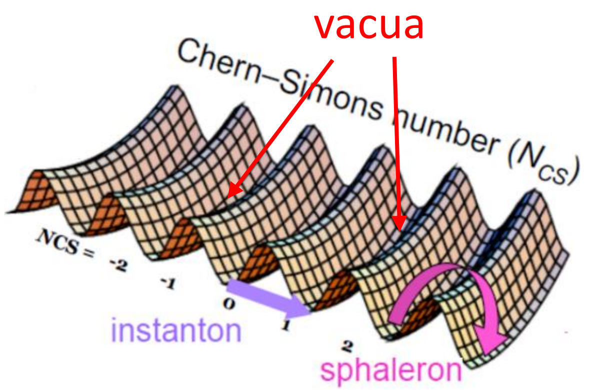
to solve the $U(1)_A$ problem (1976)

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

Explicitly breaks CP

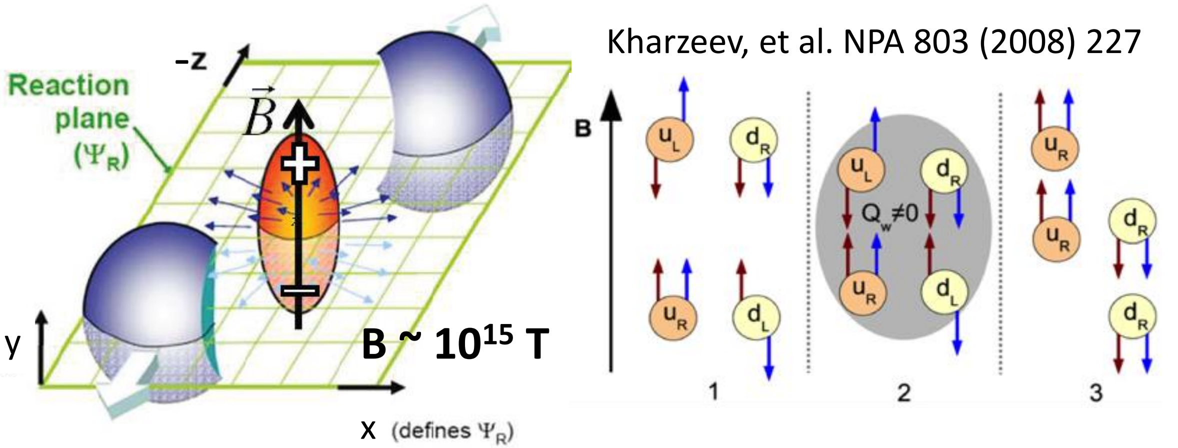
Early universe ultraviolet θ ≈ 1 ?? >> current infrared θ ≈ 0





Kharzeev,Pisarski,Tytgat,PRL81(1998)512

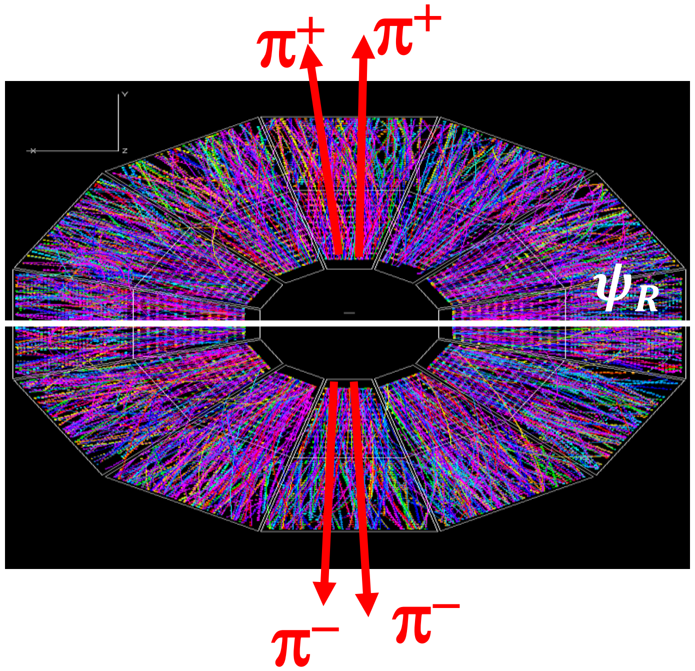
QCD vacuum fluctuation, chiral anomaly, topological gluon field



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



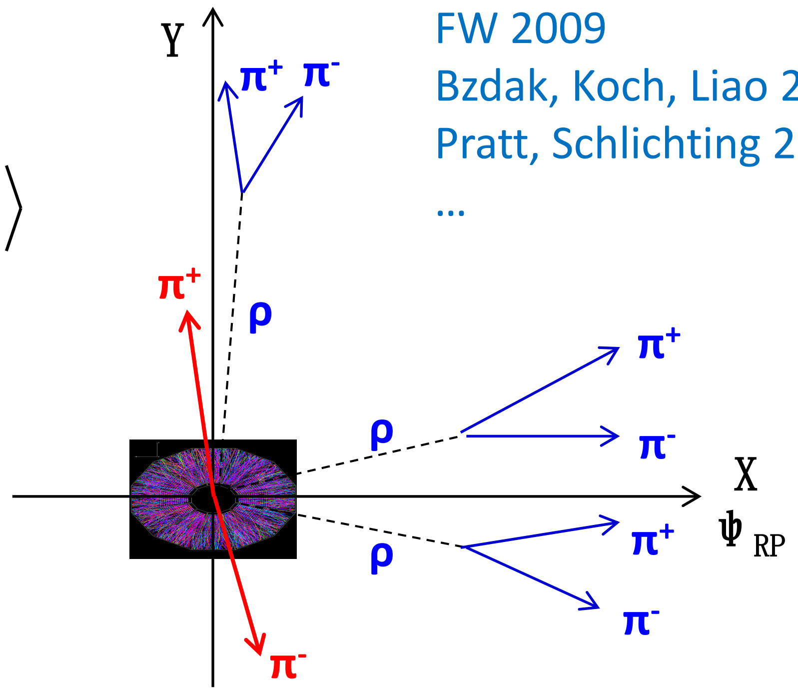
Voloshin, PRC 70 (2004) 057901

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

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

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

$$\Delta\gamma > 0$$



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

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

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

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

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.

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

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

Width of R(ΔS) distribution reduces to variance sin*sin, cos*cos → equivalently the Δγ variable

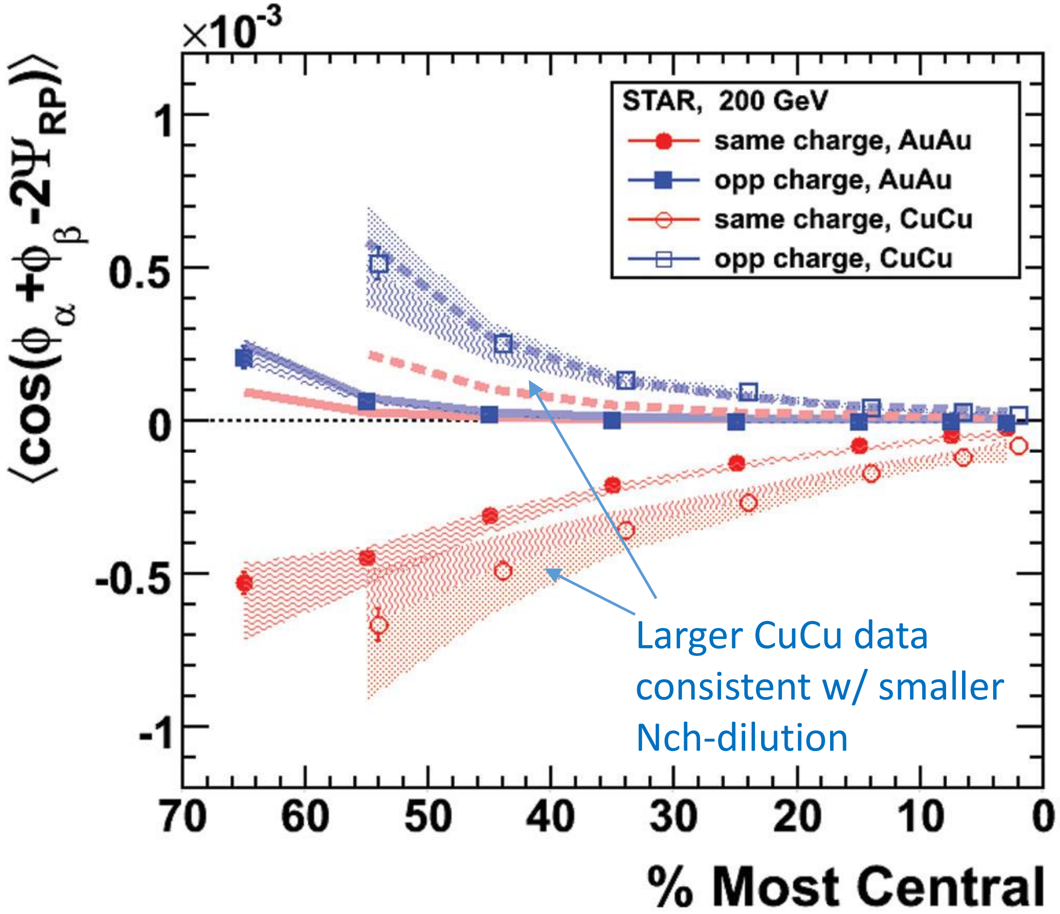
$$\frac{S_{\text{concavity}}}{\sigma^2_{R2}} \approx -\frac{M}{2}(M-1)\Delta\gamma_{112}$$

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

- 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

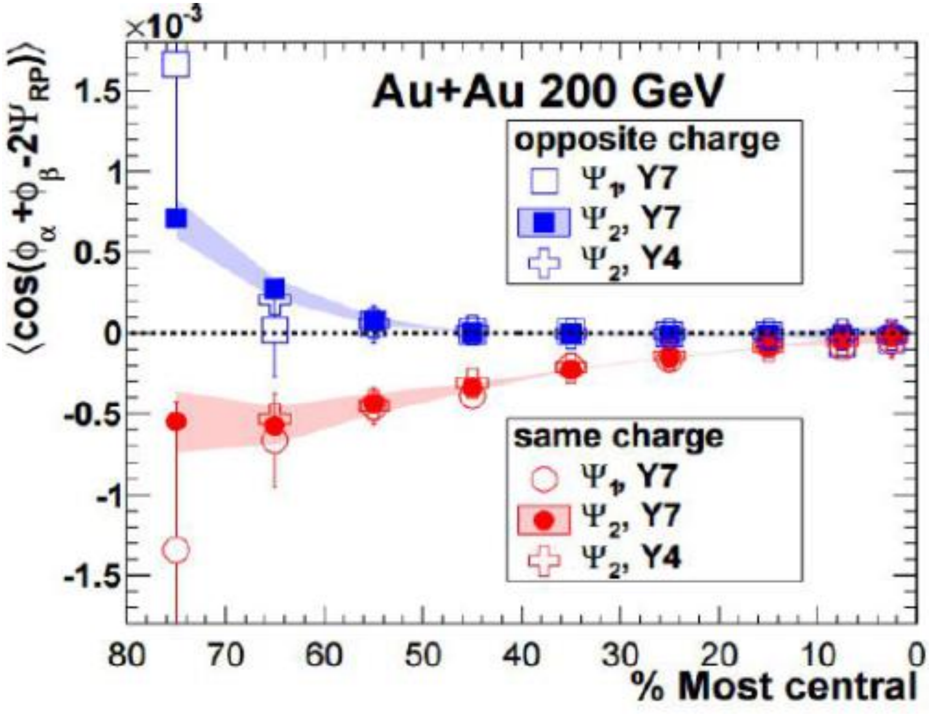
STAR, PRL 103, 251601 (2009); PRC 81, 054908 (2010)



- *"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

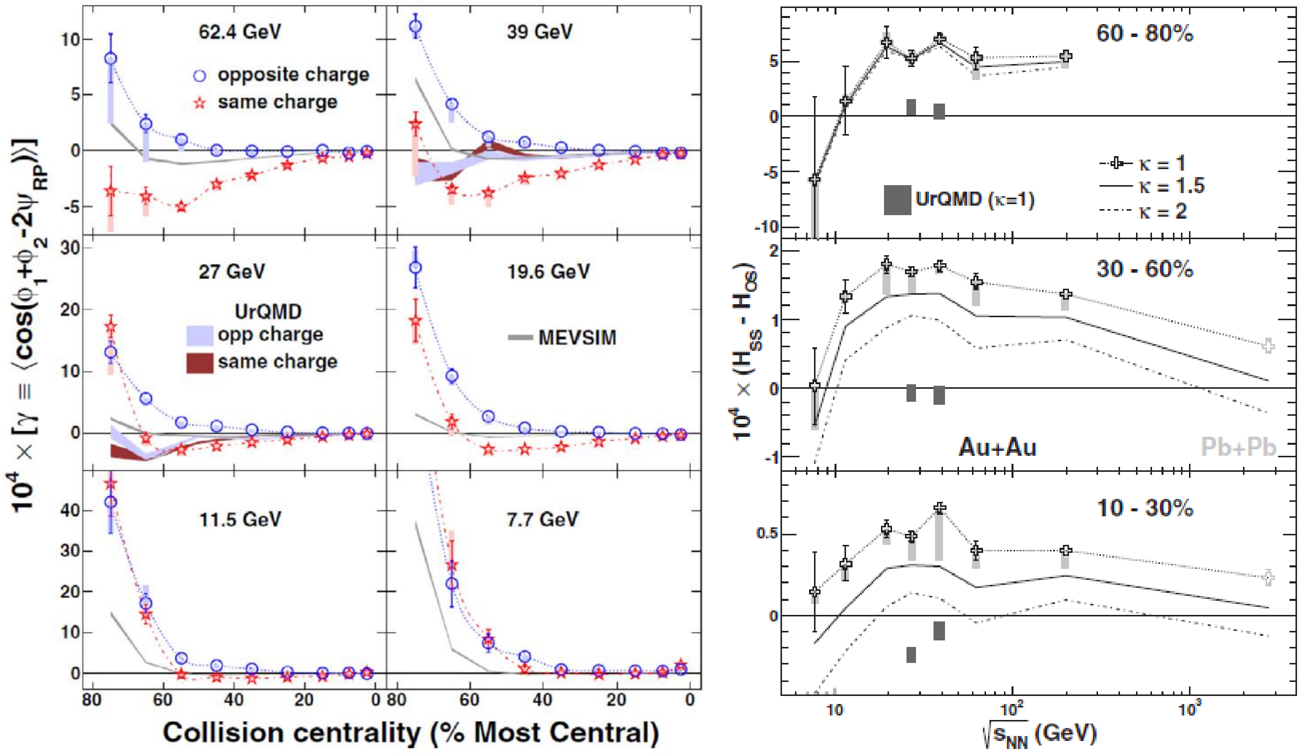
STAR, PRC 88 (2013) 064911



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

BES MEASUREMENTS, 2014

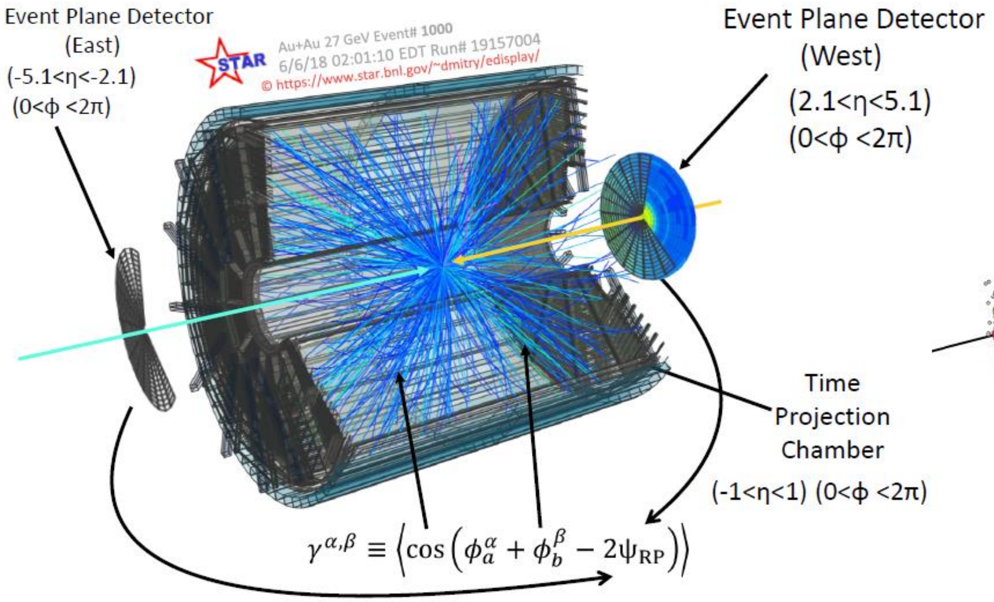
STAR, PRL 113 (2014) 052302

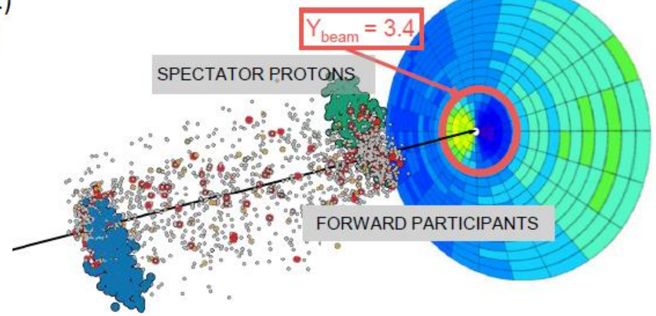


- Expect energy dependence in **B** and CME
- $\kappa \approx \Delta\gamma / (v_2\Delta\delta)$, where $\delta = <\cos(\phi_1-\phi_2)>$ as background estimator
- *"indicates a large contribution from the P-even background…"*
- *This trend may be consistent with the [CME] because there should be a smaller 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.*

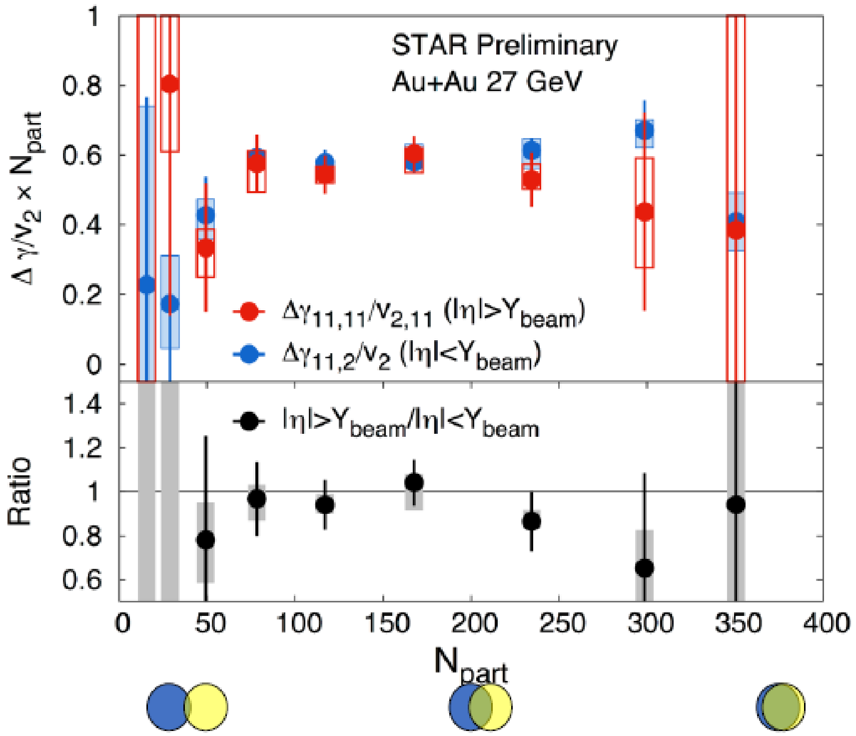
MORE RECENT LOW ENERGY (27 GeV) DATA

Yu Hu (STAR), arXiv:2110.15937, SQM 2021





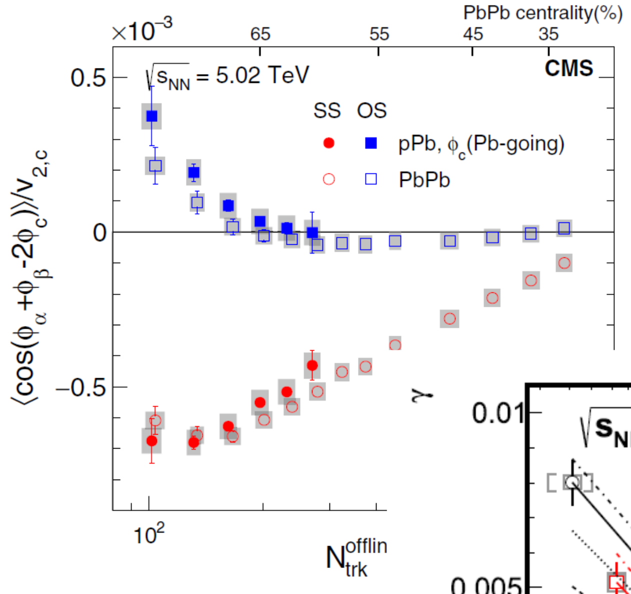
Covers both spectator and Participant regions @27 GeV

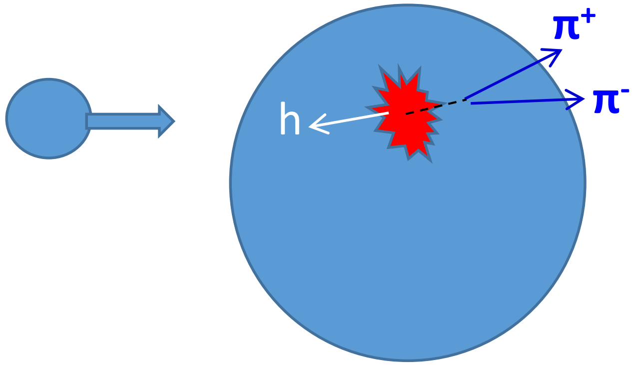


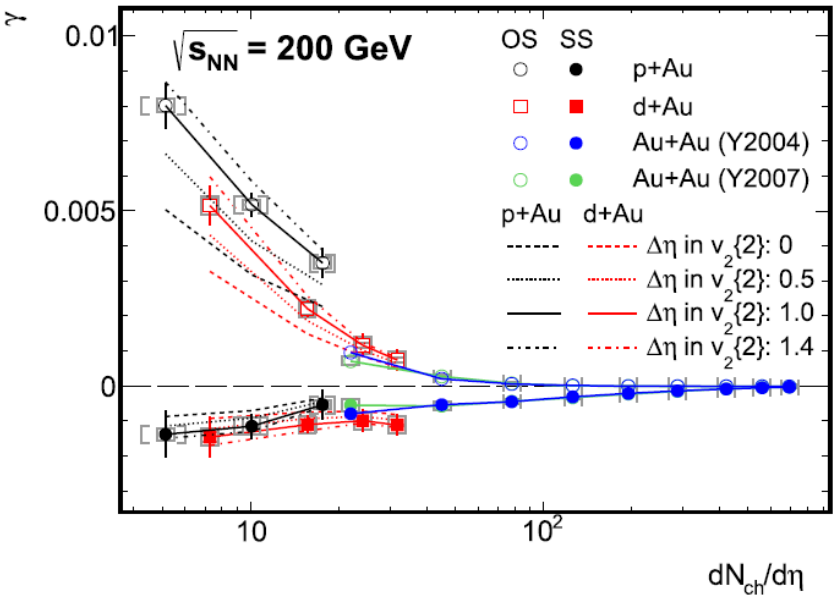
- Higher statistics, new detector (EPD)
- New approach: inner EPD -> first-order harmonic plane; Outer EPD -> second-order harmonic plane.
- Current data consistent with background contributions

SMALL SYSTEM MEASUREMENTS, 2019

CMS, PRL 118 (2017) 122301
STAR, PLB 798 (2019) 134975





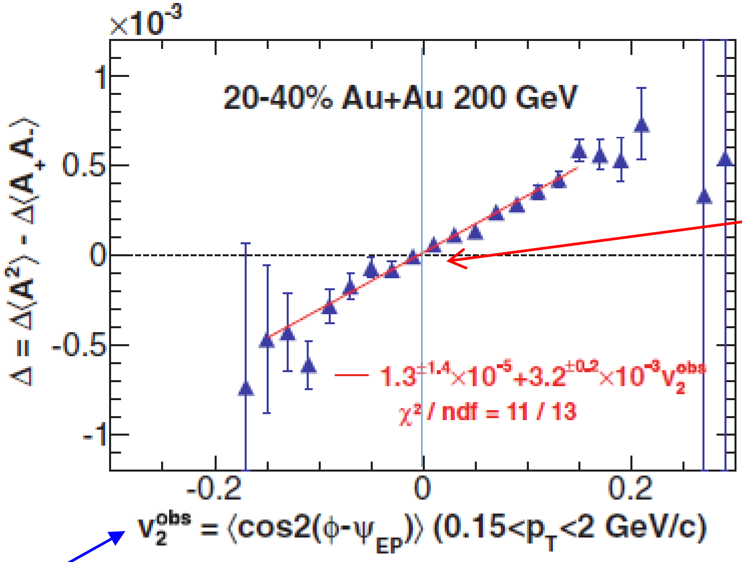


- Large $\Delta\gamma$ observed in small systems, similar to heavy ions.
- Zero signal is expected b/c random B and EP orientations
- Physics of background may differ between small systems (e.g. 3-particle nonflow) and heavy ions (flow), but raise warning for pro-CME interpretation of heavy ion data

"ESE" MEASUREMENTS, 2014

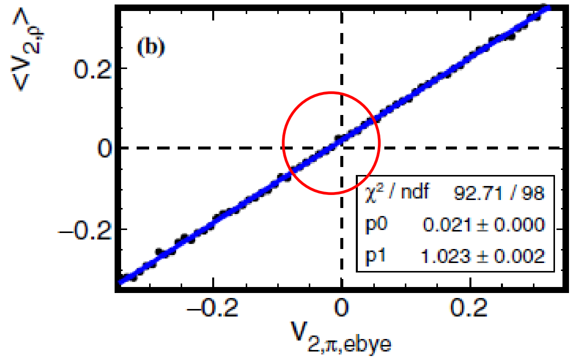
STAR, PRC 89 (2014) 044908

Here Δ is similar to
cos(α+β−2ψ) correlator



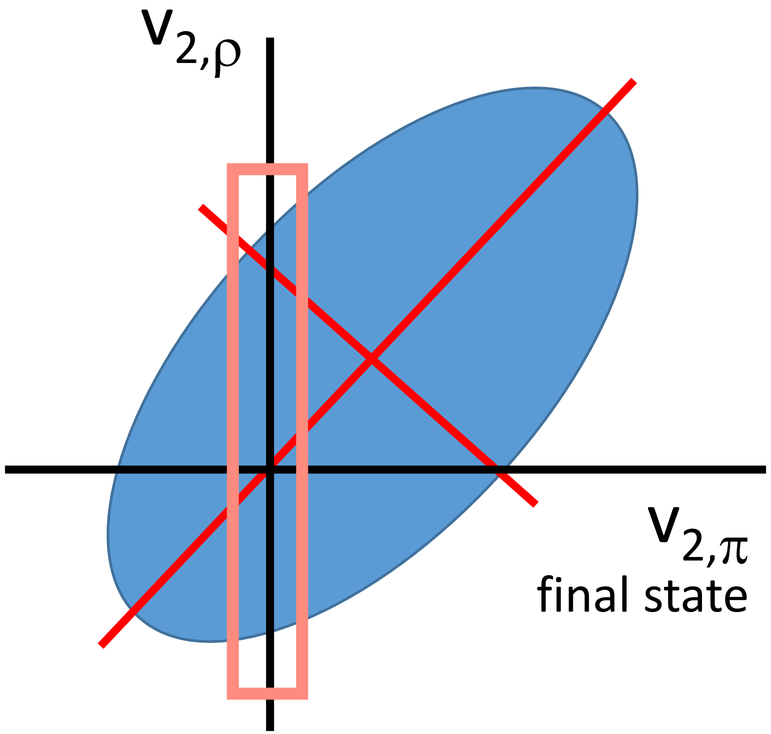
Primarily stat. fluctuations

Event-by-event v_2 technique



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

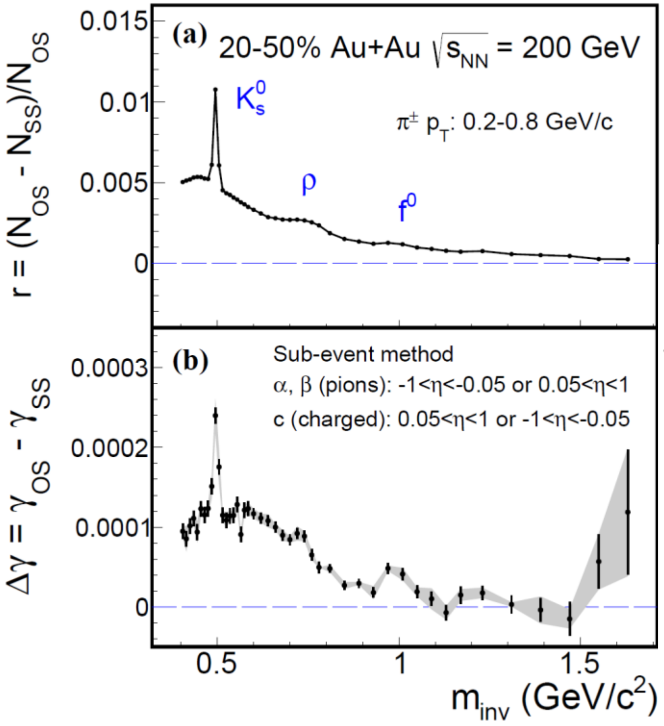
FW, Jie Zhao, PRC 95 (2017) 051901(R)



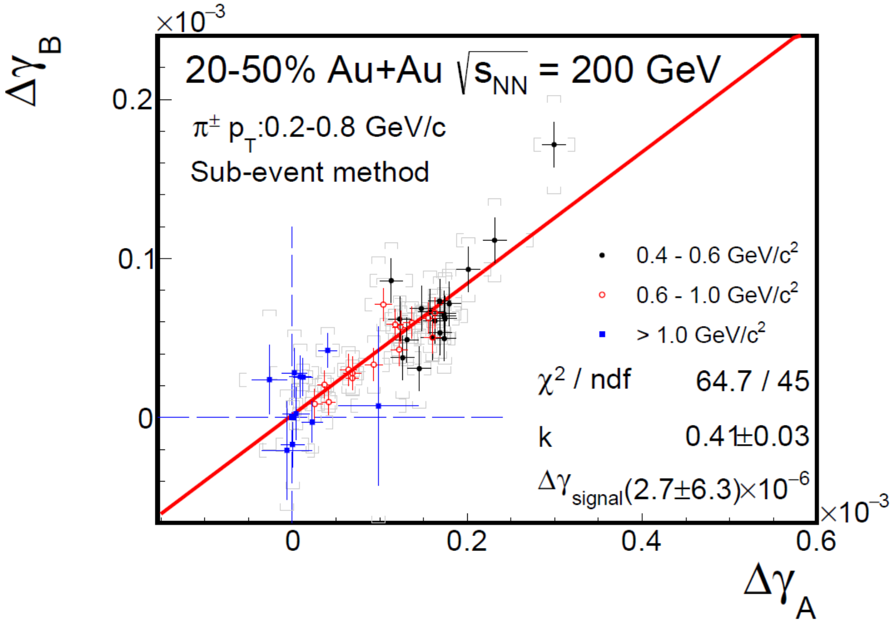
- Engineering on stat. fluctuations
- Background suppressed, but not totally eliminated
- LHC does not have this issue as v_2 selection in different phase space

MEASUREMENT IN INVARIANT MASS, 2020

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



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



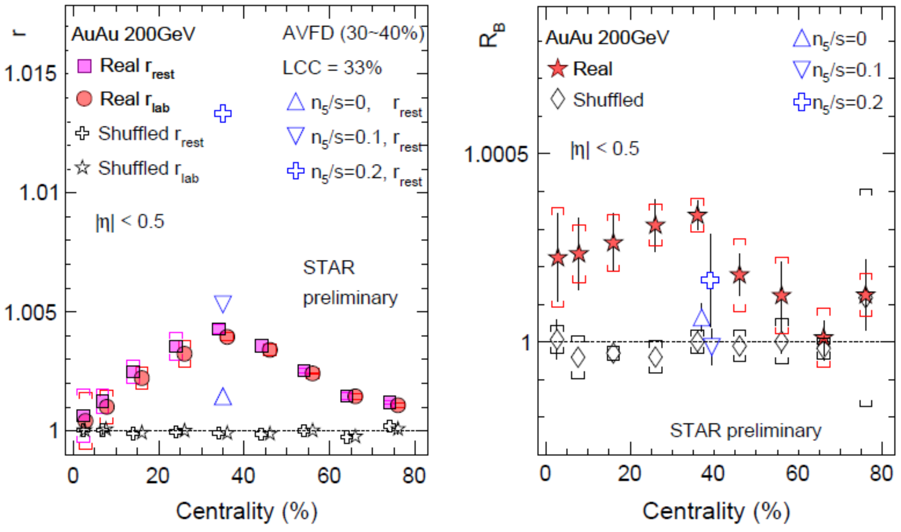
- Explicit demonstration of “resonance” background
- Exploit “ESE” to extract CME, assuming CME is mass independent
- Upper limit 15% at 95% CL

NEW OBSERVALES/APPROACHES

Signed balance function (SBF)

Tang, CPC 44 (2020) 054101

Yufu Lin (STAR), NPA 1005 (2021) 121828, QM 2019



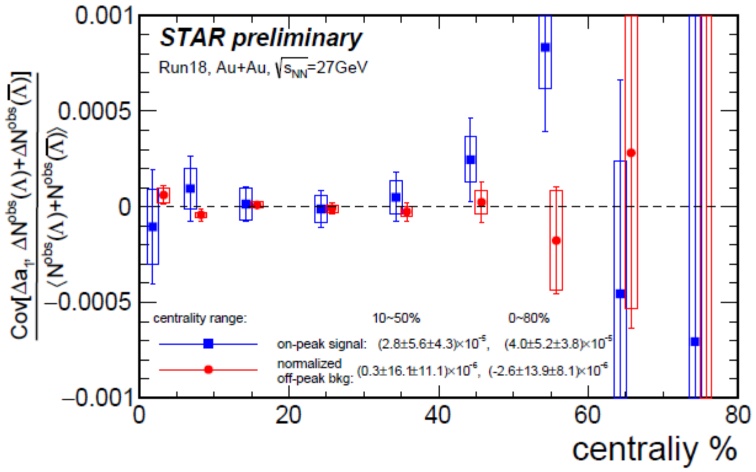
- r is out-of-plane to in-plane ratio of the SBF momentum-ordering difference
- Both r_{rest} and $R_B=r_{rest}/r_{lab}$ are larger than unity, above model calculations without CME.

CME-helicity correlation

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

Finch, Murray, PRC 96 (2017) 044911

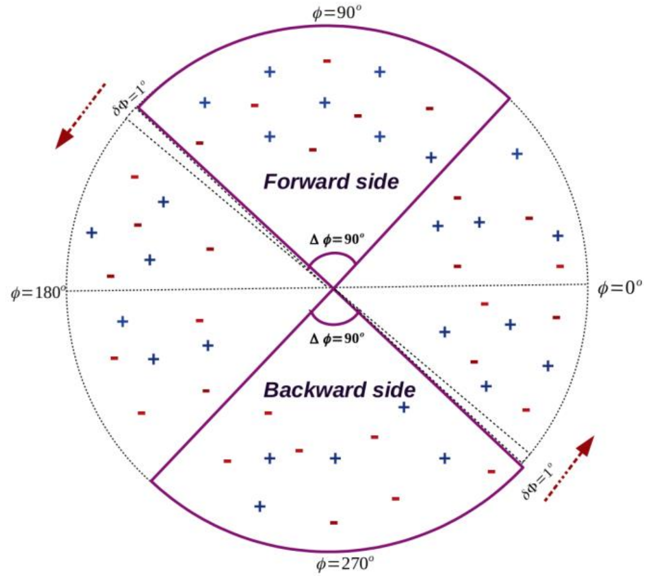
Yicheng Feng (STAR), DNP 2020



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

Sliding Dumbbell

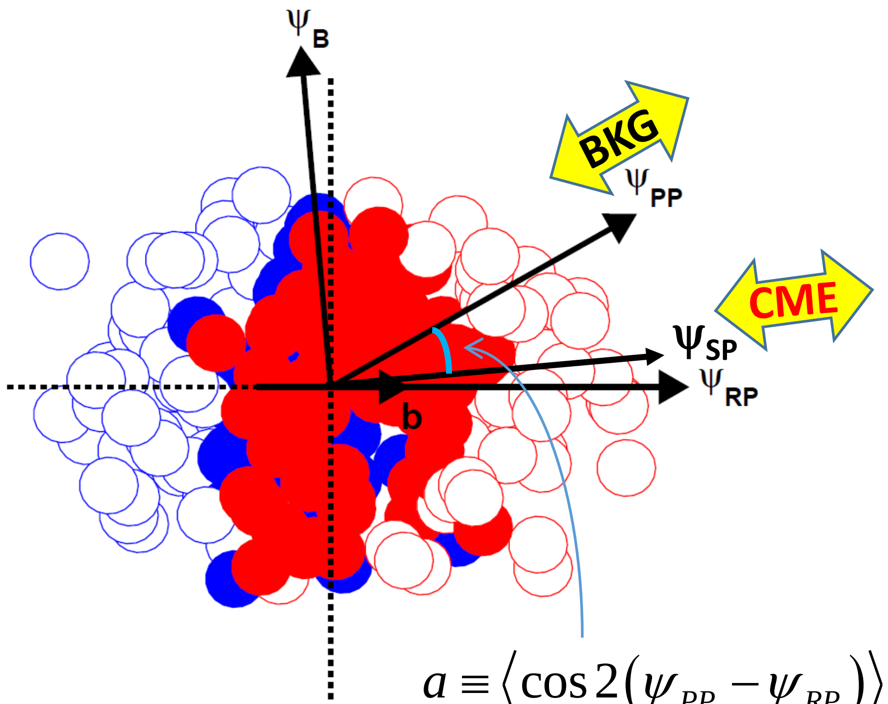
Jagbir Singh (STAR) QM 2019



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

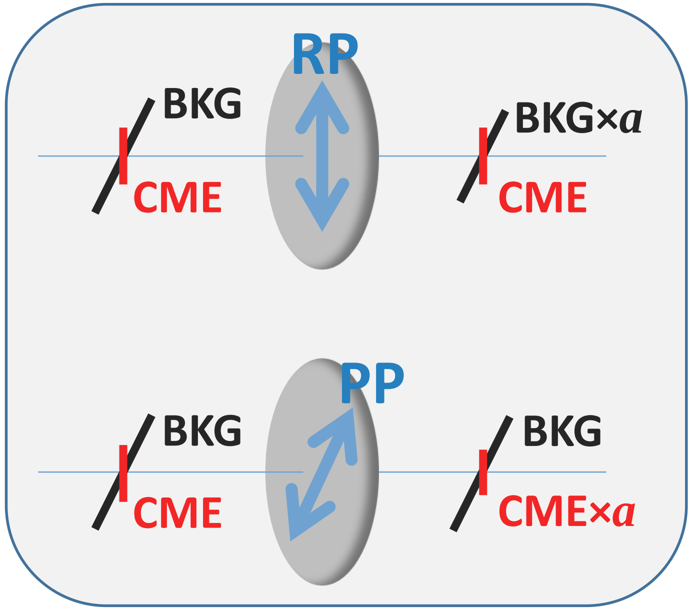
W.R.T. SPECTATOR & PARTICIPANT PLANES, 2021

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



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

INTRA-EVENT "CME-v_2 FILTER"



IN THE SAME EVENT

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

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

$$A = \Delta\gamma\{\mathrm{SP}\}/\Delta\gamma\{\mathrm{PP}\}$$

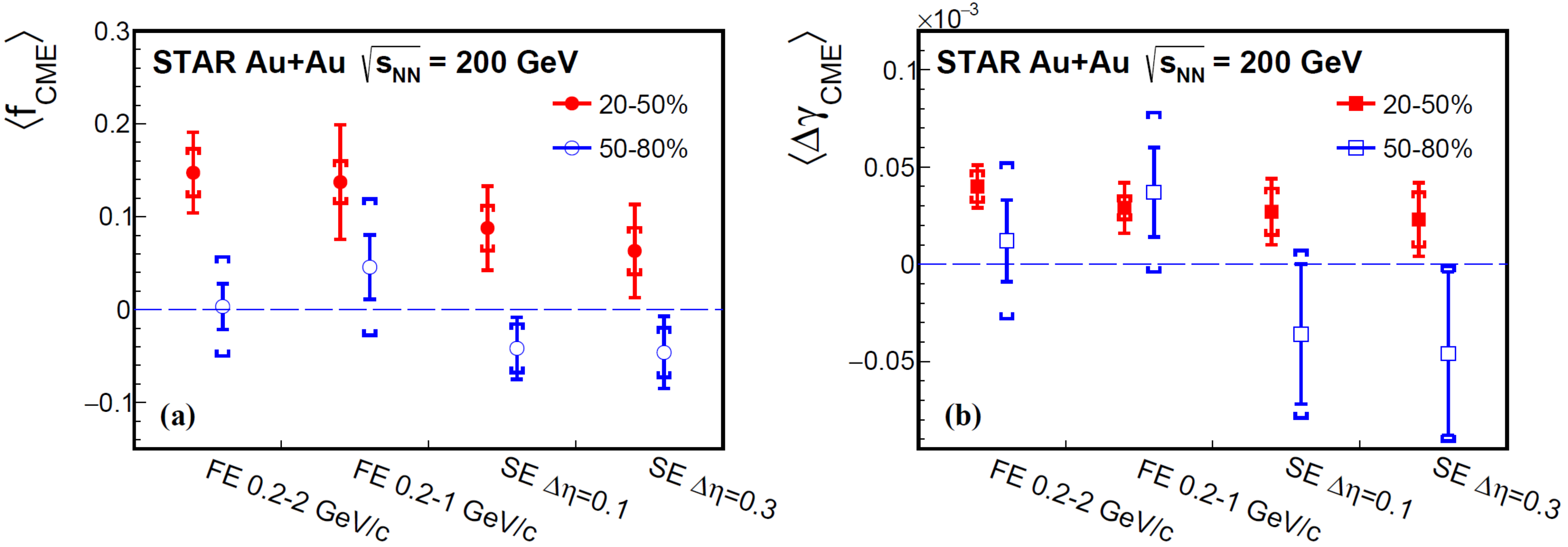
$$a = v_2\{\mathrm{SP}\}/v_2\{\mathrm{PP}\}$$

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

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

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 1-3σ significance
- Possible remaining nonflow effects

REMAINING NONFLOW EFFECTS

Feng et al., arXiv:2106.15595

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

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

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

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

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

$$\epsilon_2 \equiv \frac{C_{\rm 2p}N_{\rm 2p}v_{2,\rm 2p}}{Nv_2} \qquad \epsilon_3 \equiv \frac{C_{\rm 3p}N_{\rm 3p}}{2N}$$

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

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

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

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

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

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

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

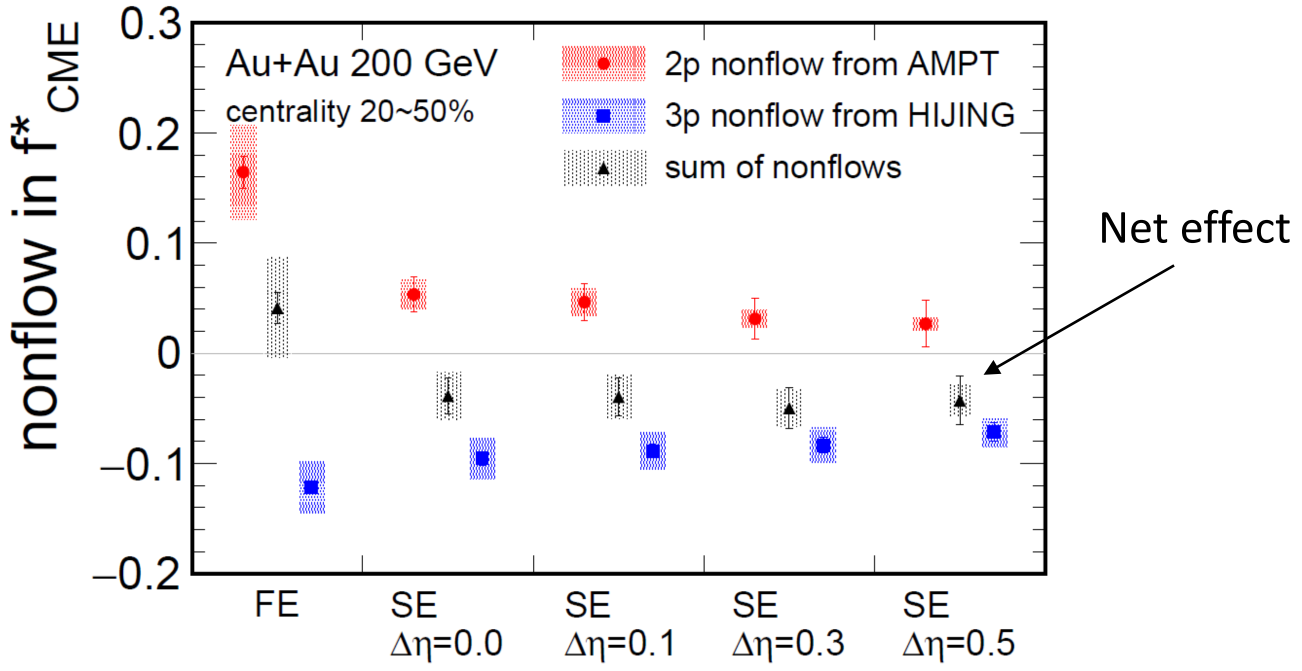
$$f_{\rm CME}^* = \left(\frac{1+\epsilon_{\rm nf}}{1+\frac{\epsilon_3/\epsilon_2}{Nv_2^2\{\rm EP\}}} - 1\right) \Big/ \left(\frac{1+\epsilon_{\rm nf}}{a^2} - 1\right)$$

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

MODEL ESTIMATES OF NONFLOW

Feng et al., arXiv:2106.15595

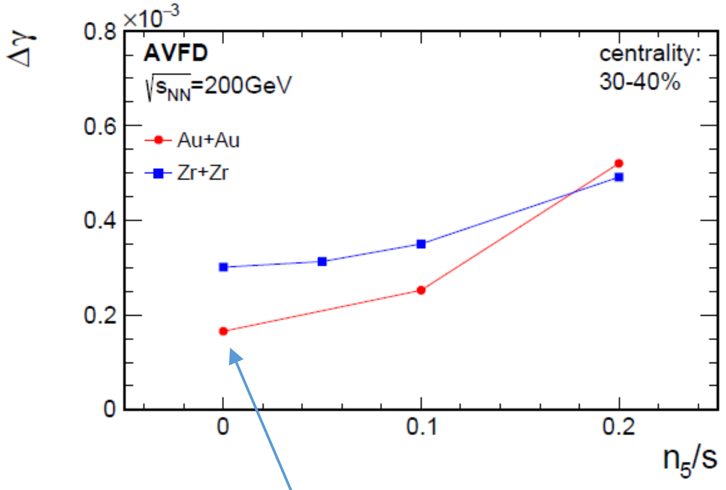
$$f^*_{\mathrm{CME}} \approx \left(\epsilon_{\mathrm{nf}} - \frac{\epsilon_3/\epsilon_2}{N v_2^2\{\mathrm{EP}\}}\right) \Big/ \left(\frac{1+\epsilon_{\mathrm{nf}}}{a^2} - 1\right)$$

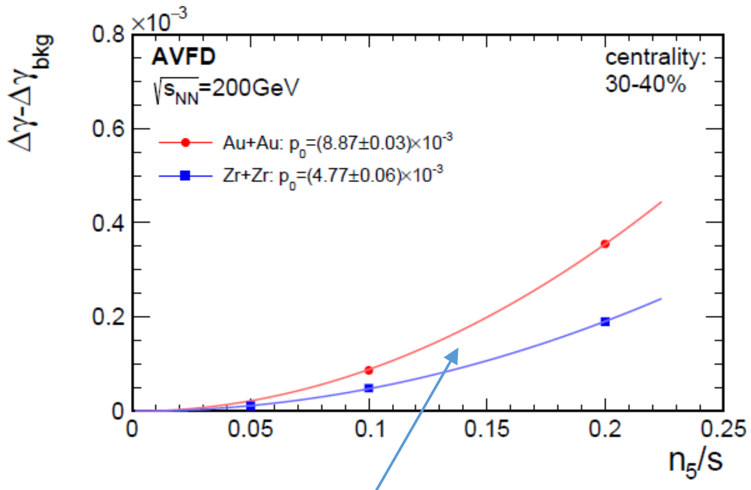


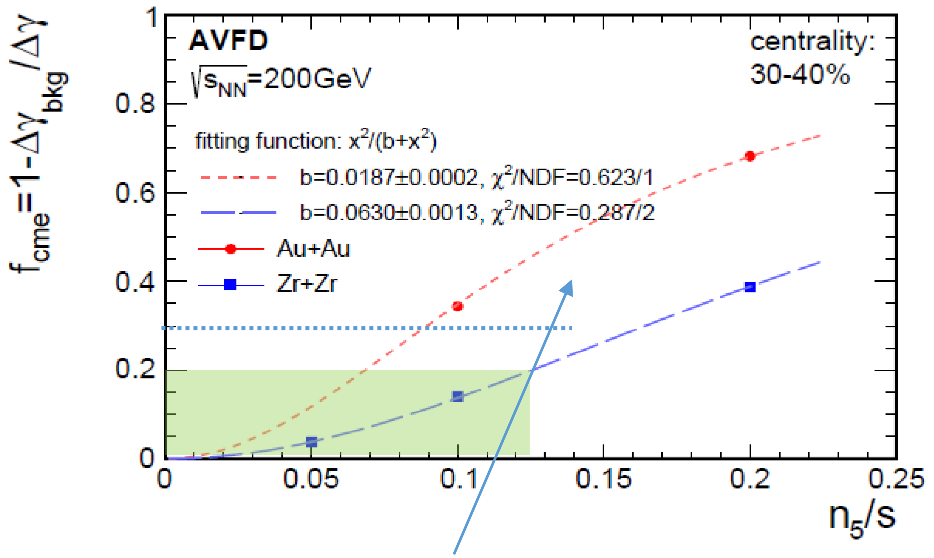
- 2-particle nonflow estimates from AMPT
- 3-particle nonflow estimates from HIJING
- Net effect on f_{CME} can possibly be negative (model dependent)
- Further, additional model studies

Au+Au DATA AND ISOBAR ARE CONSISTENT

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







Background ∝ 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 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 1-3σ 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.