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Search for CME with STAR experiment

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For the STAR Collaboration

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OUTLINE

- Physics motivation and observables
- Brief historical review of STAR (and other) measurements
- Recent CME measurements from STAR
    - Invariant mass
    - EPD measurements
    - Other observables/approaches
    - **Spectator/participant planes in Au+Au collisions**
    - **Isobar collisions**
- 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 — gluons

$$-\frac{1}{4} G^\alpha_{\mu\nu} G^{\mu\nu}_\alpha = \frac{1}{2}\left(E_\alpha^2 - B_\alpha^2\right)$$

't Hooft vacuum

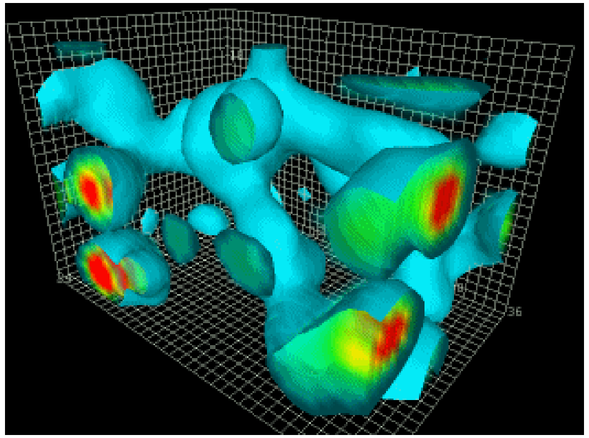
$$+\theta \frac{\alpha_s}{8\pi} G^\alpha_{\mu\nu} \tilde{G}^{\mu\nu}_\alpha = -\theta \frac{\alpha_s}{2\pi} \vec{E}_\alpha \cdot \vec{B}_\alpha$$

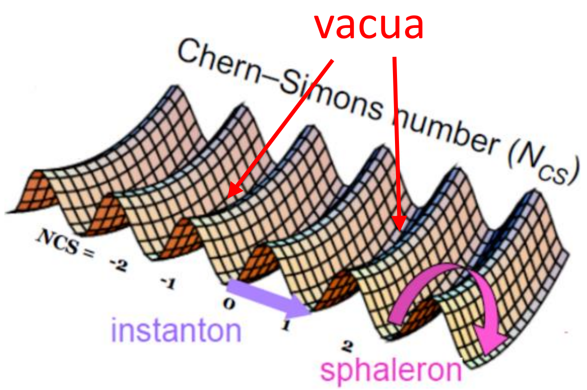
to solve the $U(1)_A$ problem (1976)

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

Explicitly breaks CP

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

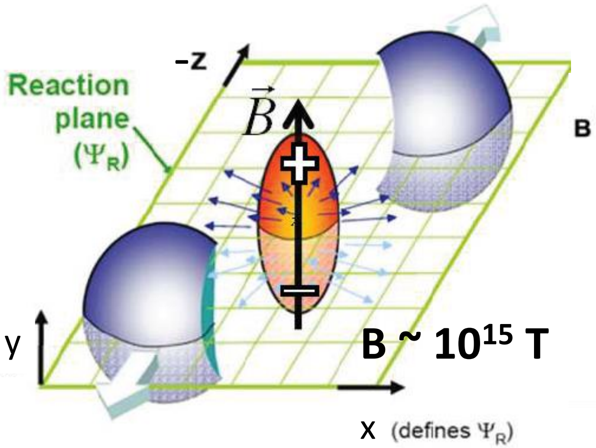


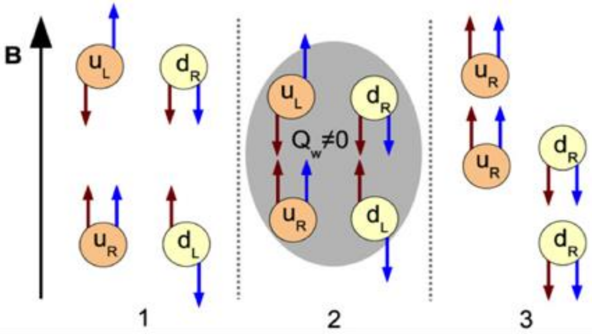


Kharzeev,Pisarski,Tytgat,PRL81(1998)512

QCD vacuum fluctuation, chiral anomaly, topological gluon field

Kharzeev, et al. NPA 803 (2008) 227



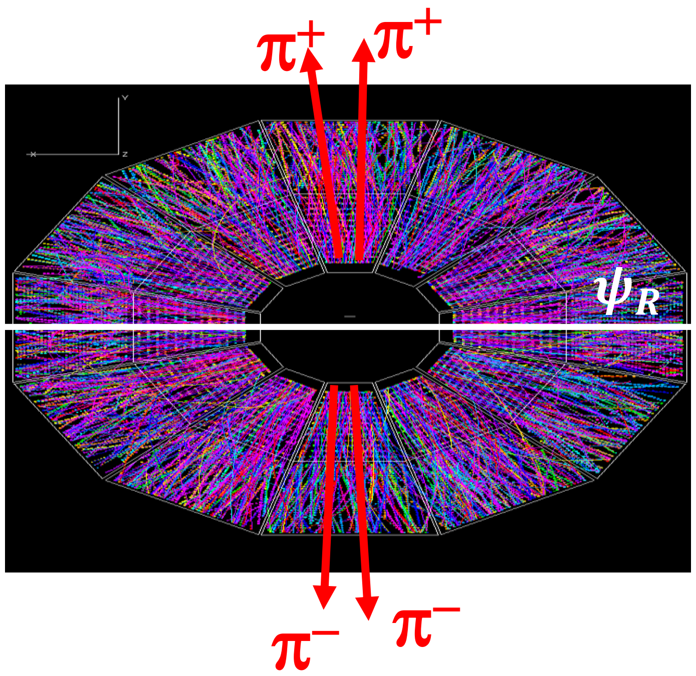


Chiral Magnetic Effect (CME)

Discovery of 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

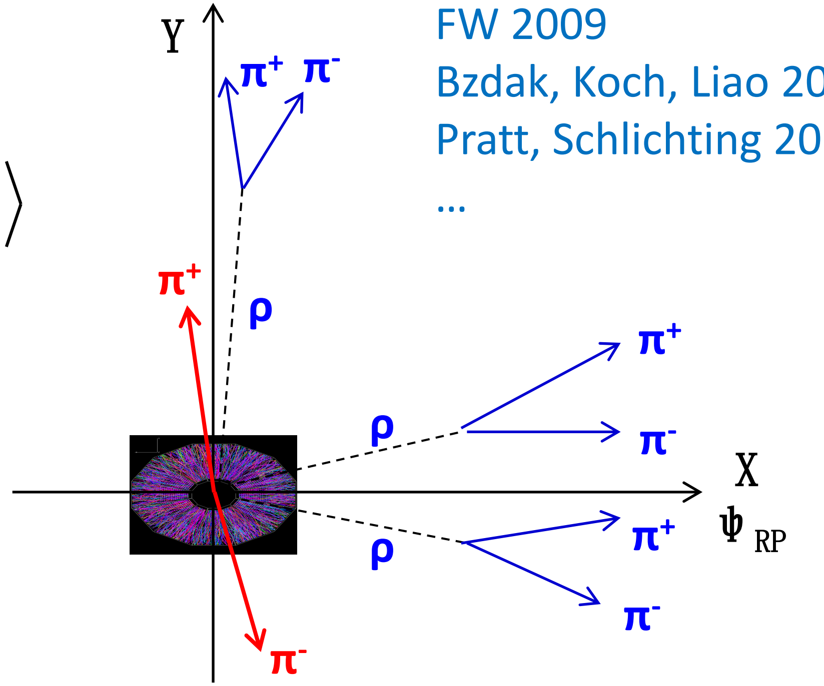


$$\gamma_{\alpha\beta} = \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{RP}) \right\rangle$$

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

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

$$\Delta\gamma > 0$$



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

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

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

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

THE R VARIABLE

Yufu Lin's talk this afternoon

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

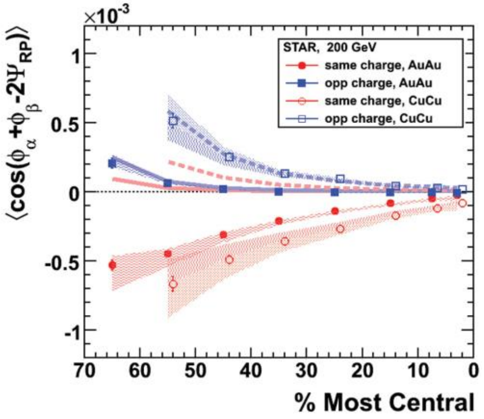
$$\frac{S_{\text{concavity}}}{\sigma^2_{R2}} \approx -\frac{M}{2}(M-1)\Delta\gamma_{112}$$

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

- 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

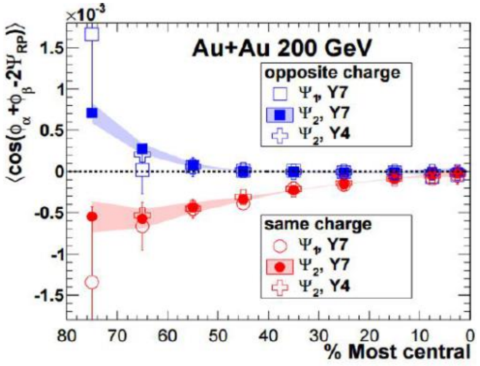
STAR (and ALICE, CMS) MEASUREMENTS

STAR, PRL 103 (2019) 251601; PRC 81, 054908 (2010)



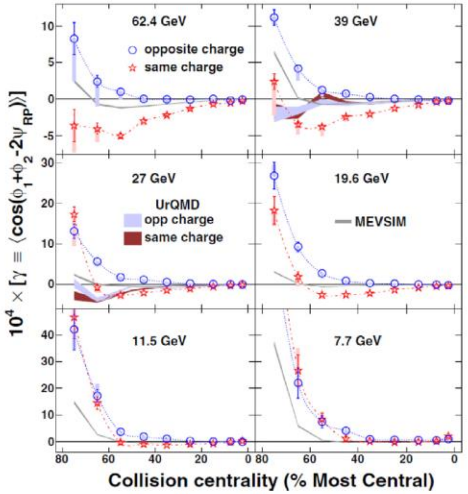
First measurement; Large signal

STAR, PRC 88 (2013) 064911



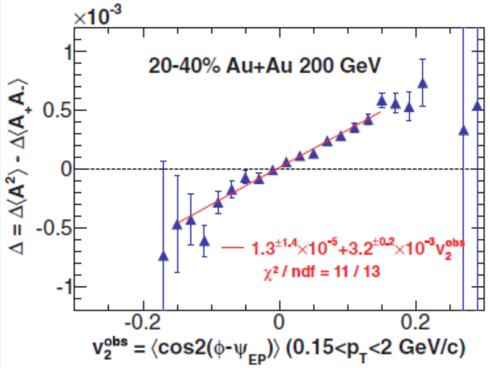
Measurement wrt ZDC ψ_1; Similar result wrt TPC ψ_2

STAR, PRL 113 (2014) 052302



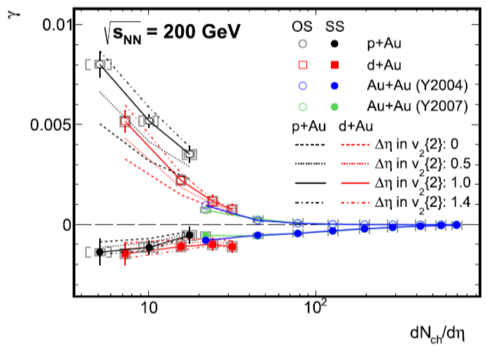
BES; signal disappears at low energy

STAR, PRC 89 (2014) 044908



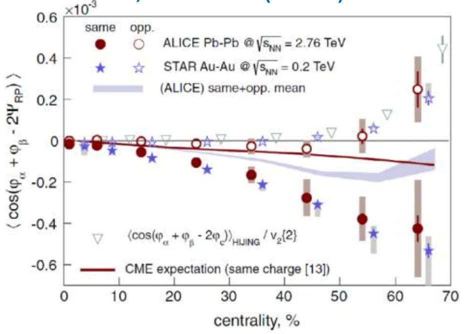
ESE projection to v_2=0; bkg significantly reduced, but not eliminated

STAR, PLB 798 (2019) 134975

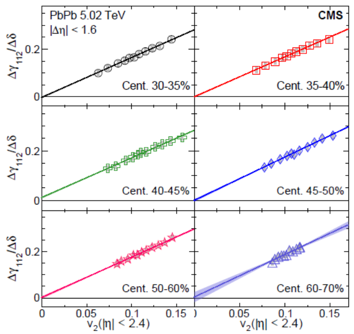


Small system; signal as large as heavy ion; large bkg contributions

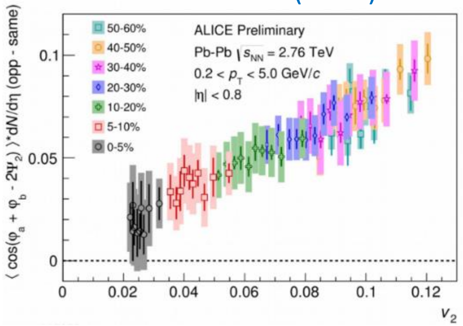
ALICE, PRL 110 (2013) 012301



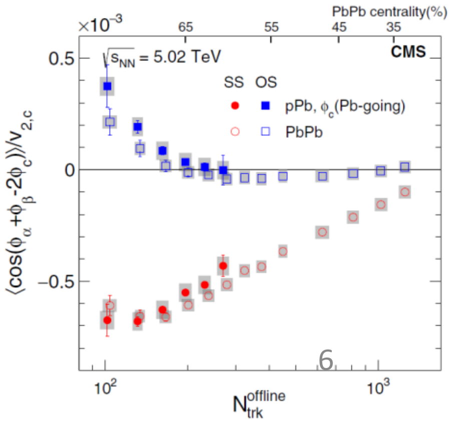
CMS PRC97 (2018) 044912



ALICE PLB777(2018)151

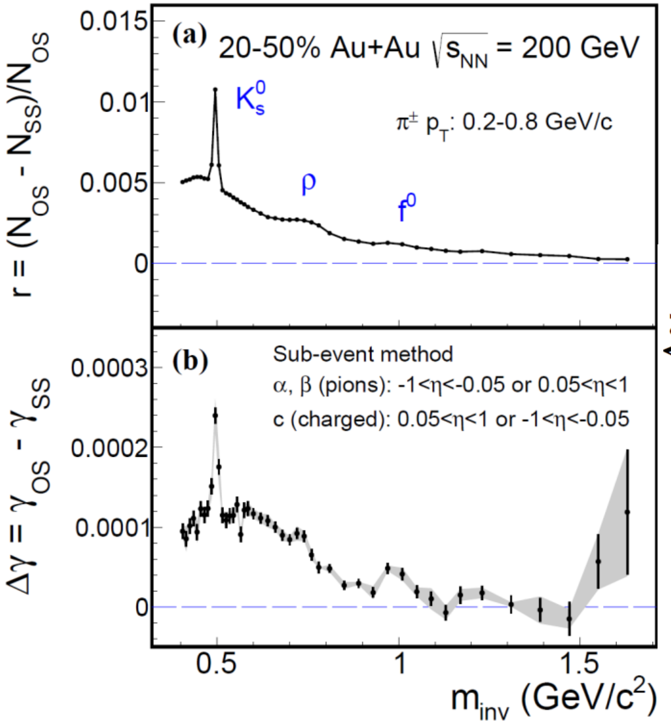


CMS, PRL 118 (2017) 122301

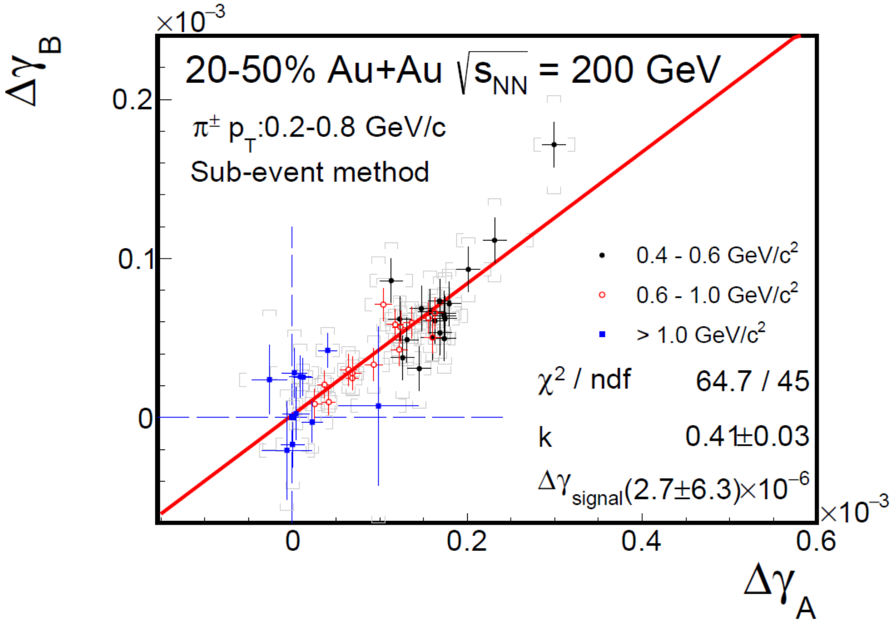


MEASUREMENT IN INVARIANT MASS

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



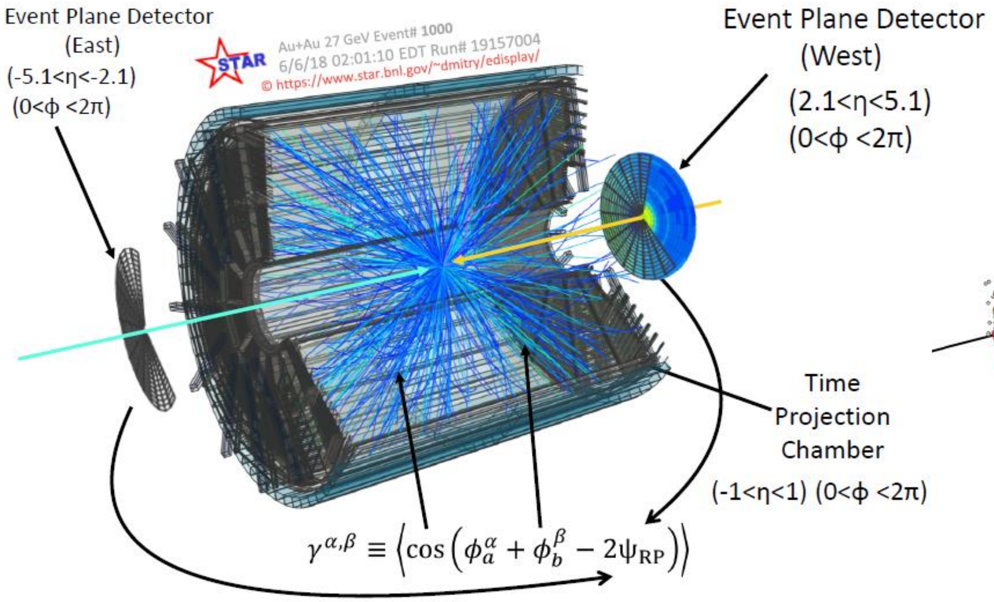
$$\frac{N_\rho}{N_\alpha N_\beta}\left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{clus}) \right\rangle \times v_{2,clus}$$

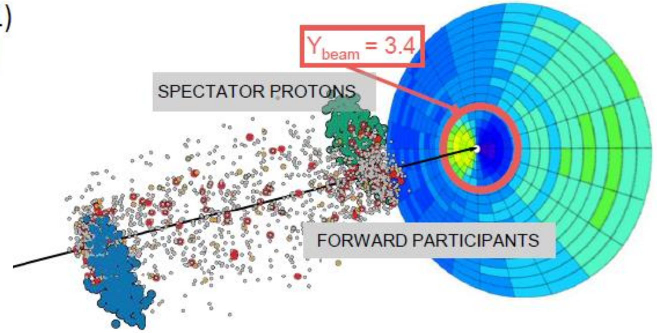


- Explicit demonstration of "resonance" background
- Exploit "ESE" to extract CME, assuming CME is mass independent
- Upper limit 15% at 95% CL

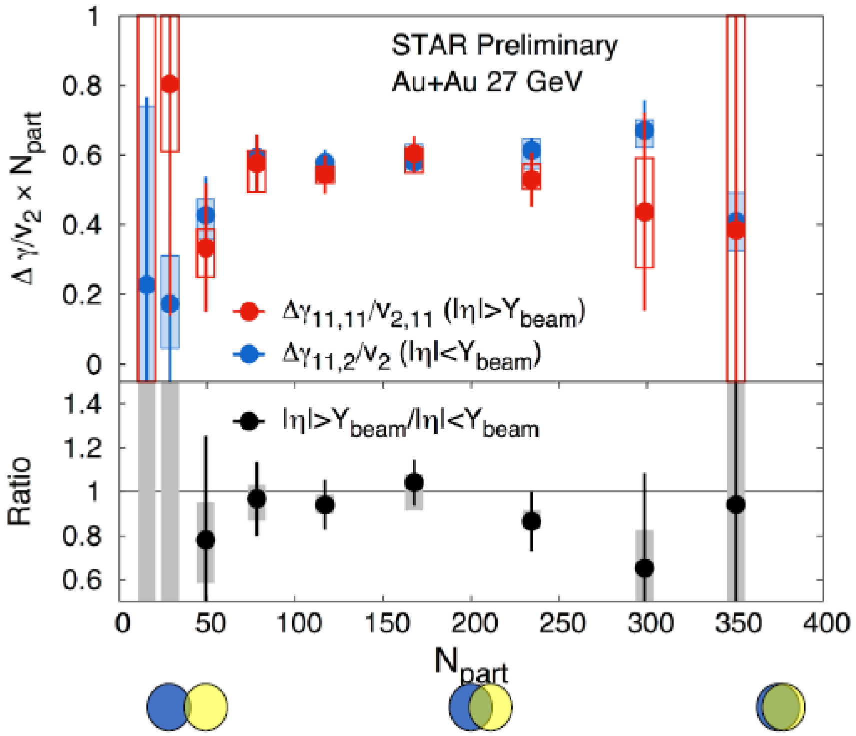
MORE RECENT LOW ENERGY (27 GeV) DATA

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





Covers both spectator and Participant regions @27 GeV



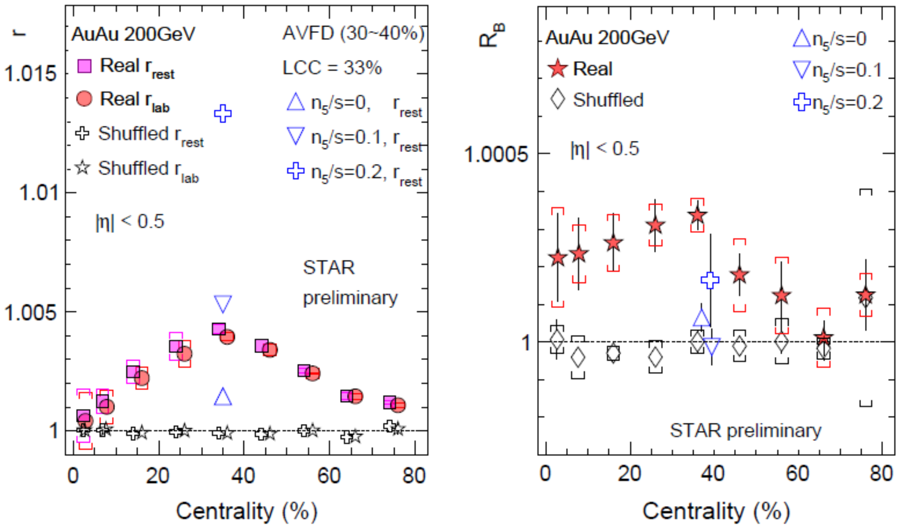
- Higher statistics, new detector (EPD)
- New approach: inner EPD -> first-order harmonic plane; Outer EPD -> second-order harmonic plane.
- Current data consistent with background contributions

NEW OBSERVALES/APPROACHES

Signed balance function (SPF)

Tang, CPC 44 (2020) 054101

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



Yufu Lin's talk this afternoon

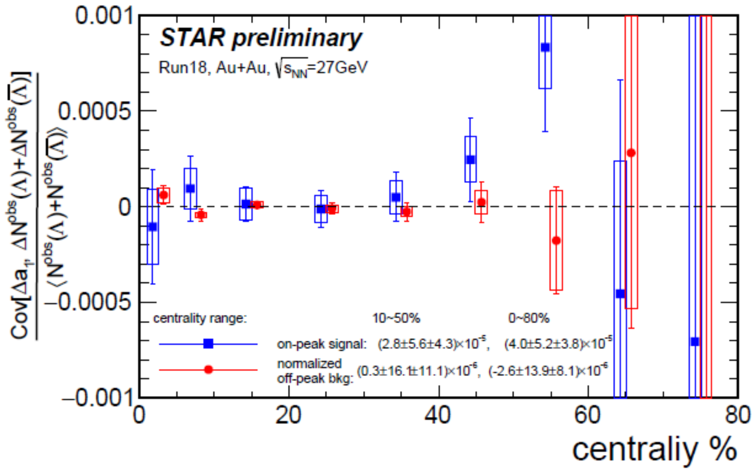
- r is out-of-plane to in-plane ratio of the SPF momentum-ordering difference
- Both r_{rest} and $R_B=r_{rest}/r_{lab}$ are larger than unity, above model calculations without CME.

CME-helicity correlation

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

Finch, Murray, PRC 96 (2017) 044911

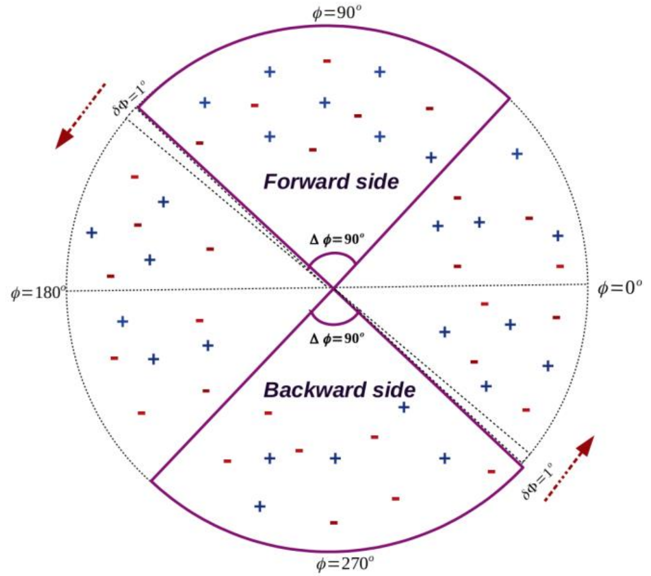
Yicheng Feng (STAR), DNP 2020



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

Sliding Dumbbell

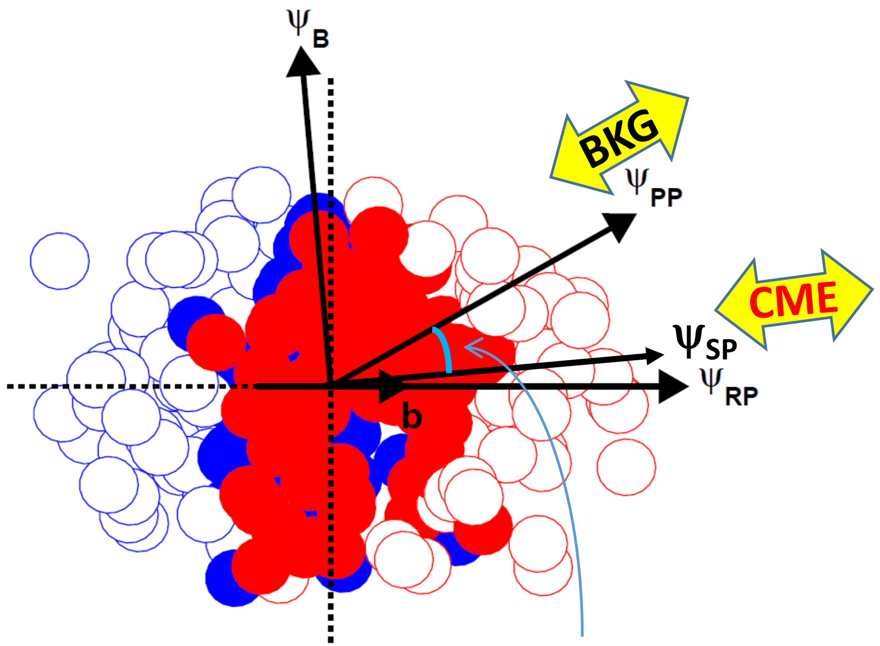
Jagbir Singh (STAR) QM 2019



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

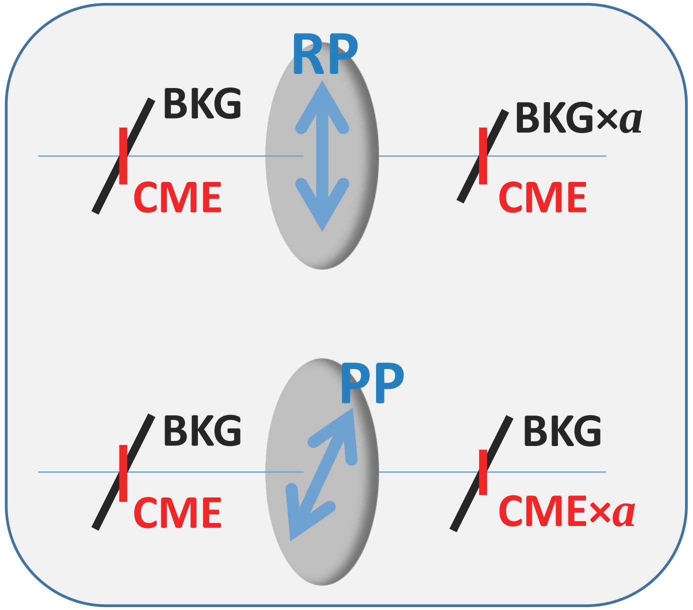
W.R.T. SPECTATOR & PARTICIPANT PLANES, 2021

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



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

INTRA-EVENT “CME-v_2 FILTER”



IN THE SAME EVENT

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

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

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

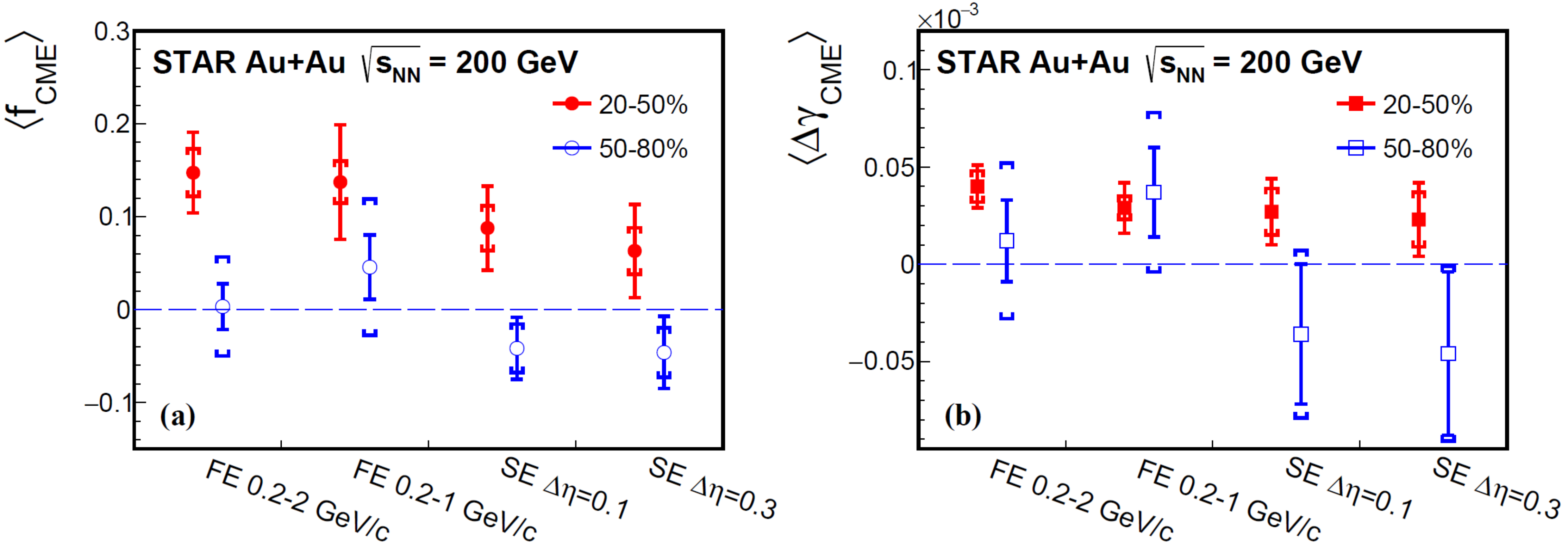
$$a = v_2\{\mathrm{SP}\}/v_2\{\mathrm{PP}\}$$

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

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

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

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

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

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 $f_{\rm CME}$

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

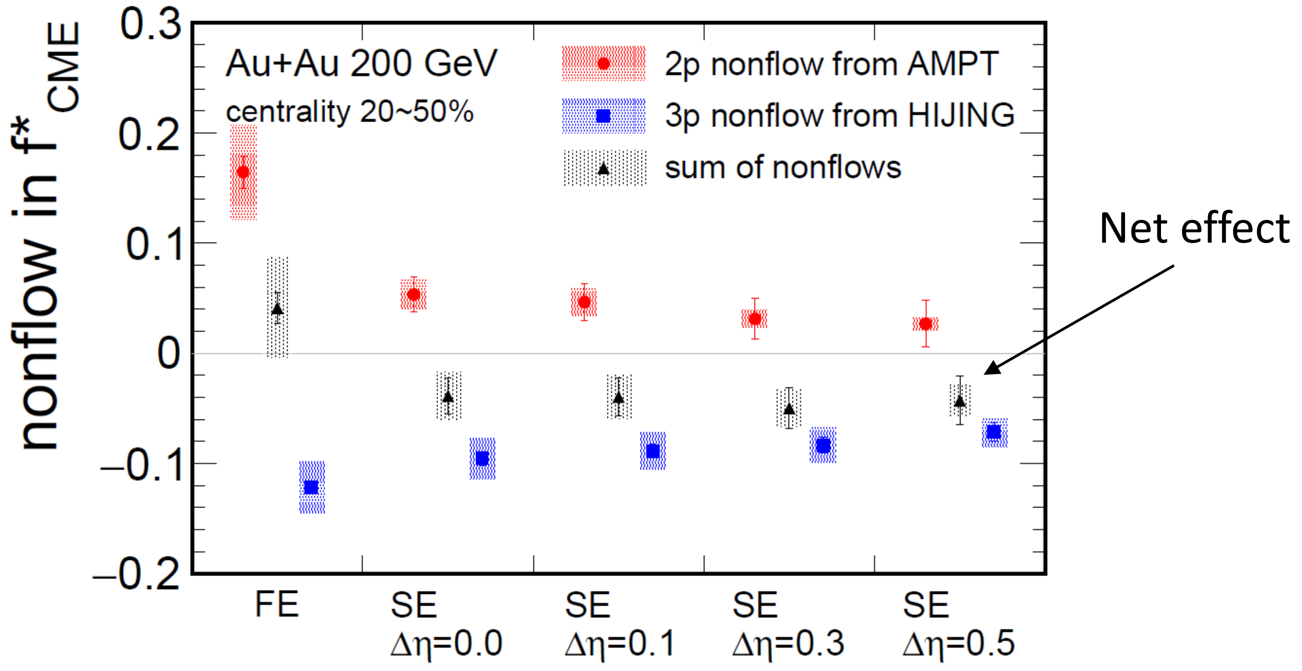
$$f_{\rm CME}^* = \left(\frac{1+\epsilon_{\rm nf}}{1+\frac{\epsilon_3/\epsilon_2}{Nv_2^2\{\rm EP\}}} - 1\right) \Big/ \left(\frac{1+\epsilon_{\rm nf}}{a^2} - 1\right)$$

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

MODEL ESTIMATES OF NONFLOW

Feng et al., arXiv:2106.15595

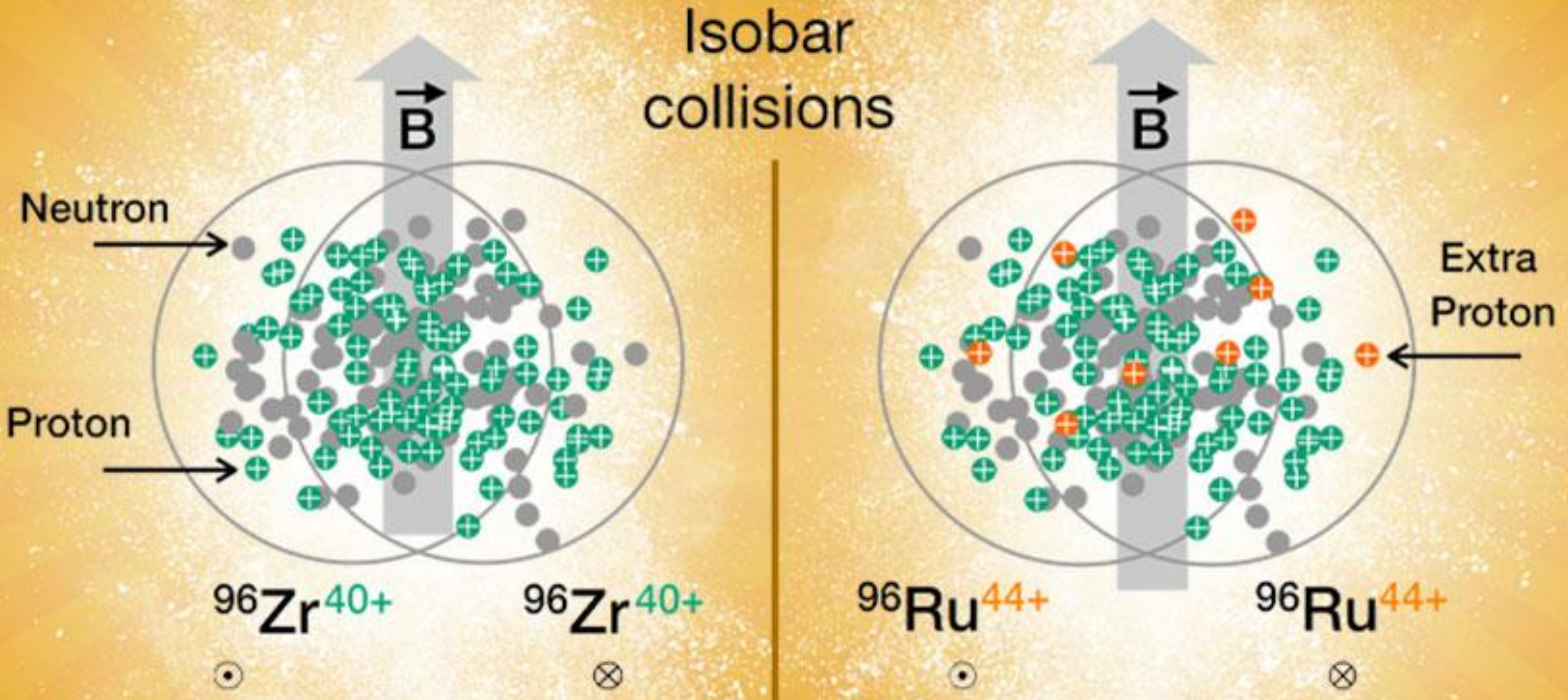
$$f^*_{\rm CME} \approx \left(\epsilon_{\rm nf} - \frac{\epsilon_3/\epsilon_2}{N v_2^2\{\rm EP\}}\right) \Big/ \left(\frac{1+\epsilon_{\rm nf}}{a^2} - 1\right)$$



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

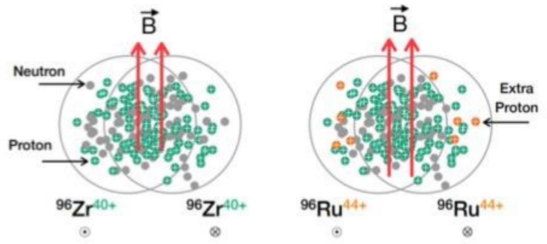
Search for the Chiral Magnetic Effect with Isobar Collisions at $\sqrt{s_{NN}}$ = 200 GeV by the STAR Collaboration at RHIC

https://arxiv.org/abs/2109.00131



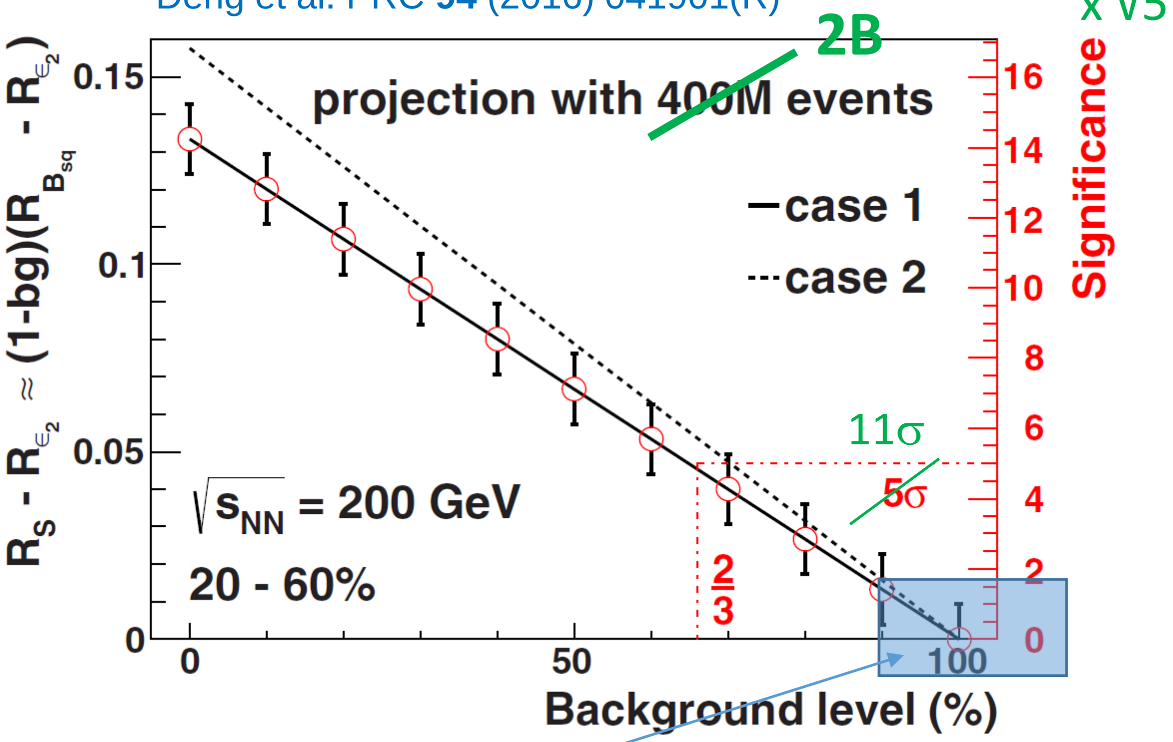
ISOBAR COLLISIONS

Voloshin, PRL 105 (2010) 172301



Same A → same background
Different Z → different signal

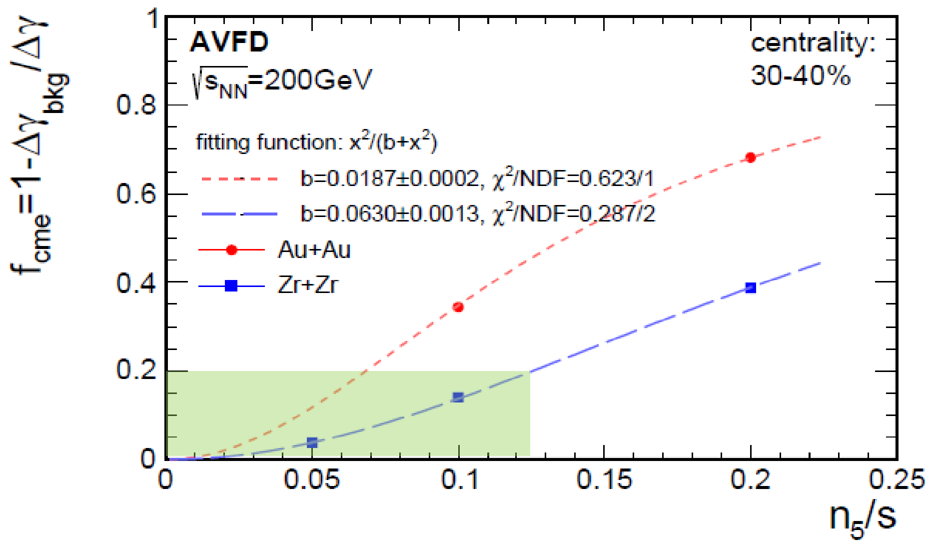
Deng et al. PRC **94** (2016) 041901(R)



3.3σ effect if isobar ≈ AuAu (f_{cme}=10%)

Ru/Zr = 1 + 15%*10% = 1.015 ± 0.004

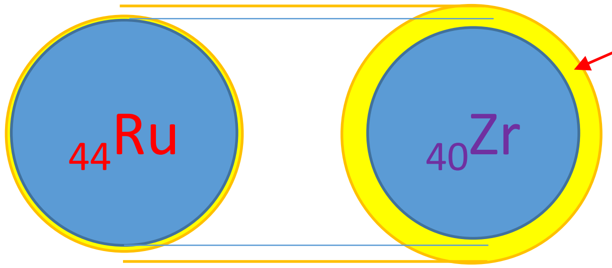
Yicheng Feng, Yufu Lin, Jie Zhao, FW, arXiv:2103.10378



Background ∝ 1/N → isobar/AuAu ~ 2
Mag. field B ~ $A^{1/3}$ → 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)

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

ISOBAR SYSTEMS ARE NOT IDENTICAL: MULTIPLICITY



Halo-type

$$\rho \propto \left[1+\exp\left(\frac{r-R}{a}\right)\right]^{-1}$$

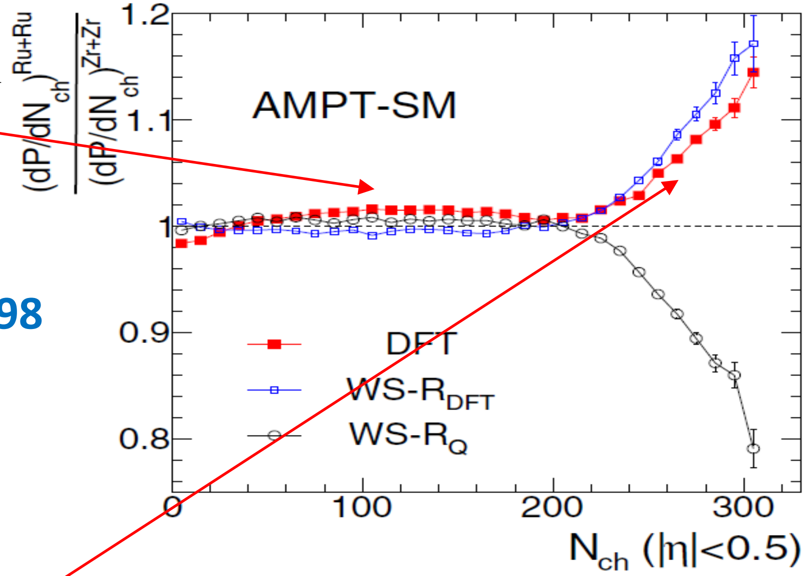
Larger charge radius
Little neutron skin

Smaller charge radius
Much thicker neutron skin

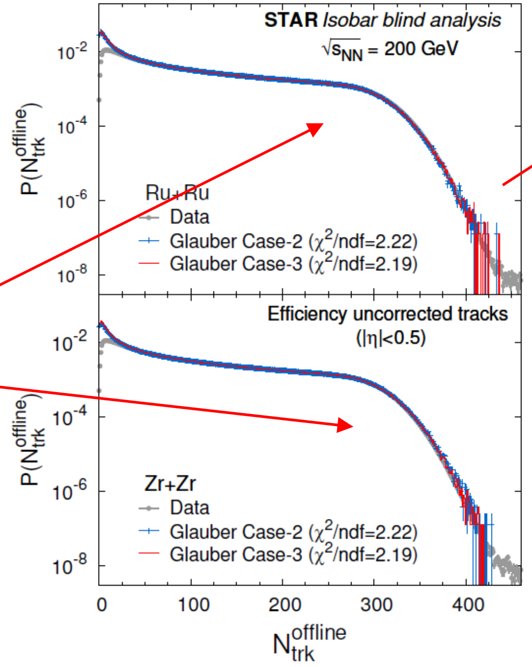
Overall size: Ru < Zr

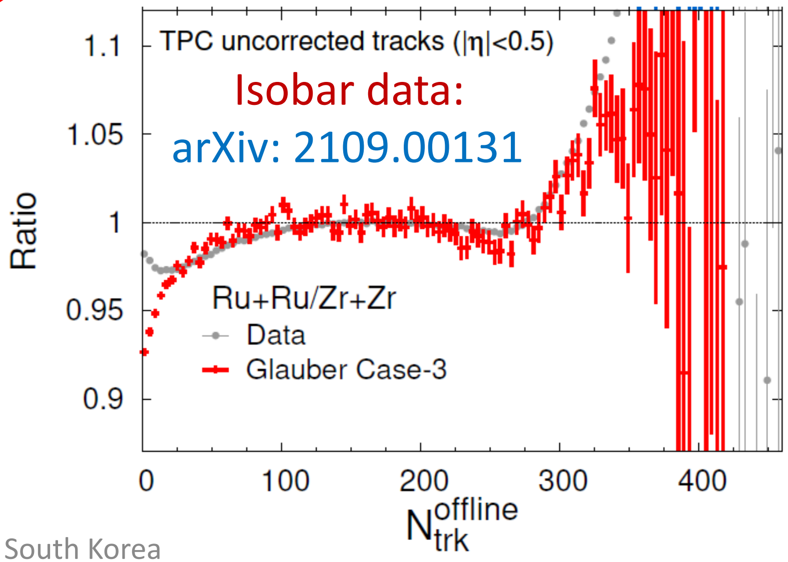
→ Larger energy density in Ru > Zr

→ Larger multiplicity in Ru > Zr



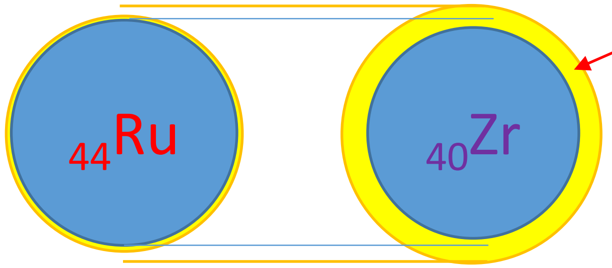
Predicted by DFT:
Hanlin Li et al. PRC **98** (2018) 054907





Isobar data:
arXiv: 2109.00131

ISOBAR SYSTEMS ARE NOT IDENTICAL: V_2



Halo-type

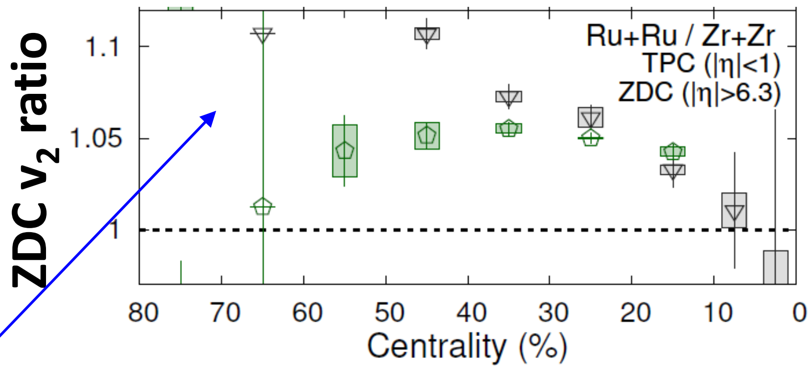
$$\Delta\gamma_{\rm bkgd} = \frac{4N_{\rm 2p}}{N^2}\langle\cos(\phi_\alpha+\phi_\beta-2\phi_{\rm 2p})\rangle v_{2,\rm 2p}$$

Normalize by v_2 and N → $N\Delta\gamma/v_2$

Larger charge radius
Little neutron skin

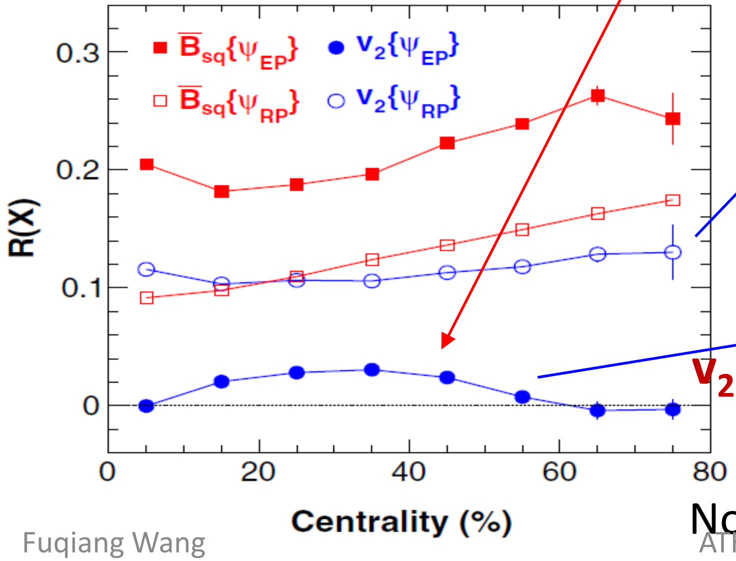
Smaller charge radius
Much thicker neutron skin

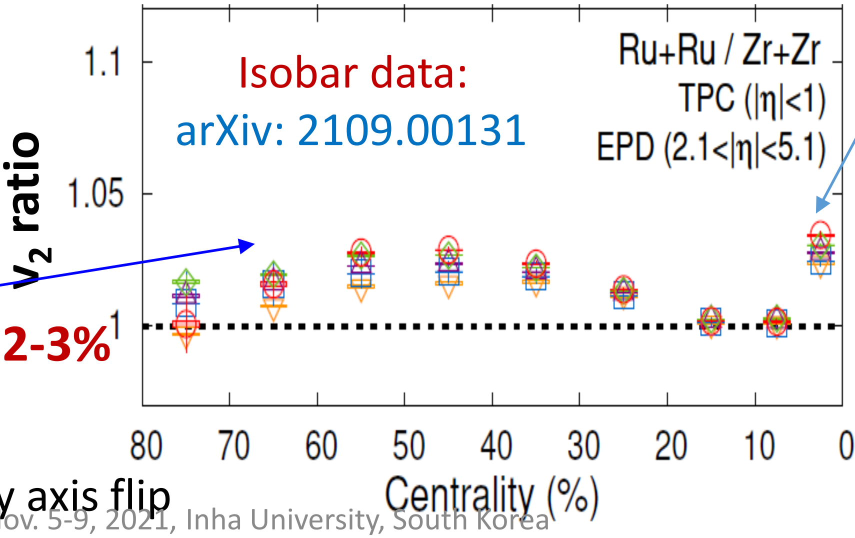
Rredicted by DFT:
Haojie Xu et al. PRL **121** (2018) 022301



J. Jia, C. Zhang (Mon.)

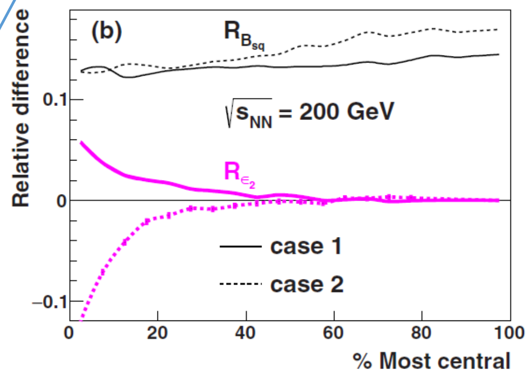
Nuclear deformity:
Deng et al. PRC 94 (2016) 041901(R)





Isobar data:
arXiv: 2109.00131

v_2 differs by 2-3%



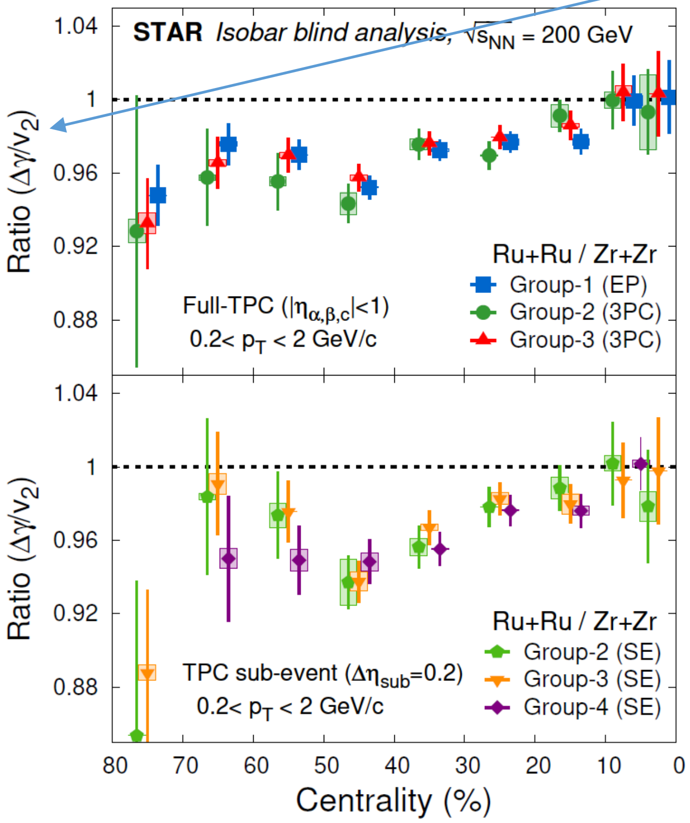
Note centrality axis flip

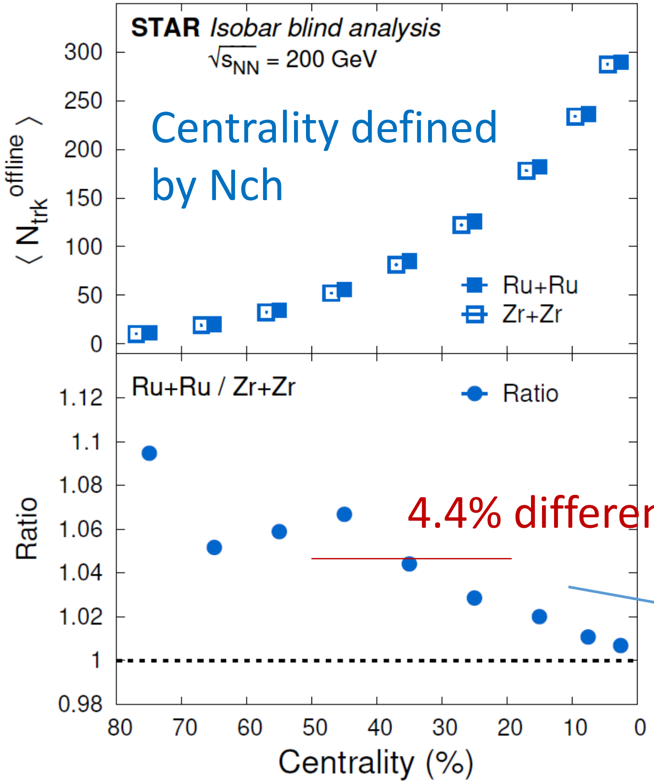
$\Delta\gamma/v_2$ RESULTS FROM MULTIPLE GROUPS

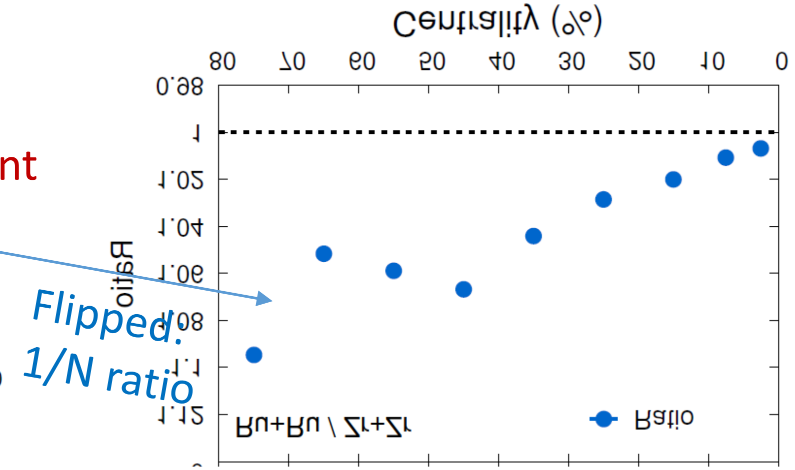
$$\Delta\gamma_{\rm bkgd} = \frac{4N_{2p}}{N^2}\langle\cos(\phi_\alpha + \phi_\beta - 2\phi_{2p})\rangle v_{2,2p}$$

Under the assumption of flowing clusters, scales with overall multiplicity, then $\Delta\gamma$ is diluted by 1/N

- Trivial multiplicity dilution effect
- Not included in the predefined observable
- $N\Delta\gamma/v_2$ would be better

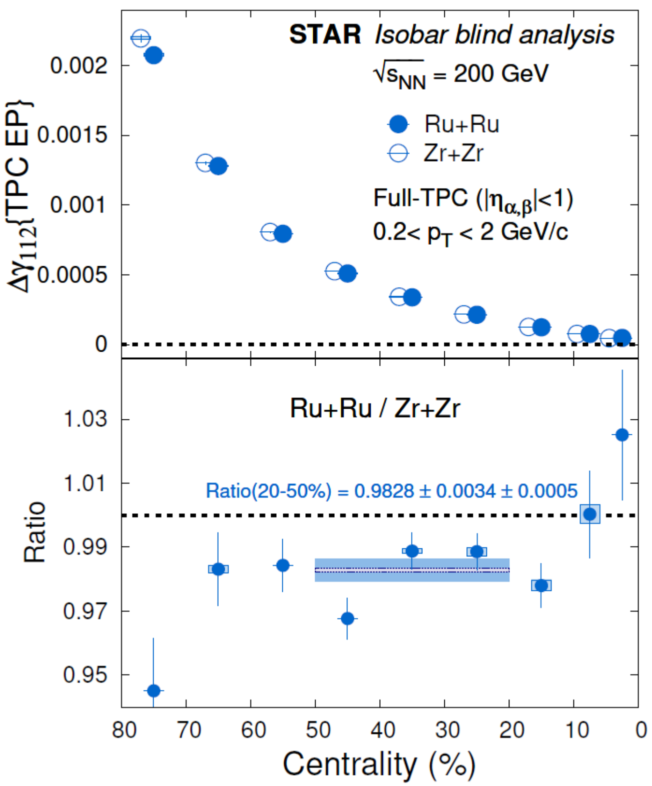


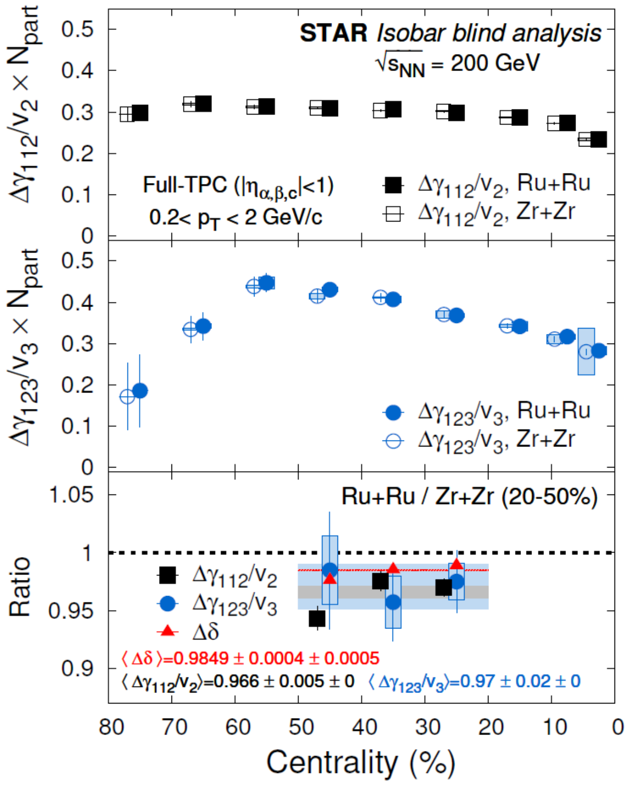


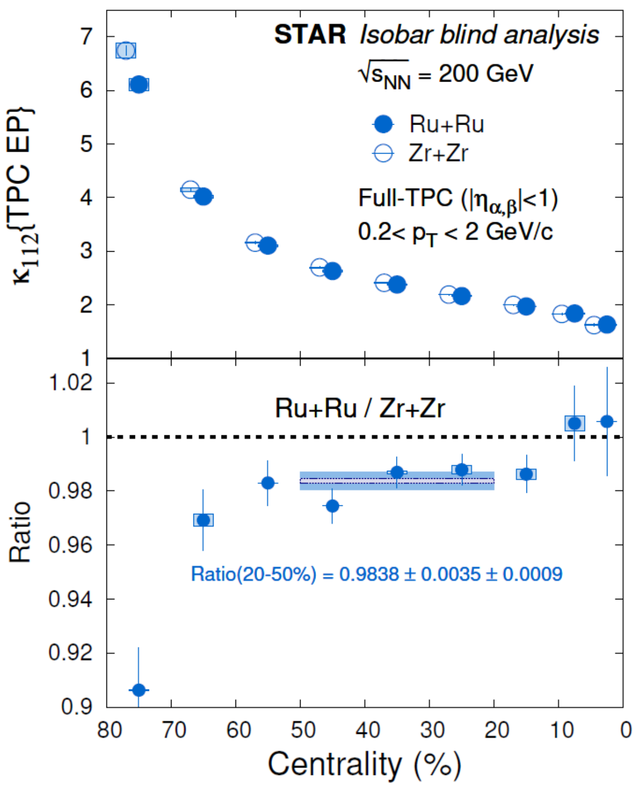


All groups are consistent. $\Delta\gamma/v_2$ follows closely with N_{ch}

$\Delta\gamma$, $\Delta\gamma/v_2$, $\kappa=\Delta\gamma/(\Delta\delta * v_2)$ MEASUREMENTS



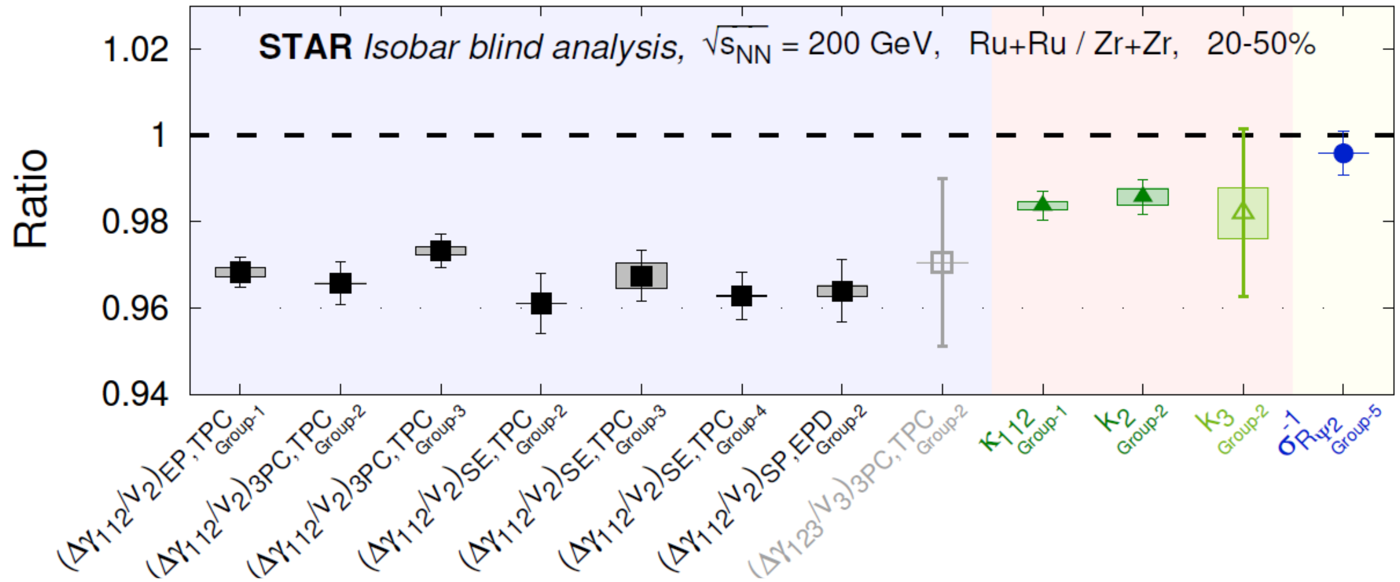


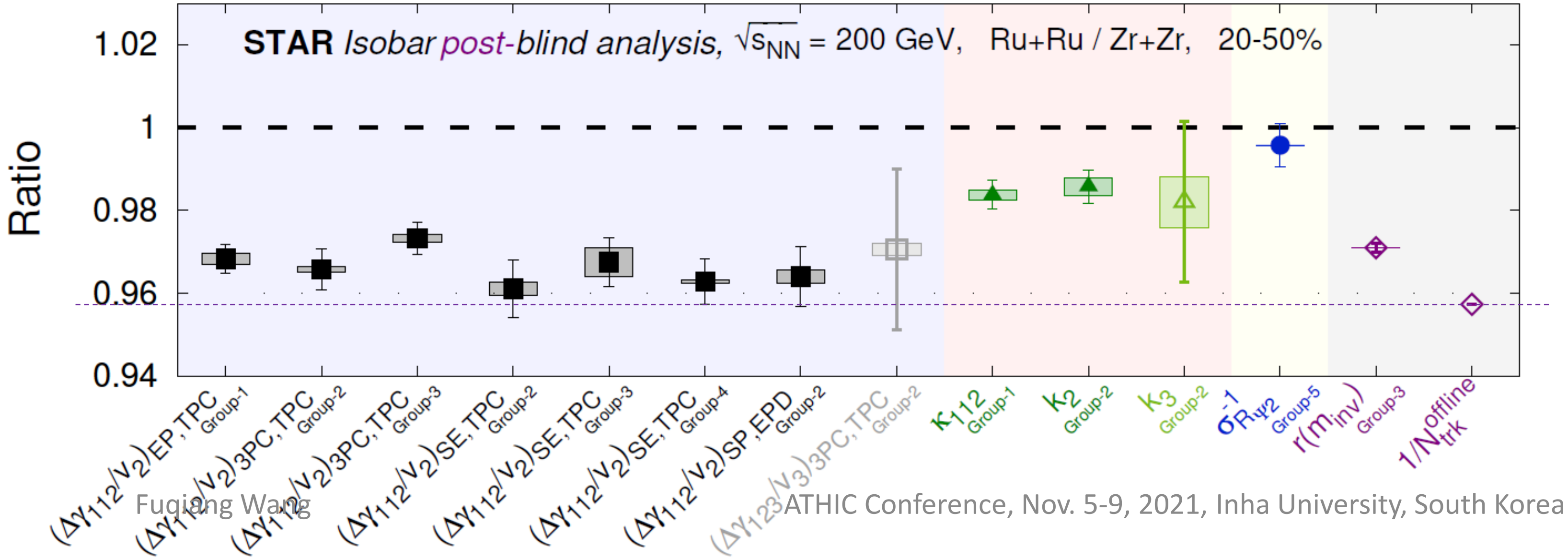


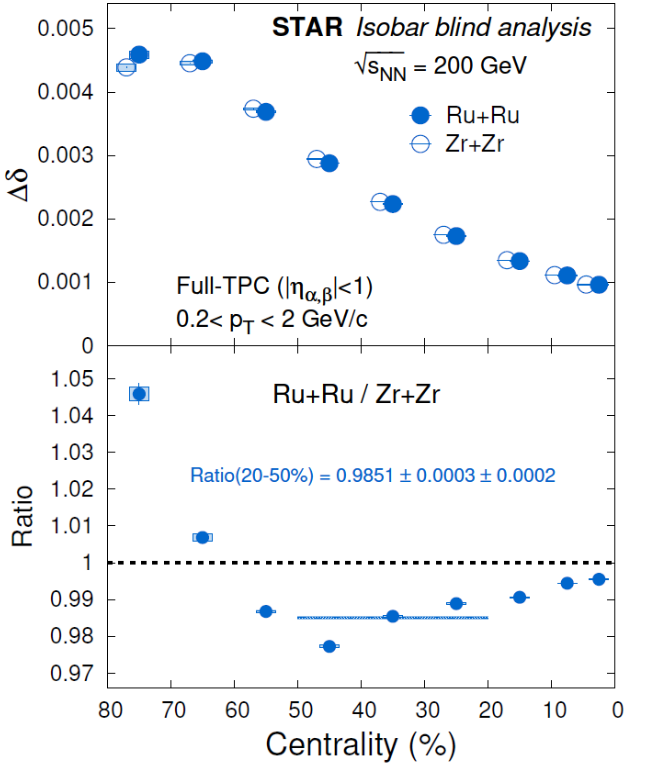
Indeed a precision of 0.4% is achieved!

Ru+Ru/Zr+Zr ratios all below unity, naively unexpected; main reason is the 4.4% Nch difference

MONEY PLOTS







Nonflow: $$\frac{(N\Delta\delta)^{\text{Ru+Ru}}}{(N\Delta\delta)^{\text{Zr+Zr}}} \approx 1.03$$

Nonflow difference is important!

REMAINING NONFLOW EFFECTS

Feng et al., arXiv:2106.15595

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

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

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

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

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

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

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

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

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

- 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**

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.
- Isobar blind analysis is a tour de force. Anticipated precision down to 0.4% is achieved. No CME signal is observed in the blind analysis; not inconsistent with Au+Au data. Further (nonflow) investigations needed to quantify significance.
- Current data 2.4B MB Au+Au, 3.8B isobar events. Expect 20B Au+Au from 2023+25 runs, together with large BES-II data samples.