STAR Results on Chiral Magnetic Effects

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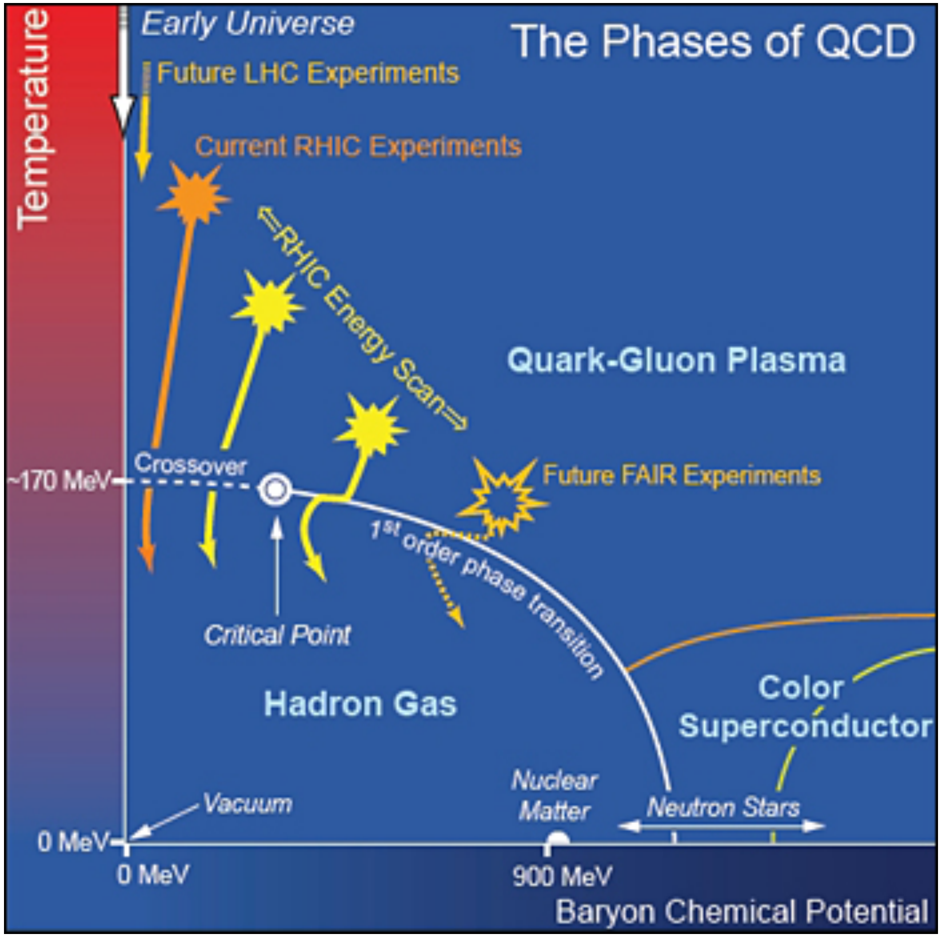
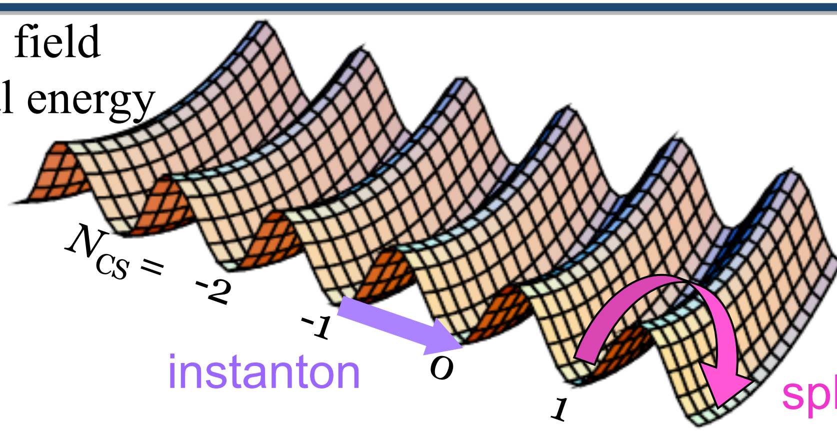
RHIC as a QCD Test Ground



- QCD is widely accepted as the theory of strong interactions
- The goal of RHIC is to study the properties of QCD matter
- RHIC Beam Energy Scan program maps a significant portion of QCD phase diagram
- QCD vacuum plays an important role in the physics produced at RHIC

QCD Vacuum Transition



- Gluonic field energy is periodic in Chern–Simons number (N_{CS}) direction
- Winding number: N_{CS} difference between initial and final states

$$Q_W = \frac{g^2}{32\pi^2} \int \mathrm{d}^4x \; F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a$$

- Axial current j^5_μ : net handedness flow

$$\partial^\mu j^5_\mu = 2 \sum_f m_f \langle \bar{\psi}_f i \gamma_5 \psi_f \rangle_A - \frac{N_f g^2}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a,$$ $m_f = 0$ when chiral symmetry restored

- Nonzero topological charge generates chirality imbalance

$$N^f_L - N^f_R = 2Q_W, \quad Q_W \neq 0 \rightarrow \mu_A \neq 0$$

- QCD vacuum transition ↔ nonzero topological charge ↔ chirality imbalance

CME, CVE & CSE

- Chiral Magnetic Effect (CME): nonzero chiral charge density (μ_A) induces an electric current ($\boldsymbol{j}_V$) along external magnetic field.

  ➔ electric charge separation along B field

- Chiral Vortical Effect (CVE): nonzero chiral charge density (μ_A) induces a baryon number current ($\boldsymbol{j}_B$) along vorticity ($\vec{\omega}$), because $\mu_B \vec{\omega}$ gives an effective magnetic field. $\boldsymbol{j}_V$ and $\boldsymbol{j}_B$ point to the same direction.

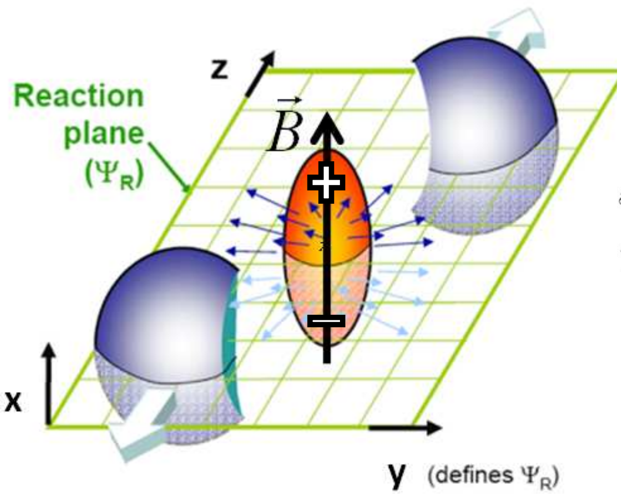
  ➔ baryon charge separation along $\vec{\omega}$

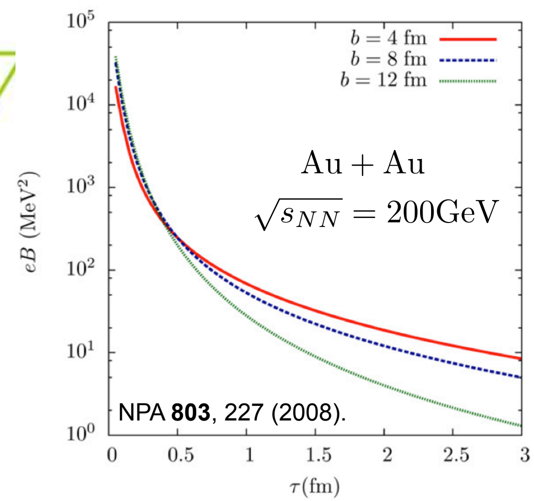
- Chiral Separation Effect (CSE): nonzero vector charge density (μ_V) induces an axial current ($\boldsymbol{j}_A$) along external magnetic field.

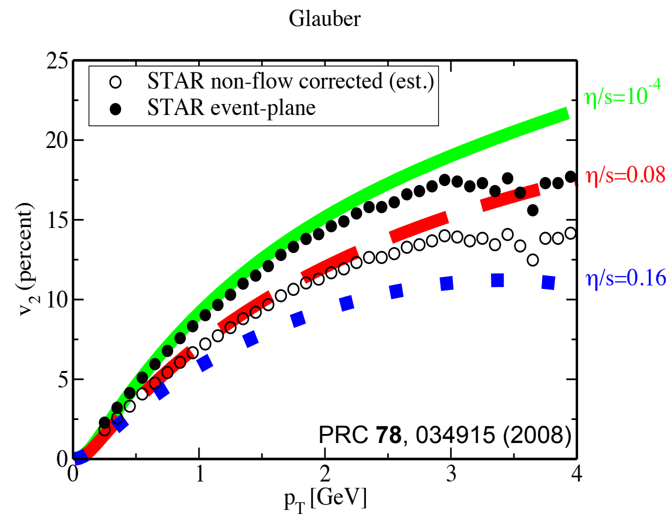
  ➔ chiral charge separation along B field

D. E. Kharzeev and D. T. Son, Phys. Rev. Lett. **106**, 062301 (2011)
D. E. Kharzeev, L. D. McLerran, and H. J. Warringa, Nuclear Physics A **803**, 227 (2008)
T. Son, D. and A. R. Zhitnitsky, Phys. Rev. D **70**, 074018 (2004)

Conditions in HI Collisions







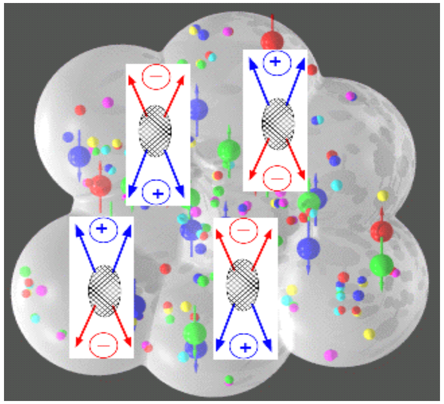
- Chiral symmetry restoration
- QCD vacuum transition in heavy ion collision, instanton and sphaleron
- Extremely strong magnetic field created in heavy ion collision, 10^{15} Tesla!
- Hydrodynamics describe the matter created in HI collisions very well
- Heavy-ion collisions find all of the necessary conditions!

Observables in HI Collisions

- Chiral Magnetic Effect (CME): electric charge separation along B field

$$\frac{dN_\alpha}{d\phi} \propto 1 + 2v_1\cos(\Delta\phi) + 2a_\alpha \sin(\Delta\phi) + 2v_2\cos(2\Delta\phi) + \cdots$$

$$\gamma \equiv \langle \cos(\phi_1 + \phi_2 - 2\Psi_{\mathrm{RP}}) \rangle$$
$$= \langle \cos(\Delta\phi_1)\cos(\Delta\phi_2) - \sin(\Delta\phi_1)\sin(\Delta\phi_2) \rangle$$



$$\gamma = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\mathrm{RP}}) \rangle, \alpha, \beta \in \{+, -\} \text{ (charge sign)}$$

- Chiral Vortical Effect (CVE): baryon number separation along B field

$$\gamma = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\mathrm{RP}}) \rangle, \alpha, \beta \in \{+, -\} \text{ (bayron number sign)}$$

- Chiral Separation Effect (CSE): chiral charge separation along B field

Need a further step to be observable.

S. A. Voloshin, Phys. Rev. C **70**, 057901 (2004)

Chiral Magnetic Wave

Chiral Magnetic Effect

$$j_V = \frac{N_c\, e}{2\pi^2}\mu_A B$$

important at high beam energy:
enough energy for "jumping" over barriers to create initial axial charge density

Chiral Separation Effect

$$j_A = \frac{N_c\, e}{2\pi^2}\mu_V B$$

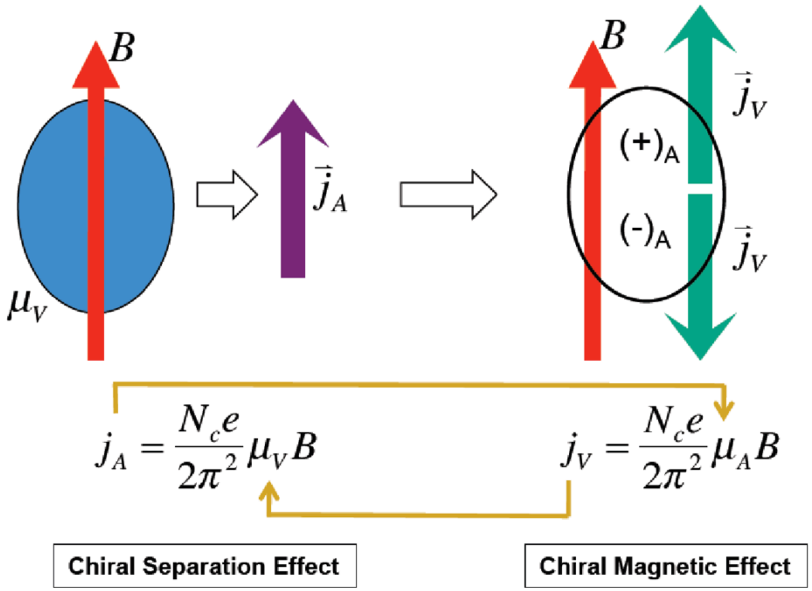
important at low beam energy:
there is sizable initial vector charge density to set off chiral magnetic waves

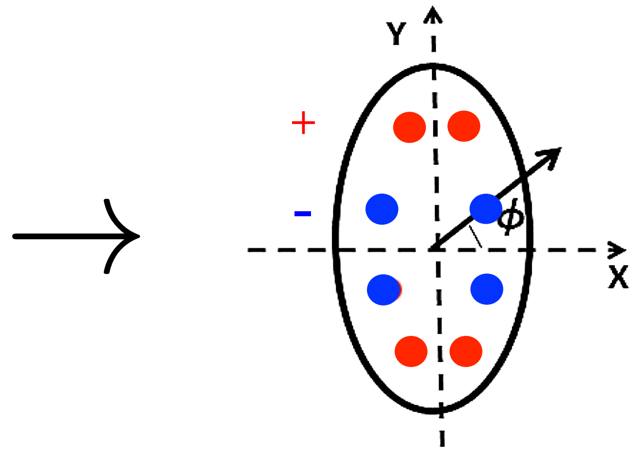
Chiral Magnetic Wave: coupling two effects

$$\left(\partial_0 \mp \frac{N_c e B \alpha}{2\pi^2}\partial_1 - D_L \partial_1^2\right) j^0_{L,R} = 0$$

D. Kharzeev and H.-U. Yee, Physical Review D **83**, 085007 (2011)

Chiral Magnetic Wave

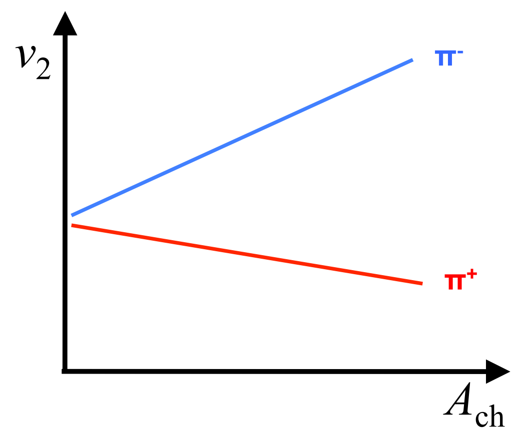




$$\frac{\mathrm{d}N_\pm}{\mathrm{d}\phi} = N_\pm \left[1 + 2v_2\cos(2\phi)\right]$$
$$\approx \bar{N}_\pm \left[1 + 2v_2\cos(2\phi) \mp A_{ch} r \cos(2\phi)\right]$$

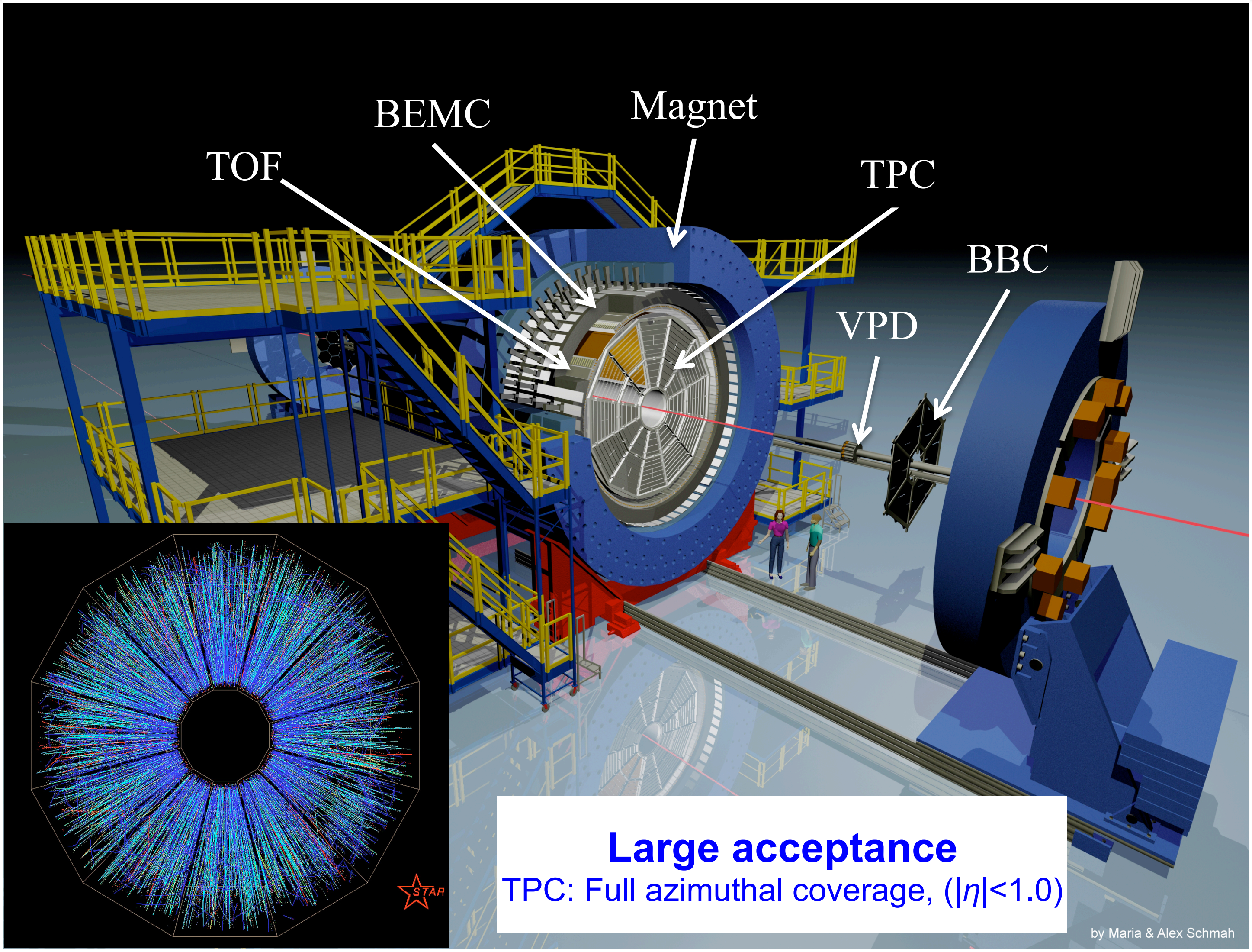
$$v_2^- - v_2^+ = 2\left(\frac{q_e}{\bar{\rho}_e}\right) A_{ch}$$

$$A_{ch} = \frac{N_+ - N_-}{N_+ + N_-} \qquad r = 2\left(\frac{q_e}{\bar{\rho}_e}\right)$$



Y. Burnier, D. E. Kharzeev, J. Liao and H-U Yee, Phys. Rev. Lett. **107**, 052303 (2011)

STAR Experiment



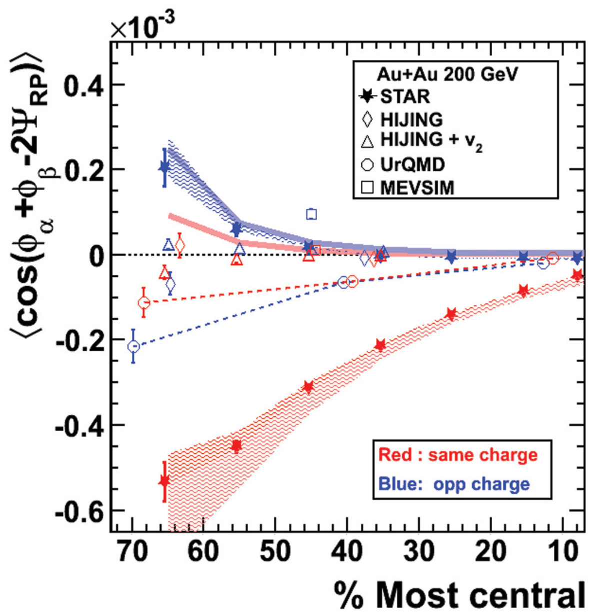
Large acceptance

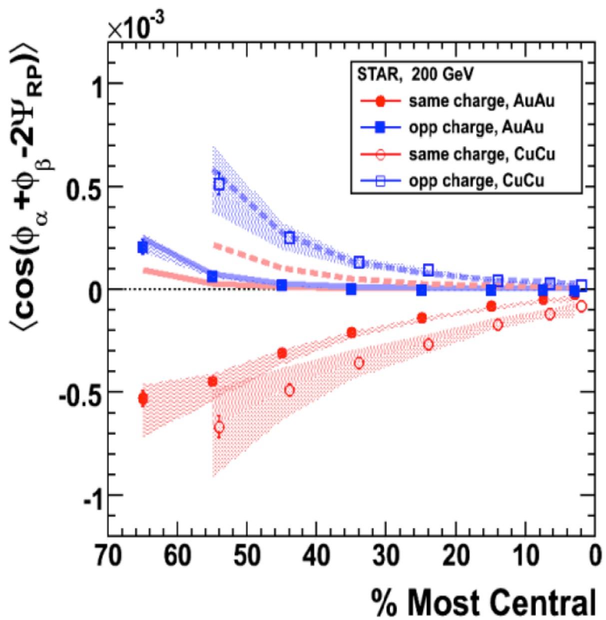
TPC: Full azimuthal coverage, ($|\eta|<1.0$)

CME in Heavy Ion Collisions

- Use three-point correlation to detect out-of-plane charge separation

$$\gamma = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\mathrm{RP}}) \rangle, \alpha, \beta \in \{+, -\} \text{ (charge sign)}$$





- Out-of-plane charge separation
  - same charge correlation < 0
  - opposite charge correlation > 0
- The observed signal cannot be described by models (HIJING, HIJING + v_2, URQMD, MEVSIM)

STAR, Phys. Rev. Lett. **103** (2009) 251601; Phys. Rev. C **81** (2010) 54908

CME in Heavy Ion Collisions

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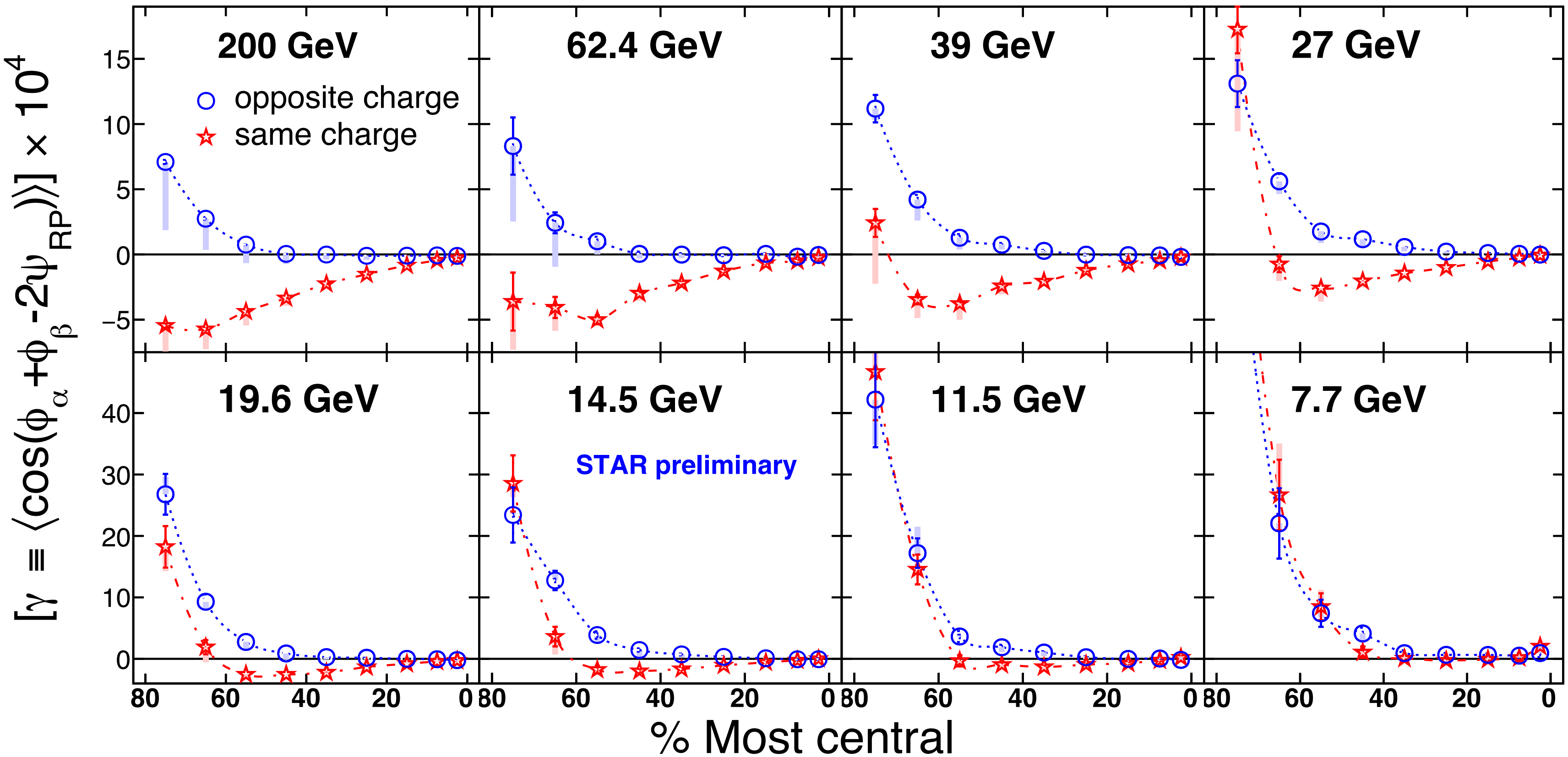
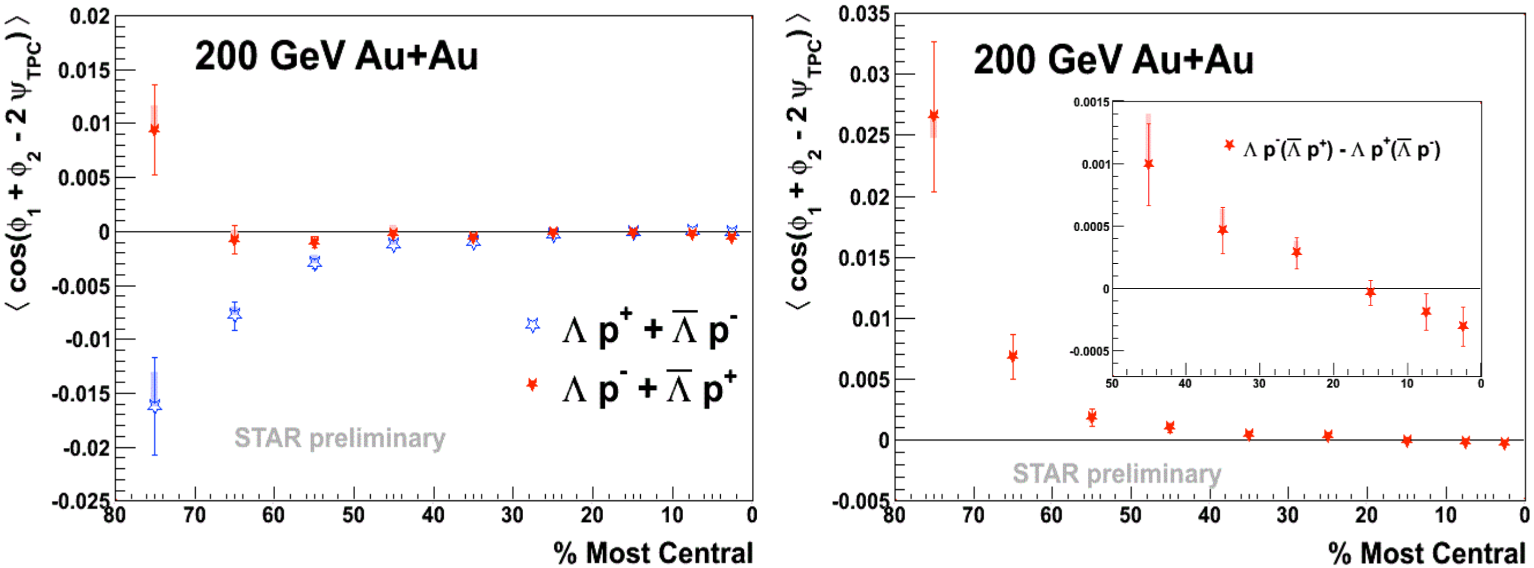


STAR, Phys. Rev. Lett. **113**, 052302 (2014)

CVE in Heavy Ion Collisions

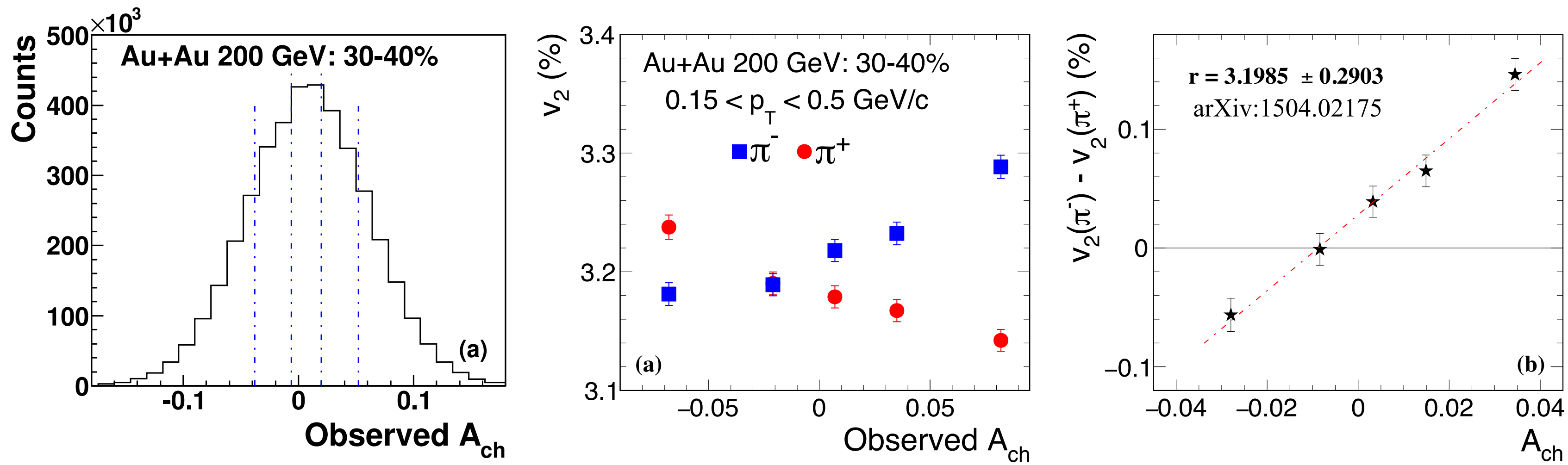
- Use three-particle correlation to detect out-of-plane baryon number separation

$$\gamma = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\mathrm{RP}}) \rangle, \alpha, \beta \in \{+, -\}\ \text{(bayron number sign)}$$



- same baryon number: Λp and $\bar{\Lambda}\bar{p}$
- opposite baryon number: $\Lambda\bar{p}$ and $\bar{\Lambda}p$
- "same B" is systematically lower than "opposite B" in the mid-central and peripheral collisions, which is consistent with the CVE expectation.

CMW in Heavy Ion Collisions



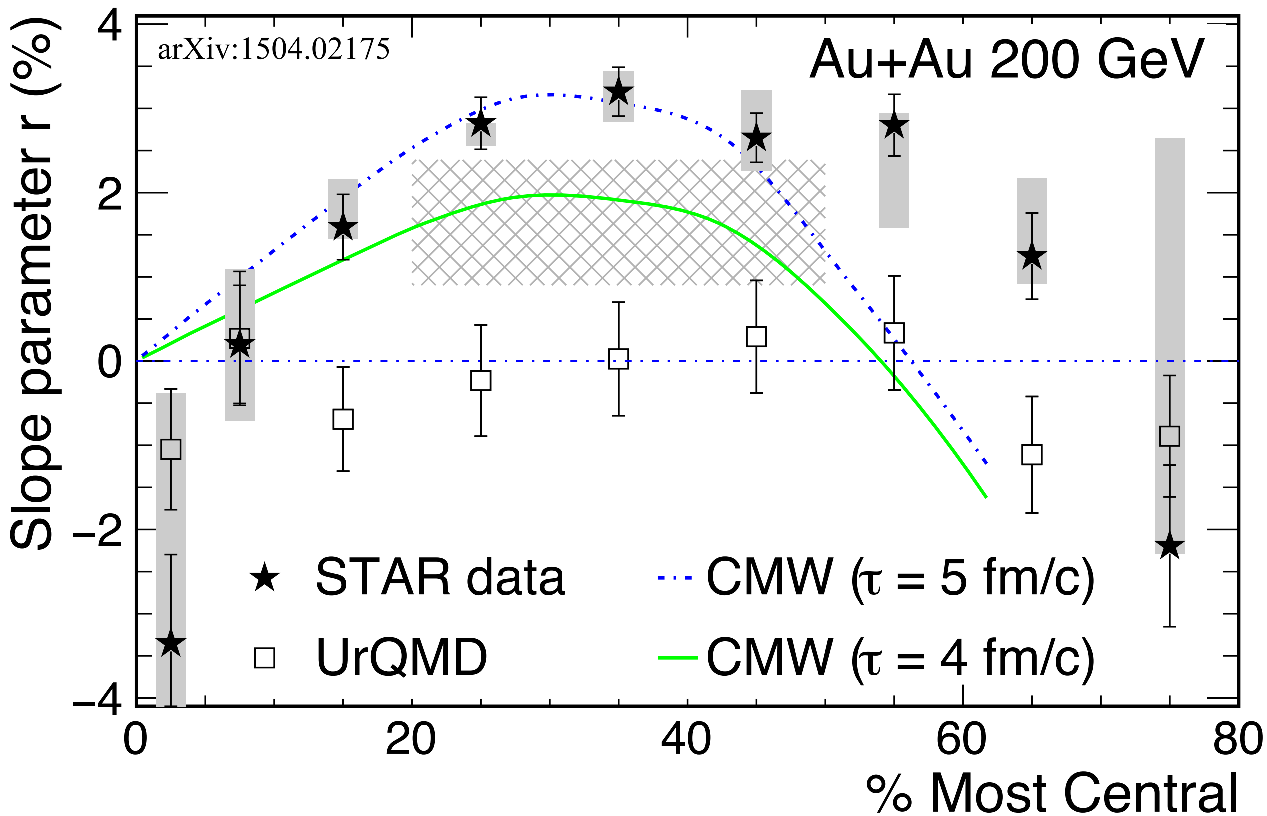
- N_+ and $N\_$: number of positive and negative particles

$$A_{ch} = \frac{N_+ - N_-}{N_+ + N_-}$$

- v_2 of π^- (π^+) linearly increase (decrease) with increasing A_{ch}
- $\Delta v_2 = v_2(\pi^-) - v_2(\pi^+)$ linearly increase with increasing A_{ch}
- Slope parameter r is extract after tracking efficiency applied on observed A_{ch}

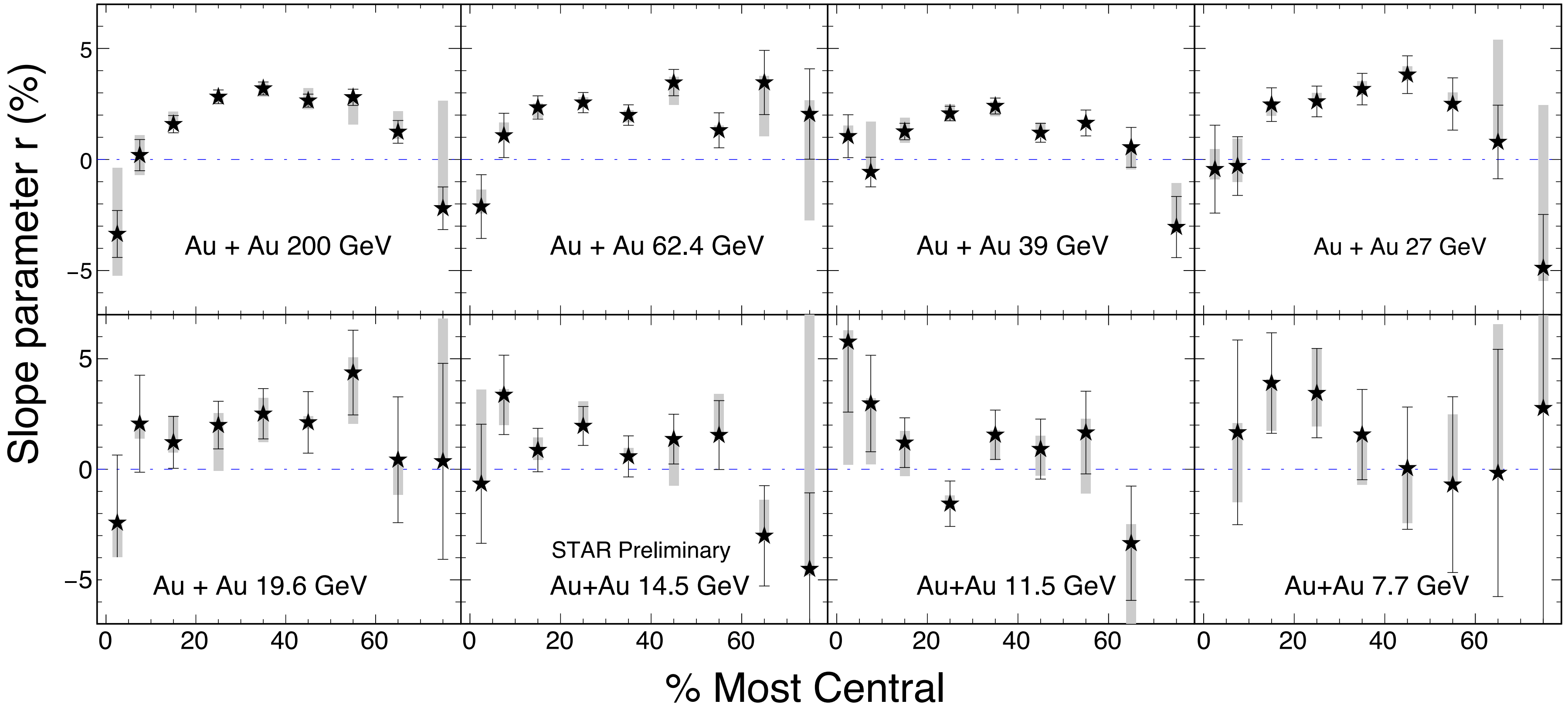
$$\Delta v_2^{\mathrm{CMW}} = v_2(\pi^-) - v_2(\pi^+) = rA_{\mathrm{ch}}$$

CMW in Heavy Ion Collisions



- Similar trends between data and theoretical calculations with CMW at $\sqrt{s_{NN}}$ = 200 GeV (arXiv: 1208.2537).
- UrQMD cannot reproduce the slopes at $\sqrt{s_{NN}}$ = 200 GeV.

CMW in Heavy Ion Collisions



- The slope parameter *r* shows a rise and fall feature from central to peripheral collisions
- Slope as a function of centrality shows weak energy dependence down to 27GeV
- Similar trend to the theoretical calculations with CMW

Accepted by PRL and selected as Editors' Suggestion, arXiv:1504.02175

Summary

- There is very rich physics due to the interplay of QGP matter, chirality imbalance and ultra-strong magnetic field in heavy ion collisions.
- CME – Using the three-particle correlation method, STAR observed the charge separation w.r.t. event plane and the signal persists from 19.6 GeV to 200 GeV.
- CVE – Baryon number separation w.r.t. event plane is also observed with the three-particle correlation method.
- CMW – STAR observed v_2 of π^- (π^+) linearly increase (decrease) with increasing A_{ch}. The centrality dependence of the slope parameter of $\Delta v_2(A_{ch})$ shows a weak collision energy dependence from 200 to 27 GeV.
- Outlook – Suggest isobar collisions, e.g. Ru+Ru and Zr+Zr to vary magnetic field while keeping all other conditions essentially the same.