STAR measurements in search of the CME and the CMW
-- a biased selection of STAR results

Gang Wang (for STAR collaboration)
UCLA
For the CME, I will discuss different types of background in $\gamma$;
I will not cover
• alternative correlator (see Roy Lacey’s talk)
• $\gamma$ as a function of invariant mass
• decomposition of $\gamma$ vs $\Delta \eta$

For the CMW,
I will discuss alternative interpretations, including
• hydro+isospin
• local charge conservation
Chiral Magnetic Effect: \[ \text{magnetic field} + \text{chirality} = \text{current} \]

spin alignment in B-field:
- opposite directions for opposite charges

left:
- negative goes up
- positive goes down

right:
- positive goes up
- negative goes down

handedness:
- momentum and spin, aligned or anti-aligned
courtesy of P. Sorensen

An excess of right or left handed quarks lead to a current flow along the magnetic field.

\[ \vec{J} = \frac{e^2}{2\pi^2} \mu_5 \vec{B} \]
CME observable: $\gamma$ correlator

$$\gamma = \langle \cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \rangle$$

$$= \left[ \langle v_{1,\alpha} v_{1,\beta} \rangle + B_{in} \right] - \left[ \langle a_\alpha a_\beta \rangle + B_{out} \right]$$

- Background effects: largely cancel out
- Directed flow: expected to be the same for SS and OS
- $P$-even quantity: still sensitive to charge separation

$$\frac{B_{in} - B_{out}}{B_{in} + B_{out}} = v_{2,cl} \frac{\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{cl}) \rangle}{\langle \cos(\phi_\alpha - \phi_\beta) \rangle}$$

$v_2$ of clusters/resonances, not final particles, containing both flow and nonflow.
Charge separation signal

\[ \cos(\phi_{\alpha} + \phi_{\beta}) \]

Au+Au 200 GeV


- \( \gamma_{os} > \gamma_{ss} \), consistent with CME expectation
- consistent between different years (2004 and 2007)
- confirmed with 1st-order EP (from spectator neutron \( v_1 \))

However, there are still different types of background:
1. Non-flow (correlations unrelated to the reaction plane)
2. apparent anisotropy (final particles)
3. hidden anisotropy (resonances)
Comparison between TPC EP and BBC EP shows significant non-flow effects in small systems.

- Non-flow effects are present in both $v_2$ and $\Delta \gamma$
- Safer in larger systems (more central Au+Au collisions)

$|\eta_{TPC}| < 1$
$3.8 < |\eta_{BBC}| < 5.1$
Anisotropy-related background

A specific configuration as shown below could solely come from statistical fluctuations.

**Apparent anisotropy:** explicit $v_2$ (of final-state particles). even w/o visual charge separation

\[ v_2 = 1 \]
\[ \gamma_{ss} = -1 \]
\[ \gamma_{os} = 0 \]

controllable with measured $v_2$

**Hidden anisotropy:** implicit $v_2$ (of resonance parents).
real charge separation, but not CME

\[ v_2 = 0 \]
\[ \gamma_{ss} = -1 \]
\[ \gamma_{os} = 1/2 \]

hard to control directly
\[ \gamma_{1,n-1,n} = \langle \cos[\varphi_\alpha + (n-1)\varphi_\beta - n\Psi_{EP}] \rangle / \text{res}_{EP} = \kappa_{1,n-1,n} \cdot \nu_{n,\beta} \cdot \delta \]

\[ \delta = \langle \cos(\phi_\alpha - \phi_\beta) \rangle \]

\( \kappa_{1,n-1,n} \) is just \( \gamma_{1,n-1,n} \) normalized by \( \nu_n \) and \( \delta \).

\text{The TPC event plane was used in these analyses.}

\( \kappa_{112} \) and \( \kappa_{123} \) are consistent with each other (except in the most central collisions), especially after removing very-short-range correlations.
divide each event into 3 sub-events.

- \( q \), flow vector of particles of interest, provides a handle on the event shape.

- data point in each \( q \) bin is averaged over that specific event sample.

- AMPT shows that \( v_2^{\text{explicit}} \) disappears when projecting \( q \) to 0, which is expected by construction.

\[
q_x \equiv \frac{1}{\sqrt{N}} \sum_{i}^{N} \cos(2\phi_i)
\]

\[
q_y \equiv \frac{1}{\sqrt{N}} \sum_{i}^{N} \sin(2\phi_i)
\]

Fufang Wen, Jacob Bryon, Liwen Wen, Gang Wang, Chinese Phys. C 42(1) (2018) 014001
Event-shape engineering

- q, flow vector of particles of interest, provides a handle on the event shape.
- AMPT shows that \( \gamma_{\text{OS}} \) and \( \gamma_{\text{SS}} \) approach each other at small q.
- The background in \( \Delta \gamma \) disappears when projecting q to 0.

consistent with zero: \( (-4.5 \pm 6.7) \times 10^{-4} \) for \( N_{\text{part}} \Delta \gamma^A \)
and \( (-3.3 \pm 10.6) \times 10^{-4} \) for \( N_{\text{part}} \Delta \gamma_{\text{observe}} / R^{B1(B2)} \).

Fufang Wen, Jacob Bryon, Liwen Wen, Gang Wang,
Chinese Phys. C 42(1) (2018) 014001

This approach only takes care of the background due to the explicit \( v_2 \).
Δγ|_{q=0} will not artificially diminish the CME signal, but will exaggerate it by a factor of 2v₂, a roughly 10% effect.

Fufang Wen, Jacob Bryon, Liwen Wen, Gang Wang, Chinese Phys. C 42(1) (2018) 014001
The $2^{\text{nd}}$-order EP resolution depends on $q$.

$v_2^{\text{explicit}}$ goes to zero at zero $q$ (also true for separate charges), which is expected by construction.
γ\textsubscript{112}: 200 GeV Au+Au

- OS and SS approach each other at small q.
- When $q^2$ is extrapolated to 0, there is a finite intercept: 
  $(7.51 \pm 0.75) \times 10^{-3}$
  A 10σ effect for 20-60% events.
- IF this is due to CME, then $a_1$ is on ~ 1% level.
- The intercept may come from some implicit-v\textsubscript{2} backgrounds.
  Need to apply the method to
  $\gamma_{123} = \langle \cos(\varphi_\alpha + 2\varphi_\beta - 3\psi_RP) \rangle$

\( <N_{\text{part}} > \) for 20-60% collisions is roughly 98.
• For 20-60% collisions, the raw signal is typically reduced to a 10-20% level with this ESE.

• It’s worth trying this ESE method for Ru+Ru and Zr+Zr, if it does remove a large portion of BG.

• Still not sure whether the ESE signal is the true CME signal.

The shaded boxes reflect the cuts of $|\Delta \eta| > 0.15$ and $|\Delta p_T| > 0.15$ GeV/c.
The $3^{\text{rd}}$-order EP resolution depends on $q_3$.

$v_3^{\text{explicit}}$ goes to zero at zero $q_3$. 

$\overrightarrow{q} = (q_x, q_y)$

$q_x \equiv \frac{1}{\sqrt{N}} \sum_i^N \cos(2\phi_i)$

$q_y \equiv \frac{1}{\sqrt{N}} \sum_i^N \sin(2\phi_i)$. 

$0.5 < \eta^{B1} < 1, -1 < \eta^{B2} < -0.5$
$\gamma_{123}: 200 \text{ GeV Au+Au}$

- $\gamma_{123}$ can be studied via the 3$^{\text{rd}}$-order flow vector, $q_3$.
- When $q_3^2$ is extrapolated to 0, there is a finite intercept: $(8.32 \pm 1.92) \times 10^{-3}$ A 4$\sigma$ effect for 20-60% events.
- The intercepts for $\gamma_{112}$ and $\gamma_{123}$ are consistent with each other. $(7.51 \pm 0.75) \times 10^{-3}$ for $\gamma_{112}$
- Should they scale with $v_2$ and $v_3$, instead of being the same? (if they are due to implicit $v_2$ or $v_3$)

$<N_{\text{part}}>$ for 20-60% collisions is roughly 98.
• The raw signals are different between $\gamma_{112}$ and $\gamma_{123}$, (a factor of 3)

• The ESE signals are, however, similar for $\gamma_{112}$ and $\gamma_{123}$.

• Origin of these finite intercepts: residue nonflow? implicit $v_2$? CME?
$\gamma_{112}$ and $\gamma_{123}$: 39 GeV Au+Au

- $\gamma_{112}$: $(1.319 \pm 0.223) \times 10^{-2}$, 6$\sigma$ effect
- $\gamma_{123}$: $(-1.316 \pm 0.756) \times 10^{-2}$, consistent with zero
- This year, 27 GeV data will provide a chance to confirm this.
- The newly installed EPD will help further suppress nonflow.
Summary on CME

- **Non-flow** backgrounds are severe in small systems
  - suppressed with \( \eta \) gap between EP and particles of interest
- **Apparent-anisotropy** background seems to be the major contribution
  - \( \kappa_{112} \) and \( \kappa_{123} \) are close to each other
  - ESE shows small but finite intercepts for both \( \gamma_{112} \) and \( \gamma_{123} \)
  - what if CME and \( v_2 \) are strongly correlated as functions of centrality
- **Hidden-anisotropy** background may be small
  - but hard to handle directly
- **Isobaric** collisions will clarify whether B field plays a role
  - will do blinding analysis
- High-statistics **BES** data and the **EPD** will further help
Peak magnetic field $\sim 10^{15}$ Tesla!

(Kharzeev et al. NPA 803 (2008) 227)

\[ j_A = \frac{N_c e}{2\pi^2} \mu_v B \]
\[ j_V = \frac{N_c e}{2\pi^2} \mu_A B \]

Chiral Separation Effect
Chiral Magnetic Effect

$\text{CSE + CME} \rightarrow \text{Chiral Magnetic Wave}$: collective excitation signature of chiral symmetry restoration
Formation of electric quadrupole: $v_2^\pm = v_2^{base} \left( \frac{q_e}{\rho_e} \right) A_{ch}^+$, 

where charge asymmetry is defined as $A_{ch} = \frac{N^+ - N^-}{N^+ + N^-}$.

Then $\pi^- v_2$ should have a positive slope as a function of $A_{ch}$, and $\pi^+ v_2$ should have a negative slope with the same magnitude.
Different collision systems

Nonflow effects are largely cancelled by the $v_2$ difference.

The slope for $\pi$ is consistent with zero in 200 GeV $p$+Au and $d$+Au, close to peripheral Au+Au or U+U collisions.

Larger signals in U+U than Au+Au for mid-central or mid-peripheral events (in line with the magnetic field difference?)

The TPC event plane was used in these analyses.
Hydrodynamics study (no CMW): kaon/proton slope should be opposite to $\pi$ slope with larger magnitude, since

$$v_2(\pi^+) < v_2(\pi^-)$$
$$v_2(K^+) > v_2(K^-)$$
$$v_2(p) > v_2(p-\text{bar})$$

Y. Hatta et al. NPA 947 (2016) 155
the isospin effect is not the dominant contribution to the pion or kaon slopes.

Hydrodynamics study (no CMW): kaon slope should be opposite to $\pi$ slope with larger magnitude, since

$$v_2(\pi^+) < v_2(\pi^-)$$

$$v_2(K^+) > v_2(K^-)$$

STAR measurements show that kaon slope parameters behave similarly to those of $\pi$, not opposite: the isospin effect is not the dominant contribution to the pion or kaon slopes.
A mixed scenario without an obvious dominant mechanism, where the positive contribution of the CMW (CVW) and/or the LCC effect is reduced by the absorption effect, and/or is counterbalanced by the isospin effect.

Hydrodynamics study (no CMW): proton slope should be opposite to $\pi$ slope with larger magnitude, since

$$v_2(\pi^+) < v_2(\pi^-)$$

$$v_2(p) > v_2(p\text{-bar})$$

**STAR measurements**: proton slopes behave differently from $\pi$ and $K$: a mixed scenario without an obvious dominant mechanism, where the positive contribution of the CMW (CVW) and/or the LCC effect is reduced by the absorption effect, and/or is counterbalanced by the isospin effect.
Clusters located close to acceptance boundary produce one pion outside boundary. $v_2$ decreases with $|\eta|$.

Clusters with low $p_T$ have particles more separated in $\eta$ than high-$p_T$ clusters. $v_2$ increases with $p_T$.

\[ \eta \] dependence of $v_2$ is weaker than what this paper used; mean $p_T$ in data is constant vs $A_{ch}$ (no 2nd effect); the LCC effect is estimated to be 10 times smaller than data.

Local charge conservation may introduce $A_{\text{ch}}$ dependence of $\Delta v_2(\pi)$. Then one should see $\text{Norm.} \Delta v_3 \sim \text{Norm.} \Delta v_2$

(Bzak & Bozek PLB 726(2013)239).

**STAR measurement:** $\text{Norm.} \Delta v_3 < \text{Norm.} \Delta v_2$ at low $p_T$. Closer at high $p_T$.

**LCC mechanism alone cannot explain data.**
• No signals in p+Au, d+Au or peripheral Au+Au/U+U
• Signals in U+U larger than Au+Au
  • magnetic field difference?
• Hydro+isospin interpretation
  • not significant in pion or kaon slopes
  • may contribute to proton slopes
• LCC interpretation alone can not explain
  • Norm.Δv₃ < Norm.Δv₂
• There is room for CMW.
Backup slides
\( \gamma_{112}: 200 \text{ GeV Au+Au} \)

**Whole multiplicity:** \((7.51 \pm 0.75) \times 10^{-3}\)

After randomly rejecting half of the particles, the q-dependence becomes stronger, but the intercept remains the same.

**Half multiplicity:** \((7.32 \pm 1.37) \times 10^{-3}\)
No $\eta$ gap: $(7.51 \pm 0.75) \times 10^{-3}$

When introducing $\eta$ gap of 0.1, the $q$-dependence and the intercept are stable. Forcing the fit to $(0,0)$ gives $\sim$6 times larger $\chi^2$. 

$\eta$ gap of 0.1: $(7.81 \pm 1.22) \times 10^{-3}$
No \( \eta \) gap: \((8.32 \pm 1.92) \times 10^{-3}\)

\[ \begin{align*}
\text{No } \eta \text{ gap: } (8.32 \pm 1.92) \times 10^{-3} \\
\text{\eta gap of 0.1: } (9.27 \pm 2.20) \times 10^{-3} \\
\text{When introducing } \eta \text{ gap of 0.1, the } q\text{-dependence and the intercept are stable.}
\end{align*} \]
For 20-60% collisions, this “BG” level is typically 75-80% of the raw signal.

If the CME is there, and if this ESE really works, we expect a better significance in the difference between Ru+Ru and Zr+Zr, because a large portion of BG has been removed.

Considering the increased error bars, we could still double the significance. Worth trying!

The shaded boxes reflect the cuts of $|\Delta \eta|>0.15$ and $|\Delta p_T|>0.15$ GeV/c.