Search of the Chiral Magnetic Wave with Anisotropic Flow of Identified Particles at RHIC

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Chiral Magnetic Wave

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

\[ j_A = \frac{N_c e}{2\pi^2} \mu_B B \]

Asymmetry in the azimuthal distributions of \( h^+ \) and \( h^- \):

\[ N_+(\phi) - N_-(\phi) = (\bar{N}_+ - \bar{N}_-)[1 - r \cos(2\phi)] \]

\[ \Delta v_2 = v_2^- - v_2^+ \approx r A_{ch} \]

\[ A_{ch} = \frac{(\bar{N}_+ - \bar{N}_-)}{(\bar{N}_+ + \bar{N}_-)} \]

\[ q_e = \int R dR d\phi \cos(2\phi)[j^0_+(R, \phi) - j^0_{-,B=0}(R, \phi)] \]

\[ r = \frac{2q_e}{\bar{\rho}_e} \]

monopole, non-zero net charge density

quadrupole, CMW contribution

\[ \bar{\rho}_e = \int R dR d\phi j^0_{e,B=0}(R, \phi) \]

Observables: \( \Delta v_2, A_{ch} \)

Possible best probe: **negative and positive pions** due to the small difference in the absorption cross sections

For **negative and positive kaons** and **antiprotons and protons**, the large differences in the absorption cross sections could **mask or reverse** the potential signal.
**Brief history of CMW**

- **First CMW prediction paper published**

- **Measurement at STAR published**

- **Hydrodynamics theory proposed**
  - Y. Hatta et al., Nuclear Physics A 947 (2016) 155–160

- **Measurement with 3-particle correlation at ALICE presented**
  - ALICE Collaboration, PRL 114, 252302 (2015)

- **Measurement at ALICE published**
  - ALICE Collaboration, PRC 93, 044903 (2016)

- **Measurement in p(d)-Au at STAR presented**

- **Measurement in p(Pb)-Pb 5 TeV at CMS presented**
  - CMS Collaboration, arXiv:1708.08901
**Brief history of CMW**

First CMW prediction paper published

Measurement at STAR published

Measurement at ALICE published

Measurement in p(Pb)-Pb 5 TeV at CMS presented

Measurement in p(d)-Au at STAR presented

Hydrodynamics theory proposed

LCC theory proposed

2012

2012

2011

2011

2013

2013

2014

2014

2015

2015

2016

2016

2017

2017

First measurement at STAR presented

Measurement with 3-particle correlation at ALICE presented


STAR Collaboration, PRL 114, 252302 (2015)

ALICE Collaboration, PRC 93, 044903 (2016)

CMS Collaboration, arXiv:1708.08901


CMS results show the consistency between p+Pb and Pb+Pb, and between \( v_2 \) and \( v_3 \), what about RHIC?
Possible background — Hydrodynamics with isospin chemical potential ($\mu_I$)

“… the STAR results can be understood within the standard viscous hydrodynamics without invoking the CMW…”

$$\Delta v_2 \propto -\mu_I; \quad A_{\text{ch}} \propto -\mu_I \text{ (assumed);} \quad \Rightarrow \Delta v_2 \propto A_{\text{ch}}$$

“… the slope $r$ for the kaons should be negative, in contrast to the pion case, and the magnitude is expected to be larger… (in wider $p_T$ coverage)”


Possible background — Local Charge Conservation

Multi-particle emission from "clusters" (resonance decays, strongly flowing fluid elements)

Low $p_T$ clusters
- larger opening angles in the lab
- more likely to miss one particle

If such a lost particle is:

**positive:**
$A_{ch}$ decreases; mean $p_T(-) <$ mean $p_T(+) ; v_2(-) < v_2(+) $

**negative:**
$A_{ch}$ increases; mean $p_T(-) >$ mean $p_T(+) ; v_2(-) > v_2(+) $

Same relationship is also valid for $v_3$
The STAR experiment at RHIC and analysis method

- **Particle identification**
  Primary tracks with DCA < 1 cm
  \[ |n\sigma| < 2, \quad 0 < m^2 < 0.1 \, (\text{GeV}/c^2)^2 \]
  \[ K: |n\sigma| < 2, \quad 0.15 < m^2 < 0.35 \, (\text{GeV}/c^2)^2 \]

- **Flow calculation**
  2-particle Q-Cumulants method
  2 subevents with 0.3 \( \eta \) gap to reduce non-flow
  

- **Event selection**
  Min. bias, |Vz| < 30 cm, |Vr| < 2 cm

- **Charge asymmetry (A_{ch})**
  \[ |\eta| < 1, \quad \text{DCA (Distance at Closest Approach)} < 1 \, \text{cm} \]
  All charged particles excluding (anti)proton with \( p_T < 0.4 \, \text{GeV}/c \)
Dependence of $\Delta \langle p_T \rangle$ and $\Delta v_2$ on $A_{ch}$ for pions in different kinematic windows

- $\langle p_T \rangle$ and $v_2$ differences of $\pi^+$ and $\pi^-$ are tested as functions of $A_{ch}$
- The relative variation of $\langle p_T \rangle$ ($\sim 0.1\%$) is typically smaller than the relative variation of $v_2$ ($\sim 1\%$) by an order of magnitude.
- A wider $p_T$ range enhances particle yields -> important for analyses involving $K$ and $p$.

- $\eta$ coverage is reduced to half

$\Delta v_2(A_{ch})$ slope does not display a significant variation, suggesting the smallness of the LCC effect in the data.
Dependence of $\langle p_T \rangle$ and $v_2$ on $A_{ch}$ for pions in different kinematic windows

The slope parameters obtained with different phase space selections show similar trends and values.
Dependence of the $\Delta v_2(A_{ch})$ slope on centrality and collision energy for K

- $\Delta v_2(A_{ch})$ slope for K is positive and close to the $\pi$ slope
- Contradicts the prediction of the viscous hydrodynamics model with $\mu_I$
  (Note that the intercept for kaons is negative)

- Centrality dependence of slopes for K behave similarly to that of $\pi$
- No significant absorption effect (see slide 4)
- Hydrodynamics with $\mu_I$ cannot be the dominant mechanism
Dependence of the $\Delta v_2(A_{ch})$ slope on centrality and collision energy for $p$

- $\Delta v_2(A_{ch})$ slopes for (anti-)protons are typically much smaller than those for $\pi$ and $K$

- The proton slopes are close to zero except for the positive values in 40 – 70% collisions.
Dependence of the $\Delta v_3(A_{ch})$ slope on centrality for $\pi$ in Au+Au collisions

- In contrast with CMS results, $\pi$ $v_3$ at RHIC depends weakly on $A_{ch}$, and the $\Delta v_3(A_{ch})$ slope is much smaller than the $\Delta v_2(A_{ch})$ slope.

$$\text{Norm.} \Delta v_n = \frac{2 v_n^- - v_n^+}{v_n^- + v_n^+}$$

- $0.15 < p_T < 0.5$ GeV/c,

the norm. $\Delta v_3(A_{ch})$ slopes are lower than or consistent with zero for all centrality intervals

- $p_T$ upper bound is increased to 1 or 2 GeV/c,

the norm. $\Delta v_3(A_{ch})$ slopes gradually approach the Norm. $\Delta v_2(A_{ch})$ slopes.
The $\Delta v_2(A_{ch})$ slopes for $\pi$ in p+Au, d+Au and U+U collisions

The CMW signals are expected to disappear in the small systems.

*The orientation decoupling between the magnetic field and the 2nd-order event plane*

The $\Delta v_2(A_{ch})$ slopes in both p+Au and d+Au (analyzed with the 2nd-order event plane from TPC) are consistent with zero.

*Demonstrates the smallness of the possible background in small systems.*

The $\Delta v_2(A_{ch})$ slopes in U+U collisions are systematically higher than the results in Au+Au collisions.

*A uranium nucleus has more protons than a gold nucleus, leading to a stronger magnetic field?*
The $\langle p_T \rangle$ dependence on $A_{ch}$ exists but is insignificant. However, one should still try to keep the $p_T$ upper limit as low as possible.

The similarity between pion and kaon slopes suggests that the hydrodynamics is not the dominant contribution to the pion or kaon slopes. The isospin effect, however, remains a potential contributor to the proton slopes in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

The difference between the normalized $v_2$ and $v_3$ slopes for pions at various $p_T$, centrality intervals suggests that the CMW picture remains a viable interpretation at RHIC.

The measured slopes are consistent with zero in p+Au and d+Au collisions demonstrating the smallness of the possible background in the small systems.

The difference in the pion $\Delta v_2(A_{ch})$ slope between Au+Au and U+U is consistent with the expectation from the CMW picture.

Thanks for your attention!
Backup
Previous experimental results from RHIC and LHC

STAR Collaboration, PRL 114, 252302 (2015)

ALICE Collaboration, PRC 93, 044903 (2016)

The linear dependence between $(\Delta) v_2$ and $A_{ch}$ is observed at RHIC-STAR and LHC-ALICE. The extracted slopes are within the expectation of CMW theory.

Note that ALICE data show weak centrality dependence comparing to STAR data, indicating the possible difference (magnetic field, collectivity...) between two collision energies.
Previous experimental results from RHIC and LHC

CMS Collaboration, arXiv:1708.08901

- Significant and similar linear relationships are observed for $v_2$ and $v_3$ at LHC-CMS, which cannot be explained by CMW but is consistent with predictions based on Local Charge Conservation. Similar linear dependences are also found in pPb and PbPb system.

- CMS results challenge CMW, and are in favor of Local Charge Conservation.
Dependence of $\langle p_T \rangle$ and $v_2$ on $A_{ch}$ for pions in different kinematic windows

- Over the same $A_{ch}$ range, the relative variation of $\langle p_T \rangle$ (~0.1%) is typically smaller than the relative variation of $v_2$ (~1%) by an order of magnitude.
- A wider $p_T$ range enhances particle yields, which is important for analyses involving K and p.

- When the $\eta$ coverage is reduced to half, the $\Delta v_2(A_{ch})$ slope, does not display a significant variation, suggesting the smallness of the LCC effect in these data.

(Some statistical uncertainties are invisible on the current scale)
Possible background — Local Charge Conservation

clusters (resonances, fluid elements)

\[ A_{\text{ch}} \text{ decrease} \]
\[ \text{mean } p_T(-) < \text{mean } p_T(+) \]
\[ v_2(-) < v_2(+) \]

\[ A_{\text{ch}} \text{ increase} \]
\[ \text{mean } p_T(-) > \text{mean } p_T(+) \]
\[ v_2(-) > v_2(+) \]
Possible background — Local Charge Conservation, another mechanism

clusters (resonances, fluid elements)

\( A_{\text{ch decrease}} \)
\[ v_2(-) < v_2(+) \]

\( A_{\text{ch increase}} \)
\[ v_2(-) > v_2(+) \]

*PHOBOS data

Intercept(K) in $\sqrt{s_{NN}}$ 200 GeV

We know

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

so both

$$v_2(\pi^-) - v_2(\pi^+) = v_2^{\pi}(\text{base}) + r_{A_{ch}} > 0$$
$$v_2(K^-) - v_2(K^+) = v_2^{K}(\text{base}) + r_{A_{ch}} < 0$$

are valid

Does this observation conflict with our knowledge of (anti-)particle flow?
No, since the intercepts are negative.
Dependence of the $\Delta v_3(A_{ch})$ slope on centrality for $\pi$ in Au+Au collisions

$v_3$ for $\pi^\pm$ as functions of $A_{ch}$ in 9 centralities in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

Comparison of $\Delta v_3$ and $\Delta v_2$ for pions as functions of $A_{ch}$ in 9 centralities in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV
Dependence of the $\Delta v_3(A_{ch})$ slope on centrality for $\pi$ in Au+Au collisions

\[ \sigma_{\text{Norm.}} = \left( \frac{d\text{Norm.} \Delta v_2}{dA_{ch}} - \frac{d\text{Norm.} \Delta v_3}{dA_{ch}} \right)/\varepsilon \]

<table>
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<tr>
<th>Centrality</th>
<th>0-5%</th>
<th>5-10%</th>
<th>10-20%</th>
<th>20-30%</th>
<th>30-40%</th>
<th>40-50%</th>
<th>50-60%</th>
<th>60-70%</th>
<th>70-80%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T &lt; 0.5$ GeV/c</td>
<td>4.2</td>
<td>4.1</td>
<td>3.9</td>
<td>2.4</td>
<td>0.7</td>
<td>1.3</td>
<td>1.9</td>
<td>1.4</td>
<td>2.2</td>
</tr>
<tr>
<td>$p_T &lt; 1$ GeV/c</td>
<td>5.9</td>
<td>4.6</td>
<td>3.7</td>
<td>2.2</td>
<td>0.2</td>
<td>-0.4</td>
<td>0.8</td>
<td>1.2</td>
<td>2.6</td>
</tr>
<tr>
<td>$p_T &lt; 2$ GeV/c</td>
<td>4.7</td>
<td>4.4</td>
<td>3.3</td>
<td>1.8</td>
<td>0.003</td>
<td>-0.6</td>
<td>0.2</td>
<td>0.7</td>
<td>2.3</td>
</tr>
</tbody>
</table>

- These $\sigma_{\text{Norm.}}$ values suggest that the STAR measurements of the $\Delta v_2(A_{ch})$ slopes are different with the CMS measurements.

- It is unlikely that a common background such as LCC could alone explain the data. There could be multiple reasons, particularly at most central and peripheral collisions. CMW picture still remains as a viable interpretation at RHIC.