Search for Chiral Magnetic Wave in Pb-Pb collisions with the ALICE detector

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Outline:
✓ Motivation
✓ Experimental observable
✓ ESE constrains CMW fraction
✓ Centrality dependence of CMW fraction
✓ Summary
Motivation

- **Chiral Magnetic Effect (CME):** \[ j_\nu = \frac{N_c e}{2\pi^2 \mu_A B} \]
- **Chiral Separation Effect (CSE):** \[ j_\lambda = \frac{N_c e}{2\pi^2 \mu_\lambda B} \]
- **Chiral Magnetic Wave (CMW):** CME+CSE

- **Chiral symmetry restoration**
- **Deconfinement**
- **QCD vacuum transitions**
- **Extremely strong magnetic field (\(\sim 10^{15} \text{ T}\))**

All the necessary conditions are possible to be achieved in heavy-ion collisions

Experimental observable

CMW observable: Normalized slope,

$$r_{\Delta v_2}^{Norm.} = \frac{d(\frac{\Delta v_2}{\langle v_2 \rangle})}{dA_{ch}}, \quad \langle v_2 \rangle = \frac{v_2^+ + v_2^-}{2}$$

$$A_{ch} = \frac{N^+ - N^-}{N^+ + N^-}, \quad \Delta v_2 = v_2^- - v_2^+ = rA_{ch}$$
Covariance observable

\[ \langle v_{2}^\pm A_{\text{ch}} \rangle - \langle A_{\text{ch}} \rangle \langle v_{2}^\pm \rangle \approx \pm r \sigma_{A_{\text{ch}}}^2 / 2 \]

\[
dN_{\text{ch}}/d\eta \left( \langle v_{2}^\pm A_{\text{ch}} \rangle - \langle A_{\text{ch}} \rangle \langle v_{2}^\pm \rangle \right)_{\text{neg-pos}}\]

Covariance observable:
✓ Proportional to slope parameter
✓ Saves statistics
✓ Has differential form (see backup)


\( 0.2 < p_T < 5.0 \text{ GeV}/c \)
\(-0.8 < \eta < 0.8 \)

\( \langle v_{2}(A) \rangle - \langle A \rangle \langle v_{2} \rangle \)

\[ \text{Pb-Pb } \sqrt{s_{NN}} = 2.76 \text{ TeV} \]
Previous experimental results

✓ Linear relationship for $\Delta v_2(h^\pm)$ vs. $A_{ch}$
✓ Significant positive signals (around 3%) in ALICE and STAR match theoretical prediction

Previous experimental results and LCC backgrounds

Most possible background: **local charge conservation (LCC)**

✓ The observable in p-Pb collision is in line with the one in Pb-Pb collisions
✓ Higher harmonic ($v_3$) observable with nonzero signal

**How to separate the signal/background?**

THE ALICE detector

Time Projection Chamber (TPC): 
\(| \eta | < 0.9 \)

✓ Primary vertex and tracking
✓ Momentum measurement
✓ Particle identification

V0: V0A (2.8 < \eta < 5.1)  V0C (−3.7 < \eta < −1.7)
✓ Trigger and centrality (also used for event-shape engineering / event-plane)
Slope in Pb-Pb collision at 5.02 TeV

**NEW**

Linear dependences between $v_2^\pm \left( \frac{\Delta v_2}{\langle v_2 \rangle} \right)$ and $A_{ch}$ in the left (middle) figure.

In the right figure, $r_{\Delta v_2}^{Norm.}$ is consistent with $r_{\Delta v_3}^{Norm.}$ within uncertainties.
Comparison with CMS results and the model


\[ r_{\Delta v^2}^{\text{Norm(ALICE)}} \approx r_{\Delta v^2}^{\text{Norm(CMS)}} \]

✓ **BW-LCC** model (engaging 100% local charge conservation) over-predicts the experimental measurements

✓ **AMPT** model (no CMW and violation of charge conservation) shows slope consistent with zero

Wu (for the ALICE Collab.)
Event Shape Engineering (ESE) method

✓ Select events corresponding to initial geometry
✓ Sensitive to anisotropy of collision
✓ Successfully used for CME


✓ Applying ESE technique to constrain CME
✓ Selects events with equivalent event numbers
✓ Estimates observables in each $q_2$ interval

ESE constrains CMW fraction

Integral covariance (Int. Cov.) is the covariance between $v_2^\pm$ and $A_{ch}$

\[ \text{Int. Cov.} \equiv \langle v_2^\pm A_{ch} \rangle - \langle A_{ch} \rangle \langle v_2^\pm \rangle \approx \pm r \sigma_{A_{ch}}^2 / 2 \]

\[ \Delta \text{Int. Cov.} \equiv (\langle v_2^\pm A_{ch} \rangle - \langle A_{ch} \rangle \langle v_2^\pm \rangle)_{\text{neg-pos}} \]

- **CMW signal (AMPT+quadrupole)**
  - $\Delta \text{Int. Cov.} \text{ vs. } v_2 : \text{finite intercept}$

- **Background (BW+LCC)**
  - $\Delta \text{Int. Cov.} \text{ vs. } v_2 : \text{zero intercept}$

- **NEW**
  - In most centralities, the proportionality of $\Delta \text{Int. Cov.}$ changes with $v_2 \rightarrow$ indication of a large background
  - Linear fit: $F(v_2) = a \times v_2 + b$
Centrality dependence of CMW fraction $f_{CMW}$

$$f_{CMW} \equiv \frac{b}{a \times \langle v_2 \rangle + b}$$

- Parameters $a$ and $b$ are extracted from the $F(v_2)$ fit to $\Delta$Int. Cov.
- $\langle v_2 \rangle$ averaged over all intervals of $q_2$
- $f_{CMW}$ consistent with 0 within uncertainties

Value of $f_{CMW}$ extracted in 10-60% centrality, $f_{CMW} \sim 0.338 \pm 0.084$(stat.) $\pm 0.198$(syst.)
✓ **Δν₂-Αₙ₅h method**: The normalized slope \( r^{\text{Norm.}}_{Δν₂} \) is consistent with \( r^{\text{Norm.}}_{Δν₃} \) within uncertainties implying that CMW signal is consistent with zero

✓ **ESE method**: First measurement of the CMW fraction with ESE method in Pb-Pb collisions, \( f^{\text{CMW}}_{\text{CMW}} \) is consistent with zero within uncertainties

✓ Those two methods imply the CMW signal is consistent with zero, or very small if it exists

Thanks for your attention!
Differential covariance:
\[ \langle v_2^\pm q_3 \rangle - \langle q_3 \rangle_1 \langle v_2^\pm \rangle \]

✓ Averaged charge around specific particle
✓ Reflect the local charge conservation in CMW measurements
\[ (|\Delta\eta| \uparrow, \text{covariance} \downarrow) \]
Backup : local charge conservation leads to background

When selecting events with a specific $A_{ch}$, in practice, one preferentially applies nonuniform $p_T(\eta)$ cuts on the charged particles

**A manifestation of LCC!**

<table>
<thead>
<tr>
<th>Type</th>
<th>$\rho^0 \rightarrow \pi^+\pi^-$</th>
<th>String frag.</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>unpaired (case b, c)</td>
<td>paired (case a)</td>
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<td>Mother $p_T$</td>
<td>0.75</td>
<td>0.97</td>
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<td>Mother $</td>
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<td>Daughter $p_T$</td>
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<td>Daughter $</td>
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<td>$</td>
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<tr>
<td>Daughter $</td>
<td>\Delta \eta</td>
<td>$</td>
</tr>
</tbody>
</table>

$A_{ch} < 0 ( > 0 ) \rightarrow B(C)$ and $b(c) \uparrow \rightarrow$ unpaired neg(pos) particles $\uparrow \rightarrow \langle p_T^- \rangle < \langle p_T^+ \rangle \left( \langle p_T^- \rangle > \langle p_T^+ \rangle \right)$

Considering the LCC effect in an event with a specific $A_{ch}$ value

- **Resonance decay** $(a,b,c)$: paired particle emitted at the same point
- **String fragmentation model** $(A,B,C)$: hadronization process with a string consisting of $q$ and $\bar{q}$ endpoints