Search for Chiral Magnetic Effects in High-Energy Nuclear Collisions

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Motivation

CSE + CME → Chiral Magnetic Wave:
• collective excitation
• signature of Chiral Symmetry Restoration

Peak magnetic field ~ $10^{15}$ Tesla!
(Kharzeev et al. NPA 803 (2008) 227)

$\vec{j}_A = \frac{N_c e}{2\pi^2} \mu_v B$

$\vec{j}_v = \frac{N_c e}{2\pi^2} \mu_A B$
Formation of electric quadrupole: $v_2^\pm = v_2 \mp \left( \frac{q_e}{\rho_e} \right) A_\pm$,

where charge asymmetry is defined as $A_\pm = \frac{N_+ - N_-}{N_+ + N_-}$.

Then $\pi^- v_2$ should have a **positive** slope as a function of $A_\pm$, and $\pi^+ v_2$ should have a **negative** slope with the same magnitude.

The integrated $v_2$ of $\pi^-$ is not necessarily bigger than $\pi^+$: (other physics) only the $A_\pm$ dependency matters for CMW testing.
This charge separation effect needs to be beyond conventional physics background.

\[
\frac{dN_{\pm}}{d\phi} \propto 1 + 2a_{\pm} \cdot \sin\left(\phi_{\pm} - \Psi_{RP}\right)
\]

CME + Parity-odd domain, => charge separation across RP

S. Voloshin, PRC 70 (2004) 057901, Kharzeev, PLB633:260 (2006)
Kharzeev, McLerran, Warringa, NPA803:227 (2008)
Observed charge asymmetry

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

• $N^+ (N^-)$ is the number of positive (negative) particles within $|\eta|<1$.

• The distribution was divided into 5 bins, with roughly equal counts.

• Tracking efficiency was corrected later.
Charge asymmetry dependency

- $v_2$ was measured with the Q-cumulant method.

- Clear $A_\pm$ dependency

- $v_2(A_\pm)$ slopes for $\pi^\pm$:
  - opposite sign
  - similar magnitude

- $v_2$ difference vs $A_\pm$ may have a non-zero intercept: other physics?

$$v_2^\pm = v_2 \pm \left( \frac{q_e}{\rho_e} \right) A_\pm$$
Correction for tracking efficiency

Tracking efficiency for π+ and π−

\[ v_2^- - v_2^+ = C + 2 \left( \frac{q_e}{\rho_e} \right) A_\pm \]

• Fit with a straight line to extract the slope \( r = 2 \frac{q_e}{\rho_e} \).

• Do the same for all centralities.
Similar trends between data and theoretical calculations with CMW (improved version). There is no specific beam energy input for the calculation. UrQMD with no CMW can not reproduce the slopes.
Similar trends are observed for different beam energies, where the errors are small.\textsuperscript{9}
Summary I

• Charge asymmetry dependency of pion $v_2$ has been observed.
  • $v_2(A)$ showed opposite slopes for $\pi^+$ and $\pi^-$.  
  • The slopes have similar centrality dependency from 200 GeV to 27 GeV.

• Similarity between real data and calculations with CMW
  • Similar trends of slope vs centrality  
  • UrQMD (w/o CMW) showed no such effects.

• Further systematic checks
  • Weak decay contribution  
  • Handle on the magnetic field B

• Other physics interpretations
  • Quark transportation?  
  • Hadronic potential?

Please also see Hongwei Ke's poster!
\[
\frac{dN^\pm}{d\phi} \propto 1 + 2a_\pm \cdot \sin(\phi^\pm - \Psi_{RP})
\]

A direct measurement of the \( P \)-odd quantity “\( a \)” should yield zero.

\[
\gamma = \left\langle \cos(\phi_\alpha + \phi_\beta - \psi_{RP}) \right\rangle
\]

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

Non-flow/non-parity effects: largely cancel out

Directed flow: expected to be the same for SS and OS

\( P \)-even quantity: still sensitive to charge separation
Beam energy scan

From 2.76 TeV to 7.7 GeV, changes start to show from the peripheral collisions.
Consider $\gamma_{OS} - \gamma_{SS}$ to be signal...

The signal seems to be disappearing at 7.7 GeV, but the statistical errors are large.
Possible physics background

charge conservation/cluster + $v_2$

Pratt, Phys. Rev. C83:014913, 2011

Seemingly correlated!

Can we disentangle the relationship with $U+U$?

STAR, Phys. Rev. C72 (2005) 014904

In RHIC run 2012, we took 350M minbias events and 14M central trigger events.
A larger and deformed system

- $v_2(M)$ in U+U is higher than that in Au+Au. Not as high as expected in central collisions. (4% expected)
- The cusp in the simulation not seen. If any, maybe in very central events.

Voloshin, Phys.Rev.Lett. 105(2010)172301
Masui, Phys.Lett.B679:440-444, 2009
If \( \frac{dN}{d\eta} \) is divided by the overlap area (\( S \)) and \( v_2 \) is divided by eccentricity, there is a split in central and mid-central collisions.

The area and eccentricity are calculated with Glauber Monte Carlo.
• A dedicated trigger selected events with 0-1% spectator neutrons.

• With the magnetic field suppressed, the charge separation signal disappears (while $v_2$ is still $\sim 2.5\%$).

• The difference between OS and SS is still there in U+U, with similar magnitudes.

• Consider OS-SS to be the signal

• $N_{\text{part}}$ accounts for dilution effects
Summary II

• The three-point correlation showed charge separation w.r.t RP
  • \((\gamma_{OS} - \gamma_{SS})\) has similar magnitudes from 2.76 TeV to 11.5 GeV
  • Similar in Au+Au, Pb+Pb and U+U (also in Cu+Cu, not shown)

• The signal of charge separation seems to disappear when
  • the beam energy is down to ~7.7GeV
  • the magnetic field from spectators is supressed \((v_2\) is still sizable)

• Further studies
  • Correlations between identified particles
    • pion, kaon, proton and Lambda
  • Collisions of isobars?

• U+U collisions show interesting features of \(v_2\), which needs further investigation and calls for interpretation...

See also Kent Riley's poster!
Backup slides
STAR: excellent PID and tracking

The correlation measurements at STAR are accurate to relative 0.1\%.
Improvement of theoretical calculations with CMW: Simplified hard-disk (pancake) type of model -> Monte Carlo Glauber
Multi-component Coalescence (MCC) + Quark Transport

$X_{dT} - X_{uT}$ vs Charge Asymmetry

only using charged hadrons

Pearson coefficient: -0.92 $\rightarrow$ Strong negative correlation

$\Delta v_2^\pi \equiv v_2^{\pi^-} - v_2^{\pi^+} = (X_{dT} - X_{uT})(v_2^T - v_2^P)$
Results with different EPs

The correlators using TPC/ZDC event planes are consistent with each other.
What do we know about the position $R_n$ after $n$ steps?

$R_n$ follows a Gaussian distribution: mean = 0, and $rms = \sqrt{n}$

Our measurement of PV is like $R_n^2$, expected to be $n$.

Compared with going in one fixed direction, where $R_n^2 = n^2$, the "random-walk" measurement is diluted by a factor $\sim n \sim N_{part}$. 

In the quark-gluon medium, there could be multiple $P$-odd domains. The net effect is like a random walk, but one-dimensional.
Two-particle correlation changes significantly with beam energy.
Possible physics background

charge conservation/cluster + $v_2$

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

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

$\approx \frac{f_{res} \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{res}) \rangle}{N_{ch}} v_{2,\text{res}}$

Pratt, Phys.Rev.C83:014913,2011
Balance function

Pratt, Phys.Rev.C83:014913,2011

MC simulation (no radial flow)
- $a_1 = 0$, $v_2 = 5\%$, $M = 200$
- $a_1 = 2\%$, $v_2 = 5\%$, $M = 200$