Probes of local strong parity violation: 
Experimental results from STAR

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for the STAR Collaboration

June 7, 2010

RHIC & AGS Annual Users' Meeting:
workshop on Local Strong Parity Violation
BNL, Upton, NY
Non-central relativistic heavy ion collision (HIC)

- Overlapped area: non-uniform particle density and pressure gradient

- Large orbital angular momentum: 
  \( L \sim 10^5 \)
  
  Liang, JPG34:323 (2007)

- Strong magnetic field:
  \[ B \sim 10^{15} \text{T} \quad (eB \sim 10^4 \text{MeV}^2) \]
  \[ (\mu_N B \sim 100 \text{MeV}) \]
  
  Rafelski, Müller PRL36:517 (1976)
  Kharzeev, McLerran, Warringa
  NPA803:227 (2008)
Particle production in HIC: asymmetries wrt. the reaction plane

- Anisotropic transverse flow
  - Initial space anisotropy of the overlapped area evolves into momentum space

- Global polarization/spin alignment
  - Preferential orientation of the spin of produced particles wrt. the system orbital momentum

- Local strong parity violation
  - Charge separation along the magnetic field/orbital momentum (focus of this talk)

**Experimental observation of these effects** provide:
- Information on initial condition & evolution of the system created in HIC
- Insight on hadronization mechanism & origin of hadronic spin
- A probe of fundamental QCD symmetries
Chiral symmetry breaking and P-violation

QCD vacuum (gluonic field energy) is periodic vs. Chern-Simons number, $N_{CS}$:

- Instanton
- Sphaleron

Localized in space & time solutions. Transitions between different vacua via tunneling/go-over-barrier

Quark interaction changes chirality, which is a P and T odd transition

P/CP invariance are (globally) preserved in strong interactions.

Evidence from neutron EDM (electric dipole moment) experiments:

- Pospelov, Ritz, PRL83:2526 (1999)

$$\theta < 10^{-10}$$

If $\theta \neq 0$, then QCD vacuum breaks P and CP symmetry.

but:

In HIC formation of (local) metastable P-odd domains is not forbidden.

T.D. Lee, PRD8:1226 (1973)
Kharzeev, Pisarski, Tytgat, PRL81:512 (1998)

Kharzeev, Krasnitz, Venugopalan, PLB545:298 (2002)
Charge separation in HIC

Magnetic field aligns quark spins along or opposite to its direction

Vacuum transitions produce local excess of left/right handed quarks:

\[ N_{\text{left}} \neq N_{\text{right}} \]

Right-handed quark momentum is opposite to the left-handed one

Induced electric field (parallel to B):

\[ E \sim \theta \cdot B \]

Positive and negative charges moving opposite to each other → charge separation in a finite volume

Kharzeev, Zhitnitsky, NPA797:67 (2007)
Why charge asymmetry wrt. the reaction plane is P-violation?

Coordinate/momentum (vectors):

\[ \vec{r} \rightarrow -\vec{r} \quad \vec{p} \rightarrow -\vec{p} \]

Orbital momentum/magnetic field (pseudo-vectors):

\[ \vec{L} \rightarrow \vec{L} \quad \vec{B} \rightarrow \vec{B} \]
Experimental observable
**Azimuthal distribution in case of P-violation**

\[
\frac{dN_{\pm}}{d\phi} \sim 1 + 2 \sum_{i=1} v_n \cos(n \Delta \phi) + 2 a_{1,\pm} \sin \Delta \phi + \ldots
\]

- \( \Psi_{RP} \) reaction plane (RP) angle
- \( \Delta \phi = \phi - \Psi_{RP} \) particle azimuth relative to RP
- \( v_n \) \( n \)-harmonic anisotropic transverse flow. \( n=1 \) – directed flow, \( n=2 \) - elliptic flow
- \( a_{\pm} \) asymmetry in charged particle production (consider only first harmonic)

Predicted asymmetry is about 1% for mid-central collisions → within an experimental reach

Observable

• Charge asymmetry is too small to be observed in a single event

• Asymmetry fluctuates event by event. P-odd observable yields zero:

\[ \langle a_{\pm} \rangle = \langle \sin (\phi_{\pm} - \Psi_{RP}) \rangle = 0 \]

• Study P-even correlations: \( \langle a_{\alpha} a_{\beta} \rangle \ (\alpha, \beta = \pm) \)

Measure the difference between in-plane and out-of-plane correlations:

\[
\langle \cos (\phi_{\alpha} + \phi_{\beta} - 2 \Psi_{RP}) \rangle = \langle \cos \Delta \phi_{\alpha} \cos \Delta \phi_{\beta} \rangle - \langle \sin \Delta \phi_{\alpha} \sin \Delta \phi_{\beta} \rangle = \\
\left[ \langle v_{1,\alpha} v_{1,\beta} \rangle + Bg^{(in)} \right] - \left[ \langle a_{\alpha} a_{\beta} \rangle + Bg^{(out)} \right]
\]

\[ \Delta \phi_{\alpha,\beta} = \phi_{\alpha,\beta} - \Psi_{RP} \]

- Large RP-independent background correlations cancel out in \( Bg^{(in)} - Bg^{(out)} \)

- RP-dependent (P-even) backgrounds contribute:

  \( \rightarrow Bg^{(in)} - Bg^{(out)} \) term

  \( \rightarrow \langle v_{1,\alpha} v_{1,\beta} \rangle \): directed flow (zero in symmetric rapidity range) + flow fluctuations
Medium effects on charge correlations

P-odd domain formation (no medium)

\[ a_+ = -a_- \]

\[ \langle a^2 \rangle = \langle a_-^2 \rangle > 0 \]
\[ \langle a_+ a_- \rangle = -\langle a_+^2 \rangle \]

Quenching in medium

orientation flips event by event

\[ \langle a_+^2 \rangle = \langle a_-^2 \rangle > 0 \]
\[ \langle a_+ a_- \rangle \ll -\langle a_+^2 \rangle \]

Expectations for charge correlations

- Magnitude: 
  \[ a_\pm = \pm \frac{4}{\pi} \frac{Q}{N_\pm} \]

  \[ Q = N_R - N_L \] - topological charge \((Q = \pm 1, \pm 2, \ldots)\)

  \[ N_\pm \] - charged particle multiplicity 
  \[ \langle Q \rangle \sim \sqrt{N_\pm} \]

For midcentral Au+Au collisions (1 P-odd domain/collision):
\[ N_\pm \sim 100 \text{ per unit of rapidity} \rightarrow a_\pm \sim 1\% \]

\[ \langle a_\alpha a_\beta \rangle \sim 10^{-4} \]

- Correlation width in rapidity: about one unit
- Localized at \( p_t < 1 \text{ GeV/c} \) (non-perturbative effect)
- Proportional to the magnetic field: \( a_\pm \sim B \)
- Stronger opposite-sign signal for a smaller colliding system (atomic number)

Kharzeev, Zhitnitsky, NPA797:67 (2007)
Measurement technique

• Goal: 2-particle correlations wrt. the reaction plane (RP):

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

• In experiment RP is unknown
  → estimated from azimuthal distribution of produced particles:

\[ \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle = \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle / \nu_{2,c} \]

\[ \nu_{2,c} \] - elliptic flow of \( c \)-particle

Implies: \( c \) and \((\alpha, \beta)\) particles are correlated only via RP
  → validity needs to be tested experimentally

• Measuring (mixed harmonics) 3-particle azimuthal correlations:

\[ \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle = -\langle a_\alpha a_\beta \rangle \nu_{2,c} + \text{[non-parity correlations]} \]
STAR probes of P-violation
The STAR experiment

TPC: $|\eta| < 1.3$
(Time Projection Chamber)

FTPCs: $2.9 < |\eta| < 3.9$
(Forward TPC)

ZDC SMDs:
recoil neutrons at beam rapidity
(Zero Degree Calorimeter - Shower Maximum Detector)

Charged particle cuts:
- Pseudo-rapidity
  $|\eta| < 1$
- Transverse momentum
  $0.15 < p_t < 2$ GeV/c

RP reconstruction with TPC, FTPCs and ZDC SMDs

Data from RHIC running in year 2004/2005

<table>
<thead>
<tr>
<th>System</th>
<th>Energy, $\sqrt{s}_{NN}$</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au+Au</td>
<td>200 / 62 GeV</td>
<td>10.6 / 7 M</td>
</tr>
<tr>
<td>Cu+Cu</td>
<td>200 / 62 GeV</td>
<td>30 / 19 M</td>
</tr>
</tbody>
</table>
Detector effects

Acceptance corrections (re-centering):

\[
\sin n \phi \rightarrow \sin n \phi - \langle \sin n \phi \rangle
\]

\[
\cos n \phi \rightarrow \cos n \phi - \langle \cos n \phi \rangle
\]

Poskanzer, Voloshin, PRC58:1671 (1998)

<table>
<thead>
<tr>
<th>symbol</th>
<th>((\alpha, \beta)) charges</th>
<th>c-particle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>opposite sign, (+ -)</td>
<td>positive</td>
</tr>
<tr>
<td></td>
<td>same sign, (++)</td>
<td></td>
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<tr>
<td></td>
<td>same sign, (- -)</td>
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- After corrections: consistent results for all charge combinations
- Conclude from a number of tests: detector effects are not responsible for observed correlations.
Testing sensitivity to 2-particle correlations wrt. RP

\[ \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle \]

\[ \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle / \nu_{2,c} \]

\( \times 10^{-3} \)

\( \times 10^{-3} \)

Au+Au@200GeV

\( \times 10^{-3} \)

\( \times 10^{-3} \)

\[ \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle \]

\[ \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle / \nu_{2,c} \]

\( \times 10^{-3} \)

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\( \times 10^{-3} \)

\( \times 10^{-3} \)

%\,\text{most central}

%\,\text{most central}

\( \nu_{2,c} \) correction gives consistent result with TPC/FTPC \( c \)-particle (similarly ZDC-SMD)

\[ \rightarrow \text{Probing 2-particle correlations wrt. RP} \]

Same- and opposite-sign correlations consistent with P-violation

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<tbody>
<tr>
<td></td>
<td>same sign</td>
<td>(</td>
</tr>
<tr>
<td></td>
<td>opposite sign</td>
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</table>

PRC81:054908 (2010)
Modeling physics backgrounds

\[ \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle = \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle / v_{2,c} \]

<table>
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<tr>
<td>▼</td>
<td>HIJING</td>
<td>true</td>
</tr>
<tr>
<td>△</td>
<td>HIJING + v_2</td>
<td>reaction</td>
</tr>
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<td>.</td>
<td>UrQMD</td>
<td>plane</td>
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<td>■</td>
<td>MEVSIM</td>
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Notes:
- Non-zero background correlations, but different from observed signal
- HIJING + v_2: added flow “afterburner”
- MEVSIM: resonances with realistic flow
- Model physics backgrounds

\[ \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle = \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle / v_{2,c} \]

\(v_{2,c}\) correction systematics

\[ \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle / v_{2,c} \]

\( |\eta| < 1.0 \)

\[ \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle = \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle / v_{2,c} \]

Notes:
- cluster production is not well modeled by event generators
- charge and momentum conservation may affect the measurements

Pratt arXiv:1002.1758v1 [nucl-th]
Pseudo-rapidity and transverse momentum dependence

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

**Au+Au@200GeV**

Centrality: 30-50%

**Transverse momenta** dependence:
→ the signal extends to higher pt?

\[ \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle = \frac{N_{corr}}{N_{all}} \]


\[ \left[ p_{t,\alpha} + p_{t,\beta} \right] / 2 \]

**Pseudo-rapidity** dependence:
→ typical “hadronclic” width

pt and eta dependence consistent with P-violation
Two particle correlations

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

Two particle correlations wrt. the RP

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

\[ = \langle \cos \Delta \phi_\alpha \cos \Delta \phi_\beta \rangle - \langle \sin \Delta \phi_\alpha \sin \Delta \phi_\beta \rangle \]

“Regular” two particle correlations

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

\[ = \langle \cos \Delta \phi_\alpha \cos \Delta \phi_\beta \rangle + \langle \sin \Delta \phi_\alpha \sin \Delta \phi_\beta \rangle \]

\[ \Delta \phi_{\alpha,\beta} = \phi_{\alpha,\beta} - \Psi_{RP} \]

Background models aren't describe even the “regular” two particle correlations.

Indicate contribution from LPV physics to \( \langle \cos(\phi_\alpha - \phi_\beta) \rangle \) term?
Summary

Local strong parity violation in heavy-ion collisions predicted to lead to charge separation wrt. the reaction plane.

STAR measurements with P-even observable reveal non-zero signal:
- Can not be described with existing background models
- Qualitatively agrees with predictions for local P-violation
- Confirmed by PHENIX (see next talk by Nuggehalli Ajitanand)

Outlook

Theory:
- Detailed calculations for P-violating signal and backgrounds are needed

Experiment:
- Reaction plane from spectator neutrons: Gang Wang WWND2010; APS2010
- Probe higher harmonics with charge multiplicity correlations: talk by Fuqiang Wang
- Future prospects: see afternoon talk by Jack Sandweiss
Backup slides
Correlations with (first harmonic) ZDC-SMD event plane from recent analysis of 2007 data yield similar result to TPC/FTPC

\[ \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle \]
Physics backgrounds

Reaction plane (RP) dependent:

• Directed flow (vanishes in symmetric eta-range), flow fluctuations:
  \[
  \langle \cos(\phi_\alpha + \phi_\beta - 2 \phi_c) \rangle_{\text{flow}} = \langle v_{1,\alpha} v_{1,\beta} \rangle v_{2,c}
  \]

• Global polarization (zero from measurement)

• RP dependent fragmentation ("flowing clusters"):
  \[
  \langle \cos(\phi_\alpha + \phi_\beta - 2 \Psi_{RP}) \rangle_{\text{clust}} = A_{\text{clust}} \langle \cos(\phi_\alpha + \phi_\beta - 2 \phi_{\text{clust}}) \rangle_{\text{clust}} v_{2,\text{clust}}
  \]

RP independent 3-particle correlations:

Can be removed by better RP determination
Different multiplicity scaling \((1/N_{ch}^2)\) compared to P-violation

• Jet fragmentation, resonances, multi-particle clusters
• HBT, Coulomb effects, etc.
Detector effects study

- Track momenta distortions due to the charge buildup in the TPC at high accelerator luminosity
  → Results for low/high luminosity runs are consistent

- Dependence on reconstructed position of the collision vertex
  → No vertex dependence found

- Displacement of track hits when it passes the TPC central membrane
  → Results from different half-barrels of the TPC are consistent

- Feed-down effects from non-primary tracks (i.e. resonance decay daughters)
  → Results for dca < 1 cm and dca < 3 cm are consistent

- Electron contribution checked via dE/dx cut
  → Effect is negligible

- Studied a correlator similar to parity observable
  → but with the reaction plane angle rotated by pi/4

- Variation depending on the charge of the third particle used to reconstruct the reaction plane and changes of the STAR magnetic field polarity
  → Variations does not change the observed signal
Energy and system size dependence

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

@ 200 GeV

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

@ 62 GeV

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<td>3-particle HIJING</td>
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<td></td>
<td>( \nu_{2,c} ) correction systematics</td>
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Opposite sign correlations:
Stronger for a smaller (Cu+Cu) system. In agreement with P-violation, but large uncertainties due to possible RP-independent correlations.

PRC81:054908 (2010)
Charge correlations and $N_{\text{part}}$ scaling @200GeV

Correlations multiplied by $N_{\text{part}}$ to remove dilution in more central collisions

Opp-sign correlations scale with $N_{\text{part}}$

Same sign signal is suggestive of correlations with the reaction plane

Stronger opposite charge correlations in Cu+Cu at the same $N_{\text{part}}$