LPV in Heavy Ion Collisions: Experiment

Sergei A. Voloshin
Local strong parity violation and new perspectives in experimental study of non-perturbative QCD

Outline:
- QCD vacuum. Chiral Magnetic Effect
- Anisotropic flow
- Observable
- Experimental results
- Future directions
- Summary
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STAR results:

QCD vacuum topology

Energy of gluonic field is periodic in $N_{cs}$ direction (~ a generalized coordinate)

Instantons and sphalerons are localized (in space and time) solutions describing transitions between different vacua via tunneling or go-over-barrier

Quark interactions with instantons
- change chirality ($\mathcal{P}$ and $T$ odd),
- lead to quark condensate

$$\langle \bar{q}q \rangle = -(230 \text{ MeV})^3, \quad \langle g^2 G^2 \rangle = (850 \text{ MeV})^4$$

$$\Rightarrow \varepsilon_0 \approx -500 \text{ MeV/fm}^3$$

Quark propagating in the background of the quark condensate obtains dynamical “constituent quark” mass


$$\Lambda_{QCD} \sim 0.2 \text{ GeV} \simeq (1 \text{ fm})^{-1}$$

$$\Lambda_{\chi SB} \sim 1 \text{ GeV}$$

Defines the confinement radius, hadron size.

Defines the size of constituent quark, size of the “small” instantons.
\[ J = \sum_{\pi^+, \pi^-} \frac{(p_{\pi^+} \times p_{\pi^-})_z}{p_{\pi^+} p_{\pi^-}}. \]

Difference in the orientation of the event plane determined with positive or negative particles!

\[ \sigma_{\sin(\Delta \phi), \text{nonstat}} \approx \alpha (1 - 3) \times 10^{-3}. \]

where \( \alpha \) is the fraction of particles originating from the P-odd domain.
EDM of QCD matter

Charge separation along the orbital momentum: EDM of the QCD matter (~ the neutron EDM) (Local Parity Violation)

Chiral magnetic effect:
\[ N_L \neq N_R \oplus \text{magnetic field} \]
Induction of the electric field parallel to the (static) magnetic field

\[ N_R - N_L = Q \]
\[ A_u = \frac{N_R - N_L}{N_R + N_L} \]
\[ A_{\pi^+} = -A_{\pi^-} \simeq \frac{Q}{N_{\pi^+}} \]

The asymmetry is too small to observe in a single event, but is measurable by correlation techniques
Anisotropic flow

\[ \frac{dN_\alpha}{d\phi} \propto 1 + 2v_{1,\alpha} \cos(\Delta \phi) + 2v_{2,\alpha} \cos(2\Delta \phi) + \ldots \]

\[ \Delta \phi = (\phi - \Psi_{RP}) \]

Anisotropic flow

\[ \frac{dN_\alpha}{d\phi} \propto 1 + 2v_{1,\alpha} \cos(\Delta \phi) + 2v_{2,\alpha} \cos(2\Delta \phi) + \ldots \]

\[ \Delta \phi = (\phi - \Psi_{RP}) \]


\[ Q_n = \sum e^{in\phi}; Q_n = |Q_n| e^{in\Psi_n} = X_n + iY_n \]

E877, PRL 73, 2532 (1994)
Anisotropic flow

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E877, PRL 73, 2532 (1994)
E877, PRC 55 (1997) 1420

Picture: © UrQMD

XZ – the reaction plane
Anisotropic flow, RHIC

\[ \frac{dN_\alpha}{d\phi} \propto 1 + 2v_{1,\alpha} \cos(\Delta \phi) + 2v_{2,\alpha} \cos(2\Delta \phi) + \ldots \]

\( \Delta \phi = (\phi - \Psi_{RP}) \)


\[ v_2 = \langle \cos(2(\varphi - \Psi_{RP})) \rangle \]

Picture: © UrQMD

XZ – the reaction plane


\[ \text{Au+Au, 200 GeV} \]

STAR Collaboration, PRL, 86 (2000) 402

\[ \frac{n_{ch}}{n_{max}} \]
\[ \frac{dN_{\alpha}}{d\phi} \propto 1 + 2v_{1,\alpha} \cos(\Delta \phi) + 2v_{2,\alpha} \cos(2\Delta \phi) + \ldots \]

\[ \Delta \phi = (\phi - \Psi_{RP}) \]


\[ \langle u_{n,a} u_{n,b}^* \rangle = \cos \left[ n \left( \phi_a - \phi_b \right) \right] = v_{n,a} \nu_{n,b} + \delta_n \]

\[ v_2 = \langle \cos(2(\varphi - \Psi_{RP})) \rangle \]
Mixed harmonics: how it works

\[ \langle u_{n,1} u_{n,2}^* \rangle = v_n^2 + \delta; \quad u \equiv e^{i \phi} \]

Poskanzer, S.V. PRC 58 (1998)1671

What to do when the reaction plane is known:

\[ \langle \cos(\varphi_a - \Psi_{RP}) \cos(\varphi_b - \Psi_{RP}) \rangle = v_1^2 + \delta / 2 \]
\[ \langle \sin(\varphi_a - \Psi_{RP}) \sin(\varphi_b - \Psi_{RP}) \rangle = \delta / 2 \]

The difference between x component and y component correlations:

\[ \langle \cos(\varphi_a - \Psi_{RP}) \cos(\varphi_b - \Psi_{RP}) \rangle - \langle \sin(\varphi_a - \Psi_{RP}) \sin(\varphi_b - \Psi_{RP}) \rangle = \langle \cos(\varphi_a + \varphi_b - 2\Psi_{RP}) \rangle = v_1^2 \]

... and when it is not exactly known:

\[ \langle \cos(\varphi_a - \Psi_{EP}) \cos(\varphi_b - \Psi_{EP}) \rangle - \langle \sin(\varphi_a - \Psi_{EP}) \sin(\varphi_b - \Psi_{EP}) \rangle = \]
\[ = \langle \cos(\varphi_a + \varphi_b - 2\Psi_{EP}) \rangle = v_1^2 \langle \cos(2\Psi_{EP} - 2\Psi_{RP}) \rangle \]

\[ \langle \cos(\varphi_a - \varphi_c) \cos(\varphi_b - \varphi_c) \rangle - \langle \sin(\varphi_a - \varphi_c) \sin(\varphi_b - \varphi_c) \rangle = v_1^2 v_{2,c} \]
\[ = \langle \cos(\varphi_a + \varphi_b - 2\varphi_c) \rangle \]

3-particle correlation:

Borghini, Dinh, Ollitrault PRC 66(2002)014905

Main non-flow contribution left is due to resonance/jets that flow themselves

Similar for \( v_4 \) via \( \langle \cos(4\varphi - 4\Psi_2) \rangle \)
Constituent quark model + coalescence

Coalescence
Low $p_t$ quarks

Fragmentation
High $p_t$ quarks

Coalescence in the intermediate region (rare products):

$$\frac{d^3n_M}{d^3p_M} \propto \left(\frac{d^3n_q}{d^3p_q} \left(p_q \approx p_M / 2\right)\right)^2$$

**Side-notes:**

a) more particles produced via coalescence vs parton fragmentation $\Rightarrow$ larger mean $p_t$...

b) $\Rightarrow$ higher baryon/meson ratio
The effect is too small to see in a single event

- The sign of $Q$ varies and $a^\wedge = 0$ (we consider only the leading, first harmonic) \(\Rightarrow\) one has to measure correlations, $a_\alpha a_\beta \wedge \ P$-even quantity (!)

- $a_\alpha a_\beta \wedge$ is expected to be $\approx 10^{-4}$

- $a_\alpha a_\beta \wedge$ can not be measured as $\sin \phi_\alpha \sin \phi_\beta \wedge$ due to large contribution from effects not related to the orientation of the reaction plane

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

$B^{in} \approx B^{out}$, $v_1 = 0$
Observable

\[
\frac{dN_{\alpha}}{d\phi} \propto 1 + 2v_{1,\alpha}\cos(\Delta \phi) + 2v_{2,\alpha}\cos(2\Delta \phi) + \ldots
\]

\[
+ 2a_{1,\alpha}\sin(\Delta \phi) + 2a_{2,\alpha}\sin(2\Delta \phi) + \ldots,
\]

\[\Delta \phi = (\phi - \Psi_{RP})\]

- The effect is too small to see in a single event
- The sign of \(Q\) varies and \(a_\wedge = 0\) (we consider only the leading, first harmonic) \(\Rightarrow\) one has to measure correlations, \(a_\alpha a_\beta \wedge\) \(P\)-even quantity (!)
- \(a_\alpha a_\beta \wedge\) is expected to be \(\sim 10^{-4}\)
- \(a_\alpha a_\beta \wedge\) can not be measured as \(\sin \phi_\alpha \sin \phi_\beta \wedge\) due to large contribution from effects not related to the orientation of the reaction plane
  - the difference in corr’s in- and out-of-plane

A practical approach: three particle correlations

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

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

\[
= \left( v_{1,\alpha}v_{1,\beta} + B^{in} \right) - \left( a_\alpha a_\beta + B^{out} \right).
\]

\(B^{in} \approx B^{out}, \quad v_1 = 0\)

Saturday, June 12, 2010
Charge separation: expectations/predictions

- Same charge particles are preferentially emitted in the same direction, along or opposite to the system orbital momentum and magnetic field.
- Unlike-sign particles are emitted in the opposite directions.
- “Quenching” in a dense medium can lead to suppression of unlike-sign (“back-to-back”) correlations.
- The effect has a “typical” $\Delta \eta$ width of order $\sim 1$.
- The magnitude of asymmetry $\sim 10^{-2}$ for midcentral collisions $\Rightarrow 10^{-4}$ for correlations.
- Effect is likely to be most pronounced at $p_t \leq \sim 1$ GeV/c, though radial flow can move it to higher $p_t$.
- Asymmetry is proportional to the strength of magnetic field.
- “Signature” of deconfinement and chiral symmetry restoration.

Kharzeev, Zhitnitsky, NPA 797 67 (2007)
Fukushima, Kharzeev, Waringa, PRD 78, 074033
This analysis used the data taken during RHIC Run IV and based on (after all quality cuts)

\begin{itemize}
  \item Au+Au 200 GeV $\sim$ 10.6 M Minimum Bias events
  \item Au+Au 62 GeV $\sim$ 7 M Minimum Bias events
  \item Cu+Cu 200 GeV $\sim$ 30 M Minimum Bias events
  \item Cu+Cu 62 GeV $\sim$ 19 M Minimum Bias events
\end{itemize}

Tracks used:
\begin{itemize}
  \item $|\eta| < 1.0$ (Main TPC)
  \item -3.9 < $\eta$ < -2.9 (FTPC East)
  \item 2.9 < $\eta$ < 3.9 (FTPC West)
  \item 0.15 < $p_T$ < 2.0 GeV/c (unless specified otherwise)
\end{itemize}

ZDC-SMD (spectator neutrons) is used for the first order reaction plane determination

Results presented/discussed in this talk are for charged particles in the main TPC region ($|\eta| < 1.0$)
Backgrounds

I. Physics (RP dependent). Can not be suppressed

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

- “Flowing clusters”/RP dependent fragmentation
  \[
  \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle = \\
  = A_{clust} \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{clust}) \rangle_{clust} v_{2,clust}
  \]
- Global polarization, \( v_1 \) fluctuations, ...

II. RP independent. (depends on method and in general can be greatly reduced)

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

(\(+,\+) and (-,-) results are combined as “same charge”
HIJING+v2 = added “afterburner” to generate flow
MEVSIM: flow as in experiment, number of resonances maximum what is consistent with experiment

Event generators: the signal is not zero, but different from expectations (e.g. same charge ~ opp. charge)
Backgrounds

I. Physics (RP dependent).
   Can not be suppressed

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\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 \\
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= A_{\text{clus}} \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{\text{clus}}) \rangle_{\text{clus}} v_2,\text{clus}
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\]

- "Flowing clusters"/RP dependent fragmentation

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\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle = \\
= A_{clust} \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{clust}) \rangle_{clust} v_{2,clust}.
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- Global polarization, \( v_1 \) fluctuations, …

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\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle v_{2,c}.
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\( \text{HIJING + } v_2 \) = added "afterburner" to generate flow

\( \text{MEVSIM} \): flow as in experiment, number of resonances maximum what is consistent with experiment

Event generators: the signal is not zero, but different from expectations (e.g. same charge ~ opp. charge)
Data vs models

- Large difference in \textit{like-sign} vs \textit{unlike-sign} correlations in the data compared to models.

- Bigger amplitude in \textit{like-sign} correlations compared to \textit{unlike-sign}.

- \textit{Like-sign} and \textit{unlike-sign} correlations are consistent with theoretical expectations.

- … but the \textit{unlike-sign} correlations can be dominated by effects not related to the RP orientation.

- The “base line” can be shifted from zero.

\[ \langle +,+ \rangle \text{ and } \langle -,- \rangle \text{ results agree within errors and are combined in this plot and all plots below.} \]
Data vs models

- Large difference in like-sign vs unlike-sign correlations in the data compared to models.
- Bigger amplitude in like-sign correlations compared to unlike-sign.
- Like-sign and unlike-sign correlations are consistent with theoretical expectations
- … but the unlike-sign correlations can be dominated by effects not related to the RP orientation.
- The “base line” can be shifted from zero.

\[ \left< +,+ \right> \text{ and } \left< -,-- \right> \text{ results agree within errors and are combined in this plot and all plots below.} \]
Data vs models

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- Like-sign and unlike-sign correlations are consistent with theoretical expectations.
- ... but the unlike-sign correlations can be dominated by effects not related to the RP orientation.
- The “base line” can be shifted from zero.

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

\[ Au+Au \, 200 \, GeV \]

\[ \ast \, \text{STAR} \]

\[ \diamond \, \text{HIJING} \]

\[ \triangle \, \text{HIJING} + v_2 \]

\[ \bigcirc \, \text{UrQMD} \]

\[ \square \, \text{MEVSIM} \]

First – let us understand uncertainties and then move to more “differential” results.

\[ \langle +,+ \rangle \text{ and } \langle -,- \rangle \text{ results agree within errors} \]

and are combined in this plot and all plots below.
Testing the technique. (RP from TPC and FTPC)

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

\[ |\eta| < 1.0 \]
\[ 2.9 < |\eta| < 3.9 \]

Center points: obtained using \( v_2 \{\text{FTPC} \} \)
bands: lower limits - using \( v_2 \{2\} \), upper – \( v_2 \{4\} \);
where \( v_2 \{4\} \) is not available it is assumed that using \( v_2 \{\text{FTPC} \} \) suppresses non-flow by 50%.

Using ZDC-SMD for the (first harmonic) event plane yields similar agreement, though with larger uncertainties (Run VII – next slide).
Testing the technique. (RP from ZDC-SMD)

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

| \(| \eta | < 1.0 \) (Main TPC)
| \(2.9 < \|\eta\| < 3.9 \) (FTPC)

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

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

---

Testing:

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

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

G. Wang (STAR), talk at 2010 April APS Meeting

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STAR AuAu 200 GeV
- same charge, TPC
- opp charge, TPC
- same charge, FTPC
- opp charge, FTPC

STAR Preliminary, Run VII
- same charge, ZDC
- opp charge, ZDC

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G. Wang (STAR), talk at 2010 April APS Meeting
Uncertainties at small multiplicities
(RP independent background)

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

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

Thick lines: uncertainties due to 3-particle correlations not related to the reaction plane orientation for the case of particle \( c \) taken from TPC region (from HIJING; UrQMD gives about factor of 2 smaller values).

Note: such uncertainty in principle can be decreased, e.g. if use particle \( c \) separated from \((\alpha, \beta)\) by a rapidity gap.

- Uncertainty is smaller for the same charge signal than for opposite charge.

- Even smaller (consistent with zero) for triplets with all particles of the same charge (not shown).
The results are independent of the charge of “c” particle. (Note results for 3 particles all of the same charge)
PHENIX (from talk of R. Lacey)

Allows studies with different $\Psi_{Rxn}$

Charged Particle Tracks
$|\eta| < 0.35$, $\pi/2 \times 2$ arms
Central Arm Spectrometer (DC, PCs)

Mid Reaction Plane
$1.0 < |\eta| < 2.8$, $0 < \varphi < 2\pi$
Reaction Plane Detector (RXN)

Forward Reaction Plane
$3.0 < |\eta| < 3.8$, $0 < \varphi < 2\pi$
Beam Beam Counter (BBC)
Muon Piston Calorimeter (MPC)
Two-particle correlation Results

**Left Panel:**
- **PHENIX preliminary**
- Au+Au 200GeV
- $\Phi_{\text{RXN}}$ ($\eta = 1.0 \sim 2.8$)
- $p_T1, p_T2 = 0.5 \sim 4.5$ (GeV/c)

**Right Panel:**
- **PHENIX preliminary**
- Au+Au 200GeV
- $\Phi_{\text{BBC+MPC}}$ ($\eta = 3.0 \sim 3.9$)
- $p_T1, p_T2 = 0.5 \sim 4.5$ (GeV/c)

Graphs show:
- $(+,−)$ pair
- $(+,+)$ pair
- $(-,−)$ pair

**Signal is sensitive to collision centrality**

Roy A. Lacey, Stony Brook University;
P- and CP-odd Workshop, BNL USA, April 26-30th, 2010
PHENIX/STAR comparison

Two-particle correlation Results

Relatively good agreement between PHENIX & STAR
Au+Au and Cu+Cu @ 200 GeV

The signal in Cu+Cu is stronger, qualitatively in agreement with “theory”, but keep in mind large uncertainties due to correlations not related to RP.
Au+Au and Cu+Cu @ 200 GeV

Opposite charge correlations scale with $N_{\text{part}}$, (suppression of the back-to-back correlations ?)

Same charge signal is suggestive of correlations with the reaction plane

Opposite charge corr’s are somewhat stronger in CuCu compared to AuAu at the same $N_{\text{part}}$
The signal is multiplied by $N_{\text{part}}$ to remove “trivial” dilution due to multiplicity increase in more central collisions.

**Opposite charge correlations** scale with $N_{\text{part}}$, (suppression of the back-to-back correlations ?)

**Same charge** signal is suggestive of correlations with the reaction plane

**Opposite charge corr’s** are somewhat stronger in CuCu compared to AuAu at the same $N_{\text{part}}$
Typical “hadronic” width, consistent with “theory”.

Not color flux tubes?

Correlations at large $\Delta \eta$ (and large $\Delta pt$, see next slide) -- it is not HBT or Coulomb.
Transverse momentum dependences (AuAu200).

Signal persists to too high $p_t$?
The transverse momentum dependence of the signal shown in the previous slide is fully consistent with a picture in which particles from a LPV cluster decay have $p_t$ distribution only slightly “harder” than the bulk.

\[
\langle \cos(\phi_\alpha + \phi_\beta) \rangle = \frac{N_{\text{corr}}}{N_{\text{all}}}
\]
Two-particle correlations

Little comments…
Where are they coming from?
How large is the contribution to them, from the same LPV physics?

Requires differential analysis.
Little comments…
Where are they coming from?
How large is the contribution to them, from the same LPV physics?
Requirements differential analysis.

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

\[ \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle = \langle c_1 c_2 - s_1 s_2 \rangle \]

\[ \langle \cos(\phi_\alpha - \phi_\beta) \rangle = \langle c_1 c_2 + s_1 s_2 \rangle \]
Two “remarkable” cancellations:
-- $\langle \cos(\varphi_1 + \varphi_2) \rangle$, opposite sign, very close to zero
-- $\langle \cos(\varphi_1 + \varphi_2) \rangle$, same sign, very close to $\langle \cos(\varphi_1 - \varphi_2) \rangle$

Consider correlations of the type
$\sim [a + 2b \cos(\varphi_1 - \varphi_2)]$

It leads to $\langle \cos(\varphi_1 - \varphi_2) \rangle \approx b$
and $\langle \cos(\varphi_1 + \varphi_2) \rangle = 2b v_2$
Summary of STAR/PHENIX results

- Measured correlations agree with the magnitude and gross features of the theoretical predictions for Chiral Magnetic Effect.

- Observables are P-even and might be sensitive to non-parity-violating effects.

- The observed signal cannot be described by the background models studied (HIJING, HIJING+v2, UrQMD, MEVSIM), which span a broad range of hadronic physics.
Future program

Dedicated experimental and theoretical program focused on the local parity violation, and more generally on non-perturbative QCD: structure of the vacuum, hadronization, etc.

Experiment:

- **U+U central body-body collisions**
- **Beam energy scan / Critical point search**
- **Isobaric beams**
- **High statistics PID studies / properties of the clusters**

Such collisions (“easy” to trigger on) will have low magnetic field and large elliptic flow – clean test of the $\text{LPV}$ effect.

Look for a critical behavior, as $\text{LPV}$ predicted to depend strongly on deconfinement and chiral symmetry restoration.

Colliding isobaric nuclei (the same mass number and different charge) and by that controlling the magnetic field

$^{96}_{44}\text{Ru} + ^{96}_{40}\text{Zr}$

Note that such studies will be also very valuable for understanding the initial conditions, baryon stopping, origin of the directed flow, etc.

in particular with neutral particles; see also next slides
Future program. Needs for theory.

Theory:

- Confirmation and detail study of the effect in Lattice QCD

Theoretical guidance and detailed calculations are needed:
- Dependence on collision energy, centrality, system size, magnetic field, PID, etc.
- Understanding physics background!
- Size/effective mass of the clusters, quark composition (e.g. equal number of q-qbar pairs of different flavors?).

Nonperturbative Phenomena and Phases of QCD
Edward V. Shuryak

\[ M_{sph} \approx \frac{30}{g^2(\rho)^2} \sim 2.5 \text{ GeV} \]
Central U+U collisions

All (“physics”) background effects scale with elliptic flow.

Correlations due to chiral magnetic effect scale with (square of ) the magnetic field.

FIG. 1: Schematic view of central U+U collisions: (a) tip-tip and (b) body-body.

In both cases the magnetic field is small, but elliptic flow is large in body-body.
Model

Nuclear parameters:

\[ \rho_w(x, y, z) = \frac{\rho_0}{1 + e^{(r-R_o(1+\beta_2y+\beta_4y^2))/a}}, \]

with deformation parameters \( \beta_2 = -0.13, \beta_4 = -0.03 \) taken from Ref. [9] for \(^{197}\text{Au} \) \( (R = 6.38 \text{ fm}, a = 0.53) \). For \( \text{U + U} \) collisions we have used \( \beta_2 = 0.28 \) in agreement with Ref. [21], and \( \beta_4 = 0.093 \) was implemented according to Ref. [9]. The deformation parameter \( \beta_4 \) for the \(^{238}\text{U} \) nucleus \( (R = 6.81, a = 0.54) \) should be taken into account in \( \text{U + U} \) simulations.

Magnetic field:

\[ eB(t, r) = \alpha_{EM} \sum_n e_n \frac{(1 - v_n^2)}{(R_n - R_n v_n)^3} v_n \times R_n, \]

Sum runs over all spectators, Calculated for \( t=0 \).

Elliptic flow:

\[ \varepsilon = \{ \varepsilon_x, \varepsilon_y \} = \left\{ \frac{\sigma_y^2 - \sigma_x^2}{\sigma_x^2 + \sigma_y^2} \text{ part}, \frac{2\sigma_{xy}}{\sigma_x^2 + \sigma_y^2} \text{ part} \right\} \]

\[ v_2 = \kappa \varepsilon_p \]

\[ \kappa = 0.2 \]
The condition $N_{sp} < 20$ selects about 1.5% of the most central events in U+U collisions and about 2.3% in Au+Au collisions.

How to select events with large $v_2$?

$$q = \frac{Q_2}{\sqrt{M}}$$

$$Q_{2,x} = \sum_{i=1}^{M} \cos(2\phi_i), \quad Q_{2,y} = \sum_{i=1}^{M} \sin(2\phi_i),$$
How to select events with large $v_2$?

The condition $N_\text{sp} < 20$ selects about 1.3% of the most central events in U+U collisions and about 2.3% in Au+Au collisions.

$q = Q_2 \sqrt{N_{ch}} \Rightarrow \frac{Q_2 x}{M} = \sum \cos(2\phi_i), \frac{Q_2 y}{M} = \sum \sin(2\phi_i)$.
Selecting on multiplicity

Note the possibility to perform test “working” on fluctuations in Au+Au collisions.
While different models make different assumptions on the cluster production mechanism (multi-peripheral, thermodynamical, uncorrelated models [41]) they generally agree on a set of simplifying assumptions which can be made without altering the essential features of the models:

i) absence of correlations among clusters,

ii) isotropic decay of clusters in their rest frames, and

iii) energy independence of the decay parameters.

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Nonperturbative Phenomena and Phases of QCD

Edward V. Shuryak

Fig. 13. (a) A typical inelastic perturbative process: two t-channel gluons collide, producing a pair of gluons; (b) Instanton-induced inelastic process incorporate collisions of multiple t-channel gluons with the instanton (the shaded circle), resulting in multi-gluon production. The intermediate stage of the process, indicated by the horizontal dashed lines, corresponds to a time when outgoing glue is in the form of coherent field configuration - the sphaleron. Since this part of the process corresponds to motion above the barrier, it does not enter the calculation of the cross section, but is only needed for prediction of the inclusive spectra, multiplicities etc.
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Pomeron out of instantons?

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QCD instantons and the soft pomeron
Dmitri Kharzeev $^{a,b}$, Yuri V. Kovchegov $^{a,c,*}$, Eugene Levin $^{a,c}$

Fig. 2. Space–time picture of soft pomeron.
We have to identify other features of the “topological bubbles”, and extend experimental search, e.g. instanton “bubble” decay isotropically, it should lead to equal number of q-qbar pairs of all flavors. We can check this.
pp2pp  Phase II

Look for: Mass distribution, multiplicities, quark flavor content of the clusters (PID correlations, KKπ vs πππ, etc.), angular distributions, unusual behavior in HBT parameters (production by coherent field)
Conclusions

- The physics of the local strong parity violation is not an exotics but an integral part of QCD: quark interactions with topologically non-trivial gluonic configurations - instantons, sphalerons, etc., the same physics as that of the chiral symmetry breaking.

- Observable effects are within reach of the experiment!

- In non-central nuclear collisions it leads to the charge separation along the system’s orbital momentum/magnetic field.

- STAR and PHENIX detect a signal that is in agreement with (mostly qualitative) theoretical predictions.

- A dedicated program aimed on a direct experimental study of non-perturbative QCD effects is developing: U+U collisions, beam energy scan, identified particle correlations, isobaric beams…