STAR probes of local strong parity violation in heavy ion collisions

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Indiana University

Joint CATHIE/RIKEN workshop

BNL, 14-18 December, 2009

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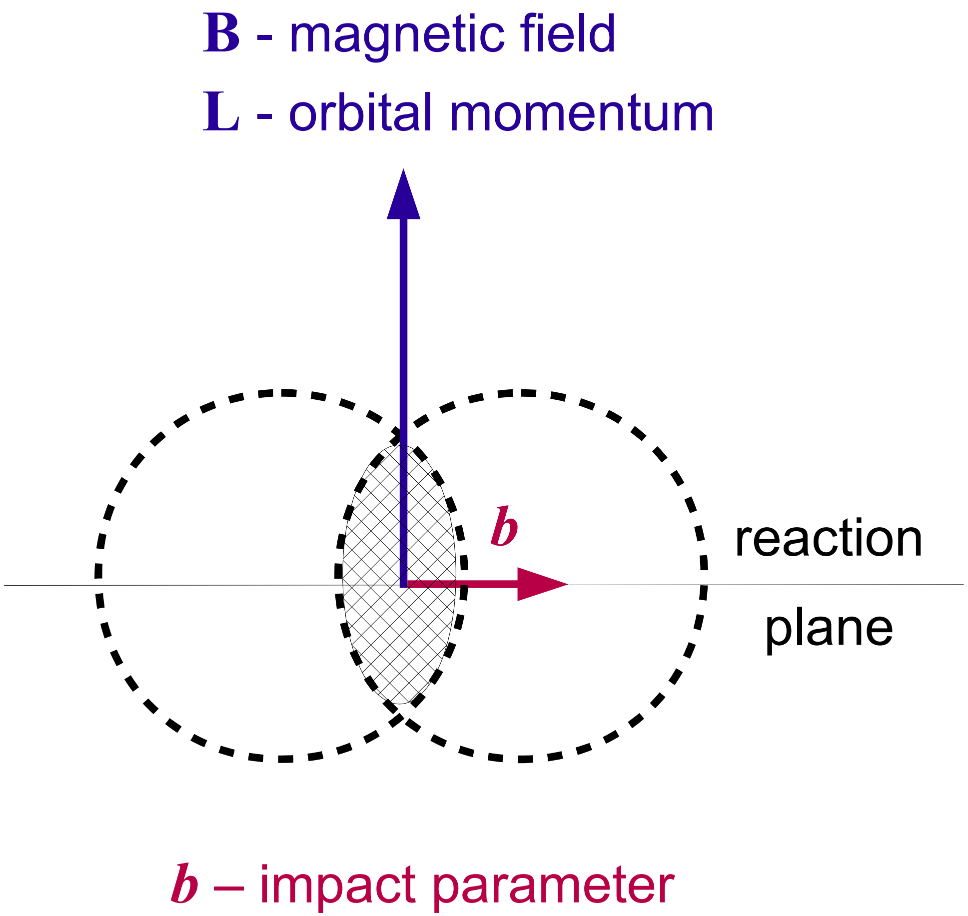
STAR

Important features of the system created in non-central heavy ion collisions (HIC)



Colliding nuclei are moving out-of-plane

- Overlapped area: non-uniform particle density and pressure gradient
- Large orbital angular momentum:

$$\mathbf{L} \sim 10^5$$

Liang, Wang, PRL94:102301 (2005)
Liang, JPG34:323 (2007)

- Strong magnetic field:

$$\mathbf{B} \sim 10^{15}\,\mathrm{T} \quad (e\mathbf{B} \sim 10^4\,\mathrm{MeV}^2)$$

$$(\mu_N \mathbf{B} \sim 100\,\mathrm{MeV})$$

Rafelski, Müller PRL36:517 (1976)
Kharzeev, PLB633:260 (2006)
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

Strong elliptic and directed flow.
Well established collective effects,
extensively studied at RHIC/SPS.

Review: arXiv:0809.2949 [nucl-ex]

Global polarization and spin alignment

Preferential orientation of
the spin of produced particles
wrt. the system orbital momentum

Experimentally consistent with zero.
Measured by STAR for strange hyperons
($\Lambda, \bar{\Lambda}$) and vector mesons (K^{*0}, ϕ).

PRC76:024915 (2007), PRC77:061902 (2008)

Local strong parity violation

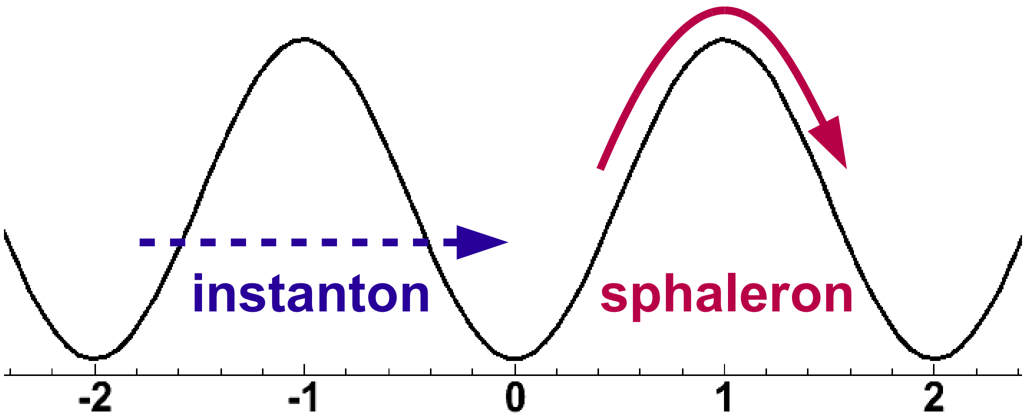
Charge separation along the
magnetic field/orbital momentum

Under experimental study at RHIC.
Focus of this talk.

Theoretical concept of P-violation in strong interactions

Chiral symmetry breaking and P-violation

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



N_{CS} (generalized coordinate)

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)
Baker *et al.*, PRL97:131801 (2006)

$$\theta < 10^{-11}$$

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

but:

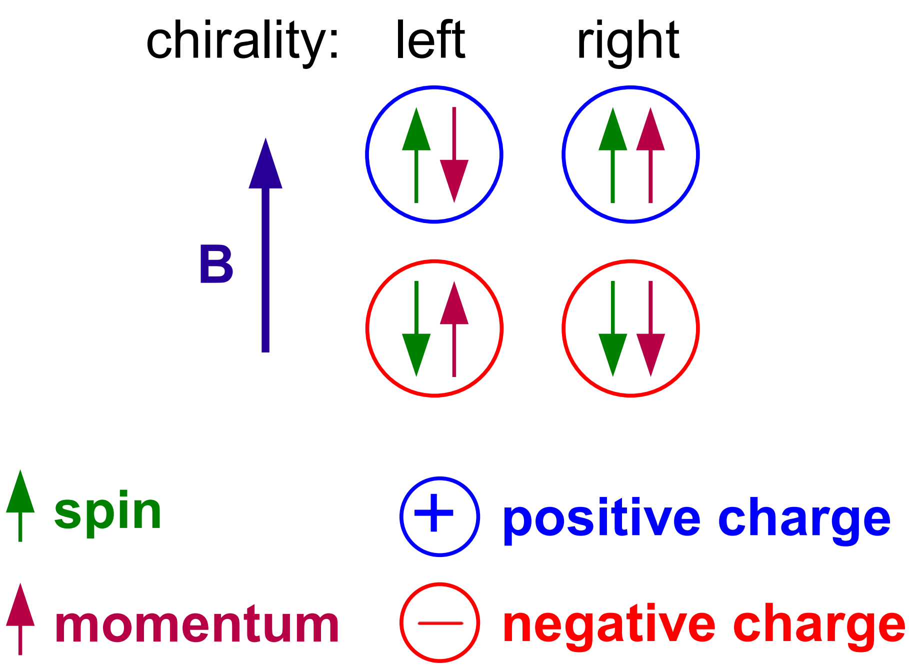
In HIC formation of (local) metastable P-odd domains is not forbidden.

T.D. Lee, PRD8:1226 (1973)
Morley, Schmidt, Z.Phys.C26:627 (1985)
Kharzeev, Pisarski, Tytgat, PRL81:512 (1998)
Kharzeev, Pisarski, PRD61:111901 (2000)

Voloshin, PRC62:044901 (2000)
Kharzeev, Krasnitz, Venugopalan, PLB545:298 (2002)
Finch, Chikanian, Longacre, Sandweiss, Thomas, PRC65:014908(2002)

Charge separation in HIC

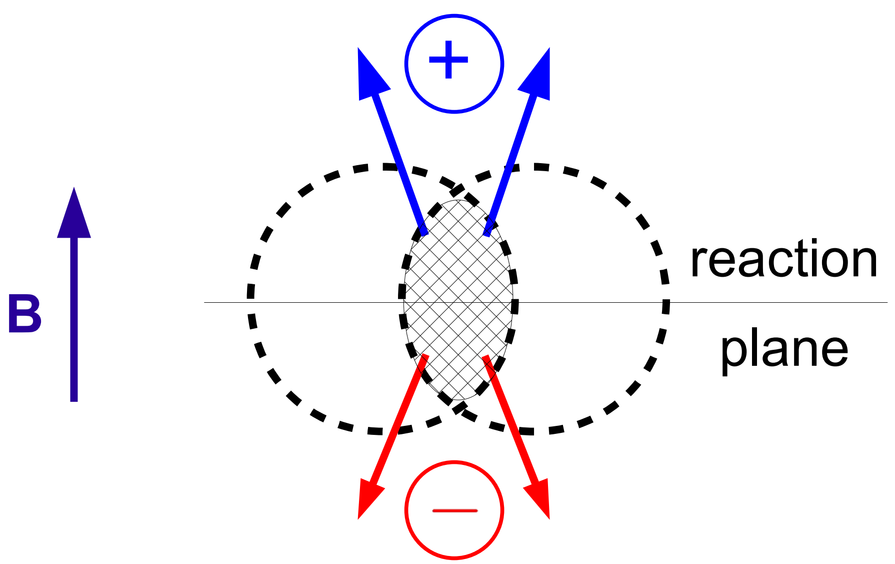
Magnetic field aligns quark spins along or opposite to its direction



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

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

$N_{left} \neq N_{right}$



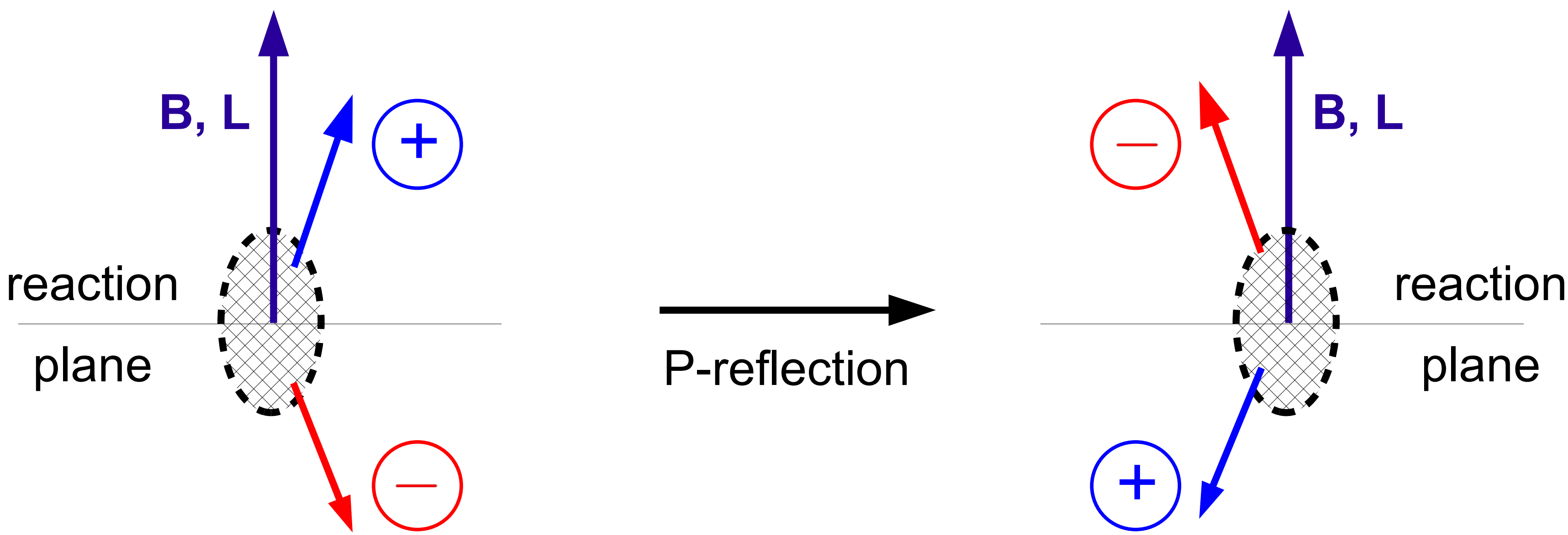
Induced electric field (parallel to B):

$$E \sim \theta \cdot B$$

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

Kharzeev, PLB633:260 (2006)
Kharzeev, Zhitnitsky, NPA797:67 (2007)
Kharzeev, McLerran, Warringa, NPA803:227 (2008)
Fukushima, Kharzeev, Waringa, PRD 78:074033 (2008)

Why charge asymmetry wrt. the reaction plane is P-violation?



Coordinate/momentum (vectors):

$$\vec{r} \to -\vec{r} \qquad \vec{p} \to -\vec{p}$$

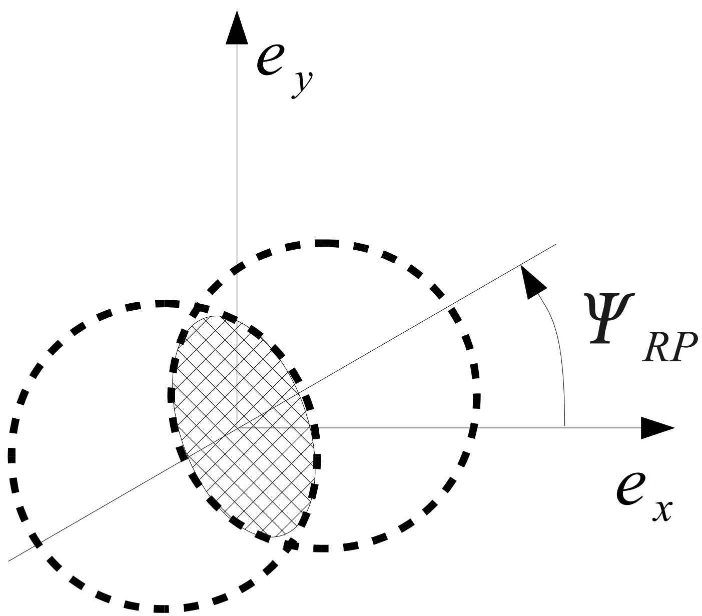
Orbital momentum/magnetic field (pseudo-vectors):

$$\vec{L} \to \vec{L} \qquad \vec{B} \to \vec{B}$$

Experimental observable

Azimuthal distribution in case of P-violation

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



Ψ_{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)

e_z beam direction (out of sheet)

$e_x e_y e_z$ laboratory frame axes

Predicted asymmetry is about 1% for mid-central collisions

→ within an experimental reach

Kharzeev, PLB633:260 (2006)

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: $<a_{\alpha} a_{\beta}>$ $(\alpha, \beta = \pm)$
  Measure the difference between **in-plane** and **out-of-plane** correlations:

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

Voloshin PRC70:057901 (2004)

$$= [\langle v_{1,\alpha} v_{1,\beta} \rangle + Bg^{(in)}] - [\langle a_{\alpha} a_{\beta} \rangle + Bg^{(out)}]$$

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

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

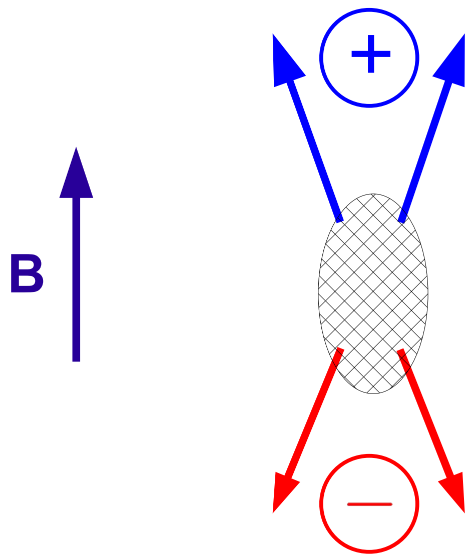
  $Bg^{(in)}$ $(Bg^{(out)})$ denotes in- (out-of) plane background correlations

- RP-dependent (P-even) backgrounds contribute:
  → $Bg^{(in)}$ - $Bg^{(out)}$ term
  → $<v_{1,\alpha} v_{1,\beta}>$: directed flow (zero in symmetric rapidity range) + flow fluctuations

Medium effects on charge correlations

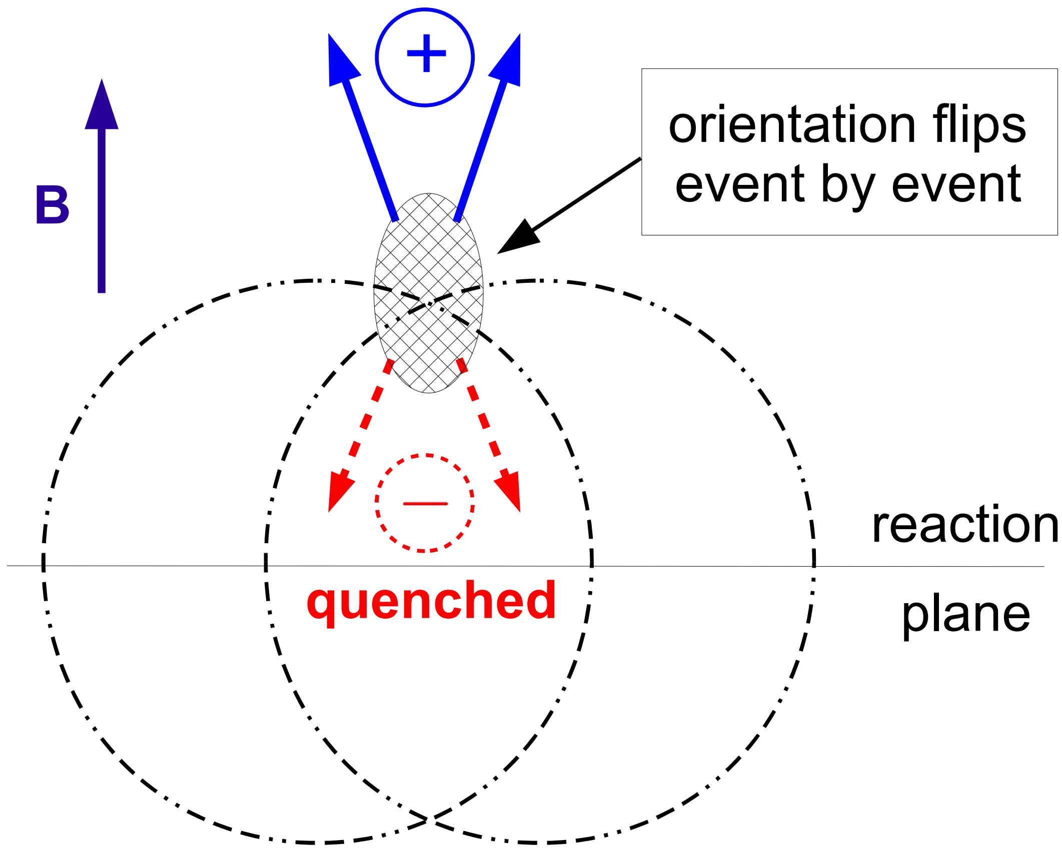
P-odd domain formation
(no medium)

$$a_{+} = -a_{-}$$



$$\langle a_{+}^{2} \rangle = \langle a_{-}^{2} \rangle > 0$$
$$\langle a_{+} a_{-} \rangle = -\langle a_{+}^{2} \rangle$$

Quenching in medium



$$\langle a_{+}^{2} \rangle = \langle a_{-}^{2} \rangle > 0$$
$$\langle a_{+} a_{-} \rangle \ll -\langle a_{+}^{2} \rangle$$

D. Kharzeev, PLB633:260 (2006)

Kharzeev, McLerran, Warringa, NPA803:227 (2008)

Expectations for charge correlations

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

  $Q = N_R - N_L$ - topological charge ($Q = \pm 1, \pm 2, ...$)

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

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

  $<a_{\alpha} a_{\beta}> \sim 10^{-4}$

- Correlation width in rapidity: about one unit
- Localized at $p_t < 1$ 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, PLB633:260 (2006)
Kharzeev, Zhitnitsky, NPA797:67 (2007)
Kharzeev, McLerran, Warringa, NPA803:227 (2008)
Fukushima, Kharzeev, Waringa, PRD78:074033 (2008)

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:

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

$v_{2,c}$ - elliptic flow of c-particle

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

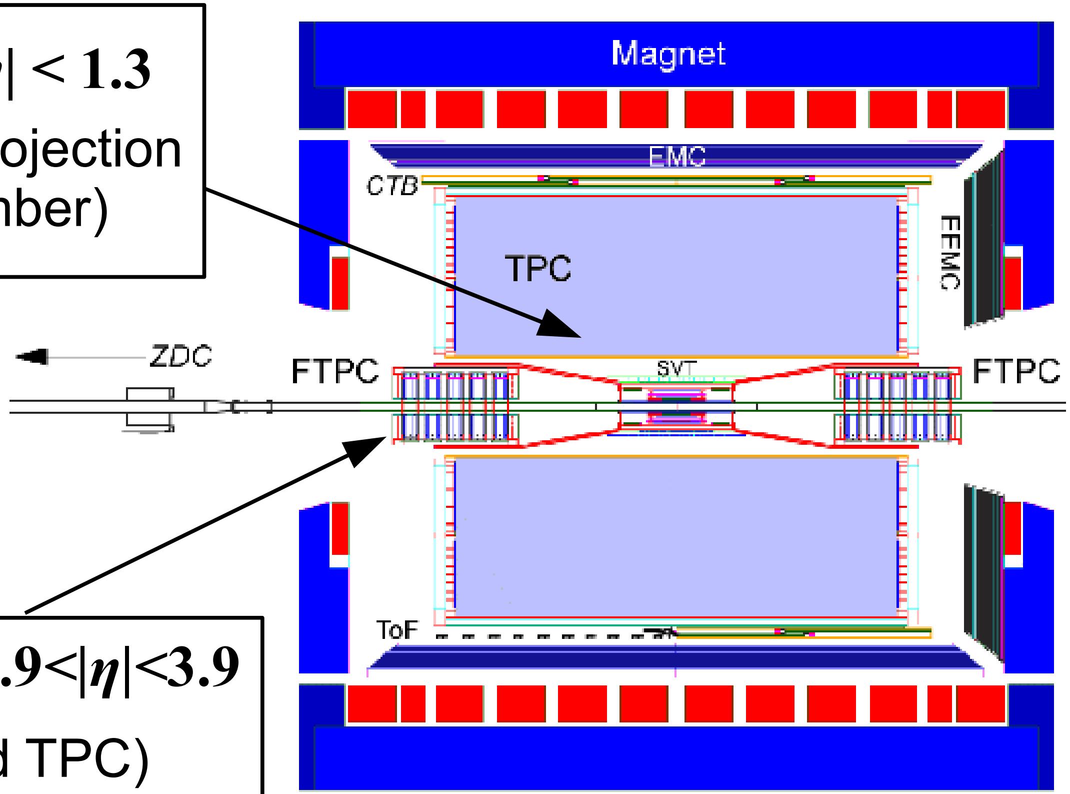
- Measuring (mixed harmonics) **3-particle azimuthal correlations:**

$$\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle = -\langle a_\alpha a_\beta \rangle v_{2,c} + \text{[non-parity correlations]}$$

STAR probes of P-violation

The STAR experiment

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



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

Charged particle cuts:

Pseudo-rapidity

$|\eta| < 1$

Transverse momentum

0.15 < p_t < 2 GeV/c

RP reconstruction with TPC, FTPCs and ZDC SMDs

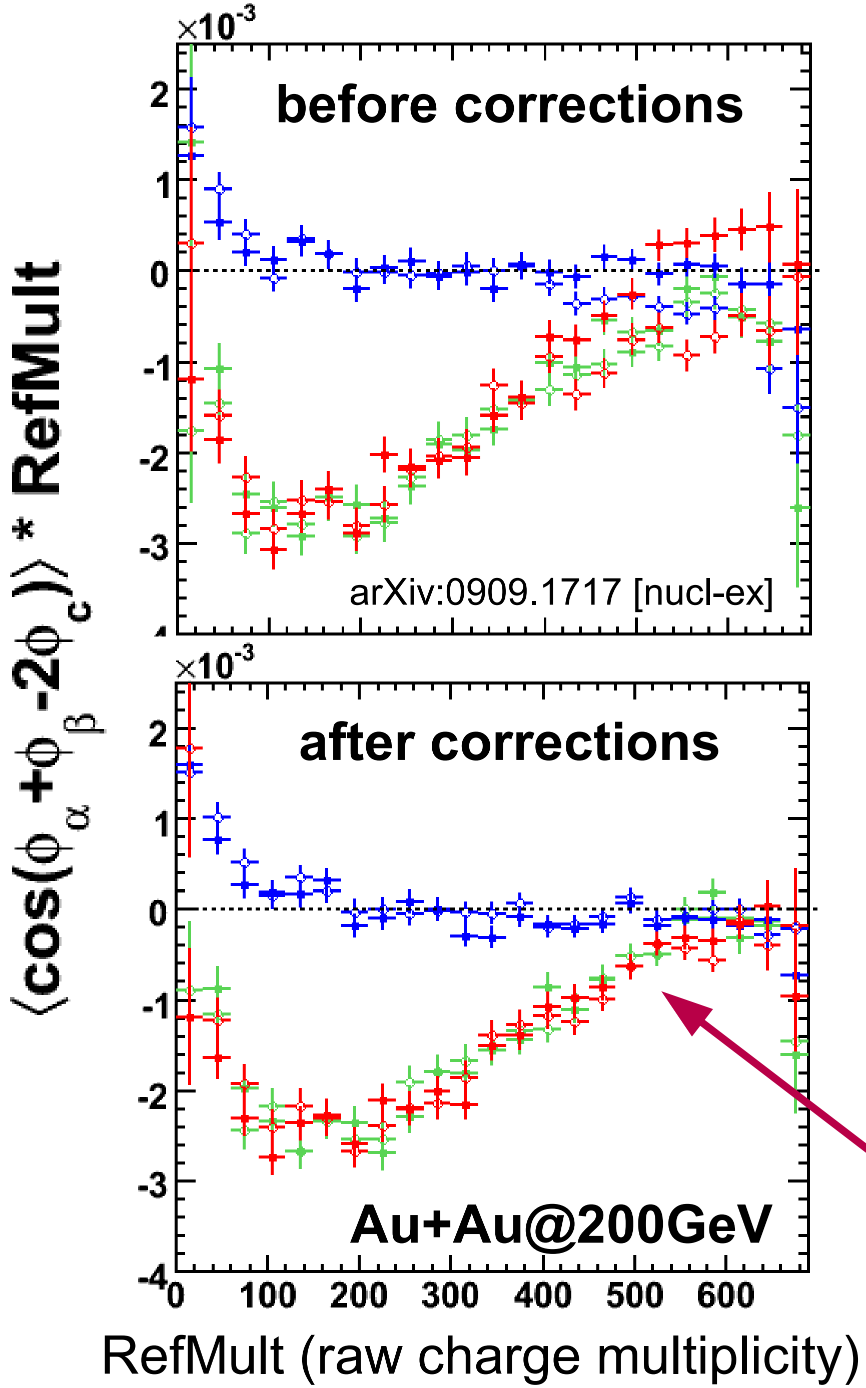
ZDC SMDs:
recoil neutrons at **beam rapidity**

(Zero Degree Calorimeter - Shower Maximum Detector)

Data from RHIC running in year 2004/2005

System	Energy, $\sqrt{s_{NN}}$	Events
Au+Au	200 / 62 GeV	10.6 / 7 M
Cu+Cu	200 / 62 GeV	30 / 19 M

Detector effects



Acceptance corrections (re-centering):

$$\sin n\phi \rightarrow \sin n\phi - \langle \sin n\phi \rangle$$

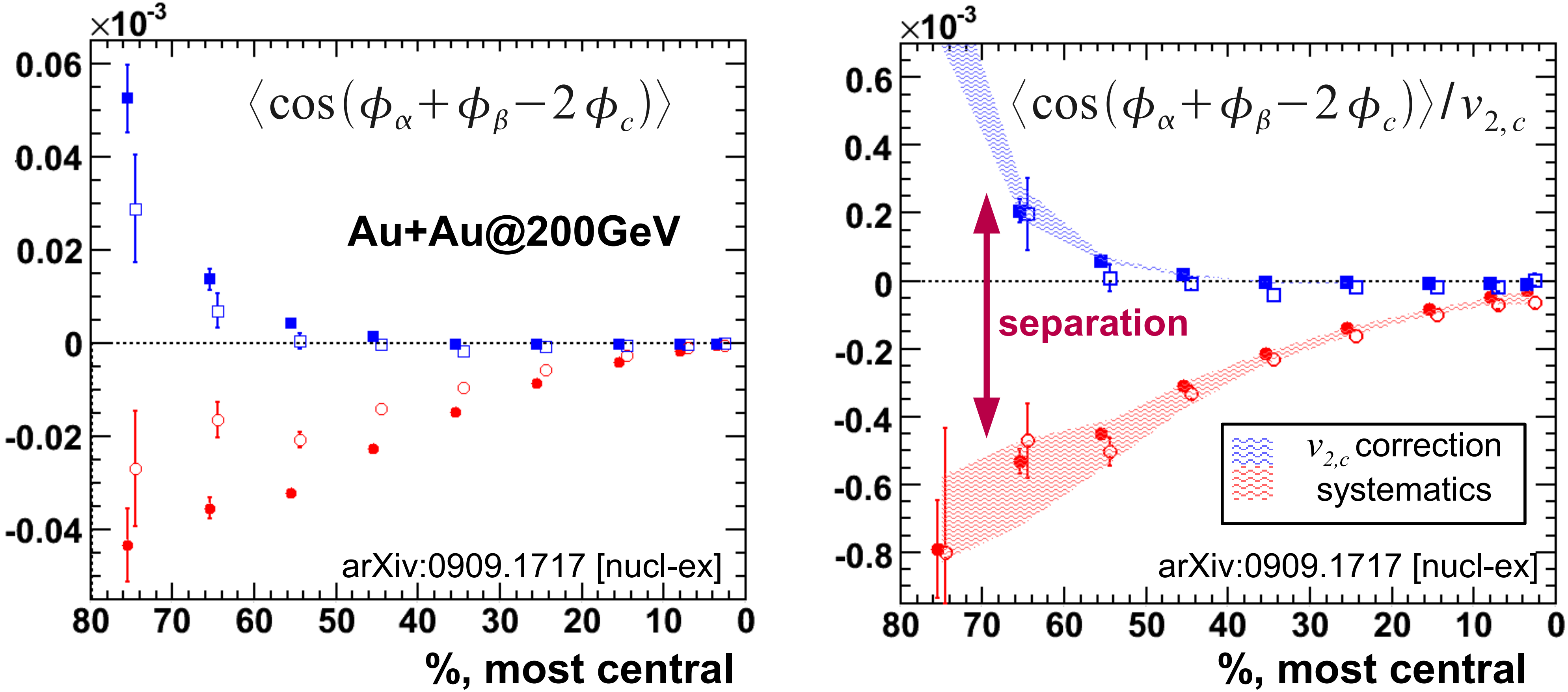
$$\cos n\phi \rightarrow \cos n\phi - \langle \cos n\phi \rangle$$

Poskanzer, Voloshin, PRC58:1671 (1998)
Borghini, Dinh, Ollitrault, PRC66:014905 (2002)
Selyuzhenkov, Voloshin, PRC77:034904 (2008)

symbol	(α, β) charges	c-particle
filled blue cross	opposite sign, + -	positive
filled red cross	same sign, ++	
filled green cross	same sign, - -	
open blue diamond	opposite sign, + -	negative
open red diamond	same sign, ++	
open green diamond	same sign, - -	

- 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



symbol	(α, β) charges	c-particle
red filled circle blue filled square	same sign opposite sign	|η|<1.0 (TPC)
red open circle blue open square	same sign opposite sign	2.9<|η|< 3.9 (FTPCs)

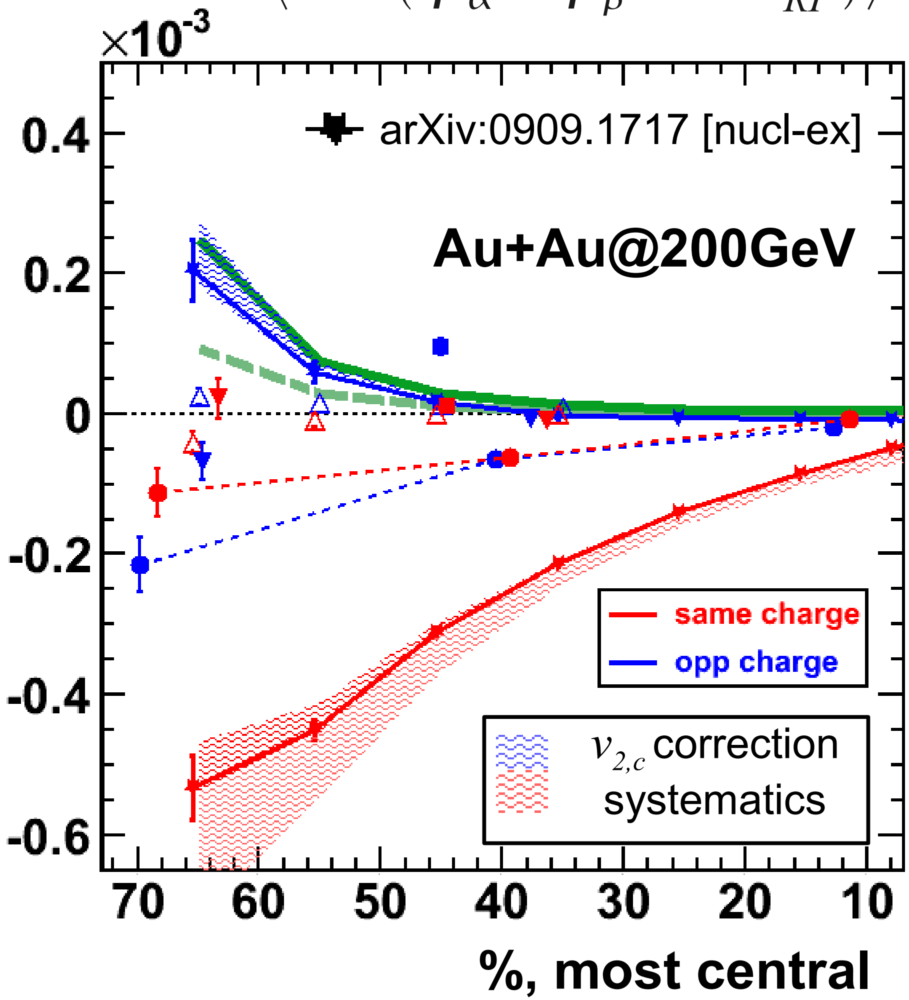
- $v_{2,c}$ correction gives consistent result with TPC/FTPC *c*-particle (similarly ZDC-SMD)

  → Probing 2-particle correlations wrt. RP

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

Modeling physics backgrounds

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



symbol	model	*c*-particle
▼ △ ● ■	**HIJING** **HIJING + v_2** **UrQMD** **MEVSIM**	true reaction plane
opposite (solid green line) same (dashed green line)	**HIJING 3-particle correlations**	$\lvert\eta\rvert<1.0$

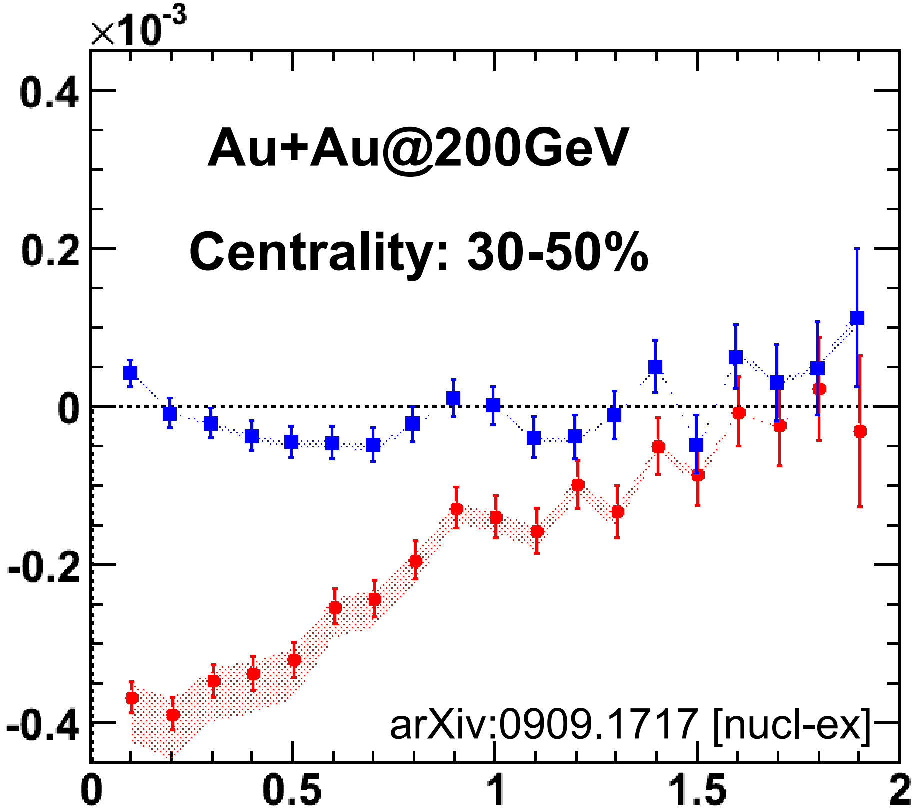
HIJING + v_2: added flow "afterburner"
MEVSIM: resonances with realistic flow

- Non-zero background correlations, but different from observed signal
- HIJING produce data-like opposite-sign 3-particle correlations:
  → opposite-sign signal can be diluted by effects not related to RP orientation

Note: cluster production is not well modeled by event generators

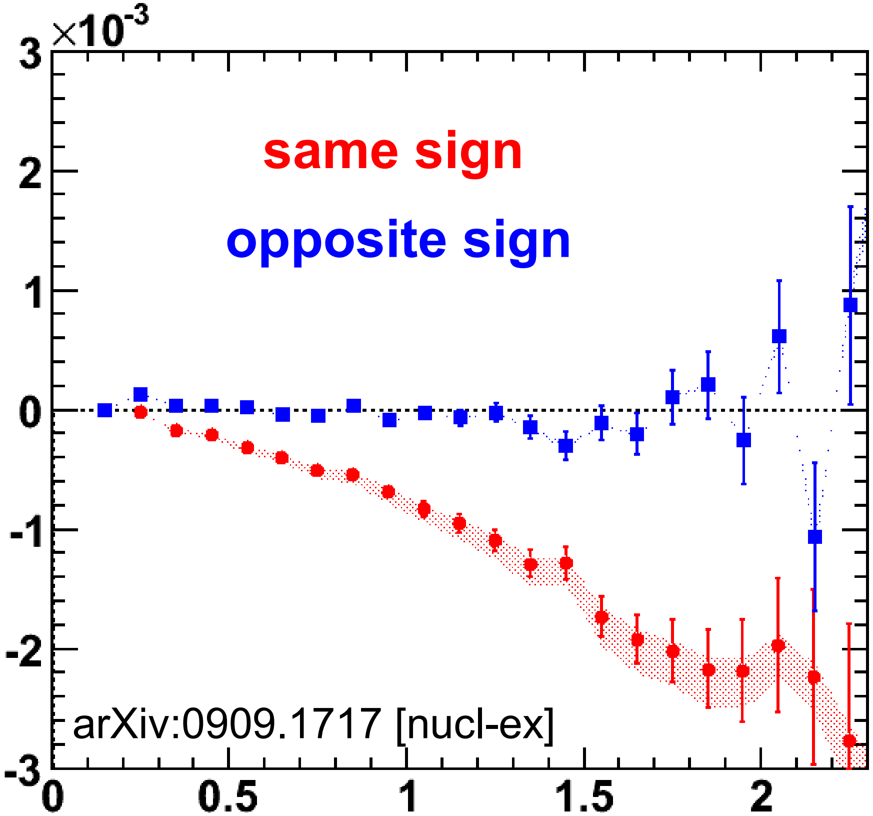
Pseudo-rapidity and transverse momentum dependence

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



$|\eta_\alpha - \eta_\beta|$

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

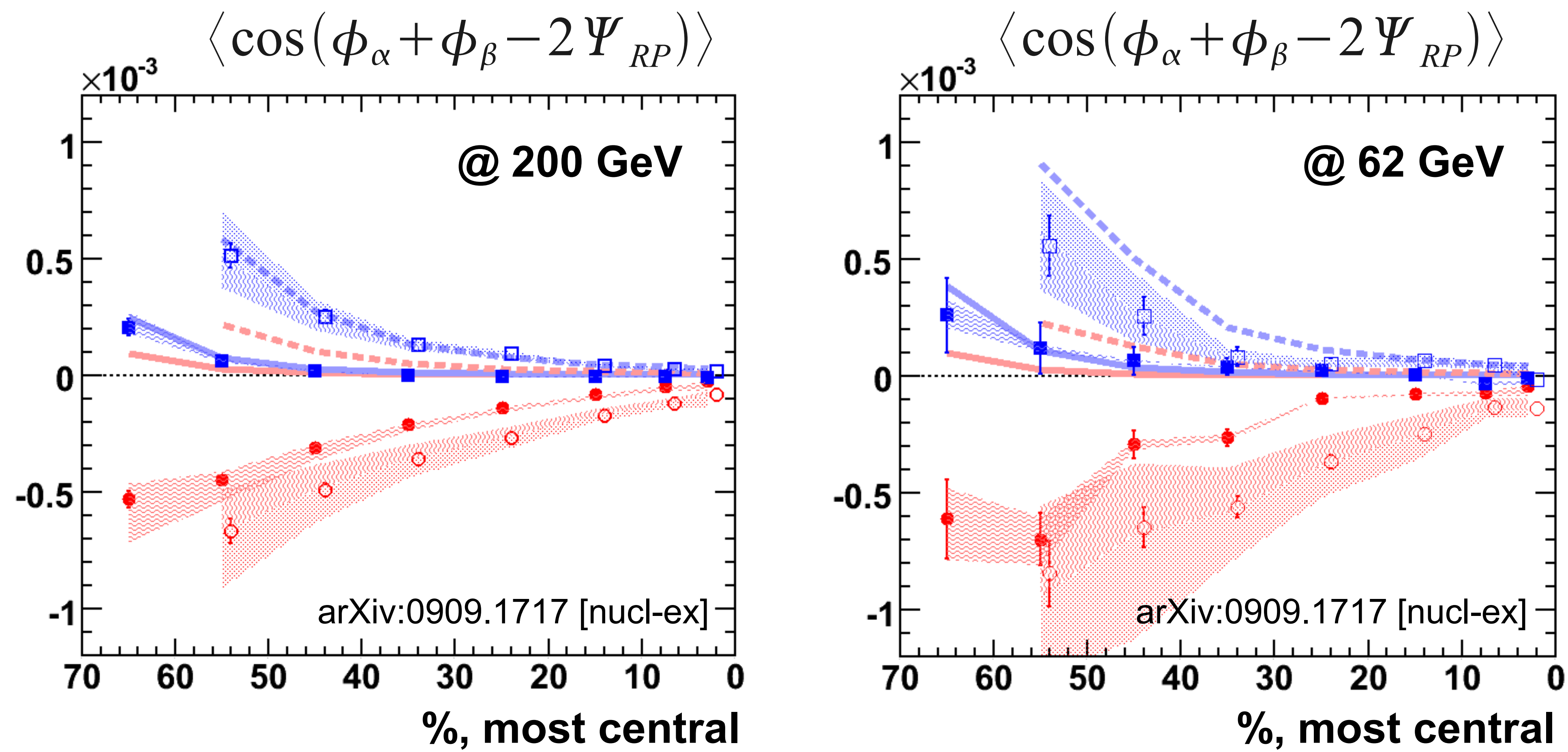


$[p_{t,\alpha} + p_{t,\beta}]/2$

Typical "hadronic" width.
Consistent with P-violation

The signal extends to
higher transverse momenta?

Energy and system size dependence



Au+Au	Cu+Cu	α and β charges
● ■	○ □	**same sign** **opposite sign**
		3-particle HIJING

$v_{2,c}$ correction systematics

Opposite sign correlations:

Stronger for a smaller (Cu+Cu) system.
In agreement with P-violation,
but large uncertainties due to possible
RP-independent correlations

Summary

- local P-odd domains predicted in nuclear collisions:
  → charge separation along the system's orbital momentum
- 3-particle azimuthal correlations are sensitive to local P-violation:
  → STAR measurements reveal non-zero signal

  Published 12/14/2009 in **PRL:** 103, 251601 (2009)
  Details submitted to **PRC:** 0909.1717 [nucl-ex]

- Observable is P-even:
  susceptible to contributions from P-conserving backgrounds
- So far could not explain the same sign correlations.
  Signal can not be described with existing background models.
- Qualitatively data agrees with predictions for local P-violation
  (though the signal persists to higher p_t than expected)

Detailed calculations for the
P-violating signal and backgrounds are needed

- P-violation and future RHIC program:
  Critical point search (beam energy scan),
  Identified particle correlations, isobaric beams.

“Physics” viewpoint by Berndt Müller

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Viewpoint

• Nuclear Physics • Particles and Fields

Physics 2, 104 (2009)
DOI: 10.1103/Physics.2.104

Looking for parity violation in heavy-ion collisions

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Published December 14, 2009

The STAR detector at RHIC has measured a signal that may indicate parity violation occurs in metastable regions of the superdense matter.

A Viewpoint on:
Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation
B. I. Abelev et al.
Phys. Rev. Lett. **103**, 251601 (2009) – Published December 14, 2009
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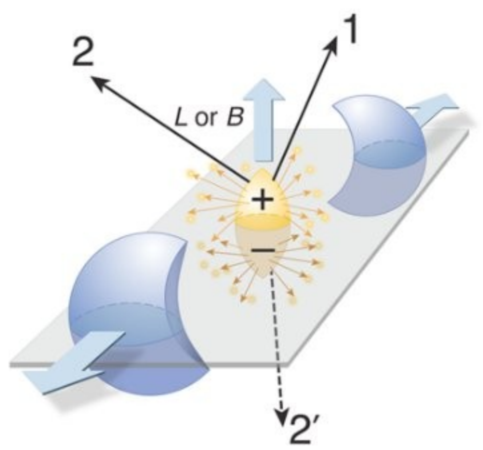

When two heavy nuclei collide at high energy, they create strongly interacting matter at energy densities far above that of normal nuclei. This has been the route for creating new phases of matter composed of quarks and gluons for almost a decade at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory in the US. The measurements performed on collisions between two gold (Au - Au) or two copper (Cu - Cu) nuclei or between two protons (p - p), with center-of-mass energies up to $200\ \mathrm{GeV}$ per nucleon pair, have shown that superdense, strongly interacting matter has an extraordinarily low shear viscosity (compared to its entropy) and is extremely opaque with respect to unbound quarks and gluons. [1, 2]

Now, writing in *Physical Review Letters*, the STAR collaboration, whose detector is based at RHIC, reports results that may constitute evidence for the violation of parity—a fundamental symmetry that says that the physics of a system and its mirror image should be the same—in local domains of hot, strongly interacting matter [3]. Although the theory of quantum chromodynamics (QCD), which governs the strong interactions, does permit parity violation, experiments have so far put stringent limits on its presence.

Collisions between heavy nuclei produce some of the strongest magnetic fields that can be generated under laboratory conditions [4]. The moving nuclei generate a coherent magnetic field that, being long-ranged, acts as an “external” field on the quarks and gluons that make up the nuclei. Interesting effects arise when the magnetic field breaks the natural symmetries of the strong interaction between quarks. Magnetic fields are “odd” under time reversal—a charge moving backward in time creates a field in the opposite direction to the forward moving charge—so the presence of a magnetic field breaks time reversal symmetry in a quantum system. This aspect has been widely employed in the study of quantum chaos and has found many applications in condensed matter physics, such as in the quantum Hall effect.

Experimentally, the strong interactions respect space and time reflection symmetry to a very high degree: this has been established by precise experiments that set limits on the intrinsic electric dipole moment (EDM) of the neutron [5]. Yet the equations of QCD permit terms that violate

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Coming Soon in *Physics*
- Surface states of a topological insulator
- Jet dynamics of heavy quarks

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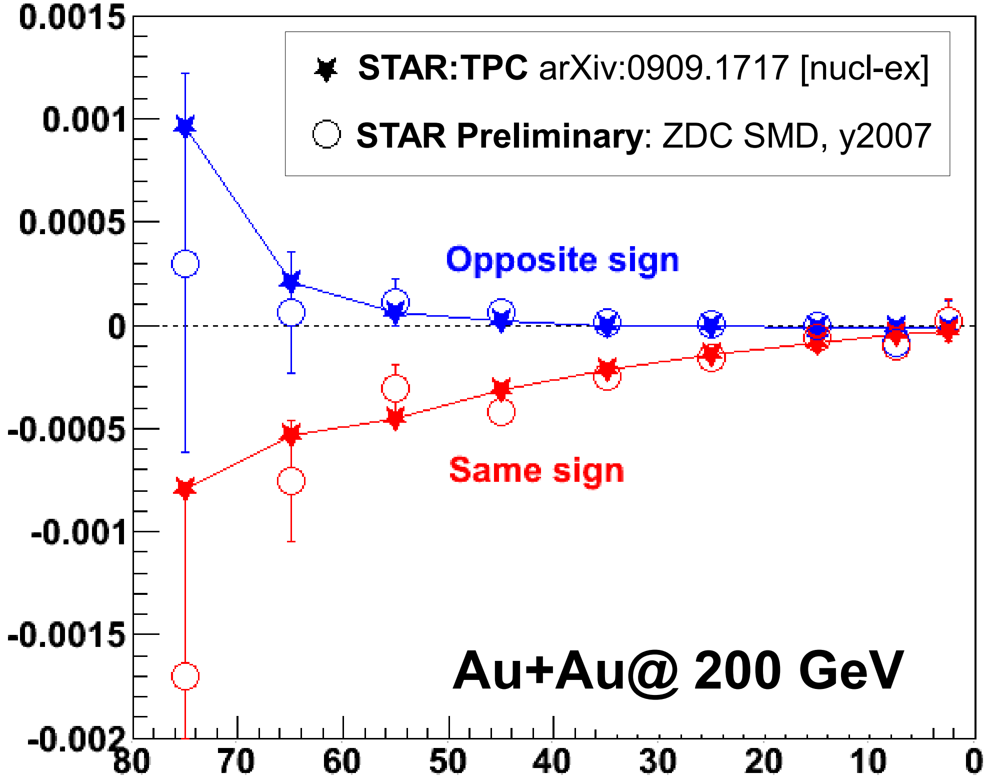
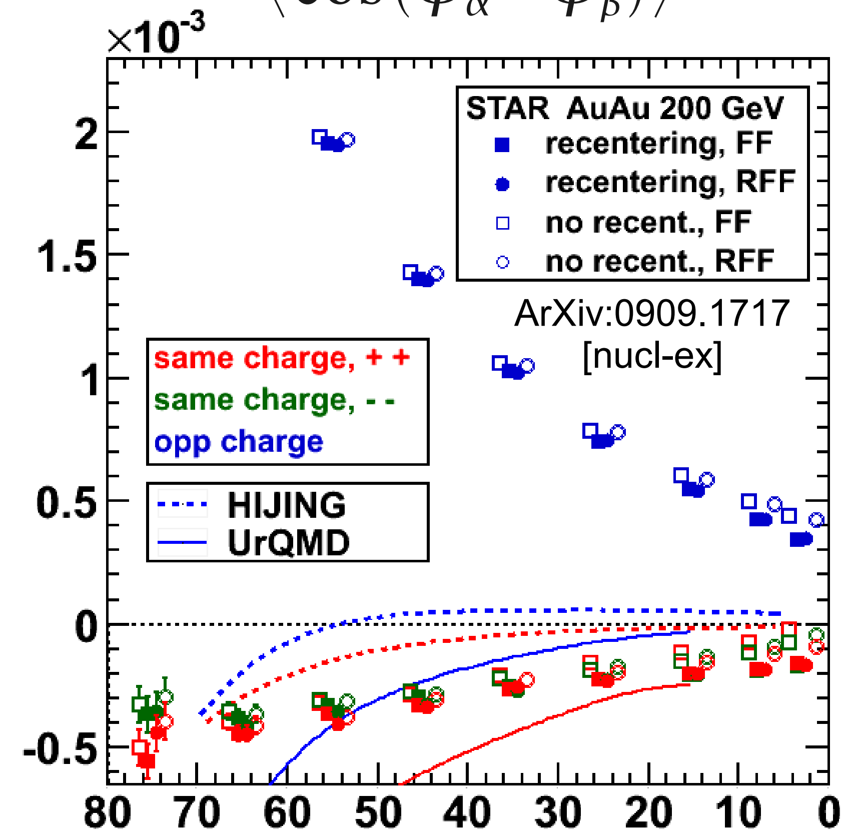
Backup slides

Results with ZDC SMD and two particle correlations

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



$$\langle \cos(\phi_\alpha - \phi_\beta) \rangle$$



Correlations with (first harmonic) ZDC-SMD event plane from recent 2007 data yield similar result to TPC/FTPC

$$\langle \cos(\phi_\alpha - \phi_\beta) \rangle =$$

$$= \langle \cos\Delta\phi_\alpha \cos\Delta\phi_\beta \rangle + \langle \sin\Delta\phi_\alpha \sin\Delta\phi_\beta \rangle$$

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

Physics backgrounds

Reaction plane (RP) dependent:

- Directed flow (vanishes in symmetric eta-range), flow fluctuations:

$$\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle_{flow} = \langle v_{1,\alpha} v_{1,\beta} \rangle v_{2,c}$$

- Global polarization (zero from measurement)

- RP dependent fragmentation (“flowing clusters”):

$$\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle_{clust} = A_{clust} \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{clust}) \rangle_{clust} v_{2,clust}$$

RP independent 3-particle correlations:

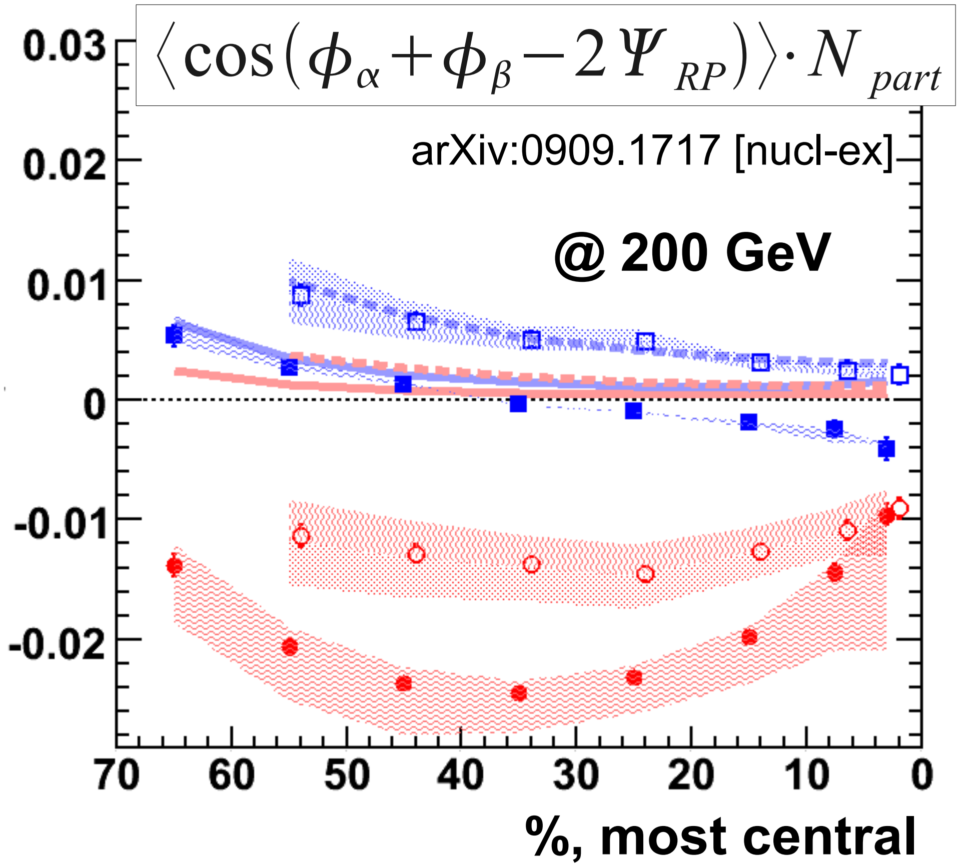
Can be removed by better RP determination
Different multiplicity scaling ($1/N_{ch}^2$) compared to P-violation

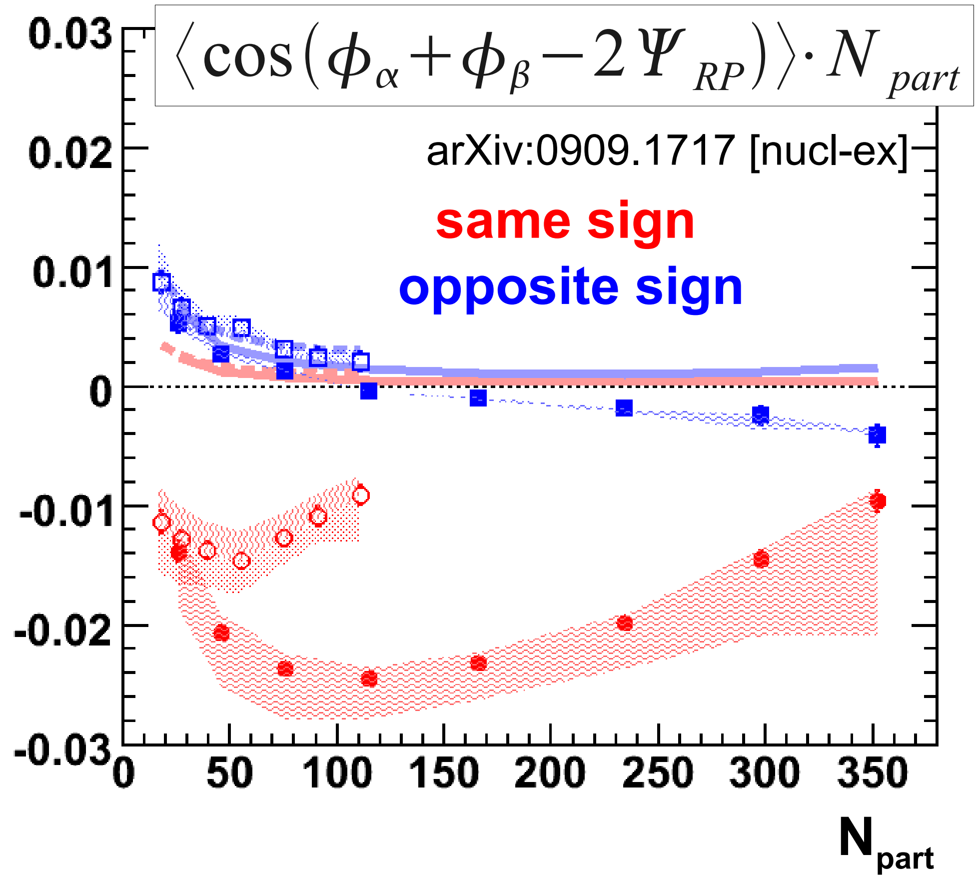
- Jet fragmentation, resonances, multi-particle clusters
- HBT, Coulomb effects, etc.

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*

Charge correlations and N_{part} scaling @200GeV





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

Au+Au	Cu+Cu	α and β charges
		same sign opposite sign
		3-particle HIJING

Opp-sign correlations scale with N_{part}

Same sign signal is suggestive of correlations with the reaction plane

Stronger opposite charge correlations In Cu+Cu at the same N_{part}