Probes of local strong parity violation: Experimental results from STAR

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for the STAR Collaboration

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workshop on Local Strong Parity Violation
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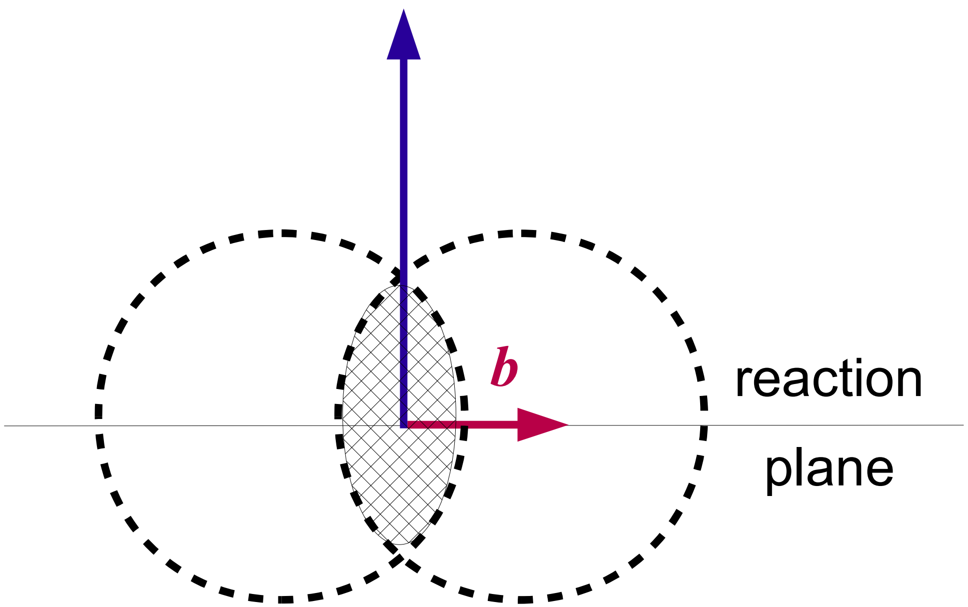
INDIANA UNIVERSITY

STAR

Non-central relativistic heavy ion collision (HIC)

B - magnetic field
L - orbital momentum



b – impact parameter

Colliding nuclei are moving out-of-list

- 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:

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

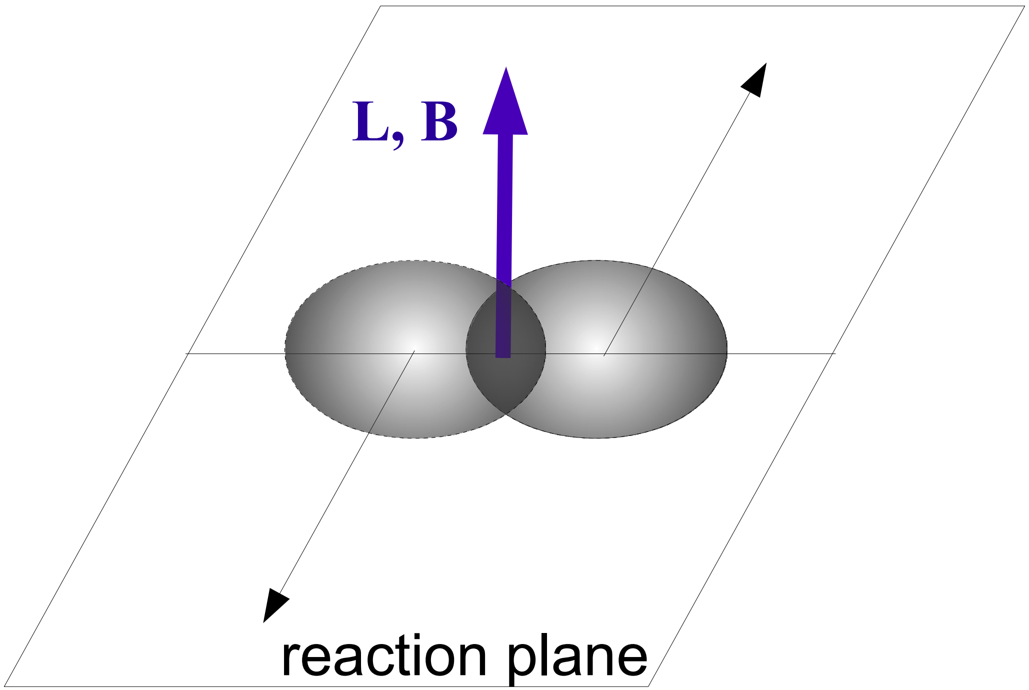
  $$(\mu_N \mathbf{B} \sim 100\,\mathrm{MeV})$$

  Rafelski, Müller PRL36:517 (1976)
  Kharzeev, PLB633:260 (2006)
  Kharzeev, McLerran, Warringa NPA803:227 (2008)

Particle production in HIC: asymmetries wrt. the reaction plane

L - orbital momentum

B - magnetic field



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

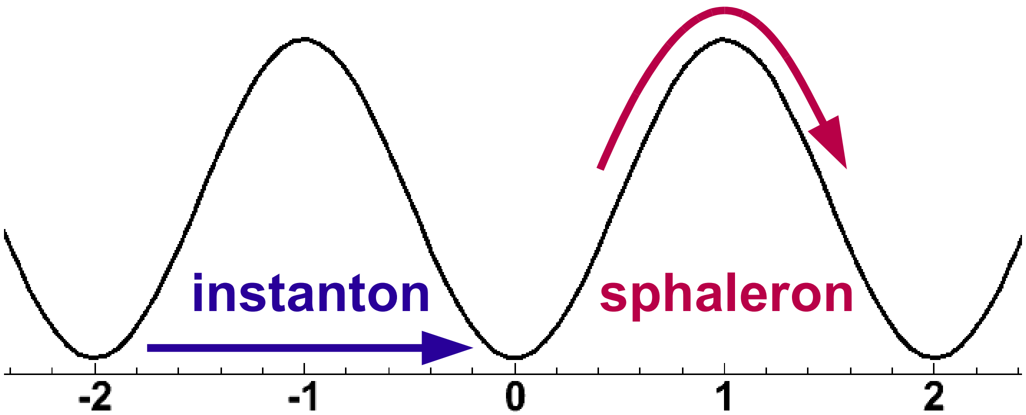
(**focus of this talk**)

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}:



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)

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

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

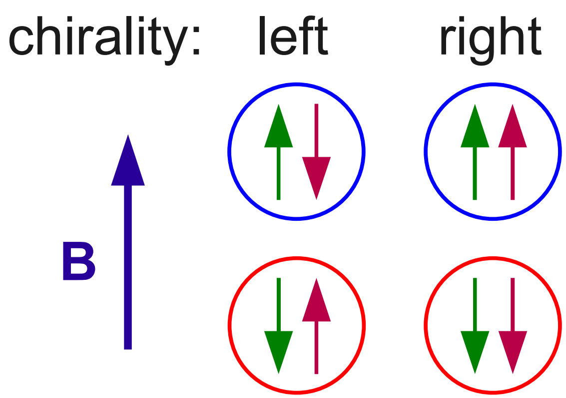
but:

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

T.D. Lee, PRD8:1226 (1973)
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



spin

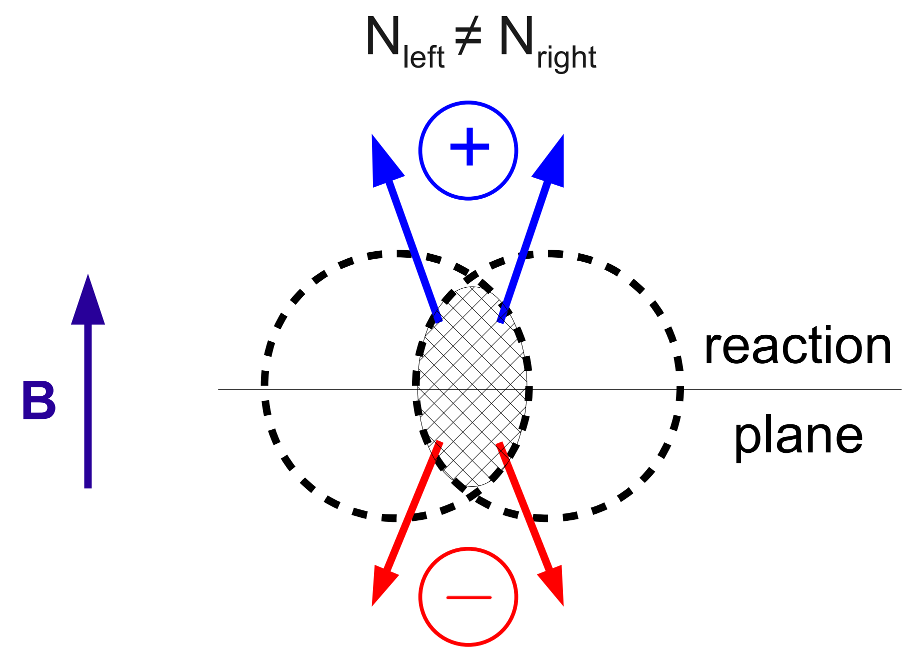
momentum

positive charge

negative charge

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

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



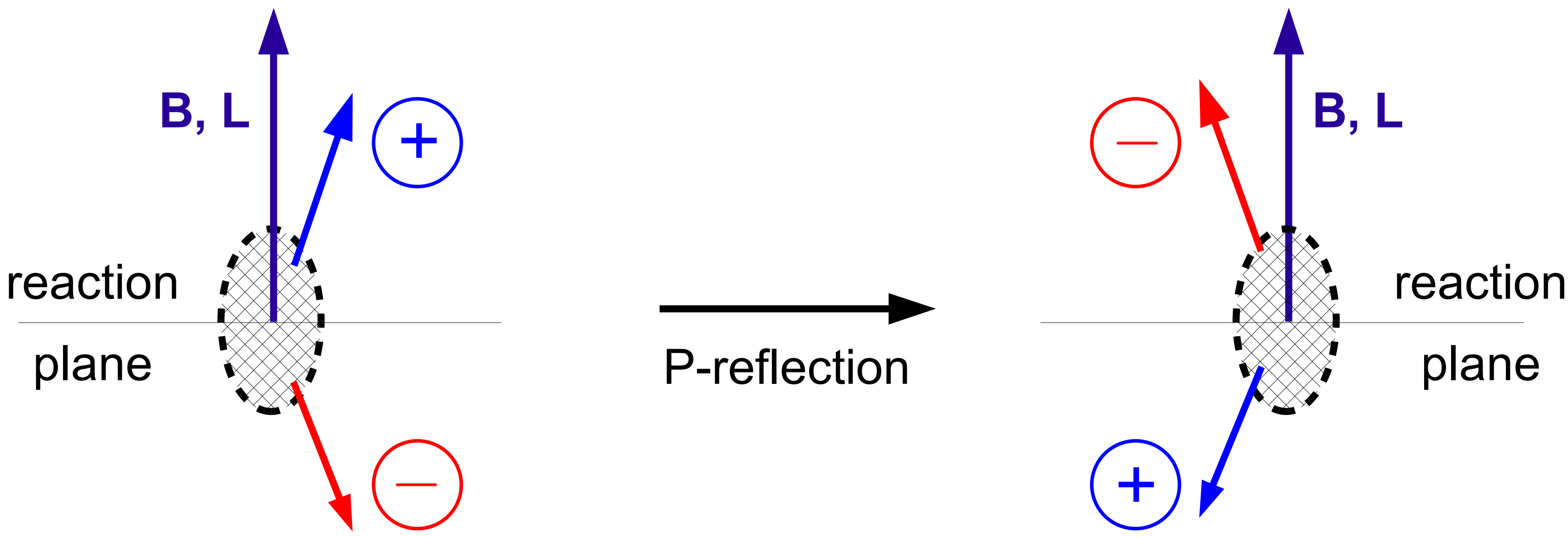
Induced electric field (parallel to B):

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

Positive and negative charges moving opposite to each other
$\rightarrow$ 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):

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

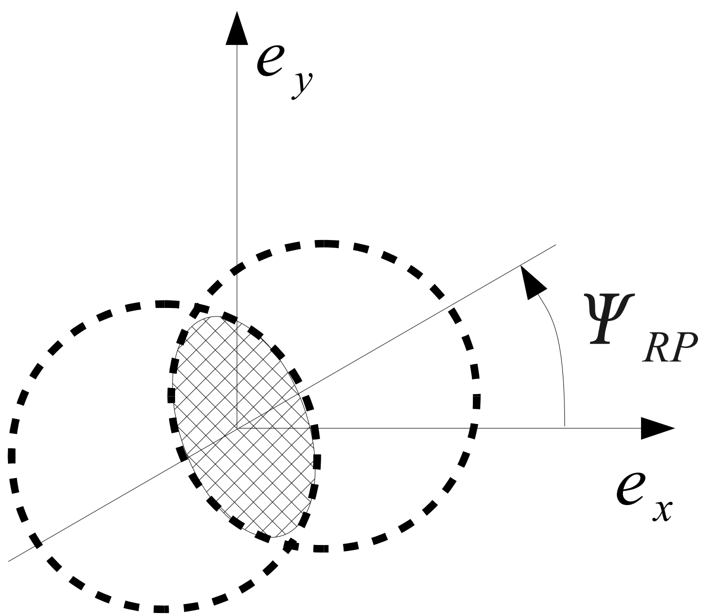
Orbital momentum/magnetic field (pseudo-vectors):

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

Experimental observable

Azimuthal distribution in case of P-violation

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



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 $Bg^{(in)}$ - $Bg^{(out)}$

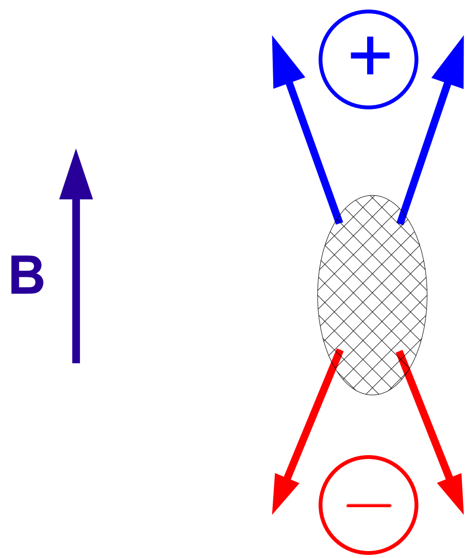
  $Bg^{(in)}$ ($Bg^{(out)}$) denotes in- (out-of) plane background correlations

- 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

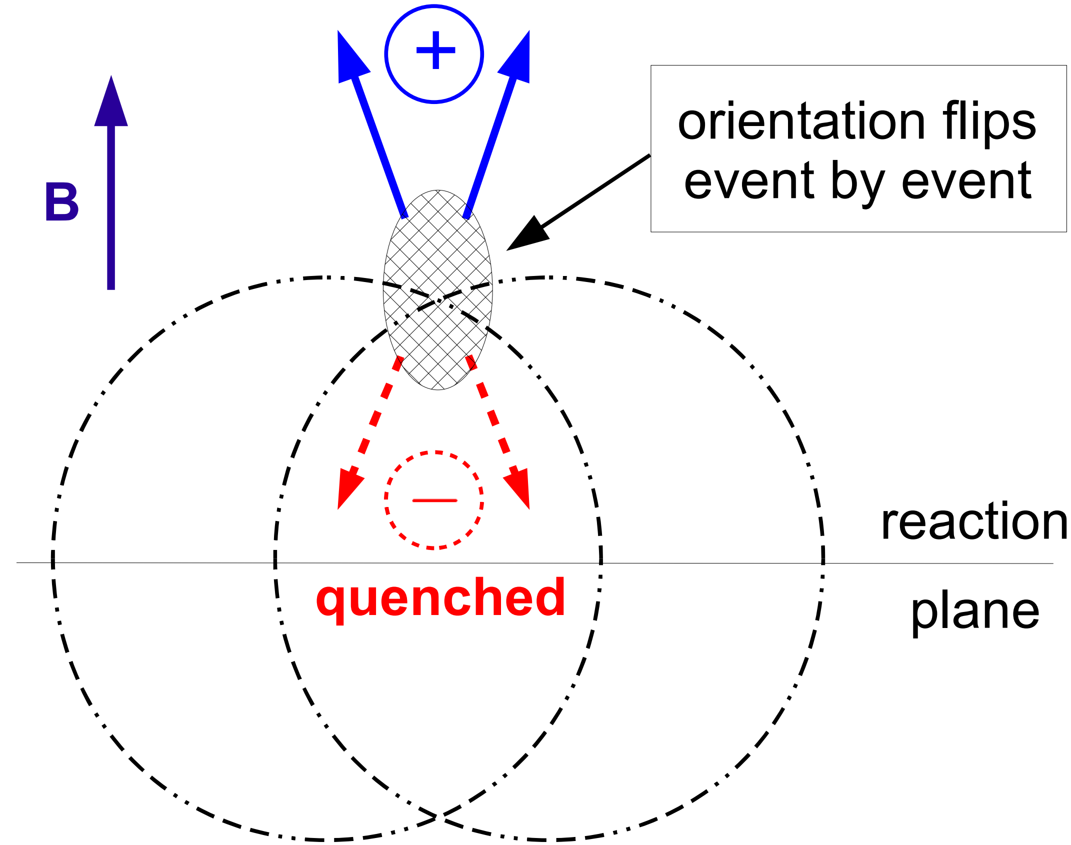
P-odd domain formation
(no medium)

$$a_+ = -a_-$$



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

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 ($Q = \pm 1, \pm 2, \ldots$)

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

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

  $$\boxed{\langle a_\alpha a_\beta \rangle \sim 10^{-4}}$$

- 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

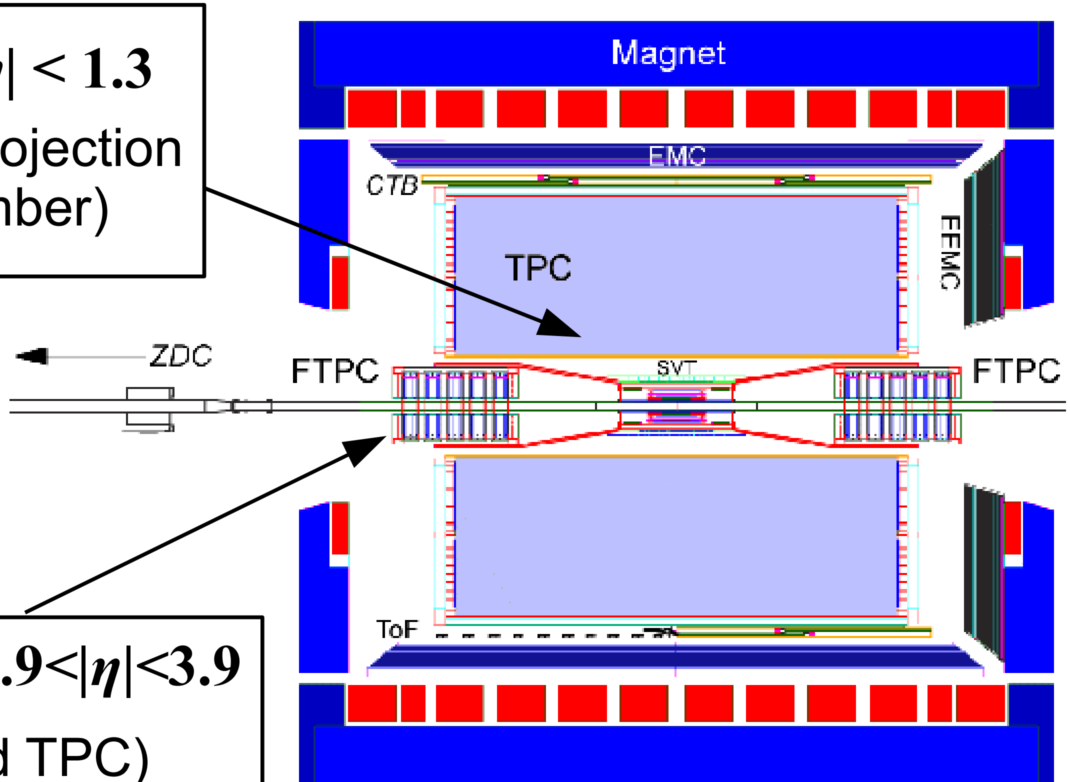
- Measuring (mixed harmonics) **3-particle azimuthal correlations:**

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

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

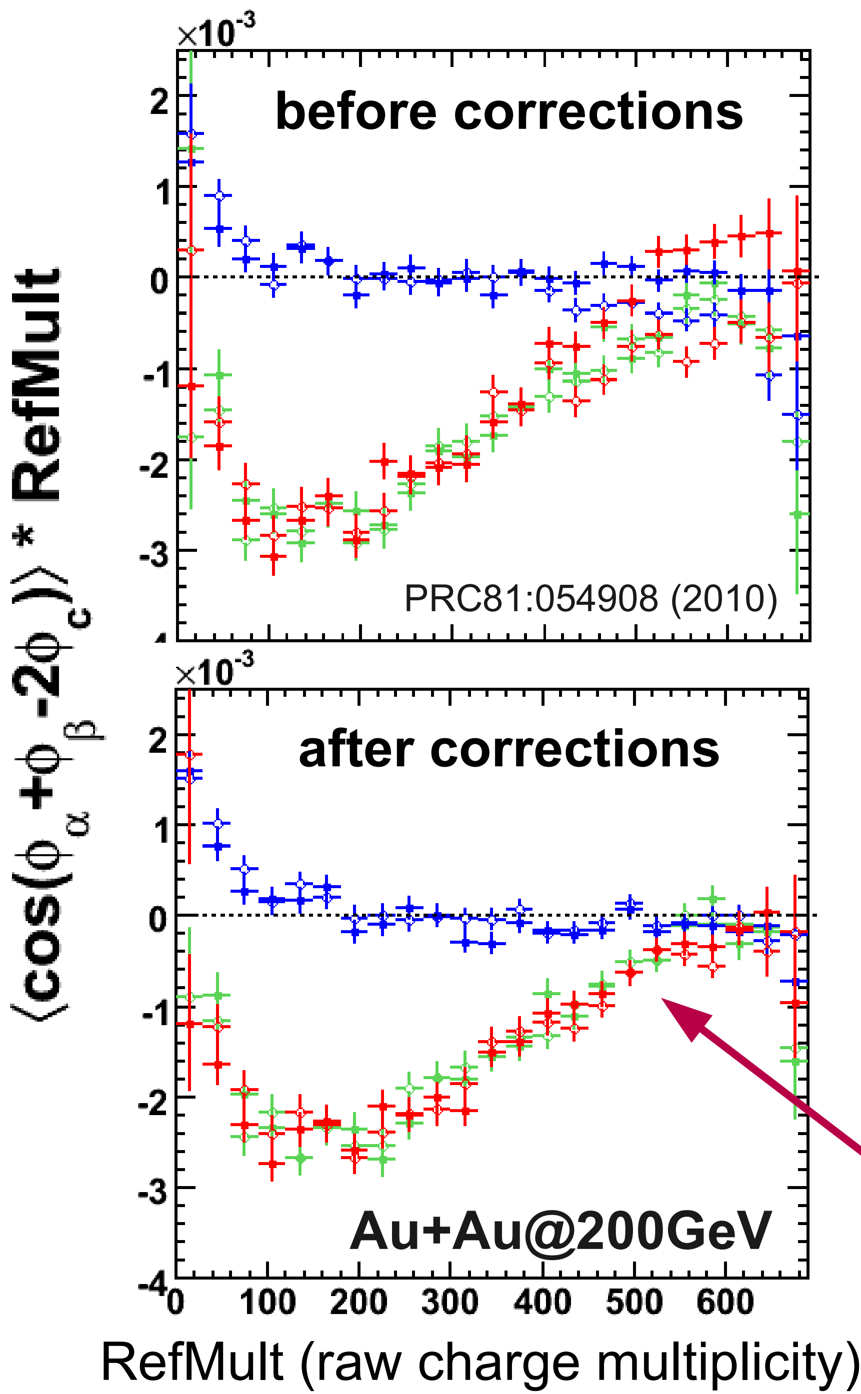
ZDC SMDs:
recoil neutrons at **beam rapidity**

(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):

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

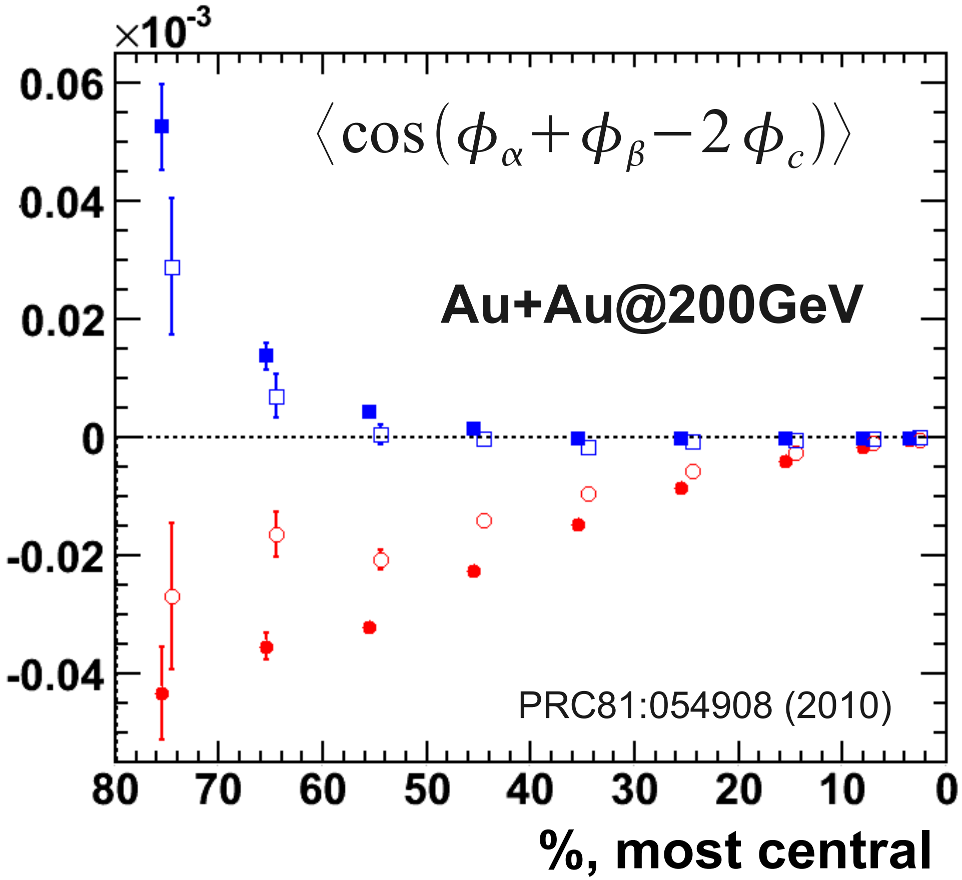
$$\cos n\phi \;\rightarrow\; \cos n\phi \;-\; \langle \cos n\phi \rangle$$

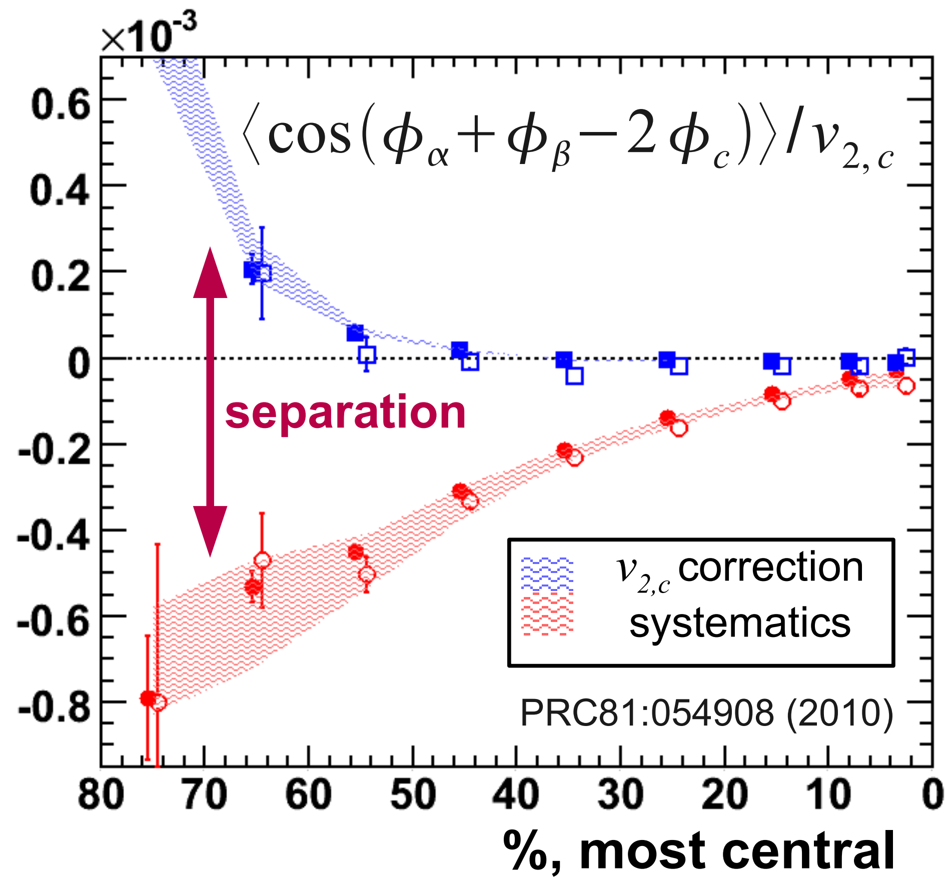
Poskanzer, Voloshin, PRC58:1671 (1998)
Borghini, Dinh, Ollitrault, PRC66:014905 (2002)
Selyuzhenkov, Voloshin, PRC77:034904 (2008)

symbol	*(α, β)* charges	*c*-particle
	opposite sign, + -	positive
	same sign, ++	
	same sign, - -	
	opposite sign, + -	negative
	same sign, ++	
	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





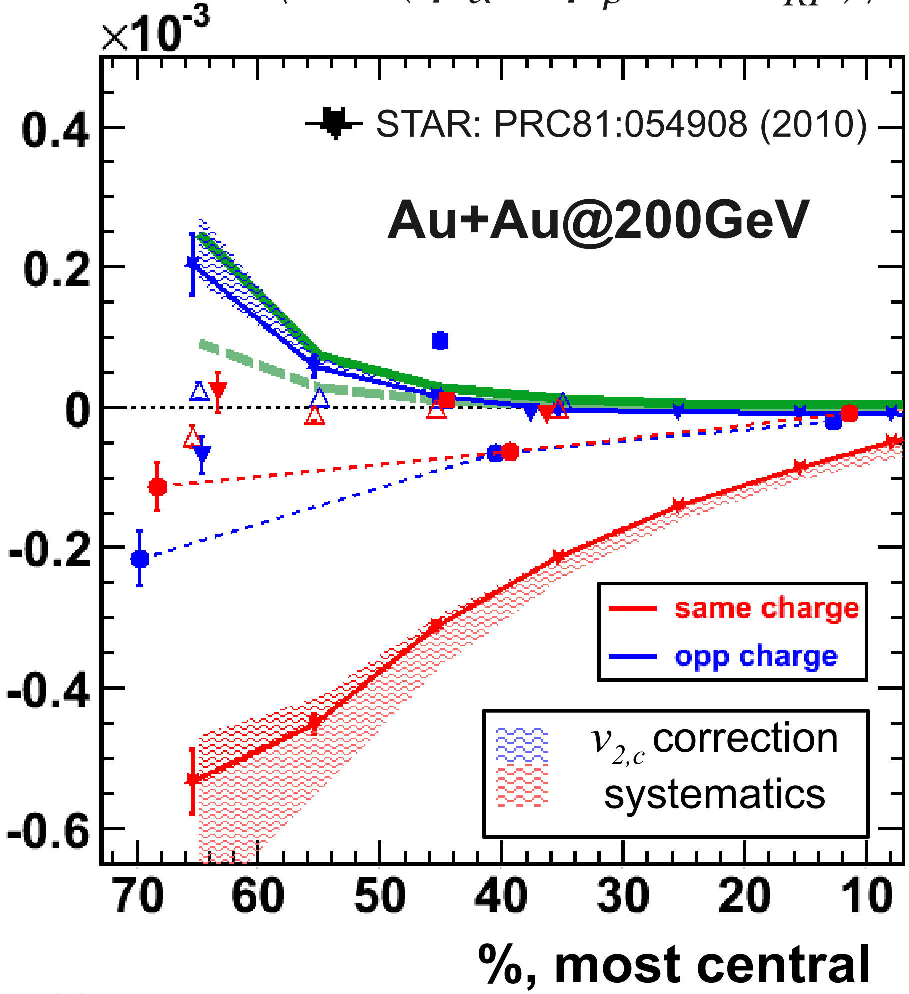
symbol	(α, β) charges	c-particle
red filled circle, blue filled square	same sign opposite sign	$\lvert\eta\rvert<1.0$ (TPC)
red open circle, blue open square	same sign opposite sign	$2.9<\lvert\eta\rvert< 3.9$ (FTPCs)

- $v_{2,c}$ 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

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



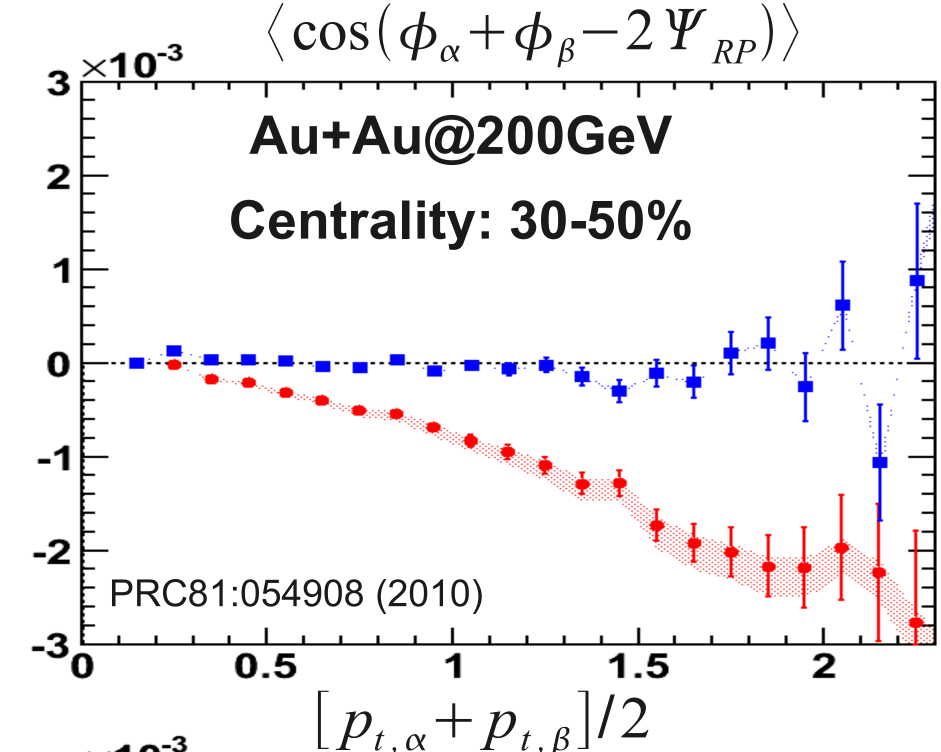
symbol	model	c-particle
▼ △ ● ■	**HIJING** **HIJING + v_2** **UrQMD** **MEVSIM**	true reaction plane
opposite same	**HIJING 3-particle correlations**	$\lvert\eta\rvert<1.0$

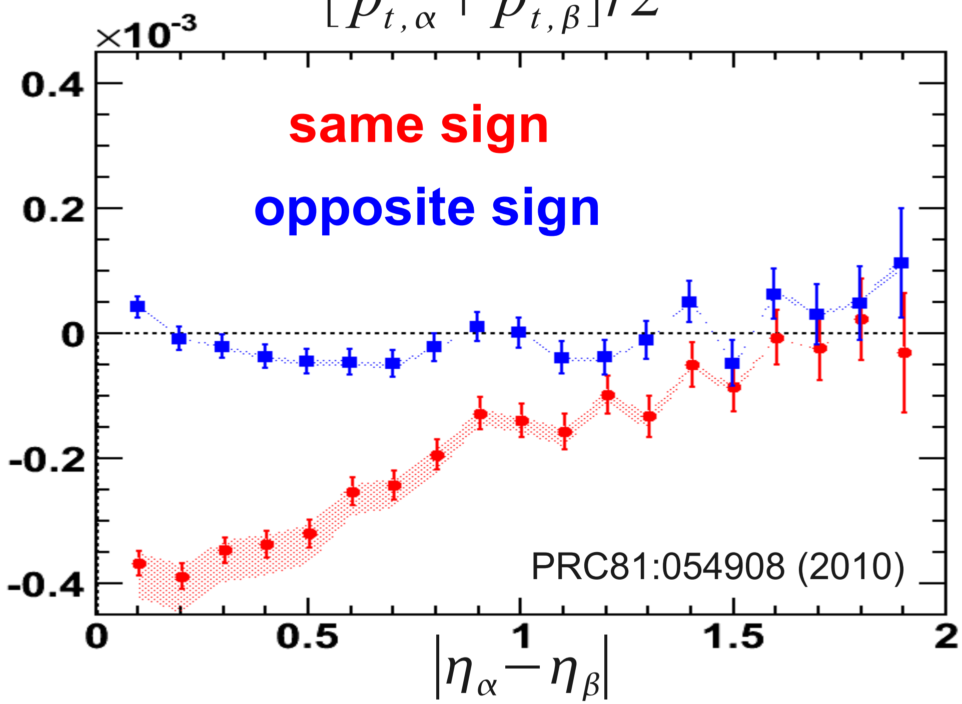
HIJING + v_2: added flow "afterburner"
MEVSIM: resonances with realistic flow

- 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

Notes:
- cluster production is not well modeled by event generators
- charge and momentum conservation may affect the measurements
  Pratt arXiv:1002.1758v1 [nucl-th]

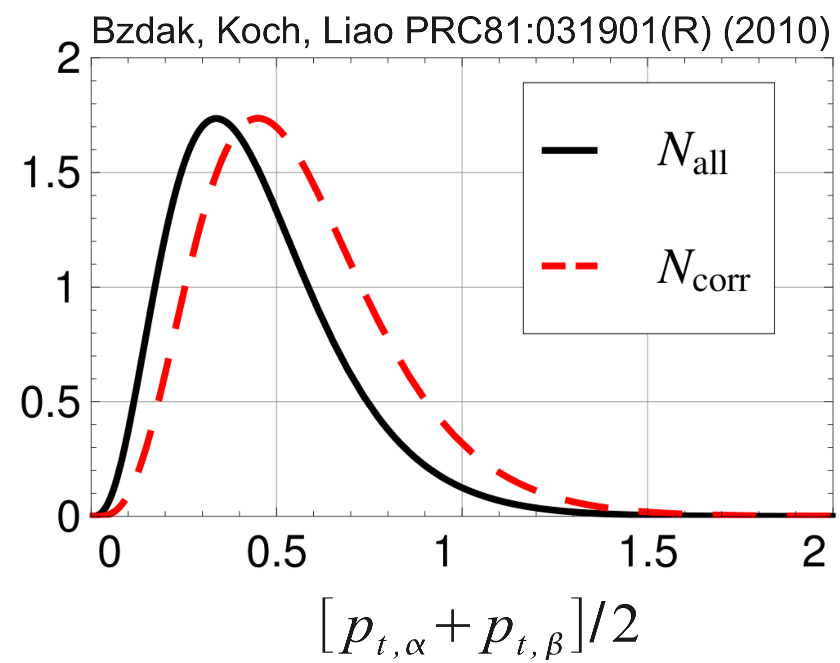
Pseudo-rapidity and transverse momentum dependence





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

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

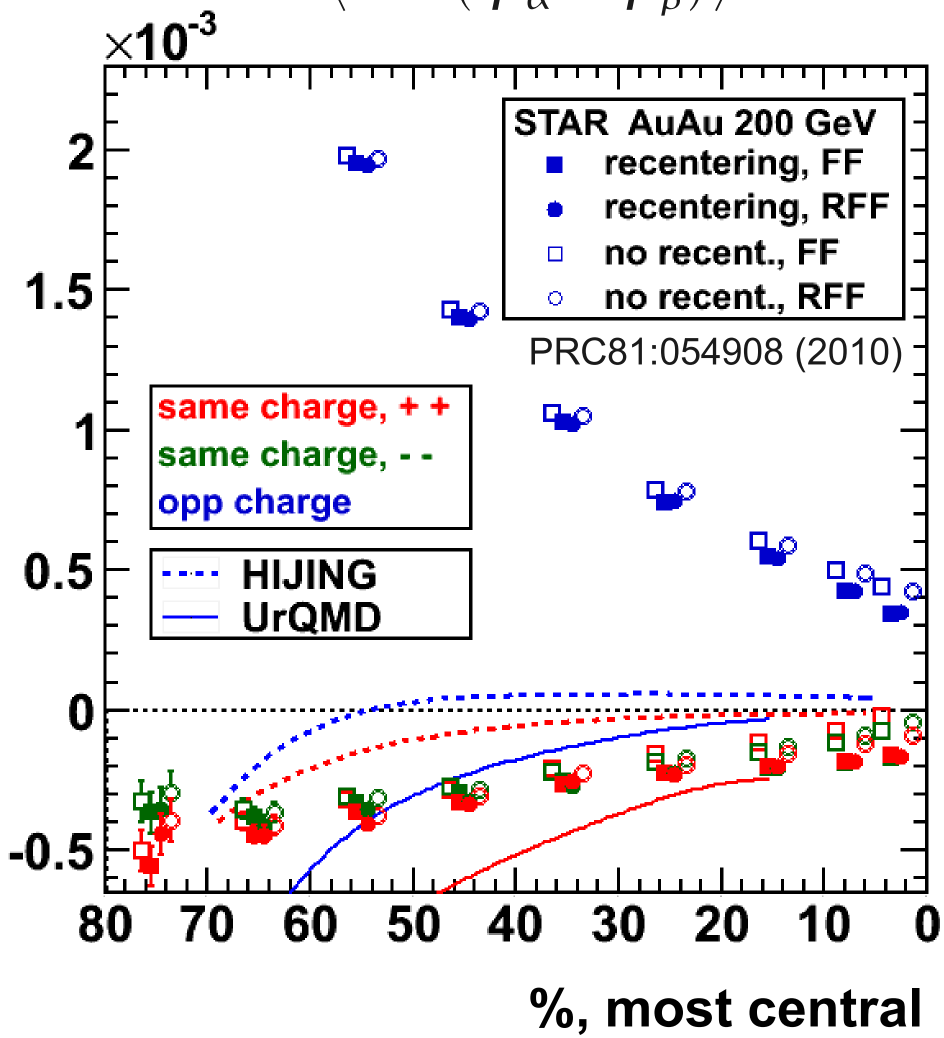


Pseudo-rapidity dependence:
→ typical “hadronic” width

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:

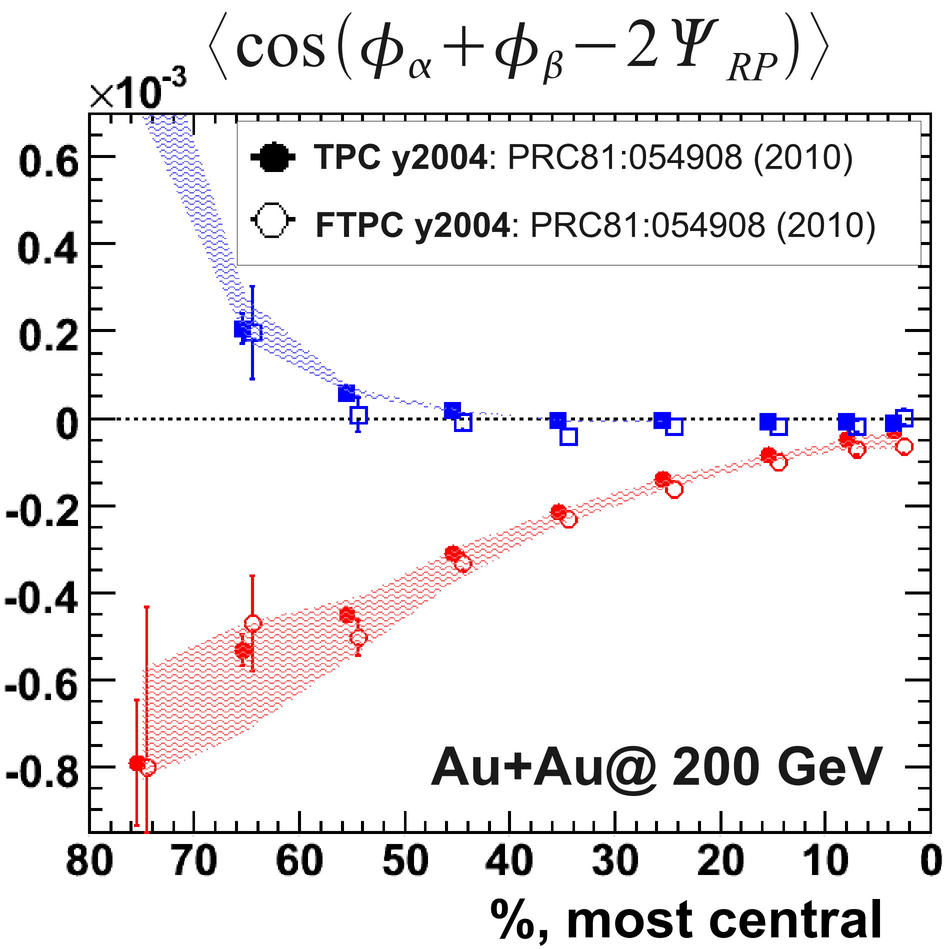
- Detailed calculations for P-violating signal and backgrounds are needed

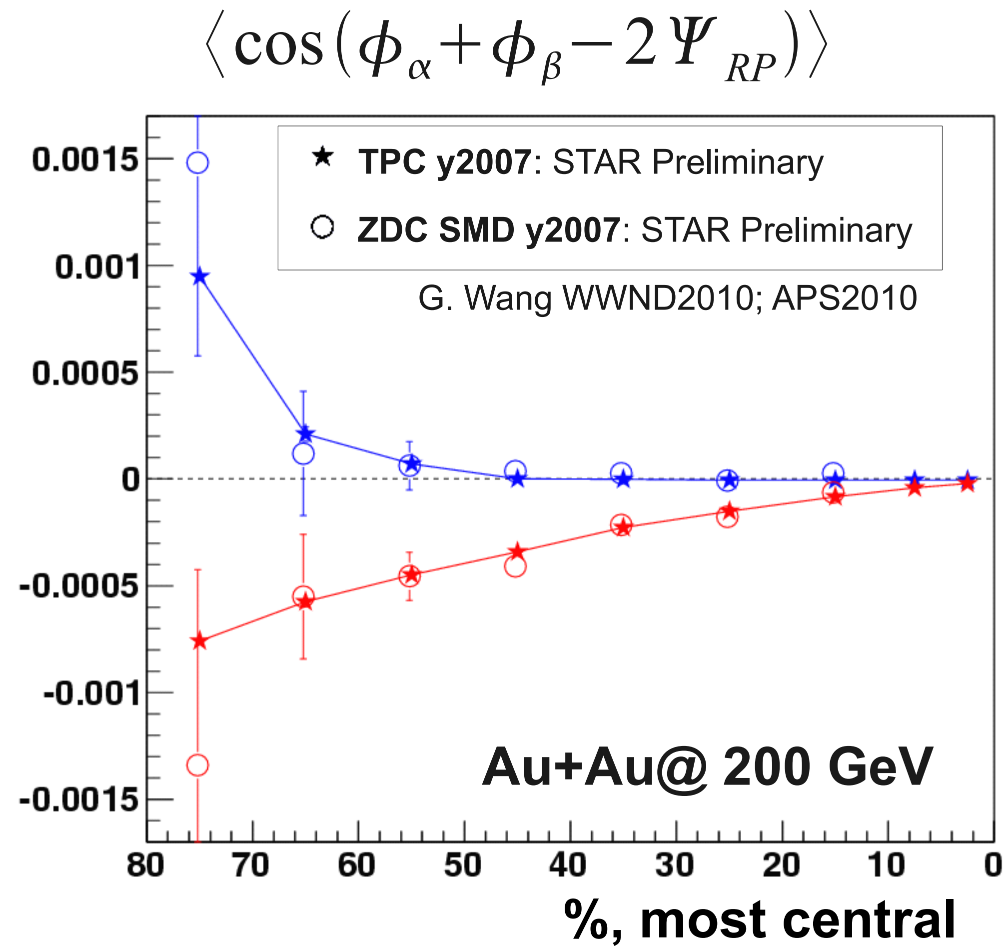
Experiment:

- 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

STAR ZDC SMD & TPC event plane from 2007 Au+Au data





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

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*

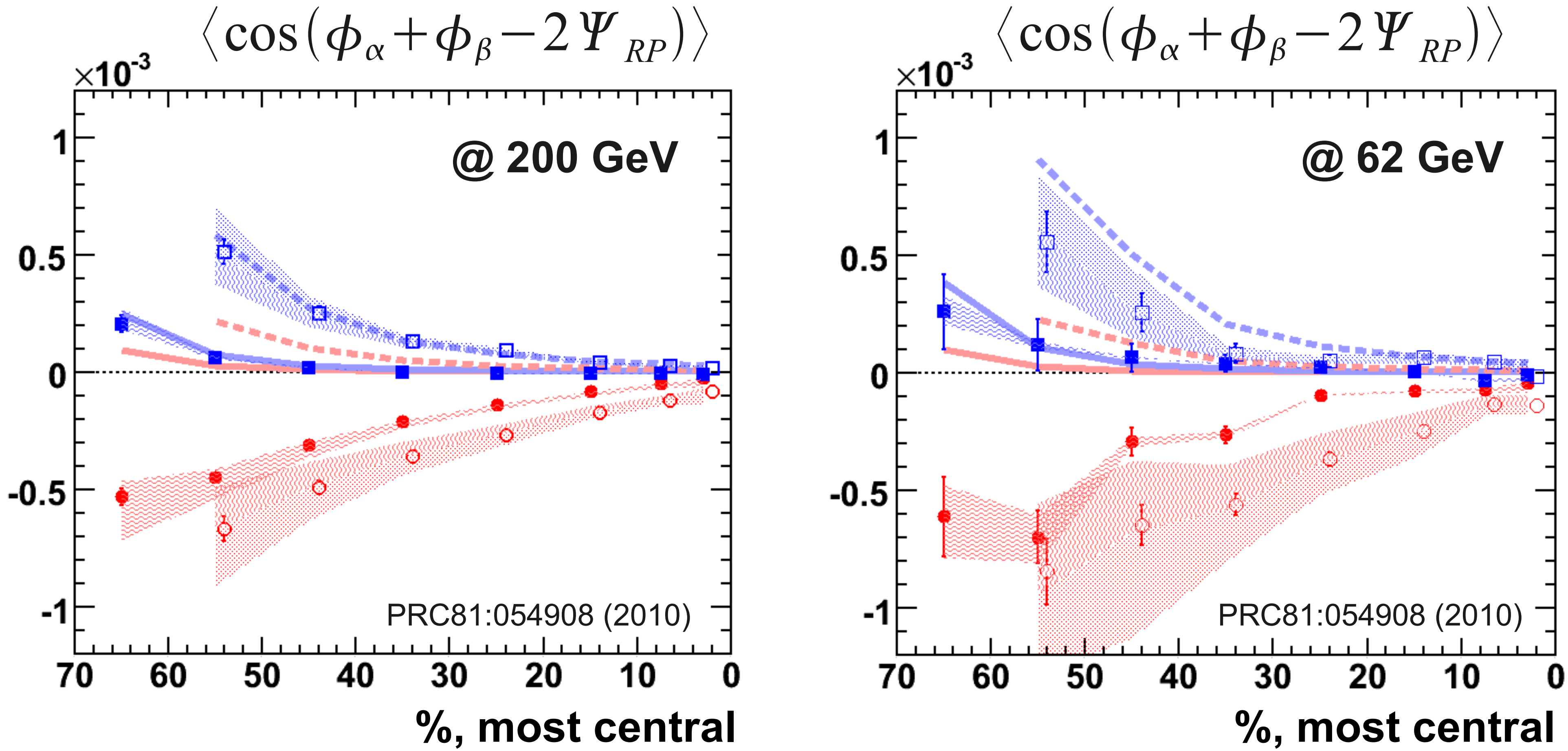
- Feed-down effects from non-primary tracks (i.e. resonance decay daughters)
  → *Results for dca < 1 cm and dca < 3 cm are consistent*

- 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*

Energy and system size dependence



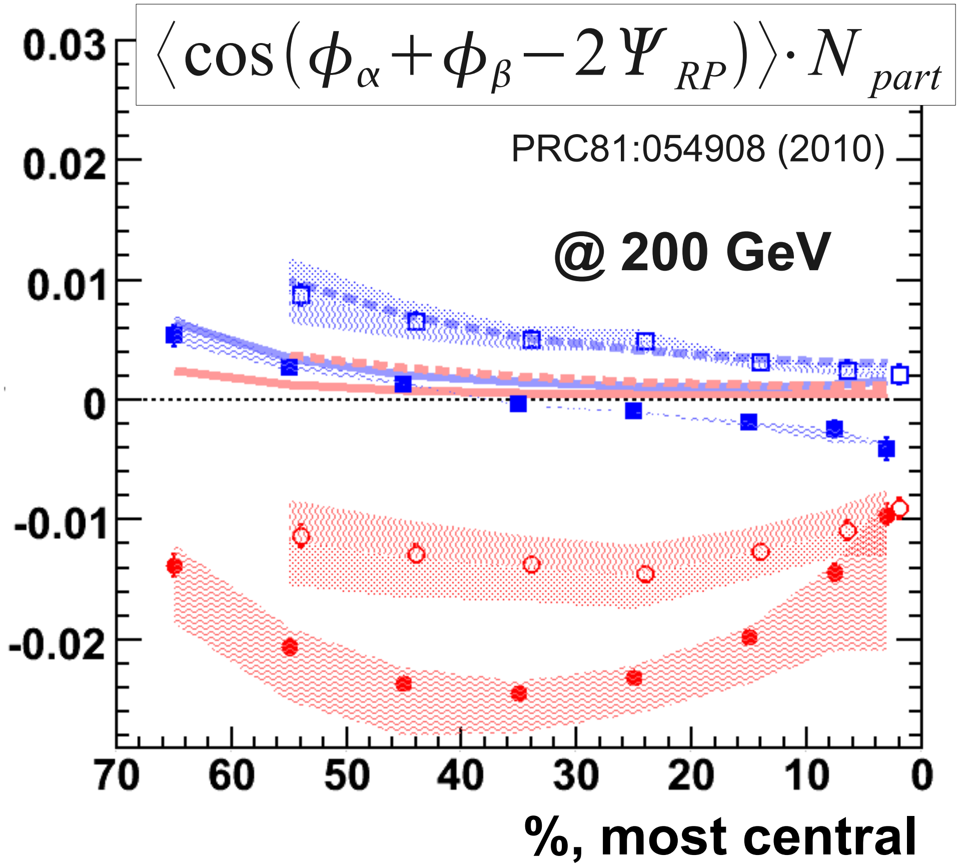
Au+Au	Cu+Cu	α and β charges
		same sign
		opposite sign
		3-particle HIJING

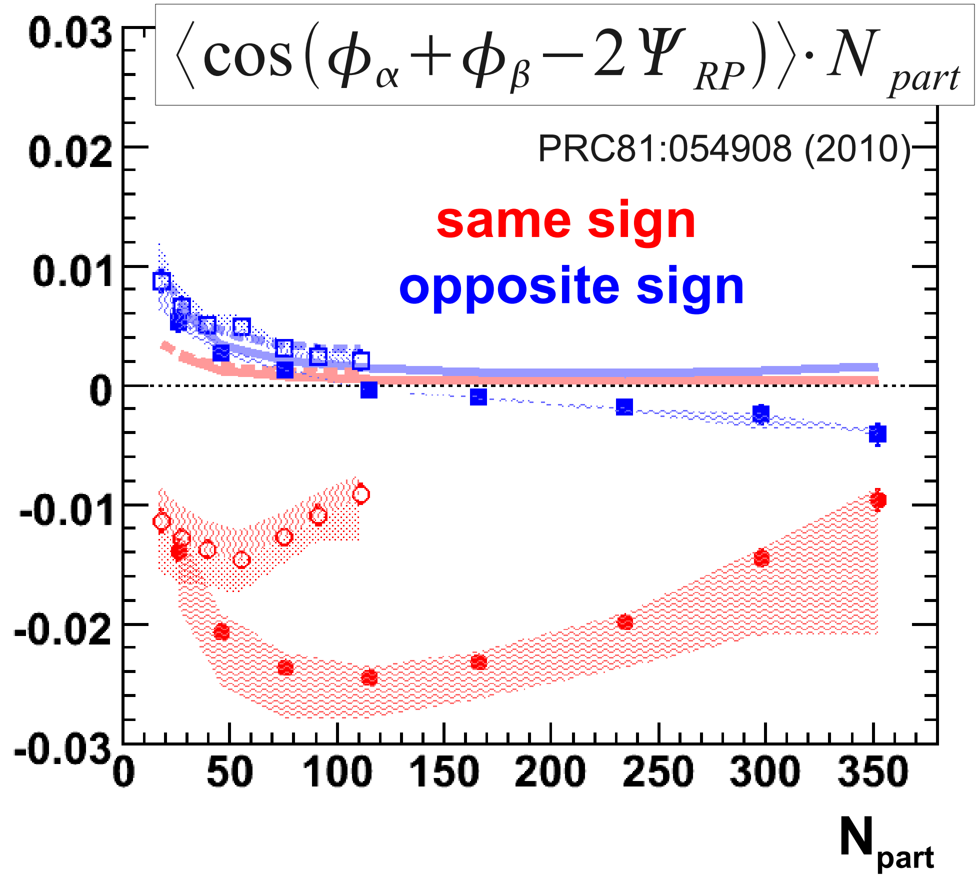
$v_{2,c}$ correction systematics

Opposite sign correlations:

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

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}