Local Parity Violation and Charge Separation at RHIC: Status and New Probes

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Outline

- Local Parity Violation at RHIC:

  Status & Problem

- Charge Separation:

  New Probes

Local Parity Violation at RHIC ?!?

Selected for a Viewpoint in *Physics*
PRL **103**, 251601 (2009) PHYSICAL REVIEW LETTERS week ending 18 DECEMBER 2009

Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

B. I. Abelev,[8] M. M. Aggarwal,[29] Z. Ahammed,[46] A. V. Alakhverdyants,[16] B. D. Anderson,[17] D. Arkhipkin,[3] G. S. Averichev,[16] J. Balewski,[21] O. Barannikova,[8] L. S. Barnby,[2] S. Baumgart,[51] D. R. Beavis,[3] R. Bellwied,[49] F. Benedosso,[26] M. J. Betancourt,[21] R. R. Betts,[8] A. Bhasin,[15] A. K. Bhati,[29] H. Bichsel,[48] J. Bielcik,[10] J. Bielcikova,[11] B. Biritz,[6] L. C. Bland,[3] I. Bnzarov,[16] B. E. Bonner,[35] J. Bouchet,[17] E. Braidot,[26] A. V. Brandin,[24] A. Bridgeman,[1]

STAR Collaboration

'Bubbles' of Broken Symmetry in Quark Soup at RHIC

Data suggest symmetry may 'melt' along with protons and neutrons

Monday, February 15, 2010

The New York Times

Science

In Brookhaven Collider, Scientists Briefly Break a Law of Nature

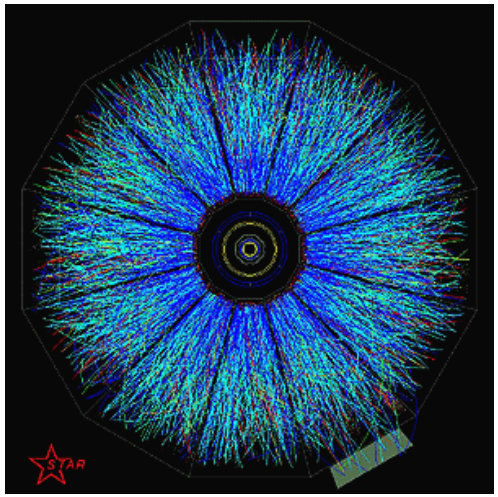
P- and CP-odd Effects in Hot and Dense Matter

RIKEN BNL Research Center Workshop
April 26-30, 2010 at Brookhaven National Laboratory

What is Local Parity Violation (LPV)

Parity
(mirror symmetry)

QCD is known to be
P and CP symmetric
to high precision.

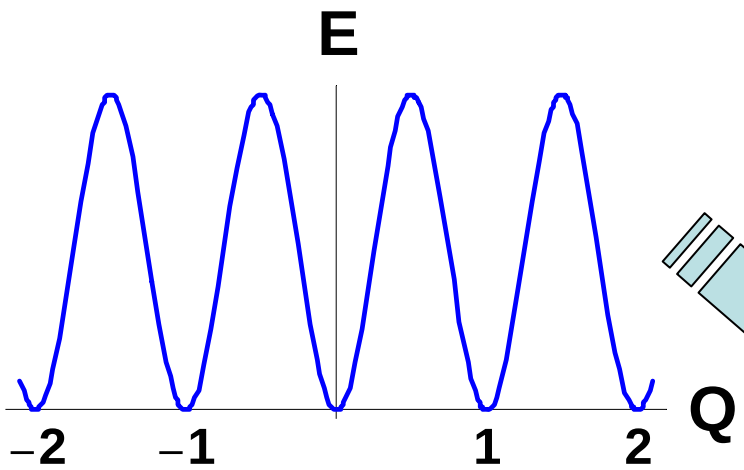


RHIC
(highly excited
QCD mater)

Parity Violation

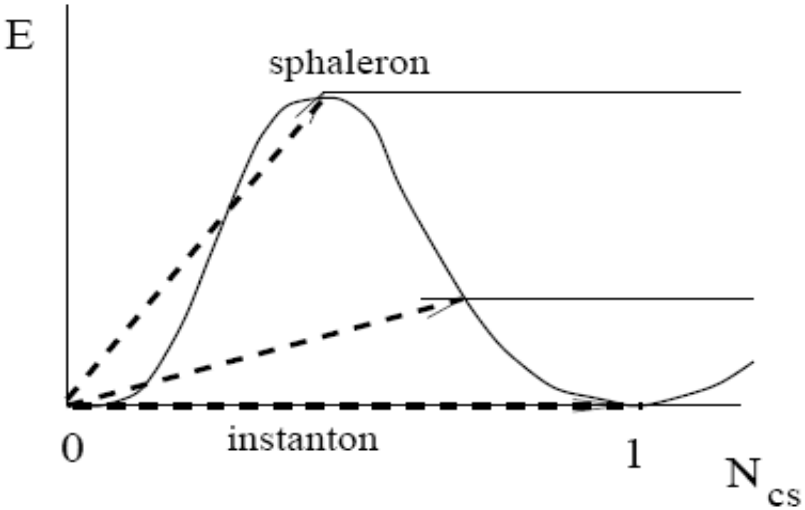
"Local":
in particular piece of
space-time domain
filled with
"abnormal" state of matter

Picking the Topology out of Vacuum



The QCD Theta Vacuum

When adequate energy is available …
(collisions; hot plasma)



QCD is topologically rich, allowing gluonic configurations with nontrivial topology

"Vacuum Engineering"
T.D. Lee (early 70's)

Topological Charge and Chirality

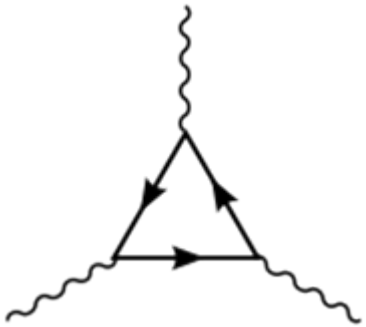
In heavy ion collisions, the space-time domain of created matter may acquire non-zero topological charge.

$$Q_{\mathrm{w}} = \frac{g^2}{32\pi^2} \int \mathrm{d}^4x \, F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a$$

!! Fluctuate E-by-E ;
+1 / -1 equally probable

When the gluons are coupled to quarks ….

$$\partial^\mu j^5_\mu = 2 \sum_f m_f \langle \bar{\psi}_f i\gamma_5 \psi_f \rangle_A - \frac{N_f g^2}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a$$



Nonzero chirality can then be generated:

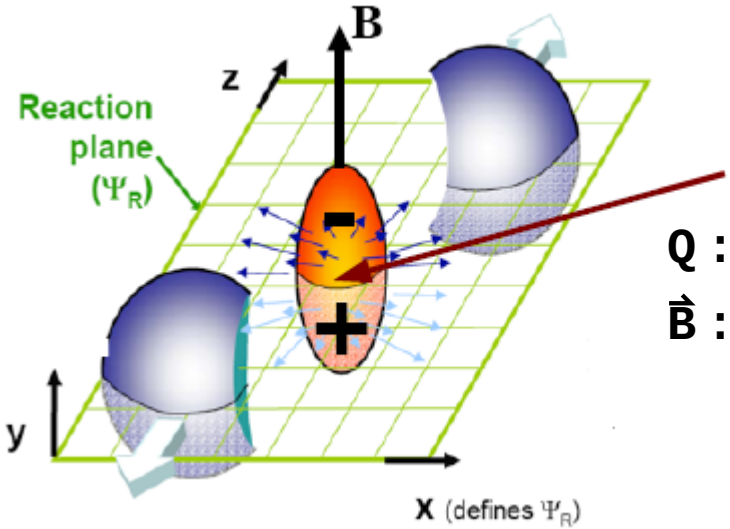
$$(N^f_L - N^f_R) = 2Q_{\mathrm{w}}$$

!! Qw>0 → more LEFT quark;
Qw>0 → more RIGHT quark

Chiral Magnetic Effect

In heavy ion collisons: we may have both Q and B → CME

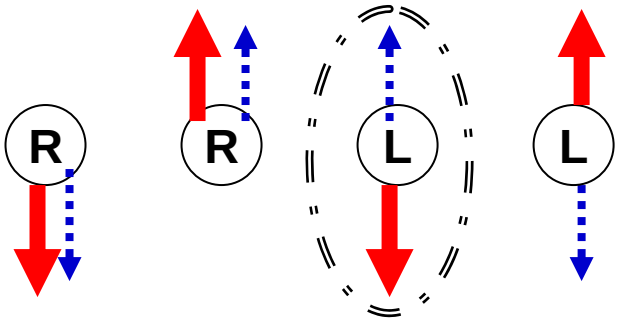
Kharzeev (06);
Kharzeev, Zhitnitsky (07);
Kharzeev, McLerran, Warringa (08)



$Q>0$

Q : helisity left – right imbalance

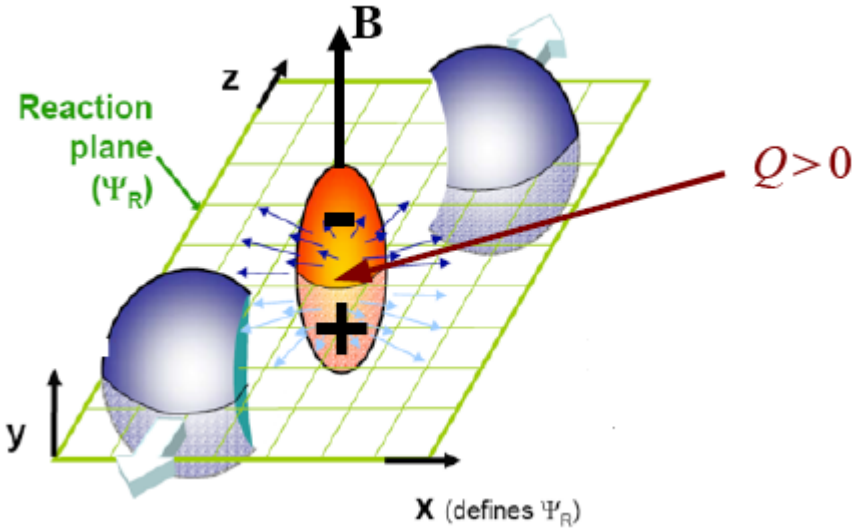
$\vec{B}$: spin up – down imbalance

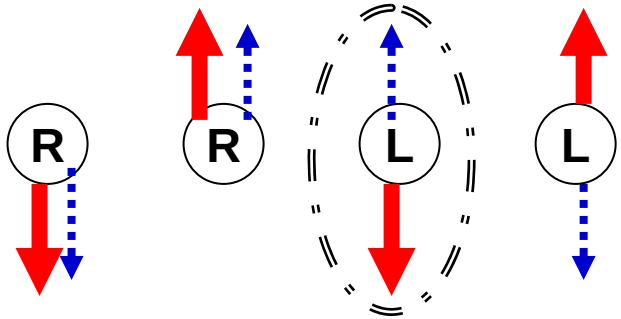


(positive charge quark moving down)
(negative moving up)

Chiral Magnetic Effect

In heavy ion collisons: we may have both Q and B → CME

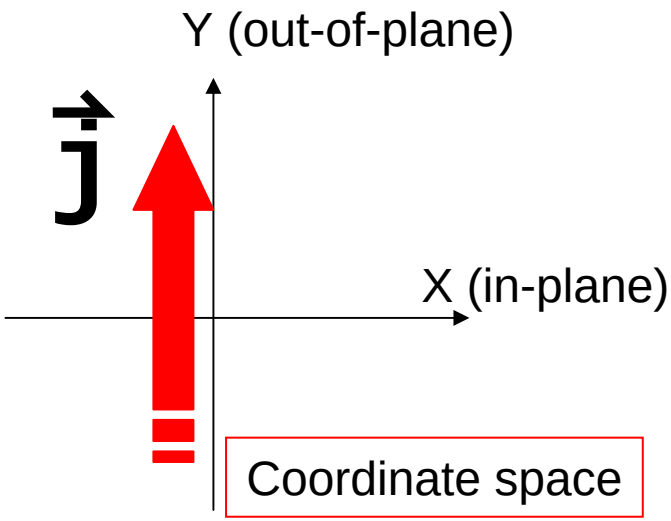


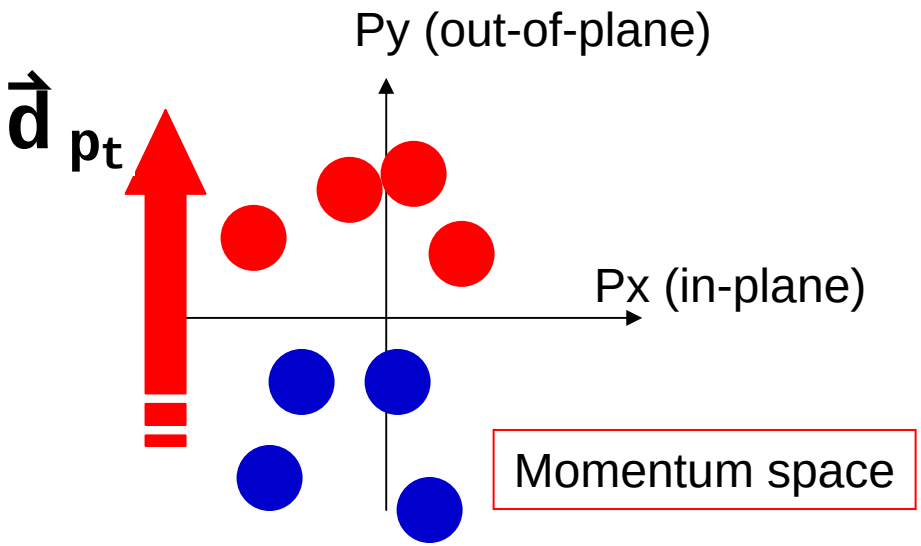


$$\vec{j} \propto (N_L - N_R)\,\vec{B} \propto Q\,\vec{B}$$

In a given event: the PESUDO-SCALAR $\vec{j} \cdot \vec{B} \neq 0$ *P & CP ODD !*

Possible CME Signal



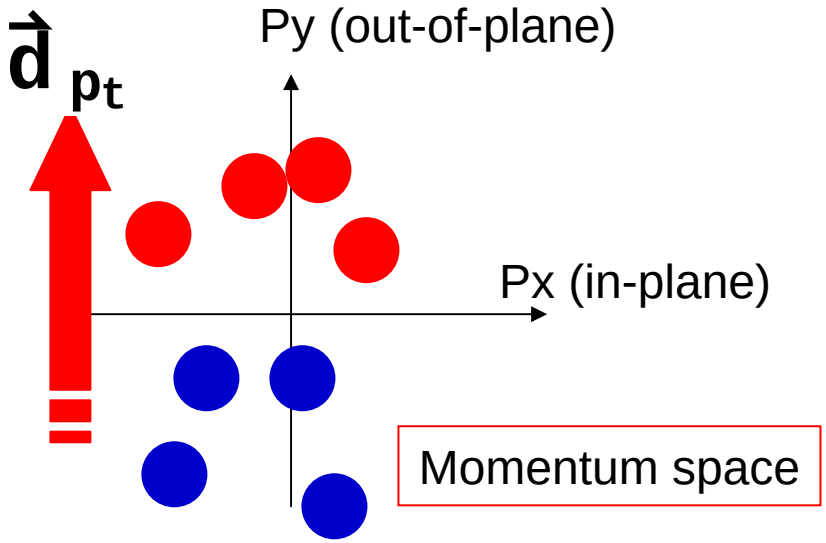


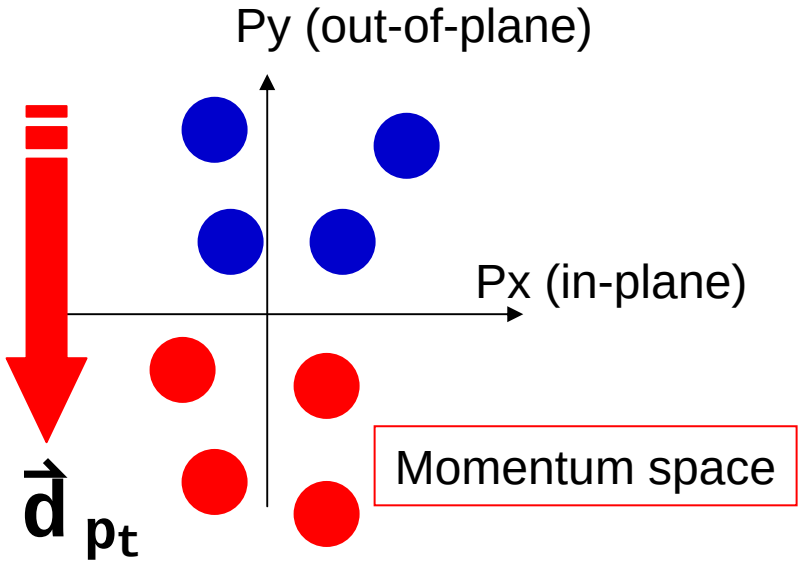
Charge Separation *or*
Electric Dipole in Pt Space
(along ***out-of-plane****)*

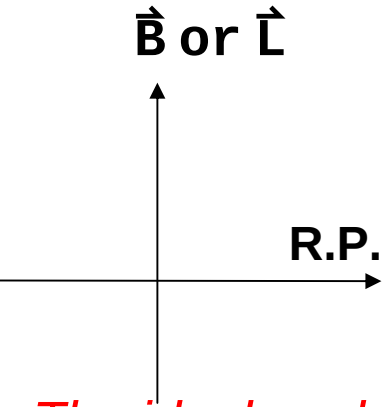
Complications:

- *dipole directions flip up and down E-by-E*

Experimental Challenge

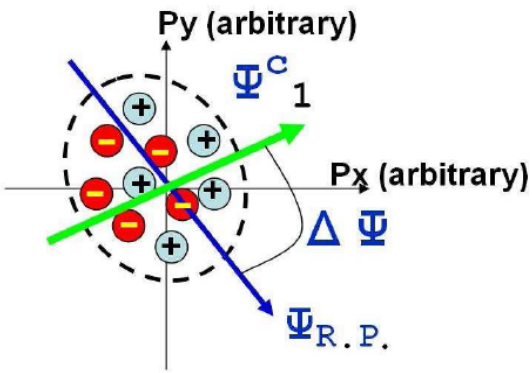






The ideal world

Challenge: to observe
a physical charge separation
(that flips from event to event)
and clearly demonstrate its
azimuthal orientation to be out-of-plane

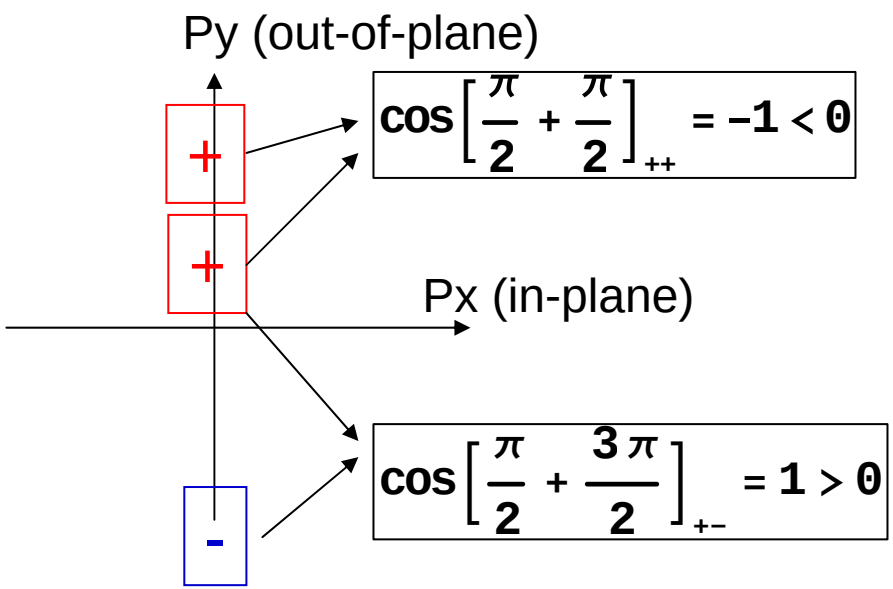


The real world

STAR Observable & Data

3P correlations: *Voloshin (04)*

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



CME expectation
(same for flipped dipole)

STAR Observable & Data

3P correlations: *Voloshin (04)*

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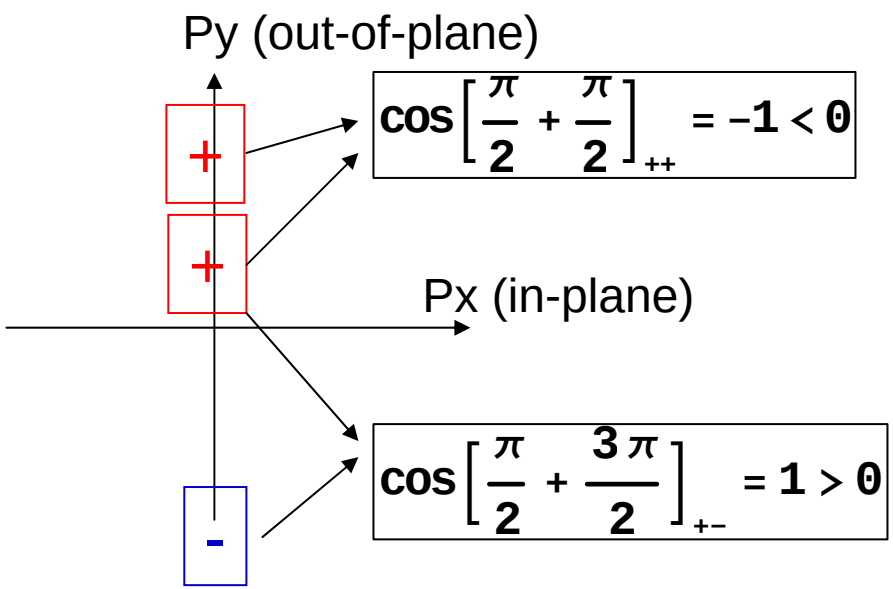
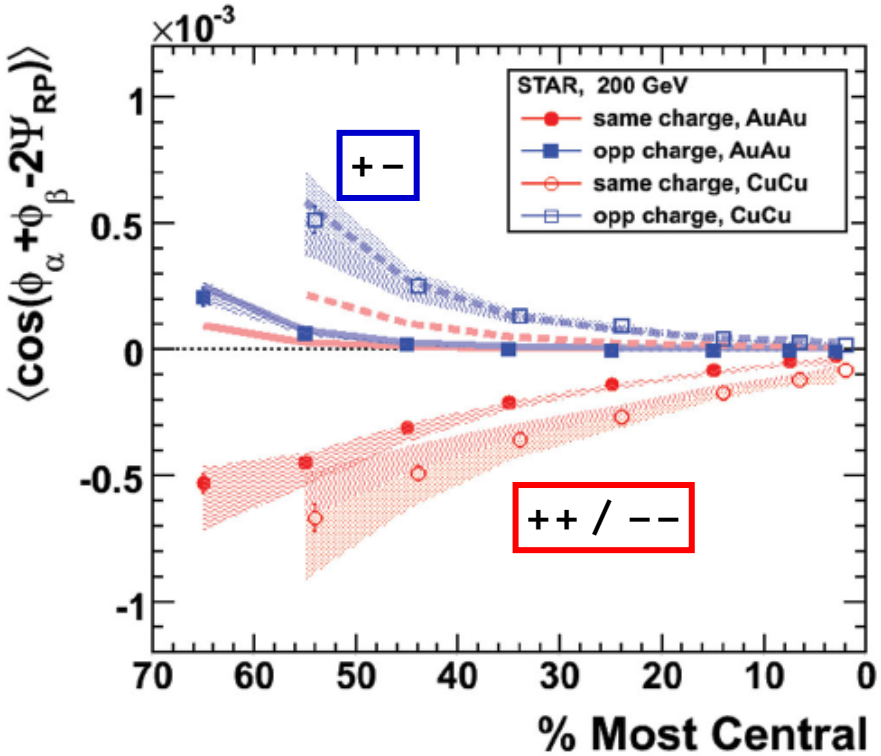


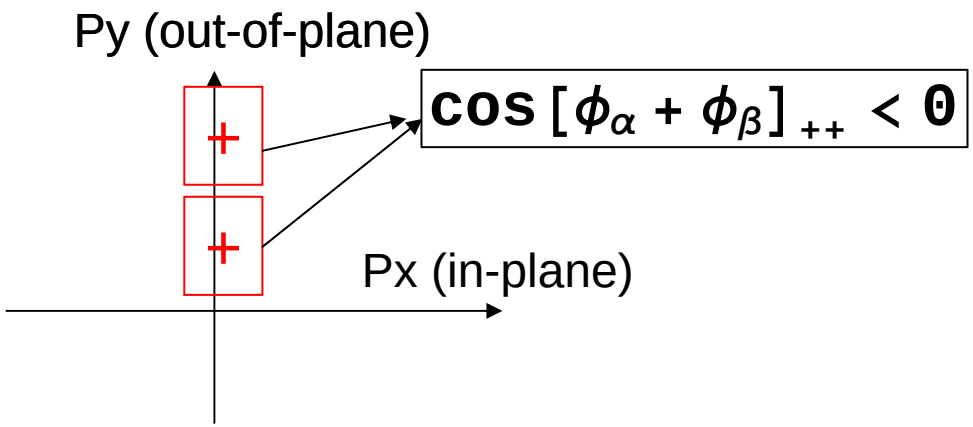
CME expectation



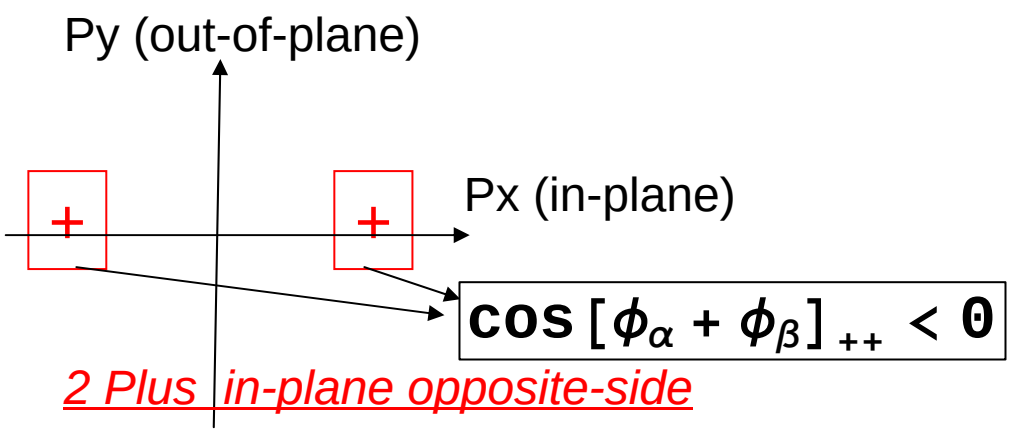
STAR (09)

In-plane v.s. Out-of-plane

Focus on the same charge pair



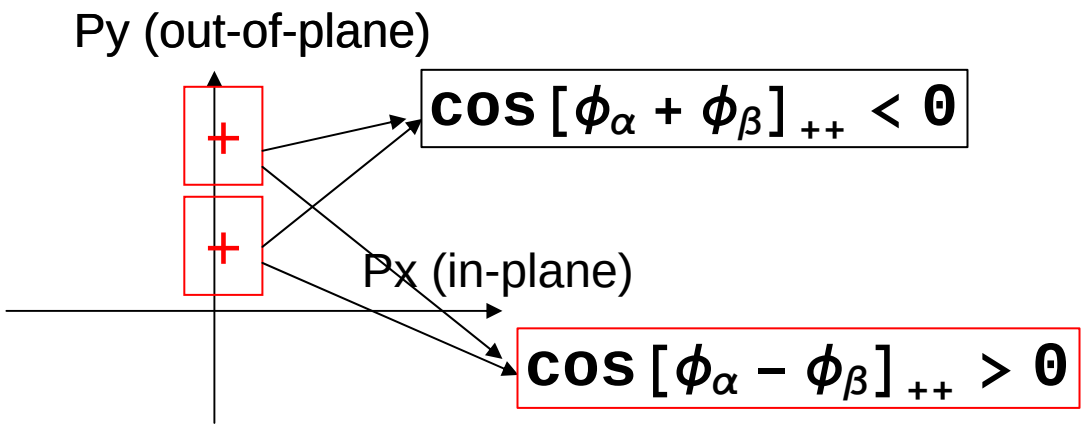
2 Plus out-of-plane same-side



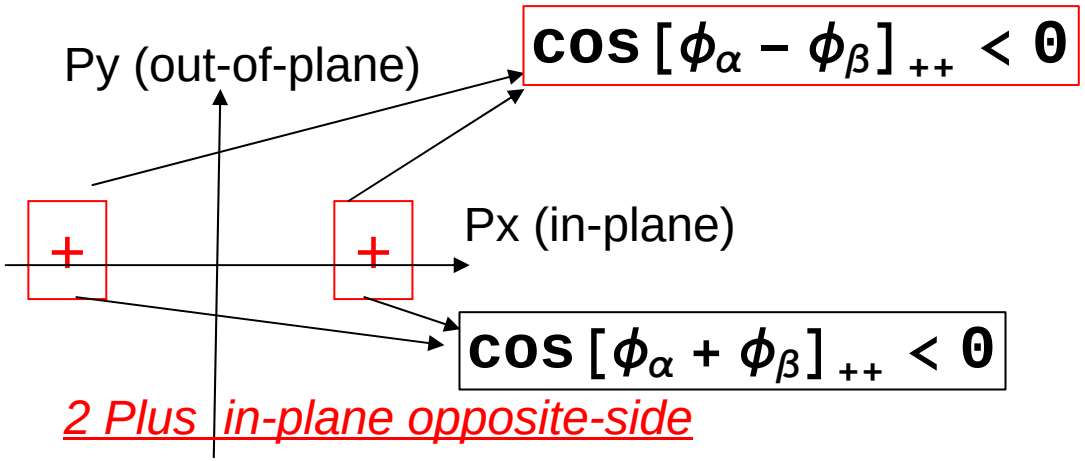
2 Plus in-plane opposite-side

In-plane v.s. Out-of-plane

Focus on the same charge pair



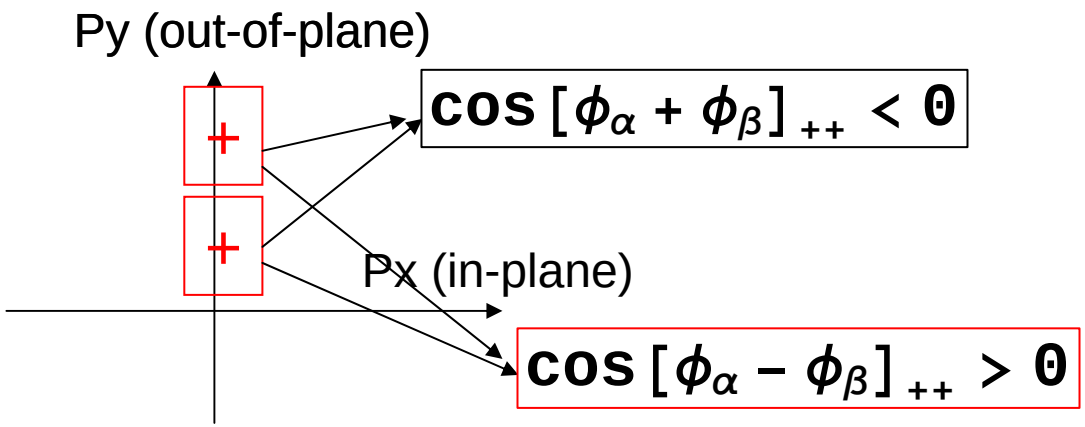
2 Plus out-of-plane same-side



2 Plus in-plane opposite-side

In-plane v.s. Out-of-plane

Focus on the same charge pair



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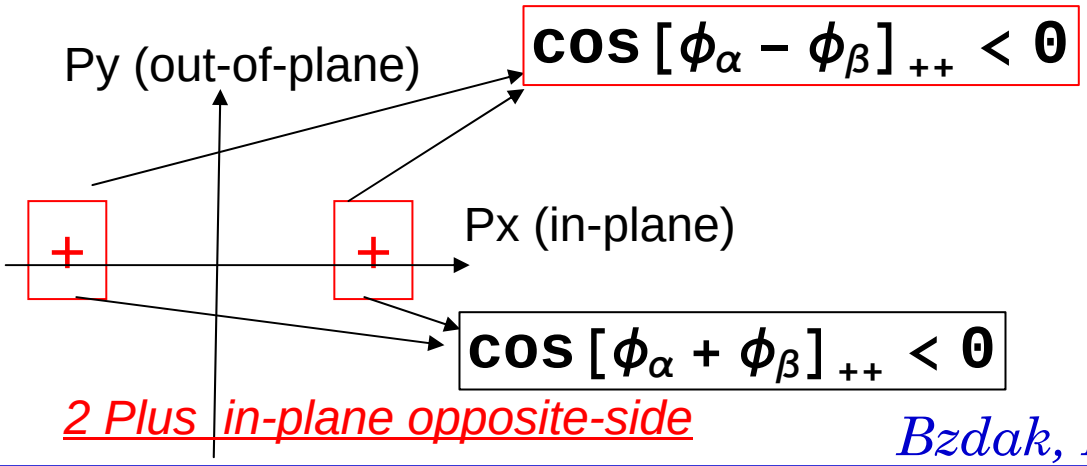
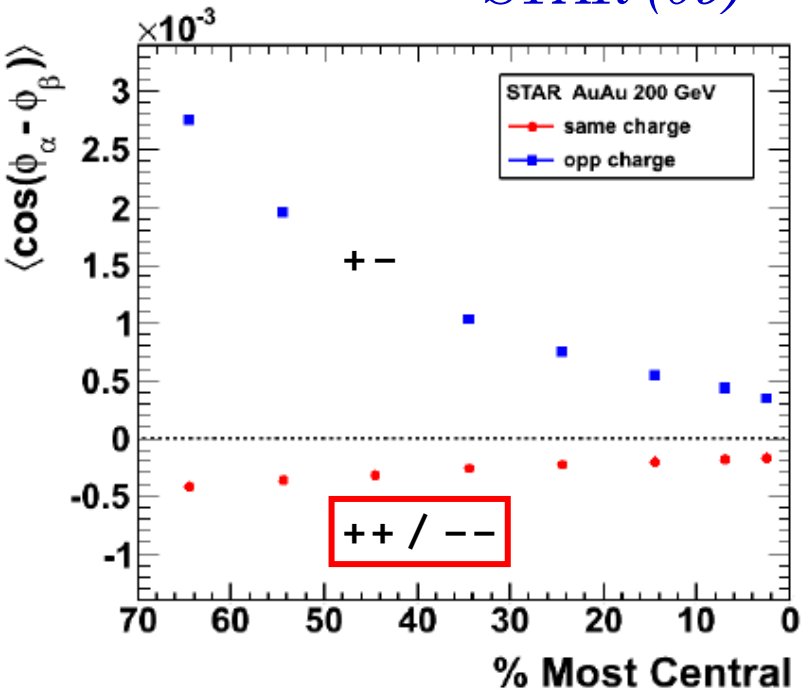


2 Plus in-plane opposite-side

STAR (09)



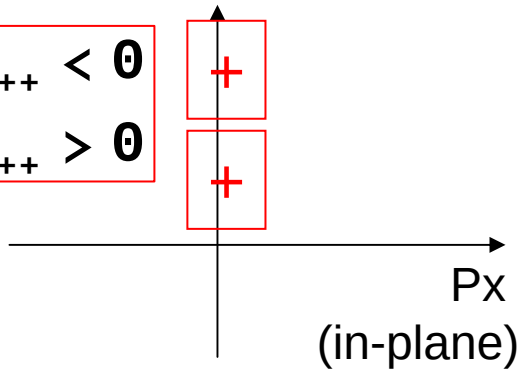
The data favors in-plane configuration.

Bzdak, Koch, JL, PRC81,031901(R),2010

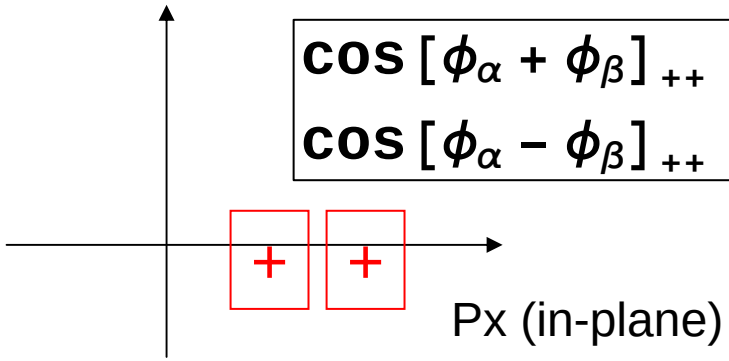
In-plane v.s. Out-of-plane

$\cos[\phi_\alpha + \phi_\beta]_{++} < 0$

$\cos[\phi_\alpha - \phi_\beta]_{++} > 0$



CME

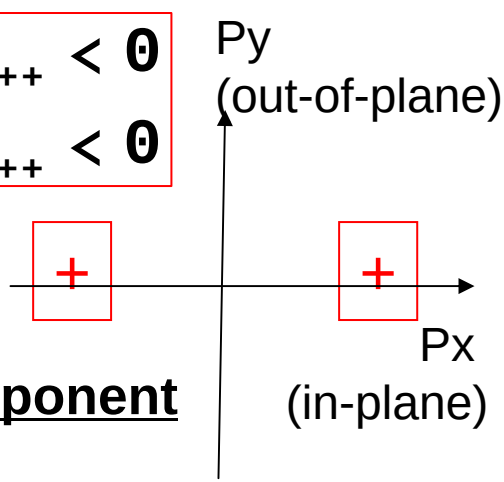


$\cos[\phi_\alpha + \phi_\beta]_{++} > 0$

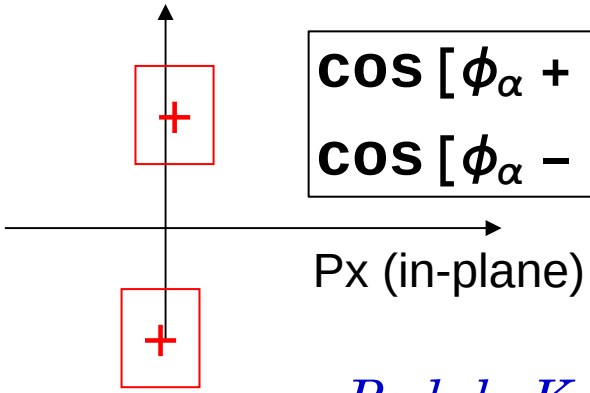
$\cos[\phi_\alpha - \phi_\beta]_{++} > 0$

$\cos[\phi_\alpha + \phi_\beta]_{++} < 0$

$\cos[\phi_\alpha - \phi_\beta]_{++} < 0$



Dominant component seen in DATA



$\cos[\phi_\alpha + \phi_\beta]_{++} > 0$

$\cos[\phi_\alpha - \phi_\beta]_{++} < 0$

Bzdak, Koch, JL (09)
PRC81,031901(R),2010

Projected Correlations

$$\langle \cos[\phi_\alpha - \phi_\beta] \rangle = \langle \cos[\phi_\alpha - \Psi_{RP}] * \cos[\phi_\beta - \Psi_{RP}] \rangle + \langle \sin[\phi_\alpha - \Psi_{RP}] * \sin[\phi_\beta - \Psi_{RP}] \rangle$$

$$\langle \cos[\phi_\alpha + \phi_\beta - 2\Psi_{RP}] \rangle = \langle \cos[\phi_\alpha - \Psi_{RP}] * \cos[\phi_\beta - \Psi_{RP}] \rangle - \langle \sin[\phi_\alpha - \Psi_{RP}] * \sin[\phi_\beta - \Psi_{RP}] \rangle$$

BOTH ARE NEEDED AND IMPORTANT !

In-plane projected correlation

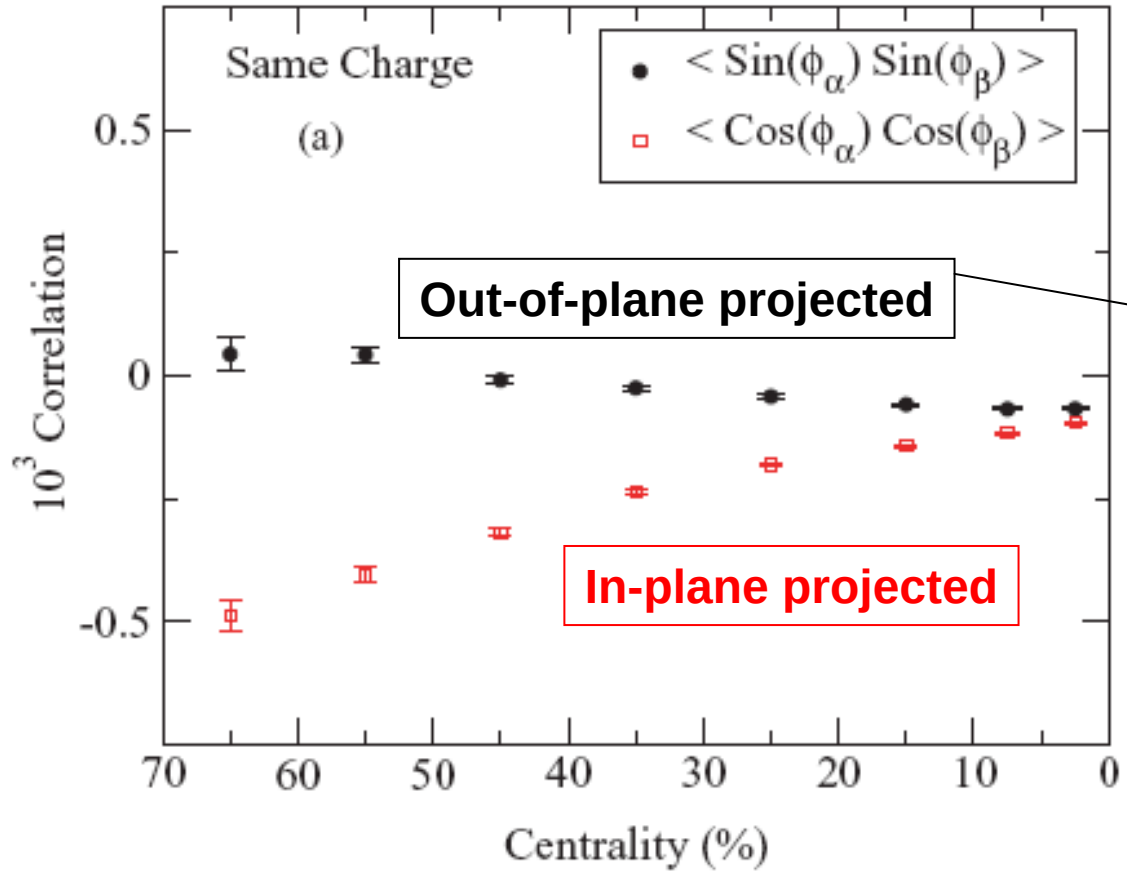
$$\langle \cos[\phi_\alpha - \Psi_{RP}] * \cos[\phi_\beta - \Psi_{RP}] \rangle$$

Out-of-plane projected correlation

$$\langle \sin[\phi_\alpha - \Psi_{RP}] * \sin[\phi_\beta - \Psi_{RP}] \rangle$$

Bzdak, Koch, JL (09)
PRC81,031901(R),2010

Same-Charge Projected Correlations

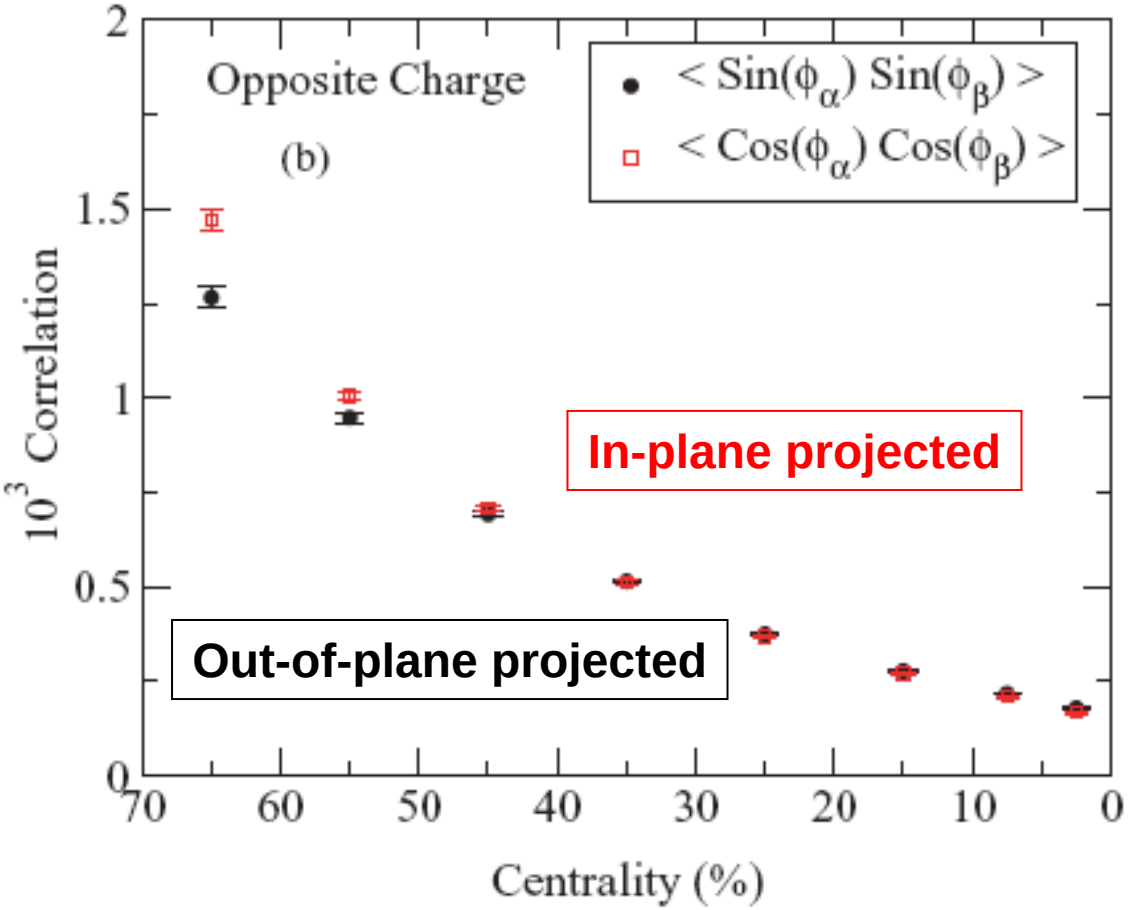


<sin*sin> ~ 0
A very strong constraint we have to live with !

In-plane-dominant, back-to-back

Bzdak, Koch, JL (09)
PRC81,031901(R),2010

Opposite-Charge Projected Correlations



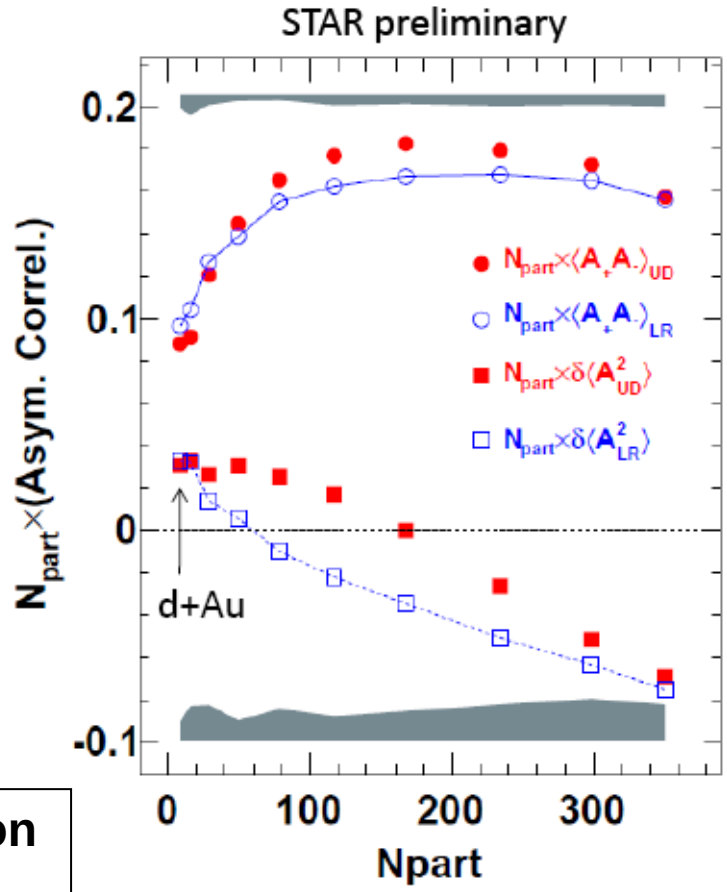
In/out-plane the same, same-side aligned

Bzdak, Koch, JL (09)
PRC81,031901(R),2010

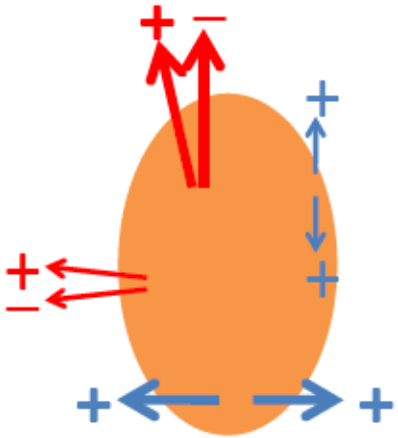
Independent Measurements

Fuqiang Wang

Charge Asym. Correl. Results



- Oppo-sign aligned; $\langle A_+A_-\rangle_{UD} > \langle A_+A_-\rangle_{LR}$
  LPV expects: $\langle A_+A_-\rangle_{UD} < \langle A_+A_-\rangle_{LR}$
  Contradicts LPV expectations.



- Same-sign back-to-back in central, unexpected from *only* LPV.
  Data: $\langle A^2\rangle_{UD} > \langle A^2\rangle_{LR}$
  LPV expects: $\langle A^2\rangle_{UD} > \langle A^2\rangle_{LR}$

Same conclusion as our analysis

4/29/2010 P- and CP-odd Effects in Hot and Dense Matter -- Fuqiang Wang 7

CURRENT STATUS

THEORY:

- basic idea is important and convincing; theoretical studies with Q and B;
- LPV interpretation: need to put in realistic modeling and be quantitative
- certain alternative non-LPV explanations proposed but need more works
- physical origin of the strong background correlation? No progress yet !

EXPERIMENT:

- interesting correlations measured by STAR; (PHENIX catching up)
- certain features of the data are consistent with LPV interpretation
- to say the very least: certain strong background correlations that are apparently from non-LPV origin → call for critical investigations!
- Pt & eta differential study of projected correlations
- Projected correlations in CuCu
- **Other observables?**

NEED BOTH !

$\cos[\phi_\alpha + \phi_\beta]$

$\cos[\phi_\alpha - \phi_\beta]$

Charged Dipole Deformation

Azimuthal distribution:

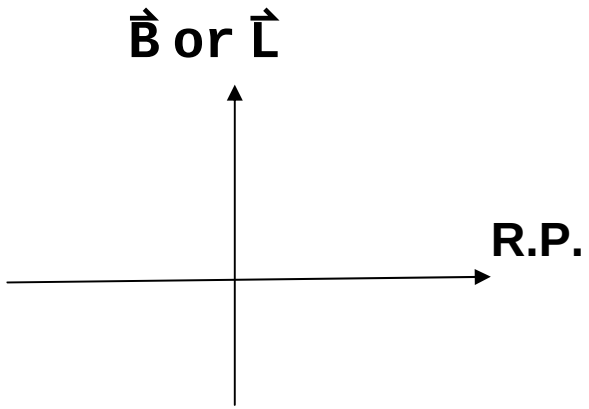
$$f_\chi(\phi, q) \propto 1 + 2\,v_2 \cos(2\phi - 2\Psi_{R.P.}) + 2\,q\,\chi\,d_1 \cos(\phi - \Psi_{C.S.})$$

Quadruple deformation

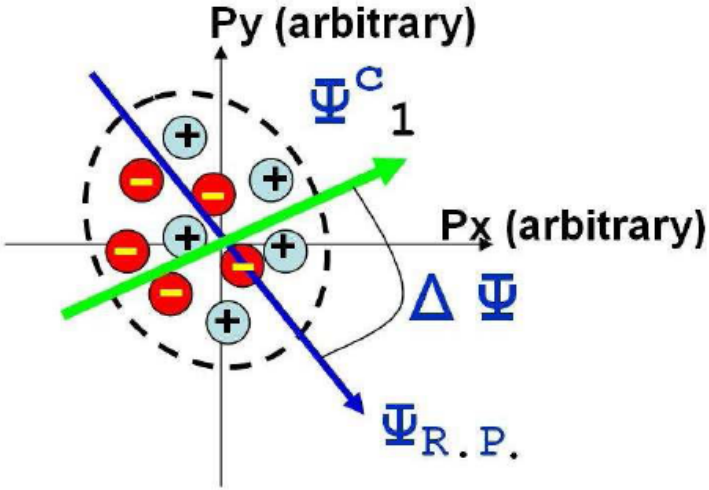
Reaction Plane angle

Charged dipole deformation

Charged dipole angle



The ideal world



The real world

Pinpoint the Dipole

In each event : N particles, (η_i, $p_{t\,i}$, ϕ_i, q_i)

Recall Q2 analysis for elliptic flow:
looking for the maximal quadruple

$$Q_2 \cos 2\Psi_2 \equiv \sum_i \cos 2\phi_i$$

$$Q_2 \sin 2\Psi_2 \equiv \sum_i \sin 2\phi_i$$

In analogy, Q^c_1 analysis:
looking for the maximal dipole

$$Q_1^c \cos \Psi_1^c \equiv \sum_i q_i \cos \phi_i$$

$$Q_1^c \sin \Psi_1^c \equiv \sum_i q_i \sin \phi_i$$

Pinpoint the Dipole

In each event : N particles, (η_i, $p_{t\,i}$, ϕ_i, q_i)

Recall Q2 analysis for elliptic flow:
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In analogy, Q^c_1 analysis:
looking for the maximal dipole

$$Q_1^c \cos \Psi_1^c \equiv \sum_i q_i \cos \phi_i$$

$$Q_1^c \sin \Psi_1^c \equiv \sum_i q_i \sin \phi_i$$

In each event ⇒ (Q_2, Ψ_2) & (Q^c_1, Ψ^c_1)

$$\Delta\Psi \equiv \Psi_1^c - \Psi_2$$

Relative orientation !

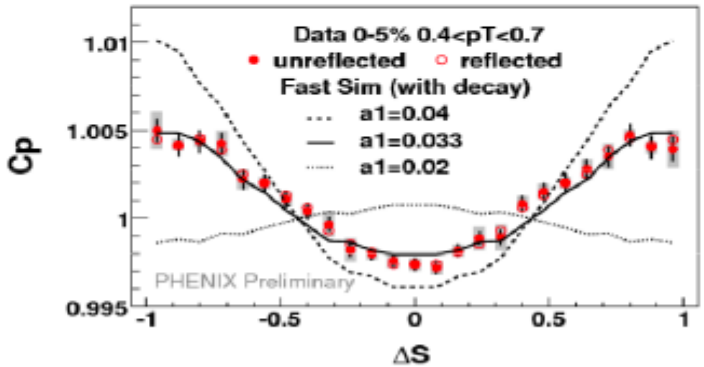
Charge Correlations from PHENIX

Charge correlations PHENIX

Roy Lacey

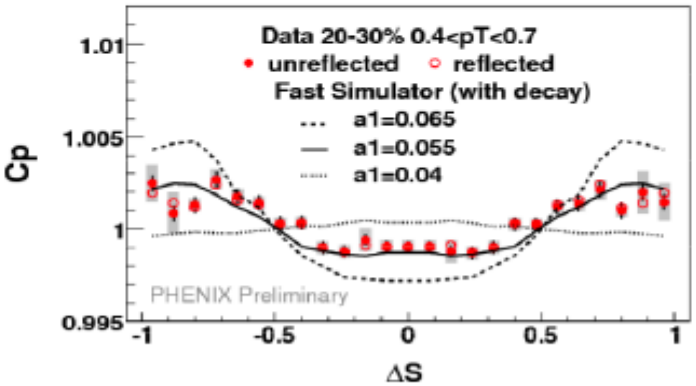
C_p insensitive to flow and jets

Multi-particle correlation Results



Concave shape validates charge asymmetry w.r.t the reaction plane
→ Note the centrality dependence

Multi-particle correlation Results



Concave shape validates charge asymmetry w.r.t the reaction plane

Distribution of out-of-plane dipole: $Q^c_1 * \mathrm{Sin}[\Delta\Psi]$

ONLY PARTIAL INFO; CANNOT TELL ANGLE

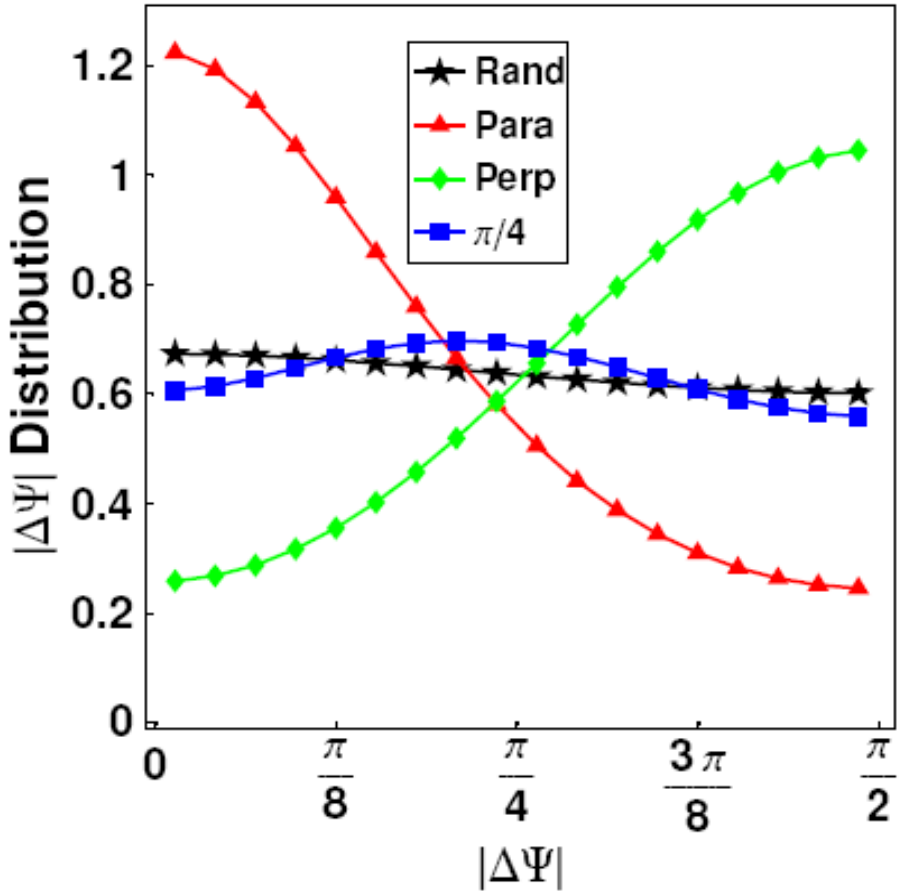
Discriminating the Angular Pattern

JL, Koch, Bzdak (to appear)

Azimuthal distribution:

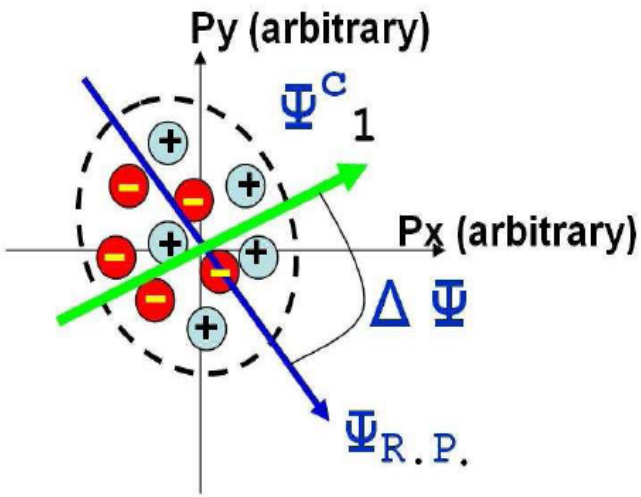
$$f_\chi(\phi, q) \propto 1 + 2\, v_2 \cos(2\phi - 2\Psi_{R.P.}) + 2\, q\, \chi\, d_1 \cos(\phi - \Psi_{C.S.})$$

Monte Carlo sampling of events according the above with different relative orientation:
(a) Random (b) parallel
(c) perpendicular (d) 45deg.
Then applying the
joint Q2 & Q^c_1 analysis !
[details: 200 +, 200 -, v2 =0.1 , d1=0.05]



* Great discriminating power, may clarify the situation;
* Robust: surviving tests with built-in cluster type correlations.

Measure the Relative Orientation



$$Q_1^c \cos \Psi_1^c \equiv \sum_i q_i \cos \phi_i$$

$$Q_1^c \sin \Psi_1^c \equiv \sum_i q_i \sin \phi_i$$

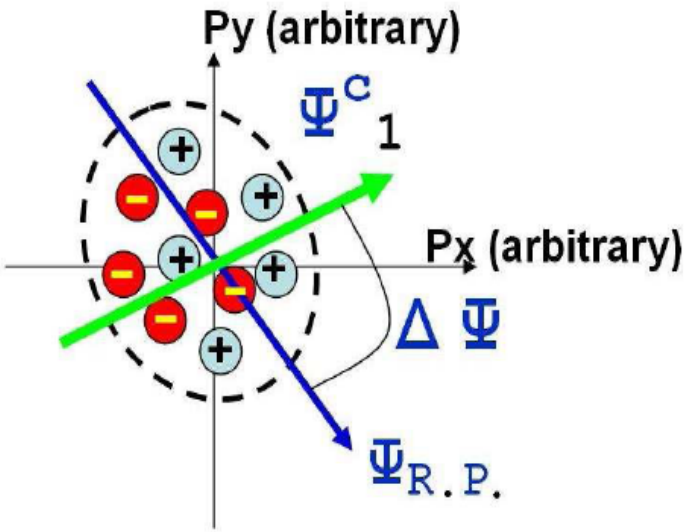
$$Q_2 \cos 2\Psi_2 \equiv \sum_i \cos 2\phi_i$$

$$Q_2 \sin 2\Psi_2 \equiv \sum_i \sin 2\phi_i$$

in a given event

$$\cos[2*(\Psi^c_1 - \Psi_2)] = \frac{N_{ch} + 2\sum q_i q_j \cos(\phi_i - \phi_j) + \sum \cos(2\phi_i - 2\phi_j) + \sum q_i q_j \cos(\phi_i + \phi_j - 2\phi_k)}{[N_{ch} + \sum \cos(2\phi_i - 2\phi_j)]^{1/2} * [N_{ch} + \sum q_i q_j \cos(\phi_i - \phi_j)]}$$

Measure the Relative Orientation



$$< \cos[2*(\Psi^c_1 - \Psi_2)] >$$

-1 — Out-of-plane

+1 — In-plane

- involves multi-particle correlations
- NO need of reaction plane
- current data can NOT tell about it: please measure !

Summary

- Local Parity Violation and Chiral Magnetic Effect; prediction for charge separation at RHIC
- STAR data showed very interesting patterns that are partly consistent with LPV interpretation
- A key aspect remains problematic --- out-of-plane orientation; Projected correlations dominated by

  same-charge: back-to-back, in-plane

  opposite-charge: aligned, in/out-plane similar
- New useful probe

  intuitive approach: relative angle between dipole/R.P.

Thank you !

Backup Slides