Remarks on possible local parity violation in heavy ion collisions

Adam Bzdak
Lawrence Berkeley National Laboratory

in collaboration with Volker Koch and Jinfeng Liao

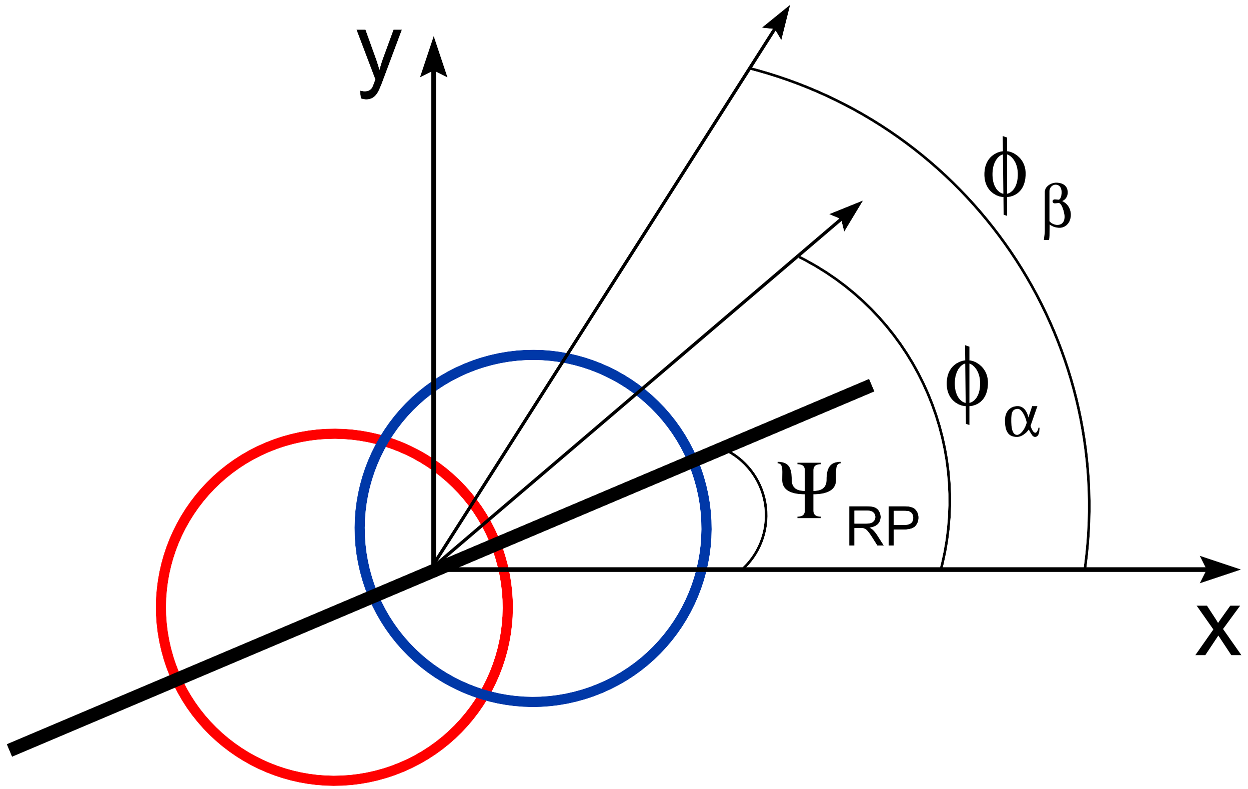
arXiv:0912.5050 [nucl-th] (PRC), arXiv:1005.5380 [nucl-th]

Outline

- introduction
- STAR data: integrated signal, p_t distribution
- v_2 contribution and Coulomb effect
- new dipole analysis
- conclusions

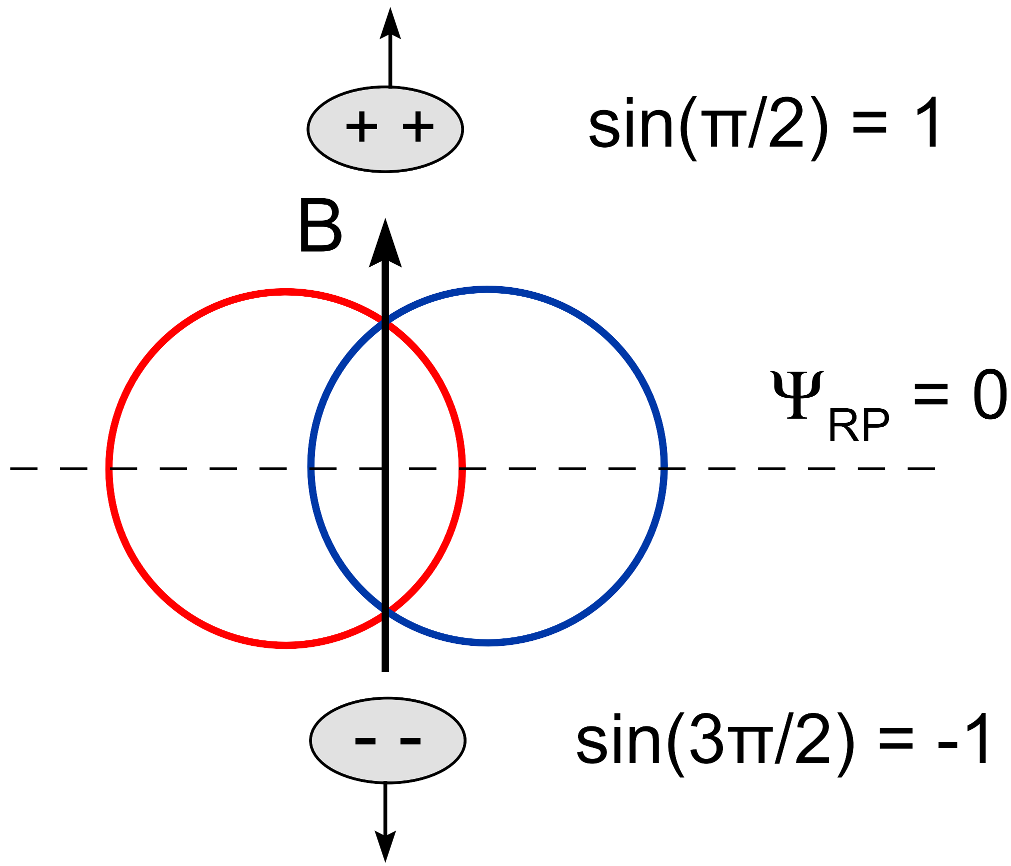
Introduction

Reaction plane



We work in the frame where $\Psi_{\mathbf{RP}} = 0$

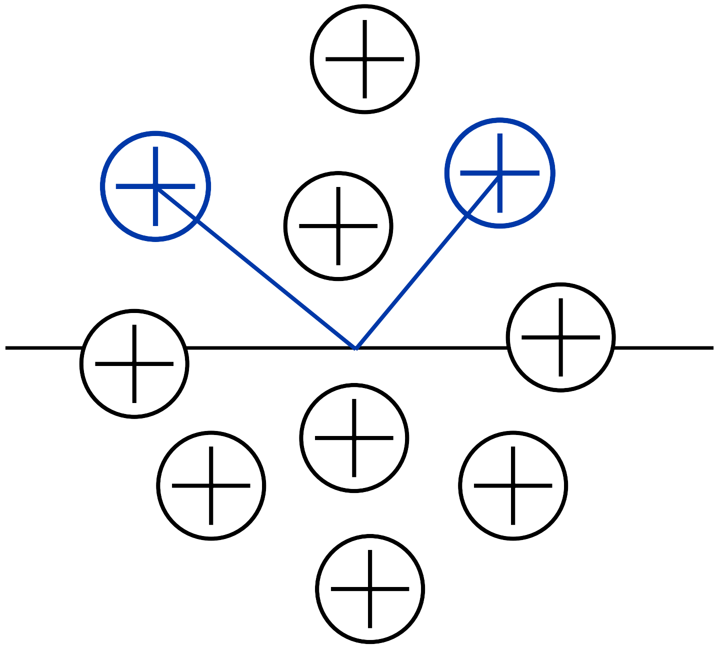
Chiral Magnetic Effect



$$\boxed{\left\langle \sin(\phi_\alpha)\sin(\phi_\beta)\right\rangle_{same} > 0, \qquad \left\langle \cos(\phi_\alpha)\cos(\phi_\beta)\right\rangle_{same} = 0}$$

$$\left\langle \cos(\phi_\alpha + \phi_\beta)\right\rangle_s = \left\langle \cos(\phi_\alpha)\cos(\phi_\beta)\right\rangle_s - \left\langle \sin(\phi_\alpha)\sin(\phi_\beta)\right\rangle_s < 0$$

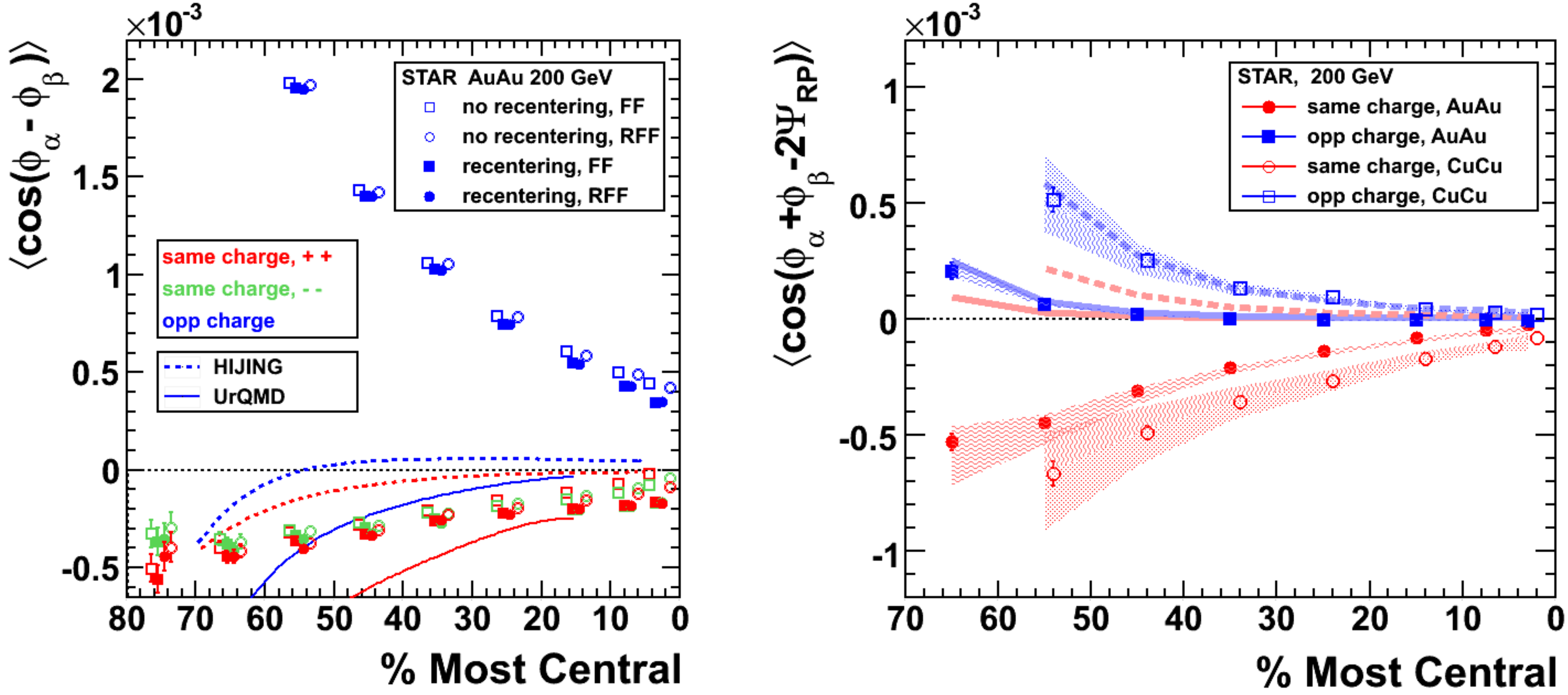
Definition:



$$\left\langle \cos(\phi_\alpha - \phi_\beta) \right\rangle_{same} = \left\langle \frac{\sum\limits_{i \neq k} \cos(\phi_i - \phi_k)}{\sum\limits_{i \neq k} 1} \right\rangle$$

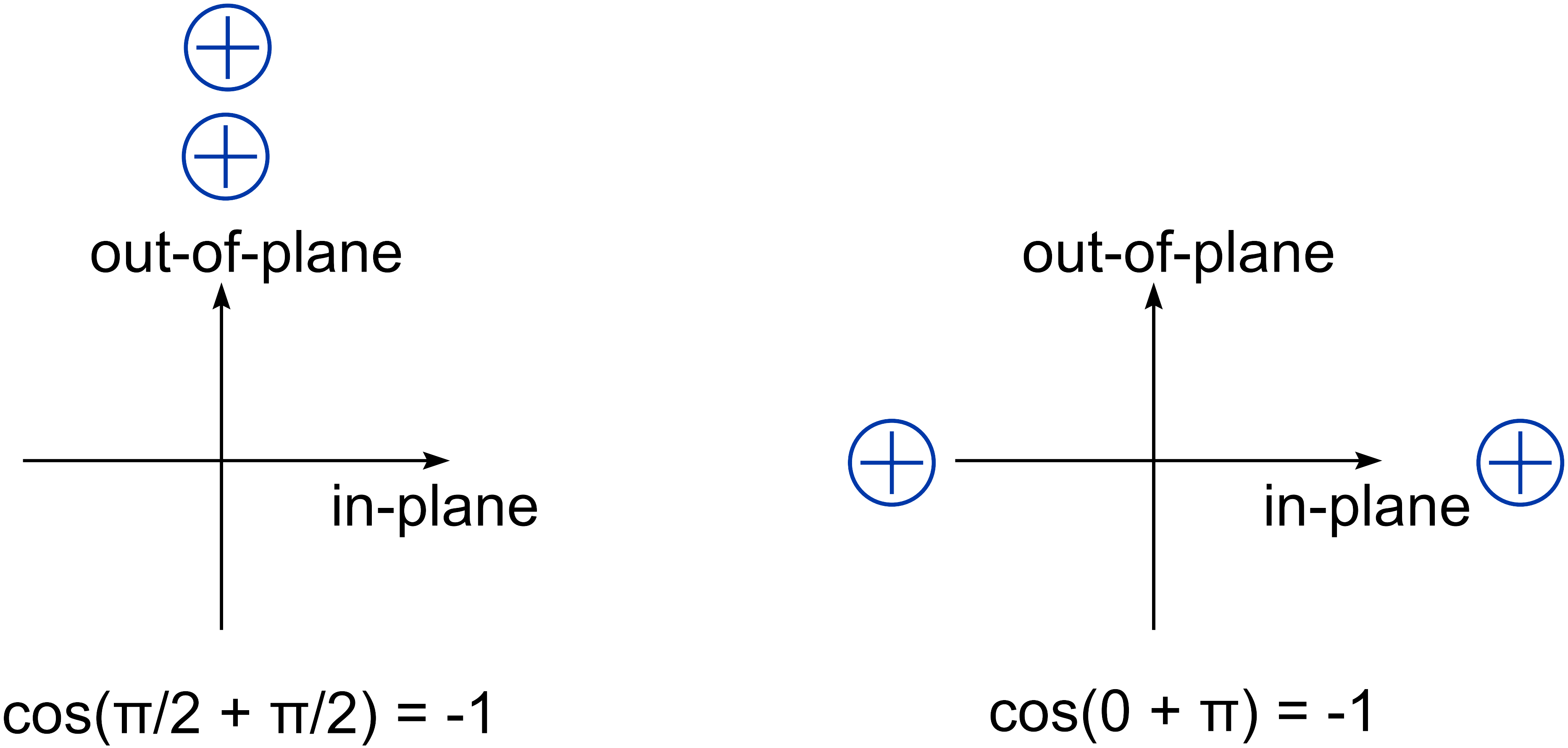
Integrated signal

STAR data: PRL 103 (2009) 251601; PRC 81 (2010) 54908



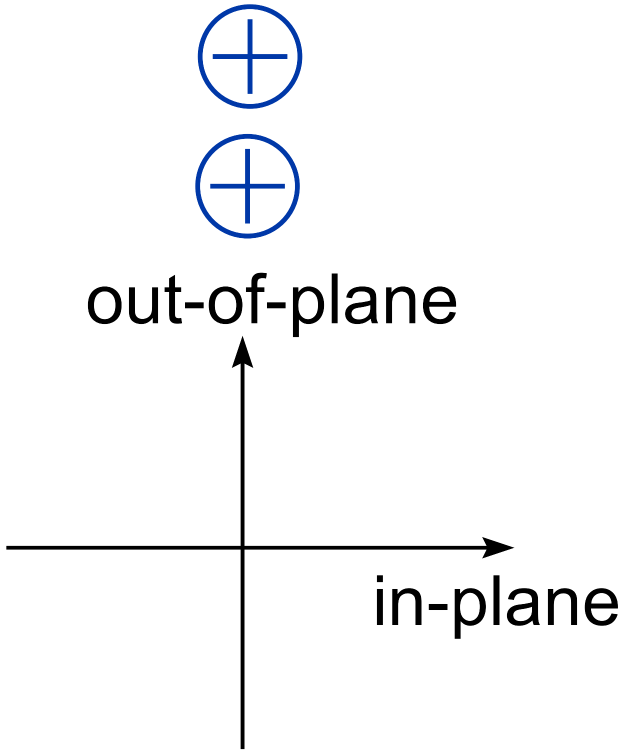
$$\langle \cos(\phi_\alpha + \phi_\beta) \rangle_{same} < 0$$

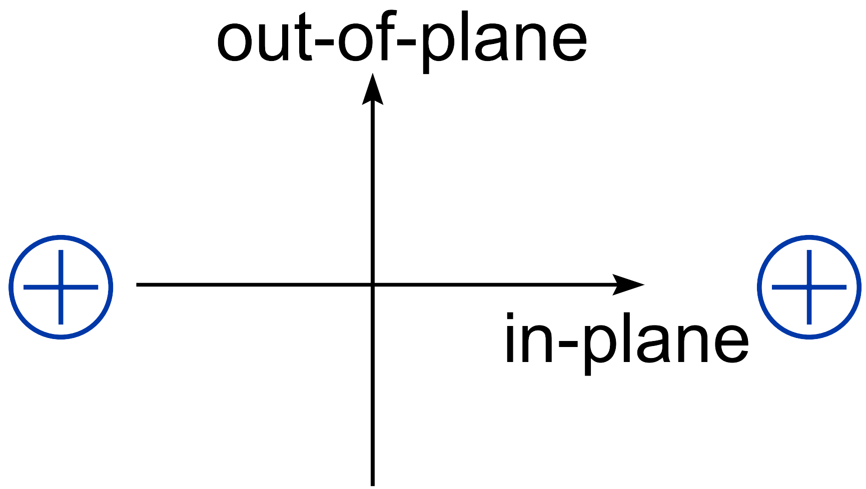
Chiral Magnetic Effect vs 'Trouble' Effect



How to distinguish between the two?

Chiral Magnetic Effect vs 'Trouble' Effect





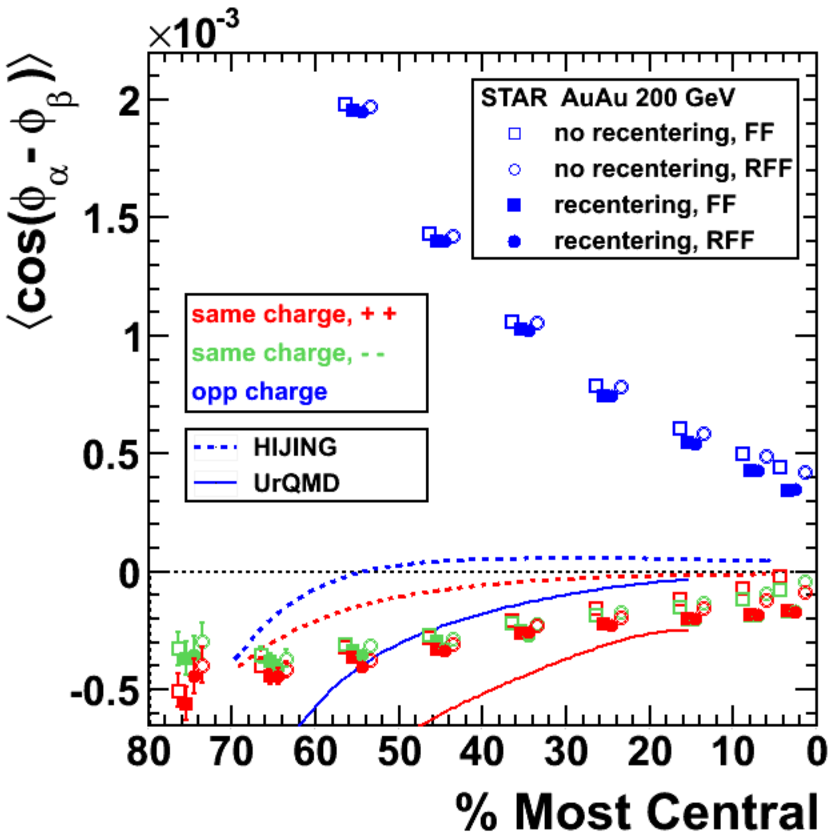
$\cos(\pi/2 + \pi/2) = -1$

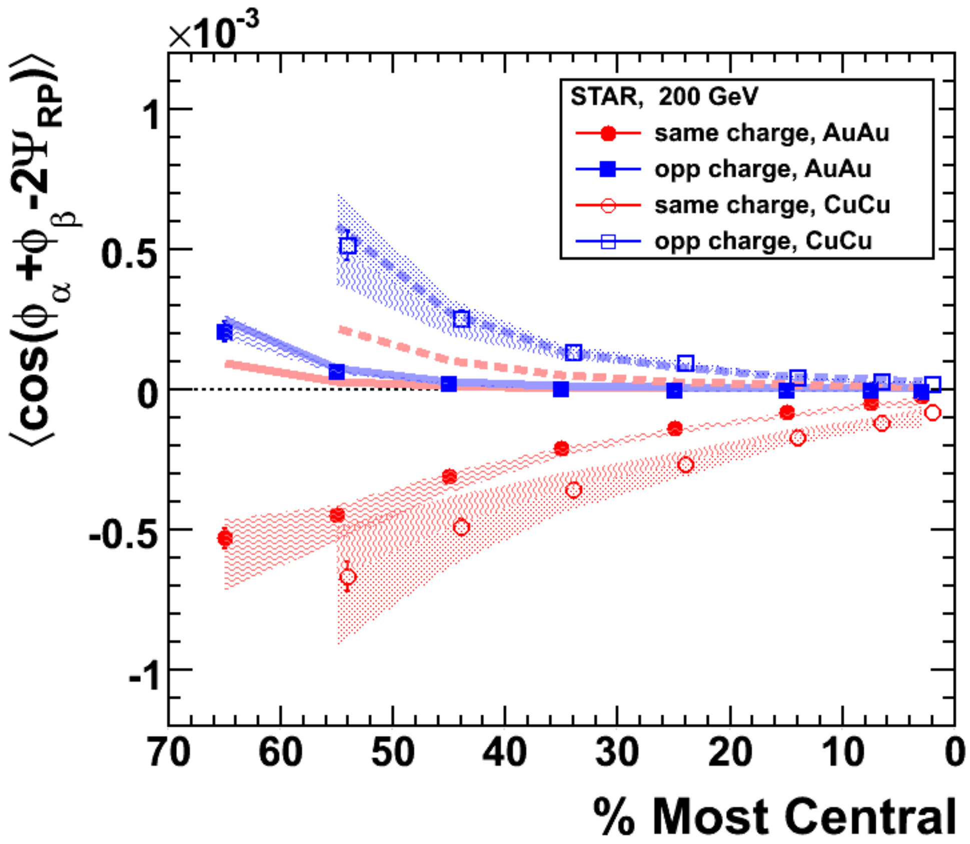
$\cos(\pi/2 - \pi/2) = +1$

$\cos(0 + \pi) = -1$

$\cos(0 - \pi) = -1$

STAR data





$$\boxed{\left\langle \cos(\phi_\alpha - \phi_\beta) \right\rangle_{same} \simeq \left\langle \cos(\phi_\alpha + \phi_\beta) \right\rangle_{same} < 0}$$

$$\left\langle \cos(\phi_\alpha - \phi_\beta) \right\rangle_{opposite} > 0; \quad \left\langle \cos(\phi_\alpha + \phi_\beta) \right\rangle_{opposite} \approx 0$$

from

$$\left\langle \cos(\phi_\alpha - \phi_\beta) \right\rangle = \left\langle \cos(\phi_\alpha) \cos(\phi_\beta) \right\rangle + \left\langle \sin(\phi_\alpha) \sin(\phi_\beta) \right\rangle$$

$$\left\langle \cos(\phi_\alpha + \phi_\beta) \right\rangle = \left\langle \cos(\phi_\alpha) \cos(\phi_\beta) \right\rangle - \left\langle \sin(\phi_\alpha) \sin(\phi_\beta) \right\rangle$$

we obtain

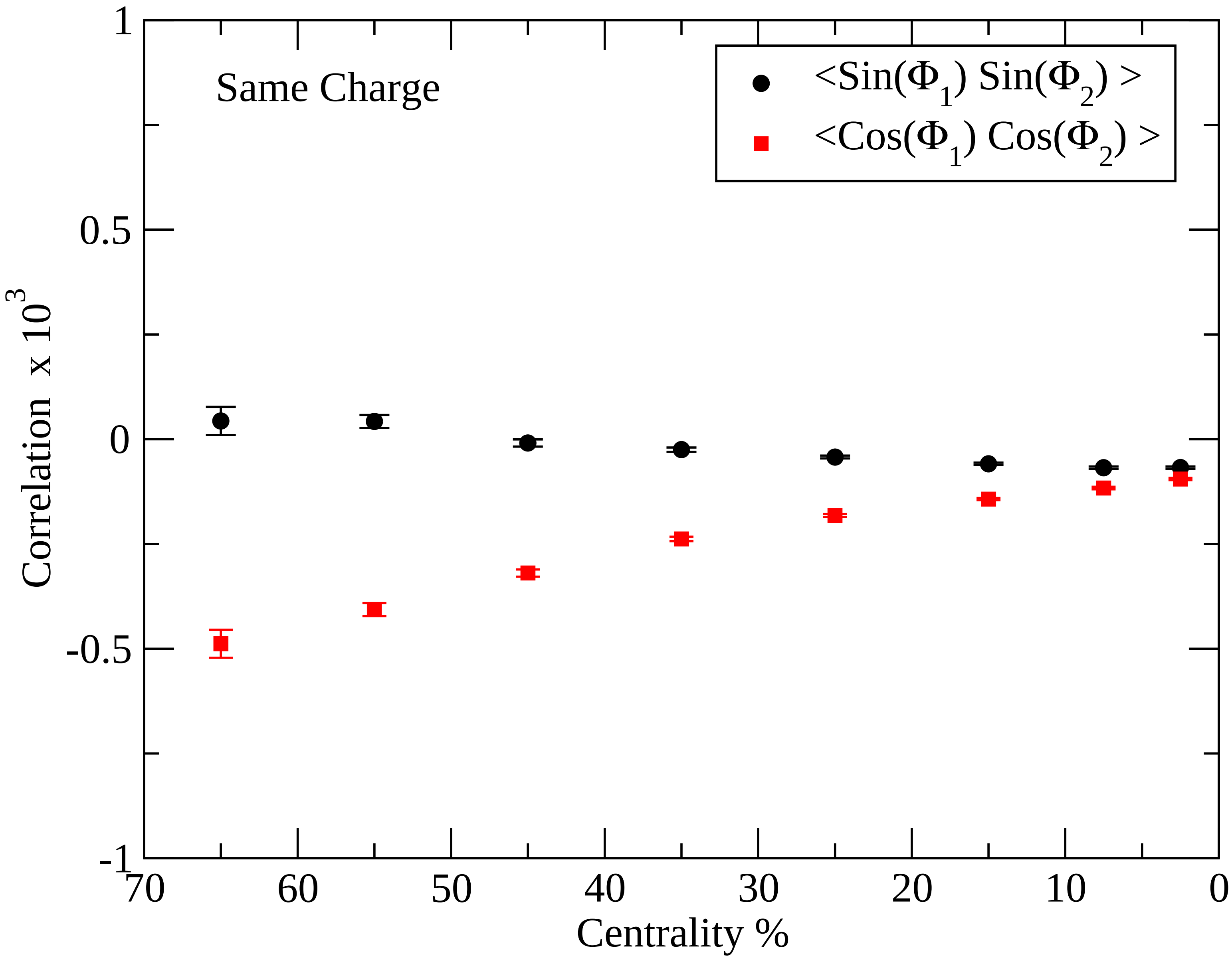
$$\left\langle \sin(\phi_\alpha) \sin(\phi_\beta) \right\rangle_{same} \simeq 0$$

$$\left\langle \cos(\phi_\alpha) \cos(\phi_\beta) \right\rangle_{same} < 0$$

and

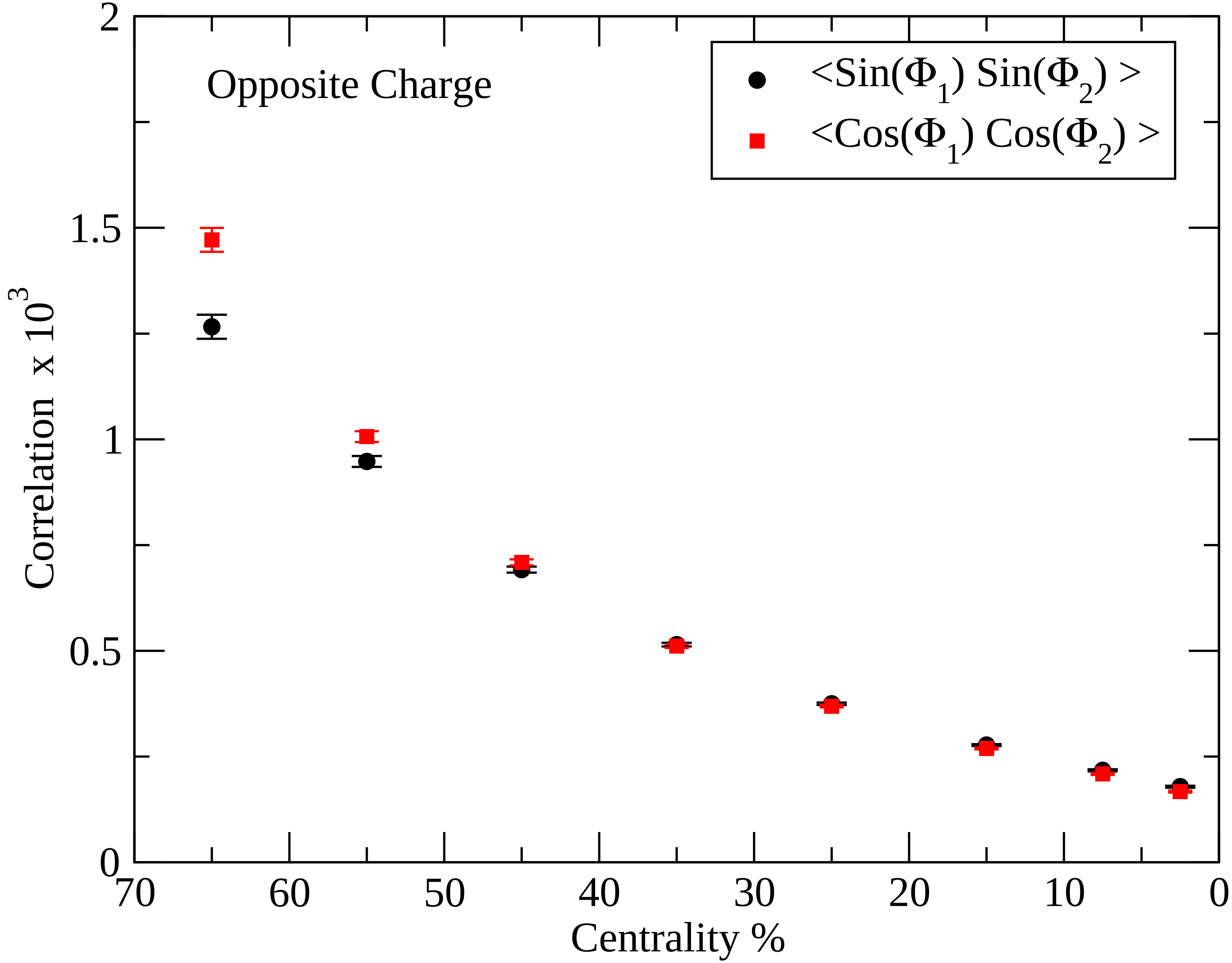
$$\left\langle \sin(\phi_\alpha) \sin(\phi_\beta) \right\rangle_{opposite} \simeq \left\langle \cos(\phi_\alpha) \cos(\phi_\beta) \right\rangle_{opposite} > 0$$

Same sign



Same Charge
<Sin(Φ1) Sin(Φ2) >
<Cos(Φ1) Cos(Φ2) >
Correlation x 10^3
Centrality %
1
0.5
0
-0.5
-1
70
60
50
40
30
20
10
0

Opposite sign



where is the parity?

$$\left\langle \sin(\phi_\alpha)\sin(\phi_\beta)\right\rangle_{same} \simeq 0$$

$$\left\langle \sin(\phi_\alpha)\sin(\phi_\beta)\right\rangle_{same} \equiv P + B_{out}$$

in consequence:

$$\boxed{\mathbf{P \simeq -B_{out}}}$$

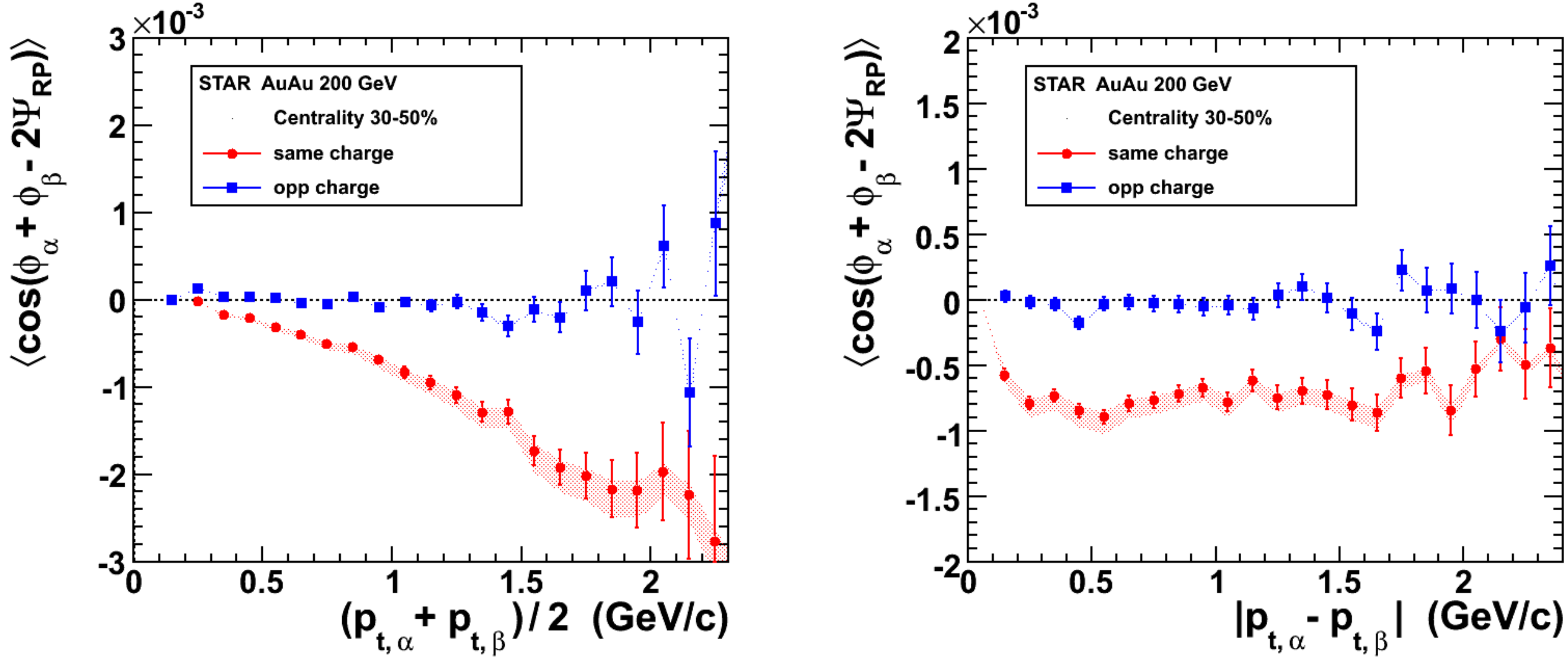
This is an unexpected relation ...

maybe it is lucky coincidence?

in order to answer that question we need differential (p_t, η) $\left\langle \cos(\boldsymbol{\phi_\alpha} + \boldsymbol{\phi_\beta})\right\rangle$ and $\left\langle \cos(\boldsymbol{\phi_\alpha} - \boldsymbol{\phi_\beta})\right\rangle$

p_t distribution

STAR data



$\langle \cos(\phi_\alpha + \phi_\beta) \rangle \propto p_{t,\alpha} + p_{t,\beta}$ and very weak dependence on $|p_{t,\alpha} - p_{t,\beta}|$

We will show that the 'true' signal is located at low p_t

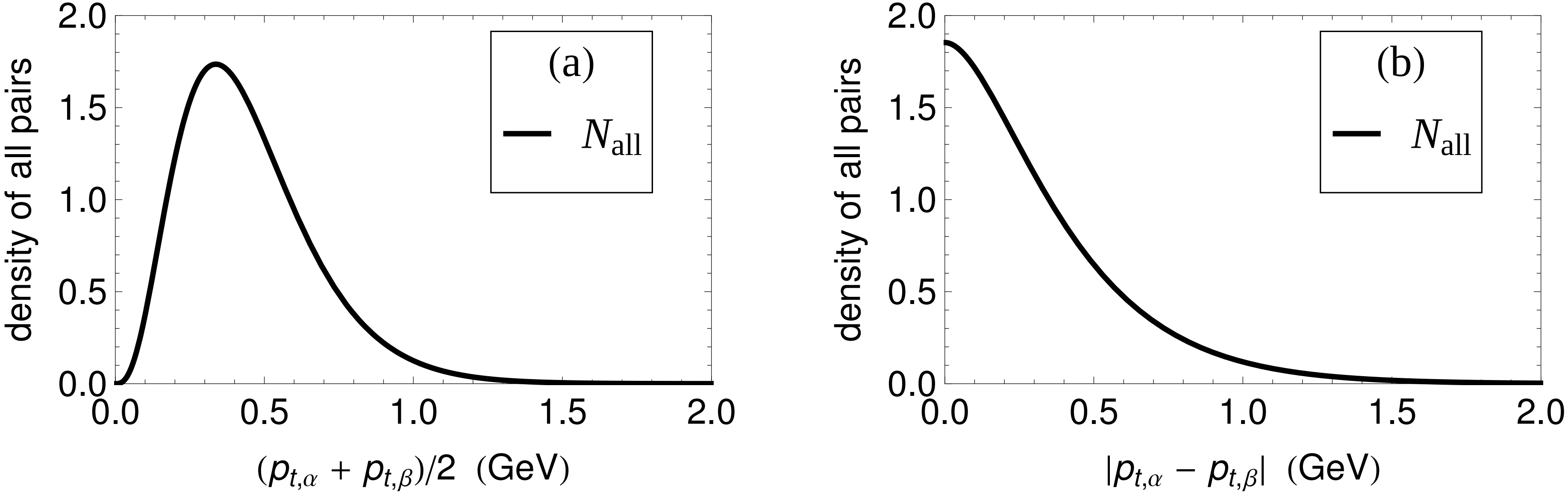
Definition

$$\langle \cos(\phi_\alpha + \phi_\beta) \rangle = \frac{\text{No. of correlated pairs } [\cos(\phi_\alpha + \phi_\beta)]}{\text{No. of all pairs}} \sim \frac{1}{1000}$$

We can calculate the (differential) number of all pairs

$$\int \exp\left(\frac{-p_{t,\alpha}}{T}\right) \exp\left(\frac{-p_{t,\beta}}{T}\right) d^2p_{t,\alpha} d^2p_{t,\beta} \Bigg|_{\substack{\text{fixed } p_{t,\alpha}+p_{t,\beta} \text{ or} \\ \text{fixed } |p_{t,\alpha}-p_{t,\beta}|}}$$

The number of all pairs vs $(p_{t,\alpha} + p_{t,\beta})$ and $\left|p_{t,\alpha} - p_{t,\beta}\right|$

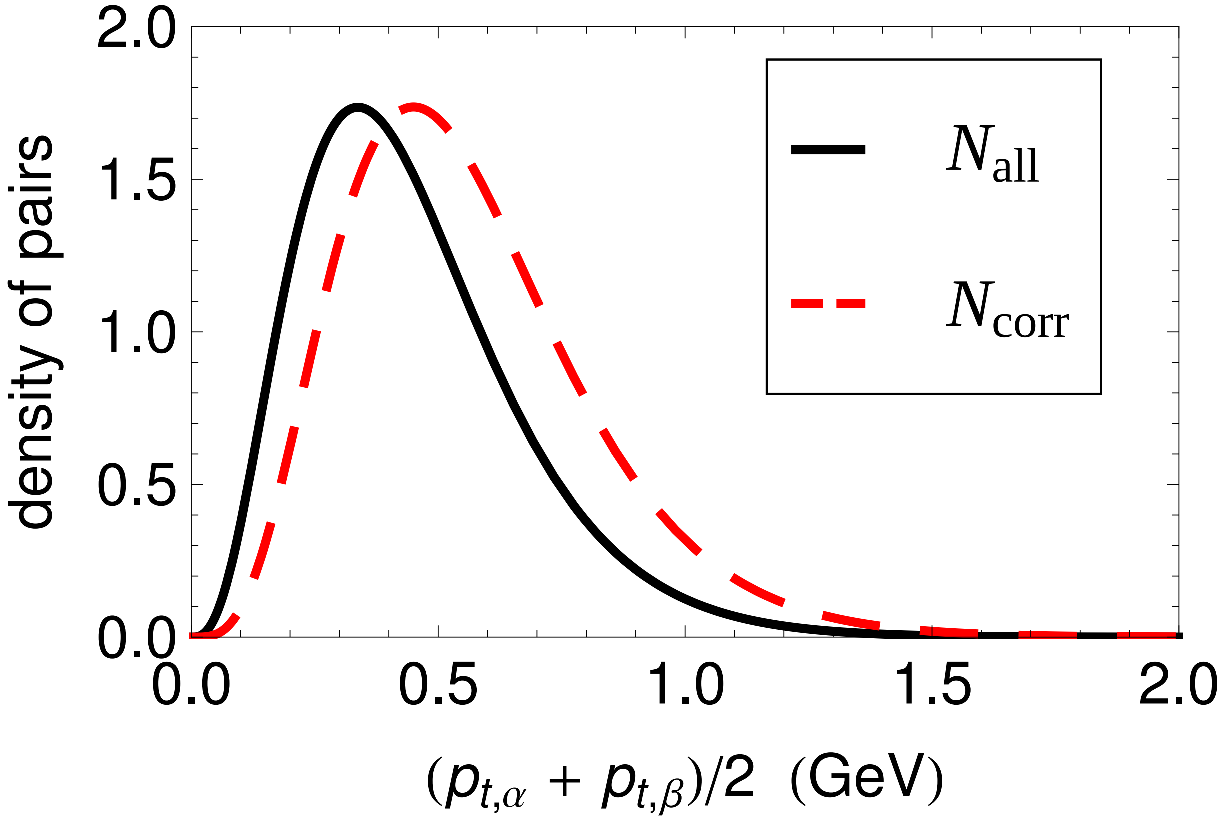


From that we can obtain p_t dependence of the number of correlated pairs:

– $\left|p_{t,\alpha} - p_{t,\beta}\right|$ distribution is as above (right plot)

– and multiply the left plot by $(p_{t,\alpha} + p_{t,\beta})$ ...

... we obtain [all pairs (black), correlated pairs (red)]



The observed signal is NOT inconsistent with the Chiral Magnetic Effect

v_2 contribution (and Coulomb effect)

$$\left\langle \sin(\phi_\alpha)\sin(\phi_\beta)\right\rangle_{same} \equiv P + B_{out}$$

$$\left\langle \cos(\phi_\alpha)\cos(\phi_\beta)\right\rangle_{same} \equiv B_{in}$$

STAR hope: $B_{in} \simeq B_{out}$ so that $|B_{in} - B_{out}| << P$, then

$$\left\langle \cos(\phi_\alpha + \phi_\beta)\right\rangle = \left\langle \cos(\phi_\alpha)\cos(\phi_\beta)\right\rangle - \left\langle \sin(\phi_\alpha)\sin(\phi_\beta)\right\rangle \approx -P$$

$$\left\langle \cos(\phi_\alpha - \phi_\beta)\right\rangle = \left\langle \cos(\phi_\alpha)\cos(\phi_\beta)\right\rangle + \left\langle \sin(\phi_\alpha)\sin(\phi_\beta)\right\rangle \approx 2B_{in} + P$$

How to define correlation that does not depend on the reaction plane?

Are there correlations that do not depend on the reaction plane?

Let us fix the reaction plane Ψ_{RP}

$$p_2(\phi_1, \phi_2, \Psi_{RP}) = p(\phi_1, \Psi_{RP}) p(\phi_2, \Psi_{RP}) \left[1 + C\left(\phi_1 - \phi_2\right)\right]$$

thus for ALL 2-particle correlations that do not depend on the reaction plane we obtain

$$\boxed{B_{in} - B_{out} \propto v_2 \quad \Rightarrow \quad \left\langle \cos(\phi_\alpha + \phi_\beta) \right\rangle \propto v_2}$$

This is also true for correlations depending on $\left|\vec{k}_1 - \vec{k}_2\right|$ or $\left|\vec{k}_1 + \vec{k}_2\right|$

Indeed: $\left|\vec{k}_1 \pm \vec{k}_2\right|^2 \sim \vec{k}_1 \cdot \vec{k}_2 \sim \cos\left(\phi_1 - \phi_2\right)$

As an example we calculated the Coulomb effect (Gamow factor):

$$\langle \cos(\phi_\alpha + \phi_\beta) \rangle_{same} \approx -0.5 \cdot 10^{-3}$$

$$\langle \cos(\phi_\alpha - \phi_\beta) \rangle_{same} \approx -2.0 \cdot 10^{-3}$$

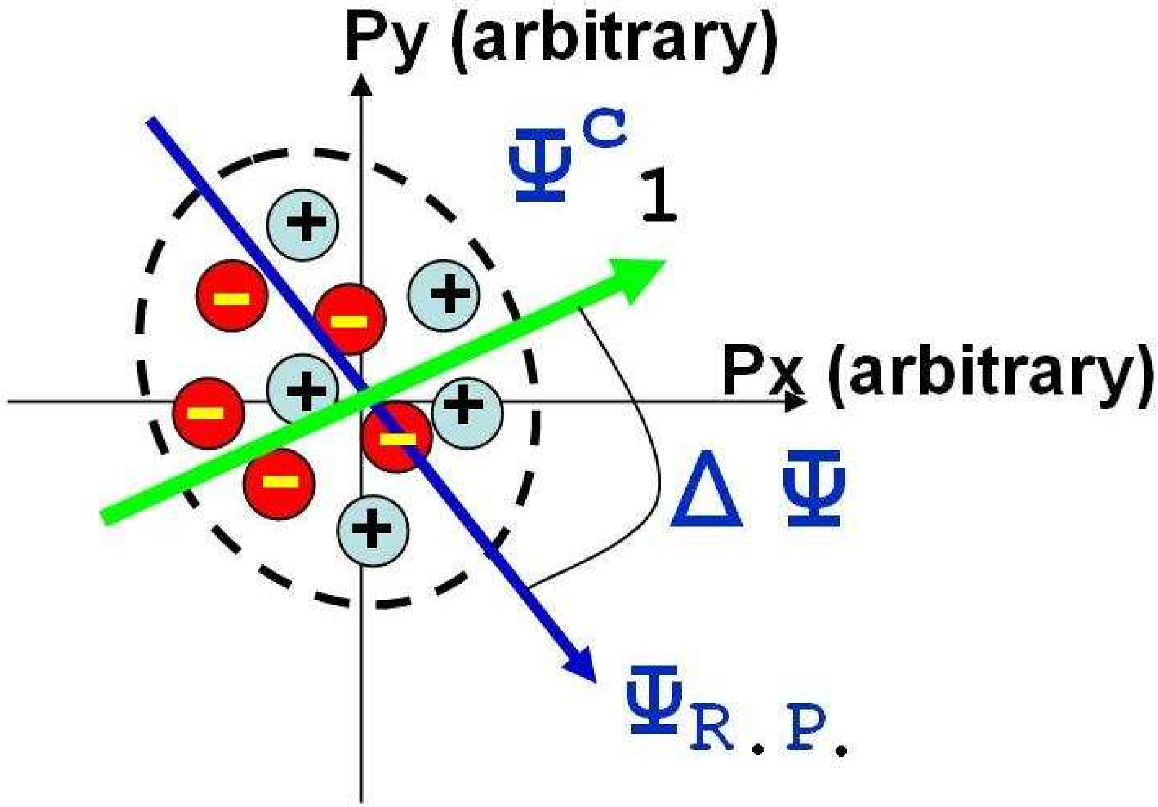
The Gamow factor is known to significantly overestimate the effect.

Probably not enough to explain the data!

It is clear that we have to study all sources of correlations, not only those explicitly dependent on the reaction plane orientation

Dipole analysis

In each event we can measure size and orientation Ψ_1^c of the dipole



We can also determine orientation of the particle reaction plane Ψ_2 and study the relation between Ψ_1^c and Ψ_2

well known Q_2 analysis for elliptic flow:

$$Q_2 \cos(2\Psi_2) = \sum_i \cos(2\phi_i)$$

$$Q_2 \sin(2\Psi_2) = \sum_i \sin(2\phi_i)$$

new Q_1^c dipole analysis:

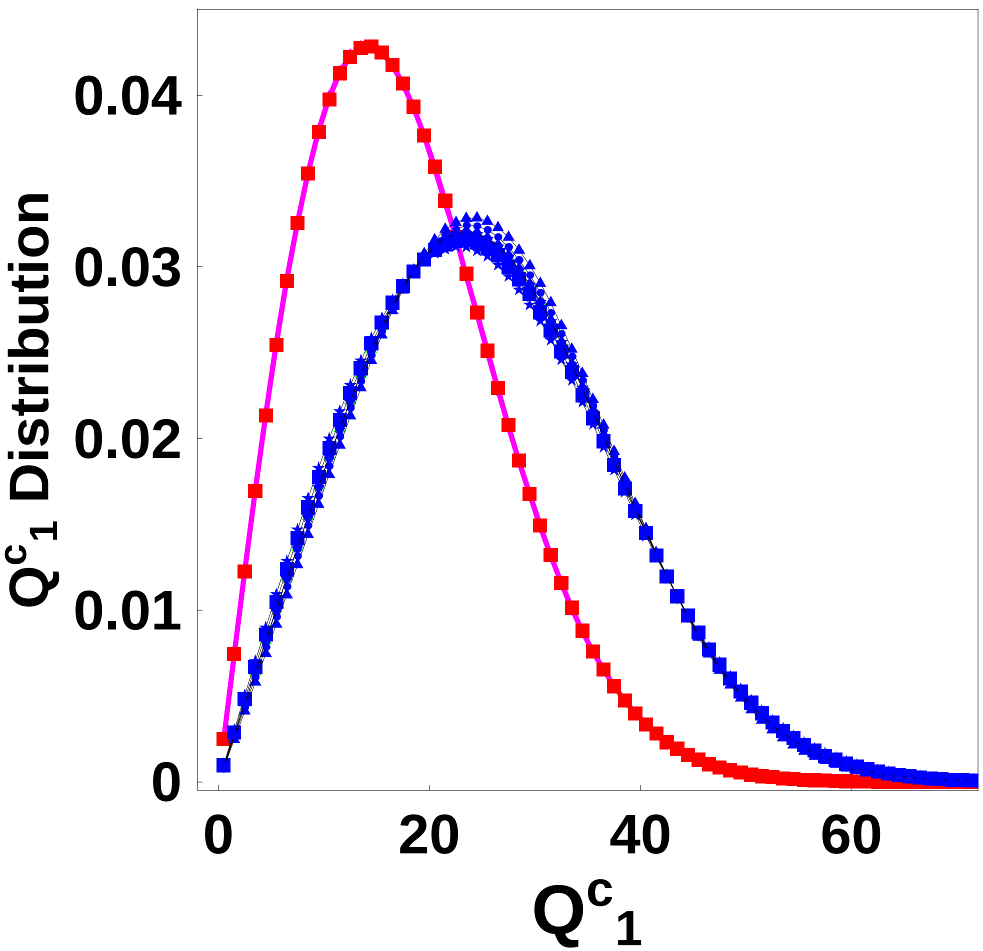
$$Q_1^c \cos\left(\Psi_1^c\right) = \sum_i q_i \cos(\phi_i)$$

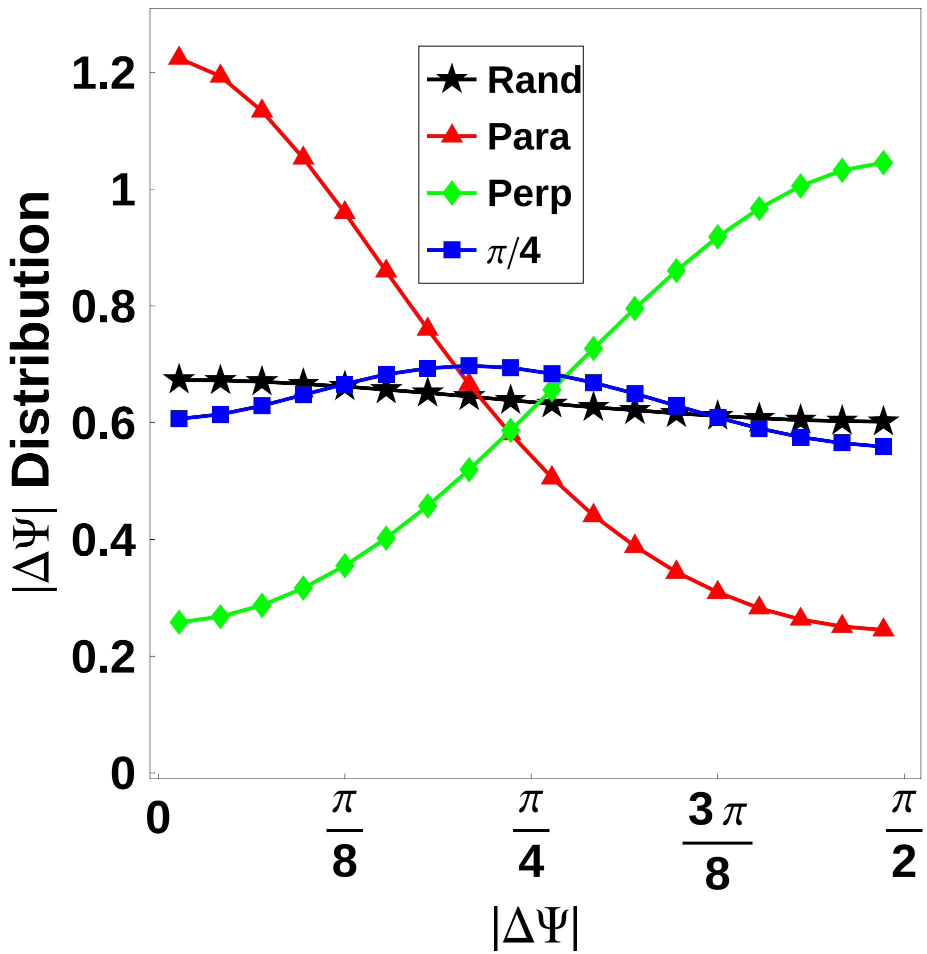
$$Q_1^c \sin\left(\Psi_1^c\right) = \sum_i q_i \sin(\phi_i)$$

In each event: (Q_2, Ψ_2) and $\left(Q_1^c, \Psi_1^c\right) \quad \Rightarrow \quad \boxed{\left\langle \cos\left(2\Psi_1^c - 2\Psi_2\right)\right\rangle}$

Monte Carlo: $f \propto 1 + 2v_2 \cos(2\phi - 2\Psi_{R.P.}) + 2q\chi d_1 \cos(\phi - \Psi_{C.S.})$

$200+$, $200-$, $v_2 = 0.1$, $d_1 = 0.05$, $\chi = \pm 1$





Good discriminating power, may clarify the situation

Conclusions

- for same sign STAR sees large signal in-plane and very week signal out-of-plane
- if there is a parity signal it must almost exactly cancel out-of-plane background
- maybe this is (un)lucky coincidence? We need differential $\langle \cos(\phi_\alpha - \phi_\beta) \rangle$ (p_t, η) to answer that question
- signal is dominated by $p_t < 1$ GeV and this is not inconsistent with the Chiral Magnetic Effect
- all two-particle correlations that do not depend on the reaction plane orientation contribute to the signal (v_2)

- as an example we estimated Coulomb effect and found it surprisingly large, however, not enough to explain the data (work still in progress)

- we proposed direct dipole analysis that may help to clarify the situation