Observation of charge-dependent azimuthal correlations and possible local strong parity violation in heavy-ion collisions

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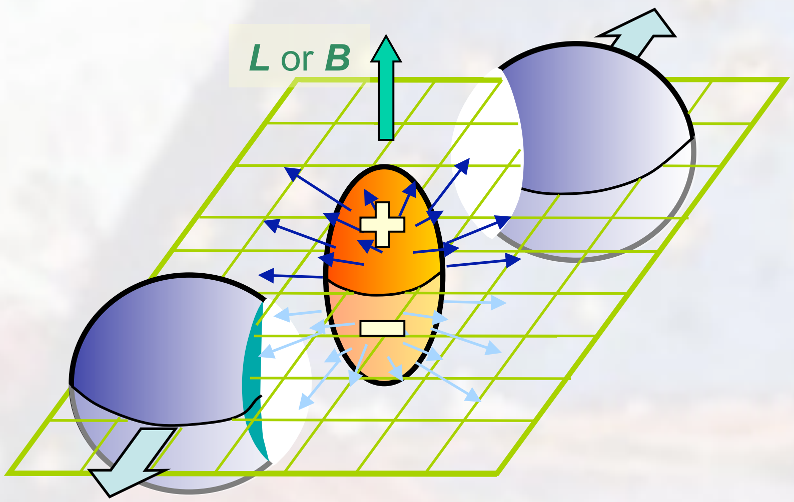
for the STAR Collaboration



Outline:

- Chiral Magnetic Effect and observables
- STAR results (PRL , long paper – arXiv: 0909.1717, submitted to PRC)
- Future directions
- Summary

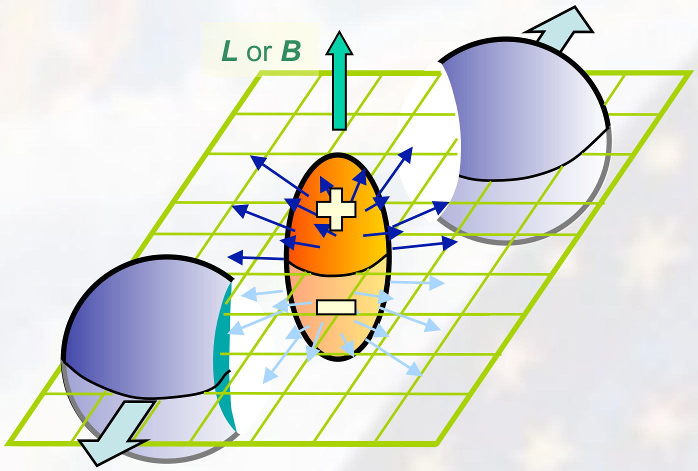
Selected for a Viewpoint in *Physics*

PRL 103, 251601 (2009) PHYSICAL REVIEW LETTERS week ending 18 DECEMBER 2009

Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

EDM of QCD matter

D. Kharzeev / Physics Letters B 633 (2006) 260–264



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

Chiral magnetic effect:

$N_L \neq N_R$ ⊕ magnetic field or
Induction of the electric field parallel to the (static) magnetic field

$$N_R - N_L = Q$$

$$A_u = \frac{N_R - N_L}{N_R + N_L}$$

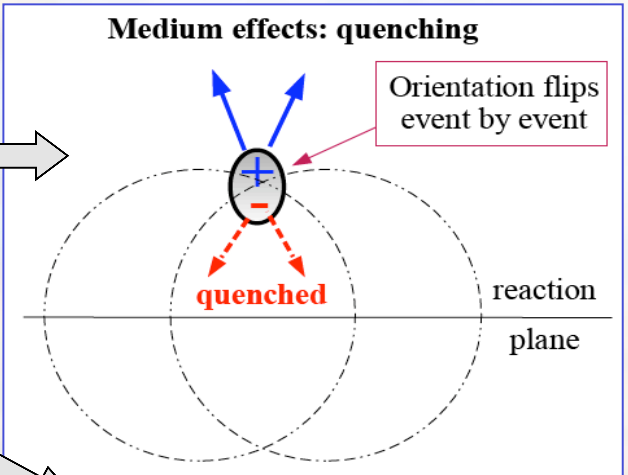
$$A_{\pi^+} = -A_{\pi^-} \simeq \frac{Q}{N_{\pi^+}}$$

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

Charge separation: expectations/predictions

Kharzeev, PLB 633 260 (2006) [hep-ph/0406125]
Kharzeev, Zhitnitsky, NPA 797 67 (2007)
Kharzeev, McLerran, Warringa, NPA 803 227 (2008)
Fukushima, Kharzeev, Waringa, PRD 78, 074033

- 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" Δη width of order ~ 1.
- The magnitude of asymmetry ~ 10^{-2} for midcentral collisions ➔ 10^{-4} for correlations.
- Effect is likely to be most pronounced at p_t ≤ ~ 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



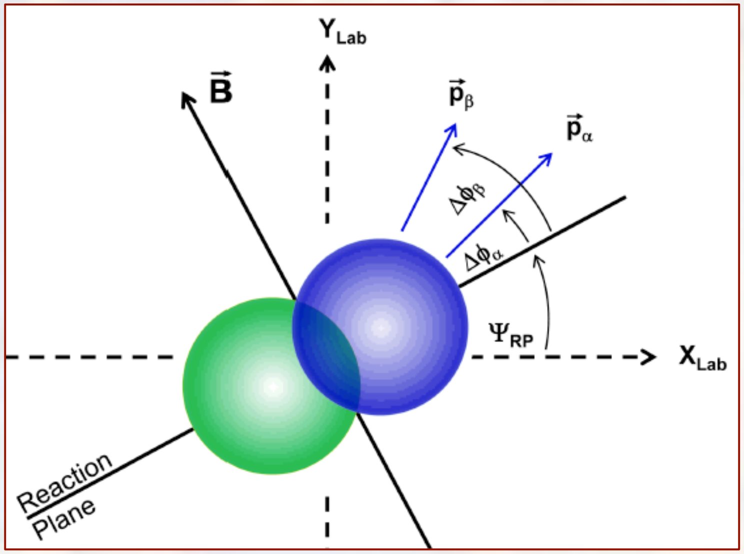
$$A_{\pi+} = -A_{\pi-} \simeq \frac{Q}{N_{\pi+}}$$

Anisotropic flow

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

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

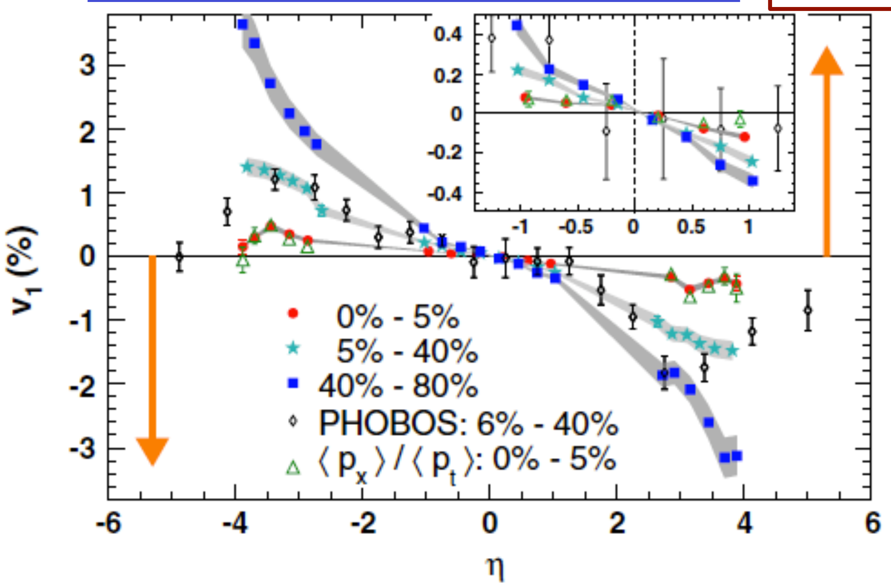
S. Voloshin and Y. Zhang, Z. Phys. C **70**, 665 (1996)
A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C **58**, 1671 (1998).

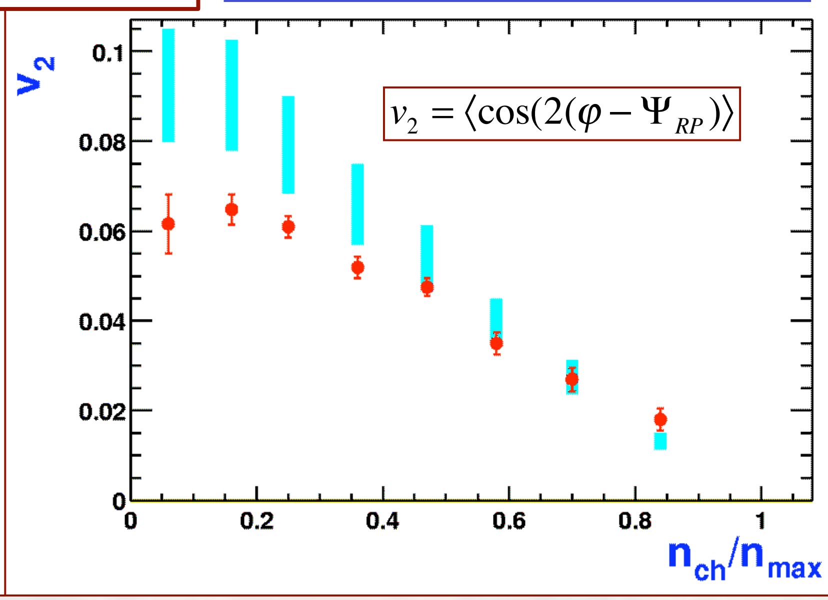


STAR Collaboration , PRL, 101 (2008) 252101

Au+Au, 200 GeV

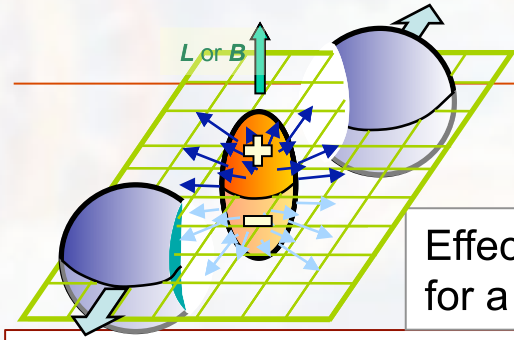
STAR Collaboration , PRL, 86 (2000) 402





Observable

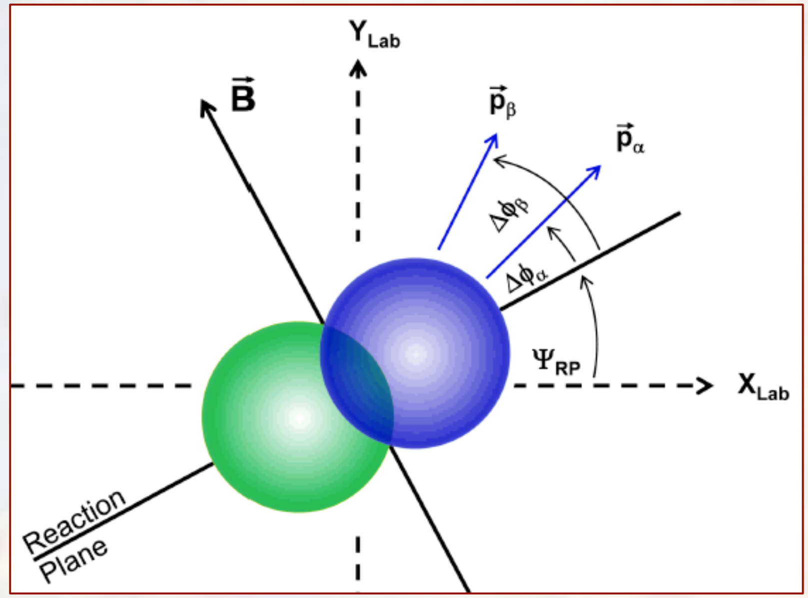
S.A. Voloshin, Phys. Rev. C 70 (2004) 057901



Effective particle distribution for a certain Q.

$$\frac{dN_\alpha}{d\phi} \propto 1 + 2v_{1,\alpha}\cos(\Delta\phi) + 2\,v_{2,\alpha}\cos(2\Delta\phi) + \dots + 2a_{1,\alpha}\sin(\Delta\phi) + 2\,a_{2,\alpha}\sin(2\Delta\phi) + \dots,$$

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



- The effect is too small to observe in a single event
- The sign of Q varies and $\langle a \rangle = 0$ (we consider only the leading, first harmonic) ➔ one has to measure correlations, $\langle a_\alpha a_\beta \rangle$, $\mathcal{P}$-even quantity (!)
- $\langle a_\alpha a_\beta \rangle$ is expected to be ~ 10^{-4}
- $\langle a_\alpha a_\beta \rangle$ can not be measured as $\langle \sin\varphi_\alpha \sin\varphi_\beta \rangle$ due to large contribution from effects not related to the orientation of the reaction plane

➔ study the difference in corr's in- and out-of-plane

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

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

A practical approach: three particle correlations: $\langle\cos(\phi_a + \phi_\beta - 2\phi_c)\rangle = \langle\cos(\phi_a + \phi_\beta - 2\Psi_{RP})\rangle\, v_{2,c}$

Backgrounds

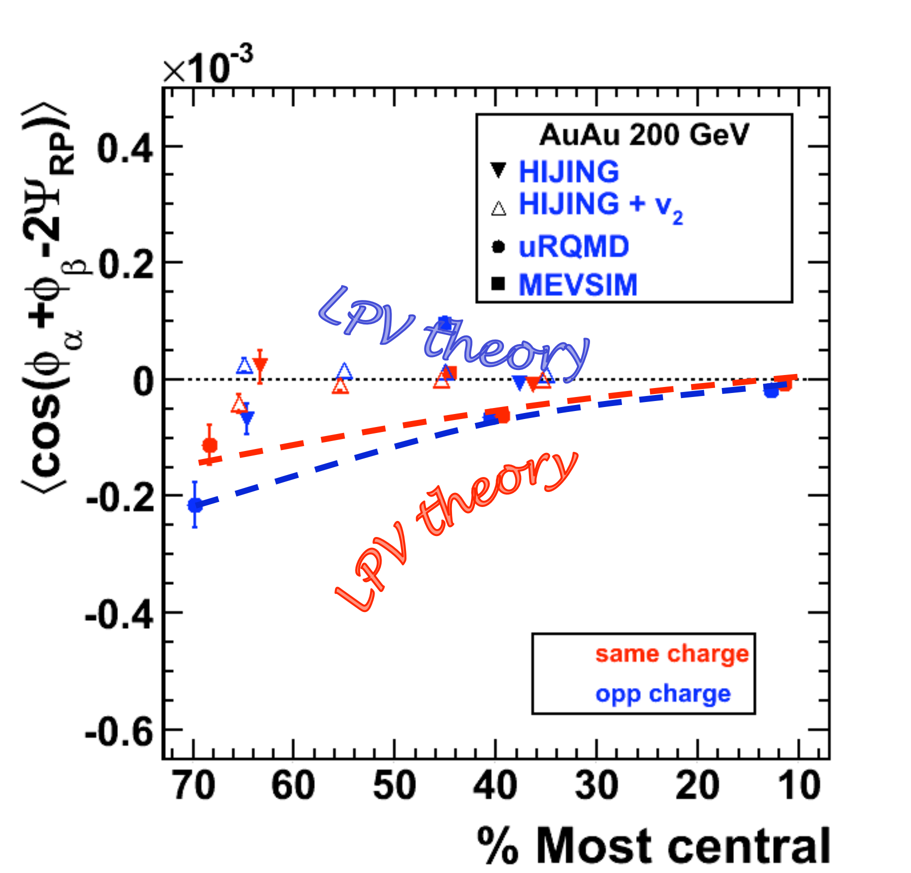
I. Physics (RP dependent).
Can not be suppressed.

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

- "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, …



(+,+) 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

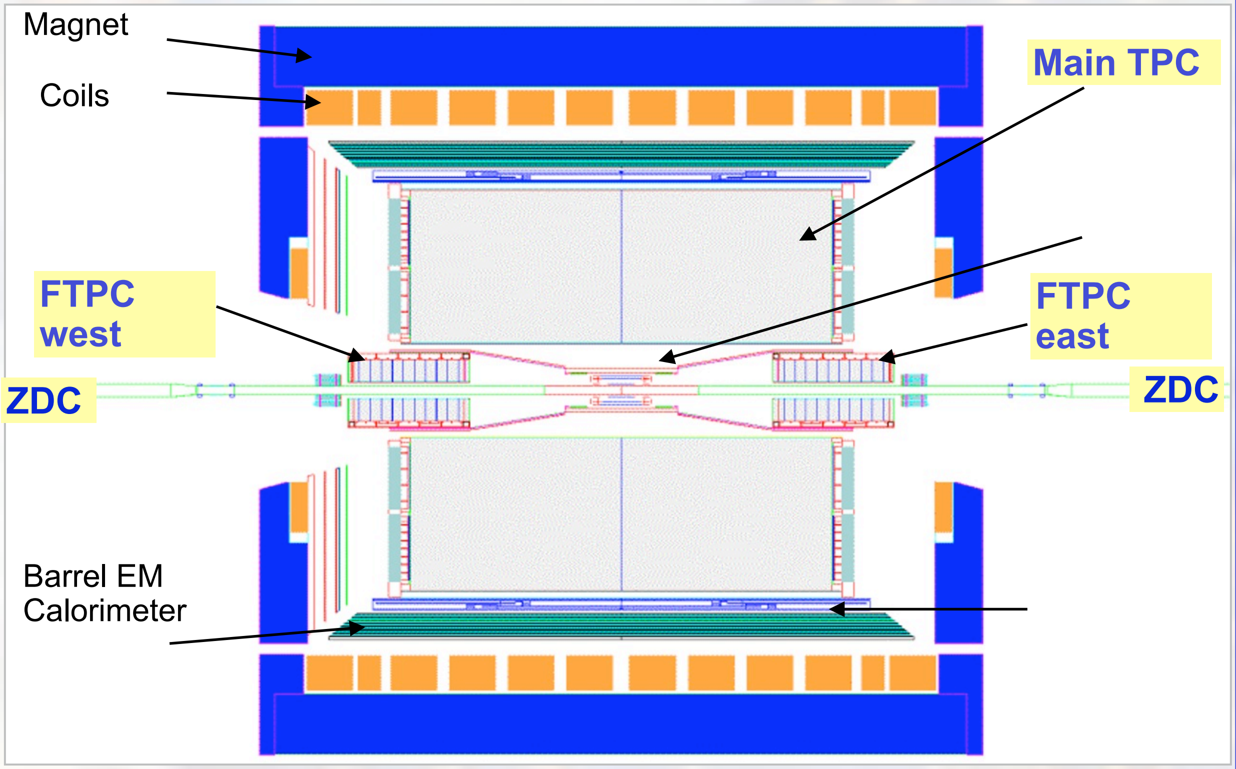
II. RP independent. (depends on method and in general can be greatly reduced)

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

Discussed later

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

STAR Experiment and Data Set



Tracking done by two Forward TPCs (East and West) and STAR Main TPC.

Tracks used:
$|\eta| < 1.0$ (Main TPC)
$-3.9 < \eta < -2.9$ (FTPC East)
$2.9 < \eta < 3.9$ (FTPC West)

$0.15 < p_T < 2.0$ GeV/c
(unless specified otherwise)

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**)**

This analysis used the data taken during RHIC Run IV and based on (after all quality cuts)
Au+Au 200 GeV ~ 10.6 M Minimum Bias events
Au+Au 62 GeV ~ 7 M Minimum Bias events
Cu+Cu 200 GeV ~ 30 M Minimum Bias events
Cu+Cu 62 GeV ~ 19 M Minimum Bias events
Some preliminary results are from Run VII

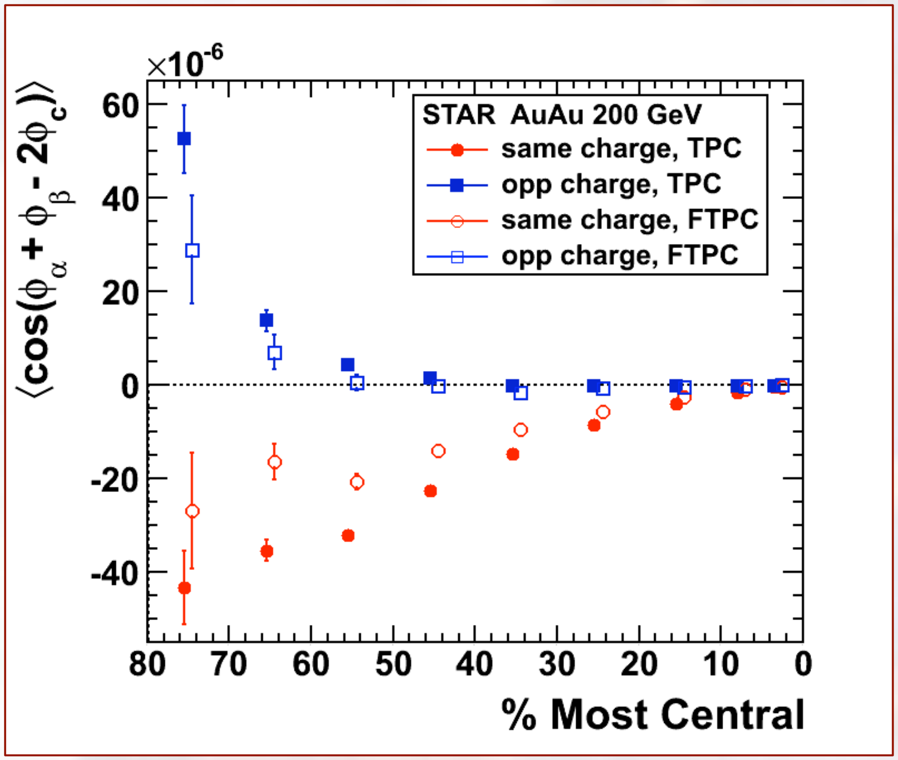
Testing the technique. (RP from TPC and FTPC)

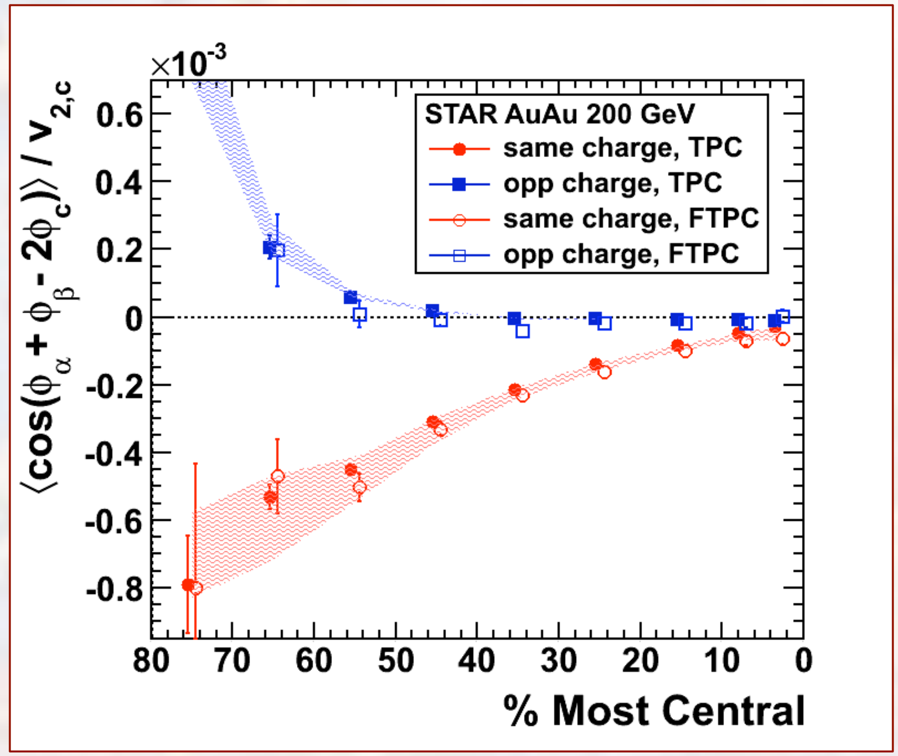
STAR

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

| η | < 1.0 (Main TPC)
2.9 < |η| < 3.9 (FTPC)

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





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

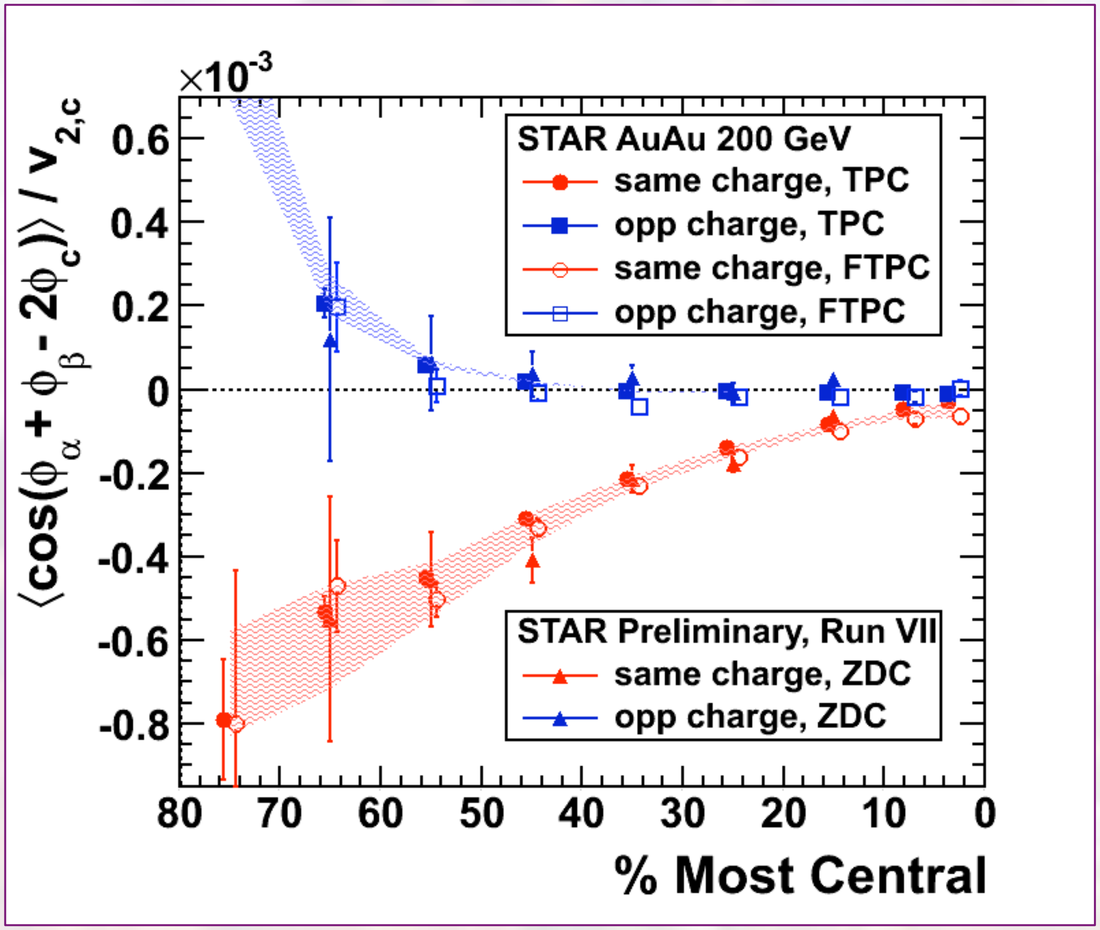
Center points: obtained using v_2\{FTPC\}
bands: lower limits - using v_2\{2\}, upper – v_2\{4\};
where v_2\{4\} is not available it is assumed that using v_2\{FTPC\} suppresses non-flow by 50%.

Testing the technique. (RP from ZDC-SMD)

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

| η | < 1.0 (Main TPC)
2.9 < |η| < 3.9 (FTPC)

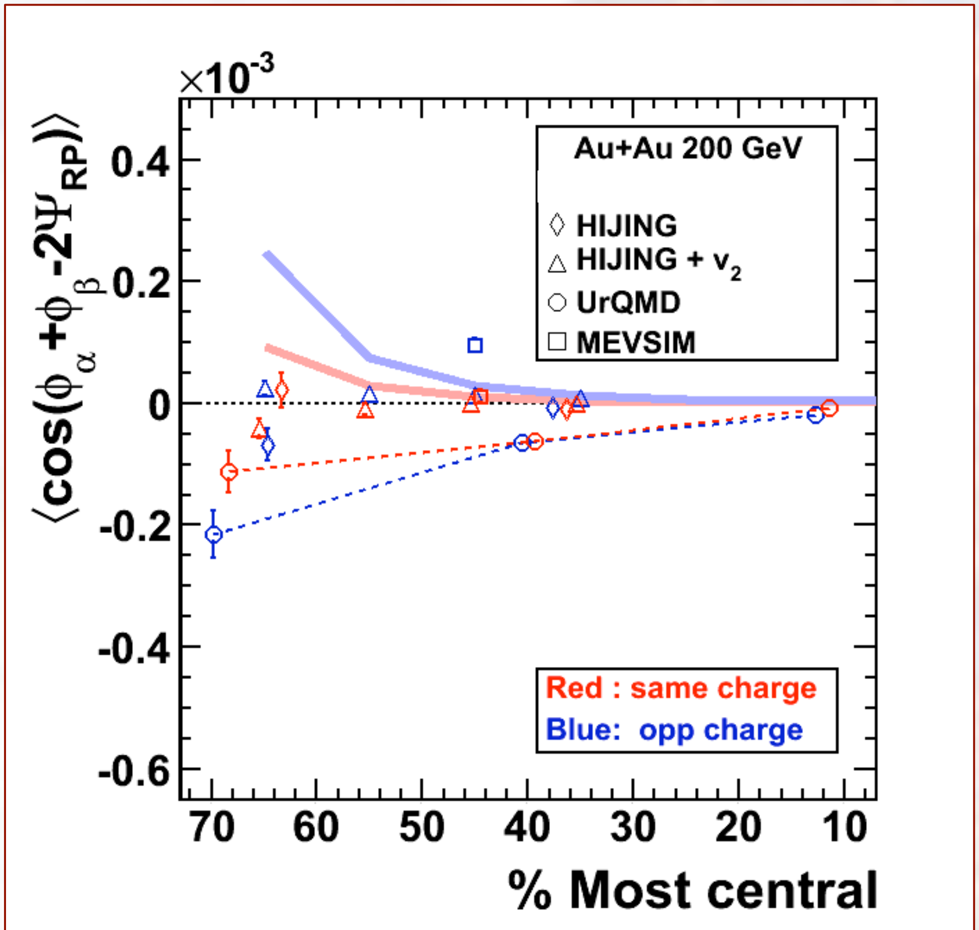
$\langle\cos(\phi_\alpha + \phi_\beta - 2\phi_c)\rangle$ → $\langle\cos(\phi_a + \phi_\beta - 2\Psi_{RP})\rangle.$



Uncertainties at small multiplicities

(RP independent background)

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



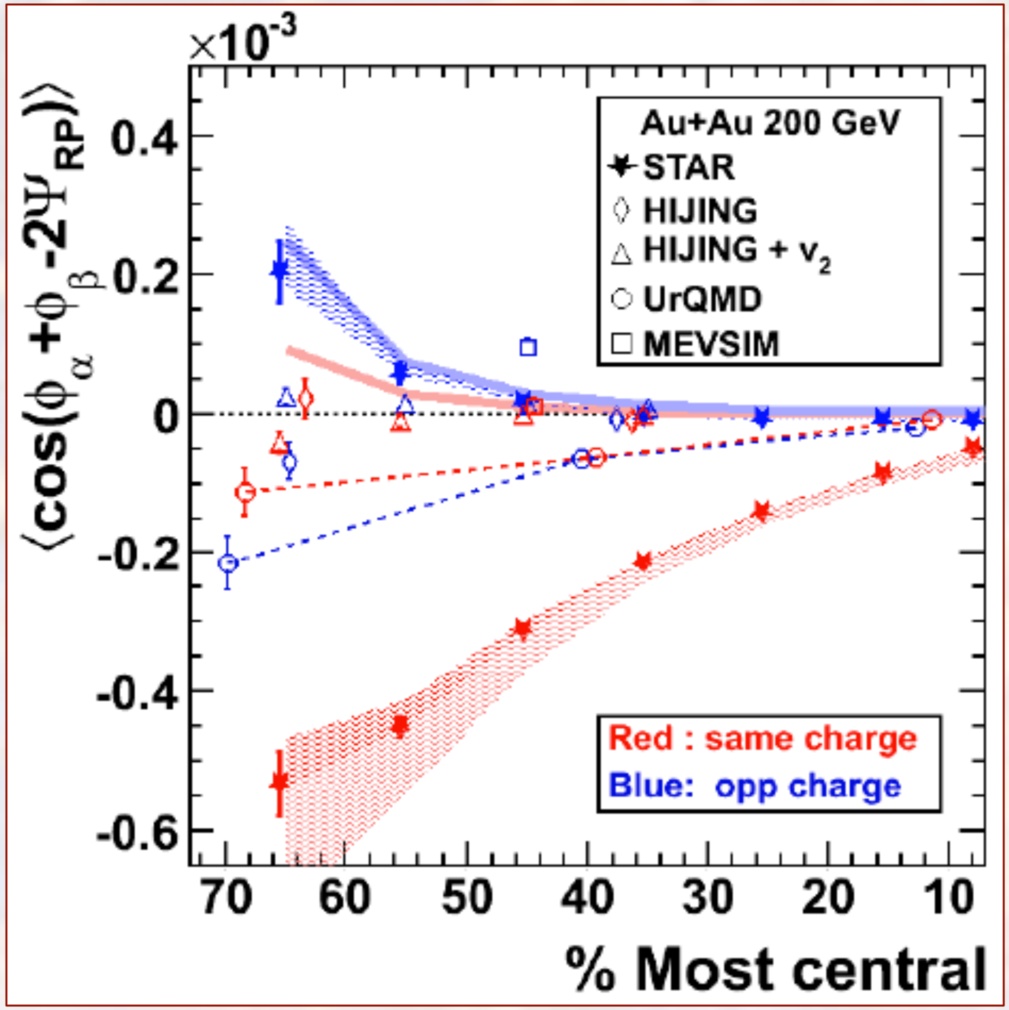
Thick lines: uncertainties due to 3-particle correlations not related to the reaction plane orientation for the case of particle *c* taken from TPC region (from HIJING).

Note: such uncertainty in principle can be decreased, e.g. if use particle *c* separated from (α,β) 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)

Data vs models

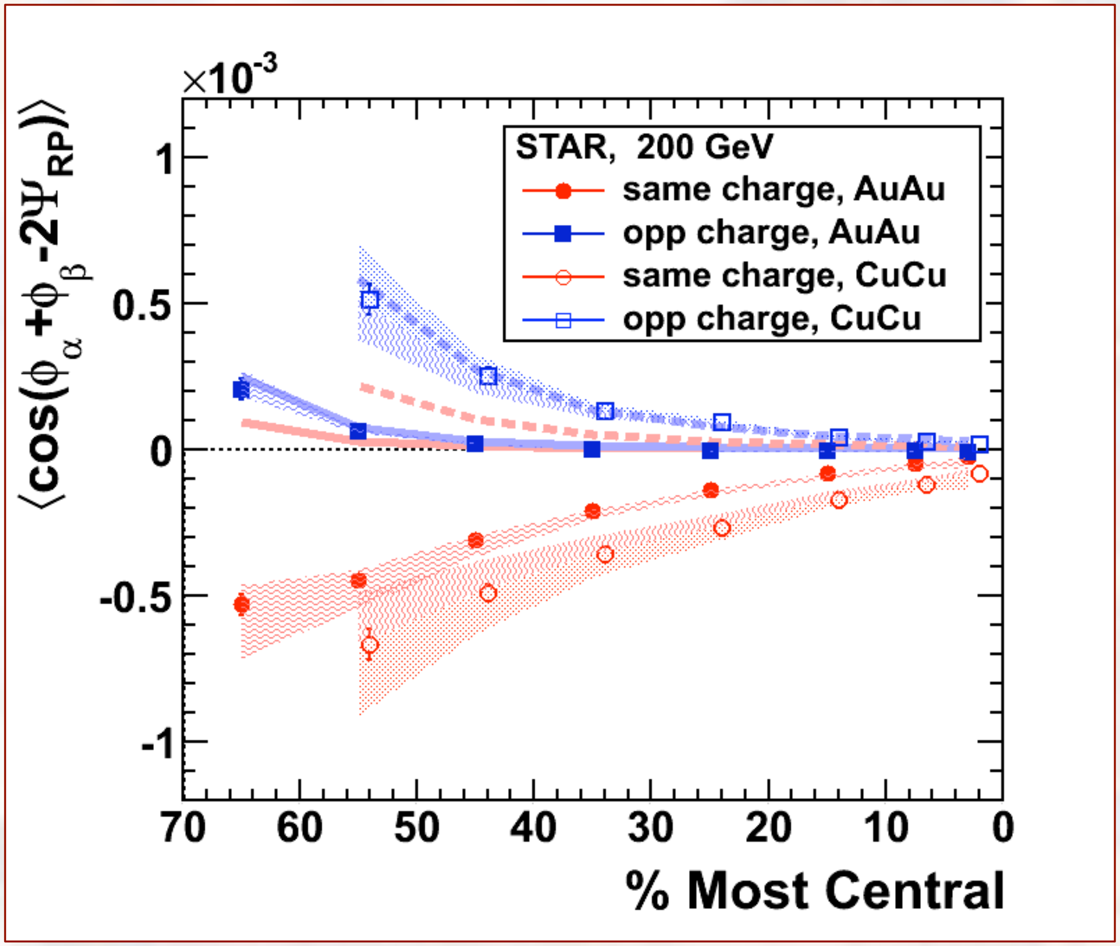
- Large difference in like-sign vs unlike-sign correlations in the data compared to models.
- Bigger amplitude in like-sign correlations compared to unlike-sign.
- Like-sign and unlike-sign correlations are consistent with theoretical expectations
- … but the unlike-sign correlations can be dominated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

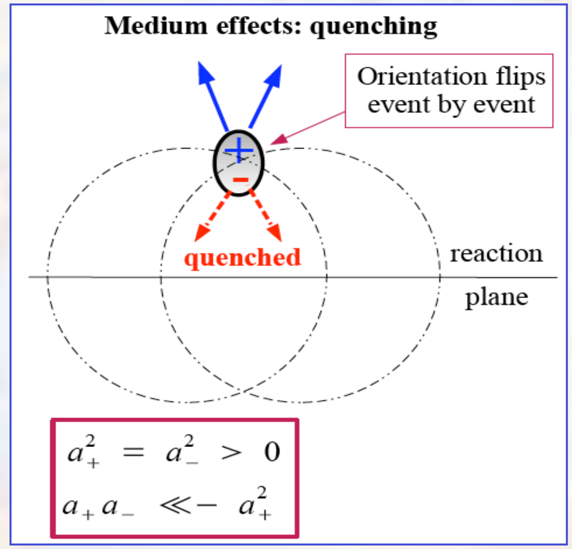


⟨ +,+ ⟩ and ⟨–,–⟩ results agree within errors and are combined in this plot and all plots below.

We proceed with more "differential" look and compare with theoretical expectations

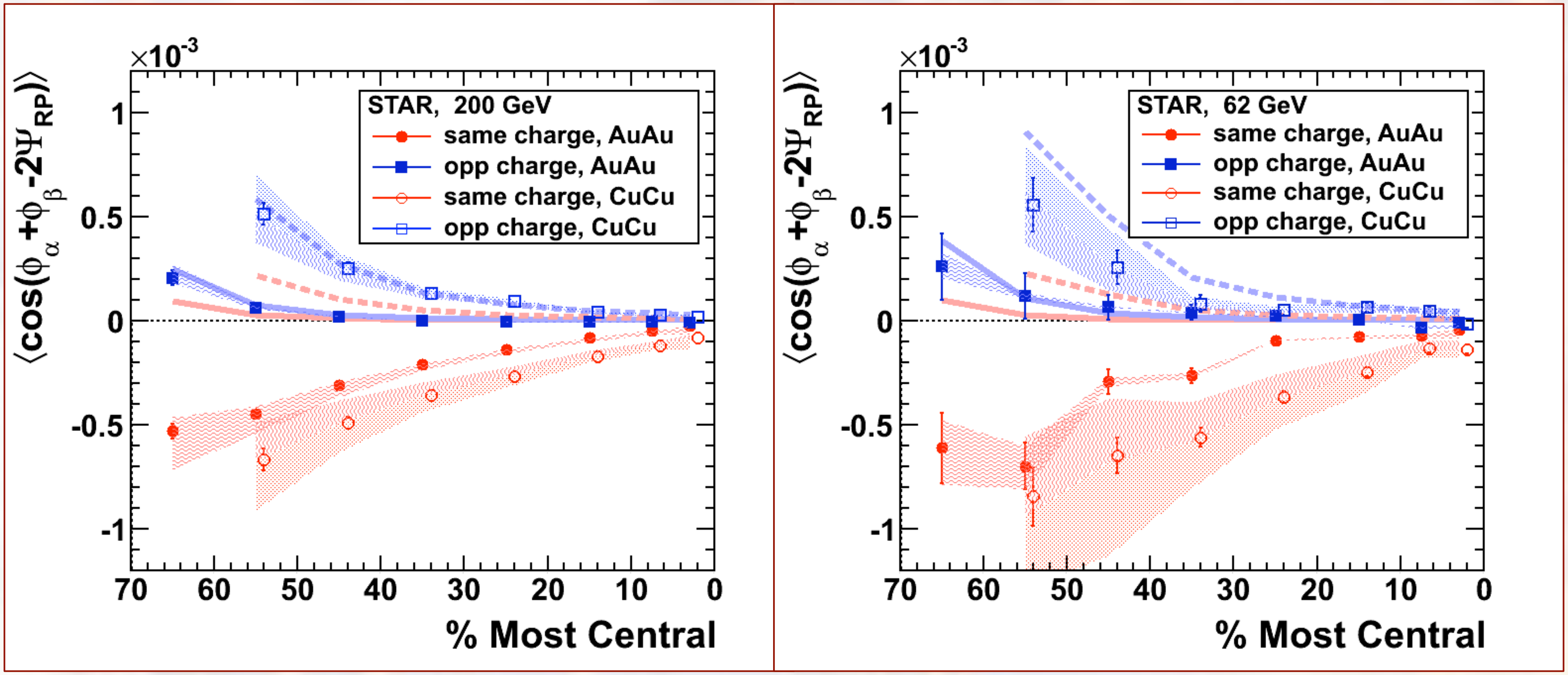
Au+Au and Cu+Cu @ 200 GeV





+/– signal in Cu+Cu is stronger, qualitatively in agreement with "theory", but keep in mind large uncertainties due to correlations not related to RP

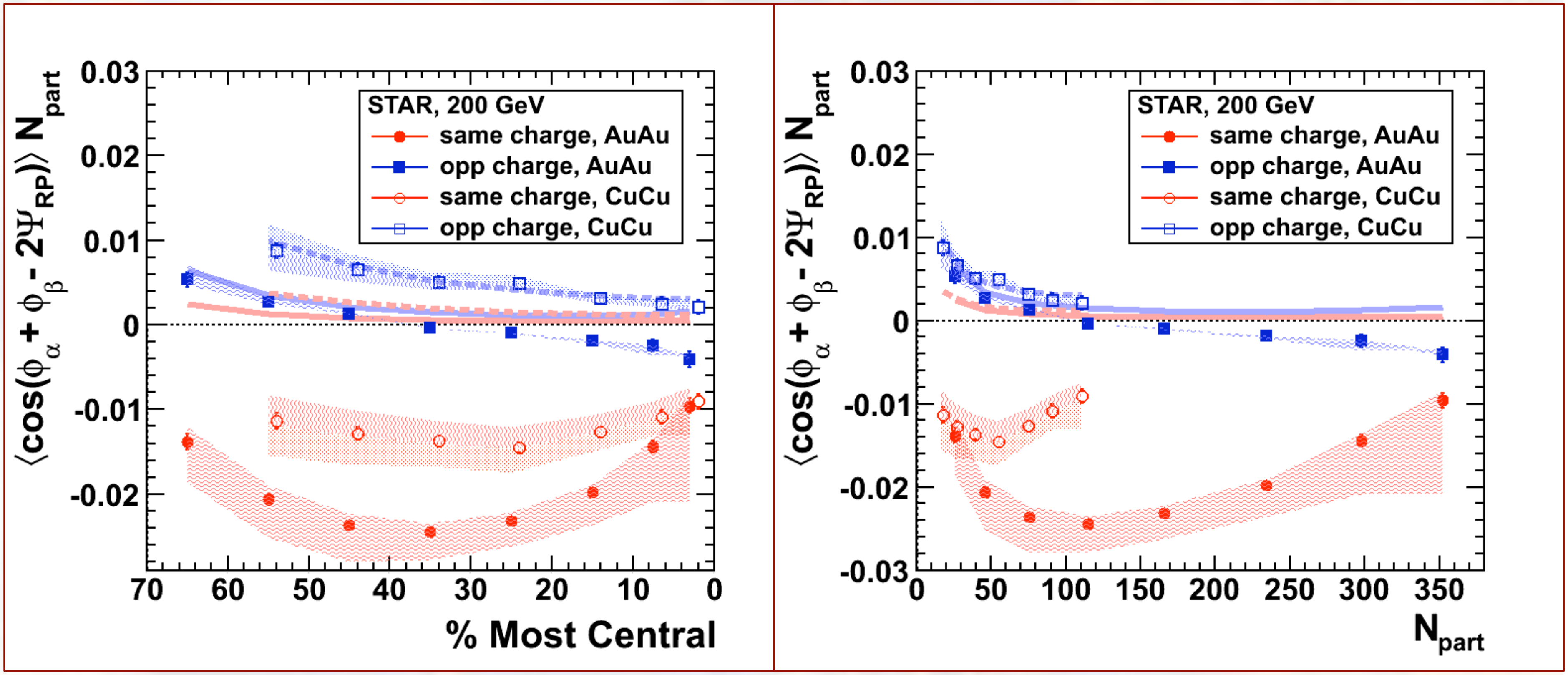
Au+Au and Cu+Cu: 200 vs 62 GeV



+/– signal at lower energy is stronger, qualitatively in agreement with "theory"

Signal is smaller at higher energies and larger systems

Au+Au and Cu+Cu @ 200 GeV



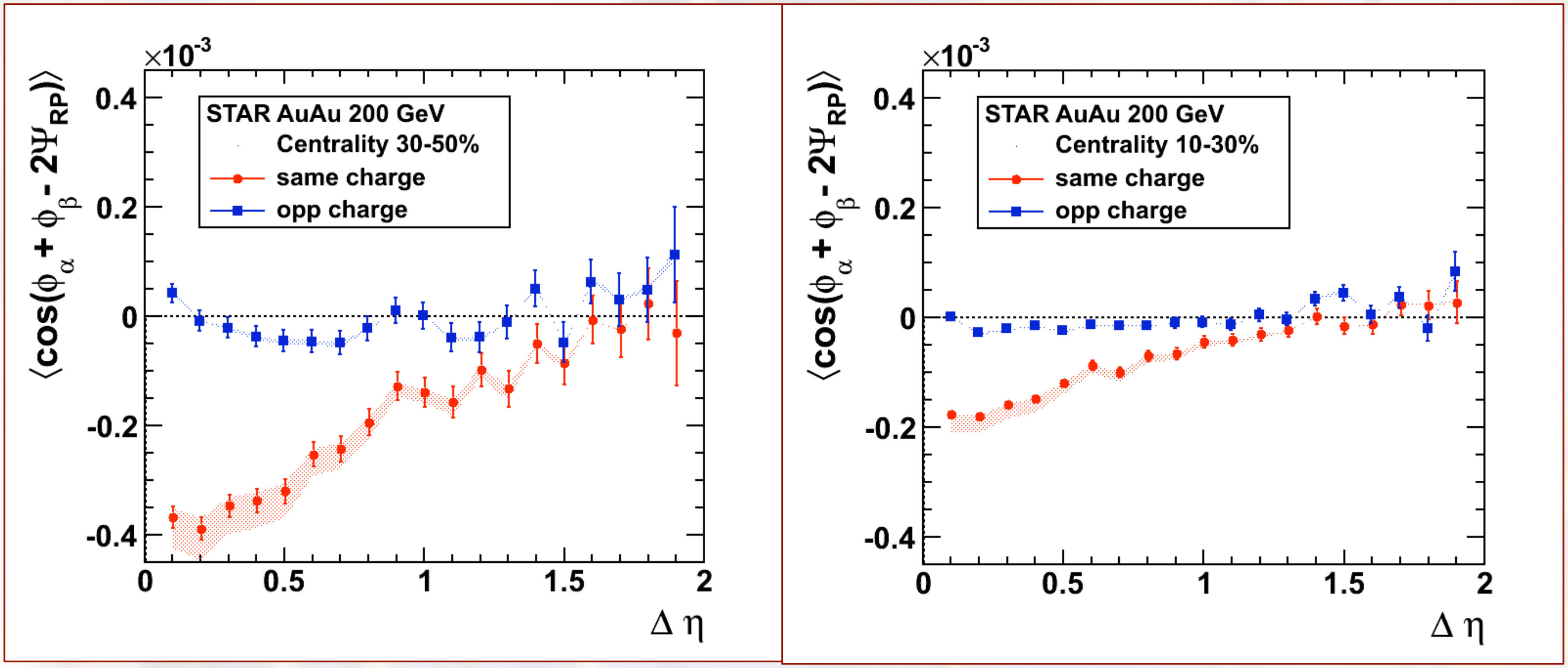
The signal is multiplied by N_{part} to remove "trivial" dilution due to multiplicity increase in more central collisions and/or lighter system.

Opposite charge correlations scale with N_{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_{part}

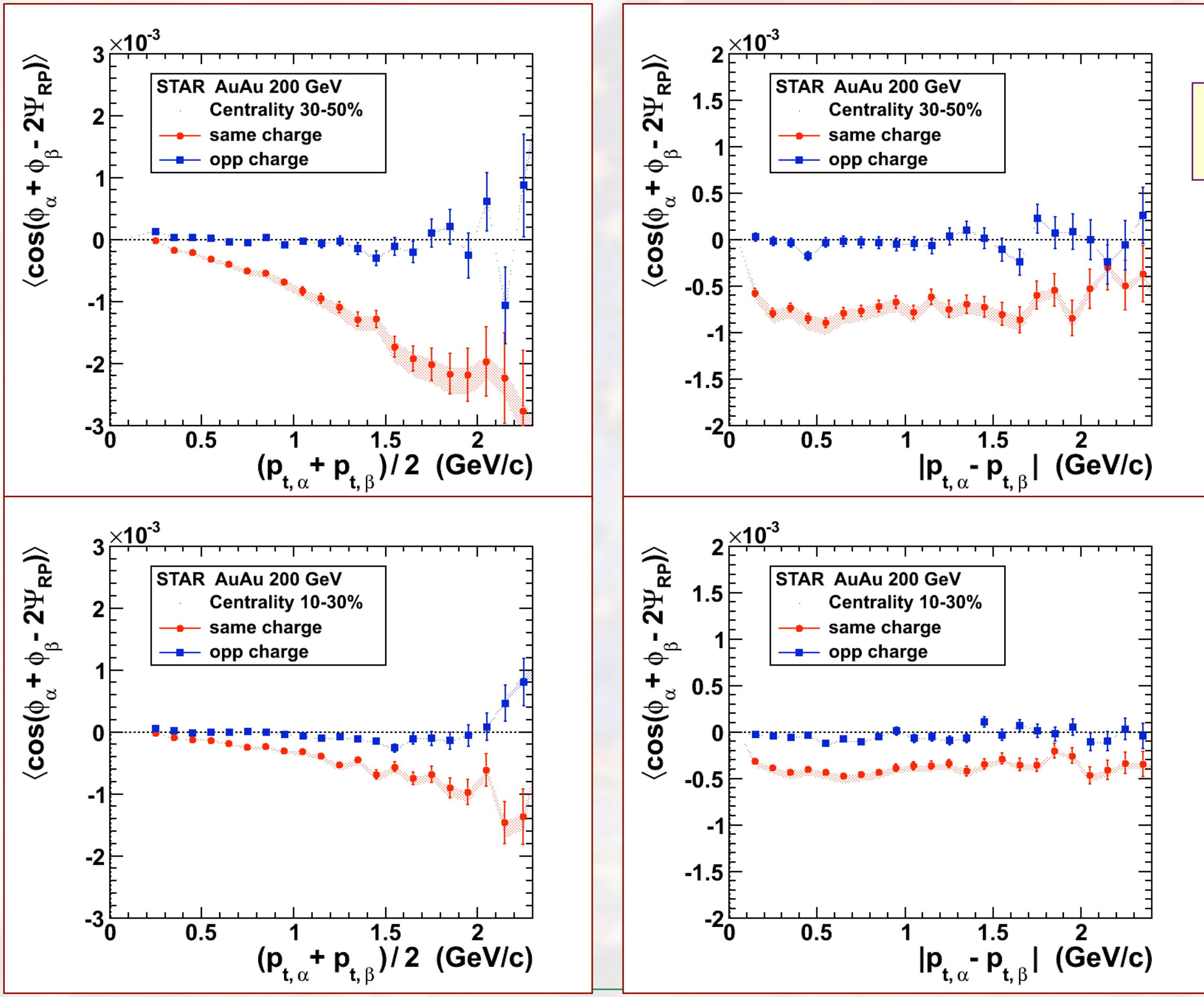
Δη dependences (AuAu200).



Typical "hadronic" width, consistent with "theory".

What about color flux tubes?

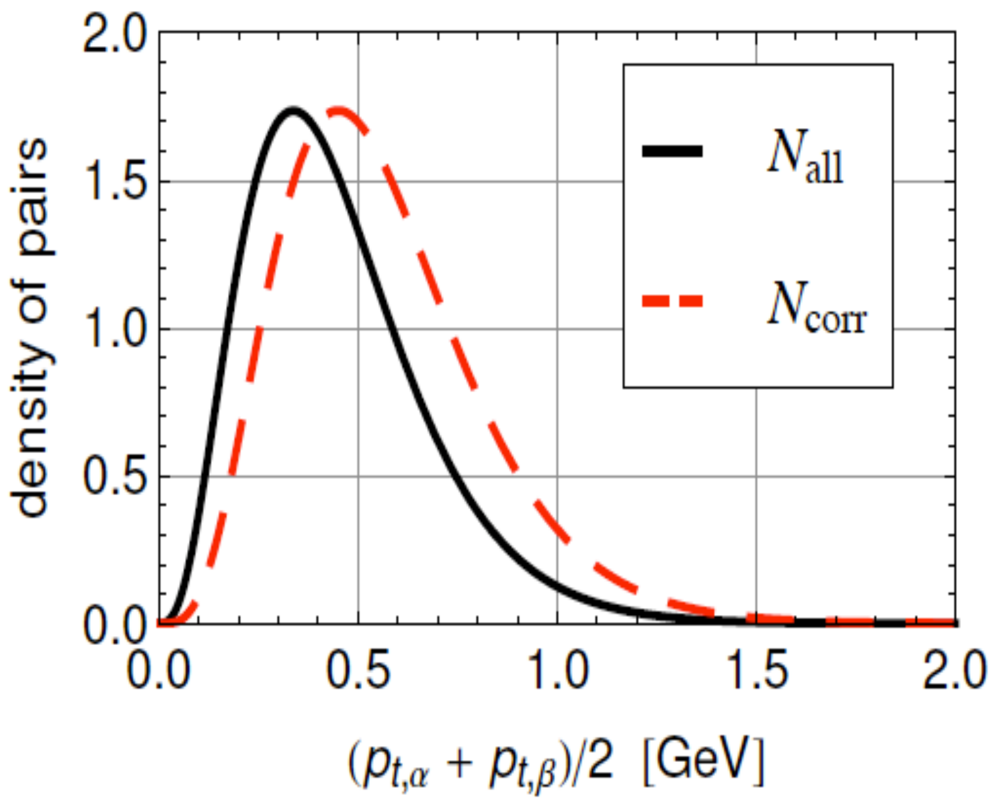
Transverse momentum dependences (AuAu200).



Signal persists to too high p_t ?

p_t dependence

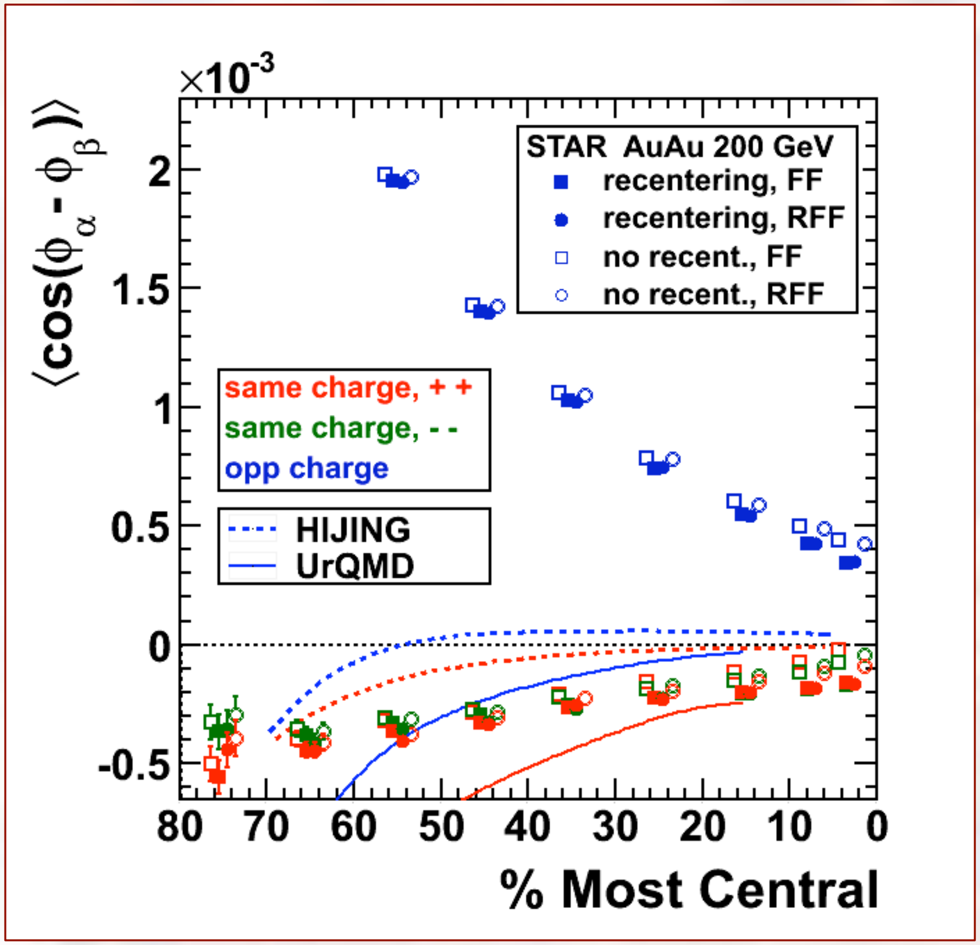
Adam Bzdak[a,b], Volker Koch[a], and Jinfeng Liao[a]
arXiv:0912.5050v1 [nucl-th] 27 Dec 2009



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 has p_t distribution only slightly "harder" than the bulk.

$$\langle \cos(\phi_\alpha + \phi_\beta) \rangle = \frac{N_{corr}}{N_{all}}$$

Two-particle correlations



Two particle distributions are not described by models as well…

Coming from the same LPV physics?

Requires differential analysis.

Summary of STAR results

- STAR results agree with the magnitude and gross features of the theoretical predictions for the local P-violation in heavy-ion collisions.

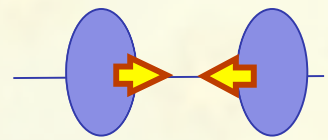
- The particular observable used in this analysis is P-even and might be sensitive to non-parity-violating effects. With the systematics checks performed so far, we have not identified effects that would explain the observed same-charge correlations.

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

Developing a 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

Such collisions ("easy" to trigger on) will have low magnetic field and large elliptic flow – clean test of the *LPV* effect.

- Beam energy scan / Critical point search

Look for a critical behavior, as *LPV* predicted to depend strongly on deconfinement and chiral symmetry restoration

- Isobaric beams

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

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

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

- **High statistics PID studies / properties of the clusters**

in particular with neutral particles; see also next slides

Central U+U collisions

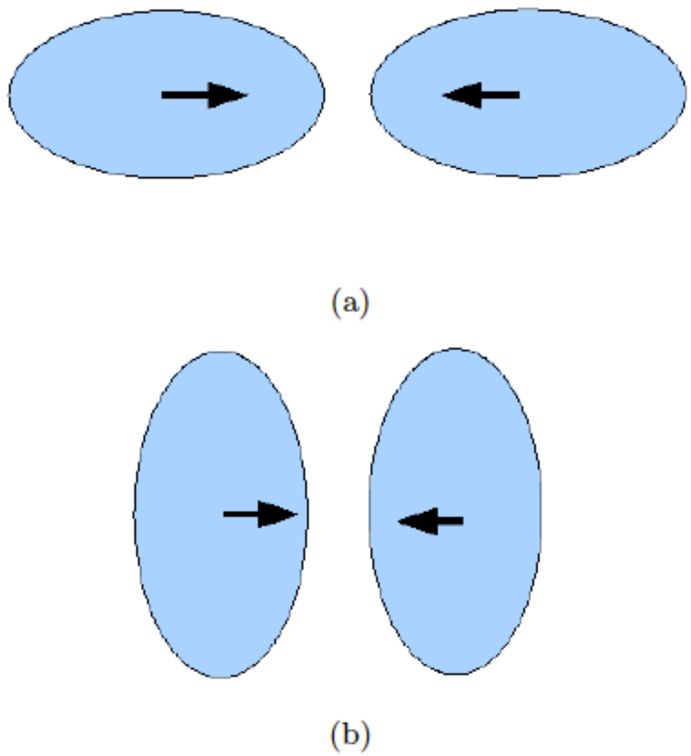


FIG. 1: Schematic view of central U+U collisions: (a) tip-tip and (b) body-body.

All ("physics") background effects scale with elliptic flow.

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

I will discuss this (and also what can be done in Au+Au collisions) in a little more quantitative way at the discussion session on Thursday.

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

Developing a 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?).

PHYSICAL REVIEW D 80, 054503 (2009)

Numerical evidence of chiral magnetic effect in lattice gauge theory

P. V. Buividovich,[1,2] M. N. Chernodub,[3,4,2] E. V. Luschevskaya,[2] and M. I. Polikarpov[2]
[1]*JIPNR "Sosny," National Academy of ...*
[2]*ITEP, B. Cheremushk...*
[3]*LMPT, CNRS UMR 6083, Fédération...*
[4]*DMPA, University of Gent,...*

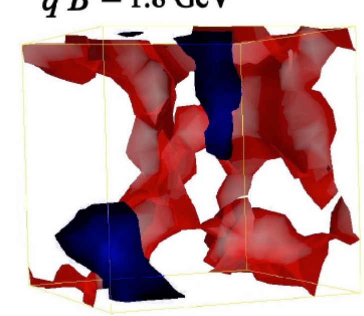


FIG. 2 (color online). The same as in Fig. 1 but for $qB = 1.8\ \mathrm{GeV}^2$ and for the configuration of non-Abelian gauge field.

Chiral magnetic effect in 2+1 flavor QCD+QED

arXiv:0911.1348v1 [hep-lat] 6 Nov 2009

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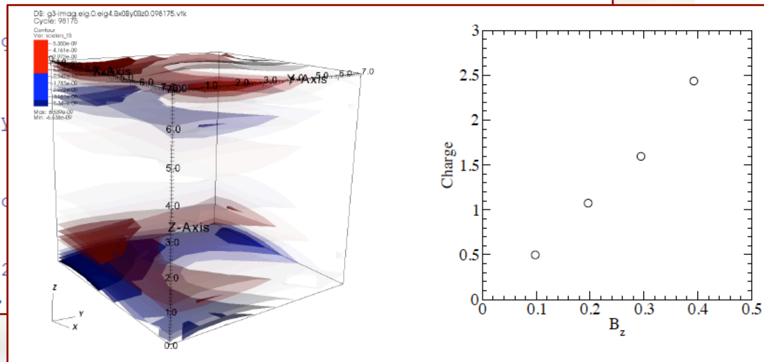
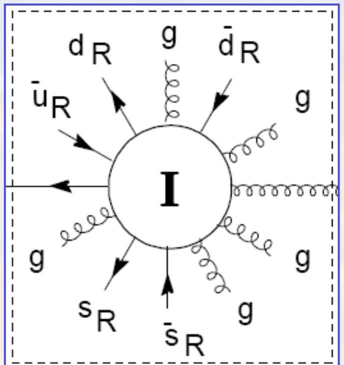


Figure 2: Left panel: Charge separation computed from a single near-zero-mode for a continuum instanton discretized on an 8^4 lattice. $B_z = 0.098175$. Translational invariance is broken in the $x-y$ plane by the Landau states of the quarks. Right panel: total amount of charge separated to the lower half of the lattice in the z direction for the same configuration. All modes with chirality close to one are included in the total. The same amount, but with opposite sign resides in the top half.

Nonperturbative Phenomena and Phases of QCD

Edward V. Shuryak

$$M_{sph} \approx \frac{30}{g^2(\rho)\rho} \sim 2.5\, GeV$$



Clusters in multi-particle production

PHYSICS REPORTS (Section C of Physics Letters) 22, no. 1 (1975) 1–56. NORTH-HOLLAND PUBLISHING COMPANY

INCLUSIVE STUDY OF HIGH-ENERGY MULTIPARTICLE PRODUCTION AND TWO-BODY CORRELATIONS

L. FOÀ

Scuola Normale Superiore, Pisa, Italy, Sezione di Pisa dell'INFN, Pisa, Italy, and CERN, Geneva, Switzerland

While different models make different assumptions on the cluster production mechanism (multiperipheral, 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) isostropic decay of clusters in their rest frames, and

iii) energy independence of the decay parameters.

The average transverse momentum of secondaries can be simply related to the average momentum of the cluster decay products in the cluster rest frame. Knowledge of this parameter and the

cluster = sphaleron?

pp2pp Phase II

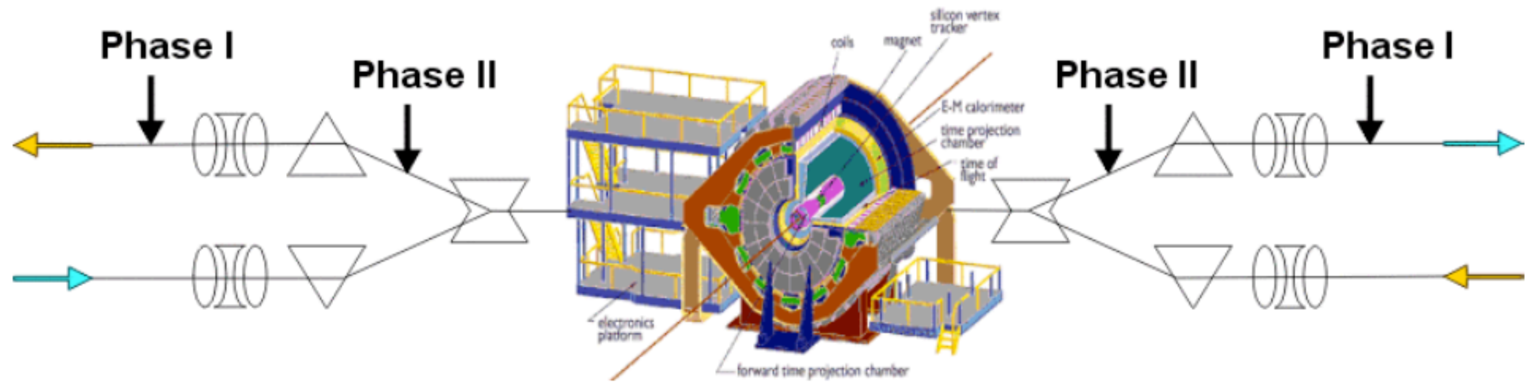
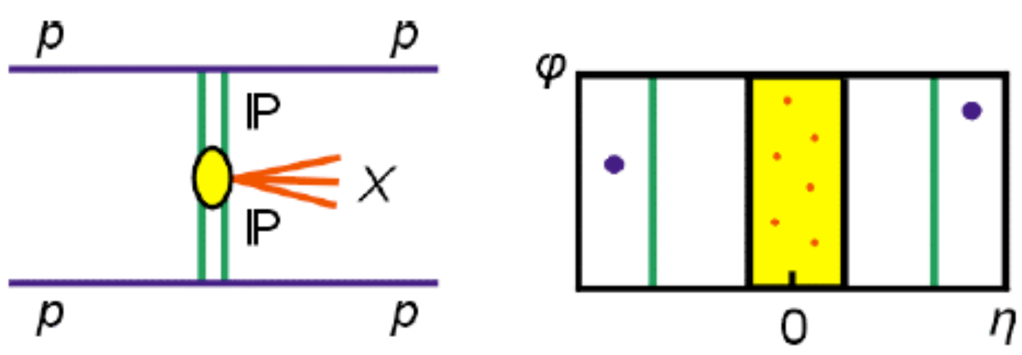


Figure 1. The Roman pots of the pp2pp experiment in the STAR interaction region, with the arrows indicating proposed locations for current Phase I and proposed Phase II.



Look for: Mass distribution, multiplicities, quark flavor content of the clusters (PID correlations, KKπ vs ππππ, 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 detects 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…

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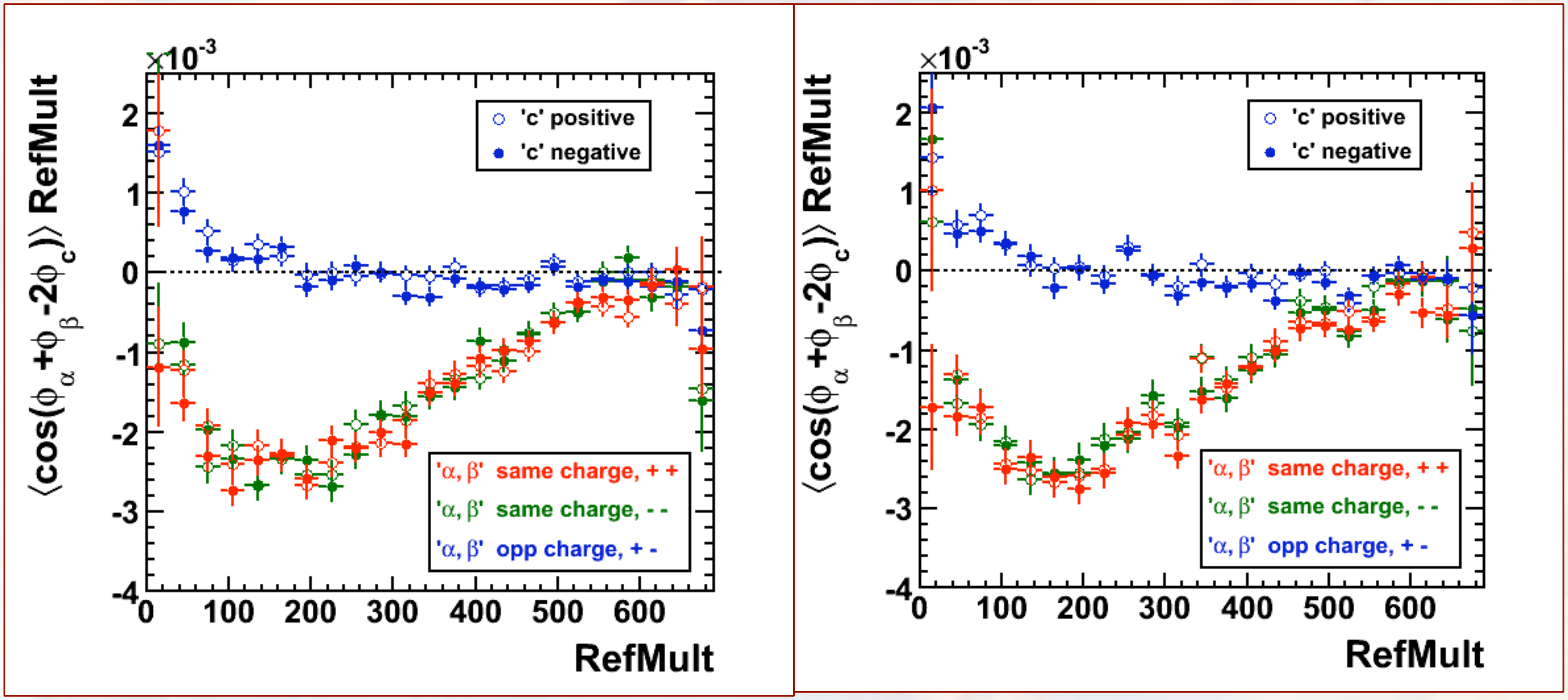
END

Charge combinations



The absence of the effect would be a problem for QCD.

Without direct measurements of non-perturbative QCD effects, the “proof” of QCD as theory of strong interaction is not complete.