# Local strong parity violation and new possibilities in experimental study of non-perturbative QCD

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Abstract. Quark interaction with topologically non-trivial gluonic fields, instantons and sphalerons, violates  $\mathcal{P}$  and  $\mathcal{CP}$  symmetry. In the strong magnetic field of a non-central nuclear collision such interactions lead to the charge separation along the magnetic field, the so called chiral magnetic effect, which manifests local parity violations. An experimental observation of the chiral magnetic effect would be a direct proof for the existence of such physics. Recent STAR results on charge and the reaction plane dependent correlations are consistent with theoretical expectations for the chiral magnetic effect. In this paper I discuss other approaches to experimental study of the local parity violation, and propose future measurements which can clarify the picture. In particular I propose to use central body-body U+U collisions to disentangle correlations due to chiral magnetic effect from possible background correlations due to elliptic flow. Further more quantitative studies can be performed with collision of isobaric beams.

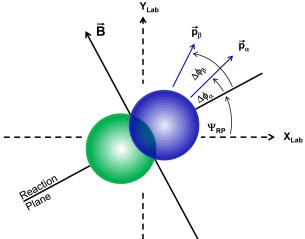
#### 1. Introduction. Local parity violation.

It is widely accepted that Quantum Chromodynamics (QCD) is the theory of strong interactions. Perturbative QCD is firmly established and thoroughly tested experimentally. In the non-perturbative sector, QCD links chiral symmetry breaking and the origin of hadron masses to the existence of topologically non-trivial classical classical gluonic fields describing the transitions between the vacuum states with different Chern-Simons numbers. Quark interactions with such fields change the quark helicity and are  $\mathcal{P}$  and  $\mathcal{CP}$  odd. For a review, see [1, 2]. It was first suggested in [3] to look for such metastable  $\mathcal{P}$  and  $\mathcal{CP}$  odd domains in ultra-relativistic heavy ion collisions. The possibilities for an experimental detection of this local strong parity violation was discussed in [3, 4, 5].

Originally [3], it was proposed to look for the effect by detecting the non-statistical fluctuations in the variable

$$J = \sum_{\pi^+,\pi^-} \frac{(\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})_z}{p_{\pi^+} p_{\pi^-}}.$$
 (1)

In [4] it was shown that J is directly related to the difference in the event planes reconstructed from positive and negative particles. This difference is similar to the effect of a (electro) magnetic field oriented along the beam direction (parallel or anti parallel). The existence of such a field in a symmetric collision would constitute parity violation. Experimental measurements of the



**Figure 1.** Schematic view of non-central nuclear collision showing the definition of angles in Eqs. 2, 4.

effect by NA49 Collaboration revealed a signal consistent with zero [6]. Unfortunately, this observable have not been measured at RHIC yet.

More recently, it was noticed [7, 8] that in non-central nuclear collisions such domains can demonstrate themselves via the asymmetry in the emission of positively or negatively charged particle perpendicular to the reaction plane. Such charge separation is a consequence of the difference in the number of particles with positive and negative helicities positioned in the strong magnetic field ( $\sim 10^{15}$  T) of a non-central nuclear collision, the so-called *chiral magnetic effect* [7, 9]. The same phenomenon can also be described in terms of the induced electric field that is parallel to the static external magnetic field, which occurs in the presence of topologically non-trivial vacuum solutions [10]. The direction of the separation varies event by event in accord with the sign of the topological charge of the domain, and the observation of the effect is possible only by correlation techniques. An observable directly sensitive to the charge separation effect, has been proposed in [13]. It is discussed in more detail below.

According to Refs. [7, 8, 9] the charge separation could lead to asymmetry in particle production  $\sim Q/N_{\pi^+}$ , where  $Q=0,\pm 1,\pm 2,...$  is the topological charge and  $N_{\pi^+}$  is the positive pion multiplicity in one unit of rapidity – the typical scale of such correlations. The charge separation effect is expected to depend strongly on deconfinement and chiral symmetry restoration [9], and the signal might be greatly suppressed or completely absent at an energy below that at which a quark-gluon plasma can be formed.

#### 2. Chiral magnetic effect and charge dependent azimuthal correlations

In non-central nuclear collisions particle distribution in azimuthal angle is not uniform. The deviation from a flat distribution is called anisotropic flow and often is described by the Fourier decomposition [11] (for a review, see [12]):

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

where  $\Delta \phi = (\phi - \Psi_{RP})$  is the particle azimuth relative to the reaction plane (see Fig. 1),  $v_1$  and  $v_2$  account for directed and elliptic flow. Subscript  $\alpha$  is used to denote the particle type. Due to the "up-down" symmetry of the collisions  $a_n$  coefficients are usually omitted. Chiral magnetic effect violates such a symmetry. Although the "direction" of the violation fluctuates

event to event and on average is zero, in events with a particular sign of the topological charge, the average is not zero. As a result, it leads to a non-zero contribution to correlations, e.g.  $\langle a_{n,\alpha}a_{n,\beta}\rangle$ , where  $\alpha$  and  $\beta$  denote the particle type. One expects that the first harmonic would account for the most of the effect. Below, if not explicitly mentioned, it is assumed that n=1. Note that only particles originated from (interacted with) the same domain are correlated. The size of the domain is expected to be less than 1 fm, which means that the correlated particles are likely to be within about one unit of rapidity from each other. To measure  $\langle a_{\alpha}a_{\beta}\rangle$ , it was proposed [13] to use the correlator:

$$\langle \cos(\phi_{\alpha} + \phi_{\beta} - 2\Psi_{RP}) \rangle = \langle \cos \Delta \phi_{\alpha} \cos \Delta \phi_{\beta} \rangle - \langle \sin \Delta \phi_{\alpha} \sin \Delta \phi_{\beta} \rangle \tag{3}$$

$$= [\langle v_{1,\alpha} v_{1,\beta} \rangle + B_{in}] - [\langle a_{\alpha} a_{\beta} \rangle + B_{out}] \approx -\langle a_{\alpha} a_{\beta} \rangle + [B_{in} - B_{out}]. \tag{4}$$

This correlator represents the difference between correlations "projected" onto the reaction plane and the correlations projected onto an axis perpendicular to the reaction plane. The key advantage of using such a difference is that it removes all the correlations among particles  $\alpha$  and  $\beta$  that are not related to the reaction plane orientation. The contribution given by the term  $\langle v_{1,\alpha}v_{1,\beta}\rangle$  can be neglected because directed flow averages to zero in a rapidity region symmetric with respect to mid-rapidity.

**RP dependent, "physics", background.** The remaining background in Eq. 4,  $B_{in} - B_{out}$ , are due to processes in which particles  $\alpha$  and  $\beta$  are products of a cluster (e.g. resonance, jet, di-jets) decay, and the cluster itself exhibits elliptic flow or decays (fragments) differently when emitted in-plane compared to out-of-plane. The corresponding contribution to the correlator can be estimated as:

$$\langle \cos(\phi_{\alpha} + \phi_{\beta} - 2\Psi_{RP}) \rangle = \frac{N_{\frac{clust}{event}} N_{\frac{pairs}{clust}}}{N_{\frac{pairs}{event}}} \langle \cos(\phi_{\alpha} + \phi_{\beta} - 2\phi_{clust}) \rangle_{clust} v_{2,clust}, \tag{5}$$

where  $\langle ... \rangle_{clust}$  indicates that the average is performed only over pairs consisting of two daughters from the same cluster. This kind of background can not be easily suppressed. To address its contribution one has to rely on model calculations or perform experiments where the relative contribution of chiral magnetic effect and background can be varied, see Section 4.

**RP** independent background. The reaction plane is not known experimentally, and has to be estimated event-by event. Note that the second order reaction plane [14], reconstructed from strong elliptic flow [15], is sufficient for this measurement. Usually, the correlator Eq. 4 is evaluated with the help of 3-particle correlations:

$$\langle \cos(\phi_{\alpha} + \phi_{\beta} - 2\phi_{c}) \rangle \approx \langle \cos(\phi_{\alpha} + \phi_{\beta} - 2\Psi_{RP}) \rangle v_{2,c}. \tag{6}$$

This factorization can be broken, e.g. by correlations from a cluster decay to all three,  $\alpha$ ,  $\beta$ , and c particles. Such contribution can be greatly suppressed by appropriate choice of particle c, see [16].

#### 3. STAR results.

Recently, the charge and reaction plane dependent correlations for Au+Au and Cu+Cu collisions at  $\sqrt{s_{NN}}$ =200 GeV and  $\sqrt{s_{NN}}$ =62 GeV have been published by the STAR Collaboration [17, 18]. The correlations are reported for charged particle in the region  $|\eta| < 1.0$  with  $p_t > 0.15$  GeV/c. Figure 2 shows STAR results for Au+Au collisions at  $\sqrt{s_{NN}}$ =200 GeV compared to predictions from different event generators. Note that the latter are not zero, and is due to discussed above reaction plane dependent background. To illustrate this better, the results from UrQMD event generator are connected by dashed lines. Reaction plane independent background, for

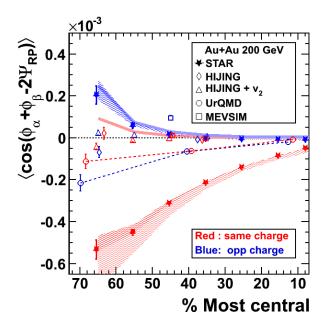


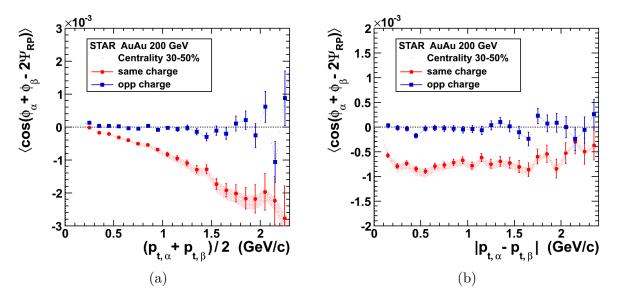
Figure 2. (Taken from [17]) STAR results compared to simulations for 200 GeV Au+Au. Blue symbols mark oppositecharge correlations, and red are samecharge. The shaded bands show the systematic error due to uncertainty in  $v_2$ measurements. In simulations the true reaction plane from the generated event was used. Thick solid lighter colored lines represent non reaction-plane dependent contribution as estimated by HIJING. Corresponding estimates from UrQMD are about factor of two smaller.

a particular method employed in this analysis, is shown by thick lines. Opposite-charge correlations are smaller than same-charge correlations. This observation led to the proposal [9] that back-to-back correlations may be suppressed due to the opacity of the medium. The correlations are weaker in more central collisions compared to more peripheral collisions, which partially can be attributed to dilution of correlations which occurs in the case of particle production from multiple sources. To compensate for the dilution effect, in particular when comparing Au+Au results to Cu+Cu, STAR also presented results multiplied by the number of participants (for a plot, see [17]). There, the same and opposite sign correlations clearly exhibit very different behavior. The opposite sign correlations in Au+Au and Cu+Cu collisions are found to be very close at similar values of  $N_{part}$  in rough qualitative agreement with the picture in which their values are mostly determined by the suppression of back-to-back correlations. The difference in magnitude between same and opposite sign correlations is considerably smaller in Cu+Cu than in Au+Au, qualitatively in agreement with the scenario of stronger suppression of the back-to-back correlations in Au+Au collisions.

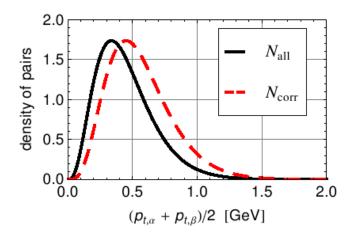
Somewhat unexpected result was the dependence of the signal on the transverse momentum of the two particles, see Fig. 3. It was found that the signal is not concentrated in the low  $p_t$  region as naively might be expected for  $\mathcal{P}$ -violation (non-perturbative) effects, and that the correlation depends very weakly on  $|p_{t,\alpha} - p_{t,\beta}|$ . An interesting possible explanation for such a dependence was found in [19]. It was found that such a dependence can be naturally understood if one assumes that the  $p_t$  distribution of correlated pairs has somewhat harder spectrum compared to that of all (random) pairs. The "trick" is that even if the distribution of pairs from clusters is only slightly harder, the relative weight of correlated pairs increases with  $p_t$ . Figure 4 shows the pair distributions in transverse momentum that was obtained in [19] using STAR data as an input.

## 4. Future program.

The STAR observation of the charge dependent azimuthal correlations consistent with the theoretical expectations for the chiral magnetic effect can be a beginning of an exciting program. Of course, one would need first to confirm that the observed correlations indeed are related to the local parity violation. If confirmed, it will open the door for direct experimental measurements



**Figure 3.** (Taken from [17, 18]). Au+Au at 200 GeV [17]. The correlations dependence (a) on sum and (b) the difference of the magnitude of transverse momenta.



**Figure 4.** Taken from [19]. Transverse momentum distribution of pairs from clusters, shown in red, compared to distribution of all pairs.

of the effects from non-perturbative sector of QCD, so far not possible.

## 4.1. Experiment.

Below I discuss several directions for a future experimental program. In particular I propose to use central body-body U+U collisions to test if the observed correlations are indeed related to the strong magnetic field, as they must be in chiral magnetic effect. More detailed study of the dependence of the effect on the magnetic field can be achieved with collisions of isobaric nuclei. Measurements aimed on understanding the properties of the clusters in multiparticle production would be another important part of the program.

• Central body-body U+U collisions. Ambiguity in the interpretation of the STAR results lies in the difficulty to eliminate/suppress the RP dependent background,  $B_{in} - B_{out}$ , which by itself originates in the anisotropy of particle production relative to the reaction plane – elliptic flow. To eliminate/suppress elliptic flow, and at the same time preserve strong magnetic field needed for the chiral magnetic effect does not look realistic. But the opposite

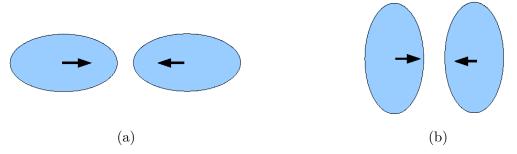
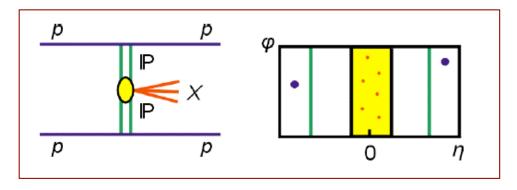


Figure 5. Schematic view of central U+U collisions: (a) tip-tip and (b) body-body.

is possible, one can have collisions with strong elliptic flow and no (or almost no) magnetic field. This can be achieved in central body-body U+U collisions. Uranium nuclei are not spherical and have roughly ellipsoidal shape. Central collision, when most of the nucleons interact, can have different geometry, ranging from the so called tip-tip collisions to body-body collisions [20], see Fig. 5. Unlike tip-tip collisions, body-body ones would exhibit strong elliptic flow. Neither would lead to a strong magnetic field; consequently, a very weak signal due to chiral magnetic effect is expected. At RHIC one can select central collisions by requiring a low signal in the zero degree calorimeters that detect spectator neutrons. Then one can analyze the dependence of the signal on the elliptic flow present in the events. If the signal is due to elliptic flow one should find a direct relations between the two. Calculations of the relative strength of the effect in different scenarios are under way [21].

- Collision of isobaric nuclei. The charge separation dependence on the strength of the magnetic field can be further studied with collision of isobaric nuclei, such as  $^{96}_{44}Ru$  and  $^{96}_{40}Zr$ . These nuclei have the same mass number, but differ by the charge. The multiparticle production in the midrapidity region would be affected very little in collision of such nuclei, and in particular one would expect very similar elliptic flow. At the same time the magnetic field would be proportional to the nuclei charge and can vary by more than 10%, which can results in 20% variation in the signal. Such variations should be readily measurable. The collisions of  $^{96}_{44}Ru$  and  $^{96}_{40}Zr$  isotopes have been successfully used at GSI [22, 23] in a study of baryon stopping. Collisions of isobaric nuclei at RHIC will be also extremely valuable for understanding the initial conditions, and in particular the initial velocity fields, the origin of directed flow, etc.
- Beam energy scan. The charge separation effect might depend strongly on the formation of a quark-gluon plasma and chiral symmetry restoration [9], and the signal can be greatly suppressed or completely absent at an energy below that at which a quark-gluon plasma is formed. Taking also into account that the life-time of the strong magnetic field is larger at smaller collision energies, it could lead to an almost threshold effect: with lowing the energy the signal might slowly increase with an abrupt drop thereafter. This questions can (and will) be addressed, for example, during the RHIC beam energy scan. But, unfortunately, the exact energy dependence of the chiral magnetic effect is not calculated yet.
- Identified particle studies. Large statistics recorded by RHIC experiments during the last runs(s) will allow identified and multiparticle correlations studies. There are several questions to be addressed in such analyses. With multiparticle correlations one can try to estimate the size of the cluster (the average multiplicity). The correlations using neutral particles should be mostly determined by background effects, and thus provide an estimate of those. The most interesting from my point of view, but also difficult, would be a study



**Figure 6.** Double Pomeron exchange reaction and particle distributing in  $\eta - \phi$  plane.

of the "quark content" of the cluster. The topological cluster decays in equal number of  $q\bar{q}$ -pairs of all flavors, the so-called 't Hooft interaction (e.g. used in instanton model to explain the difference in  $\bar{d}/\bar{u}$  in the nucleon "sea").

- Clusters, pp2pp experiment and double Pomeron collisions. From early FNAL and ISR measurements it has been known that cluster formation plays an important role in multiparticle production at high energies, for a review, see [24]. These clusters, with a size of about 2-3 charged particles per cluster, may account for production of a significant fraction of all particles. It is interesting and important to establish how these clusters are related to the topological clusters as suggested in [25] ("turning points" – QCD sphalerons). Recent progress in describing of the soft Pomeron as a multi-instanton ladder [26] also suggests that the topologically nontrivial gluonic configurations play important role played in multiparticle production. The properties of such clusters in principle can be studied in any multiparticle production processes, but one possibility stands out of the list, namely the double Pomeron exchange [27], as illustrated in Fig. 6. A specific kinematics of double Pomeron exchange process can be addressed by pp2pp experiment [28]. This reaction allows to investigate the properties of the clusters in a very clean environment, with one cluster per event and well controlled kinematics. The goal is to compare the measurements to expectations for sphaleron decays – invariant mass, angular distribution of the decay products, quark composition consistent with 't Hooft interaction, etc. Two pion Bose-Einstein correlation analysis will be of a particular interest. If the particle production indeed is due to decay of classical fields, the so-called chaoticity parameter  $\lambda$  (intercept of the correlation function at zero relative momentum) could show a significant decrease.
- *CP* forbidden decays. Not going into theoretical details, I only mention here a very exciting possibility of an observation of  $\mathcal{CP}$ -forbidden decays, e.g.  $\eta \to \pi\pi$ , which become possible in the presence of  $\mathcal{CP}$ -odd domains [30, 31].

## 4.2. Need for a "better" theory.

For new theoretical developments, including recent lattice results, I refer to the talk of D. Kharzeev [32]. Here I only emphasize, that detailed interpretation of the experimental data is not possible without realistic theoretical calculations. Many of needed calculations, such as dependence on centrality and system system size, look fully doable though require significant computing and man power (e.g. 3d hydrodynamics is needed for the calculation of the magnetic field). Detailed predictions on the transverse momentum and particle type dependence of the effect is also essential in differentiating the signal from possible background contributions. A good theoretical understanding of the background correlations themselves is also required, as at present all event generators lack a good description of correlation results.

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### 5. Summary.

Experimental observation of the chiral magnetic effect may provide a unique opportunity for a direct observation of the topological structure of QCD. The theoretical predictions are well within reach of the experiment. STAR has reported results that agree with the magnitude and gross features of the theoretical predictions for local  $\mathcal{P}$ -violation in heavy-ion collisions, but better theoretical calculations of the expected signal and potential physics backgrounds are essential for further experimental study of this phenomenon.

A very exciting future program dedicated to detail study of the effect is emerging. It includes U+U collisions, which could serve as a test of the chiral magnetic effect relation to the correlations observed by STAR.

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- [1] E. V. Shuryak and T. Schafer, Ann. Rev. Nucl. Part. Sci. 47, 359 (1997).
- [2] D. Diakonov, Prog. Part. Nucl. Phys. 51, 173 (2003).
- [3] D. Kharzeev, R. D. Pisarski and M. H. G. Tytgat, Phys. Rev. Lett. 81, 512 (1998) [arXiv:hep-ph/9804221];
   D. Kharzeev and R.D. Pisarski, Phys. Rev. D 61, 111901 (2000).
- [4] S. A. Voloshin, Phys. Rev. C 62, 044901 (2000).
- [5] L. E. Finch, A. Chikanian, R. S. Longacre, J. Sandweiss and J. H. Thomas, Phys. Rev. C 65, 014908 (2001).
- [6] S. Voloshin and the NA49 Collaboration, Search for parity violation in minimum bias Pb-Pb collisions at SPS, LBNL 1998 annual report, http://ie.lbl.gov/nsd1999/rnc/RNC.htm, report R10.
- [7] D. Kharzeev, Phys. Lett. B **633**, 260 (2006).
- [8] D. Kharzeev and A. Zhitnitsky, Nucl. Phys. A 797, 67 (2007).
- [9] D. E. Kharzeev, L. D. McLerran and H. J. Warringa, Nucl. Phys. A 803, 227 (2008).
- [10] K. Fukushima, D. E. Kharzeev and H. J. Warringa, Phys. Rev. D 78, 074033 (2008).
- [11] S. Voloshin and Y. Zhang, Z. Phys. C 70, 665 (1996) [arXiv:hep-ph/9407282]
- [12] S. A. Voloshin, A. M. Poskanzer and R. Snellings, arXiv:0809.2949 [nucl-ex].
- [13] S. A. Voloshin, Phys. Rev. C 70, 057901 (2004).
- [14] A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C 58, 1671 (1998) [arXiv:nucl-ex/9805001].
- K. H. Ackermann et al. [STAR Collaboration], Phys. Rev. Lett. 86, 402 (2001) [arXiv:nucl-ex/0009011].
- [16] Gang Wang (STAR Collaboration) This proceedings.
- [17] B. I. Abelev et al. [STAR Collaboration], arXiv:0909.1717 [nucl-ex].
- [18] B. I. Abelev et al. [STAR Collaboration], Phys. Rev. Lett. 103, 251601 (2009) [arXiv:0909.1739 [nucl-ex]].
- [19] A. Bzdak, V. Koch and J. Liao, arXiv:0912.5050 [nucl-th].
- [20] C. Nepali, G. I. Fai and D. Keane, Phys. Rev. C 76, 051902 (2007) [Erratum-ibid. C 76, 069903 (2007)] [arXiv:0709.1497 [hep-ph]].
- [21] S. A. Voloshin, in preparation.
- [22] B. Hong [FOPI Collaboration], Phys. Rev. C 66, 034901 (2002);
- [23] B. Hong [FOPI Collaboration], Nucl. Phys. A 721, 317 (2003).
- [24] L. Foa, Phys. Rept. 22, 1 (1975).
- [25] D. M. Ostrovsky, G. W. Carter and E. V. Shuryak, Phys. Rev. D 66, 036004 (2002) [arXiv:hep-ph/0204224].
- [26] D. E. Kharzeev, Y. V. Kovchegov and E. Levin, Nucl. Phys. A 690, 621 (2001) [arXiv:hep-ph/0007182].
- [27] E. Shuryak and I. Zahed, Phys. Rev. D 68, 034001 (2003) [arXiv:hep-ph/0302231].
- [28] W. Guryn, Acta Phys. Polon. B 40, 1897 (2009).
- [29] G. Bonvichini, private communication, 2008;
- [30] R. Millo and E. Shuryak, arXiv:0912.4894 [hep-ph].
- [31] G. Bonvichini, private communication, 2008;
- [32] D. Kharzeev, these proceedings;