PHYSICAL REVIEW C **78**, 044908 (2008)

Observing spontaneous strong CP violation through hyperon helicity correlations

F. Du, L. E. Finch,* and J. Sandweiss
Physics Department, Yale University, New Haven, Connecticut 06520, USA
(Received 21 August 2008; published 27 October 2008)

We report on studies of the viability of using hyperon correlations as a probe of spontaneous $\mathcal{CP}$ violation which it has been suggested may occur in heavy ion collisions. We discuss the motivation for such a search and use a simple model and statistical analysis to roughly estimate the size of an effect which may be expected to be visible in experiments.

DOI: 10.1103/PhysRevC.78.044908 PACS number(s): 25.75.Nq, 12.38.Qk, 11.30.Qc

I. INTRODUCTION

The possibility has been raised that heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) may lead to the formation of short-lived domains in which $\mathcal{CP}$ symmetry is not respected by the strong interaction [1,2]. An experimental observation of such a spontaneously broken symmetry would be extremely interesting and would clearly demonstrate the formation of a new state of matter at RHIC. However, because of the spontaneous nature of this violation, any measurement made with a $\mathcal{CP}$ odd observable must have an expectation value of zero when averaged over many events. This means that an effect can only be seen by measuring correlations within events and comparing them to the expected correlations that would exist from background sources in the absence of this spontaneous $\mathcal{CP}$ violation. Accurately accounting for all these sources of background correlations is generally a difficult task, so that unambiguous proof of the presence of $\mathcal{CP}$ violation will likely be difficult. It is particularly useful, therefore, to study as many different experimental signatures as possible for signs of an effect over background. In this paper, we study the viability of using correlations of hyperon helicities in heavy ion events for this purpose.

II. THEORETICAL MOTIVATION

It is generally understood that the presence of a heavy η' meson demonstrates [3] that (i) the $U_A(1)$ symmetry of the classical QCD equations is not broken by the QCD vacuum but is rather not a true symmetry of the quantum theory and (ii) the structure of the QCD vacuum is such that this effectively results in adding a term to the QCD Lagrangian $\mathcal{L}_\theta = \theta_{\mathrm{QCD}} \times \frac{g_s^2}{32\pi^2} F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a$ where θ_{QCD} is a free parameter, $F_{\mu\nu}$ the gluon field strength tensors, and g_s the strong coupling. (In terms of the color electric and magnetic fields, $F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a \propto \mathbf{E}_c \cdot \mathbf{B}_c$, so this is clearly a $\mathcal{CP}$ violating term.) The value of θ_{QCD} is experimentally constrained by measurements of the neutron dipole moment so that $|\bar{\theta}| < 3 \times 10^{-10}$ where $\bar{\theta}$ is equal to θ_{QCD} plus weak interaction contributions [3]. The reason for $\bar{\theta}$ to be so nearly zero is not understood and this is referred to as the strong $\mathcal{CP}$ problem.

*finch@hepmail.physics.yale.edu

In 1998, it was discussed by Kharzeev *et al.* [1] that metastable states may form in heavy ion collisions which behave as if $\bar{\theta}$ is nonzero and thus cause $\mathcal{CP}$ violation which varies from event-to-event. The size of the effect in a given event is governed by the net topological charge, $Q = \frac{g_s^2}{32\pi^2}\int d^4x\, F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a$, generated in the event. There have been theoretical efforts [4,5] to calculate (using guidance from lattice QCD calculations [6]) the distribution of Q which may be expected in heavy ion collisions, but there are large uncertainties on such calculations. Reference [4], for example, finds rms widths of the Q distribution to be of order $\sigma_Q = 1$ from the early stages of the collision, but perhaps as large as $\sigma_Q = 20$ to 40 if sphaleron [7] transitions occur later in the system's evolution.

Over the last decade, various observables have been proposed to search for this spontaneous $\mathcal{CP}$ violation. The first sort of observables [8,9] were designed to be sensitive to momentum changes caused by the passage of particles through regions of nonzero $\mathbf{E}_c \cdot \mathbf{B}_c$. More recently, it was suggested that the only reasonable choice of axis for the fields to become aligned with would be that of the collision angular momentum and that a possible signal of $\mathcal{CP}$ violation would be charge separation along this axis [10]. This is currently the most active area of investigation [11] and seems likely to be accessible to experimental observation even for a Q distribution having a width as small as of order 1. It is only experimentally accessible, however, through the observation of resulting charge and reaction plane dependent momentum correlations between charged particles. Many processes may potentially cause backgrounds for such observables; these background may of course be studied both theoretically and from data and so their effects may be constrained, but it would be very useful to also study this effect via other methods.

We note that the effect of a nonzero topological charge is to create a net helicity of the system

$$\Delta\left(N_L^f - N_R^f\right) = 2Q \tag{1}$$

[12,13], where N_L^f and N_R^f represent the numbers of left-handed and right-handed (massless) fermions of a given flavor. The net helicity of quarks and antiquarks formed in this manner should lead to a net helicity of hyperons coming from the collision which can then be analyzed through the parity violating decays of these hyperons.

By using STAR data on the production of various strange particles [14–16] in RHIC collisions and guidance from theory on the distributions of topological charge values which may be generated in these collisions, as well as making simple assumptions about the effect of quark spins on the Λ spin, we may study the viability of using correlations between Λ hyperons' helicities to probe this spontaneous $\mathcal{CP}$ violation.

III. MODEL AND CALCULATIONS

Our intention is to perform a very simplified simulation of RHIC collisions which will tell us roughly what we may expect for the event-by-event correlations of measured hyperon helicity in the presence of spontaneous strong $\mathcal{CP}$ violation under various sets of assumptions. We will then determine, as a function of two parameters—the width σ_Q of the Q distribution, and ϵ_{exp}, the Λ detection efficiency—an estimate for the number of central RHIC events that would be needed for such a spontaneous strong $\mathcal{CP}$ violation to be clearly visible.

A. Topological charge and net helicity of strange quarks

We begin each event in our simulation by randomly choosing a value of topological charge, Q_{event}, from our Q distribution. Following the theoretical calculations, we vary the width of this distribution from $\sigma_Q = 5$ to $\sigma_Q = 20$ (we assume a Gaussian distribution for simplicity).

For each event, we assume that the excess of left-handed over right-handed s and $\bar{s}$ quarks due to this topological charge is given by Eq. (1) as $2Q_{\text{event}}$. We implement this by in effect beginning each event with a sample of s and $\bar{s}$ quarks whose helicities are generated at random and then flipping the spins of Q_{event} right-handed s or $\bar{s}$ quarks to be left-handed.

In the simple quark model of hyperons [17,18], the Λ spin is completely determined by the strange quark spin. Other models [19–21] calculate lower values closer to 70% for the fraction of Λ spin carried by the strange quark. An analysis [22] of Λ longitudinal polarization in the target fragmentation region of deep inelastic $\bar{\nu}N$ collisions indicates that the polarization transfer from s quark to Λ is 70% efficient but the authors speculate that this number may be diluted by the decays of heavier hyperon resonances. In our simple model, we assume that the (anti-)Λ helicity is completely determined by the (anti-)s quark helicity and assume no contributions from the u and d quarks. The effect of changing this assumption would be to rescale the width of the Q distribution by the fraction of Λ helicity which is determined by the strange quark helicity (and the results shown in Fig. 2 would have the x-axis rescaled by this factor).

B. Resulting net helicity of Λs

To perform our calculation, we need to simulate, for each event, the number of $\Lambda + \bar{\Lambda}$ that are "measured" and the number of these that are measured to have left-handed helicity. For each event in our simulation, we assume that there are $75\Lambda + \bar{\Lambda}$ produced (this is roughly the number within $|y| < 1$ in a central RHIC collision [23] including feed-down from higher mass states as we assume for this work that such Λs are not distinguishable from primordial ones). Initially, we randomly assign each Λ and $\bar{\Lambda}$ a helicity with equal probability to be left- or right-handed.

The fraction of $s + \bar{s}$ quarks having $|y| < 1$ that go into primordial $\Lambda + \bar{\Lambda}$ production can be estimated by using STAR measurements of strange particle production at RHIC [14–16] to obtain the ratio of the number of produced $(\Lambda + \bar{\Lambda})$ to the number of produced $(s + \bar{s})$ and is roughly 5%. Following this, we assume in our model that for each unit of Q in a given event we have a 5% chance of switching one right-handed Λ (or $\bar{\Lambda}$) to be left-handed (or vice versa, if Q is negative). So for example, in an event with a value of $Q_{\text{event}} = 20$, we would then on average switch the helicity of 1 primordial Λ or $\bar{\Lambda}$ out of approximately 35. We consider here only the signal present in primordial Λs, though likely some gain could be made by also considering signal present in higher mass states.

After performing these helicity switches, we know for a given simulated event the number of $(\Lambda + \bar{\Lambda})$s produced and the number which are left-handed; we only need to know which ones are measured and the helicity measured for each. For this, we first apply an overall 63.9% probability to decay through the measurable $\Lambda \rightarrow p + \pi$ channel. We next apply randomly to each Λ and $\bar{\Lambda}$ an experimental efficiency ϵ_{exp} for finding Λs with $|y| < 1$ which we vary from 3.5% (a rough approximation of the overall current Λ detection efficiency for STAR [23] though this should increase by at least a factor of a few with currently planned detector upgrades) to 50%. Finally, for each Λ and $\bar{\Lambda}$ we assume that there is a 66% chance that the helicity will be correctly determined by the directions of the decay products and we apply this probability to each "measured" Λ helicity.

The net result of each event is then a number M of total Λs and $\bar{\Lambda}s$ "measured" and a number L_Λ of these that are measured to be left-handed.

C. Simulation results

For a given choice of σ_Q and ϵ_{exp}, we run an ensemble of N events, each giving us a value for M and L_Λ, and we want to know if this ensemble is statistically different from the case where there is no spontaneous $\mathcal{CP}$ violation. We do this with a simple χ^2 test; for the total sample of N events, we calculate

$$\chi^2 = \sum_M \frac{N_M}{N} \sum_{i=0}^{M} \frac{(n_i - \bar{n}_i)^2}{\sigma_i^2}, \tag{2}$$

where N_M is the number of events that have M "measured" $(\Lambda + \bar{\Lambda})$s, n_i is the number of events with i left-handed $(\Lambda + \bar{\Lambda})$s, and $\bar{n}_i$ is the expected value of n_i from binomial statistics. We then check for many such ensembles what fraction of the time such an ensemble has a greater than 95% confidence level not to have been produced by binomial statistics. More detail can be found in [24].

An example is shown in Fig. 1 for the case when we set $\sigma_Q = 20$ and $\epsilon_{\text{exp}} = 0.1$, and proceed to run 181 event samples of 55×10^6 events each. We find that, in this case, 95% of the event samples show a greater than 95% confidence

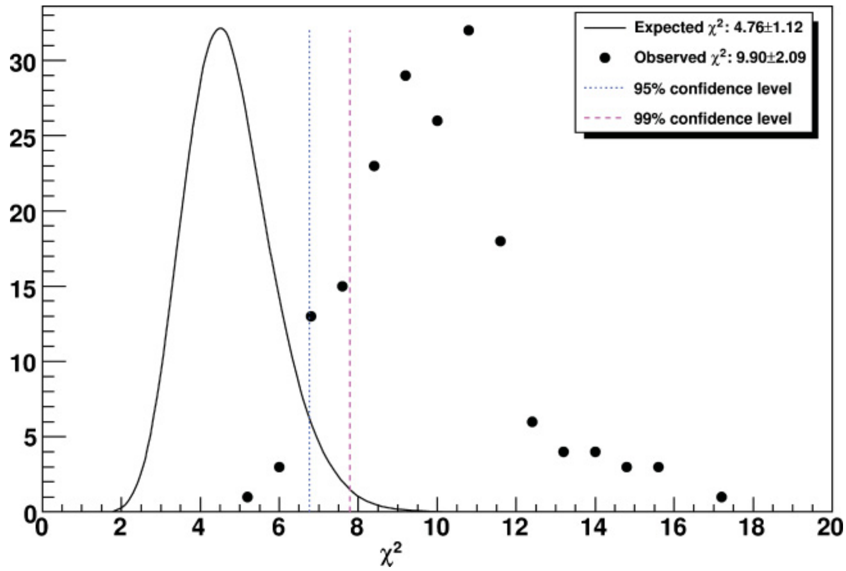

FIG. 1. (Color online) Histogram of values of the χ^2 calculation [Eq. (2)] for 181 event samples. Each sample consists of 55×10^6 events with $\sigma_Q = 20$ and $\epsilon_{\text{exp}} = 0.1$. The curve is the theoretical χ^2 curve for this same distribution with no $\mathcal{CP}$ violation (which is obtained when we set $\sigma_Q = 0$).

level of non-binomial production. We did confirm that the theoretical curve was reproduced within statistical errors when the Λs and $\bar{\Lambda}s$ were all generated with uncorrelated helicities.

In Fig. 2 we show, as a function of σ_Q and ϵ_{exp}, the number of events needed so that 95% of the event ensembles have such a 95% confidence level. We see that the number of events is strongly dependent on both of these parameters as may be expected for such a correlation analysis. Indeed, other details such as the shape of the Q distribution and the p_T dependence of the Λ efficiency are also important and may be studied, but the purpose of this initial simulation is simply to provide some rough guidance as to the size of event samples which will likely be necessary—with data samples and experimental efficiencies possible in the near future, we should hope to see sensitivity to Q distributions with σ_Q of roughly 10.

IV. DISCUSSION OF POSSIBLE BACKGROUNDS

Such an analysis relies on having the distribution of Λ helicity follow binomial statistics in the absence of $\mathcal{CP}$ violation, and so any other process that produces correlation among Λ helicities is a potential worry. We have not done a thorough study of background sources, but are aware of the following potential issues.

(i) Λs produced by Ξ decay are in general longitudinally polarized in the Ξ rest frame. In principle this may become a concern if fluctuations in the event-to-event production of Ξ are not properly accounted for. In practice, however, we find this not to be a concern—when we added this longitudinal polarization of Λs from Ξ decays to our simulation (with $\sigma_Q = 0$) we found no discernible signal in 200×10^6 events even

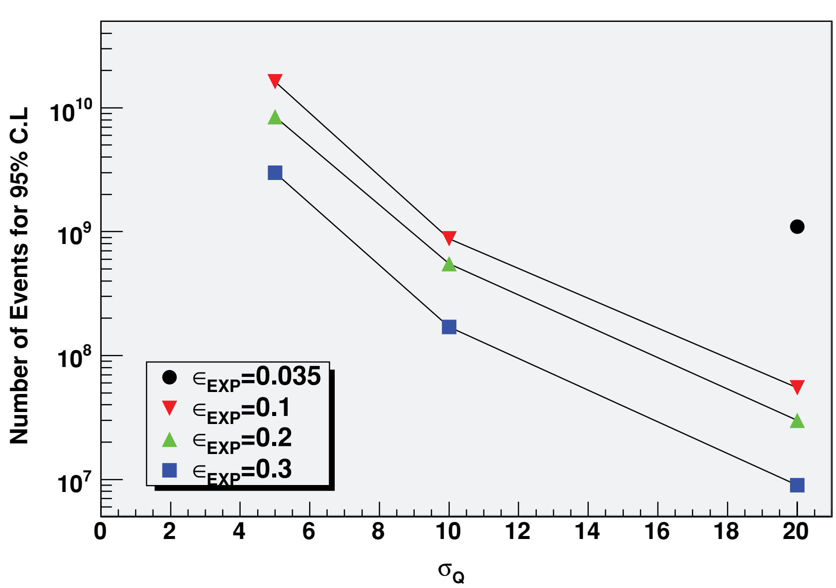

FIG. 2. (Color online) Summary of results from our simple model for number of events needed to observe the $\mathcal{CP}$ violation signal at the 95% confidence level as a function of σ_Q and ϵ_{exp}.

with extremely exaggerated fluctuations in production (choosing each event to have either 0% or 100% of Λs produced by Ξ decay)—this is apparently largely because the polarization in the Ξ rest frame leads to only a small residual polarization in the collision frame.

(ii) If there is some global difference in detection efficiency for left-handed versus right-handed Λs, the analysis can easily be adjusted for this. If the relative efficiencies vary as a function of collision parameters such as z-vertex and reaction plane, so that the relative efficiency changes event-to-event, more care must of course be taken to make sure the efficiencies for each event are properly accounted.

(iii) Also, Λ (and $\Lambda - \bar{\Lambda}$) pairs may be produced in states of correlated spin, and such a correlation may appear as a nonzero signal when analyzing helicity correlations. Our understanding is that through proper analysis, it should be apparent whether an observed helicity correlation is simply the result of a spin correlation. The only concern, then, is whether the size of a spin correlation would make the measurement of helicity correlation difficult.

V. SUMMARY

We have discussed the possibility of using helicity correlations of Λs from heavy-ion collisions as a probe of spontaneous strong $\mathcal{CP}$ violation. We find that with experimental efficiencies and data samples possible in the near future, this method will be sensitive to distributions of topological charge with widths above roughly 10. This method is not likely to be as sensitive as, for example, looking for charge separation along the angular momentum axis, but will quite possibly be affected by fewer (and certainly different) background sources and so may be a very useful addition to such studies.

ACKNOWLEDGMENTS

We gratefully acknowledge many very useful discussions on this subject with Dmitri Kharzeev. This work was supported by the U.S. Department of Energy Nuclear Physics Division under Contract No. 1011167.1.E00041.627014.

[1] D. Kharveev, R. D. Pisarski, and M. H. G. Tytgat, Phys. Rev. Lett. **81**, 512 (1998).
[2] P. D. Morley and I. A. Schmidt, Z. Phys. C **26**, 627 (1985).
[3] G. C. Branco, L. Lavoura, and J. Silva, *CP Violation* (Oxford University Press, Oxford, 1999).
[4] D. Kharzeev, A. Krasnitz, and R. Venugopalan, Phys. Lett. **B545**, 298 (2002).
[5] T. Lappi and L. McLerran, Nucl. Phys. **A772**, 200 (2006).
[6] B. Alles, M. D'Elia, and A. Di Giacomo, Phys. Lett. **B483**, 139 (2000).
[7] E. V. Shuryak, Phys. Lett. **B515**, 359 (2001).
[8] S. A. Voloshin, Phys. Rev. C **62**, 044901 (2000).
[9] L. E. Finch, A. Chikanian, R. S. Longacre, J. Sandweiss, and J. H. Thomas, Phys. Rev. C **65**, 014908 (2001).
[10] D. Kharzeev, Phys. Lett. **B633**,260 (2006).
[11] S. A. Voloshin (STAR Collaboration), arXiv:nucl-ex/0806.0029 (2008).
[12] M. E. Peskin and D. V. Schroeder, *An Introduction to Quantum Field Theory* (Perseus Books, New York, 1995).
[13] D. E. Kharzeev, L. D. McLerran, and H. J. Warringa, Nucl. Phys. **A803**, 227 (2008).
[14] J. Adams *et al.* (STAR Collaboration), Phys. Rev. Lett. **98**, 062301 (2007).
[15] J. Adams *et al.* (STAR Collaboration), Phys. Rev. Lett. **92**, 112301 (2004).
[16] C. Adler *et al.* (STAR Collaboration), Phys. Lett. **B595**, 143 (2004).
[17] M. Burkardt and R. L. Jaffe, Phys. Rev. Lett. **70**, 2537 (1993).
[18] A. Airapetian *et al*. (HERMES Collaboration), Phys. Rev. D **74**, 072004 (2006).
[19] M. Gockeler *et al.* (QCDSF Collaboration), Phys. Lett. **B545**, 112 (2002).
[20] D. Ashery and H. J. Lipkin, Phys. Lett. **B469**, 263 (1999).
[21] J.-J. Yang, Phys. Lett. **B512**, 57 (2001).
[22] J. R. Ellis, D. Kharzeev, and A. Kotzinian, Z. Phys. C **69**, 467 (1996).
[23] C. Adler *et al.* (STAR Collaboration), Phys. Rev. Lett. **89**, 092301 (2002).
[24] F. Du, Ph.D. thesis, Yale University, New Haven, CT (2008).