Role of the chromomagnetic vacuum background field in $e^+e^- \to 2$ jets and other reactions

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We propose a new type of a measurement which is sensitive to the QCD vacuum color-magnetic fluctuations: a measure of the axial asymmetry of the hadronic final states produced in the high energy e^+e^- collisions which is related to the chromomagnetic vacuum field strength.

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I. INTRODUCTION

In this paper we propose a new type of a measurement, sensitive to the presence of the chromomagnetic vacuum background field — an idea with almost 20 years of history [1] (see [2] for a recent review).

The basic idea of the effect we discuss here has been proposed more than 10 years ago by Nachtmann and Reiter [3]: the chromomagnetic vacuum field changes the trajectory of partons created in high energy collisions, giving rise to various correlations between the parton and, indirectly, the hadron momenta. Although the possibility to investigate such a basic property of QCD seems to be very attractive, no major effort has been done in this direction for two important reasons: these effects, if they exist, are very difficult to measure, and it is not obvious that they could not be interpreted in terms of the perturbative QCD theory; i.e., there might be serious problems with a unique interpretation of such effects.

A good example of the second point is the K factor in the Drell-Yan process, which can be interpreted either as the result of the color polarization of quarks traversing the domain of the vacuum chromomagnetic field [3] or, simply, as the higher-order QCD corrections.

In recent publications by Nachtmann *et al.* [4] some arguments in favor of the observability of the chromomagnetic field of the vacuum have been reiterated, refined, and some supporting experimental evidence quoted. On the theoretical side, some support for the concept of a ferromagnetic vacuum comes also from the recent lattice simulations [5].

A very large set of statistics of e^+e^- annihilations into hadrons, collected at CERN e^+e^- collider LEP and SLAC Large Detector (SLD) experiments encourages us to propose a new type of measurement designed to detect deflection of quarks and antiquarks in the chromomagnetic fields of the QCD vacuum. Its new feature is a possibility to distinguish the true QCD vacuum effect from the perturbative interpretations based on CP-parity conservation arguments. Observation of CP-parity-violating effects would provide strong support for the nonperturbative vacuum structure of QCD which, indeed, may locally violate CP parity.

Our discussion is mainly devoted to e^+e^- annihilations (Secs. II and III) where, from the phenomenological point of view, the situation is the simplest. However, the hadron-hadron and, above all, nucleus-nucleus collision data, may also provide very interesting evidence for the structured nonperturbative QCD vacuum. Such effects are briefly discussed in Sec. IV. Section V contains the summary and the conclusions.

II. QUARKS IN THE VACUUM BACKGROUND CHROMOMAGNETIC FIELD

Following Refs. [3,4], let us consider QCD vacuum as a sort of "ether." At any given time it is supposed to show a domain structure. Inside the domains there are more or less constant chromomagnetic fields. Theory does not have much to say about the space extension and the time duration of such vacuum fluctuations. Seemingly, a natural assumption [3] is the linear dimension of the domain of order $1/\Lambda$ and the frequency of fluctuations of order Λ, where Λ is the QCD scale parameter. However, we are aware that simple intuition might not be the best guide in this case. The reasoning which follows has been inspired by the model of the origin of the jet handedness by Ryskin [6].

At the stage of fragmentation of a color-electric string, spanned between the initial $(q\bar{q})_i$ pair created in e^+e^- collision, the secondary $(q\bar{q})_s$ pairs are created. Let us discuss a very simplified picture of this breakup: all quarks have the same color and antiquarks have the same anticolor. Thus, in a domain of the constant chromomagnetic vacuum field, all quarks turn, in the plane transverse to the string, in one direction and antiquarks in the

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opposite direction.

Let us consider trajectories of secondary $(q\bar{q})_s$ pairs in more detail. At the beginning, the transverse (with respect to the common axis of jets $\boldsymbol{l}$) momenta of these new partons are balanced,

$$\mathbf{q}_\perp = -\bar{\mathbf{q}}_\perp,$$

but, when moving in the color magnetic field, they acquire equal, additional momenta $\delta\mathbf{q}_\perp = \delta\bar{\mathbf{q}}_\perp$ (as they have opposite color charges and move in opposite directions in the transverse plane). As the result we get a triad of vectors

$$\mathbf{q}'_\perp = \mathbf{q}_\perp + \delta\mathbf{q}_\perp ; \bar{\mathbf{q}}'_\perp = \bar{\mathbf{q}}_\perp + \delta\mathbf{q}_\perp ; \boldsymbol{l} \tag{1}$$

with the handedness i.e., the sign of the mixed product $(\mathbf{q}'_\perp \times \bar{\mathbf{q}}'_\perp)\cdot\boldsymbol{l}$ uniquely defined by the relative orientation of $\boldsymbol{l}$ and the background chromomagnetic field $\mathbf{B}$. In a constant vacuum field all triads (in both jets) have the same handedness.

For comparison, in the Ryskin model [6] the chromomagnetic fields are produced by the color-dipole moments of the original quark and antiquark. The direction of these fields and thus the relative handedness of triads (1) in the opposite jets depends on the spin alignment for the original $(q\bar{q})_i$ pair, but is always CP symmetric. In the particular case of the aligned spins, as in the case of e^+e^- collisions, handedness produced by color-dipole chromomagnetic fields is opposite for the quark and antiquark jets. As will be discussed later the effect of a constant vacuum chromomagnetic field can be easily distinguished from the other QCD effects merely by observing the "wrong sign" handedness correlation between jets.

The value of the additional transverse momentum $|\delta\mathbf{q}_\perp|$ acquired by the parton can be roughly related to the strength of the vacuum chromomagnetic field assuming that the parton before losing its color charge traverses a typical hadronization distance $1/\Lambda$ [3]. Then

$$|\delta\mathbf{q}_\perp| = \sqrt{\alpha_s}\langle|(\mathbf{B}\cdot\boldsymbol{l})|\rangle/\Lambda. \tag{2}$$

It is interesting to note that $|\delta\mathbf{q}_\perp|$ may be quite substantial. One parameter characterizing the vacuum fields is the expectation value of the square of the gluon field strength introduced by Vainstein *et al.* [7]. Using the experimental value given in the recent review of nonperturbative methods in QCD [8],

$$\langle 0|4\pi\alpha_s \mathbf{B}^a\mathbf{B}^a|0\rangle \approx (700\ \text{MeV})^4,$$

we have $\sqrt{\alpha_s}\langle|(\mathbf{B}\cdot\boldsymbol{l})|\rangle/\Lambda \approx 200$ MeV i.e., a quantity comparable to the average parton transverse momentum (≈ 400 MeV). Thus, at the parton level the axial asymmetry induced by the vacuum field may be large enough but, of course, it is washed out to a large extent (if not completely) after the hadronization.

III. TRANSFER OF THE AXIAL ASYMMETRY FROM PARTON TO HADRON LEVEL

Transfer of the axial asymmetry from the parton level to the hadron level is possible, at least in principle, due to the local retention of the parton quantum numbers in the hadronization process. A possibility of discovering such an asymmetry may crucially depend on the proper choice of the kinematical variables which we employ in our analysis of the hadronic final state.

The "jet handedness" discussed in the literature [9–11] is an example of such quantity. Its notion was originally connected to the idea that axial asymmetry due to the polarization of the quark from which jet originates, may be induced into the jet as a quantum interference effect [10] or color-dipole field effect [6]. Apparently, such effects have to be local in the rapidity space and the quantities designed to measure it have to be based on local variables. Typically one chooses [11] the oppositely charged tracks of the highest momentum and from their momenta $\mathbf{k}_+$, $\mathbf{k}_-$ one constructs quantity (related to the jet handedness)

$$\omega = \mathbf{t}\cdot(\mathbf{k}_+ \times \mathbf{k}_-), \tag{3}$$

where $\mathbf{t}$ is the thrust axis in the jet direction. A signal would be visible as a nonzero mean $\langle\omega\rangle$, proportional to the polarization of the initial quark.

Incidentally, in the recent data from SLD [11] $\langle\omega\rangle$ was found to be consistent with zero. The correlation between ω_1 and ω_2 in the opposite jets:

$$R_\omega = (\langle\omega_1\omega_2\rangle - \langle\omega_1\rangle\langle\omega_2\rangle) \tag{4}$$

was for the first time considered by Efremov, Potashnikova, and Tkatchev [12], who observed a correlation signal in DELPHI preliminary data. In SLD data [11] no jet handedness correlation was observed, however, a large difference in the statistics of these two experiments should be noted.

In contrast, in our case the asymmetry induced into parton state by the interaction with the vacuum background chromomagnetic field has global character i.e., it is distributed over the whole interaction volume. So, we propose to build a measure of the jet handedness from cumulative variables. At first, we define cumulant of the transverse momentum for positive and negative particles separately:

$$\mathbf{P}_\perp^\pm(y_{\min}, y_{\max}) = \sum_j \mathbf{k}_{\perp j}\Theta(y_{\max} - y_j)\Theta(y_j - y_{\min})\Theta(\pm Q_j), \tag{5}$$

where $\mathbf{k}_{\perp j}, y_j, Q_j$ denote the transverse momentum, rapidity, and charge of the jth particle, $\Theta(x)$ is the step function equal to $1(0)$ for $x > 0 (x < 0)$. This quantity is the sum of the transverse momenta of all positive (negative) particles in the rapidity range $(y_{\min}, y_{\max})$:

$$P_\perp(y_{\min}, y_{\max}) = |\,[\mathbf{P}_\perp{}^+(y_{\min}, y_{\max}) + \mathbf{P}_\perp{}^-(y_{\min}, y_{\max})]\,| \tag{6}$$

is the length of the total transverse momentum vector in the above rapidity range.

The standard assumption of the local compensation of transverse momentum, equivalent to the assumption that $(q\bar{q})_s$ pairs do not carry momentum transverse to the jet axis, leads to the prediction that far from the phase space boundary $P_\perp$ remains independent of $\Delta y = | y_{\min} - y_{\max} |$ i.e., does not depend on the number of $q\bar{q}$ pairs created in the rapidity range $(y_{\min}, y_{\max})$. However, in the model with the background chromomagnetic field the situation is different: each $(q\bar{q})_s$ pair acquires the transverse momentum $2 \mid \delta \mathbf{q}_\perp \mid$. It is randomly oriented in the plane transverse to the jet direction, thus we expect that the average value of the transverse momentum cumulant grows proportionally to the square root of the average number $N_{q\bar{q}}$ of $(q\bar{q})_s$ pairs in the rapidity range $(y_{\min}, y_{\max})$:

$$\langle P_\perp(y_{\min}, y_{\max}) \rangle \approx \sqrt{N_{q\bar{q}}} \mid \delta \mathbf{q}_\perp \mid = \sqrt{\bar{n} \mid y_{\min} - y_{\max} \mid} \mid \delta \mathbf{q}_\perp \mid, \tag{7}$$

where $\bar{n}$ is the average number of $q\bar{q}$ pairs per unit rapidity interval and $\langle\ \rangle$ denotes an average over events. In other words the transverse momentum shows the effect of diffusion.

Employing the cumulative variables $\mathbf{P}_\perp^\pm$ we can construct the mixed product analogical to that in Eq. (3):

$$\Omega(y_{\min}, y_{\max}) = [\mathbf{P}_\perp^+(y_{\min}, y_{\max}) \times \mathbf{P}_\perp^-(y_{\min}, y_{\max})] \cdot \boldsymbol{l}, \tag{8}$$

where $\boldsymbol{l}$ is the direction along the common axis of the two jets. Its sign is related to the handedness of triads (1). Note that we do not use vector $\mathbf{t}$ oriented in the jet direction, as in formula (3), in order to avoid a singularity at the rapidity $y = 0$, so that we can integrate over the rapidity range which includes this point. We can define also the correlation function R_Ω:

$$R_\Omega = (\langle \Omega_1 \Omega_2 \rangle - \langle \Omega_1 \rangle \langle \Omega_2 \rangle), \tag{9}$$

where $\Omega_1 = \Omega(y_{\min}, y_{\max})$ and $\Omega_2 = \Omega(-y_{\min}, -y_{\max})$. This quantity is, in turn, analogical to R_ω defined in Eq. (4).

As we have seen before, the handedness of triads (1) induced by the chromomagnetic vacuum background field in the opposite jets is the same. Let us see how it is transferred to the quantity Ω defined above.

The assumptions of the local retention of the parton quantum numbers, of the momentum conservation, and the isospin symmetry lead to the approximate expressions in terms of the quark momenta:

$$\mathbf{P}_\perp^+(y_{\min}, y_{\max}) \approx \tfrac{1}{3}(1+\beta) \sum_i \mathbf{q}_{\perp i} + \tfrac{1}{3}(1-\beta) \sum_i \bar{\mathbf{q}}_{\perp i}, \tag{10}$$

$$\mathbf{P}_\perp^-(y_{\min}, y_{\max}) \approx \tfrac{1}{3}(1-\beta) \sum_i \mathbf{q}_{\perp i} + \tfrac{1}{3}(1+\beta) \sum_i \bar{\mathbf{q}}_{\perp i}. \tag{11}$$

$\sum_i$ extends over all $(q\bar{q})_s$ pairs falling into the rapidity range $(y_{\min}, y_{\max})$. It should be noted that relations (10) and (11) are applicable for both jets only in the central rapidity range, where parton states in both jets are neutral in charge and flavor. The situation is much less clear in the quark (antiquark) fragmentation regions — we will come back to this problem later.

The parameter β in the above formulas can be related to the experimentally measured quantity

$$\langle \Delta P_\perp \rangle = \langle | \mathbf{P}_\perp^+ - \mathbf{P}_\perp^- | \rangle \approx \tfrac{4}{3}\beta \left\langle \left| \sum_i \mathbf{q}_{\perp i} \right| \right\rangle \approx \tfrac{4}{3}\beta \sqrt{N_{q\bar{q}}} \langle q_\perp \rangle, \tag{12}$$

where, in analogy with formula (7), we have used the argument about the random walk in the transverse momentum plane to get

$$\left\langle \left| \sum_i \mathbf{q}_{\perp i} \right| \right\rangle \approx \sqrt{N_{q\bar{q}}} \langle q_\perp \rangle. \tag{13}$$

Note that this formula does not contain $\mathbf{B}$ because of cancellation of the $\delta \mathbf{q}_{\perp i}$ components in (12). From (2), (8), and (10)–(12) we get

$$\Omega(y_{\min}, y_{\max}) \approx \Omega(-y_{\min}, -y_{\max}) \approx \tfrac{8}{9}\beta \sqrt{N_{q\bar{q}}} \sqrt{\alpha_s} \langle q_\perp \rangle (\mathbf{B} \cdot \boldsymbol{l}) / \Lambda. \tag{14}$$

The average $\langle \Omega \rangle$ vanishes, as for the randomly oriented chromomagnetic vacuum field $\langle (\mathbf{B} \cdot \boldsymbol{l}) \rangle = 0$. The correlation function R_Ω has a nonzero value

$$R_\Omega(y_{\min}, y_{\max}) \approx \tfrac{4}{9} \langle \Delta P_\perp \rangle^2 \alpha_s \langle | (\mathbf{B} \cdot \boldsymbol{l}) | \rangle^2 / \Lambda^2. \tag{15}$$

where we employed the formula (12) to eliminate $\beta N_{q\bar{q}}$, so that R_Ω is related to the vacuum field strength only through the parameters which can be measured in the same experiment.

The sign of the correlation function is positive and in this respect our effect differs from Ryskin approach [6] where, by the requirement of CP parity, $\mathbf{B}$ has to change sign when going from one jet to another. The sign of the handedness correlation is completely determined at the parton level, but its transfer to the hadron level is subject to the additional assumptions. We have assumed that in the central rapidity region hadronization is blind to the identity of the original parton (source of the jet), otherwise some long range charge correlations would have been observed. In the fragmentation region of the original quark (antiquark), the process of hadronization of the $(q\bar{q})_s$ pairs is strongly influenced by this identity. In an extreme case we could consider these processes as charge conjugate, which would reverse the sign of the handedness correlation once again. For example, in the process $e^+e^- \to R\bar{R}$, where R is a hadron resonance, the final hadronic states of R and $\bar{R}$ would be described by the charge conjugate wave functions, hence, the charge conjugate of one- and two-particle distributions. This would change sign in Eq. (15). In fact such an assumption is made in papers [12], where authors claim the evidence for the handedness correlations with the sign opposite to that expected by the standard QCD arguments.

IV. CHROMOMAGNETIC VACUUM FIELDS IN HADRON-HADRON AND NUCLEUS-NUCLEUS COLLISIONS

Up to now we have discussed the effect of the chromomagnetic vacuum field on the fragmentation of a single color string, such as we encounter in e^+e^- annihilation into hadrons. In hadron-hadron and nucleus-nucleus collisions the domain of the chromomagnetic vacuum field can overlap with many strings of different colors, which complicates the situation, but at the same time may lead to stronger effects and richer and more interesting phenomenology.

As far as $\langle \Delta P_\perp \rangle$ and $\langle P_\perp \rangle$ are concerned, a multistring situation amounts to an increase of $\overline{n}$—the average number of $(q\bar{q})_s$ pairs per unit of rapidity. Thus a possibility arises to predict and study dependences of these quantities on the number of color strings generated in the process. This number is phenomenologically related to the centrality of nucleus-nucleus collisions, to the number of "wounded quarks," inelasticities, etc. The distributions of $\Delta P_\perp$ and $P_\perp$ would be broadened, and huge values of cumulant transverse momenta may arise due to the simultaneous fluctuations in n and the random walk distance.

The effect on R_Ω of many strings with different colors is more complicated. Here the non-Abelian structure of the QCD theory comes into play so that we have to add to the formula (15) an additional factor accounting for an SU(3) addition of the random color charges of strings. An accidental color coherence between strings may lead to large correlations of handedness. In any case, this problem deserves a detailed analysis.

The experimental requirement to observe the above mentioned effects is to have a sign-of-charge-sensitive measurement of the charged particles in the central rapidity region by a precision tracker. It would be interesting to investigate what are the possibilities of detectors constructed for the BNL Relativistic Heavy-Ion Collider (RHIC) accelerator in this respect.

V. SUMMARY AND CONCLUSIONS

We have seen that simultaneous measurement of $\langle P_\perp \rangle$, $\langle \Delta P_\perp \rangle$, and R_Ω permit, within our simple model, an estimate of the vacuum chromomagnetic field strength. It is certainly true that our purely classical treatment of the interaction of quarks with the vacuum chromomagnetic field has not much of a theoretical background. Although some hints of the validity of such phenomenology exist [13], a completely different picture of this interaction leading to very different results can be also considered [14]. We wish to stress here our attitude of experimental physicists: let us take the data and see what happens.

The measurement we propose can be performed in the following well-defined steps.

Select two-jet sample of the e^+e^- events.

Measure $\langle \Delta P_\perp \rangle$ as a function of $|\,(y_{\max} - y_{\min})\,|$ and establish linear dependence (12) on $\sqrt{|\,(y_{\max} - y_{\min})\,|}$ characteristic for the random walk in the transverse momentum space. It should be noted that the relation (12) reflects a property of the string fragmentation, independent of the presence of the vacuum background chromomagnetic field. Its validity, with some nonzero value of the parameter β is a necessary condition for the measurement we propose. To obtain a nonzero result for $\langle \Delta P_\perp \rangle$ we may have to apply an appropriate cut on the minimal transverse momentum of particles, in order to diminish the influence of the soft gluon emission, which is the main factor in diluting the charge correlations between partons and hadrons.

Measure $\langle P_\perp \rangle$ as a function of $|\, y_{\max} - y_{\min} \,|$ and establish relation (7), which indicates the presence of the transverse momentum of the $(q\bar{q})_s$ pairs.

Measure R_Ω and, using previously measured $\langle \Delta P_\perp \rangle$, estimate the average value of the vacuum chromomagnetic field strength.

It is important to note that measurements of $\langle P_\perp \rangle$ and R_Ω are independent, so we may choose $P_\perp$ as a "trigger" for the events with large vacuum background field fluctuations. For example, we can select for further analysis only those two-jet events for which $P_\perp$ exceeds by one or two standard deviations the average $\langle P_\perp \rangle$ for both jets.

Another important point is a judicious choice of the interval $(y_{\min}, y_{\max})$ in the central rapidity region for which the correlation R_Ω is determined. It has to be as large as possible, as the effect to be observed is proportional to the interval length, but not too large in order to avoid trivial correlations due to the momentum conservation.

In an experiment with particle identification we could employ strong flavor correlations between partons and hadrons. The $s\bar{s}$ pair should be strongly correlated with K^+K^- pair in the hadronic final state, so constructions of $P_\perp$, $\Delta P_\perp$, and Ω from $K^\pm$ momenta may be beneficial in spite of very much diminished statistics provided that the effect of secondary interactions (different for K^+ and K^-) can be taken into account.

The absence of handedness correlation in SLD data [11] should not discourage experimental physicists from the measurement we propose as it contains two distinctive features: the usage of the cumulative variables and possible enhancement of the effect through random walk mechanism and the possibility of "triggering" (through $P_\perp$) of large vacuum field fluctuations.

Most of the above remarks apply also to hadron-hadron and nucleus-nucleus reactions, except for the complications introduced to multistring situations by the non-Abelian structure of theory. There we may expect a rich and interesting phenomenology which may be of interest for the high energy heavy-ion experiments.

It is clear that the measurements we propose are not easy, they demand huge statistics and extremely careful checks of the systematic errors. On the other hand the stakes of this game, the experimental evidence for the chromomagnetic component of the vacuum, are worth the try.

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