Probing Higher-Order Quantum Chromodynamics: Charge-Conjugation Asymmetries from Two-Gluon Exchange

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We consider charge-conjugation asymmetries arising from two-gluon exchange and gluon-bremsstrahlung corrections in color-averaged quark-antiquark and quark-quark scattering. At large momentum transfers, such considerations lead to sizable predictions for forward-backward and particle-antiparticle asymmetries in hadron collisions. Jet-antijet differences are discussed and the cleanest tests involve the heavier quarks. The absence of mass singularities and the relationship to two-photon asymmetries are emphasized.

In Feynman's not-so-naive parton picture, hard constituent-constituent scattering bestrides those hadron-hadron collisions which result in debris at large transverse momentum, $p_\perp$. This picture may very well have a theoretical basis in quantum chromodynamics (QCD) and, in fact, a rather successful phenomenology has been developed.[1] With an appeal to QCD's celebrated asymptotic freedom, the hard-parton cross section is calculated in lowest-order perturbation theory with the effective coupling

$$\alpha_s(Q^2) = \frac{12\pi}{(33-2f)\ln(Q^2/\Lambda^2)}. \qquad (1)$$

There are some difficulties connected with the hard-core perturbation series. It is understood from the factorization theorem[2] that powers of $\ln m$ (m = quark mass), which arise from the treatment of the initial and final partons as free, can be absorbed into the distribution and fragmentation functions, inducing scaling violations but not affecting the smallness of the corrections in the core expansion. Nevertheless, constant terms can be moved back and forth between the two series, factored and core. Another ambiguity lies in the choice for Q^2 (and the related fits for Λ). The Mandelstam variables for two-body core scattering have to be all large and comparable and one possibility is[1]

$$Q^2 = 2\hat{s}\hat{t}\hat{u}/(\hat{s}^2+\hat{t}^2+\hat{u}^2). \qquad (2)$$

A bigger problem is that the perturbation expansion may involve large corrections even with the $\ln m$ terms gone and even with the full ambiguity in its definition exploited. In fact, large second-order corrections to scaling violations and to Drell-Yan processes have been reported.[3] Perhaps experiment will bear this out, but we worry that higher-order corrections will upset the QCD phenomenology, particularly the high-$p_\perp$ analyses. In this Letter, a correction is discussed and experiments are proposed which should shed light on what kind of a perturbation series we have.

The second-order correction we have in mind (i) has no mass divergences, (ii) leads to a sizable effect absent in lowest order, (iii) is relevant to a number of different experiments, (iv) is insensitive to the unknown confinement forces, and (v) has electromagnetic analogs which can be used as consistency checks. This effect is interesting in its own right, irrespective of the convergence question in QCD.

We begin by considering, in the c.m. system, the forward-backward symmetry in the quark reaction ($q \neq Q$)

$$q+\bar{q} \to Q+\bar{Q} \qquad (3)$$

in analogy with

$$e^+ + e^- \to \mu^+ + \mu^-. \qquad (4)$$

After an average and a sum over color, the differential cross section, which is symmetric in lowest order, picks up an angular asymmetry around 90° due to the interference of two-gluon exchange graphs with the one-gluon exchange graph and the interference of initial and final gluon bremsstrahlung graphs. See Fig. 1.

In contrast to the situation in quantum electrodynamics (QED), we find that, under $Q \leftrightarrow \bar{Q}$, these color-averaged interferences contain both even and odd terms. The presence of both even and odd charge-conjugation parity is a consequence of the non-Abelian gauge nature of QCD. But the odd contributions *are* the same, up to color factors. We find the following angular asymmetry:

$$A(\theta)\equiv[\sigma(\theta)-\sigma(\pi-\theta)]/[\sigma(\theta)+\sigma(\pi-\theta)]$$
$$=-\frac{5\alpha_s}{3\pi}\left\{2\ln\tan\frac{\theta}{2}\ln\frac{E}{\Delta E}+\frac{1}{1+\cos^2\theta}\left[\cos\theta\left(\ln^2\sin\frac{\theta}{2}+\ln^2\cos\frac{\theta}{2}\right)+\sin^2\frac{\theta}{2}\ln\cos\frac{\theta}{2}-\cos^2\frac{\theta}{2}\ln\sin\frac{\theta}{2}\right]\right\}, \qquad (5)$$

for Q detected at angle θ with respect to q and in the energy range $E-\Delta E$ to E ($\Delta E \ll E$ = c.m. energy of q or $\bar{q}$). The bremsstrahlung treatment of Brown *et al.*[4] has been used in view of its simplicity; hard-gluon corrections and variations in the detection scheme are expected to be less important for the *asymmetry*.

In the two-photon graphs, electromagnetic current conservation leads to a cancellation of mass divergences.[5] A similar cancellation occurs for the bremsstrahlung interferences. Indeed, the QCD *asymmetry* is free of $\ln m$ and $\ln^2 m$ terms[6] and we could neglect the quark mass as in Eq. (5). With the change in gauge group, however, the arguments of Ref. 5 do not apply to the symmetric two-gluon contributions, where mass divergences remain and would have to be factored out and/or canceled in jet final states. There is no cancellation by the graphs of Fig. 1(d) which are needed to complete a gauge-invariant, symmetric contribution.

Now it is easy to compare

$$Q+q\to Q+q \qquad (6a)$$

with

$$\bar{Q}+q\to\bar{Q}+q, \qquad (6b)$$

denoting their cross sections by σ_c and $\bar{\sigma}_c$, respectively. Differences arise in second order from the *same graphs* in the cross channel. (Rotate Fig. 1 by 90°.) For the final $Q(\bar{Q})$ in the c.m. system and with energy resolution ΔE, a careful analytic continuation of $A(\theta)$ yields the particle-antiparticle asymmetry at a given angle,

$$A^c(\theta)\equiv[\sigma_c(\theta)-\bar{\sigma}_c(\theta)]/[\sigma_c(\theta)+\bar{\sigma}_c(\theta)]$$
$$=-\frac{5\alpha_s}{3\pi}\left\{2\ln\cos\frac{\theta}{2}\ln\left(\frac{E\sin^2(\frac{1}{2}\theta)}{\Delta E}\right)+\frac{1}{2}\frac{\sin^2(\frac{1}{2}\theta)}{1+\cos^4(\frac{1}{2}\theta)}\times\{[1+\cos^2(\tfrac{1}{2}\theta)][\ln^2\tan(\tfrac{1}{2}\theta)+\ln^2\sin(\tfrac{1}{2}\theta)+\tfrac{1}{4}\pi^2]+\cos^2(\tfrac{1}{2}\theta)\ln\sin(\tfrac{1}{2}\theta)+\ln\tan(\tfrac{1}{2}\theta)\}\right\}. \qquad (7)$$

This can be checked against a point-proton calculation[7] for

$$e^{\pm}+p\to e^{\pm}+p \qquad (8)$$

in the massless limit, and the remarks of the previous paragraph are appropriate once again.

We ask now whether the asymmetries in the quark reactions (3) and (6) lead to measurable asymmetries in the production of (two) jets or hadrons at high $p_\perp$,

$$A+B\to C+D+X. \qquad (9)$$

The question is complicated, of course, by the different kinds of partons in the initial hadrons and by the fact that different partons can "fragment" into the same final hadron C or D. If we define the general *hadron* asymmetry to be the difference of differential cross sections for (9) divided by their sum, and use the well-known parton expansion for the hadron cross section, A or A_c enters into the numerator (inside the

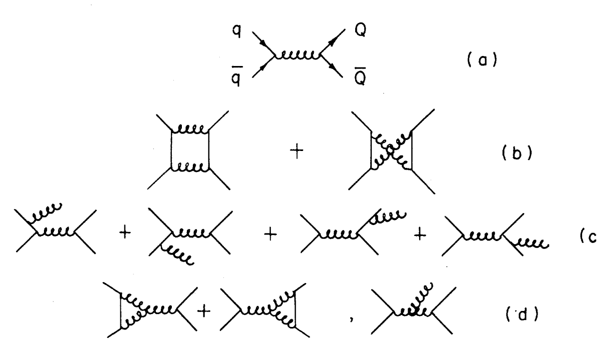

FIG. 1. (a) The one-gluon exchange, (b) two-gluon exchange, (c) gluon bremsstrahlung, and (d) trilinear coupling graphs for $q\bar{q}\to Q\bar{Q}$.

longitudinal-momentum integral and multiplied by the lowest-order quark cross section and the distribution function). The complication means that *a priori* lower-order asymmetries in parton reactions other than (3) or (6) can also enter the numerator, and that additional symmetric contributions enter the denominator. Moreover, for a given slice of laboratory (overall c.m. system of $A+B$) phase space, a range of quark c.m. angles contributes and the quark asymmetry is thus averaged. Despite all of this, the two-gluon signal remains substantial in various scheme. After a few more words about the calculational procedure, we focus on two examples.

The hadron asymmetry is insensitive to the valence distributions, an attractive feature of such a definition. A sample modification which changed the cross sections by 10% produced variations on the order of only 1% in the asymmetry. For this same reason, we can simplify matters and omit fragmentation functions for the final parton decay. Although it is then strictly a jet calculation, the results are relevant to the detection of individual, hard hadrons. Going on, we assume that the jet (quark) is observed at a given laboratory angle, cutting out energies lower than some value. In the examples this cut is put arbitrarily at 7 GeV for a total c.m. energy of 30 GeV. (It is not necessary to go to ultrahigh energies, yet another attractive feature.) Therefore, the integration over the inelastic (gluon bremsstrahlung) cross section involves a replacement of ΔE by $E - E' + \Delta E$ in which the quark c.m. quantities are the initial quark energy E and the minimum final quark energy E' corresponding to the cut. So, the integration over E washes out the sensitivity to reasonable values of ΔE. The cut remains important.

Hadron angular asymmetry.—In this example, we embed the fusion (i.e., annihilation) asymmetry of Reaction (3) in proton-antiproton collisions, and we look at the resultant asymmetry of $p\bar{p} \to Q\bar{Q}X$ as function of the laboratory angle for Q. The most effective $q\bar{q}$ pairs are valence-valence, $u\bar{u}$ and $d\bar{d}$, whose asymmetries *add*. The flavorless two-gluon effect cares only about which is the fermion and which is the antifermion. Q must be a heavier quark $(s, c, b, \ldots)$ or else we are faced with a lowest-order asymmetry: the t-channel exchange in $q\bar{q} \to q\bar{q}$. To that choice for Q, we add the fact that the *hadron sea of quarks and gluons is charge-conjugation symmetric* and thus the hadronic angular asymmetry arises only from the two-gluon correction in order α_s.

To avoid spurious contributions from small quark c.m. angles where $A(\theta)$ diverges, rather than revamping perturbation theory (exponentiation in QED comes to mind), we ask that the opposite-side jet be seen. The curve in Fig. 2 is a result of a 7-GeV cut on both Q and $\bar{Q}$ and restricting $\bar{Q}$ to laboratory angles between 30° and 150°. Only for Q within 45° or so of the forward or backward direction are the answers unreliable. Otherwise, we have a healthy $O(\alpha_s)$ signal. [α_s is reasonable (~0.25) throughout the important integration regions.] We include the sea symmetric contributions, especially from gluons ($gg \to Q\bar{Q}$). These are more important as we decrease the energy cut; with 5 GeV, the answers in Fig. 2 are reduced by about 25% where they are reliable.

Fundamental is the requirement that the quark fragments be distinguishable from antiquark fragments, and both from gluon debris. (The symmetric $gg \to gg$ contribution is large.) The parent quark and the leading daughter hadron(s) are correlated through their electric charge and flavor.[8] The problem of an original valence quark simply scattering and giving rise to the same leading hadron is solved if $Q = c$. (For even heavier quarks, we must put the mass terms back into A and redo the kinematics.) $Q = s$ is a possibility if SU(3) breaking is larger than what has been assumed[9]; the decays $u \to K^+$, $\bar{u} \to K^-$ confuse the issue in K^+K^- production. SU(4) breaking is large

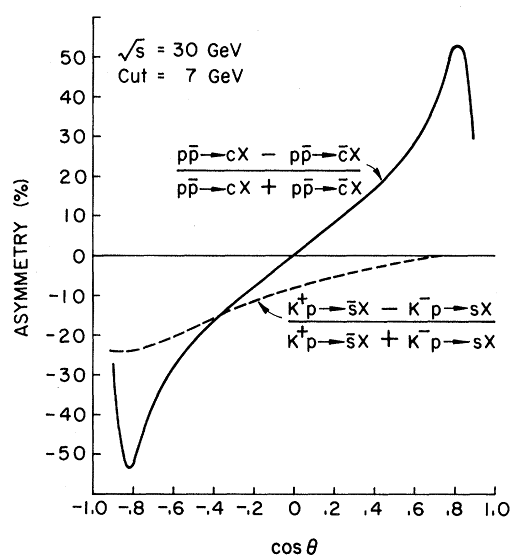

FIG. 2. Asymmetries for the examples discussed in the text. θ is the laboratory (overall c.m.) angle of c or $\bar{c}$ (s or $\bar{s}$) with respect to p ($K^{\pm}$).

and the curve in Fig. 2 *is* most clearly relevant to charmed-jet production where one might look for opposite-side charm-anticharm decay (e^-e^+, $e^-\mu^+, \ldots$).

Hadron-antihadron asymmetry.—This example is the comparison of $K^+p\to\bar{s}X$ and $K^-p\to sX$ in which the asymmetry of Reactions (6) is operative. The previous discussion carries over, with two important differences. First, we do not impose any restriction on the opposite-side jet inasmuch as the perturbation is anomalously large only at the back angles. Second, a lower-order asymmetry from $u\bar{u}\to s\bar{s}$ exists as a background, and we include it in the calculation. The results shown in Fig. 2 are again very encouraging; the background mentioned makes up less than a third of the results for angles greater than 90°.

QED analogs.—Since the soft-gluon region is important in the core asymmetry, we are concerned about gluon wavelengths larger than confinement sizes. As a check on these ideas, consider the *two-photon* asymmetries in[10] $e^+ + e^- \to Q+\bar{Q}$, $p+\bar{p}\to\mu^+ +\mu^- +X$, and $e^\pm+p\to e^\pm+X$. The forward-backward QED asymmetries in the first two of these reactions, although just a few percent, focus on final- and initial-state confinement effects, respectively, and as a "product" are related to Reaction (3). The target treatment in Reactions (6) and the third of these reactions is also similar.

These analogs, joined with (1) energy asymmetries in pp collisions, (2) pion, hyperon, and other examples, (3) mass dependence and other kinematics, and (4) additional details, comprise a future report. We are beholden to Frank Paige for discussion. The work was supported in part by the National Science Foundation, and in part by the U. S. Department of Energy.

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