# $Z^0$ Production at the $\bar{p}p$ Collider and the Spin of the Gluon

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It is suggested that an experimental verification of the relation $A_2 = A_0$ ($A_i$ are the coefficients of the angular distribution of lepton pairs arising from decays of $Z^0$ produced at hadronic collisions) would be strong evidence for the vector nature of the spin of the gluon. The above relation $A_2 = A_0$ is badly broken if the gluon coupling to quarks violates quark-helicity conservation.

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Quantum chromodynamics (QCD), the theory of quarks and gluons interacting through their color degrees of freedom, has been proved to be a very efficient tool to analyze many aspects of high-energy hadron physics. The quarks couple directly to weak-electromagnetic probes and their properties, e.g., spin, flavor quantum numbers, have been firmly established. Unlike quarks, gluons do not couple directly to weak-electromagnetic currents and therefore their properties (gluon spin, gluon self-coupling, etc.) are more elusive for experimental study. Recently, a comparison of three-jet events in $e^+e^-$ annihilation[1] and the three-gluon distribution from heavy-quarkonium decays[2] to theoretical calculations for both the vector- and scalar-gluon cases[3,4] favored the gluon spin-1 assignment. Such "tests of QCD," i.e., examining the sensitivity of various distributions to the gluon spin, are interesting in their own right and should be pursued.

A more natural and clear-cut approach to determine the spin of the gluon is to seek relations among measurable quantities that are consequences of the vector nature of the spin of the gluon. We have in mind here, as a prototype relation, the Callan-Gross relation[5] which connects the structure functions measured in deep-inelastic scattering and which is synonymous with the spin-$\frac{1}{2}$ nature of quarks. Johnson and Tung[6] derived a structure-function relation for lepton-pair production in hadronic collisions, which is respected by vector gluons but is broken by scalar gluons. However, it was not shown how this structure-function relation is related to the physical properties of the gluon, its experimental verification is not an easy task, and the amount of breaking introduced by scalar gluons is rather small. In this Letter we would like to point out that an analysis of the angular distribution of lepton pairs arising from decays of the neutral gauge boson $Z^0$ produced at the $\bar{p}p$ collider[7] can provide us with direct information about the nature of quark-gluon coupling. We derive a relation between the coefficients of the angular distribution of the lepton pairs (see below) which is respected if the gluon preserves quark helicity (vector gluon) and is badly broken if the gluon flips quark helicity (scalar gluon).

Consider the production at the $\bar{p}p$ collider of the neutral gauge boson $Z^0$, not far from its mass-shell condition but with a sizable transverse momentum, and its subsequent decay into a lepton pair. At large transverse momenta perturbative QCD is applicable and the dominant mechanism[8] is quark-antiquark annihilation with the emission of a hard gluon, balancing in transverse momentum the $Z^0$ (Fig. 1). We study the process shown in Fig. 1 for both the vector-gluon ($g_v$) and scalar-gluon ($g_s$) cases and we examine how different relations among the structure functions are related to the nature of the quark-gluon coupling.

The fully differential cross section is proportional to $W_{\mu\nu}L^{\mu\nu}$, where $L^{\mu\nu}$ is the well-known lepton tensor and $W_{\mu\nu}$ is the hadron tensor at the partonic level. The $W_{\mu\nu}$ tensor is a function of the momentum components $(p_{1\mu}, p_{2\mu}, q_\mu)$. We can construct the helicity amplitudes $W_{\sigma\sigma'}$,[9,10] defined by

$$W_{\sigma\sigma'} = \epsilon^\mu(\vec{q},\sigma) W_{\mu\nu} \epsilon^{\nu *}(\vec{q},\sigma') . \tag{1}$$

Here $\epsilon^\mu(\vec{q},\sigma)$, $\sigma = +1, 0, -1$, are the polarization vectors for the virtual $Z^0$ in its rest frame. Equivalently we can decompose the tensor $W_{\mu\nu}$

 

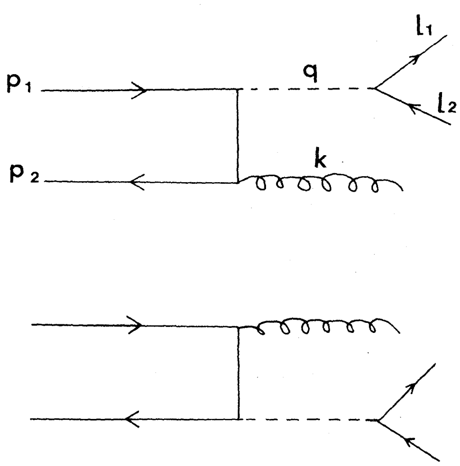


FIG. 1. Dominant diagrams for production of large-transverse-momentum lepton pairs through $Z^0$ decay. The curly lines are gluons.

into invariant structure functions $W_i$ [10,11] in much the same way as in deep-inelastic scattering:

$$W_{\mu\nu} = -g_{\mu\nu} W_1 + \dots \; . \tag{2}$$

The following relations among invariant structure functions and helicity amplitudes hold.

(i) The trace of the hadron tensor is simply related to $W_1$,

$$W_\mu{}^\mu = -2W_1 . \tag{3}$$

Lam and Tung[12,13] provided physical arguments indicating that the above relation is characteristic of spin-$\frac{1}{2}$ partons (quarks). We checked that Eq. (3) is satisfied by both vector and scalar gluons ($q\bar{q} \to Z^0 g_v$ and $q\bar{q} \to Z^0 g_s$).

(ii) The invariant structure functions $W_i$ can be expressed in terms of the helicity amplitude $W_{\sigma\sigma'}$, and vice versa. For $W_1$ we have

$$W_1 = \tfrac{1}{2}(W_{++} + W_{--}) + W_{+-} . \tag{4}$$

(iii) Since the polarization vectors $\epsilon_\mu(\vec{q}, \sigma)$ of the virtual $Z^0$ constitute an orthonormal basis, we have

$$W_{++} + W_{--} + W_{00} = -W_\mu{}^\mu + (q^\mu q^\nu / M^2) W_{\mu\nu} . \tag{5}$$

Using Eqs. (3)–(5) we obtain

$$W_{00} - 2W_{+-} = (q^\mu q^\nu / M^2) W_{\mu\nu} . \tag{6}$$

Equation (6) generalizes a previously derived structure-function relation[10,12] by taking into account the presence of nonconserved currents and parity violation.

If instead of $Z^0$ decaying into a lepton pair we have a virtual photon, since the electromagnetic current is always conserved ($q^\mu q^\nu W_{\mu\nu} = 0$) we would always have $W_{00} = 2W_{+-}$. This relation was noticed to remain valid for a wide class of two-body QCD processes involving photons and massless initial particles.[12,14–16]

On the other hand, the $Z^0$ couples to fermions through both vector and axial couplings $[\gamma^\mu(a + b\gamma_5)]$ and the axial current is not generally conserved. The calculation of the processes $\bar{q}q \to Z^0 g_v$ and $\bar{q}q \to Z^0 g_s$ (Fig. 1) gave us the following results:

$$(q^\mu q^\nu / M^2) W_{\mu\nu} = 0 \quad \text{(vector gluon)}, \tag{7a}$$

$$(q^\mu q^\nu / M^2) W_{\mu\nu} = 2b^2 \hat{s} / M^2 \quad \text{(scalar gluon)}. \tag{7b}$$

Therefore, while the relation $W_{00} = 2W_{+-}$ remains valid for a vector gluon, it is badly broken for a scalar gluon. The physical reasons behind this radically different behavior can be traced as follows.

Consider the production of a virtual $Z^0$ by a fermion-antifermion pair. If the fermion is massless we have $q^\mu q^\nu W_{\mu\nu} = 0$. Furthermore the nonzero amplitudes can arise only when the fermion is left-handed and the antifermion is right-handed (LR) or if both helicities are reversed (RL). If a vector gluon is attracted to the fermion line, since the vector coupling conserves quark helicity, the same helicity structure results and we obtain $q^\mu q^\nu W_{\mu\nu} = 0$. If the fermion is massive (with mass $m$), we know that the axial current is not conserved by terms proportional to the mass, i.e., $q^\mu q^\nu W_{\mu\nu} \propto b^2 m^2$. When a scalar gluon is attached to the massless fermion line, the scalar coupling flips the quark helicity and amplitudes of the form LL or RR appear, as if the quark was massive. We then find Eq. (7b) rather than Eq. (7a).

The angular distribution of one of the leptons in the dilepton center-of-mass system is[17,18]

$$dN/d\Omega = (3/16\pi)\left[1 + \cos^2\theta + A_0(\tfrac{1}{2} - \tfrac{3}{2}\cos^2\theta) + A_1 \sin 2\theta \cos\varphi + A_2 \tfrac{1}{2}\sin^2\theta \cos 2\varphi + A_3 \sin\theta\cos\varphi + A_4 \cos\theta\right]. \tag{8}$$

Each $A_i$ is a linear combination of the helicity amplitudes $W_{\sigma\sigma'}$. Recalling that

$$A_0 = \frac{2W_{00}}{W_{++}+W_{--}+W_{00}}, \quad A_2 = \frac{4W_{+-}}{W_{++}+W_{--}+W_{00}} \tag{9}$$

and using Eqs. (6) and (7), we conclude that

$$A_2 = A_0 \quad \text{(vector gluon)}, \tag{10a}$$

$$A_2 \neq A_0 \quad \text{(scalar gluon)}. \tag{10b}$$

We evaluated the quantity $A_0 - A_2$ for a scalar gluon at present $p\bar{p}$ energies as a function of the dilepton transverse momentum and we found that in the Gottfried-Jackson frame $A_0 - A_2$ is almost flat at a value close to 2.0.[19]

Such a striking difference between the vector and scalar gluon indicates that a study of the angular distribution of dileptons originating from $Z^0$ decay can fix the spin of the gluon.

The large breaking term $(b^2\hat{s}/M^2)$ appearing in Eq. (7b) is entirely absorbed by the angular coefficient $A_0$. Therefore we expect significant differences in the polar angular distribution between the vector- and scalar-gluon cases. Figure 2 shows the angular coefficient $\alpha$ in the polar angle distribution

$$1+\alpha\cos^2\theta+\beta\cos\theta \quad [\alpha=(2-3A_0)/(2+A_0)]$$

as a function of $x_T$. At large $x_T$ the vector and scalar gluons give indeed quite different $\alpha$ values. Notice that as $x_T$ tends to zero the vector-gluon case gives the Drell-Yan value $\alpha = 1.0$, while the scalar-gluon $\alpha$ approaches a negative value. However, at small $q_T$ values, naive perturbative QCD breaks down, multiple-soft-gluon emission becomes important, and no physical conclusion can be drawn by simply studying first-order Feynman graphs.

To summarize, we suggest that the neutral gauge boson $Z^0$, recently produced at the $\bar{p}p$ collider,[7] because of its rich coupling to fermions (both vector and axial coupling) can provide more information about the structure of strong interactions than the photon. We found that the relation $A_0 = A_2$ among the angular coefficients is closely tied to the vector nature of the gluon and therefore an analysis of the angular distribution of dileptons produced at the $\bar{p}p$ collider with large transverse momentum and invariant mass close to the mass of $Z^0$ would be rewarding.

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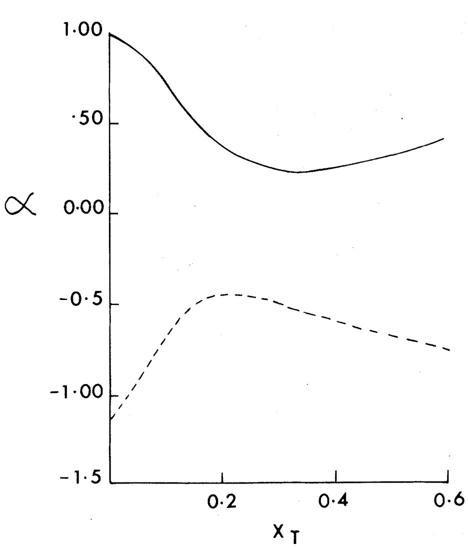


FIG. 2. The polar angular coefficient $\alpha$ for $p\bar{p} \to l^+l^-X$ through $Z^0$ production in the Gottfried-Jackson frame. The solid (dashed) line corresponds to vector (scalar) gluon.

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