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Amplitude zeros in $p\bar{p}$ collisions and the quark magnetic moment

Morten L. Laursen, Mark A. Samuel, and Achin Sen
Department of Physics, Oklahoma State University, Stillwater, Oklahoma 74078
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The effect of the quarks having an anomalous magnetic moment on the zeros (dips) in the angular distribution for the process $d\bar{u} \to W^-\gamma$ ($p\bar{p} \to W^-\gamma X$) is studied. It is found that for small values ($\lesssim 10^{-3}$) of the quark anomaly $[a \equiv (g-2)/2]$ the distributions are practically unaffected and as a increases, the dips gradually disappear. This study might provide us with a way of obtaining an upper bound for the anomalous magnetic moment of the W bosons.

The weak intermediate vector bosons $W^\pm$ and Z^0 are expected to be produced within a year or so. The next step would be the measurement of some of the weak-boson properties. The study of the differential cross section of $p\bar{p} \to W^\pm\gamma X$ has been shown to provide a sensitive test of the anomalous magnetic moment of the W boson. It has been found[1] that the basic quark cross section $d\sigma(d\bar{u} \to W^-\gamma)/d\cos\theta$ has a zero at $\cos\theta = -\frac{1}{3}$, provided the quarks and the W bosons have no anomalous magnetic moments. More examples of such zeros have been found[2] in connection with other processes, and recently Brodsky and Brown[3] and Samuel[4] have shown the existence of such zeros in a wide variety of processes, provided some basic constraints are satisfied.

The zeros occur in the various $q\bar{q} \to W^-\gamma$ cross sections and hence $d\sigma(p\bar{p} \to W^-\gamma X)/d\cos\theta$ exhibits a very prominent dip at $\cos\theta_{\text{c.m.}} = -\frac{1}{3}$ if neither the W boson nor the quarks have an anomalous magnetic moment. The effect of a nonzero anomalous magnetic moment of W^- on this dip has been investigated in detail[1] and it offers a way of measuring the W magnetic moment. In this Communication, we shall study the effect of a quark anomalous magnetic moment on the angular distributions for both $d\bar{u} \to W^-\gamma$ and $p\bar{p} \to W^-\gamma X$, assuming that the magnetic moment of the W boson has its gauge value $\mu_W = e/M_W$. We shall study the effect as a function of the quark anomaly defined as $a = (g-2)/2$. For simplicity, we have chosen $a_{\bar{u}} = a_d$. We have used the standard coupling of the W boson with the other particles. The point is that if, in an actual experiment, a deviation from the results predicted by the standard model (with no quark or W-boson anomaly) is observed, it would be of interest to know how much of this deviation could be attributed to the quark anomaly and thus place an upper bound on the W-boson anomalous magnetic moment. Of related interest, anomalous magnetic moments provide very tight constraints on possible composite models of quarks and leptons.[5]

The differential cross section for the process $d\bar{u} \to W^-\gamma$ has been calculated and can be expressed as

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{\beta}\left(1 - \frac{M_W^2}{\beta}\right)\frac{\alpha M_W^2 G_F g_{ij}^2}{2\sqrt{2}s}F(y_1,y_2,a) \quad ,$$

where

$$\beta = (1-4m^2/s)^{1/2}, \quad \sqrt{s} = E_{\text{c.m.}} \quad ,$$
$$y_1 = -\frac{1}{2}\left(\frac{s}{4M_W^2} - 1\right)(1-\beta\cos\theta) \quad , \tag{1}$$
$$y_2 = -\frac{1}{2}\left(\frac{s}{M_W^2} - 1\right)(1+\beta\cos\theta) \quad .$$

θ is the angle between the W^- and the d in the $d\bar{u}$ ($W^-\gamma$) c.m. frame.

The function $F(y_1,y_2,a)$ can be expressed in terms of y_1, y_2, a, the mass ratio $R = (M_W/m)^2$, and the combination $Z = Q_1 - Qy_2/(y_1+y_2)$ (in our case, $Q_1 = -\frac{1}{3}$ for d, $Q_2 = -\frac{2}{3}$ for $\bar{u}$, and $Q \equiv Q_1 + Q_2 = -1$) in the following form:

$$F(y_1,y_2,a)=Z^2\left[\frac{(1-y_1)^2+(1-y_2)^2}{y_1y_2}+\frac{1}{R}\left(\frac{y_2}{y_1}+\frac{y_1}{y_2}+2-\frac{6}{y_1y_2}+\frac{2}{y_1}+\frac{2}{y_2}-\frac{2}{y_1^2}-\frac{2}{y_2^2}\right)+\frac{1}{R^2}\frac{2(y_1+y_2)^2}{y_1^2y_2^2}\right]$$
$$+Za\left\{\left[\frac{Q_1-Q_2}{4}(y_1-y_2)+Q_1\left(\frac{2+y_1}{2y_1}\right)+Q_2\left(\frac{2+y_2}{2y_2}\right)-\frac{5(Q_1+Q_2)}{4}\right]\right.$$
$$\left.+\frac{1}{R}\left[(Q_1+Q_2)\frac{(y_1+y_2)^2}{2y_1y_2}-\left(\frac{Q_1}{y_1}+\frac{Q_2}{y_2}\right)\right]\right\}$$
$$+a^2\left[\frac{R}{8}(Q_1^2+Q_2^2)[y_1y_2+2(1-y_1-y_2)]-\frac{Q_1^2+Q_2^2}{4}+\frac{1}{R}Q_1Q_2\frac{(y_1+y_2)^2}{y_1y_2}\right] \quad . \tag{2}$$

The terms proportional to Z exhibit a zero at the point $Q_1/Q_2=y_2/y_1$, i.e., at $\cos\theta=-1/(3\beta)\rightarrow-\frac{1}{3}$ in our case as $\beta\approx 1$. Notice that if $\beta<\frac{1}{3}$ (nonrelativistic limit) the zero moves out of the physical region.[4] For zero quark anomaly, Eq. (2) agrees with the results obtained by Nilles.[6] We also notice that in the limit $a\rightarrow 0$ the result is proportional to Z^2 and hence the zero persists for nonzero quark masses[2] (provided, of course, that $\beta>\frac{1}{3}$). The symmetry corresponding to the interchange of particles 1 and 2,

$$F(y_1,y_2,a)=F(y_2,y_1,-a)\ \text{ with }\ q_1\leftrightarrow q_2\ ,$$

is also manifestly exhibited.

We now study the effect of having $R\gg 1$, since this is the actual situation. For small a values such that $Ra^2\ll 1$, the term proportional to Za dominates, and hence, the effect of the zero (in the form of a prominent dip) is observed. For sizable values

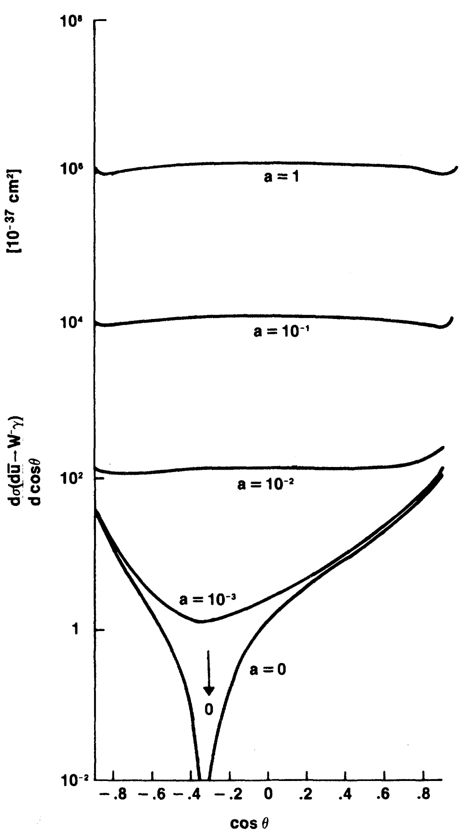

FIG. 1. The differential cross section for $d\bar{u}\rightarrow W^-\gamma$. θ is the angle between the W^- and the d in the c.m. frame. $\sqrt{s}=200$ GeV and $M_W=77.4$ GeV.

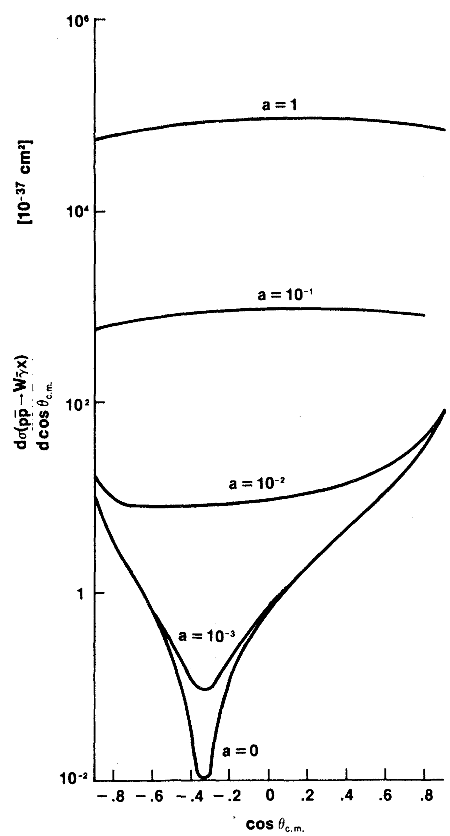

FIG. 2. The differential cross section for $p\bar{p}\rightarrow W^-\gamma X$ with a photon energy cut $E_\gamma>30$ GeV. $\theta_{\mathrm{c.m.}}$ is the angle between the W^- and the proton beam in the $W^-\gamma$ c.m. frame. $\sqrt{s}=540$ GeV and $M_W=77.4$ GeV.

of a ($Ra^2 \approx 1$) this should disappear and for large a values, i.e., $Ra^2 >> 1$, the leading term is proportional to a^2.

Figure 1 shows the differential cross section for $d\bar{u} \to W^-\gamma$ as a function of $\cos\theta$. We have taken the values $\sqrt{s} = 200$ GeV, $M_W = 77.4$ GeV, and $m_u = m_d = 0.3$ GeV. As expected, one finds the zero at $\cos\theta = -\frac{1}{3}$ for $a = 0$. For values $a \lesssim 10^{-4}$ the distribution is almost indistinguishable from the $a = 0$ case. For $a \gtrsim 10^{-3}$ there appears a significant change in the distribution and this increases as a increases. Beyond $a \approx 10^{-2}$ even a dip is hardly noticeable and the whole curve moves up higher. For $a \gtrsim 10^{-2}$, the Ra^2 term dominates the cross section, as expected.

Figure 2 shows the differential cross section for $p\bar{p} \to W^-\gamma X$ as a function of $\cos\theta_{\text{c.m.}}$ where $\theta_{\text{c.m.}}$ is the angle between the W^- and the proton beam in the $W^-\gamma$ c.m. frame. We have chosen the c.m. energy to be $\sqrt{s} = 540$ GeV, $M_W = 77.4$ GeV, and $m_d = m_u = m_s = 0.3$ GeV. We also have introduced a cut in the photon energy $E_\gamma > 30$ GeV. The effect of putting the strange-quark mass equal to the u- (and d-) quark mass has been estimated to introduce an error of less than 10%. Looking at Fig. 2, we again observe very sharp dips (at $\cos\theta_{\text{c.m.}} = -\frac{1}{3}$) for small a values. For larger values of a, the dip disappears, as expected. The parton-model formulas for the $p\bar{p}$ cross section in terms of the p and $\bar{p}$ distribution functions are given in Ref. 1.

We have not shown the $pp \to W^-\gamma X$ differential cross section—but here, even for small a, the dips at the places $\cos\theta_{\text{c.m.}} = \pm\frac{1}{3}$ tend to be washed out. One can, however, overcome this by proper binning of events. A detailed discussion of this will be published elsewhere.

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