Bounds on the Magnetic Moment of the W Boson

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(Received 2 November 1990; revised manuscript received 28 January 1991)

Using the preliminary results for $p\bar{p} \to W\gamma X$ from the Collider Detector at Fermilab, we obtain information on the magnetic moment of the W boson. At 90% C.L. we find the bound $-9.9 \le \kappa \le 12.3$, which is consistent with the standard model value $\kappa = 1$. We also consider the radiative decay $W \to e\nu\gamma$.

PACS numbers: 14.80.Er, 13.40.Fn, 13.85.Qk

It is now eleven years since it was discovered by Mikaelian, Samuel, and Sahdev [1] that the angular distribution for $d\bar{u} \to W^-\gamma (u\bar{d} \to W^+\gamma)$ vanishes at a certain angle provided the magnetic moment of the $W^\pm$ has the gauge-theory value $\mu = ge/2M_W$, with $g = \kappa + 1 = 2$ or $\kappa = 1$. They proposed using this peculiar behavior in $p\bar{p}$ and pp collisions, $p\bar{p}$ or $pp \to W^\pm \gamma X$, where a dip persists, as a means of measuring the magnetic moment of the W and testing the standard model.

Preliminary results are now available from the Collider Detector at Fermilab [2] (CDF). Although the number of events is quite limited (integrated luminosity $\mathcal{L} = 4.3$ pb^{-1}) and one cannot yet obtain an angular distribution, we wish to show in this Letter that one can already obtain bounds on κ from the total number of $W\gamma$ events as well as the number of radiative W decays, $W^+ \to e^+\nu\gamma$ and $W^- \to e^-\bar{\nu}\gamma$.

The formula for the cross section for $W\gamma$ production is given by

$$\sigma(p\bar{p} \to W^-\gamma X) = \tfrac{1}{3} \sum_{i=d,s} \int\int dx_A\, dx_B [P_i^p(x_A) P_{\bar{u}}^{\bar{p}}(x_B) \hat{\sigma}(q_i \bar{q}_u \to W^-\gamma) + P_{\bar{u}}^p(x_A) P_i^{\bar{p}}(x_B) \hat{\sigma}(q_i\bar{q}_u \to W^-\gamma)_{u \leftrightarrow i}], \tag{1}$$

where

$$\hat{\sigma}(q_i(k_1)\bar{q}_j(k_2) \to W^-(P)\gamma(k)) = \frac{4\pi\alpha}{\hat{s}} \frac{M_W^2 G_F}{\sqrt{2}} V_{ij}^2 \int_{\text{phase space}} \left[Z^2 \frac{\hat{t}^2 + \hat{u}^2 + 2\hat{s}M_W^2}{\hat{u}\hat{t}} - \eta Z \frac{\hat{u} - \hat{t}}{\hat{u} + \hat{t}} + \frac{\eta^2}{2(\hat{t} + \hat{u})^2} \left[\hat{t}\hat{u} + (\hat{t}^2 + \hat{u}^2) \frac{\hat{s}}{4M_W^2} \right] \right], \tag{2}$$

and where

$$\hat{s} = (k_1 + k_2)^2, \quad \hat{t} = (P - k_1)^2, \quad \hat{u} = (P - k_2)^2$$

with

$$\hat{s} + \hat{t} + \hat{u} = M_W^2,$$

and V_{ij} is the Kobayashi-Maskawa matrix element. Z is the zero factor,

$$Z = Q_i + \hat{u}/(\hat{t} + \hat{u}),$$

Q_i is the electric charge of the quark q_i, and $\eta = \kappa - 1$. The contribution of the sea quarks has been included in Eq. (1). This expression is in agreement with the angular distribution formula [1].

To obtain the total cross section $\sigma_{W\gamma}$, we perform the integrations over the parton fractions and over the phase space, using a Monte Carlo routine. We use the Duke-Owens [3] parton distribution functions. The following cuts are imposed, chosen to agree with the cuts imposed in the experiment [2]: (1) the transverse photon energy $E_{T\gamma} > 5$ GeV; (2) the photon pseudorapidity $|\eta_\gamma| < 3.0$; and (3) the electron-photon angular separation

$$[(\Delta\eta)^2 + (\Delta\phi)^2]^{1/2} > 0.3 .$$

With these cuts, the $W\gamma$ production $(W^+ + W^-)$ cross section is computed to be

$$\sigma_{W\gamma} = 38.68 - 0.26\eta + 0.64\eta^2 \text{ pb}. \tag{3}$$

We next calculate the number n of $p\bar{p} \to W\gamma X \to e\nu\gamma X$ events to be expected at CDF for any given η. To do this we use CDF electron and photon acceptances and their detection efficiencies as given in Ref. [2]. The electron acceptance factor $\mathcal{A}_e = 0.41$ with fudicial cuts included, and its detection efficiency $\mathcal{E}_e = 0.67$. The photon acceptance factor for $\eta_\gamma \le 3$ is estimated to be $\mathcal{A}_\gamma = 0.54$ and its detection efficiency $\mathcal{E}_\gamma = 0.50$. Reference [2] has also estimated the QCD correction factor K_{DY} (for the Drell-Yan process) as 1.3. The QCD corrections for $p\bar{p} \to W\gamma X$ have been calculated by Smith, Thomas, and van Neerven [4]. Using these factors, we get from Eq.

(3)

$$n=\sigma_{W\gamma}\mathcal{L}B(W\to e\nu)K_{DY}\mathcal{A}_e\mathcal{E}_e\mathcal{A}_\gamma\mathcal{E}_\gamma$$
$$=1.76-0.012\eta+0.029\eta^2\,, \quad (4)$$

where we have used the branching ratio $B(W\to e\nu)=0.11$.

The experimental value is $n=2$; however, these two events could be background. If, however, we use the more conservative bound, $n<5.32$ (90% C.L.), we obtain the bound

$$-9.9\leq\kappa\leq 12.3\,. \quad (5)$$

These bounds can be seen in Fig. 1.

Our results for $\sigma_{W\gamma}$ at $\sqrt{s}=1.8$ TeV are

$$\sigma_{W\gamma}=\begin{cases}38.68\text{ pb}, & \kappa=1,\\ 39.58\text{ pb}, & \kappa=0,\\ 41.74\text{ pb}, & \kappa=-1.\end{cases} \quad (6)$$

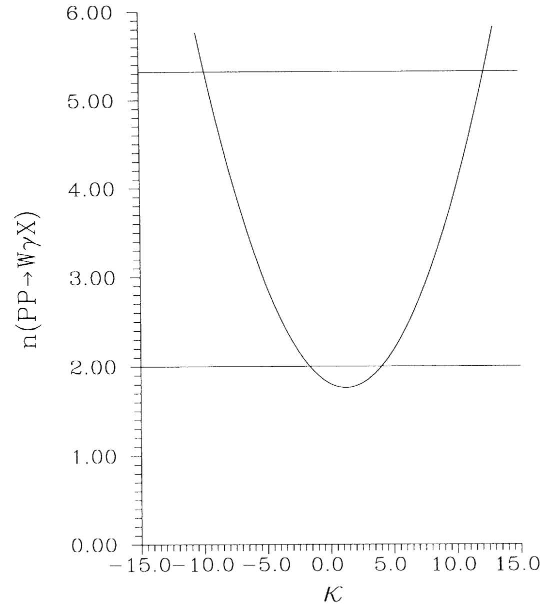

FIG. 1. The number of events $n(p\bar{p}\to W\gamma X\to e\nu\gamma X)$ as a function of κ. The lower horizontal line corresponds to 2 events and the upper one to 5.32 events (90% C.L.), respectively.

For the radiative W decay case, we obtain the result

$$\sigma(p\bar{p}\to e^-\bar{\nu}\gamma X)=\tfrac{1}{3}\sum_{i=d,s}\int\int dx_A\,dx_B\,\delta(sx_Ax_B-M_W^2)[P_i^p(x_A)P_{\bar{u}}^{\bar{p}}(x_B)\hat{\sigma}(q_i(k_1)\bar{q}_u(k_2)\to e\nu\gamma)$$
$$+P_{\bar{u}}^p(x_A)P_i^{\bar{p}}(x_B)\hat{\sigma}(q_i(k_2)\bar{q}_{\bar{u}}(k_1)\to e^-\bar{\nu}\gamma)]\,, \quad (7)$$

where we obtain $\hat{\sigma}$, using the zero-width approximation, as

$$\hat{\sigma}(q_i(k_1)\bar{q}_j(k_2)\to W^-(q)\to e^-(p_1)\bar{\nu}(p_2)\gamma(k))=\frac{48\pi^4\alpha^2}{\hat{s}\sin^2\theta_W}V_{ij}^2B(W^-\to e\bar{\nu})\int_{\text{phase space}}[Z'^2A-Z'\eta B+\eta^2C]\,, \quad (8)$$

where Z' is the zero factor,

$$Z'=Q_i/Q-P_1\cdot k/q\cdot k\,,$$

and

$$A=\frac{4}{(P_1\cdot k)(P_2\cdot k)}[(P_1\cdot k_2)^2+(P_2\cdot k_1)^2]\,,$$

$$B=\frac{1}{4(P_1\cdot k)(q\cdot k)}\Bigg[M_W^2(4k_2\cdot P_1-2k_1\cdot P_2-M_W^2)+4(P_2\cdot k)^2+4(k_1\cdot P_1)(k_1\cdot P_1+2P_2\cdot k)$$
$$-8(P_2\cdot k)(k_1\cdot P_2)\left(\frac{P_2\cdot k}{M_W^2}-1\right)+\left(1-\frac{2P_2\cdot k}{M_W^2}\right)[4k_1\cdot P_1k_1\cdot P_2+2P_1\cdot kM_W^2]$$
$$-4(k_1\cdot P_1)(k\cdot P_1)\left(\frac{2k_2\cdot P_1}{M_W^2}+1\right) \quad (9)$$
$$-\frac{2k_1\cdot P_2k\cdot P_1}{P_2\cdot k}\left(2k\cdot k_2+\frac{4(P_2\cdot k)(P_2\cdot k_1)}{M_W^2}-\frac{4(P_1\cdot k_1)(P_1\cdot k)}{M_W^2}\right)\Bigg]\,,$$

$$C=\frac{1}{4(q\cdot k)^2}\Bigg[2(P_2\cdot k)[M_W^2-2(P_2\cdot k)]-\frac{4(P_2\cdot k)}{M_W^2}(P_1+P_2)\cdot k_1(2k_2\cdot P_1-M_W^2)$$
$$-4(P_2\cdot k)k_1\cdot(2P_1+P_2)+\frac{8(P_2\cdot k_1)(P_1\cdot k)(k\cdot k_2)}{M_W^2}\Bigg]\,.$$

The standard model (SM) term given in the above equation is in agreement with the calculation of Cortes, Hagiwara, and Herzog [5].

Using the same cut, acceptances, and efficiencies as before we obtain the quadratic equation in η for the number n of $p\bar{p}\to WX\to e\nu\gamma X$ events,

$$n=12.09-0.2441\eta+0.001957\eta^2. \quad (10)$$

If $n(p\bar{p}\to WX\to e\nu\gamma X)\leq 18$ (90% C.L.) [6], we obtain the bound

$$-19.8\leq\kappa\leq 147. \quad (11)$$

Hypothetically, if instead we assume $n(p\bar{p}\to WX \to e\nu\gamma X)\leq 12$ at the 90% C.L., we find a bound $\kappa>1$ in violation of the standard model. In view of this, it is clearly necessary to establish the correct magnitude of this number experimentally. We have used the same [7] $K_{\rm DY}$ for $W\gamma X$ and for $e\nu\gamma X$. In principle, $K_{\rm DY}$ depends on the process involved and the cuts used, but the difference is much smaller than the uncertainties in $\mathcal{L}$, $\mathcal{A}$, and $\mathcal{E}$, so we have chosen to ignore the difference.

The very loose bounds that one gets in the $p\bar{p}\to WX \to e\nu\gamma X$ case compared to the $p\bar{p}\to W\gamma X\to e\nu\gamma X$ considered earlier can be traced directly to the differences in the production mechanisms for the W in the two cases, and to the effect of the cuts imposed on the SM term relative to the non-SM term in the two cases. Note that in Eq. (7) there is a δ function involving parton fractions x_A,x_B which is not there in Eq. (1), whose effect is to reduce the cross section obtained from Eq. (7) relative to that obtained from Eq. (1). The effect of the cut imposed on the SM term in the $p\bar{p}\to W\gamma X\to e\nu\gamma X$ case is such as to decrease it enormously relative to the η and η^2 terms. Had there been no cut, then the SM term in the $p\bar{p}\to W\gamma X\to e\nu\gamma X$ case would have been many times larger.

For any $\kappa\neq 1$, it is well known that there is violation of unitarity at tree level in $W\gamma$ production, and some model-dependent scheme is needed to preserve it [8]. Model-dependent schemes will give a less restrictive bound on κ. Our attitude has been to first find out whether κ sizably different from 1 is necessary for the data to be fitted. Only if such a nonstandard value is established would it be worthwhile introducing model-dependent parameters in our calculations, to preserve unitarity.

In conclusion, we have shown that the preliminary results from CDF can be used to obtain bounds on κ and the magnetic moment of the W boson. From $p\bar{p}\to W\gamma X$ we have obtained the conservative limit $-9.9\leq\kappa\leq 12.3$ with 90% C.L. Our results for the radiative decay case are much less stringent. In the future the experiment will be much improved. The integrated luminosity is expected to increase by a factor of 5 in 1991 and a further factor of 4 by 1993 reaching up to 100 $\rm pb^{-1}$ and possibly up to 1000 $\rm pb^{-1}$ by 1997. With an integrated luminosity 20 (100) times greater, with increased statistics, one can expect an improved bound $-28\leq\kappa\leq 5.2$ ($-1.5\leq\kappa \leq 3.8$) compared with the current bound in Eq. (5). With a large number of events, however, one can obtain an angular distribution for $p\bar{p}\to W\gamma X$, which is much more sensitive to κ than the total cross section used here.

One of us (M.A.S.) would like to thank Mark Timko for helpful discussions. This work was supported by the Natural Sciences and Engineering Research Council of Canada through Grant No. OGP0001574 and URF-43989IN. This work was also supported by the U.S. Department of Energy under Grant No. DE-F605-85ER 40215.

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