A Search for Heavy Pointlike Dirac Monopoles

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We have searched for central production of a pair of photons with high transverse energy in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV using 70 pb^{-1} of data collected with the DØ detector at the Fermilab Tevatron in 1994–1996. If they exist, virtual heavy pointlike Dirac monopoles could rescatter pairs of nearly real photons into this final state via a box diagram. We observe no excess of events above background, and set lower 95% C.L. limits of 610, 870, or 1580 GeV/c^2 on the mass of a spin 0, 1/2, or 1 Dirac monopole.

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One of the open questions of particle physics is the existence of Dirac monopoles [1,2], hypothetical carriers of the magnetic charge proposed by P. Dirac to symmetrize the Maxwell equations and explain the quantization of electric charge. If such magnetic monopoles exist, then the elementary magnetic and electric charges (g and e) must be quantized according to the following formula:

$$g = \frac{2\pi n}{e}, \quad n = \pm 1, \pm 2, ..., \tag{1}$$

where n is an unknown integer. Here we assume that the elementary electric charge is that of an electron. If free quarks exist, Eq. (1) should be modified by replacing e with $e/3$, which effectively increases g by a factor of three.

Dirac monopoles are expected to couple to photons with an effective coupling constant $\alpha_g = g^2/4\pi \approx 34\ n^2$ which is at least three orders of magnitude larger than the corresponding photon coupling to the electric charge ($\alpha_e = e^2/4\pi \approx 1/137$). Therefore such monopoles could give rise to photon-photon rescattering via the box diagram shown in Fig. 1 [3,4]. The contribution of this diagram for pointlike monopoles to diphoton production at hadron colliders was recently calculated [5] and shown to be significant even for monopole masses comparable to the collider beam energy.ff

Since the virtuality (Q^2) of most incoming photons in the process of Fig. 1 is small [6], the interacting partons scatter at very small angles and therefore escape the detector through the beam pipe. Thus, a signature for monopoles at hadron colliders is the production of a pair of isolated photons with high transverse energies. This process gives a unique opportunity to find evidence for Dirac monopole production or to set limits on the monopole mass in a largely model-independent way.

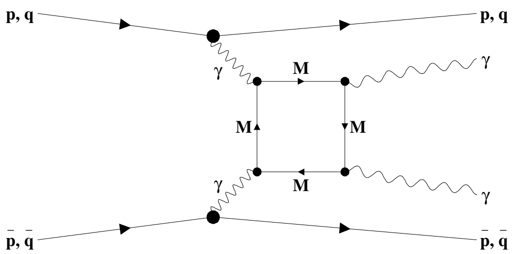

FIG. 1. Feynman diagram for $\gamma\gamma$ production via a virtual monopole loop.

The only previous study of this nature was made by the L3 experiment at the LEP e^+e^- accelerator by searching for the $Z \to \gamma\gamma\gamma$ decay via a similar monopole loop [7]. It resulted in the lower 95% confidence level (C.L.) mass limit of 510 GeV for pointlike spin 1/2 monopoles. Other accelerator experiments (see Ref. [8]) have looked for production of monopoles by searching for the high ionization traces that would be produced by these particles, and would therefore be inherently restricted to monopole masses below the beam energy. A variety of experiments which look for monopoles in cosmic rays are sensitive to the relic monopole flux, rather than the monopole mass [8]. Indirect limits on the Dirac monopole mass can be derived from measurements of the top quark mass and the axial and vector couplings of the Z to charged leptons [4].

Despite numerous studies, QED with pointlike monopoles is still not a complete theory. For example, it is not clear whether such a theory can be constructed to be renormalizable to all orders [4]. Also, arguments exist (see, e.g. [9]) that Dirac monopoles must occupy a spatial volume of radius $R \sim \mathcal{O}(g^2/M)$, where M is the monopole mass, to accommodate the self energy implied by the large coupling. The non-observation of a new distance scale in QED or the SM for $R < \mathcal{O}(1\ \text{TeV})$ requires the monopole mass to exceed ~ 100 TeV. Further theoretical work on this subject therefore is required to define the regions of validity for a theory of pointlike monopoles. In such a theory, it is possible that hard interactions of a monopole with photons would be weakened substantially by the effects of a monopole form factor.

In this Letter we report on the results of a new search for Dirac monopoles with the DØ detector (described in detail elsewere [10]) operating at the Fermilab Tevatron proton-antipoton collider with beam energies of 900 GeV. The search is based on $69.5 \pm 3.7\ \text{pb}^{-1}$ of data recorded in 1994–1996 using a trigger which required the presence of an electromagnetic (EM) object with transverse energy E_T above 40 GeV. This trigger did not require the presence of an inelastic collision, and therefore can be used to select low Q^2 events typical of the process in Fig. 1.

The following offline selection criteria are: (i) at least two photons with $E_T > 40$ GeV and pseudorapidity $|\eta_\gamma| < 1.1$; (ii) missing transverse energy in the event $\not\!\!E_T < 25$ GeV; and (iii) no jets with $E_T^j > 15$ GeV and $|\eta^j| < 2.5$. The jet veto requirement is used to select the low Q^2 process in Fig. 1. The trigger is $> 98\%$ efficient for this off-line selection.

In order to determine the hard scattering vertex, we calculate the most probable direction of each photon using the transverse and longitudinal segmentation of the EM calorimeter [11]. These directions determine the position of the interaction vertex along the beam axis. The resolution on the vertex position for this method is 14 cm, taken from $Z \to ee$ decays where the vertex can also be determined with high precision using the tracking information. This EM-cluster-based vertex finding techique is preferred since for the event topology of Fig. 1 one does not expect charged particles, causing the tracking-based vertex finding to be biased significantly toward vertices from background interactions. We calculate kinematic parameters of the event based on the vertex obtained using the EM clusters.

Each photon is required to have: (i) energy isolation [11] $I < 0.1$; (ii) more than 95% of the cluster en-

TABLE I. Signal efficiency.

Cut	Efficiency (%)
per photon	
$I < 0.10$	93.0 ± 0.7
EM fraction	99.0 ± 1.0
Shape consistency	94.7 ± 0.8
No tracks	91.1 ± 0.4
No photon conversions	92.0 ± 1.0
per event	
$\not\!\!E_T < 25$ GeV	99.0 ± 0.5
Overall	52.8 ± 1.4

ergy deposited in the EM calorimeter; (iii) cluster shape consistent with that expected for a photon; and (iv) no tracks pointing toward the EM cluster from any of the event vertices.

The overall efficiency for photon identification is $(73.0 \pm 1.2)\%$ per photon, as detailed in Table I. This includes the $(92 \pm 1)\%$ probability of the photon not to convert in the material in front of the tracking chambers. The efficiency of criteria (i)–(iii) is determined using the $Z \to ee$ events (with (ii) additionally checked using a GEANT [12] simulation of the DØ detector for possible energy dependence); the efficiency of the no track requirement (iv) was determined using simulated photons obtained by rotating the electromagnetic clusters from $Z \to ee$ decays by $\pi/2$ in azimuth [11]. The overall efficiency for the diphoton selection is $(52.8 \pm 1.4)\%$. This includes the efficiency of the $\not\!\!E_T$ veto $(99.0 \pm 0.5)\%$ as well as the identification efficiency for a pair of photons.

The above selection criteria define our base sample which contains 90 candidate events.

The main backgrounds to photon scattering through a monopole loop are due to: (i) diagrams similar to Fig. 1 with other particles in the loop; (ii) QCD production of dijets (jj) and direct photons ($j\gamma$) (with jets misidentified as photons due to fragmentation into a leading π^0 or η decaying into a pair of spatially close photons, reconstructed as one EM cluster), or direct diphotons ($\gamma\gamma$); and (iii) Drell-Yan dielectron production with electrons misidentified as photons due to tracking inefficiency.

Background (i) is dominated by a virtual W-loop and has been shown to be negligible [13]. The other two background contributions are estimated from the data. The QCD background is determined using the $j\gamma$ event sample collected with a single photon trigger, with the jet passing the same fiducial and kinematic cuts as the photon. We apply a a jet-faking probability $P(j \to \gamma)$ which we measure to be $(10.5 \pm 1.5) \times 10^{-4}$ by counting the number of photons in multijet events, and find the QCD background to be 25 ± 8 events. Direct photon and diphoton backgrounds are also included in this estimate. Their relative fractions are obtained from PYTHIA [14] Monte Carlo (MC). The 30% error assigned to the QCD background estimate reflects the uncertainty in the direct photon fractions and in the jet-faking-photon probability.

The Drell-Yan background is calculated from a sample of dielectron events passing the same fiducial and kinematic cuts as the signal sample. Multijet contamination of this sample is negligible since the probability for a jet to be misidentified as an electron is five times smaller than that for a photon. The probability for a dielectron pair to be misidentified as a diphoton pair is found to be $(11 \pm 1)\%$ by comparing the number of events in the Z peak in the ee and $\gamma\gamma$ samples passing loose kinematic cuts. The Drell-Yan background in the base sample is 63 ± 7 events. The overall background in the base sample is 88 ± 11 (syst) events, in good agreement with the 90 observed candidates.

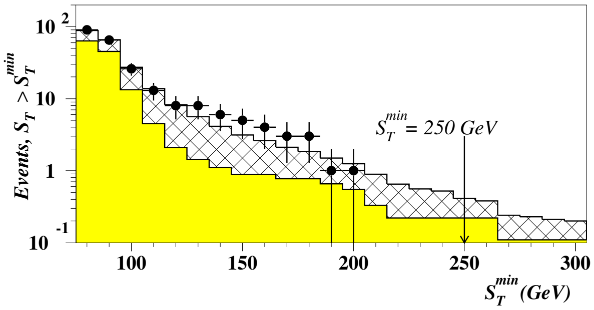

FIG. 2. Data and expected background as a function of $S_T^{\rm min}$ cut. Points are data, the upper hatched region corresponds to the Drell-Yan background, and the lower shaded region shows the QCD background. The $\approx 15\%$ systematic error on the background is not shown.

To optimize the sensitivity of this search to the monopole loop contribution we apply a cut on the scalar sum of the transverse energies of all the photons in the event: $S_T \equiv \sum_i E_T^{\gamma_i}$ [15]. We vary the S_T cut threshold ($S_T^{\rm min}$) in 10 GeV steps to achieve an expected background of 0.4 events [16]. Such an optimization is based on the fact that for this expected background one has a 67% probability of observing no candidate events in the data in the absence of a signal. In such a case [8], the limits on the signal do not depend on the exact background value or its uncertainties. The agreement between the observed number of events and the predicted background as a function of $S_T^{\rm min}$ is illustrated in Fig. 2. Note that since the plot shows the data and the backgrounds for $S_T > S_T^{\rm min}$, the points are highly correlated. The $S_T^{\rm min} = 250$ GeV cut corresponds to a background of 0.41 ± 0.11 events. The event in the base sample with highest S_T has $S_T = 203$ GeV, well below this cut. Taking into account the selection efficiency we set an upper limit for the production cross section of two or more photons with $\sum E_T^{\gamma} > 250$ GeV and $|\eta^{\gamma}| < 1.1$:

$$\sigma(p\bar{p} \to \geq 2\gamma)|_{S_T > 250\ \mathrm{GeV}, |\eta^{\gamma}| < 1.1} < 83\ \mathrm{fb} \qquad (2)$$

at the 95% C.L. This limit is obtained using a Bayesian approach with a flat prior and with the uncertainties in the efficiency and the integrated luminosity properly taken into account.

Since the data are consistent with the background hypothesis, we can set limits on the production of pointlike Dirac monopoles. We calculate the acceptance for the monopole signal using a fast MC program that generates diphoton events from a monopole loop according to the calculated differential cross section $d^3\sigma/dE_T^\gamma d\eta^{\gamma_1} d\eta^{\gamma_2}$ [5] with a subsequent parametric simulation of the DØ detector. The MC model takes into account the interaction vertex distribution; parton density distributions in the colliding protons and antiprotons, as described by the GRV [17] parton distribution functions (p.d.f.); smearing of photon momenta; and detector acceptance. Figures 3(a) and (b) show the expected signal S_T distribution and the correlation between the photon pseudorapidities, respectively. The cuts used in this analysis are indicated in the figures. The overall acceptance for the monopole signal is found to be $(51 \pm 1)\%$, where the error reflects variations due to different p.d.f. (estimated by taking the acceptance difference using GRV and CTEQ4L [18]), and uncertainty in the detector response parametrization. The acceptance does not depend on the monopole mass for masses above the typical photon energy (~ 300 GeV) [6].

The total cross section of the heavy monopole production at the Tevatron is given by [5]:

$$\sigma(p\bar{p} \to \gamma\gamma + X) = 57\, P \left(\frac{n}{M\ [\mathrm{TeV}]}\right)^8 \ \mathrm{fb}, \qquad (3)$$

where P is a spin dependent factor [19,13]: P = 0.085, 1.39, and 159 for monopole spin of 0, 1/2, and 1, respectively. The estimated error on this cross section due to choice of p.d.f. and to higher order QED effects is 30% [6].

Comparing the lower bound of the theoretical cross section corrected for acceptance with the cross section limit (2) set by this measurement, we obtain the following lower limits on the poinfftlike Dirac monopole mass (see Fig. 4):

$$M > \begin{cases} 610n \text{ GeV} & \text{for } S = 0 \\ 870n \text{ GeV} & \text{for } S = 1/2 \\ 1580n \text{ GeV} & \text{for } S = 1 \end{cases} .$$

These are currently the most stringent limits on heavy pointlike monopoles. (We do assume, if more than one type of Dirac monopole exists, that there is no cancellation among the loop diagrams involving each monopole type.)

As a cross-check of the results of this search we have selected elastic or nearly elastic collisions by requiring no hits in the forward scintillating hodoscopes used for luminosity monitoring and triggering on the inelastic collisions [10]. This requirement drastically reduces the backgrounds. The remaining background in the base sample

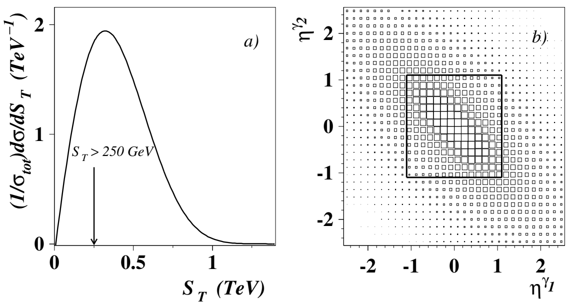

FIG. 3. a) Normalized S_T spectrum and b) photon pseudorapidities for the diphoton production via a heavy monopole loop. The arrow in a) and square in b) show the chosen cuts in the corresponding parameters.

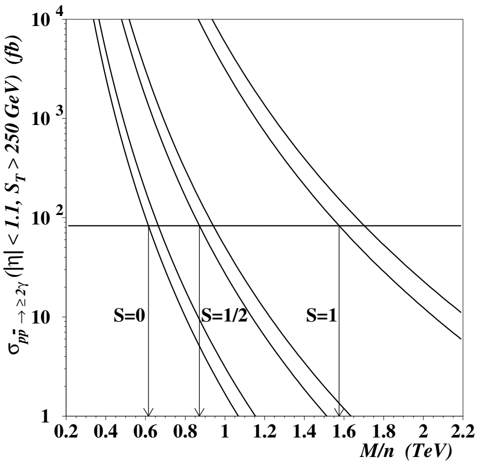

FIG. 4. The curved bands show the low and upper bounds on theoretical cross sections [5] for monopole spin, $S = 0, 1/2$, and 1. The horizontal line shows the 95% CL experimental upper limit (2) on the cross section. The arrows indicate the lower 95% CL limits on the monopole mass at each spin value.

for elastic events is 1.8 ± 0.4 events, dominated by diffractive Drell-Yan events and residual inelastic background due to inefficiency of the forward hodoscopes. We observe one candidate event in the base sample, consistent with this expected background rate. For $S_T^{\min} \approx 100$ GeV the background is 0.4 events, and no candidates are observed. We use this sample only as a cross check because the efficiency of these selection requirements is significantly lower than that of the main analysis method, primarily because of multiple interactions.

The theoretical cross section (3) was derived under the assumption that $E^\gamma/M < 1$. For low monopole masses, where this assumption is not correct, the cross section grows more slowly than $1/M^8$, and approaches the $1/M^2$ behavior typical for a QED process at low masses [6]. Also, for lower monopole masses the effective parameter of the perturbation theory used in the calculations [5] becomes too large, and therefore one would expect a non-negligible contribution of the higher order diagrams with four, six, etc. photons in the final state. The latter effect is, however, largely compensated for by our analysis cut on the sum of the photon transverse energies; if part of the signal cross section is due to the higher order diagrams, the above limits are unaffected.

When higher order calculations are available, more precise limits on the monopole mass could be obtained by comparing the modified cross section expression with the experimental limit (2). With current theory [5] the above limits are strictly valid only for monopole masses $\gtrsim$ 300 GeV. This is below the limit from the L3 experiment [7], so no window for light monopoles is left.

In conclusion, we have performed a search for pointlike Dirac monopoles by searching for high transverse energy diphotons. Our data agree with the expected background from QCD and Drell-Yan production. No candidates pass the final cuts. We set 95% C.L. lower limits on the Dirac monopole mass for minimum magnetic charge ($n = 1$) in the range 610 to 1580 GeV, depending on the monopole spin. These are the most stringent limits to date.

Our cross section limit (2) is 83 fb, and may be applicable to the other production processes, such as that of dyons or other exotic objects strongly coupled to photons.

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