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Direct Search for Dirac Magnetic Monopoles in $p\bar{p}$ Collisions at p√s = 1:96 TeV

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We search for pair-produced Dirac magnetic monopoles in 35.7 pb^{-1} of proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV with the Collider Detector at Fermilab (CDF). We find no monopole candidates corresponding to a 95% confidence-level cross-section limit $\sigma < 0.2$ pb for a monopole with mass between 200 and 700 GeV/c^2. Assuming a Drell-Yan pair-production mechanism, we set a mass limit $m > 360\ \mathrm{GeV}/c^2$.

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The existence of magnetic monopoles would add symmetry to Maxwell's equations without breaking any known physical law. More dramatically, it would make charge quantization a consequence of angular momentum quantization, as first shown by Dirac [1]. With such appeal, monopoles continue to excite interest and have been the subject of numerous experimental searches.

Grand unified theories predict monopole masses of about $10^{17}\ \mathrm{GeV}/c^2$, so cosmic ray experiments have searched extensively for high-mass monopoles produced in the early universe [2–5]. Accelerator searches for low-mass monopoles have looked for the effects of virtual monopole loops [6–8], but the results have been questioned [9]. Detector materials exposed to radiation from

$p\bar{p}$ collisions at the Tevatron have been examined for trapped monopoles, but the limit obtained depends on the model for the trapping of monopoles in matter [10]. There have been direct ionization searches using plastic track-etch detectors at accelerators, but the last one was performed more than a decade ago [11] with much lower luminosity than is now available. Despite these efforts, magnetic monopoles have not been discovered [12].

Magnetic monopoles have magnetic charge g satisfying the Dirac quantization condition:

$$\frac{ge}{\hbar c} = \frac{n}{2} \Longleftrightarrow \frac{g}{e} = \frac{n}{2\alpha} \approx 68.5n$$

where n is an integer and α is the fine structure constant. In this search, we consider an $n = 1$ monopole with mass less than 1 TeV$/c^2$, spin $\frac{1}{2}$, and no hadronic interactions. Monopoles are accelerated by a magnetic field and are highly ionizing due to the large value of g/e.

This search uses a 35.7 pb^{-1} sample of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV produced by the Fermilab Tevatron and collected by the CDF II detector during 2003 using a special trigger. The detector consists of a magnetic spectrometer including silicon strip and drift-chamber tracking detectors and a scintillator time-of-flight system, surrounded by electromagnetic and hadronic calorimeters and muon detectors [13]. CDF uses a superconducting solenoid to produce a 1.4 T magnetic field. The field is parallel to the beam direction, which is taken as the z direction, with ϕ the azimuthal angle, and r the radial distance in the transverse plane.

The important detector components for this search are the central outer tracker (COT) [14] and the time-of-flight (TOF) detector [15], both positioned inside the solenoid. The coverage of the cylindrical COT extends from a radius of 40 to 137 cm and to pseudorapidity $|\eta| \sim 1$. The COT consists of eight superlayers, each containing 12 layers of sense wires. The COT makes position measurements for track reconstruction as well as integrated charge measurements for determining a particle's ionization energy loss dE/dx. The COT is surrounded by 216 TOF scintillator bars, which run parallel to the beam line and form a cylinder of radius 140 cm. Each TOF bar is instrumented with a photomultiplier tube (PMT) on each end. The TOF measures both the time and height of PMT pulses; the pulse height is typically used to correct for discriminator-threshold time slewing. Due to their large ionization and production of δ rays, monopoles in scintillator with velocity $\beta > 0.2$ are expected to produce more than 500 times the light from a minimum-ionizing particle (MIP) [5,12].

We have built and commissioned a highly ionizing particle trigger that requires large light pulses at both ends of a TOF scintillator bar. The trigger was designed to detect monopoles efficiently while consuming less than 1 Hz of the CDF data acquisition bandwidth. The continuous low rate operation allowed us to validate the trigger performance for our entire data sample. The electronics response of the TOF has been calibrated [16,17] to account for nonlinearities and channel-to-channel differences. The trigger thresholds of about 30 MIPs are well below the expected response to a monopole and have a negligible effect on the trigger efficiency.

In the CDF detector, a monopole is accelerated along the uniform solenoidal magnetic field in a parabola slightly distorted by relativistic effects. Because no other particle mimics this behavior, the TOF acceptance must be estimated from Monte Carlo simulation. We have extended the GEANT3 simulation [17–20] to handle magnetic monopoles, including the acceleration from the magnetic field, energy loss, and multiple scattering [21]. We do not simulate bremsstrahlung as this is a negligible effect for monopoles in the mass range we consider.

Because the monopole-photon coupling is large and nonperturbative, there is no universally accepted field-theoretic calculation of magnetic-monopole production. However, monopole interactions with matter, such as scattering, require only a replacement of the electric charge with the monopole's effective charge $g\beta$. This has led the authors of Ref. [10] to adopt a heuristic production model by making the same replacement for Drell-Yan monopole pair production, which we take as our primary benchmark.

Either a monopole or antimonopole must reach the TOF detector in order to cause a trigger. To calculate the TOF acceptance for the heuristic pair-production mechanism, we produce lepton Drell-Yan events with PYTHIA [22], with the lepton mass replaced by the monopole mass, and weight events according to the additional velocity dependence. The TOF acceptance for monopole pairs simulated with GEANT is shown in Fig. 1. Light monopoles, accelerated strongly by the magnetic field, tend to be swept out of the detector before reaching the TOF. Heavy monopoles, produced near threshold, suffer the same fate.

We calculate the effect of material interactions by comparing the TOF acceptance for the full simulation with a ficticious detector consisting of the TOF only. The material

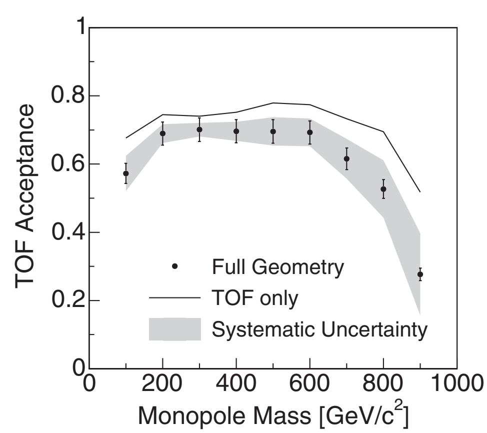

FIG. 1. The acceptance of the TOF for monopole pairs, as a function of monopole mass, for Drell-Yan monopole pair production. The band indicates the total systematic uncertainty.

in the detector lowers the acceptance by a small amount due to energy loss and multiple scattering. Although we cannot test the model for particle interactions experimentally, it is likely that additional corrections will be even smaller, so we assign a systematic error of one-half the total estimated effect, yielding a 3% systematic error for intermediate-mass monopoles. This method likely overestimates the uncertainty; varying the energy-loss model between a naive model where $e \rightarrow g\beta$ and the full treatment of Ref. [21] has a negligible effect.

The TOF acceptance depends on the monopole production kinematics. To quantify this dependence, we consider separately the Drell-Yan mechanism without the additional velocity dependence and with monopole production uniform in the cosine of the polar angle in the center of mass frame. The total variation in the acceptance is 10%. We therefore present results for our benchmark mechanism only, with the understanding that mass limits for other production mechanisms can be inferred from the cross-section limit with reasonable accuracy.

During each event, the TOF electronics makes a single measurement for each PMT. Light from other particles, called spoilers, can reach a PMT before the light from monopoles, starting the charge integration. If the monopole light does not reach the PMT within the 20 ns charge integration window, the monopole's light will not be integrated and the trigger will not fire. Our studies show that pure Monte Carlo simulation underestimates the effect of spoilers seen in data. We therefore estimate the spoiler fraction by embedding Monte Carlo produced monopoles in real $Z \rightarrow e^+e^-$ data. Because these are high-mass central events produced by a Drell-Yan mechanism, we expect the distribution of other particles in the event to be similar to that of a monopole-pair-production event. We exclude the bars with signals from the electrons and count the number of spoiler events, which have real pulses arriving more than 20 ns before the simulated pulse from a magnetic monopole.

The systematic uncertainty is dominated by the uncertainty in the time needed to integrate enough of the monopole's charge to cause a trigger. To quantify this effect, we note that rise times for TOF pulses are typically less than 1 ns and redo the calculation with a 15 ns integration window. We take one-half the difference as a systematic uncertainty. Other effects, such as the dependence on luminosity, are much smaller for our sample. For a 400 GeV$/c^2$ monopole, the spoiler fraction is $2\% \pm 1\%$ with a 3% systematic uncertainty.

Massive monopoles can have low velocities causing them to arrive at the TOF too late to cause a trigger. The timing acceptance is calculated with a Monte Carlo simulation by requiring pulses to arrive within the 54 ns timing window. Only heavy monopoles move slowly enough to be affected: a 900 GeV$/c^2$ monopole is out of time in 10% of events. This is a negligible effect on lighter monopoles.

Monopoles curve in the rz plane, in sharp contrast to electrically charged particles, which curve in the $r\phi$ plane. A specialized reconstruction program isolates monopole candidates using data from the COT. Candidates consist of coincident track segments composed entirely of hits with large ionization, consistent with a straight line in the plane perpendicular to the magnetic field.

The COT electronics encodes the integrated charge as the width of a hit, which is the ionization measurement used for monopole candidate selection. A typical MIP produces hit widths of about 20 ns. An extrapolation of the nonlinear COT response for ordinary particles predicts that monopoles would produce hit widths of about 230 ns (1000 MIPs), still within the dynamic range of the COT. We do not use this extrapolation. Instead we cut in the tail of the width distribution from ordinary tracks, found to be at 140 ns (50 MIPs) in minimum-bias data collected with an open trigger highly efficient for inelastic $p\bar{p}$ collisions. Hits with charge below this amount are not considered by the monopole reconstruction. As magnetic monopoles have much greater ionization than the tracks used to determine this cut, it has a negligible effect on the efficiency.

The default COT tracking algorithm first reconstructs track segments in each of eight superlayers. It checks for hits loosely consistent with a straight line, using a tolerance of 20 ns. The identified hits in each segment are then fit to a circular trajectory. In the monopole algorithm, the segments are required to be composed entirely of high-ionization hits. Also, because a monopole can be as slow as $\beta \sim 0.1$ with changing transverse velocity, the usual timing assumption ($t_{\text{flight}} = r/c$) cannot be used. Instead, the time of flight to each superlayer is varied between r/c and $10r/c$ in 5 ns increments.

A monopole candidate consists of several ϕ-coincident, low-curvature segments. From Monte Carlo simulation,

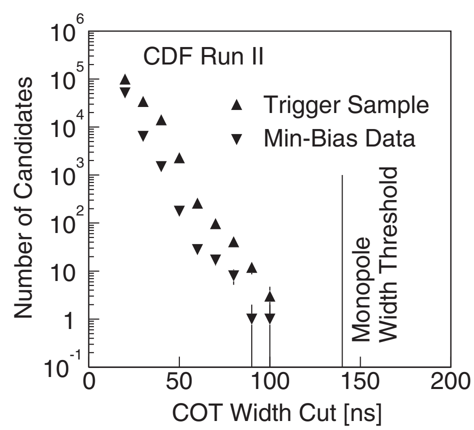

FIG. 2. Number of monopole candidates as a function of COT width cut in offline reconstruction, in 100 000 minimum-bias events and the entire 130 000 event trigger sample. A 100 ns width cut corresponds to 15 MIPs. We expect monopoles to ionize more than 1000 MIPs or 232 ns.

TABLE I. Efficiency of the monopole search with statistical and systematic uncertainties for a monopole mass of 400 GeV$/c^2$. The full mass dependence is accounted for in the limit.

Effect	Efficiency
TOF geometric (MC)	70% ± 3% ± 3%
TOF response	100%
TOF spoilers	98% ± 1% ± 3%
TOF timing (MC)	99% ± 1% ± 1%
COT width cut	100%
COT segment finding	94% ± 1% ± 3%

we choose a loose cut on the segment curvature $\rho < 0.001\ \mathrm{cm}^{-1}$, which for an electron would correspond to $p_T > 4$ GeV$/c$. Likewise, the ϕ tolerance is a loose 0.2 radians. The remaining cuts are on the minimum number of hits needed in a segment and on the total number of ϕ-coincident segments required for a monopole candidate. By ignoring the width cut, the segment-finding algorithm efficiency is measured in an independent data sample using high-p_T tracks. In this manner, we choose a highly efficient cut requiring seven coincident superlayers with at least eight hits in each segment. This has a 94% efficiency with a 1% statistical uncertainty. For these cuts, the efficiency for finding high-mass monopole pairs calculated with the Monte Carlo simulation is nearly 100%. The efficiency for high-p_T electrons in simulation, after removing the width cut, is also nearly 100%. There are real detector effects contributing a small inefficiency.

As an ionizing particle passes through matter, the most energetic electrons form δ rays. For highly relativistic low-mass monopoles, the large number of δ rays confuses the segment-finding algorithm, lowering the efficiency. We check that GEANT is properly producing δ rays by comparing the efficiency of monopoles to kinematically equivalent heavy ions simulated in the absence of a magnetic field. We scale the efficiency determined from Monte Carlo simulation to make the high-mass monopole efficiency agree with the high-p_T track efficiency. As the small inefficiency from real detector effects cannot be measured directly on monopoles, we take one-half of the total inefficiency as a systematic uncertainty: 3% for 400 GeV$/c^2$ monopoles.

To estimate how effectively the monopole reconstruction rejects background, we use minimum-bias data. In 8×10^5 events, the event most like a monopole has two coincident superlayers with seven hits per segment. Our monopole requirements are much more stringent. We require a sevenfold coincidence of eight hits or more, resulting in extremely small background. In the trigger sample the background is similarly small; the event most like a monopole has two coincident superlayers with six hits per segment. In Fig. 2, we count the number of monopole candidates passing looser cuts on the hit width.

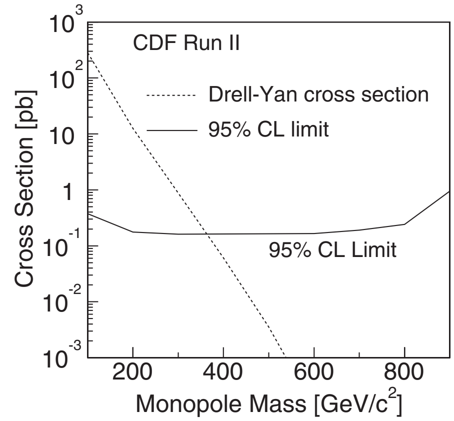

FIG. 3. The 95% CL cross-section upper limit versus magnetic-monopole mass. The theory curve for Drell-Yan monopole pair production intersects at the mass limit $m > 360$ GeV$/c^2$. The cross-section limit is 2 orders of magnitude more stringent then the results of a previous direct search in this energy range [11].

None of the 130 000 events from the monopole trigger sample passes the candidate requirements, and we report a limit [17]. Monopole production limits are typically reported by the cross-section upper limit as a function of monopole mass to minimize the dependence on a particular production model. The expected number of events N from a process with cross section σ and detector efficiency with acceptance ϵ after integrated luminosity L is given by $N = L\epsilon\sigma$. We calculate the cross-section limit for zero observed events, based on the efficiency summarized in Table I and a 6% uncertainty in the luminosity measurement [23]. We find the cross section for which pseudoexperiments with efficiency and luminosity chosen randomly according to their uncertainties yield one or more measured events 95% of the time.

Our cross-section exclusion limit is shown in Fig. 3. Our limit excludes monopole pair production for cross sections greater than 0.2 pb at the 95% confidence level for monopole masses between 200 and 700 GeV$/c^2$. For the Drell-Yan mechanism, this implies a mass limit of $m > 360$ GeV$/c^2$ at the 95% confidence level. This is currently the best limit from a direct search. Additional Run II data will improve the sensitivity: another 300 pb^{-1} extends the mass reach by 100 GeV$/c^2$.

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