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Search for Stopped Gluinos from $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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Long-lived, heavy particles are predicted in a number of models beyond the standard model of particle physics. We present the first direct search for such particles' decays, occurring up to 100 h after their

production and not synchronized with an accelerator bunch crossing. We apply the analysis to the gluino ($\tilde{g}$), predicted in split supersymmetry, which after hadronization can become charged and lose enough momentum through ionization to come to rest in dense particle detectors. Approximately 410 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV collected with the D0 detector during Run II of the Fermilab Tevatron collider are analyzed in search of such "stopped gluinos" decaying into a gluon and a neutralino ($\tilde{\chi}_1^0$). Limits are placed on the (gluino cross section) $\times$ (probability to stop) $\times$ [BR($\tilde{g} \to g\tilde{\chi}_1^0$)] as a function of the gluino and $\tilde{\chi}_1^0$ masses, for gluino lifetimes from 30 μs–100 h.

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Split supersymmetry is a relatively new variant of supersymmetry (SUSY), in which the SUSY scalars are heavy compared to the SUSY fermions [1]. Because of the scalars' high masses, gluino decays are suppressed, and the gluino can be long-lived. Other new models, such as Gauge-mediated SUSY, can also predict a long-lived gluino or other heavy, colored, long-lived particles [2]. The gluinos hadronize into "R hadrons" [3], colorless bound states of a gluino, and other quarks or gluons. As studied in Ref. [4], some 30% of R hadrons at the Tevatron can become "stopped gluinos" by becoming charged through nuclear interactions, losing all of their momentum through ionization, and coming to rest in surrounding dense material. We present the first direct search for the decays of such particles, with deposited hadronic energy not in time with a $p\bar{p}$ collision.

A data sample corresponding to an integrated luminosity of 410 ± 25 pb^{-1} [5], taken with the D0 detector [6] from November 2002 to August 2004, has been analyzed to search for stopped gluinos. The D0 detector has a magnetic central tracking system surrounded by a uranium or liquid-argon calorimeter, contained within a muon spectrometer. The tracking system, located within a 2 T solenoidal magnet, is optimized for pseudorapidities $|\eta| < 2.5$, where $\eta = -\ln[\tan(\theta/2)]$, and θ is the polar angle with respect to the proton beam direction (z). The calorimeter has a central section (CC) covering up to $|\eta| \approx 1.1$ and two end calorimeters (EC) extending coverage to $|\eta| \approx 4.2$, all housed in separate cryostats [7]. The calorimeter is divided into an electromagnetic part followed by fine and coarse hadronic sections. Calorimeter cells are arranged in pseudoprojective towers of size 0.1×0.1 in $\eta \times \phi$, where ϕ is the azimuthal angle. The muon system consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T iron toroidal magnets (the A layer), followed by two similar layers behind the toroids (the B and C layers), which provide muon tracking for $|\eta| < 2$. The luminosity is measured using scintillator arrays located in front of the EC cryostats, covering $2.7 < |\eta| < 4.4$. The trigger system comprises three levels ($L1$, $L2$, and $L3$), each performing an increasingly detailed event reconstruction in order to select the events of interest.

We search for stopped gluinos decaying into a gluon and a neutralino, $\tilde{\chi}_1^0$. The analysis has slightly reduced sensitivity for $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$, which may be a large fraction of the decays, depending on the SUSY parameters. The gluino lifetime is assumed to be long enough such that the decay event is closest in time to an accelerator bunch crossing later than the one that produced the gluino. For the $L1$ trigger to be live again during the decay even if the production event was triggered on, this lifetime must be at least 30 μs, due to trigger electronics dead time. The efficiency for recording the gluino decay is modeled as a function of the gluino lifetime, up to 100 h. When the decay occurs during a bunch crossing with no other inelastic $p\bar{p}$ collision, the signal signature is a largely empty event with a single large transverse energy (E_T) deposit in the calorimeter, reconstructed as a jet and large missing transverse energy ($\not{E}_T$).

The trigger for each event requires that neither of the luminosity scintillator arrays fired. At least two calorimeter towers of size $\eta \times \phi = 0.2 \times 0.2$ with $E_T > 3$ GeV are also required at $L1$. Jets are reconstructed with the Run II Improved Legacy Cone Algorithm [8] with a cone of radius 0.5 in $\eta \times \phi$ space. A reconstructed jet with $E_T > 15$ GeV is required at $L3$. Offline, we require exactly one jet in the event with $E > 90$ GeV and no other jets with $E_T > 8$ GeV. The calorimeter requirements in the trigger are nearly 100% efficient for events that pass the 90 GeV offline threshold.

To simulate stopped gluino decays, the PYTHIA [9] event generator is used to produce Z + gluon events, with the Z boson forced to decay to neutrinos. Initial-state radiation is turned off, as are multiple parton interactions. The spectator particles coming from the rest of the $p\bar{p}$ interaction, such as the underlying event, are removed by removing all far-forward particles with $|p_z/E| > 0.95$. The location of the interaction point is placed inside the calorimeter, and events are further weighted such that the final decay position distribution is that expected for stopped gluinos. The radial location of the gluino when it decays depends on the way gluinos lose energy via ionization and stop in the calorimeters. This calculation was performed [4] for a distribution of material similar to that of the D0 calorimeters and a gluino velocity distribution as expected from production at the Tevatron. The η distribution is determined by the fact that gluinos would tend to be produced near threshold at the Tevatron and that only slow gluinos would stop. The gluinos are thus expected to be distributed proportionally to $\sin\theta$. More than 75% of gluinos that stop have $|\eta| < 1$. Because the gluinos are at rest and with their spin randomly oriented when they decay, the gluon is

TABLE I. The selections applied, and the number of events passing in data and for a simulated signal with $M_{\tilde{g}} = 400$ GeV and $M_{\tilde{\chi}_1^0} = 90$ GeV.

Selection	Data Events	Signal Events
Total	7 199 133	2000
Exactly one jet ($E_T > 8$ GeV)	3 691 036	1678
Jet $\lvert\eta\rvert < 0.9$	2 742 353	1505
Jet $E > 90$ GeV	202 568	805
No PV	198 380	803
Data quality	189 781	772
Jet η and ϕ widths >0.08	5994	410
Jet $n90 > 10$	1402	383
No muons	109	357

emitted in a random direction. Thus a random 3D rotation is applied to the simulated particles.

The energy of the gluon, which hadronizes and fragments into a jet, depends on the gluino and neutralino masses: $E = (M_{\tilde{g}}^2 - M_{\tilde{\chi}_1^0}^2)/2M_{\tilde{g}}$. We generate four samples of stopped gluinos, containing about 1000 events each, using a GEANT-based [10] detector simulation and reconstructed using the same algorithms as data. They correspond to gluino masses of 200, 300, 400, and 500 GeV, with a neutralino mass of 90 GeV. These samples correspond to generated gluon energies of 80, 137, 190, and 242 GeV, respectively. Simulated jets are corrected for relative differences between the data and simulation jet energy scales. The calorimeter electronics sample the shaped ionization signal only once per bunch crossing, at the assumed peak of the signal for jets originating from a $p\bar{p}$ interaction, but the gluino decay can occur at any time with respect to a bunch crossing. So jet energies in the simulation are also corrected (downwards) according to a model of this "out-of-time" calorimeter response. The average degradation of energy is 30%, although more than half of the jets are not significantly degraded.

The primary source of background is cosmic muons, which are able to fake a gluino signal if they initiate a high-energy shower within the calorimeter. Hard bremsstrahlung is responsible for the majority of the showers. These showers tend to be very short, since they are electromagnetic in nature and thus have small lengths compared to hadronic showers. However, sometimes a wide, hadroniclike, shower can be created either due to deep-inelastic muon scattering, fluctuations of the shower, or detector effects. Cosmic muons can usually be identified by the presence of a reconstructed high-energy muon. A coincidence of muon hits in the B and C layers of the muon system, behind the thick iron toroid magnet, is very strong evidence of a muon. The A layer muon hits are often also caused by the signal, due to particles escaping the calorimeters, so they are difficult to use for background rejection. Sometimes the muon is not detected, due to detector inefficiencies, being out of time with the bunch crossing, or the limited acceptance.

Another source of background events is beam-halo muons, or "beam muons." These are muons, synchronized with the $p\bar{p}$ bunch crossings and traveling nearly parallel to the beam. Often, one or more muon scintillator hits can be associated with the muon, and the muon is measured to be within $\Delta t < 10$ ns of a bunch crossing. Another feature of the beam muons is that they are nearly all in the plane of the accelerator beam. Beam-muon showers are also typically very narrow in ϕ, causing this background to be negligible once wide calorimeter showers are required.

Since the trigger requires no signal in the luminosity scintillator arrays, nearly all of the $p\bar{p}$ beam produced backgrounds are eliminated. An exception is diffractive events with forward rapidity gaps in both the positive and negative η regions. Typical $p\bar{p}$ events have a primary vertex (PV) reconstructed from tracks which originate near to each other along the beam line, where the $p\bar{p}$ interaction occurred. Dijet events in the same data sample are studied to understand the $\not{E}_T$ spectrum and PV reconstruction efficiency for beam-related backgrounds. After requiring no PV to be reconstructed and large $\not{E}_T$ (implicit from the requirement of a single high-energy jet), the $p\bar{p}$ events are negligible.

Other sources of physics background considered are cosmic neutrons and neutrinos, both of which are found

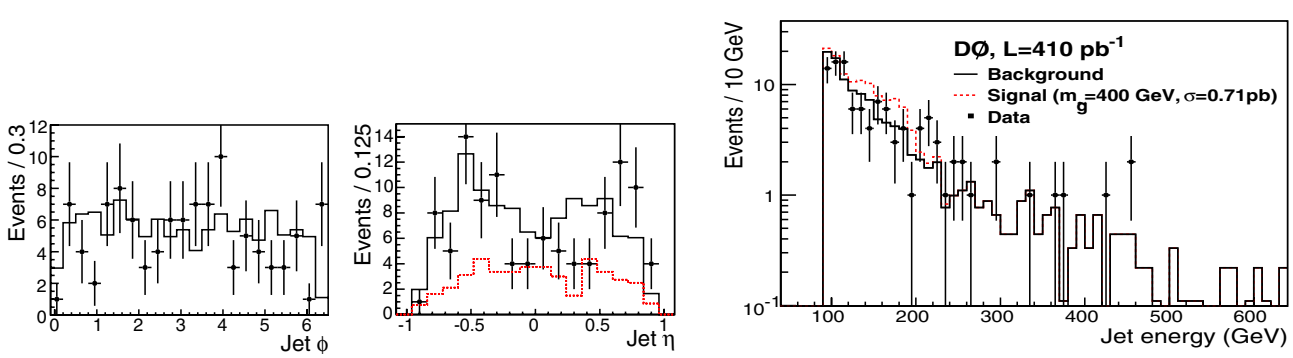

FIG. 1 (color online). A comparison of the wide-shower no-muon data (points) to the expected background from cosmic muons (solid histogram) and a simulated signal (dashed histogram).

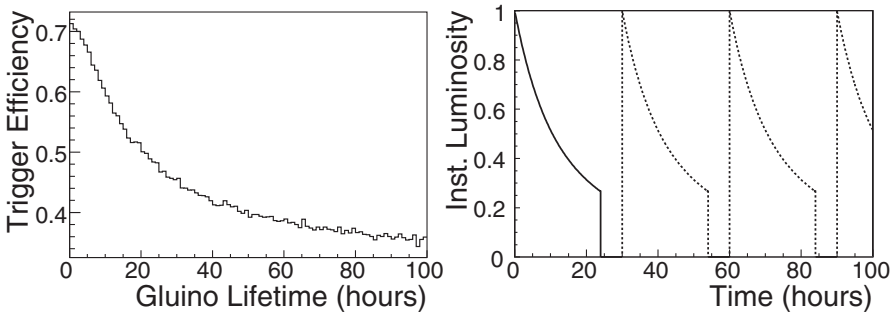

FIG. 2. Left: the trigger efficiency vs gluino lifetime. Right: the instantaneous luminosity profile used to model the trigger efficiency. Dashed lines indicate a 50% chance of the store occurring.

to be negligible. Cosmic neutrons would have to penetrate the thick iron toroid. Those neutrons that did reach the calorimeter would shower preferentially in the outer layers on the top of the calorimeter, which is not observed.

Finally, since the signal process is rare, we also consider occasional fake signals caused by detector readout errors or excessive noise. We require the jet to be in $|\eta| < 0.9$, since the forward regions of the calorimeter are observed to have more frequent (yet still rare) problems. Also, the gluino signal tends to be concentrated in the central detector region. Remaining problems are isolated to a specific set of runs, detector region, or both, and such events are removed.

The following criteria are used to select events containing "wide showers": jet η width and ϕ width >0.08 and jet $n_{90} \geq 10$, where n_{90} is the smallest number of calorimeter towers in the jet that make up 90% of the jet transverse energy. The reverse criteria define a "narrow shower." Criteria are also defined which select events containing "no muon" or a "cosmic muon." An event contains no muons if there are no *B-C* layer muon segments in the event and no *A* layer segments with $\Delta\phi > 1.5$ radians from the jet direction. Cosmic-muon events have at least one *B-C* layer muon segment with $|\Delta t| > 10$ ns from the bunch crossing time. A candidate stopped gluino decay event contains both a wide shower and no muon. Table I summarizes the selection criteria.

To estimate the number of such wide-shower no-muon events expected from cosmic-muon background, we use the assumption that the probability not to reconstruct a cosmic muon in the muon system is independent of whether the muon's shower in the calorimeter is narrow or wide. A subset of the narrow-shower data sample is defined which is nearly devoid of beam muons by requiring a shower out of the accelerator plane. This cosmic-muon narrow-shower data subset has a similar η distribution to the wide-shower data, and the η and ϕ shower width distributions are not altered significantly when requiring a muon. The probability to not reconstruct the muon in this narrow-shower data sample is measured to be 0.11 ± 0.01, independent of shower energy. This probability is applied to the wide-shower cosmic-muon data sample to predict the jet energy spectrum of wide-shower no-muon background events, as shown in Fig. 1. The data agree with the estimated background from cosmic muons. There is no significant excess in any jet energy range, and the data have the predicted shape in η and ϕ.

We search for a signal in jet energy ranges with widths chosen from the jet energy resolutions of the simulated signal samples. The ranges are from $M - \sigma/2$ to $M + 2\sigma$, where M is the mean jet energy of the sample and σ is the sample's jet energy rms. An asymmetric window is chosen since the background is steeply falling with increasing jet energy.

To first order, the detection efficiency for the decays of the stopped gluino signal events can be estimated from the simulation, but some effects are not modeled. There is a loss of efficiency at the trigger level from the requirement of neither luminosity scintillator array firing. If a minimum bias collision happens to occur during the bunch crossing when the gluino decays, a luminosity scintillator array may fire. The fraction of the time this occurs has been measured using cosmic-muon events triggered on a jet-only trigger with high threshold. The efficiency of the luminosity scintillator array trigger requirement, averaged over the data set, is 75%. The probability to have minimum bias interactions during a given crossing is Poisson distributed, with a mean proportional to the instantaneous luminosity, ap-

TABLE II. The data, background, signal efficiency (for stopped gluinos where $\tilde{g} \to g\tilde{\chi}_1^0$), and expected and observed cross section upper limits (at the 95% C.L.) for each jet energy range, for a small gluino lifetime, less than 3 h.

Energy (GeV)	Data	Background	Efficiency (%)	Experiment (pb)	Observation (pb)
92.5–104.6	30	37 ± 3.7	1.7 ± 0.34	2.61	1.81
112.4–156.6	39	40 ± 4.0	4.9 ± 0.98	0.94	0.89
141.3–213.0	34	31 ± 3.1	6.8 ± 1.36	0.56	0.71
168.7–270.6	32	26 ± 2.6	7.2 ± 1.44	0.48	0.75

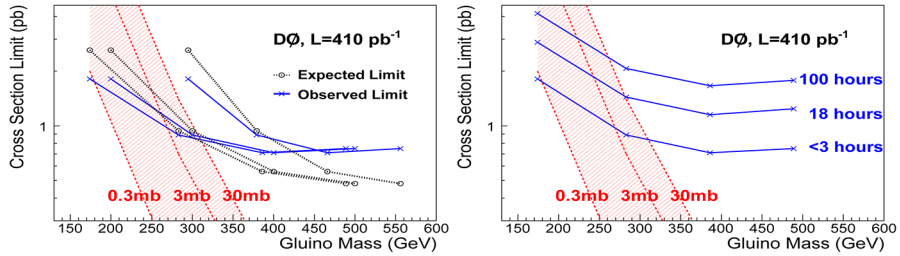

FIG. 3 (color online). Top: the expected and observed upper limits on the cross section of stopped gluinos, assuming a 100% BR of $\tilde{g} \to g\tilde{\chi}_1^0$ and a small gluino lifetime (<3 h), for three choices of the $\tilde{\chi}_1^0$ mass: 50, 90, and 200 GeV, from left to right. Bottom: the upper limits observed on the cross section of stopped gluinos, for various assumptions of the gluino lifetime, for a $\tilde{\chi}_1^0$ mass of 50 GeV. Also shown are the theoretical stopped gluino cross sections (dashed lines, shaded area), from Ref. [4], for the range of assumed conversion cross sections.

proximately 20–30 $\mathrm{cm}^{-1}\mathrm{s}^{-1}$ on average for this data set. A detailed model of the trigger efficiency is made as a function of the gluino lifetime, for lifetimes up to 100 h, using the typical Tevatron store luminosity profile as input (see Fig. 2). Stores typically last ~24 h with a 50% chance of another store following, 6 h later. The current luminosity at the time of the gluino decay, and thus the chance to have an overlapping interaction, is accounted for. Another source of inefficiency is that the trigger is not live all the time, but only during the "live superbunches," which make up 68% of the total run time.

The uncertainties from all sources which affect the signal acceptance are added in quadrature, totaling (20%–25)%. They include the modeling of the out-of-time jet response (12%), the data or simulation jet energy scale (9%), the η and radial distributions of stopped gluinos [(7%–9)%], other geometrical or kinematic acceptances (5%), and trigger efficiency [(5%–15)%].

Given an observed number of candidate events, an expected number of background events, and a signal efficiency in a certain jet energy range, we can exclude at the 95% C.L. a calculated rate of signal events giving jets of that energy, taking systematic uncertainties into account using a Bayesian approach (see Table II). This is a fairly model-independent result, limiting the rate of any out-of-time monojet signal of a given energy.

From the relation between the gluino and $\tilde{\chi}_1^0$ masses and the observed jet energy, results can be translated from the generated set of signal samples to any other set of ($M_{\tilde{g}}$, $M_{\tilde{\chi}_1^0}$) which would give the same jet energy. We can therefore place upper limits on the stopped gluino cross section versus the gluino mass, for an assumed $\tilde{\chi}_1^0$ mass, assuming a 100% branching fraction for $\tilde{g} \to g\tilde{\chi}_1^0$. These can be compared with the predicted cross sections for stopped gluinos (which include its production rate and its probability to stop) taken from Ref. [4]. Three curves are drawn to represent the large theory uncertainty, resulting from the variation of the neutral to charged R hadron conversion cross section used: 0.3, 3, and 30 mb. Figure 3 (left) shows these upper limits for $\tilde{\chi}_1^0$ masses of 50, 90, and 200 GeV, for a small gluino lifetime, less than 3 h. If the gluino lifetime is greater than 3 h, the average efficiency of the trigger degrades because signal events are not recorded between accelerator stores, and the limits become weaker, as shown in Fig. 3 (right).

This is the first search for exotic, out-of-time hadronic energy deposits at a high-energy collider. The results from 410 pb^{-1} of Tevatron data are able to exclude a cross section of ~1 pb for gluinos stopping in the D0 calorimeter and later decaying into a gluon and neutralino. For a $\tilde{\chi}_1^0$ mass of 50 GeV, we are able to exclude $M_{\tilde{g}} < 270$ GeV, assuming a 100% branching fraction for $\tilde{g} \to g\tilde{\chi}_1^0$, a gluino lifetime less than 3 h, and a neutral to charged R hadron conversion cross section of 3 mb.

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