Search for neutral, long-lived particles decaying into two muons in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV

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We present a search for a neutral particle, pair-produced in $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV, which decays into two muons and lives long enough to travel at least 5 cm before decaying. The analysis uses $\approx$380 pb^{-1} of data recorded with the D0 detector. The background is estimated to be about one event. No candidates are observed, and limits are set on the pair production cross section times branching fraction into dimuons + X for such particles. For a mass of 10 GeV and lifetime of 4×10^{-11} s, we exclude values greater than 0.14 pb (95% C.L.). These results are used to limit the interpretation of NuTeV's excess of di-muon events.

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Several models including supersymmetry with R-parity violation [1, 2] and hidden valley theories [3] predict the existence of neutral, long-lived particles that give rise to a distinctive signature of two leptons arising from a highly displaced vertex. The Fermilab neutrino experiment NuTeV observed an excess of di-muon events that could be interpreted as such a signal [4, 5, 6]. Experiments at the CERN e^+e^- Collider (LEP) have looked for short-lived neutralino and chargino decays [7] and longer-lived charged particles [8], but did not search for this topology.

In this Letter we present a search for a light, neutral, long-lived particle (N^0_{LL}) pair-produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV and recorded with the D0 detector, using 380 pb^{-1} of data from Run II of the Fermilab Tevatron Collider. The final state under study is the decay of an N^0_{LL} into two muons and possibly a neutrino after the N^0_{LL} has traveled at least 5 cm. The particle is assumed to have a mass as low as several GeV. The analysis reported here explores a region of phase space previously unexplored by collider experiments.

We use R-parity violating (RPV) decays of neutralinos (χ^0_1) to $\mu^+\mu^-\nu$ (Fig. 1) as a benchmark model and to determine signal efficiency. Here the RPV couplings are expected to be small and lead to long lifetimes [9]. The results are applicable to any pair-produced neutral particle with similar kinematics.

The D0 detector consists of a central-tracking system, a liquid-argon and uranium calorimeter, and an outer muon system [10]. Each of these is used in this analysis, with an emphasis on the muon system for particle identification and on the tracking system for momentum measurement and vertexing.

The central tracker consists of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located within a 2 T superconducting solenoidal magnet. It is optimized for tracking and vertexing at pseudorapidities $|\eta| < 3$ and $|\eta| < 2.5$, respectively, where $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle with respect to the proton beam direction. The CFT has 8 axial and 8 stereo layers with an innermost (outermost) radius of 20 (52) cm. The calorimeter consists of a central section (CC) covering $|\eta| \leq 1.1$, and two end calorimeters (EC) that extend coverage to $|\eta| \approx 4.2$, with all three housed in separate cryostats [11]. The outer muon system, at $|\eta| < 2$, consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T iron toroids, followed by two similar layers after the toroids [12].

We use the volume inside the CFT inner radius as a decay region. This allows the full CFT and muon systems to be used for detection of decay products, ensuring robust track reconstruction and muon identification. Events are required to pass a di-muon trigger.

The strategy is to identify events with at least two opposite-sign, isolated muons, defined as hits in the muon system matched to a track in the CFT. Each pair is fit to a vertex. The signal sample uses events with muon vertices that are displaced more than 5 cm (in the plane transverse to the beamline) from the primary vertex. To characterize the displacement, we define the *vertex radius*

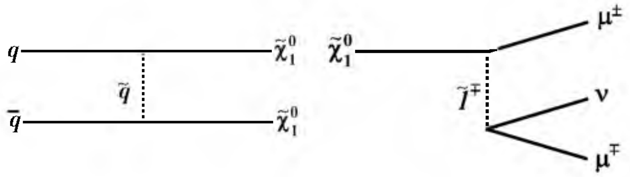

FIG. 1: Feynman diagrams for pair production (left) and decay (right) of a neutral particle, in this case neutralinos with R-parity violation.

$$r = \sqrt{(X - X_{PV})^2 + (Y - Y_{PV})^2} \quad (1)$$

where X,Y are the x,y positions of the fit di-muon vertex and X_{PV},Y_{PV} are the x,y positions of the primary vertex (PV). D0 uses a right-handed coordinate system with the positive z-axis defined by the proton direction and positive y-axis pointed upward.

Studies of K_s mesons are performed to test the reconstruction efficiency for highly displaced vertices. We search for K_s mesons in data and Monte Carlo (MC) by fitting track pairs to a common vertex and selecting those with an invariant mass around the K_s peak. We are able to observe decay lengths greater than 20 cm and demonstrate that the data and MC follow the same radial dependence. The efficiency varies by 30% in the range r=5–20 cm.

Selection criteria are chosen to minimize background while maintaining signal efficiency. All possible primary and secondary vertices are determined using tracks, except those associated with muons. The hard scatter vertex is determined by clustering tracks into seed vertices by a Kalman filter algorithm [13]. A probability function based on the p_T of tracks attached to each vertex is used to rank the likelihood that it comes from a minimum bias interaction. The primary vertex is the one with the lowest probability. The PV is required to be within 0.3 cm of the beamline in x and y and within 60 cm of the detector center in z.

We require two muons which have hits in each of the three layers of the muon system, are matched to a track in the central tracker, have a good track fit, at least 14 CFT hits associated with the track, transverse momentum > 10 GeV, and are isolated. Two methods are used to define isolation. First, the direction of the muon is projected to the calorimeter and the transverse energy in all cells within an annular cone $0.1 < R < 0.4$ is summed (calorimeter isolation), where $R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$. Second, the transverse momentum of all tracks within a cone of $R < 0.5$ (except for the muon tracks) is summed (track isolation). Both the calorimeter and track isolations are required to be less than 2.5 GeV. Cosmic ray muons are rejected by requiring the time measured by the muon scintillator counters to be that expected for a particle produced at the nominal beam crossing time. To enhance the signal, both muons must have a distance of closest approach (DCA) of greater than 0.01 cm in the $x-y$ plane and more than 0.1 cm along the z-axis from any vertices. The two muons must have an opening angle less than 0.5 radians and have opposite charge.

All pairs of muons passing the above quality cuts are fit to a common vertex requiring a $\chi^2/N_{dof} < 4$. The radial distance between the di-muon vertex and the primary vertex must be six times the resolution of the di-muon vertex measurement and be between 5 and 20 cm. This defines our signal region.

We use data to estimate the background for this search. By allowing events to pass or fail two different selection criteria (the DCA and vertex radius cuts) we define four regions. For the DCA cut, we require either: (1) one track to pass the DCA cut and one to fail it, or (2) both tracks to pass the DCA cut. For the vertex radius we define two regions: (A) $0.3 < r < 5$ cm, or (B) $5 < r < 20$ cm. This defines Samples 1A, 2A, 1B, and 2B.

We observe four events in Sample 1A, one event in Sample 1B, and three events in Sample 2A. Assuming no correlation between selection criteria and no signal, the ratio of the number of events in region to 2B to the number in 1B should equal the ratio of the number of events in region 2A to the number in 1A. This can be re-expressed to give an estimate of the background in the signal sample (Sample 2B):

$$N_{\rm bkgd} = \frac{\text{Sample 2A}}{\text{Sample 1A}} \times \text{Sample 1B.} = 0.75 \pm 1.1 \text{ events} \tag{2}$$

Due to bias from a correlation between the vertex radius and DCA criteria, we perform tests of this method and assign a systematic uncertainty using several additional samples. The spread in these results is used to assign a systematic uncertainty to account for the correlation between the vertex radius and DCA cut. Thus, we estimate the background in the signal region to be 0.75 ± 1.1 (stat) ± 1.1 (syst) events.

Figure 2 shows the vertex radius distribution for events where one or both muons pass the DCA criteria. Examination of the signal region yields 0 events passing all criteria. Therefore we set a limit on the cross section as a function of lifetime. The lifetime dependence is calculated based on the fraction of events, f, which decay within our signal region.

Signal MC events are generated using SUSYGEN [14] and an unconstrained minimal supersymmetric model with R-parity violation [1, 2, 5] using CTEQ5L parton distribution functions (PDFs) [15]. The following parameters are used: $\tan\beta = 10$, $\mu = -5000$, $M_2 = 200$ GeV, $M_3 = 400$ GeV, $M_{\rm squark} = 300$ GeV, $M_{\rm slepton} = M_{\rm snu} = M_{\rm sbottom} = M_{\rm stop} = 1500$ GeV. The χ_1^0 mass is about equal to the M_1 parameter. Similar sets are generated with $M_1 = 3$, 5, 8, 10, 15, 20, 30, and 40 GeV yielding pair production cross sections in the range 0.025–0.013 pb. While the parameters are different than those used in other neutralino searches [7], they are chosen to give a model that provides a particle consistent with the NuTeV result and does not violate limits from LEP searches (including the Z boson invisible width). The lifetime is determined primarily by the slepton mass and the λ_{122} parameter, however, in the detector simulation we choose to ignore the lifetime and force exactly one of the two χ_1^0s to decay within a cylinder of radius 25 cm. The vertex is selected along the χ_1^0 trajectory such that the radius distribution is flat over the range 0–25 cm. The other χ_1^0 is required to escape the detector. The dependence of the acceptance on the lifetime is accounted for in the interpretation of the final result. The average χ_1^0 transverse momentum (p_T) is ≈85 GeV.

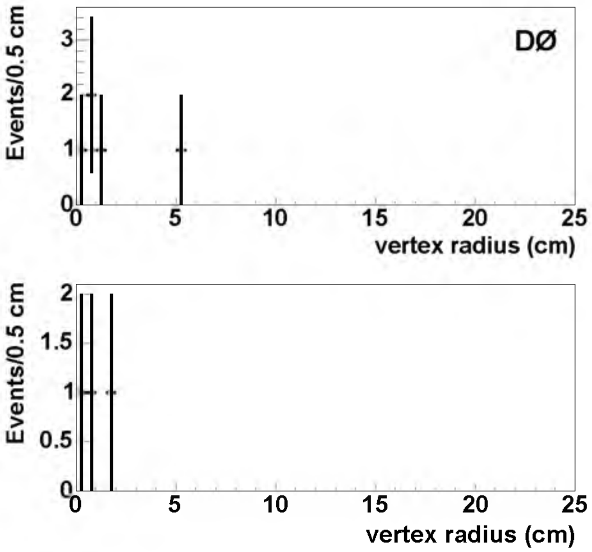

FIG. 2: Distribution of the vertex radius for events where one muon passes the DCA criteria and the second fails it (top) and where both muons pass the DCA criteria (bottom).

Our uncertainty estimate on the luminosity times signal acceptance is summarized in Table I. The MC acceptance uncertainty is statistical. Tracking, isolation, and muon reconstruction data/MC corrections are estimated using the Z boson mass peak, yielding 0.72 ± 0.07. The vertex reconstruction data/MC is found using K_s events (0.92 ± 0.14). A PDF uncertainty on the signal efficiency of ±4% is assigned using the CTEQ6.1M PDF set [16].

These event numbers, efficiencies, acceptances and uncertainties are combined to set a 95% (99%) confidence level limit on the cross section $\sigma(p\bar{p} \rightarrow N_{LL}^0 N_{LL}^0 X)$ times branching fraction BF$(N_{LL}^0 \rightarrow \mu^+\mu^- + X)$ as a function of the lifetime (Fig. 3), using a Bayesian technique [17] and assuming zero background. The limit for a 10 GeV N_{LL}^0 with a lifetime of 4×10^{-11} s is 0.14 pb (95% C.L.).

TABLE I: Acceptance, error, and limits for the MC signal points. The lifetime acceptance is the factor by which the limit is adjusted due to the fraction of events which decay within the 5–20 cm region and is given for a lifetime of 4×10^{-11} s. The luminosity × acceptance includes the MC signal acceptance, the trigger efficiency, the data/MC correction factors, and the luminosity. The limits are given for the same lifetime.

$M(\chi_0^1)$ (GeV)	Monte Carlo acceptance	Lifetime acceptance	Luminosity $\times$ acceptance (pb^{-1})	95% C.L. limit (pb)
3	0.095 ± 0.005	0.51	23.9 ± 4.8	0.28
5	0.114 ± 0.005	0.61	28.7 ± 5.8	0.19
8	0.141 ± 0.006	0.67	35.5 ± 7.1	0.14
10	0.136 ± 0.006	0.68	34.3 ± 6.8	0.14
15	0.139 ± 0.006	0.65	35.1 ± 7.0	0.15
20	0.130 ± 0.005	0.62	32.8 ± 6.5	0.17
30	0.099 ± 0.003	0.55	24.8 ± 4.9	0.25
40	0.079 ± 0.004	0.48	20.0 ± 4.1	0.35

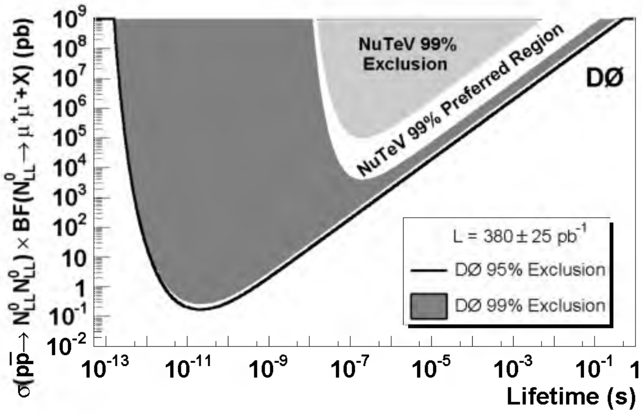

FIG. 3: Limit on cross section × branching fraction for the pair-production of neutral, long-lived particles as a function of lifetime. The dark gray area and above represents the D0 99% C.L. limit for the 5 GeV mass point. The solid line shows the D0 95% C.L. limit. The light gray region represents the NuTeV 99% C.L. exclusion [4] converted to a $p\bar{p}$ cross section at $\sqrt{s} = 1960$ GeV. The white region represents a 99% C.L. preferred region given the three events from NuTeV.

Figure 4 shows how the D0 limit varies with mass at a lifetime of 4×10^{-11} s.

In order to compare with D0, we convert the NuTeV result from pp production at $\sqrt{s} = 38$ GeV to $p\bar{p}$ production at $\sqrt{s} = 1960$ GeV using the ratio of cross sections for SUSY neutralino pair production calculated with the parameters from our 5 GeV signal simulation. The NuTeV lifetime is converted from kilometers to seconds assuming an average momentum (along the neutrino beam direction) of 121 GeV. Given that NuTeV observed three events [4], a preferred region is found using the ratio of the 99% CL lower and upper limits on three events determined using a Feldman-Cousins approach [18]. We improve on the NuTeV limit by several orders of magnitude at long lifetimes and add coverage at lower lifetimes. Our limit excludes the interpretation of the NuTeV excess as arising from any model with similar N^0_{LL} production cross sections and kinematics.

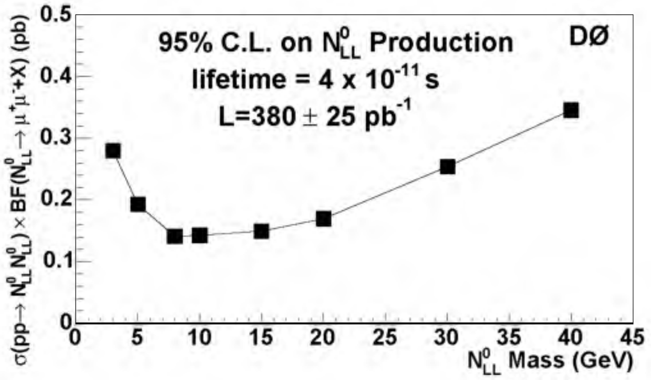

FIG. 4: Limits on N^0_{LL} pair production as a function of its mass. The limit is for a lifetime of $4 \times 10^{-11} s$.

To summarize, we have presented an analysis sensitive to neutral, long-lived particles decaying to $\mu\mu + X$ using a new technique that expands the capabilities of the D0 experiment. The background is estimated to be 0.75 ± 1.1 (stat) $\pm$ 1.1 (syst) events. The signal region contains 0 events and a limit is set. The 95% CL limit for a mass of 10 GeV and lifetime of 4×10^{-11} s is 0.14 pb. This result excludes an interpretation of the NuTeV excess of dimuon events in a large class of models.

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