DØnote 5023-CONF

Search for Neutral, Long-Lived Particles in the Dimuon Channel with 383 pb^{-1} of Run II Data

The DØ Collaboration
URL http://www-d0.fnal.gov
(Dated: March 1, 2006)

We present a search for a neutral particle, pair produced in $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV, which decays to two muons and a neutrino, and lives long enough to travel at least 5 cm before decaying. The analysis uses 383 pb^{-1} of data recorded with the DØ detector. The background is estimated to be on the order of one event. The search yields 0 events, and limits are set on the pair production cross section times branching fraction for neutral, long-lived particles decaying to two muons.

Preliminary Results for Winter 2006 Conferences

I. INTRODUCTION

The large data samples available at DØ from Run II facilitate new searches for previously unexplored signatures. Here, we present a search for a neutral particle which travels at least 5 cm before decaying to two muons and a neutrino. The particle is assumed to have a mass as low as several GeV.

We will use R-parity violating (RPV) decays of neutralinos (Sec. II) where the RPV couplings are expected to be small and lead to long lifetimes [1] as an example model. While previous collider searches for neutral, long-lived particles (N^0_{LL}) such as at LEP [2] did not look for such long decay lengths, this analysis will demonstrate that, contrary to previous reports [3], collider detectors are sensitive to long-lived, light, neutral particles. We will compare our results to those reported by NuTeV [4].

We will use the volume inside the DØ central fiber tracker (CFT) as a decay region. This allows the full CFT and muon systems to be used for detecting the decay products. By including all layers of the CFT we avoid the need to modify the tracking algorithms.

The strategy is to identify events with a pair of isolated muons matched to tracks in the CFT. Each pair is fit to a 3D vertex using a constrained vertex fitter. The final sample consists of events with good muon vertices that are displaced 5-20 cm (in the transverse plane) from the primary vertex. To characterize the displacement, we define the variable

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

where X,Y are the x,y positions of the fit muon vertex and X_{PV},Y_{PV} are the x,y positions of the primary vertex (PV).

Studies of K^0_s mesons were performed to demonstrate our ability to find highly displaced vertices. We search for K^0_s mesons in multijet data and Monte Carlo (MC). We are able to observe K^0_s meson decays out to >20 cm (Fig. 1(a)) and demonstrate that the data and MC follow the same radius dependence (Fig. 1(b)). We also observe the same opening angle dependence and proper lifetimes. This gives confidence that the Monte Carlo models the important quantities and can be used to determine the signal acceptance.

While more K^0_s mesons are observed in the MC, we use the peak in the di-track mass spectra without vertex fitting (Fig. 2) to show this is primarily due to the simulation having more K^0_s mesons rather than to differences in vertex reconstruction. Tracking studies within jets find a data/MC ratio of 0.92 $\pm$ 0.05. Combining these, we assign a data/MC correction for vertex reconstruction of 0.92 $\pm$ 0.14.

II. SIGNAL SIMULATION

The analysis is designed to search for any light, neutral, long-lived particle. We will use a SUSY point that allows pair production of low mass neutralinos with a long lifetime and subsequent decays to $\mu^+\mu^-\nu$ (Fig. 3) as an example and to determine signal efficiency. The results should be applicable to any similarly pair-produced neutral particle.

Signal Monte Carlo events have been generated (SUSYGEN [5]) using an unconstrained minimal supersymmetric model with R-parity violation (RPV) [6] and parameters: $tan\beta$ = 10, μ = -5000, M_1 = 5 GeV, M_2 = 200 GeV,

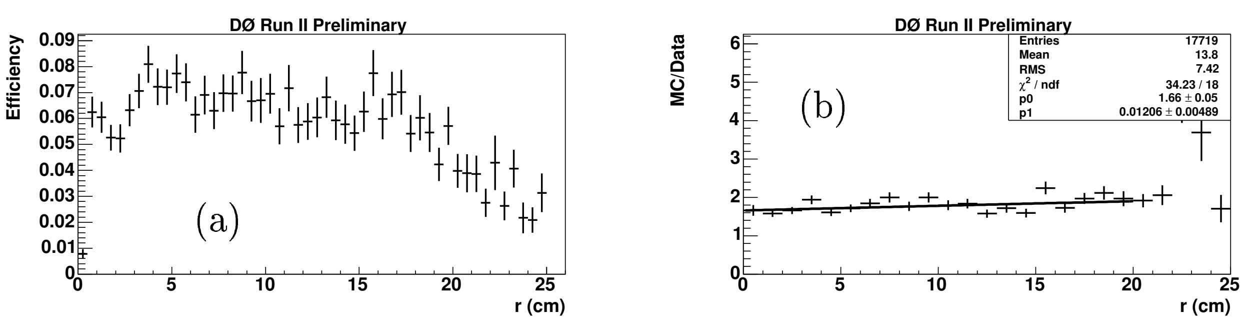

FIG. 1: (a): Distribution of the K^0_s meson reconstruction efficiency as a function of generated vertex radius for multijet MC. (b): Ratio of number of reconstructed vertices for Monte Carlo to data as a function of vertex radius for K^0_s meson candidates.

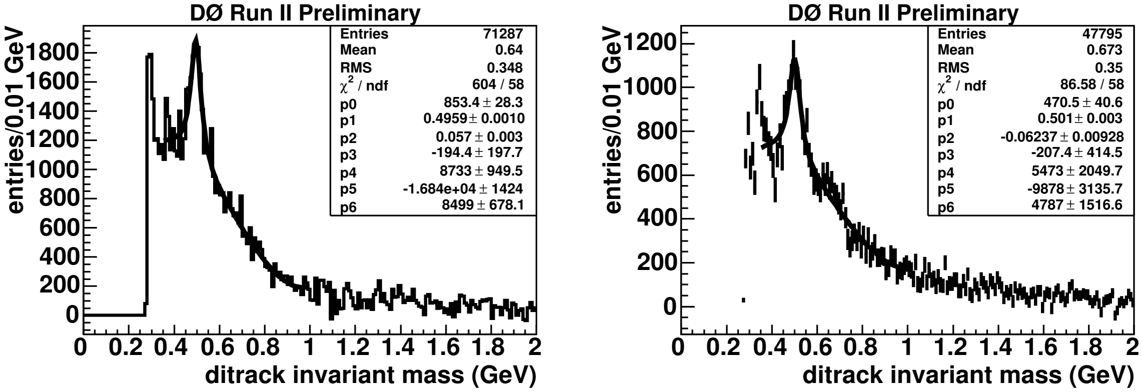

FIG. 2: Distribution of the invariant mass of all central tracks for the multijet Monte Carlo (left) and multijet data (right). The mass range 0.35-1.0 is fit to a Breit-Wigner plus a 4th order polynomial.

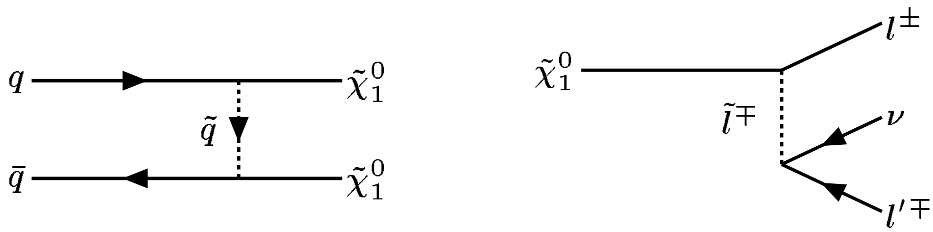

FIG. 3: Feynman diagrams for neutralino pair production (left) and decay (right).

M_3 = 400 GeV, M_{squark} = 300 GeV, $M_{sbottom,stop}$ = 1500 GeV, $\lambda_{122} < 1.0$. The M_1 parameter determines the χ_1^0 mass. Similar sets were generated with $M_1 = 3, 8, 10$ GeV yielding pair production cross sections in the range 0.022-0.025 pb (decreasing with mass). The lifetime is determined primarily by the λ_{122} parameter. For purposes of the signal simulation we have ignored the lifetime and force one of the two χ_1^0's to decay within a cylinder of radius 25 cm. The vertex is chosen along the χ_1^0 trajectory such that the radius distribution is flat over in the range 0-25 cm. The other χ_1^0 is required to escape the detector. The lifetime will be accounted for in the interpretation of the final result.

III. SELECTION CRITERIA

Selection criteria are chosen to minimize background. We require at least two muons which each have three segments in the muon system, are matched to a track in the central tracker, have $\chi^2_{track} < 4$, at least 14 CFT hits associated with the track, $p_T > 10$ GeV and are isolated in the calorimeter and central tracker. Cosmic ray muons are rejected with a timing cut. The two muons must have an opening angle less than 0.5 radians. All events were required to pass a dimuon trigger.

The primary and secondary vertices are determined after removing muons from the track list. The primary vertex 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. To enhance the signal, all muons must have a distance of closest approach (DCA) from all vertices of greater than 0.01 cm in the $x - y$ plane and more than 0.1 cm along the z-axis.

All remaining pairs of muons are fit to a common vertex requiring $\chi^2_{vertex} < 4$. The muon vertex must be at least 6σ from the primary vertex and have a radius (Eq. 1) of between 5 and 20 cm. This defines our signal region.

TABLE I: Results of several tests of the background estimation. The columns marked 1A-2B refer to the number of events passing each of the sets of cuts (Sec. IV). Sample 2B should be compared with the estimation.

	Sample					
	$1A$	$2A$	$1B$	$2B$	Estimation	Percentage Difference
Loose	406	168	23	16	9.5 ± 2.2	(-68 ± 28)%
1 μ + 1 track	6	3	6	3	3.0 ± 2.2	(0 ± 80)%
1 μ + 1 track (no isolation)	296	66	76	40	16.9 ± 3.0	(-137 ± 19)%
2 tracks p_T> 10 GeV	33	39	33	26	39 ± 11	(33 ± 28)%
Monte Carlo $b\bar{b}$	494	18	190	16	6.9 ± 1.7	(-103 ± 25)%

IV. BACKGROUND ESTIMATE

We use the data itself to estimate the background to this search. By allowing events to pass or fail two different selection criteria (the DCA and the 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 (the anti-box region); or (2) both tracks to pass the DCA cut (the signal region). For the vertex radius we define two regions: (A) 0.3 < radius < 5 cm; or (B) 5 < radius < 20 cm. Due to potential bias from a correlation between the two criteria, we performed several tests of this method (Sec. V).

We observe four events in the anti-box sample with 0.3 < r < 5 cm (Sample 1A) and one event in the r=5-20 cm region (Sample 1B). There are three events in the signal plots for 0.3 < r < 5 cm (Sample 2A). This gives us a estimate of the background in Sample 2B:

$$background = \frac{Sample\ 2A}{Sample\ 1A} \times Sample\ 1B = \frac{3}{4} \times 1 = 0.75\ events \quad (2)$$

V. TESTS OF BACKGROUND ESTIMATE METHOD

We use several complementary samples to test the background estimate and assign a systematic error. For each sample, we compare the estimate of number of events in Sample 2B (same calculation as Eq. 2) with the number of observed events. We calculate the percentage difference, (estimate - observed)/estimate in each case. The samples are:

- **Loose:** relaxed several cuts such as muon p_T (10 GeV → 7 GeV), number of CFT hits (> 13 → > 10), calorimeter isolation (< 2.5 GeV → < 5.0 GeV), track p_T isolation (removed), and χ^2_{vertex} (< 4 →< 10),
- **1 μ + 1 track:** combine a muon and a non-leptonic track with at least 7 GeV and 9 CFT hits. This is done with and without isolation cuts on the muon.
- **2 tracks:** use any 2 tracks not associated with a muon or electron that make an invariant mass between 0.6 and 0.9 GeV. This was performed with track p_T > 10 GeV.
- **$b\bar{b}$:** use generated four-vectors from Pythia $b\bar{b}$ production. We find the point of closest approach of the generated four-vectors and use that as the vertex. The DCA's of the original particles are smeared by adding a DCA randomly thrown to match data for reconstructed tracks.

The results of these tests are shown in Table I and Fig. 4. The spread in results leads us to assign a systematic error of 150% to account for the correlation between the radius and DCA cut. Thus, we estimate the background in the signal region to be 0.75 ± 1.1 (stat) ± 1.1 (sys) events.

VI. CROSS-SECTION LIMIT

Examination of the final signal region (Sample 2B as described in Section IV) yields 0 events passing all criteria. This leads us to 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 search region.

The cross section sensitivity depends upon the background estimate, the number of events in the signal region and the luminosity times signal acceptance. The limit further depends upon the uncertainty on these numbers. Table II

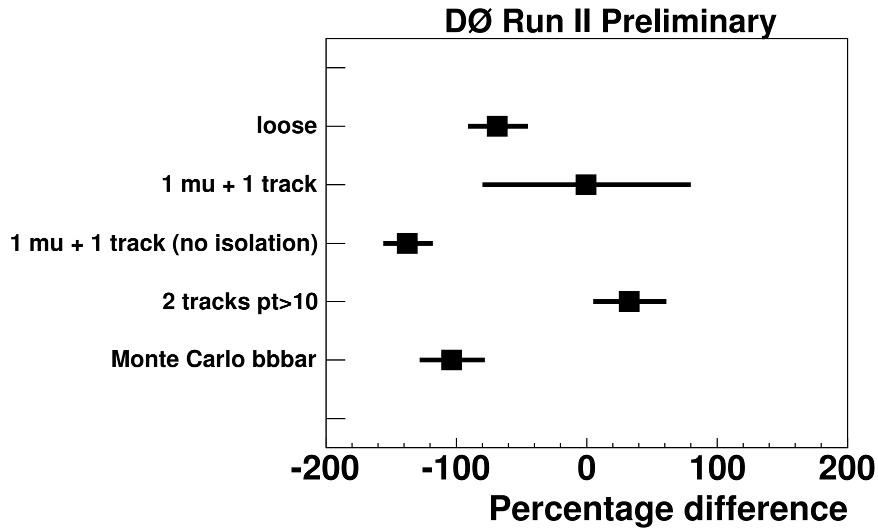

FIG. 4: Percentage difference between background estimation tests. The error bar is statistical only.

TABLE II: Acceptance, error and limits for the selected MC signal points (mass = 3,5,8,10 GeV). The limits are for a lifetime of 4×10^{-11} s.

$M_{\chi_0^1}$ (GeV)	3	5	8	10
acceptance	0.108 ± 0.0047	0.129 ± 0.0053	0.160 ± 0.0059	0.153 ± 0.0056
trigger efficiency	0.88 ± 0.06	0.88 ± 0.05	0.88 ± 0.05	0.88 ± 0.05
luminosity × acceptance	23.9 ± 4.7	28.7 ± 5.6	35.5 ± 6.9	34.3 ± 6.7
limit (pb)	0.280	0.193	0.141	0.143

show the acceptance factors and their uncertainty. The luminosity error is the standard 6.5% and the MC acceptance error is statistical. Tracking, isolation, and muon-id data/MC corrections are estimated using events in the Z-peak (mass=60-120 GeV) yielding 0.72 ± 0.07. The vertex reconstruction correction is found using events with K_s mesons (0.92 ± 0.14).

These numbers are combined to set a 95%(99%) confidence level limit on the cross section ($p\bar{p} \rightarrow N^0_{LL}N^0_{LL}$) × branching fraction ($N^0_{LL} \rightarrow \mu^+\mu^- + X$) as a function of the lifetime (Fig. 5) using a Bayesian technique [7] and assuming zero background. The NuTeV limit has been converted 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 Sec. II. The NuTeV lifetime is converted from kilometers to seconds assuming an average p (along the neutrino beam direction) of 121 GeV. The NuTeV preferred region is found using the ratio of the 99% CL upper and lower limits determined using a Feldman-Cousins approach [8]. DØ improves on the NuTeV limit by several orders of magnitude at long lifetimes and adds coverage at lower lifetimes. The DØ limit as a function of mass is shown in Fig. 6.

VII. CONCLUSIONS

We have presented an analysis looking for neutral long-lived particles decaying to $\mu\mu\nu$ using a new technique that expands the capabilities of the DØ experiment. The selection criteria identifies events with dimuon pairs that have a common vertex more than 5 cm from the primary vertex. The background is estimated to be 0.75 ± 1.1 ± 1.1 events. The signal region contains 0 events and a limit is set using a Bayesian technique. This limit excludes a SUSY (Sec. II) interpretation of the NuTeV excess.

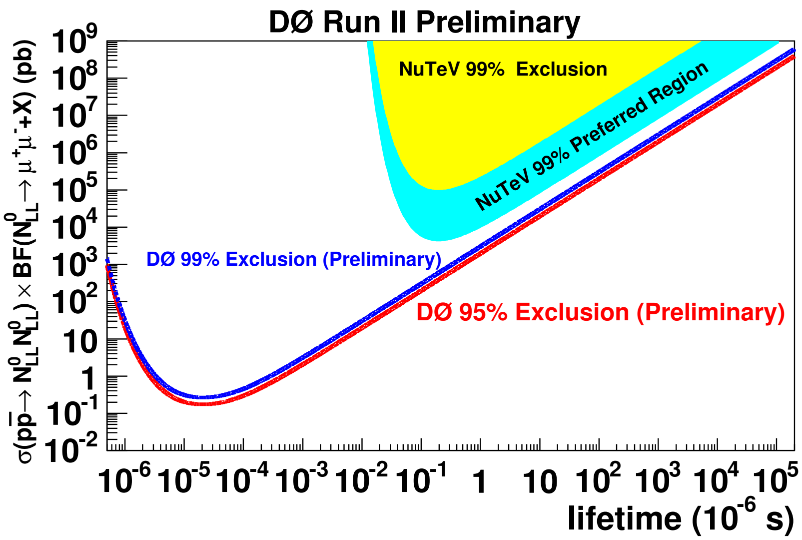

FIG. 5: Limit on cross section × branching fraction for pair-production of neutral, long-lived particles as a function of lifetime. The area above the red(blue) curve represents the DØ 95%(99%) CL limit for the 5 GeV mass point. The yellow shaded region represents the NuTeV 99% CL exclusion converted to a $p\bar{p}$ cross section at $\sqrt{s} = 1960$ GeV. The cyan shaded region represents a 99% CL preferred region given the three events from NuTeV.

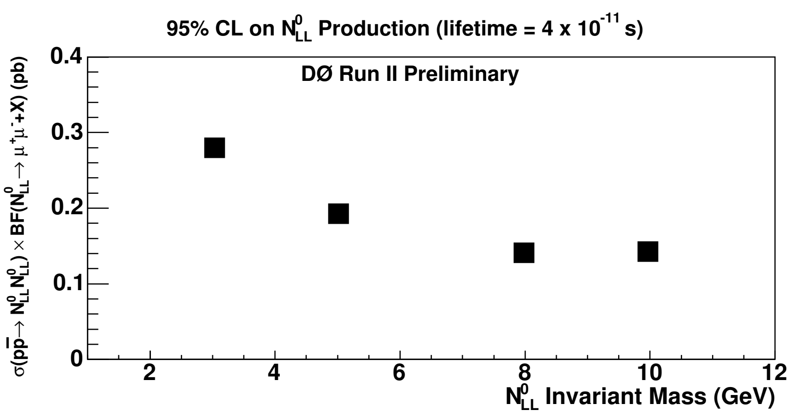

FIG. 6: Limits on pair production as a function of mass. The limit is for a lifetime of $4 \times 10^{-11} s$.

Acknowledgments

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA); CEA and CNRS/IN2P3 (France); FASI, Rosatom and RFBR (Russia); CAPES, CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACyT (Mexico); KRF (Korea); CONICET and UBACyT (Argentina); FOM (The Netherlands); PPARC (United Kingdom); MSMT (Czech Republic); CRC Program, CFI, NSERC and WestGrid Project (Canada); BMBF and DFG (Germany); SFI (Ireland); Research Corporation, Alexander von Humboldt Foundation, and the Marie Curie Program.

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