DØnote 4543

Search for Associated Chargino and Neutralino Production in $e\mu + \ell$ Final States in DØ Data from Run II

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URL: http://www-d0.fnal.gov

(Dated: August 4, 2004)

Data collected from April 2002 to March 2004 by the DØ experiment in Run II of the upgraded Fermilab Tevatron Collider at a center of mass energy of $\sqrt{s} = 1.96$ TeV have been used to search for evidence of supersymmetry in $e\mu + \ell$ final states accompanied by missing transverse energy. In supersymmetry models, such topologies are expected to contain contributions from associated chargino and neutralino production. Data corresponding to an integrated luminosity of 235$\pm$15 pb^{-1} have been analyzed. Applying all selection criteria leaves no event in the data consistent with the expectations from just the standard model. Upper limits on the cross section multiplied by the branching ratio $\sigma(p\bar{p} \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^{\pm}) \times B(3\ell)$ have been set.

Preliminary Results for Summer 2004 Conferences

I. INTRODUCTION

This Note describes a search for supersymmetry (SUSY) in final states containing one electron, one muon, one additional lepton and missing transverse energy in data collected by the DØ experiment at the Fermilab Tevatron collider at a center mass of energy of $\sqrt{s} = 1.96$ TeV. The pair production of charginos and neutralinos via a virtual W boson in the direct channel or through squark exchange is expected to contribute to this topology. If sleptons and sneutrinos are heavy, the chargino can decay into the lightest neutralino (lightest supersymmetric particle, LSP) and a virtual W boson and the W boson can decay according to its standard model branching fractions into a lepton and neutrino. If sleptons are lighter than the chargino, the chargino can decay into a slepton and neutrino, and the slepton can subsequently decay into the corresponding lepton and the lightest neutralino. The next–lightest neutralino ($\tilde{\chi}_2^0$) can decay into a Z boson and the lightest neutralino. The decay of the Z boson can yield two additional leptons in the final state. For small slepton masses, a decay of the neutralino into a slepton and lepton is also possible. A more detailed phenomenological discussion of supersymmetry and mSUGRA can be found in Ref. [1].

The analysis presented in this Note is optimized for the associated production and subsequent decay of a chargino and next–lightest neutralino into LSP's: ($p\bar{p} \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to e\mu l\tilde{\chi}_1^0\tilde{\chi}_1^0\nu$). An additional requirement of a third lepton can be used to get a better background rejection. Ongoing DØ analyses [2], [3], [4] are optimized for different combinations of leptons in the final state and a combination of these [5] will improve overall sensitivity.

This Note presents only a brief overview of the analysis. The data and Monte Carlo samples used in this analysis are presented in Sec. II of this Note followed by the event–selection criteria in Sec. III. A comparison between data and expectations from Monte Carlo simulations can be found in Sec. IV. In Sec. V upper limits on the cross section multiplied by the branching ratio $\sigma(p\bar{p} \to \tilde{\chi}_2^0\tilde{\chi}_1^{\pm}) \times B(3\ell)$ are presented.

II. DATA AND MONTE CARLO SAMPLES

The data were collected between April 2002 and March 2004 and correspond to an integrated luminosity of $\int \mathcal{L}dt = 235 \pm 15\,\mathrm{pb}^{-1}$. Both SUSY signal and standard–model backgrounds are generated using PYTHIA 6.202 [6], and processed through full detector simulation. An average of 0.8 minimum–bias events is overlaid with each event. For signal, we use reference samples generated for different points in the mSUGRA parameter space. In particular, the samples are generated for $\tan\beta = 3$, sign(μ) = +, $A_0 = 0$, in the chargino mass range between 97 and 114 GeV/c^2 and for LSP masses between 57 and 67 GeV/c^2. The cross sections multiplied by branching fraction $\sigma \times \mathrm{B}(p\bar{p} \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to 3\ell)$ are typically between 0.18 and 0.39 pb and are listed in Table I.

Major standard–model backgrounds arise from $Z/\gamma^* \to \tau\tau$, WW and $W + jet/\gamma$ production. Background from multijet ("QCD") production is determined directly from data in a like–sign sample using inverted quality cuts for the leptons. A list of the Monte Carlo background samples is presented in Table II.

III. EVENT SELECTION

Events are selected using different combinations of electron and muon triggers. The definition of the trigger definition changed during the run, and the sample is therefore divided into two parts. The decision for the muon part of the trigger is based on specific timing requirements in scintillation counters. For the electron part, one electromagnetic (EM) trigger tower with $E_T > 5$ GeV must be detected at Level 1, and one electromagnetic object with $E_T > 10$ GeV is required at Level 3. The current trigger uses a combination of four trigger requirements. Level 1 requires one EM trigger towers with $E_T > 6$ GeV or two with $E_T > 3$ GeV; the p_T threshold at Level 3 depends on additional criteria placed on the electromagnetic objects. The threshold is lowered from 12 to 7 GeV/c for EM objects that display an

TABLE I: Parameters for generated SUSY reference points.

Pt	m_0 (GeV/c^2)	$m_{1/2}$ (GeV/c^2)	A_0	$\tan\beta$	sign(μ)	$m_{\tilde{\chi}_2^0}$ (GeV/c^2)	$m_{\tilde{\chi}^{\pm}}$ (GeV/c^2)	$m_{\tilde{l}_R}$ (GeV/c^2)	$m_{\tilde{\tau}_1}$ (GeV/c^2)	$m_{\tilde{\chi}_1^0}$ (GeV/c^2)	$\sigma\times$B (pb)
1	72	165	0	3	1	102	97	102	101	57	0.39
2	76	170	0	3	1	106	101	106	105	59	0.32
3	80	175	0	3	1	110	105	110	109	62	0.27
4	84	180	0	3	1	114	110	114	113	64	0.21
5	88	185	0	3	1	118	114	118	117	67	0.18

TABLE II: Monte Carlo samples cross sections times branching ratio and their references used in comparisons with data. The cross sections are only given for a single lepton flavour. For decays with one electron and one muon in the final state, the cross section times branching ratio must be multiplied by a factor of two.

Process		$\sigma \times B$ (pb)	Reference
$Z/\gamma^* \to ll$ $(\ell = e, \mu, \tau)$	$15\,\mathrm{GeV}/c^2 < m_{ll} < 60\,\mathrm{GeV}/c^2$	465	[7]
	$60\,\mathrm{GeV}/c^2 < m_{ll} < 130\,\mathrm{GeV}/c^2$	254	[7]
	$130\,\mathrm{GeV}/c^2 < m_{ll} < 250\,\mathrm{GeV}/c^2$	2	[7]
$W \to \ell\nu$ inclusive $(\ell = e, \mu)$		2717	[7]
$WW \to \ell\nu\ell\nu$ $(\ell = e, \mu)$		0.147	[8]
$WZ \to \ell\nu\ell\ell$ $(\ell = e, \mu)$		0.014	[8]
$ZZ \to \ell\ell\ell\ell$ $(\ell = e, \mu)$		0.002	[8]
$t\bar{t} \to b\ell\nu b\ell\nu$ $(\ell = e, \mu)$		0.076	[9]

energy deposition in the EM calorimeter consistent with that of an electromagnetic shower.

Event selection starts with the selection of one electron and one muon. The electron is required to have $p_T >$ 12 GeV/c and pass standard DØ EM ID criteria, including isolation, high electromagnetic energy content, acceptable shower shape and a likelihood criterion that includes a track requirement. The muon which has to come from the same vertex must pass standard muon ID criteria and should have a matching track in the central tracker. Track isolation $(\sum_{tracks}^{R<0.5} p_T - p_T^{\mu}(track) < 4\,\mathrm{GeV}/c)$ is applied relative to the muon trajectory. A scintillator timing requirement is used to reject muons from cosmic rays. Furthermore the muon must fulfil a vertex and DCA requirement, and the p_T of the muon is required to be > 8 GeV/c (Cut 0).

This preselection leaves 1305 events in the data sample. The largest contribution is from multijet events from QCD production and from $Z/\gamma^* \to \tau\tau$ events. To enhance signal with respect to background, selection criteria are obtained based on the optimazation of signal over background using the Monte Carlo.

Most of the selected multijet and $Z/\gamma^* \to \tau\tau$ events can be rejected with a cut on the transverse mass $m_T = \sqrt{2 \cdot \not\!\!E_T \cdot p_T^{\ell} \cdot (1 - \cos(\Delta\phi))}$. The distribution in the minimal transverse mass after the initial selection (Cut 0) is presented in Fig. 1 (a). The cut is applied at

$$\min(M_W^e, M_W^{\mu}) \; > \; 25 \text{ GeV}/c^2 \qquad \text{(Cut 1)} \tag{1}$$

An upper cut of $\min(M_W^e, M_W^{\mu}) < 80$ GeV/c^2 removes a fraction of WW events without decreasing the signal efficiency.

No large missing transverse energy is expected from multijet events. In addition, events with one or more jets can be tested if the missing transverse energy is artificially generated by a mismeasurement of the jets. Thus the scaled missing transverse energy $\not\!\!E_T^{\text{Scaled}}$ is defined as

$$\not\!\!E_T^{\text{Scaled}} = \frac{\not\!\!E_T}{\sqrt{\sum_{jets}\left(\sqrt{\mathrm{E}_{jet}} \cdot \sin\theta_{jet} \cdot |\cos\Delta\phi\left(E_{jet}, E_T^{miss}\right)|\right)^2}} \; . \tag{2}$$

Fig. 1 (b) shows the distribution in the missing transverse energy at the beginning of the selection (Cut 0). The distribution in the scaled missing transverse energy after imposing the minimal tranverse mass criterion (Cut 1) is presented in Fig. 2 (a). Events are required to have a missing transverse energy of

$$\not\!\!E_T \; > 20 \text{ GeV} \tag{3}$$

and a scaled missing transverse energy of

$$\not\!\!E_T^{\text{Scaled}} \; > 15 \sqrt{\text{GeV}} \qquad \text{(Cut 2)}. \tag{4}$$

The dominant remaining backgrounds are $W + jet$ events and the pair production of W bosons. A cut on the invariant mass of the dilepton system is expected to reduce these two backgrounds, since most of these events have a large invariant mass. The distribution in the invariant mass $m_{e\mu}$ at this stage of the selection is shown in Fig. 2 (b). Requiring

$$15 \text{ GeV}/c^2 \; < \; m_{e\mu} \; < \; 100 \text{ GeV}/c^2 \qquad \text{(Cut 3)} \tag{5}$$

rejects some of the $W + jet$ and WW events without affecting the signal. After this selection 39 events remain in the

(a) (b)

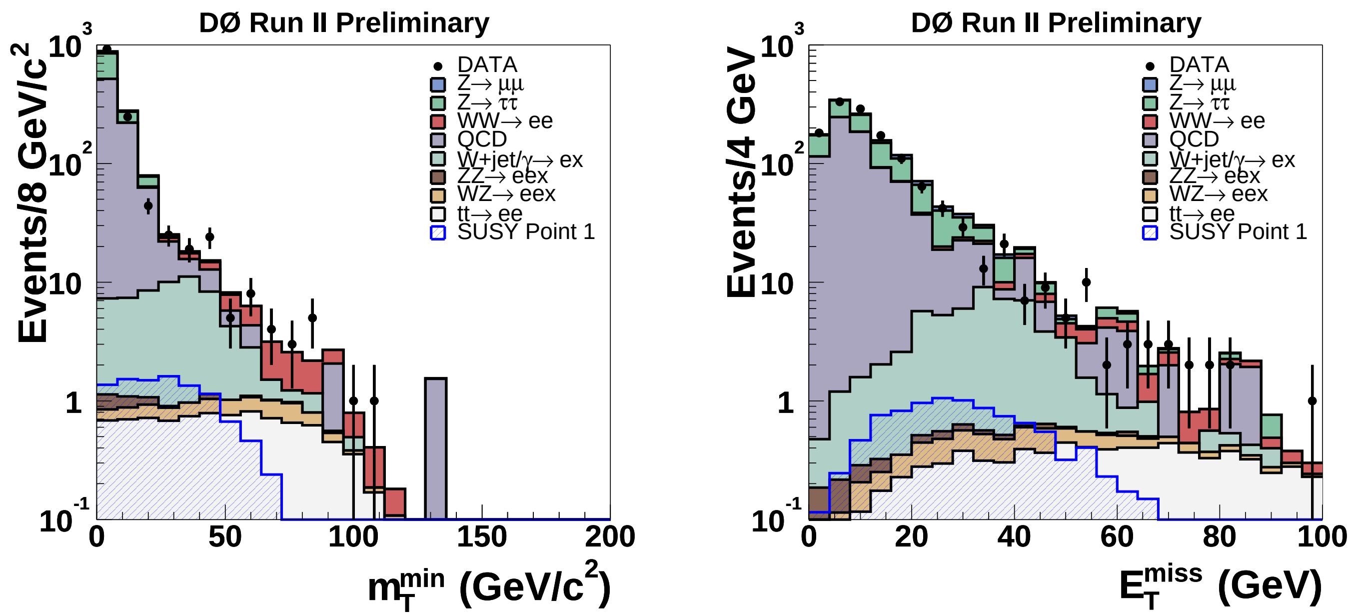

FIG. 1: (a) Distribution in the smaller of the transverse masses and (b) the missing transverse energy after lepton identification and kinematic criteria.

data. For some of the $W \rightarrow \mu$ events and also for most of the remaining $Z/\gamma^* \rightarrow \mu\mu$ events the electron originates from photon conversions. The photon has to convert into an electron–positron pair to be detected as an electron with matched central track. Since this conversion is most likely to happen not in the innermost layers of the tracker, the tracks associated with these electrons or positrons tend to have a smaller number of hits in the silicon tracker. Requiring the electron tracks to have at least one hit in the silicon tracker rejects a large fraction of the $Z/\gamma^* \rightarrow \mu\mu$ and also $W + \gamma$ events (Cut 4). This criterion is implemented only if the z position of the electron track is located within the acceptance of the silicon tracker ($|z| < 35$ cm).

The characteristic feature of the associated production of charginos and neutralinos is the existence of three charged leptons in the final state. For most of the backgrounds no additional lepton is present in the final state. Thus the selection of the third charged lepton is expected to reject most of the remaining background events. To keep the signal efficiency as high as possible only an isolated track is required as signature for this third lepton. However, some of the standard model backgrounds (WZ and ZZ production) may also have three or more charged leptons in the final state. Hence, these backgrounds will more likely pass a requirement with a third isolated track. The WZ as well as the ZZ background is characterized by two leptons of the same flavor that have an invariant mass around the Z mass. The SUSY signal has also two leptons of the same flavor in the final state, but the invariant mass of these two leptons is restricted to the mass difference of the two lightest neutralinos, which is in the order of 50–60 GeV/c^2. Thus, events are rejected, if two leptons of the same flavor are found in the event that have an invariant mass above 60 GeV/c^2 (Cut 5).

The dominant backgrounds are still $W + jet$ events, the pair production of two W bosons and multijet events from QCD production. All of these events have only additional isolated tracks with small transverse momentum. To select isolated tracks, some quality criteria are applied for the track. The track must be in the region $|\ \eta_{det}\ | < 2.6$ and come from the same vertex as the two selected leptons ($|\Delta z| < 1$ cm). In addition, a DCA cut of 0.03 cm is applied. Tracks without any hits in the fibre tracker are not considered and for tracks without any hits in the silicon tracker at least 12 hits must be found in the fibre tracker. To select isolated tracks, the sum of transverse momenta of charged tracks in a cone $0.1 < \Delta\mathcal{R} < 0.4$ around the track must be < 1 GeV/c. The distribution in the transverse momentum of the third track for all background and data is shown in Fig. 4 (a) at the beginning of the selection (Cut 0) and (b) after imposing the WZ–veto (Cut 5). Requiring

$$p_T^{3rd\ track} \ > \ 5 \text{ GeV}/c \qquad \text{(Cut 6).} \tag{6}$$

rejects a large fraction of the background.

For most of the backgrounds the final state consists of the two leptons and two neutrinos, that are detected through the missing transverse energy. Since these are all decay products, the vectorial sum of the transverse momenta

(a) (b)

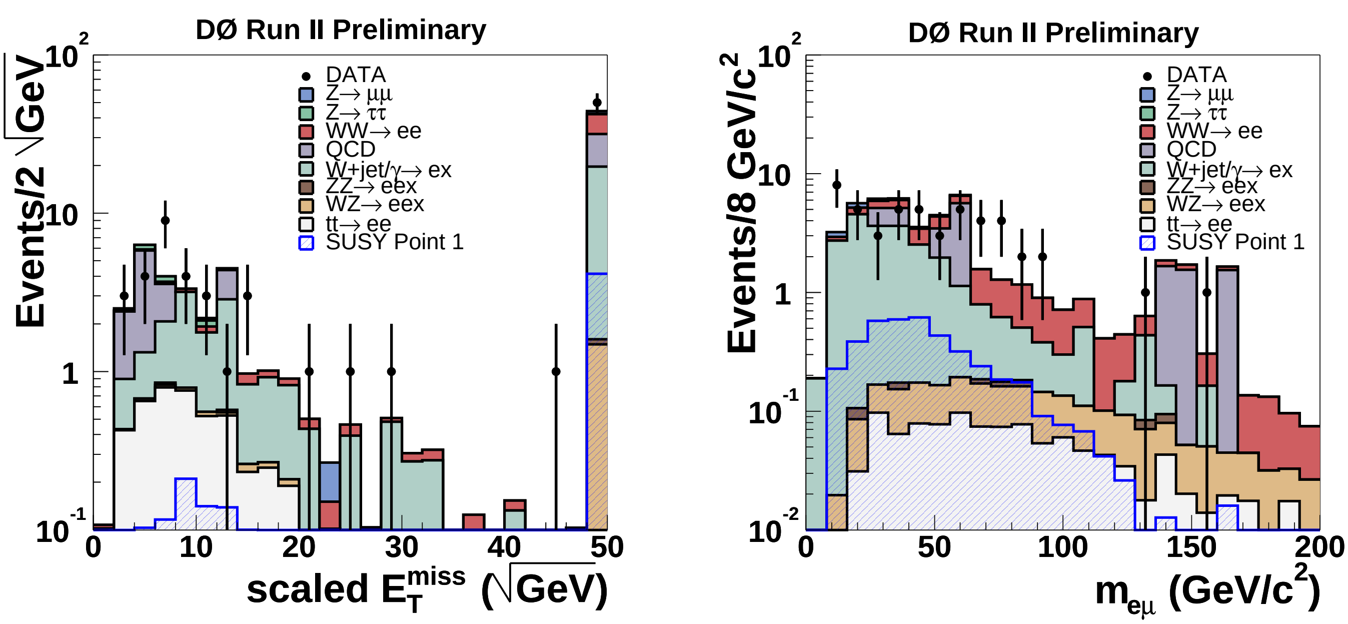

FIG. 2: (a) Distributions in the scaled missing transverse energy (a) after the minimal transverse mass criterion (Cut 1) and (b) the invariant mass for Monte Carlo and data after the $\not\!\!E_T$ selection (Cut 2). The last bin in distribution (a) reflects all the events without any good reconstructed jet.

$\vec{p}_T^{\,e} + \vec{p}_T^{\,\mu} + \vec{\not\!\!E}_T$ should be zero. This is not the case for associated chargino and neutralino production, because one of the three charged leptons in the decay is not taken into account by the selection of two leptons and missing transverse energy. Thus

$$\vec{p}_T^{\,e} + \vec{p}_T^{\,\mu} + \vec{\not\!\!E}_T = \vec{p}_T^{\,\ell 3} \tag{7}$$

reflects the momentum of the third lepton. Since the selected isolated third track should represent this third lepton, the ratio

$$\frac{|\vec{p}_T^{\,e} + \vec{p}_T^{\,\mu} + \vec{\not\!\!E}_T|}{p_T^{3rd\ track}} = \frac{p_T^{\ell 3}}{p_T^{3rd\ track}} \tag{8}$$

should peak at one. For all backgrounds without three leptons in the final state, the ratio is an arbitrary number, since there is no correlation between $|\vec{p}_T^{\,e} + \vec{p}_T^{\,\mu} + \vec{\not\!\!E}_T|$ and the selected third track. To select events the ratio should be

$$0.1 < \frac{|\vec{p}_T^{\,e} + \vec{p}_T^{\,\mu} + \vec{\not\!\!E}_T|}{p_T^{3rd\ track}} < 3.0 \qquad \text{(Cut 7)}. \tag{9}$$

Figure **??** (a) shows the distributions of $|\vec{p}_T^{\,e} + \vec{p}_T^{\,\mu} + \vec{\not\!\!E}_T|/p_T^{3rd\ track}$ after Cut 2 is applied and (b) before the application of Cut 7. After imposing all selection criteria, no event remains in the data.

IV. COMPARISON OF DATA AND MONTE CARLO EXPECTATIONS

After implementing electron and muon identification and other basic kinematic criteria, the initial data sample is reduced to 1305 events. The total number of expected events is consistent with what is observed in the data. The details of the contributions from different background sources as a function of successive selections are given in Table III, where it can be observed that the sum of the expected background events at every stage of the analysis is in agreement with the number of observed events. After all selections are applied no event is left in the data sample, which agrees with the background expectation of 0.3±0.3 events. The uncertainty is dominated by the limited statistics of multijet production, $W + jet$ and $Z/\gamma^* \rightarrow \mu\mu$ Monte Carlo.

(a) (b)

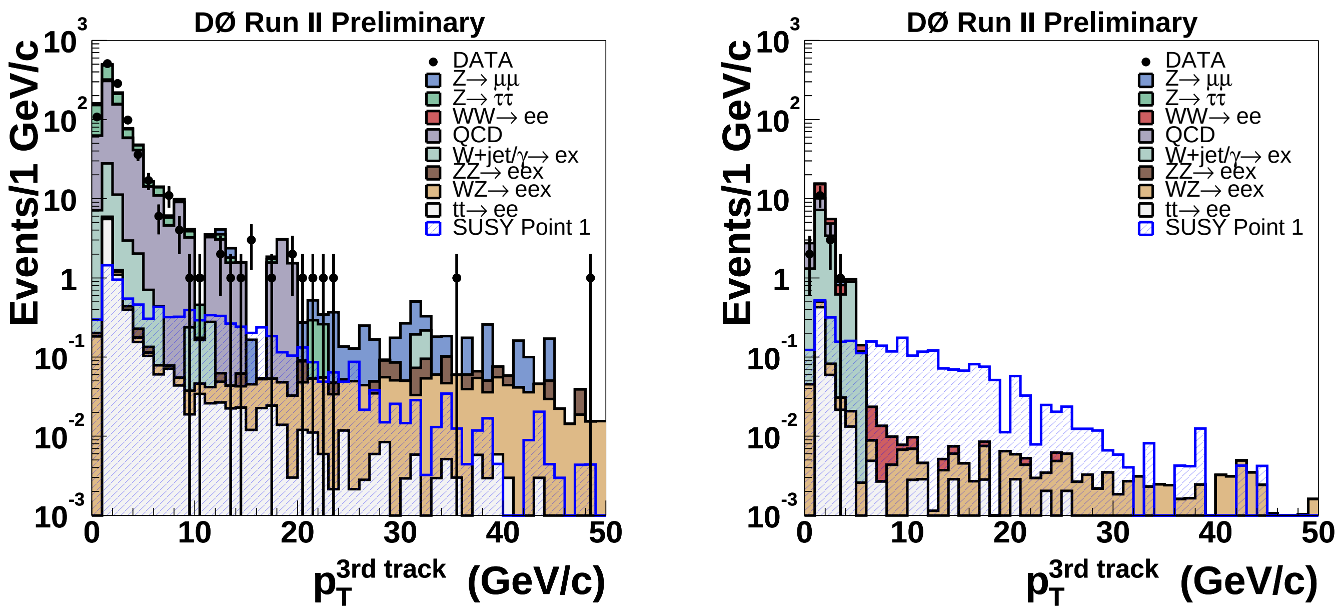

FIG. 3: Distributions in p_T of the third isolated track for the initially selected 1305 events (a, Cut 0) and (b) before the p_T requirement on the third track is imposed (Cut 5).

(a) (b)

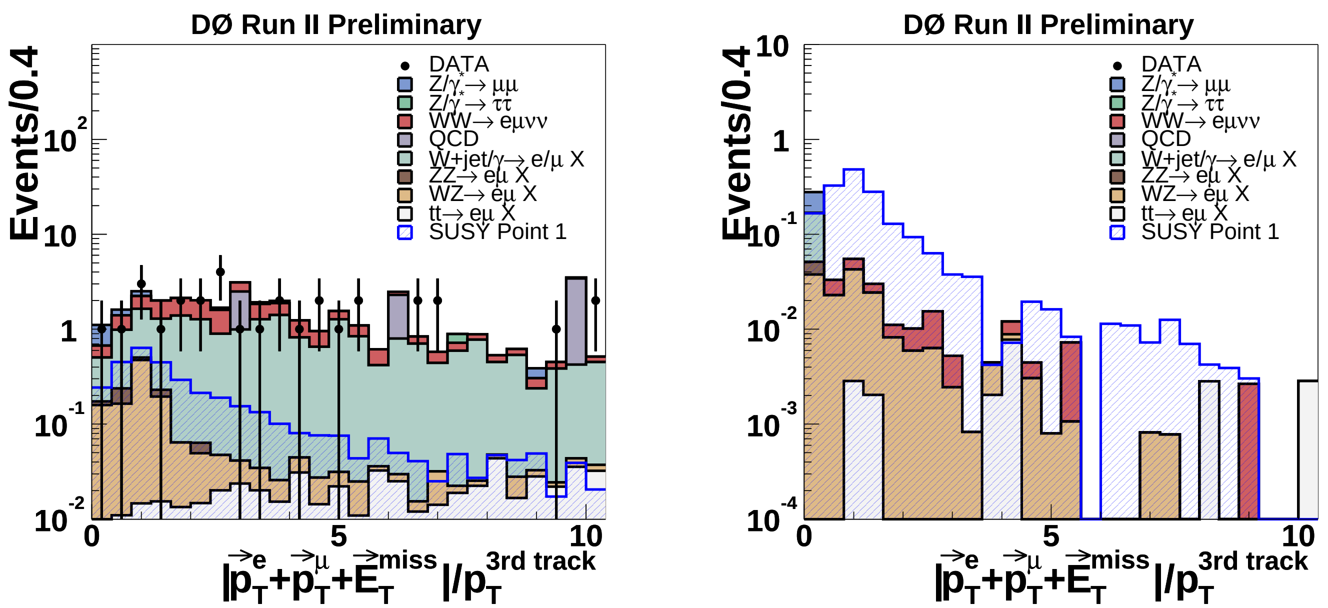

FIG. 4: Distributions in $|\vec{p}_T^{\,e} + \vec{p}_T^{\,\mu} + \vec{\not{E}}_T|/p_T^{3rd\ track}$ after applying Cut 2 (a) and (b) before applying Cut 7.

Different sources of systematic uncertainties are investigated. The systematic error is dominated by that on the jet energy scale. The total systematic uncertainty is 5.2% for signal efficiency and 10.2% for the background. The systematic error caused by the uncertainty of the luminosity measurement is ±6.5%.

The efficiencies for reference points 1–5 range between (4.5±0.2)% and (5.5±0.2)%, corresponding to 1.5±0.1 events for point 1 and 0.9±0.1 events for point 5. A detailed overview of efficiencies and expected event numbers is presented in Table IV.

TABLE III: Expected number of background events and events observed after succesive selections for an integrated luminosity of $\int \mathcal{L}dt = 235 \pm 15\,\mathrm{pb}^{-1}$. The statistical error is listed for all backgrounds. The error caused by the uncertainty on the luminosity is only given for the sum of all backgrounds.

	$t\bar{t}$	WZ	ZZ	$W + jet/\gamma$	WW
Cut 0	9.04 ± 0.16	2.67 ± 0.05	0.86 ± 0.12	53.0 ± 2.37	18.6 ± 0.2
Cut 1	5.08 ± 0.12	1.75 ± 0.04	0.17 ± 0.05	31.9 ± 1.84	12.2 ± 0.1
Cut 2	1.13 ± 0.06	1.48 ± 0.04	0.08 ± 0.03	23.0 ± 1.56	10.4 ± 0.1
Cut 3	0.74 ± 0.05	0.88 ± 0.03	0.05 ± 0.03	19.4 ± 1.44	7.73 ± 0.10
Cut 4	0.71 ± 0.04	0.84 ± 0.03	0.05 ± 0.03	16.3 ± 1.29	7.39 ± 0.10
Cut 5	0.69 ± 0.04	0.38 ± 0.02	0.01 ± 0.01	16.3 ± 1.29	7.38 ± 0.10
Cut 6	0.03 ± 0.01	0.16 ± 0.01	0.01 ± 0.01	0.12 ± 0.12	0.06 ± 0.01
Cut 7	0.0 ± 0.0	0.12 ± 0.01	0.0 ± 0.01	0.12 ± 0.10	0.05 ± 0.01

	$Z/\gamma^* \to \tau\tau$	$Z/\gamma^* \to \mu\mu$	QCD	SUM	DATA
Cut 0	399 ± 9	40.8 ± 2.0	803 ± 35	1326 ± 36 ± 86	1305
Cut 1	1.21 ± 0.40	1.84 ± 0.42	22.5 ± 5.8	76.6 ± 6.1 ± 5.0	81
Cut 2	0.0 ± 0.10	1.45 ± 0.37	13.5 ± 4.5	51.0 ± 4.8 ± 3.3	48
Cut 3	0.0 ± 0.10	1.20 ± 0.33	9.00 ± 3.67	39.0 ± 4.0 ± 2.5	39
Cut 4	0.0 ± 0.0	0.42 ± 0.19	7.21 ± 3.23	32.9 ± 3.5 ± 2.1	34
Cut 5	0.0 ± 0.0	0.34 ± 0.17	7.21 ± 3.23	32.3 ± 3.5 ± 2.1	33
Cut 6	0.0 ± 0.0	0.11 ± 0.11	0.0 ± 0.30	0.48 ± 0.34 ± 0.03	0
Cut 7	0.0 ± 0.0	0.0 ± 0.11	0.0 ± 0.30	0.29 ± 0.33 ± 0.02	0

TABLE IV: Efficiencies with statistical error for signal after lepton identification and kinematic and other selections, for the five reference SUSY points. Efficiencies are quoted with respect to the number of events with at least one electron and one muon in the final state. The last two rows show the number of expected signal events after the final selection and the excluded cross section multiplied by the branching ratio $\sigma(p\bar{p} \to \tilde{\chi}_2^0\tilde{\chi}_1^\pm) \times B(3\ell)$.

	Point 1	Point 2	Point 3	Point 4	Point 5
Cut 0	0.294 ± 0.006	0.299 ± 0.005	0.313 ± 0.005	0.323 ± 0.005	0.330 ± 0.006
Cut 1	0.160 ± 0.004	0.170 ± 0.004	0.188 ± 0.004	0.190 ± 0.004	0.201 ± 0.004
Cut 2	0.122 ± 0.004	0.130 ± 0.003	0.148 ± 0.004	0.153 ± 0.004	0.160 ± 0.004
Cut 3	0.109 ± 0.004	0.115 ± 0.003	0.130 ± 0.003	0.136 ± 0.003	0.144 ± 0.004
Cut 4	0.103 ± 0.003	0.109 ± 0.003	0.123 ± 0.003	0.129 ± 0.003	0.137 ± 0.004
Cut 5	0.103 ± 0.003	0.109 ± 0.003	0.123 ± 0.003	0.129 ± 0.003	0.137 ± 0.004
Cut 6	0.051 ± 0.002	0.053 ± 0.002	0.059 ± 0.002	0.066 ± 0.002	0.064 ± 0.002
Cut 7	0.045 ± 0.002	0.045 ± 0.002	0.050 ± 0.002	0.055 ± 0.002	0.055 ± 0.002
Exp. Events	1.51± 0.07	1.25 ± 0.06	1.18 ± 0.05	1.00 ± 0.04	0.86± 0.03
$\sigma \times B$ limit (pb)	0.79	0.78	0.70	0.64	0.63

V. LIMITS ON THE CROSS SECTION $\sigma(p\bar{p} \to \tilde{\chi}_2^0\tilde{\chi}_1^\pm) \times B(3\ell)$

Since no evidence for a SUSY signal is found, the data is used to set upper limits on the production cross section multiplied by the branching ratio $\sigma(p\bar{p} \to \tilde{\chi}_2^0\tilde{\chi}_1^\pm) \times B(3\ell)$. The limit calculation was done following the method described in Ref. [10]. The input parameters are the number of events observed, the integrated luminosity, number of expected background events and the signal efficiency with corresponding errors. The upper cross section limits are calculated with 95% C.L. Using the input parameters of Tables III and IV upper limits of 0.63 pb to 0.79 pb are found. The limits for the individual points are listed in Table IV.

VI. CONCLUSIONS

A search for associated chargino and neutralino production in final states containing electrons, muons and missing transverse energy has been performed. Data corresponding to an integrated luminosity of $\int \mathcal{L}dt = 235\,\mathrm{pb}^{-1}$ have been analyzed. The number of observed events is consistent with expectations from standard model backgrounds. Upper limits between 0.63 and 0.79 pb on the cross section multiplied by the branching ratio $\sigma(p\bar{p} \to \tilde{\chi}_2^0\tilde{\chi}_1^\pm) \times B(3\ell)$

are found.

The analysis is not as yet sensitive for a signal corresponding to any of the SUSY–parameter points under consideration. Combining the result with the other channels ($ee+\ell$ [2], $\mu\mu+\ell$ [3] and same sign dimuon analyses [4]) should increase the sensitivity. A combination of the three analyses is presented in Ref. [5].

Acknowledgments

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the Department of Energy and National Science Foundation (USA), Commissariat à l'Energie Atomique and CNRS/Institut National de Physique Nucléaire et de Physique des Particules (France), Ministry of Education and Science, Agency for Atomic Energy and RF President Grants Program (Russia), CAPES, CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil), Departments of Atomic Energy and Science and Technology (India), Colciencias (Colombia), CONACyT (Mexico), KRF (Korea), CONICET and UBACyT (Argentina), The Foundation for Fundamental Research on Matter (The Netherlands), PPARC (United Kingdom), Ministry of Education (Czech Republic), Natural Sciences and Engineering Research Council and WestGrid Project (Canada), BMBF (Germany), A.P. Sloan Foundation, Civilian Research and Development Foundation, Research Corporation, Texas Advanced Research Program, and the Alexander von Humboldt Foundation.

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