

## Search for Dark Matter in Events with One Jet and Missing Transverse Energy in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We present the results of a search for dark matter production in the monojet signature. We analyze a sample of Tevatron  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV corresponding to an integrated luminosity of  $6.7 \text{ fb}^{-1}$  recorded by the CDF II detector. In events with large missing transverse energy and one energetic jet, we find good agreement between the standard model prediction and the observed data. We set 90% confidence level upper limits on the dark matter production rate. The limits are translated into bounds on nucleon-dark matter scattering rates which are competitive with current direct detection bounds on spin-independent interaction below a dark matter candidate mass of  $5 \text{ GeV}/c^2$ , and on spin-dependent interactions up to masses of  $200 \text{ GeV}/c^2$ .

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The cosmological abundance of dark matter (DM) is now precisely known through the observation of its gravitational interactions [1]. Yet the nature of DM itself remains a mystery, with many models of physics beyond the standard model (SM) proposing DM candidates. Perhaps the best motivated DM candidate is a new weakly interacting massive particle (WIMP) with mass of  $O(1-1000) \text{ GeV}/c^2$ . This class of DM candidates appears in many models of new physics with interactions that allow for DM detection through WIMP-nucleon scattering in direct detection experiments [2].

While there is no conclusive evidence for WIMP-nucleon scattering, several recent direct detection experiments have yielded results suggestive of a low-mass ( $\sim 10 \text{ GeV}/c^2$ ) WIMP [3–5]. In light of these results, there has been significant interest [6–9] in the potential of collider searches to either observe the production of DM

particles ( $\chi$ ), or to constrain the DM production rate. The collider mode of production that is expected to yield the most stringent bounds [6] on the DM production rate is the monojet ( $p\bar{p} \rightarrow \chi\bar{\chi} + \text{jet}$ ) mode, where the jet has a transverse energy of  $O(100) \text{ GeV}$  and originates in initial state radiation. Previous studies of the monojet signature have been performed [10–12] in the context of searches for large extra dimensions.

In this Letter, we present the results of the first direct search for collider production of DM in the monojet mode. We consider several models of DM production that are relevant for direct detection experiments. We assume  $\chi$  is a Dirac fermion [13], and that production is mediated by a massive state which couples to DM and SM quarks. For this analysis, we consider three models of dark matter production which consist of vector ( $\mathcal{O}_V$ ), axial-vector ( $\mathcal{O}_{AV}$ ), and  $t$ -channel operators ( $\mathcal{O}_t$ ) as defined in [6,7].

A universal sum over all quark flavors is assumed for these operators. In direct detection experiments, the vector operator leads to spin-independent DM scattering, while the axial-vector operator is spin dependent. The  $t$ -channel operator includes both spin-dependent and spin-independent terms. By considering the three types of operators, we are able to constrain both spin-independent and spin-dependent DM-nucleon scattering cross sections.

In direct detection experiments, scattering rates are described by an effective theory containing DM in addition to SM fields. As the momentum transfer in DM scattering is far lower than the mass of the particle mediating the interaction, an effective theory provides a valid description. In a collider environment, with large momentum transfers, the effective theory approach is not necessarily valid and may change the predicted cross section and kinematics of the DM model [6,7,14]. We thus consider two possibilities: (1) that these contact interactions are also a good description of collider DM production, and (2) that the production of DM at the Tevatron proceeds through the exchange of a new particle. The new mediator particles which lead to the operators  $\mathcal{O}_V$ ,  $\mathcal{O}_{AV}$ , and  $\mathcal{O}_t$ , are a heavy vector, axial-vector, and a scalar “squark”, respectively. When constraining case 1 we implement models of DM production with very heavy mediators, well above the Tevatron reach (at 10 TeV), while for case 2 we consider light mediators, within the kinematic reach of the Tevatron (100 GeV/ $c^2$  for  $\mathcal{O}_V$  and  $\mathcal{O}_{AV}$  and 400 GeV/ $c^2$  for  $\mathcal{O}_t$ ).

We perform the analysis utilizing 6.7 fb $^{-1}$  of Tevatron  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV recorded by the CDF II detector. The CDF II detector is described in detail elsewhere [15] and consists of tracking systems immersed in a 1.4 T magnetic field, surrounded by calorimetry that provides coverage for  $|\eta| < 3.6$  [16]. A system of drift chambers external to the calorimetry provides muon detection capability for  $|\eta| < 1.5$ .

The DM candidate is expected to interact minimally with the CDF II detector resulting in large missing transverse energy ( $\cancel{E}_T$ ) [17]. We analyze a sample of events consistent with this characteristic, as collected by a  $\cancel{E}_T$  online event-selection (trigger) algorithm which selects collision events with  $\cancel{E}_T \geq 40$  GeV. We find that the trigger has a 90% selection efficiency for events with  $\cancel{E}_T = 60$  GeV, rising to an efficiency of 95% for  $\cancel{E}_T \geq 70$  GeV.

The selected events are required to have been recorded with fully-functioning calorimeter, muon, and tracking systems. We require events to have  $\cancel{E}_T = 60$  GeV. We reconstruct jets from calorimeter energy deposits using a cone algorithm [18] with a radius in pseudorapidity-azimuth space of 0.4. We do not consider jets with  $E_T < 20$  GeV. We reject events with jets reconstructed in partially instrumented regions of the calorimeter. Jet energies are corrected for variations in detector response and instrumentation, and the extra contribution from additional  $p\bar{p}$  pair interactions in the same event [19]. Events are

required to have exactly one jet with  $E_T \geq 60$  GeV. We require that this jet have  $|\eta| < 1.1$ . To reject events arising from noncollision sources, we require significant track activity within the jet’s cone. Events in which the jet does not contain a track with a transverse momentum ( $p_T$ ) of at least 10 GeV/ $c$  are rejected. To remove photons we require the electromagnetic fraction of the total energy deposited in the calorimeter systems to be below 0.85. Similarly, to remove events with muon bremsstrahlung from cosmic rays or beam-detector interactions [20] we require an electromagnetic fraction of greater than 0.35. To accommodate extra jets arising from initial state radiation, we retain events with one additional jet with an  $E_T$  of less than 30 GeV and  $|\eta| < 2.4$ .

The sample of events that pass the above selections is dominated by background contributions from QCD multi-jet processes in which one (or more) of the jets is misreconstructed. Improper reconstruction of a jet produces an event topology in which the  $\vec{\cancel{E}}_T$  is aligned with the misreconstructed jet. To reduce this background we require a minimum separation in azimuthal angle of  $\Delta\phi(\vec{\cancel{E}}_T, \text{jet}) > 0.4$  between the direction of  $\vec{\cancel{E}}_T$  and that of any jet. We also require a separation of  $\Delta\phi(\vec{\cancel{E}}_T, \text{jet}) > 2.5$  between the direction of  $\vec{\cancel{E}}_T$  and the leading jet. We achieve further reduction of the multijet background to our search by utilizing an artificial neural network (NN) designed to separate multijet events from electroweak processes [21]. The NN combines event quantities including the separation in azimuthal angle between jets and  $\vec{\cancel{E}}_T$ , jet energies,  $\cancel{E}_T$ , and the number of jets, returning a single numerical value for each event. In training, the NN was optimized to isolate simulated  $Z$  and  $W$  boson events from a sample of data events in which the most energetic jet had  $E_T < 60$  GeV, or in which there were more than three jets. We find that approximately 85% of multijet events produce a NN value of less than 0.3, and reject these events. In simulated DM samples,  $\sim 90\%$  of events produce a NN value above 0.3.

In the remaining sample of events, we expect significant contributions from  $Z$  and  $W$  boson processes, in which the  $Z$  or  $W$  decays leptonically. We reduce the contribution from these processes by vetoing events which contain one or more tracks with  $p_T \geq 10$  GeV/ $c$  that are not embedded within a jet.

The events passing the above selections form our analysis sample, and are examined for the presence of events arising from DM production. Within this sample we expect significant contributions from  $Z$  boson processes in which the  $Z$  boson decays invisibly to neutrinos. In addition, we expect  $W$  boson processes to contribute whenever the lepton from the leptonically decaying  $W$  boson is outside of the acceptance of the CDF tracking system. We model  $W$  and  $Z$  boson contributions to our analysis sample using simulated events generated by ALPGEN [22] with PYTHIA [23] for particle showering and hadronization. The  $Z$  and

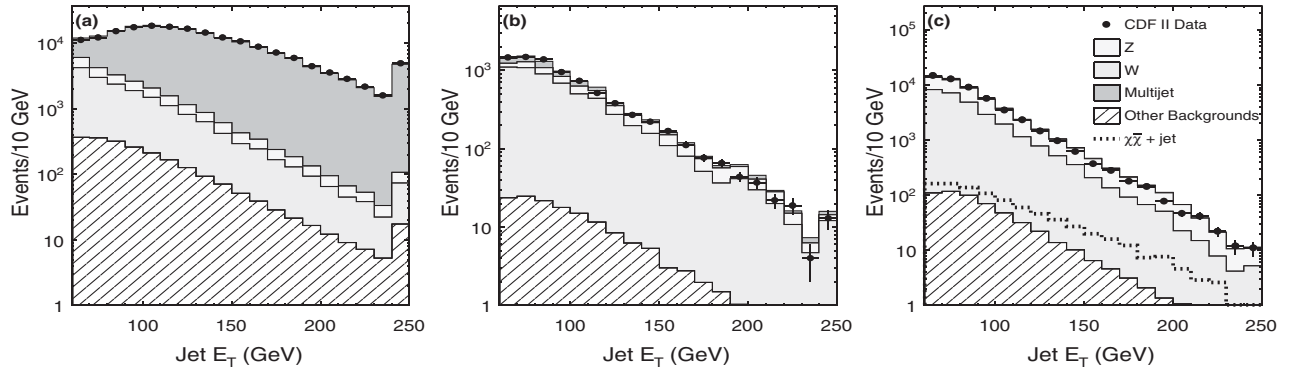


FIG. 1. Distribution of the leading jet  $E_T$  for the multijet control (a), electroweak control (b), and analysis (c) samples. The last bin contains the overflow. For the analysis sample, the jet  $E_T$  of a representative signal process ( $\chi\bar{\chi} + \text{jet}$ ,  $M_\chi = 1\text{GeV}/c^2$ ) is shown normalized to the 90% confidence level upper limit production rate of 5.9 pb.

$W$  boson background contributions are determined assuming NNLO calculations [24] of the inclusive production rates.

Minor backgrounds include  $t\bar{t}$  modeled with PYTHIA, and single-top processes modeled with MADGRAPH [25] plus PYTHIA for particle showering and hadronization. A top-quark mass of  $172.5\text{ GeV}/c^2$  is assumed for the  $t\bar{t}$  [26,27]  $s$ -channel, and  $t$ -channel [28] processes with cross sections of cross sections of 7.04, 1.05, and 2.1 pb, respectively. We account for the expected diboson ( $WW, WZ, ZZ$ ) [29] contributions to our selected sample with a PYTHIA simulation, and normalize the rates of the  $WW, WZ$ , and  $ZZ$  processes to 11.34, 3.47, and 3.62 pb. All simulated samples in this analysis include a detailed GEANT-based detector simulation [30] and assume CTEQ5L [31] parton distribution functions.

While our NN requirement rejects the main multijet contamination, we model the remaining multijet background using reweighted data events. We determine the likelihood of an event in our analysis sample to have originated from a multijet background process by utilizing a sample of events with relaxed kinematic selections such that events with any number of jets with  $E_T$  greater than 35 GeV are accepted. Events meeting this relaxed selection constitute the derivation sample. To maintain exclusivity, we remove all events entering the analysis sample from the derivation sample. In addition, we denote the probability that a given event originated in a multijet process as the multijet probability (MJP). This probability is taken as the fraction of events in the derivation sample that is unaccounted for by simulated backgrounds. The MJP is parameterized in six observables:  $\cancel{E}_T$ , the number of jets, the minimum separation in azimuthal angle between  $\cancel{E}_T$  and a jet, the ratio of the scalar sum of jet  $E_T$  to its sum with the  $\cancel{E}_T$ , the magnitude of the momentum imbalance from tracks with  $p_T \geq 10\text{ GeV}/c$ , and the  $\cancel{E}_T$  significance [32].

A given event in the analysis sample is assigned a weight by the MJP, as determined by its values of the six observables. The multijet background is modeled as the weighted

sum of all events contributing to the analysis sample. We find that the above method accurately determines the shape of the multijet background in all observables of interest. To obtain an appropriate normalization for the multijet contribution, we require that the sum of the number of events predicted by simulation and by the multijet prediction equal the number of data events observed in the sideband region which is defined such that the NN value is between 0.2 and 0.3.

To test the performance of our data model, we form two additional samples that are exclusive of the analysis sample. We define an electroweak sample that is composed of events that pass all analysis selection criteria but have one or more tracks with  $p_T \geq 10\text{ GeV}/c$ , that are not embedded within a jet. In addition, we define a multijet sample of events passing all the analysis selection requirements except that they have a NN value less than 0.3,  $\cancel{E}_T$  aligned with a jet, or have more than 2 jets. We find good agreement between the data and the SM prediction in both control samples. The  $E_T$  distribution of the leading jet is displayed in Fig. 1.

We model the potential contribution to our analysis sample from a DM signal of  $p\bar{p} \rightarrow \chi\bar{\chi} + \text{jet}$  using a MADGRAPH [25] generator that is interfaced with PYTHIA for showering and hadronization. We generate variants of the signal models, discussed previously, assuming DM masses between 1 and  $300\text{ GeV}/c^2$ . We find an efficiency

TABLE I. Event totals in the analysis and control samples. Uncertainties are systematic only.

Source	Multijet	Electroweak	Analysis
Z	$6949 \pm 840$	$1280 \pm 155$	$22\,191 \pm 2681$
W	$14\,986 \pm 2007$	$5582 \pm 747$	$27\,892 \pm 3735$
Multijet	$165\,479 \pm 82\,740$	$1066 \pm 533$	$3278 \pm 1639$
Other	$2194 \pm 233.4$	$149 \pm 10.7$	$545 \pm 39.3$
Total model	$189\,608 \pm 82\,787$	$8076 \pm 1011$	$53\,906 \pm 6022$
Data	188 361	7942	52 633

TABLE II. Expected (Exp.) and observed (Obs.) 90% C.L. upper limits (in pb) on the cross section of  $p\bar{p} \rightarrow \chi\bar{\chi} + \text{jet}$  for the three operators (defined in text)  $\mathcal{O}_{AV}$ ,  $\mathcal{O}_V$ , and  $\mathcal{O}_I$ , assuming contact interactions. The  $\pm 1\sigma$  variations on the expected limits are also shown.

$M_\chi$ (GeV/ $c^2$ )	$\mathcal{O}_{AV}$		$\mathcal{O}_V$		$\mathcal{O}_I$	
	Obs. (pb)	Exp. (pb)	Obs. (pb)	Exp. (pb)	Obs. (pb)	Exp. (pb)
1	5.9	$7.6^{+4.9}_{-3.6}$	9.1	$7.8^{+5}_{-3.5}$	6.5	$7.2^{+4.3}_{-3.6}$
5	6.9	$7.9^{+4.8}_{-3.6}$	5.4	$8.1^{+4.9}_{-4.1}$	7.5	$8.1^{+4.4}_{-3.6}$
10	4.5	$7.9^{+4.8}_{-3.5}$	6.4	$7.7^{+4.4}_{-3.6}$	5.0	$7.0^{+4.2}_{-3.1}$
50	3.4	$7.0^{+4.2}_{-3.4}$	6.6	$7.5^{+4.6}_{-3.4}$	5.3	$6.5^{+4.0}_{-3.1}$
100	4.5	$6.0^{+3.6}_{-2.9}$	5.7	$6.2^{+3.7}_{-2.8}$	4.6	$6.1^{+3.7}_{-2.9}$
200	4.8	$5.6^{+3.2}_{-2.7}$	3.9	$5.6^{+3.6}_{-2.7}$	4.2	$4.8^{+3.2}_{-2.2}$
300	3.1	$6.1^{+3.9}_{-2.7}$	3.5	$5.6^{+3.4}_{-2.4}$	2.7	$5.1^{+3.2}_{-2.4}$

of approximately 2% when imposing the analysis sample on simulated DM events.

Systematic uncertainties affecting the normalization of simulated background components and DM signal arise due to uncertainty in the integrated luminosity ( $\sim 6\%$ ), measured jet energy scale ( $\sim 7\%$ ), parton distribution function uncertainties ( $\sim 2\%$ ), efficiency of the trigger used for data collection ( $\sim 2\%$ ), choice of the renormalization scale ( $\sim 2\%$ ), and the amount of initial and final state radiation ( $\sim 1\%$ ). In addition, a 50% uncertainty is placed on the normalization of the multijet prediction. The normalization uncertainties for the top [26–28], Z/W [33], and diboson [29] processes are 10%, 8%, and 6%, respectively. We include the effect on the jet energy scale uncertainty on the shape of observed quantities, and find this to be the dominant uncertainty. We include an uncertainty on the shape of the multijet background, based on the observed variation in the multijet prediction between the analysis and electroweak samples.

The total numbers of observed and expected events in the control and analysis samples is listed in Table I. In the analysis sample, we observe 52 633 events which agrees well with the expectation of  $53\,906 \pm 6022$ . As we do not observe a significant excess over the number of events predicted by our background model, we proceed to quantify the maximum allowed DM production cross section.

We set limits on the DM production rate using a Bayesian likelihood [34] formed as a product of likelihoods over bins in the analysis region of the jet  $E_T$  distribution. We assume a flat prior on the signal rate, and a Gaussian prior for each systematic uncertainty including those affecting sample normalizations and shapes. We set Bayesian 90% confidence level upper limits on  $\sigma(p\bar{p} \rightarrow \chi\bar{\chi} + \text{jet})$  for each of the models considered. The expected upper limits at each model point are derived by randomly generating a series of pseudo data sets, derived from the background prediction, and computing the median of the distribution of resulting upper limits. The upper limits are listed in Table II. We proceed to convert the limits into constraints on the DM-nucleon cross section following [6,8]. A comparison of the CDF limits to several direct detection results is shown in Fig. 2. The CDF limits assuming light mediators are also shown. The CDF bounds extend beyond the experimental reach of direct detection searches, which are insensitive to DM with a mass of approximately 1 GeV/ $c^2$ . For a DM mass of 5 GeV/ $c^2$ , CDF bounds on spin-independent interactions are  $O(10^{-38})$  cm $^2$  and are similar to the limits reported by the DAMIC [35] collaboration. In the case of spin-dependent interactions, we report stronger bounds of  $O(10^{-40})$  cm $^2$  for a DM mass of 1 GeV/ $c^2$ , rising to  $O(10^{-39})$  cm $^2$  for a mass of 200 GeV/ $c^2$ .

In conclusion, we have performed the first collider search for DM in the monojet production mode. We have set limits on the DM production rate, and have constrained the spin-independent nucleon-DM scattering rate for a DM mass of roughly 1 GeV/ $c^2$ , and between 1 and 200 GeV/ $c^2$  for spin-dependent interactions.

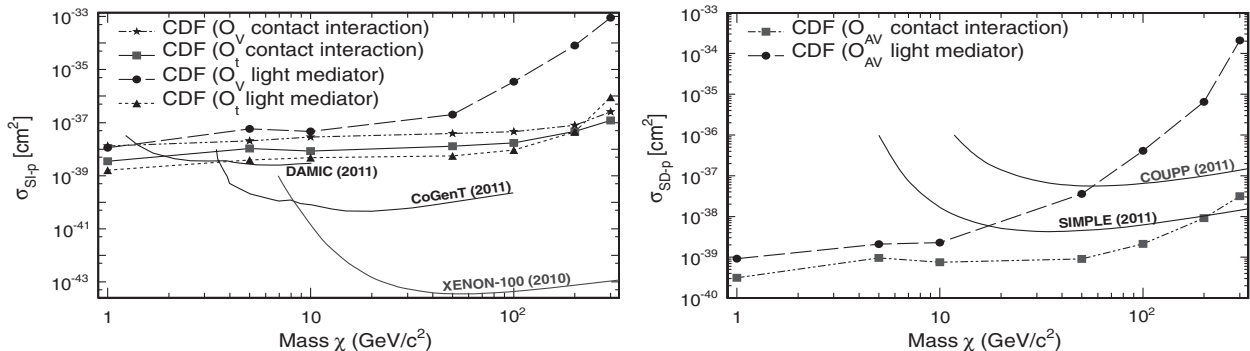


FIG. 2. Comparison of CDF results to recent results from DAMIC [35], CoGenT [4], XENON-100 [36], SIMPLE [37], and COUPP [38]. Spin-independent (left) and spin-dependent (right) bounds on dark matter-nucleon scattering cross sections are shown for the operators (defined in text)  $\mathcal{O}_{AV}$ ,  $\mathcal{O}_V$ , and  $\mathcal{O}_I$ , assuming contact interactions. For comparison we also display CDF bounds assuming light mediators.

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