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Search for Long-Lived Massive Charged Particles in 1.96 TeV $p\bar{p}$ Collisions

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Abstract

We performed a signature-based search for long-lived charged massive particles (CHAMPs) produced in 1.0 fb^{-1} of $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV, collected with the CDF II detector using a high transverse-momentum (p_T) muon trigger. The search used time-of-flight to isolate slowly moving, high-p_T particles. One event passed our selection cuts with an expected background of 1.9 ± 0.2 events. We set an upper bound on the production cross section, and, interpreting this result within the context of a stable scalar top quark model, set a lower limit on the particle mass of 249 GeV/c^2 at 95% C.L.

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Most searches for massive particles arising from physics beyond the standard model (SM) rely upon the assumption that the particles decay immediately. Long-lived or stable non-SM states could exist, however, due to a new symmetry [1], a weak coupling [2], a kinematic constraint [3], or a potential barrier [4]. If the lifetime is long compared to the transit time through the detector, then the particle may escape the detector, thereby evading the limits imposed by direct searches for decay products. However, a charged, massive stable particle (CHAMP) will be directly observable within the detector through the the distinctive signature of a slowly moving, high transverse-momentum (p_T) particle. The low velocity results in a long time-of-flight (TOF) and an anomalously large ionization-energy loss per unit distance (dE/dx). Since the particle loses energy primarily through low-momentum-transfer interactions, even if strongly interacting [5, 6], it will be highly penetrating and will likely be reconstructed as a muon.

There have been a number of previous searches for CHAMPs, the results of which have been presented within the context of a variety of models [7, 8, 9, 10]. For instance, CDF in Run I used dE/dx and set lower mass limits of 190 GeV/c^2 and 220 GeV/c^2 on stable fourth-generation down-type and up-type quarks, respectively, at 95% C.L. [7] The ALEPH experiment also used dE/dx to exclude a stable scalar top squark ($\tilde{t}$), the supersymmetric partner of the top quark, with a mass below 95 GeV/c^2 at 95% C.L. [8] A combined result from the LEP2 experiments excluded a stable supersymmetric partner for SM leptons with a mass below 99.5 GeV/c^2 at 95% C.L. [9]

In this Letter, we present a signature-based search for CHAMPs produced in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV with the CDF II detector [11] at the Fermilab Tevatron. Using an integrated luminosity of 1.0 fb^{-1} of $\bar{p}p$ collisions collected with a high p_T muon trigger, the analysis isolated CHAMP candidates by calculating their mass from their measured velocity and momentum. We interpret the results within two scenarios. The first case, production of a single CHAMP within a reference volume of the CDF II detector, is largely model independent. The second scenario assumes a benchmark model for stable top-squark-pair production within the reference volume. Since the leading-order contributions to $\tilde{t}$ production depend only upon the $\tilde{t}$ mass [12], the result will generally apply to all stable $\tilde{t}$ production models.

Complete details of the CDF II detector can be found in Ref. [11]. Here we summarize the components relevant to this analysis. CDF measures the trajectories and momenta of charged particles using an inner silicon-strip detector [13] and an open-cell drift chamber referred to as the Central Outer Tracker (COT) [14]. A time-of-flight (TOF) detector [15] surrounding the outer tracker allows precise arrival time measurements for tracks projected into the detector within a pseudorapidity [16] approximately in the range $|\eta| < 1$. Calorimeters located outside the tracking volume measure energy deposition of charged and neutral particles, and prevent all but the most penetrating particles from reaching the muon detectors [17] positioned beyond the calorimeters and additional steel shielding.

Our data sample was collected with a trigger that identifies muon candidates with $|\eta| < 0.7$ and $p_T > 18$ GeV/c. An event entered the analysis if the highest-p_T muon candidate reconstructed offline had $p_T > 20$ GeV/c, originated from the most energetic $\bar{p}p$ collision, passed quality criteria that reduce backgrounds from punch-through and particles that decay in-flight, and satisfied a calorimeter energy isolation criterion in which the ratio $\Sigma E_T(0.4)/p_T(\text{muon}) < 0.1$, where $\Sigma E_T(0.4)$ is the sum of transverse energy within a cone of $\Delta R = 0.4$ around the candidate's direction, excluding the energy deposited by the candidate itself. CHAMPs are highly ionizing, so no requirement was placed on the maximum energy in the calorimeter segments crossed by the muon candidate, as is typically done when identifying high-p_T muons.

We assign the selected events to signal or control sub-samples depending upon whether the track of the highest-p_T muon candidate is a signal-region ($p_T > 40$ GeV/c) or control-region ($20 < p_T < 40$ GeV/c) track. The second-highest-p_T muon candidate (or the highest-p_T non-muon track in events with only one muon candidate) is also a signal- or control-region track if it is in the same p_T region and originates from the same vertex as the first muon candidate. Tracks with $p_T < 20$ GeV/c are used to measure the $p\bar{p}$ interaction time (t_0) and are referred to as "t_0 tracks". The event t_0, which is needed to determine the velocity of signal- and control-region tracks, is estimated using a maximum likelihood fit to all t_0 tracks from an interaction vertex, simultaneously taking into account all possible mass hypotheses.

To separate a CHAMP signal from background, we use the velocity and momentum to calculate the mass of the candidate particle. The track velocity for all candidate and control-region tracks is measured by dividing the path length of the track (typically about 200 cm) by its TOF. The TOF is measured by subtracting the event t_0 from the track's arrival time at the TOF detector. We measure the velocity, $\beta = v/c$, of control-region tracks to be 1.000 ± 0.029, but with significant non-Gaussian tails. For the CHAMP signal, we require

β to be less than 0.9 in order to suppress SM particles.

The non-Gaussian tails in the time resolution functions introduce a large background to the CHAMP candidate sample. The residuals to the track fit in the COT can be used to estimate the production time and β for tracks independently of the TOF detector. While the individual t_0 measurements have a resolution approximately a factor of three worse than those made with the TOF detector, they are reliably parameterized by a single Gaussian distribution. We require that both the event t_0 and the candidate track velocity measurements from the TOF detector and COT agree.

Cosmic-ray muons are uncorrelated in time with $p\bar{p}$ interactions and therefore present a potentially serious background. To remove them, we first search for tracks that have opposite charge to candidate muons and have $p_T > 10$ GeV/c. We discard events in which the combined candidate and partner tracks are consistent with a cosmic-ray track passing through the detector [18]. We estimate that the algorithm removes less than 1% of signal events while leaving negligible cosmic-ray background with a reconstructed mass within our search window, above 100 GeV/c^2.

We estimate the efficiency for identifying a CHAMP candidate within our two scenarios. The efficiency estimate for detecting a single isolated, high-p_T CHAMP is independent of the production model and is determined almost entirely from data. In general, CHAMPs are expected to have very large p_T and be highly isolated. Final-state radiation is strongly suppressed, even in the case in which the CHAMP is strongly interacting [5]. These characteristics make $W \to l\nu$ and $Z \to l^+l^-$ events, where l is either an electron or muon, reasonable models for both the isolated CHAMP track and the underlying event.

We use the muons in $Z \to \mu^+\mu^-$ events selected from the original trigger sample to measure the trigger and reconstruction efficiency for a single muon to be $(94.0 \pm 0.3)\%$. To study the β dependence of the tracking efficiency, we isolate slow deuterons and pions using dE/dx in the tracking detector and measure the ratio of deuterons to pions, which we assume is constant as a function of β. We find that the efficiency is constant for $\beta > 0.4$ and drops for slower particles, a result confirmed in a CHAMP Monte Carlo simulation (MC) [19]. We therefore assume a flat efficiency of $(94.0 \pm 0.3)\%$ for $\beta > 0.4$ and zero for $\beta < 0.4$ for CHAMPs.

Using vertices and electron tracks in $W \to e\nu$ events, we determine the efficiency for finding the primary event vertex, calculating an event t_0, and for reconstructing an isolated

CHAMP track associated with the vertex to be $(71.4 \pm 0.2)\%$. The event t_0 and the track-vertex association dominate the losses in this efficiency.

The efficiency for measuring the arrival time in the TOF detector for CHAMP tracks that are within the muon detectors is determined directly from the muon data; for tracks that are not within the muon detectors, we use electron tracks in $W \to e\nu$ events. Including the efficiency for the TOF result to be consistent with COT timing information, we obtain a TOF measurement efficiency of $(62.8 \pm 2.6)\%$ for tracks within the muon detectors and $(56.3 \pm 2.7)\%$ for other tracks. The criteria used to identify well-measured arrival times account for most of the efficiency loss.

We take the systematic uncertainty in these efficiencies to be equal to the statistical uncertainties in the underlying measurements. For the arrival time efficiencies, we take a 3% uncertainty that includes both the difference between the observed efficiencies for electrons and muons, and a drop in the efficiency during the course of the run due to gain changes in the TOF detector system.

Strongly interacting CHAMPs are subject to QCD effects [5, 6] that can reduce the overall detection efficiency relative to that of weakly interacting CHAMPs. Quark-like CHAMPs, for instance, can hadronize into either charged or neutral color-singlet states. Charge-exchange interactions in the material of the detector can change an initially charged particle into a neutral particle, and visa versa, before it reaches the muon detectors. At least one CHAMP must leave a track segment in both the COT and the muon chambers to satisfy our trigger.

In order to estimate the efficiency loss due to these hadronic effects, we consider the case of an up-quark-like CHAMP, Q, that hadronizes into a $Q\bar{q}$ or $\bar{Q}q$ R-hadron state. The fraction hadronizing into a charged R-hadron is assumed to be $(52.9 \pm 2.9)\%$, based upon the rate for charged b-meson production measured at LEP [21]. The center-of-mass energy for collisions between a massive Q moving at low velocity and a light quark is small. As a result, hadronic interactions of the R-hadron with the detector material involve primarily the light quark while the Q remains a spectator [5, 6]. Since the R-hadron contains a single light valence quark, we assume the interaction length for the R-hadron to be one-third of that for a proton. Under these assumptions and using a model for the material within the detector, we estimate that the probability that an initially charged R-hadron undergoes re-hadronization before reaching the outer-most of the two layers of muon detectors is 93%. At each interaction, the Q re-hadronizes according to the same prescription as for the initial hadronization. To estimate the systematic uncertainty, we take the difference between the result above and the efficiency assuming that 100% of R-hadrons re-hadronize.

Combining all efficiencies, we estimate that the net efficiency for detecting a single, weakly interacting CHAMP within the acceptance of the muon trigger is $(38 \pm 2)\%$; for a strongly interacting up-quark-like CHAMP, the efficiency is $(8.8 \pm 1.6)\%$.

As a reference model we use PYTHIA [19] to calculate the geometric and kinematic acceptance for top squark ($\tilde{t}$) pair production. The trigger and detection efficiencies are calculated by combining the single-track and vertex-finding efficiencies as estimated for the case of a single up-quark-like CHAMP with the relative rate at which one or two top-squark R-hadrons are within the fiducial volume of the detector as predicted by the MC. We use the measured muon trigger efficiency for CHAMPs within the fiducial volume. The acceptances for various top-squark masses are listed in Table I.

Figure 1 shows the observed and predicted mass distribution for tracks in the signal region. The uncertainty in the β measurement is independent of the momentum for tracks with $\beta \approx 1$. We therefore obtain an absolute prediction for the background mass distribution for a given set of tracks by convolving the momentum distribution for those tracks with the distribution of $\sqrt{1/\beta^2 - 1}$, normalized to unit area, for control-region tracks. We find agreement between the observed and predicted mass distributions within the control and signal-region electron tracks and within the control region of the muon sample. The background prediction for the signal region is shown by the band in Fig. 1.

We find one candidate track with a mass above 100 GeV/c^2 and none above 120 GeV/c^2, consistent with the predicted background of 1.9 ± 0.2 events above 100 GeV/c^2. From this result, we set a model-independent upper limit on the production cross section for a single, isolated, weakly interacting CHAMP within the muon trigger acceptance (approximately $|\eta| < 0.7$) with $p_T > 40$ GeV/c, $0.4 < \beta < 0.9$, and a measured mass $m > 100$ GeV/c^2 to be $\sigma < 10$ fb at 95% C.L. Similarly, the cross-section limit for a up-quark-like CHAMP under the same assumptions is $\sigma < 48$ fb at 95% C.L.

To count the number of events consistent with a stable top squark of a given mass m_s, we must take into account the resolution of the mass measurement. For tracks in the β range to which we are sensitive and with momenta in the signal region, the β resolution does not significantly contribute to the mass resolution, which is instead dominated by the momentum resolution [22]. Since the momentum resolution is well modeled by the MC, we

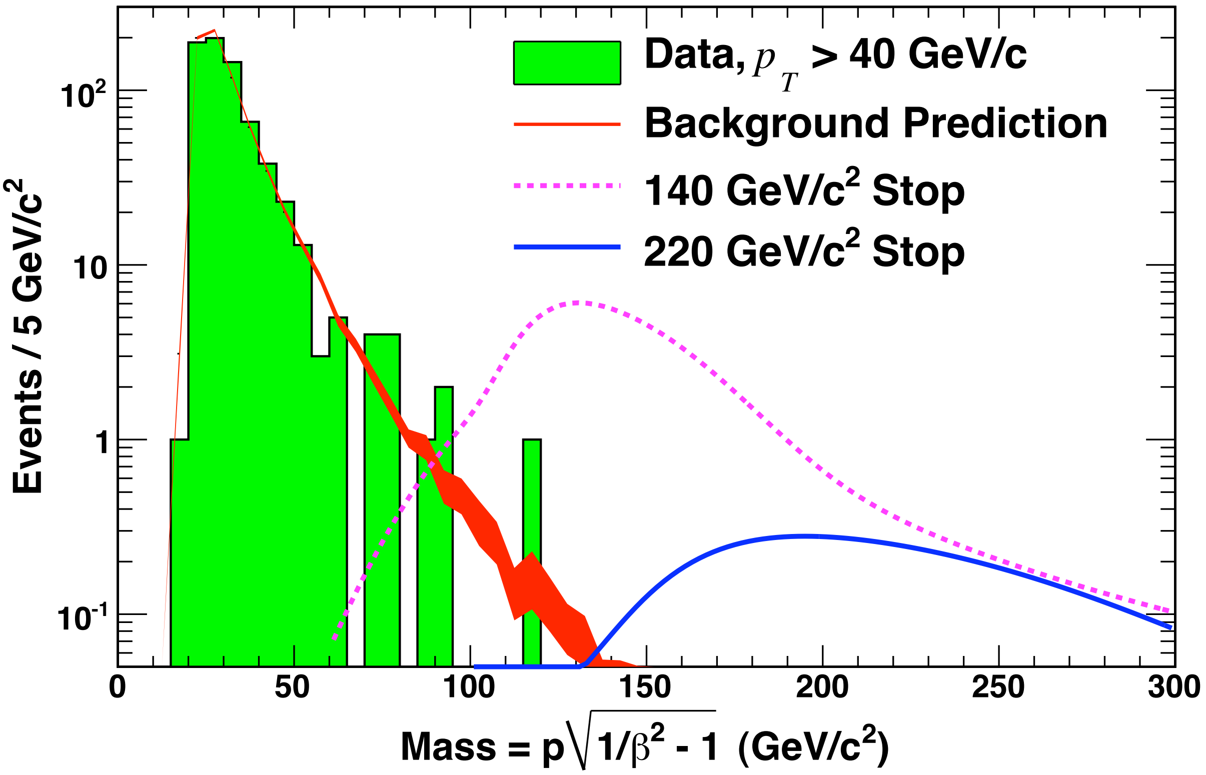

FIG. 1: Observed (histogram) and predicted (band) mass distributions for candidate tracks in the muon sample. The curves on the right show the MC distributions expected for a 140 and a 220 GeV/c^2 long-lived stop.

can accurately predict the mass line shape for a given $\tilde{t}$ mass. We search for a top-squark signal by integrating all events within a one-sided window from $0.8m_s$ upward. Table I shows the resulting number of events as a function of the top-squark mass. From the efficiencies discussed earlier and the number of observed events, we calculate the 95% C.L. upper limit on the cross section shown in Fig. 2. The theoretical NLO top-squark production cross section, as calculated using the Prospino2 program [23], is represented by the band. From the intersection of these two curves, we infer a 95% C.L. lower limit on the mass of a stable $\tilde{t}$ to be 249 GeV/c^2. This is the most stringent limit to date.

In conclusion, we have used the CDF II time-of-flight and Central Outer Tracker systems to measure the masses of highly penetrating, high-momentum tracks. The observed mass distribution is consistent with the expected background, which is dominated by mis-

TABLE I: Results of the search for stable top squarks in 1.0 fb^{-1} of $p\bar{p}$ collisions, as a function of the $\tilde{t}$ mass.

$\tilde{t}$ mass (GeV/c^2)	100	120	140	160	180	200	220	240	260
Expected background	4.7±0.3	1.9±0.2	0.8±0.1	0.37±0.05	0.18±0.03	0.09±0.02	0.05±0.01	0.03±0.01	0.016±0.005
Observed events	4	1	1	0	0	0	0	0	0
Total acceptance (%)	3.6±0.5	4.2±0.5	4.5±0.6	5.1±0.7	5.5±0.8	5.8±0.8	5.9±0.9	5.9±0.8	6.2±0.9
Expected limit (fb)	190	120	90	71	61	56	55	53	51
95% C.L. limit (fb)	160	90	100	60	56	53	52	52	50

measurement of the particle velocity or momentum. From this result, we set upper limits for the production cross section times acceptance of single weakly (up-quark-like strongly) interacting CHAMPs to be less than 10 (48) fb at 95% C.L. The 95% C.L. lower limit on the mass of a stable top squark is 249 GeV/c^2.

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[1] See R. Barbieri, L. J. Hall, and Y. Nomura, Phys. Rev. D **63**, 105007 (2001); T. Appelquist, H. C. Cheng, and B. A. Dobrescu, Phys. Rev. D **64**, 035002 (2001).

[2] See for instance P.H. Frampton and P.Q. Hung, Phys. Rev. D **58**, 057704 (1998); M. Dine, A. E. Nelson, and Y. Shirman, Phys. Rev. D **51**, 1362 (1995); M. Dine, A.E. Nelson, Y. Nir,

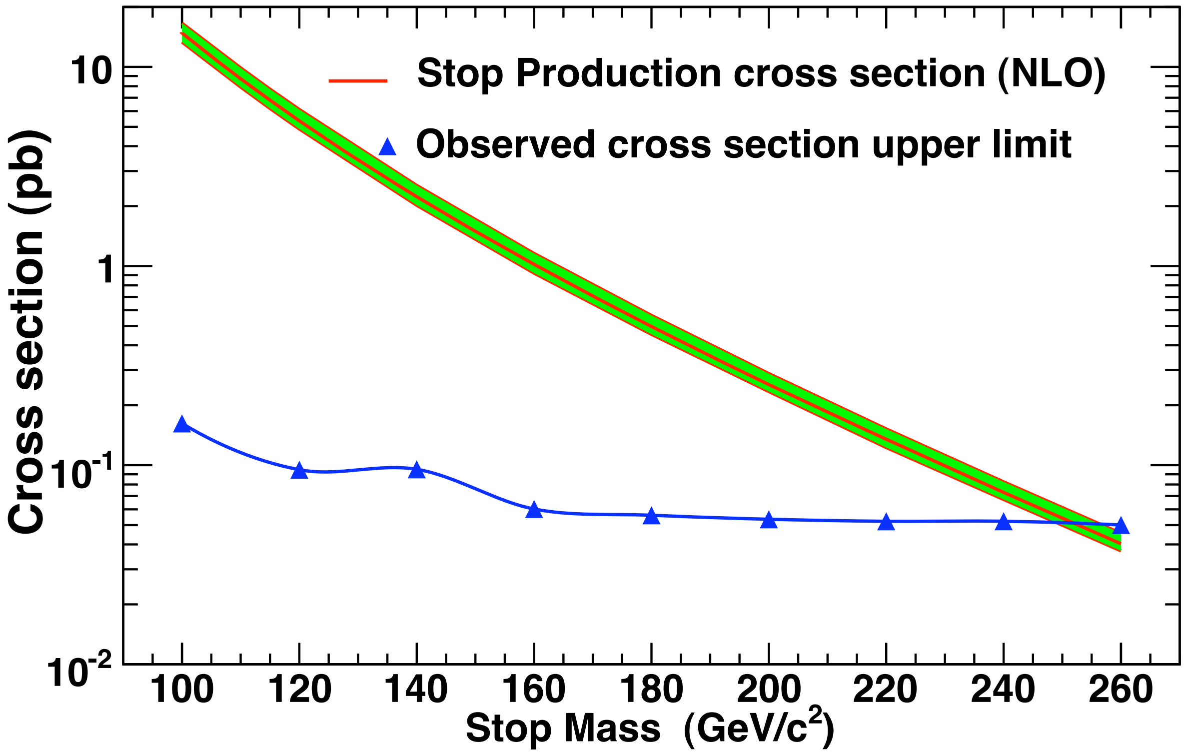

FIG. 2: The observed 95% C.L. limits on the cross section for production of a stable top-squark pair (points), compared to the theoretical NLO cross section [12] (curve). The band represents theoretical and parton distribution function uncertainties. The intersection of these two curves yields a lower mass limit for a stable top squark of 249 GeV/c^2.

and Y. Shirman, Phys. Rev. D **53**, 2658 (1996); N. Arkani-Hamed and S. Dimopoulos, J. High Energy Phys. 06 (2005) 073.

[3] J.L. Feng, T. Moroi, L. Randall, M. Strassler, and S. Su, Phys. Rev. Lett. **83**, 1731 (1999); J.L. Feng and T. Moroi, Phys. Rev. D **61**, 095004 (2000).

[4] M. Strassler and K. Zurek, Phys. Lett. B **651**, 374 (2007).

[5] M. Drees and X. Tata, Phys. Lett. B **252**, 695 (1990).

[6] M. Fairbairn *et al.*, Phys. Rept. **438**, 1 (2007).

[7] F. Acosta *et al.*, Phys. Rev. Lett. **90**, 131801 (2003).

[8] A. Heister *et al.* (ALEPH Collaboration), Phys. Lett. B **537**, 5 (2002).

[9] LEP SUSY Working Group, ALEPH, DELPHI, L3 and OPAL collaborations, note

LEPSUSYWG/02-05.1 (http://lepsusy.web.cern.ch/lepsusy/Welcome.html).

[10] P.F. Smith *et al.*, Nucl. Phys. **B206**, 333 (1982); M. Byrne, C.F. Kolda, and P. Regan, Phys. Rev. D **66**, 075007 (2002).

[11] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 032001 (2005).

[12] W. Beenakker *et al.*, Nucl. Phys. **B515**, 3 (1998); E.L. Berger, M. Klasen, and T. Tait, Phys. Rev. D **59**, 074024 (1999).

[13] A. Sill *et al.*, Nucl. Instrum. Meth. A **447**, 1 (2000); A. Affolder *et al.*, Nucl. Instrum. Meth. A **453**, 84 (2000).

[14] T. Affolder *et al.*, Nucl. Instrum. Meth. **526**, 249 (2004).

[15] D. Acosta *et al.*, Nucl. Instrum. Meth. A **518**, 605 (2004).

[16] We use a coordinate system where ϕ is the azimuthal angle around the beam axis and θ is the polar angle measured with respect to the proton direction. The pseudo-rapidity, η, is defined by $\eta \equiv -\log\tan(\theta/2)$ and $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$.

[17] G. Ascoli *et al.*, Nucl. Instrum. Meth. A **268**, 33 (1988).

[18] A.V. Kotwal, H.K. Gerberich, and C. Hays, Nucl. Instrum. Meth. A **506**, 110 (2003).

[19] T. Sjöstrand, S. Mrenna, and P. Skands, J. High Energy Phys. 05 (2006) 026. See also http://home.thep.lu.se/∼torbjorn/Pythia.html

[20] "R-hadron" refers to hadrons containing an R-parity-conserving supersymmetric particle. From G. R. Farrar and P. Fayet, Phys. Lett. B **76**, 575 (1978).

[21] E. Barberio *et al.* (Heavy Flavor Averaging Group (HFAG)), arXiv:hep-ex/0704.3575.

[22] A. Abulencia *et al.* (CDF Collaboration), J. Phys. G **34**, 2457 (2007).

[23] See http://www.ph/ed.ac.uk/∼tplehn/prospino for details on Prospino2. The calculation for top-squark pair production is based upon Ref. [12].