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

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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 long-lived particle (CHAMP) will be directly observable within the detector through 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 rate (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.

Previous CHAMP search results have been presented within the context of a variety of models [7–10]. CDF in Run I, for instance, used dE/dx and set 95% C.L. lower mass limits on stable fourth-generation down-type (190 GeV/c^2) and up-type (220 GeV/c^2) quarks [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 blind signature-based search for isolated CHAMPs promptly 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.

Details of the CDF II detector can be found in Ref. [11]. CDF measures the trajectories and momenta of charged particles using an inner silicon-strip detector [13] and an open-cell drift chamber (COT) [14]. A TOF detector [15] surrounding the outer tracker allows precise arrival time measurements for tracks projected into the detector with a pseudorapidity [16] in the range $|\eta| \lesssim 1$. Calorimeters located outside the tracking volume measure energy deposition of particles, and prevent all but the most penetrating from reaching the muon detectors [17] positioned beyond the calorimeters.

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.

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. The t_0 resolution of single tracks is about 120 ps, so a single t_0 track is adequate to obtain the interaction time.

To separate a CHAMP signal from background, we use the velocity and momentum to calculate the mass of the candidate particle. In events with two signal-region or control-region tracks, both are considered. The track velocity for all candidate and control-region tracks is mea-

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sured by dividing the path length of the track by its TOF. The measured average velocity, $\beta = v/c$, and single-track resolution of control-region tracks is 1.000 ± 0.029, but with significant non-Gaussian tails. For signal-region tracks, we require $\beta < 0.9$ 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 t_0 and track β with resolutions that are about a factor of three worse than those made with the TOF detector, but that are reliably parameterized by single Gaussian distributions. Requiring that the event t_0 and candidate track β measurements from the TOF detector and COT agree reduces this background.

Cosmic-ray muons are uncorrelated in time with $p\bar{p}$ interactions and present a potentially serious background. In a sample of 1.5×10^5 cosmic rays, only four pass the CHAMP selection. After applying a cosmic-ray filter [18], we expect negligible residual cosmic-ray background. The filter removes less than 1% of signal events.

We estimate the efficiency for identifying a CHAMP candidate within our two scenarios. In general, CHAMPs are expected to have very large p_T and be highly isolated. Final-state radiation is strongly suppressed, even if 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 track 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 reconstructing an isolated CHAMP track from the vertex to be $(71.4 \pm 0.2)\%$. The event t_0 and track-vertex association dominate the losses in this efficiency (87% and 86% respectively).

The efficiency for measuring the arrival time in the TOF detector for CHAMP tracks that are within the muon detector acceptance is determined directly from the muon data; for tracks that are not within the muon detector's acceptance, 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.

The dominant systematic uncertainties in the efficiencies are a 5% value to cover the effect of errors in the modeling of initial and final state radiation and track multiplicities in CHAMP events on the vertex and t_0 efficiencies, and a 3% uncertainty in the arrival time efficiency to cover differences observed for electrons, muons, and changes in the TOF detector gain during the run.

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 [20]. 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 three times that for a proton. Under these assumptions, 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, the net efficiency for detecting a single, weakly interacting CHAMP within the muon trigger acceptance 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 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. The acceptances for various $\tilde{t}$ 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

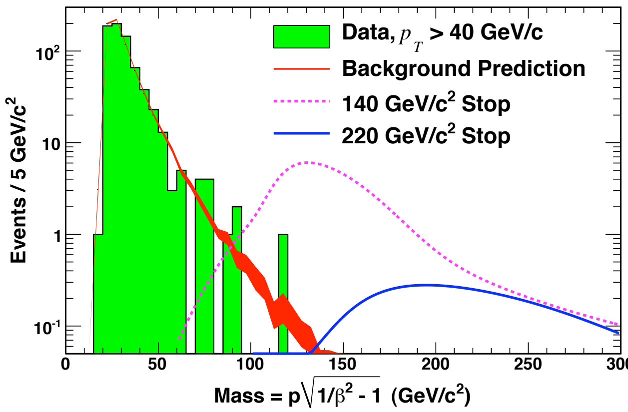

FIG. 1: Observed (histogram) and predicted (band) mass distributions for candidate tracks in the muon sample. The curves on the right show the MC distributions expected for a 140 and a 220 GeV/c^2 long-lived stop.

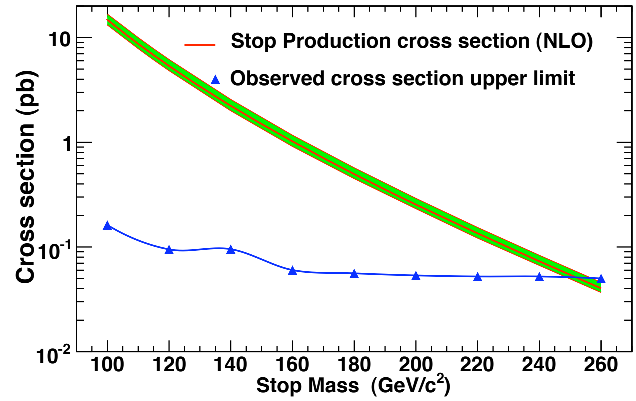

FIG. 2: The observed 95% C.L. limits on the cross section for production of a stable top-squark pair (points), compared to the theoretical NLO cross section [12] (curve). The band represents theoretical and parton distribution function uncertainties. The intersection of the band with the limit curve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

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 $\tilde{t}$ of a given mass m_s, we must take into account our mass resolution. For tracks with $\beta > 0.4$ and momenta in the signal region, the mass resolution is determined by the momentum resolution [22], which is well modeled by the MC. We can therefore accurately predict the $\tilde{t}$ mass line shape. We search for a $\tilde{t}$ 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 $\tilde{t}$ mass. From the estimated efficiencies and the number of observed events, we calculate the 95% C.L. upper limit on the cross section shown in Fig. 2. The band represents the theoretical NLO $\tilde{t}$ pair production cross section, as calculated using the Prospino2 program [23]. From the intersection of the edge of the band and the limit curve, we infer a 249 GeV/c^2 95% C.L. lower limit on the mass of a stable $\tilde{t}$. This is the most stringent limit to date.

In conclusion, we have used the CDF II TOF and COT systems to measure the masses of highly penetrating, high-p_T tracks. The observed mass distribution is consistent with the expected background, which is dominated by SM particles with mis-measured 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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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

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