Searches for Physics Beyond the Standard Model at the Tevatron

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Abstract

The detector experiments at the Tevatron, CDF and D0, have a broad program to search for particles beyond the standard model of particle physics. The searches cover a large number of final states composed of standard-model particles, plus a range of non-standard signatures unique to new-physics models. In organizing the many searches, supersymmetry is a useful benchmark; its large number of parameters allows almost any signature to be cast in terms of this model. The results presented here are an inclusive survey of the searches pursued by the CDF and D0 collaborations using up to 6.3 fb^{-1} of data.

Introduction

The standard model of particle physics (SM) is a remarkably elegant description of fermionic matter interacting via gauge-boson exchange, and is arguably consistent with all collider data. However, when viewed in the context of the known universe, the SM is remarkably deficient. It explains only 5% of the universe's energy density and is unable to account for the observed asymmetry between matter and antimatter. Going beyond the contents of the universe to the structure of spacetime itself, the SM provides no connection between this structure and the observed force of gravity.

In order to address these deficiencies, the Fermilab Tevatron collides protons and antiprotons at a center of mass energy of 1.96 TeV, with the hope of producing new non-SM particles. At this energy, the Tevatron is the world's highest energy proton-antiproton collider. The two detectors of these high-energy collisions, CDF and D0, have a history of discovery with their observation of the top quark in 1994. Today, with the largest data sets ever produced by a hadron collider (over 9 fb^{-1} of data per detector), the two experiments are in vigorous pursuit of another discovery.

The CDF and D0 collaborations cast a broad net for new particles by testing the predictions of many models, including supersymmetry, extra spatial dimensions, extended gauge groups, and four-generation models. Generic searches extend sensitivity into the realm of the unexpected, through complete probes of 399 and 180 standard final states at CDF [1] and D0, respectively.

Supersymmetry is a particularly valuable tool for new-particle searches. While detractors complain that supersymmetry's many parameters allow it to evade any constraint, proponents note that this same variety forces experimentalists to search in all possible final states. In reviewing the status of CDF and D0 searches for new particles, supersymmetry provides a useful framework for organizing the numerous results.

Supersymmetry

Supersymmetric models [2] have many attractive features: they typically provide a dark matter candidate; they suppress the fine-tuning of the Higgs boson mass; and they facilitate the unification of the SM forces at a high mass scale. The minimal supersymmetric standard model (MSSM) doubles the number of fermion and gauge-boson degrees of freedom by adding

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supersymmetric partners to the SM particles, along with three new Higgs bosons. To remove interactions that would allow proton decay, the MSSM conserves a global "R-parity" that takes values of -1 (+1) for SM (supersymmetric) particles. All told, the MSSM has 105 new parameters, most of which relate to the breaking of supersymmetry. Given a particular supersymmetry-breaking scheme and making mild assumptions, one can reduce the number of new parameters to 5 (in gravity-mediated breaking) or 6 (in gauge-mediated breaking).

In gravity-mediated models, results are typically presented in the plane of the common scalar (m_0) and fermion ($m_{1/2}$) masses at the unification scale for a given value of the ratio of vacuum expectation values of the two Higgs fields ($\tan\beta$). Relevant parameters in gauge-mediated supersymmetry breaking include the supersymmetry-breaking scale Λ and the mass scale M_{mess} of the messengers that communicate this breaking to SM particles.

Searches for supersymmetry can be ordered in terms of the mass of the particle to which the search is sensitive. Particles with the largest couplings, such as the supersymmetric partners to the quarks (squarks) and gluons (gluinos), have the highest production rates, giving searches the highest mass sensitivity. However, the expected sparticle mass spectrum generally has the same hierarchy as the couplings (Fig. 1), so the various sparticle searches typically have similar discovery sensitivity.

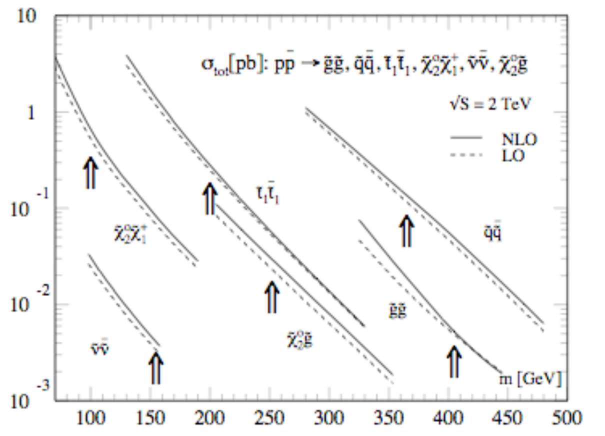

Fig. 1: *Sparticle production cross sections as a function of mass at next-to-leading order in QCD [2]. The arrows show predicted cross sections for masses given by a gravity-mediated model with* $\tan\beta = 4$, $m_0 = 100$ *GeV/*c^2, $m_{1/2} = 150$ *GeV/*c^2, *and Higgs trilinear coupling* $A_0 = 300$ *GeV and mass parameter* $\mu > 0$.

Squark and Gluino Searches

In the MSSM, squarks and gluinos are produced strongly and in pairs through the s-channel annihilation of two quarks or gluons, or a quark and a gluon. A squark decays to a quark and neutralino, while a gluino decays to a quark and squark, leaving two quarks and a neutralino after the squark decay. The event signatures are an imbalance in transverse momentum p_T (from the escaping neutralinos) plus two jets (squark pair production), three jets (squark plus gluino production), or four jets (gluino pair production).

Searches in final states with jets plus "missing" p_T, or $\not{p}_T$, are particularly challenging at a hadron collider due to the high rate of jet production and the relatively poor energy resolution of jets. To reduce the jet background, events are typically required to have large $\not{p}_T$ that is not collinear with any jet. With sufficiently stringent requirements, the dominant backgrounds become *W/Z* boson + jets and top-antitop production.

Both D0 and CDF have probed these final states with ~2 fb^{-1} of data [3], and found the data to be well modelled by the SM backgrounds. The resulting lower limits on the squark and gluino masses are ~400 GeV/c^2. Limits on m_0 and $m_{1/2}$ are as high as ~300 GeV/c^2 and ~150 GeV/c^2, respectively, for particular values of $\tan\beta$. The D0 exclusion region in the m_0-$m_{1/2}$ plane is shown in Fig. 2.

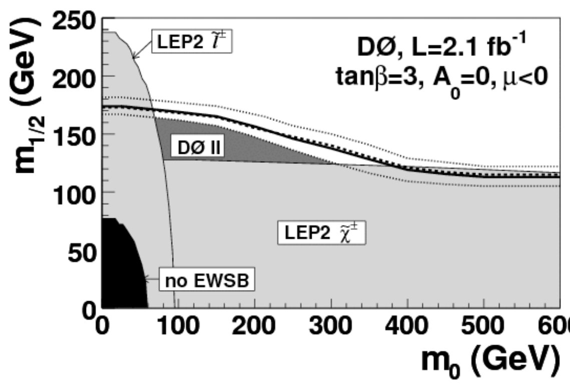

Fig. 2: *Limits in the* m_0-$m_{1/2}$ *plane from a D0 search for squarks and gluinos ("D0 II") [3]. The shaded region corresponds to the predicted cross section minus one standard deviation, the solid line to the predicted cross section.*

Background	Loose Sample	Tight Sample
$Z \to \nu\bar{\nu}$	888 ± 54	86.4 ± 12.7
$W \to \tau\nu$	669 ± 42	50.6 ± 8.0
$W \to \mu\nu$	399 ± 25	32.9 ± 5.2
$W \to e\nu$	256 ± 16	14.0 ± 2.2
Top quark production	74 ± 9	10.8 ± 1.7
Multi-jet production	49 ± 30	9.0 ± 9.0
γ+jets	75 ± 11	4.8 ± 1.1
Total expected	2443 ± 151	211.2 ± 29.8
Data observed	2506	186

Fig. 3: *The numbers of background and data events for a CDF search in the dijets + $\not\!\!E_T$ final state using 2 fb^{-1} of data [4]. The search defines loose ($\not\!\!E_T$ > 80 GeV/c, H_T > 125 GeV/c) and tight ($\not\!\!E_T$ > 100 GeV/c, H_T > 225 GeV/c) kinematic regions, and normalizes the W/Z + jets background to data in the same kinematic regions.*

An alternative approach has been pursued by CDF in studying the dijet plus $\not\!\!E_T$ final state [4]. Two thresholds are defined for $\not\!\!E_T$ and H_T, the scalar sum of the p_T of the jets. The *W/Z* boson plus jets backgrounds are then measured with the same thresholds, using their decays to charged lepton(s). This method significantly reduces the uncertainties on these backgrounds, and provides a model-independent probe of the dijets plus $\not\!\!E_T$ final state. Figure 3 shows the predictions of the individual SM backgrounds for the loose ($\not\!\!E_T$ > 80 GeV/c, H_T > 125 GeV/c) and tight ($\not\!\!E_T$ > 100 GeV/c, H_T > 225 GeV/c) thresholds, as well as the observed numbers of data events. The data agree well with the SM predictions, and two representative points are excluded in the plane of gluino and squark masses. Limits are also set on pair production of scalar leptoquarks that couple directly to a quark and a neutrino. Such leptoquarks are generic, and also appear as squarks in supersymmetric models where R-parity is violated. For leptoquarks coupling to either first- or second-generation fermions, masses below 187 GeV/c^2 are excluded.

D0 has performed its own dedicated search in the dijet + $\not\!\!E_T$ final state with 2.5 fb^{-1} of data [5], interpreting the results in terms of leptoquark and "little Higgs" models. In the little Higgs model there are additional particles with electroweak-scale masses that contribute to the Higgs boson mass through loops, naturally giving the Higgs boson its electroweak-scale mass. Additional unknown particles with

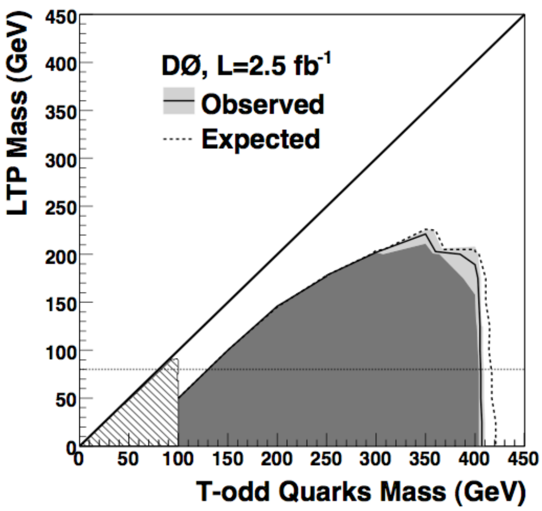

Fig. 4: *Limits on the masses of the lightest T-odd particle and the T-odd quarks, which are assumed to be degenerate in mass for the first two generations. The limits are obtained from a D0 search in the dijet + $\not\!\!E_T$ final state with 2.5 fb^{-1} of data [5].*

masses above 10 TeV/c^2 are assumed to regulate the Higgs boson mass above that mass scale. The new electroweak-scale particles have a conserved quantity called T-parity and can only be produced in pairs. The lightest new state is a stable dark-matter candidate and there are six new T-odd partners of the quarks. The phenomenology of these particles at the Tevatron is virtually the same as the MSSM, which replaces T-parity with R-parity and the spin-1/2 quark partners with spin-0 squarks.

The D0 search optimized combinations of p_T and H_T cuts for two leptoquark masses (140 and 200 GeV/c^2) and five combinations of the T-odd quark masses (150-400 GeV/c^2) and the lowest-mass T-odd state (100-200 GeV/c^2). The data are in good agreement with the SM prediction in all cases, and limits are set on leptoquarks coupling to quarks and neutrinos (mass > 205 GeV/c^2) and on combinations of T-odd quarks and the lowest mass T-odd state, as shown in Fig. 4.

In addition to final states with exclusive jets plus $\not\!\!E_T$, final states with leptons can also be used to search for squark production. The squark can decay to a quark and a neutralino or chargino, with the latter decaying to leptons and the lowest mass supersymmetric particle (LSP). At high tanβ, the gaugino preferentially decays to a stau lepton and a tau lepton or tau neutrino. To probe this region of parameter

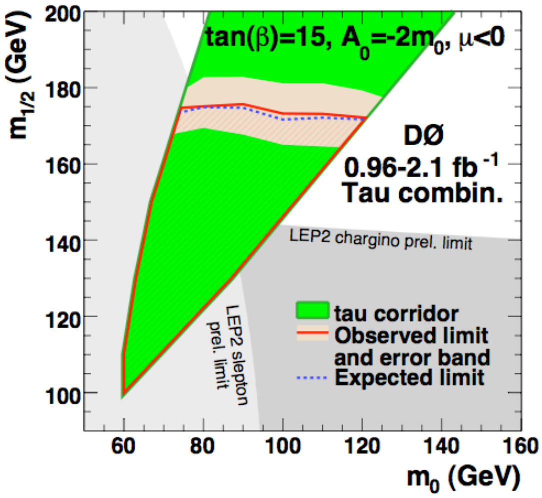

Fig. 5: *The excluded region in the m_0-$m_{1/2}$ plane for tanβ = 15, derived from D0 searches in the dijet plus $\not{p}_T$ final state with and without a tau lepton requirement [6].*

space, D0 has searched data with two jets, one tau, and $\not{p}_T$, using 1 fb^{-1} of data [6]. The tau requirement suppresses jet background, leaving *W/Z* + jets and top-antitop production as the dominant backgrounds. In the search region, the data agree with the SM background prediction, and limits are thus set in the m_0-$m_{1/2}$ plane. These limits, combined with those from the exclusive dijet + $\not{p}_T$ search for squarks, are shown in Fig. 5.

Another method of suppressing QCD jet background is to focus on gluino decays to sbottom quarks, and identify jets originating from *b* quarks ("*b*-tagged jets"). CDF has performed a search for gluinos using the final state with at least two *b*-tagged jets and $\not{p}_T$ using 2.5 fb^{-1} of data [7]. The analysis validates the modelling of QCD jet background using events where the direction of the $\not{p}_T$ is aligned with one of the jets, and the modelling of *W/Z* + jets and top-antitop production using events with a lepton in addition to the *b*-tagged jets and $\not{p}_T$. After testing these background predictions, two search regions are probed for gluino production: one with a large mass difference (Δm) between the gluino and sbottom, giving four high-momentum jets; and one with a small Δm between the gluino and sbottom, giving two high-momentum jets from the sbottom decay and two low-momentum jets from the gluino decay. The 5 (2) data events in the high (low) mass region are in good

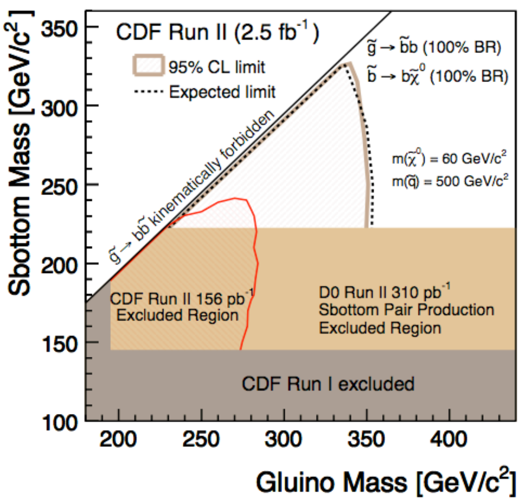

Fig. 6: *The excluded region in the m_{gluino}-$m_{sbottom}$ plane assuming exclusive gluino decay to sbottom plus bottom and sbottom to bottom plus the lowest mass neutralino. The limits are derived from a CDF search in events with at least two b-tagged jets and $\not{p}_T$ [7].*

agreement with the SM prediction of 4.7 ± 1.5 (2.4 ± 0.8) events. Using these results, CDF sets limits (Fig. 6) on the gluino and sbottom masses, assuming 100% branching ratios for gluino decays to sbottom plus bottom and sbottom decays to bottom plus LSP. The limits exclude sbottom masses up to ~300 GeV/c^2 and gluino masses up to ~350 GeV/c^2.

Extending beyond the standard prompt decay of gluinos to squarks and quarks, scenarios have been proposed where the gluino can have a very long lifetime. An example is "split supersymmetry" [8], where gaugino masses are of the order of a TeV/c^2 and squark and slepton masses are orders of magnitude larger. In this case, the gluino width is related to the inverse of the squark mass and the gluino lifetime can be hours or more. This scenario motivates a unique search, performed by D0 [9], with a signature of a large calorimeter energy deposit at times when there is no beam. The dominant background comes from cosmic ray muons producing bremsstrahlung radiation in the calorimeter, and is suppressed by removing events with tracks in the muon detector. D0 finds good agreement between the data and the total background, and sets limits on the cross section of long-lived gluino production as a function of gluino mass and lifetime. Gluino masses between 200 and 300 GeV/c^2 are excluded, depending on the lifetime

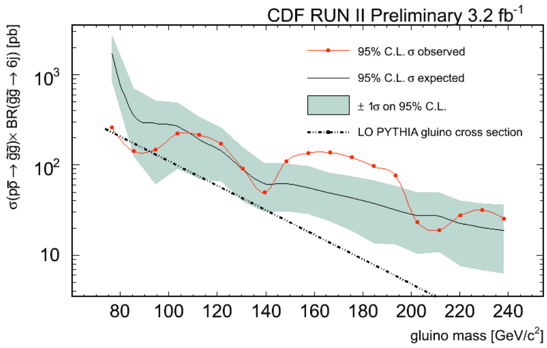

Fig. 7: *Experimental cross section limits on gluino pair production (points), as a function of gluino mass in the case of R-parity-violating squark decays. Also shown are the expected limits in the absence of signal (solid line and shaded region), and the leading-order gluino cross section (dashed).*

and the cross section for the gluino to produce a charged hadron in the detector.

Perhaps the simplest extension to the MSSM is to allow one or two of the three possible R-parity-violating interactions (but not the combination that would mediate proton decay). If one allows the interaction coupling a squark to a pair of quarks, a gluino decay to a quark plus a squark can be followed by a squark decay to two quarks. CDF has searched for pair-production of gluinos decaying to three quarks each. The search probes the two-dimensional plane of 3-jet mass and the sum of the magnitude of the p_T of the jets. A gluino signal would appear in an isolated mass region at high sum p_T. The 3-jet mass distribution is fit for the possible presence of a signal on top of the background, and no significant signal is observed. Limits are set on the cross section times branching ratio as a function of gluino mass, as shown in Fig. 7.

Stop and Sbottom Searches

The large top mass leads to a large mass splitting between the two stop quark eigenstates, and typically one of these eigenstates has a mass significantly lower than the other squarks. Additionally, stop and sbottom quarks have a wider variety of decays than other squarks, with unique characteristics that help distinguish them experimentally.

The dominant stop quark decay depends heavily on mass differences in the sparticle spectrum. A likely scenario is for the stop quark to decay to a charm quark and the LSP, as the stop quark mass only needs to be a couple of GeV/c^2 greater than the LSP mass in this case. D0 and CDF have developed dedicated algorithms to identify charm-quark jets, and searched for stop quark pair production in the final state with two charm jets and $\not{p}_T$. To further suppress background, D0 selects a region of high sum p_T of the jets, and requires large azimuthal angles between each jet and $\not{p}_T$, and between the two jets [10]. CDF has implemented a neural network based on all the basic event kinematic and topological variables, in order to separate the signal from the QCD multijet background. In the absence of evidence for signal, D0 and CDF exclude regions of the plane of LSP and stop masses, as shown in Fig. 8.

If the difference between the mass of the stop quark and the LSP is larger than the sum of the *W*-boson and *b*-quark masses, then the stop quark can decay to these particles. In this case, the final states of stop-quark pair production are the same as those of top-quark pair production, except for two additional neutralinos in the stop quark case. These neutralinos carry significant momentum, reducing the p_T of the observed objects in the event. D0 has exploited this property to form a discriminant separating stop and top quark production in the lepton plus four jets plus $\not{p}_T$ final state [11]. Agreement between the data and the SM background is good for the entire distribution of the discriminant. D0 sets cross section limits of 5-10 pb for stop quark masses between 130-190 GeV/c^2, whereas the prediction of a particular class of models is about half of these cross section limits.

A similar set of final states ensues from the stop quark decay to a chargino and a *b*-quark. CDF probes events with two leptons, two jets, and $\not{p}_T$ ("dilepton + jets"), directly fitting the mass of the hypothesized stop quark particles using the event kinematics [12]. Good agreement is observed in this mass distribution between the data and the SM background, and limits are set in the plane of LSP mass and stop quark mass for various branching ratios of the chargino to a lepton, neutrino and LSP (Fig. 9).

The dilepton + jets final state is also sensitive to stop quark production if the chargino decays to a lepton and sneutrino (instead of a lepton

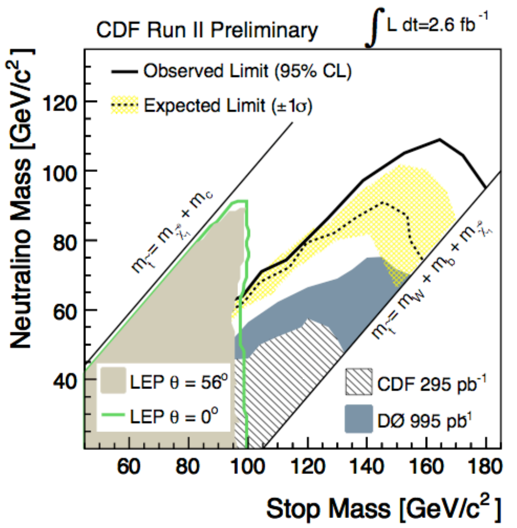

Fig. 8: Dark solid line: Limits on the stop and neutralino masses derived from a CDF search for stop pair production, with the stop decaying to a charm quark and LSP. Also shown are previous limits from D0 and CDF. The diagonal lines show the minimum stop quark mass for decay to a charm quark plus LSP (top) and for decay to a W boson, b quark and LSP (bottom). In the latter case, the branching ratio for stop decay to a charm quark and LSP is expected to be small.

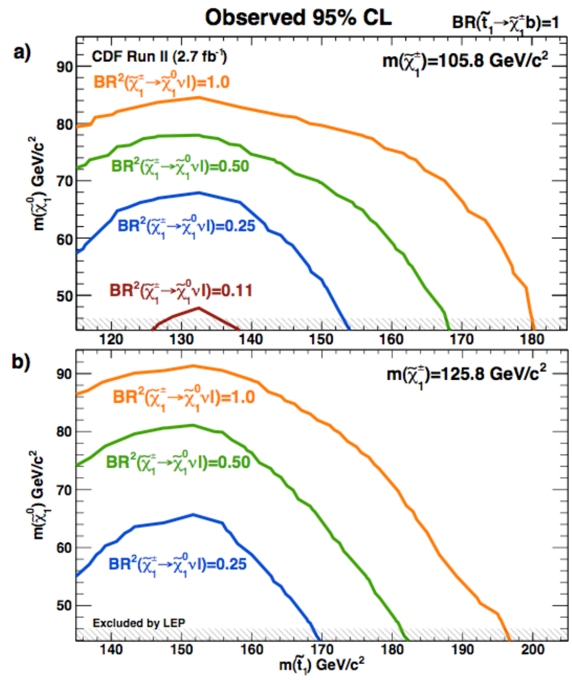

Fig. 9: Exclusion regions in the plane of stop quark and LSP mass, for different values of the branching ratio for the chargino to decay to LSP plus lepton and neutrino [12]. The two plots are for chargino masses of 105.8 GeV/c² (top) and 125.8 GeV/c² (bottom).

and neutralino). Typically one assumes a smaller mass difference between the chargino and sneutrino than the chargino and neutralino, since the sneutrino further decays to a neutrino and LSP. Thus, the charged lepton has lower momentum, making the experimental search more challenging. Both D0 and CDF have searched for stop quark production with this chain of decays, using as primary discriminants the sum p_T of the jets and leptons, and the $\not{p}_T$. The searches focus on relatively low sum p_T, to discriminate from the large SM background of top quark pair production. The D0 and CDF exclusions in the plane of stop quark and sneutrino mass, based on 1 fb^{-1} of data [13], are shown in Fig. 10.

An interesting phenomenological possibility arises in the case of a small mass difference between the stop quark and the LSP. For a mass difference of a GeV/c^2 or less, the stop quark can have a long lifetime before decaying. In this case the experimental signature is a slow-moving charged particle measured in the tracking and time-of-flight detectors. CDF has performed a search for such a particle [14] using detectors with a timing resolution of ~100 ps for a single charged particle. Selecting tracks that traverse the entire detector, including the muon system, CDF uses the time and momentum information to measure the mass of the charged particle. At large masses no excess is observed in 1 fb^{-1} of data over the background of muons measured with large masses due to resolution. The absence of a signal results in an exclusion of long-lived stop quarks with masses below 249 GeV/c^2.

More generally, one expects a long-lived charged particle if there is a small mass difference between the supersymmetric particle with the next-to-lowest mass (NLSP) and the LSP. D0 has searched for long-lived charged particles in 1.1 fb^{-1} of data [15], using its muon scintillators to determine the particle's speed. Finding good agreement between data and background at all masses, D0 sets upper bounds on the number of signal events for three different particles: stau leptons, gaugino-like charginos, and higgsino-like charginos. Masses below 206 (171) GeV/c^2 are excluded for gaugino-like (higgsino-like) charginos.

The bottom quark has a significantly lower mass than the top quark, but also a significantly higher mass than the rest of the quarks. The sbottom mass is thus expected to reside

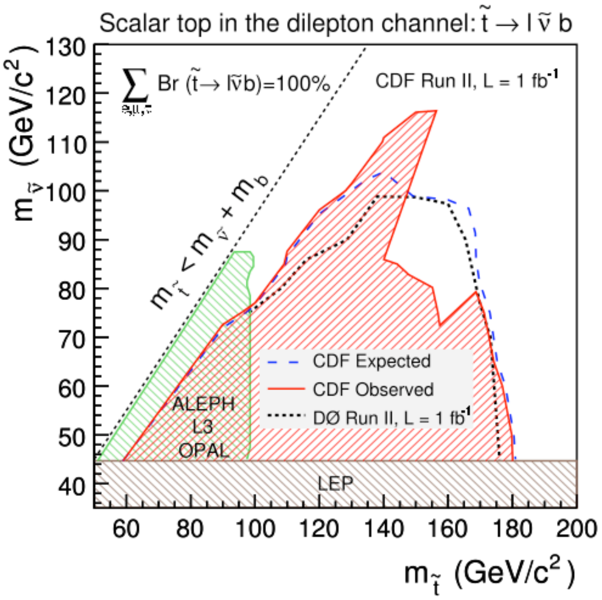

Fig. 10: Exclusion regions in the plane of stop quark and sneutrino mass, for CDF and D0 searches with 1 fb^{-1} of data [13]. The dashed diagonal line corresponds to the threshold where the decay is kinematically allowed.

between those of the supersymmetric partners of the top quark and the light quarks. Good sensitivity can be achieved by searching for sbottom quark pair production, with the sbottom quarks decaying to a bottom quark and the LSP. The final state is two b-jets and $\not{p}_T$. CDF separates its search of this final state into two regions of mass difference between the sbottom quark and the LSP [16]. Smaller mass differences lead to lower momentum b-jets and lower $\not{p}_T$, and consequently larger backgrounds. The observed 139 (38) events in the region of low (high) mass difference are consistent with the expected SM background of 133.8±26.4 (47.6±8.8) events in 2.65 fb^{-1} of data. CDF excludes sbottom masses below ≈240 GeV/c^2 for neutralino masses below ≈80 GeV/c^2. D0 has performed a search using 5.2 fb^{-1} of data, and excluded both sbottom quarks and third-generation leptoquarks with masses below 247 GeV/c^2. The D0 exclusion in the mass plane of the sbottom quark and the LSP is shown in Fig. 11 [17].

Chargino and Neutralino Searches

Charginos and neutralinos tend to have the lowest masses of the supersymmetric states, and associated chargino-neutralino production can lead to the low-background final states of

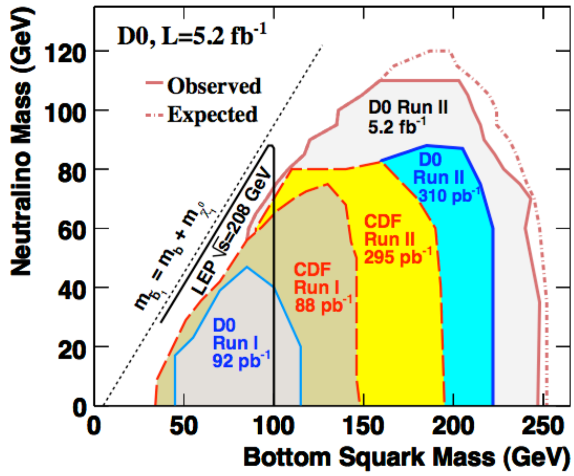

Fig. 11: Limits in the mass plane of sbottom quarks and the lightest neutralino, derived from D0 and CDF searches for sbottom quark pair production in Runs 1 and 2 of the Tevatron. Not shown are recent results from CDF with 2.65 fb^{-1} of data.

three leptons plus $\not{p}_T$ or two photons plus $\not{p}_T$. At high values of tanβ, the stau lepton has a significantly lower mass than the other sleptons and can be a decay product of a chargino or neutralino. In this case, final states with tau leptons are dominant. Other gaugino decays through *W* and *Z* bosons produce leptons at a reduced rate, motivating searches in final states with quark jets.

CDF and D0 have performed searches for chargino-neutralino production, where the chargino decays to a charged lepton, neutrino, and LSP, and the neutralino decays to two charged leptons and the LSP. The event signature of three leptons and $\not{p}_T$ has little SM background, which comes primarily from *WZ* production. The D0 search combines five charged-lepton combinations, where the individual leptons are explicitly identified or captured with a generic lepton-track identification [18]. The CDF search combines three channels where two of the leptons are an electron or muon, and the third is a generic lepton track [19]. Results based on 2.3 (3.2) fb^{-1} of D0 (CDF) data are shown in Fig. 12.

CDF has searched for the process $\chi^\pm\chi_2^0 \rightarrow WZ\chi_1^0\chi_1^0 \rightarrow qqee\chi_1^0\chi_1^0$, where χ_1^0 is the LSP and χ_2^0 is the neutralino with the second lowest mass. To suppress SM production of *WZ* pairs, CDF requires $\not{p}_T$ > 40 GeV/c. In 2.7 fb^{-1} of data with dielectrons (dijets) with mass near the Z (W) boson mass, CDF observes 7 events

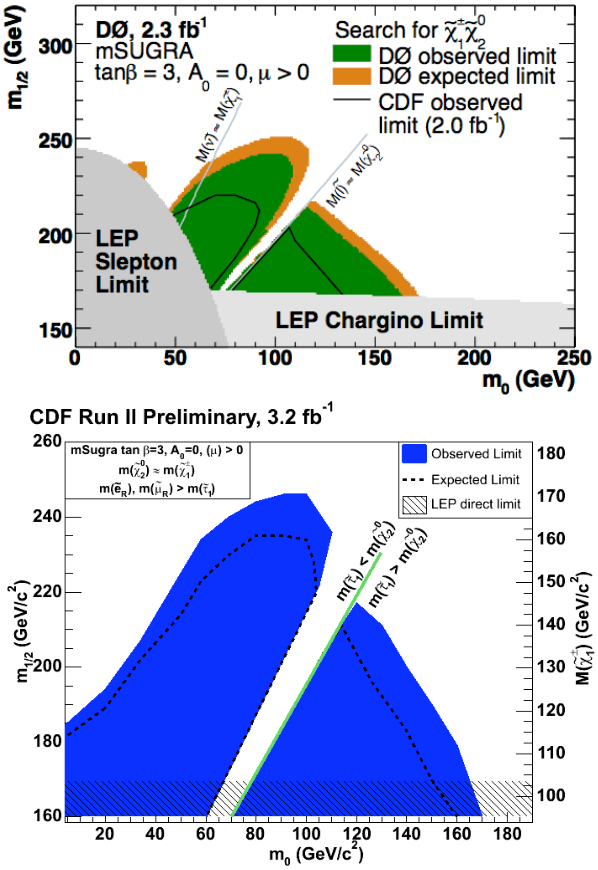

Fig. 12: Top: Limits in the plane of the m_0 and $m_{1/2}$ parameters of the constrained MSSM from searches for chargino plus neutralino production at D0 (CDF) with 2.3 (2.0) fb^{-1} of data. Bottom: Limits in the same plane (but different ranges) derived using 3.2 fb^{-1} of CDF data.

compared to 6.4±0.9 expected SM background events. For the supersymmetry parameters investigated, the cross section limits are about a factor of ten larger than the predicted cross section for an LSP mass of ~200 GeV/c^2.

In models with gauge-mediated supersymmetry breaking, the gravitino is typically the LSP, with a mass on the order of a keV/c^2. The supersymmetric partner of the photon ("photino") also has a relatively low mass and can decay to a gravitino and a photon. Pair production of photinos can thus result in a pair of photons and $\not{p}_T$. Since the photon is massless, the photino coupling to the gravitino is small and the photino can have a long lifetime (a few ns or more). A photino with a lifetime of ~10 ns and a mass of ~150 GeV/c^2 would account for the observed dark matter in the universe. D0 and CDF have searched for photinos with either prompt decays or a non-negligible lifetime. The CDF search for prompt

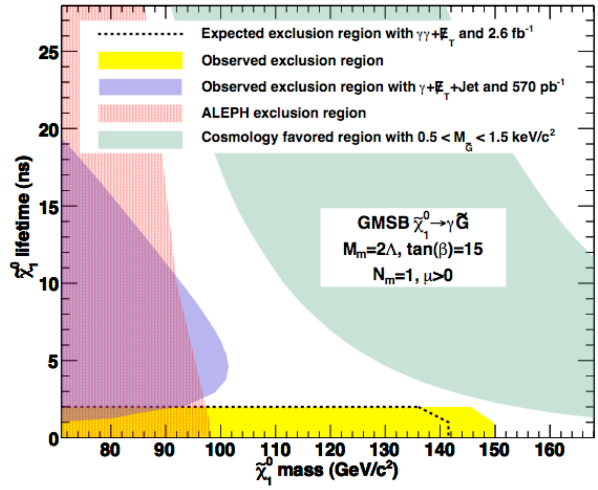

Fig. 13: Limits in the plane of the lifetime and mass of the photino from CDF searches of data with two photons and $\not{p}_T$, and from ALEPH at LEP.

decays [20] uses the significance of the $\not{p}_T$ in the event, based on object resolutions measured in independent data samples. This quantity is used to suppress direct diphoton background and no events are observed in the signal region (with 1.4±0.2 SM events expected). CDF has also performed a dedicated search for long-lived photinos using timing information in the EM calorimeter to measure the lifetime [21]. Results from both searches are shown in the plane of photino mass and lifetime in Fig. 13. D0 has searched 6.3 fb^{-1} of data with two photons plus $\not{p}_T$ [22]. To improve sensitivity, D0 performs a likelihood fit of the $\not{p}_T$ distribution, which shows good agreement between data and SM background. D0 sets a lower bound of 175 GeV/c^2 on the photino mass, though it does not explicitly quote any lifetime dependence on this limit.

It is reasonable to expect that supersymmetry is not the only extension to the SM realized in nature. If there is, for example, an additional gauge group, the phenomenology of the new particles can change significantly. A particularly interesting scenario is an additional U(1) gauge group whose gauge boson mixes weakly with the photon and has a mass as low as an MeV/c^2. New particles charged under this group, and not under an SM group, would have very weak coupling to SM particles and be difficult to produce directly in colliders. Such particles could have masses at the scale of the new gauge boson (the "dark photon"). New states with both SM charges and the new U(1) charge would have high mass (a few hundred

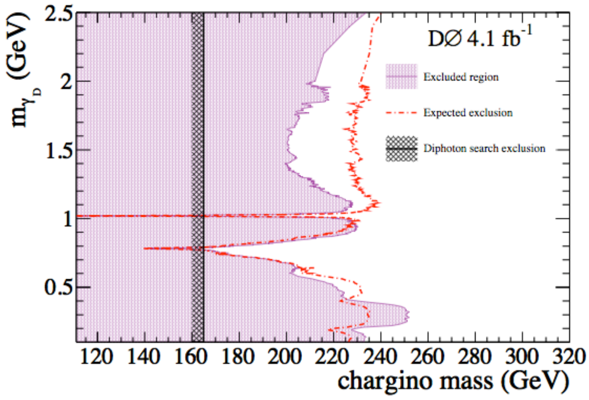

Fig. 14: Limits in the plane of the masses of the dark photon and the chargino (light shaded region), as well as limits from a search for two photons and $\not{p}_T$ (dark shaded region).

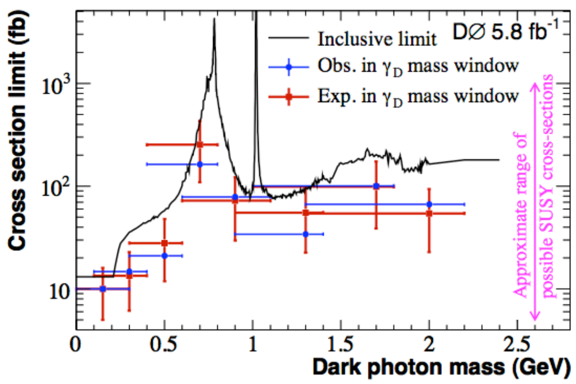

Fig. 15: Cross section limits as a function of dark photon mass from a D0 search for two dark photons resulting from decays of a chargino and a neutralino.

GeV/c^2 or more), but could decay to low-mass states with only the new U(1) charge, or simply radiate a dark photon. The preferred dark photon decay depends on its mass, but is determined entirely by the electromagnetic charge of its decay products.

D0 has searched for the production of a chargino and a neutralino using decays where the lowest mass neutralino partner to SM particles decays to a dark photino, the LSP of the model, and a dark or SM photon. There are two such decays following the production of a chargino and neutralino, and D0 has probed the cases where one includes a dark photon and the other a SM photon [23], and where both include a dark photon [24]. The final states probed are either a high p_T photon and a pair of tracks pointing to an electron energy cluster or a muon track stub, or two such pairs of tracks with similar mass. The search for one dark photon results in limits in the plane of the dark photon mass and the chargino mass, and in the plane of the chargino mass and the branching ratio for the neutralino to decay to a photon and photino. The search excludes chargino masses of around 200 GeV/c^2 for dark photon masses around 1 GeV/c^2 (Fig. 14). Limits on production cross section as a function of dark photon mass are produced from the search for two dark photons, and are about 100 fb for a dark photon mass of 1 GeV/c^2 (Fig. 15).

Sneutrino and Slepton Searches

Direct sneutrino production is typically difficult to observe, as the sneutrino decays to a neutrino and LSP, leaving no trace in the detector. However, when there are R-parity violating couplings. the sneutrino can decay directly into a pair of charged leptons. If there are also R-parity violating couplings between a pair of quarks and the sneutrino, then sneutrino resonances can be observed in hadron collisions. If only the terms relevant for sneutrino production and decay are present, then proton decay is not allowed and the proton actually has a longer lifetime than with R-parity conservation alone (the motivation for keeping just these terms is to invoke baryon number parity conservation).

CDF and D0 have searched for resonant sneutrino production in decays to μμ, eμ, eτ, and μτ, setting limits on the sneutrino mass for various values of the R-parity violating couplings [25]. For example, for a d-d-sneutrino coupling of 0.003 and an e-μ-sneutrino coupling of 0.07, D0 sets a lower mass limit of 280 GeV/c^2. The experiments also interpret their searches in terms of a new gauge boson resonance, or Z', and in terms of graviton production. New limits on a Z' boson from CDF (D0) using the μμ (ee) final state with 4.6 (5.4) fb^{-1} of data exclude a Z' boson with mass below 1071 (1023) GeV/c^2, assuming it has the same couplings to fermions as the Z boson [26]. New limits on gravitons from searches for resonances in 5.4 fb^{-1} of diphoton data (at CDF), and in 5.4 fb^{-1} of diphoton and dielectron data (at D0 [27]), constrain the graviton mass to be greater than about 500 GeV/c^2 for a value of the ratio of curvature of the extra dimension to the Planck mass (k/M_{Pl}) equal to 0.01.

Non-supersymmetry Searches

Even with the large number of supersymmetry parameters, there are signatures that have not (yet) been cast in terms of supersymmetry. It is therefore important to continue to pursue models outside the confines of supersymmetry.

One particularly unusual model adds a new SU(3) gauge group, and particles charged under this group ("quirks") have masses of about 100 GeV/c^2. The strong dynamic energy scale of the group is less than 1 MeV, so quirks bind into diquirk particles that are highly ionizing when they pass through a detector. D0 has searched for such highly-ionizing tracks in events with a high-p_T hadronic jet and an imbalance of momenta measured using the calorimeter [28]. The distribution of track ionization energy is well modelled by SM backgrounds, and D0 sets a lower limit of 107 GeV/c^2 on the mass of a new SU(3) quirk.

Many additional searches are possible when one considers extended gauge groups. If there is, for example, a right-handed version of the weak force, there would be new *W′* and *Z′* gauge bosons coupling to fermions and mixing with the *W* and *Z* gauge bosons. CDF and D0 have searched for resonances decaying to *WZ* and *WW* [29] using final states where one boson decays to quarks, or where both bosons decay to leptons. No evidence for such a resonance has been observed, and a new *W′* boson with the same couplings to SM fermions as the *W* boson has been excluded if its mass is below 500 GeV/c^2.

Summary

The Tevatron experiments are exhaustively searching for new particles with masses spanning several orders of magnitude, from dark photons (m≈1 GeV/c^2) to *Z′* bosons (m≈1 TeV/c^2). Supersymmetry provides a useful context to organize the wide variety of searches, covering slow charged particles, particles decaying in the detector, final states with many combinations of SM particles, and more. The experiments at the Tevatron are also pursuing unique signatures with motivations outside of the framework of supersymmetry, and even signatures with no current motivation (through model-independent approaches). The Tevatron will continue to produce data and provide opportunities for discovery for the next few years.

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