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Supersymmetry Searches at the Tevatron in Run I and Run II

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Supersymmetry Searches at the Tevatron in Run I and Run II

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Abstract

We review the searches for supersymmetric particles achieved by the CDF and D0 collaborations at the $p\bar{p}$ Tevatron collider at FNAL, at $\sqrt{s}$ = 1.8 TeV and with a total integrated luminosity of 110 pb^{-1}, per experiment. The prospects for the forthcoming run at $\sqrt{s}$ = 2 TeV and an integrated luminosity reaching ultimately at least 20 fb^{-1}, are also discussed.

1. Introduction

CDF and D0 collaborations took data from 1992 to 1995 at the $p\bar{p}$ Tevatron collider at $\sqrt{s}$ = 1.8 TeV, in two run periods: Run IA collected about 20 pb^{-1} and Run IB about 90 pb^{-1}. In their "Run I version", the two detectors were rather different.

The D0 detector [1] was characterized by fine-grained high performance e.m. and hadronic calorimetry, entirely based on the liquid argon sampling technique. This detector achieved particularly good electron and photon identification. Moreover with its full coverage and large acceptance for muons, it very accurately measured the total missing transverse energy ($\not{E}_T$).

The CDF detector [2] since its beginning in 1986 relied on a high resolution tracking system, comprised of central tracking tilted cell drift chamber with a relatively large level arm, in a 1.4 T solenoidal field, associated with a level-2 trigger processor. For Run I, a silicon microstrip vertex detector in the innermost part was added to the inner tracker. This overall tracking system provided excellent P_T measurements for charged particles. Furthemore, for the first time, a microvertex detector was succesfully operated in the harsh $p\bar{p}$ environment, allowing for b-tagging.

Both experiments have been actively searching for supersymmetry (SUSY) with some analyses still in progress. An impressive set of results has been obtained in searches for gluinos and squarks, charginos and neutralinos, photon enriched SUSY, third generation squarks, and gravitinos. No evidence has yet been obtained, but in many respects the limits that have been set are beyond or complementary to the ones found at LEP.

2. CDF and D0 SUSY scenarios

Both experiments have considered the Minimal Supersymmetric Standard Model (MSSM), where Minimal stands for *minimal field content* [3]. Additional, and slightly different inputs to the MSSM framework have been introduced by each experiment.

D0 also considered Minimal Supergravity (mSUGRA) [4], which assumes universality at the Grand Unification (GUT) or Planck mass (M_{Pl}) scales. In mSUGRA, there is a common mass ($M_{1/2}$) for all gauginos and a common scalar mass (M_0) at the unification scale, and a common trilinear coupling among scalars (A_0). By adding $\tan\beta$ and sign(μ), the mSUGRA scenario is characterized by only these five parameters. In most of the analyses, D0 uses: $\mu<0$, $\tan\beta$=2 (or varied up to 6 or 10), A_0=0, and in some cases, performs a scan in the (M_0, $M_{1/2}$) space.

In most cases, CDF stays in the MSSM framework, assuming in addition squark and gaugino universality. All the squarks (except the stop) are degenerate in mass: $m(\tilde{q}_R)^2 = m(\tilde{q}_L)^2 = 0.9\ m(\tilde{g})^2 + M_0^2$. Besides these parameters there are also $\tan\beta$, μ (because no universality is assumed in the Higgs sector), and M_{A0} which is set at 500 GeV/c^2. In most studies CDF uses: $\mu = -400$ GeV/c^2, $\tan\beta$=2 or 4, and $A_t=\mu/\tan\beta$. Consequently, the SUSY models used by CDF and D0, although similar, present some differences that can render a direct comparison between the experiments, misleading, if not incorrect.

In the MSSM, R-parity (R_p) defined as $R_p = -1^{3B+L+2S}$ (where B,L,S are respectively the baryon number, lepton number, and particle spin) is a discrete symmetry that is assumed to be conserved, thus leading to a stable lighest SUSY particle. More generally, R_p can be violated (RPV) [5]. So a more general supersymmetry potential is: $W_{SUSY} = W_{RPV} + W_{MSSM}$. After rotating away the Higgs term, the RPV component of the potential is: $W_{RPV} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} U \bar{D}_j \bar{D}_k$, where the first two terms violate lepton number, and the third term violates baryon number. The search for B-violation, characterized by no missing energy and multijets, is extremely difficult to perform at hadron colliders because of the large QCD backgrounds. So both CDF and D0 have focused on lepton violation searches by looking for like-sign dilepton and multilepton signatures.

Other SUSY scenarios studied at the Tevatron are Gauge Mediated Supersymmetry Breaking (GMSB) models [6], which assume a relatively low SUSY breaking scale ($F^{1/2}$). The graviton has a spin 3/2 partner, the gravitino ($\tilde{G}$). A small $F^{1/2}$ leads to a low $m_{\tilde{G}} \propto F/M_{Pl}$ and the gravitino is then the lightest SUSY particle (LSP). The phenomenology depends upon what particle is the next heavier sparticle (NLSP): the neutralino ($\tilde{\chi}_1^0$), or a slepton. The decay length of the NLSP into $\tilde{G}$ is proportional to $m(\tilde{G})$ and can be quite long. Both experiments have chosen to consider $\tilde{\chi}_1^0$ as the NLSP, and assume that it decays promptly into $\gamma\tilde{G}$. In this case the signatures are γ-enriched.

3. SUSY signatures at the Tevatron

A striking evolution in the search for SUSY at hadron colliders has taken place since the early 80's. This has been due to the impressive progress in the theory, accompanied by major advances in detection techniques; for instance, the developments of silicon-based tracking techniques, and advanced microelectronics as well as fast processing systems. Also, there has been the major impact from searches performed at LEP [7].

As a result there is now a large variety of SUSY signatures made of cocktails of elementary triggering "objects", namely the electrons, muons, $\not{E}_T$, γs, jets, bs and τs. The presentation of results follows, as a guideline, the studied signatures.

4. Results from Run I at the Tevatron

This section provides a brief review of the main results obtained at the Tevatron during Run I.

4.1. Missing Energy and Mono- or Multi-jets events

Interest in a monojet signature has been "revived" by the possibility of having a light $\tilde{G}$ in GMSB

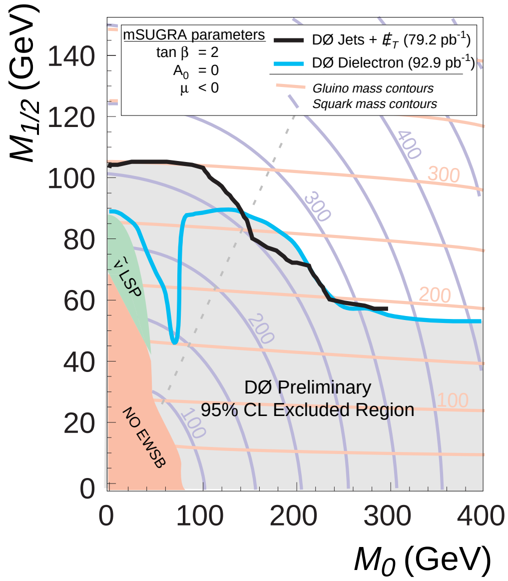

Figure 1. D0 results on $\tilde{g}$, $\tilde{q}$ searches (mSUGRA)

[8]. The search is performed by CDF, using the full Run I integrated luminosity. In this scenario, $\tilde{G}$ is light, all the other superpartners are heavy, and so $\tilde{G}$ could be the only superpartner produced at the Tevatron, through $qq, qg, gg \to \tilde{G}\tilde{G}+(g$ or $q)$. An inclusive monojet selection required the leading jet with E_T >80 GeV and $\not{E}_T$ >200 GeV. The backgrounds include instrumental and known standard model (SM) backgrounds (i.e. W/Z+jets, $t\bar{t}$, WW, WZ and ZZ).

The irreducible background from W/Z+jets was normalized to the $Z \to ee$+jets process. Five events were observed with 10.1 ± 3.4 expected from background. This led to an effective cross section for $\not{E}_T$>200 GeV, of 93 fb, at 95% C.L. and therefore a lower limit on the coupling constant $F^{1/2}$ of 225 GeV. This set a direct limit on $m(\tilde{G})$ of 1.2×10^{-5} eV/c^2, comparable to the results obtained by LEP200 [9].

D0 searched for multijet plus $\not{E}_T$ events from direct or cascade decays of $\tilde{g}$ and $\tilde{q}$ using 80 pb^{-1} of data [10]. The analysis was optimized for mSUGRA models with A_0=0, μ <0, $\tan\beta$=2 and used the next to leading order cross-section calculated by PROSPINO [11]. The selection required at least 3 jets of E_T >25 GeV, the leading jet having E_T > 115 GeV, and $\not{E}_T$ above 75 GeV. The dominant backgrounds are QCD multijets, $t\bar{t}$ and W/Z+jets. A shape analysis was performed to estimate the residual QCD background. The detection efficiency was typically on the order of several %. No excess of

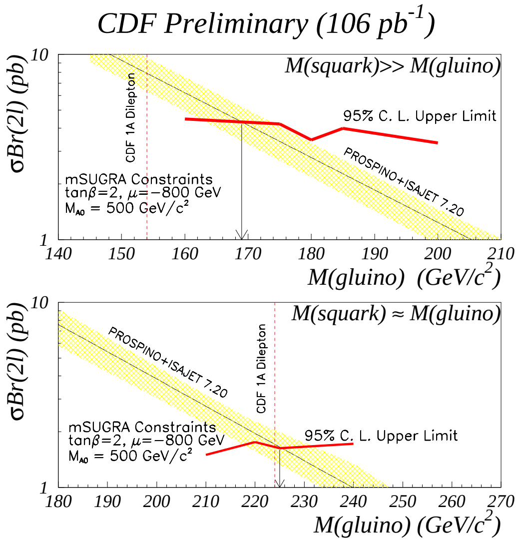

Figure 2. CDF results on $\tilde{g}$, $\tilde{q}$ searches with same sign dileptons (MSSM)

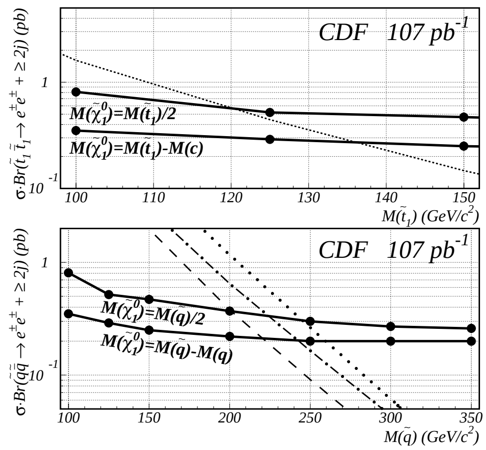

Figure 3. CDF results on $\tilde{q}$, $\tilde{t}_1$, if R_p violation.

events was found. Figure 1 shows the results plotted in the (M_0, $M_{1/2}$) space: for instance, m($\tilde{g}$) $>$ 260 GeV/c^2 if m($\tilde{g}$) $\simeq$ m($\tilde{q}$). A similar analysis is in progress at CDF [12].

4.2. Multilepton Enriched SUSY signatures

Cascade decays of $\tilde{g}$s and $\tilde{q}$s can produce dileptons in addition to multijets and $\not\!\!E_T$ in the MSSM framework. Moreover, for gluino pair production, the probability for like sign or opposite sign dileptons is equal, as the gluinos are Majorana particles. CDF exploited this feature since like sign dileptons have low SM backgrounds. CDF and D0 searched for $ee, e\mu, \mu\mu$ dilepton and $\not\!\!E_T$ events, using the full Run I luminosity. D0 required 2 leptons with around 15 GeV E_T electrons and a number of threshold between 4 and 20 GeV E_T for muons, and a $\not\!\!E_T$ cut varying from 20 to 40 GeV [13]. D0 used SPYTHIA [14] for the M.C. simulations of the signal. The main SM backgrounds are QCD, $t\bar{t}$ and W/Z+jets. D0 observed no excess of events and using mSUGRA set m($\tilde{g}$) $>$ 129 GeV/c^2, m($\tilde{q}$) $>$ 135 GeV/c^2 , as lower limits for M_0 <300 GeV and $\tan\beta$ <10.

CDF performed this search [15] by requiring the 2 leptons to be of same sign, applied both a calorimetry and track isolation cut, and used ISAJET [16] with PROSPINO next to leading order (NLO) calculations. No events were observed when 0.6±0.3 were expected from background. The obtained limits are shown in Figure 2. They indicate a limit of 226 GeV/c^2 for m($\tilde{g}$) $\simeq$ m($\tilde{q}$) and of 169 GeV/c^2 for m($\tilde{q}$) $\gg$ m($\tilde{g}$).

If R_p is not conserved, the above signature loses its "$\not\!\!E_T$-ness". If $\tilde{g} \rightarrow \bar{c}\tilde{c}_L$ then the λ'_{121} coupling in the $L_1Q_2D_1^c$ interaction allows for $\tilde{c_L} \rightarrow e^+d$. The process is thus: $p\bar{p} \rightarrow \tilde{g}\tilde{g} \rightarrow \bar{c}\tilde{c}_L\bar{c}\tilde{c}_L \rightarrow \bar{c}\bar{c}(l^+d)(l^+d)$. This scenario assumes m($\tilde{c}_L$) = 200 GeV/c^2, because of HERA results [17]. No like sign dileptons events passed the selection. Limits were obtained in the ($\tilde{g}$,$\tilde{q}$) mass plane with m($\tilde{g}$) $>$ 260 GeV/c^2 for m($\tilde{q}$) = 800 GeV/c^2 and Br($\tilde{c_L} \rightarrow ed$) = 1.0 [18].

This analysis also looked for $\tilde{q}$, including $\tilde{t}$, pair production. The decays of the $\tilde{q}$ (or $\tilde{t}$) into q (or c) and $\tilde{\chi}_1^0$ were considered with a lepton number violating $\tilde{\chi}_1^0$ decay into $qq'l^+$. This gives: $\tilde{t}\bar{\tilde{t}} \rightarrow c\tilde{\chi}_1^0\bar{c}\tilde{\chi}_1^0 \rightarrow c(qq'e^+)\bar{c}(qq'e^+)$, and similarly for $\tilde{q}\bar{\tilde{q}} \rightarrow q(q'q''e^+)\bar{q}(q'q''e^+)$, resulting in like sign dileptons and multijets. CDF assumed a branching ratio of 100% for the decay of $\tilde{q} \rightarrow q\tilde{\chi}_1^0$, equal rates for all the possible lepton violation LSP decays and, m($\tilde{\chi}_1^\pm$) $>$ m($\tilde{q}$) $>$ m($\tilde{\chi}_1^0$). Thus an upper limit of 135 GeV/c^2 was obtained for m($\tilde{t}_1$) and m($\tilde{q}$) $>$ 200, or 260 GeV/c^2, depending on m($\tilde{g}$) and m($\tilde{\chi}_1^0$). Figure 3 shows the limits as solid lines and the broken lines are the NLO cross sections multiplied by the appropriate branching ratio. The muon channel analysis is underway.

D0 performed a similar RPV search for $\tilde{q}$ and $\tilde{g}$ by looking for dielectrons, without charge sign requirement, but enhacing the "multijetiness" of the event by asking for at least 4 jets [19]. They assumed mSUGRA with A_0=0, μ <0 and $\tan\beta$=2; 1.8±0.4 events were expected from SM

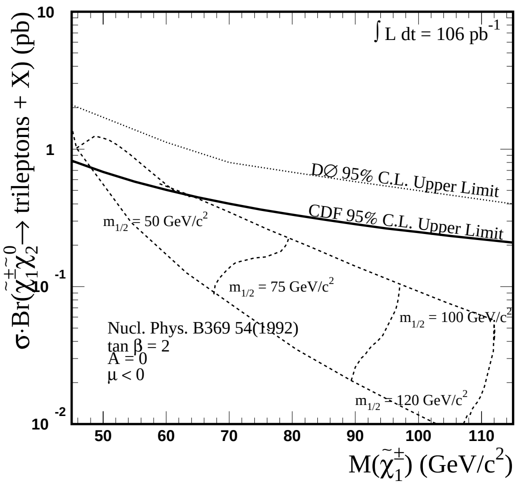

Figure 4. D0 and CDF limits on m($\tilde{\chi}_1^{\pm}$) from the trilepton search (MSSM), where the expected $\sigma\times$ Br expressed as a function of the mSUGRA masses are overlaid.

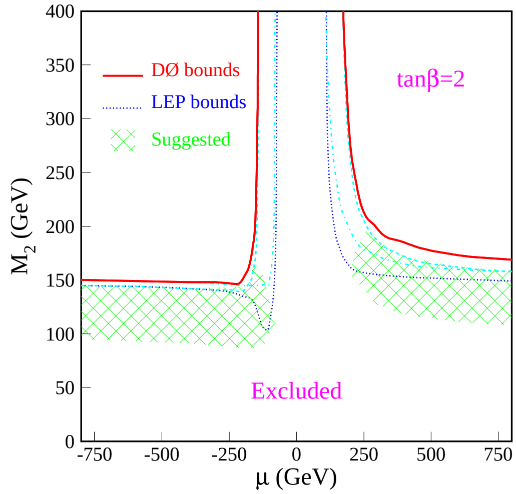

Figure 5. D0 results on diphoton events from $p\bar{p}\to\tilde{\chi}_i\tilde{\chi}_j$ in GMSB framework.

backgrounds, and 2 observed. D0 set the following limits: m($\tilde{q}$) $>$ 243 GeV/c^2 and m($\tilde{g}$) $>$227 GeV/c^2, if m($\tilde{g}$) $\neq$ m($\tilde{q}$), and, m($\tilde{g}$) $>$277 GeV/c^2, if m($\tilde{g}$) $\simeq$ m($\tilde{q}$).

Multilepton signatures become quite striking in the RPV scheme when looking at the process: $p\bar{p}\to\tilde{\chi}_1^0\tilde{\chi}_1^0+X$. It produces 4 lepton events if the LSP decays promptly. The main SM background is instrumental, namely fake leptons and standard $b\bar{b}$ and $c\bar{c}$. CDF performed this analysis in a mSUGRA framework, observed 1 event with 1.3$\pm$0.4 expected, and set a limit on m($\tilde{q}$) above 360 GeV/c^2 for M$_0>$ 130 GeV, and m($\tilde{g}$) $>$ 380 GeV/c^2 for m($\tilde{\nu}$) $>$55 GeV/c^2 [20].

The promising trilepton and $\not{E}_T$ signature is produced by $p\bar{p}\to\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ where $\tilde{\chi}_1^{\pm}\to l^{\pm}\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0\to l^+l^-\tilde{\chi}_1^0$ [21]. CDF (106pb^{-1}) [22] and D0 (95pb^{-1}) [23] searched for $eee, ee\mu, e\mu\mu, \mu\mu\mu$ events with additional requirements on the electric charges of the leptons by CDF. No events were observed in either experiment, with 1.2$\pm$0.2 in CDF and 1.3$\pm$0.4 in D0 expected from the SM backgrounds (i.e. $WZ, ZZ, Zb, Wbb, t\bar{t}, Z/\gamma+$fake leptons). The typical efficiency was 3 to 12% in CDF and 2 to 6% in D0, for m($\tilde{\chi}_1^{\pm}$) between 50 and 100 GeV/c^2. The results were interpreted in the MSSM framework with tan β=2, $\mu<$0 and m($\tilde{\chi}_1^{\pm}$) $\sim$ m($\tilde{\chi}_2^0$) $\sim$ 2m($\tilde{\chi}_1^0$) (see Figure 4). For m($\tilde{q}$) $\simeq$ m($\tilde{g}$) and $\mu=-600$ GeV/c^2, it gives m($\tilde{\chi}_1^{\pm}$) $>$ 81.5 GeV/c^2, which is slightly lower than the direct limit from LEP [24].

CDF is currently pursuing this analysis [25] by searching for like sign dileptons, thereby extending the present reach, and by looking for τ signatures, which dominate at high tan β [26].

4.3. Enriched-Photon SUSY signatures

Both GMSB and MSSM models can give γ-enriched events. Indeed if the $\tilde{G}$ is the LSP, and the $\tilde{\chi}_1^0$ decays promptly into $\gamma\tilde{G}$, processes like: $p\bar{p}\to\tilde{\chi}_i\tilde{\chi}_j\to\tilde{\chi}_1^0\tilde{\chi}_1^0+\mathrm{X}\to\gamma\gamma\tilde{G}\tilde{G}+X$, produce diphotons with large $\not{E}_T$.

D0 performed this analysis with data corresponding to 106pb^{-1} [27]. Two events were observed, with 2.3$\pm$0.9 expected from the SM and instrumental backgrounds. A lower limit of 150 GeV/c^2 was set for the chargino at 95%C.L (see Figure 5).

The MSSM can also produce γ-enriched signatures such as single photon and $\not{E}_T$ with multijets, if the decay $\tilde{\chi}_2^0\to\gamma+\tilde{\chi}_1^0$ is dominant. D0 looked at this case with 99 pb^{-1} of data, and found: m($\tilde{g}$) $>$ 310 GeV/c^2, for m($\tilde{q}$) $\simeq$ m($\tilde{g}$), and m($\tilde{g}$) $>$ 240 GeV/c^2, for m($\tilde{q}$) $\gg$ m($\tilde{g}$) [28].

At CDF, a search is underway for an excess of events over SM background, with different possible signatures, all including at least one hard photon [29].

4.4. Heavy-Flavour-tagged SUSY events

These searches focused mainly on looking for $\tilde{t}_1$ and $\tilde{b}_1$ pair production. The stop can be the lightest squark because of the high top mass, which leads to large mixing and a large Yukawa coupling. It is strongly produced in gg fusion and $q\bar{q}$ annihilation

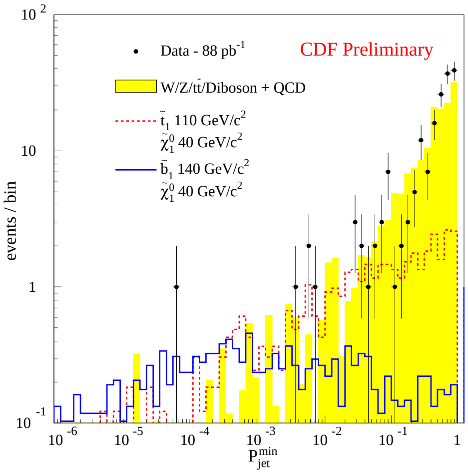

Figure 6. Primary jet probability (JP) for b and c tagging in CDF.

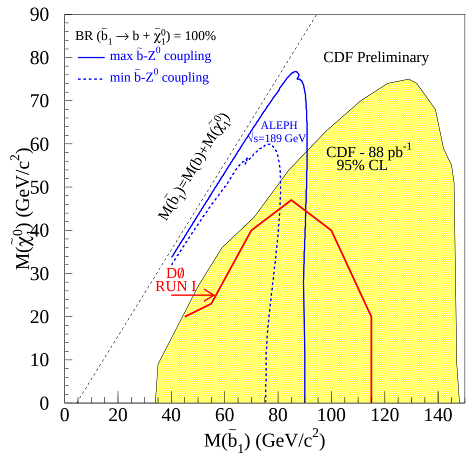

Figure 7. CDF and D0 results on $\tilde{b}_1 \to b\tilde{\chi}^0_1$. Comparison with ALEPH at $\sqrt{s}$ = 189 GeV.

and the cross-section for $p\bar{p} \to \tilde{t}_1\bar{\tilde{t}}_1$ depends only on m($\tilde{t}_1$). For tan $\beta \geq$10, large $\tilde{b}_L - \tilde{b}_R$ mixing can make $\tilde{b}_1$ the lightest squark. Both CDF and D0 looked for $\tilde{b}$ pair production, which provides 2 b jets and 2 $\tilde{\chi}^0_1$ i.e., $\not{E}_T$. D0 required 2 jets and missing energy above 40 GeV, and performed b identification by requesting one of the jets to have an associated muon. No excess of events was observed [30].

CDF looked for 2 or 3 jets vetoing any extra jet or leptons and asked for large $\not{E}_T$ [31]. Moreover, CDF performed heavy flavour tagging, using the microvertex information. This tagging is based on constructing the probability (JP) that the ensemble of tracks in a jet is consistent with being from the primary vertex [32]. For jets originating from the primary vertex JP gives a flat distribution between 0 and 1. If a jet originates from a secondary vertex, JP peaks at 0 (Figure 6). This algorithm was also used to tag c jets, and was checked on a charm enriched sample. CDF observed 5 events, while expecting 5.8±1.8 from SM backgrounds. Figure 7 shows the results of this analysis and compares them with those of D0 and ALEPH. A similar analysis was used by CDF [31] and D0 [33] (Run IB data) to look for $\tilde{t}_1 \to c\tilde{\chi}^0_1$, with flavour tagging at CDF optimized for charm selection. The obtained limits are beyond those found at LEP. However, it should be noted that only LEP was able to cover the case where m($\tilde{t}_1, \tilde{b}_1$)-m($\tilde{\chi}^0_1$) $\leq$ 30 GeV/c^2, down to a very small mass splitting between $\tilde{t}$ or $\tilde{b}$ and $\tilde{\chi}^0_1$ [34].

Exploiting its b-tagging ability, CDF looked for other stop decay channels. A search for $\tilde{t}_1 \to b\tilde{\chi}^{\pm}_1$ where $\tilde{\chi}^{\pm}_1 \to \tilde{\chi}^0_1 l^{\pm}\nu_l$ was performed making use of $bl\not{E}_T$ signature [35]. The b-tag was based on the selection of tracks with a significant impact parameter inside a given jet and for the reconstructed secondary vertex. There were 81 events observed, with 86.2±5.2 expected from SM and instrumental backgrounds.

If the above decay is not kinematically allowed and if the $\tilde{\nu}$ is light, the decay of $\tilde{t}_1$ into $bl^{\pm}\tilde{\nu}$ dominates [35]. By applying the same selection as before, and assuming an equal branching ratio for e, μ or τ, CDF obtained the limit m($\tilde{t}_1$) >120 GeV/c^2 for m($\tilde{\nu}$)=45 GeV/c^2, assuming a 100% branching ratio in this decay mode of $\tilde{t}_1$.

A possible SUSY-decay of the top quark into $\tilde{t}_1 + \tilde{\chi}^0_1$ was also addressed, where $\tilde{t}_1 \to b\tilde{\chi}^{\pm}_1$ [36]. The main background is the SM process $t\bar{t} \to WbW\bar{b}$ with semi-leptonic or hadronic decays of bs. A likelihood method based on the E$_T$ of the second and third highest E$_T$ jets in the event, retained 9 events, all compatible with SM expectations.

In conclusion, with the Run I data sample, D0 and CDF searched for $\tilde{g}, \tilde{q}, \tilde{\chi}^0_{1,2}, \tilde{\chi}^{\pm}_1, \tilde{t}_1, \tilde{b}_1, \tilde{G}$, in various SUSY-scenarios. Some analyses are still underway. Many possible signatures have been looked for by fully exploiting the potential of these detectors. Athough no evidence has yet been found, very valuable experience has been gained for Run II.

5. SUSY Discovery Prospects at the Tevatron in Run II

Run II at the Tevatron will provide a unique window in the SUSY phase space, and a unique opportunity for examination between LEP200 and LHC. It will benefit from major improvements, both in the machine and in the detectors. The Collider has a new Main Injector. The c.m.s energy will be increased from 1.8 to 2 TeV, giving an increase in the cross sections by 20% to 100%, depending on the process. Moreover the total integrated luminosity will increase, first by a factor of 20, and then by a factor of at least 200, as compared to Run I, and this before the LHC starts running.

Both CDF [37] and D0 [38] are undergoing vigorous upgrades including: the calorimetry (CDF), the muons (extended coverage in CDF), the tracking (both D0 and CDF), the front-end and readout electronics (both D0 and CDF), the DAQ and triggering system (both D0 and CDF). The major challenges are certainly the tracking systems, including the silicon microstrip trackers and the central outer trackers. In CDF, the outer tracker is a remake of the Run I drift chamber, but adapted to the more demanding conditions of Run II. In D0, the tracker is based on a new tracking technique using scintillating fibers; additionally, a 2T solenoid is now installed. Another key element is the sophisticated triggering systems to cope with much larger event rates than in Run I. The experience gained in Run I will be a major bonus.

Many analyses are in progress to study the physics prospects in Run II [39]. As example, Figure 8 shows the CDF sensitivity to look for the stop [40]. A limit of 150 GeV/c^2 could be reached with 2 fb^{-1}, in the $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$, with m($\tilde{\nu}$) = 50 GeV/c^2. The access to channels such as $\tilde{g} \to t\tilde{t}_1$ and $t \to \tilde{t}_1\tilde{\chi}_1^0$, will permit better coverage of the case of low mass splitting between $\tilde{t}_1$ and $\tilde{\chi}_1^0$, thanks also to the improved microvertex detectors. Figure 9 summarizes the limits obtained in Run I, and the prospects for reach in Run II.

In conclusion, Run I at the Tevatron has been marked by the top discovery, the demonstration that hadronic colliders can compete with lepton machines in B-physics, and an impressive activity to explore issues beyond the standard model. Run II will provide a unique opportunity for the coming 5 to 7 years to penetrate the SUSY-world, in a crucial mass-range. So stay tuned!

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Many thanks to all my D0 and CDF scolleagues.

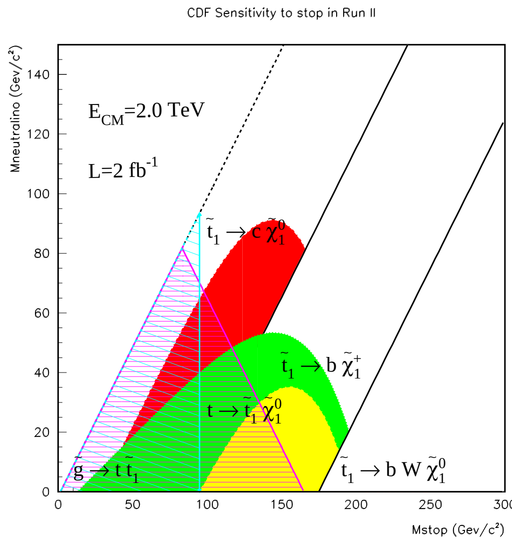

Figure 8. Sensitivity to stop in Run II for L=2fb^{-1}.

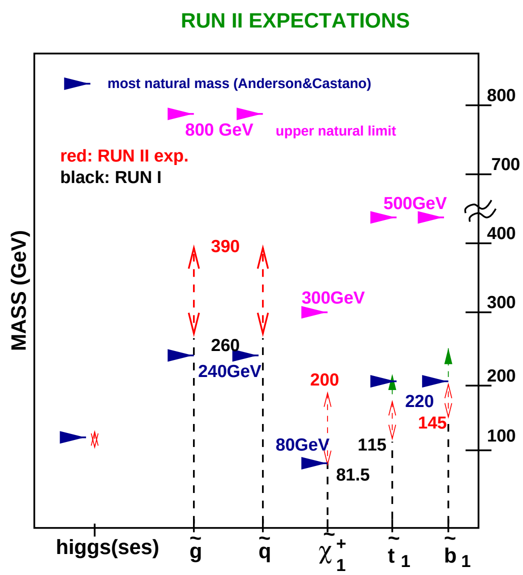

Figure 9. Run I results and Run II prospects (MSSM).

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