Beyond the Standard Model at Tevatron

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This article presents recent results of searches for physics beyond the Standard Model using the CDF and the DØ detector at the Fermilab Tevatron Collider. All results shown correspond to analysis performed using the past 1992-1996 Fermilab Tevatron run I data (roughly 100 pb$^{-1}$ per each experiment). In particular we describe recent Tevatron searches for scalar top in the $b+\ell+\text{missing-}E_T$ channel, for squark and gluinos using like-sign dileptons (LS), for large extra space-time dimensions and the search for leptoquarks and technicolor in the missing-\text{\emph{E}}$_T$+heavy flavour jet events. Tight limits on the existence of such models have been set.

1 Introduction

The Standard Model (SM) represents the simplest and most economical theory which describes jointly weak and electromagnetic interactions. At present it continues to survive all experimental tests at accelerators, providing a remarkably successful description of known phenomena; some precision observable tests it at 10$^{-3}$ levels. In spite of that, there are plenty of aspects that we do not understand yet and that may suggest the SM to be most likely, a low energy effective theory of spin-1/2 matter fermions interacting via spin-1 gauge bosons. The physical motivations for the searches described below come from the attempt to check various possible extensions of the SM.

2 Supersymmetry Searches

An excellent candidate to a new theory, able to describe physics at arbitrarily high energies, is Supersymmetry (SUSY). SUSY is a larger space-time symmetry, that relates bosons to fermions so that, in the vast space of all viable physics theories, SUSY is not simply a point. Almost any theory can be supersymmetrized and the large array of choices for spontaneous SUSY breaking (SB) just enhance these possibilities. A comprehensive SUSY search is almost impossible: i.e. the most general minimal supersymmetric extension of the SM (MSSM) counts 124 truly independent parameters. The strategy is then to search for signals suggested by particular models in which theoretical assumptions are also adopted to reduce the number of free parameters to a few. Even if we don’t have direct experimental evidences of SUSY, there are remarkable theoretical properties that provide ample motivation for its study. SUSY describes electroweak data equally well as SM but, in addition, allows the unification of the gauge couplings constants, the unification of the Yukawa couplings and do not require the incredible fine tuning, endemic to the SM Higgs sector. Naturally, SUSY cannot be an exact symmetry of the nature, as none of the predicted spin 0 partners of the quarks or leptons and none of the spin 1/2 partners of the gauge bosons have been observed so far.
In SUSY models fermions can couple to a sfermion and a fermion, violating lepton (L) and/or baryon number (B). To avoid this problem, a new quantum number, the $R$-parity ($R_P$), has been introduced. $R$-parity is a multiplicative quantum number defined as $R_P = (-1)^{3B+L+2S}$, where $S$ is the spin of the particle. For the SM particles $R_P = +1$; $R_P = -1$ for the SUSY partners. Most searches for supersymmetric particles assume $R_P$ conservation. This assumption has deep phenomenological consequences. SUSY particles can only be pair produced; the Lightest Supersymmetric Particle (LSP) does exist and it is stable and interacts very weakly with the ordinary matter, leading to a robust missing transverse energy signature ($E_T^M$): the LSP is a natural candidate for the dark matter. However, SUSY does not require $R_P$ conservation and viable $R_P$ violating models ($\mathcal{R}_P$) can be built by adding explicitly $B$-violating and/or $L$-violating couplings to the SUSY Lagrangian.

In this article we present both searches based or not on the assumption of $R_P$ conservation.

### 2.1 Scalar top quark searches

Search for scalar top is particularly interesting since in many SUSY models the top-squark eigenstate $\tilde{t}_1$ (stop) is expected to be the lightest squark. The strong Yukawa coupling between top/stop and Higgs fields gives rise in fact to potentially large mixing effects and mass splitting.

Both the CDF and DØ experiments have already reported searches for direct stop quark pair production: $pp \rightarrow \tilde{t}_1\bar{\tilde{t}}_1$ with the $\tilde{t}_1$ decaying into $\tilde{t}_1 \rightarrow c\tilde{\chi}^0_1$ or $\tilde{t}_1 \rightarrow b\tilde{\chi}^\pm_1$, as well as for SUSY top decays: $t \rightarrow \tilde{t}_1\tilde{\chi}^0_1$ with $\tilde{t}_1 \rightarrow b\tilde{\chi}^+_1$.

CDF recently searched for $\tilde{t}_1\bar{\tilde{t}}_1$ production, assuming $R_P$ conservation, within the framework of the MSSM, for the case where $m_{\tilde{t}_1} < m_t$. Two separate $\tilde{t}_1$ decay modes have been considered: $\tilde{t}_1 \rightarrow b\tilde{\chi}^+_1$, with the chargino decaying into $\ell^+\nu\tilde{\chi}^0_1 (\ell = e, \mu)$ and $\tilde{t}_1 \rightarrow b\ell^+\tilde{\nu}$, dominant whenever $\tilde{t}_1 \rightarrow b\tilde{\chi}^+_1$ is not kinematically allowed. The search have been done assuming the following branching ratios for the involved processes: $B(\tilde{t}_1 \rightarrow b\tilde{\chi}^+_1) = 100\%$, $B(\tilde{\chi}^+_1 \rightarrow \ell^+\nu\tilde{\chi}^0_1) = 11\%$ and $B(\tilde{t}_1 \rightarrow b\ell^+\tilde{\nu}) = 33.3\%$. In these two scenarios, either the $\tilde{\chi}^0_1$ or the $\tilde{\nu}$ is the LSP. The event signature is $2b$-jets+$\ell+$ $E_T$ in both the cases; hence events have been selected requiring the presence of at least one $e$ or $\mu$ with $p_T > 10$ GeV/c, two or more jets, with cone size of $R = \sqrt{\Delta y^2 + \Delta \phi^2} = 0.7$ and $E_T^{\text{jet}}> 12$ GeV, $E_T^{\text{miss}} > 8$ GeV (jets have been ordered by energy) and large missing-$E_T$ from the neutral LSP's: $E_T > 25$ GeV with $\Delta \phi(E_T, \text{jet}) > 0.5$. At least one jet has to be identified as a $b$-jet candidate using a method known as SVX tagging. The significant SM backgrounds: $t\bar{t}$, $b\bar{b}$, $W^\pm(\rightarrow \ell^\pm \nu) + 2$ jets and fake lepton events are predicted to contribute for $87.3 \pm 8.8$ events while 81 are observed in the data. To determine the number of potential signal events in this final data sample for both decay scenarios we used an extended unbinned likelihood fits for each $\tilde{t}_1$ mass considered. The likelihood fits compare the shapes of the signal and backgrounds distributions, and Kolmogorov tests are used in order to determine the most sensitive kinematic distribution to use in the fit. All fit results at all masses are consistent with zero signal events. The 95% C.L. limits on $\sigma_{\tilde{t}_1\tilde{t}_1}$ for $\tilde{t}_1 \rightarrow b\tilde{\chi}^+_1$ and for $\tilde{t}_1 \rightarrow b\ell^+\tilde{\nu}$ as function of $m_{\tilde{t}_1}$ are
shown in Figure 1 and 2. The resulting excluded regions (m_{\tilde{t}_1} versus m_{\tilde{\nu}}), for \tilde{t}_1 \rightarrow b\ell^+\bar{\nu} are given in Figure 3.

2.2 Search for squarks and gluinos using LS dileptons

Gluinos (\tilde{g}) and squarks (\tilde{q}) can decay, via charginos (\chi^\pm) and neutralinos (\chi^0), to final states containing two or more leptons. Since the gluino is a Majorana particle, a large fraction of like-sign dilepton (LS) events will be produced. Squarks and gluinos have been searched by Tevatron experiments looking mainly for \tilde{B}T+multijet events. Complementary to these classic \tilde{E}T+multijet searches, recently CDF looked for gluinos decaying through charginos or neutralinos giving the LS signature: \ell^\pm + jets + \tilde{B}_T.

Data have been selected by asking for an isolated central lepton (e or \mu) with E_T^{\ell} > 11 GeV and for a second one with E_T^{\ell2} > 5 GeV. In order to reject background from B's, leptons were asked to be well separated in the \eta-\phi plane. Events were also required to contain two jets in the pseudorapidity region |\eta| < 2.4 with E_T > 15 GeV and at least 25 GeV of \tilde{E}_T. Then the like-sign requirement on the dilepton event sample has been applied.

No candidate events have been observed, which is consistent with the SM background expectations (mostly t\bar{t}, b\bar{b}, diboson, and Drell-Yan processes). The results of the analysis are shown in Figure 3 where the 95% C.L. exclusion region is plotted as function of squark versus gluino mass. The model assumes tan\beta = 2, \mu = -800 GeV/c^2, A_t = \mu/\tan\beta, A_b = A_t = \mu \tan\beta, and m_{\chi^0} = 500 GeV/c^2. Constraining the squark masses to have an infinite value, we can exclude gluino masses up to 168 GeV/c^2; assuming the squark and sgluinos masses nearly equal then we reach a limit of 221 GeV/c^2.
2.3 Search for $R$-parity violation in multilepton channel

There exists a well-motivated Minimal SUSY extension of the SM in which supersymmetry breaking is communicated to the SM particles and to the sparticles via gravitational interactions (mSUGRA). A mSUGRA model with $R_P$ conservation has only 5 free parameters. Allowing $R_P$ non-conservation requires 45 more parameters. Then general super-potential can be written as: $W_{MSSM} + \lambda_{ijk} L_i \tilde{L}_j \tilde{E}_k + \lambda'_{ijk} L_i Q_j \tilde{D}_k + \lambda''_{ijk} \tilde{U}_j \tilde{D}_k + \mu_i H_2 L_i$ where we have 45 Yukawa-type coupling terms (9 $\lambda_{ijk}$, 27 $\lambda'_{ijk}$ and 9 $\lambda''_{ijk}$). If the $B$-violating terms ($\lambda''$) lead to events with multijet signatures, difficult to study at hadron colliders, $L$-violating terms ($\lambda$ and $\lambda'$) give rise to multilepton and multijet final states. Recently DØ searched for mSUGRA with $R_P$ assuming non-zero $\lambda_{ijk}$ couplings then allowing the decay of LSP (assumed to be $\tilde{\chi}^0_1$) into two charged leptons and a neutrino. The model also assumes that only one $\lambda_{ijk}$ is non-zero at a time and that 0.001 $< \lambda < 0.01$ that means that $R_P$ introduces negligible changes in the production and decay of SUSY particles and that LSP is forced to decay at least 1 cm from the vertex ($\lambda > 0.001$). The event signature is then 2 LSPs that decay, yelding events with $\geq 4\ell + E_T$. This search reinterpreted the results of a previous DØ search for gaugino pair production ($\tilde{\chi}^\pm_1 \tilde{\chi}^0_2$) in multilepton channel. The event selection and background estimations used are the same of this work; trilepton events (\(\ell = e, \mu\)) are selected requiring $0 < |\eta(e)| < 1.2$, $1.4 < |\eta(e)| < 3.5$ and $0 < |\eta(\mu)| < 1.2$ and by applying cuts on $E_T^{\ell}$, $\Delta \phi(\ell, E_T)$ and $\Delta \phi(\mu, E_T)$ to remove instrumental background and cosmic rays. No candidate events have been observed, which is consistent with the expected SM background (see table 1).
Figure 5: $D\Phi$ Search for $R$-Parity SUSY in multilepton events. The plots show results in the mSUGRA mass plane for $A_0 = 0$, $\tan\beta = 5$ and $\mu < 0$ (left) or $\mu > 0$ (right).

Figure 6: $D\Phi$ Search for $R$-Parity SUSY in multilepton events. The plots show results in the mSUGRA mass plane for $A_0 = 0$, $\tan\beta = 10$ and $\mu < 0$ (left) or $\mu > 0$ (right).
Limits on $R_P$ mSUGRA models can be set as a function of the following 5 parameters: $m_0$, $m_{1/2}$, $A_0$, tan $\beta$ and $\mu$. Figures 3 and 4 show, respectively, the exclusion regions in the $(m_0, m_{1/2})$ plane for the three chosen couplings, for tan $\beta = 5$ and tan $\beta = 10$ for both $\mu > 0$ and $\mu < 0$. The dashed lines indicates the limit of sensitivity in $m_{1/2}$ for at least favourable case. The exclusion regions correspond to the spaces below the solid lines labelled with the coupling types, and above the higher of the dashed line and the dash-dotted curves specifying the numerical values of $\lambda$. In the regions beyond the dash-dotted curves, the average decay length of the LSP calculated for the value of the coupling indicated on the curve, is less than 1 cm.

3 Searches for Large Extra Dimensions

Motivated in part by naturalness issues, recently, it has been pointed out that there are more reasons to suggest extra dimensions than just having a self-consistent description of gravity. The additional motivations include new directions to attack the hierarchy problem and the cosmological constant problem, unifying the gravitational coupling with the gauge couplings, perturbative supersymmetry breaking in string theory, and low-scale compactifications of string theory. In such scenario, the hierarchy problem could be solved by having gravity play a role at the electroweak scale. The SM fields are then confined to propagate on a $3 + 1$ d-brane, and the gravity lives in the bulk of the $(4 + n)$ dimensional space-time, where the $n$ dimensions are compactified. The size of extra dimensions is $M_{pl}^2 \sim M_S^{n+2} R^2$ where $M_S$, the compactification-scale, is the only fundamental scale of the nature. As $M_S$ could lie in the TeV range this would offer the possibility that effects might be visible at Tevatron Collider. In particular indirect effects of massive graviton exchange may be enhanced by the sum of the Kaluza-Klein states ($KK$) and provide various signals in the collider phenomenologies. Moreover the spin-two nature of gravitons will also result in some characteristic effects on the polarisation observables. In the absence of evidence for extra dimensions is becoming common to set 95% CL limits as function of $F/M_S^2$, where $F$ is a dimensionless parameter related to the number of extra dimensions. DØ has recently carried out a search on the effect of $KK$ tower exchange on Drell-Yan dielectron and diphoton production, fitting 127 pb$^{-1}$ of data to 2-dimensional templates in $M_{ll}$ versus $\cos \theta^*$. No evidence for these effects has been found and lower limit on the parameter $F/M_S^2$ as function of the number of extra dimensions have been obtained. For $n$ values between 2 and 7, $M_S$ values below 1.3 $\sim$ 1.0 are respectively ruled out (see Figure 5).
Analogous searches for extra dimension in the Drell-Yan, diphoton and $E_T$ channels are in progress at CDF.

4 Search for Leptoquark and Technicolor

The observed symmetry, in the spectrum of fundamental particles, between quarks and leptons suggests that, if there exists a more fundamental theory, it should also introduce a more fundamental relation between them. Such lepton-quark unification is achieved in the context of different theories. Leptons and quarks may be arranged in common multiplets, like in Grand Unified Theories (GUT) or superstring motivated $E_6$ models or they may have a common substructure as in composite models. Whenever quarks and leptons are allowed to couple directly to each other, a quark-lepton bound state can also exist. Such particles, called leptoquarks, are color triplet bosons ($SU(3)_C$) of spin 0 or 1, carrying lepton ($L$) and baryon ($B$) number and a fractional electric charge. At Tevatron, leptoquarks are predicted to be produced dominantly via gluon-gluon fusion and $q\bar{q}$ annihilation: $p\bar{p} \rightarrow g + X \rightarrow LQ\bar{LQ} + X$. The production cross section is nearly independent from the Yukawa couplings between the $LQ$s and their decay lepton-quark pairs. Both CDF and DØ performed in the past years a number of searches for leptoquarks. In this paper we report the most recent Tevatron results.

In contrast to the previous searches, sensitive to branching ratios $B(LQ \rightarrow \ell + jets) > 0$, CDF has searched for second and third generation leptoquarks in two different theoretical context: a) continuum $LQ$s pair production with $LQ2 \rightarrow e\nu\ell$ and $LQ3 \rightarrow b\nu\tau$ ($LQ$s are either scalar or vector); b) resonant Technicolor $LQ$s.

Final states which contain two heavy flavor jets ($c$-jets or $b$-jets for second or third...
generations of LQs), large missing-\(E_T\) (from neutrinos), and no high-\(p_T\) leptons were searched. This signature is the same of the CDF’s search for FCNC decay of the scalar top and scalar bottom quark: \(\tilde{t}_1 \rightarrow c\tilde{\chi}_0^1, \tilde{b}_1 \rightarrow c\tilde{\chi}_0^1\).

Data have been selected using online triggers that requires large missing-\(E_T\) (\(\not{E}_T > 35\) GeV). The QCD background is reduced by requiring 2 or 3 jets with \(E_T > 15\) GeV with \(|\eta| < 2\) and by excluding events containing jets with \(7 \text{ GeV} < E_T < 15\) GeV in the region \(|\eta| < 3.6\). Further cuts have been applied in order to remove fake sources of \(E_T\): \(\Delta\phi(B_T, jet_{1,2}) > 45, \Delta\phi(B_T, jet_1) < 165\) and \(\Delta\phi(jet_1, jet_2) > 165\) and \(W\) and \(Z^0\) are reduced by vetoing events with high-\(p_T\) leptons (\(e, \mu\)). Heavy flavour jets are then identified using a method known as jet probability tag that calculates, using the SVX informations, the probability that a cluster tracks form a jet originated from the primary vertex. In the \(c\bar{c}nu, \bar{\nu}_\tau\) channel, 11 events are observed with an expected SM contribution of \(14.5 \pm 4.2\); in the \(b\bar{b}nu, \bar{\nu}_\tau\) 5 events are observed with an expected number of SM events of \(5.8 \pm 1.8\). Figures 8 and 9 show respectively the limits on \(\pi_{LQ}\) production via color-octet technirho decays and the continuum leptoquark limits for \(LQ2\) and \(LQ3\).

5 Conclusions

Tevatron experiments performed extensive searches for physics beyond the Standard Model. No positive results have been found so far showing that the data are consistent with the SM expectations. CDF and D0 continue the analysis of Run I data placing limits on new physics, including Supersymmetry, large space-time dimensions and leptoquark models. With the Run II upgrades, providing an higher acceptance and higher luminosity, it will be possible to make important progresses.
Figure 9: CDF Comparison between the 95% C.L. upper limit on the production cross section for \( LQ_2 \rightarrow \nu_\mu c \) and \( LQ_3 \rightarrow \nu_\tau b \) and the theoretical predictions.

in the search for new phenomena as well as in setting limits on a larger variety of theoretical models.

6 Acknowledgments

I would like to express my appreciation to the organizers and to the other speakers for the immensely stimulating and enjoyable conference.

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$p_T = p \sin \theta$. If the magnitude of this vector is obtained using the calorimeter energy rather than the spectrometer momentum, it becomes the transverse energy $E_T$. Jets are defined as clusters of energy in $\eta - \phi$ space with a fix cone size. The missing transverse energy ($\not\! E_T$) is defined as the difference between the vector sum of all the transverse energies and zero.

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