SEARCHES IN LEPTON FINAL STATES AT THE TEVATRON

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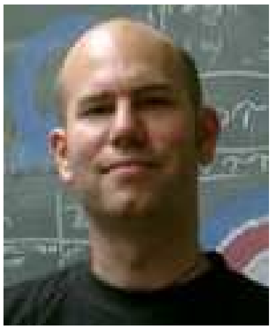

In this report, searches for new physics in final states involving leptons from the CDF and DØ experiments will be presented. Different theories beyond the Standard Model will be considered, including supersymmetry, extra gauge bosons and extra dimensions. The results presented here are based on integrated luminosities ranging from 1 to 3 fb^{-1}.

1 Introduction

Although the Standard Model (SM) provides a good description of the experimental data, it is known, that it cannot be the final theory of nature, since it has some caveats and does not provide answers to many problems. Thus there have been many attempts to extend the SM to answer at least some of the open questions.

One of the most promising theories is Supersymmetry (SUSY), which is the only possible extension of the Poincaré group. In the Minimal Supersymmetric Model (MSSM) [1], a new superpartner is introduced for every SM particle, differing only in spin by 1/2. Since no supersymmetric particles have been observed so far, SUSY must be broken if it exists. But this SUSY breaking mechanism is unknown. One of the most studied scenarios is the so–called mSUGRA model, where the SUSY breaking from the hidden sector at very high energies is transmitted to the visible sector at the TeV scale via gravity. In mSUGRA the huge number of free parameters in general SUSY models can be reduced to five by making certain assumptions of unifications at the GUT scale. Thus, the model is fully defined by the common scalar mass m_0, the common gaugino mass $m_{1/2}$, the ratio $\tan\beta$ of the vacuum expectation values of the two Higgs doublets, the common trilinear coupling A_0 and the sign of the Higgs mass parameter μ. Also other SUSY breaking mechanism like gauge mediated (GMSB) or anomaly mediated SUSY breaking (AMSB) are studied in theory and experiment.

Other possible extensions of the SM are grand unified theories (GUTs), where the gauge group of the SM SU(3)×SU(2)×U(1) is embedded in a larger group. Possible groups are SU(5), SO(10) or E_6. The U(1) gauge group can survive down to reasonable low energies, giving rise to additional gauge bosons (Z'). Other models like left–right symmetric models ($SU(2)_L \times SU(2)_R \times U(1)_{B-L}$) or little Higgs models also predict the existence of extra gauge bosons.

Yet another approach of extending the SM is the increase of the space dimensions. There are many types of extra–dimension models. In this report, only the Randall Sundrum (RS) model [2] is considered. In this model only one extra dimension is added and the weak scale is generated from the large scale through an exponential hierarchy, which arises from a curved background metric.

All exclusion limits shown later in this report are quoted at the 95% confidence level.

2 SUSY Searches

In this section, searches for several different SUSY particles are presented. At first, searches are considered that assume the conservation of R–parity R_P [a]. As a consequence of R–parity conservation, supersymmetric particles are always produced in pairs and the lightest supersymmetric particle (LSP) is stable. At the end, also a search with R_P violation is discussed.

2.1 Search for Charginos and Neutralinos

The golden channel for the search for supersymmetry at the Tevatron is the pair production of charginos $\tilde{\chi}_1^{\pm}$ and neutralinos $\tilde{\chi}_2^0$, the supersymmetric partners of the gauge and Higgs bosons. These gauginos may decay into a final state consisting of three charged leptons and missing transverse energy $\not{E}_T$ due to the escaping LSPs. This channel is very clean because of the small SM background. Nevertheless this search is challenging due to the very small cross section times branching ratio related to the electroweak production and the potentially small transverse momenta of the leptons.

To cope with these challenges, the search strategy relies only on two identified leptons with very small transverse momenta. The third lepton is selected as an isolated track to increase the efficiency and to be sensitive to all three lepton flavors. To further reduce the background, additional cuts based on $\not{E}_T$–related quantities are applied to account for the escaping LSPs.

The DØ search [3] combines analyses from five different final states ($ee+\ell$, $\mu\mu+\ell$, $e\mu+\ell$ $\mu\tau+\ell$ and $\mu\tau+\tau$). In addition, two different selections optimized for different regions in the mSUGRA parameter space are performed in the $ee+\ell$, $\mu\mu+\ell$ and $e\mu+\ell$ channels. Using a dataset corresponding to an integrated luminosity of 2.3 fb^{-1}, the numbers of expected background events are 5.4 ± 0.6 events for a selection with low p_T requirements and 3.3 ± 0.4 events in a selection with tighter p_T cuts. For these two selections 9 and 4 events observed in the data, respectively. The probability to observe 9 events given the expected background is around 10%. These results can be translated into an exclusion region in the $m_0 - m_{1/2}$ plane, which is shown in Fig. 1 (left) for $\tan\beta = 3$, $A_0 = 0$ and $\mu > 0$. Chargino masses up to 167 GeV are excluded while masses as high as 178 GeV are probed. For a fixed mass difference of 1 GeV between the the lightest stau $\tilde{\tau}_1$ and the second lightest neutralino $\tilde{\chi}_2^0$ and a fixed chargino mass of 130 GeV, values of $\tan\beta$ up to 9.6 can be ruled out, which is shown in Fig. 1 (right).

The analysis from CDF [4], which is based on 2.0 fb^{-1} of data, expects 5.5 ± 1.1 events from SM background in the lepton+track final state while 6 events are observed in the data. CDF also performs an analysis with three identified leptons, where 0.88 ± 0.14 events are expected with one event observed in the data. In both cases, only electrons and muons are considered as

[a] $R_P = (-1)^{3(B-L)+2S}$ where B and L are the baryon and lepton number and S is the spin of the particle.

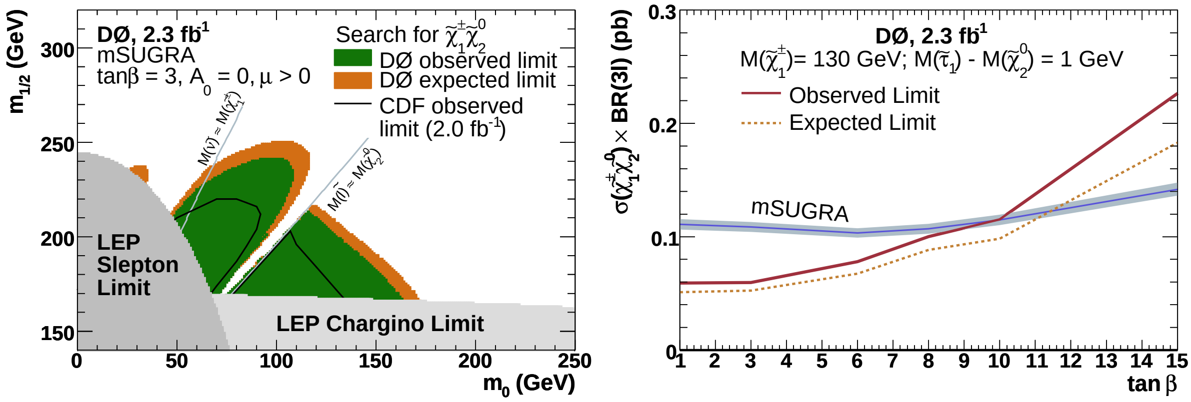

Figure 1: Excluded region in the $m_0 - m_{1/2}$ plane (left) and cross section limit as a function of $\tan\beta$ (right) from the DØ search for charginos and neutralinos.

leptons. For fixed m_0 values of 60 and 100 GeV, chargino masses below 145 GeV and 127 GeV can be excluded, respectively.

2.2 Search for Stops

The pair production of stops, the supersymmetric partners of the top quark, can result in a final state of two b–jets, two leptons and $\not{E}_T$ due to two neutrinos and two LSPs. If the stops are lighter than the top quark, they decay into a chargino and a b–quark. Depending on the SUSY parameters, the subsequent decay of the chargino can proceed via a W boson, a sneutrino or a slepton, resulting in different fractions of multilepton final states.

To deal with the major background from top–pair production, CDF uses the reconstructed stop mass to enhance the signal over background [5]. Combining all three dilepton final states ee, $e\mu$ and $\mu\mu$, 56.0 ± 7.3 events are expected from SM processes for a dataset of 2.7 fb^{-1}, while 57 events are observed in the data. Depending on the branching fraction BR($\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^0 \ell\nu$), different exclusion areas in the $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ plane are obtained. The different exclusion regions for BR^2 = 0.25, 0.5 and 1.0 are shown in Fig. 2 (left) for a fixed chargino mass of $m_{\tilde{\chi}_1^{\pm}} = 125.8$ GeV.

DØ has also performed a search for pair produced stops in the dilepton+$\not{E}_T$ final state using 1.0 fb^{-1} of data [6]. Only the dielectron and electron+muon channels are studied. In this analysis the topological variables H_T[b] and S_T[c] are used to separate signal from background. In all bins of H_T and S_T good agreement between SM prediction and the data is observed. The resulting exclusion limit in the $m_{\tilde{t}_1} - m_{\tilde{\nu}}$ plane is pictured in Fig. 2 (right).

2.3 Search for Charged Massive Stable Particles

GMSB or AMSB models can lead to long lived massive stable particles (CHAMPs). For example in GMSB SUSY models, the lightest stau can traverse the detector without decaying, since the decay can be sufficiently suppressed. Similarly, AMSB models predict a long lifetime for the lightest chargino, resulting also in a similar signature of "slow muons".

To distinguish between signal and background, one can use the time information of the reconstructed muon objects as well as their invariant mass. In the analysis from DØ [7], corresponding to an integrated luminosity of 1.1 fb^{-1}, 1.9 ± 0.5 background events are expected for a chargino with a mass of 200 GeV while one event is observed in the data. Also for other mass hypotheses, good agreement between SM prediction and data is found. The results are translated into

[b] H_T is the scalar sum of all jet transverse momenta.
[c] S_T is the scalar sum of lepton transverse momenta and $\not{E}_T$.

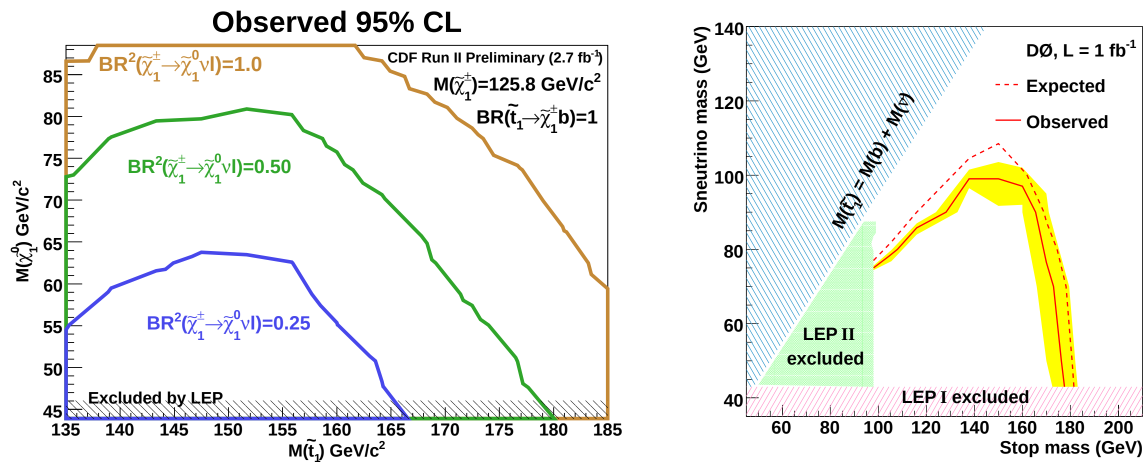

Figure 2: Excluded region in the $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ for different values of $\mathrm{BR}^2(\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \ell\nu)$ of the CDF stop search (left) and exclusion area in the $m_{\tilde{t}_1} - m_{\tilde{\nu}}$ plane from the DØ stop analysis (right).

mass limits for the lightest chargino. For gaugino–like charginos, masses below 206 GeV can be excluded, while for higgsino–like charginos the mass limit is reduced to 171 GeV. It was shown in Ref. [8] that this search can exclude a larger fraction of models in the more general pMSSM [d].

The CDF collaboration also performed a search for CHAMPs [9]. A small mass difference between stop and LSP results in a long lifetime for the stop. Using the time–of–flight detector to distinguish between stops and muons, CDF can exclude stops with masses up to 250 GeV.

2.4 Search for Sneutrino Resonances

In R–parity violating models the superpotential is of the form

$$W = \frac{1}{2}\varepsilon_{ab}\lambda_{ijk}\hat{L}_i^a\hat{L}_j^b\hat{E}_k + \varepsilon_{ab}\lambda'_{ijk}\hat{L}_i^a\hat{Q}_j^b\hat{D}_k + \frac{1}{2}\varepsilon_{\alpha\beta\gamma}\lambda''_{ijk}\hat{U}_i^\alpha\hat{D}_j^\beta\hat{D}_k^\gamma + \varepsilon_{ab}\delta_i\hat{L}_i^a\hat{H}_2^b \,. \tag{1}$$

In the analyses presented here, only the couplings λ'_{311} and $\lambda_{321} = \lambda_{312}$ are different from zero. With these assumptions the processes $\tilde{\nu} \to e^\pm\mu^\mp$, $\tilde{\nu} \to e^\pm\tau^\mp$ and $\tilde{\nu} \to \mu^\pm\tau^\mp$ are possible. In the $e\mu$ final state, the invariant mass of the sneutrino can be reconstructed and a mass window selection based on the assumed sneutrino mass can be used to enhance signal over background. In the final states involving τ leptons only the visible mass can be reconstructed due to the escaping neutrino in the τ lepton decay, thus degrading the performance of the analysis.

The CDF experiment has looked for resonant sneutrino production in all three final states in a dataset of 1.0 fb^{-1} [10]. For invariant electron muon masses above 500 GeV, 0.1 ± 0.1 background events are expected while no events are observed in the data. Similarly, 1.4 ± 0.3 (1.0 ± 0.3) events from SM processes are predicted in the $e\tau$ $(\mu\tau)$ final state for visible masses above 310 (280) GeV, while in both cases two events are observed in the data. Since no excess in the data is found, only limits on the production cross section times branching ratio are obtained, which are in the order of 10^{-2} pb to 10^{-1} pb, depending on the sneutrino mass.

The DØ collaboration has also performed a search for the production of sneutrinos in the final state involving one electron and one muon [11]. Using the same amount of data as the CDF analysis, 59.2 ± 5.3 events are expected from SM processes over the whole $m_{e\mu}$ mass range with 68 events observed in the data. Similar cross section limits in the range of 10^{-2} pb to 10^{-1} pb are found.

[d] pMSSM is the general CP conserving MSSM with minimal flavor violation.

3 Extra Dimensions and Additional Gauge Bosons

As already mentioned, in the RS model, the weak scale is generated from the Planck scale through an exponential hierarchy, which arises from the curved background metric and not gauge interactions. The curvature of the 5–dimensional Anti–deSitter space–time is given by the parameter k. In this model, spin–2 excitations with masses of the order of a few hundred GeV couple to the SM particles with weak scale. These heavy gravitons can decay to pairs of fermions or bosons. Results are presented dependent on the parameter $k/\overline{M}_{Pl}$, where $\overline{M}_{Pl}$ is the reduced effective Planck mass $M_{Pl}/\sqrt{8\pi}$.

In grand unified theories, the SM gauge group is embedded into larger groups. In these models, heavy gauge bosons (Z', W') are predicted. These heavy bosons can couple to SM fermions with electroweak strength, thus a Z' boson could be observed as a peak in the invariant dilepton mass spectrum.

3.1 Search for High Mass Resonances

The CDF collaboration has searched for a heavy resonance in the dielectron [12] and the dimuon channel [13]. The process under consideration is $\sigma(p\bar{p} \to X) \cdot BR(X \to \ell^+\ell^-)$, where X can be a spin–0 (e.g. a sneutrino), spin–1 (e.g. a Z' boson) or spin–2 particle (e.g. a RS graviton). The searches are based on 2.5 and 2.3 fb^{-1} of data, respectively.

A RS graviton G^* would show up as a deviation in the dimuon invariant mass spectrum. Figure 3 (left) shows the inverse invariant dimuon mass, where no deviation from the SM can be observed. The inverse invariant mass is used because the muon resolution is flat in this variable. The invariant dielectron mass is pictured in Fig. 3 (right).

While no deviation from the SM prediction is observed in the dimuon channel, a small excess corresponding to a significance of 2.5σ at a mass of 240 GeV is found in the dielectron channel. The RS model is tested for values of $k/\overline{M}_{Pl}$ in the range of 0.01 to 0.1. Assuming $k/\overline{M}_{Pl} = 0.1$, RS gravitons with masses M_{G^*} below 848 GeV and 921 GeV can be excluded in the dielectron and dimuon channel, respectively.

The same analyses can also be used to search for heavy gauge bosons, for example the Z' bosons predicted in the E_6 model. Using this model, Z' masses below 735 GeV for the lightest and 877 GeV for the heaviest Z' boson are ruled out in the dielectron channel. The corresponding limits from the dimuon channel are 789 GeV and 982 GeV. Assuming SM like couplings, the limits increase to 963 GeV and 1030 GeV in the dielectron and dimuon channel, respectively.

In the dimuon channel, the result is also interpreted in an R–parity violating SUSY model. For a value of $\lambda^2 \cdot BR = 0.01$, where λ is the $d\bar{d}\tilde{\nu}$ coupling in the superpotential (compare Eq. 1) and BR denotes the branching ration $\tilde{\nu} \to \mu^+\mu^-$, sneutrinos with masses below 810 GeV are forbidden.

The DØ experiment has also searched for heavy gauge bosons in a dataset corresponding to 1 fb^{-1} of integrated luminosity [14]. Studying the distribution of the transverse mass in the electron+$\not\!\!E_{\mathrm{T}}$ channel, W' bosons with masses below 1000 GeV are excluded.

As mentioned earlier, the RS gravitons can also decay into a pair of Z bosons. To cover this decay, CDF has looked at final states consisting either of four leptons or two leptons and two jets [15]. To increase the sensitivity, very loose lepton identification criteria have been imposed. Using a dataset corresponding to integrated luminosities of 2.5 to 2.9 fb^{-1}, RS gravitons with masses below 491 GeV can be excluded for $k/\overline{M}_{Pl} = 0.1$.

4 Conclusion and Outlook

In this report, many searches for physics beyond the SM have been presented. So far, no indication of new physics have been found, but many models have been probed in so far untouched

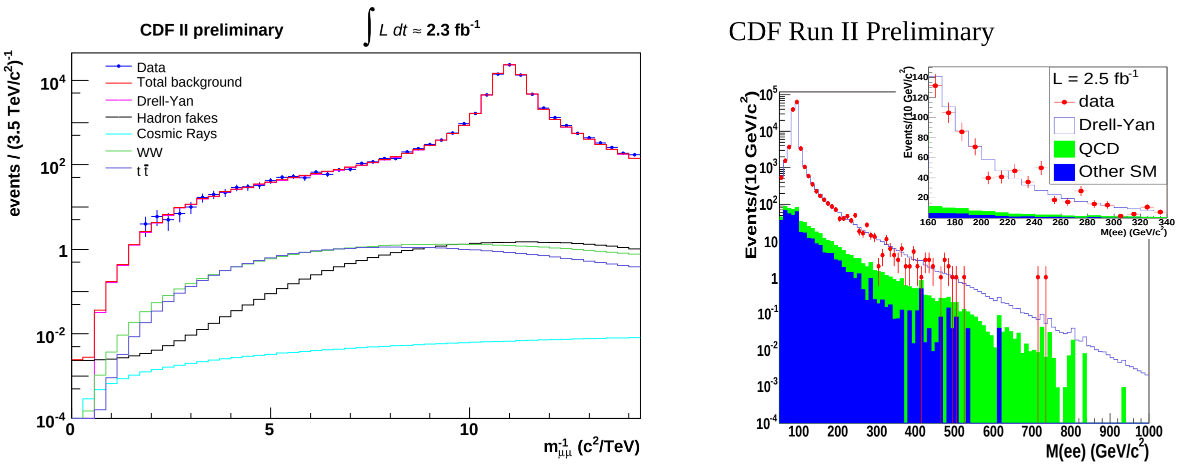

Figure 3: Distribution of the inverse invariant dimuon mass (left) and distribution of the invariant dielectron mass (right) from the CDF analyses.

territory. Thus, many new exclusion limits well beyond previously existing bounds have been established.

With the Tevatron running smoothly, the datasets collected by the CDF and DØ collaborations are increased by a factor of 2 to 6 compared to the results presented here. In addition, improved analyses techniques and reduced systematics as well as combinations of CDF and DØ results will allow further probing of new parameter space. Thus there is still the possibility of a discovery before the LHC turns on.

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