NEW PHENOMENA II: RECENT RESULTS FROM THE FERMILAB TEVATRON

DAVE TOBACK
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The CDF and DØ collaborations continue to search for new physics using more than 100 pb$^{-1}$ of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV collected at the Fermilab Tevatron. We present recent results from both experiments on R-parity violating Supersymmetry and $Z'$/Technicolor production with $ee$ and $t\bar{t}$ final states. In addition we introduce Sherlock, a new quasi-model-independent search strategy.

1 Introduction

In these, and other, proceedings we summarize some recent results of searches for new physics at the Fermilab Tevatron. Specifically, we review new results on R-parity violating Supersymmetry (SUSY) and $Z'$/Technicolor models in the $ee$ and $t\bar{t}$ channels. We conclude by introducing Sherlock, a new quasi-model-independent search strategy.

2 R-parity Violating SUSY

Motivated in part by the interpretation of the reported HERA excess of high $Q^2$ events and in part for theoretical reasons, many recent searches for SUSY have focused on the possibility that R-parity is not conserved. In such a scenario at the Tevatron, pairs of SUSY particles will typically be produced and then decay to standard model particles and two neutralinos. However, instead of leaving the detector without depositing any energy (as in R-parity conserving models), R-parity violating terms, $\lambda_{ijk} \tilde{\ell}_i \tilde{\ell}_j \tilde{\ell}_k + \lambda'_{ijk} \tilde{u}_i \tilde{d}_j \tilde{d}_k + \lambda''_{ijk} \tilde{d}_i \tilde{d}_j \tilde{d}_k$, allow each neutralino to decay via three body decay to standard model particles. For example in a scenario with a non-zero all-leptonic coupling term, a neutralino could decay via a $\nu_e$ and a virtual $\tilde{\nu}_e$ with the $\tilde{\nu}_e$ decaying via a $\lambda_{121}$ coupling and producing $\mu^-e^+$. A similar decay of the other neutralino in the event
allows the event to produce a total of 4 charged leptons as well as two neutrinos each of which can contribute to missing transverse energy. The CDF and DØ collaborations have both searched for this type of production and decay.

At DØ the search for R-parity violating SUSY is performed by looking in the $eee$, $ee\mu$, $e\mu\mu$ and $\mu\mu\mu$ channels for excesses of events with missing transverse energy. Since the search is identical to that for $\tilde{\chi}_1^\pm \tilde{\chi}_0^0$ production and decay in mSUGRA, identical data sets and selection criteria are employed. The results, along with the luminosity for each sample, are shown in Table 1 with no candidates in the data. A similar search for R-parity violating SUSY was performed at CDF in 87.5 pb$^{-1}$ of data. It is complementary in that it requires four leptons, but does not require missing transverse energy. Using all combinations of electrons and muons in the final state, there is one candidate event in the data, consistent with the background prediction of 1.3$\pm$0.4 events.

| Event categories | $eee$ | $ee\mu$ | $e\mu\mu$ | $\mu\mu\mu$ |
|------------------|-------|---------|-----------|-------------|
| $L_{int}$ (pb$^{-1}$) | 98.7 $\pm$ 5.2 | 98.7 $\pm$ 5.2 | 93.1 $\pm$ 4.9 | 78.3 $\pm$ 4.1 |
| Events observed | 0 | 0 | 0 | 0 |
| Background | 0.34 $\pm$ 0.07 | 0.61 $\pm$ 0.36 | 0.11 $\pm$ 0.04 | 0.20 $\pm$ 0.04 |

Table 1: The result of the search for R-parity violating SUSY in the trilepton signature at DØ. All errors are combinations of both statistical and systematic errors.

Limits on R-parity violating models, which can be set as a function of the mSUGRA SUSY model parameters ($m_0, m_{1/2}, A_0, \tan\beta$ and $\mu$), are shown Figures 1 and 2 for different values of the $\lambda$ coupling constant and $\tan\beta$. In both cases the regions of 95% C.L. exclusion correspond to the space below the dark solid lines. The lighter curves on Figure 1 indicate the value of $\lambda$ such that the average decay length of the LSP is less than 1 cm. Since the search is not sensitive to displaced decays of the neutralino, the region below the curves labeled with $\lambda_{121}$ and above the $10^{-3}$ line is excluded if $\lambda_{121} > 10^{-3}$.
3 Technicolor and Neutral Heavy Vector Bosons

In Technicolor models and models which have additional neutral heavy vector bosons, new heavy particles (labeled $\rho_T$, $\omega_T$ or $Z'$ respectively) are produced and can decay via $e^+e^-$. In both cases, a straightforward search for a resonance, or excess at high mass, in the $ee$ invariant mass spectra could easily illuminate a signal. At DØ this analysis uses the same data set as the recently published paper setting limits on quark and lepton compositeness. The luminosity for this data set is 120.9 pb$^{-1}$. The backgrounds are dominated by standard model production of $Z/\gamma^* \rightarrow ee$, and instrumental backgrounds (fakes). The invariant mass spectrum for the data and backgrounds is shown in Figure 3. There is no evidence for resonant production in the data or for an excess at high mass. A similar search using both $ee$ and $\mu\mu$ final states by CDF was recently published. In both searches there is no evidence for new physics.

Figure 4 shows the DØ preliminary 95% C.L. cross section upper limits on production of $\rho_T/\omega_T \rightarrow e^+e^-$. Also shown on the plot are theoretical production curves for two different scenarios in which the decay $\rho_T \rightarrow W\pi_T$ is allowed or not allowed, affecting the branching ratio to $ee$. Assuming the $\rho_T$ and $\omega_T$ have the same mass, the mass limits are $M_{\rho_T} > 225$ GeV if the decay $\rho_T \rightarrow W\pi_T$ is kinematically disallowed or if $M_{\omega_T} > 200$ GeV which suppresses the decay $\omega_T \rightarrow \gamma\pi_T$. While CDF does not set specific limits on Technicolor particles in this channel, their sensitivity is comparable.

Similarly, CDF and DØ also set limits on neutral heavy vector bosons which decay via $Z' \rightarrow ee$. Assuming the couplings to known fermions are the same as in the standard model, DØ sets a mass limit of $M_{Z'} > 670$ GeV in the electron only channel at 95% C.L. CDF’s combined 95% C.L. limit from $ee$ and $\mu\mu$ is $M_{Z'} > 690$ GeV. CDF goes further and sets limits on other $Z'$ models with extended gauge group.

Another search for neutral heavy vector bosons was carried out by the CDF collaboration in the $t\bar{t}$ channel. The analysis, representing 106 pb$^{-1}$ of data, uses the ‘lepton+jets’ data set ($e$ and $\mu$) which was used for the top quark mass measurements. Using the same fitting
techniques which are used to measure the mass, the final state objects are fit to the $tt$ hypothesis constraining the mass of the top quark mass to be 175 GeV. The best fit is then used to calculate the invariant mass of the $\bar{t}t$ system which is searched for resonant structure or excesses. There is no evidence for new physics seen. While this channel is not competitive with $Z'$ limits from $ee$ and $\mu\mu$ searches (assuming standard model couplings), Technicolor models with leptophobic topcolor production could make this channel highly produced at the Tevatron. Experimental 95% C.L. cross section upper limits are at the few picobarn level and are compared with theoretical production cross sections in Figure 5.

4 Sherlock: A New Quasi-Model-Independent Method for Searches for New Physics

Finally, we introduce Sherlock, a new quasi-model-independent search method developed at DØ. This method provides a prescription for searching for new physics by systematically looking for excesses in multi-dimensional data distributions. Since we assume that the physics responsible for electroweak symmetry breaking occurs at mass scales large compared to standard model backgrounds, we currently add in the assumption that the new physics is characterized by high $P_T$ final state particles. It is this feature which makes it quasi-model-independent.

The method consists of a three part prescription and algorithm. The first part is to pick a data set (such as the inclusive $e\mu+X$ sample) and categorize each event according to its observed final state particles (number of electrons, jets, photons etc.). For each category of events, the kinematic variables for the sample are uniquely specified by an a priori prescription. A region, $R$, is then defined in the multi-variable space surrounding one or more of the data points. By giving a precise definition of the region for an event, or set of events, an amount of parameter space is determined and the probability for the background in that region to fluctuate up to or above the number of observed events in the region gives a quantitative measure of the degree of interest of the region. The algorithm then searches for the most interesting region (largest excess relative to background) in all of variable space including the high $P_T$ region. Once this
Figure 7: The significance of the region of greatest excess in standard deviations, denoted $\tilde{P}_[\sigma]$, using Sherlock for an ensemble of mock data experiments using $e\mu X$ for two cases: with a signal (solid line) and with no signal (dashed line). In both cases the backgrounds are $Z/\gamma \rightarrow \tau\tau$ and fakes. In the ‘no signal’ case the ‘data’ is drawn only from the background distributions. As expected, the results are basically Gaussian and centered on 0 with unit width. When ‘signal’ events of WW and $t\bar{t}$ are added to the ‘data’ samples but not to the background, Sherlock reports that in the over 50% of the mock experiments it finds a statistically significant excess at or greater than $2\sigma$. All samples with $\tilde{P}_[\sigma] > 2\sigma$ are in the right most bin.

Figure 8: The significance of the region of greatest excess in standard deviations, denoted $\tilde{P}_[\sigma]$, using Sherlock for an ensemble of mock data experiments using $e\mu X$ as in Figure 7. Here the backgrounds are $Z/\gamma \rightarrow \tau\tau$, fakes and WW. When ‘signal’ events of $t\bar{t}$ are added to the ‘data’ but not to the background, Sherlock reports that in greater than 25% of the mock experiments it finds a statistically significant excess at or greater than $2\sigma$. All samples with $\tilde{P}_[\sigma] > 2\sigma$ are in the right most bin.

most interesting region is found, it is compared to the most interesting region found in a large sample of hypothetical similar experiments (HSEs) drawn from the parent distributions of the backgrounds (according to statistical and systematic uncertainties). In this way, the true degree of interest of the region of largest excess is quantified in terms of the fraction of HSEs which give regions which are more interesting than the one observed in our data (again due simply to statistical fluctuations or systematic misunderstanding of the data).

Sherlock is run on 108 pb$^{-1}$ of inclusive high $P_T$ $e\mu+X$ data taken at DØ. As a test and an illustration of the sensitivity of the method, we have used this algorithm on a set of mock experiments drawn from the background estimations. The $e\mu X$ sample has the advantage of having two known ‘signals’ which give high $P_T$ physics in the final state: WW and $t\bar{t}$ production. Figure 7 shows the results of running a series of mock experiments in which the ‘known’ backgrounds include only $Z/\gamma \rightarrow \tau\tau$ and fakes and the ‘data’ is drawn only from the background distributions. The results are shown in the figure with the dashed lines which shows the significance in standard deviations. As expected, the results are basically Gaussian and centered on 0 with unit width. When ‘signal’ events of WW and $t\bar{t}$ are added to the ‘data’ (according to expected standard model production expectations, smeared by statistical and systematic uncertainties) but not to the background expectations, as shown by the solid line in Figure 7, Sherlock reports that in the over 50% of the mock experiments it finds a statistically significant excess at or greater than $2\sigma$. All samples with $\tilde{P}_[\sigma] > 2\sigma$ are in the right most bin.

We again note that Sherlock doesn’t know anything about WW or $t\bar{t}$ and that it is in no way optimized for finding them. It is simply looking for an excess of events in the high-$P_T$ region. 

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as the background, Sherlock picks out significant excesses (> 2σ) in both the $e\mu E_T$ (WW) and $e\mu E_{Tjj}$ (tt) data correctly indicating the presence of both WW and tt in the data.

Figure 8 shows the results when WW are added to the background expectations so that we may see the sensitivity to tt alone. Again, in an ensemble of mock experiments Sherlock picks out an excess in the data at greater than or equal to the 2σ level in over 25% of the cases. Running on the data we observe an excess at the 1.9σ level in the $e\mu E_{Tjj}$ data, correctly identifying tt in the data.

Including all known standard model sources in the backgrounds and running Sherlock yields no evidence of an excess in any $e\mu X$ channel indicating agreement with the standard model. Specifically, in 71% of hypothetical similar experiments we expect to see an excess more interesting than the most interesting region of excess than is observed in our data.

The Sherlock method is a novel approach to searching for new physics in the data. While a dedicated search is always best for a specific signal hypothesis (e.g. SM Higgs with $M_H=130$ GeV), the number of possible models to search for is very large. Sherlock is a very powerful method for being sensitive to a large number of new physics models by being much more model independent. While we have only applied the method to a single data set, it is generally applicable and should prove to be an immensely valuable tool in Run II to complement the dedicated searches.

5 Conclusions

We have presented the results of a number of recent searches for new physics from the Fermilab Tevatron based on the data taken during 1992-1996. While the next run with upgraded detectors and high luminosity is just over a year away, we continue to make progress in searching for new physics as well as setting limits on important theoretical models. The future at the Tevatron appears bright, and the lab should continue to be an interesting and exciting place to search for new physics in the coming years.

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Backgrounds: Fakes, $Z/\gamma' \rightarrow \tau\tau$, WW
--- Mock Samples: Fakes, $Z/\gamma' \rightarrow \tau\tau$, WW
--- Mock Samples: Fakes, $Z/\gamma' \rightarrow \tau\tau$, WW, $tt$
Combination of $e\mu E_{T}$, $e\mu E_{Tj}$, $e\mu E_{Tjj}$ and $e\mu E_{Tjjj}$