Searches for BSM (non-SUSY) physics at the Tevatron

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Abstract. Results of searches at the Tevatron for physics (non-SUSY and non-Higgs) beyond the Standard Model using 200 pb\textsuperscript{-1} to 480 pb\textsuperscript{-1} of data are discussed. Searches at DØ and CDF for $Z'$, Lepton-Quark compositeness, Randall-Sundrum Gravitons, Large Extra Dimensions, $W'$, Leptoquarks and Excited Electrons are presented here.

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1 Introduction

The discovery of anomalous behavior in data collected at high energy physics experiments could provide non-SUSY and non-Higgs explanations to questions associated with the Standard Model and provide deeper understanding to the fundamental particles and interactions in nature. Such questions include whether quarks and leptons are composite particles, the existence of extra dimensions, and the answer to the hierarchy problem in the Standard Model (SM).

Generally, a search is approached by first understanding the SM prediction for a given signal and detector backgrounds which could mimic that signal. Analyses are optimized for signal, not according to model, prior to looking in the signal region of the data. If no anomalous behavior is found, the signal acceptances of various models can be used to set limits.

2 High Mass Dilepton Searches

High mass dilepton searches are experimentally motivated by the small source of background, with the exception of the well-understood, irreducible Standard Model $Z'/\gamma^*$ production. Search results can be used to study many theories: extended gauge theories ($Z'$), technicolor, lepton-quark compositeness, large extra dimensions (LED), and Randall-Sundrum gravitons.

2.1 $Z'$

The majority of extensions to the SM predict new gauge interactions, many of which naturally result in the prediction of neutral or singly charged bosons, such as a highly massive "$Z'$" particle.

2.1.1 $Z'$ Searches using $M_{ee}$ and $\cos \theta^*$

Using 448 pb\textsuperscript{-1} of data, CDF searched for $Z'$ production by studying the distributions dielectron mass at high mass and the angular distribution $\cos \theta^*$. Figures 1 and 2 show the $M_{ee}$ and $\cos \theta^*$ distributions, respectively.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Expected and observed dielectron mass distributions.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{Expected and observed $\cos \theta^*$ distribution for $M_{ee} > 116$ GeV/c\textsuperscript{2}.}
\end{figure}
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2.1 Traditional \(Z'\) Searches

CDF and DØ both performed “traditional” \(Z'\) searches which focus on the dilepton mass distributions. All three channels - electron, muon, and tau - were studied with no evidence for a signal beyond the Standard Model expectations. Table 1. shows a summary of the limits set at the 95% C.L. for various \(Z'\) models.

2.2 Quark-Lepton Compositeness

Contact Interaction composite models introduce hypothetical constituents of quarks and leptons called “preons” which are bound together by a characteristic energy scale known as the compositeness scale \(\Lambda\). The differential cross-section can be written as in Equation 1.

\[
\frac{d\sigma_T}{dM} = \frac{d\sigma_{SM}}{dM} + \frac{I}{A^2} + \frac{C}{A^4}
\]

For energies accessible at the Tevatron, the interference term (the second term) dominates and quark-lepton compositeness would be discovered as an excess in the tail of the dilepton distributions, an example of which is shown in Figure 4.

No evidence for signal is found in a dielectron search of 271 pb\(^{-1}\) or in a dimuon search of 400 pb\(^{-1}\) at DØ. The dimuon results are shown in Figure 5. Limits are set on \(\Lambda\) for several models as shown in Table 2.

2.3 Extra Dimensions

2.3.1 Large Extra Dimensions

Large Extra Dimensions (LED) provide a non-SUSY alternative solution to the “hierarchy” problem in the SM
2.3.2 Warped Extra Dimensions

The Warped Extra Dimension model predicts one extra dimension that is highly curved and the production of Randall-Sundrum (RS) gravitons[6]. The model depends on the curvature scale and the production of gravitons is predicted at the EW and Planck scales. The RS model can be extended by adding new particles, such as W', which are predicted to decay into an electron and a neutrino, where the neutrino is assumed to be SM-like: light and stable. Thus, the final state signature in the detector is a high p_T electron with high missing E_T. CDF performs a direct search for W' production and Figure 8 shows the background due to W' production.

The production of charged heavy vector bosons, referred to as W' particles, are predicted in theories based on the extension of the gauge group[7]. The W' is modeled to decay to an electron and neutrino, where the neutrino is assumed to be SM-like: light and stable. Thus, the final state signature in the detector is a high p_T electron with high missing E_T. CDF performs a direct search for W' production and Figure 8 shows the background due to W' production.

and an explanation for the large difference between the electroweak and Planck scales (M_EW << M_{Pl}). The signature for LED is dilepton or diphoton production. The Large ED (ADD) model predicts an increase in cross-section at high mass and depends on parameter η_G = F/M_s^4 where F is a model dependent dimensionless parameter and M_s is the UV cutoff, M_s = M_{Pl}(4 + n \_dim). An example M_{ee} + M_{γγ} distribution for η_G = 0.6 is shown in Figure 6 along with the background prediction and observed data for 200 pb^{-1} of dielectron and diphoton data at DØ. Figure 7 shows no anomaly in the ee, γγ cos θ* distribution. By fitting M_{ee}, M_{γγ}, and cos θ*, DØ extracts limits on η_G at the 95% C.L. such that η_G^{95%} < 0.292 TeV^{-4} for λ > 0 and η_G^{95%} > -0.432 TeV^{-4} for λ < 0.

Fig. 5. M_{μμ} distribution for using 400 pb^{-1} of data collected at DØ.

Fig. 6. Background prediction and observation of M_{ee}, M_{γγ} distributions. The dotted blue spectrum shows the LED theoretical prediction for η_G = 0.6.

Fig. 7. cos θ* predicted and observed distributions for ee and γγ.

Fig. 8. Limits set on Randall Sundrum Graviton production at DØ and CDF.

3 Charged Heavy Vector Boson (W')

The production of charged heavy vector bosons, referred to as W' particles, are predicted in theories based on the extension of the gauge group[7]. The W' is modeled to decay to an electron and neutrino, where the neutrino is assumed to be SM-like: light and stable. Thus, the final state signature in the detector is a high p_T electron with high missing E_T. CDF performs a direct search for W' production and Figure 8 shows the background due to W' production.
SM $W \rightarrow ev$ production with the predicted transverse mass distributions for $W'$ production at three different $W'$ masses.

Figure 9 shows the expected background distributions and the observations in the data. No $ev$ signal above the SM expectation is observed. However, the agreement between the data and the background prediction indicate good understanding of the calorimeter energy at CDF and the detector missing energy.

Having observed no signal above the SM expectation, the limit at the 95% C.L. is set on $W'$ production using a binned likelihood fitting method. The CDF Run II search excludes $W'$ masses less than 842 GeV/c$^2$. The CDF Run I limit was $M_{W'}^{SM} > 754$ GeV/c$^2$.

4 Leptoquarks

Many extensions of the SM assume additional symmetry between lepton and quarks which requires the presence of a “new” particle, a leptoquark (LQ). Leptoquarks, which could be scalar or vector particles, carry both lepton and baryon numbers. They are assumed to couple to $W$ in a flavor-changing form. Leptoquarks would be pair produced at the Tevatron. Their decay is controlled by parameter $\beta$, where $\beta = B.R.(LQ \rightarrow lq)$. There are three final state signatures for LQ pair production at the Tevatron: two charged leptons and two jets ($lljj$); one charged, one neutral lepton and two jets ($lvjj$); and two neutral leptons and two jets ($vjjj$). The experimental signal is a resonance in the lepton-jet invariant mass spectrum.

No evidence of LQ production is found at DØ or CDF. Figure 11 shows the exclusion regions for generation leptoquarks.

5 Excited Electrons

The observation of excited states of leptons or quarks would be a first indication that they are composite particles. CDF searches for singly produced excited electrons ($e^*$) in association with an oppositely charged electron, where the $e^*$ decays to an electron and a photon. Thus, the final state signature is two electrons and a photon where...
the search signal is a resonance in the electron+photon invariant mass spectrum.

Two models are studied: a Contact Interaction (CI) model\textsuperscript{9} and a Gauge Mediated (GM) model\textsuperscript{10}. The CI model depends on the mass of the $e^*$ ($M_{e^*}$) and the composite energy scale ($A$). In the GM model, an excited electron is produced via the decay of SM $\gamma/Z$. This model depends on $M_{e^*}$ and $f/A$, where $f$ is a phenomenological coupling constant.

In the first search for excited leptons at a hadron collider, CDF found no excess of dielectron+photon events in 200 pb$^{-1}$ of data. Exclusion regions for each model are established. Figure 12 shows the exclusion region at the 95% C.L. in the $M_{e^*}/A - M_{e^*}$ parameter space. There are no previously published limits for $e^*$ production using the CI model. For the GM model, it is conventional to plot the 95% C.L. exclusion region in the $f/A - M_{e^*}$ parameter space, as shown in Figure 13. CDF extends the previously published limits from 280 GeV/c$^2$ to $\approx 430$ GeV/c$^2$.

6 Summary

Searches for physics beyond the Standard model using 200 pb$^{-1}$ to 450 pb$^{-1}$ of data collected at CDF and DØ are presented. Currently, the experiments are actively pursuing further exotic topics and analyzing up to the full 1 fb$^{-1}$ of delivered luminosity. New and exciting results are coming out quickly. Further information regarding the analyses presented in this paper and new results can be found at\textsuperscript{11} and\textsuperscript{12}.

Fig. 12. Exclusion region at the 95% C.L. established by CDF for $e^*$ production via a Contact Interaction model.

Fig. 13. Exclusion region at the 95% C.L. established by CDF for $e^*$ production via a Gauge Mediated model.

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