Fermilab FERMILAB-CONF-08-127-E

# NON-SUSY EXOTICS SEARCHES AT THE TEVATRON

Alexandre Pronko
*Fermilab, Batavia, IL, USA*
(For the CDF and DØ Collaborations)

Abstract

We present results of searches for signs of physics beyond the Standard Model. The focus of this paper is on analyses not driven by SUSY models. Most of the presented results are based on $\sim$2 $\text{fb}^{-1}$ of data and obtained since summer of 2007. No significant excess of data over predicted background is observed. We report kinematic distributions, data and background counts, as well as limits on some parameters of selected models of new physics.

## 1 Introduction

Experimental results of the past few decades have demonstrated a phenomenal success of the Standard Model (SM). Nonetheless, we also know that our picture of particle physics is incomplete. There are many questions that the Standard Model fails to answer. For example, we do not know why there are only three generations of fermions, why the masses of particles have values we observe, what are dark energy and matter, or what explains the hierarchy between the electroweak and gravitational scales. Although supersymmetry (or SUSY) is one of the most popular extensions of the Standard Model, there are other equally well-motivated models of new physics, such as extra dimensions, compositeness, and technicolor. In this paper, we focus on non-SUSY searches for signs of new physics beyond the Standard Model. We present recent results of signature-based and model-dependent measurements performed by the CDF and DØ Collaborations. The event selection in model-inspired analyses is optimized to gain the best sensitivity for a model of interest. The result of such measurements is usually a limit on some parameters of a selected model. The analysis strategy for signature-based searches is to apply generic selection criteria to reduce backgrounds in order to be sensitive to as wide range as possible of scenarios for new physics (some of them yet unknown) with a signature of interest. Observation of an excess of data over the predicted background in such analyses would indicate the presence of new physics. In signature-based searches, increased attention is also given to examining kinematic distributions.

## 2 Search for High-Mass $e^+e^-$ Resonances

Lepton-antilepton pairs have been discovery signatures for new particles such as the $J/\psi$, $\Upsilon$ mesons, and the $Z$ boson. Even though leptonic decay rates are usually smaller than hadronic ones, leptons have relatively low background contamination at a hadron collider. Many models beyond the SM predict the existence of new particles decaying into lepton-antilepton pairs. Examples of such new resonances are $Z'$ bosons in the $E_6$ model [1] and Randall-Sundrum (RS) gravitons [2]. The CDF Collaboration has performed a search for high mass $e^+e^-$ resonances in 2.5 fb$^{-1}$ of data collected in Run II between March 2002 and August 2007. In this analysis, events are required to have two well measured electrons of opposite sign with transverse energy of $E_T \geq 25$ GeV. Both electron candidates are required to have tracks pointing to energy depositions in the calorimeter and originating from the same collision vertex. One of the electrons must be in the central part of the calorimeter (pseudo-rapidity range of $|\eta|<1.1$) and the second electron can be either central or forward (pseudo-rapidity range of $|\eta|<2$). The search for resonances is performed in the invariant mass range 150 GeV$/c^2 < M_{e^+e^-} < 1000$ GeV$/c^2$ using an unbinned likelihood ratio. The dominant source of background is Drell-Yan production, which is estimated using the Pythia [3] event generator. The other sources of background are di-boson production and events where one or two jets are mis-identified as an electron. Figure 1 shows the measured invariant mass spectrum of $e^+e^-$ pairs from 2.5 $\text{fb}^{-1}$ of data. The most significant excess of data over the total SM background is found in the window 228 GeV/$c^2$<$M_{e^+e^-}$<250 GeV/$c^2$. It corresponds to 3.8 standard deviations from the SM prediction. The probability of observing a background fluctuation with significance $S/\sigma_B$>3.8 anywhere in the mass range 150 GeV/$c^2$<$M_{e^+e^-}$<1000 GeV/$c^2$ is about 0.6%. The upper limits on $\sigma \cdot BR(X \to e^+e^-)$ at 95% C.L. are set as a function of mass for a $Z'$ with SM coupling and six eigenstates of $Z'$ bosons in $E_6$ model. These results are presented in Table 1. The lower mass limits for $Z'$ bozons with SM coupling and in $E_6$ model are 966 GeV/$c^2$ and 737/933 (lightest/heaviest) GeV/$c^2$, respectively.

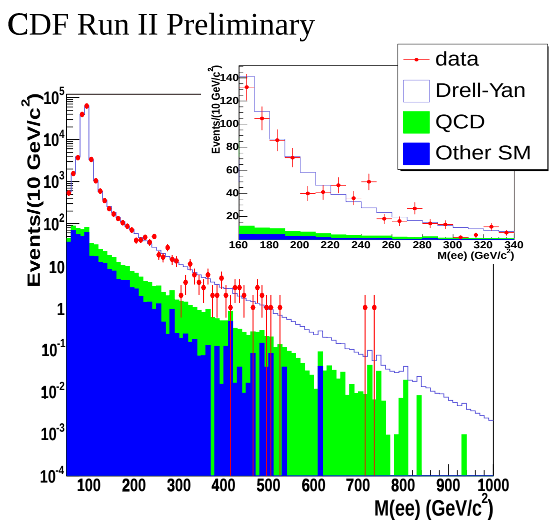


Figure 1: *Invariant mass distribution of $e^+e^-$ pairs in data (red dots) compared to background predictions. The insert shows the same distribution for 160 GeV/$c^2$ <$M_{e^+e^-}$< 340 GeV/$c^2$ using a linear scale.*

## 3 Search for High-Mass Di-Jet Resonances

The di-jet mass spectrum is sensitive to new high-mass particles decaying into a pair of partons (quarks or gluons). Many beyond-the-SM scenarios predict

Table 1: *Observed and expected 95% C.L. lower limits on $Z'$ masses.*

| | $Z'_{SM}$ | $Z'_{\psi}$ | $Z'_{\chi}$ | $Z'_{\eta}$ | $Z'_{I}$ | $Z'_{sq}$ | $Z'_{N}$ |
|---|---|---|---|---|---|---|---|
| Exp. Limit (GeV/$c^2$) | 965 | 849 | 860 | 932 | 757 | 791 | 834 |
| Obs. Limit (GeV/$c^2$) | 966 | 853 | 864 | 933 | 737 | 800 | 840 |

much larger production cross sections for new particles decaying into hadrons rather than leptons, photons, or electroweak bosons (in some models the latter decay modes can be completely suppressed). Examples of such particles include axigluons [4] ($A \rightarrow q\bar{q}$), excited quarks [5] ($q^* \rightarrow qg$), color octet technirhos [6] ($\rho_T \rightarrow q\bar{q}, gg$), $W'/Z' \rightarrow q'\bar{q}/q\bar{q}$ [7], di-quarks ($D/D^c \rightarrow qq/\bar{q}\bar{q}$) in the $E_6$ model [1], and RS gravitons [2] ($G \rightarrow q\bar{q}, gg$). Searches for resonances in di-jet channel are challenging due to the huge QCD background. However, the earlier observation of $W$ and $Z$ bosons in the hadronic decay mode by the UA2 Collaboration demonstrated the feasibility of finding di-jet resonances at hadron colliders.

The CDF Collaboration has performed a search for high-mass di-jet resonances in 1.1 fb$^{-1}$ of data. In this analysis, events are required to have at least two central ($|y|<1.0$) jets with invariant mass $M_{jj}>180$ GeV/$c^2$ and no significant transverse energy imbalance. Jet energy is corrected to the hadron level. The background for this analysis is completely dominated by regular QCD di-jet production. The search for resonances is performed by fitting the measured $M_{jj}$ spectrum by a smooth function and looking for data points with a significant excess over the fit. The shape of the smooth background parameterization is motivated by the shape of the $M_{jj}$ spectrum predicted by Pythia and Herwig Monte Carlo and LO and NLO calculations by the NLOJET++ program:

$$\frac{d\sigma}{dM_{jj}} = \frac{p_0(1-x)^{p_1}}{x^{p_2+p_3 \ln x}}, \quad x = M_{jj}/\sqrt{s}. \qquad (1)$$

Figure 2 shows the measured $M_{jj}$ spectrum and a fit by the function from Eq. 1. No significant excess of data over the fit is observed; therefore CDF has set upper limits on new-particle production cross sections. Table 2 presents the observed 95% C.L. exclusion limits on masses of new particles. These results are currently the world best limits.

## 4 Search for Long-lived Particles Decaying into $Z$ Bosons

The DØ Collaboration has performed a search for long-lived particles that travel tens of centimeters before decaying into $Z$ bosons. There are many models that predict the existence of such particles, for example: gauge mediated

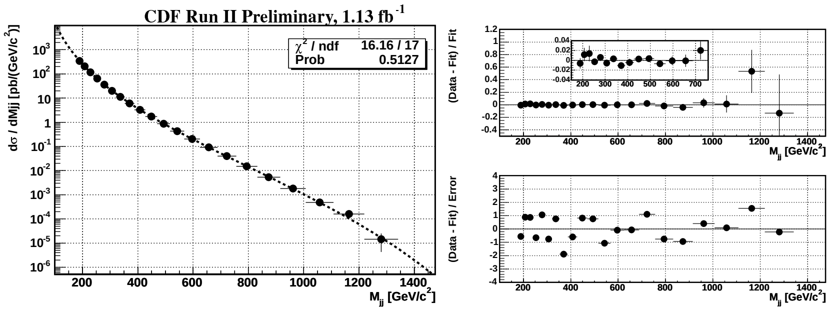


Figure 2: *Left: measured $M_{jj}$ spectrum fitted to Eq.1. Right top: (data-fit)/fit as a function of $M_{jj}$. Right bottom: (data-fit)/$\sigma_{stat}$ as a function of $M_{jj}$.*

Table 2: *Observed 95% C.L. exclusion limits on masses of new particles.*

| Model | Observed mass exclusion (GeV/$c^2$) |
|---|---|
| Excited quarks | 260-870 |
| Color octet technirho | 260-1110 |
| Axigluon and coloron | 260-1250 |
| $E_6$ diquarks | 260-630 |

SUSY [8]; hidden valley models [9]; models with an extended Higgs sector [10]; and fourth generation quarks ($b'$) [11].

The search is performed with 1.1 fb$^{-1}$ of data. Events are required to have two central ($|\eta|<1.1$) isolated electromagnetic (EM) objects with $E_T \geq 20$ GeV and invariant mass of $M>75$ GeV/$c^2$. The analysis is based on the unique capability of the DØ detector to reconstruct a vertex of origin for two EM clusters by using solely the position and shape of electromagnetic showers in the calorimeter and preshower system, with a resolution of $\approx$2 cm. In this search, displaced vertices of $Z$ bosons are reconstructed in the azimuthal ($xy$) plane only. The presence of long-lived particles would reveal itself as an excess of events with positive radii $R_{xy}$ compared to negative $R_{xy}$. Figure 3 shows the measured $R_{xy}$ distribution. No excess of events with $R_{xy}>0$ is observed, therefore DØ has set 95% C.L. limits on the production cross-section and lifetime of a fourth generation quark ($b'$). The exclusion region can be found in Fig.4.

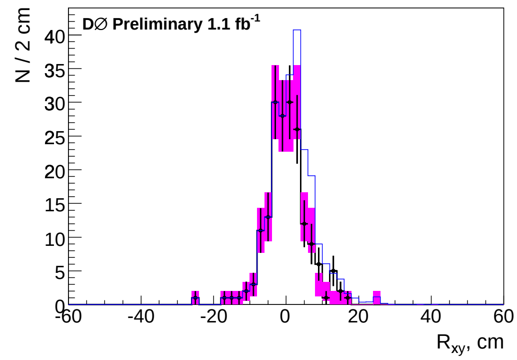


Figure 3: *Vertex radius ($R_{xy}$) distribution. Points with errors bars are data, the purple histogram is a reflection of the negative part of the distribution, and the blue line corresponds to an expected signal from $b'$-quark with mass of 160 GeV/$c^2$ and $c\tau$ of 30 cm.*

## 5 Search for Anomalous Production of Exclusive $\gamma + \not\!\!E_T$ Events

The exclusive production of a photon in association with a large imbalance in transverse energy ($\not\!\!E_T$) is a relatively rare process in the Standard Model dominated by $Z\gamma \to \nu\bar{\nu} + \gamma$. Such a signature is a promising way to observe the production of high-energy invisible particles [17], since a photon or gluon radiated by incoming quarks is the only detectable evidence of this process in a given event. Exclusive $\gamma + \not\!\!E_T$ events also appear in models of Large Extra Dimensions [12] (LED), where an undetectable Kaluza-Klein (KK) graviton is produced in association with a photon ($q\bar{q} \to \gamma G_{KK}$).

The CDF and DØ Collaborations have performed a search for signs of the anomalous production of exclusive $\gamma + \not\!\!E_T$ events in 2 fb$^{-1}$ and 1 fb$^{-1}$ of data, respectively, optimizing the analyses for maximum sensitivity to the benchmark model of KK graviton production. Both experiments select events with only one central ($|\eta|$<1/1.1 at CDF/DØ) photon with $E_T$>90 GeV. Events with energetic jets ($E_T$>15 GeV) and tracks ($P_T$>10/6.5 GeV/$c$ at CDF/DØ) are rejected. The DØ Collaboration also requires events to have $\not\!\!E_T$>70 GeV. The exclusive $\gamma + \not\!\!E_T$ signature suffers from large non-collision backgrounds such as cosmic rays depositing significant amount of energy in the electromagnetic calorimeter. This search would not be possible without an effective rejection of cosmic-ray events. For this purpose, the CDF Collaboration requires an EM shower to be in time with a $p\bar{p}$ collision. The DØ Collaboration rejects cosmic rays by vetoing events where an EM shower is aligned with hits in

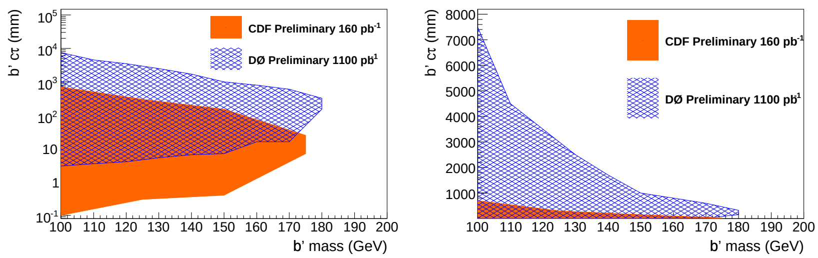


Figure 4: *The 95% C.L. exclusion limits on the $b'$-quark lifetime versus its mass (left: log scale; right: linear scale).*

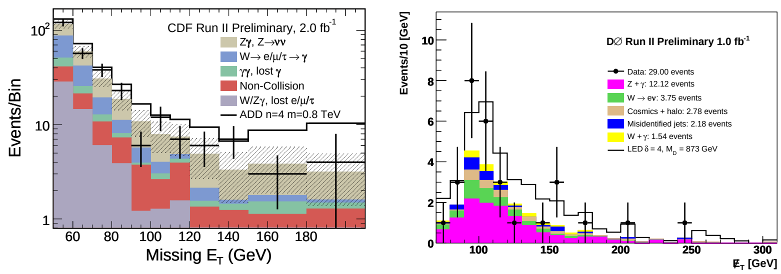


Figure 5: *The $\not\!\!E_T$ distribution is exclusive $\gamma + \not\!\!E_T$ events (left: CDF results; right: DØ results).*

the muon system. Figure 5 shows the observed $\not\!\!E_T$ distributions in exclusive $\gamma + \not\!\!E_T$ events. Neither of the experiments see any significant excess of data over the predicted background. Therefore, 95% C.L. lower exclusion limits are set on the fundamental Planck mass scale [12], $M_D$, as a function of the number of extra dimensions, $N_{ED}$. The results can be found in Fig. 6. The CDF Collaboration also combines the results of the exclusive $\gamma + \not\!\!E_T$ analysis with an earlier search in the exclusive $jet + \not\!\!E_T$ channel. The combined limit exceeds earlier world-best results obtained at LEP for $N_{ED}$>4.

## 6 Search for Anomalous Production of $\gamma\gamma + \not\!\!E_T$ Events

The $\gamma\gamma + \not\!\!E_T$ signature is predicted in many well-motivated models of new physics beyond the Standard Model. Examples include gauge-mediated SUSY [13], fermiophobic Higgs [16, 10], $4^{th}$ generation fermions [14], and the $E_6$ model [15]. Rather than trying to optimize for these or other models, the CDF Collabo-

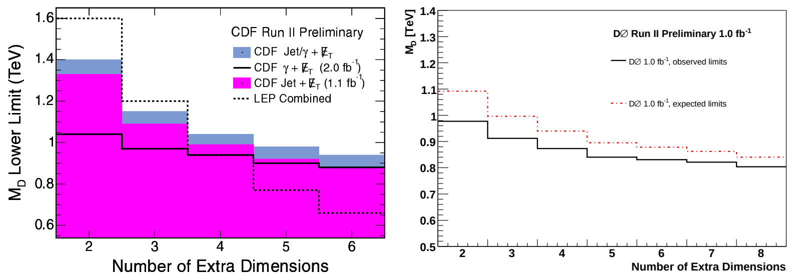


Figure 6: *The observed exclusion limits on the fundamental mass scale, $M_D$, as a function of the number of extra dimensions (left: CDF results; right: DØ results).*

ration takes a model-independent approach. The analysis is performed with 2 fb$^{-1}$ of data. Events are required to have two central photons ($|\eta|<1.1$) with $E_T>13$ GeV. Both photons are required to be in time with a $p\bar{p}$ collision to reduce a contamination from non-collision sources. The dominant backgrounds are regular di-photon and QCD jet events with fake $\not\!\!E_T$ due to energy mismeasurement in the calorimeter, and electroweak (EWK) processes with real $\not\!\!E_T$. In this search, the CDF Collaboration applies a novel approach to discriminate events with unobserved particles producing the $\gamma\gamma+\not\!\!E_T$ signature. Events are selected based on a significance of the measured $\not\!\!E_T$, unlike the majority of similar analyses where a fixed cut (usually with a large value) on $\not\!\!E_T$ is applied. The $\not\!\!E_T$-significance is estimated on an event-by-event basis according to the measured resolution for jet and soft unclustered (due to the underlying event and multiple interactions) energy, and helps to efficiently separate events with fake and true $\not\!\!E_T$. Figure 7 shows the observed $\not\!\!E_T$-significance distribution in $\gamma\gamma$ events, and Fig. 8 illustrates how a cut on significance>5 helps to select EWK events with $\not\!\!E_T$ as low as 20 GeV, which otherwise would be buried under the huge di-photon and QCD jet background. This plot demonstrates the major advantage of the $\not\!\!E_T$-significance method: it allows sensitivity to new physics processes even with moderate values of $\not\!\!E_T$ ($\not\!\!E_T\approx$20-40 GeV). Table 3 shows the observed and predicted numbers of $\gamma\gamma+\not\!\!E_T$ events for three values of the $\not\!\!E_T$-significance cut. The data agree with the predicted background for all values of the significance cut.

## 7 Search for Anomalous Production of $jj+\not\!\!E_T$ Events

The search for anomalous production of $jj+\not\!\!E_T$ is sensitive to processes not accessible by the previously discussed $\gamma\gamma+\not\!\!E_T$ analysis. Events with large

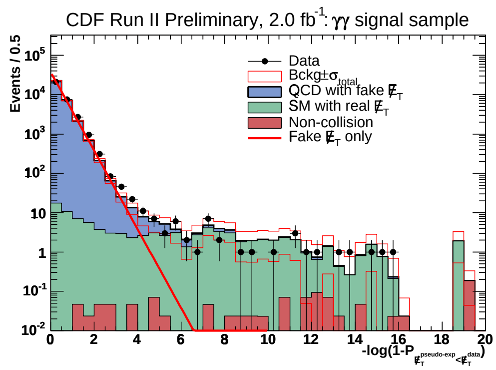


Figure 7: *The $\not\!\!E_T$-significance distribution in $\gamma\gamma$ events.*

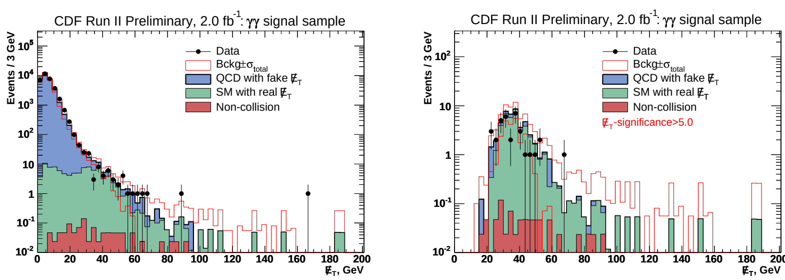


Figure 8: *The observed $\not\!\!E_T$ distribution in all (left) $\gamma\gamma$ events and events with $\not\!\!E_T$-significance$>5$ (right).*

Table 3: *Observed and expected number of $\gamma\gamma + \not\!\!E_T$ events for three values of the $\not\!\!E_T$-significance cut. Systematic and MC statistical uncertainties of the background are added in quadrature.*

| | $\not\!\!E_T$-sig>3 | $\not\!\!E_T$-sig>4 | $\not\!\!E_T$-sig>5 |
|---|---|---|---|
| Non-collision | 0.90±0.32 | 0.85±0.30 | 0.80±0.27 |
| QCD (fake $\not\!\!E_T$) | 52.1±11.5 | 15.4±3.8 | 6.2±2.7 |
| EWK (real $\not\!\!E_T$) | 53.6±8.9 | 47.3±8.0 | 41.6±7.0 |
| Total background | 106.6±14.5 | 63.6±8.9 | 48.6±7.5 |
| Data | 120 | 52 | 34 |

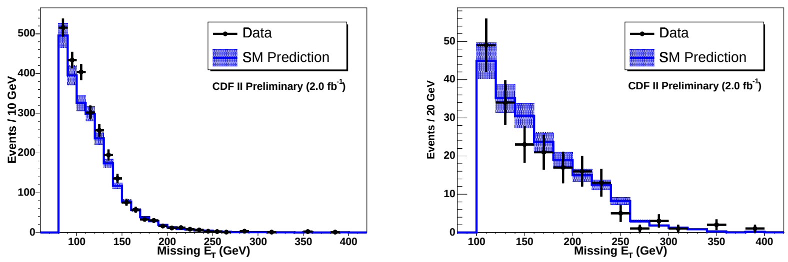


Figure 9: *The observed $\not{E}_T$ distribution in $jj + \not{E}_T$ events from region 1 (left) and region 2 (right).*

$\not{E}_T$ and one or more energetic jets can be produced in models of new physics beyond the Standard Model. The CDF Collaboration has previously performed a signature-based search for exclusive $jet + \not{E}_T$ events [18] and now extends the analysis to an exclusive $jj + \not{E}_T$ channel. This signature, for example, appears in MSSM [19], Universal Extra Dimensions [20], and Littlest Higgs [21] models. In this search, events are required to have exactly two jets with $E_T$>15 GeV and $|\eta|$<2.4. The second jet has to satisfy the requirement of $E_T$>30 GeV. Clean-up cuts are applied to remove events with poorly measured jets and events due to cosmic rays. The data sample is split into two regions that can be sensitive to different models: events in region 1 must have $\not{E}_T$>80 GeV and $H_T = E_T^{jet1} + E_T^{jet2}$>125 GeV, and events in region 2 must have $\not{E}_T$>100 GeV and $H_T$>225 GeV. The dominant background in this search are $W/Z + jets$ events. Figure 9 shows the observed $\not{E}_T$ distributions for $jj + \not{E}_T$ events from the two kinematic regions. Data agree well with the total predicted background: region-1 has 2,506 events compared to 2,312±140 predicted events; region-2 contains 186 events compared to 196±29 expected events. The CDF Collaboration has recently used these results to set limits on the leptoquark production [22].

## 8 Search for $3^{rd}$ Generation Scalar Leptoquarks Using the $b\tau b\tau$ Final State

The observed symmetry between leptons and quarks leads to prediction of existence of the Leptoquark bosons in models of new physics such as grand unification [23], Technicolor [24], and compositeness [25]. Since flavor-changing currents have not been observed, it is expected that there are three generations of leptoqurks (LQ), and each couples only to fermions of the same generation.

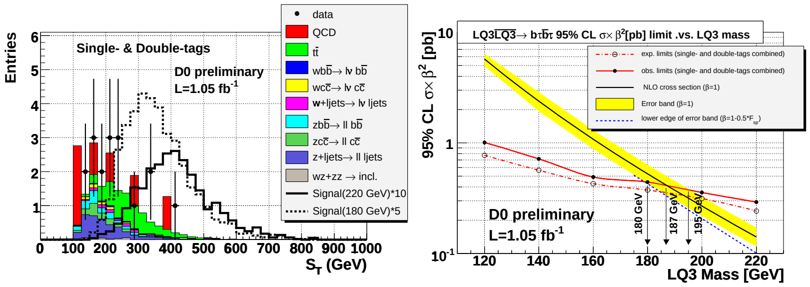


Figure 10: *The observed $S_T$ distribution (left plot) and the cross section upper limits as a function of $LQ_3$ mass (right plot).*

The DØ Collaboration has performed a search for $3^{rd}$ generation scalar leptoqurks in the $b\tau b\tau$ final state with 1.1 fb$^{-1}$ of data. Selected events are required to have a muon with $P_T$>15 GeV/$c$, hadronic tau with visible $P_T$>15 GeV/$c$, at least two good jets with $E_T$>25,20 GeV and $|\eta|$<2.6, and transverse mass $M_T(\not{E}_T, \mu)$<50 GeV/$c^2$. At least one of the reconstructed jets is required to be tagged as a $b$-jet with a displaced decay vertex. The dominant backgrounds are QCD, $t\bar{t}$, and $W/Z + jets$ events. In this search, DØ finds 17 data events, which agrees well with the expected background of 18.4±0.5 events. Since no excess is observed, DØ excludes $3^{rd}$ generation scalar leptoqurks with masses up to 180 GeV/$c^2$ at 95% C.L. Figure 10 shows the observed distribution of the $S_T = P_T(\mu) + P_T(\tau) + E_T(jet1) + E_T(jet2) + \not{E}_T$ parameter (left plot) and the cross section upper limits as a function of LQ$_3$ mass (right plot).

## 9 Search for $H^{++}H^{--} \to \mu^+\mu^+\mu^-\mu^-$

Doubly-charged Higgs bosons appear in such scenarios of new physics as left-right symmetric models [26], Higgs triplet models [27], and little Higgs models [28]. The major production mechanism of a doubly-charged Higgs at the Tevatron is via $p\bar{p} \to Z/\gamma^* \to H^{++}H^{--} + X$. Since the $H^{\pm\pm}$ coupling to $W$ pairs is suppressed by the measured $m_W^2/(\cos^2\theta_W m_Z^2) \approx 1$, the dominant final states are expected to be like-sign lepton pairs. Since these decays violate lepton flavor conservation, mixed flavor states are also possible. Left-handed and right-handed states are distinguished by their decays into left-handed and right-handed leptons.

The DØ Collaboration has performed a search for pair production of doubly-charged Higgs bosons in the $\mu^+\mu^+\mu^-\mu^-$ final state with 1.1 fb$^{-1}$ of data. Events are required to have three isolated muons with $P_T$>15 GeV/$c$ and $|\eta|$<2.0. At least one muon pair should satisfy $M_{\mu\mu}$>30 GeV/$c^2$ and $\Delta\phi_{\mu\mu}$<2.5

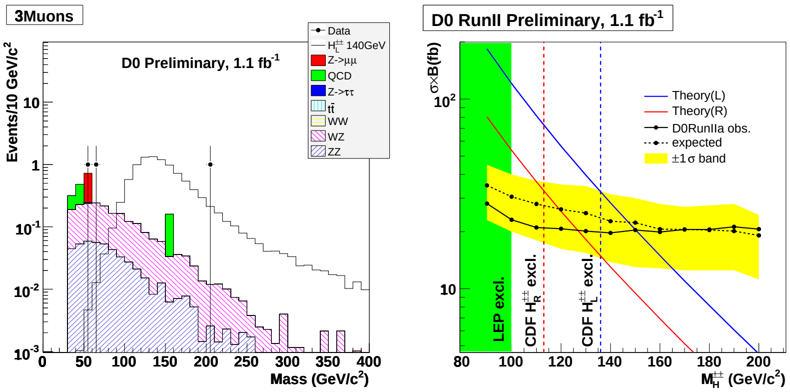


Figure 11: *The observed and predicted $M_{\mu\mu}$ distribution (left plot) and the cross section limit as a function of the Higgs mass ($M_{H^{\pm\pm}}$) at 95% C.L. (right plot).*

requirements to suppress $Z \to \mu^+\mu^-$ and QCD events. The largest background comes from $WZ$ events. Other backgrounds include $ZZ$, $Z \to \mu^+\mu^-$, and QCD events, each at about the same level. After all cuts, DØ finds 3 data events, which is in good agreement with an expected background of 3.1±0.5 events. Since no excess is observed, the DØ Collaboration sets limits on the production of doubly-charged Higgs bosons. At 95% C.L., the left-handed state is excluded with masses up to 150 GeV/$c^2$, and the right-handed state is excluded with masses up to 126.5 GeV/$c^2$. This analysis significantly extends the previous CDF result. Figure 11 shows the observed and predicted invariant mass distribution for $\mu\mu$ pairs (left plot) and the cross section limit as a function of the Higgs mass ($M_{H^{\pm\pm}}$) at the 95% confidence level (right plot).

## 10 Search for $H \to \gamma\gamma + X$

There exist models of new physics where, unlike in the Standard Model and most common MSSM scenarios, the Higgs coupling to fermions is greatly suppressed. Such a "fermiophobic" Higgs appears in top-color models [16, 10], theories with large extra dimensions [29], and even in the MSSM where decays to $b\bar{b}$ can be suppressed by 1-loop SUSY corrections [30]. In all these cases, a light Higgs boson ($m_h$<100 GeV/$c^2$) will predominantly decay into a $\gamma\gamma$ pair. Decays are mediated by either a $W$ or a heavy quark loop. The DØ Collaboration has looked for signs of "fermiophobic" Higgs produced via two mechanisms: $p\bar{p} \to VV \to h_f \to \gamma\gamma + X$ and $p\bar{p} \to h_f V \to \gamma\gamma + X$, where $V = W, Z$. The analysis is done with 1.1 fb$^{-1}$ of data. Events are re-

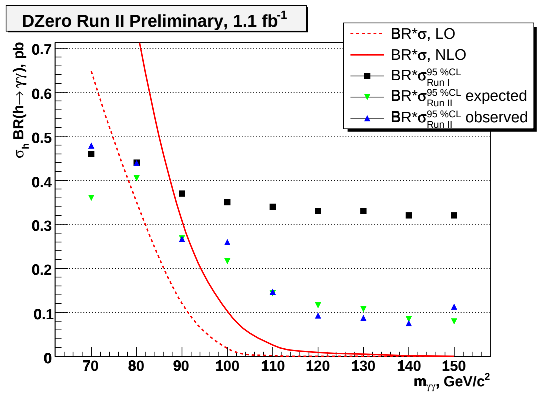


Figure 12: *The cross section limit as a function of the "fermiophobic" Higgs mass at 95% C.L.*

quired to have two central ($|\eta|$<1.1) photons with $E_T$>25 GeV and $M_{\gamma\gamma}$>65 GeV/$c^2$. The data sample is split in two parts according to the di-photon pair momentum ($q_T$): signal sample with $q_T$>35 GeV/$c$, and control sample with $q_T$<35 GeV/$c$. The backgrounds are regular QCD and QED events: $\gamma\gamma$, $\gamma + jet \rightarrow \gamma\gamma_{fake}$, and $jet + jet \rightarrow \gamma_{fake}\gamma_{fake}$. The control sample is used to test and tune the background estimation technique. The $\gamma\gamma$ background template is taken from MC simulation. The $\gamma + jet$ and di-jet background templates are derived from data. Since no excess of data over the predicted background is observed, the 95% C.L. limit on the production cross section is set. A "fermiophobic" Higgs boson with mass up to 92 GeV/$c^2$ is excluded in this study. The limits obtained are shown at Fig. 12.

## 11 Summary and Conclusion

The CDF and DØ Collaborations continue to search for signs of new physics beyond the Standard Model in both signature-based and model-dependent analyses. Many signatures have been explored, but no significant excess of data over the predicted background is observed. An interesting result is found by the CDF Collaboration in the $M_{e^+e^-}$ spectrum using 2.5 fb$^{-1}$ of data. In this study, the most significant excess of data over the total background is observed in the window 228 GeV/$c^2$<$M_{e^+e^-}$<250 GeV/$c^2$. It corresponds to 3.8 standard deviations from the SM prediction. The probability of observing a background fluctuation with significance $S/\sigma_B$>3.8 anywhere in the mass range 150 GeV/$c^2$<$M_{e^+e^-}$<1000 GeV/$c^2$ is about 0.6%. More data and a similar analysis in the $\mu^+\mu^-$ channel and by the DØ Collaboration should reveal whether this is a sign of new physics or just a rare statistical fluctuation.

Both the CDF and DØ Collaborations continue to explore new signatures and analysis techniques. This increases our potential to see something new. One example of signatures that were not thoroughly explored before is the search for "delayed" $Z$ bosons by the DØ Collaboration. Photon pointing (DØ), $\not\!\!E_T$-significance (CDF), and EM-timing (CDF) are examples of new promising analysis techniques.

The Tevatron has already delivered 3.7 fb$^{-1}$ of data per experiment and continues to set performance records. With 2-5 fb$^{-1}$ still to come in the Run II program, we can expect many new interesting results.

## 12 Acknowledgments

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Science and Technology Facilities Council and the Royal Society, UK; the Institut National de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Ministerio de Educación y Ciencia and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; and the Academy of Finland.

## References

1. D. London and J.L. Rosner, Phys. Rev **D34**, 1530 (1986); J.L. Hewett and T.G. Rizzo, Phys. Rep. **183**, 193 (1989).

2. L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 3370 (1999).

3. T. Sjöstrand *et al.*, Comput. Phys. Commun. **135**, 238 (2001).

4. J. Bagger, C. Schmidt, and S. King, Phys. Rev **D37**, 1188 (1988); P.H. Frampton and S.L. Glashow, Phys. Lett. B **190**, 157 (1987).

5. U. Baur, I. Hinchliffe, and D. Zeppenfeld, Int. J. Mod. Phys. A **2**, 1285 (1987); U. Baur, M. Spira, and P.M. Zerwas, Phys. Rev **D42**, 815 (1990).

6. K.D. Lane and M.V. Ramana, Phys. Rev **D44**, 2678 (1991); E. Eichten and K.D. Lane, Phys. Lett. B **327**, 129 (1994); K.D. Lane and S. Mrenna, Phys. Rev **D67**, 115011 (2003).

7. E. Eichten *et al.*, Rev. Mod. Phys. **56**, 579 (1984); *Addendum-ibid.* **58**, 1065 (1986).

8. P. Fayet, Phys. Lett. B **70**, 461 (1977); *ibid.* **86**, 272 (1979); *ibid.* **175**, 471 (1986).

9. M. Strassler and K. Zurek, arXiv:hep-ph/0604261v2.

10. B. Dobrescu, G. Landsberg, and K. Matchev, Phys. Rev **D63**, 075003 (2001).

11. H. Frampton, P.Q. Hung, and M. Sher, Phys. Rep. **330**, 263 (2000).

12. N. Arkani-Hamed, S. Dimopoulos, and G. Dvali, Phys. Lett. B **429**, 263 (1998).

13. S. Dimopoulos, S.D. Thomas and J.D. Wells, Nucl. Phys. B **488**, 39 (1997); S. Ambrosanio, G.D. Kribs and S.P. Martin, Phys. Rev. D **56**, 1761 (1997); G.F. Giudice and R. Rattazzi, Phys. Rep. **322**, 419 (1999); S. Ambrosanio, G.L. Kane, G.D. Kribs, S.P. Martin and S. Mrenna, Phys. Rev. D **55**, 1372 (1997);

14. G. Bhattacharyya and R.N. Mohapatra , Phys. Rev. D **54**, 4204 (1996).

15. J.L. Rosner, Phys. Rev. D **55**, 3143 (1997).

16. B. Dobrescu, Phys. Rev. **D63**, 015004 (2001).

17. S. Ambrosanio *et al.*, Phys. Rev. Lett. **76**, 3498 (1996); B.C. Allanach *et al.*, hep-ph/0112321.

18. A. Abulencia *et al.* [CDF Collaboration], Phys. Rev. Lett. **97**, 171802 (2006).

19. H. Goldberg, Phys. Rev. Lett. **50**, 1419 (1983); J.R. Ellis *et al.*, Nucl. Phys. B **238**, 453 (1984).

20. G. Servant and T.M.P. Tait, Nucl. Phys. B **650**, 391 (2003); H.C. Cheng, J.L. Feng, and K.T. Matchev, Phys. Rev. Lett. **89**, 211301 (2002).

21. H.C Cheng and I. Low, JHEP **0309**, 051 (2003).

22. P.H. Beachemin, "Searches for Leptoquarks", talk presented at the *Deep Inelastic Scattering (DIS 08)* conference, London, 2008.

23. J.C. Pati and A. Salam, Phys. Rev **D10**, 275 (1974); H. Georgi and S.L. Glashow, Phys. Rev. Lett. **32**, 438 (1974).

24. S. Dimopoulos and L. Susskind, Nucl. Phys. B **155**, 237 (1979); S. Dimopoulos, *ibid.* **168**, 69 (1980); E. Eichten and K. Lane, Phys. Lett. B **90**, 125 (1980).

25. B. Schrempp and F. Schrempp, Phys. Lett. B **153**, 101 (1985); W. Buchmüller, R. Rückl, and D. Wyler, *ibid.* **191**, 442 (1987); *Erratum-ibid.* **448**, 320 (1999).

26. N.G. Deshpande, J.F. Gunion, and B. Kayser, Phys. Rev. **D44**, 837 (1991); J.G. Gunion *et al.*, *ibid.* **D40**, 1546 (1989); T. Rizzo, *ibid.* **D25**, 1355 (1982), *Addendum-ibid.* **D27**, 657 (1983); C.P. Hays, "Doubly-Charged Higgs Boson", in *Search for the Higgs Boson*, Ed. J.V. Lee (Nova Science Publishers, 2006).

27. J.F. Gunion, C. Loomis, and K.T. Pitts, hep-ph/9610237 (1996); J.F. Gunion, R. Vega, and J. Wudka, Phys. Rev. **D42**, 1673 (1990); E. Accomando *et al.*, "CP Studies and Non-Standard Higgs Physics", hep-ph/0608079.

28. N. Arkani-Hamed *et al.*, JHEP **0208**, 021 (2002).

29. L. Hall and C. Kolda, Phys. Lett. B **459**, 213 (1999); H.-C. Cheng, B.A. Dobrescu, and C.T. Hill, Nucl. Phys. B **589**, 249 (2000).

30. M. Carena, S. Mrenna, and C.E. Wagner, Phys. Rev **D60**, 075010 (1999).