NON-SUSY SEARCHES FOR PHYSICS BEYOND THE STANDARD MODEL AT THE TEVATRON*

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Recent results on searches for physics beyond the Standard Model from the CDF and DØ Collaborations at the $p\bar{p}$ collider Tevatron are presented and their impact on LHC physics discussed.

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1. Introduction

The Standard Model (SM) has been enormously successful, but it leaves many important questions unanswered. It is also widely acknowledged that, from a theoretical standpoint, the SM is at best an effective theory, and must be part of a larger theory, "beyond" the SM, which is as yet unknown. Supersymmetry (SUSY) is most commonly invoked to address these, but there are a large number of important and well-motivated theoretical models that seek to answer some or all of fundamental questions. These theories make a strong case for looking for new physics, and include Extra Dimensions (ED), Grand Unified Theories, Composite models, Anomalous couplings and Higgs models.

In this article we summarize the current Tevatron experimental results of searches for physics beyond the Standard Model.

2. Searches for heavy gauge bosons

Many extensions of the SM gauge group predict the existence of electrically-neutral, massive gauge bosons commonly referred to as Z'. The leptonic decays $Z' \to l^+l^-$ provide the most distinctive signature for observing the Z' signal at Tevatron.

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CDF has searched for massive Z' bosons in the dielectron channel using 448 pb^{-1} dataset [1]. To identify the Z' signal, CDF use both the dielectron invariant mass M_{ee} distribution, and the angular distribution $\cos(\theta^*)$ of the electron pair in the Collins–Soper frame Fig. 1 (left). The CDF data is found to be consistent with the null hypothesis, with a probability greater than the values obtained in 87% of pseudo-experiments. Thus CDF set 95% C.L. upper limits on the Z' mass for many Z' models: the sequential Z' SM, the canonical superstring-inspired E6 models, the four general U(1) model-lines, the "littlest" Higgs ZH model, and contact-interaction searches.

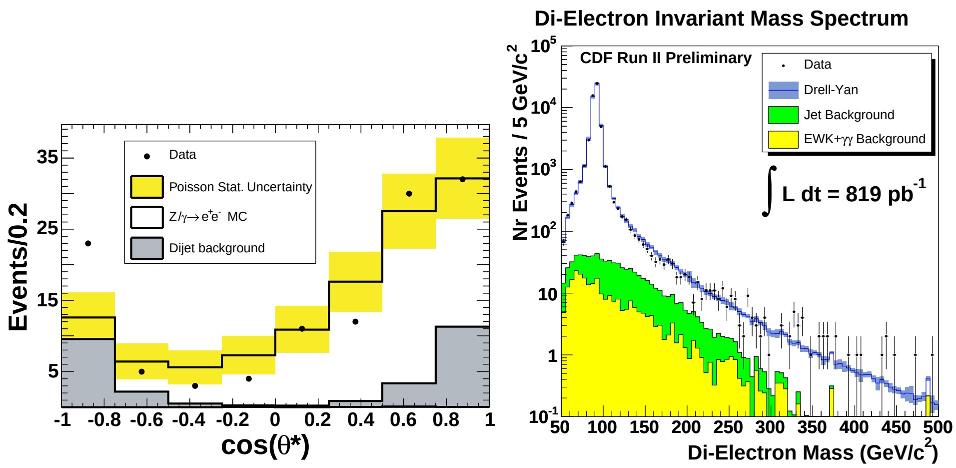

Fig. 1. Distribution of $\cos(\theta^*)$ for the high mass region $M_{ee} > 200$ GeV$/c^2$ (left) and the measured di-electron mass spectrum with the expected background for the central–central and central–plug channels combined (right).

CDF has also performed a model independent search for $X \to ee$, where X has a mass between 150 GeV and 950 GeV, in the final state using 819 pb^{-1} of Run II data [2]. Both the central ($|\eta| < 1.1$) and plug ($1.2 < |\eta| < 3.0$) detectors were used and events were required to be either central–central or central–plug. Fig. 1 (right) shows the data mass spectrum together with the background estimates for the central–central and central–plug channels combined. The SM Drell–Yan contribution is estimated using MC simulated events normalized to the data in an Z invariant mass window. The dijet and W+jet background normalizations are estimated by extrapolating from events where the leptons are not isolated. Electroweak and $\gamma\gamma$ backgrounds are all normalized to the theoretically expected cross-section. Since no significant excess over the SM prediction is observed the limits are placed on new spin-1 and new spin-2 bosons. The SM-like Z' is found to be excluded at 95% C.L. for masses below 850 GeV$/c^2$ and the RS Graviton with

$k/M_{\rm pl} = 0.1$ (0.01) is excluded at 95% for masses below 764 (230) GeV/c^2. By combining with the diphoton channel, the RS Graviton exclusion region is increased to mass below 875 (244) GeV/c^2 for $k/M_{\rm pl} = 0.1$ (0.01).

DØ has also searched for a heavy partner of the Z boson with SM-like couplings to fermions in the dimuon channel using 250 pb^{-1} in Run II data [3]. The data are in excellent agreement with Drell–Yan production and do not exhibit any evidence for new physics beyond the SM, therefore DØ set a lower limit on the mass of the Z' boson with the SM-like couplings to fermions of 680 GeV at the 95% C.L. Fig. 2 shows the 95% C.L. limits on $\sigma\times$ BR($Z' \to \mu\mu$). The arrow indicates the mass limit attained in the analysis of 680 GeV for a SM-like Z'. Dashed vertical lines indicate mass limit that would be found if the theoretical cross section was varied by $\pm 1\sigma$.

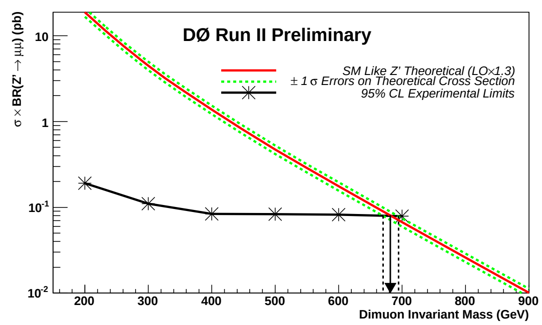

Fig. 2. The 95% C.L. limits on $\sigma\times$ BR($Z' \to \mu\mu$) for a SM-like Z'.

CDF has searched for new particles decaying to tau pairs using a 195 pb^{-1} data [4]. Hypothetical particles such as Z' and MSSM Higgs boson A can potentially produce such pairs. The low-mass region, dominated by $Z \to \tau\tau$, is used as a control region. No significant excess of events over the estimated backgrounds is observed in the high-mass region, and CDF set upper limits on the cross section times branching ratio as function of the Z' and A mass.

Recently CDF has performed a search for a new heavy charged vector boson W' which decays to an electron–neutrino pair with a light and suitable neutrino by using a data sample corresponding to 205 pb^{-1} [5]. CDF observe no evidence of this decay mode and set limits on the production cross section times branching fraction, assuming the neutrino from W' boson decays to be light. CDF exclude a W' boson with mass less 788 GeV/c^2 at 95% C.L., assuming the manifest left-right symmetric model. The upper limits in the production cross section times branching fraction are plotted as a function of W' boson mass in Fig. 3.

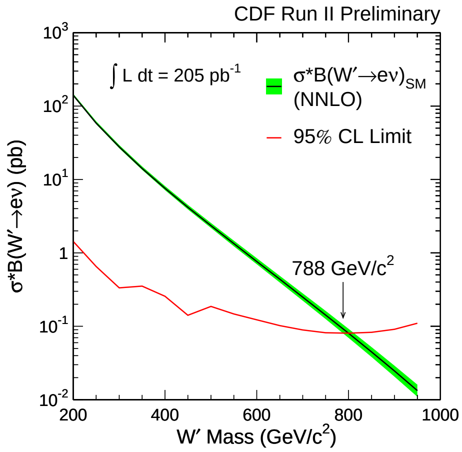

Fig. 3. The 95% C.L. limits on cross section times branching fraction as a function of W' boson mass.

3. Searches for extra dimensions

Events with large missing transverse energy, $\not\!\!E_{\mathrm{T}}$, and one or more energetic jets can be produced in numerous models of new physics, in addition to SM production from electroweak and QCD processes. One model of new physics that can produce such a signature is the compacted Large Extra Dimensions (LED) model of Arkani-Hamed, Dimopoulos, and Dvali (ADD). In such a model, gravitons are produced directly in processes such as $q\bar{q} \to gG, qg \to qG, gg \to gG$, where G is the emitted graviton. The emitted graviton will be undetected, leaving the final state quark or gluon to produce a jet. In all cases, the signature will be jets plus missing energy.

CDF has performed a search for direct graviton production using 368 pb^{-1} of Run II data [6]. A comparison is made of the data to the expected SM backgrounds. No significant excess is observed, and CDF interpret this null result in terms of lower limits on the n-dimensional effective Planck scale (M_D) for the LED scenario. CDF set limit on the value of M_D for different values of n based on the maximum possible number of observed events. These limit on M_D for $n = 2$–6 are shown in Fig. 4 (left). A comparison of the limits on M_D from DØ and CDF with the LEP averages is also shown in Fig. 4. For $n = 5$ and $n = 6$, CDF measurement places the world's best limit on M_D.

DØ has performed the first dedicated search for Randall–Sundrum (RS) gravitons in the dielectron, dimuon, and diphoton channels using 246–275 pb^{-1} of data [7]. DØ see no evidence for resonant production of the Kaluza–Klein (KK) mode of the graviton. Lower limits on the mass of the first KK mode at the 95% C.L. have been set between 250 and 785 GeV, depending on its coupling to SM particles. Fig. 4 (right) shows 95% C.L. exclusion limits on the RS model parameters M_1 and $k/M_{\rm pl}$.

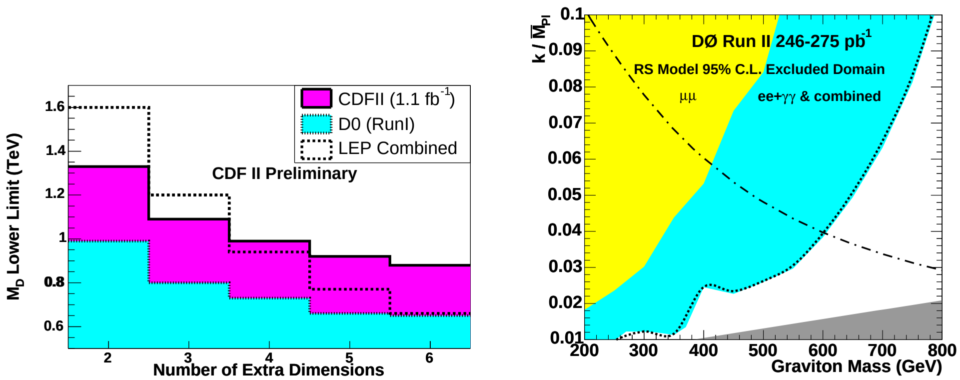

Fig. 4. Comparison of limits on M_D based on the Run II CDF and Run I DØ results with the combined LEP averages (left) and 95% C.L. exclusion limits on the RS model parameters M_1 and $k/M_{\rm pl}$ (right).

4. Searches for leptoquarks

The SM of particle physics has an intriguing symmetry. This symmetry between leptons and quarks motivates the possibility of a new kind of lepton–quark force, mediated through so-called leptoquarks (LQ). Leptoquark would have both lepton and quark properties, and decay into a lepton (a charged lepton or a lepton neutrino) and a quark.

DØ has searched for the first generation scalar LQ pair production for two cases: when both LQs decay to an electron and a quark, and when one of the LQs decays to an electron and a quark and the other to a neutrino and a quark [8]. The final states consist of two electrons and two jets ($eejj$) or of an electron, two jets, and $\not\!\!E_{\rm T}$ corresponding to the neutrino ($e\nu jj$). The data are consistent with the expected SM background and no evidence for LQ production is observed in the $eejj$ and $e\nu jj$ channels. Therefore, DØ derives 95% C.L. lower limits on the LQ mass as a function of β, where β is the branching fraction for LQ $\rightarrow eq$. The limits are 241 and 218 GeV/c^2 for $\beta = 1$ and 0.5, respectively. These results are combined with those obtained by DØ at $\sqrt{s} = 1.8$ TeV, which increases these LQ mass limits to 256 and 234 GeV/c^2. The combined results from Run I and II are shown in Fig. 5 (left).

DØ also reports on a search for the pair production of second generation scalar leptoquarks (LQ2), using 294 pb^{-1} data [9]. No evidence for a LQ signal in the LQ2 LQ2 $\to \mu q \mu q$ channel has been observed, and upper bounds on the product of cross section times branching fraction were set. This yields lower mass limits of $\mathrm{m}_{\mathrm{LQ2}} > 247$ GeV for $\beta = \mathrm{B}(\mathrm{LQ2} \to \mu q) = 1$ and $\mathrm{M}_{\mathrm{LQ2}} > 251$ GeV for $\beta = 1/2$. Combining these limits with previous DØ results, the lower limits on the mass of a LQ2 are $\mathrm{m}_{\mathrm{LQ2}} > 251$ GeV and $\mathrm{m}_{\mathrm{LQ2}} > 204$ GeV for $\beta = 1$ and $\beta = 1/2$. respectively. These results are, for large β, the most stringent limits on LQ2 from direct measurement to date. Fig. 5 (right) shows the excluded region in the β versus $\mathrm{m}_{\mathrm{LQ2}}$ parameter space.

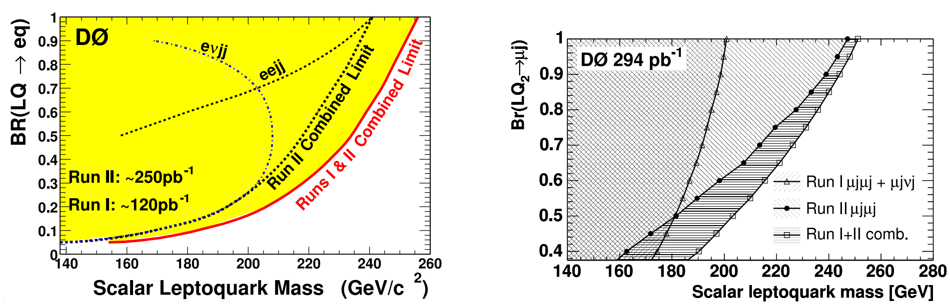

Fig. 5. Excluded region (shaded area) at the 95% C.L. in the β versus LQ mass plane for the production of first-generation scalar leptoquarks.

CDF has performed a search for third generation vector leptoquarks (VLQ3) in the ditau plus dijet channel using 322 pb^{-1} of data [10]. The final decay products, two b quarks and two tau leptons, yield an experimental signature of two jets from the b quarks, an electron or muon from a leptonic tau decay, and a hadronic tau decay. The results are shown in Fig. 6, as a function of VLQ3 mass, along with the theoretical predictions. With a 95% C.L. CDF set an upper limit on the VLQ3 pair production cross section of 344 fb, and set a lower limit on the VLQ3 mass of 317 GeV$/c^2$, assuming Yang–Mills couplings and $\mathrm{Br}(\mathrm{VLQ3} \to b\tau) = 1$. If the uncertainties on the theoretical cross section are applied, the upper limit on the cross section is 360 fb and the lower limit on the mass is 294 GeV$/c^2$. For a theory with so-called Minimal couplings, the upper limit on the cross section is 493 fb and the lower limit on the mass is 251 GeV$/c^2$ for the nominal choice of parton distribution functions and Q^2 scale, while the corresponding limits are 610 fb and 223 GeV$/c^2$ if the theoretical uncertainties on the cross section are applied.

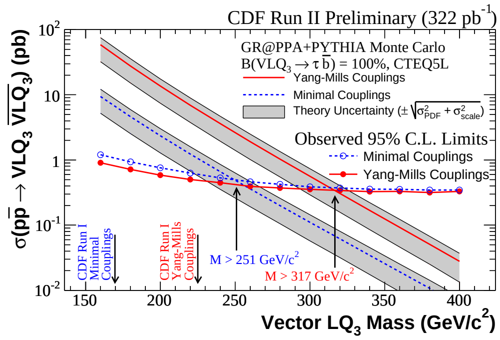

Fig. 6. Pair production cross section as a function of VLQ3 mass, including the measurement results and the theory predictions, with bands for uncertainties due to the PDF and Q2 choices.

5. Searches for new fermions

Heavy resonance decaying into a quark and a gauge boson may signal the existence of excited quarks and thereby indicate quark substructure.

DØ has searched for a heavy resonance produced by the fusion of a gluon and a quark which decays into a Z boson and a quark in the $Z \rightarrow e^+e^-$ decay channel using 370 pb^{-1} of data [11]. Since no significant excess of events is observed, which would indicate the presence of a resonance, DØ has determined the upper limits on the production cross section of a hypothetical resonance as a function of its mass and width. In Fig. 7 (left), the leading-order production cross section of an excited quark times its decay branching fraction into $Z+$ jet and $Z \rightarrow e^+e^-$, for $\xi = 1$. DØ find a lower limit of 510 GeV at the 95% C.L. for the mass of an excited quark for $\xi = 1$ within the framework of the model considered.

An open question in particle physics is the observed mass hierarchy of the quark and lepton SU(2) doublets in the SM. According to compositeness model, a quark or lepton is a bound state of three fermions, or of a fermion and a boson and compositeness models imply a large spectrum of excited states.

DØ has searched for the production of an excited muons in the process $p\bar{p} \rightarrow \mu^*\mu^*$ with $\mu^* \rightarrow \mu\gamma$, using 380 pb^{-1} [12]. No excess above the SM expectation is observed in data. Interpreting DØ data in the context of a model that describes μ^* production by four-fermion contact interactions and μ^* decay via electroweak processes, DØ exclude production cross sections higher than 0.057 pb–0.112 pb at the 95% C.L., depending on the mass of the excited muon. Choosing the scale for contact interactions to be λ=1 TeV, excited muon masses below 618 GeV are excluded. (See Fig. 7 (left)).

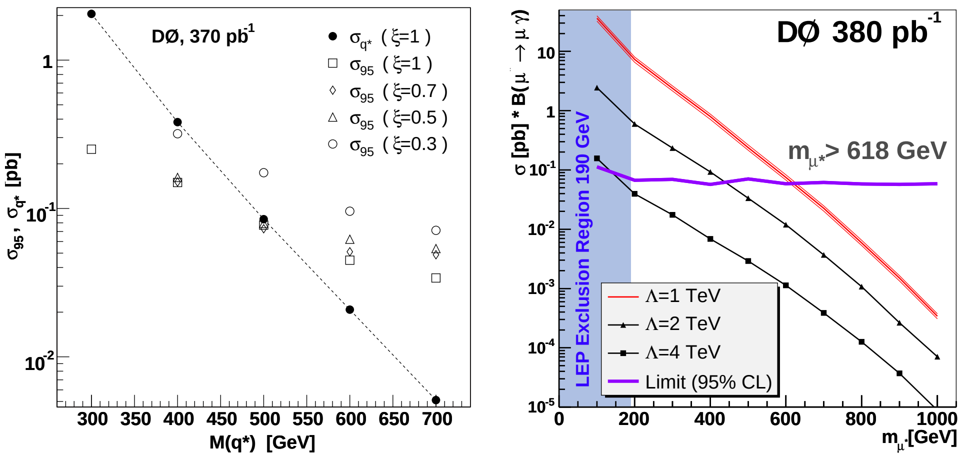

Fig. 7. Upper limits on the resonance cross section times branching fraction at the 95% C.L. for different ξ values as function of the resonance mass (left) and the measured cross section times branching fraction limit, compared to the contact interaction model prediction for different choices of Λ (right).

6. Signature based searches

Some models of new physics that predict two photons in the final state include Gauge-mediated SUSY, fermiphobic Higgs, $\chi_2^0 \to \gamma\chi_1^0$, b' pairs, and production of a pair of excited particles which decay to γ+X. With the large range of exotics models, both known and not yet imagined, and vanishing odds of selecting the correct model, CDF chose to perform model-independent searches for new physics based on the final state photon signature. The basic signatures are those containing final-state photons and contain one additional final-state object. These are $\gamma\gamma$, $l\gamma$ (where l is an electrons or a muon) signatures. Accompanying searches are made within these signatures for anomalous production of additional reconstructed objects (jets, electrons, muons, taus, b-quarks, and additional photon) with large $\not{E}_{\mathrm{T}}$. This work significantly extends previous CDF diphoton searches. CDF find that the numbers of events in the $\gamma\gamma+\not{E}_{\mathrm{T}}$ and $\gamma\gamma + e$, $\gamma\gamma + \mu$, $\gamma\gamma+\gamma$ subsamples of $\gamma\gamma+$ X sample agree with SM predictions. Fig. 8 shows a three-body invariant mass distributions of $\gamma\gamma e$ events and $\gamma\gamma\mu$ events from the SM plus fake lepton prediction and those observed in the data [13].

CDF has also performed a search for anomalous production of events containing a charged lepton (e or μ) and a photon, both with high transverse momentum, accompanied by additional signature X, including $\not{E}_{\mathrm{T}}$ and additional leptons and photons [14]. CDF find 42 $l\gamma+$ $\not{E}_{\mathrm{T}}$ events versus a standard model expectation of 37.3 $\pm$ 5.4 events. Fig. 9 shows the distributions for events in the $l\gamma + \not\!\!E_{\mathrm{T}}$ sample (points) in (a) the E_{T} of the photon; (b) the E_{T} of the lepton, (c) the $\not\!\!E_{\mathrm{T}}$, and (d) the transverse mass of the $l\gamma + \not\!\!E_{\mathrm{T}}$ transverse energy system. The histograms show the expected SM contributions, including estimated backgrounds from misidentified photons and leptons. The level of excess observed in Run I, 16 events with an expectation of 7.6 ± 0.7 events (corresponding to a $2.7\,\sigma$ effect), is not supported by the new Run II data. In the signature of $ll\gamma + \not\!\!E_{\mathrm{T}}$ we observe 31 events versus an expectation of 23.0 ± 2.7 events. There is no significant excess in either signature. In this sample CDF find no events with an extra photon and so find no events like the one $ee\gamma\gamma + \not\!\!E_{\mathrm{T}}$ event observed in Run I.

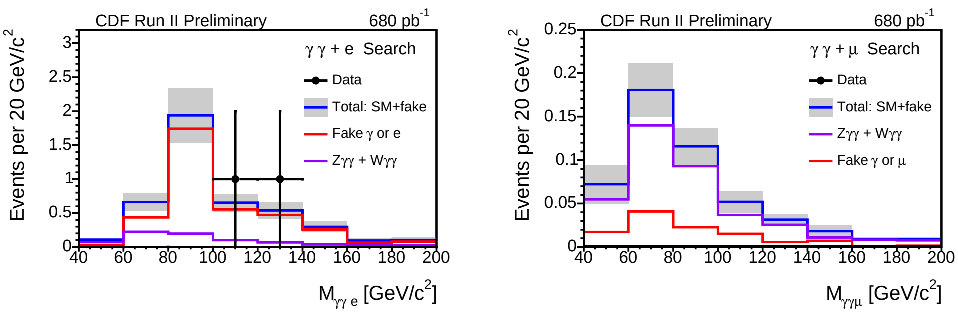

Fig. 8. Three-body invariant mass distributions of $\gamma\gamma e$ events (left) and $\gamma\gamma\mu$ events from the SM plus fake lepton prediction and those observed in the data (right).

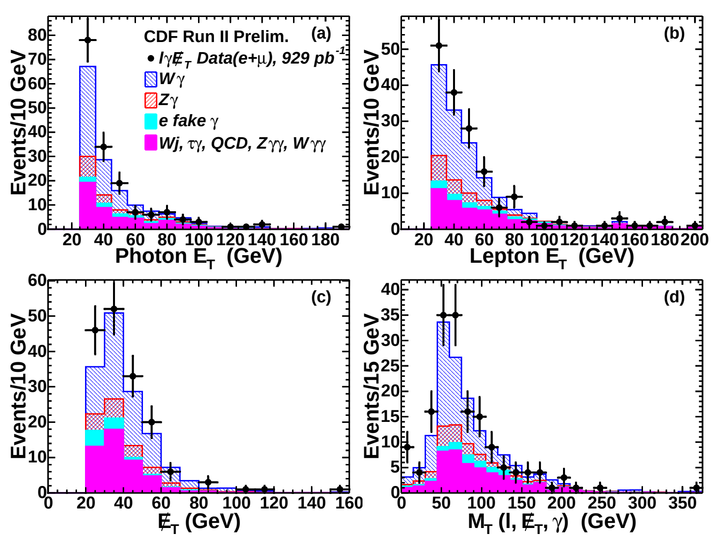

Fig. 9. Three-body invariant mass distributions of $\gamma\gamma e$ events (left) and $\gamma\gamma\mu$ events from the SM plus fake lepton prediction and those observed in the data (right).

7. Conclusion

Both CDF and DØ has searched for the new physics using 300–700 pb^{-1} of Run II data. No evidence for new physics signature has yet been observed at the Tevatron. Tevatron experiments expect to collect 4 to 8 fb^{-1} of data by 2009. The new data that will be collected by CDF and DØ experiments will provide an opportunity for new physics discovery before the LHC starts.

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