

Exotic Searches at the Tevatron

Gustaaf Brooijmans
on behalf of the CDF and DØ Collaborations

Columbia University, New York, NY

Abstract. Recent results on searches for new physics at Run II of the Tevatron are reported. The searches cover many different final states and previous hints of signals, but all analyses have at this point led to negative results.

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INTRODUCTION

In the standard model of particle physics, the $W_L W_L$ scattering amplitude violates the unitarity bound at a center of mass energy ≈ 1.7 TeV [1]. One solution to this problem is offered by the Higgs mechanism [2] through the introduction of a massive scalar particle with non-zero vacuum expectation value. Loop corrections to this “Higgs boson’s” mass involving other massive particles are quadratically divergent, implying that the physical mass of the Higgs boson corresponds to a scale at which new physics is present. To successfully address the $W_L W_L$ scattering amplitude problem the Higgs boson mass is constrained to $m_H \lesssim 1$ TeV/ c^2 , and if fermions acquire their masses through coupling to the Higgs boson, then $m_H \lesssim 200$ GeV/ c^2 [3]. If the Higgs boson, whether elementary or composite, doesn’t exist, some other form of new physics must be present at the TeV scale to prevent the $W_L W_L$ scattering amplitude from violating the unitarity bound. Among the models of new physics, supersymmetric ones are certainly, and justifiably, the most popular. These address the divergences in the corrections to the Higgs mass in a very natural way, improve the unification of couplings at a high scale, provide a good dark matter candidate and lead to radiative electroweak symmetry breaking. Unfortunately, they do not tell us anything about the origin of the number of generations of fermions, their mass spectrum, charges, etc. In this talk, recent results from the CDF and DØ collaborations on searches for manifestations of non-supersymmetric new physics are presented.

NEW GAUGE BOSONS

New heavy gauge bosons are predicted in many extensions of the standard model:

- In so-called Little Higgs models, the quadratically divergent radiative corrections to the Higgs mass are canceled “individually”, leading to the appearance of partners of the W and Z bosons at the TeV scale.
- In Grand Unified Theories (GUTs) and Left-Right Symmetric Models (LRSMs) heavy partners of the electroweak bosons generally appear, although their masses are less well constrained.
- In extra dimensional models where the gauge bosons are allowed to propagate in (some of) the additional space dimensions Kaluza-Klein excitations will be observable. To address the hierarchy problem, these should typically have masses $m \lesssim 10$ TeV/ c^2 .
- If the Higgs field is a triplet rather than a doublet, doubly charged Higgs bosons exist.

It should also be noted that graviton resonances which appear in Randall-Sundrum type models [4] lead to similar signatures.

CDF recently released a new result in the search for dielectron resonances using almost 900 pb^{-1} of data. The invariant mass spectrum of dielectron events used in this search is shown in Figure 1. No significant excess is seen at any mass value leading to a limit on the mass of a sequential, standard model-like Z' of $m(Z') > 850$ GeV/ c^2 at 95% C.L.

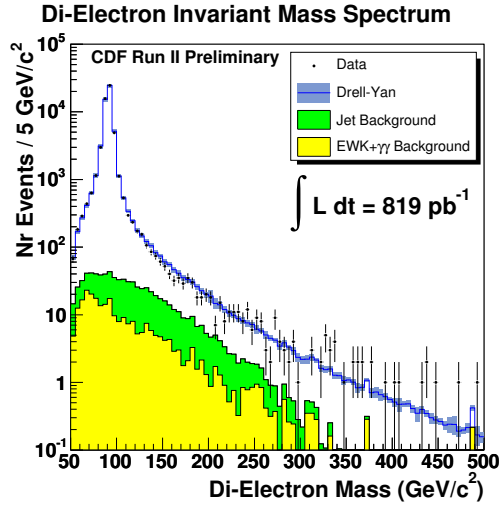


FIGURE 1. Dielectron invariant mass spectrum in the CDF search for electron-positron resonances.

CDF also searches for pair production of doubly charged Higgs bosons in the lepton flavor violating modes $H^{++} \rightarrow e^+ \tau^+$ and $H^{++} \rightarrow \mu^+ \tau^+$ (and charge conjugates). At least three leptons are required in the final states so that the backgrounds are very small, and no events are observed in approximately 350 pb^{-1} of data. Interpreted in a left-right symmetric model, the corresponding mass limit on doubly charged Higgs bosons coupling to left-handed particles is $m(H^{++}) > 114(112) \text{ GeV}/c^2$ at 95% C.L. in the $e\tau(\mu\tau)$ channel.

In the search for singly charged gauge bosons, CDF looked for a W' decaying to an electron and a neutrino in 205 pb^{-1} and derived a limit $m(W') > 788 \text{ GeV}/c^2$ from a study of the transverse mass spectrum.

LEPTOQUARKS

Leptoquarks are a natural consequence of the unification of quarks and leptons into a single multiplet, and as such are expected to be gauge bosons as well. While their masses can logically be expected to be of the order of the unification scale, in some models they can be relatively light. Experimentally, it is customary to consider one leptoquark per generation. These are assumed to be very short-lived and decay to a quark and a lepton. The branching ratio to a charged lepton and a quark is then denoted as β .

At hadron colliders, leptoquarks can be pair-produced through the strong interaction or singly produced. In the latter case the production cross-section depends on the (unknown) quark-lepton coupling, which is generally taken to be of the same order of magnitude as the fine structure constant.

There are two recent results from leptoquark searches at the Tevatron. $D\bar{O}$ has searched for leptoquarks decaying to a quark and a neutrino ($\beta = 0$) in the jets plus missing transverse energy in 370 pb^{-1} of data. Experimentally this is a difficult analysis which suffers from substantial QCD dijets background due to mismeasured jets. To mitigate this, $D\bar{O}$ requires exactly two acoplanar jets. The ensuing missing transverse energy distribution, before final analysis cuts, is shown in Figure 2. The background from QCD dijets, dominant at low missing transverse energy, is extrapolated to higher values using two different fitting functions as shown in the inset. The dominant non-QCD standard model background is Z boson plus jets production with the Z decaying to a pair of neutrinos. No excess is observed so $D\bar{O}$ sets a limit at $m(LQ) > 136 \text{ GeV}/c^2$ at 95% C.L.

CDF has released results on a search for vector leptoquarks of the third generation in the $LQ_3 \rightarrow b\tau$ decay channel. The signature consists of a dijet plus ditau final state, in which one tau is required to decay leptonically and the other hadronically. The main discriminating variables are the number of jets and an H_T -type variable which is a scalar sum of the transverse energies of all jets, leptons and the event's missing transverse energy. This allows CDF to set a limit at $m(LQ_3) > 294 \text{ GeV}/c^2$ assuming $\beta = 1$. Note that this limit is much higher than the typical limits on leptoquark masses at the Tevatron due to the model choice of vector leptoquarks, which have a much larger production cross-section than the scalar leptoquarks which are usually chosen.

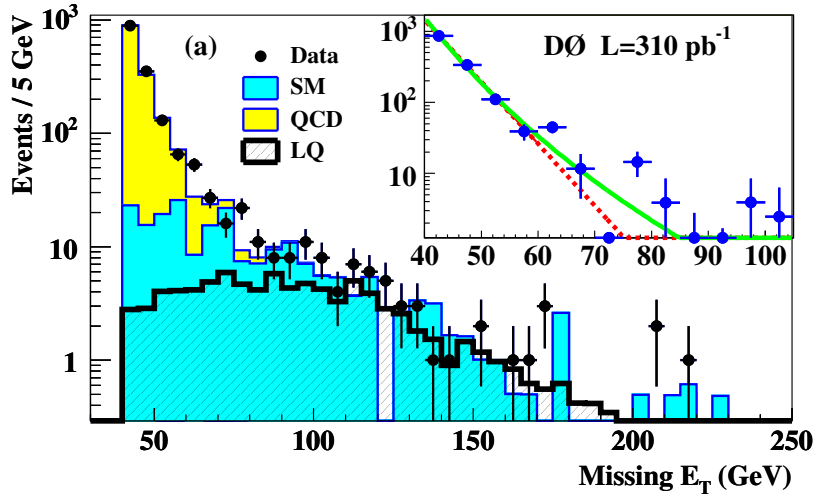


FIGURE 2. Missing transverse energy distribution in the $D\bar{O}$ search for $\beta = 0$ leptoquarks before final cuts. The inset shows the two different fitting functions used to evaluate the background from mismeasured QCD dijet events.

LARGE EXTRA DIMENSIONS

In the original large extra dimensions model of Arkani-Hamed, Dimopoulos and Dvali [5] in which only gravitons propagate in the bulk but all standard model fields are confined to a 3-brane, a tower of Kaluza-Klein excitations of the graviton emerges. The graviton states are too close in mass to be distinguished individually, and the coupling remains small, but the number of accessible states is very large. It is therefore possible to produce gravitons which immediately disappear into bulk space, leading to an excess of events with a high transverse energy jet and large missing transverse energy, the so-called monojet signature. The dominant standard model backgrounds are the production Z or W bosons plus jets, with the Z decaying to a pair of neutrinos or the lepton from W decay escaping detection. Using 368 pb^{-1} of data, CDF sets limits on the fundamental Planck scale between $M_D > 1.16 \text{ TeV}/c^2$ and $M_D > 0.83 \text{ TeV}/c^2$ for a number of extra dimensions ranging from 2 to 6.

OTHER RESONANCES

Both CDF and $D\bar{O}$ have new results on the search for resonances decaying to $Z + X$. CDF has two analyses, with the first using H_T as its main discriminating variable. After selecting events with leptonic Z decays, a control region with $H_T < 200 \text{ GeV}$ is used to establish a good understanding of the data, and the signal region is chosen to have $H_T > 400 \text{ GeV}$, including at least two jets, each with transverse energy $E_T > 50 \text{ GeV}$. Using 305 pb^{-1} of data, no events are observed in the signal region. A limit is set on the production cross-section of $m(D) = 300 \text{ GeV}/c^2$ right-handed down-type quarks as proposed in reference [6] at $\sigma < 1.3 \text{ pb}$ at 90% C.L.

In a second analysis, CDF studies the transverse momentum distribution of Z bosons. This has the advantage of being insensitive to the nature of the other decay products, but is of course more difficult and potentially less sensitive than a direct resonance search. Selecting events with a dielectron invariant mass compatible with the mass of the Z boson, $66 \text{ GeV}/c^2 < M(ee) < 116 \text{ GeV}/c^2$, CDF measures the Z transverse momentum distribution shown in Figure 3. From this they determine an upper limit on the anomalous production of Z bosons as a function of transverse momentum using 305 pb^{-1} of data. The 95% C.L. limit ranges from about 1 pb for $p_T(Z) = 20 \text{ GeV}/c$ to approximately 2 fb for $p_T(Z) = 200 \text{ GeV}/c$.

$D\bar{O}$ explicitly searches for a Z boson plus jet resonance by combining the Z boson plus jet mass spectrum and the Z boson transverse momentum distribution as discriminating variables. The invariant mass distribution measured in 380 pb^{-1} of data is shown in Figure 4. No excess is observed and a limit is set on the mass of an excited quark as proposed in Reference [7] at $m_{q^*} > 520 \text{ GeV}/c^2$ at 95% C.L.

In the search for excited muons both CDF and $D\bar{O}$ have results as well. Both experiments search for associated

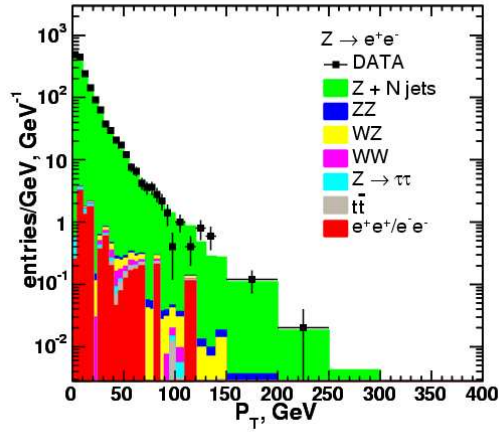


FIGURE 3. Transverse momentum distribution of Z bosons decaying to electron-positron pairs measured by CDF in 305 pb^{-1} of data.

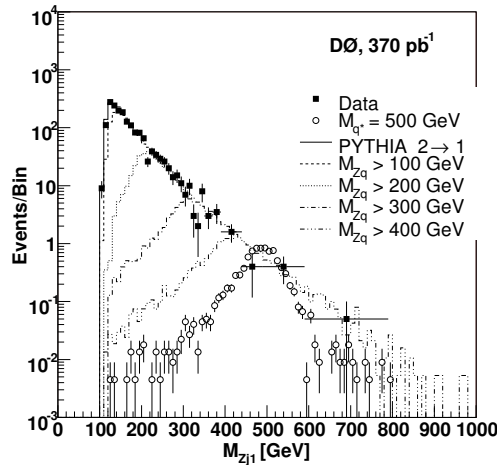


FIGURE 4. Invariant mass of the Z boson and leading jet as measured by DØ in 380 pb^{-1} of data. The curves with different M_{Zq} thresholds correspond to different generation thresholds for $2 \rightarrow 2$ processes in Pythia, and the open circles represent the signal due to an excited quark of mass $m_{q^*} = 500 \text{ GeV}/c^2$ and narrow width.

production of a muon and an excited muon, with the latter decaying to a muon and a photon. The production is approximated as a contact interaction, while the decay is assumed to proceed either through a gauge interaction (CDF) or a combination of a gauge and a contact interaction, with the relative fraction of the two depending on the mass of the excited muon and the compositeness scale. Both experiments obtain very similar results using 371 (CDF) and 380 (DØ) pb^{-1} of data. To make comparison with LEP results easier, CDF also reinterprets the result in a gauge mediated model with Drell-Yan-like production of the $\mu\mu^*$ pair with coupling f/Λ . This result is shown in Figure 5.

EVENTS WITH LEPTONS AND PHOTONS

In Run I, CDF reported an excess of events with a photon, a lepton and large missing transverse energy compared to standard model expectations [8]. This excess, corresponding to a 2.7 sigma effect, was deemed “an interesting result”,

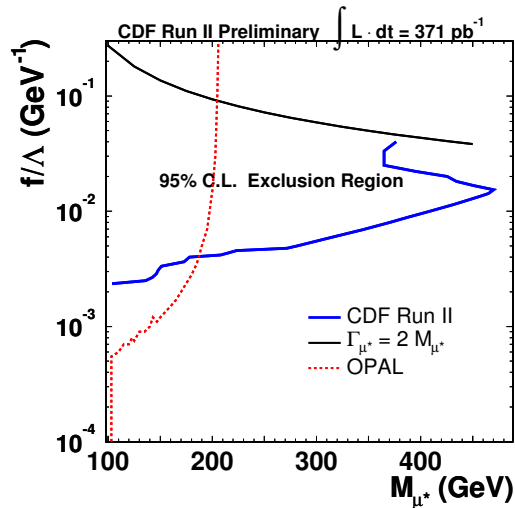


FIGURE 5. Exclusion region from the CDF search for excited muons in a gauge mediated model with coupling f/Λ for comparison with LEP results.

but not “a compelling observation of new physics.” CDF has repeated this analysis in Run II using 305 pb^{-1} of data [9]. The data is now compatible with standard model expectations in all channels, suggesting that the excess observed in Run I was due to a statistical fluctuation.

In a similar spirit, CDF searches for events with two photons and an electron or muon (700 pb^{-1}), or three photons (1 fb^{-1}). This is primarily a counting experiment, and again, unfortunately, no excess is observed over expectations.

DISPLACED DIMUONS

In 2000, The NuTeV Collaboration reported [10] on a search for heavy neutral leptons decaying to $\mu\mu\nu$ and a few other final states. In the dimuon channel, they observed three events while only 0.07 were expected. Because of the asymmetry in the muon momenta, and the absence of signal in other channels, NuTeV argued that the signal was unlikely to be due to neutral heavy leptons. To further investigate this, DØ has searched for pairs of muons originating from a common vertex located between 5 and 20 *cm* from the beamline. This allows a good calibration of efficiencies using K_S mesons. No signal is seen in 380 pb^{-1} of data, and to compare results the momentum of the hypothetical new particles in the neutrino beam was converted to the Tevatron center of mass frame. The result, which is weakly dependent on assumptions made in regard to the new particle’s decay process, is illustrated in Figure 6 in terms of the particle’s production cross-section times branching ratio and lifetime.

CONCLUSIONS

As the Tevatron continues its good performance, CDF and DØ collect large amounts of data and search for new physics in many channels. Only recent results have been reported here, and many other analyses are in progress. There is *still* nothing interesting, and previous excesses have been shown to be due to fluctuations. So far, new physics has remained hidden, but a substantial amount of data is yet to be recorded at the Tevatron and the LHC is scheduled to start operations soon. Positive results should be obtained in the next few years.

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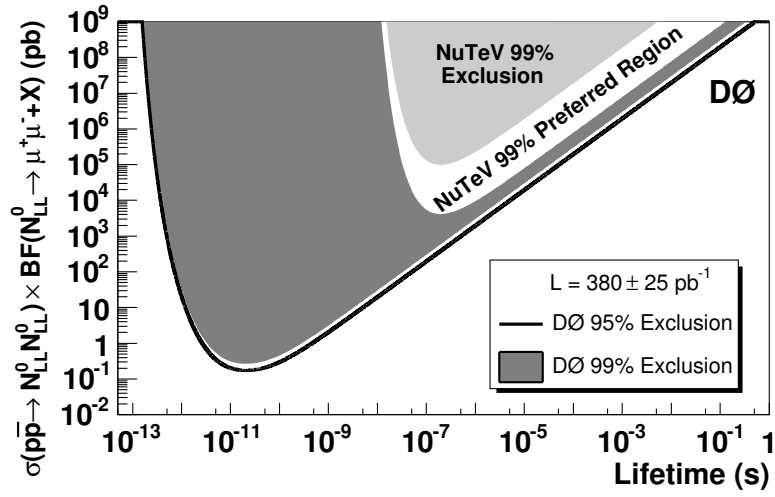


FIGURE 6. Excluded area in the search for a long-lived particle decaying to muon pairs plus anything in terms of the particle's production cross-section times branching ratio, and lifetime.

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