Search for Higgs Bosons and New Particles at the Tevatron

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With the completion of Run IIa in spring 2006, the Tevatron collider has delivered $p\bar{p}$ collisions corresponding to about 1.4 fb^{-1} to the CDF and DØ experiments. This report presents a brief summary of recent results based on this dataset from the searches for Higgs bosons and new particles.

1. INTRODUCTION

Since the start of Run II in March 2001, the Tevatron collider has delivered proton-antiproton collisions corresponding to about 1.4 fb^{-1} to each of the two experiments CDF and DØ. At a centre-of-mass energy of 1.96 TeV, this dataset provides the opportunity to search for particles that have not been observable previously. This includes Higgs bosons as predicted by the Standard Model and its supersymmetric extensions, as well as a large variety of new particles predicted in models of physics beyond the Standard Model. In this talk a selection of recent[1] Tevatron results from these areas is discussed. For a complete and uptodate set of results, the reader is referred to [1].

2. HIGGS BOSONS

Electroweak precision measurements strongly indicate that the Standard Model Higgs boson must be relatively light. The upper limit on the mass of the Higgs boson of 166 GeV at 95% C.L. [2] leaves only little room above the mass limit of 114.4 GeV set by direct searches at LEP. Similarly, at least one light Higgs boson is expected within the Minimal Supersymmetric Standard Model. This Higgs boson mass range is potentially accessible to the Tevatron experiments once enough integrated luminosity has been accumulated. The current status of searches for Standard Model and SUSY Higgs bosons is reviewed in the following sections.

2.1. Heavy Standard Model Higgs Boson

Within the mass range of interest at the Tevatron, the Standard Model Higgs boson is expected to decay dominantly either into a pair of b-quarks for a Higgs boson mass m_H below about 135 GeV, or into a pair of W bosons for $m_H \gtrsim$ 135 GeV. Exploiting the leptonic decay mode of the W boson, it is possible to search for heavy Higgs bosons produced via gluon fusion, with a relatively high cross section of the order of 1 pb.

Both CDF and DØ collaborations have searched for H→WW→ $\ell\nu\ell\nu$ (ℓ =e,μ) in datasets corresponding to 0.36 and 0.95 fb^{-1}, respectively. Requiring two isolated electrons or muons with high transverse momentum and well-measured large missing transverse energy, backgrounds are dominated by W+jet production and irreducible background from WW production. After more cuts on event kinematics, the signal can be isolated further by exploiting spin correlations between the leptons: since for signal both W bosons originate from the decay of a scalar Higgs boson, the two leptons are preferentially emitted in the same direction. As visible in Fig. 1, signal events therefore accumulate at small azimuthal opening angle $\Delta\Phi$ between the leptons.

After all cuts, 1.8 events from H→WW are expected for a Higgs boson mass of 160 GeV in the DØ analysis [3], on top of a background of 45±8 events. 37 data events have been observed, consistent with the Standard Model

[1] as of July 2006

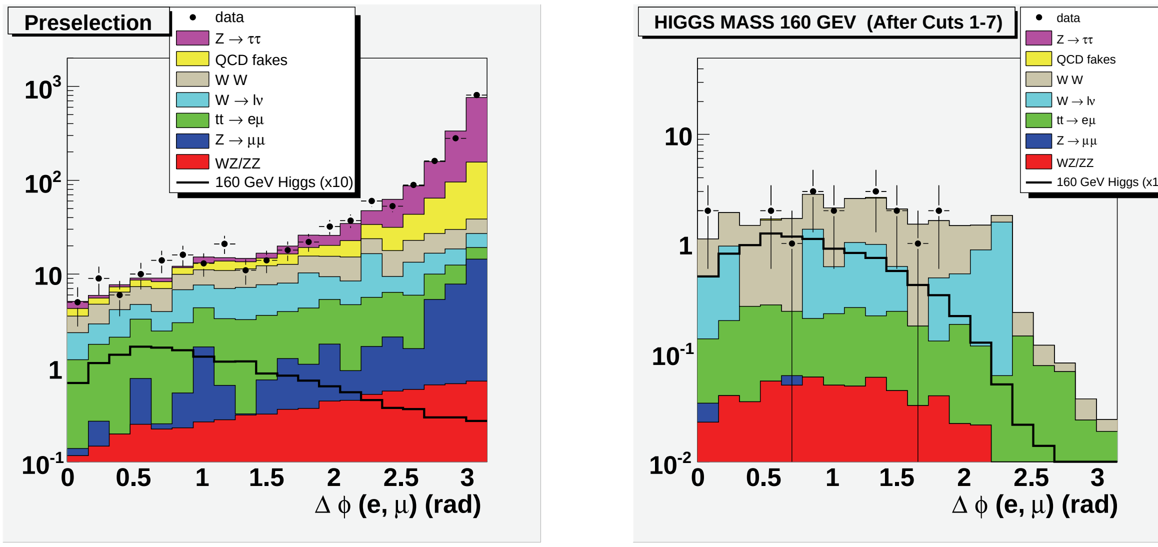

Figure 1: Difference in azimuthal angle $\Delta\Phi$ of electron and muon in the search for H→WW→$e\nu\mu\nu$ at preselection level (left) and at the end of the selection (right). Data (points) are compared to backgrounds (shaded histograms) and signal (open histogram) with a cross section enhanced by a factor of 10 (from [3]).

expectation. An interpretation in terms of an upper limit on the Higgs boson production cross section is discussed in Section 2.3.

2.2. Light Standard Model Higgs Boson

For a Standard Model Higgs boson with mass below about 135 GeV, the decay into a pair of b-quarks is dominant. To be able to separate events with H→bb from the massive multijet backgrounds, the search relies on Higgs production in association with a W or Z boson. For these production channels, the leptonic decays of the vector bosons allow to trigger efficiently and to suppress the multijet background to an acceptable level.

After selecting events with W→ $\ell\nu$, Z→ $\ell\ell$ or Z→ $\nu\nu$ plus two jets using requirements for isolated leptons and/or missing transverse energy, the sample can be further enhanced in signal by requiring one or both jets to be b-tagged. Irreducible background from vector boson production in association with b-quarks can be distinguished from Higgs events by reconstructing the dijet invariant mass to test for the presence of a Higgs resonance. Fig. 2 shows the invariant mass of two b-tagged jets in the CDF WH search, based on a dataset corresponding to 0.95 fb^{-1}[4].

A variety of channels have been analyzed by both collaborations, so far without any evidence for a significant excess compared to the expected backgrounds. Limits on production cross sections of light Higgs bosons have been set as presented in the following section.

2.3. SM Higgs Combination

Given the amount of integrated luminosity that will be available at the Tevatron, sensitivity to the Standard Model Higgs boson can only be achieved by combining the information from all search channels and both experiments. Currently, results from the channels listed above based on datasets of 0.26 fb^{-1} up to 1.0 fb^{-1} have been combined to set upper limits on Higgs production at the Tevatron [5]. The combined 95%. C.L. limit is shown as a function of Higgs boson mass in Fig. 3. The limit is expressed as multiple of the cross section expected for the Standard Model Higgs boson. Clearly, more luminosity and additional analysis improvements will be needed before sensitivity can be reached.

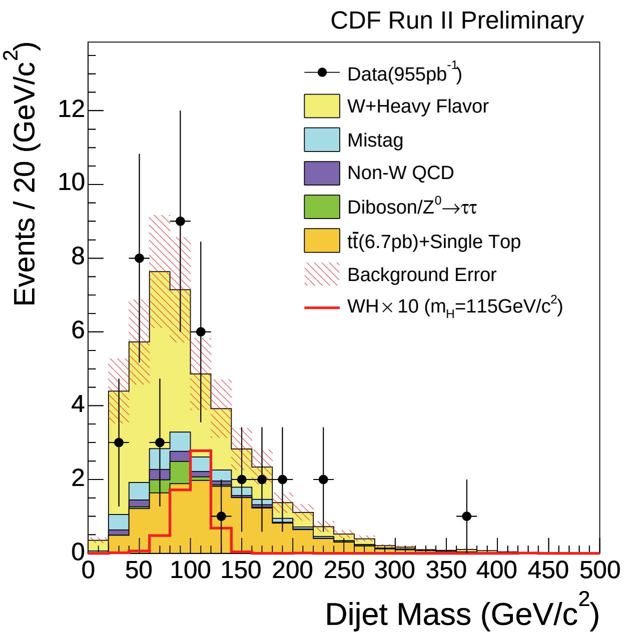

Figure 2: Dijet mass distribution after all cuts in the search for WH production with two b-tagged jets. Data (points) are compared to backgrounds (shaded histograms) and signal (open histogram) with a cross section enhanced by a factor of 10 (from [4]).

2.4. Higgs bosons in Supersymmetry

Supersymmetric extensions of the Standard Model require the introduction of five physical Higgs bosons: two CP-even Higgs bosons h and H, one CP-odd Higgs boson A, and two charged Higgs bosons $H^{\pm}$. Within the Minimal Supersymmetric Standard Model (MSSM), all Higgs boson masses and couplings are specified at tree level by two parameters, typically chosen as the mass of the A boson m_A and the ratio of vacuum expectation values $\tan\beta$.

The searches for a light Standard Model Higgs boson discussed in Section 2.2 can be re-interpreted as a search for the MSSM Higgs boson h, which is predicted to have a mass of less than ≈135 GeV. However, since the Wh and Zh production cross sections are suppressed with respect to the Standard Model, there is no sensitivity with the limited amount of integrated luminosity currently available.

On the other hand, the cross section of MSSM Higgs boson production via gluon fusion is enhanced by a factor of $\tan^2\beta$ (at tree level) with respect to the Standard Model. For large enough $\tan\beta$, the enhancement is sufficient to achieve sensitivity with the data currently available to the inclusive production of Higgs bosons decaying to two tau leptons. Both CDF and DØ collaborations have searched for Higgs bosons in this channel in datasets corresponding to about 320 pb^{-1}.

The analyses require at least one leptonic tau decay to trigger the events and to suppress multijet backgrounds. Hadronic tau decays are separated from the jet background by relying on differences in shower shape, track multiplicity, isolation and a number of kinematic quantitities. Significant irreducible background from Z→ $\tau\tau$ production remains, and can only be distinguished from the signal by reconstructing the invariant mass of the visible ditau system. As illustrated in Fig. 4a, this allows a separation of massive Higgs bosons from Z decays, even though the neutrinos from tau decays cannot be fully reconstructed. Since no significant excess above Standard Model expectations has been observed, limits on $\tan\beta$ can be derived as a function of m_A as shown in Fig. 4b [6].

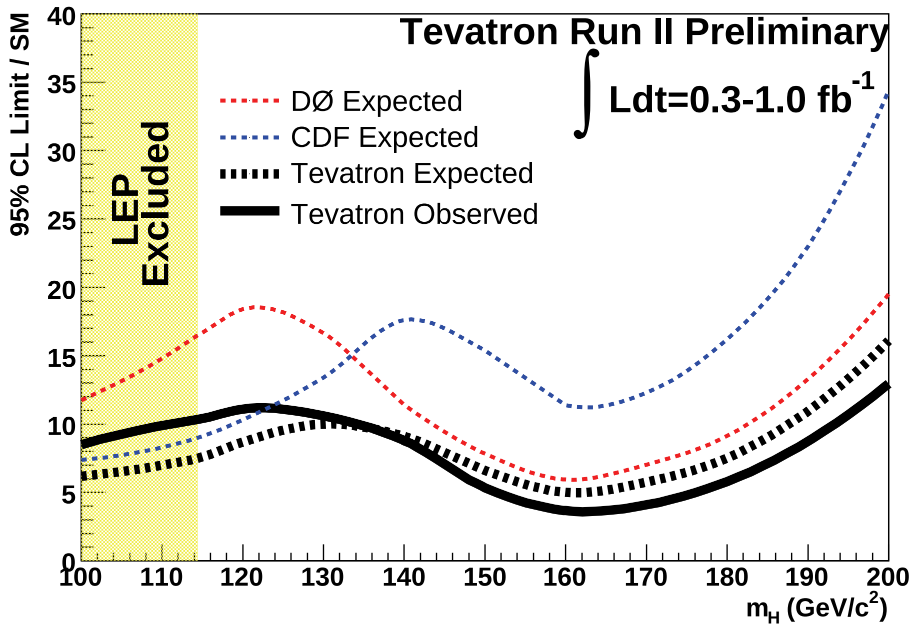

Figure 3: Ratio of expected (dashed lines) and observed (solid line) cross section limits to the Standard Model Higgs boson production cross section for the individual and combined CDF and DØ analyses as a function of Higgs boson mass (from [5]).

3. SUPERSYMMETRY

In addition to an enlarged Higgs sector, supersymmetry (SUSY) predicts a new particle for each Standard Model particle. The partner particles have the same quantum numbers except for the spin, i.e. each fermionic (bosonic) degree of freedom in the Standard Model is associated with a new bosonic (fermionic) superpartner. Since no superpartners have been observed experimentally, supersymmetry is assumed to be broken by an unknown mechanism that results in higher masses for the superpartners. Searches for supersymmetry at the Tevatron consider a large variety of SUSY breaking mechanisms, each leading to substantially different mass hierarchies which result in different final state signatures.

3.1. Squarks/Gluinos

Squarks and gluinos, the superpartners of quarks and gluons, are generally expected to be heavier than most SUSY particles. Therefore they can decay via cascades into the lightest supersymmetric particle (LSP), which in this context is assumed to be the lightest neutralino, one of the partners of the neutral gauge and Higgs bosons. This leads to final states with at least two jets, missing transverse energy from the LSPs escaping undetected, and potentially additional leptons from the cascade decays.

Both CDF and DØ have designed inclusive searches for multijet final states with missing transverse energy $\not\!\!E_{\rm t}$, with results available based on datasets corresponding to about 300 pb^{-1}. To suppress the massive background from Standard Model multijet production, the selections have to rely on a combination of requirements of high jet multiplicities or large jet transverse momenta as well as high $\not\!\!E_{\rm t}$. As shown in Fig. 5, a SUSY signal would then manifest itself as an excess on top of irreducible background from production of vector bosons in association with jets, where W$\rightarrow \ell\nu$ or Z$\rightarrow \nu\nu$ decays give rise to high missing transvere energy. The modeling of these backgrounds is a challenge, since the differential cross sections directly depend on higher-order QCD corrections. The implementation of these corrections in Monte Carlo generators has to be validated with data, as demonstrated in Fig. 6: Tevatron data for e.g. the transverse momentum spectrum of the third-leading jet in Z+jets events is insufficiently modelled

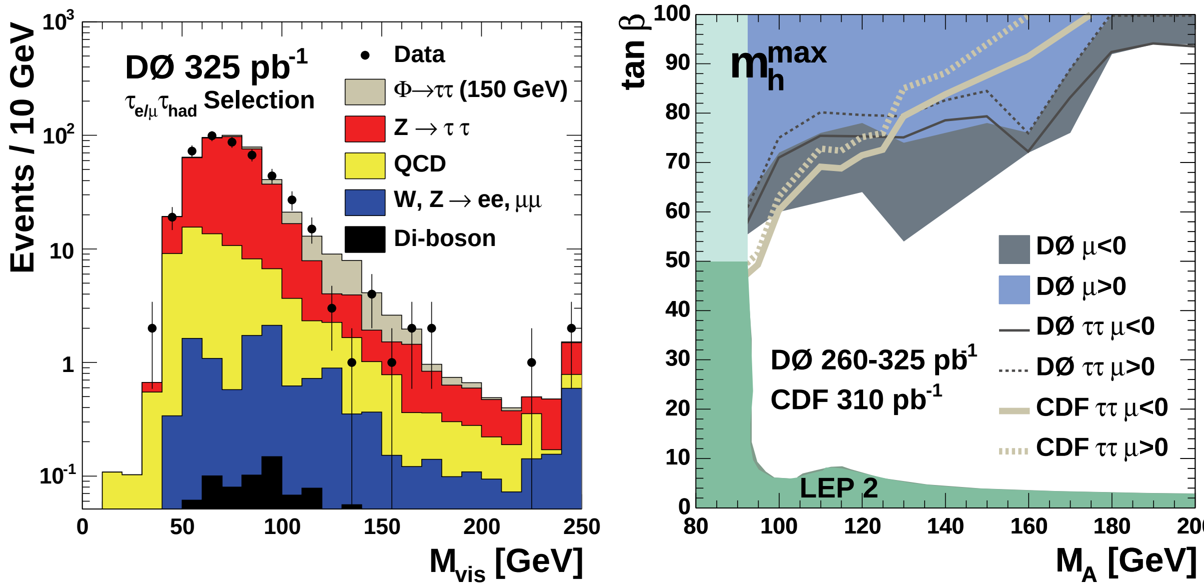

Figure 4: Left: Visible ditau mass distribution in the search for Higgs bosons Φ decaying into two tau leptons for data (points), sum of all backgrounds (red histogram) and signal (grey histogram); Right: Regions in the $(\tan\beta,\, m_A)$-plane excluded by Tevatron and LEP searches for the m_h-max scenario with $\mu > 0$ and $\mu < 0$ (from [6]).

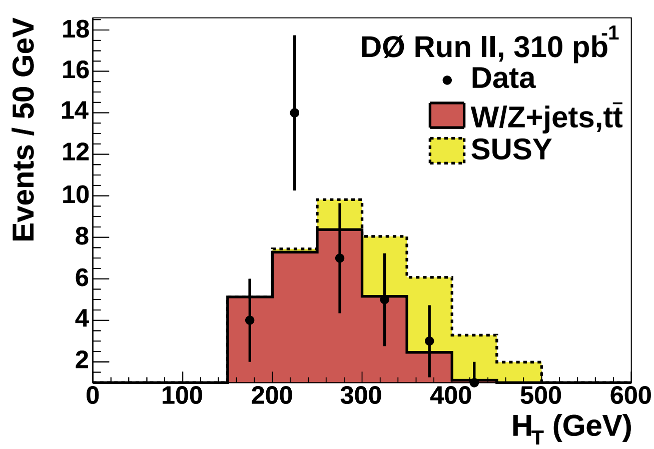

Figure 5: Distribution of the scalar sum H_T of all jet transverse energies in the search for squarks and gluinos for data (points), Standard Model background (red histogram) and SUSY signal (yellow histogram) at the end of the selection (from [8]).

by the pythia generator (leading-order matrix element), whereas the inclusion of higher orders as implemented in the sherpa generator allows to model the data within statistical and systematic uncertainties [7].

Neither CDF nor DØ have observed any significant excess in their searches for squarks and gluinos [8][9], and therefore have placed limits on squark/gluino masses as displayed in Fig. 7. In addition to these inclusive searches, dedicated analyses exist that have been optimized to detect the decays of bottom- or top-squarks, since these particles are potentially significantly lighter than all other squarks. Improved mass limits are available for the decays $\tilde{t} \rightarrow c\tilde{\chi}_1^0$, $\tilde{t} \rightarrow b\ell\tilde{\nu}$ and $\tilde{b} \rightarrow b\tilde{\chi}_1^0$ [1].

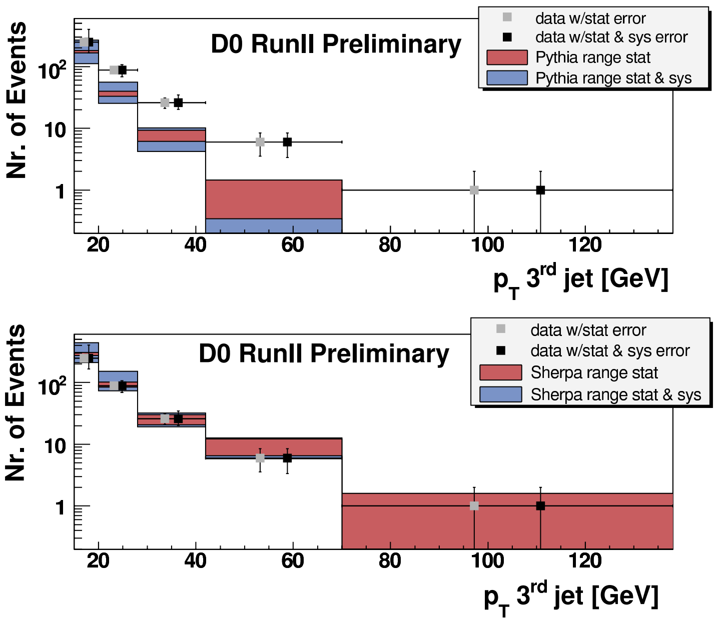

Figure 6: Distribution of transverse momentum of the third-leading jet in Z+jets events for data (points) in comparison with the predictions by the Pythia (upper plot) and Sherpa (lower plot) generators (from [7]).

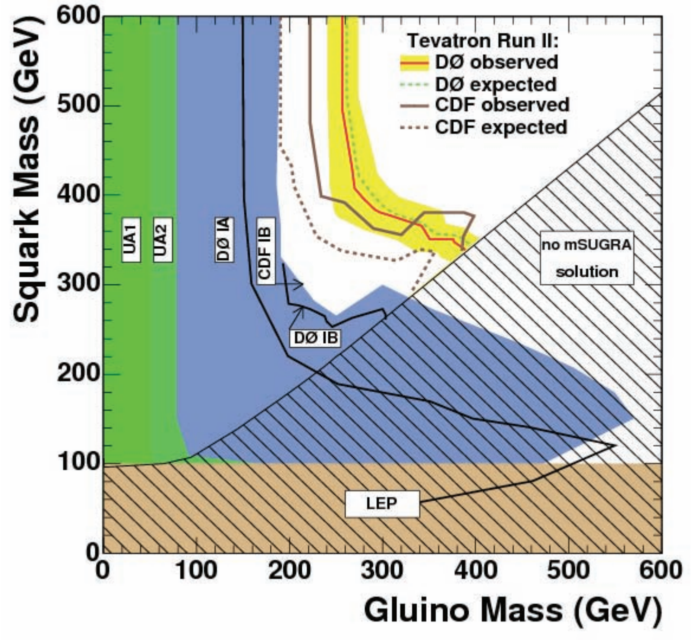

Figure 7: Regions in the plane of squark versus gluino mass excluded by searches at UA1, UA2, CDF, DØ and LEP (from [10]).

3.2. Charginos,Neutralinos

Another promising avenue for the discovery of supersymmetry at the Tevatron is the search for production of charginos and neutralinos, the fermionic partners of the gauge and Higgs bosons. The lightest chargino $\widetilde{\chi}_1^{\pm}$ can be as light as 100 GeV, the mass limit set by the LEP experiments. Searches at the Tevatron therefore focus on charginos and neutralinos decaying directly to the LSP via the exchange of virtual W/Z bosons or sfermions. A particularly

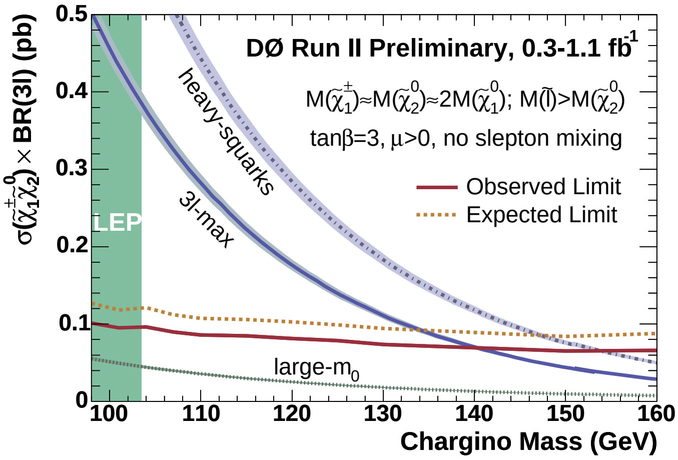

Figure 8: Limit on the product of production cross section and branching fraction for $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0 \rightarrow 3\ell + \not{E}_{\rm t}$ as a function of the chargino mass in comparison with the prediction from a selection of MSSM model choices (from [11]).

clean SUSY signature is provided by the associated production of the lightest chargino with the second-lightest neutralino $\tilde{\chi}_2^0$, with both decaying leptonically into a total of three charged leptons plus missing transverse energy carried away by neutrinos and the two LSPs.

Both CDF and DØ collaborations have searched for this signal in a number of multilepton analyses, based on datasets of up to 1.1 fb^{-1}. The combination of requirements for three relatively loosely identified leptons and significant missing transverse energy is sufficient to reduce the background to the small but irreducible component from WZ$\rightarrow \ell\nu\ell\ell$ production. No hint for a signal from chargino/neutralino production has been observed by either experiment, resulting in limits on the product of cross section and leptonic branching fraction as shown in Fig. 8. Currently, chargino masses of up to 140 GeV are probed for favourable SUSY scenarios with large leptonic branching fractions [11].

4. EXTRA DIMENSIONS

A number of models postulate the presence of extra space-time dimensions to explain the vast difference between the Planck and the electroweak scale. For instance, in the model by Arkani-Hamed, Dimopoulos, and Dvali (ADD), gravity can propagate in compactified large extra dimensions, leading to a suppression of the strength of gravity as observed in the projection to four dimensions and allowing to accomodate true Planck scales M_D as small as $O(1$ TeV$)$. Similarly, in the model by Randall and Sundrum (RS), gravity is localized to a brane separated from the Standard Model brane by a 5th dimension with warped metric, leading to an exponential suppression of the strength of gravity as seen by Standard Model particles. The presence of these extra dimensions can be probed via gravitons, which in their interaction with Standard Model particles appear as Kaluza-Klein towers of a large number of graviton states.

For the ADD model, the mass spacing of these graviton states is small. At the Tevatron, graviton exchange can lead to observable effects in dilepton and diphoton production at high masses, or as missing transverse energy from direct production of gravitons. For the latter, a new search for graviton plus jet production has been presented by CDF in a dataset corresponding to 1 fb^{-1}. Since gravitons escape detection, the final state as observed by the detector consists of a single jet and missing transverse energy. By placing hard cuts on the transverse momentum of the jet and on $\not{E}_{\rm t}$, these monojet events can be separated from multijet production, leaving mostly irreducible background from production of vector bosons plus jet. No excess of events has been observed, which allows to place lower limits on the Planck scale of, for instance, 1.33 TeV for two extra dimensions [12].

For the RS Model, the mass spacing of the graviton states is relatively large, with the first excited state expected

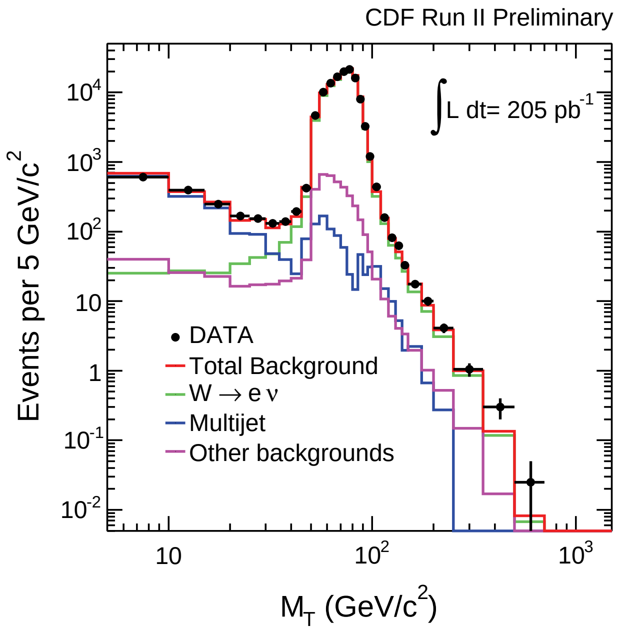

Figure 9: Transverse mass distribution in the search for W'$\rightarrow e\nu$ for data (points) in comparison with Standard Model backgrounds (histogram) at the end of the selection (from [14]).

to have a mass of the order of 1 TeV. It should therefore be possible to observe individual graviton excitations in the dilepton and diphoton mass spectrum, assuming the coupling κ to Standard Model particles is large enough. In a search for such resonances in datasets corresponding to up to 1.2 fb^{-1}, both CDF and DØ collaborations have observed no signs of new resonances. Accordingly, mass limits have been set as a function of the coupling. For the maximum coupling strength allowed by precision electroweak data ($\kappa = 0.1$), RS-gravitons with a mass below 865 GeV are excluded at 95% C.L. [13].

5. NEW HIGH-MASS STATES

Many models of new physics, including one of the models discussed in the previous section, predict new high-mass states decaying to Standard Model fermions. Prominent examples are the so-called W' and Z' bosons, which would manifest their presence as resonances in the transverse or invariant difermion mass spectrum, respectively. They can be searched for at the Tevatron in leptonic decays W'$\rightarrow \ell\nu$ and Z'$\rightarrow \ell\ell$. Figures 9 and 10 present examples of these mass spectra in 0.2 fb^{-1} and 0.8 fb^{-1} of CDF data. The comparison with the Standard Model prediction for W and Z/Drell-Yan production shows that no evidence for W' or Z' resonances has been observed. This result can be used to set lower mass limits for a given set of quantum numbers of the W' and Z'. For sequential vector bosons, i.e. heavy copies of the W and Z bosons, mass limits of 788 and 850 GeV have been set, respectively [14][15].

Another common prediction of models that try to connect quarks and leptons are heavy particles that couple to both quarks and leptons, the so-called leptoquarks. Both Tevatron collaborations have searched for leptoquarks in their decays into two quarks, two leptons or one lepton and one quark. No evidence for the presence of leptoquarks has been observed in up to 0.3 fb^{-1} of data. Mass limits have been set as a function of branching fraction for various leptoquark flavours. The best sensitivity is achieved for leptoquarks decaying into eq or μq with a branching fraction of 100%, which have been excluded for masses below 256 and 251 GeV, respectively [16][17].

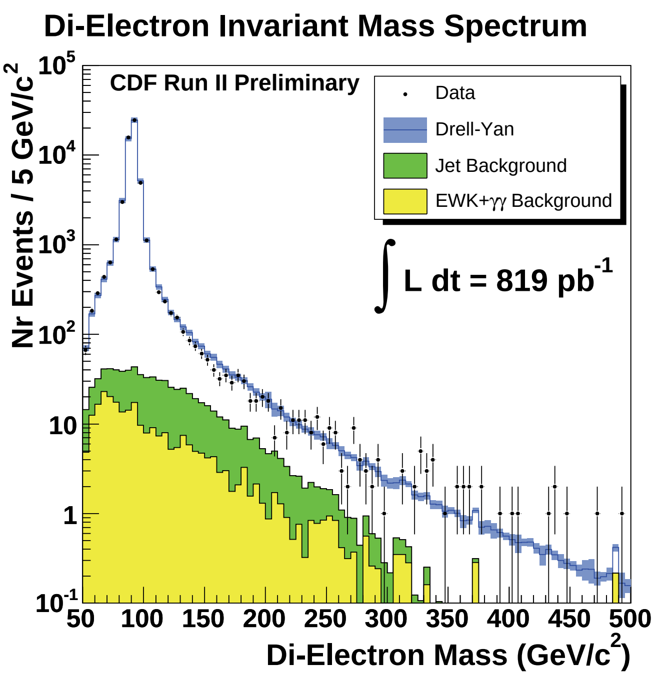

Figure 10: Invariant di-electron mass distribution in the search for Z'→ee for data (points) in comparison with Standard Model backgrounds (histogram) at the end of the selection (from [15]).

6. SUMMARY

With an integrated luminosity of 1.4 fb^{-1} already delivered, and bright prospects for much more data to be accumulated over the next few years, the Tevatron collider continues to provide unique opportunities to search for Higgs bosons and new particles.

Combined Tevatron results from the search for the Standard Model Higgs boson are available based on all major channels, but so far do not provide sensitivity. With more data and further analysis improvements, it is hoped to reach sensitivity over the course of the next two years. Searches for SUSY Higgs bosons are already probing the high $\tan\beta$ region, but have not uncovered any significant excess.

A large variety of signatures is considered in searches for new particles, including signals expected within models of supersymmetry or with large extra dimensions. No hint of any deviation with respect to expectations from the Standard Model has been observed, and limits well beyond the reach of previous experiments have been set.

Acknowledgments

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