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Top quark and Higgs Physics at the Tevatron

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This is a writeup of my lectures given at the International Workshop on Frontiers of High Energy Physics, held at CCAST, Beijing, China during July 2-10. I discuss some basic experimental techniques for studying the Top quark and Higgs boson at the Tevatron, and review some recent results from CDF and D0 and their future prospects.

I. INTRODUCTION

For several decades, the standard model has been remarkably successful in explaining and predicting experimental data. However, the mechanism of electroweak symmetry breaking (EWSB) is still not known. The most popular mechanism to induce spontaneous symmetry breaking of a gauge theory, resulting in the gauge bosons and fermions messes, is the Higgs mechanism [1], which predicts the existence of a Higgs particle. The current direct searches for the Standard Model (SM) Higgs boson at LEP 2 set a limit on the Higgs mass $m_h \geq 114$ GeV/c^2 at 95% C.L. [2]. With the recently improved top mass measurement, the global fit of electroweak precision data yields an estimation of the Higgs boson mass $m_h = 113^{+60}_{-50}$ GeV/c^2 or $m_h \leq 240$ GeV/c^2 at 95% C.L. [3]. The Tevatron, the highest energy collider in the world, will have a window of opportunity to unlock the secrets of EWSB before the LHC via either direct searches or precision measurements of the Top quark and W boson masses for better constraining the Higgs boson mass (indirect searches).

The discovery of the top quark in 1995 at the Fermilab Tevatron [4] completes the spectrum of fundamental fermions required in the Standard Model. However, its mass is much heavier than other quarks. The study of this unique and still relative new particle is a major goal of Run II at the Fermilab Tevatron. Measurement of the top production cross section serves as a test of perturbative calculations of the strong interaction. The mass of the top provides an excellent probe into the mechanism underlying the generation of fundamental particle mass.

II. THE TEVATRON AND THE CDF AND D0 UPGRADED DETECTORS

Both accelerators and detectors have undergone major upgrades in order to handle the increase in luminosity and energy during Run II. The introduction of the Main Injector has allowed the Tevatron to achieve a much higher luminosity than it had during Run I (1992-1995). The increase of the center-of-mass energy from 1.8 to 1.96 TeV is roughly equivalent to an increase of the production cross section, which is 30% in the case of the top quark pair production.

The upgraded CDF and D0 detectors have completely new tracking systems, extended muon coverage and redesigned trigger and DAQ systems [5]. CDF has replaced their Run I silicon detector with a new device providing 3D tracking up to $|\eta| < 2$. Further improvements in tracking come from a new faster drift chamber with 96 layers (COT). They have also significantly enhanced their capabilities in particle identification with a new Time-of-Flight (TOF) detector, in the forward region with a new plug calorimeter and a new forward muon system. Finally, CDF has upgraded its trigger system and added a new track trigger (XFT) at Level-1, based on information from the drift chamber as well as constructing a new impact parameter trigger (SVT) at Level-2 using data from the silicon detector. D0 has also completely replaced its old, non-magnetic tracking system with a new 3D silicon micro-vertex detector and a new central tracker (CFT) using 8 super-layers of scintillating fibers immersed in a 2.0 Tesla axial magnetic field. Because of the increased amount of material in the tracking system, pre-shower detectors have been added in the central and forward regions. The D0 uranium-liquid argon calorimeter has been retained, but its readout electronics have been completely replaced. The muon system in the central region is also largely unchanged from Run I. However, trigger scintillator counters have been added and the muon system in the forward region has been completely replaced. Finally, totally new trigger and data acquisition systems have been installed.

Both detectors are now operating quite well with a data taken efficiency at about 90%.

III. TOP QUARK PHYSICS

The top quark, as a weak-partner of the b quark, has a mass of $M_{top} = 178.0 \pm 4.3$ GeV/c^2, which is intriguingly close to the scale of EWSB. This raises a number of interesting possibilities that the top quark may play a special role in the origin of EWSB. Despite the limited statistics we had in Run 1, the CDF and D0 collaboration have made many interesting measurements about the top quark including the production cross section, mass and decay properties [6]. The results so far are consistent with SM.

The dominant top quark production at the Tevatron is pair production through 85% of $q\bar{q}$ annihilation and 15% of gluon-gluon fusion while at LHC, the gluon-gluon fusion dominates. The theoretical calculation of the $p\bar{p} \to t\bar{t}$ cross section gives $6.7^{+0.7}_{-0.9}$ pb for $M_t = 175$ GeV/c^2 at 1.96 TeV [7]. Smaller contributions are also expected from the electroweak single top production processes via $gW \to tb$ at 40% of the $t\bar{t}$ pair cross section, but not observed experimentally yet.

Within the framework of the Standard Model the top quark decays almost exclusively into a real W boson and a b quark. The observed event topology is then determined by whether the W bosons decay leptonically or hadronically, which can be classified into three distinct decay channels.

The dilepton channel has about a 5% branching ratio where both W bosons decay to $e\nu$ or $\mu\nu$, which result in a clean final state, but limited statistics. In the lepton + jets channel, one W decays to $e\nu$ or $\mu\nu$ and the other W decays to a $q\bar{q}'$ pair 30% of the time. This is a golden mode for studying $t\bar{t}$ production and measuring its mass. The main background for this channel is the production of W boson recoiling against jets, which can be reduced significantly using b-tagging. The last channel is the all-hadronic channel where both W decay hadronically. It has the largest branching fraction of 44%, but suffers from a huge QCD multi-jet background. In Run1, the top signal has been seen in all the channels by both CDF and D0. The tau lepton from the W boson decay can contribute to either a lepton if the tau itself decays leptonically or a hadronic jet if it decays hadronically.

A. Cross Section Measurements

The measurement of a production cross section is one of the questions about the top quark that we would like to answer in Run II. It requires a careful counting of the signal and the background presented in the sample. It also provides a first hand test of the QCD calculations for the Standard Model top production and consistency checks among the different channels. Any deviations from the SM could be a sign for new physics. Both CDF and D0 have measured the $t\bar{t}$ cross section in many different channels and many different ways using the first part of Run II data, an integrated luminosity of approximately 200 pb^{-1}.

In the lepton + jets analysis, we select events which contain one isolated high P_T lepton, large missing transverse energy ($\not\!\!E_T$), and 3 or more jets. But there are significant contributions from backgrounds in this selection. In order to suppress the background, we attempt to identify b quarks by reconstructing secondary vertices from b decay using the Silicon Vertex Detector (SVX) or by finding additional leptons from b semileptonic decay (SLT). With a larger data set and much improved Monte Carlo tools and detector simulations, CDF has re-analyzed the heavy flavor fraction in the W events and improved the understanding of b tagging efficiencies and the contribution of extra material interaction to fake b tags [8]. The efficiency for tagging at least one b quark in the $t\bar{t}$ event with ≥ 3 jets is about 55% for CDF and 65% for D0. Figure 1 shows the results from the SVX b-tagging selection as a function of the number of jets; the excess in the 3 or 4 jet bins above the background is used to extract the $t\bar{t}$ cross section while the number of events in the 1 or 2 jet is used to verify the background calculations. Instead of requiring b-tagging, one can exploit the fact that the jets in $t\bar{t}$ decay tend to be more energetic than those in the W+jets background because of the heavy top quark mass. By fitting kinematic distributions in the data to a sum of signal and background templates, one can determine the fraction of top in the sample and measure the production cross section with or without b-tagging. The kinematic methods are less precise than the counting method (b-tagging) but complementary to each other. They give consistent results for the top production cross section and are currently the world's most precise measurements.

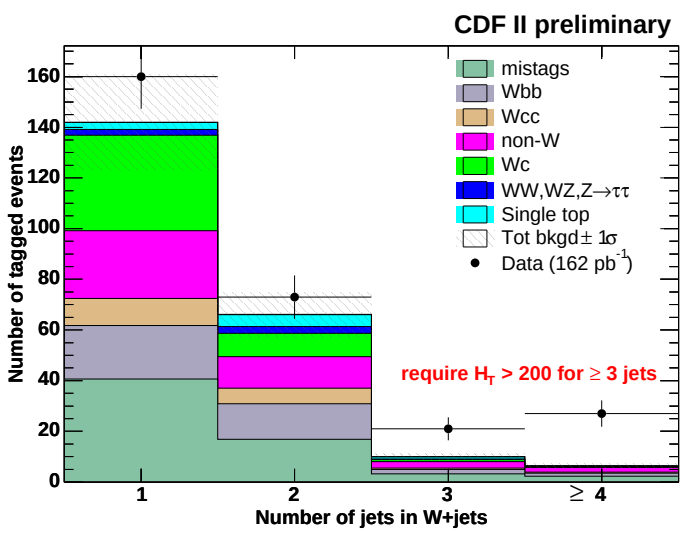

FIG. 1: Number of events passing selection criteria with at least one tagged jet, and the background prediction.

The dilepton analysis is very similar to that previously reported in Run I, except for slight modifications to the lepton identification in order to increase acceptance[9]. There are two dilepton selections, one requiring two identified

leptons, and other requiring an identified lepton plus an isolated track, resulting in tight and loose dilepton samples which yield cross sections consistent with each other, as well as with the Standard Model predictions. Figure 2 shows the results from two dilepton selections as a function of number of jets; the excess in the 2 or more jet bins above the background is used to extract the $t\bar{t}$ dilepton cross section and the lower multiplicities are used to cross-check background calculations. In addition, CDF has employed a new technique to measure the $t\bar{t}$ cross section in the dilepton events by fitting the expected distributions from the signal and background in the missing transverse energy and jet multiplicity plane, which improves the statistical power.

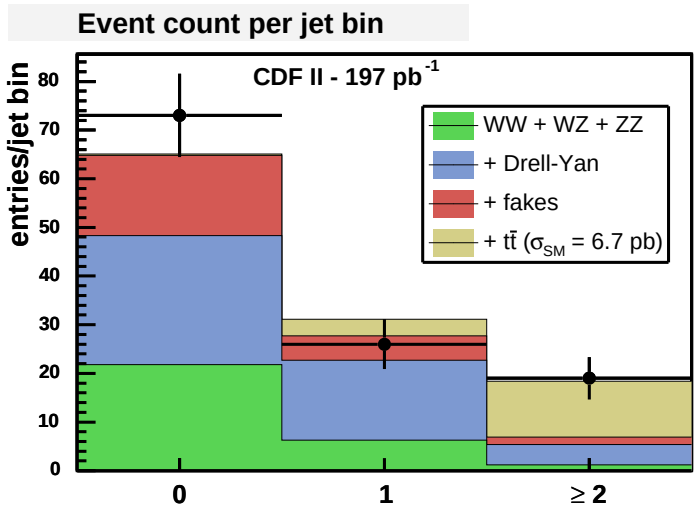

FIG. 2: Number of dilepton events passing selection criteria, and the background prediction.

As mentioned before, the most difficult channel to study the top is the all hadronic channel in which both W decay into dijets. With two b jets this gives a nominal 6-jet topology. The signal is isolated using a combination of kinematic selection and b-tagging. CDF measures the cross section by counting the number of excess b-tags in the events with at least 6 or more jets while D0 extracts the cross section by fitting the b-tagged data to the output of an artificial neutral network constructed from discriminant topological variables.

The summary of the cross section measurements are shown in Figure 3 for CDF and Figure 4 for D0. All results are still statistically limited but are consistent with the SM predictions.

B. Top Mass Measurements

The top quark mass is a fundamental parameter in the Standard Model. It has an important role in precision electroweak (EW) observables via loop corrections because of its very large mass. With a precise measurement of the top quark mass, a global fit to precision EW data will allow one to do a stringent consistency test of the Standard Model. More importantly, it will yield a clue on the Higgs mass. The success of Run II depends on how accurate the top quark mass will be measured. Aiming for $\Delta M_{top} \approx 3$ GeV/c^2 and $\Delta M_W \approx 25$ MeV/c^2, the Tevatron data will constrain the Higgs mass with an uncertainty of 40% before LHC. It requires multi-prong approaches using different techniques and many different channels in order to achieve a significant improvement of systematic uncertainties, such as the jet energy scale and the jet-parton association, which are major limiting factors to the top mass measurement.

Recently the D0 collaboration has revised its Run I top mass measurement using a more advanced dynamic likelihood method in the lepton + jets sample, which yields the most precise measurement in a single channel [10]. As a result, the combined CDF and D0 top mass has improved from $M_{top} = 174.3 \pm 5.1$ GeV/c^2 to $M_{top} = 178 \pm 4.8$ GeV/c^2.

The advantage of measuring a top quark mass in the Lepton + Jets channel is its relatively large branching ratio and the ability to fully reconstruct the top mass on an event-to-event basis. The events are selected to have a high P_T single isolated lepton, large missing transverse energy and four leading jets. The events are then kinematically fitted to the hypotheses of $t\bar{t}$ decay in the lepton + jets channel ($t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow (l^+\nu b)(q\bar{q}'\bar{b})$). There are twelve distinct ways of assigning the four leading jets to the four partons b, $\bar{b}$, q and $\bar{q}'$. In addition, there is a quadratic ambiguity in the determination of the longitudinal component of the neutrino momentum. This yields up to twenty-four different configurations for reconstructing an event according to the $t\bar{t}$ hypothesis with no b-tag, 12 configurations for events

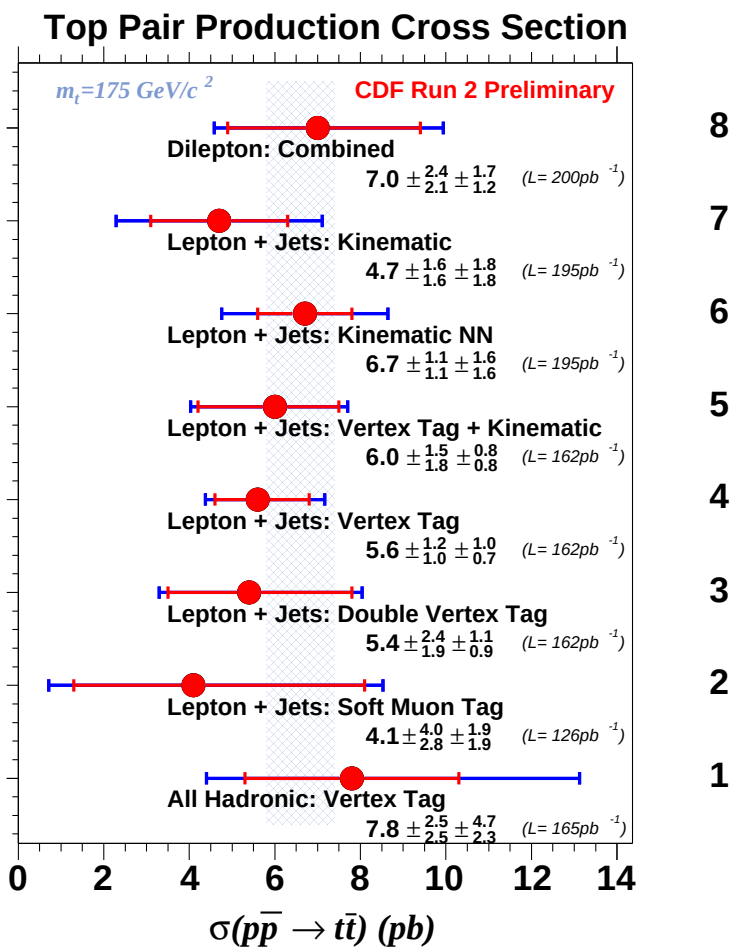

FIG. 3: Summary of Run II $t\bar{t}$ production cross section measured from CDF.

with a single b-tag, and 4 configurations for events with double b-tags. In mean time, we also can impose some matrix element decay dynamic information into the likelihood besides the χ^2 to improve the measurement further.

Measuring a top quark mass in the dilepton channel is also attractive and complementary to the analysis in the lepton + jets channel. Any inconsistency between the two could be a sign of new physics or something that we do not understand. The dilepton system is under-constrained due to the two missing neutrinos in the final state, but by hypothesizing a top mass and solving event kinematics up to four-fold ambiguity for each lepton-jet pairing, we can obtain a probability function by comparing how likely these solutions fit to the top decay in the dilepton channel. CDF has measured the top mass using a likelihood fit to the data with the Monte Carlo templates for signal and background.

CDF performs several measurements of the top mass in the lepton + jets and the dilepton channel with Run 2 data, which are shown in Figure 5. All the results are consistent with each other and are soon going to be systematically limited, where the jet energy correction is one of the major limiting factors.

C. Other Properties and Future Prospects

Another way to search for new physics is to measure the top branching ratios(Br($t \to Wb$)), which is expected to be 100% in the Standard Model. A value significantly different from this could be a signal of new physics. CDF performed the measurement using the number of top candidate events in the lepton + jets sample with one or two

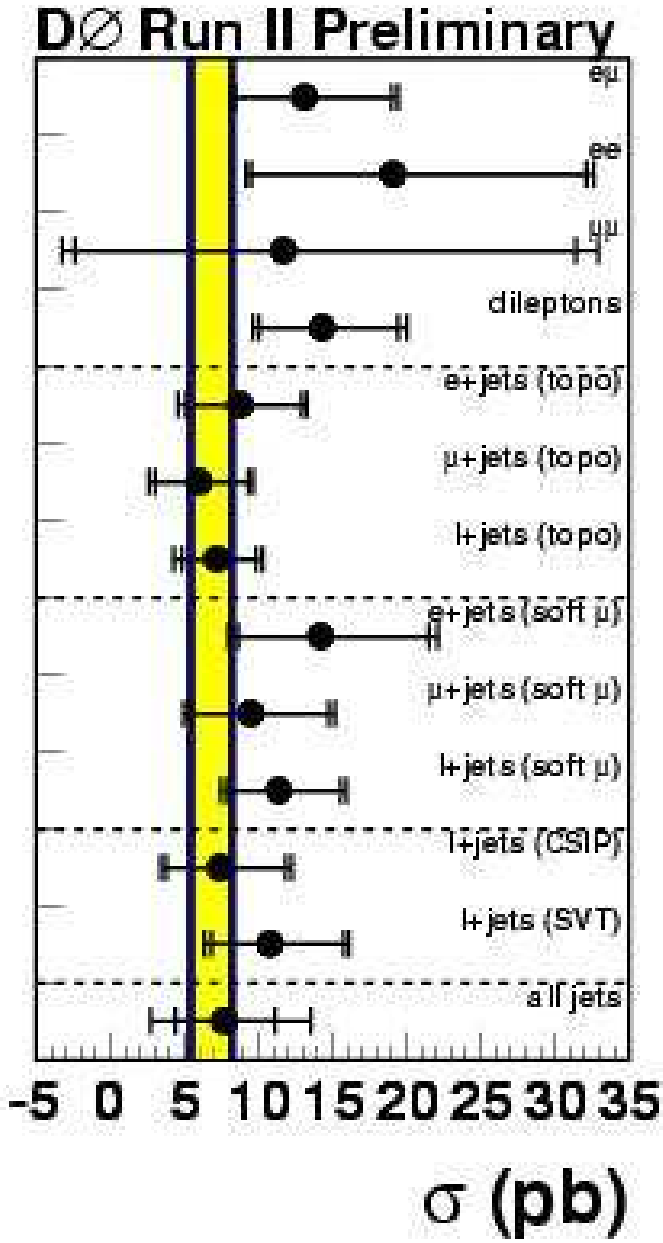

FIG. 4: Summary of Run II $t\bar{t}$ production cross section measured from D0.

jets tagged as b quarks. We found $\frac{Br(t\to Wb)}{Br(t\to Wq)} = 0.54^{+0.49}_{-0.39}$. The measurement can be further improved by including the no-tagged events in the lepton + jets channel, as well as the events in the dilepton channel.

A direct measurement of the helicity of the W boson from the top decay also provides an important test of the electroweak V-A interaction at the most massive particle. The Standard Model predicts that a fraction $F_0 \approx 0.703$ of the W bosons from the top decay are longitudinally-polarized while the remaining(1-F_0) of W bosons are left-handed polarized.

There are several ways to measure the helicity of W boson, for example, $cos\theta^*$, the angle between the charged lepton and the W in the W rest frame, and the P_T of charged leptons in the lab frame, which are both strong functions of the

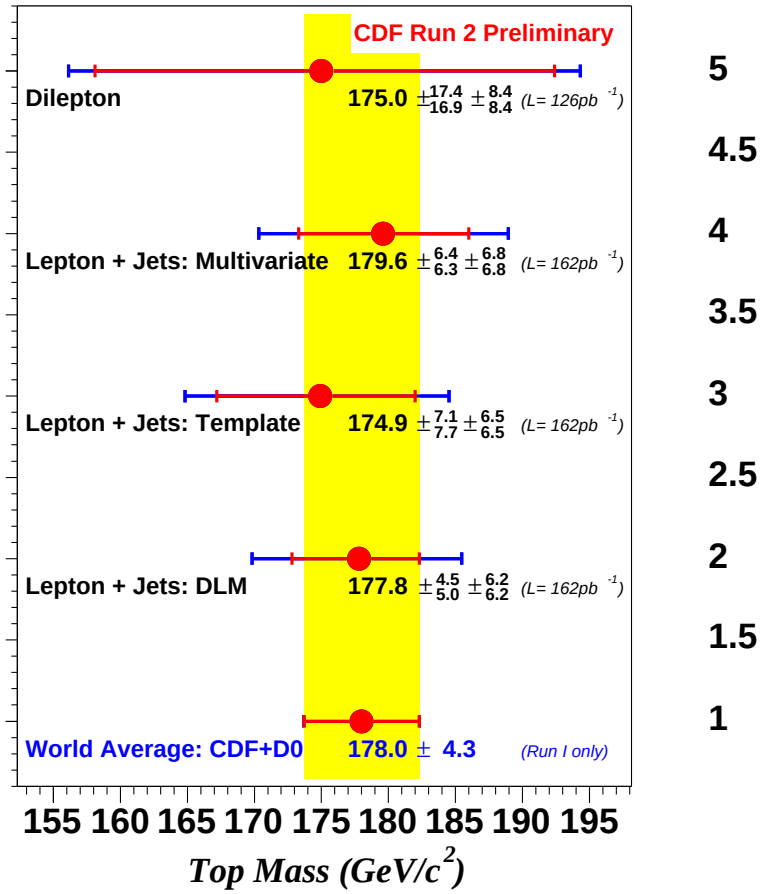

FIG. 5: Summary of Run II top mass measurements.

W helicity. Charged leptons from the decay of left-handed (longitudinally-polarized) W's are emitted in a direction opposite (transverse) to the flight path of the W, giving rise to a relatively soft (harder) P_T distribution in the lab frame. CDF has measured F_0 in Run II by analyzing the lepton P_T spectrum of $t\bar{t}$ candidate events in the lepton + jets and the dilepton channels, finding $F_0 = 0.27^{+0.35}_{-0.24}$, consistent with but about 1 σ lower than the SM expectation.

With 2 fb^{-1} of integrated luminosity, we expect more than 1000 single tagged and about 600 double tagged $t\bar{t}$ events. It will allow us to measure the top mass, one of the fundamental electroweak parameters, to within approximately 3 GeV/c^2. Measurements of branching ratios, angular distributions and the $t\bar{t}$ production cross section will be performed. In addition, searches for the rare decay of the top quark along with searches for exotic physics with the $t\bar{t}$ system will be carried out.

IV. HIGGS PHYSICS

At the Tevatron, the world's energy frontier before the LHC era, one of the crucial modes of discovery is associated production Wh for $m_h \leq 130$ GeV/c^2. With the W boson decaying to a lepton (l) and a neutrino (ν), and the Higgs decaying to two b quarks, a relatively clean experimental signature is obtained. For the Higgs mass above 130 GeV/c^2, single Higgs production with the decay $h \to WW^* \to ll\nu\nu$ offers an additional promising signature. Despite these clean signatures, substantial backgrounds exist, which come predominantly from a higher-order production of W bosons, top and direct WW pair production. If the Higgs boson turns out to be super symmetrical (MSSM), there

is an significant enhancement of $tan\beta^2$(see Section IV A 3) for the production of Higgs associated with the bottom quark pair, which results in much less luminosity required for discovery with respect to the SM Higgs.

A. Recent Results

Both CDF and D0 have re-established the top signal from the Run II data as described in Section III A, more importantly, the readiness of the tools required for lepton identification, b-tagging, jet clustering, and detector simulation. With these tools and a well-understood dataset in hand, many Higgs searches are performed. The results presented here are still at the engineering stage and much improved analyses with full datasets will emerge soon.

1. SM or SM-like Higgs Searches

The experimental signature being considered is Wh with $W \to e\nu$ or $\mu\nu$, and $h \to b\bar{b}$, giving final states with one high-P_T lepton, large missing transverse energy ($\not\!\!E_T$) due to the undetected neutrino, and two b jets. The ability to tag b jets using a secondary vertex detection with high efficiency and a low mistag rate is vital for searching for the decay of $h \to b\bar{b}$. Both CDF and D0 select the b-tagged $W+$ 2 jet events since it is expected to contain most of the signal, while b-tagged $W+ \geq 3$ jet events are dominated by $t\bar{t}$ decays.

CDF observed 62 events with at least one b-tagged jet, consistent with the background expectation of 66 ± 9 events, which are predominately from $Wb\bar{b}$, $Wc\bar{c}$, mistags, and $t\bar{t}$ decays. The dijet mass distribution is shown in Figure 6, along with the background expectation. The likelihood fit to the mass distributions yields a limit at 95% C.L. on the production cross section times branching ratio as a function of Higgs mass, shown in Figure 7. The sensitivity of the present search is limited by statistics to a cross section approximately one order of magnitude higher than the predicted cross section for the Standard Model Higgs boson production, but is getting close to some theoretical cross section of technicolor particle production [11].

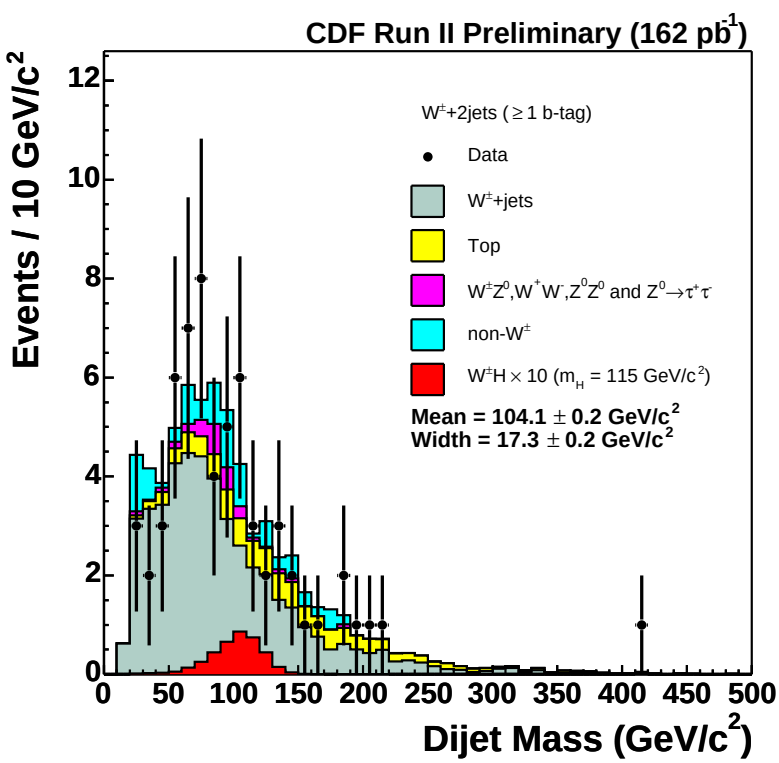

FIG. 6: The dijet invariant mass distribution of the b-tagged W + 2 jets events along with the background expectation, and a possible Higgs signal at mass 115 GeV/c^2 scaled by a factor of 10.

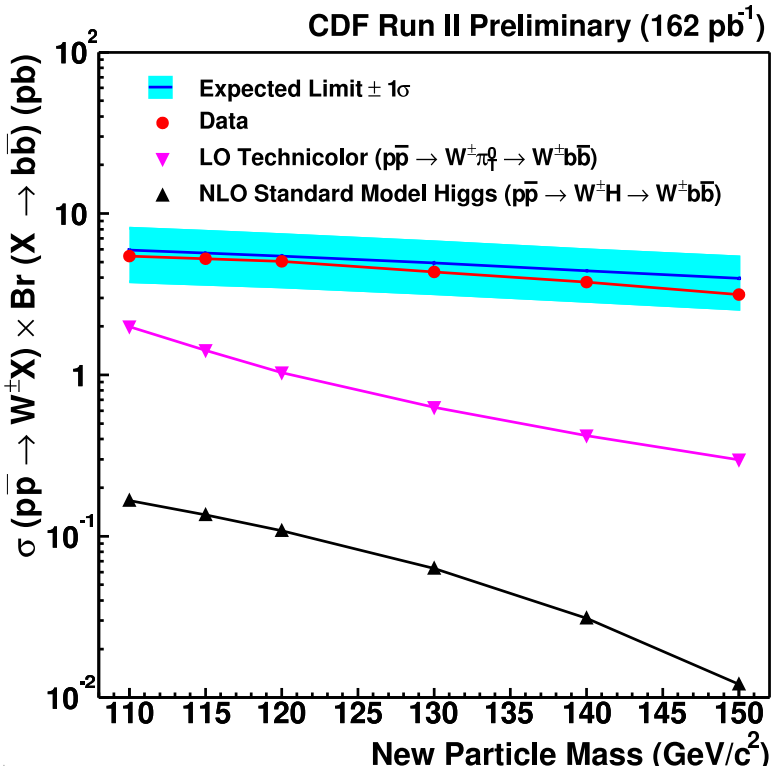

FIG. 7: The 95% C.L. upper limit (red circle) on the $W^{\pm}H$ cross section as a function of the Higgs boson mass. Also shown is the theoretical cross section (black triangle) for the production of a Standard Model Higgs boson in association with a $W^{\pm}$ boson, and the pseudo experiment results (blue line). As for the comparison, the production cross section of the Technicolor process ($p\bar{p} \to W^{\pm}\pi_T^0$) is also included (purple triangle).

D0 also performed a similar search with double b-tagging using an integrated luminosity of approximately 174 pb^{-1}. They observed 2 events with an expectation of 2.5 ± 0.7 and set a limit of 12.4 pb at 95% C.L. on the production cross section times branching ratio for the Higgs mass of 115 GeV/c^2. They also searched for anomalous heavy-flavor decay in the lepton + jets sample containing both secondary vertex and soft lepton tags in the same jets (superjet). No significant deviation was found with a cross section limit of 25.0 pb or 9.3 pb at 95% C.L. for anomalous production of $Wb\bar{b}$-like or top-like events.

2. *Search for $h \to W^+W^- \to l^+l^-\nu\bar{\nu}$*

For the Higgs mass above 130 GeV/c^2, the predominant decay mode of the Higgs boson is to a pair of W bosons, which offers an additional promising signature to look for the Higgs by taking full advantage of large inclusive Higgs production with the decay $h \to WW^* \to ll\nu\nu$. We select the events with two opposite-sign high momentum lepton and large missing transverse energy. In order to reduce the significant WW background, we exploit the spin correlations of $h \to WW^*$, which tends to produce the leptons close together. No signal is found and both CDF and D0 set a limit of 5.6 pb for the Higgs production cross section times branching ratio at 95% C.L., shown in Figure 8, compared with predictions from the Standard Model and alternative models (Topcolor [12] and 4th generation [13]) as a function of Higgs mass.

3. *MSSM Higgs Searches*

In the context of the minimal supersymmetric standard model (MSSM) the Higgs sector has two doublets, one coupling to up-type quarks and the other to down-type quarks. There are five physical Higgs boson states, denoted h, A, H, and $H^{\pm}$. The masses and couplings of the Higgses are determined by two parameters, usually taken to be m_A and $\tan\beta$ (the ratio of the vacuum expectation value of the two Higgs doublets), with corrections from the scalar top

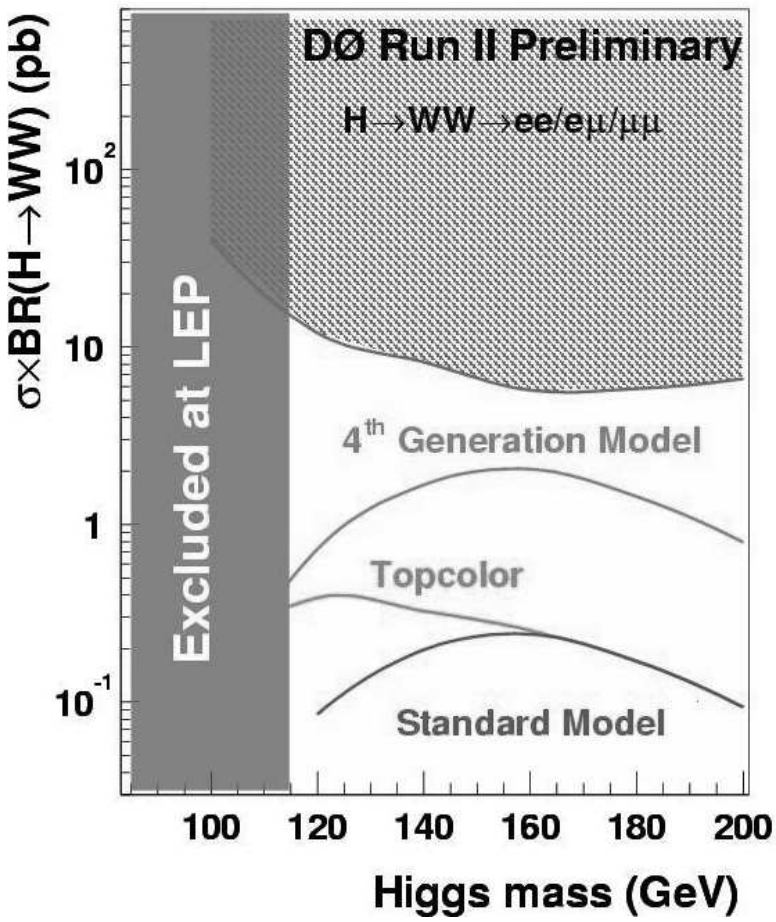

FIG. 8: The excluded cross section times branching ratio $\sigma \times BR(h \to WW^*)$ at 95% C.L. together with expectations from Standard Model Higgs boson production and alternative models.

mixing parameters. In the case of large $\tan\beta$, there is an enhancement of $\tan^2\beta$ for the production of $b\bar{b}\phi, \phi = h, A, H$ relative to the SM rate. This leads to a distinct signature of four b jets in the final states including two b's from Higgs decay.

D0 performed a search for neutral Higgs using approximately 130 pb^{-1} of the multi-jet sample. After optimization, they selected events containing 3 or 4 jets and required that at least three of jets be tagged. The invariant mass distribution of two leading b-tagged jets are consistent with the main backgrounds from QCD, fake tags and $t\bar{t}$, as well as the expected Higgs mass peak for $m_h = 120$ GeV/c^2. There is no evidence of signal found in the plot, which excludes the value of $tan\beta > 80 - 120$ at 95% C.L. in the region of m_A between 90 and 150 GeV/c^2 in MSSM parameter space, as shown in Figure 9.

CDF also performed a search for a neutral MSSM Higgs decaying to tau pairs using a sample with an integrated luminosity of approximately 200 pb^{-1}, collected with the dedicated Run II lepton + track triggers. The events are required to have one isolated lepton ($E_T > 10GeV$ for electron or $P_T > 10$ GeV/c for muon) and one identified hadronic tau candidate. Lots of good work has gone into developing a more efficient tau finding algorithm, which has been cross checked using $W \to \tau\nu$ data. CDF see no evidence of signal and perform a fit to the reconstructed visible di-tau mass to set limits on the product of Higgs production cross-section and its branching fraction to taus, as shown in Figure 10.

4. *Other Higgs Searches: $h \to \gamma\gamma$*

In the Standard Model the Higgs boson decays mostly to b-quark, W, or Z boson pairs depending on the mass, while the branching fraction for $h \to \gamma\gamma$ is too small to be useful for probing SM Higgs at the Tevatron. However

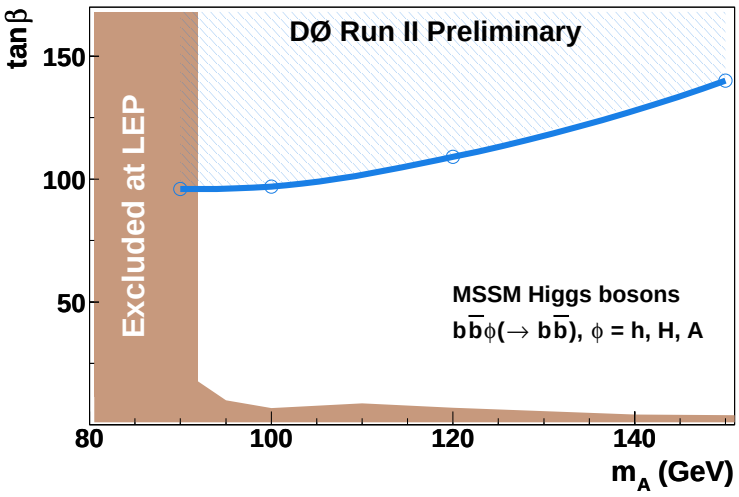

FIG. 9: The 95% C.L. lower limit on $tan\beta$ set as a function of m_A (thick, blue). The top hatched area indicates the excluded side of the line, and the shared area indicates the LEP limits.

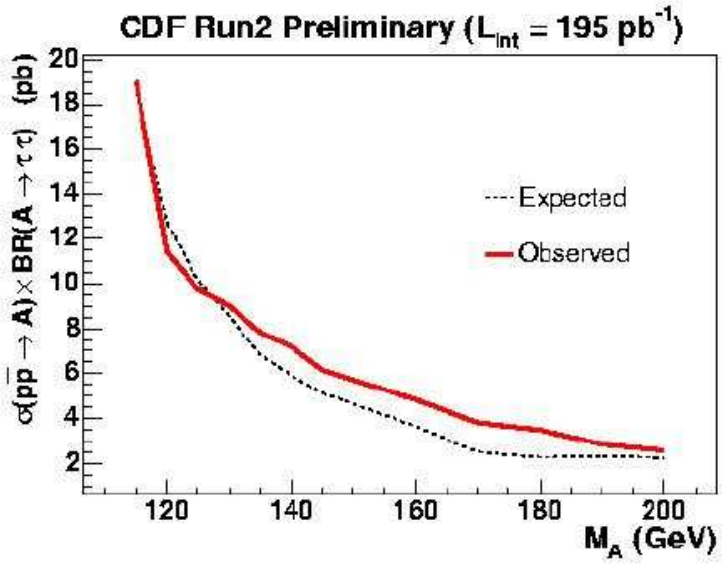

FIG. 10: The 95% C.L. lower limit on the production cross section times branching ratio $\sigma \times BR(A \rightarrow \tau^+\tau^-)$ as a function of Higgs mass.

many extensions of the SM allow enhanced decay of $h \rightarrow \gamma\gamma$ largely due to suppressed couplings of fermions, such as Fermiophobic Higgs [14] or Topcolor Higgs [12] scenarios. The data used for this analysis were collected with the D0 detector, which corresponds to a total integrated luminosity of 191 pb^{-1}. The events are selected with two reconstructed EM objects with $E_T > 25$ GeV in the Central Calorimeter (CC) or End Calorimeter (EC) in the detector η range of $|\eta| < 1.05$ and $1.5 < |\eta| < 2.4$, respectively. In addition, the P_T of the diphoton system is required to be above 35 GeV to reduce the di-jet background.

The invariant mass of diphoton distribution for the data and predicted background, as well as the event yields, are shown in Figure 11 for CC-CC, CC-CE, and EC-EC, respectively. In the absence of evidence of a signal, D0 is able to set an upper 95% C.L. limit on the diphoton branching ratio (≈ 0.8) as a function of Higgs mass for Fermiophobic and Topcolor Higgs models.

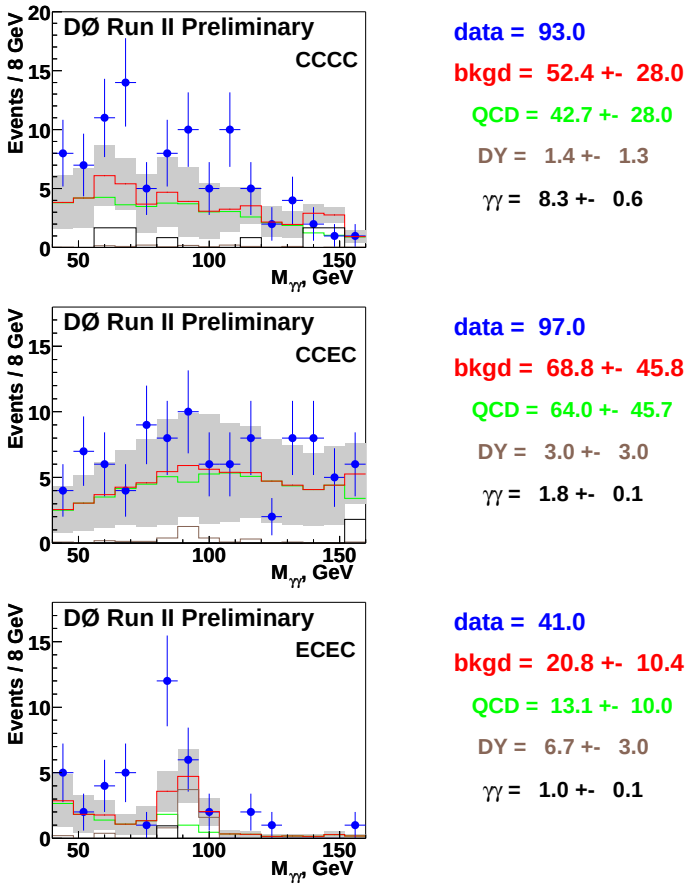

FIG. 11: Diphoton invariant mass distributions and event yields for different event topologies. Points are data and the shaded rectangles indicate the background with +- 1 σ.

B. Future Prospects

In 2003, the CDF and D0 collaboration were asked by DOE to provide a new estimation of the Higgs Sensitivity based on current Run II detector performance [15]. The studies focus on a number of important improvements including the detectors, b-tagging, dijet mass resolution, and the advanced analysis techniques.

The updated integrated luminosity required to discover or exclude the SM Higgs, combining all search channels and combining the data from both experiments, is shown in Figure 12. The finding is consistent with the SUSY-Higgs Workshop report, also shown in the plot. We have not included the impact of systematic uncertainties in the curve yet. Controlling the systematic errors, especially dijet mass resolution will be important. The understanding of the Higgs sensitivity will improve over time once we get more data, a better understood detector, and more clever ideas, but finding the Higgs at the Tevatron will be challenging. With 5 fb^{-1} data, the Tevatron should be able to observe a 3 σ excess for Higgs mass up to 120 GeV/c^2 or exclude the Higgs Mass up to about $M_h = 130$ GeV/c^2 at 95% CL if it is not present. The prospects for an MSSM Higgs is much better and 5 fb^{-1} allows us to cover most of the MSSM SUSY space for exclusion.

V. CONCLUSIONS

In the next a few years, the Tevatron Collider is in a unique position to search for the dynamics responsible for electroweak symmetry breaking. We will be able to either see some glimmer of the new physics or constrain the Standard Model at an unprecedented level. The top quark may play a unique role because of its heavy mass. With 5 fb^{-1}, we will be able to fully reconstruct several thousand $t\bar{t}$ pairs and measure the top quark mass accurately within 3 GeV. We can search for new physics in the top decay by studying the kinematic and angular distributions in great

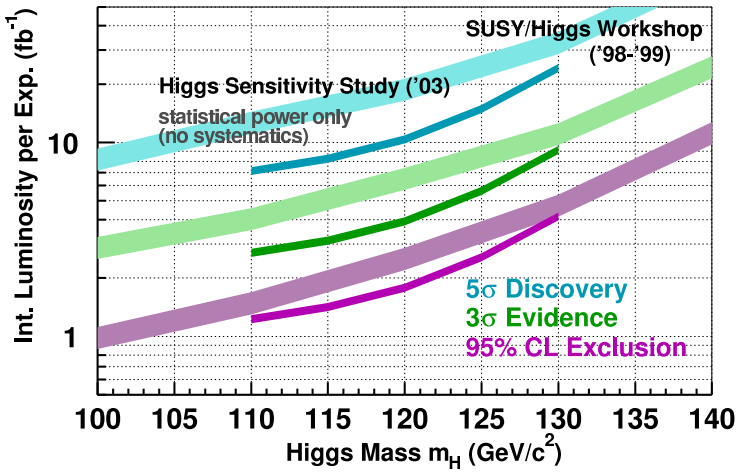

FIG. 12: The updated luminosity required for 95% C.L. exclusion, 3 and 5 σ discovery as a function of Higgs mass. The effects of systematic uncertainties are not included yet.

detail. More importantly, the techniques being developed for studying the top quark are directly applicable to other searches for the new particles at CDF and LHC.

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