Annual Progress Report for JFY 2010

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CDF Experiment

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The CDF experiment at the Fermilab Tevatron proton-antiproton collider continued to accumulate high-statistics data and produce rich physics results in 2010. The accelerator performance has been superb. The instantaneous luminosity at the beginning of stores consistently exceeds $\mathcal{L} = 3 \times 10^{32}$ cm^{-2} s^{-1}, with a record luminosity of 4.02×10^{32} cm^{-2} s^{-1} in April 2010 (Figure 1 (top)). A weekly integrated luminosity in excess of 60 pb^{-1} has also been achieved regularly. The integrated luminosity in the calendar year 2010 amounted to about 2.5 fb^{-1} and the Run II total to date is now about 10.5 fb^{-1} (Figure 1 (bottom)).

The upgraded CDF detector has been operational very smoothly and efficiently. The integrated luminosity recorded by CDF amounts to 8.8 fb^{-1}, roughly 80 times that of Run I (Figure 2). CDF expects to collect a total of about 10 fb^{-1} at the end of US fiscal year 2011.

CDF has analyzed up to 7.1 fb^{-1} of data thus far, depending on data sets and physics topics, and many important and interesting results have emerged. In this report we summarize these physics results, with an emphasis on contributions from the Japan group.

1 Physics Results

1.1 Top quark physics

The top quark and its properties have been studied extensively since its discovery by CDF in 1995. With increased statistics of Run-II data, these studies are now performed with high precision.

The top quark analyses with Run-II data include measurements of the mass and production cross section using various decay channels.

The top quark mass is extracted using various techniques and channels. By combining all measurements, CDF finds the top quark mass to be $m_t = 173.1 \pm 0.7 \pm 0.9$ GeV/c^2. The precision has long surpassed the original Run-II (2 fb^{-1}) goal of 3 GeV/c^2 and is now better than 1%. Using also the measurements by the D0 experiment, we derive the combined top quark mass of $m_t = 173.3 \pm 0.6 \pm 0.9$ GeV/c^2 (July 2010).

A measurement of the W boson mass has been performed by CDF. Combining it with top quark mass measurements provides indirect information on the Higgs boson mass through electroweak radiative corrections. Figure 3 shows the results as of July 2010. A constraint on the standard model Higgs boson mass is obtained to be $96\,^{+31}_{-24}$ GeV/c^2 at 68% CL, and is less than 171 GeV/c^2 at 95% CL (Figure 4).

Other production and decay properties of the top quark are also studied, including $t\bar{t}$ spin correlations and forward-backward asymmetry at production, and the $W^\pm$ boson helicity in the decay.

The $t\bar{t}$ forward-backward asymmetry at production in proton-antiproton collisions is of interest. Since the initial state is CP symmetric, and the strong interaction conserves parity, one naively expects there should exist no forward-backward asymmetry. However, it is predicted that the interferences between the lowest order and higher order processes produce a small asymmetry, of order 10%. And if a new strong interaction beyond the standard model exists and it violates parity (such as axi-gluons), an asymmetry will be naturally introduced.

At CDF, a measurement using the lepton plus jet final state produced an intriguing result, $A_{\rm FB} = +0.475 \pm 0.114$, to be compared with a QCD prediction of $+0.088 \pm 0.013$. A similar analysis is performed using the di-lepton final state, giving $A_{\rm FB} = +0.42 \pm 0.15 \pm 0.05$ [1], to be compared with a QCD prediction of $+0.06 \pm 0.01$. The observed raw asymmetry is shown in Figure 5. Both of the channels give asymmetries larger than the predictions, and they are larger at higher $t\bar{t}$ mass regions. Therefore it could be a hint of new physics at high mass. The di-lepton analysis is performed by Y. Takeuchi (Tsukuba).

1.2 Bottom quark physics

Since the observation of the particle-antiparticle oscillations of the B_s^0 meson and a measurement of their frequency Δm_s in 2006, CDF has turned its attention to more detailed studies of B-hadron decays and searches for possible new effects originationg from physics beyond the standard model and the CKM theory.

For example, we have looked for CP violation in B_s^0-$\bar{B}_s^0$ mixing, which modulates with the frequency Δm_s. The decay mode $B_s^0 \to J/\psi\,\phi$ is the most useful for this purpose. A measurement based on a 2.8 fb^{-1} dataset is published, and an update using a 5.2 fb^{-1} dataset is now available. A constraint on the phase β_s is obtained and a wide range of the parameter space has been already eliminated.

Another interesting field of study is the B-hadron decays through the FCNC processes $b \to s$. H. Miyake (Tsukuba) has observed signals for $B^+ \to K^+\,\mu^+\mu^-$, $B_d^0 \to K^{*0}\,\mu^+\mu^-$, and $B_s^0 \to \phi\,\mu^+\mu^-$. The last mode is the first observation of the mode, and represents the rarest decay mode ever for the B_s^0 meson. The muon pair invariant mass distributions are examined, and the corresponding differential branching fractions are determined. The interesting observables in these decays are the polarization and the the lepton angle forward-backward asymmetry. The standard model processes have both vector and axial-vector couplings in these decays, and therefore an asymmetry is expected to be non-zero and has been observed in previous measurements. However, the existence of new physics could change drastically those distributions, and a hint of possible effects has been observed by the Bell and BaBar experiments. The CDF asymmetry distribution [2] follows the trend of the Belle/BaBar measurements, and remains to be an important subject to be studied with higher statistics. An analysis using 6.7 fb^{-1} of data and additional trigger paths and decay modes is under way, and we expect an increase of a factor of two in signal statistics. The new result will be available very soon.

1.3 New particle searches

Searches for the Higgs boson, supersymmetric particles and other new particles have been performed. Cross sections for the standard model Higgs boson production at the Tevatron is shown in Figure 6 (left) for various subprocesses. The largest contribution comes from single production through gluon fusion, with the top quark in the loop. Associated production with a weak boson, $W^{\pm}H$ and Z^0H, is smaller. The decay branching fractions of the Higgs boson are shown in Figure 6 (right). At a low mass, below 135 GeV/c^2, the decay to $b\bar{b}$ pairs is dominant, while at a high mass the decays to weak boson pairs become dominant.

CDF has searched for the Higgs boson production using many different final states. The first, aimed at a low mass Higgs, looks for the associated production $\bar{p}p \to VHX$, where V is a weak gauge boson $W^{\pm}$ or Z^0, with the $W^{\pm}$ (Z^0) boson decaying into $\ell^{\pm}\nu$ ($\ell^+\ell^-$, $\nu\bar{\nu}$) pairs, and the Higgs boson to $b\bar{b}$ pairs. The b quark jets are identified with displaced vertices. The main background comes from heavy flavor ($b\bar{b}$, $c\bar{c}$) production in association with a vector boson V, and top quark pair production. Various kinematic distributions, including the di-jet mass distribution (Figure 7 (left)), are examined for possible production of the Higgs boson. Also an artificial neural network discriminant is employed (Figure 7 (right)). No excess of events over known backgrounds is found in 5.7 fb^{-1} of data, and upper limits on the Higgs boson production cross section are set, in the range of 2.0 to 44 times the standard model value, depending on the assumed Higgs boson mass (100 to 150 GeV/c^2) [3]. Y. Nagai (Tsukuba) has performed the analysis. M. Kurata (Tsukuba) is applying the Dynamical Likelihood Method to the Higgs search in this channel.

The second analysis looks for single production of the Higgs boson followed by its decays to W boson pairs. The channel is sensitive to a high mass Higgs. The W^+W^- final state is identified with their decays to leptons, thus the signature is two energetic leptons and a large missing transverse energy and nothing else. The dominant background comes from electroweak W^+W^- production, which leads to the same signature. However, there exists a difference in event topology, for example the lepton azimuthal angle correlations. Again, no excess of events is observed and upper limits on Higgs production have been placed. This is presently the most sensitive search channel at CDF, and the upper limit for the mass of 160 GeV/c^2 is 0.83 times the standard model value using 7.1 fb^{-1} of data (March 2011). An upper limit of less than unity means that the Higgs boson at the assumed mass is excluded. An attempt is being made to improve the sensitivity further by using the same production mode and a different decay channel, where one of the W bosons decays leptonically and the other hadronically to two quark jets. Y. Sudo and K. Sato (Tsukuba) are working on the analysis.

The third method looks for associated production of the Higgs boson with a weak boson $W^\pm$ or Z^0, where the Higgs boson decays to W^+W^- pair and one or both of the W bosons can be off mass shell. There exist three W bosons in the final state, where two of them have the same charge. They are required to decay leptonically, leading to a very distinctive final state of isolated, same-charge lepton pairs, such as $e^+\mu^+$.

The results from different analyses as of summer 2010 (luminosity up to 5.9 fb^{-1}) are combined and summarized in Figure 8, where the ratio of the obtained upper limits on production cross sections to the standard model predictions is presented. The limits are at about unity for a Higgs mass near 160 GeV/c^2, and are less than two at low mass [4]. Figure 9 shows the limits where the results from both CDF and D0 experiments are combined. Again data up to 5.9 fb^{-1} have been analyzed. Mass ranges $100 < m_H < 109$ GeV/c^2 and $158 < m_H < 175$ GeV/c^2 have been excluded at 95% CL [5]. It is expected that the exclusion region becomes wider as more data are analyzed and improvements to analysis techniques are implemented.

If the results from both indirect and direct searches for the Higgs boson are combined, we obtain a likelihood distribution shown in Figure 10. The constraint on the Higgs mass is $m_H = 120.6^{+17.9}_{-\ 5.2}$ GeV/c^2, and an upper limit at 95% CL is 155.3 GeV/c^2. Obviously it favors a light Higgs boson, which may require a lot of data to observe even at the LHC.

Tevatron running will be terminated at the end of the US fiscal year 2011. As mentioned earlier, CDF will accumulate roughly 10 fb^{-1} of data that are good for analysis. After that, CDF will continue data analyses and continue to produce important physics results, at least for a few more years. Some of them will be competitive with and others will be complementary to LHC results.

References

[1] "Measurement of the forward backward asymmetry in the dilepton decay channel using 5.1 fb^{-1}",
CDF Collaboration, CDF public note 10436 (2011).

[2] "Measurement of the forward-backward asymmetry in the $B \to K^{(*)}\mu^+\mu^-$ decay and first observation of the $B_s^0 \to \phi\mu^+\mu^-$ decay",
CDF Collaboration, submitted to Phys. Rev. Lett., arXiv:1101.1028v2 [hep-ex] (2011).

[3] "Search for standard model Higgs boson production in association with a $W^\pm$ boson at CDF with 5.7 fb^{-1}",
CDF Collaboration, CDF public note 10239 (2010).

[4] "Combined upper limit on standard model Higgs boson production in up to 5.9 fb^{-1} of data,
CDF Collaboration, CDF public note 10223 (2010).

[5] "Combined CDF and D0 upper limits on standard model Higgs-boson production with up to 6.7 fb^{-1} of data",
CDF and D0 Collaborations, arXiv:01007.4587 [hep-ex] (2010).

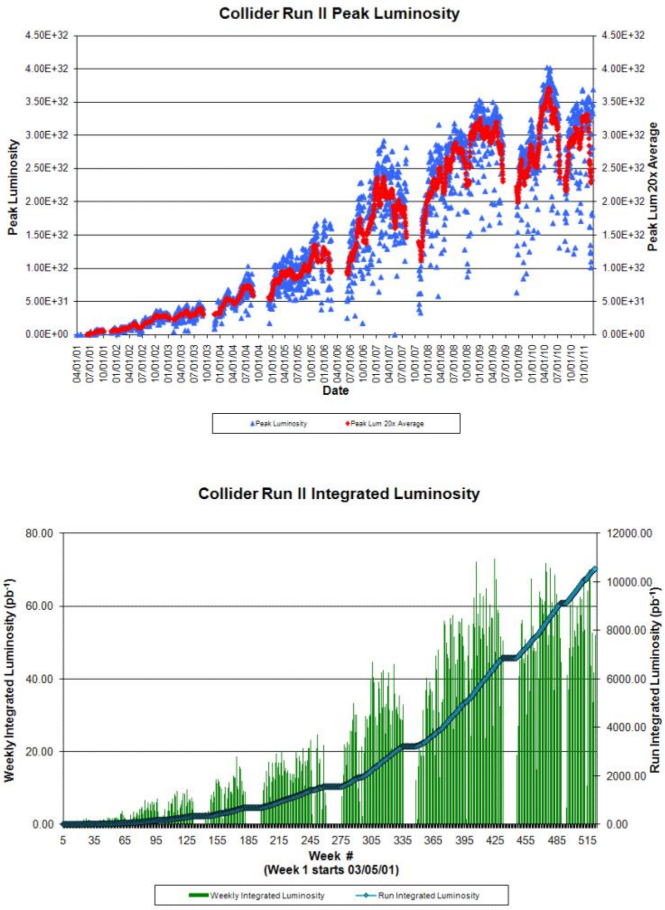

Figure 1: Tevatron performance in Run II. Top: instantaneous luminosity at the beginning of each store. Bottom: integrated luminosity delivered by week.

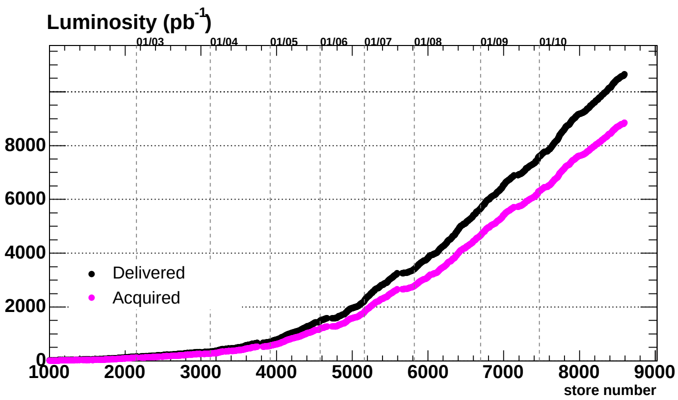

Figure 2: Integrated luminosity (top) delivered to and (bottom) recorded by CDF in Tevatron Run II.

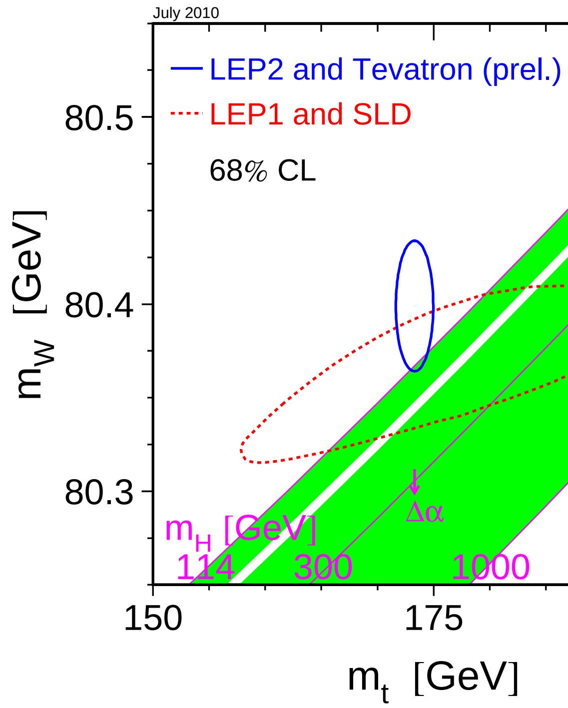

Figure 3: Measurements of the top quark and W boson masses as of July 2010, and indirect information on the Higgs boson mass.

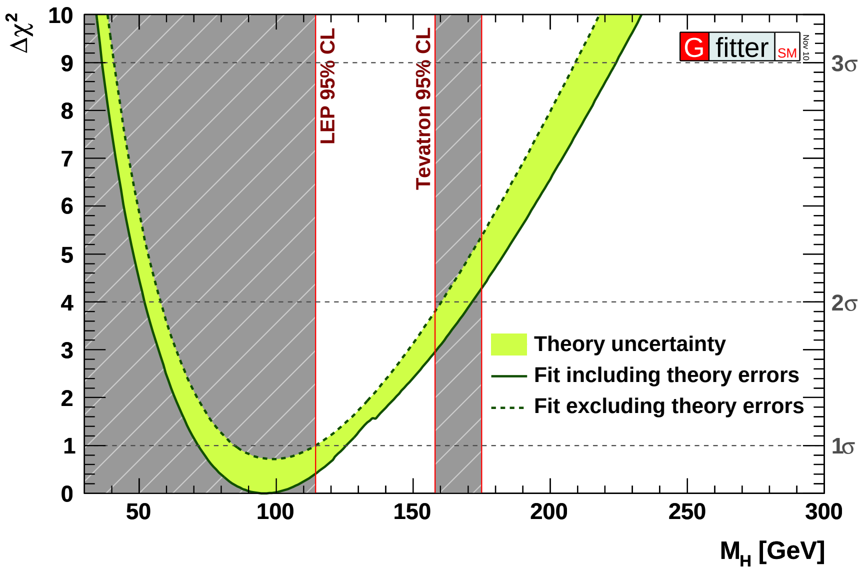

Figure 4: Likelihood distribution for the Higgs boson mass derived from global fits to electroweak measurements.

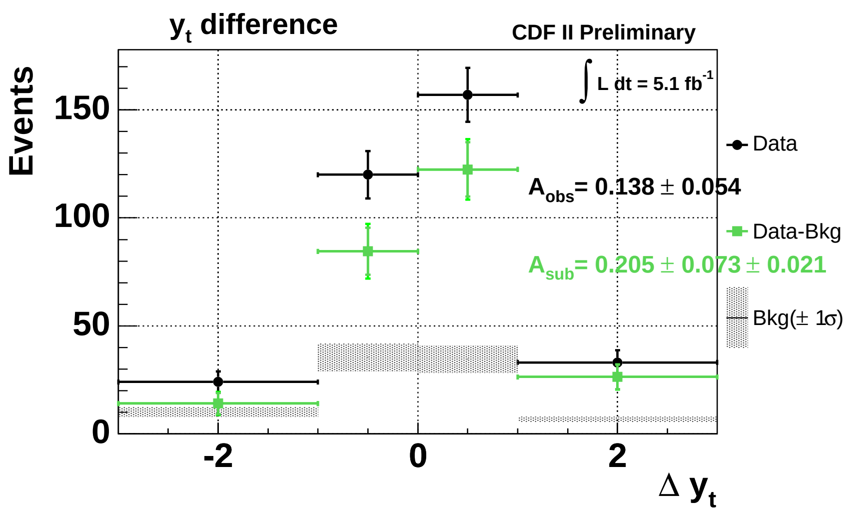

Figure 5: Study of $t\bar{t}$ forward-backward asymmetry in production using the di-lepton final state. The distribution of the difference in the t and $\bar{t}$ rapidities after background subtraction is shown.

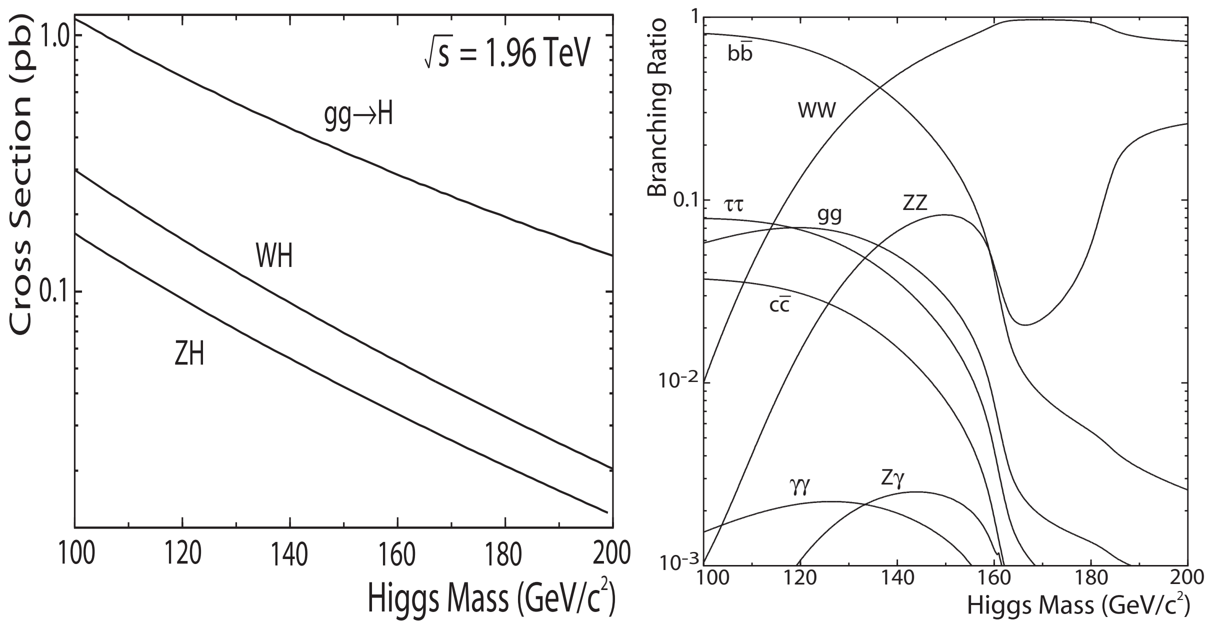

Figure 6: Left: Cross section for the production of the standard model Higgs boson at Tevatron. right: Branching fractions of the standard model Higgs boson to various final states. Both plots show dependences on the Higgs boson mass.

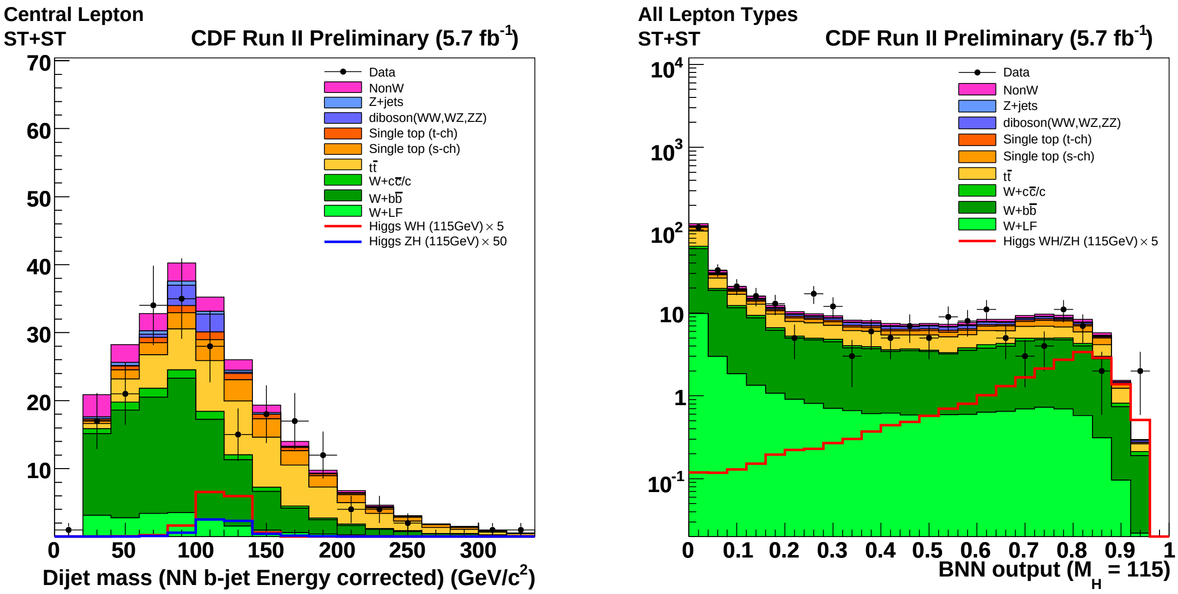

Figure 7: Higgs boson search in the $p\bar{p} \to W^{\pm}HX \to (\ell^{\pm}\nu)\,(b\bar{b})\,X$ channel. Left: Invariant mass distribution of the two b-quark candidate jets produced in association with a W boson. Right: Output of the Bayesian neural network discriminant.

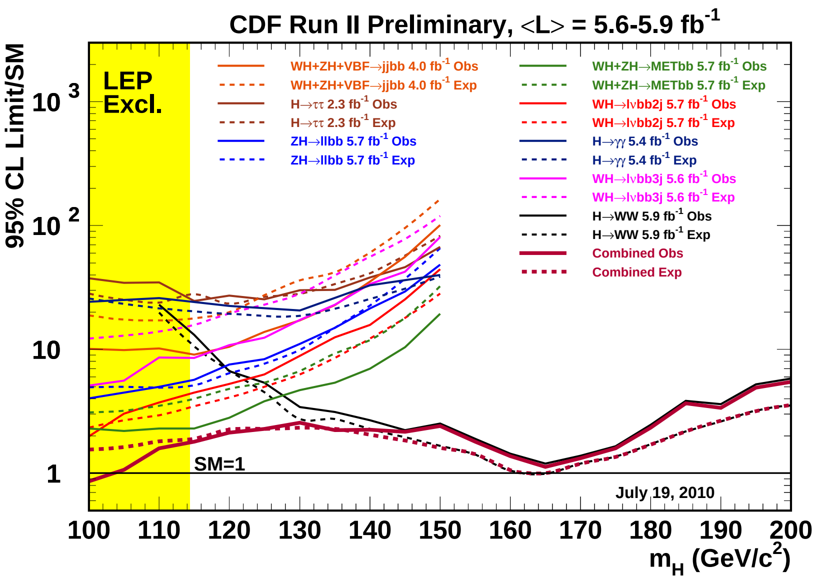

Figure 8: Summary of CDF results on the searches for the standard model Higgs boson. The experimental upper limits on production cross sections, normalized to the theoretical predictions, are shown for all search channels.

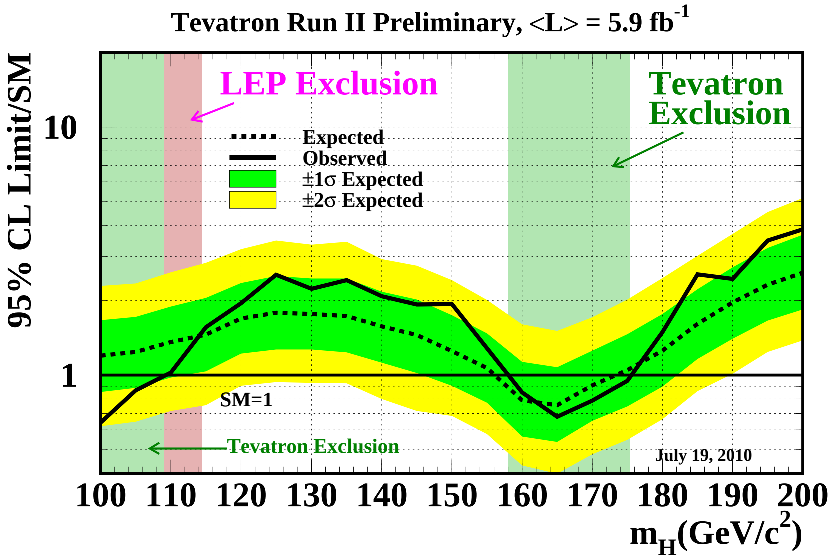

Figure 9: Summary of combined CDF and D0 results on the searches for the standard model Higgs boson. The experimental upper limits on production cross sections, normalized to the theoretical predictions, are shown after combining all search channels. The mass ranges $100 < m_H < 109$ GeV/c^2 and $158 < m_H < 175$ GeV/c^2 have been excluded at 95% CL.

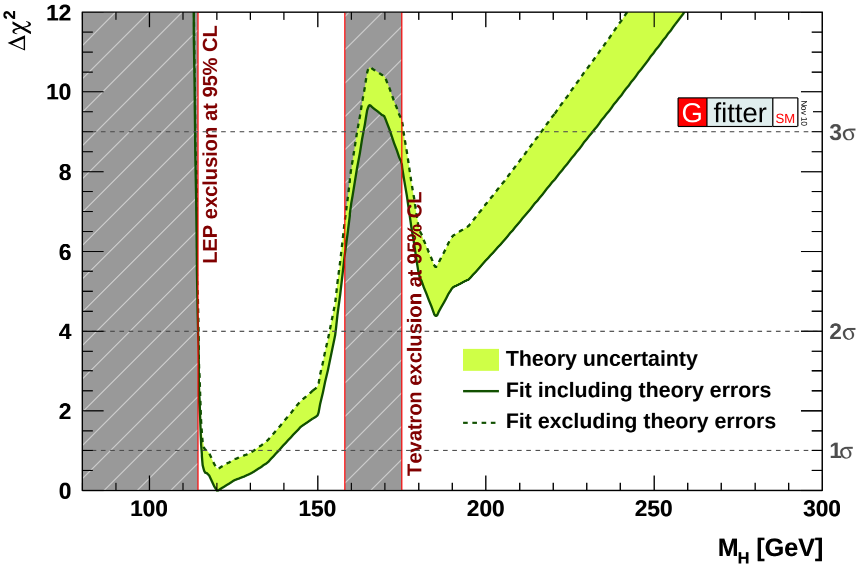

Figure 10: Likelihood distribution for the Higgs boson mass including both indirect measurements and direct searches.