Annual Progress Report for JFY 2007

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CDF Experiment

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The Tevatron Run-II program and the CDF experiment enjoyed another fruitful year in 2007. The improvement in the accelerator performance seen in the previous years continued in 2007, resulting in more smooth and reliable operations and maximization in the integrated luminosity delivered to the experiments. The instantaneous luminosity at the beginning of the stores consistently exceeds the design luminosity of $\mathcal{L} = 2 \times 10^{32}$ cm^{-2} s^{-1}, with a record luminosity of 2.9×10^{32} cm^{-2} s^{-1} (Figure 1 (top)). A weekly integrated luminosity in excess of 40 pb^{-1} has also been achieved regularly. The total integrated luminosity in the calendar year 2007 amounted to about 1150 pb^{-1} despite a shutdown in summer, and the Run II total to date has exceeded 3.6 fb^{-1} (Figure 1 (bottom)).

The upgraded CDF detector has been operational very successfully with high efficiency. The integrated luminosity recorded by CDF amounts to 3.0 fb^{-1}, roughly 30 times that of Run I (Figure 2). We expect to collect a total of 6 to 7 fb^{-1} before the Tevatron shuts down in 2009 as currently scheduled. For operations at a high luminosity, the CDF detector has completed upgrades to some of the detector components, in particular the DAQ system that allows efficient data taking and data logging. They include the upgrades to the silicon-based trigger system (SVT) and to the consumer server/logger system (CS/L).

CDF has analyzed up to 2 fb^{-1} of data thus far, depending on data sets and physics topics, and many important and interesting results have emerged from Run-II data. We summarize these physics results, as well as detector upgrade efforts, with an emphasis on contributions from the Japan group.

1 Physics Results

1.1 Electroweak physics

The measurement of the $W^{\pm}$ boson mass using the Run-II data, reported in early 2007, is now published [1]. The result, $m_W = 80413 \pm 48$ MeV/c^2, represents the single most precise measurement of the quantity, as illustrated in Figure 3. The impact of this measurement on constraints on the Higgs boson mass will be discussed later in this document. With more than 2 fb^{-1} of data that CDF has collected already, the $W^{\pm}$ boson mass will be measured with a precision of about 25 MeV/c^2. Combined with top quark mass measurements, it will provide constraints on the Higgs boson mass with a relative precision of 20%.

Another area of study concerns pair production of gauge bosons. The unified electroweak theory has a non-Abelian gauge structure, resulting in self-couplings of the gauge bosons, such as $W^+W^-Z^0$ and $W^+W^-\gamma$ vertices.

Associated production of a $W^{\pm}$ boson and a Z^0 boson was observed in 2006 for the first time. The study continued with 2 fb^{-1} of data. The leptonic decays of the $W^{\pm}$ and Z^0 bosons are used, leading to a very distinctive signature of three energetic leptons, a large transverse missing energy, and no extra jets. The production cross section is measured to be $\sigma(\bar{p}p \to W^{\pm}Z^0X) = 4.3\,^{+1.4}_{-1.1}$ pb, in good agreement with a theory prediction of 3.7 ± 0.3 pb.

Production of $W^{\pm}\gamma$ pairs is also studied. The electron decay channel of the W boson is newly added in 2007. 908 (857) candidate events with photons above 7 GeV/c have been observed in the $W \to e\nu$ ($\mu\nu$) channel among 1 fb^{-1} of data. Kinematic distributions such as the photon transverse momentum and the transverse mass of the lepton-photon-missing E_T system are examined (Figure 4). A good agreement with expectations is found. The production cross section is measured to be $\sigma(\bar{p}p \to W^{\pm}\gamma X) \cdot \mathcal{B}(W^{\pm} \to \ell^{\pm}\nu) = 18.03 \pm 0.65 \pm 2.55 \pm 1.05$ pb [2], in very good agreement with theory prediction of 19.3 ± 0.4 pb. A. Nagano (Tsukuba) has performed the analysis and completed her PhD thesis. Efforts are also under way to search for possible anomalous couplings in the gauge boson self-interactions and to study radiation amplitude zero in the photon angular distributions.

1.2 Top quark physics

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

The top quark analyses with Run-II data include measurements of the mass and production cross section using various decay channels. The production cross section has been measured in di-lepton, lepton + jet and all-hadronic channels. The cross section from the di-lepton channel (1.2 fb^{-1}) is $\sigma = 6.2 \pm 1.1 \pm 0.7 \pm 0.4$ pb [3]. In the lepton + jet channel with secondary vertex b-jet tagging, the $t\bar{t}$ production cross section is measured to be $\sigma = 8.2 \pm 0.5 \pm 0.8 \pm 0.5$ pb [4]. The all-hadronic channel measures $\sigma = 8.3 \pm 1.0\,^{+2.0}_{-1.5} \pm 0.5$ pb [5]. They all are in agreement with a next-to-leading order QCD calculation of $6.7\,^{+0.71}_{-0.88}$ pb for $m_{\rm top} = 175$ GeV/c^2. N. Kimura and Y. Takeuchi (Tsukuba) have contributed to the di-lepton analysis, and Y. Kusakabe (Waseda) and T. Masubuchi (Tsukuba) to the lepton +

jet channel analysis.

The top quark mass is extracted using various techniques and channels. T. Kubo (Tsukuba) and J. Naganoma (Waseda) have used the lepton + jet channel and applied the Dynamical Likelihood Method (DLM) in extracting the top quark mass. The DLM maximizes sensitivity by utilizing information such as subprocess matrix elements and parton distribution functions. Understanding the calorimeter scale of jet energy measurements is very important and it is calibrated by using $W \to q\bar{q}'$ decays in $t\bar{t}$ candidate events themselves. The reconstructed mass distribution is shown in Figure 5, and the extracted mass value is $m_{\rm top} = 171.6 \pm 2.0 \pm 1.3$ GeV/c^2 (1.7 fb^{-1}) [6]. T. Kubo finished his Ph.D. with the subject [6].

By combining various measurements, CDF finds the top quark mass to be $m_t = 172.9 \pm 1.2 \pm 1.5$ GeV/c^2. The uncertainty is already below the Run-II (2 fb^{-1}) goal of 3 GeV/c^2 and is approaching a precision of better than 1%. Using also the measurements by the D0 experiment, we derive the combined top quark mass of $m_t = 172.6 \pm 0.8 \pm 1.1$ GeV/c^2.

As noted earlier, a new measurement of the W boson mass has been performed by CDF recently. Combining it with top quark mass measurements provides indirect information on the Higgs boson. Figure 6 shows the results as of winter 2008, along with a constraint on the standard model Higgs boson mass, which is $76\,^{+33}_{-24}$ GeV/c^2, and less than 144 GeV/c^2 at 95% CL.

Other production and decay properties of the top quark are being measured, including $t\bar{t}$ spin correlations and $W^{\pm}$ boson helicity. Y. Takeuchi (Tsukuba) has been working on spin correlations using the dilepton channel, and N. Kimura (Tsukuba) attempts to measure initial parton fractions ($q\bar{q}$ vs. gluons) for $t\bar{t}$ production. Evidence for single top-quark production has been presented for the first time in 2007, and it has allowed a direct measurement of the partial width $\Gamma(t \to W^+b)$, and thus a determination of the CKM matrix element $|V_{tb}|$ with a 15% precision. K. Nakamura (Tsukuba) is working on single top production for his Ph. D. thesis. Also, searches have been performed for new particles such as a charged Higgs boson through the top decay $t \to H^+b$, and for new resonant states decaying into $t\bar{t}$ pairs. J. Naganoma (Waseda) has been performing the latter analysis, in particular the searches for massive gluons that can decay to top quark pairs. Figure 7 shows the invariant mass distribution of the $t\bar{t}$ pair candidates. It agrees with the standard model expectations. The distribution was fitted including possible contributions of the massive gluons (Figure 7 (right)), and limits on its coupling strength λ have been placed [7].

1.3 Bottom quark physics

Last year CDF succeeded in observing the particle-antiparticle oscillations of the B_s^0 meson and in measuring their frequency Δm_s [8]. It has led to a very precise determination of the elements of the CKM matrix, $|V_{td}/V_{ts}| = 0.2060 \pm 0.0007\,^{+\,0.0081}_{-\,0.0060}$, and provided test of and support for the Kobayashi-Maskawa picture of CP violation.

The observation now allows us to look 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. Figure 8 (left) shows the signal, and Figure 8 (right) illustrates the allowed region in the β_s-$\Delta\Gamma$ plane, along with the standard model prediction, where β_s is the CP-violating phase and $\Delta\Gamma$ is the width difference in the mass/lifetime eigenstates of the B_s^0-$\bar{B}_s^0$ system. This is the first constrained obtained for the phase β_s [9], and more data are eagerly awaited.

As a related subject, H. Miyake (Tsukuba) is involved in the B_s^0 meson lifetime and width difference measurement using the semileptonic decays $\bar{B}_s^0 \to \ell^- \bar{\nu} D_s^+ X$.

1.4 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 9 (left) for various subprocesses. The largest contribution comes from the single production through gluon fusion, with the top quark in the loop. Associated production with weak bosons $W^{\pm}H$ and Z^0H are smaller. The decay branching fractions of the Higgs boson are shown in Figure 9 (right). At a low mass, below 120 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 $\ell^{\pm}\nu$ ($\nu\bar{\nu}$) 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 the W boson, and top quark pair production. The number of events as well as the di-jet mass distribution (Figure 10 (left)) are examined for possible production of the Higgs boson. Also an artificial neural network discriminant is employed (Figure 10 (right)). No excess of events over known backgrounds is found in 1.9 fb^{-1} of data, and upper limits on the Higgs boson production cross section are set, in the range from 1.38 to 0.93 pb, depending on the assumed Higgs boson mass (110 to 150 GeV/c^2) [10]. They are roughly ten times larger than the standard model predictions. T. Masubuchi (Tsukuba) has performed the analysis and completed his Ph.D. thesis, and Y. Nagai (Tsukuba) has extended the search using the electrons produced in the endplug region. 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 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 limits for masses around 160 GeV/c^2 are less than twice the Standard Model values.

The results from different analyses are combined and summarized in Figure 11, where the obtained upper limits on cross sections are normalized to standard model predictions. The limits are roughly ten times larger than the predictions. Various attempts at increasing the sensitivity are vigorously pursued.

2 Detector Operations and Upgrades

2.1 Detector operations

The original upgrades to the CDF detector for Run II have been completed for a few years now. The involvement and contributions of the Japan group included :

- plug calorimeter (Tsukuba)
- silicon detectors SVX-II (Hiroshima, Okayama) and ISL (Tsukuba, Osaka City)
- data acquisition system : consumer server/logger (Tsukuba, Nagasaki), silicon vertex trigger (Tsukuba), and online monitoring (Waseda, Tsukuba)
- muon detector system (Waseda)
- time-of-flight counters (Tsukuba)
- silicon detectors for Run-IIb (Tsukuba, Okayama)
- central calorimeter preshower detector (Tsukuba)

Now that the experiment is in a stable data-taking mode, the detector activities have mostly shifted to daily operations and monitoring.

However, there are still activities for further upgrades of the detector designed for expected increase in the Tevatron luminosity. We describe them here in the following subsections.

2.2 Consumer server/logger

M. Shimojima (Nagasaki), and T. Masubuchi and H. Miyake (Tsukuba) are currently responsible for the consumer-server/logger system, which, as part of the online data acquisition system, receives events from the level-3 trigger and sends to disk and tape storage devices as well as to online monitoring programs. In the original design of the system, the data transfer rate is 20 MB/s (or 80 events per second) and it has been achieved. However, with

the continuous improvements in the accelerator luminosity, an upgrade was needed. The upgrade has been implemented in several stages, and from 2004 to 2005 a new software program was developed that allows recording of data in parallel. It has been operational already and has achieved a recording rate of 45 MB/s. In 2006 a new hardware system based on a PC farm was introduced. It has been operational since November 2006 and has achieved a rate of 60 MB/s. The old system based on SGI computers were decommissioned in 2007. Gradual improvements to the PC farm, disk storage and software would bring us to close to 100 MB/s.

2.3 Silicon vertex trigger SVT

SVT is a hardware at the second level of the trigger system and utilizes information from the silicon vertex detector (SVX-II) and selects tracks that have large impact parameters with respect to the production point, which is approximated with the position of the Tevatron beam. The device is implemented in Run II for the first time and has been operational very successfully. It has enabled CDF to collect particles originating from decays of long-lived heavy quark hadrons such as D and B mesons, and to reconstruct their decays which include only hadrons in the final state, such as $\bar{B}_s^0 \to K^+K^-$ and $\bar{B} \to D\pi$.

The device also needed a speed-up for operations under high luminosity. From 2005 to 2006, both hardware and software were upgraded, and significant improvements in the processing time have been achieved. T. Maruyama and T. Kubo (Tsukuba) are involved in the SVT work.

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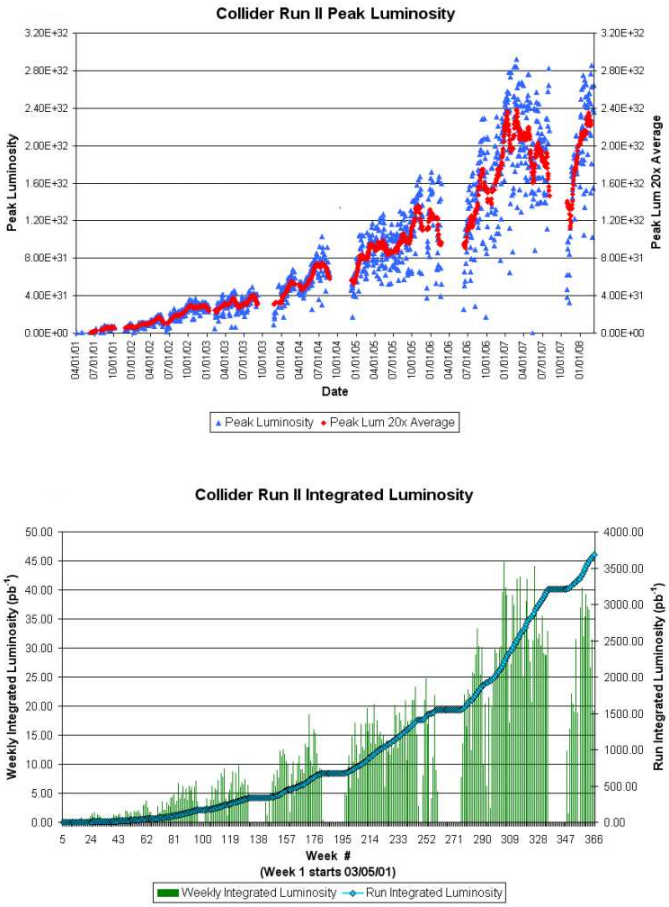

Figure 1: Tevatron performance in Run II. Top: instantaneous luminosity at the beginning of each store. Bottom: integrated luminosity delivered by week.

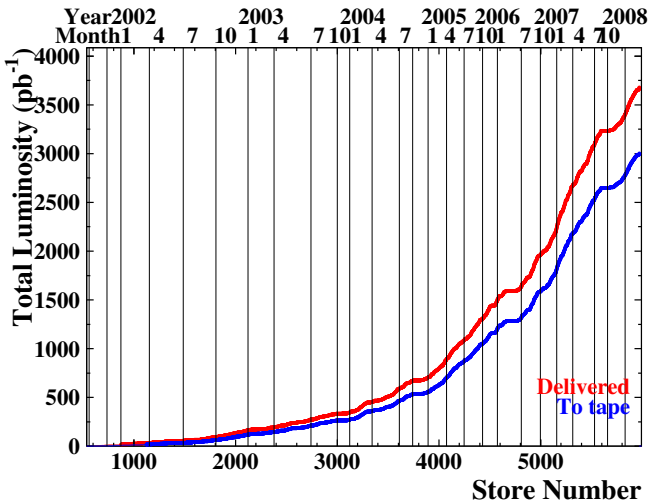

Figure 2: Integrated luminosity (top) delivered to and (bottom) recorded by CDF in Tevatron Run II.

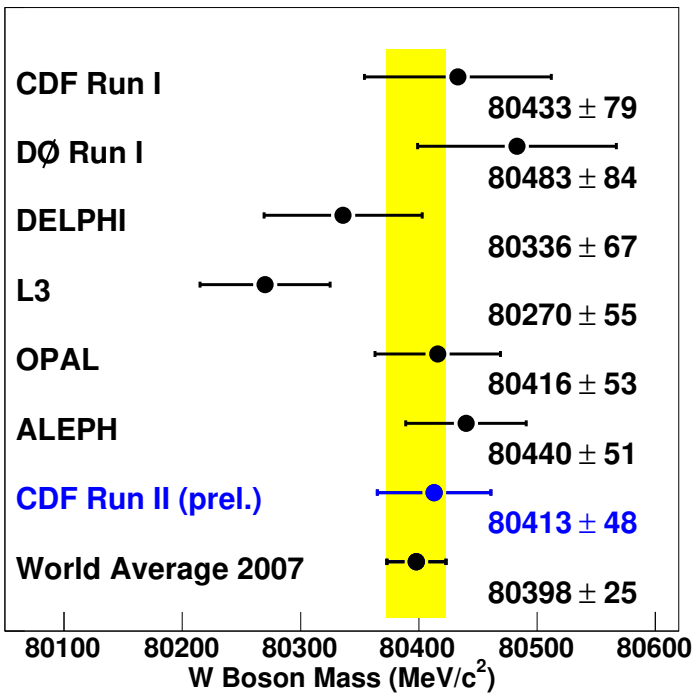

Figure 3: A summary of $W^{\pm}$ boson mass measurements.

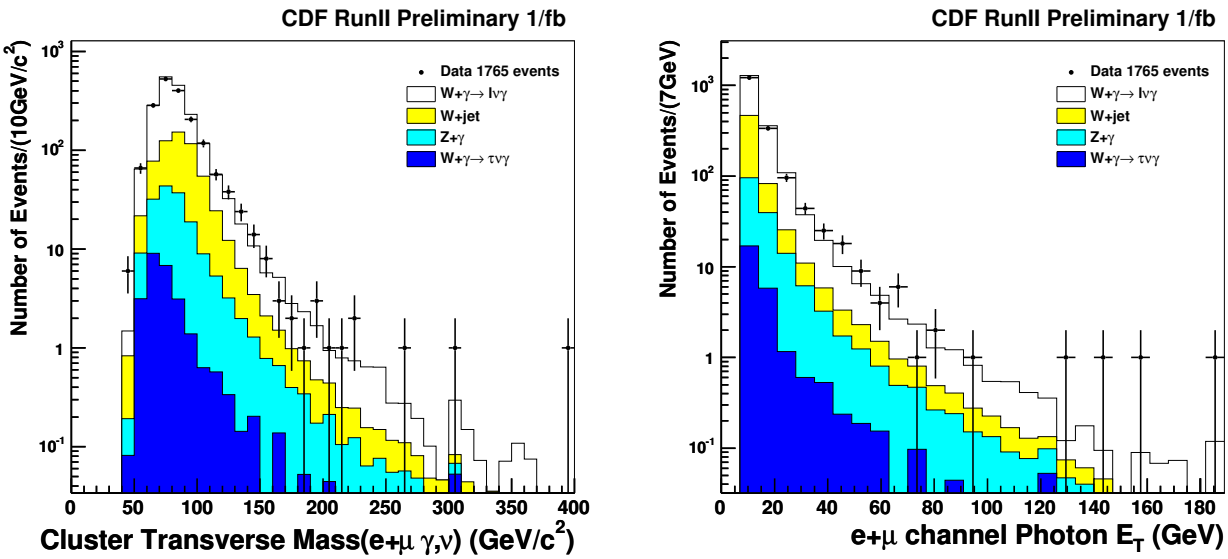

Figure 4: Transverse mass distribution of the lepton-photon-missing energy system (left), and transverse momentum distribution of photons (right), in $W\gamma$ pair production candidate events.

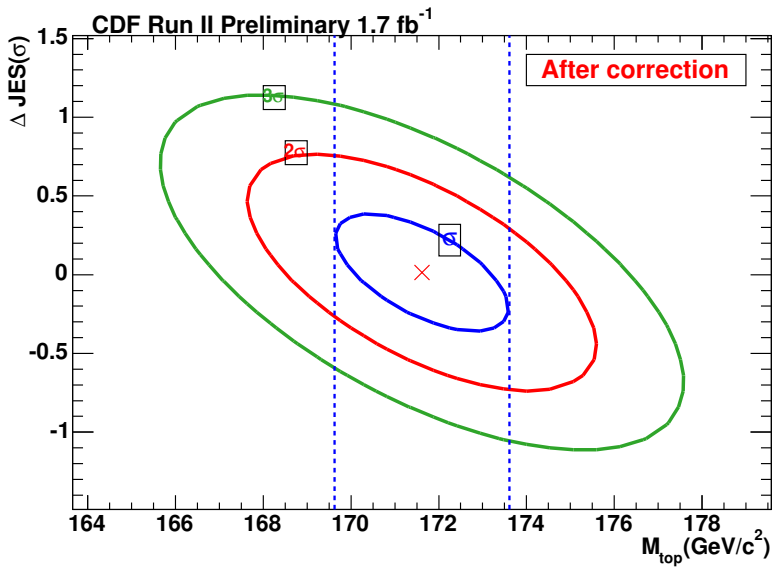

Figure 5: Top quark mass measurement from the lepton + jet channel in Run II data (1.7 fb^{-1}) with the Dynamical Likelihood Method. Two-dimensional likelihood distribution for the top quark mass and the jet energy scale.

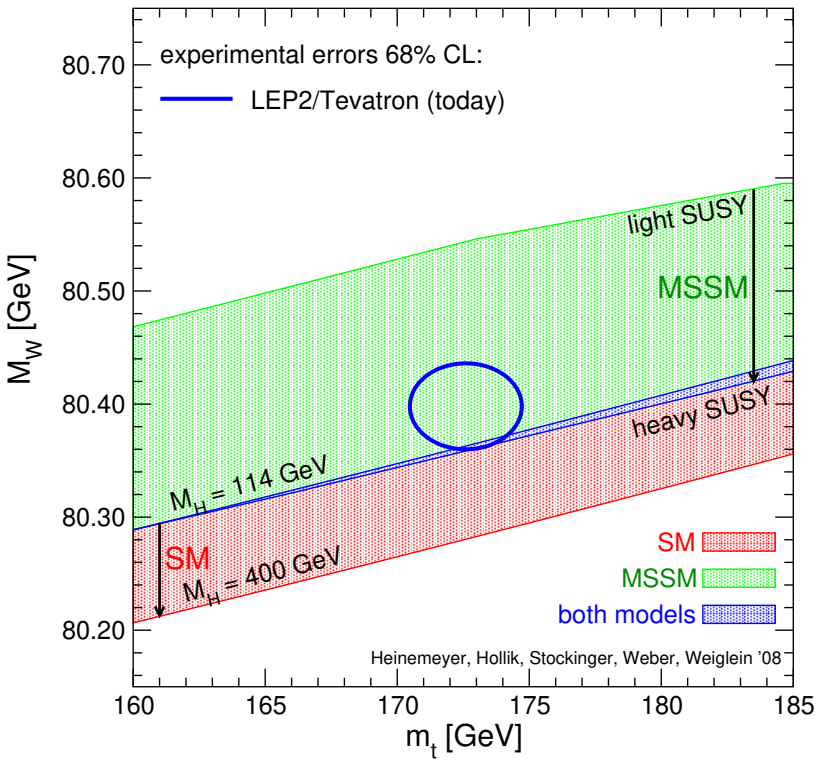

Figure 6: Measurements of the top quark and W boson masses as of winter 2008, and indirect information on the Higgs boson mass.

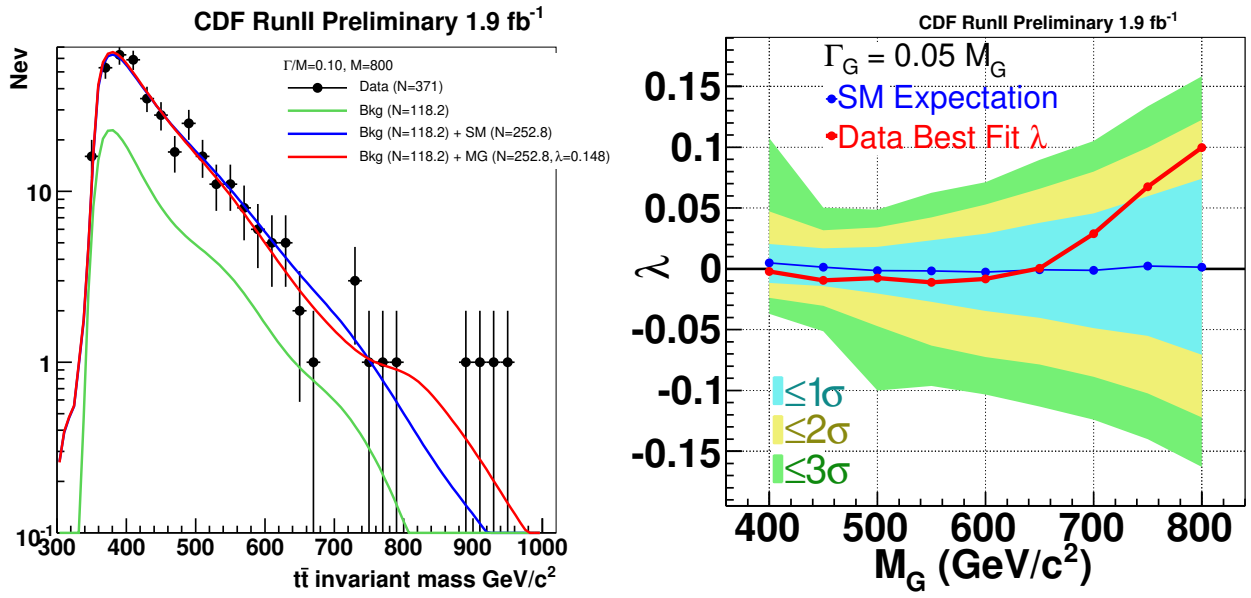

Figure 7: Search for massive gluons in $t\bar{t}$ events. Left: Invariant mass distribution of $t\bar{t}$ candidates. Right: Fit for the strength of the coupling λ to a possible massive gluon with an assumed relative width of 0.05, shown as a function of the gluon mass. The standard model corresponds to $\lambda = 0$.

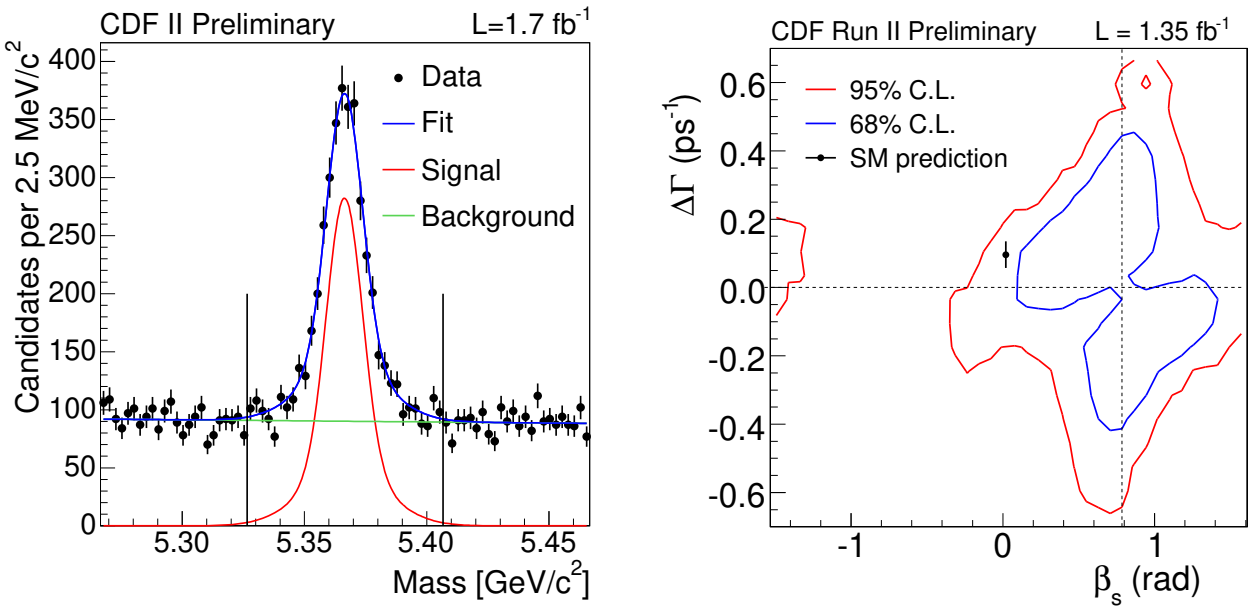

Figure 8: Search for CP violation in B_s^0-$\bar{B}_s^0$ mixing. Left: B_s^0 meson signal in $B_s^0 \to J/\psi\,\phi$ mode. Right: Constraints obtained on the CP-violating phase β_s and the width difference $\Delta\Gamma_s$, as well as the standard model prediction.

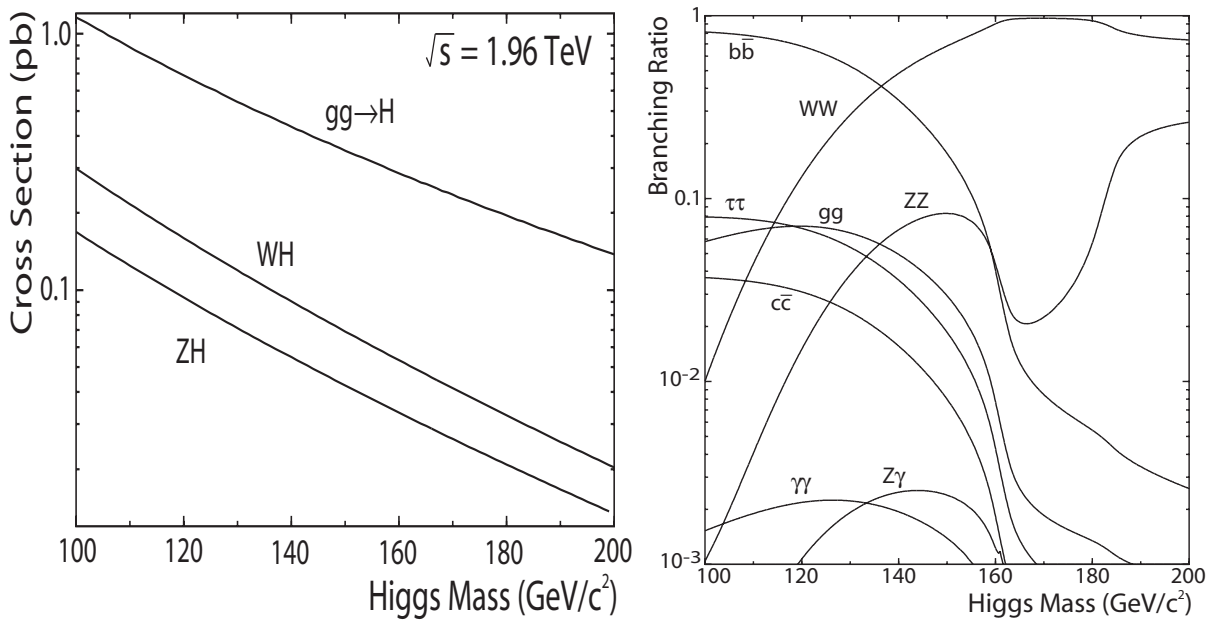

Figure 9: Left: Cross section for the production of the standard model Higgs boson at Tevatron. right: Branching fractions of the standard model Higgs boson to various final states. Both plots show dependences on the Higgs boson mass.

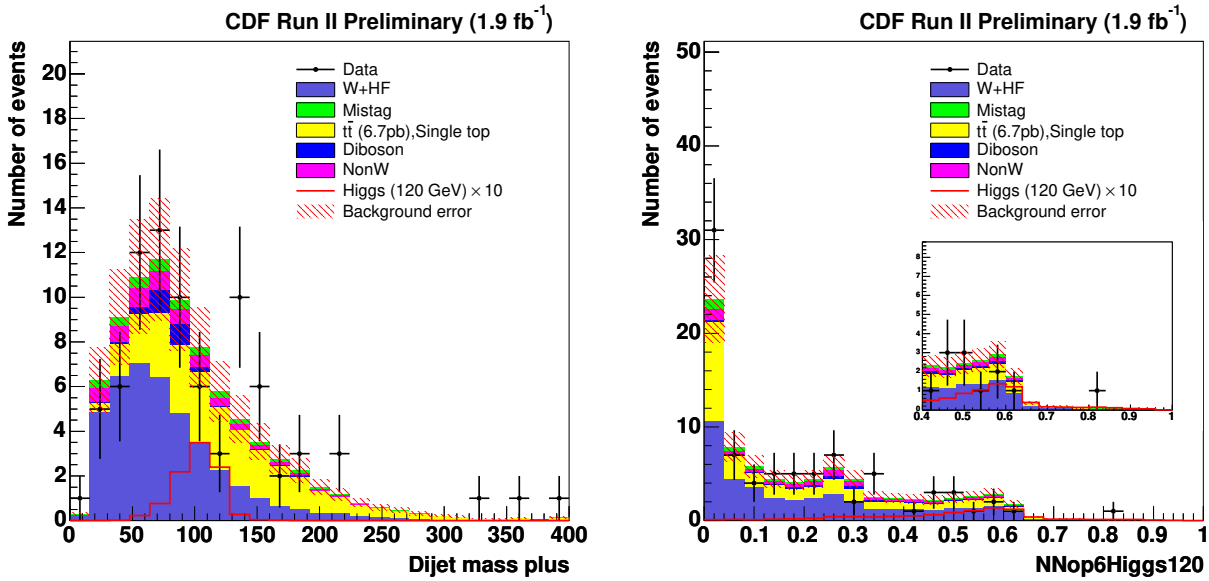

Figure 10: Higgs boson search in the $p\bar{p} \to W^{\pm}HX \to (\ell^{\pm}\nu)\,(b\bar{b})\,X$ channel. Left: Invariant mass distribution of the two b-quark candidate jets produced in association with a W boson. Right: Output of the artificial neural network discriminant.

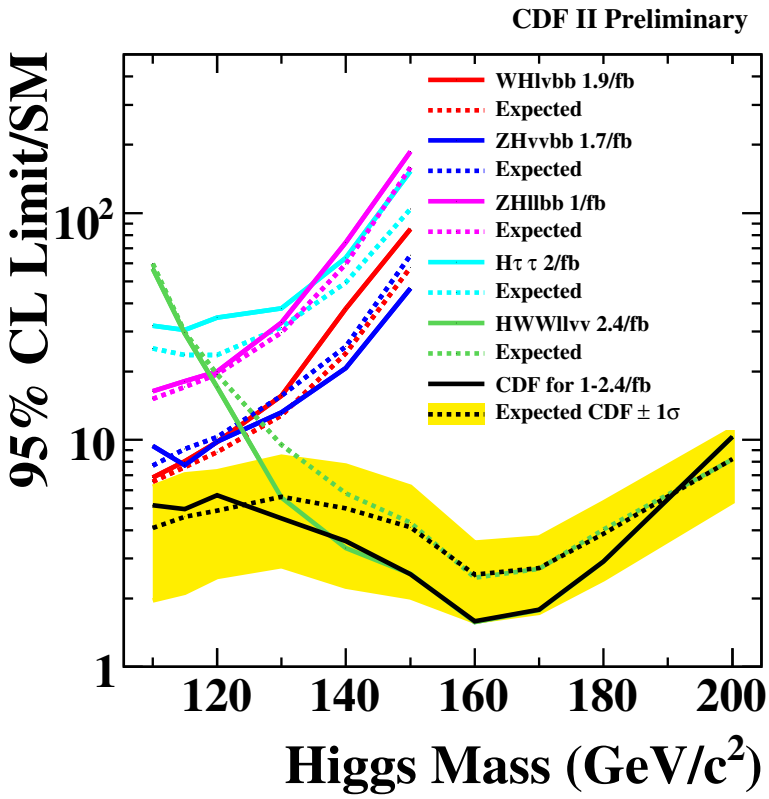

Figure 11: Summary of CDF results on the searches for the standard model Higgs boson. The experimental upper limits on production cross sections, normalized to the theoretical predictions, are shown for all search channels.