FERMILAB-CONF-08-642-E

IL NUOVO CIMENTO Vol. ?, N. ? ?

Electroweak and top physics results and direct Higgs searches at CDF

S. Leone([1]), for the CDF Collaboration

([1]) *Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, Pisa, Italy*

Summary. — We report a selection of CDF results based on Tevatron Run 2 data. The large datasets of W and Z bosons allow a very precise measurement of the W mass and detailed studies of vector boson production and asymmetries. Associated production of vector boson pairs has been observed. The top quark is being studied in great detail, and a precision of 0.8% in the measurement of its mass has been achieved. The single top production has been observed. Direct searches for the Standard Model Higgs boson are approaching the sensitivity necessary to exclude relevant mass regions.

PACS 14.70.Fm – W bosons.
PACS 14.65.Ha – Top quarks.
PACS 14.80.Bn – Standard-model Higgs bosons.

1. – Introduction

CDF is a multipurpose detector taking data at the Tevatron Collider. The Tevatron provides proton–antiproton collisions at a center-of-mass energy $\sqrt{s} = 1.96$ TeV. In 2001, after a five year period of upgrade of the accelerator and of the CDF and D0 experiments, the Tevatron Run 2 began. Accelerator performances kept improving since the start of Run 2. A peak luminosity of 3.15×10^{32} cm^{-2}s^{-1} was recently achieved, and more than 3.9 fb^{-1} of integrated luminosity has been delivered. CDF collects data with an average efficiency of about 85%. As of these proceedings, $\simeq 3.2$ fb^{-1} were written to tape. A description of the CDF upgraded detector can be found in [1].

2. – W and Z Cross Section Measurements

W and Z bosons are produced at the Tevatron through $q\bar{q}$ annihilation and are identified by their leptonic decay into electrons, muons and taus. The signature is given by high energy charged leptons and large missing transverse energy for W candidates and two oppositely charged high energy leptons for Z candidates. W and Z identification is a key ingredient for top physics and searches for processes beyond the standard model (SM). Moreover, being relatively well known processes, Ws and Zs are used for calibrations and

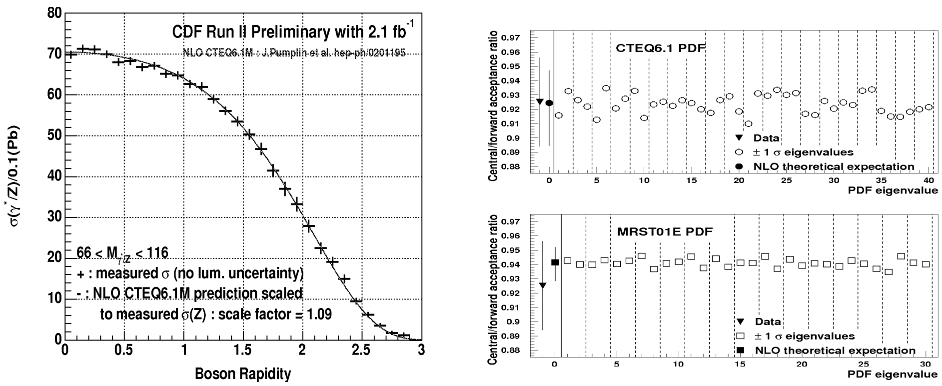

Fig. 1. – Left plot: the measured $d\sigma/dy$ (crosses) compared to theory prediction (solid line) for $Z \to e^+e^-$ events. Right plot: experimental ratio of central-to-forward W cross sections (solid triangles) compared to the CTEQ6.1 [5] (upper plot) and MRST01E [6] (lower plot) acceptance ratios (solid circles and squares). Dashed lines separate PDF eigenvectors.

detector checks. The samples of W and Z boson decays collected by CDF now number in the millions of events, and have been used to produce excellent measurements of electroweak observables. Inclusive cross sections of both W and Z production have been measured in all the three lepton decay channels [2]. All measurements are in agreement with the NNLO calculations [3]. The accuracy is limited by systematic effects (dominated by the luminosity uncertainty of $\approx 6\%$).

The large statistics allows CDF to produce a $d\sigma(Z)/dy$ measurement for $Z^0/\gamma^* \to e^+e^-$ events obtained from 2.1 fb^{-1} of data. Fig. 1-left shows the $d\sigma(Z)/dy$ distribution compared to theory prediction. The total cross section integrated over all dielectron rapidities is $\sigma(Z) = 258.2 \pm 0.7(\text{stat}) \pm 4.8(\text{syst})$ pb. This measurement, with increased statistics, can be used to constrain the parton distribution functions (PDFs).

CDF measured the ratio R of central-to-forward cross sections for $p\bar{p} \to W \to e\nu$ and obtained $R = 0.925 \pm 0.033$ [4]. The largest experimental uncertainty, due to luminosity, cancels in this ratio. The measurement can be compared to theoretical predictions obtained using different PDFs (see fig. 1-right). This quantity is sensitive to the W rapidity distribution, and provides a novel way to constrain the PDFs.

3. – W Mass Measurement

The W mass (M_W) is measured in the $e\nu$ and $\mu\nu$ channels from a maximum likelihood fit to the lepton transverse momentum p_T and the transverse mass spectrum M_T, defined as: $M_T = \sqrt{2p_T^\ell p_T^\nu(1-\cos\Delta\phi)}$, where $\Delta\phi$ is the difference in azimuthal angle between the two leptons. There are two main components leading to a precise M_W measurement: calibration of the detector to the highest possible precision and simulation of the p_T (M_T) spectrum. CDF measured the W mass using a sample of 200 pb^{-1} of electron and muon data, with the result: $M_W = 80413 \pm 34$ (stat) $\pm$ 34 (syst) MeV/c^2 = 80413 $\pm$ 48 MeV/c^2 [7]. This is the most precise single measurement of the W mass to date. The updated world average is $M_W = 80398 \pm 25$ MeV/c^2 [7, 8]. The dominant uncertainties are due to the W boson statistics and to the lepton energy scale calibration. They will be

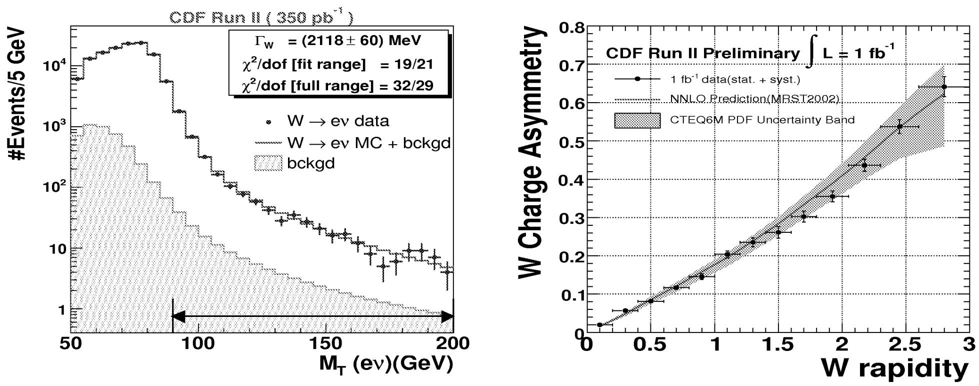

Fig. 2. – Left: the M_T fit for Γ_W in $W \to e\nu$ events. The fit is performed in the region 90–200 GeV. Right: Measured $A(|y_W|)$ compared to an NNLO prediction using MRST2002 PDF. The band illustrates the range of uncertainty on the CTEQ PDF prediction.

reduced with more data in the W boson and calibration samples. Since many simulation parameters are constrained by data control samples, their uncertainties are expected to be reduced with more data as well. By the end of Run 2 the Tevatron experiments should be able to reduce the uncertainty on M_W below 20 MeV/c^2.

4. – Direct W Width Measurement

CDF measured directly the W boson width Γ_W using the high tail of the M_T distribution. The width is determined by normalizing the predicted signal and background M_T distribution in the region of $50 < M_T < 90$ GeV/c^2 and then fitting the shape of the candidate events in the tail region $90 < M_T < 200$ GeV/c^2 which is most sensitive to the width. CDF has the most precise measurement of this quantity, based on 350 pb^{-1} of data: $\Gamma_W = 2032 \pm 73$ MeV/c^2, in good agreement with SM predictions [9]. Fig. 2-left shows the M_T distribution in the electron channel used for the Γ_W measurement. The updated world average is: $\Gamma_W = 2106 \pm 50$ MeV/c^2 [9].

5. – W Charge Asymmetry

W bosons at the Tevatron are primarily produced by annihilation of valence u (d) and $\bar{d}$ ($\bar{u}$) quarks to $W^+(W^-)$. Since u quarks carry, on average, a higher fraction of the proton momentum than d quarks, a W^+ (W^-) tends to be boosted in the (anti-)proton direction. This results in a charge asymmetry defined as: $A_{y_W} = \frac{d\sigma(W^+)/dy_W - d\sigma(W^-)/dy_W}{d\sigma(W^+)/dy_W + d\sigma(W^-)/dy_W}$, where y_W is the W rapidity and $d\sigma(W^\pm)/dy_W$ is the differential cross section for $W^\pm$ production. A measurement of the charge asymmetry is sensitive to the ratio of u and d quark components of the PDFs. However, since the longitudinal component of the neutrino momentum is not measured, the measured asymmetry has been traditionally: $A(\eta_e) = \frac{d\sigma(e^+)/d\eta_e - d\sigma(e^-)/d\eta_e}{d\sigma(e^+)/d\eta_e + d\sigma(e^-)/d\eta_e}$, where η_e is the electron pseudorapidity [10]. CDF has recently implemented a new analysis method that directly reconstructs y_W from $W \to e\nu$ events, using 1 fb^{-1} of data. The ambiguity due to the longitudinal neutrino component can be partly resolved on a statistical basis from the known $V-A$ decay distribution and

$d\sigma(W^{\pm})/dy_W$. Fig. 2-right shows the measured asymmetry as a function of y_W compared to an NNLO prediction [3] using MRST2002 PDF [6] and to the band obtained from the CTEQ6M error PDF [5], described by 20 parameters.

6. – Diboson Production

The SM implies that the electroweak gauge bosons W and Z can interact with one another through trilinear and quartic gauge boson vertices. Study of events containing pairs of vector bosons provides a sensitive test of the SM since physics beyond the SM could alter the cross sections and the production kinematics. In addition, diboson production represents a test bed for search and detection of the Higgs boson.

All associated production processes involving pairs of W, Z and γ bosons have been detected, with cross sections in excellent agreement with SM predictions [11] [12].

6·1. *WZ Production.* – At $\sqrt{s}$ = 1.96 TeV, the SM predicts $\sigma(WZ)$= 3.7 ± 0.25 pb [13]. In winter 2007 CDF presented the observation of the WZ process based on 1.1 fb^{-1} of data [14]. In this analysis a significant improvement was obtained by exploiting all the available detector information in defining leptons, therefore increasing the lepton acceptance. Recently CDF measurement was updated on 1.9 fb^{-1} of data. The measured cross section is $\sigma(WZ) = 4.3\ ^{+1.4}_{-1.1}$ pb.

6·2. *ZZ Production.* – The ZZ production cross section predicted by the SM at the Tevatron is $\sigma(ZZ)$ = 1.4±0.1 pb at NLO. CDF combined the final states with 4 charged leptons and 2 charged leptons plus 2 neutrinos, and did a measurement of the ZZ production cross section $\sigma(ZZ) = 1.4\ ^{+0.7}_{-0.6}$ pb, based on 1.9 fb^{-1} of data. The observed signal has a significance of 4.4σ [15]. This is the smallest cross section measured at the Tevatron.

7. – Top Quark Physics

The first evidence for the top quark was obtained by CDF in 1994 [16] and confirmed one year later by both Tevatron experiments [17].

At the Tevatron energy top quarks are produced primarily in $t\bar{t}$ pairs via the strong process $p\bar{p} \to t\bar{t}$. In the SM each top quark decays through charged current weak interaction almost exclusively into a real W and a b quark ($t \to Wb$). Each W subsequently decays into either a charged lepton and a neutrino or two quarks. The $t\bar{t} \to W^+bW^-\bar{b}$ events can thus be identified by means of different combinations of energetic leptons and jets. When both W's from a $t\bar{t}$ pair decay leptonically we have the *dilepton channels*. Decay modes of $t\bar{t}$ pairs in which one W decays hadronically and the other leptonically into an e or a μ define the *single lepton + jets channel*. When both W's decay hadronically we have the *all hadronic channel*.

By measuring the $t\bar{t}$ production cross section $\sigma_{t\bar{t}}$ in many channels and comparing it to perturbative QCD calculations, we can test the SM predictions in great detail. The experimental uncertainty on the top quark pair production cross section has become comparable to the theoretical one (≈ 12 %) [18]. Fig. 3-left shows a summary of the top pair cross section measurements in the various channels at CDF. All the measurements are consistent with each other and with the theoretical expectations, which are indicated by the vertical band.

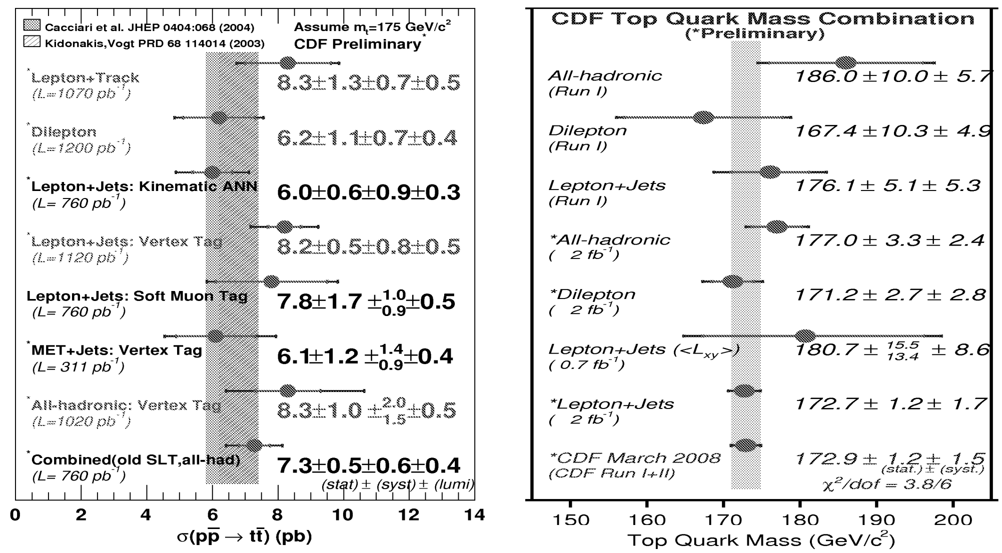

Fig. 3. – Left: compilation of CDF $t\bar{t}$ production cross section measurements assuming $M_{top} = 175$ GeV/c^2. Right: compilation of the most recent CDF top quark mass measurements and last Tevatron combined result.

8. – Top Mass Measurement

The top quark mass M_{top} is a fundamental parameter of the SM. Precise measurements of the top quark and W boson masses constraint the mass of the Higgs boson.

The reconstruction of the top quark mass presents several experimental challenges. The neutrinos from leptonically decaying W's escape the detector. The quarks hadronize and form jets of particles whose energy must be corrected back to the parton level (the precision of the jet energy scale is crucial in this respect). The assignment of jets to partons usually has many possible permutations. Finally, there are background processes which mimic $t\bar{t}$ events.

CDF performed many determinations of M_{top}, using different techniques and all the top decay final states. In the single lepton + jets and all hadronic channels the uncertainty from jet energy scale (JES) can be reduced by using the reconstructed invariant dijet mass of the hadronically decaying W boson in top candidate events as an internal constraint. This method converts the dominant systematic uncertainty into a statistical uncertainty, which will improve with more data.

Fig. 3-right summarizes the most recent CDF M_{top} measurements. The combined CDF top mass is: $M_{top} = 172.9 \pm 1.2$ (stat.) $\pm$ 1.5 (syst) GeV/c^2. CDF and D0 provided a new combined Tevatron top mass $M_{top} = 172.6 \pm 0.8$ (stat) $\pm$ 1.1 (syst) GeV/c^2 = 172.6 $\pm$ 1.4 GeV/c^2, using up to 2 fb^{-1} of data [19].

The top quark mass is known with a precision that was thought to be unreachable at the Tevatron only a few years ago: $\Delta M_{top}/M_{top} \approx 0.8\%$. Therefore, both experiments are now addressing a number of effects that, too small to have an impact on the previous measurements, could now become important. At the same time, they are figuring out which theoretical aspects are relevant, at the 1 GeV/c^2 level, and whether they are sufficiently well under control. Before the end of Run 2 the Tevatron experiments are likely to reach a 1 GeV/c^2 experimental precision on the top quark mass.

9. – Evidence for Single Top Production

The single top production mechanism involves electroweak production of a top quark via the Wtb vertex (t and s channel exchange of a virtual W boson). The experimental signature consists of the W decay products plus two or three jets, including one b quark jet from the decay of the top quark. In s-channel events a second b quark jet comes from the Wtb vertex. In t-channel events a second jet originates from the recoiling light-quark and a third low-E_T jet is produced at larger η through the splitting of the initial state gluon into a $b\bar{b}$ pair.

The production cross section is predicted to be 0.88 and 1.98 pb in the s and t channels respectively [20] for $M_{top} = 175$ GeV/c^2, about half than the pair production and with a much larger background. On the other hand, this mechanism allows a direct access to the V_{tb} CKM matrix element, and can be used to test the $V - A$ structure of the top charged current interaction.

In order to extract the single top signal from the background dominated dataset, both Tevatron experiments use various multivariate techniques. D0 presented the first evidence of single top quark production using 0.9 fb^{-1} of data [21]. CDF confirmed the evidence for single top production in 1.5 fb^{-1} of data. There are currently three separate CDF searches for single top production: an analysis using neural networks, an analysis using a multivariate likelihood function technique, and an analysis using matrix element discriminants. The combination uses neural networks taking the discriminant outputs from these three techniques as inputs to form a single, more powerful discriminant. A combined single top s- and t-channel cross section of 2.2$\pm$ 0.7 pb has been measured, using 2.2 fb^{-1} of data. The observed signal has a significance of 3.7σ. From the cross section measurement we extract a value for $V_{tb} = 0.88 \pm 0.14$ (exp.) $\pm$ 0.07 (theory).

10. – Direct searches for the Higgs boson

The search for a mechanism for electroweak symmetry breaking, and in particular for a SM Higgs boson has been a major goal of High Energy Physics for many years, and is a central part of Fermilab's Tevatron program. The Higgs boson is the last remaining SM particle to be observed, and the one responsible for generating the W and Z boson masses. Direct searches at LEP experiments have excluded a Higgs boson with mass less than 114.4 GeV/c^2 at 95% C.L. in the production mode $e^+e^- \rightarrow ZH$ [22]. The mass of the W is related to the top quark and Higgs masses through radiative effects. Since the Higgs mass is unknown, experimental measurements of the top and W boson masses provide the strongest indirect constraints on the Higgs mass. Based on global fits to electroweak observables in the SM framework, the preferred value for the Higgs mass is $M_H = 87^{+36}_{-27}$ GeV/c^2, with an upper limit of 160 GeV/c^2 at 95% C.L. which becomes 190 GeV/c^2 if one takes into account the LEP 2 direct limit [8].

Fig. 4-left shows the dominant SM Higgs production mechanisms at the Tevatron energy, while 4-right shows the branching ratios, as a function of the Higgs mass. Gluon fusion $gg \rightarrow H$ is the dominant production mechanism. For low Higgs masses (< 140 GeV/c^2), the highest branching ratio corresponds to $H \rightarrow b\bar{b}$. For higher masses, the $H \rightarrow WW$ decay becomes dominant.

CDF searched for the SM Higgs boson production looking for associate WH and ZH production at low mass (with W and Z decaying leptonically), and $H \rightarrow WW$ at

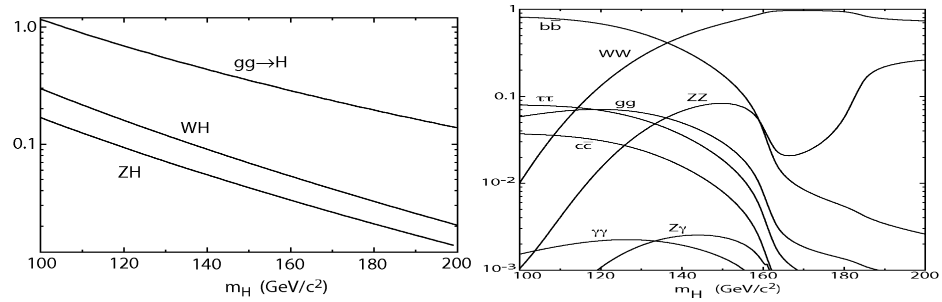

Fig. 4. – SM Higgs production cross section (left) and branching ratios (right) as a function of M_H at the Tevatron energy.

higher mass. Since the Higgs signal is 2 to 3 orders of magnitude below the backgrounds, optimal detector performance and analysis technique are crucial. Recently a combination of several searches for SM Higgs production has been performed, using data samples ranging from 1 to 2.4 fb^{-1} of integrated luminosity. We have calculated combined upper limits on the ratio of Higgs boson cross section times the branching ratio to its SM prediction, for M_H between 110 and 200 GeV/c^2. The 95% C.L. upper limits observed (expected) are factors of 5.0 (4.5) and 1.6 (2.6) higher than the SM production cross sections for M_H of 115 and 160 GeV/c^2, respectively (see fig. 5-left). Combining CDF and D0 results, the observed (expected) 95% C.L. upper limits on Higgs boson production are a factor of 5.1 (3.3) higher than the SM cross section for a Higgs boson mass of M_H =115 GeV/c^2 and a factor of 1.1 (1.6) higher for M_H =160 GeV/c^2 (see fig. 5-right). These results represent about a 40% improvement in expected sensitivity over those obtained on the combinations of results of each single experiment.

11. – Conclusions

The Run 2 of the Tevatron is being very successful. Tevatron experiments have in their hands a gold mine of more than 3 fb^{-1} of data. Both CDF and D0 are producing interesting results in the electroweak sector, bringing SM tests to a level of precision which meets or exceed that of electron-positron colliders. The top quark mass is known with a 0.8% precision, the W boson mass with a 0.04% precision. CDF will continue to collect data (6-8 fb^{-1} are expected by the end of Run 2) and to improve the precision on top and W masses over the next few years. The search for a SM Higgs boson is well underway. Cross section limits are scaling much better than by just a luminosity factor. The evidence for the Higgs boson at the Tevatron (or at least the exclusion of relevant mass regions) is becoming a real possibility.

REFERENCES

[1] T. Lecompte and H.T. Diehl, Ann. Rev. Nucl. Part. Sci. 50 (2000) 71.
[2] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **94**, (2005) 091803; A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. D **75**, (2007) 092004; A. Abulencia *et al.* (CDF Collaboration), J. Phys. G.: Nucl. Part. Phys. **34**, (2007) 2457.

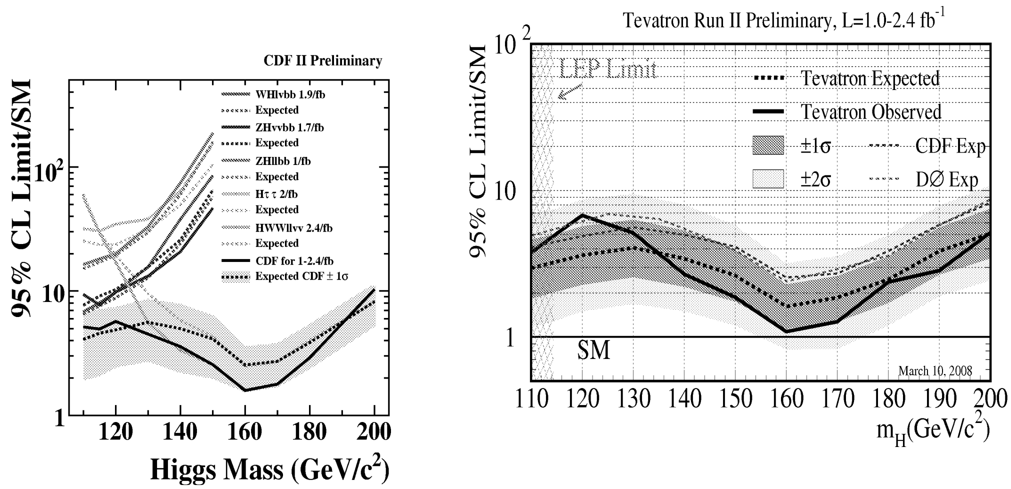

Fig. 5. – Left: CDF 95% C.L. upper limit on the ratios to the SM cross section, as a function of M_H. Solid (dashed) lines mean observed (expected) upper limit for each channel separately and combined result. Right: CDF and D0 combined 95% C.L. upper limits. The bands indicate the 68% and 95% probability regions where the limits can fluctuate, in the absence of signal.

[3] C. Anastasiou *et al.*, Phys. Rev. D **69**, (2004) 094008.
[4] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. Lett. **98**, (2007) 251801.
[5] J. Pumplin *et al.*, J. High Energy Phys. 07 (2002) 012.
[6] A. D. Martin *et al.*, Eur. Phys. J. C **28**, (2003) 455.
[7] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **99**, (2007) 151801; T. Aaltonen *et al.* (CDF Collaboration), arXiv:0708.3642v1 (2007), submitted to Phys. Rev. D.
[8] The LEP Electroweak Working Group, http://lepewwg.web.cern.ch/LEPEWWG/
[9] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **100**, (2008) 071801.
[10] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, (2005) 061104.
[11] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **94**, (2005) 211801.
[12] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **94**, (2005) 041803.
[13] J.M. Campbell and R.K. Ellis, Phys. Rev. D **60**, (1999) 113006.
[14] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. Lett. **98**, (2007) 161801.
[15] T. Aaltonen *et al.* (CDF Collaboration) arXiv:0801.4806, (2008), submitted to Phys. Rev. Lett..
[16] F. Abe *et al.* (CDF Collaboration), Phys. Rev. D **50**, (1994) 2966.
[17] F. Abe *et al.* (CDF Collaboration), Phys. Rev. Lett. **74**, (1995) 2626; S. Abachi *et al.* (D0 Collaboration), Phys. Rev. Lett. **74**, (1995) 2632.
[18] N. Kidonakis and R. Vogt, Phys. Rev. D **68** (2003) 114014; M. Cacciari *et al.*, JHEP **0404**, (2004) 068; N. Kidonakis, Int. J. Mod. Phys. A **19**, (2004) 1793.
[19] Tevatron electroweak working group, for the CDF and D0 Collaborations, arXiv:0803.1683 (2008).
[20] B. W. Harris *et al.*, Phys. Rev. D **66**, (2002) 054024; Z. Sullivan, Phys. Rev. D **70**, (2004) 114012; J. Campbell, R. K. Ellis, F. Tramontano, Phys. Rev. D **70**, (2004) 094012; N. Kidonakis, Phys. Rev. D **74**, (2006) 114012.
[21] V.M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **98**, (2007) 181802.
[22] R. Barate *et al.*, Phys. Lett. B **565**, (2003) 61.