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Search for the low mass Higgs boson at the Tevatron

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Summary. — We present the recent results on the search for the low mass Higgs boson at the Tevatron by the CDF and DØ Collaborations. With up to 5.9 fb^{-1} of data analyzed at CDF and up to 6.7 fb^{-1} at DØ, the 95% C.L. upper limits on Higgs boson production are factors of 1.56 times the values of the standard model cross section for a Higgs boson mass of $m_H = 115\,\mathrm{GeV}/c^2$.

PACS 14.80.Bn – Standard-model Higgs bosons.

1. – Introduction

The Higgs boson is the last unobserved particle postulated in the standard model, and could help explain the origin of mass in the universe. A longstanding key objective in observing the Higgs boson is to probe the mechanism of electroweak symmetry breaking. The direct search from LEP and global fit of precision electroweak data constrain the Higgs mass between 114.4 GeV/c^2 and 186 GeV/c^2 at 95% C.L., which therefore places the SM Higgs boson within the Tevatron's reach. With a full dataset and improved analysis the Tevatron could add crucial information about $H \to b\bar{b}$, which is more difficult to detect at LHC. Not seeing a low mass Higgs guarantees that there might be new physics waiting to be found at LHC. Of course, it would be exciting if we started to see something soon. We need to measure as many of its properties as possible since any new physics may influence the Higgs boson's production and decays.

The Tevatron is doing very well and has delivered more than 10 fb^{-1} data, with the record luminosity exceeding $4.1 \times 10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Additional 2 fb^{-1} data is expected by the end of FY2011, which gives a final dataset close to 12 fb^{-1}. In this report, we present the recent results from the direct searches for the low mass SM Higgs boson at the Tevatron [1]. Most results presented are based on 6 fb^{-1} data and major improvements in the low mass searches are expected to be completed in the summer of 2011.

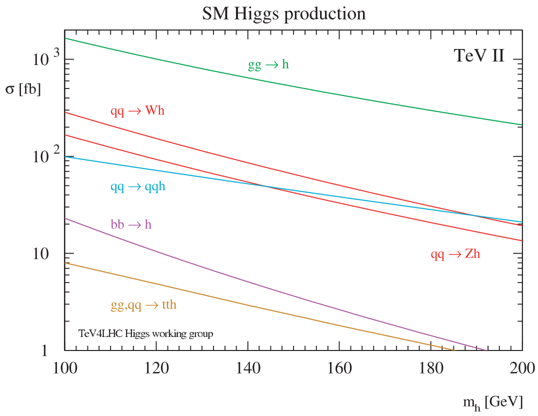

Fig. 1. – SM Higgs production cross sections for $p\bar{p}$ collisions at the Tevatron as a function of the Higgs boson mass.

2. – Search strategies and analysis techniques

The dominant Higgs production processes from $p\bar{p}$ collisions at the Tevatron are gluon-gluon fusion and associated production with either a W or Z boson. The cross sections for the production of SM Higgs bosons are summarized in fig. 1, and the branching fractions for the most relevant decay modes of the SM Higgs boson are shown in fig. 2 as a function of the Higgs boson mass between 100 and 200 GeV/c^2. For Higgs masses above 135 GeV/c^2, the Higgs boson will decay predominantly into WW^* which will be covered elsewhere [2]. For Higgs masses below 135 GeV/c^2, the Higgs boson predominantly decays into $b\bar{b}$, which makes the associated production with W and Z semileptonic decay most assessible at the Tevatron while the direct production $gg \to H \to b\bar{b}$ is limited by the multi-jet QCD background. The detection of $H \to b\bar{b}$ is difficult at LHC due to a large $t\bar{t}$ background and it needs to rely on $H \to \gamma\gamma$ instead [3].

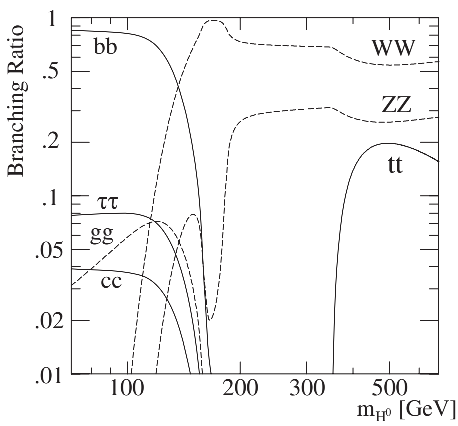

Fig. 2. – Branching factions for the main decay of the SM Higgs boson as a function of the Higgs boson mass.

For the low mass Higgs boson signatures we look for a dijet mass resonance from the Higgs boson decay associated with the W or Z boson, where the W decays into $l\nu$ and $Z \to \nu\bar{\nu}, l^+l^-$, which gives final states of either $l\nu b\bar{b}$, $\nu\bar{\nu}b\bar{b}$, or $l^+l^-b\bar{b}$. Just to set the scale on how rare these processes are, we would expect 30 $WH \to l\nu b\bar{b}$ events, 15 $ZH \to \nu\bar{\nu}b\bar{b}$ events, 5 $ZH \to l^+l^-b\bar{b}$ events, respectively, per fb^{-1} per experiment for Higgs mass at 115 GeV before any detector acceptances. At the same time, the backgrounds are $W +$ jets, $t\bar{t}$, single top, and diboson, and are copiously produced at a rate many orders of magnitude greater. The challenge is to separate the small signal from the huge background using multivariate analysis techniques. Recent observations of single top [4, 5] and diboson [6, 7] provide solid evidence that these advanced tools do work.

The strategies we employed for the low mass Higgs search are quite similar for the corresponding CDF and DØ analyses. The primary gains in recent years are mainly from improved signal acceptance, more triggers, loose lepton identification, better b-tagging, improved dijet mass resolution, and advanced analysis techniques, which we will go over in some detail. These are essential for the low mass Higgs searches.

The first thing we can do to improve the acceptance is to improve lepton identification and corresponding triggers. For example, selecting high-P_T leptons with multivariate lepton identification could gain 20% more Z's than a simple cut-based selection. We also gain lepton acceptance by including the loose muon as an isolated track from $\not{E}_T +$ jets triggers.

Identifying b-quark jets is another way to reduce backgrounds that do not contain heavy flavor content. The typical b-tag efficiency is between 50 and 70% for the b-jets, with the mistag rate ranging between 1 and 6% for the light flavor jets. Requiring b-tagging for both jets would significantly reduce the background from both charm and mistags in the $W +$ jets.

We can also improve the dijet mass by combining the calorimeter and tracking information with a neural network [8]. The new b-jet neural network correction improves the dijet mass resolution from 15% to 11% for the mass ranges we are interested in.

Finally, we could be more aggressive by employing advanced multivariate techniques to suppress the background since we know exactly what we are looking for. For example, the leading order matrix element (ME) is used to calculate event probabilities based on a set of observed inputs and likelihood ratios with respect to other backgrounds. Alternatively, these inputs could be fed into an artificial neural network (NN) or boosted decision tree (BDT) to find a discriminant variable. A typical improvement of using the advanced multivariate techniques is about 25% with respect to using a single variable, such as dijet mass.

3. – Highlights of the low mass searches

We will describe the searches performed by the CDF and DØ Collaborations for the low mass Higgs boson in some detail.

3˙1. *Search for* $WH \to l\nu b\bar{b}$. – One of the gold channels for the low mass Higgs boson search is the Higgs production association with a W boson, where the W decays semileptonically and the Higgs boson decays into $b\bar{b}$ [9, 10]. We select events with one isolated high P_T lepton (electron, muon, or isolated track), and two jets, with one or more b-tagged jets, identified as containing a weakly decaying B hadron. Selected events must also have a significant imbalance in transverse momentum as missing transverse

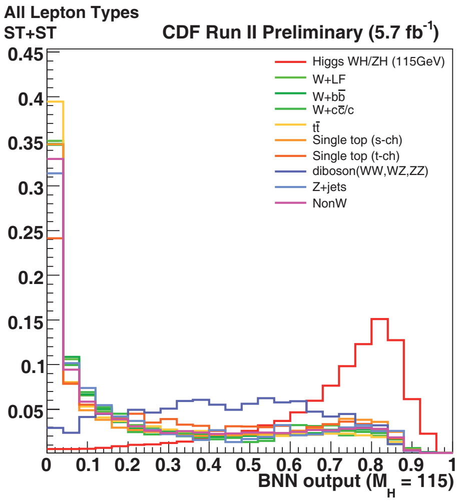

Fig. 3. – The Bayesian Neural Network Output is shown from the CDF $WH \to l\nu b\bar{b}$ analysis.

energy or $\not{E}_T$. Events with more than one isolated lepton are vetoed. For multivariate discriminants, CDF and DØ use slightly different multivariate techniques. CDF trained a Bayesian neural network discriminant (BNN) at each Higgs mass in $W+2$jets, separately for each lepton and b-tagging category, while for the three jet sample a ME discriminant is used. DØ trained the Random Forest Decision (RFD) discriminant separately for both $W + 2$ and 3 jets for each Higgs mass.

Figure 3 shows the BNN output in double tight tagged $W+2$jet at CDF and fig. 4 shows the RFD output in double tagged $W + 2$jets from DØ. Both data are consistent with the background expectations. The expected Higgs signals are also shown, but rescaled by a large factor.

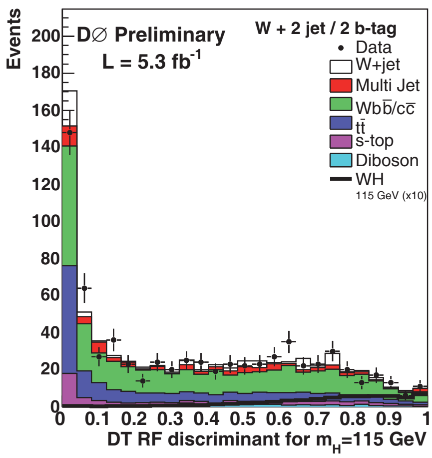

Fig. 4. – The boosted decision tree discriminant distribution is shown from the DØ $WH \to l\nu b\bar{b}$ analysis.

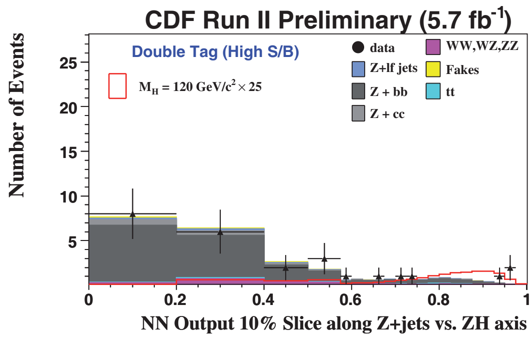

Fig. 5. – The Neural Network Output is shown from the CDF $ZH \to l^+l^-b\bar{b}$ analysis.

Since there is no excess of signal observed in the data, we can set an upper limit at 95% C.L. on the Higgs production cross section times branching ratio with respect to the SM predictions as a function of Higgs mass. For $m_H = 115\,\text{GeV}/c^2$, CDF set an observed (expected) limit at 3.3 (3.1) $\times$ SM while DØ set a limit at 4.1 (4.8) $\times$ SM. We are not yet competitive for a single channel, and we need to combine all other channels and both CDF and DØ results together.

3$\cdot$2. *Search for* $ZH \to l^+l^-b\bar{b}$. – Another interesting channel to pursue in the search for the Higgs boson is the Higgs production associated with a Z boson, where the Z boson decays into a charged lepton pair and the Higgs boson decays into $b\bar{b}$ [11,12]. This channel has a low event yield due to a small branching fraction of $Z \to e^+e^-$, $\mu^+\mu^-$, but it provides a clean signature. We select two high P_T leptons from $Z+$ 2jet. DØ's $ZH \to l^+l^-b\bar{b}$ analyses separate events into non-overlapping samples of events with one and two b-tags. CDF separates events into single tag, double tag, and loose double tag samples. To increase signal acceptance DØ has loosened the selection criteria for one of the leptons to include either an isolated track not reconstructed in the muon detector or an electron from the inter-cryostat region. CDF has added additional sub-channels for candidate events with two loose muon candidates selected using a neural network discriminant. For the DØ analysis the random forests of decision trees provide the final variables for setting limits, while CDF utilizes outputs of two-dimensional neural networks. These networks incorporate likelihoods based on event probabilities, which are obtained from ME calculations as additional inputs.

Figure 5 shows the NN output 10% slice along Z+jets *vs.* ZH in double tags from CDF. Figure 6 shows the RFD output in double tags from DØ. Again, the data agree quite well with the background expectation. CDF has a few candidates that are very Higgs-like, but it is not statistically significant yet. CDF is able to set an observed limit at 95% C.L. at $6.5 \times$ SM while at $8.0 \times$ SM for DØ with comparable expected sensitivity to $6 \times$ SM for $m_H = 115\,\text{GeV}/c^2$.

3$\cdot$3. *Search for* $VH \to \nu\bar{\nu}b\bar{b}$. – We also have looked for the Higgs boson in the ZH channel where the Z decays into two neutrinos, or WH where the lepton from the W decay is undetected [13, 14]. The channel has a large signal rate, and it has a large QCD multijet background as well. However, the final state is relatively clean, containing two b-jets and large $\not{E}_T$. We require $\not{E}_T > 50\,\text{GeV}$ and two b-tagged jets. Both CDF and DØ analyses use a track-based missing transverse momentum calculation as

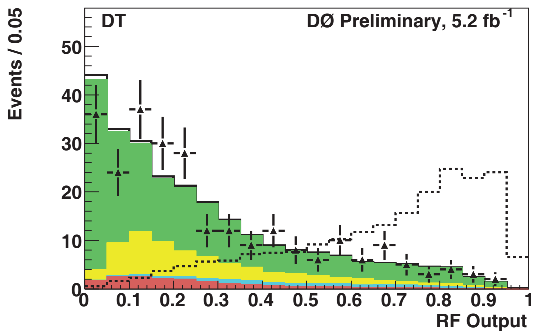

Fig. 6. – The boosted decision tree discriminant distribution is shown from the DØ $ZH \to l^+l^-b\bar{b}$ analysis.

a discriminant against false $\not{E}_T$. In addition both CDF and DØ utilize multivariate techniques, a boosted decision tree at DØ and a neural network at CDF, to further discriminate against the multi-jet background. Figure 7 shows the boosted decision tree discriminant distribution used by DØ for rejecting multi-jet QCD backgrounds before b-tagging.

The final discriminant is obtained by combining dijet mass, track $\not{E}_T$ and other kinematic variables, shown in fig. 8. Again there is no Higgs signal observed. CDF set an observed limit at 95% C.L. at $2.3 \times$ SM, compared to $4.0 \times$ SM expected. D0 set an observed limit at $3.4 \times$ SM with $4.2 \times$ SM expected for Higgs mass at $115\,\text{GeV}/c^2$.

3·4. *Other searches.* – Due to time constraints, we did not get a chance to show the results from other searches that are still one order of magnitude away from the SM predictions. They are $VH \to jjb\bar{b}$, ttH, $H \to \tau^+\tau^-$, and $H \to \gamma\gamma$. For more information, you are welcome to check out CDF and DØ public web pages at

– `http://www-cdf.fnal.gov/physics/new/hdg/Results.html`

– `http://www-d0.fnal.gov/Run2Physics/ResultsWinter2011.html`.

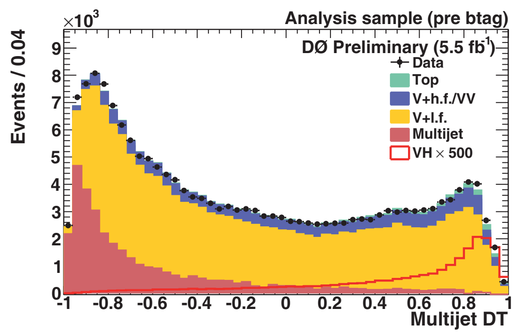

Fig. 7. – The boosted decision tree discriminant distribution for rejecting multi-jet QCD background used by the DØ $ZH \to \nu\bar{\nu}b\bar{b}$ analysis.

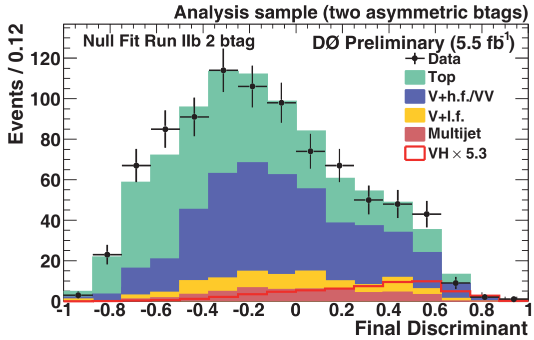

Fig. 8. – The boosted decision tree discriminant distribution is shown from the DØ $ZH \rightarrow \nu\bar{\nu}b\bar{b}$ analysis.

4. – The Tevatron combination

We performed two types of combinations, using Bayesian and Modified Frequentist (CL_s) approaches [1], which yield results that agree within 10% to gain confidence that the final result does not depend on the details of the statistical method. Both methods rely on distributions of final discriminants, not just on event counts, for their likelihood calculations. Systematic uncertainties are treated as nuisance parameters with truncated Gaussian distributions.

The combinations of results of each single experiment, as used in the Tevatron combination, yield the following ratios of 95% C.L. observed (expected) limits to the SM cross section: 1.79 (1.90) for CDF and 2.52 (2.36) for DØ at $m_H = 115\,\text{GeV}/c^2$. Figure 9 shows the Tevatron combination after combining CDF and DØ together. We start to exclude the Higgs mass at the low end between $100 < m_H < 109\,\text{GeV}/c^2$. We obtain the observed limit of 1.56 with expected 1.45 for $m_H = 115\,\text{GeV}/c^2$. The observed and median expected ratios are listed for the tested Higgs boson masses in table I for $m_H \leq 150\,\text{GeV}/c^2$, as obtained by the Bayesian and the CL_s methods.

The combined results we presented significantly extend the individual limits of each collaboration and those obtained in our previous combination. The sensitivity of our

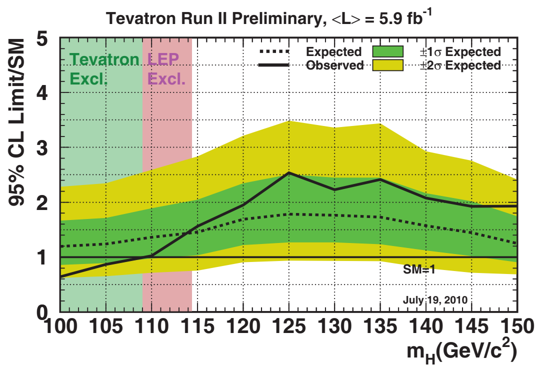

Fig. 9. – The Tevatron combination of Higgs limit for the Higgs mass below 150 GeV.

TABLE I. – *Ratios of expected and observed 95% C.L. limit to the SM prediction for the combined CDF and DØ data as a function of the Higgs mass, obtained with the Bayesian and the CL_s method.*

Bayesian	100	110	115	120	130	140	150
Expected	1.20	1.36	1.45	1.69	1.76	1.57	1.25
Observed	0.64	1.02	1.56	1.95	2.23	2.07	1.93
CL_s	100	110	115	120	130	140	150
Expected	1.17	1.36	1.50	1.66	1.78	1.56	1.20
Observed	0.61	1.06	1.64	2.05	2.38	2.07	1.79

combined search is expected to improve significantly in the future as more data are added and future improvements are made to our analysis techniques. We may start to see some deviation between the observed and expected limits if the Higgs boson does exist somewhere in the low mass range. In order to test that, we did the exercise of injecting a standard model Higgs boson signal at $m_H = 115\,\mathrm{GeV}/c^2$ in several CDF low mass channels. The new exclusion limit is shown in fig. 10, which jumps up like it had a 1σ fluctuation on a rather large mass range, over the limits where the Higgs signal is absent. The effect would be more pronounced with more channels including DØ's.

5. – Future prospects

Figure 11 shows the higgs sensitivity obtained over time from CDF, which improves better than $1/\sqrt{L}$. The sensitivity has been improved more than a factor of 2 since 2005. The shaded band is what we expected with future improvements. Figure 12 shows the luminosity required to achieve the expected number of sigma as a function of the Higgs boson mass. With $10\,\mathrm{fb}^{-1}$ data, the Tevatron could exclude a significant fraction of the low mass Higgs allowed region.

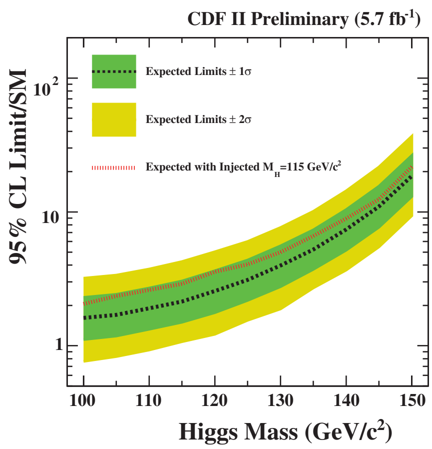

Fig. 10. – The CDF VH limit by injecting the SM Higgs signal.

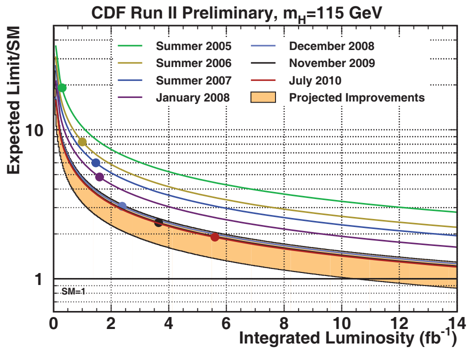

Fig. 11. – The Higgs sensitivity obtained over time from CDF, which improves better than $1/\sqrt{L}$.

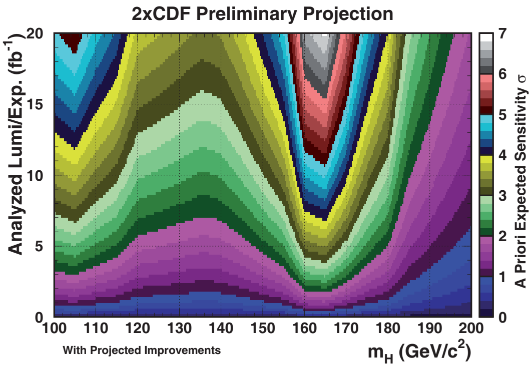

Fig. 12. – The Tevatron luminosity required to achieve certain Higgs sensitivity as a function of the Higgs mass.

6. – Conclusion

We present the recent results of searches for a low mass standard model Higgs boson by the CDF and D0 experiments at the Tevatron $p\bar{p}$ collider at $\sqrt{s} = 1.96\,\text{TeV}$. The data correspond to an integrated total luminosity up to 5.9 (CDF) and 6.7 (D0) fb^{-1} of $p\bar{p}$ collisions. No excess is observed above background expectation, and resulting limits on Higgs boson production are a factor of 1.56 times the value of the SM cross section for a Higgs boson mass of $m_H = 115\,\text{GeV}/c^2$.

The Tevatron is doing remarkably well and has delivered an integrated luminosity of more than $10\,\text{fb}^{-1}$. Both CDF and D0 continue to add additional Higgs sensitivity with "no channel too small" strategies. With a $10\,\text{fb}^{-1}$ analyzable dataset and improved analysis, the Tevatron could exclude a significant fraction of the low mass Higgs allowed region by the winter of 2012. Unfortunately, the Tevatron is scheduled to shutdown at the end of FY2011, but the ideas and techniques developed at the Tevatron will certainly benefit LHC.

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