Extending the Higgs Boson Reach at the Upgraded Fermilab Tevatron

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We study the observability for a Standard Model-like Higgs boson at an upgraded Tevatron via the modes $p\bar{p} \to gg \to W^*W^* \to \ell\nu jj$ and $\ell\nu\ell\nu$. We find that with c. m. energy of 2 TeV and an integrated luminosity of $30 \text{ fb}^{-1}$ the signal may be observable for the mass range of $135 \text{ GeV} \lesssim m_h \lesssim 180 \text{ GeV}$ at a $3 - 5\sigma$ statistical level. We conclude that the upgraded Tevatron may have the potential to detect a SM-like Higgs boson in the mass range from the LEP2 reach to 180 GeV.

The leptonic decays of $W, Z$ can be observed up to a mass of about 120 GeV. It might be possible to extend the mass reach to about 130 GeV via the decay mode $h \to \tau^+\tau^-$ [8]. On the other hand, from the theoretical point of view, weakly coupled supersymmetric models generally predict the lightest Higgs boson to have a mass $m_h \lesssim 150 \text{ GeV}$ [8]. It would be of the greatest theoretical significance for the upgraded Tevatron to extend the Higgs boson coverage over this range.

It is important to note that the leading production mechanism for a SM-like Higgs boson at the Tevatron is the gluon-fusion process via heavy quark triangle loops. Although the decay mode $h \to b\bar{b}$ in this case would be swamped by the QCD background, $h \to W^*W^*$ mode (where $W^*$ generically denotes a $W$ boson of either on- or off-mass-shell) will have an increasingly large branching fraction for $m_h \gtrsim 130$ GeV and may have a chance to be observable. In this paper, we study in detail the observability of a SM-like Higgs boson at an upgraded Tevatron for the modes

$$p\bar{p} \to gg \to W^*W^* \to \ell\nu jj \quad \text{and} \quad \ell\nu\ell\nu,$$

(1)

where $\ell = e, \mu$ and $j$ is a light quark jet. In Fig. [8], we show the cross section for $gg \to h$ versus $m_h$ with $p\bar{p}$ c. m. energy $\sqrt{s} = 2 \text{ TeV}$. Along with the inclusive total cross section [solid curve], we show the $W^*W^*$ (dashes) and $Z^*Z^*$ (dots) channels, as well as their various decay modes $W^*W^* \to \ell\nu jj$, $\ell\nu\ell\nu$ and $Z^*Z^* \to \ell\ell\nu\nu, 4\ell$. The scale on the right-hand side gives the number of events expected for $30 \text{ fb}^{-1}$. We see that for the $m_h$ range of current interest, there may be about 1000 events produced for $W^*W^* \to \ell\nu jj$ and about 100 events for $W^*W^* \to \ell\nu\ell\nu$. This latter channel has been studied at the SSC and LHC energies [10] and at a 4 TeV Tevatron [8]. We find that at $\sqrt{s} = 2 \text{ TeV}$, after nontrivial optimization for the signal identification for Eq. (1) over the substantial SM backgrounds, it is promising to extend the Higgs boson reach at the upgraded Tevatron with an integrated luminosity of $30 \text{ fb}^{-1}$ to $m_h \approx 135 - 180 \text{ GeV}$ at a $3 - 5\sigma$ statistically significant level.

$W^*W^* \to \ell\nu jj$:

For this mode, we require the final state to have an isolated charged lepton ($\ell$), large missing transverse energy ($E_T$), and two hard jets. The leading SM backgrounds are

$$p\bar{p} \to W + 2 \text{ QCD jets}, \quad p\bar{p} \to WW \to \ell\nu jj, \quad (2)$$

$$p\bar{p} \to WZ(g^*) \to \ell\nu jj, \quad p\bar{p} \to t\bar{t} \to \ell\nu jjb\bar{b}.$$  

The background processes are calculated with the full SM matrix elements at tree level.

* We have normalized our signal cross section to include next-to-leading order QCD corrections [8], and we use the CTEQ4M distribution functions [8].
The subsequent decay modes are also depicted. The gluon-fusion process versus \(m_{WW}\) at the 2 TeV Tevatron. The \(h \to W^+W^-\) (dashes) and \(Z^0Z^0\) (dots) channels and various subsequent decay modes are also depicted.

To roughly simulate the detector effects, we use the following energy smearing

\[
\begin{align*}
\Delta E_j/E_j &= 0.8/\sqrt{E_j} \oplus 0.05 \quad \text{for jets}, \\
\Delta E_\ell/E_\ell &= 0.3/\sqrt{E_\ell} \oplus 0.01 \quad \text{for leptons},
\end{align*}
\]

where \(\oplus\) denotes a sum in quadrature. The basic acceptance cuts used here are

\[
\begin{align*}
\mathcal{P}_{T\ell} &> 15 \text{ GeV}, \quad |\eta_\ell| < 1.1; \\
\mathcal{P}_{Tj} &> 15 \text{ GeV}, \quad |\eta_j| < 3; \\
\mathcal{E}_T &> 15 \text{ GeV}; \\
\Delta R(\ellj) &> 0.3, \quad \Delta R(jj) > 0.7.
\end{align*}
\]

For the sake of illustration, we present our study mostly for \(m_h = 140\) and 160 GeV and we will generalize the results to the full \(m_h\) range of interest. The cut efficiency for the signal is about 35% (60%) for \(m_h \approx 140\) (160) GeV.

Since there are only two jets naturally appearing in the signal events, the \(t\bar{t}\) background can be effectively suppressed by rejecting events with extra hard jets. We therefore impose

\[
\text{Jet veto } \mathcal{P}_{Tj} > 15 \text{ GeV in } |\eta_j| < 3.
\]

The QCD background in \(W^*W^*\) has the largest rate. The di-jet in the signal is from a \(W\) decay, while that in the QCD background tends to be soft and collinear. We thus impose the cuts on the di-jet:

\[
\begin{align*}
65 < m(jj) < 95 \text{ GeV}, \quad \phi(jj) > 140^\circ; \\
70 < m(jj) < 90 \text{ GeV}, \quad \phi(jj) > 160^\circ,
\end{align*}
\]

for \(m_h = 140\) and 160 GeV respectively, where \(m(jj)\) is the invariant mass of the di-jet and \(\phi(jj)\) the opening angle of the two jets in the transverse plane. For \(m_h \geq 160\) GeV, the \(m(jj)\) distribution has a unique peak because both \(W\) bosons are on shell, so the \(m(jj)\) cuts in Eq. (3) would not significantly harm the signal. On the other hand, for \(m_h \leq 160\) GeV, nearly half of the signal will be cut off by the \(m(jj)\) cuts, making this region of the Higgs mass more difficult to explore from this mode.

We have also examined other mass variables, such as the \(W\)-boson transverse mass \(M_T(W)\), di-jet-lepton invariant mass \(m(jj\ell)\), and the cluster transverse mass \(M_C\), which are defined as

\[
\begin{align*}
M_T(W) &= \sqrt{(\mathcal{P}_{T\ell} + \mathcal{E}_T)^2 - (\bar{\mathcal{P}}_{T\ell} + \bar{\mathcal{E}}_T)^2}, \\
M_C &= \sqrt{\mathcal{P}_{T}^2(jj\ell) + m^2(jj\ell) + \mathcal{E}_T}.
\end{align*}
\]

The \(M_T(W)\) develops a peak near \(m_W\) for on-shell \(W\) decay. An upper cut on this variable below \(M_W\) can help remove the background from real \(W\) decay as long as \(m_h\) is less than 160 GeV. The cluster transverse mass \(M_C\) would be the most characteristic variable for the signal. It peaks near \(m_h\) and yields a rather sharp end-point above \(m_h\). To further improve the signal-to-background ratio \(S/B\), we find the following tighter cuts helpful

\[
\begin{align*}
100 < m(jj\ell) < 120 \text{ GeV}, \quad \mathcal{E}_T < 30 \text{ GeV}, \\
120 < m(C) < 140 \text{ GeV}, \quad \mathcal{E}_T < 50 \text{ GeV}, \quad \mathcal{E}_T < 170 \text{ GeV}, \quad \mathcal{E}_T < 90 \text{ GeV}, \quad 50 < m(C) < 70 \text{ GeV}, \quad 2.8 < \Delta R(jj) < 3.5,
\end{align*}
\]

for \(m_h = 140\) and 160 GeV respectively.

We show the results progressively at different stages of the kinematical cuts in Table 1. We see that for an integrated luminosity of 30 fb\(^{-1}\), the signal for \(m_h = 140\) GeV is very weak while that for \(m_h \sim 160\) GeV can reach a 3\(\sigma\) statistical significance.

\[
W^*W^* \to \ell\bar{\ell}\nu\bar{\nu}.
\]

For the pure leptonic channel, we identify the final state signal as two isolated charged leptons and large missing transverse energy. The leading SM background processes are

\[
\begin{align*}
p\bar{p} \to W^+W^- \to \ell\bar{\ell}\nu\bar{\nu}, \\
p\bar{p} \to Z\gamma \to \nu\bar{\nu}\ell\bar{\ell}, \\
p\bar{p} \to t\bar{t} \to \ell\bar{\ell}\nu\bar{\nu}b\bar{b}, \\
p\bar{p} \to Z\gamma^* \to \tau^+\tau^- \to \ell\bar{\ell}\nu\bar{\nu}r\bar{r}.
\end{align*}
\]

We first impose basic acceptance cuts

\[
\begin{align*}
\mathcal{P}_{T\ell} > 10 \text{ GeV}, \quad |\eta_\ell| < 1.1; \\
\mathcal{P}_{T\ell} > 5 \text{ GeV}, \quad |\eta_\ell| < 2.5; \\
\mathcal{P}_{T\ell} > 10 \text{ GeV}, \quad \mathcal{E}_T > 25 \text{ GeV}.
\end{align*}
\]

The cut efficiency for the signal is about 70%. We also smear the lepton momenta according to Eq. (5), and veto the hard central jets via Eq. (6) to effectively remove the \(t\bar{t}\) background. At this level, the largest background comes from the Drell-Yan process for \(\tau^+\tau^-\) production. However, this background can be essentially eliminated by removing the back-to-back lepton pair events by requiring

\[
\phi(\ell\ell') < 150^\circ.
\]

2
The $W^*W^*$ mass cannot be accurately reconstructed due to the two undetectable neutrinos. However, both the transverse mass $M_T$ and the cluster transverse mass $M_C$, defined as

$$M_T = 2\sqrt{p_T^2(\ell\ell) + m^2(\ell\ell)},$$
$$M_C = \sqrt{p_T^2(\ell\ell) + m^2(\ell\ell) + E_T},$$

yield a broad peak near $m_h$. We note that these transverse mass variables are very important for the signal identification and for controlling the systematic error.

In Eq. (1) would be very limited. A higher luminosity is strongly called for in this regard.

Finally, a few remarks are in order. (a) In our analyses, we have not considered the $W \to \tau\nu$ mode. Including this decay channel would increase the signal rate by a factor of 3/2 (9/4) for $\ell\nujj$ ($\ell\bar{\nu}\nu$) mode. But some angular variables implement the information for decay lepton spin correlations and are powerful in discriminating against the backgrounds. With some further selective cuts on the angular distributions, we find that the $S/B$ can be improved to about 8% and 21%, with the signal rates 2.6 and 3.3 fb for $m_h = 140$ and 160 GeV, respectively. We show in Fig. 2(b) the event rate distributions for the SM background (solid) and signal plus background (dashes) for $m_h = 160$ GeV. The statistical error bars on the background are also indicated.

In Fig. 3 we show the integrated luminosities needed to reach 3$\sigma$ and 5$\sigma$ statistical significance versus $m_h$. The dotted and dashed curves are for the $\ell\nujj$ mode and the dashed for $\ell\bar{\nu}\nu$. We consider that these two modes have rather different systematic errors, so that we can combine the results for them quadratically. This is shown by the solid curves. We see that with an integrated luminosity of 30 fb$^{-1}$, one may be able to reach at least a 3$\sigma$ signal for 135 GeV $\lesssim m_h \lesssim 180$ GeV. Taking into account the previous studies, we conclude that the upgraded Tevatron with $\sqrt{s} = 2$ TeV and 30 fb$^{-1}$ may have the potential to detect the SM-like Higgs boson in the mass range from the LEP2 reach to 180 GeV. On the other hand, if there is only about 10 fb$^{-1}$ data available, the sensitivity to the Higgs boson search via the modes of Eq. (1) would be very limited. A higher luminosity is strongly called for in this regard.

FIG. 2. The cluster transverse mass distributions for $\ell\bar{\nu}\nu$ mode (a) for the signal $m_h = 140$, 160 and 180 GeV and the leading SM backgrounds with cuts (I) and (II). With further selective cuts, we show the event rates in (b) for SM background (solid) and background plus signal (dashes) for $m_h = 160$ GeV. The statistical error bars are also indicated on the background curve in (b).

In Fig. 3(a), we show the $M_C$ distributions for the $\ell\bar{\nu}\nu$ signal with $m_h = 140$, 160 and 180 GeV along with the leading backgrounds after the cuts in (I) and (II). Although the mass peaks in $M_C$ are hopeful for signal identification, they are rather broad. We may have to rely on the knowledge of the SM background distribution. We hope that with the rather large statistics of the data sample, one may obtain good fit for the normalization of the background shape outside the signal region in Fig. 3(a), so that the deviation from the predicted background can be identified as signal. Some additional useful cuts are

$$m(\ell\ell) < 80 \text{ GeV (70 for } m_h \leq 140 \text{ GeV),}$$
$$E_T < m_h/2, \ m_h/2 < M_C < m_h.$$  

The results at different stages of kinematical cuts are shown in Table III. Due to the absence of the large QCD background in (1), this pure leptonic mode seems to be statistically more promising than the $\ell\nujj$ mode. One may expect a more than 3$\sigma$ (4$\sigma$) effect for $m_h = 140$ (160) GeV with 30 fb$^{-1}$. It was pointed out in [11] that...
only for the SM Higgs boson, but also for SM-like ones such as the lightest Higgs boson in SUSY at the decoupling limit. If there is an enhancement from new physics for $\Gamma(h \rightarrow gg) \times \text{BR}(h \rightarrow WW, ZZ)$ over the SM expectation, the signal of Eq. (1) would be more viable. If $\text{BR}(h \rightarrow b\bar{b})$ is suppressed, such as in certain parameter region in SUSY, then the signal under discussion may complement the $Wh, Zh \ (h \rightarrow b\bar{b})$ channels at a lower $m_h$ region.

Our results summarized in Fig. 3 based on the parton-level simulation are clearly encouraging to significantly extend the reach for the Higgs boson search at the upgraded Tevatron. The more comprehensive results with full Monte Carlo simulations in a realistic environment will be reported elsewhere.

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| $\sigma$ [fb] | Basic Cuts in (1) | Cuts in (3) | Cuts in (5) |
|------------|-----------------|-------------|-------------|
| $m_h$ [GeV] | 140 160         | 140 160     | 140 160     |
| signal     | 23 49           | 8.8 21      | 2.2 15      |
| background |                 |             |             |
| $Wjj$      | $6.5 \times 10^5$ | $6.1 \times 10^3$ | $1.4 \times 10^2$ |
| $WW$       | $1.3 \times 10^3$ | $5.5 \times 10^2$ | $17$ $55$ |
| $WZ$       | 66              | 20 7.0      | 0.3 1.3     |
| $t\bar{t}$ | 0.4             | 0.1         | 0.0         |
| $S/B$      |                 | 0.1% 0.9%   | 1.4% 2.5%   |
| $S/\sqrt{B}$ (30 fb$^{-1}$) | -              | 0.6 2.4     | 1.0 3.3     |

TABLE I. $h \rightarrow W^+W^- \rightarrow \ell\nu jj$ signal and background cross sections (in fb) for $m_h = 140$ and 160 GeV, after different stages of kinematical cuts. A jet-veto cut in Eq. (5) has been implemented for the $t\bar{t}$ background.

| $\sigma$ [fb] | Basic Cuts in (10) | $\phi(\ell\ell) < 150^\circ$ | Cuts in (13) | Refined Cuts |
|------------|-----------------|-------------------------------|-------------|-------------|
| $m_h$ [GeV] | 140 160         | 140 160                       | 140 160     | 140 160     |
| signal     | 7.3 10          | 7.0 9.9                       | 6.3 9.1     | 2.6 3.3     |
| background |                 |                               |             |             |
| $WW$       | $2.7 \times 10^2$ | $2.4 \times 10^2$             | $1.1 \times 10^2$ | $1.4 \times 10^2$ | 32 16  |
| $ZZ(\gamma^*)$ | 24              | 18                           | 1.8 1.8     | 0.3 0.1     |
| $Z(\gamma^*)$ | $3.9 \times 10^2$ | 0.0                          | 0.0         | 0.0         |
| $t\bar{t}$ | 0.2             | 0.1                          | 0.0         | 0.0         |
| $S/B$      | 1.1% 1.5%       | 2.7% 3.9%                    | 5.6% 6.4%   | 8.0% 21%    |
| $S/\sqrt{B}$ (30 fb$^{-1}$) | 1.5 2.1         | 2.4 3.4                      | 3.3 4.2     | 2.5 4.5     |

TABLE II. $h \rightarrow W^+W^- \rightarrow \ell\bar{\nu}\ell\nu$ signal and background cross sections (in fb) for $m_h = 140$ and 160 GeV, after different stages of kinematical cuts. The last column corresponds to the refinement of mass cuts and various angular distribution cuts. A jet-veto cut in Eq. (5) has been implemented for the $t\bar{t}$ background.