Exploiting $h \rightarrow W^*W^*$ Decays
at the Upgraded Fermilab Tevatron

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Abstract

We study the observability of a Standard Model-like Higgs boson at an upgraded Fermilab Tevatron via the mode $h \rightarrow W^*W^*$. We concentrate on the main channel $gg \rightarrow h \rightarrow W^*W^* \rightarrow \ell \bar{\ell} \nu \bar{\nu}$. We also find the mode $q q' \rightarrow W^\pm h \rightarrow W^\pm W^*W^* \rightarrow \ell^\pm \nu \ell^\pm \nu jj$ useful. We perform detector level simulations by making use of a Monte Carlo program SHW. Optimized searching strategy and kinematical cuts are developed. We find that with a c. m. energy of 2 TeV and an integrated luminosity of 30 fb$^{-1}$ the signal should be observable at a 3$\sigma$ level or better for the mass range of $145 \text{ GeV} \lesssim m_h \lesssim 180 \text{ GeV}$. For 95% confidence level exclusion, the mass reach is $135 \text{ GeV} \lesssim m_h \lesssim 190 \text{ GeV}$. We also present results of studying these channels with a model-independent parameterization. Further improvement is possible by including other channels. We conclude that the upgraded Fermilab Tevatron will have the potential to significantly advance our knowledge of Higgs boson physics.

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I. INTRODUCTION

The mass generation mechanisms for electroweak gauge bosons and for fermions are among the most prominent mysteries in contemporary high energy physics. In the Standard Model (SM) and its supersymmetric (SUSY) extensions, elementary scalar doublets of the SU\textsubscript{L}(2) interactions are responsible for the mass generation. The scalar Higgs bosons are thus crucial ingredients in the theory, and searching for the Higgs bosons has been one of the major motivations in the current and future collider programs [1]. Although the masses of Higgs bosons are free parameters in the models, they are subject to generic bounds based on theoretical arguments. The triviality bound indicates that the Higgs boson mass \( m_h \) should be less than about 800 GeV for the SM to be a consistent low-energy effective theory [2]. Vacuum stability argument, on the other hand, suggests a correlation between the \( m_h \) lower bound and the new physics scale \( \Lambda \) beyond which the SM is no longer valid [3]. In other words, the discovery of SM-like Higgs boson implies a scale \( \Lambda \) at which new physics beyond the SM must set in; and the smaller \( m_h \) is, the lower \( \Lambda \) would be. In the minimal supersymmetric Standard Model (MSSM), it has been shown that the mass of the lightest neutral Higgs boson must be less than about 130 GeV [4], and in any weakly coupled SUSY theory \( m_h \) should be lighter than about 150 GeV [5]. On the experimental side, the non-observation of Higgs signal at the LEP2 experiments has established a lower bound on the SM Higgs boson mass of 89.8 GeV at a 95\% Confidence Level (CL) [6]. Future searches at LEP2 will eventually be able to discover a SM Higgs boson with a mass up to 105 GeV [7]. The CERN Large Hadron Collider (LHC) is believed to be able to cover up to the full \( m_h \) range of theoretical interest, about 1000 GeV [8], although it will be challenging to discover a Higgs boson in the “intermediate” mass region 110 GeV < \( m_h < 150 \) GeV, due to the huge SM background to \( h \rightarrow b \bar{b} \) and the requirement of excellent di-photon mass resolution for the \( h \rightarrow \gamma\gamma \) signal.

More recently, it has been discussed intensively how much the Fermilab Tevatron upgrade can do for the Higgs boson search [9]. It appears that the most promising processes continuously going beyond the LEP2 reach would be the associated production of an electroweak gauge boson and the Higgs boson [10–12]

\[ p\bar{p} \rightarrow WhX, \ ZhX. \] (1)

The leptonic decays of \( W, Z \) provide a good trigger and \( h \rightarrow b \bar{b} \) may be reconstructible with adequate \( b \)-tagging. It is now generally believed that for an upgraded Tevatron with a c. m. energy \( \sqrt{s} = 2 \) TeV and an integrated luminosity \( \mathcal{O}(10 – 30) \) fb\textsuperscript{-1} a SM-like Higgs boson can be observed at a 3 – 5\( \sigma \) level up to a mass of about 120 GeV [13]. The Higgs discovery through these channels crucially depends on the \( b \)-tagging efficiency and the \( b \bar{b} \) mass resolution. It is also limited by the event rate for \( m_h > 120 \) GeV. It may be possible to extend the mass reach to about 130 GeV by combining leptonic \( W, Z \) decays [13] and slightly beyond via the decay mode \( h \rightarrow \tau^+\tau^- \) [12]. It is interesting to note that this mass reach is just near the theoretical upper bound in MSSM. In the context of a general weakly-coupled SUSY model, it would be of great theoretical significance for the upgraded Tevatron to extend the Higgs boson coverage to \( m_h \sim 150 \) GeV. Moreover, it would have interesting implications on our knowledge for a new physics scale \( \Lambda \) if we do find a SM-like Higgs boson or exclude its existence in the mass range 130 GeV–180 GeV, the so-called
FIG. 1. The leading Higgs boson production cross sections (in fb) versus $m_h$ at the 2 TeV Tevatron. The solid curves are for $gg \rightarrow h$, $q\bar{q}' \rightarrow W^\pm h$ and $q\bar{q} \rightarrow Zh$. The dashed curves are for $W^+W^-$ and $ZZ$ fusion to $h$. The scale on the right-hand side indicates the number of events per 30 fb$^{-1}$ integrated luminosity. QCD corrections \cite{13–17} have been included.

“chimney region” between the triviality upper bound and the vacuum stability lower bound \cite{14}.

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

$$p\bar{p} \rightarrow ggX \rightarrow hX.$$  \hspace{1cm} (2)

There are also contributions to $h$ production from the vector boson fusion processes\footnote{Here and henceforth, $W^*(Z^*)$ generically denotes a $W(Z)$ boson of either on- or off-mass-shell.}

$$W^*W^*, \ Z^*Z^* \rightarrow h,$$  \hspace{1cm} (3)

where $W^*W^*$ and $Z^*Z^*$ are radiated off the quark partons. In Fig. 1, we present cross sections for SM Higgs boson production at the Tevatron for processes (1), (2) and (3). We see that the gluon fusion process yields the largest cross section, typically a factor of four above the associated production (1). For $m_h > 160$ GeV, $WW, ZZ$ fusion processes become comparable to that of (1). In calculating the total cross sections, the QCD corrections have been included for all the processes \cite{15–17}, and we have used the CTEQ4M parton distribution functions \cite{18}.

Although the decay mode $h \rightarrow b\bar{b}$ in Eqs. (2) and (3) would be swamped by the QCD background, the decay modes to vector boson pairs

$$h \rightarrow W^*W^*, \ Z^*Z^*$$  \hspace{1cm} (4)

\hspace{1cm}
will have increasingly large branching fractions for $m_h \gtrsim 130$ GeV and are natural channels to consider for a heavier Higgs boson. In Fig. 2(a), we show the cross sections for $gg \rightarrow h$ with $h \rightarrow W^*W^*$ and $Z^*Z^*$ versus $m_h$ at $\sqrt{s} = 2$ TeV. The leptonic decay channels are also separately shown by solid and dashed curves, respectively, for
\begin{align}
h \rightarrow W^*W^* & \rightarrow \ell\nu jj \quad \text{and} \quad \ell\bar{\ell}\nu\nu, \\
Z^*Z^* & \rightarrow \ell\bar{\ell}jj \quad \text{and} \quad \ell\bar{\ell}\nu\nu,
\end{align}
where $\ell = e, \mu$ and $j$ is a quark jet. The scale on the right-hand side gives the number of events expected for 30 fb$^{-1}$. We see that for the $m_h$ range of current interest, there will be about 1000 events produced for the semi-leptonic mode $W^*W^* \rightarrow \ell\nu jj$ and about 300 events for the pure leptonic mode $W^*W^* \rightarrow \ell\nu\ell\nu$. Although the $\ell\nu jj$ mode has a larger production rate, the $\ell\bar{\ell}\nu\nu$ mode is cleaner in terms of the SM background contamination. The corresponding modes from $Z^*Z^*$ are smaller by about an order of magnitude. It is natural to also consider the $h \rightarrow W^*W^*$ mode from the $Wh$ associated production in Eq. (1). This is shown in Fig. 2(b) by the solid curves for
\begin{align}
W^\pm h \rightarrow \ell^\pm\nu, \\
W^*W^* \rightarrow \ell\nu\ell\nu, \\
\ell^\pm\nu \ell^\pm\nu jj.
\end{align}
The trilepton signal is smaller than the like-sign lepton plus jets signal by about a factor of three due to the difference of $W$ decay branching fractions to $\ell = e, \mu$ and to jets. For
comparison, also shown in Fig. 2(b) are Wh → b¯bℓν (solid) and Zh → b¯bℓℓ (dashed) via h → bb. We see that the signal rates for these channels drop dramatically for a higher mh. Comparing the h decays in Fig. 2(a) and (b), it makes the gauge boson pair modes of Eq. (4) a clear choice for Higgs boson searches beyond 130 GeV.

In fact, the pure leptonic channel in Eq. (5) has been studied at the SSC and LHC energies [19,20] and at a 4 TeV Tevatron [11]. Despite the difficulty in reconstructing mh from this mode due to the two missing neutrinos, the obtained results for the signal identification over the substantial SM backgrounds were all encouraging. In a more recent paper [21], two of the current authors carried out a parton-level study for the W*W* channels of Eq. (5) for the 2 TeV Tevatron upgrade. We found that the di-lepton mode in Eq. (5) is more promising than that of ℓνjj due to the much larger QCD background to the latter. While the results were encouraging, realistic simulations including detector effects were called for to draw further conclusions.

In this paper, we concentrate on the pure leptonic channel and carry out more comprehensive analyses for the signal and their SM backgrounds. We perform detector level simulations by making use of a Monte Carlo program SHW developed for the Run-II SUSY/Higgs Workshop [22]. We present optimized kinematic cuts which can adequately suppress the large SM backgrounds and, moreover, have been structured so as to provide a statistically robust background normalization. For the Wh → WW*W* channel, although the trilepton signal of Eq. (7) is rather weak, the like-sign leptons plus two jets in Eq. (8) can be useful to enhance the signal observability. For completeness, we have also included the contributions from the vector boson fusion of Eq. (3) and W → τν → νℓνℓ decay mode, although they are small. We also comment on the systematic effects on the signal and background measurements which would degrade signal observability. After combining all the channels studied, we find that with a c. m. energy of 2 TeV and an integrated luminosity of 30 fb−1, the signal of h → W*W* can be observable at a 3σ level or better for the mass range of 145 GeV < mh < 180 GeV. For 95% CL exclusion, the mass reach is 135 GeV < mh < 190 GeV. We thus conclude that the upgraded Fermilab Tevatron will have the potential to significantly advance our knowledge of Higgs boson physics. This provides strong motivation for luminosity upgrade of the Fermilab Tevatron beyond the Main Injector plan.

Our signal and background Monte Carlo simulation was performed using the PYTHIA package [23] interfaced with the SHW detector simulation [22]. For pair production of resonances, e.g. WW, PYTHIA incorporates the full 2 → 2 → 4 matrix elements thereby insuring proper treatment of the final state angular correlations. Similarly for h → WW, the angular correlations between the four final state fermions have been taken into account. The full Z/γ* interference is simulated for ZZ production; however, the WZ process considers only the pure Z contribution. For Higgs boson production in association with a gauge boson in Eq (1), the associated W and Z decay angular distributions are treated properly. The production cross-sections for the principal background processes were normalized to σ(WW) = 10.4 pb, σ(tt) = 6.5 pb, σ(WZ) = 3.1 pb, and σ(ZZ) = 1.4 pb.

The rest of the paper is organized as follows. In sections II and III, we present in details our studies for the pure leptonic and like-sign leptons plus jets signals, respectively. In section IV, we first summarize our results. We then present a study of these channels with a model-independent parameterization for the signal cross section. We conclude with a few remarks.
II. DI-LEPTONS PLUS MISSING TRANSVERSE ENERGY SIGNAL

For the pure leptonic channel in Eq. (5), we identify the final state signal as two isolated opposite-sign charged leptons and large missing transverse energy. The leading SM background processes are

\[ p\bar{p} \rightarrow W^+W^- \rightarrow \ell\bar{\nu}\ell\nu, \quad ZZ(\gamma^*) \rightarrow \nu\bar{\nu}\ell\ell, \quad WZ(\gamma^*) \rightarrow \ell\nu\ell\bar{\nu}, \]
\[ p\bar{p} \rightarrow t\bar{t} \rightarrow \ell\nu\ell\nu\bar{b}\bar{b}, \quad p\bar{p} \rightarrow Z(\gamma^*) \rightarrow \tau^+\tau^- \rightarrow \ell\nu\ell\nu, \bar{\nu} \tau. \]

We first impose basic acceptance cuts for the leptons\(^2\).

\(^2\)The cuts for leptons were chosen to reflect realistic trigger considerations. It is desirable to extend the acceptance in \( \eta_\ell \).
FIG. 4. Normalized distributions $\frac{1}{\sigma} \frac{d\sigma}{d\theta}$ for the opening angle in Eq. (11) for the signal $gg \rightarrow h \rightarrow W^+W^- \rightarrow \ell\bar{\nu}\ell\nu$ with $m_h = 170$ GeV and backgrounds $WW$, $tt$, $\tau^+\tau^-$, $WZ$ and $ZZ$.

\[ p_T(e) > 10 \text{ GeV}, \quad |\eta_e| < 1.5, \]
\[ p_T(\mu_1) > 10 \text{ GeV}, \quad p_T(\mu_2) > 5 \text{ GeV}, \quad |\eta_\mu| < 1.5, \]
\[ m(\ell\ell) > 10 \text{ GeV}, \quad \Delta R(\ell j) > 0.4, \quad E_T > 10 \text{ GeV}, \]

(10)

where $p_T$ is the transverse momentum and $\eta$ the pseudo-rapidity. The cut on the invariant mass $m(\ell\ell)$ is to remove the photon conversions and leptonic $J/\psi$ and $\Upsilon$ decays. The isolation cut on $\Delta R(\ell j)$ removes the muon events from heavy quark ($c, b$) decays.\(^3\)

At this level, the largest background comes from the Drell-Yan process for $\tau^+\tau^-$ production. However, the charged leptons in this background are very much back-to-back and this feature is also true, although to a lesser extent, for other background processes as well.

\(^3\)The electron identification in the SHW simulation imposes strict isolation requirements already.
FIG. 5. Normalized distributions $\frac{1}{\sigma} \frac{d\sigma}{dM_T}$ for the two-body transverse-mass defined in Eq. (13) for the signal $gg \to h \to W^+W^- \to \ell\bar{\nu}\ell\nu$ with $m_h = 170$ GeV and backgrounds $WW$, $t\bar{t}$, $\tau^+\tau^-$, $WZ$ and $ZZ$. The minimum of $M_T(\ell_1 E_T)$ and $M_T(\ell_2 E_T)$ is shown.

On the other hand, due to the spin correlation of the Higgs boson decay products, the two charged leptons tend to move in parallel. We demonstrate this point in Figs. 3 and 4 where the distributions of the azimuthal angle in the transverse plane $[\phi(\ell\ell)]$ and the three-dimensional opening-angle between the two leptons $[\theta(\ell\ell)]$ for the signal and backgrounds are shown. This comparison motivates us to impose the cuts

$$\phi(\ell\ell) < 160^\circ, \quad \theta(\ell\ell) < 160^\circ.$$  

(11)

The $\tau^+\tau^-$ background can be essentially eliminated with the help of additional cuts

$$p_T(\ell\ell) > 20 \text{ GeV}, \quad \cos \theta_{\ell\ell-\not{E}_T} < 0.5, \quad M_T(\ell E_T) > 20 \text{ GeV},$$  

(12)

Since we are mainly interested in the shapes of the kinematic distributions, we present them normalized to unity with respect to the total cross section with appropriate preceding cuts.
FIG. 6. Normalized like-flavor lepton-pair invariant mass distributions \( \frac{1}{\sigma \, d\sigma/dm(\ell\ell)} \) for the signal \( gg \rightarrow h \rightarrow W^+W^- \rightarrow \ell\bar{\nu}\ell\bar{\nu} \) with \( m_h = 170 \) GeV and backgrounds \( WW, t\bar{t}, \tau^+\tau^-, WZ \) and \( ZZ \).

where \( \theta_{\ell\ell-\slashed{E}_T} \) is the relative angle between the lepton pair transverse momentum and the missing transverse momentum, which is close to 180° for the signal and near 0° for the Drell-Yan \( \tau^+\tau^- \) background. The two-body transverse-mass is defined for each lepton and the missing energy as

\[
M_T^2(\ell\slashed{E}_T) = 2p_T(\ell\slashed{E}_T)(1 - \cos \theta_{\ell\ell-\slashed{E}_T}),
\]

and the distributions are shown in Fig. 6.

We can further purify the signal by removing the high \( m(\ell\ell) \) events from \( Z \rightarrow \ell\bar{\ell} \) as well as from \( t\bar{t}, W^+W^- \), as demonstrated in Fig. 6. We therefore impose

\[
m(\ell\ell) < 78 \text{ GeV} \quad \text{for } e^+e^-, \mu^+\mu^-, \\
m(\ell\ell) < 110 \text{ GeV} \quad \text{for } e\mu.
\]

As suggested in Ref. [20], the lepton correlation angle between the momentum vector of the lepton pair and the momentum of the higher \( p_T \) lepton (\( \ell_1 \)) in the lepton-pair rest frame,
\( \cos \Theta^* \) also has discriminating power between the signal and backgrounds. This is shown in Fig. 7. We thus select events with

\[-0.3 < \cos \theta_{\ell_1}^* < 0.8. \]

A characteristic feature of the top-quark background is the presence of hard \( b \)-jets. We thus devise the following jet-veto criteria\(^5\)

veto if \( p_T^{j_1} > 95 \text{ GeV, } |\eta_j| < 3, \)

\(^5\)The previous study \cite{21} at the parton-level suggested a more stringent jet-veto cut. It turns out that it would be too costly for the signal and the more sophisticated jet-veto criteria of Eq. (16) is thus desirable.
TABLE I. \( h \to W^*W^* \to \ell\bar{\ell}\ell\bar{\ell} \) signal cross section (in fb) for \( m_h = 140-190 \) GeV and various SM backgrounds after the kinematical cuts of Eqs. (10)–(16). The signal efficiencies are also shown (in percentage). \( W + \text{fake} \) refers to the background where a jet mimics an electron with a probability of \( P(j \to e) = 10^{-4} \). The backgrounds are independent of \( m_h \).

\[
\begin{array}{cccccc}
\hline
m_h [\text{GeV}] & 140 & 150 & 160 & 170 & 180 & 190 \\
\text{signal [fb]} & 3.9 & 4.4 & 5.2 & 4.8 & 3.6 & 2.5 \\
\text{effic. [%]} & 35 & 34 & 38 & 39 & 36 & 37 \\
\text{bckgrnds [fb]} & WW & t\bar{t} & \tau^+\tau^- & WZ & ZZ & W+fake \\
\hline
\end{array}
\]

Furthermore, if either of the two hard jets \((j_1, j_2)\) is identified as a \( b \) quark, the event will be also vetoed. The \( b \)-tagging efficiency is taken to be \( \epsilon_b = 1.1 \times 57\% \tanh\left(\frac{\eta_b}{36.05}\right) \).

We wish to evaluate the likelihood for a candidate event to be consistent with one of five event classes: a Higgs boson signal \((140 < m_h < 190 \text{ GeV})\), \( WW \), \( t\bar{t} \), \( WZ \) or \( ZZ \). For a single variable \( x_i \), the probability for an event to belong to class \( j \) is given by

1. \( \cos \theta_{\ell\ell} \), the polar angle with respect to the beam axis of the di-lepton [20];
2. \( \phi(\ell\ell) \) as in Eq. (11);
3. \( \theta(\ell\ell) \) as in Eq. (11);
4. \( \cos \theta_{\ell\ell-\eta_T} \) as in Eq. (12);
5. \( p_T^{j_1} \) as in Eq. (16);
6. \( p_T^{j_2} \) as in Eq. (16).
FIG. 8. Distributions for the likelihood variable defined in Eq. (19) for the signal $m_h = 170$ GeV and the leading SM backgrounds $WW$ and $t\bar{t}$.

$$P_j^i(x_i) = \frac{f_j^i(x_i)}{\sum_{k=1}^{5} f_k^i(x_i)},$$

(18)

where $f_j^i$ denotes the probability density for class $j$ and variable $i$. The likelihood of an event to belong to class $j$ is given by the normalized products of the individual $P_j^i(x_i)$ for the $n = 6$ kinematical variables:

$$L_j = \prod_{i=1}^{n} \frac{P_j^i(x_i)}{\prod_{k=1}^{5} P_k^i(x_i)},$$

(19)

The value of $L_j$ for a Higgs boson signal hypothesis ($j = 1$) is shown in Fig. 8 where it can be seen that a substantial fraction of the $t\bar{t}$ and $WW$ background can be removed for a modest loss of acceptance. The $WZ$ and $ZZ$ backgrounds have similar distributions to the $WW$ and have been omitted for clarity. We thus impose the requirement

$$L_j = 1 > 0.10.$$  

(20)

The improved results are summarized in Table II. In identifying the signal events, it is crucial to reconstruct the mass peak of $m_h$. Unfortunately, the $W^*W^*$ mass from the $h$ decay 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
| $m_h$ [GeV] | 140 | 150 | 160 | 170 | 180 | 190 |
|------------|-----|-----|-----|-----|-----|-----|
| signal [fb] | 3.1 | 3.6 | 4.5 | 4.1 | 2.9 | 2.0 |
| bckgrnds [fb] | WW | $t\bar{t}$ | $\tau^+\tau^-$ | WZ | ZZ | $W$+fake |
| 83 | 4.5 | 0 | 3.1 | 1.8 | 13 |

TABLE II. $h \rightarrow W^*W^* \rightarrow \ell\nu\bar{\ell}\nu$ signal cross section (in fb) for $m_h = 140$–190 GeV and various SM backgrounds after the kinematical cuts of Eqs. (10)–(16) and the likelihood cut Eq. (20). $W$+fake refers to the background where a jet mimics an electron with a probability of $P(j \rightarrow e) = 10^{-4}$. The backgrounds are independent of $m_h$.

\[
M_T = 2\sqrt{p_T^2(\ell\ell) + m^2(\ell\ell)}, \quad (21)
\]

\[
M_C = \sqrt{p_T^2(\ell\ell) + m^2(\ell\ell)} + E_T, \quad (22)
\]

yield a broad peak near $m_h$ and have a long tail below. The cluster transverse mass $M_C$ has a Jacobian structure with a well defined edge at $m_h$. We show the nature of these two variables for the signal with $m_h = 170$ GeV and the leading $WW$ background in Fig. 9(a) for $M_T$ and (b) for $M_C$ after application of the likelihood cut. For a given $m_h$ to be studied, one can perform additional cut optimization. In Table III, we list $m_h$-dependent criteria for the signal region defined as

$$m_h - 60 < M_C < m_h + 5 \text{ GeV}. \quad (23)$$

We illustrate the effect of the optimized cuts of Table III in Fig. 10, where the cluster transverse mass distribution for a $m_h = 170$ GeV signal and the summed backgrounds, normalized to 30 fb$^{-1}$, are shown before (a) and after the final cuts (b). A clear excess of events from the Higgs signal can be seen in Fig. 10(b). It is important to note that before application of the final cuts, the dominant backgrounds are $WW$ and the $W$+fake with other sources accounting for less than 10% of the total. Moreover, for 30 fb$^{-1}$ integrated luminosity, the statistical error in the background is less than 2% before application of the

| $m_h$ [GeV] | 140 | 150 | 160 | 170 | 180 | 190 |
|------------|-----|-----|-----|-----|-----|-----|
| $\cos \theta_{\ell_1}$ | - | <0.6 | 0.35 | 0.35 | 0.55 | 0.75 |
| $E_T$ | >25 | 25 | 30 | 35 | 40 | 40 |
| min[$M_T(\ell_1 E_T)$, $M_T(\ell_2 E_T)$] | >40 | 40 | 75 | 80 | 85 | 75 |
| $M_T(\ell_1 E_T)$ | >60 | 60 | - | - | - | - |
| $m(\ell\ell)$ | <65 | 65 | 65 | 75 | 85 | - |
| $p_T(\ell\ell)$ | >40 | 50 | 65 | 70 | 70 | 70 |
| $\theta(\ell\ell)$ | <100 | 100 | 70 | 70 | 90 | 90 |
| $M_T$ | - | >110 | 120 | 130 | 140 | 140 |

TABLE III. Summary of the optimized cuts additional to those in Eqs. (10)–(16) for various Higgs boson mass.
FIG. 9. Normalized distributions $\frac{1}{\sigma} \frac{d\sigma}{dM}$ for the signal $gg \rightarrow h \rightarrow W^*W^* \rightarrow \ell\bar{\nu}\ell\bar{\nu}$ with $m_h = 170$ GeV (histogram) and the leading $WW$ background (shaded) for (a) the transverse mass defined in Eq. (21), and (b) the cluster transverse mass defined in Eq. (22).

final cuts. We therefore argue that one should be able to normalize the SM background curve ($WW$) with sufficient precision to unambiguously identify a significant excess attributable to Higgs boson signal. It should also be noted that by selectively loosening the final cuts, it is possible to maintain the same $S/\sqrt{B}$ while increasing the accepted background by up to factor of 5, and the accepted signal by a factor of 2.5. This can provide a powerful cross-check of the predicted background $M_C$ shape and can be used to demonstrate the stability of any observed excess.

Our final results for the channel $h \rightarrow W^*W^* \rightarrow \ell\bar{\nu}\ell\bar{\nu}$ are summarized in Table IV. We have included the contributions to $h \rightarrow W^*W^*$ from the signal channels in Eqs. (1) and (3). Although they are small to begin with, they actually increase the accepted signal cross section by 12–18%. We have also included the contribution from $W \rightarrow \tau\nu \rightarrow \ell\nu\ell\nu$. It can be seen that one may achieve a $S/B$ of at least 6% for $140 \text{ GeV} < m_h < 190 \text{ GeV}$ and reach 45% for $m_h = 170$ GeV. The statistical significance, $S/\sqrt{B}$, for 30 fb$^{-1}$ integrated luminosity, is 3$\sigma$ or better for $150 < m_h < 180$ GeV. In Fig. IV(a), we present the integrated luminosities needed to reach a 3$\sigma$ significance and 95% CL exclusion computed assuming Poisson probabilities for $m_h$.

To assess the effect of inherent systematic uncertainties, we re-evaluate the corresponding

\[\text{From consideration of the } W+(j \rightarrow e) \text{ background, it should be clear that improving the sensitivity by incorporating hadronic tau decays will be a difficult task. We nonetheless encourage the effort.}\]
FIG. 10. Cluster transverse mass distributions for the leading $WW$ background (shaded) and the background plus the signal $gg \rightarrow h \rightarrow W^*W^* \rightarrow \ell\bar{\ell}\nu\bar{\nu}$ with $m_h = 170$ GeV (histogram) (a) before the optimized cuts in Table \[1\] and (b) after the cuts. The vertical axis gives the number of events per 5 GeV bin for $30 \text{ fb}^{-1}$.

curves in Fig. (b) assuming a 10% systematic error for the signal and SM backgrounds. The results are somewhat degraded, but they are still encouraging.

### III. LIKE-SIGN DI-LEPTON PLUS JETS SIGNAL

When considering the $h \rightarrow W^*W^*$ mode in the associated production channels of Eq. (1), it is natural to consider the trilepton mode of Eq. (7) [26]. However, the leptonic branching fractions for the $W$ decays limit the signal rate. Also, the leading irreducible SM background $WZ(\gamma^*) \rightarrow 3\ell$ is difficult to suppress to a sufficient level. On the other hand, the $W^*W^* \rightarrow \ell\nu jj$ mode gives like-sign leptons plus two-jets events \[10,26\] as in Eq. (8) with a three times larger rate than the trilepton mode; while the leading background is higher order than $WZ(\gamma^*)$. In this case, the contributing channels include

\[
\begin{align*}
Wh \rightarrow WW^*W^* \rightarrow \ell^+\nu\ell^+\nu jj, \\
Wh \rightarrow WZ^*Z^* \rightarrow \ell^+\nu\ell^+\ell^- jj, \\
Zh \rightarrow ZW^*W^* \rightarrow \ell^+\ell^-\ell^+\nu jj, \\
Zh \rightarrow ZZ^*Z^* \rightarrow \ell^+\ell^-\ell^+\ell^- jj.
\end{align*}
\]

\[7\]

For the purposes of computing the effects of systematic errors on the sensitivity to a Higgs signal, we have scaled the expected background upward by a given percentage and the expected signal downward by the same percentage simultaneously.
| $m_h$ [GeV] | 140 | 150 | 160 | 170 | 180 | 190 |
|------------|-----|-----|-----|-----|-----|-----|
| $gg \to h$ [fb] | 2.2 | 2.4 | 1.3 | 0.93 | 0.85 | 0.73 |
| associated $VH$ [fb] | 0.26 | 0.31 | 0.13 | 0.09 | 0.06 | 0.06 |
| $VV$ fusion [fb] | 0.12 | 0.12 | 0.09 | 0.06 | 0.05 | 0.05 |
| signal sum [fb] | 2.6 | 2.8 | 1.5 | 1.1 | 0.96 | 0.83 |
| SM backgrounds [fb] | 39 | 27 | 4.1 | 2.3 | 3.8 | 7.0 |
| fake $j \to e$ [fb] | 5.1 | 3.4 | 0.34 | 0.15 | 0.08 | 0.45 |
| backgrounds sum [fb] | 44 | 30 | 4.4 | 2.4 | 3.8 | 7.5 |
| $S/B$ [%] | 5.8 | 9.4 | 34 | 45 | 25 | 11 |
| $S/\sqrt{B}$ [30 fb$^{-1}$] | 2.1 | 2.8 | 3.9 | 3.8 | 2.7 | 1.7 |

TABLE IV. Summary table for $h \to W^*W^* \to \ell\bar{\ell}\nu\bar{\nu}$ signal for $m_h = 140-190$ GeV and various SM backgrounds after the kinematical cuts of Eqs. (10)–(16) and the likelihood cut Eq. (20). $W+$fake refers to the background where a jet mimics an electron with a probability of $P(j \to e) = 10^{-4}$. The backgrounds are independent of $m_h$.

We identify the final state signal as two isolated like-sign charged leptons plus jets. A soft third lepton may be present. The SM backgrounds are

\[
\begin{align*}
pp &\to WWW, WWZ, WZZ, ZZZ, t\bar{t}W, t\bar{t}Z \to \ell^+\ell^- jj X, \\
pp &\to W^\pm Z(\gamma^*) + jj \to \ell^\pm\ell^\pm jjX, \quad Z(\gamma^*) + jj \to \ell^\pm\ell^\pm jjX, \quad t\bar{t} \to \ell\bar{\nu}jj\bar{b}, \\
pp &\to Wjj, Z(\gamma^*)jj + fake.
\end{align*}
\]

Although the triple gauge boson production \cite{27} in Eq. (24) constitutes the irreducible backgrounds, the $WZjj$, $t\bar{t}$ through $b$ or $c$ semileptonic decay and the background from $j \to e$ fakes turn out to be larger.

The basic acceptance cuts required for the leptons are

\[
\begin{align*}
p_T(\ell) &> 10 \text{ GeV}, \quad |\eta_\ell| < 1.5, \quad m(\ell\ell) > 10 \text{ GeV}, \\
0.3 &< \Delta R(\ell j) < 6, \quad \mathbf{E}_T > 10 \text{ GeV}.
\end{align*}
\]

For a muon, we further demand that the scalar sum of additional track momenta within $30^\circ$ be less than 60% of the muon momentum. We require that there are at least two jets with

\[
p_T^j > 15 \text{ GeV}, \quad |\eta_j| < 3.
\]

To suppress the $WZ$ background, we require the leading jet to be within $|\eta_{j_1}| < 1.5$ and to have a charged track multiplicity satisfying $2 \leq N \leq 12$; while the sub-leading jet to be within $|\eta_{j_2}| < 2.0$. The $t\bar{t}$ background typically exhibits greater jet activity; we therefore veto events having

\[
p_T^{j_3} > 30 \text{ GeV},
\]

and events with a fourth jet satisfying Eq. (27). To suppress backgrounds associated with heavy flavor jets, we veto the event if any of the jets have a $b$-tag.
FIG. 11. The integrated luminosity required to reach 3σ statistical significance and 95% exclusion versus $m_h$ in the $h \rightarrow W^*W^* \rightarrow \ell\bar{\ell}\ell\bar{\ell}$ channel for (a) statistical effects only; (b) 10% systematic error for the signal and SM backgrounds included. The contribution from $W \rightarrow \tau \rightarrow \ell$ decays, associated production and gauge boson fusion have also been included.

In Fig. 12, we present the di-jet mass distributions for the signal and backgrounds. Since the di-jets in the signal are mainly from a $W^*$ decay, $m(jj)$ is close to or lower than $M_W$. This motivates us to further require

$$m(jj) < 110 \text{ GeV}, \quad \Sigma_j|p_T^j| < 150 \text{ GeV}. \quad (29)$$

Finally, it is interesting to note that the lepton correlation angle introduced in Eq. (15) has strong discriminating power to separate the signal from backgrounds as shown in Fig. 13. We then impose a final cut

$$\cos\theta^*_{\ell_1} < 0.95. \quad (30)$$

| $m_h$ [GeV] | 120 | 130 | 140 | 150 | 160 | 170 | 180 | 190 | 200 |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| signal sum [fb] | 0.093 | 0.20 | 0.34 | 0.52 | 0.45 | 0.38 | 0.29 | 0.20 | 0.16 |
| bckgrnd channels | $WZ$ | $ZZ$ | $WW$ | $tt$ | $VVV$ | $ttV$ | $W/Z jj+fake$ | Sum |
| $\sigma$ [fb] | 0.27 | 0.06 | 0.01 | 0.15 | 0.07 | 0.02 | 0.26 [31] | 0.83 |
| $S/B$ [%] | 11 | 24 | 41 | 63 | 54 | 46 | 35 | 24 | 19 |
| $S/\sqrt{B}$ [30 fb$^{-1}$] | 0.56 | 1.2 | 2.0 | 3.1 | 2.7 | 2.3 | 1.7 | 1.3 | 0.96 |

TABLE V. $Vh \rightarrow \ell^+\ell^-jj$ signal for $m_h = 120-200$ GeV and the SM backgrounds after the kinematical cuts of Eqs. (26)–(29).
FIG. 12. Normalized di-jet mass distributions $\frac{1}{A} \frac{d\sigma}{dm jj}$ for the signal $W^\pm h \rightarrow W^\pm W^* W^* \rightarrow \ell^\pm \ell^\pm jj$ with $m_h = 170$ GeV and the backgrounds $WZ$, $ZZ$ and $t\bar{t}$.

With these cuts, we present the results for the signal and backgrounds in Table V. We can see that for a given $m_h$, the $S/B$ is larger than that for the di-lepton plus $E_T$ signature, reaching as high as 63%. One can consider further optimization of cuts with $m_h$ dependence. However, the rather small signal rate for a 30 fb$^{-1}$ luminosity limits the statistical significance. Also, the systematic uncertainty in the background may be worse than the pure leptonic channel.

IV. DISCUSSIONS AND CONCLUSION

We have carried out comprehensive studies for $h \rightarrow W^* W^*$ via the two channels

$$p\bar{p} \rightarrow h \rightarrow W^* W^* \rightarrow \ell\bar{\ell}\nu,$$  \hspace{1cm} (31)

$$p\bar{p} \rightarrow W^\pm h, \ Z h \rightarrow W^\pm (Z) W^* W^* \rightarrow \ell^\pm \ell^\pm jj.$$  \hspace{1cm} (32)
FIG. 13. Normalized distributions $\frac{1}{\sigma} \frac{d\sigma}{d\cos \Theta}$ for the correlation angle defined above Eq. (15) for the signal $W^{\pm} h \rightarrow W^{\pm} W^* W^* \rightarrow \ell^+ \ell^- j j$ with $m_h = 170$ GeV and backgrounds $WZ$, $ZZ$ and $t\bar{t}$.

In combining both channels, we present our summary figure in Fig. 14, again for (a) statistical effects only; (b) 10% systematic error for the signal and SM backgrounds included for both channels. We conclude that with a c. m. energy of 2 TeV and an integrated luminosity of 30 fb$^{-1}$ the Higgs boson signal via $h \rightarrow W^* W^*$ should be observable at a 3$\sigma$ level or better for the mass range of $145 \text{ GeV} \lesssim m_h \lesssim 180 \text{ GeV}$. For 95% CL exclusion, the mass reach is $135 \text{ GeV} \lesssim m_h \lesssim 190 \text{ GeV}$.

Our results presented here are valid not only for the SM Higgs boson, but also for SM-like ones such as the lightest supersymmetric Higgs boson in the decoupling limit [28]. A Higgs mass bound can be translated into exploring fundamental parameters for a given theoretical model, as shown in Ref. [29]. Furthermore, if there is an enhancement for $\Gamma(h \rightarrow gg) \times BR(h \rightarrow WW, ZZ)$ over the SM expectation, or if $BR(h \rightarrow b\bar{b})$ is suppressed, such as in certain parameter region in SUSY [30], the signals of Eq. (4) would be more substantial and more valuable to study. We can make our study more general in this regard by considering the quantity $\sigma(h) \times BR(h \rightarrow W^* W^*)$ as a free parameter. Define a ratio of this parameter
FIG. 14. The integrated luminosity required to reach 3σ statistical significance and 95% CL exclusion versus \( m_h \) in combining both channels \( h \to W^*W^* \to \ell\bar{\ell}\nu\bar{\nu} \) and \( W^\pm h \to W^*W^*, Z^*Z^* \to \ell^\pm\ell^\pm jj \) for (a) statistical effects only; (b) 10% systematic error included for these two channels.

to the SM expectation for the signal to be

\[
R = \frac{\sigma(h) \times BR(h \to W^*W^*)_{\text{NewPhysics}}}{\sigma(h) \times BR(h \to W^*W^*)_{\text{SM}}}.
\] (33)

Measuring \( R \) would represent a generic Higgs boson search in a model-independent way. Figure 15 gives the 95% CL exclusion for the ratio \( R \) versus \( m_h \) for several values of the integrated luminosity, where \( R = 1 \) corresponds to the SM expectation. Figure 15(a) is for the channel Eq. (31) where we have only included the gluon-fusion contribution, and Fig. 15(b) for Eq. (32). On the other hand, once a Higgs boson signal is established, a careful examination of \( R \) would help confirm the SM or identify possible new physics.

Finally, we would like to point out that further improvement on our results is still possible by including other channels. Although there would be even larger SM backgrounds, the channel \( h \to W^*W^* \to \ell\nu jj \) was found [21] to be helpful in improving the Higgs boson coverage. Combining with \( h \to Z^*Z^* \to \ell\ell jj \) as shown in Fig. 2 we would expect some possible improvement which deserves further study. The channels \( h \to Z^*Z^* \to \ell\ell\nu\bar{\nu}, 4\ell \) may have smaller SM backgrounds, especially for the 4\ell mode. Unfortunately, the signal rate would be very low for the anticipated luminosity at the Tevatron. It is nevertheless prudent to keep them in mind in searching for the difficult Higgs boson signal.

In summary, we have demonstrated the feasibility for an upgraded Tevatron to significantly extend the Higgs boson mass coverage. The Fermilab Tevatron with luminosity upgrade will have the potential to significantly advance our knowledge of Higgs boson physics.

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FIG. 15. 95% CL exclusion for the ratio $R$ [Eq. (33)] versus $m_h$ for several values of the integrated luminosity, (a) for the channel Eq. (31), and (b) for Eq. (32).

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