Possible Detection of a Higgs Boson at Higher Luminosity

Hadron Colliders

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Abstract

We have examined how a Standard Model or Supersymmetric Higgs boson $h$ might be detected at possible hadron colliders. The channels $W(\rightarrow \ell\nu)h(\rightarrow b\bar{b})$, $Z(\rightarrow \ell\bar{\ell})h(\rightarrow b\bar{b})$ and $W,Z(\rightarrow q\bar{q})h(\rightarrow \tau^+\tau^-)$ are most useful. The results imply that $h$ with mass $M_h$ can be detected or excluded for $80 \text{ GeV} \lesssim M_h \lesssim 130 \text{ GeV}$ at any hadron collider with energy $\sqrt{s} \gtrsim 2 \text{ TeV}$ and an integrated luminosity $L \gtrsim 10 \text{ fb}^{-1}$; high luminosity is the essential requirement. For $L \gtrsim 30 \text{ fb}^{-1}$, the $M_h$ reach is expanded beyond 130 GeV. A $p-\bar{p}$ collider is slightly better than a $p-p$ collider of equal $\sqrt{s}$ and $L$ for Higgs detection. We comment on measuring $h$ couplings and branching ratios.
I. INTRODUCTION

Understanding the physics of the Higgs sector is the central task of particle physics today. This is necessary to complete the Standard Model (SM), and the result will help point the way to extending the SM and strengthening its foundations. Probably it will be necessary to detect or exclude a Higgs boson to make progress.

Discussing a Higgs boson in the SM is subtle, because no way is known to maintain a light Higgs boson if any high scale exists. If the apparent perturbative unification of the SM gauge couplings \[1\] at a scale of the order \(10^{16}\) GeV is not dismissed as a meaningless accident, then there is an upper limit of about 200 GeV on the mass of the SM Higgs boson \(h_{SM}\) \[2\]. In any supersymmetric theory, this upper limit drops to about 150 GeV \[3\]. These arguments are general. While such indirect reasoning may not satisfy everyone, they surely imply that the highest priority should be to search for the Higgs boson in the mass range below about 200 GeV. Its discovery will indicate that supersymmetry (SUSY) is probably realized in Nature, while its exclusion will be the final chapter of low energy SUSY.

To put it succinctly, the best arguments known today imply that the region \(M_h = 60–200\) GeV is the most important one, and we have focussed on the most difficult part: \(80\) GeV \(\lesssim M_h \lesssim 130\) GeV. The region below 80 GeV will be covered at LEP2, while the region above 145 GeV is rather easily studied at a hadron collider with enough energy and luminosity in any case. For 130–145 GeV, the situation needs to be analyzed in detail for a given collider; we think this region can also be covered. The remaining mass region, covering the gap from LEP2 up to about 125 GeV, is generally thought to be coverable by the rare two photon decay of \(h\) at the CERN LHC. This requires an LHC electromagnetic calorimeter with excellent energy resolution and pointing capabilities that is, additionally, radiation hard.

We find that the inclusive production \(p + p(\bar{p}) \rightarrow h + X\) is not helpful to detect or exclude \(h\), because of a combination of small cross sections and large QCD backgrounds, for hadron colliders with \(\sqrt{s} \lesssim 14\) TeV and instantaneous luminosity \(L < 10^{34}\)cm\(^{-2}\)s\(^{-1}\).
However, the associated production processes $W + h$ and $Z + h$ can provide a signal for $h$ in several decay channels: $W(\rightarrow \ell\nu)h(\rightarrow b\bar{b})$, $Z(\rightarrow \ell\ell)h(\rightarrow b\bar{b})$ and $W, Z(\rightarrow qq)h(\rightarrow \tau^+\tau^-)$. The channels with $W, Z \rightarrow$ quark jets and $h \rightarrow \tau^+\tau^-$ have not been considered elsewhere to our knowledge.

We have examined many backgrounds to these processes, and present most of our results in terms of the number of signal events $S$ divided by the square root of the number of background events $B$, $S/\sqrt{B}$. We think it is appropriate to combine channels, so the final results are the combined significance for the four channels listed above. Somewhat surprisingly, we find that the behavior of signal and background with collider energy are such that there is little or no gain in going to higher energies. Rather, luminosity is the key variable for $M_h \lesssim 130$ GeV.

We find that, with an instantaneous luminosity $L$ of order $10^{33}\text{cm}^{-2}\text{s}^{-1}$, it is possible to detect or exclude $h_{SM}$ in the region $80$ GeV $\lesssim M_{h_{SM}} \lesssim 130$ GeV at a hadron collider with $\sqrt{s} \gtrsim 2$ TeV. Studies of supersymmetric theories [4] have shown that if the combined constraints of unification of the couplings, electroweak symmetry breaking and consistency with data are imposed, then the lightest SUSY Higgs boson behaves essentially identically to a light SM Higgs in all ways, so our results apply equally as well to the lightest SUSY Higgs boson of the constrained models. In this paper, we show results for a 2 TeV $p-\overline{p}$, 4 TeV $p-p$, and a 14 TeV $p-p$ collider with $L \gtrsim 10^{33}\text{cm}^{-2}\text{s}^{-1}$.

We assume a typical SSC or LHC detector is available to detect $h$. The detailed properties used in the analysis are described in Section 2. The most difficult requirement is that the detector must operate efficiently at luminosities of order $10^{33}\text{cm}^{-2}\text{s}^{-1}$. Sections 3–5 present the results for different channels, section 6 the combined results, section 7 comments on measuring $h$ properties, and section 8 some concluding remarks.

While we were preparing this paper, two other papers [5, 6] appeared on the same topic. Where we overlap, the cross sections and results are consistent. We have considered in addition the $W, Z(\rightarrow qq)h(\rightarrow \tau^+\tau^-)$ channels, so our conclusions are more favorable for Higgs detection.
II. EVENT SIMULATION

Calculations are parton level, unless a full simulation is needed for a given signal or background, based on the PAPAGENO \cite{7} and PYTHIA \cite{8} generators. We use $m_t = 150$ GeV, 2nd order running of $\alpha_s$ and CTEQ-1M structure functions. The signal and backgrounds to $\tau^+ \tau^- + \text{jets}$ (such as $W^{\pm} \rightarrow \tau^{\pm}\nu_{\tau} + \text{jets}$, with a real $\tau$ and a jet that fakes the hadronic decay of a $\tau$ in the final state) were estimated using PYTHIA with initial and final state showering and fragmentation. We use no “K-factors” for the signals or backgrounds in the individual channels considered, so our results will improve when radiative corrections are included. However, when presenting the combined significance of all channels in Figure 2, the effect of varying K over the region $1 \lesssim K \lesssim 1.2$ is illustrated by a light shaded band.

The following detector properties are implicit to this analysis:

- Hadron calorimetry resolution $60%/\sqrt{E} \oplus 4\%$ covering $|\eta| \leq 2.5$.
- Electromagnetic calorimetry resolution $7%/\sqrt{E} \oplus .5\%$ covering $|\eta| \leq 2.5$.
- Muon acceptance and momentum resolution comparable to electrons.
- Forward calorimetry covering to $|\eta| = 5$ and $\vec{E}_t$ resolution $40%/\sqrt{\vec{E}_t}$.
- A central tracker with good impact resolution and a high reconstruction efficiency to allow the tagging of $b$–jets and $\tau$ decays.

The choice of hadronic calorimetry is slightly worse than that available presently at the D0 detector at FNAL, but is slightly better than that at CDF. The excellent electromagnetic energy resolution was chosen for optimizing the $h \rightarrow \gamma \gamma$ and $h \rightarrow Z^{(*)}Z^{(*)}$ detection studies. Since these channels were found not to be significant with the Higgs mass range and integrated luminosity considered, such electromagnetic resolution is not essential to the remainder of this study.
III. $Z(\rightarrow \ell\bar{\ell})H(\rightarrow B\bar{B})$

The signal considered is $Z + h$, $Z \rightarrow \nu\bar{\nu}, e^+e^-$, or $\mu^+\mu^-$, and $h \rightarrow b\bar{b}$. In the SM, $BR(h \rightarrow b\bar{b}) = .83 (.65)$ for $M_h = 80 (120)$ GeV. The $Z$ boson decays to the lepton final states $\nu\bar{\nu}, e^+e^-$, and $\mu^+\mu^-$ with a branching ratio $\approx 27\%$.

The kinematic cuts requested for the leptons are:

- $p_\ell^2 > 20$ GeV, $|\eta| < 2.5$, and $|M_{\ell\bar{\ell}} - M_Z| < 5$ GeV, for $Z \rightarrow \ell\bar{\ell}, \ell = e, \mu$, and
- $E_t > 20$ GeV, for $Z \rightarrow \nu\bar{\nu}$.

We also require the reconstruction of 2 jets $j$, where $j$ is defined in the standard manner with $R = .6$ as the jet cone size, such that:

- $E_t^j > 20$ GeV and $|\eta^j| < 2.5$.

In addition, one can demand a $|\cos\theta^*|$ distribution for the jets, where $\theta^*$ is the decay angle of the jets in the jet–jet rest frame, that is consistent with higgs decay. We find that, after the previous cuts, such an additional cut is not effective and only reduces the significance of the signal.

Each jet $j$ is required to pass a single or double heavy flavor tag, where the efficiencies for tagging $b$–jets, $c$–jets, and $g, u, d, s$–jets as $b$–jets are $(\epsilon_b^b, \epsilon_c^b, \epsilon_j^b)$. We considered several sets of tagging efficiencies for both tagging scenarios. In this paper, we only report results for one scenario, $(40\%, 5\%, 1\%)$. We think this number is quite reasonable, since the optimal tagging efficiency will result from a combination of impact parameter, soft lepton, multivariate regression analysis, and other techniques. Recently, CDF estimated their b-tagging efficiency to be $\epsilon_b^b \approx .22$ [1].

The backgrounds considered are:

- $Z(\rightarrow \ell\bar{\ell})j_1j_2$, where $j_1, j_2$ are any combination of $g, u, d, s, c, or b$ (and their anti-particles),
• $Z(\rightarrow \ell\ell)Z(\rightarrow b\bar{b})$, and
• $t\bar{t} \rightarrow bW^+\bar{b}W^-$. The $W$-bosons produced in $t$–decay are allowed to decay to leptons or jets.

We emphasize that the $Z_{j_1 j_2}$ background includes $Zb j$ and $Zc j$ (where $j$ is specifically $g, u, d, s$ and their anti-particles) final states which are single tagged with efficiency $\simeq \epsilon_j^b$ and $\epsilon_c^b$ and double tagged with an efficiency $\epsilon_j^b \times \epsilon_j^b$ and $\epsilon_c^b \times \epsilon_j^b$, respectively. In Table 1(a) we list the signal and background for various hadron colliders, using a single $b$–tag at a 2 TeV $p\bar{p}$ collider and a double $b$–tag for a 4 TeV and 14 TeV $p\bar{p}$ collider, assuming 30 fb$^{-1}$ of integrated luminosity. The cross sections listed are those after all cuts and $b$–tag requirements. We also show the Gaussian width of the reconstructed signal and the significance.

Once a candidate bump is detected in the invariant mass spectrum of the reconstructed $b\bar{b}$ pair, the “signal” is the number of excess events over a smooth – relatively flat – background within $\pm 2 \sigma_M$ of the central value of the bump, where $\sigma_M$ is the Gaussian width of the observed signal. For $M_h = 80$ (120) GeV, $\sigma_M \simeq 5.5$ (7.2) GeV.

As pointed out by Gunion and Han [6], the semi–leptonic decays of the $b$– and $c$–quarks affect the reconstructed invariant mass of the $b$-quark pair from $h$ decay. In addition, final state showering will have an affect. From a full analysis of the fragmentation and decays of $h \rightarrow b\bar{b}$ using JETSET 7.4 [10], we find that the peak of the invariant mass distribution is nearly the same as for $h \rightarrow q\bar{q}$, where $q$ is a light quark, but the shape is skewed to lower values. The average of the distribution is typically 3–4 GeV below the peak. We feel that a $b$–jet reconstruction algorithm can be developed based on our knowledge of the $B$–meson mass and lifetime, the $b$–quark fragmentation function, the kinematics of semi–leptonic decays and a measurement of the $E_t$. If uncorrected, we find that tighter cuts on the non–Gaussian invariant mass distribution retain a signal with a significance reduced by 8–10%.
IV. $W(\rightarrow \ell \nu)H(\rightarrow B\bar{B})$

The signal considered is $W + h, W \rightarrow e\nu_e$ or $\mu\nu_\mu$, and $h \rightarrow b\bar{b}$. The $W$ boson decays to $e\nu_e$ and $\mu\nu_\mu$ with a branching ratio $\approx 2/9 = .22\%$.

The kinematic cuts requested for the leptons are:

- $p_t^\ell > 20$ GeV and $|\eta^\ell| < 2.5$, $\ell = e, \mu$, and
- $E_t^\ell > 20$ GeV.

The same jet and tagging requirements are used as previously stated. The backgrounds considered are:

- $W^\pm(\rightarrow \ell^\pm\nu)j_1j_2$, where $j_1j_2$ are any combination of $g, u, d, s, c$, or $b$ (and their anti–particles),
- $W^\pm(\rightarrow \ell^\pm\nu)Z(\rightarrow b\bar{b})$,
- $t\bar{t} \rightarrow bW^+\bar{b}W^-$, and
- $q\bar{q}' \rightarrow W^* \rightarrow t\bar{b} \rightarrow b\bar{b}W^\pm(\rightarrow \ell^\pm\nu)$.

The $W$–bosons from $t$–decay are allowed to decay to leptons or jets.

In Table 1(b), we summarize the results for various hadron colliders in the same manner as for the $Z(\rightarrow \ell\ell)h(\rightarrow b\bar{b})$ channel. In Figure 1(a), we show a simulation of the signal and the background, with the background subtracted, in this channel for $M_h \simeq M_Z$ at a 2 TeV $p\bar{p}$ collider with an integrated luminosity of 30 fb$^{-1}$. In this figure, we have applied a single $b$-tag to all events.

V. $W/Z(\rightarrow JJ)H(\rightarrow \tau^+\tau^-)$

The final signal considered here is $W/Z + h, W/Z \rightarrow$ jets, $h \rightarrow \tau^+\tau^-$. In the SM, the $BR(h \rightarrow \tau^+\tau^-)$ is .080 (.067) for $M_h = 80$ (120) GeV. For this channel, we do not use the
leptonic decays of the heavy gauge bosons to reduce backgrounds, but, rather, the fact that \( \tau \) decays have a low multiplicity of secondaries and can produce a large \( E_t \). The dominant \( \tau \) decay modes are:

- \( BR(\tau^\pm \rightarrow \ell^\pm \nu_\ell \nu_\tau) \simeq 35\%, \ell = e, \mu, \) and

- \( BR(\tau^\pm \rightarrow h^\pm + \geq 0 \text{ neutrals}) \simeq 50\% , \)

where \( h^\pm \) includes \( \pi^\pm, \rho^\pm, \) and \( K^\pm \). The remaining significant decay modes contain 3 charged pions and zero or more neutral particles.

Since the \( \tau \) pairs produced from \( h \) decay are extremely energetic compared to \( m_\tau \) and have low multiplicities, the decay products of each \( \tau \) travel nearly in the same direction as the parent \( \tau \). Therefore, the measurement of the momentum of the secondary charged track determines, to high accuracy, the primary \( \tau \)'s direction of motion. The measured \( E_t \) vector, projected onto the charged track’s direction, determines the full \( p_t \) of the \( \tau \). Given the \( p_t \) of the \( \tau \) and assuming all the decay products point in the direction of the observed charged track (which is also, by assumption, the moving direction of the \( \tau \)), we fully reconstruct the \( \tau \) momentum. The reconstruction works much better if the \( \tau \) pair system is boosted, thereby removing the possibility that the \( E_t \) of the neutrinos totally destructively interfere.

Once the momentum of the \( \tau \)'s has been reconstructed in this method, the validity of the approximation can be tested. Taking, for example, the case \( \tau^\pm \rightarrow \pi^\pm \nu_\tau \), the goodness of the reconstruction is tested by evaluating \( \cos \delta = 1 - \frac{m_\tau^2}{E_\pi E_\nu} \) for each \( \tau \), where \( E_\nu \) and \( E_\pi \) are the energies of the reconstructed neutrino and measured charged track, respectively. The \( \tau \) with the smallest value of \( \cos \delta \) has been reconstructed more poorly than the other. For this \( \tau \), the \( E_t \) should not be projected onto the charged track’s direction of motion, but, rather, onto a vector lying on a cone with opening angle \( \delta \) with respect to the charged track. By proceeding in this manner and choosing the neutrino direction of motion on this cone that minimizes the invariant mass of the \( \tau \) pair, a better estimate is made of the invariant mass. This method is just a crude attempt at obtaining a better measurement of \( m_{\tau^+\tau^-} \), and a more detailed algorithm will do better.
Since a good measurement of $E_t$ is needed, we do not consider the leptonic decays of the $W$ or the neutrino channels of the $Z$, but, instead, reconstruct the $W$ or $Z$ in jets. Fortunately, this still leads to a detectable signal. Concentrating on the one-prong final states of the $\tau$, there are $\tau^+\tau^-$ final states $\ell^+\ell^-$, $\ell^+\pi^-$, $\pi^+\ell^-$, and $\pi^+\pi^-$. Here, and in the following discussion, $\ell$ refers to $e$ or $\mu$, while $\pi$ includes $\rho$ and $K$ mesons. The previously discussed channels all contained a high $p_t$ charged lepton, $E_t$, or combination of these to use as a trigger. It is reasonable that a combination of $E_t$ and the isolation of the $\pi$ from neighboring hadronic activity can be used to trigger on the $\pi^+\pi^-$ final states. We considered two cases, without and with an isolated $\pi$ trigger. The $\ell^+\ell^-$, $\ell^+\pi^-$, and $\pi^+\ell^-$ final states have a combined branching ratio of .47, while including the $\pi^+\pi^-$ final states increases this to .72.

Each event must contain at least 2 jets $j$, defined with $R = .6$, and 2 reconstructed $\tau$’s satisfying the following requirements:

- $E_t^j > 15$ GeV, $|\eta|^j < 2.5$,
- $M_W - 15$ GeV $< M_{jj} < M_Z + 15$ GeV,
- $p_\tau^j > 20$ GeV and $|\eta^\tau|^j < 2.5$,
- $E_t > 20$ GeV, and
- $m_T^{(lo)} > 20$ GeV, $m_T^{(hi)} > 40$ GeV, where $m_T$ is the transverse mass of the leptons or hadrons from the $\tau$ decays and $E_t$, and (lo) and (hi) refer to the smaller and larger values of $m_T$.

The one-prong decays of the $\tau$ are reconstructed by finding a charged track ($t$), with $p_t^{(t)} > 5$ GeV, $|\eta^{(t)}| < 2.5$, pointing to the center of a narrow calorimeter bump, so that $\Delta R_{(t)j} \leq .15$. $m_{\tau+\tau-}$ is reconstructed by projecting the measured $E_t$ onto the two charged tracks, as explained previously, keeping only those events that give a positive magnitude for the reconstructed $p_t^\tau$. 
The backgrounds are events with two leptons or one lepton and a jet that fakes the hadronic decay of a $\tau$, a large $E_t$, and a combination of jets that give an invariant mass near the $W$ or $Z$ mass. The jet that fakes the hadronic decay of a $\tau$ must not only have a single charged track pointing to the core of its calorimetric cluster, but also a $E_t$ component pointing in its direction. We ignore the possibility of a large fake $E_t$ measurement because this is kinematically limited by the beam energy and $|\eta|$ coverage of the forward calorimeter. Even if a jet with the beam energy were lost “down the beam–pipe”, the maximal $E_t = E_{\text{beam}} \sin \theta \simeq \frac{1}{2} E_{\text{beam}} \exp^{-|\eta|}$, for small $\theta$ measured from the beam–pipe. All the backgrounds considered, then, have at least one neutrino from the decays of $W$’s or $Z$’s.

The backgrounds considered are:

- $W^\pm(\rightarrow jj)Z(\rightarrow \tau^+\tau^-)$,
- $Z(\rightarrow jj)Z(\rightarrow \tau^+\tau^-)$,
- $t\bar{t} \rightarrow \ell + \text{jets or } \ell\ell' + \text{jets}$, where $\ell, \ell' = e, \mu, \tau$,
- $W^\pm(\rightarrow \ell^\pm\nu)+\text{jets}$, where $\ell = e, \mu, \tau$, and
- $Z(\rightarrow \tau^+\tau^-)jj$.

The probability that a jet is tagged as a $\tau$ is estimated, very conservatively, at 5%, based on a particle–level simulation including fragmentation. This estimate relies only on the charged track multiplicity, not on a shower–shape analysis, which could significantly reduce this number [12]. The $t\bar{t}$ and $W^\pm + \text{jets}$ backgrounds are estimated by first finding a candidate jet that can fake the hadronic decay of the $\tau$, then multiplying the final event rate by this probability. The decay $b \rightarrow c\tau\nu_\tau$ is included in the JETSET decay tables, which were used in estimating the jet misidentification probability for $b$–, $c$– and light quarks and gluons.

We considered the scenario where only the leptonic $\tau$ decays can be used as a trigger ($\ell$ trigger) and where the single-charged track decays can be used as well ($\pi$ trigger). The results
presented assume an isolated $\pi$ trigger. The loss of significance of the signal in using only the $\ell$ trigger is typically 35%. Because of the importance of the resonant background $Z(\rightarrow \tau^+\tau^-)jj$, the significance of the signal is calculated using MINUIT, which accounts for the shape of the signal and background. We stress that this background will be normalized to high accuracy by observed $e^+e^-jj$ and $\mu^+\mu^-jj$ events and assuming lepton universality. In Table 1(c), we summarize our significance results for various hadron colliders by presenting the number of signal events for 30 fb$^{-1}$ of data and the error on this number as determined by a functional fit to the signal and background. The significance is the ratio of these numbers, which correspond to $S$ and $\sqrt{B}$ in the previous discussion of significance. We do not present results for $M_h \simeq M_Z$ or for a collider with $\sqrt{s} = 14$ TeV, since, for those cases, a significant signal could not be found in this channel. In Figure 1(b), we show a simulation of the signal and the background, with the background subtracted, in this channel for $M_h = 120$ GeV at a 2 TeV $p-\bar{p}$ collider with an integrated luminosity of 30 fb$^{-1}$.

Since $\tau$ signatures at hadron colliders have not been well-studied, we suggest several improvements which will increase the significance of this channel once they are included:

- A better estimate of jet rejection will eliminate backgrounds to the hadronic $\tau$ decay modes.
- Incorporating the correct polarization for $\tau$ decays may be useful, since $\tau$’s from $h$ decay lead to a soft-soft and hard-hard momentum correlation between the two charged hadrons.
- An impact parameter cut would reduce drastically all but the real $\tau$ and heavy quark backgrounds.
- Inclusion of the 3-prong decays of the $\tau$ will increase the signal event rate by 28%. Jet backgrounds can be reduced by using the kinematic constraint $m_{\pi\pi\pi} < m_\tau$ for the three charged tracks $\pi$.
- Better mass resolution, based on a more sophisticated $\tau$ reconstruction algorithm, will
reduce the contribution of $Z(\rightarrow \tau^+\tau^-)jj$.

- If all or some of the above improvements can be realized, the direct production process $p + p(\bar{p}) \rightarrow h(\rightarrow \tau^+\tau^-) + X$ [14], which has a larger cross section but potentially more backgrounds, may be accessible.

VI. COMBINED SIGNIFICANCE

The significance of a signal $S$ above a background $B$, $S/\sqrt{B}$ in the case of large statistics for a signal bump on a flat background, is a measure of the probability that the background has fluctuated up to fake the signal. The probability is the same as exceeding $S/\sqrt{B}$ standard deviations of a Gaussian probability function. When combining two signals, where the probability that the background has fluctuated up to the signal is $p_1$ and $p_2$, respectively, one has several options: (1) use $p_1 \times p_2$ as the combined probability, (2) use $\alpha(1 - \ln \alpha)$, where $\alpha = p_1 \times p_2$, as a statistic, and determine the probability that a second measurement $\alpha' = p_1' \times p_2' < \alpha$, or (3) combine the two signals and backgrounds as though coming from the same experiment. Method (1) will reject the hypothesis that the signal is consistent with background if $p_1$ is very small, even if $p_2 \approx 1$. Method (2) compensates for this by sampling all combinations of $p_1$ and $p_2$ that could lead to a given $\alpha = p_1 \times p_2$. Method (3) treats the two measurements as independent data sets which are used to test the hypothesis that the signal is consistent with background in exactly the same way. Methods (1) and (2) will differ significantly only in extreme cases, which are not present in this analysis. For the cases when all channels yield a significance $\sim 5$, we simply use method (3); otherwise, we use method (1), since we desire a high significance in only one channel.

Figure 2 shows the combined significance of all channels considered in this study as a function of $M_h$. Figure 2 contains three graphs, one for each hadron collider option, and each graph contains two separated bands, which are further divided by different shadings. The upper bands show the significance for an integrated luminosity of 30 fb$^{-1}$, the lower bands for 10 fb$^{-1}$. The dark shading shows the range of significance from varying the $Q^2$
scale of the Electroweak-QCD background processes from $\bar{m}^2_T$ to $\hat{s}/2$. $\bar{m}^2_T$ is the square of the average transverse mass $m_{Tj}$ of the outgoing partons $j$ of mass $m_j$, $m_{Tj} = \sqrt{p_{Tj}^2 + m_j^2}$, and $\hat{s}$ is the invariant mass of the hard-scattering parton process. The lower bound of the dark band corresponds to $Q^2 = \bar{m}^2_T$, the upper bound to $Q^2 = \hat{s}/2$. For example, at a $\sqrt{s} = 2$ TeV hadron collider with and integrated luminosity $\mathcal{L} = 30$ fb$^{-1}$, the significance of the signal for $M_h = 100$ GeV varies from 7.3 to 8.3 by choosing $Q^2 = \bar{m}^2_T$ or $\hat{s}/2$. Also, when radiative corrections are applied, typically the shape of kinematic distributions of a given process are only slightly changed, but the magnitude of the distribution is scaled by a “K–factor”. The light shading shows the range of significance from multiplying the signal by a “K-factor” of 1 to 1.2. Therefore, the absolute lower bound for each band in Figure 2 corresponds to $Q^2 = \bar{m}^2_T$ and K=1, the absolute upper bound to $Q^2 = \hat{s}/2$ and K=1.2.

Several comments concerning the results presented in Figure 2 are in order. First, the $Q^2$ dependence of the $W/Zjj$ backgrounds, which arises in evaluating the structure functions $f_i(x, Q^2)$ and $\alpha_s(Q^2)$, is more important at a lower energy collider \cite{13}. Since the kinematic cuts have been chosen to accept the signal efficiently, it is expected that the background which passes these same cuts has a topology similar to the signal with the Higgs resonance replaced by an off-shell gluon. In this case, a choice of $Q^2 = \hat{s}/2$ is better motivated than $\bar{m}^2_T$. Secondly, the $W, Z(\rightarrow q\bar{q})h(\rightarrow \tau^+\tau^-)$ channel increases the reach of the lower energy colliders. The increase of the $Zjj$, $t\bar{t}$, and $W +$ jet backgrounds and the decrease in importance of the $p + p \rightarrow W/Z + h$ processes make a signal in this channel untenable at $\sqrt{s} = 14$ TeV. Of course, higher luminosity and consideration of $p + p \rightarrow h(\rightarrow \tau^+\tau^-) + X$ might change this conclusion. Finally, though for brevity not presented here, we also considered a 4 TeV $p - \bar{p}$ hadron collider. For the same integrated luminosity, a 4 TeV $p - \bar{p}$ collider has a significance $\sim 20–30\%$ higher than a 4 TeV $p - p$ collider.
Ideally, it would be possible not only to detect a Higgs boson, but also to study its properties, establish that it interacted like a Higgs boson, and even distinguish $h_{SM}$ from $h_{SUSY}$. Showing that the spin of a detected $h$ is zero will not be hard. The important observables at a hadron collider are of the form $\sigma \times BR$. The full width $\Gamma_h$, for example, is probably too narrow to overcome experimental resolution. Using the decay modes discussed in this paper, the following set of equations can be written:

\[
\mathcal{L} \times \sigma_{W h} \times BR_b = N_b \\
\mathcal{L} \times \sigma_{W h} \times BR_\tau = N_\tau \\
BR_b + BR_\tau \approx 1,
\]

where $\sigma_{W h}$ is the cross section for the associated production of $h$ with $W$ or $Z$, $BR_b$, $BR_\tau$ are the branching ratios for $h(\rightarrow b\bar{b})$ and $h(\rightarrow \tau^+\tau^-)$, respectively, and $\mathcal{L}$ is the integrated luminosity of the collider in units of inverse cross section. Solving these equations allows us to write $\mathcal{L} \times \sigma_{W h} = N_b + N_\tau$. $N_i$ is the number of $i$ type events corrected for reconstruction efficiencies, tagging efficiencies, etc. From the number of observed events at a hadron collider, it will be possible to measure $g_{WW h}^2 \times BR_b, g_{ZZ h}^2 \times BR_b, g_{WW h}^2 \times BR_\tau,$ and $g_{ZZ h}^2 \times BR_\tau$. The ratio $BR_\tau/BR_b$ is predicted to be $\frac{m_\tau^2}{3m_b^2(M_h)} \simeq \frac{1}{9}$ for any gauge theory, since $b$ and $\tau$ are in the same position in any doublet; thus its measurement could establish that a detected boson was indeed coupling proportional to mass, but could never distinguish among theories. Similarly, since $BR_\mu/BR_\tau = \frac{m_\mu^2}{m_\tau^2} \simeq \frac{1}{300}$, no excess of events should be seen in $\mu^+\mu^-$ final states. Given $BR_b/BR_\tau$, the equality of the $WW h$ and $ZZ h$ couplings could be checked at a 2 TeV hadron collider.

We have not found a way to measure the $t\bar{t}h$ or $c\bar{c}h$ coupling at a low energy hadron collider; the first of them can be measured at LHC, which corresponds to the $\sqrt{s} = 14$ TeV collider considered here but with an instantaneous luminosity of $L = 10^{34}\text{cm}^{-2}\text{s}^{-1}$, and NLC. Measuring the $t\bar{t}h$ or $c\bar{c}h$ coupling could, in principle, distinguish among theories, since the relative coupling of $T_3 = \pm \frac{1}{2}$ states does depend on the theory, though in constrained SUSY
theories these couplings are expected to be very close to their SM values. The important \( \gamma \gamma \) coupling, with \( BR \simeq 10^{-3} \), can only be measured at LHC, where the cross section and luminosity are both large, or at a photon collider.

**VIII. CONCLUSIONS**

Developing the ability to do \( \tau \) physics at a hadron collider is a natural extension of the present ability to do heavy quark physics, and can have a significant impact on the ability to do Higgs physics at a hadron collider.

We see from Tables 1(a)–(c) and Figure 2 that the detection or exclusion of \( h \) for \( M_h \lesssim 130 \text{ GeV} \) is not only possible at a 2 TeV high luminosity p–p collider (10–30 fb\(^{-1}\)), it is competitive with – if not better than – hadron colliders at a higher \( \sqrt{s} \), because of the relative behavior of signal and backgrounds. The \( W, Z (\rightarrow jj)h(\rightarrow \tau^+\tau^-) \) channel is the strongest far enough above \( M_h \simeq M_Z \); near \( M_Z \), the \( W (\rightarrow \ell\nu)h(\rightarrow b\bar{b}) \) and \( Z (\rightarrow \ell\ell)h(\rightarrow b\bar{b}) \) channels are adequate. It is probably possible to detect \( h \) above 130 GeV, but more analysis is needed to establish that. The ratio of \( \tau^+\tau^- \) and \( b\bar{b} \) branching ratios and the ratio of the couplings of \( h \) to \( WW \) and \( ZZ \) can be measured at a 2 or 4 TeV hadron collider. The \( t\bar{t}h \) coupling and the \( \gamma \gamma \) branching ratio will probably only be accessible at LHC or NLC.

Our analysis shows that a p–p collider with \( \sqrt{s} = 2 \text{ TeV} \) and integrated luminosity \( \mathcal{L} \gtrsim 10 \text{ fb}^{-1} \) can detect or exclude a Higgs boson with a mass ranging from the present upper limit up to about 130 GeV (and perhaps higher), thus covering the region of greatest interest. This is a remarkable physics opportunity.
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TABLE I. (a) Sensitivity for the $Z(\rightarrow \ell\ell)h(\rightarrow b\bar{b})$ channel

| Mass (GeV) | 80 | 90 | 100 | 110 | 120 |
|------------|----|----|-----|-----|-----|
| $\sigma_M$ (GeV) | 5.5 | 6.0 | 6.5 | 7.0 | 7.4 |

| Cross Section (fb) | SM Higgs | 23. | 18. | 14. | 11. | 7. |
| $\sqrt{s} = 2$ TeV, $p\bar{p}$ | Backgrounds | 242. | 246. | 212. | 176. | 152. |
| $S/\sqrt{B}$ for 30 fb$^{-1}$ | 1 Tag | 8.0 | 6.2 | 5.0 | 4.2 | 3.0 |

| Cross Section (fb) | SM Higgs | 9.1 | 7.0 | 5.2 | 3.8 | 2.6 |
| $\sqrt{s} = 4$ TeV, $p\bar{p}$ | Backgrounds | 56. | 62. | 52. | 43. | 40. |
| $S/\sqrt{B}$ for 30 fb$^{-1}$ | 2 Tags | 6.7 | 4.8 | 4.0 | 3.1 | 2.3 |

| Cross Section (fb) | SM Higgs | 40.0 | 32.0 | 25.4 | 19.4 | 13.4 |
| $\sqrt{s} = 14$ TeV, $p\bar{p}$ | Backgrounds | 494. | 552. | 508. | 459. | 449. |
| $S/\sqrt{B}$ for 30 fb$^{-1}$ | 2 Tags | 9.7 | 7.4 | 6.2 | 5.0 | 3.5 |
### TABLE I. (b) Sensitivity for the $W(\to \ell\nu)h(\to b\bar{b})$ channel

| Mass (GeV) | 80 | 90 | 100 | 110 | 120 |
|------------|----|----|-----|-----|-----|
| $\sigma_M$ (GeV) | 5.5 | 6.0 | 6.5 | 7.0 | 7.4 |
| Cross Section (fb) | SM Higgs | 26. | 20. | 15. | 11. | 7. |
| $\sqrt{s} = 2$ TeV, $p\bar{p}$ | Backgrounds | 303. | 303. | 272. | 240. | 207. |
| $S/\sqrt{B}$ for 30 fb$^{-1}$ | 1 Tag | 8.1 | 6.1 | 4.8 | 3.8 | 2.7 |
| Cross Section (fb) | SM Higgs | 10.5 | 7.9 | 6.0 | 4.4 | 2.9 |
| $\sqrt{s} = 4$ TeV, $p\bar{p}$ | Backgrounds | 42. | 48. | 41. | 36. | 34. |
| $S/\sqrt{B}$ for 30 fb$^{-1}$ | 2 Tags | 8.8 | 6.2 | 5.2 | 4.0 | 2.8 |
| Cross Section (fb) | SM Higgs | 41.3 | 32.2 | 26.1 | 20.0 | 13.8 |
| $\sqrt{s} = 14$ TeV, $p\bar{p}$ | Backgrounds | 458. | 518. | 511. | 520. | 540. |
| $S/\sqrt{B}$ for 10 fb$^{-1}$ | 2 Tags | 10.5 | 7.8 | 6.4 | 4.9 | 3.3 |

### TABLE I. (c) Sensitivity for the $Z/W(\to jj)h(\to \tau^+\tau^-)$ channel

| $\sqrt{s}$ = 2 TeV | Signal Events | 83.8 | 47.3 |
|---------------------|---------------|------|------|
| $p\bar{p}$          | Error on Signal | 14.5 | 9.1  |
| $\mathcal{L} = 30$ fb$^{-1}$ | Significance | 5.8  | 5.2  |
| $\sqrt{s}$ = 4 TeV | Signal Events | 127.5 | 72.1 |
| $p\bar{p}$ | Error on Signal | 30.2 | 23.7 |
| $\mathcal{L} = 30$ fb$^{-1}$ | Significance | 4.2  | 3.0  |
FIGURES

FIG. 1. (a) $W(\rightarrow \ell\nu)h(\rightarrow b\bar{b})$ signal. We show the case $M_h \simeq M_Z$ to illustrate the ability to discriminate $h$ from $Z$.

FIG. 1. (b) $W/Z(\rightarrow jj)h(\rightarrow \tau^+\tau^-)$ signal. $M_h = 120$ GeV.

FIG. 2. Combined significance. See the text for details.

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