Standard model Higgs physics at a 4 TeV upgraded Fermilab Tevatron

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We compute an array of standard model Higgs boson (H) signals and backgrounds for a possible upgrade of the Fermilab Tevatron to $\sqrt{s}$=4 TeV. Taking $m_t \geq 140$ GeV, and assuming a total accumulated luminosity of L=30 fb^{-1}, we find that a standard model Higgs boson with $m_H \lesssim 110$ GeV could almost certainly be detected using the $W^{\pm}H \to l\nu b\bar{b}$ mode. A Higgs boson with a mass between $\sim$120 GeV and $\sim$140 GeV or above $\sim$ 230–250 GeV almost certainly would not be seen. A Higgs boson with $m_H \sim 150$ GeV or $200 \lesssim m_H \lesssim$ 230–250 GeV has a decent chance of being detected in the $ZZ \to 4l$ mode. There would also be some possibility of discovering the H in the $WW \to l\nu jj$ mode for $150 \lesssim m_H \lesssim 200$ GeV. Finally, hints of an event excess in the $WW \to ll\nu\nu$ mode due to the H might emerge for $140 \lesssim m_H \lesssim 180$ GeV. Given the difficult nature of the Higgs boson signals for m_H values beyond the reach of CERN LEP 200, and the discontinuous m_H range that could potentially be probed, a 4 TeV upgraded Tevatron would allow a much less comprehensive search for a standard model Higgs boson than the CERN LHC.

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I. INTRODUCTION

Given the cancellation of the Superconducting Super Collider (SSC), it is important to reassess the possibilities for exploring the electroweak symmetry breaking (EWSB) sector at possibly available machines. Here we focus on the standard model (SM) Higgs boson (H). It is well known that the CERN Large Hadron Collider (LHC) can find the H for all masses between about 80 GeV and $\sim$800 GeV [1], and possibly explore a strongly interacting EWSB sector that would arise for very large effective m_H values [2]. However, the time scale for construction of the LHC may be quite long without significant U.S. participation. The question arises as to whether the U.S. should consider an alternative investment of the same money in existing U.S. laboratories. A Fermilab Tevatron upgrade to the $p\bar{p}$ center-of-mass energy $\sqrt{s}$=4 TeV with yearly luminosity of L=10 fb^{-1} has emerged as a subject of discussion in this context [3]. The possibility of a pp collider with L=100 fb^{-1} is even being considered. Here, we present a first-level examination of the ability of such upgraded Tevatrons (UT's) to probe the SM Higgs sector. In particular, we wish to establish the extent to which an upgraded Tevatron can search for Higgs bosons with mass beyond the reach of LEP-200 (i.e., LEP-II operated at $\sqrt{s}$=200 GeV). We compute signals and those backgrounds that are not highly detector dependent for all conceivably useful channels. In some cases we compare results for a detector similar to the current Collider Detector at Fermilab (CDF) and D0 detectors to those for a more optimized detector.

Current LEP and Tevatron data are on the verge of playing a significant role in placing limits on the allowed range of m_H in the SM. For instance, should m_t be of order 170 GeV, fits to the precision electroweak data from LEP and elsewhere imply that $m_H \gtrsim 150$ GeV in order

to be less than 2 standard deviations away from the best fit value of $m_H \sim 800$ GeV [4]. While this indication of a heavy Higgs boson in the SM is clearly quite preliminary at this point in time, a determination at the Tevatron of m_t, coupled with still more precise LEP data, may well pinpoint a favored region for m_H.

We now list the discovery channels for the H that we have considered. For those modes that contain charged leptons (l) we retain only events with $l = e, \mu$. The production and/or decay modes of interest in rough order of utility are the following.

(1) Associated $W^{\pm}H$ production followed by $W \to l\nu$ and $H \to b\bar{b}$, leading to an $lb\bar{b}$ final state. This final state has been considered in the context of the SSC and/or LHC (where $t\bar{t}H$ production with $t \to Wb$ is the dominant source) in Ref. [5] and for the Tevatron (where $W^* \to WH$ dominates) in Ref. [6]. For $W^* \to WH$, single or double b tagging is employed to isolate the final state of interest. However, even with b tagging, the $W^{\pm}jj$ background is significant, and the $W^{\pm}b\bar{b}$ and $W^{\pm}Z \to W^{\pm}b\bar{b}$ processes are irreducibly present.

(2) Associated ZH production followed by $Z \to 2l$ and $H \to b\bar{b}$. Backgrounds are the Z versions of the ones noted above [6].

(3) Inclusive H production followed by $H \to ZZ^* \to 4l$ decay. It is well established [7–9] that there is no sizable background to this channel for $m_H < 2m_Z$. The only significant background for $m_H > 2m_Z$ is from the $ZZ \to 4l$ continuum. However, the signal rates are low [10].

(4) Inclusive H production followed by $H \to W^+W^- \to l\nu jj$. Backgrounds include the mixed QCD-EW $W^{\pm}jj$ processes, the W^+W^- continuum, and $t\bar{t} \to W^+W^-X$. However, this latter background is easily eliminated by vetoing against extra jet activity.

(5) Inclusive H production followed by $H \to W^+W^- \to 2l2\nu$. Assuming we stay away from $2l$ masses in the vicinity of m_Z, and veto events with significant jet

activity in the central region (such as those that might come from $t\bar{t}$ production [11]), the only large backgrounds are from continuum W^+W^- and $\tau^+\tau^-$ production. The latter background can be reduced to a negligible level by an appropriate cut on the transverse-plane angle between the two final leptons.

(6) Inclusive H production followed by $H \rightarrow ZZ \rightarrow ll\nu\nu$. The $ZZ \rightarrow ll\nu\nu$ continuum background is certainly present (and will be the only one considered here), but there are other detector-dependent backgrounds that could be large, e.g., Zg production with g yielding little visible energy. This latter background can be eliminated at high ZZ invariant mass by requiring very small transverse hadronic energy in association with the two leptons [12,8], but no studies have been performed at the low ZZ masses of relevance here.

(7) Inclusive H production followed by $H \rightarrow ZZ \rightarrow 2ljj$. Backgrounds include the mixed QCD-EW Zjj processes and the ZZ continuum.

(8) Inclusive H production followed by $H \rightarrow \gamma\gamma$ decay. The primary background for a detector with excellent jet and/or photon discrimination power is the irreducible $q\bar{q} \rightarrow \gamma\gamma$ continuum.

(9) Inclusive H production followed by $H \rightarrow \tau^+\tau^- \rightarrow 2l4\nu$ decay. The primary backgrounds are the Drell-Yan processes $\gamma^*, Z \rightarrow \tau^+\tau^-$ and $l\bar{l}$, and $W^+W^- \rightarrow 2l2\nu$.

Of these processes we find that only four have any real chance of being useful. Assuming a total accumulated luminosity of L=30 fb^{-1}, we will see that the $W^\pm H \rightarrow l\nu b\bar{b}$ channel, with single or double b tagging, can be used to detect a standard model Higgs boson for $m_H \lesssim$ 110–120 GeV. However, other modes must be considered at higher mass. A Higgs boson with $m_H \sim$150 GeV or $200 \lesssim m_H \lesssim$230 GeV has a decent chance of being detected in the rather clean, but event-rate-limited, $ZZ \rightarrow 4l$ mode. There would also be some possibility of discovering the H in the $WW \rightarrow l\nu jj$ mode for $150 \lesssim m_H \lesssim$200 GeV. However, to do so requires detection of a $\sim$30 GeV wide mass peak over a broadly peaked background that is 50 to 100 times larger. In the $WW \rightarrow 2l2\nu$ mode, the H leads to a broad 10–20% event excess in the dilepton mass distribution for $140 \lesssim m_H \lesssim$180 GeV. But, the signal and WW continuum background have very similar shapes. Since systematic uncertainties in the background normalization are unlikely to be brought much below the 10% level, this channel will probably at best provide only a hint of the presence of an H in this mass range. Regarding the $ZZ \rightarrow ll\nu\nu$ mode, nominal $S/\sqrt{B}$ values including only the ZZ continuum background are encouraging in the mass range $200 \lesssim m_H \lesssim$230–250 GeV, but we are unable to draw any final conclusions without further study of the very severe gZ and related backgrounds that were found to dominate at supercollider energies (depending upon the precise machine and detector design), but could easily be substantially smaller at the lower energy being considered here. A Higgs boson with mass between $\sim$120 GeV and $\sim$140 GeV or above $\sim$230–250 GeV almost certainly would not be seen. Our results are insensitive to m_t for values of $m_t \gtrsim$140 GeV.

Of course, it is interesting to know how crucial the up-

grade in energy to 4 TeV is for extending the Tevatron's ability to search for the SM Higgs boson, as compared to simply increasing the luminosity at the standard 2 TeV Tevatron energy. We briefly comment on this comparison for the $W^\pm H \rightarrow l\nu b\bar{b}$ channel, and present results for the $ZZ \rightarrow 4l$ mode in the Appendix.

At times we will quote $S/\sqrt{B}$ values for a given channel as an indication of the absolute best that one can achieve in the absence of systematic effects and/or additional backgrounds. The reader is warned to pay close attention to the comments associated with each channel, as for some channels these nominal $S/\sqrt{B}$ values are far higher than will be achieved in reality, serving only to indicate an initial "starting point" before including all additional effects. In the absence of systematic effects we regard $S/\sqrt{B} \sim$5 as an appropriate criterion for discovery.

Before proceeding to our detailed results, it is useful to first present the total cross sections for the various production reactions of interest. These appear in Fig. 1. In this figure, as well as later graphs, we have included K factors of 1.5 and 1.2 for the $gg \rightarrow H$ [13] and $W^\pm H$ (and ZH) [14] associated production processes, respectively.[1] We have chosen to use the D0′ set of parton distribution functions by Martin, Roberts, and Stirling (MRS) [15]. The most important point to note from Fig. 1 is the fact that in the low m_H region of interest the gg fusion cross section is relatively independent of m_t once $m_t \gtrsim$140 GeV, i.e., once m_H is substantially below $2m_t$. (A curve for m_t=80 GeV is shown to illustrate the much larger cross sections that were anticipated for H production in the $m_H \lesssim$200 GeV mass region when the top quark was not thought to be so heavy.) Second, we observe that the $VV \rightarrow H$ ($V = W^\pm, Z$) fusion cross section is at best about 10% of the $gg \rightarrow H$ fusion cross section, and that it will be difficult to separate out the low event rates and Higgs boson masses relevant for a 4 TeV Tevatron. Thus, we do not consider VV fusion in our analysis. Finally, we note that the $t\bar{t}H$ and $b\bar{b}H$ associated production processes are substantially smaller (by at least factors of order 20 and 5, respectively) than WH associated production, due to the relatively small gg luminosity at the UT. Consequently, these processes do not appear in the figure and are not considered further.

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[1]For many of the processes we consider the K factor adopted for the signal (K_S) is larger than that for the background (K_B). Thus, a more conservative approach would be to take $K_S = K_B$=1. The signal statistical significance $N_{SD} \equiv S/\sqrt{B}$ (where S and B are the signal and background rates, respectively) behaves as $N_{SD} \propto K_S/\sqrt{K_B}$ and the luminosity required to achieve a given N_{SD} level scales as K_B/K_S^2. The K factors employed in the paper reflect the best information available as of the moment. Certainly, the K factor for the $gg \rightarrow H$ process has been rather thoroughly studied and is known to be large in comparison to K factors for the typical background processes initiated by $q\bar{q}$ collisions that have been computed.
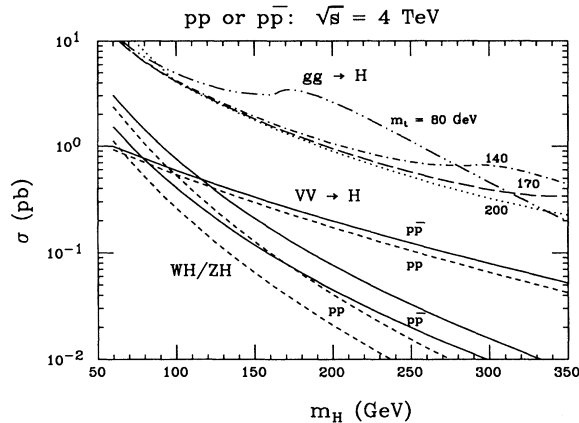
FIG. 1. Total cross sections for SM Higgs boson production (without cuts) are presented versus m_H at the upgraded Tevatron for the major reactions of interest.

II. FEASIBILITY FOR SM HIGGS BOSON SEARCHES AT AN UPGRADED TEVATRON

A. Detector characteristics and acceptance cuts

It is hardly necessary to dwell on the reasons for considering the various production and/or decay modes for H detection that we have outlined in the introduction. Thus, we shall proceed quickly to graphs of signal and background event rates, once some detector issues and choices have been discussed. Our approach with regard to the detector is to consider generic resolutions for (i) a detector very much like the current CDF and D0 detectors and (ii) a much more optimized detector, significantly upgraded from the current CDF and D0 detector characteristics. For case (i) we adopt energy resolutions given by

$$\frac{\Delta E}{E} = \begin{cases} \frac{0.3}{\sqrt{E}} \oplus 0.01 & \text{for } l = e, \mu , \\ \frac{0.8}{\sqrt{E}} \oplus 0.05 & \text{for jets} , \end{cases} \quad (1)$$

whereas for the optimized detector, case (ii), our resolutions are assumed to be

$$\frac{\Delta E}{E} = \begin{cases} \frac{0.2}{\sqrt{E}} \oplus 0.01 & \text{for } l = e, \mu \\ \frac{0.5}{\sqrt{E}} \oplus 0.03 & \text{for jets} . \end{cases} \quad (2)$$

While these latter performance characteristics exceed those of the existing CDF and D0 detectors, they are not dramatically better and could be achieved in an upgraded detector for the UT. Note that for simplicity we have chosen the same energy resolution for both e and μ. For μ's, our resolution parametrization may be rather optimistic, especially for very energetic muons, since their momenta are measured by bending in a magnetic field. For e's, a tracking detector with magnetic field may do better than assumed above.

We will also consider two possibilities for acceptance cuts. In the first, labeled as case (a), we impose the

following cuts on leptons included in our triggering or mass distributions:

$$\begin{aligned} & p_T^l > 20 \text{ GeV} , \\ & |y_l| < 2.5 , \quad \Delta R_l > 0.7 , \quad (3) \\ & p_T^{\text{miss}} > 20 \text{ GeV} . \end{aligned}$$

Here, ΔR_l is the minimum separation of the lepton in question from all other jets and leptons. The p_T^{miss} cut is, of course, only relevant for processes with $W \to l\nu$. These conservative acceptance cuts will be contrasted with more optimistic choices, labeled as case (b):

$$\begin{aligned} & p_T^l > 10 \text{ GeV} , \\ & |y_l| < 2.5 , \quad \Delta R_l > 0.3 , \quad (4) \\ & p_T^{\text{miss}} > 15 \text{ GeV} . \end{aligned}$$

Non-b jets that are specifically utilized are required to have

$$p_T^j \geq 15 \text{ GeV}, \quad |y_j| \leq 2.5, \quad \Delta R_j \geq 0.7 , \quad (5)$$

where ΔR_j is the separation from other jets. We assume that any given b jet can be tagged with 30% efficiency and 99% purity for

$$p_T^b \geq 15 \text{ GeV}, \quad |y_b| < 2 , \quad (6)$$

provided the b is separated by an appropriate ΔR_b from neighboring b and light quark and/or gluon jets. For case (a) cuts we require $\Delta R_b > 0.7$, while for case (b) we require $\Delta R_b > 0.5$. We note that trigger rate should not be a problem for the less severe lepton acceptances. The issue is whether or not they can be employed in the analysis for a given type of signal without increasing the contamination from background processes other than those we explicitly compute. Clearly, this is at least partly a machine and detector dependent issue.

For some of the processes under consideration, the H signal is to be revealed as a mass peak in the $b\bar{b}$ decay channel. It is clearly important to consider the effect of the semileptonic b decays upon the mass resolution that can be achieved in this channel. In our analysis b quarks are allowed to decay semileptonically to $cl\nu$ according to the measured branching ratio. The result is a moderate broadening of the $b\bar{b}$ mass distribution compared to that obtained if semileptonic decays are not included. The broadening we compute could be either greater or less than that which will in fact occur. The fact that the b jet puts only a fraction of its momentum into the B meson that actually decays means that the neutrinos from the primary $b \to cl\nu$ decay of our computation are on the average more energetic than would be predicted in a full simulation. This effect means our broadening could be an overestimate. On the other hand, we do not include c decays, which sometimes also yield neutrinos (although relatively soft ones). Such neutrinos would cause additional broadening. We believe that our approximate treatment is adequate for this first survey of Higgs boson physics at

an upgraded Tevatron. Of course, one might also wish to consider the possibility of eliminating semileptonic b decays by rejecting events in which leptons are visible within the tagged b jet(s). This will yield a narrower $b\bar{b}$ distribution, but some events will be lost from the signal and background. Our estimate is that this would not result in a significant improvement in the observability of the signals being considered.

B. Detailed results

1. $W^{\pm}H \rightarrow l\nu b\bar{b}$

The most promising channel for H detection in the mass region $m_H \lesssim 120$ GeV is $W^{\pm}H \rightarrow l\nu b\bar{b}$ associated production, leading to the $lb\bar{b}X$ final state. In Fig. 2 we plot the event rate distribution as a function of the

$b\bar{b}$ mass, in the cases of both 1-b and 2-b tagging. For these plots we have demanded that the l satisfy the conservative acceptance cuts (a) outlined earlier. Resolutions employed are those for the conservative detector (i). Semileptonic b decays are incorporated using the procedure described above. (The effect of not including them is to narrow the signal peak, increasing the peak height by about 10%.) A QCD K factor of 1.2 has been included in the signal rates; no K factors are included in the background rates.

In order to assess the observability of these signals we have computed signal and background rates by simply looking for a peaking in $M_{b\bar{b}}$ and subtracting a smooth background estimated from surrounding mass bins. The statistical significances that could be achieved after optimizing the signal mass intervals appear in Tables I and II. The tables give signal and background rates, S and B, along with $S/\sqrt{B}$ for $L=30$ fb^{-1} at both a $p\bar{p}$ and
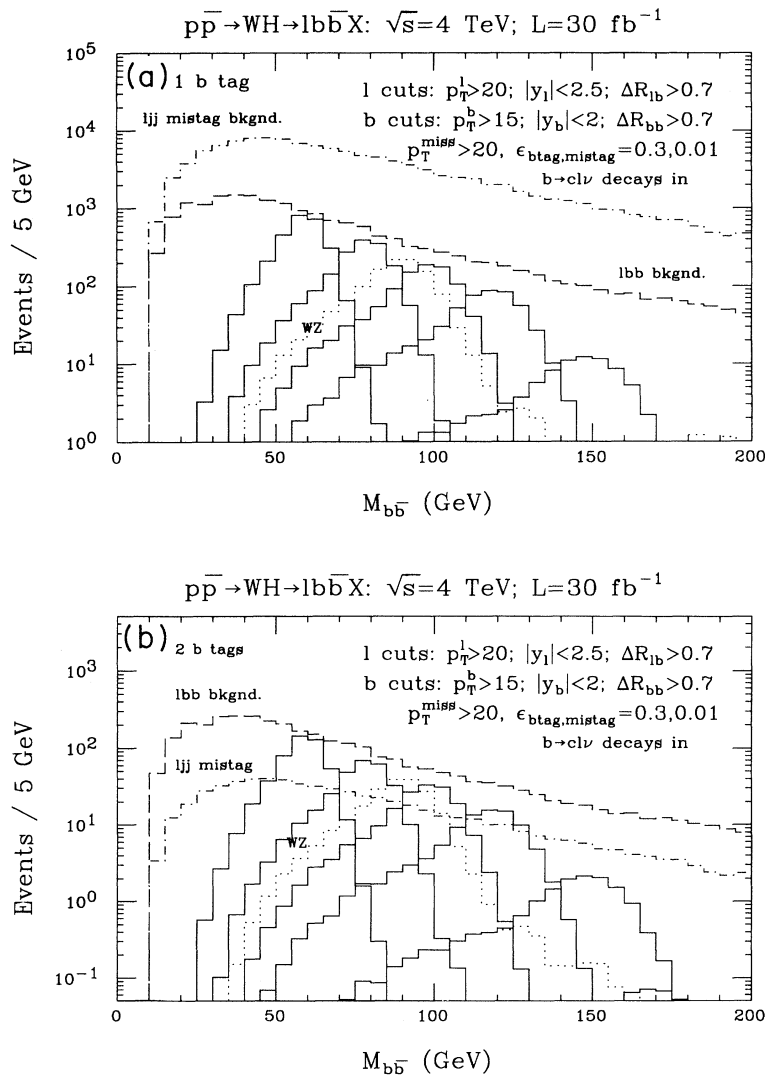

FIG. 2. The $M_{b\bar{b}}$ event rate distribution for $W^{\pm}H \rightarrow l\nu b\bar{b}$ associated production is plotted in 5 GeV bins, for the indicated lepton and b-jet cuts (see text for more details). Signals for m_H=60, 80, 100, 120, and 150 GeV are shown as the solid histograms. Also shown are the electroweak $WZ \rightarrow l\nu b\bar{b}$ background (dots) and the mixed QCD-EW continuum backgrounds from $W + 2j$ (dash-dot) and $W + b\bar{b}$ (dashes) production. Semileptonic b decays are included. b tagging is assumed to have 30% efficiency and 99% purity for the stated cuts. Graphs for both 1 and 2 b tags are shown. a K factor of 1.2 is included for the H signals. Conservative detector and/or cuts case (i)-(a) is employed.

TABLE I. We tabulate S, B, and $S/\sqrt{B}$ for $WH \to l b \bar{b} X$, at $p\bar{p}$ and pp colliders with L=30 fb^{-1} and $\sqrt{s}$=4 TeV, for a series of m_H values, using the tabulated mass bins. Also given is the L (in fb^{-1}) required for $S/\sqrt{B}$=5. This table is for a conservative detector, case (i), and conservative cuts (a).

m_H	ΔM	$n_{b\ tag}$	$p\bar{p}$				pp			
			S	B	$S/\sqrt{B}$	$L(5\sigma)$	S	B	$S/\sqrt{B}$	$L(5\sigma)$
60	20	1	2300	30358	13.2	4.3	1731	26663	10.6	6.7
60	20	2	406	780	14.5	3.6	306	594	12.5	4.8
80	20	1	1200	20844	8.3	10.8	850	18020	6.3	18.7
80	20	2	212	480	9.7	8.0	150	343	8.1	11.4
100	30	1	755	19996	5.3	26.3	503	17747	3.8	52.6
100	30	2	133	425	6.5	18.0	89	306	5.1	29.1
110	30	1	549	15931	4.3	39.7	354	14238	3.0	85.1
110	30	2	97	330	5.3	26.4	63	232	4.1	44.5
120	30	1	385	12985	3.4	65.9	241	11650	2.2	151
120	30	2	68	260	4.2	42.3	43	179	3.2	74.2
130	30	1	244	10460	2.4	148	148	9358	1.5	321
130	30	2	43	207	3.0	84.2	26	141	2.2	156

a pp collider. Also shown is the L required to achieve[2] $S/\sqrt{B}$=5. Results are presented for both single and double b tagging with 30% efficiency and 99% purity. The numbers in Table I are for the conservative detector case (i) and employ the conservative set of acceptance cuts (a). Table II is for the more optimized detector case (ii) and more optimistic cuts (b).

Overall, the tables show that the $Wb\bar{b}$ signal is almost certainly viable for $m_H \lesssim 100$ GeV, i.e., over a range comparable to that for which the H will be found at LEP-200. The most difficult signal in this general mass region would be for $m_H \sim m_Z$. As indicated by the dotted histogram in Fig. 2, the WZ and WH final states yield mass peaks of very similar magnitude. Thus, the H would have to be recognized as an excess over that which would be expected from the WZ continuum. The ability to normalize the WZ continuum by using other channels, in particular the three-lepton channel, would be limited by event rate and uncertainties in the b-tagging efficiency. However, L=30 fb^{-1} might still suffice to establish a Higgs boson signal, even in the conservative (i)-(a) case.

The most crucial question is whether or not a 4 TeV Tevatron can go beyond the reach of LEP-200. We see from the tables that to reach m_H=110 GeV, either $L > 10$ fb^{-1} is required or the optimized detector (ii) and less stringent acceptance cuts (b) must prove possible.

Since a comparison of the single b-tag and double b-tag results in the two tables makes clear that double tagging has a clear advantage,[3] let us quote the corresponding numbers. To obtain a N_{SD}=5 signal at m_H=110 GeV requires 26 fb^{-1} in $p\bar{p}$ collisions and 44 fb^{-1} in pp collisions, for the conservative detector and/or cuts choices, Table I. The former is feasible after 3 or so years of running at an instantaneous luminosity of $\mathcal{L} = 10^{33}$ cm^{-2} s^{-1}, while the latter would require about 5 years running at the same instantaneous luminosity. Of course, a redesigned pp collider would probably be able to achieve higher luminosity than a $p\bar{p}$ machine, in which case it could have an advantage. For instance, for $\mathcal{L} = 0.5 \times 10^{34}$ cm^{-2} s^{-1} at a pp collider, only one year of running would be required for an N_{SD}=5 signal at M_H=110 GeV. However, to maintain purity of b tagging, operation somewhat below this level might be necessary.

To detect a signal for m_H=120 GeV will be exceedingly difficult without an optimized detector and an ability to employ weaker cuts. From Table II we see that an m_H=120 GeV signal at the N_{SD}=5 level in these optimal circumstances requires L=22 fb^{-1} and 40 fb^{-1} for $p\bar{p}$ and pp collisions, respectively, i.e., very similar to the requirements for m_H=110 GeV with conservative detector and/or cuts choices.

Thus, we conclude that $m_H \lesssim 110$ GeV could be probed in the $WH \to l b \bar{b} X$ mode, reaching possibly as high as m_H=120 GeV if an optimized detector is available and optimal acceptance cuts can be employed.

[2] These results are for K_S=1.2 and K_B=1, as quoted above. In the conservative limit of setting K_S=1 instead of 1.2, the luminosity required for N_{SD}=5 would increase by a factor of about 1.4. This is typical of the type of adjustment required by a very conservative approach is adopted in which the K_S and K_B factors are set to unity throughout the paper.

[3] This advantage would be even greater if the purity of b tagging were not as great as assumed. This would be especially likely at instantaneous luminosities substantially above $\mathcal{L} = 10^{33}$ cm^{-2} s^{-1}, such as clearly required for $m_H \gtrsim 110$ GeV.

TABLE II. We tabulate S, B, and $S/\sqrt{B}$ for $WH \to l b \bar{b} X$, at $p\bar{p}$ and pp colliders for L=30 fb^{-1} and $\sqrt{s}$=4 TeV, for a series of m_H values, using the tabulated mass bins. Also given is the L (in fb^{-1}) required for $S/\sqrt{B}$=5. This table is for an optimistic detector, case (ii), and optimistic acceptance cuts (b).

m_H	ΔM	$n_{b\ \text{tag}}$	$p\bar{p}$				pp			
			S	B	$S/\sqrt{B}$	$L(5\sigma)$	S	B	$S/\sqrt{B}$	$L(5\sigma)$
60	10	1	2649	19 593	18.9	2.1	1994	17 777	15.0	6.7
60	10	2	467	505	20.8	1.7	352	375	18.2	2.3
80	10	1	1300	14 854	10.7	6.6	924	12 005	8.4	10.6
80	10	2	229	320	12.8	4.6	163	228	10.8	6.4
100	20	1	948	17 664	7.1	14.7	634	15 602	5.1	28.9
100	20	2	167	372	8.7	10.0	112	263	6.9	15.6
110	20	1	691	14 270	5.8	22.4	451	12 610	4.0	46.5
110	20	2	122	278	7.3	14.0	80	196	5.7	23.2
120	20	1	483	11 373	4.5	36.6	306	10 118	3.0	8.1
120	20	2	85	217	5.8	22.4	54	155	4.3	40.0
130	20	1	309	9470	3.2	74.4	190	8020	2.1	167
130	20	2	55	182	4.0	46.1	34	127	3.0	84.5

2. $ZH \to 2l(2\nu)b\bar{b}$

The analogous signal in the $ZH \to 2l b \bar{b}$ channel is also possibly interesting. The $M_{b\bar{b}}$ distributions for signal and backgrounds are qualitatively similar to those appearing in Fig. 2, but the overall event rates are much lower, roughly by a factor of 9–10 in the case of the signal. As a result, even at m_H=60 GeV, for optimized detector case (ii) and cuts (b) only $N_{SD} \sim 6$ is achieved in both the 1 and 2 b-tag cases. By m_H=100 GeV, N_{SD} has declined to ~ 2.5.

One could also consider the $ZH \to 2\nu b\bar{b}$ channel. This channel has a good event rate, but is subject to many detector-dependent backgrounds and to triggering problems. One background is $gb\bar{b}$ production, where the g disappears down the beam-pipe hole or fragments to very soft particles that are not reconstructed as jets. Since the signal for a light H is concentrated at low $Zb\bar{b}$ subprocess energies, it would be necessary to retain events for which the missing energy lies significantly lower than m_Z. But, it is far from clear that the very high $gb\bar{b}$ rate can be sufficiently reduced unless the lower threshold for the missing energy is rather substantial. Indeed, missing energy would provide one of the main triggers for this mode, and it is not clear how far below m_Z the threshold can be set while providing even an acceptable trigger rate. This is a very detector-dependent issue that we have not pursued further. We are very doubtful that this mode can be useful, and it surely would never be competitive with the $Wb\bar{b}$ mode that we have analyzed in detail.

3. $gg \to H \to ZZ^* \to 4l$

The next channel we consider is $gg \to H \to ZZ^* \to 4l$ for $m_H < 2m_Z$. Here, it is absolutely critical to accept leptons with as low a momentum as possible, since the light Higgs boson signals generally yield leptons that are

not terribly energetic. Thus, we employ the case (b) cuts delinated in Eq. (4). The acceptance cuts of case (a) are not considered since too much of the light Higgs boson signals of interest would be eliminated for this mode to have even a chance of yielding a signal. The signal $4l$ event rate as a function of the $4l$ mass is plotted in 5 GeV bins in Fig. 3, for several m_H values. The signal rates include a K factor of 1.5. Lepton momenta have been smeared using the more optimistic resolution values of detector case (ii) and event numbers reflect the optimistic acceptance cuts (b). As noted earlier, for $m_H < 2m_Z$ there is no significant background so long as the two leptons that do not reconstruct to an on-shell
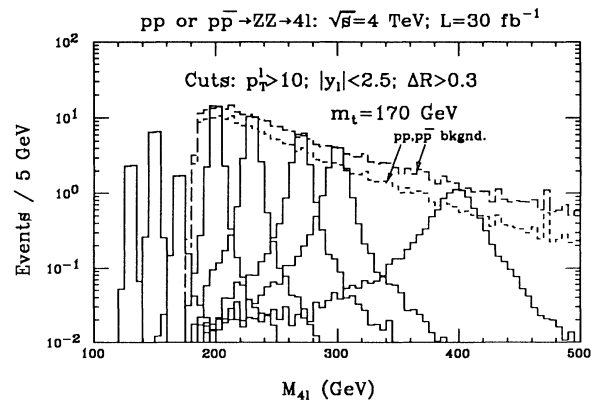

FIG. 3. The $gg \to H \to ZZ^{(*)} \to 4l$ ($l = e, \mu$) signal and $q\bar{q} \to ZZ^{(*)} \to 4l$ background as a function of the four-lepton mass M_{4l} in 5 GeV bins. Higgs boson signals for m_H=130, 150, 170, 200, 230, 270, 300, and 400 GeV are illustrated, after including a K factor of 1.5. Effects of the Higgs boson width are incorporated in order to obtain the correct signal shapes at large m_H values. Optimistic lepton resolution and/or acceptance choices, case (ii)-(b), are employed.

Z are constrained to have significant mass [7-9]. The signal automatically leads to large $2l$ mass values for the leptons from the Z^*, whereas backgrounds from virtual photons yield very low $2l$ mass values. Meanwhile, the continuum ZZ^* background, included in Fig. 3, quickly falls to a negligible level below $2m_Z$, in common with the higher energy LHC and/or SSC energy results [7]. Note that we have required that the charged leptons be isolated from each other and from other hadrons, so that the backgrounds from heavy quark decays, such as $Zb\bar{b}$, $Zc\bar{c}$, can be effectively removed.

In Table III we give event rates after summing over a 10 GeV mass interval centered on m_H. We see immediately that, even for these optimistic choices, there are very few events. For the best case of $m_H \sim 150$ GeV, there are only about 13 events altogether for $L=30$ fb^{-1}. Increasing the threshold for lepton detection to the more conservative case (a) value would further decrease the event rates. Finally, including a charged lepton tracking efficiency (for tracks within the already imposed fiducial cuts) of order 0.95 for each lepton would decrease the rates by a factor of ~ 0.8. Thus, the feasibility of detecting the H in this very clean channel is clearly limited by the small event rate.

For $m_H > 2m_Z$, the $H \to ZZ \to 4l$ event rate increases somewhat, but the $ZZ \to 4l$ continuum background becomes significant, as shown in Fig. 3 and tabulated in Table III. For the optimum $m_H=200$ GeV choice and optimistic lepton resolution and acceptance cuts, $S/\sqrt{B} = 28/\sqrt{28} \sim 5$ is achieved for $L=30$ fb^{-1} (keeping the two central 5 GeV bins). After including our estimate of 0.8 for the net efficiency of finding all four lepton tracks, this signal retreats below the 5σ level. However, the cleanliness of this channel is such that the signal still could probably be observed even for peaks down to the 3σ level, provided there are an adequate number of events, say, at least 15 or so, in the signal peak. With this more optimistic criteria, even after including the 0.8 track-finding efficiency the H would be detectable for $2m_Z \lesssim m_H \lesssim 250$ GeV. However, changing the lepton acceptance cuts to the more conservative case (a) value would significantly decrease the event rates to

an extent that it would be difficult to detect the H for any value of m_H. For instance, for $200 \lesssim m_H \lesssim 270$ GeV, the change from case (b) to case (a) cuts results in a decrease of event rate by a factor of about 2. What would it take to research $m_H=300$ GeV in this mode? Certainly, the situation is best for a pp collider, which, in any case, is the only type of collider that could reach the required luminosities. Table III shows that nominal statistical significance (before including tracking efficiencies) of $S/\sqrt{B} \sim 5$ could be achieved for $L \sim 60$ fb^{-1} in pp collisions, *provided* that optimistic acceptance cuts and both e and μ signals could be employed at the high instantaneous luminosities required.

4. $gg \to H \to WW \to l\nu jj$

Next, we discuss the $H \to WW \to l\nu jj$ channel. Aside from the irreducible WW continuum background, there are also backgrounds from the mixed QCD-EW Wjj channels and from $t\bar{t} \to WWb\bar{b}$ production. In order to reduce these backgrounds it is necessary to impose a cut on the jj mass in the vicinity of m_W. We have accepted events which (after smearing) yield jj mass between $m_W \pm 10$ GeV. (For our resolutions, this choice is near optimum.) The resulting signal and event rates are plotted in Fig. 4 as a function of the cluster transverse mass defined by $M_{ljj}^{clus} \equiv \sqrt{m_{ljj}^2 + p_{Tljj}^2} + p_T^{miss}$. This figure is for the optimistic detector and/or cuts scenario (ii)-(b).

Mass peaks with large numbers of events emerge for the signal, but background event rates, especially from the mixed QCD-EW Wjj process, are very much larger. The $t\bar{t}$ background can, however, be effectively eliminated by vetoing events with extra jets in the central region (at least one of the b's from the t decays nearly always will appear as an energetic central jet). In addition, we have found several cuts that help to increase S/B and the statistical significance of the mass peaks. First, consider the ratio of the total three-momentum of the less energetic jet relative to that of the more energetic jet, $r \equiv |\mathbf{p}_j^{min}|/|\mathbf{p}_j^{max}|$. A cut of $r \geq 0.3$ reduces the Wjj background by about 10% without affecting the signal rates significantly. Second, consider the ΔR separation between the two jets. Higgs boson signals always fall in a well-defined range of ΔR, whereas the Wjj and WW backgrounds have a larger spread, even if one retains only M_{ljj}^{clus} values in the vicinity of m_H. Thus, we impose a ΔR cut that depends upon the Higgs boson mass. (Practically, the experimental groups would examine the M_{ljj}^{clus} distribution for each of the proposed cuts and look for a peak in the corresponding mass region.) The best choices are $\Delta R \in [2.8,3.5]$, [2.6,3.5], [2.3,3.5], [2.0,3.5], [2.0,3.5], [1.8,3.5], [1.5,3.0], [1.2,3.0], [1.0,3.0], for $m_H=110$, 120, 130, 150, 170, 200, 230, 270, and 300 GeV, respectively.

Finally, we have examined the distribution for $\cos\phi_{min}$, where ϕ_{min} is the smaller of the transverse plane azimuthal angles between the observed lepton and the two jets. (Note that we cannot determine which jet is the fermion vs antifermion, so that the analogue of ϕ_{2l} that
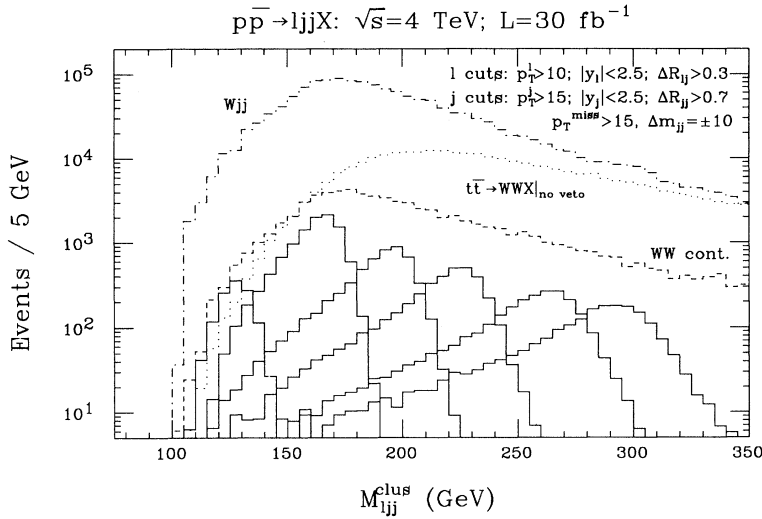
TABLE III. For $ZZ \to 4l$ we tabulate as a function of Higgs boson mass: the signal and background rates S and B (summed over a 10 GeV interval), for $p\bar{p}(pp)$, for $L=30$ fb^{-1}; the associated $S/\sqrt{B}$ values; and the L (in fb^{-1}) required for a $S/\sqrt{B}=5$ signal level. The background rate for $M_{4l} < 2m_Z$ is negligible. Optimistic lepton resolution/acceptance choices, case (ii)-(b), are employed.

m_H	S	B	$S/\sqrt{B}$	$L(5\sigma)$
130	5			
150	13			
170	4			
200	28	28(21)	5.3(6.2)	27(20)
230	20	21(15)	4.3(5.2)	41(28)
270	12	12(8)	3.5(4.3)	61(41)
300	8	8(5)	2.8(3.6)	96(58)

pp̄ →ljjX: √s=4 TeV; L=30 fb⁻¹

FIG. 4. The $gg \to H \to WW \to l\nu jj$ signal and various background event rates as a function of the cluster transverse mass M_{ljj}^{clus} in 5 GeV bins, for L=30 fb⁻¹, $\sqrt{s}$-=4 TeV $p\bar{p}$ collisions. Signals for m_H=130, 170, 200, 230, 270, and 300 GeV are shown. The $t\bar{t}$ background is shown before vetoing against additional central jets (m_t=170 GeV). A QCD K factor of 1.5 is included in the signal rate. Optimistic detector resolutions and acceptance cuts are employed.

will be employed in the $2l$ analysis is unfortunately not available.) At the higher masses of m_H=270 and 300 GeV, we find that the signal distributions in $\cos\phi_{min}$ develop a double peaked structure, with a $\cos\phi_{min}$ peak below 0.5 as well as the peak near 1 that is present at all masses. Meanwhile, the backgrounds only exhibit a peak above 0.5, and are quite suppressed for $\cos\phi_{min} < 0.5$. Thus, it is highly advantageous to impose a cut of $\cos\phi_{min} < 0.5$ in searching for a Higgs boson with $m_H \gtrsim 270$ GeV.

After imposing these (m_H-dependent) cuts (which typically enhance the signal to background ratio by about a factor of 2), the signal and background rates, and nominal statistical significances ($N_{SD} = S/\sqrt{B}$) at L=30 fb⁻¹, are tabulated in Tables IV and V, for conservative detector and/or cuts (i)-(a) and optimistic detector and/or cuts (ii)-(b), respectively. Also given are the L values required for a N_{SD}=5 level signal. Results for both $p\bar{p}$ and pp collisions are tabulated. The N_{SD} values are, of course, computed purely on a statistical basis. We notice that S/B ratios are typically at the 1% level, so that systematics will play a crucial role. Even though there are

distinct mass peaks (in contrast to the shapeless distributions we shall encounter in the $WW \to 2l2\nu$ channel) the very small S/B level will mean that the shape of the background distribution must be very well understood. Uncertainties in the theoretical computations and detector response and efficiencies are likely to be large enough that extraction of these ljj signals may be very difficult, especially in the lower mass region $m_H \lesssim 170$ where the background does not have a simple shape, and depends significantly on cut thresholds, etc.

From Tables IV and V it seems that for m_H between about 150 GeV and 200 GeV there would be some possibility of discovery in this mode at either a $p\bar{p}$ or pp collider, with the optimistic detector and/or cuts choices yielding a substantially better chance. However, even the m_H=170 GeV signal does not reach a level that one can say would certainly be seen, given the above-discussed systematic uncertainties (that are not reflected in the nominal $S/\sqrt{B}$ values quoted). And, going beyond the 150–200 GeV mass interval would surely be extremely difficult given the small S/B ratios. In particular, even

TABLE IV. For $WW \to l\nu jj$ we tabulate S, B, and $S/\sqrt{B}$ for L=30 fb⁻¹, for $p\bar{p}$ and pp colliders at $\sqrt{s}$=4 TeV, for a series of m_H values, using the tabulated mass bins. Also given is the L (in fb⁻¹) required for $S/\sqrt{B}$=5. This table is for the conservative detector, case (i), and conservative acceptance cuts (a).

m_H	ΔM	S	$p\bar{p}$ B	$S/\sqrt{B}$	$L(5\sigma)$	pp B	$S/\sqrt{B}$	$L(5\sigma)$
130	20	271	16 200	2.1	165	12 800	2.4	131
150	30	1539	133 000	4.2	42	109 000	4.7	35
170	30	4542	251 000	9.1	9.1	226 000	9.5	8.2
200	30	1918	200 000	4.3	41	174 000	4.6	35
230	40	1290	113 000	3.8	51	102 000	4.0	46
270	40	724	42 300	3.5	61	37 600	3.7	54
300	40	558	20 300	3.9	49	20 700	3.9	50

TABLE V. For $WW \rightarrow l\nu jj$ we tabulate S, B, and $S/\sqrt{B}$ for $L=30$ fb^{-1}, for $p\bar{p}$ and pp colliders at $\sqrt{s}=4$ TeV, for a series of m_H values, using the tabulated mass bins. Also given is the L (in fb^{-1}) required for $S/\sqrt{B}=5$. This table is for the optimized detector, case (ii), and optimistic acceptance cuts (b).

m_H	ΔM	S	B	$p\bar{p}$ $S/\sqrt{B}$	$L(5\sigma)$	B	pp $S/\sqrt{B}$	$L(5\sigma)$
130	20	834	45 500	3.8	51	30 664	4.8	33
150	30	2633	215 600	5.7	23	169 300	6.4	18
170	30	6736	331 200	11.7	5.5	296 600	12.4	4.9
200	30	2767	239 000	5.7	23	225 000	5.8	22
230	40	1739	144 000	4.6	36	125 000	4.9	31
270	40	887	46 500	4.1	44	57 200	3.7	55
300	40	697	22 100	4.1	44	31 400	3.9	49

the nominal $S/\sqrt{B}$ values for masses 230 GeV and above show a slow deterioration in the likelihood for discovery. Keeping in mind that the signal is becoming quite broad in this region, so that systematics would play a very major role, it is not reasonable to suppose that m_H much above 200 GeV could be detected. Of course, we cannot rule out the possibility that there are other cuts which would improve the situation.

5. $gg \rightarrow H \rightarrow WW \rightarrow 2l2\nu$

A less promising, but not necessarily useless, channel for H detection is $gg \rightarrow H \rightarrow WW^* \rightarrow 2l2\nu$. As for the $ZZ \rightarrow 4l$ signal, it is critical to accept low-momentum leptons, so we employ case (b) acceptance cuts. We also implicitly assume that only events with very low jet activity will be accepted. This eliminates $t\bar{t}$ backgrounds. The $2l$ mass distributions for a variety of m_H values are illustrated in Fig. 5, where we have included a QCD K factor
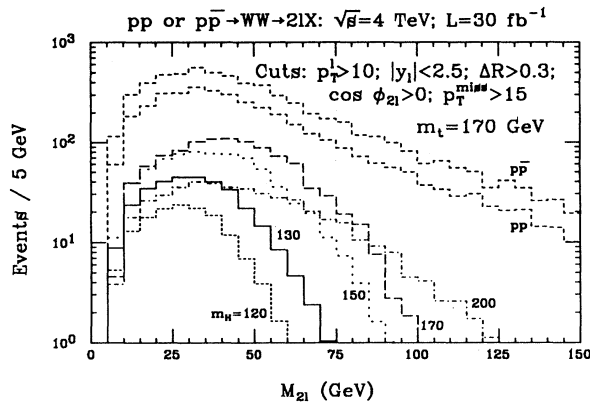

FIG. 5. The $gg \rightarrow H \rightarrow WW^{(*)} \rightarrow 2l2\nu$ signal and $q\bar{q} \rightarrow WW \rightarrow 2l2\nu$ background event rates as a function of the two-lepton mass M_{2l} in 5 GeV bins. Signals for $m_H=120$, 130, 150, 170, and 200 GeV are shown. A $\cos\phi_{2l} > 0$ cut is imposed to eliminate the background from $\tau^+\tau^-$ continuum pair production. QCD K factors of 1.5 and 1.1, respectively, are included in the gg fusion and WW continuum event rates.

of 1.5 for the "0-jets" gg fusion reaction. Also shown is the WW continuum contribution with a K factor of 1.1 for the 0-jets restriction. In both cases we have imposed a cut on the azimuthal angle between the two leptons of $\cos\phi_{2l} > 0$. This cut has two important functions. First, it eliminates an otherwise very large background from $\tau^+\tau^-$ pair production (which we computed including the p_T distribution of the pair as obtained by simulating standard resummation techniques). Second, the WW continuum $\cos\phi_{2l}$ distribution is strongly peaked for $\cos\phi_{2l} \sim -1$, whereas the light Higgs boson signals exhibit peaking also for $\cos\phi_{2l} \sim +1$. (For $m_H \gtrsim 230$ GeV, this latter is no longer true and the cut is better chosen nearer -1; e.g., $\cos\phi_{2l} > -0.9$ eliminates most of the $\tau^+\tau^-$ background. However, even this bit of optimization does not raise $m_H \gtrsim 230$ GeV signals to an observable level.)

Assessing the observability of the signals illustrated in Fig. 5 is difficult. Because of the broad nature of the M_{2l} signal distribution, the signals and background are very similar in shape, and it is not possible to simply look for a mass peak. Thus, it is necessary to detect an event excess integrated over a fairly broad mass interval relative to expectations in the absence of a Higgs boson resonance. Since the signal to background ratios are not large, this will require an extremely accurate determination of the WW continuum normalization. In order to quantify these difficulties we present in Table VI the $L=30$ fb^{-1} signal and background rates for optimally chosen M_{2l} intervals as a function of m_H. Also given is the nominal statistical significance that could be achieved if there were no systematic uncertainty in the background level. The accuracy below which the systematic uncertainty in the background would have to be reduced in order that statistics dominate is indicated by the S/B ratio, also tabulated.

To what level can the systematic background uncertainty be reduced? Let us assume that QCD corrections to the WW continuum are computed to two loops (note that we require the "0-jets" component of the WW continuum), that precision quark and antiquark distributions are available from data from the DESY ep collider HERA, and that gluon resummation technology continues to improve. It is then not inconceivable that the shape of the M_{2l} distribution could be predicted with

TABLE VI. For $WW \to 2l2\nu$ we tabulate as a function of Higgs boson mass: the optimum mass interval for detecting an excess of events; the signal and background rates, S and B, for $p\bar{p}$ (pp), for $L=30$ fb^{-1} summed over that interval; the associated $S/\sqrt{B}$ values, as the absolute upper bound on the observability of the signal, ignoring the systematics issues discussed in the text; and finally the S/B ratios as an indicator of the level of systematics difficulty.

m_H	Mass interval	S	B	$S/\sqrt{B}$	S/B
120	7–43	133	3302(2102)	2.3(2.9)	0.040(0.063)
130	12–53	297	3956(2521)	4.7(5.9)	0.075(0.12)
150	12–68	674	4697(2987)	9.8(12.3)	0.14(0.22)
170	12–83	993	5150(3258)	13.8(17.4)	0.19(0.30)
200	12–113	434	5626(3524)	5.8(7.3)	0.077(0.12)

good accuracy. However, the predicted *normalization* would almost certainly have a substantial uncertainty. Thus, one would make an experimental determination of absolute normalization by measuring the $2l$ spectrum at large M_{2l}. In combination with the shape prediction, this would yield the best "theoretical" prediction for the normalization in the lower M_{2l} mass region of interest. But, bringing the systematic error in the "theoretically" computed background normalization below the critical 10% level seems quite problematical.

Further, there would remain the question of detector efficiency and such as a function of lepton momentum (which feeds into detector efficiency for a given M_{2l}). This distorts the theoretical expectations so as to reduce the accuracy for the above procedure. Aside from detection efficiencies, isolation cuts could be p_T dependent and perhaps hard to understand. These would be critical questions for the experimental groups. Clearly, they would have to understand their detector(s) very well. Reducing uncertainties from this source to something like the 5% level is possibly achievable in a mature well-studied detector [16].

If data were available one would take the signal shape, estimate some uncertainties coming from production model variations, then do the same for the background, and try fitting the data with these variations, and assess the significance of an "excess." This would not be an easy job and it would be difficult to claim discovery of the source of EWSB as a 10% excess in a ~50 GeV wide region sitting on top of a complex background. In addition, it is entirely possible that the necessity of employing a low threshold in p_T^l would allow other detector-dependent backgrounds to creep into the "0-jets" M_{2l} distributions. Thus, the observability of the H in the $2l$ mode seems quite questionable. At best it can be noted that hints of an H even excess begin to emerge for $m_H \gtrsim 140$ GeV, where S/B exceeds 10%. For the best case of $m_H \sim 170$ GeV, the signal could possibly be detected given that S/B has reached a level of order 20(30)% for $p\bar{p}(pp)$ collisions. However, by $m_H=200$ GeV the anticipated systematic uncertainties will probably prohibit seeing even a hint of the ~8% signal event excess, given even an optimistic assumption as to the accuracy with which the normalization of the WW continuum background will be determined. Because of the larger S/B values (not to mention higher instantaneous luminosity), a pp machine

would have a clear advantage in searching for an excess of $2l2\nu$ events.

6. $gg \to H \to ZZ \to ll\nu\nu$

For $m_H \gtrsim 2m_Z$, it is also worth examining the $H \to ZZ \to ll\nu\nu$ mode, in which one of the Z's decays to neutrinos [10]. The main irreducible background arises, of course, from ZZ continuum production. Several variables can be used to reveal the Higgs boson mass peak. Here we have chosen to employ the transverse mass defined by $M_T \equiv 2\sqrt{m_Z^2 + p_{TZ}^2}$. Although rather nice mass peaks are revealed in Fig. 6 and event rates are reasonable, there will certainly be additional backgrounds, as discussed below. As in previous channels we first tabulate nominal S and B values and associated $L=30$ fb^{-1} $S/\sqrt{B}$ statistical significance, ignoring the additional backgrounds. Focusing on the two largest 5 GeV bins (which yields the best results) we obtain the results in Table VII. At $m_H=200$ and 230 GeV acceptable val-
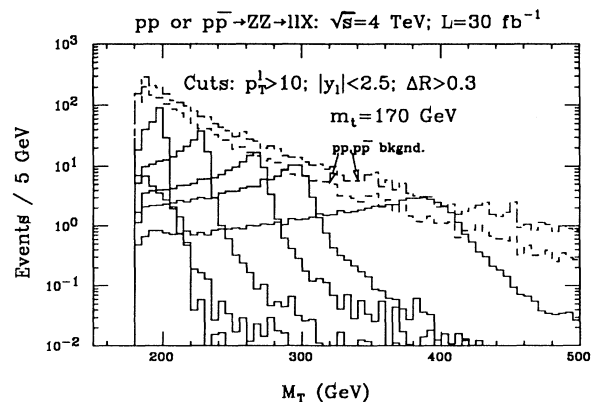

FIG. 6. The $gg \to H \to ZZ \to ll\nu\nu$ ($l = e, \mu$) signal and $q\bar{q} \to ZZ \to ll\nu\nu$ background event rates as a function of the transverse mass M_T in 5 GeV bins. Signals for $m_H=170$, 200, 230, 270, 300, and 400 GeV are shown. QCD K factors of 1.1 and 1.5 have been included in the ZZ continuum background and gg fusion signal, respectively. Optimistic lepton resolution and/or acceptance choices, case (ii)-(b), are employed.

TABLE VII. For $ZZ \to ll\nu\nu$ we tabulate as a function of Higgs boson mass: the signal and background rates S and B, for $p\bar{p}$ (pp), for $L=30$ fb^{-1} summed over a 10 GeV interval; the associated $S/\sqrt{B}$ values, as the absolute upper bound on the observability of the signal; and the L (in fb^{-1}) required for a $S/\sqrt{B}=5$ signal level. Optimistic lepton resolution/acceptance choices, case (ii)-(b), are employed.

m_H	S	B	$S/\sqrt{B}$	$L(5\sigma)$
200	144	390(330)	7.3(8.0)	14(12)
230	66	132(78)	5.6(7.3)	25(14)
270	29	54(30)	3.8(5.2)	52(28)
300	21	21(13)	4.2(5.7)	40(22)

ues for $S/\sqrt{B}$ appear. However, this ignores the possibly large reducible backgrounds from processes such as Zg production in which the g occasionally produces very little visible energy in the detector. The Zg process has a very high event rate and could lead to a background for this signal if the detector does not have large rapidity coverage and few cracks, etc. At the SSC, the Solenoidal Detector Collaboration (SDC) studies [8] found that these backgrounds were so large at low transverse hadronic energies that a Higgs boson with mass below about 500 GeV could not be detected in this way. Presumably the backgrounds are somewhat less severe at the lower $\sqrt{s}=4$ TeV energy of interest here. Given the promising level of the nominal $S/\sqrt{B}$ values obtained without including these backgrounds, it would clearly be worthwhile to pursue this issue.

7. $gg \to H \to ZZ \to 2ljj$

The $H \to ZZ \to 2ljj$ channel yields signal and event rate distributions in the M_{2ljj} mass that are somewhat narrower than those obtained using M_{ljj}^{clus} in the WW channel. However, the event rates in the $2ljj$ channel are about a factor of 6 lower. Meanwhile, the Zjj and ZZ continuum backgrounds have about the same relative size as in the WW case. The largest statistical significance is $N_{SD} \sim 4.8$ for $L=30$ fb^{-1} at $m_H=170$ GeV, for the optimistic detector and/or cuts case. Keeping in mind the additional systematic errors not included in this N_{SD} estimate, this channel does not appear to be useful.

8. $gg \to H \to \gamma\gamma$

For the inclusive $\gamma\gamma$ channel we find that even if the resolution is such that the entire Higgs boson signal is contained within a 1 GeV bin, which gives a signal rate of about 100 events for $100 \lesssim m_H \lesssim 140$ GeV, the statistical significance N_{SD}, computed as $N_{SD} = S/\sqrt{B}$, is never much above 1 due to the overwhelming background from the $q\bar{q} \to \gamma\gamma$ continuum. This channel does not appear to be useful at a 4 TeV Tevatron.

9. $gg \to H \to \tau^+\tau^- \to 2l4\nu$

Finally, one may consider the possibility of using $H \to \tau^+\tau^- \to 2l4\nu$ channel, since the branching fraction for $H \to \tau^+\tau^-$ can be as high as 4% for $m_H \lesssim 140$ GeV, and the Higgs boson mass peak could be reconstructed if we require some finite transverse momentum for the τ pair [17]. Unfortunately, the Drell-Yan backgrounds γ^*, $Z \to \tau^+\tau^-$, and $l\bar{l}$, as well as $W^+W^- \to 2l2\nu$ are so overwhelming that there is little hope to extract the signal.

III. CONCLUSION

We have studied the ability of an upgraded Tevatron with $\sqrt{s}=4$ TeV to search for a standard model Higgs boson with mass beyond the reach of LEP-200. Since such an upgrade would be most useful if detection were possible prior to the full luminosity operation of the LHC, we have employed an integrated luminosity of $L=30$ fb^{-1} in our evaluations of discovery potential.

At low m_H, the $Wb\bar{b}$ mode provides clear signals [18], especially if double b tagging is employed. However, this mode cannot be pushed beyond $m_H \sim 120$ GeV, and is most likely restricted to $m_H \lesssim 110$ GeV. Thus, other modes must be considered for $m_H \gtrsim 110$ GeV.

In the very clean $ZZ \to 4l$ mode the feasibility of detecting the H is clearly limited by the small event rate. However, at $m_H=150$ GeV one expects about 13 events (with negligible background) and at $m_H=200$ GeV the signal and background rates yield $S/\sqrt{B} = 28/\sqrt{28} \sim 5$ for $L=30$ fb^{-1}, before including track-finding efficiency. An H with mass as large as 230–250 GeV yields a 3σ level signal which might be adequate for discovery given the cleanliness of this mode. However, to achieve the above rates requires that leptons with transverse momentum down to 10 GeV be retained.

For m_H between about 150 GeV and 200 GeV H detection in the $WW \to l\nu jj$ channel would also be difficult. For instance, the $m_H=170$ GeV signal reaches a nominal $S/\sqrt{B}$ of order 10, but might not be easy to detect given the systematic uncertainties associated with a signal-to-background ratio of $S/B \sim 0.01$ and a background that peaks in this same mass region.

In the $WW \to 2l2\nu$ mode, event rates and/or systematics will certainly prevent detection of the H in the 110–140 GeV mass range. For $140 \lesssim m_H \lesssim 180$ GeV, where S/B exceeds 10%, there is a remote chance that systematics problems could be overcome and a broad event excess due to the H distinguished. However, as discussed, this should be regarded as very borderline. The need for employing low thresholds for accepting leptons makes this $2l$ mode especially detector dependent.

In the $H \to ZZ \to ll\nu\nu$ channel, the Higgs boson signals exhibit a decent ($\gtrsim 5\sigma$) nominal statistical significance with respect to the ZZ continuum background for $2m_Z \lesssim m_H \lesssim 250$ GeV. However, we have not computed the background from $ll + jets$ that arises when the jets deposit only a small amount of transverse hadronic
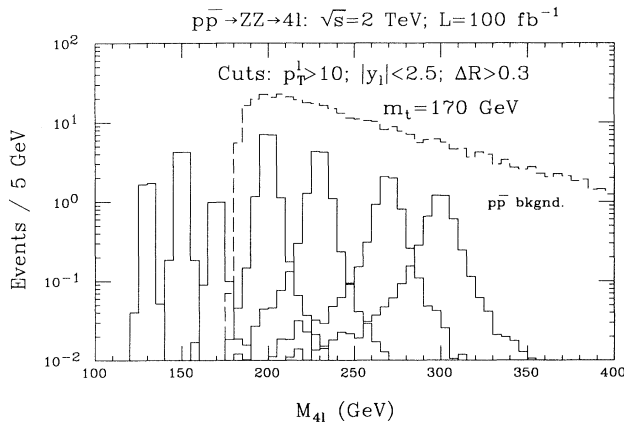
FIG. 7. The $gg \to H \to ZZ^{(*)} \to 4l$ ($l = e, \mu$) signal and $q\bar{q} \to ZZ^{(*)} \to 4l$ background at $\sqrt{s}=2$ TeV as a function of the four-lepton mass M_{4l} in 5 GeV bins. Higgs boson signals for $m_H=130$, 150, 170, 200, 230, 270, and 300 GeV are illustrated, after including a K factor of 1.5. Effects of the Higgs boson width are incorporated in order to obtain the correct signal shapes at large m_H values. Optimistic lepton resolution and/or acceptance choices, case (ii)-(b), are employed.

energy in the detector. A particularly problematical example is gZ production (where the g leaves little trace in the detector, e.g., goes down the beam line). Although a problem at SSC and/or LHC energies, this background may not be that large at the lower 4 TeV energy being considered here, for a detector with good hermeticity and resolution.

Finally, for 110–$120 \lesssim m_H \lesssim 140$–$150$ GeV and $m_H \gtrsim 250$ GeV there is little hope of detecting the H at a $\sqrt{s}=4$ TeV Tevatron upgrade.

We emphasize that to obtain potential signals for Higgs boson masses beyond the reach of LEP-200 will require multiple years of running at $L=10$ fb^{-1} per year, even in the more favored $\lesssim 110$–120 GeV and 150–230 GeV mass ranges. Overall, we do not think that a 4 TeV upgrade of the Tevatron can be justified on the basis of its potential for standard model Higgs boson discovery.

Believers in the minimal supersymmetric model (MSSM) will note that if the CP-odd scalar has mass $m_H \gtrsim 2m_Z$, then the light CP-even scalar, the h^0, will have relatively SM-like couplings. Meanwhile, its mass, even after radiative corrections would certainly be below about 160 GeV [19], and most probably (i.e., for top squark mass below about 500 GeV) would lie in the $m_{h^0} \lesssim 140$ GeV region. That is the h^0 mass may well reside in exactly the region of greatest weakness for a 4 TeV Tevatron. Even for $m_{h^0} < 100$–110 GeV there could be a problem due to the possibly present $h^0 \to I$ invisible decay modes, such as $I = \tilde{\chi}_1^0 \tilde{\chi}_1^0$, where $\tilde{\chi}_1^0$ is the lightest supersymmetric particle. Further investigation is needed to determine if there is a detectable signal in the associated $Wh^0 \to lp_T^{\text{miss}}$ production and/or decay

mode. Meanwhile, the other MSSM Higgs bosons are almost certainly undetectable at this minimally upgraded machine.

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APPENDIX

It is instructive to compare our results at 4 TeV with those at 2 TeV. For the channel $W^{\pm}H \to l\nu b\bar{b}$, the signal significance at 4 TeV is only slightly larger than that at 2 TeV for a given integrated luminosity. This is because there are gg initiated backgrounds that rise faster with increasing energy than the $q\bar{q}$ initiated signal.

In contrast, for the gluon initiated signal processes, such as $gg \to H \to ZZ^{(*)}, WW$, the signal significance declines substantially in going from 4 TeV to 2 TeV (at fixed L). This is because the primary background sources are proportional to the $q\bar{q}$ luminosity functions which decrease less rapidly with decreasing energy than does the gg luminosity function to which the signals are proportional. This is illustrated qualitatively in Fig. 7, which shows the reconstructed mass distribution for the cleanest $4l$ channel. Table VIII presents the $L=100$ fb^{-1} signal and background rates, the corresponding statistical significance, and the accumulated luminosity needed to observe 3σ and 5σ effects. Clearly very large integrated luminosities (requiring multiple years of operation at high instantaneous luminosity) would be required to establish a SM Higgs signal in the $4l$ channel.

TABLE VIII. For $ZZ \to 4l$ we tabulate as a function of Higgs boson mass: the signal and background rates S and B, (summed over a 10 GeV interval), for $p\bar{p}$ at 2 TeV, for $L=100$ fb^{-1}; the associated $S/\sqrt{B}$ values; and the L (in fb^{-}) required for $S/\sqrt{B} = 3$ and 5 signal levels. The background rate for $M_{4l} < 2m_Z$ is negligible. Optimistic lepton resolution/acceptance choices, case (ii)-(b), are employed.

m_H	S	B	$S/\sqrt{B}$	$L(3\sigma)$	$L(5\sigma)$
130	3				
150	9				
170	2				
200	14	43	2.1	204	567
230	9	34	1.5	400	1110
270	4	17	1.0	900	2500
300	2	12	0.6	2500	6940

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