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DISCOVERING A LIGHT MASS HIGGS BOSON AT THE TEVATRON COLLIDER

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A light mass Higgs boson h can be discovered at the Tevatron in the associated production modes $p\bar{p} \rightarrow W^\pm h$ and $\rightarrow Z^0 h$ with enough integrated luminosity. For $M_h = 120$ GeV, a signal can be established independently in the $W^\pm(\rightarrow \ell^\pm \nu)h(\rightarrow b\bar{b})$ channel, where $\ell^\pm = e^\pm, \mu^\pm$, or in the $Z^0(\rightarrow \nu\bar{\nu}, \ell^+ \ell^-)h(\rightarrow b\bar{b})$ channel with 20 fb^{-1} . Much less data ($\simeq 10 \text{ fb}^{-1}$) is needed if these channels are combined, even less if the $h(\rightarrow \tau^+ \tau^-)$ decays can be used. The presence or absence of such a signal is a test of weak scale Supersymmetry, which predicts a lightest Higgs boson with mass $M_h \lesssim 130$ GeV. For some regions of Supersymmetric parameter space, signals containing several b quarks or τ leptons in the final state may be more important.

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1 Introduction

With the discovery of the top quark at the Tevatron collider,¹ the predicted particle spectrum of the Standard Model (SM) is nearly complete. Specifying the rest of the theory demands explicit treatment of how the gauge symmetry of $SU(2)_L \times U(1)_Y$ breaks to $U(1)_{em}$. The Higgs mechanism² is the only known way to generate masses M_W and M_Z for the W^+, W^- and Z^0 bosons while maintaining the renormalizability of the SM. One way to implement the Higgs mechanism is to add fundamental scalars to the theory which have the correct quantum numbers and degrees of freedom to become the Goldstone bosons for the gauge bosons. At the lowest order in perturbation theory, $\rho \equiv M_W^2 / (M_Z^2 \cos^2 \theta_W)$, where θ_W is the Weinberg angle, is identically unity if at least one scalar is in a doublet representation of $SU(2)_L$ and there are any number of additional doublets and singlets. Since ρ is very close to unity, and higher order corrections in perturbation theory can naturally explain the difference, the SM chooses the minimal particle content: a single, complex, scalar doublet ϕ . After symmetry breaking, the four degrees of freedom of ϕ are reduced to a single physical Higgs boson h , which couples to the massive electroweak gauge bosons proportionally to the gauge boson mass. The $W^\pm$ and Z^0 bosons acquire masses $M_W = \frac{1}{2} g v$ and $M_Z = \frac{1}{2} \sqrt{g^2 + g'^2} v$, where g' and g are the $U(1)_Y$ and $SU(2)_L$ gauge couplings. The Higgs field vacuum expectation value (vev) v at tree level is determined to be about 246 GeV from

measuring the Fermi decay constant G_F .

The residual coupling of the Higgs boson to the electroweak gauge bosons is a direct consequence of electroweak symmetry breaking. It is a straightforward, but purely conjectural, extension to use the Higgs mechanism to generate fermion masses by introducing Yukawa couplings between the scalar doublet ϕ and the fermions. Then, after symmetry breaking, each fermion f acquires a mass $m_f = g_f v$ and a coupling to the Higgs boson proportional to the fermion mass. While it is expedient to do so, little is gained in terms of parameter counting, since each distinct fermion mass is traded for a distinct Yukawa coupling g_f . On the other hand, the Standard Model is a renormalizable theory with a dynamic explanation for mass. The measurement of the top quark Yukawa coupling g_t leaves only a determination M_h to complete the particle spectrum (here, we ignore the possibility of neutrino masses).

Determining how electroweak symmetry is broken through the Higgs mechanism is arguably the central task of particle physics today. Probably, it will be necessary to unambiguously detect or exclude a Higgs boson to make progress. Presently, all that is firmly known about the Higgs boson is that it has not been directly detected at collider experiments. The best experimental limit on M_h in the SM comes from the 4 LEP experiments at CERN, which place the lower bound $M_h \geq 71$ GeV.³ This limit comes from not observing the process $e^+e^- \rightarrow Z \rightarrow Z^*(\rightarrow f\bar{f})h(\rightarrow b\bar{b})$, where b is a bottom quark. Until a discovery is made, all one can do is test the consistency of the SM and set indirect limits on M_h . Since some values of M_h are inconsistent with the SM, much can be learned by convincingly excluding a Higgs boson experimentally.

1.1 Indirect Limits On The Higgs Boson Mass

Precision measurements of the SM parameters, when interpreted in the context of perturbation theory, are sensitive to virtual electroweak corrections. The indirect determination of the top quark mass m_t from the LEP and SLD experiments running at an energy on or near the Z boson resonance yields

$$m_t = 179_{-9}^{+8+17}_{-20} \text{ GeV},$$

where the second set of errors results from varying M_h between 60 and 1000 GeV.⁴ This is consistent with the kinematically reconstructed value from CDF at the Tevatron, $m_t = 176.8 \pm 4.4 \pm 4.8$ GeV.⁵ Using the CDF measurement, the LEP result bounds M_h between about 60 and 1000 GeV. The weakness of this limit is a direct consequence of the "Veltman screening theorem",⁶ which guarantees that all such electroweak observables are only logarithmically dependent on M_h . Similar limits can be set by demanding consistency between M_W and m_t with Tevatron data.

In the SM implementation of the Higgs mechanism, a scalar potential is added to the Lagrangian, which, at the lowest order in perturbation theory, can be written

$$V(\phi^\dagger \phi) = \lambda(\phi^\dagger \phi - v^2/2)^2,$$

where λ is the Higgs self-coupling and $v/\sqrt{2}$ is the minimum of the potential. After symmetry breaking, $\phi^\dagger \phi \simeq (v + h)^2/2$, which can be substituted into V and expanded to isolate the Higgs boson mass term, so that $2v^2\lambda = M_h^2$. At the next order in perturbation theory, the top quark Yukawa coupling g_t renormalizes λ , changing the shape of the scalar potential and developing a lower minimum if $\lambda < 0$. Therefore, studying the limit $\lambda \rightarrow 0$ can constrain the allowed values of M_h . An energy cutoff Λ must be introduced, and below this scale we treat the SM as an effective theory. The vacuum stability criteria gives the bound $M_h \gtrsim 135$ GeV for $\Lambda \sim M_P$, the Planck scale.⁷ The bounds are less stringent for lower values of Λ .

Using similar techniques, one can also study the limit of large λ as a function of the scale Λ .⁸ Certainly, $M_h \lesssim \Lambda$ for the SM to make sense even as an effective theory. This places an upper bound of $M_h \lesssim 1$ TeV. Similar bounds can be set by calculating a scattering cross section in perturbation theory for certain processes, such as $W_L W_L \rightarrow W_L W_L$, where W_L is a longitudinally polarized W or Z boson, and studying the breakdown of partial wave unitarity.⁹ It is difficult to interpret such bounds, since they only point out where perturbation theory breaks down. Whether this is bad behavior for the theory or not is pure prejudice. However, there is some evidence that the SM *does* remain perturbative up to at least the scale of $\Lambda_{\text{GUT}} = 10^{16}$ GeV from studying the evolution of the gauge couplings measured precisely at the scale M_Z using renormalization group equations.¹⁰ Not only do they remain perturbative, but, with certain additional assumptions, they can be made to unify. An exact unification is expected if the SM gauge groups are embedded inside a spontaneously broken non-Abelian gauge group. If this apparent unification is not dismissed as an accident, then it seems highly improbable that the Higgs sector could become nonperturbative. In fact, it has been known for some time that if perturbative validity up to Λ_{GUT} is accepted, then there is an upper limit of about 200 GeV on M_h .¹¹

1.2 Future Prospects For Determining The Higgs Boson Mass

Running above the Z resonance, the upgraded LEP2 will be sensitive to the process $e^+e^- \rightarrow Z^* \rightarrow Z(\rightarrow f\bar{f})h(\rightarrow b\bar{b})$, excluding or discovering a Higgs boson up to a mass of about 80 GeV. (The mass reach goes roughly as $\sqrt{s} - 100$ GeV, with an additional 5 GeV of reach for a proposed longer running time).¹²

The CERN LHC should easily discover a heavy ($M_h > 2M_Z$) or intermediate ($M_h \gtrsim 130$ GeV) mass Higgs boson, through decays $h \rightarrow ZZ$ or $h \rightarrow Z^*Z^*$, respectively.¹³ The gold-plated final states contain four leptons. A lighter Higgs boson might be too challenging for the LHC, because of the increasing backgrounds accompanying an increase in Higgs boson production cross section. The present experimental program is based on observing the rare decay mode $h \rightarrow \gamma\gamma$ above a large background of photons from jets.

After the discovery of the top quark by CDF using high p_T leptons as a trigger and heavy flavor tagging to reduce backgrounds, it was quickly realized that the Tevatron collider had a unique opportunity to search for the Higgs boson in a similar fashion and cover the interesting range $80 < M_h < 130$ GeV. The reasons for this will be reviewed in the following sections.

In the following, the Higgs boson considered is very SM like. This means that any deviation from SM behavior can be accounted for by multiplicative factors. Until Section 4, the Higgs boson will be discussed only within the Standard Model.

2 Properties Of A Light Standard Model Higgs Boson

The Higgs boson of the Standard Model has several properties which make its detection possible at the Tevatron. Fortunately, these properties are believed to be generic to any physics of electroweak symmetry breaking, so it is useful to study the SM Higgs boson even if one does not believe in its ultimate correctness. First, the Higgs boson couples strongly to the electroweak gauge bosons. In the high energy limit ($E \gg M_W$), the Higgs boson behaves like the Goldstone bosons which are absorbed to become the longitudinal polarization of the gauge bosons. Therefore, the Higgs boson can be produced in association with a $W^\pm$ or Z^0 boson through its coupling to a virtual W^* or Z^* . The branching ratios $BR(W^\pm \rightarrow e^\pm \nu_e, \mu^\pm \nu_\mu) \approx .22$ and $BR(Z^0 \rightarrow \nu\bar{\nu}, e^+e^-, \mu^+\mu^-) \approx .27$ are high and the kinematics of the leptons are distinctive from the usual QCD backgrounds.

The SM predicts that the Higgs boson decays to fermion pairs with a width proportional to the fermion mass squared. Therefore, a light Higgs boson decays predominantly to a $b\bar{b}$ pair. The resultant b hadrons can be identified with a high efficiency due to a displaced decay vertex or a soft lepton tag. The next largest branching ratio is for Higgs boson decays into $\tau^+\tau^-$. It may be possible to identify this decay mode using the low multiplicity decays of the τ . For the values of M_h considered here, $BR(h \rightarrow b\bar{b}) \simeq 80\%$ and $BR(h \rightarrow \tau^+\tau^-) \simeq 9\%$. Unfortunately, the decay rates to off-shell W or Z bosons are highly suppressed except for heavier Higgs boson masses, which

probably are not accessible with a high rate at the Tevatron.

Since the Higgs boson is a scalar, the decay distribution of the $b\bar{b}$ pair is determined by two body phase space. In the Higgs boson rest frame, $\cos\theta^*$ is flat, where θ^* is the angle between the b quark and the Higgs boson moving direction. As a result, there is a high efficiency for both the b and $\bar{b}$ quarks to have a high p_T in the central rapidity region. This is to be compared to the $(1 \pm \cos\theta^{*2})$ distribution from transversely polarized vector bosons.

There are other sources of SM Higgs production besides the $W^\pm h$ and $Z^0 h$ processes, but none are as promising at the Tevatron. At tree level, quark anti-quark annihilation into a Higgs boson ($q\bar{q} \rightarrow h$) is suppressed by the light quark masses. The one-loop gluon gluon fusion process ($gg \rightarrow h$) is limited by the falling gluon luminosity at high momentum fraction. Production in association with b quarks ($q\bar{q}, gg \rightarrow b\bar{b}h$) would be difficult to trigger on and maintain a high signal efficiency, while the production in association with t quarks has too small of a rate. Of course, these conclusions can be negated if the Higgs boson has non-SM couplings.

3 SM Higgs Boson Searches at the Tevatron

Relying on a mixture of Monte Carlo simulations and present Tevatron data, one can make a strong argument that the Tevatron can successfully discover or exclude a light Higgs boson with enough integrated luminosity. To this end, several studies have been performed with varying levels of sophistication.^{14,15,16,17,18} The results presented here are based on a parton level simulation using the ONETOP code¹⁹ including realistic detector resolution.^{20,21} The analysis closely follows the Snowmass studies of Kim, Kuhlmann and Yao¹⁷ and Yao¹⁸ with the addition of important higher order radiative corrections and exact treatment of spin correlations. The following reviews the details of this and similar analyses and presents the Tevatron's discovery prospects. For reference, Run II of the Tevatron collider will collect 2 fb^{-1} of data at an energy of $\sqrt{s} = 2 \text{ TeV}$. It is assumed that the detectors will be modestly upgraded from their present state and that more than 2 fb^{-1} will eventually be collected in a Run III.

3.1 Triggering Considerations

The detectors at the Tevatron collider acquire data at a precipitous rate, a rate so high that it cannot all be saved and analyzed. Furthermore, if the data were saved on a first-come first-served basis, one would only study QCD. Fortunately, it is possible to distinguish electrons and muons fairly quickly from jets, allowing studies of electroweak theory. If the electron or muon is

in the central rapidity region and at high transverse momentum $p_T^{(\ell)}$, then the probability that a jet mimics an isolated lepton is minimal. Also, large missing transverse momentum $\cancel{E}_T$ can be used as a trigger, though mismeasuring jet energies is a source of fake $\cancel{E}_T$. High $p_T^{(\ell)}$ leptons or large $\cancel{E}_T$ are both signatures of $W^\pm$ and Z^0 boson production. Therefore, either of these can be used as a trigger that the event is worth the precious time needed to save it for future analysis. Experience at the Tevatron shows that events with $p_T^{(\ell)} > 10\text{--}20$ GeV or $\cancel{E}_T 20\text{--}30$ GeV have a high triggering efficiency with manageable background rates. These thresholds can be lower if there are many leptons in an event or leptons and $\cancel{E}_T$. The effective pseudorapidity η coverage for leptons is detector dependent, but is typically $|\eta| < 2$. Further analysis might prove that tighter cuts enhance a desired signal over a background, but, at the trigger level, these cuts are adequate.

3.2 Heavy Flavor Tagging

Either of the triggers discussed above select mainly $W^\pm$ or Z^0 bosons, sometimes in association with jets. When viewed in the context of a perturbative calculation in QCD, most of these jets result at the parton level from gluons or light quarks. With no further restrictions, $W^\pm h(\rightarrow jj)$ and $Z^0 h(\rightarrow jj)$ would be insignificant compared to pure $W^\pm jj$ and $Z^0 jj$ production over a typical invariant mass range, with a signal to background ratio of about 10^{-3} . The fact that the Higgs decays predominantly to $b\bar{b}$ can be used to significantly increase this ratio. The technique for b tagging has been well established by CDF using both a silicon vertex (SVX) tag and a soft lepton tag. Presently, a conservative value for the tagging and mistagging probabilities for jets are 50% and .5%, respectively, where taggable jets have $E_T > 15$ GeV and $|\eta| < 2$. Jets are clustered using the CDF cone algorithm with $R = .7$ and their energies are corrected for weak decays. Using these numbers, the efficiency for two b tags per event is $\epsilon_{b\bar{b}} = .25$. This tagging efficiency is expected to be much improved using an upgraded SVX in Run II, which will use a full three dimensional reconstruction. A remarkable increase in the double tag efficiency can also be accomplished by loosening the requirements for the second tag.¹⁷ Once the tight b tagging criteria have been satisfied, potential fake backgrounds are so reduced that looser criteria can be used for a second tag. In particular, using the soft lepton tag and the loose SVX tag, the double tag efficiency is increased by a factor 1.8 without a substantial increase in fake tags or dilution of the dijet mass resolution. Therefore, it is assumed that the double tagging efficiency in Run II is at least $\epsilon_{b\bar{b}} = .5^2 \times 1.8 = .45$.

3.3 Signal Definition and Backgrounds Using Heavy Flavor Tagging

Given a high b tagging efficiency and a low mistagging rate, the most important backgrounds are those with a real charged lepton $\ell^\pm$ and two real b taggable jets. Therefore, the only backgrounds considered are $W^\pm g^* (\rightarrow b\bar{b})$, $W^\pm Z^0 (\rightarrow b\bar{b})$, $t(\rightarrow bW^+) \bar{t}(\rightarrow \bar{b}W^-)$, $W^{+\ast} \rightarrow t(\rightarrow bW^+) \bar{b}$, and $qg \rightarrow q t(\rightarrow bW^+) \bar{b}$, and hermitian conjugate (h.c.) processes where appropriate. The $W^\pm$ boson decays leptonically, $W^\pm (\rightarrow \ell^\pm \nu)$, where $\ell^\pm = e^\pm$ or $\mu^\pm$, except in the $t\bar{t}$ background, where the second $W^\pm$ boson can decay hadronically. These processes have been studied also in some detail as signals and backgrounds to SM single top quark production.

As a trigger, events are required to have one lepton with $p_T^{(\ell)} > 20$ GeV and $|\eta^{(\ell)}| < 2$. The lepton must be isolated from jets with a separation $R = \sqrt{\Delta\phi^2 + \Delta\eta^2} > .4$, where $\Delta\phi$ and $\Delta\eta$ are the difference in azimuthal angle and pseudorapidity between the lepton and jets. Jets which can be heavy flavor tagged must have $E_T^{(b)} > 15$ GeV and $|\eta^{(b)}| < 2$. Additional jets are resolved if $E_T^{(j)} > 15$ GeV and $|\eta^{(j)}| < 2.5$, and leptons if $p_T^{(\ell)} > 10$ GeV and $|\eta^{(\ell)}| < 2$. Jets must be separated from each other by $R > .7$. A Higgs signal is defined as an excess above backgrounds in the invariant mass distribution of the $b\bar{b}$ pair, $M_{b\bar{b}}$. Since the major background, $W^\pm g^* (\rightarrow b\bar{b})$, has a continuous $M_{b\bar{b}}$ distribution, the smallest mass window containing a substantial fraction of signal events is the best. In the ideal case of a flat background distribution and a Gaussian signal distribution, the best choice is a mass bin with a half width of two standard deviations of the Gaussian signal. Following previous studies, the mass windows of Stange, *et al.*,¹⁴ are used. For $M_h = 100$ GeV, this means a window $84 < M_{b\bar{b}} < 117$ GeV, which is appropriate for the mass resolution of the detector used for this study. The Snowmass study of Kim, Kuhlmann, and Yao¹⁷ used the same mass windows, but a mass resolution that is almost a factor of two worse, so that some signal was lost.²²

3.4 Further Kinematic Cuts

Even though there is a neutrino (or antineutrino) present in the signal events, the full momentum of the $W^\pm$ boson can be reconstructed with a very high efficiency. The ν momentum along the beam axis is determined up to a twofold ambiguity by using the M_W constraint and the measured momentum of the lepton and missing transverse energy. In the $u\bar{d} \rightarrow W^+ h$ production process, there is a larger contribution to the rate from a u quark in the proton and a $\bar{d}$ antiquark in the antiproton than vice versa, and the harder u quark distribution boosts the W^+ into the proton beam direction. The twofold ambiguity is

resolved, then, on a statistical basis, by choosing the most positive momentum component. Just the opposite holds for the neutrino from the $d\bar{u} \rightarrow W^- h$ process. Once the $W^\pm$ boson is reconstructed, it is possible to study the correlation between the $W^\pm$ and h bosons and choose a kinematic variable to enhance the signal over the background. The angle between the $W^\pm$ and h in the $W^\pm h$ center of mass system, θ_h , can be exploited.²³ The dominant background from $W^\pm g^* (\rightarrow b\bar{b})$ tends to peak at $\cos \theta_h = \pm 1$. A cut of $|\cos \theta_h| < .8$ is optimal, even after accounting for the asymmetric distributions from the individual processes $W^+ h$ and $W^- h$.

Top quark pair production $t\bar{t}$ events, which are a large potential background, produce an additional $W^\pm$ boson, which can decay hadronically or leptonically. The extra decay products from this W decay can be used to veto such events. Vetoing events with at least one jet with $E_T > 30$ GeV, a pair of jets separately having $E_T > 15$ GeV, or extra leptons with $p_T > 10$ GeV successfully limits this background.

Other kinematic variables are worth studying, such as the angle between the b and $\bar{b}$ in the rest frame of the $W^\pm h$ system, $\theta_{b\bar{b}}$, the angle between the b and the $b\bar{b}$ moving direction in the $b\bar{b}$ rest frame, θ_b , or the transverse momentum of the $b\bar{b}$ pair, p_T^h . Cuts on $\cos \theta_{b\bar{b}}$, $\cos \theta_b$, and p_T^h were tried, but none could increase the significance. The ratio S/B could be increased for high p_T^h , which might be useful for performing more detailed measurements once a Higgs signal is established. Also, there is a correlation between p_T^h and $\cos \theta_h$ which will be discussed later.

3.5 Event Simulation

The rates for signal and backgrounds are predicted using perturbation theory with modern parton distribution functions (CTEQ3).²⁴ Previous studies have relied on one of two methods to generate samples of event: (1) parton level simulations, where the final state quarks and gluons are treated as jets, and (2) leading log showering simulations with full event evolution, where the final product is a listing of stable particles including some higher order QCD effects in the shapes of distributions, but not in the rate. The present study employs a parton level calculation, but including the full spin correlations between the initial and the final state and some radiative corrections to the production rates.

The NLO QCD corrections to those processes which are order α_s^0 at tree level are large. The order α_s correction to $W^\pm Z^0$ production at Tevatron energies is about 1.3.²⁵ A similar enhancement occurs for the signal process $W^\pm h$, which has the same initial state, and the rate for the process $u\bar{d} \rightarrow$

M_h (GeV)	80	100	120
$W^\pm h(\rightarrow b\bar{b})$	190	110	55
$W^\pm g^*(\rightarrow b\bar{b})$	215	140	100
$W^\pm Z(\rightarrow b\bar{b})$	60	70	10
$t(\rightarrow bW^+)\bar{t}(\rightarrow \bar{b}W^-)$	25	45	30
$W^{+-}(\rightarrow t(\rightarrow bW^+)\bar{b}) + \text{h.c.}$	65	75	80
$q't(\rightarrow bW^+)\bar{b} + \text{h.c.}$	30	25	20
S/B	.50	.32	.22
$S/\sqrt{B}$	9.8	5.9	3.4

Table 1: The number of $\ell^\pm \cancel{E}_T b\bar{b}$ events from various sources and the significance of the Higgs signal in 10 fb^{-1} at the Tevatron with $\sqrt{s} = 2 \text{ TeV}$ for several Higgs masses M_h using the cuts described in the text. The decay $W^\pm(\rightarrow \ell^\pm \nu)$ is imposed, where $\ell^\pm = e^\pm$ or $\mu^\pm$. If a second $W^\pm$ is present in the event, it may decay leptonically or hadronically. Hermitian conjugate processes are denoted by h.c.

$W^{+-} \rightarrow t\bar{b}$, with both initial and final state corrections, is enhanced by a factor of 1.66 over the lowest result using CTEQ3L structure functions.²⁶ The single top production processes $qb \rightarrow q't$ increases by a factor of about 1.3.²⁷ Results are normalized to these numbers. In addition, $t\bar{t}$ and $W^\pm g^*(\rightarrow b\bar{b})$ are evaluated at the scale m_t , which gives good agreement with the present data.

The final state partons are interfaced to a detector simulation to account for finite detector resolution in measuring energies and angles.²¹ This is particularly important for final states involving jets, since the experimentally measured width of the Higgs boson mass is many orders of magnitude larger than the intrinsic width. In this study, the lepton energy resolution is $\Delta E^{(\ell)}/E^{(\ell)} = \sqrt{(.15)^2/E^{(\ell)} + (.03)^2}$, while, for hadrons, $\Delta E^{(h)}/E^{(h)} = \sqrt{(.80)^2/E^{(h)} + (.05)^2}$, where energies are measured in units of GeV.

3.6 Results for the $W^\pm(\rightarrow \ell^\pm \nu)h(\rightarrow b\bar{b})$ Channel

The results of this study are summarized in Table 1, which presents the number of $\ell^\pm \cancel{E}_T b\bar{b}$ events from various sources and the significance of the Higgs signal in 10 fb^{-1} at the Tevatron with $\sqrt{s} = 2 \text{ TeV}$. Several Higgs masses M_h are considered using the cuts described previously. These results are in general agreement with previous studies after accounting for some higher order QCD corrections and different double tagging efficiencies.

The significance of a particular Higgs signal is defined as $S/\sqrt{B}$. This formula is usually only applied to a narrow resonance over a flat background. In the present case, when the resonance is not so narrow, the ratio of signal

to background S/B should also be considered. Ideally, both of these would be large, and this is verified in the table. Based on these results, an integrated luminosity of about 20 fb^{-1} is necessary to establish a signal for $M_h = 120 \text{ GeV}$ in the $W^\pm(\rightarrow \ell^\pm \nu)h(\rightarrow b\bar{b})$ channel alone.

3.7 Signal and Backgrounds for the $Z^0(\rightarrow \nu\bar{\nu}, \ell^+\ell^-)h(\rightarrow b\bar{b})$ Channel

In the SM, the couplings of the Higgs boson to the Z^0 and $W^\pm$ bosons are identical at tree level. The only differences in the $W^\pm h$ and $Z^0 h$ production rates arise from the distribution of initial state partons and the phase space for Z^0 versus $W^\pm$. The decay of the Z^0 boson to leptons occurs with branching ratios $Z^0(\rightarrow \nu\bar{\nu})=.192$ and $Z^0(\rightarrow e^+e^-, \mu^+\mu^-)=.067$, which are comparable to the leptonic branching ratios of the $W^\pm$. Therefore, it may be possible to establish also a $Z^0(\rightarrow \nu\bar{\nu}, \ell^+\ell^-)h(\rightarrow b\bar{b})$ signal.

The results of the Snowmass study by Yao¹⁸ are discouraging. After including the QCD correction for single top production and the correct branching ratio for $h(\rightarrow b\bar{b})$ to those results, the significance for $M_h = 100$ and 120 GeV is 3.7 and 2.0, respectively, in 30 fb^{-1} . Since most of the signal is defined using a $\cancel{E}_T$ trigger, which might suffer a systematic bias, the significance is defined as $S/\sqrt{S+B}$, but this is only marginally different from using $S/\sqrt{B}$. What is surprising is, if one takes the result of the study of Stange, *et al.*,¹⁴ includes the decays of $Z^0(\rightarrow \nu\bar{\nu})$ and scales the background accordingly, corrects for the increased b tagging efficiency, and defines significance in the same manner, the significance for $M_h = 100$ and 120 GeV is 4.4 and 3.3 in 10 fb^{-1} . Since these results are so different, an independent study was performed also for this channel to find the source of this discrepancy.

Since it is most of the signal, only the $Z^0(\rightarrow \nu\bar{\nu})h(\rightarrow b\bar{b})$ channel is considered here. Following Yao, a trigger $\cancel{E}_T > 35 \text{ GeV}$ and an azimuthal angle separation between $\cancel{E}_T$ and any jet of at least .5 is required. Otherwise, the analysis is similar to that for the $W^\pm(\rightarrow \ell^\pm \nu)h(\rightarrow b\bar{b})$ channel. Additional leptons and jets are vetoed as before. After these cuts, the main backgrounds are $Z^0(\rightarrow \nu\bar{\nu})g^*(\rightarrow b\bar{b})$, $Z^0(\rightarrow \nu\bar{\nu})Z^0(\rightarrow b\bar{b})$, $W^{+\ast} \rightarrow t(\rightarrow bW^+)\bar{b} + \text{h.c.}$, and $qg \rightarrow q't(\rightarrow bW^+)\bar{b} + \text{h.c.}$ The decays $W^\pm(\rightarrow \ell^\pm \nu)$ are assumed. In these last two backgrounds, some of the final state products are lost due to finite detector acceptance. Additional cuts were not found to be useful, but, since $\cancel{E}_T \simeq p_T^h$, the trigger requirement is similar to a $\cos \theta_h$ cut, which was found to increase the significance of the $W^\pm h$ signal.

3.8 Results for the $Z^0(\rightarrow \nu\bar{\nu}, \ell^+\ell^-)h(\rightarrow b\bar{b})$ Channel

The results for the $Z^0(\rightarrow \nu\bar{\nu})h(\rightarrow b\bar{b})$ channel with 10 fb^{-1} of data are

M_h (GeV)	100	110	120
$Z^0(\rightarrow \nu\bar{\nu})h(\rightarrow b\bar{b})$	78	61	41
$Z^0(\rightarrow \nu\bar{\nu})g^*(\rightarrow b\bar{b})$	91	75	70
$Z^0(\rightarrow \nu\bar{\nu})Z^0(\rightarrow b\bar{b})$	130	60	18
$W^{\pm}(\rightarrow t(\rightarrow bW^{\pm})\bar{b})$	9	9	10
$q't(\rightarrow bW^{\pm})\bar{b}$	3	3	3
S/B	.34	.40	.41
$S/\sqrt{S+B}$	4.4	4.2	3.4

Table 2: The number of $\cancel{E}_T b\bar{b}$ events from various sources and the significance of the Higgs signal in 10 fb^{-1} at the Tevatron with $\sqrt{s} = 2 \text{ TeV}$ for several Higgs masses M_h using the cuts described in the text.

summarized in Table 2 for $M_h = 100, 110$, and 120 GeV . Based on this table, a Higgs boson with $M_h = 120 \text{ GeV}$ can be discovered in the $Z^0(\rightarrow \nu\bar{\nu})h(\rightarrow b\bar{b})$ channel alone with about 20 fb^{-1} of data. Some significance can be gained using the decays $Z^0(\rightarrow e^+e^-, \mu^+\mu^-)$, but these suffer additional backgrounds from $t\bar{t}$ production. These results are much different than those of Yao¹⁸, and more in line with the scaled results of Stange, *et al.*¹⁴ There are some obvious differences between this and the Yao study. First, the latter study used a larger mass window ($\pm 28 \text{ GeV}$) instead of those of Stange, *et al.*, (roughly $\pm 16 \text{ GeV}$). The effect of detector resolution is also apparent in the $M_{b\bar{b}}$ distribution of the $Z^0 Z^0$ background, which is closer to M_Z in this study. Also, the assumed mass resolution will probably be diluted some by the $\cancel{E}_T$ associated with the semileptonic decays of the b quarks. On the other hand, the background rates of both studies are comparable, and the main difference lies in the signal acceptance. Finally, the trigger $\cancel{E}_T > 35 \text{ GeV}$ is an optimization based on the present sample of CDF data. Clearly, the $M_{b\bar{b}}$ mass window will decrease and the $\cancel{E}_T$ resolution will increase with an improved detector and/or event reconstruction techniques.

3.9 Combined Significance

The significance, as it has been defined, is a measure of the probability that the background fluctuates upward to the size of the mean number of background plus signal events or more. The definition is slightly modified for the $\cancel{E}_T$ signature to account for a scale uncertainty in the background. After performing a multichannel search for a signal, a number of signals may be only marginally significant. If the signal and background in two channels are similar in magnitude, then they can be combined, increasing the significance by roughly a

factor of $\sqrt{2}$. When the channels are sufficiently distinct, it makes more sense to multiply the probabilities of background fluctuations and define the significance in this manner. Concentrating on $M_h = 120$ GeV, the combined significance of the $W^\pm(\rightarrow \ell^\pm \nu)h(\rightarrow b\bar{b})$ and $Z^0(\rightarrow \nu\bar{\nu}, \ell^+\ell^-)h(\rightarrow b\bar{b})$ channels in 10 fb^{-1} of data is 5.0. Adding a $W/Z(\rightarrow jj)h(\rightarrow \tau^+\tau^-)$ channel, the significance is 6.1. Equivalently, about 6.5 fb^{-1} of data is needed to establish a signal if all three channels can be combined. The ability to exploit the $h(\rightarrow \tau^+\tau^-)$ decays depends on the $\cancel{E}_T$ resolution of a given detector, and might require improvements over the present designs.¹⁵ However, given such a detector, the direct Higgs boson production processes, such as $gg \rightarrow h(\rightarrow \tau^+\tau^-)$, might be reconstructable by concentrating on Higgs bosons produced at high p_T .

3.10 Testing The Higgs Boson Properties

Finding the Higgs boson will be a great step forward. However, establishing the existence of a particle which decays primarily to $b\bar{b}$ pairs and couples strongly to the $W^\pm$ and Z^0 bosons will not satisfy our curiosity. The Higgs boson might be a fundamental scalar, in which case its properties will depend upon the existence of other scalar singlets or doublets in the theory. If the Higgs boson is composite, then one could hope to observe non-point like behavior in its production or decay. Since the Tevatron produces Higgs bosons in both the neutral and charged currents, it can determine the ratio $g_{WW_h}^2/g_{ZZ_h}^2$, after correcting for the different parton contributions to $W^\pm h$ and $Z^0 h$ production and the difference between M_W and M_Z . In the SM, this ratio is $\rho \times g^2(Q = M_{Wh})/g^2(Q = M_{Zh}) \simeq 1$, where the running coupling g is evaluated at the Wh and Zh invariant mass.

One should also test the decay modes of the Higgs boson. The ratio of final states containing b quarks compared to τ leptons tests the SM relation $m_b^2(M_h)/m_\tau^2(M_h) \simeq 9$, for $M_h \simeq M_Z$, where m_f is the running fermion mass evaluated at the scale M_h . The ability to perform this measurement will depend on how well a detector can identify the low multiplicity decays of the τ and discriminate them from jets.

If the Higgs boson has substantial couplings g_{WW_h} and g_{ZZ_h} , then it is probably CP positive. In principle, the CP properties can be probed by studying the decays $h(\rightarrow \tau^+\tau^-)$, but this requires large statistics. Finally, the angular distribution of the final decay products should be consistent with the decay of a spin zero resonance. This might be hard to test with limited statistics, since some of the cuts used to define the signal have exploited the spin properties of the SM Higgs boson.

4 Supersymmetry and the Higgs sector

As it stands, the Standard Model with a light Higgs boson is puzzling, because it is not clear why a light Higgs boson at tree level would remain light. The Higgs self coupling λ , which can be constrained indirectly by demanding self consistency of the theory, provides a one loop correction to M_h . There is an infinity associated with this correction which must be canceled by a counterterm if the theory is to remain renormalizable. *A priori*, this wouldn't bother us, except that the coefficient of the counterterm must be tuned to an extremely high precision (roughly one part in 10^{17}). We might be satisfied with this if only one such tuning was necessary, but each order of perturbation theory demands another such tuning. This is a phenomenon of field theories containing fundamental scalars. Fermions have a chiral symmetry and gauge bosons have a gauge symmetry, which enable them to remain light, but there is no such symmetry for scalars in the Standard Model.

Fortunately, the Higgs boson can inherit a protective symmetry if it is paired with a fermion or gauge boson. Such a symmetry is a supersymmetry (SUSY), and it necessarily relates particles of spin J with particles of $J \pm 1/2$. Since the Higgs boson receives radiative corrections from all fermions and bosons in the theory, a working application of supersymmetry requires a superpartner for each SM particle. Each fermion has a scalar partner and each Higgs and gauge boson has a fermion partner. This is the minimal supersymmetric extension of the Standard Model (MSSM). Unfortunately, it is clear that such a symmetry is not exact, if it exists at all. However, there are ways to break the supersymmetry in a mild enough manner that the superpartners are heavy enough to evade experimental searches and light enough to maintain a light Higgs boson. Such a shell game cannot be played *ad infinitum* without reintroducing fine tuning into the theory.

Anomaly cancellation within the MSSM requires two scalar doublets, one coupling to u type quarks, ϕ_u , and one to d type quarks, ϕ_d . Since two doublets have eight degrees of freedom, 5 physical Higgs bosons remain after electroweak symmetry breaking. Three Higgs bosons are neutral (h , H , and A) and two are charged ($H^\pm$). h and H are CP positive ($M_h \leq M_H$), while A is CP negative. Their masses are not entirely arbitrary, and the self coupling is now related to gauge couplings and not M_h . The two scalar doublets acquire individual vev's v_u and v_d , which are described by one parameter $\tan\beta = v_u/v_d$, and h and H are an admixture of the the CP positive neutral components of ϕ_u and ϕ_d with mixing angle α .

At tree level, the lightest neutral Higgs boson must be lighter than M_Z . However, the large top quark Yukawa coupling can modify this result by pro-

viding large radiative corrections to the scalar potential. At the same time, a large top Yukawa coupling breaks the electroweak symmetry radiatively. Presently, given the Tevatron measurements of the top quark mass, one finds that the Higgs boson can be as heavy as about 130 GeV within the MSSM,²⁸ and as heavy as 150 GeV for any supersymmetric extension of the Standard Model.²⁹ This is an exciting result, since the SM Higgs boson mass $M_h \gtrsim 130$ GeV based on the vacuum stability argument presented earlier. Discovering a light Higgs boson, then, is strong evidence for weak scale SUSY.

4.1 Phenomenological Consequences of Supersymmetry

An excellent review of the phenomenology of the SM and SUSY Higgs boson can be found in "The Higgs Hunter's Guide".³⁰

For the $W^\pm h$ and $Z^0 h$ production processes, the effect of SUSY is included in a multiplicative factor $\sin^2(\beta - \alpha)$ for each Higgs boson mass. Likewise, for the $W^\pm H$ and $Z^0 H$ production process, one can use the SM Higgs boson results and multiply by the factor $\cos^2(\beta - \alpha)$. This is relevant if LEP2 finds h and the Tevatron searches for H . A further difference from SUSY arises in the branching ratios for the Higgs decays, but this can also be accounted for by a multiplicative factor for each Higgs boson mass. Since there are many decay modes to consider, there is no simple scaling rules for the branching ratios.

The associated production of a Higgs boson with heavy quarks, which is not considered viable for a SM Higgs boson at the Tevatron, can become important in SUSY. If the Higgs boson is the CP negative A , then the production rate is greatly enhanced for large $\tan\beta$, and the decay rate $A(\rightarrow b\bar{b})$ is large. Studies claim that $M_A \lesssim 300$ GeV is accessible for $\tan\beta \sim 60$ with 30 fb^{-1} of data by tagging three or four of the b jets.³¹ The decay $A(\rightarrow \tau^+\tau^-)$ also occurs at about 1/9 the $A(\rightarrow b\bar{b})$ rate. Since m_τ/M_A is small, the τ decay products point in the same direction as the τ , so the A rest frame can be found, and M_A can be partially reconstructed and distinguished from backgrounds. M_A can be better reconstructed in events with high p_T^A . For such large values of $\tan\beta$ as considered here, this decay mode should also be visible.

Also, there are some entirely new production processes in SUSY involving the coupling of different Higgs bosons. The heavy CP positive H can decay to both hh and AA pairs, leading to a $b\bar{b}b\bar{b}$ final state. Since H is a narrow resonance, backgrounds can be significantly reduced by the additional mass constraint on the 4 b jets. A signal can be established in two different regimes. First, when M_A is small, $M_A \simeq M_h$, so the two signals can combine for $M_A \lesssim 60$ GeV. Second, when $90 \lesssim M_A \lesssim 170$ GeV, $H \rightarrow hh$ can be observed for small $\tan\beta$.³¹ The process $q\bar{q} \rightarrow Z^* \rightarrow hA$, which can have a large rate for

$M_A \simeq M_h$, probably cannot be observed at the Tevatron, since the 4 b jets do not reconstruct to a narrow mass. The double Higgs processes will also have final states $b\bar{b}\tau^+\tau^-$ and $\tau^+\tau^-\tau^+\tau^-$ at approximately 2/9 and 1/81 the rate $b\bar{b}b\bar{b}$, and are worth considering.

Finally, in what has been considered so far, the only modification of SUSY to the decay rates is to change the relative importance of various SM final states. However, it is possible that there is a light sparticle in the spectrum which has otherwise eluded detection, but has a strong coupling to the Higgs. For example, $h \rightarrow \tilde{N}_1\tilde{N}_1$, where $\tilde{N}_1$ is the lightest superpartner (LSP), would lead to invisible decays of the Higgs boson. In this case, assuming that fake $\cancel{E}_T$ is not a problem, the only substantial background to $W^\pm(\rightarrow \ell^\pm\nu)h(\rightarrow \tilde{N}_1\tilde{N}_1)$ would be $W^\pm(\rightarrow \ell^\pm\nu)Z(\rightarrow \nu\bar{\nu})$, assuming the tail of the direct $W^\pm$ production process can be controlled. This is open to future study.

5 Conclusions

With 20 fb^{-1} of data, the Tevatron can discover or rule out a Standard Model Higgs boson h with a mass of 120 GeV in the $W^\pm(\rightarrow \ell^\pm\nu)h(\rightarrow b\bar{b})$ channel. A measurement of equal significance can be made in the $Z^0(\rightarrow \nu\bar{\nu}, \ell^+\ell^-)h(\rightarrow b\bar{b})$ channel. Combining these channels, a signal can be established with 10 fb^{-1} of data. Only 6.5 fb^{-1} is necessary if the $W/Z(\rightarrow jj)h(\rightarrow \tau^+\tau^-)$ channel can be used. With a 5 standard deviation signal established in both the $W^\pm(\rightarrow \ell^\pm\nu)h(\rightarrow b\bar{b})$ and $Z^0(\rightarrow \nu\bar{\nu}, \ell^+\ell^-)$ channels, the SM prediction for the relative couplings $g_{WW_h}^2/g_{ZZ_h}^2 = 1$ can be tested. If the decays $h \rightarrow \tau^+\tau^-$ can be detected, then the relation $BR(h \rightarrow b\bar{b})/BR(h \rightarrow \tau^+\tau^-) \simeq 9$ can also be tested. Of course, the results are even more encouraging for smaller M_h . An 80 GeV Higgs boson can be found in the $W^\pm(\rightarrow \ell^\pm\nu)h(\rightarrow b\bar{b})$ channel alone with only 2.5 fb^{-1} of data.

If Supersymmetry is realized in Nature, then these results may be only marginally modified. The ability to discover or rule out a Higgs boson within the mass reach of the Tevatron will be strong evidence for or against weak scale Supersymmetry. Additional signatures of Supersymmetry can contain final states with several b jet and τ lepton pairs, and it is well worth the effort to develop good triggers and increase the tagging efficiency for such signatures.

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