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Prospects for Higgs at the Tevatron

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Abstract. The current status of simulation studies for the observation of a standard-model or lightest supersymmetric Higgs boson at TeV33 are reviewed. Latest studies indicate that the mass range $60 < m_H \lesssim 130$ GeV can be covered at the 5-standard-deviation level with 30 fb^{-1}, using the WH and ZH channels. This is the full allowed mass range for the lightest Higgs h of minimal supersymmetry.

INTRODUCTION

The observation of a Higgs boson is possibly the most exciting physics prospect for the Tevatron. Understanding the mechanism of electroweak symmetry breaking and the scalar sector of the standard model is the most pressing issue confronting high energy physics today.

The current best limit on the mass of a light Higgs boson H decaying to $b\bar{b}$ is $m_H > 77$ GeV (from LEP2) [1].

Fits to electroweak data from LEP and SLD, using the Tevatron top mass, show some (weak) sensitivity to m_H; the latest results [1] give $m_H = 115^{+116}_{-66}$ GeV and exclude $m_H > 420$ GeV (95% C.L.). Additionally, in the minimal supersymmetric standard model (MSSM), the lightest Higgs h has

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a mass $m_h < 125$ GeV (< 112 GeV in the absence of stop-quark mixing); even with a non-minimal Higgs sector the lightest neutral Higgs has a mass $m_h \lesssim 150$ GeV [2]. Thus both the available experimental evidence, and theoretical prejudice, point to the existence of a light Higgs. In the following we shall not distinguish between a standard model and MSSM Higgs since both are expected to have similar couplings and decays (predominantly to $b\bar{b}$) in the mass range of interest.

The first accelerator to explore this mass region is likely to be LEP2. Its mass sensitivity should extend to $m_H < \sqrt{s} - m_Z - (5 - 10)$ GeV; with $\sqrt{s} = 200$ GeV, masses up to ~ 105 GeV will be probed by 1999. This covers much, but not all, of the light Higgs mass range. We may therefore set a goal for TeV33: to discover (or exclude) a light Higgs over the whole range $60 < m_H < 130$ GeV before significant data from the LHC becomes available. We shall conclude that this goal is attainable, and that 30 fb^{-1} of integrated luminosity is required to meet it.

HIGGS DISCOVERY MODES

The most promising modes for Higgs discovery are those where the H is produced in association with a vector boson, as proposed by Stange, Marciano and Willenbrock [3].

$p\overline{p} \to WH$ with $W \to \ell\nu$ and $H \to b\overline{b}$

This channel was investigated in some detail for the TeV2000 report [4]. The signal is a $W \to \ell\nu$ decay together with two jets; the invariant mass of the jets reconstructs to the Higgs mass. The dominant background, $W + 2$jet production, can be reduced by requiring that both jets be b-tagged; in the TeV2000 study the tagging efficiency was assumed to be 0.5 and the mistag rate 0.005 for both jets. After double-tagging, the remaining backgrounds are $W + b\bar{b}$ and $W + c\bar{c}$, WZ with $Z \to b\bar{b}$, $t\bar{t}$ and single top production (both $W^* \to t\bar{b}$ and Wg fusion $\to tqb$ processes). Background estimates were verified against CDF data wherever possible.

The study concluded that Higgs signals would be observable up to $m_H = 120$ GeV with 25 fb^{-1} of luminosity. However, it made two assertions. Firstly a factor of two improvement in signal-to-background ratio was put in "by hand" to model the expected improvement from optimized selection cuts [5]. This resulted in an artificial suppression of the irreducible $WZ(b\overline{b})$ background. Secondly, it was assumed that dijet resolutions of order $100\%/\sqrt{m_{jj}}$ were attainable. This gives $\Delta m_{jj} = 11$ GeV at $m_{jj} = 80$ GeV compared with 16 GeV from the full simulation.

A Snowmass study [6] aimed to quantify possible improvements in significance. Events were selected having:

- $p_T(\ell) > 20$ GeV/c;
- $\not\!\!E_T > 25$ GeV;
- At least two jets with $E_T > 15$ GeV and $|\eta| < 2.5$;
- No more than two jets with $E_T > 30$ GeV and $|\eta| < 2.5$;
- Two b-tags.

Based on CDF Run I results, an improvement in signal efficiency of a factor 1.8 was obtained by adding leptonic b-tags and using a looser silicon vertex tag for the second of the two jets. Background rejection remains adequate. Possible cuts on various center-of-mass angles were also investigated. It was found that requiring $|\cos\theta_H| < 0.8$ (where θ_H is the Higgs scattering angle in the WH center of mass) improves signal-to-background by 50%. Cutting on θ_{bb}, the center of mass angle between the b and $\overline{b}$, or on θ_b, the b decay angle in the Higgs rest frame, did not improve the signal significance. This study did not assume any improvement in dijet mass resolution. A mass window of $84 < m_{jj} < 117$ GeV/c^2 was used for $m_H = 100$ GeV/c^2. Higgs discovery at the 5 standard deviation level is demonstrated up to $m_H \lesssim 125$ GeV in 30 fb^{-1}.

$p\overline{p} \to ZH$ with $Z \to \ell\ell$ or $\nu\nu$ and $H \to b\overline{b}$

This channel was not investigated for TeV2000 but a Snowmass study [7] shows it to be very promising. The signal is either a leptonic Z or missing E_T, together with two jets. Once again, the second jet is allowed to be more loosely-tagged than the first, and Run I CDF tagging efficiencies are applied. The backgrounds are ZZ, $Z + b\overline{b}$, $Z + c\overline{c}$, and for the $\not\!\!E_T$ signal, QCD $b\overline{b}$ production, $W + b\overline{b}$ with the lepton lost, and $t\overline{t}$. These backgrounds were all estimated from CDF data. Requiring $\not\!\!E_T > 35$ GeV and $\Delta\phi > 0.5$ between the $\not\!\!E_T$ and any jet, together with a third-jet veto ($E_T > 8$ GeV in $|\eta| < 2.4$)

and a veto on isolated tracks with $p_T > 10$ GeV/c, reduces the backgrounds to a tolerable level for the $\not\!\!E_T + 2$jets final state.

For the $\ell\ell + 2$jets final state, events are required to have two leptons with $p_{T1,2} > 20,\ 10$ GeV and $|\eta_{1,2}| < 1.0,\ 2.0$. The mass must be within 15 GeV of m_Z. Both final states are required to have two b-tagged jets with $E_T > 15$ GeV and $|\eta| < 2.0$.

The overall ZH acceptance is found to be comparable to that for WH and a Higgs could be observed as a 3 standard deviation effect up to $m_H = 110$ GeV with 30 fb^{-1}.

OTHER MODES STUDIED

$p\overline{p} \rightarrow (W,Z)H$ with $(W,Z) \rightarrow jj$ and $H \rightarrow \tau^+\tau^-$

This channel was suggested by Mrenna and Kane [8]. The signal is two tau-jets together with two hadronic jets having a mass consistent with a W or Z boson. The TeV2000 study [9] used only one-prong tau decays and assumed that the neutrino direction was parallel to the hadronic track; in this case, the tau-tau invariant mass can be reconstructed (provided the opening angle is not 180°). The dominant background is Z+jets with $Z \rightarrow \tau^+\tau^-$. Suitable selections can improve the signal to background ratio for Higgs from $1/2 \times 10^4$ at the cross section level to 1/60; in a mass window for a 120 GeV Higgs the signal to background is 1/10. One would therefore need to know the shape of the $Z \rightarrow \tau^+\tau^-$ mass peak to better than a few percent, off-resonance, to claim any discovery. This does not seem very credible given the difficulties understanding $\not\!\!E_T$ response. This channel is not regarded as very promising.

An alternative method of tau-tau reconstruction was also investigated [10]. Here the $\tau\tau \rightarrow \ell j\ \not\!\!E_T$ final state is used and a three-body transverse mass constructed. A Higgs signal for $m_H = 130$ GeV was simulated but again there does not appear to be sufficient signal-to-background to distinguish it from the high-side tail of the $Z \rightarrow \tau^+\tau^-$ transverse mass peak.

Inclusive $H \to b\bar{b}$

At Snowmass [13] the possibility of observing inclusive $H \to b\bar{b}$ production in double-tagged jet final states was investigated. The inclusive Higgs cross section is relatively large ($\sim$ 1 pb) but there is an overwhelming background from QCD $b\bar{b}$ production. The first difficulty is triggering; in this study it was assumed that a semileptonic b-decay would be required for a lepton plus jets trigger, and the resulting overall efficiency is ~ 0.05. In 30 fb^{-1} there would be 2.5×10^6 QCD background events in the Higgs mass window and a signal cross section of > 10 pb would then be required for a 3 standard deviation effect, making this impossible as a Higgs observation (unless the efficiency can be raised tenfold). However, it is worth noting that a clear $Z \to b\bar{b}$ signal should be observable even in Run II (with 50,000 signal events). This will provide an important event sample for development of the b-tagging and dijet mass reconstruction algorithms needed for Higgs discovery at TeV33.

Four-b Final States

Gunion and collaborators [11] have studied $4b$ final states as signals of Higgs production. Only parton-level simulations have been performed. In the MSSM, four b-jet final states could offer signals for:

- $gg \to b\bar{b}H \to 4b$ $(H = h, H, A)$,
- $p\bar{p} \to H \to hh \to 4b$,
- $p\bar{p} \to H \to AA \to 4b$.

Backgrounds arise from combinatorics, from $p\bar{p} \to b\bar{b}g$, $c\bar{c}b\bar{b}$, $t\bar{t}$ and $t\bar{t}g$ (reducible); and from $p\bar{p} \to 4b$ and $b\bar{b}Z(Z \to b\bar{b})$ (irreducible). They concluded that, with 30 fb^{-1} at TeV33, signals would be observable for $gg \to b\bar{b}H$ for large $\tan\beta$ or small m_A (roughly $\tan\beta > 0.2 m_A(\mathrm{GeV})$), and for $H \to hh/AA$ for $\tan\beta \gtrsim 2$ or $m_A \lesssim 60$ GeV.

Shortcomings with this analysis are that the dijet resolution assumed was probably over-optimistic, and there are no clear peaks above background (making observation of a signal a matter of confidence in the background estimation).

The authors were concerned about the ability to trigger on such $4b$ final states. At Snowmass it was estimated [12] that an efficiency as high as 60%

could be obtained using a lepton plus jets trigger. Also, both CDF and DØ are investigating the use of a displaced vertex trigger to select multi-jet final states rich in b's, which may allow these processes to be selected.

DIJET MASS RESOLUTION

The mass resolution attainable on the $b\bar{b}$ dijet system was identified as a critical issue in the TeV2000 report. It directly feeds into the signal-to-background ratio which can be achieved in the Higgs search. A number of studies have been conducted [13–15], all of which reach broadly similar conclusions.

In realistic simulations, both the CDF and DØ detectors appear capable of a di-b-jet resolution of about $\Delta m_{jj}/m_{jj} \sim 15 - 20\%$ at $m_{jj} \sim 100$ GeV. This contains contributions of about 6% from the intrinsic calorimeter resolution, about 10% from neutrinos in the b-decays, and about 10% from gluon radiation effects. Since these three effects are comparable in magnitude, it seems hard to dramatically improve the resolution. In a DØ study, jets found using cones with radii $R = 0.3, 0.5$ and 0.7 and "k_T" (successive recombination) jets with separation parameter $d = 0.4$ and 1.0 were compared; the k_T jets give slightly (about 20%) better resolution but their use is clearly not the panacea that had been hoped by some. Cutting on jet widths, or vetoing events with nearby third jets, can also improve $\Delta m_{jj}/m_{jj}$ somewhat (10–20%) but at the cost of losing up to one-third of the signal events. Energy deposition from pileup events does not seem to significantly degrade the mass resolution [4].

In summary, then, one may hope to reduce dijet resolutions by perhaps 20% compared with those obtained from the current CDF and DØ detector simulations. More dramatic improvements would be welcome but should not be regarded as particularly likely. The conclusions of this review do not depend on any improvements in dijet resolution being obtained.

DETERMINATION OF HIGGS PROPERTIES

In 30 fb^{-1} of data we expect about 200 Higgs events at $m_H = 100$ GeV. The statistical error on the mass would then be as small as ~ 1 GeV. Systematic effects would probably dominate but with a large sample of $Z \to b\bar{b}$ events available for calibration these should be controllable.

Observation of both $WH \to \ell\nu b\bar{b}$ and $ZH \to (\nu\nu, \ell\ell)b\bar{b}$ could be used to

TABLE 1. Number of signal and background events expected in 30 fb^{-1} for WH and ZH processes, and signal significance, as a function of Higgs mass.

m_H (GeV/c^2)	60	80	90	100	110	120
WH signal (S)	681	420		228		117
Background (B)	2085	1260		789		456
S/B	0.33	0.33		0.29		0.26
$S/\sqrt{B}$	14.9	11.8		8.1		5.5
ZH signal (S)			108	92	82	51
Background (B)			533	495	462	378
S/B			0.20	0.19	0.18	0.13
$S/\sqrt{B}$			4.7	4.1	3.8	2.6

fix the ratio of couplings $(WWH)^2/(ZZH)^2$ to $\pm 15\%$ [16]. If $m_H < 95$ GeV this ratio could be combined with the LEP determination of $(ZZH)^2$ and $B(H \to b\bar{b})$ in order to fix $(WWH)^2$ to about $\pm 20\%$ [16].

Unfortunately it is unlikely that a light standard model Higgs could be distinguished from the lightest SUSY Higgs on the basis of Tevatron measurements.

SUMMARY AND CONCLUSIONS

Table 1 summarizes the number of signal events S, background events B, and signal significance $S/\sqrt{B}$, attainable in the $p\overline{p} \to WH \to \ell\nu b\bar{b}$ and $p\overline{p} \to ZH \to (\ell\ell, \nu\nu)b\bar{b}$ channels. Numbers are taken from Refs. [6] and [7] and scaled to 30 fb^{-1}. By combining these two final states it appears that the whole mass range $60 < m_H \lesssim 130$ GeV can be covered at TeV33.

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