Standard Model Higgs Boson Branching Ratio Measurements at a Linear Collider

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We obtain expected Standard Model Higgs Boson branching ratio errors assuming a $\sqrt{s}$ = 500 GeV e^+e^- linear collider with 500 fb^{-1} integrated luminosity. Six masses ($m_{h_{SM}}$ = 115, 120, 140, 160, 180, and 200 GeV) are considered. Our results also hold in the decoupling limit of the Minimal Supersymmetric Model.

1. Introduction

While the Standard Model of particle physics has enjoyed remarkable success, one major phenomenological prediction has yet to be experimentally observed: the Higgs Boson. The mechanism of electroweak symmetry breaking is likely to be discovered at a facility already operating or one which will be operating shortly. But the ideal tool for precision studies of the properties of the agent of electroweak symmetry breaking is the future e^+e^- linear collider.

We report here the expected precision on Standard Model Higgs Boson branching ratios at such a collider for six values of the Higgs mass. The clean event environment at the linear collider, where hadronic contamination is low, guarantees small errors on these measurements. Since what lies beyond the Standard Model is also of interest, we point out that our results also apply in the decoupling limit of the Minimal Supersymmetric Model.

2. Event Analysis

2.1. Data and Detector Simulation

The Pandora v2.1 generator [1] with interface to Tauola for τ decay and Pythia v6.125 for parton shower and hadronization was used for both signal and background events. Beamstrahlung and initial state radiation were turned on. We assume a center of mass energy $\sqrt{s}$ = 500 GeV and an integrated luminosity $\int dt\mathcal{L}$ = 500 fb^{-1}. The NLD Large detector geometry was simulated using the LCD Fast Simulator [2].

Since the $h_{SM} \to b\bar{b}$ and $h_{SM} \to c\bar{c}$ measurements rely on a precise vertex detector, we have taken great care to simulate vertex reconstruction with the tools developed for SLD [3]. Track assignment to jets and to primary and secondary vertices within each jet is done on every event for use in flavor tagging.

2.2. Event Selection and Background

We select for the Higgsstrahlung production mode $e^+e^- \to Zh_{SM}$ in which $Z \to l^+l^-$ ($l = e, \mu$). The Z mass is reconstructed using all possible oppositely charged lepton pair tracks, and the pair with reconstructed mass closest to m_Z is chosen. The cut $m_{l^+l^-} \in [m_Z - 10$ GeV, $m_Z + 10$ GeV$]$ is then applied. The recoil mass is calculated from the center of mass energy and reconstructed Z momentum. The cut $m_{recoil} \in [m_{h_{SM}} - 10$ GeV, $m_{h_{SM}} + 20$ GeV$]$ is applied, a wide cut to

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Table I Reconstructed Higgs mass cuts to reduce $e^+e^- \to ZZ$ and $e^+e^- \to W^+W^-$ background.

Mode	Reconstructed Higgs Mass Cuts
$h_{SM} \to WW^\star \to 4j$	$m_{h_{recon}} \in [m_{h_{SM}} - 10$ GeV, 200 GeV]
$h_{SM} \to WW^\star \to 2jl\nu_l$	$m_{h_{recon}} \in [0, m_Z - 20$ GeV$] \cup [m_Z + 20$ GeV, 200 GeV]
$h_{SM} \to b\bar{b}$	$m_{h_{recon}} \in [m_{h_{SM}} - 20$ GeV, 200 GeV]
$h_{SM} \to c\bar{c}$	$m_{h_{recon}} \in [m_{h_{SM}} - 10$ GeV, 200 GeV]
$h_{SM} \to \tau^+\tau^-$	$m_{h_{recon}} \in [5$ GeV, 200 GeV]
$h_{SM} \to gg$	$m_{h_{recon}} \in [m_{h_{SM}} - 10$ GeV, 200 GeV]

Table II Event parameters and their discriminating values for $m_{h_{SM}} = 120$ GeV.

Parameter (p)	Discriminating Value (p_{disc})	Parameter (p)	Discriminating Value (p_{disc})
$p_{l^\pm}^{max}$	10 GeV	N_{sig}	10
E_{cone}	10 GeV	$n_{vertices}$ (jet 1)	2
m_{jj}	m_W	$n_{vertices}$ (jet 2)	2
$thrust_{Higgs}$	0.88	m_{p_t} (jet 1)	2 GeV
y_{32}	0.04	m_{p_t} (jet 2)	2 GeV
n_{tracks}	6	p_{jet}/p_{kin} (jet 1)	0.45
$m_{h_{recon}}$	110 GeV	p_{jet}/p_{kin} (jet 2)	0.45

accommodate beamstrahlung and initial state radiation. In signal events $e^+e^- \to Zh_{SM}$ with $Z \to l^+l^-$, approximately 29% of $m_{h_{SM}} = 115$ GeV events pass the reconstructed Z and recoil cuts. For the remaining mass cases, 31%, 36%, 39%, 41% and 41% of signal events pass these cuts for Higgs masses 120, 140, 160, 180, and 200 GeV.

From experience at LEP2 [4], it is expected that for each successful leptonic reconstruction of the Z, there will be at least three successful hadronic reconstructions of the Z. Therefore the number of signal event tags has been scaled up by a conservative factor of four to account for the inclusion of hadronic Z decays.

A significant number of large cross section background channel events ($e^+e^- \to ZZ$ and $e^+e^- \to W^+W^-$) pass these cuts. Therefore the Higgs mass is reconstructed after excluding the Z daughter leptons and including unassociated clusters. Different cuts on the reconstructed Higgs mass are then applied at the Higgs decay mode tagging level. Finally, requiring that the reconstructed Higgs mass be less than 200 GeV significantly reduces the $e^+e^- \to W^+W^-$ background (a lepton momentum asymmetry cut then eliminates it). These cuts are defined in Table I.

2.3. Signal Event Parameters

The $h_{SM} \to \tau^+\tau^-$ event is characterized by low track multiplicity (n_{tracks}), a distinct signature. The $h_{SM} \to WW^\star \to 2jl\nu_l$ event contains an isolated high momentum lepton, so the energy in a cone (E_{cone}) around the highest momentum ($p_{l^\pm}^{max}$) lepton in the event is small. The four-jet character of the $h_{SM} \to WW^\star$ events is a powerful discriminant. These events are identified by the large jet algorithm metric cut value required to force the event to two jets (y_{32}) and also the thrust ($thrust_{Higgs}$) calculated after boosting to the Higgs frame. The mass in the dijet (m_{jj}) closest to the W mass is in fact close to m_W.

The h_{SM} decays to quarks or gluons are two-jet events characterized by a low jet algorithm metric cut value. The jet p_t corrected mass (m_{p_t}) and number of vertices ($n_{vertices}$), calculated using the method based on 3D topological vertex finding [3] then serve to separate the two-jet events by flavor. For one-prong decays, the two-jet events are separated by the number of tracks (N_{sig}) with 3D impact parameter significance greater than 3. The kinematic expectation for the momentum in each jet, compared to the measured momentum (p_{jet}/p_{kin}), provides a small further separation.

Particular values of these fourteen parameters were found to be useful in discriminating between the various signal and background modes. Table II summarizes the parameters and their discriminating values.

Table III Signal and background for each optimized tag ($m_{h_{SM}} = 120$ GeV case).

Sample	$WW^\star$-tag	$b\bar{b}$-tag	$c\bar{c}$-tag	$\tau^+\tau^-$-tag	gg-tag
$h_{SM} \to WW^\star$	214(50%)	12.7(0.6%)	3.3(2.5%)	0.5(0.23%)	98(24.6%)
$h_{SM} \to b\bar{b}$	27.9(6.5%)	1599(74%)	59.7(44.6%)	0	13.9(3.5%)
$h_{SM} \to c\bar{c}$	7.0(1.6%)	13.6(0.6%)	29.3(22%)	0.02	12.2(3.1%)
$h_{SM} \to \tau^+\tau^-$	0.3(0.5%)	0	0	189.6(88.2%)	0
$h_{SM} \to gg$	52.7(12.4%)	9.8(0.45%)	3.0(2.2%)	0	112.8(28.3%)
$h_{SM} \to ZZ^\star$	1.0(0.2%)	0.6(0.03%)	0.1(0.07%)	0	0
$e^+e^- \to ZZ$	123.2(28.9%)	524.7(24.3%)	38.6(28.8%)	24.8(11.5%)	161.1(40.5%)
$e^+e^- \to W^+W^-$	0	0	0	0	0
$e^+e^- \to q\bar{q}$	0	0	0	0	0
$e^+e^- \to t\bar{t}$	0	0	0	0	0

Table IV Relative branching ratio errors δ_{BR}/BR.

Mode	115 GeV	120 GeV	140 GeV	160 GeV	180 GeV	200 GeV
$h_{SM} \to WW^\star$	0.16	0.10	0.03	0.02	0.03	0.04
$h_{SM} \to b\bar{b}$	0.027	0.029	0.038	0.13	0.59	-
$h_{SM} \to \tau^+\tau^-$	0.07	0.08	0.10	0.36	-	-
$h_{SM} \to c\bar{c}$	0.31	0.39	0.44	–	-	-
$h_{SM} \to gg$	0.16	0.18	0.23	-	-	-
$h_{SM} \to c\bar{c} + gg$	0.15	0.16	0.20	-	-	-

2.4. Neural Network Tagging

In order to optimize tagging, these parameters and their discriminating values were used in constructing a neural network implemented on the Stuttgart Neural Network Simulator v4.2 [5]. Eight event-level parameters and six jet-level parameters are the neural network inputs. In each event, each parameter value is mapped to the unit interval by $p \mapsto 1 - \exp[-(p/p_{disc})^2 \ln 2]$. Then $0 \mapsto 0$, $p_{disc} \mapsto 1/2$, and for $p \gg p_{disc}$, $p \mapsto 1$. These values are then used as inputs to the neural network. There are fifteen hidden units. The six output units are $h_{SM} \to b\bar{b}, c\bar{c}, \tau^+\tau^-, gg, WW^\star \to 4j, WW^\star \to 2jl\nu_l$; each output is trained to output 1 for signal events and 0 for other events. The network is fully connected and standard back propagation is the learning algorithm. Each Higgs decay mode tag is defined by a set of six cut values on the neural network outputs, so each point in the six-dimensional unit cube maps to a signal S and background B for that mode. To optimize the tags for branching ratio error, we maximized $S/(S+B)^{1/2}$ by sampling on a lattice with 10^6 points.

For one mass case, Table III gives the signal and background for each tag, optimized for branching ratio error. Table IV gives the relative branching ratio errors δ_{BR}/BR for all six mass cases considered.

Other studies similar to this one [6] [7] assume different center of mass energies, luminosities and Higgs masses. Some include the WW-fusion production mode $e^+e^- \to \nu\bar{\nu}h_{SM}$. When scaled by $(\sigma \int dt\mathcal{L})^{1/2}$, the results show remarkable uniformity across these studies with the exception of the $h_{SM} \to c\bar{c}$ mode. This mode is particularly sensitive to background from $h_{SM} \to b\bar{b}$ and $Z \to b\bar{b}, c\bar{c}$ from Z pair production. We expect that our treatment of the backgrounds, including our careful simulation of the vertex detector reconstruction, account for the differences. We find that the purity-efficiency curves for simple monojets underestimate the flavor confusion in the $e^+e^- \to Zh_{SM}$ events where some tracks are left misassigned or unassigned to vertices.

3. Conclusions

We have investigated the precision of Standard Model Higgs Boson branching ratio measurements at the future e^+e^- linear collider and find that the linear collider will provide excellent sensitivity. The $h_{SM} \to c\bar{c}$ precision is limited by the contamination from the $h_{SM} \to b\bar{b}$ decay mode and the $e^+e^- \to ZZ$ background. Much care has been taken to simulate the vertex detector reconstruction based on experience with SLD.

References

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