SEARCH STRATEGIES FOR NON-STANDARD HIGGSES AT $E^+E^-$ COLLIDERS

J. KALINOWSKI

Instytut Fizyki Teoretycznej UW, ul. Hoże 69, 00681 Warsaw, Poland
E-mail: kalino@fuw.edu.pl

The Higgs search strategies in minimal non-supersymmetric extensions of the SM are discussed.

1 Motivation

If no new physics is assumed up to the grand unification or $M_{Pl}$ scales, the requirement of perturbativity and vacuum stability of the Standard Model constraints the Higgs boson mass to lie within the range of 130 – 190 GeV. This is in perfect agreement with the electroweak precision fits which strongly point to a light Higgs boson with $m_{H_{SM}} = 62^{+53}_{-30}$ GeV, and with the 95% CL upper limit 170 GeV. This mass range, well above the ultimate LEP2 reach (the current experimental LEP limit is $m_{H_{SM}} > 113$ GeV) and rather difficult at Tevatron (particularly in its upper part), will be fully covered at the LHC by exploiting the $gg \rightarrow H \rightarrow \gamma\gamma$ or associate production $t\bar{t}H$, $WH$ processes. For the future $e^+e^-$ colliders this mass range is particularly easy. The “standard” Higgs hunting strategies at $e^+e^-$ collisions rely on the Higgs-strahlung, $e^+e^- \rightarrow ZH$, and (for higher energies and heavier Higgs bosons) on the $WW$ fusion, $e^+e^- \rightarrow \nu\bar{\nu}$, processes.

It should be stressed that the above implications for a light Higgs boson with substantial $ZZh$ coupling can be altered if we admit new physics. By adding $O_{\text{NEW}}^{i}$ to the electroweak observables $O_{i}$, the SM contributions can be compensated resulting in a higher value of the Higgs mass.

In fact, the Higgs sector may turn out to be more complicated than just one doublet, as realised in the SM. Even in non-supersymmetric world, and adding additional SU(2) singlet or doublet Higgs fields only (to keep the tree-level $\rho = 1$), Higgs boson couplings may change considerably and thus complicate the Higgs boson searches. Particularly worrisome is the case of a light Higgs $h$ with suppressed $ZZh$ and $WWh$ couplings; we will refer to it as a “bosophobic” Higgs. If such a Higgs boson with mass below 113 GeV exists, negative searches at LEP2 in $e^+e^- \rightarrowZH$ translate into an upper limit on the $g_{ZZh}$ coupling. Are we guaranteed to discover the bosophobic Higgs with other Higgs bosons too heavy to be produced? The answer turns out to be model dependent. The absence of $ZZ$ coupling implies that the $h$ will not be detectable at the Tevatron, and very difficult, if not impossible, at the LHC. Therefore we will consider a $\sqrt{s} = 500 – 800$ GeV $e^+e^-$ linear collider (LC) assuming an integrated luminosity $L > \sim 500 \text{ fb}^{-1}$.

2 Adding singlets

Adding singlet Higgs fields does not pose any particular theoretical problems nor benefits. However, if many singlet fields mix with the SM doublet in such a way that the physical Higgs bosons $h_{i}$ share the SM $WW/ZZ$-Higgs coupling, the cross sections in $e^+e^- \rightarrow Zh_{i}$ ($i = 1, \ldots, N$) for individual channels will be suppressed. The scenario considered in assumes $h_{i}$ spaced more closely than the experimental mass resolution and spread out over some substantial range around 200 GeV. The
individual resonance peaks will overlap making a diffuse signal not much different from the background. If in addition Higgs bosons decay to a large number of different channels, identification of individual final states will not be possible nor useful due to large background. Another possibility, the so called stealthy Higgs, is considered in [4], where the usual Higgs doublet couples to many singlets (called Phions) which interact among themselves strongly. The net effect is that the SM-like Higgs boson is very broad and decays invisibly into Phions.

At hadron colliders such scenarios are real nightmare. On the other hand, it has been demonstrated [4] that by looking for an excess in the recoil mass \( m_X \) distribution due to a “continuum” of Higgses in \( e^+e^- \rightarrow ZX \), the signal can be observed at an \( e^+e^- \) collider with \( \sqrt{s} = 500 \text{ GeV} \) and integrated luminosity \( > 100 \text{ fb}^{-1} \). Since the inclusive \( e^+e^- \rightarrow ZX \) process can be used irrespectively of Higgs decay modes, the stealthy Higgs can cleanly be detected [4] by looking for a signal of leptons and missing energy.

3 Adding one Higgs doublet

Even the simplest two-Higgs-doublet model (2HDM) extension of the SM exhibits a rich Higgs sector structure. The CP-conserving (CPC) 2HDM predicts the existence of two neutral CP-even Higgs bosons \( (h^0 \text{ and } H^0, \text{ with } m_{h^0} \leq m_{H^0} \text{ by convention}) \), one neutral CP-odd Higgs \( (A^0) \) and a charged Higgs pair \( (H^\pm) \). The same spectrum of Higgs bosons is found in the minimal supersymmetric model (MSSM), where it has been demonstrated [4] that the detection of at least one of the Higgs bosons is possible either at LEP2 or LHC.

The situation is more complex in the non-supersymmetric 2HDM. Here we consider the type-II 2HDM, wherein one of the doublets couples to down-type quarks and leptons and the other to up-type quarks. The 2HDM allows for spontaneous and/or explicit CP violation (CPV) in the scalar sector at the tree level. In the CPV case the physical mass eigenstates, \( h_i (i = 1, 2, 3) \), are mixtures (specified by three mixing angles \( \alpha_i \), in addition to the mixing angle \( \beta \) related to Higgs vev’s) of the real and imaginary components of the original neutral Higgs doublet fields; as a result, the \( h_i \) have undefined CP properties.

If there are two light Higgs bosons \( h_1 \) and \( h_2 \), in the sense that \( Zh_1, Zh_2 \) and \( h_1h_2 \) channels are kinematically open, then at least one will be observable in \( Zh_1, Zh_2 \) production or both in \( h_1h_2 \) pair production. This is because of the sum rule [4] for the couplings of any two of neutral Higgses to the \( Z \) boson

\[
C_i^2 + C_j^2 + C_{ij}^2 = 1, \tag{1}
\]

where \( g_{Zh_i} \equiv \frac{g_{WZ}}{\sqrt{2}c_W} C_{ii} \) and \( g_{Zh_ih_j} \equiv \frac{g_{WZ}}{2c_W^2} C_{ij} \), which says that all three couplings cannot be simultaneously suppressed. For example, if both \( C_1 \) and \( C_2 \) are dynamically suppressed, then from the above sum rule it follows that Higgs pair production is at full strength, \( C_{12} \sim 1 \). In Fig.1 contour lines are shown for the minimum value of the pair production cross section, \( \sigma(e^+e^- \rightarrow h_1h_2) \) as a function of Higgs boson masses. The minimum
of $\sigma(h_1h_2)$ is found by scanning over the mixing angles $\alpha_i$ consistent with present experimental constraints on $C_i$ (which roughly exclude $m_{h_1} + m_{h_2} \lesssim 180$ GeV) and the assumption of less that 50 $Zh_i$ events. With $L = 500$ fb$^{-1}$ a large number of events is predicted for a broad range of Higgs boson masses. If 50 $h_1h_2$ events before cuts and efficiencies prove adequate (i.e. $\sigma > 0.1$ fb), one can probe reasonably close to the kinematic boundary.

The main question, however, is whether a single neutral Higgs boson $h_1$ will be observed in $e^+e^-$ collisions if it is sufficiently light, regardless of the masses and couplings of the other Higgs bosons. Such a scenario can easily be arranged by choosing model parameters so that the $ZZ/WW h_1$ couplings are too weak for its detection in Higgs-strahlung or $WW$ fusion processes, and all other Higgs bosons are too heavy to be produced via $Zh_1$ or $h_1h_2$ processes at a given energy. In the CPC for example, one can simply choose $h_1 = A^0$ (the tree-level $ZZ/WW A^0$ coupling is zero), or in the general CPV model choose mixing angles $\alpha_i$ to zero the $ZZ/WW h_1$ coupling. Since the other Higgs bosons are assumed to be quite heavy to avoid production, implying no light Higgs with substantial $ZZ/WW$ couplings, it would seem that the fit to precision electroweak constraints is likely to be poor. However, as shown in [4], a good global fit to EW data is possible even for very light $h^0$ or $A^0$ (with $m \sim 20$ GeV) in the CPC 2HDM.

If one of the two processes, $Zh_2$ and $h_1h_2$, is beyond the LC’s kinematical reach, the sum rule in Eq. (1) is not sufficient to guarantee $h_1$ discovery if $C_i \ll 1$. However, in this case we can exploit other sum rules which constrain the Yukawa couplings of any Higgs boson $h_i$. For $C_i \ll 1$ they read (for obvious reasons we consider the third generation fermions)

\[
(S_i^f)^2 + (P_i^f)^2 = \cot^2 \beta
\]

where the fermionic Higgs couplings are given by $g_{m}\bar{f}_{i}\gamma_{5}f_{i}h_{1}$, i.e. $S_i^f$ and $P_i^f$ are defined relative to the SM strength. Combining the two sum rules we find that the Yukawa couplings to top and bottom quarks cannot be simultaneously suppressed, i.e. at least one $h_i$ Yukawa coupling must be large. Therefore the Higgs hunting strategies should include not only the Higgs-strahlung and Higgs-pair production but also Yukawa processes with Higgs radiation off top and bottom quarks in the final state. The current experimental limits in the $m_{h_1}$-$\tan \beta$ parameter space are rather weak, see [5].

It turns out that for large (small) $\tan \beta$, the $bbh_1$ ($tth_1$) cross sections are comfortably large for $h_1$ discovery. However, scanning over mixing angles $\alpha_i$ we find the difficult region of moderate $\tan \beta$, where even at very high integrated luminosity of 2500 fb$^{-1}$ none of the $Zh_1$, $tth_1$ and $bbh_1$ processes yields more than 50 events, see Fig.2.

The non-discovery wedge begins at $m_{h_1} \sim 50$ GeV at $\sqrt{s} = 500$ GeV ($\sim 80$ GeV for $\sqrt{s} = 800$ GeV) and expands rapidly as
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$m_{h_1}$ increases. Thus, it is apparent that, despite the sum rules guaranteeing significant fermionic couplings for a light 2HDM Higgs boson that is unobservable in $Z$+Higgs production, $\tan \beta$ and the $\alpha_i$ mixing angles can be chosen so that the cross section magnitudes of the two Yukawa processes are simultaneously so small that detection of such an $h_1$ cannot be guaranteed for integrated luminosities that are expected to be available.

Is the whole wedge consistent with electroweak constraints? This question, in the context of CPC 2HDM, is analysed in \cite{Chankowski:2000} with the general result that for LC $\sqrt{s} = 500$ (800) GeV, the $\tan \beta \sim 2$ portions of the 2HDM no-discovery wedges in $m_{h_1}$-$\tan \beta$ parameter space have $\Delta \chi^2 < 1$ ($\sim 1.5$) (relative to the best SM fit) and all of the no-discovery wedges’ portions with $\tan \beta \gtrsim 1$ have $\Delta \chi^2 < 2$. Thus the discrimination from current EW data between the SM and the no-discovery scenarios in the 2HDM is rather weak at the LC with $\sqrt{s} = 500 – 800$ GeV.

4 Conclusions

In a general CPV 2HDM a light bosophobic Higgs boson, with all other Higgs bosons heavier than the kinematical reach of a 500-800 GeV $e^+e^-$ collider, may escape detection. If $\sqrt{s}$ is pushed beyond 1 TeV, and the next lightest Higgs $H$ is still not seen in $ZH$ or $\nu\bar{\nu}H$, implying $m_H \gtrsim 1$ TeV, one would expect to see strong $WW$ scattering behavior at both the LHC and the LC. As a result, only an LC with sufficiently large energy to probe a strongly interacting $WW$ sector could be certain of seeing a Higgs signal, unless the electroweak fits really do indicate a relatively light Higgs boson.

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