Observing a Light CP-Violating Higgs Boson in Diffraction

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Abstract

Light CP-violating Higgs bosons with mass lower than 70 GeV might have escaped detection in direct searches at the LEP collider. They may remain undetected in conventional search channels at the Tevatron and LHC. In this Letter we show that exclusive diffractive reactions may be able to probe for the existence of these otherwise elusive Higgs particles. As a prototype example, we calculate diffractive production cross-sections of the lightest Higgs boson within the framework of the Minimal Supersymmetric Standard Model with explicit CP violation. Our analysis shows that the challenging regions of parameter space corresponding to a light CP-violating Higgs boson might be accessible at the LHC provided suitable proton tagging detectors are installed.
Ultra-violet completion of the Standard Model (SM) suggests the existence of a new fundamental scalar, known as the Higgs boson. The SM Higgs boson has not yet been discovered and this provides a motivation for studies of non-standard Higgs sectors. A natural extension of the SM is to add an additional Higgs doublet, thereby permitting CP violation in the Higgs sector of the theory. In particular, theories based on supersymmetry (SUSY) require the existence of additional Higgs doublets on pure field-theoretic grounds [1]. A minimal realization of a softly-broken SUSY theory is the so-called Minimal Supersymmetric Standard Model (MSSM) [2]. It is known [3] that third generation squark loops can introduce sizeable CP violation into the Higgs potential of the MSSM. Within this predictive CP-violating framework, the neutral Higgs bosons will mix to produce three physical mass eigenstates of indefinite CP parity, labelled as $H_1$, $H_2$ and $H_3$ in order of increasing mass [4]. After the inclusion of CP-violating quantum effects, each of these three mass eigenstates may have appreciable couplings to $W$ and $Z$ bosons. A salient feature of this model is that the $H_1 ZZ$ coupling can be significantly suppressed, reducing the LEP II mass limit on the $H_1$ boson to as low as 60 GeV [5]. In addition, if the two heavier Higgs bosons $H_{2,3}$ decay predominantly into pairs of the lightest Higgs boson $H_1$ [6], then almost no lower bound on the $H_1$ mass can be derived at LEP, while all three neutral Higgs particles may still remain hidden in the large $b\bar{b}$ background at the Tevatron and LHC [7].

In this Letter we show that diffractive collisions at the LHC may offer a unique probe for the possible existence of light CP-violating MSSM Higgs bosons, which could otherwise escape detection in conventional search channels. To this end, we calculate production cross-sections for the process $p + p \rightarrow p + H_1 + p$ in which the final state consists only of two intact protons and the decay products of the Higgs boson. The reaction $p + p \rightarrow p + H_1 + p$ is often termed the exclusive process [8,9,10,11,12,13] and has both experimental and theoretical advantages over the conventional non-diffractive case. If both outgoing protons are tagged in detectors a long way downstream of the interaction point, a Higgs mass resolution of the order of 1 GeV is possible [14] using the so-called missing mass method. Furthermore, because of the requirement that the outgoing protons remain intact and scatter through small angles, only $0^{++}$ systems can be produced. This has the effect of suppressing the QCD background to the dominant $b\bar{b}$ decay mode [15,16]. It has been shown that signal to background ratios of order 3 could be achieved for a SM Higgs boson of mass 120 GeV in the $b\bar{b}$ channel at the LHC, using a combination of proton and $b$ jet tagging [14], for an integrated luminosity of 30 fb$^{-1}$. At the Tevatron, with an estimated rate of 0.2 fb [17], the situation is not so promising. The main reason for a such low cross-section is the size of the Higgs mass relative to the total center-of-mass energy available for Higgs production. In an exclusive diffractive
collision, the fractional longitudinal momentum loss of the protons $\xi$ is typically less than $10\%$, and therefore the maximum available energy for Higgs production at the Tevatron is $\sqrt{s} = \sqrt{\xi_1 \xi_2 s} \sim 200$ GeV.

In stark contrast to the SM case, the kinematic situation changes drastically for the case of light CP-violating MSSM Higgs bosons with masses smaller than 60 GeV. As we will explicitly demonstrate below, it may be possible to detect their production using exclusive diffractive collisions at the LHC.

Our calculation of the diffractive production cross-section closely follows that of [17]. In particular, we consider the Higgs boson to be produced by gluon fusion, just as in the inclusive process, except that an additional gluon is exchanged between the incoming protons in order to neutralize the colour and allow the protons to continue their journey unscathed. Appropriate suppression factors are included to account for the probability not to radiate any further particles into the final state.

We write the cross-section for the exclusive diffractive production of a colour singlet state, such as a CP-violating Higgs boson $H_i$ (with $i = 1, 2, 3$), as

$$\frac{\partial \sigma}{\partial y} = \int \frac{\partial^2 \mathcal{L}(M^2, y)}{\partial M^2 \partial y} \hat{\sigma}(M^2) dM^2,$$

where $\hat{\sigma}$ is the cross-section for the hard subprocess producing the Higgs (i.e. $gg \rightarrow H_i$) and $\partial^2 \mathcal{L}/\partial M^2 \partial y$ is the differential luminosity associated with Higgs production at rapidity $y$ and mass $M$. For further information on the luminosity we refer to [17] where all of the formulae we use are presented and discussed in detail. Here we focus on the hard scattering cross-section.

The amplitude for resonant Higgs production via gluon fusion, $gg \rightarrow H_i$, is [18,19,20]

$$\mathcal{M}_{ggH_i} = \frac{-M^2_{H_i} \alpha_s \delta^{ab}}{4\pi v} \left[ S^g_i(M^2_{H_i}) \left( \epsilon_1 \cdot \epsilon_2 - \frac{2 k_1 \cdot \epsilon_2 k_2 \cdot \epsilon_1}{M^2_{H_i}} \right) - P^g_i(M^2_{H_i}) \left( \epsilon_1 \epsilon_2 k_1 k_2 \right) \right].$$

where $v \approx 246$ GeV, the indices $a,b$ count gluon colours, $k_{1,2}$ and $\epsilon_{1,2}$ denote the four-momenta and polarization vectors of the incoming gluons, and $\langle \epsilon_1 \epsilon_2 k_1 k_2 \rangle = \epsilon_{\mu \nu \rho \sigma} \epsilon'^{\mu}_{1} \epsilon'^{\nu}_{2} k'^{\rho}_{1} k'^{\sigma}_{2}$. In addition, the scalar and pseudo-scalar form factors $S^g_i$ and $P^g_i$ are

$$S^g_i(M^2_{H_i}) = \sum_{f=b,t} g^S_{H_i \bar{f} f} F_{sf} \left( M^2_{H_i}/4m_f^2 \right) - \sum_{f=b,t} \sum_{j=1,2} g_{H_i \bar{j} f} \frac{v^2}{4m_{f_j}^2} F_0 \left( M^2_{H_i}/4m_{f_j}^2 \right),$$

$$P^g_i(M^2_{H_i}) = \sum_{f=b,t} g^P_{H_i \bar{f} f} g_{H_i \bar{f} f} \left( M^2_{H_i}/4m_f^2 \right).$$

The loop functions $F_{sf}(\tau)$, $F_0(\tau)$ and $F_{pf}(\tau)$ may be found in [21]. In the limit $\tau \rightarrow 0$, $F_{sf}(0) = 2/3$, $F_0(0) = 1/3$ and $F_{pf}(0) = 1$. The quantities $g^S_{H_i \bar{f} f}$ and $g^P_{H_i \bar{f} f}$ are the
reduced scalar and pseudo-scalar couplings of the Higgs bosons $H_i$ to a fermion $f$ in units of $g m_f/(2M_W)$ \cite{5}. If only CP-violating Higgs-mixing effects are considered, $g_{H_i ff}^S$ and $g_{H_i ff}^P$ assume the simple forms

$$
\begin{align*}
    g_{H_i bb}^S &= O_{1i}/\cos \beta, & g_{H_i bb}^P &= -O_{3i} \tan \beta, \\
    g_{H_i tt}^S &= O_{2i}/\sin \beta, & g_{H_i tt}^P &= -O_{3i} \cot \beta,
\end{align*}
$$

(4)

where $O_{\alpha i}$ is a 3-by-3 orthogonal matrix which relates the weak eigenstates $\alpha = (\phi_1, \phi_2, a) = (1, 2, 3)$ to the mass eigenstates $i = (H_1, H_2, H_3) = (1, 2, 3)$, with $(\phi_1, \phi_2, a)^T = O_{\alpha i} (H_1, H_2, H_3)^T$. In our numerical analysis, we also take into account CP-violating finite threshold effects on the effective Higgs–fermion–fermion couplings generated by the exchange of gluinos and charged Higgsinos \cite{22,7,23}. Finally, the diagonal couplings of the neutral Higgs bosons $H_i$ to sfermions $\tilde{f}_j$ are real and given by

$$
\begin{align*}
    v g_{H_i \tilde{f}_j \tilde{f}_j} &= \sum_{\alpha=\phi_1,\phi_2,a} \sum_{\beta,\gamma=L,R} \left(\Gamma^\alpha \tilde{f}_j^* \tilde{f}_j\right)_{\beta\gamma} O_{\alpha i} U_{\tilde{f}_j} U_{\tilde{f}_j}^\dagger.
\end{align*}
$$

(5)

In the above, $U_{\tilde{f}_j}$ are the sfermion mixing matrices that relate the weak to mass eigenstates: $(\tilde{f}_L, \tilde{f}_R)^T = U_{\tilde{f}_j} (\tilde{f}_1, \tilde{f}_2)^T$, where the coupling matrices $\Gamma^\alpha \tilde{f}_j^* \tilde{f}_j$ are presented in \cite{19,5}. The amplitude (2) should be averaged over all gluon colours and polarizations, leading to

$$
\mathcal{M}_{ggH_i} = \frac{M_{H_i}^2 \alpha_s}{4\pi v} S_i^g (M_{H_i}^2).
$$

(6)

The corresponding cross-section for $gg \to H_i$ is

$$
\sigma^{\text{excl}}(gg \to H_i; M^2) = K_i \frac{\alpha_s}{16\pi v^2} \left| S_i^g (M_{H_i}^2) \right|^2 \delta\left(1 - \frac{M_{H_i}^2}{M^2}\right),
$$

(7)

where $K_i = 1 + \frac{\alpha_s(M_{H_i}^2)}{\pi}(\pi^2 + \frac{11}{2})$ accounts for virtual QCD corrections \cite{17}. Note that this cross-section is not the same as the subprocess cross-section which would be used in inclusive production, the latter would include an additional factor of $1/[2(N_c^2 - 1)]$, where $N_c = 3$ is the number of colours.

For illustration, we consider the CPX scenario of \cite{5} with $M_{\text{SUSY}} = 0.5$ TeV, $\Phi_{\text{CP}} = 90^\circ$ and $\tan \beta = 4$ and 5. The phase $\Phi_{\text{CP}}$ is defined as

$$
\Phi_{\text{CP}} \equiv \arg(\mu A_t) = \arg(\mu A_b) = \arg(\mu m_{\tilde{g}}).
$$

(8)

In the CPX scenario, moderate values of $\tan \beta$ ($3 \lesssim \tan \beta \lesssim 6$) and large CP phases ($90^\circ \lesssim \Phi_{\text{CP}} \lesssim 120^\circ$) define a MSSM parameter space for which a light CP-violating Higgs boson, with $M_{H_i} \lesssim 50$ GeV, cannot be excluded by the latest analysis of LEP2 data \cite{7}. In addition,
Figure 1: The ratio $R \equiv |S^g_1(M^2_{H_1})/S^g_1(M^2_{H_{SM}})|$ assuming $M_{H_{SM}} = M_{H_1}$ in the CPX scenario [5] with $M_{SUSY} = 0.5$ TeV, $\Phi_{CP} = 90^\circ$, and (a) $\tan \beta = 4$ and (b) $\tan \beta = 5$.

it will be difficult to observe such a light Higgs boson in the channels: $(W/Z)H_i(\rightarrow bb)$ at the Tevatron, and $gg \rightarrow H_i(\rightarrow \gamma\gamma)$, $ttH_i(\rightarrow bb)$ and $WW \rightarrow H_i(\rightarrow \tau^+\tau^-)$ at the LHC [7].

Apart from the aforementioned direct constraints on the CPX scenario based on standard Higgs-search channels, one may worry about the impact of indirect limits on the large CP-violating phase $\Phi_{CP}$ considered here that arise due to non-observation of electron and neutron electric dipole moments (EDMs). However, it has been shown recently [22] that if the first two generation of squarks are heavier than about 3 TeV, the required degree of cancellation [24] between the one- and higher-loop contributions to EDMs due to large gluino and third-generation squark phases [25] is not excessive. In particular, for low and moderate values of $\tan \beta \lesssim 6$, the different EDM contributions may add destructively [22] and the required degree of cancellation is always smaller than 60%.* Hence, we expect that a full implementation of EDM constraints will not alter the results of the present analysis in a significant way.

In Fig. 1 we show the absolute value of the ratio of $S^g_1(M^2_{H_1})$ for the lightest MSSM Higgs boson to that of the SM Higgs boson with $M_{H_{SM}} = M_{H_1}$ as a function of $M_{H_1}$. As is seen in Eq. (3), the form factor $S^g_1(M^2_{H_1})$ can be decomposed into contributions from the bottom quark, the top quark and the four squarks. The dashed lines show the contribution from the bottom quark, the dotted lines from the bottom and top quarks, and the dash–dotted lines from the lighter top squark $\tilde{t}_1$ plus the top and bottom quarks. Finally, the

*We note that 100% corresponds to complete cancellation.
solid lines show the total contribution from the two quarks and four squarks. We note that $S_{g_{SM}(0)} = 4/3$ in the limit of vanishing $M_{H_{SM}}$. For small $\tan\beta$, the dominant contribution comes from the lighter top squark $\tilde{t}_1$, the contributions from the other three heavier squarks being small and destructive.

In Fig. 2, we present the exclusive diffractive production cross-section for the lightest neutral MSSM Higgs boson. We use the same values of $\tan\beta$ and $\Phi_{CP}$ as in Fig. 1. Results are shown at both Tevatron (dashed line) and LHC (solid line) energies. In both cases we integrate over all $\xi < 0.1$.

Our results should be compared to the exclusive diffractive SM Higgs production cross-section of $\sim 3$ fb at the LHC for $M_H = 120$ GeV [14]. The conclusion of [14] is that a signal to background ratio $\sim 3$ is possible for the 120 GeV Higgs, detected through its decay to $b\bar{b}$.

For the lighter Higgs considered here, the signal to background ratio will be reduced considerably since one anticipates a $S/B \propto \Gamma(H \to gg)/\Delta M \propto G_F M_H^3/\Delta M$ where $\Delta M$ is the experimental resolution on the mass of the central system (assumed to be 1 GeV in [14]). There is a further suppression since the $J_z = 0$ selection rule becomes less effective at Higgs masses not much larger than the $b\bar{b}$ threshold, i.e. the cross-section for exclusive $b\bar{b}$

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**Figure 2:** The cross-section for the process $p + p \to p + H_1 + p$ at the Tevatron (dashed line) and LHC (solid line) in the CPX scenario with $M_{SUSY} = 0.5$ TeV, $\Phi_{CP} = 90^\circ$, and (a) $\tan\beta = 4$ and (b) $\tan\beta = 5$. 

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production is proportional to $m_b^2/M_H^2$. More detailed studies are clearly required before any definite conclusions can be drawn, however a rough estimate, based upon the calculation of the $b\bar{b}$ background in [14] in conjunction with the signal cross-sections shown in Fig.2 suggests that a statistical significance $(S/\sqrt{S+B})$ above 2σ should be obtainable at the LHC for Higgs masses above 20 GeV, provided suitable detectors are installed†. Similar estimates indicate that the $b\bar{b}$ background will most likely be prohibitive at the Tevatron.

Although our focus here has been on light CP-violating Higgs bosons, our study could be extended to a number of other scalar particles with analogous phenomenological features. For example, light radions predicted in certain higher-dimensional scenarios with warped geometry [26,27] may couple significantly to gluons, but feebly to $Z$ and $W$ bosons, thus escaping detection in the conventional Higgs-search channels.

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References

[1] H.P. Nilles, Phys. Rept. 110 (1984) 1; H.E. Haber and G.L. Kane, Phys. Rept. 117 (1985) 75.

[2] For a recent review on Higgs phenomenology in the MSSM, see M. Carena and H.E. Haber, hep-ph/0208209.

[3] A. Pilaftsis, Phys. Rev. D58 (1998) 096010; Phys. Lett. B435 (1998) 88.

[4] A. Pilaftsis and C.E.M. Wagner, Nucl. Phys. B553 (1999) 3; D.A. Demir, Phys. Rev. D60 (1999) 055006; S.Y. Choi, M. Drees and J.S. Lee, Phys. Lett. B481 (2000) 57; G.L. Kane and L.-T. Wang, Phys. Lett. B488 (2000) 383; T. Ibrahim and P. Nath, Phys. Rev. D63 (2001) 035009; Phys. Rev. D66 (2002) 015005; S. Heinemeyer, Eur. Phys. J. C22 (2001) 521; M. Frank, S. Heinemeyer, W. Hollik and G. Weiglein, hep-ph/0212037.

†The significance is aided by the fact that the number of signal events rises rapidly with decreasing Higgs mass.
[5] M. Carena, J.R. Ellis, A. Pilaftsis and C.E.M. Wagner, Phys. Lett. B495 (2000) 155; Nucl. Phys. B586 (2000) 92; Nucl. Phys. B625 (2002) 345.

[6] S.Y. Choi and J.S. Lee, Phys. Rev. D61 (2000) 015003; S.Y. Choi, K. Hagiwara and J.S. Lee, Phys. Rev. D64 (2001) 032004.

[7] M. Carena, J. Ellis, S. Mrenna, A. Pilaftsis and C.E. Wagner, arXiv:hep-ph/0211467.

[8] A. Schäfer, O. Nachtmann and R. Schöpf, Phys. Lett. B249 (1990) 331.

[9] A. Bialas and P.V. Landshoff, Phys. Lett. B256 (1991) 540.

[10] H-J. Lu and J. Milana, Phys. Rev. D51 (1995) 6107.

[11] J.R. Cudell and O.F. Hernandez, Nucl. Phys. B471 (1996) 471.

[12] E. Levin, arXiv:hep-ph/9912402.

[13] V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J. C14 (2000) 525; ibid. C19 (2001) 477.

[14] A. De Roeck, V.A. Khoze, A.D. Martin, R. Orava and M.G. Ryskin, Eur. Phys. J. C25 (2002) 391.

[15] V.A. Khoze, A.D. Martin and M. G. Ryskin, arXiv:hep-ph/0006005.

[16] V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J. C19 (2001) 477 [Erratum-ibid. C20 (2001) 599].

[17] V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J. 23 (2002) 311.

[18] A. Dedes and S. Moretti, Phys. Rev. Lett. 84 (2000) 22; Nucl. Phys. B576 (2000) 29.

[19] S.Y. Choi and J.S. Lee, Phys. Rev. D61 (2000) 115002.

[20] S.Y. Choi, K. Hagiwara and J.S. Lee, Phys. Lett. B529 (2002) 212.

[21] S.Y. Choi and J.S. Lee, Phys. Rev. D62 (2000) 036005.

[22] A. Pilaftsis, Nucl. Phys. B644 (2002) 263.

[23] The Fortran code cph+ that computes the Higgs-boson pole masses $M_{H_i}$ and the respective mixing-matrix elements $O_{ai}$ in the MSSM with explicit CP violation is available from http://home.cern.ch/p/pilaftsi/www.
[24] T. Ibrahim and P. Nath, Phys. Rev. D58 (1998) 111301; Phys. Rev. D61 (2000) 093004; M. Brhlik, L. Everett, G.L. Kane and J. Lykken, Phys. Rev. Lett. 83 (1999) 2124; Phys. Rev. D62 (2000) 035005; S. Pokorski, J. Rosiek and C.A. Savoy, Nucl. Phys. B570 (2000) 81; E. Accomando, R. Arnowitt and B. Dutta, Phys. Rev. D61 (2000) 115003; A. Bartl, T. Gajdosik, W. Porod, P. Stockinger and H. Stremnitzer, Phys. Rev. D60 (1999) 073003; T. Falk, K.A. Olive, M. Pospelov and R. Roiban, Nucl. Phys. B60 (1999) 3; S.A. Abel, S. Khalil and O. Lebedev, Nucl. Phys. B606 (2001) 151.

[25] D. Chang, W.-Y. Keung and A. Pilaftsis, Phys. Rev. Lett. 82 (1999) 900.

[26] See, e.g., D. Dominici, B. Grzadkowski, J.F. Gunion and M. Toharia, hep-ph/0206192; T.G. Rizzo, JHEP 0206 (2002) 056; hep-ph/0207113

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