

Hunting a light CP -violating Higgs boson via diffraction at the LHC

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Abstract. We study the central diffractive production of the (three neutral) Higgs bosons, with a rapidity gap on either side, in an MSSM scenario with CP -violation. We consider the $b\bar{b}$ and $\tau\bar{\tau}$ decay for the light H_1 boson and the four b -jet final state for the heavy H_2 and H_3 bosons, and discuss the corresponding backgrounds. A direct indication of the existence of CP -violation can come from the observation of either an azimuthal asymmetry in the angular distribution of the tagged forward protons (for the exclusive $pp \rightarrow p + H + p$ process) or of a $\sin 2\varphi$ contribution in the azimuthal correlation between the transverse energy flows in the proton fragmentation regions for the process with the diffractive dissociation of both incoming protons ($pp \rightarrow X + H + Y$). We emphasise the advantage of reactions with the rapidity gaps (that is, production by pomeron–pomeron fusion) to probe CP -parity and to determine the quantum numbers of the produced central object.

1 Introduction

It is known that third generation squark loops can introduce sizeable CP -violation in the Higgs potential of the minimal supersymmetric standard model (MSSM), if the soft-supersymmetry-breaking mass parameters of the third generation are complex; see, for example, [1]. As a result, the neutral Higgs bosons will mix to produce three physical mass eigenstates with mixed CP -parity, which we denote H_1, H_2 and H_3 in order of increasing mass. A benchmark scenario of maximal CP -violation, called CPX , was introduced in [2]. In this scenario

$$\begin{aligned} |A_t| &= |A_b| = 2M_{\text{SUSY}}, & |\mu| &= 4M_{\text{SUSY}}, \\ M_{\tilde{Q}_3, \tilde{U}_3, \tilde{D}_3} &= M_{\text{SUSY}}, & |M_3| &= 1 \text{ TeV}, \end{aligned} \quad (1)$$

where A_f are the soft-supersymmetry-breaking trilinear parameters of the third generation squarks and μ is the supersymmetric higgsino mass parameter. The phenomenological consequences of this model may be quite spectacular. In particular, the $H_1 ZZ$ coupling of the lightest Higgs boson can be significantly suppressed; see, for example, [2] and references therein. In this case, it was shown that the LEP2 data do not exclude the existence of a light Higgs boson with mass $M_H < 60 \text{ GeV}$ (40 GeV) in the minimal SUSY model with $\tan \beta \sim 3\text{--}4$ (2–3) and CP -violating phase

$$\begin{aligned} \phi_{CPX} &\equiv \arg(\mu A_t) = \arg(\mu A_b) \\ &= \arg(\mu A_\tau) = \arg(\mu m_{\tilde{g}}) = 90^\circ \text{ (} 60^\circ \text{)}. \end{aligned} \quad (2)$$

Since the H_1 couplings to the W and Z gauge bosons become rather small, it would be hard to detect the light

Higgs via the processes $e^+e^- \rightarrow Z^* \rightarrow ZH_i$ or $e^+e^- \rightarrow Z^* \rightarrow H_i H_j$.

It is therefore interesting to consider the possibility of observing a light Higgs boson at the LHC or Tevatron collider. However, in general, it will be hard to observe a light Higgs at hadron colliders via the $b\bar{b}$ decay mode because, in particular, the transverse momenta of the outgoing b and \bar{b} jets are not large. As a consequence the signal is swamped by the QCD $b\bar{b}$ background¹. Therefore it was proposed [5] to search for a CP -violating light Higgs boson in the *exclusive* process $pp \rightarrow p + H + p$ at hadron colliders, where the + signs denote the presence of large rapidity gaps. Over the past few years such exclusive diffractive processes have been considered as a promising way to search for manifestations of new physics in high energy proton–proton collisions; see, for instance, [5–10]. These processes have both unique experimental and theoretical advantages in hunting for Higgs bosons as compared to the traditional non-diffractive approaches. In particular, in the exclusive diffractive reactions, the $b\bar{b}$ background is suppressed [9, 11–13], and it may be feasible to isolate the signal.

In the present paper we discuss the central *exclusive* diffractive production (CEDP) in more detail. We compare the signal and the background for observing a light neutral Higgs boson via $H_1 \rightarrow b\bar{b}$ and $H_1 \rightarrow \tau\tau$ decay modes. Then we evaluate the asymmetry arising from the interference of the P -even and P -odd production amplitudes.

¹ The prospects for observing such a light Higgs in conventional search channels, at the Tevatron and the LHC, were studied in [3, 4].

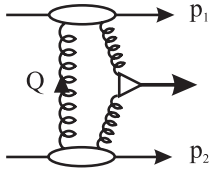


Fig. 1. Schematic diagram for the exclusive central production of a light Higgs boson

Note that this asymmetry is the most direct manifestation of CP -violation in the Higgs sector. Finally, we consider the exclusive diffractive production of the heavier neutral Higgs bosons, H_2 and H_3 , followed by the decays H_2 or $H_3 \rightarrow H_1 H_1 \rightarrow 4b$ jets.

For numerical estimates, we use the formalism to describe central production in diffractive exclusive processes of [7], and the parameters (that is the masses, width and couplings of the Higgs bosons) given by the code “CP-superH” [14], where we choose $\phi_{CPX} = 90^\circ$, $\tan\beta = 4$, $M_{\text{SUSY}} = 0.5 \text{ TeV}$, (that is $|A_f| = 1 \text{ TeV}$, $|\mu| = 2 \text{ TeV}$, $|M_{\tilde{g}}| = 1 \text{ TeV}$) and the charged Higgs boson mass $M_{H^\pm} = 135.72 \text{ GeV}$ so that the mass of the lightest Higgs boson, H_1 , is $M_{H_1} = 40 \text{ GeV}$.²

The exclusive process is shown schematically in Fig. 1. The cross section may be written [7] as the product of the effective gluon–gluon luminosity \mathcal{L} , and the square of the matrix element of the subprocess $gg \rightarrow H$. Note that the hard subprocess is mediated by the quark/squark triangles. For a CP -violating Higgs, there are two different vertices of the Higgs–quark interaction: the scalar Yukawa vertex and the vertex containing the γ_5 Dirac matrix. Therefore the $gg \rightarrow H$ matrix element contains two terms:³

$$\mathcal{M} = g_S \cdot (e_1^\perp \cdot e_2^\perp) - g_P \cdot \varepsilon^{\mu\nu\alpha\beta} e_{1\mu} e_{2\nu} p_{1\alpha} p_{2\beta} / (p_1 \cdot p_2), \quad (3)$$

where e^\perp are the gluon polarisation vectors and $\varepsilon^{\mu\nu\alpha\beta}$ is the antisymmetric tensor. In (3) we have used a simplified form of the matrix element which already accounts for gauge invariance, assuming that the gluon virtualities are small in comparison with the Higgs mass. In forward exclusive central production, the incoming gluon polarisations are correlated, in such a way that the effective luminosity satisfies the P -even, $J_z = 0$ selection rule [7, 13]. Therefore only the first term contributes to the strictly forward cross section. However, at non-zero transverse momenta of the recoil protons, $p_{1,2}^\perp \neq 0$, there is an admixture of the P -odd $J_z = 0$ amplitude of order $p_1^\perp p_2^\perp / Q_\perp^2$, on account of the g_P term becoming active. Thus we consider non-zero recoil proton transverse momenta, and demonstrate that the interference between the CP -even (g_S) and CP -odd (g_P) terms leads to left–right asymmetry in the azimuthal distribution of the outgoing protons. First, we consider the background. Unfortunately, even in the exclusive process, we show below that the QCD $b\bar{b}$ background is too large. However, we shall see that it may be possible to observe such a CP -violating light Higgs boson in the $H \rightarrow \tau\tau$ decay mode, where the QED background can be suppressed

² The values are chosen to provide an “optimistic” scenario for the observation of a CP -violating Higgs boson in CEDP.

³ For calculations of g_S and g_P in the MSSM with CP -violation, see, for example, [15].

by selecting events with relatively large outgoing proton transverse momenta; say, $p_{1,2}^\perp > 300 \text{ MeV}$.

2 Exclusive diffractive H_1 production followed by $b\bar{b}$ decay

First, we consider the exclusive double-diffractive process

$$pp \rightarrow p + (H \rightarrow b\bar{b}) + p \quad (4)$$

The signal-to-background ratio is given by the ratio of the cross sections for the hard subprocesses, since the effective gluon–gluon luminosity \mathcal{L} cancels out. The cross section for the $gg \rightarrow H$ subprocess⁴ [7]

$$\begin{aligned} \hat{\sigma}(gg \rightarrow H) &= \frac{2\pi^2 \Gamma(H \rightarrow gg)}{M_H^3} \delta \left(1 - \frac{M_{b\bar{b}}^2}{M_H^2} \right) \\ &\sim \text{constant} \times \delta \left(1 - \frac{M_{b\bar{b}}^2}{M_H^2} \right), \end{aligned} \quad (5)$$

as the width⁵, $\Gamma(H \rightarrow gg)$, behaves as $\Gamma \sim \alpha_S^2 G_F M_H^3$, where G_F is the Fermi constant. On the other hand, at leading order, the QCD background is given by the $gg \rightarrow b\bar{b}$ subprocess

$$\frac{d\hat{\sigma}_{\text{QCD}}}{dE_T^2} \sim \frac{m_b^2}{E_T^2} \frac{\alpha_S^2}{M_{b\bar{b}}^2 E_T^2}, \quad (6)$$

where E_T is the transverse energy of the b and \bar{b} jets. At leading order (LO), the cross section is suppressed by the $J_z = 0$ selection rule (which gives rise to the m_b^2/E_T^2 factor) in comparison with the inclusive process. The extra factor was crucial to suppress the background. It was shown in [9] that it is possible to achieve a signal-to-background ratio of about 3 for the detection of a standard model Higgs with mass $M_H \sim 120 \text{ GeV}$, by selecting $b\bar{b}$ exclusive events where the polar angle θ between the outgoing jets lies in the interval $60^\circ < \theta < 120^\circ$ if the missing mass resolution $\Delta m_{\text{missing}} = 1 \text{ GeV}$. The situation is much worse for a light Higgs, since the signal-to-background ratio behaves as

$$\begin{aligned} &\frac{\int \frac{d\mathcal{L}}{d \ln M_{b\bar{b}}^2} \hat{\sigma}(gg \rightarrow H) d \ln M_{b\bar{b}}^2}{\int \frac{d\mathcal{L}}{d \ln M_{b\bar{b}}^2} \hat{\sigma}_{\text{QCD}} d \ln M_{b\bar{b}}^2} \\ &\simeq \frac{G_F}{\left(\frac{m_b^2}{M_{b\bar{b}}^2} \frac{1}{M_{b\bar{b}}^2} \right) \frac{2\Delta M_{b\bar{b}}}{M_{b\bar{b}}}} \sim M_{b\bar{b}}^5, \end{aligned} \quad (7)$$

⁴ In [7] we denoted the initial state by gg^{PP} to indicate that each of the incoming gluons belongs to colour-singlet pomeron exchange. Here this notation is assumed to be implicit.

⁵ Strictly speaking, we should consider CP -even and CP -odd contributions to the width separately, but it does not change the conclusion qualitatively.

where we have used $\Delta \ln M_{b\bar{b}}^2 = 2\Delta M_{b\bar{b}}/M_{b\bar{b}}$. The M^5 behaviour comes just from dimensional counting. As the experimental resolution $\Delta M_{b\bar{b}}$ is larger than the width of the Higgs, Γ_H , the Higgs cross section (in the numerator) is driven by G_F , while the QCD background is proportional to m_b^2 and the size of the $\Delta M_{b\bar{b}}$ interval. To restore the dimensions we have to divide $m_b^2 \Delta M_{b\bar{b}}$ by $M_{b\bar{b}}^5$. Thus, in going from $M_H \sim 120$ GeV to $M_H \sim 40$ GeV, the expected leading-order QCD $b\bar{b}$ background increases by a factor of 240 in comparison with that for $M_{b\bar{b}} = 120$ GeV.

Strictly speaking, there are other sources of background [9]. There is the possibility of the gluon jet being misidentified as either a b or a \bar{b} jet, or a contribution from the NLO $gg \rightarrow b\bar{b}g$ subprocess, where the extra gluon is not separated from either a b or a \bar{b} jet. These contributions have no $m_b^2/M_{b\bar{b}}^2$ suppression, and hence increase only as M_H^{-3} , and not as M_H^{-5} , with decreasing M_H . For $M_H \sim 120$ GeV, the LO $b\bar{b}$ QCD production was only about 30% of the total background. However, for $M_{H_1} \sim 40$ GeV, the LO $b\bar{b}$ contribution dominates. Finally, with the cuts of [9], we predict that the cross section of the H_1 signal is⁶

$$\sigma^{\text{CEDP}}(pp \rightarrow p + (H_1 \rightarrow b\bar{b}) + p) \simeq 14 \text{ fb}$$

as compared to the QCD background cross section, with the same cuts⁷, of

$$\sigma^{\text{CEDP}}(pp \rightarrow p + (b\bar{b}) + p) \simeq 1.4 \frac{\Delta M}{1 \text{ GeV}} \text{ pb.}$$

That is, the signal-to-background ratio is only $S/B \sim 1/100$, and so even for an integrated luminosity $\mathcal{L} = 300 \text{ fb}^{-1}$ for $\Delta M = 1$ GeV the significance of the signal is only 3.7σ . Here we have taken a K factor of $K = 1.5$ for the QCD $b\bar{b}$ background, and again used the cuts and efficiencies quoted in [9]. Therefore, to identify a light Higgs, it is desirable to study a decay mode other than $H_1 \rightarrow b\bar{b}$. The next largest mode is $H_1 \rightarrow \tau\tau$, with a branching fraction of about 0.07.

The dependence of the results on the mass of the H_1 Higgs boson is illustrated in Table 1. Clearly the cross section decreases with increasing mass. On the other hand

⁶ Note that our CEDP cross section is about two times larger than that quoted in [5]. This difference occurs mainly because we use an improved approximation for the unintegrated gluon densities. To be specific, we use (26) of [16], rather than the simplified formula (4) of [9] used in [5]. In addition we allow for the transverse momenta $p_{T,2}^+$ of the recoil protons in the gluon loop of Fig. 1. For smaller boson masses, $M_H \sim 40$ GeV, this leads to a steeper $p_{T,2}^+$ dependence of the amplitude, which emphasises larger values of the impact parameter, b_\perp , where the absorptive effects are weaker. Therefore we obtain a larger soft survival factor, $S^2 \simeq 0.029$, at the LHC energy. However, recall that a factor of 2 difference is within the accuracy of the approach [8, 9].

⁷ Here and in what follows we assume that the proton and b -tagging efficiencies and the missing mass resolution in the case of a light Higgs boson are the same as for the case of $M_{\text{Higgs}} = 120$ GeV [9]. Likely, this assumption is not well justified. In particular, the missing mass resolution and proton tagging efficiency may worsen at lower masses.

Table 1. The cross sections (in fb) of the central *exclusive* diffractive production of H_i neutral Higgs bosons, together with those of the QCD ($b\bar{b}$) and QED ($\tau\tau$) backgrounds. The acceptance cuts applied are (a) the polar angle cut $60^\circ < \theta(b \text{ or } \tau) < 120^\circ$ in the Higgs rest frame, (b) $p_T^+ > 300$ MeV for the forward outgoing protons and (c) the polar angle cut $45^\circ < \theta(b) < 135^\circ$. The azimuthal asymmetries A_i are defined in (12)

$M(H_1)$ GeV	cuts	30	40	50
$\sigma(H_1)\text{Br}(b\bar{b})$	<i>a</i>	45	14	6
$\sigma^{\text{QCD}}(b\bar{b})$	<i>a</i>	16000	1400	200
$A_{b\bar{b}}$		0.14	0.07	0.04
$\sigma(H_1)\text{Br}(\tau\tau)$	<i>a, b</i>	1.9	0.6	0.3
$\sigma^{\text{QED}}(\tau\tau)$	<i>a, b</i>	0.2	0.1	0.04
$A_{\tau\tau}$	<i>b</i>	0.2	0.1	0.05
$M(H_2)$ GeV		103.4	104.7	106.2
$\sigma\text{Br}(H_2 \rightarrow 2H_1 \rightarrow 4b)$	<i>c</i>	0.5	0.5	0.5
$\sigma\text{Br}(H_2 \rightarrow 2b)$	<i>a</i>	0.1	0.1	0.2
$M(H_3)$ GeV		141.9	143.6	146.0
$\sigma\text{Br}(H_3 \rightarrow 2H_1 \rightarrow 4b)$	<i>c</i>	0.14	0.2	0.18
$\sigma\text{Br}(H_3 \rightarrow 2b)$	<i>a</i>	0.04	0.07	0.1

the signal-to-background ratio increases. Therefore for the case $M_{H_1} = 50$ GeV we see a slightly improved statistical significance of 4.4σ for the $b\bar{b}$ decay mode.

3 The $\tau\tau$ decay mode

At the LHC energy, the expected cross section for exclusive diffractive H_1 production, followed by $\tau\tau$ decay, is

$$\sigma(pp \rightarrow p + (H \rightarrow \tau\tau) + p) \sim 1.1 \text{ fb}, \quad (8)$$

where the $60^\circ < \theta < 120^\circ$ polar angle cut has already been included. Despite the low Higgs mass, we note that the exclusive cross section is rather small. As we already saw in (5), the cross section of the hard subprocess $\hat{\sigma}(gg \rightarrow H)$ is approximately independent of M_H . Of course, we expect some enhancement from the larger effective gluon-gluon luminosity \mathcal{L} for smaller M_H . Indeed, it may be approximated by [7, 17]

$$\mathcal{L} \propto 1 / (M_H + 16 \text{ GeV})^{3.3}, \quad (9)$$

and gives an enhancement of about 18.8 (for $M_H = 40$ GeV in comparison with that for $M_H = 120$ GeV).

On the other hand, in the appropriate region of SUSY parameter space, the CP -even $H \rightarrow gg$ vertex, g_S , is almost 2 times smaller [5, 14] than that of a standard model Higgs, giving a suppression of 4. Also the ratio $B(H \rightarrow \tau\tau)/B(H \rightarrow b\bar{b})$ gives a further suppression of about 12. Although the $\tau\tau$ signal has the advantage that there is practically no QCD background⁸, exclusive $\tau^+\tau^-$ events may be produced by $\gamma\gamma$ fusion; see Fig. 2. The cross

⁸ There may be background caused by a pair of high E_T (~ 15 GeV) gluons being misidentified as a $\tau\tau$ pair. To suppress

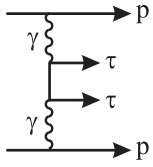


Fig. 2. The QED background to the $H \rightarrow \tau\tau$ exclusive signal

section for this latter QED process is appreciable. It is enhanced by two large logarithms, $\ln^2(t_{\min} R_p^2)$, arising from the integrations over the transverse momenta of the outgoing protons (that is, of the exchanged photons). The lower limit of the logarithmic integrals is given by

$$t_{\min} \simeq -(xm_p)^2 \simeq -\left(\frac{M_H}{\sqrt{s}} m_p\right)^2, \quad (10)$$

while the upper limit is specified by the slope R_p^2 of the proton form factor. To suppress the QED background, one may select events with relatively large transverse momenta of the outgoing protons. For example, if $p_{1,2}^\perp > 300$ MeV, then the cross section for the QED background, for $M_{\tau\tau} = 40$ GeV, is about⁹

$$\sigma_{\text{QED}}(pp \rightarrow p + \tau\tau + p) \simeq 0.1 \frac{\Delta M}{1 \text{ GeV}} \text{ fb}, \quad (11)$$

while the signal (8) contribution is diminished by the cuts, $p_{1,2}^\perp > 300$ MeV, down to 0.6 fb. Thus, assuming an experimental missing mass resolution of $\Delta M \sim 1$ GeV, we obtain a healthy signal-to-background ratio of $S/B \sim 6$ for $M_{H_1} \sim 40$ GeV.

Note that in all the estimates given above, we include the appropriate soft survival factors S^2 – that is, the probabilities that the rapidity gaps are not populated by the secondaries produced in the soft rescattering. The survival factors were calculated using the formalism of [19]. Moreover, here we account for the fact that only events with proton transverse momenta $p_{1,2}^\perp > 300$ MeV were selected. In particular, for the QED process, we have $S^2 \simeq 0.7$, rather than the value $S^2 \simeq 0.9$, which would occur in the absence of the cuts on the proton momenta¹⁰.

4 Azimuthal asymmetry of the outgoing protons

A specific prediction, in the case of a CP -violating Higgs boson, is the asymmetry in the azimuthal φ distribution of

such a background down to the level of $S/B \sim 1$, the probability, $P_{g/\tau}$, that a gluon is misidentified as a τ must be less than about 1/750, assuming that the missing mass resolution is $\Delta M = 1$ GeV. In [18], for an inclusive event, the probability $P_{g/\tau}$ was evaluated as 1/500. Thus it seems reasonable to suppose that the probability $P_{g/\tau} < 1/750$ can be achieved in the much cleaner environment of an exclusive diffractive (CEDP) event.

⁹ As we consider sizeable $p_{1,2}^\perp$, we account for both the F_1 and F_2 electromagnetic proton form factors.

¹⁰ Without the momenta cuts, the main QED contribution comes from small $p_{1,2}^\perp$, that is, from large impact parameters $b^\perp \gg R_p$, where the probability of soft rescattering is already small; see [20] for details.

the outgoing protons, caused by the interference of the CP -odd and CP -even vertices, that is, between the two terms in (3). The polarisations of the incoming active gluons are aligned along their respective transverse momenta, $Q_\perp - p_1^\perp$ and $Q_\perp + p_2^\perp$. Hence the contribution caused by the second term, g_P , is proportional to the vector product

$$\mathbf{n}_0 \cdot (\mathbf{p}_1^\perp \times \mathbf{p}_2^\perp) \sim \sin \varphi,$$

where \mathbf{n}_0 is a unit vector in the beam direction, \mathbf{p}_1 . The sign of the angle φ is fixed by the four-dimensional structure of the second term in (3); see [8] for a detailed discussion. Of course, due to the P -even, $J_z = 0$ selection rule, this (P -odd) contribution is suppressed in the amplitude by $p_1^\perp p_2^\perp / Q_\perp^2$, in comparison with that of the P -even g_S term. Note that there is a partial compensation of the suppression due to the ratio $g_P/g_S \sim 2$. Also the soft survival factors S^2 are higher for the pseudoscalar and interference terms, than for the scalar term.

An observation of the azimuthal asymmetry may therefore be a direct indication of the existence of CP -violation (or P -violation in the case of CEDP) in the Higgs sector¹¹. Neglecting the absorptive effects (of soft rescattering), we find, for example, an asymmetry

$$\begin{aligned} A &= \frac{\sigma(\varphi < \pi) - \sigma(\varphi > \pi)}{\sigma(\varphi < \pi) + \sigma(\varphi > \pi)} \\ &= 2\text{Re}(g_S g_P^*) r_{S/P} (2/\pi) / (|g_S|^2 + |r_{S/P} g_P|^2/2). \end{aligned} \quad (12)$$

Here the (numerically small) parameter $r_{S/P}$ reflects the suppression of the P -odd contribution due to the selection rule discussed above.

At the LHC energy in the absence of rescattering effects, $A \simeq 0.09$ for $M_{H_1} = 40$ GeV. However, we find that soft rescattering tends to wash out the azimuthal distribution, and to weaken the asymmetry. Besides this the real part of the rescattering amplitude multiplied by the imaginary part of the pseudoscalar vertex g_P (with respect to g_S) gives some negative contribution. So finally we predict $A \simeq 0.07$. For the lower Tevatron energy, the admixture of the P -odd amplitude is larger, while the probability of soft rescattering is smaller. Therefore, at $\sqrt{s} = 2$ TeV, we find that the asymmetry is twice as large, $A \sim 0.17$. On the other hand the effective gg^{PP} luminosity \mathcal{L} and the corresponding cross section of H_1 (CEDP) production is 10 times smaller (for $M_{H_1} = 40$ GeV).

The asymmetries expected at the LHC, with and without the cut $p_{1,2}^\perp > 300$ MeV on the outgoing protons, are shown for different H_1 masses in Table 1. The asymmetry decreases with increasing Higgs mass; first, due to the decrease of $|g_P|/|g_S|$ ratio in this mass range, and second, due to the extra suppression of the P -odd amplitude arising from the factor $p_1^\perp p_2^\perp / Q_\perp^2$ in which the typical value of Q_\perp in the gluon loop increases with mass.

¹¹ In [21] (see also [22–24]) a suggestion, along the same lines, was made for the explicit observation of CP -violating effects. There, various polarisation asymmetries in two-photon fusion Higgs production processes were discussed. In the absence of absorptive effects, the azimuthal asymmetry A may be expressed, via gluon helicity amplitudes, in the same way as the quantity A_2 of [21], written in terms of photon helicities.

5 Heavy H_2 and H_3 Higgs production with H_1H_1 decay

Another possibility to study the Higgs sector in the CPX scenario is to observe central exclusive diffractive production (CEDP) of the heavy neutral H_2 and H_3 Higgs bosons, using the $H_2, H_3 \rightarrow H_1 + H_1$ decay modes. For the case we considered above ($\tan\beta = 4$, $\phi_{CPX} = 90^\circ$, $M_{H_1} = 40$ GeV), the masses of the heavy bosons are $M_{H_2} = 104.7$ GeV and $M_{H_3} = 143.6$ GeV. At the LHC energy, the CEDP cross sections of the H_2 and H_3 bosons are not too small – $\sigma^{\text{CEDP}} = 1.5$ and 0.9 fb, respectively. When the branching fractions, $\text{Br}(H_2 \rightarrow H_1H_1) = 0.84$, $\text{Br}(H_3 \rightarrow H_1H_1) = 0.54$ and $\text{Br}(H_1 \rightarrow b\bar{b}) = 0.92$, are included, we find

$$\sigma(pp \rightarrow p + (H \rightarrow b\bar{b} b\bar{b}) + p) = 1.1 \text{ and } 0.4 \text{ fb}$$

for H_2 and H_3 , respectively. Thus there is a chance to observe, and to identify, the central exclusive diffractive production of all three neutral Higgs bosons, H_1, H_2 and H_3 , at the LHC.

The QCD background for exclusive diffractive production of four b jets is significantly less than the signal. Other decay channels are also worth mentioning. For a very light boson, say $M_{H_1} = 30$ GeV, it is also possible to produce four b jets via the cascade $H_3 \rightarrow H_2H_1 \rightarrow 4b$ jets. However, the expected cross section is about 0.02 fb, which looks too low to be useful. A larger cross section is expected for the direct $H_2 \rightarrow b\bar{b}$ decay, where the branching fraction $\text{Br}(H_2 \rightarrow b\bar{b}) = 0.14$ for $M_{H_1} = 40$ GeV leads to the cross section $\sigma(p + (H_2 \rightarrow b\bar{b}) + p) = 0.2$ fb. Note that in this case, we only need to tag two, and not four, b jets. So the detection efficiency is about a factor of $1/0.6$ larger. The situation is even better for $M_{H_1} = 50$ GeV, where $\text{Br}(H_2 \rightarrow b\bar{b}) = 0.25$ and $\sigma(p + (H_2 \rightarrow b\bar{b}) + p) = 0.4$ fb. If it is possible to compare the $4b$ and $2b$ jet signals, then it will allow a probe of the nature of the H_2 boson. Finally, for the heaviest boson, H_3 , the decay mode $H_3 \rightarrow H_1 + Z$ is not small, with a branching fraction of $\text{Br}(H_3 \rightarrow H_1 + Z) = 0.27$ for $M_{H_1} = 40$ GeV.

6 Central Higgs production with double-diffractive dissociation

To enhance the Higgs signal we study a less exclusive reaction than $pp \rightarrow p + H + p$, and allow both of the incoming protons to dissociate. In [7] it was called double-diffractive *inclusive* production, and was written

$$pp \rightarrow X + H + Y. \quad (13)$$

Now there is no form factor suppression as the initial protons are destroyed. Also the cross section is larger due to the increased p_i^\perp phase space. Moreover the cross section is also enhanced because we no longer have the P -even selection rule, and so the pseudoscalar $gg \rightarrow H$ coupling, g_P , becomes active. The cross section for inclusive production, via the central double dissociation (CDD) process, is found

Table 2. The cross sections (in fb) for the central production of H_i neutral Higgs bosons by *inclusive* double-diffractive dissociation, together with that of the QED ($\tau\tau$) background. A polar angle acceptance cuts of $60^\circ < \theta(b \text{ or } \tau) < 120^\circ$ ($45^\circ < \theta(b) < 145^\circ$) in the Higgs rest frame is applied for the case of H_1 (H_2, H_3) bosons. The numbers in brackets correspond to the imposition of the additional cut of $E_i^\perp > 7$ GeV for the proton dissociated systems

$M(H_i)$ GeV	30	40	50
$\sigma(H_1)\text{Br}(\tau\tau)$	19 (4)	6 (2)	2.6 (0.8)
$\sigma^{\text{QED}}(\tau\tau)$	66 (2.2)	30 (1.5)	15 (0.9)
$M(H_2)$ GeV	103.4	104.7	106.2
$\sigma\text{Br}(H_2 \rightarrow 2H_1 \rightarrow 4b)$	4 (2)	4 (2)	3.5 (2)
$M(H_3)$ GeV	141.9	143.6	146.0
$\sigma\text{Br}(H_3 \rightarrow 2H_1 \rightarrow 4b)$	1.5 (0.8)	2.2 (1.2)	2 (1.1)

by using

- (i) the effective gg^{PP} luminosity of [7];
- (ii) the probability, S^2 , that the gaps survive soft rescattering, calculated using model II of [25], and
- (iii) the opacity of the proton given in [19].

Typical results, for the LHC energy, are shown in Table 2. For the Tevatron energy, the cross section appears to be too small, and even for a light boson of mass $M_{H_1} = 30$ GeV we have $\text{Br}(H_1 \rightarrow \tau\tau)\sigma < 1.5$ fb, while the QED background is about 15 fb.

Of course, the missing mass method cannot be used to measure the mass of the Higgs boson for central production with double dissociation (CDD). Therefore the mass resolution will not be so good as for CEDP; we evaluate the background for $\Delta M = 10$ GeV. Moreover, with the absence of the $J_z = 0$ selection rule, the LO QCD $b\bar{b}$ -background is not suppressed. Hence we study only the $\tau\tau$ decay mode for the light boson, H_1 , and the four b jet final state for the heavy H_2 and H_3 bosons.

The background to the $H_1 \rightarrow \tau\tau$ -signal arises from the $\gamma\gamma \rightarrow \tau\tau$ QED process. It is evaluated in the equivalent photon approximation. The photon flux,

$$N_\gamma = \frac{\alpha}{\pi} \frac{dq^2}{q^2} \frac{dx}{x} F_2(x, q^2), \quad (14)$$

was calculated using LO MRST2001 partons [26], with the integral over the photon transverse momentum running from $q = m_\rho$ up to $q = M_{\tau\tau}/2$. The lower limit is approximately where the γ^*p cross section becomes flat and loses its $\sigma(\gamma^*p) \sim 1/q^2$ behaviour. The upper limit reflects the dependence of the $\gamma\gamma \rightarrow \tau\tau$ matrix element on the virtuality of the photon. From Table 2 we see that the H_1 -signal for inclusive diffractive production, (13), exceeds the exclusive signal by more than a factor of ten. On the other hand the signal-to-background ratio is worse; S/B_{QED} is about $1/5$. Moreover there could be a huge background due to the misidentification of a gluon dijet as a $\tau\tau$ -system. To make this QCD background satisfy $B_{\text{QCD}} < S$ would require the probability of misidentifying a gluon as a τ lepton to be $P_{g/\tau} < 1/1500$.

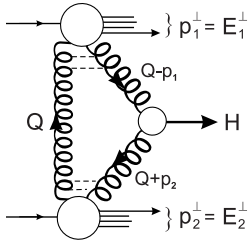


Fig. 3. Central Higgs production with double-diffractive dissociation (CDD), in which the incoming protons dissociate into systems with transverse energies E_i^\perp

For the four b jet signals of the heavy H_2 and H_3 bosons, the QCD background can be suppressed by requiring each of the four b jets to have polar angle in the interval $(45^\circ, 135^\circ)$, in the frame where the four b jet system has zero rapidity. However, in the absence of a good mass resolution, that is, with only¹² $\Delta M = 10$ GeV, we expect the four b jet background to be 3–5 times the signal. Nevertheless these signals are still feasible, with cross sections of the order of a few fb. For example, with an integrated luminosity of $\mathcal{L} = 300$ fb⁻¹ and an efficiency of $4b$ -tagging of $(0.6)^2$ [9], we predict about 400 H_2 events and 200 H_3 events. Taking the background-to-signal ratio to be $B/S = 4$, we then have a statistical significance of about 10σ for H_2 and 6σ for H_3 .

The inclusive CDD kinematics allow a study of CP -violation to be made, and of the separation of the contributions coming from the scalar and pseudoscalar $gg \rightarrow H$ couplings, g_S and g_P of (3), respectively. Indeed, the polarisations of the incoming active gluons are aligned along their transverse momenta, $\mathbf{Q}_\perp - \mathbf{p}_1^\perp$ and $\mathbf{Q}_\perp + \mathbf{p}_2^\perp$. Hence the $gg \rightarrow H$ fusion vertices take the forms

$$V_S = (\mathbf{Q}_\perp - \mathbf{p}_1^\perp) \cdot (\mathbf{Q}_\perp + \mathbf{p}_2^\perp) g_S, \quad (15)$$

$$V_P = \mathbf{n}_0 \cdot [(\mathbf{Q}_\perp - \mathbf{p}_1^\perp) \times (\mathbf{Q}_\perp + \mathbf{p}_2^\perp)] g_P, \quad (16)$$

where g_S and g_P are defined in (3).

For the exclusive (CEDP) process the momenta $p_{1,2}^\perp$ were limited by the proton form factor, and typically $Q^2 \gg p_{1,2}^2$. Thus

$$V_S = g_S Q_\perp^2 \quad \text{while} \quad V_P = g_P (\mathbf{n}_0 \cdot [\mathbf{p}_2^\perp \times \mathbf{p}_1^\perp]). \quad (17)$$

On the contrary, for double-diffractive dissociation production (CDD) $Q^2 < p_{1,2}^2$. In this case

$$V_S = g_S p_1^\perp p_2^\perp \cos\varphi \quad \text{and} \quad V_P = g_P p_1^\perp p_2^\perp \sin\varphi. \quad (18)$$

Moreover we can select events with large outgoing transverse momenta of the dissociating systems, say $p_{1,2}^\perp > 7$ GeV, in order to make reasonable measurements of the directions of the vectors $\mathbf{p}_1^\perp = \mathbf{E}_1^\perp$ and $\mathbf{p}_2^\perp = \mathbf{E}_2^\perp$. Here $E_{1,2}^\perp$ are the transverse energy flows of the dissociating systems of the incoming protons. At LO, this transverse energy is carried mainly by the jet with minimal rapidity in the overall centre-of-mass frame. The azimuthal angular

¹² However this resolution is still sufficient to separate the H_2 and H_3 bosons.

Table 3. The coefficients in the azimuthal distribution $d\sigma/d\varphi = \sigma_0(1 + a \sin 2\varphi + b \cos 2\varphi)$, where φ is the azimuthal angle between the E^\perp flows of the two proton dissociated systems. If there were no CP -violation, then the coefficients would be $a = 0$ and $|b| = 1$

$M(H_1)$ GeV	30		40		50	
	a	b	a	b	a	b
H_1	-0.53	-0.73	-0.56	-0.55	-0.53	-0.33
H_2	0.44	0.90	0.41	0.91	0.37	0.92
H_3	-0.38	0.92	-0.40	0.91	-0.42	0.90

distribution has the form¹³

$$\frac{d\sigma}{d\varphi} = \sigma_0(1 + a \sin 2\varphi + b \cos 2\varphi), \quad (19)$$

where the coefficients are given by

$$a = \frac{2\text{Re}(g_S g_P^*)}{|g_S|^2 + |g_P|^2} \quad \text{and} \quad b = \frac{|g_S|^2 - |g_P|^2}{|g_S|^2 + |g_P|^2}. \quad (20)$$

Note that the coefficient a arises from scalar–pseudoscalar interference, and reflects the presence of a T -odd effect. Its observation would signal an explicit CP -violating mixing in the Higgs sector. On the other hand, in the absence of CP -violation, the sign of the coefficient b reveals the CP -parity of the new boson¹⁴.

The predictions for the coefficients are given in Table 3 for different values of the Higgs mass, namely $M_{H_1} = 30, 40$ and 50 GeV. The coefficients are of appreciable size and, given sufficient luminosity, may be measured at the LHC. Imposing the cuts $E_i^\perp > 7$ GeV reduces the cross sections by about a factor of two, but does not alter the signal-to-background ratio, S/B_{QCD} . However the cuts do give increased suppression of the QED $\tau\tau$ background and now, for the light H_1 boson, the ratio S/B_{QED} exceeds one. We emphasise here that, since we have a relatively large E^\perp , the angular dependences are quite insensitive to the soft rescattering corrections.

7 Conclusions

We have evaluated the cross sections, and the corresponding backgrounds, for the central double-diffractive production of the (three neutral) CP -violating Higgs bosons at the LHC. This scenario is of interest since even a very light

¹³ In the CP -conserving case, an idea similar in spirit was considered in [27], where it was suggested to measure the azimuthal correlations of the two tagged jets in inclusive Higgs production. However the proof of the feasibility of such an approach in non-diffractive processes requires further detailed studies of the possible dilution of the effect due to the parton showers in the inclusive environment of the jets.

¹⁴ Note that we may search for any new pseudoscalar boson produced by the CDD process by looking for the corresponding azimuthal distribution, $d\sigma/d\varphi \sim \sin^2\varphi$.

boson of mass about 30 GeV is not experimentally ruled out for some ranges of the MSSM parameters.

We have studied the production of the three states, H_1, H_2, H_3 , both with exclusive kinematics, $pp \rightarrow p + H + p$ which we denoted CEDP, and in double-diffractive reactions where both the incoming protons may be destroyed, $pp \rightarrow X + H + Y$ which we denoted CDD. Recall that a $+$ sign denotes the presence of a large rapidity gap. Proton taggers are required in the former processes, but not in the latter. Typical results are summarised in Tables 1 and 2, respectively. The cross sections are not large, but should be accessible at the LHC. The uncertainties in the calculation of the exclusive cross sections were discussed in [8, 17]. For the light H_1 boson, where the contribution from the low Q_\perp region is more important, the uncertainty is much larger. Recall that for the semi-inclusive CDD processes the effective gluon–gluon (gg^{PP}) luminosity is calculated using the LO formula. Thus we cannot exclude rather large NLO corrections. On the other hand, for CDD, the values of the cross sections are practically insensitive to the contributions from the infrared domain. Moreover, with the *skewed* CDD kinematics, the NLO BFKL corrections are expected to be much smaller than in the forward (CEDP) case. So we may expect an uncertainty of the predictions to be about a factor of 3 to 4, or even better.

It would be very informative to measure the azimuthal angular dependence of the outgoing proton systems, for both the CEDP and CDD processes. Such measurements would reveal explicitly any CP -violating effect, via the interference of the scalar and pseudoscalar $gg \rightarrow H$ vertices.

Finally, we recall the advantages of diffractive, as compared to the non-diffractive, production of Higgs bosons: (i) a much better mass Higgs resolution is obtained by the missing mass method for exclusive events; (ii) a clean environment, which may be important to identify four b jets with transverse momenta $p_T \sim M_{H_1}/2 \sim 20$ GeV (for the non-diffractive process, at the LHC energy, the QCD background may be too large); (iii) a possibility to measure the CP -property of the Higgs boson and to detect CP -violation (note that the asymmetries $A_{b\bar{b}}$ and $A_{\tau\tau}$ are explicit manifestations of CP -violation at the quark level). Next, assuming that P and C parities are conserved, (iv) the existence of the P -even, $J_z = 0$ selection rule for LO central exclusive diffractive production, which means that we observe an object of natural parity (most probably 0^+); the analysis of the azimuthal angular distribution of the outgoing protons may give additional information about the spin of the centrally produced object [8]; (v) in addition we know that an object produced by the diffractive process (that is, by pomeron–pomeron fusion) has positive C -parity, is an isoscalar and a colour singlet¹⁵.

¹⁵ An instructive topical example, which illustrates the power of CEDP as a spin-parity analyser, concerns the determination of the quantum numbers of the recently discovered $X(3872)$ resonance [28]. Knowledge of its C -parity is important to understand its nature. If it is a $C = +1$ state with spin-parity 0^+ or 2^+ then it may be even seen in CDD production with a large rapidity gap on either side of its $J/\psi \pi^+\pi^-$ decay. For-

The properties listed above should help to distinguish the H_2 and H_3 four-jet decay channels from the production of a SUSY particle, followed by a “cascade”-like decay. In our view, this study gives further support to the importance of observing forward particles and of the advantages of installing proton taggers.

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