BSM Higgs Studies at the LHC in the Forward Proton Mode

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The prospects for central exclusive diffractive (CED) production of BSM Higgs bosons at the LHC are reviewed. This comprises the production of MSSM and 4th generation Higgs bosons. The sensitivity of the searches in the forward proton mode for the Higgs bosons as well as the possibility of a coupling structure determination are briefly discussed.

1 Introduction

In recent years, there has been a growing interest in the possibility to complement the standard LHC physics menu by installing near-beam proton detectors in the LHC tunnel. Projects to install the proton detectors at 220 m and 420 m from the interaction points are now under review inside ATLAS and CMS [1–4]. The combined detection of both outgoing protons and the centrally produced system gives access to a rich program of studies of QCD, electroweak and BSM physics, see for instance [3,5]. Importantly, these measurements will provide valuable information on the Higgs sector of MSSM and other popular BSM scenarios, see [6–11].

As it is well known, many models of new physics require an extended Higgs sector. The most popular extension of the SM is the MSSM, where the Higgs sector consists of five physical states. At lowest order the MSSM Higgs sector is $\mathcal{CP}$-conserving, containing two $\mathcal{CP}$-even bosons, the lighter h and the heavier H, a $\mathcal{CP}$-odd boson, A, and the charged bosons $H^\pm$. It can be specified in terms of the gauge couplings, the ratio of the two vacuum expectation values, $\tan\beta \equiv v_2/v_1$, and the mass of the A boson, M_A. The Higgs phenomenology in the MSSM is strongly affected by higher-order corrections (see [12] for reviews).

Another very simple example of physics beyond the SM is a model which extends the SM by a fourth generation of heavy fermions (SM4), see, for instance, [13]. Here the masses of the 4th generation quarks and leptons are assumed to be (much) heavier than the mass of the top-quark. In this case, the effective coupling of the Higgs boson to two gluons is three times larger than in the SM, and all branching ratios change correspondingly.

Proving that a detected new state is, indeed, a Higgs boson and distinguishing the Higgs boson(s) of the SM, the SM4 or the MSSM from the states of other theories will be far from trivial. In particular, it will be of utmost importance to determine the spin and $\mathcal{CP}$ properties of a new state and to measure precisely its mass, width and couplings.

The CED processes are of the form $pp \to p \oplus H \oplus p$, where the $\oplus$ signs denote large rapidity gaps on either side of the centrally produced state. If the outgoing protons remain

intact and scatter through small angles then, to a very good approximation, the primary di-gluon system obeys a $J_z = 0$, $\mathcal{CP}$-even selection rule [14]. Here J_z is the projection of the total angular momentum along the proton beam. This permits a clean determination of the quantum numbers of the observed resonance which will be dominantly produced in a 0^+ state. Furthermore, because the process is exclusive, the proton energy losses are directly related to the central mass, allowing a potentially excellent mass resolution, irrespective of the decay channel. The CED processes allow in principle all the main Higgs decay modes, $b\bar{b}$, WW and $\tau\tau$, to be observed in the same production channel. In particular, a unique possibility opens up to study the Higgs Yukawa coupling to bottom quarks, which, as it is well known, may be difficult to access in other search channels at the LHC. Here it should be kept in mind that access to the bottom Yukawa coupling will be crucial as an input also for the determination of Higgs couplings to other particles [15, 16].

Within the MSSM, CED production is even more appealing than in the SM. The lightest MSSM Higgs boson coupling to $b\bar{b}$ and $\tau\tau$ can be strongly enhanced for large values of $\tan\beta$ and relatively small M_A. On the other hand, for larger values of M_A the branching ratio of $H \to b\bar{b}$ is much larger than for a SM Higgs of the same mass. As a consequence, CED $H \to b\bar{b}$ production can be studied in the MSSM up to much higher masses than in the SM case.

Here we briefly review the analysis of [7] where a detailed study of the CED MSSM Higgs production was performed (see also Refs. [6, 8, 17] for other CED studies in the MSSM). This is updated by taking into account recent theoretical developments in background evaluation [18, 19] and using an improved version [20] of the code `FeynHiggs` [21] employed for the cross section and decay width calculations. The regions excluded by LEP and Tevatron Higgs searches are evaluated with `HiggsBounds` [22]. These improvements are applied for the CED production of MSSM Higgs bosons [7] in the M_h^{max} benchmark scenario (defined in [23]), and in the SM4.

2   Signal and Background Rates and Experimental Aspects

The Higgs signal and background cross sections can be approximated by the simple formulae given in [6, 7]. For CED production of the MSSM h, H-bosons the cross section σ^{excl} is

$$\sigma^{\mathrm{excl}} \mathrm{BR}^{\mathrm{MSSM}} = 3\,\mathrm{fb} \left(\frac{136}{16 + M}\right)^{3.3} \left(\frac{120}{M}\right)^3 \frac{\Gamma(h/H \to gg)}{0.25\ \mathrm{MeV}} \mathrm{BR}^{\mathrm{MSSM}}, \tag{1}$$

where the gluonic width $\Gamma(h/H \to gg)$ and the branching ratios for the various MSSM channels, $\mathrm{BR}^{\mathrm{MSSM}}$, are calculated with *FeynHiggs*2.6.2 [20]. The mass M (in GeV) denotes either M_h or M_H. The normalization is fixed at $M = 120$ GeV, where $\sigma^{\mathrm{excl}} = 3$ fb for $\Gamma(H^{\mathrm{SM}} \to gg) = 0.25$ MeV. In Ref. [6, 7] the uncertainty in the prediction for the CED cross sections was estimated to be below a factor of ~ 2.5. According to [1, 7, 18, 24], the overall background to the 0^+ Higgs signal in the $b\bar{b}$ mode can be approximated by

$$\mathrm{d}\sigma^B/\mathrm{d}M \approx 0.5\,\mathrm{fb/GeV} \left[A(120/M)^6 + 1/2\,C(120/M)^8\right] , \tag{2}$$

with $A = 0.92$ and $C = C_{\mathrm{NLO}} = 0.48 - 0.12 \times (\ln(M/120))$. The expression (2) holds for a mass window $\Delta M = 4 - 5$ GeV and summarizes several types of backgrounds: the prolific $gg^{PP} \to gg$ subprocess can mimic $b\bar{b}$ production due to the misidentification of the gluons as b jets; an admixture of $|J_z| = 2$ production; the radiative $gg^{PP} \to b\bar{b}g$ background; due to the

non-zero b-quark mass there is also a contribution to the $J_z = 0$ cross section of order m_b^2/E_T^2. The first term in the square brackets corresponds to the first three background sources [7], evaluated for $P_{g/b} = 1.3\%$, where $P_{g/b}$ is the probability to misidentify a gluon as a b-jet for a b-tagging efficiency of 60%. The second term describes the background associated with bottom-mass terms in the Born amplitude. The NLO correction suppresses this contribution by a factor of about 2, or more for larger masses [18].

The main experimental challenge of running at high luminosity, $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, is the effect of pile-up, which can generate fake signal events within the acceptances of the proton detectors as a result of the coincidence of two or more separate interactions in the same bunch crossing, see [2, 3, 7, 8] for details. Fortunately, as established in [8], the pile-up can be brought under control by using time-of-flight vertexing and cuts on the number of charged tracks. Also in the analysis of [7] the event selections and cuts were imposed such as to maximally reduce the pile-up background. Based on the anticipated improvements for a reduction of the overlap backgrounds down to a tolerable level, in the numerical studies in [2, 7] and in the new results below the pile-up effects were not included.

At nominal LHC optics, proton taggers positioned at a distance ±420 m from the interaction points of ATLAS and CMS will allow a coverage of the proton fractional momentum loss ξ in the range 0.002–0.02, with an acceptance of around 30% for a centrally produced system with a mass around 120 GeV. A combination with the foreseen proton detectors at ±220 m [4, 25] would enlarge the ξ range up to 0.2. This would be especially beneficial because of the increasing acceptance for higher masses [7]. The main selection criteria for $h, H \to b\bar{b}$ are either two b-tagged jets or two jets with at least one b-hadron decaying into a muon. Details on the corresponding selection cuts and triggers for $b\bar{b}$, WW and $\tau\tau$ channels can be found in [2, 7, 26]. Following [7] we consider four luminosity scenarios: "60 fb^{-1}" and "600 fb^{-1}" refer to running at low and high instantaneous luminosity, respectively, using conservative assumptions for the signal rates and the experimental sensitivities; possible improvements of both theory and experiment could lead to the scenarios where the event rates are higher by a factor of 2, denoted as "60 fb^{-1} eff$\times$2" and "600 fb^{-1} eff$\times$2".

3   Updated Sensitivities for CED Production of the $\mathcal{CP}$-Even MSSM Higgs Bosons

Below we extend the analysis of the CED production of $H \to b\bar{b}$ and $H \to \tau\tau$ carried out in [7] and consider the M_h^{max} benchmark scenario of [23]. The improvements consist of the incorporation of the one-loop corrections to the mass-suppressed background [18] and in employing an updated version of *FeynHiggs* [20, 21] for the cross section and decay width calculations. Furthermore we now also display the limits in the M_A–$\tan\beta$ planes obtained from Higgs-boson searches at the Tevatron. For the latter we employed the new code `HiggsBounds`, see [22] (where also the list of CDF and D0 references for the incorporated exclusion limits can be found).

The two plots in Fig. 1 exemplify our new results for the case of h production in the M_h^{max} scenario [23]. They display the contours of 3σ statistical significance (left) and 5σ discovery (right) in the $h \to b\bar{b}$ channel. The left-hand plot shows that while the allowed region at high $\tan\beta$ and low M_A can be probed also with lower integrated luminosity, in the "600 fb^{-1} eff$\times$2" scenario the coverage at the 3σ level extends over nearly the whole M_A–$\tan\beta$ plane, with the exception of a window around $M_A \approx 130 - 140$ GeV (which widens up for small values of $\tan\beta$). The coverage includes the case of a light SM-like Higgs, which corresponds to the region

of large M_A. It should be kept in mind that besides giving an access to the bottom Yukawa coupling, which is a crucial input for determining all other Higgs couplings [15], the forward proton mode would provide valuable information on the Higgs $\mathcal{CP}$ quantum numbers and allow a precise Higgs mass measurement and maybe even a direct determination of its width.
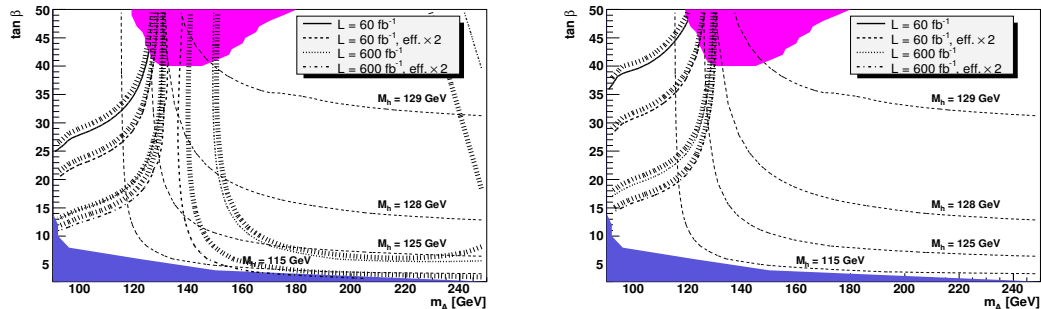

Figure 1: Contours of 3σ statistical significance (left) and 5σ discovery (right) contours for the $h \to b\bar{b}$ channel in the $M_h^{\max}$ benchmark scenario with $\mu = +200$ GeV. The results were calculated using Eqs. (1) and (2) for $A = 0.92$ and $C = C_{\mathrm{NLO}}$ for effective luminosities of "60 fb^{-1}", "60 fb^{-1} eff$\times$2", "600 fb^{-1}" and "600 fb^{-1} eff$\times$2". The values of M_h are shown by the contour lines. The medium dark shaded (blue) regions correspond to the LEP exclusion bounds, while the Tevatron limits are shown by the dark shaded (purple) regions.
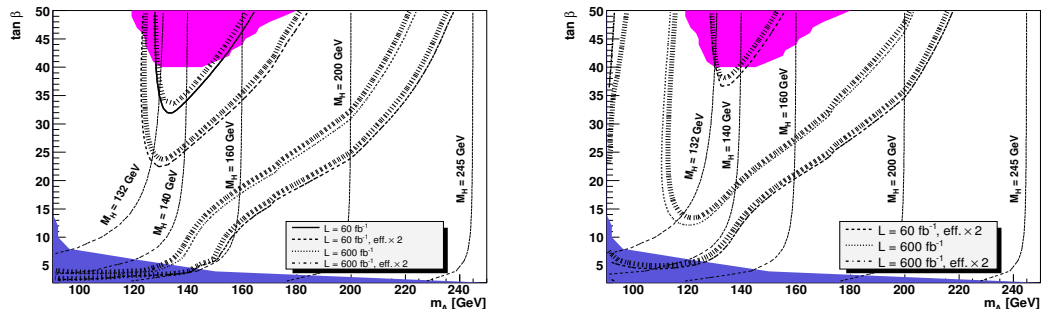

Figure 2: Contours of 3σ statistical significance (left) and 5σ discovery (right) contours for the $H \to b\bar{b}$ channel, see Fig. 1.

The properties of the heavier boson H differ very significantly from the ones of a SM Higgs with the same mass in the region where $M_H \gtrsim 150$ GeV. While for a SM Higgs the BR($H \to b\bar{b}$) is strongly suppressed, the decay into bottom quarks is the dominant mode for the MSSM Higgs boson H. The 3σ significance and 5σ discovery contours in the M_A–$\tan\beta$ plane are displayed in the left and right plot of Fig. 2, respectively. While the area covered in the "60 fb^{-1}" scenario is to a large extent already ruled out by Tevatron Higgs searches [22], in the "600 fb^{-1} eff$\times$2" scenario the reach for the heavier Higgs at the 3σ level goes beyond $M_H \approx 235$ GeV in the large $\tan\beta$ region. At the 5σ level the reach is slightly reduced, but still extends beyond $M_H \approx 200$ GeV. Thus, CED production of the H with the subsequent decay to $b\bar{b}$ provides a unique opportunity for accessing its bottom Yukawa coupling in a mass range where for a SM Higgs boson the $b\bar{b}$ decay rate would be negligibly small. In the "600 fb^{-1} eff$\times$2" scenario the

discovery of a heavy $\mathcal{CP}$-even Higgs with $M_H \approx 140$ GeV will be possible for all allowed values of $\tan\beta$.

Concerning the determination of the spin and the CP properties of Higgs bosons the standard methods rely to a large extent on the coupling of a relatively heavy SM-like Higgs to two gauge bosons. The first channel that should be mentioned here is $H \to ZZ \to 4l$. This channel provides detailed information about spin and $\mathcal{CP}$-properties if it is open [27].

Within a SM-like set-up it was analyzed how the tensor structure of the coupling of the Higgs boson to weak gauge bosons can be determined at the LHC [28–30]. A study exploiting the difference in the azimuthal angles of the two tagging jets in weak vector boson fusion has shown that for $M_{H^{\mathrm{SM}}} = 160$ GeV the decay mode into a pair of W-bosons (which is maximal at $M_{H^{\mathrm{SM}}} = 160$ GeV) allows the discrimination between the two extreme scenarios of a pure $\mathcal{CP}$-even (as in the SM) and a pure $\mathcal{CP}$-odd tensor structure at a level of 4.5 to 5.3 σ using only about 10 fb^{-1}(assuming the production rate is that of the SM, which is currently probed by the Tevatron [31].) A discriminating power of two standard deviations at $M_{H^{\mathrm{SM}}} = 120$ GeV in the tau lepton decay mode requires an integrated luminosity of 30 fb^{-1} [30].

For $M_H \approx M_A \gtrsim 2M_W$ the lightest MSSM Higgs boson couples to gauge bosons with about SM strength, but its mass is bounded from above by $M_h \lesssim 135$ GeV [21], i.e. the light Higgs stays below the threshold above which the decay to $WW^{(*)}$ or $ZZ^{(*)}$ can be exploited. On the other hand, the heavy MSSM Higgs bosons, H and A, decouple from the gauge bosons. Consequently, the analysis for $M_{H^{\mathrm{SM}}} = 160$ GeV cannot be taken over to the MSSM. This shows the importance of channels to determine spin and $\mathcal{CP}$-properties of the Higgs bosons without relying on (tree-level) couplings of the Higgs bosons to gauge bosons. CED Higgs production can yield crucial information in this context [5–7]. The $M_{H^{\mathrm{SM}}} = 120$ GeV analysis, on the other hand, can in principle be applied to the SUSY case. However, the coupling of the SUSY Higgs bosons to tau leptons, in this case does not exhibit a (sufficiently) strong enhancement as compared to the SM case, i.e. no improvement over the 2σ effect within the SM can be expected. The same would be true in any other model of new physics with a light SM-like Higgs and heavy Higgses that decouple from the gauge bosons.

4 Sensitivity to Higgs Bosons in the SM4

A very simple example of physics beyond the SM is a model, "SM4", which extends the SM by a fourth generation of heavy fermions, see, for instance, [13]. In particular, the masses of the 4th generation quarks and leptons are assumed to be (much) heavier than the mass of the top-quark. In this case, the effective coupling of the Higgs boson to two gluons is three times larger than in the SM. No other coupling, relevant to LEP and Tevatron searches, changes significantly. Essentially, only the partial decay width $\Gamma(H \to gg)$ changes by a factor of 9 and, with it, the total Higgs width and therefore all the decay branching ratios [32]. The new total decay width and the relevant decay branching ratios can be evaluated as,

$$\Gamma_{\mathrm{SM}}(H \to gg) = \mathrm{BR}_{\mathrm{SM}}(H \to gg)\,\Gamma_{\mathrm{tot}}^{\mathrm{SM}}(H)\,,$$
$$\Gamma_{\mathrm{SM4}}(H \to gg) = 9\,\Gamma_{\mathrm{SM}}(H \to gg)\,,$$
$$\Gamma_{\mathrm{tot}}^{\mathrm{SM4}}(H) = \Gamma_{\mathrm{tot}}^{\mathrm{SM}}(H) - \Gamma_{\mathrm{SM}}(H \to gg) + \Gamma_{\mathrm{SM4}}(H \to gg)\,.$$

In Fig. 3 we show the bounds on $M_{H^{\mathrm{SM4}}}$ from LEP and Tevatron searches (taken from [22], where also an extensive list of experimental references can be found.) Shown is the experimen-

tally excluded cross section divided by the cross section in the SM and the SM4, respectively. The SM4 (SM) is given by the dashed (solid) line. In the red/light grey part the LEP exclusion provides the strongest bounds, while for the blue/dark grey part the Tevatron yields stronger limits. On can see that the exclusion bounds on $M_{H^{\mathrm{SM4}}}$ are much stronger than on $M_{H^{\mathrm{SM}}}$, and only a window of 112 GeV $\lesssim M_{H^{\mathrm{SM4}}} \lesssim$ 145 GeV is still allowed. At larger masses (not shown) $M_{H^{\mathrm{SM4}}} \gtrsim$ 220 GeV also remains unexcluded. Consequently, we can focus our studies on the still allowed regions.
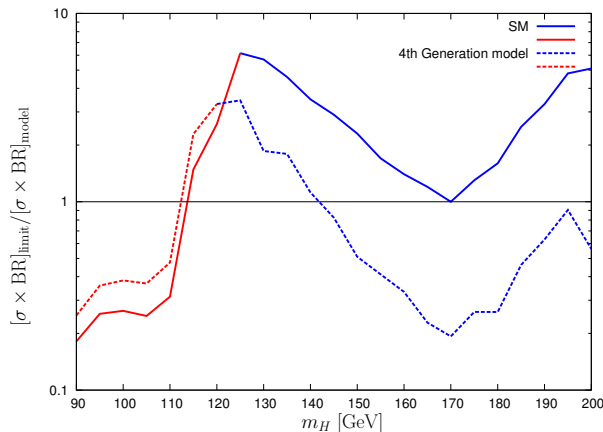

Figure 3: Cross section ratio (see text) for the most sensitive channel as a function of the Higgs mass m_H: 4th Generation Model versus SM. The colors indicate whether the most sensitive search channel is from LEP (lighter grey) or the Tevatron (darker grey), taken from [22].
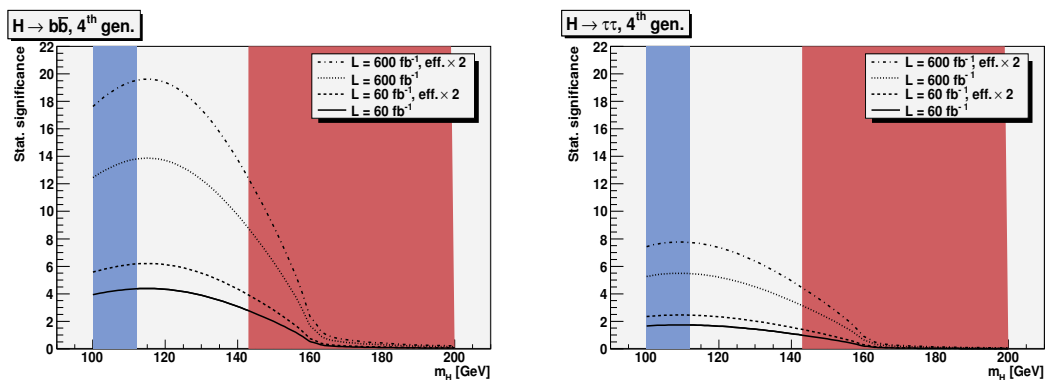
Figure 4: Significances reachable in the SM4 in the $H \to b\bar{b}$ (left) and $H \to \tau^+\tau^-$ (right) channel for effective luminosities of "60 fb^{-1}", "60 fb^{-1} eff×2", "600 fb^{-1}" and "600 fb^{-1} eff×2". The regions excluded by LEP appear as blue/light grey for low values of $M_{H^{\mathrm{SM4}}}$ and excluded by the Tevatron as red/dark grey for larger values of $M_{H^{\mathrm{SM4}}}$.

As for the MSSM we have evaluated the significances that can be obtained in the channels $H \to b\bar{b}$ and $H \to \tau^+\tau^-$. The results are shown in Fig. 4 as a function of $M_{H^{\mathrm{SM4}}}$ for the four luminosity scenarios. The regions excluded by LEP appear as blue/light grey for low values of $M_{H^{\mathrm{SM4}}}$ and regions excluded by the Tevatron appears as red/dark grey for larger values of $M_{H^{\mathrm{SM4}}}$. The $b\bar{b}$ channel (left plot) shows that even at rather low luminosity the remaining window of 112 GeV $\lesssim M_{H^{\mathrm{SM4}}} \lesssim$ 145 GeV can be covered by CED Higgs production. Due to the smallness of BR($H^{\mathrm{SM4}} \to b\bar{b}$) at $M_{H^{\mathrm{SM4}}} \gtrsim$ 160 GeV, however, the CED channel becomes

irrelevant for the still allowed high values of $M_{H^{\text{SM4}}}$. The $\tau^+\tau^-$ channel (right plot) has not enough sensitivity at low luminosity, but might become feasible at high LHC luminosity. At masses $M_{H^{\text{SM4}}} \gtrsim 220$ GeV it might be possible to exploit the decay $H \to WW, ZZ$, but no analysis has been performed up to now.

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