BSM Higgs physics at the LHC in the forward proton mode

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We review the prospects for central exclusive diffractive (CED) production of Higgs bosons in the SM with a fourth generation of fermions at the LHC using forward proton detectors installed at 220 m and 420 m distance around ATLAS and/or CMS. We discuss the determination of Higgs spin-parity and coupling structures at the LHC and show that the forward proton mode would provide a crucial information on the $\mathcal{CP}$ properties of the Higgs bosons.

1 Introduction

In the recent years there has been a growing interest in the possibility to complement the standard LHC searches for a Higgs boson by the options offered by forward and diffraction physics. These assume the installation of near-beam proton detectors in the LHC tunnel installed at 220 m and 420 m around ATLAS and/or CMS, see Refs. [1–6] and references therein. The combined detection of the centrally produced system and both outgoing protons can provide valuable information on the Higgs sector of MSSM and other popular BSM scenarios [3, 7–10]. Another 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, [11–13]. Here it is assumed that the masses of the 4th generation quarks are (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.

The central exclusive diffractive (CED) processes are of the form

$$pp \to p \oplus H \oplus p \;, \tag{1}$$

where the $\oplus$ signs denote large rapidity gaps on either side of the centrally produced state. However, proving that a detected new state is, indeed, a Higgs boson will be far from trivial. In particular, it will be of great importance to determine the spin and $\mathcal{CP}$ properties of a new state and to measure precisely its mass, width and couplings.

Following [8] 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 allow for the scenarios where the event rates are higher by a factor of 2, denoted as "60 fb^{-1} eff×2" and "600 fb^{-1} eff×2".

2 The Higgs boson in the SM4

A 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, Refs. [11, 12, 14]. In particular, the masses of the 4th generation quarks are assumed to be (much) heavier than the mass of the top-quark (whereas the masses of the 4th generation leptons, which do not play a role here, are less restricted). 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, see for instance Ref. [13, 15]. The new total decay width and the relevant decay branching ratios can be evaluated as,

$$\Gamma_{\rm SM}(H \to gg) = {\rm BR}_{\rm SM}(H \to gg)\, \Gamma^{\rm SM}_{\rm tot}(H)\,, \tag{2}$$

$$\Gamma_{\rm SM4}(H \to gg) = 9\, \Gamma_{\rm SM}(H \to gg)\,, \tag{3}$$

$$\Gamma^{\rm SM4}_{\rm tot}(H) = \Gamma^{\rm SM}_{\rm tot}(H) - \Gamma_{\rm SM}(H \to gg) + \Gamma_{\rm SM4}(H \to gg)\,. \tag{4}$$

The Higgs boson searches at LEP [16, 17] have been re-interpreted with `HiggsBounds` [18] in the SM4. The bound on the SM Higgs boson at LEP of $M_{H^{\rm SM}} \geq 114.4$ GeV at the 95% C.L. is modified to $M_{H^{\rm SM4}} \geq 112$ GeV. On the other hand Higgs boson searches in the SM4 at the Tevatron [19] have been performed. The range 130 GeV $\lesssim M_{H^{\rm SM4}} \lesssim$ 210 GeV is found to be excluded. Combining the two analyses leaves us with a window of allowed Higgs masses in the SM4 of 112 GeV $\lesssim M_{H^{\rm SM4}} \lesssim$ 130 GeV.

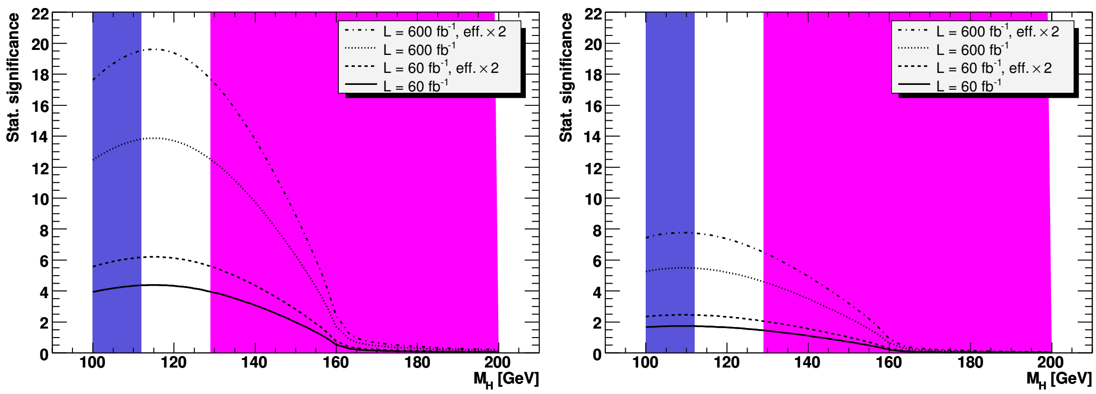

Figure 1: Significances reachable in CED Higgs production in the SM4 in the $H \to b\bar{b}$ (left plot) and $H \to \tau^+\tau^-$ (right plot) channel for effective luminosities of "60 fb^{-1}", "60 fb^{-1} eff×2", "600 fb^{-1}" and "600 fb^{-1} eff×2". The regions excluded by LEP appear as blue/light grey for low values of $M_{H^{\rm SM4}}$ and excluded by the Tevatron as red/dark grey for larger values of $M_{H^{\rm SM4}}$.

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. 1 as a function of $M_{H^{\rm SM4}}$ for the four luminosity scenarios. The regions excluded by LEP appear as blue/light grey for low values of $M_{H^{\rm SM4}}$ and regions excluded by the Tevatron appear as red/dark grey for larger values of $M_{H^{\rm SM4}}$. The $b\bar{b}$ channel (left plot) shows that even at rather low luminosity the remaining window of 112 GeV $\lesssim M_{H^{\rm SM4}} \lesssim$ 130 GeV can be covered by CED Higgs production. Due to the smallness of BR($H^{\rm SM4} \to b\bar{b}$) at $M_{H^{\rm SM4}} \gtrsim$ 160 GeV, however, the CED channel becomes irrelevant for the still allowed high values of $M_{H^{\rm SM4}}$, and we do not extend our analysis beyond $M_{H^{\rm SM4}} \leq 200$ GeV. The $\tau^+\tau^-$ channel (right plot) has not enough sensitivity at low luminosity, but might become feasible at high LHC luminosity. At masses $M_{H^{\rm SM4}} \gtrsim 220$ GeV it might be possible to exploit the decay $H \to WW, ZZ$, but no detailed analysis has been performed up to now.

3 Coupling structure and spin-parity determination

The determination of the spin and the $\mathcal{CP}$ properties of Higgs bosons using 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 [20]. 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 [21–23]. One study for $M_{H^{\rm SM}} = 160$ GeV was based on Higgs production in weak vector boson fusion with the subsequent decay to SM gauge bosons. It was shown that 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 is possible at a level of 4.5 to 5.3 σ using about 10 fb^{-1}. A discriminating power of two standard deviations at $M_{H^{\rm SM}} = 120$ GeV in the tau lepton decay mode requires an integrated luminosity of 30 fb^{-1} [23].

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 [24], i.e. the light Higgs is in a mass range where the decay to $WW^{(*)}$ or $ZZ^{(*)}$ is difficult to exploit. On the other hand, the heavy MSSM Higgs bosons, H and A, decouple from the gauge bosons. Consequently, the analysis for $M_{H^{\rm SM}} = 160$ 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 [2, 7, 8].

The $M_{H^{\rm SM}} = 120$ GeV analysis, on the other hand, can in principle be applied to the SUSY case. However, in this case the coupling of the SUSY Higgs bosons to tau leptons does not exhibit a (sufficiently) strong enhancement as compared to the SM case. Consequently, 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.

The CED production channels may provide crucial information on the $\mathcal{CP}$ properties of Higgs-like states detected at the LHC, for instance via the J_z selection rule [25]. Thanks to this selection rule in the CED case we already know that the observed new object has even parity ($\mathcal{P} = +$), and the projection of its spin is $J_z = 0$. This knowledge will greatly simplify the determination of the detected new state.

As discussed in [7,8] it will be challenging to identify a $\mathcal{CP}$-odd Higgs boson, for instance the

A boson of the MSSM, in the CED processes. The strong suppression, caused by the P-even selection rule, effectively filters out its production. However, in the semi-inclusive diffractive reactions the pseudoscalar production is much less suppressed. As shown in a recent study [5] there are certain advantages of looking for the $\mathcal{CP}$-odd Higgs particle in the semi-inclusive process $pp \to p + gAg + p$ with two tagged forward protons and two large rapidity gaps. The amplitude of $\mathcal{CP}$-odd A boson production can be of the same order as the $\mathcal{CP}$-even boson amplitude if events with relatively hard gluons, whose energy is comparable with the energy of the whole gAg system, are selected.

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References

[1] M. Albrow and A. Rostovtsev, arXiv:hep-ph/0009336.
[2] V.A. Khoze, A.D. Martin and M. Ryskin, *Eur. Phys. J.* **C 23** (2002) 311.
[3] M. Albrow, T. Coughlin and J. Forshaw, arXiv:1006.1289 [hep-ph].
[4] A. De Roeck, V.A. Khoze, A. Martin, R. Orava and M. Ryskin, *Eur. Phys. J.* **C 25** (2002) 391.
[5] V. A. Khoze, A. Martin, M. Ryskin and A. Shuvaev, *Eur. Phys. J.* **C 68** (2010) 125.
[6] M. Albrow et al. [FP420 R&D Collaboration], *JINST* **4** (2009) T10001.
[7] A. Kaidalov, V.A. Khoze, A.D. Martin and M. Ryskin, *Eur. Phys. J.* **C 33** (2004) 261.
[8] S. Heinemeyer, V. A. Khoze, M. G. Ryskin, W. J. Stirling, M. Tasevsky and G. Weiglein, *Eur. Phys. J.* **C 53** (2008) 231.
[9] B. Cox, F. Loebinger and A. Pilkington, *JHEP* **0710** (2007) 090.
[10] M. Chaichian, P. Hoyer, K. Huitu, V. A. Khoze and A. Pilkington, *JHEP* **0905** (2009) 011.
[11] P. Frampton, P. Hung and M. Sher, *Phys. Rept.* **330** (2000) 263.
[12] B. Holdom et al., *PMC Phys.* **A 3** (2009) 4 [arXiv:0904.4698 [hep-ph]].
[13] G. Kribs, T. Plehn, M. Spannowsky and T. Tait, *Phys. Rev.* **D 76** (2007) 075016.
[14] J. Erler and P. Langacker, *Phys. Rev. Lett.* **105** (2010) 031801.
[15] C. Anastasiou, R. Boughezal and E. Furlan, *JHEP* **1006** (2010) 101.
[16] G. Abbiendi et al. [ALEPH, DELPHI, L3, OPAL Collaborations and LEP Working Group for Higgs boson searches], *Phys. Lett.* **B 565** (2003) 61.
[17] S. Schael et al. [ALEPH, DELPHI, L3, OPAL Collaborations and LEP Working Group for Higgs boson searches], *Eur. Phys. J.* **C 47** (2006) 547.
[18] P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein and K. Williams, *Comput. Phys. Commun.* **181** (2010) 138; arXiv:0909.4664 [hep-ph]; see: `www.ippp.dur.ac.uk/HiggsBounds` .
[19] TEVNPH Working Group Collaboration for the CDF Collaboration and D0 Collaboration, CDF note 10101, DØ note 6039.
[20] V. Buescher and K. Jakobs, *Int. J. Mod. Phys.* **A 20** (2005) 2523.
[21] T. Plehn, D. Rainwater and D. Zeppenfeld, *Phys. Rev. Lett.* **88** (2002) 051801.
[22] V. Hankele, G. Klamke, D. Zeppenfeld and T. Figy, *Phys. Rev.* **D 74** (2006) 095001.
[23] C. Ruwiedel, N. Wermes and M. Schumacher, *Eur. Phys. J.* **C 51** (2007) 385.
[24] G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich and G. Weiglein, *Eur. Phys. J.* **C 28** (2003) 133.
[25] V.A. Khoze, A. Martin and M. Ryskin, *Eur. Phys. J.* **C 19** (2001) 477 [Erratum-ibid. **C 20** (2001) 599].