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New Physics Insights from Two-Higgs-Doublet Models and Beyond

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For specific models beyond the Standard Model, the following questions will be discussed: What can we learn from precision measurements in the Higgs sector about New Physics? Can we identify the underlying model? Can we gain insight in the mechanism of electroweak symmetry breaking? For this, the impact of theoretical and experimental constraints on extended Higgs sectors will be illustrated, the potential of Higgs rates for identifying the model and possible CP violation will be discussed, and the specific features of Higgs pair production in New Physics extensions will be analysed.

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1. Introduction

With the discovery of the Higgs boson by the Large Hadron Collider (LHC) experiments ATLAS [1] and CMS [2] the Standard Model (SM) is structurally complete. Although the discovered Higgs boson behaves very SM-like open questions that cannot be answered within the SM call for extensions beyond the SM (BSM). The experiments, however, have not found any direct sign of New Physics (NP) yet, and the exclusion limits for new particles are pushed to ever higher scales. In this situation the Higgs sector plays an important role. The question is: What can we learn from Higgs physics? Besides obvious direct signs like the discovery of additional Higgs bosons from extended Higgs sectors, NP manifests itself indirectly in the Higgs sector through deviations from the SM properties: Higgs couplings can be modified through the mixing with other Higgs bosons that can be of singlet or doublet nature, that can be CP-even, CP-odd or of indefinite CP quantum numbers. The properties can be changed through loop effects of non-SM particles. The total width and branching ratios can deviate from the SM values due to decays into lighter non-SM states. Due to the SM-like nature of the 125 GeV Higgs boson indirect NP effects are expected to be small. Besides advanced experimental techniques, precision in the theory predictions of Higgs observables is indispensable. This is also required in case of discovery to be able to identify the underlying model, in particular as different NP models lead to similar effects.

In view of the plethora of NP models, we need a strategy how to efficiently explore the NP landscape and to make sure not to miss any sign of NP. On the one hand the effective theory approach (EFT) provides a rather model-independent framework to explore NP appearing at high scales. This has to be complemented by investigations in specific UV-complete models to be able to explore the effects of light states that cannot be covered by the EFT approach. The predictions of these NP models have to comply with all relevant experimental and theoretical constraints and should solve some or even all of the flaws of the SM. Among the simplest NP Higgs sectors that are also compatible with the experimental ρ parameter are singet or doublet extensions. In the latter case, the compability with the non-observation of flavour-changing neutral currents (FCNCs) has to be ensured by imposing e.g. a discrete symmetry on the Higgs sector. Further experimental constraints arise from electroweak precision measurements, flavour constraints, Higgs data, direct searches for BSM particles, low-energy observables, DM data (in case of models with a DM candidate) and the measurements of electric dipole moments (EDMs), relevant for Higgs sectors with CP violation. Additionally, theory constraints have to be fulfilled. Thus, the Higgs potential of the extended Higgs sectors featured by the NP models, has to be bounded from below, the electroweak minimum must be ensured to be the global minimum and perturbative unitarity must not be violated. By performing extensive scans in the parameter spaces of the NP models taking into account the experimental and theoretical constraints their parameter space is reduced to the allowed one. This way the predictions for NP models will be sharpened, and some of them may even be excluded. Precision is inevitable here to make meaningful predictions.

I will discuss what we can learn about NP from precise investigations of the Higgs sector. The information gained from experimental and theoretical constraints will be analysed in Sec. 2. Section 3 shows how Higgs rates can be exploited to disinguish between different NP models. These can also be used to identify possible CP violation that can still be substantial in certain models, as discussed in Sec. 4. Section 5 is devoted to NP aspects in Higgs pair production.

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2. Information from Experimental and Theoretical Constraints

The Two-Higgs-Doublet Model (2HDM) [3] belongs to the simplest extensions of the SM and provides an excellent benchmark to study physics beyond the SM. With two complex Higgs doublets its scalar potential is more involved than in the SM. An interesting question to be asked is whether the potential remains stable and perturbative when progressively larger energy scales are considered. In [4], we investigated what is the effect of the renormalization group equation (RGE) running of the 2HDM quartic couplings up to high scales on the decoupling or alignment limit of the model, when combined with the theoretical and experimental constraints.[1]

In Fig. 1, the charged Higgs mass is shown versus $\cos(\beta-\alpha)$, with $\tan\beta$ denoting the ratio of the vacuum expection values (VEVs) of the two Higgs doublets and α the mixing angle in the neutral CP-even Higgs sector, for the Type I 2HDM and the case where the lighter of the two neutral CP-even Higgs bosons is SM-like. The coloured points are those points from a parameter scan in the 2HDM space that survive all relevant experimental and theoretical constraints. The colour code shows up to which scale these are fulfilled by applying 2-loop RGEs and 1-loop matching on the quartic couplings. As can be inferred from the figure, the model can substantially deviate from the alignment limit, i.e. $\cos(\beta-\alpha)=0$, and still be valid up to the Planck scale, for light enough charged Higgs masses. On the contrary, for the Type II model (not shown here) to be close to the alignment limit it is enough to require it to be valid up to about 1 TeV and at the same time have one of the scalar masses above about 500 GeV, which is the case for Type II as B-physics bounds force the charged Higgs mass to be above 580 GeV [6].

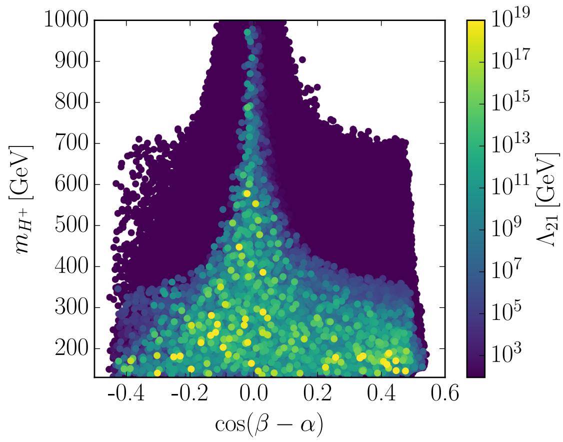

Figure 1: Charged Higgs mass versus $\cos(\beta-\alpha)$ in the 2HDM Type I, colour coded with the cut-off scale. The points passed all constraints at the scale of the Z-boson mass m_Z and survived up to a given cut-off scale; from [4].

3. Information from Higgs Rates and Coupling Measurements

Higgs rates and coupling measurements can be used to identify NP and differentiate between specific models, as shown in [7]. There the predictions for the Higgs sectors of the SM extended by

[1] For recent works on similar aspects in this context, see also [5].

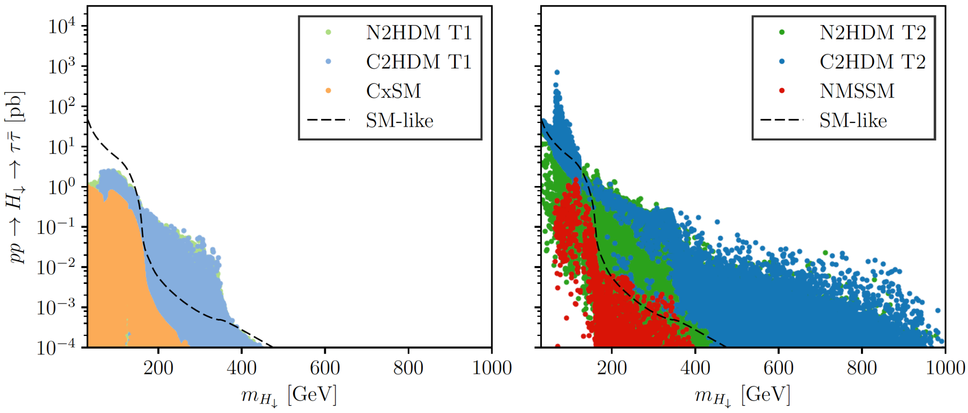

Figure 2: Signal rates for $H_\downarrow$ production with subsequent decay into $\tau\bar{\tau}$ at the $\sqrt{s} = 13$ TeV LHC as a function of $m_{H_\downarrow}$. Left: the CxSM (orange), the Type I N2HDM (fair green) and C2HDM (fair blue). Right: the NMSSM (red) and the Type II N2HDM (dark green) and C2HDM (dark blue). The dashed line denotes the SM reference (see text); from [7].

a complex singlet field (CxSM), the singlet extensions of the 2HDM (N2HDM) and the Next-to-Minimal Supersymmetric SM extension (NMSSM) were compared. All of these feature 3 CP-even neutral Higgs bosons. Additionally, the CP-violating 2HDM (C2HDM) was analysed, which provides 3 neutral CP-mixing Higgs bosons. While having similar neutral Higgs sectors, the models differ in their underlying symmetries - with consequences for Higgs phenomenology.

Figure 2 displays the rates for the production of the lighter among the two non-SM-like neutral Higgs bosons, $H_\downarrow$, with subsequent decay into $\tau^+\tau^-$ as function of its mass $m_{H_\downarrow}$ for the N2HDM Type I ($\equiv$ T1), the C2HDM T1 and the CxSM in the left and for the N2HDM Type II ($\equiv$ T2), C2HDM T2 and the NMSSM in the right plot. The points have survived the relevant theoretical and experimental constraints (for details, see [7]) after performing a scan over each model's parameter space. The dashed line shows the rate of a Higgs boson with same mass but SM properties. In the CxSM, all Higgs couplings to SM particles are suppressed compared to the SM so that the CxSM rates can never exceed those of the SM, as is confirmed by the left plot. In all other models the $H_\downarrow$ couplings to τ leptons can be enhanced, inducing enhanced rates in case the production cross section is not too strongly suppressed. The enhanced points at $m_{H_\downarrow} = 70 - 80$ GeV for C2HDM T2 and N2HDM T2 arise from associated production with bottom quarks for large values of $\tan\beta$. Since in this mass region no exclusion limits exist, large rates are still allowed. This underlines the importance for the experiments to test the low-mass region. The NMSSM rates are much lower compared to the other two T2 models. This is due to supersymmetric (SUSY) relations combined with exclusion limits on SUSY particle masses. The figure demonstrates that there is potential to distinguish the models based on rate measurements, in particular when combined with measurements of rates in other SM final states. Moreover, coupling sum rules can be exploited and even give insights on the mass patterns. For details, we refer the reader to [7].

4. CP Violation

Extended Higgs sectors feature additional sources of CP violation. In particular, CP violation in the Higgs sector is an immediate sign of BSM physics. Moreover, one of the three Sakharov

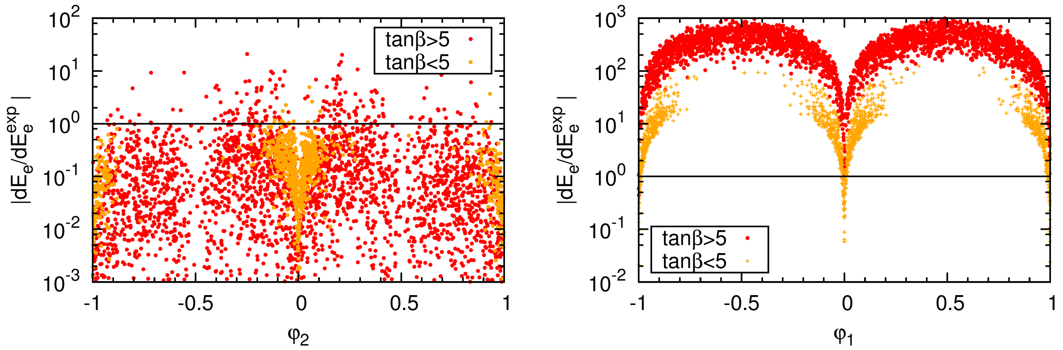

Figure 3: Absolute value of the electron EDM normalized do to the experimental upper bound as a function of φ_2 (left) and φ_1 (right) for $\tan\beta < 5$ (orange) and $\tan\beta > 5$ (red); from [9].

conditions [8] for successful baryogenesis is C and CP violation. In contrast to the Minimal Supersymmetric extension (MSSM) the NMSSM Higgs sector features CP violation already at tree level. The measurement of the EDMs, however, strongly constrains the possible amount of CP violation, with the strongest constraint coming from the electron EDM [9]. Figure 3 shows the electron EDM calculated within the NMSSM for parameter points that result from a scan in the NMSSM parameter space. All points have been checked for compatibility with the LHC Higgs data and with the relevant LHC exclusion limits on SUSY particle masses, for details see [9]. The EDM is normalized to the experimentally measured value [10]. All points above 1, indicated by the black line, are excluded. The left plot shows the variation with the NMSSM specific CP-violating phase φ_2. Being a combination of the CP-violating phases of NMSSM specific Higgs sector parameters, it only appears in the NMSSM. The variation with the MSSM specific CP-violating phase φ_1 is shown in the right plot. This phase also generates CP violation in the higgsino and in the sfermion sector as it occurs in the MSSM. For the specific definitions of φ_1 and φ_2, see [9]. The figure shows that in the NMSSM non-trivial CP-violating phases are still compatible with the EDMs in contrast to the MSSM where the chargino contributions to the EDMs through a complex phase of the effective higgsino parameter generate EDMs that are above the experimental constraints (see also [11]).

The 2HDM, a non-SUSY benchmark model for the MSSM, features CP violation in the tree-level Higgs sector with one CP-violating phase. In the C2HDM all three neutral Higgs bosons mix to CP-violating mass eigenstates H_i $(i = 1,2,3)$, ordered by ascending mass. Although the 125 GeV Higgs boson behaves very SM-like the CP admixture can still be as large as 20% for C2HDM T1 while being compatible with all relevant experimental and theoretical constraints. The C2HDM T2 is more constrained with a possible admixture of 10%, [7, 12]. Also for detecting possible CP violation, Higgs rate measurements can be used. The simultaneous measurement of different Higgs decays into final states involving Higgs bosons and/or gauge bosons can be an indicator of CP violation, see e.g. [13] for the C2HDM and [9] for the CP-violating NMSSM.

5. Information from Higgs Pair Production

Higgs pair production gives access to the trilinear Higgs self-coupling and hence insight in the mechanism of electroweak symmetry breaking [14]. At the LHC, the dominant Higgs pair production cross section is gluon fusion. The process is loop-induced by heavy fermion, i.e. top and bottom, triangle and box diagrams. The cross section is therefore rather small. At next-to-leading order (NLO) QCD with the full top-quark mass dependence included it amounts to 33 fb [15, 16]. (For a recent overview of the status of higher-order corrections to Higgs pair production, see [16].) The small signal combined with a large QCD background makes the measurement an experimental challenge.

In models beyond the SM Higgs pair production can be considerably enhanced due to resonantly produced heavy Higgs production with subsequent decay into a lighter Higgs pair, due to novel particles in the loop, due to new couplings, but also due to a different Higgs self-coupling than in the SM. For the SM value of the trilinear Higgs self-coupling there is desctructive interference between the triangle and box diagrams. Although the discovered Higgs boson behaves very SM-like, the trilinear Higgs self-coupling can still deviate substantially from the SM-value (for recent works, see [17]). In composite Higgs models the Higgs boson arises as a pseudo-Goldstone boson from a strongly interacting sector. Higgs pair production is sensitive to the trilinear Higgs self-coupling but also to anomalous couplings like the novel 2-Higgs-2-fermion coupling emerging in composite Higgs models. It could even be that, taking into account the Higgs coupling constraints, NP could first be seen in Higgs pair production. Figure 4 depicts the number of signal events from NLO QCD Higgs pair production with subsequent decay in the final state XY,

$$S = \sigma_{HH}^{\rm NLO} \cdot 2 \cdot {\rm BR}(H \to X) \cdot {\rm BR}(H \to Y) \cdot A \cdot L\,, \qquad (5.1)$$

where BR denotes the branching ratio into the final state $XY = b\bar{b}\tau^+\tau^-$ (left) and $b\bar{b}\gamma\gamma$ (right), A the acceptance due to cuts applied on the cross section and L the integrated luminosity, chosen to be $L = 300$ fb^{-1} in the left and 3000 fb^{-1} in the right plot. The acceptances have been extracted from [18]. The Higgs boson is the 125 GeV Higgs boson of a composite Higgs model, MCHM10, with heavy top and bottom partners based on the minimal $SO(5) \times U(1)_X / SO(4) \times U(1)_X$ symmetry breaking pattern, with the additional $U(1)_X$ introduced to guarantee the correct fermion charges. The cross section includes the NLO QCD corrections in the limit of heavy loop particle masses [19]. The rates are shown as function of the compositeness parameter $\xi = (v/f)^2$, with f being the compositeness scale and $v \approx 246$ GeV the vacuum expectation value. All displayed points have

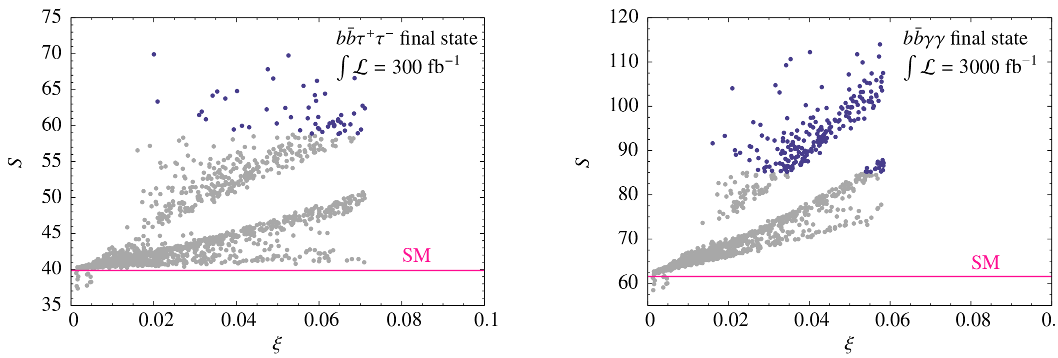

Figure 4: Number of signal events S for NLO Higgs pair production in the final state $b\bar{b}\tau^+\tau^-$for an integrated luminosity of $L = 300$ fb^{-1} (left) and in $b\bar{b}\gamma\gamma$ for $L = 3000$ fb^{-1} (right). All points pass the applied constraints, blue points deviate from the NLO SM signal rate (in pink) by more than 3σ. Plots taken from [19].

been obtained from a parameter scan in the MCHM10 parameter space and passed the applied constraints, namely also the projected precisions on the measurements of the Higgs couplings to the SM particles (for details, see [19]). The blue color denotes those scenarios for which Higgs pair production is sensitive to NP in the sense that the number of signal events in MCHM10 differs from the corresponding number of signal events in the SM (denoted by the pink line) by more than 3σ standard deviations. Already for an integrated luminosity of 300 fb^{-1} New Physics could first be seen in Higgs pair production in the $b\bar{b}\tau^+\tau^-$ final state, for 3000 fb^{-1} also in the $b\bar{b}\gamma\gamma$ final state.

6. Conclusions

The Higgs sector has been shown to be an excellent playground in the hunt for New Physics. In view of the SM-like properties of the disovered Higgs boson sophisticated exerimental techniques have to be combined with high precision predictions from theory to be sensitive to possibly small BSM effects. From the measurement of the Higgs rates we can then get insights on the Higgs spectrum and also be able to distinguish between different extended Higgs sectors. The combination of different Higgs decay rates can also be used to identify CP violation that is realized already at tree-level in 2HDMs and the NMSSM. Although stringent constraints from EDMs have to be taken into account, the 125 GeV Higgs boson can still feature sizeable CP violation in the C2HDM T1 and the NMSSM. Higgs pair production gives further information on the mechanism of electroweak symmetry breaking. While in the SM its cross section is small it can be considerably enhanced in BSM Higgs sectors due to resonantly produced Higgs bosons and/or novel couplings. In composite Higgs models New Physics could even first be seen in Higgs pair production. Although we do not have any direct sign of New Physics yet precise measurements in the Higgs sector can give us now and in the future important insights in possible New Physics extensions, their specific nature and the way electroweak symmetry breaking is realized.

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