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Charged-Higgs phenomenology in the Aligned two-Higgs-doublet model

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The alignment in flavour space of the Yukawa matrices of a general two-Higgs-doublet model results in the absence of tree-level flavour-changing neutral currents. In addition to the usual fermion masses and mixings, the aligned Yukawa structure only contains three complex parameters, which are potential new sources of *CP*-violation. For particular values of these three parameters all known specific implementations of the model based on discrete $\mathscr{Z}_2$ symmetries are recovered.

One of the most distinctive features of the two-Higgs-doublet model is the presence of a charged scalar. In this talk, I will discuss its main phenomenological consequences in flavour-changing processes at low energies, ranging from leptonic decays to the recently widely discussed like-sign dimuon charge asymmetry.

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1. Introduction

The confirmation by the B-factories of the CKM-mechanism as the main source for low-energy CP-violation has opened a new chapter in the search for physics beyond the Standard Model (SM). While the direct search for the mediator(s) of electroweak symmetry breaking and new heavy particles is being performed at the Tevatron and the LHC, their effects should be visible in (low-energy) flavour observables as well. Loosely speaking, the infamous *flavour problem* is the fact, that this is not the case (yet), implying a highly non-trivial flavour-structure of any new physics (NP) scenario. While not conclusive, some tensions are present in flavour-data, two of which will be discussed here: the different values for $\sin 2\beta$ when extracted with the help of $B\to J/\psi K$ and $B\to\tau\nu$ [1,2], and hints for a large phase in B_s-mixing, especially the measurement of the sign-like dimuon asymmetry by D0 [3].

Regarding two-Higgs-doublet models (2HDM) [4], the many models in the literature (for references, see e.g. [5]) basically differ by the mechanism to avoid this problem, which renders their most general version unplausible. In this talk, the focus lies on the Aligned Two-Higgs-Doublet Model (A2HDM) [6, 7]. The alignment in flavour space of the Yukawa matrices of a general two-Higgs-doublet model results in the absence of tree-level flavour-changing neutral currents. In addition to the usual fermion masses and mixings, the aligned Yukawa structure only contains three complex parameters, which are potential new sources of CP violation. For particular values of these three parameters all known specific implementations of the model based on discrete $\mathscr{Z}_2$-symmetries are recovered. This model is introduced in the next section, together with a scenario discussed recently [8,9], which expands around the limit of the Type II 2HDM in a minimal flavour violation (MFV) scenario assuming the decoupling limit, allowing for complex parameters. Their phenomenology is discussed in section 3 by examining selected flavour observables, followed by the conclusion in section 4.

2. Models

The quark Yukawa sector of the most general 2HDM is given by

$$-\mathscr{L}_Y^q \;=\; \bar{Q}_L'(\Gamma_1\phi_1+\Gamma_2\phi_2)\,d_R' + \bar{Q}_L'(\Delta_1\widetilde{\phi}_1+\Delta_2\widetilde{\phi}_2)\,u_R' + \text{h.c.}\,, \tag{2.1}$$

with Γ_i,Δ_i being $F\times F$ matrices, where F denotes the number of families, and otherwise common notation (for details here and in the following see [7]). In models with a $\mathscr{Z}_2$-symmetry, each field gets assigned an additional parity-like quantum number, effectively forbidding one of the two possible couplings between identical fermion fields [10][1]. Recent phenomenological analyses include [2, 11–14]. Minimal flavour violation (MFV), defined according to [15], is an effective field theory framework, in which the flavour symmetry of the SM Lagrangian without quark Yukawa couplings, namely $\mathscr{G}_F = SU(3)_L\times SU(3)_{U_R}\times SU(3)_{D_R}$[2], is extended to the full Lagrangian by promoting the Yukawa couplings to spurion fields, transforming accordingly under $\mathscr{G}_F$. In addition

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[1] The symmetry holds also for quantum corrections. However, once the 2HDM is embedded into another theory providing a UV completion, typically quantum corrections break it, and potentially too large FCNCs are generated [8]. Here the 2HDM without UV-completion is considered

[2] The discussion of the additional $U(1)$ symmetries is omitted here.

it is assumed, that the CKM phase is the only source of *CP* violation. This constrains heavily the structure of higher-dimensional operators, suppressing FCNCs effectively by powers of (light) quark masses and CKM mixing angles. In [15] and [8, 9], this program is carried out as an expansion around the limit of a 2HDM Type II, relevant for SUSY, and assuming the decoupling limit $M_{H^\pm} \gg M_W$, resumming $\tan\beta$-enhanced terms. In the latter papers, the restriction regarding new *CP*-violating sources has been dropped[3]. The decoupling limit implies, that charged Higgs effects are usually negligible. In the A2HDM it is assumed that each pair of coupling matrices is aligned, $\Delta_1 \sim \Delta_2, \Gamma_1 \sim \Gamma_2$, leading to

$$\mathscr{L}^{\mathrm{q}}_{Y,H^\pm} = -\frac{\sqrt{2}}{v} H^+(x) \left\{ \bar{u}(x) \left[\varsigma_d V_{CKM} M_d \mathscr{P}_R - \varsigma_u M_u^\dagger V_{CKM} \mathscr{P}_L \right] d(x) \right\} + \text{h.c.} \tag{2.2}$$

for the charged scalar Yukawa interaction and the absence of FCNCs at tree level. The universal (flavour-blind) couplings ς_f $(f = u, d, l)$ introduce three new complex phases and, therefore, a new source of *CP* violation. For particular (real) values of these parameters the usual *CP*-conserving models based on discrete $\mathscr{Z}_2$ symmetries are recovered. Quantum corrections induce a misalignment of the Yukawa matrices, generating small FCNC effects [6, 7, 21, 22]. The flavour symmetries of the A2HDM strongly constrain the allowed FCNC structures, providing at the quantum level an explicit implementation of the MFV scenario, but allowing at the same time for new *CP*-violating phases.

3. Phenomenology

The leptonic decay rate is modified in the presence of a charged scalar as $\frac{\Gamma(P^+_{ij} \to l^+ \nu_l)_{\text{full}}}{\Gamma(P^+_{ij} \to l^+ \nu_l)_{\text{SM}}} = |1 - \Delta_{ij}|^2$, where i, j represent the valence quarks of the meson P under consideration and Δ_{ij} encodes model-dependent information about the charged Higgs couplings. In the A2HDM it is given by $\Delta_{ij} = \left(\frac{m_{P^\pm_{ij}}}{M_{H^\pm}}\right)^2 \varsigma_l^* \frac{\varsigma_u m_{u_i} + \varsigma_d m_{d_j}}{m_{u_i} + m_{d_j}}$. Obviously, in the decoupling limit the large charged Higgs mass renders the influence tiny, allowing to use $B \to \tau\nu$ in the unitarity triangle (UT) fit. In $\mathscr{Z}_2$-models, the two contributions are related and have fixed signs, allowing e.g. in Type II models only for a reduction of the rate in $B \to \tau\nu$ [4], while in the A2HDM the two contributions are independent and their relative influence is determined by the corresponding phases.

Semileptonic decays receive contributions from a charged scalar as well, but in this case the leading SM amplitude is not helicity suppressed, therefore the relative influence is smaller. In addition, there are momentum-dependent form factors involved. The decay amplitude $M \to M' l \bar{\nu}_l$ is characterized by two form factors, $f_+(t)$ and $f_0(t)$ associated with the P-wave and S-wave projections of the crossed-channel matrix element $\langle 0 | \bar{u}_i \gamma^\mu d_j | M \bar{M}' \rangle$. The scalar-exchange amplitude only contributes to the scalar form factor; it amounts to a multiplicative correction $\tilde{f}_0(t) = f_0(t)\ (1 + \delta_{ij} t)$, where the δ_{ij} is the analogue to Δ_{ij} in leptonic decays discussed above, in the A2HDM given by $\delta_{ij} \equiv -\frac{\varsigma_l^*}{M^2_{H^\pm}} \frac{\varsigma_u m_{u_i} - \varsigma_d m_{d_j}}{m_{u_i} - m_{d_j}}$, and the above qualitative discussion applies here as well.

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[3] Regarding MFV with new sources of *CP* violation, see also [16–20].

[4] A huge NP contribution $\Delta_{ub} > 2$ could lead to an enhancement, but is ruled out by other observables.

The results of a global fit to the available (semi-)leptonic decay data in the A2HDM are shown in Fig. 1. Note that in both cases there are two real solutions, one of which can be excluded mainly due to the correlation provided by $B \to D\tau\nu$, but in the case of the combination $\varsigma_d\varsigma_l^*/M_{H^\pm}^2$ only with help of additional information [7]. For models with $\mathscr{Z}_2$-symmetry, only the projections on the real axes are relevant, the resulting constraint for the 2HDM Type II is shown on the right.

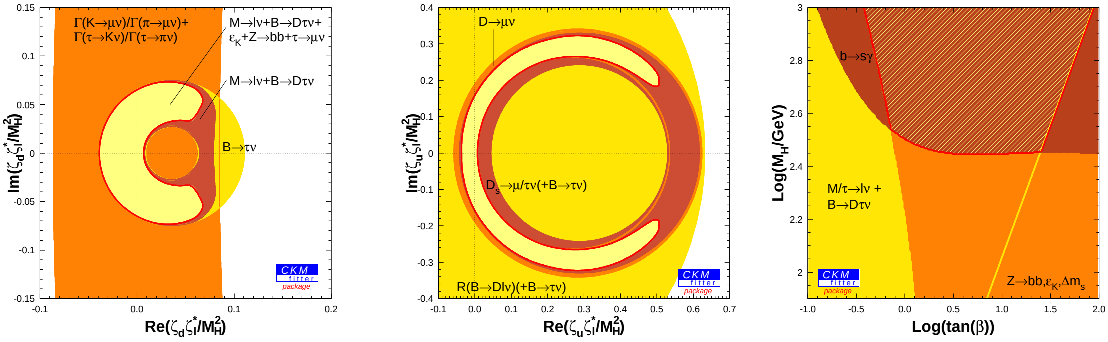

Figure 1: *$\varsigma_d\varsigma_l^*/M_{H^\pm}^2$ (left) and $\varsigma_u\varsigma_l^*/M_{H^\pm}^2$ (center) in the complex plane, in units of GeV^{-2}, constrained by leptonic and semileptonic decays. The inner yellow area shows the allowed region at 95% CL, in the case of $\varsigma_d\varsigma_l^*/M_{H^\pm}^2$ using additional information [7]. Shown on the right is the projection to the Type II 2HDM in the* $\tan\beta - M_{H^\pm}$*-plane, including information from loop-induced processes.*

Turning to loop-induced processes, maybe the most prominent example is the raditative decay $b \to s\gamma$, calculated basically up to NNLO in the SM [23, 24], see e.g. [25] for recent developments and references. Combining high theoretical and experimental precision, it provides a very sensitive probe for FCNC effects. In the Type II 2HDM it is famous for giving a bound on the Higgs mass basically independent of $\tan\beta$, as is illustrated in Fig. 1, whose strength implies compatibility with the decoupling limit scenario. This cancellation is absent in general. In the A2HDM, the constraint on the single parameters is relatively weak as more parameters are involved [7]. However, the strength of the constraint appears now in the form of correlations with a large impact on related observables [26].

Finally the effects in meson mixing are discussed. Models with $\mathscr{Z}_2$-symmetry do not effect these systems largely as long as $\tan\beta \gtrsim 2$, which is generally assumed there. In the A2HDM , the relevant coupling is independent, therefore effects from the top-coupling in K-mixing (ε_K) and B-mixing are potentially large and constrain the parameter $|\zeta_u| \lesssim 1$. They are universal in $B_{d,s}$, therefore the ratio $\Delta m_d/\Delta m_s$ can still be used in the UT fit. The mixing phase receives a moderate contribution from charged Higgs effects, up to ~ 5 times the SM value, taking into account the correlation from $b \to s\gamma$ [26]. In the decoupling scenario the dominant effects are from neutral Higgs exchange and proportional to down-type quark masses. Therefore the effect in K-mixing is tiny, while it is non-universal and potentially large in the $B_{d,s}$-systems [8]. The hint for a large NP phase in B_s-mixing can be accomodated here by a large phase, which implies a small shift in the B_d-system as well, in the right direction concerning the tension in the UT-fit.

4. Conclusions

2HDMs remain an active field, providing a relatively simple extension of the SM with interesting influence on flavour observables. Models with $\mathscr{Z}_2$-symmetry are the best constrained, but do not offer new sources of *CP*-violation and might be problematic regarding their UV-completion [8]. The A2HDM introduces new sources of *CP* violation in the flavour sector while avoiding FCNCs at tree level, and provides an explicit counter-example to the widespread assumption that in 2HDMs without tree-level-FCNCs all *CP*-violating phenomena should originate in the CKM matrix. Since all Yukawa couplings are proportional to fermion masses, the A2HDM gives rise to an interesting hierarchy of FCNC effects, avoiding the stringent experimental constraints for light-quark systems and allowing at the same time for interesting signals in heavy-quark transitions. It affects all of the present tensions; however, a very large effect in B_s-mixing seems difficult to accomodate with charged-Higgs-effects only. The focus of the decoupling MFV-scenario is very different: it describes radiatively induced corrections to the Type II model, providing a very different pattern of NP effects, capable of addressing the present tensions in the UT-fit and *B*-mixing. Note that these contributions are present in the A2HDM as well. With the LHC up and running, and several experiments under planning and construction, prominently Super-*B* factories, the experimental situation will greatly improve in the coming years, allowing a determination of the couplings in the different models discussed here, or their exclusion.

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