The muon $g - 2$ for low-mass pseudoscalar Higgs in the general 2HDM*

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Abstract. The two-Higgs doublet model is a simple and attractive extension of the Standard Model. It provides a possibility to explain the large deviation between theory and experiment in the muon $g - 2$ in an interesting parameter region: light pseudoscalar Higgs A, large Yukawa coupling to τ-leptons, and general, non-type II Yukawa couplings are preferred. This parameter region is explored, experimental limits on the relevant Yukawa couplings are obtained, and the maximum possible contributions to the muon $g - 2$ are discussed.

1 Introduction

So far the experiments at the LHC have not identified clear evidence for physics beyond the Standard Model (SM). This is regularly taken as an indication that new physics particles, if they exist, must be rather heavy. The persisting discrepancy between measurement and SM theory in the muon anomalous magnetic moment a_μ, however, cannot be explained by arbitrarily heavy new particles. Currently it is given by

$$a_\mu^{\text{Exp}-\text{SM}} = \begin{cases} (26.8 \pm 7.6) \times 10^{-10}[1], \\ (28.1 \pm 7.3) \times 10^{-10}[2], \\ (31.3 \pm 7.7) \times 10^{-10}[3]. \end{cases} \tag{1}$$

This situation has motivated extensive studies of a_μ in cases with high-mass new physics. E.g. Ref. [4] has studied the largest possible a_μ contributions in the MSSM and identified the largest possible SUSY mass scale for which the current a_μ deviation could be fully explained. Ref. [5] considered precision computations in the MSSM, which are particularly important in cases with a partially heavy spectrum of supersymmetric particles, and all these results were implemented in the program GM2Calc [6].

In the remainder of these proceedings we focus on an alternative idea, to consider models which can provide significant contributions to a_μ only for very light new particles, which however are nevertheless still viable. Specifically we focus on the two-Higgs doublet model (2HDM), the model realizing a non-minimal scalar sector breaking electroweak symmetry in the simplest possible way. It has been known for a long time that it can give rise to significant contributions to a_μ only if one of the extra Higgs bosons, specifically the pseudoscalar A-boson, is fairly light, lighter than the observed SM-like Higgs boson with mass of 125 GeV. Recently it has been stressed that the parameter space relevant for this is still viable, see particularly Refs. [7, 8].

In Ref. [9] the 2HDM prediction for a_μ has been derived at the full two-loop level (which corresponds to leading order), and in reference [10], experimental constraints are exploited to obtain the possible allowed ranges of all contributions and thus identify the parameter space of the general 2HDM, which can explain a_μ. Here we review these results.

2 Two-Higgs doublet model

We consider the general 2HDM, with only few restrictions on the parameters. We take the Higgs potential to be [11, 12]

$$\begin{aligned} V(\phi_1, \phi_2) =& m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2 - m_{12}^2 \left(\phi_1^\dagger \phi_2 + \phi_2^\dagger \phi_1\right) \\ &+ \frac{\lambda_1}{2}\left(\phi_1^\dagger \phi_1\right)^2 + \frac{\lambda_2}{2}\left(\phi_2^\dagger \phi_2\right)^2 + \lambda_3 \phi_1^\dagger \phi_1 \phi_2^\dagger \phi_2 \\ &+ \lambda_4 \phi_1^\dagger \phi_2 \phi_2^\dagger \phi_1 + \frac{\lambda_5}{2}\left[\left(\phi_1^\dagger \phi_2\right)^2 + \left(\phi_2^\dagger \phi_1\right)^2\right], \end{aligned} \tag{2}$$

where we only neglect the so-called $\lambda_{6,7}$ parameters, which we checked to have negligible influence on our later results.

The potential parameters determine the physical masses $M_{h,H,A,H^\pm}$, where h corresponds to the SM-like Higgs boson, H is assumed to be heavier, A is a CP-odd scalar, and $H^\pm$ is a charged Higgs boson. Further, the potential determines the ratio between the two vacuum expectation values, $\tan\beta$, and the mixing angle $\eta \equiv \frac{\pi}{2} - (\beta - \alpha)$, which LHC-data forces to be small.

The Yukawa couplings are assumed to be "aligned" in the sense of Ref. [13]. I.e. we do not assume one of the usual type I,II,X,Y models but only require that the couplings of both Higgs doublets to fermions are proportional to each other, to prevent violations of FCNC bounds. The

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Yukawa couplings between the scalar $\mathcal{S}$ and fermion f are then determined by the factors Y_f^S given for small η by

$$Y_f^h = 1 + \eta\zeta_f,\ Y_f^H = -\zeta_f + \eta,$$
$$Y_f^A = -\Theta_f^A \zeta_f,\ \Theta_{d,l}^A = 1,\ \Theta_u^A = -1. \quad (3)$$

The units are such that the respective SM-coupling would correspond to $Y_f^h = 1$. The couplings depend on the fermion type, $f \in \{u, d, l\}$.

In contrast to the usual type I,II,X,Y models, the Yukawa couplings are determined by free parameters $\zeta_{u,d,l}$ for each fermion type, but they are independent of $\tan\beta$. $\tan\beta$ is a parameter whose role is confined to the Higgs sector.

3 Muon $g-2$ in the 2HDM at two-loop order

In the 2HDM the muon $g-2$ receives contributions from one- and two-loop diagrams. The one-loop diagrams, however, are suppressed by two additional powers of the muon mass and thus very small (except at Higgs masses below around 20 GeV). The parametrically leading diagrams are of two-loop order. In this sense Ref. [9] has completed the full leading-order computation of a_μ in the 2HDM; see Ref. [14] for a previous advanced calculation and references to earlier works.

The full result, including one- and two-loop contributions can be written as

$$a_\mu^{\text{2HDM},2} = a_\mu^{\text{2HDM},1} + a_\mu^{\text{B}} + a_\mu^{\text{F}} + a_\mu^{\Delta r\text{-shift}}. \quad (4)$$

We now briefly discuss all contributions.

- $a_\mu^{\text{2HDM},1}$ are the 2HDM one-loop contributions (which are not contained in the SM prediction). They arise from one-loop diagrams with a single Higgs exchange and are suppressed by two powers of the muon mass divided by the Higgs mass. We will later consider the case of light CP-odd scalar mass M_A. In this case the one-loop contributions are negative and make it more difficult to explain the deviation (1).
- a_μ^{B} are the bosonic two-loop contributions, i.e. the contributions arising from diagrams without closed fermion loop. They contain the diagrams with three vertices on the muon line, computed for the first time in Ref. [9], but also Barr-Zee-type diagrams with charged Higgs loop, computed in Ref. [14] and Ref. [9] using different methods. They turn out to be rather small and dominated by diagrams which involve the triple Higgs coupling $C_{HH^+H^-}$ between H and two charged Higgs bosons.
- a_μ^{F} are the two-loop contributions with closed fermion loop. These are dominated by the 3rd generation fermions, which have the largest Yukawa couplings. Among the common type I,II,X,Y models, only the type X (or lepton-specific) model is capable of providing significant contributions [7]; in this case the τ-loop contributions are proportional to $\zeta_l = -\tan\beta$ and dominate by far, but top- and bottom-loop contributions are suppressed as $1/\tan\beta$. In the more general aligned model, the top-loop can also contribute significantly (see later and Ref. [8]).
- $a_\mu^{\Delta r\text{-shift}}$ is a shift required because the SM contribution is parametrized in terms of the muon decay constant which receives additional 2HDM contributions. This contribution is below 2×10^{-12} and will hence be neglected in the following.

Useful numerical approximations for the contributions are [10], using $\hat{x}_\mathcal{S} \equiv M_\mathcal{S}/100$ GeV and setting $M_{H^\pm} = M_H$,

$$a_\mu^{\text{2HDM},1} \simeq \left(\frac{\zeta_l}{100}\right)^2 \left\{\frac{-3 - 0.5\ln(\hat{x}_A)}{\hat{x}_A^2}\right\} \times 10^{-10}, \quad (5)$$

$$a_\mu^{\text{F}} \simeq \left[\left(\frac{\zeta_l}{100}\right)^2 \left\{\frac{8+4\hat{x}_A^2+2\ln(\hat{x}_A)}{\hat{x}_A^2}\right\} + \left(\frac{-\zeta_l\zeta_u}{100}\right)\left\{54 - 14\ln(\hat{x}_A) - 15\ln(\hat{x}_H)\right\}\right] \times 10^{-10} \quad (6)$$

$$|a_\mu^{\text{B}}| \simeq \rho |C_{HH^+H^-}/\text{GeV}|\,|\zeta_l| \times 10^{-15} \quad (7)$$

The terms in the second line are mainly due to two-loop diagrams with τ-loop and top-loop, respectively, and in the result for a_μ^{B}, ρ is typically in the range $1\ldots6$ for $M_H, M_{H^\pm} = 150\ldots300$ GeV and the triple Higgs coupling $C_{HH^+H^-}$ is limited by perturbativity to values up to around 1000 GeV.

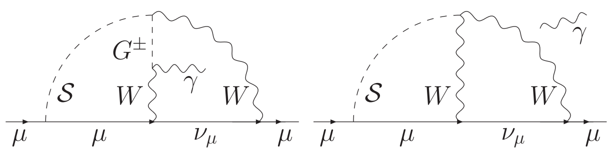

Figure 1. Bosonic two-loop diagrams with three vertices on the fermion line. From [9].

4 Muon $g-2$ contributions constrained by experiment

In this section we provide an overview of the three single largest contributions to a_μ in the 2HDM and describe how they are constrained by current experiments.

- τ-loop contribution: the most important contribution is given by the Barr-Zee-like two-loop diagram with a τ-loop generating a γ–γ–A interaction. The diagram has a behaviour proportional to ζ_l^2/M_A^2, see the approximation (6). Hence it is of interest to determine in general the constraints on the lepton Yukawa parameter ζ_l.

  Such constraints have already been studied in the literature, particularly in Refs. [7, 15], for the type X model, where $\zeta_l = -\tan\beta$. The constraints found there arise from τ-decays, which can be influenced by additional 2HDM-contributions, and by universality of $Z \to ll$ decays. Fig. 2(left) shows a scatter plot of allowed parameter points in the 2HDM in the M_A–ζ_l plane, for fixed $M_H = M_{H^\pm} = 200$ GeV and $\zeta_u = 0$, where consistency with τ-decays and $Z \to ll$ was checked as described in

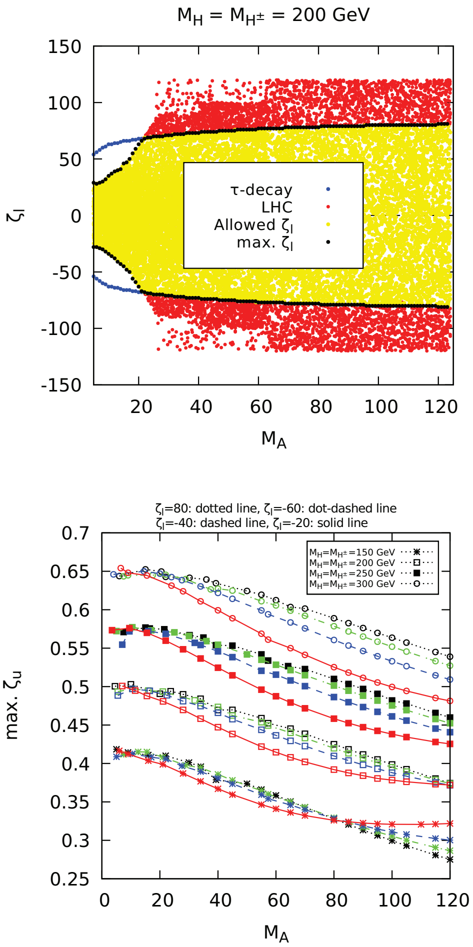

Figure 2. *Top:* Scatter plot of the possible parameter points in the 2HDM in the M_A–ζ_l plane, for fixed $M_H = M_{H^\pm} = 200$ GeV and $\zeta_u = 0$. Yellow points correspond to the points allowed both by collider constraints (labelled by "LHC") and τ-physics constraints, red and blue corresponds to the points allowed by one of these constraints, ignoring the other one. The maximum and minumum boundary of ζ_l is depicted as black points. The result for the allowed ζ_l values corresponds to the maximum allowed values of $\tan\beta$ in the 2HDM type X, studied in Ref. [15]. *Bottom:* Maximum values of the top-Yukawa parameter ζ_u allowed by B-physics (see text), as a function of M_A.

Ref. [15] and consistency with Higgs measurements was checked using 2HDMC and HiggsBounds [16, 17]. The scatter plot shows that the τ-decay and $Z \to ll$ constraints carry over from the type X model to the more general model without change, and that there is a small region at very small M_A, which turns out to be excluded by LEP measurements. We refer to Ref. [10] for further details.

The exclusion bound depends slightly on the chosen values of M_H and $M_{H^\pm}$, but generally the maximum allowed value of $|\zeta_l|$ varies between around 40 (for smaller Higgs masses) and 100 (for larger Higgs masses).

- top-loop contribution: the next important contribution is given by the Barr-Zee like two-loop diagram with a top-loop. It depends on $\zeta_u\zeta_l$ and on M_A and M_H, and hence the constraints on ζ_u are now crucial.

  ζ_u is constrained by B-physics and by direct Higgs searches. It is clear that the corresponding Feynman diagrams depend on the same parameters ζ_u, ζ_l, M_A as the desired a_μ-contribution. Using the results of Ref. [18] we found that the most constraining B-physics observables are $b \to s\gamma$ and $B_s \to \mu\mu$. Implementing them and checking consistency with data, we obtain the plot of Fig. 2(right), showing the maximum allowed values of ζ_u, as a function of M_A, for various choices of ζ_l and the other Higgs masses. The maximum allowed values are between $\zeta_u < 0.3$ and $\zeta_u < 0.7$.

  The constraints from LHC Higgs searches place additional limits on ζ_u, which have a more intricate parameter dependence. We provide an example of the LHC constraints for $M_A = 80$ GeV and $\zeta_l = -40$ and $M_H = M_{H^\pm} \in [200, 300]$ GeV in Fig. 3(left). The colours show parameter points in the ζ_u–$C_{HH^+H^-}$-plane which successively fulfil bounds from S, T, U parameters, HiggsBounds, HiggsSignals, and tree-level stability, unitarity and perturbativity (checked by 2HDMC [17]). The decisive constraints are perturbativity, which provides an upper limit on the triple Higgs coupling $C_{HH^+H^-}$, and the LHC constraint on the $H \to \tau\tau$ decay. The latter constraint limits ζ_u as a function of the triple Higgs coupling, because Higgs production is governed by ζ_u, while the branching fraction for the decay to $\tau\tau$ can be suppressed by large triple Higgs coupling. In the example of Fig. 3(left), the LHC constraints on ζ_u are weaker than the ones from B-physics. This is true in a significant part of the parameter space, hence we will not discuss these LHC constraints further here and refer to Ref. [10] for details.

- bosonic contributions: in the promising parameter region with small M_A, the bosonic contributions are dominated by the Barr-Zee-like diagram with charged Higgs loop and scalar H exchange. It is proportional to the triple Higgs coupling, which appears in Fig. 3(left). Inserting the upper limit on the triple Higgs coupling we obtain a possible range for $a_\mu^{\rm B}$ in agreement with the approximation Eq. (7).

Combining all the results on upper limits on ζ_l, ζ_u, and on the bosonic contributions, we can obtain the maximum possible 2HDM two-loop contribution to a_μ, as a function of M_A, for fixed values of the other Higgs masses. Fig. 3(right) shows the resulting maximum contribution for $M_H = M_{H^\pm} = 150, 200, 250, 300$ GeV. For each M_A and $M_H, M_{H^\pm}$, we first maximize ζ_l. This provides the lower (dotted) curves, which correspond to the τ-loop alone, equivalent to the result in the type X model. Then, for the given M_A and ζ_l we maximize ζ_u, given B-physics and LHC constraints. This provides the middle (dashed) curves, corresponding to the maximum full fermionic two-loop contribution in the general 2HDM. Adding the maximum bosonic two-loop contribution then yields the upper (continuous) curves.

The figure shows that the 2HDM is well capable of providing large contributions to a_μ, even larger than the deviation (1). However, the necessary parameter region is quite specific: the CP-odd Higgs boson mass must be smaller than M_Z, and ζ_u and ζ_l must both be close to their respective maximum values. In particular going beyond the type X model, i.e. having ζ_u of order 1 instead of order $1/|\zeta_l|$, increases the maximum a_μ almost by a factor two.

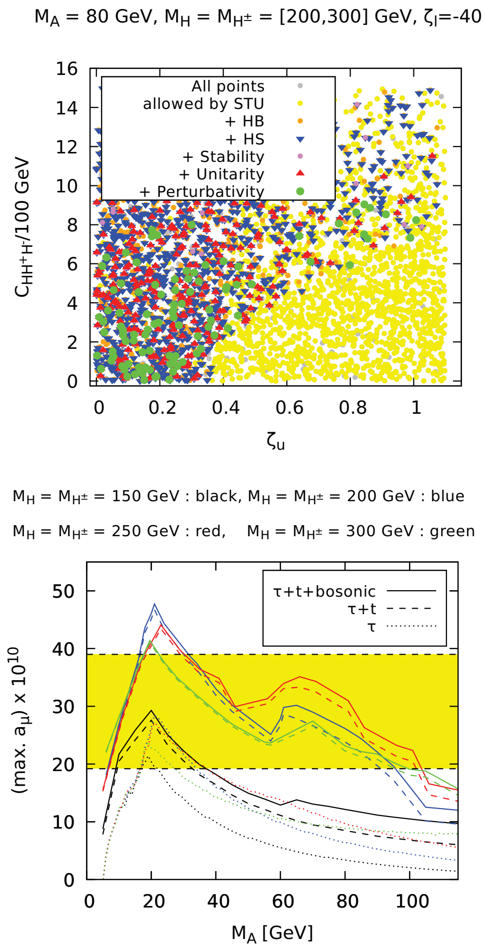

Figure 3. *top:* Allowed ranges of ζ_u and the triple Higgs coupling $C_{HH^+H^-}$, given certain constraints, see legend and text. The constraints are applied successively. *Bottom:* Maximum values of the two-loop contribution to $g-2$ in the general 2HDM for several values of $M_H = M_{H^\pm}$, given the constraints discussed in the text (from [10]). For each mass choice, the lowest line (dotted) corresponds to the maximum contribution from the τ-loop alone, equivalent to the type X model. The middle lines (dashed) correspond to adding the maximum possible top-loop contribution, and the top lines (continuous) to the overall maximum contribution, including bosonic two-loop contributions.

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