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Distinguishing a SM-like MSSM Higgs boson from SM Higgs boson at muon collider

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Abstract. We explore the possibility of distinguishing the SM-like MSSM Higgs boson from the SM Higgs boson via Higgs boson pair production at future muon collider. We study the behavior of the production cross-section in SM and MSSM with Higgs boson mass for various MSSM parameters $\tan\beta$ and m_A. We observe that at fixed CM energy, in the SM, the total cross-section increases with the increase in Higgs boson mass whereas this trend is reversed for the MSSM. The changes that occur for the MSSM in comparison to the SM predictions are quantified in terms of the relative percentage deviation in cross-section. The observed deviations in cross-section for different choices of Higgs boson masses suggest that the measurements of the cross-section could possibly distinguish the SM-like MSSM Higgs boson from the SM Higgs boson.

Keywords. Higgs boson; standard model; minimal supersymmetric standard model; SM-like MSSM Higgs boson.

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1. Introduction

The existence of the scalar Higgs boson (H) of the standard model (SM) is still not confirmed experimentally [1,2]. Direct searches for the SM Higgs boson at the LEP II have achieved a 95% CL bound of $m_H > 114.4$ GeV [2]. The fits to all precision data including the results of the direct searches gives upper limit $m_H <$ 189 GeV (95% CL) [3]. It has been argued that if such a Higgs boson exists, it fits more naturally into the minimal supersymmetric standard model (MSSM) than into SM itself [4,5]. Moreover, a Higgs boson with mass ∼115 GeV in the context of the supersymmetry would mesh nicely with the evidence of anomalous magnetic moment of muon [5].

The Higgs sector of the MSSM contains two scalar doublet fields leading to five Higgs particles: two CP-even (h and H^0), a CP-odd (A) and two charged ($H^{\pm}$) Higgs bosons. At tree level, the masses and couplings of the MSSM Higgs bosons are determined by just two free parameters; conventionally chosen as the ratio of vacuum expectation values of each doublet ($\tan\beta = v_2/v_1$) and mass of CP-odd Higgs boson (m_A) [6]. An important prediction of the MSSM at the tree level is the upper bound $m_h \leq m_Z|\cos 2\beta|$. Such a light Higgs particle is essentially ruled out by the searches at LEP II [1]. However, this bound is modified by radiative corrections and is restricted to $m_h < 135$ GeV [7,8].

The MSSM possesses a limit, called decoupling limit that is experimentally almost indistinguishable from the SM [9]. This occurs when the pseudoscalar mass is large (i.e., $m_A \gg m_Z$), then the CP-even (H^0), CP-odd (A^0) and charged ($H^\pm$) Higgs bosons are mass degenerate and the mass of the lightest CP-even Higgs boson (h) approaches its upper bound value for a given $\tan\beta$. In this limit the lightest MSSM Higgs boson (h) and the SM Higgs boson (H) have very similar properties, i.e., in this limit the SM-like MSSM Higgs boson mimics the signature of the SM Higgs boson, and therefore even if a neutral scalar boson is discovered in the near future, the task of discriminating between SM-like MSSM Higgs boson and SM Higgs boson will be quite hard [10].

It is hoped that at least one Higgs boson within the mass range allowed by the MSSM will be discovered at Tevatron and/or LHC [11]. It has been argued that precision measurements of the Higgs sector properties at a linear collider may allow one to discriminate between SM and SM-like MSSM Higgs bosons and further extract or constrain the model parameters [12]. Therefore, it is interesting to explore the possibility of distinguishing between these two particles.

In recent years an increasing amount of work has been dedicated to the physics possibilities of $\mu^+\mu^-$ colliders [13–18]. It has been suggested that a muon collider might prove essential to understand the Higgs sector of a SUSY model by accurately measuring the properties of a light SM-like Higgs boson and to distinguish it from a supersymmetric Higgs boson [5].

The process $e^+e^- \to$ neutral Higgs boson pair is not of much interest due to the smallness of Hee couplings. However, the amplitude for the process $\mu^+\mu^- \to$ neutral Higgs boson pair at the tree level is enhanced by a factor $\sim m_\mu/m_e$. At tree level, in (i) SM and (ii) MSSM, this process occurs via s-channel and t-channel (diagrams shown in figures 1 and 2 respectively). The contribution of one extra s-channel diagram in MSSM and corresponding interference term in $|\text{amplitude}|^2$ may open a possibility of distinguishing the SM-like MSSM Higgs boson from the SM Higgs boson at a muon collider. In view of this, we study the neutral Higgs boson pair production at muon collider. Although, even a single Higgs produced in $\mu^+\mu^-$ fusion will carry a signal of the MSSM mixing angles in the $H\mu^+\mu^-$ couplings, the process considered here presents one more possibility to distinguish the lightest MSSM Higgs boson from the SM Higgs boson. In fact, if it is not possible to tune muon collider energy to the Higgs boson resonance, this procedure may become one of the important Higgs boson production channels at a muon collider.

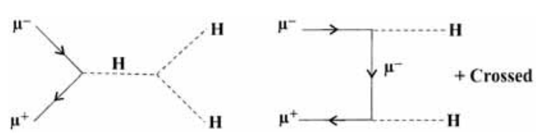

Figure 1. Tree level Feynman diagrams for the process $\mu^+\mu^- \to HH$.

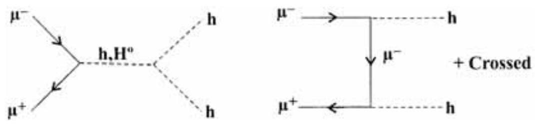

Figure 2. Tree level Feynman diagrams for the process $\mu^+\mu^- \to hh$.

In §2 we calculate the cross-sections for the processes $\mu^+\mu^- \to HH(hh)$. The behavior of cross-sections and the relative percentage deviation are presented in §3. Section 4 contains discussions and conclusions.

2. Calculations

2.1 *The process* $\mu^+\mu^- \to HH$

In the SM at tree level this process proceeds via H-exchange in s-channel and μ-exchange in t- and crossed t-channels (figure 1). The s-channel γ- and Z-exchange are forbidden by CP-invariance [19]. The relevant SM couplings (in unitary gauge) are [20]

$$H\mu^+\mu^- : \quad -\frac{igm_\mu}{2m_W}, \qquad HHH : \quad -\frac{3igm_H^2}{2m_W}.$$

To take into account the running of the couplings with mass scale (we take the weak scale in this case), we introduce [21]

$$G = \frac{g^2}{4\sqrt{2}m_W^2} = \frac{e^2/\sin^2\theta_W}{4\sqrt{2}m_W^2} = \frac{\pi\alpha(m_Z)}{\sqrt{2}\sin^2\theta_W m_W^2}. \tag{1}$$

We evaluate the amplitude following Renard [22] and obtain

$$M_{\rm SM}(\sigma,\bar{\sigma}) = 3\sqrt{2s}Gm_\mu\left[\frac{m_H^2}{s-m_H^2}\delta_{\sigma,\sigma} - \frac{8\sigma m_\mu\beta^2\sin\theta\cos\theta}{3\sqrt{s}((1/\gamma^4)+4\beta^2\sin^2\theta)}\delta_{\sigma,-\sigma}\right], \tag{2}$$

where

$$\beta = \sqrt{1-\frac{4m_{H(h)}^2}{s}}, \quad \gamma = \frac{\sqrt{s}}{2m_{H(h)}}.$$

The differential cross-section is obtained as

$$\frac{{\rm d}\sigma_{\rm SM}}{{\rm d}\cos\theta} = \frac{9G^2m_\mu^2\beta}{64\pi}\left[\left(\frac{m_H^2}{s-m_H^2}\right)^2 + \left(\frac{8m_\mu\beta^2\sin\theta\cos\theta}{3\sqrt{s}\left(1/\gamma^4+4\beta^2\sin^2\theta\right)}\right)^2\right]. \tag{3}$$

The total cross-section is obtained by integrating the above and is found to be

$$\sigma_{\rm SM} = \frac{9G^2 m_\mu^2 \beta}{32\pi}\left[\left(\frac{m_H^2}{s-m_H^2}\right)^2 + \frac{8m_\mu^2\beta^2}{9s}\right.$$
$$\left.\left\{4\gamma^4 + \frac{9}{4\beta^2} + \frac{1}{2\beta\xi}\left(1+\frac{3}{8\gamma^4\beta^2}\right)\log\left(\frac{\xi+2\beta}{\xi-2\beta}\right)\right\}\right], \quad (4)$$

with

$$\xi = \sqrt{\frac{1}{\gamma^4} + 4\beta^2}. \quad (5)$$

2.2 *The process* $\mu^+\mu^- \to hh$

The contributions to the process $\mu^+\mu^- \to hh$ arise due to s-channel h- and H^0-exchange and t- and crossed t-channels μ-exchange (see figure 2). The Bose symmetry forbids the *Zhh*-vertex [23]. Below we summarize the couplings needed for our study [23]:

$$h\mu^+\mu^- : \frac{-igm_\mu}{2m_W}\left(-\frac{\sin\alpha}{\cos\beta}\right), \quad H^0\mu^+\mu^- : \frac{-igm_\mu}{2m_W}\left(\frac{\cos\alpha}{\cos\beta}\right),$$

$$hhh : \frac{-3ig}{2m_W} m_Z^2 \cos 2\alpha \sin(\alpha+\beta),$$

$$H^0hh : \frac{-ig}{2m_W} m_Z^2 \left[2\sin 2\alpha \sin(\alpha+\beta) - \cos 2\alpha \cos(\alpha+\beta)\right].$$

The amplitude for the process is found to be

$$M_{\rm MSSM}(\sigma,\bar\sigma) = -3\sqrt{2s}Gm_\mu\left[\left(\frac{a}{s-m_h^2} - \frac{b}{s-m_{H^0}^2}\right)\delta_{\sigma,\sigma}\right.$$
$$\left. + \frac{8\sigma m_\mu \beta^2}{3\sqrt{s}} \frac{\sin\theta\cos\theta}{(1/\gamma^4 + 4\beta^2\sin^2\theta)}\left(\frac{\sin\alpha}{\cos\beta}\right)^2 \delta_{\sigma,-\sigma}\right], \quad (6)$$

where

$$a = m_Z^2 \frac{\sin\alpha\cos 2\alpha\sin(\alpha+\beta)}{\cos\beta} \quad (7)$$

and

$$b = m_Z^2 \frac{\cos\alpha[2\sin 2\alpha\sin(\alpha+\beta) - \cos 2\alpha\cos(\alpha+\beta)]}{3\cos\beta}. \quad (8)$$

Here α is the mixing angle that rotates the weak CP-even Higgs eigenstates into the mass eigenstates h and H^0 [24].

The differential cross-section is

$$\frac{\mathrm{d}\sigma_{\mathrm{MSSM}}}{\mathrm{d}\cos\theta} = \frac{9G^2 m_\mu^2 \beta}{64\pi}\left[\left(\frac{a}{s-m_h^2} - \frac{b}{s-m_{H^0}^2}\right)^2 + \left(\frac{\sin\alpha}{\cos\beta}\right)^4 \times \left(\frac{8m_\mu \beta^2 \sin\theta\cos\theta}{3\sqrt{s}(1/\gamma^4 + 4\beta^2\sin^2\theta)}\right)^2\right], \tag{9}$$

and the total cross-section is found to be

$$\sigma_{\mathrm{MSSM}} = \frac{9G^2 m_\mu^2 \beta}{32\pi}\left[\left(\frac{a}{s-m_H^2} - \frac{b}{s-m_{H^0}^2}\right)^2 + \left(\frac{\sin\alpha}{\cos\beta}\right)^4 \frac{8m_\mu^2\beta^2}{9s} \times \left\{4\gamma^4 + \frac{9}{4\beta^2} + \frac{1}{2\beta\xi}\left(1 + \frac{3}{8\gamma^4\beta^2}\right)\log\left(\frac{\xi+2\beta}{\xi-2\beta}\right)\right\}\right]. \tag{10}$$

3. Behavior of cross-sections and relative percentage deviation

For numerical evaluation, we note that the limit from direct searches at LEP II in the MSSM context excludes $m_h < 91.0$ GeV and $m_A < 91.9$ GeV at 95% CL [1] and m_h is theoretically restricted to be < 135 GeV with the inclusion of radiative corrections. For SM Higgs boson the current experimental bound is $m_H > 114.4$ GeV. Therefore we take the Higgs boson mass ($m_{\mathrm{Higgs}} = m_{H(h)}$) ranging from 115 to 135 GeV.

In figure 3 we plot the total cross-section as a function of Higgs boson mass for the production of Higgs boson pair in the SM (solid line) and in the MSSM (dashed and dotted lines), for $\tan\beta = 5$ to 50 and $m_A = 100$ to 300 GeV. We note that in the case of SM Higgs boson pair production the cross-section increases with the increase in the Higgs boson mass. On the other hand, for the SM-like MSSM Higgs boson pair production, the cross-section decreases with the increase in the Higgs boson mass. Furthermore, for a given Higgs boson mass the cross-section depends on the choice of $\tan\beta$ and m_A.

The cross-sections presented in figure 3 are calculated without any kinematical cuts. However, at a muon collider there will certainly be very little coverage/efficiency in the forward direction. In view of this the cross-sections for $|\cos\theta| \le 1$, 0.9 and 0.8 are displayed in table 1.

In order to quantify the changes that occur for the SM-like MSSM Higgs boson pair production in comparison to SM Higgs boson pair production we define the relative percentage deviation in the cross-section by the relation

$$\Delta\sigma\% = \left(\frac{\sigma_{\mathrm{MSSM}} - \sigma_{\mathrm{SM}}}{\sigma_{\mathrm{SM}}}\right) \times 100\%. \tag{11}$$

It is a measure of deviation from the SM predictions for the production of neutral Higgs boson pairs in the $\mu^+\mu^-$ annihilation.

The behavior of $\Delta\sigma\%$ with Higgs boson mass for $\tan\beta = 5$ (solid line), 25 (dashed line) and 50 (dotted line) and $m_A = 100$ and 300 GeV at fixed $\sqrt{s} = 500$ GeV is shown in figure 4. The value of $\Delta\sigma\%$ depends on m_A and tan β for a given Higgs

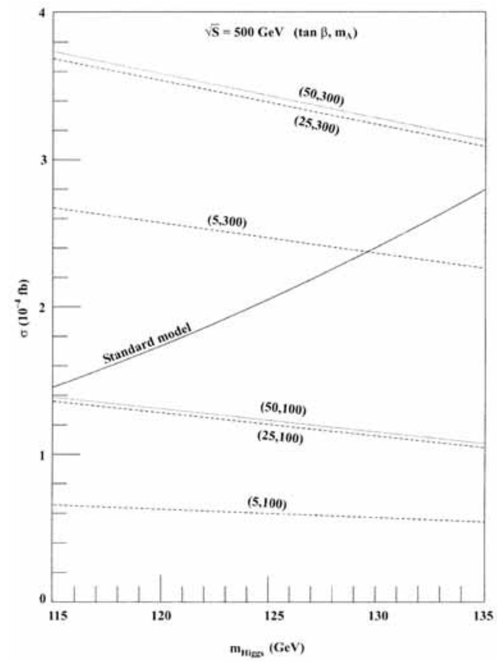

Figure 3. Variation of total cross-section (σ) with Higgs boson mass (m_{Higgs}) for different values of $\tan\beta$ and m_A at fixed $\sqrt{s} = 500$ GeV. The solid line is for SM. The dashed and dotted lines are for MSSM.

Table 1. The behavior of pair production cross-section with Higgs boson mass at $\sqrt{s} = 500$ GeV for $|\cos\theta| \leq 1$, 0.9 and 0.8.

m_{Higgs}	SM cross section (10^{-4} fb)			MSSM cross-section (10^{-5} fb) ($m_A = 100$ GeV and $\tan\beta = 5$)		
(GeV)	$\lvert\cos\theta\rvert \leq 1$	$\lvert\cos\theta\rvert \leq 0.9$	$\lvert\cos\theta\rvert \leq 0.8$	$\lvert\cos\theta\rvert \leq 1$	$\lvert\cos\theta\rvert \leq 0.9$	$\lvert\cos\theta\rvert \leq 0.8$
115	1.456	1.309	1.162	6.516	5.858	5.200
120	1.722	1.549	1.377	6.179	5.555	4.931
125	2.022	1.819	1.617	5.852	5.260	4.690
130	2.358	2.122	1.886	5.534	4.975	4.416
135	2.733	2.459	2.186	5.207	4.681	4.160

boson mass. It is found that for $m_A = 100$ GeV, the $\Delta\sigma\%$ is negative and the magnitude increases with increase in Higgs boson mass. For $m_A = 300$ GeV, we note that $\Delta\sigma\%$ is positive at $m_{\text{Higgs}} = 115$ GeV and the magnitude decreases with increasing Higgs boson mass. The $\Delta\sigma\%$ depends significantly on the values of m_{Higgs}, $\tan\beta$ and m_A.

The variation of $\Delta\sigma\%$ as a function of $\tan\beta$ is displayed in figure 5 for $m_A = 100$, 200 and 300 GeV and $m_{\text{Higgs}} = 115$ (solid line) and 135 GeV (dashed line) at fixed

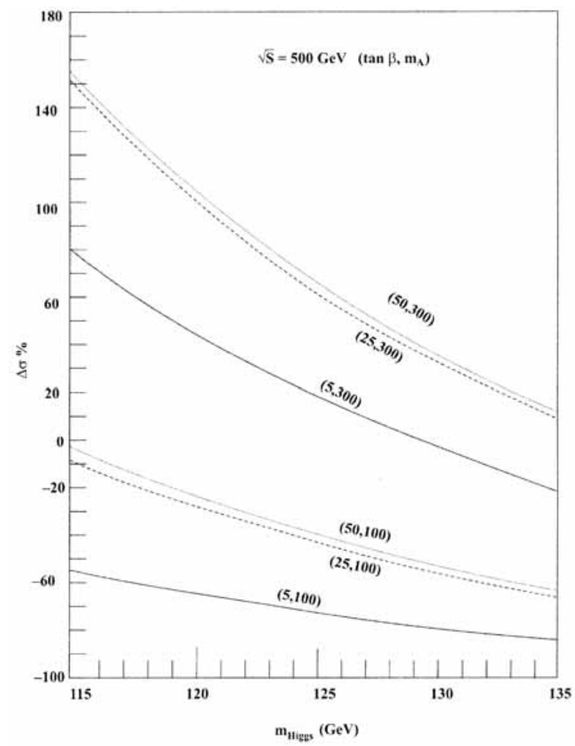

Figure 4. Behavior of $\Delta\sigma\%$ with Higgs boson mass ($m_{\rm Higgs}$) for different values of $\tan\beta$ and m_A (in GeV) at fixed $\sqrt{s} = 500$ GeV. The solid lines are for $\tan\beta = 5$, dashed lines are for $\tan\beta = 25$ and dotted lines are for $\tan\beta = 50$.

$\sqrt{s} = 500$ GeV. It demonstrates the dependence on choice of $m_{\rm Higgs}$ and m_A for a given $\tan\beta$. Further, we note that for a given set of $\sqrt{s}$, m_A and $m_{\rm Higgs}$ the variation in $\Delta\sigma\%$ is more prominent in lower $\tan\beta$ region than in higher $\tan\beta$ region.

4. Conclusions and discussion

We have considered the pair production of the SM Higgs bosons and the SM-like MSSM Higgs bosons in $\mu^+\mu^-$ collisions and examined the production cross-section (σ) and relative percentage deviation ($\Delta\sigma\%$) for various values of $m_{\rm Higgs}$ and MSSM parameters $\tan\beta$ and m_A. Our conclusions are:

(i) At fixed $\sqrt{s} = 500$ GeV, the total cross-section increases with the increase in Higgs boson mass in the case of SM Higgs boson pair production. However, for SM-like MSSM Higgs boson pair production, the cross-section decreases with the increase of Higgs boson mass.

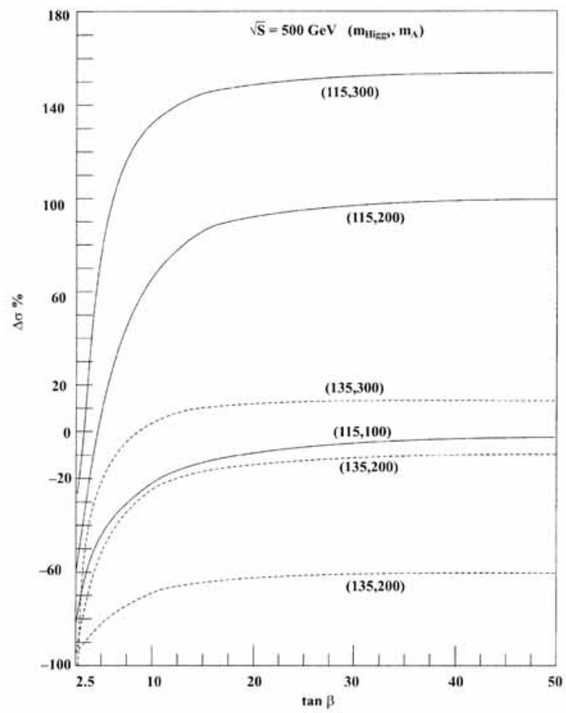

Figure 5. Behavior of $\Delta\sigma\%$ as a function of $\tan\beta$ for different values of m_{Higgs} and m_A at fixed $\sqrt{s} = 500$ GeV. The solid lines are for $m_{\text{Higgs}} = 115$ GeV, dashed lines are $m_{\text{Higgs}} = 135$ GeV.

(ii) We have studied the behavior of relative percentage deviation in cross-section with m_{Higgs}, $\tan\beta$ and m_A and observe the following:

(a) At $\sqrt{s} = 500$ GeV and $m_A = 100$ GeV ($\tan\beta = 5$ to 50), $\Delta\sigma\%$ is negative and its magnitude increases with the increase in Higgs boson mass.

(b) At $\sqrt{s} = 500$ GeV and $m_A = 300$ GeV ($\tan\beta = 5$ to 50), $\Delta\sigma\%$ is positive (for $m_{\text{Higgs}} = 115$ GeV) and decreases with increasing Higgs boson mass. It approaches zero (e.g., at $\tan\beta = 5$ and $m_{\text{Higgs}} = 130$ GeV) and then becomes negative.

(c) For fixed $\sqrt{s}$, m_A and Higgs boson mass the variations in $\Delta\sigma\%$ are more prominent in low $\tan\beta$ region (e.g., $\Delta\sigma\% = -80.05\%$ and -25.36% for $\tan\beta = 2.5$ and 10 respectively at $\sqrt{s} = 500$ GeV, $m_A = 100$ GeV and $m_{\text{Higgs}} = 115$ GeV) than in large $\tan\beta$ region (e.g., $\Delta\sigma\% = -05.21\%$ and -03.06% for $\tan\beta = 30$ and 50 respectively at $\sqrt{s} = 500$ GeV, $m_A = 100$ GeV and $m_{\text{Higgs}} = 115$ GeV).

(iii) The observed large deviation in total cross-section for different choices of Higgs boson masses indicates that the measurements of the cross-section could possibly distinguish the SM-like MSSM Higgs boson from the SM Higgs boson.

(iv) For a given Higgs boson mass $\Delta\sigma\%$ depends on the parameters $\tan\beta$ and m_A, and as such these measurements may provide some information about $\tan\beta$ and m_A.

In arriving at the above conclusions we have considered the SM Higgs boson pair production and SM-like MSSM Higgs boson production at tree level. However, these processes also occur at loop level. The process $\mu^+\mu^- \rightarrow HH$ at one loop level is mediated only by W and Z loops, while in MSSM, additional contributions to the corresponding process $\mu^+\mu^- \rightarrow hh$ will originate from chargino, neutralino, s-muon, s-neutrino loops as well as loops built up by the associated A and $H^\pm$ bosons. In this regard we note that the influence of supersymmetric particles on the precision electroweak measurements is generally negligible [25], since radiative corrections mediated by SUSY particles are suppressed by a factor of m_Z^2/m_S^2, where m_S is the scale characterizing the scale of the SUSY particles. For example, loop-induced pair production of SM Higgs boson and SM-like MSSM Higgs boson in e^+e^- collisions has been considered in [19] and it was found that for hh production, contribution of SUSY loops are in general rather small: in fact at high energies the SUSY boxes practically do not contribute; but at low energies, and specially below the decoupling limit, the SUSY contribution can be of the order of $\sim$10%, and maximum contribution of SUSY loops (for some parameter space) was found to be $\sim$−15% [19]. In the decoupling limit, the SUSY contributions are at the most of the order of a few per cent and the cross-sections are therefore of the same order as in the SM and deviation from the SM prediction is small at one loop level [19]. As such we expect that the inclusion of radiative corrections will not substantially change our conclusions.

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