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Implications of the upper bound on $h \to \mu^+\mu^-$ on the baryon asymmetry of the Universe

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The upper bounds from the ATLAS and CMS experiments on the decay rate of the Higgs boson to two muons provide the strongest constraint on an imaginary part of the muon Yukawa coupling. This bound is more than an order of magnitude stronger than bounds from $\mathcal{CP}$-violating observables, specifically the electric dipole moment of the electron. It excludes a scenario – which had been viable prior to these measurements – that a complex muon Yukawa coupling is the dominant source of the baryon asymmetry. Even with this bound, the muon source can still contribute $\mathcal{O}(16\%)$ of the asymmetry.

I. INTRODUCTION

Following the discovery of the Higgs boson by the ATLAS and CMS experiments [1, 2], an intensive program to study its properties has been pursued. This experimental program is relevant to many open questions in particle physics and in cosmology [3]. One of the most intriguing questions relates to the fact that the Kobayashi-Maskawa phase of the Standard Model (SM) fails to account for the baryon asymmetry of the Universe by many orders of magnitude [4, 5], and thus additional sources of $\mathcal{CP}$ violation must exist in Nature. In this work we show that searches at the LHC for the Higgs decay to two muons, $h \to \mu^+\mu^-$, give a definite answer to the question of whether a complex Yukawa coupling of the muon can provide the $\mathcal{CP}$ violation necessary for baryogenesis.

The possibility that the baryon asymmetry is generated by electroweak baryogenesis requires the SM to be extended in two ways: The scalar potential has to be modified in such a way that the electroweak phase transition is strongly first order, and new sources of $\mathcal{CP}$ violation must be introduced. The former aspect has been intensively discussed in the literature (for reviews see e.g. Refs. [6, 7]), and we do not elaborate on it here. For the latter, we ask whether the *dominant* source of $\mathcal{CP}$ violation can be a complex Yukawa coupling of the muon, coming from a dimension-six term in the SM effective field theory (SMEFT). Thus, similar to the studies in Ref. [8, 9], we assume the following:

- Whatever the extension of the SM that modifies the nature of the electroweak phase transition, it does not affect in a significant way the other aspects of the baryon asymmetry, such as the rates of $\mathcal{CP}$-conserving and $\mathcal{CP}$-violating fermion processes in the transport equations;
- The new degrees of freedom that are relevant to $\mathcal{CP}$ violation are heavy enough that their effects on electroweak baryogenesis and on the $h \to \mu^+\mu^-$ decay can be represented by the SMEFT.

The plan of this paper is as follows. In Section II we introduce our theoretical framework and notations, and derive the effective muon Yukawa coupling in this framework. The contributions of the complex Yukawa coupling to the rate of Higgs decay to two muons, $\Gamma(h \to \mu^+\mu^-)$, to the electric dipole moment (EDM) of the electron, d_e, and to the baryon asymmetry of the Universe, Y_B, are discussed in Sections III, IV and V, respectively. In Section VI we analyze the interplay between these three observables, and reach our conclusions.

II. THE FRAMEWORK

Within the SMEFT with terms up to dimension (dim) six, the muon mass and the muon Yukawa coupling arise from the following terms:

$$\mathcal{L}^\mu_{\rm Yuk} = y_\mu \overline{L_\mu}\mu_R H + \frac{1}{\Lambda^2}(X^\mu_R + iX^\mu_I)|H|^2\overline{L_\mu}\mu_R H + {\rm h.c.}, \tag{1}$$

where $L_\mu = (\nu_\mu\ \mu^-_L)^T$ is the left-handed muon doublet, μ_R is the right-handed muon singlet, $H = (0\ \frac{v+h}{\sqrt{2}})^T$ is the Higgs doublet, and Λ is the scale of new physics. The couplings y_μ, X^μ_R and X^μ_I are dimensionless and, without loss of generality, we take y_μ to be real. From here on, we omit the flavor index μ from y, X_R, X_I.

We are interested in obtaining the muon mass m_μ and $h\mu\mu$ Yukawa coupling λ_μ:

$$\mathcal{L}^\mu \supset m_\mu \overline{\mu_L}\mu_R + \frac{\lambda_\mu}{\sqrt{2}}\overline{\mu_L}\mu_R h + {\rm h.c.}\,. \tag{2}$$

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It is convenient to define

$$T_R \equiv \frac{v^2}{2\Lambda^2}\frac{X_R}{y}, \quad T_I \equiv \frac{v^2}{2\Lambda^2}\frac{X_I}{y}. \tag{3}$$

We obtain:

$$m_\mu = \frac{yv}{\sqrt{2}}\left(1+T_R+iT_I\right), \quad \lambda_\mu = \frac{y}{\sqrt{2}}\left(1+3T_R+3iT_I\right). \tag{4}$$

Transforming to a basis where the muon mass is real, we have

$$m_\mu = \frac{yv}{\sqrt{2}}\sqrt{(1+T_R)^2+T_I^2}\,, \tag{5}$$

$$\lambda_\mu = \frac{y}{\sqrt{2}}\frac{1+4T_R+3T_R^2+3T_I^2+2iT_I}{\sqrt{(1+T_R)^2+T_I^2}}\,. \tag{6}$$

In this basis,

$$\mathcal{I}m(\lambda_\mu) = \frac{v}{m_\mu}y^2 T_I. \tag{7}$$

An equivalent statement, valid in any basis, is that $\mathcal{I}m(m_\mu^*\lambda_\mu) = vy^2T_I$.

As we will see below, the various constraints allow $|T_{R,I}| \not\ll 1$, and thus the terms of $\mathcal{O}(T_{R,I}^2)$ can be non-negligible. These terms are of order v^4/Λ^4, yet taking them into consideration and not the dim-8 terms of the SMEFT is a consistent procedure. This is due to the smallness of the dim-4 Yukawa coupling of the muon: at order v^4/Λ^4, the contribution from the product of the dim-4 and dim-8 terms will be suppressed by y_μ compared to the contribution from the dim-6 term squared.

The modification of the SM relation between the Yukawa coupling and the mass, $\lambda_\mu \neq m_\mu/v$, and, in particular, the generation of an imaginary part, $\mathcal{I}m(\lambda_\mu/m_\mu) \neq 0$, entail interesting consequences:

- The decay rate of the Higgs boson to two muons, $\Gamma(h\to\mu^+\mu^-)$, is modified;
- The muon Yukawa coupling contributes to the EDM of the electron d_e;
- The muon Yukawa coupling contributes to the baryon asymmetry Y_B.

These observables will be discussed in the next three sections.

III. THE $h \to \mu^+\mu^-$ DECAY

The ATLAS and CMS experiments report their measurements of $pp \to h \to f\bar{f}$ via

$$\mu_{f\bar{f}} \equiv \frac{\sigma_i(pp\to h)\mathrm{BR}(h\to f\bar{f})}{[\sigma_i(pp\to h)\mathrm{BR}(h\to f\bar{f})]_{\mathrm{SM}}}, \tag{8}$$

where $\sigma_i(pp \to h)$ denotes the cross section of a specific Higgs production mode i, such as gluon-gluon fusion (ggF) or vector-boson fusion (VBF). If the contribution of the dim-6 terms modifies neither the Higgs production cross section, nor the total Higgs width in a significant way, as is the case for $\mathcal{O}(1)$ (or smaller) modification of λ_μ, then Eq. (8) simplifies to

$$\mu_{\mu^+\mu^-} = \frac{\Gamma(h\to\mu^+\mu^-)}{[\Gamma(h\to\mu^+\mu^-)]_{\mathrm{SM}}}. \tag{9}$$

Using Eq. (4), we obtain

$$\mu_{\mu^+\mu^-} = \frac{(1+3T_R)^2+9T_I^2}{(1+T_R)^2+T_I^2}. \tag{10}$$

Taking into account that $y_f^{\mathrm{SM}} = \sqrt{2}m_f/v$, we can write

$$1 = (y/y^{\mathrm{SM}})^2\left[(1+T_R)^2+T_I^2\right], \tag{11}$$

$$\mu_{\mu^+\mu^-} = (y/y^{\mathrm{SM}})^2\left[(1+3T_R)^2+9T_I^2\right]. \tag{12}$$

An upper bound $\mu_{\mu^+\mu^-} \leq \mu^{\max}$, yields then the following bounds on $|T_I|$, on $y|T_I|$, and on $y^2|T_I|$,

$$|T_I| \leq \frac{2\sqrt{\mu^{\max}}}{9-\mu^{\max}}\,, \tag{13}$$

$$(y/y^{\mathrm{SM}})|T_I| \leq \min\left[\frac{\sqrt{\mu^{\max}}}{3}, 1\right], \tag{14}$$

$$(y/y^{\mathrm{SM}})^2|T_I| \leq \frac{\sqrt{\mu^{\max}}}{2}\,. \tag{15}$$

We note that bounds of the form (13) – (15) apply to any fermion, as long as the Higgs production rate and total width are not significantly modified. Such a case will be discussed in Ref. [10].

In fact, at present there are only upper bounds on $\mu_{\mu^+\mu^-}$ by CMS combining the $\sqrt{s} = 7$ and 8 TeV data sets with 35.9 fb^{-1} at 13 TeV [11] and by ATLAS with the full data set of 139 fb^{-1} at 13 TeV [12]:

$$\mu_{\mu^+\mu^-}^{\mathrm{CMS}} < 2.9 \text{ at } 95\% \text{ C.L.}\,, \tag{16}$$

$$\mu_{\mu^+\mu^-}^{\mathrm{ATLAS}} < 1.7 \text{ at } 95\% \text{ C.L.}\,. \tag{17}$$

A bound on the signal strength of Eq. (10) translates into an allowed region within a circle in the $T_R - T_I$ plane, centered around $(T_R, T_I) = \left(-1+\frac{6}{9-\mu}, 0\right)$ with a radius of $\frac{2\sqrt{\mu}}{9-\mu}$. The bound from Eq. (17) is plotted in Fig. 1. It provides the allowed range for T_R:

$$-0.5 \lesssim T_R \lesssim 0.2, \tag{18}$$

and the following upper bounds on $\mathcal{CP}$ violation from the complex Yukawa coupling of the muon:

$$|T_I| \leq 0.36\,, \tag{19}$$

$$(y/y^{\mathrm{SM}})|T_I| \lesssim 0.44\,, \tag{20}$$

$$(y/y^{\mathrm{SM}})^2|T_I| \lesssim 0.65\,. \tag{21}$$

IV. THE EDM OF THE ELECTRON

The dimension-six term in the Lagrangian contributes to the electric dipole moment of the electron [13]:

$$\frac{d_e^{(\mu)}}{e} \simeq -4Q_\mu^2 \frac{e^2}{(16\pi^2)^2} \frac{m_e m_\mu}{m_h^2} \frac{v}{\Lambda^2} X_I^\mu \left(\frac{\pi^2}{3} + \ln^2 \frac{m_\mu^2}{m_h^2}\right), \quad (22)$$

where $Q_\mu = -1$ is the electromagnetic charge of the muon, and the equation is written in the basis where m_μ is real. Eq. (22) translates into the following numerical estimate:

$$d_e^{(\mu)} \simeq -1.0 \times 10^{-30} \, (y/y^{\rm SM})^2 T_I \; e \text{ cm}. \quad (23)$$

Given the upper bound of Eq. (21), we obtain an upper bound on the contribution to d_e from a complex muon Yukawa coupling:

$$|d_e^{(\mu)}| \leq 6.5 \times 10^{-31} \; e \text{ cm}. \quad (24)$$

The ACME collaboration provided an upper bound on $|d_e|$ at 90% CL [14]:

$$|d_e^{\rm max}| = 1.1 \times 10^{-29} \; e \text{ cm}. \quad (25)$$

We learn that the bound on a $\mathcal{CP}$ violating muon Yukawa coupling from the measurement of the $\mathcal{CP}$ conserving observable $\mu_{\mu^+\mu^-}$ is much stronger than the bound from the $\mathcal{CP}$ violating observable d_e. To compete with the LHC current bound, the d_e sensitivity has to improve by a factor of $\mathcal{O}(15)$. For a comparison of EDM and LHC constraints on real and imaginary parts of Yukawa couplings of third-generation fermions see also Refs. [10, 15].

V. THE BARYON ASYMMETRY

We calculate the baryon asymmetry using the Closed Time Path formalism, similar to Ref. [9]. The details of our calculation and the innovations it introduces will be described in a more detailed report [10], where we will also present the contributions from other modified Yukawa couplings and their combinations.

The process whereby the baryon asymmetry is generated by the complex Yukawa coupling of the muon can be summarized as follows. During the electroweak phase transition, the Yukawa interaction of the muon across the expanding wall produces a $\mathcal{CP}$ asymmetry. While relaxation processes wash out the asymmetry in the broken phase, part of the asymmetry diffuses into the symmetric phase. For the muon the diffusion is more efficient than for quarks, which is helpful in overcoming the suppression of the asymmetry due to the smallness of the muon Yukawa coupling. Weak sphaleron interactions act on the net chiral density that has diffused into the symmetric phase, while strong sphaleron interactions, which would wash out asymmetries in the quark sector, do not act on the lepton sector. Finally, the bubble wall catches up with the region of net asymmetry, and freezes in the resulting baryon asymmetry in the broken phase.

The baryon asymmetry is proportional to the muon source $Y_B \propto S_\mu$, with $S_\mu \propto y^2 T_I$. The T_R dependence is mild and enters only at second order in $T_{R,I}$. Explicitly, the relaxation rate Γ_M and the Yukawa rate Γ_Y are modified in the presence of the dimension-six term as follows:

$$\Gamma_M \to \left[\frac{(1+r_{N0}^2 T_R)^2 + (r_{N0}^2 T_I)^2}{(1+T_R)^2 + T_I^2}\right] \Gamma_M \, , \quad (26)$$

$$\Gamma_Y \to \left[\frac{(1+3r_{N0}^2 T_R)^2 + (3r_{N0}^2 T_I)^2}{(1+T_R)^2 + T_I^2}\right] \Gamma_Y . \quad (27)$$

Here $r_{N0} \equiv v(T=T_N)/v(T=0)$, where T_N is the nucleation temperature. For $T_R = 0$, our calculation yields

$$Y_B^{(\mu)} = -2.1 \times 10^{-11} (y/y^{\rm SM})^2 T_I . \quad (28)$$

Given the upper bound of Eq. (21), we obtain an upper bound on the contribution to Y_B from a complex muon Yukawa coupling:

$$|Y_B^{(\mu)}| \leq 1.4 \times 10^{-11}. \quad (29)$$

The observed value of the baryon asymmetry was measured by PLANCK [16, 17] as $\Omega_b h^2 = 0.02226(23)$ or, equivalently,

$$Y_B^{\rm obs} = (8.59 \pm 0.08) \times 10^{-11}. \quad (30)$$

Given the mild dependence on T_R, we conclude that a complex Yukawa coupling of the muon cannot account for the baryon asymmetry of the Universe. Yet, its contribution to the overall asymmetry created by different $\mathcal{CP}$-violating sources, could be non-negligible, of order 16%.

Due to the same scaling of d_e and Y_B as $(y/y^{\rm SM})^2 T_I$, see Eqs. (23) and (28), we obtain the following relation between the muon contributions to d_e and to Y_B:

$$\frac{Y_B^{(\mu)}}{8.6 \times 10^{-11}} = \frac{d_e^{(\mu)}}{4.1 \times 10^{-30} \; e \text{ cm}}. \quad (31)$$

This relation shows that the current bound on d_e could not, by itself, exclude a scenario where a complex muon Yukawa coupling accounts for the baryon asymmetry.

VI. DISCUSSION

Within the SM as a low-energy effective field theory, the leading modification to the SM Yukawa couplings and to their relation to the corresponding fermion masses comes from dimension-six terms. The contributions from these terms to the Yukawa couplings are suppressed by the ratio of scales, v^2/Λ^2. However, for small dimension-four Yukawa couplings, such contributions can be significant and even dominant.

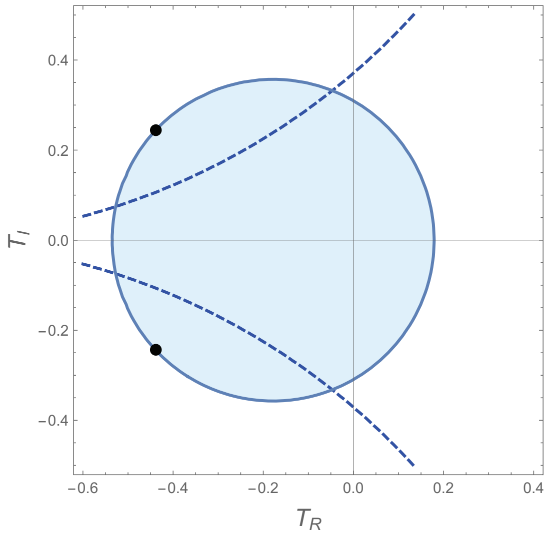

FIG. 1. The blue region within the circle is the allowed region for $\mu_{\mu^+\mu^-} \leq 1.7$ [12]. The two points on the circle correspond to maximal values of $|Y_B^{(\mu)}|_{\max} = 1.4 \times 10^{-11}$ and of $|d_e^{(\mu)}|_{\max} = 6.5 \times 10^{-31}$ e cm. The dashed lines correspond to $|Y_B^{(\mu)}|_{\max}/2$ and $|d_e^{(\mu)}|_{\max}/2$.

In the case of the muon, which is the focus of this study, $y_\mu^{\rm SM} \sim 6 \times 10^{-4}$, the contribution to λ_μ from the dimension-six term can be comparable or dominant for $\Lambda \lesssim 10$ TeV. If the dimension-six term dominates over the dimension-four, $(T_R^2 + T_I^2) \gg 1$, then $\mu_{\mu^+\mu^-} \simeq 9$. The fact that the experimental upper bound is well below this value leads to a first important conclusion:

- The effective muon Yukawa coupling is not dominated by contributions from non-renormalizable terms.

The presence of dimension-six terms opens the door to a complex effective muon Yukawa coupling. Two $\mathcal{CP}$-violating observables can reveal the existence of this new source of $\mathcal{CP}$ violation: The electric dipole moment of the electron and the baryon asymmetry of the Universe. Examining Eqs. (23) and (28) we learn that, interestingly, for $y \sim y^{\rm SM}$, the baryon asymmetry could have been generated by λ_μ as the dominant $\mathcal{CP}$ violating source, while the d_e bound is respected.

It is surprising then that the scenario of a complex muon Yukawa coupling generating the baryon asymmetry is unambiguously excluded by a measurement of a $\mathcal{CP}$-conserving observable, the Higgs decay rate into two muons, as can be seen by examining Eqs. (20) and (28). The strong upper bound on $\mu_{\mu^+\mu^-}$ leads to a second important conclusion:

- The baryon asymmetry is not dominated by a complex muon Yukawa coupling.

Note that the modification of $\mu_{\mu^+\mu^-}$ depends quadratically on the $\mathcal{CP}$ violating parameter, $[\mathcal{I}m(\lambda_\mu)]^2 \lesssim 10^{-6}$. The fact that the leading constraint on this parameter comes from the ATLAS and CMS measurements shows the power of these experiments to probe very rare processes.

Yet, the muon contribution to the baryon asymmetry is not necessarily negligible. We are led to a third conclusion:

- A complex λ_μ could account for as much as 16% of Y_B, given current collider constraints.

If, in the future, $\mu_{\mu^+\mu^-}$ will be measured to be very close to 1, the bounds on the maximal contribution to the $\mathcal{CP}$ violating observables will become stronger, but not by much: $|d_e^{(\mu)}/d_e^{\max}| \lesssim 0.05$ and $|Y_B^{(\mu)}/Y_B^{\rm obs}| \lesssim 0.12$. It may happen, however, that experiments will establish $\mu_{\mu^+\mu^-} < 1$. In this case, while the bound on $|Y_B^{(\mu)}|$ will become even stronger, it will make it plausible that also the third generation Yukawa couplings differ from their SM values and may carry $\mathcal{CP}$ violating phases which play a role in electroweak baryogenesis.

We conclude that the Higgs program at the LHC experiments leads to progress not only on open questions in particle physics, such as whether various Yukawa couplings are dominated by higher-dimensional terms, but also in particle cosmology, such as whether the baryon asymmetry is generated by complex Yukawa couplings. Specifically for the muon, the answers provided to both questions are negative. For other fermions, the answer to the latter question might be in the affirmative [9], as will be discussed in [10].

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