A LETTERS JOURNAL EXPLORING THE FRONTIERS OF PHYSICS

Società Italiana di Fisica

edp sciences IOP Institute of Physics

LETTER

Flavorful vector-like leptons and the lepton-flavor-violating decays $Z \to l_i l_j$

To cite this article: Dong Wan Li *et al* 2022 *EPL* **137** 34003

A LETTERS JOURNAL EXPLORING THE FRONTIERS OF PHYSICS

February 2022

EPL, **137** (2022) 34003
doi: 10.1209/0295-5075/ac5360

www.epljournal.org

Flavorful vector-like leptons and the lepton-flavor-violating decays $Z \rightarrow l_i l_j$

DONG WAN LI[(a)], CHONG XING YUE[(b)], YUE QI WANG[(c)] and XIAO CHEN SUN[(d)]

Department of Physics, Liaoning Normal University - Dalian 116029, PRC

received 5 November 2021; accepted in final form 9 February 2022
published online 22 April 2022

Abstract – The singlet and doublet VLS models are one kind of interesting new physics scenarios, which predict the existence of the $SU(2)_L$ singlet and doublet vector-like leptons (VLLs), respectively. Taking into account the constraints on these VLS models, we investigate their contributions to the LFV decays $Z \rightarrow l_i l_j$ $(i \neq j)$. Our numerical results show that, for the singlet VLS model, the values of the branching ratios $Br(Z \rightarrow \tau e)$ and $Br(Z \rightarrow \tau\mu)$ can be larger than 5×10^{-9} in a wide range of the parameter space, which might be detected by CEPC/FCC-ee in the near future.

Introduction. – The standard model (SM) has achieved great success in describing the elementary particles as well as the fundamental interactions. However, the SM cannot resolve some theoretical and experimental issues. For example, it cannot explain the origin of hierarchical structure for masses and mixings of elementary fermions in a peculiar pattern. It is widely considered to be a low-energy effective theory and new physics beyond the SM (BSM) should exist. Asymptotic safety [1] provides a new idea for model building which keeps both fundamental and predictive at the highest energies [2]. Search for asymptotically safe extensions of the SM is very interesting.

In order to make extensions of the SM asymptotically safe, new matter fields and Yukawa couplings should be introduced, which are essential to generate weakly interacting UV fixed points [2]. Such specific kind of models predicts the existence of vector-like fermions as well as additional scalars. These new particles might generate significant contributions to low-energy observables, explain the anomaly of the lepton anomalous magnetic moment a_l, and produce observable signals in current or future high-energy collider experiments [3–7].

The electroweak gauge boson Z can be copiously produced at high-energy collider experiments. Observables related to Z have been precisely measured [8] and will be further measured with higher accuracy in the future collider experiments, such as the international linear collider (ILC) [9], the circular electron-position collider (CEPC) [10] and the future circular collider (FCC-ee) [11]. The excellent measurement of the decay widths and branching ratios of the gauge boson Z will provide a very suitable tool for us to further test the SM and probe the new physics effects.

New physics models inspired by asymptotic safety contain vector-like leptons (VLLs) and new scalars [3,4,6], which are called the VLS models in this paper. After spontaneous symmetry breaking, VLLs and new scalars mix with the SM leptons and Higgs boson, respectively, which would modify the Z, W and Higgs boson couplings. If the new Yukawa couplings between VLLs and leptons have non-vanishing flavor off-diagonal couplings, then the VLS models would contribute to the lepton-flavor-violating (LFV) processes. Thus, the effects of the VLS models can be probed via electroweak precision tests, the LFV decay and production processes. The LFV Z decays $Z \rightarrow l_i l_j (i \neq j)$ are one kind of processes, which are accessible at high-energy colliders and have been extensively studied in the literature (for example see [12] and its references). Taking into account the constraints on the VLS models, we will investigate the LFV decays $Z \rightarrow l_i l_j$ in this paper and see whether the contributions of the VLS models to $Z \rightarrow l_i l_j$ can be detected in future e^+e^- collider experiments, such as CEPC and FCC-ee.

The remaining parts of this paper are organized as follows. The couplings of VLLs to other particles and the constraints on the LFV VLL couplings are reviewed in the next section. We calculate in the third section the

(a) E-mail: llddd www@163.com
(b) E-mail: cxyue@lnnu.edu.cn (corresponding author)
(c) E-mail: wyq13889702166@163.com
(d) E-mail: xcsun0315@163.com

contributions of the singlet and doublet VLS models to the LFV decays $Z \to \bar{l}_i l_j$. Our conclusions are given in the fourth section.

The VLL couplings. – In this paper we focus on the singlet and doublet VLS models described for details in refs. [3,4,6], which predict the existence of VLLs $\psi_{L,R}$ being $SU(2)_L$ singlets with hypercharge $Y = -1$ and $SU(2)_L$ doublets with $Y = -\frac{1}{2}$, respectively. Both models also contain complex scalars S_{ij} with two flavor indices $i, j = 1, 2, 3$, which are singlets under the SM in flavor space, number of the VLL generations is taken as 3. Then the new Yukawa Lagrangian for these two models can be respectively written as

$$\begin{aligned}\mathcal{L}_Y^S &= -\kappa_{ij}\bar{L}_i H\psi_{Rj} - \kappa'_{imnj}\bar{E}_i S^\dagger_{mn}\psi_{Lj} \\ &\quad -y_{imnj}\bar{\psi}_{Li}S_{mn}\psi_{Rj} + \text{h.c.}, \qquad (1)\\ \mathcal{L}_Y^D &= -\kappa_{ij}\bar{E}_i H^\dagger\psi_{Lj} - \kappa'_{imnj}\bar{L}_i S_{mn}\psi_{Rj} \\ &\quad -y_{imnj}\bar{\psi}_{Li}S_{mn}\psi_{Rj} + \text{h.c.}, \qquad (2)\end{aligned}$$

where E, L and H denote the SM lepton singlet, doublet, and Higgs doublet, respectively. As stated in ref. [6], imposing $SU(3)$-flavor symmetries on the VLS models would make the new Yukawa couplings κ, κ' and y universal couplings, instead of being tensors. However, the main goal of this paper is to investigate the contributions of the VLS models to the LFV decays $Z \to l_i l_j$. So we will follow ref. [6] and allow for additional flavor off-diagonal Yukawa couplings between VLLs and leptons, *i.e.*, $\kappa_{ij} \neq 0$ and $\kappa'_{ij} \neq 0$ with $i \neq j$. For simplicity, we write them as

$$\alpha_\kappa^{ij} = \frac{1}{(4\pi)^2}\sum_{m=1}^{3}\kappa_{mi}\kappa_{mj}, \quad \alpha_{\kappa'}^{ij} = \frac{1}{(4\pi)^2}\sum_{m,n,l=1}^{3}\kappa'_{mnli}\kappa'_{mnlj},$$
$$\alpha_y = \frac{y^2}{(4\pi)^2}. \qquad (3)$$

For the singlet and doublet VLS models, the leading-order couplings of VLLs with other particles, which are related to our calculations, are given by [6,7]

$$\begin{aligned}\mathcal{L}^S &= -e\bar{\psi}_i\gamma^\mu\psi_i A_\mu + \frac{e}{S_W C_W}\bar{\psi}_i\gamma^\mu\psi_i Z_\mu - \frac{\kappa_{ij}}{\sqrt{2}}\bar{l}_{Li}\psi_{Rj}h \\ &\quad -\kappa'_{ij}\bar{l}_{Ri}S^\dagger\psi_{Lj} + \text{h.c.}, \qquad (4)\\ \mathcal{L}^D &= -e\overline{\psi_i^-}\gamma^\mu\psi_i^- A_\mu + \frac{e}{S_W C_W}\left(S_W^2 - \frac{1}{2}\right)\overline{\psi_i^-}\gamma^\mu\psi_i^- Z_\mu \\ &\quad -\frac{\kappa_{ij}}{\sqrt{2}}\bar{l}_{Ri}\psi^-_{Lj}h - \kappa'_{ij}\bar{l}_{Li}S\psi^-_{Rj} + \text{h.c.}, \qquad (5)\end{aligned}$$

where $S_W = \sin\theta_W$ and $C_W = \cos\theta_W$ with θ_W being the weak mixing angle.

If the new Yukawa couplings between VLLs and leptons have non-vanishing flavor off-diagonal couplings, they can induce some LFV decay processes, such as $l_i \to l_j\gamma$ and $l_i \to l_j l_k l_l$ [6]. Following ref. [13], in the case of $m_i \gg m_j$, the branching ratio $Br\,(l_i \to l_j\gamma)$ induced by the new Yukawa coupling $h\bar{l}_{Li}\psi_{Rj}$ can be written as

Table 1: The upper limits of $Br\,(l_i \to l_j\gamma)$ and the experimental measured values of $Br\,(l_i \to l_j\nu_i\bar{\nu_j})$. All data are taken from ref. [8], except for $Br\,(\tau \to \mu\gamma)$ [14].

Upper limits	$\mu \to e\gamma$	$\tau \to e\gamma$	$\tau \to \mu\gamma$
	4.2×10^{-13}	3.3×10^{-8}	4.2×10^{-8}
Measured values	$\mu \to e\nu_\mu\bar{\nu}_e$	$\tau \to e\nu_\tau\bar{\nu}_e$	$\tau \to \mu\nu_\tau\bar{\nu}_\mu$
	1	17.82%	17.39%

$$Br\,(l_i \to l_j\gamma) = \frac{24\pi^3\alpha_e}{G_F^2}\left(\frac{M_F}{m_i}\right)^2\frac{\left(\alpha_\kappa^{ij}\right)^2}{M_h^2} \times\left|f_1\left(\frac{M_F^2}{M_h^2}\right)\right|^2 Br\,(l_i \to l_j\nu_i\bar{\nu_j}), \quad (6)$$

with

$$f_1(x) = \frac{x-3}{2(x-1)^2} + \frac{\ln x}{(x-1)^3}, \qquad (7)$$

where $Br\,(l_i \to l_j\nu_i\bar{\nu_j})$ denotes the branching ratio of the flavor conservation (FC) decay process $l_i \to l_j\nu_i\bar{\nu_j}$. The VLL mass M_F is assumed to be equal for three generations of VLLs, where their contributions to the oblique T parameter is zero [15]. The values of the fine structure constant α_e, the Fermi coupling constant G_F, the lepton mass m_i and the mass of the SM Higgs boson M_h are taken from ref. [8].

Using the upper limits of the LFV decays $l_i \to l_j\gamma$ and the experimental measured values of $Br\,(l_i \to l_j\nu_i\bar{\nu_j})$, which are shown in table 1, one can easily obtain the constraints on the coupling factor α_κ^{ij}. The calculation formula can be written as

$$(\alpha_\kappa^{ij})^2 \leq \frac{G_F^2 M_h^2}{24\pi^3\alpha_e}\left(\frac{m_i}{M_F}\right)^2\frac{1}{\left|f_1\left(\frac{M_F^2}{M_h^2}\right)\right|^2} \times\frac{Br^{limit}\,(l_i \to l_j\gamma)}{Br^{exp}\,(l_i \to l_j\nu_i\bar{\nu_j})}. \qquad (8)$$

In the following numerical estimation, we will take the maximum value of α_κ^{ij}.

Reference [6] has shown that the mixing between the SM boson h and scalar S can induce chirally enhanced contributions to dipole operators, which are responsible for the lepton anomalous magnetic moment a_l, electric dipole moment d_e and LFV decays $l_i \to l_j\gamma$. Thus, these low-energy observables can generate constraints on the relevant free parameters, such as κ' and the mixing angle β. References [4,6] have shown that the constraints on κ' are much weaker than those on κ. For simplicity, we will take $\kappa_{ij}/\kappa'_{ij} = 10^{-2}$ in our numerical calculation, as done in ref. [7].

Table 2: Current upper limits on the LFV decays $Z \to l_i l_j$ from LEP and LHC experiments and expected sensitivities of CEPC/FCC-ee.

Modes	LEP limits (95%CL)	LHC limits (95% CL)	CEPC/FCC-ee
$Br\,(Z \to \mu e)$	1.7×10^{-6}	7.5×10^{-7}	10^{-8}–10^{-9}
$Br\,(Z \to \tau e)$	9.8×10^{-6}	5.0×10^{-6}	10^{-9}
$Br\,(Z \to \tau \mu)$	1.2×10^{-5}	6.5×10^{-6}	10^{-9}

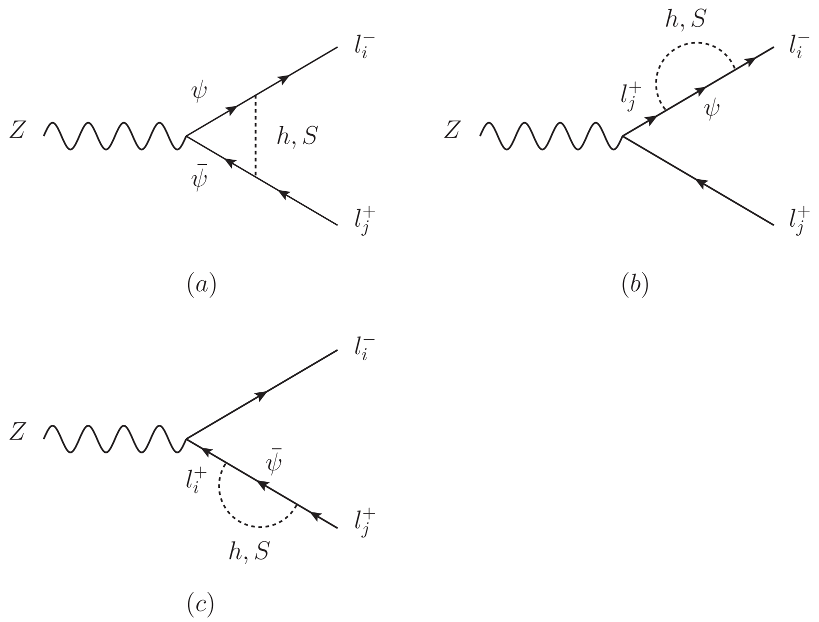


Fig. 1: The one-loop Feynman diagrams for the LFV Z decays $Z \to l_i^- l_j^+$.

The VLS models can also contribute to the LFV three lepton decays $l_i \to l_j \bar{l}_\kappa l_l$ and the μ-to-e conversion process in nuclei. Reference [6] has discussed the constraints on the VLS models from these processes and found that the constraints are comparable with those from the LFV decays $l_i \to l_j\gamma$. Thus, taking into account the constraints from $l_i \to l_j\gamma$, we calculate the branching ratios $Br\,(Z \to l_i l_j)$ induced by the singlet and doublet VLS models in the follwing section.

The VLS models and the LFV Z decays $Z \to l_i l_j$. – It is well known that observables related to the gauge boson Z have been precisely measured and will be further measured with higher accuracy in the future collider experiments. For the LFV Z decays $Z \to l_i l_j$, the upper limits on the branching ratios $Br\,(Z \to l_i l_j)$ have been superseded by searches performed at the LHC [16]. The expected sensitivities of the CEPC/FCC-ee have been estimated in ref. [17], which are at least two orders of magnitude more than the LEP experiments, as shown in table 2. So it is very interesting to study the constributions of new physics to the LFV Z decays $Z \to l_i l_j$.

From discussions given in the second section, we can see that the new Yukawa couplings given in eqs. (4) and (5) can contribute to the LFV Z decays $Z \to l_i l_j$ at the one-loop level [18]. The relevant Feyman diagrams are shown in fig. 1.

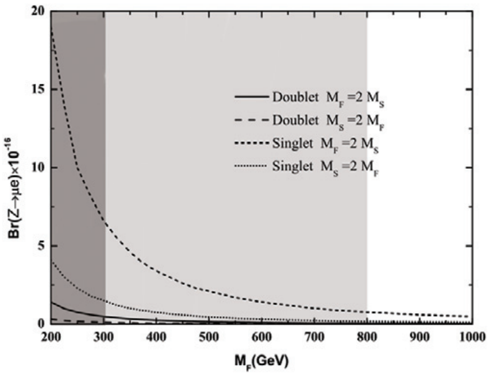
After summing up three diagrams and neglecting the masses of the final state leptons, the branching ratios of the decays $Z \to l_i l_j$ for the singlet and doublet VLS models can be respectively written as

$$Br^S(Z \to l_i l_j) = \frac{\sqrt{2}G_F m_Z^3}{3\pi\Gamma_Z}\Big|\sum_{I=h,S} C_I \alpha_{kI}^{ij}[f_2(M_F, M_I) + f_3(M_F, M_I)]\Big|^2, \quad (9)$$

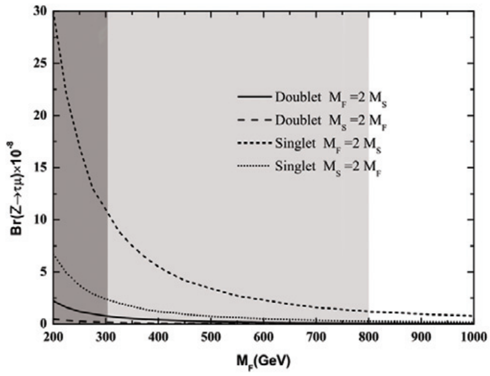
$$Br^D(Z \to l_i l_j) = \frac{\sqrt{2}G_F m_Z^3}{3\pi\Gamma_Z}\Big(-\frac{1}{2} + S_W^2\Big)^2 \times\Big|\sum_{I=h,S} C_I \alpha_{kI}^{ij}[f_2(M_F, M_I) + f_3(M_F, M_I)]\Big|^2, \quad (10)$$

where the functions $f_2(a,b)$ and $f_3(a,b)$ are given by

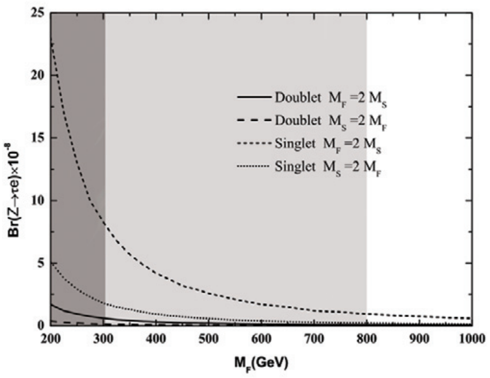
$$f_2(a,b) = \int_0^1 \mathrm{d}x\,(1-x)\ln\left[x m_a^2 + (1-x)\,m_b^2\right], \quad (11)$$



(a)



(b)



(c)

Fig. 2: The branching ratios $Br\,(Z \to l_i l_j)$ as functions of the mass parameter M_F. The dark and light gray areas indicate the excluded regions given by the LHC data for singlet and doublet VLS models, respectively.

$$f_3(a,b) = \int_0^1 \mathrm{d}x \times \int_0^{1-x} \mathrm{d}y \frac{2xym_Z^2 + \left(m_a^2 - m_b^2\right)(1-x-y) - \Delta \ln \Delta}{\Delta}, \tag{12}$$

with $\Delta = -xym_Z^2 + (x+y)\left(m_a^2 - m_b^2\right) + m_b^2$. The factor $C_I = \frac{1}{2}$ and 1 correspond to the SM Higgs boson h and the new scalar S, respectively. The total decay width $\Gamma_Z = 2.4952 \pm 0.0023$ GeV and the mass $m_Z = 91.1876 \pm 0.0021$ GeV are taken from ref. [8]. In eqs. (9) and (10) we have summed over the two possible combinations of lepton charges, $l_i^{\pm} l_j^{\mp}$.

From eqs. (8)–(10) we can see that the branching ratios $Br\,(Z \to l_i l_j)$ only depend on the free parameters M_S and M_F in the case of $\kappa_{ij}/\kappa'_{ij} = 10^{-2}$ $\left(\alpha_{\kappa'}^{ij} = 10^4 \alpha_{\kappa}^{ij}\right)$. Our numerical results are given in the two cases $M_F = 2M_S$ and $M_S = 2M_F$. Our numerical results are summarized in figs. 2(a), (b) and (c), corresponding to the branching ratios $Br\,(Z \to \mu e)$, $Br\,(Z \to \tau\mu)$ and $Br\,(Z \to \tau e)$, respectively.

One can see from fig. 2 that the contributions of the singlet VLS model to the branching ratios $Br\,(Z \to l_i l_j)$ are larger than those of the doublet VLS model. The reason is that the coupling of the gauge boson Z with a pair of VLLs in the singlet VLS model is larger than that in the doublet VLS model and the VLL mass M_F is assumed to be equal for three generations of VLLs. For the LFV decay $Z \to \mu e$, both the singlet and doublet VLS models cannot make its branching ratio reach observable level even if for the future e^+e^- high-energy colliders. This is not the case for the LFV decays $Z \to \tau\mu$ and τe. A certain range of the parameter space for the singlet or doublet VLS model can be detected by CEPC/FCC-ee via $Z \to \tau\mu$ and τe processes. However, using the CMS data collected at the $\sqrt{s} = 13\,\text{TeV}$ LHC with the integrated luminosity $\mathcal{L}$ =77.4 fb^{-1} [19], ref. [7] has given the lower limits on the mass parameter M_F, which are around 300 GeV and 800 GeV for the singlet and doublet VLS models, respectively, as shown in fig. 2. Considering the lower limits on the mass parameter M_F, we have that the value of the branching ratio $Br\,(Z \to \tau\mu)$ or $Br\,(Z \to \tau e)$ is smaller than 8×10^{-10} in the doublet VLS model. For

$300\,\mathrm{GeV} \le M_F \le 1000\,\mathrm{GeV}$ and $M_F = 2M_S$ in the singlet VLS model, there are $1.1 \times 10^{-7} \le Br\,(Z \to \tau\mu) \le 7.7 \times 10^{-9}$ and $8.3 \times 10^{-8} \le Br\,(Z \to \tau e) \le 5.9 \times 10^{-9}$, which might be detected by CEPC/FCC-ee in the near future.

Conclusions. – Asymptotically safe extensions of the SM are one kind of interesting new physics scenarios, which predict the existence of new singlet scalars and vector-like fermions producing significant contributions to some low-energy observables and rich collider phenomenology. The singlet and doublet VLS models are two specific models featuring three generations of either $SU(2)_L$ singlet or doublet VLLs, which can induce some LFV processes. Taking into account the constraints on these VLS models from the LFV decays $l_i \to l_j\gamma$ and the LHC data, we investigate their contributions to the LFV decays $Z \to l_i l_j\,(i \ne j)$. Our numerical results show that the new scalars and VLLs can indeed generate significant contributions to these decay processes. For the singlet VLS model, the values of the branching ratios $Br\,(Z \to \tau e)$ and $Br\,(Z \to \tau\mu)$ can be larger than 5×10^{-9} in a wide range of the parameter space, which might be detected by CEPC/FCC-ee in the near future.

* * *

This work was partially supported by the National Natural Science Foundation of China under Grant Nos. 11875157 and 12047570.

REFERENCES

[1] Wilson K. G., *Phys. Rev. B*, **4** (1971) 3174; Bailin D. and Love A., *Nucl. Phys. B*, **75** (1974) 159.

[2] Litim F. and Sannino F., *JHEP*, **12** (2014) 178; Bond A. D. and Litim D. F., *Eur. Phys. J. C*, **77** (2017) 429; 525; Bond A. D., Hiller G., Kowalska K. and Litim D. F., *JHEP*, **08** (2017) 004; Bond A. D. and Litim D. F., *Phys. Rev. Lett.*, **122** (2019) 211601.

[3] Hiller G., Hormigos-Feliu C., Litim D. F. and Steudtner T., arXiv:1905.11020.

[4] Hiller G., Hormigos-Feliu C., Litim D. F. and Steudtner T., *Phys. Rev. D*, **102** (2020) 071901.

[5] Kowalska K. and Sessolo E. M., *Phys. Rev. D*, **103** (2020) 115032.

[6] Hiller G., Hormigos-Feliu C., Litim D. F. and Steudtner T., *Phys. Rev. D*, **102** (2020) 095023.

[7] Bißmann S., Hiller G., Hormigos-Feliu C. and Litim D. F., *Eur. Phys. J. C*, **81** (2021) 101.

[8] Particle Data Group (Zyla P. A. *et al.*), *Prog. Theor. Exp. Phys.*, **2020** (2020) 083C01.

[9] Behnke T., Brau J. E. Foster B. *et al.*, arXiv:1306.6327; Irles A., Pöschl R., Richard F. and Yamamoto H., arXiv:1905.00220; LCC Physics Working Group (Fujii K. *et al.*), arXiv:1908.11299.

[10] CEPC Study Group, arXiv:1809.00285; arXiv:1811.10545.

[11] FCC Collaboration (Abada A. *et al.*), *Eur. Phys. J. ST*, **228** (2019) 261; *Eur. Phys. J. C*, **79** (2019) 474.

[12] Calibbi L., Marcano X. and Roy J., arXiv:2107.10273.

[13] Lavoura L., *Eur. Phys. J. C*, **29** (2003) 191; Lindner M., Platscher M. and Queiroz F. S., *Phys. Rep.*, **731** (2018) 1.

[14] Belle Collaboration (Abdesselam A. *et al.*), arXiv:2103.12994.

[15] Lavoura L. and Silva J. P., *Phys. Rev. D*, **47** (1993) 2046.

[16] ATLAS collaboration (Aad G. *et al.*), *Phys. Rev. D*, **90** (2014) 072010; *Nat. Phys.*, **17** (2021) 819; arXiv:2105.12491.

[17] Dam M., *SciPost Phys. Proc.*, **1** (2019) 041.

[18] Chiang C. W., Okada H. and Senaha E., *Phys. Rev. D*, **96** (2017) 015002.

[19] Sirunyan A. M. *et al.*, *Phys. Rev. D*, **100** (2019) 052003.