Explaining the Cabibbo Angle Anomaly and Lepton Flavour Universality Violation in Tau Decays with a Singly-Charged Scalar Singlet

Fiona Kirk[1,2]

[1]*Physik-Institut, Universität Zürich, Winterthurerstrasse 190, CH–8057 Zürich, Switzerland*

[2]*Paul Scherrer Institut, CH–5232 Villigen PSI, Switzerland*

Abstract

The singly charged $SU(2)_L$ singlet scalar, with its necessarily flavour violating couplings to leptons, lends itself particularly well for an explanation of the Cabibbo Angle Anomaly and of hints for lepton flavour universality violation in tau decays.

Keywords: lepton flavour universality violation, lepton flavour violation, collider, neutrinos
DOI: 10.31526/ACP.BSM-2021.6

1. INTRODUCTION

The Cabibbo angle, which is the angle describing the mixing of the first two generations of quarks in the Standard Model, can be determined from V_{ud} extracted from superallowed β-decays, from V_{us} from τ-decays or K-decays, or from V_{cd} from $D \to \mu\nu$. Recent improvements in the computation of the γW-box contributions to superallowed β decays reduced the uncertainty on V_{ud}, however, they also shifted the central value, leading to a 3σ deviation from first-row Cabibbo Kobayashi Maskawa (CKM) unitarity,[1, 2, 3, 4, 5] commonly referred to as the Cabibbo Angle Anomaly (CAA).[10, 11, 12, 13, 14] This tension is illustrated in Fig. 1(a), where we show the values for V_{us} quoted by the PDG,[6, 8, 5] as well as $|V_{us}^{\beta}| = 0.22805(64)$ determined, using (first row) CKM unitarity ($|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$), from $|V_{ud}| = 0.97365(15)$ [9].

A number of models involving physics beyond the Standard Model (SM) can account for this experimental situation,[15] however, they all adopt one of the following strategies (see also Fig. 1(b) for an illustration): they may

- lead to new contributions to β-decays and thus affect the extraction of V_{us} from β-decays [16, 17] (shown in purple in Fig. 1(b)),
- modify the Wud-coupling, leading to a "direct" violation of CKM unitarity [10, 18, 19] (orange),
- modify $W\ell\nu$-couplings, which enter both β-decays and μ-decays [20, 21, 13, 22, 23, 24, 25] (blue), or
- lead to new contributions to μ-decays, which modify the Fermi constant and enter the extraction of V_{ud} from superallowed beta decays in that way[10, 26, 27, 28, 29](green).

Here we consider the last of these possibilities.[1] Defining

$$\delta(\mu \to e\bar{\nu}\nu) = \frac{\mathcal{A}_{NP}(\mu \to e\bar{\nu}\nu)}{\mathcal{A}_{SM}(\mu \to e\bar{\nu}\nu)}, \tag{1}$$

which is simply the new physics (NP) contribution to $\mu \to e\bar{\nu}\nu$, at amplitude level, normalised to the SM amplitude, the Fermi constant takes the form

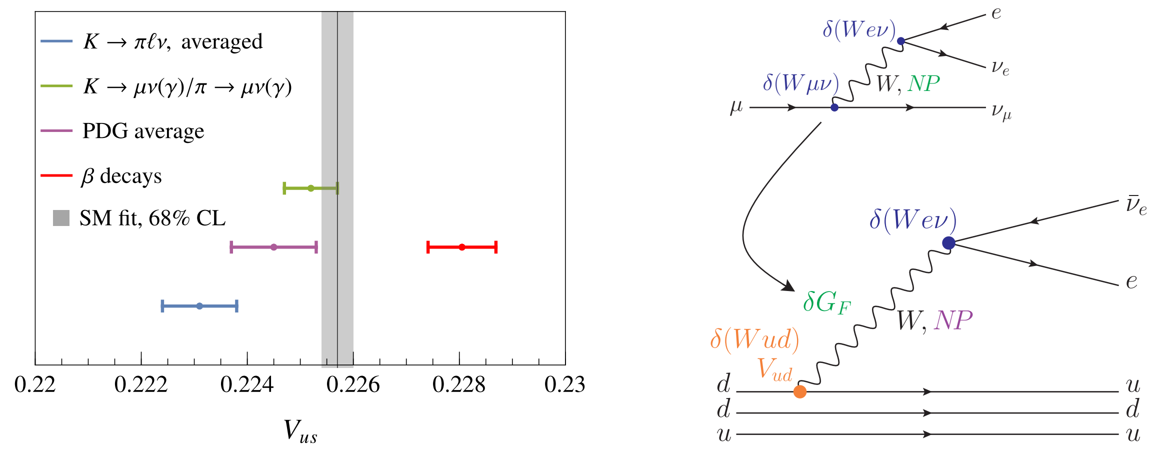
$$G_F = G_F^{\text{SM}}(1 + \delta(\mu \to e\bar{\nu}\nu)), \tag{2}$$

where G_F^{SM} stands for the Fermi constant determined in presence of SM physics only. A modification of the Fermi constant can alleviate the tension between the different determinations of V_{us} by shifting V_{ud}, extracted from β-decays, to $V_{ud}^{\beta} = V_{ud}^{\text{SM}}(1 - \delta(\mu \to e\bar{\nu}\nu))$, where V_{ud}^{SM} is the $(1,1)$-element of the (unitary) CKM matrix. Using CKM-unitarity, we find

$$V_{us}^{\beta} \equiv \sqrt{1 - \left|V_{ud}^{\beta}\right|^2 - |V_{ub}|^2} \simeq V_{us}^{\text{SM}} \left[1 + \left(\frac{V_{ud}^{\text{SM}}}{V_{us}^{\text{SM}}}\right)^2 \delta(\mu \to e\bar{\nu}\nu)\right], \tag{3}$$

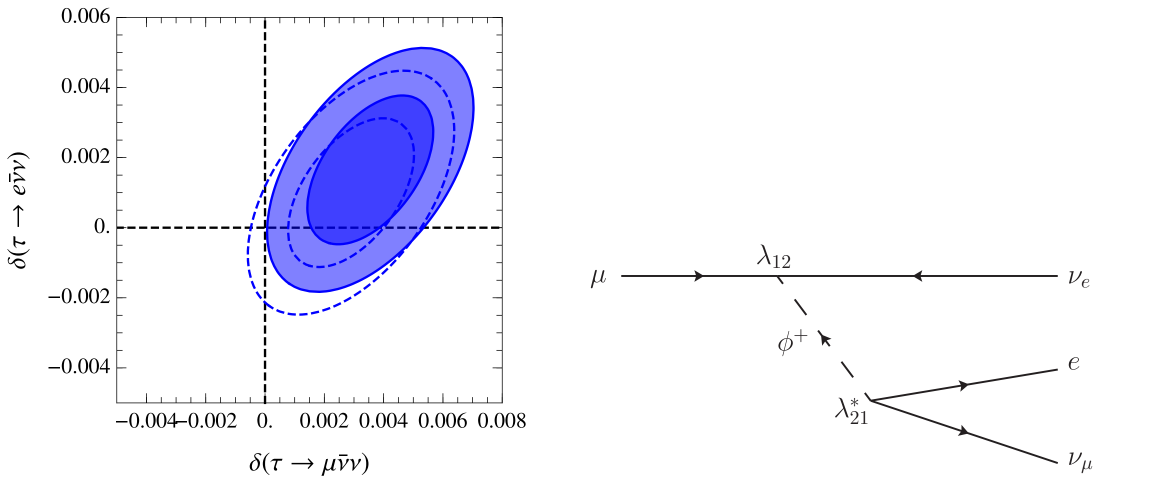
which indeed is larger than V_{us}^{SM}, if $\delta(\mu \to e\bar{\nu}\nu)$ is positive. Note that the enhancement by $\left(V_{ud}^{\text{SM}}/V_{us}^{\text{SM}}\right)^2 \approx 19$ makes V_{us} particularly sensitive to modifications of the type $\delta(\mu \to e\bar{\nu}\nu)$.[13]

[1] Indeed, the singly charged scalar can generate a new contribution to μ decays (see Fig. 2(b)).



(a) (b)

FIGURE 1: (a) Determinations of V_{us} from different sources (b) Possible NP interpretations



(a) (b) $\mu \to e\bar{\nu}\nu$

FIGURE 2: (a) The regions preferred by the ratios in Eq. 4 in terms of $\delta(\tau \to \mu\bar{\nu}\nu)$ and $\delta(\tau \to e\bar{\nu}\nu)$. The dashed lines show the 1σ and 2σ contours for $\delta(\mu \to e\bar{\nu}\nu) = 0$, the blue regions show the 1σ and 2σ preferred regions for $\delta(\mu \to e\bar{\nu}\nu) = 0.00065$, which is the value favoured by our global fit. (b) Feynman diagram showing the contribution of $\phi^\pm$ to the muon decay $\mu \to e\bar{\nu}\nu$ and the Fermi constant. The corresponding diagrams for $\tau \to \mu\bar{\nu}\nu$ and $\tau \to e\bar{\nu}\nu$ are found by exchanging the flavour indices.

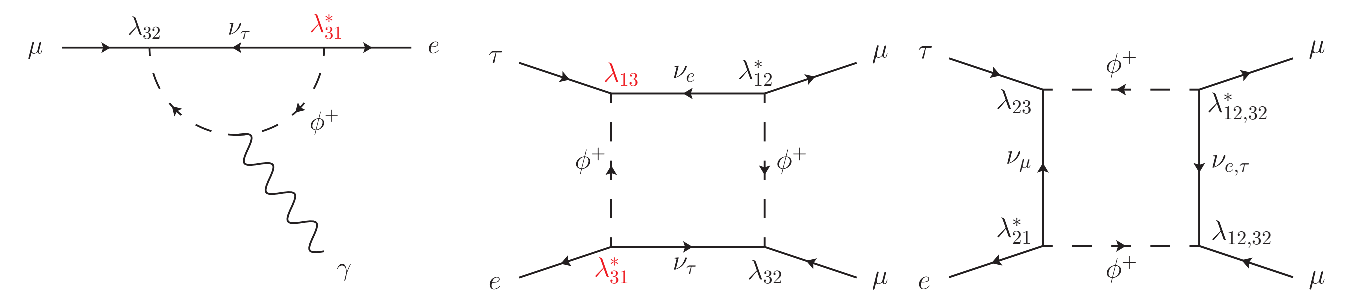
Besides the CAA, the singly charged scalar can address the 2σ deviation from SM predictions encoded in the experimentally determined amplitude fractions [30]

$$\frac{\mathcal{A}(\tau \to \mu\bar{\nu}\nu)}{\mathcal{A}(\mu \to e\bar{\nu}\nu)} = 1.0029(14), \quad \frac{\mathcal{A}(\tau \to \mu\bar{\nu}\nu)}{\mathcal{A}(\tau \to e\bar{\nu}\nu)} = 1.0018(14), \quad \frac{\mathcal{A}(\tau \to e\bar{\nu}\nu)}{\mathcal{A}(\mu \to e\bar{\nu}\nu)} = 1.0010(14). \tag{4}$$

Expressing this data in terms of $\delta(\tau \to \mu\bar{\nu}\nu)$ and $\delta(\tau \to e\bar{\nu}\nu)$, which are defined in analogy with $\delta(\mu \to e\bar{\nu}\nu)$ (see Eq. 1), we observe a preference for positive $\delta(\tau \to \mu\bar{\nu}\nu)$ and $\delta(\tau \to e\bar{\nu}\nu)$ (see Fig. 2(a)).

2. THE SINGLY CHARGED $SU(2)_L$ SINGLET SCALAR

Let us now introduce the singly charged $SU(2)_L$ singlet scalar, ϕ^+, which can lead to the desired effects in muon and tau decays. This field has been extensively studied in the context of Zee models,[31, 32, 33, 34] Babu-Zee models,[34, 35, 36, 37] and other models where singly charged scalars radiatively generate neutrino masses,[38, 39, 40, 41, 42, 43, 45, 44] however, in the following we will remain agnostic about the underlying theory and consider the singly charged scalar as a minimal extension of the SM.



(a) $\mu \to e\gamma$ (b) $\tau \to e\bar{\mu}\mu$, I (c) $\tau \to e\bar{\mu}\mu$, II

FIGURE 3: Feynman diagrams showing the contribution of $\phi^\pm$ to (a) the radiative leptonic decay $\mu \to e\gamma$ and (b,c) an example of charged lepton flavour violation. The coupling λ_{13}, which is strongly constrained by $\mu \to e$ conversion and $\mu \to e\gamma$, is shown in red.

The singly charged scalar is a $(1,1,1)$-representation of the SM gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$, which leaves only one way for it to couple to SM matter fields:

$$\mathcal{L}_{int} = -\frac{\lambda_{ij}}{2}\,\bar{L}^c_{a,i}\,\varepsilon_{ab}\,L_{b,j}\,\phi^+ + \text{h.c.}\,. \tag{5}$$

Here a, b are $SU(2)_L$ indices, ε_{ab} is the 2-dimensional Levi-Civita tensor, c stands for charge conjugation, i, j are flavour indices, and λ_{ij} can be chosen to be antisymmetric in flavour. Hence this extension of the SM automatically leads to lepton flavour violation, and to lepton flavour universality violation, should the three new couplings not be equal. The fact that only three new couplings and one mass are needed to fully describe the singly charged scalar, makes this model very predictive.

2.1. *Flavour Bounds*

Equipped with the Lagrangian in Eq. 5 we can derive the leading contributions of the singly charged scalar to the relevant flavour observables (see Figs. 2(b) and 3 for the corresponding Feynman diagrams). The first interesting observation we can make is that the modifications of $\mu \to e\bar{\nu}\nu$ (see Eq. 1), $\tau \to e\bar{\nu}\nu$ and $\tau \to \mu\bar{\nu}\nu$,

$$\delta(\ell_i \to \ell_j \bar{\nu}\nu) = \frac{\mathcal{A}_{NP}(\ell_i \to \ell_j \nu_i \bar{\nu}_j)}{\mathcal{A}_{SM}(\ell_i \to \ell_j \nu_i \bar{\nu}_j)} = \frac{\left|\lambda_{ij}\right|^2}{g_2^2}\frac{m_W^2}{m_\phi^2}\,, \tag{6}$$

are necessarily positive. This fits into the picture described in the context of the CAA, in particular to Eq. 3, and to the experimental data shown in Eq. 4 and in Fig 2(a). A global fit to EW data and the CKM elements states a preference for $\delta(\mu \to e\nu\nu) = 0.00065(15)$.

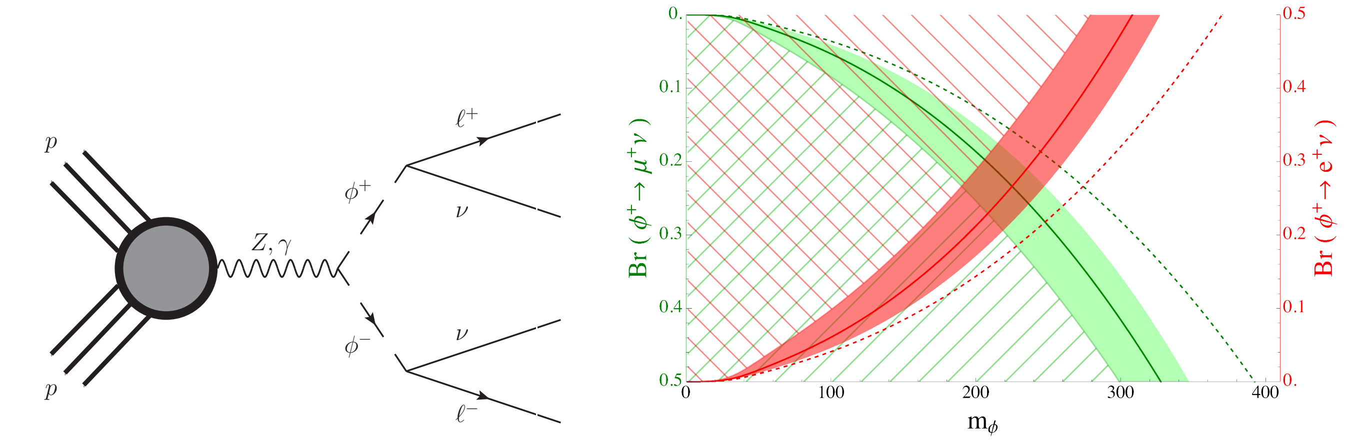
Radiative leptonic decays provide strong bounds on the couplings λ_{ij} of the singly charged scalar to the SM leptons. In fact, the bound from $\mu \to e\gamma$ is so strong that we can set $\lambda_{13} \approx 0$ (marked in red in Fig. 3). We reach a similar conclusion considering $\mu \to e$ conversion in nuclei. This has consequences for charged lepton violation, which is loop-suppressed in this model (see e.g. Figs. 3(b) and 3(c)). Processes mediated by λ_{13}, such as $\tau \to e\bar{\mu}e$, are expected to be vanishingly small.

2.2. *Collider Constraints*

Since the singly charged scalar has the same quantum numbers as right-handed sleptons, we can simply recast selectron and smuon searches into searches for the singly charged scalar. The dominant channel here is Drell-Yan pair production of the singly charged scalar, which consecutively decays into a pair of charged leptons with missing transverse energy (see Fig 4(a) for the corresponding Feynman diagram). Reinterpreting the most recent dedicated ATLAS search, which is based on 139 fb^{-1} of proton-proton collisions, [46] we obtain the bounds, shown in Fig. 4(b), on the mass m_ϕ of the singly charged scalar and on the branching ratios $\text{Br}(\phi^+ \to \mu^+\nu)$ and $\text{Br}(\phi^+ \to e^+\nu)$. The hatched regions are excluded by the e^+e^- (red) or $\mu^+\mu^-$ (green) channels. The bounds depicted in Fig. 4(b) allow us to set a coupling-independent lower limit of $m_\phi \approx 220$ GeV on the mass of the singly charged scalar. The scenario of $\lambda_{13} = 0$, mentioned in Section 2.1, translates into a branching ratio of $\text{Br}(\phi^+ \to \mu^+\nu) = 1/2$. (The corresponding branching ratio into electrons cannot be fixed in this scenario without making additional assumptions on the relation between λ_{12} and λ_{23}.) The projected exclusion limits of the High Luminosity (HL) LHC are indicated by dashed curves.

3. COMBINED ANALYSIS AND CONCLUSIONS

Combining the flavour bounds and collider constraints in the scenario with $\lambda_{13} = 0$, we can determine best fit regions in the $\delta(\tau \to \mu\nu\nu)$–$\delta(\mu \to e\nu\nu)$ plane. In Fig. 5, the region preferred by electroweak data and the Cabibbo Angle Anomaly at the level of 1σ is shown in red, while the region preferred at the level of 1σ by the ratios listed in Eq. 4 is shown in orange. The combined best fit region is indicated in green. In this region of parameter space we find $\text{Br}(\tau \to e\bar{\mu}\mu) \sim 10^{-10} m_\phi^4/(5\,\text{TeV})^4$, $10^{-11} \lesssim \text{Br}(\tau \to e\gamma) \lesssim 5 \times 10^{-11}$ and $|\lambda_{12}|^2 \sim 0.05/(1\,\text{TeV})^2$, which can be probed by monophoton searches at future e^+e^- colliders.



(a) (b)

FIGURE 4: (a) Feynman diagram showing Drell-Yan pair production of the singly charged scalar, $\phi^{\pm}$, and the decay of $\phi^{\pm}$ into SM leptons (b) Recast ATLAS bounds (see text for the details)

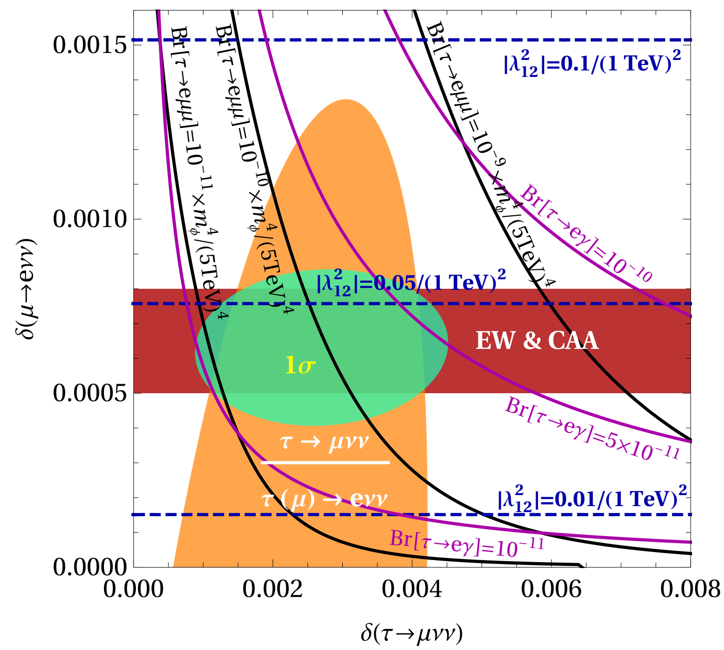


FIGURE 5: Regions in the $\delta(\tau \to \mu\nu\nu)$–$\delta(\mu \to e\nu\nu)$ plane preferred at the level of 1σ by electroweak data, the CAA and $\ell \to \ell'\bar{\nu}\nu$ (see Eq. 4). The combined region is shown in green. The curves indicate predictions for $\tau \to e\gamma$ (magenta), $\tau \to e\mu\mu$ (black) and $|\lambda_{12}^2|/m_\phi^2$ (blue).

ACKNOWLEDGMENTS

I would like to thank the organisers for giving me the opportunity to share my work.

References

[1] C. Y. Seng, M. Gorchtein, H. H. Patel and M. J. Ramsey-Musolf, Phys. Rev. Lett. **121** (2018) no.24, 241804 doi:10.1103/PhysRevLett.121.241804 [arXiv:1807.10197 [hep-ph]].
[2] A. Czarnecki, W. J. Marciano and A. Sirlin, Phys. Rev. D **101** (2020) no.9, 091301 doi:10.1103/PhysRevD.101.091301 [arXiv:1911.04685 [hep-ph]].
[3] L. Hayen and A. R. Young, [arXiv:2009.11364 [nucl-th]].
[4] K. Shiells, P. G. Blunden and W. Melnitchouk, [arXiv:2012.01580 [hep-ph]].
[5] P. A. Zyla *et al.* [Particle Data Group], PTEP **2020** (2020) no.8, 083C01 doi:10.1093/ptep/ptaa104
[6] M. Antonelli *et al.* [FlaviaNet Working Group on Kaon Decays], Eur. Phys. J. C **69** (2010), 399-424 doi:10.1140/epjc/s10052-010-1406-3 [arXiv:1005.2323 [hep-ph]].
[7] E. Blucher and W.J. Marciano, "Vud, Vus, the Cabibbo Angle and CKM Unitarity", PDG review

[8] S. Aoki *et al.* [Flavour Lattice Averaging Group], Eur. Phys. J. C **80** (2020) no.2, 113 doi:10.1140/epjc/s10052-019-7354-7 [arXiv:1902.08191 [hep-lat]].
[9] C. Y. Seng, X. Feng, M. Gorchtein and L. C. Jin, Phys. Rev. D **101** (2020) no.11, 111301 doi:10.1103/PhysRevD.101.111301 [arXiv:2003.11264 [hep-ph]].
[10] B. Belfatto, R. Beradze and Z. Berezhiani, Eur. Phys. J. C **80** (2020) no.2, 149 doi:10.1140/epjc/s10052-020-7691-6 [arXiv:1906.02714 [hep-ph]].
[11] Wanpeng Tan [arXiv:1906.10262 [physics.gen-ph]].
[12] Y. Grossman, E. Passemar and S. Schacht, JHEP **07** (2020), 068 doi:10.1007/JHEP07(2020)068 [arXiv:1911.07821 [hep-ph]].
[13] A. Crivellin and M. Hoferichter, Phys. Rev. Lett. **125** (2020) no.11, 111801 doi:10.1103/PhysRevLett.125.111801 [arXiv:2002.07184 [hep-ph]].
[14] A. Crivellin, M. Hoferichter and C. A. Manzari, [arXiv:2102.02825 [hep-ph]].
[15] M. Kirk, Phys. Rev. D **103** (2021) no.3, 035004 doi:10.1103/PhysRevD.103.035004 [arXiv:2008.03261 [hep-ph]].
[16] A. Crivellin, C. A. Manzari and M. Montull, [arXiv:2103.12003 [hep-ph]].
[17] A. Crivellin and L. Schnell, [arXiv:2104.06417 [hep-ph]].
[18] B. Belfatto and Z. Berezhiani, [arXiv:2103.05549 [hep-ph]].
[19] G. C. Branco, J. T. Penedo, P. M. F. Pereira, M. N. Rebelo and J. I. Silva-Marcos, [arXiv:2103.13409 [hep-ph]].
[20] A. M. Coutinho, A. Crivellin and C. A. Manzari, Phys. Rev. Lett. **125** (2020) no.7, 071802 doi:10.1103/PhysRevLett.125.071802 [arXiv:1912.08823 [hep-ph]].
[21] D. A. Bryman and R. Shrock, Phys. Rev. D **100** (2019), 073011 doi:10.1103/PhysRevD.100.073011 [arXiv:1909.11198 [hep-ph]].
[22] A. Crivellin, F. Kirk, C. A. Manzari and M. Montull, JHEP **12** (2020), 166 doi:10.1007/JHEP12(2020)166 [arXiv:2008.01113 [hep-ph]].
[23] B. Capdevila, A. Crivellin, C. A. Manzari and M. Montull, Phys. Rev. D **103** (2021) no.1, 015032 doi:10.1103/PhysRevD.103.015032 [arXiv:2005.13542 [hep-ph]].
[24] M. Endo and S. Mishima, JHEP **08** (2020) no.08, 004 doi:10.1007/JHEP08(2020)004 [arXiv:2005.03933 [hep-ph]].
[25] A. K. Alok, A. Dighe, S. Gangal and J. Kumar, [arXiv:2010.12009 [hep-ph]].
[26] A. Crivellin, F. Kirk, C. A. Manzari and L. Panizzi, Phys. Rev. D **103** (2021) no.7, 073002 doi:10.1103/PhysRevD.103.073002 [arXiv:2012.09845 [hep-ph]].
[27] A. Crivellin, C. A. Manzari, M. Alguero and J. Matias, [arXiv:2010.14504 [hep-ph]].
[28] D. Marzocca and S. Trifinopoulos, [arXiv:2104.05730 [hep-ph]].
[29] A. J. Buras, A. Crivellin, F. Kirk, C. A. Manzari and M. Montull, [arXiv:2104.07680 [hep-ph]].
[30] Y. S. Amhis *et al.* [HFLAV], [arXiv:1909.12524 [hep-ex]].
[31] A. Zee, Phys. Lett. B **93** (1980), 389 [erratum: Phys. Lett. B **95** (1980), 461] doi:10.1016/0370-2693(80)90349-4
[32] L. Wolfenstein, Nucl. Phys. B **175** (1980), 93-96 doi:10.1016/0550-3213(80)90004-8
[33] S. T. Petcov, Phys. Lett. B **115** (1982), 401-406 doi:10.1016/0370-2693(82)90526-3
[34] A. Zee, Nucl. Phys. B **264** (1986), 99-110 doi:10.1016/0550-3213(86)90475-X
[35] K. S. Babu, Phys. Lett. B **203** (1988), 132-136 doi:10.1016/0370-2693(88)91584-5
[36] D. Chang, W. Y. Keung and P. B. Pal, Phys. Rev. Lett. **61** (1988), 2420-2423 doi:10.1103/PhysRevLett.61.2420
[37] Y. Irie, O. Seto and T. Shindou, [arXiv:2104.09628 [hep-ph]].
[38] K. R. S. Balaji, W. Grimus and T. Schwetz, Phys. Lett. B **508** (2001), 301-310 doi:10.1016/S0370-2693(01)00532-9 [arXiv:hep-ph/0104035 [hep-ph]].
[39] D. A. Dicus, H. J. He and J. N. Ng, Phys. Rev. Lett. **87** (2001), 111803 doi:10.1103/PhysRevLett.87.111803 [arXiv:hep-ph/0103126 [hep-ph]].
[40] M. Drees, S. Pakvasa, X. Tata and T. ter Veldhuis, Phys. Rev. D **57** (1998), 5335-5339 doi:10.1103/PhysRevD.57.R5335 [arXiv:hep-ph/9712392 [hep-ph]].
[41] G. Bhattacharyya, H. V. Klapdor-Kleingrothaus and H. Pas, Phys. Lett. B **463** (1999), 77-82 doi:10.1016/S0370-2693(99)00947-8 [arXiv:hep-ph/9907432 [hep-ph]].
[42] K. m. Cheung and O. C. W. Kong, Phys. Rev. D **61** (2000), 113012 doi:10.1103/PhysRevD.61.113012 [arXiv:hep-ph/9912238 [hep-ph]].
[43] N. Haba, M. Matsuda and M. Tanimoto, Phys. Lett. B **478** (2000), 351-357 doi:10.1016/S0370-2693(00)00275-6 [arXiv:hep-ph/9911511 [hep-ph]].
[44] L. M. Krauss, S. Nasri and M. Trodden, Phys. Rev. D **67** (2003), 085002 doi:10.1103/PhysRevD.67.085002 [arXiv:hep-ph/0210389 [hep-ph]].
[45] Y. Cai, J. Herrero-García, M. A. Schmidt, A. Vicente and R. R. Volkas, Front. in Phys. **5** (2017), 63 doi:10.3389/fphy.2017.00063 [arXiv:1706.08524 [hep-ph]].
[46] G. Aad *et al.* [ATLAS], Eur. Phys. J. C **80** (2020) no.2, 123 doi:10.1140/epjc/s10052-019-7594-6 [arXiv:1908.08215 [hep-ex]].