Role of the Right-Handed Neutrino in $B_c^+ \to B_s\mu^+\nu_\mu$ Decay

Priyanka Boora[1,*] *Dinesh* Kumar[2,**] *Kavita* Lalwani[1,***]

[1]Malaviya National Institute of Technology Jaipur, Jaipur 302017 Rajasthan, India
[2]Department of Physics, University of Rajasthan, Jaipur 302004 Rajasthan, India

Abstract. We perform a model-independent study of $c \to s\mu\nu$ mediated transitions to analyze the new physics effects in the presence of right-handed neutrinos. We have adopted the effective field theory approach and write the low-energy effective Hamiltonian including all possible dimension-six operators. The Wilson coefficients introduced through low energy effective Hamiltonian encode all New Physics that can enter in $c \to s$ transition at the dimension-six operator level. These Wilson coefficients are determined through a χ^2 fit by using the Miniut package to available experimental data of leptonic $D_s^+ \to \mu^+\nu_\mu$ and semileptonic decays $D^0 \to K^-\mu^+\nu_\mu$, $D^+ \to \bar{K}^0\mu^+\nu_\mu$ and $D^0 \to K^{*-}\mu^+\nu_\mu$, $D^+ \to \bar{K}^{*0}\mu^+\nu_\mu$, $D_s^+ \to \phi\mu^+\nu_\mu$. The differential decay width of $B_c^+ \to B_s\mu^+\nu_\mu$ is derived to investigate the role of right-handed neutrinos in the search for new physics through the three-body decay process. We also make the predictions of q^2 spectra for the mode $B_c^+ \to B_s\mu^+\nu_\mu$ to inspect the effect of the allowed new physics in $c \to s$ sector through right-handed neutrinos to motivate the future measurements.

1 Introduction

The B_c^+ meson was first observed by the Collider Detector at Fermilab (CDF collaboration) [1, 2]. It is an exciting meson for study, because of its structure of heavy quarkonium and decay via weak interaction. The semileptonic decay $B_c^+ \to B_s\mu^+\nu_\mu$ have been studied in the standard model (SM) and for beyond the standard model signal [3]. The observables in this decay can deviate from the SM predictions when some new physics is present. We consider the role of the right-handed neutrinos (RHNs) in this decay to investigate the effects of new physics. Right-handed neutrinos or sterile neutrinos are well-motivated hypothetical particles that can resolve phenomena beyond the standard model (SM). In B-decays, the inclusion of right-handed neutrinos is a clean probe to search the NP [4–6]. The extension of the effective Hamiltonian at low energy scale is done by including right-handed neutrinos, and in effective field theory, this extension provides a platform to analyse the effect of these hypothetical particles (RHNs) on the sensitive observables of the pseudoscalar three-body decay $B_c^+ \to B_s\mu^+\nu_\mu$. The right-handed neutrinos are present in the leptonic current, so they only modify the leptonic current of the decay, which can alter the measurements from the SM predictions.

*e-mail: 2020rpy9601@mnit.ac.in
**e-mail: dineshsuman09@gmail.com
***e-mail: kavita.phy@mnit.ac.in

2 Theoretical Framework

2.1 Effective Hamiltonian

The low energy effective Hamiltonian for semileptonic decay $B_c^+ \to B_s \mu^+ \nu_\mu$ induced by the $c \to s\mu\nu$ quark level transistion can be given as:

$$H_{eff} = \frac{4G_F V_{cs}}{\sqrt{2}}\Big[O^V_{LL} + C^V_{LL}O^V_{LL} + C^V_{RL}O^V_{RL} + C^V_{LR}O^V_{LR} + C^V_{RR}O^V_{RR} + C^S_{LL}O^S_{LL} \\ + C^S_{RL}O^S_{RL} + C^S_{LR}O^S_{LR} + C^S_{RR}O^S_{RR} + C^T_{LL}O^T_{LL} + C^T_{RR}O^T_{RR}\Big] + h.c., \tag{1}$$

with the left-handed (L) and right-handed (R) neutrino operators given by

$$\begin{aligned} O^V_{LL(R)} &= (\bar{s}\gamma^\alpha P_L c)(\bar{\nu_\mu}\gamma_\alpha P_{L(R)}\mu) \\ O^V_{L(R)L} &= (\bar{s}\gamma^\alpha P_{L(R)} c)(\bar{\nu_\mu}\gamma_\alpha P_R\mu) \\ O^S_{LL(R)} &= (\bar{s}P_L c)(\bar{\nu_\mu}P_{L(R)}\mu) \\ O^S_{L(R)L} &= (\bar{s}P_{L(R)} c)(\bar{\nu_\mu}P_L\mu) \\ O^T_{L(R)L(R)} &= \delta_{ij}(\bar{s}\sigma^{\alpha\beta}P_{L(R)}c)(\bar{\nu_\mu}\sigma_{\alpha\beta}P_{L(R)}\mu) \end{aligned} \tag{2}$$

where the $P_{R(L)} = \frac{(1\pm\gamma_\alpha)}{2}$ are the projection operators, and V_{cs} is the corresponding CKM matrix element. Note that for the tensor operator case leptons and quarks with different chirality case vanishes identically. The 10 Wilson Coefficients (WCs) C^X_{AB} (X = S,V,T and A, B = L, R) corresponding to the four fermion operators are defined in Eq. 2.

2.2 Observable

The two fold differential decay width for $B_c^+ \to B_s \mu^+ \nu_\mu$ decay can be given as [4]

$$\frac{d\Gamma(B_c^+ \to B_s\mu^+\nu_\mu)}{dq^2 d\cos\theta_\mu} = \frac{G_F^2 V_{cs}^2}{256 m_{B_c}^3 \pi^3} q^2 \lambda_{B_s}^{1/2}(q^2)\left(1 - \frac{m_\mu^2}{q^2}\right)^2 \left\{\mathcal{L}_0(q^2) + \mathcal{L}_1(q^2)\cos\theta_\mu + \mathcal{L}_2(q^2)\cos^2\theta_\mu\right\} \tag{3}$$

where, $q^2 = (p_{\mu^+} + p_{\nu_\mu})$ the square momentum transferred to the muon pair, θ_μ is the polar angle between the muon momentum and the z-axis of the B_c^+ meson momentum, where muon momentum is in the $\mu^+\nu_\mu$ pair rest frame and B_c^+ momentum is in theB_c^+ rest frame respectively, and λ_{B_s} is the triangle function given by

$$\lambda_{B_s}\left(q^2\right) \equiv \lambda\left(m_{B_c}^2, m_{B_s}^2, q^2\right) = m_{B_c}^4 + m_{B_s}^4 + q^4 - 2m_{B_c}^2 m_{B_s}^2 - 2m_{B_s}^2 q^2 - 2m_{B_c}^2 q^2 \tag{4}$$

The coefficients $\mathcal{L}_0(q^2)$, $\mathcal{L}_1(q^2)$ and $\mathcal{L}_2(q^2)$ are giving the dependence of decay width on hadronic helicities amplitudes along with a linear combination of WCs:

$$\begin{aligned} \mathcal{L}_0\left(q^2\right) &= \left|\mathcal{W}_0^L - \frac{2m_\mu}{\sqrt{q^2}}\mathcal{W}_T^L\right|^2 + \frac{m_\mu^2}{q^2}\left|\mathcal{W}_t^L + \frac{\sqrt{q^2}}{m_\mu}\mathcal{W}_S^L\right|^2 + (L \leftrightarrow R), \\ \mathcal{L}_1\left(q^2\right) &= \frac{2m_\mu^2}{q^2} Re\left[\left(\mathcal{W}_0^L - \frac{2\sqrt{q^2}}{m_\mu}\mathcal{W}_T^L\right)\left(\mathcal{W}_t^{L*} + \frac{\sqrt{q^2}}{m_\mu}\mathcal{W}_S^{L*}\right)\right] + (L \leftrightarrow R), \\ \mathcal{L}_2\left(q^2\right) &= -\left(1 - \frac{m_\mu^2}{q^2}\right)\left(\left|\mathcal{W}_0^L\right|^2 - 4\left|\mathcal{W}_T^L\right|^2\right) + (L \leftrightarrow R), \end{aligned} \tag{5}$$

where

$$
\begin{aligned}
\mathcal{W}_0^L &= \left(1 + C_{LL}^V + C_{RL}^V\right) H_{V,0}^s, & \mathcal{W}_0^R &= \left(C_{LR}^V + C_{RR}^V\right) H_{V,0}^s,\\
\mathcal{W}_t^L &= \left(1 + C_{LL}^V + C_{RL}^V\right) H_{V,t}^s, & \mathcal{W}_t^R &= \left(C_{LR}^V + C_{RR}^V\right) H_{V,t}^s,\\
\mathcal{W}_S^L &= \left(C_{RL}^S + C_{LL}^S\right) H_S^s, & \mathcal{W}_S^R &= \left(C_{RR}^S + C_{LR}^S\right) H_S^s,\\
\mathcal{W}_T^L &= 2C_{LL}^T H_T^s, & \mathcal{W}_T^R &= 2C_{RR}^T H_T^s.
\end{aligned} \tag{6}
$$

The helicity amplitudes $H_{V,0}^s$, $H_{V,t}^s$, H_S^s and H_T^s are q^2 dependent and their expresssions with hadrnoic matrix elements are given in [3].

We get the differential decay width as

$$
\begin{aligned}
\frac{d\Gamma}{dq^2}(B_c^+ \to B_s\mu^+\nu_\mu) =& \frac{G_F^2 V_{cs}^2}{192 m_{B_c}^3 \pi^3} q^2 \lambda_{B_s}^{1/2}\left(q^2\right)\left(1 - \frac{m_\mu^2}{q^2}\right)^2\\
&\times\Bigg\{\left(\left|1 + C_{LL}^V + C_{RL}^V\right|^2 + \left|C_{LR}^V + C_{RR}^V\right|^2\right)\left[\left(H_{V,0}^s\right)^2\left(\frac{m_\mu^2}{2q^2} + 1\right) + \frac{3m_\mu^2}{2q^2}\left(H_{V,t}^s\right)^2\right]\\
&+ \frac{3}{2}(H_S^s)^2\left(\left|C_{RL}^S + C_{LL}^S\right|^2 + \left|C_{RR}^S + C_{LR}^S\right|^2\right) + 8\left(\left|C_{LL}^T\right|^2 + \left|C_{RR}^T\right|^2\right)(H_T^s)^2\left(1 + \frac{2m_\mu^2}{q^2}\right)\\
&+ 3Re\left[\left(1 + C_{LL}^V + C_{RL}^V\right)\left(C_{RL}^S + C_{LL}^S\right)^* + \left(C_{LR}^V + C_{RR}^V\right)\left(C_{RR}^S + C_{LR}^S\right)^*\right]\frac{m_\mu}{\sqrt{q^2}} H_S^s H_{V,t}^s\\
&- 12Re\left[\left(1 + C_{LL}^V + C_{RL}^V\right) C_{LL}^{T*} + \left(C_{RR}^V + C_{LR}^V\right) C_{RR}^{T*}\right]\frac{m_\mu}{\sqrt{q^2}} H_T^s H_{V,0}^s\Bigg\}.
\end{aligned} \tag{7}
$$

3 Numerical Analysis

The form factors $f_0(q^2)$ and $f_+(q^2)$ of handronic matrix elements used over the full range of the q^2; $0 < q^2 < (M_{B_c^+} - M_{B_s})^2$. These form factors are computed from the results of Highly Improved Staggered Quark (HISQ) method and NRQCD, which are given by the truncated power series of z_p [7]:

$$
f(q^2) = P(q^2)\sum_n^N A_n z_p(q^2)^n \tag{8}
$$

with $P(q^2) = (1 - \frac{q^2}{M_{res}^2})^{-1}$ is a pole structure function with suitably choosen mass parameter M_{res} gives the dependence on q^2, and $z_p\left(q^2\right) = \frac{z(q^2)}{|z(M_{res}^2)|}$ where $z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+}}{\sqrt{t_+ - q^2} + \sqrt{t_+}}$ with $t_+ = (m_{B_c} + m_{B_s})^2$. A_n denotes the covriance matrix of the respective form factor.
The new physics Wilson Coefficient (given in Eq. 1) can be constrained by using the available experimental measurements of the charm decays listed in table 1.

We adopted the χ^2 minimization methodology for the best fit value of WCs

$$
\chi^2(C_i) = \sum_n \frac{[O_m^{th}(C_i) - O_m^{exp}]^2}{\sigma^2_{O_m^{exp}}} \tag{9}
$$

Here $O^{th}(C_i)$ are the theoretical prediction value for the respective NP Wilson Coefficient C_i. O^{exp} is the experimental measurement and $\sigma_{O^{exp}}$ is the corresponding experimental uncertainity. We use the MINUIT library [13, 14] to get the most likely values by minimizing the χ^2 function. The standard model χ^2 value is 14.94.

Table 1. Experimental measurements available in charm sector used in our analysis [12].

Mode	Branching Fraction
$D_s^+ \to \mu^+ \nu_\mu$	$(5.50 \pm 0.23) \times 10^{-3}$
$D^0 \to K^- \mu^+ \nu_\mu$	$(3.41 \pm 0.04) \times 10^{-2}$
$D^+ \to \bar{K}^0 \mu^+ \nu_\mu$	$(8.76 \pm 0.19) \times 10^{-2}$
$D^0 \to K^{*-} \mu^+ \nu_\mu$	$(1.89 \pm 0.24) \times 10^{-2}$
$D^+ \to \bar{K}^{*0} \mu^+ \nu_\mu$	$(5.27 \pm 0.15) \times 10^{-2}$
$D_s^+ \to \phi \mu^+ \nu_\mu$	$(1.90 \pm 0.50) \times 10^{-2}$

4 Results

We are considering the assumption that the new physics come only through the second generation of leptons and the WCs are real. We have analysed the q^2 spectrum of differential branching fraction by considering four different scenarios based on the nature of the mediator particle [4]. The set of four scenarios that we analyze with involved operators are as follows:

4.1 Scenario 1: V_μ

The vector Boson mediator V_μ(1,1,-1) involves only the one right-handed vector operator O_{RR}^V. This scenario gives a new contribution with $c \to s\mu\nu_R$ interaction. The best fit value for this wilson coefficient with a $\chi^2 = 12.15$ is calculated by using Eq. 9 is

$$C_{RR}^V = (-12.64 \pm 3.78) \times 10^{-2} \tag{10}$$

This scenario depends only on one operator, and the branching ratio for semileptonic decay $B_c^+ \to B_s \mu^+ \nu_\mu$ in this scenario is similar to the SM (figure 1). The new physics band overlaps entirely with the SM band.

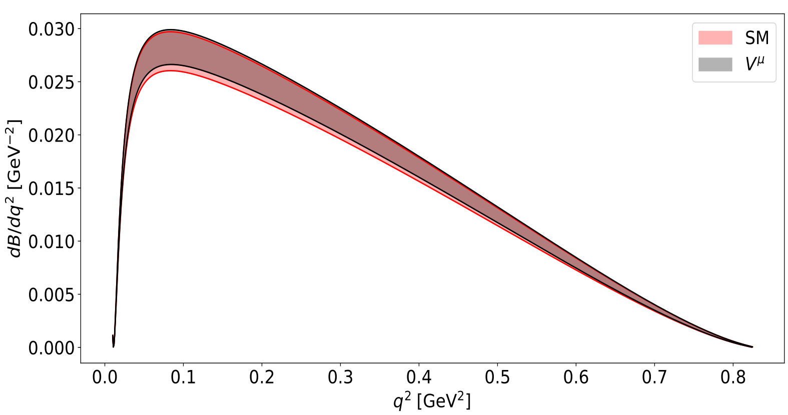

Figure 1. q^2 spectrum for the V^μ vector boson scenario. The standard model (SM) result includes the uncertainity of the form factors.The new physics scenario V^μ (grey band) is obtained by adding the WCs C_{RR}^V.

4.2 Scenario 2: $\tilde{R}_2$

Scenario 2 is for the nature of the mediator particle $\tilde{R}_2$ (3,2,1/6) scalar leptoquark. This scenario provides the NP contribution through C^S_{RR} and C^T_{RR} operators but these operators are related through the Fierz identity $C^S_{RR} = 4rC^T_{RR}$ where r ≈ 2 at b-quark scale.

The best fit values with $\chi^2 = 1.74$ calculated from the Eq. 9 are:

$$C^T_{RR} = (-8.10 \pm 1.11) \times 10^{-2} \tag{11}$$

In this scenario the new physics band is deviated from the SM band and it can provide a signal of new physics above the $q^2 = 0.3GeV^2$ in the q^2 spectrum of the branching ratio as shown in figure 2. In the higher range of $q^2 \approx$ (0.35 - 0.8) the NP band is distinguished from the SM band.

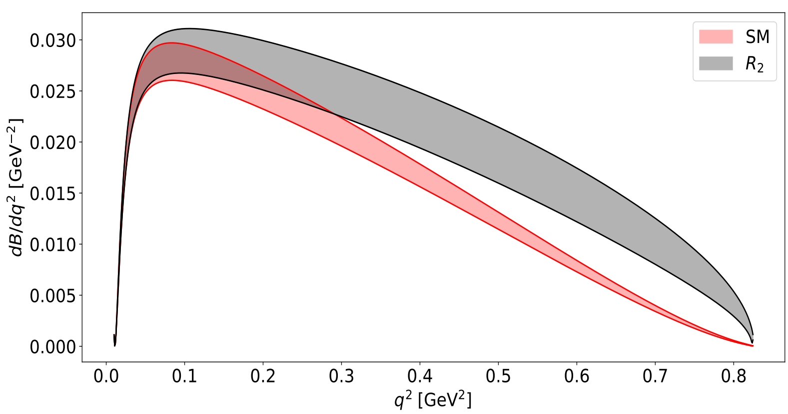

Figure 2. q^2 spectrum for the $\tilde{R}_2$ scalar boson scenario. The standard model (SM) result includes the uncertainity of the form factors.The new physics scenario $\tilde{R}_2$ (grey band) is obtained by using the WCs C^T_{RR}, $C^S_{RR} = 4rC^T_{RR}$.

4.3 Scenario 3: S_1

The scenario 3 is for the mediator scalar leptoquark $S_1 = (\bar{3}, 1, 1/3)$ particle. Here the involved right-handed operators are O^V_{RR}, O^S_{RR} and O^T_{RR}. However, in this scenario, the scalar operator is also related to the tensor operator through Fierz identity relation $C^S_{RR} = -4rC^T_{RR}$, so vector and scalar are the two free operators. The best fit values of these operators with χ^2 = 1.63 are;

$$C^V_{RR} = (6.95 \pm 9.41) \times 10^{-2}$$
$$C^T_{RR} = (-7.57 \pm 1.51) \times 10^{-2} \tag{12}$$

This scenario is also giving a deviation of branching ratio q^2 spectrum from the SM as shown in figure 3. The deviation above the $q^2 = 0.38\,GeV^2$ can be distinguished from the SM.

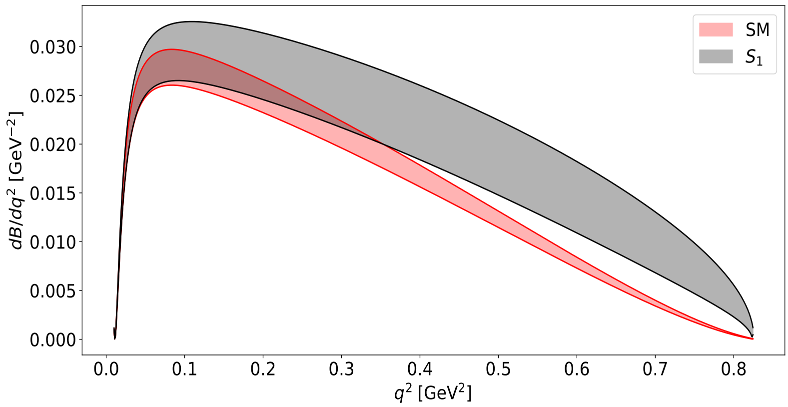

Figure 3. q^2 spectrum for the S_1 scalar leptoquark scenario. The standard model (SM) result includes the uncertainity of the form factors.The new physics scenario S_1 (grey band) is obtained by adding the WCs C^V_{RR}, C^T_{RR} and $C^S_{RR} = -4rC^T_{RR}$.

4.4 Scenario 4: $\tilde{V}_2^\mu$

The scenario 4 involves only one scalar right handed operator $\mathcal{O}^S_{LR}$ and the nature of the mediator particle is vector leptoquark $\tilde{V}_2^\mu = (\bar{3}, 2, -1/6)$. The most likely value ($\chi^2 = 14.43$) of the WCs is

$$C^S_{LR} = (-0.65 \pm 0.45) \times 10^{-3} \tag{13}$$

This scenario is also similar to the SM because the NP band is entirly overlap with the SM band over the full range of the q^2 (figure 4).

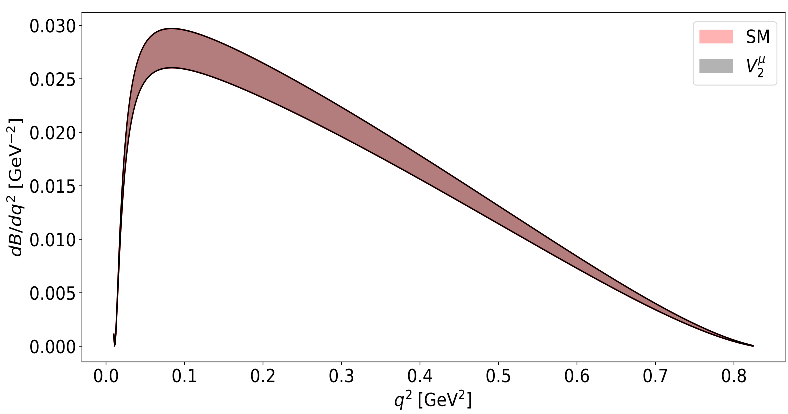

Figure 4. q^2 spectrum for the $\tilde{V}_2^\mu$ vector leptoquark scenario. The standard model (SM) result includes the uncertainity of the form factors.The new physics scenario $\tilde{V}_2^\mu$ (grey band) is obtained by using the WCs C^S_{LR}.

5 Conclusion

The role of the right-handed neutrinos in the semileptonic decay $B_c^+ \to B_s \mu^+ \nu_\mu$ is analyzed in the low energy effective field theory approach in model independent approach. We constrained the new physics by using the available relevant measurements in the charm sector. We predict the q^2 spectrum of the differential branching fraction for four different scenarios which arises in the models $V_\mu(1, 1, -1)$, $\tilde{R}_2(3, 2, 1/6)$, $S_1(\bar{3}, 1, 1/3)$ and $\tilde{V}_2^\mu(\bar{3}, 1, -1/6)$. We observed that among all the four scenarios, the scenario $\tilde{R}_2$ & S_1 provide a enhancement in the branching ratio. It might be interesting to look for the forward-backward asymmetry (A_{FB}) which may give distinguish about the different scenarios.

References

[1] F. Abe et al. (CDF), Observation of B_c Mesons in p-bar p Collisions at sqrt {s}= 1.8 TeV PRD **58**, 11 (1998). https://doi.org/10.1103/PhysRevLett.81.2432

[2] Neelesh Sharma, RC Verma, Predictions of Bc meson decay emitting pseudoscalar and heavy scalar mesons using ISGW II model PRL **82**, 9 (2010) https://doi.org/10.1103/PhysRevD.82.094014

[3] P. Colangelo, F. De Fazio, and F. Loparco, Role of $B_c^+ \to B_{s,d}^{(*)} \ell \nu_\ell$ in the Standard Model and in the search for BSM signals, PRD **103**, 7 (2021). https://doi.org/10.1103/PhysRevD.103.075019

[4] M. Rusa, C. Murgui, A. Peñuelas, A. Pich, The role of right-handed neutrinos in $b \to c\tau\nu$ anomalies, JHEP **2020**, 8 (2020). https://doi.org/10.1007/JHEP08(2020)062

[5] N. Penalva, E. Hernández, J. Nieves, The role of right-handed neutrinos in $b \to c\tau(\pi\nu_\tau, \rho\nu_\tau, \mu\nu_\mu, \nu_\tau)\nu_\tau$ from visible final-state kinematics, JHEP **2021**, 10 (2021). https://doi.org/10.1007/JHEP10(2021)147

[6] A. Datta, H. Liu, D. Marfatia, $B \to D^{(*)}\ell\bar{X}$ decays in effective field theory with massive right-handed neutrinos, PRD **106**, L011702 (2022). https://doi.org/10.1103/PhysRevD.106.L011702

[7] L. J. Cooper, C. T. Davies, J. Harrison, J. Komijani, M. Wingate (HPQCD) $B_c \to B_{s(d)}$ form factors from lattice QCD , PRD **102**, 1 (2020). https://doi.org/10.1103/PhysRevD.102.014513

[8] S. Fajfer, I. Nisandzic, U. Rojec, Discerning new physics in charm meson leptonic and semileptonic decays, PRD **91**, 9 (2015). https://doi.org/10.1103/PhysRevD.91.094009

[9] R. Fleischer, R. Jaarsma, G. Koole Testing Lepton Flavour Universality with (Semi)-Leptonic $D_{(s)}$ Decays, EPJC **80**, 2 (2020). https://doi.org/10.1140/epjc/s10052-020-7702-7

[10] X. Leng, X. L. Mu, Z. T. Zou, Y. Li, Investigation on effects of new physics in $c \to (s, d)\ell^{(+)}\nu_{(l)}$ transitions, Chinese Physics C **45**, 6 (2021). https://doi.org/10.1088/1674-1137/abf489

[11] Bečirević, Damir and Jaffredo, Florentin and Peñuelas, Ana and Sumensari, Olcyr, New Physics effects in leptonic and semileptonic decays, JHEP **2021**, 05 (2021). https://doi.org/10.1007/JHEP05(2021)175

[12] P.A. Zyla et al. (Particle Data Group), Review of Particle Physics, Prog. Theor. Exp. Phys. **2020**, 8 (2020). https://doi.org/10.1093/ptep/ptaa104

[13] F. James MINUIT: function minimization and error analysis reference manual, CERN **1998**. https://cds.cern.ch/record/2296388/files/minuit.pdf

[14] F. James and M. Roos, Minuit: A System for Function Minimization and Analysis of the Parameter Errors and Correlations, Comput. Phys. Commun. **343**, 10 (1975). https://doi.org/10.1016/0010-4655(75)90039-9