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BSM searches with (semi)leptonic charm decays

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Physics Beyond Standard Model usually explain anomalies in B-meson semileptonic decays. The same kind of new physics has a minor impact on charm semileptonic decays, rare charm decays, and $D^0 - \bar{D}^0$ oscillations. I present the latest results on the search of BSM in the exclusive rare $D \to Pl^+l^-$, $D \to P_1P_2l^+l^-$, $D \to missing\ \ energy$, and $D \to P\ missing\ \ energy$ decays. Most important constraints come from the experimental results on $\mathcal{B}(D^0 \to \mu^+\mu^-)$, $D^0 - \bar{D}^0$ oscillations allowing to predict the BSM contributions in $D \to Pl^+l^-$, $D \to P_1P_2l^+l^-$, and $D \to missing\ \ energy$ decays.

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1. Introduction

In the last decade, several experiments indicated a possible violation of the lepton number universality in B-meson semileptonic decays. The deviations from the Standard Model (SM) predictions are explained by the Beyond Standard Model (BSM) contributions. Most general treatment of BSM relies on effective Lagrangians. These effective Lagrangian approaches respect the symmetries of the SM. Most favourable solutions of the BSM is the modification of the SM $V - A$ currents [1, 2]. As an example of BSM fits, we recall that in the SM flavour changing neutral current (FCNC) processes $b \to s\mu^+\mu^-$. The left-handed operators $(\bar{s}_L\gamma^\alpha b_L)(\bar{\mu}_L\gamma_\alpha\mu_L)$ lead to to the explanation of the dimension-6 effective Hamiltonian (see [1] for the latest update). If we want to compare the effects of such BSM physics in $c \to u\ell^+\ell^-$ one has to account the product of the CKM matrix elements $V_{ub}V_{cs}^* \simeq 0.004$. Such a factor leads to the relatively small BSM effects in rare charm decays. Nevertheless, the studies independent of B physics anomalies are necessary to perform to establish BSM bounds. In Section 2, I introduce effective Lagrangians for $c \to u\ell^+\ell^-$. Section 3 is devoted to study of NP in $D^+ \to \pi^+\mu^+\mu^-$, $D \to P_1P_2\mu^+\mu^-$, while Section 4 is dedicated to D-meson decays to invisible fermions. Section 5 contains a brief summary and outlook.

2. The $c \to u\ell^+\ell^-$ and $c \to u\nu\bar{\nu}$ decays and BSM

The effective Hamiltonian [3–5] can explain the SM dynamics in the $c \to u\ell^+\ell^-$ and $c \to u\nu\bar{\nu}$ decays

$$\mathcal{L}_{\rm eff} = \frac{4G_F}{\sqrt{2}}\frac{\alpha_e}{4\pi}V_{ub}V_{cb}^*\Big[\sum_{k=7,9,10}(C_kO_k + C_k'O_k') + \sum_{ij}(C_L^{ij}Q_L^{ij} + C_R^{ij}Q_R^{ij})\Big], \tag{1}$$

where the dimension six operators O_k for di-lepton and $Q^{ij}_{L/R}$ for di-neutrino modes are given as

$$\begin{aligned} O_7 &= \tfrac{m_c}{e}(\bar{u}_L\sigma_{\mu\nu}c_R)F^{\mu\nu}, & O_7' &= \tfrac{m_c}{e}(\bar{u}_R\sigma_{\mu\nu}c_L)F^{\mu\nu},\\ O_9 &= (\bar{u}_L\gamma_\mu c_L)(\bar{l}\gamma^\mu\ell), & O_9' &= (\bar{u}_R\gamma_\mu c_R)(\bar{l}\gamma^\mu\ell),\\ O_{10} &= (\bar{u}_L\gamma_\mu c_L)(\bar{l}\gamma^\mu\gamma_5\ell), & O_{10}' &= (\bar{u}_R\gamma_\mu c_R)(\bar{l}\gamma^\mu\gamma_5\ell),\\ Q_L^{ij} &= (\bar{u}_L\gamma_\mu c_L)(\bar{\nu}_{Lj}\gamma^\mu\nu_{Li}), & Q_R^{ij} &= (\bar{q}_R\gamma_\mu c_R)(\bar{\nu}_{Lj}\gamma^\mu\nu_{Li}). \end{aligned} \tag{2}$$

As usual $F^{\mu\nu}$ is the electromagnetic field strength tensor and $\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$. In the primed operators O_i' left-handed quark fields in O_i are replaced by the right-handed quark fields. SM contributions to the effective coefficients of O_7 and O_9 are explained in detail in [4–7]. The SM two-loop virtual corrections depend on the di-lepton invariant mass squared, q^2, as given in [3, 8]. The authors of [3, 4, 7, 8] found that SM contributions in $c \to u\ell^+\ell^-$ are of the order of few permille for $|C_7^{\rm eff}|$ and few percent for $|C_9^{\rm eff}|$ above $q^2 > 0.1\,\mathrm{GeV}^2$. Due to the GIM-mechanism $C_{10}^{\rm SM} = 0$. Contributions of primed operators are significantly suppressed, allowing us to neglect them.

3. BSM in $D^+ \to \pi^+\mu^+\mu^-$, $D \to P_1P_2\mu^+\mu^-$

Experiments are able to reach only the upper bound on the branching ratio $\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2(7.6) \times 10^{-9}$ [9]. Luckily, the LHCb collaboration found limits on the branching fractions

$\vert\tilde{C}_i\vert_{max}$	$BR(D \to \pi\mu\mu)$	$BR(D \to \pi\mu\mu)$
$\vert\tilde{C}_7\vert_{max}$	1.4	-
$\vert\tilde{C}_9\vert_{max}$	1.2	-
$\vert\tilde{C}_{10}\vert_{max}$	0.83	0.51
$\vert\tilde{C}_S\vert_{max}$	0.34	0.038
$\vert\tilde{C}_P\vert_{max}$	0.33	0.038
$\vert\tilde{C}_T\vert_{max}$	0.76	-
$\vert\tilde{C}_{T5}\vert_{max}$	0.69	-
$\vert\tilde{C}_9\vert_{max} = \pm\tilde{C}_{10}\vert_{max}$	0.73	0.51

Table 1: Bounds on Wilson coefficients calculated for different models of NP, following [3] ($\tilde{C}_i \equiv V_{cb}V_{ub}^* C_i$).

in several di-lepton invariant mass bins in $(D^+ \to \pi^+\mu^+\mu^-) < 7.3(8.3) \times 10^{-8}$ [10]. Careful studies require the extension of the effective Lagrangian in (2) by the scalar, pseudoscalar and tensor operators $O_S = \frac{e^2}{(4\pi)^2}(\bar{u}P_R c)(\bar{\ell}\ell)$, $O_P = \frac{e^2}{(4\pi)^2}(\bar{u}P_R c)(\bar{\ell}\gamma_5\ell)$, $O_T = \frac{e^2}{(4\pi)^2}(\bar{u}\sigma_{\mu\nu}c)(\bar{\ell}\sigma^{\mu\nu}\ell)$, and $O_{T5} = \frac{e^2}{(4\pi)^2}(\bar{u}\sigma_{\mu\nu}c)(\bar{\ell}\sigma^{\mu\nu}\gamma_5\ell)$. In Table 1 we present the bounds on the extended set of the Wilson coefficients. Actually, it was pointed out already in [3] that the upper bound on the $\mathcal{B}(D^0 \to \mu^+\mu^-)$, are more restrictive, lowering the bounds on the Wilson coefficients by factor 10.

Similarly as in the case of B mesons, various scenarios of BSM were considered in the literature. Relaying on the work of [3, 4] the limits on leptoquark contributions, Two-Higgs doublet model type III, Z'-model are presented in Table 2.

LHCb collaboration in [11] found

$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-)|_{[0.565-0.950]\,\mathrm{GeV}} = (40.6 \pm 5.7) \times 10^{-8}, \tag{3}$$
$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-)|_{[0.950-1.100]\,\mathrm{GeV}} = (45.4 \pm 5.9) \times 10^{-8}, \tag{4}$$
$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-)|_{[>0.565]\,\mathrm{GeV}} = (12.0 \pm 2.7) \times 10^{-8}, \tag{5}$$

On the theory side, analyses of the paper [7] indicate that the SM angular distribution in semileptonic four-body D-decays is significantly simpler than in B-decays. Namely, the long-distance dominance in charm simplifies the picture. The authors of [7] discovered a few angular coefficients that can serve as null tests of the SM. In the same study, NP-induced CP violation was studied and suggested to be searched by experiment. However, the LHCb found that the CP asymmetries, the forward-backward asymmetry of the di-muon pair, the triple-product asymmetry, and the charge-parity-conjugation asymmetry are consistent with SM predictions [12].

4. D meson decays to invisible fermions

Instead of charged lepton pair in the final state, the decay $c \to u\nu\bar{\nu}$ can occur in the SM [6]. The severe Glashow-Iliopoulos-Maiani mechanism is at work in the amplitude for $c \to u\nu\bar{\nu}$. The

Model of BSM	effect on W.C.	size of the effect
Scalar LQ (3,2,7/6)	$C_{S,P}, C'_{S,P}, C_{T,T5}, C_{9,10}, C'_{9,10}$	$V_{cb}V^*_{ub}\|C_9, C_{10}\| < 0.31$
Vector LQ (3,1,5/3)	$C'_9 = C'_{10}$	$V_{cb}V^*_{ub}\|C'_9\| < 0.22$
Two Higgs doublet III	$C_{S,P}, C'_{S,P}$	$V_{cb}V^*_{ub}\|C_S - C'_S\| < 0.0045$, $V_{cb}V^*_{ub}\|C_P - C'_P\| < 0.0045$
Z'	$C'_{9,10}$	$V_{cb}V^*_{ub}\|C'_9\| < 0.001$, $V_{cb}V^*_{ub}\|C'_{10}\| < 0.001$

Table 2: Bounds on Wilson coefficients for different models of NP, following [3].

authors of [13] calculated the SM branching ratio $\mathcal{B}(D^0 \to \nu\bar{\nu}) = 1.1 \times 10^{-31}$. Since experimental searches instead of neutrino pair can see missing energy, the authors of [13] instead of neutrinos considered dark matter candidates. Eventually, it might be important to investigate the process with $\chi\bar{\chi}\gamma$ in the final state. Namely, a massless photon lifts the helicity suppression. In our paper [14] we considered branching ratios for such decay modes. The authors of Ref. [6] deterrmined the expected event rate for the charm hadron decays to a final hadronic state and neutrino - anti-neutrino states. They found out that in Belle II experiment, these processes can be seen. The future FCC-ee might measure branching ratios of $O(10^{-6})$ down to $O(10^{-8})$, in particular D^0, $D^+_{(s)}$ and Λ^+_c decay modes. The Belle collaboration produced the bound of the branching ratio for $\mathcal{B}(D^0 \to invisibles) \leq 9.4 \times 10^{-5}$. The authors of Refs. [6] considered in detail general framework of BSM in $c \to u$ *invisibles*, using $SU(2)_L$ invariance and data on charged lepton processes [15]. They determined that these assumptions lead to upper limits of few 10^{-5}, while assuming lepton universality, branching ratios can reach 10^{-6}. The effective Lagrangian describing the invisible fermions in $c \to u$ transitions is of the form

$$\begin{aligned}\mathcal{L}_{\rm eff} =& \sqrt{2}G_F\Big[c^{LL}(\bar{u}_L\gamma_\mu c_L)(\bar{\nu}_L\gamma^\mu\nu'_L) + c^{RR}(\bar{u}_R\gamma_\mu c_R)(\bar{\nu}_R\gamma^\mu\nu'_R)\\ &+ c^{LR}(\bar{u}_L\gamma_\mu c_L)(\bar{\nu}_R\gamma^\mu\nu'_R) + c^{RL}(\bar{u}_R\gamma_\mu c_R)(\bar{\nu}_L\gamma^\mu\nu'_L) + g^{LL}(\bar{u}_L c_R)(\bar{\nu}_L\nu'_R)\\ &+ g^{RR}(\bar{u}_R c_L)(\bar{\nu}_R\nu'_L) + g^{LR}(\bar{u}_L c_R)(\bar{\nu}_R\nu'_L) + g^{RL}(\bar{u}_R c_L)(\bar{\nu}_L\nu'_R)\\ &+ h^{LL}(\bar{u}_L\sigma^{\mu\nu}c_R)(\bar{\nu}_L\sigma_{\mu\nu}\nu'_R) + h^{RR}(\bar{u}_R\sigma^{\mu\nu}c_L)(\bar{\nu}_R\sigma_{\mu\nu}\nu'_L)\Big] + \text{h. c.}.\end{aligned} \tag{6}$$

The authors of [6] analysed the right-handed massless neutrinos. We considered massive right-handed fermions denoting $\nu_R \equiv \chi_R$ [14]. One of coloured scalar mediators (see Table I of [14]) which can contribute to the transition $c \to u\chi\bar{\chi}$ at the tree level is $\bar{S}_1(\bar{3}, 1, -2/3)$. The Lagrangian is

$$\mathcal{L}(\bar{S}_1) \supset \bar{y}^{RR}_{1\,ij}\bar{u}^{C\,i}_R\,\chi^j_R\,\bar{S}_1 + \text{h.c.}. \tag{7}$$

The matching of this Lagrangian to the effective Lagrangian (6) results in the Wilson coefficient

$$c^{RR} = \frac{v^2}{2M^2_{\bar{S}_1}}\bar{y}^{RR}_{1\,c\chi}\,\bar{y}^{RR*}_{1\,u\chi}. \tag{8}$$

In Tables 3, 4, and 5 we give the bounds on the $\mathcal{B}(D^0 \to \chi\bar{\chi})$, $\mathcal{B}(D^0 \to \chi\bar{\chi}\gamma)$, and $\mathcal{B}(D \to \pi\chi\bar{\chi})$ for three typical values of m_χ.

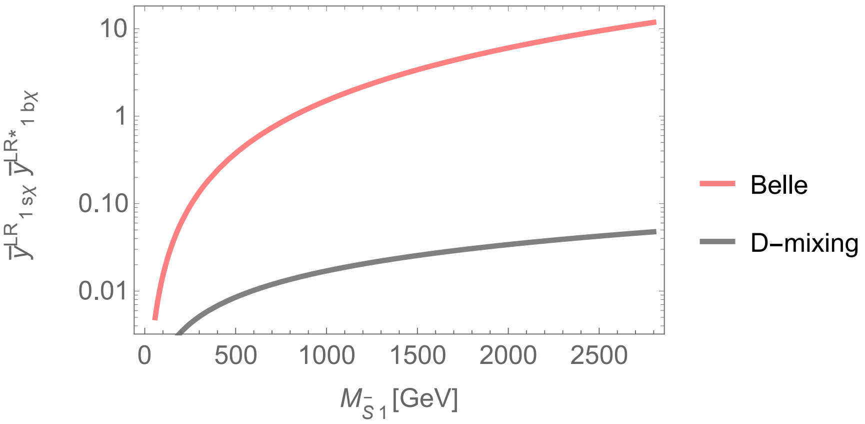

Figure 1: The allowed product of two Yukawaas as a function of the coloured scalar mass derived by using Belle experimental bound and constraints from $D^0 - \bar{D}^0$ oscillations

The most robust constraints on c^{RR} are derived from the $D^0 - \bar{D}^0$ oscillations [14]. In Fig. 1 we present the dependence of the product of the two Yukawa couplings as a function of the coloured scalar mass derived by using Belle experimental bound and constraints from $D^0 - \bar{D}^0$ oscillations [14]. In Table 3 we present the upper bounds on the branching ratio $\mathcal{B}(D^0 \to \chi\bar{\chi})$ for three

m_χ (GeV)	$\mathcal{B}(D^0 \to \chi\bar{\chi})_{D-\bar{D}}$
0.2	$< 2.8 \times 10^{-9}$
0.5	$< 1.5 \times 10^{-8}$
0.8	$< 2.3 \times 10^{-8}$

Table 3: Branching ratios for $\mathcal{B}(D^0 \to \chi\bar{\chi})$ for three selected values of m_χ. The constraints from the $D^0 - \bar{D}^0$ mixing is used, with $c^{RR} \leq 5.18 \times 10^{-4}$, assuming $M_{\bar{S}_1} = 1000$ GeV.

m_χ (GeV)	$\mathcal{B}(D^0 \to \chi\bar{\chi}\gamma)_{D-\bar{D}}$	$\mathcal{B}(D^0 \to \chi\bar{\chi}\gamma)_{Belle}$
0	$< 3.9 \times 10^{-12}$	–
0.2	$< 3.0 \times 10^{-12}$	$< 1.3 \times 10^{-7}$
0.5	$< 1.0 \times 10^{-12}$	$< 6.3 \times 10^{-9}$
0.8	$< 5.4 \times 10^{-14}$	$< 2.2 \times 10^{-10}$

Table 4: Bounds on the branching ratio for $\mathcal{B}(D^0 \to \chi\bar{\chi}\gamma)$. In the second column we use, the constraint from the $D^0 - \bar{D}^0$ mixing assuming $M_{\bar{S}_1} = 1000$ GeV. We use the Belle bound $\mathcal{B}(D^0 \to \textit{missing energy} < 9.4 \times 10^{-5}$ in the third column. With this bound the Wilson coefficient for $m_\chi = 0$ cannot be fixed, reflecting in the third column's missing bound.

masses $m_\chi = 0.2,\ 0.5,\ 0.8$ GeV, using the constraints from the $D^0 - \bar{D}^0$ mixing, $c^{RR} \leq 5.18 \times 10^{-4}$, with $M_{\bar{S}_1} = 1000$ GeV. We give the branching ratios for $D^0 \to \chi\bar{\chi}$, $D^0 \to \chi\bar{\chi}\gamma$ and $D \to \pi\chi\bar{\chi}$ in Tables 3, 4, and 5. The charm meson mixing leads to strong constraints on the branching ratio

m_χ (GeV)	$\mathcal{B}(D^0 \to \pi^0 \chi\bar{\chi})_{D-\bar{D}}$	$\mathcal{B}(D^+ \to \pi^+ \chi\bar{\chi})_{D-\bar{D}}$
0	$< 1.5 \times 10^{-8}$	$< 5.8 \times 10^{-8}$
0.2	$< 1.2 \times 10^{-8}$	$< 6.1 \times 10^{-8}$
0.5	$< 6.6 \times 10^{-9}$	$< 3.3 \times 10^{-8}$
0.8	$< 3.0 \times 10^{-10}$	$< 1.5 \times 10^{-9}$

Table 5: Branching ratios for $\mathcal{B}(D \to \pi\chi\bar{\chi})$. In the second and the third columns the constraint from the $D^0 - \bar{D}^0$ mixing is used, assuming the mass of $M_{\bar{S}_1} = 1000$ GeV. In the case $m_\chi = 0.2$ GeV, the cut in integration variable is done by taking q^2_{cut}, as described in the paper [14].

$D^0 \to \chi\bar{\chi}$. Current Belle bound on the branching ratio $D^0 \to$ *missing energy* gives up to three orders of magnitude more significant rates than the charm mixing. The branching ratios $D \to \pi\chi\bar{\chi}$, derived by using charm mixing constraint, are of the order 10^{-8}. Such are rates might be searched at future tau-charm factories. Hopefully, current experiments BESIII and Belle II can reach a sensitivity of the order 10^{-6}.

5. Conclusions

In the last few years, theoretical studies of rare charm meson decays resulted in the highly precise knowledge of SM contributions. The most general studies of BSM were performed within the effective Lagrangian framework. The long-distance contributions are found by using existing models, and hopefully, the lattice calculation will improve the current precision of hadronic quantities. Lepton flavour universality in rare charm semileptonic decays is necessary to check. However, the existing experimental data lead to negligible deviations from the SM [4]. Lately, charm meson decays to invisibles motivated several analyses. Any deviations from the SM prediction in these decays would be a smoking gun of the BSM.

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References

[1] A. Angelescu, D. Bečirević, D. A. Faroughy, F. Jaffredo and O. Sumensari, Phys. Rev. D **104** (2021) no.5, 055017 doi:10.1103/PhysRevD.104.055017 [arXiv:2103.12504 [hep-ph]].

[2] S. Fajfer, PoS **ICHEP2018** (2019), 715 doi:10.22323/1.340.0715

[3] S. Fajfer and N. Košnik, Eur. Phys. J. C **75** (2015) no.12, 567 doi:10.1140/epjc/s10052-015-3801-2 [arXiv:1510.00965 [hep-ph]].

[4] R. Bause, M. Golz, G. Hiller and A. Tayduganov, Eur. Phys. J. C **80** (2020) no.1, 65 [erratum: Eur. Phys. J. C **81** (2021) no.3, 219] doi:10.1140/epjc/s10052-020-7621-7 [arXiv:1909.11108 [hep-ph]].

[5] M. Golz, G. Hiller and T. Magorsch, JHEP **09** (2021), 208 doi:10.1007/jhep09(2021)208 [arXiv:2107.13010 [hep-ph]].

[6] R. Bause, H. Gisbert, M. Golz and G. Hiller, Phys. Rev. D **103** (2021) no.1, 015033 doi:10.1103/PhysRevD.103.015033 [arXiv:2010.02225 [hep-ph]].

[7] S. De Boer and G. Hiller, Phys. Rev. D **98** (2018) no.3, 035041 doi:10.1103/PhysRevD.98.035041 [arXiv:1805.08516 [hep-ph]].

[8] S. de Boer, Eur. Phys. J. C **77** (2017) no.11, 801 doi:10.1140/epjc/s10052-017-5364-x [arXiv:1707.00988 [hep-ph]].

[9] R. Aaij *et al.* [LHCb], Phys. Lett. B **725** (2013), 15-24 doi:10.1016/j.physletb.2013.06.037 [arXiv:1305.5059 [hep-ex]].

[10] R. Aaij *et al.* [LHCb], Phys. Lett. B **724** (2013), 203-212 doi:10.1016/j.physletb.2013.06.010 [arXiv:1304.6365 [hep-ex]].

[11] R. Aaij *et al.* [LHCb], Phys. Rev. Lett. **119** (2017) no.18, 181805 doi:10.1103/PhysRevLett.119.181805 [arXiv:1707.08377 [hep-ex]].

[12] R. Aaij *et al.* [LHCb], Phys. Rev. Lett. **121** (2018) no.9, 091801 doi:10.1103/PhysRevLett.121.091801 [arXiv:1806.10793 [hep-ex]].

[13] A. Badin and A. A. Petrov, Phys. Rev. D **82** (2010), 034005 doi:10.1103/PhysRevD.82.034005 [arXiv:1005.1277 [hep-ph]].

[14] S. Fajfer and A. Novosel, Phys. Rev. D **104** (2021) no.1, 015014 doi:10.1103/PhysRevD.104.015014 [arXiv:2101.10712 [hep-ph]].

[15] R. Bause, H. Gisbert, M. Golz and G. Hiller, Phys. Rev. D **101** (2020) no.11, 115006 doi:10.1103/PhysRevD.101.115006 [arXiv:2004.01206 [hep-ph]].