Rare Charm Decays

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Although the Standard Model has been firmly established, the search for physics beyond the SM is ongoing by investigating new experimental probes. Rare charm decays are a unique tool to access New Physics studies. The high luminosity achieved by the modern experiments and their high precision allow for rare charm decay studies in different scenarios. In this work, some of the most recent experimental results will be discussed in detail.

I. INTRODUCTION

Three of the four fundamental forces (electromagnetic, weak and strong interactions) existing in the universe are described by the Standard Model (SM) theory, which offers as well a classification of all the known particles. The discovery of the Higgs boson in 2012 allowed to firmly establish the SM. Despite this, some of the observed phenomena such as baryon-antibaryon asymmetry, possible existence of dark matter particles, neutrino oscillations and their non-zero masses, are still unexplained. For this reason, theoretical and experimental efforts are pointing toward extensions of the SM, collectively referred to as New Physics (NP) models, in order to define a more fundamental theory [1].

NP searches involve different kind of processes: allowed in SM, forbidden in SM at tree level, and forbidden in SM [2]. In the first case, some processes are expected to hold in SM, but not necessarily in models beyond SM. In the second case, processes (such as the ones involving flavor-changing neutral current) which change charm quantum number by one or two units are forbidden in SM at tree level, but can happen in SM at loop levels, thus becoming rare. The latter case, includes processes which are allowed by space-time symmetries, but forbidden in SM, such as baryon or lepton number violating transitions: they require high statistics, but an observation would be a hint of physics beyond the SM [2]. In the first case, some processes are expected to hold in SM, forbidden in SM at tree level, and forbidden in SM [2]. In the second case, processes (such as the ones involving flavor-changing neutral current) which change charm quantum number by one or two units are forbidden in SM at tree level, but can happen in SM at loop levels, thus becoming rare. The latter case, includes processes which are allowed by space-time symmetries, but forbidden in SM, such as baryon or lepton number violating transitions: they require high statistics, but an observation would be a hint of physics beyond the SM [2].

The order of the branching fractions of the SM forbidden processes range from $10^{-5}$ to lower values.

II. RARE CHARM DECAYS

In this scenario, the search for hints of NP was focused on the study of rare processes in kaon and beauty sectors, in order to find possible discrepancies with the SM predictions. For long time, rare charm decays have been considered less promising, due to the different dynamics involved (lack of effective methods to describe its low energy dynamics) and to the possibly different couplings with respect to $d$-type quarks [3]. Rare charm decays are sensitive to $|\Delta c| = |\Delta u| = 1$ transitions, but the low statistics available allows only to set upper limits to the different decay processes. In order to search for NP, clean null-test observable can be constructed exploiting exact or approximate symmetries of the SM. Those studies are complementary to the ones already performed. One of the main issues in this type of decays is the separation of the short-distance (SD) and long-distance (LD) information. Indeed, the Glashow–Iliopoulos–Maiani (GIM) mechanism strongly suppress the Feynman diagrams which describe those decays, so the LD contributions become dominant. Away from LD contributions, NP should become visible.

Rare charm decays can be investigated by the modern experiments, due to the high luminosity and precision achieved. The different experimental scenarios allow those studies in $e^+e^-$ (BESIII [4], CLEO-c [5], BELLE [6], BELLE2 [7], and BABAR [8]) and $p-p$ (LHCb [9], CDF [10], and D0 [11]) collisions. The first scenario is characterized by extremely clean environments, in some cases the double-tag technique allows almost background free studies, quantum coherence, high trigger efficiency, and easy detection of neutral particles. On the other side, the latter scenario offers large production rate, and excellent time resolution.

In the following, some of the latest results will be discussed.

III. FLAVOR CHANGING NEUTRAL CURRENT

Strong or electromagnetic interactions dominate the $\psi(nS) (n = 1, 2)$ decays below the open charm threshold. Flavor changing weak decays are anyway allowed in the SM through the exchange of a virtual $W$ boson. Flavor changing neutral current (FCNC) transitions $c \rightarrow u\gamma$ and $c \rightarrow ul$ (where $l$ indicate a lepton) mediate some of the $D$ mesons decays. In this scenario, the GIM cancellation mechanism strongly suppress those decays; the suppression in charm decays is much more effective than in kaon or beauty systems decays due to a stronger diagram cancellation. The SD contributions of FCNC in the SM are expected to be well beyond the current experimental sensitivity, but some theoretical model suggests that they could be enhanced by LD effects by several orders of magnitude. Hence, larger FCNC transition rates are predicted by some NP scenario: the observation of such...
an enhancement would directly indicate NP.

**A. $D^0 \rightarrow h^+ h^- \mu^+ \mu^-$**

The LHCb Collaboration, taking advantage of p-p annihilation data collected during Run 1 (7 and 8 TeV) and Run 2 (13 TeV) for a total of 9 fb$^{-1}$, investigated the decay $D^+ \rightarrow D^0 \pi^+$, $D^0 \rightarrow h^+ h^- \mu^+ \mu^-$, where $h$ indicate either a pion or a kaon [12]. The semileptonic decays are described by means of five independent kinematic variables: $q^2 = m^2(\mu^+ \mu^-)$ and $p^2 = m^2(h^+ h^-)$, the dimuon and dihadron squared invariant masses, and the three decay angles $\vartheta_\mu$, $\vartheta_h$, and $\varphi$, defined as depicted in Fig. 1. The differential decay rate can be described as the sum of nine angular coefficients $I_{1-9}$, which depend on $q^2$, $p^2$, and $\cos \vartheta_h$, multiplied by $c_{1-9}$ terms, functions of $\vartheta_\mu$ and $\varphi$. $I_1$ is a normalization factor, while $I_{2-9}$ are expressed as angular asymmetries. The decay rate asymmetries are the observables experimentally measured, for example $< I_2 > = \frac{\Gamma(\cos \vartheta_\mu > 0.5) - \Gamma(\cos \vartheta_\mu < 0.5)}{\Gamma(\cos \vartheta_\mu > 0.5) + \Gamma(\cos \vartheta_\mu < 0.5)}$, where $\Gamma$ is the decay rate. For those angular asymmetries it is possible to define their CP average as $< S_1 > = \frac{1}{2}[< I_1 > + < I_- >]$ and the asymmetry as $< A_1 > = \frac{1}{2}[< I_1 > - < I_- >]$. The observables $< S_{5,6,7} >$ and the CP asymmetries $< A_{2-9} >$ are expected to vanish and they can constitute the SM null test, if only SM amplitudes contribute to the decay processes. The $D^0$ invariant masses were fitted with an Hypatia distribution for the signal and a Johnson $S_U$ distribution plus an exponential function for the background. The signal yields for $D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ and $D^0 \rightarrow K^+ K^- \mu^+ \mu^-$ were found to be $3579 \pm 71$ and $318 \pm 19$, respectively. The values for the observables $< S_{5,6,7} >$ and $< A_{2-9} >$ are in agreement with the SM null hypothesis.

**B. $D^0 \rightarrow \pi^0 \nu \bar{\nu}$**

The BESIII Collaboration searched for neutrino pair in the final state of charm decays for the first time [13], taking advantage of 2.93 fb$^{-1}$ of data collected at the energy of 3.773 GeV. The $e^+ e^- \rightarrow D^0 D^0$ process, where $D_0 \rightarrow \pi^0 \nu \bar{\nu}$ was investigated. In this decay, LD contributions become insignificant and the SD contributions from Z-penguin and box diagrams are dominant. The final state was reconstructed by means of the double-tag technique: first the single-tag $D^0$ was reconstructed in three different hadronic channels $(K^+ \pi^-, K^+ \pi^- \pi^0$, and $K^+ \pi^- \pi^- \pi^0)$, then the $D^0$ decay signal was reconstructed recoiling against the single-tag $D^0$, searching for two $\gamma$s from $\pi^0$ decay. Two more variables were investigated: the beam-constrained mass $M_{BC} = \sqrt{E_{beam}^2 - |p_D|^2/c^2}$ and the energy difference $\Delta E = E_{D0} - E_{beam}$, where $E_{beam}$ is the energy of the electron beam. In order to be able to investigate the $D_0 \rightarrow \pi^0 \nu \bar{\nu}$ decay, a reliable modeling of the background contributions is mandatory. To achieve this result, a data-driven method was used: the data-driven analysis procedure was validated by means of one third of the full data sample. Finally, the signal was searched in the energy deposited in the electromagnetic calorimeter. The energy distribution, shown in Fig. 2, depict the data distribution with a global fit and the different contributions. The signal, modeled on MC simulations, is indicated by the gray area and it is normalized to 20 times the central value of the fit result for visibility; 14±30 signal events were found. Since the number of reconstructed events is compatible with zero, the branching ratio upper limit for the $D_0 \rightarrow \pi^0 \nu \bar{\nu}$ decay was calculated to be $2.1 \times 10^{-4}$ at 90% confidence level (C.L.).

**IV. LEPTON FLAVOR VIOLATING PROCESSES**

In the charm sector, lepton flavor conserving processes, such as $D \rightarrow X e^+ e^-$ and $D \rightarrow X \mu^+ \mu^-$, are predicted in the SM. They can occur through SD and LD processes and they are expected to have branching fractions of the order of $\mathcal{O}(10^{-9})$ and $\mathcal{O}(10^{-6})$, respectively [16]. The lepton flavor violating (LFV) neutral decays, such as $D^0 \rightarrow X^0 e^+ e^-$, are prohibited in the SM, since they can occur only through lepton mixing [14]; their branching ratio are expected to be in the order of $\mathcal{O}(10^{-50})$. However, different NP models, such as leptoquarks, two-Higgs doublets, and those involving Majorana neutrinos, allow both LFV and lepton number violation [13], with branching fractions of the order of $\mathcal{O}(10^{-5})$. The discovery of neutrino oscillations confirmed the LFV in the neutral lepton sector as well as the existence of neutrino masses, while a detection of LFV in the charged lepton sector would
FIG. 2: Fit of the energy deposited in the electromagnetic calorimeter and different contributions together with the pull. Dots with error bars indicate the data, the red solid line indicates the global fit, the green long dashed line indicates the $D^0 \rightarrow \pi^0 K^0_S X$ contribution, the blue middle dashed line include the other $D^0$ decays, the magenta dashed line indicates the wrong tags, and the signal is depicted by the grey shaded area.

provide direct evidence of NP.

A. $D^0 \rightarrow X^0 e^\pm \mu^\mp$

The BABAR Collaboration investigated the decay $D^{*+} \rightarrow D^0 \pi^+$, $D^0 \rightarrow X^0 e^\pm \mu^\mp$, where $X^0$ indicates a neutral meson ($\pi^0$, $K^0_S$, $K^{*0}$, $\rho^0$, $\varphi$, $\omega$, or $\eta$), exploiting 424 fb$^{-1}$ of data collected at the $\Upsilon(4S)$ resonance (10.58 GeV) and additional 44 fb$^{-1}$ of data collected 0.04 GeV below the $\Upsilon(4S)$ resonance. The decays $D^0 \rightarrow \pi^\mp \pi^+ \pi^-$ (for $X^0 = K^0_S$, $\rho^0$, $\omega$), $D^0 \rightarrow K^- \pi^+ \pi^+$ (for $X^0 = K^{*0}$), and $D^0 \rightarrow K^- K^+ \pi^+ \pi^-$ (for $X^0 = \varphi$) were used to normalize the branching fractions for the different signal modes. After the full reconstruction of the signal modes, an unbinned maximum-likelihood fit is performed to the variable $\Delta m = m(D^{*+}) - m(D^0)$. The distributions for each signal mode are shown in Fig. 3, where dots with error bars are the experimental data, the red dashed line is the signal, the green dotted line is the background, end the black solid line is the total fit. No significant signal was observed; the extracted upper limits at 90% C.L. are reported in Tab. I. The obtained values are between 1 and 2 orders of magnitude more stringent with respect to the previous results.

V. LEPTON NUMBER VIOLATING PROCESSES

In the SM, neutrinos are postulated to be massless, due to the absence of right-handed neutrino. However, the first evidence for physics beyond the SM is due to the small neutrino masses observed as consequence of

| Decay mode          | BR U.L. ($\times 10^{-7}$) |
|---------------------|----------------------------|
| $D^0 \rightarrow \pi^0 e^\pm \mu^\mp$ | 8.0                        |
| $D^0 \rightarrow K^0_S e^\pm \mu^\mp$ | 8.7                        |
| $D^0 \rightarrow K^{*0} e^\pm \mu^\mp$ | 12.5                       |
| $D^0 \rightarrow \rho^0 e^\pm \mu^\mp$ | 5.0                        |
| $D^0 \rightarrow \varphi e^\pm \mu^\mp$ | 5.7                        |
| $D^0 \rightarrow \omega e^\pm \mu^\mp$ | 17.1                       |
| $D^0 \rightarrow \eta e^\pm \mu^\mp$ | 22.5                       |
| with $\eta \rightarrow \gamma \gamma$ | 24.0                       |
| with $\eta \rightarrow \pi^0 \pi^\pm \pi^\mp$ | 43.0                       |
neutrino oscillation. Moreover, it is still an open question whether neutrinos are Dirac or Majorana particles. If they are Majorana particles, lepton number violating (LNV) processes by two units ($\Delta L = 2$) can be observed. Different NP models involving LNV have been proposed at different energy regime [17]. The exchange of a single Majorana neutrino with a mass on the order of the heavy flavor mass scale could be a source of LNV processes.

A. $D \rightarrow K\pi e^+e^-$

The BESIII Collaboration searched for LNV processes with $\Delta L = 2$ in D meson decays [13], taking advantage of 2.93 fb$^{-1}$ of data collected at the energy of 3.773 GeV. The processes $D^0 \rightarrow K^-\pi^-e^+e^+$, $D^+ \rightarrow K^0_S\pi^-e^+e^+$, and $D^+ \rightarrow K^-\pi^0e^+e^+$ are mediated by a Majorana neutrino $\nu_m$ and can occur through Cabibbo-favoured (CF) and doubly Cabibbo-suppressed (DCS) decays. The latter are expected to be suppressed by a factor 0.05 with respect to CF processes. In this analysis, the single-tag method was used. For the signal determination, two variables were taken into account: the beam energy constrained mass $M_{BC} = \sqrt{E_{beam}^2 - |\vec{p}_D|^2}$ and the energy difference $\Delta E = E_D - E_{beam}$, where $E_{beam}$ is the beam energy, and $E_D$ and $\vec{p}_D$ are the energy and momentum of $D$ candidates. In order to extract the signal yields, an unbinned maximum likelihood fit was performed on the $M_{BC}$ distributions; here the signal was described by a MC simulated shape convolved with a Gaussian, while the background was described by an ARGUS function. No obvious signal was observed. By means of the Bayesian approach, the branching fraction upper limits at 90% CL were calculated to be $2.8 \times 10^{-6}$ for $D^0 \rightarrow K^-\pi^-e^+e^+$, $3.3 \times 10^{-6}$ for $D^+ \rightarrow K^0_S\pi^-e^+e^+$, and $8.5 \times 10^{-6}$ for $D^+ \rightarrow K^-\pi^0e^+e^+$. With different $\nu_m$ mass hypothesis the branching fractions upper limits at 90% CL for the processes $D^0 \rightarrow K^-e^+\nu_m(\pi^-e^-)$ and $D^+ \rightarrow K^0_{e^+}e^+\nu_m(\pi^-e^-)$ were found to be at level of $10^{-6}$ - $10^{-7}$, as shown in Fig. 4.

VI. BARYON NUMBER VIOLATING PROCESSES

In the SM, as a consequence of the $SU(2) \times U(1)$ and $SU(3)$ gauge symmetries, the baryon number is conserved. However, the existence of baryon number violating (BNV) processes is suggested by the excess on baryon with respect to antibaryon in the Universe. Thus, the investigation of BNV processes could allow to understand the evolution of the Universe. Some extensions of the SM include BNV processes [19], for example under dimension six operators BNV can happen with a change in the baryon and lepton numbers

\[ \Delta(B - L) = 0, \] under dimension seven operators $\Delta(B - L) = 2$ is allowed. The Feynman diagrams describing those processes include the presence of heavy gauge boson $X$ with charge $\frac{1}{2}$ and gauge boson $Y$ with charge $\frac{1}{3}$, which can couple a quark to a lepton.

A. $D^+ \rightarrow \Lambda(\Sigma^0)e^+$

The BESIII Collaboration measured for the first time BNV processes with $\Delta(B - L) = 0$ in $D^+ \rightarrow \Lambda(\Sigma^0)e^+$ and $\Delta(B - L) = 2$ in $D^+ \rightarrow \Lambda(\Sigma^0)e^+$ decays [20], taking advantage of 2.93 fb$^{-1}$ of data collected at the energy of 3.773 GeV. The hyperons were reconstructed through the channels $\Lambda \rightarrow p\pi^-\pi^0$ and $\Sigma^0 \rightarrow \gamma\Lambda$. The BNV decays were investigated by means of the beam energy constrained mass $M_{BC} = \sqrt{E_{beam}^2 - |\vec{p}_D|^2}$ and the energy difference $\Delta E = E_D - E_{beam}$, where $E_{beam}$ is the beam energy, and $E_D$ and $\vec{p}_D$ are the energy and momentum of $D^+$ candidates. Figure 4 shows the performed maximum likelihood fit to the $M_{BC}$ distributions; here the signal is modeled with a MC simulated shape convolved with a Gaussian, while the background is described by an ARGUS function. No obvious signal was found. The branching fractions upper limits at 90% CL were found to be $1.1 \times 10^{-6}$ for $\Lambda e^+$, $6.5 \times 10^{-7}$ for $\Lambda e^+$, $1.7 \times 10^{-6}$ for $\Sigma^0 e^+$, and $1.3 \times 10^{-6}$ for $\Sigma^0 e^+$. 

FIG. 4: Upper limits on branching fractions as function of different $\nu_m$ masses for the decays (a) $D^0 \rightarrow K^-e^+\nu_m(\pi^-e^-)$ and (b) $D^+ \rightarrow K^0_{e^+}e^+\nu_m(\pi^-e^-)$.
FIG. 5: Fits to the $M_{BC}$ distributions. Dots with error bars are the data, the solid lines are the fits, the red dashed lines indicate the background, and the blue hatched histograms are the MC simulated backgrounds scaled to the data according to the luminosity $\mathcal{L}$.

**B. $D^0 \rightarrow pe^-$**

The BESIII Collaboration measured baryon and lepton production in $D^0$ meson decays [21], taking advantage of 2.93 fb$^{-1}$ of data collected at the energy of 3.773 GeV. The double-tag technique was applied to reconstruct the $\psi(3770)$ decays into $D^0\bar{D}^0$ meson pairs. At first, the $D^0$ was reconstructed via its hadronic decay modes $K^+\pi^-$, $K^+\pi^0$, and $K^+\pi^-\pi^-\pi^+$ (single-tag ST). Two more variables were investigated: the beam-constrained mass $M_{BC} = \sqrt{E_{beam}^2/c^4 - |\mathbf{p}_{D^0}|^2/c^4}$, and the energy difference $\Delta E = E_{D^0} - E_{beam}$, where $E_{beam}$ is the energy of the electron beam, and $E_{D^0}$ and $\mathbf{p}_{D^0}$ are the energy and the momentum of the candidate $D^0$. In order to extract the yield of the ST mesons, the $M_{BC}$ distributions were fitted with a MC simulated shape convolved with a double-Gaussian for the signal and an ARGUS function for the background; 2321009±1875 events were reconstructed. In order to extract the double-tag signal $D^0 \rightarrow \bar{p}e^+$ and $D^0 \rightarrow pe^-$, the variables $M_{BC}^{sig}$ and $\Delta E^{sig}$ were defined in a similar way to the ST ones. The signal yields were obtained by counting the events in the selected region as shown in Fig. 5; no obvious signals were found. The branching fractions upper limits at 90% CL were found to be $< 1.2 \times 10^{-6}$ for $D^0 \rightarrow \bar{p}e^+$, and $< 2.2 \times 10^{-6}$ for $D^0 \rightarrow pe^-$. 

**C. $D^+_{(S)} \rightarrow hhll$**

The LHCB Collaboration, taking advantage of p-p annihilation data collected during Run 1 at 8 TeV for a total of 1.6 fb$^{-1}$, investigated the decays $D^+_{(S)} \rightarrow h^\pm l^\mp l'^\pm l'^\mp$, where $h$ indicate either a pion or a kaon, and $l'^\mp$ is an electron or a muon [22]. FCNC transitions are involved in four decay channels ($D^+ \rightarrow \pi^+e^+e^-, \pi^+\mu^+\mu^-$, and $D_S^0 \rightarrow K^+e^+e^-, K^+\mu^+\mu^-$); LFV processes are involved in eight decays ($D_{(S)}^0 \rightarrow \pi^+e^+\mu^-, \pi^+\mu^+e^-, K^+e^+\mu^-, K^+\mu^+e^-,$). Nine decay modes involve both LFV and LNV ($D^0 \rightarrow \pi^-e^+e^+, \pi^-\mu^+\mu^+, \pi^-\mu^+e^+$, and $D_S^0 \rightarrow K^-e^+e^+, K^-\mu^+\mu^+, K^-\mu^+e^+$). For calibration and normalization four resonant decays (NRD) ($D_{(S)}^0 \rightarrow (\phi \rightarrow \mu^-\mu^+)\pi^+, (\phi \rightarrow e^-e^+)\pi^+$) were exploited. Those decays are dominated by LD tree level contributions, and the regions dominated by resonances in dilepton mass were vetoed when fitting. The NRD invariant masses were fitted with a double Gaussian and an exponential function or a third order Chebyshev polynomial for muons and electrons final states, respectively. No significant deviation from the background was found for the 25 decay modes investigated. The branching fractions upper limits at 90% CL are reported in Tab. 11 and represent an improvement of 1 or 2 orders of magnitude with respect to the existing limits.

**D. $D^0 \rightarrow hhll$**

The BABAR Collaboration investigated the decay $D^{*+} \rightarrow D^{0}\pi^+$, with $D^{0}$ decays into $h^-h^-l^+l^+$ (nine LNV decays) or into $h^-h^+l^+l^+$ (three LFV decays), where $h$ and $h'$ indicate a K or a $\pi$ meson, and $l$ and $l'$ an electron or a muon [23]. The 424 fb$^{-1}$ of data collected at the $\Upsilon(4S)$ resonance (10.58 GeV) and additional 44 fb$^{-1}$ of data collected 0.04 GeV below the $\Upsilon(4S)$ resonance were exploited. The decays $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$, $D^0 \rightarrow K^-\pi^+\pi^-\pi^-$, and $D^0 \rightarrow K^-K^+\pi^-\pi^-$ were used to normalize the branching fractions for the different signal modes. In order to reject semileptonic charm decays or final states containing a neutral particle, a multivariate selection, based
TABLE II: Upper limits at 90% C.L for each signal decay channel $D_{(S)}^{0} \rightarrow hll$.

| Decay mode | BR U.L. $\times 10^{-7}$ |
|------------|--------------------------|
| $D_{(S)}^{0} \rightarrow \pi^{+} \mu^{+} \mu^{-}$ | 67 | 180 |
| $D_{(S)}^{0} \rightarrow \pi^{+} \mu^{+} \mu^{-}$ | 14 | 86 |
| $D_{(S)}^{0} \rightarrow K^{+} \mu^{+} \mu^{-}$ | 54 | 140 |
| $D_{(S)}^{0} \rightarrow K^{+} \mu^{+} \mu^{-}$ | - | 26 |
| $D_{(S)}^{0} \rightarrow \pi^{+} e^{+} \mu^{-}$ | 210 | 1100 |
| $D_{(S)}^{0} \rightarrow \pi^{+} e^{+} e^{-}$ | 220 | 940 |
| $D_{(S)}^{0} \rightarrow \pi^{+} e^{+} e^{-}$ | 130 | 630 |
| $D_{(S)}^{0} \rightarrow K^{+} e^{+} \mu^{-}$ | 75 | 790 |
| $D_{(S)}^{0} \rightarrow K^{+} e^{+} e^{-}$ | 100 | 560 |
| $D_{(S)}^{0} \rightarrow K^{+} e^{+} e^{-}$ | - | 260 |
| $D_{(S)}^{0} \rightarrow K^{-} e^{-} e^{+}$ | 1600 | 5500 |
| $D_{(S)}^{0} \rightarrow K^{-} e^{-} e^{+}$ | 530 | 1400 |
| $D_{(S)}^{0} \rightarrow K^{-} e^{-} e^{+}$ | 850 | 4900 |
| $D_{(S)}^{0} \rightarrow K^{-} e^{-} e^{+}$ | - | 770 |

on a Fisher discriminant which uses nine input observables, was applied; the discriminants were trained and tested using MC for the signal modes. An unbinned maximum-likelihood fit was performed to the variable $\Delta m = m(D^{+}) - m(D^{0})$ for the normalization modes and for the signal ones. In the fit, the signal was described with the sum of multiple Crucijff and Crystal Ball functions, while the background was described with an ARGUS function. For all the signal modes, the yields were found compatible with zero. The extracted upper limits at 90% C.L. are reported in Tab. III. The obtained values are between 1 and 3 order of magnitude more stringent with respect to the previous results.

TABLE III: Upper limits at 90% C.L for each signal decay channel $D^{0} \rightarrow hll$.

| $D^{0}$ decay mode | BR U.L. $\times 10^{-7}$ |
|---------------------|--------------------------|
| $\pi \pi e^{+} e^{-}$ | 9.1 |
| $\pi \pi \mu^{+} \mu^{-}$ | 15.2 |
| $\pi \pi e^{+} e^{-}$ | 30.6 |
| $\pi \pi e^{+} e^{-}$ | 17.1 |
| $K \pi e^{+} e^{-}$ | 5.0 |
| $K \mu^{+} \mu^{-}$ | 5.3 |
| $K \pi e^{+} e^{-}$ | 21.0 |
| $K \pi e^{+} e^{-}$ | 19.0 |
| $K K e^{+} e^{-}$ | 3.4 |
| $K K \mu^{+} \mu^{-}$ | 4.0 |
| $K K e^{+} e^{-}$ | 5.8 |
| $K K e^{+} e^{-}$ | 10.0 |

VII. FUTURE PLANS

The BelleII experiment will have the capability to investigate rare or forbidden charm decays. In particular, those involving neutral particles or missing energy in the final states (such as neutrinos, dark matter, axions, other non-SM particles) will be well suited. Among the others, the $D^{0} \rightarrow \gamma \gamma$, $c \rightarrow u$ FCNC will be unique for the experiment. The branching fraction upper limit for this process is about $8.7 \times 10^{-7}$ [24] and it is still two order of magnitude higher with respect to the SM predictions; the expectation is to reach about 1 order of magnitude more stringent upper limit, when 50 ab$^{-1}$ of data will be collected. The BelleII Collaboration plans as well to study the $D \rightarrow h\nu \bar{\nu}$ and the $\Lambda_{c}^{+} \rightarrow p\nu \bar{\nu}$ final states, which are strongly suppressed in the SM due to the GIM mechanism, taking advantage of the powerful reconstruction method developed.

On the other hand, the BESIII Collaboration, which get an extended operation time, is planning to collect more data in the charm region. In particular, 20 fb$^{-1}$ and 6 fb$^{-1}$ are expected at the 3.773 GeV and 4.18 GeV energies, in order to further improve our knowledge on rare charm decays [2].

VIII. CONCLUSIONS

Rare charm decays are a great tool for NP investigations. They can pin down the $u$-quark dynamics, and deliver complementary information with respect to the strange and the beauty sectors. Unfortunately, the collected statistics is increasing, but it is still too low to be able to reach the SM predictions. So far, no NP effect has been found. New results are expected from the different experiments and, possibly, from next generation facilities.

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