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Experimental status of rare D decays

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The flavor changing neutral current (FCNC) and lepton number violation (LNV) processes in D decays are very rare within the standard model and beyond the reach of current collider experiments. Any evidence of a signal in such decay processes would be a clear indication of new physics. The new physics models propose several weakly interacting light dark matter particles to explain the features of astrophysical observations. The possibility of such a low-mass invisible particle in different decay modes has recently been explored by several collider experiments. This report summarizes the current experimental status of the FCNC, LNV and invisible decays of D mesons.

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1. Introduction

The flavor changing neutral current (FCNC) processes in charm sector are highly suppressed by the Glashow-Iliopoulos-Maiani mechanism due to absence of high mass down-type quarks [1]. The FCNC D decays are very rare and beyond the scope of any running or planned experiments [2, 3]. However, the contributions of long-distance [4, 5] and new physics [6] may enhance the branching fractions up to the level of current experimental sensitivity. The lepton number violating (LNV) decays of charged D mesons can be induced by the existence of Majorana neutrinos and are sensitive of neutrino masses and lepton mixing [7]. The branching fraction of such an LNV process depends on the on- and off-shell contributions of the Majorana neutrino masses [7]. In the standard model (SM), the D meson decaying to a neutrino pair is helicity suppressed and considered to be very rare [8]. But the contribution of the light dark matter particles beyond the SM may enhance the branching fraction [9]. There are several rare D decays which have already been explored by current collider experiments, but so far only negative results are available except for the radiative charm decays $D \to \gamma V$ ($V = \rho, \phi..$) [10]. We summarize herein some recent experimental results of the FCNC [11, 12], LNV [11] and invisible [13] decays of D mesons.

2. Search for the rare decay of $D^+ \to D^0 e^+ \nu_e$

In the $D^+ \to D^0 e^+ \nu_e$ decay, the charm quark remains as a spectator while the light quark participates in the weak decay. Within the limit of SU(3) symmetry in the light quark sector, the branching fraction of $D^+ \to D^0 e^+ \nu_e$ is predicted to be 2.78×10^{-13} [14]. The search is performed using 2.92 fb^{-1} of $\psi(3770)$ data collected by the BESIII experiment. The e^+ is not detected being very soft in the BESIII detector. The search uses a double tag technique pioneered by the MARK III Collaboration [15]. The single tag D^- candidate is reconstructed by following 6 hadronic modes in the final states: $K^+\pi^-\pi^-$, $K^+\pi^-\pi^-\pi^0$, $K^0_S\pi^-$, $K^0_S\pi^-\pi^0$, $K^0_S\pi^+\pi^-\pi^-$ and $K^+K^-\pi^-$, comprising approximately 28% [16] of all D^- decays. The variables, $\Delta E = \sum_i E_i - E_{\rm beam}$ and $m_{BC} = \sqrt{E^2_{\rm beam} - |\sum_i \vec{p}_i|^2}$, are exploited to identify the D^- candidate, where E_i and $\vec{p}_i$ are the energy and momentum, respectively, of D^- products in the center-of-mass system of the $\psi(3770)$, and $E_{\rm beam}$ the beam energy. For a correctly reconstructed D^- candidate, ΔE peaks at zero and m_{BC} is consistent with the nominal D^- mass [16]. The recoil side of the D^- meson candidate is used to perform the search for the rare decay $D^+ \to D^0 e^+ \nu_e$. The D^0 meson is reconstructed using $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$ and $K^-\pi^+\pi^0$. A two-dimensional (2D) fit to $M^{D^-}_{BC}$ and $M^{D^0}_{inv}$ distributions is performed to extract the signal events (Figure 2), where $M^{D^0}_{inv}$ is the invariant mass of D^0 mesons. The contribution of the peaking background for each D^0 candidate is estimated using an inclusive Monte Carlo (MC) sample with 10 times more statistics than the data. No significant signal is found in any of the decay modes, and 90% confidence level (C.L.) upper limit on the branching fraction, including the systematic uncertainties, is calculated to be $\mathscr{B}(D^+ \to D^0 e^+ \nu_e) < 8.7 \times 10^{-5}$. All the results are preliminary.

3. Search for rare decays of $D^+ \to h^\pm e^+ e^\mp$ ($h = K, \pi$)

The FCNC decays of $D^+ \to h^+ e^+ e^-$ ($h = K, \pi$) can occur via the short-distance process of $c \to$

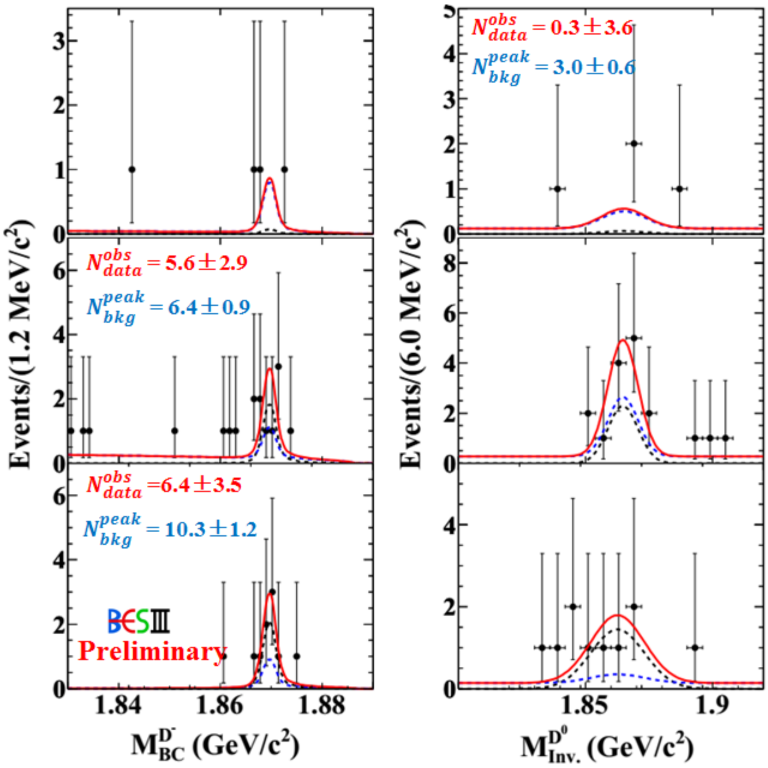

Figure 1: The projection plots of $M_{BC}^{D^-}$ (left) and $M_{inv}^{D^0}$ (right) distributions for the D^0 decay modes of $D^0 \to K^-\pi^+$ (top), $K^-\pi^+\pi^+\pi^-$ (middle) and $K^-\pi^+\pi^0$ (bottom). The data are shown by the dots with the error bars, signal by black dashed curves, background by blue dashed curves and total fit result by solid red curves. The extracted signal event (N_{data}^{obs}) contains both signal and peaking background (N_{peak}^{bkg}), estimated using the inclusive MC samples, contributions.

ue^+e^- with the expected branching fraction in the range of $10^{-8} - 10^{-6}$ [2]. But the contribution of new physics, such as the minimal supersymmetric standard model (MSSM) [6], the R-parity violating supersymmetry [17], the fourth generation [18], or the long-distance effect occurring via $D^+ \to h^+V$, $V \to e^+e^-$ (V = vector meson) [4] may enhance the branching fraction up to the level of $10^{-6} - 10^{-5}$. The LNV decays of $D^+ \to h^-e^+e^+$ can be induced by an on-shell Majorana neutrino within the framework of beyond the SM with a branching fraction predicted to be up to the level of 10^{-10} [7]. BESIII uses 2.92 fb^{-1} of $\psi(3770)$ data to perform the search of $D^+ \to h^\pm e^+e^\mp$ decays.

The events of interest for $D^+ \to h^\pm e^+e^\mp$ decays, based on a single tag technique, are required to be within the signal region of the scatter plot of M_{BC} vs. ΔE [11]. The signal region is defined as the within $\pm 3\sigma$ regions of M_{BC} and ΔE distributions. Table 1 summarizes the number of events counted in the signal region ($N_{\rm in}^{\rm data}$) and sideband ($N_{\rm out}^{\rm data}$) of M_{BC} and ΔE distributions for all the four D^+ decay processes. We finally extract the signal yield as $N_{\rm sig} = N_{\rm in}^{\rm data} - f_b.N_{\rm out}^{\rm data}$, where f_b is the scale factor of the background in and outside of the signal region determined by the MC simulations. No evidence of signal is observed and 90% C.L. upper limit on $\mathscr{B}(D^+ \to h^\pm e^+e^\mp)$ is set using a profile likelihood treatment method [19] (Table 1). The new BESIII results on $D^+ \to \pi^+e^+e^-$ and $D^+ \to K^-e^+e^+$ decays are better than the existing results [16].

Table 1: The number of events inside ($N_{\rm in}^{\rm data}$) and outside ($N_{\rm out}^{\rm data}$) of the signal box, scale factor (f_b), detection efficiency (ε), systematic uncertainty ($\Delta_{\rm syst}$), 90% C.L. upper limits of the observed events, and the branching fraction ($\mathscr{B}$). All the results are preliminary.

Decay Mode	$N_{\rm in}^{\rm data}$	$N_{\rm out}^{\rm data}$	f_b	ε (%)	$\Delta_{\rm syst}$ (%)	f_{90}	$\mathscr{B}$ (10^{-6})
$D^+ \to K^+e^+e^-$	5	69	0.08 ± 0.01	22.53	5.4	19.4	< 1.2
$D^+ \to K^+e^+e^+$	3	55	0.08 ± 0.01	24.08	6.1	10.2	< 0.6
$D^+ \to \pi^+e^+e^-$	3	65	0.09 ± 0.02	25.72	5.9	4.2	< 0.3
$D^+ \to \pi^-e^+e^+$	5	68	0.06 ± 0.02	28.08	6.8	20.5	< 1.2

4. Search for the rare decay of $D^0 \to \gamma\gamma$

The decay of the neutral charm meson to two photons, $D^0 \to \gamma\gamma$, is mediated by $c \to u\gamma\gamma$ transitions. The branching fraction of this mode for short- and long-distance contributions is predicted to be 3×10^{-11} [3, 5] and $(1-3) \times 10^{-8}$ [5], respectively. However, the MSSM predicts the exchange of gluinos, the supersymmetric partner of gluons, can enhance the branching fraction up to 6×10^{-6} [20]. The searches of $D^0 \to \gamma\gamma$ have been previously performed by CLEO [21] and BaBar experiments [22] using the data collected at the $\Upsilon(4S)$ resonance and more recently by BESIII [23] with a data sample of $\psi(3770)$ resonance. BESIII uses a double tag technique [15] setting the 90% C.L. upper limit at $\mathscr{B}(D^0 \to \gamma\gamma) < 3.8 \times 10^{-6}$ [23], which is compatible with the BaBar result, i.e. $\mathscr{B}(D^0 \to \gamma\gamma) < 2.2 \times 10^{-6}$ [22].

The Belle experiment recently also performed a search for $D^0 \to \gamma\gamma$ using 832 fb^{-1} of $\Upsilon(4S)$ data. The D^0 meson candidate is selected from the $D^{*+} \to D^0\pi^+$ decay, where D^0 decaying to photon-pair in the final state. In order to veto the π^0 mesons from the event, all the photons which can be used for reconstructing a good π^0 are rejected. Besides the combinatorial backgrounds, the data also include the peaking background contributions from $D^0 \to \pi^0\pi^0$, $\eta\pi^0$, $\eta\eta$ etc.. A 2D maximum-likelihood fit to the di-photon invariant mass (Figure 2 (left)) and $\Delta M (= M_{D^{*+}} - M_{D^0})$ (Figure 2 (middle)) distributions is performed to extract the signal yield, where $M_{D^{*+}}$ (M_{D^0}) is the invariant mass distribution of D^{*+} (D^0) candidate. The 2D fit is then applied to a normalization channel of $D^0 \to K_S^0\pi^0$, using the same signal and background shapes as used for $D^0 \to \gamma\gamma$. No evidence of signal is observed and 90% C.L. upper limit is set at $\mathscr{B}(D^0 \to \gamma\gamma) < 8.5 \times 10^{-7}$. The new Belle result [12] is the most stringent to date and can be used to constrain a large fraction of new physics parameter space (Figure 2 (right)).

5. Search for $D^0 \to$ invisible

The heavy (D or B) meson decay to $\nu\overline{\nu}$ is helicity suppressed in the SM with an expected branching fraction of $\mathscr{B}(D^0 \to \nu\overline{\nu}) = 1.1 \times 10^{-20}$ [8], which is impossible to be reached by current collider experiments. But the contribution of new physics, introducing the light dark matter invisible particles may enhance the branching fraction up to the level of 10^{-15} [9]. More recently, Belle has reported the result from a first search for the D^0 decays to invisible final states using 924 fb^{-1} data collected at and near the $\Upsilon(4S)$ and $\Upsilon(5S)$ resonances [13]. Belle uses charm tagging in the process $e^+e^- \to c\overline{c} \to D_{\rm tag}^{(*)} X_{\rm frag} \overline{D}_{\rm sig}^{*-}$ with $\overline{D}_{\rm sig}^{*-} \to \overline{D}_{\rm sig}^0 \pi_s^-$ to select an inclusive D^0 sample (Figure 3 (left)). Here $D_{\rm tag}^*$ represents a charmed particle used as a tag: D^{*0}, D^{*+}, D_s^{*+} or Λ_c^+. Since

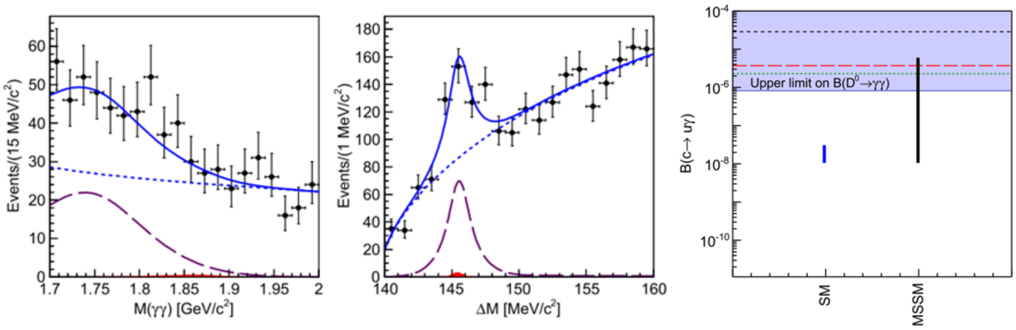

Figure 2: The projection plots of $M_{\gamma\gamma}$ (left) and ΔM (middle) distributions. Points with error bars are the data, blue dot curve for combinatorial background, magenta dashed curve for peaking background, red histogram for signal and solid blue curve for total fit. The right side plot is for $\mathscr{B}(c \to u\gamma)$ predicted in the SM and MSSM, and measured upper limits of $\mathscr{B}(D^0 \to \gamma\gamma)$ by Belle (purple), BaBar (green), BESIII (red) and CLEO (black).

Belle accumulates the data above the open charm threshold, a fragmentation system ($X_{\rm frag}$) with a few light unflavored mesons may also be produced. The information of the e^+e^- four-momentum is used to identify a D^0 candidate that escapes detection by fully reconstructing the remainder of the event, where D^0 is allowed to decay to either visible or invisible final states. A 2D fit to the invariant mass distributions of D^0 (Figure 3 (middle)) and E_{ECL} (Figure 3 (right)) is used to extract the signal events, where E_{ECL} is the residual energy in the electromagnetic calorimeter. The fit yields $N_{\rm sig} = -10.2^{+22.2}_{-20.8}$ events. As no significant signal event is observed, a 90% C.L. upper limit is set at $\mathscr{B}(D^0 \to \text{invisible}) < 9.4 \times 10^{-5}$ [13].

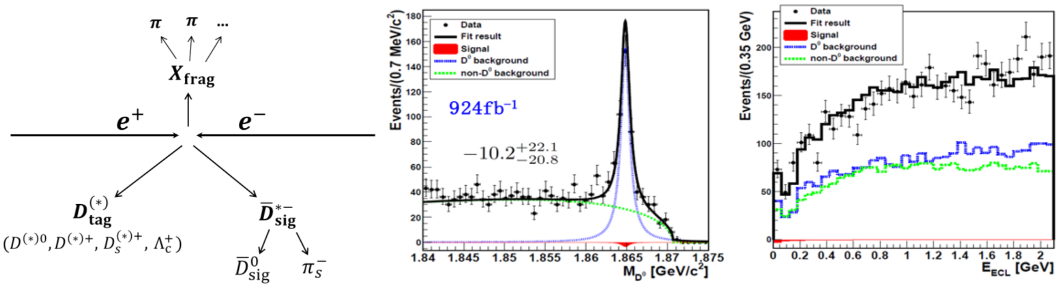

Figure 3: An illustration of the charm tagging method (left), and the projection plots of M_{D^0} distribution for $E_{ECL} < 0.5$ GeV (middle) and E_{ECL} distribution for $M_{D^0} > 1.86$ GeV/c^2 (right). The points with error bars are data, the blue dotted line is D^0 background, the green dashed line is non-D^0 background, the red filled area is the signal of D^0 decaying to invisible final states and the solid black line is total fit result.

6. Summary

Using 2.92 fb^{-1} of $\psi(3770)$ data, BESIII has set one of the most stringent limits on the decay processes of $D^+ \to D^0 e^+ \nu_e$ and $D^+ \to h^\pm e^+ e^\mp$ ($h = K, \pi$). The large data sample collected by the Belle detector has enabled a further improvement in the upper limit of $D^0 \to \gamma\gamma$. The first exclusion limit on $D^0 \to$ invisible decays has also been reported by Belle. Present upper limits are still above the SM predictions. Therefore, large data samples to be collected by current and future flavor physics experiments would further improve the results and may provide a signature of new physics.

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