PROCEEDINGS OF SCIENCE

Rare Charm decays at BESIII

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In the Standard Model, rare charm decays have tiny, almost unobservable, branching ratios. Any discrepancy from its predictions can be used to enhance our comprehension of additional contributions and, eventually, lead to New Physics. The BESIII experiment profits from the clean environment of its leptonic collisions to search for rare decays in charm mesons and charmonium decays. In this presentation, a general review of the BESIII results in these searches will be discussed, with a focus on three main areas: FCNC decays, J/ψ weak decays, and forbidden processes.

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1. BESIII: the experiment, the physics program, and its datasets

The BESIII (Beijing Spectrometer III) experiment is a multipurpose central detector, optimized for studies in the τ − charm energy region (2-4.9 GeV in the center of mass). It is hosted at the BEPCII (Beijing Electron Positron Collider), at the Institute of the High Energy Physics of the Chinese Academy of Science (IHEP), in Beijing. Details of the spectrometer are discussed in Ref. [1].

Owing to the high luminosity of the collider, the energy range, and the capability of shifting the center of mass energy, the BESIII experiment plays a unique role in the high-intensity frontier landscape, with the possibility to directly produce large data sample of charmonia (integrated samples: 10B J/ψ mesons, 3B $\psi(2S)$) and quantum-correlated charmed hadrons at their production threshold. An overview of the physics program can be found in Ref. [2].

This article focuses on the BESIII collaboration contributions in three main areas of the rare charm decays: search for the flavor-changing neutral currents decays, that are forbidden in the Standard Model (SM) at tree level; the J/ψ weak decays, that are allowed in the SM at tree level, but are rare due to the *weakness* of the weak force in this energy regime; forbidden process in the SM, like lepton number violation ones. A recent discussion of BESIII capabilities in this kind of search can be found in Ref. [3].

2. FCNC decays

The first rare decays discussed are the flavor-changing neutral currents (FCNC) processes. They have been under deep investigation in the intensity frontier for a long time. Due to the presence of loops, any new particle from beyond Standard Model physics may appear as a mediator of the process, providing a discrepancy with the pure SM prediction. The pure FCNC loop process is usually called *short-distance* (SD) contribution and in the SM they are heavily suppressed by GIM mechanism [4], to the order of 10^{-15} for D meson decays. However, in the case of the final state with two charged leptons, a long-distance contribution may appear to enhance the branching ratio of a rare process. This is due to the presence of an interfering process where a vector meson mediates the production of the two leptons. This is called *long distance* (LD) contribution, it is not FCNC, but it contributes to enhancing the branching ratio with respect to the pure short-distance contribution. Recently, the LHCb collaboration has measured four-body D meson decays with muons at the 10^{-7} level [5, 6] showing the importance of long-distance contribution in rare FCNC process.

The BESIII experiment can perform the search for D meson FCNC process by using the *double-tag* technique, a method in which first a $\bar{D}$ meson is tagged using known hadronic final state, then the signal is searched in the recoil of these events. Given the closed kinematics of leptonic colliders and the threshold production, by reconstructing one side, the information on the other is fixed. By using this technique, it is also possible to search for events with neutrinos in the final state.

FCNC processes with di-neutrino final states are very rare in the SM since no LD contribution is present to enhance the BR. For the $D^0 \to \pi^0 \nu_l \nu_l$ process, the predicted BR is about 10^{-15}, so tiny that is experimentally un-observable. Any observation of this process would lead to New Physics. In Ref. [7], the BESIII collaboration reports the first-ever search of this process. The main

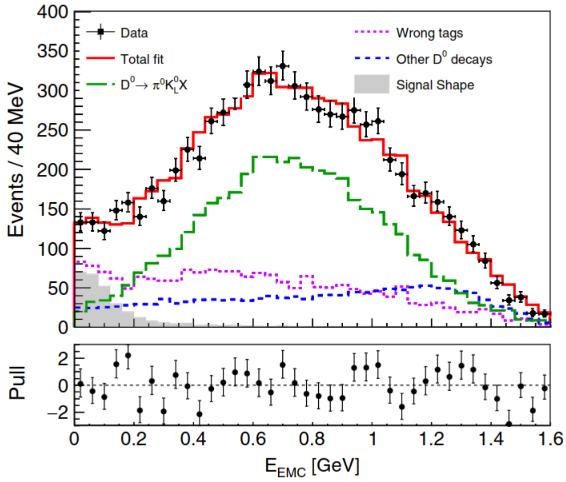


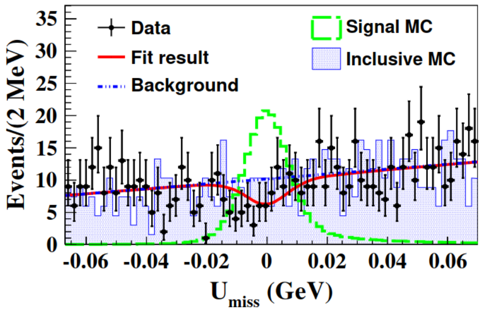
Figure 1: $D \to \pi^0 \nu\nu$ process. In the upper plot, the E_{EMC} distributions for data, signal (arbitrary scale), and the different components, with the fit represented as the solid red line. In the bottom plot, the pull distribution shows fit-data agreement.

background is the $D \to \pi^0 K_L X$ process since in the BESIII experiment K_L mesons go undetected. A data-driven approach is followed to estimate this background, using two different control samples ($D^0 \to \pi^0 K_S X$ and a K_L control sample) studying their energy deposition in the calorimeter (E_{EMC}). The number of events is then extracted using an extended maximum likelihood fit to the E_{EMC}, fixing the number of wrong $\bar{D}$ tags from MC estimation. Figure 1 shows the fit result. No signal is observed and an upper limit is calculated to be $\mathcal{B}(D^0 \to \pi^0 \nu\nu) < 2.1 \times 10^{-4}$ @90% C.L.. This is the first-ever measurement of the $c \to u\nu\nu$ process. The BESIII experiment will finish collecting 20/fb for the $\psi(3770)$ meson sample by early 2024 to put a more stringent limit on this process.

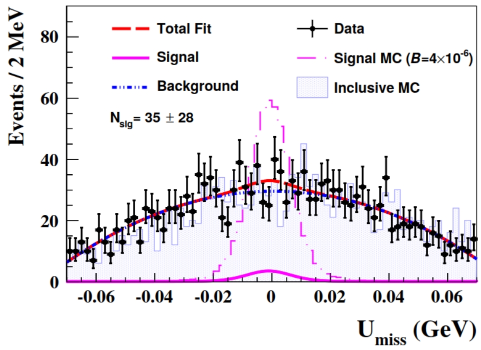
3. J/ψ weak decays

Despite being a rare process, J/ψ weak decays are allowed at tree level in the SM. These are indeed rare due to the nature of the weak coupling, which far away from the W mass peak is small compared to the J/ψ predominant strong and electromagnetic ones. The SM predicts these decays with BR $\sim 10^{-8}$ or lower.

The BESIII collaboration has performed several searches for them: in particular, Ref. [8] and Ref. [9] present the search for $J/\psi \to Dl\nu_l$, with $l = e$ and $l = \mu$, respectively. In both analyses, the D meson is reconstructed in the favored $D \to K\pi\pi$ decay and the signal is searched in the missing mass. For the $J/\psi \to De\nu_e$ process, the background is removed by requiring that the extra energy in the calorimeter (*i.e.* the energy of the remaining signal after the reconstruction of the electron and the D meson) is below 0.2 GeV. Figure 2a shows the results. The upper limit is extracted to be $\mathcal{B}(J/\psi \to De\nu_e) < 7.1 \times 10^{-8}$ @ 90% C.L.. The $J/\psi \to D\mu\nu_\mu$ process is more difficult, due to the π/μ misidentification. To remove it, variable $|P_{\rm miss}|+|P_\mu|$ is required to be between 0.98 GeV/c and 1.23 GeV/c, where $P_{\rm miss}$ and P_μ are the missing momentum and the muon one, respectively. Figure 2b shows the results. Since no signal is observed, also in this case, an upper limit is extracted



(a) $J/\psi \to De\nu_e$ process. Signal shape has arbitrary normalization.



(b) $J/\psi \to D\mu\nu_\mu$ process. Signal shape has arbitrary normalization.

Figure 2: $J/\psi \to Dl\nu_l$ processes studied at BESIII. Data are the black dots. The colored histograms represent the different components.

Mode	Ref.[15] $\mathcal{B}$ (90%C.L.)	PDG [17] $\mathcal{B}$ (90%C.L.)
$J/\psi \to \bar{D}^0\pi^0$	$< 4.7 \times 10^{-7}$	...
$J/\psi \to \bar{D}^0\eta$	$< 6.8 \times 10^{-7}$	...
$J/\psi \to \bar{D}^0\rho^0$	$< 5.2 \times 10^{-7}$	...
$J/\psi \to D^-\pi^+$	$< 7.0 \times 10^{-8}$	$< 7.5 \times 10^{-5}$
$J/\psi \to D^-\rho^+$	$< 6.0 \times 10^{-7}$	...

Table 1: Upper limit for $J/\psi \to D + h$ from Ref. [15].

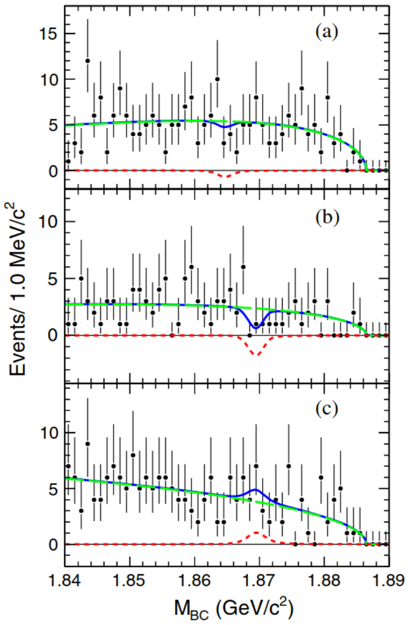
to be $\mathcal{B}(J/\psi \to D\mu\nu_\mu) < 5.6 \times 10^{-7}$ @ 90% C.L.. Both measurements are the most precise to date and are 3 orders of magnitude less stringent than the SM predictions ([10–14]).

In Ref. [15], the BESIII collaboration investigates the possibility of searching for fully hadronic weak decays, *i.e.* $J/\psi \to D+h$, where $h = \pi^0$, η, ρ^0, π^+, ρ^-. In order to avoid the large background from J/ψ strong decays, the D mesons are tagged via their semileptonic decay: $D^0 \to K^+e^-\nu_e$ or $D^- \to K_S e^-\nu_e$. The signals are extracted from the h hadron recoil mass. No signal is observed, and upper limits at 90% C.L. are calculated as shown in Tab. 1. All the results are the first measurements except for $J/\psi \to D^-\pi^+$ that has been already measured in Ref. [16], where an improvement of three orders of magnitude is achieved. All the measurements are close to the 10^{-8} level needed to start constraining New Physics models.

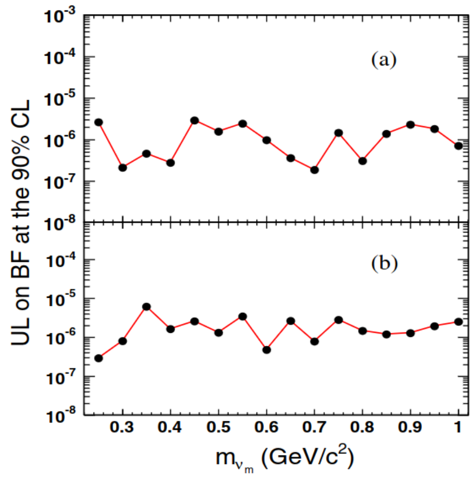
4. Forbidden processes

The third example of rare processes studied by the BESIII collaboration is the forbidden ones. These processes cannot happen in the SM since they violate some quite (up-to-now) fundamental symmetry (*e.g.* lepton number, baryon number). So any observation of these processes would immediately lead to New Physics (and probably to Stockholm around December).

The BESIII collaboration has studied the $D \to K\pi e^+e^+$ process in Ref. [18], an SM-forbidden $|\Delta L = 2|$ transition to studying the possible contribution of Majorana neutrinos with mass at heavy



(a) $D \to K\pi e^+e^+$ for different final state. (a) $D^0 \to K-\pi^+e^+e^+$, (b) $D^+ \to K_S\pi^-e^+e^+$, (c) $D^+ \to K-\pi^0e^+e^+$. In each plot, the green line represents the total fit, the blue line the signal, and the red dotted line the signal minus the background.



(b) Upper limit for the BF of the process as a function of the hypothetical Majorana's neutrino mass (m_{ν_m}). (a) $D^0 \to K^-e^+\nu_m$ process. (b) $D^+ \to K_Se^+\nu_m$ process.

Figure 3: $D \to K\pi e^+e^+$ processes at BESIII from Ref. [18].

flavor scale (200 MeV/c^2 to 1 GeV/c^2) decaying into πe^+ final state. L is the lepton number. The analysis uses both charged and neutral D mesons, produced at $\psi(3770)$ meson mass. Owing to the closed kinematic of the production at the charmonium resonance, only one D meson is reconstructed in this analysis, without any information from the other side D one. This technique sometimes called *single-tag* guarantees almost double the statistics, with a higher background level. The number of events is extracted using the variable $M_{\rm BC} = \sqrt{E^2_{\rm beam} - p^2_{\rm candidate}}$, where $E_{\rm beam}$ is the single beam energy at the investigated center of mass energy, and $p_{\rm candidate}$ is the reconstructed 3-momentum of the D meson candidate. It shall peak at nominal D meson mass.

Figure 3a shows the results for three different final states investigated. No signal is observed and upper limits are extracted to be of the order of 10^{-6} at 90% C.L.. It is also possible to extract upper limits with respect to the hypothetical Majorana's neutrino ν_m mass. The results for $D^0 \to K^-\pi^+e^+e^+$ and $D^+ \to K_S\pi^-e^+e^+$ are shown in Fig. 3b in the top and bottom part, respectively.

5. Final remarks and perspective from BESIII rare searches

Rare decays in the charm sector are really tiny, due to the strong suppression from the GIM mechanism. Any search is mainly motivated by the possibility of finding enhancements, that cannot be justified within the calculation of the SM and thus could spot New Physics contributions that may be out of reach for direct production at the energy frontier.

The BESIII collaboration has an extensive program for rare searches that exceeds the few examples shown today, covering also charged lepton flavor universality violation, axions, and dark matter searches. BESIII is accumulating a larger dataset at $\psi(3770)$ peak energy, to further improve the knowledge of the rare D meson decays, it has already the world's largest sample of J/ψ and $\psi(2S)$ charmonia to study their weak decays. In addition to the large statistics, the BESIII collaboration is starting to exploit more advanced analysis techniques (say machine learning) to boost the analysis. Finally, both BESIII and BEPCII are undergoing upgrades, well motivated by a program [2] that will continue until 2030: this will allow exploring the region between 4 and 5.2 GeV, with new possibilities coming from charmed baryon rare decays.

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