International Journal of Modern Physics A

Precision studies at BESIII in charm and new physics search

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Received Day Month Year
Revised Day Month Year

The investigation of charm physics plays an important role in checking the Standard Model's description of strong and weak interactions, validating its predictions for particle physics, and exploring new physics beyond the Standard Model. Using a large dataset from e^+e^- annihilation, BESIII has conducted comprehensive and extensive studies in the areas of hadronic, leptonic and semileptonic decays. This proceeding presents an overview of the recent researches and discoveries by BESIII on decays of charmed baryons, charmed mesons and charmonium states, highlighting their significance in advancing the understanding of new physics, experimental determination of physical parameters and improvement of measurement precision.

Keywords: BESIII experiment; Charm physics; New physics.

PACS numbers:

1. Introduction

The Standard Model (SM) serves as the foundational theoretical framework for understanding elementary particles and their interactions. Charm physics research plays a essential role in advancing the field of physics by either validating the SM's predictions or exploring new physics beyond the SM.

Since the discovery of the first charmonium particle J/ψ in the 1970s, an increasing number of particles containing charm quark have been explored and studied. Over the past few decades, a significant amount of charm mesons have been produced, leading to remarkable advancements in charmed mesons sector. Besides, in 2014, a large amount of data above the $\Lambda_c^+\bar{\Lambda}_c^-$ threshold has been accumulated, which leads to a series important progress on the studies of charmed baryon. The charm quark energy scale lies between perturbative and non-perturbative regimes, providing an ideal platform for studying non-perturbative effects of the Standard Model at low energy scales, which helps better understanding of the SM. Another way to extend our knowledge of the particles physics is to search for new physics beyond the SM, which encompasses the exploration of new particles, interactions, and fundamental principles.

Physicists have conducted researches on charm physics at experimental facilities such as BESIII, BELLE and LHCb, among which the BESIII has made notable contributions to the progress in the field of charm mesons, charm baryons and new physics searches. BESIII is a spectrometer designed for τ-charm physics research, with the current center-of-mass (c.m.) energies ranging from 2.0 to 4.95 GeV.[1] BESIII records e^+e^- collisions generated by the BEPCII storage ring and has accumulated a large amount of dataset within this energy range, including 2.96 fb^{-1} J/ψ events, 3.87 fb^{-1} $\psi(2S)$ events, 20 fb^{-1} of data at 3.773 GeV and 20 fb^{-1} of data above 4.0 GeV in total.[2–6]

In this proceeding, we present the recent progress on the experimental studies of charmed hadrons and new physics at BESIII.

2. Recent studies on the Λ_c^+ measurements at BESIII

Since most of the charmed baryons eventually decay to Λ_c^+, the studies on Λ_c^+ can contribute to further understanding of the heavy flavour baryon spectroscopy and its decay properties.

2.1. *Semileptonic decay of* Λ_c^+

In recent years, using the 4.5 fb^{-1} of data collected at c.m. energies ranging from 4.600 GeV to 4.699 GeV, BESIII Collaboration has investigated the semileptonic decay of Λ_c^+, with the results presented in Table 1. The precision of their branching fraction (BF) measurements has been improved.

Table 1. Recent BESIII Measurements on Semileptonic Decays of Λ_c^+

Decay Mode	Branching Fraction	Additional Results
$\Lambda e^+\nu_e$	$(3.56 \pm 0.11 \pm 0.07) \times 10^{-2}$	$\lvert V_{cs}\rvert = 0.936 \pm 0.017 \pm 0.024 \pm 0.007$
$Xe^+\nu_e$	$(4.06 \pm 0.10 \pm 0.09) \times 10^{-2}$	$\Gamma(\Lambda_c^+ \to Xe^+\nu_e)/\Gamma(D \to Xe^+\nu_e) = (1.28 \pm 0.05)$
$\Lambda\mu^+\nu_\mu$	$(3.48 \pm 0.14 \pm 0.10) \times 10^{-2}$	$\langle A^e_{FB}\rangle = -0.24 \pm 0.03 \pm 0.01$ $\langle A^\mu_{FB}\rangle = -0.22 \pm 0.04 \pm 0.01$
$pK^-e^+\nu_e$	$(0.88 \pm 0.17 \pm 0.07) \times 10^{-3}$	
$\Lambda(1520)(\to pK^-)e^+\nu_e$	$(0.23 \pm 0.12 \pm 0.02) \times 10^{-3}$	
$\Lambda(1405)(\to pK^-)e^+\nu_e$	$(0.42 \pm 0.19 \pm 0.04) \times 10^{-3}$	
$\Lambda\pi^+\pi^-e^+\nu_e$	$< 3.9 \times 10^{-4}(90\%)$	
$pK_S^0\pi^-e^+\nu_e$	$< 3.3 \times 10^{-4}(90\%)$	

Among the semileptonic decay modes of Λ_c^+, one of the dominated process is $\Lambda_c^+ \to \Lambda e^+\nu_e$. By analyzing this channel, BESIII provided the first direct comparisons on the differential decay rates and form factors (FFs) with those obtained from lattice quantum chromodynamics (LQCD) calculations in Ref. 7. The differential decay rate is roughly consistent with LQCD calculation while differences can be noticed on FFs. Additionally, the $|V_{cs}|$ element has been measured, which is consistent with the value obtained in charmed meson decay.

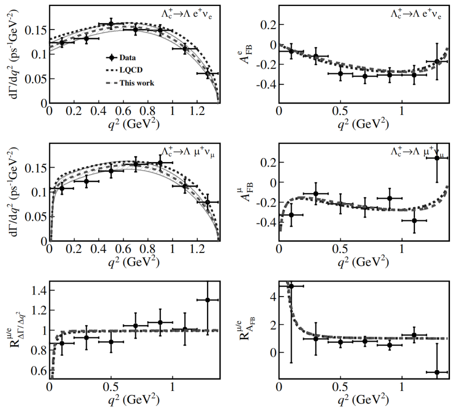

Fig. 1. Comparison of the differential decay rates and the model-independent forward-backward asymmetries of $\Lambda_c^+ \to e^+\nu_e$ and $\Lambda_c^+ \to \mu^+\nu_\mu$ with LQCD predictions.The dash-dotted curves show the derived values using the FFs measured in this work, while the dashed curves show those predicted by LQCD. The bands show the total uncertainties of $d\Gamma/dq^2$ using the FFs measured in this work.

Furthermore, BESIII investigated the $\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$ decay channel and conducted a test of lepton flavor universality (LFU) in conjunction with the study of $\Lambda_c^+ \to \Lambda e^+\nu_e$,[8] revealing no significant violation of LFU. Moreover, the forward-backward asymmetries of these decays were examined, showing consistency with the predictions of the SM. Details of the comparison can be found in Fig. 1.

In addition, other semileptonic decay modes are also investigated, for example, $\Lambda_c^+ \to pK^-e^+\nu_e$ were measured with a significance of 8.2 σ.[9] By examining the invariant mass spectra of pK^- observed during the study, evidence was found for $\Lambda_c^+ \to \Lambda(1520)e^+\nu_e$ and $\Lambda_c^+ \to \Lambda(1405)e^+\nu_e$, with significances of 3.3 σ and 3.2 σ, respectively. Besides, the potential decay $\Lambda_c^+ \to \Lambda^* e^+\nu_e$ was explored by searching $\Lambda_c^+ \to \Lambda\pi^+\pi^-e^+\nu_e$ and $\Lambda_c^+ \to pK^0_S\pi^-e^+\nu_e$.[10] Despite the absence of significant signals for these decays, the upper limits of the decay BFs at the 90% confidence level are presented in Table 1. Comparing these values with theoretical calculations helps constrain and improve the theoretical modeling.

To explore the potential of unknown exclusive semileptonic decay modes of Λ_c^+, BESIII further delved into inclusive decays of $\Lambda_c^+ \to Xe^+\nu_e$, the precision has been improved by a factor of 3 compared to previous measurements. The ratio of the inclusive semileptonic decay width for the Λ_c^+ and D has been calculated, as listed in Table 1. It is consistent with the value of 1.2 predicted from the heavy quark expansion but disfavors the value of 1.67 predicted from the effective quark method.[11–13]

Presently, the statistical uncertainty is dominated in the above studies, indicating that further improvements on precision can be achieved with additional experimental data in the future.

2.2. *Hadronic decay of* $\boldsymbol{\Lambda_c^+}$

The investigation of Λ_c^+ hadronic decays is important for understanding the complex internal structure and interaction mechanisms of hadrons. The research on Λ_c^+ hadronic decays conducted by the BESIII Collaboration in recent years has addressed the relative scarcity of studies on singly Cabibbo suppressed (SCS) decays compared to Cabibbo favored (CF) decays. The results of the BFs measurements are displayed in Table 2.

Table 2. Recent BESIII Measurements on Hadronic Decays of Λ_c^+

Decay Mode	Branching Fraction	Significance
$\Lambda_c^+ \to n\pi^+$	$(6.6 \pm 1.2 \pm 0.4) \times 10^{-4}$	7.3σ
$\Lambda_c^+ \to p\eta'$	$(5.62^{+2.46}_{-2.04} \pm 0.26) \times 10^{-4}$	3.6σ
$\Lambda_c^+ \to p\eta$	$(1.57 \pm 0.11 \pm 0.04) \times 10^{-3}$	$>10\sigma$
$\Lambda_c^+ \to p\omega$	$(1.11 \pm 0.20 \pm 0.07) \times 10^{-3}$	5.7σ
$\Lambda_c^+ \to \Sigma^0 K^+$	$(4.7 \pm 0.9 \pm 0.1 \pm 0.3) \times 10^{-4}$	-
$\Lambda_c^+ \to \Sigma^+ K_S^0$	$(4.8 \pm 1.4 \pm 0.2 \pm 0.3) \times 10^{-4}$	-
$\Lambda_c^+ \to n\pi^+\pi^0$	$(0.64 \pm 0.09 \pm 0.02) \times 10^{-2}$	7.9σ
$\Lambda_c^+ \to n\pi^+\pi^-\pi^+$	$(0.45 \pm 0.07 \pm 0.03) \times 10^{-2}$	7.8σ
$\Lambda_c^+ \to \Lambda K^+$	$(6.21 \pm 0.44 \pm 0.26 \pm 0.34) \times 10^{-4}$	-
$\Lambda_c^+ \to \Lambda K^+\pi^0$	$(1.49 \pm 0.27 \pm 0.05 \pm 0.08) \times 10^{-3}$	5.7σ
$\Lambda_c^+ \to \Lambda K^+\pi^+\pi^-$	$(4.13 \pm 1.48 \pm 0.20 \pm 0.33) \times 10^{-4}$	3.1σ
$\Lambda_c^+ \to nK^-\pi^+\pi^+$	$(1.90 \pm 0.08 \pm 0.09) \times 10^{-2}$	$>10\sigma$
$\Lambda_c^+ \to \Xi^0 K^+\pi^0$	$(7.79 \pm 1.46 \pm 0.71) \times 10^{-3}$	8.6σ
$\Lambda_c^+ \to \Lambda\rho(770)^+$	$(4.06 \pm 0.30 \pm 0.35 \pm 0.23) \times 10^{-2}$	$>10\sigma$
$\Lambda_c^+ \to \Sigma(1385)^+\pi^0$	$(5.86 \pm 0.49 \pm 0.52 \pm 0.35) \times 10^{-3}$	$>10\sigma$
$\Lambda_c^+ \to \Sigma(1385)^0\pi^+$	$(6.47 \pm 0.59 \pm 0.66 \pm 0.38) \times 10^{-3}$	$>10\sigma$
$\bar{\Lambda}_c^- \to \bar{n}X$	$(32.4 \pm 0.7 \pm 1.5) \times 10^{-2}$	-

The research cited as Ref. 14 marks the first observation by BESIII of the SCS decay of $\Lambda_c^+ \to n\pi^+$. The measured BFs, as presented in Table 2,are consistent with SU(3) flavor asymmetry predictions[15] but twice larger than the dynamical calculation based on pole model and current algebra (CA).[16] By combining it with Belle's estimate of the upper limit of $\Lambda_c^+ \to p\pi^0$ BF, the ratio of BFs is determined to be greater than 7.2, contradicting SU(3) flavor asymmetry and dynamic calculations (2∼4.7), while also being inconsistent with topological-diagram approach (9.6).[15–21] Additionally, an extension of the measurements of $\Lambda_c^+ \to \Lambda\pi^+$ and $\Lambda_c^+ \to \Sigma^0\pi^+$ BFs is in agreement with previous BESIII measurements.[22]

Furthermore, the BESIII Collaboration has also measured the BF of additional two-body SCS decays,[23–26] as presented in Table 2. For the measurement reported in Ref. 23, the BF measured of $\Lambda_c^+ \to p\eta'$ is consistent with the previous Belle result and certain SU(3) flavor symmetry predictions[15,17] but significantly higher than the prediction of CA.[19]

The measured BF of $\Lambda_c^+ \to p\eta$ in Ref. 24 is found to be inconsistent with SU(3) flavor symmetry and CA predictions.[17,19] Similarly, the measured BF of $\Lambda_c^+ \to p\omega$

is inconsistent with certain predictions from heavy quark effective theory.[27]

The study presented in Ref. 25 measured the BF of $\Lambda_c^+ \to \Lambda K^+$ relative to $\Lambda_c^+ \to \Lambda\pi^+$, which is consistent with the measurements performed by the Belle and BABAR collaborations within uncertainties, but closer to that of BABAR. The measured BF of $\Lambda_c^+ \to \Lambda K^+$ is significantly lower ($\sim 40\%$) than the predictions based on the SU(3) flavor symmetry, constituent quark model or CA.[16] Besides, by comparing the measured relative BFs with those calculated from purely factorizable contributions, it is demonstrated that the non-factorizable contributions in Λ_c^+ decays are important and have been significantly underestimated in current theoretical models.

The investigation presented in Ref. 26 focused on measuring the BFs of $\Lambda_c^+ \to \Sigma^0 K^+$ and $\Lambda_c^+ \to \Sigma^+ K_S^0$. The BF of $\Lambda_c^+ \to \Sigma^+ K_S^0$ shows a deviation of 2.5 σ from the theoretical prediction in Ref. 28, indicating a possible need for a reassessment of the irreducible representation amplitude method. Although the measured results in the paper are generally consistent with theory within 1$\sim$2 σ, previous predictions tend to overestimate the BFs.

It is worth mentioning that the recent research conducted by the BESIII Collaboration includes exploration of the asymmetry parameters in the $\Lambda_c^+ \to \Xi^0 K^+$ process,[29] which occurs only through the exchange of a W-boson. By deriving the angular distribution from helicity amplitudes and performing a 7-dimensional fit to the data, the decay asymmetry has been measured for the first time to be $\alpha_{\Xi^0 K^+} = 0.01 \pm 0.16 \pm 0.03$, indicating non-interference effects between S-wave and P-wave amplitudes. The specifics of the fitting process are outlined in Figure 2. The phase shift between S-wave and P-wave amplitudes presents two solutions $\delta_p - \delta_s = -1.55 \pm 0.25 \pm 0.05\ rad$ or $1.59 \pm 0.25 \pm 0.05\ rad$, which is not considered in previous literature.The measurement of these asymmetry parameters can assist in validating predictions from various theoretical models and explain the long-standing puzzle on how to model $\alpha_{\Xi^0 K^+}$ and $B(\Lambda_c^+ \to \Xi^0 K^+)$ simultaneously.

In addition, the first measurements of the SCS $\Lambda_c^+ \to n\pi^+\pi^0$ and $\Lambda_c^+ \to n\pi^+\pi^-\pi^+$ process alongside the CF $\Lambda_c^+ \to nK^-\pi^+\pi^+$ process have provided BF values,[30] offering insights into the isospin and $SU(3)$ symmetry tests within charm baryon decays. The initial measurement results of the $\Lambda_c^+ \to \Lambda K^+\pi^0$ BF significantly deviate from the theoretical predictions based on quark $SU(3)$ flavor symmetry.[31] Additionally, the BF of the $\Lambda_c^+ \to \Xi^0 K^+\pi^0$ is smaller than the theoretical prediction,[32] while upper limits on the BFs of $\Lambda_c^+ \to nK^+\pi^0$, $\Lambda_c^+ \to \Sigma^0 K^+\pi^0$ and $\Lambda_c^+ \to \Lambda K^+\pi^0$ process have been set, providing valuable references for the improvement of phenomenological models. These results of the BFs measurements are displayed in Table 2.

In 2023, the absolute BF of the inclusive decay $\bar{\Lambda}_c^- \to \bar{n}X$, where X represents any possible final state particles, was measured.[33] The identification of antineutrons was achieved by utilizing the deposited energy in the electromagnetic calorimeter (EMC), and the detector effects of antineutrons were simulated using data-driven

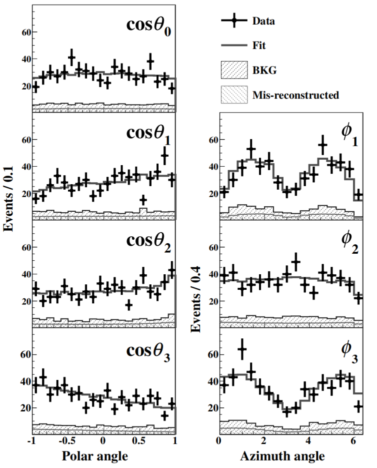

Fig. 2. Illustrations of the optimal fit projections onto various variables. The data points with error bars represent the observed data, the solid lines depict the fitting results, and the shaded regions indicate background events.

techniques. Under the assumption of CP symmetry, this measurement suggests that approximately one-fourth of the $\Lambda_c^+(\bar{\Lambda}_c^-)$ decay modes involving a neutron (antineutron) in the final state have not yet been observed. The investigation of the isospin symmetry between $\Lambda_c^- \to nX$ and $\Lambda_c^- \to pX$ is important input to theoretical estimation of the lifetime of the charmed baryon Λ_c^+.

In 2022, a partial wave analysis of the charmed baryon hadronic decay $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ has been performed,[34] and the decays $\Lambda_c^+ \to \Lambda\rho(770)^+$ and $\Lambda_c^+ \to \Sigma\pi$ have been studied for the first time at BESIII. The derived partial wave amplitudes have enabled the determination of decay asymmetry parameters $\alpha_{\Lambda\rho(770)^+}$ = -0.763 ± 0.053 ± 0.045, $\alpha_{\Sigma(1385)^+\pi^0}$ = -0.917 ± 0.069 ± 0.056 and $\alpha_{\Sigma(1385)^0\pi^+}$ = -0.789 ± 0.098 ± 0.056. These findings are particularly significant as no theoretical models are able to explain both BFs and decay asymmetries simultaneously. It provides valuable information for testing theoretical calculations, particularly in clarifying interference effects among different partial waves.

Experimental measurements provide valuable inputs to constrain these phenomenological models, contributing to the refinement of theoretical frameworks and enhancing our understanding of the dynamics of charmed baryons.

3. Recent studies on the charmed mesons measurements at BESIII

Compared with charm baryons, charm mesons has a more simple structure, making theoretical calculations of their decay mechanisms more straightforward and precise. This section will present the work conducted by BESIII, focusing on the decay properties of charm mesons, including leptonic decays, semileptonic decays, hadronic decays, inclusive decays, strong phase determinations, and exploration of excited states.

3.1. *Purely leptonic decays of charmed mesons*

The purely leptonic decays of charmed-strange mesons, $D_s^+ \to \ell\nu_\ell$, represent the most straightforward and well-studied avenues for investigating the $c \to s$ quark transition. By parameterizing the impact of strong interactions using the decay constant f_D, this decay process can be described in terms of key parameters such as mass, $|V_{cs}|$ and f_D. Through the utilization of experimentally determined $|V_{cs}|$ derived from comprehensive fits within the global SM framework to compute f_D, we can verify the projections of f_D originating from LQCD calculations. Conversely, using the LQCD computations of f_D as input permits the determination of $|V_{cs}|$, thereby facilitating a more precise examination of the Cabibbo-Kobayashi-Maskawa (CKM) matrix unity. Recent investigations conducted by BESIII on purely leptonic decays[35–38] are presented in Table 3.

Table 3. Recent BESIII Measurements on Purely Leptonic Decays of Charmed Mesons

Decay Mode	Branching Fraction	Decay Constant	$\lvert V_{cs}\rvert$
$D_s^{*+} \to e^+\nu_e$	$(2.1^{+1.2}_{-0.9} \pm 0.2) \times 10^{-5}$	$214^{+61}_{-46} \pm 44$	-
$D_s^+ \to \mu^+\nu_\mu$	$(5.29 \pm 0.11 \pm 0.09) \times 10^{-3}$	$248.4 \pm 2.5 \pm 2.2$	$0.968 \pm 0.010 \pm 0.009$
$D_s^+ \to \tau^+\nu_\tau$ via $\tau \to \mu^+\nu_\mu\bar{\nu}_\tau$	$(5.37 \pm 0.17 \pm 0.15) \times 10^{-2}$	$253.4 \pm 4.0 \pm 3.7$	$0.987 \pm 0.016 \pm 0.014$
$D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \pi^+\bar{\nu}_\tau$	$(5.44 \pm 0.17 \pm 0.13) \times 10^{-2}$	$255.0 \pm 4.0 \pm 3.2 \pm 1.0$	$0.993 \pm 0.015 \pm 0.012 \pm 0.004$

These measurements of the BFs are important for validating the theoretical predictions. Furthermore, tests have been conducted on lepton flavor universality with $D_s^+ \to \ell\nu_\ell$ decays, revealing no evidence of $\tau - \mu$ lepton flavor universality violation.

At present, the statistical uncertainties associated with these measurements surpass the systematic uncertainties. Improved measurements are foreseen with the larger data sets that BESIII is expected to accumulate in the coming years.

3.2. *Semileptonic decays of charmed mesons*

Within the framework of the SM, semileptonic decays of charmed mesons play a significant role in revealing the dynamics of weak and strong interactions within the charm sector. Therefore, it is essential to seek additional insights into semileptonic charmed meson decays. In 2023, BESIII Collaboration investigated the decay channel $D_s^+ \to \eta e^+\nu_e$ and $D_s^+ \to \eta' e^+\nu_e$,[39] with the measurement results detailed in Table 4.

This study not only measured BFs but also determined the product of $f_+^{\eta^{(\prime)}}(0)$ and $|V_{cs}|$ by incorporating various hadronic transition factors (refer to Table 4). Additionally, in conjunction with previous measurements, the mixing angle of η-η' was determined to be $(40.0 \pm 2.0 \pm 0.6)^\circ$. The theoretical value of $f_+^{\eta^{(\prime)}}(0)$ cited in

Table 4. Research on $D_s^+ \to \eta(\eta')e^+\nu_e$

Decay Mode	Branching Fraction	$f_+^{\eta^{(\prime)}}(0)\ \lvert V_{cs}\rvert$
$D_s^+ \to \eta e^+\nu_e$	$(2.255 \pm 0.039 \pm 0.051) \times 10^{-2}$	$0.452 \pm 0.007 \pm 0.007$
$D_s^+ \to \eta' e^+\nu_e$	$(0.810 \pm 0.038 \pm 0.024) \times 10^{-2}$	$0.525 \pm 0.024 \pm 0.009$

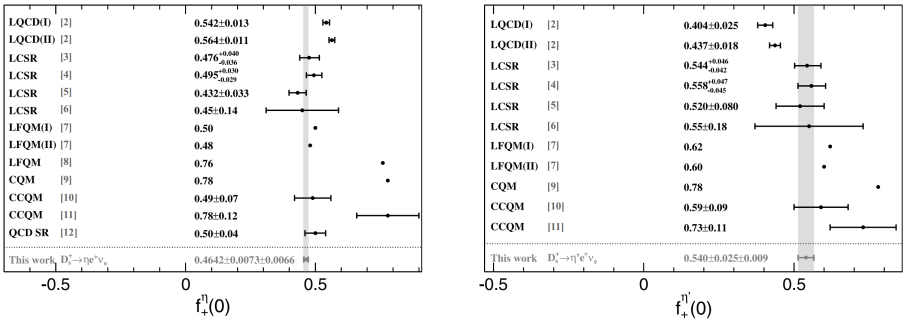

Fig. 3. Comparisons between the FFs measured in this study and theoretical calculations are presented. The bands indicate the $\pm 1\sigma$ limits of the FFs measured in this study.

this study was employed to determine $|V_{cs}|$, thereby assessing the consistency of the CKM matrix. Figure 3 presents a comparison between the obtained value of $f_+^{\eta^{(\prime)}}(0)$ in this study and various theoretical predictions, which holds substantial significance. Besides, a mistake in the construction of χ^2 under partial decay rates as reported in the previous article Ref. 40 was found and corrected, with all results updated in this study.

Furthermore, BESIII conducted searches for the decays of $D_s^+ \to K_1(1270)^0 e^+\nu_e$ and $D_s^+ \to b_1(1235)^0 e^+\nu_e$,[41] but no significant signals was observed. The upper limits on the (product) BFs are set to be $B[D_s^+ \to K_1(1270)^0 e^+\nu_e] < 4.1 \times 10^{-4}$ and $B[D_s^+ \to b_1(1235)^0 e^+\nu_e] \cdot B[b_1(1235)^0 \to \omega\pi^0] < 6.4 \times 10^{-4}$ at 90% confidence level. It is the first measurement of D_s^+ decays to axial-vector mesons. It provide important input for study of photon helicity in $b \to s\gamma$.

3.3. *Hadronic decays of charmed mesons*

Limited information is available for $D_s^\pm$ decays, with a significant portion of the hadronic BFs remaining unmeasured. BESIII Collaboration investigated $D_s^+ \to \omega\pi^+\eta$,[42]with the measurement results detailed in Table 5. The BF measured in this work is consistent with that of the CLEO Collaboration, but the precision is improved by a factor of 2.7. Besides, it offers an important input for estimating the $D_s^+ \to \pi^+\pi^+\pi^- X$ background contribution in tests of the LFU with semileptonic B decays. Larger statistics data to be taken in the future will help to search for potential intermediate processes $D_s^+ \to \omega a_0(980)^+$ and $D_s^+ \to \eta b_1(1235)^+$.

Furthermore, in the $D^+ \to K_S^0\pi^+\pi^0\pi^0$ decay channel,[43] the BESIII Collabora-

Table 5. Measurement of Charmed Mesons Hadronic Decays

Decay Mode	Branching Fraction
$D^+ \to K_s^0\pi^+\pi^0\pi^0$	$(2.888 \pm 0.058 \pm 0.069) \times 10^{-2}$
$D^+ \to K_s^0 a_1(1260)^+(\to \rho^+\pi^0)$	$(8.66 \pm 1.04 \pm 1.39) \times 10^{-3}$
$D^+ \to \bar{K}^{*0}\rho^+$	$(9.70 \pm 0.81 \pm 0.53) \times 10^{-3}$
$D_s^+ \to \omega\pi^+\eta$	$(0.54 \pm 0.12 \pm 0.04) \times 10^{-2}$

tion has conducted an amplitude analysis for the first time, as presented in Table 5. The method of obtaining detection efficiency can be improved by using an amplitude model. Besides, it can also help us better understand the more complicated dynamics and substructures in the processes $D^+ \to VV$ and $D^+ \to AP$ decays, where V , A, and P denote vector, axial-vector and pseudoscalar mesons, respectively. The BF of $D^+ \to K_s^0\pi^+\pi^0\pi^0$ is consistent with the previous BESIII result within 1 σ. And the absolute BFs of $D^+ \to K_s^0 a_1(1260)^+(\to \rho^+\pi^0)$ and $D^+ \to \bar{K}^{*0}\rho^+$ are consistent with the previous BESIII result within 1.5 σ and the MARK III result within 1 σ. The specifc BFs of $D \to K_1(1270)\pi$ and $D \to K_1(1400)\pi$ from amplitude analyses can provide inputs to further investigations of the mixing between these two axial-vector kaon mesons. Future employment of larger statistical datasets will enable the exploration of potential intermediate processes.

3.4. *Inclusive decays of charmed mesons*

In recent years, BESIII has also provided measurements of inclusive decays of charm mesons,[44–46] as summarized in Table 6.

Table 6. Measurement of Charmed Mesons Inclusive Decays

Decay Mode	Branching Fraction
$D^+ \to K_s^0 X$	$(33.11 \pm 0.13 \pm 0.36)\times10^{-2}$
$D^0 \to K_s^0 X$	$(20.75 \pm 0.12 \pm 0.20)\times10^{-2}$
$D^+ \to \pi^+\pi^+\pi^- X$	$(15.25 \pm 0.09 \pm 0.18) \times 10^{-2}$
$D^0 \to \pi^+\pi^+\pi^- X$	$(17.60 \pm 0.11 \pm 0.22) \times 10^{-2}$
$D_s^+ \to \pi^+\pi^+\pi^- X$	$(32.81 \pm 0.35 \pm 0.63) \times 10^{-2}$

For the measurement of D^0 and D^+, the BFs of $D^0 \to K_S^0 X$ and $D^+ \to K_S^0 X$ are consistent with previous measurements and improved by factors of 7.1 and 7.6, respectively. The differences between the inclusive and exclusive decay BFs indicate that there may be some missing decay modes involving K_S^0 for both D^0 and D^+ yet to be observed. Besides, the BF of $D^0(D^+) \to \pi^+\pi^+\pi^- X$ indicate that there is little room for possible missing $D^0(D^+)$ decays containing $\pi^+\pi^+\pi^-$.

Since the BFs of $D_s^+ \to \pi^+\pi^+\pi^- X$ is larger than the sum of all observed exclusive BFs of $\sim 25\%$ based on the particle data group and recent measurements, this hints at potentially unobserved decay modes with at least three charged pions in the final states.

Futhermore, in LFU tests, the analyses adopt the decay chain of $B^0 \to D^{*-}\tau^+\nu_\tau$ with $\tau^+ \to \pi^+\pi^+\pi^-\bar{\nu}_\tau$, where the leading and subleading background sources are from $B^{0,+} \to D_s^+ X$ with $D_s^+ \to \pi^+\pi^+\pi^- X$ and $B^{0,+} \to D^0(D^+)X$ with $D^0(D^+) \to \pi^+\pi^+\pi^- X$ respectively. Measurements of the full and partial decay BFs of the inclusive decays $D_s^+ \to \pi^+\pi^+\pi^- X$ and $D^0(D^+) \to \pi^+\pi^+\pi^- X$ offer important inputs to precisely test LFU with semileptonic B decays.

3.5. *Strong phase in charmed mesons decays*

The *CP*-even fraction serves as a fundamental parameter in the investigation of *CP* violation within the realm of particle physics. In the year 2023, the BESIII Collaboration undertook the measurement of the *CP*-even fraction associated with the decays $D^0 \to K_s^0\pi^+\pi^-\pi^0$ and $D^0 \to K^+K^-\pi^+\pi^-$,[47,48] with the measurement results detailed in Table 7.

Table 7. *CP*-even Fraction Measurement of Charmed Mesons

Decay Mode	CP-even fraction
$D^0 \to K_s^0\pi^+\pi^-\pi^0$	$0.235 \pm 0.010 \pm 0.002$
$D^0 \to K^+K^-\pi^+\pi^-$	$0.730 \pm 0.037 \pm 0.021$

The result of $D^0 \to K_s^0\pi^+\pi^-\pi^0$ is consistent with that obtained from CLEO-c data, but is 1.7 times more precise. And the investigation of $D^0 \to K^+K^-\pi^+\pi^-$ is the first model-independent measurement of the CP-even fraction. This measurement is dominated by statistical uncertainty and it will improve significantly with the larger charm-threshold dataset that BESIII is expected to collect in the coming years.

These measurements not only enhance the comparison with other experimental measurements of strong phases, but also provide essential inputs for future analyses of γ and $D_0 - \bar{D}_0$ oscillations using these channels.

3.6. *Research in excited charmed mesons*

The quark model has effectively predicted masses and spin-parity assignments, but validations are still lacking in numerous instances. Significantly, the assumed classification of D_s^{*+}, D^{*0} and D^{*+} as states with quantum numbers $J^P = 1^-$ has not been validated by any experiment so far.

In 2023, utilizing experimental data from the BESIII, the spin and parity of charmed mesons D_s^{*+}, D^{*0} and D^{*+} were conclusively determined for the first time to be $J^P = 1^-$.[49] Furthermore, a helicity amplitude analysis of the processes $e^+e^- \to D_s^{*+}D_s^-$,$D^{*0}D^0$ and $D^{*+}D^-$, with $D_s^{*+} \to D_s^+\gamma$, $D^{*0} \to D^0\pi^0$ and $D^{*+} \to D^+\pi^0$ was conducted to test various spin-parity hypotheses, confirming the predictions of the quark model. This experimental determination of the spin and parity of the D_s^{*+} mesons represents a significant milestone in the exploration of the properties of heavier charm and beauty mesons, serving as a cornerstone for further research in this field.

Besides, BESIII Collaboration measure the BF of $D_s^{*+} \to D_s^+\pi^0$ relative to that of $D_s^{*+} \to D_s^+\gamma$ to be $(6.16 \pm 0.43 \pm 0.18)\%$.[50] By using the world average value of the BF of $D_s^{*+} \to D_s^+e^+e^-$, the BFs of $D_s^{*+} \to D_s^+\gamma$ and $D_s^{*+} \to D_s^+\pi^0$ were determined to be $(93.57 \pm 0.38 \pm 0.22)\%$ and $(5.76 \pm 0.38 \pm 0.16)\%$, respectively. The world-leading precision of this BF measurement will provide improved inputs to the measurements of $f_{D_s^+}$ and $|V_{cs}|$ in $e^+e^- \to D_s^{*\pm}D_s^{\mp}$.

4. Recent studies on the new physics at BESIII

This section will highlight the contributions of the BESIII Collaboration in recent years to advancing new physics through the exploration of these fascinating phenomena.

4.1. *Symmetry violation*

Identifying suitable decay channels with potential symmetry violation is an important approach for investigating new physics. The BESIII Collaboration has conducted tests in the realms of baryon number violation (BNV), lepton number violation (LNV), or lepton flavor violation (LFV),[51–54] as documented in Table 8.

Table 8. Symmetry Violation of New Physics

Decay Mode	Types of symmetry violation	Branching Fraction
$\Xi^0 \to K^-e^+$	BNV,LNV	$< 3.6 \times 10^{-6}$
$\Xi^0 \to K^+e^-$	BNV,LNV	$< 1.9 \times 10^{-6}$
$D^\pm \to n(\bar{n})e^\pm(\Delta\|B-L\| = 0)$	BNV,LNV	$< 1.43 \times 10^{-5}$
$D^\pm \to n(\bar{n})e^\pm(\Delta\|B-L\| = 2)$	BNV,LNV	$< 2.91 \times 10^{-5}$
$D^0 \to \bar{p}e^+$	BNV,LNV	$< 1.2 \times 10^{-6}$
$D^0 \to pe^-$	BNV,LNV	$< 2.2 \times 10^{-6}$
[54] $J/\psi \to e^\pm\mu^\mp$	LFV	$< 4.5 \times 10^{-9}$

In addition, the investigation of $\bar{\Lambda}$-Λ oscillations in the decay $J/\psi \to pK^-\bar{\Lambda}+c.c.$ represents a meaningful endeavor.[55] No evidence for hyperon oscillations is observed in the study. The upper limit for the oscillation rate of $\bar{\Lambda}$ to Λ hyperons is determined to be $\mathcal{P}(\Lambda) = [\mathcal{B}(J/\psi \to pK^-\Lambda + c.c.)/\mathcal{B}(J/\psi \to pK^-\bar{\Lambda} + c.c.)] < 4.4 \times 10^{-6}$ corresponding to an oscillation parameter $\delta m_{\bar{\Lambda}\Lambda}$ of less than 3.8 $\times 10^{-18}$ GeV at the 90% confidence level.

While no signals have been detected yet, these findings could help constrain the parameter space of the new physics model. The results presented in these papers also provide insights into future possibilities and encourage additional theoretical and experimental research.

4.2. *Rare decays*

In Standard Model ,the flavor changing neutral current (FCNC) decays in charm sector and the weak decays of charmonium states are highly suppressed. Observation of these decay with the current experimental sensitivity would imply new physics beyond the SM. The exploration by BESIII in this regard is documented in Table 9.

For the investigation of FCNC decay,[56] the BF upper limit for $\Lambda_c^+ \to p\gamma'$ is below the sensitivity of the theoretical prediction in Ref. 57. A more stringent constrain on it is expected in the near future with larger Λ_c^+ samples at BESIII.

Besides, BESIII Collaboration also explore weak decay and semileptonic of charmonium.[58] The BF upper limit for $\psi(3686) \to \Lambda_c^+ \bar{\Sigma}^- + c.c.$ is far above the prediction in the SM. The upper limit on the BF of $J/\psi \to D^-\pi^+ + c.c$ has been improved by three orders of magnitude compared to the previous result. These results is compatible with the SM based predictions.

Table 9. Rare Decays of New Physics

Decay Mode	Branching Fraction
$\psi(3686) \to \Lambda_c^+ \bar{\Sigma}^- + c.c.$	$< 1.4 \times 10^{-5}$
$J/\psi \to D^-\mu^+\nu_\mu + c.c.$	$< 5.6 \times 10^{-7}$
$J/\psi \to \bar{D}^0\pi^0 + c.c$	$< 4.7 \times 10^{-7}$
$J/\psi \to \bar{D}^0\eta + c.c$	$< 6.8 \times 10^{-7}$
$J/\psi \to \bar{D}^0\rho^0 + c.c$	$< 5.2 \times 10^{-7}$
$J/\psi \to D^-\pi^+ + c.c$	$< 7.0 \times 10^{-8}$
$J/\psi \to D^-\rho^+ + c.c$	$< 6.0 \times 10^{-7}$
$\Lambda_c^+ \to p\gamma'$	$< 8.0 \times 10^{-5}$

4.3. *Exotic searches*

Exotic exploration refers to the effort to seek and study new particles, phenomena, or interactions that fall outside the predictive scope of the SM using experimental methods. In recent years, BESIII has been dedicated to explore the exotic states in areas such as invisible decays, CP-odd light Higgs bosons, axion-like particles.

For invisible decays, exploring the dark photon in the radiative annihilation process $e^+e- \to \eta\eta'$, followed by an invisible decay of η', presents an fascinating avenue for exotic searches. Although no significant signals was detected, the study provided constraints on the coupling strength of the dark photon with an ordinary photon, yielding a range of ϵ values between 1.6×10^{-3} and 5.7×10^{3}.[59] Furthermore, efforts have been made to investigate the invisible decays of Λ baryons, despite the absence of any observable signal. The upper limit for the BF of this invisible decay has been constrained to 7.4×10^{-5},[60] which is consistent with the prediction of 4.4×10^{-7} from the mirror model. This is the first search for invisible decays of baryons, such searches will play an important role in constraining dark sector models related to the baryon asymmetry.

The next-to-minimal supersymmetric SM introduces the hypothesis of a light Higgs boson, A^0, with a mass potentially below twice the charm quark mass, thus presenting the possibility of its detection through the process $J/\psi \to \gamma A^0$. While no signal has been observed on the BESIII experiment, investigations have yielded the determination of the upper limit of the BF $B(J/\psi \to \gamma A^0) \times B(A^0 \to \mu^+\mu^-)$ within the range of $(1.2 - 778.0)$ $\times 10^{-9}$ for $0.212 \leq m_{A^0} \leq 3.0 \mathrm{GeV}/c^2$.[61] The new measurement is a 6–7 times improvement over our previous measurement, and is also slightly better than the BABAR measurement in the low-mass region for $tan\beta = 1$.

Besides, an exploration for axion-like particles (ALPs) through the process $\psi(3686) \to \pi^+\pi^- J/\psi$, $J/\psi \to \gamma a$, $a \to \gamma\gamma$ was conducted. No significant ALP signal was detected, and upper limits on the decay BF and ALP-photon coupling constant were established. In the mass range of $0.165 \leq m_a \leq 2.84 \mathrm{GeV}/c^2$, the upper limits on $B(J/\psi \to \gamma a)$ range from 8.3×10^{-8} to 1.8×10^{-6}.[62] The constraints on the ALP-photon coupling are the most stringent to date for $0.165 \leq m_a \leq 2.84 \mathrm{GeV}/c^2$.

These experimental findings offer crucial clues and data support for conducting exotic explorations in the field of high-energy physics.

5. Summary

The BESIII has accumulated a large data sample at the energy points from 2.0 to 4.95 GeV. These data samples have played a important role in BESIII's contributions to the study of charm physics and the search for new physics. This proceeding presents the results of BESIII in charm baryons, charm mesons and new physics during the years from 2022 to 2024, providing valuable information for theoretical studies, facilitating the experimental determination of physical parameters, and improving the precision of measurement. Further upgrades and explorations of BESIII in the near future are expected to yield more comprehensive results.

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