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Recent results on (semi)-leptonic D decays and charm baryons at BESIII

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The BESIII collaboration has collected the world's largest datasets at the energy thresholds for producing a variety of open-charm hadrons. Most recently, the BESIII collaboration has collected datasets that significantly increase the number of D^0, D^+, and Λ_c^+ hadrons for analysis, further improving on previous datasets collected by BESIII. These proceedings highlight recent results that leverage these datasets to study the pure leptonic and semileptonic decays of these hadrons, as well as study the polarization of baryon pairs produced in electron-positron collisions.

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The BESIII experiment [1] records data of symmetric e^+e^- collisions provided by the Beijing Electron Positron Collider Mk. II [2] (BEPCII). BEPCII produces collisions at center-of-mass energies of 2 – 5 GeV with a design luminosity of 10^{33} cm^{-2}s^{-1} achieved in April 2016. The BESIII detector covers 93% of the full solid angle, and is equipped with gaseous tracking system, a plastic scintillator time-of-flight system for particle identification, a caesium-iodide calorimeter, and a resistive-plate-chamber muon system. BEPCII and BESIII finished construction in 2008, upgrading on the original Beijing Electron-Positrion Collider and BESII detector. BESIII began taking data in 2009, and has collected many large datasets in this energy regime[3]. These proceedings report results on D^0 and D^+ decays[1] 20.3 fb^{-1} sample collected at the $\psi(3770)$ threshold, whose collection was completed in 2024. This contains the previous largest sample at this energy, a sample of 2.9 fb^{-1} collected in 2011. These proceedings also report results which use a 6.4 fb^{-1} BESIII sample collected between 2022-2024 at center-of-mass energies between $E_{\rm cm} = 4.60 - 4.95$ GeV, which contain sizable samples of $e^+e^- \to \Lambda_c^+\Lambda_c^-$.

Electron-positron collisions near open-charm pair-production energy thresholds allow for various unique studies of fundamental physics. These proceedings summarize recent results on two classes of such measurements: pure leptonic and semileptonic decays of charmed hadrons, and other results relating to charmed baryons. Precision measurements of the leptonic and semileptonic decays of charmed hadrons enable:tests of CKM unitarity through precision measurements of $|V_{cd}|$ and $|V_{cs}|$; studies of non-perturbative QCD through determinations of decay constants and form factors that can be compared with lattice QCD and other theoretical calculations; tests of lepton flavor universality by comparing decay rates to electrons versus muons; and a laboratory for light hadron physics, including the structure of scalar mesons such as the $a_0(980)$.

The double-tag method[4, 5] exploits the pair production of charmed hadrons to measure the branching fractions of decay modes with particles that are difficult to reconstruct, such as neutrinos. First, one charmed hadron (the "tag") is reconstructed through a clean hadronic decay mode. The presence of the tag then guarantees the existence of another charmed hadron of opposite flavour in the event, whose decay can be studied inclusively by searching for signal particles in the remainder of the event. Missing particles such as neutrinos can be identified through kinematic variables such as the missing mass squared $M^2_{\rm miss} = (p_{e^+e^-} - p_{\rm tag} - p_{\rm visible})^2$ or the missing energy-momentum $U_{\rm miss} \equiv E_{\rm miss} - p_{\rm miss}$, where $p_{e^+e^-}$ is the four-momentum of the initial e^+e^- system. The branching fraction of the signal decay is then given by

$$\mathcal{B}(D \to \text{signal}) = \frac{N_{\rm signal}/\epsilon_{\rm tag\ \&\ signal}}{N_{\rm tag}/\epsilon_{\rm tag}}, \tag{1}$$

where $N_{\rm tag}$ and $N_{\rm signal}$ are the yields of tag and signal decays, respectively, and ϵ denotes the corresponding efficiencies. This method offers several advantages compared to only reconstructing the signal decay channel: combinatorial backgrounds are greatly reduced, and the full kinematic information of the recoiling system is accessible for differential measurements.

The full 20.3 fb^{-1} dataset collected at $E_{\rm CM} = 3.773$ GeV was analyzed to measure the purely leptonic decay $D^+ \to \mu^+\nu_\mu$ [6]. Nine D^- tag modes were employed: $K^+\pi^-\pi^-$, $K^0_S\pi^-$, $K^+\pi^-\pi^-\pi^0$, $K^0_S\pi^-\pi^0$, $K^0_S\pi^-\pi^+\pi^-$, $K^+K^-\pi^-$, $\pi^+\pi^-\pi^-$, and $K^+\pi^-\pi^-\pi^-\pi^+$. Tag yields were determined from

[1] Charge conjugation is implied throughout these proceedings, except where explicitly stated.

fits to the beam-constrained mass $M_{\rm BC} \equiv \sqrt{E^2_{\rm beam} - |\vec{p}_D|^2}$. Muon candidates were identified through selections on electromagnetic calorimeter energy deposition and muon chamber penetration depth. Signal yields were extracted from a fit to the $M^2_{\rm miss}$ distribution, with the dominant peaking backgrounds arising from $D^+ \to \pi^0\mu^+\nu$ and $D^+ \to \tau^+\nu \to \pi^+\pi^0\nu\nu$ decays. The final sample, and the fit to determine the signal yields is shown in Fig. 1. The measured branching fraction is $\mathcal{B}(D^+ \to \mu^+\nu_\mu) = (3.98\pm0.08\pm0.04)\times10^{-4}$, representing a 2.3-fold improvement in precision over previous measurements. Using the D^+ lifetime from PDG2022[7], this results in the determination $f_{D^+}|V_{cd}| = (47.53\pm0.48\pm0.24\pm0.12_{\rm ext})$ MeV. This result is complemented by a new measurement of $D^+ \to \tau^+\nu$ using 7.9 fb^{-1} of data at the $\psi(3770)$ resonance [8], which comprises a subset of the full 20.3 fb^{-1} dataset.

The golden channels for $|V_{cs}|$ determination, $D^0 \to K^-(e^+/\mu^+)\nu$ and $D^+ \to K^0_S(e^+/\mu^+)\nu$, were analyzed using 7.9 fb^{-1} collected at $E_{\rm CM} = 3.773$ GeV [9]. Six $\bar{D}^0$ tag modes and six D^- tag modes were employed. Signal yields were extracted from fits to $U_{\rm miss}$, with peaking backgrounds in the muon sample arising from challenges in low-momentum μ/π separation. The measured branching fractions achieve relative precisions of 0.5%–1.1%, enabling the most precise test of lepton flavor universality in charm decays: $R^{D^+}_{\mu/e} = 0.978(7)_{\rm stat}(13)_{\rm syst}$ and $R^{D^0}_{\mu/e} = 0.971(4)_{\rm stat}(6)_{\rm syst}$, consistent with the Standard Model expectation of 0.975(1) [10].The differential decay rate $\mathrm{d}\Gamma/\mathrm{d}q^2$, where q^2 is the invariant mass squared of the lepton-neutrino system, was measured and the form factors were parametrized using a power-series expansion. A simultaneous fit to both D^0 and D^+ modes yields $f^K_+(0)|V_{cs}| = 0.7171(11)_{\rm stat}(13)_{\rm syst}$. Taking $|V_{cs}|$ from the PDG2022 global fit [7], the form factor $f^K_+(0) = 0.7366 \pm 0.0011 \pm 0.0013$ is obtained. This result is compared to previous experimental and theoretical determinations in Fig. 1, where a $\sim 2\sigma$ tension is observed with the most recent lattice results[11, 12].

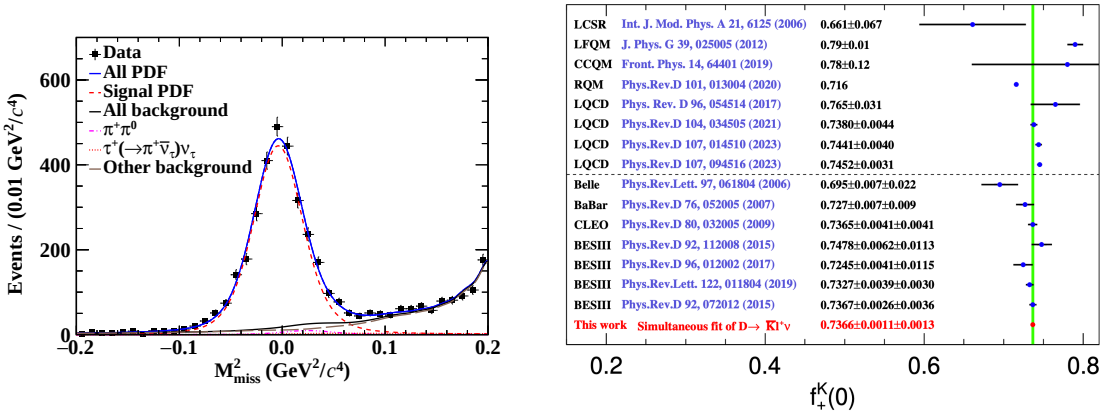

Figure 1: (Left) Fit to determine $D^+ \to \mu^+\nu$ signal yields from Ref. [6]. (Right) Comparison of $f^K_+(0)$ determined in Ref. [9] to various other experimental and theoretical determinations.

The semileptonic decays $D^+ \to K^0_S\pi^0\ell^+\nu$, where $\ell^+ = e^+$ or μ^+, were studied using the full 20.3 fb^{-1} dataset at the $\psi(3770)$ resonance with six D^- tag modes [13]. Signal yields were determined from fits to $U_{\rm miss}$ for both e^+ and μ^+ final states. In these decays, the $K\pi$ system is seen to be dominated by the $K^*(892)$ resonance, whose amplitude structure and form factor ratios were extracted from a five-dimensional fit to the variables $m^2_{K\pi}$, q^2, $\cos\theta_\ell$, $\cos\theta_K$, and χ, where

θ_ℓ and θ_K are helicity angles and χ is the angle between decay planes. A smaller contribution from S-wave $K\pi$ decays is also observed. The fit yields the $K^*(892)$ mass and width, the form factor ratios $r_2 = A_1(0)/A_2(0)$ and $r_V = V(0)/A_1(0)$, the shape parameters of the form factors, and the $K\pi$ S-wave fraction $f_{S\text{-wave}}$. Observables associated with CP violation, lepton flavor universality, and forward-backward asymmetries were measured in different q^2 regions of the sample. All CP asymmetries and angular observables are consistent Standard Model predictions, and the ratio $R_{\mu/e}$ is consistent with unity across all q^2 bins. This analysis is part of a recent series of BESIII measurements of $D \to KX\ell\nu$ decays, including $D^0 \to K^0_S\pi^-\mu^+\nu$ [14], $D^+ \to \bar{K}_1(1270)^0\ell^+\nu$ [15], and $D^0 \to K^0_S\pi^-e^+\nu$ [16].

A new measurement of the semileptonic decay $D^0 \to a_0(980)^-e^+\nu$ was performed using 7.9 fb^{-1} at the $\psi(3770)$ resonance with six D^- tag modes [17], providing the first analysis of the differential decay rate and the first experimental determination of the $D \to a_0$ form factor. The $a_0(980)^-$ state was studied through its decay to $\eta\pi^-$, with the η reconstructed via $\gamma\gamma$. Signal yields were extracted from a two-dimensional fit to $U_{\rm miss}$ and $m_{\eta\pi^-}$. The $a_0(980)$ resonance was parametrized using the Flatté formalism, and the contribution from non-resonant $\eta\pi^-$ production was found to be negligible. The measured branching fraction is $\mathcal{B}(D^0 \to a_0(980)^-[\to\eta\pi^-]e^+\nu_e) = (0.86 \pm 0.17 \pm 0.05) \times 10^{-4}$. The differential decay rate $\mathrm{d}\Gamma/\mathrm{d}q^2$ and the form factor $f_+^{a_0}(q^2)$ were measured as functions of q^2. Using $|V_{cd}|$ from PDG2024[18], the form factor was determined to be $f_0^{D\to a_0} = (0.550 \pm 0.056 \pm 0.013)$. This result provides important discriminating power between different theoretical models of the $a_0(980)$ structure[19–23].

The first observation of the semileptonic decay $\Lambda_c^+ \to ne^+\nu_e$ was achieved using 4.5 fb^{-1} collected at $E_{\rm CM}$ = 4.6–4.7 GeV [24]. This decay represents the first measurement of a $c \to d$ transition in the charmed baryon sector. The major experimental challenge is the background from $\Lambda_c^+ \to \Lambda[\to n\pi^0]e^+\nu_e$, where the π^0 is not reconstructed. To suppress this background, a graph neural network (GNN) was trained on control samples of J/ψ decays to discriminate between neutrons and Λ baryons decaying to $n\pi^0$. Signal yields were determined from a simultaneous fit to the corrected GNN output distributions for $\Lambda_c^+ \to ne^+\nu$ and the charge-conjugate mode $\bar{\Lambda}_c^- \to \bar{n}e^-\bar{\nu}$, shown in Fig. 2. The measured branching fraction is $\mathcal{B}(\Lambda_c^+ \to ne^+\nu) = (0.357 \pm 0.034 \pm 0.014)\%$. Combining this result with lattice QCD predictions for the $\Lambda_c \to n$ differential decay rate [25] and the Λ_c^+ lifetime from Belle II [26] yields $|V_{cd}| = 0.208 \pm 0.011_{\rm exp} \pm 0.007_{\rm LQCD} \pm 0.001_{\tau_{\Lambda_c}}$, providing an independent determination of this CKM matrix element.

Electron-positron collisions allow for unique probes of baryonic structure through the study of polarization in $e^+e^- \to H\overline{H}$, where H is any baryon. The production cross section for a baryon pair, such as $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$, is parametrized by the electric and magnetic timelike form factors G_E and G_M. If these form factors have a relative phase $\Delta\Phi$ and $|G_E|/|G_M| \neq 1$, the produced Λ_c baryons can exhibit transverse polarization parameterized by

$$P_y(\theta_0) = \frac{3}{2(3+\alpha_0)}\sqrt{1-\alpha_0^2}\sin\theta_0\cos\theta_0\sin\Delta\Phi, \tag{2}$$

where θ_0 is the Λ_c^+ momentum angle in the e^+e^- rest grame and $\alpha_0 = \alpha_0(|G_E|/|G_M|)$ is a function of the form factor ratio. Using 6.4 fb^{-1} of data collected between $E_{\rm cm}$ = 4.60 – 4.95 GeV, this polarization was measured in Ref. [27] through the helicity angle distributions in Λ_c^+ decays to pK^0_S, $\Lambda\pi^+$, $\Sigma^0\pi^+$, $\Sigma^+\pi^-$, and $pK^-\pi^+$ (using decay parameters measured by the LHCb collaboration [28,

29]). A simultaneous fit to the helicity angle distributions in all decay modes was performed at multiple center-of-mass energies to determine $|G_E|/|G_M|$ and $\sin\Delta\Phi$, shown in Fig. 2. These measurements provide the first evidence for transverse polarization in charm baryon pair production. The results show good agreement with recent theoretical predictions [30, 31] of the magnitude ratio $|G_E|/|G_M|$, but significant deviations are seen between the predictions and experimental determinations of $\sin\Delta\Phi$.

Additional recent measurements of Λ_c^+ decays at BESIII include the first observation of the singly-Cabibbo-suppressed decay $\Lambda_c^+ \to p\pi^0$ [32], measurements of $\Lambda_c^+ \to \Lambda K_S^0 h^+$, $\Sigma K_S^0 h^+$, and $\Xi K_S^0 h^+$ ($h = \pi, K$) branching fractions [33], the branching fractions for $\Lambda_c^+ \to \Sigma^+\eta$ and $\Lambda_c^+ \to \Sigma^+\eta'$ [34], and an inclusive measurement of $\Lambda_c^+ \to K_S^0 X$ [35].

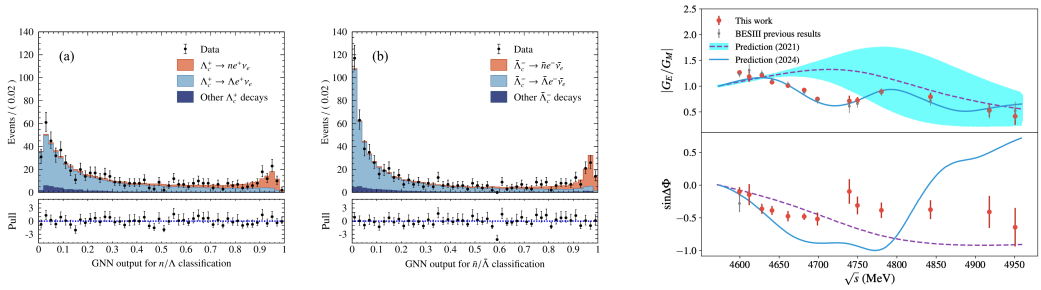

Figure 2: (Left, Center) Fits of GNN output to determine $\Lambda_c^+ \to ne^+\nu$ and $\Lambda_c^- \to \bar{n}e^-\nu$ signal yields from Ref. [24]. (Right) Comparison of $|G_E|/|G_M|$ and $\sin\Delta\Phi$ determined in Ref. [27] to predictions [30, 31].

In summary, BESIII has produced a wealth of precision measurements in charm semileptonic decays and charmed baryon physics using datasets collected at the $\psi(3770)$ resonance and at higher center-of-mass energies. These proceedings highlight the most precise single determination of $|V_{cs}|$ from $D \to K\ell\nu$ decays and stringent tests of lepton flavor universality in the charm sector; comprehensive studies of $D \to K\pi X\ell\nu$ transitions, the first measurement of the $D \to a_0(980)$ form factor; the first observation of the $c \to d$ transition in charmed baryons through $\Lambda_c^+ \to ne^+\nu$; and the first measurement of transverse polarization in $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ production.

Much additional physics remains to be extracted from the existing BESIII datasets. Many new and updated measurements of D^0 and D^+ decays are underway with the full 20.3 fb^{-1} dataset collected at the $\psi(3770)$ resonance. Looking forward, the recently completed BEPCII upgrade will provide substantially higher instantaneous luminosity and extend the accessible center-of-mass energy range to 5.6 GeV, enabling studies of Σ_c, Ξ_c, and Ω_c baryon pair production. An additional 9 fb^{-1} of Λ_c^+ data is planned for 2025–2026, with data collection above 5 GeV scheduled for 2028. These future datasets will enable further precision tests of the Standard Model and searches for new physics in the charm sector.

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