Charm physics at BESIII

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Abstract. The study of mesons and baryons which contain at least one charm quark is referred to as open charm physics. It offers the possibility to study up-type quark transitions. Since the $\bar{c}$ quark can not be treated in any mass limit, theoretical predictions are difficult and experimental input is crucial. BESIII collected large data samples of $e^+e^-$ collisions at several charm thresholds. The at-threshold decay topology offers special opportunities to study open charm decays.

We present a selection of recent BESIII results: The measurement of the branching fraction $D_s^+ \rightarrow p\pi$, the form factor of neutral D decays to $K^-\mu^+\nu_\mu$ as well as the search for rare decays $D \rightarrow h(h')e^+e^-$. Recent results on $\Lambda_c^+$ decays are presented in [1].

1. Introduction
The BESIII experiment is located at the Beijing Electron-Positron Collider. The accelerator is an $e^+e^-$ storage ring located at the Institute of High Energy Physics in Beijing. It provides symmetric collisions in the energy range between 2.0 GeV and 4.6 GeV. The maximum luminosity of BEPCII surpasses $1 \times 10^{33}$ cm$^{-2}$ s$^{-1}$ at $\sqrt{s} = 3.773$ GeV. The detector measures charged track momenta with a relative precision of 0.5% (@1.0 GeV/c) using a multi-wire drift chamber in a 1 T magnetic field. Electromagnetic showers are measured in a cesium iodide calorimeter with a relative precision of 2.5% (@1.0 GeV) and good particle identification is achieved by combining information from energy loss in the drift chamber, from the time-of-flight system and from the calorimeter. Muons can be identified using nine layers of resistive plate chambers integrated in the magnet return yoke. The BESIII experiment is described in detail elsewhere [2]. BESIII has collected large data samples in the tau-charm region. The interesting samples for the study of charmed hadrons are usually at a center-of-mass energy close to a charm-related threshold.

The most relevant thresholds in the BESIII energy range are the $D^0\bar{D}^0/D^+D^- (\sqrt{s} = 3.773$ GeV), the $D_s^+D_s^- (\sqrt{s} = 4.009$ GeV) and the $\Lambda_c\bar{\Lambda}_c (\sqrt{s} = 4.5995$ GeV) threshold. Samples with an integrated luminosity of 2.81 fb$^{-1}$, 0.482 fb$^{-1}$ and 0.5669 fb$^{-1}$ were recorded at these thresholds, respectively. The at-threshold decay topology at a center-of-mass energy of 3.773 GeV is illustrated in figure 1. A pair of particles is produced close to threshold in a quantum-entangled state. The available phase space does not allow for the production of another hadron, therefore the at-threshold decay topology offers a clean environment. The constraint kinematics allows for the reconstruction of the four-momenta of undetected particles. In particular, the study of leptonic...
and semi-leptonic decays benefits from this. The reconstruction of both decays in each event is referred to as double tag technique.

2. Branching fraction $D_s^+ \rightarrow p \bar{n}$

The process $D_s^+ \rightarrow p \bar{n}$ is the only kinematically allowed baryonic $D$ decay mode. It is of interest in the study of the weak annihilation decays of charmed mesons. The theoretical prediction of the short distance process is of the order of $10^{-6}$. However, experimental evidence for the decay was found by CLEO-c [3] at a level of $4\sigma$ and a central value of $(1.3 \pm 0.36^{+0.12}_{-0.16}) \times 10^{-3}$. A branching fraction at the level of $O(10^{-3})$ is expected for long distance contributions for which various phenomenological models exist. BESIII has collected a data sample of $0.482 \text{ fb}^{-1}$ at the $D_s D_{s}^{*}$ threshold which corresponds to $5 \times$ the statistics of CLEO-c. An independent confirmation of the result as well as an improved accuracy is critical to distinguish between different theoretical models.

The decay was analysed using the previously mentioned double tag technique. The $D_s^{*+}$ is reconstructed using the radiative decay $D_s^{*} \rightarrow \gamma D_s$. The tag decay is reconstructed using 11 different $D_s^-$ modes and a sample of $N_{\text{tot}} \approx 350 \times 10^3$ events with one reconstructed tag decay is obtained. Among the remaining tracks in those events a charged track and a photon are required. Either the tag decay or the signal decay originate from the $D_s^*$ via a radiative decay. A $\chi^2$ fit is used to distinguish both possibilities. The unobserved four-momentum of the $\bar{n}$ is
3. Observation of $D \to a_0(980)e^+\nu_e$

The nature of the light scalar resonances $a_0(980)$ and $f_0(980)$ is a long standing puzzle of nonperturbative quantum chromodynamics (QCD). Their structure seems to be more complicated than predicted by simple $q\bar{q}$ models [4, 5]. The decay $D \to a_0(980)e^+\nu_e$ is suited to shed light into this problem since the production of the $a_0(980)$ can be naturally separated from the electromagnetic system. Therefore, this process offers a clean production without any hadronic final state interaction. BESIII has collected a data sample of $2.91 \text{ fb}^{-1}$ of $e^+e^-$ collisions at the $D\bar{D}$ threshold ($\sqrt{s} = 3.773 \text{ GeV}$) which is used for this analysis.

We analyse the charged as well as the neutral $D$ decay mode and apply - similar to the previously presented analysis - a double tag technique. The $D^0$ and $D^+$ tag decay is reconstructed using three and six flavour specific decay modes, respectively. We obtain a total number of $N^{\text{obs,tot}}_{\text{tag}} = 2288060 \pm 1238$ and $1595019 \pm 1711$ tag decays for $D^0$ and $D^+$, respectively. Among those events we search for the signal decay. The $a_0(980)$ is reconstructed via its prominent decay channels $\eta\pi^-$ and $\eta\pi^0$. Furthermore, another charged track positively identified as positron is required. The signal is defined as a peak in the invariant mass of the $\eta\pi$ system and, due to the unmeasured neutrino, in the missing energy $U = E_{\text{miss}} - cp_{\text{miss}}$. The distributions are shown in figure 3. The signal shape is modeled from a Flatté formula for the $U$ unmeasured neutrino, in the missing energy $U$ collisions at the $D\bar{D}$ threshold ($\sqrt{s} = 3.773 \text{ GeV}$) which is used for this analysis.

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$$B(D^0 \to a_0(980)^-e^+\nu_e) \times B(a_0(980)^- \to \eta\pi^-) = (1.33^{+0.33}_{-0.29} \pm 0.09) \times 10^{-4} \quad \text{and}$$

$$B(D^+ \to a_0(980)^0e^+\nu_e) \times B(a_0(980)^0 \to \eta\pi^0) = (1.66^{+0.81}_{-0.66} \pm 0.11) \times 10^{-4}. \quad \text{(2)}$$

Assuming the branching fractions of $a_0(980)$ to $\eta\pi$ are the same we find for the ratio of both branching fractions a value of $2.03 \pm 0.95 \pm 0.06$.

This is first observation of the $a_0(980)$ in a semi-leptonic $D$ decay. The result was published recently [6]. Together with another ongoing analysis on the decay $D^+ \to f_0(980)e^+\nu_e$ this result is a valuable input to the understanding of the nature of $f_0(980)$ and $a_0(980)$ [7].

4. Form factor measurement $D^0 \to K^-\mu^+\nu_\mu$

We analyse the decays of neutral $D$ mesons to the semi-leptonic final state $K^-\mu^+\nu_\mu$. The coupling strength in semi-leptonic systems depends on the four momentum transfer $q^2$ and is referred to as form factor $f_+(q^2)$ which can be inferred from the decay rate via

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{8\pi^3 m_D} \left| V_{c\bar{s}} \right|^2 \left| \sum K^- \right|^2 \left| f_+(q^2) \right|^2 D(q^2), \quad \text{(4)}$$
**Figure 3**: Projections of the 2D fit for the case of a $D^0$ decay (a)-(b) and a $D^+$ decay (c)-(d) to $a_0(980)e^+\nu_e$. The data sample is shown as points with error bars and the fit model (solid line) has a background (dashed line) and a signal (dotted line) component.

**Figure 4**: Decay width in bins of $q^2$ (a) and the derived form factor (b). The ratio of the decay width of $D^0 \to K^-\mu^+\nu_\mu$ and $D^0 \to K^-e^+\nu_e$ (c) does confirm lepton flavour universality.

with the Fermi constant $G_F^2$, the three momentum of the hadronic system $|\vec{p}_{K^-}|$ and the CKM matrix element $|V_{cs}|^2$.

From the measurement of the decay width in bins of $q^2$, the product of matrix element and form factor can be extracted. Then, using external measurements as input for the CKM matrix element, the form factor can be extracted, or, vice-versa, from a lattice QCD calculation of the form factor, the matrix element can be calculated.

Since the final state contains a neutrino which is not detected we use the constrained kinematics of the at-threshold production of $D^0\bar{D}^0/D^0/D^-\bar{D}^+\bar{D}^-$ at $\sqrt{s} = 3.773$ GeV. A - now familiar - double tag analysis is performed. The $q^2$ dependence of the form factor is shown in figure 4(a). It is then extrapolated to $q^2 = 0$ using various models in figure 4(b).

For the product of form factor and CKM matrix element we obtain a preliminary result of:

$$f^K_+\,(0)|V_{cs}| = 0.7148 \pm 0.0038\text{(stat.)} \pm 0.0029\text{(sys.)}.$$

Using external input for $|V_{cs}|$ [4] and $f^K_+(0)$ [8] we obtain $f^K_+(0) = 0.7343 \pm 0.0039\text{(stat.)} \pm 0.0030\text{(sys.)}$ and $|V_{cs}| = 0.957 \pm 0.006\text{(exp.)} \pm 0.024\text{(theory)}$, respectively.

Furthermore, we combine the result with a previous BESIII measurement on $D^0 \to K^-e^+\nu_e$ [9] to perform a test of lepton flavour universality. The ratio of both decay widths in bins of $q^2$ is shown in figure 4(c). No significant deviation from the expectation can be observed.
5. Search for $D \to h(h')e^+e^-$

The process $c \to u\ell^+\ell^-$ is a flavour changing neutral current, and, therefore, the branching fractions due to short distance effects are strongly suppressed in the standard model ($\mathcal{O}(10^{-9})$). Enhancements could arise from physics beyond the standard model or long distance (LD) effects. Those effects could lead to branching fractions up to $\mathcal{O}(10^{-6})$ and therefore, could be in reach of the BESIII sensitivity. The disentanglement of LD effects and new physics would require an analysis of the angular dependence which is beyond the scope of this analysis. In recent years semi-leptonic rare decays with a $\mu^-\mu^+$ pair in the final state were observed $[10, 11]$. BESIII provides the possibility to study complementary channels with an $e^-e^+$ pair. A double tag analysis is applied as described previously. For various combinations of hadrons $h(h')$ no evidence for a signal is observed. We report significantly improved upper limits for several channels, and for other channels this is the first result so far. An overview is given in table 1. Results were published recently in Ref. $[12]$.

6. Summary

We present a selection of recent BESIII results in the field of charm physics. Among those, the first observations of the decay $D^0 \to a_0(980)^-e^+\nu_e$ and an accurate measurement of the form factor $f^K_+(0)$ in the decay $D^0 \to K^-e^+\nu_e$ are reported. Using the previous BESIII results on the decay $D^0 \to K^-e^+\nu_e$ we test for lepton flavour universality. Finally, an extensive search for decay modes $D \to h(h')e^+e^-$ is performed and improved upper limits are reported.

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