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Singly Cabibbo Suppressed Charm Decays: CP Violation and Amplitude Analysis

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We present a summary of the activities of the Belle and Belle II group at the Technische Universität München concerning the decay of charmed mesons D^+, D^0, and D_s into multi-hadronic final states. The need for new amplitude analysis for spectroscopy and CP asymmetry measurements is highlighted.

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In 2012, LHCb caused a stir in the flavor community by reporting the first signs of relatively large CP asymmetry in the charm sector through a measurement[1] of ΔA_{CP} [2]:

$$\Delta A_{\mathsf{CP}} \equiv A_{\mathsf{CP}}(\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-) - A_{\mathsf{CP}}(\mathrm{D}^0 \to \pi^+\pi^-) = (-0.82 \pm 0.21 \pm 0.11)\%. \tag{1}$$

The unexpectedly large value prompted a flurry of activity amongst theorists: including calculations that the standard model can explain it ([6, 9, 11, 20] to list only a few) and calculations that the standard model cannot explain it ([4, 7, 12, 14], again only to list a few).

Grossman, Kagan, and Zupan, in [13] and Atwood and Soni, in [5], avoided the problems of calculation with perturbative QCD in the charm sector by listing observable quantities that one could roughly predict values for based on $\mathsf{SU}(3)_\mathrm{F}$ symmetry arguments. These observables (and sum rules built from them) all involve measurements of singly Cabibbo suppressed (SCS) decays of charmed mesons (D^+, D^0, $\mathrm{D_s}$): both CP asymmetries and amplitudes for intermediate resonances in the cases of multihadronic final states.

Luckily for all the theorists, LHCb updated its measurement in 2013 and its new value is again consistent with the previous expectations for no significant CP asymmetry:

$$\Delta A_{\mathsf{CP}} = (-0.49 \pm 0.30 \pm 0.14)\% \text{ from B and} \tag{2}$$

$$= (-0.34 \pm 0.15 \pm 0.10)\% \text{ from D}^*. \tag{3}$$

The upper measurement is from an analysis tagging D flavor through semileptonic decays of B mesons into D mesons [3]. The lower measurement is from an analysis tagging D flavor through decays of D^* mesons into D mesons [1].

Though the excitement died down, it highlighted the lack of measurements in the charm sector, especially in light of the large data sets collected by experiments of the last 15 years, namely Belle, BABAR, and LHCb. Our group at the Technische Universität München is analyzing several final states for these D decays. For several of these channels, we will produce the world's first measurements of their CP asymmetries; for some we will update in the light of larger data sets.

For decays with more than two hadrons in the final state we will perform amplitude analyses with unprecedentedly large data sets. Orders of magnitude larger data sets are both a blessing and a burden: they will allow us to shrink statistical uncertainties significantly, and, by having more data to help us understand our amplitude model, shrink systematic uncertainties related to model selection; however, the massive data sets require careful and quick handling of computation. This latter concern has led us to investigate using Hamiltonian-Monte-Carlo Markov chain solutions in the framework of a Bayesian amplitude analysis. We are also gauging the potential of the so-called de-isobared amplitude analysis technique currently being developed in detail by the COMPASS group of the Technische Universität München.

1. Our SCS Charm Decay Channels

1.1 $\mathrm{D}^+ \to \pi^+\pi^0$

The decay of D^+ to two pions, one charged and one neutral, requires a change of isospin by $3/2$. Neglecting the effects of isospin symmetry breaking, the CP asymmetry in this channel is

[1] Throughout, uncertainties when listed in pairs denote statistical uncertainty first and systematic uncertainty second.

theoretically expected to be zero in the standard model, since the involved weak phase is nearly zero [13]. Isospin symmetry breaking—a percent-level effect—induces a CP asymmetry equal to the level of its breaking times that of the ratio of the electroweak penguin contribution to the decay to that of the tree-level contribution. Thus, any observed CP asymmetry (at a level above 10^{-4}), must be due to non-standard-model contributions to the decay amplitude.

Only one measurement of the asymmetry in this decay has been made. The CLEO-c collaboration measured it to be

$$A_{\mathsf{CP}}(\mathrm{D}^+ \to \pi^+\pi^0) = (2.9 \pm 2.9 \pm 0.3)\%,$$

with an analysis of 2649 $\pm$ 76 signal events from data collected in 586 pb^{-1} of integrated luminosity at the $\psi(3770)$ resonance [17]. This measurement is consistent with zero CP asymmetry. But then again, it is also consistent with wildly large CP asymmetry. Further measurement is required to say which one is the case. At Belle we expect a data set containing of order 10^4 signal events, allowing us to shrink the (currently dominating) statistical uncertainty by an order of magnitude.

The reconstruction of the two-body decay of the D meson to one charged and one neutral pion (reconstructed from two photons) at Belle is plagued by background without further identification criteria. To aid background suppression we require our D mesons to be produced by D^* meson decays

$$\mathrm{D}^{*+} \to \mathrm{D}^+\pi^0 = (\pi^+\pi^0)_{\mathrm{D}^+}\pi^0.$$

This requirement allows us to use the mass difference between the reconstructed D meson and the reconstructed D^* meson as a discriminator against background. We reconstruct decays by combining a charged pion that passes pion-identification criteria with a neutral pion and accepting the combination if its invariant mass is within range of the true mass of the D^+ meson.[2] This is then combined with a remaining π^0 to form the D^*, and the combination is accepted as a D^* if the difference between its invariant mass and that of the reconstructed D is within range of the true mass difference. The neutral pions are reconstructed from photon pairs with invariant masses within range of the neutral pion mass.

To further reduce background event rates, we focus on the most energetic reconstructed D^* mesons—reducing the probability of reconstructing fake D^* mesons from random combinations of a pion and four photons—by cutting on a minimum normalized D^* momentum in the event's center-of-momentum (COM) frame,

$$x_{\mathrm{D}^*} \equiv \left| p_{\mathrm{D}^*}^{(\mathrm{COM})} \right| \Big/ \sqrt{\frac{s}{4} - m_{\mathrm{D}^*}^2} \,,$$

where $\sqrt{s}$ is the interaction energy of the initial colliding e^- and e^+. The normalized momentum is maximum for a true D^* when it is a direct fragmentation product of the charm quark pair formed by the annihilation of the initial $\mathrm{e}^-\mathrm{e}^+$ pair. A minimum normalized momentum also rejects reconstructed D^* mesons that are the daughters of B mesons (which would have lower energies since they are further down a decay chain). This is necessary to avoid inheriting any asymmetries from B production and decay. A minimum x_{D^*} of 0.55 accomplishes this.

[2] Since these analysis are still in progress, we don't offer specific numbers on any of the selection criteria described. They will, naturally, be published when the analyses are complete.

Even with all the above measures, background rates are quite large, and must be carefully understood. We are currently investigating the background components and refining a multivariate discriminator based on boosted decision trees using over twenty variables related to the kinematics of the decay and pion particle identification.

1.2 $D^0 \to \pi^+\pi^-\pi^+\pi^+$

The decay of D^0 to four charged pions also allows to search for signs of new physics through measurement of CP asymmetries. However, the asymmetries in question do not relate to the total decay rate—across the whole available phase space of the decay—but rather to individual intermediate resonances that mediate the decay from the initial charm meson to the final-state pions.

The amplitude for the four-body decay is the sum of all amplitudes for quasi-two-body and quasi-three-body decays and a completely nonresonant amplitude. A previous analysis of this channel from FOCUS [16] using 6360 $\pm$ 115 events decomposed the amplitude into the following isobars: two-body decays into $a_1^+\pi^-$ and $\rho^0\rho^0$; three-body decays into $\sigma\pi^+\pi^-$, $f_0(980)\pi^+\pi^-$, and $f_2(1270)\pi^+\pi^-$. The a_1^+ decay itself in turn was decomposed into amplitudes for decays into $\rho^0\pi^+$ in S wave, $\rho^0\pi^+$ in D wave, and $\sigma\pi^+$; and the $\rho^0\rho^0$ decay was decomposed into three polarizations measured in the transversity basis [21]. Nonresonant four-body amplitudes were ignored.

This model is not complete, but is apt for an isobar decomposition to model the distribution of the small data set of FOCUS in a five-dimensional Dalitz space. Our data set at Belle contains over four-hundred thousand signal events, and we can naturally therefore extend our model to include, for example, $D^0 \to VS$, $D^0 \to SS$, $D^0 \to T\pi^+\pi^-$, where V is a vector meson (a_1 and ρ), S a scalar meson (*e.g.* f_0), and T a tensor meson (*e.g.* f_2). We can also extend our list of $\pi\pi$ S-wave resonances to include more of the light mesons and try parameterizations of the tricky σ "particle" beyond a Breit Wigner and which are based on elastic $\pi\pi$ scattering.

To tag the flavor of reconstructed D^0 mesons (as D^0 or $\overline{D}^0$) for CP violation studies we require our D mesons be the product of D^* decays. We reconstruct a decay by first requiring an event to contain five charged particles that survive pion-identification cuts. Neutral combinations of four charged particles that have invariant masses near the D^0 mass and originate from a common vertex (as measured by the p value of a vertexing algorithm) are accepted. These D^0 mesons are combined with remaining charged pions and accepted as D^* mesons if the difference between the five-pion invariant mass and the four-pion invariant mass is within range of the true D^{*+}–D^0 mass difference. We also constrain the $D^0\pi^+$ vertex to originate from the beam-interaction region. Since the pion from the D^* decay is much slower than the daughters of the D^0, owing to the smallness of the D^*–D^0 mass difference, it is referred to as the slow pion.

As with the $D^+ \to \pi^+\pi^0$ channel, we further reduce background event rates by focusing on the most energetic reconstructed D^* mesons through a lower-threshold cut on the normalized momentum: $x_{D^*} > 0.25$ for spectroscopy; this cut will be raised for CP asymmetry studies so as to reject D^0 mesons coming from B meson decays.

We will first perform an amplitude analysis of this decay channel with all events, both D^0 and $\overline{D}^0$ decays. To reduce any biases for the subsequent CP asymmetry measurement, we will remain blind of the CP state of the decaying mesons, by ignoring the charge of the slow pion. To allow for proper modeling of intermediary resonances that differ only by charge—for example $D^0 \to a_1^+\pi^-$ and $D^0 \to a_1^-\pi^+$—before blinding the soft-pion charge, we relabel the charges of the D^0 daughter particles as so: a positive charge for pions with the same charge as the slow pion, a negative charge for pions with the opposite charge as the slow pion.

Using Monte Carlo pseudo-data, we have optimized our event selection criteria for this decay channel and developed a model of the distribution of events of the various background components and the signal as functions of the four-pion (D) invariant mass and the difference between the five-pion and four-pion invariant masses (the D^*–D mass difference). This has lead to signal-to-background ratio in the signal region[3] of approximately 58%. Our model of the background and signal distributions fit to the data showed a signal yield of $(4.06 \pm 0.02) \times 10^5$ events with a signal-to-background ratio of 46%.

Unfortunately the background in this final state contains its own resonant structures, since background events can also contain, for example, true ρ and a_1 mesons. To further increase the background-to-signal ratio and reduce the relative sizes of quasi-resonant features in the background of the five-dimensional Dalitz distribution, we are investigating selection criteria and an event weighting scheme using boosted decision trees that consider the transverse momenta and particle identification values of all particles in the decay, the *p* values of both vertex fits, the reconstructed D^0 mass, the reconstructed D^{*+}–D^0 mass difference and the normalized D^* momentum.

1.3 $D^+_{(s)} \to K^+K^-\pi^+$

Like the four-pion decay, the decays of D^+ and D_s to $K^+K^-\pi^+$ offer the opportunity for both decay spectroscopy and CP asymmetry measurement. One previous analysis of the related decay $D^+ \to \phi\pi^+$ was published by Belle, but focused specifically on decays with K^+K^- invariant masses in a narrow window around the ϕ mass [23].

In the two-pion decay described above, $D^+ \to \pi^+\pi^0$, a raw measured asymmetry contains a component due to an asymmetry in the efficiencies for detecting π^+ and π^- in the Belle detector. The $\phi\pi^+$ final state is used as a normalizing channel (also in other experiments), to subtract out this detection efficiency asymmetry, with the assumption that any measured asymmetry is due to the pion detection efficiency asymmetry. However, influence from K^*K intermediary resonances leading to the same three-body final state create so-called K^+K^- detection efficiency asymmetries (with respect to the charge of the accompanying pion). The ϕ-focused analysis accounted for these influences through clever but inherently limited statistical techniques. Through a careful amplitude analysis, we can measure asymmetries separately in all channels contributing to the three-body decay.

Amplitude analyses have been published for $D^+ \to K^+K^-\pi^+$ by the E687 experiment using 915 events [10], CLEO using 1.8×10^4 events [22], and BABAR using 2.2×10^3 events [15]; and for $D_s \to K^+K^-\pi^+$ by the E687 experiment using 701 events [10], CLEO using 1.2×10^4 events [18], and BABAR using 9.6×10^4 events [8].

The ϕ-focused Belle analysis utilized 2.4×10^5 D signal decays and 7.2×10^5 D_s signal decays. The Particle Data Group reports its averages for the fit fractions of $\phi\pi^+$ as 27.8% for D^+ and 41.6% for D_s [19]. We therefore expect more than 8×10^5 signal events in $D^+ \to K^+K^-\pi^+$ and more than 1.7×10^6 signal events in $D_s \to K^+K^-\pi^+$, when we expand the di-kaon invariant mass range out beyond the narrow ϕ mass region.

[3] within 3σ of the nominal D^0 mass and D^{*+}–D^0 mass difference

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To reconstruct decays, we require events to have two charged kaons passing kaon selection criteria, and one charged pion passing pion selection criteria, with all three combining to have an invariant mass in the region of either that of the D^+ meson or the D_s meson. We employ the same normalized momentum cuts described above to reduce background. Vertex-fit results from the vertices of the $D^+_{(s)}$ meson's decay and production—confined to the interaction region—can be used to further suppress background. We are currently optimizing selection criteria in this channel.

1.4 $D^+ \to \pi^+\pi^-\pi^+\pi^0$

No amplitude analysis of the decay of $D^+ \to \pi^+\pi^-\pi^+\pi^0$ has yet been undertaken. Like the four-pion decay of the neutral D meson, this channel will allow us to detect signs of new physics in CP asymmetries in $\rho\rho$ intermediary states—here $\rho^+\rho^0$—and measure asymmetries in any other intermediary resonances present. Work on this channel has just begun, and we have not yet started to set selection criteria.

2. Summary

The large data set collected by the Belle experiment holds great potential for updating spectroscopy analyses and CP asymmetry measurements in the intermediary resonances of multi-hadronic decays of charmed mesons. The ample data set also provides opportunities to test out complicated analysis tools that can be used for B meson decay in the large data set to be collected by Belle II, and that can be extended to analyze the even larger numbers of such D decays to be measured by Belle II.

Refining the analysis tools and removing model dependence as far as possible will become more and more necessary as Belle II provides similarly large data sets in the decay of B mesons to multiple light hadrons.

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