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Measurement of ϕ_3 at Belle II: minutes of WG4

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These minutes review the issues related to the measurement of the unitarity triangle angle ϕ_3 at Belle II. Theoretical calculations related to these decays are also summarised. The importance of inputs from the charm sector in determining ϕ_3 from $B \to D^{(*)}K^{(*)}$ decays is discussed.

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1 Introduction

These minutes summarise the presentations and discussions in Working Group 4 at the first workshop of the Belle II Theory Interface Platform (B2TIP).* This working group is dedicated to examining the potential to determine the unitarity triangle angle ϕ_3 at Belle II. During the first meeting measurements of ϕ_3 in $B^- \to DK^-$ [2] and related modes were discussed. In future meetings we will consider the determination of ϕ_3 in charmless B decay and in time-dependent analyses in conjunction with Working Groups 5 and 3, respectively.

In general when we talk about $B^- \to DK^-$ we refer to a family of related decays like B^- decay into DK^-, D^*K^-, DK^{*-} and D^*K^{*-} as they are all sensitive to ϕ_3 as well. Only the hadronic part of the amplitude is different.

The key feature of $B^- \to DK^-$ decays is that they arise solely from the interference of first-order tree diagrams of differing weak and strong phases. Here, D represents a general superpostion of D^0 and $\overline{D}^0$. The tree-level nature of the amplitudes involved in $B^- \to DK^-$ allows the theoretically clean extraction of ϕ_3 (also denoted as γ) definded as $\phi_3 \equiv -\arg\left(V_{ub}^* V_{ud} / V_{cb}^* V_{cd}\right)$. Improved knowledge of the unitarity triangle angle ϕ_3 is necessary for testing the Standard Model description of CP violation. The current precision on ϕ_3 is an order of magnitude worse than that on ϕ_1 [3] and it is the only measurement of the unitarity triangle that can be improved significantly by experimental advances alone.

Sensitivity to ϕ_3 can be obtained by studying CP-violating observables in $B \to DK^+$ decays. There are two tree amplitudes contributing to $B^- \to DK^-$ decays: $B^- \to D^0K^-$ and $B^- \to \overline{D}^0K^-$. The amplitude for the second decay is both CKM and colour suppressed with respect to that for the first. The ratio of the suppressed to favoured amplitudes is written as

$$\frac{A(B^- \to \overline{D}^0 K^-)}{A(B^- \to D^0 K^-)} = r_B e^{i(\delta_B - \phi_3)} \ ,$$

where $r_B \approx 0.1$ is the ratio of magnitudes and δ_B is the strong phase difference. The fact that the hadronic parameters r_B and δ_B can be determined from data together with ϕ_3 makes these measurements essentially free of theoretical uncertainties.

Several different types of D decay are utilized to determine ϕ_3. Examples of D decays include CP-eigenstates [4], Cabibbo-favoured (CF) and doubly-Cabibbo-suppressed (DCS) decays [5], self-conjugate modes [6,7] and singly Cabibbo-suppressed (SCS) decays [8]. The different methods are known by their proponents initials, which are given in Table 1, along with the D final states that have so far been studied. Note that $K_S^0\phi$ has also been included in early GLW measurements but has been dropped

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[*] It should be noted that there is significant textual overlap with Ref. [1] where many similar issues are discussed.

Type of D decay	Method name	D final states studied
CP-eigenstates	GLW	CP-even: K^+K^-, $\pi^+\pi^-$; CP-odd $K^0_S\pi^0$, $K^0_S\eta$
CF and DCS	ADS	$K^\pm\pi^\mp$, $K^\pm\pi^\mp\pi^0$, $(K^\pm\pi^\mp\pi^+\pi^-)$
Self-conjugate	GGSZ	$K^0_S\pi^+\pi^-$, $(K^0_SK^+K^-)$, $(\pi^+\pi^-\pi^0)$
SCS	GLS	$(K^0_SK^\pm\pi^\mp)$

Table 1: Methods and D decay modes used in $B^- \to DK^-$ measurements. Those in parentheses have not been studied by Belle.

from more recent analyses given that the same data forms part of the $K^0_SK^+K^-$ sample, which can be studied with the GGSZ method.

In the following four sections (i) advances in understanding the theoretical cleanliness of these modes to extract ϕ_3, (ii) experimental measurements, (iii) external inputs and (iv) the outlook, are reviewed in turn.

2 The ultimate precision

Significant corrections to the value of ϕ_3 extracted from $B^- \to DK^-$ might arise from few sources: mixing and direct CP violation (DCPV) in D and K decay and higher-order diagrams that contribute with differing CKM matrix elements to the tree diagrams. Several studies of the impact of mixing and DCPV in charm decays have been made [9–18]. These studies show that ϕ_3 can be extracted without bias as long as appropriate modifications of the formalism are made and the measured values of the mixing and DCPV parameters are included as external inputs. Even if the effect of mixing is neglected the size of the induced bias is less than 1° [17].

Measurements of ϕ_3 can be made using the $B^- \to D\pi^-$ decay mode, which has sensitivity to ϕ_3 in the same manner as $B^- \to DK^-$. However, the size of the DCPV is much smaller due to the ratio of the suppressed to favoured amplitudes being approximately 0.005. The reduced sensitivity due to the smaller interference is somewhat compensated by the much larger branching fraction for $B^- \to D\pi^-$ compared to $B^- \to DK^-$ [3]. However, D mixing and DCPV must be accounted for carefully in $B^- \to D\pi^-$ measurements of ϕ_3 because the bias on the extracted value of ϕ_3 would be $\mathcal{O}(10^\circ)$ otherwise [17].

The impact of the irreducible uncertainty due to higher-order diagrams has been studied recently [19] to ascertain the ultimate precision with which ϕ_3 can be measured. Second-order weak-box diagrams are the first processes to have a differing CKM dependence from the tree diagrams. An effective-field-theory calculation of the shift in ϕ_3, $\delta\phi_3$, including resumming the large logarithms of m_b/m_W in the corrections to the Wilson coefficients, gives $\delta\phi_3 \sim 2 \times 10^{-8}$. Long distance contributions are at most a factor of a few larger than the calculated short-distance contribution. Therefore, the relative shift in ϕ_3 due to the neglect of these weak-box diagrams is $\lesssim 10^{-7}$, which is many orders of magnitude below the experimental precision anticipated at future experiments. The ultimate theoretical precision due to electroweak effects for $B \to D\pi$ decays has been investigated further [20]. Due to cancellations in these corrections the relative shift in ϕ_3 from $B \to D\pi$ may be enhanced compared to $B \to DK$ up to 10^{-4}.

The effect of new physics in tree-level amplitudes has also been reported recently [21]. Accounting for current experimental bounds, a new-physics induced shift of up to 4° on the Standard Model value of ϕ_3 is still possible. This result is a strong motivation for the 1° precision being pursued by Belle II.

3 Review of $B \to D^{(*)}K^{(*)}$ measurements

The value of ϕ_3 from a combination of Belle measurements alone is $(73^{+13}_{-15})^\circ$ [1] and is dominated by the GGSZ measurement of $B^- \to D^{(*)}(K^0_S\pi^+\pi^-)K^-$ [22], which should be considered the **Golden Mode** for Belle II. However, there have also been measurements using the ADS and GLW techniques [23–25] that have non-negligible weight in the combination. This includes an ADS/GLW analysis of $B^+ \to D^*(D\{\gamma, \pi^0\})K^+$ [24], which has only been measured at the e^+e^- B factories. Therefore, ϕ_3 programme at Belle II must also include all these modes and possibly others (see Sec. 5) to realise its full potential.

LHCb have recently updated their ϕ_3 average using the data collected at a centre-of-mass energy of 7 TeV and 8 TeV. The combination of $B \to DK$ modes gives $\phi_3 = (72.9^{+9.2}_{-9.9})^\circ$ [26], the most precise determination from a single experiment. The balance of the contributions to the average at LHCb is somewhat different due to the lower relative selection efficiency for K^0_S in the forward hadronic environment. Here GGSZ and ADS/GLW are on an almost equal footing in terms of sensitivity to ϕ_3.

4 Auxiliary measurements

The precise determination of ϕ_3 using $B^- \to DK^-$ is reliant upon external inputs from the charm sector. The accurate determination of charm-mixing parameters [27] means that any bias from this source in the determination of ϕ_3 can be corrected for as discussed in Sec. 2. In addition, D meson branching fractions of both CF and DCS decays provide important inputs to ADS measurements [28, 29].

However, the most important auxiliary measurements are related to D decay strong-phases, which are an essential input to interpret the measurements related to ϕ_3. In principle these parameters could be extracted from the B data along with

ϕ_3, δ_B and r_B, but the sensitivity to ϕ_3 would be diluted significantly. Therefore, measurements of the strong-phases are taken from elsewhere.

The strong-phase difference between the D^0 and $\overline{D}^0$ decays to $K^+\pi^-$ is required for the two-body ADS measurement and it is accurately determined using the combination of charm-mixing measurements [27]. For multibody ADS measurements two parameters must be determined due to the variation of the strong-phase difference over the allowed phase-space: the coherence factor R and average strong-phase difference δ_D. Recently there has been a new analysis to determine the R and δ_D for $D \to K^-\pi^+\pi^0$ and $D \to K^-\pi^+\pi^+\pi^-$ [30], which uses quantum-correlated $D^0\overline{D}^0$ pairs produced at the $\psi(3770)$. (For a comprehensive review of quantum-correlated measurements relevant to ϕ_3 see Ref. [31].) At the $\psi(3770)$ the D decay of interest is tagged in events where the other D decays to a CP-eigenstate, a state with a kaon of opposite or same-sign charge as the signal or $K^0_{S,L}\pi^+\pi^-$. The last of these tags is an addition since the first determination of R and δ_D reported by the CLEO-c collaboration [32]. The updated results are used to perform the combinations reported elsewhere in these proceedings.

The model-independent GGSZ method requires two parameters related to the strong-phase difference to be determined for each bin of the Dalitz plot. Such measurements have been reported by the CLEO Collaboration [33] using a data sample corresponding to an integrated luminosity of 818 pb^{-1}. These measurements have been used by both the Belle [34] and LHCb [35] collaborations to determine ϕ_3 from $B^- \to DK^-$ data. The systematic uncertainty on ϕ_3 related to the statistical precision of the CLEO measurements is not dominant at present, but will become much more significant with the future running of LHCb and Belle II. Therefore, improvements in the measurements of the strong phase parameters are desirable. BESIII has accumulated an integrated luminosity of 2.92 fb^{-1} at the $\psi(3770)$ which is 3.5 times larger than that analysed by CLEO. Preliminary results for the $D \to K^0_S\pi^+\pi^-$ parameters using the same binning as CLEO have been reported [36], which give a significant improvement in the statistical uncertainty on the measurements. BESIII can accumulate around 4 fb^{-1} of integrated luminosity per year of running at the $\psi(3770)$; therefore, a two year run at the $\psi(3770)$ by BESIII would reduce the uncertainty on ϕ_3 from the determination of strong phases in the GGSZ method to a negligible level.

Quantum-correlated measurements are also opening up new pathways to determining ϕ_3. A measurement of the CP content of $D \to \pi^+\pi^-\pi^0$ and $D \to K^+K^-\pi^0$ [37] using the full CLEO-c $\psi(3770)$ data set has shown that $D \to \pi^+\pi^-\pi^0$ is $(96.8 \pm 1.7 \pm 0.6)\%$ CP-even. Therefore, this mode can be used as an additional GLW measurement to augment $D \to h^+h^-$, given it has a significantly larger branching fraction [3].

5 Outlook and conclusions

The naïve luminosity scaling of the Belle results to the final Belle II luminosity of 50 ab^{-1} suggest a precision of 1 to 2° can be achievied. However, after the first workshop it is apparent that there are still several issues to be considered with regard to achieving and possibly improving this projected performance. Regarding improvements from an experimental point of view there are still several $B \to DK$ modes that need to be exploited that have not been studied at Belle. The four-body modes $D \to K^-\pi^+\pi^+\pi^-$, $D \to \pi^+\pi^-\pi^+\pi^-$, $D \to K^-K^-\pi^+\pi^+$ and $D \to K^0_S\pi^+\pi^-\pi^0$ are of interest, particularly the latter given its large branching fraction - twice $D \to K^0_S\pi^+\pi^-$ - and the rich interference pattern, which should make for an excellent GGSZ analysis. The exploitation of $D \to K^0_S\pi^+\pi^-\pi^0$ will also require that charm-threshold measurements of the appropriate strong-phase parameters are made at BESIII. Another type of measurement that appears to have excellent potential is the double-Dalitz analysis of $B^0 \to D(K^0_S\pi^+\pi^-)K^+\pi^-$ [38], which so far has received no attention at Belle or Belle II. Within the context of this workshop we will also want to explore the impact of the anticipated improvements to the detector performance. Relevant to the measurement of ϕ_3 is the improved particle identification, energy resolution in the electromagnetic calorimeter and in the continuum suppression algorithms. Furthermore, we must look for robust signal extraction techniques that will have non-limiting systematic uncertainties.

There are two other experimental issues that need to be addressed. Firstly, the binning of the GGSZ $D \to K^0_S\pi^+\pi^-$ analysis, which divides the Dalitz plot into 16 regions, is known to give only 90% of the statistical power of an unbinned analysis [33]. It has been shown that nearly 100% of the statistical sensitivity of an unbinned analysis can be reached by increasing the number of bins [39]. Given the larger statistics available to determine the relevant strong-phase parameters at BES III it may well be worth revisiting whether additional precision can be obtained by using a finer binning of the Dalitz space. Secondly, the impact of regenerated $D \to K^0_L\pi^+\pi^-$ events has not been considered in the golden mode; this can now be done given the final detector configuration is well described in the simulation.

Finally, we should reiterate that in future meetings we will broaden the scope of the discussion to include both ϕ_3 determination in charmless decay and in time-dependent measurements such as $B^0 \to D^*\pi$ and $B^0 \to D^*\rho$.

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