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Recent Belle II results on time-dependent CP violation and charm physics

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We present recent measurements of time-dependent CP violation and charm physics results from the Belle II experiment. Time-dependent CP violation studies include $B^0 \to \phi K^0_S$, $B^0 \to K^0_S \pi^0$, and $B^0 \to K^0_S K^0_S K^0_S$ decay channels. Recent lifetime measurements for charmed hadrons, including the Λ_c^+, Ω_c^0, and D_s^+, are also presented, along with a novel charm flavor tagger.

21st Conference on Flavor Physics and CP Violation (FPCP 2023)
29 May - 2 June 2023
Lyon, France

1. Introduction

The next generation of particle physics experiments provides a unique opportunity to search for signs of physics beyond the standard model. A major goal for the Belle II experiment is to use the enormous projected total data set to make extremely precise measurements of suppressed flavor physics reactions, in which contributions from new particles and interactions via internal loops can be exposed, opening a window to new physics beyond the 10 TeV range.

The unprecedented luminosity of the new SuperKEKB asymmetric-energy electron-positron collider at the KEK research facility in Tsukuba, Japan will enable Belle II to collect a projected total data set of 50 ab^{-1}, about 50 times more than the first-generation B-factory experiments, over the next decade. This will be achieved using the nano-beam scheme, in which the beam size at the interaction point is reduced to a target beam height of 50 nm. At present, SuperKEKB holds the world-record maximum instantaneous luminosity, 4.7×10^{34} cm^{-2} s^{-1} [1]. This high instantaneous luminosity has allowed Belle II to collect a data set of 428 fb^{-1}, about half that collected at Belle, after only a few years.

The Belle II detector, which is described in detail elsewhere [2], incorporates state-of-the-art technology to enable high-precision measurements. The innermost layers of the vertex detector use silicon pixels to improve track impact parameter and vertex resolution by a factor of two relative to Belle and BaBar. The Belle II detector also includes a large-volume tracking chamber, powerful particle identification detectors, a new K_L and muon detector, and state-of-the-art readout and data acquisition systems. The Belle II software [3] reflects the changes in the detector and includes significant improvements to simulation and reconstruction algorithms to cope with the high beam backgrounds expected at SuperKEKB. The analysis software also includes significant improvements that will enable a strong physics program including precision measurements.

2. Time-dependent CP violation Results

The impact of physics beyond the standard model (BSM) can be probed using rare and suppressed B meson decays, since new physics may contribute at the same level as loop-suppressed standard model processes. Gluonic-penguin decay modes involving $b \to q\bar{q}s$ transitions are sensitive to BSM amplitudes that carry additional weak phases. A deviation in the mixing-induced CP asymmetry $S \approx \sin 2\phi_1$ with respect to the standard model reference mode involving $b \to c\bar{c}s$ transitions, beyond expectations from the standard model of at most 0.02 ± 0.01, could indicate the presence of new physics [4]. The direct CP asymmetry A is expected to be zero in the standard model. Belle II has recently measured the direct and mixing-induced CP-violating parameters in several B decay channels using a data set of 362 fb^{-1}, corresponding to $(387 \pm 6) \times 10^6$ $B\bar{B}$ pairs.

To study CP violating parameters in $B^0 \to \phi K^0_S$ events, a Boosted Decision Tree (BDT) is employed to isolate signal and background events. An extended maximum-likelihood fit is applied to the unbinned distributions of beam-constrained mass, M_{bc}, the BDT output, the helicity angle, and the B lifetime to extract the CP violating parameters $A = 0.31 \pm 0.20 \pm 0.05$ and $S = 0.54 \pm 0.26^{+0.06}_{-0.08}$, where the first uncertainties are statistical and the second are systematic [5]. The fit projections onto Δt are shown in Fig. 1. These results are consistent with the world average

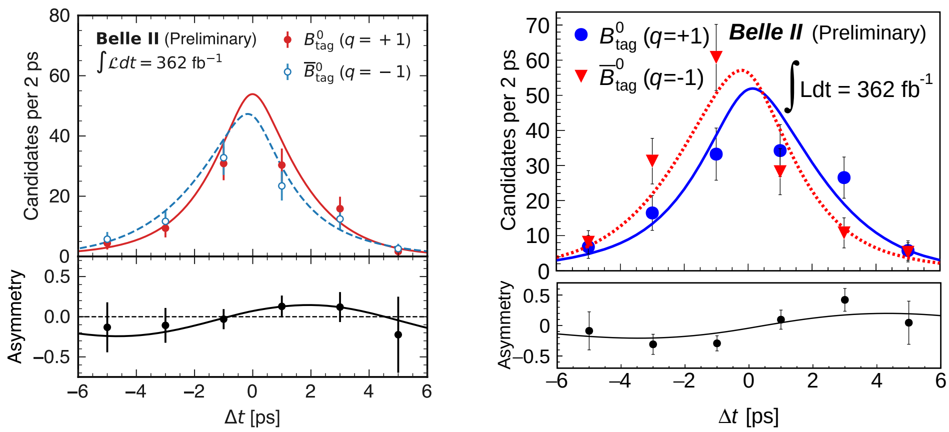

Figure 1: Background subtracted projection of fit results onto Δt for tagged B^0 and $\bar{B}^0$ candidates and the asymmetry, $[N(B^0_{\mathrm{tag}}) - N(\bar{B}^0_{\mathrm{tag}})/N(B^0_{\mathrm{tag}}) + N(\bar{B}^0_{\mathrm{tag}})]$, for $B^0 \to \phi K^0_S$ (left) and $B^0 \to K^0_S \pi^0$ (right).

values of $A = -0.01 \pm 0.14$ and $S = 0.59 \pm 0.14$ and are on par with the best measurements of this kind, despite using a sample that is half that used in the Belle measurement [6].

A similar analysis was performed to measure CP violating parameters in $B^0 \to K^0_S \pi^0$ decays [7]. The fit projections onto Δt are shown in Fig. 1. The results, $A = 0.04 \pm 0.15 \pm 0.05$ and $S = 0.75^{+0.20}_{-0.23} \pm 0.04$, are consistent with the world-average values $A = 0.00 \pm 0.13$ and $S = 0.58 \pm 0.17$ and are on par with the best measurements. Combining the results from a time-dependent analysis with those from a time-integrated analysis gives $A = -0.01 \pm 0.12 \pm 0.05$, with a precision on par with the world-average value.

Finally, Belle II measured the CP violating parameters in $B^0 \to K^0_S K^0_S K^0_S$. The topology for this analysis is particularly challenging due to the fact that all reconstructed final-state particles are displaced from the decay vertex of the B^0. A three dimensional fit is applied to the distributions for M_{bc}, the B mass, and the output of a BDT. Despite the complex vertexing, Belle II was able to measure $A = 0.07^{+0.15}_{-0.20} \pm 0.02$ and $S = -1.37^{+0.35}_{-0.45} \pm 0.03$, in good agreement with the world average values of $A = 0.15 \pm 0.12$ and $S = -0.83 \pm 0.17$.

3. Charm Results

The excellent detector performance and very small beam spot, along with large samples of exclusive charm decays that are collected without lifetime-biased triggers and event selection criteria, allows Belle II to make precise, absolute lifetime measurements for charmed hadrons. These measurements provide sensitive tests for predictive tools like the heavy quark expansion (HQE) [8–14], in which decay widths for hadrons containing a heavy quark are calculated with an expansion in terms of the heavy quark mass. Effective models like these are useful to provide theoretical descriptions for strong interactions at low energy, which complicate studies of physics beyond the standard model.

The lifetimes of charmed hadrons are determined at Belle II by measuring the distance between production and decay vertices and therefore rely on precise calibration of final state particle momenta and excellent vertex detector and beam spot alignment. In this sense, precise lifetime measurements

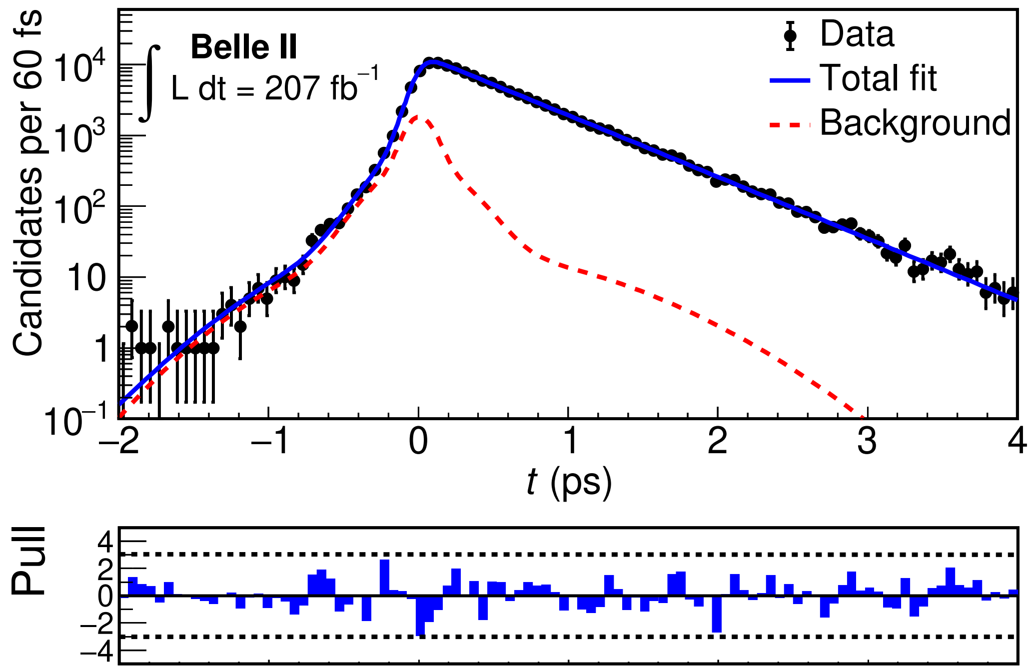

Figure 2: Decay time distribution for $D_s^+ \to \phi\pi^+$ candidates, with fit results overlaid in blue. The background component is given by the red dashed curve.

also provide a tool to understand the Belle II detector resolution. Belle II recently published a world-leading lifetime measurement for the Λ_c^+, as well as a measurement of the Ω_c^0 lifetime that is longer than that of the Λ_c^+, confirming a recent LHCb measurement that challenged earlier determinations and HQE expectations. Belle II has also published world-leading measurements for the D^0, D^+ and D_s^+ lifetimes. The D_s^+ lifetime, $(498.7 \pm 1.7^{+1.1}_{-0.8})$ fs, is consistent with and about twice as precise as the current world-average, (504 ± 4) fs, and is consistent with theory predictions that place it on par with the D^0 lifetime.

Belle II will make precise studies of CP violation in the charm sector, which provides the only environment in which to study up-type quark mixing. To aid these studies, a novel charm flavor tagger (CFT) is used to identify the production flavor of neutral charmed mesons. The CFT exploits the correlation between the flavor of a reconstructed neutral D meson and the electric charges of the rest of the event, similar to the process used to tag B meson flavors. The charm system is more complicated due to charmed hadrons not being produced at threshold, allowing for the presence of fragmentation particles to be produced in conjunction with a charmed hadron pair. Nevertheless, the CFT has an effective tagging efficiency of $(47.91 \pm 0.07 \pm 0.51)\%$, where the first uncertainty is statistical and the second systematic. This efficiency is independent of the decay mode. The CFT approximately doubles the effective size of samples used for many CPV and mixing measurements in the charm sector, as shown in Fig. 3. The basic principles used to develop the CFT can also be applied at other experiments.

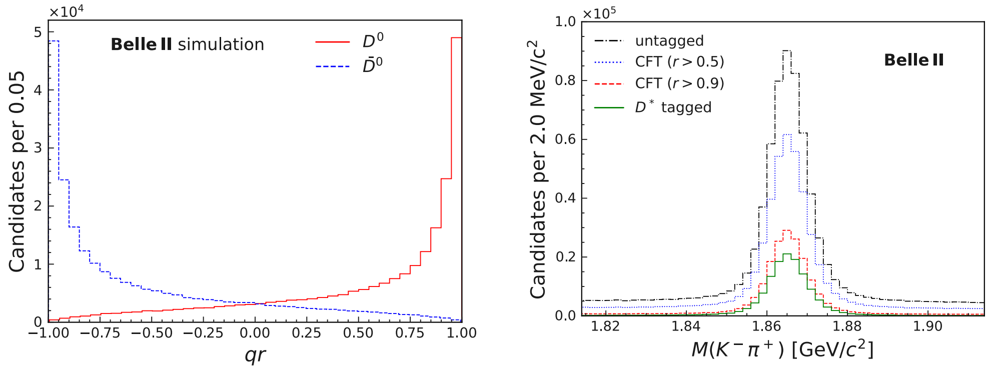

Figure 3: Distributions of (left) the predicted tagging decision, multiplied by a dilution factor, by the charm flavor tagger for simulated D^0 and $\bar{D}^0$ mesons and (right) the mass of $D^0 \to K^-\pi^+$ decays reconstructed in data with different requirements on the predicted (uncalibrated) dilution in comparison with D^{*+}-tagged decays.

4. Summary

The major upgrades of the SuperKEKB accelerator and improvements to the Belle II detector, along with refined analysis techniques, support a physics program that has outstanding potential for discovering physics beyond the standard model over the next decade. Belle II physics analysis efforts will include a broad program for fundamental weak interaction measurements. Several searches with discovery potential are uniquely accessible to Belle II and new tools and techniques are being developed and used to enhance the physics capabilities of the experiment. With a dataset about half the size of the previous B-factories, Belle II is already producing competitive results. As the current dataset represents a very small fraction of the target integrated luminosity, many more impactful measurements are still to come.

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