Recent measurements in the beauty, charm, and tau sectors at Belle II

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The first e^+e^- collisions at SuperKEKB took place in the early 2019, and since then more than $100\,\mathrm{fb}^{-1}$ of data have been collected by the Belle II detector. Although, for many measurements, the collected data is still not large enough to compete with previous measurements at Belle and BaBar, the improvements in the detector and analysis techniques have allowed many measurements to be already competitive in terms of systematic uncertainties. This document will briefly summarize some of the recent preliminary measurements in the beauty, charm and tau sectors at the Belle II.

1 Introduction

SuperKEKB [1] is an energy asymmetric e^+e^- collider, located in Tsukuba, Japan and is operating at nominal center-of-mass energy of $10.58\,\mathrm{GeV}$, near the mass of $\Upsilon(4S)$ resonance. The peak instantaneous luminosity of the machine is expected to reach 30 times that of its predecessor, which will make it possible the Belle II [2] detector to collect up to $50\,\mathrm{ab}^{-1}$ of collision data in its lifetime.In addition to being well known as a 2nd generation B-factory, the Belle II detector is a charm and tau factory as well since around a billion b, c, and τ pair events are expected to be produced in every ab^{-1} of collected data by the experiment.

2 Results towards inclusive and exclusive measurements of V_{cb}

Precision measurements of Cabibbo–Kobayashi–Maskawa (CKM) matrix parameters are one of the main goals of the Belle II detector. In particular, studying the semileptonic decays of B-mesons has been the leading method for V_{cb} measurement. There has been, however, a long-standing tension between the inclusive and exclusive measurements of these decay modes and the upcoming measurements at Belle II are expected to improve the precision in both inclusive and exclusive measurements. An exclusive measurement of the branching fraction of $B^0 \to D^{*-}\ell^+\nu$ decay mode [3] has already been performed using $34.6\,\mathrm{fb}^{-1}$ of data. However, currently, these measurements are limited by the uncertainties arising from the reconstruction efficiencies of the slow-pions. These uncertainties are expected to decrease as larger control samples are collected for further investigations. Using, the same dataset, the hadronic mass moments have also been measured in $B \to X_c\ell\nu$ channel [4], where X_c represents the charm system. Moreover, an alternative method for measuring V_{cb} using the q^2 moments is also currently in progress at Belle II and expected to become public soon.

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3 Measurement of the time-integrated mixing probability χ_d

The goal of this analysis [5] is to measure the time-integrated mixing probability χ_d, which can be used to set constraints on the mixing parameters of the neutral B-mesons. For this measurements, both reconstructed B-mesons in the event are required to decay semi-leptonically and the flavor of each B-meson is then inferred from the charge of its daughter lepton. By using the number of same-sign (N_{SS}) and opposite-sign (N_{OS}) BB events, the χ_d parameter can be calculated as:

$$\chi_d = \frac{N_{SS}}{N_{SS} + N_{OS} \cdot (\epsilon_{OS}/\epsilon_{SS})^{-1}} \cdot (1 + r_B), \tag{1}$$

where r_B is a correction factor taking into account the contribution from the semi-leptonic decays of charged B mesons and ϵ_{OS} (ϵ_{SS}) is the selection efficiencies for the opposite-sign (same-sign) modes and is measured using signal MC samples. In this analysis only the electron channel is used where the electrons are required to momentum of at least 1 GeV in the center-of-mass frame and must also also pass a tight electron identification likelihood. The signal yields in each channel are extracted after fitting the sum of magnitudes of the electron momenta (p_{ee}) to data. Using the post-fit distributions shown in Fig. 3, χ_d is measured as:

$$\chi_d = 0.187 \pm 0.010 \text{ (stat.)} \ \pm \ 0.019 \text{ (syst.)}, \tag{2}$$

where the dominating source of systematic is due to the corrections for electron identification. However, these corrections are expected to improve as larger control samples are obtained. The measured value of χ_d is compatible with the world-average value and has a competitive precision compared to the world average of time-independent measurements.

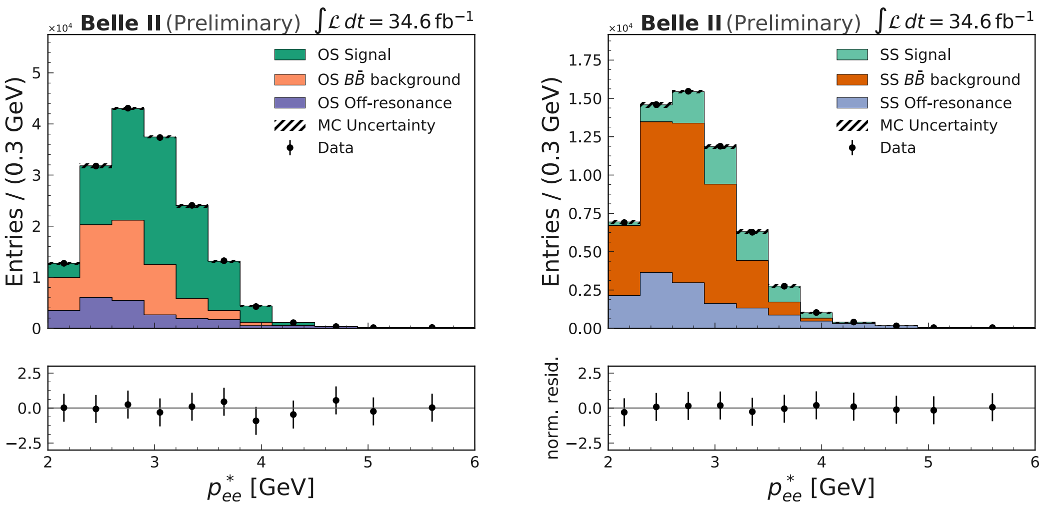

Figure 1 – The p_{ee} post-fit distributions for the opposite-sign (left) and same-sign (right) channels are shown. The lower plots show the pull between the data and the fit results, including the statistical uncertainty in data and the total uncertainty in the MC.

4 Rediscovery of the $B \to \eta' K$

The decay of the B meson into $\eta' K$ is a charmless hadronic decay, mediated via hadronic penguin diagrams which are also sensitive to the contributions of possible new physics in the hadronic loop. Although this is a rare decay mode, the branching fraction is large enough to make time-dependent measurements of CP violation parameters in this channel possible. The rediscovery [6] of this decay mode at Belle II marks an important step towards improving these measurements.

For the reconstruction of the signal decay mode, both neutral and charged B mesons are used, and for the decay modes of η', $\eta' \to \eta(\to \gamma\gamma)\pi^+\pi^-$ and $\eta' \to \rho(\to \pi^+\pi^-)\gamma$ are used. The background processes contributing to this measurement are mostly due to continuum events, but there is also non-negligible contamination due to misreconstructed signal events, referred to as signal-cross-feed or SxF. In order to suppress the continuum backgrounds, a dedicated multivariate classifier, CS_{var}, is trained on event shape variables such as Fox-Wolfram moments and CLEO cones. The performance of this variable is validated by comparing the output in simulation and the off-resonance dataset and assigning the differences as a source systematic uncertainty.

In order to extract the signal yields, an extended unbinned three-dimensional maximum likelihood fit is used. The three observables used in the fit are M_{bc}, ΔE and the continuum suppression variable (CS_{var}) and three components of the fit include signal, continuum and peaking backgrounds. The contribution due to signal-cross-feed is considered together with the signal component. The PDF used for modeling each contribution in each observable was determined based on the MC. The fit process was also validated using toy MC with injected signals. Figure 2 shows the result of the fit in each of the observables. The measurement of the branching fraction and comparison to the world average are shown in Table 1.

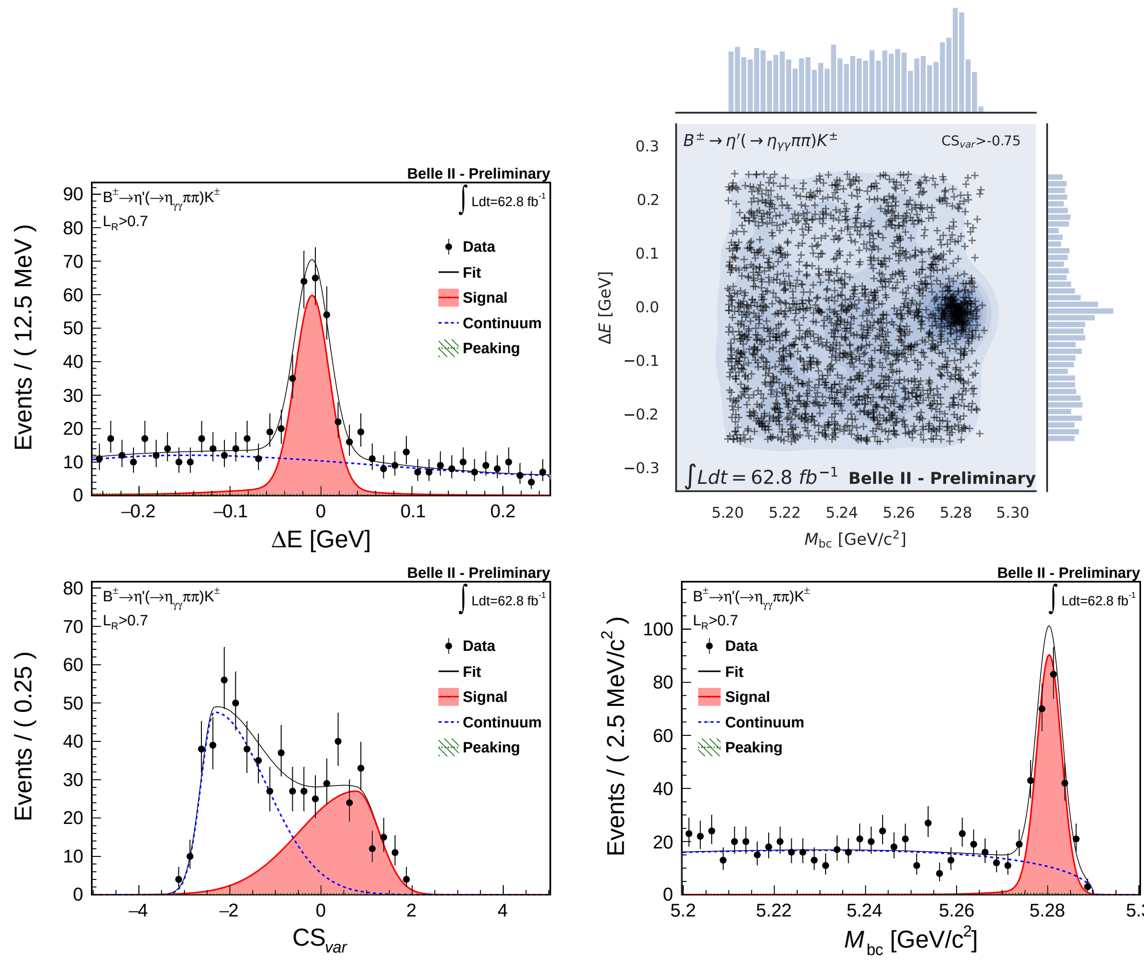

Figure 2 – Data and MC distributions and the corresponding fit results of M_{bc} and ΔE, and CS_{var} in the channel $B^{\pm} \to \eta' K^{\pm}$ with $\eta' \to \eta\pi^+\pi^-$ are shown. Additionally the plot of M_{bc} versus ΔE in the same channel are also shown.

Table 1: Summary of the results on the branching ratios of $B \to \eta' K$ obtained by Belle II and the comparison with world averages.

Channel	$\mathcal{B}$ $(\times 10^6)$ Belle II $(62.8\,\text{fb}^{-1})$	World average
$B^{\pm} \to \eta' K$	$63.4\ ^{+3.4}_{-3.3}(\text{stat}) \pm 3.4(\text{syst})$	70.4 ± 2.5
$B^0 \to \eta' K^0$	$59.9\ ^{+5.8}_{-5.5}(\text{stat}) \pm 2.7(\text{syst})$	66 ± 4

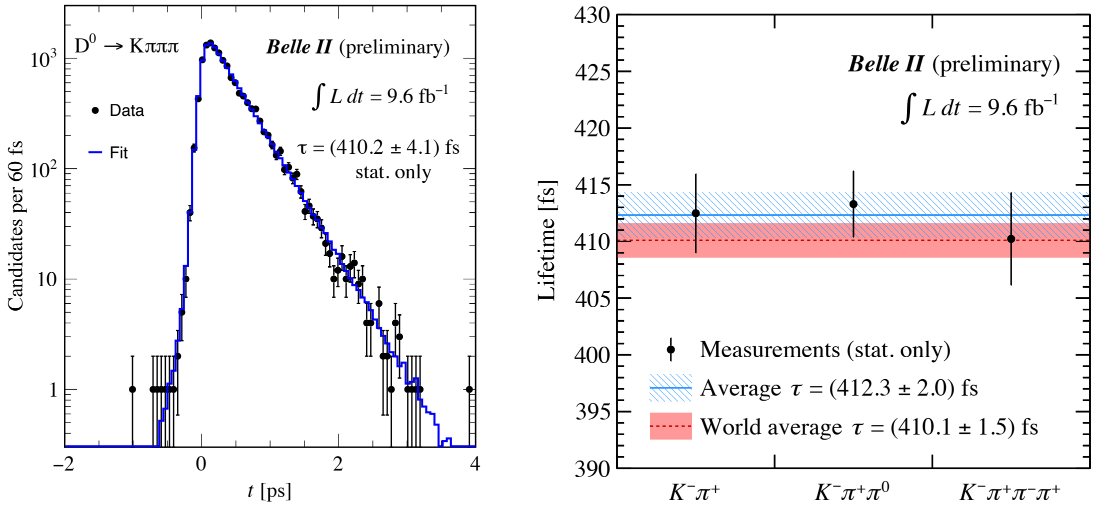

Figure 3 – The left plot shows the fit of the proper-time distribution of the D^*-tagged candidates in the $D^0 \to K^{-1}\pi^+$ channel. The right plot shows the comparison of the D^0 measurements at Belle II and their comparison to the world average values.

5 D^0 lifetime measurement

For this preliminary measurement of the D^0 lifetime in $9.6\,\text{fb}^{-1}$ of Belle II data, $D^{*+} \to D^0\pi_s^+$ candidates are used, in which the D^0 decays to $K^-\pi^+$, $K^-\pi^+\pi^0$, or $K^-\pi^+\pi^+\pi^-$. Here, π_s^+ refers to a soft-pion which due to the small mass difference between the D^* and D^0, has a relatively small momentum. In order to avoid any bias due to the non-zero lifetime of the B-meson, D^* candidates from a B-meson are vetoed by requiring their momentum in the center-of-mass frame to be larger than 2.5 GeV. The D^0 decay time and decay-time uncertainty are determined from the vertex fits of the production and decay vertices. The decay vertex is fitted using the K and π candidates, and for the production vertex the measured position of the beams interaction point is also used as an additional constraint. As seen in Fig. 3, the measurements in the three channels are compatible with each other and with the world-average value within the statistical uncertainties. An updated measurement of the D^0 and D^+ lifetimes, using $72\,\text{fb}^{-1}$ of data, with a precision competitive to the world-average values is expected to become public soon.

6 Yield extraction of $D^{*+} \to D^0(\pi^+\pi^-\pi^0)\pi^+$

The large number of the charm sample which is expected to be collected at Belle II in the coming years, will allow for in depth investigations into CP violation (CPV) in the charm sector as well. In particular, the time-integrated Dalitz analysis of $D^0(\pi^+\pi^-\pi^0)$ mode could be used to search for CPV in the decay of D^0. As a step towards such a measurement, the current dataset is used to demonstrate the ability of the experiment to extract the yield for the signal candidates. The signal yield is extracted using the distribution ΔM, where $\Delta\text{M} = m(D^*) - m(D^0)$. Figure 4 shows the result of the fit on data corresponding to an integrated luminosity of $72\,\text{fb}^{-1}$. The

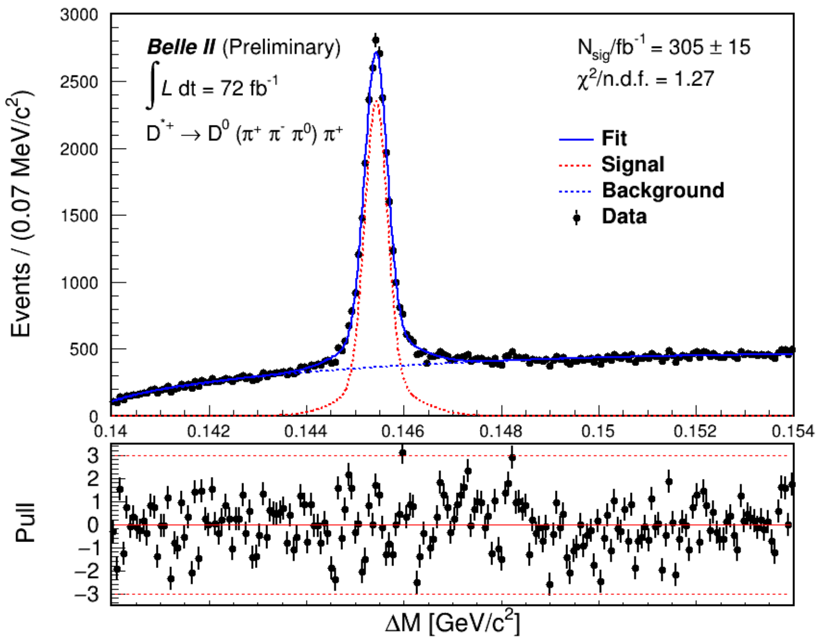

Figure 4 – The distribution of ΔM in the $D^{*+} \to D^0(\pi^+\pi^-\pi^0)\pi_s^+$ decay channel is shown. The black dots represent the data and the blue, dotted red and dotted blue lines represent the total fit, the signal and background components of the fit respectively.

signal yield is measured to be 305 ± 15 per fb^{-1} of collected data. The uncertainty in the measurement includes the statistical uncertainty and the uncertainty in the correction factor for the peaking backgrounds which was measured using MC samples.

7 Tau mass measurement

Precise measurement of the properties of the tau lepton, in particular, its mass and lifetime, can provide important tests of lepton flavor universality of SM. Currently, the relative precision of these measurements for the tau lepton are nearly three orders of magnitude worse than those for muon and electron. For the measurement of the mass of the tau lepton at Belle II [9], the tau-pair production events are selected by reconstructing events compatible with a 3-prong ($\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}_\tau$) and a 1-prong ($\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau$, $\tau^- \to h^-\nu_\tau$ or $\tau^- \to \pi^-\pi^0\nu_\tau$) decay of the tau pair.

To measure the tau mass, the pseudomass variable, M_{min} , is used which is defined in the following way in order to have a kinematical edge at the tau mass:

$$M_{min} = \sqrt{M_{3\pi}^2 + 2(E_{\mathrm{beam}} - E_{3\pi})(E_{3\pi} - P_{3\pi})} \leq m_\tau, \tag{3}$$

where, $M_{3\pi}$, $E_{3\pi}$, and $P_{3\pi}$, are the mass, energy and momentum of the 3π system and E_{beam} is the beam energy. An empirical edge function is used to extract the mass of the tau lepton from the the kinematical end-point in the M_{min} distribution. The bias in the fit procedure is estimated by using simulated samples with shifted values for the generated tau mass. Using $8.8\,\mathrm{fb}^{-1}$ of data, the tau mass is measured as:

$$\tau = 1777.28 \pm 0.75\ (\mathrm{stat.}) \pm 0.33\ (\mathrm{syst.})\,\mathrm{MeV} \tag{4}$$

Currently the precision of this measurement is limited by the size of the data that was used and the systematical uncertainties due to corrections in the tracking and the fit bias. However, as can be seen in left plot in Figure 5, the systematical uncertainties are already comparable to those at Belle.

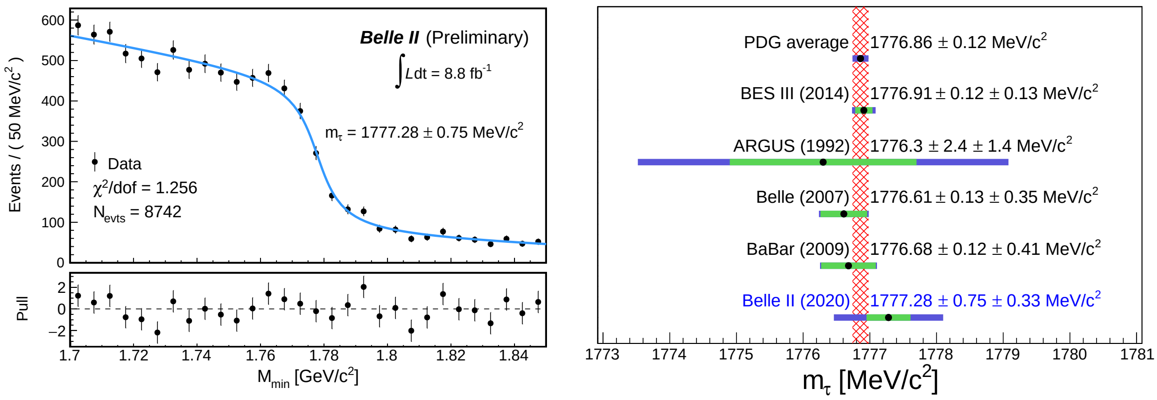

Figure 5 – Left plot shows the distribution of the data and the fit results on the M_{min} distribution and the extracted value for τ and the corresponding statistical uncertainty after the fit bias correction. The right plot shows the comparision of the different τ measurements, where the hashed red band shows the world average and the green and blue bars represent the systematical and statistical uncertainties respectively.

8 Summary

Thanks to the heroic efforts of the colleagues stationed in Tsukuba, the Belle II and SuperKEKB have been performing persistently even through the difficult times caused by the current pandemic. Even though the size of the data collected so far is still a fraction of the ones at Belle and BaBar, many Belle II analyses already have competitive systematic precisions and many of the currently limiting systematic sources of uncertainties are expected to be reduced as larger control samples are collected and the over understanding of the detector is improved.

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