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Recent Belle II results on decay-time-dependent CP violation

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Measurements of decay-time-dependent CP violation are chief goals of the Belle II physics program. These kind of measurements are sensitive probes of non-SM physics. This talk presents first Belle II results on the mixing rate and lifetime of B^0 mesons, an essential validation of time-dependent measurements that requires detailed control of complex high-level capabilities such as flavor tagging and decay-time resolution modeling. Recent results on $B^0 \to J/\Psi K_s$, $B^0 \to K_s^0 \pi^0$ and $B^0 \to K_s^0 K_s^0 K_s^0$ are reported.

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1. Introduction

In the last twenty years we assisted to an extraordinary advance in the understanding of flavour dynamic. Belle and Babar experiments operating at first generation of asymmetric B factories (KEKB and PEP-II) gave significant contributions to B physics measuring CP violation outside the kaon system and experimentally establishing the CKM mechanism [1]. Then in the last ten years experiments at the LHC, such as LHCb, allowed tremendous progresses by measuring the parameters of the Unitarity Triangle (UT) and of the CKM matrix placing several constraints on non-Standard Model scenarios. Belle II, a next generation B-factory experiment, will search for observable signatures of virtual contributions from non-SM particles in a complementary way to the LHC experiments. In particular, thanks to constrained kinematics and a lower-background environment, Belle II can observe processes otherwise non accessible at the LHC. The scientific program proposed by the Belle II experiment is wide [2] and CP-violation (CPV) measurements represent one of the main goals. Despite the CKM parameter ϕ_1 ([= arg$[-V_{cb}^* \; V_{cd}/V_{tb}^* \; V_{td}]$) is currently the most precisely measured angle of the CKM unitarity triangle, there is still a big interest on this measurement. The measurement of $\sin 2\phi_1$ gives a unique access to non-SM physics if we perform a comparison between results obtained by "tree" decays (e.g $B^0 \to J/\Psi K^0$) and "penguin" decays (e.g. $B^0 \to K^0 K^0 K^0$). With the first measurement we can precisely probe non-SM physics in the mixing whereas the penguin-dominated channels probe non-SM physics in the mixing and in the decay. And since non-SM physics in the B^0 mixing is currently much better constrained than that in penguins, by comparing results across $B^0 \to J/\Psi K^0$ and penguins we probe (poorly constrained) non-SM physics in penguin decays.

2. Decay-time-dependent analysis

The CKM parameter $\sin 2\phi_1$ is measured by performing a decay-time-dependent analysis. In a B factory the neutral B mesons are produced through the transition $e^+e^- \to \Upsilon(4s) \to B^0\bar{B^0}$ in an entangled state. Both B mesons evolve in this coherent state, where there are only one B^0 and one $\bar{B^0}$ until one decays. We use the flavour algorithm to determine the flavour of that B (the B_{tag}). Since the two B mesons are in an entangle state, the flavor of the other B (the B_{sig}) is known at that instant. B_{sig} then continues to propagate and oscillates between a B^0 and $\bar{B^0}$ until it decays into a final state common to B^0 and $\bar{B^0}$. In this measurement, the B_{sig} decay is fully reconstructed, and the B_{tag} flavor and decay vertex position is determined. CP asymmetry arises from the interference between a decay without mixing $B^0 \to f_{CP}$ and a decay with mixing $B^0 \to \bar{B^0} \to f_{CP}$. We can access $\sin 2\phi_1$ parameter through the measurement of the asymmetry:

$$A^{raw}(\Delta t) = \frac{N(\bar{B^0} \to f_{CP}) - N(B^0 \to f_{CP})}{N(\bar{B^0} \to f_{CP}) + N(B^0 \to f_{CP})}(\Delta t) = A_{CP}\cos(\Delta m_d \Delta t) + S_{CP}\sin(\Delta m_d \Delta t) \quad (1)$$

where $S_{CP} = \sin 2\phi_1$.

2.1 Key aspects of the measurement

There are two key aspects for this measurement:

- The Δt reconstruction

- The flavor identification of the B_{tag}

The Δt is measured from the vertex displacement along the boost direction Δz of the two B mesons: $\Delta t \approx \Delta z/\beta\gamma c$ (where $\beta\gamma c$ is the boost factor). Belle II operates at a smaller boost than Belle, so the precision on Δt is recovered using a pixel detector that improves the precision of the vertex position. The small beam size is used to constrain the B_{tag} vertex position improving the Δt resolution. The effect of the Δt resolution function (R(Δt)) is taken into account to perform a reliable measurement of Δt.

A complex multivariate algorithm is used instead to identify the flavor of the B_{tag} [3]. It uses discriminating input variables from the particles on the tag side (kinematic, track-hit, and particle-identification information) by looking for flavor-specific signatures. The possibility to wrongly tag the flavour of the B_{tag} introduces a dilution effect (1-2w, where w is the wrong tag fraction) in the measurement.

Taking into account both these two effects the measured asymmetry is $A(\Delta t) = A^{raw}(\Delta t) \times(1-2\mathrm{w}) \otimes R(\Delta t)$

3. CP violation measurement

In this section we will describe some of the most recent Belle II time-dependent CP violation (TDCPV) measurements.

3.1 Lifetime and mixing measurement

The lifetime and oscillation frequency measurements constitute a precision test of the CKM structure of the SM. In addition, it is an important bench test of the essential tools needed for $\sin 2\phi_1$ measurement (Δt resolution model and flavor tagger). This measurement has been performed by using around 30k events from flavor specific decay $B^0 \to D^{(*)-}\pi^+$ (signal yield: 33317 ± 203). The B^0 mixing frequency is extracted from the asymmetry:

$$A(\Delta t) = \frac{N_{B\bar{B}} - N_{BB,\bar{B}\bar{B}}}{N_{B\bar{B}} - N_{BB,\bar{B}\bar{B}}} = \cos(\Delta m_d \Delta t)(1-2w) \otimes R(\Delta t) \tag{2}$$

In fig. 1 (right) the Δt distributions for $B^0\bar{B}^0$ and $\bar{B}^0\bar{B}^0$, B^0B^0 events are shown. The lifetime and mixing frequency values obtained in this analysis ($\tau_{B^0} = 1.499 \pm 0.013(stat.) \pm 0.008(syst.)$ ps and $\Delta m_d = 0.516 \pm 0.008(stat.) \pm 0.005(syst.)$ ps^{-1}), compatible with world average, demonstrate the good performance of Belle II for decay-time-dependent analyses.

3.2 The $\sin 2\phi_1$ measurement

To measure $\sin 2\phi_1$ parameter, a B^0 is first reconstructed in the $B^0 \to J/\Psi K_s$ decay. The signal yield (=2774 ± 55) and signal fraction are extracted from an unbinned extended maximum likelihood fit to the ΔE distribution (ΔE = E_B - E_{beam} where E_B is the reconstructed energy of the B. See fig. 2 (left)). Then event-by-event fractions from ΔE fit are used in the sWeight method to obtain a background-subtracted Δt distribution. The $B^0 \to D^{(*)-}\pi^+$ events reconstructed in the lifetime and mixing analysis are used as calibration for the flavor tagger and the Δt resolution function. The CP fit procedure is validated by performing the extraction of CP-violation parameters

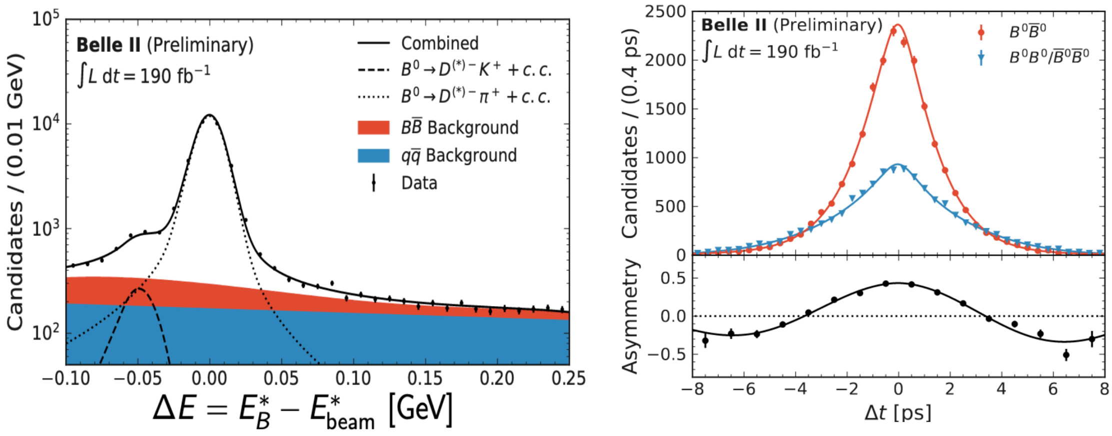

Figure 1: Left: ΔE distribution. Right: Δt distributions for $B^0\bar{B}^0$ and $\bar{B}^0\bar{B}^0$, B^0B^0 events.

using null-CP violation samples of $B^+ \to J/\Psi K^+$ decays. after obtaining null asymmetries as expected ($S^{B^+} = 0.016 \pm 0.029$, $A^{B^+} = 0.021 \pm 0.021$), an unbinned maximum likelihood fit is performed to the sWeighted Δt distribution for $B^0 \to J/\Psi K_s$ decays. The measured CP observables S_{CP} and A_{CP}, consistent with the world averages, are:

$$S_{CP} = 0.720 \pm 0.062(stat) \pm 0.016(syst), \tag{3}$$

$$A_{CP} = 0.094 \pm 0.044(stat)^{+0.042}_{-0.017}(syst). \tag{4}$$

In fig. 2 (right) the sWeighted Δt distribution of $B^0 \to J/\Psi K_s$ is shown with fit overimposed. The

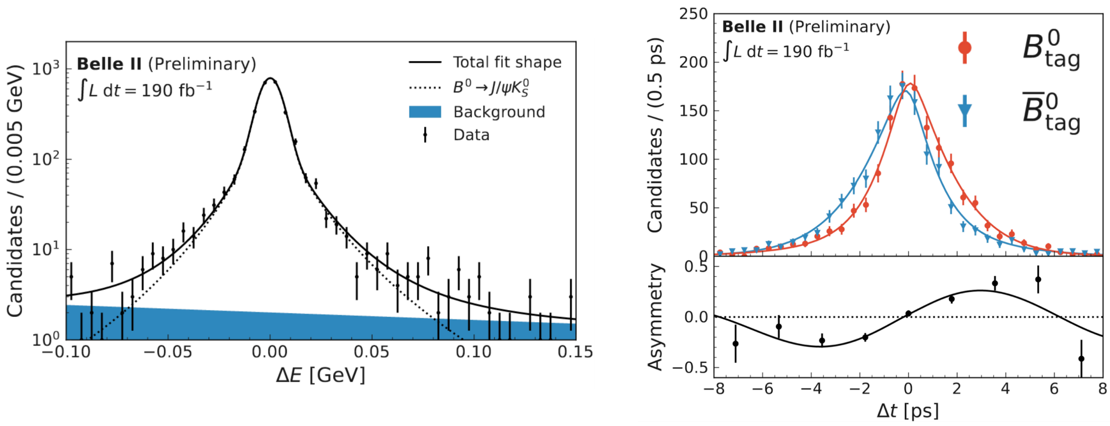

Figure 2: Left: ΔE distribution. Right: Δt distribution for $B^0 \to J/\Psi K_s$ events separated by flavor of the B_{tag}.

largest contributions to the systematic uncertainty comes from the size of the calibration sample and the tag-side interference.

3.3 $B^0 \to K^0_s K^0_s K^0_s$ measurement

In this section we will describe the first time-dependent-measurement of Belle II in $B^0 \to K^0_s K^0_s K^0_s$ decays. This is a charmless three-body decay mediated by the $b \to sq\bar{q}$ quark transition corresponding to a "penguin" one-loop amplitude. The final state consisting of three identical, neutral pseudo-scalar mesons (K_s). Since K_s mesons fly, there is no track coming directly from the B_{sig} vertex, making the vertex reconstruction challenging. Belle II will have a unique impact on this measurement. The signal is extracted in a simultaneous fit of three variables: the beam-constrained mass (M_{bc}), the B^0 invariant mass and the output of a multivariate classifier used to suppress the main background contribution that comes from random combination of the tracks from $e^+e^- \to u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$ (signal yield: 53 ± 8). The analysis procedure is validated by reconstructing $B^+ \to K_s^0 K_s^0 K^+$ where no TDCPV is expected. The extracted value of $S^{B^+} = 0.37 + 0.31$, consistent with no CP violation, supports the robustness of the analysis. The CP parameters are then extracted from the unbinned maximum-likelihood fit of Δt that is shown in fig.3 (right). The measured values are:

$$S_{CP} = -1.86^{+0.91}_{-0.46}(stat) \pm 0.09(syst), \tag{5}$$

$$A_{CP} = -0.22^{+0.30}_{-0.27}(stat) \pm 0.04(syst). \tag{6}$$

This analysis is still statistically limited.

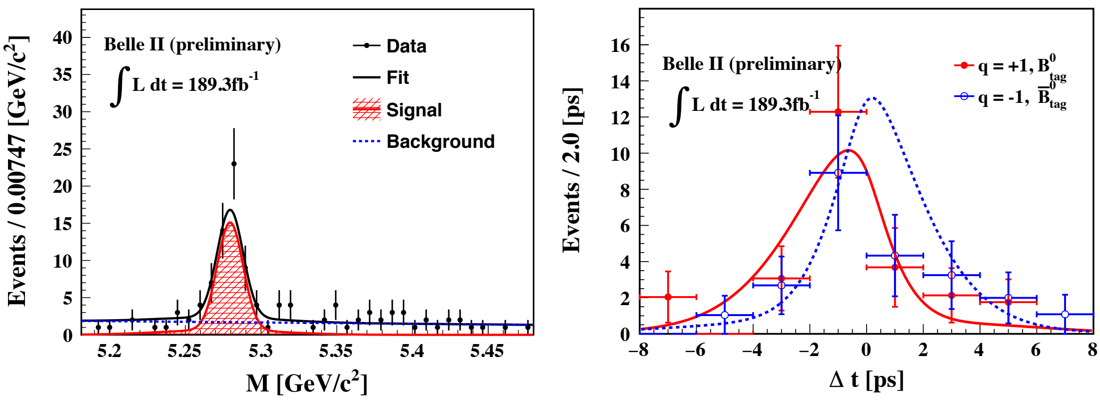

Figure 3: Left: B^0 invariant mass M. Right: Δt distributions for $B^0 \to K_s^0 K_s^0 K_s^0$ events separated by flavor of the B_{tag}.

3.4 $B^0 \to K_s^0 \pi^0$ measurement

The $B \to K\pi$ isospin sum rule offers a stringent null test of the SM:

$$I_{K\pi} = A_{K^+\pi^-} + A_{K^0\pi^+}\frac{Br(K^0\pi^+)}{Br(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{K^+\pi^0}\frac{Br(K^+\pi^0)}{Br(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{K^0\pi^0}\frac{Br(K^0\pi^0)}{Br(K^+\pi^-)} \tag{7}$$

in the SM, it is expected to be close to 0. The dominant uncertainty on $I_{K\pi}$ determination comes from the 10% experimental uncertainty on $A_{K^0\pi^0}$ measurement. The excellent neutral-particle reconstruction capability of Belle II allows for a unique measurement of CP violation parameter $A_{K^0\pi^0}$ in $B^0 \to K_s^0\pi^0$ decay [4]. The signal yield ($=135\ ^{+16}_{-15}$) and direct CP asymmetry $A_{K^0\pi^0}$ are extracted from a four-dimensional fit to M_{bc}, ΔE, Δt and the BDT output distributions used to suppress the $e^+e^- \to q\bar{q}$ background. τ_{B^0}, Δm_d and S_{CP} are fixed in the fit to the world-average values obtained from previous measurements. Fig.4 (rigth) shows the fit to the Δt distribution. The

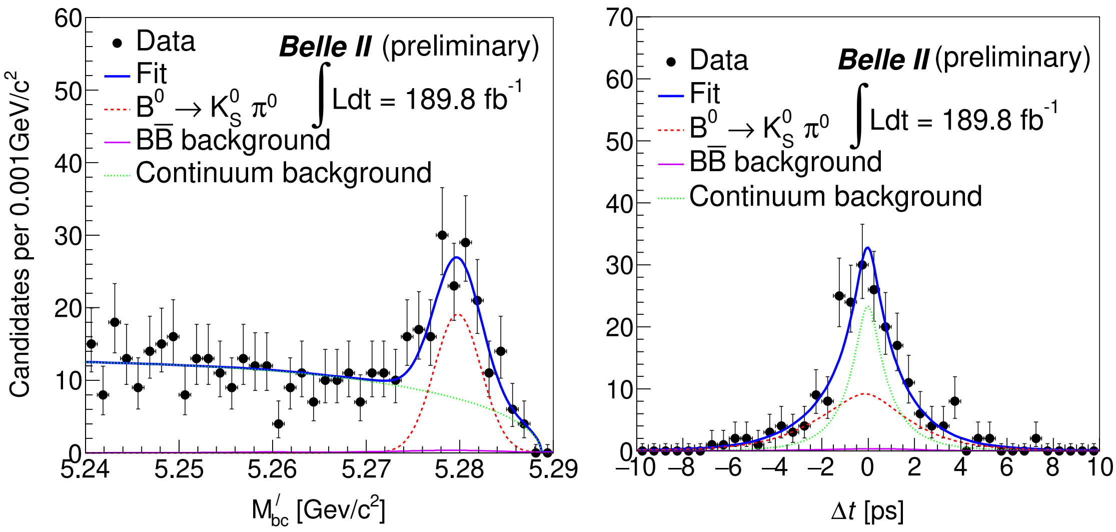

Figure 4: Left: M_{bc} distribution. Right: Δt distributions for $B^0 \to K_s^0\pi^0$ events with fit over-imposed.

measured branching ratio and direct CP asymmetry

$$A_{K^0\pi^0} = -0.41^{+0.30}_{-0.32}(stat.) \pm 0.09(syst.), \tag{8}$$

$$Br = (11.0 \pm 1.2(stat.) \pm 1.0(syst.)) \times 10^{-6}, \tag{9}$$

are still limited by the statistical uncertainty.

4. Summary

A very powerful probe of non-SM physics are B^0 decay-time-dependent analyses, which play a very important role in the Belle II physics program. These are sophisticated analyses that require control of many low- and high-level capabilities such as vertex reconstruction and flavor tagging performance. We presented some first results that demonstrate that we gained the command of all these tools and that we are ready for impactful results.

References

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