CP Violation and Charmless B Decays at Belle II

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On behalf of the Belle II Collaboration
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Asymmetric $e^+e^-$ collider with CM energy at $\Upsilon(4S) = 10.58$ GeV resonance
$\Upsilon(4S) \rightarrow B^+B^- (~51.5\%), \ Upsilon(4S) \rightarrow B^0\bar{B}^0 (~48.5\%)$

Belle II is a general purpose $4\pi$ detector
Good charged tracking reconstruction efficiency, gamma reconstruction, and particle identification for kaon, pion, proton, electron, muon and $K_L$

Design instantaneous luminosity: $6.5 \times 10^{35}$ cm$^2$s$^{-1}$
30 times higher than its predecessor KEKB
Achieved: $4.14 \times 10^{34}$ cm$^2$s$^{-1}$
Belle II Luminosity

Data taking efficiency ~ 90%
Recorded Lumi ~ 382 fb⁻¹
Expected total 50 ab⁻¹
Belle Lumi ~ 1 ab⁻¹
Babar Lumi ~ 500 fb⁻¹

Belle II has a broad and comprehensive physics program
✓ CP violation in B meson decays is only one part of program
✓ This talk only covers few selected recent analysis results

<table>
<thead>
<tr>
<th>Physics process</th>
<th>Cross section [nb]</th>
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<tbody>
<tr>
<td>$\Upsilon(4S)$</td>
<td>1.110 ± 0.008</td>
</tr>
<tr>
<td>$u\bar{u}(\gamma)$</td>
<td>1.61</td>
</tr>
<tr>
<td>$d\bar{d}(\gamma)$</td>
<td>0.40</td>
</tr>
<tr>
<td>$s\bar{s}(\gamma)$</td>
<td>0.38</td>
</tr>
<tr>
<td>$c\bar{c}(\gamma)$</td>
<td>1.30</td>
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</table>
How to measure CP Violation

Electron and positron collide producing an Upsilon meson boosted in the lab frame

\[ \Upsilon(4S) \rightarrow B^0 \bar{B}^0 \quad 1^- \rightarrow 0^- + 0^- \]

\[ \beta\gamma = 0.28 \]

After a time \( \Delta t \), the second \( B \) (call it signal \( B \)) decays into a CP or flavor eigenstate that is fully reconstructed

(\( \Delta t \) can be negative)

\[ \Delta t = \frac{\Delta z}{\beta\gamma c}, \quad \sigma(\Delta t) \sim 70\mu m \]

Upsilon decays to \( B/\bar{B} \) pair in coherent angular momentum state

(same technique used for all time-dependent CP analyses)

Flavor tagging:
- \( \Upsilon(4S) \) produces coherent \( B\bar{B} \) pair, \( B^0 \rightarrow \text{flavor eigenstates} \sim 100\% \)
- Determine the flavor of \( B_{\text{tag}} \) \( \Rightarrow \) infer the initial flavor of \( B_{\text{rec}} \)
Flavor tagging performance at Belle II

- Category based flavor tagging based on the BDT
- Calibrate using fully reconstructed flavor-eigenstate $B^0$ events: $\sim 500$ signal/fb$^{-1}$
- Time-integrated measurement

$\epsilon_{\text{eff}} = (30.0 \pm 1.2\text{(stat.)} \pm 0.4\text{(syst.)})\%$ [BelleII]
$\epsilon_{\text{eff}} = (30.1 \pm 0.4)\%$ [Belle]
$\epsilon_{\text{eff}} = (31.2 \pm 0.3)\%$ [Babar]

Ref: European Physical Journal C 82, 283 (2022); arXiv:2110.00790 [hep-ex]

- Sys error dominated by MC statistics
- Expect improvement of performance
  - Improve the current PID performance at Belle II
Precision Measurement of mixing parameter and lifetime is critical to time-dependent CPV measurements

$$\mathcal{A}_{CP}(t) = \frac{N(B^0 \rightarrow f_{CP}) - N(\bar{B}^0 \rightarrow f_{CP})}{N(B^0 \rightarrow f_{CP}) + N(\bar{B}^0 \rightarrow f_{CP})}(t) = (S_{CP} \sin(\Delta m_d t) + A_{CP} \cos(\Delta m_d t))$$

S: mix induced CP violating parameter, A: direct CP violating parameter

Precision Measurement of mixing parameter and lifetime is critical to time-dependent CPV measurements

$$\text{mix}(t) = \frac{N(B^0 \rightarrow B^0) - N(B^0 \rightarrow \bar{B}^0)}{N(B^0 \rightarrow B^0) + N(B^0 \rightarrow \bar{B}^0)}(t) = \cos(\Delta m_d t)$$

- Vertex resolution for decay time measurement
- Flavor tagging calibration and validation
Mixing and Lifetime measurement

- Using hadronic $B^0 \to D^{(*)-}\pi^+ / K^+$ final states: ~ 40K signal yields
- Distinguish signal and background (bg) using $\Delta E$ and event-shape multivariate classifier
  - Subtract bg from sideband (sWeights) to obtain bg-free signal sample
  - Fit signal $\Delta t$ distribution with wrong-tag fraction and vertex resolution model
- Result consistent with the world average

$$\tau_{B^0} = 1.499 \pm 0.013\text{(stat.)} \pm 0.008\text{(syst.)}\text{ ps} \quad \tau_{B^0} = 1.519 \pm 0.004\text{ ps} \quad [\text{PDG}]$$
$$\Delta m_d = 0.516 \pm 0.008\text{(stat.)} \pm 0.005\text{(syst.)}\text{ ps}^{-1} \quad \Delta m_d = 0.5065 \pm 0.0019\text{ ps}^{-1} \quad [\text{PDG}]$$

- Important milestone: we are ready for time-dependent analysis

Also see: BELLE2-TALK-CONF-2022-031
CP Violation of $B^0 \rightarrow K_S \pi^0$

- Test new physics based on isospin sum-rule

\[
I_{K\pi} = A_{K^{+}\pi^{-}} + A_{K^{0}\pi^{+}} \frac{B(K^{0}\pi^{+})}{B(K^{+}\pi^{-})} \frac{\tau_{B^{0}}}{\tau_{B^{+}}} - 2A_{K^{0}\pi^{0}} \frac{B(K^{+}\pi^{0})}{B(K^{+}\pi^{-})} \frac{\tau_{B^{0}}}{\tau_{B^{+}}} - 2A_{K^{+}\pi^{-}} \frac{B(K^{0}\pi^{0})}{B(K^{+}\pi^{-})} \frac{\tau_{B^{0}}}{\tau_{B^{+}}}
\]

- Uncertainty of $I_{K\pi} = 0$ test dominated by $A_{CP}(B^0 \rightarrow K_S \pi^0)$; only feasible at Belle II

- Time-dependent analysis needs good vertex measurement with beam spot constraint
  - Using $B^0 \rightarrow J/\psi K_S$ to calibrate $\Delta t$ resolution and bias

Also see: BELLE2-TALK-CONF-2022-031
Decay of $B^0 \to K_S \pi^0 \gamma$

- No time-dependent CP asymmetry in the SM
  - Right (Left) handed photon in $B^0 \to K_S \pi^0 \gamma$ ($\bar{B}^0 \to K_S \pi^0 \gamma$)
- Possible non-zero CP asymmetry from NP contribution
- Similar challenge for time-dependent analysis as $B^0 \to K_S \pi^0$
  - Still on going
  - Branching fraction measurement compatible to the world average

$$B = (7.3 \pm 1.8 \text{(stat.)} \pm 1.0 \text{(syst.)}) \times 10^{-6}$$

$$B = (7.0 \pm 0.4) \times 10^{-6} \quad [\text{PDG}]$$
\[ B^+ \rightarrow \rho^+ \rho^0 \ (\rho^+ \rightarrow \pi^+ \pi^0, \rho^0 \rightarrow \pi^+ \pi^-) \]

- **Measure CKM angle** \( \phi_2/\alpha \) **using hadronic** \( B \rightarrow \rho\rho \) \((\rho^0\rho^0, \rho^+\rho^-\rho^\pm\rho^0)\) **final states**
- **Possible direct CP violation** due to interference between tree and penguin diagram
- **Measure longitudinal polarization** \( f_L \) **using angular distribution**
  - Helicity angle distribution \( \cos \Theta \): angle between \( \pi^+ \) momentum and opposite momentum of \( B^+ \) measured in \( \rho \) rest frame
- **6D template fit** **taking into account** of correlation
  - \( M_{bc}, \cos \Theta, \Delta E, m(\pi^+\pi^-), m(\pi^+\pi^0) \), event-shape multivariate classifier
  - Charge asymmetry of track reconstruction determined using \( D^+ \rightarrow K_s \pi^+ \)

Also see: BELLE2-TALK-CONF-2022-031

\[ \Delta E = E_B^* - E_{\text{beam}}^* \ [\text{GeV}] \]

\[ A_{CP} = -0.069 \pm 0.068 \ (\text{stat.}) \pm 0.060 \ (\text{syst.}) \]

\[ B(B^+ \rightarrow \rho^+ \rho^0) = (23.2^{+2.2}_{-2.1} \ (\text{stat.}) \pm 2.7 \ (\text{syst.})) \times 10^{-6} \]

\[ f_L = 0.943^{+0.035}_{-0.033} \ (\text{stat.}) \pm 0.027 \ (\text{syst.}) \]

**World average:** \( A_{CP} = -0.05 \pm 0.05 \)
A few selected recent results from Belle II

- Measurement precisions are limited by the data sample
- Demonstrate key ingredients for Time-dependent analysis for CPV
- Expect exciting physics results and reach from Belle II in the future

**Belle II** (Preliminary)

$I_{K\pi} = -0.11 \pm 0.13$  
Belle+BaBar+LHCb+Belle II Winter 2021

- Projected uncertainty without Belle II
- Projected uncertainty with Belle II

arXiv: 2104.14871 [hep-ex]
Backup
Short-term SuperKEKB Plan

Int. Lumi (Delivered)

Long Shutdown (LS) 1 starting summer 2022 to fall 2023 to replace VXD

LS2 shutdown under discussion for machine improvement between 2026-27