Measurement of $\gamma (\phi_3)$ and first results on CP violation at Belle II

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Outline

- Introduction
- SuperKEKB and Belle II
- Prospects for $\phi_3$
- Prospects for $\phi_1$ → First TDCPV measurement
- Summary
Introduction

Measuring SM CP violation ⇒ Measure complex phase of CKM elements.

$$V_{ij} \approx \begin{pmatrix}
1 & \lambda & \lambda^3 \rho \\
-\lambda & 1 & \lambda^2 \\
-\lambda^3 & -\lambda^2 & 1
\end{pmatrix}$$

Unitarity condition

$$(1^\text{st} \leftrightarrow 3^\text{rd})$$

$$\lambda \approx 0.22 : \text{Cabbibo angle}$$

$$\phi_1/\beta \equiv \arg(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*})$$

$$\phi_3/\gamma \equiv \arg(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*})$$

This talk is focused on:

$$\phi_2 : \text{see Eldar Ganiev’s talk.}$$
CKM: Current status

World average (HFLAV)  
[hflav.web.cern.ch/]

\[ \beta \equiv \phi_1 = (22.2 \pm 0.7) \degree \]
\[ \alpha \equiv \phi_2 = (84.9^{+5.1}_{-4.5}) \degree \]
\[ \gamma \equiv \phi_3 = (71.1^{+4.6}_{-5.3}) \degree \]

Global fit (CKM fitter)  
[ckmfitter.in2p3.fr/]

\[ \beta \equiv \phi_1 = (22.51^{+0.55}_{-0.40}) \degree \]
\[ \alpha \equiv \phi_2 = (91.6^{+1.7}_{-1.1}) \degree \]
\[ \gamma \equiv \phi_3 = (65.81^{+0.99}_{-1.66}) \degree \]

- New physics (NP) prospects:
  - \( \phi_1 \): comparison of TD CP-asymmetry in tree- and loop-dominated processes.
  - \( \phi_3 \): test of direct vs indirect disagreement (requires improvement of precision in direct measurement).
SuperKEKB accelerator

- **SuperKEKB**: 4 GeV $e^+$ and 7 GeV $e^-$ asymmetric collider at KEK.
- A 30-fold increase in instantaneous luminosity over Belle, $\mathcal{L} \sim 6 \times 10^{35}$ cm$^{-2}$s$^{-1}$.

20× smaller beam spot and 1.5× increase in beam current $\Rightarrow$ 30× Lumi
Belle II detector and status

- Improved tracking, vertexing.
- Better particle identification.
- Better calorimeter resolution.

Challenge:
- Higher beam background
- Higher trigger rate
- Improved tracking, vertexing.
- Better calorimeter resolution.
Improved tracking, vertexing.
Better particle identification.
Better calorimeter resolution.

World Record by SuperKEKB on June 15th 2020:
\[ \mathcal{L} = 2.4 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \]
Extraction of $\phi_3$

- Only CKM angle accessible at tree level.
- Very precise theoretical prediction $\delta \phi_3 / \phi_3 \sim 10^{-7}$ [J. Brod, J. Zupan, arxiv:1308.5663].
- $\phi_3$ is the phase between $b \to u$ and $b \to c$ transition:

$$\frac{A^{\text{suppr.}}(B^- \to D^0 K^-)}{A^{\text{favor.}}(B^- \to D^0 K^-)} = r_B e^{i(\delta_B - \phi_3)}$$

- Measured via the interference between $B^- \to D^0 K^-$ and $B^- \to \bar{D}^0 K^-$ with various $D^0$ channels.
  - **GLW method**: $CP$ eigenstates: $K^- K^+, \pi^- \pi^+, K_S^0 \pi^0$ [Phys. Lett. B 253, 483]
  - **ADS method**: DCS modes: $K^+ \pi^-, K \pi \pi^0$ [Phys. Rev. Lett. 78, 3257]
  - **BPGGSZ method**: self-conjugate multibody final states: $K_S^0 \pi^- \pi^+, K_S^0 \pi^- \pi^+ \pi^0, K_S^0 K^- K^+$ [Phys. Rev. D 68, 054018]
Belle II prospects for $\phi_3$

- Golden mode in Belle II: $B^\pm \rightarrow D^0(K_S^0\pi^-\pi^+)K^\pm$
  - Model-independent binned Dalitz plot approach.
  - Number of events in $i^{th}$ bin is a function of $x_\pm/y_\pm$:
  \[
  N^\pm_i = h_B[K_{\pm i} + r_B^2 K_{\mp i} + \sqrt{K_i K_{-i}}(x_{\pm i} c_i \pm y_{\pm i} s_i)]
  \]

\[
(x_\pm, y_\pm) = r_B(\cos(\pm \phi_3 + \delta_B), \sin(\pm \phi_3 + \delta_B))
\]

- Precise strong phase measurement needed to match Belle II stat. precision: expected from $20 \text{ fb}^{-1}$ BESIII data set.

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Measurement of $\phi_3$ and CPV at Belle II
More sensitive to $\phi_3$ than $B \rightarrow D\pi$ because of its higher $r_B$ value.

Rediscovery of $B \rightarrow DK$ with more than $5\sigma$ evidence using the continuum suppression tool and particle identification technique of Belle II.

Total 53 $\pm$ 9 signal candidates are obtained with a 1D maximum likelihood fit to the $\Delta E$. 
Future prospects

- Expect Belle II and LHCb upgrade to match each other’s performance!
- $\delta(\phi_3) < 1.6^\circ$ with 50 ab$^{-1}$ data set.

- Modes that are good for Belle II:
  - $D^* \rightarrow D^0\pi^0, D^0\gamma$
  - $D^0 \rightarrow K^0_S\pi^0, K^0_S\pi\pi\pi^0$...


- Belle II strength:
  - Increasing statistics
  - Good neutral reconstruction
  - Better $K/\pi$ separation
  - Better continuum suppression

- LHCb will clearly have more precise results in fully-charged final states.
TDPCPV at Belle II

- Decay rate of $B^0$ meson to $CP$ eigen-states:

$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} [1 + q (A_{CP} \cos \Delta m_d \Delta t + S_{CP} \sin \Delta m_d \Delta t)]$$

- Key element: Vertex position measurement, $B$ meson flavor tagging.

see Cyrille Praz’s talk.
First calibration of flavor tagging at Belle II

Good data-simulation agreement

Effective tagging efficiency: $33.8 \pm 3.9\%$

⇒ Comparable with best of Belle and BaBar.
First sin $2\phi_1$ measurement: $B^0 \rightarrow J/\psi K_S^0$

- Most precisely measured UT parameter so far.
- Tree-dominated $b \rightarrow c\bar{c}s$ golden mode.
- Theoretically and experimentally precise.

$S_{\text{CP}} = 0.55 \pm 0.21(\text{stat.}) \pm 0.04(\text{syst.})$; good agreement with the PDG value.
Future prospects

- Challenge both for experiment and theory: penguin pollution.
- Can be controlled experimentally: $B^0 \rightarrow J/\psi\pi^0$.
- Other modes which can also contribute ($b \rightarrow q\bar{q}s$):
  $B^0 \rightarrow \phi K_S, \eta' K_S, \omega K_S$: specifically NP sensitive if any significant deviation from $B^0 \rightarrow J/\psi K_S^0$ is observed.
- Rediscovery of $B^0 \rightarrow \phi K_S^0$ at Belle II.
- Measured B.F. $B(\times10^{-6}) = 3.0 \pm 0.9 \pm 0.4$
- In agreement with the world average.

$\sin 2\phi_1$

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<thead>
<tr>
<th></th>
<th>Belle II</th>
<th>LHCb</th>
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<tbody>
<tr>
<td>$5 \text{ ab}^{-1}$</td>
<td>$50 \text{ ab}^{-1}$</td>
<td>$8 \text{ fb}^{-1}$</td>
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<tr>
<td>$0.4^\circ$</td>
<td>$0.3^\circ$</td>
<td>$0.6^\circ$</td>
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Measurement of $\phi_3$ and CPV at Belle II
Flavor physics at high luminosity B-factories offers good probe for testing SM and looking for NP.

Belle II will play a key role in particle physics.
- Experience from Belle and Babar.
- Good complementarity with LHCb.
- CKM angle measurements can be improved with just 5 -10 ab\(^{-1}\) data set.
- Huge data set of 50 ab\(^{-1}\): several measurements will be syst. limited $\rightarrow$ lots of work ahead!

First sin2$\phi_1$ results at Belle II: $B^0 \rightarrow J/\psi K^0_S$; good agreement with W.A.
Expected experimental performance often better w.r.t Belle despite 20x higher beam background and lower boost.
Looking forward to the next decade of Belle II results!!
Thank you!
Belle II highlights at ICHEP 2020

- CPV and CKM: Experimental overview: Doris Kim
- First results and prospects for $\tau$ LFV decays: Francesco Tenchini
- First results on $V_{ub}$ and $V_{cb}$ with Belle II: Racha Cheaib
- Leptonic and semileptonic decays with $\tau$s at the Belle II experiment: Marco Milesi
- Early charmless B decay physics at Belle II: Eldar Ganiev
- Tau physics prospects at Belle II: Kenji Inami
- Charm potential at Belle II: Giulia Casarosa
- Results and Prospects of Radiative and EWP Decays at Belle II: Yo Sato
- First results from Belle II on exotic and conventional quarkonium: Roberto Mussa
- Dark Sector first results at Belle II: Enrico Graziani
- The Belle II Experiment: Status and Prospects: Kodai Matsuoka
- Status and Future development of the FEI Algorithm at Belle II: William Sutcliffe
- B lifetimes at Belle II: Cyrille Praz
- Track rec. eff. measurement using $e^+e^- \rightarrow \tau^+\tau^-$ events at Belle II: Laura Zani
- Trg eff measurement using $e^+e^- \rightarrow \tau^+\tau^-$ events at Belle II: Petar Rados

Stay tuned!!

Niharika Rout Measurement of $\phi_3$ and CPV at Belle II
Backup
Vertex detectors

- 1st pixel layer at $r = 14$ mm to IP. [Belle $r = 20$ mm]
- Improves vertex resolution along z-axis.
- Larger SVD outer layer at $r = 135$ mm. [Belle $r = 88$ mm]
- Higher fraction of $K_S$ with vertex hits improves vertex resolution.
Flavor tagger

Measurement of $\phi_3$ and CPV at Belle II
### Systematic uncertainty

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<tr>
<th>source</th>
<th>$\Delta \Delta m_d$ [%]</th>
<th>$\Delta S_f$ [%]</th>
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</thead>
<tbody>
<tr>
<td>1. BKG scale &amp; shift</td>
<td>-0.2</td>
<td>-0.3</td>
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<tr>
<td>2. Peaking BKG $J/\psi K_S \pm 100%$</td>
<td>-</td>
<td>-2.7</td>
</tr>
<tr>
<td>3. $b\bar{b}$ frac. $D_\pi \pm 50%$</td>
<td>+0.03</td>
<td>-2.1</td>
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<td>4. $\Delta m_{\text{eff}}$ for $b\bar{b}$ free</td>
<td>+0.8</td>
<td>+0.4</td>
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<tr>
<td>5. $w_{\text{eff}}$ for $b\bar{b}$ free</td>
<td>-0.15</td>
<td>+4.9</td>
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<tr>
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<th>$\Delta \Delta m_d$ [%]</th>
<th>$\Delta S_f$ [%]</th>
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<tbody>
<tr>
<td>6. $w$ difference $J/\psi K_S$ vs $D_\pi$</td>
<td>-</td>
<td>+2.9</td>
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<td>7. Res. function tail scale</td>
<td>+1.2</td>
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<td>8. Res. function tail fraction $\pm 50%$</td>
<td>+1.4</td>
<td>+0.4</td>
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<tr>
<td>9. Kin approx $w$, $\Delta m_d$</td>
<td>+1.2</td>
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<tr>
<td>10. Kin approx $S_f$</td>
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<td>-0.9</td>
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<tr>
<td>11. VXD alignment</td>
<td>+0.4</td>
<td>+2.0</td>
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<tr>
<td><strong>total</strong></td>
<td><strong>2.4</strong></td>
<td><strong>7.1</strong></td>
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