Measurement of time-dependent CP violation in $B^0 \rightarrow J/\psi K_s$ decays using early Belle II data

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Unitarity Triangle from B Decays

- Quark interactions are described by the CKM unitary matrix $V_{\text{CKM}}$.
- Off-diagonal elements of $V^\dagger V=I$ can be represented by triangles in complex plane.
  - Sides ~ Amplitudes ~ Branching fractions
  - Angles ~ Phases ~ CPV
- Most common triangle from $\Sigma_i V_{id} V_{ib}^*$, $i=u,c,t$ (be aware that $\phi_1 = \beta$, $\phi_2 = \alpha$, $\phi_3 = \gamma$ !)
- All angles can be accessed at B-factories $\rightarrow$ BaBar (SLAC) and Belle (KEK) together with LHCb (CERN) $\rightarrow$ precise determination of unitarity triangle.
Belle → Belle II

- Belle II is an upgrade of the Belle detector designed to improve performance, especially in spite of the harsh SuperKEKB machine conditions, in particular:
  - much higher background environment w.r.t. KEKB (40x higher luminosity)
  - reduced CM boost w.r.t. Belle
- New Vertex detector:
  - 2 layers of pixels
  - 4 DSSD layers with extended coverage
- EM calorimeter:
  - new electronics with waveform readout
- Particle-ID:
  - new TOP + ARICH (FWD)
- Drift chamber:
  - smaller cell size, longer lever arm
- $K_L$ & muons:
  - Inner (barrel) and FWD RPCs replaced with scintillators
CPV at B-factories

- $B^0 \bar{B}^0$ mixing and decay amplitudes interfere → time-dependent CP asymmetry
- Need to measure the difference in decay time $\Delta t$, hence the decay vertex
- $B^0 \bar{B}^0$ are produced threshold → $Y(4S) \rightarrow B^0 \bar{B}^0$ pairs at rest in the CM frame
- Asymmetric beam energies $e^+ = 4, e^- = 7$ GeV

\[ \Delta t = \frac{\Delta z}{\beta \gamma c} \]

\[ a_{f_{cp}}(\Delta t) \equiv \frac{\Gamma_{\bar{B}\rightarrow f_{cp}}(\Delta t) - \Gamma_{B\rightarrow f_{cp}}(\Delta t)}{\Gamma_{\bar{B}\rightarrow f_{cp}}(\Delta t) + \Gamma_{B\rightarrow f_{cp}}(\Delta t)} = S \sin(\Delta M \Delta t) - C \cos(\Delta M \Delta t) \]
$\sin(2\varphi_1)$ in $b \to c\bar{c}s$

- Tree dominated modes, golden channel $B \to J/\psi K_s$
- Theoretically clean process, $S = -\xi_f \sin(2\varphi_1)$, $C \sim 0$
- Clean experimental signature: 4 tracks
- Recent theoretical improvements in the calculation of penguin pollution \textbf{arXiv:1503.00859}

- Resolution on $\Delta t$ dominated by the resolution of the tagging $B$ vertex fit
- Thanks to the huge Belle II dataset, comparison with other final states could help disentangle new physics effects

$S \simeq \sin(2\beta)$

$\rightarrow$ key ingredients:
- vertex fit, flavor tagging

\textbf{arXiv:1808.10567}
Vertex resolution

Thanks to the new vertex detector (DSSD + pixels) and the update of the fitting strategy (RAVE) we achieve a better vertex resolution w.r.t. Belle in spite of reduced CM boost! ($\beta\gamma=0.28$ vs 0.45)

$$\langle \Delta l \rangle_{\text{Belle}} \sim 200 \ \mu m$$

$$\langle \Delta l \rangle_{\text{Belle II}} \sim 130 \ \mu m$$

### $\Delta z$ resolution

<table>
<thead>
<tr>
<th></th>
<th>Belle</th>
<th>Belle II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias</td>
<td>29 $\mu$m</td>
<td>6 $\mu$m</td>
</tr>
<tr>
<td>Resolution</td>
<td>89 $\mu$m</td>
<td>53 $\mu$m</td>
</tr>
</tbody>
</table>

### $\Delta t$ resolution

<table>
<thead>
<tr>
<th></th>
<th>Belle</th>
<th>Belle II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias</td>
<td>0.2 ps</td>
<td>$-0.03$ ps</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.92 ps</td>
<td>0.77 ps</td>
</tr>
</tbody>
</table>

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Vertex resolution

Belle II resolution on the transverse impact parameter with full vertex detector (red) and without pixel layers (blue)
Flavor tagging

- Charged leptons, kaons, pions and Λs from the unreconstructed $B^0$ (rest of event) are used to determine its flavor.
- New algorithms have been developed for Belle II, using more variables and different MVA discriminators which benefit also of the improved PID system.
- The new algorithm has already been tested on Belle data.

\[
\varepsilon_{\text{eff}} = \sum_i \varepsilon_i (1 - 2 w_i)^2
\]

Old FT - Belle data: $\varepsilon_{\text{eff}} = (30.1 \pm 0.4)\%$

New FT - Belle data: $\varepsilon_{\text{eff}} = (33.6 \pm 0.5)\%$

New FT - Belle MC: $\varepsilon_{\text{eff}} = (34.18 \pm 0.03)\%$

New FT - Belle II MC: $\varepsilon_{\text{eff}} = (37.16 \pm 0.03)\%$
First data

- First collisions of SuperKEKB during commissioning run from April to July 2018 (Phase2): total data sample collected corresponding to about 500 pb\(^{-1}\) → first “rediscoveries”:

- Phase3 has started in March 2019 with full vertex detector → data analysis is ongoing (about 6 fb\(^{-1}\) to date)
- Hard work on understanding the detector → physics performance is constantly improving
Belle vs Belle II

Comparison of sensitivities for the measurement of $S \sim \sin (2\beta)$ in Belle and Belle II using full dataset (1 and 50 ab$^{-1}$ respectively):

<table>
<thead>
<tr>
<th>Sample</th>
<th>Value (1 ab$^{-1}$)</th>
<th>Stat. ($\times 10^{-3}$)</th>
<th>Syst. ($\times 10^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \to J/\psi K_S$</td>
<td>+0.67</td>
<td>29</td>
<td>13</td>
</tr>
<tr>
<td>$b \to c\bar{c}s$</td>
<td>+0.667</td>
<td>23</td>
<td>12</td>
</tr>
</tbody>
</table>

Worst case scenario, same systematics as Belle

<table>
<thead>
<tr>
<th>Sample</th>
<th>Stat. ($\times 10^{-3}$)</th>
<th>Syst. (1) ($\times 10^{-3}$)</th>
<th>Syst. (2) ($\times 10^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \to J/\psi K_S$</td>
<td>3.5</td>
<td>1.2</td>
<td>8.3</td>
</tr>
<tr>
<td>$b \to c\bar{c}s$</td>
<td>2.7</td>
<td>2.6</td>
<td>7.0</td>
</tr>
</tbody>
</table>

Statistically limited!

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arXiv:1808.10567

With expected improvement due to better vertexing
Pictorial Outlook

Before B-factories

\[ \Delta m_d \text{ and } \Delta m_s \]

\[ |V_{ub}/V_{cb}| \]

\[ \sin 2\beta_{WA} \]

Belle II 50 ab\(^{-1}\) projection, CPV modes only

After B-factories

\[ \Delta m_d \text{ and } \Delta m_s \]

\[ \gamma \]

\[ |V_{ub}| \]

\[ |V_{ub}|_{\text{CPV}} \]


Belle II 50 ab\(^{-1}\) projection, all constraints

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Belle and BaBar have been very successful in testing the CKM paradigm.
Belle II and SuperKEKB represent a new generation B-factory.
The huge dataset along with improved detector performance will allow to test CKM mechanism at 1% level.
\[ \sin(2\phi_1) \]: precision better than 1% using \( c\bar{c}s \) modes.

Second “First” SuperKEKB collision on March 11\textsuperscript{th}.
Phase III - Full detector installed and operating.
Thanks for your attention!