Mixing and mixing related CP violation in the $B$ system

Thibaud Humair, on behalf of the Belle and Belle II collaborations
thumair@mpp.mpg.de

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CKM measurements at the B factories

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CP violation in interference between mixing and decay

CKM parameter $\phi_1$ is accessible using $B^0$ decays to certain CP-eigenstates $f_{CP}$:

Measure asymmetry between number of $B^0 \to f_{CP}$ and $\bar{B}^0 \to f_{CP}$ decays as a function of the $B^0$ decay time $t$.

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

Will discuss two types of TD measurements with different purposes:

**With tree level decays:** e.g. $B^0 \to J/\psi K_S$ to measure $\phi_1$ precisely

$\Rightarrow$ in SM, $A = 0$ and $S = \sin 2\phi_1$

**With penguin decays:** e.g. $B^0 \to \phi K_S$ or $B^0 \to \eta' K_S$. Rare, so sensitive to NP

$\Rightarrow A, S$ could be significantly shifted from SM expectation
Time-dependent CP violation at the $B$ factories

- Only two $B$s are produced in $e^+e^-$ collisions and fly along the slide boost direction;
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Only two $B$s are produced in $e^+e^-$ collisions and fly along the slide boost direction;

- When the tag $B$ decays, the signal $B$ has opposite flavour;
- Time between flavour tagging and decay determined from the distance between tag and signal vertices.
The Belle and Belle II detectors

Although all sub-detectors underwent a major upgrade switching from Belle to Belle II, the general layout of the detectors look similar:

- **Tracking:** drift chamber
- **Vertexing:** 4 layer silicon strip detector (+ 2 layer pixel at Belle II)
- **PID:** EM calorimeter (also for $\pi^0/\gamma$ detection), Cherenkov counters (also TOF at Belle), and $dE/dx$ from drift chamber;
- **$\mu/K_L$:** outer part of the detector to differentiate $\mu$’s and $K_L$’s.
Between 1999 and 2010, the Belle detector collected 711 fb\(^{-1}\) of data at the \(\Upsilon(4S)\) resonance \(\Rightarrow 772\) mio \(B\bar{B}\) pairs
Using the full Belle dataset, get

\[
\sin 2\phi_1 = 0.667 \pm 0.023 \pm 0.012 \quad (PRL108(2012)171802)
\]

Final aim at Belle II: reduce uncertainty by factor \(\sim 5\) to reach \(\sim 0.5\%\) precision. Systematic uncertainties will have to be tackled!

Today, one recent Belle measurement:

- \(B^0 \rightarrow K_S K_S K_S\) TD analysis;

After that: highlights from Belle II in the preparation for precision time-dependent measurements.
Belle

$B^0 \rightarrow K_SK_SK_S$ TD analysis
$B^0 \rightarrow K_S K_S K_S$: purpose and selection

**Purpose:**

$B^0 \rightarrow K_S K_S K_S$ is mediated by a penguin transition

$\Rightarrow$ rare and sensitive to NP.

In SM, expect:

- $A = 0$ as tree diagram negligible wrt penguin;
- $S = -\sin(2\phi_1) \approx -0.70$ (opposite of $B^0 \rightarrow J/\psi K_S$).

**Reconstruction and selection:**

Reconstruct $K_S \rightarrow \pi^+\pi^-$ and use Neural Network (NN) to suppress bkg with $\pi^+\pi^-$ not from $K_S$.

Remaining bkg: almost exclusively continuum $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, c, s$)

$\Rightarrow$ train an event-shape based NN to suppress it.

Main idea: In CoM, $q\bar{q}$ is jet-like and $B\bar{B}$ spherical.
$B^0 \to K_SK_SK_S$: fit for signal fraction

Perform 3D fit to extract signal/bkg fractions:

1) **Energy difference** $\Delta E \equiv E^*(B^0) - E_{CMS}/2$
   $\Rightarrow$ Width dominated by momentum resolution

2) **beam energy-constrained mass** $M_{bc} \equiv \sqrt{(E_{CMS}/2)^2 - p^*(B^0)^2}$
   $\Rightarrow$ Width dominated by beam energy resolution

3) $q\bar{q}$ Neural Network output.

Fit finds $258 \pm 17$ signal candidates with purity $\approx 74\%$ in the signal region ($M_{bc} > 5.27$ GeV and $|\Delta E| < 0.1$ GeV).
These events are then then used for the TD fit...
Experimental effects in time-dependent measurements

When measuring the CP asymmetry, have to take into account two experimental effects:

▶ asymmetry is diluted by the wrong-tag-fraction $w$,
▶ $\Delta t$ distribution smeared out by resolution function $\mathcal{R}$.

$w$ and some of the resolution function parameters are extracted by performing a time-dependent measurement of the mixing probability using abundant $B^0 \rightarrow D^- h^+$ decays as flavour specific signal:

![Graph showing Belle II Simulation with MC Truth]
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\[ w \approx 20\% \text{ and } R \]
$B^0 \rightarrow K_S K_S K_S$: time-dependent fit

At Belle, $B^0$ fly $\sim 200 \, \mu m$ and $K_S \sim 1 \, cm$, so:

1. Use only $K_S$ from two pions with hits in the vertex detector;
2. Use constraint that $B^0$ flies along the boost direction.

Time dependent fit returns:

$S = -0.71 \pm 0.23 \, (\text{stat.}) \pm 0.05 \, (\text{syst.})$,

$A = 0.12 \pm 0.16 \, (\text{stat.}) \pm 0.05 \, (\text{syst.})$.

Result compatible with SM expectation and 2.5 $\sigma$ away from “no CPV” hypothesis.

⇒ large room for improvement with this mode and other penguin modes with Belle II in future.
Belle II
Recent results and prospects
Achieving high luminosity at Belle II

Upgraded collider SuperKEKB provide very high luminosity to Belle II using so-called nano-beam scheme.

Final Belle II goal wrt Belle:

▶ 30× peak luminosity 
   \(6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}\);

▶ 50× integrated luminosity 
   \(50 \text{ ab}^{-1}\).

So far achieved:

▶ Peak luminosity:
   \(3.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\), world record!

▶ Integrated luminosity recorded between February 2019 and November 2021:
   \(220 \text{ fb}^{-1}\) (\(\sim 30\%\) of Belle)

Higher luminosity means higher beam background \(\Rightarrow\) Sub-detectors were upgraded from Belle to cope with that (some more detail later in the talk)
Boost and $\Delta t$ precision

New beam scheme means Belle II has a reduced boost wrt Belle:

$$\beta\gamma = 0.43 \rightarrow \beta\gamma = 0.29$$

⇒ added a two-layer pixel detector directly around the beam pipe (radius $\approx 1.4$ cm) to recover precision on $\Delta t$.

Pixels (and not strips) used because of high bkg close to beam.

Second layer partially installed. One layer is currently enough as the machine needs time to ramp up to the nominal luminosity.

Simulation studies show the precision on $\Delta t$ should be comparable to that of Belle:
Time-dependent mixing result

Using 34.6 fb\(^{-1}\) Belle II performed mixing frequency measurement using \(B^0 \rightarrow D^-\pi^+\).

\[ \Delta m_d = (0.531 \pm 0.046 \text{ (stat.)} \pm 0.013 \text{ (syst.)}) \text{ ps}^{-1} \]

Compatible with PDG: \(\Delta m_d = (0.5065 \pm 0.0019) \text{ ps}^{-1}\).
Time-dependent CP-violation result

Using the same data, Belle II performed the first Time-Dependent analysis using $B^0 \rightarrow J/\psi K_S$.

\[
\sin(2\phi_1) = 0.55 \pm 0.21 \text{ (stat.)} \pm 0.04 \text{ (syst.)}
\]

Good early demonstration that Belle II can perform TD analyses.
Belle II data taken so far

It’s just the beginning!

Not yet enough data to be competitive with Belle with $\phi_1$-related measurement, but getting ready for precision measurements.

Outline of the rest of the talk:

- Flavour tagger performance;
- $D$ lifetime measurement;
- $B^0 \rightarrow J/\psi K_L$ reconstruction;
- $B^0 \rightarrow \eta' K_S$ branching fraction.
Flavour tagger performance
Flavour tagger performance characterised by

- wrong tag fraction \( w \);
- effective efficiency \( \varepsilon_{\text{eff}} = \varepsilon_{\text{tag}} \cdot (1 - 2w)^2 \).

\( w \) is measured with 2019 data, time-integrated:

- Reconstruct signal in flavour specific \( B^0 \rightarrow D^{(*)} h^+ \) final states;
- Measure asymmetry between mixed/unmixed events:

\[
\frac{N(\bar{B}B) - N(B\bar{B}, \bar{B}B)}{N(\bar{B}B) + N(B\bar{B}, \bar{B}B)} = (1 - 2w)(1 - 2\chi_d)
\]

(\( \chi_d \) mixing prob from PDG)

Find \( \varepsilon_{\text{eff}} \) compatible with Belle:

Belle: \( \varepsilon_{\text{eff}} = (30.1 \pm 0.4)\% \),

Belle II: \( \varepsilon_{\text{eff}} = (30.0 \pm 1.3)\% \)

Algorithm being improved at the moment.
**$D$ lifetime: beam spot constraint**

Measurement of $D^0$ and $D^+$ lifetimes performed with 72 fb$^{-1}$ data. Not $B$ physics, but high precision test of Belle II capabilities to perform time-dependent measurements.

$D$ decay time computed from distance between beam spot and $D$ decay vertex:

\[
D^* ightarrow \pi^+ D^0 \
K^- ightarrow \pi^+ D^0
\]

Compute $D$ decay time from its momentum $\vec{p}$ and flight vector $\vec{d}$:

\[
t = \frac{m_D}{p} \left( \vec{d} \cdot \hat{p} \right)
\]
Result is the most precise measurement of $D^0$ and $D^+$ lifetimes:

$$\tau(D^0) = 410.5 \pm 1.1 \text{ (stat.)} \pm 0.8 \text{ (syst.)} \text{ fs},$$
$$\tau(D^+) = 1030.4 \pm 4.7 \text{ (stat.)} \pm 3.1 \text{ (syst.)} \text{ fs}.$$ 

This precise result gives confidence about Belle II performance in:

1. Vertex detector and tracking;
2. Beam spot size measurement (using $ee \rightarrow \mu\mu$ events);
3. Detector alignment.
$K_L$ detection and $B^0 \rightarrow J/\psi K_L$

Measuring $\sin(2\phi_1)$ not only with $B^0 \rightarrow J/\psi K_S$ but also $B^0 \rightarrow J/\psi K_L$ has two advantages:

1. Boost statistics: double the number of signal events (albeit with less good purity)
2. Will help for systematics: $B^0 \rightarrow J/\psi K_S$ is CP-odd and $B^0 \rightarrow J/\psi K_L$ is CP-even. This can help reduce systematic related to the CP violation on the tag side.

At Belle and Belle II, use KLM detector to detect $K_L$, i.e. alternance of iron plates and flat detectors.

At Belle, detectors were gas based (RPCs).
At Belle II, RPCs would not be able to withstand high flux of neutrons from the beam.
⇒ In the inner layers of the barrel and in the endcaps, RPCs replaced by scintillators.

⇒ important to test Belle II capabilities to reconstruct $K_L$s.
Compute $B^0 \to J/\psi K_L$ candidates’ energy using known beam energy and position of the $K_L$ cluster in the KLM.

In 62.8 fb$^{-1}$ of Belle II data, find:

\[ N(B^0 \to J/\psi(\mu\mu)K_L) = 267 \pm 21 \text{ (stat.)} \pm 28 \text{ (peaking bkg)}, \]
\[ N(B^0 \to J/\psi(ee)K_L) = 226 \pm 20 \text{ (stat.)} \pm 31 \text{ (peaking bkg)}. \]

Yields and purities comparable to Belle.

Work ongoing to:

- Boost statistics including neutral clusters from the calo;
- Include this mode to the TD measurement of $\sin 2\phi_1$.  

![Graph showing $B^0 \to J/\psi K_L$ reconstruction](image)
$B^0 \to \eta' K_S$: aim and selection

$B^0 \to \eta' K_S$ is penguin-dominated and sensitive to NP. Neutrals in final state make it challenging at the LHC.

⇒ TD analysis with this mode is a high priority at Belle II.

So far, measured branching fraction with 62.8 fb$^{-1}$ of data.

Reconstruct $\eta' \to \eta(\gamma\gamma)\pi^+\pi^-$ and $\eta' \to \rho^0\gamma$.

Train a BDT based on event shape variables to suppress continuum background.

⇒ BDT validated using off-resonance data

⇒ Remaining data/MC differences accounted for as systematic uncertainties.
The signal yield per fb$^{-1}$ is larger than a previous Belle analysis (PRL97-061802(2006)), thanks to improved continuum suppression.

PID and tracking efficiencies are extracted using control modes.

Branching fraction result:

$$\mathcal{B}(B^0 \to \eta' K^0) = (63.4 \pm 3.4 \text{ (stat.)} \pm 3.2 \text{ (syst.)}) \times 10^{-6}$$

Dominant systematics come from the peaking background and BDT calibration.

Next step: time-dependent CPV analysis!
Conclusion and outlook

With its 711 fb$^{-1}$ dataset, Belle has had a very rich program related to mixing-induced CPV,

- Recent result: time-dependent CP violation analysis with $B^0 \rightarrow K_S K_S K_S$.

After collecting 220 fb$^{-1}$ of data, Belle II has shown:

- Ability to perform complete time-dependent CPV analyses;
- Good vertex resolution and ability to measure $D$ lifetime;
- Good flavour tagging performance;
- Good performance with neutrals and re-discovery of penguin modes.

Plan for the direct future at Belle II:

- Measurement of $B^0$ lifetime and mixing frequency;
  ⇒ already statistically limited, so good check of time-dependent machinery;
- Time-dependent analyses with penguin and charmless modes;
- Measurement of $\sin 2\phi_1$ with $B \rightarrow J/\psi K_S$ and related modes.