$B$-lifetime and time-dependent $CP$-violation measurement at Belle II

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

Beauty 2020, Tokyo IPMU

22\textsuperscript{nd} September, 2020
Status of $\sin 2\phi_1$ measurements

In the SM, CP violation arises via non-zero phase in CKM matrix...
... or equivalently: CKM triangle has non-zero area;
Over-constraining the CKM triangle by measuring its sides and angles provides a stringent precision test of the Standard Model.

Today: focus on Belle II’s preparation for precision measurement of $\sin 2\phi_1$

▶ World average: $\sin 2\phi_1 = 0.699 \pm 0.017$ (HFLAV2019)
▶ Result using full Belle dataset: $\sin 2\phi_1 = 0.667 \pm 0.023 \pm 0.012$ (PRL108(2012)171802)
▶ Final aim at Belle II: reduce uncertainty by factor $\sim 5$ to reach $\sim 0.5\%$ precision.
CP violation in interference between mixing and decay

CKM parameter $\phi_1$ is accessible using $B^0$ decays to CP-eigenstates such as $J/\psi K^0_S$:

\[
\begin{array}{c}
B^0 \\
\downarrow^{2\phi_1} \\
\bar{B}^0
\end{array} \quad \xrightarrow{\text{CP}} \quad \begin{array}{c}
J/\psi K^0_S
\end{array}
\]

Measure asymmetry between number of $B^0 \to J/\psi K^0_S$ and $\bar{B}^0 \to J/\psi K^0_S$ decays as a function of the $B^0$ decay time.

\[
A_{CP}(t) = \frac{\mathcal{B}(\bar{B}^0 \to J/\psi K^0_S)(t) - \mathcal{B}(B^0 \to J/\psi K^0_S)(t)}{\mathcal{B}(\bar{B}^0 \to J/\psi K^0_S)(t) + \mathcal{B}(B^0 \to J/\psi K^0_S)(t)} = \sin(2\phi_1) \sin(\Delta m_D t)
\]
Three main ingredients are necessary for precise $\phi_1$ measurement in a $B$ factory environment:

1. Large dataset, $\mathcal{B}(B^0 \rightarrow J/\psi(\ell^+\ell^-)K^0_S(\pi^+\pi^-)) \approx 3.6 \times 10^{-5}$;
2. Precise decay-time difference $\Delta t$ measurement;
Time dependent CP violation at the $B$ factories

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Achieving high luminosity at Belle II

Belle II will achieve a very high luminosity using so-called nano-beam scheme.

Final Belle II goal wrt Belle:
- $40 \times$ peak luminosity ($6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$);
- $50 \times$ integrated luminosity ($50 \text{ ab}^{-1}$).

So far achieved:
- Peak luminosity:
  $2.4 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, world record!
- Integrated luminosity for physics data recorded between February 2019 and July 2020:
  $74.1 \text{ fb}^{-1}$ ($\sim 1/10$ of Belle)
Boost and $\Delta t$ precision

Belle II has a reduced boost compared to Belle:

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

⇒ added a two-layer pixel detector directly around the beam pipe (radius ≈ 1.8 cm) to recover precision on $\Delta t$.

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:
Lifetime measurement

$B^0$ lifetime measured using 2019 data ($8.7 \text{ fb}^{-1}$).

Important test of Belle II time measurement capabilities with real data.

- Use hadronic $B^0$ decays:
  
  $B^0 \rightarrow D^{(*)-}\pi^+$ and $B^0 \rightarrow D^{(*)-}\rho^+$;

- Select events based on PID, kinematic and event shape variables;

- Perform kinematic fit to extract signal fraction; shown here: fit to $M_{bc} = \sqrt{E_{\text{beam}}^2 - p_B^2}$

- Perform fit to the $\Delta t$ distribution to extract lifetime;

Result:

$$\tau_{B^0} = 1.48 \pm 0.28 \pm 0.06 \text{ ps}$$
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 $B^0 \to D^*(\pm) h^+$ final states;
- Measure asymmetry between mixed/unmixed events:

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

($\chi_d$ mixing prob from PDG)

Find $\varepsilon_{\text{eff}}$ compatible with Belle:

Belle: $\varepsilon_{\text{eff}} = (30.1 \pm 0.4)\%$,  
Belle II: $\varepsilon_{\text{eff}} = (33.8 \pm 3.9)\%$
Belle II first time-dependent CPV measurement

Using 8.7 fb$^{-1}$ of data, could show that Belle II performs well in measuring decay time and in flavour tagging.

⇒ use 34.6 fb$^{-1}$ to perform first time-dependent CPV measurement.

Use signal $B^0 \rightarrow J/\psi K_S$ with $J/\psi \rightarrow \mu^+\mu^-$, $e^+e^-$ to measure

$$a_{CP}(\Delta t) = \frac{N(B^0_{tag}) - N(\bar{B}^0_{tag})}{N(B^0_{tag}) + N(\bar{B}^0_{tag})}(\Delta t) = \sin(2\phi_1)\sin(\Delta m_d \Delta t)(1 - 2w) \ast R(\Delta t),$$

where $a_{CP}$ is the raw asymmetry and $R$ the $\Delta t$ resolution function.

$w$ is extracted by performing a time-dependent measurement of the mixing probability using $B^0 \rightarrow D^- \pi^+$ as flavour specific signal:

$$p_{mix}(\Delta t) = \frac{N(B\bar{B}) - N(BB, \bar{B}\bar{B})}{N(B\bar{B}) + N(BB, \bar{B}\bar{B})}(\Delta t) = \cos(\Delta m_d \Delta t)(1 - 2w) \ast R(\Delta t)$$
Time-dependent mixing result

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

Compatible with PDG: \( \Delta m_d = (0.5065 \pm 0.0019) \text{ ps}^{-1} \).
\[ \sin(2\phi_1) = 0.55 \pm 0.21 \text{ (stat.)} \pm 0.04 \text{ (syst.)} \]

Belle II already able to see first 2.7 \( \sigma \) hint for time-dependent CPV!
Towards precision measurements

The Belle II measurements presented so far show that the detector performs well and as expected.
⇒ next step is to get ready for precision measurements!

This involves:

- Refining description of the $\Delta t$ resolution. So far simple 1D model is used, a more complex parametric model can be used to reduce detector-related systematics;
- Adding other modes, i.e. $\psi(2S)K_S$, $J/\psi K_L$, $J/\psi K^*(K_S\pi^0)$, etc;
- Improving vertex resolution;
- ...

![Graph of $\Delta t - \Delta t_{MC}$ with candidates and Belle II 2019, simulation data]

$\int L dt = 100 \text{ fb}^{-1}$
**Beam spot constraint**

Time-dependent measurements can benefit from the small beamspot.

- Measure beam spot size and position using $ee \rightarrow \mu\mu$ events;
- Use momentum conservation to constrain $B^0_{\text{tag}}$ vertex.

![Diagram](image)

Will be utilised in future analyses to improve $\Delta t$ resolution.
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Charmless modes

Analyses of charmless $B^0$ decays interesting:
small branching-fraction $\Rightarrow$ potentially sensitive to NP
Look for differences wrt $J/\psi K_S$ mode in TDCPV analysis.

Full analyses require more data, but some work started:

$B^0 \rightarrow \eta' K_S$:
- Rediscovery of the $\eta' \rightarrow \eta(\gamma\gamma)\pi^+\pi^-$ decay.

$B^0 \rightarrow \phi(K^+K^-)K(\ast)\bar{K}(\ast)$:
- Used multivariate selection to rediscover this mode;
- Fitted $K^+K^-$ helicity angle to isolate $\phi$ (P-wave);
  necessary for time dependent study as P- and S-wave have difference CP eigenvalues.
  (See Yun-Tsung Lai’s talk for more detail)
Conclusions and outlook

Using up to 34.6 fb\(^{-1}\) of data (out of 74.1 fb\(^{-1}\) recorded), Belle II has shown:
- Good vertex resolution and ability to measure \(B\) lifetime;
- Good flavour tagging performance;
- Ability to perform complete time-dependent CPV analyses.

We are now accumulating more data and improving our analysis techniques to:
- Perform precision measurements of the flavour parameters;
- Analyse rare modes sensitive to New Physics.

So far Belle II performs nominally in all aspects of TDCPV analyses. Getting ready for the ultimate precision!