CP violation measurements at Belle II

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Conference on Flavor Physics and CP Violation
**CP violation for neutral B-mesons**

The CP symmetric system in time $t_2$ is not CP symmetric at time $t_1$.

\[ A(\Delta t) = \frac{P_{\bar{B}_0 \to B_{CP}}(\Delta t) - P_{B_0 \to B_{CP}}(\Delta t)}{P_{\bar{B}_0 \to B_{CP}}(\Delta t) + P_{B_0 \to B_{CP}}(\Delta t)} = A \cos \Delta m \Delta t + S \sin \Delta m \Delta t \]

- **Direct CPV**
- **Mixing-induced CPV**
Sin $2\beta$ and the Unitarity Triangle

- Constructed from CKM matrix
  \[ V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \]
- Angles and sides are well-defined (physical) quantities

Hints for BSM physics
- Do the angles sum to 180°?
- Are sides consistent with angles?
- Do all processes indicate a consistent picture?

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Belle II with full lumi can achieve 0.5% precision for sin $2\beta$
Trick of asymmetric beams

- $\Upsilon(4S)$ is a first $b\bar{b}$ resonance above $m_B + m_{\bar{B}}$ → Bs nearly in rest in $\Upsilon(4S)$ frame

$\Upsilon(4S) = \frac{1}{\sqrt{2}} (B^0 \bar{B}^0 - \bar{B}^0 B^0)$

Entangled system like in EPR exp.

<table>
<thead>
<tr>
<th></th>
<th>$e^-$ energy [GeV]</th>
<th>$e^+$ energy [GeV]</th>
<th>Lumi</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar</td>
<td>9.0</td>
<td>3.1</td>
<td>477 fb$^{-1}$</td>
</tr>
<tr>
<td>Belle</td>
<td>8.0</td>
<td>3.5</td>
<td>866 fb$^{-1}$</td>
</tr>
<tr>
<td>Belle II</td>
<td>7.0</td>
<td>4.0</td>
<td>50,000 fb$^{-1}$ (50 ab$^{-1}$)</td>
</tr>
</tbody>
</table>

Belle II: $\Delta z \approx 130 \mu$m
Belle: $\Delta z \approx 200 \mu$m
The $\Delta t$ Measurement

- At Belle II there is smaller boost, but better vertex resolution than at Belle
- We continuously measure the probability density for:
  - $\Upsilon(4S)$ velocity (boost vector)
  - $\Upsilon(4S)$ energy (CM energy)
  - $\Upsilon(4S)$ vertex position (beam spot)

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

$$\Delta t = \frac{(\vec{v}_{CP} - \vec{v}_{tag}) \cdot \vec{n}_{boost}}{\gamma^*\gamma\beta c}$$

- Depends on collision energy
- Boost vector magnitude
- Boost vector direction
- Difference of vertex positions

$\tau(B^0) \approx 1.5$ ps
Tracker Alignment

- **Alignment** is a data driven method to determine positions of sensors/wires of the Tracker
  - Crucial for precise TD-CPV measurements
- Recently all the 14336 wires has been included into the alignment
  - 60,000 parameters
    (for Pixel Detector, Strip Detector & Central Drift Chamber)

Hadronic events  Di-muon events  Cosmic events

See slides from CHEP2021
Beam spot constraint

- At Belle II the much higher peak luminosity is achieved by so-called nano-beam scheme
- The small beam size can be used to better constraint the kinematics of the event (e.g. improving $B_{\text{tag}}$ vertex precision and consequently $\Delta t$ resolution)

$$\sigma_{Y'} = 0.2\mu m, \sigma_{X'} = 10\mu m, \sigma_{Z'} = 240\mu m$$

Beam spot calibration

- Based on $\mu\mu$ events with high-stat
- Calibrated every ~30min
- All parameters of the 3D Gaussian PDF measured (3 sizes + 3 angles)
Flavor tagging

- Determination of the $B_{\text{tag}}$ flavor using all the particles not belonging to signal $B$
- The $|q_r|$ is split into 7 bins to test the performance in hadronic $B$ decays data
- The efficiency evaluated from $B\bar{B}/B\bar{B}$ asymmetries in all $|q_r|$ bins

$$\varepsilon_{\text{eff}} = \sum_{i \in |q_r| \text{ bins}} \varepsilon_i (1 - 2w_i)^2$$

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

$$\varepsilon_{\text{eff, Belle II}} = (33.8 \pm 3.9)\%$$

It is $\bar{B}$

We don’t know

It is $B$

Dilution factor: $r_{\text{FBDT}} \approx 1 - 2w$

Flavor tag: $q = \pm 1$
Mixing measurement: $B^0 \rightarrow D^- \pi^+$

- Measurement dominated by sys. unc. at Belle already with 140 fb$^{-1}$
  - Mixing measurement in hadronic B decays probes the TD analysis framework
- Both B mesons in the flavor eigenstate, one fully reconstructed

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

Beam-constrained invariant mass

Results consistent with PDG, soon competitive with Belle/BaBar

PDG value: $0.507 \pm 0.002 \text{ ps}^{-1}$
CPV measurement: $B^0 \rightarrow J/\psi K_s$

- Performed on 35 fb$^{-1}$ of data
- Both $J/\psi \rightarrow \mu\mu$ and $J/\psi \rightarrow ee$ analyzed

$$S_f = \sin 2\beta = 0.55 \pm 0.21\text{(stat.)} \pm 0.04\text{(sys.)}$$

PDG value:
$$0.670 \pm 0.029\text{(stat.)} \pm 0.013\text{(sys.)}$$

First CPV measurement consistent with PDG, more data needed
Penguin-dominated processes

\[ B^0 \to J/\psi K_S \]
\[ (\sin 2\beta)_{\text{PDG}} = 0.70 \pm 0.02 \]

\[ B^0 \to (\phi, \eta') K_S \]
\[ (\sin 2\beta)_{\text{PDG}} = 0.68 \pm 0.08 \]

Tree channels & loop processes should give consistent $\beta$

→ New particle in loop can shift the SM phase
Time-integrated $B^0 \to \eta' K_s$ and $B^0 \to \phi K_s$

- Belle II performed the time-integrated analyses of the $b \to s$ penguin decay channels → work on the time-dependent CPV analyses

arXiv: 2104.06224

\[
\begin{align*}
B^0 &\to (\eta' \to \eta \pi^+ \pi^-) K^0_s \quad \text{BR} \quad (65 \pm 8 \pm 7) \times 10^{-6} \\
B^0 &\to (\eta' \to \rho \gamma) K^0_s \quad \text{BR} \quad (67 \pm 9 \pm 8) \times 10^{-6}
\end{align*}
\]

PDG value: $(66 \pm 4) \times 10^{-6}$

\[
\text{BR}(B^0 \to \phi K^0_s) = (5.9 \pm 1.8 \pm 0.7) \times 10^{-6}
\]

PDG value: $(7.3 \pm 0.7) \times 10^{-6}$

Observed branching fractions compatible with the world average
Conclusions

• The analysis of 35 fb\(^{-1}\) of Belle II data shows better vertex resolution & comparable flavor tagging performance to Belle
  → First CPV analysis in the \(B^0\) decays

• First time-integrated analysis of the rare penguin \(B^0 \rightarrow (\eta', \phi) K_s\) performed
  → first step towards CPV measurement in the \(b \rightarrow s\) decays

• With increasing data statistics the systematic unc. more and more matter
  → Detector alignment
  → Beam Spot
  → Flavor tagging

https://confluence.desy.de/display/BI/Belle+II+Luminosity
Belle2 & SuperKEKB

- The target luminosity $6 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ (50 ab$^{-1}$ in total) (continuous injection allows long runs)

Crucial for $\Delta t$ measurement