Measurement of the CKM angle $\phi_3$ at Belle II

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Outline of the talk

- Introduction
  - CKM matrix
  - Current experimental status of parameters
- CKM angle $\phi_3/\gamma$
  - Estimation
  - Different methods
  - World average values
- Status of Belle II experiment
- $\phi_3$ sensitivity at Belle II
- Summary
The CKM matrix is of the form

\[
\begin{pmatrix}
  d & s & b \\
  u & & \\
  c & & \\
  t & &
\end{pmatrix}
\]

Unitarity conditions between 1\textsuperscript{st} and 3\textsuperscript{rd} columns

\[ (\rho, \eta) \]

\[
\begin{align*}
  V_{ud}V_{ub}^* & = V_{cd}V_{cb}^* \\
  V_{td}V_{tb}^* & = V_{cd}V_{cb}^*
\end{align*}
\]

\[ (0, 0) \quad (1, 0) \]

\[ \phi_3, \gamma, \beta, \phi_1, \alpha \]

\textit{CP} violation is measured as the complex phase coming in CKM elements $V_{ub}$ and $V_{td}$.

A precise measurement required to establish SM description of \textit{CP} violation.
Current best results for CKM angles [1,2]

- $\phi_1^{\text{measured}} = (21.9^{+0.7}_{-0.7})^\circ$
- $\phi_3^{\text{measured}} = (73.5^{+4.2}_{-5.1})^\circ$
- $\phi_3^{\text{predicted}} = (65.3^{+1.0}_{-1.7})^\circ$

Constraints on CKM parameters [1].

Constraints from tree quantities.

Constraints from loop quantities.

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Determine $\phi_3$ via interference between $B^- \to D^0 K^-$ and $B^- \to \bar{D}^0 K^-$, tree-level diagrams $\Rightarrow 10^{-7}$ theoretical uncertainty $[3]$. 

\[ B^- \to D^0 K^- \approx V_{cb} V_{us}^* A_1 \]

\[ B^- \to \bar{D}^0 K^- \approx V_{ub} V_{cs}^* A_1 r_B e^{i(\delta_B - \phi_3)} \]

Statistically limited due to small branching fractions of decays involved.

The statistical uncertainty on $\phi_3 \propto r_B$.

$r_{DK}^B \approx 0.1$ and $r_{D\pi}^B \approx 0.005$; So $B \to D\pi$ decays are not sensitive!

But they serve as excellent calibration modes due to similar topology as of $B \to DK$. Larger sample $\left( \frac{B(B \to D\pi)}{B(B \to DK)} \approx 10 \right)$ due to Cabibbo-favoured nature.

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$^3$ J. Brod, J. Zupan, JHEP 01, 051 (2014)
The methods differ according to the $D$ final state considered.

**GLW** [PLB 253, 483 (1991), PLB 265, 172 (1991)]
- $CP$ eigenstates like $K^+K^-$, $\pi^+\pi^-$, $K^0\pi^0$ etc.
- $CP$-content as external input for multibody decays like $\pi^+\pi^-\pi^0$.

**ADS** [PRL 78, 3357 (1997)]
- DCS modes
  - $K^+\pi^-, K^+\pi^-\pi^0, K^+\pi^-\pi^+\pi^-$
- $\delta_D$, $r_D$ - charm inputs.

**GGSZ** [PRD 68, 054018 (2003)]
- Multibody self-conjugate states
- Model-dependent and independent approaches
Model-independent method

- Model-independent method by binning the Dalitz plot of multibody $D$ final states like $K_S^0\pi^+\pi^-$, $K_S^0K^+K^-$, $K_S^0\pi^+\pi^-\pi^0$.

- For the decay $B^- \rightarrow D(K_S^0h^+h^-)K^-$,
  \[ \Gamma_i^- = K_i + r_B^2 \bar{K}_i + 2 \sqrt{K_i\bar{K}_i}(c_i x^- + s_i y^-), \]
  and similarly for the $B^+$ decay.

- Dalitz plot binning for $K_S^0\pi^+\pi^-$.
  \[ \text{PRD82, 112006(2010)} \]

- $x_\pm = r_B \cos(\delta_B \pm \phi_3)$; $y_\pm = r_B \sin(\delta_B \pm \phi_3)$.

- $c_i$, $s_i$ - cos and sin of the strong phase difference between $D^0$ and $\bar{D}^0$ averaged over the region of phase space $\Rightarrow$ input from CLEO-c or BESIII.

- $K_i$, $\bar{K}_i$ - fraction of flavour-tagged $D^0$ and $\bar{D}^0$ events from $D^{*\pm} \rightarrow D\pi^{\pm}$ decays.

$B^+$ and $B^-$ yields for $D$ final state $K_S^0\pi^+\pi^-$ at Belle.
  \[ \text{PRD85, 112014(2012)} \]
\( \phi_3: \) Average values

- From all measurements of \( B \to D(*)K(*) \) from GLW, ADS, and GGSZ.

**Belle + BaBar + LHCb run I**

\[
\begin{align*}
(\phi_3)_{\text{Belle}} &= (73^{+13}_{-15})^\circ [4] \\
(\phi_3)_{\text{BaBar}} &= (69^{+17}_{-16})^\circ [5] \\
(\phi_3)_{\text{LHCb}} &= (74.0^{+5.0}_{-5.8})^\circ [6]
\end{align*}
\]

- Dominated by LHCb result and GGSZ method.

\[
(\phi_3)_{\text{Combined}} = (73.5^{+4.2}_{-5.1})^\circ
\]

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4 PRD 85, 112014 (2012)
5 PRD 87, 052015 (2013)
6 LHCb-CONF-2018-002

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Center-of-mass energy at Υ(4S) resonance which decays to $B\bar{B}$ pair.

**Important improvements for $\phi_3$**

- Improved $K_S^0$ reconstruction efficiency
- Better $K/\pi$ separation
Status of Belle II

- **Phase II** ⇒ 25 April to 17 July 2018.
  - Without full vertex detectors.
  - Accumulated $\approx 0.5 \text{ fb}^{-1}$ data.

- **Phase III** ⇒ First collisions on 25 March 2019.

The ultimate goal is

- $\mathcal{L}_{\text{int}} = 50 \text{ ab}^{-1}$ (50 × Belle)
- $\mathcal{L}_{\text{peak}} = 8 \times 10^{35} \text{ cm}^{-1} \text{s}^{-1}$ (40 × KEKB)

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Results from phase II

- $D^{*\pm} \rightarrow D(K_S^0 \pi^0)\pi^\pm_{slow}$ decays: $CP$-odd eigenstate

- $D^{*\pm} \rightarrow D(K^+K^-)\pi^\pm_{slow}$ decays: $CP$-even eigenstate

- Belle II is capable of reconstructing a variety of final states including neutrals.
Results from phase II

- $D^{*\pm} \to D(K_S^0 \pi^+ \pi^-)\pi^{\pm}_{\text{slow}}$ decays

- $D^{*\pm} \to D(K_S^0 \pi^+ \pi^- \pi^0)\pi^{\pm}_{\text{slow}}$ decays

- Multibody self-conjugate final states, important for $\phi_3$ estimation.
- About 245 $B$ candidates reconstructed from hadronic final states.

- $B \rightarrow D \pi$ decays are good calibration modes for $\phi_3$ estimation from $B \rightarrow DK$ decays.
$\phi_3$ sensitivity at Belle II

- $B^\pm \to D(K_S^0\pi^+\pi^-)K^\pm$: golden mode at Belle II.
- $\delta(\phi_3)^{50 \text{ ab}^{-1}} = 3.0^\circ$ (with 10 fb$^{-1}$ BESIII data)
- $B^\pm \to D(K_S^0\pi^+\pi^-\pi^0)K^\pm$: another promising mode.
- $\delta(\phi_3)^{50 \text{ ab}^{-1}} = 4.4^\circ$[7] (Assuming $\epsilon \times BF$ similar to $K_S^0\pi^+\pi^-$).

- The GLW modes from $B \to D(\ast)K$ also has significant impact on the projected uncertainty.

- Better PID, $K_S^0$ selection, continuum suppression would bring further improvements.

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7 JHEP 01, 82 (2018)
• Current precision on average value of $\phi_3$ is $\approx 5^\circ$.

• Precise measurement is crucial for establishing SM picture of $CP$ violation.

• A combined sensitivity of $1.6^\circ$ is expected with
  - full 50 ab$^{-1}$ data,
  - additional $D(\ast)$ modes.

• Measurements of $D$ hadronic parameters from 10 fb$^{-1}$ BESIII data is crucial.

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