Precision measurements of the CKM parameters (Mainly $\gamma/\phi_3$ measurements)

Prasanth Krishnan
(On behalf of Belle II Collaboration)

TIFR

July 17, 2018

16th FPCP, Hyderabad
Outline of the talk

▶ Status of CKM parameters

▶ CKM angle $\gamma/\phi_3$
  ▶ Methods
  ▶ Constraints

▶ Belle II experiment

▶ $\phi_3$ from Belle II

▶ Summary

\[
\frac{\gamma}{\phi_3} \equiv \arg \left( -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right)
\]
Current experimental limit on CKM parameters

Figure: Current status of the CKM parameters\cite{1}.

- \( \phi_3 = (73.5^{+4.2}_{-5.1})^\circ \) \( [\phi_1 = (21.9 \pm 0.7)^\circ] \) \cite{2}
- \( \delta(\phi_3)/\phi_3 = \mathcal{O}(10^{-7}) \) \cite{3}

\cite{1}ckmfitter.in2p3.fr/www/html/ckm_results.html
\cite{2}www.slac.stanford.edu/xorg/hflav/triangle/moriond2018/index.shtml
\cite{3}J. Brod, J. Zupan, arxiv:1308.5663
Extraction of CKM angle $\phi_3$

- Via the interference between $B^- \to D^0 K^-$ and $B^- \to \bar{D}^0 K^-$

\[
A \sim A \lambda^3
\]

\[
r_B = \frac{|A_{\text{suppressed}}|}{|A_{\text{favored}}|} \sim 0.1 \quad \text{for } B^{\pm} \to DK^{\pm} \text{ decays}
\]

- Generally three types of $D$ final states used:
  - $CP$ eigenstates ($GLW^4$): $K^+ K^-, \pi^+ \pi^-, K^0 \pi^0$
  - $K^+ X^-$ ($ADS^5$) DCS: ($X^- = \pi^-, \pi^- \pi^0, \pi^- \pi^- \pi^+$)
  - Self-conjugate multi-body states ($GGSZ^6$): $K^0 h^+ h^-, K^0 \pi^+ \pi^- \pi^0$

---

5. PRD 63, 036005 (2001)
Methods to extract $\phi_3$: GLW and ADS

**GLW method:**

- Both $D^0$ and $\bar{D}^0$ are decaying to same $CP$ eigenstate
- Four observables are

$$R_{CP}^\pm = 2 \frac{\Gamma(B^- \to D_{CP}^\pm K^-) + \Gamma(B^+ \to D_{CP}^\pm K^+)}{\Gamma(B^- \to K^-_{fav} K^-) + \Gamma(B^+ \to K^-_{fav} K^+)}$$

$$A_{CP}^\pm = 2 \frac{\Gamma(B^- \to D_{CP}^\pm) - \Gamma(B^+ \to D_{CP}^\pm K^+)}{\Gamma(B^- \to D_{CP}^\pm) + \Gamma(B^+ \to D_{CP}^\pm K^+)}$$

Then,

$$R_{CP}^\pm = 1 + r_B^2 \pm 2r_B \cos \delta_B \cos \phi_3$$

$$A_{CP}^\pm = \pm 2r_B \sin \delta_B \sin \phi_3 / R_{CP}^\pm$$

- No need of external inputs

**ADS method:**

- $D$ from a favored amplitude decays to a DCS state
- Two observables are

$$R_{ADS} = \frac{\Gamma(B^- \to [K^+ \pi^-]_D K^-) + \Gamma(B^+ \to [K^- \pi^+]_D K^+)}{\Gamma(B^- \to [K^- \pi^+]_D K^-) + \Gamma(B^+ \to [K^+ \pi^-]_D K^+)}$$

$$A_{ADS} = \frac{\Gamma(B^- \to [K^+ \pi^-]_D K^-) - \Gamma(B^+ \to [K^- \pi^+]_D K^+)}{\Gamma(B^- \to [K^- \pi^+]_D K^-) + \Gamma(B^+ \to [K^+ \pi^-]_D K^+)}$$

Then,

$$R_{ADS} = r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D) \cos \phi_3$$

$$A_{ADS} = 2r_B r_D (\sin \delta_B + \phi_3) / R_{ADS}$$

- $r_D$ and $\delta_D$ from charm factories
Methods to extract $\phi_3$: GGSZ

- For self-conjugate multi-body $D$ final states such as $K_S^0\pi^+\pi^-$ \[7\]
- Bin the Dalitz plot symmetrically about $m_2^- = m_2^+$
- Fraction of $D$ events for $K_i$ & $\bar{K}_i$ from $D^{*\pm} \rightarrow D\pi^{\pm}_{\text{slow}}$
- External charm factory inputs needed- avg. cosine ($c_i$) and sine ($s_i$) of the strong phase difference between $D^0$ and $\bar{D}^0$ decay amplitude $i^{th}$ bin
- $e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0$
- Advantage: $r_B$ and $\delta_B$ from single mode

\[7\] PRD 85 (2012) 112014
Constraints on $\gamma/\phi_3$

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

All data from $B$ factories: Belle & BaBar

+ LHCb run I

$\phi_3$ Measurements from Belle, BaBar, and LHCb:

- Belle: $(73^{+13}_{-15})^\circ$
- BaBar: $(69^{+17}_{-16})^\circ$
- LHCb: $(74.0^{+5.0}_{-5.8})^\circ$

Combined: $(73.5^{+4.2}_{-5.1})^\circ$

Figure: Current status of $\phi_3$ [1].

→ Dominated by GGSZ

→ PRD 87 (2013) 052015

→ LHCb-CONF-2018-002
SuperKEKB and Belle II experiment

- Improved $K_S^0$ reconstruction efficiency
- Better $K/\pi$ separation

Prasanth Krishnan (On behalf of Belle II Collaboration)

Precision measurements of the CKM parameters (Mainly $\gamma/\phi_3$ measurements)
Status of phase 2 of Belle II experiment

- First collision on 25 April 2018 & completes on 17 July
- Accumulated $> 0.5 \text{ fb}^{-1}$ data
- Phase 3 kick-off from early 2019
- $\mathcal{L}_{\text{int}} = 50 \text{ ab}^{-1}$ (50 $\times$ Belle)
- $\mathcal{L}_{\text{peak}} = 8 \times 10^{35} \text{ cm}^{-1}\text{s}^{-1}$ (40 $\times$ KEKB)

Prasanth Krishnan (On behalf of Belle II Collaboration)

Precision measurements of the CKM parameters (Mainly $\gamma/\phi_3$ measurements)
$\phi_3$ sensitivity with $B^\pm \rightarrow D(K_S\pi^+\pi^-)K$ decays in Belle II

- Goal to go for precision $\approx 1^\circ$ \cite{8}
- Dominated by $B^\pm \rightarrow D(K_0^0\pi\pi)K^\pm$ mode
  - improvements, even modest, will have large impact on $\phi_3$ sensitivity
- **GLW like states:** Interference of $B^- \rightarrow DK^-$, $D \rightarrow K_0^0\rho$
- **ADS like states:** Interference of $B^- \rightarrow DK^-$, $D \rightarrow K^*\pi$
- **Golden mode to determine $\phi_3$!**
  - $\delta(\phi_3)^{50 \text{ ab}^{-1}} = 3.0^\circ$ by GGSZ (with 10 fb$^{-1}$ BES III data)
  - $\delta(\phi_3)^{50 \text{ ab}^{-1}} = 1.6^\circ$ when Belle GLW + ADS + GGSZ extrapolated

**Further improvements:**
- Additional modes
- Improved $K_S^0$ reconstruction
- $q\bar{q}$ background suppression ($q = u, d, s, c$)

---

8 J. Brod et. al, arXiv:1412.1446; BELLE2-PUB-DRAFT-2016-009
Results from phase 2 data-$K_S^0$ reconstruction

- Already resolutions in MC (left) & data (right) are in good agreement

- Inclusive $D^0 \rightarrow K_S^0\pi^+\pi^-$ decays
Rediscovering the **CP modes** from phase 2

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

- $D^{*\pm} \rightarrow D(K^+K^-)\pi^{\pm}_{\text{slow}}$ decays
Rediscovery of $D^*\pm \rightarrow D(K^0_S \pi^+ \pi^-)\pi^\pm_{\text{slow}}$ & $B$ from phase 2

- Found $\approx 100$ $B \rightarrow D \pi$ candidates, control modes for $B \rightarrow DK$ for $\phi_3$!
Summary

- Current precision on $\phi_3$ is $\approx 5^\circ$
- With 50 ab$^{-1}$ of Belle II data:
  - $B^\pm \rightarrow D(K^0_S \pi^+ \pi^-)K^\pm$: $\phi_3$ sensitivity will improve to $3.0^\circ$
  - $B^\pm \rightarrow D(K^0_S \pi^+ \pi^- \pi^0)K^\pm$: $\phi_3$ sensitivity will improve to $4.4^\circ$ [9]
    (See talk by P.K. Resmi)
- Combined $\phi_3$ sensitivity is $1.6^\circ$

Backup slides
$\phi_3$ sensitivity with $B \to D(K_S^0\pi^+\pi^-\pi^0)K$ decays

- Four-body final state$^9$
- $\epsilon \times B$ similar to $D^0 \to K_S^0\pi^+\pi^-$
- Many interesting resonant substructures such as $K_S^0\omega$, $K^{*\pm}\rho^\mp$

- From 1200 events in Belle, $\delta(\phi_3) = 25^\circ$
- Projection to 50 ab$^{-1}$ Belle II sample $\delta(\phi_3) = 4.4^\circ$

$^9$JHEP, 01 (2018) 82