Measurement of the $\gamma/\phi_3$ CKM Angle with 

**Belle II**

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• Introduction
• Measurements from $B^\pm \rightarrow D(\ast)K(\ast)\pm$
• Current status
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• Summary
Introduction

\[ \gamma = \phi_3 \equiv \arg \left( -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right) \]

- least well measured CKM angle.
- limited by the small branching fractions of the processes used in its measurement.
- can be determined using tree-level processes only.
- theoretically clean.
- provides a Standard Model (SM) benchmark.
γ/φ₃ measurements from $B^\pm \rightarrow D(\*)K(\*)^\pm$

Tree level determination of $\gamma/\phi_3$ angle

$B^- \rightarrow D^0 K^-$

$B^- \rightarrow \bar{D}^0 K^-$

Favored

$A_1$

Suppressed

Sensitivity depending on size of hadronic ratio.

$$r_B = \left| \frac{A_{\text{Suppressed}}}{A_{\text{Favored}}} \right| \sim \left| \frac{V_{ub} V_{cs}^*}{V_{cb} V_{us}^*} \right| \times c_{\text{colorSupp}} \sim 0.1$$

$A_1 r_B e^{i(\delta_B - \gamma)}$

$r_B$ : magnitude of the ratio of amplitudes.

$\delta_B$ : strong phase difference

Different $B$ ($\rightarrow D K$, $D^* K$, $D K^*$) decays have different hadronic factors ($r_B$, $\delta_B$)
Three primary methods for measuring $\gamma/\phi_3$ from $B^\pm \rightarrow D^{(*)} K^{(*)\pm}$

- Reconstruct D in final states accessible to both $D^0 \overline{D}^0$

**GLW Method (Gronau-London-Wyler)**
- Interference with CP eigenstates
  - *final state of $D^0 = CP$ eigenstates as $K^+K^-, \pi^+\pi^- , K_s^0\pi^0$*

**ADS Method (Atwood-Dunietz-Soni)**
- Interference with flavor specific
  - *final state of $D^0 =$ Doubly-Cabbibo-Suppressed (DCS) decays as $K^+\pi^-$*

**GGSZ (Dalitz) Method (Giri-Grossman-Soffer-Zupan)**
- Self conjugate $D$ decays using Dalitz plot
  - *final state of $D^0 =$ Three-body decays as $D \rightarrow K_s^0\pi^+\pi^- , K_s^0 K^+ K^-$*
\[ \gamma / \phi_3 = \left( 73^{+13}_{-15} \right) \circ \]

**B^{-} \rightarrow D^{(*)} K^{(*)-}**

\((D^{*} \rightarrow D \pi^{0}, D \gamma)\)

<table>
<thead>
<tr>
<th>Type of D Final States</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>K^+ K^-, \pi^+ \pi, K_s^0 \pi^0, K_s^0 \eta</td>
<td>GLW</td>
</tr>
<tr>
<td>K \pi, K \pi^+ \pi^0</td>
<td>ADS</td>
</tr>
<tr>
<td>K_s^0 \pi^+ \pi</td>
<td>GGSZ</td>
</tr>
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</table>

\[ \gamma / \phi_3 = \left( 69^{+17}_{-16} \right) \circ \]

**B^{-} \rightarrow D^{(*)} K^{(*)-}**

\((D^{*} \rightarrow D \pi^{0}, D \gamma)\)

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<tr>
<td>K^+ K^-, \pi^+ \pi, K_s^0 \pi^0, K_s^0 \omega</td>
<td>GLW</td>
</tr>
<tr>
<td>K \pi, K \pi^+ \pi^0</td>
<td>ADS</td>
</tr>
<tr>
<td>K_s^0 \pi^+ \pi, K_s^0 K^+K^-</td>
<td>GGSZ</td>
</tr>
</tbody>
</table>
**$\gamma/\phi_3$ Current Status @ LHCb**

**list of LHCb measurements used in combination**

<table>
<thead>
<tr>
<th>$B$ decay</th>
<th>$D$ decay</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow h^+h^-$</td>
<td>GLW <strong>Updated to Run 1 + 2 fb$^{-1}$</strong></td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow h^+\pi^-\pi^+\pi^-$</td>
<td>GLW/ADS</td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow h^+h^-\pi^0$</td>
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</tr>
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<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow K^0_S h^+h^-$</td>
<td>GGSZ</td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow K^0_S K^+\pi^-$</td>
<td>GLS</td>
</tr>
<tr>
<td>$B^+ \rightarrow D^*K^+$</td>
<td>$D \rightarrow h^+h^-$</td>
<td>GLW <strong>New</strong> [LHCb-PAPER-2017-021]</td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^{*+}$</td>
<td>$D \rightarrow h^+h^-$</td>
<td>GLW/ADS <strong>New</strong> [LHCb-CONF-2016-014]</td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^{+\pi-\pi^-}$</td>
<td>$D \rightarrow h^+h^-$</td>
<td>GLW/ADS</td>
</tr>
<tr>
<td>$B^0 \rightarrow DK^{*0}$</td>
<td>$D \rightarrow K^+\pi^-$</td>
<td>ADS</td>
</tr>
<tr>
<td>$B^0 \rightarrow DK^{+\pi-}$</td>
<td>$D \rightarrow h^+h^-$</td>
<td>GLW-Dalitz</td>
</tr>
<tr>
<td>$B^0 \rightarrow DK^{*0}$</td>
<td>$D \rightarrow K^0_S\pi^+\pi^-$</td>
<td>GGSZ</td>
</tr>
<tr>
<td>$B^0_s \rightarrow D^s_\mp K^\pm$</td>
<td>$D^+_s \rightarrow h^+h^-\pi^+$</td>
<td>TD <strong>Updated to 3 fb$^{-1}$ Run 1</strong> [LHCb-PAPER-021]</td>
</tr>
</tbody>
</table>

**TD* Time-dependent**

\[\gamma = (76.8^{+5.1}_{-5.7})^\circ\]

- 30% improvement with respect to the 2016 combination.
New HFLAV $\gamma/\phi_3$ combination

\[ \gamma = (76.2^{+4.7}_{-5.0})^\circ \]

- The world average is now slightly better than 5°.
The Belle II detector

- Full solid angle detector; clean event environment; well defined initial state.
- Increase $K_s^0$ efficiency.
- Improved $K/\pi$ separation.
- Improved reconstruction, selection and tagging algorithms.

**Goal of Belle II/SuperKEKB**

- $L_{int} > 50 \text{ ab}^{-1}$ by 2025 (50 x Belle)
- $L_{peak} = 8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ (40 x KEKB)

More details by Jake Bennett (September 3)
Measurement of $\gamma/\phi_3$ @ Belle II

- Determination of $\gamma/\phi_3 \Rightarrow$ dominated by Dalitz-plot (GGSZ) analysis at Belle.

- $B^\pm \to D \ (\to K_s^0 \pi^+ \pi^-) K^\pm$ → the most sensitive single analysis.

Each point on the Dalitz plot has different $r_D$ and $\delta_D$.

$$r_D = \left| \frac{A(D^0 \to f)}{A(\bar{D}^0 \to f)} \right|$$

$\delta_D$: strong phase difference

**Model-dependent GGSZ method**

- $r_D$ and $\delta_D$ determined via amplitude model.
- Large systematic uncertainty (i.e. 8.9°) due to amplitude model.

**Model-independent GGSZ method**

- Used by Belle II

- Use quantum coherence in $e^+e^- \to \gamma^* \to D\bar{D}$ (CLEO-c, BESIII) to measure amplitude-averaged strong phase differences, $c_i$, $s_i$.

$$c_i = \langle \cos \Delta \delta_D \rangle, \quad s_i = \langle \sin \Delta \delta_D \rangle$$
Model-independent Dalitz plot analysis of $B^\pm \rightarrow D^0(K_s^0\pi^+\pi^-)K^\pm$

- Dalitz plot is divided into symmetrical bins.
- Number of events from $D$ flavor eigenstates, $K_{\pm i}$, measured in $D^{*\pm} \rightarrow D \pi^\pm$.
- $c_i$ and $s_i$, measured at CLEO or BES III.
- Number of events $N_i^\pm$ in a particular bin in a $B^\pm \rightarrow DK^\pm$:

$$N_i^\pm \propto K_{\mp i} + r_i^2 K_{-i} + 2\sqrt{K_i K_{-i}} (x_i c_i \pm y_i s_i)$$

- Fit in $B^\pm \rightarrow DK^\pm$

$$(x_i, y_i) = r_B (\cos(\pm \gamma + \delta_B), \sin(\pm \gamma + \delta_B))$$
**Assuming 10 fb$^{-1}$ $\psi(3770)$ BES III dataset**

we estimate for GGSZ

\[
\delta(\gamma / \phi_3)^{50ab^{-1}} = 3^\circ
\]

once the combination of Belle GLW, ADS, GGSZ results is extrapolated

\[
\delta(\gamma / \phi_3)^{50ab^{-1}} = 1.6^\circ
\]

**future improvements**

- including additional channels such as $K_s^0 K^+ K^-$ and $B^+ \rightarrow D^{*0} K^+$.
- including continuum suppression variable in the fit.
New Decay Mode

- A new model-independent GGSZ measurement in $B^{\pm} \rightarrow D^{0}(K_s^0 \pi^+ \pi^- \pi^0) K^{\pm}$.
  - $D^0 \rightarrow K_s^0 \pi^+ \pi^- \pi^0$ decays from CLEO-c, BES III.
    - Large branching fraction (BF) (5.2 %).
  - Quantum-correlated measurement of $D^0 \rightarrow K_s^0 \pi^+ \pi^- \pi^0$ [arXiv:1703.10317]
    - 818 pb$^{-1}$ CLEO-c data at the $\psi(3770)$ resonance.
    - CP-even fraction $0.246 \pm 0.018$.

The uncertainties shown are statistical only.
A toy simulation study:

- **Assuming**: increase in BF is compensated by loss of efficiency due to $\pi^0$.
- with 1200 events (from Belle sample of $B^\pm \to D (K_s^0 \pi^+ \pi^-) K^{\pm}$) - under investigation
- $\delta(\gamma/\phi_3) = 25^\circ$ ($c_i$, $s_i$, $K_{\pm i}$ values from [arXiv:1703.10317])
- Project to a 50 ab$^{-1}$ Belle II sample.

Single mode uncertainty on $\gamma/\phi_3$

$$\delta(\gamma / \phi_3)_{50ab^{-1}} = 3.5^\circ$$

**Caveat**: background to be studied.
The traditional way: compare $\gamma/\phi_3$ from tree-level decays with the one from penguin-dominated processes.

Recent studies show that NP contributions to tree-level Wilson coefficients $C_1$ and $C_2$ of $\mathcal{O}(40\%)$ and $\mathcal{O}(20\%)$ are not excluded. 


Shifts in $\gamma/\phi_3$ of the order of $\pm 4^\circ$ can not be eliminated [arXiv:1412.1446].

Strong motivation to $1^\circ$ precision.
• $\gamma/\phi_3$ precision is now better than 5°.

• First preliminary sensitivity analysis at Belle II
  
  • $B^\pm \rightarrow D (\rightarrow K_s^0 \pi^+ \pi^-) K^\pm$: at 50 ab$^{-1}$ $\delta(\gamma/\phi_3) = 3^\circ$
  
  • $B^\pm \rightarrow D (\rightarrow K_s^0 \pi^+ \pi^- \pi^0) K^\pm$: at 50 ab$^{-1}$ $\delta(\gamma/\phi_3) = 3.5^\circ$

• Conservatively, combined sensitivity:
  
  $\delta(\gamma / \phi_3)^{50 ab^{-1}} = 1.6^\circ$
EXTRA
• Both $D^0$ or $\bar{D}^0$ decay to the same $CP$ eigenstate.

• The four (only three independent) GLW observables are:

\[
R_{CP^\pm} = 2 \frac{\Gamma(B^- \rightarrow D_{CP^\pm} K^-) + \Gamma(B^+ \rightarrow D_{CP^\pm} K^+)}{\Gamma(B^- \rightarrow D_{fav} K^-) + \Gamma(B^+ \rightarrow D_{fav} K^+)}
\]

\[
A_{CP^\pm} = 2 \frac{\Gamma(B^- \rightarrow D_{CP^\pm} K^-) - \Gamma(B^+ \rightarrow D_{CP^\pm} K^+)}{\Gamma(B^- \rightarrow D_{CP^\pm} K^-) + \Gamma(B^+ \rightarrow D_{CP^\pm} K^+)}
\]

\[
R_{CP^\pm} = 1 + r_B^2 \pm 2 r_B \cos \delta_B \cos \gamma
\]

\[
A_{CP^\pm} = \pm 2 r_B \sin \delta_B \sin \gamma / R_{CP^\pm}
\]

• no need of external inputs.
• Select events where the (anti)$D^0$ from the favored amplitude decays to a DCS final state (and the (anti)$D^0$ from the suppressed amplitude decays to the same Cabibbo favored final state):

\[
B^+ \rightarrow \bar{D}^0 K^+, \quad \bar{D}^0 \rightarrow K^\pi^+
\]
\[
B^- \rightarrow \bar{D}^0 K^-, \quad \bar{D}^0 \rightarrow K^\pi^-
\]

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

\[
= r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D) \cos(\gamma)
\]

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

\[
= 2r_B r_D \sin(\delta_B + \delta_D) \sin(\gamma) / R_{ADS}
\]

Additional variables $r_D$ and $\delta_D$ can be provided by charm factories.
• For self-conjugate multi-body $D$ final states, i.e $K_s^0 \pi^+ \pi^-$
• The amplitude for $B^+ \rightarrow DK^+$, with $m^2_\pm = m^2_{K_s^0 \pi^\pm}$

$$A_{B^+}(m^2_+, m^2_-) = \overline{A}_D + r_B e^{i(\delta_B + \gamma)} A_D$$

$$A_{B^-}(m^2_+, m^2_-) = A_D + r_B e^{i(\delta_B - \gamma)} \overline{A}_D$$

• $A_D(m^2_+, m^2_-)$ is the amplitude of the $D^0 \rightarrow K_s^0 \pi^+ \pi^-$ decay.
• Generic Monte Carlo (MC) corresponding to 2 ab\(^{-1}\) data (no beam background).

• \(D^{\pm} \rightarrow D\pi^{\pm},\ B^{\pm} \rightarrow D\pi^{\pm}\) and \(B^{\pm} \rightarrow DK^{\pm}\) with \(D \rightarrow K_{S}^{0}\pi^{+}\pi^{-}\).

  • \(D^{\pm} \rightarrow D\pi^{\pm}\) to find the flavor Dalitz.

  • \(B^{\pm} \rightarrow D\pi^{\pm}\) control mode and background in the signal \(B^{\pm} \rightarrow DK^{\pm}\).

• \(D^{*}\) fit in \(M(D)\) and \(\Delta M = M(D\pi^{\pm}) - M(D)\)

  • Fit per Dalitz bin to obtain \(K_{i}\) flavor inputs.

• signal and background separation,

• fit in two dimensions (\(\Delta E, M_{bc}\))

\[
\Delta E = E_{B}^{*} - E_{\text{beam}}^{*},\ \ M_{bc} = \sqrt{E_{\text{beam}}^{*2} - p_{B}^{*2}}
\]

• Combine fit to all bins in \(B^{\pm} \rightarrow D(K_{S}^{0}\pi^{+}\pi^{-})K^{\pm}\).
Examples of $D$ final states that have been studied so far:

<table>
<thead>
<tr>
<th>Type of D decay</th>
<th>Method</th>
<th>$D$ Final states</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP - eigenstates</td>
<td>GLW</td>
<td>CP-even: $K^+K^-$, $\pi^+\pi$; CP-odd: $K_s^0\pi^0$, $K_s^0\eta$</td>
</tr>
<tr>
<td>CF and DCS</td>
<td>ADS</td>
<td>$K^\pm\pi^\mp$, $K^\pm\pi^\mp\pi^0$</td>
</tr>
<tr>
<td>Self - conjugate</td>
<td>GGSZ</td>
<td>$K_s^0\pi^+\pi^-$</td>
</tr>
</tbody>
</table>

More modes with neutral particles:

- CP-even: $K_s^0\eta\pi^0$, $K_L^0\pi^0$, $K_s^0\pi^0\pi^0$, $K_s^0K_s^0K_s^0$
- CP-odd: $K_s^0K_s^0K_L^0$, $\eta\pi^0\pi^0$, $\eta'\pi^0\pi^0$, $K_s^0K_s^0\pi^0$, $K_s^0K_s^0\eta$
- Self-conjugate: $K_s^0\pi^+\pi^-\pi^0$, $K_s^0K^+K^-$, $\pi^+\pi^-\pi^0$, $K^+K^-\pi^0$, $\pi^+\pi^-\pi^0\pi^0$, $K_L^0\pi^+\pi^-$, $K_L^0K^+K^-$, $\pi^+\pi^-\pi^0\pi^0$

*ongoing studies by Belle
Determination of $\gamma/\phi_3$ is dominated by GGSZ (Dalitz) method.

$B^\pm \rightarrow D^0 K^\pm$, $D^0 \rightarrow K_s^0 \pi \pi$

**The first model-independent Dalitz analysis**

Model uncertainty is replaced by statistical uncertainty from CLEO-c.

$\gamma/\phi_3 = (77.3^{+15.1}_{-14.9} \pm 4.1 \pm 4.3)^\circ$

**The model-dependent unbinned Dalitz analysis for** $B^\pm \rightarrow D K^\pm$ and $B^\pm \rightarrow D^* K^\pm$

$\gamma/\phi_3 = (78.4^{+10.8}_{-11.6} \pm 3.6 \pm 8.9)^\circ$

- Model uncertainty is expected to be dominant for future experiments.
- More statistics and BES III results will take place CLEO-c.
$B^\pm \to D^{(*)} K^{(*)\pm}$ @ Belle (GLW and ADS)

$B^- \to D^{*0} K^-, D^* \to D^0 \pi^0, D^0 \gamma$

- To be published soon. Full Belle data set: 770 M. BB events.
- involve low energy $\pi^0$ or $\gamma$.

**GLW**
- Combining results for $D^* \to D^0 \pi^0, D^0 \gamma$ yields:

\[
A_{CP^+} = -0.14 \pm 0.10 \pm 0.001 \\
A_{CP^-} = +0.22 \pm 0.11 \pm 0.001
\]

**ADS**

\[
R_{D^*K,D\pi^0} = \left[ 1.0_{-0.7}^{+0.8} (stat)_{-0.2}^{+0.1} (syst) \right] \times 10^{-2}
\]

\[
R_{D^*K,D\gamma} = \left[ 3.6_{-1.2}^{+1.4} (stat) \pm 0.2 (syst) \right] \times 10^{-2}
\]

- $D^* \to D^0 \gamma$ mode $\to 3.5 \sigma$ significance.