BELLE RESULTS FOR $\phi_3 (= \gamma)$ AND PROSPECTS FOR BELLE II BY 2021

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Methods for measuring $\phi_3$

- Best theoretically clean way of measuring $\phi_3$ is based on **interference** between $b \rightarrow \bar{u}cs$ and $b \rightarrow u\bar{c}s$ tree level amplitudes
- E.g., $B^\pm \rightarrow D(*)K^\pm$ followed by $D \rightarrow f$ and $B^\pm \rightarrow \bar{D}(*K)^\pm$ followed by $\bar{D} \rightarrow f$, where $f$ is a **common final state**

No penguin contribution $\Rightarrow$ theoretically clean
- The only CP-violating parameter that can be measured solely in tree-level processes
- $\phi_3$ precision is limited by small branching ratios
GLW Method [8, 9]

- $D$ meson is reconstructed from **CP-even** ($D_{CP^+}$) or **CP-odd** ($D_{CP^-}$) final states
- $B$ can decay weakly to either $D^0$ or $\bar{D}^0$, but when reconstructing a CP eigenstate, actually selecting superposition $(D^0 \pm \bar{D}^0)/\sqrt{2}$

$$R_{CP^\pm} = 2 \frac{\Gamma(B^- \rightarrow D_{CP^\pm} K^-) + \Gamma(B^+ \rightarrow D_{CP^\pm} K^+)}{\Gamma(B^- \rightarrow D_{fav} K^-) + \Gamma(B^+ \rightarrow D_{fav} K^+)} = 1 + r_B^2 \pm 2 r_B \cos(\delta_B) \cos(\phi_3)$$

$$A_{CP^\pm} = \frac{\Gamma(B^- \rightarrow D_{CP^\pm} K^-) - \Gamma(B^+ \rightarrow D_{CP^\pm} K^+)}{\Gamma(B^- \rightarrow D_{CP^\pm} K^-) + \Gamma(B^+ \rightarrow D_{CP^\pm} K^+)} = \pm r_B \sin(\delta_B) \sin(\phi_3)/R_{CP^\pm}$$
**Methods for measuring $\phi_3$**

**ADS Method [2]**

- Doubly Cabibbo suppressed (DCS) $D$ decays can also be used to measure $\phi_3$
- E.g., $[K^+\pi^-]_D K^-$ can be reached in two ways:
  - Cabibbo favored (CF) $B^- \to D^0 K^- \to K^+ \pi^-$
  - DCS $B^- \to \bar{D}^0 K^- \to K^- \pi^+$

\[
R_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^-\pi^+]_D K^-) + \Gamma(B^+ \to [K^+\pi^-]_D K^+)}
= r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D) \cos(\phi_3)
\]

\[
A_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) - \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^-\pi^+]_D K^-) + \Gamma(B^+ \to [K^+\pi^-]_D K^+)}
= 2r_B r_D \sin(\delta_B + \delta_D) \sin(\phi_3)/R_{ADS}
\]

- Additional vars $r_D$ and $\delta_D$
- Can be obtained from charm factories
GGSZ Method (Dalitz) [7, 4]

- For self-conjugate multi-body $D$ final states, e.g., $K_S^0\pi^+\pi^-$
- The amplitude for $B^+ \rightarrow DK^+$, with $s_\pm = m_{K^0_S\pi^\pm}^2$:

$$A_{B^+}(s_+, s_-) = \bar{A}_D + r_B e^{i(\delta_B + \phi_3)} A_D$$
$$A_{B^-}(s_+, s_-) = A_D + r_B e^{i(\delta_B + \phi_3)} \bar{A}_D$$

- $A_D(s_+, s_-)$ is the amplitude of the $D$ decay
**B− → D0K−**, **D0 → Ks0π+π−** (GGSZ)

- Dominating measurement of $\phi_3$ at B-factories
- **First model-independent** Dalitz analysis
  
  $\phi_3 = (77^{+15.1}_{-14.9} \pm 4.1 \pm 4.3)°$ [1]

- In recent model-dependent analyses, model uncertainty $3° - 9°$
- Latest **model-dependent** result (incl. $D^*K$)
  
  $\phi_3 = (78.4^{+10.8}_{-11.6} \pm 3.6 \pm 8.9)°$ [14]

- For future experiments, model uncertainty is expected to dominate (more statistics and BES-III results will supersede CLEO-c)

**Model independent**

- Model uncertainty replaced by statistical uncertainty from CLEO-c
- But $\sim 80\%$ of statistical precision
- Full data set: 772M B pairs
- B-factory exclusive measurement (low $E \pi^0/\gamma$; CP-)
- Combining results for $D^* \to D\pi^0, D\gamma$ yields:
  $A_{CP^+} = -0.14 \pm 0.10 \pm 0.01$
  $A_{CP^-} = +0.22 \pm 0.11 \pm 0.01$
- GLW
- ADS
  $R_{D^*K,D\pi^0} = [1.0^{+0.8}_{-0.7}\text{ (stat)}^{+0.1}_{-0.2}\text{ (syst)}] \times 10^{-2}$
  $R_{D^*K,D\gamma} = [3.6^{+1.4}_{-1.2}\text{ (stat)} \pm 0.2\text{ (syst)}] \times 10^{-2}$
- To be published soon
\[ B^- \rightarrow D^0 K^- , \] \[ D^0 \rightarrow K^+ \pi^- \pi^0 \] (ADS)

- Full data set: 772M B pairs
- Caveat: strong phase from the D decay \( \delta_D \) can vary over multi-particle phase space, which can dilute CP-violation effects
- However, this effect is quite small here (coherence factor close to 1 [10])

\[
R_{DK} = (1.98 \pm 0.62 \pm 0.24) \times 10^{-2}
\]
\[
A_{DK} = 0.41 \pm 0.30 \pm 0.05
\]

- First evidence for suppressed \( B \rightarrow DK \) decay; significance 3.2\( \sigma \) [11]
$\phi_3$ COMBINATION FOR CHARGED $B$

$\phi_3 = (73^{+13}_{-15})^\circ$
\[ B^0 \rightarrow D^0 K^{*0}, K^{*0} \rightarrow K^+ \pi^-, D^0 \rightarrow K^- \pi^+ \text{(ADS)} \]

- Full data set: 772M B pairs
- **Self-tagging** channel because of the \( K^* \) decay
- ADS but with \( D[K^+ \pi^-]_{K^*} \rightarrow \) slightly different \( R_{DK^{*0}} \) definition

\[ R_{DK^{*0}} = (4.1^{+5.6+2.8}_{-5.0-1.8}) \times 10^{-2} \]

- As the \( R_{DK^{*0}} \) value is not significant, an upper limit was established [12]
- \( R_{DK^{*0}} < 0.16 \) (95% C.L.)
1st model-independent Dalitz analysis of $B^0 \rightarrow D^0 K^{*0}$ [13]

- Full data set: 772M B pairs
- Results given in Cartesian coordinates (Gaussian, easy to combine)

$$
\begin{align*}
  x_- &= +0.4^{+1.0+0.0}_{-0.6-0.1} \pm 0.0 \\
  y_- &= -0.6^{+0.8+0.1}_{-1.0-0.0} \pm 0.1 \\
  x_+ &= +0.1^{+0.7+0.0}_{-0.4-0.1} \pm 0.1 \\
  y_+ &= +0.3^{+0.5+0.0}_{-0.8-0.1} \pm 0.1 \\
  r_S &< 0.87 \quad 68\% \ C.L.
\end{align*}
$$

Model independent

- Model uncertainty replaced by statistical uncertainty from CLEO-c
- But $\sim 80\%$ of statistical precision

$$
\begin{align*}
  x_\pm &= r_S \cos(\delta_S \pm \phi_3) \\
  y_\pm &= r_S \sin(\delta_S \pm \phi_3)
\end{align*}
$$
Time-dependent Measurements

- All of the measurements presented so far were time-independent.
- Time-dependent measurements also possible.
- Channels like:
  - $B^0 \rightarrow D(\ast)\pi$ [3]
  - $B^0 \rightarrow D(\ast)\rho$
- Mixing induced CPV
- In order to extract $\phi_3$ from $B \rightarrow SS/SV$ decays we must supply $r = |A_{DCS}/A_{CF}|$ externally, usually assuming $SU(3)$ symmetry.
- In $B \rightarrow VV$ decays one can extract all physics parameters from data.
\( B \rightarrow VV \)

- 3 helicity configurations; \( A = \sum_\lambda A_\lambda \)
- \( \Gamma = |A|^2 \Rightarrow \) interference terms (more info about \( A_\lambda \) gets preserved)
- In principle we can extract \( \rho_\lambda = r_\lambda e^{i(-2\phi_1-\phi_3+\delta_\lambda)} \) and \( \bar{\rho}_\lambda = r_\lambda e^{i(+2\phi_1+\phi_3+\delta_\lambda)} \)
- However, when \( r_\lambda \) are small fitting can fail (\( r = 0 \) is a pole in sensitivity of other vars)
- We use Cartesian coordinates \( \{r_\lambda, \delta_\lambda, \phi_w\} \rightarrow \{x_\lambda, y_\lambda, \bar{x}_\lambda, \bar{y}_\lambda\} \)
- \( \rho_\lambda = x_\lambda + iy_\lambda \) and \( \bar{\rho}_\lambda = \bar{x}_\lambda + i\bar{y}_\lambda \)
- This introduces 5 new vars; successive step has to be made to extract the physical parameters
• 60k events in the Belle dataset
• $r = |A_{DCS}/A_{CF}|$ is expected to be $\sim 1 - 2\%$; small CPV effect
• Realistic yield fits
MC sample generated with:

- 60k events
- Helicity amplitudes from CLEO [6]
- $r_\lambda = 1\%$
- Random values for strong phases:
  - $\delta_+ = -0.393$
  - $\delta_0 = 0.785$
  - $\delta_- = 1.571$
- $2\phi_1 + \phi_3 = 1.79371$

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Realistic Toy Fit
Based on simpler (generator level) more optimistic (higher yield) toy MC

Robust $2\phi_1 + \phi_3$ extraction from $x, y$

Adjusted for actual yield, resolution, flavor tagging:

- $\sigma(2\phi_1 + \phi_3) \approx 80^{\circ}\text{(stat)}$ for Belle
- $\sigma(2\phi_1 + \phi_3) \approx 11^{\circ}\text{(stat)}$ for Belle II at 50$\text{ab}^{-1}$

Without any external input

We can decrease $\sigma$, if we take, e.g., $r_\lambda$ from other measurements ($D^*_S \rho$)
### Sensitivity simulation study

- $B \rightarrow [K_S h^+ h^-] D K$ (GGSZ)

- The study was **not finalized**, not fully tuned:
  - Continuum suppression
  - Particle ID

- Full Belle II simulation w/ reconstruction

- Statistical uncertainties (for the chosen channel)
  - $\sigma(\phi_3) = 9.5^\circ$ with 10 ab$^{-1}$
  - $\sigma(\phi_3) = 2.9^\circ$ with 50 ab$^{-1}$

- Overall precision improvement as expected

- Incomplete, conservative estimate
• Belle II based on $B \rightarrow D(*)K(*)$
• LHCb based on $B \rightarrow DK^+$, $D\pi^+$ and $DK^*$
Both with
• $D \rightarrow KK$, $D \rightarrow \pi\pi$, $D \rightarrow K\pi$
• $D \rightarrow K\pi\pi\pi$
• $D \rightarrow KS\pi\pi$
Both experiments have/will include more modes
Work ongoing to estimate sensitivity more precisely

LHCb values based on extrapolation from LHCb-PAPER- 2014-041
New Physics (NP) in $\phi_3$ searches: usually compare tree-level with penguins

- Recent studies show that NP contributions to tree-level $C_1$ and $C_2$ of $O(40\%)$ and $O(20\%)$ are not excluded
- Rough estimate shows that deviations in $\phi_3$ of $O(4^\circ)$ are consistent with current experimental constraints [5]
- Motivation for theoretical and experimental study of $\phi_3$
Thank you!
First measurement of $\phi_3$ with a model-independent dalitz plot analysis of $B^{\pm} \to dK^{\pm}, \, d \to K_S^0\pi^+\pi^-$ decay.

Improved methods for observing CP violation in $B^{\pm} \to KD$ and measuring the ckm phase $\gamma$.

Measurements of time-dependent $cp$ asymmetries in $b \to d * \mp \pi^{\pm}$ decays using a partial reconstruction technique.

Belle dalitz analysis meeting.
unpublished, Belle Dalitz analysis meeting, (2002).
New physics effects in tree-level decays and the precision in the determination of the quark mixing angle $\gamma$.

Measurements of the branching fractions and helicity amplitudes in $B \rightarrow D^* \rho$ decays.

Determining $\gamma$ using $B^\pm \rightarrow dK^{\mp}$ with multibody $D$ decays.

How to determine all the angles of the unitarity triangle from $B(d)0 \rightarrow D K(s)$ and $B(s)0 \rightarrow D0$.

On determining a weak phase from CP asymmetries in charged B decays.
New determination of the and coherence factors and average strong-phase differences.

Evidence for the suppressed decay $B^- \to dK^-, d \to K^+ \pi^- \pi^0$.

Search for the decay $B^0 \to dK^{*0}$ followed by $d \to K^- \pi^+$.  

First model-independent dalitz analysis of $b0\to dk^0, d\to ks0\pi^+\pi^-$ decay.
*Progress of Theoretical and Experimental Physics, 2016(4), 2016.*

Evidence for direct $cp$ violation in the decay $B^\pm \to D(\ast)K^\pm, d \to K^0_S \pi^+ \pi^-$ and measurement of the ckm phase $\phi_3$.
The world combination doesn’t include LHCb’s recent measurements. LHCb alone now reached $\gamma = (72.2^{+6.8}_{-7.3})^\circ$