$\phi_3$ measurements at Belle with $B \rightarrow DK$

Jim Libby
Indian Institute of Technology, Madras
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Outline

• The Canonical Slide
• The measurements
  • ADS/GLW
    • ADS $K\pi\pi^0$ - New since CKM 2012
  • GGSZ
• Combination
• Outlook
\( B \to DK \)

- Tree-level determination \( \phi_3 \)
  
  \[
  A_1 \begin{array}{c}
  b \\
  W^- \\
  \bar{u} \\
  V_{cb} \\
  c \\
  D^0
  \end{array} \Rightarrow K^- 
  \]

  
  \[
  A_1 r_B e^{i(\delta_B - \phi_3)} \begin{array}{c}
  b \\
  V_{ub} \\
  \bar{u} \\
  V^{*}_{cs} \\
  c \\
  \bar{K}^-
  \end{array} \Rightarrow \bar{D}^0 
  \]

  
  Also, an annihilation process, but depends on same CKM elements

- Same final state for \( D \) and \( \bar{D} \) \( \Rightarrow \) interference \( \Rightarrow \) the possibility of DCPV
- Three types of final states generally used
  - CP-eigenstates [GLW]
  - \( K^+ X^- (X^- = \pi^-, \pi^- \pi^0, \pi^- \pi^- \pi^+) \) - CF and DCS [ADS]
    - Atwood, Dunietz & Soni, PRD 63, 036005 (2001)
  - Self-conjugate multibody states: \( K_S h^+ h^- \) [Dalitz]
    - Giri, Grossman, Soffer and Zupan, PRD 68, 054018 (2003); Bondar (unpublished)
THE MEASUREMENTS
Overview of measurements

- $D_{CP}^*K$ GLW 772
  CKM2012 (Preliminary)

- $D_{CP}K$ GLW 772M
  LP2011 (Preliminary)

- $D^*[D_{\pi^0},D_{\gamma}]K$ ADS 772M

- $D[K_{\pi\pi}]K(\ast)$ GGSZ 657M
  PRD 81,112002 (2010)

- $D(K_{\pi\pi})K(\ast)$ GGSZ 386M
  PRD 73,112009 (2006)

- $D_{CP}K$ GLW 275M
  PRD 73,051106 (2006)

- $D[K\pi]K^{\ast0}$ ADS 772M
  PRD 86,011101 (2012)

- $D[K\pi]K$ ADS 772M
  PRL 106,231803 (2011)

- Y(4S): 711 fb$^{-1}$
  Y(5S): 121 fb$^{-1}$
  Y(3S): 3.0 fb$^{-1}$
  Y(2S): 24 fb$^{-1}$
  Y(1S): 5.7 fb$^{-1}$

- Off-resonance: 87 fb$^{-1}$

- Only GLW, ADS and Dalitz
  Not including
  TCPV of $\sin(2\phi_1 + \phi_3)$
Belle results with GLW and ADS

- **Classic measurements** $B \rightarrow DK$
  - ADS: $D \rightarrow K\pi$
  - GLW: CP-even ($D \rightarrow \pi\pi, D \rightarrow KK$) CP-odd ($D \rightarrow K_s\pi^0, D \rightarrow K_s\eta$)

- **Extensions**
  - ADS and GLW
    - $B \rightarrow D*K, D^* \rightarrow D\gamma$ or $D^* \rightarrow D\pi^0$
    - Two $D^*$ decays have $180^\circ$ difference in strong phase
  - ADS only
    - Multibody ADS $B \rightarrow DK, D \rightarrow K\pi\pi^0$
      - Exploits quantum correlated measurements at open charm threshold
    - $B^0 \rightarrow DK^*$
      - Both diagrams colour suppressed
        - Pro: larger interference
        - Con: reduced satatistics

B factory only
Continuum suppression

- The main background comes from $e^+e^- \rightarrow q\bar{q}$ with $q=u, d, s, c$
- Multivariant discriminant (NeuroBayes) is used to differentiate between the events based on
  - event shape
    - modified Fox-Wolfram moments, thrust, decay angles
  - vertexing - $\Delta z$
  - flavour tagging

\[ NB' = \log\left(\frac{NB - NB_{low}}{NB_{high} - NB}\right) \]
Classic GLW and ADS

**GLW result:**
- Clear asymmetry of \((28.7\pm6.0)\%\) in CP-even \(D\rightarrow h^+h^-\)
- Less significant \((-12.4\pm6.4)\%\) in CP-odd \(D\rightarrow K_s\pi^0\) and \(K_s\eta\)
  - Unique to B-factories
- Also, D*K mode investigated
- LP11 preliminary

**ADS**
- First observation of the suppressed mode with \(D\rightarrow K^+\pi^-\)
- \(56\pm15\) events
- PRL 106, 231803 2013
B$\rightarrow$D$^*$K (GLW)

CKM 2012 – preliminary
Full data set: 772M B pairs

Clean signals with hints of opposite sign asymmetries

$B \rightarrow D h$ background in upper $\Delta E$ sideband

GLW combined results for both D$^*$ decays

GLW CP odd: D$^*$ $\rightarrow$ D$\pi^0$

$$R_{CP^+} = 1.19 \pm 0.13 \pm 0.03$$
$$R_{CP^-} = 1.03 \pm 0.13 \pm 0.03$$
$$A_{CP^+} = -0.14 \pm 0.10 \pm 0.01$$
$$A_{CP^-} = +0.22 \pm 0.11 \pm 0.01$$
ADS and GLW independent observables unique to the B factories
$B^0 \rightarrow DK^*$ ADS

- Modified formula
  \[ R_{DK^*0} = r_s^2 + r_D^2 + 2kr_S r_D \cos(\delta_S + \delta_D) \cos\phi_3 \]

  Coherence factor of $K^*$ region $k \sim 0.95$
  BABAR, PRD 80 031102 (2009)

- Upper limit on $R_{DK^*0} < 0.16$ at 95% c.l.

Naïve interpretation has $r_S \sim 2 \times r_B$ so potential for large interference

- More study: model dependent GGSZ with this channel

PRD 86 011101 (2012)
772 M BB
ADS with D→Kππ^0

Any D→K^+X^- (X^-=π^-, π^-π^0, π^-π^-π^+) can exhibit significant DCPV

However, the D strong phase difference varies over phase space for three or more body final states – can dilute DCPV effects

Correlated D\bar D production is used to quantified this dilution – so called coherence factor
- CLEO-c data: PLB, 731C (2014), 197
- K^+π^-π^0 coherent – can observe DCPV
- K^+ π^-π^-π^+ incoherent - good measure of r_B

Observation of suppressed mode : yield 77±24

Similar yield to Kπ but larger background
Belle results with Dalitz method

Model dependent – 657 M BB pairs

First evidence of direct CPV in a single mode

But with more statistics model uncertainty can start to dominate

Model independent

Con: ~80% of the statistical precision

Pro: model uncertainty replaced by statistical uncertainty from CLEO-c

\[ \phi_3 = (80.8^{−13.1}_{+14.8} \pm 5.0 \pm 8.9)° \]

PRD 81 (2010) 112002

\[ \phi_3 = (77.3^{−15.1}_{+14.9} \pm 4.1 \pm 4.3)° \]

PRD 85 (2012) 112014
Belle combination

CKMfitter plots and numbers from K Trabelsi

\[ \phi_3 = \left(73^{+13}_{-15}\right)^\circ \]

\[ r_B = 0.117 \pm 0.014 \]
OUTLOOK
Prospects: $B \to DK$

- GGSZ model-independent results the most accurate measurement from Belle

- ADS and GLW measurements
  - CP odd eigenstates and D*K unique to B-factories
  - Added three-body ADS $D \to K\pi\pi^0$

- Is this final word?
  - GLW, D*K ADS and combination publication
  - Still some analyses underway
    - Model-independent $B^0 \to DK^*$
    - Model-dependent $B \to DK, D \to K_S K\pi$
  - Still some potential in the data
    - $D \to K_S \pi\pi\pi^0$ (Nearly twice BF of $K_S \pi\pi$)
    - $D \to \pi\pi\pi^0$

- Belle II – Pablo Goldenzweig’s talk later in this session