Hadronic $b\rightarrow c$ decays at Belle

$(B^+ \rightarrow D(\ast)K, B^0 \rightarrow D_s(\ast)h, B^- \rightarrow \bar{p}\Lambda D)$

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Outline

Efforts put

• in the direct determination of $\varphi_3$
  • $B^{\pm}\rightarrow D^{(*)}K^{\pm}$ Dalitz or GGSZ (ref: Giri et al, Phys. Rev. D, 68, 054018 (2003))
• towards indirect determination of $\varphi_3$
  • $B^{0}\rightarrow D_{s}^{(*)}h$ in $B^{0}\rightarrow D^{(*)}\pi$ TCPV (ref: Dunietz et al, Phys. Rev. D, 65, 054025 (2002))
• in testing of the generalized factorization
  • $B^{-}\rightarrow \overline{p}\Lambda D$ (ref: C. Chen, Phys. Rev. D, 78, 054016 (2008))
CKM matrix and $\Phi_3 (\gamma)$ Angle

- Current CKM picture, as shown in FPCP10 by the CKMfitter group

$$\phi_1 = (21.15^{+0.90}_{-0.88})$$
$$\phi_2 = (89.0^{+4.4}_{-4.2})$$
$$\phi_3 = (70^{+14}_{-21})$$

(in degree)

Angle $\varphi_3$ needs more efforts and is more difficult to estimate
Event Selection

- charged tracks:
  - $|dr| < 0.2$ cm, $|dz| < 4$ cm
- photon:
  - $E_\gamma > 100$ MeV
- charged hadron ($K/\pi$):
  - $L_{\text{Total}} = L_{\text{CDC}} \times L_{\text{TOF}} \times L_{\text{ACC}}$
  - $L(K/\pi) > 0.6$ for a kaon
  - efficiency $\sim 85\%$, fake rate $\sim 10\%$
- $K_S^0$:
  - reconstructed from $\pi^+\pi^-$
  - quality check based on vertex topology
  - $|M(K_S^0) - M_{\text{PDG}}| < 10$ MeV/$c^2$

Continuum suppression:
Likelihood based on event topology
- Fisher $F$,
- $B$ meson thrust angle $\cos \theta_{\text{th}}$,
- $B$ meson polar angle $\cos \theta_B$
B meson Reconstruction:

- $B^0$ candidate selection based on kinematically uncorrelated $\Delta E$ and $M_{bc}$ variables

\[
M_{bc} = \sqrt{E_{\text{beam}}^2 - (\sum_i p_i^*)^2}
\]

\[
\Delta E = \sum_i E_i^* - E_{\text{beam}}
\]

where,

$(E_i^*, p_i^*)$ are the $i^{th}$ final-state 4-momentum in the center-of-mass frame, and

$E_{\text{beam}}$ is the beam energy

All results on 657 M BB̄ events!

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$B^\pm \rightarrow D^{(*)} K^\pm$

(Dalitz)
$B^\pm \to DK^\pm$

**ADS**

- $f = K^+\pi^-$
- col. sup. x Cabibbo allowed ~ col. allowed x Cabibbo sup.
- no control over strong phases
- statistically limited
- simpler analysis-wise

**Dalitz**

- $f = K_S^0\pi^+\pi^-$
- Cabibbo allowed modes
- large strong phases due to resonances
- most sensitive
- needs Dalitz analysis

\[
D^{0}_{1,2} = \frac{D^0 \pm \bar{D}^0}{\sqrt{2}}
\]

Model dependent/independent dependency:
- $D^0$ decay model (Isobar, BW)
**B→D(*K Dalitz (model dependent)**

- Amplitude for $B^{\pm} \rightarrow D K^{\pm}$ process can be expressed as
  \[
  M_{\pm} = f(m_{\pm}^2, m_{\mp}^2) + r_{\pm} e^{\pm i\phi_3 + i\delta} f(m_{\mp}^2, m_{\pm}^2)
  \]

\[m_{\pm}^2 = m_{K_S^0 \pi^\pm}^2\]

- Amplitude of $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decay:
  1. determined from Dalitz plot of large continuum data,
  2. flavor-tagged by soft pion charge in $D^{*\pm} \rightarrow D \pi_s^{\pm}$
  3. assuming isobar model, BW shapes for resonances

**Analysis procedure:**
- first step: background fractions are obtained from $\Delta E-M_{bc}$ 2D unbinned maximum likelihood (UML) fit
- Second step: Dalitz, with likelihoods (continuum separation) inside the fit using $x_{\pm} = r_{\pm} \cos(\pm \phi_3 + \delta)$ and $y_{\pm} = r_{\pm} \sin(\pm \phi_3 + \delta)$

(ref: A. Poluektov et al, Phy. Rev. D 81, 112002(2010))
$B \to DK \Delta E - M_{bc}$

A 2D UML fit with free parameters: background relative fractions

Note: continuum background is separated into charm and $u,d,s$ components

(ref: A. Poluektov et al, Phy. Rev. D 81, 112002(2010))
$B \to D^* K \Delta E - M_{bc}$

- $D^* \to D\pi^0$

- $D^* \to D\gamma$

(photon cross-feed)

(ref: A. Poluektov et al, Phy. Rev. D 81, 112002(2010))
B\rightarrow DK Dalitz

B^+\rightarrow DK^+

B^-\rightarrow DK^-
To improve sensitivity, combine various $B^\pm \to D^{(*)}K^\pm$ modes.

combined $B^\pm \to D^{(*)}K^\pm$ results:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$1\sigma$ interval</th>
<th>$2\sigma$ interval</th>
<th>Systematic error</th>
<th>Model uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_3$</td>
<td>$(78.4^{+10.8}_{-11.6})^\circ$</td>
<td>$54.2^\circ &lt; \phi_3 &lt; 100.5^\circ$</td>
<td>3.6$^\circ$</td>
<td>8.9$^\circ$</td>
</tr>
<tr>
<td>$r_{DK}$</td>
<td>$0.160^{+0.038}_{-0.038}$</td>
<td>$0.084 &lt; r_{DK} &lt; 0.239$</td>
<td>0.011</td>
<td>$+0.050 - 0.010$</td>
</tr>
<tr>
<td>$r_{D^*K}$</td>
<td>$0.196^{+0.064}_{-0.069}$</td>
<td>$0.061 &lt; r_{D^*K} &lt; 0.271$</td>
<td>0.012</td>
<td>$+0.062 - 0.012$</td>
</tr>
<tr>
<td>$\delta_{DK}$</td>
<td>$(136.7^{+13.0}_{-15.8})^\circ$</td>
<td>$102.2^\circ &lt; \delta_{DK} &lt; 162.3^\circ$</td>
<td>4.0$^\circ$</td>
<td>22.9$^\circ$</td>
</tr>
<tr>
<td>$\delta_{D^*K}$</td>
<td>$(341.9^{+18.0}_{-19.6})^\circ$</td>
<td>$296.5^\circ &lt; \delta_{D^*K} &lt; 382.7^\circ$</td>
<td>3.0$^\circ$</td>
<td>22.9$^\circ$</td>
</tr>
</tbody>
</table>

possible to remove model uncertainty: perform a fit in the momentum-binned Dalitz plot (much along the original idea of GGSZ)
$B \to D_s(\ast) h$

$(h = K/\pi)$
Time dependent CP Analysis

\[ B^0 \rightarrow D^{(*)} \mp \pi^\pm \]

- theoretically cleanliest method of extracting the \( \sin(2\phi_1 + \phi_3) \) and hence the \( \phi_3 \)

- Initial state \( B^0 \) can be found in the state \( D^{(*)-} \pi^+ \) state in two ways: either through CFD or via mixing followed by DCSD

\[ \begin{align*}
B^0 \rightarrow D^{(*)-} \pi^+ \\
\bar{B}^0 \rightarrow \bar{D}^{(*)-} \bar{\pi}^+
\end{align*} \]

(a) CFD  (b) DCSD

- The DCSD involves \( b \rightarrow u \) transition, and the phase \( \phi_3 \) shows up due to the interference between the two as,

\[ R_{D^{(*)} \pi} \sin(2\phi_1 + \phi_3) \]

where, \( R_{D^{(*)} \pi} \) is the ratio of magnitude of DCSD and CFD amplitude and must be provided externally.
$B^0 \rightarrow D_s^{(*)} h$

- $B^0 \rightarrow D_s^{(*)} \pi^-$ is related to $B^0 \rightarrow D^* \pi^-$ (DCSD) by SU(3) symmetry

DCSD

\[
\begin{align*}
B^0 & \rightarrow D_s^* \rightarrow D^{(*)+} \\
D_s^*(\pi^+) & \rightarrow D_s^{(*)+} + \pi^-
\end{align*}
\]

which means, $\mathcal{R}_{D^{(*)}\pi} = \tan \theta_C \frac{f_{D^{(*)}}}{f_{D_s^{(*)}}} \sqrt{\frac{\mathcal{B}(B^0 \rightarrow D_s^{(*)}+ \pi^-)}{\mathcal{B}(B^0 \rightarrow D^{(*)}+ \pi^+)} \frac{\mathcal{B}(B^0 \rightarrow D^{(*)}+ \pi^+)}{\mathcal{B}(B^0 \rightarrow D_s^{(*)}+ \pi^-)}}$

**Theory predicts**

$R_{D^{(*)}\pi} \sim 2\%$
$B^0 \rightarrow D_s(*)h$

- $B^0 \rightarrow D_s^* K^+$ is related to CFD $W$-exchange by SU(3) symmetry

\[
\begin{align*}
B^0 & \rightarrow D_s^* K^+ \\
\end{align*}
\]

\[
\begin{align*}
\begin{array}{c}
\bar{b} & \rightarrow & \bar{c} \\
B^0 & \rightarrow & D^{(*)} \\
d & \rightarrow & \bar{d} \\
\end{array} \\
W^+ & \rightarrow & \pi^+ \\
d & \rightarrow & u
\end{align*}
\]

CFD $W$-exchange

\[
\begin{align*}
\begin{array}{c}
\bar{b} & \rightarrow & \bar{c} \\
B^0 & \rightarrow & D_s^{(*)} \\
\bar{s} & \rightarrow & s \\
\end{array} \\
W^+ & \rightarrow & K^+ \\
d & \rightarrow & u
\end{align*}
\]

$B^0 \rightarrow D_s^* K^+$

- $B^0 \rightarrow D_s^* K^+$ is expected to be enhanced due to re-scattering effects $\Rightarrow$ needs check!

$B^0 \rightarrow D_s h$

A $\Delta E$-$M_{Ds}$ 2D UML fit is performed

- signal is reconstructed in three $D_s^+$ decay channels: $\varphi \pi$, $K^*(892)^0 K$, $K_S^0 K$
- $B^0 \rightarrow D_s^+ \pi^-$ and $B^0 \rightarrow D_s^+ K^-$ cross-feed each other
- data fitted simultaneously in 3 x 2 mutually exclusive samples

We obtained,

$$B(B^0 \rightarrow D_s^+ \pi^-) = (1.99 \pm 0.26 \pm 0.18) \times 10^{-5}$$

and

$$B(B^0 \rightarrow D_s^- K^+) = (1.91 \pm 0.24 \pm 0.17) \times 10^{-5}$$

with significances 8.0$\sigma$ and 9.2$\sigma$, respectively.

$$R_{D\pi} = [1.71 \pm 0.11{\text{(stat)}} \pm 0.09{\text{(syst)}} \pm 0.02{\text{(th)}}] \%$$
B^0 \rightarrow D_s^* h

An UML fit to $\Delta E$ is performed to six exclusive samples

$|M_{D_s} - M_{PDG}| < 15 \text{ MeV/c}^2$

$132 \text{ MeV/c}^2 < \Delta M < 168 \text{ MeV/c}^2$

We obtain,

$BR(B^0 \rightarrow D_s^{*+}\pi^-) = (1.75^{+0.32}_{-0.34}) \times 10^{-5}$

and

$BR(B^0 \rightarrow D_s^{-}K^+) = (2.02^{+0.33}_{-0.31}) \times 10^{-5}$,

with significances 6.1$\sigma$ and 8.0$\sigma$, respectively

$D_s^+ \rightarrow K^0 K^+$

$D_s^+ \rightarrow K_s^0 K^+$

$R_{D^*\pi} = [1.58 \pm 0.15(\text{stat}) \pm 0.10(\text{syst}) \pm 0.03(\text{th})] \%$

(ref: N. J Joshi et al, Phy. Rev. D 81, 031101(2010))
$B^- \rightarrow \bar{\rho} \Lambda D$
B⁻ → ̅pΛD : A test for generalized factorization

- The vertex (and the penguin correction thereof) of the hadronic matrix elements of four quark operators can be absorbed in the effective Wilson coefficients c_{eff}, so that the momentum dependence is smeared out.

- Under generalized factorization:
  - three body amplitudes
    1. current type
    2. transition type
    3. hybrid

- Under generalized factorization approximation, one predicts the decay amplitude

\[ \mathcal{B}(B^- \rightarrow ̅pΛD^0) \sim 1.1 \times 10^{-5} \]

proceeding via threshold enhancement.

**FIG. 1.** Two types of the \( B \rightarrow B'B'M_c \) decay process: (a) current type and (b) transition type.
\( B^- \rightarrow \bar{p} \Lambda D^0 \)

An UML fit to \( \Delta E - M_{bc} \) is performed

- \( \mathcal{L}(p/h) > 0.6 \) for a proton
- \( \Lambda \) selection
  1. quality check vertex topology
  2. \( 1.111 \text{ GeV}/c^2 < M_\Lambda < 1.121 \text{ GeV}/c^2 \)
- D meson is reconstructed in two decay channels
  1. \( D^0 \rightarrow K \pi \)
  2. \( D^0 \rightarrow K \pi \pi^0 \)

We report,

\[
B(B^- \rightarrow \bar{p} \Lambda D^0) = (1.40^{+0.27}_{-0.24} \pm 0.16) \times 10^{-5}
\]

with a significance of 8.6\( \sigma \).
B$^- \rightarrow p\Lambda D$

We also observe $p\Lambda$ threshold enhancement near 2 GeV/$c^2$
Conclusion

• We report results from $B^{\pm}\to D^{(*)}K^{\pm}$ Dalitz analysis done using isobar model, as

$$\phi_3 = (78.4^\circ \pm 10.8^\circ \pm 3.6^\circ \text{ (syst)} \pm 8.9^\circ \text{ (model)})$$

• A model-independent study is undertaken to reduce the model-uncertainties.

• $B^0\to D_s h$ measurements yield $R_{D\pi} = [1.71 \pm 0.11 \text{ (stat)} \pm 0.09 \text{ (syst)} \pm 0.02 \text{ (th)}] \%$, consistent with the theoretical predictions of 2%.

• $B^0\to D_s^* h$ measurements yield $R_{D^*\pi} = [1.58 \pm 0.15 \text{ (stat)} \pm 0.10 \text{ (syst)} \pm 0.03 \text{ (th)}] \%$

• $B^-\to p\Lambda D^0$ study shows agreement with the expectations from the generalized factorization approach.
Back up
B→D*K Dalitz

D*→Dπ^0

D*→Dγ
Result:
Fit Explained

- Contribution from $B^0 \rightarrow D_s^- K^+$ cross-feed (a misidentified $K$)
- Contribution from $B^0 \rightarrow D_s^+ \pi^-$ cross-feed (a misidentified $\pi$)
- Combinatorial background
- Contribution from rare three body decays to same final state

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Result:  
Fit Explained

Combinatorial background: 1st order polynomial

Contribution from $B^0 \rightarrow D_s^{(*)+} \rho^-$ with a missing $\pi^0$

Contribution from $B^0 \rightarrow D_s^{*+} \pi^-$ with a missing $\pi^0$

Contribution from $B^0 \rightarrow D_s^{*+} K^+$ crossfeed (a misidentified $K$)

Contribution from $B^0 \rightarrow D_s^{*+} \pi^-$ crossfeed (a misidentified $\pi$)

Contribution from $B^0 \rightarrow D_s^- K^+$ (additional $\gamma$)
Individual branching fractions of $B^{-} \rightarrow p \Lambda D$

$D^{0} \rightarrow K_{\pi}$

$$\mathcal{B}(B^{-} \rightarrow \bar{p} \Lambda D^{0}(K\pi)) = (1.43^{+0.34}_{-0.30} \pm 0.14) \times 10^{-5}$$

with a significance of 7.70$\sigma$.

$D^{0} \rightarrow K_{\pi\pi^{0}}$

$$\mathcal{B}(B^{-} \rightarrow \bar{p} \Lambda D^{0}(K\pi\pi^{0})) = (1.35^{+0.44}_{-0.40} \pm 0.18) \times 10^{-5}$$

with a significance of 3.85$\sigma$. 