Charmless hadronic B-decays from Belle

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(https://sfde16.0x1115.org/images/du-lich-guy-nhon-01.jpg)
Outline

• $B^\pm \rightarrow K^+ K^- \pi^\pm$, Branching Fraction, $(B), A_{CP}$
• $B \rightarrow \pi^0 \pi^0$ - $B$, $A_{CP}$, $\phi_2$

$$A_{CP} = \frac{\mathcal{B}(B^- \rightarrow K^+ K^- \pi^-) - \mathcal{B}(B^+ \rightarrow K^+ K^- \pi^+)}{\mathcal{B}(B^- \rightarrow K^+ K^- \pi^-) + \mathcal{B}(B^+ \rightarrow K^+ K^- \pi^+)}$$
KEKB - Worlds most intense collider

Maximum Luminosity $2.1 \times 10^{34} \text{cm}^2\text{s}^{-1} \Rightarrow 21 \text{ B-pairs/sec}$

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The Belle Experiment

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Direct CP Violation

- Requires Interference of multiple Feynman diagrams.
- For non-zero DCPV, $A_1$ and $A_2$ need to have different weak phases $\Phi$ and different CP invariant (e.g. strong) phases $\delta$.

$|A|^2 = A_1^2 + A_2^2 + 2A_1A_2 \cos(\Delta\delta + \Delta\phi)$

$|\bar{A}|^2 = A_1^2 + A_2^2 + 2A_1A_2 \cos(\Delta\delta - \Delta\phi)$
Br and $A_{CP}$ for $B^{\pm} \rightarrow K^{+} K^{-} \pi^{\pm}$

Cabibbo and color suppressed tree
And Penguin diagrams

$\text{Br}(B^{\pm} \rightarrow K^{-} K^{+} \pi^{\pm}) = (5.0 \pm 0.5 \pm 0.5) \times 10^{-6}$
PRL 99, 221801 (2007) BaBar

$A_{CP} = 0.123 \pm 0.017 \pm 0.012 \pm 0.007$
PRD 90, 112004 (2014) LHCb

Unquantified:
Large enhancement
Large $A_{CP}$ at low $M_{KK}$
Investigate and quantify
At Belle

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Slide 6
Kinematic Variables in B-Factory measurements

\[ M_{bc} = \sqrt{E_{\text{beam}}^* - p_B^*} \quad \Delta E = E_B^* - E_{\text{beam}}^* \]

\( M_{bc} \) peaks at B mass for fully reconstructed signal
\( \Delta E \) peaks at zero for fully reconstructed signal
Continuum Background

• Continuum background ($e^+e^- \rightarrow q\bar{q}(u,d,s,c)$):
  – Dominant background
  – Event topology differs from BB decays

  \begin{align*}
  \text{Continuum Background} \quad & \quad \text{Jet-like} \\
  q\bar{q} & \\
  e^+ & \quad e^-
  \end{align*}

  \begin{align*}
  \text{BB event} \quad & \quad \text{spherical} \\
  \text{Signal} & \\
  \text{Other} & \\
  B & \quad B
  \end{align*}

  – Combined variables describing the event topology in an artificial neural network.

  – Selection criteria is determined by optimizing figure of merit:

  \[
  \text{F.O.M.} = \frac{N_{\text{sig}}}{\sqrt{N_{\text{sig}} + N_{\text{bck}}}}
  \]

  \[
  \text{NN}>0.88, \text{ rejects 99\% of background}
  \]

  \[
  \text{Signal} \quad \text{Continuum}
  \]
\[ B^{\pm} \rightarrow K^+ K^- \pi^{\pm} \] Backgrounds

- Background from other B decays
- Same final state particles from charmful B decays
- Misidentified tracks from either charmful or charmless B decays
Analysis strategy

- Continuum suppression KSFW moments, $\cos\theta_B$, $\cos\theta_{thr}$, $\Delta Z$, q.r $\Rightarrow$ NeuroBayes
- Place cut on continuum suppression variable from NeuroBayes
- Cut charm backgrounds
- 2D fit for Signal yield and $A_{CP}$ in $M_{bc}$ and $\Delta E$ in bins of $M_{KK}$

Other fit components

- Continuum background
- Generic $B\bar{B}$ background
- $B \rightarrow KKK$ background (K misidentified as $\pi$)
- $B \rightarrow K\pi\pi$ background ($\pi$ misidentified as K)
Fit for $B^{\pm} \rightarrow K^+ K^- \pi^{\pm}$ in $M_{KK}$ Bins

<table>
<thead>
<tr>
<th>$M_{K+K-}$ (GeV/$c^2$)</th>
<th>$N_{\text{sig}}$</th>
<th>Eff. (%)</th>
<th>$d\mathcal{B}/dM \times 10^{-7}$</th>
<th>$A_{CP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8-1.1</td>
<td>$59.8 \pm 11.4 \pm 2.6$</td>
<td>19.7</td>
<td>$14.0 \pm 2.7 \pm 0.8$</td>
<td>$-0.90 \pm 0.17 \pm 0.04$</td>
</tr>
<tr>
<td>1.1-1.5</td>
<td>$212.4 \pm 21.3 \pm 6.7$</td>
<td>19.3</td>
<td>$37.8 \pm 3.8 \pm 1.9$</td>
<td>$-0.16 \pm 0.10 \pm 0.01$</td>
</tr>
<tr>
<td>1.5-2.5</td>
<td>$113.5 \pm 26.7 \pm 18.6$</td>
<td>15.6</td>
<td>$10.0 \pm 2.3 \pm 1.7$</td>
<td>$-0.15 \pm 0.23 \pm 0.03$</td>
</tr>
<tr>
<td>2.5-3.5</td>
<td>$110.1 \pm 17.6 \pm 4.9$</td>
<td>15.1</td>
<td>$10.0 \pm 1.6 \pm 0.6$</td>
<td>$-0.09 \pm 0.16 \pm 0.01$</td>
</tr>
<tr>
<td>3.5-5.3</td>
<td>$172.6 \pm 25.7 \pm 7.4$</td>
<td>16.3</td>
<td>$8.1 \pm 1.2 \pm 0.5$</td>
<td>$-0.05 \pm 0.15 \pm 0.01$</td>
</tr>
</tbody>
</table>
$B^\pm \rightarrow K^+ K^- \pi^\pm$

Total $\mathcal{B} = (5.38 \pm 0.40 \pm 0.35) \times 10^{-6}$
$A_{CP} = -0.170 \pm 0.073 \pm 0.017$

To be published in PRD(RC)
arXiv:1705.02640

Unusual dynamics showing a large enhancement and very large direct CP-violation
$A_{CP} = -0.9 \pm 0.17 \pm 0.03$ at $M_{KK} < 1.1 \text{ GeV (4.8 } \sigma)$
Hard to make a model do both.
Br and Acp for $B^0 \rightarrow \pi^0 \pi^0$

Time dependent measurements of $B \rightarrow \pi^- \pi^+$ are sensitive to $\Phi_2$

Contribution of penguin diagram which gives rise to direct CPV

“Penguin Pollution”

$B^0 \rightarrow \pi^0 \pi^0$ vital to unravel these effects
$B \rightarrow \pi^0 \pi^0$

Penguin pollution can be isolated via an isospin analysis
(M. Gronau and D. London, PRL 65, 3381 (1990))

$A^\pm = \overline{B^0} \rightarrow \pi^+ \pi^-$
$\overline{A^\pm} = \overline{B^0} \rightarrow \pi^+ \pi^-$
$A^0 = B^0 \rightarrow \pi^0 \pi^0$
$\overline{A^0} = \overline{B^0} \rightarrow \pi^0 \pi^0$
$A^{+0} = B^+ \rightarrow \pi^+ \pi^0$
$A^{-0} = B^- \rightarrow \pi^- \pi^0$
Fit Components $B^0 \rightarrow \pi^0 \pi^0$

- For $B \rightarrow \pi^0 \pi^0$ we have 4 components to fit to $M_{bc}$, $\Delta E$ and $T_C$ (Continuum suppression variable)
  - Signal
  - Continuum
  - $B \rightarrow \rho^+ \pi^0$ (rho-pi)
  - Other rare charmless (rare)
- Simultaneous fit to 14 bins in flavor tag q.r for SVD1 (2)
- $T_C$ Fisher Discriminant of KSFW Likelihood, $\cos\theta_B$, $\cos\theta_{thrust}$
- $T_c$ PDF obtained from analytic anzatz fit to Full Detector simulation for Signal MC and off-resonance for Continuum
- $M_{bc}$ and $\Delta E$ for signal obtained with analytic function which accounts for correlation due to energy leakage
Results $B^0 \rightarrow \pi^0\pi^0$

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Results $B^0 \rightarrow \pi^0\pi^0$

$\mathcal{B} = (1.31 \pm 0.19 \pm 0.19) \times 10^{-6}$

$A_{CP} = 0.14 \pm 0.36 \pm 0.10$

$\phi_2$ excluded from the range:

$15.5^\circ < \phi_2 < 75.0^\circ$ at $2\sigma$

Belle only $B \rightarrow \pi\pi\pi$ data
Summary

- $B^{\pm} \to K^+ K^- \pi^\pm$ arXiv:1705.02640 (PRD(RC))
- $\mathcal{B} = (5.38 \pm 0.40 \pm 0.35) \times 10^{-6}$
- $A_{CP} = -0.170 \pm 0.073 \pm 0.017$
- $A_{CP} = -0.9 \pm 0.17 \pm 0.03$ at $M_{KK} < 1.1$ GeV (4.8 $\sigma$)
- $B^0 \to \pi^0 \pi^0$ arXiv:1705.02083 (PRD)
- $\mathcal{B} = (1.31 \pm 0.19 \pm 0.19) \times 10^{-6}$
- $A_{CP} = 0.14 \pm 0.36 \pm 0.10$
- $\phi_2$ excluded from the range (Belle data):
  $15.5^\circ < \phi_2 < 75.0^\circ$ at $2\sigma$
Thank you!
Theory for BR $B^0 \rightarrow \pi^0\pi^0$

- Besides determination of $\Phi_2$
- BR ($B \rightarrow \pi^0\pi^0$) < BR ($B \rightarrow \rho^0\rho^0$) (Hsiang-nan Li and Satoshi Mishima. Phys.Rev.D73:114014,2006)
- Same diagrams and stronger coupling to $\rho^0$
- At most BR ($B \rightarrow \pi^0\pi^0$) < $1 \times 10^{-6}$ (H.L. & SM Phys.Rev.D83:034023,2011)

- Previously published results
- Belle PRL 94, 181803(2005) = $(2.32 \pm 0.4 - 0.5(\text{stat})) \times 10^{-6}$ (253 fb$^{-1}$)
- BABAR PR D87 052009 $(1.83 \pm 0.21 \pm 0.13) \times 10^{-6}$
- PDG Average $(1.62 \pm 0.31) \times 10^{-6}$

=> Update to full Belle Data Set
Signal Shape

- Energy Leakage from ECL causes correlation between $M_{bc}$ and $\Delta E$
- Account with 2D $M_{bc}$ and $\Delta E$ anstanz

\[
\begin{align*}
\text{CB}_{\Delta E}(f(\Delta E), \mu_{\Delta E}, \sigma_{\Delta E}, \alpha_{\Delta E}, n_{\Delta E}) \\
\text{CB}_{M_{bc}}(M_{bc}, \mu_{M_{bc}}, \sigma_{M}, \alpha_{M}, n_{M_{bc}})
\end{align*}
\]

where

\[
\begin{align*}
\sigma_{M} &= \sigma_{M_{bc}} + A \Delta E \\
\alpha_{M} &= \alpha_{M_{bc}} + Be\frac{-1}{2}(\frac{\Delta E}{C})^2 \\
f(\Delta E) &= \Delta E + \mu_{\Delta E} + Ce\frac{-1}{2}(\frac{\mu_{M_{bc}} - \mu_{M}}{D})^2 \\
\text{PDF}(M_{bc}, \Delta E) &= CB_{\Delta E}CB_{M_{bc}}
\end{align*}
\]

Where CB = “Crystal Ball function”
Backgrounds - Continuum

$e^+ e^- \rightarrow q \bar{q}$ "Continuum" background

Fisher Discriminant of KSFW Likelihood,
$\cos \theta_B, \cos \theta_{\text{thrust}} = T_c$

5.24 < $M_{bc}$ < 5.26
Out of time ECL background

- “Pile-up” from $e^+e^-(\gamma)$ scatter within a few microseconds of $e^+e^- \rightarrow B\bar{B}$ event.

$e^+e^-(\gamma)$ scatter is Back-to-back In CM
Out of time ECL background

Output of CsI crystals is processed with 1μsec shaping time

Tracking trigger

T=0
T=-1.5μs  T=+3.5μs

Trigger from B B_bar event within a few microseconds samples non-peak part of ECL. Shows up as high energy photons located back-to-back in ECL. Photons pick up low energy photon from rest of BB-bar event to form fake pi0’s. Momentum dominated by high energy deposits. Vector sum ~ 0 So Mbc ≈ B_mass
Out of time ECL background

Logarithmic plots of 4γ’s from $B^0 \rightarrow \pi^0(\gamma_0, \gamma_1)\pi^0(\gamma_2, \gamma_3)$
Data with timing cuts

\[ \frac{E_{\gamma_1} - E_{\gamma_2}}{E_{\gamma_1} + E_{\gamma_2}} \]

\( \pi^0 \) Invariant mass
Out of time Data

\[ \frac{E_{\gamma_1} - E_{\gamma_2}}{E_{\gamma_1} + E_{\gamma_2}} \]

\[ \pi^0 \text{ Invariant mass} \]

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$B^0 \rightarrow \pi^0\pi^0$ - Out of time Background

- substantial background from out of time showers in the electromagnetic calorimeter ($\tau_{\text{ECL}} = 1.5 \mu s$) (Pileup)
- out of time ECL hit + BB event $\rightarrow$ peaking background

Timing cut on ECL Trigger crystals removes 99% of the background and keeps 99% of the signal
Backgrounds - $B \rightarrow \rho\pi$

$M_{bc}$

$\Delta E$

Entries = 5728

$\text{nrhopi}_\text{bck} = 5728 \pm 76$
Background from other charmless B-decays

Entries = 1735

Nnrare_bck = 1735 ± 42

M_{bc}

ΔE

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