Recent Results from Belle

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9th June 2015
Outline

* Introduction to KEKB and Belle
* Introduction to the measurement of CP violation
  * $\sin 2\varphi_1$ measurement $B^0 \rightarrow J/\psi K^0$
  * CP violation in $B^0 \rightarrow D_{cp}^{(*)} h^0$
* $\sin 2\varphi_1^{\text{eff}}$ measurement
* New physics searches in $B \rightarrow D^{(*)}\tau\nu$
* Search for dark photon and dark Higgs
* Search for $B^0 \rightarrow \pi^0\pi^0$
* Conclusion

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KEKB and Belle

KEKB
8GeV×3.5GeV@γ(4S)

Belle
High resolution 4π spectrometer with particle identification capability
Integrated luminosities

Belle recorded more than 1 ab⁻¹!

On resonance:
- Y(5S): 121 fb⁻¹
- Y(4S): 711 fb⁻¹
- Y(3S): 3 fb⁻¹
- Y(2S): 25 fb⁻¹
- Y(1S): 6 fb⁻¹

Off reson./scan:
- ~100 fb⁻¹

772 X 10⁶ BB pairs
Amplitudes and Phases in the Weak Interaction

\[ V_{\text{CKM}} = V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \]

\[ V = \begin{pmatrix} 1 - \frac{1}{2} \lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2} \lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} \]
ICHEP 2014: New Belle result on $\pi^0$ $\pi^0$

Big Questions: *Are determinations of angles consistent with determinations of the sides of the triangle? Are angle determinations from loop and tree decays consistent?*

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Time-dependant CP Asymmetry in decays to CP eigenstates

\[ \sin 2\phi_1 \text{ from } B \rightarrow f_{CP} + B \leftrightarrow \bar{B} \rightarrow f_{CP} \text{ interf.} \]

\[ \frac{N(\bar{B}^0(t) \rightarrow f) - N(B^0(t) \rightarrow f)}{N(\bar{B}^0(t) \rightarrow f) + N(B^0(t) \rightarrow f)} = S \sin \Delta m_d t + A \cos \Delta m_d t \]

\[ \lambda = \frac{q}{p} \frac{A(\bar{B}^0 \rightarrow f)}{A(B^0 \rightarrow f)} = e^{-i2\beta} \frac{A_f}{\bar{A}_f} \]

- \( A = 0 \) and \( S = -\xi_f \sin 2 \phi_1 \) for \((c\bar{c})K_{S/L}\) (\( \xi_f = \pm 1 \))
- \( A = 0 \) and \( S = \sin 2 \phi_2 \) for \( \pi^+ \pi^- \) (if tree only)

\[ C = -A \]

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Measuring the CP parameters $S$ and $A$
Measurement of $\sin(2\phi_1)$ in Charmonium $K^0$ modes

$\sin(2\phi_1) = 0.667 \pm 0.023 \pm 0.012$

$A_f = 0.006 \pm 0.016 \pm 0.012$

PRL 108, 171802 (2012)

Overpowering evidence for CP violation (matter-antimatter asymmetries).

$>>>>>$ The phase of $V_{td}$ is in good agreement with Standard Model expectations

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CP violation in $B^0 \rightarrow D_{cp}(*) h^0$

- $D = D_{cp}$, CP eigenstates as $K^+K^-$, $K_s \pi^0$, $K_s \omega$
- $h^0 = \pi^0$, $\eta \omega$

CP violation measurement performed using

$$\ln \mathcal{L} = \sum_i \ln P^\text{BABAR}_i + \sum_j \ln P^\text{Belle}_j$$

Indices $i$ and $j$ denotes the event reconstructed from BABAR and Belle data respectively.
CP violation in \( B^0 \rightarrow D_{cp} (*) h^0 \)

\[
\sin(2\phi_1) = 0.66 \pm 0.10 \pm 0.06
\]

The measurement is consistent with measurement from \( J/\psi K^0 \)

Purity = 63%

Purity = 55%
CPV in $b \rightarrow sqq$ decays $B^0 \rightarrow \eta'K^0$

**JHEP 10 (2014) 165**

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9th June 2015
CPV in $b \rightarrow sqq$ decays $B^0 \rightarrow \eta'K^0$

Consistent with $\sin 2\phi_1$ measured from $B^0 \rightarrow J/\psi K^0$
Process with third generation quarks and leptons

New physics could change:

• Branching fraction
• Tau polarization
• Effect could be different for D and D*

Experimental Challenge: 2 (hadronic tau decay) or 3 (leptonic tau decay) undetected neutrinos

\[
R = \frac{\mathcal{B}(\bar{B} \to D\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D\ell^-\bar{\nu}_\ell)} \quad R^* = \frac{\mathcal{B}(\bar{B} \to D^*\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^*\ell^-\bar{\nu}_\ell)}
\]

\( \ell^- = e^- \) or \( \mu^- \)
Signal Reconstruction

Four $D^{(*)}\ell^-$ ($\ell^-=e^-$ or $\mu^-$) samples:

- $D^+ \rightarrow K^-\pi^+\pi^+$, $K^0_S\pi^+\pi^+$, $K^0_S\pi^+\pi^0$, $K^0_S\pi^+\pi^+\pi^-$
- $D^0 \rightarrow K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$, $K^-\pi^+\pi^0$, $K^0_S\pi^0$
- $D^{*+} \rightarrow D^0\pi^+$, $D^+\pi^0$
- $D^{*0} \rightarrow D^0\pi^0$, $D^0\gamma$

$$M^2_{\text{miss}} = (p_{\text{beam}} - p_{B_{\text{tag}}} - p_{D^{(*)}} - p_{\ell})^2$$
- $-0.2 < M^2_{\text{miss}} < 8.0 \text{ GeV}^2/c^4$
- $q^2 > 4 \text{ GeV}^2/c^2$
Fit Projections High $M^2_{\text{miss}}$
Result

\[ R = 0.375^{+0.064}_{-0.063} \text{(stat.)} \pm 0.026 \text{(syst.)} \]

\[ R^* = 0.293^{+0.039}_{-0.037} \text{(stat.)} \pm 0.015 \text{(syst.)} \]

Correlation of stat. uncertainties: -0.56

SM: \quad R = 0.297 \pm 0.017
\quad R^* = 0.252 \pm 0.003

BaBar: \quad R = 0.440 \pm 0.058 \pm 0.042
\quad R^* = 0.332 \pm 0.024 \pm 0.018

PRL109,101802, PRD88,072012
How About New Physics?

Consistent with 2HDM of type at \( \tan\beta / m_{H^+} \approx 0.5 \text{ } c^2 / \text{GeV} \)

- Analysis repeated for 2HDM of type II with \( \tan\beta / m_{H^+} = 0.5 \text{ } c^2 / \text{GeV} \):
  
  \[
  R = 0.329 \pm 0.060 \pm 0.022 \\
  R^* = 0.301 \pm 0.039 \pm 0.015 \\
  R_{2HDM} = 0.590 \pm 0.125 \\
  R^*_{2HDM} = 0.241 \pm 0.007
  \]
Search for the dark photon and dark Higgs boson


Production and Decay: \[ e^+e^- \rightarrow A'h' \quad A' \rightarrow e^+e^-, \mu^+\mu^-, \text{ or } \pi^+\pi^- \]

(a) $m_{h'} < m_{A'}$:
(b) $m_{A'} < m_{h'} < 2m_{A'}$: $h' \rightarrow A'A^*$
(c) $m_{h'} > 2m_{A'}$: $h' \rightarrow A'A'$
Candidate Selection

Final Events summary after final selection

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<tr>
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<tr>
<td>$2(\mu^+\mu^-)X$</td>
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No significant Signal

$\alpha_D$: Dark photon coupling to dark Higgs boson: $\varepsilon^2 = \alpha'/\alpha_{em}$

90%CL upper limit on the product $\alpha_D \times \varepsilon^2$
The branching fraction $B^+ \to \tau^+ \nu_{\tau}$ is given by:

$$B(B^+ \to \tau^+ \nu_{\tau})_{SM} = \frac{G_F^2 m_B m_{\tau}^2}{8\pi} \left(1 - \frac{m_{\tau}^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

This is expected to be highest for leptonic decay:

$$B(B^+ \to \tau^+ \nu_{\tau}) = (0.75^{+0.10}_{-0.05}) \times 10^{-4}$$

From unitarity constrained.

B-decay constant from lattice calculation.

$B^+ \rightarrow \tau^+ \nu_\tau$ Result

\[ \mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau) = [1.25 \pm 0.28 \text{(stat.)} \pm 0.27 \text{(syst.)}] \times 10^{-4} \]
• Proceeds via $b \rightarrow u$ tree and ( EWP + QCD ) penguin
• $B \rightarrow \pi^0\pi^0$ needed to remove “penguin pollution”
• Theory (QCD fact.) $B \leq 1 \times 10^{-6}$ Nucl. Phys. B675 333(2003)
$B \rightarrow \pi^0 \pi^0$ Results (preliminary)

$B( B^0 \rightarrow \pi^0 \pi^0 ) = (0.90 \pm 0.12 \pm 0.10) \times 10^{-6}$
Conclusion

- Measured angles and phase are consistent with SM.
- But 10-20% NP effects are consistent with data.
Conclusion

\[ R = 0.375^{+0.064}_{-0.063} \text{(stat.)} \pm 0.026 \text{(syst.)} \]
\[ R^* = 0.293^{+0.039}_{-0.037} \text{(stat.)} \pm 0.015 \text{(syst.)} \]

Consistent with 2HDM of type at \( \tan \beta / m_{H^+} \approx 0.5 \text{ c}^2 / \text{GeV} \)

No significant signal for dark photon and dark Higgs

Measured branching ratio for B decays \( \tau \nu \) is consistent with SM

Measured branching ratio for B decays to \( \pi^0 \pi^0 \) is consistent with SM