Electroweak Penguin decays at Belle

Akimasa Ishikawa
KEK
Flavor Changing Neutral Current Decays

- Flavor Changing Neutral Current decays, $b \rightarrow s\gamma$, $b \rightarrow sll$
  - Forbidden at tree level
  - induced through Penguin or Box diagrams at lowest order
  - sensitive to heavy particles (SUSY, heavy Higgs)

- Observables
  - Decay Width (Branching Fraction)
    - Inclusive decay, theoretically clean, experimentally hard.
    - Exclusive decays, large uncertainty due to form factor
      - test of QCD in B decays
  - Ratio of Decay Width
    - Some theoretical and experimental uncertainties cancel
    - Good probe also for exclusive decays!
      - CP Asymmetry
      - Isospin Asymmetry
      - Up-Down Asymmetry
      - BF ratio of electron mode to muon mode
      - Forward-Backward Asymmetry
OPE and Wilson Coefficient

- Effective Hamiltonian is expressed in term of Operator Product Expansion.

\( \mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} C_i(\mu) O_i(\mu) \)

- \( O_{1,2} \): current current operator
- \( O_{3-6} \): QCD penguin operator
- \( O_{7,8} \): electro- and chromo-magnetic operator
- \( O_{9,10} \): semileptonic operator
- \( C_i \): Wilson coefficient

- Wilson coefficient is a strength of corresponding short distance operator.

- Precise measurement of Wilson coefficients is one of the goals for B physics.

- For \( b \rightarrow s \gamma \) and \( b \rightarrow ll \) case, only \( O_7, O_9 \) and \( O_{10} \) appear in the Hamiltonian.

New Physics changes the Wilson Coefficients
b$\rightarrow$s$\gamma$ and b$\rightarrow$sll decays

Decay widths for b$\rightarrow$s$\gamma$ and b$\rightarrow$sll can be described with Wilson coefficients.

- $\Gamma(b \rightarrow s\gamma) = \frac{G_F^2 \alpha_{em} m_b^5 |V_{ts}^* V_{tb}|^2}{32\pi^3} |C_7^{\text{eff}}|^2$  $\rightarrow$ Absolute value of $C_7^{\text{eff}}$ can be measured.

- $\frac{d\Gamma(b \rightarrow s\ell^+\ell^-)}{ds} = \left(\frac{\alpha_{em}}{4\pi}\right)^2 \frac{G_F^2 m_b^5 |V_{ts}^* V_{tb}|^2}{48\pi^3} (1 - s)^2$
  $$\times \left[ (1 + 2s) \left( |C_7^{\text{eff}}|^2 + |C_{10}^{\text{eff}}|^2 \right) + 4 \left( 1 + \frac{2}{s} \right) |C_7^{\text{eff}}|^2 + 12 \text{Re}(C_7^{\text{eff}} C_{10}^{\text{eff}}*) \right]$$

$\frac{d}{ds}(\Gamma_F^K - \Gamma_B^K) = \frac{G_F^2 m_b^5 |V_{ts}^* V_{tb}|^2}{32\pi^5} \bar{s}u(s)^2$
  $$\times \left[ \text{Re}(C_{9}^{\text{eff}}) C_{10}^{\text{eff}} VA_1 + \frac{\hat{m}_b}{\hat{s}} C_{7}^{\text{eff}} C_{10}^{\text{eff}} (VT_2(1 - \hat{m}_K^*) + A_1 T_1(1 + \hat{m}_K^*)) \right].$$

$\rightarrow$Relative signs can be also determined from interference terms!!

$C_7^{\text{eff}}, C_9^{\text{eff}}$ and $C_{10}^{\text{eff}}$ can be extracted from B(b$\rightarrow$s$\gamma$), B(b$\rightarrow$s$l^+l^-$) and A$_{FB}$ (b$\rightarrow$s$l^+l^-$)!

(sometimes we do not use $C_i$ but $A_i$ which is leading coefficient)

In the SM $\Lambda_7 = -0.330, \Lambda_9 = 4.069, \Lambda_{10} = -4.213$ at $\mu = 2.5$GeV
Branching Fraction of $B \rightarrow K^{*\gamma}$

- $b \rightarrow s \gamma$ was observed at CLEO in $K^{*\gamma}$
- $K^{*}$ is reconstructed from 4 modes
  - $K^+\pi^-, K_s\pi^0, K^+\pi^0, K_s\pi^+$
  - $|M_{K^*} - M_{K\pi}| < 75\text{MeV}$
- $B(B^0 \rightarrow K^{*0\gamma}) = (40.9 \pm 2.1 \pm 1.9) \cdot 10^{-6}$
- $B(B^+ \rightarrow K^{*+\gamma}) = (44.0 \pm 3.3 \pm 2.4) \cdot 10^{-6}$

- Better than 10% accuracy!
- Theoretical prediction
  - QCD fact. $\sim 70 \pm 25 \cdot 10^{-6}$
  - LEET $\sim 68 \pm 23 \cdot 10^{-6}$
  - pQCD $\sim 35 \pm 10 \cdot 10^{-6}$
  - Lattice $\sim 35 \pm 16 \cdot 10^{-6}$

Theoretical uncertainties are large

80/fb data
Asymmetry in $B \to K^{*\gamma}$

- Isospin Asymmetry $\Delta_{0+}$ is sensitive to sign of Wilson coefficients $C_6/C_7$
  \[
  \Delta_{0+} = \frac{\tau_{B^+}/\tau_{B^0}}{\tau_{B^0}/\tau_{B^0}} \frac{B(B^0 \to K^{0\gamma}) - B(B^+ \to K^{+\gamma})}{B(B^0 \to K^{0\gamma}) + B(B^+ \to K^{+\gamma})}
  \]

- $\Delta_{0+} = +5\text{~to}~10\%$ and $C_6/C_7 > 0$ in the SM
- If $C_6/C_7 < 0$, $\Delta_{0+} < 0$.

\[
\Delta_{0+} = (+3.4 \pm 4.4\text{(stat)} \pm 2.6\text{(syst)} \pm 2.5(f_+/f_{00}))\%
\]

- Direct CPV is less than 1% in the SM
- 5% CPV is allowed in new physics

$A_{CP} = (-0.1 \pm 4.4 \pm 0.8)\%$

Not only the $K^*0\gamma$, but any $K_s\pi^0\gamma$ can be used for TCPV measurement.

$$A_{CP} = \frac{\Gamma(B^0(t) \rightarrow K^0_s\pi^0\gamma) - \Gamma(B^0(t) \rightarrow K^0_s\pi^0\gamma)}{\Gamma(B^0(t) \rightarrow K^0_s\pi^0\gamma) + \Gamma(B^0(t) \rightarrow K^0_s\pi^0\gamma)} = S \sin \Delta m \Delta t + A \cos \Delta m t$$

In the SM, $S < 0.1$, $A < 0.01$.

Right handed currents induce large value of S

- $S$ corresponds to fraction of $C_{7R}$ to $C_{7L}$

$M_{K_s\pi^0} < 1.8$GeV

$$S(K_s^0\pi^0\gamma) = -0.58^{+0.46}_{-0.38} (stat) \pm 0.11 (syst)$$

$$A(K_s^0\pi^0\gamma) = +0.03 \pm 0.34 (stat) \pm 0.11 (syst)$$

Atwood, Gershon, Hazumi, Soni
PRD71 (2005) 076003

First Measurement

250/fb data
Observation of $B \rightarrow K \eta \gamma$

- $K_s \eta \gamma$ can be used for time dep. CPV measurement to search for right handed currents.
- $B \rightarrow K^+ \eta \gamma$, $K_s \eta \gamma$
  - $\eta$ is reconstructed from $\gamma \gamma$ and $\pi \pi \pi^0$
  - $M_{K\eta} < 2.4$GeV

$$B(B^+ \rightarrow K^+ \eta \gamma) = \left(8.4 \pm 1.5^{+1.2}_{-0.9}\right) \cdot 10^{-6}$$

$$B(B^0 \rightarrow K^0_s \eta \gamma) = 8.4^{+3.1}_{-2.7} \cdot 10^{-6}$$

$$A_{CP}(B^+ \rightarrow K^+ \eta \gamma) = 16 \pm 9 \pm 6\%$$

250/fb data
Observation of $B \to K_1(1270)\gamma$

- $B \to K\pi\pi^0\gamma$ final state via $K_1\gamma$ can be used for up-down Asymmetry to search for right handed currents.
  - $K_1(1270)$ is reconstructed from $K^+\pi^+\pi^-$ and $K^0\pi^+\pi^-$.  
  - $0.6 < M_{\pi\pi} < 0.9\text{GeV}$ ($\rho$ mass region) to enhance $K_1(1270)$  
  - Resonance components are extracted by fitting to the hadronic mass distribution.

$$B(B^+ \to K_1(1270)^+ \gamma) = (4.3 \pm 0.9 \pm 0.9) \cdot 10^{-5}$$

$$B(B^0 \to K_1(1270)^0 \gamma) < 5.8 \cdot 10^{-5}$$

$$B(B^+ \to K_1(1400)^+ \gamma) < 1.5 \cdot 10^{-5}$$

![Graphs showing $M_{bc}$ and $M(K^+\pi^+\pi^-)$ distributions](140/fb data)
Observation of $B \rightarrow p\Lambda\gamma$

- Baryon production via weak decay of meson
- Near threshold enhancement of dibaryon system is observed in $B \rightarrow p\Lambda\pi$ ($b \rightarrow s$ process)

$$B(B^+ \rightarrow p\Lambda\gamma) = \left(2.16^{+0.58}_{-0.53} \pm 0.20\right) \cdot 10^{-6}$$

Theoretical prediction $\sim 10^{-6}$

- Near threshold enhancement also observed
  - Fragmentation?

140/fb data
Inclusive $B\rightarrow X_s\gamma$

- Full inclusive $b\rightarrow\gamma$
- Photon with $E>1.8\text{GeV}$
- Veto photons from $\pi^0$ and $\eta$
- Subtract continuum with off-resonance data
- Moment analysis to extract HQET parameter

$$<E_\gamma> = 2.289 \pm 0.026 \pm 0.035 \text{ GeV}$$

$$<E_\gamma^2> - <E_\gamma>^2 = 0.0311 \pm 0.0073 \pm 0.0063 \text{ GeV}$$

$\rightarrow$ HQET parameter

$$\Lambda = 0.66^{+0.08}_{-0.05} \text{ GeV}/c^2$$

used to extract $V_{cb}$ and $V_{ub}$

140/fb data
BF of Inclusive $B \rightarrow X_s \gamma$

- Subtract $b \rightarrow d\gamma$ assuming $B(b \rightarrow d\gamma)/B(b \rightarrow s\gamma) = 3.8 \pm 0.6\%$

$$B(B \rightarrow X_s \gamma) = (3.59 \pm 0.32{\text{(stat)}} + 0.30{\text{(syst)}} + 0.11{\text{(theo)}}) \cdot 10^{-4}$$

- Measured BF is consistent with theoretical predictions.
  - $M_{H^+} > 200\text{GeV}$ 95%CL (M.Neubert CKM2005)

- Limit on Wilson coefficient $A_7$
  - $-0.36 < A_7 < -0.17$ or $0.21 < A_7 < 0.42$
  - In the SM $A_7 = -0.33$ at $\mu = 2.5\text{GeV}$
  - G.Hiller and F.Krueger
  - PRD 69 (2004) 074020
40% of $b \rightarrow s \gamma$ are measured exclusively.

Next step: $B^0 \rightarrow K^0 S^0 \gamma$ for TCPV analysis.

- $K_{\eta}$, $K_{f_0}$, $K_{a_0}$...
Search for $B \to \rho \gamma \omega \gamma$

- $b \to d \gamma$ process has not been observed
- Simultaneous fit to $B^- \to \rho^- \gamma$, $B^0 \to \rho^0 \gamma$ and $B^0 \to \omega \gamma$
- From isospin relations:
  \[
  B(B^- \to \rho^- \gamma) = 2 \left( \frac{\tau(B^-)}{\tau(B^0)} \right) \cdot B(B^0 \to \rho^0 \gamma) = 2 \left( \frac{\tau(B^-)}{\tau(B^0)} \right) \cdot B(B^0 \to \omega \gamma) 
  \]
  \[
  B(B \to (\rho, \omega) \gamma) = B(B \to \rho^- \gamma) < 1.4 \cdot 10^{-6}
  \]
  SM predictions:
  \[
  B(B^- \to \rho^- \gamma) = (0.90 \pm 0.34) \cdot 10^{-6} \text{ (Ali-Parkhomenko)}
  \]
  \[
  B(B^- \to \rho^- \gamma) = (1.50 \pm 0.50) \cdot 10^{-6} \text{ (Bosch-Buchalla)}
  \]
  Just above the SM prediction!!
- constrain $|V_{td}/V_{ts}|$
  \[
  \frac{B(B \to (\rho, \omega) \gamma)}{B(B \to K^* \gamma)} = \frac{|V_{td}|^2 (1 - m_{(\rho, \omega)/m_B^2})^3}{(1 - m_{K^*/m_B^2})^3} \zeta^2 (1 + \Delta R)
  \]
  \[
  \left| \frac{V_{td}}{V_{ts}} \right| < 0.22
  \]

$\Delta R$ : form factor ratio
$\zeta$ : SU(3) breaking effect
250/fb data
Inclusive $B \rightarrow X_s \ell \ell$

- Semi-inclusive technique
- Electron or muon pair
  - $M_{\ell \ell} > 0.2\text{GeV}$
  - Charmonium veto
- $X_s$ is reconstructed from $K^+$ or $K_s^0 + 0-4\pi$ (at most one $\pi^0$ is allowed)
  - $M_{X_s} < 2.0\text{ GeV}$

$$B(B \rightarrow X_s \ell^+ \ell^-) = \left(4.11 \pm 0.83^{+0.85}_{-0.81}\right) \cdot 10^{-6}$$

$$B(B \rightarrow X_s \mu^+ \mu^-) = \left(4.13 \pm 1.05^{+0.85}_{-0.81}\right) \cdot 10^{-6}$$

$$B(B \rightarrow X_s e^+ e^-) = \left(4.04 \pm 1.30^{+0.87}_{-0.83}\right) \cdot 10^{-6}$$

Theoretical prediction by Ali et al.

$$B(B \rightarrow X_s \ell^+ \ell^-) = \left(4.2 \pm 0.70\right) \cdot 10^{-6}$$

140/fb data
Clean prediction of BF of $B(B \to X_s \bar{l}l)$ for $1 < q^2 < 6 \text{GeV}^2$ is available.

- Combine Belle and Babar results
- Sign of $C_7$ flipped case with SM $C_9$ and $C_{10}$ value is unlikely.

<table>
<thead>
<tr>
<th>BF</th>
<th>Belle</th>
<th>Babar</th>
<th>WA</th>
<th>SM</th>
<th>$C_7 = -C_{7}^{\text{SM}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q^2 &gt; (2m_\mu)^2$</td>
<td>$4.11 \pm 1.1$</td>
<td>$5.6 \pm 2.0$</td>
<td>$4.5 \pm 1.0$</td>
<td>$4.4 \pm 0.7$</td>
<td>$8.8 \pm 0.7$</td>
</tr>
<tr>
<td>$1 &lt; q^2 &lt; 6 \text{GeV}^2$</td>
<td>$1.5 \pm 0.6$</td>
<td>$1.8 \pm 0.9$</td>
<td>$1.60 \pm 0.5$</td>
<td>$1.57 \pm 0.16$</td>
<td>$3.30 \pm 0.25$</td>
</tr>
</tbody>
</table>

![Graphs](image)

- $C_{10}^{\text{NP}}$
- $C_7^{\text{SM}}$
- $C_{10}^{\text{NP}}$
- $C_7 = -C_{7}^{\text{SM}}$
- $C_{9}^{\text{NP}}$
Branching Fraction of $B \to K^{(*)}ll$

- $K^+, K_s$ or $K^{(*)}(K^+\pi^-, K_s\pi^+, K^+\pi^0) + e^+e^-$ or $\mu^+\mu^-$
  - $M_{ll}>0.14\text{GeV}$

$$B(B \to K\ell^+\ell^-) = (5.50^{+0.75}_{-0.70} \pm 0.27 \pm 0.02) \times 10^{-7}$$
$$B(B \to K^{*}\ell^+\ell^-) = (16.5^{+2.3}_{-2.2} \pm 0.9 \pm 0.4) \times 10^{-7}$$

Prediction by Ali et al.
$$B(B \to K\ell^+\ell^-) = (3.5 \pm 1.2) \times 10^{-7}$$
$$B(B \to K^{*}\ell^+\ell^-) = (11.9 \pm 3.9) \times 10^{-7}$$

- A ratio of BF of $K^{(*)}\mu\mu$ to $K^{(*)}ee$ is sensitive to neutral heavy Higgs in 2HDM with large $\tan\beta$. In the SM, the ratio is $1.00$ and $\sim0.75$ for $Kll$ and $K^{*}ll$

$$\mathcal{R}_K = \frac{B(B \to K\mu\mu)}{B(B \to Kee)} = 1.38^{+0.39+0.06}_{-0.41-0.07}$$
$$\mathcal{R}_{K^*} = \frac{B(B \to K^{*}\mu\mu)}{B(B \to K^{*}\mu\mu)} = 0.98^{+0.30}_{-0.31} \pm 0.08$$

250/fb data

First look at $A_{FB}$ in $K^{*}ll$

- Sign of $C_7C_{10}$ can be determined from Forward-Backward Asymmetry in $K^{*}ll$.
- Raw $A_{FB}$ in each $q^2$ region is extracted from $M_{bc}$ fit.
- $K^{ll}$ has no asymmetry, so it is a good control sample.
- Curves show theoretical distributions including experimental efficiency effect (not fitted lines!).
- Both curves are in agreement with data, so far.

\[ \frac{d}{d\hat{s}}(\Gamma_F - \Gamma_B) = \frac{G_F^2 \alpha^2 m_b^5}{2^6 \pi^5} |V_{tb}^* V_{ts}|^2 \tilde{s}(\hat{s})^2 \times \left[ \text{Re}(C_9^{\text{eff}})C_{10}V A_1 + \frac{m_s}{\hat{s}} C_7^{\text{eff}} C_{10}(V T_2(1 - \bar{m}_{K^*}) + A_1 T_1(1 + \bar{m}_{K^*})) \right]. \]
Summary

- Many results for BF are consistent with the SM
  - Precision of BF($b\rightarrow s\gamma$) is 15% level.
    - Negative $A_7$ solution is consistent with the SM $A_7$ value
  - Upper limit on $B(B\rightarrow(\rho,\omega)\gamma)$ is just above the predictions
    - Constrain $|V_{td}/V_{ts}|$
  - Improved measurement of inclusive $B\rightarrow X_{sll}$ decay
    - Sign of $C_7$ flipped case with SM $C_9$ and $C_{10}$ values is unlikely
    - Stringent limits on $C_9$ and $C_{10}$

- Many measurements of Ratio
  - Precisions of $\Delta_{0+} (B\rightarrow K^{*}\gamma)$ are 5% level
    - Towards sign of $(C_6/C_7)$.
  - Time dep. CPV in $B\rightarrow K_s\pi^0\gamma$ is measured for the first time
    - Search for right handed component in $C_7$
  - First look at Forward-Backward Asymmetry in $B\rightarrow K^{*ll}$
    - Will be used for measurement of $A_9$ and $A_{10}$

- New results will be presented at Lepton Photon 05.
- Stay tuned
Backup Slides
**A_{FB} at Super Belle**

- 1 year running at $5 \times 10^{35}$/nb/sec
- $5/\text{ab}$ integrated luminosity, 10 billion B mesons!!
  - We have accumulated $\sim 0.46/\text{ab}$, about $x10$
- $\Delta A_9/A_9 \sim 11\%$, $\Delta A_{10}/A_{10} \sim 13\%$
  - $A_7$ fixed to SM value
  - Systematic error is not included

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**Belle Toy MC with 5/ab**

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**Donut**: $B(B \rightarrow Xsll)$ with $140/\text{fb}$

- $C_{10}^{NP}$
- $C_{9}^{NP}$

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**A_{FB} K^*ll with 5/ab**