b\rightarrow s\gamma \text{ Exclusive Decays}

Akimasa Ishikawa
(Tohoku University)
Evidence for $b \rightarrow s\gamma$

- CLEO found an evidence for $b \rightarrow s\gamma$ process using exclusive $B \rightarrow K^*(892)\gamma$ decays in 1993 with only $1.38\text{fb}^{-1}$ data on $Y(4S)$.

More than 20 years has passed from the evidence and now....
Now we are here

- Now we (Babar and Belle) have more than \(800\) times larger data of \(1144\text{fb}^{-1}\) \((433\text{fb}^{-1} + 711\text{fb}^{-1})\) on \(Y(4S)\) than data with which CLEO found an evidence for \(b \rightarrow s\gamma\).

- Further, LHCb collected \(3\text{fb}^{-1}\) at \(7\text{TeV}\) and \(8\text{TeV}\) at \(pp\) collisions.
  - \(\sigma_{bb} = 7.7\mu\text{b}\) for \(p_T^{bb} > 5\text{GeV}\) and \(2.5 < \eta < 4.0\) at \(7\text{TeV}\)

**Integrated luminosity of B factories**

Copious numbers of B hadrons are available.
Ideal tool to search for new physics

• Exclusive $b \to s \gamma$ decays can be used to measure
  – Branching fraction (BF)
    • Fragmentation of $X_s$
  – Direct CP Violation ($A_{CP}$)
    • To Search for New phase
  – Time dependent CP Violation ($S_{CP}$)
    • For $B^0 \to f_{CP} \gamma$ modes
    • to search for right handed current/new phase
    • CPV is suppressed by $O(m_s/m_b)$
  – Isospin Violation ($\Delta_{0+}$ or $A_I$)
    • Spectator dependent operator
  – Up-Down Asymmetry ($A_{UD}$)
    • For $B \to K_1 \gamma \to K \pi \pi \gamma$
    • To search for right handed current
    • New physics makes $|A_{UD}|$ value smaller than the SM
  – Photon Polarization from conversion (no groups measure yet)
    • To search for right handed current
Observed Exclusive Decays

- Now we observed:
  - $B \rightarrow K^*(892)\gamma$ in 1993
  - $B \rightarrow K_2^*(1430)\gamma$ in 2000
  - $B \rightarrow K\phi\gamma$ in 2004
  - $B \rightarrow K\eta\gamma$ in 2005
  - $B \rightarrow K_1(1270)\gamma$ in 2005
  - $B \rightarrow p\Lambda\gamma$ in 2007
  - $B \rightarrow K\eta'\gamma$ in 2010

Only 40% are exclusively known!
Direct CPV

- In the SM, $b \rightarrow s\gamma$ process is dominated by single EW penguin diagram, and further weak phase in $V_{ts}$ is suppressed by $O(\lambda^2)$, so direct CPV in $b \rightarrow s\gamma$ is small.
  - E.g. $A_{CP}(B \rightarrow K^*(892)\gamma) = -0.6 \pm 0.4\%$

- If new physics contribution to $b \rightarrow s\gamma$ has sizable amplitude and weak (+strong) phase, direct CPV could appear.

- Is the difference of direct CPV btw $B^0$ and $B^+$ interesting/sensitive NP also for exclusive decays?
  - Benzke, Lee, Neuber and Paz propose it for inclusive decays as a sensitive probe for new physics.
Direct CPV in $B \rightarrow K^*(892)\gamma$

- LHCb reported $A_{CP}$ with 1fb$^{-1}$
  - Only with $K^0 \rightarrow K^+\pi^-$
- W.A. consistent with null asymmetry predicted in the SM
  - $-0.6 \pm 0.4 \%$

- exp error 3times larger than theo
  - LHCb $1fb^{-1} \rightarrow 3fb^{-1}$
  - Belle $78fb^{-1} \rightarrow 711fb^{-1}$

<table>
<thead>
<tr>
<th>$A_{CP}$</th>
<th>$B^0$</th>
<th>$B^+$</th>
<th>$B$</th>
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<tbody>
<tr>
<td>Babar 347fb$^{-1}$</td>
<td>$-1.6 \pm 2.2 \pm 0.7 %$</td>
<td>$1.8 \pm 2.8 \pm 0.7 %$</td>
<td>$-0.3 \pm 1.7 \pm 0.7 %$</td>
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<tr>
<td>Belle 78fb$^{-1}$</td>
<td>n.a.</td>
<td>n.a.</td>
<td>$-1.5 \pm 4.5 \pm 1.2 %$</td>
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<tr>
<td>LHCb 1fb$^{-1}$</td>
<td>$0.8 \pm 1.7 \pm 0.9 %$</td>
<td>n.a.</td>
<td>$0.8 \pm 1.7 \pm 0.9 %$</td>
</tr>
<tr>
<td>Average</td>
<td>$0.7 \pm 1.9 %$</td>
<td>$1.8 \pm 2.9 %$</td>
<td>$0.1 \pm 1.3 %$</td>
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Isospin Violation

• Isospin Violation can be calculated in the SM.
\[ \Delta_{0-} = \frac{\Gamma(\bar{B}^0 \to \bar{K}^*0\gamma) - \Gamma(B^- \to K^-\gamma)}{\Gamma(\bar{B}^0 \to \bar{K}^*0\gamma) + \Gamma(B^- \to K^-\gamma)} \]
  
  – \( +5.0 \sim +10 \% \) \quad Kagan, Neubert
  
  – \( +2.7 \pm 0.8 \% \) \quad Matsumori, Sanda, Keum

• If new physics has isospin breaking contributions, such as spectator dependent diagrams, \( \Delta_{0-} \) could be deviated from the SM value
  
  – Even sign of Isospin Violation flips
Isospin Violation in $B \rightarrow K^* (892) \gamma$

- Babar and Belle measured isospin violation
  - thanks to high reconstruction efficiency for $K_s$ and $\pi^0$ involved modes at $e^+e^-$ machine

- Consistent with SM Predictions
  - $+5.0 \sim +10 \%$ Kagan, Neubert
  - $+2.7 \pm 0.8 \%$ Matsumori, Sanda, Keum

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<th>$\Delta_0$</th>
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<tr>
<td>Babar 347fb$^{-1}$</td>
<td>$6.6 \pm 2.1 \pm 2.2 %$</td>
</tr>
<tr>
<td>Belle 78fb$^{-1}$</td>
<td>$1.2 \pm 4.4 \pm 2.6 %$</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>$5.2 \pm 2.6 %$</td>
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Time dependent CPV

- In the SM, photon emitted from b is predominantly left handed. Time dependent CPV in $B \to f_{CP} \gamma$ is small due to small interference.

$$S^{SM} = -\sin 2\phi_1 \frac{m_s}{m_b} [2 + \mathcal{O}(\alpha_s)] + S^{SM, s\gamma g}$$

- If new physics has right handed current, time dependent CPV emerges by interference.
- Gluon emission $b \to s\gamma g$ processes make $S^{SM}$ larger than naive calculation?

$$S^{SM} \sim O(0.1)$$  
$$|S^{SM}| \sim 8\%$$

$$S^\text{SM}_{PQCD} = -(3.5 \pm 1.7)\%$$
$$S^{SM} = -0.022 \pm 0.015^{+0.01}_{-0.01}$$

References:
- Atwood, Gronau, Soni
- Atwood, Gershon, Hazumi, Soni
- Grinstein, Grossman, Ligeti, Pirjol
- Grinstein, Pirjol
- Matsumori, Sanda
- Ball, Zwicky
Time Dependent CPV in $B \rightarrow K\eta\gamma$

- Recently Belle reported measurement of time dependent CPV in $B \rightarrow K\eta\gamma$ with full data.
- Measured values are out of physical boundary but consistent with null CPV.

$$S_{CP} = -1.32 \pm 0.77(\text{stat.}) \pm 0.36(\text{syst.})$$
$$A_{CP} = -0.48 \pm 0.41(\text{stat.}) \pm 0.07(\text{syst.})$$
Summary of time dependent CP Violation

- Four decay modes are used to search for time dependent CPV.
  - \( f_{CP} = K_s\pi^0(K^0), K_s\eta, K_s\rho, K_s\phi \)
- All are consistent with null with stat errors.

\[ b \rightarrow s\gamma \quad S_{CP} \]

<table>
<thead>
<tr>
<th>( f_{CP} )</th>
<th>Babar</th>
<th>Belle</th>
</tr>
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<tr>
<td>( K_s\pi^0(K^0) )</td>
<td>427 fb(^{-1})</td>
<td>495 fb(^{-1})</td>
</tr>
<tr>
<td>( K_s\eta )</td>
<td>427 fb(^{-1})</td>
<td>711 fb(^{-1})</td>
</tr>
<tr>
<td>( K_s\rho )</td>
<td>n.a.</td>
<td>605 fb(^{-1})</td>
</tr>
<tr>
<td>( K_s\phi )</td>
<td>n.a.</td>
<td>711 fb(^{-1})</td>
</tr>
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Up Down Asymmetry

- Polarization of photon can be extracted from the $B \rightarrow K_1 \gamma \rightarrow (K \pi \pi) \gamma$ process by measuring up down asymmetry (photon polarization from $K_1$ polarization).
  - Angle $\theta$ btw photon and normal vector to $K_1$ decay plane.
  - Interference btw $\rho K$ and $K^*\pi$ generates imaginary part.
    - $\rightarrow$ modes involving $\pi^0$ gives larger $A_{UD}$
    - Need theoretical calculation of the amplitudes

\[
A_{up-down} \left( \frac{d\Gamma(B \rightarrow K_1 \gamma)}{dsd\phi d\cos \theta} \right) = \frac{1}{(s - m_{K_1}^2)^2 + m_{K_1}^2 \Gamma_{K_1}^2} \times \left\{ \frac{1}{4} |\mathcal{F}|^2 (1 + \cos^2 \theta) + \lambda_\gamma \frac{1}{2} Im[\bar{n} \cdot (\mathcal{F} \times \mathcal{F}^*)] \cos \theta \right\}
\]

\[
K^+_{res} \rightarrow \begin{cases} K^{*+} \pi^0 \\ K^{*0} \pi^+ \\ \rho^0 K^0 \end{cases} \rightarrow K^0 \pi^+ \pi^0
\]

\[
K^0_{res} \rightarrow \begin{cases} K^{*+} \pi^- \\ K^{*0} \pi^+ \\ \rho^0 K^+ \end{cases} \rightarrow K^+ \pi^- \pi^0
\]
Up Down Asymmetry in $B \rightarrow K\pi\pi\gamma$

- LHCb observed $A_{ud}$ with $3\text{fb}^{-1}$ in $B \rightarrow K^+\pi^-\pi^+\gamma$
  - With $13876\pm153$ signal events
- Measure $A_{ud}$ with 4 bins of $M_{K\pi\pi}$
  - No resonance separation
- $5.2\sigma$ significance from null polarization
- No interpretation to photon polarization yet

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<tr>
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<th>[1.1, 1.3]</th>
<th>[1.3, 1.4]</th>
<th>[1.4, 1.6]</th>
<th>[1.6, 1.9]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_1$</td>
<td>6.3±1.7</td>
<td>5.4±2.0</td>
<td>4.3±1.9</td>
<td>−4.6±1.8</td>
</tr>
<tr>
<td>$c_2$</td>
<td>31.6±2.2</td>
<td>27.0±2.6</td>
<td>43.1±2.3</td>
<td>28.0±2.3</td>
</tr>
<tr>
<td>$c_3$</td>
<td>−2.1±2.6</td>
<td>2.0±3.1</td>
<td>−5.2±2.8</td>
<td>−0.6±2.7</td>
</tr>
<tr>
<td>$c_4$</td>
<td>3.0±3.0</td>
<td>6.8±3.6</td>
<td>8.1±3.1</td>
<td>−6.2±3.2</td>
</tr>
<tr>
<td>$A_{ud}$</td>
<td>6.9±1.7</td>
<td>4.9±2.0</td>
<td>5.6±1.8</td>
<td>−4.5±1.9</td>
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b\rightarrow d\gamma Exclusive Decays

Given title is b\rightarrow s\gamma exclusive decays
but I would add b\rightarrow d\gamma
b→dγ Decays

• The b→dγ is suppressed by Vtd
  – About 30 times smaller than b→sγ ( |Vtd/Vts|^2 )
  – Need very good PID detector and EM Calorimeter

• The observables to search for NP are the same as the b→sγ but NP contribution could be different.
  – Branching fraction (BF)
  – Direct CP Violation (A_{CP})
  – Time dependent CP Violation (S_{CP})
  – Isospin Violation (\Delta_{\rho})
  – Up-Down Asymmetry (A_{UD})
  – Photon Polarization from conversion (no groups measure yet)
Observation of $b \rightarrow d\gamma$

- Belle had observed $b \rightarrow d\gamma$ process using exclusive $B \rightarrow (\rho, \omega)\gamma$ with 357fb$^{-1}$ data in 2006
\[ |V_{td}/V_{ts}|, A_{CP} \text{ and } \Delta_\rho \]

- \( |V_{td}/V_{ts}| \) can be measured from the ratio of BF of \( B \to (\rho, \omega)\gamma \) and \( B \to K^*\gamma \)
  - Consistent with the SM
- Direct CPV in \( B \to \rho^+\gamma \) consistent with null
- \( \Delta_\rho \) Isospin Violation large?
  \[ \Delta_\rho = \frac{\Gamma(B^- \to \rho^-\gamma)}{2\Gamma(B^0 \to \rho^0\gamma)} - 1 \]
  - 2~3\sigma deviation
  - + 4^{+14}_{-7} \%
  - − 10±6 \%
  - − 5.4±3.9 \% if \( \phi_3 = 60\text{deg} \)
  - − 4.6±7 \%

|                | \( |V_{td}/V_{ts}| \)       | \( A_{CP}(B^+ \to \rho^+\gamma) \) | \( \Delta_\rho \)          |
|----------------|-----------------------------|---------------------------------|---------------------------|
| Babar 423fb⁻¹  | \( 0.233^{+0.025+0.022}_{-0.024-0.021} \) | n.a.                           | \(-0.43^{+0.25}_{-0.22} \pm 0.10 \) |
| Belle 605fb⁻¹  | \( 0.195^{+0.020}_{-0.019} \pm 0.015 \)       | \( 0.11 \pm 0.32 \pm 0.09 \)    | \(-0.48^{+0.21+0.08}_{-0.19-0.09} \) |
| Average        | n.a.                         | \( 0.11 \pm 0.33 \)            | \(-0.46^{+0.17}_{-0.16} \) |
Time Dependent CPV in $B^0 \rightarrow \rho^0 \gamma$

- Only Belle had measured time dependent CPV in $B^0 \rightarrow \rho^0 \gamma$
- $48 \pm 14$ signal events are used for fits.
  - Though signal yield is smaller than $B^0 \rightarrow K\pi \pi^0 \gamma$, fraction of events used for time dependent fit is larger thanks to easier vertex reconstruction with $\rho^0 \rightarrow \pi^+ \pi^-$
- The results are consistent with null asymmetry

$$S_{CP} = -0.83 \pm 0.65 \pm 0.18$$

$$A_{CP} = -0.44 \pm 0.49 \pm 0.14$$
Summary

• Many studies of $b \rightarrow s\gamma$ are performed in more than 20 years to search for new physics.
  – No hint of new physics yet.
• New window $b \rightarrow d\gamma$ was opened since 2006.
  – A hint in Isospin Asymmetry??
• Some analyses in $b \rightarrow s\gamma$ and all analyses in $b \rightarrow d\gamma$ are still statistical error dominant
  – Need higher luminosity experiments
  – $\rightarrow$ Belle II and LHCb upgrade
• Some theoretical predictions are different btw groups.
  – Isospin violation
  – Time dependent CPV
  – Hope the predictions improved in coming several years.
backup
$C_{CP} = -A_{CP}$