Experimental issues for measurements of the time-dependent CPV in $b \rightarrow s\gamma$ decays

Super B Factory Workshop, Hawaii April 2005

Wouter Hulsbergen (Maryland)

Outline

- motivation for studying TDCPV in $b \rightarrow s\gamma$
- experimentally accessible modes
- main experimental issues
- expected sensitivity in a super $B$ factory
Motivation

- standard model: photon in $b \rightarrow q\gamma$ is predominantly left-handed

- Atwood, Gronau, Soni (1997): time-dependent CPV in $B^0 \rightarrow M_{CP}^0 \gamma$ decays is probe for photon polarization

\[
B^0 \rightarrow M^0\gamma_R \\
\bar{B}^0 \rightarrow M^0\gamma_L \rightarrow M^0\gamma_R
\]

interference suppressed by $\frac{2m_q}{m_b}$

- in the standard model, neglecting final state effects

\[
S(B^0 \rightarrow K^{*0}(\rightarrow K_s^0\pi^0)\gamma) = \eta_{CP} \times \sin(2\beta + 2\beta_s) \times 2m_s/m_b
\]

\[
S(B^0 \rightarrow \rho^0\gamma) = \eta_{CP} \times '0' \times 2m_d/m_b
\]

- Atwood, Gershon, Hazumi, Soni (2004): value of $S$ independent of resonance structure in $B^0 \rightarrow P_1P_2\gamma$ can extend analysis to inclusive $B^0 \rightarrow K_s^0\pi^0\gamma$

- Grinstein, Grossman, Ligeti, Pirjol (2004): $b \rightarrow q\gamma g$ contribution not negligible

  - contribution from opposite helicity photon of order 0.1

  - contribution depends on $m_{P_1P_2}$
Which modes do we consider?

The most accessible modes are

<table>
<thead>
<tr>
<th>mode</th>
<th>$B \times 10^6$</th>
<th>typical efficiency</th>
<th>typical $S/B$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to K^*(890)^0\gamma \to K^0\pi^0\gamma$</td>
<td>13.4</td>
<td>0.055</td>
<td>1.5</td>
<td>[1,2]</td>
</tr>
<tr>
<td>$B^0 \to K_2^*(1430)^0\gamma \to K^0\pi^0\gamma$</td>
<td>2.1</td>
<td>0.05</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>other $B^0 \to K^0\pi^0\gamma$</td>
<td>$0 - 4?,$</td>
<td>0.05</td>
<td>0.5?</td>
<td></td>
</tr>
<tr>
<td>$B^0 \to K^0\eta\gamma$</td>
<td>$9 \pm 3,$</td>
<td>0.01?</td>
<td>0.8</td>
<td>[3]</td>
</tr>
<tr>
<td>$B^0 \to K^0\eta'\gamma$</td>
<td>$\sim 10?,$</td>
<td>0.01?</td>
<td>0.5?</td>
<td></td>
</tr>
<tr>
<td>$B^0 \to K^0\phi\gamma$</td>
<td>$\sim 3,$</td>
<td>0.013</td>
<td>3</td>
<td>[4]</td>
</tr>
<tr>
<td>$B^0 \to \rho^0\gamma$</td>
<td>$\sim 1,$</td>
<td>0.15</td>
<td>0.2?</td>
<td>[5,6]</td>
</tr>
<tr>
<td>$B^0 \to \omega\gamma$</td>
<td>$\sim 1?,$</td>
<td>0.09</td>
<td>0.3?</td>
<td>[5,6]</td>
</tr>
</tbody>
</table>


Note:

- not all these modes have been seen yet
- efficiencies and $S/B$ not necessarily optimal for CPV measurement
What are the experimental issues?

- small branching fractions
  → need large data samples

- large backgrounds
  - physics background: continuum, other $B \rightarrow X\gamma$ decays, other $B$ decays
  - machine background? → not in this talk

- for the most prominent $b \rightarrow s\gamma$ modes: $\Delta t$ reconstruction

This talk: concentrate on $B^0 \rightarrow K^0_s\pi^0\gamma$, since that is where we have experience
What do we know about $B^0 \rightarrow K\pi\gamma$?

- branching fraction and direct $CP$ asymmetry well measured in the self-tagging decays (charged kaon)

- contributions to $B^0 \rightarrow K\pi\gamma$ from

<table>
<thead>
<tr>
<th></th>
<th>$\mathcal{B}$ to $K\pi$</th>
<th>$\mathcal{B} \times 10^6$</th>
<th>$\mathcal{A}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*(890)^0$</td>
<td>1</td>
<td>$40.1 \pm 2.0$</td>
<td>$-0.03 \pm 0.03$</td>
</tr>
<tr>
<td>$K_2^*(1430)^0$</td>
<td>0.5</td>
<td>$12.4 \pm 2.4$</td>
<td>$-0.08 \pm 0.15$</td>
</tr>
<tr>
<td>$K^*(1410)^0$</td>
<td>$&gt; 0.4$</td>
<td></td>
<td>$&lt; 130$</td>
</tr>
<tr>
<td>N.R. $(1.25 &lt; m_X &lt; 1.6)$</td>
<td></td>
<td></td>
<td>$&lt; 2.6$</td>
</tr>
</tbody>
</table>

- note I: results for $K^*(1410)^0$ and N.R. obtained by BELLE on only 29.4/fb

  → more experimental input will help to understand how much statistics there actually is

- note II: signal-to-background-ratio depends on $m_{K\pi}$

  → this is of some relevance for systematic uncertainties
\(K\pi\) invariant mass distribution

- \(K^+\pi^-\gamma\) in 29/fb
  **Belle** hep-ex/0205025

\[ \begin{array}{c}
\text{Events/(50MeV/c}^2) \\
\end{array} \]

- \(K^+\pi^-\gamma\) in 81/fb
  **Babar** hep-ex/0409035

\[ \begin{array}{c}
\text{Events/(0.06 GeV/c}^2) \\
\end{array} \]

- \(K^0\pi^0\gamma\) in 253/fb
  **Belle** hep-ex/0503008

  \(\text{signal yield from binned fit}\)

- \(K^0\pi^0\gamma\) in 210/fb
  **Babar** Moriond 2005

\[ \begin{array}{c}
\text{Weighted events} \\
\end{array} \]
$\Delta t$ reconstruction for $B^0 \rightarrow K^0_S\pi^0\gamma$

Challenging vertexing problem:

- $\Delta t$ requires $z$ position of $B_{CP}$
- no charged tracks from $B$ vertex!
  $\rightarrow K^0_S$ provides single 'trajectory'

Can we reconstruct the $B$ vertex with only one trajectory?
Challenging vertexing problem:

- $\Delta t$ requires $z$ position of $B_{CP}$
- no charged tracks from $B$ vertex!
  $\rightarrow K^0_S$ provides single ‘trajectory’

Solution (*BABAR* 2003)

- exploit small $B$ lifetime + large boost
  $\rightarrow$ small transverse motion
- intersect $K^0_S$ with beam trajectory
  - size and position of interaction region (IR) known
  - increase size to account for transverse motion of $B_{CP}$
  - intersect $K^0_S$ trajectory and IR in transverse plane
- resolution not much worse than for ‘normal’ decays, because tagvertex ‘dominates’ uncertainty
**$\Delta t$ reconstruction for $B^0 \rightarrow K^0_S \pi^0 \gamma$**

Challenging vertexing problem:
- $\Delta t$ requires $z$ position of $B_{CP}$
- no charged tracks from $B$ vertex! $\rightarrow K^0_S$ provides single 'trajectory'

New development in 2004
- 'beam-constraint' on $B$ decay vertex does not really account from transverse motion $\rightarrow$ leads to small bias in $\Delta t$ scale
- used new vertexing algorithm (arxiv:physics/0503091) to apply constraint to $B$ production vertex instead
- $\Delta t$ now extracted from vertex fit to complete $\Upsilon(4S) \rightarrow B^0\bar{B}^0$ decay tree $\rightarrow$ requires sum-of-B-lifetime constraint to retain accuracy of old method

Remaining systematic uncertainty from vertex technique is small
Resolution depends on number of SVT layers traversed by pions from $K_S^0 \ldots$
Vertexing inefficiency

Events with $\sigma(\Delta t) > 2.5$ ps are not used for time-dependent fits

Fraction of usable events depends on $K^0_S$ momentum spectrum:

- $B^0 \rightarrow K^0_S\pi^0$, $\epsilon_{\text{vtx}} \approx 0.61$
- $B^0 \rightarrow K^{*0}\gamma$, $\epsilon_{\text{vtx}} \approx 0.72$
**$\Delta t$ resolution**

**$\sigma(\Delta t)$ for different samples**

- $J/\Psi K_s^0$, mean = 0.66
- $K_s^0\pi^0$, mean = 1.01
- $K_s^0\pi^0\gamma$, mean = 1.14
- 'mangled' $J/\Psi K_s^0$

**error on $S$ from 100 perfectly tagged events**

\[
0.136 \sqrt{1 + x^2/1.26^2}
\]

**Loss in sensitivity due to loss in vertexing resolution:**

- $\sim 15\%$ from 'vertexing efficiency'
- $\sim 20\%$ from resolution effect

---

<table>
<thead>
<tr>
<th></th>
<th>$\langle \sigma(\Delta t) \rangle$</th>
<th>$\sigma(S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi K_s^0$</td>
<td>0.66</td>
<td>$\sim 0.15$</td>
</tr>
<tr>
<td>$K_s^0\pi^0\gamma$</td>
<td>1.14</td>
<td>$\sim 0.18$</td>
</tr>
</tbody>
</table>
SVT geometry

Babar and Belle vertex detectors

Beam Pipe 27.8mm radius
Layer 5a
Layer 5b
Layer 4b
Layer 4a
Layer 3
Layer 2
Layer 1

<table>
<thead>
<tr>
<th></th>
<th>BELLE SVD1</th>
<th>BELLE SVD2</th>
<th>BABAR SVT</th>
</tr>
</thead>
<tbody>
<tr>
<td>outer radius [cm]</td>
<td>6.0</td>
<td>8.8</td>
<td>14.2</td>
</tr>
<tr>
<td>inner radius [cm]</td>
<td>3.0</td>
<td>2.0</td>
<td>3.2</td>
</tr>
<tr>
<td>beam pipe [cm]</td>
<td>2.0</td>
<td>1.5</td>
<td>2.8</td>
</tr>
<tr>
<td>’vertexing efficiency’</td>
<td>0.41</td>
<td>0.55</td>
<td>0.72</td>
</tr>
</tbody>
</table>

Size matters!

need precision tracking up to large distances
Backgrounds

Background sources

- combinatorial background from the continuum
- $B \rightarrow X\gamma$ background, for example $B^+ \rightarrow K_s^0\pi^+\gamma$
  → real photon, but soft/fake $\pi^0$ from the other $B$
- ‘generic’ $B$ background, for example $B \rightarrow XK_s^0\pi^0$, $B \rightarrow XK_s^0\eta$
  → photon background from hard $\pi^0$ or $\eta$
  → partially removed with explicit $\pi^0/\eta$ vetoes

Estimated composition of data sample per 1/ab, using current BABAR selection:

<table>
<thead>
<tr>
<th></th>
<th>$0.8 &lt; m_{K\pi} &lt; 1.0$</th>
<th>$1.1 &lt; m_{K\pi} &lt; 1.8$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>fit region</td>
<td>signal region</td>
</tr>
<tr>
<td>signal</td>
<td>840</td>
<td>650</td>
</tr>
<tr>
<td>continuum</td>
<td>6200</td>
<td>230</td>
</tr>
<tr>
<td>$B\bar{B}$</td>
<td>200</td>
<td>40</td>
</tr>
</tbody>
</table>

Fit region: $m_{ES} > 5.2$, $-0.25 < \Delta E < 0.25$. Signal box: $m_{ES} > 5.27$, $-0.2 < \Delta E < 0.1$, $L_2/L_0 < 0.4$

There is a substantial background from other $B$ decays
**Fitting for background composition**

*BABAR* data + fit for $B^0 \rightarrow K^{*0}\gamma$

![Graphs showing data and fit for $B^0 \rightarrow K^{*0}\gamma$.](image)

Compare fitted $B\bar{B}$ yield to expectation (*BABAR*, Moriond 2005):

<table>
<thead>
<tr>
<th></th>
<th>$K^{*}(890)$ region</th>
<th>above the $K^{*}(890)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$0.8 &lt; m_{K_S^0\pi^0} &lt; 1.0$</td>
<td>$1.1 &lt; m_{K_S^0\pi^0} &lt; 1.8$</td>
</tr>
<tr>
<td>MC expectation</td>
<td>$\sim 44$</td>
<td>$\sim 170$</td>
</tr>
<tr>
<td>fit</td>
<td>$8 \pm 9$</td>
<td>$125 \pm 40$</td>
</tr>
</tbody>
</table>

Can we really fit for this? How do we deal with background *asymmetries*?
Systematic uncertainties due to background

- continuum background is not a real problem
  - expect no correlation between asymmetry and main $B$ selection variables
  - extract average asymmetry from 'sidebands'

- background from $B$ decays is *much larger problem*
  - different decays contribute with different (unknown) asymmetries:
    - asymmetry depends on $\Delta E$ and $m_{ES}$
    - cannot extract meaningful asymmetry from fit
  - current approach (babar)
    - use MC to estimate $B\bar{B}$ background yield
    - vary asymmetry within suitable range

Current uncertainty from $B\bar{B}$ background from BABAR:

<table>
<thead>
<tr>
<th>$0.8 &lt; m_{K_S^0\pi^0} &lt; 1.0$</th>
<th>$1.1 &lt; m_{K_S^0\pi^0} &lt; 1.8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{syst}^{B\bar{B}}(S)$</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>0.24</td>
</tr>
</tbody>
</table>

- resonant/non-resonant differ due to ratio of signal to $B\bar{B}$ yield
- errors will decrease with better understanding of $B\bar{B}$ background composition and/or tighter cuts
Total systematic uncertainty for $S(K^*\gamma)$

From most recent measurements:

<table>
<thead>
<tr>
<th></th>
<th>BABAR (Moriond)</th>
<th>BELLE (hep-ex/0503008)</th>
</tr>
</thead>
<tbody>
<tr>
<td>resolution function</td>
<td>0.01</td>
<td>0.05</td>
</tr>
<tr>
<td>vertexing technique</td>
<td>0.02</td>
<td>0.06</td>
</tr>
<tr>
<td>svt misalignment</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>background fraction</td>
<td></td>
<td>0.02</td>
</tr>
<tr>
<td>signal/background pdfs</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>$B\bar{B}$ background asymmetry</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>tag side interference, $\Delta m_B, \tau_B$</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>total</td>
<td>0.05</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Experience/outlook from BABAR:

- current $B\bar{B}$ background asymmetry is ‘conservative’: just needs more work
- ‘vertexing/resolution function’ systematics limited by control sample size
- other contributions will become as small as for other $CP$ measurements, like $\sin 2\beta_{\psi K_S}^0$

$\text{systematic uncertainty of } \lesssim 0.03 \text{ not unrealistic}$
Expected errors for some modes

Expected uncertainties for various modes, using efficiencies and $S/B$ from slide 3:

![Graph showing statistical error in $S$ for 50/ab and estimated error on $S$ for $B^0 \rightarrow K^{*0} \gamma$.]

Large uncertainties in some of these numbers: branching fractions, efficiencies, background rates

At $\sim 50/ab$, "systematic uncertainty $\approx$ statistical uncertainty" for $B^0 \rightarrow K^{*0} \gamma$
Summary

- measuring photon polarization in $B^0 \to X\gamma$ decays via time-dependent CPV feasible for a handful of modes

- systematic uncertainty on $S$ is

$$\sigma(\psi K^0_s) \oplus \sigma(\text{vertexing}) \oplus \sigma(B\bar{B}\text{background}) \lesssim 0.03$$

- for $B^0 \to K^{*0}\gamma$ statistical uncertainty matches systematic at about 50 ab$^{-1}$

  $\Rightarrow$ at 50 ab$^{-1}$, $\sigma(S) \lesssim 0.04$

- for other modes, statistical errors dominate even at 50 ab$^{-1}$

  $\Rightarrow$ uncertainty on $S$ typically between 0.05 and 0.1
Backup Slides
How to estimate the error for other modes?

Used following expressions to estimate error in measured asymmetry:

\[
\sigma(A) = \frac{1}{\sqrt{N_S}} \times \sqrt{\frac{N_S + N_B}{N_S}} \times \sqrt{\frac{1}{\epsilon_{\text{tag}}} \times f(\sigma(\Delta t))}
\]

\[
\epsilon_{\text{tag}} = 0.30
\]
\[
\langle f_S \rangle \approx 1.4\sqrt{1 + \langle \sigma(\Delta t)/1.26 \rangle^2 / \epsilon_{\text{vtx}}}
\]
\[
\langle f_C \rangle \approx 1.3
\]

- parameters tuned to match toy MC expectations for \( K_S^0 \pi^0 \)
- expression within \( \sim 5\% \) accurate for \( K_S^0 \pi^0, K_S^0 \pi^0 \gamma \) and \( J/\psi K_S^0 \)
Separating background in $m_{ES}/\Delta E$

Typical for $B\bar{B}$ background:
- (sort of) peaks in $m_{ES}$
- occupies low sideband in $\Delta E$
**B** background and low momentum $\pi^0$

Most $B\bar{B}$ background associated with low momentum $\pi^0$ candidates:

- Use hard cuts on $\pi^0$ energy.