Measurements of resonant
$B^+ \rightarrow K^+ \gamma \gamma$ at Belle

Jean Wicht
LPHE-EPFL, Lausanne
Monday morning seminar, 5 December 2005
History of $B^+ \rightarrow K^+ \gamma \gamma$

T. Schietinger™

- 2003: Choudhury et al. find $1.477 \times 10^{-6} < \text{BF}(B^+ \rightarrow K^+ \gamma \gamma) < 1.748 \times 10^{-6}$ !!1!
- 2004: for his master thesis, Mathias Knecht repeats the Choudhury calculation using EvtGen, finds a much smaller branching fraction!
- 2005: Hiller and Safir publish a SCET calculation that gives $\text{BF} = O(10^{-9})$!
  Choudhury et al. acknowledge a mistake and publish an erratum.
- 2005: Mathias shows that the resonant decay $B^+ \rightarrow K^{*+}(K^+\gamma) \gamma \rightarrow K^+ \gamma \gamma$ eclipses the non-resonant $B^+ \rightarrow K^+ \gamma \gamma$ everywhere in phase space. This means: we will never be able to measure $B^+ \rightarrow K^+ \gamma \gamma$!
- New goal: search for charmonium resonances in $B^+ \rightarrow K^+ \gamma \gamma$
  - Radiative decay not well known
  - Interference between $K \eta_c(\gamma\gamma)$ and $K^*(K\gamma)\gamma$ (seminar in two weeks by Mathias Knecht)
Lausanne, 05.12.2005

J. Wicht : B to K gamma gamma

Belle Experiment

B mesons production : $e^+e^- \rightarrow \gamma(4S) \rightarrow BB$

Background : $e^+e^- \rightarrow u\bar{u},d\bar{d},s\bar{s}$ (uds)
           $e^+e^- \rightarrow c\bar{c}$ (charm)

1:3

continuum
Belle Experiment : data

- KEKB reached $500\text{fb}^{-1}$ on 22. november 2005
  - $446\text{fb}^{-1}$ on $\Upsilon(4S)$ ($E_{\text{beam}} = 5.289 \text{GeV}$)
  - $52\text{fb}^{-1}$ off-resonance ($E_{\text{beam}} = 5.258 \text{GeV}$)
  - $2\text{fb}^{-1}$ on $\Upsilon(5S) : B_s$
- Currently taking about $1\text{fb}^{-1}/\text{day}$
- Available for analysis:
  - $\Upsilon(4S)$: on resonance data: $414.37 \text{fb}^{-1}$ (about $447 \times 10^6$ BB pairs)
    off resonance data: $47.13 \text{fb}^{-1}$
- Summer 2003: SVD upgrade $\Rightarrow$ two sets of data
  - SVD1: $140\text{fb}^{-1}$
  - SVD2: $274\text{fb}^{-1}$

Results for today
Search for resonant decays

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>J PC</th>
<th>B to K X</th>
<th>X to gam gam</th>
<th>Total (10^-7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B K η</td>
<td>0.548</td>
<td>0+</td>
<td>2.1 x 10^-6 [1]</td>
<td>(39.43 ± 0.26) % [2]</td>
</tr>
<tr>
<td>B K η'</td>
<td>0.958</td>
<td>0+</td>
<td>78 x 10^-6 [2]</td>
<td>(2.12 ± 0.14) % [2]</td>
</tr>
<tr>
<td>B K η_c</td>
<td>2.980</td>
<td>0+</td>
<td>9.0 x 10^-4 [2]</td>
<td>(4.3 ± 1.5) x 10^-4 [2]</td>
</tr>
<tr>
<td>B K η'_c</td>
<td>3.654</td>
<td>0+</td>
<td>3 x 10^-4 [3]</td>
<td>&lt; 0.01 [2]</td>
</tr>
<tr>
<td>B K χ_c0</td>
<td>3.415</td>
<td>0''</td>
<td>6.0 x 10^-4 [2]</td>
<td>(2.6 ± 0.5) x 10^-4 [2]</td>
</tr>
<tr>
<td>B K χ_c2</td>
<td>3.556</td>
<td>2++</td>
<td>&lt; 2.5 x 10^-4 [4]</td>
<td>(2.46 ± 0.23) x 10^-4 [2]</td>
</tr>
</tbody>
</table>

[1] BELLE
[3] BELLE
[4] BELLE preliminary
Analysis overview

• Cuts
  – \( m_{bc} > 5.2 \text{ GeV/c}^2 \) and \(-0.3 < \Delta E < 0.3 \text{ GeV}\)
  – \( \pi^0 \) suppression \( (E_\gamma > 100 \text{ MeV}) \)
  – low energy gamma background suppression : \( E_\gamma > 100 \text{ MeV} \)
  – gamma energy asymmetry = \(|(E_{\gamma_1} - E_{\gamma_2})/(E_{\gamma_1} + E_{\gamma_2})| < 0.9\)

• Selection
  – Kaon identified via \( L(K/\pi) > 0.6 \) (all others charged tracked assumed as pions)
  – Association of photons : if \( m_{\gamma\gamma} \) in large sel. window -> mass constrained fit
  – Best candidate selection
    • Smallest \( \chi^2 \) of the mass fit
    • If multiple kaons can associate : best kaon = \( L(K/\pi) \) max
  – Multiple candidates per event is possible but only one per resonance
Continuum suppression

Events topology is used to suppress continuum:

- Super Fox-Wolfram (SFW): event sphericity
- $\theta_B^{CM}$: $B$ decays from $\Upsilon(4S)$
- $\Delta z$: $B$ mesons fly
- Flavor tagging: tool intended to work with $B$
Event sphericity : SFW

**Continuum**: because of the lights quarks, most of the energy is used to create momenta (jets)

**BB**: most of the energy is used to create B mesons mass

---

Lausanne, 05.12.2005

J. Wicht : B to K gamma gamma
\[ |\cos(\theta_B)\rangle_{\text{CM}} \]

**B mesons decay from \( \Upsilon(4S) \)**

<table>
<thead>
<tr>
<th>ID</th>
<th>1500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>46074</td>
</tr>
<tr>
<td>Mean</td>
<td>0.3823</td>
</tr>
<tr>
<td>RMS</td>
<td>0.2506</td>
</tr>
</tbody>
</table>

- \( \chi^2 / n \text{d.f.} = 70.94 / 57 \)
- \( A0 = 1166. \pm 12.14 \)
- \( A1 = -229.7 \pm 48.05 \)
- \( A2 = -852.7 \pm 41.27 \)

**Continuum don’t**

<table>
<thead>
<tr>
<th>ID</th>
<th>1600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>369532</td>
</tr>
<tr>
<td>Mean</td>
<td>0.5040</td>
</tr>
<tr>
<td>RMS</td>
<td>0.2867</td>
</tr>
</tbody>
</table>

- \( \chi^2 / n \text{d.f.} = 120.1 / 57 \)
- \( A0 = 5807. \pm 30.02 \)
- \( A1 = 1523. \pm 139.5 \)
- \( A2 = -1234. \pm 135.1 \)
Found by some "Belle Toolkit" (not 100% efficient)
Flavor tagging

- Flavor tagging from $B_{\text{other side}}$ by some “Belle Toolkit”
  - I get flavor ($\pm 1$) and a quality indicator (0<qual<1)
  - I use as variable: $q_{\text{kaon}} \times \text{flavor} \times \text{qual}$

![Graphs showing continuum and signal distributions]
Continuum suppression

- I build a Likelihood Ratio with the PDFs of the three first variables for both signal ($SFW_s, acthb_s, \Delta z_s$) and continuum ($SFW_B, acthb_B, \Delta z_B$):

\[
LR(SFW, acthb, \Delta z) = \frac{SFW_s(SFW) acthb_s(\Delta z) \Delta z_s(\Delta z)}{SFW_s(SFW) acthb_s(\Delta z) \Delta z_s(\Delta z) + SFW_B(SFW) acthb_B(\Delta z) \Delta z_B(\Delta z)}
\]

2D cut between LR and “$q_B$ flavor quality” to optimize significance (statistical signification):

\[
\frac{S}{\sqrt{S+B}}
\]
Expected significance and efficiency

- Signal: 160'000 signal events for each resonance
- Continuum: about 1.5 * luminosity

<table>
<thead>
<tr>
<th>Channel</th>
<th>Assumed BF (10^{-7})</th>
<th>Signal Window</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B \rightarrow K X \rightarrow K \gamma \gamma</td>
<td>nSig</td>
</tr>
<tr>
<td>K \eta</td>
<td>8.67</td>
<td>44.4</td>
</tr>
<tr>
<td>K \eta'</td>
<td>14.42</td>
<td>97.3</td>
</tr>
<tr>
<td>K \eta_c</td>
<td>5.76</td>
<td>26.8</td>
</tr>
<tr>
<td>K \eta_c'</td>
<td>5.76</td>
<td>18.4</td>
</tr>
<tr>
<td>K \chi_{c0}</td>
<td>1.60</td>
<td>4.9</td>
</tr>
<tr>
<td>K \chi_{c2}</td>
<td>1.60</td>
<td>4.0</td>
</tr>
<tr>
<td>K J/\psi</td>
<td>1.60</td>
<td>6.7</td>
</tr>
</tbody>
</table>
BB background

- We have multiple samples of MC:
  - Generic MC ($b \to c$): negligible for every channel
  - Rare MC (charmless: EW Penguin, HH, $\{\eta, \eta', \phi, \omega\}X$, $\{a_0, a_1, f_0, f_1, b_1, h_1\}X$, ...): not negligible
- Two cases:
  - $\eta$: two components
  - $\eta'$, $\eta_c$, ...: one component
Rare distribution for $K \eta$

- Strategy for the real data fit will be: **subtract** the “other rare decays” and **measure** the $K^* \eta$ component (and the $K \eta$...)

![Graph showing distributions of $\Delta E$ (GeV) and $m_{bc}$ (GeV)]
Rare distribution for $K \eta'$ (similar for $\eta_c$, $\eta_c'$, ...)

- Subtract the rare component

![Graph showing distribution](image-url)
Fit Procedure

- Unbinned Simultaneous Bidimensional ($m_{bc}$, $\Delta E$) Extended Maximum Likelihood Fit (RooFit)
  - **Signal**: shape from MC (constrained) : crystalball (gaussian with a tail) for $m_{bc}$, 3 gaussians for $\Delta E$
  - **Continuum**: argus function for $m_{bc}$, 2$^{\text{nd}}$ order polynomial function for $\Delta E$. Everything is free to float except $E_{\text{beam}}$ (endpoint of the argus function)
  - Rare : histo from MC (shape and yield constrained)
  - For K $\eta$ fit : $K^* \eta$ bkg : histo from MC (shape constrained)

- $\eta$, $\eta'$ : 4 datasets : {svd1, svd2} $\otimes \{B^+, B^*\}$

- $\eta_c$, ... : no significant signal, work in progress to extract limits... so for today : approximation to one dataset : I use the lowest efficiency of SVD1/2 to get the limit (not wrong but **not optimal**)
Fit : $B \rightarrow K \eta \rightarrow K \gamma \gamma$

Fit

Projections

DATA
Signal
Continuum
Rare
$K^* h$
Results : $B \rightarrow K \eta \rightarrow K \gamma \gamma$

- Significance = $\log(2(L-L_0)) = 7.3$

- HFAG 2005 : $\text{BR}(B \rightarrow K \eta) = (2.5 \pm 0.3) \times 10^{-6}$ (average between Belle and BABAR)

<table>
<thead>
<tr>
<th>Yield</th>
<th>Efficiency (%)</th>
<th>$\text{BF}(B \rightarrow K \eta) \times 10^{-6}$</th>
<th>$A_{CP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.9</td>
<td>$11.83 \pm 0.06$</td>
<td>$2.8 \pm 0.9$</td>
<td>$0.01 \pm 0.33$</td>
</tr>
<tr>
<td>35.4</td>
<td>$12.46 \pm 0.05$</td>
<td>$2.4 \pm 0.6$</td>
<td>$-0.49 \pm 0.26$</td>
</tr>
<tr>
<td>55.3</td>
<td></td>
<td>$2.6 \pm 0.5$</td>
<td>$-0.30 \pm 0.20$</td>
</tr>
</tbody>
</table>

- Everything is fine
Fit : $B \rightarrow K \eta' \rightarrow K \gamma \gamma$

Lausanne, 05.12.2005

J. Wicht : B to K gamma gamma
Results: $B \rightarrow K \eta' \rightarrow K \gamma \gamma$

- Significance = 11.8
- HFAG 2005: $BR(B \rightarrow K \eta') = (69.4 \pm 2.7) \times 10^{-6}$

<table>
<thead>
<tr>
<th>Category</th>
<th>Yield</th>
<th>Efficiency (%)</th>
<th>$BF(B \rightarrow K \eta') (10^{-6})$</th>
<th>$A_{CP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVD1</td>
<td>23.6</td>
<td>15.10+-0.06</td>
<td>48.5+-14.2</td>
<td>0.25+-0.29</td>
</tr>
<tr>
<td>SVD2</td>
<td>80.1</td>
<td>16.41+-0.07</td>
<td>78.0+-11.4</td>
<td>0.01+-0.15</td>
</tr>
<tr>
<td>TOT</td>
<td>103.8</td>
<td></td>
<td>66.5+-8.9</td>
<td>0.06+-0.13</td>
</tr>
</tbody>
</table>

- Discrepancy between SVD1 and SVD2 but still acceptable
Fit : $B \to K \eta_c \to K \gamma \gamma$
Fit : $B \rightarrow K \eta_{c}' \rightarrow K \gamma \gamma$
Fit : $B \to K \chi_{c0} \to K \gamma \gamma$
Fit : $B \rightarrow K \ J/\psi \rightarrow K \ \gamma \ \gamma$
Preliminary

Limits for $B \rightarrow K \{ \eta_c, \eta'_c, \chi_{c0}, J/\psi \} \gamma$

<table>
<thead>
<tr>
<th>$K \eta_c$</th>
<th>Significance = 1.30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category</td>
<td>Yield</td>
</tr>
<tr>
<td>SVD1</td>
<td>2.9+3.8-2.9</td>
</tr>
<tr>
<td>SVD2</td>
<td>3.5+5.1-4.1</td>
</tr>
<tr>
<td>Yield90</td>
<td>16.25</td>
</tr>
<tr>
<td></td>
<td>BF $[10^{-7}]$ (CL 90%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$K \chi_{c0}$</th>
<th>Significance = 2.56</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category</td>
<td>Yield</td>
</tr>
<tr>
<td>SVD1</td>
<td>1.2+2.6-1.8</td>
</tr>
<tr>
<td>SVD2</td>
<td>7.1+4.3-3.5</td>
</tr>
<tr>
<td>Yield90</td>
<td>15.42</td>
</tr>
<tr>
<td></td>
<td>BF $[10^{-7}]$ (CL 90%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$K \eta'_c$</th>
<th>Significance = 2.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category</td>
<td>Yield</td>
</tr>
<tr>
<td>SVD1</td>
<td>-0.6+3.0-1.9</td>
</tr>
<tr>
<td>SVD2</td>
<td>4.6+3.5-2.7</td>
</tr>
<tr>
<td>Yield90</td>
<td>12.08</td>
</tr>
<tr>
<td></td>
<td>BF $[10^{-7}]$ (CL 90%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$K J/\psi$</th>
<th>Significance = 1.76</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category</td>
<td>Yield</td>
</tr>
<tr>
<td>SVD1</td>
<td>1.5+2.5-1.6</td>
</tr>
<tr>
<td>SVD2</td>
<td>4.5+4.2-3.3</td>
</tr>
<tr>
<td>Yield90</td>
<td>12.92</td>
</tr>
<tr>
<td></td>
<td>BF $[10^{-7}]$ (CL 90%)</td>
</tr>
</tbody>
</table>
Fit: $B \rightarrow K \chi_{c2} \rightarrow K \gamma \gamma$

Fit doesn't work
B → K χ_{c2} → K γ γ

- This is not a RooFit bug: it is known that likelihood fit can produce weird result if there is no (not enough) event in the signal region.

- In fact: SVD1 fit is fine. SVD2 is the problem here.

- Frequentist Toy MC to get the 90% CL limit: add n=1..10 signal MC events into the data and do the fit (repeat N=2000 times)

- The 90% CL limit is the smallest n that results in 90% of the fits giving a positive signal
$B \rightarrow K \chi_{c2} \rightarrow K \gamma \gamma$

- 2$^{\text{nd}}$ order polynomial fit on positives $n\text{Sig}_{90\%}$ gives a 2.38 events limit
- $\text{BF}(B \rightarrow K \chi_{c2} \rightarrow K \gamma \gamma)_{SV2} < 1.3 \times 10^{-7}$ (CL 90%)
Plans

• Optimize the continuum suppression assuming pessimistic branching fractions for charmonium resonances

• Properly extract the 90% CL limits

• Write a Belle Note

• Answer questions?