Quarkonium non exotic decays at BaBar and Belle

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Moriond QCD
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Outline

• Introduction
• The ground state
• Decays to open charm
• Study of (L=2, S=1) states
  \( \Upsilon(\text{NS}) \rightarrow \Upsilon(\text{MS})\pi^+\pi^-, \ \Upsilon(4S) \rightarrow \eta \Upsilon(1S) \)
• \( \sigma_{bb} \) above the \( \Upsilon(4S) \)
• \( \Upsilon(5S) \rightarrow B\bar{B}X \)
• For the exotic quarkonium states (XYZ) see talk by P. Pakhlov
• For charmonium studies in 2\( \gamma/\text{ISR} \) events see talk by F. Anulli

15 March 2010  G.Simi - MORIOND QCD
Introduction

- $b\bar{b}$ states have been extensively studied ($\Upsilon$ states discovered in 1977) and it has proven to be a powerful testing ground for QCD
  - quarkonium potential models, QCDME, pNRQCD, lattice NRQCD
- $b\bar{b}$ states are the heaviest $qq$ states: $v/c \approx 0.08 \Rightarrow$ small relativistic effects

### $\Upsilon(nS)$ resonances

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$\Upsilon(1S)$</th>
<th>$\Upsilon(2S)$</th>
<th>$\Upsilon(3S)$</th>
<th>Above $\Upsilon(4S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar</td>
<td>100M</td>
<td>120M</td>
<td>~4fb$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>Belle</td>
<td>100M</td>
<td>20M</td>
<td>11M</td>
<td>~30fb$^{-1}$</td>
</tr>
<tr>
<td>CLEO</td>
<td>20M</td>
<td>9M</td>
<td>6M</td>
<td></td>
</tr>
</tbody>
</table>
Bottomonium spectrum and transitions

- Not much is still known about their:
  - Spin singlets, L=2 spectroscopy
  - Hadronic transitions
  - Exclusive Decay BF
    - (often < 50% is known)

- Hadronic Transitions
- Magnetic Dipole Transitions
- Electric dipole Transitions
- Spin Singlets (S=0)
- This Talk

\[ S = S_1 + S_2 \]
\[ J = L + S \]
\[ P = (-1)^{L+S} \]
\[ C = (-1)^{L+S} \]
Bottomonium ground state
Motivation

- Measurement of the mass and width helpful to test pNRQCD, lattice NRQCD and potential models
  
  - $\eta_b(1S)$: $L=0, S=0$
  - $\Upsilon(1S)$: $L=0, S=1$

- $\Upsilon(1S)$ mass well measured $\Rightarrow$ $\eta_b(1S)$ mass $\Leftrightarrow$ hyperfine splitting: tests the role of the spin-spin interaction potential

  - In pNRQCD $\Delta m \sim 41 \text{MeV}/c^2$  
  - Lattice NRQCD $\Delta m \sim 60-80 \text{MeV}/c^2$

- Hyperfine splitting very sensitive to $\alpha_s$
  
  - $\Delta m \propto \alpha_s^4 m_b$

\[ V_{ss}(r) = \frac{\sigma Q \cdot \sigma Q}{6 m_Q^2} \nabla^2 V_V(r), \]

hep-ph/0312086v2

η_b analysis overview

- η_b decays are little known
  - search for \( \Upsilon(2,3S) \rightarrow \gamma \eta_b \)
  - fit the inclusive photon energy spectrum in the \( \Upsilon(2,3S) \) CM
  - Search for a peak at the \( E_\gamma^{\text{CM}} \)
    
    \[
    E_\gamma = \frac{s - M_{\eta_b}^2}{2 \sqrt{s}} \approx 900 \text{ MeV}
    \]

- Event selection
  - High track multiplicity
  - Sphericity \( (R_2/R_0) \) & \( \cos(\theta_{\text{thrust}}) \) to remove continuum
  - Cluster quality & isolation
  - Barrel calorimeter only (better resolution) & \( \pi^0 \) veto

- Non peaking background:
  - Continuum qq events, \( \Upsilon(3S) \) cascade decays, \( \Upsilon(1S) \rightarrow \gamma \eta \) etc...
  - Modeled with exponential shape determined from data
Peaking Backgrounds

- From $\chi_b$ transitions
  - $\Upsilon(3S) \to \gamma_1 \chi(J(2P))$, $\chi(J(2P)) \to \gamma_2 \Upsilon(1S)$
  - Shape determined on data excluding signal region
  - Energy shift of +3.8MeV used to correct all other peaks
- From ISR
  \[ e^+ e^- \to \gamma_{ISR} \Upsilon(1S) \]
  \[ E_{\gamma_{ISR}} = \frac{s - M_{\Upsilon(1S)}^2}{2 \sqrt{s}} = 856 \text{ MeV}/c^2 \]
- Very important to model correctly the line shape and the yield because it can overlap with the signal depending on the $\eta_b$ mass
  - Shape determined from MC
  - Yield obtained from $\Upsilon(4S)$-off peak data
\( \Upsilon(2S) \rightarrow \gamma \eta_b \)

- Mass in agreement with unquenched QCD:
  \[ M_{\eta_b}^{\text{combined}} = 9390.8 \pm 3.2 \, \text{MeV} / c^2 \quad M_{\eta_b}^{\text{theory}} = 9340 \pm 10 \, \text{MeV} / c^2 \]

- HFS in agreement with lattice QCD
  \[ \delta M_{\Upsilon(1S)-\eta_b}^{\text{combined}} = (69.5 \pm 3.2) \, \text{MeV} / c^2 \quad \delta M_{\Upsilon(1S)-\eta_b}^{\text{theory}} = (61 \pm 14) \, \text{MeV} / c^2 \]

- \( R_B = \frac{B(\Upsilon(2S) \rightarrow \gamma \eta_b)}{B(\Upsilon(3S) \rightarrow \gamma \eta_b)} = 0.82 \pm 0.24^{+0.20}_{-0.19} \) in agreement with \( R_B^{\text{theory}} \approx 0.3 - 0.7 \)

\( N(Y_{2S}) = 92M, 3\sigma \) significance

\( N(Y_{3S}) = 109M, 10\sigma \) significance

15 March 2010
Bottomonium \rightarrow \text{Open Charm}
ϒ(1S)→Open Charm: Motivation

- Y(1S) measured decay BF ~ 10%
- Decays to open charm not yet observed
- $c\bar{c}$ production in ggg diagram is suppressed=>sensitive to octet

In $\chi_{bJ}$ decays color octet is ~9% of color singlet (CLEO)

In $\Upsilon(1S)$ octet contribution ~1/2 of singlet

- =>more sensitive to octet contribution

$c$ quark momentum distribution can be used

- to disentangle singlet and octet contribution
$\Upsilon(1S) \rightarrow \text{Open Charm: Analysis}$

**Strategy**

- $Y(2S) \rightarrow \pi^+ \pi^- Y(1S), Y(1S) \rightarrow D^{*\pm} + X$
  - 18M $Y(1S)$

- Reconstruct only the $\pi\pi$ system and the $D^{*} \rightarrow D^{0}\pi^+$, $D^{0} \rightarrow K\pi^+$

- Select $\Upsilon(1S)$ events using $M_{\text{recoil}}$

- Reduce soft pion combinatoric background using $M(D^*) - M(D^0)$

- Subtract remaining soft pion combinatoric background using a control sample

- Subtract $D^0$ combinatoric using recoil mass sidebands
$\Upsilon(1S) \rightarrow \text{Open Charm: Analysis}

\text{Strategy}

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$M_{\text{recoil}} = \sqrt{P^2_{\text{beams}} - M_{\pi\pi}^2}$
**D* momentum distribution**

Efficiency corrected Y(1S) → D*X yield

CLEO xp shape from e+e− → D*X normalized using the expected rate from virtual photon (1.52 +/- 0.2)%

Excess mainly at low $x_p$ => three gluon process contribution

Divide the sample in bins of $x_p = p_D^*/P_{max}$

$P_{max} = \sqrt{s/4 - m_D^2}$

PR, D81, 011102 (2010)
Branching Fraction

- Yield is obtained summing the result in each bin
- The $x_p$ range <0.1 is dominated by background and is discarded
  \[ B[Y(1S) \rightarrow D^* + X] = 2.52 \pm 0.13 \text{(stat)} \pm 0.15 \text{(syst)} \]
  \( X_p \text{ in } [0.1:1.0] \)
- Compare to the expected values

\[
\begin{align*}
B_{vpho}[\Upsilon(1S) \rightarrow \gamma^* \rightarrow D^* + X] &= \frac{\sigma_{D^*+\sigma_{qq}}}{\sigma_{qq}} \times R_{\text{had}} \times B[\Upsilon(1S) \rightarrow \mu^+\mu^-] = (1.52 \pm 0.2)\% \\
B_{vpho}[\Upsilon(1S)_1 \rightarrow ggg^* \rightarrow D^* + X] &= \frac{\sigma_{D^*+\sigma_{qq}}}{\sigma_{qq}} \times \frac{10}{4} \times B[\Upsilon(1S)_1 \rightarrow ggg^* \rightarrow ggcc] = (1.2 \pm 0.3)\% \\
B_{vpho}[\Upsilon(1S)_8 \rightarrow g^* \rightarrow D^* + X] &= \frac{\sigma_{D^*+\sigma_{qq}}}{\sigma_{qq}} \times \frac{10}{4} \times B[\Upsilon(1S)_8 \rightarrow g^* \rightarrow cc] = (0.7)\% 
\end{align*}
\]
- Octet contribution is disfavored
Study of (L=2, S=1) states

New
Motivation and Analysis Overview

- $1^3D_J$ state of bottomonium: observed by CLEO in $\Upsilon(1D) \rightarrow \gamma \gamma \Upsilon(1S)$
  - State interpreted as $J=2$, needs confirmation
- BABAR uses $\Upsilon(1D) \rightarrow \pi^+\pi^- \Upsilon(1S)(\rightarrow l^+l^-)$: first observation
  - better mass resolution
  - $L,P,J$ tested trough the angular distribution of $\pi^+, l^+$
- Decay chain $\Upsilon(3S) \rightarrow \gamma \chi_b(2P), \rightarrow \gamma \gamma \Upsilon(1D)$
  - => final state $\gamma \gamma \pi^+\pi^- l^+l^-$
  - Lepton ID, $|m_{ll} - m_{\Upsilon 1S}| < 0.2\text{GeV}$, $\cos(\theta_{\pi l}) > 0.95$
  - Photons chosen by minimizing $\chi^2 = \sum (E_i^\gamma - E_{\exp}^i)^2/\sigma_{\gamma}^2$
  - Signal extracted from from ML fit to $M(\pi^+\pi^- l^+l^-)$
Article in preparation

$\Upsilon(1D) \rightarrow \pi^+\pi^- \Upsilon(1S)$ observation

<table>
<thead>
<tr>
<th>J</th>
<th>#Evts</th>
<th>#σ</th>
<th>BR$/10^{-4}$</th>
<th>Mass/[GeV/c^2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.6+5.7−4.9</td>
<td>1.8</td>
<td>0.42+0.27−0.23 +/− 0.10%</td>
<td>10151.6</td>
</tr>
<tr>
<td>2</td>
<td>33.9+8.2−7.5</td>
<td>5.8</td>
<td>0.66+0.15−0.14 +/− 0.06%</td>
<td>10164 ± 0.8 ± 0.5</td>
</tr>
<tr>
<td>3</td>
<td>9.4+10.5−9.5</td>
<td>1.5</td>
<td>0.29+0.22−0.18 +/− 0.06%</td>
<td>10172.9</td>
</tr>
</tbody>
</table>

L=2

P=-1
$\Upsilon(\text{NS}) \rightarrow \pi^{+}\pi^{-}\Upsilon(\text{MS}), \eta \Upsilon(1S)$

PR, D79, 051103 (2009)
$\Upsilon(4S) \rightarrow \pi \pi \Upsilon(1S)$
$\text{BF} = (0.85 \pm 0.13) \times 10^{-4}$

PR, D78, 112002 (2008)
$\Upsilon(4S) \rightarrow \eta \Upsilon(1S)$
$\text{BF} = (1.96 \pm 0.11) \times 10^{-4}$
Above the $\Upsilon(4S)$
BaBar Energy scan

- Search for unexpected structures in inclusive $b\bar{b}$ cross section

\[ R_b(s) = \frac{\sigma_{bb}}{\sigma_{\mu\mu}^0}, \quad \sigma_{\mu\mu}^0 = 4\pi \alpha^2/3s \]

- Large statistics 3.3 fb$^{-1}$, small energy steps 5 MeV => clear structures corresponding to opening of thresholds

- $Y(5S)$ and $Y(6S)$ candidates affected by interference

- Plateau above the $Y(6S)$

- Consistent with coupled channel

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- Fit: flat component + flat component interfering with two relativistic BW

<table>
<thead>
<tr>
<th>$Y(5S)$</th>
<th>$Y(6S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M[MeV]$</td>
<td>10876 ± 2</td>
</tr>
<tr>
<td>$\Gamma[MeV]$</td>
<td>43 ± 4</td>
</tr>
<tr>
<td>$\phi[rad]$</td>
<td>2.11 ± 0.12</td>
</tr>
<tr>
<td>$M_{PDG}[MeV]$</td>
<td>10865 ± 8</td>
</tr>
<tr>
<td>$\Gamma_{PDG}[MeV]$</td>
<td>110 ± 13</td>
</tr>
</tbody>
</table>
$\Upsilon(5S)$: Enhanced $\pi\pi\Upsilon(\text{NS})$ production

- 6 steps, 15-60MeV spacing, measure cross section $e^+e^-\rightarrow\Upsilon(nS)\pi^+\pi^-$ to search for the process analogous to $\Upsilon(4260)\rightarrow J/\psi\pi\pi \Rightarrow$ enhancement in 10.83-11.02

$\sigma(b\bar{b})$ fit with $A_\pi^2 + |A_0 + e^{i\phi}A_{BW}|^2$

- Mass shift: $9\pm4$ MeV w.r.t $\pi\pi\Upsilon(\text{NS})$
- $\Gamma$ shift: $-15\pm11$ MeV w.r.t $\pi\pi\Upsilon(\text{NS})$
- Consistent with BaBar result

$\sigma(\text{YNS}\pi\pi)$ fit with $|R_0 + e^{i\phi}R_{BW}|^2$

- $M=10888.4\pm2.6\pm1.2$ MeV/c$^2$
- $\Gamma=30.7^{+8.3}_{-7.0}\pm3.1$ MeV:
- $M$ incompatible with $\sigma(b\bar{b})$ at 2.3$\sigma$
- Missing $\Upsilon(6S)$ contribution
$\Upsilon(5S) \rightarrow B^*(B^*(\pi)(\pi)$
\[ \Upsilon(5S) \rightarrow B(\ast)\overline{B}(\ast)X \]

- Determine B mesons multiplicity
  - hadronization/spectroscopy
- Exclusive reconstruction of one B meson
  - \( B^{(+0)} \rightarrow J/\psi K^{(+\ast)} \)
  - \( B^{(+0)} \rightarrow D^{(0-)} \pi^+ \)
- \( M_{bc} = \sqrt{(E_{\text{beam}}^\text{CM} - P_{CB}^\text{CM} B^2)} \) used to separate BB, BB*, B*B*,

<table>
<thead>
<tr>
<th>Channel</th>
<th>Fraction, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>BB</td>
<td>5.5 \pm 1.0 \pm 0.4</td>
</tr>
<tr>
<td>BB* + B*B</td>
<td>13.7 \pm 1.3 \pm 1.1</td>
</tr>
<tr>
<td>B*B</td>
<td>37.5 \pm 2.1 \pm 3.0</td>
</tr>
<tr>
<td>Large ( M_{bc} )</td>
<td>17.5 \pm 1.8 \pm 1.3</td>
</tr>
</tbody>
</table>

23.6 fb\(^{-1}\) data
bg subtracted
\( \gamma(5S) \rightarrow B^{(*)} \bar{B}^{(*)} \pi X \)

- Reconstruct \( B \pi \), look for \( B^{(*)} \) in missing \( E \), \( M_{bc} \)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Yield (( \pi^+ )), Fraction over events</th>
<th>Fraction over large ( M_{bc} ), %</th>
<th>Fraction per ( b \bar{b} ) event, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B \bar{B} \pi )</td>
<td>0.2 ±7.2 (-6.9)</td>
<td>0.2 ±6.8 (-6.5)</td>
<td>0.0 ±1.2 ±0.3</td>
</tr>
<tr>
<td>( B \bar{B}^{<em>} \pi + B^{</em>} \bar{B} \pi )</td>
<td>38.3 ±10.5 (-9.8)</td>
<td>41.6 ±12.1 (-11.4)</td>
<td>7.3 ±2.3 ±0.8</td>
</tr>
<tr>
<td>( B^{<em>} \bar{B}^{</em>} \pi )</td>
<td>4.8 ±6.4 (-5.9)</td>
<td>5.9 ±7.8 (-7.2)</td>
<td>1.0 ±1.4 ±0.4</td>
</tr>
<tr>
<td>Residual</td>
<td>52.3 ±15.9 (-15.0)</td>
<td>9.2 ±3.0 (-2.8)</td>
<td>1.0 ±1.3 ±1.0</td>
</tr>
<tr>
<td>Large ( M_{bc} )</td>
<td>100.</td>
<td>17.5 ±1.8 (-1.6)</td>
<td>1.3</td>
</tr>
</tbody>
</table>

New interpretation

ISR events
Summary and conclusions

- $\eta_b$ observation has been confirmed in $\Upsilon(2S)$ decays
- $b\bar{b}$ decays to open charm have been observed for the first time
- $1D_j$ states have been studied in $\pi\pi\Upsilon(1S)$ for the first time
- Hadronic transitions studies have been improved
- $\sigma_{b\bar{b}}$ above $\Upsilon(4S)$ measured with unprecedented precision
- Puzzling $\pi\pi\Upsilon(\text{NS})$ cross section measured at the $\Upsilon(5S)$
- $B(^*)$ meson production fractions @ $\Upsilon(5S)$ measured precisely
Backup
Background subtraction

Recoil mass
Sidebands
Signal region

$D^0$ mass

$A_{SB - high}$
$A_{SB - low}$

Right sign $(k^-\pi^+)\pi^+$
Wrong sign $(k^-\pi^+)\pi^-$
Transitions: \( \gamma \rightarrow \pi^+ \pi^- \)
\( \eta \rightarrow \pi^0 \pi^0 \)

Mass (MeV)

\( \eta_b(3S) \)
\( Y(3S)^3 S_1 \)
\( \chi_b(2P) \)
\( h_b(2P) \)
\( D(1D) \)

\( \eta_b(2S) \)
\( Y(2S)^3 S_1 \)
\( \chi_b(1P) \)
\( h_b(1P) \)

\( \eta_b(1S) \)
\( Y(1S) \)

\( 0^+ \)
\( 1^- \)
\( 0,1,2^{++} \)
\( 1^+ \)
\( 1,2,3^- \)

Hyperfine (spin-spin) splitting

\( \sim 900 \text{ MeV} \)