Recent Bottomonium Results from BaBar

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On behalf of the BaBar Collaboration

DIS Workshop, Madrid, Spain, 04-27-2009
OVERVIEW

• Observation of the Bottomonium Ground State, $\eta_b(1S)$ in $\Upsilon(3S) \rightarrow \gamma \eta_b(1S)$ Decay

• Confirmation of the Observation of the $\eta_b(1S)$ in $\Upsilon(2S) \rightarrow \gamma \eta_b(1S)$ Decay

• Searches for light Higgs-like particle in $\Upsilon(3S, 2S)$ decays

• Search for the Lepton-Flavor Violating Decays $\Upsilon(3S) \rightarrow e^\pm \tau^\mp$ and $\Upsilon(3S) \rightarrow \mu^\pm \tau^\mp$

• $R_b$ Scan above the $\Upsilon(4S)$
BaBar RUN 7 (Dec. 2007 – Apr. 2008)

PEP-II $e^+e^-$ Asymmetric Collider Running at the $\Upsilon(2S,3S)\ldots$

**BABAR DATASETS:**

- $\sim 120 \times 10^6$ $\Upsilon(3S)$ events
- $\approx 20 \times$ previous dataset (CLEO)
- $\sim 100 \times 10^6$ $\Upsilon(2S)$ events
- $\approx 11 \times$ previous dataset (CLEO)

- $\mathcal{L} = 54 \text{ fb}^{-1}$
- $\mathcal{L} = 30.2 \text{ fb}^{-1}$
- $\mathcal{L} = 14.5 \text{ fb}^{-1}$
- $\mathcal{L} = 8.5 \text{ fb}^{-1}$

End of data taking 07/04/2008
The Observation of the Bottomonium Ground State, $\eta_b(1S)$, at BaBar
Current Picture of the Bottomonium Spectrum

\[ \begin{align*}
\text{Y(11020)} \\
\text{Y(10860)} \\
\text{Y(4S)}
\end{align*} \]

\[ \text{B\bar{B} threshold} \]

(nL) where \( n \) is the principal quantum number and \( L \) indicates the \( \bar{b}b \) angular momentum in spectroscopic notation (\( L=S, P, D,... \))

\[ J^{P\ C} = \begin{cases} 
0^+ & \text{S-wave} \\
1^- & \text{P-wave} \end{cases} \]

\[ \text{Orbital Ang. Momentum between quarks} \]
Current Picture of the Bottomonium Spectrum

- $\bar{b}b$ states below $Y(3S)$ not yet discovered: 3 S-wave ($\eta_b$), 2 P-wave ($h_b$), 4 D-wave & possibly 4 F-wave.
- Among the undiscovered states is the ground state, the $\eta_b(1S)$, expected to be $< 100$ MeV/c$^2$ below the $Y(1S)$.
The Search for the $\eta_b$ at BaBar
The Search for the $\eta_b$ at BaBar

- Decays of $\eta_b$ not known $\rightarrow$ Search for $\eta_b$ signal in inclusive photon spectrum
The Search for the $\eta_b$ at BaBar

- Decays of $\eta_b$ not known $\Rightarrow$ Search for $\eta_b$ signal in inclusive photon spectrum
  
  - Search for the radiative transition $\Upsilon(3S) \rightarrow \gamma \eta_b(1S)$

- In c.m. frame: $E_\gamma = \frac{s - m^2}{2\sqrt{s}}$ \begin{align*}
\sqrt{s} &= \text{c.m. energy} = m(\Upsilon(3S)) \\
m &= m(\eta_b)
\end{align*}

- For $\eta_b$ mass $m = 9.4$ GeV/$c^2$ $\Rightarrow$ monochromatic line in $E_\gamma$ spectrum at 911 MeV, i.e. look for a bump near 900 MeV in inclusive photon energy spectrum from data taken at the $\Upsilon(3S)$
The Inclusive Photon Spectrum
The Inclusive Photon Spectrum

- Use ~9% of the Full Y(3S) Data Sample

Non-Peaking background components:

~1/10 Y(3S) Analysis Sample

Large background
The Inclusive Photon Spectrum

- Use ~9% of the Full Y(3S) Data Sample

Non-Peaking background components:

- Look for a bump near 900 MeV in the inclusive photon spectrum

![Graph showing inclusive photon spectrum with a bump near 900 MeV]
The Inclusive Photon Spectrum

- Use ~9% of the Full Y(3S) Data Sample

Non-Peaking background components:

Non-peaking background parametrization:
- Empirical function: \( A \left( C + e^{-\alpha E_\gamma - \beta E_\gamma^2} \right) \)

Look for a bump near 900 MeV in the inclusive photon spectrum

\( \sim 1/10 \text{ Y}(3S) \) Analysis Sample

Large background
The Inclusive Photon Spectrum

Peaking background components:
The Inclusive Photon Spectrum

Peaking background components (1):

\[ Y(3S) \rightarrow \chi_{b0}(2P) \gamma^{\text{soft}} \]
\[ E(\gamma^{\text{soft}}) = 122 \text{ MeV} \]

\[ Y(3S) \rightarrow \chi_{b1}(2P) \gamma^{\text{soft}} \]
\[ E(\gamma^{\text{soft}}) = 99 \text{ MeV} \]

\[ Y(3S) \rightarrow \chi_{b2}(2P) \gamma^{\text{soft}} \]
\[ E(\gamma^{\text{soft}}) = 86 \text{ MeV} \]
The Inclusive Photon Spectrum

Peaking background components (1):

\[
\begin{align*}
\Upsilon(3S) \rightarrow \chi_{b0}(2P) \gamma^{\text{soft}} & \quad E(\gamma^{\text{soft}}) = 122 \text{ MeV} \\
& \rightarrow \Upsilon(1S) \gamma^{\text{hard}} \quad E(\gamma^{\text{hard}}) = 743 \text{ MeV} \\
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& \rightarrow \Upsilon(1S) \gamma^{\text{hard}} \quad E(\gamma^{\text{hard}}) = 764 \text{ MeV} \\
\Upsilon(3S) \rightarrow \chi_{b2}(2P) \gamma^{\text{soft}} & \quad E(\gamma^{\text{soft}}) = 86 \text{ MeV} \\
& \rightarrow \Upsilon(1S) \gamma^{\text{hard}} \quad E(\gamma^{\text{hard}}) = 777 \text{ MeV}
\end{align*}
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The Inclusive Photon Spectrum

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\[ \chi_{bJ}(2P) \rightarrow \gamma Y(1S) \text{ (Peaking)} \]

PDF: 3 Crystal Ball fct
Relative peak positions and yield ratios are taken from PDG
The Inclusive Photon Spectrum

Peaking background component:

Radiative return from $Y(3S)$ to $Y(1S)$: $e^+e^- \rightarrow \gamma_{ISR} Y(1S)$

$$\sqrt{s} = M(Y(3S))$$
$$\sqrt{s'} = M(Y(1S))$$

$$q_{ISR} = \frac{s-s'}{2\sqrt{s}}$$

$[ E_{\gamma_{ISR}} = 856 \text{ MeV} ]$
The Inclusive Photon Spectrum

e^+e^- \rightarrow \gamma_{ISR} Y(1S) \text{ (Peaking) background parametrization:}

Peaking background component:

Radiative return from Y(3S) to Y(1S):  
\[ e^+e^- \rightarrow \gamma_{ISR} Y(1S) \]

\[ \sqrt{s} = M(Y(3S)) \]

\[ q_{ISR} = \frac{s - s'}{2\sqrt{s}} \]

[ \( E_{\gamma_{ISR}} = 856 \text{ MeV} \) ]

\[ \gamma_{ISR} \to Y(1S) \quad \gamma_{ISR} \quad \gamma_{ISR} \quad \gamma_{ISR} \quad ISR \quad Y(1S) \]

\[ E_{\gamma_{ISR}} = 856 \text{ MeV} \]

\[ s_{ssq}^{\prime} = \]

\[ \sim 1/10 \text{ Analysis Sample} \]

\[ E_{\gamma} (\text{GeV}) \]

\[ \text{Events} / (0.005 \text{ GeV}) \]
The Inclusive Photon Spectrum

\[ e^+e^- \rightarrow \gamma_{\text{ISR}} \ Y(1S) \] (Peaking) background parametrization:
  
  - Very important to determine both lineshape and yield
  
  \( \gamma_{\text{ISR}} \) parameterization:
  
  - Depending on \( \eta_b \) mass, the peaks may overlap!

**Peaking background component:**

Radiative return from \( Y(3S) \) to \( Y(1S) \):

\[ e^+e^- \rightarrow \gamma_{\text{ISR}} \ Y(1S) \]

\[ q_{\text{ISR}} = \frac{s-s'}{2\sqrt{s}} \]

\[ E_{\gamma_{\text{ISR}}} = 856 \text{ MeV} \]
The Inclusive Photon Spectrum

e^+e^- \rightarrow \gamma_{ISR} \ Y(1S) \ (Peaking) \ background \ parametrization:

- Very important to determine both lineshape and yield
  
  Depending on \( \eta_b \) mass, the peaks may overlap!

- Estimate the expected yield using \( Y(4S) \) Off-Peak data [high statistics, no other peaking background near ISR signal], and extrapolating the yield to \( Y(3S) \) On-Peak data

**Peaking background component:**

Radiative return from \( Y(3S) \) to \( Y(1S) \): 
\[ e^+e^- \rightarrow \gamma_{ISR} \ Y(1S) \]

\[ \sqrt{s} = M(Y(3S)) \]
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\[ q_{ISR} = \frac{s - s'}{2\sqrt{s}} \]

\[ E_{\gamma_{ISR}} = 856 \text{ MeV} \]

~1/10 Analysis Sample
The Inclusive Photon Spectrum

\[ e^+e^- \rightarrow \gamma_{\text{ISR}} \ Y(1S) \ (\text{Peaking}) \text{ background parametrization:} \]

- Very important to determine both lineshape and yield

\[ \text{Depending on } \eta_b \text{ mass, the peaks may overlap!} \]

- Estimate the expected yield using \( Y(4S) \) Off-Peak data [high statistics, no other peaking background near ISR signal], and extrapolating the yield to \( Y(3S) \) On-Peak data

**Peaking background component:**

Radiative return from \( Y(3S) \) to \( Y(1S) \):

\[ e^+e^- \rightarrow \gamma_{\text{ISR}} \ Y(1S) \]

\[ q_{\text{ISR}} = \frac{s - s'}{2\sqrt{s}} \]

\[ E_{\gamma}\text{ISR} = 856 \text{ MeV} \]

![Graph showing the radiative return to the \( Y(1S) \) with inset highlighting the expected yield estimation process.](image)
Signal Parametrization

$Y(3S) \rightarrow \gamma \eta_b(1S)$ parametrization:

**PDF:** Crystal Ball $\otimes$ Breit-Wigner

Width of the Breit-Wigner fixed 10 MeV

- Crystal Ball lineshape obtained from simulated events

![Graph showing Crystal Ball lineshape](image)
Fit Result

\[ \chi_{bJ}(2P) \text{ peak} \]

\[ L = 25.6 \text{ fb}^{-1} \]

\[ \Rightarrow (109 \pm 1) \times 10^6 \text{ Y(3S) events} \]
The Observation of the $\eta_b$
The Observation of the $\eta_b$

- $\chi_{bj}$ Peak Yield: $821841 \pm 2223$
- $\gamma_{ISR}$ Y(1S) Yield: $25153$ (fixed)
- $\eta_b$ Yield: $19152 \pm 2010$

- $R(ISR/\chi_{bj}) \sim 1/33$
- $R(\eta_b/\chi_{bj}) \sim 1/43$
The Observation of the $\eta_b$

- $\chi_{bJ}$ Peak Yield: 821841 ± 2223
- $\gamma_{\text{ISR}}$ Y(1S) Yield: 25153 (fixed)
- $\eta_b$ Yield: 19152 ± 2010

- $R(\text{ISR}/\chi_{bJ}) \sim 1/33$
- $R(\eta_b/\chi_{bJ}) \sim 1/43$

19152 ± 2010 events

Non-peaking Background subtracted

Entries/(0.005 GeV), $E_\gamma$ (GeV)
Summary of Results

• Signal Yield:
  – Estimate of Branching Fraction (expected transition rate):
    \[
    \text{BF} \ (Y(3S) \rightarrow \gamma \eta_b) = (4.5 \pm 0.5 \ [\text{stat.}] \pm 1.2 \ [\text{syst.}] \ ) \times 10^{-4}
    \]

• Mass of the $\eta_b(1S)$:
  – Peak in $\gamma$ energy spectrum at $E_\gamma = 921.2^{+2.1}_{-2.8} \ (\text{stat}) \text{ MeV}$
  – Corresponds to $\eta_b$ mass $9388.9^{+3.1}_{-2.3} \ (\text{stat}) \text{ MeV}/c^2$
  – The hyperfine ($Y(1S) - \eta_b(1S)$) mass splitting is $71.4^{+2.3}_{-3.1} \ (\text{stat}) \text{ MeV}/c^2$
The Search for the $\eta_b$ in $\Upsilon(3S) \rightarrow \gamma \eta_b(1S)$ Decay
The Search for the $\eta_b$ in $Y(2S) \rightarrow \gamma \eta_b(1S)$ Decay
The Search for the $\eta_b$ in $Y(2S) \rightarrow \gamma \eta_b(1S)$ Decay

In c.m. frame: $E_\gamma = \frac{s - m^2}{2\sqrt{s}} \quad \sqrt{s} = \text{c.m. energy}$
$m = m(\eta_b)$

- For $\eta_b$ mass $m = 9.4$ GeV/$c^2 \Rightarrow$ monochromatic line in $E_\gamma$ spectrum at 604 MeV, i.e. look for a bump near 600 MeV in inclusive photon energy spectrum from data taken at the $Y(2S)$
The Search for the $\eta_b$ in $\Upsilon(2S) \rightarrow \gamma \eta_b(1S)$ Decay

In c.m. frame: \[ E_\gamma = \frac{s - m^2}{2\sqrt{s}} \] \( \sqrt{s} \) = c.m. energy \( m = m(\eta_b) \)

- For $\eta_b$ mass $m = 9.4$ GeV/$c^2$ \( \rightarrow \) monochromatic line in $E_\gamma$ spectrum at 604 MeV, i.e. look for a bump near 600 MeV in inclusive photon energy spectrum from data taken at the $\Upsilon(2S)$

Data Sample $\sim 100 \times 10^6 \ \Upsilon(2S)$ events

Similar analysis strategy in $\Upsilon(2S) \rightarrow \gamma \eta_b$ as for $\Upsilon(3S) \rightarrow \gamma \eta_b$
Comparison of $E_\gamma$ Spectra

Results from $Y(2S)$ and $Y(3S)$ analyses are consistent!
Summary of $\eta_b$ Results

• $\eta_b$ mass:

  $Y(3S)$ analysis: \[ m(\eta_b) = 9388.9^{+3.1}_{-2.3} \pm 2.7 \text{ MeV} / c^2 \]

  $Y(2S)$ analysis: \[ m(\eta_b) = 9392.9^{+4.6}_{-4.8} \pm 1.8 \text{ MeV} / c^2 \]
  arXiv:0903.1124 (submitted to PRL)

• Hyperfine splitting:

  $Y(3S)$ analysis: \[ m(Y(1S)) - m(\eta_b) = 71.4^{+2.3}_{-3.1} \pm 2.7 \text{ MeV} / c^2 \]

  $Y(2S)$ analysis: \[ m(Y(1S)) - m(\eta_b) = 67.4^{+4.8}_{-4.6} \pm 1.9 \text{ MeV} / c^2 \]

\[ \text{Combined mass is } m(\eta_b(1S)) = 9390.4 \pm 3.1 \text{ MeV} / c^2 \]
resulting in a hyperfine splitting of $69.9 \pm 3.1 \text{ MeV} / c^2$
Searches for light *Higgs-like* particle in \( \Upsilon (3S, 2S) \) decays
Light Higgs in NMSSM

• Next-to-Minimal Supersymmetric Standard Model (NMSSM) introduces a singlet Higgs field, which combines with electroweak doublet member to produces a light CP-odd Higgs state $A^0$, $m(A^0) < 2 m_b$ (accessible to decays of $Y$ resonances).

• NMSSM parameter search $\Rightarrow$ $BF(Y(3S) \rightarrow \gamma A^0) \sim 10^{-4}$
Search Strategies

- Search for an invisibly decaying particle recoiling against a single photon

\[ E_\gamma^* = \frac{m_\gamma^2 - m_{A^0}^2}{2m_\gamma} \]
Search Strategies

- Search for an invisibly decaying particle recoiling against a single photon

- Search in the radiative decays of the narrow Υ(2S) and Υ(3S) resonances: Υ(2S, 3S) → γ A⁰, A⁰ → μ⁺μ⁻
Search in $Y(3S) \to \gamma A^0, A^0 \to \text{invisible}$

Individual steps much finer than missing mass resolution, i.e. neighboring points highly correlated.

No significant excess found; largest significance 2.6 $\sigma$ at 5.2 GeV.

Combine to extract upper limits on BF as a function of $A^0$ mass.
Search in $Y(2S, 3S) \rightarrow \gamma A^0, A^0 \rightarrow \mu^+\mu^-$

No significant signal found

Upper limits (90% CL) range: $(0.25-5.2) \times 10^{-6}$

mass region $m_{\mu\mu} < 2m_\tau$:
$BF \in (0.25 - 4.7) \times 10^{-6}$

mass region $m_{\mu\mu} = 0.214 \text{GeV} / c^2$:
$BF = (0.12^{+0.43}_{-0.41} \pm 0.17) \times 10^{-6}$
$BF < 0.8 \times 10^{-6}$ (90% CL)
Upper limits rule out much of the parameter space allowed by the light Higgs models.
The Search for the Lepton-Flavor Violating Decays

$Y(3S) \rightarrow e^{\pm}\tau^\mp$ and $Y(3S) \rightarrow \mu^{\pm}\tau^\mp$
Search for the Lepton-Flavor Violating Decays

\( \Upsilon(3S) \rightarrow e^\pm \tau^\mp \) and \( \Upsilon(3S) \rightarrow \mu^\pm \tau^\mp \)

- If new particles contributing to charged lepton-flavor violation couple to \( b \) quarks,
- such processes may be observable in \( \Upsilon(3S) \) Decays.

- leptonic \( e\tau \) channel: \( \Upsilon(3S) \rightarrow e^\pm \tau^\mp, \tau^- \rightarrow \mu^- \nu_{\tau} \bar{\nu}_\mu \)
- hadronic \( e\tau \) channel: \( \Upsilon(3S) \rightarrow e^\pm \tau^\mp, \tau^- \rightarrow \pi^- \pi^0 \nu_{\tau} / \pi^- \pi^0 \pi^0 \nu_{\tau} \)
- leptonic \( \mu\tau \) channel: \( \Upsilon(3S) \rightarrow \mu^\pm \tau^\mp, \tau^- \rightarrow e^- \nu_{\tau} \bar{\nu}_e \)
- hadronic \( \mu\tau \) channel: \( \Upsilon(3S) \rightarrow \mu^\pm \tau^\mp, \tau^- \rightarrow \pi^- \pi^0 \nu_{\tau} / \pi^- \pi^0 \pi^0 \nu_{\tau} \)

**Strategy:** unbinned extended maximum likelihood fit to \( x \) distribution

Primary discriminant variable \( x \):
- \( x = p_e/E_B \) for \( \Upsilon(3S) \rightarrow e\tau \) channels
- \( x = p_\mu/E_B \) for \( \Upsilon(3S) \rightarrow \mu\tau \) channels

**Signal** (\( \mu\tau \) production)

**Signal** (\( e\tau \) production)

**Continuum** \( \tau^+\tau^- \)

**Resonant** \( \tau \)-pairs

**Bhabha events**

**Continuum** \( \mu^+\mu^- \)
$Y(3S) \rightarrow e^\pm \tau^\mp$ and $Y(3S) \rightarrow \mu^\pm \tau^\mp$ BF Measurements

$BF(Y(3S) \rightarrow e\tau) < 5.0 \times 10^{-6}$
(first upper limit)

$BF(Y(3S) \rightarrow \mu\tau) < 4.1 \times 10^{-6}$
(>4 times lower than previous upper limit)
The $e^+e^-$ Cross Section Scan

Precision scan in $E_{\text{CM}}$ from 10.54 GeV to 11.20 GeV
- 5 MeV steps with 25 pb$^{-1}$ at each step ($\int L \approx 3.3$ fb$^{-1}$)
- 8 steps at $\Upsilon(6S)$ ($\int L \approx 0.6$ fb$^{-1}$)

Inclusive approach
Search for unexpected structures in the inclusive hadronic cross section

$$R_b(s) = \frac{\sigma_{bb(\gamma)}(s)}{\sigma_{\mu\mu}^0(s)}$$

$\sigma_{bb(\gamma)}$: cross section of $e^+e^- \rightarrow b\bar{b}(\gamma)$
$\sigma_{\mu\mu}^0 = 4\pi\alpha^2/3s$: cross section of $e^+e^- \rightarrow \mu^+\mu^-$

Fit with flat component + two interfering relativistic Breit-Wigner functions

PRL 102, 012001 (2009)

$R_b$ accuracy of $\sim$5%

$\Upsilon(5S)$ and $\Upsilon(6S)$ candidates are affected by threshold effects and interference
Plateau above $\Upsilon(6S)$

Clear structures corresponding to the $B\bar{B}$ opening thresholds

$\Upsilon(4S)$ $\Upsilon(5S)$ $\Upsilon(6S)$

$\sqrt{s}[\text{GeV}]$ $R_b$

$B\bar{B}$ $B^+\bar{B}^*$ $B_s\bar{B}_s^*$ $B_s^*\bar{B}_s^*$

$\Upsilon(5S)$ $\Upsilon(6S)$

<table>
<thead>
<tr>
<th>$\Upsilon(5S)$</th>
<th>$\Upsilon(6S)$</th>
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<tr>
<td>$M[\text{MeV}]$</td>
<td>10876 $\pm$ 2</td>
</tr>
<tr>
<td>$\Gamma[\text{MeV}]$</td>
<td>43 $\pm$ 4</td>
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SUMMARY

- First observation of the $\eta_b(1S)$ bottomonium ground state in the decay $\Upsilon(3S) \rightarrow \gamma \eta_b(1S)$

- Confirmation from $\Upsilon(2S) \rightarrow \gamma \eta_b(1S)$

- No significant $\Upsilon(3S) \rightarrow \gamma A^0$ observed
  -- Upper limits (90% CL) range from $(0.7-31) \times 10^{-6}$ for $A^0 \rightarrow \text{invisible}$
  -- Upper limits (90% CL) range from $(0.25-5.2) \times 10^{-6}$ for $A^0 \rightarrow \mu^+\mu^-$
  \[ \Rightarrow \] limits rule out much of the parameter space allowed by the light Higgs models.

- No charged LFV observed

\[
\text{BR}(\Upsilon(3S) \rightarrow e^\pm \tau^\pm) < 5 \times 10^{-6} \quad (90\% \text{ CL}) \\
\text{BR}(\Upsilon(3S) \rightarrow e^\pm \tau^\mp) < 4.1 \times 10^{-6} \quad (90\% \text{ CL})
\]

arXiv:0812.1021[hep-ex]

- Precision scan of $R_b$ in the energy range of $10.54 \text{ GeV} < \sqrt{s} < 11.20 \text{ GeV}$ yields parameters for $\Upsilon(5S)$ and $\Upsilon(6S)$, which differ from the PDG averages (also confirmed by BELLE 's exclusive studies)