Observation of the $\eta_b(1S)$ in $\Upsilon(3S)\rightarrow\gamma\eta_b(1S)$ and bottomonium physics at BaBar

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representing the BaBar collaboration

Bottomonium physics at BaBar:
- Hadronic transitions: $\Upsilon(4S)\rightarrow\pi\pi\Upsilon(1,2S)$, $\Upsilon(4S)\rightarrow\eta\Upsilon(1S)$
- $\Upsilon(3S)\rightarrow\gamma\eta_b(1S)$
- Scan above the $\Upsilon(4S)$

Search for CP-odd light Higgs in bottomonium decays
Bottomonium

b\bar{b} bound states: spectroscopic notation: \( n^{2S+1} L_J \)
fermion-antifermion: \( P = (-1)^{L+1} \quad C = (-1)^{L+S} \)

\( \Upsilon(nS) \equiv n^3S_1 \quad \eta_b(nS) \equiv n^1S_0 \)
\( \chi_{bJ}(nP) \equiv n^3P_J \quad h_b(nP) \equiv n^1P_1 \)

Heavy quarks ⇒ non relativistic
  • relativistic corrections in b\bar{b} smaller than in c\bar{c}

Potential models: “Cornell” (Coulomb +linear term)
  but also
Lattice NRQCD, pNRQCD: \( \alpha_s, m_b, \) lattice spacing, ...

See e.g.:
Brambilla et al, hep-ph/0412158
Eichten et al., hep-ph/0701208
Bottomonium physics

• **Spectroscopy:**
  fine and hyperfine splitting (spin-dependent terms)
  mass splitting between $\Upsilon(nS)$ and $\eta_b(nS)$ depend strongly on $\alpha_s$
  singlet states conspicuously missing!

• **Decay widths:**
  below “open” $B\bar{B}$ threshold, $b\bar{b}$ annihilate to gluons (or virtual photon)
  “OZI-rule” $\Rightarrow$ narrow states
  $\Upsilon(nS) \rightarrow ggg$, $\gamma g g [2.5\%]$ or $\gamma^* [\ell^+\ell^- \sim 2\%]$ $\Gamma=20-50$ keV
  other states decay to $ggg$ or $gg$ depending on $J$ odd/even
  $\eta_b(nS)$, $\chi_{b_0}(nP)$, $\chi_{b_2}(nP) \rightarrow gg$
  $h_b(nP)$, $\chi_{b_1}(nP) \rightarrow ggg$ or $gq\bar{q}$ $\}$ in the MeV range
  None measured
  very few exclusive hadronic modes observed

• **Radiative and hadronic transitions**
  photon or gluons radiation from $b\bar{b}$ state
  multipole expansion if radius $\ll$ wavelength
  many more allowed transitions in $b\bar{b}$ than in $c\bar{c}$
Bottomonium spectrum – before summer

From: Eichten, Godfrey, Mahlke, Rosner, hep-ph/0701208

Spectrum of spin triplets with $L=0$ and $L=1$ below $b\bar{b}$ threshold is complete

All spin singlet states missing:
- $\eta_b(1S)$, $\eta_b(2S)$, $\eta_b(3S)$
- $h_b(1P)$, $h_b(2P)$
- 3 D states, [4 F states?]

Rich cascade structure from the $\Upsilon(3S)$ and $\Upsilon(2S)$:
- almost all states virtually accessible [$B'$s]
Bottomomium production in $e^+e^-$

Copious production of $1^-$ in $e^+e^-$ annihilations when $\sqrt{s} = M(\Upsilon)$

Initial State Radiation (ISR) yields large samples also when running at the $\Upsilon(4S)$

- $\sigma(e^+e^-\rightarrow \Upsilon(3S)\gamma_{\text{ISR}}) \sim 29 \text{ pb}$
- $\sigma(e^+e^-\rightarrow \Upsilon(2S)\gamma_{\text{ISR}}) \sim 17 \text{ pb}$
- $\sigma(e^+e^-\rightarrow \Upsilon(1S)\gamma_{\text{ISR}}) \sim 19 \text{ pb}$

Few $M$ events for “free” while running at the $\Upsilon(4S)$ can be used to study $\Upsilon(nS)$ in fully reconstructed final states

Inclusive searches or final states with missing particles require on-peak running
The BaBar detector and PEP-II

Electromagnetic Calorimeter
6580 CsI(Tl) crystals
e± ID, \( \pi^0 \) & } reco, } detection

Instrumented Flux Return
19 layers of RPC’s (upgrade to LST’s)
\( \mu \pm \) ID & } detection

Cherenkov Detector (DIRC)
144 synthetic fused silica bars
K, \( \pi \) separation

\( e^+ [3.1 \text{ GeV}] \)

Drift Chamber
40 layers
Tracking + dE/dx

Silicon Vertex Tracker
5 layers of double-sided silicon strips

Solenoidal Coil
1.5 T B-field

Excellent tracking and particle ID
CM boost crucial for BB time dependent measurement

Designed to study CP violation
yet gave a flood of exciting new results on many diverse topics

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CERN, September 16, 2008
Bottomonium physics at the $\Upsilon(4S)$: non-$B\bar{B}$ decays of the $\Upsilon(4S)$

- It is usually assumed that $\mathcal{B}(\Upsilon(4S)\rightarrow B\bar{B}) = 100\%$
  
  non-$B\bar{B}$ decays $<4\%$ [PDG]

  [ B-factories] ... several $10^8 \Upsilon(4S)$ to search for rare $B$ decays...
can search for rare $\Upsilon(4S)$ decays as well!

- First non-$B\bar{B}$ decays observed by BaBar with $211 \text{ fb}^{-1}$

  $\Upsilon(4S) \rightarrow \pi^+\pi^- \Upsilon(1S)$ also by Belle:
  
  PRD 75,071103 (2007).

Selecting $\Upsilon(nS) \rightarrow \mu^+\mu^-$

1D-fit to

$\Delta M = M(\pi^+\pi^-\mu^+\mu^-) - M(\mu^+\mu^-)$

[... not really a surprise... ]

PRL 96, 232001(2006)

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CERN, September 16, 2008
$M(\pi^+\pi^-) \text{ in } \Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(1S,2S)$

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"Double bump" structure?
Similar to $\Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(1S)$?


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\( \Upsilon(4S) \) hadronic decays

- Updated measurement with 347 fb\(^{-1}\):
  \( \Upsilon(4S) \) and also \( \Upsilon(3S) \) and \( \Upsilon(2S) \) from ISR
  reconstruct \( \Upsilon(mS) \rightarrow \pi^+\pi^- \Upsilon(nS) \) and \( \Upsilon(mS) \rightarrow \eta \Upsilon(1S) \)
  \([m=4,3,2 \quad n=2,1]\)
  with \( \Upsilon(nS) \rightarrow \mu^+\mu^- / e^+e^- \) and \( \eta \rightarrow \pi^+\pi^-\pi^0 \)

\[
\mathcal{B}(\Upsilon(4S) \rightarrow \pi^+\pi^- \Upsilon(1S)) = (0.800 \pm 0.064 \pm 0.027) \times 10^{-4}
\]
\[
\mathcal{B}(\Upsilon(4S) \rightarrow \pi^+\pi^- \Upsilon(2S)) = (0.86 \pm 0.11 \pm 0.07) \times 10^{-4}
\]

- Observation of \( \Upsilon(4S) \rightarrow \eta \Upsilon(1S) \):

\[
\mathcal{B}(\Upsilon(4S) \rightarrow \Upsilon(1S)\eta) = (1.96 \pm 0.06 \pm 0.09) \times 10^{-4}
\]

\[
\frac{\mathcal{B}(\Upsilon(4S) \rightarrow \eta \Upsilon(1S))}{\mathcal{B}(\Upsilon(4S) \rightarrow \pi^+\pi^- \Upsilon(1S))} = 2.41 \pm 0.40 \pm 0.12
\]

QCD multipole expansion:

\begin{align*}
\text{E1- M2} & \quad \text{E1- E1} \\
\text{Other mechanisms? Simonov,Veselov arXiv:0806.2919} & \quad \text{Meng,Chao,arXiv0806:3259}
\end{align*}
### $\Upsilon(nS)$ Hadronic Transitions in the $\Upsilon(4S)$ Sample

<table>
<thead>
<tr>
<th>Transition</th>
<th>Formula</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_{ee}(2S) \times B(\Upsilon(2S) \to \pi^+ \pi^- \Upsilon(1S))$</td>
<td>(eV)</td>
<td></td>
<td>$105.4\pm1.0\pm4.2$</td>
</tr>
<tr>
<td>$\Gamma(\Upsilon(2S) \to \eta \Upsilon(1S))/\Gamma(\Upsilon(2S) \to \pi^+ \pi^- \Upsilon(1S))$</td>
<td>($\times 10^{-3}$)</td>
<td></td>
<td>$&lt; 5.2$</td>
</tr>
<tr>
<td>$\Gamma_{ee}(3S) \times B(\Upsilon(3S) \to \pi^+ \pi^- \Upsilon(1S))$</td>
<td>(eV)</td>
<td></td>
<td>$18.46\pm0.27\pm0.77$</td>
</tr>
<tr>
<td>$\Gamma(\Upsilon(3S) \to \pi^+ \pi^- \Upsilon(2S))/\Gamma(\Upsilon(3S) \to \pi^+ \pi^- \Upsilon(1S))$</td>
<td>($\times 10^{-2}$)</td>
<td></td>
<td>$0.577\pm0.026\pm0.060$</td>
</tr>
<tr>
<td>$\Gamma(\Upsilon(3S) \to \eta \Upsilon(1S))/\Gamma(\Upsilon(3S) \to \pi^+ \pi^- \Upsilon(1S))$</td>
<td>($\times 10^{-4}$)</td>
<td></td>
<td>$&lt; 1.9$</td>
</tr>
<tr>
<td>$B(\Upsilon(4S) \to \pi^+ \pi^- \Upsilon(1S))$</td>
<td>(%)</td>
<td></td>
<td>$0.800\pm0.064\pm0.027$</td>
</tr>
<tr>
<td>$\Gamma(\Upsilon(4S) \to \pi^+ \pi^- \Upsilon(2S))/\Gamma(\Upsilon(4S) \to \pi^+ \pi^- \Upsilon(1S))$</td>
<td></td>
<td></td>
<td>$1.16\pm0.16\pm0.14$</td>
</tr>
<tr>
<td>$\Gamma(\Upsilon(4S) \to \eta \Upsilon(1S))/\Gamma(\Upsilon(4S) \to \pi^+ \pi^- \Upsilon(1S))$</td>
<td></td>
<td></td>
<td>$2.41\pm0.40\pm0.12$</td>
</tr>
<tr>
<td>$B(\Upsilon(2S) \to \pi^+ \pi^- \Upsilon(1S))$</td>
<td>(%)</td>
<td></td>
<td>$17.22\pm0.17\pm0.75$</td>
</tr>
<tr>
<td>$B(\Upsilon(2S) \to \eta \Upsilon(1S))$</td>
<td>($\times 10^{-4}$)</td>
<td></td>
<td>$&lt; 9$</td>
</tr>
<tr>
<td>$B(\Upsilon(3S) \to \pi^+ \pi^- \Upsilon(1S))$</td>
<td>(%)</td>
<td></td>
<td>$4.17\pm0.06\pm0.19$</td>
</tr>
<tr>
<td>$B(\Upsilon(3S) \to \pi^+ \pi^- \Upsilon(2S))$</td>
<td>(%)</td>
<td></td>
<td>$2.40\pm0.10\pm0.26$</td>
</tr>
<tr>
<td>$B(\Upsilon(3S) \to \eta \Upsilon(1S))$</td>
<td>($\times 10^{-4}$)</td>
<td></td>
<td>$&lt; 8$</td>
</tr>
<tr>
<td>$B(\Upsilon(4S) \to \pi^+ \pi^- \Upsilon(2S))$</td>
<td>($\times 10^{-4}$)</td>
<td></td>
<td>$0.86\pm0.11\pm0.07$</td>
</tr>
<tr>
<td>$B(\Upsilon(4S) \to \eta \Upsilon(1S))$</td>
<td>($\times 10^{-4}$)</td>
<td></td>
<td>$1.96\pm0.06\pm0.09$</td>
</tr>
</tbody>
</table>

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**Note:**

had just started considering physics reach of a SMALL bottomonium program in BaBar

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CERN, September 16, 2008
Run 7 at BaBar

- Dec. 15th: first collisions at \( \Upsilon(4S) \) energy
- Dec. 19th: FY08 Budget Disaster faced with immediate shutdown of PEP-II
  BaBar proposed to run at \( \Upsilon(3S) \) energy by reducing the \( \text{HER}(e-) \) energy
- Dec. 21\(^{st}\), 1:30PM: PEPII-BaBar mtg.
  Decision to move to \( \Upsilon(3S) \)
- Dec. 22\(^{nd}\), 7:00 PM:
  \( \Upsilon(3S) \) scan completed!
  – moved to \( \Upsilon(3S) \) peak
  – initial luminosity at \( 3.5 \times 10^{33} \)
- Move to \( \Upsilon(2S) \) energy in March (in 10 hrs)
- Scan above \( \Upsilon(4S) \) for 10 days
- Last data taken on Apr. 7, 2008
Physics goals of Run 7 at the $\Upsilon(3S)$ and $\Upsilon(2S)$

Explore bottomonium physics with unprecedented statistics:

<table>
<thead>
<tr>
<th></th>
<th>CLEO III</th>
<th>BaBar</th>
<th>BELLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Upsilon(1S)$</td>
<td>20 M</td>
<td>--</td>
<td>100 M (June, 2008)</td>
</tr>
<tr>
<td>$\Upsilon(2S)$</td>
<td>9 M</td>
<td>110 M</td>
<td></td>
</tr>
<tr>
<td>$\Upsilon(3S)$</td>
<td>6 M</td>
<td>120 M</td>
<td>11 M</td>
</tr>
</tbody>
</table>

- “New physics”: search for light Higgs, light Dark Matter
- Bottomonium physics:
  - search for $b \bar{b}$ singlet states: $\eta_b(1S)$, $\eta_b(2S)$, $h_b(1P)$
  - precision measurements of radiative and hadronic transitions...

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Previous searches for $\eta_b(1S)$

- **Inclusive search in radiative transitions**

  \[ B(\Upsilon(2S) \to \gamma \eta_b) < 5.1 \times 10^{-4} \]
  \[ B(\Upsilon(3S) \to \gamma \eta_b) < 4.3 \times 10^{-4} \]

- **Double transitions**

  $\Upsilon(3S) \to \pi^0 h_b(1P)$ or $\pi^+\pi^- h_b(1P)$ with $h_b(1P) \to \gamma \eta_b$

  \[ B < 1.8 \times 10^{-3} \text{ (CLEO)} \]

  $\Upsilon(3S) \to \gamma \chi_{b0}(2P)$; with $\chi_{b0}(2P) \to \gamma \eta_b$

  \[ B < 2.5 \times 10^{-4} \text{ (CLEO III)} \]

- **Exclusive searches**

  $\eta_b \to 4$- and 6-prong Final States in 2-photon Production

  ALEPH at LEP II (2002)

  One 6-prong candidate around $M=9300$ MeV

  1 expected background event

  $\eta_b \to 4$-, 6-, 8-prong Final States in 2-photon Production

  DELPHI at LEP II (2006)

  $\eta_b \to J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$

  CDF II at Tevatron (2006)
Expected properties of $\eta_b(1S)$

- Spin-0 partner of $\Upsilon(1S)$
  - hyperfine splitting: 35 to 100 MeV (potential models, LQCD)
- Decay rates:
  \[
  \frac{\Gamma_{\gamma\gamma}(\eta_b)}{\Gamma_{gg}(\eta_b)} = \frac{9}{2} Q_b^4 \frac{\alpha_{em}^2}{\alpha_s^2} \left(1 - 7.8 \frac{\alpha_s}{\pi}\right)
  \]
  using estimates of $\Gamma_{\gamma\gamma}(\eta_b(1S)) = (0.2-0.7) \text{ keV}$
  \[\Gamma(\eta_b(1S)) = 5-15 \text{ MeV}\]

- Radiative transitions $\Upsilon(nS) \rightarrow \gamma \eta_b(1S)$
  - magnetic dipole (M1)
    \[k=60,600,900 \text{ MeV}\]
    - $[\text{for } 1S,2S,3S]$ “hindered” ($n \neq n'$) transitions strongly suppressed
  - $h_b(1P) \rightarrow \gamma \eta_b(1S)$ dominant [but need to produce $h_b(1P)$]
  - $B's$ of hadronic $\chi_b(2P) \rightarrow \eta_b(1S)$ transitions?
Predictions for $\Upsilon(mS) \rightarrow \gamma \eta_b(nS)$

Predictions for M1 $B$'s depend on wave-functions (potential, relativistic corrections, etc....)

Strong dependence from $\eta_b$ mass

$\mathcal{B}(\Upsilon(3S) \rightarrow \gamma \eta_b(2S)) = (1.4 - 7) \times 10^{-4}$

$\mathcal{B}(\Upsilon(2S) \rightarrow \gamma \eta_b(1S)) = (3 - 5) \times 10^{-4}$

$\mathcal{B}(\Upsilon(3S) \rightarrow \gamma \eta_b(1S)) = (1 - 20) \times 10^{-4}$
The search for the $\eta_b(1S)$ at BaBar

- Decays of $\eta_b$ not known
  
  - **inclusive search**

- Search for the radiative transition $Y(3S) \rightarrow \gamma \eta_b(1S)$

- In c.m. frame: $E_\gamma = \frac{s - m^2}{2\sqrt{s}}$

- For $\eta_b$ mass $m = 9.4$ GeV/c$^2$  
  
  $E_\gamma \sim 911$ MeV

  - look for a bump near $900$ MeV in inclusive photon energy spectrum from data taken at the $Y(3S)$

BLIND ANALYSIS
Search for $\eta_b(1S)$ in the $\Upsilon(3S)$ inclusive $\gamma$ spectrum

Very high background rate

- **Smooth background** from many sources
  - Photons from hadrons decays: $\pi^0, \eta, \omega, \eta', \varphi, ...$
  - Direct photons from bottomonium decays:
    - $e.g., \mathcal{B}(\Upsilon(1S) \rightarrow \gamma g g) = 2.5\%$
  - ISR photons from $e^+e^- \rightarrow \gamma_{\text{ISR}}$ $q\bar{q}$ events

Not reliably modeled by MC

- Large "peaking-backgrounds" close to signal region
  - $\chi_b(2P) \rightarrow \gamma \Upsilon(1S)$ from $\Upsilon(3S) \rightarrow \gamma\chi_b(2P)$
  - $\Upsilon(1S)$ ISR production: $e^+e^- \rightarrow \gamma_{\text{ISR}}$ $\Upsilon(1S)$

Estimated sensitivity:

if $\mathcal{B}(\Upsilon(1S) \rightarrow \gamma\eta_b) = (1 \times 10^{-4})$

with 100 M $\Upsilon(3S)$ and $\varepsilon = \sim 40\%$

expected background (after selection/optimization cuts) in the signal region: 4 M

$\rightarrow$ Signal Yield = $(4000 \pm 2000)$ Events
Selection optimization

“Optimal” cuts selected by maximizing the $S/\sqrt{B}$

$\Upsilon(3S) \rightarrow \gamma \eta_b \ (Signal)$ MC simulation

1+cos$^2$\theta distribution relative to beam axis

JETSET is used for hadronization of quarks/gluons

Detector Simulations via GEANT

- Inclusive properties of $\eta_b \rightarrow gg$ not known:
  Use $\chi_b(2P)$ to validate MC efficiency

Cannot rely on MC to model smooth background: use data...

- Use \sim 9\% of the data sample for optimization [signal region blind]

\begin{center}
\textbf{2.5fb}^{-1} \quad \text{a sample larger than the previous largest sample...}
\end{center}

- Perform the measurement on the remaining 91\% of the sample

\begin{center}
\textbf{25.6 fb}^{-1} \quad \textbf{109\pm1 \ M \ Upsilon(3S)}
\end{center}
Preliminary event selection

- Hadronic event selection
  - Track multiplicity of the event > 3
  - R2 (ratio of 2\textsuperscript{nd} to 0\textsuperscript{th} Fox-Wolfram moment) < 0.98 to suppress QED background

- Photon Selection
  - Neutral clusters in EMC; Isolated from charged tracks
  - Shower shape consistent with EM shower profile
  - central barrel section of the CsI Calorimeter
    -0.762 < \cos (\theta_{\gamma,\text{lab}}) < 0.890
    \Rightarrow \text{Better energy resolution \& reduced ISR photon background}
Event shape

![Diagram of event shape](image)

e^+e^- \rightarrow q\bar{q} \ (q=u,d,s,c)

Strong correlation between the candidate photon and event jet axis (thrust axis of the rest of the event)

Signal photon has little correlation with the $\eta_b$ (spin-0) decay

No other useful event shape variables found...

More isotropic distribution for the photon background from bottomonium decays (3-gluon, $\gamma$ gg, gg)
\( \pi^0 \) veto

Reject photon candidate if \( |M(\gamma\gamma) - M(\pi^0)| < 15 \text{ MeV}/c^2 \)

\( E(\gamma_2) > 50 \text{ MeV} \)

Same optimization criteria obtained from \( \chi_b \) signal yield in test sample

Similar \( \eta \rightarrow \gamma\gamma \) veto does not improve S/B ratio...
Selection efficiency

Efficiency determined on MC

<table>
<thead>
<tr>
<th>Cut</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconstruction</td>
<td>70.5</td>
</tr>
<tr>
<td>Hadronic selection</td>
<td>97.2</td>
</tr>
<tr>
<td>LAT &lt; 0.55</td>
<td>98.0</td>
</tr>
<tr>
<td>In barrel</td>
<td>89.9</td>
</tr>
<tr>
<td>$</td>
<td>\cos \theta_T</td>
</tr>
<tr>
<td>$\pi^0$ - 50 MeV cut</td>
<td>89.8</td>
</tr>
<tr>
<td>Total</td>
<td>37.0</td>
</tr>
</tbody>
</table>

Net efficiencies:

ε(signal) = 37%
ε(bkgr.) = 6%

30 % of Background from continuum processes
Fit to the $E_\gamma$ spectrum

- binned Maximum likelihood Fit with 4 components
  1) Smooth non-peaking background
  2) $e^+e^- \rightarrow \gamma_{\text{ISR}} \ Y(1S) \ \text{Peak (850 MeV)}$
  3) $\chi_b(2P) \rightarrow \gamma Y(1S) \ \text{Peak (750 MeV)}$
  4) $Y(3S) \rightarrow \gamma \eta_b(1S) \ \text{Signal (920 MeV)}$

- PDF shape of each component studied in advance on MC and/or test samples
- PDF parameters estimated before the final fit
1) Non-peaking Background

Empirical function used to parameterize the smooth non-peaking background

\[ A \left( C + e^{-\alpha E_\gamma - \beta E_\gamma^2} \right) \]

Fit parameters \( C, \alpha, \beta, \) and \( \gamma \) determined here are used as the starting values in the final fit.
2) Peaking Background: $e^+e^- \rightarrow \gamma_{\text{ISR}} \Upsilon(1S)$

Shape/Rate determined using the sample collected at $\sqrt{s} \sim 40$ MeV below the $\Upsilon(4S)$

“$\Upsilon(4S)$ Off-peak”

ISR Peak at $E_\gamma = 1.025$ GeV

Crystal Ball function with power law, transition point and width parameters obtained from the fit

$N_{\text{ISR}}(\Upsilon(4S) \text{ Off-peak}) = 35800 \pm 1600$ evt

Extrapolate ISR yield and PDF from $\Upsilon(4S)$ Off-peak to $\Upsilon(3S)$

Extrapolated yield (25153) and PDF fixed in the final fit

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Cross check: use $Y(3S)$ Off-peak for ISR extrapolation

Repeat the exercise with the sample collected $\sim 40$ MeV below the $Y(3S)$ “$Y(3S)$ Off-peak”

<table>
<thead>
<tr>
<th>Sample</th>
<th>Lumi $[\text{fb}^{-1}]$</th>
<th>Cross Section $[\text{pb}]$</th>
<th>Reconstruction Efficiency</th>
<th>Yield $[\text{pb}]$</th>
<th>Extrapolation to $Y(3S)$ On-Peak $[\text{pb}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y(3S)$ Off-Peak</td>
<td>2.415</td>
<td>25.4</td>
<td>$5.78 \pm 0.09$</td>
<td>$2773 \pm 473$</td>
<td>$29393 \pm 5014$</td>
</tr>
<tr>
<td>$Y(4S)$ Off-Peak</td>
<td>43.9</td>
<td>19.8</td>
<td>$6.16 \pm 0.12$</td>
<td>$35759 \pm 1576$</td>
<td>$25153 \pm 1677$</td>
</tr>
</tbody>
</table>

- ISR yields extrapolated from $Y(4S)$ Off-peak and $Y(3S)$ Off-peak samples in good agreement
  - ✓ ISR Yield varied by $\pm 1 \sigma$ as part of the study of the systematic uncertainties on the $\eta_b$ peak position and yield.

- Systematic error on extrapolation (5%)

<table>
<thead>
<tr>
<th>Calculation</th>
<th>$\sigma_{Y(3S)} [\text{pb}]$</th>
<th>$\sigma_{Y(4S)} [\text{pb}]$</th>
<th>Ratio</th>
<th>Asymmetric collider correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benayoun, et. al., 2nd order</td>
<td>25.4</td>
<td>19.8</td>
<td>1.283</td>
<td>Yes</td>
</tr>
<tr>
<td>Benayoun, et. al., 1st order</td>
<td>28.46</td>
<td>21.62</td>
<td>1.316</td>
<td>No</td>
</tr>
<tr>
<td>Benayoun, et. al., 2nd order</td>
<td>26.12</td>
<td>20.21</td>
<td>1.292</td>
<td>No</td>
</tr>
<tr>
<td>Blümlein, et. al., 1st order</td>
<td>28.46</td>
<td>21.62</td>
<td>1.316</td>
<td>No</td>
</tr>
<tr>
<td>Blümlein, et. al., 2nd order</td>
<td>27.02</td>
<td>20.46</td>
<td>1.320</td>
<td>No</td>
</tr>
<tr>
<td>Blümlein, et. al., 3rd order</td>
<td>27.13</td>
<td>20.54</td>
<td>1.321</td>
<td>No</td>
</tr>
</tbody>
</table>

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CERN, September 16, 2008
3) Peaking Background: $\chi_{bJ}(2P) \rightarrow \gamma \gamma(1S)$

- Model each transition by a Crystal Ball function
  Transition point and power law tail parameter fixed to same value for each peak
- Peak positions fixed to PDG values shifted by a common offset:
  - Offset: 3.8 MeV in data (shift in $\gamma$ energy calibration) used to correct energy scale of other peaks
- Ratio of yields taken from PDG
  -- $R(\chi_{b1}/\chi_{b2}) = 1.2$
    consistent with the value measured using soft $\gamma(3S) \rightarrow \gamma \chi_{b1,2}(2P)$ transition photons
  -- $R(\chi_{b1}/\chi_{b0}) = 21$
    $\chi_{b0}(2P)$ contrib. very small

Incorporate ISR peak contribution to model tail of $\gamma$ peak from $\chi_b(2P)$ properly
4) $\eta_b$ Signal PDF

Signal Shape from MC Simulations

Signal PDF: Crystal Ball $\otimes$ Breit-Wigner Function
- Fix signal Crystal Ball parameters from zero-width MC
- Fix the S-wave Breit-Wigner width to 10 MeV
  Fit the data with 5, 15, 20 MeV widths to study systematic errors
Fit result

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

\[(109 \pm 1) \times 10^6 \gamma(3S) \text{ events}\]
Non-peaking background subtracted

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

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

- $R(ISR/\chi_b) \sim 1/33$
- $R(\eta_b/\chi_b) \sim 1/43$
Observation of the $\eta_b(1S)$

$\eta_b$ signal observed with a statistical significance of 10 $\sigma$

Peak position: $921.2^{+2.1}_{-2.8}$ (stat only) MeV
Could this be a fake signal?

- **detector effects?**
  (hot channels in the electromagnetic calorimeter (EMC), crystal defects, etc...)
- Noisy channels in the EMC would have been detected by our online data monitoring
- Check of the angular distribution of inclusive photons reveals that there are no hot spots
  - A tighter Lateral Moment criterion would eliminate such problems
    - $\eta_b$ signal remains after tighter Lateral Moment requirement

- **Artifacts?**
  - Random overlap of photons with $\gamma$ from $\chi_{b}(2P)$?
    - tight Lateral Moment cut reduces also the potential overlap of random photons
  - Check of fit quality in the signal region floating the ISR $\Upsilon(1S)$ yield:
    - ISR fitted yield (24799) consistent with expected yield from extrapolation (25153)
      background parameterization in the signal region is good

How do we know this is the $\eta_b$?

... alternatives? glueball, Higgs...

below the $\Upsilon(1S)$ – only candidate is the $\eta_b$
Systematic uncertainties

- Systematic uncertainties associated with the $\eta_b$ mass
  - Vary ISR yield by $\pm 1\sigma$ (stat $\otimes$ 5% syst) $\rightarrow$ $\delta N = 180$, $\delta E_\gamma = 0.7$ MeV
  - Vary ISR PDF parameters by $\pm 1\sigma$ $\rightarrow$ $\delta N = 50$, $\delta E_\gamma = 0.3$ MeV
  - Vary Signal PDF parameters by $\pm 1\sigma$ $\rightarrow$ $\delta N = 98$, $\delta E_\gamma = 0.1$ MeV
  - Vary $\chi_b$ peak PDF parameters by $\pm 1\sigma$ $\rightarrow$ $\delta N = 642$, $\delta E_\gamma = 0.3$ MeV

- Systematic uncertainties associated with the $\eta_b$ yield
  - Includes systematic uncertainties associated with the $\eta_b$ mass
  - Fit with BW width fixed to 5, 15, 20 MeV $\rightarrow$ $\delta N = 2010$, $\delta E_\gamma = 0.8$ MeV
  - efficiency [data/MC comparison on $\chi_b(2P)$] $\rightarrow$ $\delta N/N = 12.6\%$
  - $\chi_b(2P)$ $B$'s [fixed in fit, from PDG] $\rightarrow$ $\delta N/N = 18.2\%$

- Study of Significance
  - Vary BW width
  - Vary all parameters independently
  - Vary all parameters in the direction resulting in lowest significance $\rightarrow$ No significant change!
Summary of measurements

\[ M(\eta_b) = 9388.9^{+3.1}_{-2.3} \pm 2.7 \text{ MeV}/c^2 \]
\[ M(Y(1S)) - M(\eta_b) = 71.4^{+2.3}_{-3.1} \pm 2.7 \text{ MeV}/c^2 \]

\[ \Delta M = 61 +/- 14 \text{ MeV}/c^2 \]
- lattice spacing: +/- 4 MeV/c^2
- QCD radiative corrections: +/- 12 MeV/c^2
- relativistic corrections: +/- 6 MeV/c^2

\[ \Delta M = 60 \text{ MeV}/c^2 \]
( Relativized Quark Model with Chromodynamics)

\[ \mathcal{B}(Y(3S)\rightarrow\gamma\eta_b(1S)) = (4.5 \pm 0.5 \pm 1.2) \times 10^{-4} \]

cf. upper limit: \[ \mathcal{B}(Y(3S)\rightarrow\gamma\eta_b(1S)). <4.3 \times 10^{-4} @ 90\% \text{ [CLEO III]} \]
Bottomonium spectrum - UPDATE

From: Eichten, Godfrey, Mahlke, Rosner, hep-ph/0701208

All spin singlet states missing:
- $\eta_b(1S)$, $\eta_b(2S)$, $\eta_b(3S)$
- $h_b(1P)$, $h_b(2P)$
- 3 D states, [4 F states?]
Other inclusive searches for $\eta_b$ at BaBar

- $\Upsilon(2S) \rightarrow \gamma \eta_b(1S)$
  
  100 M $\Upsilon(2S)$ events, $\mathcal{B}(\Upsilon(2S) \rightarrow \gamma \eta_b(1S)) = 3-5 \times 10^{-4}$
  
  E$\gamma$ Signal : 611 MeV
  $\chi_b(1P) \rightarrow \gamma \Upsilon(1S)$ 455 MeV
  ISR-$\Upsilon(1S)$ peak 544 MeV  STAY TUNED

- $\Upsilon(1S) \rightarrow \gamma \eta_b(1S)$
  
  Use 18 M tagged $\Upsilon(1S)$ in the $\pi^+\pi^-$ recoil mas of $\Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S)$
  
  E$\gamma$ signal 74 MeV
  no $\chi_b(1P)$ or ISR-$\Upsilon(1S)$ peaking background

- $\Upsilon(3S) \rightarrow \gamma \eta_b(2S)$
  
  E$\gamma$ signal = 360 MeV Difficult region!

- $\Upsilon(3S) \rightarrow \pi^0 h_b(1P)$ or $\Upsilon(3S) \rightarrow \pi^+ \pi^- h_b(1P)$ where $h_b(1P) \rightarrow \gamma \eta_b(1S)$
  
  “requires” to observe also the singlet P state $h_b(1P)$
Scan above the $\Upsilon(4S)$

The charmonium spectrum has many states above open $c\bar{c}$ threshold that are not well-understood (molecules?, 4-quark state?, hybrids? etc.)

[large widths for $\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(nS)$ observed by Belle ]

✧ look for analogues in bottomonium spectrum!

Last detailed scan $\sim 25$ yrs ago (CUSB)

BaBar:

$\sqrt{s} = 10.54$ GeV $\rightarrow 11.20$ GeV

5 MeV steps, $\sim 25$ pb$^{-1}$/step ✧ 3.3 fb$^{-1}$

$\sqrt{s} = 10.96$ GeV $\rightarrow 11.10$ GeV

additional 600 pb$^{-1}$ in the $\Upsilon(6S)$ region
BaBar measurement of $R_b$

- $R_b(s) = \sigma_b(s)/\sigma_\mu(s)$, where $\sqrt{s} = E_{cm}$
  - $\sigma_b$ is the total cross section for $e^+e^- \rightarrow b\bar{b}(\gamma)$ including $b\bar{b}$ states produced in initial state radiation (ISR) below open beauty threshold
  - $\sigma_\mu$ is the tree-level X-section for $e^+e^- \rightarrow \mu^+\mu^-$

- b-enriched sample selected for $R_b$ measurement
- Off-peak $Y(4S)$ data ($\sqrt{s} = 10.54$ GeV) used as reference sample.
BaBar measurement of $R_b$

- Distribution indicates significant features above $\Upsilon(4S)$.
- Interpretation of structure at $\sim 10.62$ & $\sim 10.7$ GeV dependent on threshold openings
Searching for Higgs...

Additional extensions to the MSSM (NMSSM) allow for a light CP-odd Higgs ($A^0$)

In such picture the SM Higgs decays to $A^0A^0$

Depending on the mass

$$A^0 \rightarrow \tau^+\tau^-, \mu^+\mu^- , \gamma\gamma \, \text{or even invisible!}$$

(Dark Matter)

and the SM Higgs would end in final states to which LEP limits do not apply

... even best: $Y$ radiative decays to $A^0$ could be as large as $10^{-4}$
Search for invisible decay of light CP-odd Higgs

Best limits from CLEO
$\mathcal{B}(\Upsilon(1S) \rightarrow \gamma + \text{invisible}) < 10^{-5} - 6 \times 10^{-4}$

[ No limits at $\Upsilon(2S)$ or $\Upsilon(3S)$ ]

Need dedicated trigger:
$\gamma + \text{missing energy}$

More and more difficult with lower $\gamma$ energy:

- “Isolated $\gamma$” [HE]: $E_\gamma > 2\text{GeV}$
  (no additional constraints)

- “Single-$\gamma$” [LE]: $E_\gamma > 1\text{GeV}$
  no additional tracks from IP

20 fb$^{-1}$
82M $\Upsilon(3S)$
Event Selection

<table>
<thead>
<tr>
<th>Variable</th>
<th>$3.2 &lt; E_\gamma^* &lt; 5.5$ GeV</th>
<th>$2.2 &lt; E_\gamma^* &lt; 3.7$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of crystals in EMC cluster</td>
<td>$20 &lt; N_{crys} &lt; 48$</td>
<td>$12 &lt; N_{crys} &lt; 36$</td>
</tr>
<tr>
<td>LAT shower shape</td>
<td>$0.24 &lt; LAT &lt; 0.51$</td>
<td>$0.15 &lt; LAT &lt; 0.49$</td>
</tr>
<tr>
<td>$a_{42}$ shower shape</td>
<td>$a_{42} &lt; 0.07$</td>
<td>$a_{42} &lt; 0.07$</td>
</tr>
<tr>
<td>Polar angle acceptance</td>
<td>$-0.31 &lt; \cos \theta_\gamma^* &lt; 0.6$</td>
<td>$-0.46 &lt; \cos \theta_\gamma^* &lt; 0.46$</td>
</tr>
<tr>
<td>2nd highest cluster energy (CMS)</td>
<td>$E_2^* &lt; 0.2$ GeV</td>
<td>$E_2^* &lt; 0.14$ GeV</td>
</tr>
<tr>
<td>Extra photon correlation</td>
<td>$\cos(\phi_2^* - \phi_1^*) &gt; -0.95$</td>
<td>$\cos(\phi_2^* - \phi_1^*) &gt; -0.95$</td>
</tr>
<tr>
<td>Extra EMC energy (Lab)</td>
<td>$E_{extra} &lt; 0.1$ GeV</td>
<td>$E_{extra} &lt; 0.22$ GeV</td>
</tr>
<tr>
<td>IFR veto</td>
<td>$\cos(\Delta \phi_{NH}^*) &gt; -0.9$</td>
<td>$\cos(\Delta \phi_{NH}^*) &gt; -0.95$</td>
</tr>
<tr>
<td>IFR fiducial</td>
<td>$\cos(6\phi_\gamma^*) &lt; 0.96$</td>
<td>...</td>
</tr>
</tbody>
</table>

**Efficiency:**

- **High Energy Region:** 10-11%
- **Low Energy Region:** 20%

Selection of high-quality photons, with tighter criteria for lower photon energies (increasing backgrounds)

Data taken at the Y(4S)

Veto $e^+e^-\rightarrow\gamma\gamma$ where one of the photons ends up in a dead EMC region.
Maximum Likelihood Fit

- 1-D fit to the missing mass-squared: \( m_X^2 = M_{Y(3S)}^2 - 2 E_y^* M_{Y(3S)} \)
- Signal model
  - parameterized as a single “Crystal Ball” Function
  - parameters vary with assumed Higgs mass, due to EMC response
- Background models
  - determined from control samples and a small test-sample of the on-resonance Y(3S) data
  - Major backgrounds: \( e^+e^- \rightarrow \gamma\gamma \text{ (HE,LE), } \gamma\gamma\gamma \text{ (LE), } e^+e^-\gamma \text{ (LE), } \gamma\gamma \text{ background PDF modeled on data before the IFR veto.} \)

\[ M_{Y(3S)} = \text{Mass of } Y(3S) \]

\[ E_y^* = \text{Energy of } \gamma \text{ in } E_y \]

\[ m_X = \text{Missing Mass} \]

\[ \gamma\gamma \text{ background PDF modeled on data before the IFR veto.} \]

\[ \text{Off-Resonance } Y(3S) \text{ Data} \]

\[ \text{After the IFR veto} \]
Fits to the Spectrum

\[ \chi^2/\text{df} = 58.5/57 \]

**BABAR** Preliminary

Non-peaking background

- \( e^+ e^- \rightarrow \gamma\gamma(\gamma) \)

Signal Model

**High-Energy region**

\[ \chi^2/\text{df} = 22.5/42 \]

**BABAR** Preliminary

Non-peaking background

- \( e^+ e^- \rightarrow \gamma\gamma \)

Signal Model

**Low-Energy region**

arXiv:0808.0017 [hep-ex]

C. Patrignani - Genova

CERN, September 16, 2008
Results

\[ B_{\bar{A}A}R \]

Preliminary

\[ B_{\bar{A}A}R \]

Preliminary

\[ \text{HE-PHOTON REGION} \]

\[ \text{Upper Limit vs. Higgs Mass} \]

\[ \text{LE-PHOTON REGION} \]

\[ \text{arXiv:0808.0017 [hep-ex]} \]

\[ \tan\beta=10, \mu=150 \text{ GeV}, \ M_{1,2,3}=100, 200, 300 \text{ GeV} \]
Conclusions

- After a long successful run at the $\Upsilon(4S)$ primarily devoted to CP violation and CKM measurements, BaBar managed to reshape its physics program almost overnight in response to the budget crisis.
- Still mining our $B\bar{B}$ sample [$\tau^{+}\tau^{-}, D\bar{D},...$]
- The bottomonium harvest just started:
  - The observation of $\eta_b(1S)$ thirty years after the discovery of the narrow $\Upsilon$ resonances is the first great result from the Run7
  - The region above the $\Upsilon(4S)$ scanned in fine steps
  - New physics searches extended to $\Upsilon(3S)$ and $\Upsilon(2S)$ as well
backup slides
Bottomonium decays

only $J^{PC}=1$
Exponentially clean

Dominant above $B\bar{B}$

Radiative transitions

2 [3] gluons  $J$ odd[even]
$\alpha_s$ suppressed

Hadronic transitions
Next to Minimal Supersymmetric Standard Model (NMSSM)

Higgs self-coupling diverges in the Standard Model at high energies

Loops involving superpartners cancel divergences

\[ \mu H_u H_d \]

gives the two Higgs doublets non-zero vacuum-expectation values

\[ \mu \] expected to have a value of order the weak scale, much smaller than the next natural scale (Planck scale, “

One Solution: NMSSM
Next-to-Minimal Supersymmetric Standard Model

\[ \mu H_u H_d \rightarrow \lambda N H_u H_d \]

Add an additional Higgs singlet field, effectively promoting \( \mu \) to a gauge singlet, chiral superfield

Adding a CP-odd Higgs \( (A^0) \) can change the phenomenology of the Higgs sector
Radiative transitions

• QED multipole expansion

E1 transitions:

\[
\Gamma (n^{2S+1} L_i J_i \rightarrow n^{'2S+1} L_f J_f + \gamma) = \frac{4\alpha e^2 Q k^3}{3} (2J_f + 1) S_{if} |\langle f | r | i \rangle|^2
\]

M1 transitions: (spin flip)

\[
\left\{ \begin{align*}
\Gamma (n^3 S_1 \rightarrow n^{'1} S_0 + \gamma) \\
\Gamma (n^1 S_0 \rightarrow n^{'3} S_1 + \gamma)
\end{align*} \right. = 4\alpha e^2 Q k^3 (2J_f + 1) |\langle f | j_0(kr/2) | i \rangle|^2 / 3m^2_Q
\]
Estimate of branching fraction

With \( N(Y(3S)) = (109 \pm 1) \times 10^6 \) \( \varepsilon = 37\% \)

\[
\mathcal{B}(Y(3S) \rightarrow \gamma \eta_b(1S)) = \frac{N(\eta_b(1S))}{\varepsilon N(Y(3S))} = (4.5 \pm 0.5[\text{stat}]) \times 10^{-4}
\]

- **Systematic Uncertainties:**
  - Uncertainty on Signal efficiency
    - Obtained by comparing \( \chi_b \) efficiency in data (39.4%) and MC (35.0%) \( \Rightarrow 12.6\% \)
  - Uncertainty from \( \chi_b(2P) \) BF (PDG)
    - Focus on Observation not BF measurement
    - Will be improved in the future ….
    \( \Rightarrow 18.2\% \)
  - Uncertainty on BW width \( \Rightarrow 11\% \)
  - **Total Systematic Uncertainty** \( \Rightarrow 25\% \)

\[
\mathcal{B}(Y(3S)\rightarrow\gamma\eta_b(1S))= (4.5 \pm 0.5 \text{ [stat.]} \pm 1.2 \text{ [syst.]}) \times 10^{-4}
\]