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

Veronique Ziegler (SLAC)

Representing the BaBar Collaboration

BNL Seminar, Oct. 1, 2008
Current Picture of the Bottomonium Spectrum

- $b\bar{b}$ 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 $Y(1S)$. 

\[ J^{PC} \] = \begin{array}{c}
0^+ \\
1^-
\end{array}  \quad \begin{array}{c}
1^+ \\
0^{++} \\
1^{++} \\
2^{++}
\end{array}
Expected Mass Splitting

- Bottomonium systems are described by QCD-motivated potential models.

- The spin-triplet S-wave $\Upsilon(nS)$ states are produced in hadronic interactions or by virtual photons $e^+e^-$ interactions

- Spin-dependent interactions give rise to splittings within multiplets
  - can predict $\Upsilon - \eta_b$ splittings (analogous to hyperfine splittings in positronium).
  - Spin-spin splitting between the singlet and triplet S-wave $b\bar{b}$ states is predicted to be small.
  - $\Upsilon - \eta_b$ mass splitting is key test of the applicability of perturbative quantum chromodynamics (pQCD) to the bottomonium system & useful check of lattice QCD results.
Expected Mass Splitting

- $Y(nS)$ resonances undergo:
  - Hadronic transitions via $\pi^0$, $\eta$, $\omega$, $\pi\pi$ emission
  - Electric dipole transitions [E1: between states with the same total spin]
  - Magnetic dipole transitions [M1: between states of opposite quark spin configurations and same orbital angular momentum].
  - Electromagnetic transitions between the levels can be calculated in the quark model → important tool in understanding the bottomonium internal structure

- Hyperfine splitting of bottomonium ground state very sensitive to $\alpha_s$
  - Experimental measurement of $M(\eta_b)$ with a few MeV error sufficient to improve $\alpha_s(M_Z)$ accuracy.

- $Y(1S)$-$\eta_b$ mass splitting varies from 35-100 MeV (Lattice-QCD, pQCD, quark potential models)
Expected Transition Rates

- Singlet S-state, $\eta_b$, may be produced in the decay of the Y through the M1 transition $Y(nS) \rightarrow \eta_b(n'S) \gamma \ (n' \leq n)$.

- In the non-relativistic approximation:
  \[
  \Gamma[Y(nS) \rightarrow \eta_b(n'S)\gamma] = \frac{4}{3} \alpha \frac{e_b^2}{m_b^2} I^2 k^3
  \]
  \[
  I = \langle f \mid j_0(kr/2)\mid i \rangle, \ \alpha = 1/137.036, \ e_b = -1/3|e|, \ m_b \approx 4.8 \text{ GeV} / c^2
  \]

- For hindered\(^{\dagger}\) transitions ($n \neq n'$):

  \(^{\dagger}\) In the non-relativistic limit the spatial overlap integrals for M1 transitions equal one between $S$-wave states within the same multiplet and zero for transitions between states with different radial quantum numbers.

  Relativistic corrections $\Rightarrow$ small overlaps ($I$); can be compensated by large phase space factor $k^3$ $\Rightarrow$ rates expected to be observable

  $\Rightarrow$ Essential to measure rate to test relativistic correction factors

- Transition rate: $\text{BF}(Y(3S) \rightarrow \gamma \eta_b) \sim 1 \times 10^{-4} - 2 \times 10^{-3}$

- Upper limit on B.F.$(Y(3S) \rightarrow \gamma \eta_b) < 4.3 \times 10^{-4} @ 90\%$ [CLEO]
Expected $\eta_b$ Decay Properties

- $\eta_b$ expected to decay almost entirely through 2 gluons (OZI-suppressed decay)

- $\eta_b$ expected to decay almost entirely through 2 gluons (OZI-suppressed decay)

- Width expected to be smaller than for the $\eta_c$ [$\Gamma = 26.5$ MeV]

- smaller relativistic correction & smaller strong coupling constant at the b mass than at the c mass.

- Predictions for $\Gamma[\eta_b \rightarrow gg]$: [5 – 20] MeV
The study of bottomonium began with …
Evidence for the bottom quark

**Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions**

S. W. Herb, D. C. Horn, L. M. Lederman, J. C. Sens, H. D. Snyder, and J. K. Yoh
Columbia University, New York, New York 10027

and

Fermilab National Accelerator Laboratory, Batavia, Illinois 60510

and

A. S. Ito, H. Jostlein, D. M. Kaplan, and R. D. Kephart
State University of New York at Stony Brook, Stony Brook, New York 11794
(Received 1 July 1977)

**Accepted without review** at the request of Edwin L. Goldwasser under policy announced 26 April 1976

Dimuon production is studied in 400-GeV proton-nucleus collisions. A strong enhancement is observed at 9.5 GeV mass in a sample of 9000 dimuon events with a mass $m_{\mu^+\mu^-} > 5$ GeV.

**FIG. 3.** (a) Measured dimuon production cross sections as a function of the invariant mass of the muon pair. The solid line is the continuum fit outlined in the text. The equal-sign-dimuon cross section is also shown. (b) The same cross sections as in (a) with the smooth exponential continuum fit subtracted in order to reveal the 9–10-GeV region in more detail.
My desktop...

Opened the door...
30 years of discoveries in the Bottomonium Sector!
PEP-II Running at the Y(3S)…

Dec. 12th - 17th: Start-up after upgrade aimed at $\mathcal{L} = 2 \times 10^{34} \text{ cm}^2\text{s}^{-1}$

Dec. 15th: first collisions at Y(4S) energies

Dec. 17th: first delivery to BaBar

Dec. 19th: Budget gloom and doom 😞

Dec. 20th – 21st: Discussions about immediate move to Y(3S)

Dec. 21st, 3:00 p.m.: Start to lower the energy of the $e^-$ beam for Y(3S) running

Dec. 22nd: LINAC & PEP-II problems related to start-up blues sorted out…

Y(3S) scan completed – moved to Y(3S) peak, began data-taking …

BaBar Run 7

Scan Data from Dec. 22, 2007

Data taken here is “on-resonance”

Data taken here is “off-resonance”

Visible $\sigma_{\text{had}}$ (nb) per 1 MeV

$\sqrt{s}$ (GeV)
THE PEP-II STORAGE RINGS AT SLAC

- Proton – Electron Project (original idea)
- Positron – Electron Project
- Positron – Electron Project II

Symmetric-energy collider-
- single ring
Asymmetric-energy collider-
- HER: old PEP ring
- LER: new ring built on top of HER

End Station A
- DIS / partons
- SPEAR / SSRL
- J/ψ, charm mesons, τ lepton

SLAC / LBL / LLNL
SLAC-Based B Factory:
PEP-II and BaBar

SLC / SLD
- Precision Z studies

BaBar

HER

LER

* Steve Williams pointing to B factory TTU (bottom of picture)
- World Match Superpower 180° scan
- Baby USU 2 MP looking straight down
- ©-adobe by www.ex.com
- electric brushless motor
- ©-adobe 1990
- Picture 21 software
- Feb 28, 2001
- more info at www.subplots.org
The Silicon Vertex Tracker

Designed for very high precision measurements of **angles** and **positions** of **charged tracks** just outside the beam pipe.

- 5 layers of double-sided Si micro-strip detectors
- Strips pitched at 20-50 µm → provides \( \phi, z \) measurements

Some dE/dx info for PID

- e+ (3.1 GeV)
- e- (8.65 GeV)

(for Y(3S) running)
The Drift Chamber
Momentum measurement for charged particle tracks; dE/dx measurements for PID

- 40 layers of approximately hexagonal drift cells

Courtesy of GARFIELD
The Detector of Internally Reflected Cherenkov Radiation

Charged particle identification by means of velocity measurement

Charged particle (velocity $\beta c$) emits Cherenkov radiation in medium (refractive index $n$) when $\beta c > c/n$

So that

\[ \cos \theta_c(\lambda) = \frac{1}{\beta n(\lambda)} \]
The ElectroMagnetic Calorimeter
Designed to detect electromagnetic showers over the energy range from 20 MeV to 4GeV

Segmented array of 6580 Thallium-doped CsI crystals 16 to 17.5 radiation lengths deep (Rad. L. >1.85 cm)

Also used to:
- detect $K_L$’s
- identify electrons

energy & position resolution:

$$\frac{\sigma_E}{E} = \frac{(2.30 \pm 0.03 \pm 0.3)\%}{\sqrt{E(\text{GeV})}} \oplus (1.35 \pm 0.08 \pm 0.2)\%$$

$$\sigma_\theta = \sigma_\phi = \frac{(4.16 \pm 0.04) \text{ mrad}}{\sqrt{E(\text{GeV})}}$$
The Instrumented Flux Return

Designed to identify muons and detect neutrons & $K_L$ mesons

- Resistive Plate Chambers (RPC’s) are inserted between the iron plates comprising the magnet flux return
- Muons ($p > \sim 1 \text{ GeV/c}$) should reach the IFR and be detected; charged hadrons should not
- Neutrons and $K_L$ mesons can also deposit energy in the IFR

Muon detection efficiency degraded significantly over the years. The barrel IFR was upgraded to use Limited Streamer Tubes (LST’s) rather than RPC’s with a significant increase in efficiency.
The Search for the $\eta_b$ at BaBar

- Decays of $\eta_b$ not known ➔ Search for $\eta_b$ signal in inclusive photon spectrum

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

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

  - For $\eta_b$ mass $m = 9.4$ GeV/c$^2$ ➔ monochromatic line in $E_\gamma$ spectrum at 915 MeV, i.e. look for a bump near 900 MeV in inclusive photon energy spectrum from data taken at the $Y(3S)$

BLIND ANALYSIS
ANALYSIS STRATEGY

1. Look for a bump near 900 MeV in the inclusive photon spectrum
   - Large background
     - Non-peaking components
     - Peaking components

2. Reduce the background
   - Selection Criteria
   - Optimization of Criteria
   - Optimization Check (using data)

3. Fitting Procedure
   - One-dimensional fit to the $E_{\gamma}$ distribution
     - Obtain lineshapes of the various components
     - Binned Maximum Likelihood Fit
DATA SETS

- **Y(3S) On-peak data**
  - Full data sample: $L = 28.6 \text{ fb}^{-1}$
    - $122 \times 10^6$ Y(3S) events
  - Analysis sample: $L = 25.6 \text{ fb}^{-1}$
    - $109 \times 10^6$ Y(3S) events
    - Expect $\sim 20 \times 10^3$ Y(3S) $\rightarrow \gamma \eta_b$ events
  - Test sample: $L = 2.6 \text{ fb}^{-1}$
    - $11 \times 10^6$ Y(3S) events
    - Expect $\sim 2 \times 10^3$ Y(3S) $\rightarrow \gamma \eta_b$ events
    - Use since no reliable event generator for Y(3S) background photon simulation

- **Y(3S) & Y(4S) Off-peak data**: $L = 2.4$ & $43.9 \text{ fb}^{-1}$
  (used for background studies)
1. Look for a bump near 900 MeV in the inclusive photon spectrum
The Inclusive Photon Spectrum

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

Non-Peaking background components:

- continuum q\( \bar{q} \)(udsc) events
- generic Initial State Radiation events
- \( \Upsilon(3S) \) cascade decays
- \( \Upsilon(1S) \) decays to \( \gamma \)gg, ggg with final state \( \pi^0 \)'s, \( \eta \)'s, etc…

Look for a bump near 900 MeV in the inclusive photon spectrum
The Inclusive Photon Spectrum

Peaking background components:

\[ Y(3S) \rightarrow \chi_{b0}^{(2P)} \gamma^{\text{soft}} \quad \text{\( E(\gamma^{\text{soft}}) = 122\text{ MeV} \)} \]
\[ \rightarrow Y(1S) \gamma^{\text{hard}} \quad \text{\( E(\gamma^{\text{hard}}) = 743\text{ MeV} \)} \]

\[ Y(3S) \rightarrow \chi_{b1}^{(2P)} \gamma^{\text{soft}} \quad \text{\( E(\gamma^{\text{soft}}) = 99\text{ MeV} \)} \]
\[ \rightarrow Y(1S) \gamma^{\text{hard}} \quad \text{\( E(\gamma^{\text{hard}}) = 764\text{ MeV} \)} \]

\[ Y(3S) \rightarrow \chi_{b2}^{(2P)} \gamma^{\text{soft}} \quad \text{\( E(\gamma^{\text{soft}}) = 86\text{ MeV} \)} \]
\[ \rightarrow Y(1S) \gamma^{\text{hard}} \quad \text{\( E(\gamma^{\text{hard}}) = 777\text{ MeV} \)} \]

\[ Y(3S) \rightarrow \chi_{bJ}^{(2P)} \gamma^{\text{soft}} \quad \text{\( (J=0,1,2) \)} \]
\[ \rightarrow Y(1S) \gamma^{\text{hard}} \]

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

Large background
The Inclusive Photon Spectrum

Peaking background component:

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

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

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

Look for a bump near 900 MeV in the inclusive photon spectrum
2. Reduce the background
Selection Criteria

- Selection Criteria aimed at reducing background while retaining high efficiency

- Optimization done using $S/\sqrt{B}$:
  - $S$ from Signal MC
  - $B$ from 2.6 fb$^{-1}$ On-peak data (Test sample ~ 9% of full statistics sample)

  Test sample not used in final fit (avoid any bias)
Event Selection

- **Hadronic event selection:**
  - $\eta_b$ decays mostly via 2 gluons $\rightarrow$ high track multiplicity
  - Require $\geq 4$ Charged Tracks / Event
  - $R2$ (ratio of 2$^{nd}$ to 0$^{th}$ Fox-Wolfram moment) $< 0.98$
    [Sphericity criterion: suppresses QED background]

- **Candidate photon:**
  - Isolated from charged tracks (i.e. energy deposit in the EMC not matched with any track)
  - Shape consistent with electromagnetic shower (i.e. Lateral moment $< 0.55$)
  - Photon required to be in EMC barrel
    - $-0.762 < \cos(\theta_{\gamma,\text{lab}}) < 0.890$
      - Ensures good energy resolution & high efficiency
      - Reduces contribution from $e^+e^- \rightarrow \gamma (1S)$ [peaks @ $|\cos\theta^*| \sim 1$]
    - Strong correlation between thrust axis and photon direction for continuum events ($e^+e^- \rightarrow q \bar{q}$), weak correlation for spin 0 $\eta_b$ $\rightarrow$ photon satisfies $|\cos\theta_{\text{thrust}}| < 0.7$
  - $\pi^0$ Veto ($|M(\gamma_2) - M(\pi^0)| < 15 \text{ MeV}/c^2$, $E_{\gamma_2} > 50 \text{ MeV}$)

<table>
<thead>
<tr>
<th>Criterion</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$ Veto</td>
<td>89.8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>37.0</strong></td>
</tr>
</tbody>
</table>
Checking the Optimization

• Can we trust our $\eta_b$ signal MC? [$\eta_b \rightarrow gg$ generated using JETSET]

• Use of exclusive decay: $Y(3S) \rightarrow \chi_{bJ}(2P) \gamma_{soft}$ [ $J = 0, 1, 2$ ]
  $E(\gamma_{hard})$ close to $E(\gamma)$ for $Y(3S) \rightarrow \gamma \eta_b$ $\rightarrow Y(1S) \gamma_{hard}$

• Data from $\sim 2.5$ fb$^{-1}$ Test Sample
  • Very reasonable agreement between efficiencies in $\eta_b$ signal MC

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Eff. (from $\eta_b$ peak)</th>
<th>Eff. (signal MC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cut</td>
<td>-</td>
<td>0.629</td>
</tr>
<tr>
<td>BGF MultiHardron</td>
<td>0.973</td>
<td>0.977</td>
</tr>
<tr>
<td>$\geq 4$ Charged Tracks</td>
<td>0.903</td>
<td>0.995</td>
</tr>
<tr>
<td>LAT $&lt; 0.55$</td>
<td>0.997</td>
<td>0.991</td>
</tr>
<tr>
<td>$-0.762 &lt; \cos(\theta_{\gamma,LAB}) &lt; 0.890$</td>
<td>0.928</td>
<td>0.901</td>
</tr>
<tr>
<td>$</td>
<td>\cos(\theta_T)</td>
<td>&lt; 0.7$</td>
</tr>
<tr>
<td>$\pi^0$ - Veto</td>
<td>0.849</td>
<td>0.899</td>
</tr>
</tbody>
</table>
3. Fitting Procedure
Modeling of the Non-Peaking Background Components

- **Large background** (dominated by $q\bar{q}(u\bar{d}sc)$, generic ISR events, $Y(3S)$ cascade decays, $Y(1S)$ decays)

- Small amount of off-$Y(3S)$-peak data ($2.4 \text{ fb}^{-1}$) compared to on-$Y(3S)$-peak data ($25.6 \text{ fb}^{-1}$) makes direct subtraction imprecise

- Model each component with a separate Probability Density Function (PDF), or model all components with the same PDF?
  - Examined both options carefully; chose to **fit using one PDF to describe the combined background**
Non-Peaking Background Parametrization

- Fit combined non-peaking background with a single PDF:
  - Empirical function used to parameterize this background:
    \[ A \left( C + e^{-\alpha E_{\gamma} - \beta E_{\gamma}^2} \right) \rightarrow 4 \text{ free parameters} \]

Fit to the Full Dataset, but with Peaking Bg + Signal Region Excluded

Fit parameters $C, \alpha, \beta$, then used as starting values in the final fit.
Understanding the Various Peaking Background Components

- Accurate parametrization of dominant $\chi_{bJ}(2P)$ contributions essential
  - Monochromatic lines from $\chi_{bJ}(2P) \rightarrow \gamma Y(1S)$ close to $\eta_b$ signal
    ➔ correct modeling of $\gamma$ from $\chi_{bJ}(2P)$ lineshape very important!
  - Use $\chi_{bJ}$ transitions to determine absolute photon energy scale
  - Use $\gamma$ from $\chi_{bJ}$ peak to validate signal reconstruction efficiency

- Radiative return to the Y(1S) produces a peak near 860 MeV in the photon spectrum
  - Crucial to model the lineshape correctly as the signal $\gamma$
    associated with the $\eta_b$ is expected to sit on the high-energy tail of
    the ISR peak
  - Essential to estimate the ISR yield because of this expected
    overlap (due to energy resolution)
Peaking Background Components Modeled with Crystal Ball Functions

Crystal Ball Function*: Gaussian with transition to a Low-side Power-law Tail

\[
f(x; \alpha, n, \bar{x}, \sigma) = N \cdot \begin{cases} 
\exp\left(-\frac{(x - \bar{x})^2}{2\sigma^2}\right), & \text{for } \frac{x - \bar{x}}{\sigma} > -\alpha \\
A \cdot \left(B - \frac{x - \bar{x}}{\sigma}\right)^{-n}, & \text{for } \frac{x - \bar{x}}{\sigma} \leq -\alpha
\end{cases}
\]

where

\[
A = \left(\frac{n}{|\alpha|}\right)^n \cdot \exp\left(-\frac{|\alpha|^2}{2}\right).
\]

\[
B = \frac{n}{|\alpha|} - |\alpha|.
\]

\(N\) is a normalization factor and \(\alpha, n, \bar{x}\) and \(\sigma\) are parameters which are fitted with the data.

Peaking Background from $\chi_{bJ}(2P) \rightarrow \gamma Y(1S)$

- Model each transition using 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 parameter
  - Offset ($\gamma$ energy calibration shift) of +3.8 MeV in data
    - used to correct energy scale of other peaks
- Ratio of yields taken from PDG
  - $R(\chi_{b1}/\chi_{b2}) = 1.2$ (consistent with value we measure using soft $Y(3S) \rightarrow \chi_{b1,2}(2P)$ transition photons)
  - $R(\chi_{b1}/\chi_{b0}) = 21 \Rightarrow \chi_{b0}(2P)$ contrib. very small
- Incorporate ISR peak contribution
  - Model tail of $\gamma$ peak from $\chi_b(2P)$ properly
Peaking Background from $e^+ e^- \rightarrow \gamma_{\text{ISR}} Y(1S)$

Photon c.m. energy for $Y(3S) \rightarrow \gamma_{\text{ISR}} Y(1S)$: 856.4 MeV

- Very important to determine both lineshape and yield
  - Depending on $\eta_b$ mass, the peaks may overlap!
- Estimate the expected lineshape using Signal MC
- Estimate the expected yield: Several options Investigated
  - Use of $e^+ e^- \rightarrow \gamma_{\text{ISR}} Y(1S) \rightarrow \mu^+ \mu^-$ decay: no sign of ISR peak, too much $\gamma \mu \mu$ radiative QED background ....
  - Use of $Y(3S)$ Off-Peak data: $\sim 2.4$ fb$^{-1}$ → large stat. error [$\sigma_{3S,\text{Off}}^{\text{ISR}} (Y(1S)) = 25.4$ pb ]
  - Use of $Y(4S)$ Off-Peak data: 43.9 fb$^{-1}$ → high statistics, smaller error [$\sigma_{4S,\text{Off}}^{\text{ISR}} (Y(1S)) = 19.8$ pb ]

- Use $Y(4S)$ Off-Peak data, and extrapolate yield to $Y(3S)$ On-Peak data using proper cross sections, efficiencies, and integrated luminosities
- In good agreement with yield extrapolated from $Y(3S)$ Off-Peak data to $Y(3S)$ On-peak data
Peaking Background from $e^+e^- \rightarrow \gamma_{\text{ISR}} Y(1S)$

- Use Y(4S) Off-peak Data

- Fit $\gamma$ energy spectrum with:
  - Non-Peaking Background PDF proportional to:
    $$ (C + \exp[-\alpha E_\gamma - \beta E_\gamma^2]) $$
  - ISR Signal Component
    - Crystal Ball function with power law, transition point, and width parameters obtained from a fit to $e^+e^- \rightarrow \gamma_{\text{ISR}} Y(1S)$ (@ Y(4S) off-peak c.m. energy) Signal MC $E_\gamma$ distribution.

- Fitted Yield:
  $$ 35800 \pm 1600 \text{ events} $$
Yield for $e^+e^- \to \gamma_{\text{ISR}} Y(1S)$ at $Y(3S)$
Estimated using $Y(4S)$ Off-Peak Data

The cross section for ISR production of a narrow vector meson is given by

$$\sigma_V(s) = \frac{12\pi^2 \Gamma_{ee}}{m_V s} \cdot W(s, x_V)$$

where $\Gamma_{ee}$ is the di-electron width of the vector meson, $m_V$ is the mass of the vector meson, $s$ is the center of mass energy, $x_V = 2E_\gamma/\sqrt{s}$, and $W(s, x_V)$ is the probability function of photon emission. $W(s, x_V)$ is often referred to as the “radiator function”.

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

- Extrapolated numbers from $Y(3S/4S)$ Off-peak samples consistent
- Systematic error on extrapolation (5%)
- $Y(3S)$ ISR Yield (25153) fixed in the final fit
  - ISR Yield varied by ±1σ in the study of systematic uncertainty in the $\eta_b$ peak position and yield.
FIT STRATEGY

- Allow non-peaking-background parameters to vary
  - \( A (C + \exp[-\alpha E - \beta E^2]) \)

- Fix lineshape parameters for \( \gamma \) from \( \chi_{bJ} \) transitions
  - 3 CB functions describing \( \gamma \chi_{b0,1,2}(2P) \) (≠ widths, common energy scale shift \( \rightarrow \) obtained from fit with ISR \( Y(1S) \) and signal excluded)

- Fix ISR \( Y(1S) \) yield from \( Y(4S) \) off-peak analysis
  - CB lineshape from \( Y(3S) \) on-peak MC; yield fixed to value obtained from \( Y(4S) \) off-peak to \( Y(3S) \) on-peak extrapolation

- Signal PDF: Crystal Ball function convolved with BW 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 Validation

✓ MC simulation studies (toys)
  – Events simulated according to fit component PDFs
  – To test the fitting procedure, we generate 500 MC samples for all combinations of
    • Yield: 15000, 20000, 30000 events
    • Peak position: 890, 895, 900, 910, 920 MeV
  – No bias seen in fitted peak position, even near ISR peak

✓ Fit Procedure checked on 2.6 fb$^{-1}$ Test Sample
FIT RESULT

\[ L = 25.6 \text{ fb}^{-1} \]
\[ \Rightarrow (109 \pm 1) \times 10^6 \text{ Y(3S) events} \]
FIT RESULT

Non-peaking background-subtracted

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

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

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

next slide
The Observation of the $\eta_b$

- $\eta_b$ signal observed with a statistical significance of 10 $\sigma$ ($S = \sqrt{2 \log(L_{\text{max}} / L_0)}$)
- Peak position of $921.2_{-2.8}^{+2.1}$ MeV

(*) after $\gamma$ energy calib. shift of +3.8 MeV
• Could it result from detector effects, e.g. hot channels in the 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
• Could this signal result from random overlap of photons with $\gamma$ from $\chi_{bf}(2P)$?
  – Similarly tight Lateral Moment requirement reduces the potential overlap of random photons
  – Check of fit quality in the signal region is provided by the ISR $Y(1S)$ yield
    • Floating the ISR $Y(1S)$ yield $\rightarrow$ fitted yield $(24799\pm2500)$ consistent with 25153, from extrapolation; assurance that the background parametrization near the signal region is good
• How do we know this is the $\eta_b$?
  Peak $\gamma$ energy $\rightarrow$ State has mass $< m(Y(1S))$ – only expected candidate is the $\eta_b$
  - But if light Higgs, glueball…? $\rightarrow$ New physics ! We’ll take it !!
SUMMARY OF FIT RESULTS

• Signal Yield:
  – Fitted Yield (with BW width of 10 MeV)
    ~19200 ± 2000 (stat)
  – Signal Significance of 10 standard deviations

• Mass of the \( \eta_b \):
  – 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 \( [\gamma(1S) - \eta_b(1S)] \) mass splitting is \( 71.4^{+2.3}_{-3.1}(\text{stat}) \text{ MeV}/c^2 \)
STUDY OF SYSTEMATIC UNCERTAINTIES

- 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 $\chi_{bJ}$ peak PDF parameters by $\pm 1\sigma$ $\rightarrow \delta N = 642, \delta E_\gamma = 0.3$ MeV
- Fit with BW width fixed to 5, 15, 20 MeV $\rightarrow \delta N = 2010, \delta E_\gamma = 0.8$ MeV

* Study of Significance
  - Vary BW width
  - Vary all parameters independently
  - Vary all parameters in the direction resulting in lowest significance

  $\rightarrow$ No significant change!

main source of systematic uncertainty in the $\eta_b$ yield

Systematic uncertainty in the $\eta_b$ mass associated with the $\gamma$ energy calibration shift obtained from the fit to the $\chi_b$ peak $\rightarrow \delta E_\gamma = 2.0$ MeV
Estimate of Branching Fraction

• With $N(Y(3S)) = (109 \pm 1) \times 10^6$
  
  $BF \ (Y(3S)\rightarrow \gamma \eta_b) = \frac{N(\eta_b)}{[N(Y(3S)) \times \text{Eff.}]} = (4.5 \pm 0.5 \ [\text{stat.}]) \times 10^{-4}$
  
  ▪ Signal Efficiency = 37%

• Systematic Uncertainties:
  
  – Uncertainty in Signal efficiency (don't trust MC $\varepsilon$) $\rightarrow$ 12.6%
    • Obtained by comparing $\chi_{bJ}$ efficiency
      in data (39.4%) and MC (35.0%)
    • Uncertainty from $\chi_b(2P)$ BF (PDG) $\rightarrow$ 18.2%
      ▪ Focus on Observation not BF measurement
      ▪ Will be improved in the future ….

  – Uncertainty on BW width $\rightarrow$ 11%

  – Total Systematic Uncertainty $\rightarrow$ 25%

$\Rightarrow BF \ (Y(3S)\rightarrow \gamma \eta_b) = (4.5 \pm 0.5 \ [\text{stat.}] \pm 1.2 \ [\text{syst.}]) \times 10^{-4}$
SUMMARY OF MEASUREMENTS

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

\[ \Delta M = 61 \pm 14 \text{ MeV}/c^2 \]
- 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)

Estimated BF\( (Y(3S) \rightarrow \gamma\eta_b) = (4.8 \pm 0.5 \pm 1.2) \times 10^{-4} \)

cf. upper limit on B.F. < 4.3 x 10^{-4} @ 90% [CLEO III]
CONCLUDING REMARKS

In conclusion, we have observed the decay $\Upsilon(3S) \rightarrow \gamma \eta_b$ with a significance of 10 standard deviations. This is the first evidence for the $\eta_b$ bottomonium state, the pseudoscalar partner of the $\Upsilon(1S)$. The mass of the $\eta_b$ is $9388.9^{+3.1}_{-2.3} \pm 2.7$ MeV/$c^2$, which corresponds to a mass splitting between the $\Upsilon(1S)$ and the $\eta_b$ of $71.4^{+2.3}_{-3.1} \pm 2.7$ MeV/$c^2$. The estimated branching fraction of the decay $\Upsilon(3S) \rightarrow \gamma \eta_b$ is found to be $(4.8 \pm 0.5 \pm 1.2) \times 10^{-4}$.


- Charged-track multiplicity studies indicate a pattern consistent with $\eta_b \rightarrow g g$
- Confirmation from $\Upsilon(2S) \rightarrow \gamma \eta_b(1S)$; analysis is ongoing …

- Observation of $\Upsilon(1S) \rightarrow \gamma \eta_b(1S)$ (although favored $n=n'$ decay) — hard to observe due to very soft photon transition; very large background

- Observation of $\Upsilon(3S) \rightarrow \gamma \eta_b(2S)$ nearly impossible to obtain due to overlap of $\Upsilon(3S) \rightarrow \gamma \eta_b(2S)$ monochromatic photon peak with peaks in photon energy spectrum due to transitions from decays to and from $\chi_{bJ}(1P)$ states
BACK-UP SLIDES
The B-Factory Collision Region (IR-2)

Ring circumference = 2.2 km
# of stored bunches / ring = 1728

Bunch separation = 1.27 m
⇒ ~ 4 ns between collisions

Bunch Dimensions:
(Gaussian ellipsoid)

σ(z) = 11 mm
σ(x) = 120 µm
σ(y) = 5 µm
\{i.e. “flat” beams

Collision Region Dimensions:
• σ(z) = 7.5 mm
• σ(x) = 85.0 µm
• σ(y) = 3.5 µm

3.1 GeV
8.0 x 10^10 e^+ / bunch
Equivalent current 3.0 Amps

3.0 Amps

9.0 GeV
4.8 x 10^10 e^- / bunch
Equivalent current 1.8 Amps

Dipole Permanent Magnets:
(Samarium Cobalt)
Bend beams into head-on collision

✓ best shift: 339 pb^{-1}
✓ best day: 911 pb^{-1}
✓ best week: 5.4 fb^{-1}
✓ best month: 19.7 fb^{-1}
✓ Peak L: 12.1 x 10^{33} cm^2 s^{-1}

Bunch separation = 1.27 m

H_2O

Cooling H_2O
HOW THIS ALL CAME ABOUT…

December Start-Up

Dec. 12th: first beam stored in HER
Dec. 14th: first positrons in LER at Y(4S) energies
Dec. 15th: first collisions
Dec. 17th: first delivery to BaBar

Dec. 19th: Budget gloom and doom 😞

Dec. 20th – 21st: Discussions about immediate move to Y(3S); had run there briefly and scanned the peak in Nov. 2002; Mike Sullivan indicated that could reduce HER energy to get there.

Dec. 21st, 1:30PM: PEPII-BaBar meeting: decision to move to Y(3S) immediately

3:00PM: Start to lower the HER energy
December Start-Up (continued)

Dec. 21st, 3:00PM + : Began by following procedure for c.m. energy shift to off-peak value (10.54 GeV). This is done with the beam in the HER in order to check that everything is O.K.
Found a problem as lowered the energy further; quadrupole magnets in the transport line from LINAC to HER were not changing with the dipoles (not noticeable for small change to off-peak running); messes up the injection!
Mike Sullivan and Uli Wienands calculated necessary quadrupole strengths & changed the quad. power supplies by hand to keep them in line with the dipole magnets.

Swing Shift : LINAC & PEP-II problems related to start-up blues

Midnight : Reached first scan point – but beam injection & storage problems during OWL shift

Dec. 22nd, 9:00 AM : Problems sorted out; scan over Y(3S) begun [Mike Sullivan quote: “lumi was only ~3.5 x 10^{33}”, which is actually slightly over the design value!!]
Injection backgrounds bad – beams coasted for data taking - filled with BaBar turned down

7:00 PM : Y(3S) scan completed – moved to Y(3S) peak
December Start-Up (continued)

- However, beam energy drifted – required **manual intervention in order to remain on the peak**.
- Great job of doing this by our BaBar run coordinators
- Stabilized by the 3rd week of January
- After a month of running, tunnel temperature stabilized & ring geometry stopped changing
- This learning experience made the subsequent change to the Y(2S) much more smooth – accomplished in ~ 10 hrs
- Moving to the Y(1S) would require changing both HER & LER energy; fortunately we did not have to worry about that 😊
<table>
<thead>
<tr>
<th>M(PDG) (GeV/c²)</th>
<th>Transition</th>
<th>BF</th>
<th>E*(γ) (GeV)</th>
<th>Transition</th>
<th>BF</th>
<th>E*(γ) (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y(3S) 10.3552</td>
<td>Y(3S) → Y(2S)</td>
<td>10.60%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y(2S) 10.0233</td>
<td>ee(Y3S) → γ Y(2S)</td>
<td>0.001%</td>
<td>0.3266</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y(1S) 9.4603</td>
<td>ee(Y3S) → γ Y(1S)</td>
<td>0.8562</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>χb2(2P) 10.2687</td>
<td>Y(3S) → γ χb2(2P)</td>
<td>13.1%</td>
<td>0.0862 → χb2(2P) → γ Y(2S)</td>
<td>0.0212%</td>
<td>0.2425 → Y(2S) → γ χb2(1P)</td>
<td>0.758%</td>
</tr>
<tr>
<td>χb1(2P) 10.2555</td>
<td>Y(3S) → γ χb1(2P)</td>
<td>12.6%</td>
<td>0.0993 → χb1(2P) → γ Y(2S)</td>
<td>0.0204%</td>
<td>0.2296 → Y(2S) → γ χb1(1P)</td>
<td>0.731%</td>
</tr>
<tr>
<td>χb0(2P) 10.2325</td>
<td>Y(3S) → γ χb0(2P)</td>
<td>5.9%</td>
<td>0.1220 → χb0(2P) → γ Y(2S)</td>
<td>0.0096%</td>
<td>0.2071 → Y(2S) → γ χb0(1P)</td>
<td>0.403%</td>
</tr>
<tr>
<td>χb2(1P) 9.9122</td>
<td>Y(3S) → γ χb2(1P)</td>
<td>0.4335</td>
<td>χb2(1P) → γ Y(1S)</td>
<td>0.0005%</td>
<td>0.4416</td>
<td></td>
</tr>
<tr>
<td>χb1(1P) 9.8928</td>
<td>Y(3S) → γ χb1(1P)</td>
<td>0.4521</td>
<td>χb1(1P) → γ Y(1S)</td>
<td>0.0005%</td>
<td>0.4230</td>
<td></td>
</tr>
<tr>
<td>χb0(1P) 9.8594</td>
<td>Y(3S) → γ χb0(1P)</td>
<td>0.003%</td>
<td>0.4839 → χb0(1P) → γ Y(1S)</td>
<td>0.0004%</td>
<td>0.3911</td>
<td></td>
</tr>
<tr>
<td>ηb(1S) 9.3889</td>
<td>Y(3S) → γ ηb(1S)</td>
<td>0.9212</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ηb(2S) 9.9633</td>
<td>Y(3S) → γ ηb(2S)</td>
<td>0.3845</td>
<td>ηb(2S) → γ Y(1S)</td>
<td>0.4903</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Copious production of $l^+l^-$ in $e^+e^-$ annihilations when $\sqrt{s} = M(\Upsilon)$

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

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

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
QCD Calculations of the $\eta_b$ mass and branching fraction

- Godfrey and Isgur, PRD 32, 189 (1985)
- Fulcher, PRD 44, 2079 (1991)

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

\[ \sigma_V(s) = \frac{12\pi^2 \Gamma_{ee}^2}{m_{V} s} \cdot W(s, x_v) \]

- $x_v = \frac{2E_{\gamma}^2}{s}$

$\gamma_{\text{ISR}}$ production cross section for $e^+e^- \rightarrow \gamma_{\text{ISR}} Y(1S)$ at $\sqrt{s} = 10.3252 \text{GeV}$ ($\sigma_{Y(3S)}$), production cross section for $e^+e^- \rightarrow \gamma_{\text{ISR}} Y(1S)$ at $\sqrt{s} = 10.55 \text{GeV}$ ($\sigma_{Y(4S)}$), and their ratio for various theoretical calculations. The assumed di-electron width of the $Y(1S)$ is $1.340 \text{MeV}$.  

<table>
<thead>
<tr>
<th>Calculation</th>
<th>$\sigma_{Y(3S)}$ (pb)</th>
<th>$\sigma_{Y(4S)}$ (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>1.321</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>
Charged Track Multiplicity

+ ISR Yield/Multiplicity Interval fixed to value obtained from MC
+ ISR Yield/Multiplicity Interval floated
Calculation of photon energy range limits in the $Y(3S)$ rest-frame for net $Y(3S) \rightarrow Y(1S)$ transitions

Consider the transition $Y(3S) \rightarrow \gamma_X X$, where $X$ represents some $\chi_c$ state, and where $X$ further decays to photon, $\gamma_R$, and a recoil system, $R$. The boost to the $Y(3S)$ rest-frame produces a spread in photon $\gamma_R$ energy distribution; in this frame this change in photon frequency as a result of the boost is sometimes called a Doppler shift. Here we calculate the spread in energy for certain $\chi_c$ transitions.

- In the $Y(3S)$ rest-frame
  \[ m_{Y(3S)} = \not{p}^\gamma + E_X^\gamma, \]
  where $p^\gamma$ and $E_X^\gamma$ are the energies of the photon and of the $\chi_c$ state in the $Y(3S)$ frame, respectively. In that frame,
  \[ p^\gamma = \frac{m_{Y(3S)}^2 - m_X^2}{2m_{Y(3S)}} \]
  \[ E_X^\gamma = \frac{m_{Y(3S)}^2 + m_X^2}{2m_{Y(3S)}} \]

- In the $X$ rest-frame
  Consider the case where $X \rightarrow \gamma_R R$, where $R$ is now the recoil system. The energy of the photon, $\gamma_R$, in the $X$ rest-frame is:
  \[ E_X^{(\gamma_R)} = \frac{m_X^2 - m_R^2}{2m_X} \]

- Boosting to the $Y(3S)$ rest-frame gives
  \[ \tilde{\gamma}_X = \frac{E_X^{(\gamma_R)}}{m_X} = \frac{m_{Y(3S)}^2 + m_X^2}{2m_{Y(3S)}m_X} \]
  \[ (\tilde{\gamma}_X \beta_X) = \frac{\tilde{p}_X}{m_X} = \frac{m_{Y(3S)}^2 - m_X^2}{2m_{Y(3S)}m_X} \]
  where $\beta_X$ is the velocity of $X$ and $\tilde{\gamma}_X = (1 - \beta_X^2)^{-1/2}$.
  The momentum of the photon, $\gamma_R$, in the $Y(3S)$ rest-frame is then
  \[ p^\gamma = \tilde{\gamma}_X \left[ \cos \theta E_X^{(\gamma_R)} + (\tilde{\gamma}_X \beta_X) E_X^{(\gamma_R)} \right] \]
  where $\theta$ is the angle between the direction of $\gamma_R$ w.r.t. $X$.

In the case where $\gamma_R$ and $X$ are collinear, the momentum range of $\gamma_R$, in the $Y(3S)$ rest-frame is
\[ p^\gamma = \tilde{\gamma}_X \left[ \pm \frac{E_X^{(\gamma_R)}}{\tilde{\gamma}_X} + (\tilde{\gamma}_X \beta_X) E_X^{(\gamma_R)} \right] \]
\[ = E_X^{(\gamma_R)} \left( \frac{m_{Y(3S)}^2 + m_X^2}{2m_{Y(3S)}m_X} \right) \left[ \frac{m_{Y(3S)}^2 - m_X^2}{m_{Y(3S)}^2 + m_X^2} \pm 1 \right], \]

so that
\[ p^\gamma = E_X^{(\gamma_R)} \left[ \frac{m_X}{m_{Y(3S)}}, \frac{m_{Y(3S)}}{m_X} \right], \]

where
\[ \frac{m_X}{m_{Y(3S)}} > \frac{m_{Y(3S)}}{m_X} \sim 0.914. \]

Then the effect on the photon from $X \rightarrow \gamma Y(1S)$ is:
- For $X = \chi_c(2P)$:
  \[ m_X = 10.268 \text{GeV}, \quad \frac{m_X}{m_{Y(3S)}} = 0.992, \quad \frac{m_{Y(3S)}}{m_X} = 1.008 \Rightarrow \pm 0.8\% \text{ energy spread} \]
- spread on 777 MeV peak = $\pm 6.2$ MeV
Candidate photons are required to be within calorimeter barrel
Optimization of Selection Criteria

Figure 4: Cluster lateral moment (left), number of ChargedTracks in event (right), cosine of photon momentum direction with the thrust axis of the rest of the event (bottom), for truth-matched signal (red) and data (blue). The distributions are prior to any cuts except except a preliminary energy cut of $0.85 < E_{\gamma,CM} < 0.95$. The arrows show the cut values.
\[ \pi^0 \text{ veto} \]

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…
Example of MC Validation Study

Signal Events

\[ \sqrt{2 \log \left( \frac{L_{\text{max}}}{L_0} \right)} \]

Peak Position

Pull of Yield

\[ \text{Mean} \]
Entries 373
Mean 0.9103
RMS 0.002634

\[ \text{Mean} \]
Entries 373
Mean -0.2124
RMS 1.08
Previous searches for $\eta_b(1S)$

- **Inclusive search in radiative transitions**  
  \[
  B(Y(2S) \rightarrow \gamma \eta_b) < 5.1 \times 10^{-4} \\
  B(Y(3S) \rightarrow \gamma \eta_b) < 4.3 \times 10^{-4}
  \]
  \[\text{[CLEO III, PRL 94, 0322002, 2005]}\]

- **Double Transitions**
  \[
  Y(3S) \rightarrow \pi^0 h_b(1P) \text{ or } \pi^+\pi^- h_b(1P); \quad h_b(1P) \rightarrow \gamma \eta_b \\
  BF < 1.8 \times 10^{-3} \quad \text{(CLEO)}
  \]
  \[
  Y(3S) \rightarrow \gamma \chi_{b0}(2P); \quad \gamma \chi_{b0}(2P) \rightarrow \gamma \eta_b \\
  BF < 2.5 \times 10^{-4} \quad \text{(CLEO III)}
  \]

- **Exclusive Searches**
  \[
  \eta_b \rightarrow \text{4- and 6-prong Final States in 2-photon Production} \\
  \text{ALEPH at LEP II (2002)}
  \]
  One 6-prong candidate in the signal region, $M=9300$ MeV
  1 expected background event

  \[
  \eta_b \rightarrow \text{4-, 6-, 8-prong Final States in 2-photon Production} \\
  \text{DELPHI at LEP II (2006)}
  \]

  \[
  \eta_b \rightarrow J/\psi J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^- \\
  \text{CDF II at Tevatron (2006)}
  \]
Search for $\eta_b$ decay into $J/\psi J/\psi$ at CDF

\[
\frac{\sigma(p\bar{p} \to \eta_b X; |y(\eta_b)| < 0.6, p_T(\eta_b) > 3.0 \text{GeV}) \cdot Br(\eta_b \to J/\psi J/\psi)}{\sigma(p\bar{p} \to H_b \to J/\psi X; |y(J/\psi)| < 0.6, p_T(J/\psi) > 3.0 \text{GeV})} < 5.0 \times 10^{-3}
\]

CDF II Preliminary 1.1 fb$^{-1}$

$\eta_b \to J/\psi J/\psi$

Search window
Fit to soft photon transitions c.m. energy distribution

\[ R = \frac{BF(\Upsilon(3S) \rightarrow \gamma \chi_{b1}) \times BF(\chi_{b1} \rightarrow \gamma \Upsilon(1S))}{BF(\Upsilon(3S) \rightarrow \gamma \chi_{b2}) \times BF(\chi_{b2} \rightarrow \gamma \Upsilon(1S))} = 1.2 \]
The diagram for the $e^+e^- \rightarrow \gamma_{ISR} Y(1S)$ process.
Simulation of a Signal event in the BaBar Detector

$\eta_b$ expected to decay to many hadrons.
Bottomonium family