First Observation of the Bottomonium Ground State
\( \eta_b(1S) \)

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Discovery of the bottom quark

E288 at Fermilab: $p + (\text{Cu, Pt}) \rightarrow \mu^+ \mu^- X$
S.W. Herb et al, PRL 39, 252 (1977)

Bound states of $(b\bar{b})$: Bottomonium!
Upsilon Family

FIT WITH 3 PEAKS

\[ M(Y) = 9.40 \pm 0.013 \text{ GeV/c}^2 \]
\[ M(Y') = 10.00 \pm 0.04 \text{ GeV/c}^2 \]
\[ M(Y'') = 10.43 \pm 0.12 \text{ GeV/c}^2 \]

W.R. Innes et al, PRL 39, 1240 (1977)

Upsilon states quickly confirmed at DORIS/CESR (1978-1979)
DASP II, LENA, PLUTO, CLEO Experiments
Original proposals for \( E_{\text{cm}} = 8.4 \text{ GeV} \) (DORIS) and 8 GeV (CESR)

Most of bottomonium physics come from experiments at e+e- Storage Rings and now at the B-factories.
Production in e+e- Annihilation

- Copious production of Upsilon states (1−−) that couple to virtual photon
- Upsilon in clean environment: nothing else in the rest of the event.

- Continuum q̅q cross section: ~3.3 nb
- Visible cross section at PEP-II: 7 nb (Y2S) and 4 nb (Y3S)
Bottomonium Physics

- Bottomonium states are the heaviest and most compact bound states of quark and anti-quark in nature

- Tests of NRQCD and lattice QCD predictions: $\alpha_s, m_b$
  
  Spectroscopy: Hyperfine and fine splitting
  Hadronic and radiative transitions
  Decays

Some puzzles in the Bottomonium system

- Many different $M(\pi^+\pi^-)$ distributions in di-pion transitions between the Upsilon states
- Unexpectedly large hadronic transition rates (via $\eta$ or $\omega$ meson)
- Transitions to lower $(b\bar{b})$ bound states observed at $E_{cm}$ above the B-meson pair production threshold
Spectroscopy and Transitions

Difficult to observe spin-singlet's: no easy access to leptonic final states…

Observation of $\eta_b$ in $Y(3S) \rightarrow \gamma \eta_b$ [BABAR] PRL 101, 071801 (2008).
Hadronic Decays

• **Narrow widths of \( Y(nS) \) states**: \( \Gamma = 20-55 \text{ KeV} \)

\[ e^+e^- \rightarrow \gamma \rightarrow Y(nS) \rightarrow ggg \text{ or } \gamma g (~2.5\%) \]

In lowest order QCD, other states will annihilate to either 2 or 3 gluons, depending on \( J = \text{Odd or Even} \).

\[ \eta_b, \chi_{b0}(nP), \chi_{b2}(nP) \rightarrow gg \]
\[ h_b, \chi_{b1}(nP) \rightarrow g (q\bar{q}) \]

[High multiplicity hadronic final states: each hadronic decay mode has \( BF = \sim 10^{-5} \)]

• **Widths of \( \eta_b, \text{ even all } \chi_b(1P), \chi_b(2P) \) states are not known**

\[ \eta_c, \chi_{c0}(1P), \chi_{c1}(1P), \chi_{c2}(1P) : \Gamma = 25, 10, 1, 2 \text{ MeV (Charmonia in PDG)} \]

Theo. extrapolation (NRQCD, Potential models)

\[ \rightarrow \text{ Smaller values for the Bottomonium} \]
• **Spin-0 partner of $Y(1S)$: pseudoscalar**
  Theoretical predictions in Potential models and lattice QCD calculations

• **Decay Width**
  – Quarkonium decay rates (LO)
    Kwong, Mackenzie, Rosenfeld, Rosner, PRD 37, 3210 (1988)
    $$\frac{\Gamma_{\gamma\gamma}(\eta_b)}{\Gamma_{gg}(\eta_b)} = \frac{9}{2} Q_b^4 \frac{\alpha_{em}^2}{\alpha_s^2} \left( 1 - 7.8 \frac{\alpha_s}{\pi} \right)$$
  – Theoretical Estimates of $\Gamma_{\gamma\gamma}(\eta_c) = (0.2 - 0.7) \text{ keV}$
    $\Gamma_{\gamma\gamma}(\eta_c) = 7 \text{ keV}$ and $\Gamma(\eta_c) = 25 \text{ MeV}$
  – $\Gamma(\eta_b) = 5 - 15 \text{ MeV}$

• **Radiative Production: $Y(nS) \rightarrow \gamma \eta_b(1S)$**
  – Magnetic Dipole (M1) transitions
    – $k= 70, 610, 920 \text{ MeV}$ for 1S,2S,3S
    – Forbidden transitions suppressed by $\sim 1/100$
    Godfrey and Rosner, PRD 64, 074011 (2001)
Previous Searches for $\eta_b$

- **Inclusive search in radiative transitions**
  
  \[ B(Y(2S) \rightarrow \gamma \eta_b) < 5.1 \times 10^{-4} \]
  \[ B(Y(3S) \rightarrow \gamma \eta_b) < 4.3 \times 10^{-4} \]

  \[ Y \text{ Data Sample: 9 Million} \]
  \[ 6 \text{ Million} \]

- **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**
  
  $\eta_b \rightarrow 4$- and 6-prong Final States in 2-photon production

  \[ \text{ALEPH at LEP II (2002)} \]
  \[ \text{One 6-prong candidate in the signal region, } M=9300 \text{ MeV} \]
  \[ 1 \text{ background event expected} \]

  $\eta_b \rightarrow 4$-, 6-, 8-prong Final States in 2-photon production

  \[ \text{L3 & DELPHI at LEP II (2006)} \]

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

  \[ \text{CDF II at Tevatron (2006)} \]
**Inclusive Search in $E_{\gamma}$ Spectrum [$Y(3S) \rightarrow \gamma \eta_b$]**

- $M(\eta_b) = 9.4 \text{ GeV/c}^2 \rightarrow E_\gamma = 911 \text{ MeV (in E\text{\_cm frame)}}$

- Very high background rate
  - Photons from hadronic decays: $\pi^0$, $\eta$, $\omega$, $\eta$, $\phi$ . . .
  - Direct photons from Bottomonium decays:
    - e.g., $B(Y(1S) \rightarrow \gamma \ g \ g) = 2.5 \%$
  - ISR photons from $e^+e^- \rightarrow \gamma (qq)$ events
  - Transition photons between the $b\bar{b}$ bound states

- **BABAR Measurements**

  \[ N_{\text{signal}} = 19152 \pm 2010 \text{ events} \]

  \[ BF (Y(3S) \rightarrow \gamma \eta_b) = (4.8 \pm 0.5 \text{ [stat]} \pm 1.2 \text{ [syst]} ) \times 10^{-4} \]

  Mass is $\eta_b = 9388.9^{+3.1}_{-2.3} \pm 2.7 \text{ MeV/c}^2$

  Mass splitting $M(Y(1S)) - M(\eta_b) = 71.4^{+2.3}_{-3.1} \pm 2.7 \text{ MeV/c}^2$
Run7 BaBar at PEP-II

- Plan for Final Run: 250 fb⁻¹ of Y(4S) data
- Dec. 15th: first collisions at Y(4S) energy
- Dec. 19th: FY08 Budget announced → Immediate Shutdown of BaBar/PEP-II or Run at Y(3S) E_CM by reducing the HER(e-) energy
  (BaBar Higgs/Exotics Workshop, Oct. 2007)
- Dec. 21st Decision to move to Y(3S)
- Dec. 22nd Y(3S) scan completed
  - Run at the Y(3S) peak (10.3553 GeV)
  - Peak Luminosity at 1.2 x 10³⁴
    HER 8.5923 GeV (-247 MeV)
    LER 3.1200 GeV
- 2S (10.0327 GeV)
  - HER 8.0653 GeV (-920 MeV, 1 mrad)
  - LER 3.1200 GeV
- Move to Y(2S) energy in March (in 10 hrs)
- Scan above Y(4S) for 10 days
- Last Data Taken on Apr. 7, 2008

Data Sample

Y(3S): 30.2 fb⁻¹  120 Million Y(3S) Events
Y(2S): 14.5 fb⁻¹  100 Million Y(2S) Events
Scan above Y(4S) Energy: 5 fb⁻¹
BaBar Detector

$\sigma(E) = 2.5\%$ at 1 GeV

**DIRC (PID)**
- 144 quartz bars
- 11000 PMs

**1.5T solenoid**

**EMC**
- 6580 CsI(Tl) crystals

**Drift Chamber**
- 40 stereo layers

**Silicon Vertex Tracker**
- 5 layers, double sided strips

+ LST muon detectors
Event Selection

• Hadronic Event Selection
  – Track multiplicity of the Event > 3
  – $R^2$ (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 Better energy resolution & Reduced ISR photon background
Photon Shower Shape Cut

Lateral Shower Shapes in EMC clusters

\[ \text{LAT} = \frac{\sum_{i=3}^{n} E_i r_i^2}{(E_1 r_0^2 + E_2 r_0^2 + \sum_{i=3}^{n} E_i r_i^2)} \]

where the \( n \) crystals in the EMC cluster are ranked in order of energy deposited in that crystal, \( E_i \), and \( r_0 = 5\text{cm} \) is the average distance between crystal centers. \( r_i \) is the distance between crystal \( i \) and the cluster centroid calculated from an energy-weighted average of the \( n \) crystals.

Signal MC Photon

\[ 0.85 < E_{\gamma} < 0.95 \text{ GeV} \]

No. of Crystals

LAT

Neutral Clusters in Data

Signal MC Photon

LAT<0.55
• Monte Carlo simulations

\[ Y(3S) \rightarrow \gamma \, \eta_b, \, 1+\cos^2\theta_\gamma \] distribution relative to beam axis

JETSET is used for hadronization of quarks/gluons

Detector simulations using GEANT

• Inclusive properties of \( \eta_b \) hadronic decays (via 2-gluons) not known

Use the \( \chi_b(2P) \) peak in data to calibrate Reconstruction Efficiency

• Non-peaking background shape/yield also not well-known

2.4 fb\(^{-1}\) of \( Y(3S) \) data set aside for optimization study [Test Sample]

25.6 fb\(^{-1}\) of \( Y(3S) \) data for Analysis: \((109 \pm 1)\) Million \( Y(3S) \) Events
Signal photon has very little correlation with the details of the \( \eta_b \) decay, as the \( \eta_b \) is spinless.

- Strong correlation between the candidate photon and the thrust Axis calculated from the tracks in the rest of the event (Continuum events)
- Signal photon has very little correlation with the details of the \( \eta_b \) decay, as the \( \eta_b \) is spinless.
- No other useful event-shape variables were found...
- The background photons from bottomonium decays (3-gluon, \( \gamma \) gg, gg), are more isotropically distributed, making these events harder to distinguish from the \( \eta_b \) signal.
$\pi^0$ Veto

$\left| M(\gamma_2) - M(\pi^0) \right| < 15 \text{ MeV}/c^2$

$\rightarrow$ Photon candidate rejected

Selection Cuts:

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

$|\cos \theta(\text{Thrust})| < 0.7$

Optimization criteria verified with the $\chi_b(2P)$ yield in Test Sample

Similar ($\eta \rightarrow \gamma\gamma$) veto does not improve the S/B ratio...
Signal Detection Efficiency

- Determined from MC simulations

<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:
$\varepsilon$(signal) = 37%
$\varepsilon$(bkgd) = 6%

Background Composition:
Continuum (30%)
Bottomonium decays (70%)
Inclusive Photon Spectrum in 2.5 fb⁻¹ Y(3S) Test Sample

\[ \eta_b \text{ signal at 910 MeV} \]

\[ \chi_b(2P) \]

\[ Y(3S) \rightarrow \gamma \chi_{bJ}(2P) \]
\[ \rightarrow \gamma Y(1S) \]

\[ \chi_{b0}(2P) \rightarrow \gamma Y(1S) \quad E_\gamma = 743 \text{ MeV} \]
\[ \chi_{b1}(2P) \rightarrow \gamma Y(1S) \quad E_\gamma = 764 \text{ MeV} \]
\[ \chi_{b2}(2P) \rightarrow \gamma Y(1S) \quad E_\gamma = 777 \text{ MeV} \]

Peaks are merged
Doppler broadening
15 MeV-wide box
Photon energy smearing
\[ \sigma(E_\gamma) = 20 \text{ MeV} \]
$\chi_b(2P)$ Peaking Background
Fitting the $E_{\gamma}$ Spectrum

Simple 1-D histogram fit (binned Maximum likelihood Fit) with 4 components

1) Smooth non-peaking Background

2) $Y(3S) \rightarrow \gamma \eta_b$ Signal (920 MeV)

3) $e^+e^- \rightarrow \gamma_{ISR} Y(1S)$ Peak (850 MeV)

4) $\chi_b(2P) \rightarrow \gamma Y(1S)$ Peak (750 MeV)

PDF of each component studied in advance & the parameters are estimated, without looking at the Signal Region.
1) Non-peaking Background

Empirical function is used to parameterize the smooth non-peaking background

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

Fit parameters C, $\alpha$, $\beta$ determined here is used as the “starting values” in the Final Fit
2) $\eta_b$ Signal PDF

Signal PDF: Crystal Ball Function $\otimes$ Breit-Wigner

Fix the S-wave Breit-Wigner width to 10 MeV

The width is varied 5, 15, 20 MeV to determine systematics
Crystal Ball Function  [www.wikipedia.org]

A probability density function commonly used to model the photon energy line shape. It consists of a Gaussian core portion and a power-law low-end tail, below a certain threshold.

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

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 \(\alpha\), \(n\), and \(\sigma\) are parameters.

Examples of the Crystal Ball Function
Red: \(\alpha = 10\), Green: \(\alpha = 1\), Blue: \(\alpha = 0.1\)
3) $e^+e^- \rightarrow \gamma_{\text{ISR}} Y(1S)$ Background

(Initial State Radiation)

$e^+e^-$ QED process at 10.355 GeV

Cross section: 25 pb
$E(\gamma_{\text{ISR}}) = 0.855$ GeV

Cross section measurements at 10.58 GeV $E_{\text{cm}}$

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

Potentially a very large background source
(Not considered in previous CLEO Analyses)
Photon momentum peaked along beam direction

We use Continuum events in Off-$Y(3S)$ Data and Off-$Y(4S)$ Data to determine the background rate and shape.

- 2.4 fb$^{-1}$ at $E_{\text{cm}}$ 30 MeV below the $Y(3S)$
- 44 fb$^{-1}$ at $E_{\text{cm}}$ 40 MeV below the $Y(4S)$
\( e^+e^- \rightarrow \gamma_{\text{ISR}} Y(1S) \) at 10.54 GeV

Shape & Rate determined using Off-Y(4S) data where \( E_\gamma(\text{ISR}) \) peaks at 1.025 GeV

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

\[ N_{\text{sig}} = 35800 \pm 1600 \]
Yield Estimate for $e^+e^- \rightarrow \gamma_{\text{ISR}} Y(1S)$ In Y(3S) On-Resonance Data Sample Using Y(4S) Off-Resonance Data

<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</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y(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>
<tr>
<td>Y(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>
</tbody>
</table>

- Extrapolated numbers from Y(3S/4S) Off-peak samples in good agreement
- Systematic error on extrapolation (5%)
- ISR Yield obtained from extrapolation (25153) fixed in the final fit
  ✓ ISR Yield varied by ±1 $\sigma$ as part of the study of the systematic uncertainties on the $\eta_b$ peak position and yield.

<table>
<thead>
<tr>
<th>Calculation</th>
<th>$\sigma_{T(3S)}$ (pb)</th>
<th>$\sigma_{T(4S)}$ (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>1.316</td>
<td>No</td>
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<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>
4) $\chi_{bJ}(2P) \rightarrow \gamma Y(1S)$

- 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 due to PEP-II energy meas. and $\gamma$ energy calibration: $+3.8$ MeV in data
  - Used to set the energy scale of other peaks
- Ratio of yields is 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)
  ($\chi_{b0}(2P)$ contribution is very small)
- Incorporate ISR peak contribution
  - Model tail of $\gamma$ peak from $\chi_{b}(2P)$ properly
FIT RESULT

$\mathcal{L} = 25.6 \text{ fb}^{-1}$
$\Rightarrow (109 \pm 1) \times 10^6 \text{ } Y(3S) \text{ events}$

![Graph showing the distribution of events versus $E_\gamma$ (GeV). Markers indicate $\chi_b$ peak, $\gamma_{ISR}Y(1S)$, and $\eta_b$? with normalized counts $\times 10^3$.](image)
FIT RESULT

Non-peaking background-subtracted

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

- $R(ISR/\chi_b) \sim 1/30$
- $R(\eta_b/\chi_b) \sim 1/40$
Observation of the $\eta_b$

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

Fit $\chi^2/\text{ndof} = 147/113$
More Checks

• **Detector Effects**
  – Noisy EMC channels monitored online; no hot spots in EMC photon distribution
  – Remove photons with small Lateral Moment to veto possible hot crystals
    - $\eta_b$ signal remains strong
  – Remove photons with large Lateral Moment to veto accidental photon overlaps
    - e.g., two photons from $\chi_b(2P)$ transitions
    - No effect on $\eta_b$ signal significance

• $\chi_b$ line shape
  – Float the ISR $Y(1S)$ yield $\rightarrow$ fitted yield (24800+/-4000) consistent with expected number of ISR events (25000); No effect on the $\eta_b$ yield
  – $\chi_b$ line shape consistent with the shape from the exclusive reconstruction:
    $Y(3S) \rightarrow \gamma \chi_b(2P); \chi_b(2P) \rightarrow \gamma Y(1S); Y(1S) \rightarrow \mu^+\mu^-$

• **Is it really the $\eta_b$?**
  The only Bottomonium state below the $Y(1S)$ mass is the $\eta_b$
  Event properties such as track multiplicity and photon direction consistent with $\eta_b$
STUDY OF SYSTEMATIC UNCERTAINTIES

• Systematic uncertainties associated with the $\eta_b$ yield and mass
  – Vary ISR yield by $\pm 1\sigma$ (stat $\otimes$ 5% syst) $\rightarrow \delta N = 180, \delta M = 0.7$ MeV
  – Vary ISR PDF parameters by $\pm 1\sigma$ $\rightarrow \delta N = 50, \delta M = 0.3$ MeV
  – Vary Signal PDF parameters by $\pm 1\sigma$ $\rightarrow \delta N = 98, \delta M = 0.1$ MeV
  – Vary $\chi_b$ peak PDF parameters by $\pm 1\sigma$ $\rightarrow \delta N = 642, \delta M = 0.3$ MeV
  – Fit with BW width fixed to 5, 15, 20 MeV $\rightarrow \delta N = 2010, \delta M = 0.8$ MeV

• Additional systematic uncertainties in Branching Fraction calculation
  – $\chi_b(2P)$ yield in data and MC at PDG rates: 22%

• Significance test
  Vary BW width and fit parameters; Vary all parameters in the direction
  result in lowest significance: NO Change in Significance ($> 10\sigma$)
SUMMARY OF Y(3S) MEASUREMENTS

\[ \eta_b = 9388.9^{+3.1}_{-2.3} \pm 2.7 \text{ MeV}/c^2 \]

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

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


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


\[ \Delta M = 60 \text{ MeV}/c^2 \]
(Relativistic Quark Model; LO)
Theorists faced with BABAR Hyperfine Splitting measurement

Summation of next-to leading logarithmic corrections using the nonrelativistic renormalization group (A. Penin @QWG2008)

Very good agreement between data and theory in charmonium system

QCD NLL approximation:

\[ E_{\text{hfs}}^{\text{th}} = 39 \pm 11 \text{ (th)} + ^{9}_{-8} \text{ (}\delta \alpha_s\text{) MeV} \]

Experiment:

\[ E_{\text{hfs}}^{\text{exp}} = 71.4 \pm 2.7 \text{ (syst)} + ^{2.3}_{-3.1} \text{ (stat) MeV} \]

\[ E_{\text{hfs}} = M(\Upsilon_{1S}) - M(\eta_b) \]

\[ M(\eta_b) \text{ and } a(s) \text{ from nonrelativistic renormalization Group, Kniehl et al, PRL 92:242001 (2004)} \]
Inclusive Search in $E_\gamma$ Spectrum [$Y(2S) \rightarrow \gamma \eta_b$ ]

100 Million $Y(2S)$ Events; $BF$ expected $= (1 - 5) \times 10^{-4}$

$E_\gamma$ Signal at 611 MeV
ISR-$Y(1S)$ peak at 545 MeV
$\chi_b(1P) \rightarrow \gamma Y(1S)$ peak at 420 MeV

Analysis almost identical to the $Y(3S)$ case with minor modifications

Comparison to $Y(3S)$ Analysis

30% better photon energy resolution at lower energy
$\rightarrow$ better separation between peaks

More (x3) random photon background at lower energy
$\rightarrow$ less significance at similar $BF$
Photon Selection and Optimization

• Same hadronic event selection and photon candidate selection as in Y(3S) analysis

• Event Shape: $|\cos \theta(\text{Thrust})| < 0.8$
  Less continuum background as the Y(2S) cross section is twice the Y(3S) cross section

• Pi0 Veto: $E(g2) > 40 \text{ MeV}$

• MC signal detection efficiency = 35.8%
Fitting the Photon Energy Spectrum

$\chi^2$ fit of 1-D histogram with 4 components

1) Smooth non-peaking Background
   Parameterization with exponential of 4th order polynomial

2) $Y(3S) \rightarrow \gamma \eta_b$ Signal (610 MeV)
   Shape from MC simulation

3) $e^+e^- \rightarrow \gamma_{ISR} Y(1S)$ Peak (545 MeV)
   Sharpe determined using Off-4S data
   Normalization floated in the fit

4) $\chi_b(1P) \rightarrow \gamma Y(1S)$ Peak (420 MeV)
   Relative rates of $\chi_b$ states fixed to exclusive $\gamma\mu^+\mu^-$ measurement
   Photon lineshape uses Crystal Ball function convoluted with
   Doppler Broadening
Fit Result

Non-peaking
Background subtracted

$Y(2S) \rightarrow \gamma X$

$E_{\gamma,CM}$ (GeV)

Events / (0.005 GeV)

$\times 10^3$
Close-up View

Non-peaking Background subtracted
Y(2S) Fit Result

- $\eta_b$ yield: $13915^{+3555}_{-3452}$
- $\eta_b$ peak position: $610.5^{+4.5}_{-4.3} \pm 1.8$ MeV

- ISR yield of 15000 $\pm$ 4200 is consistent with the expected rate of 16700 $\pm$ 700 $\pm$ 1200

- Goodness of Fit: $\chi^2$/ndof=116.2/93
- Significance including systematics: $>3.5 \sigma$

- The bump at 680 MeV is too narrow for the detector resolution of photons at that energy
- No detector artifacts or random photon overlaps seen
Yield and peak position systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>Δ N [Evts]</th>
<th>Δ peak pos. [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_b$ width, 5 MeV</td>
<td>-1519</td>
<td>-0.5</td>
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<tr>
<td>$\eta_b$ width, 15 MeV</td>
<td>1195</td>
<td>0.4</td>
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<td>$\eta_b$ width, 20 MeV</td>
<td>2328</td>
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<td>ISR PDF, N</td>
<td>133</td>
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<tr>
<td>ISR PDF, A</td>
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<td>ISR PDF, $\sigma$</td>
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<tr>
<td>signal PDF, N</td>
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<tr>
<td>signal PDF, A</td>
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<tr>
<td>signal PDF, $\sigma_{CB}$</td>
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<td>0.01</td>
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<tr>
<td>$\chi_b$ PDF, N</td>
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<td>0.01</td>
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<tr>
<td>$\chi_b1/\chi_b2$ ratio</td>
<td>150</td>
<td>0.14</td>
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<tr>
<td>$\chi_b0/\chi_b1$ ratio</td>
<td>145</td>
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<tr>
<td>$\chi_b0$ $\sigma$</td>
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<td>0.03</td>
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<td>Extra $\chi_bJ$ tail</td>
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<td>exp Pol(3) pdf</td>
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<td>Total, fit variations</td>
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<td>Energy scale offset</td>
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<tr>
<td>$\chi_b$ masses</td>
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<tr>
<td>Total</td>
<td>+2811</td>
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</tr>
</tbody>
</table>

$\eta_b$ width Variation
$\chi_b$ shape variation
Smooth background shape variation
\[ Y(2S) \rightarrow \gamma \eta_b \]

\[ E_\gamma = 610.5^{+4.5}_{-4.3} \pm 1.8 \text{ MeV} \]

\[ B(\Upsilon(2S) \rightarrow \gamma \eta_b) = [4.2^{+1.1}_{-1.0} \pm 0.9] \times 10^{-4} \]

\[ Y(3S) \rightarrow \gamma \eta_b \]

\[ E_\gamma = 921.2^{+2.1}_{-2.8} \pm 2.4 \text{ MeV} \]

\[ B(\Upsilon(3S) \rightarrow \gamma \eta_b) = [4.8 \pm 0.5 \pm 1.2] \times 10^{-4} \]

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

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

**BABAR Preliminary**
Other Searches for $\eta_b$ at BaBar

- \( Y(2S) \rightarrow \pi^+\pi^- Y(1S); \ Y(1S) \rightarrow \gamma \ \eta_b(1S) \) INCLUSIVE
  
  18 M \( Y(1S) \) events in \( \pi^+\pi^- \) Recoil
  \( E_\gamma \) signal at 71 MeV
  No \( \chi_b \) background; No peaking ISR background

- \( Y(3S) \rightarrow \gamma \ \eta_b(2S) \) INCLUSIVE
  
  \( E_\gamma \) Signal at 360 MeV (Difficult Region with nearby E1 transitions)

- \( Y(3S) \rightarrow \pi^0 \ h_b(1P) \) or \( \pi^+\pi^- h_b(1P) \); \( h_b(1P) \rightarrow \gamma \ \eta_b \) INCLUSIVE

- \( Y(3S) \rightarrow \omega \ \eta_b(1S) \) INCLUSIVE

- \( Y(nS) \rightarrow \gamma \ \eta_b(1S) \): Full reconstruction of exclusive channels
Next steps in $\eta_b$ physics

- Measurement of the $\eta_b$ width
- More precise mass splitting determination
- Improved branching fraction measurements
- Investigate the properties of the $\eta_b$ events
- Reconstruction of exclusive decay modes

$\eta_b \rightarrow \gamma\gamma \quad (BF = \text{few } \times 10^{-4})$

<table>
<thead>
<tr>
<th></th>
<th>CLEO III</th>
<th>BaBar</th>
<th>BELLE</th>
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</thead>
<tbody>
<tr>
<td>$Y(1S)$</td>
<td>20 M</td>
<td></td>
<td>100 M</td>
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<tr>
<td>$Y(2S)$</td>
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<td>100 M</td>
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<tr>
<td>$Y(3S)$</td>
<td>6 M</td>
<td>120 M</td>
<td>11 M</td>
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</table>

100 Million events are not enough to achieve all these goals…

We will need a Super-B Factory.
Summary

• First Observation of the $\eta_b$ in $\Upsilon(3S) \rightarrow \gamma \, \eta_b$
  
  Hyperfine Splitting of 71.5 MeV, a challenge to the Theorists

• Confirmation with Further Evidence in $\Upsilon(2S) \rightarrow \gamma \, \eta_b$

• Exciting results on $\eta_b$ and other bottomonium physics are expected from BABAR, BELLE, and CLEO experiments in the near future
Thank you!