



The η_b at BaBar

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Bottomonium Physics

- Bottomonium states are the heaviest mesons in Nature
- Tests of NRQCD and lattice QCD predictions: α_s , m_b

Spectroscopy: Hyperfine and fine splitting

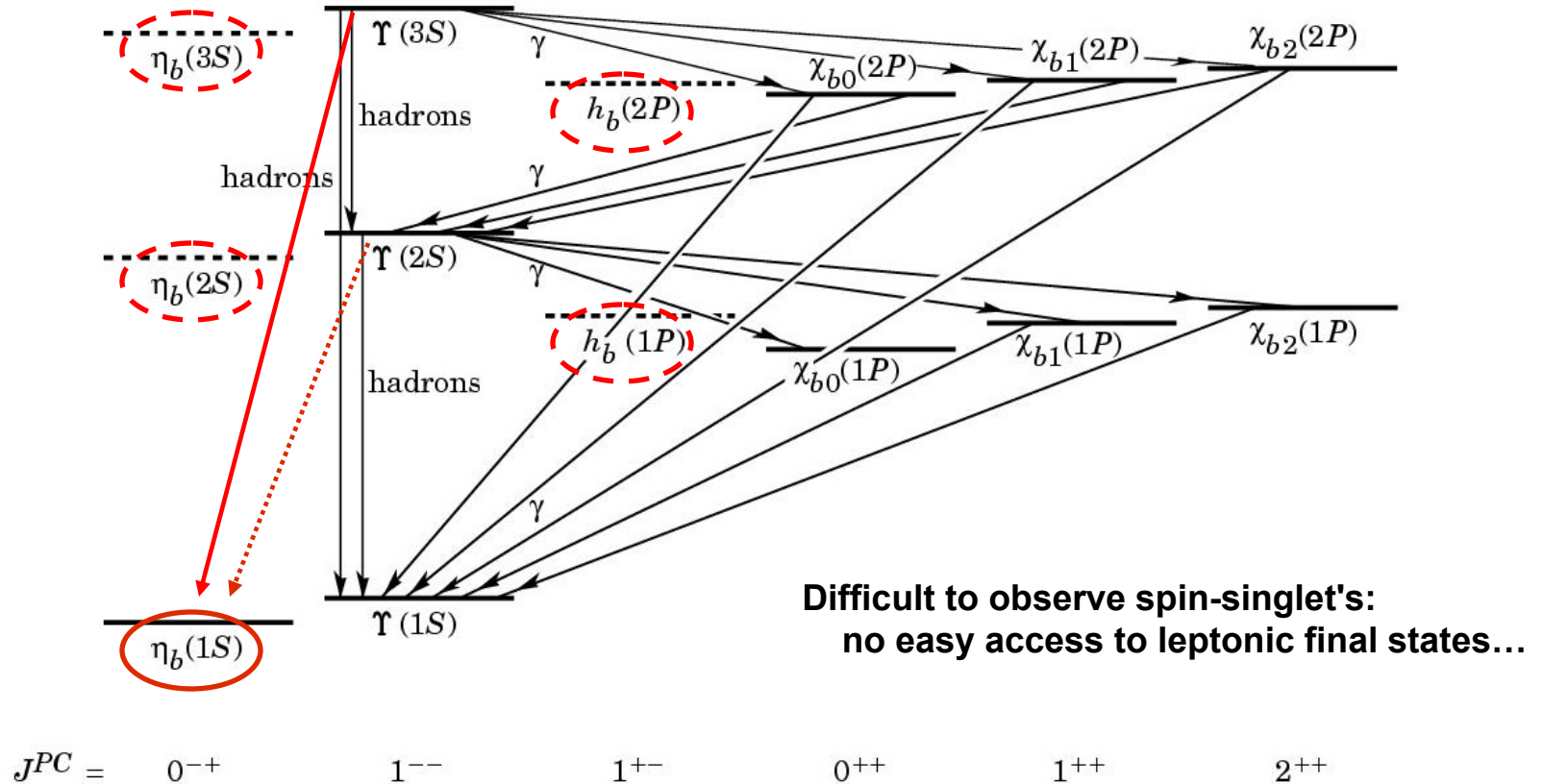
Hadronic and radiative transitions

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 η or ω meson)
- Transitions to lower ($b\bar{b}$) bound states observed at E_{cm} above the B-meson pair production threshold

Spectroscopy



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

Hadronic Decays

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

$$e^+e^- \rightarrow \gamma^* \rightarrow Y(nS) \rightarrow ggg \text{ or } \gamma gg (\sim 2.5\%)$$

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

$$\begin{aligned} \eta_b, \chi_{b0}(nP), \chi_{b2}(nP) &\rightarrow gg \\ h_b, \chi_{b1}(nP) &\rightarrow ggg \text{ or } (q\bar{q})g \end{aligned}$$

[Exclusive hadronic final state: $BF \sim 10^{-5}$]

- **Width of η_b , 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. expectations (NRQCD, Potential models)

→ Smaller values for the Bottomonium

η_b

- **Spin-0 partner of $Y(1S)$: pseudoscalar**

- Hyperfine mass splitting: 71.5 MeV (BABAR)

Theoretical predictions in Potential models and lattice QCD calculations

- **Decay Width**

- Quarkonium decay rates

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 $\Gamma_{\gamma\gamma}(\eta_b) = (0.2 - 0.7) \text{ keV} \rightarrow \Gamma(\eta_b) = 5 - 15 \text{ MeV}$
[$\Gamma_{\gamma\gamma}(\eta_c) = 7 \text{ keV}$ and $\Gamma(\eta_c) = 25 \text{ MeV}$]

- **Radiative Production: $Y(nS) \rightarrow \gamma \eta_b(1S)$**

- Magnetic Dipole (M1) transitions

$$\Gamma_{M1} \propto k^3/m_Q^2 \cdot |\langle f | j_0(kr/2) | i \rangle|^2$$

- $k = 70, 610, 920 \text{ MeV}$ for 1S, 2S, 3S

- Forbidden transitions are suppressed by $\sim 1/100$

Godfrey and Rosner, PRD 64, 074011 (2001)

Previous Searches for η_b

- Inclusive search in radiative transitions**

[CLEO III, PRL 94, 0322002, 2005]

$$B(Y(2S) \rightarrow \gamma \eta_b) < 5.1 \times 10^{-4}$$
$$B(Y(3S) \rightarrow \gamma \eta_b) < 4.3 \times 10^{-4}$$

Data Sample: 9 Million Y(2S)
6 Million Y(3S)

- Double transitions**

$$Y(3S) \rightarrow \pi^0 h_b(1P) \text{ or } \pi^+\pi^-h_b(1P); h_b(1P) \rightarrow \gamma \eta_b$$

$$BF < 1.8 \times 10^{-3} \text{ (CLEO)}$$

$$Y(3S) \rightarrow \gamma \chi_{b0}(2P); \gamma \chi_{b0}(2P) \rightarrow \gamma \eta_b$$

$$BF < 2.5 \times 10^{-4} \text{ (CLEO III)}$$

- Exclusive searches**

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

ALEPH at LEP II (2002)

One 6-prong candidate in the signal region, $M=9300$ MeV

1 background event expected

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

DELPHI at LEP II (2006)

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

CDF II at Tevatron (2006)

Inclusive Search in E_γ Spectrum [$Y(3S) \rightarrow \gamma \eta_b$]

- $M(\eta_b) = 9.4 \text{ GeV}/c^2 \rightarrow E_\gamma = 911 \text{ MeV}$ (in E_{cm} frame)
- Very high background rate
 - Photons from hadronic decays: $\pi^0, \eta, \omega, \eta, \phi \dots$
 - 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**

$N_{\text{signal}} = 19152 \pm 2010$ events

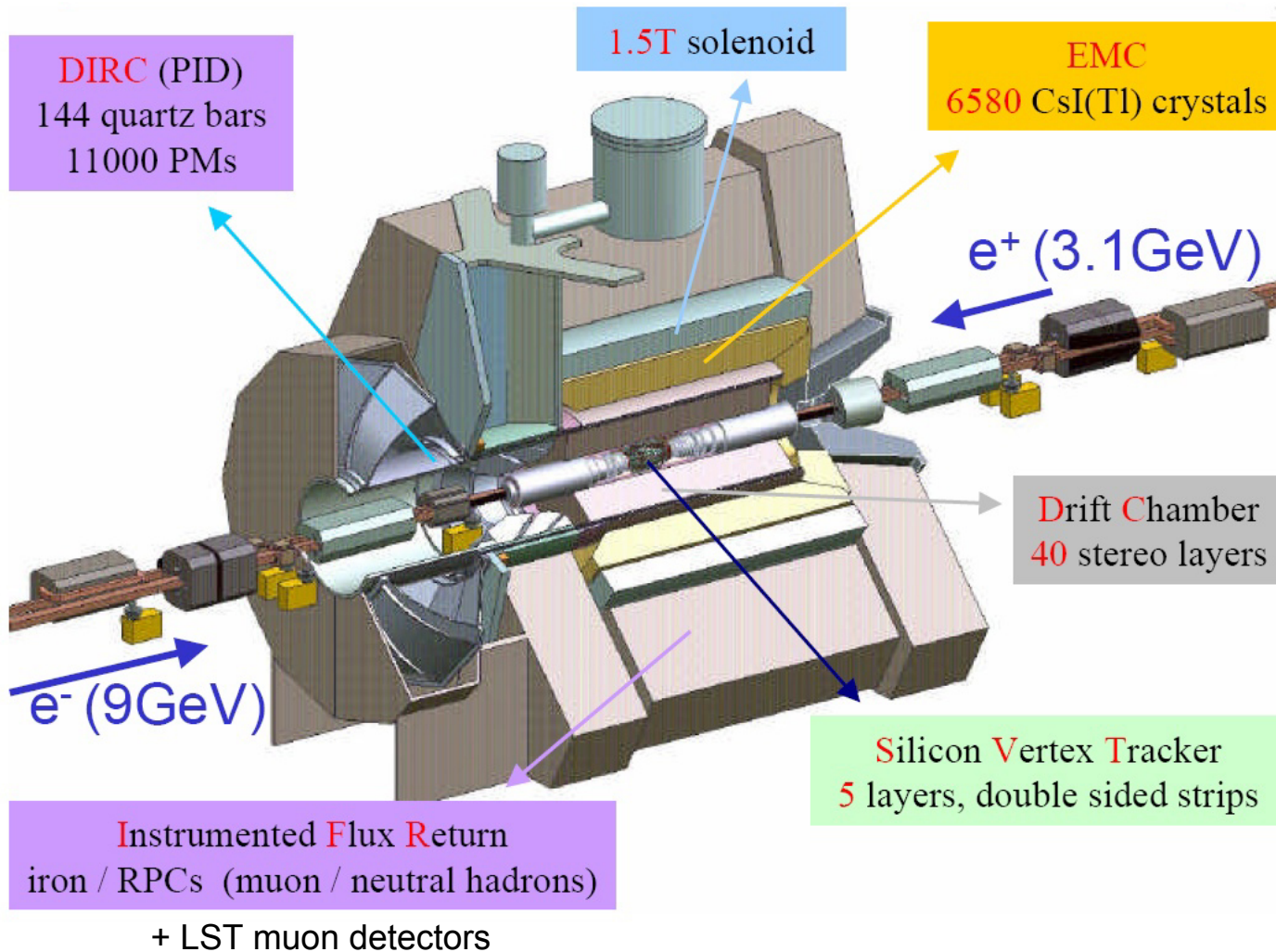
$BF(Y(3S) \rightarrow \gamma \eta_b) = (4.8 \pm 0.5 [\text{stat}] \pm 1.2 [\text{syst}]) \times 10^{-4}$

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

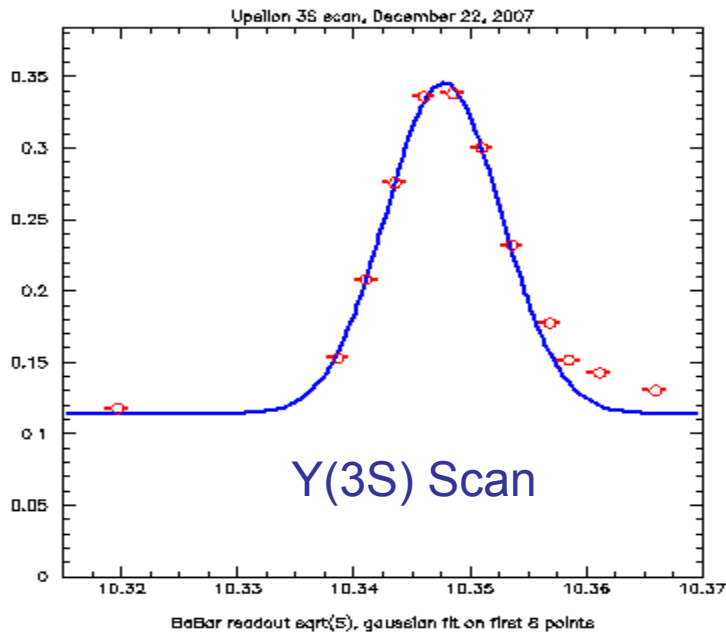
Mass splitting $M(Y(1S)) - M(\eta_b) = 71.4_{-3.1}^{+2.3} \pm 2.7 \text{ MeV}/c^2$

BaBar Detector

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



Run7 BaBar at PEP-II



Data Sample

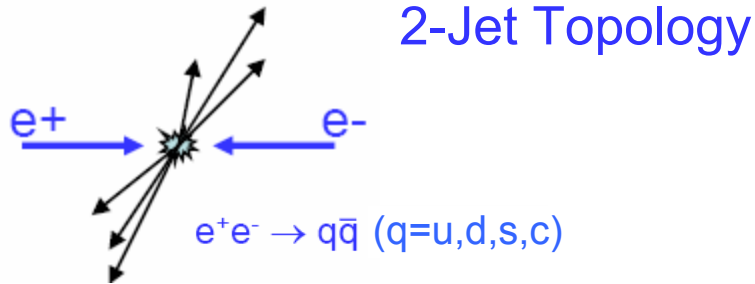
Y(3S): 30.2 fb⁻¹ 120 Million Y(3S) Events
Y(2S): 14.5 fb⁻¹ 100 Million Y(2S) Events

- Dec. 19th: FY08 Budget announced
→ Immediate Shutdown of BaBar/PEP-II
or
Run at Y(3S) E_CM
([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 1.2×10^{34}
 - HER 8.5923 GeV (-247 MeV)
 - LER 3.1200 GeV
- 2S (10.0327 GeV) in March, 2008
 - HER 8.0653 GeV (-920 MeV, 1 mrad)
 - LER 3.1200 GeV
- Scan above Y(4S) for 10 days (5 fb⁻¹)
- **Last Data Taken on Apr. 7, 2008**

Selection Criteria and Optimization

- **Hadronic Event Selection**
 - Track multiplicity of the Event > 3
 - R2 (Ratio of 2nd to 0th 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 section of the CsI calorimeter: $-0.762 < \cos(\theta_{\gamma, \text{lab}}) < 0.890$
 - Better energy resolution & reduced ISR photon background
- **Inclusive properties of η_b hadronic decays (via 2-gluons) not known**
 - Use the $\chi_b(2P)$ peak in data to calibrate detection 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 ± 1 Million Y(3S) events

EVENT SHAPE



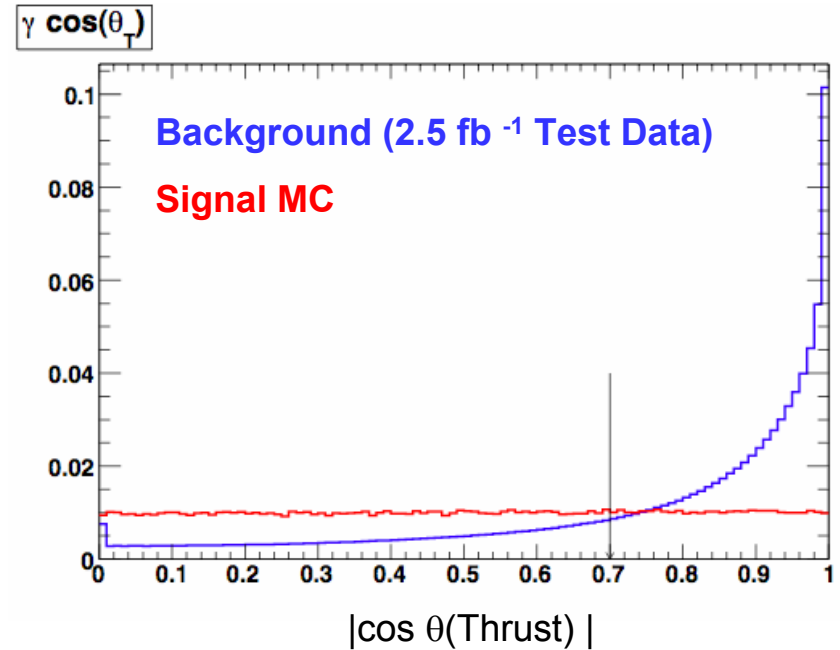
Strong correlation between the candidate photon and the Thrust Axis calculated from the tracks in the rest of the event

Signal photon has very little correlation with the details of the η_b decay, as the η_b is spinless.

π^0 Veto

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

→ Photon candidate rejected



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

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

Signal Detection Efficiency

Monte Carlo simulations

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

JETSET is used for hadronization of quarks/gluons

Detector simulations using GEANT4

Cut	Efficiency (%)
Reconstruction	70.5
Hadronic selection	97.2
LAT < 0.55	98.0
In barrel	89.9
$ \cos\theta_T < 0.7$	68.9
π^0 - 50 MeV cut	89.8
Total	37.0

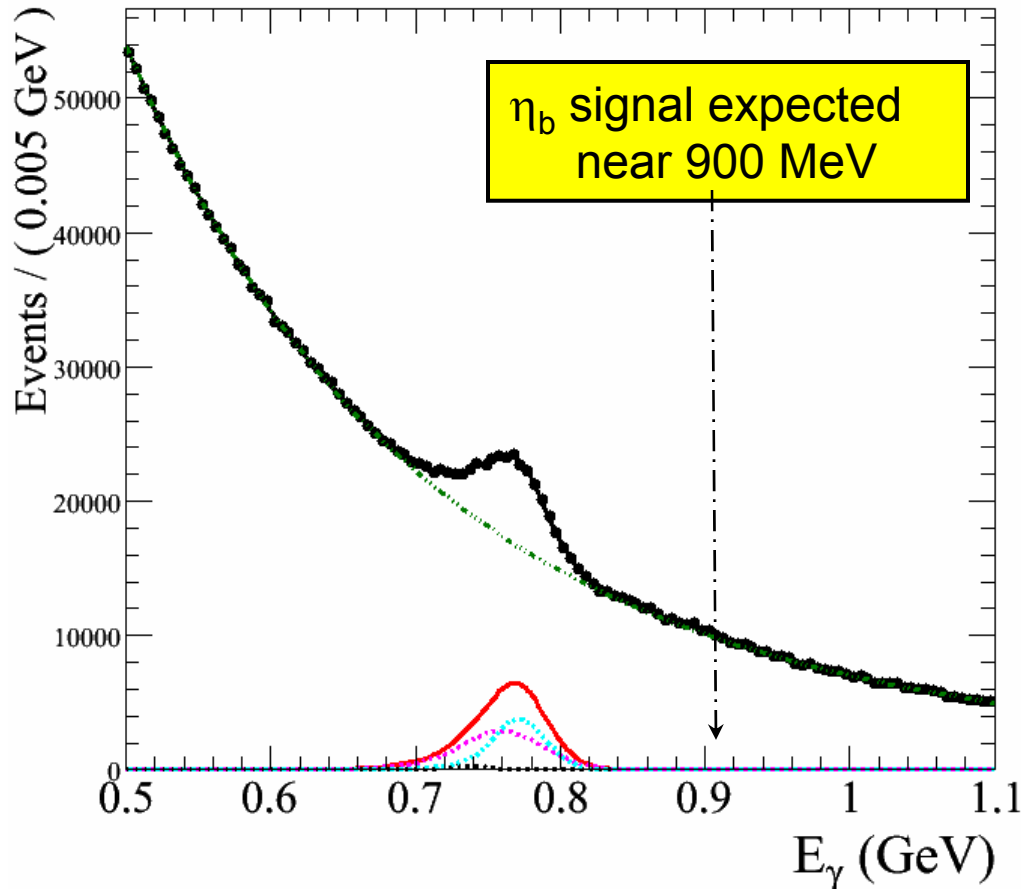
Net efficiencies:

$$\varepsilon(\text{signal}) = 37\%$$

$$\varepsilon(\text{bkgd}) = 6\%$$

30% of background photons
are from Continuum processes

Inclusive Photon Energy Spectrum in 2.5 fb^{-1} Test Sample



$$Y(3S) \rightarrow \gamma \chi_b(2P)$$

$$\quad \quad \quad \downarrow \rightarrow \gamma Y(1S)$$

$$\chi_{b0}(2P) \rightarrow \gamma Y(1S) \quad E_\gamma = 743 \text{ MeV}$$

$$\chi_{b1}(2P) \rightarrow \gamma Y(1S) \quad E_\gamma = 764 \text{ MeV}$$

$$\chi_{b2}(2P) \rightarrow \gamma Y(1S) \quad E_\gamma = 777 \text{ MeV}$$

Peaks are merged:

Doppler broadening

15 MeV box

Photon energy smearing

$\sigma(E_\gamma) = 20 \text{ MeV}$

Fitting the E_γ 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)

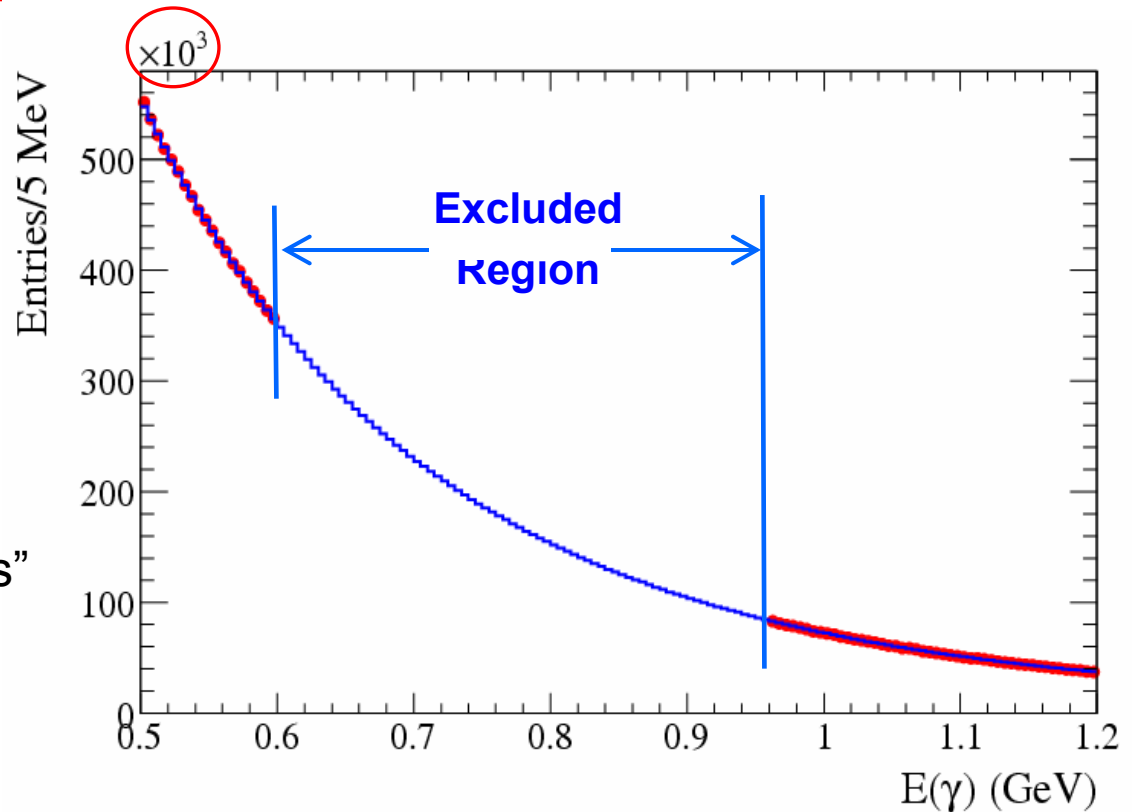
PDF of each component studied in advance & the parameters are estimated, without looking at the Signal Region.

1) Non-peaking Background

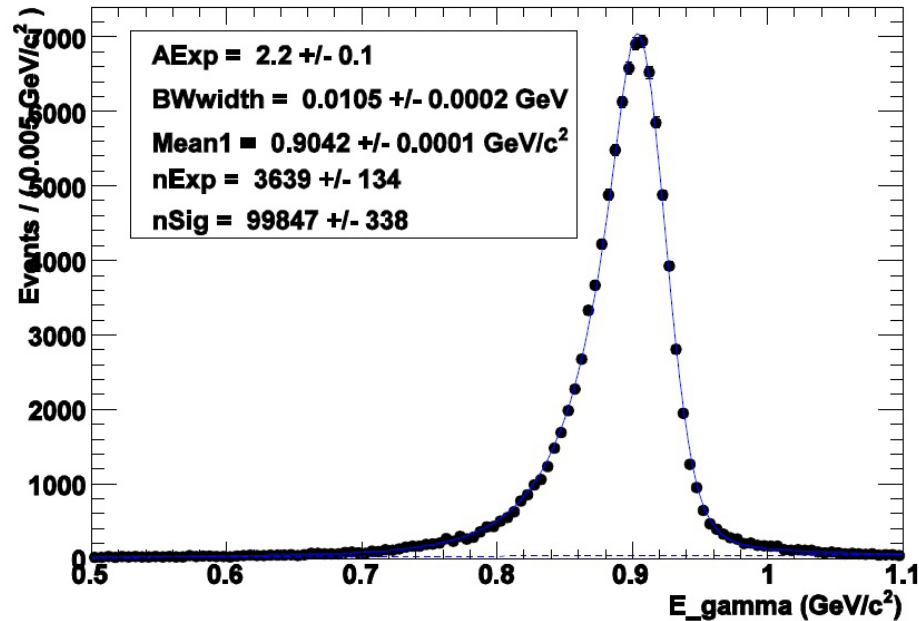
Empirical function is used to parameterize the smooth non-peaking background

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

Fit parameters C , α , β determined here is used as the “starting values” in the Final Fit



2) η_b Signal PDF



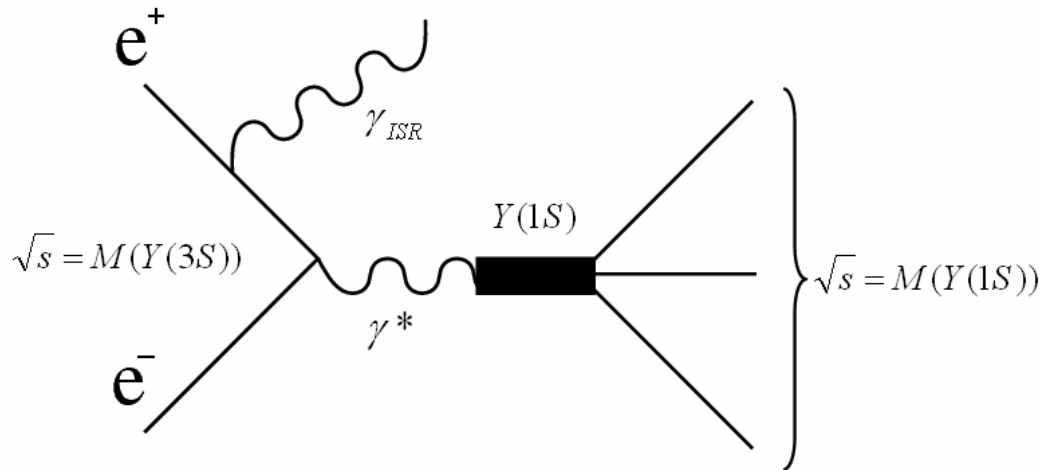
Signal Shape
from
MC Simulation

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

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



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

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

**Cross sections measurements
at 10.58 GeV E_{CM}**

**$\sigma(e^+e^- \rightarrow \gamma_{ISR} Y(3S)) \sim 29$ pb
 $\sigma(e^+e^- \rightarrow \gamma_{ISR} Y(2S)) \sim 17$ pb
 $\sigma(e^+e^- \rightarrow \gamma_{ISR} Y(1S)) \sim 19$ 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_{CM} 30 MeV below the $Y(3S)$

44 fb⁻¹ at E_{CM} 40 MeV below the $Y(4S)$

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

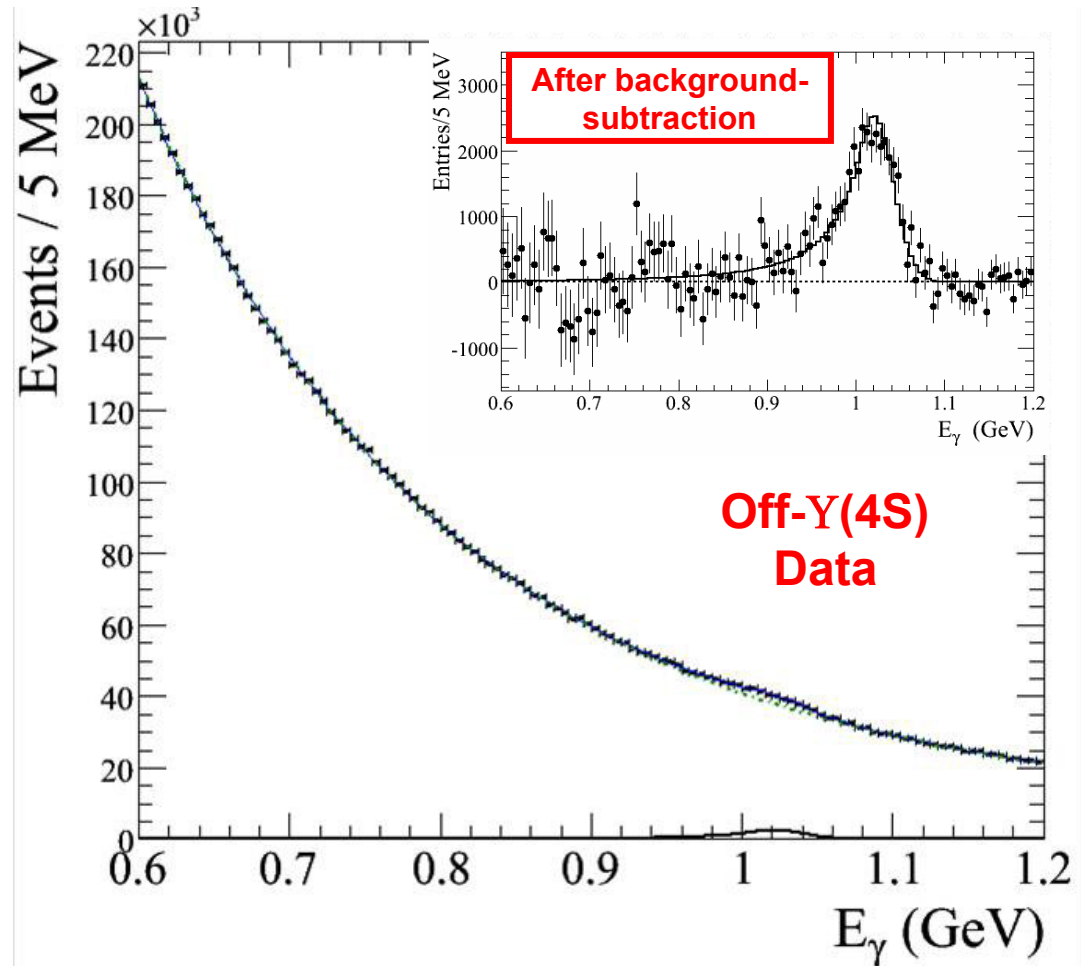
Shape/Rate Determined using
Off-Y(4S) Data where $E_\gamma(\text{ISR})$
Peaks at 1.025 GeV

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

$$N_{\text{sig}} = 35800 \pm 1600$$

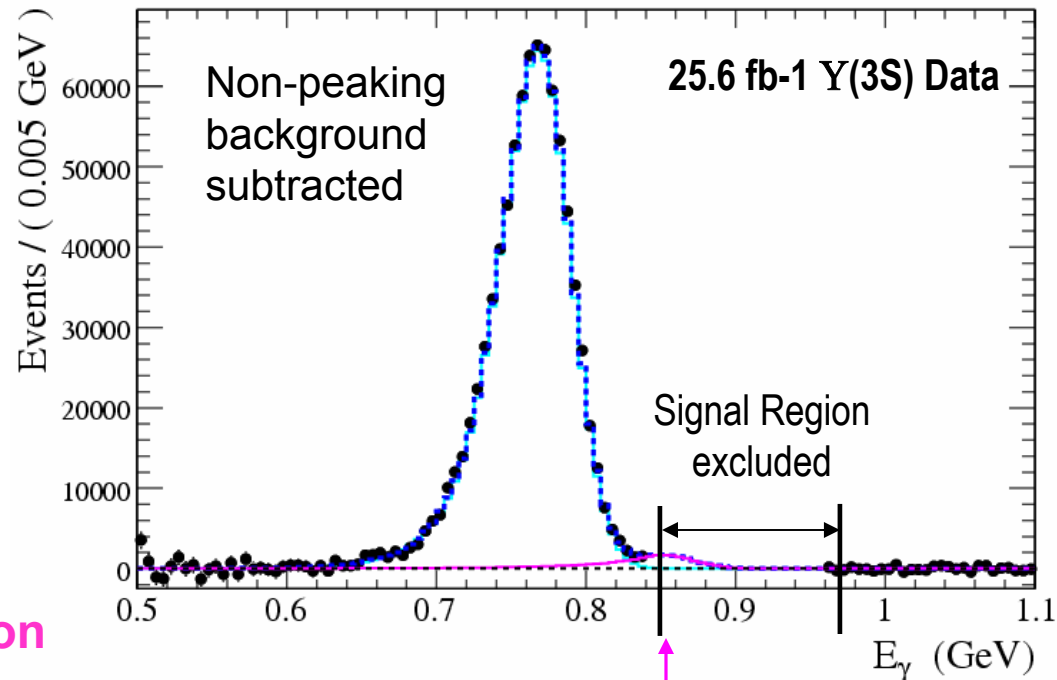
Extrapolated to Y(3S) On-peak:

$$N_{\text{ISR}} = 25153 \pm 1677$$



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 γ energy calibration:
 - +3.8 MeV** in data
 - used to set the 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)
($\chi_{b0}(2P)$ contribution is very small)
- Incorporate ISR peak contribution
 - Model tail of γ peak from $\chi_{bJ}(2P)$ properly

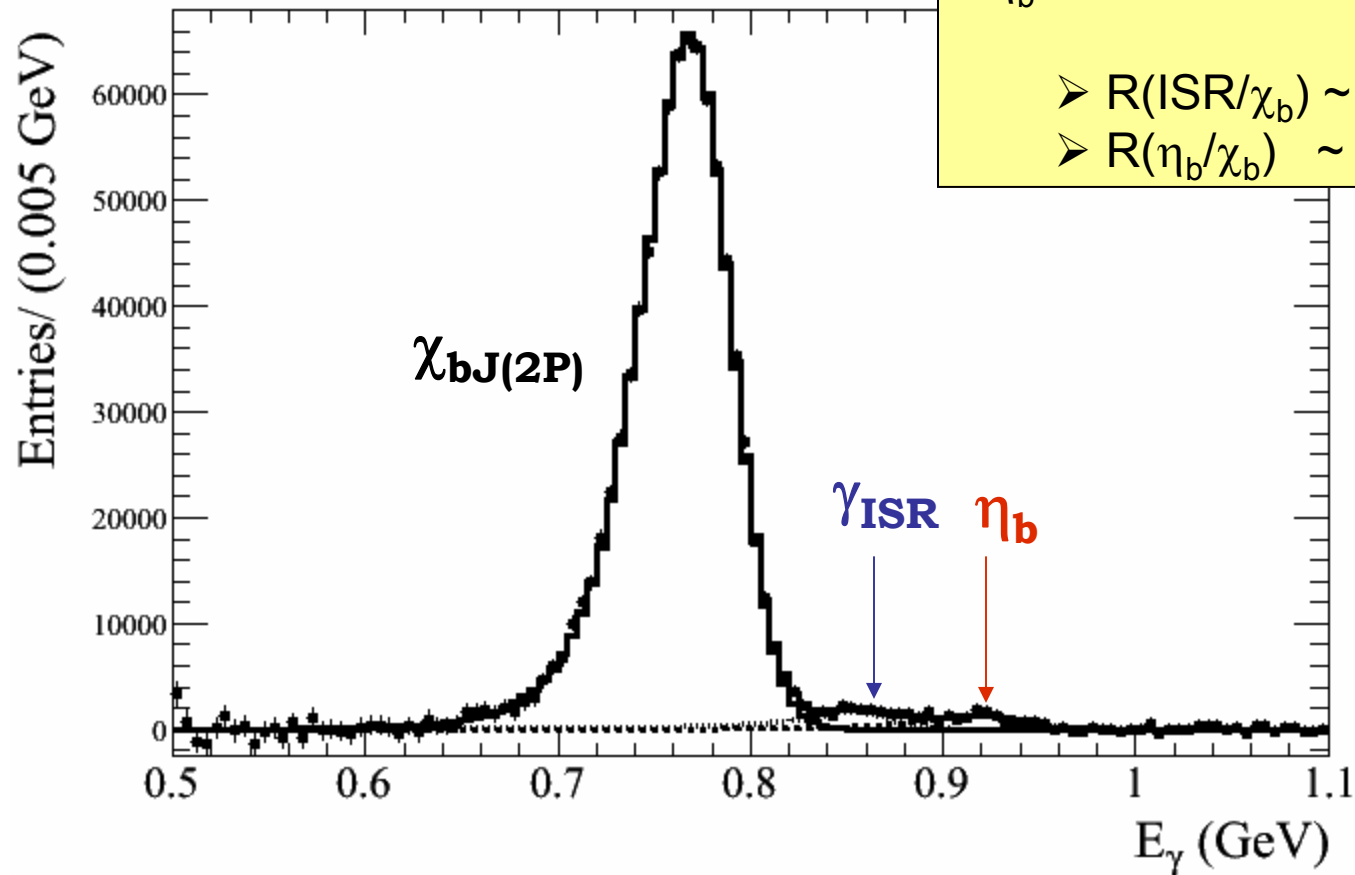


FIT RESULT

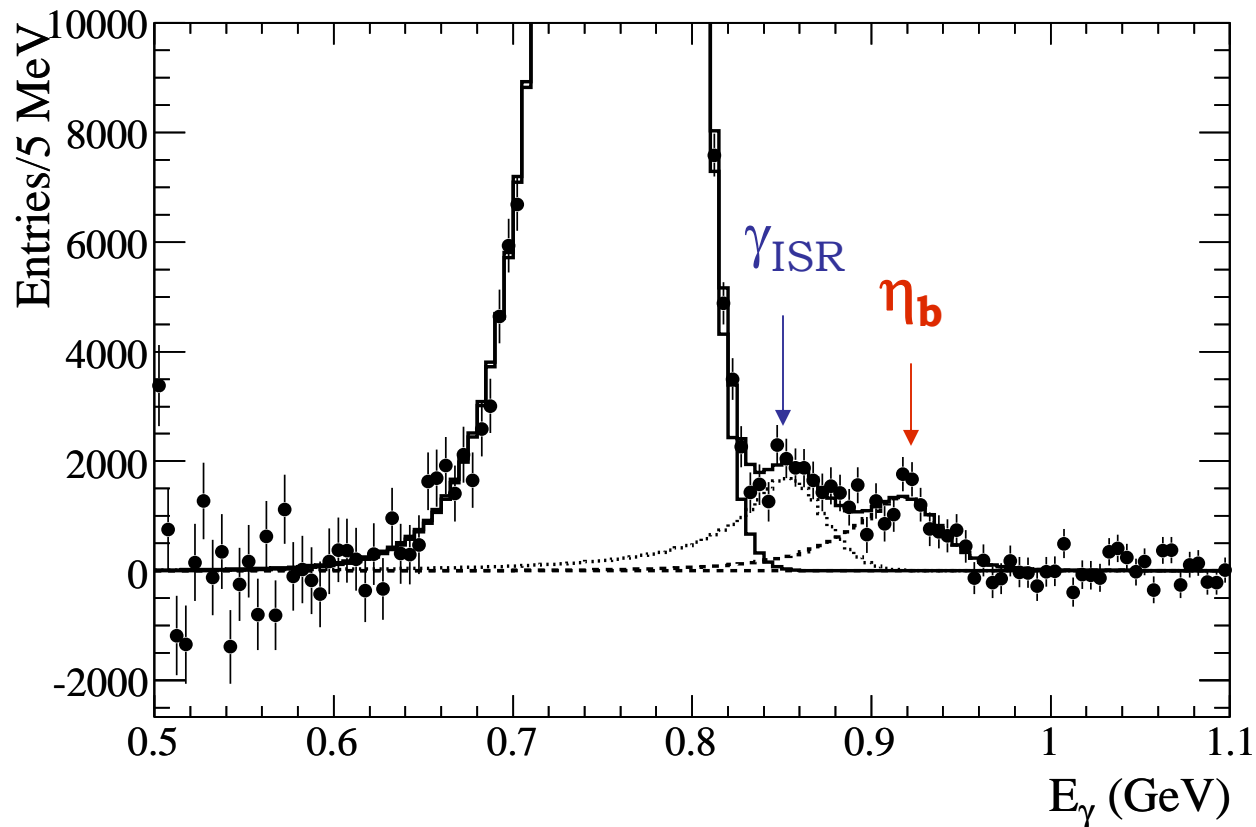
Non-peaking
background-subtracted

- χ_b Peak Yield : 821841 ± 2223
- γ_{ISR} Y(1S) Yield : 25153 (fixed)
- η_b Yield : 19152 ± 2010

- $R(\text{ISR}/\chi_b) \sim 1/30$
- $R(\eta_b/\chi_b) \sim 1/40$



Observation of the η_b



- η_b signal observed with a statistical significance of 10σ ($S = \sqrt{2 \log(L_{\max} / L_0)}$)

Fit $\chi^2 = 147$ for 113 ndof

- Peak position of $921.2_{-2.8}^{+2.1}$ MeV

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
 - η_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 η_b signal significance

- **χ_b line shape**

- Float the ISR $Y(1S)$ yield \rightarrow fitted yield (24800 \pm 4000) consistent with expected number of ISR events (25000); No effect on the η_b yield
- χ_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 η_b ?**

The only Bottomonium state below the $Y(1S)$ mass is the η_b

Event properties such as track multiplicity and photon direction consistent with η_b

STUDY OF SYSTEMATIC UNCERTAINTIES

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

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

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

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

(Comparison to 2 Theoretical Values)

A. Gray et al., Phys. Rev. D 72, 094507(2005) (L. QCD)

$$\Delta M = 61 \pm 14 \text{ MeV}/c^2$$

- lattice discretization: $\pm 4 \text{ MeV}/c^2$
- QCD radiative corrections: $\pm 12 \text{ MeV}/c^2$
- relativistic corrections: $\pm 6 \text{ MeV}/c^2$

S. Godfrey and N. Isgur, Phys. Rev. D 32, 189(1985)

$$\Delta M = 60 \text{ MeV}/c^2$$

(Relativistic Quark Model)

Inclusive Search in E_γ Spectrum [$Y(2S) \rightarrow \gamma \eta_b$]

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

E_γ Signal at 611 MeV

ISR- $Y(1S)$ peak at 545 MeV

$\chi_b(1P) \rightarrow \gamma Y(1S)$ peak at 455 MeV

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

Comparison to $Y(3S)$ Analysis

Better photon energy resolution at lower energy

→ better separation between peaks

More random photon background at lower energy

→ 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
- Pi^0 Veto: **$E(g_2) > 40 \text{ MeV}$**
- MC signal detection efficiency = 35.8%

Fitting the Photon Energy Spectrum

χ^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)

Shape determined using Off-4S data

Normalization floated in the fit

4) $\chi_b(1P) \rightarrow \gamma Y(1S)$ Peak (420 MeV)

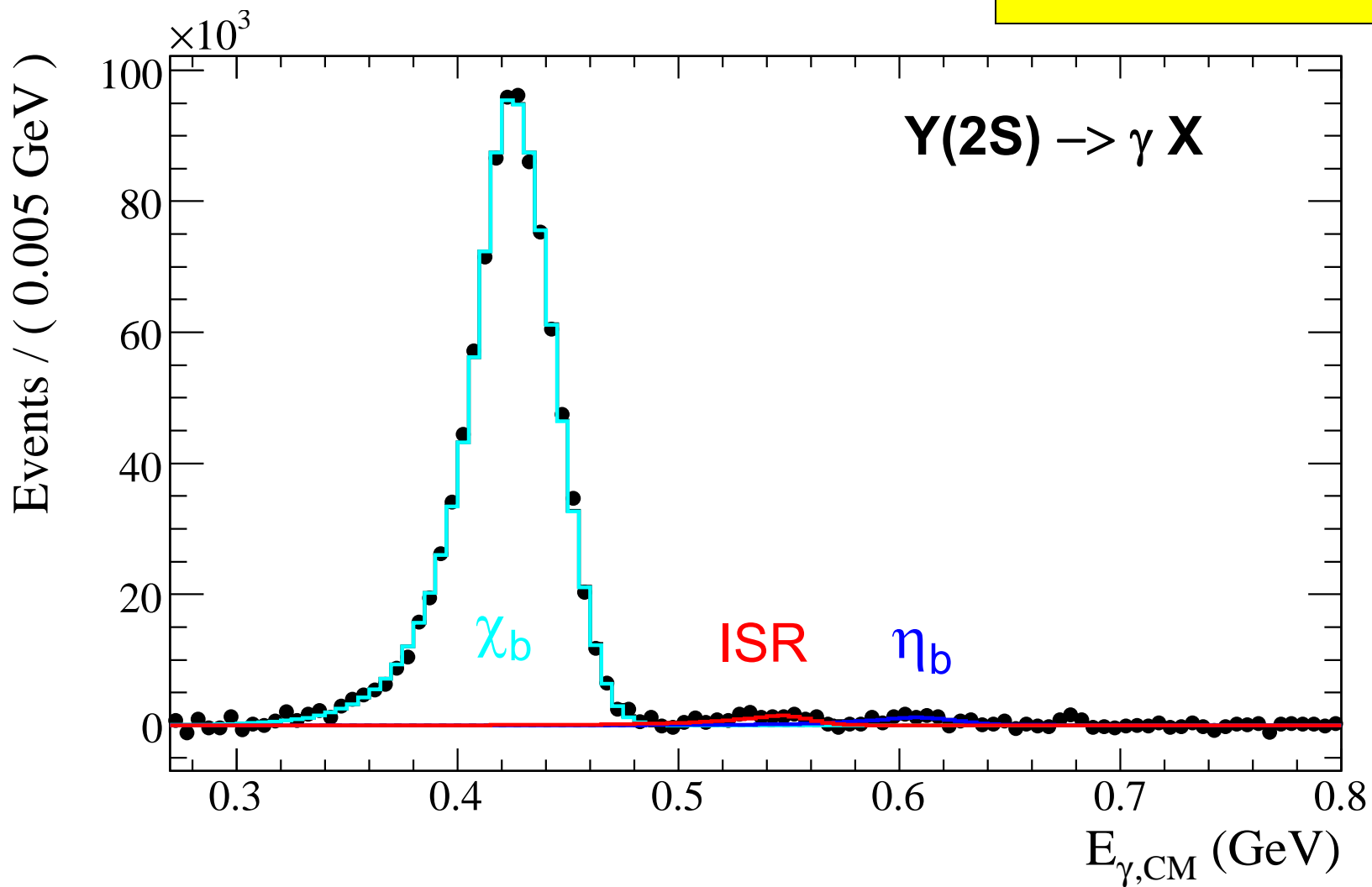
Relative rates of χ_b states fixed to exclusive $\gamma\gamma\mu^+\mu^-$ measurement

Photon line shape uses Crystal Ball function convoluted with

Doppler Broadening

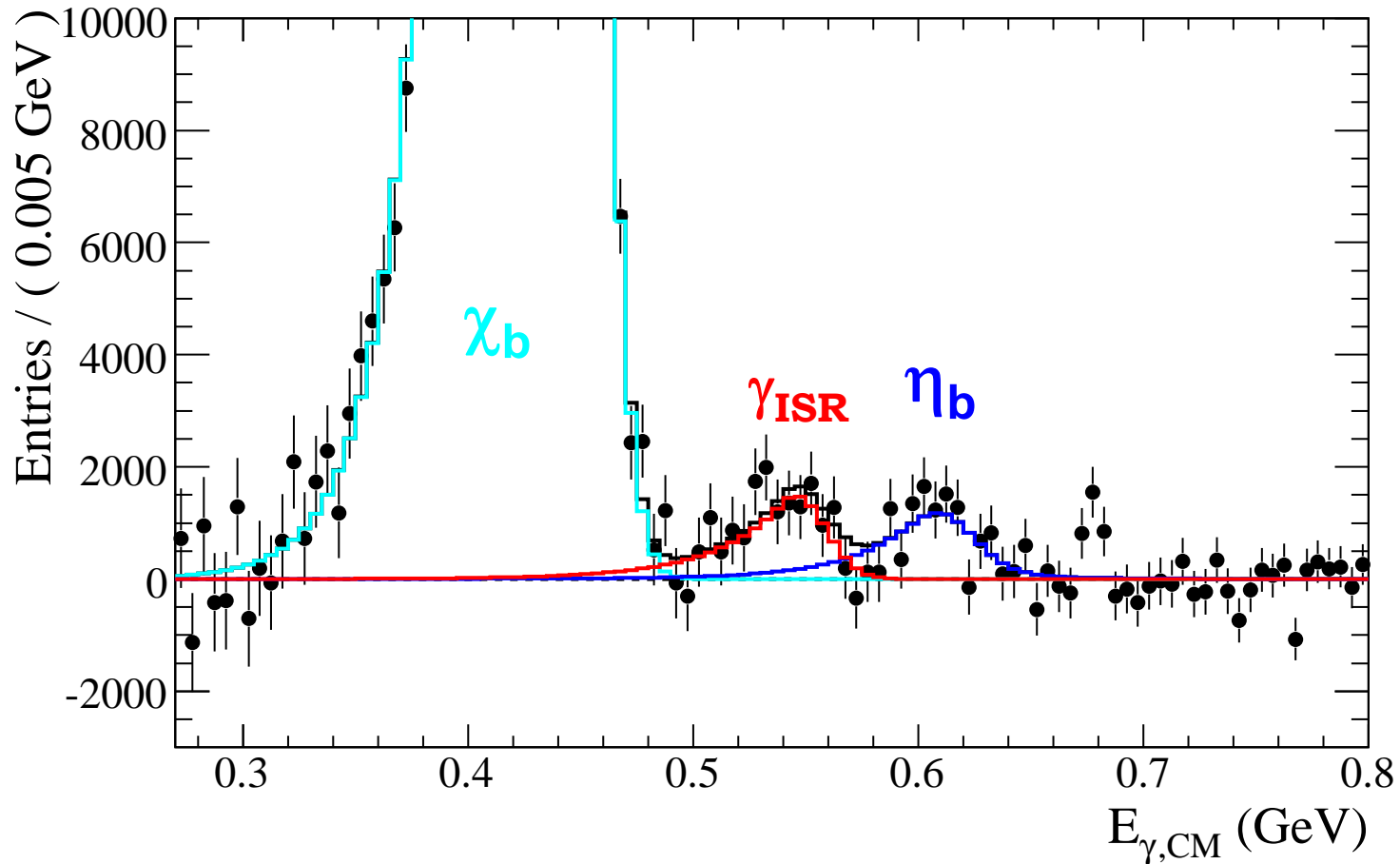
Fit Result

Non-peaking
background-subtracted

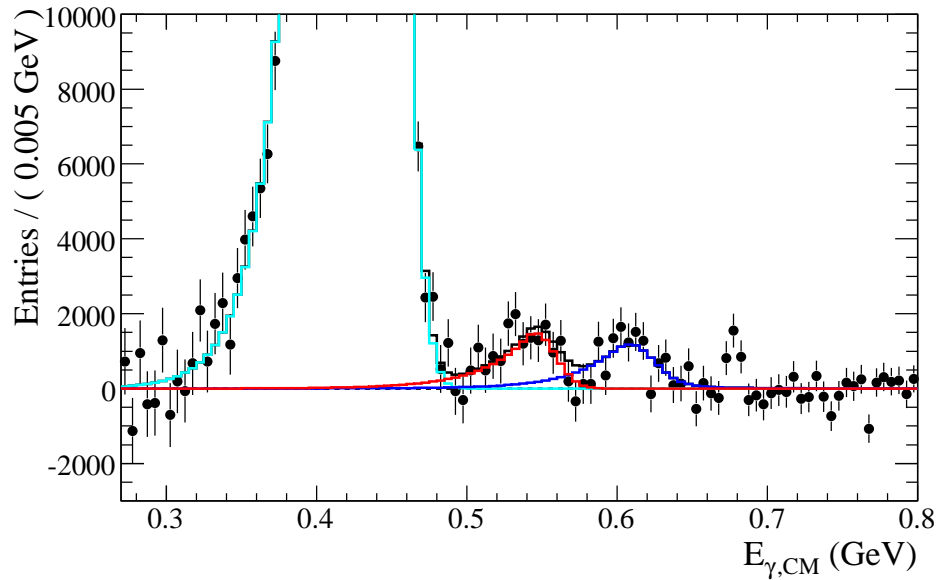


Close-up View

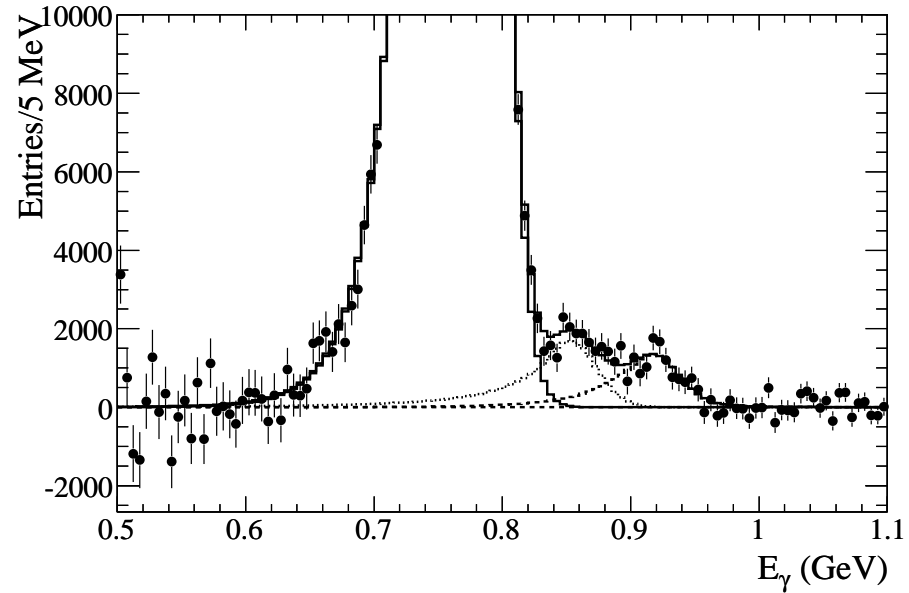
Non-peaking
background-subtracted



Comparison of E_γ Spectra



Y(2S) spectrum



Y(3S) spectrum

$\Upsilon(2S)$ Fit Result

- η_b yield: 13915^{+3555}_{-3452}
- η_b peak position: $610.5^{+4.5}_{-4.3} \pm 1.8$ MeV
- Goodness of Fit: $\chi^2/\text{ndof}=116.2/93$
- 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

Source	ΔN [Evts]	Δ peak pos. [MeV]
η_b width, 5 MeV	-1519	-0.5
η_b width, 15 MeV	1195	0.4
η_b width, 20 MeV	2328	0.9
ISR PDF, N	133	0.10
ISR PDF, A	180	0.05
ISR PDF, σ	43	0.05
signal PDF, N	44	0.01
signal PDF, A	62	0.05
signal PDF, σ_{CB}	53	0.01
χ_{bJ} PDF, N	33	0.01
χ_{b1}/χ_{b2} ratio	150	0.14
χ_{b0}/χ_{b1} ratio	145	0.03
χ_{b0} σ	121	0.03
Extra χ_{bJ} tail	+1537	0.07
exp $Pol(3)$ pdf	-2237	1.3
Total, fit variations	+2811 -2726	1.6
Energy scale offset	0	0.9
χ_b masses	0	0.4
Total	+2811 -2726	1.8

η_b width Variation

χ_b shape variation

Smooth background
shape variation

Summary of $Y(2S)$ results

BABAR
Preliminary

- Branching fraction:

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

- η_b mass:

$$9392.9_{-4.8}^{+4.6}(\text{stat}) \pm 1.8(\text{syst}) \text{ MeV}/c^2$$

- Hyperfine splitting:

$$67.4_{-4.5}^{+4.8}(\text{stat}) \pm 1.9(\text{syst}) \text{ MeV}/c^2.$$

- consistent with result from $Y(3S)$ analysis:

$$71.4_{-3.1}^{+2.3}(\text{stat}) \pm 2.7(\text{syst}) \text{ MeV}/c^2$$

Further Searches for the η_b

- $Y(3S) \rightarrow \pi^+\pi^-Y(1S); Y(1S) \rightarrow \gamma \eta_b(1S)$ **INCLUSIVE**
18 M $Y(1S)$ events in $\pi^+\pi^-$ Recoil
 E_γ signal at 71 MeV
No χ_b background; No peaking ISR background
- $Y(3S) \rightarrow \gamma \eta_b(2S)$ **INCLUSIVE**
 E_γ Signal at 360 MeV (Difficult Region)
- $Y(3S) \rightarrow \pi^0 h_b(1P)$ 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

Summary

- **First Observation of the η_b in $Y(3S) \rightarrow \gamma \eta_b$**
- **Confirmation with Further Evidence in $Y(2S) \rightarrow \gamma \eta_b$**
- **More η_b results expected from BABAR, BELLE, and CLEO experiments in near future**