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

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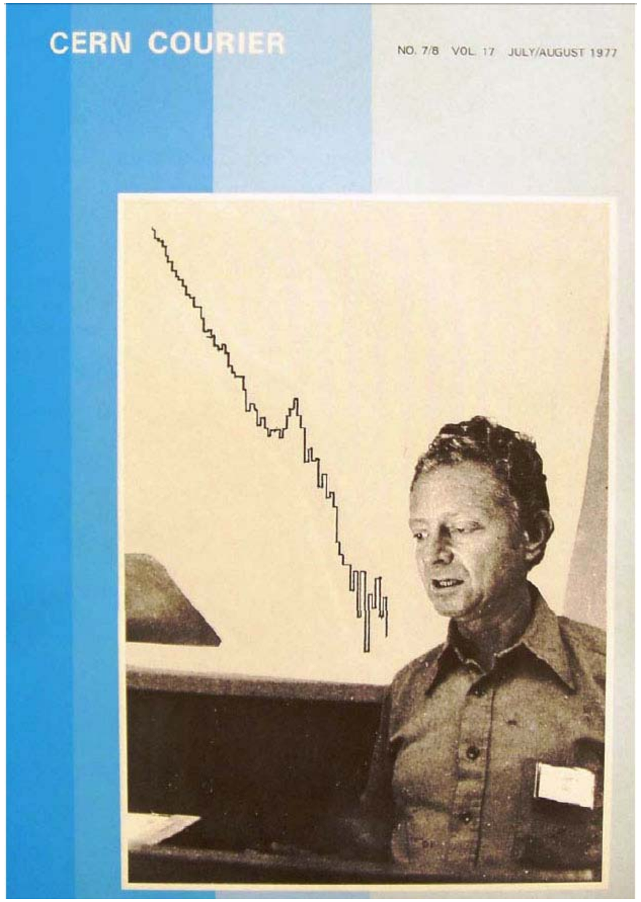
(BaBar Collaboration)

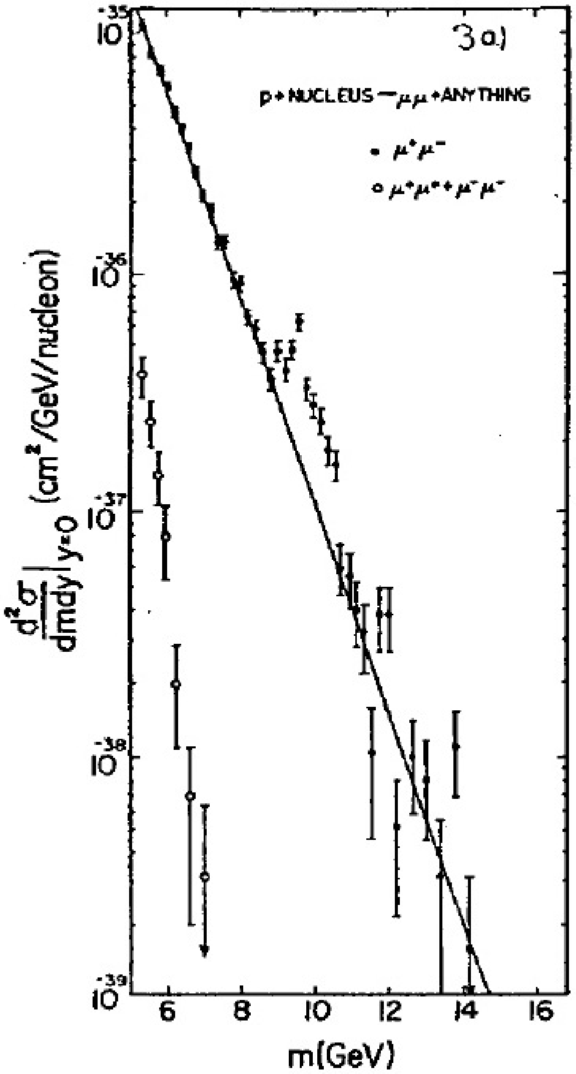
KEK Seminar   Dec. 8, 2008

Discovery of the bottom quark

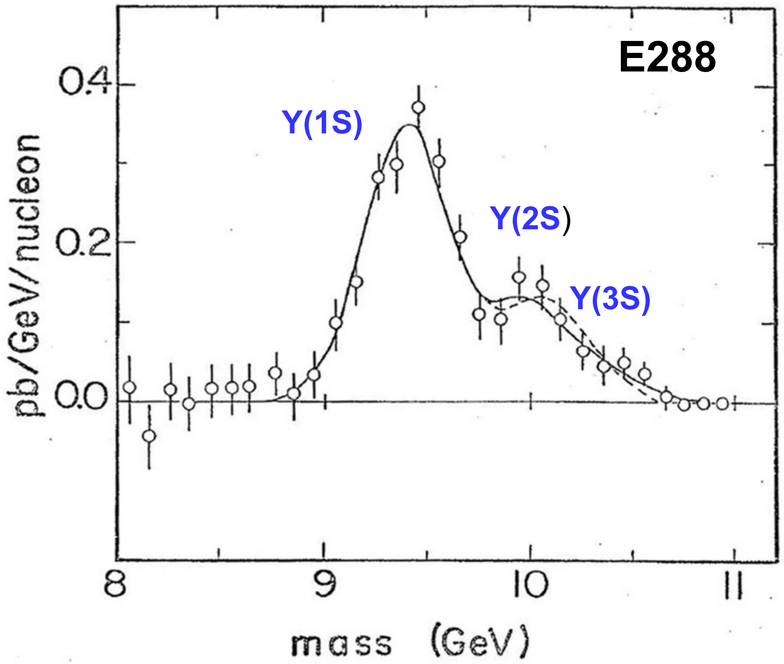
E288 at Fermilab: p + (Cu, Pt) → $\mu^+ \mu^-$ X
S.W.Herb *et al*, PRL 39, 252 (1977)

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





Upsilon Family



<u>FIT WITH 3 PEAKS</u>

M(Υ) = 9.40 ± 0.013 GeV/c^2
M(Υ') =10.00 ± 0.04 GeV/c^2
M(Υ'') =10.43 ± 0.12 GeV/c^2

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

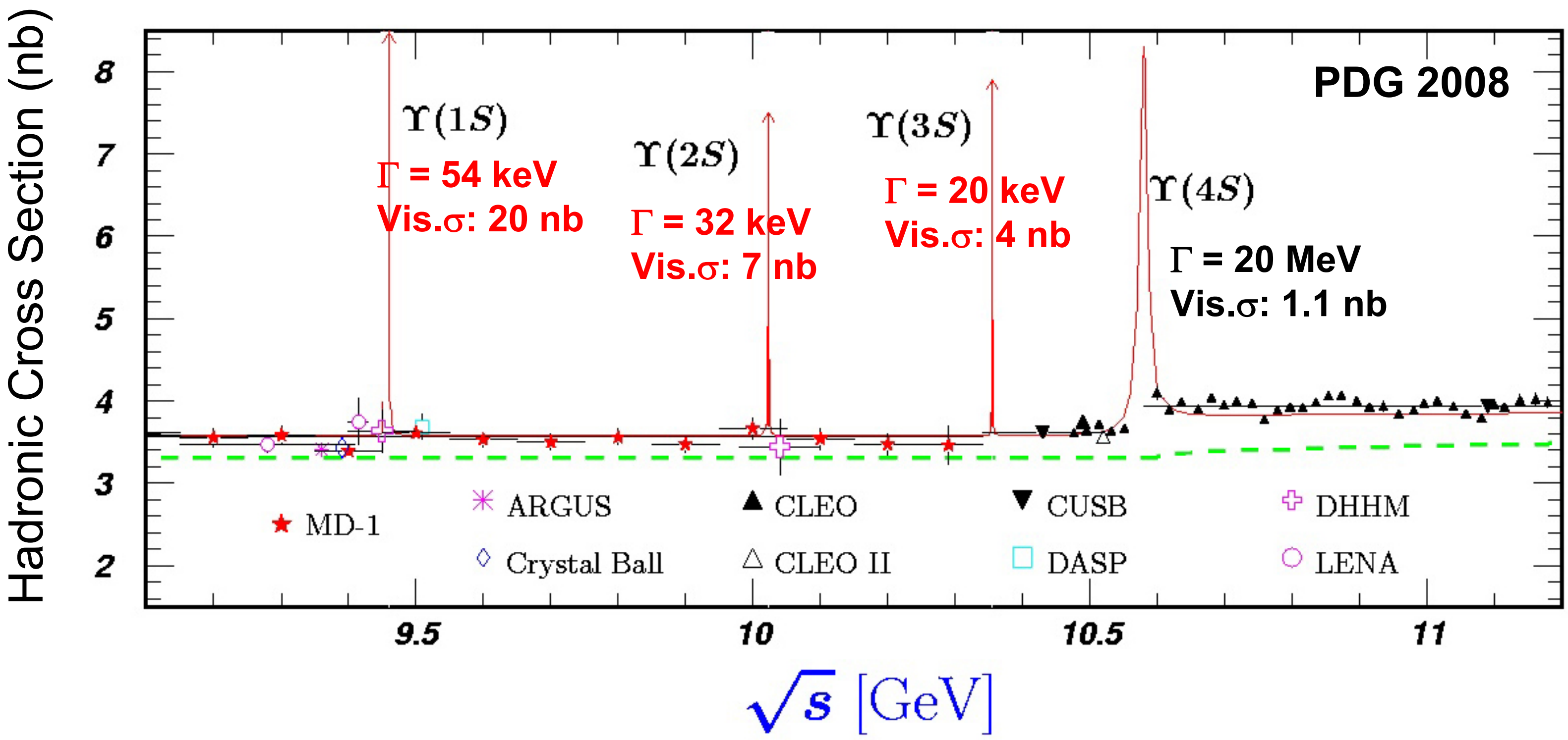
Upsilon states quickly confirmed at DORIS/CESR (1978-1979)
DASP II, LENA, PLUTO, CLEO Experiments
Original proposals for E_cm = 8.4 GeV (DORIS) and 8 GeV (CESR)

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
- Upsilons in clean environment: nothing else in the rest of the event.

- Continuum $q\bar{q}$ 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

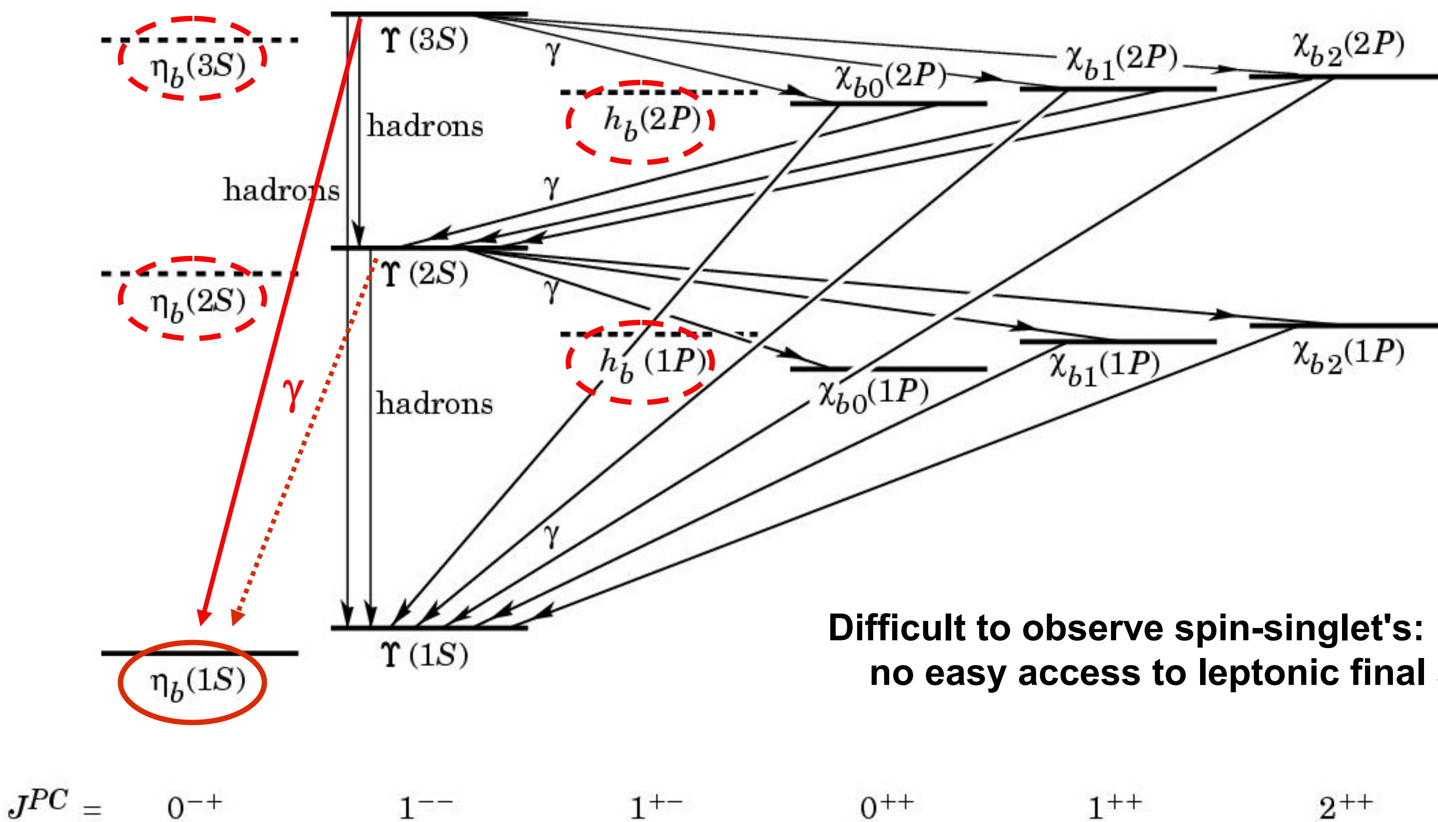
- Tests of NRQCD and lattice QCD predictions: α_s, m_b

  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 and Transitions



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

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

Hadronic Decays

- **Narrow widths of Υ(nS) states**: Γ = 20-55 KeV

  $e^+e^- \rightarrow \gamma^* \rightarrow \Upsilon(nS) \rightarrow ggg$ or γgg (~2.5%)

  In lowest order QCD, other states will annihilate to either
  2 or 3 gluons, depending on J = 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* = ~10^{-5}]

- **Widths of η_b, even all χ_b(1P), χ_b(2P) states are not known**

  η_c, χ_{c0}(1P), χ_{c1}(1P), χ_{c2}(1P) : Γ = 25, 10, 1, 2 MeV (Charmonia in PDG)

  Theo. extrapolation (NRQCD, Potential models)
  → Smaller values for the Bottomonium

η_b

- **Spin-0 partner of Υ(1S): pseudoscalar**
  - Hyperfine mass splitting: 71.5 MeV BABAR, PRL 101, 071801 (2008).
    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 $\Gamma\gamma\gamma(\eta_b)$ = (0.2 – 0.7) keV $\rightarrow$ $\boxed{\Gamma(\eta_b) = 5 - 15 \text{ MeV}}$
    [$\Gamma\gamma\gamma(\eta_c)$ = 7 keV and $\Gamma(\eta_c)$ = 25 MeV)]

- **Radiative Production: Υ(nS) $\rightarrow \gamma\, \eta_b$(1S)**
  - Magnetic Dipole (M1) transitions
  - k= 70, 610, 920 MeV for 1S,2S,3S
  - Forbidden transitions suppressed by ~1/100

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

Godfrey and Rosner, PRD 64, 074011 (2001)

Previous Searches for η_b

- **Inclusive search in radiative transitions**

[CLEO III, PRL 94, 0322002, 2005]

$B(\Upsilon(2S) \to \gamma\, \eta_b) < 5.1 \times 10^{-4}$ — Υ Data Sample: 9 Million

$B(\Upsilon(3S) \to \gamma\, \eta_b) < 4.3 \times 10^{-4}$ — 6 Million

- **Double transitions**

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

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

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

$BF < 2.5 \times 10^{-4}$ (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 in the signal region, M=9300 MeV

1 background event expected

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

L3 & DELPHI at LEP II (2006)

$\eta_b \to J/\psi\, J/\psi \to \mu^+ \mu^- \mu^+ \mu^-$ — CDF II at Tevatron (2006)

Inclusive Search in Eγ Spectrum [$\Upsilon(3S) \rightarrow \gamma\, \eta_b$]

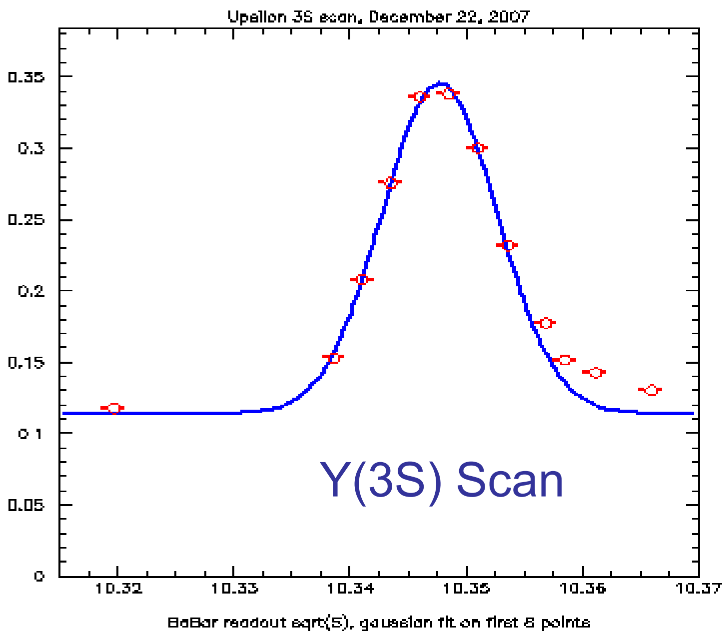
- M(η_b) = 9.4 GeV/c^2 $\rightarrow$ E_γ = 911 MeV (in E_cm frame)
- Very high background rate
  - Photons from hadronic decays: $\pi^0, \eta, \varpi, \eta, \phi \ldots$
  - Direct photons from Bottomonium decays:
    e.g., B(Υ(1S) $\rightarrow \gamma$ g g) = 2.5 %
  - ISR photons from e+e- $\rightarrow \gamma$ (qq) events
  - Transition photons between the bb-bar bound states
- **BABAR Measurements**

N_signal = 19152 ± 2010 events
BF (Y(3S)$\rightarrow \gamma\, \eta_b$) = (4.8 ± 0.5 [stat] ± 1.2 [syst]) x 10^{-4}

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

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

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
Scan above Y(4S) Energy: 5 fb^{-1}

- Plan for Final Run: 250 fb^{-1} of Υ(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 10^{34}

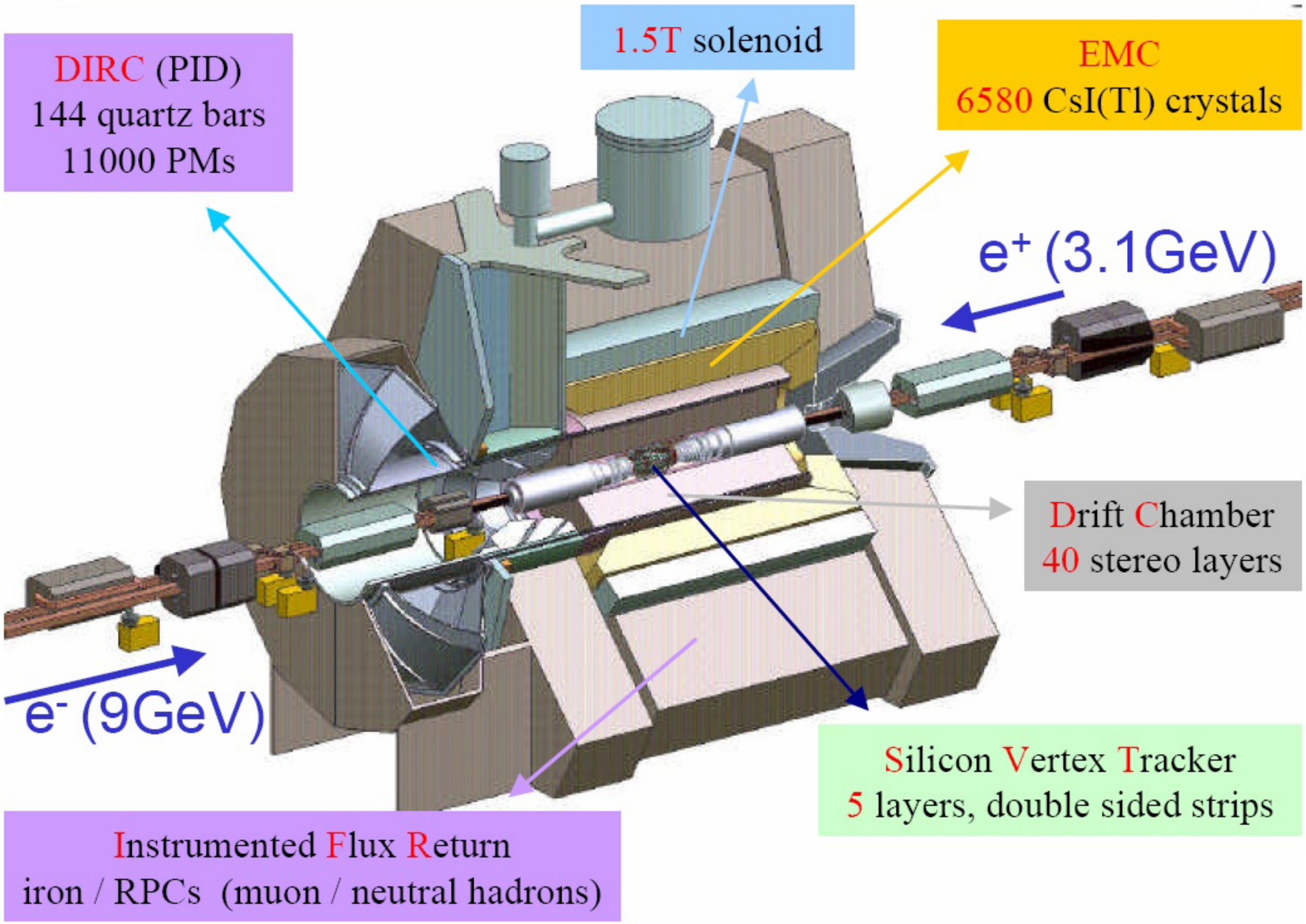
  HER 8.5923 GeV (-247 MeV)
  LER 3.1200 GeV

- 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

BaBar Detector



σ(E) = 2.5% at 1 GeV

+ LST muon detectors

Event Selection

- Hadronic Event Selection
  - Track multiplicity of the Event > 3
  - R2 (Ratio of 2^{nd} to 0^{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
    $-0.762 < \cos(\theta\gamma,\mathrm{lab}) < 0.890$
    → Better energy resolution &
    Reduced ISR photon background

.

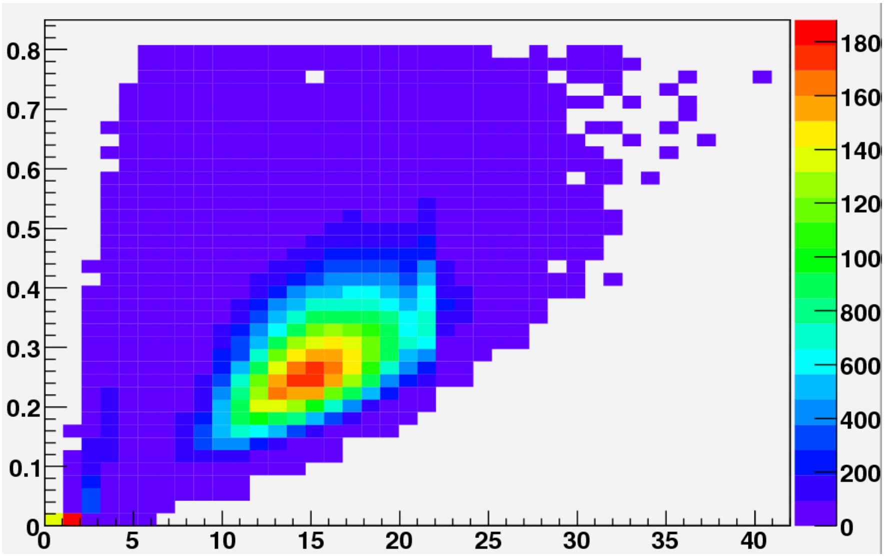
Photon Shower Shape Cut

Lateral Shower Shapes in EMC clusters

$$\mathrm{LAT} = \sum_{i=3}^{n} E_i r_i^2 / (E_1 r_0^2 + E_2 r_0^2 + \sum_{i=3}^{n} E_i r_i^2)$$

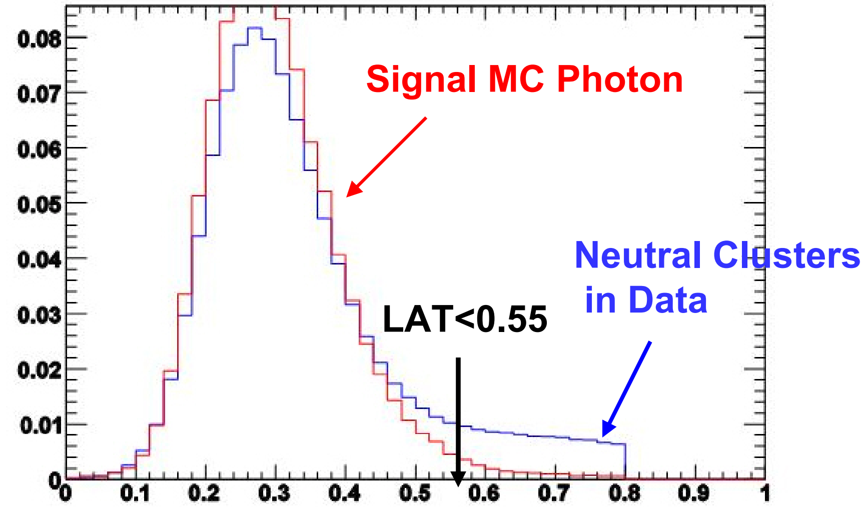
where the *n* crystals in the EMC cluster are ranked in order of energy deposited in that crystal, *Ei*, and *r*0 = 5cm is the average distance between crystal centers. *ri* is the distance between crystal *i* and the cluster centroid calculated from an energy-weighted average of the *n* crystals.

Signal MC Photon



No. of Crystals

0.85 < Eγ < 0.95 GeV



LAT

- **Monte Carlo simulations**

  $\Upsilon(3S) \rightarrow \gamma\, \eta_b$, $1+\cos^2\theta\gamma$ distribution relative to beam axis
  JETSET is used for hadronization of quarks/gluons
  Detector simulations using GEANT

- **Inclusive properties of η_b hadronic decays (via 2-gluons) not known**

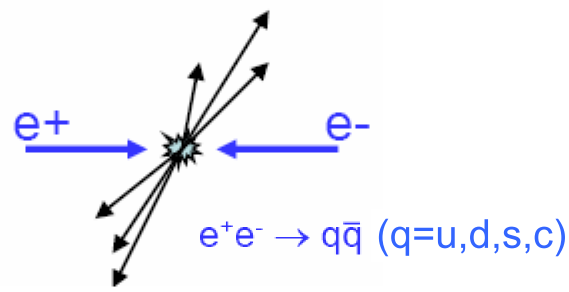
  Use the $\chi_b(2P)$ peak in data to calibrate Reconstruction Efficiency

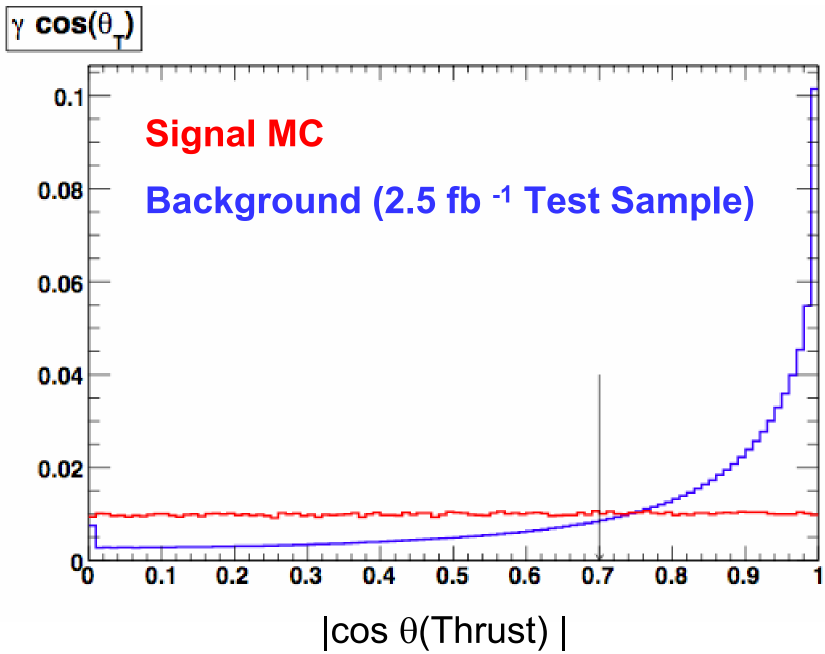
- **Non-peaking background shape/yield also not well-known**

  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 ± 1) Million Y(3S) Events

Event Shape





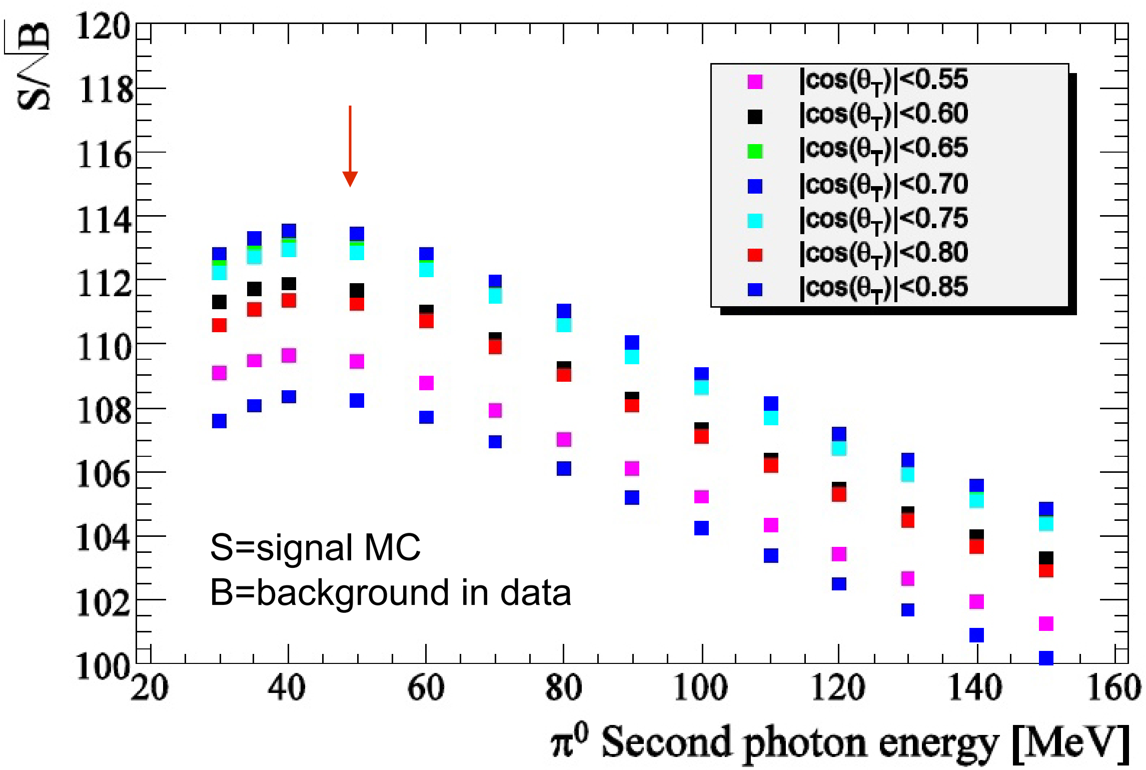
- Strong correlation between the candidate photon and the thrust Axis calculated from the tracks in the rest of the event (Continuum events)
- Signal photon has very little correlation with the details of the η_b decay, as the η_b is spinless.
- No other useful event-shape variables were found…
- The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

π^0 Veto

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

→ Photon candidate rejected

S/B Optimization



Selection Cuts:

$E(\gamma_2) > 50$ 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

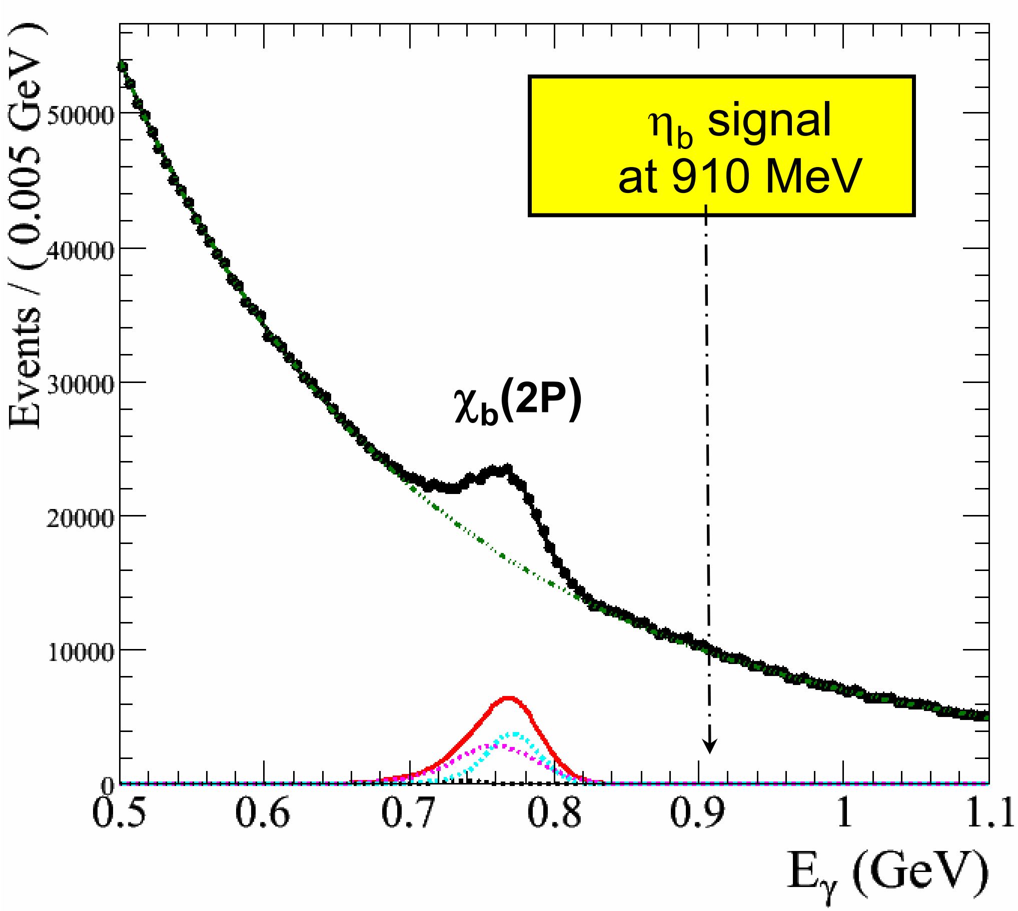
Cut	Efficiency (%)
Reconstruction	70.5
Hadronic selection	97.2
LAT<0.55	98.0
In barrel	89.9
$\lvert\cos\theta_T\rvert < 0.7$	68.9
π^0 - 50 MeV cut	89.8
Total	37.0

Net efficiencies:

ε(signal) = 37%
ε(bkgd) = 6%

Background Composition:
Continuum (30%)
Bottomonium decays (70%)

Inclusive Photon Spectrum in 2.5 fb^{-1} $\Upsilon(3S)$ Test Sample



$\Upsilon(3S) \rightarrow \gamma\ \chi_{bJ}(2P)$

$\quad\quad\quad\quad \hookrightarrow \gamma\ \Upsilon(1S)$

$\chi_{b0}(2P) \rightarrow \gamma\ \Upsilon(1S)$ $E\gamma$=743 MeV

$\chi_{b1}(2P) \rightarrow \gamma\ \Upsilon(1S)$ $E\gamma$=764 MeV

$\chi_{b2}(2P) \rightarrow \gamma\ \Upsilon(1S)$ $E\gamma$=777 MeV

Peaks are merged

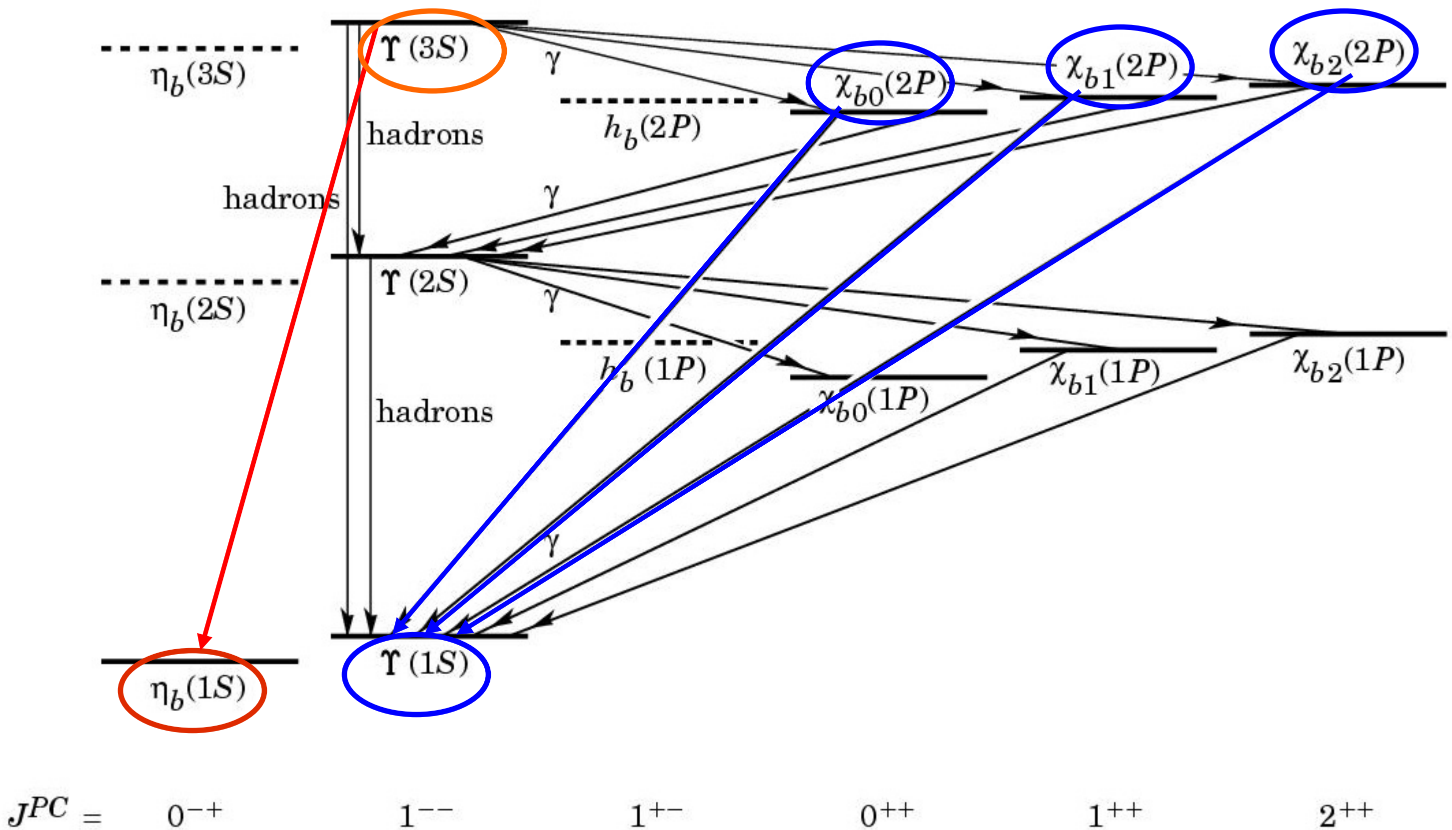
Doppler broadening

15 MeV-wide box

Photon energy smearing

$\sigma(E\gamma)$ = 20 MeV

χ_b(2P) Peaking Background



Fitting the Eγ Spectrum

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

1) Smooth non-peaking Background

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

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

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

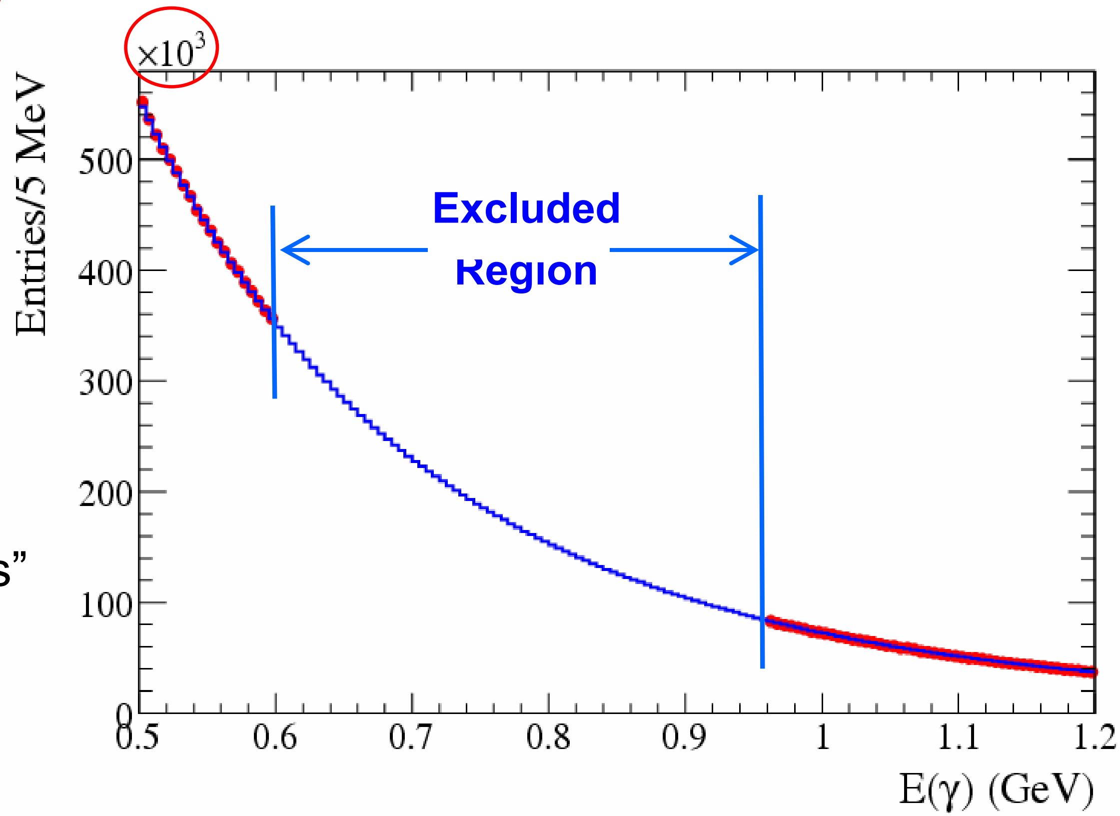
PDF of each component studied in advance & the parameters are estimated, without looking at the Signal Region.

1) Non-peaking Background

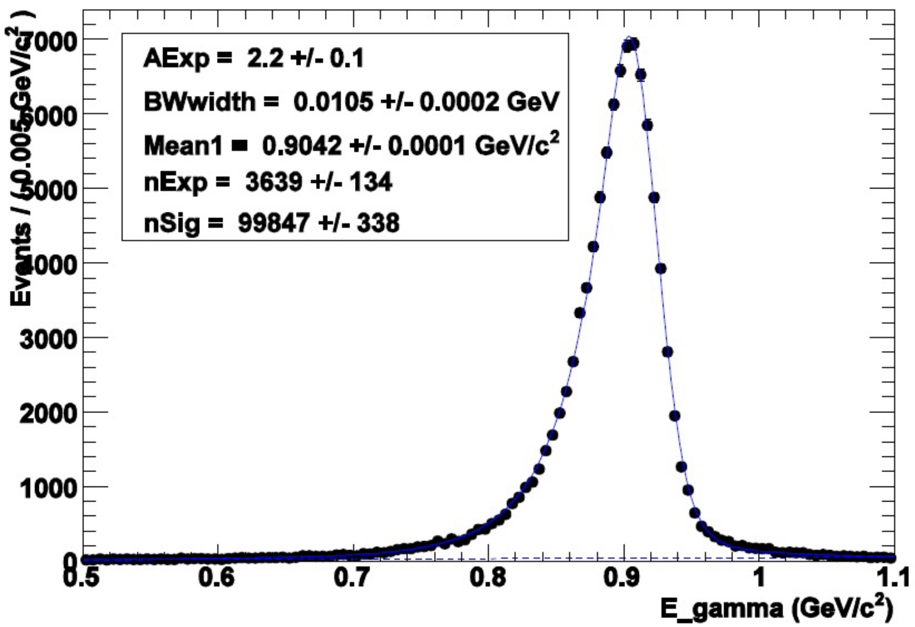
Empirical function is used to parameterize the smooth non-peaking background

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

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 ⊗ 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.

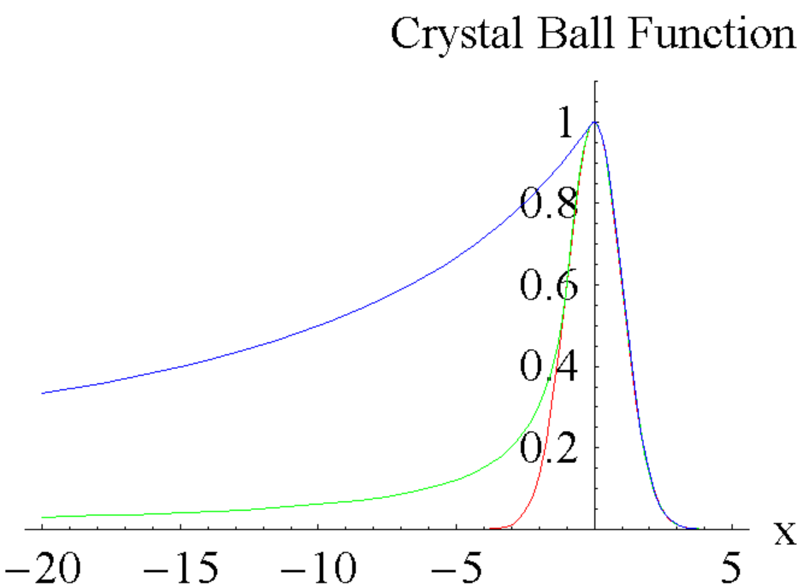
$$f(x;\alpha,n,\bar{x},\sigma) = N \cdot \begin{cases} \exp(-\frac{(x-\bar{x})^2}{2\sigma^2}), & \text{for } \frac{x-\bar{x}}{\sigma} > -\alpha \\ A \cdot (B - \frac{x-\bar{x}}{\sigma})^{-n}, & \text{for } \frac{x-\bar{x}}{\sigma} \leqslant -\alpha \end{cases}$$

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 α, *n*, and σ are parameters.

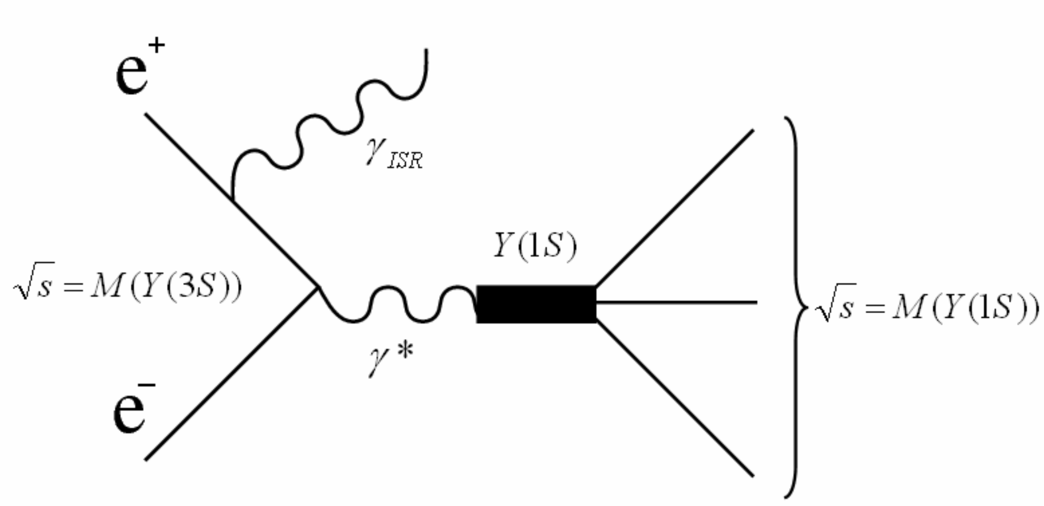


Examples of the Crystal Ball Function

Red: α = 10, Green: α = 1, Blue: α = 0.1

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

(Initial State Radiation)



e^+e^- QED process
at 10.355 GeV

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

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

Cross section measurements
at 10.58 GeV E_cm

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

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

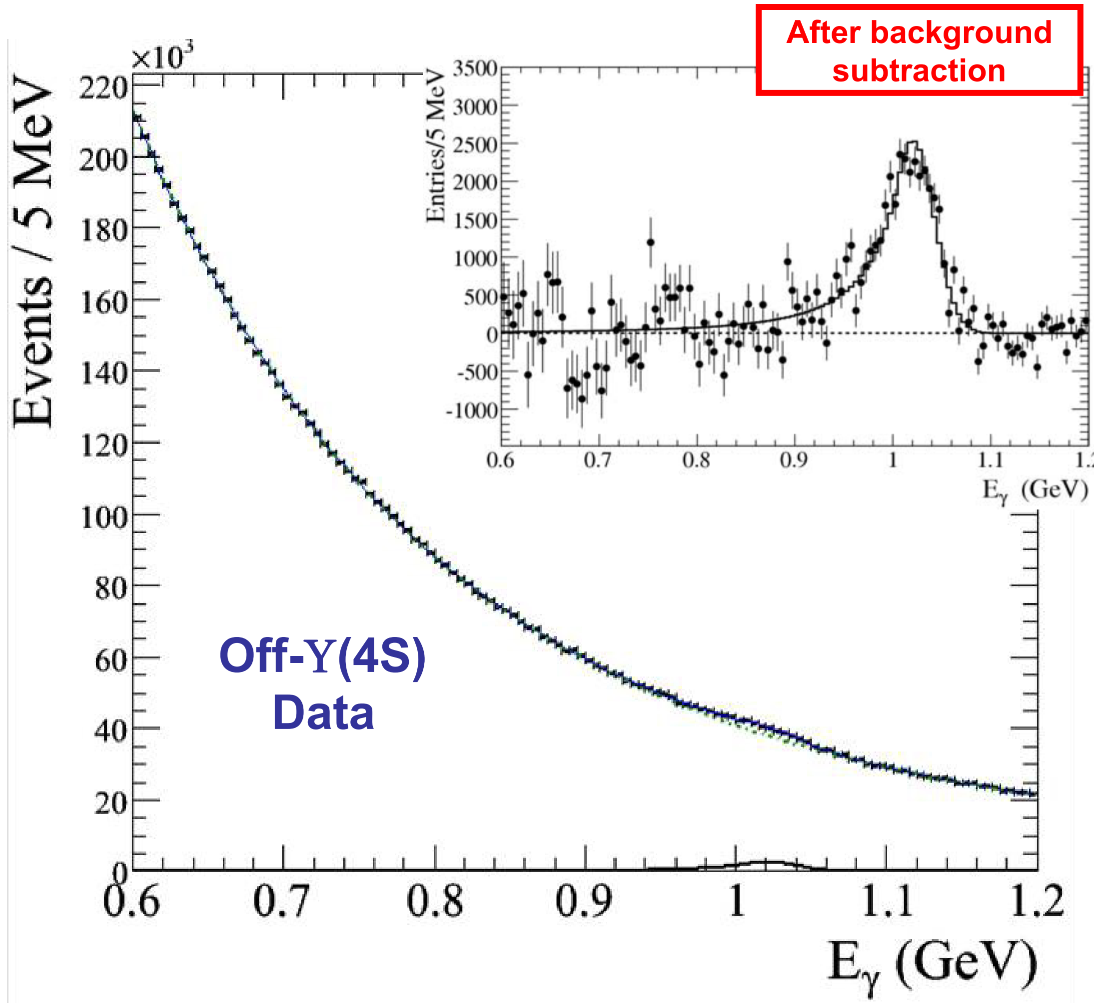
2.4 fb^{-1} at E_cm 30 MeV below the Υ(3S)
44 fb^{-1} at E_cm 40 MeV below the Υ(4S)

$e^+e^- \to \gamma_{ISR}\Upsilon(1S)$ at 10.54 GeV

Shape & Rate determined using Off-Υ(4S) data where E_γ(ISR) peaks at 1.025 GeV

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

N_sig = 35800 ± 1600



Yield Estimate for $e^+e^- \to \gamma_{ISR}\Upsilon(1S)$ In $\Upsilon(3S)$ On-Resonance Data Sample Using $\Upsilon(4S)$ Off-Resonance Data

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

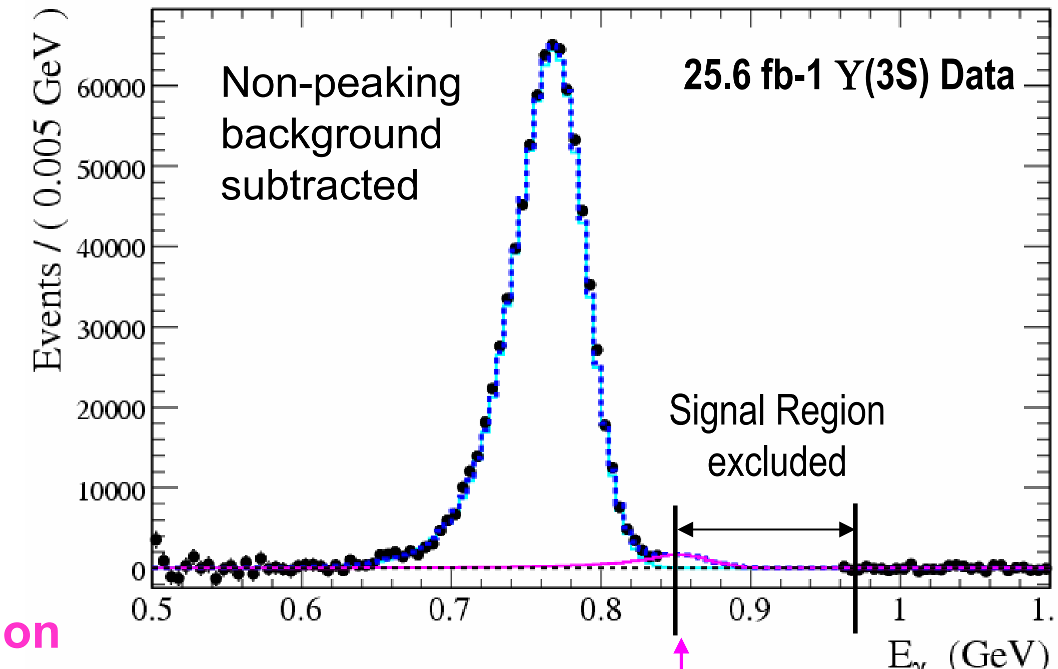
Stat. Error

- 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 σ as part of the study of the systematic uncertainties on the η_b peak position and yield.

Calculation	$\sigma_{\Upsilon(3S)}$ (pb)	$\sigma_{\Upsilon(4S)}$ (pb)	Ratio	Asymmetric collider correction
Benayoun, et. al., 2nd order	25.4	19.8	1.283	Yes
Benayoun, et. al., 1st order	28.46	21.62	1.316	No
Benayoun, et. al., 2nd order	26.12	20.21	1.292	No
Blümlein, et. al., 1st order	28.46	21.62	1.316	No
Blümlein, et. al., 2nd order	27.02	20.46	1.320	No
Blümlein, et. al., 3rd order	27.13	20.54	1.321	No

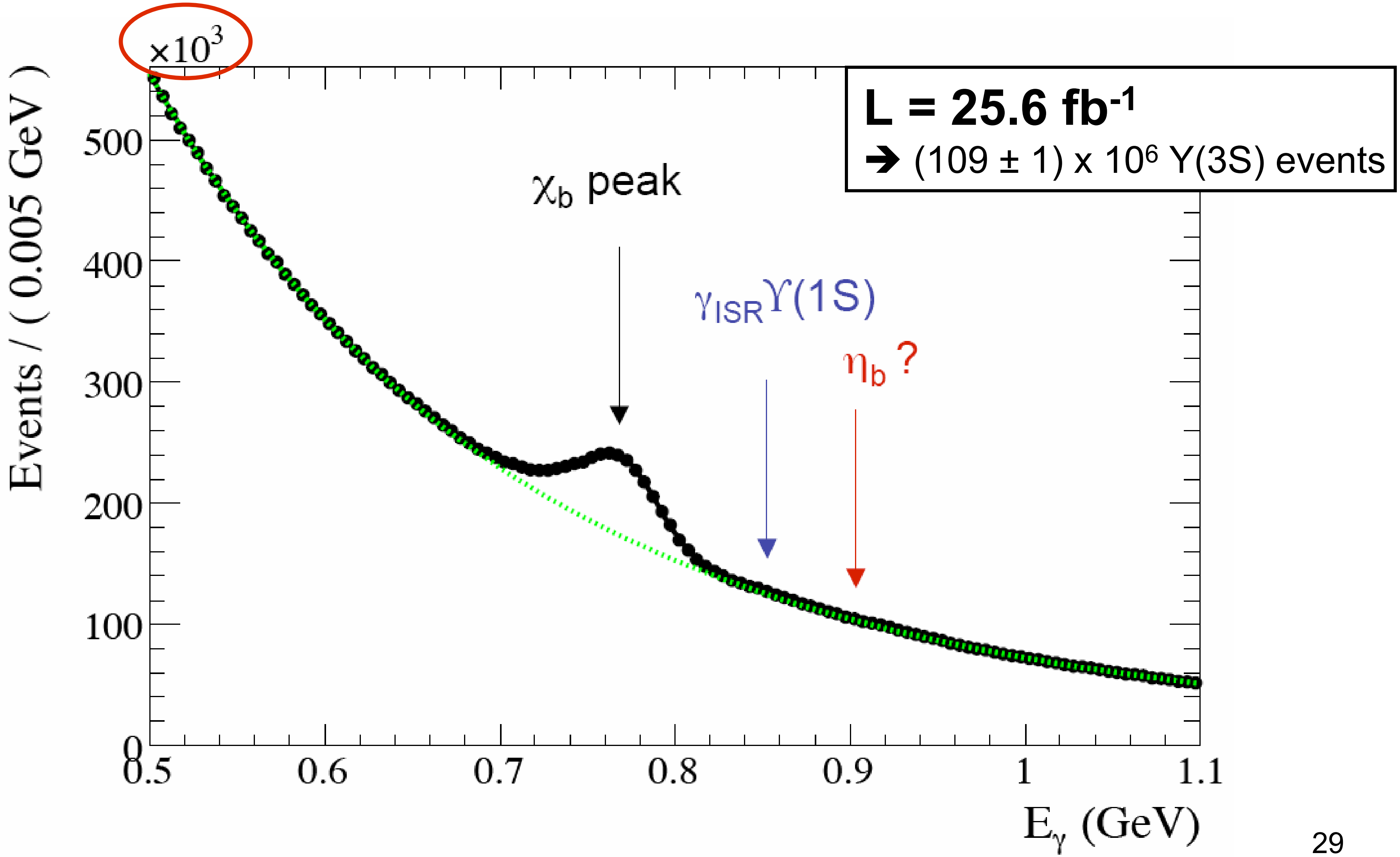
4) χ_{bJ}(2P)→γΥ(1S)

- 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 is taken from PDG
  -- R(χ_{b1}/χ_{b2}) = 1.2 (consistent with value we measure using soft Υ(3S) → $\chi_{b1,2}$(2P) transition photons)
  (χb_0(2P) contribution is very small)



- **Incorporate ISR peak contribution**
  - **Model tail of γ peak from χ_b(2P) properly**

FIT RESULT



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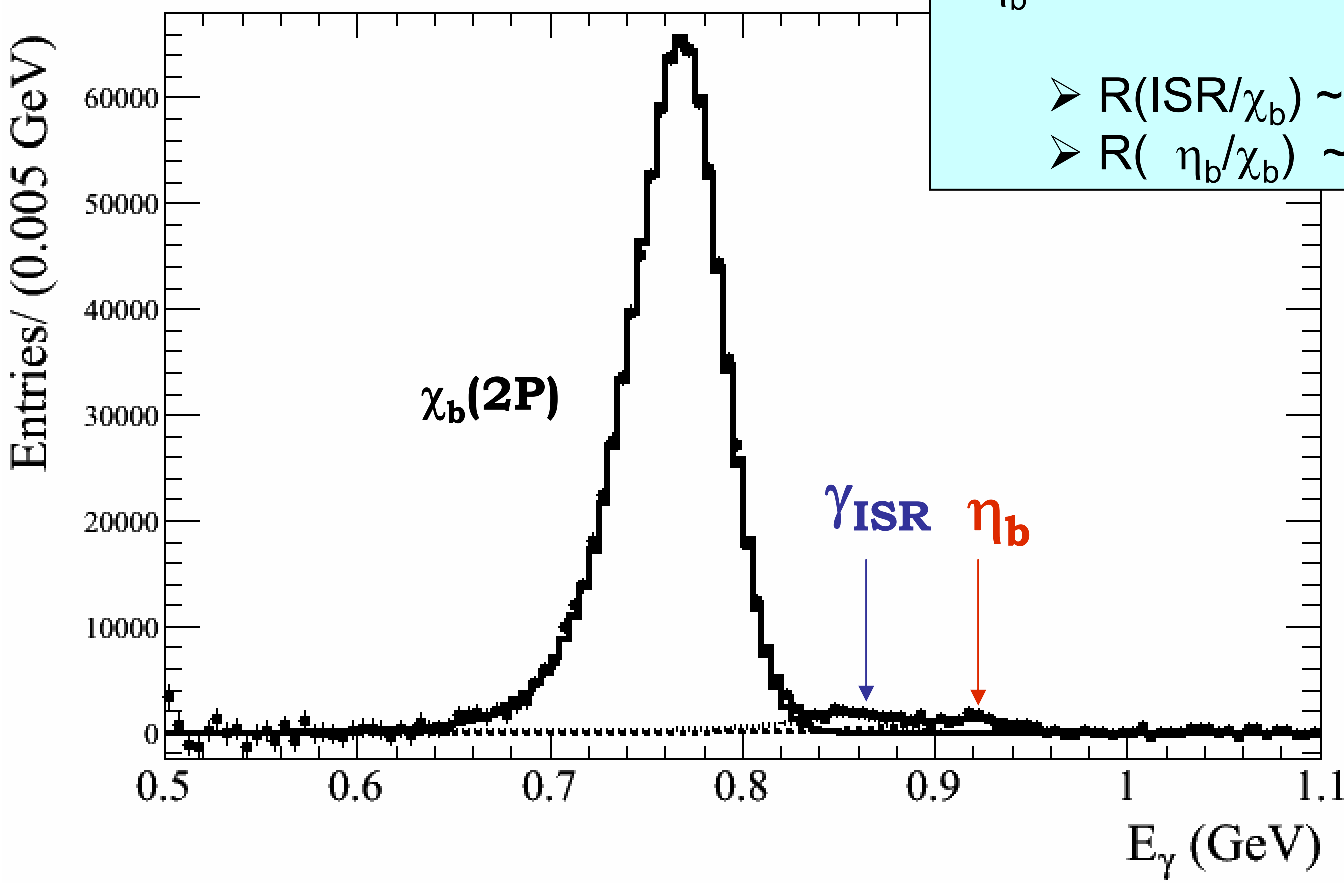
FIT RESULT

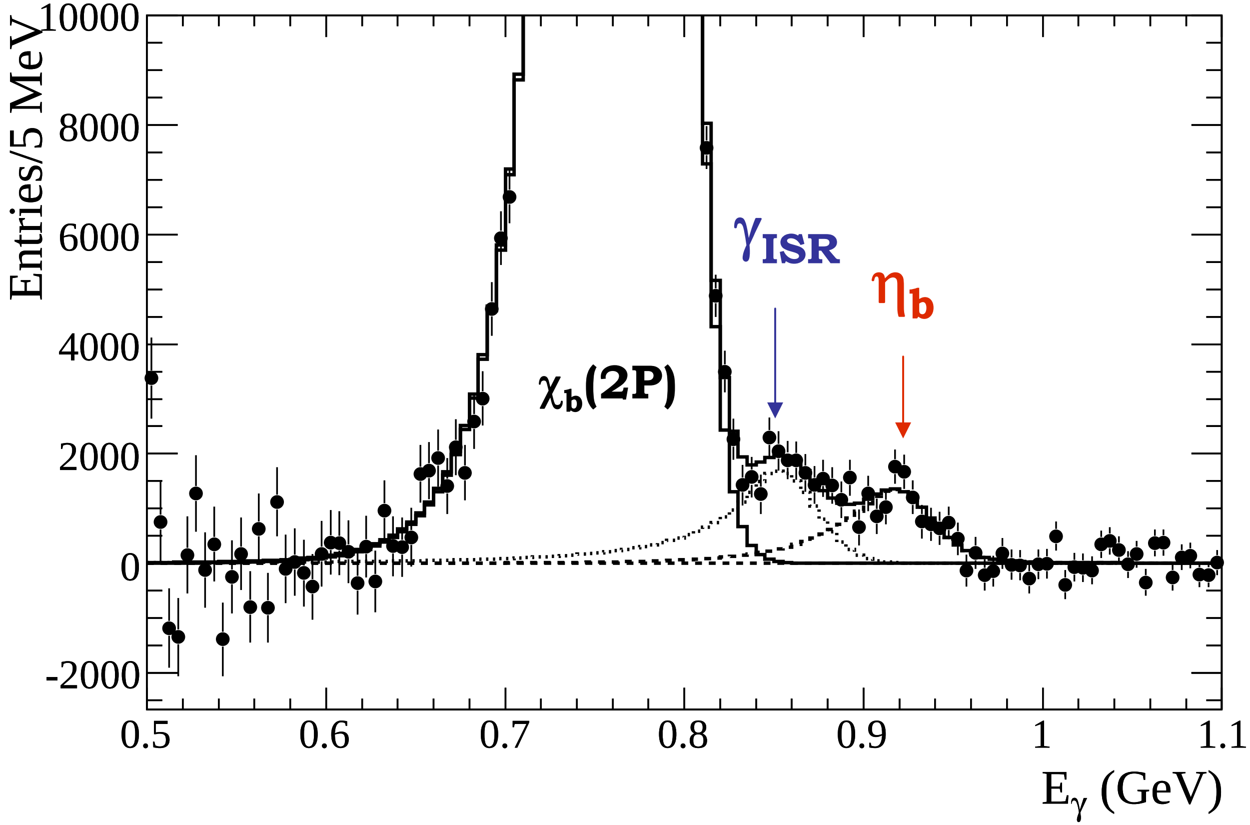
Non-peaking background-subtracted

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

  - R(ISR/χ_b) ~ 1/30
  - R(η_b/χ_b) ~ 1/40



Observation of the η_b



Non-peaking
Background subtracted

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

Fit χ^2/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
    - ➢ 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 → fitted yield (24800+/-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:

    $\Upsilon(3S) \rightarrow \gamma\ \chi_b(2P)$; $\chi_b(2P) \rightarrow \gamma\ \Upsilon(1S)$; $\Upsilon(1S) \rightarrow \mu+\mu-$

- **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 ± 1σ (stat $\otimes$ 5% syst) → δN = 180, δM=0.7 MeV
  - Vary ISR PDF parameters by ± 1σ → δN = 50, δM=0.3 MeV
  - Vary Signal PDF parameters by ± 1σ → δN = 98, δM=0.1 MeV
  - Vary χ_b peak PDF parameters by ± 1σ → δN = 642, δM=0.3 MeV
  - Fit with BW width fixed to 5, 15, 20 MeV → *δN = 2010*, δM=0.8 MeV

- Additional systematic uncertainties in Branching Fraction calculation
  - χ_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 σ)

SUMMARY OF Y(3S) MEASUREMENTS

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

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

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

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

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

- lattice discretisation: +/- 4 MeV/c^2
- QCD radiative corrections: +/- 12 MeV/c^2
- relativistic corrections: +/- 6 MeV/c^2

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

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

(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

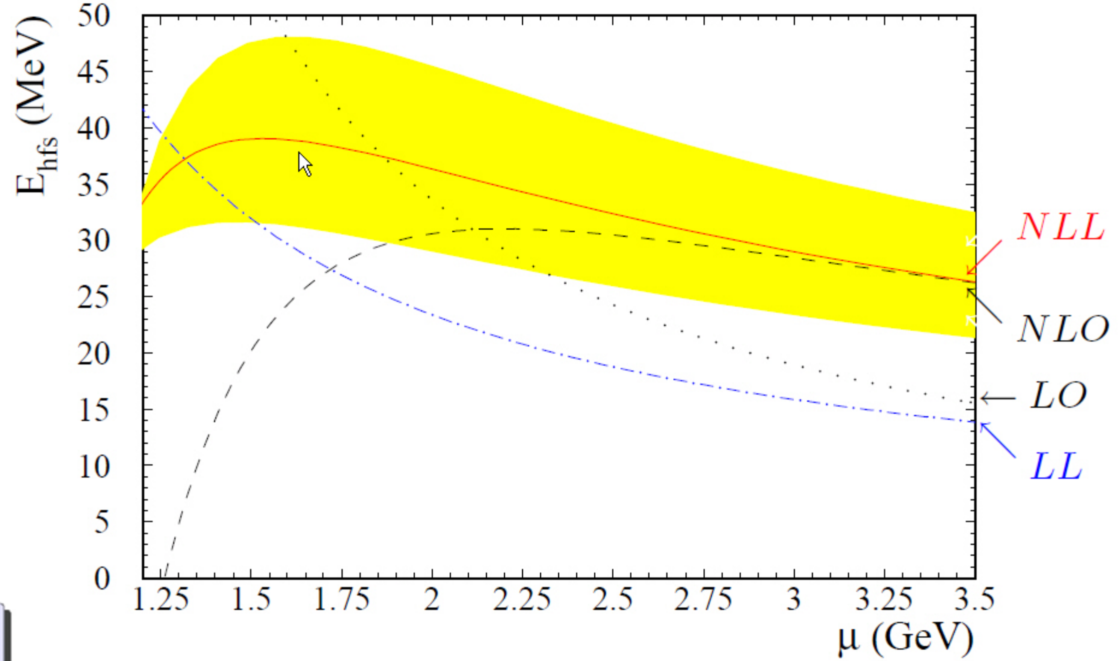
QCD NLL approximation:

$$E_{\rm hfs}^{\rm th} = 39 \pm 11\,({\rm th})\,{}^{+9}_{-8}\,(\delta\alpha_s)\ {\rm MeV}$$

Experiment:

$$E_{\rm hfs}^{\rm exp} = 71.4 \pm 2.7\,({\rm syst})\,{}^{+2.3}_{-3.1}\,({\rm stat})\ {\rm MeV}$$

$$E_{\rm hfs} = M(\Upsilon_{1S}) - M(\eta_b)$$



$M(\eta_b)$ and a(s) from nonrelativistic renormalization Group, Kniehl et al, PRL 92:242001 (2004)

Inclusive Search in $E\gamma$ Spectrum [$\Upsilon(2S) \to \gamma\, \eta_b$]

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

$E\gamma$ Signal at 611 MeV
ISR-Υ(1S) peak at 545 MeV
$\chi_b(1P) \to \gamma\Upsilon(1S)$ 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
➔ better separation between peaks

More (x3) 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 as the Y(2S) cross section is twice the Y(3S) cross section
- Pi0 Veto: **E(g2) > 40 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 4^{th} order polynomial

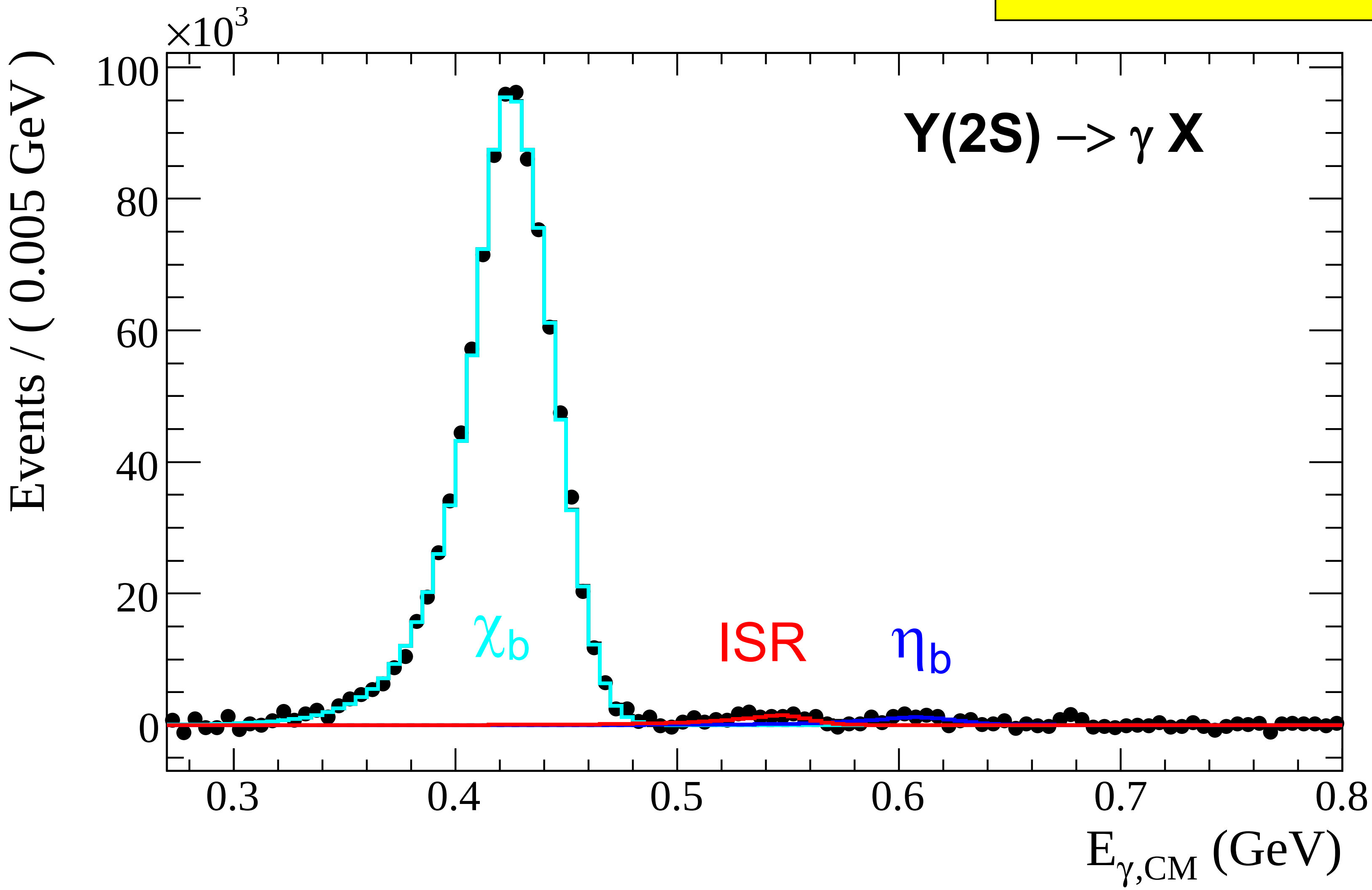
2) $\Upsilon(3S) \rightarrow \gamma\, \eta_b$ Signal (610 MeV)
   Shape from MC simulation

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

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

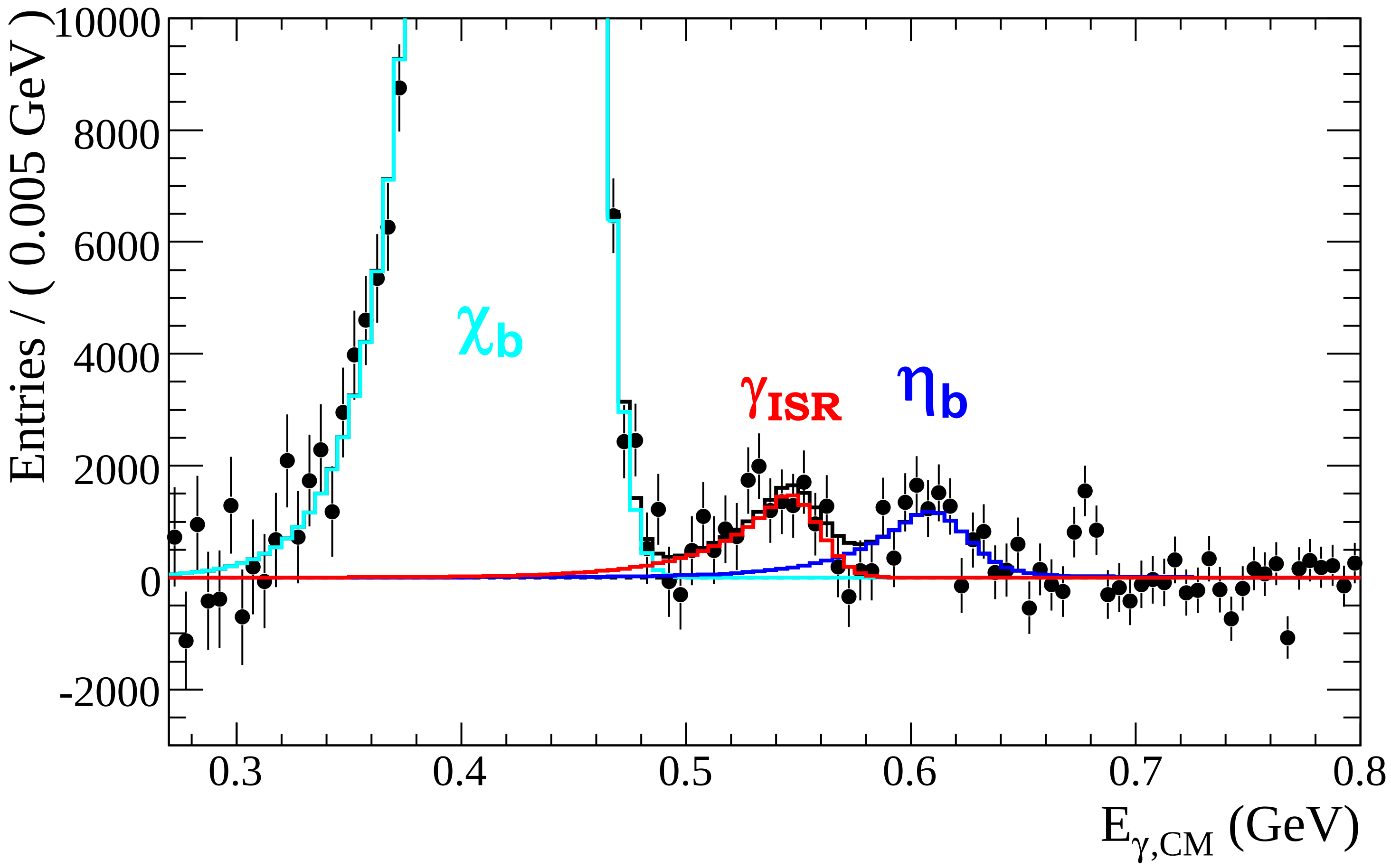
Fit Result

Non-peaking
Background subtracted



Close-up View

Non-peaking
Background subtracted



BABAR Preliminary

Υ(2S) Fit Result

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

- ISR yield of 15000 ± 4200 is consistent with the expected rate of 16700 ± 700 ± 1200

- Goodness of Fit: χ^2/ndof=116.2/93
- Significance including systematics: >3.5 σ

- 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	Δ N [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

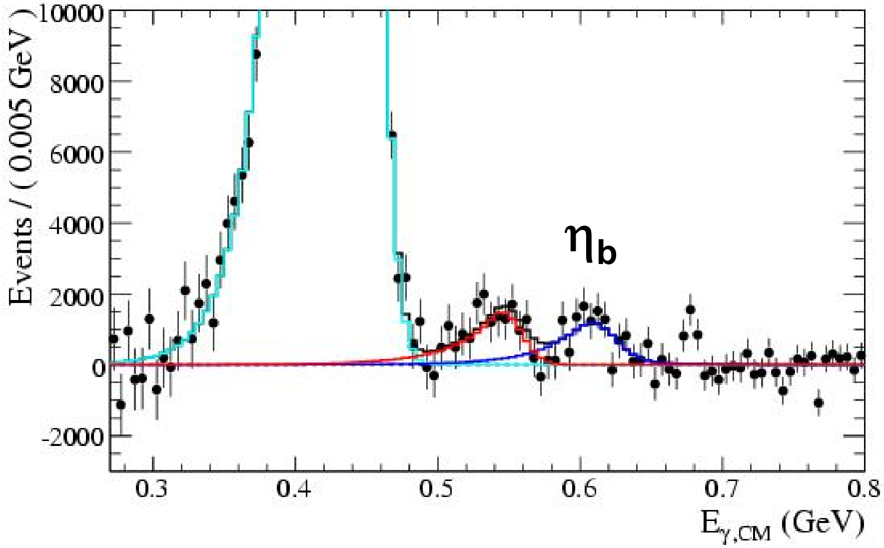
η_b width Variation

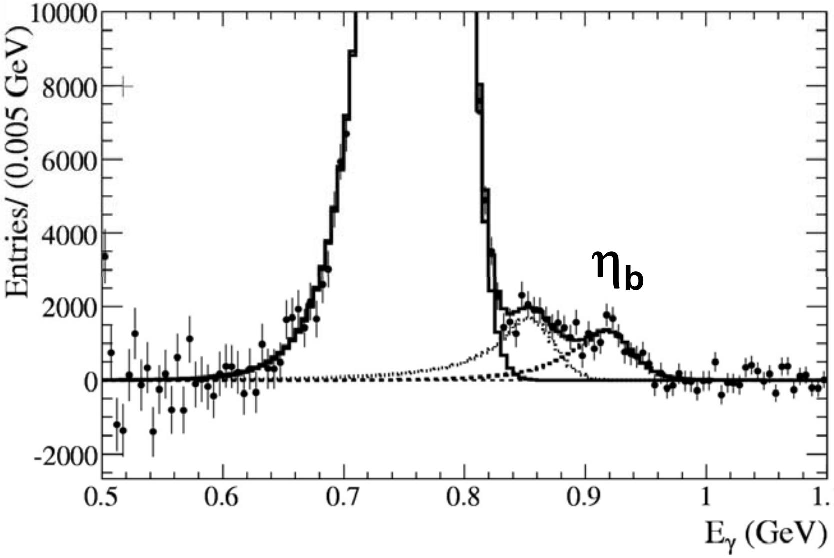
χ_b shape variation

Smooth background shape variation

$\Upsilon(2S) \to \gamma\, \eta_b$

$\Upsilon(3S) \to \gamma\, \eta_b$





$$\mathbf{E}_\gamma = \mathbf{610.5^{+4.5}_{-4.3} \pm 1.8\ MeV}$$

$$\mathrm{M}(\eta_\mathrm{b}) = \mathbf{9392.9^{+4.6}_{-4.8} \pm 1.8\ MeV/c^2}$$

$$\mathrm{M}(\Upsilon(1S)) - \mathrm{M}(\eta_\mathrm{b}) = \mathbf{67.4^{+4.8}_{-4.5} \pm 1.9\ MeV/c^2}$$

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

$$\mathbf{E}_\gamma = \mathbf{921.2^{+2.1}_{-2.8} \pm 2.4\ MeV}$$

$$\mathrm{M}(\eta_\mathrm{b}) = \mathbf{9388.9^{+3.1}_{-2.3} \pm 2.7\ MeV/c^2}$$

$$\mathrm{M}(\Upsilon(1S)) - \mathrm{M}(\eta_\mathrm{b}) = \mathbf{71.4^{+2.3}_{-3.1} \pm 2.7\ MeV/c^2}$$

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

BABAR Preliminary

Other Searches for η_b at BaBar

- $\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$; $\Upsilon(1S) \rightarrow \gamma\, \eta_b(1S)$ INCLUSIVE

  18 M Y(1S) events in $\pi^+\pi^-$ Recoil
  Eγ signal at 71 MeV
  No χ_b background; No peaking ISR background

- $\Upsilon(3S) \rightarrow \gamma\, \eta_b(2S)$ INCLUSIVE

  Eγ Signal at 360 MeV (Difficult Region with nearby E1 transitions)

- $\Upsilon(3S) \rightarrow \pi^0\, h_b(1P)$ or $\pi^+\pi^- h_b(1P)$; $h_b(1P) \rightarrow \gamma\, \eta_b$ INCLUSIVE
- $\Upsilon(3S) \rightarrow \omega\, \eta_b(1S)$ INCLUSIVE
- $\Upsilon(nS) \rightarrow \gamma\, \eta_b(1S)$: Full reconstruction of exclusive channels

Next steps in η_b physics

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

$\eta_b \to \gamma\gamma$ **(*BF* = few x 10^{-4})**

	CLEO III	**BaBar**	**BELLE**
Υ(1S)	20 M		**100 M**
Υ(2S)	9 M	**100 M**	
Υ(3S)	6 M	**120 M**	11 M

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

We will need a Super-B Factory.

Summary

- **First Observation of the η_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 η_b and other bottomonium physics are expected from BABAR, BELLE, and CLEO experiments in the near future**

Thank you!