Bottomonium Spectroscopy and the η_b Discovery at BaBar

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for the BaBar collaboration

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DESY

Outline

- Quarkonium Spectroscopy - Reminder
- Experiment and Dataset
- Hadronic Bottomonium Transitions
- Scan above the $\Upsilon(4S)$ resonance
- The Bottomonium Ground State: The Discovery of the η_b
- Summary and Outlook

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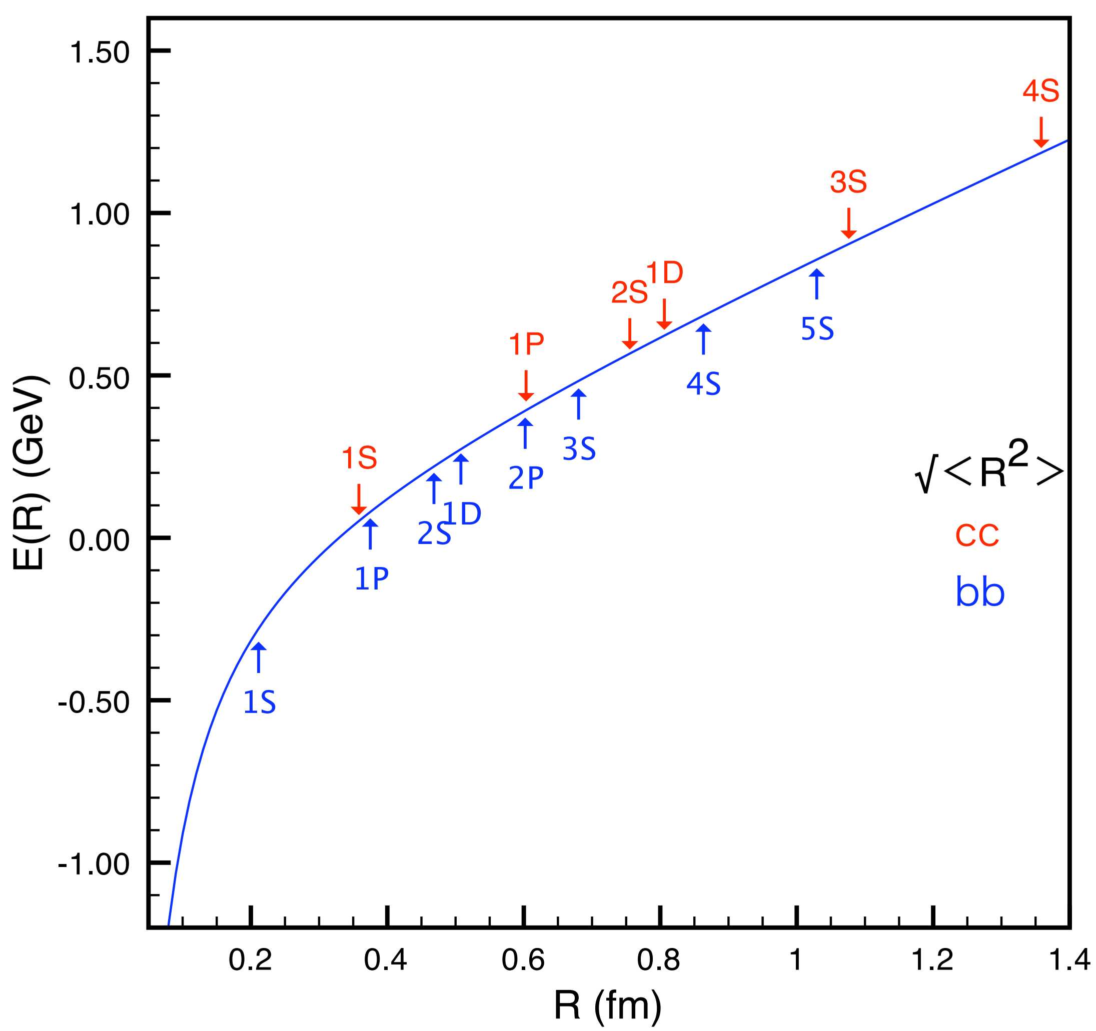
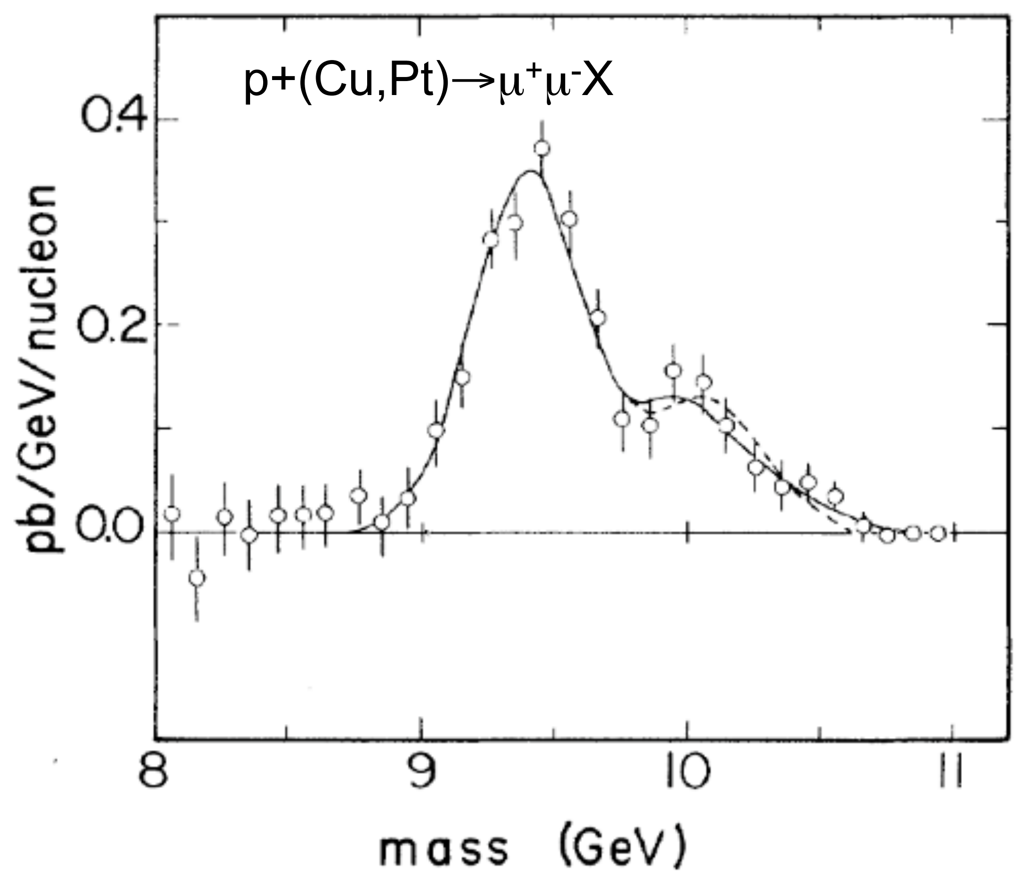
Basics of Quarkonium Spectroscopy

- $Q\overline{Q}$ bound state, with
  - Spin: S_{QQ} = 1/2x1/2 = 0 + 1 → singlet + triplet (-1,0,+1) for same L
    - conserved is total angular momentum $\vec{J} = \vec{L} + \vec{S}$
  - Parity: $P=(-1)^{L+1}$
  - C-parity: $C=(-1)^{L+S}$
  - some J^{PC} forbidden: $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$,...
- Heavy Quarks : non-relativistic

Potential model

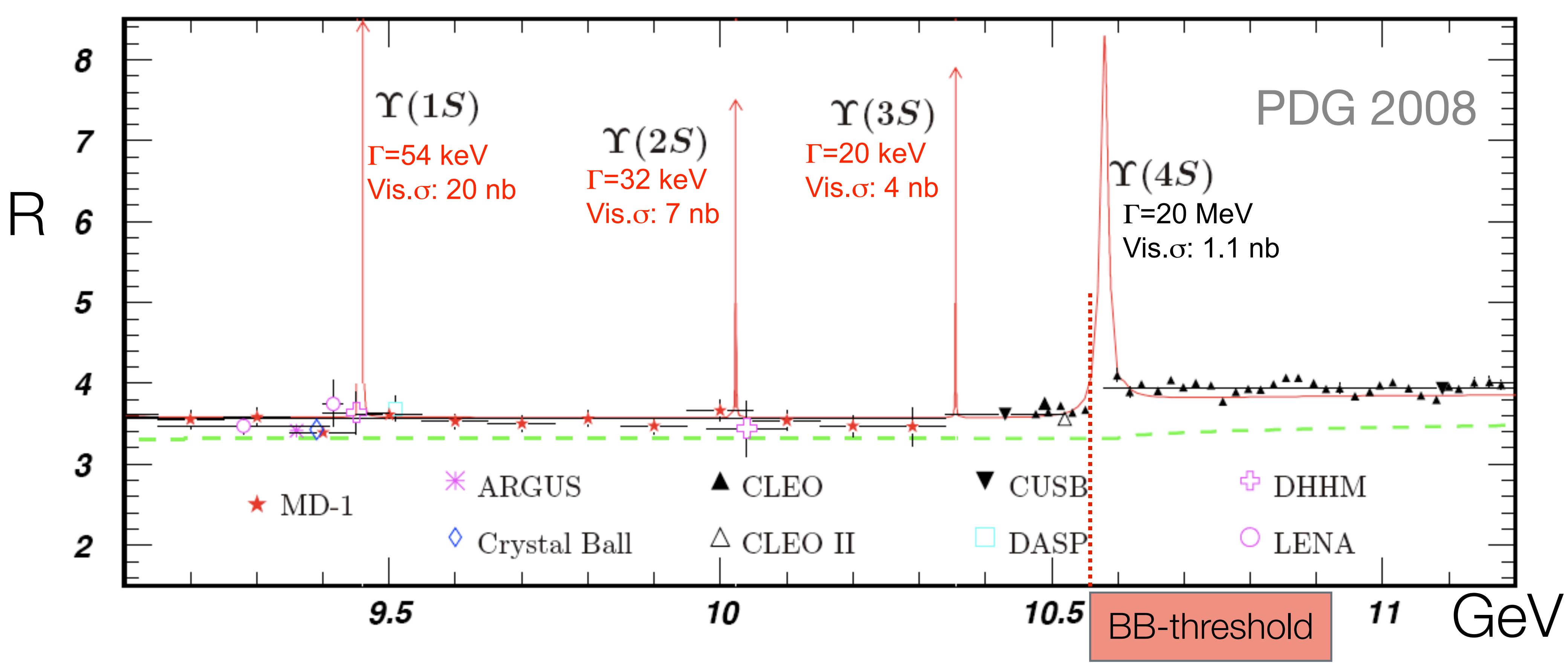


(PRL 39, 242 (1977) and PRL 39,1240 (1977))



Bottomonium

- Bottomonium (bb) history started 30 years ago
- states below threshold usually narrow
  - annihilation through virtual gluons/photons (OZI-rule)
- states above threshold broad

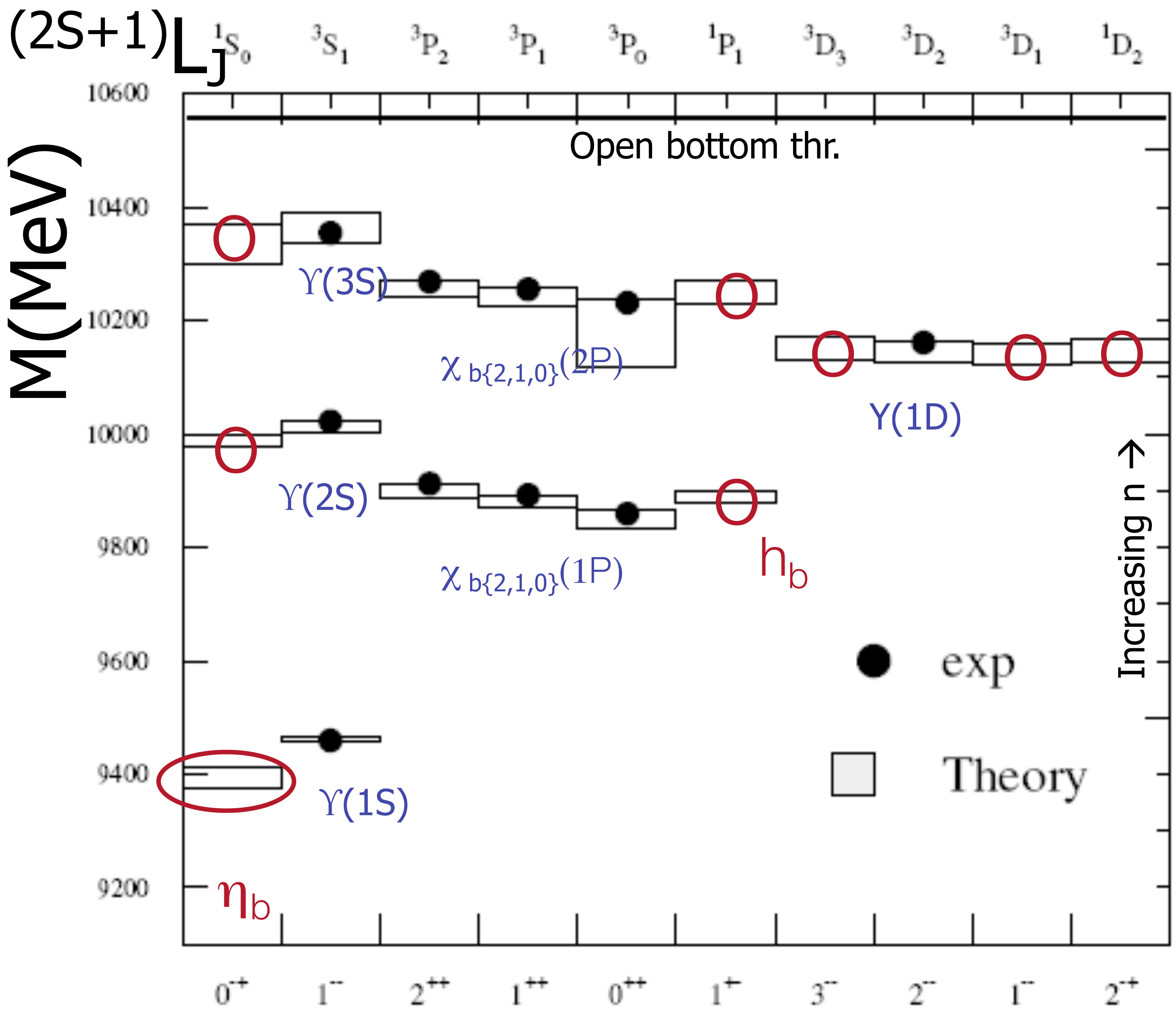


M(ϒ(1S))=9.40±0.013 GeV

M(ϒ(2S))=10.00±0.04 GeV

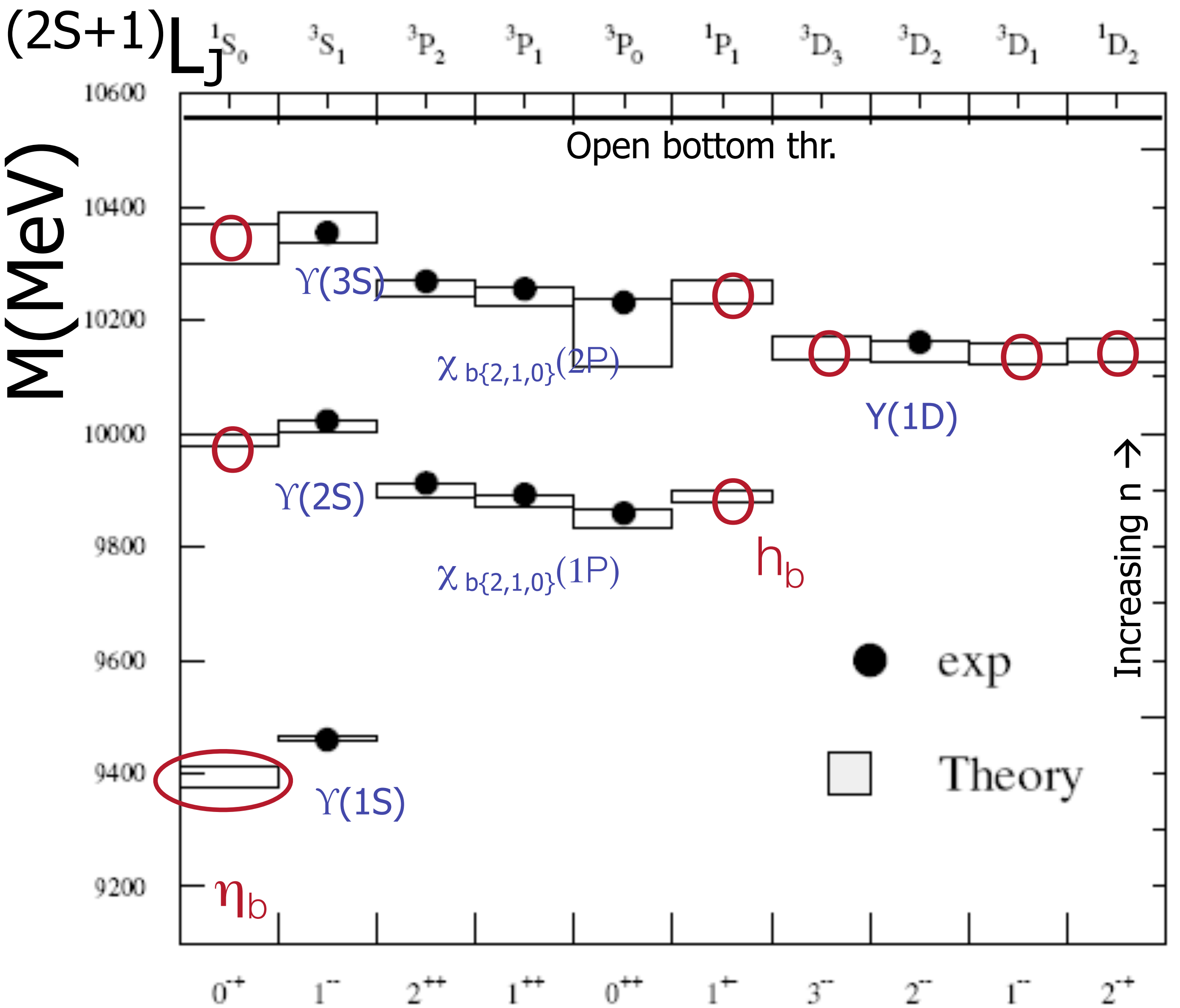
M(ϒ(3S))=10.43±0.12 GeV

Bottomonium Spectrum



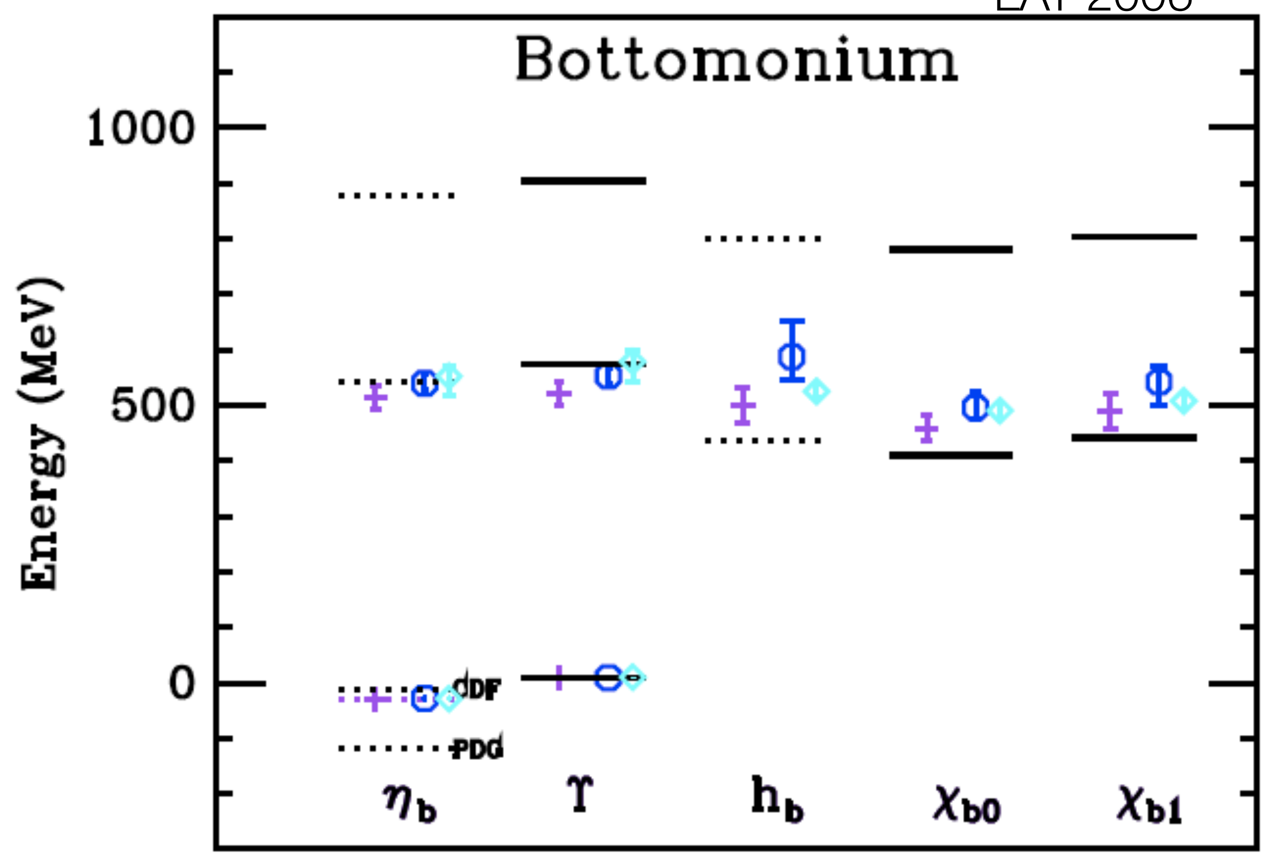
- Below $B\bar{B}$ threshold, 8 states are still missing
  - S-wave η_b(1S,2S,3S)
  - P-wave h_b(1P,2P)
  - D-wave 1^3D_1, 1^3D_2, 1^3D_3
- ground state still to be observed
- above BB threshold: further resonances

Bottomonium Spectrum



- study the strong interaction
- measure masses, transition rates, splitting
  - test of NRQCD, Lattice QCD, potential models

S. Gottlieb et al, LAT 2006



- QCD models are important for implications for “New Physics” from B-measurements

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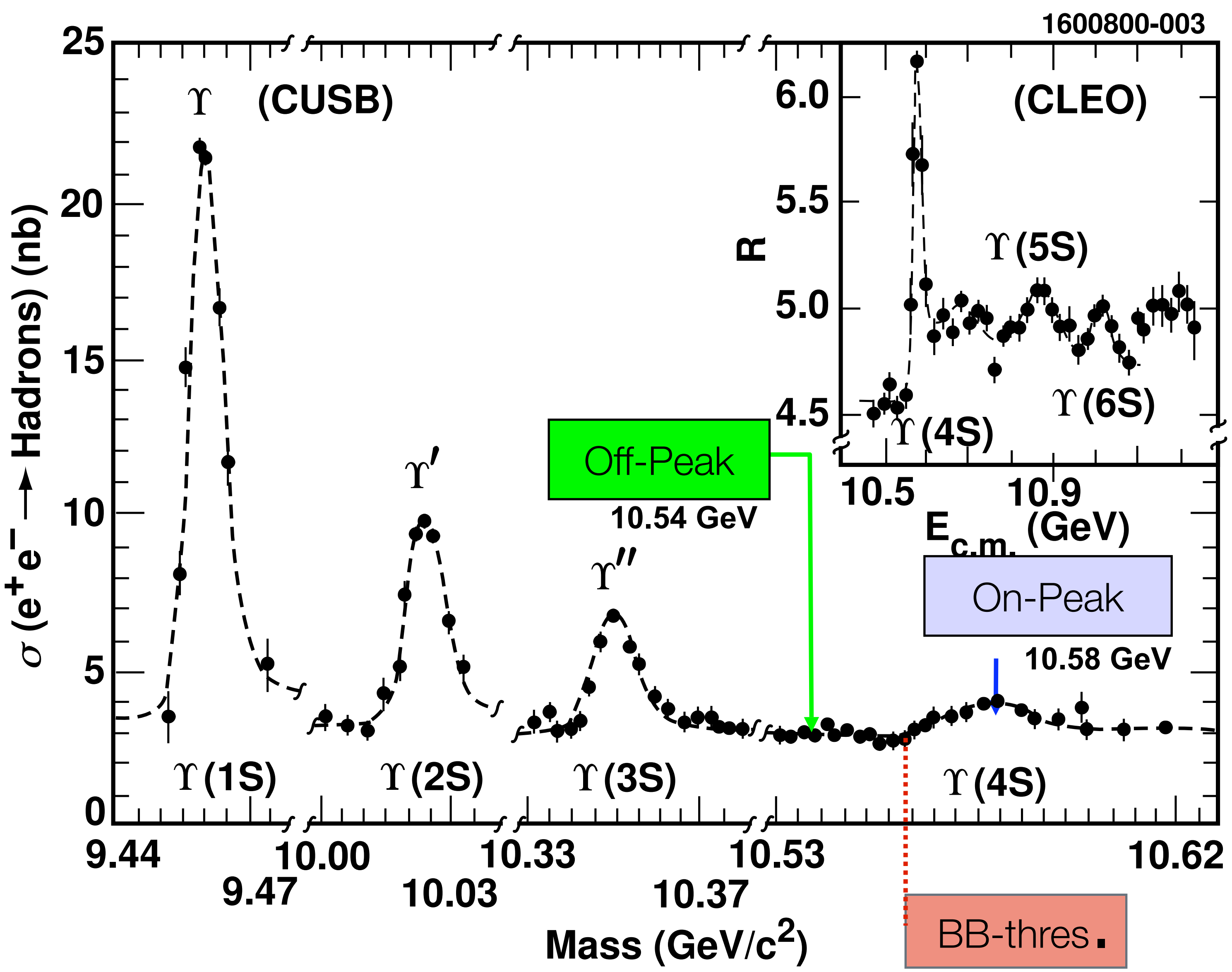
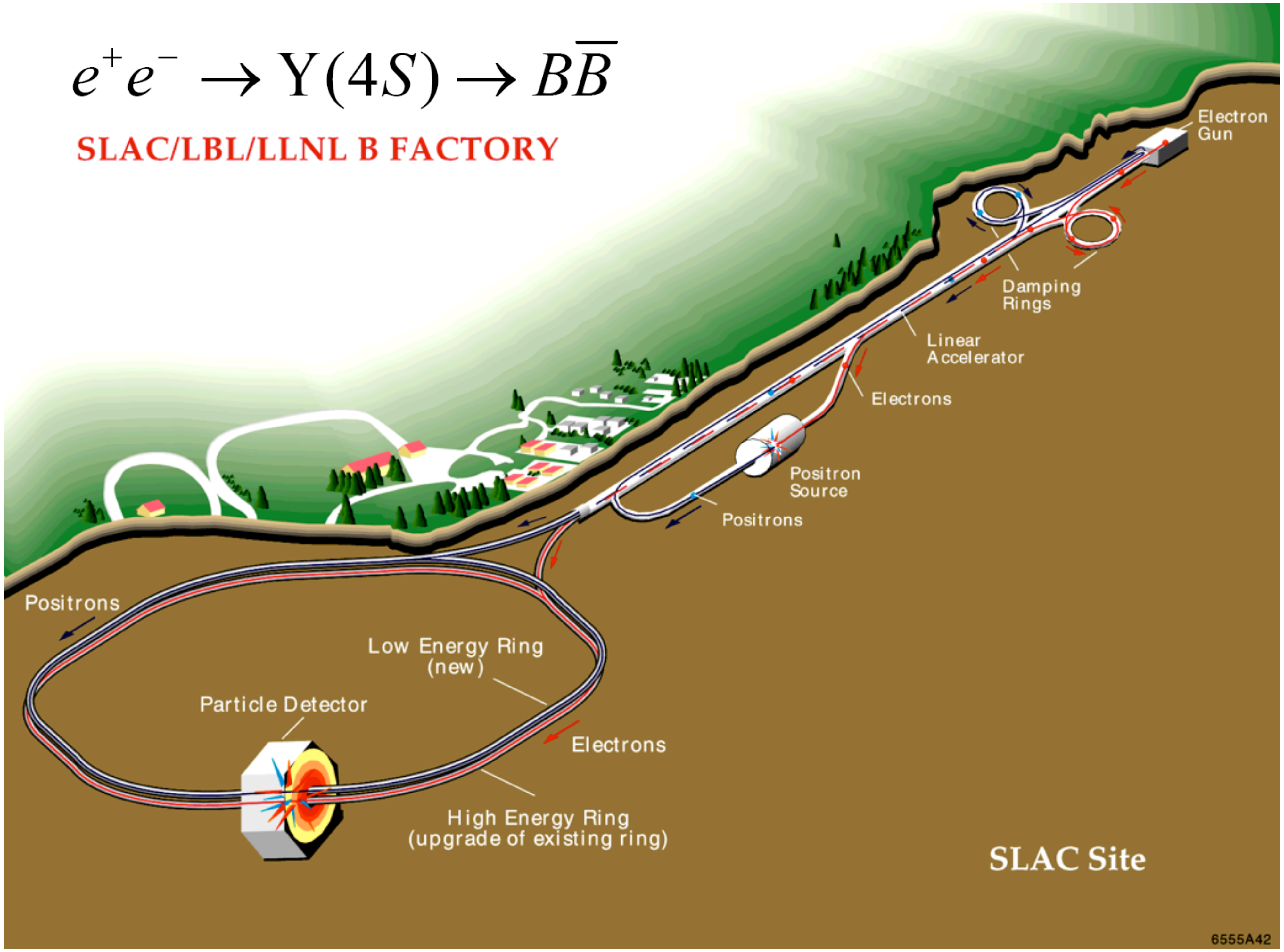
The Upsilon Resonances



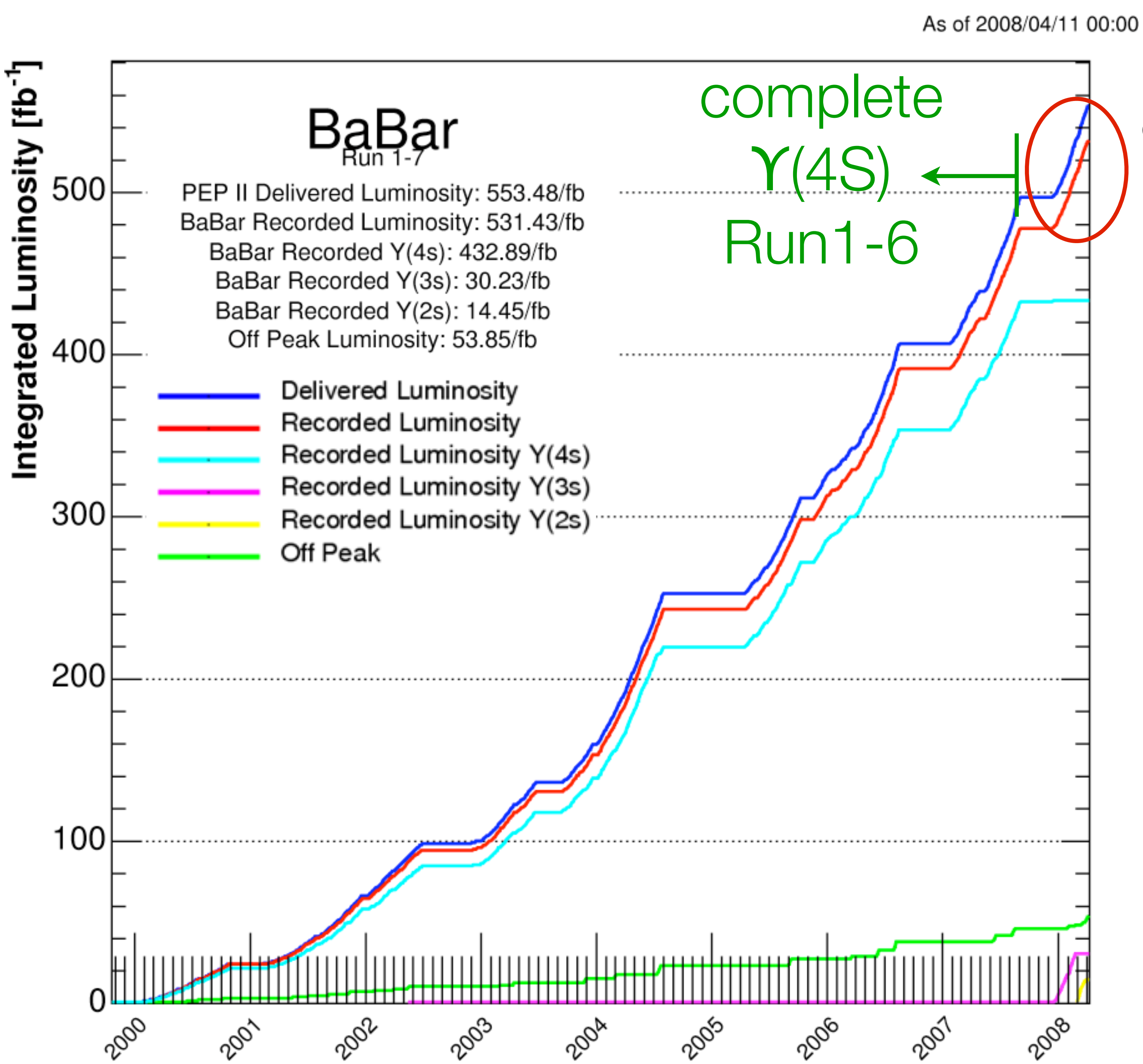
- Υ(4S) wider than Υ(1-3S) resonances: above BB-threshold
- also "continuum" reactions:
  - $e^+e^- \rightarrow u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}, \tau\bar{\tau}$
- take data at "Off-Peak" energy to obtain event sample containing only continuum events

Experimental Setup: PEP-II

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\overline{B}$$

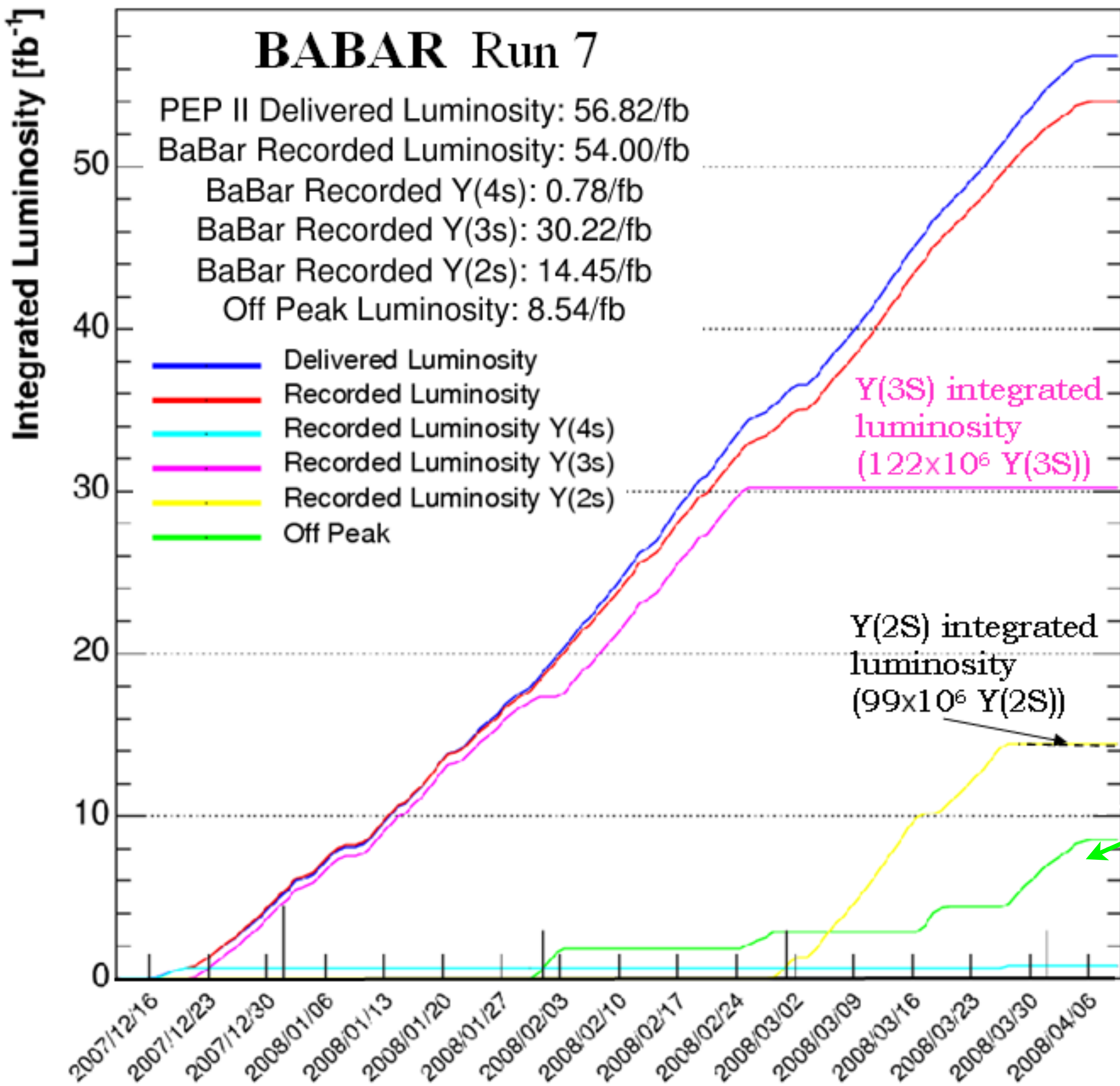


Experimental Setup: Dataset



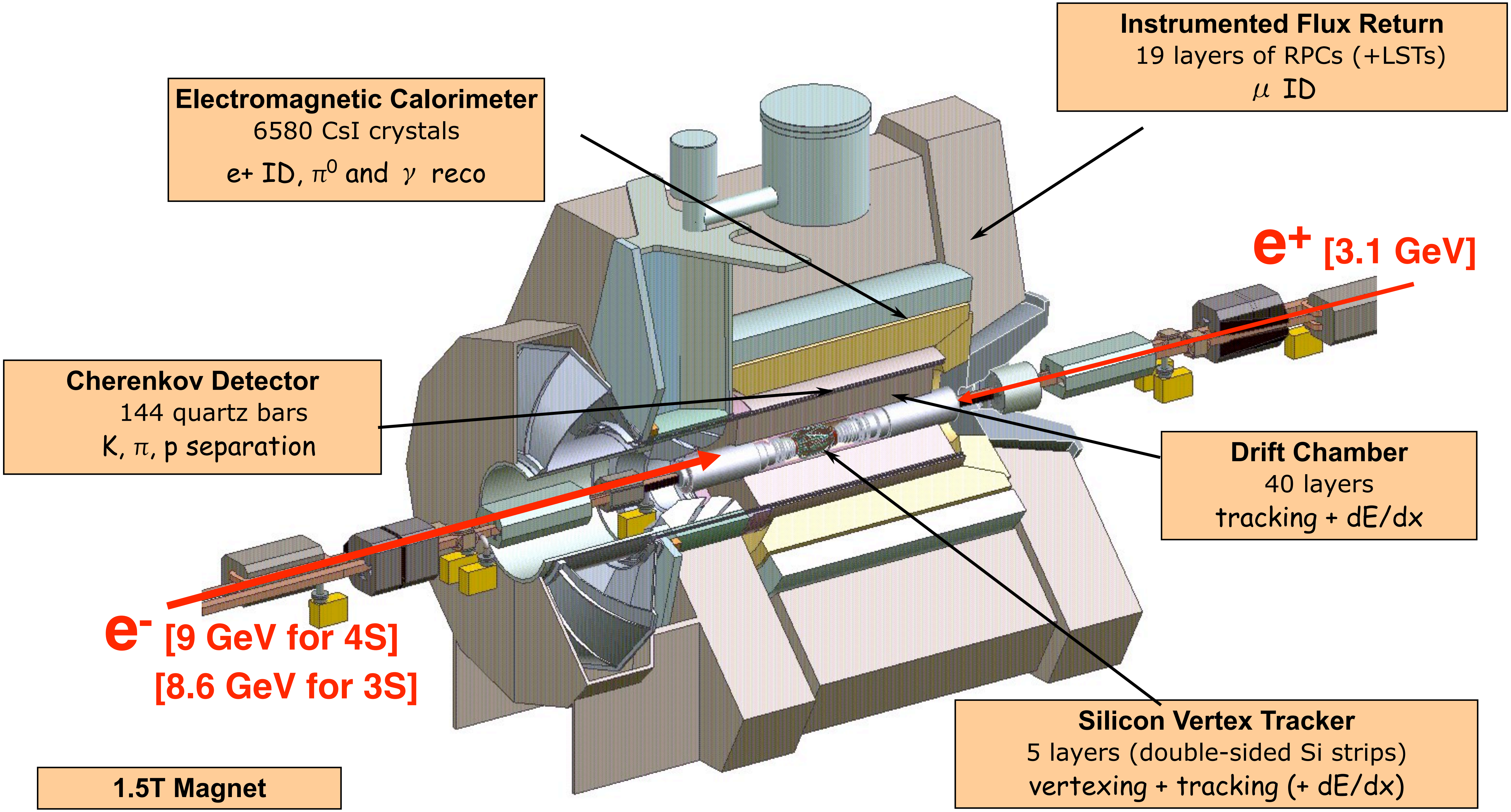
- collected 433 fb^{-1} at the ϒ(4S) resonance (~475×10^6 M BB-pairs)
- with shortened Run 7: proposed to run on ϒ(3S) as best way to use remaining beam time

Experimental Setup: Dataset



- collected 433 fb^{-1} at the Υ(4S) resonance (~475x10^6 M BB-pairs)
- with shortened Run 7: proposed to run on Υ(3S) as best way to use remaining beam time
  - collected 33 fb^{-1} (122x10^6 M Υ(3S))
- also added run on Υ(2S) (14 fb^{-1})
- and energy scan above Υ(4S) (4 fb^{-1})

Experimental Setup: BaBar - Detector



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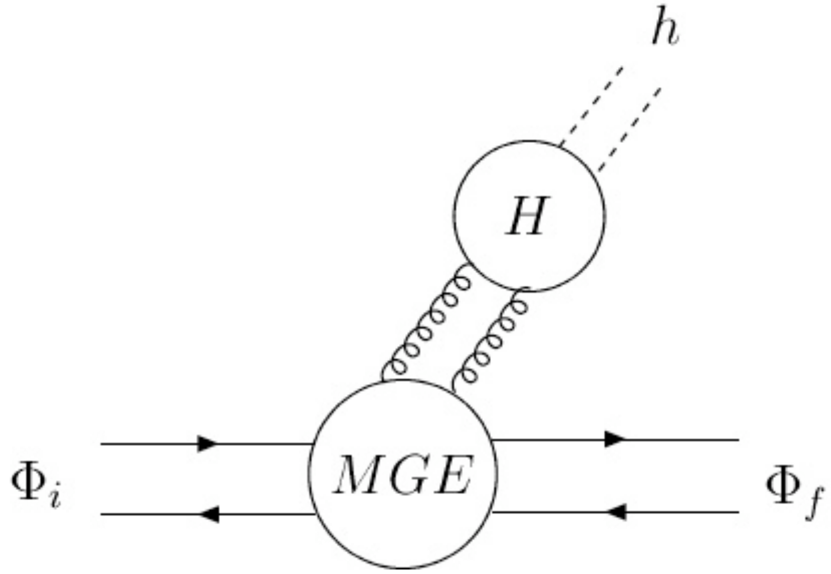
Hadronic Υ(mS) →Υ(nS) Transitions

- Hadronic transitions between heavy quarkonia generally described in the framework of the QCD Multipole Expansion QCDME

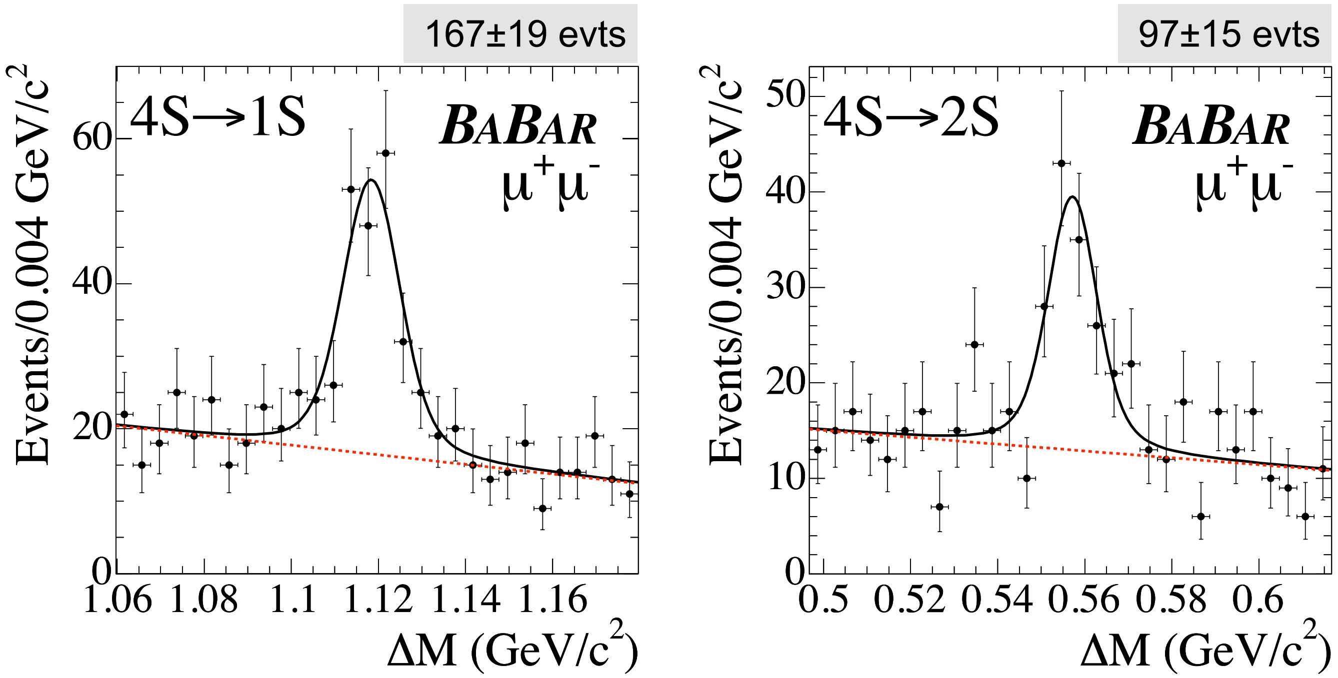


- In analogy to Electromagnetism, expand in power of ak gluon radiation from the QQ bound state, with radius a much smaller than wavelength a/λ≈ak<<1
  - in cc system: only a few possible transitions and data fitted well by predictions
    - $\Gamma(\psi(2S)\to J/\psi\eta)$ / $\Gamma(\psi(2S)\to J/\psi\pi^+\pi^-)$ well explained
    - $M(\pi^+\pi^-)$ shape in $\psi(2S)\to J/\psi\pi^+\pi^-$ well explained
  - in bb system: many more transitions are possible

$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(4S) \to \Upsilon(2S)\pi^+\pi^-$

- Reconstruct $\Upsilon(4S) \to \Upsilon(nS)\pi^+\pi^-$ with $\Upsilon(nS) \to l^+l^-$
  - $M(l^+l^-)$ compatible with $\Upsilon(nS)$
  - $\Delta M = M(\pi^+\pi^- l^+l^-) - M(l^+l^-)$ compatible with $M(4S)-M(nS)$
  - signal extraction: 1D fit to ΔM

PRL 96, 232001(2006)



$$B(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(1S)) = (0.90\pm0.15)\times10^{-4}$$

$$\Gamma(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(1S)) = (1.8\pm0.4)\ \text{keV}$$

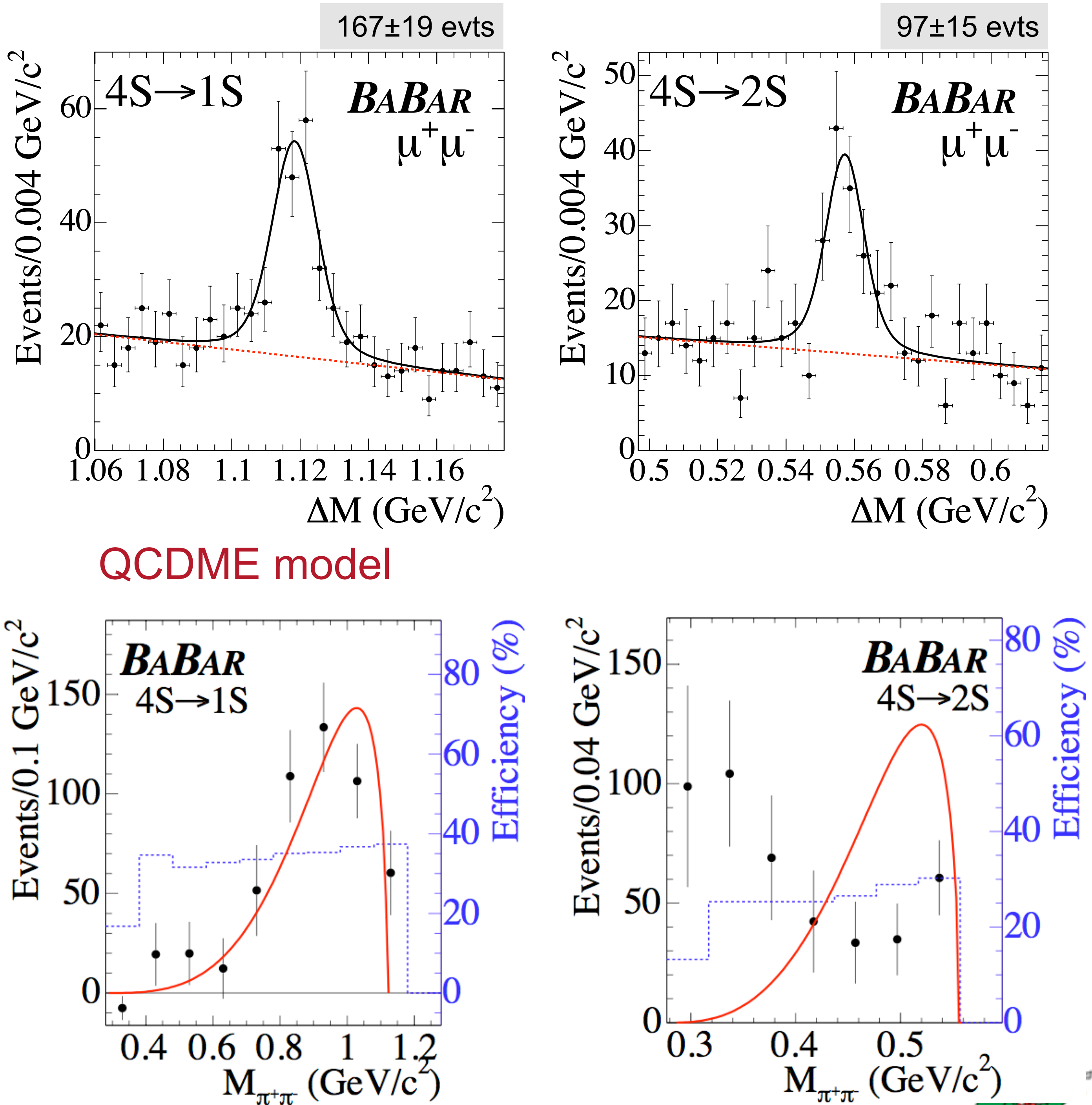
$$B(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(2S)) = (1.29\pm0.32)\times10^{-4}$$

$$\Gamma(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(2S)) = (2.7\pm0.8)\ \text{keV}$$

$\Upsilon(4S) \rightarrow \Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(4S) \rightarrow \Upsilon(2S)\pi^+\pi^-$

- Reconstruct $\Upsilon(4S) \rightarrow \Upsilon(nS)\pi^+\pi^-$ with $\Upsilon(nS) \rightarrow l^+l^-$
  - $M(l^+l^-)$ compatible with $\Upsilon(nS)$
  - $\Delta M = M(\pi^+\pi^- l^+l^-) - M(l^+l^-)$ compatible with $M(4S)-M(nS)$
  - signal extraction: 1D fit to ΔM
- Look at $\pi^+\pi^-$ invariant mass distribution and compare to QCDME model
  - good agreement for $\Upsilon(4S) \rightarrow \Upsilon(1S)$ transitions
  - structure in $\Upsilon(4S) \rightarrow \Upsilon(2S)$ transitions ?

PRL 96, 232001(2006)



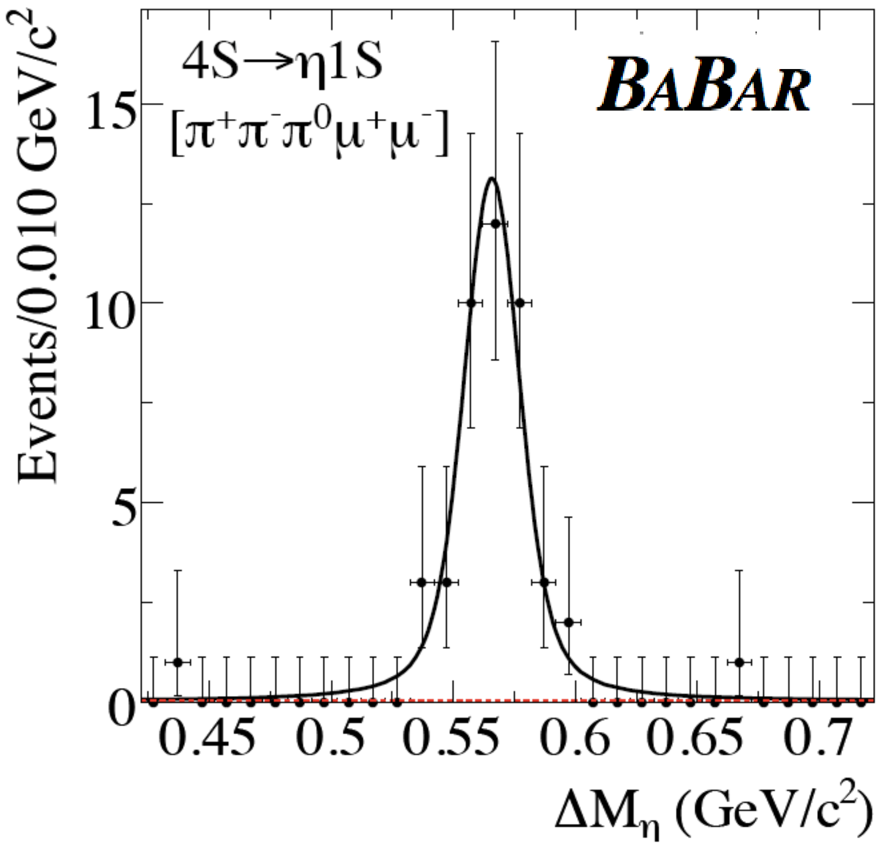
$\Upsilon(4S) \rightarrow \Upsilon(1S)\eta$

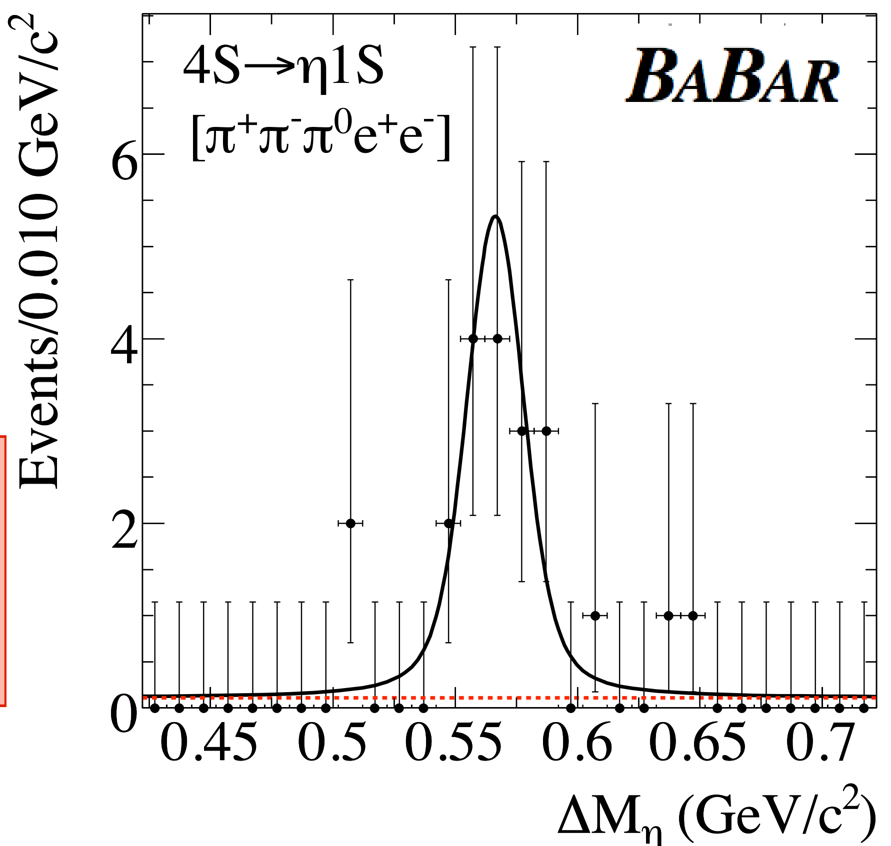
- Reconstruct $\Upsilon(mS)\rightarrow\Upsilon(nS)\eta$ with $\Upsilon(nS)\rightarrow l^+l^-$
  - $\eta\rightarrow \pi^+\pi^-\pi^0$
  - $\Delta M_\eta = M(3\pi\, l^+l^-) - M(l^+l^-) - M(3\pi) \equiv M(mS)-M(nS)-M(\eta)$
  - signal extraction: 1D fit to ΔM_η
  - m=2,3 selected from ISR production
  - Data compatible with background for n=2,3
- First Observation of $\Upsilon(4S)\rightarrow\Upsilon(1S)\eta$

$B(\Upsilon(4S)\rightarrow\Upsilon(1S)\eta) = (1.96\pm0.06\pm0.09)10^{-4}$

$$\frac{\Gamma(\Upsilon(4S)\rightarrow\Upsilon(1S)\eta)}{\Gamma(\Upsilon(4S)\rightarrow\Upsilon(1S)\pi+\pi^-)} = 2.41\pm0.40\pm0.12$$

- Unexpected ratio ⇒
  - expect E1M2/E1E1 < 1!





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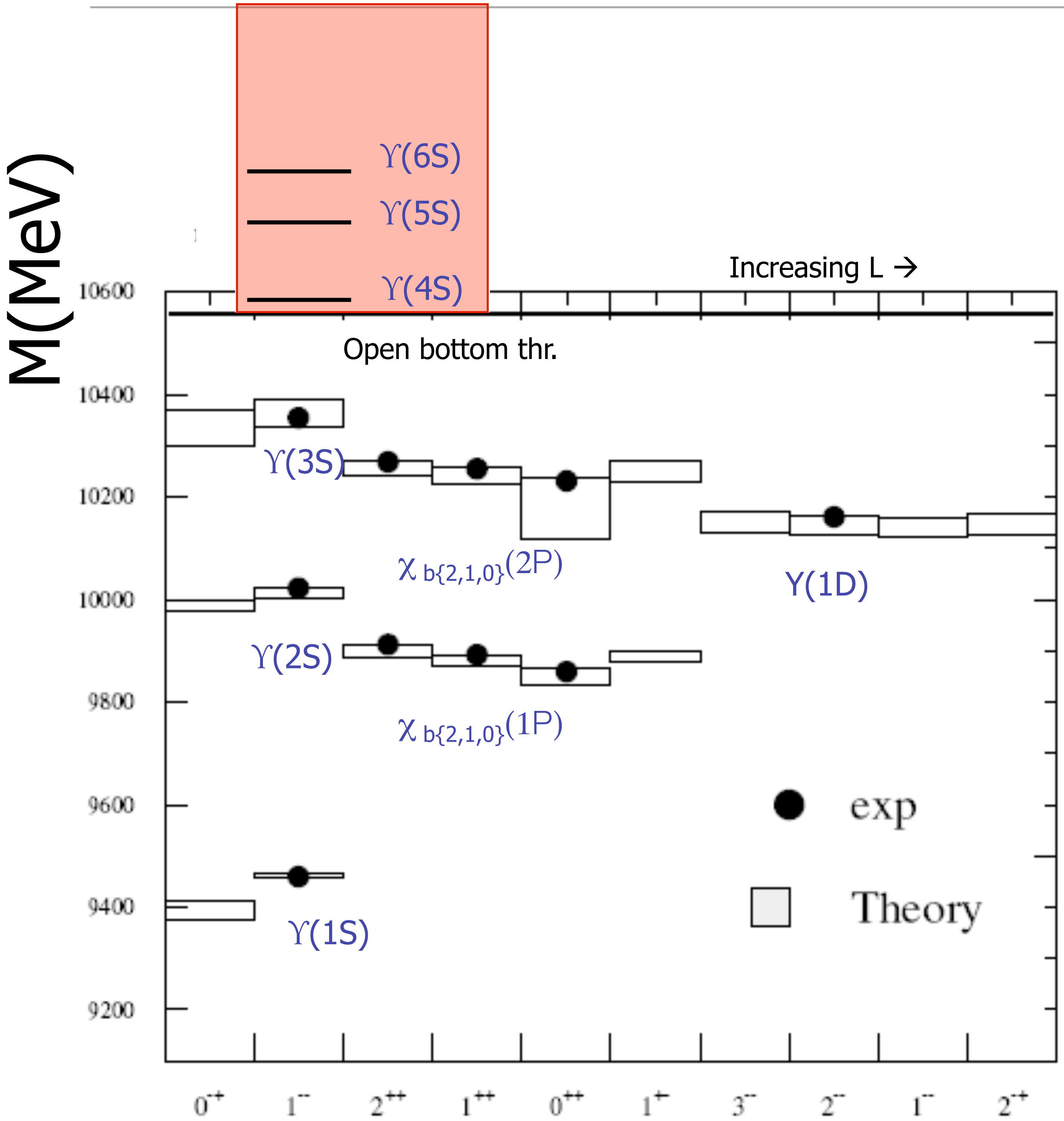
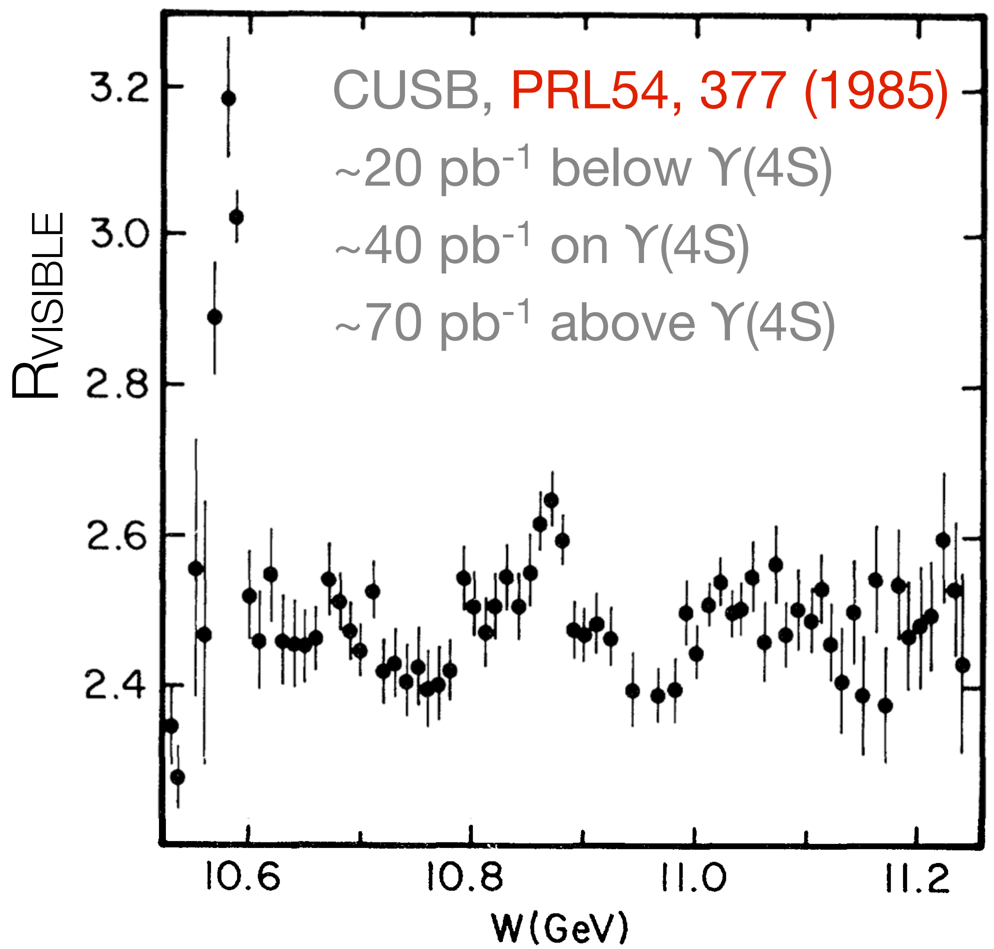
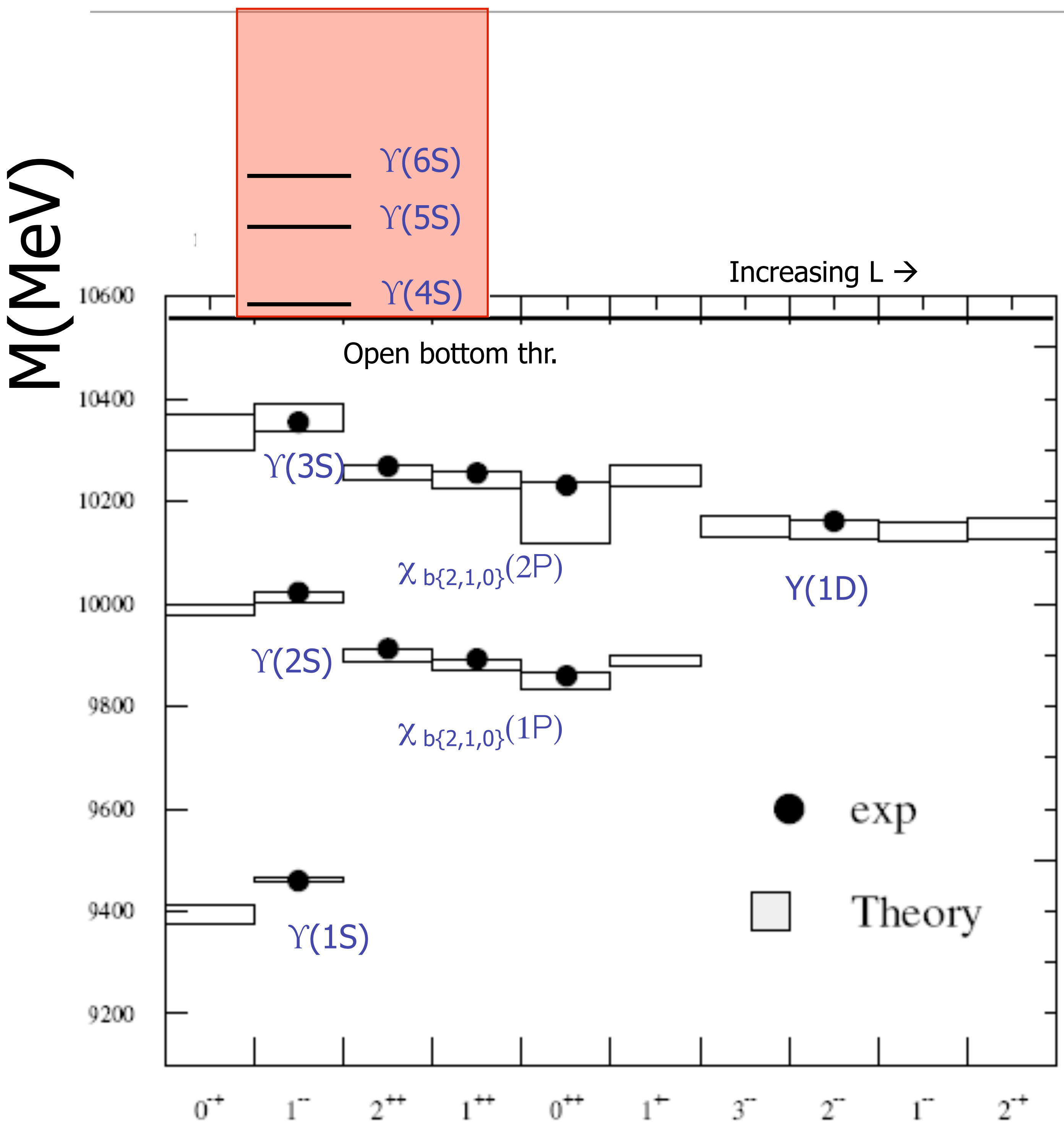
Bottomonium Spectrum



- many not well understood exotic states in charmonium spectrum
  - Y(4260)→J/ψ $\pi^+\pi^-$
- look for analog in bottomonium
- last detailed scan ~ 25 years ago



Bottomonium Spectrum

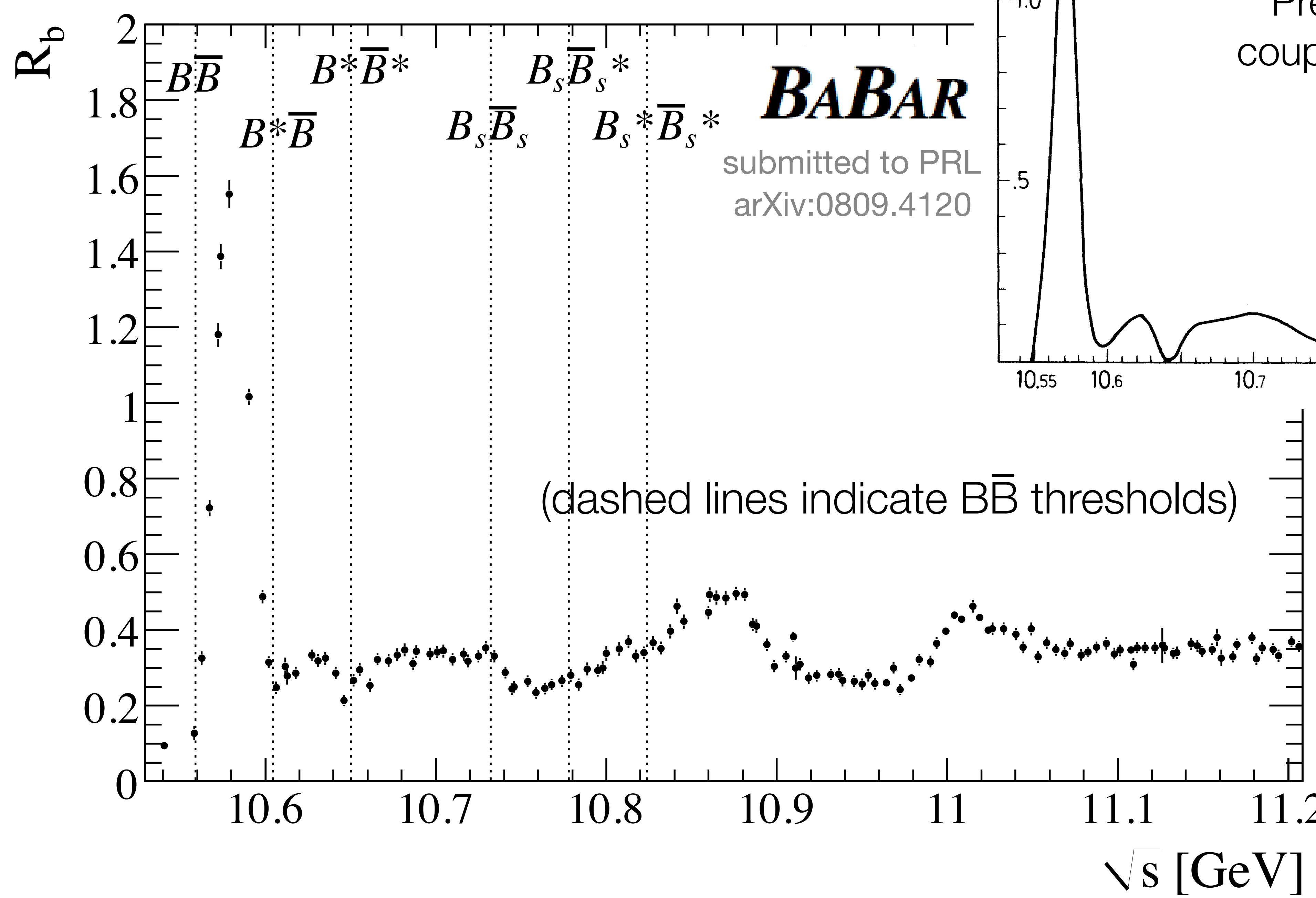


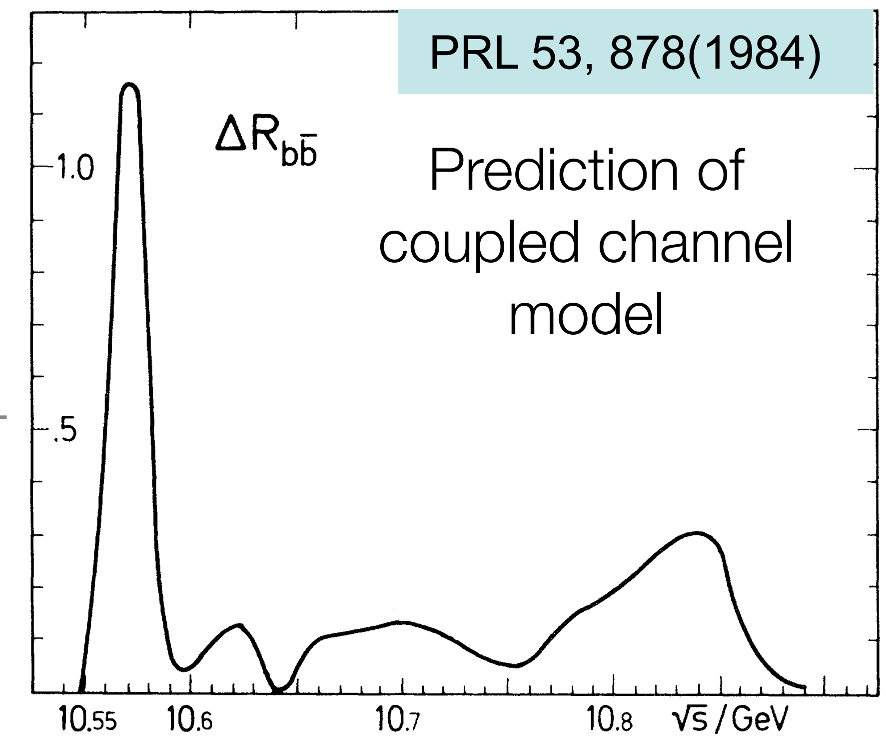
- many not well understood exotic states in charmonium spectrum
    - $\Upsilon(4260) \rightarrow J/\psi\ \pi^+\pi^-$
- look for analogue in bottomonium
- last detailed scan ~ 25 years ago
- BaBar took data from 10.54 GeV → 11.2 GeV from
    - 5 MeV steps, ~25 pb^{-1}/step, ~3.3 fb^{-1} total
    - Υ(6S) region not well measured
    - collected 600 pb^{-1} in scan from 10.96 to 11.10 GeV

Measurement of R_b above the $B\bar{B}$-threshold

- $R_b = \sigma_b(s)/\sigma_\mu(s)$ ($\sqrt{s} = E_{cm}$)
  - $\sigma_b(s)$: total cross section for $e^+e^- \to b\bar{b}$ including bound $b\bar{b}$ states below open B-threshold produced by ISR (initial state radiation)
  - $\sigma_\mu(s)$: Born cross section
- select B-enriched sample for measurement
  - require minimal number of tracks, event shape
- use off-peak $\Upsilon(4S)$ data ($\sqrt{s}$=10.54 GeV) as reference sample

Measurement of R_b





not yet all states discovered

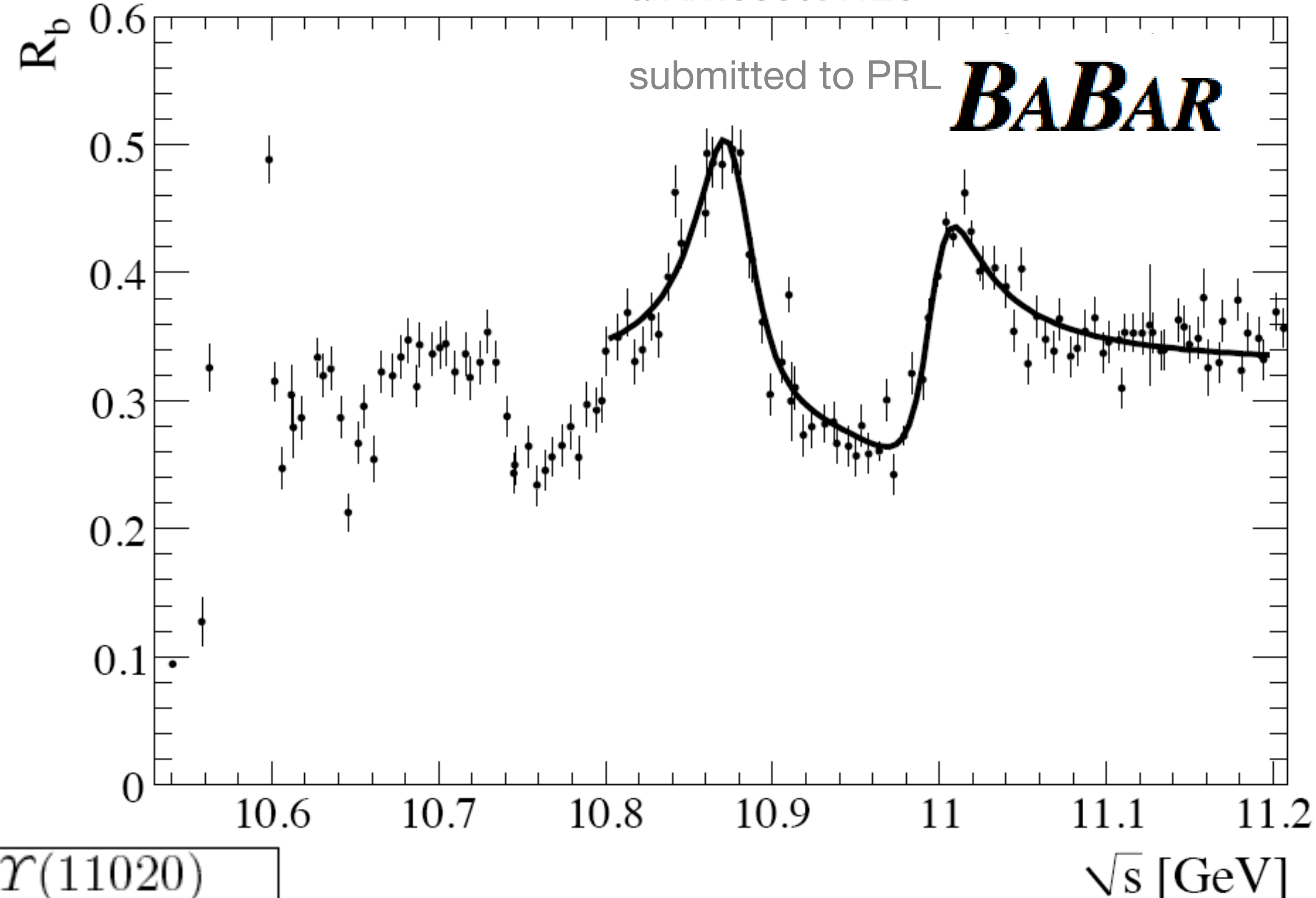
improved mass measurements

- interpretation of structures at ~10.62 GeV and ~10.7 GeV depend on threshold openings

Fitting beyond the Υ(4S)

- Fit using simple model:
  - two Breit-Wigner resonances
  - flat component, not interfering with BW, added incoherently to
  - flat component, interfering with BW

arXiv:0809.4120



	$\Upsilon(10860)$	$\Upsilon(11020)$
mass (GeV)	10.876 ± 0.002	10.996 ± 0.002
width (MeV)	43 ± 4	37 ± 3
ϕ (rad)	2.11 ± 0.12	0.12 ± 0.07
PDG mass (GeV)	10.865 ± 0.008	11.019 ± 0.008
PDG width (MeV)	110 ± 13	79 ± 16

- replace non-resonant term with threshold function $\sqrt{s}=2m_B$
  - mass Υ(10860) = (10869±2) MeV
  - width: (74±4) MeV

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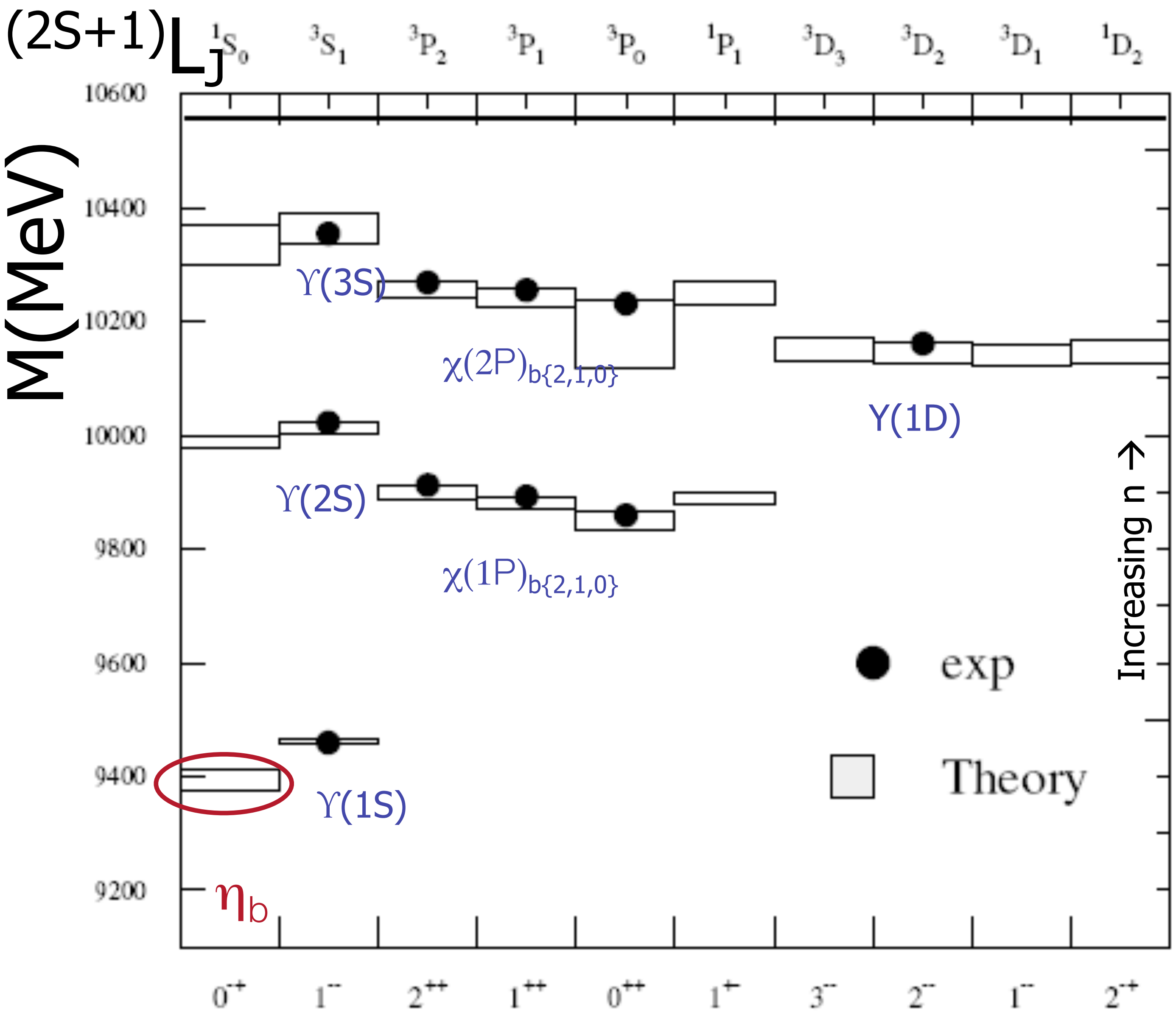
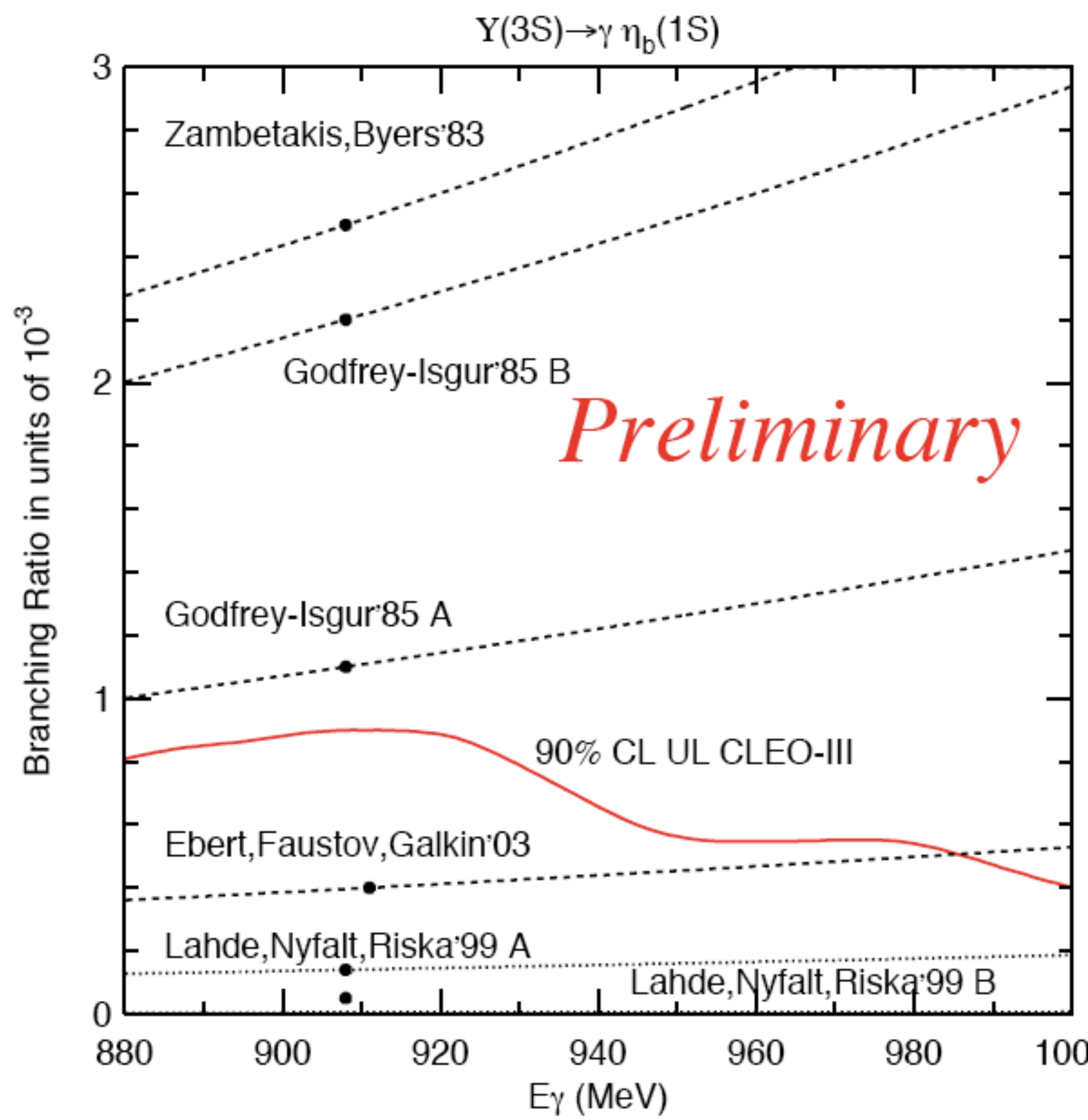


- Ground state not found until recently
- Measurement of its mass and width helpful to test Lattice QCD, pNRQCD and Potential models
- Hyperfine splitting $M(\Upsilon(1S))-M(\eta_b)$
  - role of spin-spin interaction in heavy meson system
    - analogue to positronium
  - sensitive to α_s: measurement of $M(\eta_b)$ with a few MeV can measure $\alpha_s(M_Z)$ with accuracy similar to current PDG value

The Bottomonium Ground State

- Previous searches
  - ALEPH: 1 candidate compatible with background in $\gamma\gamma \rightarrow \eta_b$ (PL B530(2002) 56)
  - DELPHI: $\gamma\gamma \rightarrow \eta_b$ in 4-6-8 prong final states (PL B634(2006) 340)
  - CDF(2006): $\eta_b \rightarrow J/\psi J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$
  - CLEO: (PRL 94(2005) 032001)
    - Upper Limit on BF[$\Upsilon(3S) \rightarrow \gamma\eta_b$]<$4.3\times10^{-4}$ @ 90% CL
    - Upper Limit on BF[$\Upsilon(2S) \rightarrow \gamma\eta_b$]<$5.1\times10^{-4}$ @ 90% CL

Predictions
(Quarkonium Yellow Report)



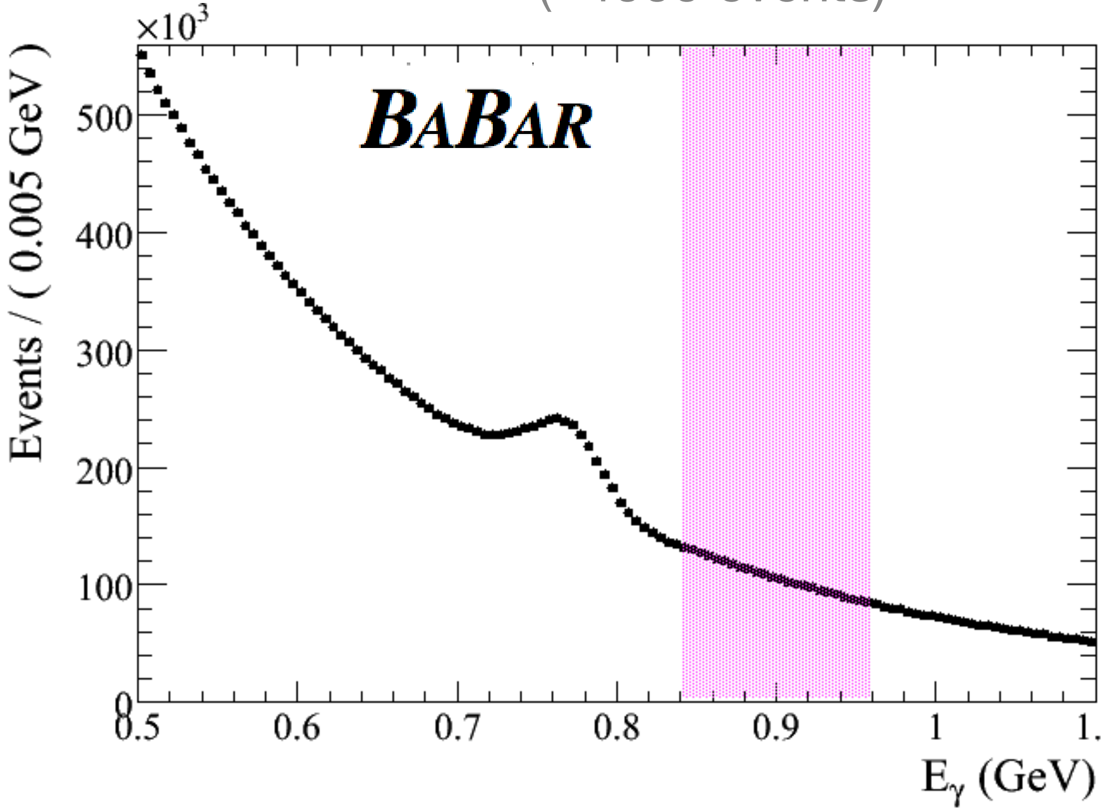
Search for η_b: Analysis Outline

- Decay modes of η_b not known well
- Search in the inclusive γ spectrum: process is $e^+e^- \rightarrow \Upsilon(3S) \rightarrow \gamma\eta_b$
- Monochromatic line in E_γ spectrum: perform 1-D binned maximum-likelihood fit to E_γ spectrum
  - η_b Mass at 9.4 GeV → E_γ peak = 911 MeV

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

- Large Background
  - reject as much as possible
  - understand background components for fitting procedure
- Blind Analysis

Expected BF~10^{-4} (~4000 events)

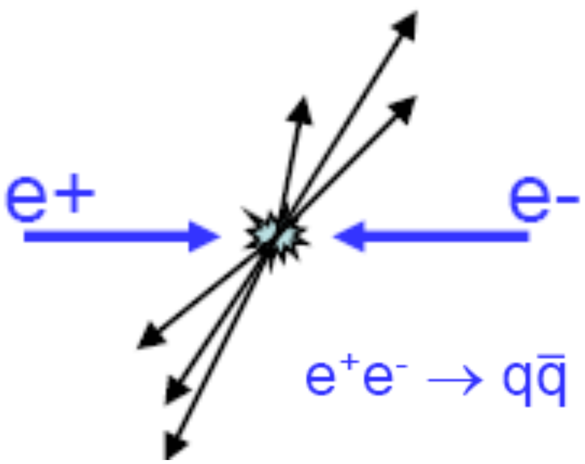


Event Selection

- Aim to reduce background while retaining high signal efficiency: use $S/\sqrt{B}$
  - S (number of signal events): from signal MC
  - B (number of background events): from Data - no reliable event generator
    - use a fraction (9%) of the data (~10×10^6 Υ) - not used in final fit
- Need to be careful not to rely too much on signal MC
- expect η_b decay mostly via two gluons: high track multiplicity
- reject QED background by requiring spherical events
- Candidate Photon:
  - isolated from tracks
  - shower shape consistent with electromagnetic shower
  - photon in barrel region of EMC
  - π^0-veto
  - use angle between photon and the "rest-of-the-event"

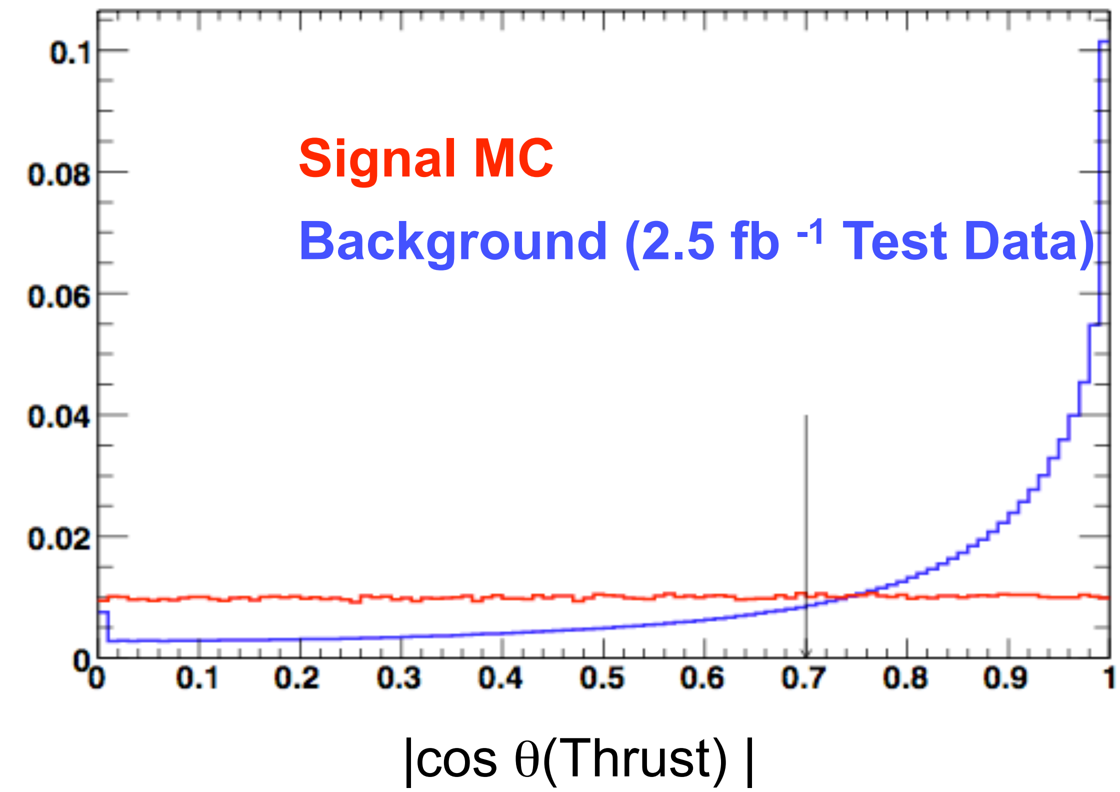
Total Efficiency
ε(signal)=37%
ε(background)= 6%

Event Selection (II)

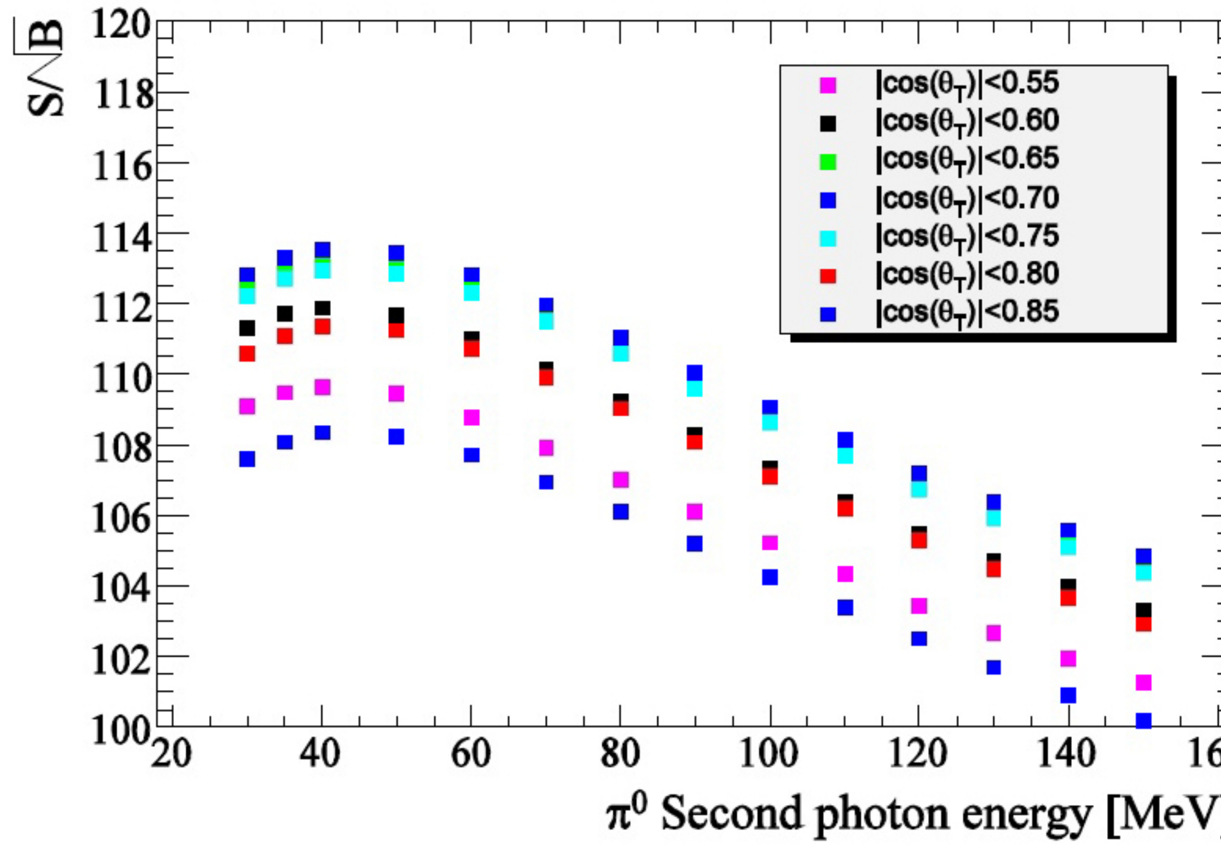


(q=u,d,s,c)

- strong correlation between photon direction and thrust axis of other particles in event



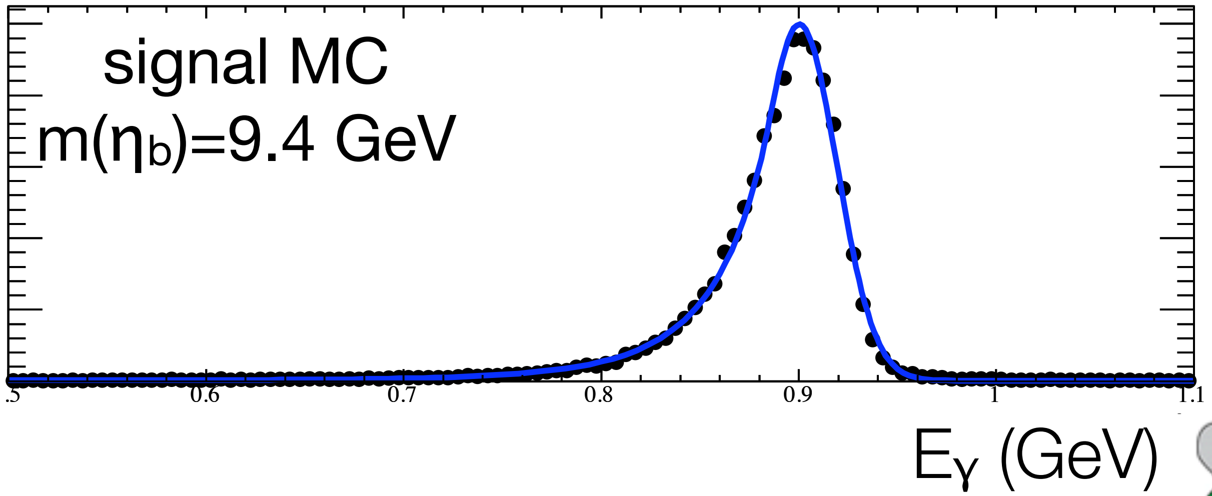
- π^0-veto
  - $|M(\gamma\gamma_2)\text{-}M(\pi^0)|< 15$ MeV
- optimize minimum energy of second photon and cut on $\cos\theta_T$ simultaneously
- similar veto on η did not improve $S/\sqrt{B}$
- cuts: $|\cos\theta_T|<0.7$ and $E(\gamma_2)>50$ MeV



The η_b Signal Model

- Signal model determined from MC simulation
- Functional form: $P(E\gamma) = CB(E\gamma) \otimes BW(E\gamma, \Gamma\eta_b)$
- BW: Breit-Wigner function, the natural shape of the η_b
  - expect $\Gamma(\eta_b) < \Gamma(\eta_c)$ with $\Gamma(\eta_c)$=26.5 MeV
  - Width set to 10 MeV, and varied as a systematic
- CB: Crystal Ball function (Gaussian + power-law low side)
  - Models the detector energy resolution
  - CB shape, determined with signal

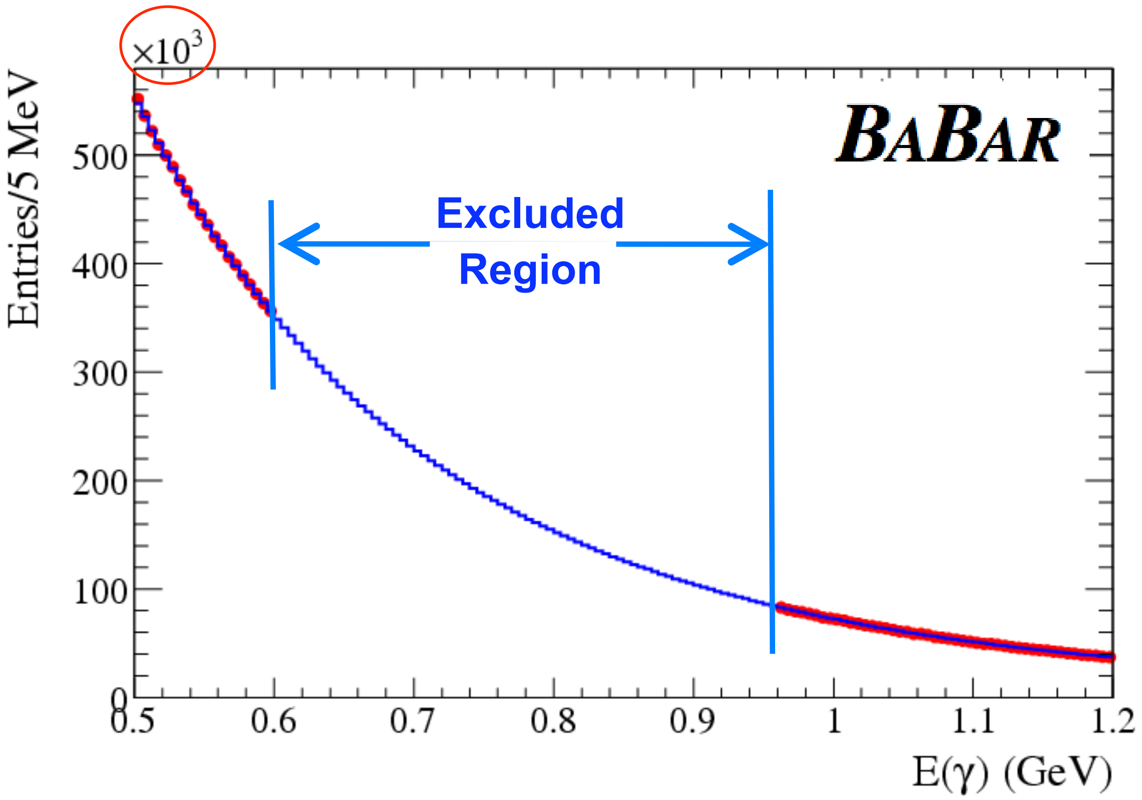
    MC generated with Γ=0.0 MeV



Background to the E_γ Spectrum

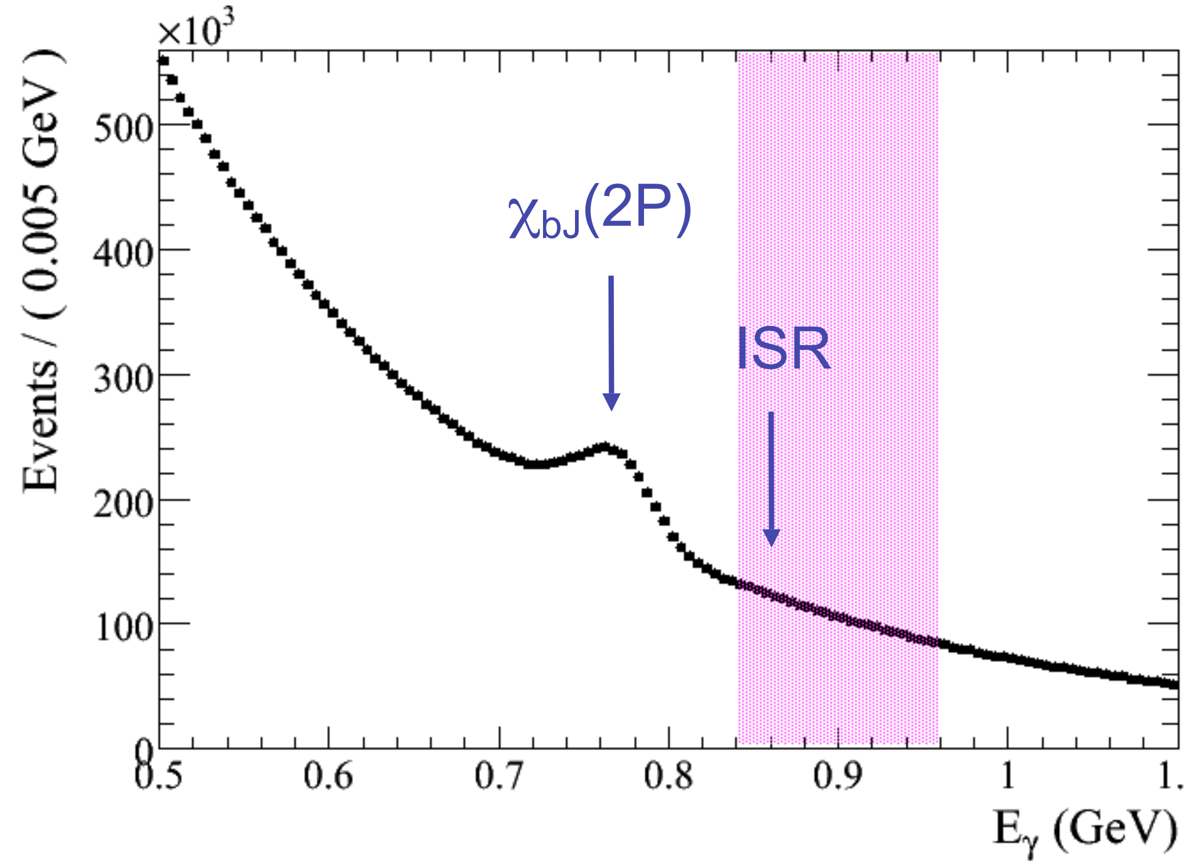
- Non-peaking background:
  - $q\bar{q}$ (udsc)
  - Υ(3S) decays
  - fitted by a single component:

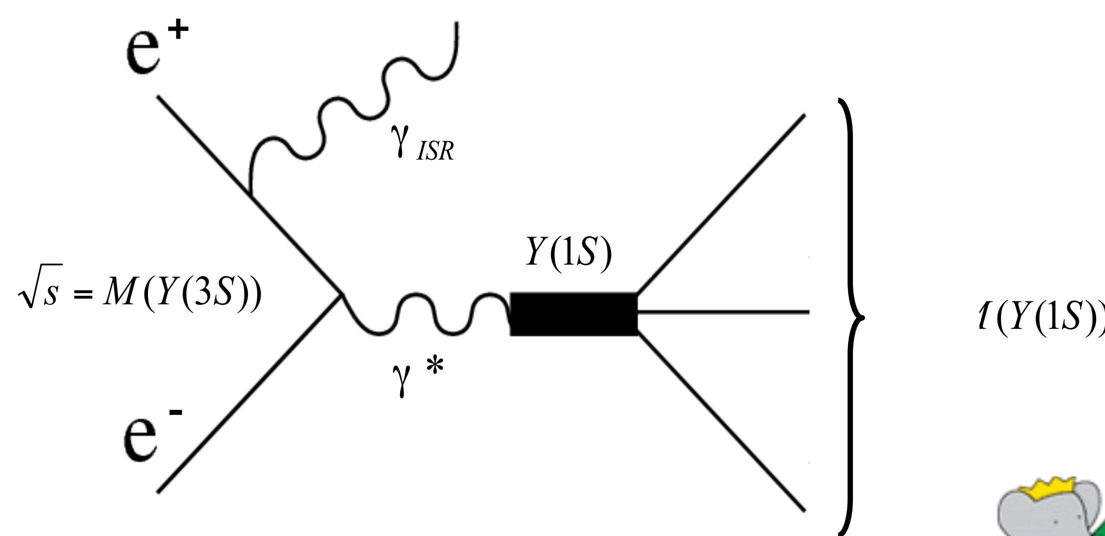
$$A(C + e^{-\alpha E_\gamma - \beta E_\gamma^2})$$



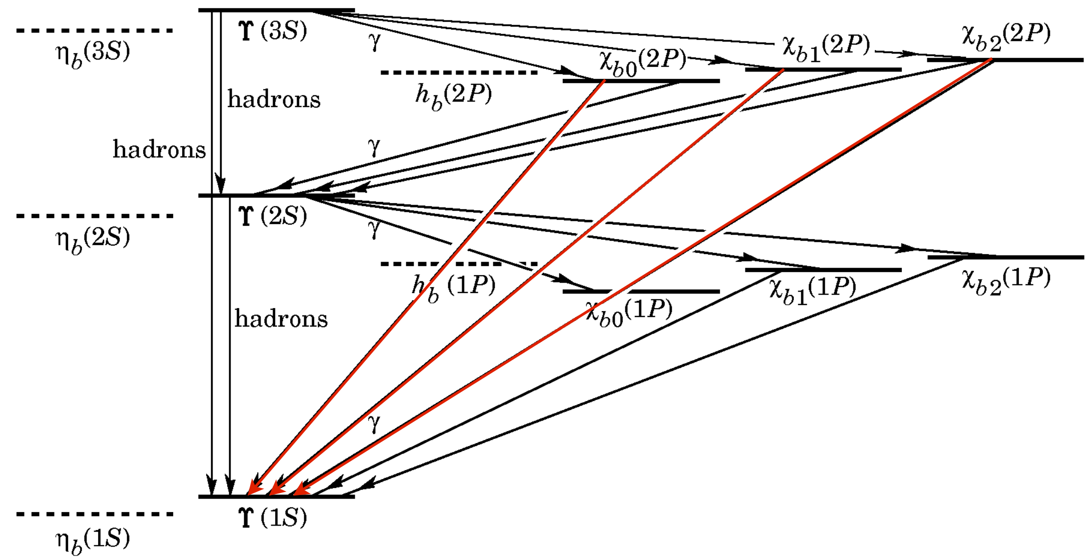
Background to the E_γ Spectrum

- Peaking backgrounds next to signal (~900 MeV)
- $\Upsilon(3S) \to \gamma_s \chi_{bJ}(2P)$, $\chi_{bJ}(2P) \to \gamma_h \Upsilon(1S)$, J=0,1,2 $E(\gamma_h)$~760 MeV
- $e^+e^- \to \gamma_{ISR}\, \Upsilon(1S)$: 856 MeV ("ISR")
  - ISR-line very close to expected unknown signal position
  - both line-shape + yield very important





Peaking Background: $\chi_{bJ}(2P)$ Events



- $\Upsilon(3S) \to \gamma \chi_{bJ}(2P)$, $\chi_{bJ}(2P) \to \gamma \Upsilon(1S)$, J=0,1,2
- three transitions: model each as a Gaussian+power law tail (Crystal Ball function)
  - transition point+power tail parameter fixed to same value for all peaks
  - peaks fixed to PDG values, allow for common offset for photon calibration scale
  - yield ratios fixed to PDG values (cannot resolve separate peaks)
    - cross-checked using soft transition in tagged dataset ($\Upsilon(1S) \to l^+l^-$)
- peaks overlap $\langle E_\gamma \rangle \approx 760$ MeV due to detector resolution and broadening as result of the motion of $\chi_{bJ}(2P)$ in $\Upsilon(3S)$ rest-frame
- PDF parameters obtained from fit to full dataset, with the ISR and signal regions excluded

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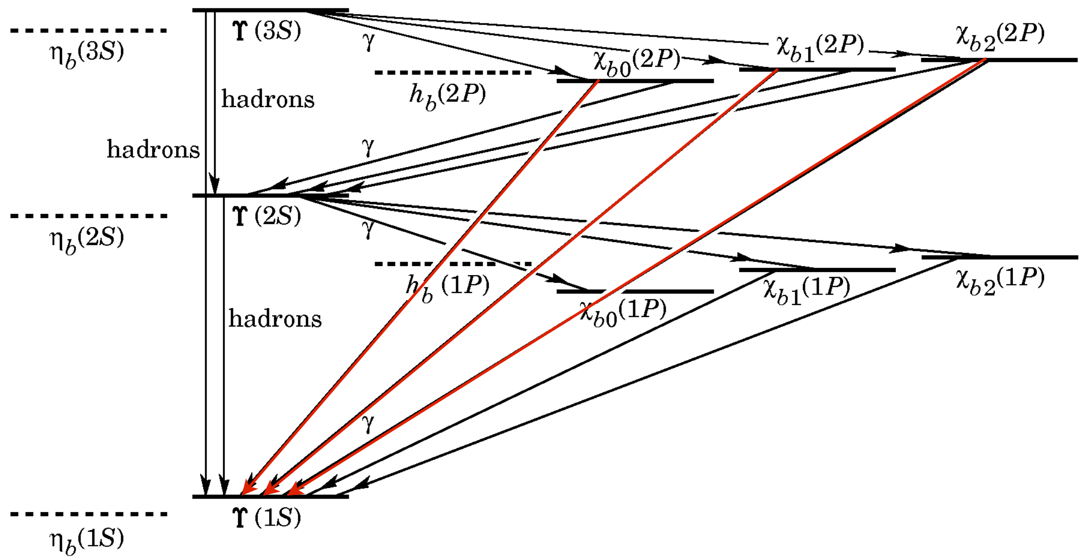
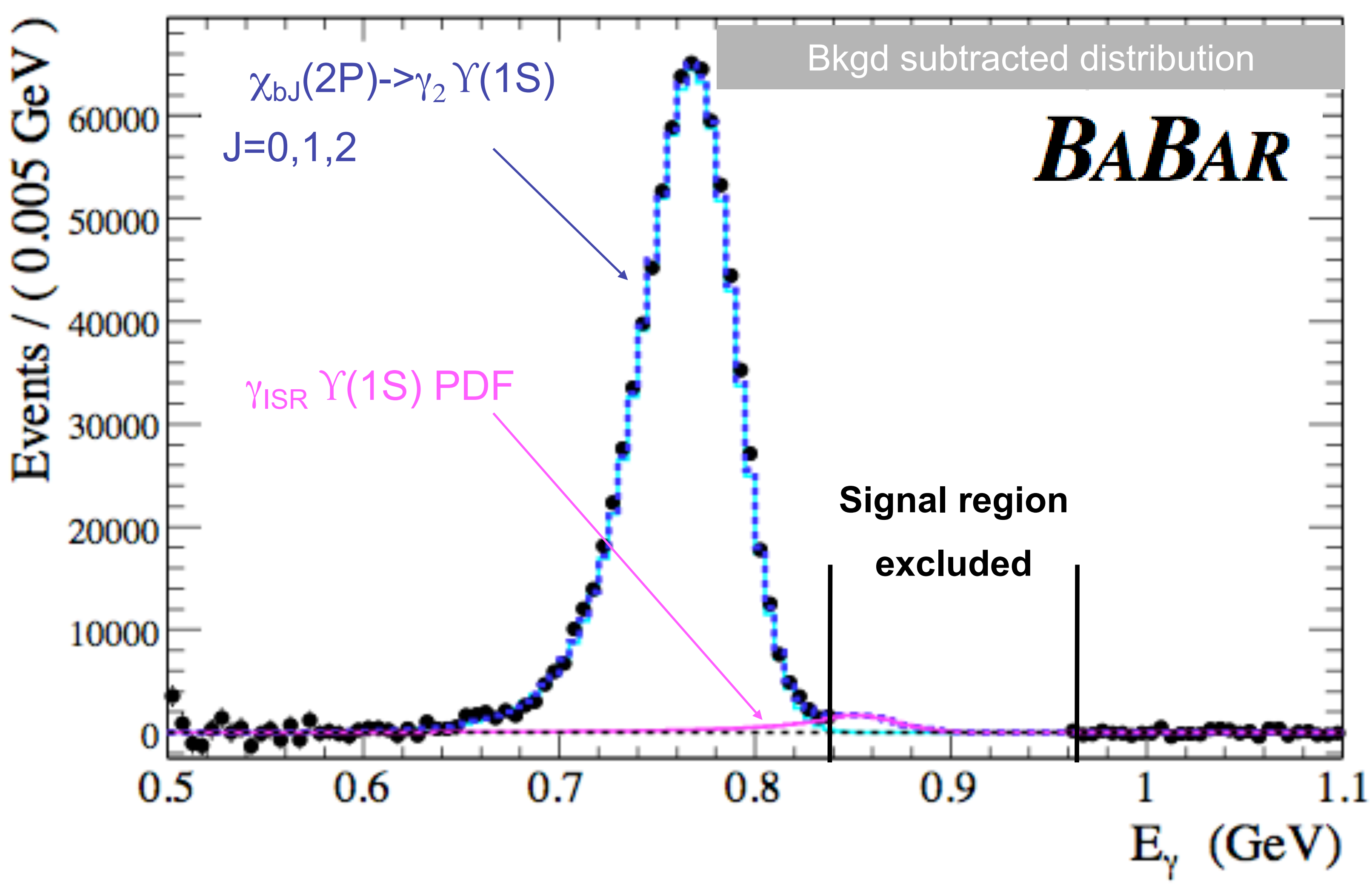
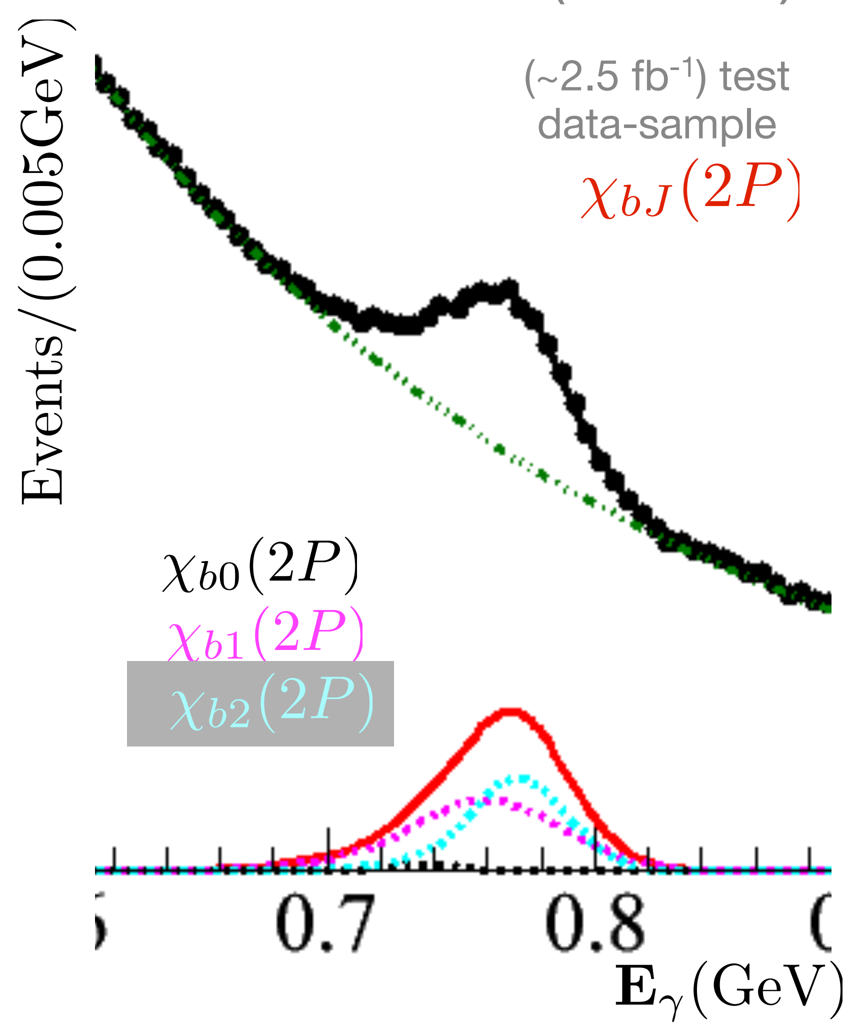


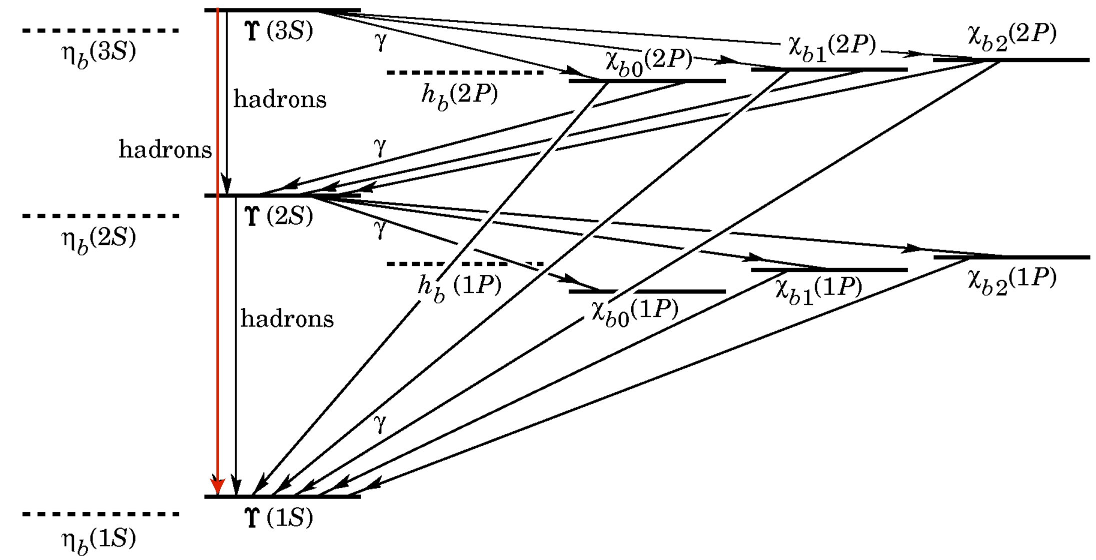
- Υ(3S)→γχ_{bJ}(2P), χ_{bJ}(2P) →γΥ(1S)
- PDF parameters obtained from fit to full dataset, with the ISR and signal regions excluded



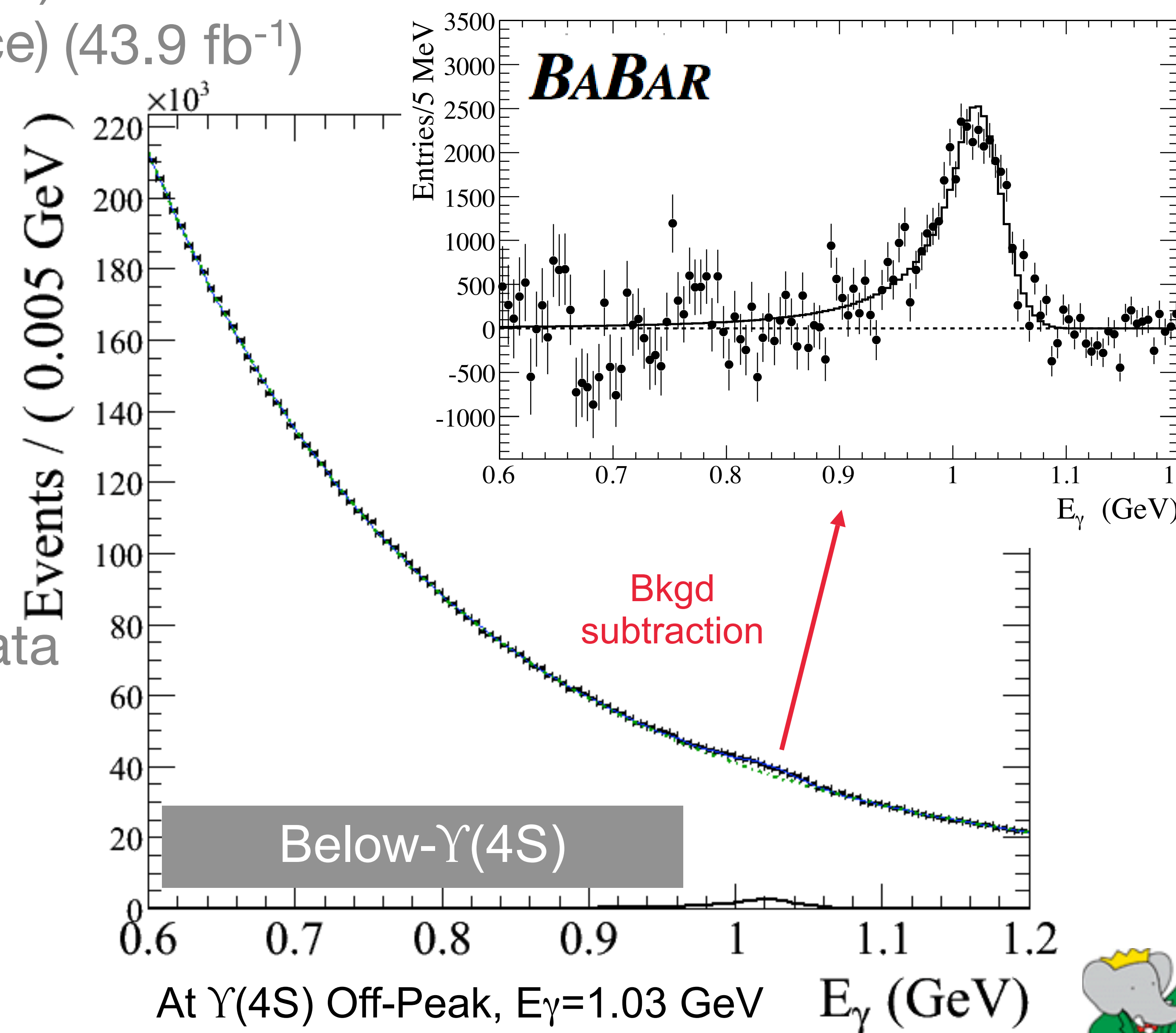
- common offset: (3.8±2.0) MeV



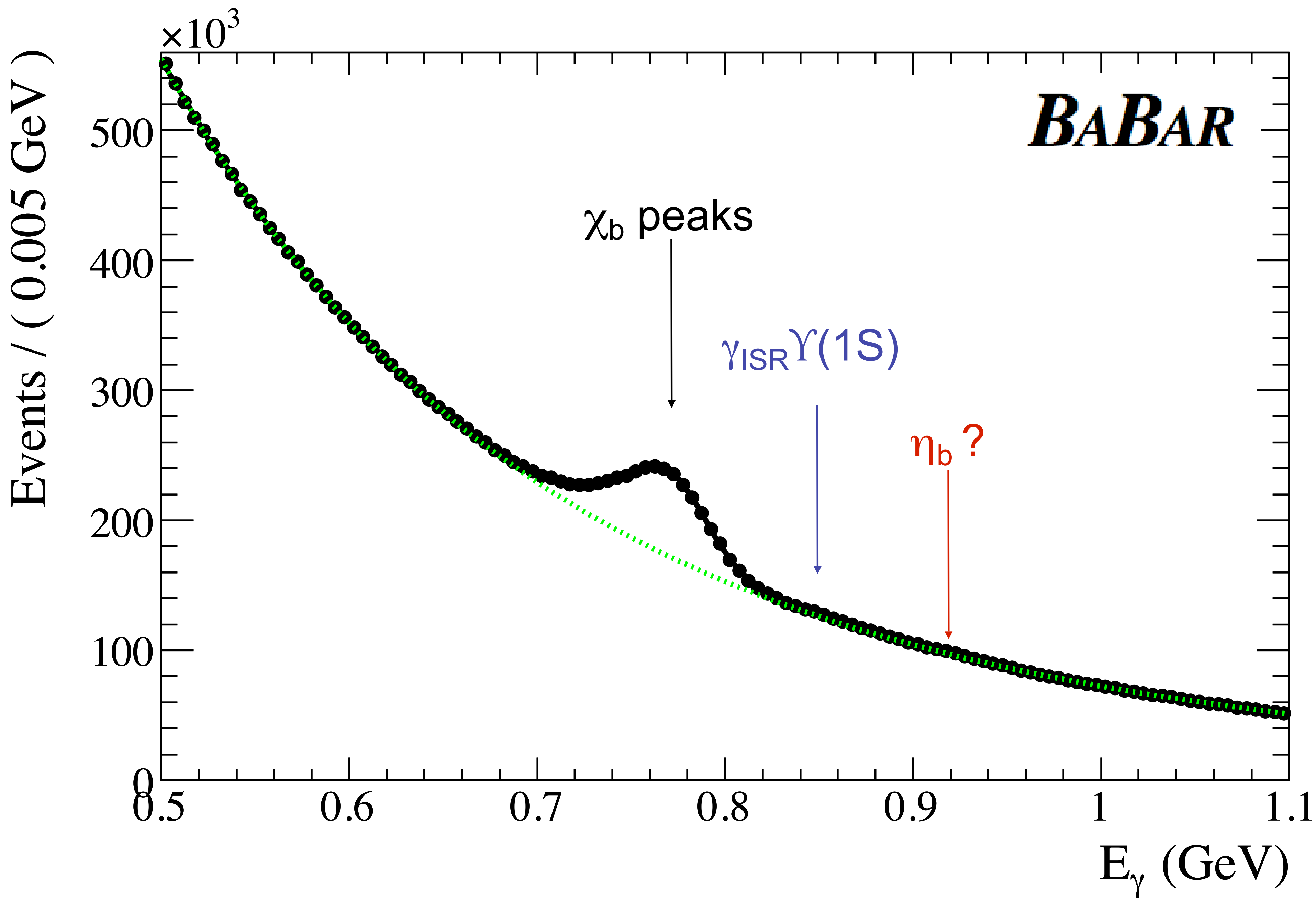
Peaking Background:
ISR Events



- Take line shape from Monte Carlo
- Yield estimated from measurement in Υ(4S) "Off-Peak" data (40 MeV below resonance) (43.9 fb^{-1})
  - correct for ratio of theoretical cross-sections, efficiencies and luminosities
    - Fitted yield: 35800±1600
    - Extrapolated to Υ(3S): 25200±1700
  - check with yield in Υ(3S) "Off-Peak" data (2.4 fb^{-1}):
    - extrapolated to 29400±5000: good agreement

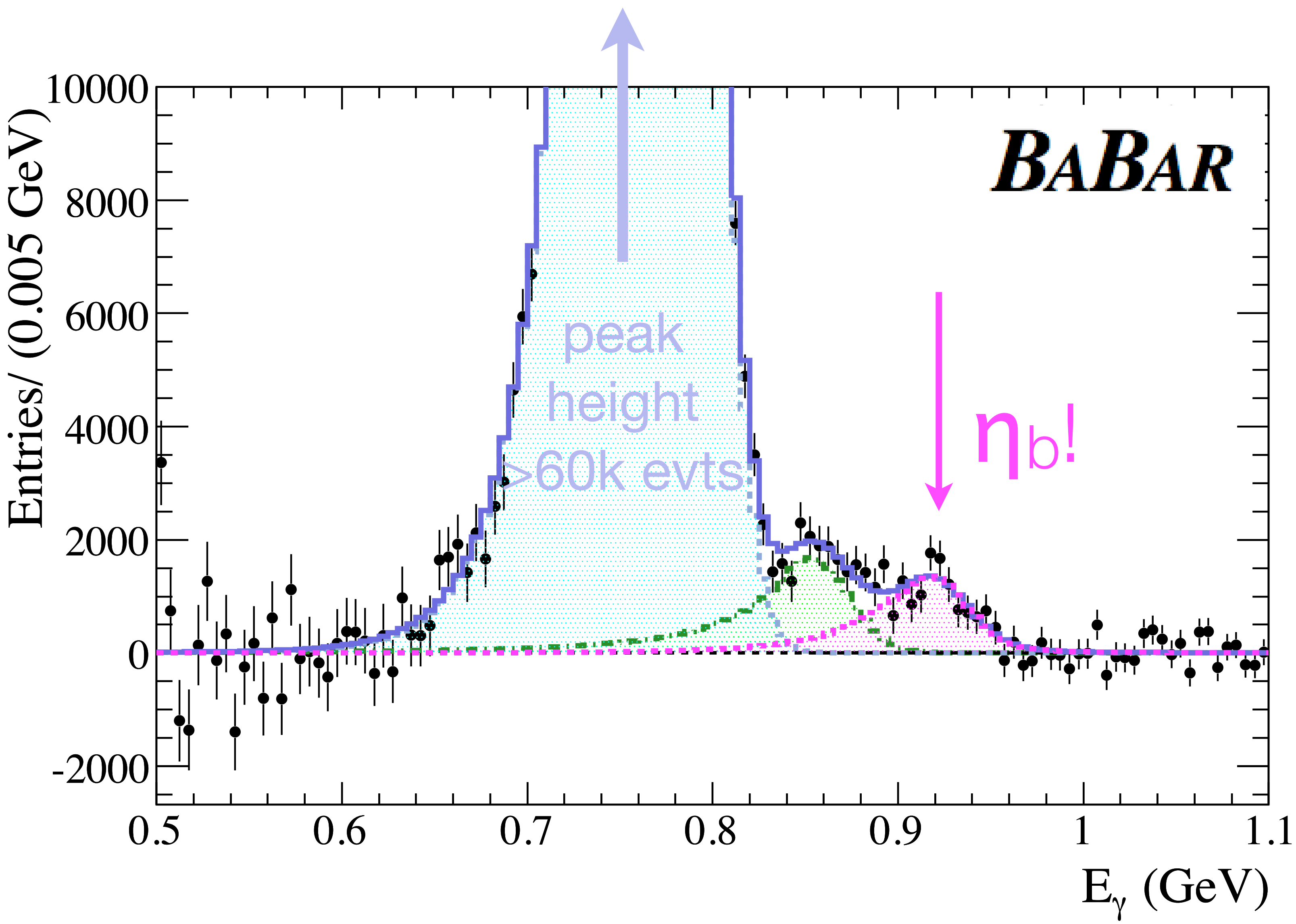


Fit to Analysis Dataset: 109x10^6 Υ(3S)



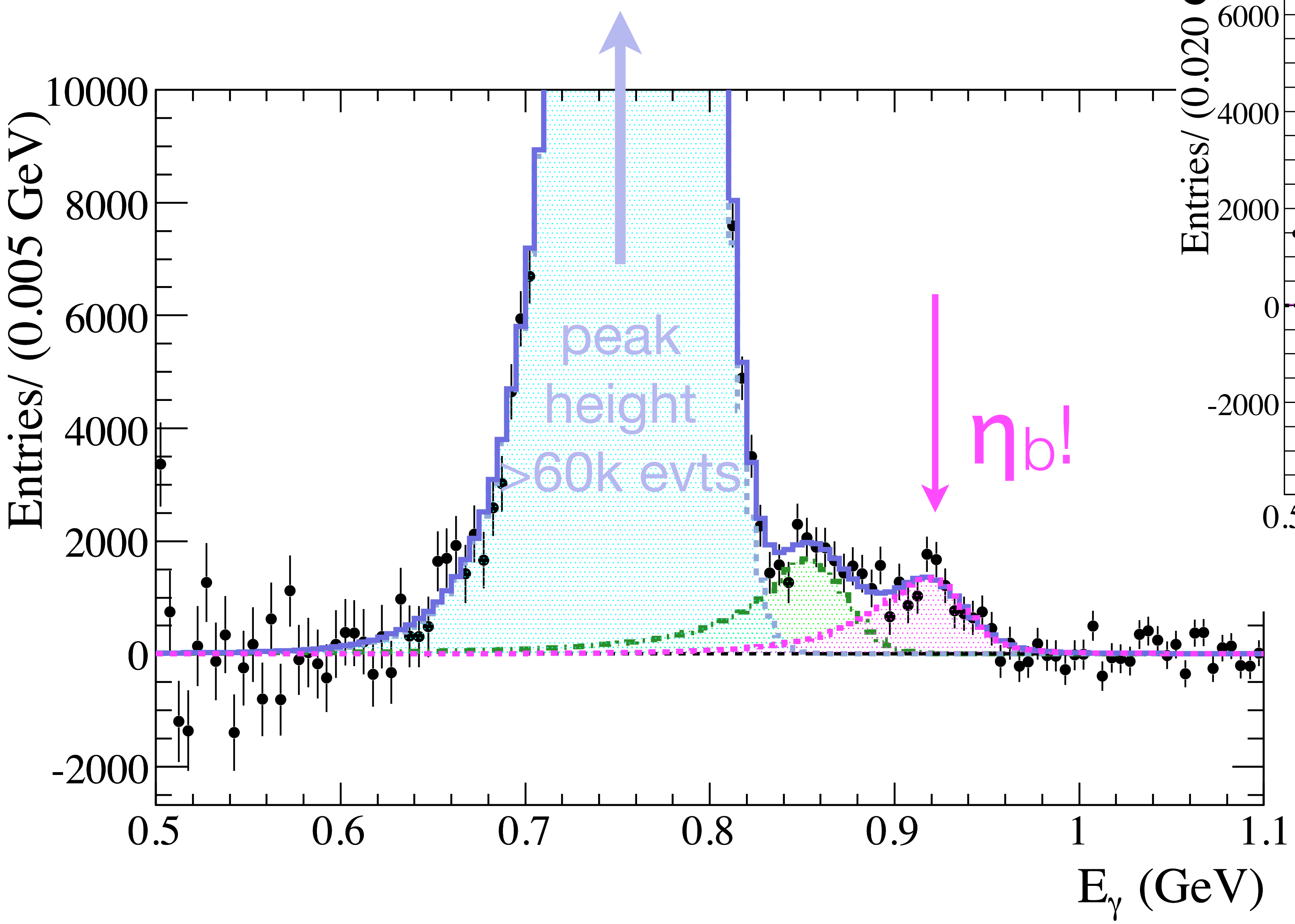
- now subtract non-peaking background...

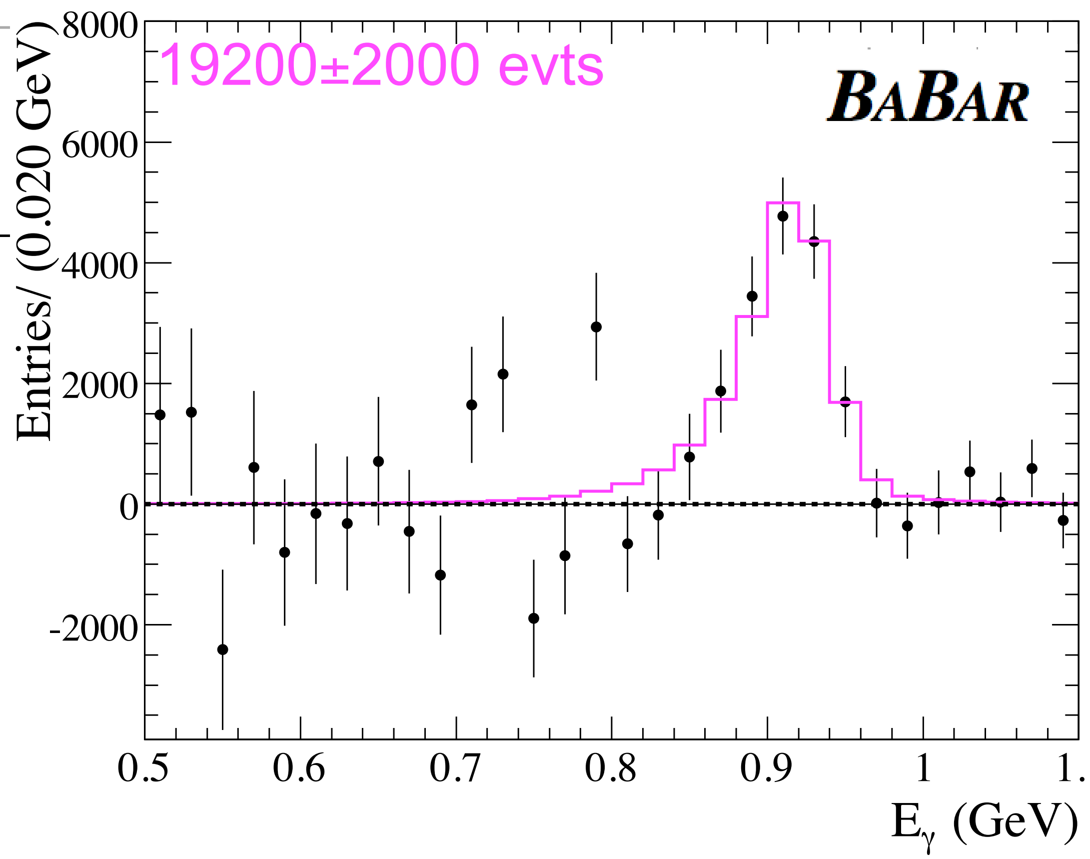
Fit to Analysis Dataset: $109 \times 10^6\ \Upsilon(3S)$



- and subtract peaking backgrounds also ...

Fit to Analysis Dataset: $109 \times 10^6\ \Upsilon(3S)$





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

- η_b signal observed with a statistical significance of 10σ

Additional Checks

- Detector Effects
  - noisy channels are monitored online; no hot spots in EMC
  - remove photon candidates with small lateral moment to veto possible hot crystals
    - signal remains strong
  - remove photon candidates with large lateral moment to veto accidental photon overlaps
    - no effect on signal significance
- χ_b line shape
  - floating the ISR yield: yield (24800±4000) consistent with expectation (25000)
  - line shape also consistent with exclusive reconstruction
    $\Upsilon(3S) \rightarrow \gamma\, \chi_b(2P)$; $\chi_b(2P) \rightarrow \gamma\, \Upsilon(1S)$; $\Upsilon(1S) \rightarrow \mu^+\mu^-$

Systematic Uncertainties

- Signal Yield:
  - vary ISR yield by ±1σ (stat + syst)
  - vary all PDF parameters by ±1σ
  - fits with BW width set to 5,15 and 20 MeV
    - Largest systematic error: 10%
- Mass:
  - main error from $\chi_b(2P)$ peak shift: 3.8±2.0 MeV
- Branching fraction:
  - efficiency: data/MC comparison on $\chi_b(2P)$: 12.6%
  - PDG branching fractions: 18%
    - Total error: 25%
- Significance:
  - varied all parameters
    - independently
    - all in dis-favorable direction
  - no significant change

Observation of the η_b: Summary of Results (PRL 101, 701801 (2008))

- Is this indeed the η_b?
  - only candidate for the state below the $\Upsilon(1S)$, but other explanations as a low-mass Higgs not ruled out.

- Assuming this is the η_b:
  - Mass $m(\eta_b)$:

$$9388.9^{+3.1}_{-2.3}(\mathrm{stat}) \pm 2.7(\mathrm{syst})\mathrm{MeV}/c^2$$

  - Hyperfine Splitting:

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

  - Branching fraction $\Upsilon(3S) \to \gamma \eta_b$:

$$[4.8 \pm 0.5(\mathrm{stat}) \pm 1.2(\mathrm{syst})] \times 10^{-4}$$

wide range of LQCD results: some agree with measurement

Splitting larger than predicted by most Potential Models

Observation of the η_b: Summary of Results (PRL 101, 701801 (2008))

- Is this indeed the η_b?
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- Assuming this is the η_b:
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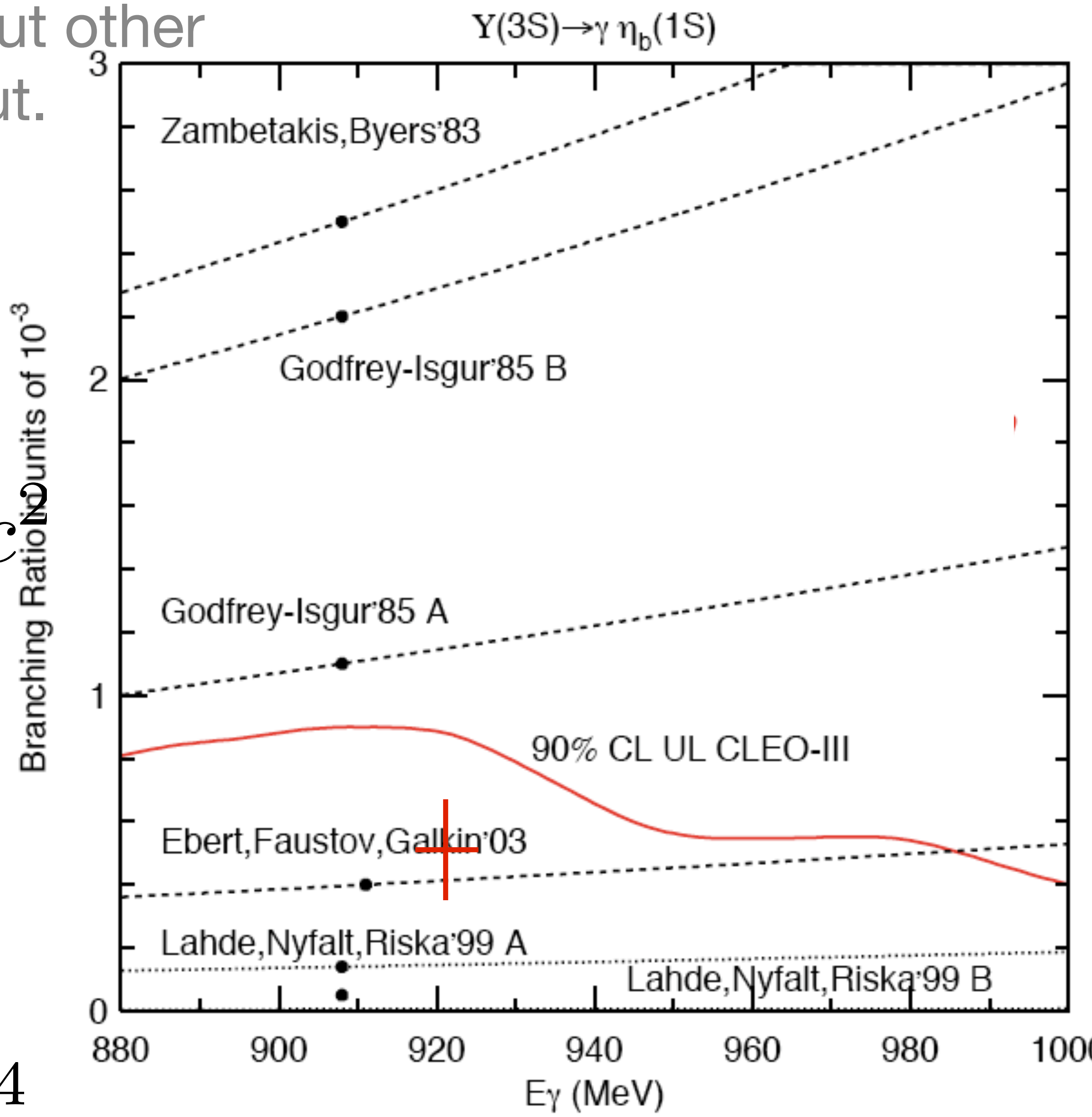


Search for η_b: Inclusive search in the $\Upsilon(2S)$ Dataset

- Dataset contains ~100 M $\Upsilon(2S)$ Events
  - Branching Fraction of $\Upsilon(2S)\to\gamma\eta_b$ is expected to be 1-5 10^{-4}
  - E_γ is 611 MeV for Signal
    - $e^+e^- \to\gamma_{ISR}\,\Upsilon(1S)$: 545 MeV
    - $\Upsilon(3S)\to\gamma_s\chi_{bJ}(1P)$, $\chi_{bJ}(1P)\to\gamma_h\Upsilon(1S)$, J=0,1,2: $E(\gamma_h)$~455 MeV
- Analysis is very similar to $\Upsilon(3S)$
  - photon resolution is better at lower energies: better peak separation
  - more random photon background at lower energies: less significance for similar BF

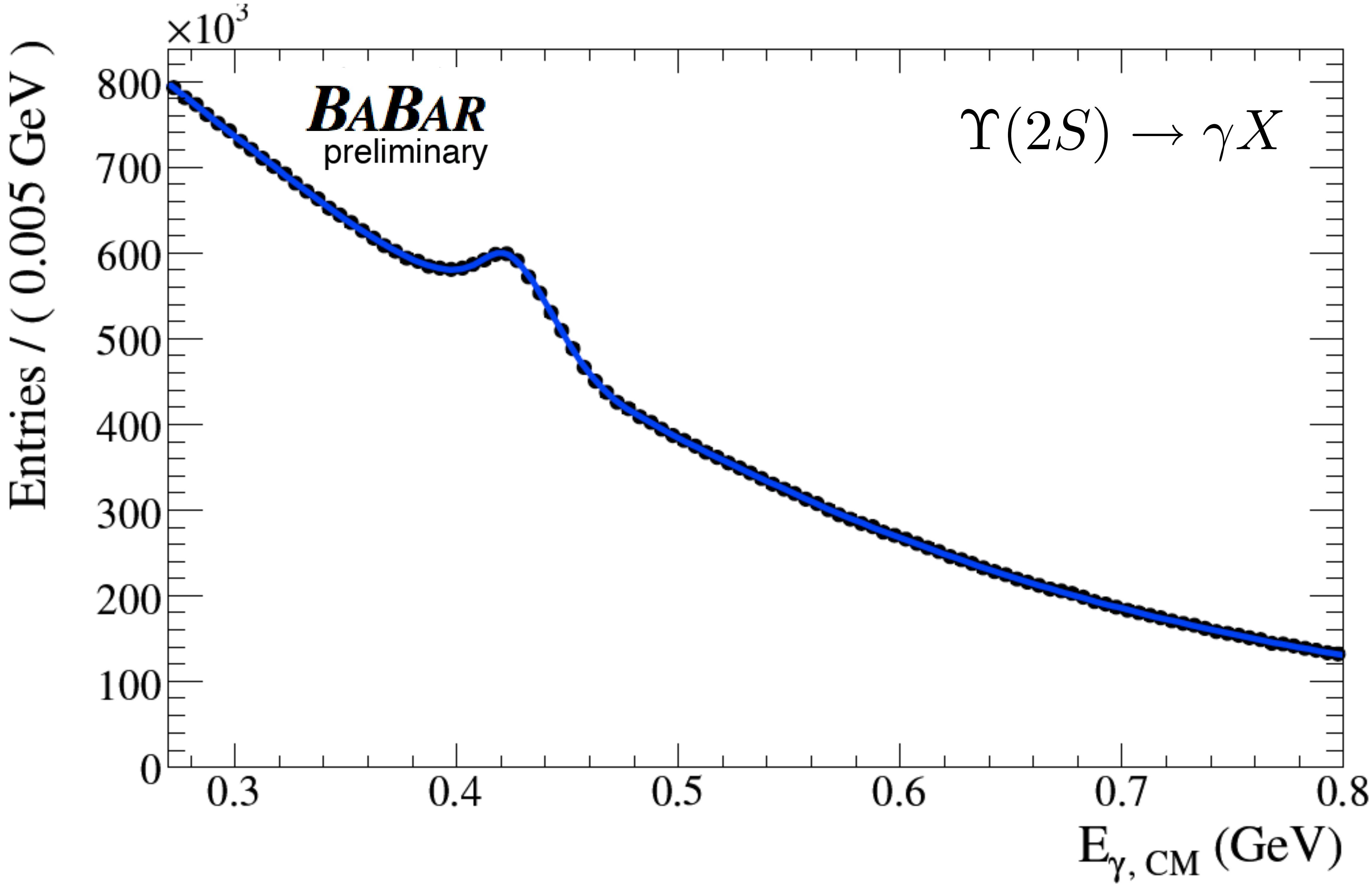
Photon Selection and Optimization

- same selection of hadronic events and signal candidates
- except:
  - Event shape: loosen cut on angle between photon and “rest-of-event”
    - relatively less continuum background: $\sigma(\Upsilon(2S)) > \sigma(\Upsilon(3S))$
  - π^0- veto: lower energy threshold for second photon as for $\Upsilon(3S)$-analyses
    - 50 MeV @ 3S -> 40 MeV @2S

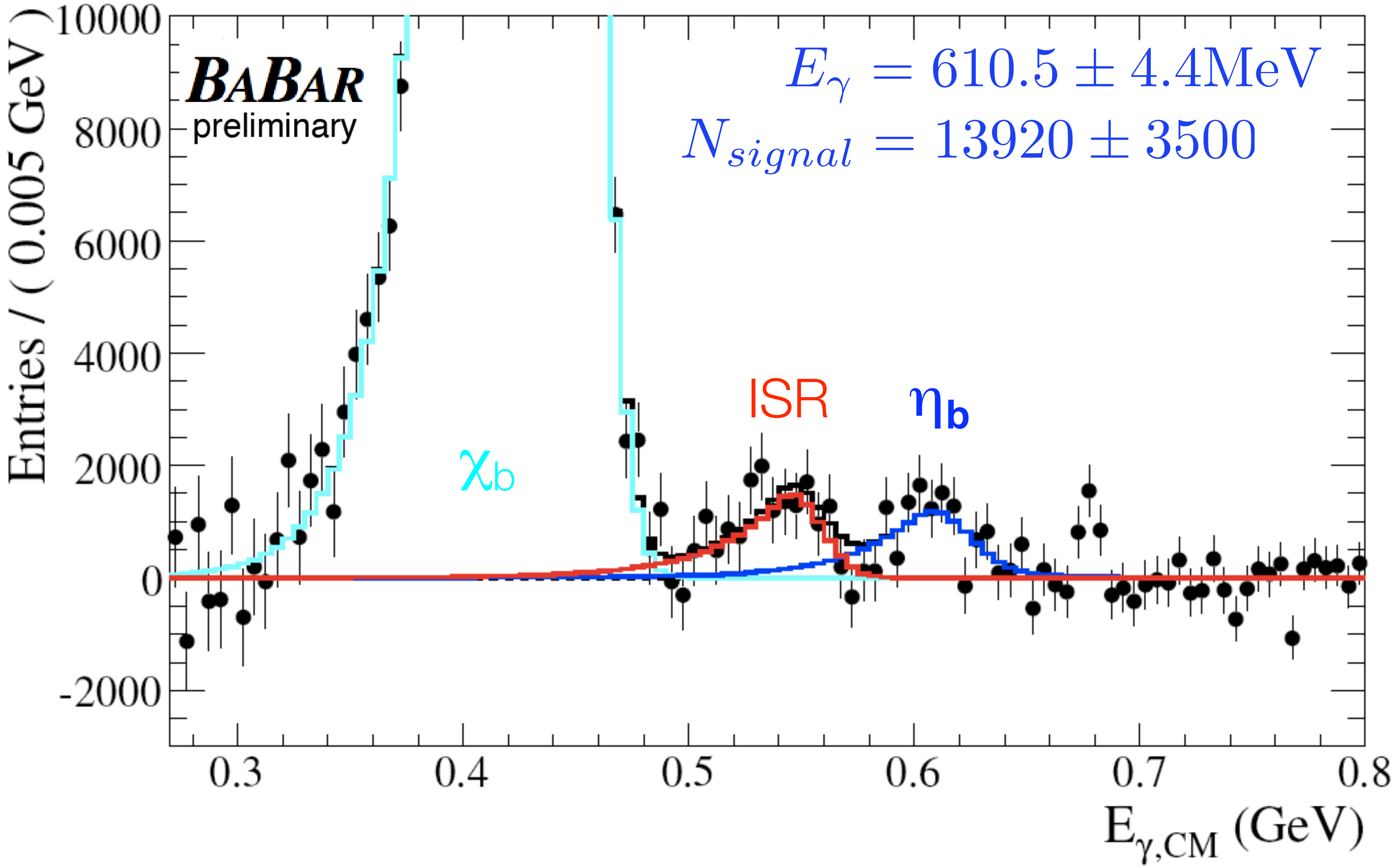
Fitting the E_γ Spectrum: χ^2 fit to E_γ spectrum

- Smooth non-peaking background
  - use a exponential polynomial of 4th order: higher order needed as spectrum changes faster than in signal region of the $\Upsilon(3S)$
- $\Upsilon(2S)\rightarrow\gamma\eta_b$ signal events
  - take shape from MC simulation
- $e^+e^- \rightarrow\gamma_{ISR}\ \Upsilon(1S)$: 545 MeV
  - shape from MC simulation, normalization floated in fit
- $\Upsilon(3S)\rightarrow\gamma_s\chi_{bJ}(1P)$, $\chi_{bJ}(1P) \rightarrow\gamma_h\Upsilon(1S)$, J=0,1,2:
  - shape is a Crystal Ball function convolved with a flat-top (Doppler Broadening)
  - 3 components, relative yields determined from measurement in exclusive $\gamma\gamma\mu^+\mu^-$ events

Fit Result


×10³
800
700
600
500
400
300
200
100
0
Entries / (0.005 GeV)
BABAR
preliminary
$\Upsilon(2S) \rightarrow \gamma X$
0.3
0.4
0.5
0.6
0.7
0.8
$E_{\gamma,\,CM}$ (GeV)

Fit Result, Smooth Background subtracted



Systematic Uncertainties on Υ(2S) Result

- Signal Yield:
  - vary all PDF parameters by ±1σ
  - fits with BW width set to 5,15 and 20 MeV; adding an extra $\chi_b(1P)$ tail, different pdf for smooth background
    - latter two largest errors each ~16%
- Mass:
  - error from $\chi_b(2P)$ peak shift/χ_b masses: 0.9/0.4 MeV
  - different pdf for smooth background: 1.3 MeV → 1.8 MeV total
- Branching fraction:
  - efficiency: data/MC comparison on $\chi_b(2P)$: 6.1%
    - Total error: 22%

Fit Results

- η_b signal yield 13915^{+3555}_{-3452}
- η_b peak position $610.5^{+4.5}_{-4.3} \pm 1.8\,\mathrm{MeV}$
- Significance including systematics: 3.5 σ
- Goodness-of-fit: χ^2/ndof = 116.2/93
- Bump at 680 MeV: too narrow for detector resolution of photon at this energy
    - interpret as statistical fluctuation

Summary of Υ(2S) Results

- Mass m(η_b):

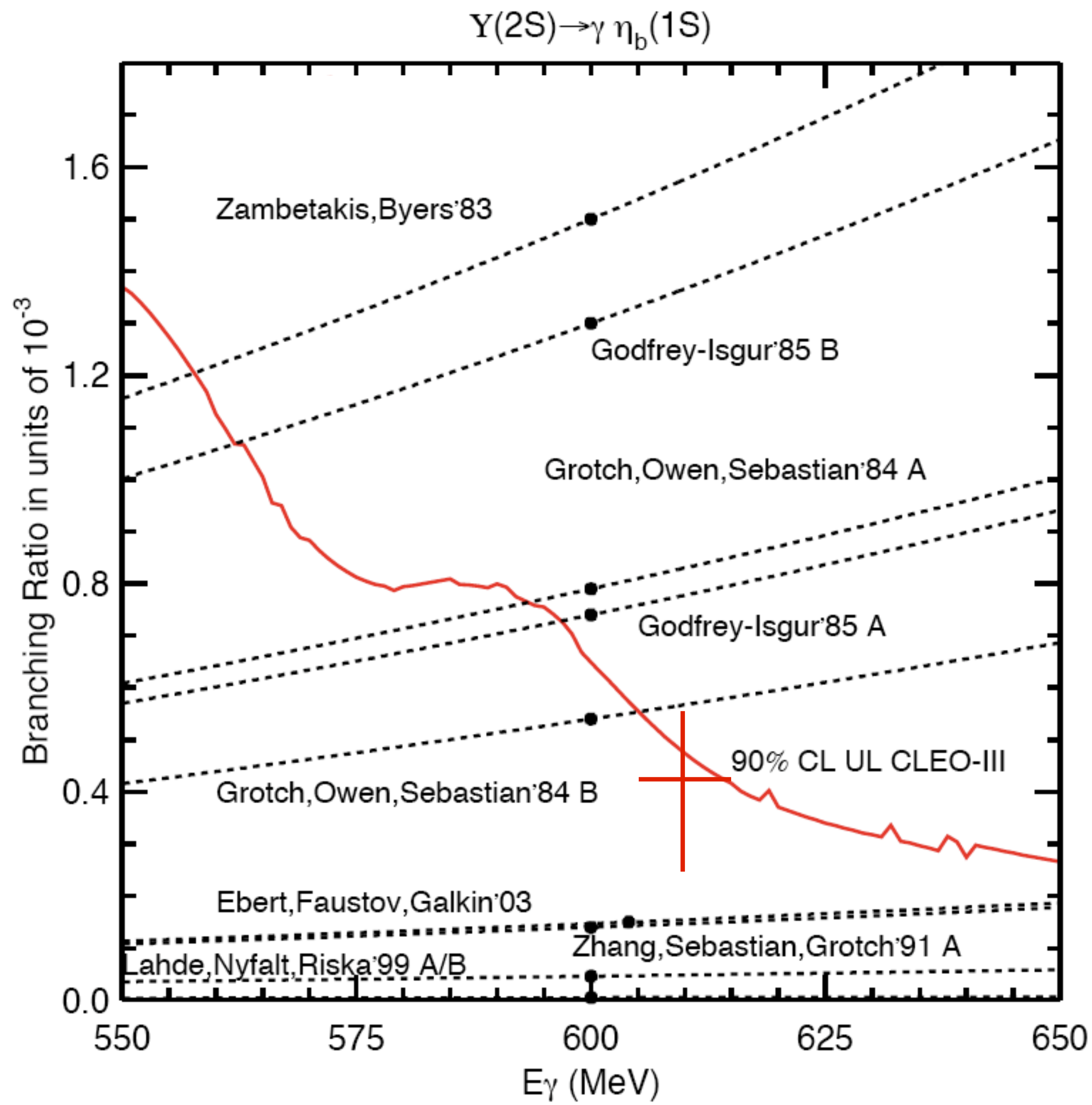
$$9392.9^{+4.6}_{-4.8} \pm 1.8\ \mathrm{MeV}/c^2$$

- Hyperfine Splitting:

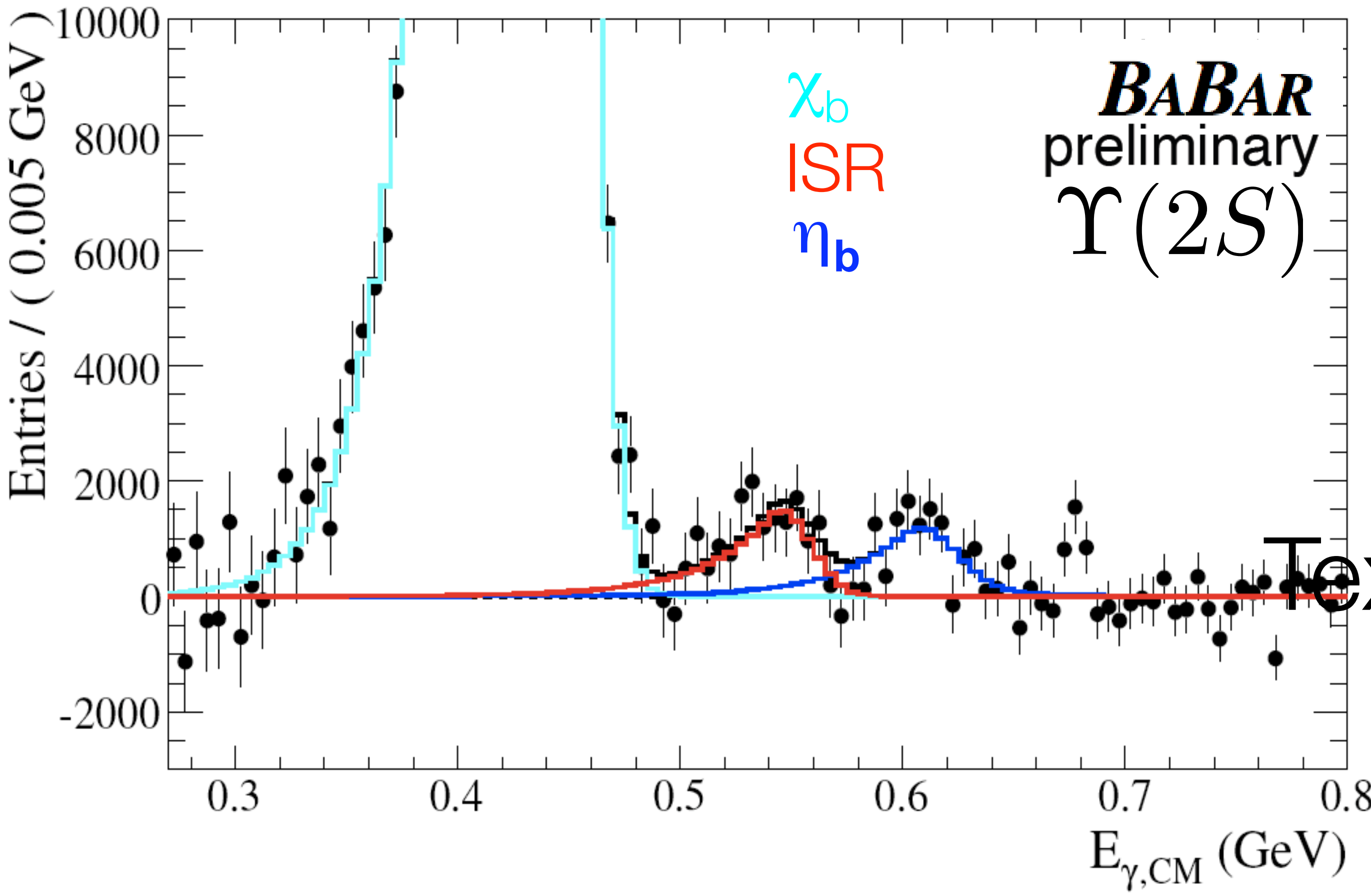
$$m_{\Upsilon} - m_{\eta_b} = 67.4^{+4.8}_{-4.6} \pm 2.0\,\mathrm{MeV}$$

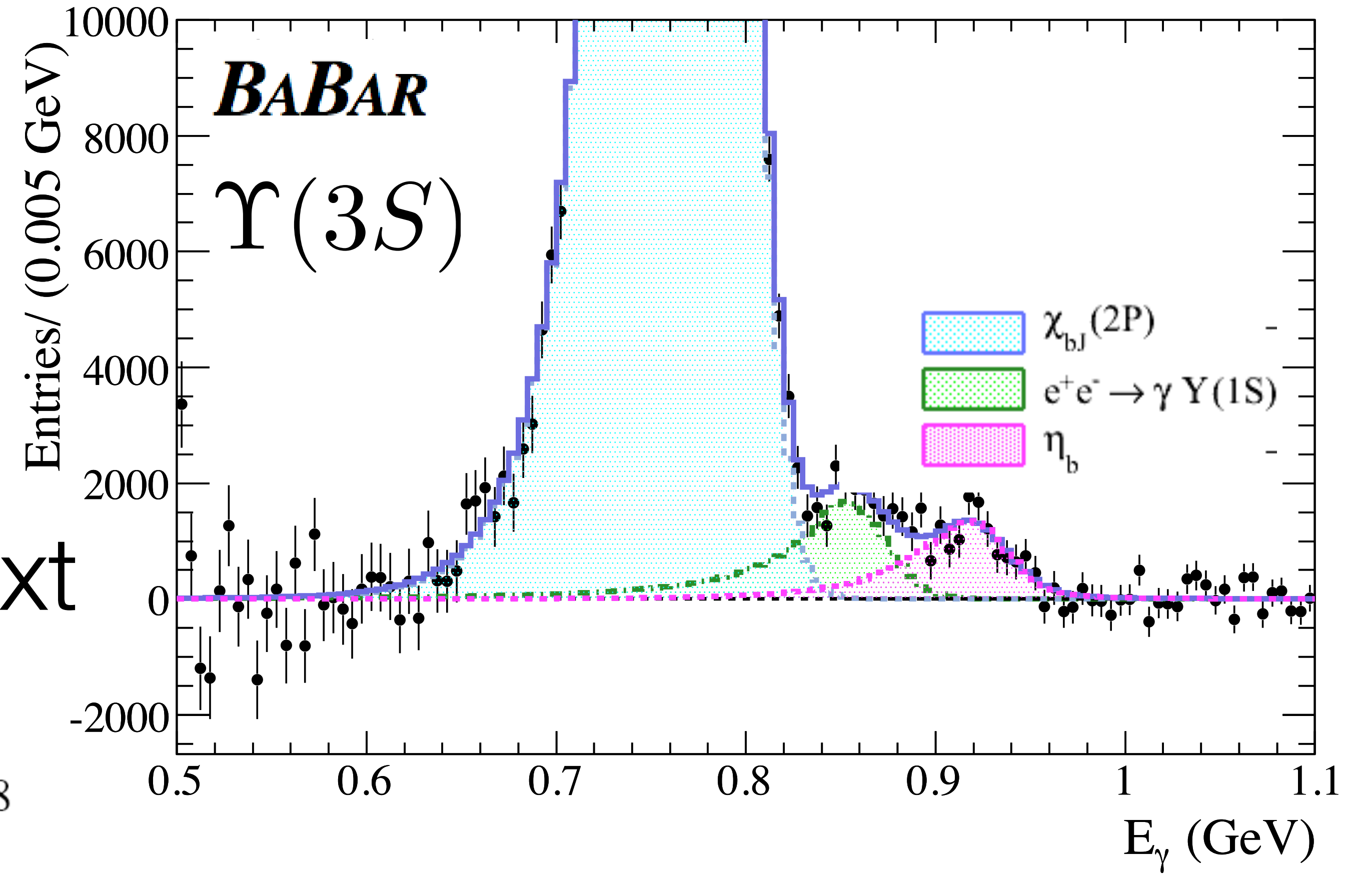
- Branching fraction Υ(2S)→γη_b :

$$(4.2^{+1.1}_{-1.0} \pm 0.9) \times 10^{-4}$$



Comparison of the Υ(3S) and the Υ(2S) Results





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

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

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

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

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

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

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

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

Outline

- Quarkonium Spectroscopy - Reminder
- Experiment and Dataset
- Hadronic Bottomonium Transitions
- Scan above the ϒ(4S) resonance
- The Bottomonium Ground State: The Discovery of the η_b
- **Summary and Outlook**

Summary

- The BaBar Run 7 has already produced a lot of interesting physics
  - R_b scan above the $\Upsilon(4S)$
  - Observation and Confirmation of the η_b
  - Dedicated searches for New Physics
    - light Higgs $\Upsilon(3S)\rightarrow\gamma\, a_0,\ a_0\rightarrow\mu^+\mu^-,\tau^+\tau^-$
    - Dark Matter candidates $\Upsilon(3S)\rightarrow\ \pi^+\pi^-\ \Upsilon(1S),\ \Upsilon(1S)\rightarrow$nothing
    - Lepton Universality in $\Upsilon(nS)$ decays
- much more to come!