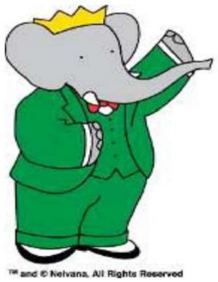
Observation of the bottomonium ground state, $\eta_b(1S)$, at BaBar

PHENO 2009

Madison, 11-13th May 2009



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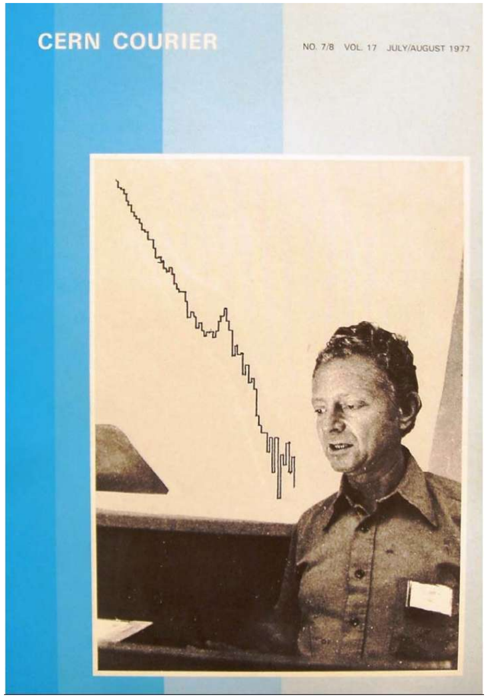
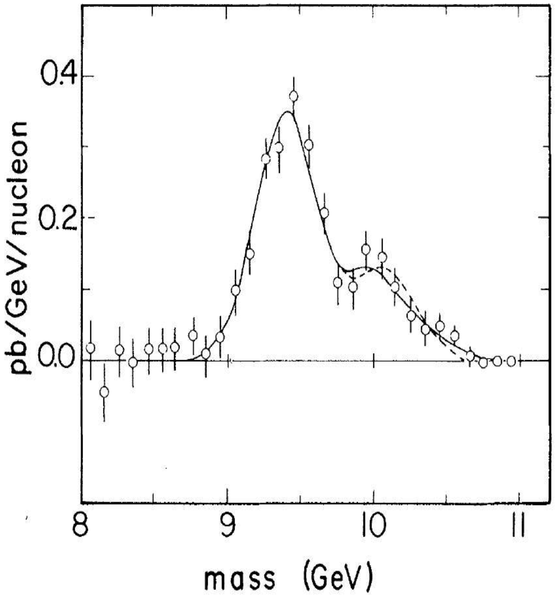
On behalf of the BaBar Collaboration

The bottomonium history started in 1977 with the observation of new resonances in the $p+(Cu,Pt) \rightarrow \mu^+\mu^- X$ spectrum[1,2]



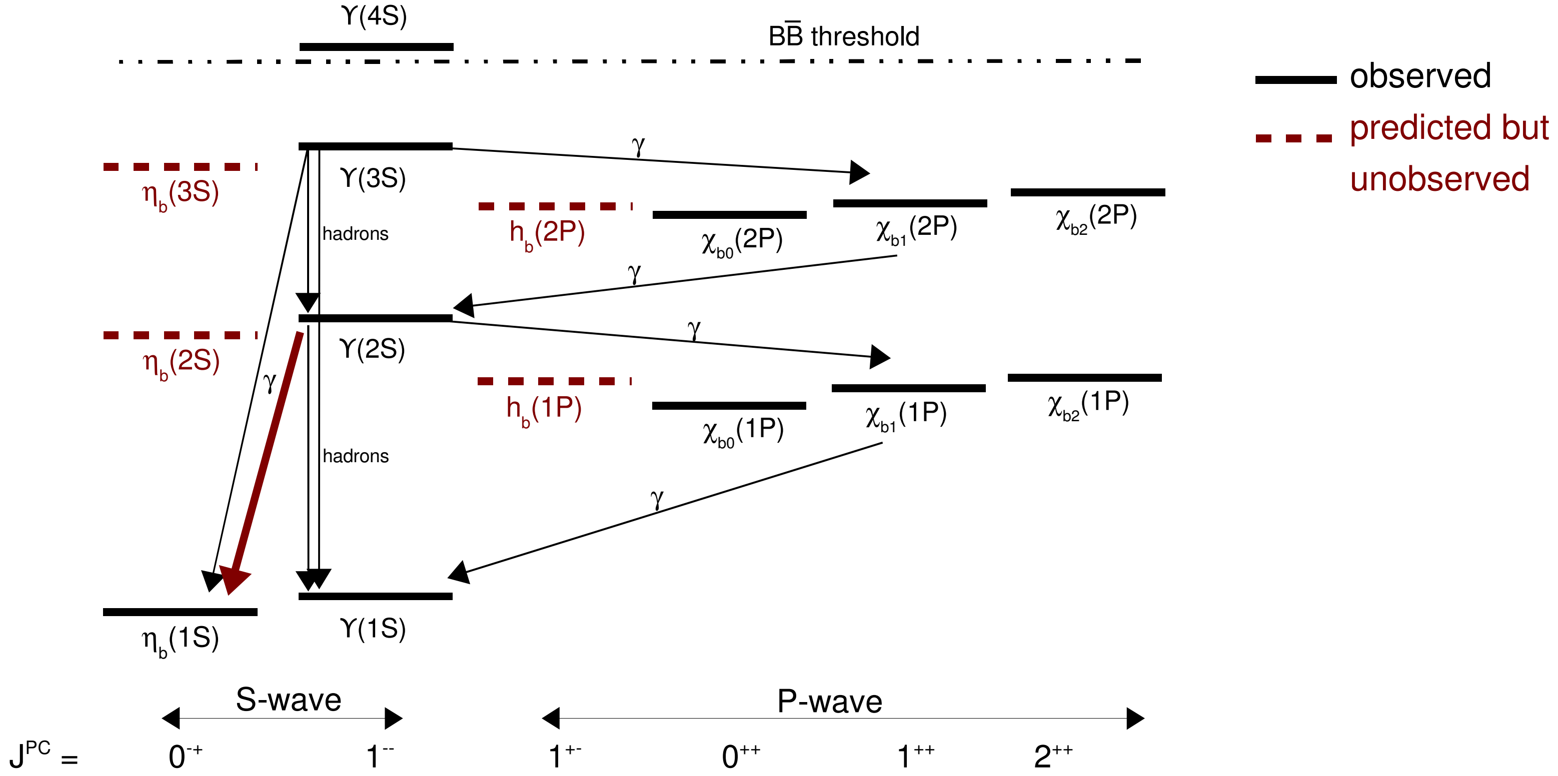


$M(\Upsilon) = 9.40 \pm 0.013$ GeV
$M(\Upsilon') = 10.00 \pm 0.04$ GeV
$M(\Upsilon'') = 10.43 \pm 0.12$ GeV

The Upsilon resonances are identified as resonances of a new quark, the bottom quark

1. PRL 39 (1977) 252.
2. PRL 39 (1977) 1240; Erratum PRL 39 (1977) 1640.

30 years later, a candidate for the bottomonium ground state, $\eta_b(1S)$, was finally observed in the reaction $\Upsilon(3S) \rightarrow \gamma\eta_b$



Search for η_b in $\Upsilon(2S)$ radiative decays to confirm this observation

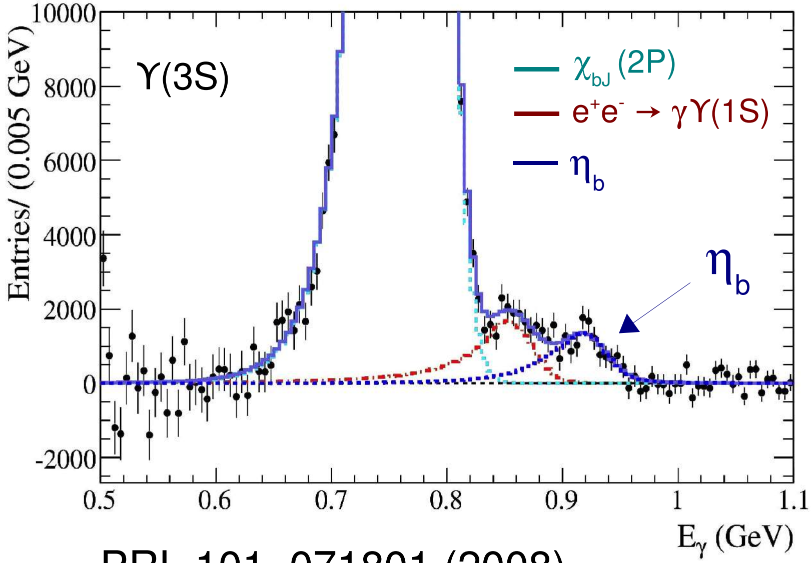
Bottomonium ground state, η_b

What do we know so far?

η_b candidate observed at BaBar with:

Mass = $9388.9^{+3.1}_{-2.3} \pm 2.7$ MeV

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



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From the theory

BF(Υ(2S)→ $\gamma\eta_b$) / BF(Υ(3S)→ $\gamma\eta_b$) = 0.3 – 0.7

Beyond a simple observation

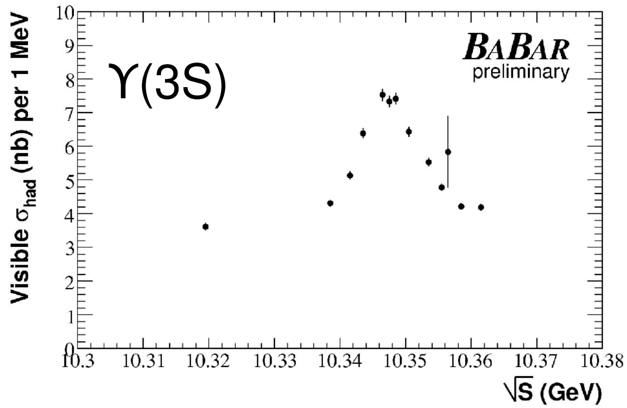
Test / improve lattice QCD, pNRQCD, potential models

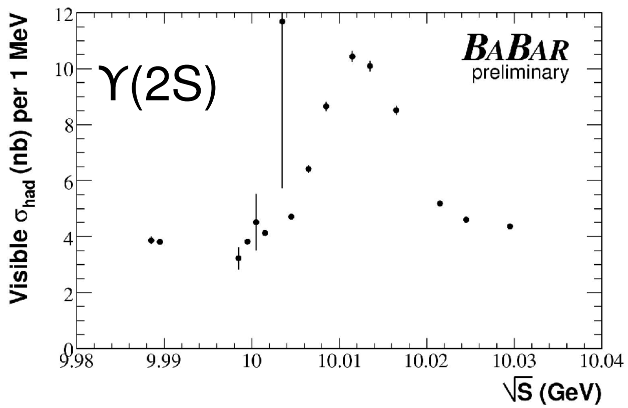
Study spin-spin interaction in heavy meson systems

Datasets

During its last months of data-taking, BaBar has collected large data samples at the ϒ(3S) and ϒ(2S) resonances (On-peak data) as well as 30 MeV below the resonances (Off-peak data)

	ϒ(3S) data*		ϒ(2S) data*	
	On-peak	Off-peak	On-peak	Off-peak
$\sqrt{s}$ (GeV)	10.355	10.325	10.012	9.982
Int. luminosity (fb^{-1})	28.0	2.4	14.4	1.5
Number of ϒ(2,3S) $\times 10^6$	119	-	99	-





Monte Carlo

- Signal η_b generated with different masses and widths
- **No reliable generator to model the background, use 1/10th of the data to describe it (not used in the final analysis)**

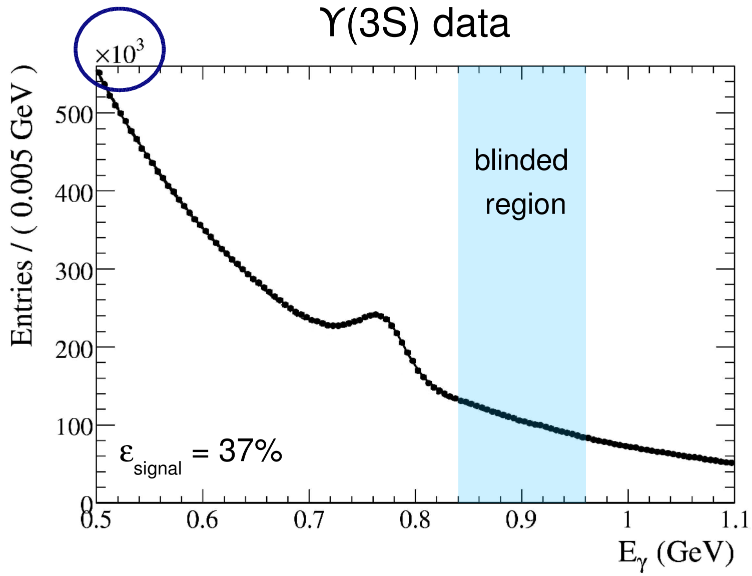
* for these analyses

Search strategy

- Decay modes of η_b unknown → inclusive search
- Search for the radiative transitions

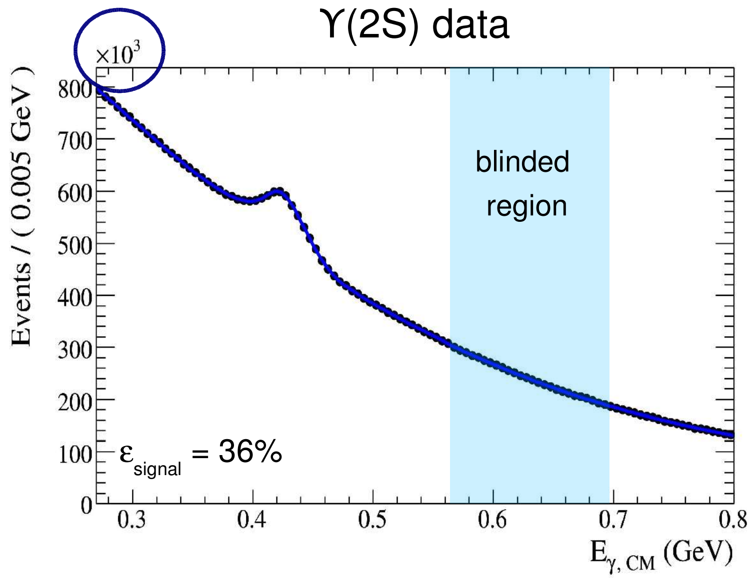
$\Upsilon(3S) \to \gamma \eta_b$ and $\Upsilon(2S) \to \gamma \eta_b$

- Signal is a monochromatic peak in $E\gamma$ spectrum, extracted using a 1D fit



Selection

- High track multiplicity (η_b expected to decay mainly into two gluons)
- Sphericity + angle between photon and the rest of the event to reject e+e- → qqbar (q=u,d,s,c) background
- Photons are selected as high-quality isolated cluster in the EM calorimeter (barrel only)
- Veto against photons produced by π^0 decays



Huge background
Blind analysis

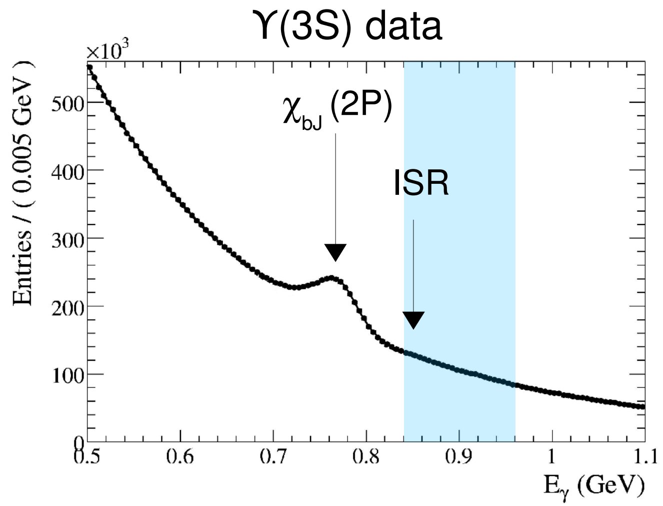
Non-peaking background

- $e^+e^- \to$ qqbar (q=u,d,s,c)
- Υ(3S) / Υ(2S) generic decays

Described with a single function

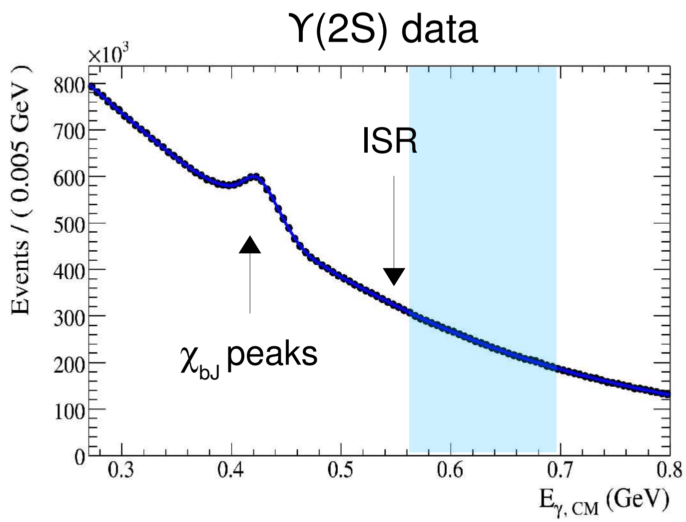
$A(C + \exp(-\alpha E\gamma + \beta E\gamma^2))$ for Υ(3S)

$A(C + \exp(-\alpha E\gamma + \beta E\gamma^2 + \delta E\gamma^3 + \varepsilon E\gamma^4))$ for Υ(2S)



Peaking background for Υ(3S)

- Initial state radiation (ISR): $e^+e^- \to \gamma_{ISR}\Upsilon(1S)$: 856 MeV
- $\Upsilon(3S) \to \gamma\chi_{bJ}(2P)$, $\chi_{bJ}(2P) \to \gamma\Upsilon(1S)$: ~760 MeV



Peaking background for Υ(2S)

- Initial state radiation (ISR): $e^+e^- \to \gamma_{ISR}\Upsilon(1S)$: 547 MeV
- $\Upsilon(2S) \to \gamma\chi_{bJ}(1P)$, $\chi_{bJ}(1P) \to \gamma\Upsilon(1S)$: ~420 MeV

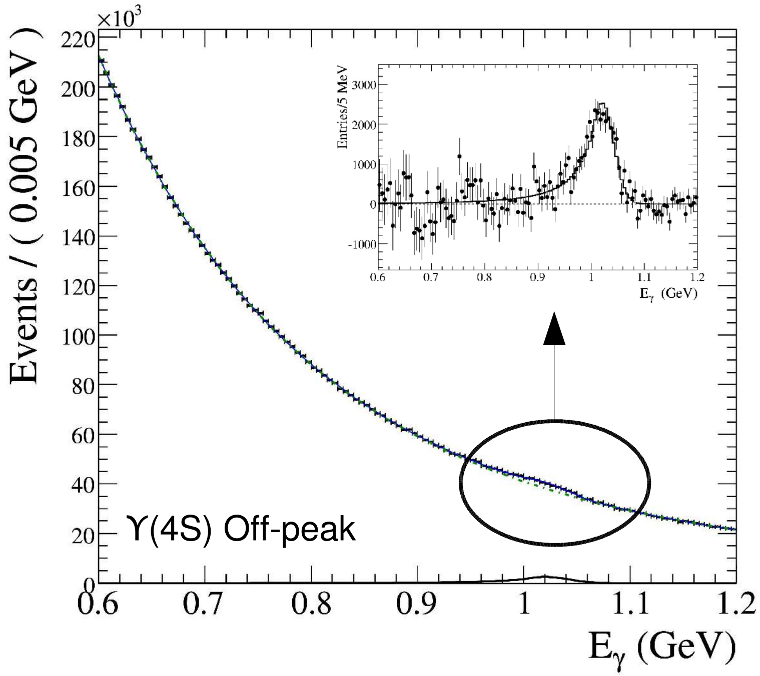
Need a very good description of these backgrounds

Photon energy for $\gamma_{ISR}\Upsilon(1S)$ production

856 MeV for ϒ(3S) - 547 MeV for ϒ(2S) → can overlap with η_b peak

ISR peak parametrization

- Line shape estimated from signal MC
- Yield estimated from ϒ(4S) Off-peak data (40 MeV below resonance) and extrapolated to ϒ(3S) / ϒ(2S) data (correcting for luminosity, efficiency, cross-section)



ϒ(3S) selection:

Fitted Yield ϒ(4S) off-peak = 35800 ± 1600

Extrapolated Yield ϒ(3S) = 25200 ± 1700

ϒ(2S) selection:

Fitted Yield ϒ(4S) off-peak = 41800 ± 1900

Extrapolated Yield ϒ(2S) = 16700 ± 1400

Yield extrapolated to ϒ(3S) / ϒ(2S)

Off-peak data shows good agreement

Peaking χ_{bJ}(2P) background

Photon from second transition $\Upsilon(3S) \rightarrow \gamma\,\chi_{bJ}(2P)$, $\chi_{bJ}(2P) \rightarrow \gamma\,\Upsilon(1S)$ J=0,1,2

Three peaks overlap due to Doppler broadening and detector resolution → $\langle E\gamma \rangle$ = 760 MeV

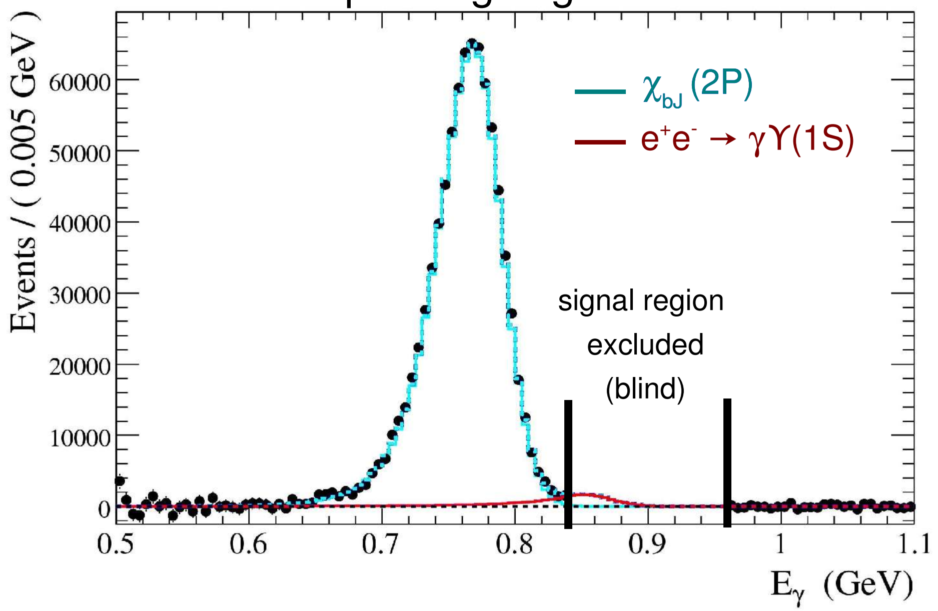
χ_{bJ}(2P) peaks parametrization

- Each resonance is modeled by a Crystal Ball function (Gaussian + power-law tail), power law parameters are fixed to same value for all peaks
- Peak position fixed to PDG values minus a common offset
- Ratio of χ_{b0}(2P), χ_{b1}(2P) and χ_{b2}(2P) yields fixed to PDG values

PDF parameters obtained by fitting the full data excluding the signal and ISR region

Offset of 3.8 MeV observed w.r.t. PDG value
→ correct other peaks

Υ(3S) data,
non-peaking bkg subtracted



Peaking $\chi_{bJ}(1P)$ background

Photon from second transition $\Upsilon(2S) \to \gamma\chi_{bJ}(1P)$, $\chi_{bJ}(1P) \to \gamma\Upsilon(1S)$ J=0,1,2

Three peaks overlap due to Doppler broadening and detector resolution → $\langle E\gamma \rangle$ = 420 MeV

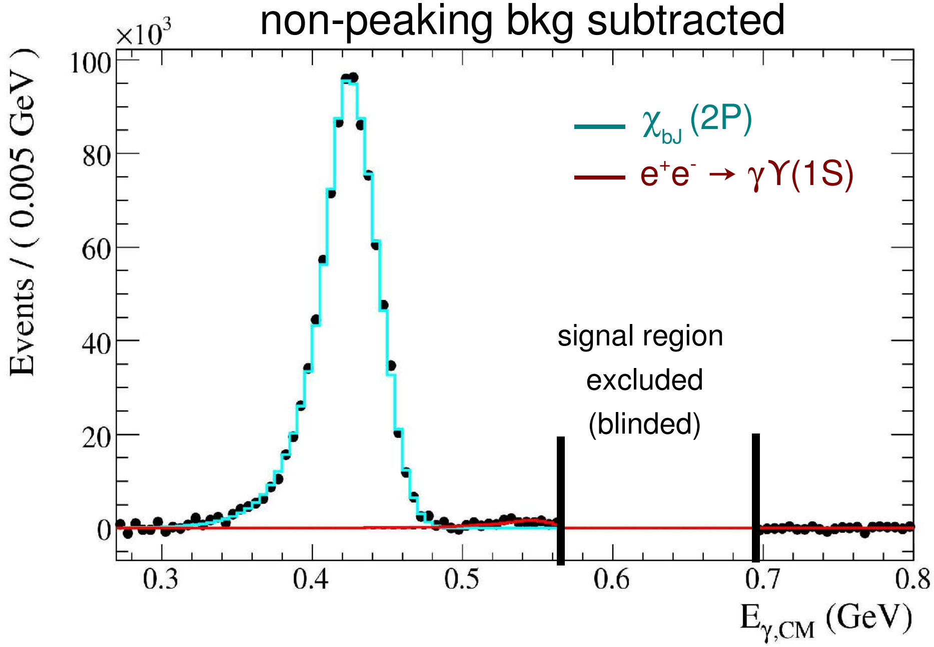
$\chi_{bJ}(1P)$ peaks parametrization

- Each resonance is modeled by a Crystal Ball function (Gaussian + power-law tail), power law parameters are fixed to same value for all peaks
- Peak position fixed to PDG values minus a common offset
- Ratio of $\chi_{b0}(1P)$, $\chi_{b1}(1P)$ and $\chi_{b2}(1P)$ yields fixed to PDG values

PDF parameters obtained by fitting the full data excluding the signal region

Offset of 1.6 MeV observed w.r.t. PDG value → correct other peaks

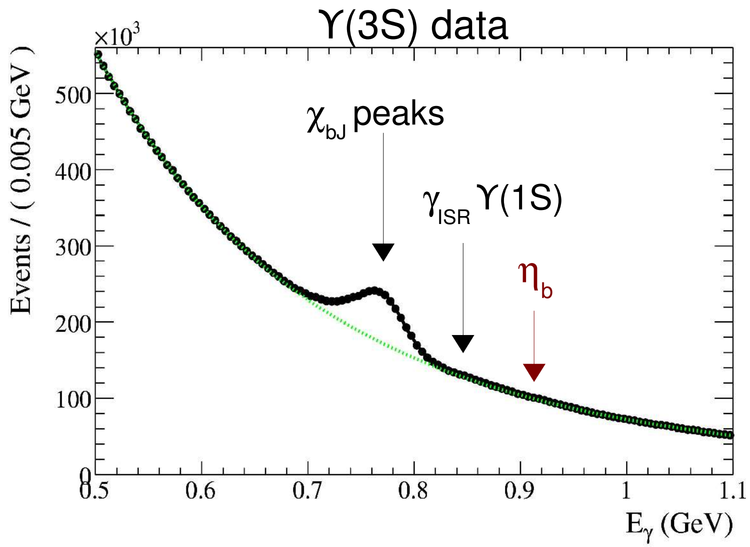
$\Upsilon(2S)$ data, non-peaking bkg subtracted



Fit strategy

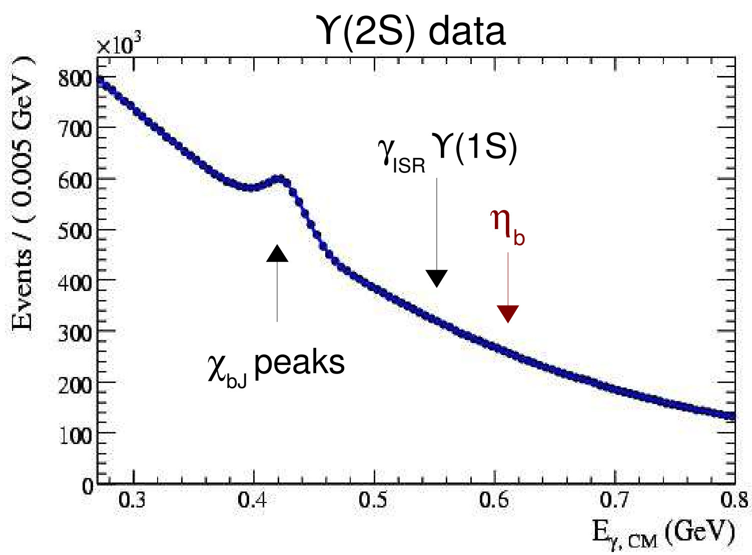
Signal η_b parametrization

- Convolution of Crystal Ball (CB) and Breit-Wigner
- CB parameters fixed to MC generated with $\Gamma(\eta_b)$ = 0 MeV
- MC studies: need to fix η_b width if close to ISR peak
  - → nominal fit with $\Gamma(\eta_b)$ = 10 MeV,
  - → systematic studies $\Gamma(\eta_b)$ = 5-20 MeV



Other components

- Non-peaking background : float all parameters
- χ_{bJ}(2P) background : line shape fixed, yield floated
- χ_{bJ}(1P) background : line shape* and yield floated
- ISR background : line shape fixed (MC), yield fixed** for Υ(3S), float for Υ(2S)



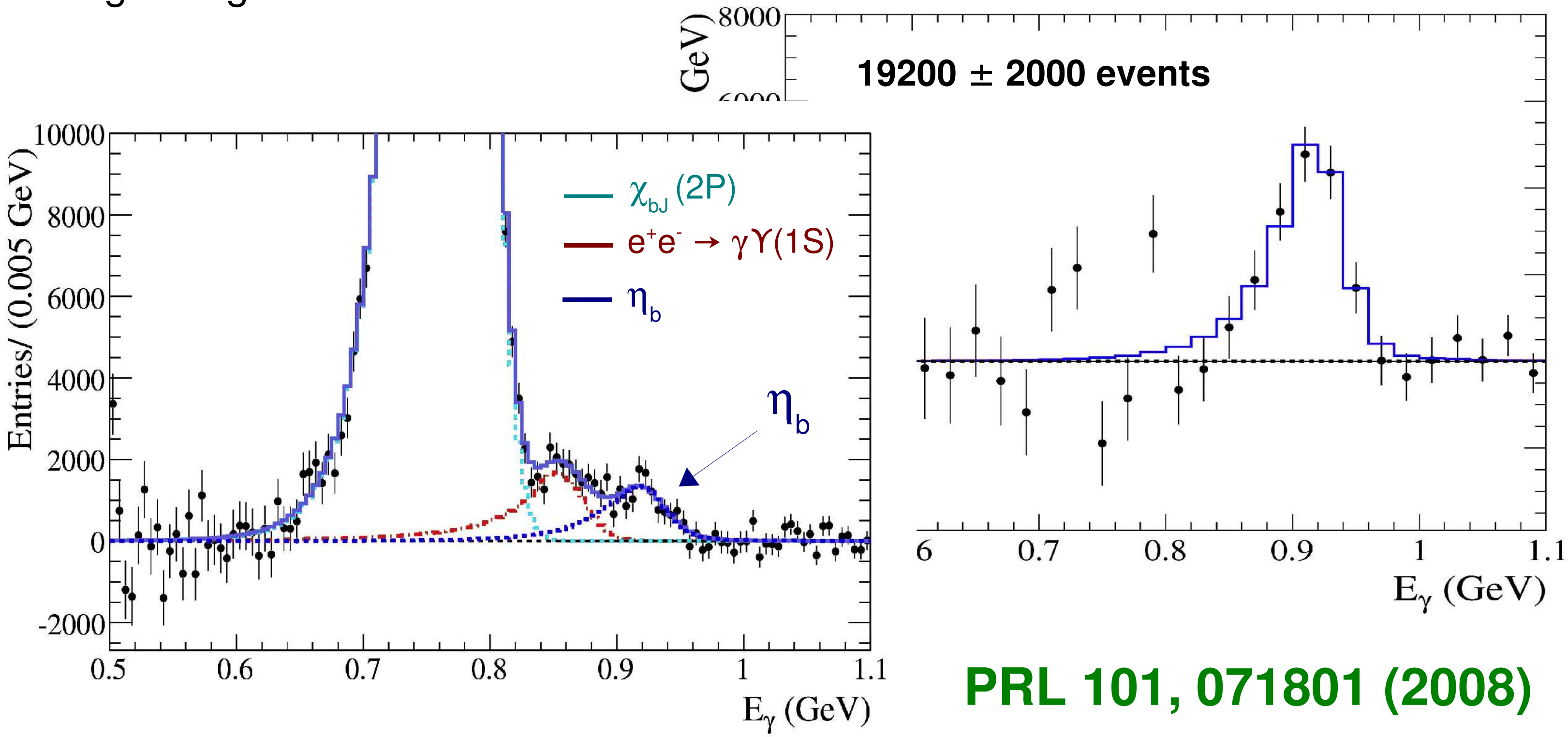
Fit validation

- Large number of toy MC → no bias introduced by fit
- Procedure validated on 1/10th of the data

* The resolution, transition point and offset parameters for the CB are floated, other parameters are fixed

** The fit is also performed floating the ISR yield Υ(3S), results are consistent with the fixed yield and no effect on the η_b yield or peak position is seen

Non-peaking background subtracted



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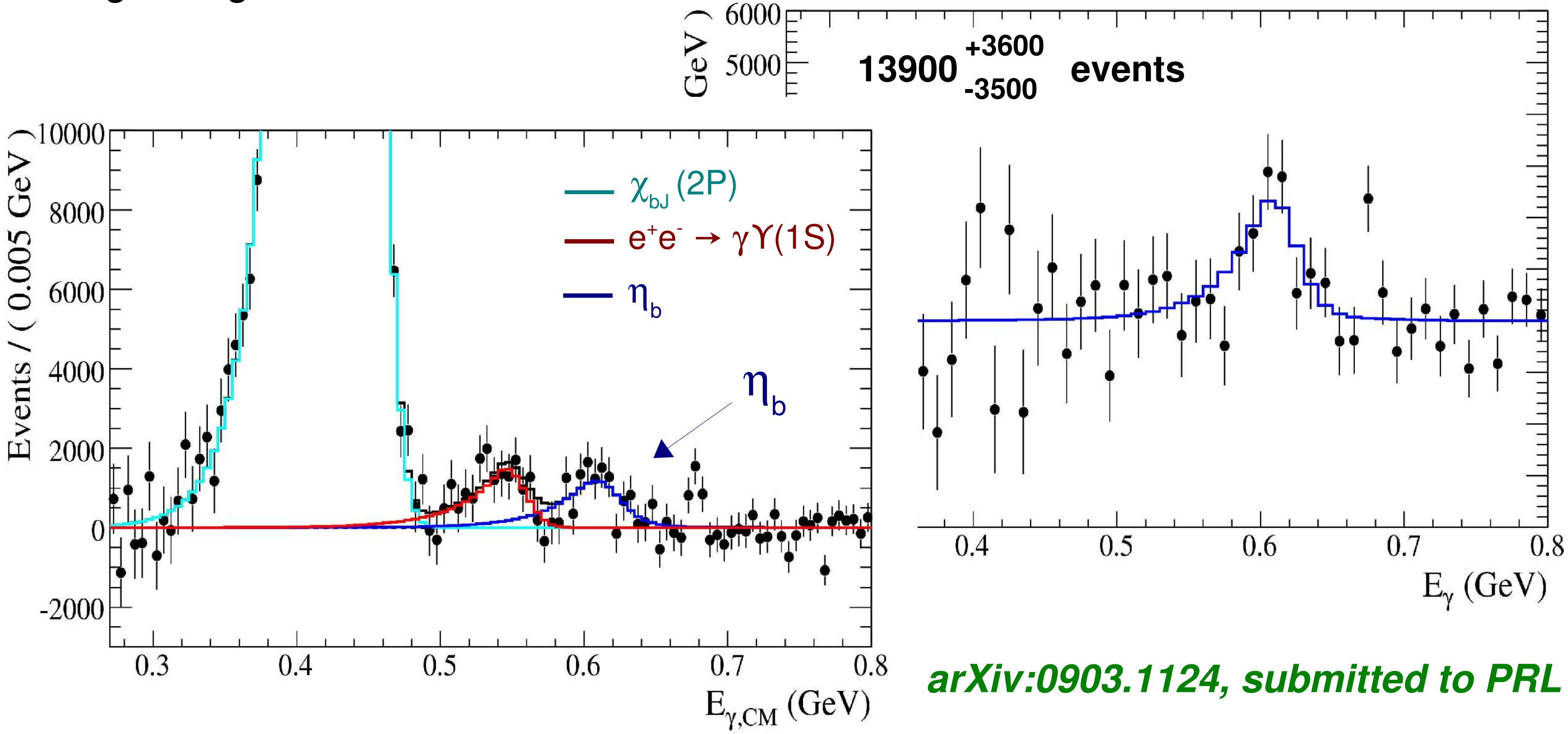
η_b signal observed with a 10σ significance,

peak position $921.2^{+2.1}_{-2.8} \pm 2.4$ MeV

Non-peaking background subtracted



arXiv:0903.1124, submitted to PRL

η_b signal observed with a 3.5σ significance,

peak position $610.5^{+4.5}_{-4.3} \pm 1.8$ MeV

Summary of results

Is it really the η_b?

The only expected state below the $\Upsilon(1S)$ is the η_b, but other interpretations (e.g low mass Higgs) are possible. The ratio of branching fractions is found to be consistent with the η_b hypothesis.

Assuming the η_b hypothesis:

	$\Upsilon(3S)$ data	$\Upsilon(2S)$ data	Combined (stat + syst combined)
η_b mass:	$9388.9^{+3.1}_{-2.3} \pm 2.7$ MeV	$9392.9^{+4.6}_{-4.8} \pm 1.9$ MeV	9390.4 ± 3.1 MeV
$\Upsilon(1S) - \eta_b(1S)$ mass splitting:	$71.4^{+3.1}_{-2.3} \pm 2.7$ MeV	$67.4^{+4.6}_{-4.8} \pm 2.0$ MeV	69.9 ± 3.1 MeV
BF ($\Upsilon(3,2\,S) \rightarrow \gamma\,\eta_b$) ($10^{-4}$) :	$4.8 \pm 0.5 \pm 0.6$	$4.2^{+1.1}_{-1.0} \pm 0.9$	

Hyperfine mass splitting predictions (MeV):

- Potential models: 36-100 (36-87 recent models)
- pNRQCD: 39-44 (~25% uncertainty)
- Lattice QCD: 40-71 (10-25% uncertainty)

Conclusion

BaBar has obtained evidence for the radiative decay of the $\Upsilon(2S)$ to a narrow state with a mass slightly below that that of the $\Upsilon(1S)$, confirming the previous observation at the $\Upsilon(3S)$ resonance.

The ratio of radiative production rates for this states at the $\Upsilon(2S)$ and $\Upsilon(3S)$ are consistent with the η_b hypothesis. Under this interpretation, the average η_b mass is

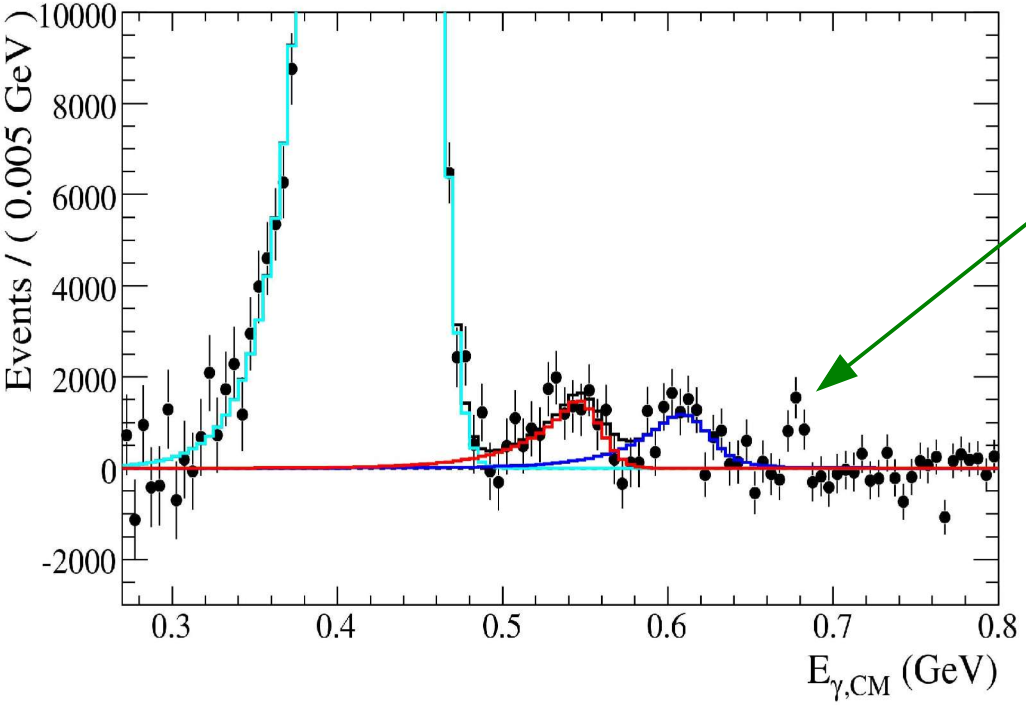
$$M(\eta_b) = 9390.4 \pm 3.1 \text{ MeV},$$

corresponding to a hyperfine mass splitting of

$$M(\Upsilon(1S)) - M(\eta_b) = 69.9 \pm 3.1 \text{ MeV}$$

BACKUP

Additional structure in Υ(2S) data



Additional "peak" around
Eγ ~ 680 MeV

Photons not localized in specific time / detector location, no anomaly observed

Probability to observe such a fluctuation = 5%

Width smaller than detector resolution → most likely a statistical fluctuation

Systematic uncertainties

Systematic uncertainties on the branching fractions:

Yield

η_b width varied in fit (5, 15, 20 MeV)

PDF parameters – varied by $\pm 1\sigma$

Use alternative parametrization for the continuum background

Selection efficiency

Photon selection

Hadronic selection

π^0 veto

Thrust cut

Source	$\Upsilon(3S)$	$\Upsilon(2S)$
Photon detection	*1.8*	*1.8*
Hadronic selection	*4.9*	*4.9*
Photon selection	0.5	0.5
Thrust cut	1.0	0.6
π^0 veto	1.5	4.1
Total (excluding canceling systematics)	1.9	4.2
Total (including canceling systematics)	5.5	6.7

ϒ(2S) / ϒ(3S) counting

MC statistics

TOTAL 22% for ϒ(2S) 13% for ϒ(3S)

RATIOS ϒ(3S) / ϒ(2S) +13% -18%

ϒ(2S)

Source	Uncertainty (in %)
Fit variations	21
$\Upsilon(2S)$ counting	0.93
η_b MC efficiency	0.5
Selection efficiency	6.7
Total	22

ϒ(3S)

Source	Uncertainty (in %)
$\Upsilon(3S)$ selection efficiency	5.5
$\Upsilon(3S)$ yield	2.5
η_b width	11
Total	13

BF ($\Upsilon(3S)\to\gamma\,\eta_b$) / BF ($\Upsilon(2S)\to\gamma\,\eta_b$)

Source	Uncertainty (in %)
$\Upsilon(2S)$ selection efficiency	4.2
$\Upsilon(2S)$ yield	$^{+11}_{-16}$
$\Upsilon(3S)$ selection efficiency	1.9
$\Upsilon(3S)$ yield	2.5
η_b width	$^{+5.4}_{-4.9}$
Total	$^{+13}_{-18}$