BOTTOMONIUM SPECTROSCOPY AT BABAR

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On behalf of the BaBar Collaboration

The Lomonosov-XIV Conference
Moscow (2009/08/24)

Outline

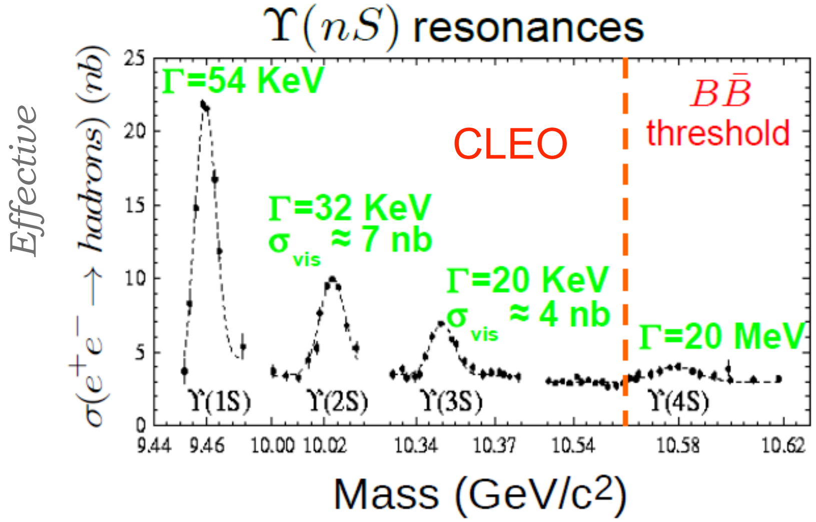
- Brief overview: BaBar Data
- Bottomonium Spectra

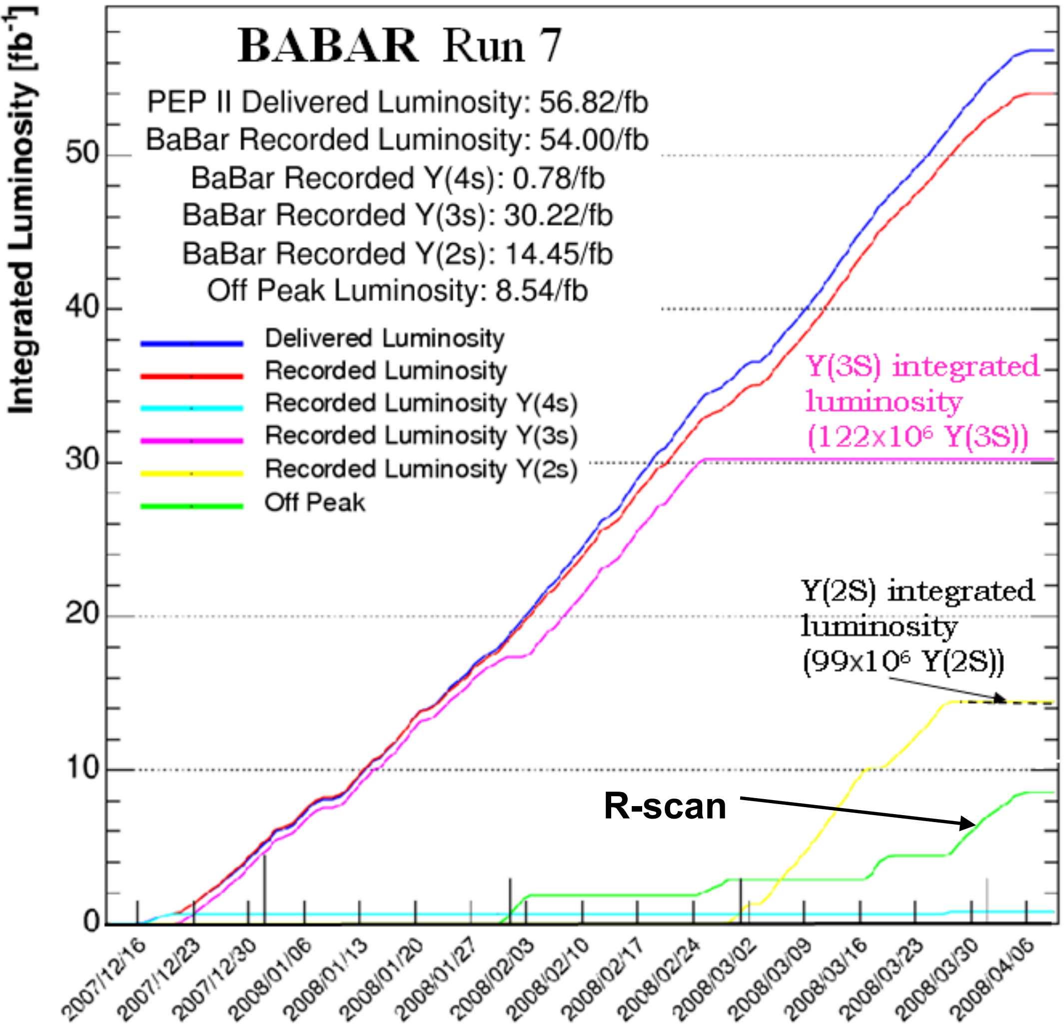
- Report on selected BaBar analyses of
    - Radiative transitions to the $\eta_b(1S)$ state
    - A few hadronic transitions
    - the Y(5S)-Y(6S) scan

- Conclusions

BaBar RUN 7 (Dec. 2007 – Apr. 2008)

PEP-II e^+e^- Asymmetric Collider Running at the Υ(2S,3S)…





BABAR DATASETS:

~ 120 x 10^6 **Y(3S)** events

≈ 20 x previous dataset (CLEO)

~ 100 x 10^6 **Y(2S)** events

≈ 11 x previous dataset (CLEO)

~ 8.54 fb^{-1} above **Y(4S)**

≈ 30 x previous datasets (CLEO, CUSB)

Current Picture of the Bottomonium Spectrum

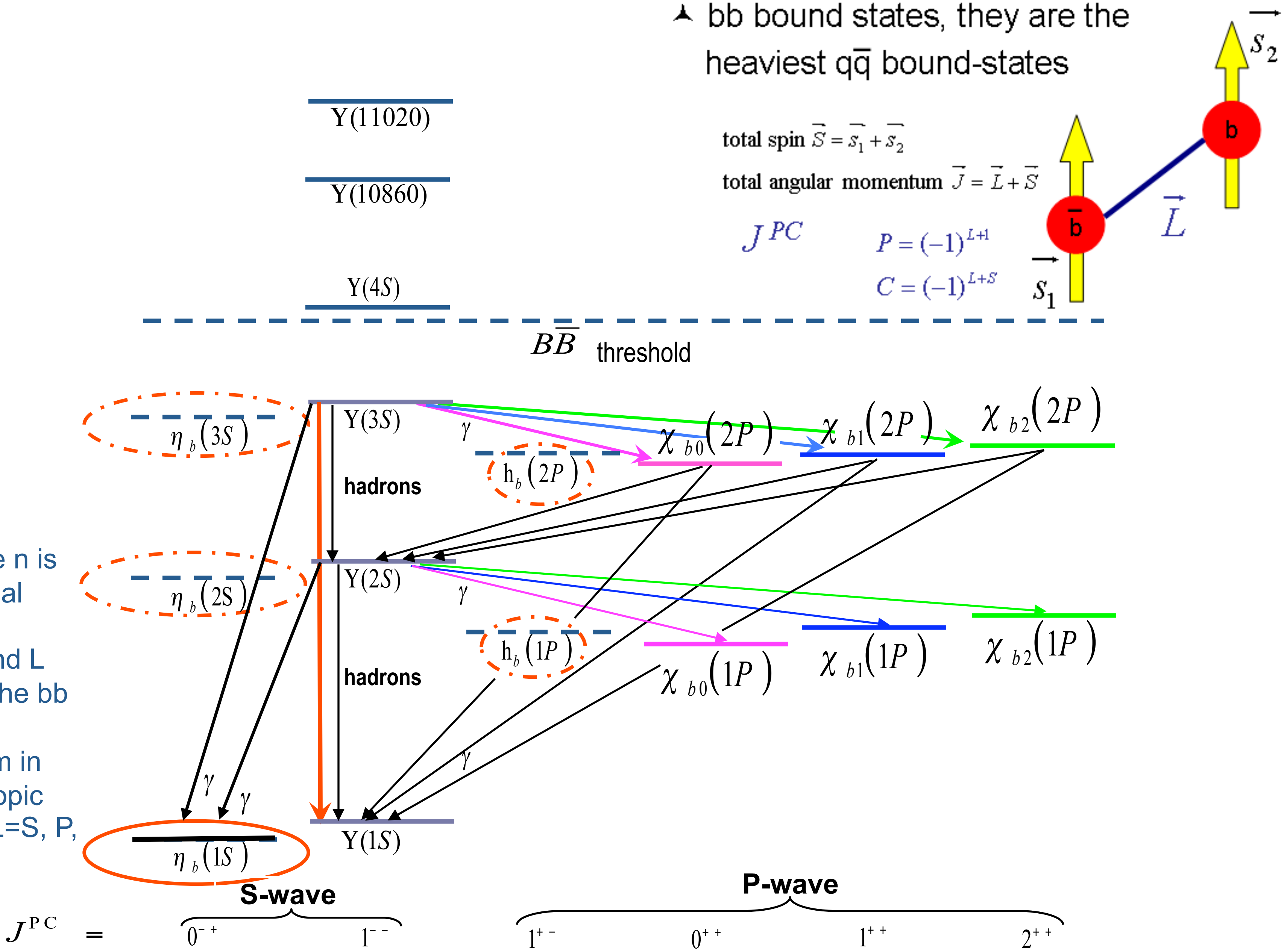
- $b\bar{b}$ bound states, they are the heaviest $q\bar{q}$ bound-states

total spin $\vec{S}=\vec{s}_1+\vec{s}_2$

total angular momentum $\vec{J}=\vec{L}+\vec{S}$

J^{PC} $P=(-1)^{L+1}$

$C=(-1)^{L+S}$



(nL) where n is the principal quantum number and L indicates the bb angular momentum in spectroscopic notation (L=S, P, D,…)

Bottomonium Transitions

- Υ(nS) resonances undergo:

  - Hadronic transitions via π^0, η, ω, ππ emission

  - Electric dipole transitions

$$\Gamma_{\mathrm{E1}} \propto e_Q^2 \left| \langle n_f L_f | r | n_i L_i \rangle \right|^2 E_\gamma^{\,3}$$

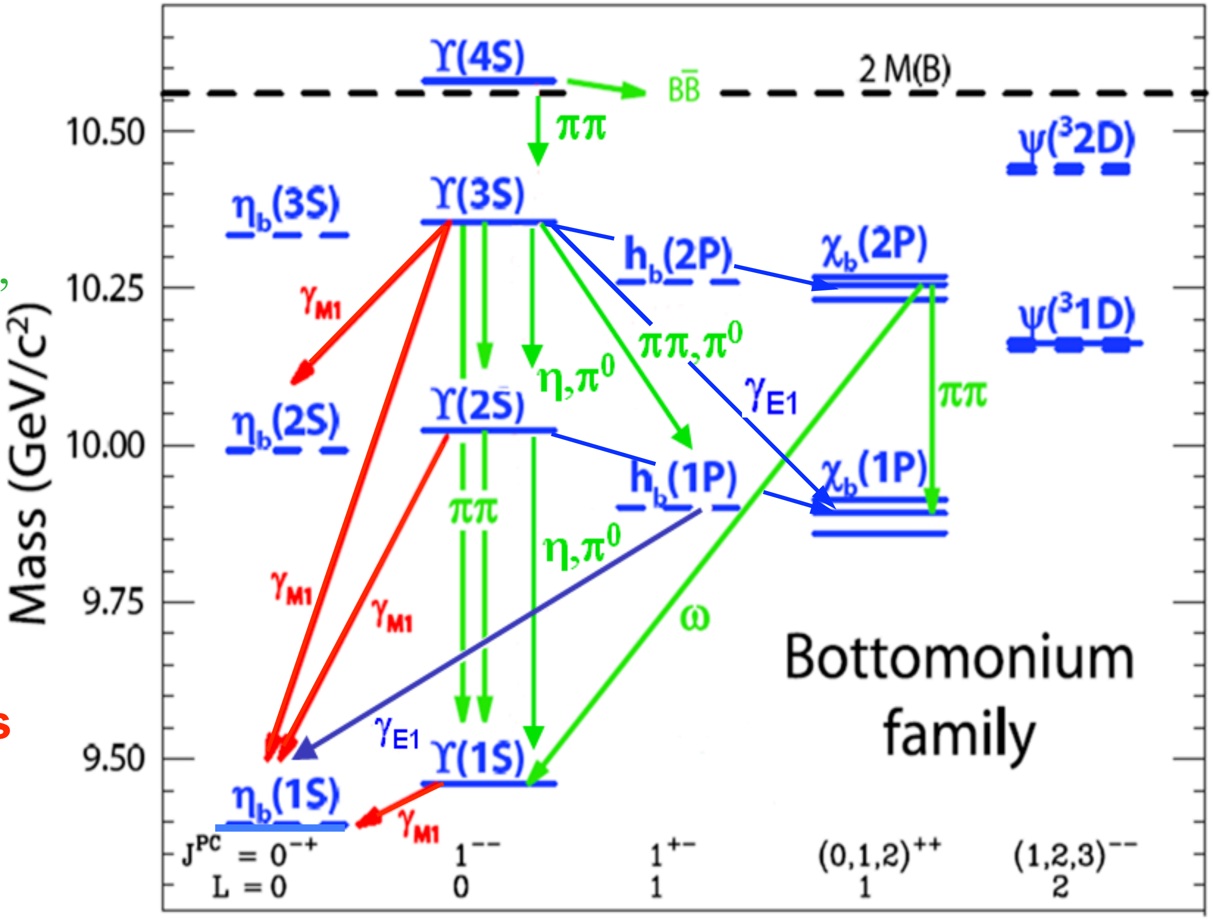
  - **Magnetic dipole transitions**

$$\Gamma_{\mathrm{M1}} \propto \frac{e_Q^2}{m_Q^2} \left| \langle n_f L | n_i L \rangle \right|^2 E_\gamma^{\,3}$$

DIRECT

$n_i = n_f$

$\langle n_f L | n_i L \rangle = 1$

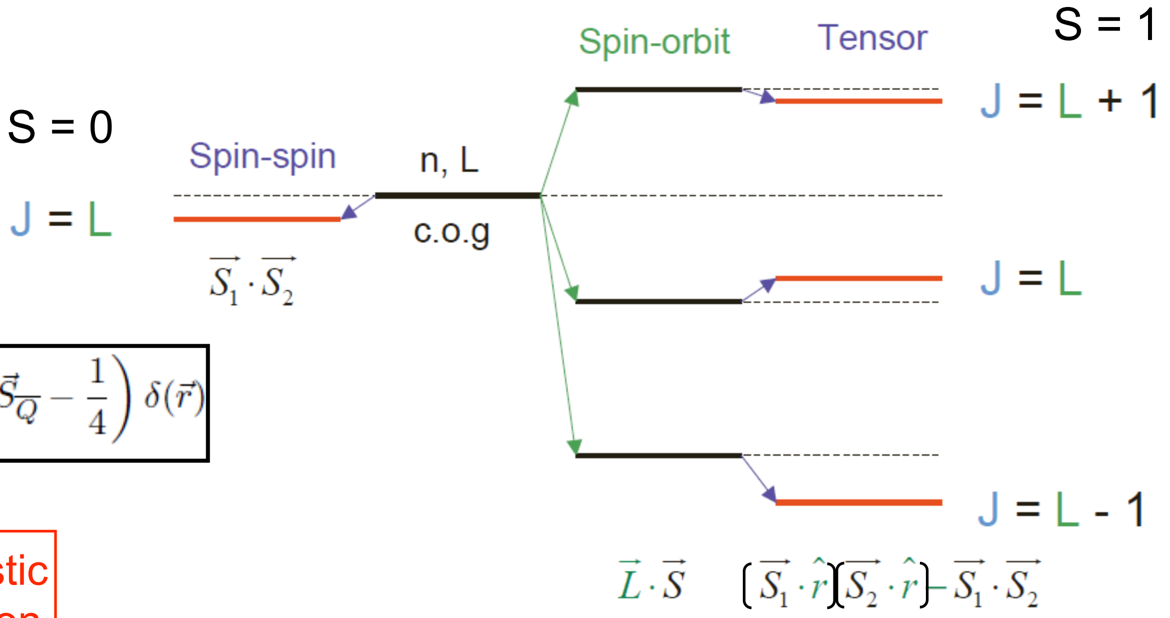


- Electromagnetic transitions between the levels can be calculated in the quark model → important tool in understanding the bottomonium internal structure

Mass Splittings in Heavy Quarkonia

Hyperfine splitting **Fine splitting**

Triplet-Singlet mass splitting of quarkonium states



S = 0

J = L

Spin-spin

n, L

c.o.g

$\vec{S}_1 \cdot \vec{S}_2$

S = 1

Spin-orbit

Tensor

J = L + 1

J = L

J = L - 1

$\vec{L} \cdot \vec{S}$

$(\vec{S}_1 \cdot \hat{r})(\vec{S}_2 \cdot \hat{r}) - \vec{S}_1 \cdot \vec{S}_2$

Mass splitting of triplet nP quarkonium states: $\chi_{c,b}(n^3P_0)$, $\chi_{c,b}(n^3P_1)$, $\chi_{c,b}(n^3P_2)$

$$\boxed{H_{HF} = \frac{32\pi\alpha_s}{9m_Q m_{\overline{Q}}}\left(\vec{S}_Q \cdot \vec{S}_{\overline{Q}} - \frac{1}{4}\right)\delta(\vec{r})}$$

Non-relativistic approximation

$$\boxed{\Delta E_{HF} = \frac{32\pi\alpha_s}{9m_Q m_{\overline{Q}}}|\psi(0)|^2}$$

= 0 for L≠ 0 ($\psi \rightarrow 0$ for r → 0), if long-range spin forces are negligible

$$\Delta M_{HF}(nL) = \underbrace{\langle M(n^3L_J)\rangle}_{\sum_J (2J+1)M_J \,/\, \sum_J (2J+1)} - M(n^1L_{J=L}) \sim 0$$

≠ 0 for L=0

$\rightarrow significant: M(\Upsilon(1S)) - M(\eta_b) = 61 \pm 14$ MeV/c^2

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

$\Upsilon(1S)-\eta_b(1S)$ mass splitting meas^t.→ key test of applicability of *perturbative* QCD to the bottomonium system

The Search for the η_b at BaBar

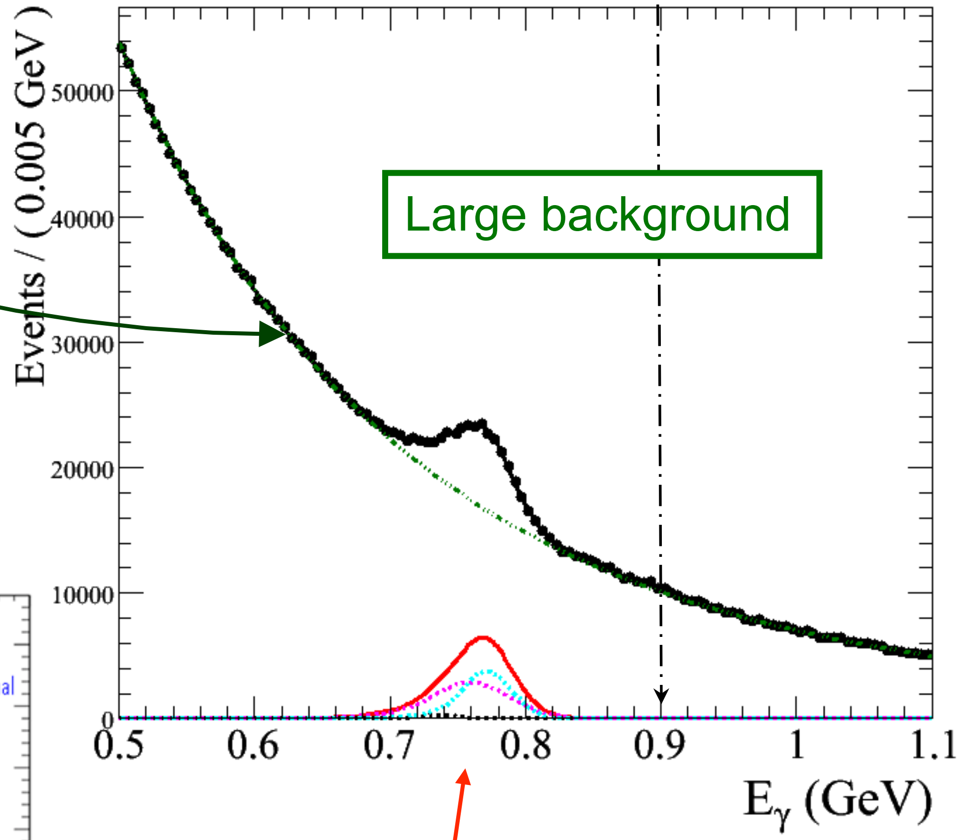
- Decays of η_b not known ➔ Search for η_b signal in **inclusive photon spectrum**
  - **Search for the radiative transition $\Upsilon(3S) \rightarrow \gamma\eta_b(1S)$**
- In c.m. frame: $E_\gamma = \frac{s - m^2}{2\sqrt{s}}$ $\left\{ \begin{array}{l} \sqrt{s} = \text{c.m. energy} = m(\Upsilon(3S)) \\ m = m(\eta_b) \end{array} \right\}$
  - For η_b mass m = 9.4 GeV/c^2 ➔ monochromatic line in E_γ spectrum at 915 MeV, i.e. look for a bump near 900 MeV in inclusive photon energy spectrum from data taken at the $\Upsilon(3S)$

The Inclusive Photon Spectrum

- Use ~9% of the Full Υ(3S) Data Sample

Look for a bump near 900 MeV
in the inclusive photon spectrum

Non-Peaking background components:

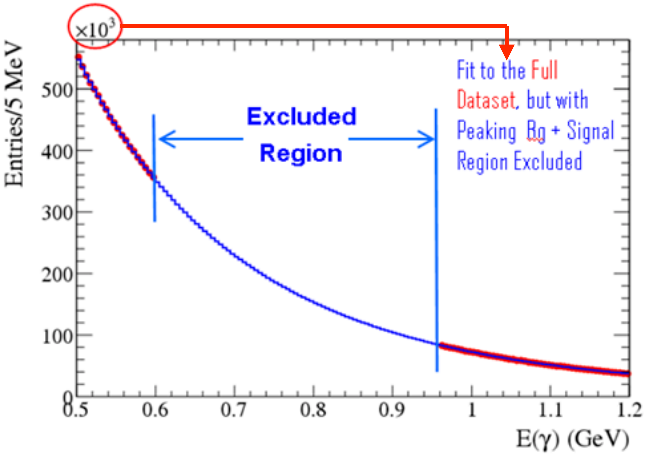


Large background

from $\chi_{bJ}(2P)$ decay
(next slide)

Non-peaking background parametrization:

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



Excluded Region

Fit to the Full Dataset, but with Peaking Bg + Signal Region Excluded

The Inclusive Photon Spectrum

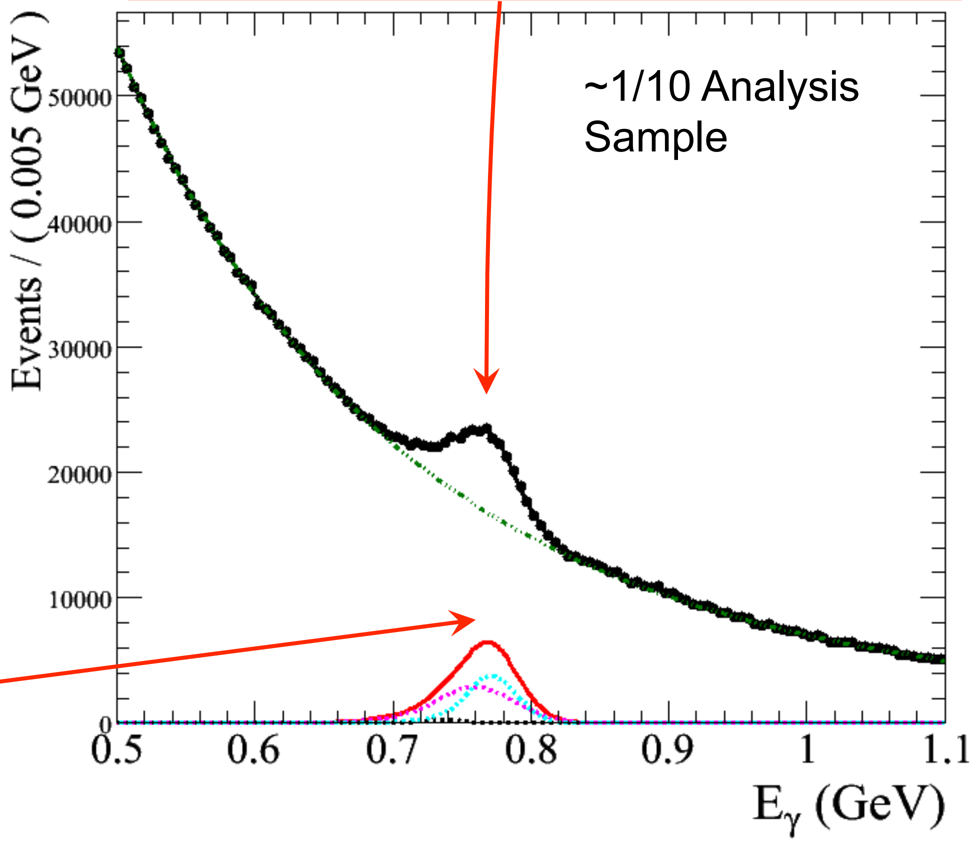
$\chi_{bJ}(2P) \to \gamma\,\Upsilon(1S)$ (Peaking) background parametrization:
PDF: 3 Crystal Ball functions
→relative peak positions and yield ratios are taken from PDF

Peaking background components (1):

$\Upsilon(3S) \to \chi_{b0}(2P)\,\gamma^{\text{soft}}$ $E(\gamma^{\text{soft}}) = 122$ MeV
↳$\Upsilon(1S)\,\gamma^{\text{hard}}$ $E(\gamma^{\text{hard}}) = 743$ MeV

$\Upsilon(3S) \to \chi_{b1}(2P)\,\gamma^{\text{soft}}$ $E(\gamma^{\text{soft}}) = 99$ MeV
↳$\Upsilon(1S)\,\gamma^{\text{hard}}$ $E(\gamma^{\text{hard}}) = 764$ MeV

$\Upsilon(3S) \to \chi_{b2}(2P)\,\gamma^{\text{soft}}$ $E(\gamma^{\text{soft}}) = 86$ MeV
↳$\Upsilon(1S)\,\gamma^{\text{hard}}$ $E(\gamma^{\text{hard}}) = 777$ MeV



~1/10 Analysis Sample

$\Upsilon(3S) \to \chi_{bJ}(2P)\,\gamma^{\text{soft}}$
(J=0,1,2) ↳$\Upsilon(1S)\,\gamma^{\text{hard}}$

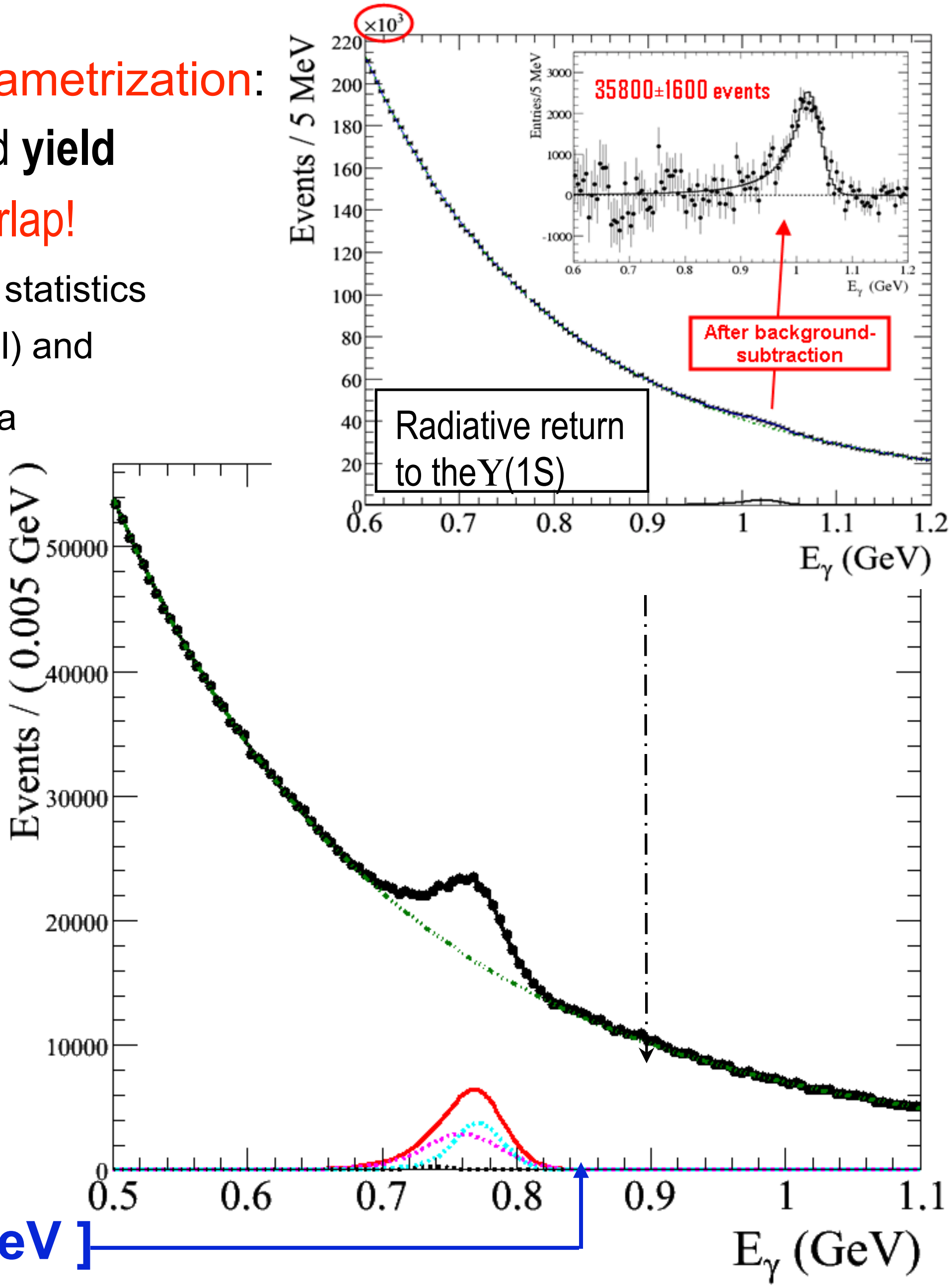
The Inclusive Photon Spectrum

$e^+e^- \to \gamma_{ISR}\ \Upsilon(1S)$ (Peaking) background parametrization:

–Very important to determine both **lineshape** and **yield**

Depending on η_b mass, the peaks may overlap!

Estimate the expected yield using Υ(4S) Off-Peak high statistics Data (no other peaking background near ISR signal) and extrapolate the yield to Υ(3S) On-Peak data



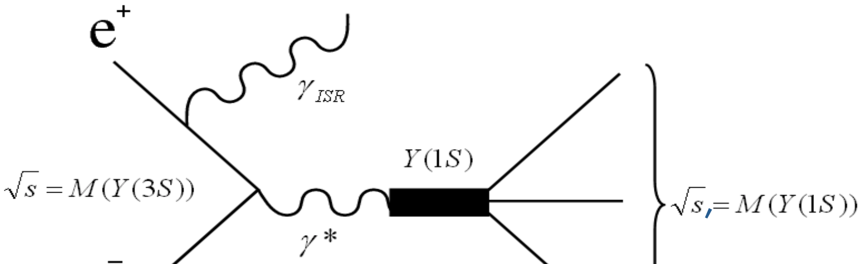
35800±1600 events

After background-subtraction

Radiative return to the Υ(1S)

Peaking background component:

Radiative return from Υ(3S) to Υ(1S): $e^+e^- \to \gamma_{ISR}\ \Upsilon(1S)$

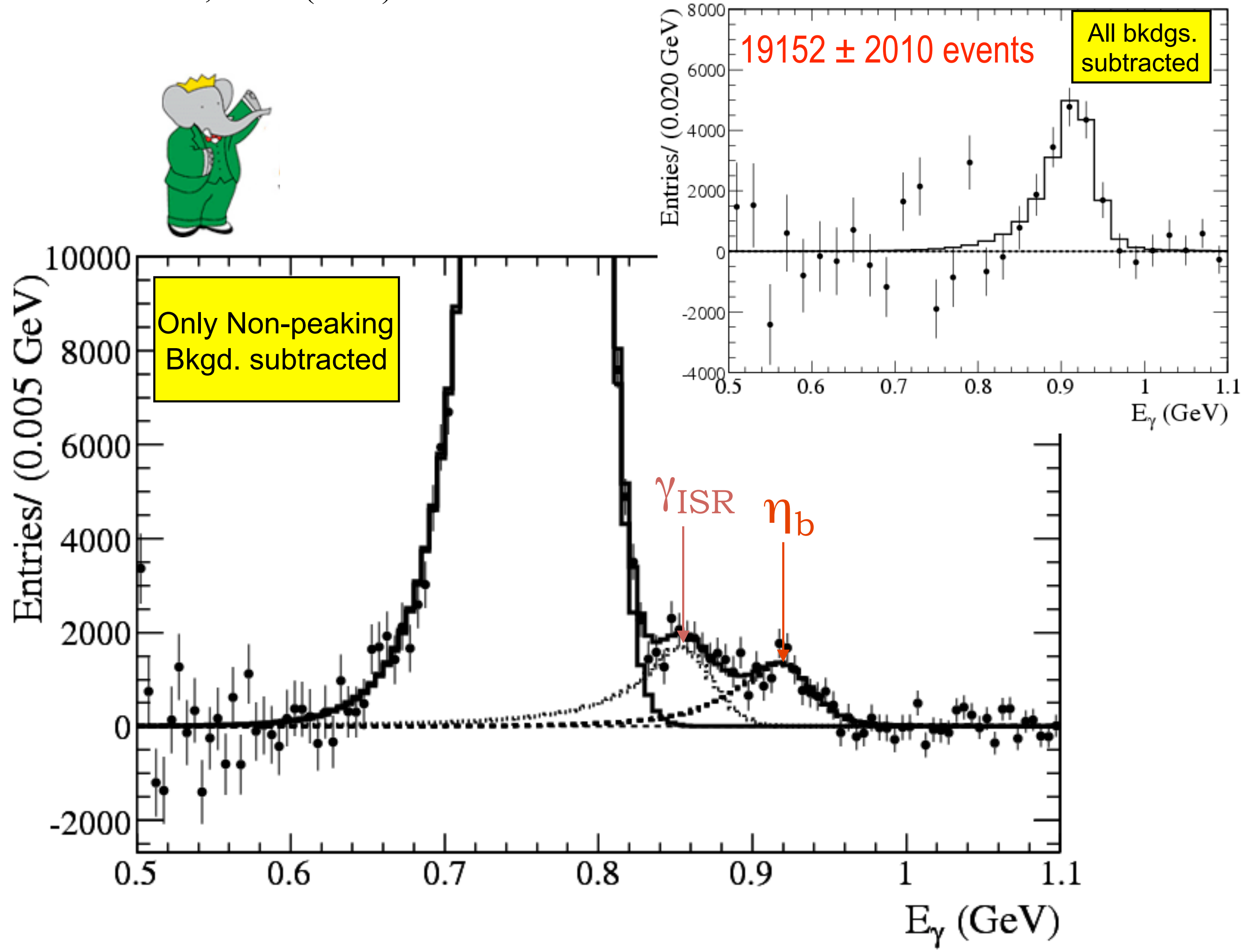


$$q_{ISR} = \frac{s - s'}{2\sqrt{s}}$$

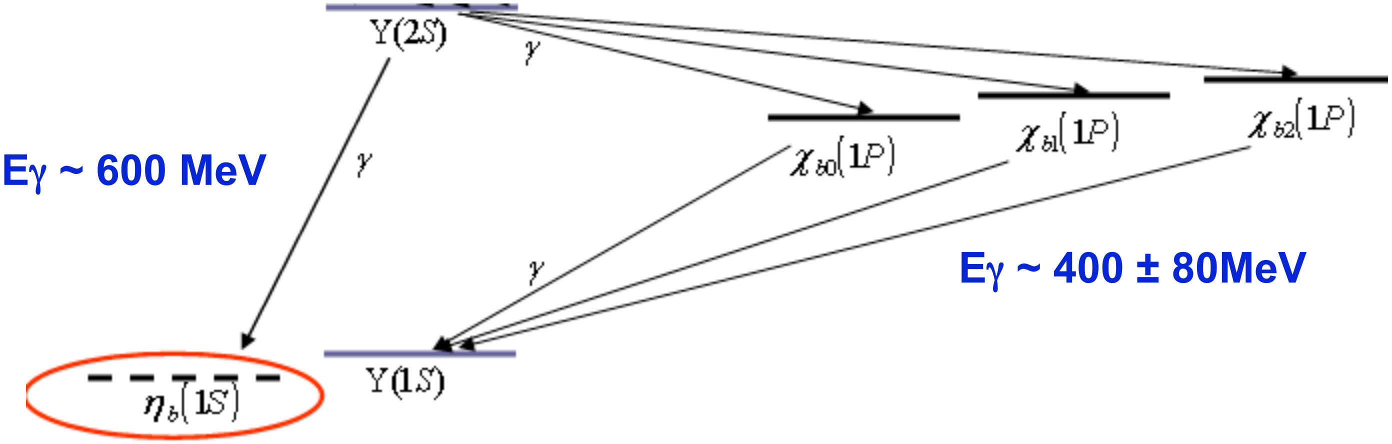
[$E_{\gamma_{ISR}}$ = 856 MeV]

The Observation of the η_b

Phys.Rev.Lett.100;06200 (2008)



The Search for the η_b in $\Upsilon(2S) \rightarrow \gamma\, \eta_b(1S)$ Decay



Eγ ~ 600 MeV

Eγ ~ 400 ± 80MeV

In c.m. frame: $E_\gamma = \dfrac{s - m^2}{2\sqrt{s}}$

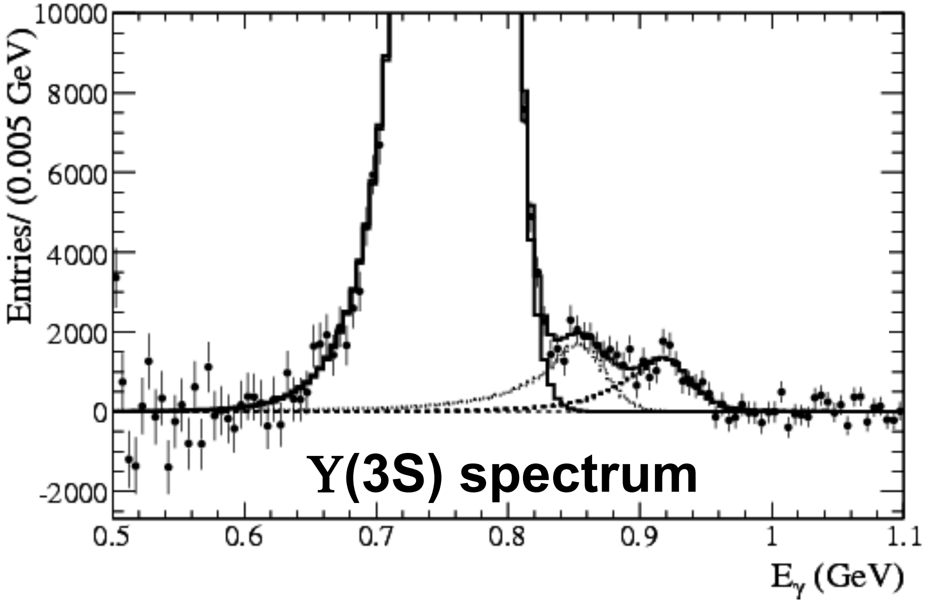
$\sqrt{s}$ = c.m. energy
m = m(η_b)

- For η_b mass m = 9.4 GeV/c^2 ➔ monochromatic line in E_γ spectrum at 604 MeV, i.e. look for a bump near 600 MeV in inclusive photon energy spectrum from data taken at the Υ(2S)

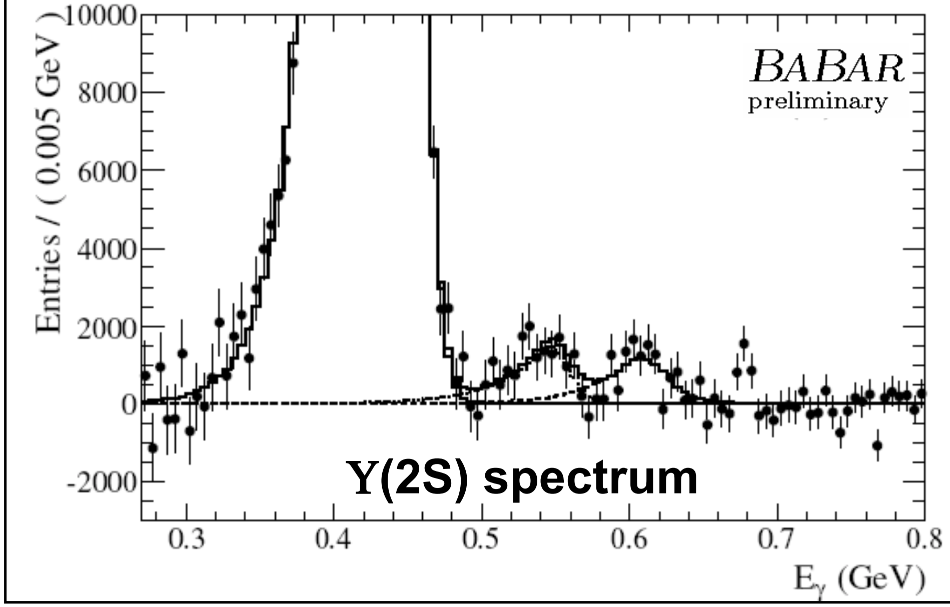
Data Sample ~ 100 x 10^6 Υ(2S) events

Similar analysis strategy in $\Upsilon(2S) \rightarrow \gamma\, \eta_b$ as for $\Upsilon(3S) \rightarrow \gamma\, \eta_b$

Comparison of Eγ Spectra



Only Non-peaking Background subtracted



Comparison with Υ(3S) → $\gamma\, \eta_b$ Analysis:

- ☛ **Better photon energy resolution at lower energy**
  - → **better separation between peaks**
- ☛ **More random photon background at lower energy**
  - → **less significance at similar BF**

Summary of η_b Results

- η_b mass:

$$Y(3S) \quad \text{analysis:} \qquad m(\eta_b) = 9388.9^{+3.1}_{-2.3} \pm 2.7 \;\; \text{MeV}/c^2$$

Phys.Rev.Lett.100;06200 (2008)

$$Y(2S) \quad \text{analysis:} \qquad m(\eta_b) = 9392.9^{+4.6}_{-4.8} \pm 1.8 \;\; \text{MeV}/c^2$$

arXiv : 0903.1124 (submitted to PRL)

Hyperfine splitting:

$$Y(3S) \quad \text{analysis:} \qquad m(\Upsilon(1S)) - m(\eta_b) = 71.4^{+2.3}_{-3.1} \pm 2.7 \;\; \text{MeV}/c^2$$

$$Y(2S) \quad \text{analysis:} \qquad m(\Upsilon(1S)) - m(\eta_b) = 67.4^{+4.8}_{-4.6} \pm 1.9 \;\; \text{MeV}/c^2$$

- Combined mass is $m(\eta_b(1S)) = 9390.4 \pm 3.1$ MeV/c^2 resulting in a hyperfine splitting of 69.9 ± 3.1 MeV/c^2

Hadronic transitions between bottomonium states

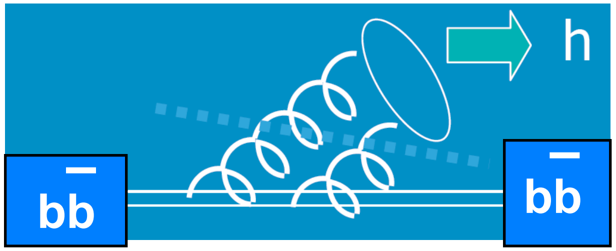
$\Upsilon(mS) \rightarrow \pi\pi + \Upsilon(nS)$, n=1, m-1

Hadronic transitions among heavy quarkonium states (low q^2 hadronization processes) → excellent testing ground for non-perturbative QCD

QCDME

gluon radiation from a heavy qq bound state calculated in terms of chromo-electric and chromo-magnetic fields in analogy to electromagnetism – transitions between colorless hadrons require emission of at least two gluons

Factorization low momentum gluon emission followed by hadronization multipole picture :
2xE1 → h= $\pi\pi$



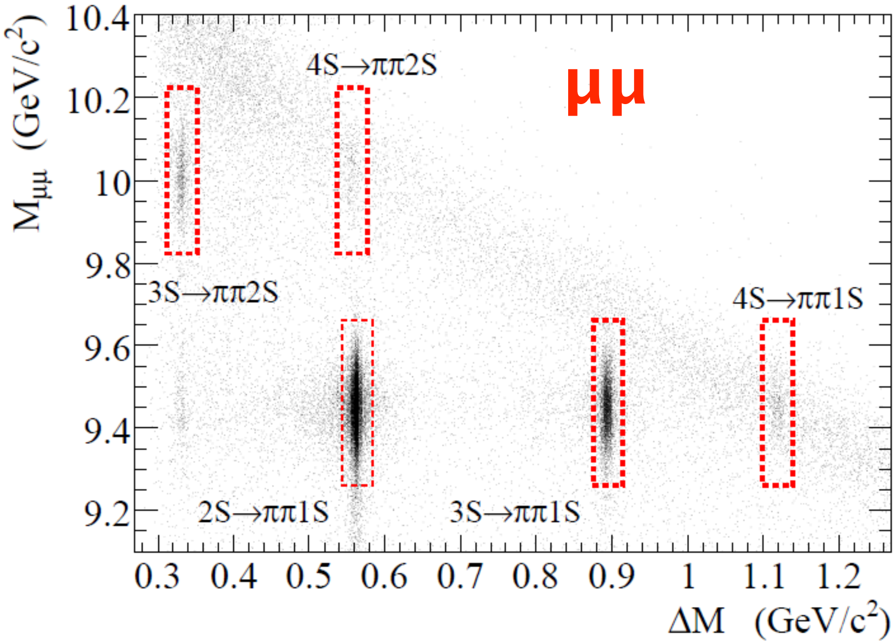
Hadronic transitions between bottomonium states

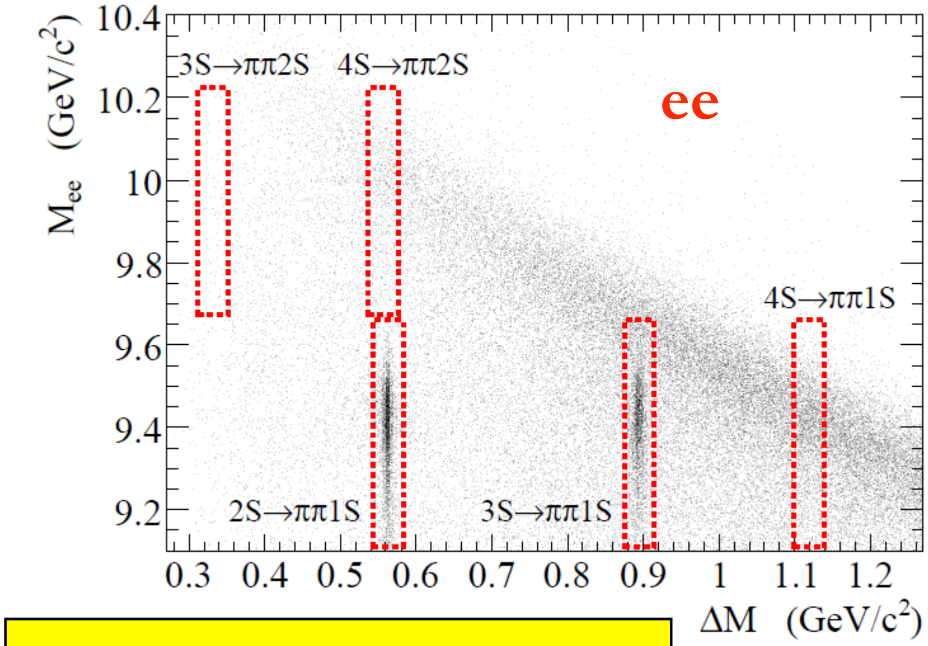
$\Upsilon(mS) \rightarrow \pi\pi + \Upsilon(2,\ 1S)$

BABAR **PRD 78, 112002(2008)**

$(383.2 \pm 4.2) \times 10^6$ $\Upsilon(4S)$

use $\Upsilon(4S) \rightarrow \pi^+\pi^- \Upsilon(nS)$ $(n=1,2)$ by reconstructing $\Upsilon(nS)$ meson via leptonic decay $\mu^+\mu^-$ or e^+e^-, look at l^+l^- invariant mass M_{ll} and invariant mass difference $\Delta M = M_{\pi\pi ll} - M_{ll}$ compatible with $M(\Upsilon(4S)) - M(\Upsilon(nS))$





$\Delta M = M_{\pi\pi ll} - M_{ll}$ $\quad l = e, \mu$

Hadronic transitions between bottomonium states

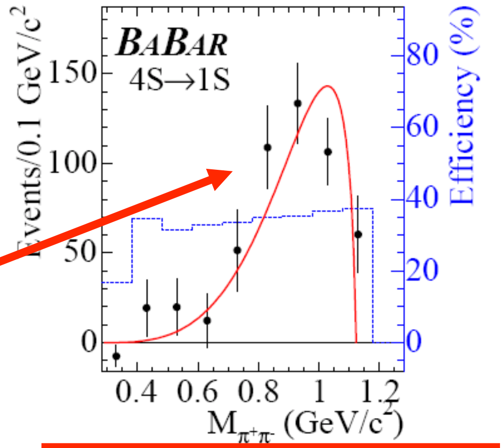
Υ(mS) → ππ + Υ(nS), n=1, m-1

*Primary Observable dipion system invariant mass M(**ππ**-recoil) = M(Υ(nS))*

QCD multipole expansion model QCDME explains

- Relative rates ψ(2S) → η J/ψ and ψ(2S)→ ππ J/ψ
- ππ invariant mass distributions in ψ(2S→ππ J/ψ, Υ(2S) → ππ Υ(1S), Υ(3S) → ππ Υ(2S) and

  Υ(4S) → ππ Υ(1S)



PRL96, 232001 (2006)

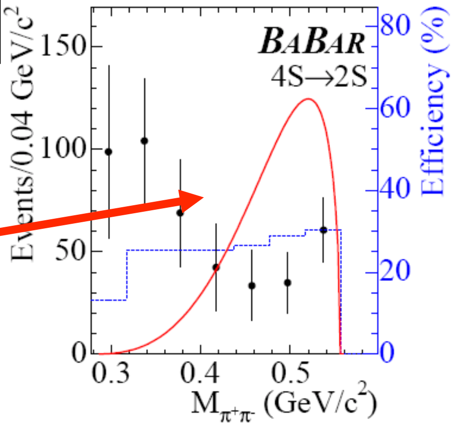
QCD multipole expansion model QCDME does not explain

- Dipion invariant mass distributions in Υ(3S) → ππ Υ(1S)

  CLEO PRD 49, 40(1994)

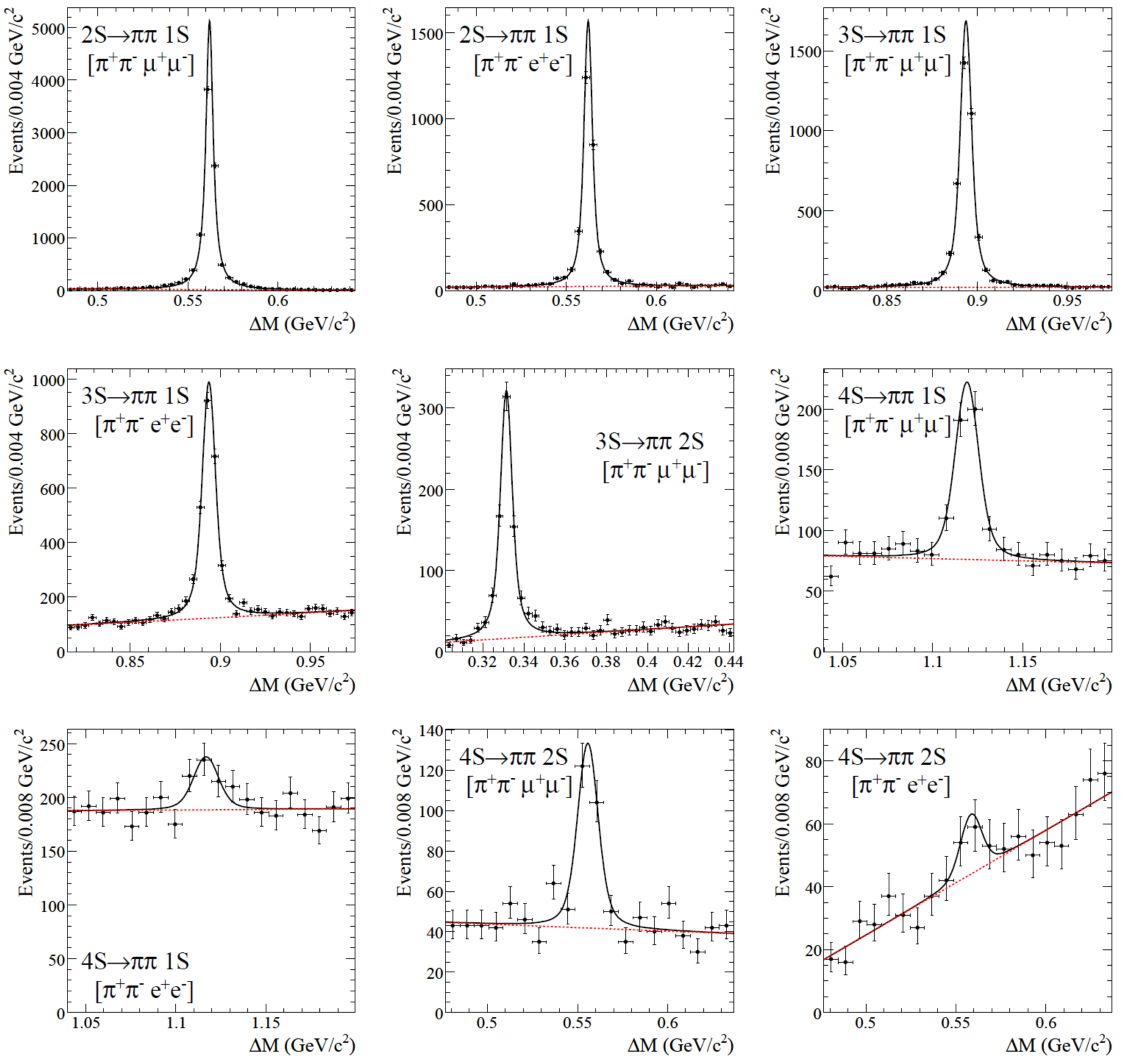
  and in

  Υ(4S) → ππ Υ(2S) *BABAR PRL96, 232001 (2006)*



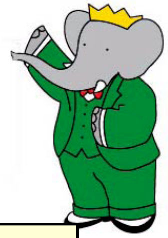
Hadronic transitions between bottomonium states

$\Upsilon(mS) \rightarrow \pi\pi + \Upsilon(2, 1S)$



BABAR **PRD 78, 112002(2008)**

Transitions from 2S, 3S, 4S observed: e^+e^- and $\mu^+\mu^-$ modes



2S → 1S

(17.22±0.17±0.75)%

3S → nS

1S: (4.17±0.06±0.19)%

2S: (2.40±0.10±0.26)%

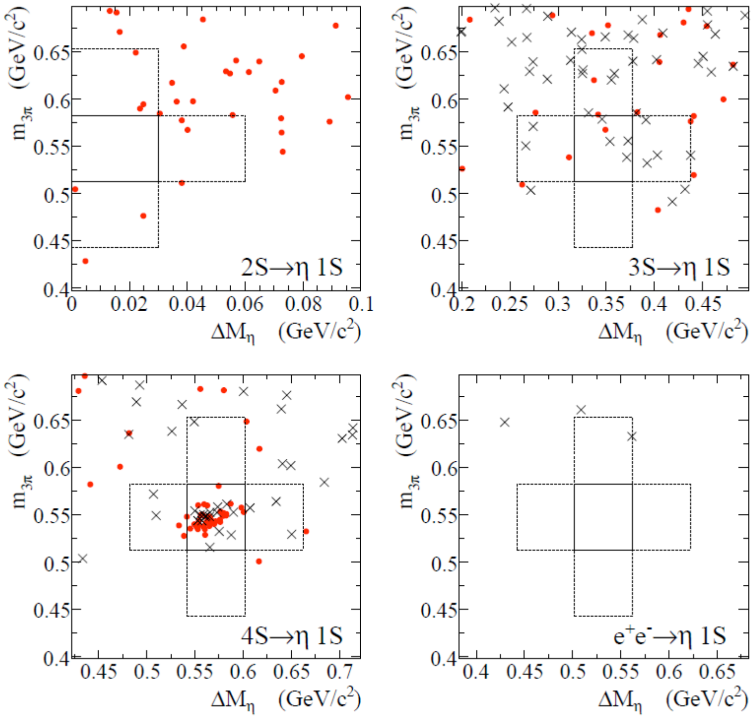
4S → nS

1S: (0.800±0.064±0.027) x 10^{-4}

2S: (0.86±0.11±0.07) x 10^{-4}

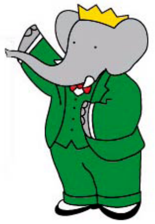
Hadronic transitions between bottomonium states

ϒ(mS) → η + ϒ(2, 1S)



ϒ(2, 3S) → ηϒ(1S) searched for in ISR sample

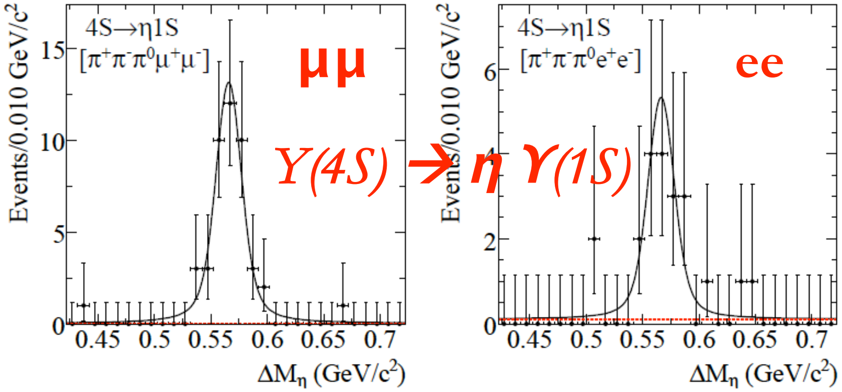
BABAR PRD 78, 112002(2008)



90% C.L. upper limits

B(ϒ(2S) → ηϒ(1S)) < 9 x 10^{-4}

B(ϒ(3S) → ηϒ(1S)) < 8 x 10^{-4}



Y(4S) → η Y(1S)

$$\mathcal{B}(\Upsilon(4S) \to \eta\Upsilon(1S)) = (1.96 \pm 0.06_{stat} \pm 0.09_{syst}) \times 10^{-4}$$

$$\Gamma(\Upsilon(4S) \to \eta\Upsilon(1S))/\Gamma(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)) = 2.41 \pm 0.40_{stat} \pm 0.12_{syst}$$

$$\Gamma(\Upsilon(2S) \to \eta\Upsilon(1S))/\Gamma(\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)) < 5.2 \times 10^{-3}$$

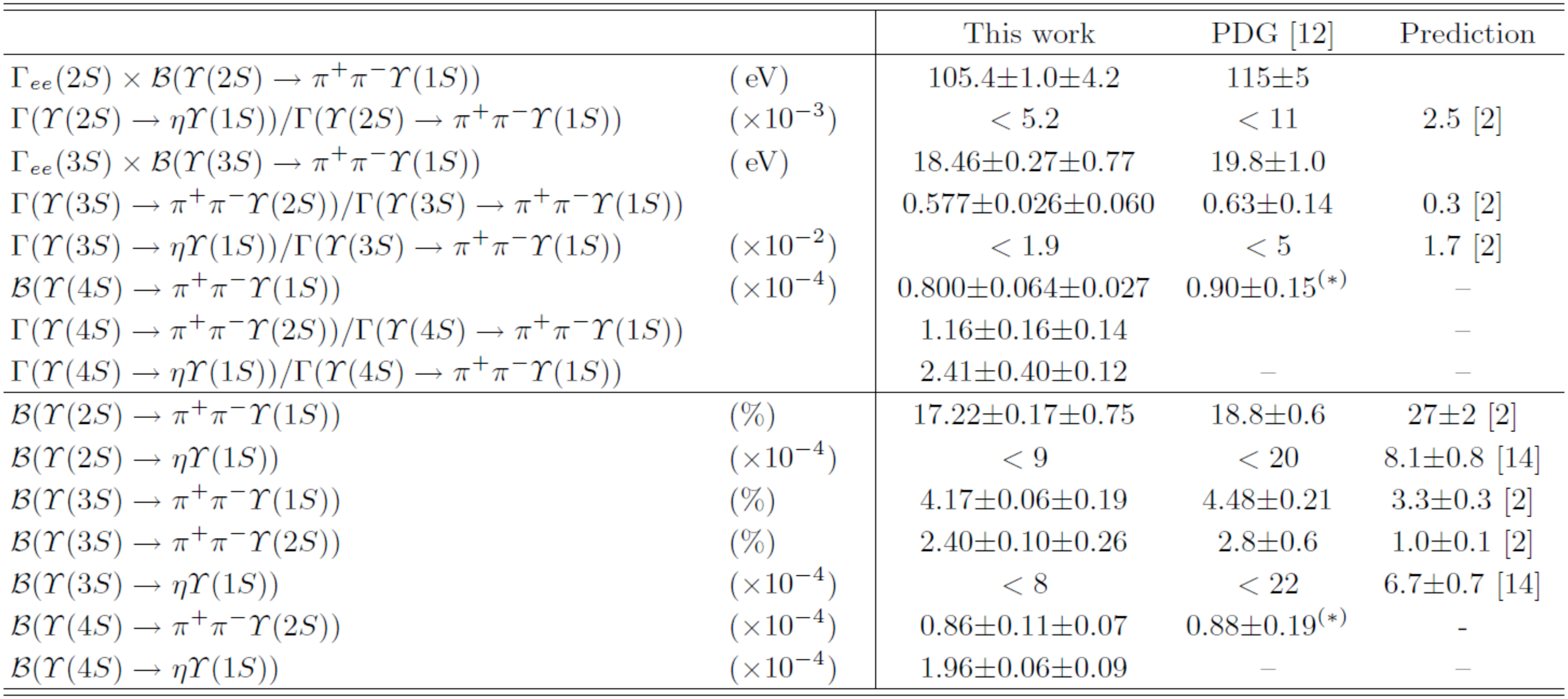
$$\Gamma(\Upsilon(3S) \to \eta\Upsilon(1S))/\Gamma(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)) < 1.9 \times 10^{-2}$$

Hadronic transitions between bottomonium states

$\Upsilon(mS) \rightarrow \pi\pi + \Upsilon(2,\ 1S)$

All 90% C.L. upper limits

BABAR PRD 78, 112002(2008)



		This work	PDG [12]	Prediction
$\Gamma_{ee}(2S) \times \mathcal{B}(\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S))$	(eV)	$105.4 \pm 1.0 \pm 4.2$	115 ± 5	
$\Gamma(\Upsilon(2S) \to \eta\Upsilon(1S))/\Gamma(\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S))$	$(\times 10^{-3})$	< 5.2	< 11	2.5 [2]
$\Gamma_{ee}(3S) \times \mathcal{B}(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S))$	(eV)	$18.46 \pm 0.27 \pm 0.77$	19.8 ± 1.0	
$\Gamma(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(2S))/\Gamma(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S))$		$0.577 \pm 0.026 \pm 0.060$	0.63 ± 0.14	0.3 [2]
$\Gamma(\Upsilon(3S) \to \eta\Upsilon(1S))/\Gamma(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S))$	$(\times 10^{-2})$	< 1.9	< 5	1.7 [2]
$\mathcal{B}(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S))$	$(\times 10^{-4})$	$0.800 \pm 0.064 \pm 0.027$	$0.90 \pm 0.15^{(*)}$	–
$\Gamma(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S))/\Gamma(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S))$		$1.16 \pm 0.16 \pm 0.14$		–
$\Gamma(\Upsilon(4S) \to \eta\Upsilon(1S))/\Gamma(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S))$		$2.41 \pm 0.40 \pm 0.12$	–	–
$\mathcal{B}(\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S))$	(%)	$17.22 \pm 0.17 \pm 0.75$	18.8 ± 0.6	27 ± 2 [2]
$\mathcal{B}(\Upsilon(2S) \to \eta\Upsilon(1S))$	$(\times 10^{-4})$	< 9	< 20	8.1 ± 0.8 [14]
$\mathcal{B}(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S))$	(%)	$4.17 \pm 0.06 \pm 0.19$	4.48 ± 0.21	3.3 ± 0.3 [2]
$\mathcal{B}(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(2S))$	(%)	$2.40 \pm 0.10 \pm 0.26$	2.8 ± 0.6	1.0 ± 0.1 [2]
$\mathcal{B}(\Upsilon(3S) \to \eta\Upsilon(1S))$	$(\times 10^{-4})$	< 8	< 22	6.7 ± 0.7 [14]
$\mathcal{B}(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S))$	$(\times 10^{-4})$	$0.86 \pm 0.11 \pm 0.07$	$0.88 \pm 0.19^{(*)}$	-
$\mathcal{B}(\Upsilon(4S) \to \eta\Upsilon(1S))$	$(\times 10^{-4})$	$1.96 \pm 0.06 \pm 0.09$	–	–

Energy Scan above the Υ(4S)

- Motivation
  - Search for bottomonium states that do not behave as two-quark states (in analogy to Y(4260), Y(4350) and Y(4660) exotic states); such states would have a mass above the Υ(4S) and below 11.2 GeV.
- Procedure
  - Precision scan in √s from 10.54 to 11.20 GeV
    - 5 MeV steps collecting ~25 pb^{-1} at each step **(3.3 fb^{-1} total)**
    - **600 pb^{-1}** scan in energy range 10.96 to 11.10 GeV in 8 steps with unequal energy spacing (investigation of Υ(6S))
- Measurement
  - Inclusive hadronic cross section

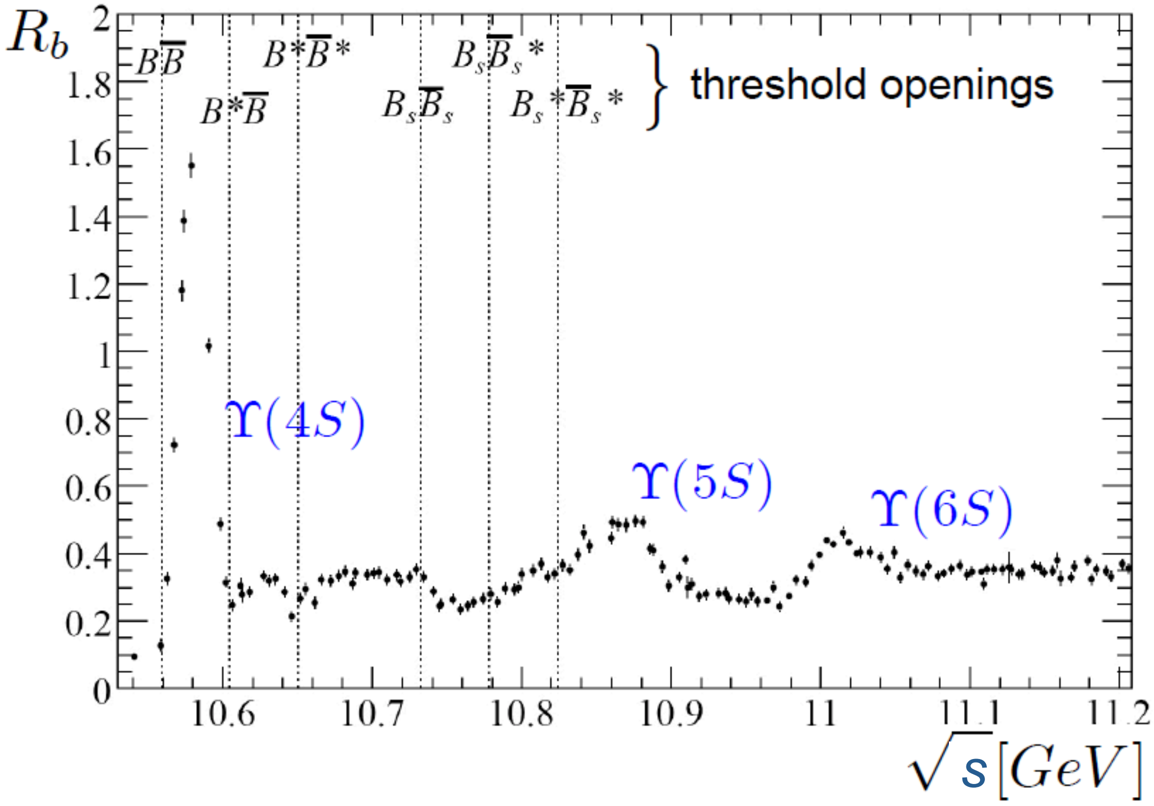
$$R_b(s) = \frac{\sigma_{bb(\gamma)}(s)}{\sigma^0_{\mu\mu}(s)}$$

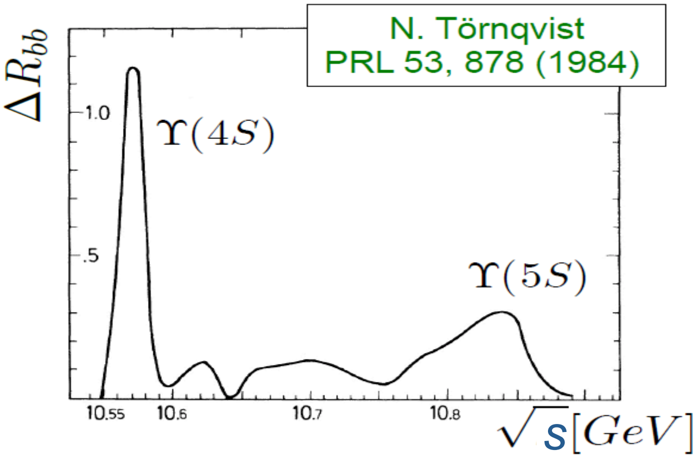
$\sigma_{bb(\gamma)}$: cross section for $e^+e^- \to b\bar{b}(\gamma)$

$\sigma^0_{\mu\mu} = 4\pi\alpha^2/3s$: 0th order cross section for $e^+e^- \to \mu^+\mu^-$

Energy Scan above the Y(4S): Results

Inclusive hadronic cross section measurement (PRL 102,012001 (2009))





N. Törnqvist
PRL 53, 878 (1984)

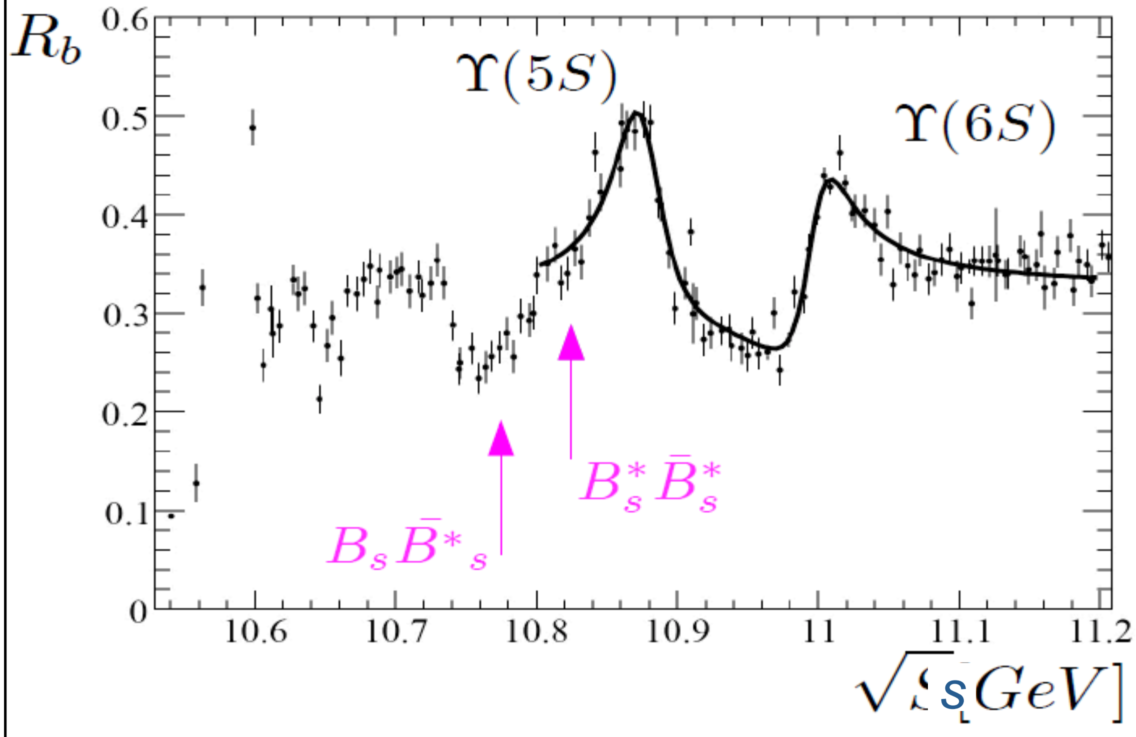
Consistent with
coupled channel predictions

Clear structures corresponding to the $b\overline{b}$ opening thresholds

Y(5S) and Y(6S) Mass and Width Measurement

Fit with non-resonant amplitude & flat component added coherently with two interfering relativistic Breit-Wigner functions

$$\sigma = \underbrace{|A_{nr}|^2}_{} + \underbrace{|B_r + A_{5S}e^{i\phi_{5S}}BW(M_{5S},\Gamma_{5S}) + A_{6S}e^{i\phi_{6S}}BW(M_{6S},\Gamma_{6S})|^2}_{}$$



re

PRL 102, 012001 (2009)

	$\Upsilon(5S)$	$\Upsilon(6S)$
$M[MeV]$	10876 ± 2	10960 ± 2
$\Gamma[MeV]$	43 ± 4	37 ± 3
$\phi[rad]$	2.11 ± 0.12	0.12 ± 0.07
$M_{PDG}[MeV]$	10865 ± 8	11019 ± 8
$\Gamma_{PDG}[MeV]$	110 ± 13	79 ± 16

Incoherent superposition of Gaussians and bckgr.

$\Upsilon(5S)$ and $\Upsilon(6S)$ candidates are affected by threshold effects and interference

Plateau above $\Upsilon(6S)$

Compared to CLEO & CUSB,
BaBar has:
- >30 x more data
- 4 x smaller energy steps
- Much more precise definition of shape

Summary

- First observation and confirmation of the $\eta_b(1S)$ bottomonium ground state was truly a tour de force piece of physics and unique experience for all who were intimately involved in in BaBar Run 7 and analyses of the data.

- The mass is $m(\eta_b(1S)) = 9390.4 \pm 3.1\ \mathrm{MeV}/c^2$
  and hyperfine splitting is $\Delta M_{HFS} = 69.9 \pm 3.1\ \mathrm{MeV}/c^2$.

- Theoretical work on these numbers - especially lattice QCD computations- continues but the dust has not settled.

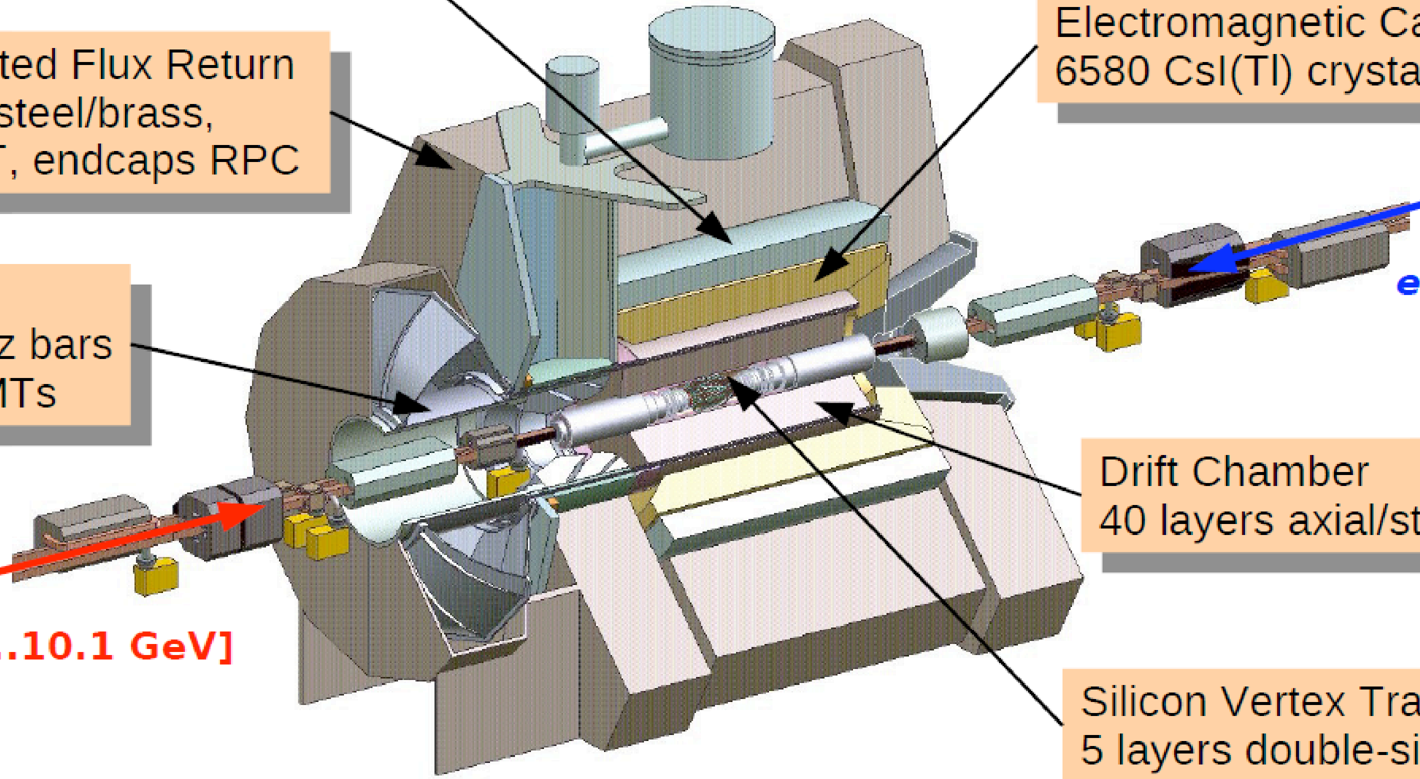
- There are a lot of new results in hadronic transitions between the bottomonium states, but a lot more effort is needed - especially in manpower. Needless to say, theoretical predictions which are at the 10% to 20% level need to be sharpened to a few percent level. There are hints that some of the qualtitative expectations are not born out by experiment - e.g. the di-pion mass spectra. Stay tuned for decays of Bottomonium to open charm etc.; for exotics and beyond SM, see Yury's talk.

- Precision scan of R_b in the energy range $10.54 < \sqrt{s} < 11.20$ GeV yields parameters for $\Upsilon(5S)$ and Y (6S), which differ from the PDG averages. Threshold effects remain to be understood in detail.

BACK-UP SLIDES

BaBar

$\sigma(E)/E \sim 2.5\%$
at 1 GeV



1.5 T Solenoid

Instrumented Flux Return
18 layers steel/brass,
barrel LST, endcaps RPC

Electromagnetic Calorimeter
6580 CsI(Tl) crystals

DIRC
144 quartz bars
11000 PMTs

e^+ [3.1 GeV]

Drift Chamber
40 layers axial/stereo wires

e^- [8.0...10.1 GeV]

Silicon Vertex Tracker
5 layers double-sided strips

Designed to study *CP* violation in the *B* system, yet produced a diverse portfolio of results in many areas

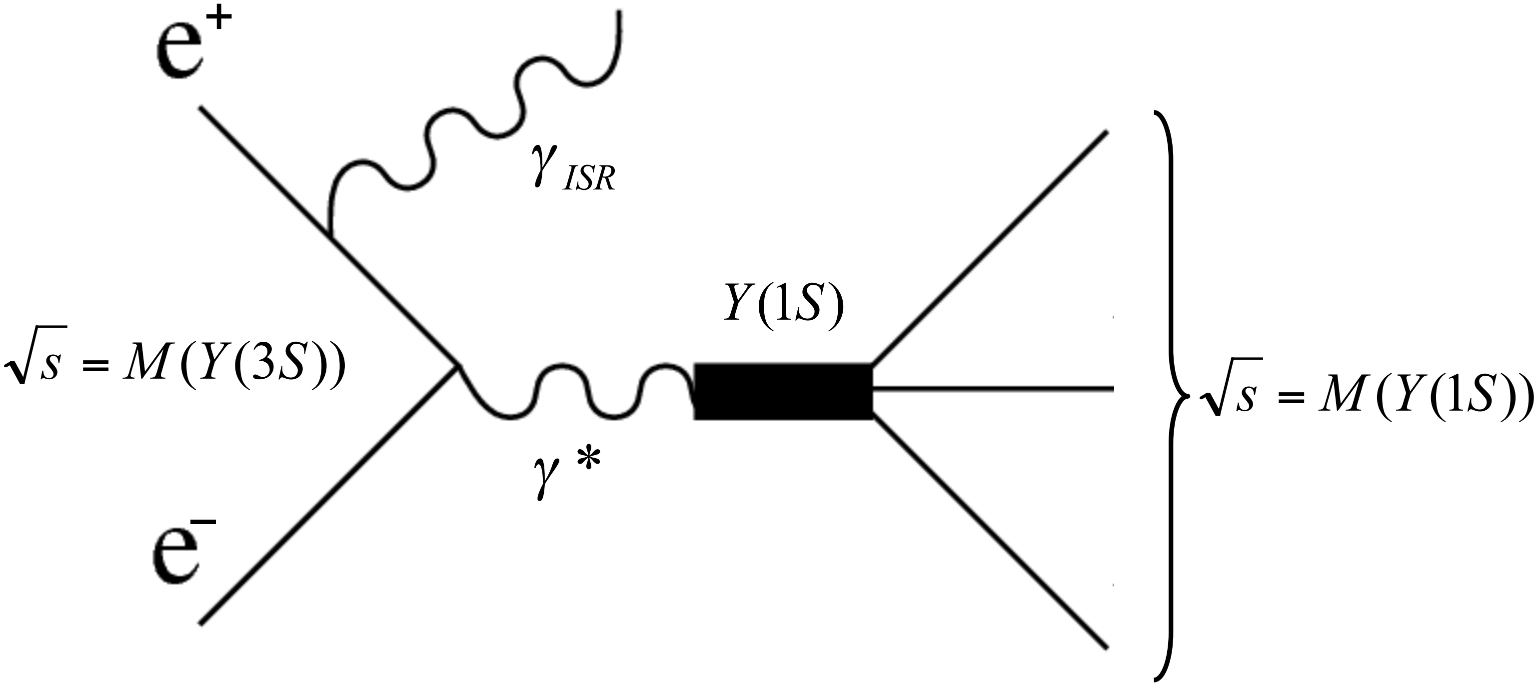


Figure 1: The diagram for the $e^+e^- \to \gamma_{ISR}\, Y(1S)$ process.

Summary of Results

Phys.Rev.Lett.100;06200 (2008)

- Signal Yield :
  - Estimate of Branching Fraction (expected transition rate):

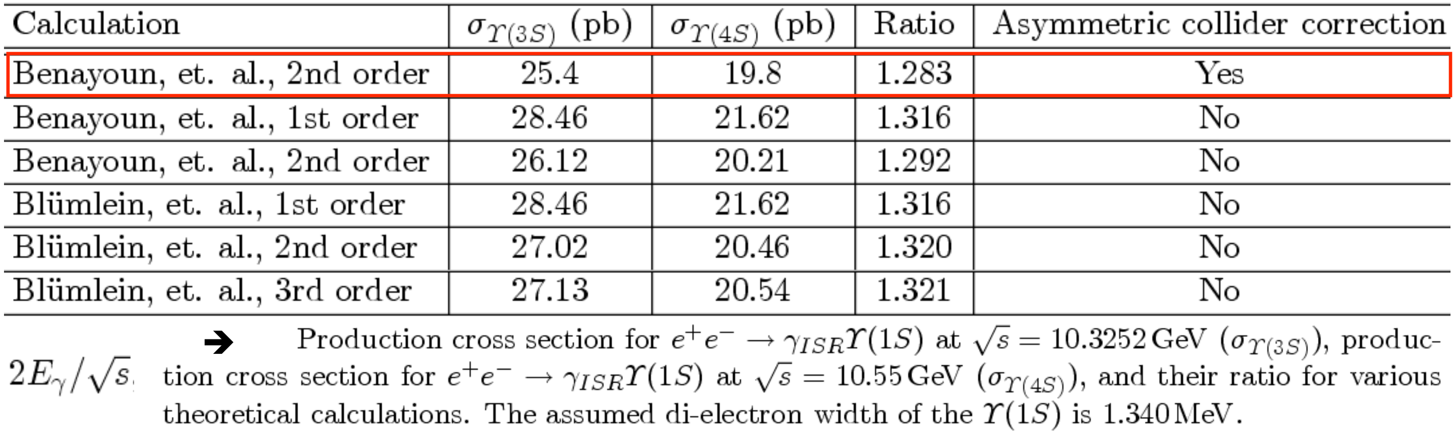
➔ BF ($\Upsilon(3S)\rightarrow \gamma\ \eta_b$) = (4.5 ± 0.5 [stat.] ± 1.2 [syst.]) x 10^{-4}

- Mass of the $\eta_b(1S)$:
  - Peak in γ energy spectrum at $E_\gamma = 921.2^{+2.1}_{-2.8}(\mathrm{stat})\,\mathrm{MeV}$
  - Corresponds to η_b mass $9388.9^{+3.1}_{-2.3}(\mathrm{stat})\,\mathrm{MeV}/c^2$
  - The hyperfine ($\Upsilon(1S)$-$\eta_b(1S)$) splitting is $71.4^{+2.3}_{-3.1}(\mathrm{stat})\,\mathrm{MeV}/c^2$

QCD Calculations of the η_b mass and branching fraction

- Recksiegel and Sumino, Phys. Lett. B 578, 369 (2004) [hep-ph/0305178]
- Kniehl et al., PRL 92 242001 (2004) [hep-ph/0312086]
- Godfrey and Isgur, PRD 32, 189 (1985)
- Fulcher, PRD 44, 2079 (1991)
- Eichten and Quigg, PRD 49, 5845 (1994) [hep-ph/9402210]
- Gupta and Johnson, PRD 53, 312 (1996) [hep-ph/9511267]
- Ebert et al., PRD 67, 014027 (2003) [hep-ph/0210381]
- Zeng et al., PRD 52, 5229 (1995) [hep-ph/9412269]

$e^+e^- \to \gamma_{ISR}Y(1S)$ Calculations



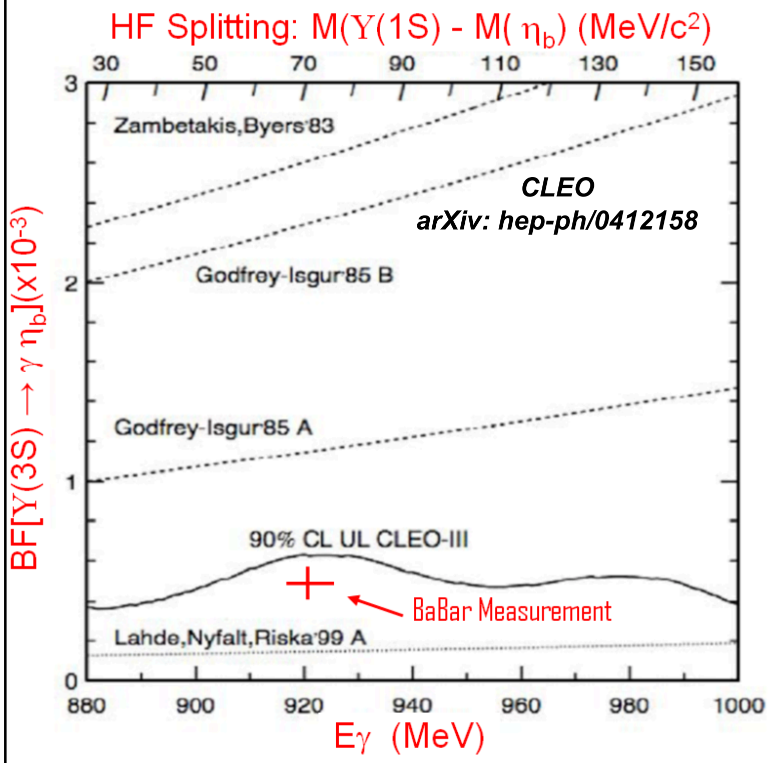
Calculation	$\sigma_{\Upsilon(3S)}$ (pb)	$\sigma_{\Upsilon(4S)}$ (pb)	Ratio	Asymmetric collider correction
Benayoun, et. al., 2nd order	25.4	19.8	1.283	Yes
Benayoun, et. al., 1st order	28.46	21.62	1.316	No
Benayoun, et. al., 2nd order	26.12	20.21	1.292	No
Blümlein, et. al., 1st order	28.46	21.62	1.316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

$$\sigma_V(s) = \frac{12\pi^2\Gamma_{ee}}{m_V s} \cdot W(s, x_v)$$

$$x_v = 2E_\gamma/\sqrt{s}$$

➔ Production cross section for $e^+e^- \to \gamma_{ISR}\Upsilon(1S)$ at $\sqrt{s} = 10.3252\,\mathrm{GeV}$ ($\sigma_{\Upsilon(3S)}$), production cross section for $e^+e^- \to \gamma_{ISR}\Upsilon(1S)$ at $\sqrt{s} = 10.55\,\mathrm{GeV}$ ($\sigma_{\Upsilon(4S)}$), and their ratio for various theoretical calculations. The assumed di-electron width of the $\Upsilon(1S)$ is $1.340\,\mathrm{MeV}$.

SUMMARY OF η_b MEASUREMENTS from Y(3S)



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

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

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

ΔM = 61 +/- 14 MeV/c²

- lattice spacing: +/- 4 MeV/c²
- QCD radiative corrections: +/- 12 MeV/c²
- relativistic corrections: +/- 6 MeV/c²

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

ΔM = 60 MeV/c²

(Relativized Quark Model with Chromodynamics)

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

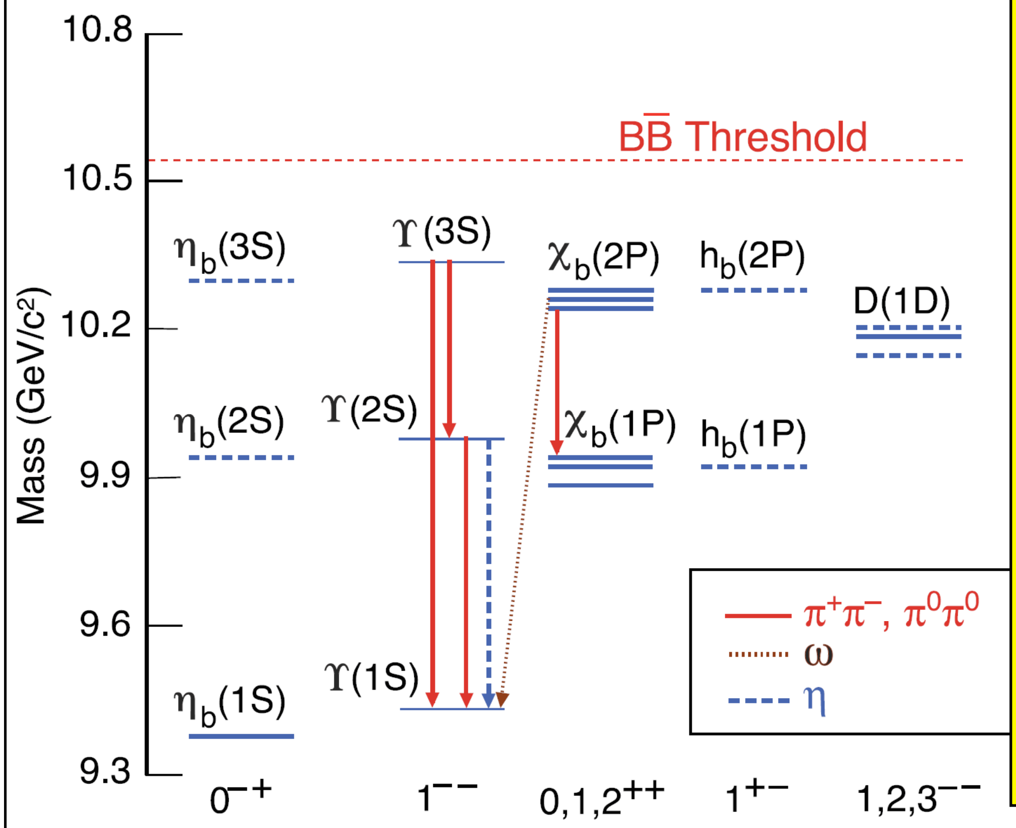
cf. upper limit on B.F. **< 4.3 x 10⁻⁴ @ 90%** [CLEO III]

	M(PDG) (GeV/c^2)		Transition	BF	E*(γ) (GeV)		Transition	BF	E*(γ) (GeV)			BF	E*(γ) (GeV)
Y(3S)	10.3552						Y(3S)->Y(2S)	10.60%					
Y(2S)	10.0233		ee(@Y3S) → γ Y(2S)	0.001%	0.3266								
Y(1S)	9.4603		ee(@Y3S) → γ Y(1S)		0.8562								
χ_{b2}(2P)	10.2687		Y(3S) → γ χ_{b2}(2P)	13.1%	0.0862	→	χ_{b2}(2P) → γ Y(2S)	0.0212%	0.2425	→	Y(2S) → γ χ_{b2}(1P)	0.758%	0.1104
χ_{b1}(2P)	10.2555		Y(3S) → γ χ_{b1}(2P)	12.6%	0.0993	→	χ_{b1}(2P) → γ Y(2S)	0.0204%	0.2296	→	Y(2S) → γ χ_{b1}(1P)	0.731%	0.1296
χ_{b0}(2P)	10.2325		Y(3S) → γ χ_{b0}(2P)	5.9%	0.1220	→	χ_{b0}(2P) → γ Y(2S)	0.0096%	0.2071	→	Y(2S) → γ χ_{b0}(1P)	0.403%	0.1625
χ_{b2}(1P)	9.9122		Y(3S) → γ χ_{b2}(1P)		0.4335	→	χ_{b2}(1P) → γ Y(1S)	0.0005%	0.4416				
χ_{b1}(1P)	9.8928		Y(3S) → γ χ_{b1}(1P)		0.4521	→	χ_{b1}(1P) → γ Y(1S)	0.0005%	0.4230				
χ_{b0}(1P)	9.8594		Y(3S) → γ χ_{b0}(1P)	0.003%	0.4839	→	χ_{b0}(1P) → γ Y(1S)	0.0004%	0.3911				
η_b(1S)	9.3889		Y(3S) → γ η_b(1S)		0.9212								
η_b(2S)	9.9633		Y(3S) → γ η_b(2S)		0.3845	→	η_b(2S) → γ Y(1S)		0.4903				

Hadronic transitions between bottomonium states

"…for the first 22 years after the observation of hadronic transitions among bottomonium states only 6 ππ transitions among the vector Υ(nS) bottomonia were known…"

CLEO PRD79, 011103(R) (2009)



Recently…

CLEO observed

$\chi_{b1,2}$ (2P) → ω Υ(1S) **PRL92,222002(2004)**

χ_b(2P) → ππχ_b(1P) **PRD73, 012003(2006)**

Υ(2S) → η Υ(1S) **PRL101, 192001(2008)**

BABAR reported extensive measurements of hadronic transitions between Υ states using, in particular, bottomonium states Υ(3S) and Υ(2S) produced via ISR from Υ(4S) on-peak recorded data **PRD78, 112002(2008) & PRL96, 232001(2006)**

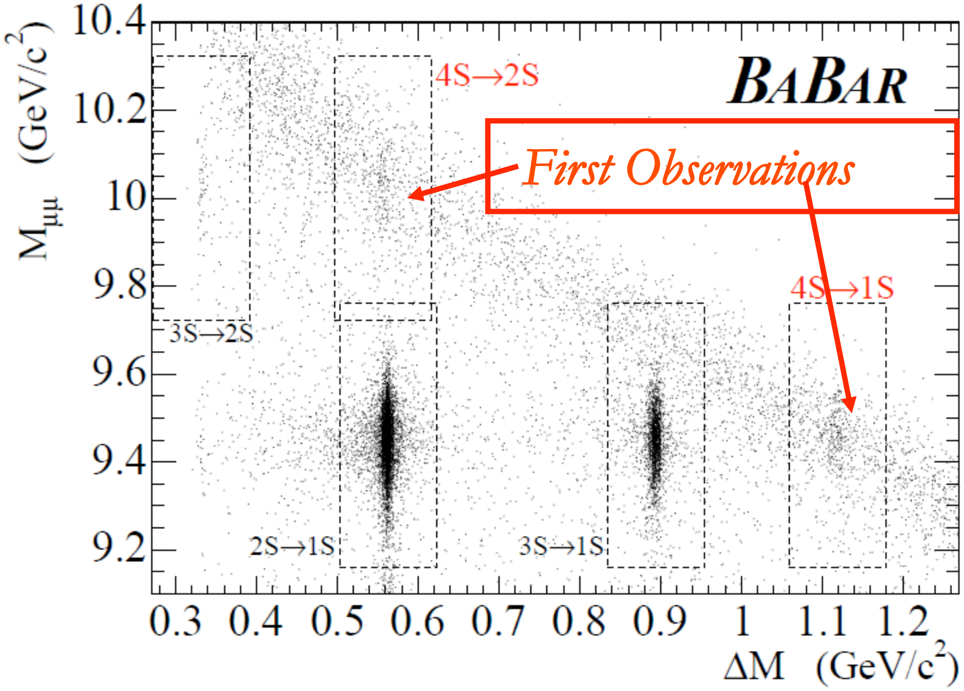
Hadronic transitions between bottomonium states

$\Upsilon(mS) \rightarrow \pi\pi + \Upsilon(2,\ 1S)$

BABAR PRL96, 232001(2006)

$230 \times 10^{6}\ \Upsilon(4S)$

use $\Upsilon(4S) \rightarrow \pi^{+}\pi^{-}\ \Upsilon(nS)$ (n=1,2) by reconstructing $\Upsilon(nS)$ meson via its leptonic decay to $\mu^{+}\mu^{-}$ and look at $\mu^{+}\mu^{-}$ invariant mass $M_{\mu\mu}$ and invariant mass difference $\Delta M = M_{\pi\pi\mu\mu} - M_{\mu\mu}$ compatible with $M(\Upsilon(4S)) - M(\Upsilon(nS))$



First Observations

$B(\Upsilon(4S) \rightarrow \pi^{+}\pi^{-}\Upsilon(1S)) \times B(\Upsilon(1S) \rightarrow \mu^{+}\mu^{-}) = (2.23 \pm 0.25 \pm 0.27) \times 10^{-6}$

$\Gamma(\Upsilon(4S) \rightarrow \pi^{+}\pi^{-}\Upsilon(1S)) = (1.8 \pm 0.4)$ keV

$B(\Upsilon(4S) \rightarrow \pi^{+}\pi^{-}\Upsilon(2S)) \times B(\Upsilon(2S) \rightarrow \mu^{+}\mu^{-}) = (1.69 \pm 0.26 \pm 0.20) \times 10^{-6}$

$\Gamma(\Upsilon(4S) \rightarrow \pi^{+}\pi^{-}\Upsilon(2S)) = (2.7 \pm 0.8)$ keV

Hadronic transitions between bottomonium states

$\Upsilon(mS) \to \pi\pi/\eta/\pi^0 + \Upsilon(nS)$

Branching Fractions *%*	*BaBar* *PRD78, 112002(2008)* *PRL96, 232001(2006)*	*Belle* *PRD(RC)79,051103(2009)*	*CLEO* *PRD79, 011103(2009)* *PRL101, 192001(2008)*
$\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$	$17.22\pm0.17\pm0.75$		$18.02\pm0.02\pm0.61$
$\Upsilon(2S) \to \pi^0\pi^0\Upsilon(1S)$			$8.43\pm0.16\pm0.42$
$\Upsilon(2S) \to \eta\,\Upsilon(1S)$	$<9 \times 10^{-2}$		$2.1^{+0.7}_{-0.6}\pm0.3$
$\Upsilon(2S) \to \pi^0\,\Upsilon(1S)$			$<1.8 \times 10^{-2}$
$\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$	$4.17\pm0.06\pm0.19$		$4.46\pm0.01\pm0.13$
$\Upsilon(3S) \to \pi^0\pi^0\Upsilon(1S)$			$2.24\pm0.09\pm0.11$
$\Upsilon(3S) \to \eta\,\Upsilon(1S)$	$<8 \times 10^{-2}$		$<1.8 \times 10^{-2}$
$\Upsilon(3S) \to \pi^0\,\Upsilon(1S)$			$<0.7 \times 10^{-2}$
$\Upsilon(3S) \to \pi^+\pi^-\Upsilon(2S)$	$2.40\pm0.10\pm0.26$		
$\Upsilon(3S) \to \pi^0\pi^0\Upsilon(2S)$			$1.82\pm0.09\pm0.12$
$\Upsilon(3S) \to \pi^0\,\Upsilon(2S)$			$<5.1 \times 10^{-2}$
$\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)$	$(0.90\pm0.15) \times 10^{-2}$	$(0.85\pm0.12\pm0.06) \times 10^{-2}$	
$\Upsilon(4S) \to \eta\Upsilon(1S)$	$(1.96\pm0.06\pm0.09) \times 10^{-2}$		
$\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S)$	$(0.86\pm0.11\pm0.07) \times 10^{-2}$		