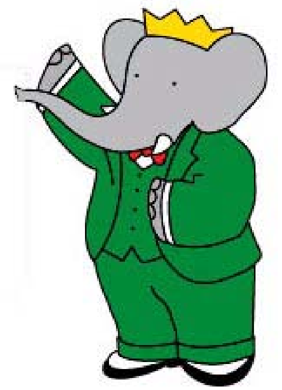
Recent results on bottomonium spectroscopy from Babar

J. William Gary

University of California, Riverside

for the Babar Collaboration

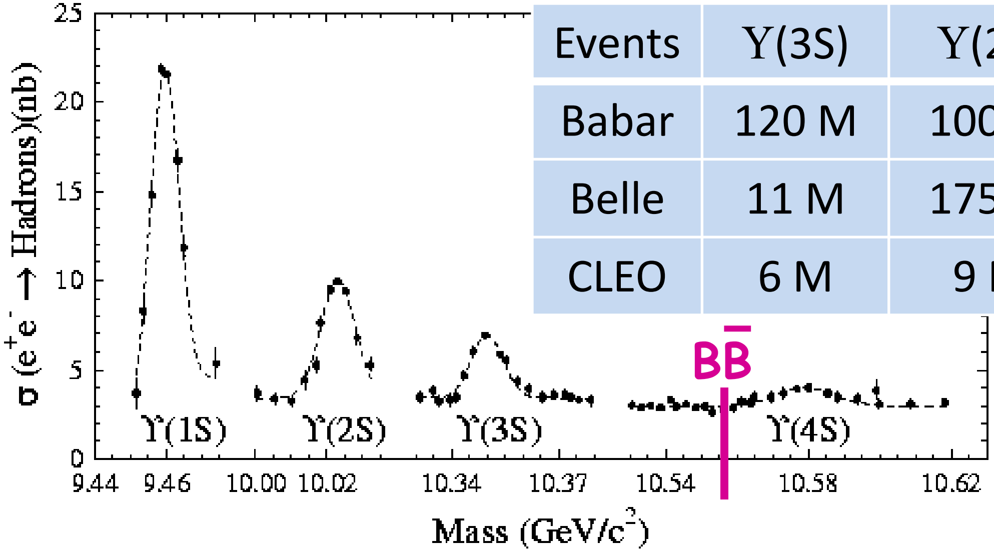
UC RIVERSIDE UNIVERSITY OF CALIFORNIA



Babar experiment

- PEP-II rings: Asymmetric e+e- collider @ SLAC
- Collected data 1999-2008; data analysis still very active

$\Upsilon(4S)$	430 fb^{-1}
$\Upsilon(3S)$	30 fb^{-1}
$\Upsilon(2S)$	14 fb^{-1}
Other (mostly off-resonant)	~60 fb^{-1}



Events	$\Upsilon(3S)$	$\Upsilon(2S)$
Babar	120 M	100 M
Belle	11 M	175 M
CLEO	6 M	9 M

- CPV in B decays, CKM physics **~465x10^6 $\Upsilon(4S) \to B\bar{B}$ events**
- ~650x10^6 $e^+e^- \to c\bar{c}$ events: 1st observation of D^0-$\bar{D}^0$ mixing [2007]
- ~430x10^6 $e^+e^- \to \tau^+\tau^-$ events (360 x combined LEP sample): LFV
- ISR events: unique access to low energy e^+e^- cross sections
- **Spectroscopy**

Topics

<u>Bottomonium</u>: $\Upsilon(3S)$ sample

(I) Search for η_b using $\gamma \to e^+e^-$ conversions
(singlet L=0) [also uses the $\Upsilon(2S)$ sample]

(II) Search for $h_b(1P)$ state (singlet L=1)

(III) Observation of $1D_{J=2}$ state (triplet L=2)
[arXiv:1004.0175]

All results are preliminary

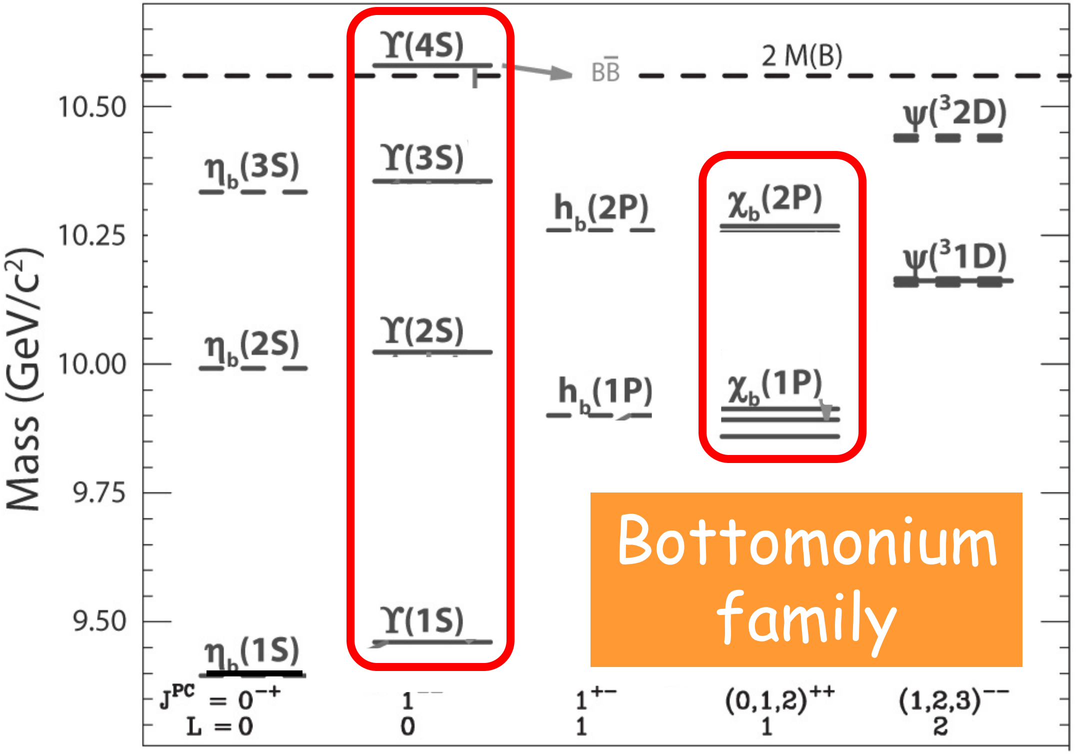
Bottomonium

→ Spectrum below open-flavor threshold richer than charmonium

→ Masses & BFs important to test potential models & lattice QCD

→ Hadronic transitions probe non-perturbative QCD

- Bottomonium states with L=0,1 & S=1
  → known since 1970s & 1980s
- $\Upsilon(1D_{J=2})$ observed by CLEO (2004)
- η_b by Babar (2008)
- $h_b(1P)$ state not yet observed



Bottomonium family

From Eichten et al.,
Rev. Mod. Phys. 80 (2008) 1161

—— = seen
- - - - = unseen

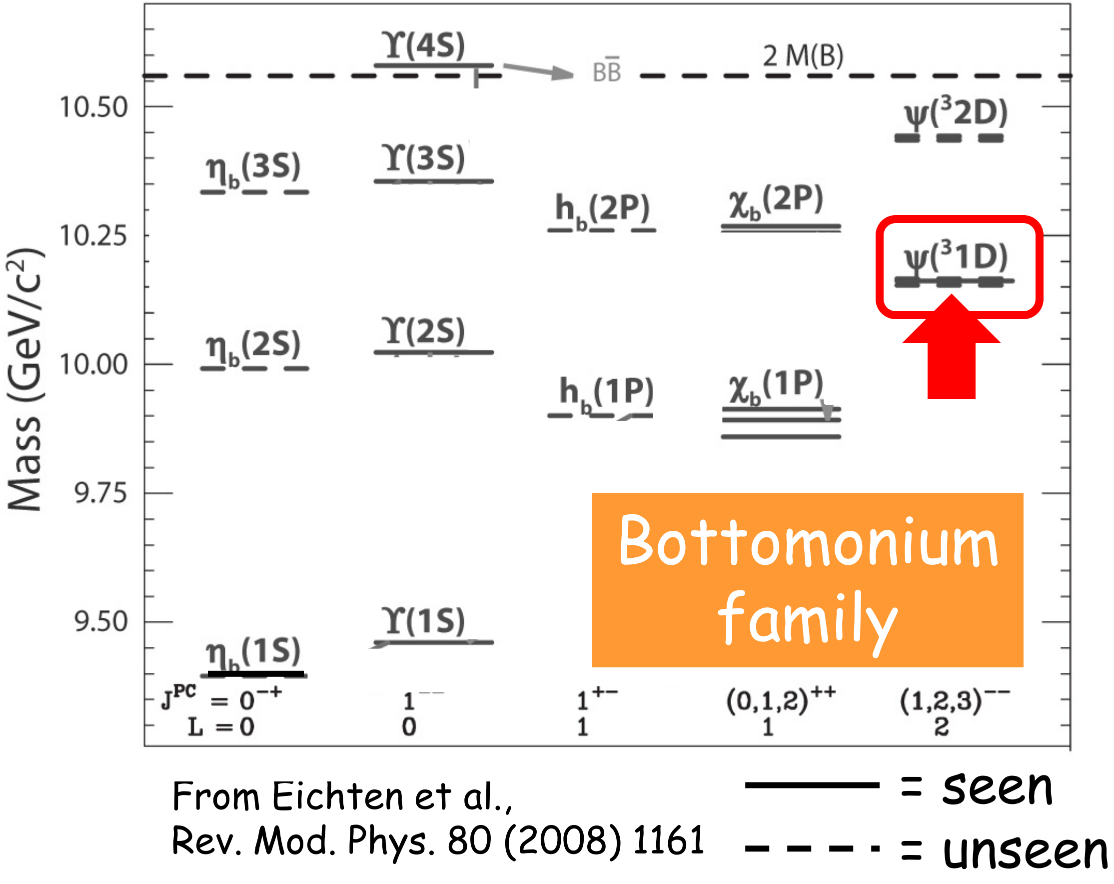
Bottomonium

→ Spectrum below open-flavor threshold richer than charmonium

→ Masses & BFs test potential models & lattice QCD

→ Hadronic transitions probe non-perturbative QCD

- Bottomonium states with L=0,1 & S=1 → known since 1970s & 1980s
- $\Upsilon(1^3D_{J=2})$ observed by CLEO (2004)
- η_b by Babar (2008)
- $h_b(1P)$ state not yet observed



From Eichten et al., Rev. Mod. Phys. 80 (2008) 1161

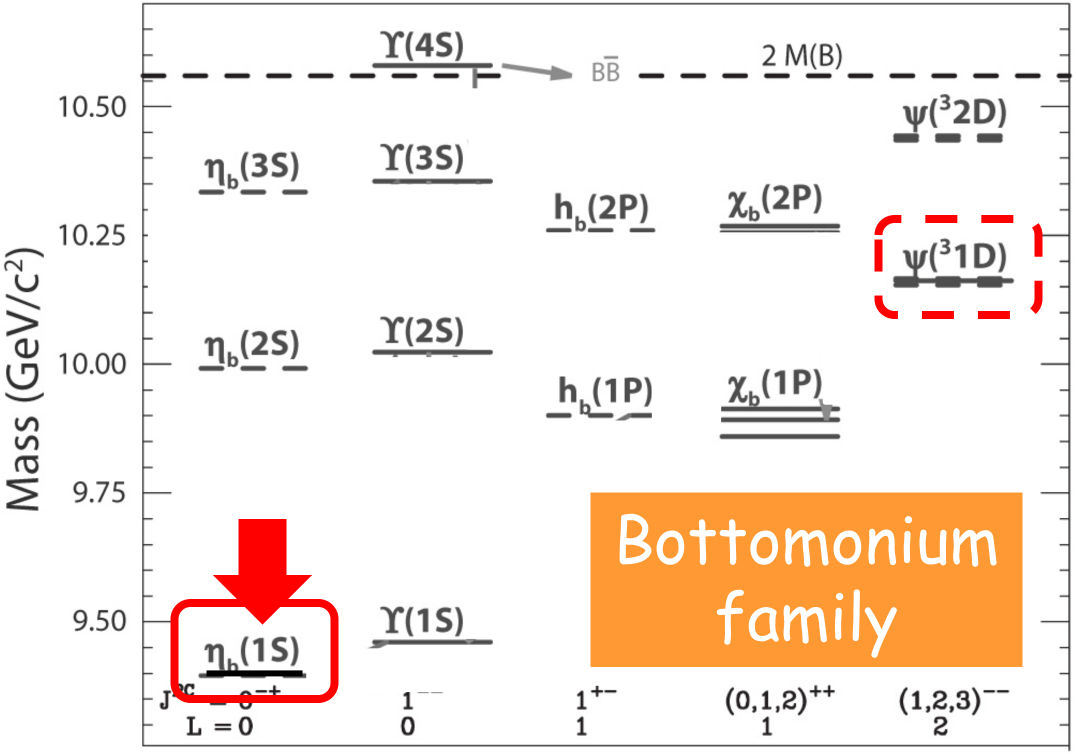
Bottomonium

→ Spectrum below open-flavor threshold richer than charmonium

→ Masses & BFs test potential models & lattice QCD

→ Hadronic transitions probe non-perturbative QCD

- Bottomonium states with L=0,1 & S=1
  → known since 1970s & 1980s
- $\Upsilon(1D_{J=2})$ observed by CLEO (2004)
- **η_b by Babar (2008)**
- $h_b(1P)$ state not yet observed



Bottomonium family

From Eichten et al., Rev. Mod. Phys. 80 (2008) 1161

—— = seen

- - - - = unseen

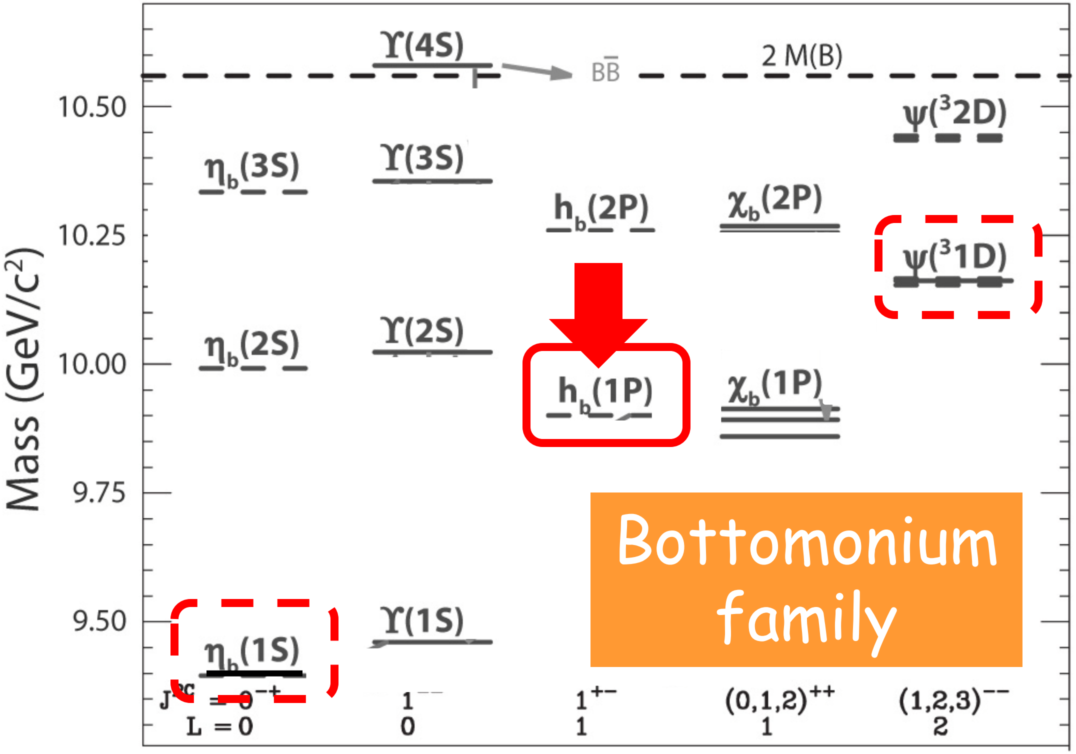
Bottomonium

→ Spectrum below open-flavor threshold richer than charmonium

→ Masses & BFs test potential models & lattice QCD

→ Hadronic transitions probe non-perturbative QCD

- Bottomonium states with L=0,1 & S=1
  → known since 1970s & 1980s
- $\Upsilon(1D_{J=2})$ observed by CLEO (2004)
- η_b by Babar (2008)
- $h_b(1P)$ state not yet observed



From Eichten et al.,
Rev. Mod. Phys. 80 (2008) 1161

—— = seen

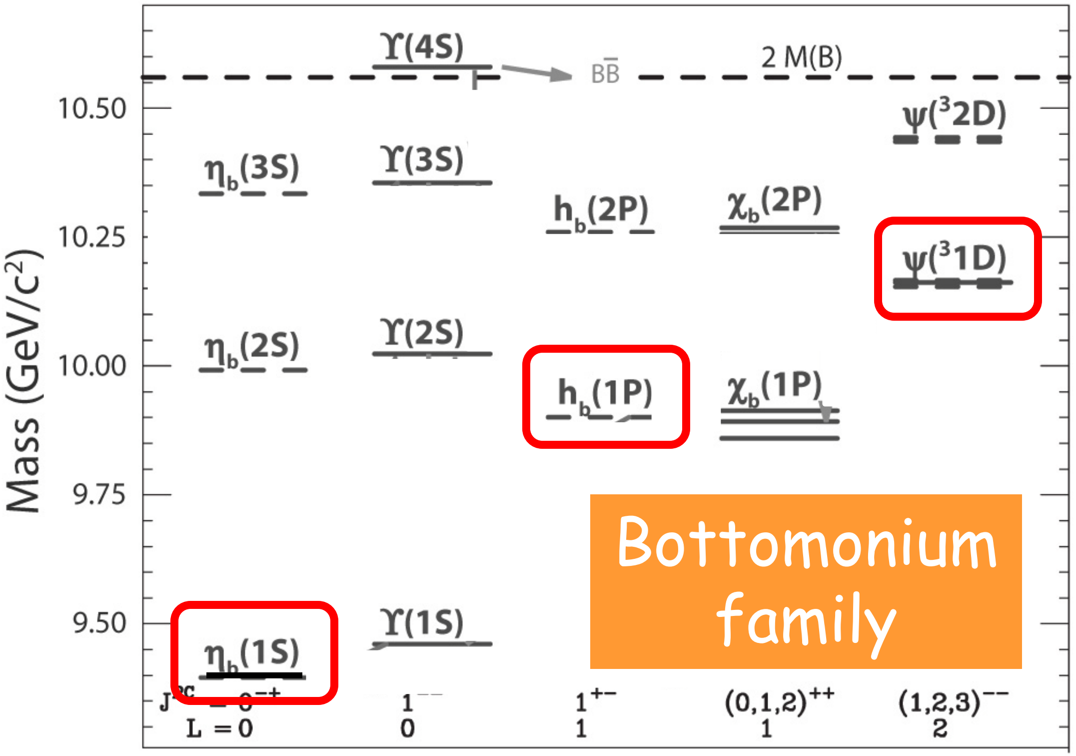
- - - - = unseen

Bottomonium

□ = the states discussed here

η_b and h_b : hyperfine mass splittings
→ spin dependence of the $q\bar{q}$ potential

- Bottomonium states with L=0,1 & S=1 → known since 1970s & 1980s
- $\Upsilon(1D_{J=2})$ observed by CLEO (2004)
- η_b by Babar (2008)
- $h_b(1P)$ state not yet observed

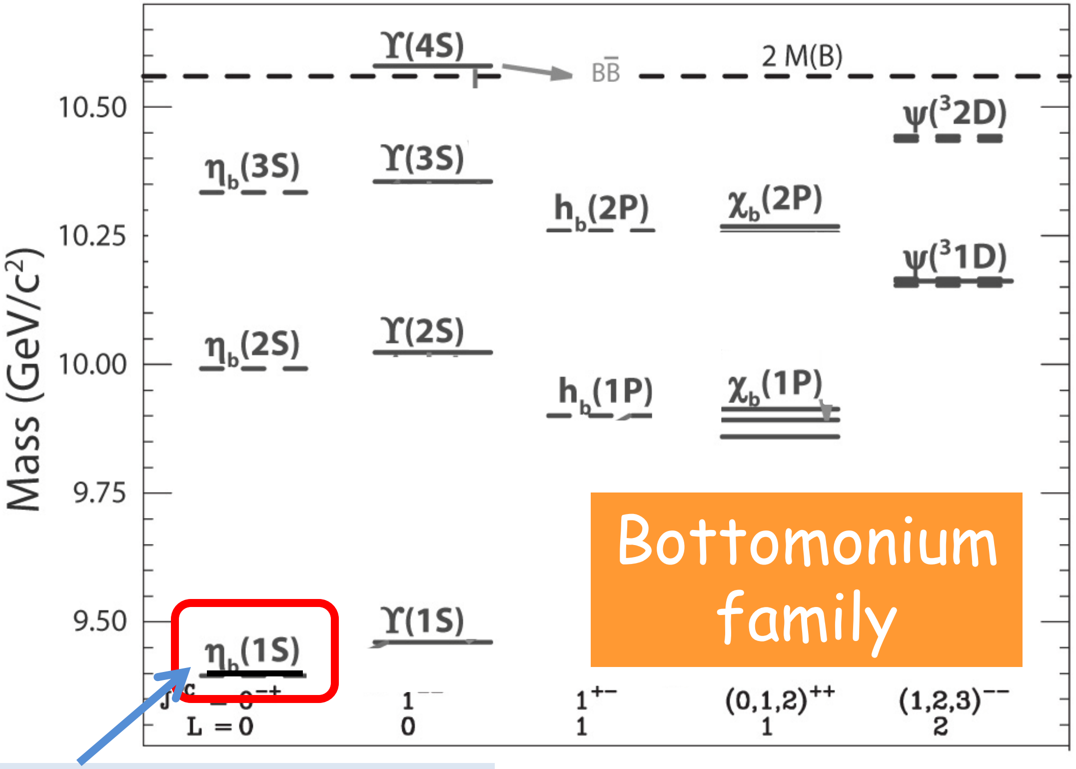


Bottomonium family

From Eichten et al.,
Rev. Mod. Phys. 80 (2008) 1161

—— = seen
- - - - = unseen

(I) η_b search using $\gamma \to e^+e^-$ conversions

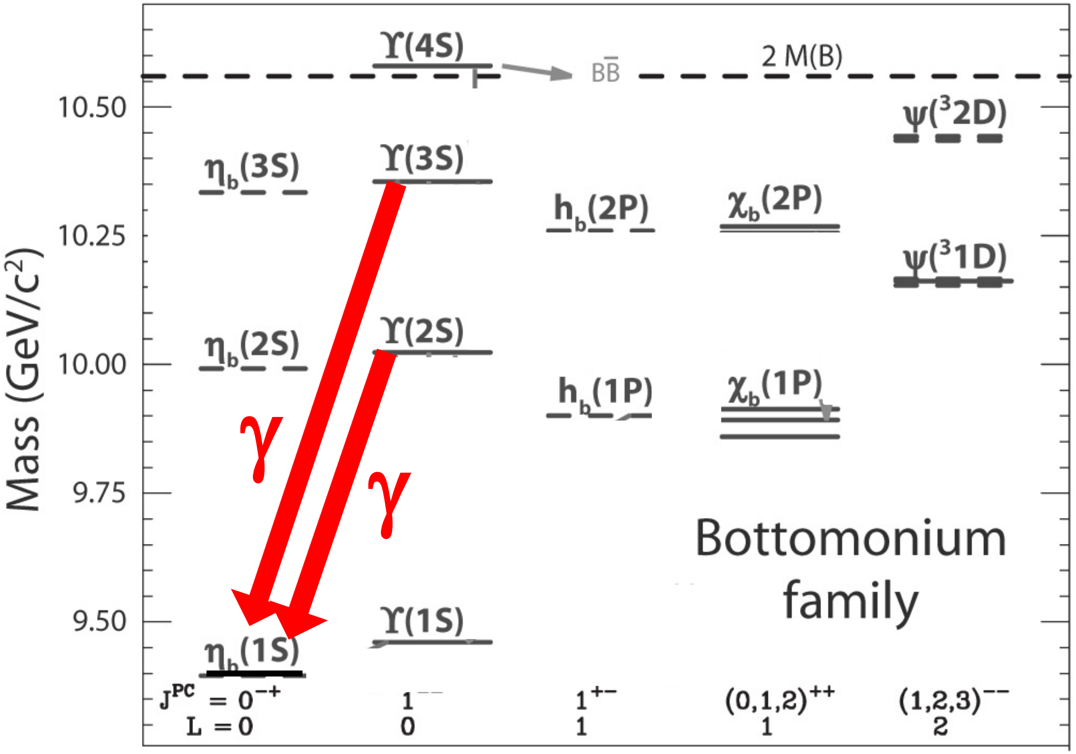


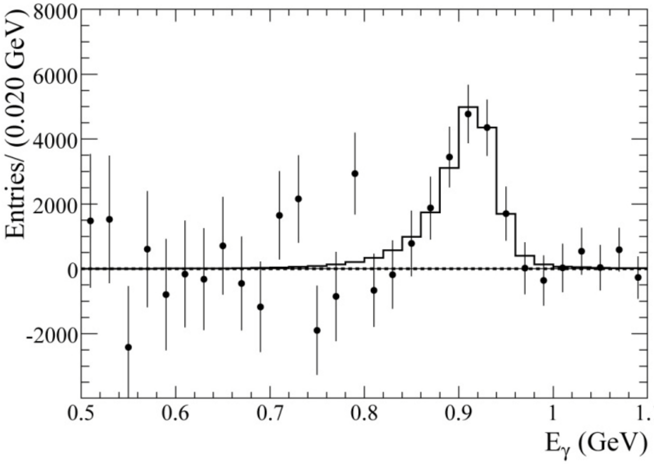
Bottomonium family

L=0, S=0 singlet

η_b search using $\gamma \rightarrow e^+e^-$ conversions

- η_b discovered in the recoil γ spectrum in $\Upsilon(3S) \rightarrow \gamma\eta_b$
- Confirmed by Babar in $\Upsilon(2S)$ [2009] and by CLEO in $\Upsilon(3S)$ [2010]





[Babar, PRL 101(2008)071801]

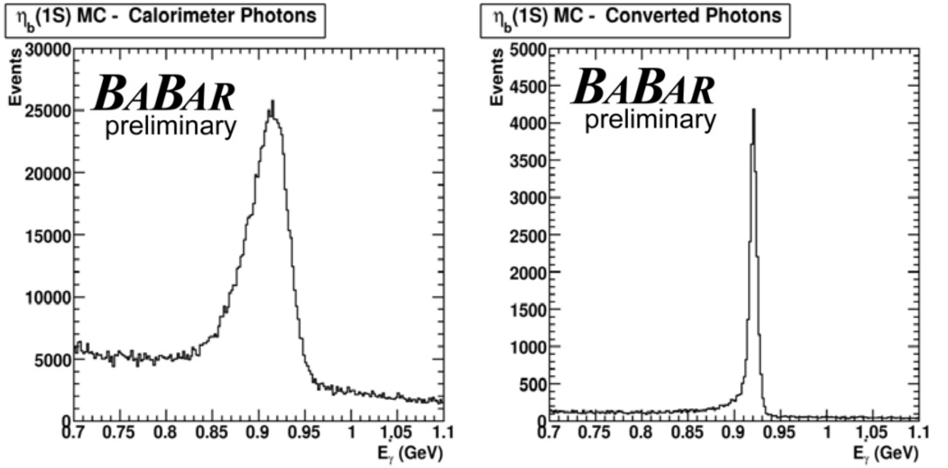
World average mass:
9390.9±2.8 MeV

η_b search using $\gamma \rightarrow e^+e^-$ conversions

New study: $\Upsilon(3S)$ & $\Upsilon(2S) \rightarrow \gamma\, \eta_b$ using $\gamma \rightarrow e^+e^-$

Converted photons: 5x better energy resolution (25→5 MeV)

Reconstructed E_γ in $\Upsilon(3S) \rightarrow \gamma\eta_b$ MC events (CM frame)



Detection efficiency lower but still expect ~ 3σ significance

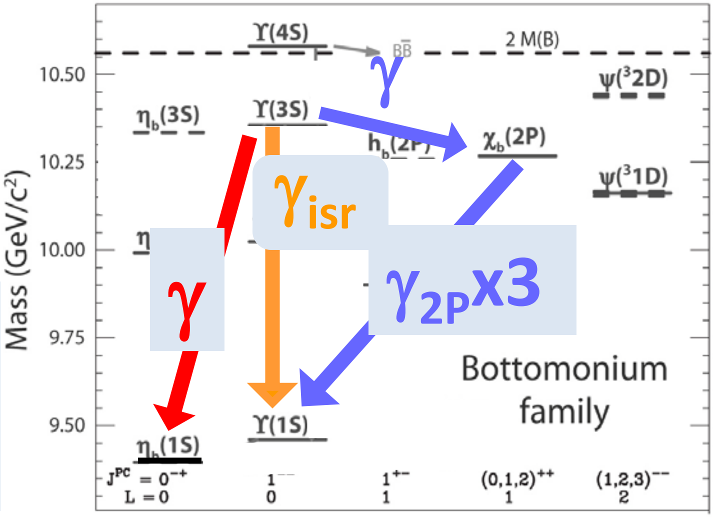
→ independent measurement of η_b mass

5 monochromatic γs in η_b region:

1-3) $\chi_{bJ}(2p) \rightarrow \gamma_{2P}\Upsilon(1S)$; J=0,1,2

4) ISR $e^+e^- \rightarrow \gamma_{isr}\Upsilon(1S)$

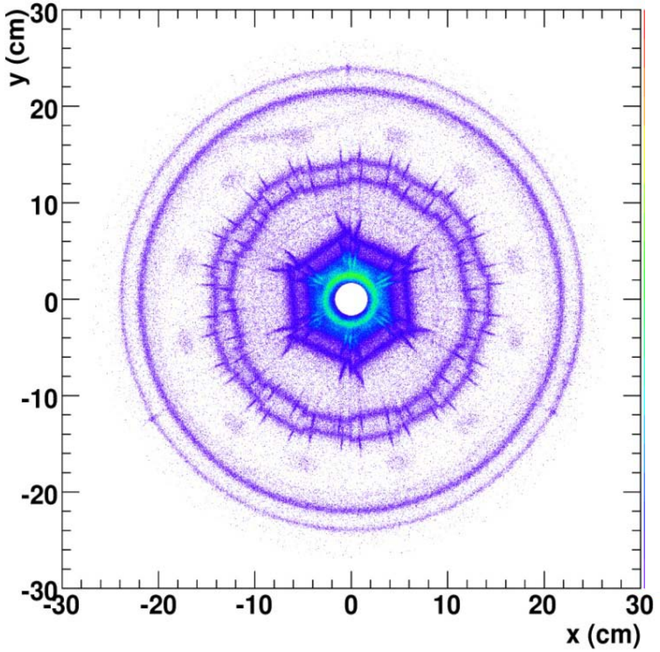
5) Signal γ



η_b search using $\gamma \rightarrow e^+e^-$ conversions

- Identify $\gamma \rightarrow e^+e^-$ conversions (χ^2 test; require $m_\gamma < 30$ MeV)
- Veto $\gamma \rightarrow e^+e^-$'s that form a π^0 candidate with any other γ
- Other cuts: thrust, multiplicity
- χ^2 fit to γ recoil energy spectrum
  - → Combinatoric background
  - → 5 "peaking" components

γ-ray "photograph" of Babar



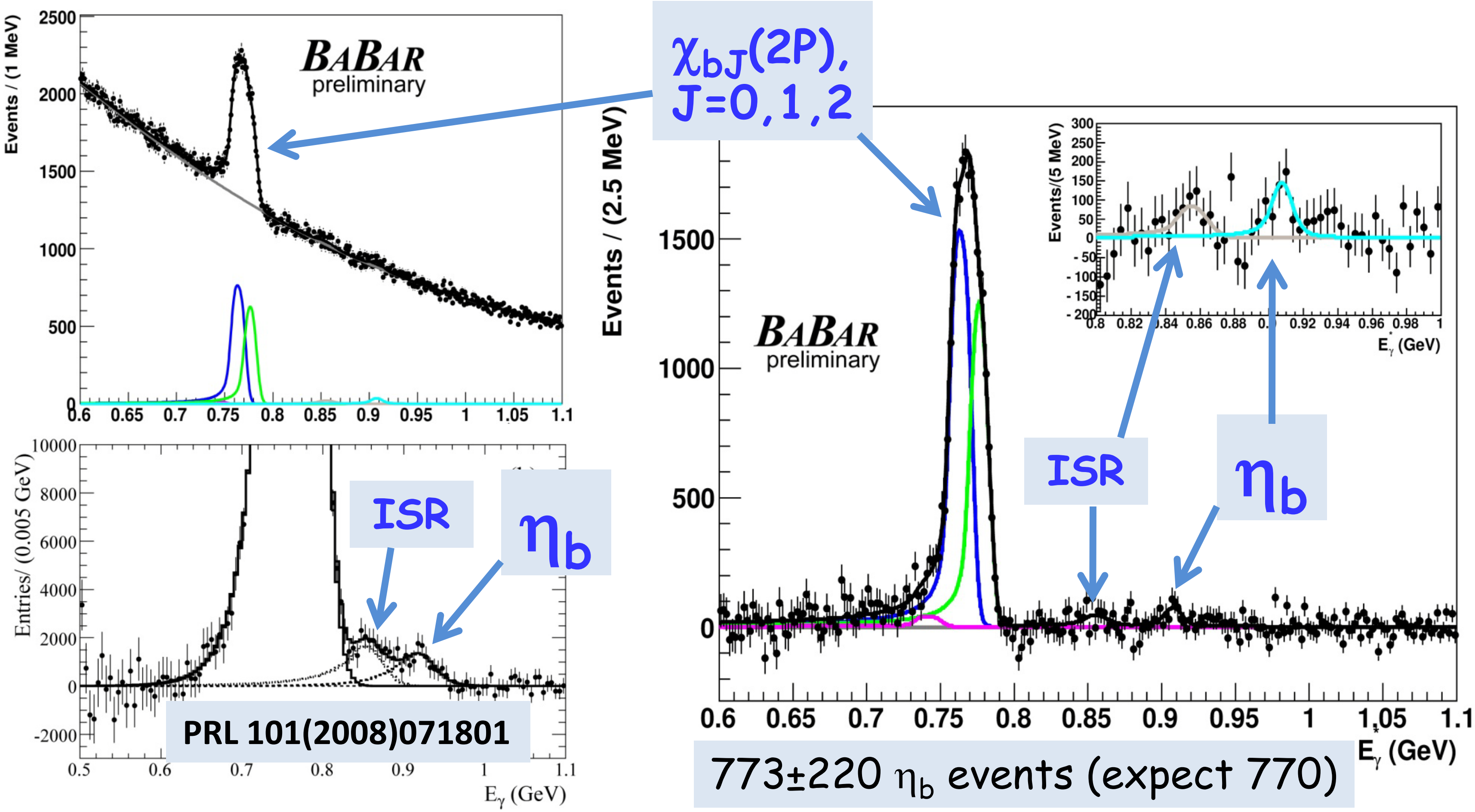
γ conversions in inner region

→ Simultaneous fit to the $\Upsilon(3S)$ & $\Upsilon(2S)$ samples with the η_b mass a fitted parameter

η_b search using $\gamma \rightarrow e^+e^-$ conversions

Υ(3S) sample

Signal efficiency=1.4%



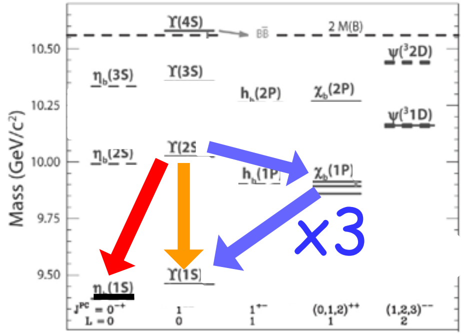
PRL 101(2008)071801

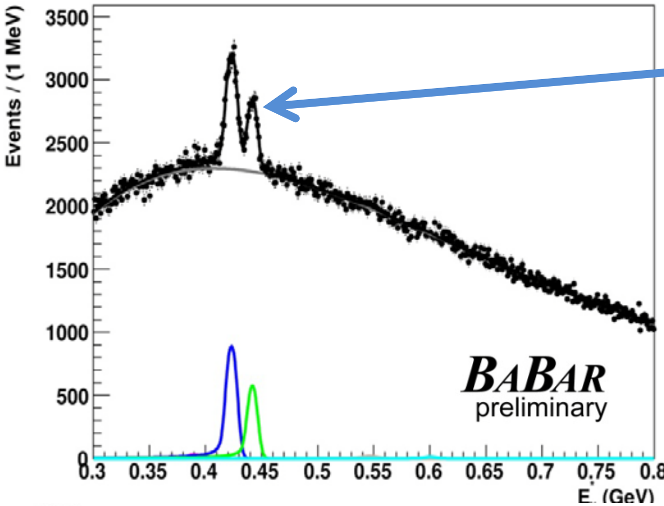
773±220 η_b events (expect 770)

η_b search using $\gamma \rightarrow e^+e^-$ conversions

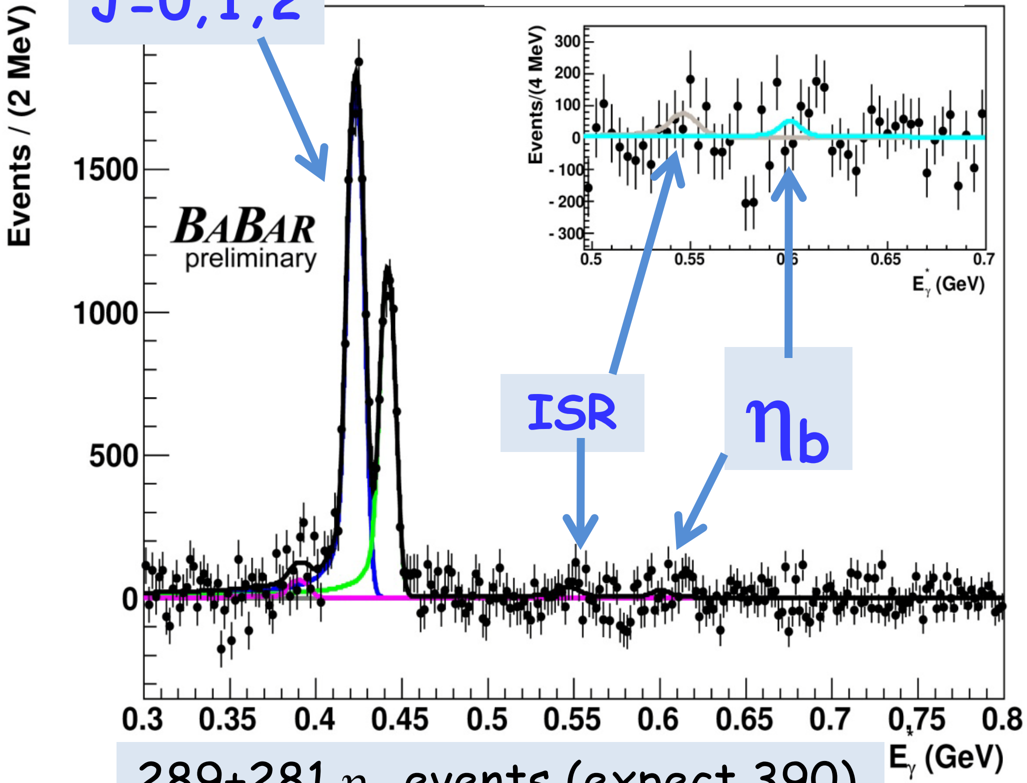
Υ(2S) sample

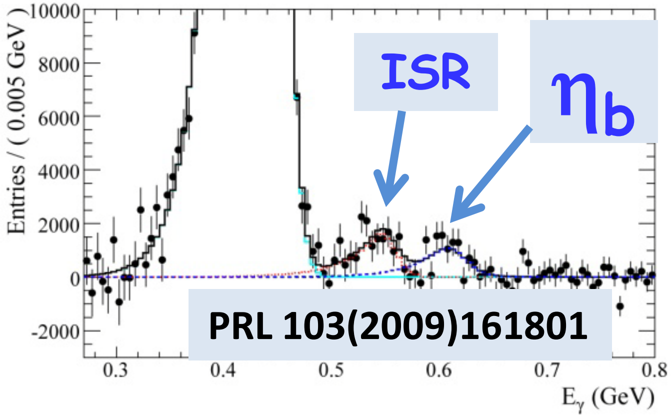
Signal efficiency =1.1%





χ_{bJ}(1P), J=0,1,2





PRL 103(2009)161801

289±281 η_b events (expect 390)

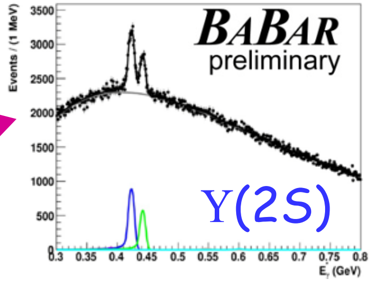
η_b search using $\gamma \rightarrow e^+e^-$ conversions

- Simultaneous fit to Υ(2S) & Υ(3S) sample

  → η_b : 3.3σ (stat.) ; 2.6σ (stat.+syst.),

Fitted η_b mass:
$9403.3 \pm 2.4^{+0.9}_{-1.5}$ MeV

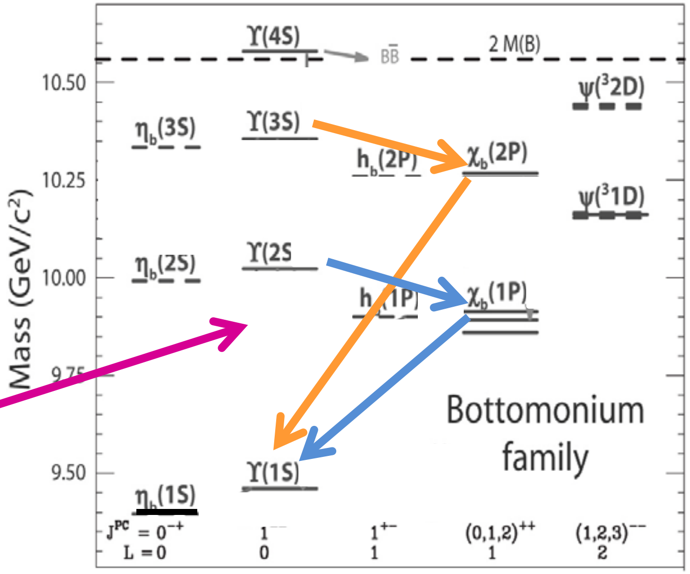
- Fitted η_b mass shifted +12 MeV from world average: significance of shift (~2.5σ) under investigation



- Side-benefit of analysis: the separated Υ(nS) → $\gamma\chi_{bJ}$(n-1P) → $\gamma\gamma\Upsilon$(1S) BFs

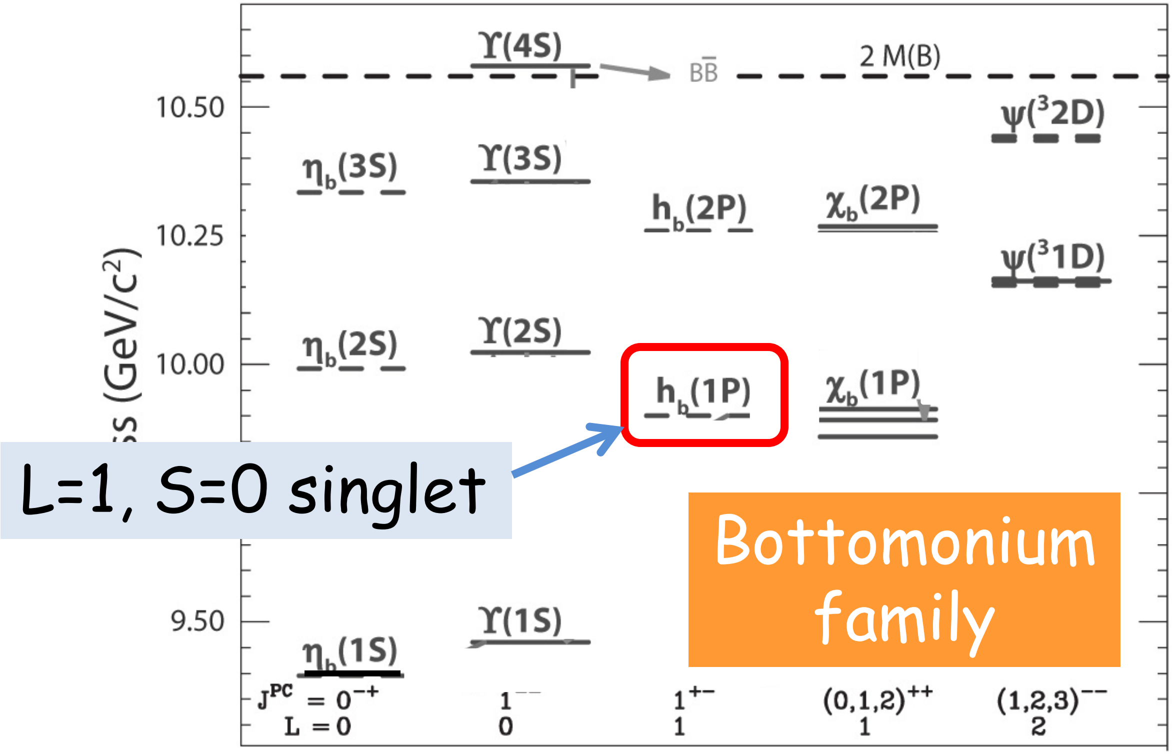
→ uncertainties reduced by ~3-4 compared to current world averages

nS	mP	J	BF (x10^{-3})	PDG	Improvement
3	2	1	13.0±0.3±0.7	10.7±1.9	2.5
3	2	2	9.6±0.3±0.5	9.3±1.7	2.9
2	1	1	25.2±0.6±1.2	24.2±5.7	4.2
2	1	2	14.4±0.5±0.8	15.7±3.0	3.2



(II) Search for $h_b(1P)$ state

Expect $m_{h_b(1P)} = [m_{\chi_{b0}(1P)}+3m_{\chi_{b1}(1P)}+5m_{\chi_{b2}(1P)}] / 9 \approx$ 9900 MeV



L=1, S=0 singlet

Bottomonium family

Intrinsic width ~ 0.1 MeV

Search for $h_b(1P)$

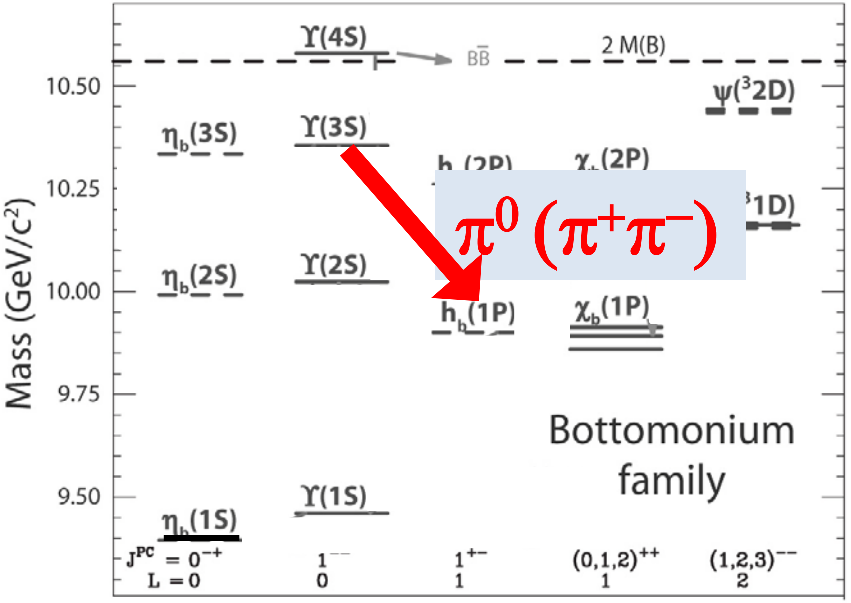
- $\Upsilon(3S) \rightarrow \gamma h_b$ forbidden (*C*-parity)
- Favored production mechanisms

$B[\Upsilon(3S) \rightarrow \pi^0 h_b]$ ~ $4\text{x}10^{-4}$ [Voloshin]

$B[\Upsilon(3S) \rightarrow \pi^+\pi^- h_b]$ ~ 10^{-5} [Voloshin]

~10^{-3}-10^{-4} [KTY]

Voloshin, Sov. J. Nucl. Phys. 43 (1986) 1210
Kuang, Tuan & Yan, PR D37 (1988) 1210



- Expected decays: $h_b \rightarrow \gamma\eta_b$ (~41%), *ggg* (57%), γ*gg* (2%)

[Godfrey & Rosner, PR D66 (2002) 014012]

Search for $h_b(1P)$

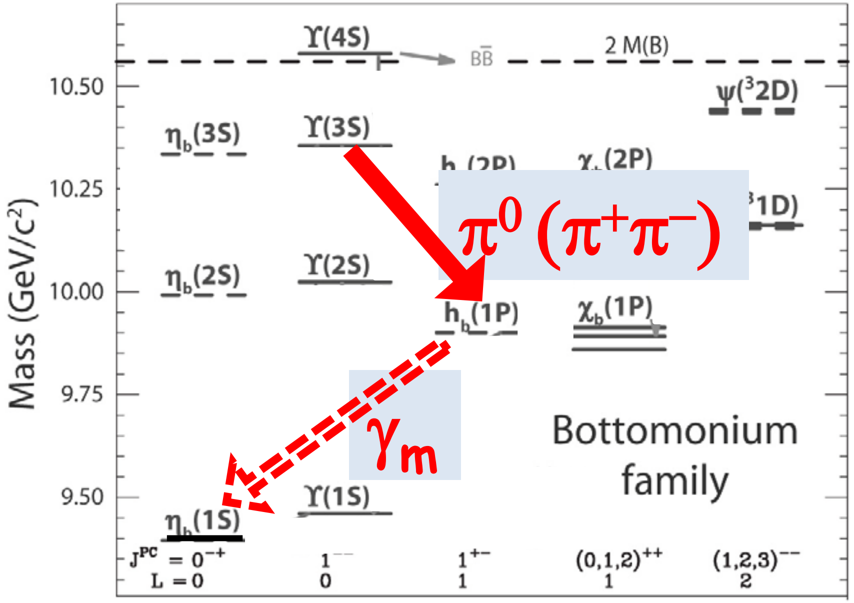
- $\Upsilon(3S) \rightarrow \gamma h_b$ forbidden (C-parity)
- Favored production mechanisms

$B[\Upsilon(3S) \rightarrow \pi^0 h_b]$ ~ $4\text{x}10^{-4}$ [Voloshin]

$B[\Upsilon(3S) \rightarrow \pi^+\pi^- h_b]$ ~ 10^{-5} [Voloshin]

~10^{-3}-10^{-4} [KTY]

Voloshin, Sov. J. Nucl. Phys. 43 (1986) 1210
Kuang, Tuan & Yan, PR D37 (1988) 1210



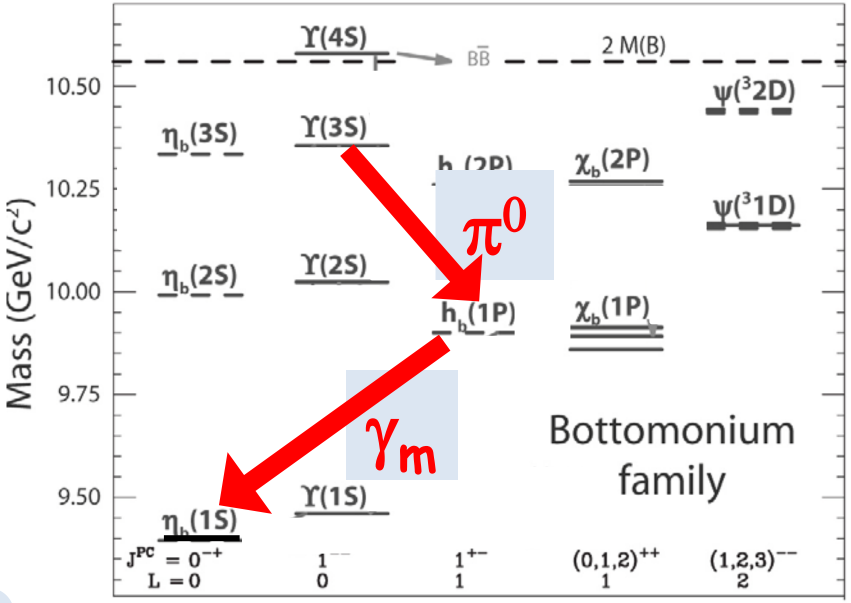
- Expected decays: $h_b \rightarrow \gamma\eta_b$ (~41%), ggg (57%), γgg (2%)
  [Godfrey & Rosner, PR D66 (2002) 014012]
- S/B enhanced by requiring monochromatic γ_m: $h_b \rightarrow \gamma_m \eta_b$
- Expect $E_{\gamma m}$ = 490 MeV (resolution 25 MeV)
- $h_c(1P)$ observed in analogous decay chain: $\psi(2S) \rightarrow \pi^0 h_c$; $h_c \rightarrow \gamma_m \eta_c$
  [CLEO 2005; BES 2010]

$\Upsilon(3S) \to \pi^0 h_b$ channel

- Reconstruct $\pi^0 \to \gamma\gamma$ candidate [$50 < m_{\gamma\gamma} < 200$ MeV]
- Reject if a signal $\pi^0 \to \gamma\gamma$ photon forms a π^0 with any other photon (<15 MeV of $m_{\pi 0}$)
- γ helicity $|\cos\Theta_h|<0.7$ in π^0 CM
- Recoil mass against the π^0

$$M_{recoil} \equiv \sqrt{(E^*_{\Upsilon(3S)} - E^*_{\pi^0})^2 - (\vec{p}^{\,*}_{\pi^0})^2}$$

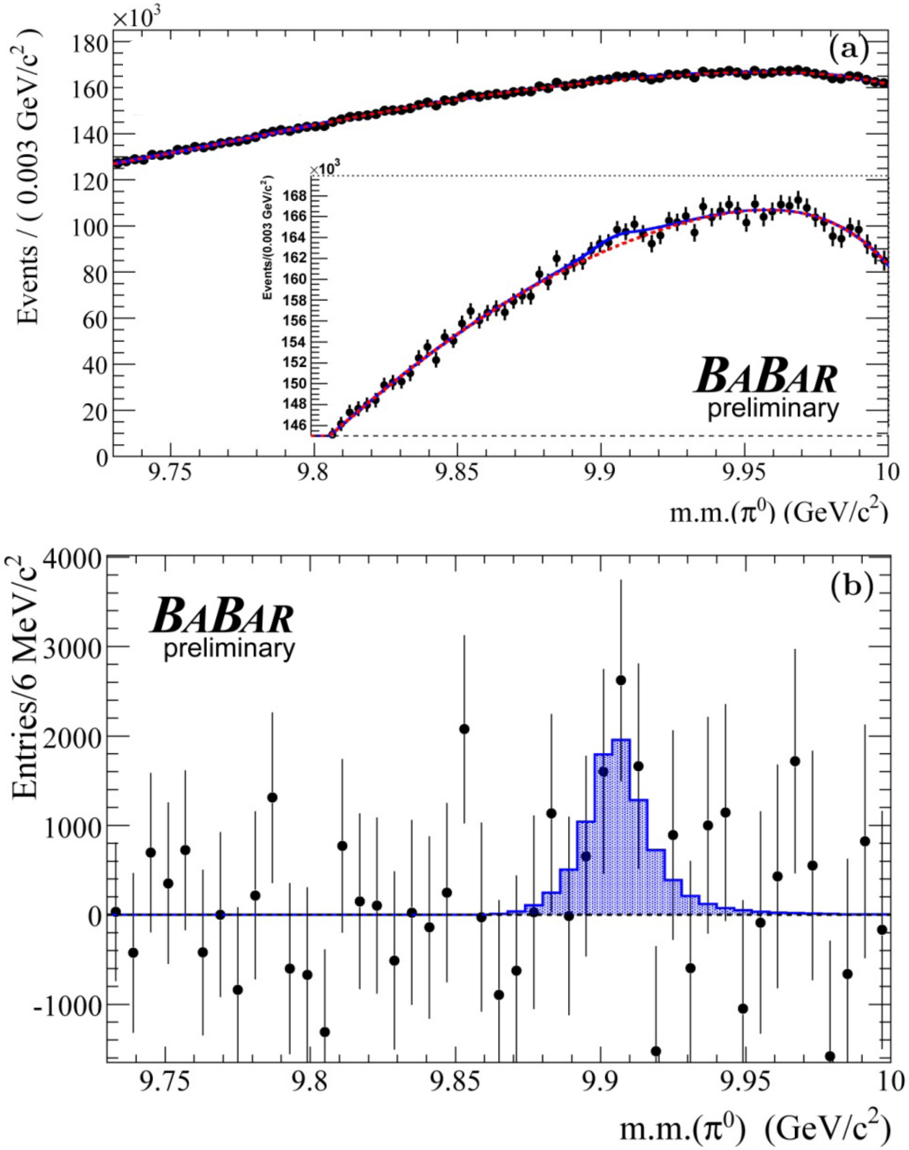
(peaks at h_b mass for signal)



$*$ = CM [=$\Upsilon(3S)$] frame

- Require a photon consistent with $h_b \to \gamma_m \eta_b$: $420 < E^*_{\gamma_m} < 540\ \mathrm{MeV}$
- Reject event if γ_m forms a π^0 candidate with any other photon
- Overall reconstruction efficiency ~ 22%

Recoil mass: $\Upsilon(3S) \to \pi^0 h_b$



- χ^2 fit: smooth combinatoric background + signal peak
- h_b mass and yield free

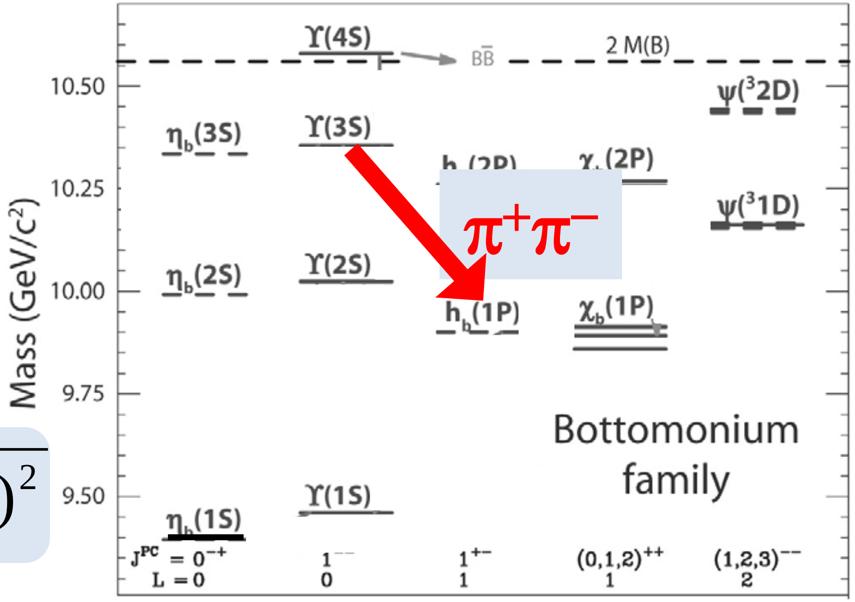
  → 8682 ± 2981 signal events

  ~3σ (stat.), 2.7σ (stat.+syst.)
- Fitted mass: 9903±4 MeV agrees with expectation (9900)
- Product BF $B[\Upsilon(3S) \to \pi^0 h_b] \times B[h_b \to \gamma\eta_b]$ $= (3.3 \pm 1.1 \pm 0.4) \times 10^{-4}$

  → agrees with Voloshin (1986) [$=4 \times 10^{-4}$]

[CLEO (1994): $<2.7\times10^{-3}$ for $m_{hb}=9.9$ GeV]

$\Upsilon(3S) \rightarrow \pi^+\pi^- h_b$ channel



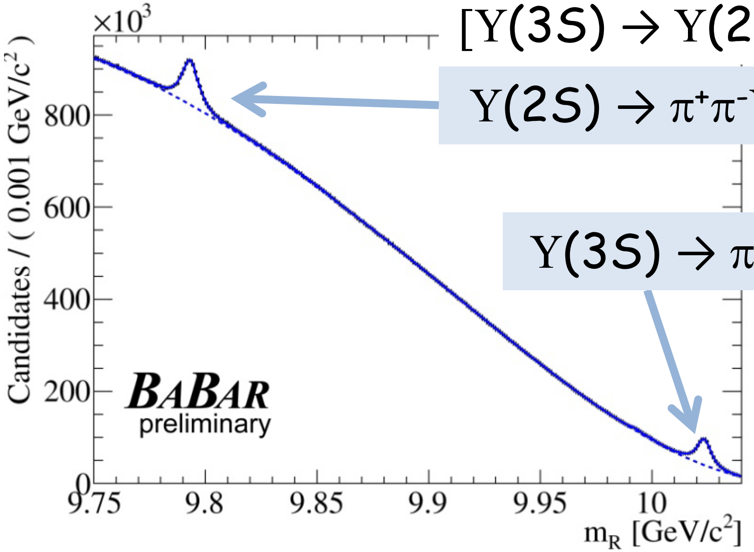
- Select identified $\pi^+\pi^-$ pair that originates at IP
- Remove obvious K_S candidates
- Recoil mass against the $\pi^+\pi^-$

$$M_{recoil} \equiv \sqrt{(E^*_{\Upsilon(3S)} - E^*_{\pi^+\pi^-})^2 - (\vec{p}^{\,*}_{\pi^+\pi^-})^2}$$

* = CM [$=\Upsilon(3S)$] frame

- Fully inclusive search (no $h_b \rightarrow \gamma_m \eta_b$ requirement to increase efficiency)
- Reconstruction efficiency ~42%

Recoil mass: $\Upsilon(3S) \rightarrow \pi^+\pi^- h_b$



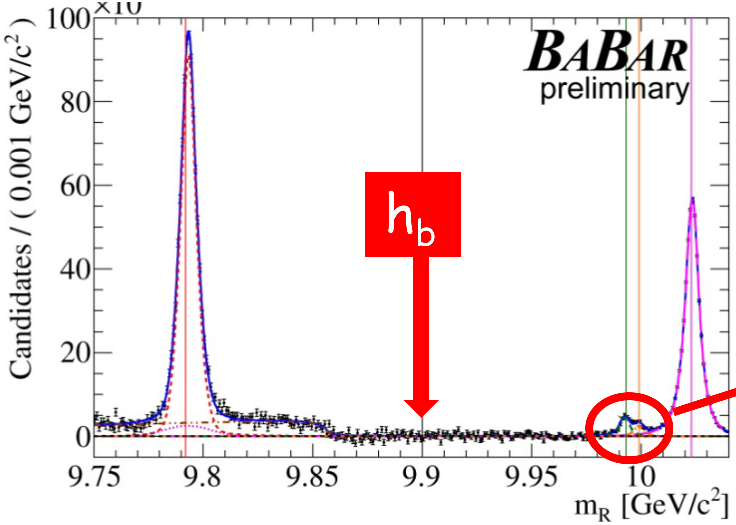
[$\Upsilon(3S) \rightarrow \Upsilon(2S)$+X]

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

$\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(2S)$

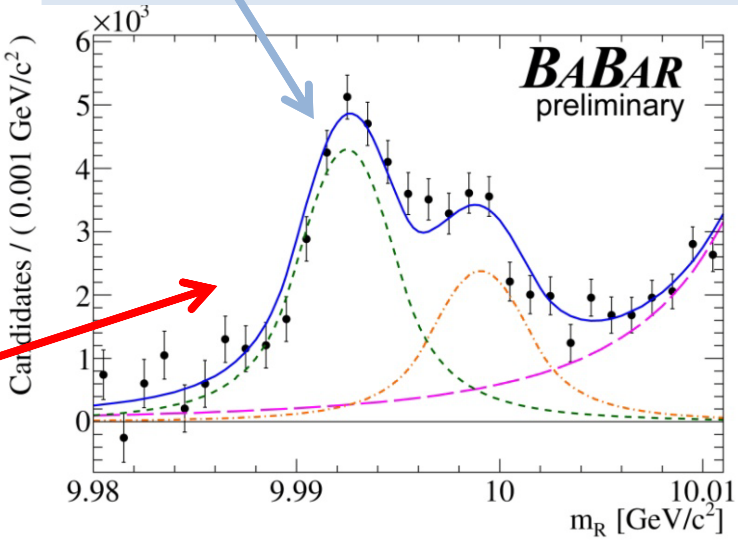
χ^2 fit→ Fitted signal yield (m_{hb}=9900 MeV):

-1106±2432 events



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

$\chi_{bJ}(2P) \rightarrow \pi^+\pi^-\chi_{bJ'}(1P)$; J=J'=1,2



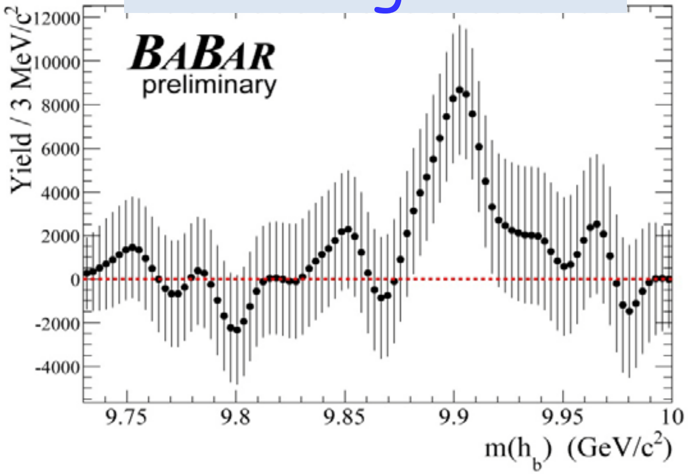
h_b mass scan

→ No indication of a signal in the $\Upsilon(3S) \to \pi^+\pi^- h_b$ channel

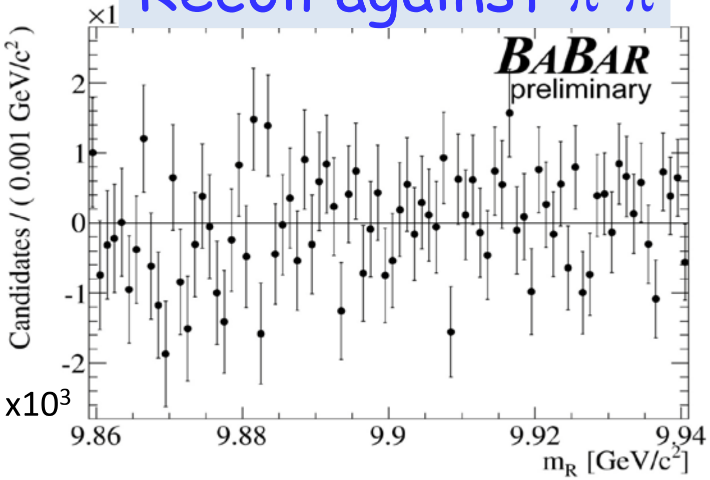
$B[\Upsilon(3S) \to \pi^+\pi^- h_b] < 1.0\times10^{-4}$ at 90% CL for $m_{hb} = 9.9$ GeV

[CLEO 1994: $< 1.8\times10^{-3}$ for $m_{hb}=9.9$ GeV]

Recoil against π^0



Recoil against $\pi^+\pi^-$



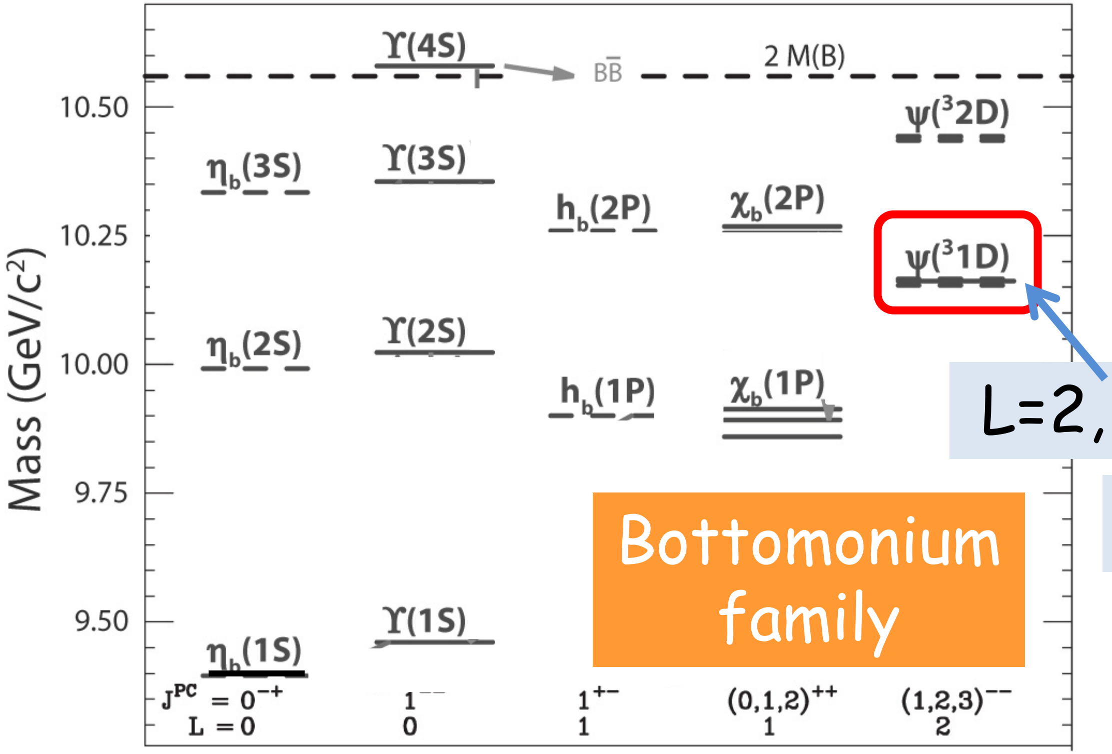
→ Predictions for ratio $B[\Upsilon(3S) \to \pi^0 h_b]$ / $B[\Upsilon(3S) \to \pi^+\pi^- h_b]$:

~ 20 [Voloshin] ; ~ 1/20 [Kuang et al.]

→ data more consistent with Voloshin

(III) Observation of 1^3D_J state

- Predicted mass ~ 10160 ± 10 MeV [Godfrey & Rosner, PRD64 (2001) 097501]



Bottomonium family

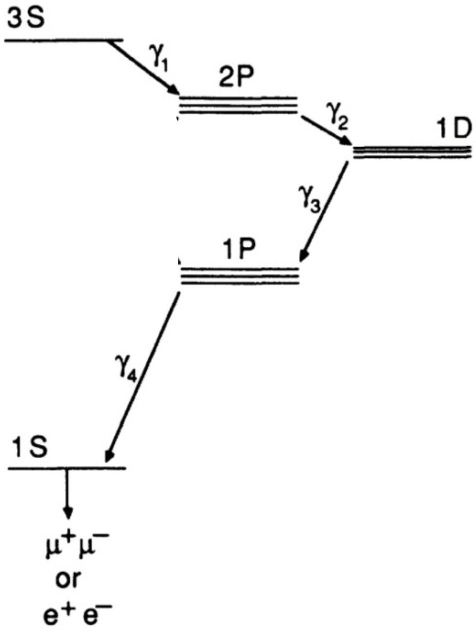
L=2, S=1 triplet

J=1,2,3

- Predicted separation between triplet states ~ 5-12 MeV
- Expected intrinsic widths ~30 KeV << exptl. resolution

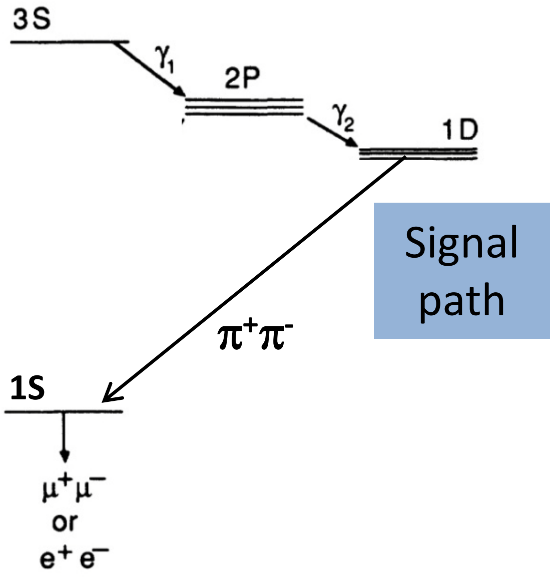
CLEO [PRD70 (2004) 032001]

- Observation of $\Upsilon(1^3D_{J=2}) \rightarrow \gamma\gamma\Upsilon(1S)$ (radiative decay channel)
- 4γ transition from the $\Upsilon(3S)$ to the $\Upsilon(1S)$
- Mass: 10161.1 ± 0.6 ± 1.6 MeV
- Single state seen, interpreted as J=2 based on comparison of the measured & expected BFs and the observed γ energies
- Awaits confirmation of L, J, P



Babar: $\Upsilon(1^3D_J) \rightarrow \pi^+\pi^-\Upsilon(1S)$

→ hadronic decay channel, with $\Upsilon(1S) \rightarrow e^+e^-$ or $\mu^+\mu^-$



- $\pi^+\pi^-l^+l^-$ invariant mass
  - → provides best $\Upsilon(1^3D_J)$ mass resolution (~ 3 MeV)
  - → Smallest systematic uncertainties
- The L, J & parity P can be tested from the $\pi^+\pi^-$ invariant mass, and angular distributions of the tracks

CLEO upper limit on branching fraction product:

$\Upsilon(3S) \rightarrow 2\gamma\Upsilon(1D) \rightarrow 2\gamma\pi^+\pi^-\Upsilon(1S) \rightarrow 2\gamma\pi^+\pi^-l^+l^- < 6.6\times10^{-6}$

or **$\Upsilon(1D) \rightarrow \pi^+\pi^-\Upsilon(1S) < 4\%$** @ 90% C.L.

$\Upsilon(3S) \rightarrow \gamma\gamma\Upsilon(1D) \rightarrow \gamma\gamma\pi^+\pi^-\Upsilon(1S) \rightarrow \gamma\gamma\pi^+\pi^-l^+l^-$

(1) Charged tracks:

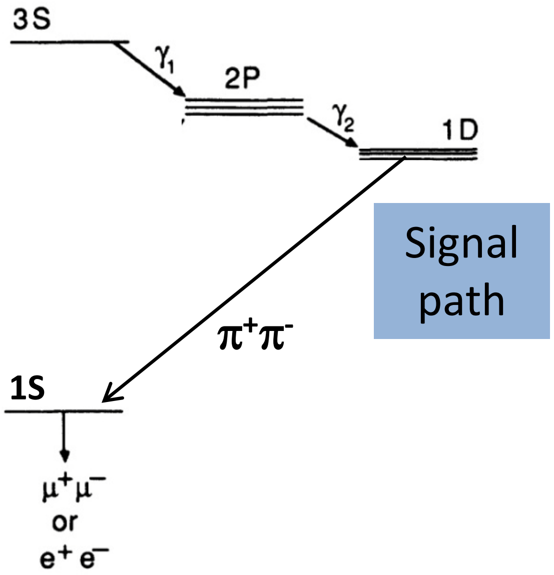
- Require exactly 4 charged tracks
  - 2 identified as a $\pi^+\pi^-$ pair
  - 2 identified as an e^+e^- or $\mu^+\mu^-$ pair
- $\Upsilon(1S)$ candidate: require

$$|m_{\Upsilon(1S)} - m_{\mu+\mu-}| < 0.2 \text{ GeV} \quad \text{, or}$$

$$-0.35 < m_{\Upsilon(1S)} - m_{e+e-} < 0.2 \text{ GeV} \quad (\sim 3\sigma)$$

and then constrain m_{l+l-} to the $\Upsilon(1S)$ mass

- $\Upsilon(1D)$ candidate: combine $\Upsilon(1S)$ candidate with $\pi^+\pi^-$

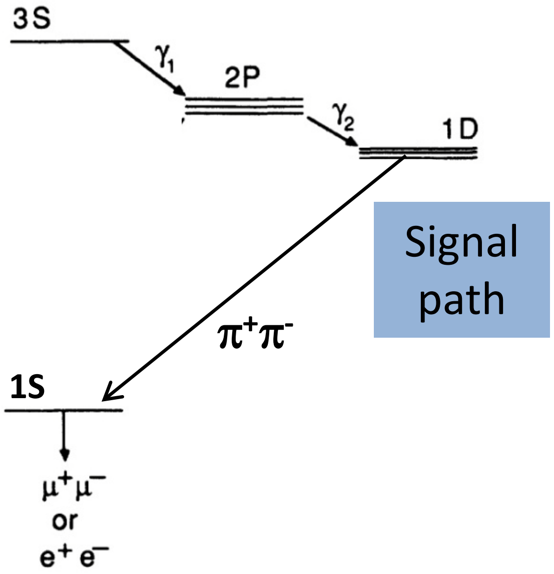


(2) Photons:

Add 2 photons consistent with the decay chain to form a $\Upsilon(3S)$ candidate …

$\Upsilon(3S) \rightarrow \gamma\gamma\Upsilon(1D) \rightarrow \gamma\gamma\pi^+\pi^-\Upsilon(1S) \rightarrow \gamma\gamma\pi^+\pi^- l^+ l^-$

(3) Υ(3S) candidate: sanity checks



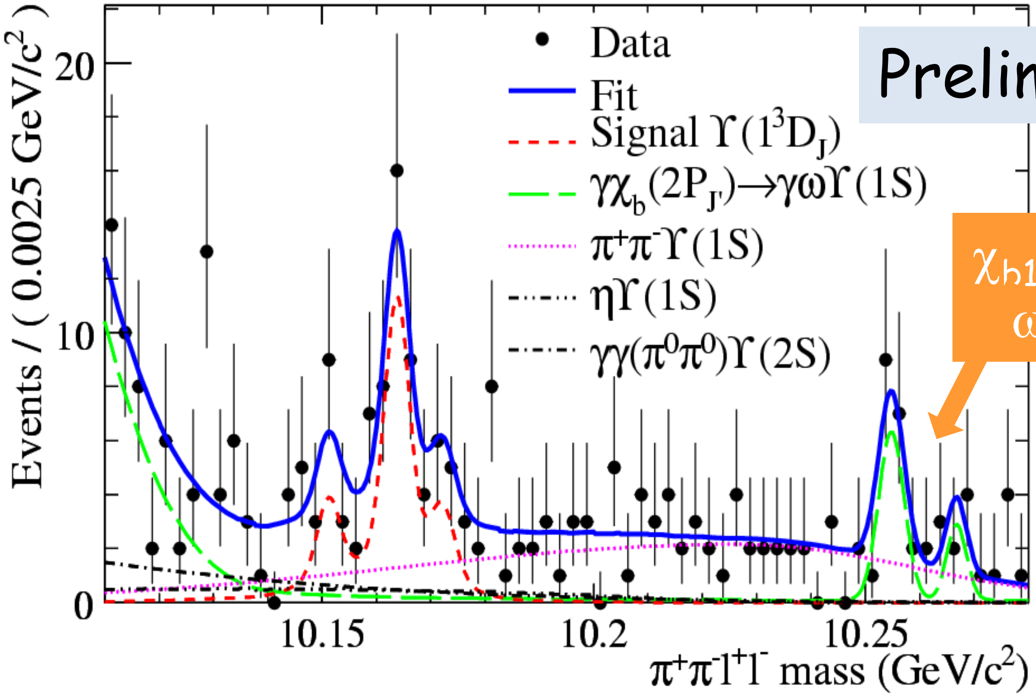
- Require Υ(3S) CM momentum < 0.3 GeV
- Υ(3S) energy (resolution 25 MeV) equals sum of beam energies within 100 MeV

→ very loose, ~100% efficient for signal;

(4) Maximum Likelihood fit

- 3 signal peaks (J=1,2,3), mass and yield of each peak is floated
- All known backgrounds, which are small and non-peaking in the $\Upsilon(1^3D_J)$ signal region

Fit results



Preliminary

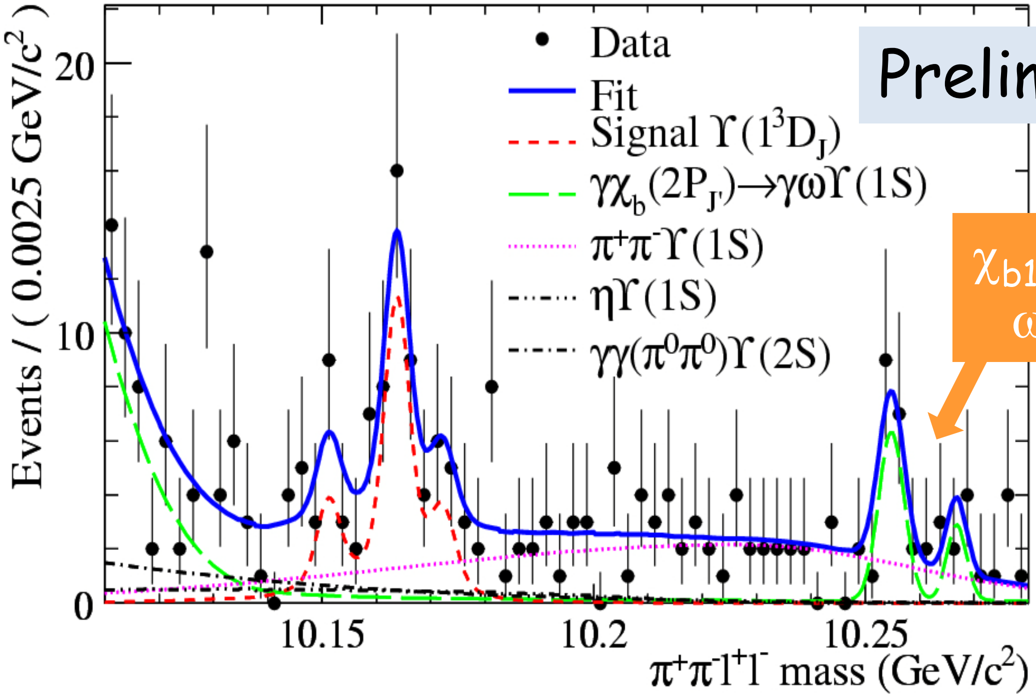
$\chi_{b1,2}(2P)\to$ $\omega(\to\pi^+\pi^-)\ \Upsilon(1S)$

J=1,2,3 combined: $53.8^{+10.2}_{-9.5}$ events

7.6 σ (stat. only)
6.2 σ (stat. + syst.)

→ First observation of hadronic $\Upsilon(1^3D_J)$ decays

Fit results



Preliminary

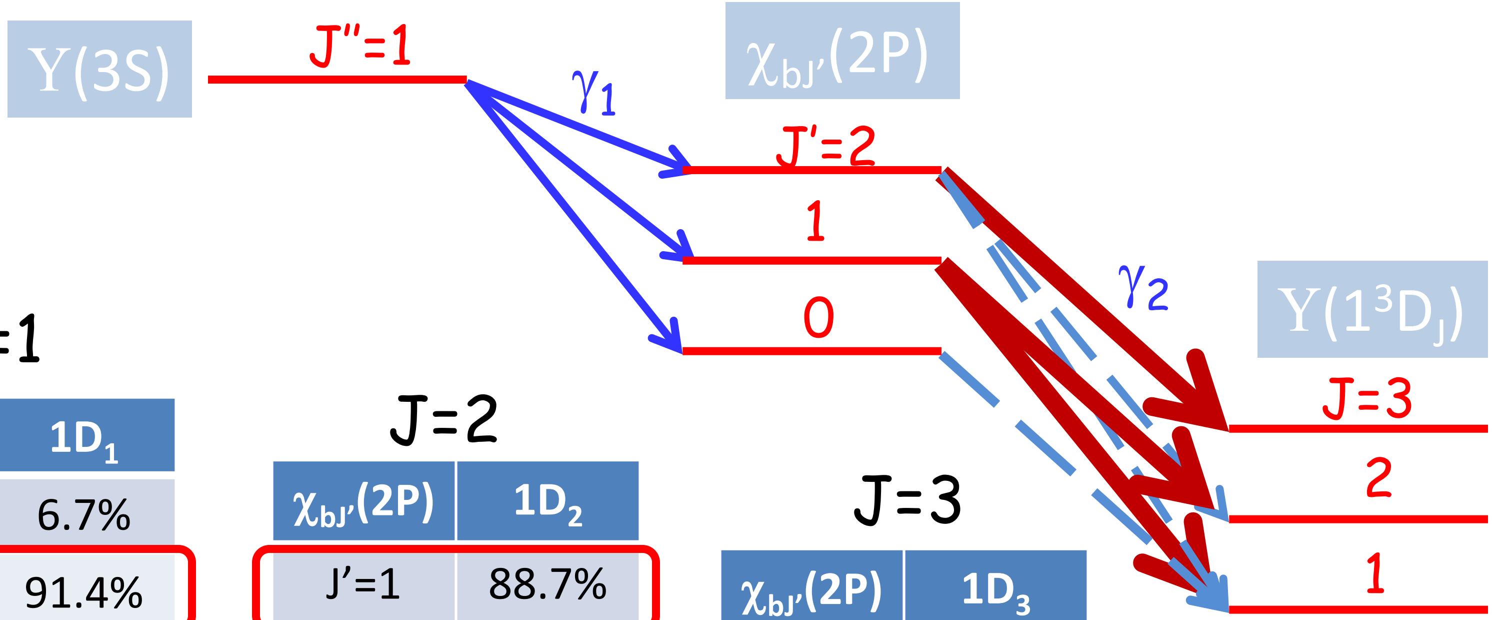
$\chi_{b1,2}(2P)\to$ $\omega(\to\pi^+\pi^-)\ \Upsilon(1S)$

J	Event yields	Significance (w.syst.)	Fitted mass value
1	$10.6_{-4.9}^{+5.7}$	2.0 (1.8) σ	
2	$33.9_{-7.5}^{+8.2}$	6.5 (5.8) σ	10164.5 ± 0.8 ± 0.5
3	$9.4_{-5.2}^{+6.2}$	1.7 (1.6) σ	

CLEO:
10161.1±0.6
±1.6 MeV

Uncertainty of J=2 mass reduced by ~45%

Branching Fractions



J=1

$\chi_{bJ'}(2P)$	$1D_1$
J′=0	6.7%
J′=1	91.4%
J′=2	1.9%

J=2

$\chi_{bJ'}(2P)$	$1D_2$
J′=1	88.7%
J′=2	11.7%

J=3

$\chi_{bJ'}(2P)$	$1D_3$
J′=2	100%

→ 6 unknown BFs with efficiencies that differ by up to ~7.5%

→ Only 3 measured yields

→ Determine the 3 dominant BFs only

→ Ratios relative to the minor BFs fixed according to theory

[Kwong & Rosner, PRD38 (1988) 279]

Preliminary Branching Fractions

- BF = (yield – bias) / [efficiency x $N_{\Upsilon(3S)}$]
- Efficiency ≈ 26% averaged over $\Upsilon(1S) \rightarrow \mu^+\mu^-$ & e^+e^-, for J=1,2,3
- $N_{\Upsilon(3S)} = 122 \times 10^6$ events

Branching fraction product for entire decay chain,

$\Upsilon(3S) \rightarrow \gamma\chi_{bJ'}(2P) \rightarrow 2\gamma\Upsilon(1^3D_J) \rightarrow 2\gamma\pi^+\pi^-\Upsilon(1S) \rightarrow 2\gamma\pi^+\pi^- l^+l^-$,

and for the dominant modes only:

$\chi_{bJ'}(2P)$	1^3D_J	Product BF	90% C.L. upper limit
J'=1	J=1	$(1.27_{-0.69}^{+0.81} \pm 0.28) \times 10^{-7}$	$< 2.50 \times 10^{-7}$
J'=1	J=2	$(4.9_{-1.0}^{+1.1} \pm 0.3) \times 10^{-7}$	
J'=2	J=3	$(1.34_{-0.83}^{+0.99} \pm 0.24) \times 10^{-7}$	$< 2.80 \times 10^{-7}$

CLEO upper limit: $< 6.6 \times 10^{-6}$

Compare Branching Fractions to theory

Divide measured branching fraction products by

- the known $\Upsilon(3S) \rightarrow \gamma_1\chi_b(2P)$ BF's
- the Kwong & Rosner predictions for the $\chi_b(2P) \rightarrow \gamma_2\Upsilon(1^3D)$ BF's

from J. Rosner, PRD67 (2003) 097504

1^3D_J	**BF [$\Upsilon(1^3D_J) \rightarrow \pi^+\pi^-\Upsilon(1S)$]**	**90% C.L. upper limit**	**Kwang & Yan (1981)**	**Ko (1993)**	**Moxhay (1988)**
J=1	$(0.42_{-0.23}^{+0.27}\pm0.10)\%$	< 0.82%	40%	1.6%	0.20%
J=2	$(0.66_{-0.14}^{+0.15}\pm0.06)\%$		46%	2.0%	0.25%
J=3	$(0.29_{-0.18}^{+0.22}\pm0.06)\%$	< 0.62%	49%	2.2%	0.27%

Kwang & Yan don't account for centrifugal barrier [see Kwong & Rosner, PRD38 (1988) 279]

CLEO limit < ~4% @ 90% C.L. already excludes Kwang & Yan

Multiply predictions by 2/3 to obtain $\pi^+\pi^-$ contribution:

→ data halfway between Ko ~ 1.3% & Moxhay ~ 0.16%

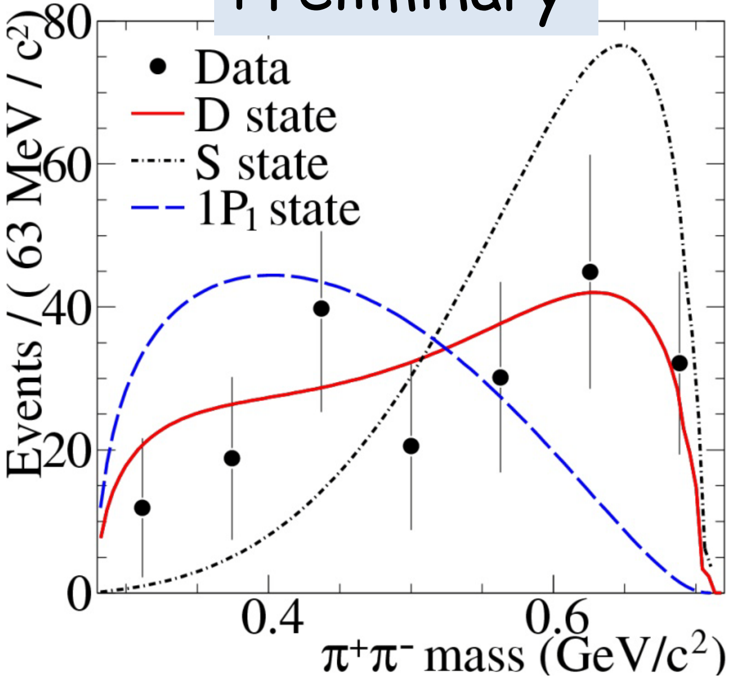
The $\pi^+\pi^-$ invariant mass

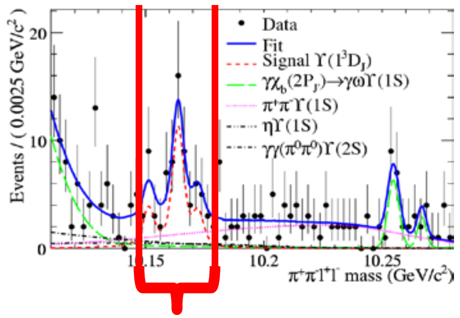
[T.-M. Yan, PRD22 (1980) 1652; Y.-P. Kuang et al., PRD37 (1988) 1210]

Background subtracted using the estimates from the ML fit

Corrected for mass-dependent variation in efficiency

Preliminary

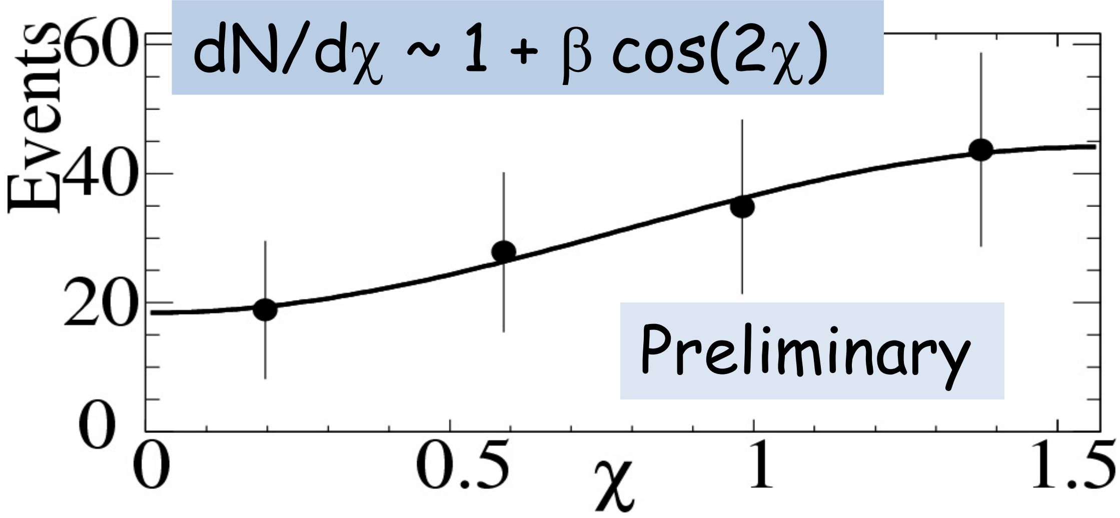




Select events in $\Upsilon(1^3D_J)$ region: 10.14 to 10.18 GeV

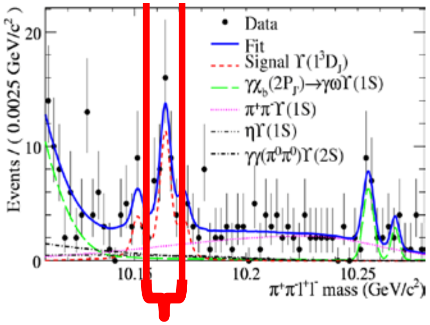
χ^2 probability for decay of a D, S, or $^1P_1$ bottomonium state to $\pi^+\pi^-\Upsilon(1S)$: 84.6, 3.1, or 0.3%

Angle χ between the $\pi^+\pi^-$ & l^+l^- planes



$dN/d\chi \sim 1 + \beta \cos(2\chi)$

Define χ in the $\Upsilon(1^3D_{J=2})$ rest frame



Select events in $\Upsilon(1^3D_{J=2})$ region:
10.155 to 10.168 GeV

$|\beta|$: depends on unknown helicity amplitudes, etc. → determine from data

Sign of β: $\boxed{\mathrm{sign}(\beta)= (-1)^{J}P}$ P=parity

[J.R. Dell'Aquila & C.A. Nelson, PRD33 (1986) 80]

Fit: $\beta = -0.41 \pm 0.29 \pm 0.10$ → consistent with J=2 & P=-1

[were J odd, $dN/d\chi$ would decrease with increasing χ for P=-1]

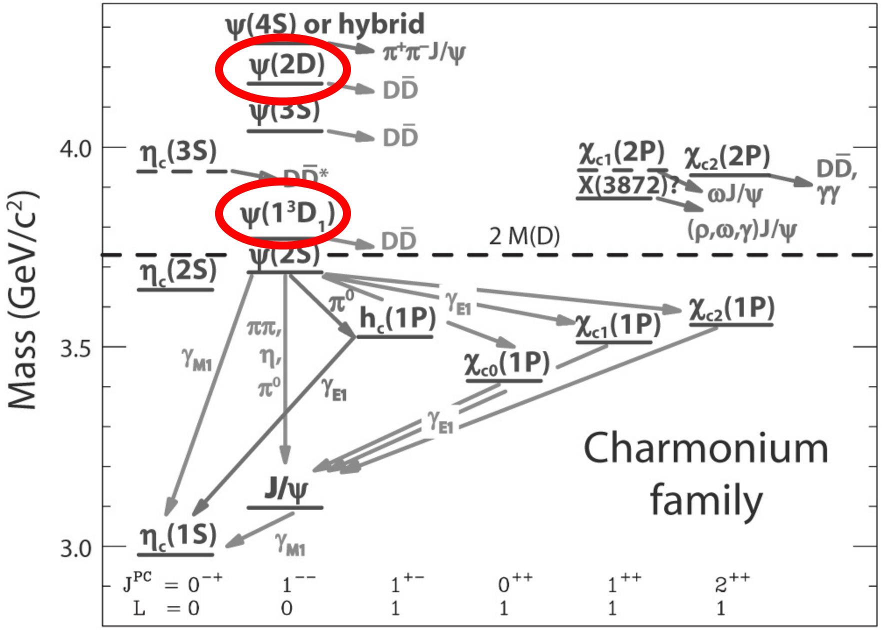
Summary

Preliminary

- Collected World's largest sample of $\Upsilon(3S)$ in 2008
- Converted photons in $\Upsilon(3S)$ & $\Upsilon(2S) \rightarrow \gamma\eta_b$:
  - → η_b observed @ 2.6σ significance (3.3σ stat.)
  - → Improvements in the η_b mass determination (under study)
  - → Improvement in $\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(1S)$ and $\chi_{bJ}(1P) \rightarrow \gamma\Upsilon(1S)$ BFs (J=1,2) by factors of ~3-4
- Search for the $h_b(1P)$ state
  - → No evidence for $\Upsilon(3S) \rightarrow \pi^+\pi^- h_b(1P)$
  - → Evidence @ 2.7σ (~3σ stat.) for $\Upsilon(3S) \rightarrow \pi^0 h_b(1P)$
- First observation of the $\Upsilon(1^3D_J)$ through hadronic decays (6.2σ)
  - → Factor of 2 improvement in J=2 mass measurement
  - → First tests of L, J, P assignments

BACKUP

Charmonium



From Eichten et al., Rev. Mod. Phys. 80 (2008) 1161

Two D-wave states observed: ψ(3770) and ψ(4153)

→ Above open-flavor threshold, decay to $D\bar{D}$, broad widths

→ QCD calculations above open threshold more difficult

→ Test of the calculations lacks precision

Backgrounds

4 categories of background events within the fit interval

In roughly decreasing order of importance, these are:

1. $\Upsilon(3S) \rightarrow \gamma\chi_b(2P) \rightarrow \gamma\omega\Upsilon(1S)$
   - $\omega \rightarrow \pi^+\pi^-\pi^0$
   - $\omega \rightarrow \pi^+\pi^-$, combine with a random (noise) γ
2. $\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$ with FSR γ's
3. $\Upsilon(3S) \rightarrow \eta\Upsilon(1S)$ with $\eta \rightarrow \pi^+\pi^-\pi^0(\gamma)$
4. $\Upsilon(3S) \rightarrow \gamma\gamma\Upsilon(2S)$ or $\pi^0\pi^0\Upsilon(2S)$
   with $\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$

The backgrounds are small and non-peaking in the $\Upsilon(1^3D_J)$ signal region $10.14 < m_{\pi+\pi-l+l-} < 10.18$ GeV/c^2

Branching Fraction Calculation

e.g., for transitions through the $\Upsilon(1^3D_{J=2})$ state

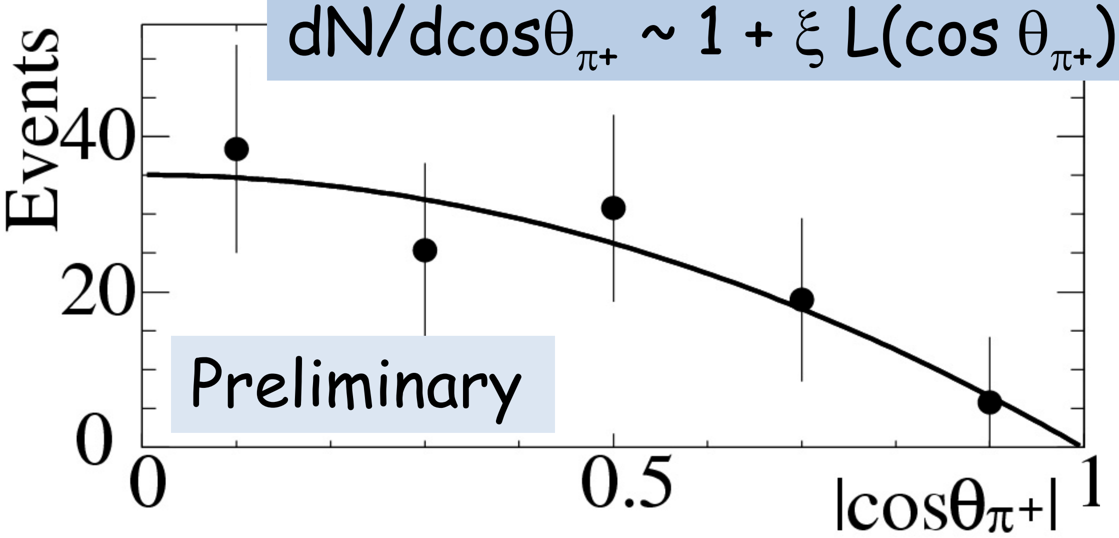
$$\begin{aligned} N_{1D_2} \quad = \quad & N_{3S}\Big[\left(\epsilon^e_{12}+\epsilon^\mu_{12}\right)\mathcal{B}_{3S\to 2P_1}\mathcal{B}_{2P_1\to 1D_2}\mathcal{B}_{1D_2\to\pi\pi\Upsilon(1S)}\mathcal{B}_{\Upsilon(1S)\to\ell\ell} \\ & \quad +\left(\epsilon^e_{22}+\epsilon^\mu_{22}\right)\mathcal{B}_{3S\to 2P_2}\mathcal{B}_{2P_2\to 1D_2}\mathcal{B}_{1D_2\to\pi\pi\Upsilon(1S)}\mathcal{B}_{\Upsilon(1S)\to\ell\ell}\Big]\,, \end{aligned}$$

$\varepsilon_{J'J}$ = efficiency for the transition path through the $\chi_{bJ'}$ and $\Upsilon(1^3D_J)$

$$= \quad N_{3S}\underbrace{\mathcal{B}_{3S\to 2P_1}\mathcal{B}_{2P_1\to 1D_2}\mathcal{B}_{1D_2\to\pi\pi\Upsilon(1S)}\mathcal{B}_{\Upsilon(1S)\to\ell\ell}}_{\text{Quoted branching fraction product}}\left[1+\frac{\left(\epsilon^e_{22}+\epsilon^\mu_{22}\right)\mathcal{B}_{3S\to 2P_2}\mathcal{B}_{2P_2\to 1D_2}}{\left(\epsilon^e_{12}+\epsilon^\mu_{12}\right)\underbrace{\mathcal{B}_{3S\to 2P_1}\mathcal{B}_{2P_1\to 1D_2}}_{\text{Kwong \& Rosner}}}\right]$$

π^+ helicity angle $\theta_{\pi+}$

$dN/d\cos\theta_{\pi+} \sim 1 + \xi\, L(\cos\theta_{\pi+})$



Preliminary

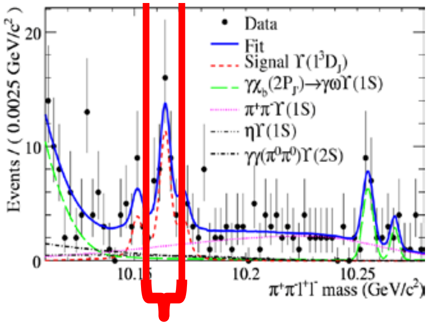
ξ → determine from data

Were the observed "Υ(1D)" an S state, the $\pi^+\pi^-$ would be emitted in an S-wave → $\xi = 0$

For a D state with J=2, need $L_{\pi\pi}=2$

$dN/d\cos\theta_{\pi+} \sim 1 + \xi\,(3\cos^2\theta_{\pi+}-1)/2$

Angle of π^+ in $\pi^+\pi^-$ rest frame wrt boost from $\Upsilon(1^3D_{J=2})$ frame



Select events in $\Upsilon(1^3D_{J=2})$ region:
10.155 to 10.168 GeV/c^2

Fit: $\xi = -1.0 \pm 0.4 \pm 0.1$ → Disfavors S-wave hypothesis
Consistent with J=2