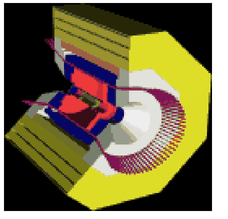
Recent Results In Bottomonium Physics



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SLAC National Laboratory

BaBar Collaboration

Flavor Physics and CP Violation 2010

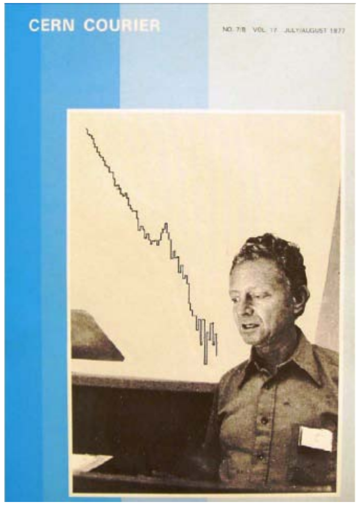
May 28, 2010 Torino - Italy

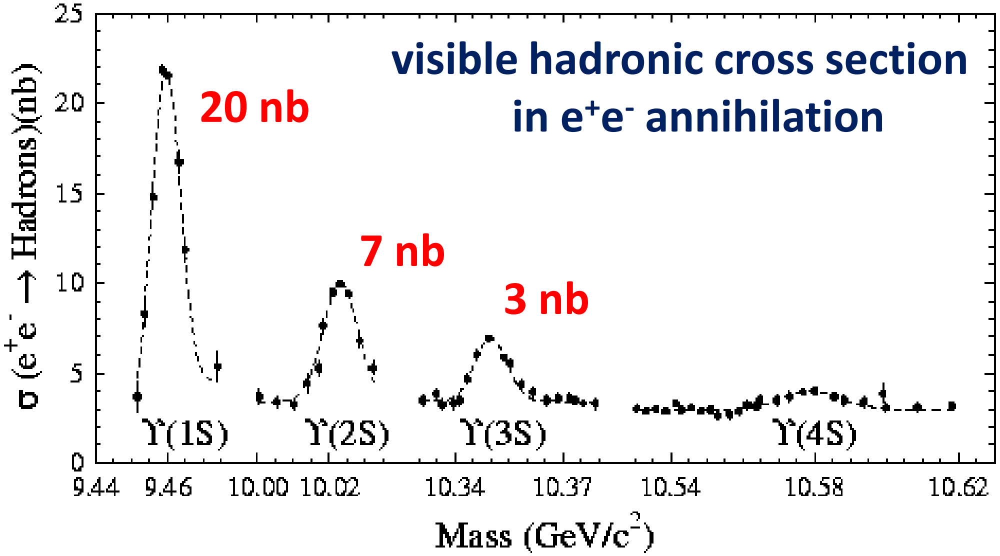
Bottomonium Production

Upsilons discovered in di-muon channel (1977)
E288 at Fermilab: p + (Cu, Pt) → $\mu^+ \mu^-$ X

Production studies at hadron machines continue:
quarkonia production rate, polarization

Detailed study of ($b\bar{b}$) states in spectroscopy, transitions between the states, and decays ➡ e^+e^- storage rings.





Upsilon data samples

- Until 2008, CLEO has contributed most to bottomonium physics
- Then,

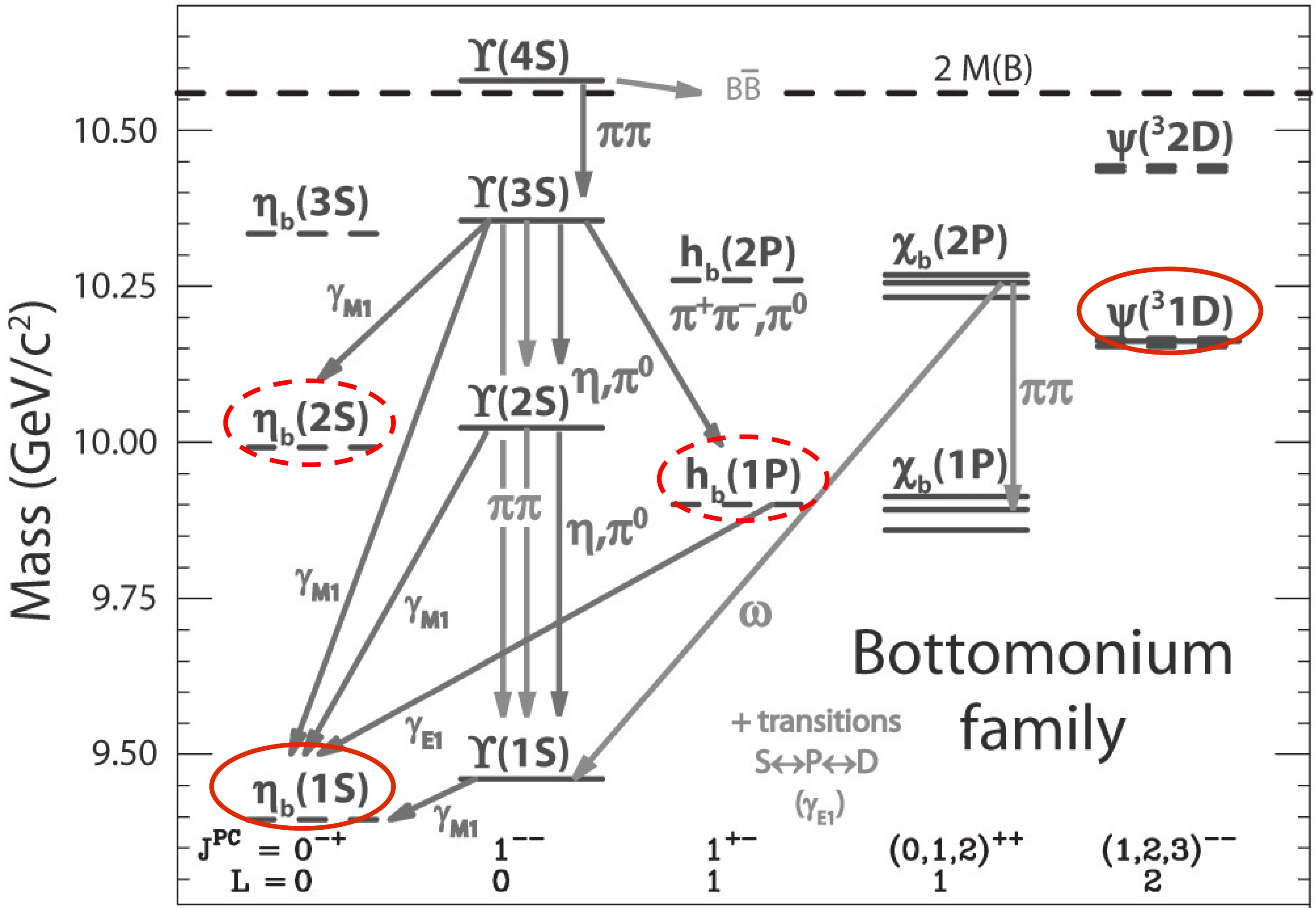
BaBar	01-02/2008:	120 M Υ(3S)
	03/2008:	100 M Υ(2S)
BELLE	06/2008:	100 M Υ(1S)
	12/2008:	46 M Υ(2S)
	11/2009:	124 M Υ(2S) (Processed data available now)

		CLEO III	BaBar	BELLE
N_events	**Υ(1S)**	20 M		**100 M**
	Υ(2S)	9 M	**100 M**	**175 M**
	Υ(3S)	6 M	**120 M**	11 M

[Current data sample, till Super B Factories]

OUTLINE

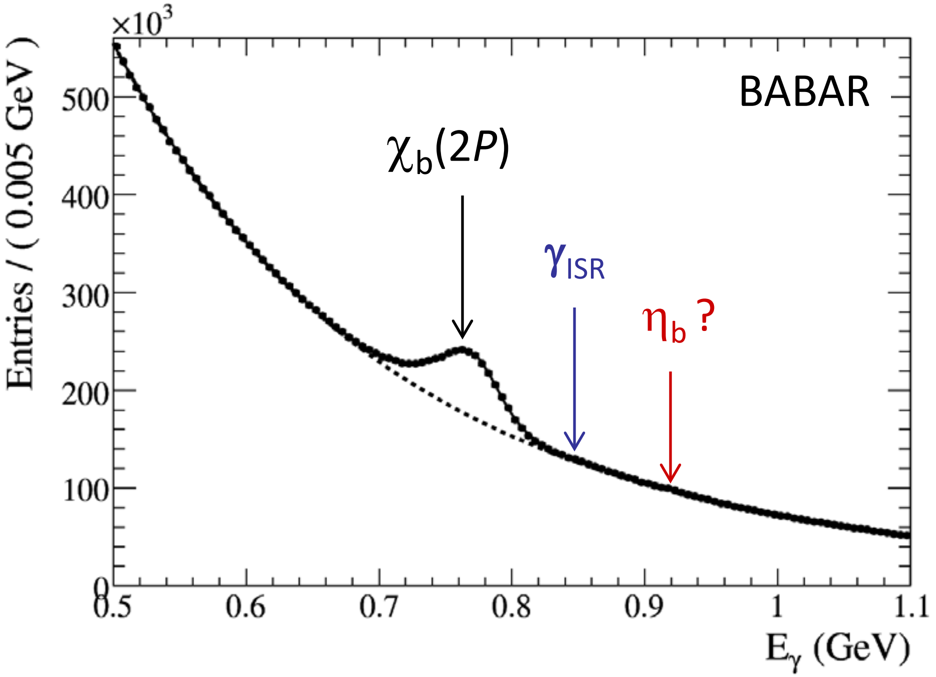
- η_b
- $\Upsilon(1^3D_J) \rightarrow \pi^+\pi^- \Upsilon(1S)$
- $\Upsilon(nS) \rightarrow \gamma$ charmonium
- $\Upsilon(1S) \rightarrow$ Inclusive open charm (D^*X)
- Summary

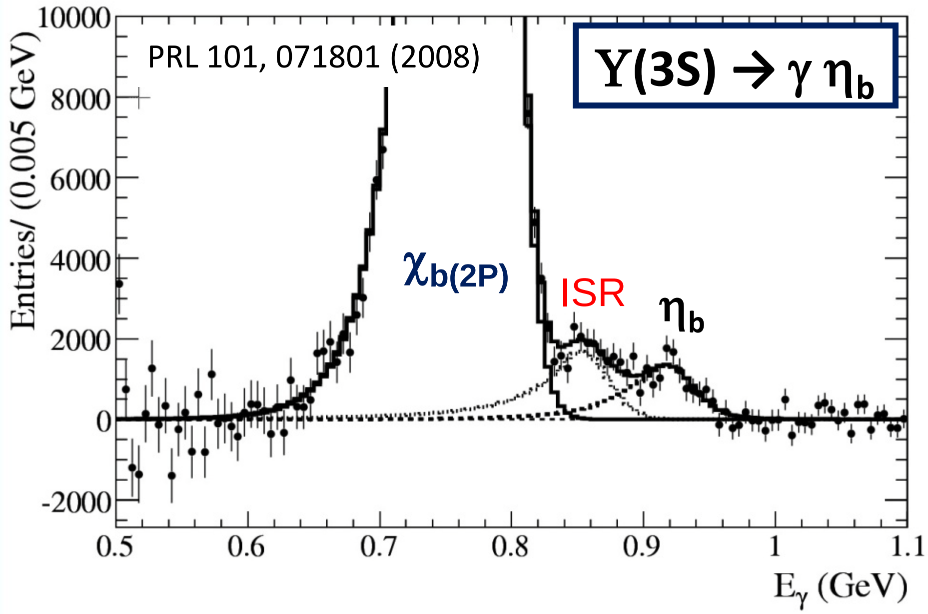


Eichten et al, Rev. Mod. Phys. 80, 1161 (2008)

Inclusive Analysis of $\Upsilon(2S,3S) \rightarrow \gamma\, \eta_b$

- Non-peaking backgrounds
  - *udsc* production
  - Generic ISR
  - Bottomonium decays
- Peaking backgrounds
  - $\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(2P)$;
    $\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(1S)$ (J=0, 1, 2)
  - $e^+e^- \rightarrow \gamma_{ISR}\, \Upsilon(1S)$
- To reduce continuum background:
  π^0 veto and $|\cos\theta_T|$ event shape cut





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

$$M(\eta_b) = 9388.9^{+3.1}_{-2.3} \pm 2.7 \text{ MeV/c}^2$$
$$M(\Upsilon(1S)) - M(\eta_b) = 71.4^{+2.3}_{-3.1} \pm 2.7 \text{ MeV/c}^2$$

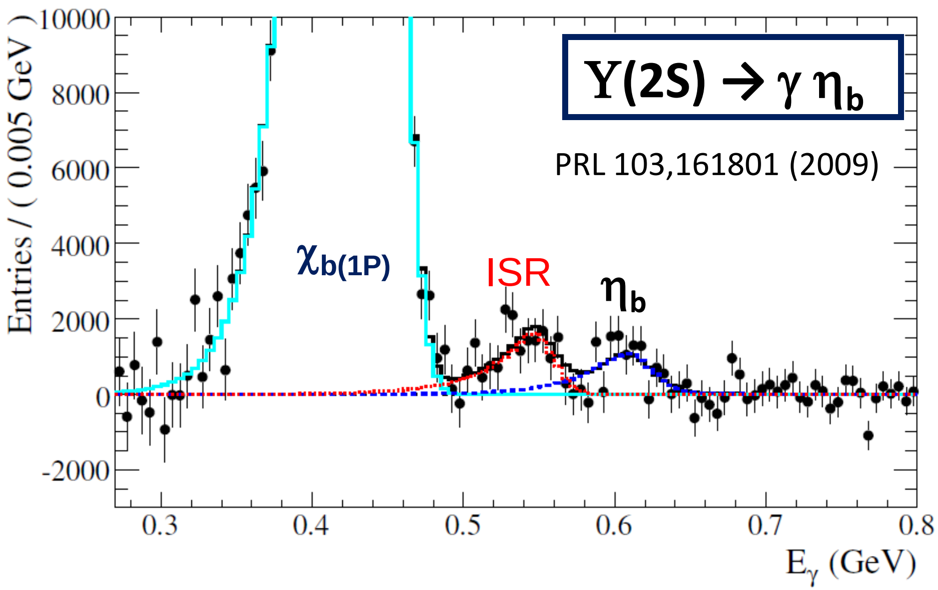
$$B(\Upsilon(3S) \to \gamma\,\eta_b) = [4.8 \pm 0.5 \pm 1.2] \times 10^{-4}$$

Combined result

$$M(\eta_b) = 9390.8 \pm 3.2 \text{ MeV/c}^2$$

$$M(\Upsilon(1S)) - M(\eta_b) = 69.5 \pm 3.2 \text{ MeV/c}^2$$

$$\frac{B(\Upsilon(2S) \to \gamma\,\eta_b)}{B(\Upsilon(3S) \to \gamma\,\eta_b)} = 0.82 \pm 0.24^{+0.20}_{-0.19}$$

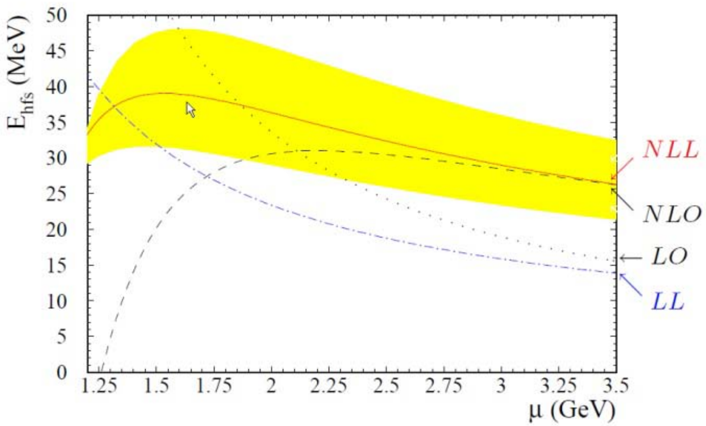


$$E_\gamma = 609.3^{+4.6}_{-4.5} \pm 1.9 \text{ MeV}$$

$$M(\eta_b) = 9394.2^{+4.8}_{-4.9} \pm 2.0 \text{ MeV/c}^2$$
$$M(\Upsilon(1S)) - M(\eta_b) = 66.1^{+4.9}_{-4.8} \pm 2.0 \text{ MeV/c}^2$$

$$B(\Upsilon(2S) \to \gamma\,\eta_b) = [3.9^{+1.1}_{-1.0}\,{}^{+0.7}_{-0.9}] \times 10^{-4}$$

Hyperfine Splitting: theory



pNRQCD in NLL

Summation of next-to leading logarithmic corrections using the nonrelativistic renormalization group

Kniehl et al, PRL 92, 242001 (2004)
A. Penin, hep-ph/0905.4296

$$E_{hfs} = M(\Upsilon(1S)) - M(\eta_b) = 41 \pm 11\ {}^{+8}_{-9}\,(\alpha_s)\ \text{MeV}$$

Lattice QCD

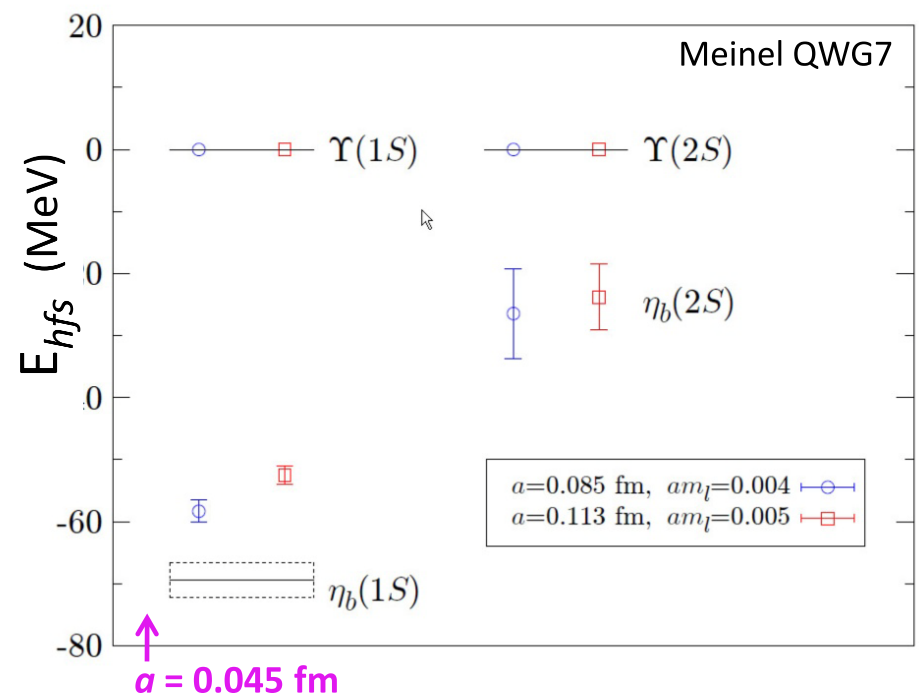
61.0 ± 14 [HPQCD] PR D72, 094507(2005)

54.0 ± 12.4 [Fermilab Lattice and MILC] PR D81, 034508 (2010)

52.5 ± ? S. Meinel [Lattice/NRQCD] PR D79, 094501 (2009) QWG7 2010 (preliminary)

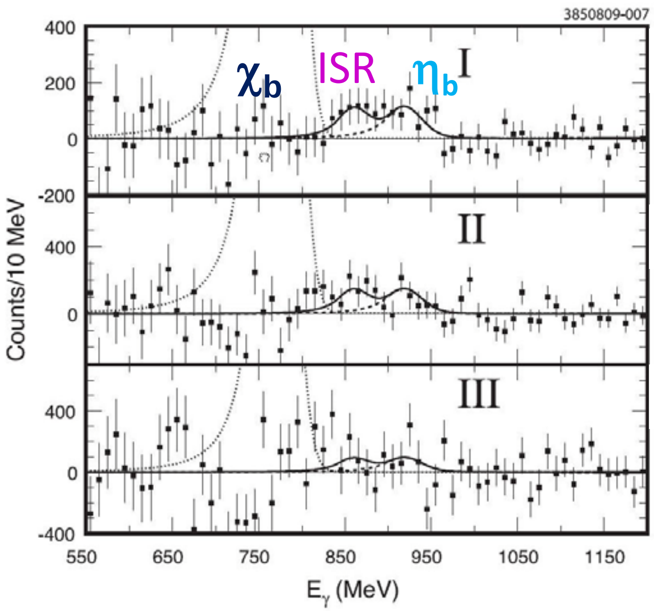
Lattice spacing *a* is important for the b quark

Converging with Exp. Meas. at small *a* ?



CLEO: Reanalysis of $\Upsilon(3S) \to \gamma\, \eta_b$

PR D 81, 031104(R) (2010)



- Joint fit of 3 $|\cos\theta_T|$ regions
- Include ISR component in the fit

4σ significance

$$\mathcal{B}(\Upsilon(3S) \to \gamma\eta_b) = (7.1 \pm 1.8 \pm 1.3) \times 10^{-4}$$

$$M(\eta_b) = 9391.8 \pm 6.6 \pm 2.0 \text{ MeV}/c^2$$

(Consistent with BABAR measurements)

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

Inclusive search for η_b with 170 Million $\Upsilon(2S)$ events: results expected soon

More pathways to η_b (1S) and η_b(2S)

- $\Upsilon(1S) \rightarrow \gamma\, \eta_b(1S)$ INCLUSIVE

  $E\gamma$ signal at 70 MeV
  No χ_b background; No peaking ISR background

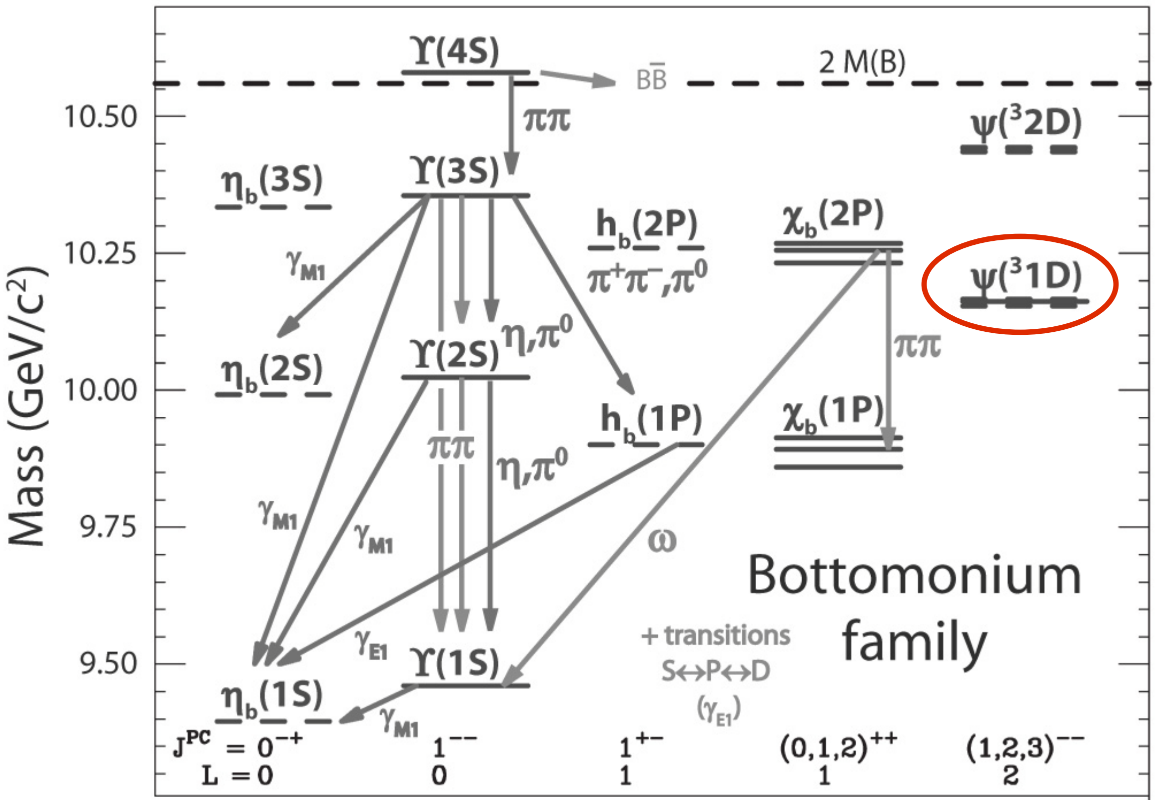
- $\Upsilon(3S) \rightarrow \gamma\, \eta_b(2S)$ INCLUSIVE

  $E\gamma$ Signal at 360 MeV (Difficult region with nearby E1 transitions)

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

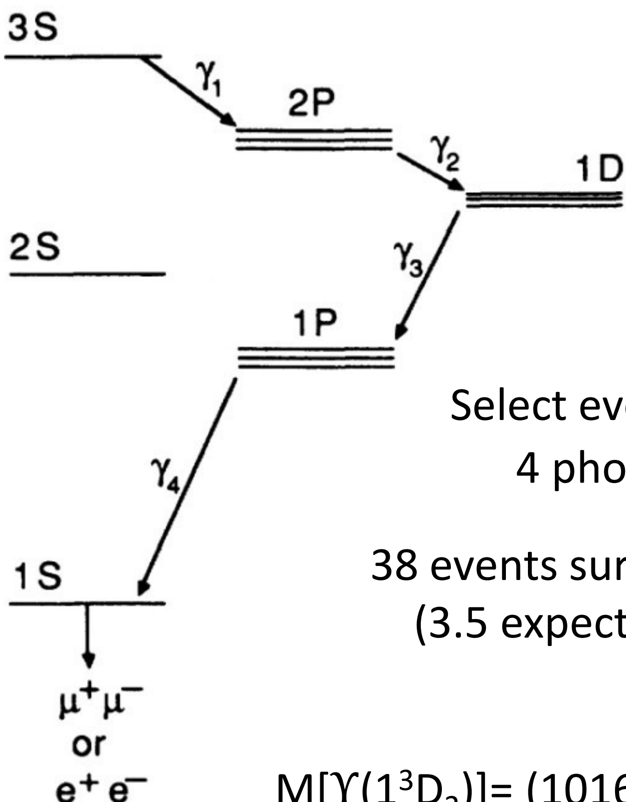
  Photon conversion rate at BaBar at a few %
  Good energy resolution of 5 MeV vs. 25 MeV calorimeter photons
  With a larger data set the η_b width measurement might be possible

$\Upsilon(1^3D_J)$



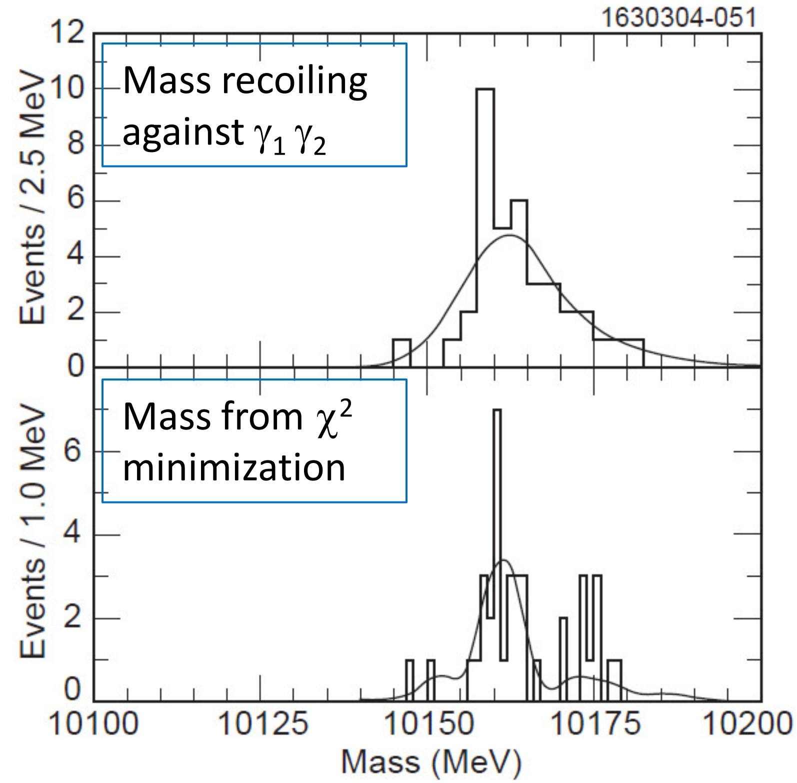
- L = 2 narrow triplet states (J = 1,2,3)
- Accessible from the Υ(3S) via double photon transitions through χ_b(2P)

Observation of $\Upsilon(1^3D_J)$ in 4-photon transition [CLEO] PR D70, 032001 (2004)



Select events with exactly 4 photons and $l^+ l^-$

38 events survive final cuts (3.5 expected background)



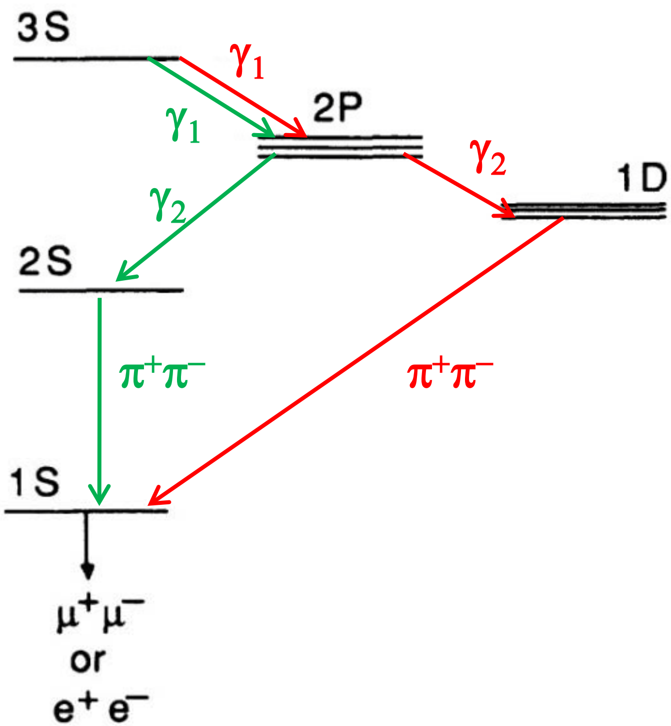
$M[\Upsilon(1^3D_2)] = (10161.1 \pm 0.6 \pm 1.6)\ \mathrm{MeV}/c^2$

$BF[\Upsilon(3S) \to \gamma\gamma\Upsilon(1D) \to \gamma\gamma\gamma\gamma\ \Upsilon(1S) \to \gamma\gamma\gamma\gamma\ l^+l^-] = (2.5 \pm 0.5 \pm 0.5) \times 10^{-5}$

Consistent with $M = 10160 \pm 10$ MeV Godfrey and Rosner, PR D64, 097501 (2001)
$BF = 3.7 \times 10^{-5}$ Kwong and Rosner, PR D38, 279 (1988)

Observation of $\Upsilon(1^3D_J) \to \pi^+\pi^-\Upsilon(1S)$

BaBar PRELIMINARY
arXiv:1004.0175 [hep-ex]



Y(3S) → $\gamma_1\gamma_2$Y(2S); Y(2S)→$\pi^+\pi^-$Y(1S)
Control channel for systematic studies
(calibration with Y(2S) mass

Reconstruction of 1D states in $\pi^+\pi^-$ Y(1S)

- Very good mass resolution with charged tracks
- The L,J, and parity P can be tested from the $\pi^+\pi^-$ invariant mass and decay angular distributions

- Theoretical predictions
  - 0.2% P. Moxhay, PR D37, 2557 (1988)
  - 2% P. Ko, PR D47, 208 (1993)
  - 40% Y.P. Kuang & T.M. Yan, PR D24, 2874 (1981)
- Upper limit of <4% at 90%CL [CLEO]

- Allow exactly 4 tracks in the event: $\pi^+ \pi^- l^+ l^-$
- Y(1S) → $l^+ l^-$ candidate mass kinematically constrained
- Require 2 photons (Eγ>60MeV) when combined with the 1D candidate, have energy/momentum consistent with the Y(3S)

Backgrounds

The backgrounds are small and non-peaking in the signal region
$10.14 < M(\pi^+\pi^- l^+ l^-) < 10.18$ GeV/c^2

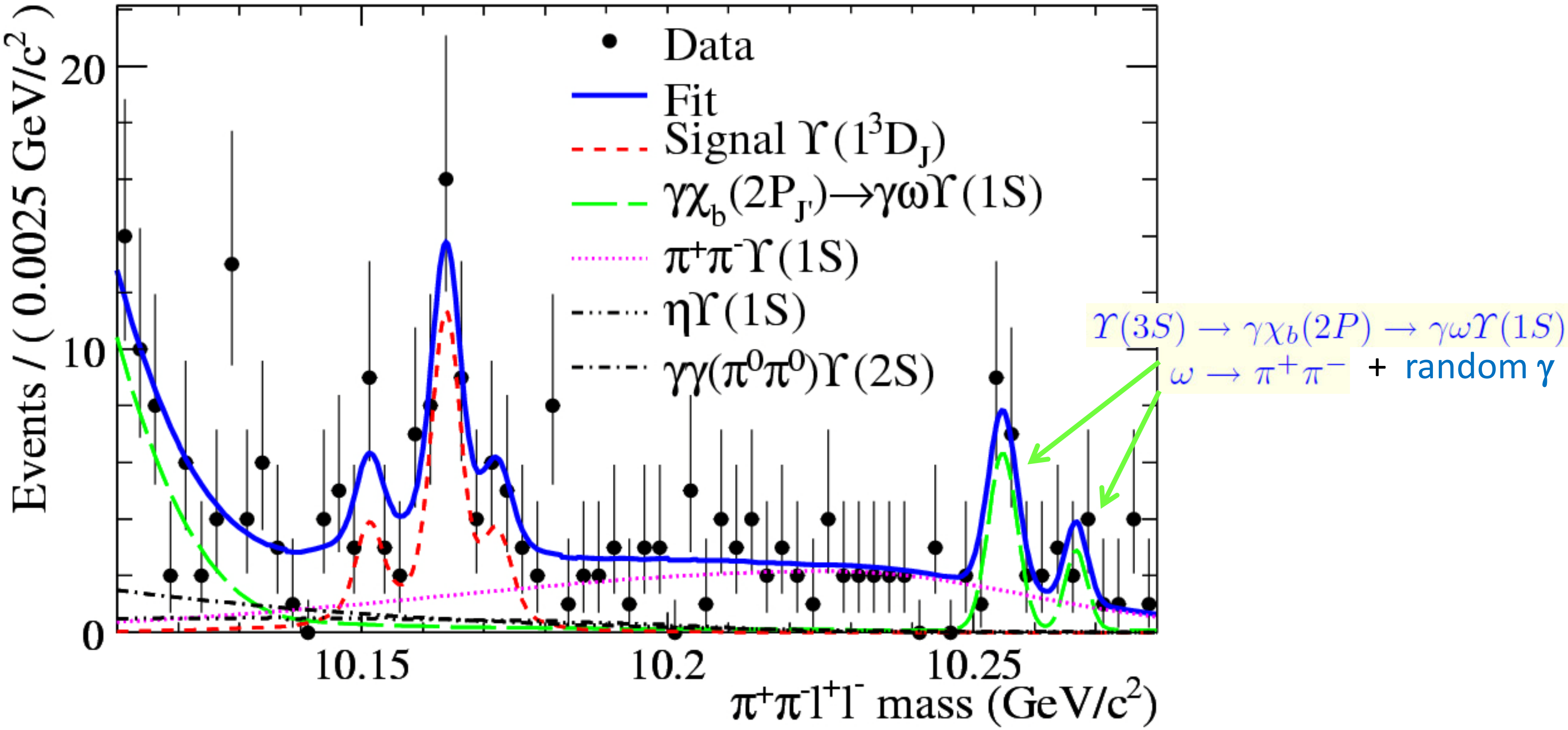
1. $\Upsilon(3S) \to \gamma\chi_b(2P) \to \gamma\omega\Upsilon(1S)$
   - $\omega \to \pi^+\pi^-\pi^0$
   - $\omega \to \pi^+\pi^-$, combine with a random (noise) γ
2. $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ with FSR γ's
3. $\Upsilon(3S) \to \eta\Upsilon(1S)$ with $\eta \to \pi^+\pi^-\pi^0(\gamma)$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

Maximum Likelihood fit

- Three $\Upsilon(1D_J)$ signal PDFs: double-Gaussian + Gaussian w. exponential tail
- Each of the 4 background PDFs determined from MC simulations
- 11 free parameters: 3 signal yields and 3 signal masses + 5 background parameters
  (BG 1 and 2 yields, $\chi_{b1}(2P)$ mass, $\chi_{b1,2}(2P) \to w(\to \pi^+\pi^-)$ yields)

Fit results

BaBar PRELIMINARY

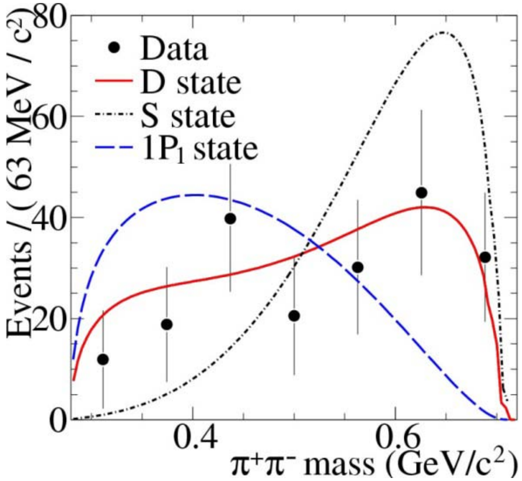


J=1,2,3 combined:

$53.8^{+10.2}_{-9.5}$ events

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

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	



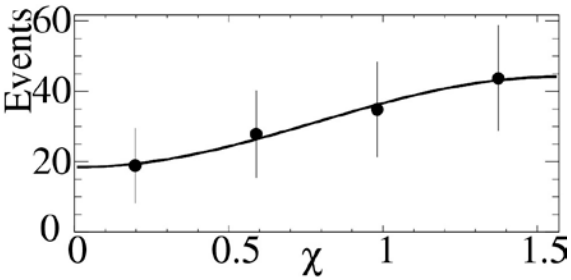
BaBar PRELIMINARY

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

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

Signal yields are background subtraced & efficiency corrected

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



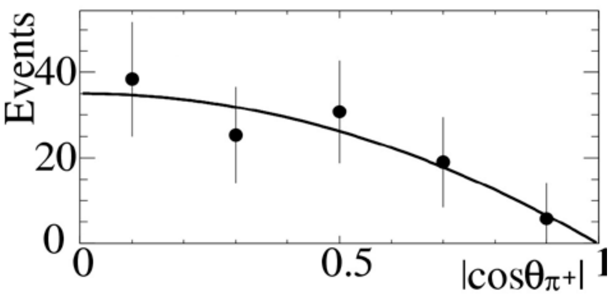
Angle χ between the $\pi^+\pi^-$ and l^+l^- planes

[Dell'Aquila and Nelson, PRD33, 80 (1986)]

$$\mathrm{d}N/\mathrm{d}\chi \sim 1 + \beta\cos(2\chi) \qquad \mathrm{sign}(\beta) = (-1)^J P$$

$$\text{Fit: } \beta = -0.41 \pm 0.29 \pm 0.10$$

Consistent with J=2 and P=-1



π^+ helicity angle θ_{π^+}

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

$$\text{Fit: } \xi = -1.0 \pm 0.4 \pm 0.1$$

Consistent with J=2

- Mass calibration with $\Upsilon(2S)$ mass: 0.7 MeV/c^2 shift; 0.5 MeV/c^2 sys. uncertainty

- Signal yield: Background variations → sys. uncertainty of 2 events
- Efficiency: Differ up to 7.5% for different $E\gamma_1$ and $E\gamma_2$ combinations
  Use the dominant decay modes from theory & vary for systematics

Branching Fractions

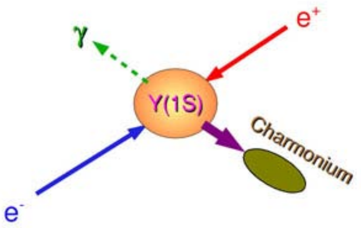
1^3D_J	BF $[\Upsilon(1^3D_J)\rightarrow\pi^+\pi^-\Upsilon(1S)]$	90% C.L. upper limit	Kwang & Yan (1981)	Ko (1993)	Moxhay (1988)
J=1	$(0.42_{-0.23}^{+0.27}\pm0.10)\%$	< 0.82%	40%	1.6%	0.20%
J=2	$(0.66_{-0.14}^{+0.15}\pm0.06)\%$		46%	2.0%	0.25%
J=3	$(0.29_{-0.18}^{+0.22}\pm0.06)\%$	< 0.62%	49%	2.2%	0.27%

SUMMARY

- First observation of $\Upsilon(1^3D_J)$ in hadronic decays to $\pi^+\pi^-\Upsilon(1S)$
- The dominant peak is consistent with J=2 assignment
  Mass = $(10164.5\pm0.8\pm0.5)$ MeV/c^2

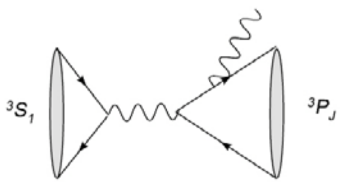
CLEO: $(10161.1\pm0.6\pm1.6)$ MeV/c^2

Radiative Y(1S) decay to Charmonium

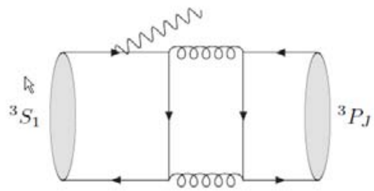


BELLE Preliminary, R. Mussa (QWG7 2010)

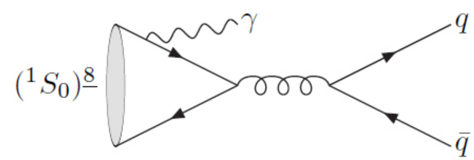
NRQCD predictions of short-distance transitions between bb and cc including color-octet contributions (Y-J Gao et al., hep-ph/0701009)



QED



Typical QCD



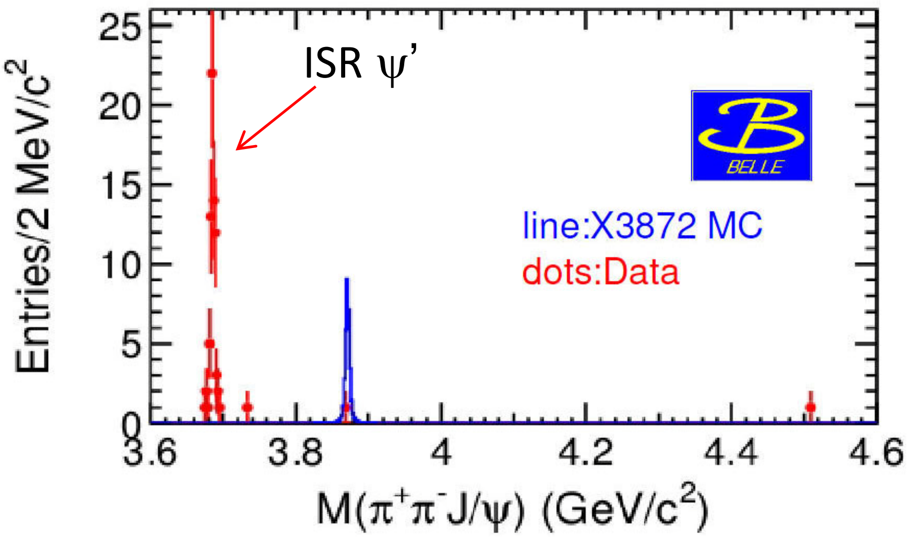
Color octet

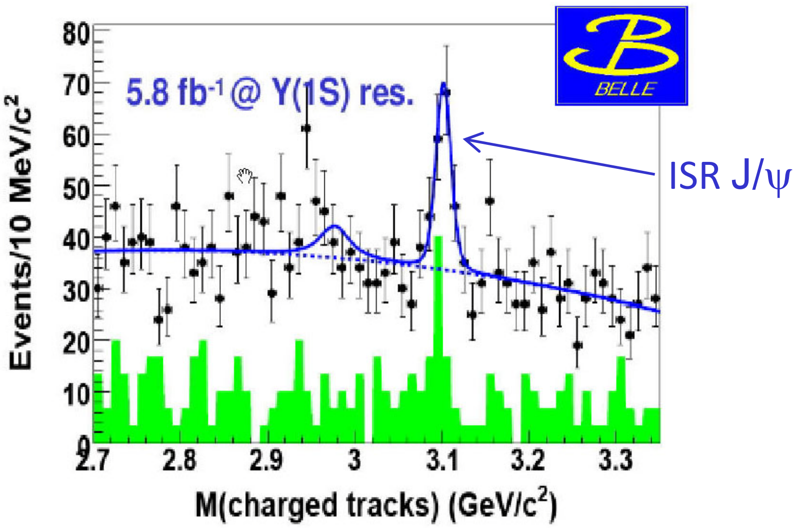
- Many predictions for 2-body radiative decay channels
  $\Upsilon(1S) \rightarrow \gamma\eta_c$, $\gamma\chi_c$, $\gamma f_0(980)$, $\gamma f_2(1270)$
  $\chi_b \rightarrow \gamma J/\psi$, $\gamma\rho$, $\gamma\omega$, $\gamma\phi$

- Interference between QED and QCD amplitudes could enhance the rates
- Search for exotics: X(3872), X(3915), Y(4140)

$\Upsilon(1S) \rightarrow \gamma J/\psi \pi^+\pi^-$

$\Upsilon(1S) \rightarrow \gamma \eta_c$





$\Upsilon(1S) \rightarrow \gamma J/\psi \pi^+\pi^-$; $J/\psi \rightarrow l^+l^-$

Reject e+ and e- from photon conversion
$|\cos\theta\gamma| < 0.9$ to suppress ISR events

1 event at X(3872) for J/ψ signal region
(none in the J/ψ side bands)
Large ISR background peak at ψ' mass

$Br(\Upsilon(1S) \rightarrow \gamma X(3872) \rightarrow \gamma J/\psi \pi^+\pi^-) < 2.2 \times 10^{-6}$

$\eta_c \rightarrow K_S K^-\pi^+$ +c.c., $K^+K^-\pi^+\pi^-$, $2(K^+K^-)$, $2(\pi^+\pi^-)$, $3(\pi^+\pi^-)$

Exclusive decay of η_c in 4 or 6 charged tracks

No η_c signal observed
Peaking ISR J/ψ background

$Br(\Upsilon(1S) \rightarrow \gamma \eta_c) < 6.4 \times 10^{-5}$

Υ(1s) → γ+charmonium: exp vs theory

BELLE PRELIMINARY

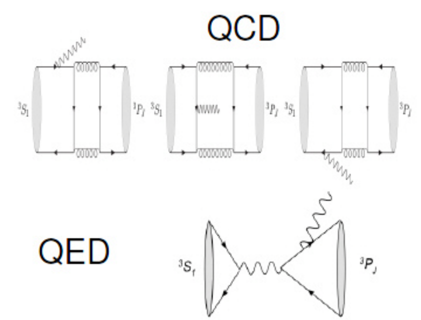
BR(Υ(1S) → f)*10^6

	90%CL UL
$\Upsilon(1S) \to \gamma\chi_{c0}$	500
$\Upsilon(1S) \to \gamma\chi_{c1}$	15
$\Upsilon(1S) \to \gamma\chi_{c2}$	12
$\Upsilon(1S) \to \gamma\eta_c$	64
$\Upsilon(1S) \to \gamma$ X3872 $\to \gamma\ \pi^+\pi^-$ J/ψ	2.2
$\Upsilon(1S) \to \gamma$ X3872 $\to \gamma\ \pi^0\pi^+\pi^-$ J/ψ	3.4
$\Upsilon(1S) \to \gamma$ X3915 $\to \gamma\ \pi^0\pi^+\pi^-$ J/ψ	3.4
$\Upsilon(1S) \to \gamma$ Y4140 $\to \gamma\ \phi$J/ψ	2.6

NRQCD predictions

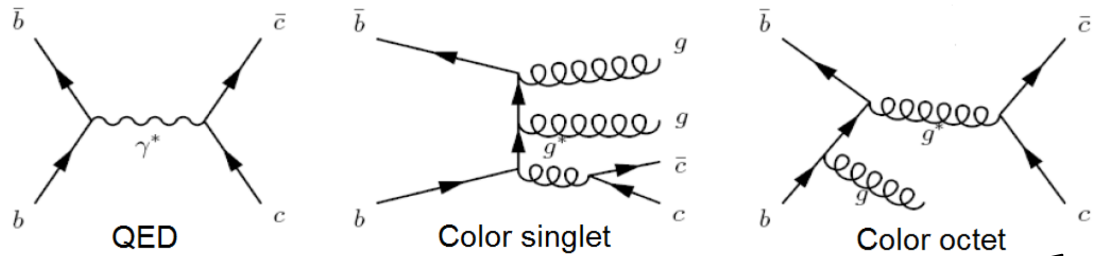
[K. T. Chao et al., hep-ph/0701009]

QCD	QCD+QED
4.0	3.2
4.5	9.8
5.1	5.6
2.9	4.9



- Experimental sensitivity with 100 M Υ(1S) events still above theory predictions
  Exotics searches with J/ψ decaying to lepton pairs especially could use more data!
- [$\pi^+\pi^-$ recoil] tagging of Υ(1S) in Υ(2S) → $\pi^+\pi^-$ Υ(1S) could provide clean Υ(1S) sample without QED/ISR background: very useful in analysis of low-multiplicity final states

$\Upsilon(1S) \to D^{*\pm} + X$

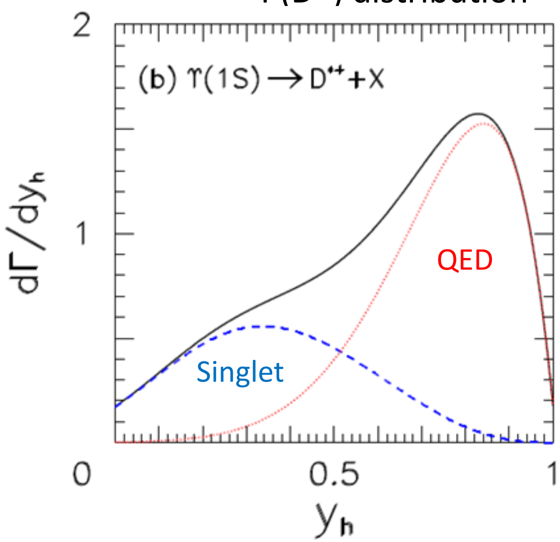


Octet component could be ~50% of singlet; Zhang & Chao, PR D78, 094017 (2008)

Singlet rate: (1.20 ± 0.29)%

Kang et al. PRD 76, 114018 (2007)

P(D*) distribution



<u>Observation of $\chi_b \to D^0$ X</u> [CLEO: PR D78, 092007 (2008)]

- Mostly from J=1 χ_b state
- Octet component is estimated at ~9% of singlet
- No measurement of D^0 momenta

BF($\Upsilon(1S) \to D^{*\pm} + X$) < 1.9 % [ARGUS, Z Phys C55, 25 (1992)]

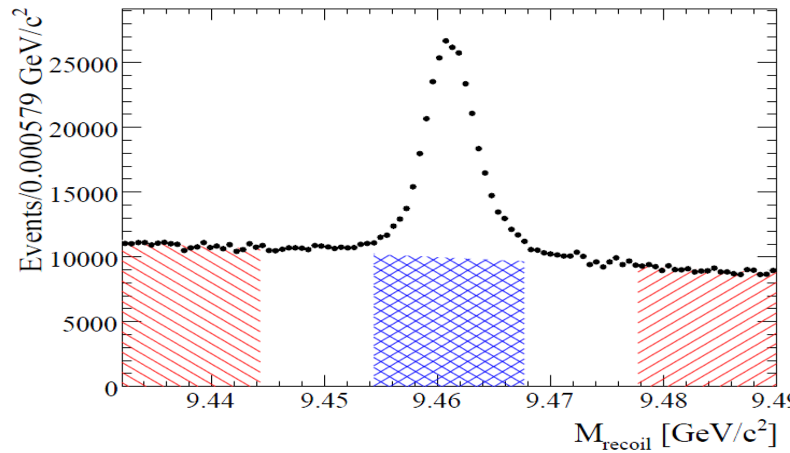
Observation of Inclusive $D^{*\pm}$ Production in $\Upsilon(1S)$ Decay

PR D81, 011102(R) (2010)

$\Upsilon(2S) \to \pi^+\pi^- \Upsilon(1S)$: 18 M events

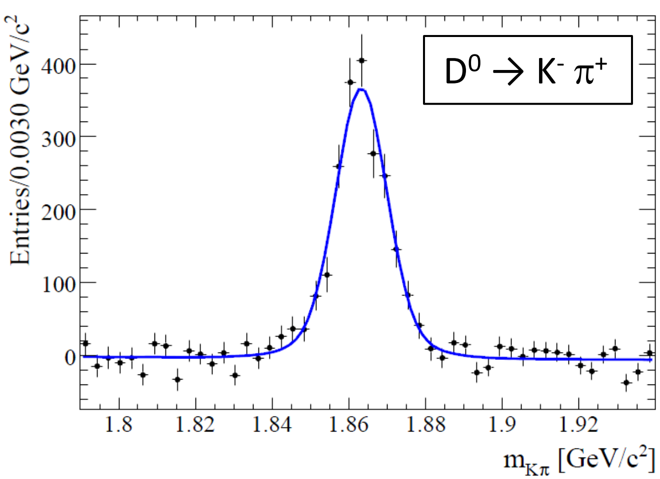
Use $M\_\pi^+\pi^-$ recoil to tag $\Upsilon(1S)$

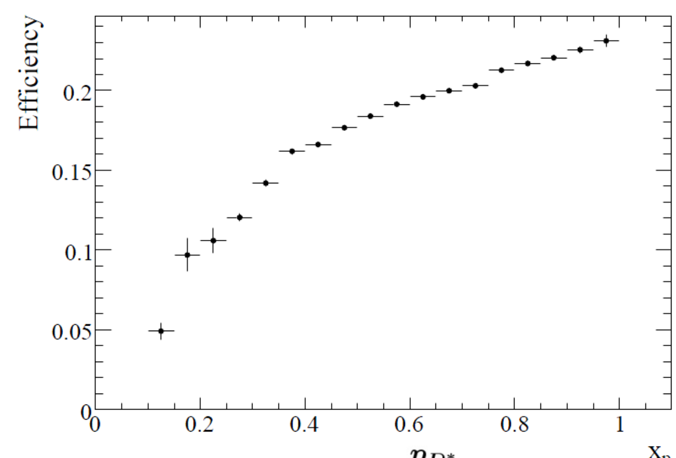
(No continuum $c\bar{c}$ background!)



- Standard D^{*+} construction with narrow M(D*)-M(D) cut
- Subtract combinatorial background using the $M\_\pi^+\pi^-$ recoil side bands and wrong-sign $K\pi$ combinations
- Fit $M(D^0)$ in momentum bins of Xp = [0.1, 1.0]

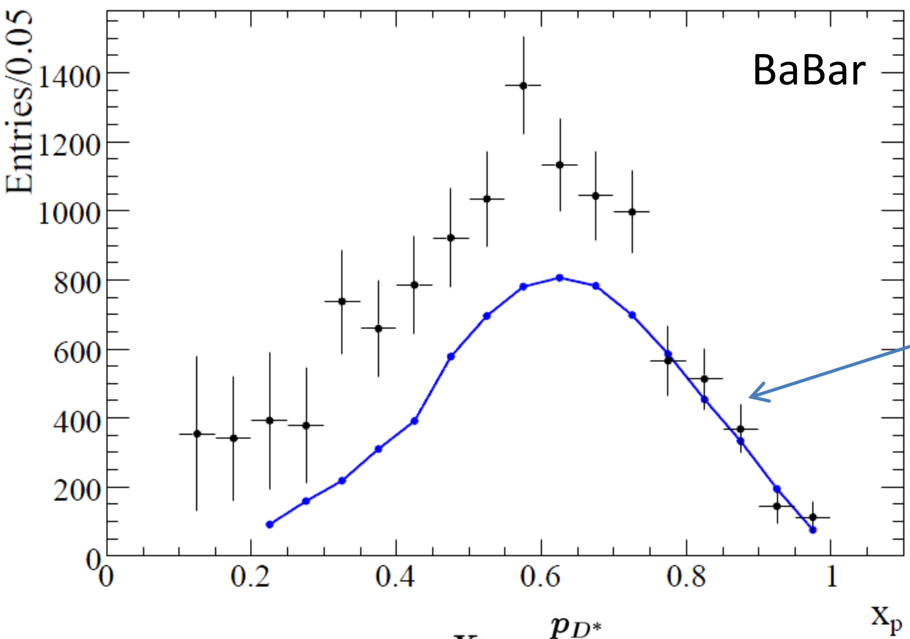
Reconstruction efficiency from Monte Carlo signal events





$$X_p = \frac{p_{D^*}}{p_{max}}$$

Inclusive D* momentum distribution



$$X_p = \frac{p_{D^*}}{p_{max}}$$

Use CLEO measurement of continuum D* fragmentation function at 10.5 GeV

[PR D70, 112001 (2004)]

- Scaled to match the cross section at Y(1S)

$x_p > 0.75$: consistent with QED

$x_p < 0.75$: significant excess

- $Br(\Upsilon(1S) \rightarrow D^{*\pm} + X) = (2.52 \pm 0.13 \pm 0.15)\%$
- Exceeds QED rate by $(1.00 \pm 0.28)\%$ (3.6σ)
- Consistent with color singlet prediction $(1.20 \pm 0.29)\%$ [Kang et al.]

First evidence for open charm: more work to follow

- With 10^8 Y(nS) events, new exciting results from BaBar and BELLE

- However, we are already facing statistical limits in rare decay modes

- 10^{10} data samples can be collected in a few months at

Conclusions

- Hyperfine splitting between the Υ(1S) and the η_b provides a valuable testing ground for NRQCD and Lattice QCD theories
- First observation of hadronic decay of the $\Upsilon(1^3D_J)$ states and more precise mass measurement of the J=2 state
- Searches for charmonium production in radiative 2-body decays of Υ(1S)
- First measurement of inclusive D* meson production in Υ(1S) decay
- More new results are expected soon