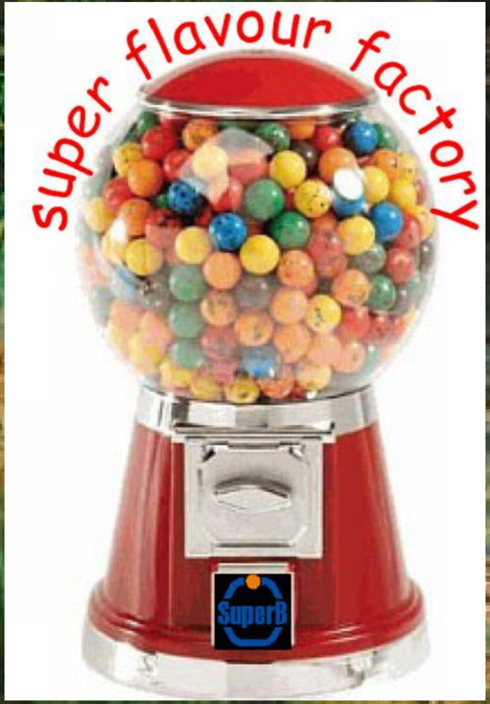
Ideas on $\Upsilon(nS, n\neq 4)$ physics potentialities at superB factories



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Roberto Mussa
INFN Torino

XI SuperB
Workshop

LNF 2/12/2009

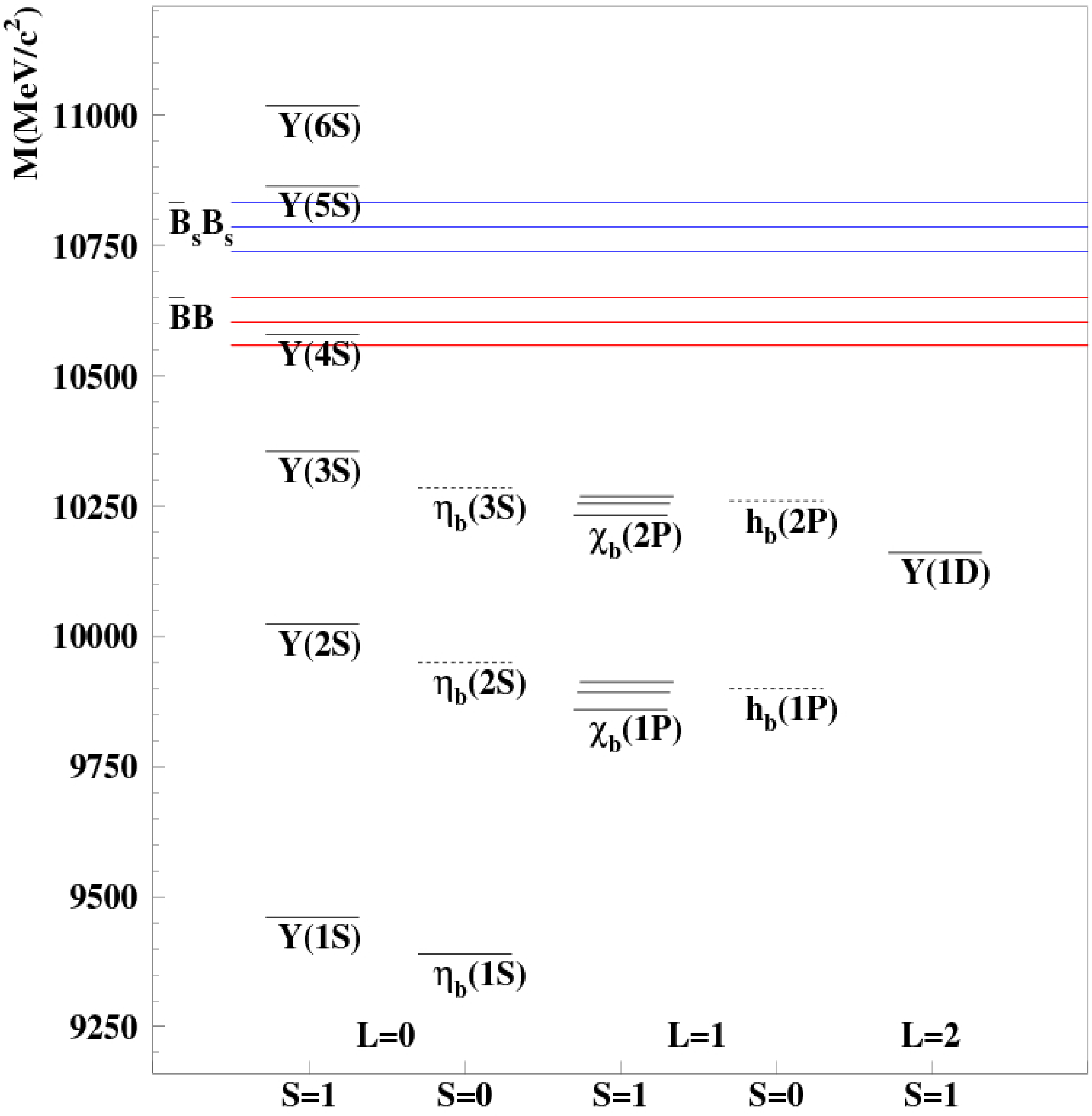
Bottomonium

In principle, this is the BEST SYSTEM for testing QCD predictions on bound states.

Ideal place to challenge our understanding of strong interactions.

Succesfully described at tree level by QCD, perturbative approach solid in theory, at least for lower lying states.

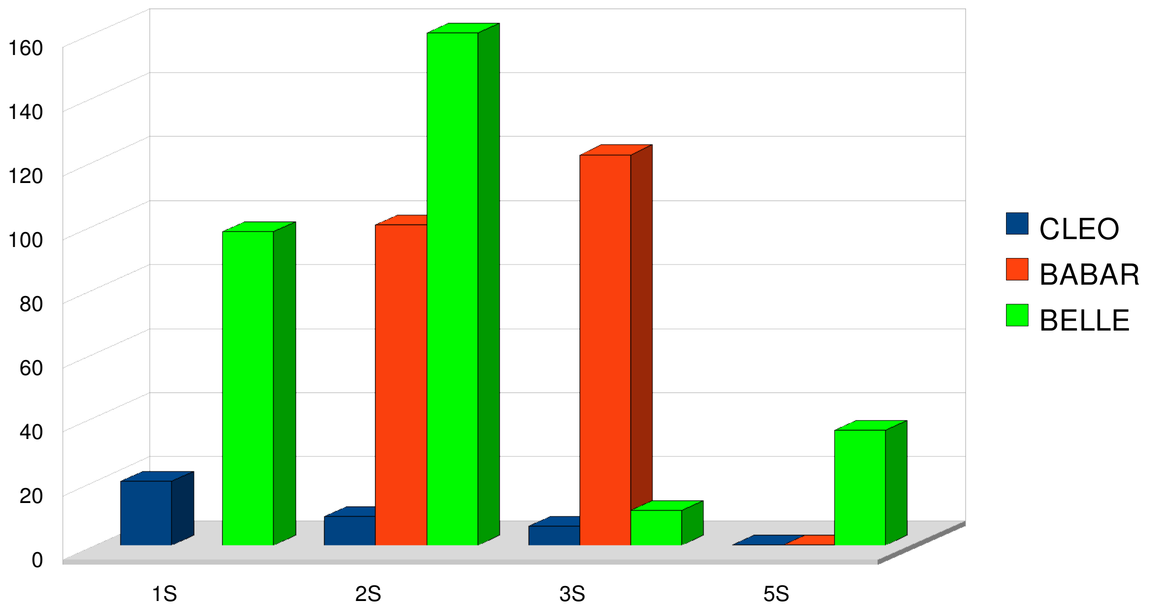
BUT:
- at least 4 states missing
- many surprises in hadronic transitions
- ... and in hyperfine splitting



Data Samples (units 10^6)

Y(nS) Peak Running
2002-3: CLEO-III 1,2,3S
2006: Belle 3,5S
2007: Belle 5S
2008: Babar 2,3S
Belle 1,2,5S
2009: Belle 2,5S

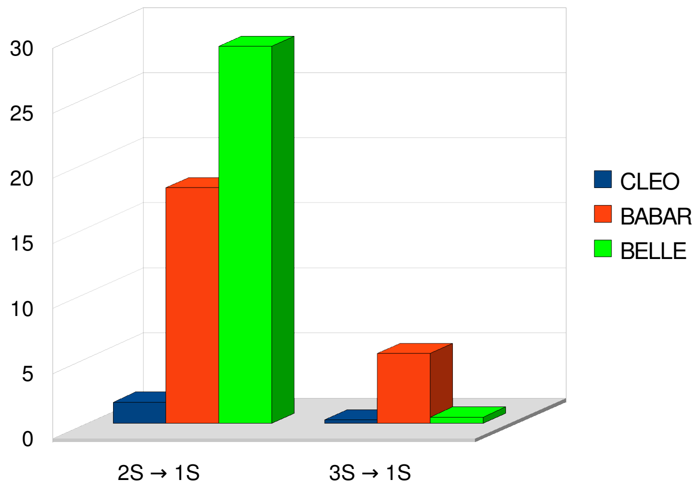
Decays on Resonance Peak

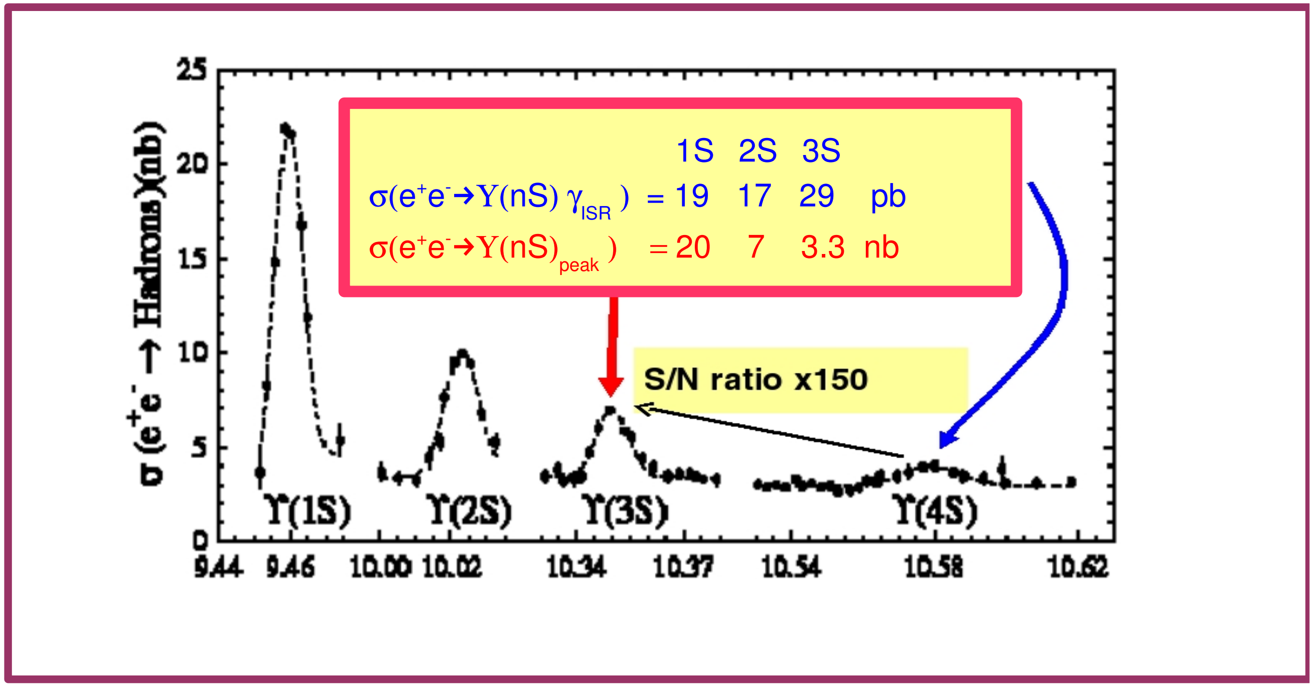


Y(2,3S) Peak Bonus:
Tagged 1S from

$\Upsilon(2,3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$

PI+PI-Tagged Decays





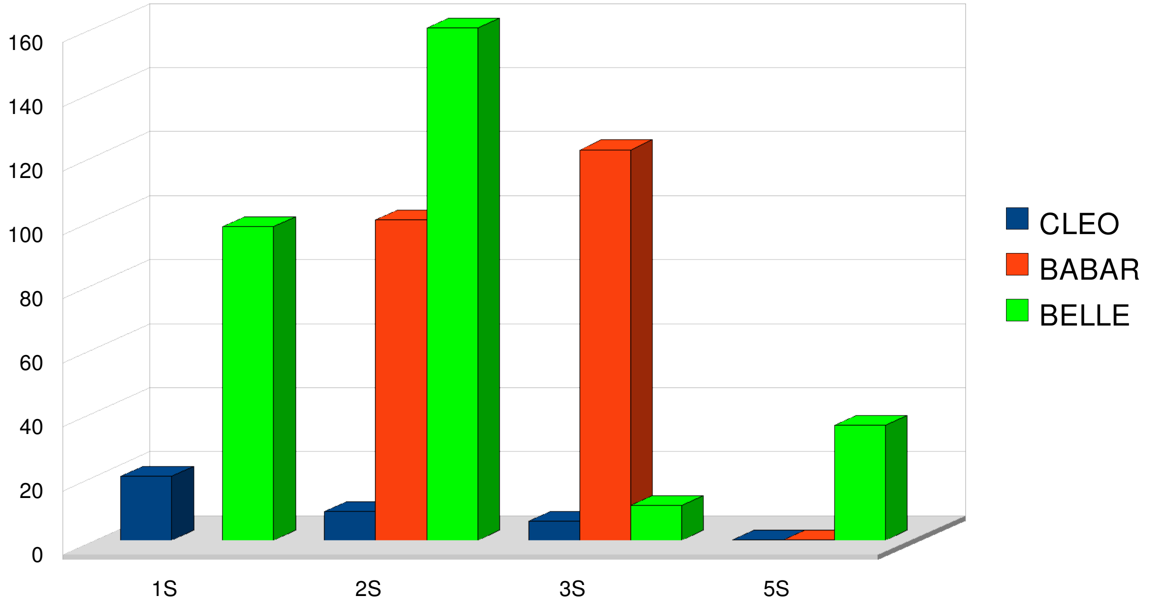
	1S	2S	3S	
$\sigma(e^+e^- \to \Upsilon(nS)\,\gamma_{ISR})$ =	19	17	29	pb
$\sigma(e^+e^- \to \Upsilon(nS)_{peak})$ =	20	7	3.3	nb

S/N ratio x150

Data Samples (units 10^6)

Y(nS) Peak Running

2002-3: CLEO-III 1,2,3S
2006: Belle 3,5S
2007: Belle 5S
2008: Babar 2,3S
Belle 1,2,5S
2009: Belle 2,5S



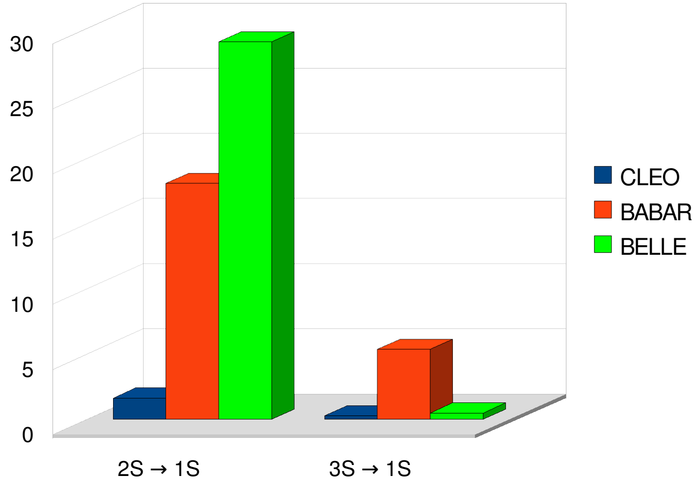
Decays on Resonance Peak

Y(2,3S) Peak Bonus:

Tagged 1S from

$\Upsilon(2,3S) \rightarrow \pi+\pi-\Upsilon(1S)$

PI+PI-Tagged Decays

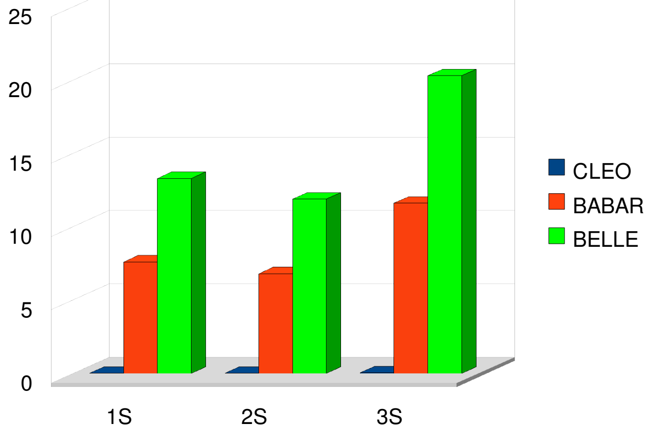


Y(4S) Peak Running

$e^+e^- \rightarrow \Upsilon(nS)\ \gamma_{ISR}$

σ(1S@10580) =19 pb
σ(2S@10580) =17 pb
σ(3S@10580) =29 pb
(*) untagged γ_{ISR}

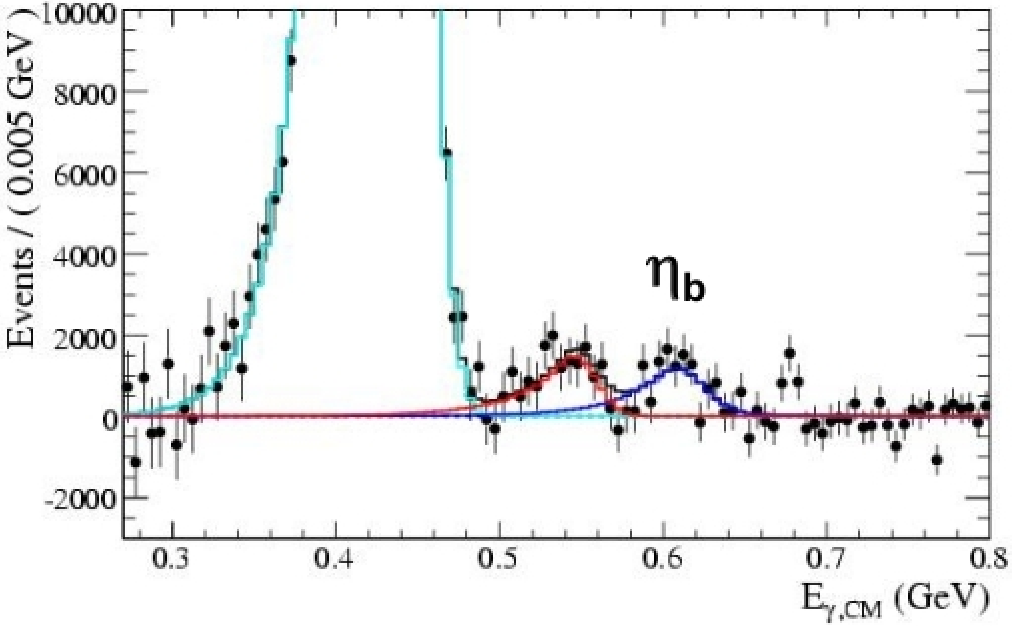
ISR untagged decays from 4S



η_b(1S) discovery

Υ(2S) → γ η_b

[14.5 fb^{-1} = 100 M Υ(2S), Mar.2008]



PRL 103,161801(2009)

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

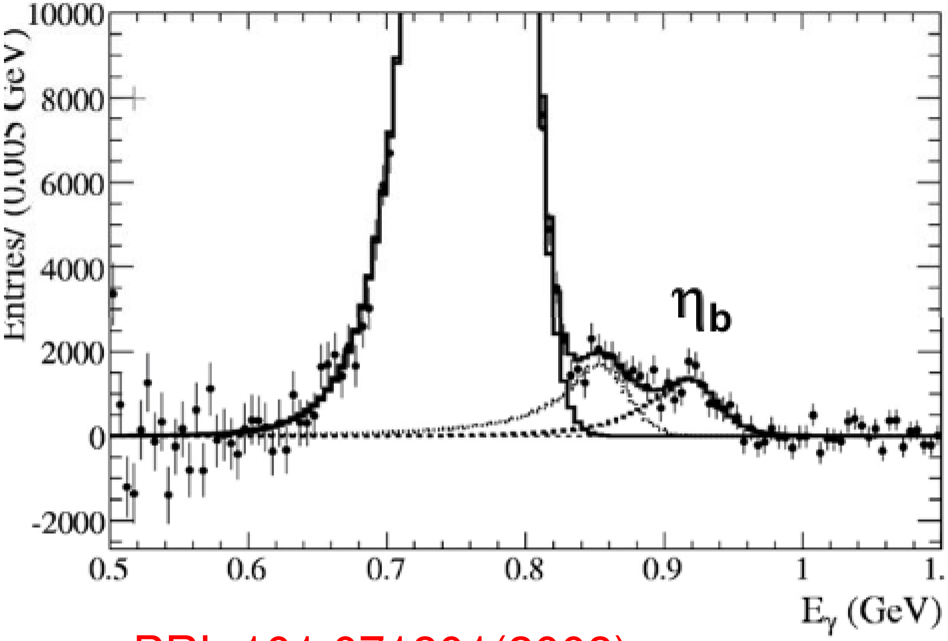
$$M(\eta_b) = 9392.9^{+4.6}_{-4.8} \pm 1.8 \text{ MeV}/c^2$$

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

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

Υ(3S) → γ η_b

[30.2 fb^{-1} = 120 M Υ(3S), Jan-Feb.2008]



PRL 101,071801(2008)

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

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

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

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

New physics???

NRQCD:

NLL calculation of δM_{hf} :

δM_{hf}=39±10(th)±9($\delta\alpha_S$) MeV/c^2

Kniehl et al., PRL 92(2004),242001

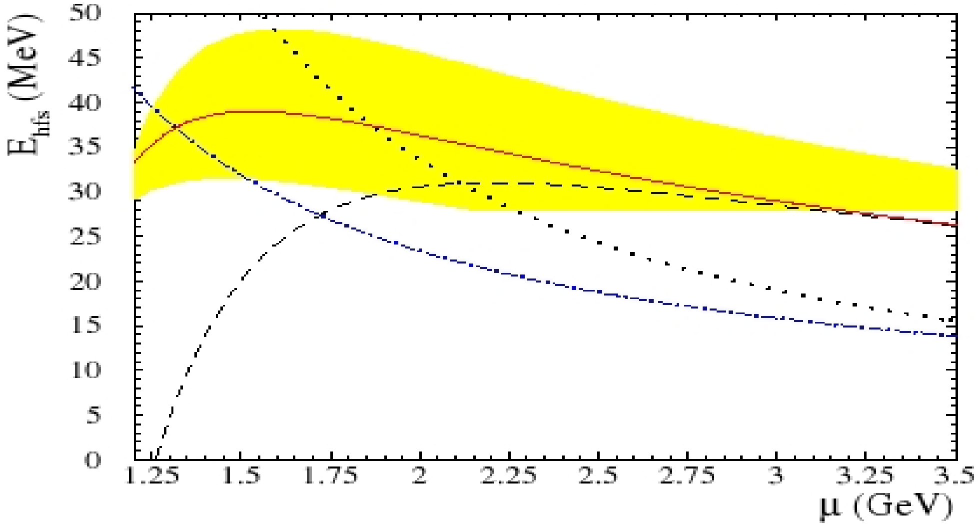


FIG. 1: HFS of 1S bottomonium as a function of the renormalization scale μ in the LO (dotted line), NLO (dashed line), LL (dot-dashed line), and NLL (solid line) approximations. For the NLL result, the band reflects the errors due to $\alpha_s(M_Z) = 0.118 \pm 0.003$.

Lattice QCD (δM_{hf} at LO)

M(Y1S)-M(η_b)=61±14 MeV/c^2

(th. error dominated by QCD radiative corrections)

Gray et al, PRD72(2005),094507

Experiment: (BABAR from Y3S)

$$E_{\rm hfs}^{\rm exp} = 71.4 \pm 2.7\,({\rm syst})\,^{+2.3}_{-3.1}\,({\rm stat})\ {\rm MeV}$$

Rel.Quark Model, LO pQCD:

δM_{hf}=60 MeV/c^2

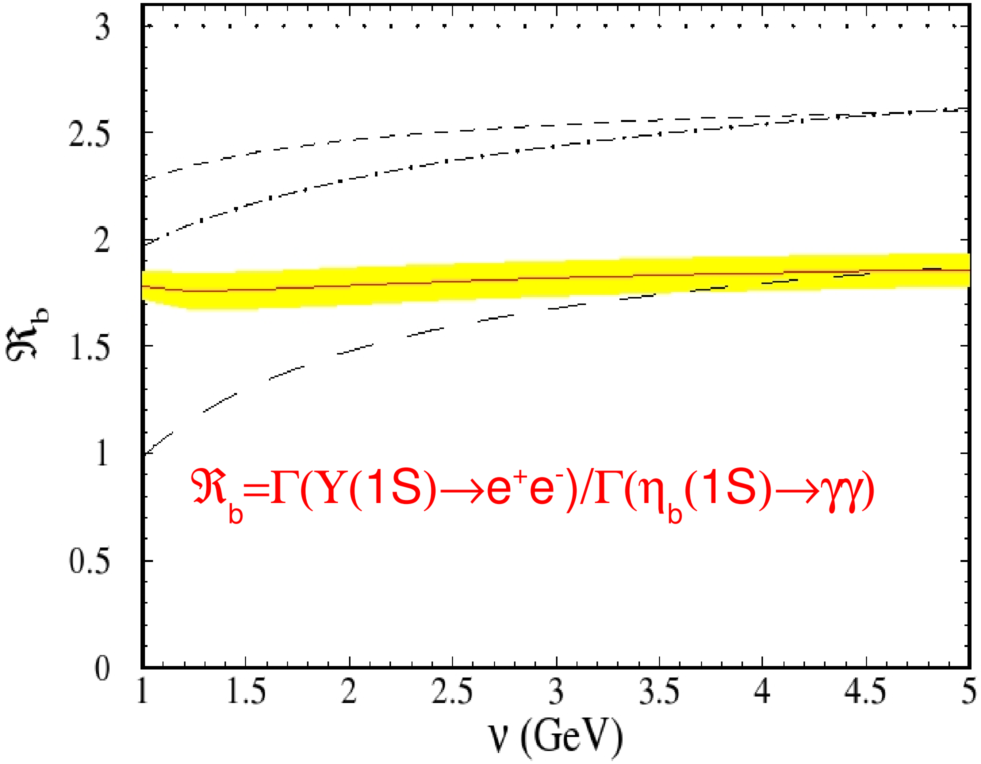
Godfrey,Isgur, PRD32(1985),189

Surely, more work for theorists .....

Next challenge

$\eta_b(1S) \to \gamma\gamma$

NRQCD prediction on 2-photon width at NNLL does not depend on the choice of renormalization energy scale:



$$\Gamma(\eta_b(1S) \to \gamma\gamma) = 0.659 \pm 0.089(\text{th.})^{+0.019}_{-0.018}(\delta\alpha_s) \pm 0.015(\text{exp.})\ \text{keV}$$

Penin et al., NP B699 (2004),183

Figure 3: The spin ratio as the function of the renormalization scale ν in LO≡LL (dotted line), NLO (short-dashed line), NNLO (long-dashed line), NLL (dot-dashed line), and NNLL (solid line) approximation for the bottomonium ground state with $\nu_h = m_b$. For the NNLL result the band reflects the errors due to $\alpha_s(M_Z) = 0.118 \pm 0.003$.

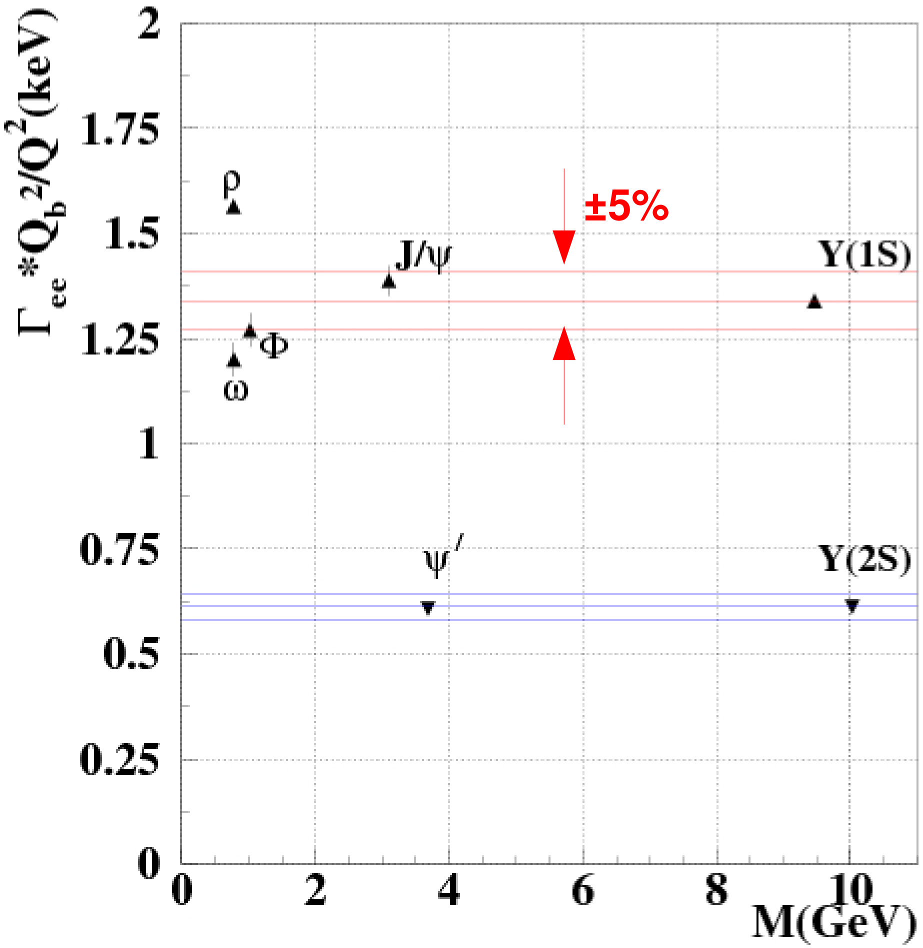
Next challenge

$\eta_b(1S) \to \gamma\gamma$

NRQCD prediction on 2-photon width at NNLL does not depend on the choice of renormalization energy scale:

$\Gamma(\eta_b(1S)\to\gamma\gamma) = 0.66\pm0.09$ keV

Penin et al., NP B699 (2004),183



Notice: theory prediction is on $\Re_b=\Gamma(\Upsilon(1S)\to e^+e^-)/\Gamma(\eta_b(1S)\to\gamma\gamma)$

... *and* $\Gamma(V\to e^+e^-)/q^2$ *is quite constant from 1 to 10 GeV ...*

Next challenge

$\eta_b(1S) \to \gamma\gamma$

$\Gamma(\eta_b(1S)\to\gamma\gamma) = 0.66\pm0.09$ keV

Penin et al., NP B699 (2004),183

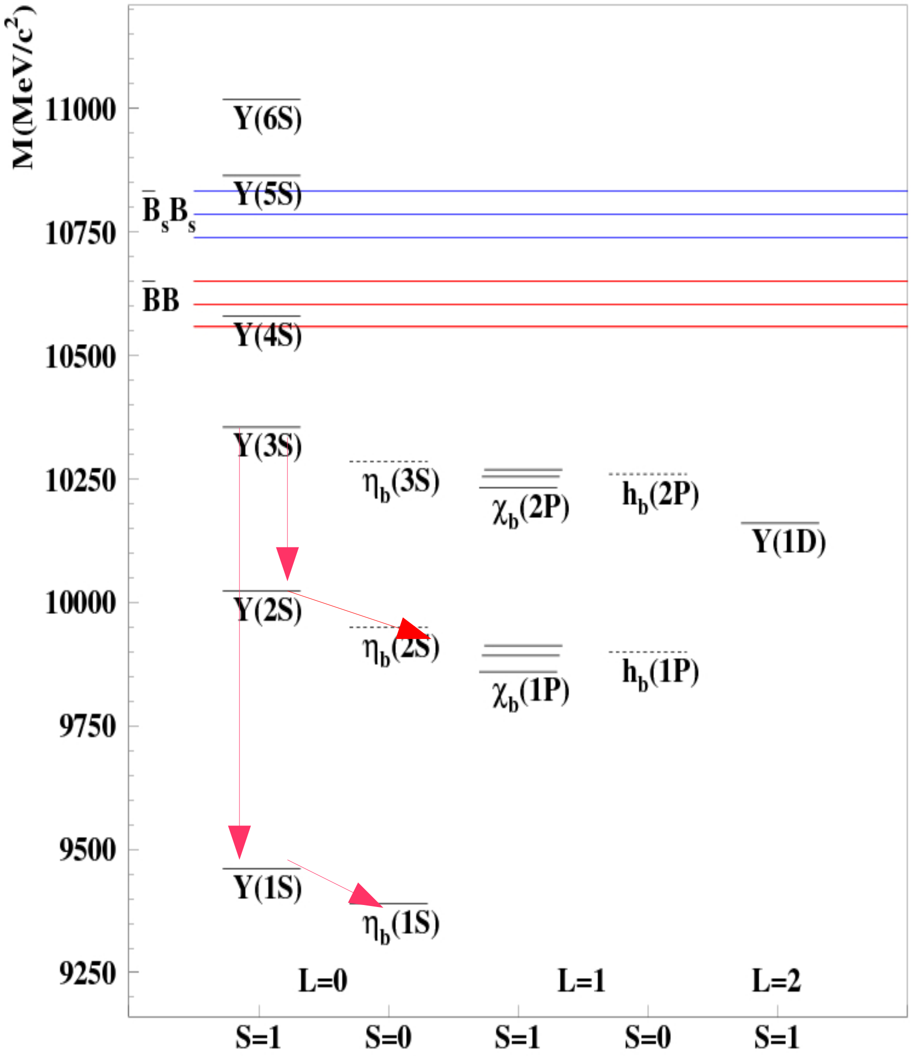
With $\Gamma(\eta_b) = 10$ MeV,

$BR(\eta_b(1S)\to\gamma\gamma) = 0.66*10^{-4}$

$BR(Y(2,3S) \to \gamma\eta_b(1S)\to\gamma\gamma\gamma) \sim 3*10^{-8}$

$\sigma(Y(2,3S)\to\gamma\,\eta_b\to\gamma\gamma\gamma) \sim 0.2$ fb

BUT $<<$ $\sigma(Y(2,3S)\to\gamma_{ISR}\,\gamma\gamma)$



SuperB stats, with 10G 3S decays are needed

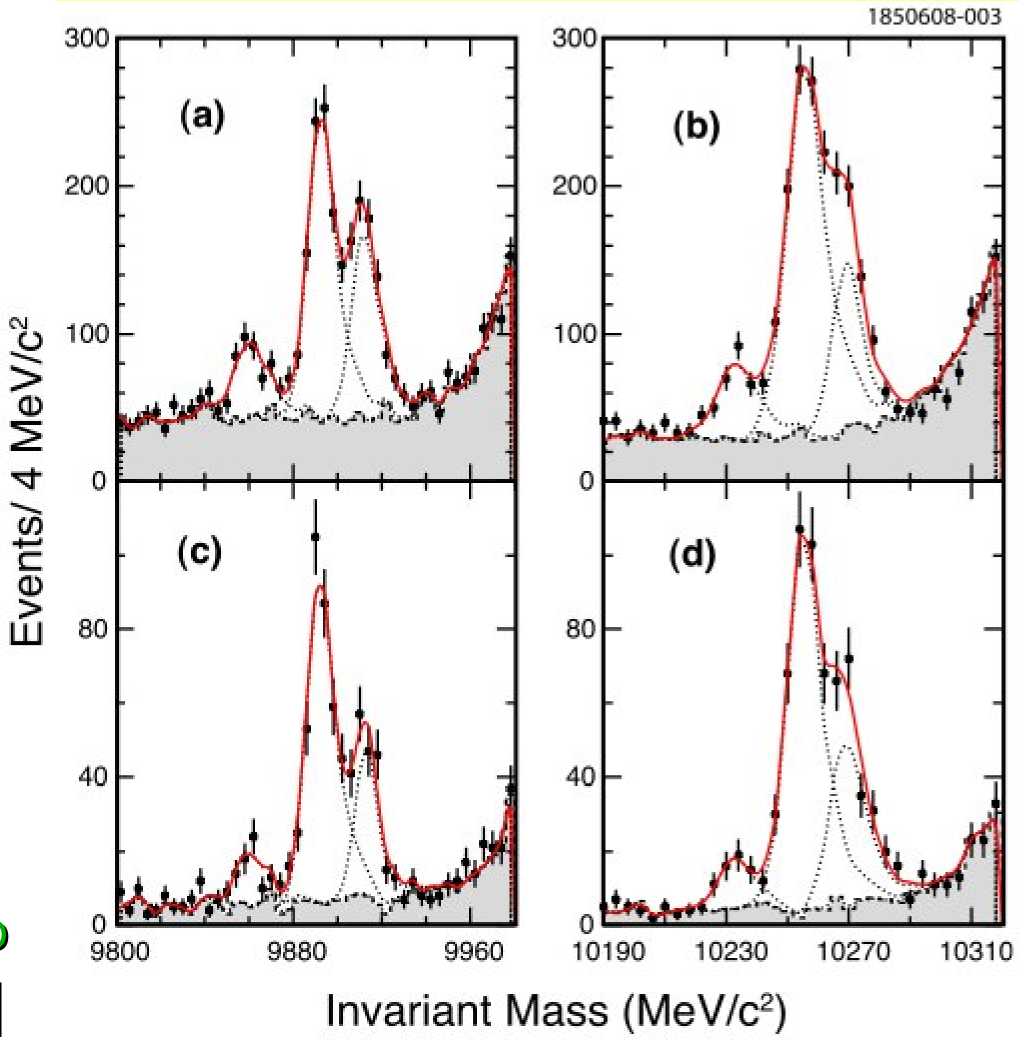
Need hi efficiency on $\pi\pi$ tagging at superB

Even for 3S → 2S $\pi\pi$

Esclusive modes

CLEO-III *Phys.Rev.D78:091103,2008*

$\Upsilon(2S) \to \gamma \chi_b(1P)$ $\Upsilon(3S) \to \gamma \chi_b(2P)$



Total width of η_b

Full reconstruction of 659 exclusive χ_b(1,2P) decay modes from Y(2S,3S) radiative decays.

Only 14 decays modes detected with >5σ significance

We might use them to tag exclusive $\Upsilon \to \gamma \eta_b$ transitions, BUT:

$BR(\Upsilon \to \gamma \eta_b) < 10^{-2} BR(\Upsilon \to \gamma \chi_b)$

Exclusive reconstruction of η_b from direct M1 transitions will eventually allow super-B factories to do the ultimate total width measurement.

Higher Parabottomonia: $\eta_b(3S)$ and $h_b(2P)$

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

Within Babar reach

$\Upsilon(3S) \rightarrow \pi\, h_b\,(1P) \rightarrow \pi\gamma\eta_b\,(1S)$

Within Babar reach

$\Upsilon(3S) \rightarrow \pi\pi\, h_b\,(1P) \rightarrow \pi\pi\,\gamma\eta_b\,(1S)$

Within Babar reach

Voloshin (Sov.J.Nucl.Phys. 43,1011) $< 10^{-4}$
Kuang (hep-ph/0601044) $\sim 10^{-4}$

$\Upsilon(3S) \rightarrow \gamma\eta_b\,(3S)$ Good for superB

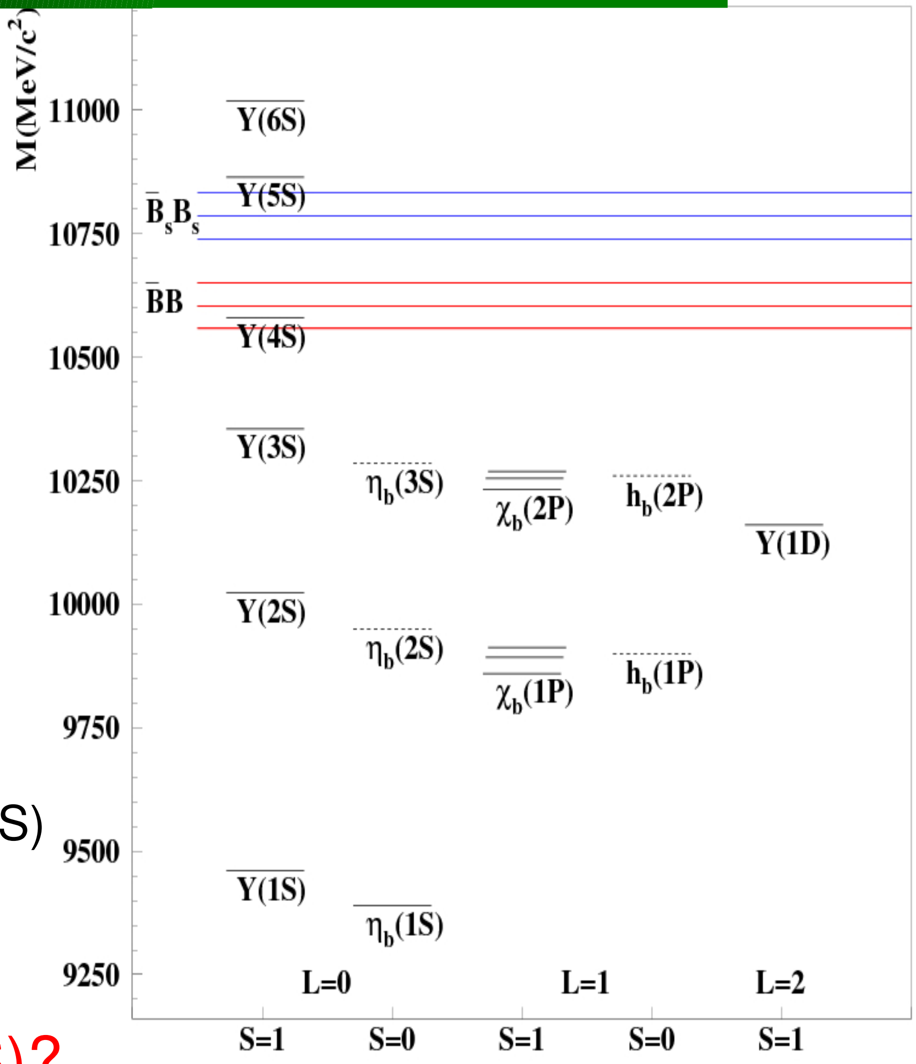
essential to identify exclusive decay modes of η_b (1,2S)

and assume it does not *misbehave* as η_c (2S)

[seen only in $\gamma\gamma$ and $B \rightarrow \eta_c\,(2S)K$ so far]

How can we make h_b (2P)? from Y(5,6S)?

No clue: good homework for next workshop

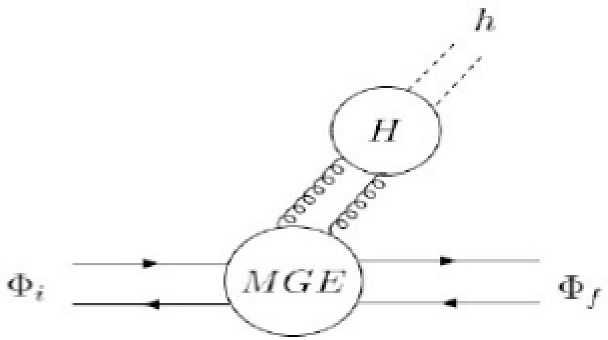


Y(nS) →Y(mS) hadronic transitions

Hadronic transitions between heavy quarkonia are described by the QCD multiple expansion (QCDME) approach.

(Kuang and Yan, PRD24 (1981),2874)

Like in EM transitions, a perturbative series in ak , where a is the size of bound state and k is the gluon momentum, is used to calculate the transition amplitudes, classified in terms of cromoelectric and cromomagnetic multipoles.

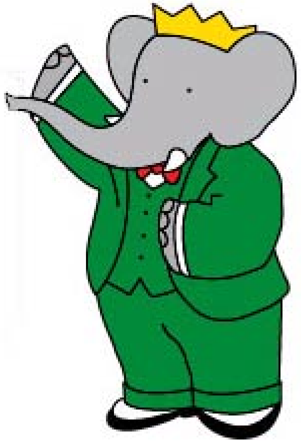


Y(nS) →ππY(mS) : E1E1

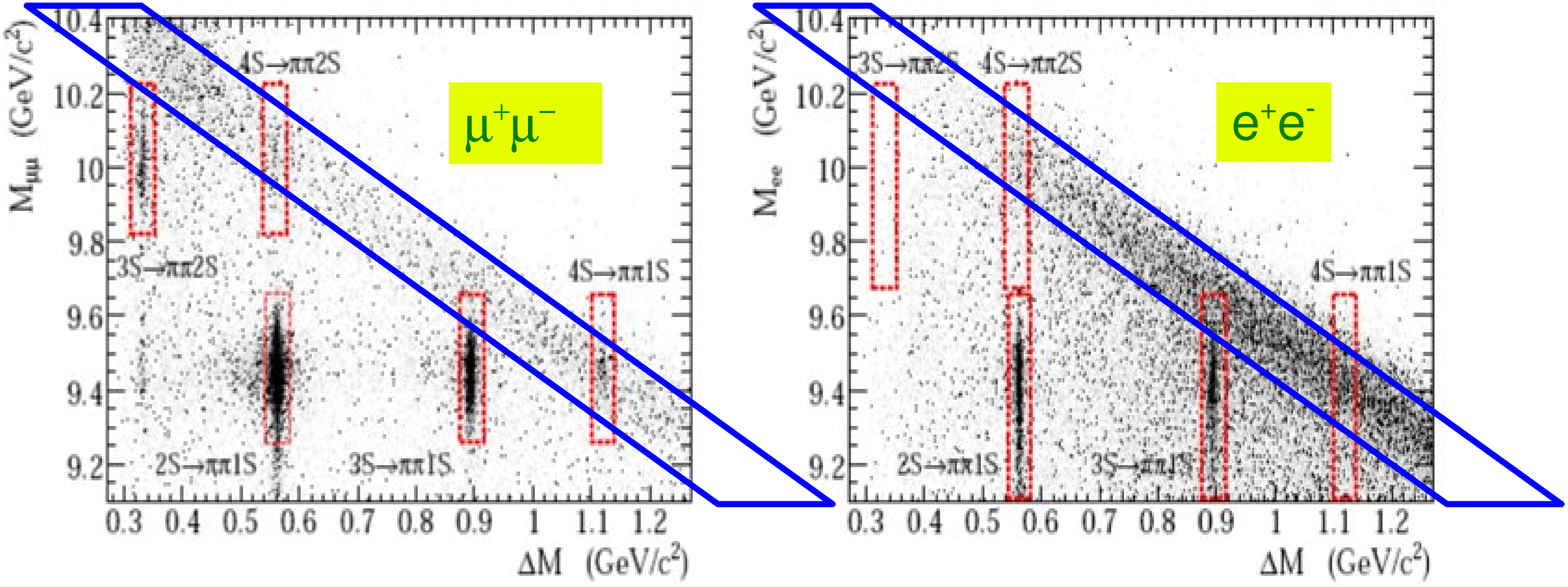
Y(nS) →ηY(mS): E1M2 or M1M1

Bottomonium offers a large variety of such transitions to be tested

$\Upsilon(4S) \rightarrow \Upsilon(nS)\pi\pi$



PRL96,232001: 230 M Y(4S)
PRD78,112002 (2008) : 382 MY(4S), 347.5 fb^{-1}

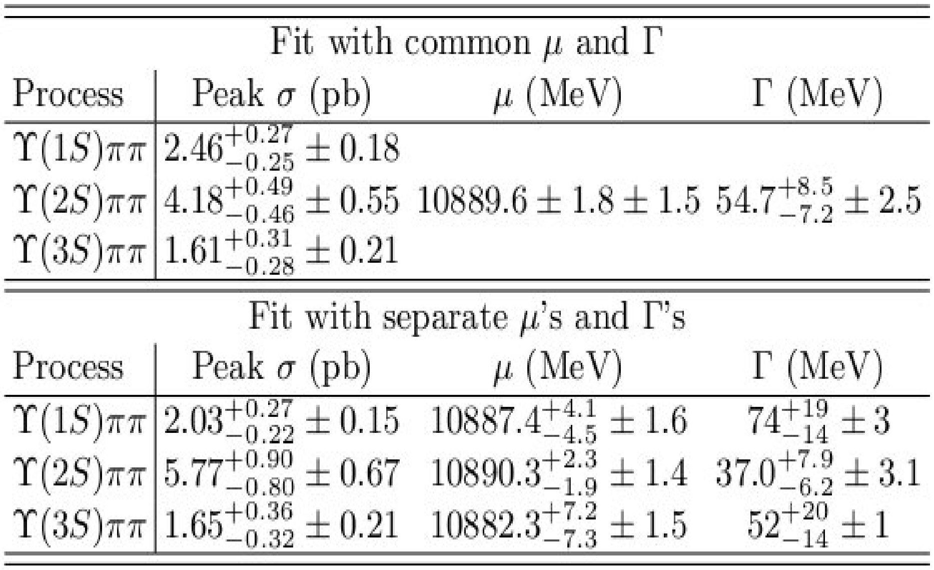


$M(\mu^+\mu^-\pi^+\pi^-)-M(\mu^+\mu^-)$ $M(e^+e^-\pi^+\pi^-)-M(e^+e^-)$

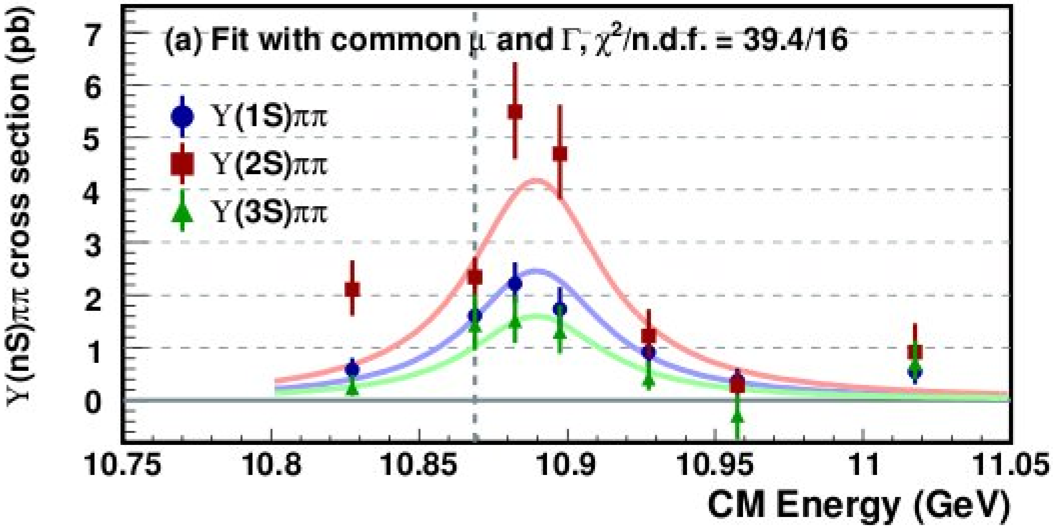
Events in the BLUE band are decays from the Y(4S) peak
Events on the left of the band are from ISR production of Y(2,3S)

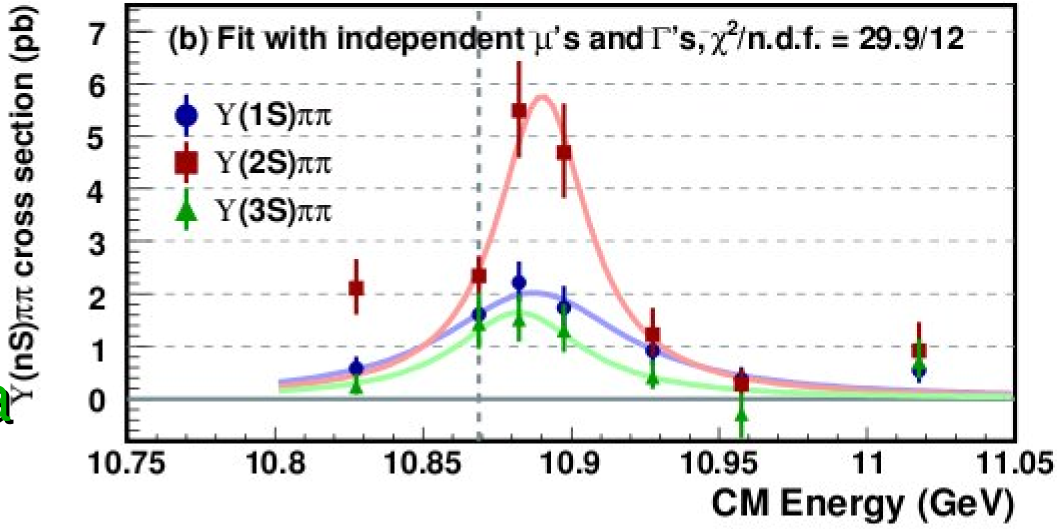
Υ(5S-6S) →Υ(nS)ππ

arXiv: 0808.2445



Fit with common μ and Γ			
Process	Peak σ (pb)	μ (MeV)	Γ (MeV)
$\Upsilon(1S)\pi\pi$	$2.46^{+0.27}_{-0.25} \pm 0.18$		
$\Upsilon(2S)\pi\pi$	$4.18^{+0.49}_{-0.46} \pm 0.55$	$10889.6 \pm 1.8 \pm 1.5$	$54.7^{+8.5}_{-7.2} \pm 2.5$
$\Upsilon(3S)\pi\pi$	$1.61^{+0.31}_{-0.28} \pm 0.21$		
Fit with separate μ's and Γ's			
Process	Peak σ (pb)	μ (MeV)	Γ (MeV)
$\Upsilon(1S)\pi\pi$	$2.03^{+0.27}_{-0.22} \pm 0.15$	$10887.4^{+4.1}_{-4.5} \pm 1.6$	$74^{+19}_{-14} \pm 3$
$\Upsilon(2S)\pi\pi$	$5.77^{+0.90}_{-0.80} \pm 0.67$	$10890.3^{+2.3}_{-1.9} \pm 1.4$	$37.0^{+7.9}_{-6.2} \pm 3.1$
$\Upsilon(3S)\pi\pi$	$1.65^{+0.36}_{-0.32} \pm 0.21$	$10882.3^{+7.2}_{-7.3} \pm 1.5$	$52^{+20}_{-14} \pm 1$





Need the next generation to truly understand, with a high lumi scan above threshold, the pattern of hadronic transitions to bottomonia

Hadron Transitions: $\pi\pi$

CLEO *PRD75,072001(2007)*

$\chi_{b1}(2P)$

$\rightarrow \pi^+\pi^- \chi_{b1}(1P)$ 0.86±0.31%

EM ratios:

- $\rightarrow \gamma\, \Upsilon(1S)$ 8.5±1.3%
- $\rightarrow \gamma\, \Upsilon(2S)$ 21±4%

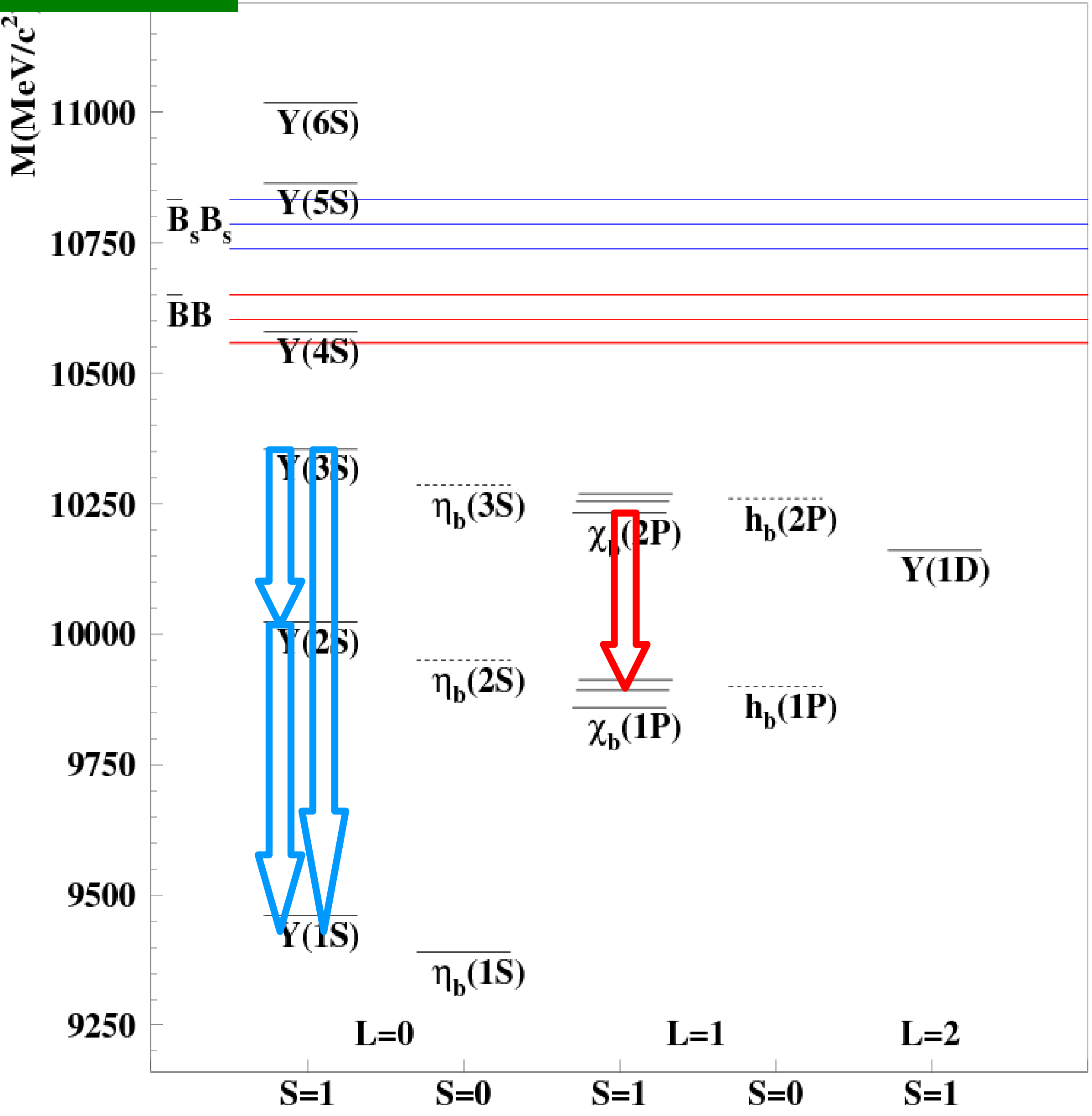
$\chi_{b2}(2P)$

$\rightarrow \pi^+\pi^- \chi_{b2}(1P)$ 0.60±0.21%

EM ratios:

- $\rightarrow \gamma\, \Upsilon(1S)$ 7.1±1.0%
- $\rightarrow \gamma\, \Upsilon(2S)$ 16.2±2.4%

Stat. error on BR's:
Babar:10% SuperB: 2%
Angular distributions,
$M_{\pi\pi}$ spectrum



Hadron Transitions: 2body

CLEO *PRL92,222002(2004)*

$\chi_{b1}(2P)$

$\to \omega\,\Upsilon(1S)$ 1.63±0.40%
(Q=13MeV)

EM ratios:

- $\to \gamma\,\Upsilon(1S)$ 8.5±1.3%
- $\to \gamma\,\Upsilon(2S)$ 21±4%

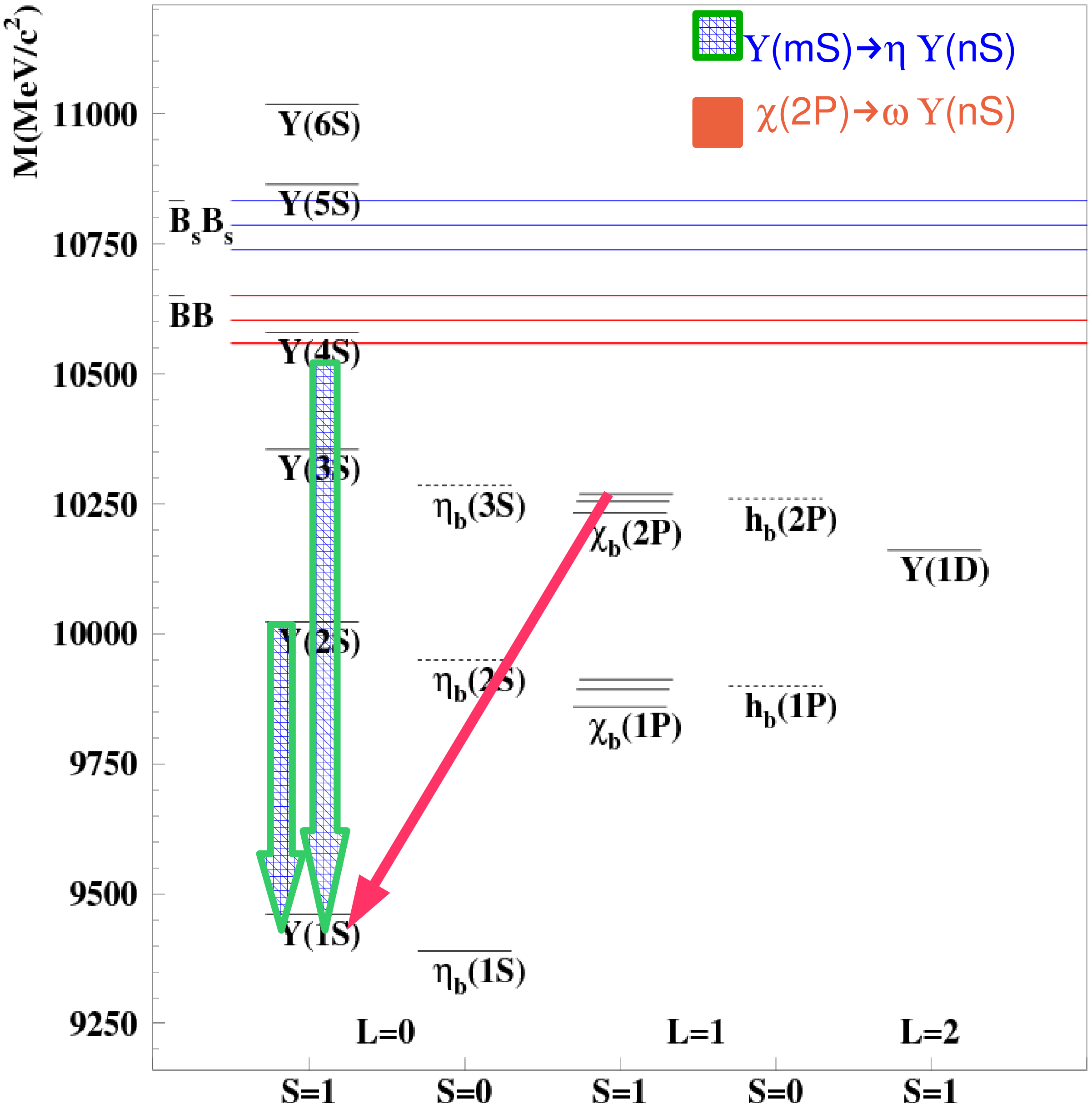
$\chi_{b2}(2P)$

$\to \omega\,\Upsilon(1S)$ 1.10±0.34%
(Q=27MeV)

EM ratios:

- $\to \gamma\,\Upsilon(1S)$ 7.1±1.0%
- $\to \gamma\,\Upsilon(2S)$ 16.2±2.4%

Stat. error on BR's:
Babar:10% SuperB: 2%



Hadron Transitions: 2body

CLEO *PRL101,192001(2008)*

[$\eta\to\gamma\gamma$, $\pi^+\pi^-\pi^0$, $3\pi^0$ reconstructed]

BR(Y(2S) →ηY(1S)) = $(2.1^{+0.7}_{-0.6}\pm0.5)\times10^{-4}$

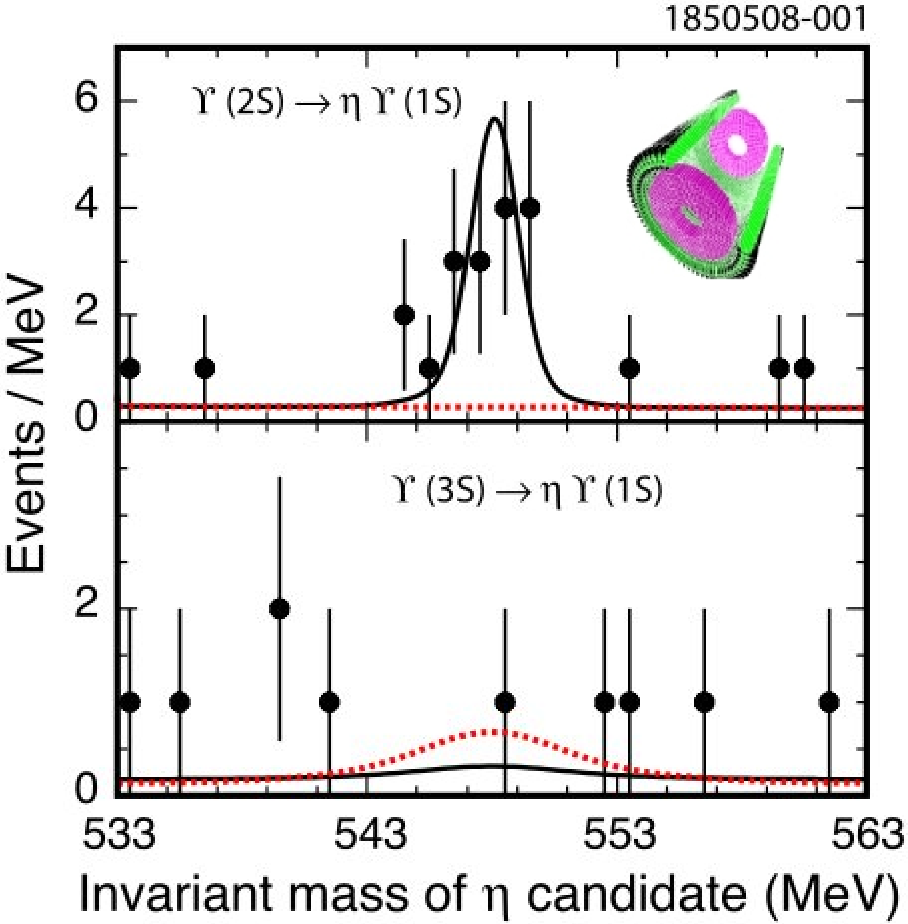
Theory: $\Gamma \sim (P_{cm})^3 / (m_Q)^4$

Scaling from charmonium we get:

$$\frac{\Gamma(\Upsilon(2S,3S)\to\eta\Upsilon(1S))}{\Gamma(\psi(2S)\to\eta J/\psi)} = (0.0025, 0.0013),$$

and then BR_{th}(Y(2S) →ηY(1S)) ~ 8×10^{-4}

<u>was optimistic</u>.



Hadron Transitions: 2body

CLEO *PRL101,192001(2008)*

[$\eta \to \gamma\gamma$, $\pi^+\pi^-\pi^0$, $3\pi^0$ reconstructed]

$BR(Y(2S) \to \eta Y(1S)) = (2.1^{+0.7}_{-0.6} \pm 0.5) \times 10^{-4}$

Theory: $\Gamma \sim (P_{cm})^3 / (m_Q)^4$

Scaling from charmonium we get:

$$\frac{\Gamma(\Upsilon(2S,3S) \to \eta\Upsilon(1S))}{\Gamma(\psi(2S) \to \eta J/\psi)} = (0.0025, 0.0013),$$

and then $BR_{th}(Y(2S) \to \eta Y(1S)) \sim 8 \times 10^{-4}$

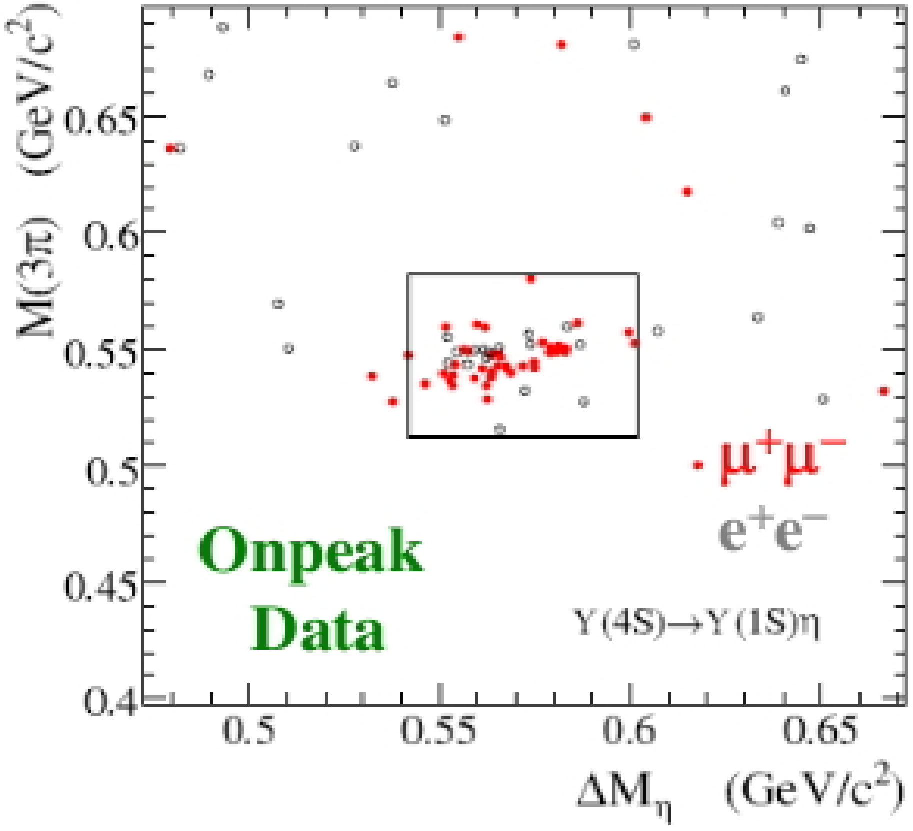
was optimistic.

BABAR *PRD78,112002(2008)*

Totally unexpected observation of $Y(4S) \to \eta Y(1S)$

$BR(Y(4S) \to \eta Y(1S)) = (1.96 \pm 0.06 \pm 0.09) \times 10^{-4}$

$= 2.41 * BR(Y(4S) \to \pi^+\pi^- Y(1S))$!



$\Delta M_\eta = M_{ll\pi\pi\pi} - M_{ll} - M_{\pi\pi\pi}$

(10580-9460-548~572)

Hadron Transitions: 2body

$\Upsilon(nS) \rightarrow \eta^0\Upsilon(mS)$

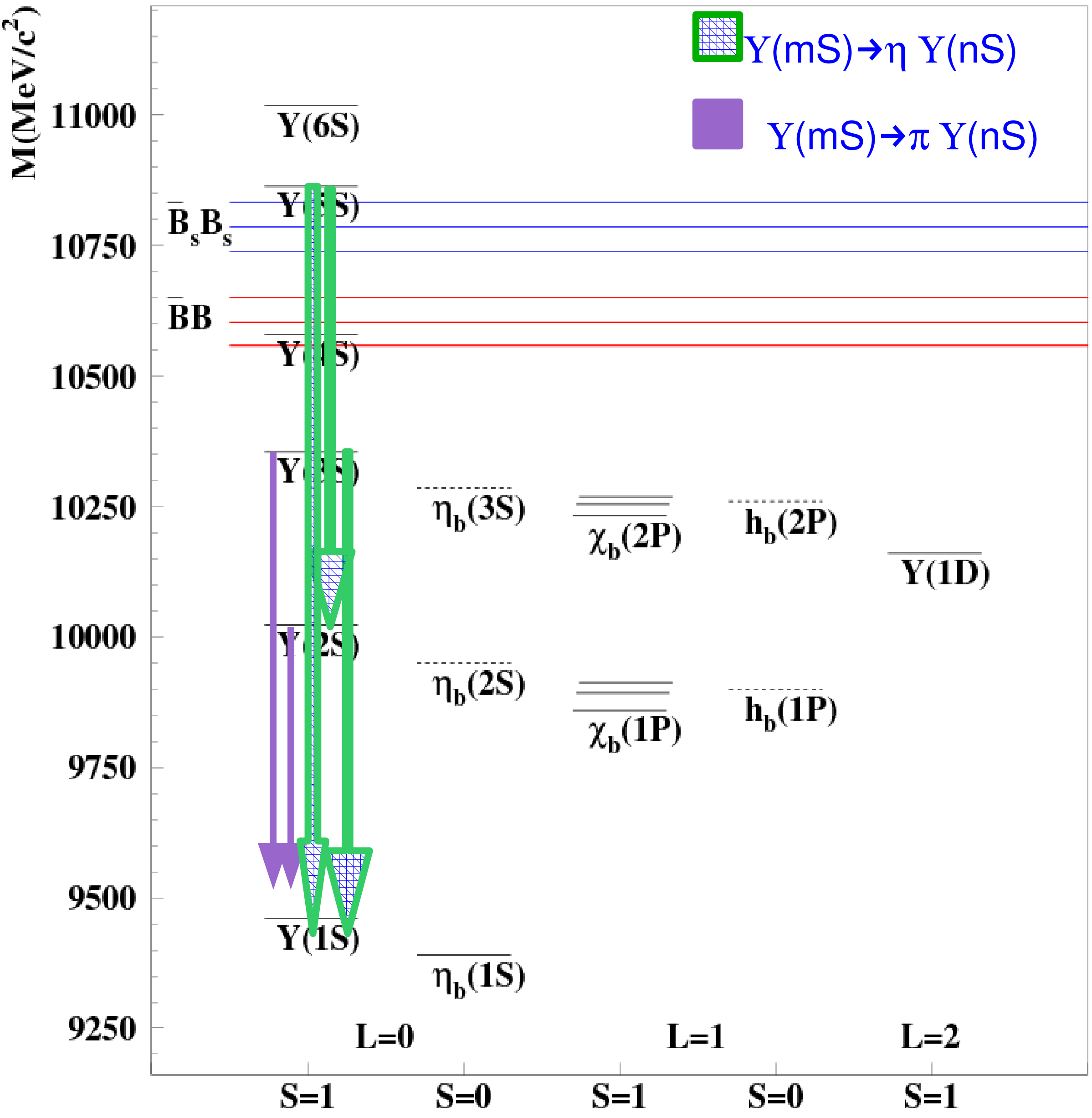
Belle: 5S → η 1S,2S
Babar: 3S → η 1S

$\Upsilon(nS) \rightarrow \pi^0\Upsilon(mS)$

Scaling predictions:

$$\frac{\mathcal{B}(\Upsilon(2S,3S)\to\pi^0\Upsilon(1S))}{\mathcal{B}(\Upsilon(2S,3S)\to\eta\Upsilon(1S))}=(16\pm2, 0.42\pm0.04)\%.$$

Babar/Belle: 2S → π 1S
SuperB: 3S → π 1S



Hadron Transitions: 2body

$\chi_{b0}(2P) \to \eta\eta_b(1S)$: ~ 10^{-3}

Voloshin 2004

[Mod.Phys.Lett.:A19,2985]

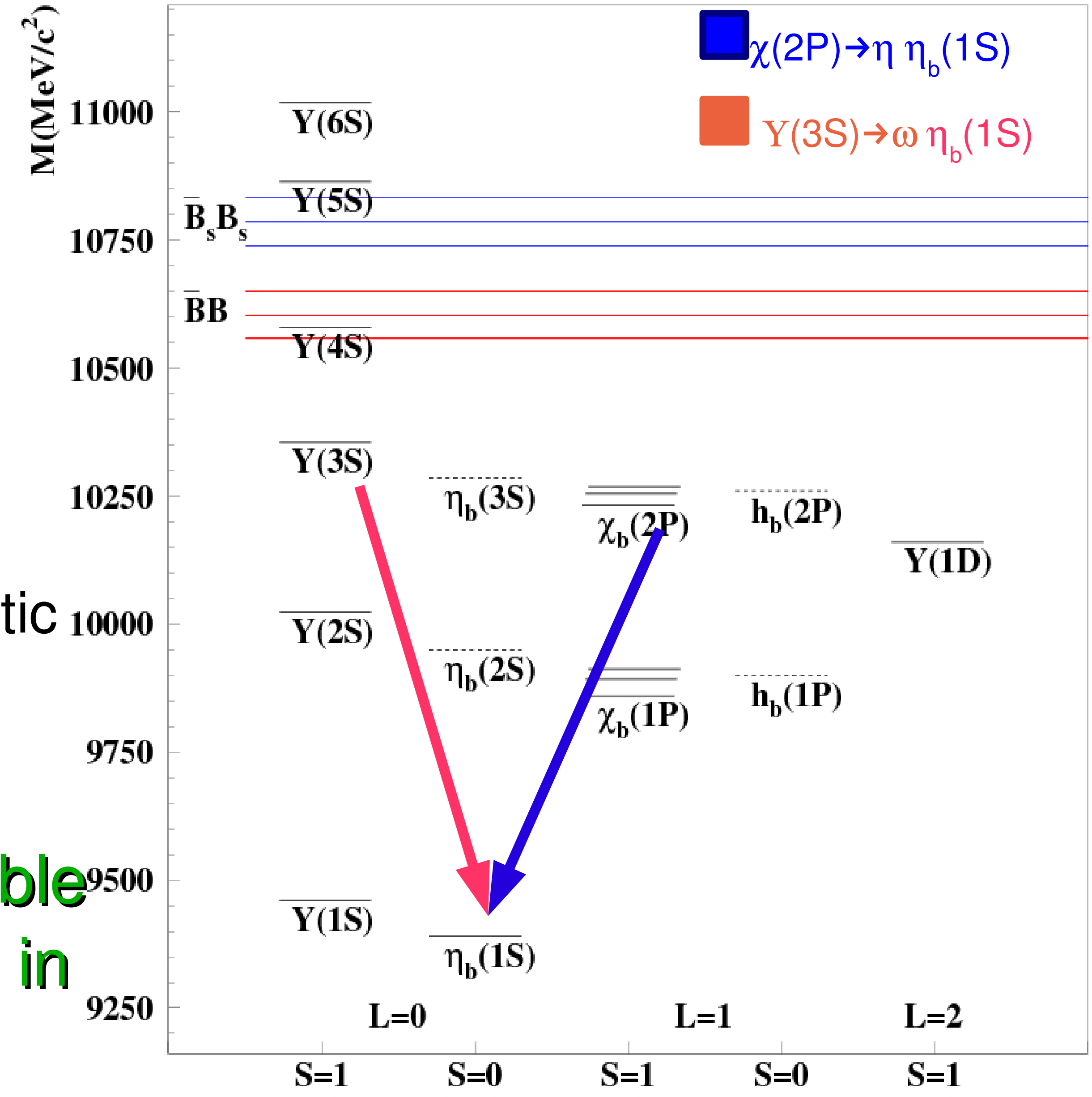
inclusive search for $\gamma\eta$

$\Upsilon(3S) \to \omega\eta_b(1S)$: ~$10^{-4}$?

(Q~180MeV)

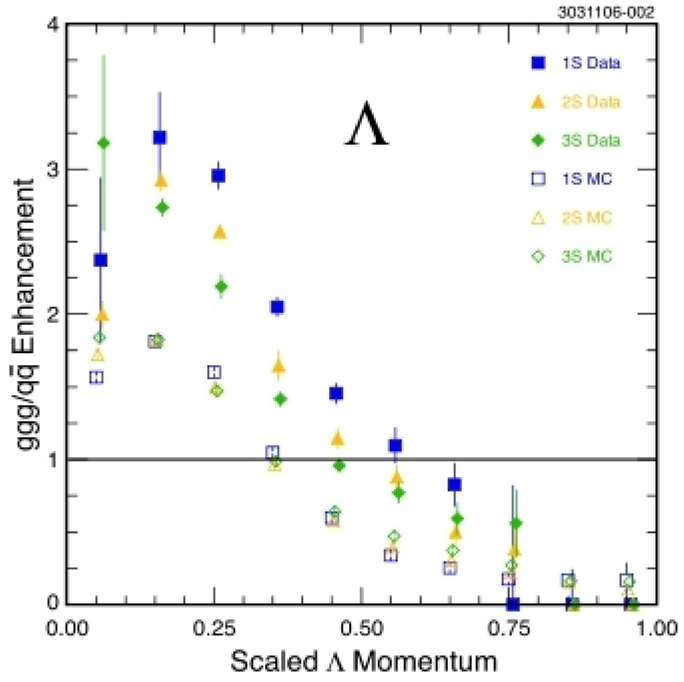
search for monochromatic peak in inclusive ω spectrum

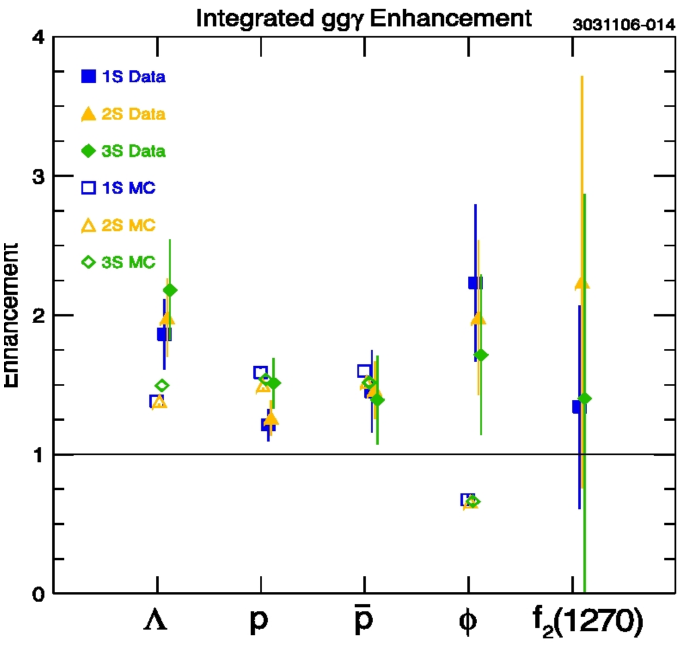
If not already reachable by Babar, should be in SuperB reach



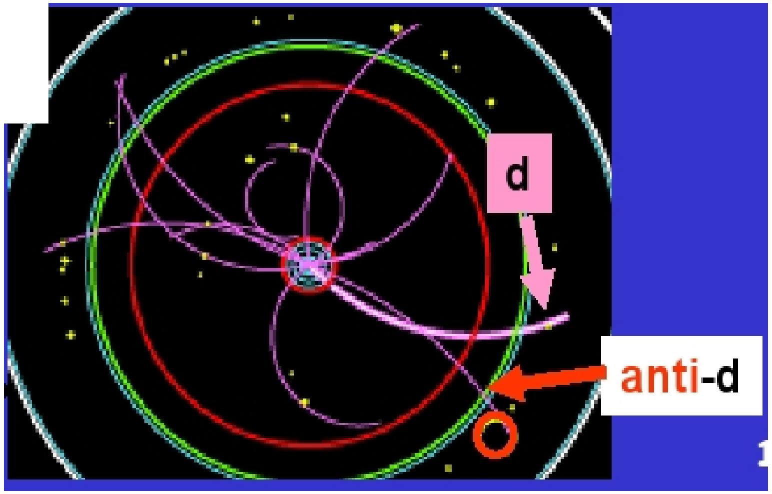
Υ(1,2,3S) *decays to nuclei*

Enhanced production of low P protons, antiprotons, Λ's in Υ(1,2,3 S) decays if compared to continuum .
[Cleo: *PRD76,12005(2007)*]





Anti-deuteron production observed in Υ(1S) and Υ(2S) decays (BR=3.3±0.5 10^{-5}) and not in continuum (BR< 10^{-5})
[Argus: *PLB236,102(1990)*
Cleo: *PRD 75,12009(2007)]*



Unique method for inclusive production of tritium, helium, dihyperon bound states

(not many) conclusions

In the last two years Babar and Belle collected O(100M) samples of narrow bottomonium decays and O(150 fb^{-1}) above open bottom threshold.

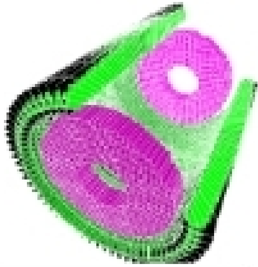
Before looking for NEW bottomonia, we better find all the OLD ones, and check whether we understand their phenomenology. Analysis under way....

Hadronic transitions between bottomonia are already rising many questions.

Puzzles also arising above threshold, fine high lumi scan needed to get everything well understood

Exclusive modes

CLEO-III *Phys.Rev.D78:091103,2008*



All Branching Ratios in 10^{-4} units

$\chi_b(nP)$	J=0		J=1		J=2	
	$2S \rightarrow 1P$	$3S \rightarrow 2P$	$2S \rightarrow 1P$	$3S \rightarrow 2P$	$2S \rightarrow 1P$	$3S \rightarrow 2P$
$2\pi 2K 1\pi^0$	< 0.6	< 0.2	$1.4 \pm 0.3 \pm 0.3$	$3.9 \pm 0.8 \pm 0.9$	$0.6 \pm 0.3 \pm 0.2$	< 1.4
$3\pi 1K 1K_S^0$	< 0.2	< 0.3	$0.9 \pm 0.3 \pm 0.2$	$1.4 \pm 0.5 \pm 0.3$	< 0.7	< 1.2
$3\pi 1K 1K_S^0 2\pi^0$	< 1.8	< 1.3	< 4.2	$9.7 \pm 3.0 \pm 2.6$	$3.8 \pm 1.4 \pm 1.0$	< 8.7
$4\pi 2\pi^0$	< 0.8	< 1.4	$5.5 \pm 0.9 \pm 1.4$	$7.4 \pm 1.6 \pm 1.9$	$2.5 \pm 0.8 \pm 0.6$	$5.1 \pm 1.6 \pm 1.3$
$4\pi 2K$	$0.4 \pm 0.2 \pm 0.1$	< 0.9	$1.0 \pm 0.3 \pm 0.2$	$1.2 \pm 0.4 \pm 0.3$	$0.8 \pm 0.2 \pm 0.2$	$1.2 \pm 0.4 \pm 0.3$
$4\pi 2K 1\pi^0$	< 1.0	< 1.3	$2.4 \pm 0.6 \pm 0.6$	$6.9 \pm 1.3 \pm 1.7$	$1.5 \pm 0.5 \pm 0.4$	$3.2 \pm 1.1 \pm 0.8$
$4\pi 2K 2\pi^0$	< 2.0	< 6.3	$5.9 \pm 1.4 \pm 1.7$	$12.1 \pm 2.9 \pm 3.3$	$2.8 \pm 1.1 \pm 0.7$	$6.2 \pm 2.3 \pm 1.7$
$5\pi 1K 1K_S^0 1\pi^0$	< 0.6	< 3.9	$6.4 \pm 1.6 \pm 1.6$	$8.5 \pm 2.3 \pm 2.2$	< 3.6	< 5.8
6π	< 0.3	< 0.4	$1.3 \pm 0.3 \pm 0.3$	$1.5 \pm 0.4 \pm 0.3$	$0.5 \pm 0.2 \pm 0.1$	$1.2 \pm 0.4 \pm 0.3$
$6\pi 2\pi^0$	< 2.2	< 7.2	$11.9 \pm 1.8 \pm 3.2$	$15.0 \pm 3.0 \pm 4.0$	$7.3 \pm 1.6 \pm 2.0$	$15.9 \pm 3.3 \pm 4.3$
$6\pi 2K$	$0.9 \pm 0.4 \pm 0.2$	< 0.9	$1.8 \pm 0.4 \pm 0.4$	$2.5 \pm 0.7 \pm 0.6$	< 0.6	$1.9 \pm 0.7 \pm 0.5$
$6\pi 2K 1\pi^0$	< 3.7	< 4.3	$5.2 \pm 1.1 \pm 1.4$	$7.7 \pm 1.7 \pm 2.1$	$2.6 \pm 0.8 \pm 0.7$	$5.5 \pm 1.6 \pm 1.5$
8π	< 0.3	< 1.0	$1.8 \pm 0.4 \pm 0.5$	$2.2 \pm 0.6 \pm 0.5$	$0.6 \pm 0.2 \pm 0.2$	$1.2 \pm 0.5 \pm 0.3$
$8\pi 2\pi^0$	< 7.7	< 3.8	$9.6 \pm 2.4 \pm 2.9$	$24.1 \pm 4.7 \pm 7.2$	$13.2 \pm 3.1 \pm 4.0$	$16.5 \pm 4.6 \pm 5.0$

Modes in RED are the only ones above 10^{-3}
Modes with $N\pi^0$ favored on ones with $0\ \pi^0$

Dominant modes have 8,10 π's
Sum of all BR's does not exceed 1%

Effective field theories (EFT)

- Great progress in understanding EFT's during last 15 years
  NRQED (Caswell, Lepage) --> NRQCD(Bodwin,Braaten, Lepage)

- NRQCD, pNRQCD, vNRQCD: progress in calculation of perturbative terms
- Rigorous factorization of non-perturbative terms to be computed on the lattice

- Applicable to all aspects of the dynamics of heavy quarkonia:
  spectroscopy, decays, production

e.g.: Estraction of $\alpha_s(m_\Upsilon)$ from $\Upsilon\to\gamma gg$ / $\Upsilon\to ggg$

$\alpha_s(m_{\Upsilon 1S}) = 0.184 \pm 0.014$

$\to \alpha_s(m_Z) = 0.119 \pm 0.006$

(PDG: 0.118 ±0.003)

CLEO: PRD74(2006),012003
Brambilla et al: hep-ph/0702079