Some Topics on Finding η_b

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About η_b

- It is a heavy quarkonium which is composed of a bottom-quark-antiquark pair in a color-singlet state, like Υ(at leading order in Fock Space exp).

- Its J^{pc} is 0^{-+} and L=0 , S=0.

- Its mass is about 9.3 GeV (n=1)， and

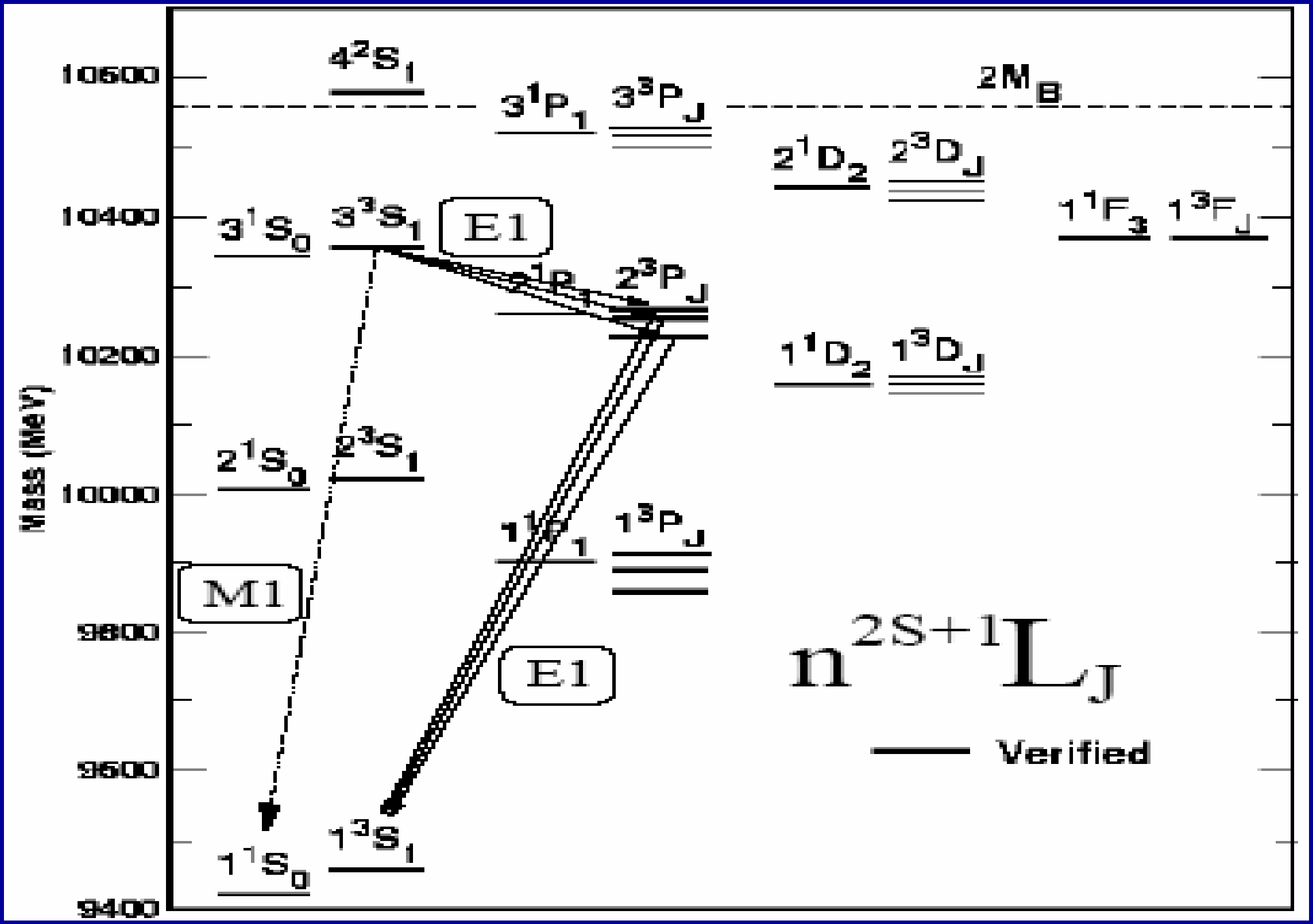
$\Gamma_{tot} \cong \Gamma(\eta_b \rightarrow g\, g) \cong 11.4$ MeV

Various theoretical estimates for the mass splitting $\Delta m = m(\Upsilon) - m(\eta_b)$

	Δm(MeV)
lattice NRQCD	19 – 100
lattice potential	60 – 110
pQCD	36 – 55
1/m expansion	34 – 114
potential model	57 – 141

The bottomonium spectrum

(CLEO Collaboration July 19, 2002)



Production of η_b

There are three ways to produce η_b in nowadays experiments :

1. Υ(nS)→ η_b + γ or Υ(nS)→ h_b + nπ followed by h_b → η_b + γ (CLEO)
2. In e^+e^- collision, followed by virtual photons collision $\gamma^*\gamma^* \to \eta_b$ or $\gamma^* \to \eta_b\,\gamma$ (LEP)
3. In hadron collision, $p + \bar{p} \to \eta_b + X$ (Tevatron)

Case I: $\Upsilon(nS)$ decay into η_b

- Because the Υ (nS) resonances have a rich spectroscopy, it's convenient to use either favored magnetic dipole (M1) transitions or hindered M1 transitions to get η_b .
- The branching ratio has been calculated by many papers in various modes, one of the results is about:

$$Br[\Upsilon(nS) \to \eta_b(1S) + \gamma] \sim 10^{-4} (n = 1,2)$$

Godfrey & Rosner (Phys. Rev. D64: 074011, 2001)

Another prediction:

- Kuang and Yan predicted **(Phys. Rev. D24, 2874 (1981))**

$$Br[\Upsilon(3S) \to h_b(1P) + 2\pi] = 10^{-3} \sim 10^{-4}$$

and

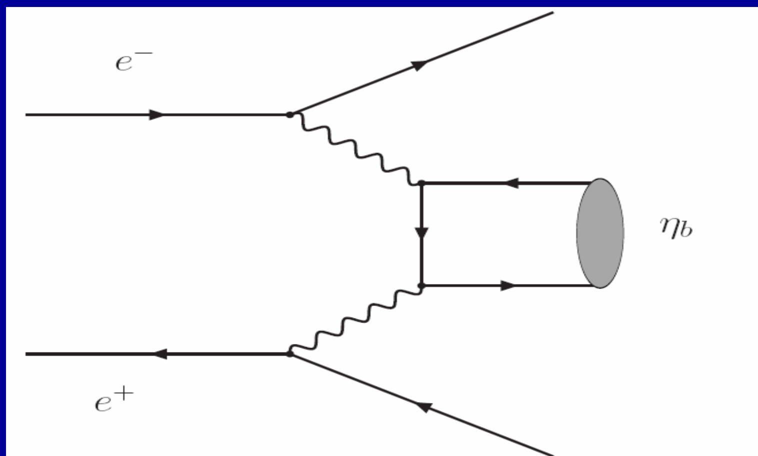
$$Br[h_b(1P) \to \eta_b(1S)\gamma] \sim 0.5$$

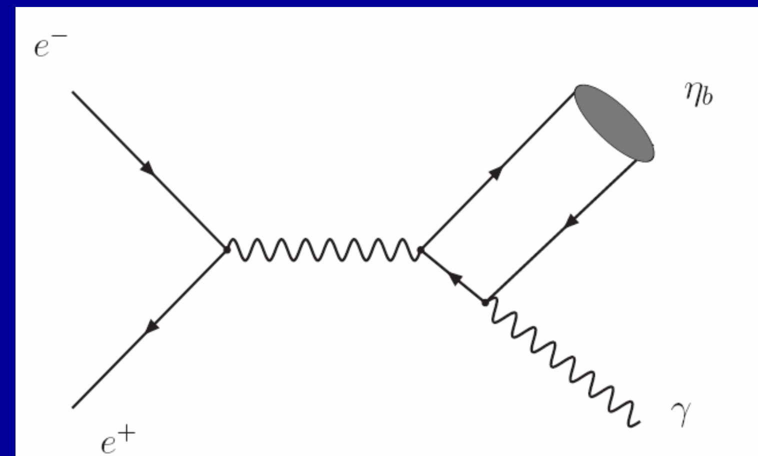
- So, the branching ratio

$$Br[\Upsilon(3S) \to h_b(1P)\pi\pi \to \eta_b(1S)\gamma\pi\pi] = 10^{-3} \sim 10^{-4}$$

Case II: The production of in e^+e^- Collision

- **Two processes to product η_b**



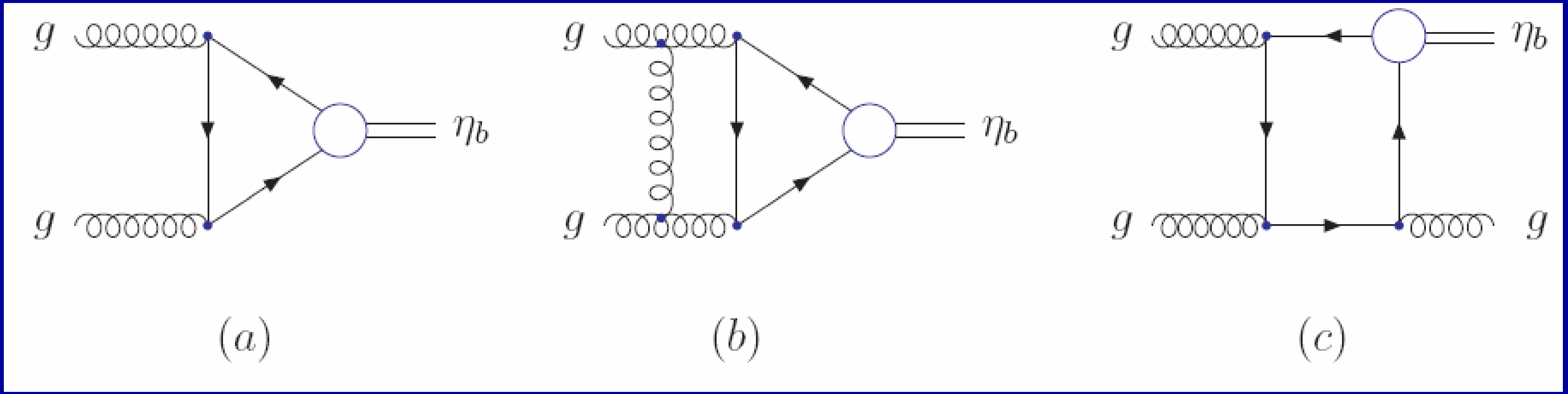


$\sigma(1) \sim 0.0021\,pb$ $\sigma(2) \sim 0.0018\,pb$

$$\sqrt{s} = 10.58\ GeV$$

- **The first process dominates in very high energy.**

Case III: The production of η_b In hadron collision



Representative Feynman diagrams for b hadroproduction at LO(a), and virtual (b) and real (c) contributions at NLO

Maltoni & Polosa (Phys.Rev.D70:054014,2004)

- This process was also calculated by Kuhn, et al.

(Phys. Rev. D48, 179 (1993)) (Nucl. Phys. B514, 245 (1998))

- The result for the total cross section in $p\bar{p}$ collisions at 1.96 TeV of center-of-mass energy is

$$\sigma[\,p+\bar{p}\rightarrow\eta_b+X\,]=2.5\pm0.3\mu b$$

The existence of the η_b

- The existence of the η_b is a solid prediction of the quark model.

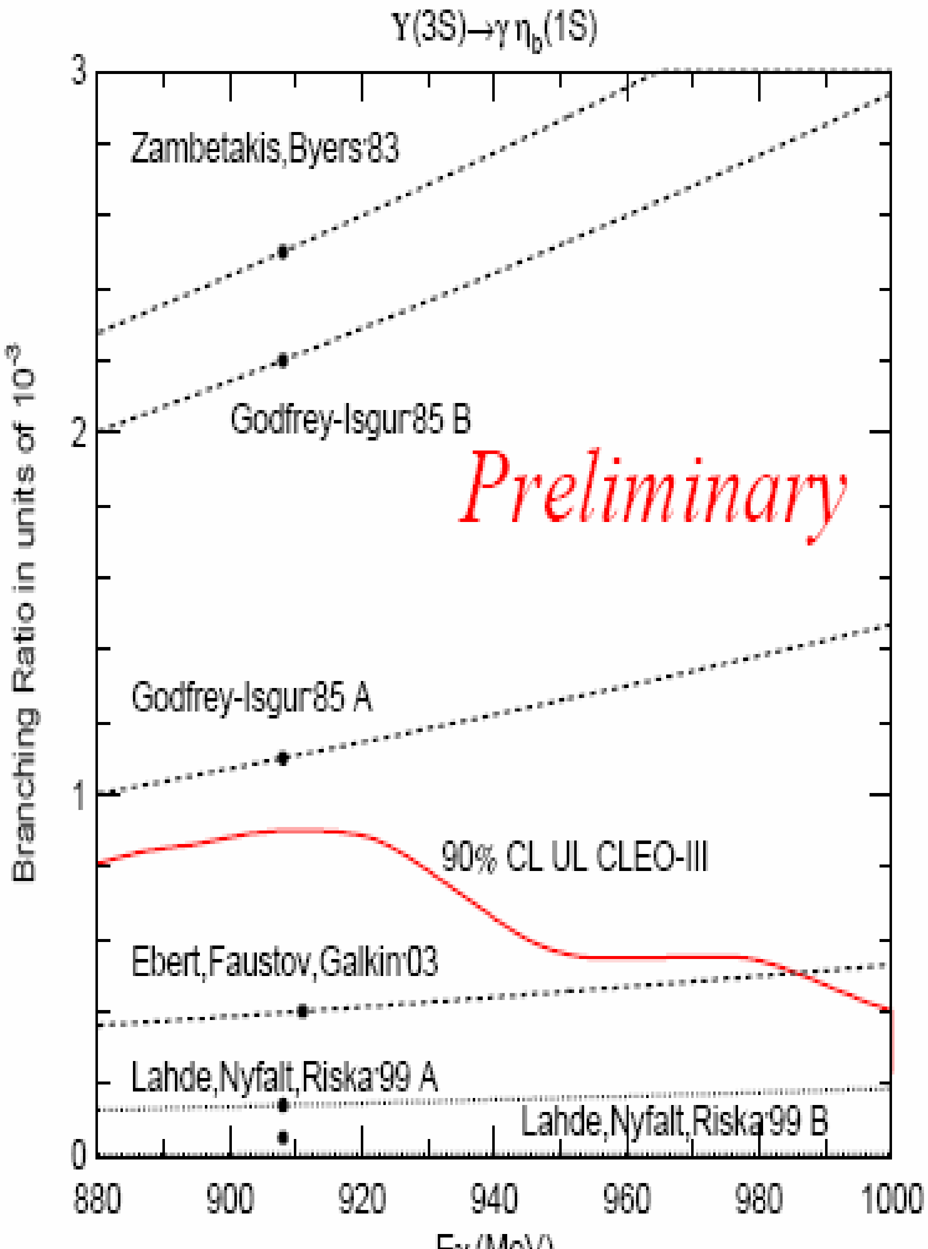
- In recent years, the search for η_b has been conducted at CLEO, LEP, and CDF, using both inclusive and exclusive methods.

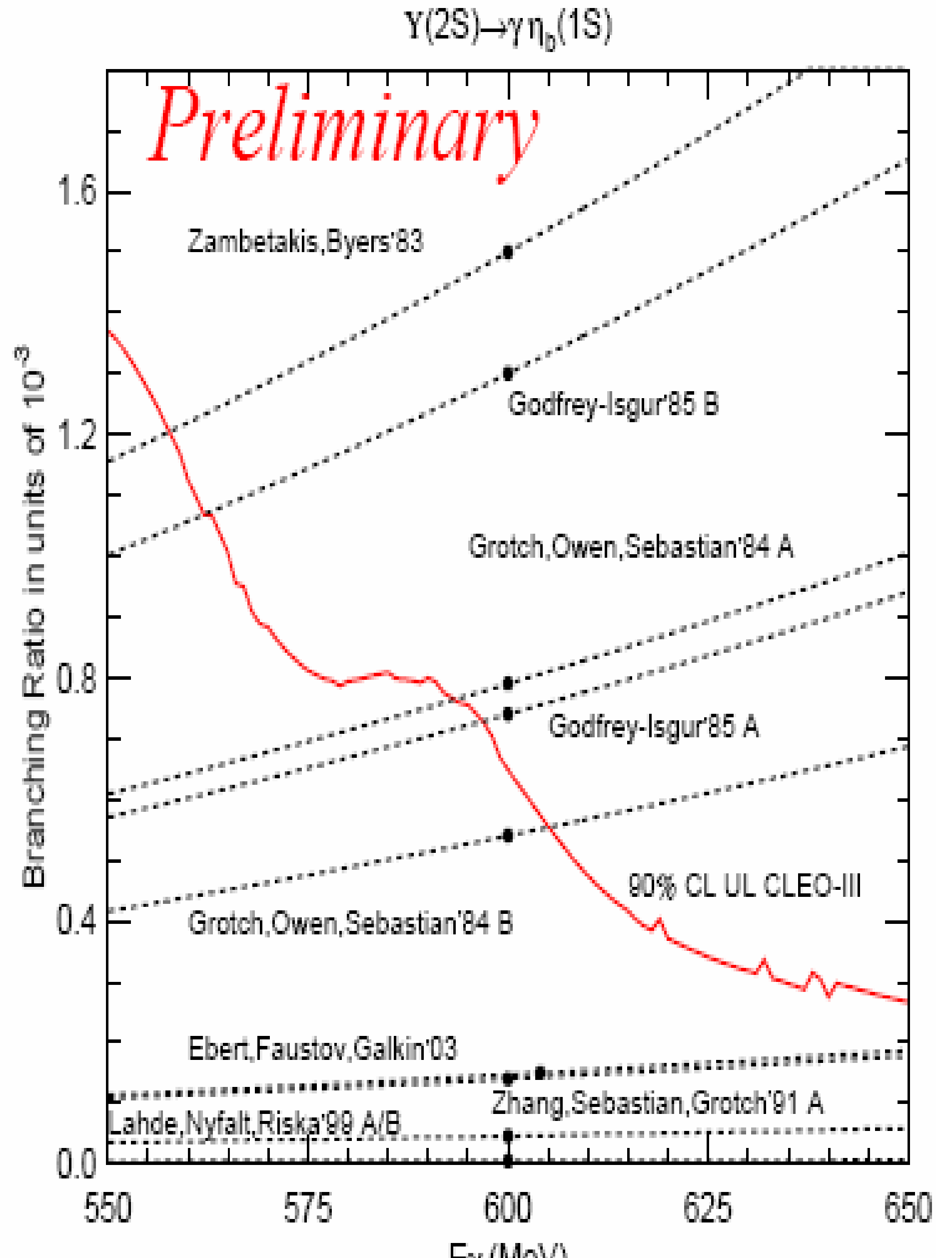
The CLEO search

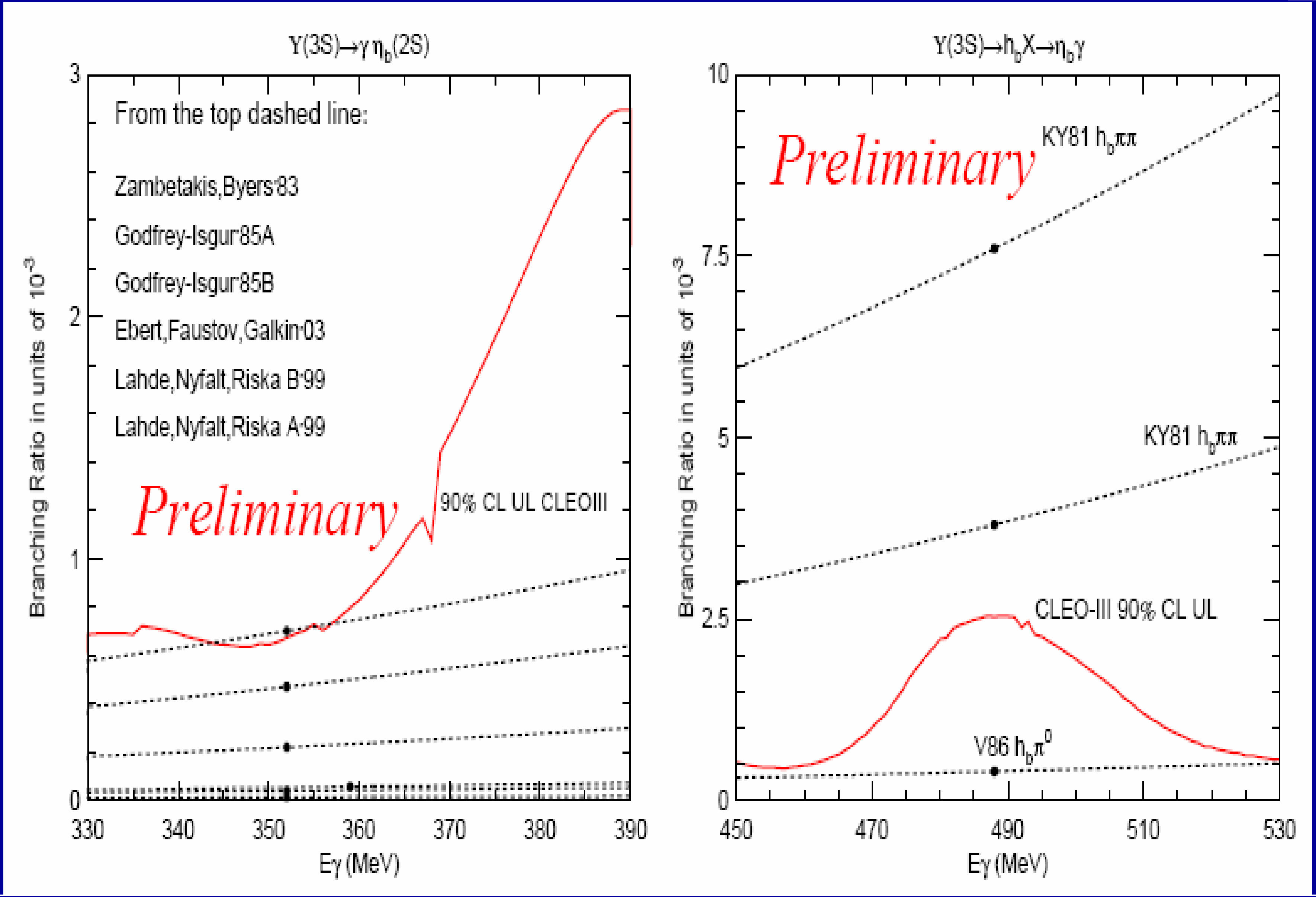
- $\Upsilon(3S) \rightarrow \eta_b + \gamma$, $\Upsilon(2S) \rightarrow \eta_b + \gamma$,
  $\Upsilon(3S) \rightarrow \eta_b(2S) + \gamma$

- $\Upsilon(3S) \rightarrow h_b + \pi^0$, $\Upsilon(3S) \rightarrow h_b + \pi^+ + \pi^-$
  followed by $h_b \rightarrow \eta_b + \gamma$

CLEO 90%C.L. upper limits on $B(\Upsilon(3S)or(2S)\to\gamma\eta_b(2S)or(1S))$ and $B(\Upsilon(3S)\to h_b\pi^0, h_b\pi^+\pi^-)\times B(h_b\to\eta_b\gamma)$ as a function of the photon energy E, along with various theoretical predictions

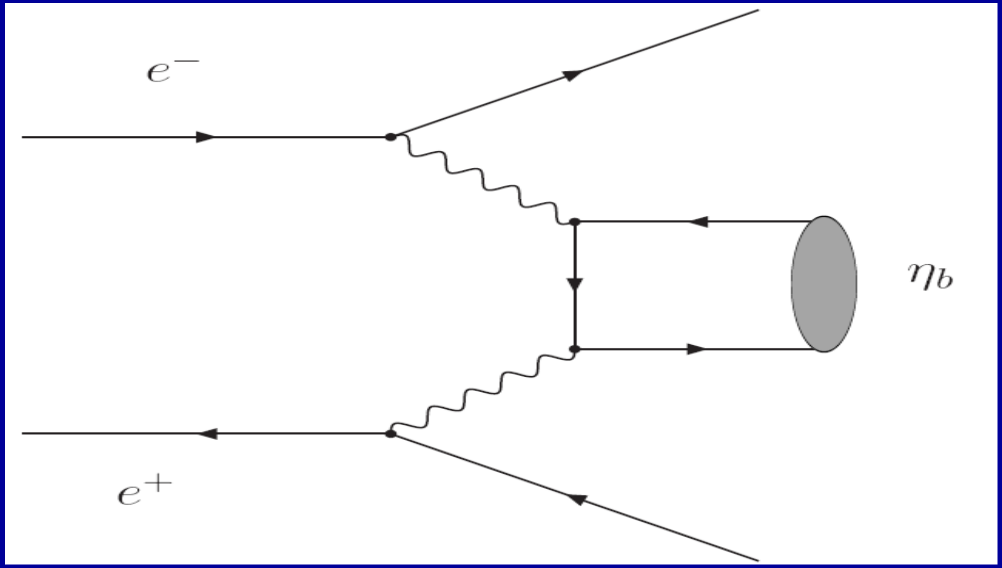





Υ(3S)→γ η_b(2S)
From the top dashed line:
Zambetakis,Byers'83
Godfrey-Isgur'85A
Godfrey-Isgur'85B
Ebert,Faustov,Galkin'03
Lahde,Nyfalt,Riska B'99
Lahde,Nyfalt,Riska A'99
Preliminary
90% CL UL CLEOIII
Branching Ratio in units of 10^-3
Eγ (MeV)
Υ(3S)→h_bX→η_bγ
Preliminary
KY81 h_bππ
KY81 h_bππ
CLEO-III 90% CL UL
V86 h_bπ^0
Branching Ratio in units of 10^-3
Eγ (MeV)

The LEP search

$$e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-\eta_b$$



LEP Search Results

Expt	Reaction of η_b	event	background
ALEPH	$\eta_b \to$ 4charged	0	0.30 ± 0.25
	$\eta_b \to$ 6charged	1	0.70 ± 0.34
L3	$\eta_b \to K^+K^-\pi^0$, $\eta_b \to$ 4charged, $\eta_b \to$ 4charged+π^0, $\eta_b \to$ 6charged, $\eta_b \to \pi^+ \pi^- \eta'$ $\eta_b \to$ 6charged+π^0,	6	2.5
DELPHI	$\eta_b \to$ 4charged	0	1.2
	$\eta_b \to$ 6charged	2	1.1
	$\eta_b \to$ 8charged	1	1.5

95% C.L. upper limits on η_b . The two-photon decay width times branching ratio into various hadronic states. Searches at LEP.

Expt	Final state	$\Gamma_{\gamma\gamma} \times B(keV)$
ALEPH	4 charged	< 0.048
	6 charged	< 0.132
L3	$K^+K^-\pi^0$	< 2.83
	4 charged	< 0.21
	4 charged+ π^0	< 0.50
	6 charged	< 0.33
	6 charged+ π^0	< 5.50
	$\pi^+\pi^-\eta'$	< 3.00
DELPHI	4 charged	< 0.093
	6 charged	< 0.270
	8 charged	< 0.780

η_b Search at CDF (Tseng, CDF, 2002)

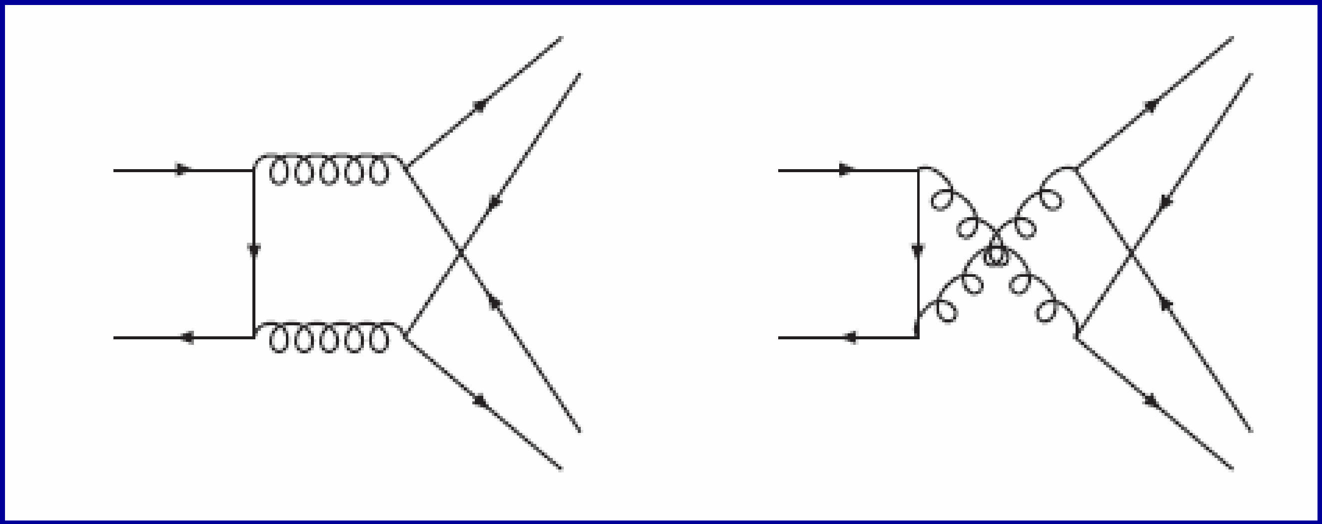
- $\eta_b \rightarrow J/\psi\ J/\psi$

- A small cluster of 7 events can be seen, where 1.8 events are expected from background.

- If this cluster is due to η_b decay, then the product of its production cross-section and decay branching fractions are near the upper end of expectation of Braaten et al. (Phys. Rev. D63, 094006, 2001)

Theoretical Expectations

- Feynman Diagrams for η_b → 2 Vector particles



- η_b → J/ψ J/ψ and η_c → φ φ

- According Braaten, Fleming and Leibocich (01) , though helicity suppressed,

$$Br[\eta_b \to J/\psi + J/\psi] = 7\times10^{-3} \sim 7\times10^{-5}$$

- Which seems to be overestimated, since

$$Br[\eta_b \to c + c + \bar{c} + \bar{c}] \sim 10^{-5}$$

Maltoni and Polosa (04)

- A recent analysis shows: (Jia, hep-ph/0611130)

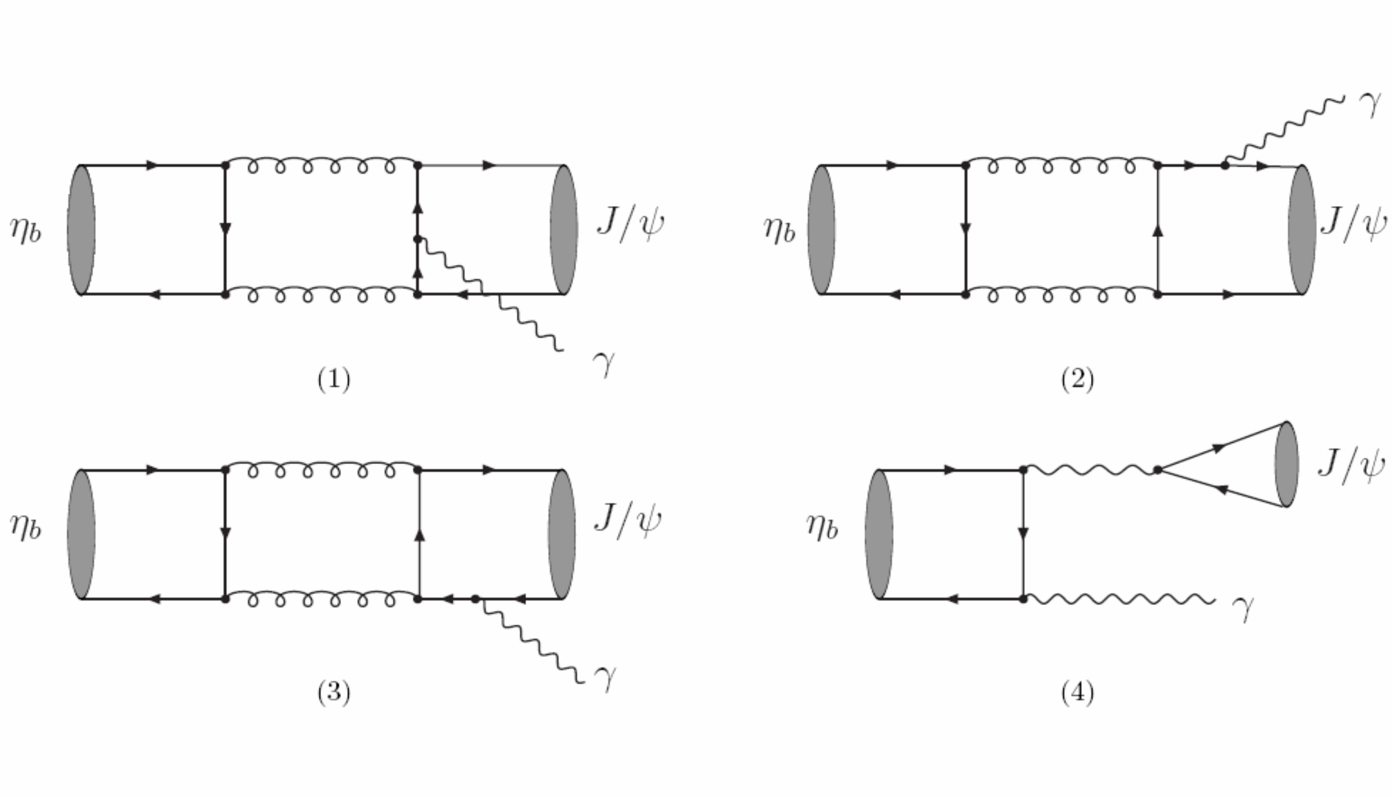
$$Br[\eta_b \to \phi + \phi] \approx (0.9 - 1.4)\times 10^{-9}$$

$$Br[\eta_b \to J/\psi + J/\psi] = 2.4^{+4.2}_{-1.9}\times 10^{-8}$$

- Hence, such a rare decay mode perhaps will not be observed in the foreseeable future in experiment.

$\eta_b \rightarrow \gamma + V$ (Hao, Jia, Qiao, Sun, JHEP,2007)

- $\eta_b \rightarrow \gamma + J/\psi$ and $\eta_b \rightarrow \gamma + \phi$



- Direct calculation gives us:

$$\mathrm{Br}[\eta_b \to J/\psi\gamma] = \frac{8\, e_c^2\, \alpha\, \alpha_s^2}{3\,\pi} \frac{m_c\, \psi_{J/\psi}^2(0)}{m_b^2\,(m_b^2 - m_c^2)} \left| f\left(\frac{m_c^2}{m_b^2}\right) - g\left(\frac{m_c^2}{m_b^2}\right)\right|^2 ,$$

where $$g(u) = \frac{9\,\pi\, e_b^2\, \alpha}{2\,\alpha_s^2} \frac{1-u}{u}$$

$$\begin{aligned}
\mathrm{Re} f(u) &= \frac{2(1-u)}{2-u} \ln\left[\frac{u}{2(1-u)}\right] - \frac{2}{1+u} \left\{ \ln^2 2 + \frac{1}{2}\ln^2 u + \ln[2-u] \ln\left[\frac{u}{2(1-u)}\right] \right. \\
&+ \ln u \ln\left[\frac{2}{1-u}\right] - u \ln\left[\frac{u}{2-u}\right] \ln\left[\frac{u}{2(1-u)}\right] + 2\,\mathrm{Li}_2[-u] + \mathrm{Li}_2\left[\frac{u-1}{2u}\right] \\
&+ \left. 2\,\mathrm{Li}_2\left[\frac{u}{2}\right] - \mathrm{Li}_2\left[\frac{u^2-u}{2}\right] - u\,\mathrm{Li}_2\left[2 - \frac{2}{u}\right] \right\} , \\
\mathrm{Im} f(u) &= 2\pi \left\{ \frac{1-u}{2-u} + \frac{u \ln u}{1+u} - \ln[2-u] \right\} ,
\end{aligned}$$

- The QCD process is found having:

$$Br[\eta_b \to J/\psi + \gamma] = 3.5 \times 10^{-7}$$

- In QED +QCD we find

$$Br[\eta_b \to J/\psi + \gamma] = 1.5 \times 10^{-7}$$

- In agreement with another similar work (Chao et al. arXiv: hep-ph/0701009)

$\eta_b \rightarrow \gamma\ J/\psi$ versus $\eta_b \rightarrow 2\ J/\psi$

- The explicit calculation reveals that the branching ratio of $\eta_b \rightarrow \gamma\ J/\psi$ process is indeed rather small.

- Nevertheless, it is still bigger than the hadronic double J/ψ decay mode.

- This channel may have a clean signature at the comparable level as double J/ψ channel.

Other ways to pin down the η_b

Maltoni & Polosa (04): $\eta_b \rightarrow$ 2 V

Process $\eta_b \rightarrow K^* \bar{K}^*$

with branching ration: $Br[\eta_b \rightarrow K^* \bar{K}^*] \sim 10^{-8}$

And, similarly process $\eta_b \rightarrow D^* \bar{D}^*$

with $Br[\eta_b \rightarrow D^* \bar{D}^*] \sim 10^{-8}$

$\eta_b \rightarrow$ V + P (Jia, hep-ph/0611130)

It is found that the $\eta_b \rightarrow$ V + P processes give bigger branching ratios than the $\eta_b \rightarrow$ V + V processes.

For $\eta_b \rightarrow K^* \bar{K} + c.c.$

$$Br[\eta_b \rightarrow K^* \bar{K}] \sim 10^{-5}$$

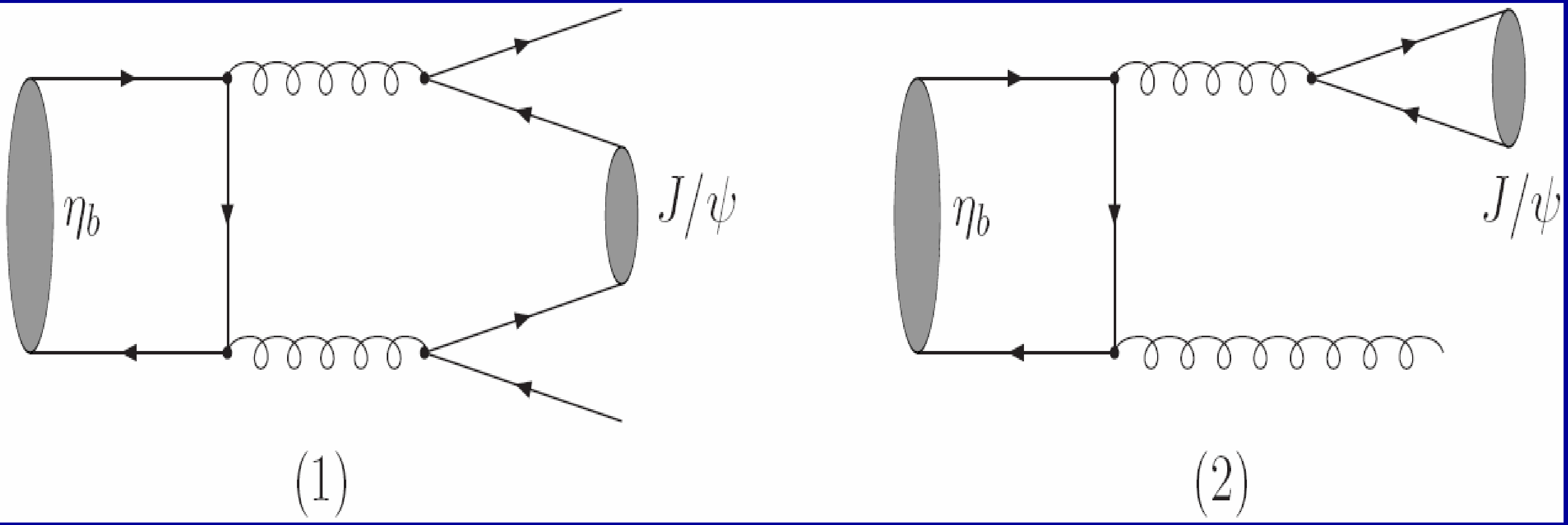
For $\eta_b \rightarrow D^* \bar{D} + c.c.$

$$Br[\eta_b \rightarrow D^* \bar{D}] \sim 10^{-5}$$

However, these processes are still too small.

Inclusive J/ψ Production in η_b decays

- **The Feynman Diagram at the leading order**



- Diagram(1) is for the contribution of color-singlet $c\bar{c}$.
- Diagram(2) is for the contribution of color-octet $c\bar{c}$.

- The diagram 1 shows that η_b → J/ψ(color-singlet state)+X

$$Br_1[\eta_b \to J/\psi + X] \sim 10^{-5}$$

- The diagram 2 shows that η_b → J/ψ(color-octet state)+X

$$Br_8[\eta_b \to J/\psi + X] \sim 10^{-4}$$

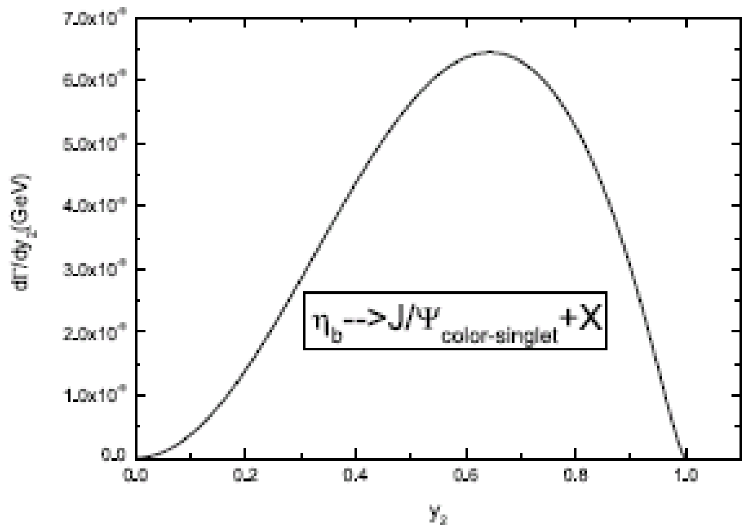


FIG. 7: Lowest-order diagrams that contribute to the inclusive process: $\eta_b \to J/\Psi_{color-singlet} + X$.

Summary

- At present there is no place where the η_b is claimed to be discovered.
- We find that the process $\eta_b \rightarrow \gamma + J/\psi$ has a relatively larger branching ratio in comparison with the prevailing ones.

- No doubt, the η_b physics will keep on being an challenge to both theorists and experimenters.

- Hopefully, the Tevatron II, or at least LHC, Super-B and ILC can tell us more about η_b .

Thank you for your attention