# Searches for parabottomonia in current and future B factories

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BNM 2008 Workshop, Atami 24-26/1/2007

# Bottomonium

$b\bar{b}$ bound state
non-relativistic quark motion,
in perturbative regime
$\alpha_S \sim 0.1$

J,S,L are good quantum numbers

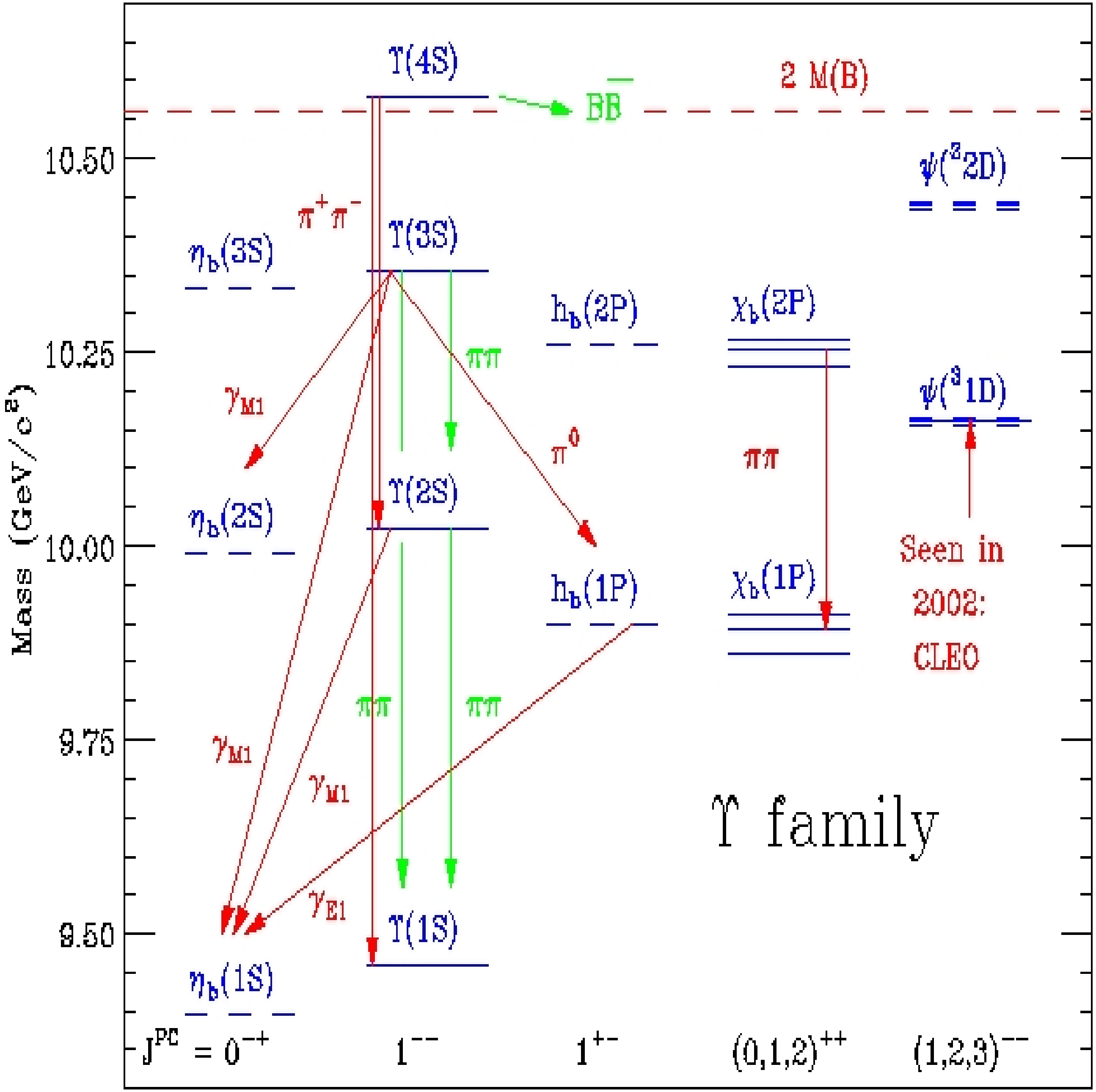
S=0 : *para*bottomonium
*Not yet observed*

S=1 : *orto*bottomonium
$\Upsilon$ decay to 3 gluons
$\Gamma[\Upsilon(1,2,3S)]$ = 53, 44, 26 keV

No 2S-2P Degeneration

Hyperfine Splitting : unknown

Fine Splitting : 15-30 MeV (1P)



# Quarkonium Working Group Activities

YELLOW REPORT : CERN-2005-005, ArXiv: hep-ph/0412158

QWG Workshops on Heavy Quarkonium:

- QWG1: CERN, November 8 to 10, 2002
- QWG2: Fermilab, September 20 to 22, 2003
- QWG3: Beijing, October 12 to 15, 2004
- QWG4: Brookhaven, June 27 to 30 , 2006
- QWG5: DESY Hamburg, October 17 to 20, 2007
- QWG6: NARA, 2-5 December 2008

*Priority Number 1:*

*FIND THE MISSING BOTTOMONIA!!!*

# 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

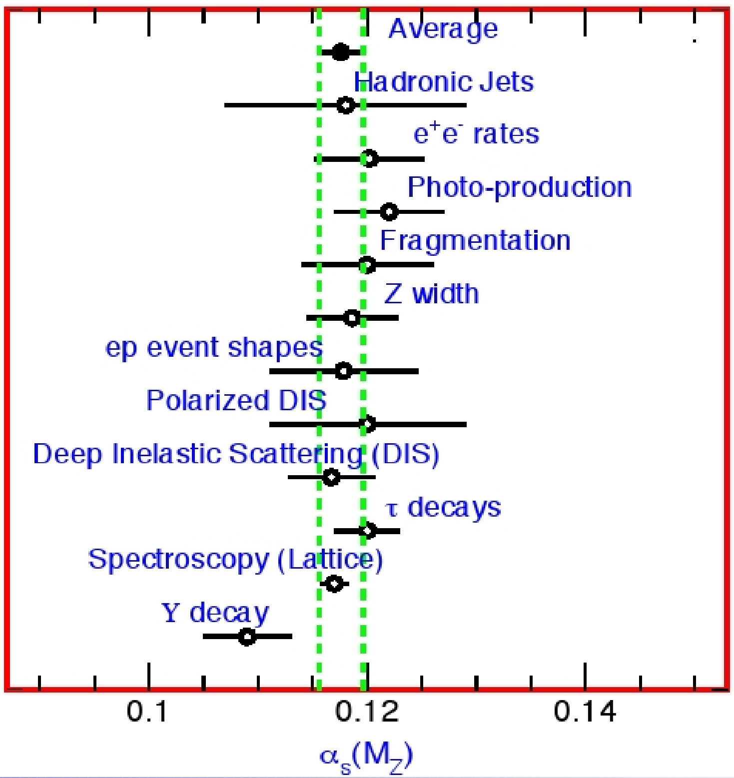
- Applicable to all aspects of the dynamics of heavy quarkonia:
  spectroscopy, decays, production

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: $0.118 \pm 0.003$ )

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



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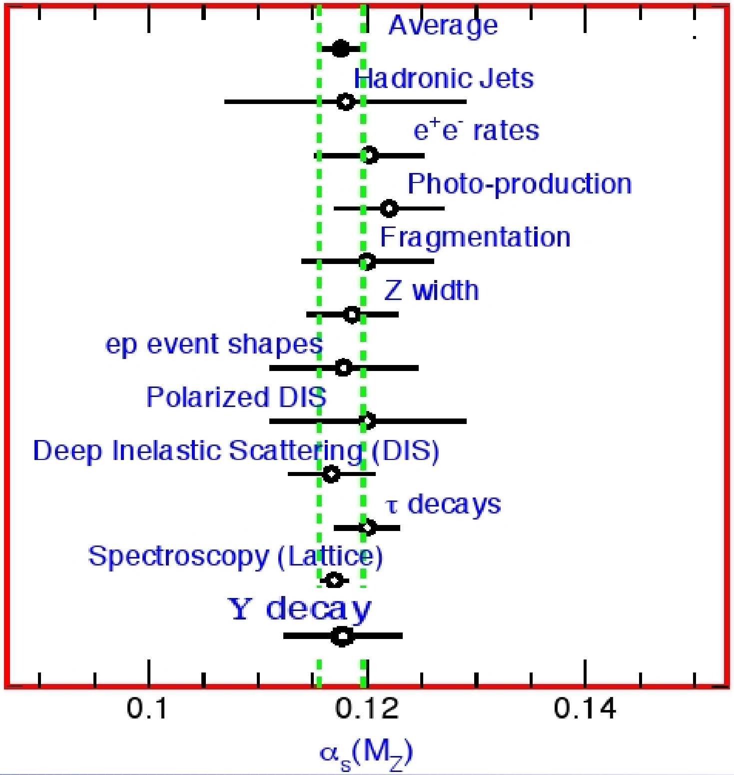


# NRQCD predictions

NLL calculation of $M(\eta_b)$:

$M(\eta_b) = 9421 \pm 10(\text{th}) \pm 9(\delta\alpha_s)$ MeV/$c^2$

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

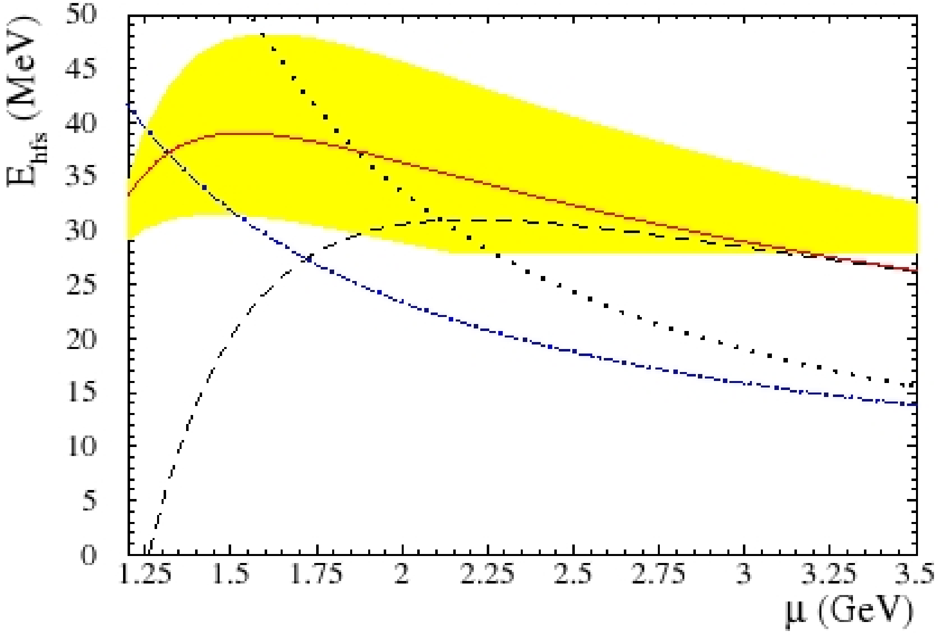
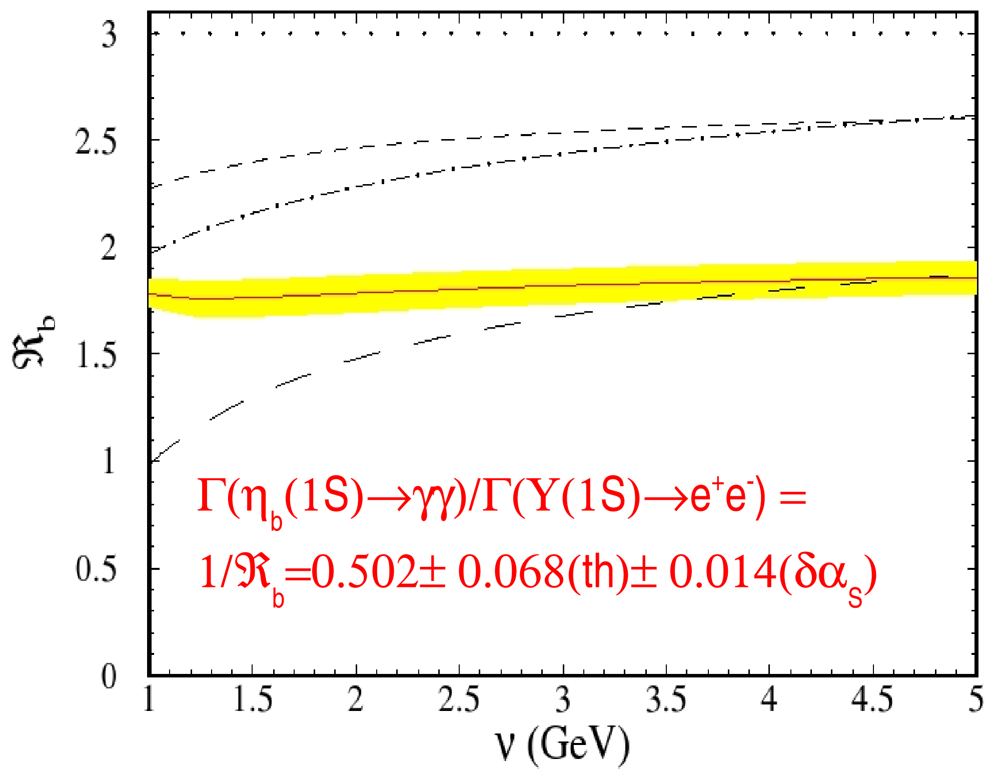



FIG. 1: HFS of 1S bottomonium as a function of the renormalization scale $\mu$ in the LO (dotted line), NLO (dashed line), LL (dot-dashed line), and NLL (solid line) approximations. For the NLL result, the band reflects the errors due to $\alpha_s(M_Z) = 0.118 \pm 0.003$.

# NRQCD predictions

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2-photon width at NNLL:

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

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

Figure 3: The spin ratio as the function of the renormalization scale $\nu$ 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 $\alpha_s(M_Z) = 0.118 \pm 0.003$.

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

2-gluon width at NLO (for charmonium) :

$\Gamma(\eta_c \to gg)/\Gamma(\eta_c \to \gamma\gamma) = 3.1 \pm 0.5(th) \pm 0.3(\delta\alpha_S) * 10^3$ Exp$=3.6 \pm 1.2 * 10^3$

Bodwin, Chen, PRD64(2001),114008; Bodwin, Petrelli, PRD66(2002),094011

# NRQCD predictions

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

$\Gamma(\eta_b)$~30 MeV ??

$BR(\eta_b \to \gamma\gamma) \sim 0.2*10^{-4}$ ??

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

2-gluon width at NLO (for bottomonium) :

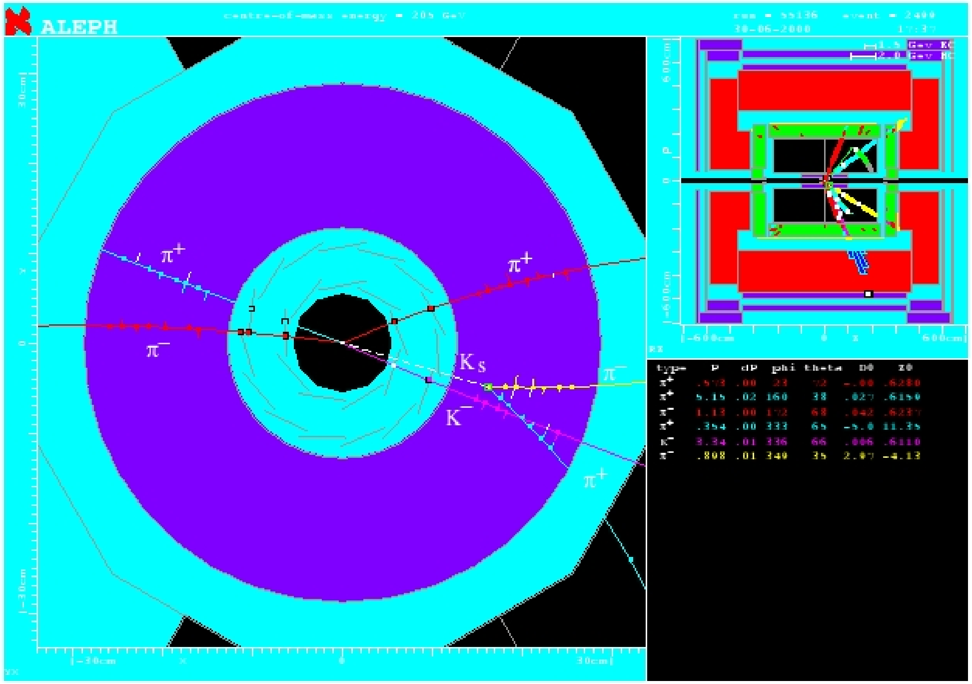
$$\Gamma(\eta_b \to gg)/\Gamma(\eta_b \to \gamma\gamma) = (Z_c/Z_b)^4\ \Gamma(\eta_c \to gg)/\Gamma(\eta_c \to \gamma\gamma) \sim 5*10^4$$

Bodwin, Chen, PRD64(2001),114008; Bodwin, Petrelli, PRD66(2002),094011

# Searches for $\eta_b$(1,2,3S) at LEP and Tevatron

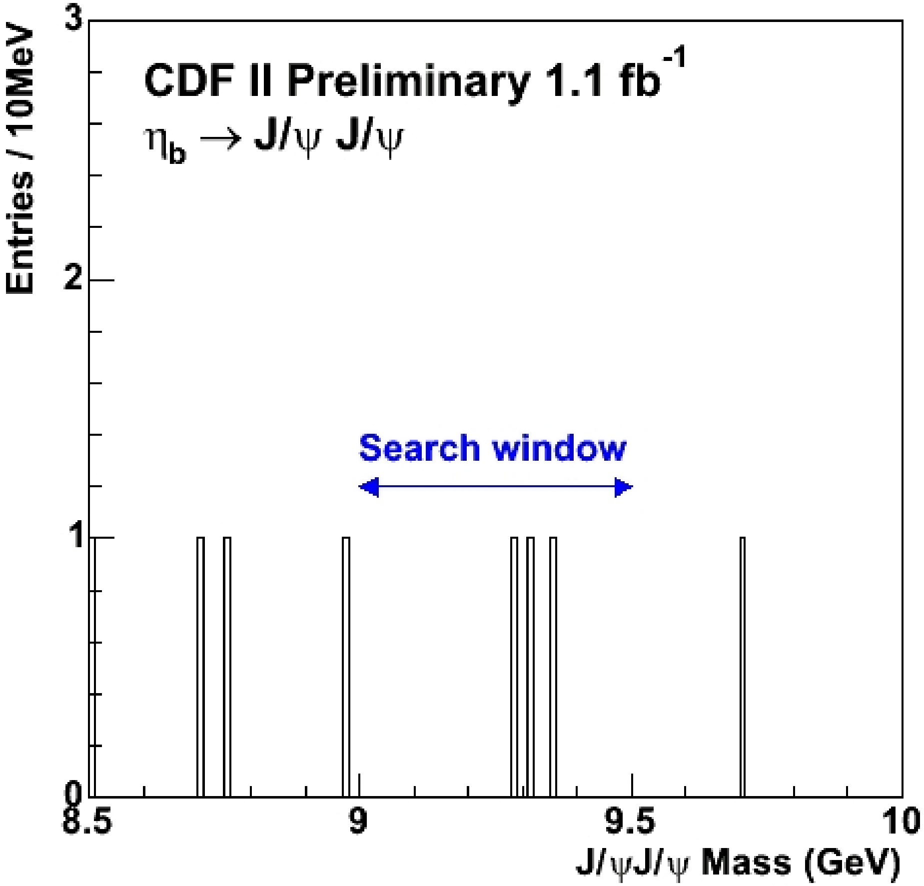
Aleph, Delphi, L3 @ LEP
($\gamma\gamma \rightarrow \eta_b \rightarrow$ 4,6 prongs)
few events, compatible with background

$\eta_b$ Candidate Event




mass $m = 9.30 \pm 0.02 \pm 0.02$ GeV

CDF @ Tevatron($\eta_b \rightarrow J/\psi\ J/\psi$ )




... but theory predicts $10^9\ \eta_b$/fb$^{-1}$ (=μb) ....

[Braaten et al. , PRD 63, 094006 (2001)]

# Inclusive searches in Υ(nS) decays

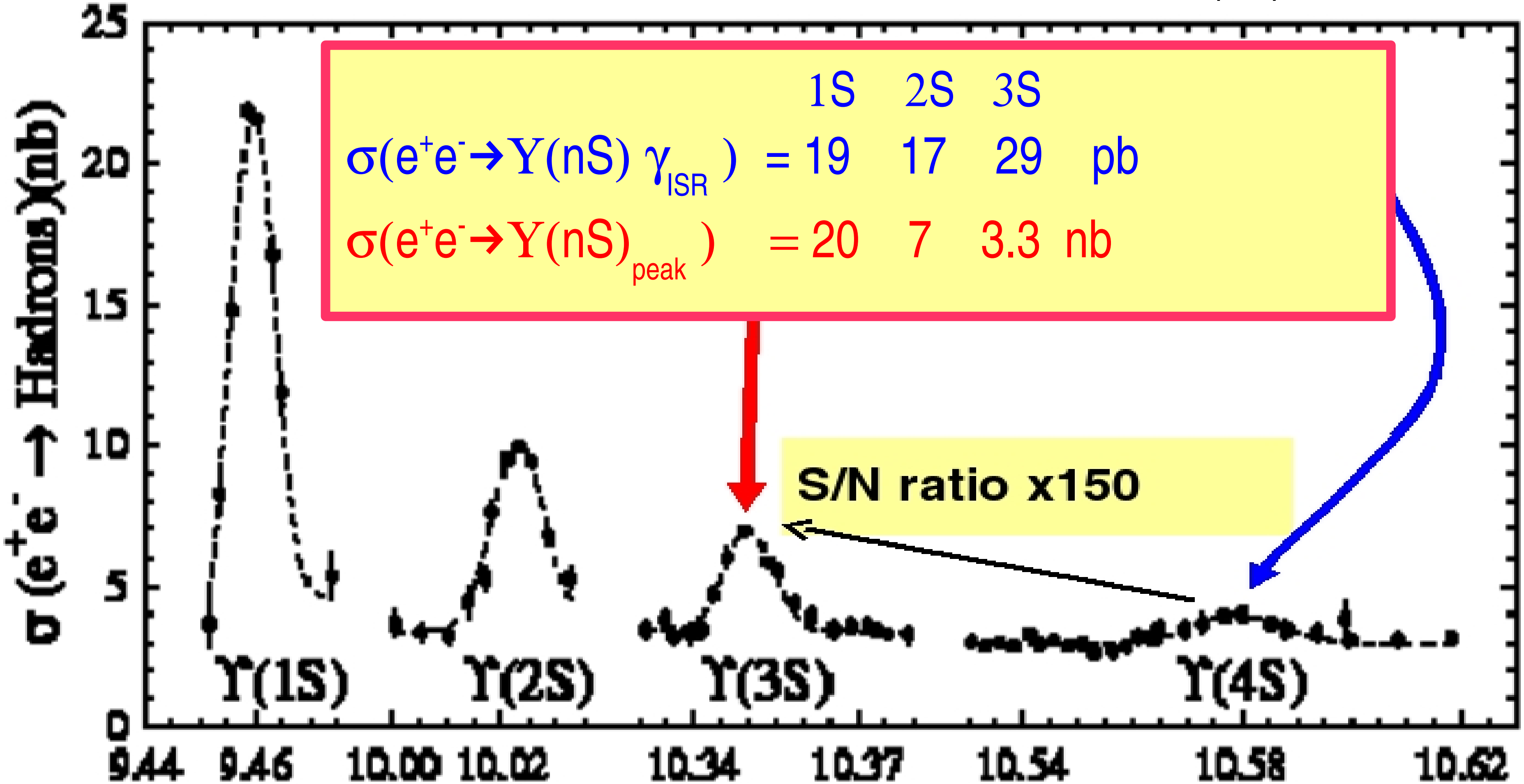
PRO's

- Do not pay the penalty of small exclusive Branching Ratios.
- If unbiased, allow to determine absolute BR's

CON's : ISR samples are unusable:

- w/ tagged ISR photon (~0.9 M in 1 $ab^{-1}$) : limited statistics
- w/ untagged ISR photon (~28 M in 1 $ab^{-1}$ ) : smearing in resolution

NEED RUNNING ON Y(nS) PEAK



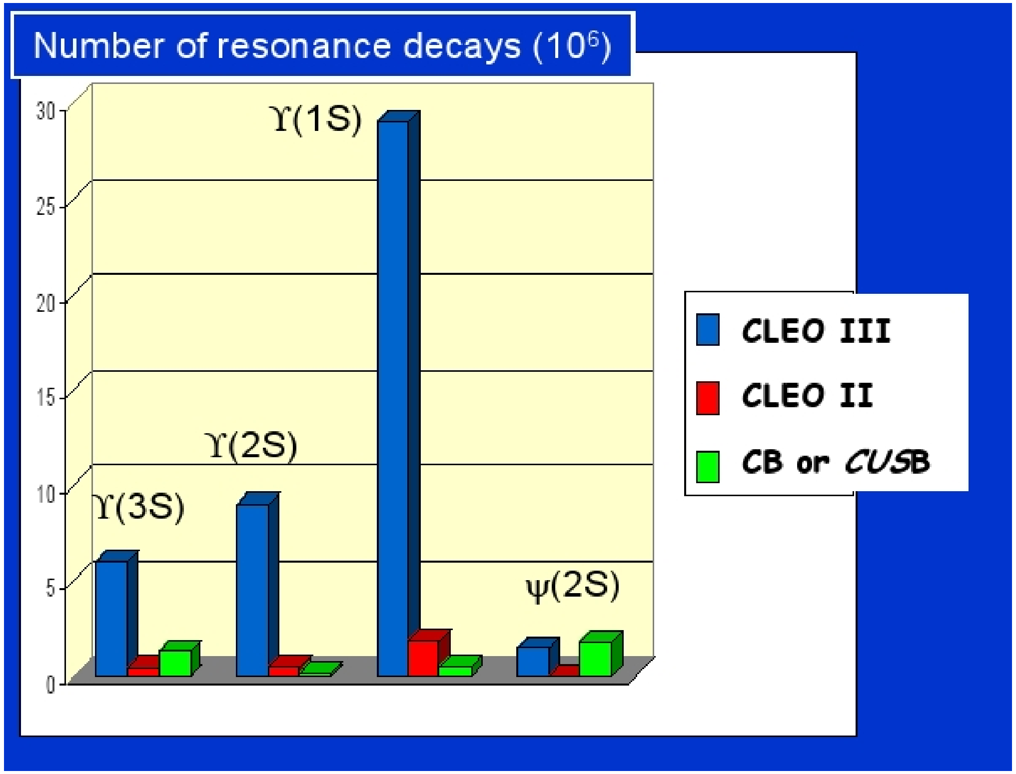

$\sigma(e^+e^- \to \Upsilon(nS)\,\gamma_{ISR}) = 19 \quad 17 \quad 29$ pb

$\sigma(e^+e^- \to \Upsilon(nS)_{peak}) = 20 \quad 7 \quad 3.3$ nb

# Data Samples in B factories

CLEO-III (2003):

1.06 $fb^{-1}$==> 21M Y(1S)
1.31 $fb^{-1}$==> 9.3M Y(2S)
1.39 $fb^{-1}$==> 5.9M Y(3S)




BELLE (2006):
2.9 $fb^{-1}$ => 11 M Y(3S)

BaBar (now!)
goal: 30 $fb^{-1}$ ==>100 M Y(3S)

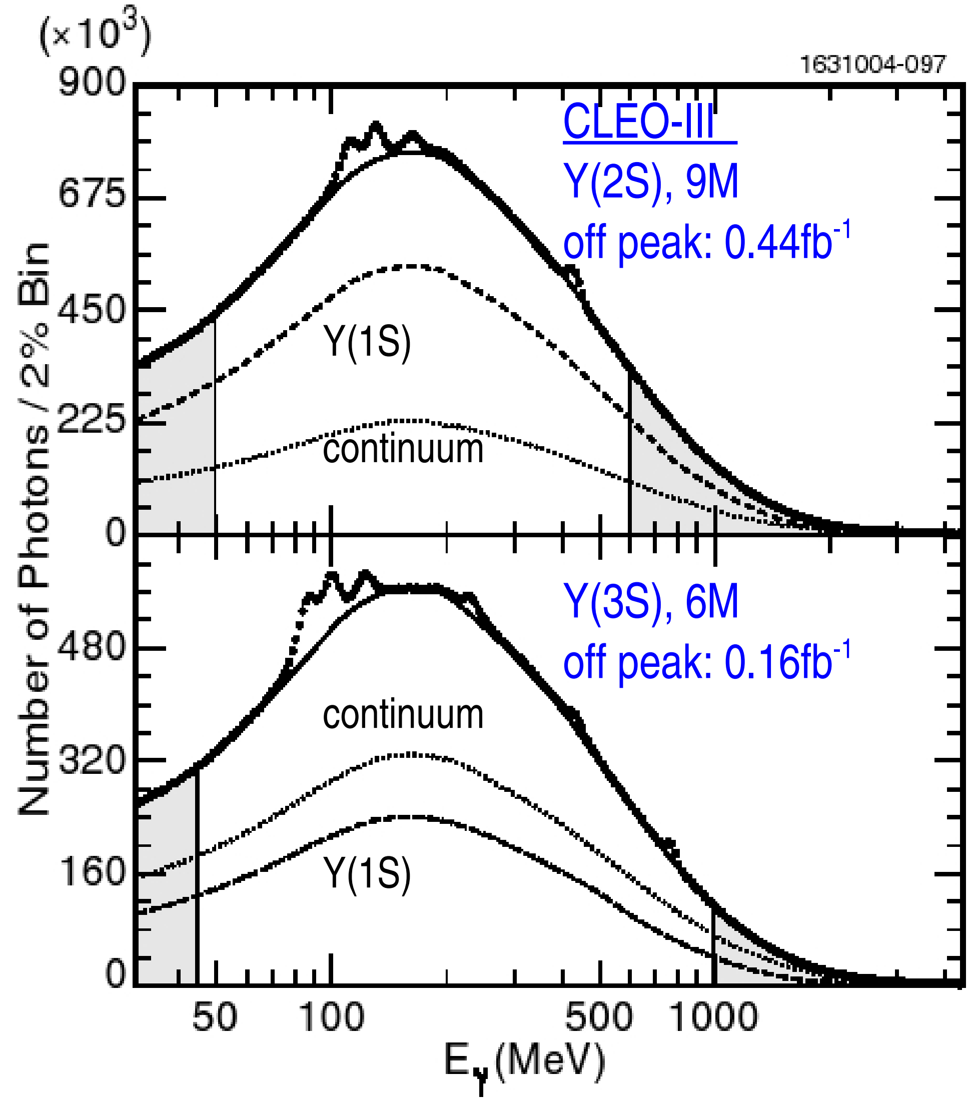
# The challenge

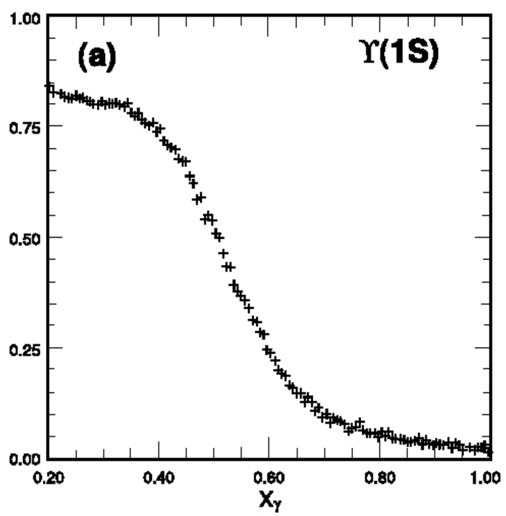
Inclusive photon spectra at Y(nS) are populated by comparable amounts by photons from transitions to other charmonia, and annihilations to LH.

On average about 7-8 photons per hadronic event are observed, a large fraction from decays of $\pi,\eta,\omega$ and other light hadrons.

The visible peaks are from known single photon transitions to $\chi_b$'s at 10% level or cascades at 1% level.

(see CLEO:
ArXiv:0704.2766)



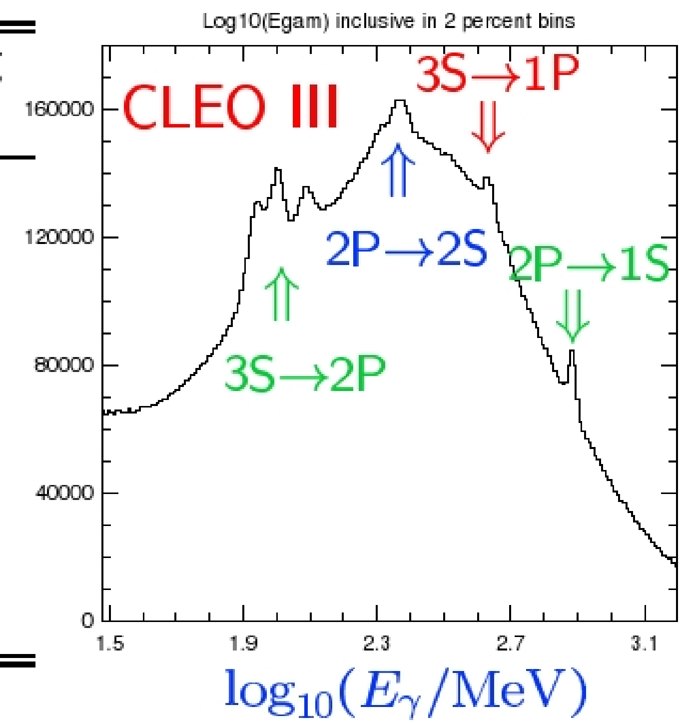
# Inclusive searches w/ current data

Expected significances with current CLEO samples (assuming BR=10-4 and Gamma=10MeV)

| | Emin-Emax (MeV) | FWHM (2%bins) | Bkg/ sample | Signal/ sqrt(Bkg) |
|---|---|---|---|---|
| 3S->3S | 30 100 | 10 | 3M/6M | 0.6k/1.7k |
| 3S->2S | 330 426 | 3 | 1.1M/6M | 0.6k/1k |
| 3S->1S | 856 947 | 1 | 160k/6M | 0.6k/0.4k |
| 2S->2S | 30 100 | 10 | 4M/9M | 0.9k/2k |
| 2S->1S | 544 638 | 2 | 0.55M/9M | 0.9k/0.75k |
| 1S->1S | 30 100 | 10 | 10M/20M | 2k/3k |

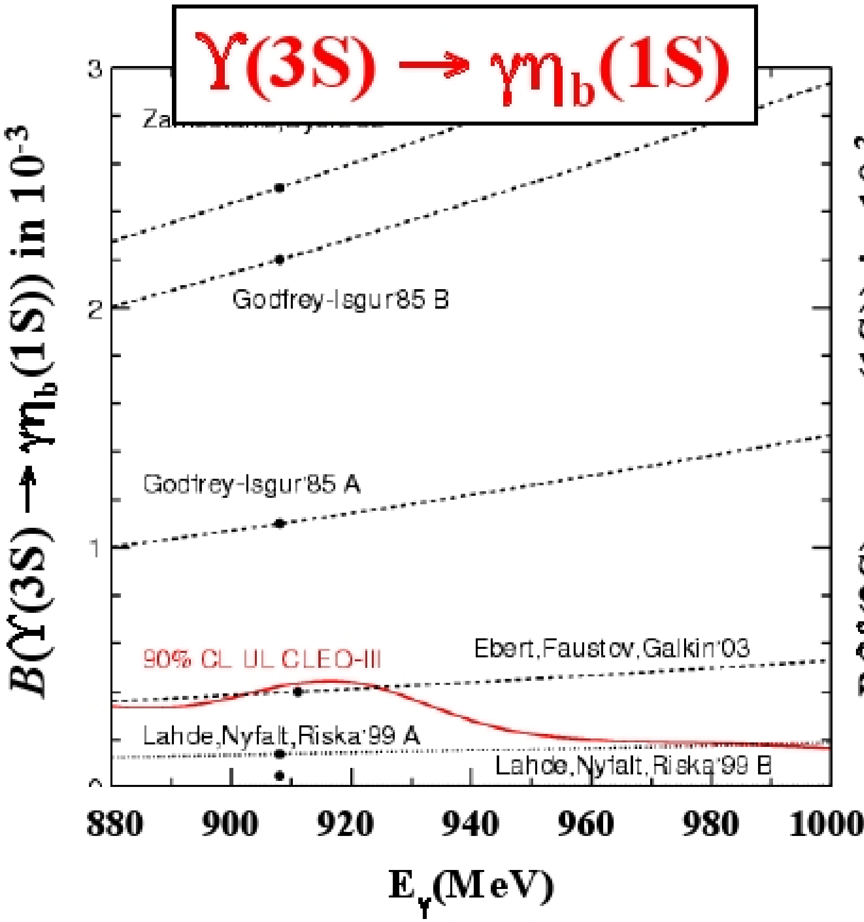
Photons above 400 MeV in 5.88 M $\Upsilon(3S)$ (Kwong + JLR, 1988, updated):

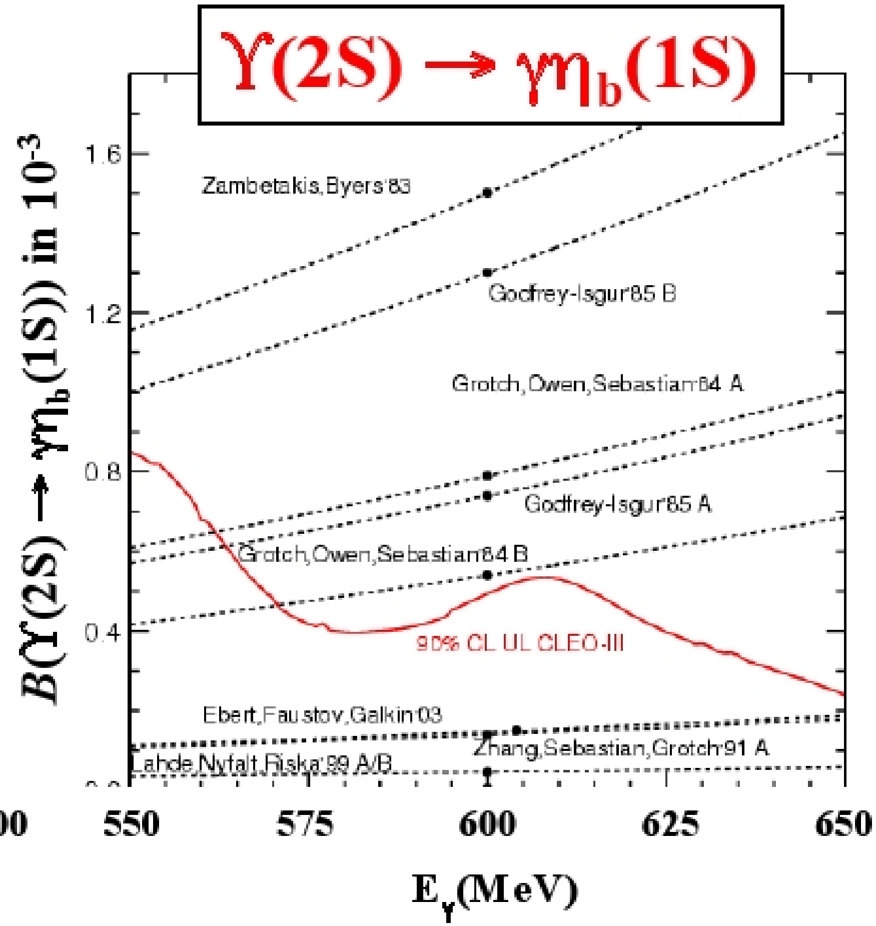
| Energy (MeV) | Transition | Number of events (K) | Doppler broadening % | MeV |
|---|---|---|---|---|
| 422 | $\chi_{b1} \to \Upsilon(1S)$ | 32.3 | 4.7 | 20 |
| 433 | $\Upsilon(3S) \to \chi_{b2}$ | 63.4 | 0 | 0 |
| 443 | $\chi_{b2} \to \Upsilon(1S)$ | 24.3 | 4.5 | 20 |
| 453 | $\Upsilon(3S) \to \chi_{b1}$ | 43.2 | 0 | 0 |
| 484 | $\Upsilon(3S) \to \chi_{b0}$ | 17.6 | 0 | 0 |
| 741 | $\chi'_{b0} \to \Upsilon(1S)$ | 2.1 | 1.2 | 8.9 |
| 765 | $\chi'_{b1} \to \Upsilon(1S)$ | 75.3 | 1.0 | 7.5 |
| 777 | $\chi'_{b2} \to \Upsilon(1S)$ | 45.6 | 0.8 | 6.4 |

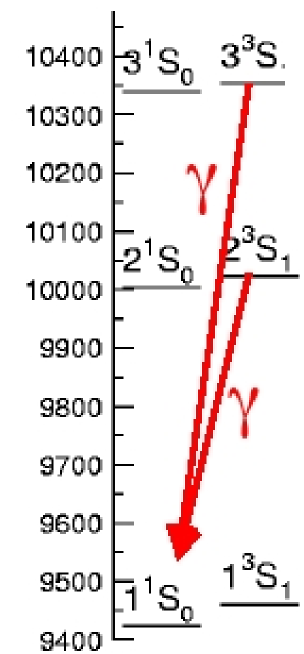


# Inclusive searches of $\eta_b(1S)$ at CLEO

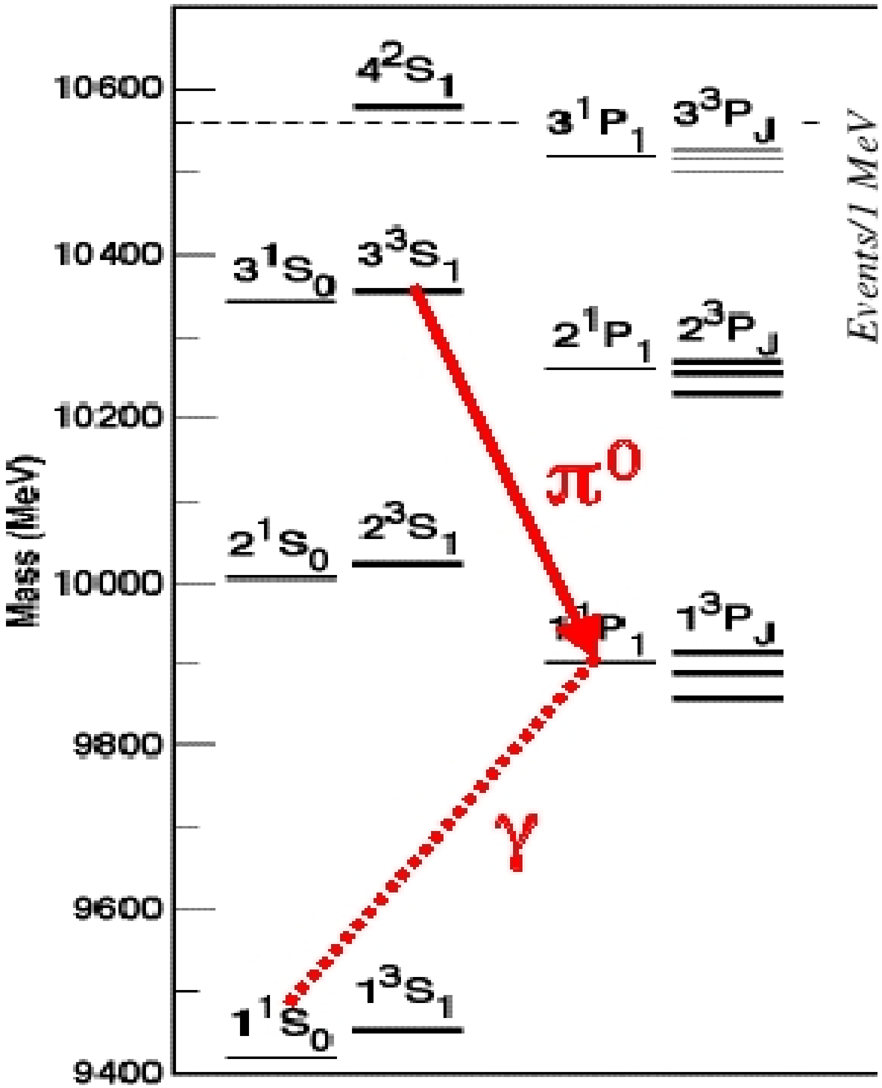
- **Hindered M1 transition:** $\Gamma_{M1} \propto \frac{e_Q^2}{m_Q^2} \left|\langle nL | n'L \rangle\right|^2 E_\gamma^3$
- **But $E_\gamma$ ~911 (604) MeV from $\Upsilon$(3S) ($\Upsilon$(2S)) → $\gamma\eta_b$(1S) with M($\eta_b$)~9400 MeV/c².**
- **CLEO has already set ULs (90%CL) on these *BR*'s (PRL94,032001)**



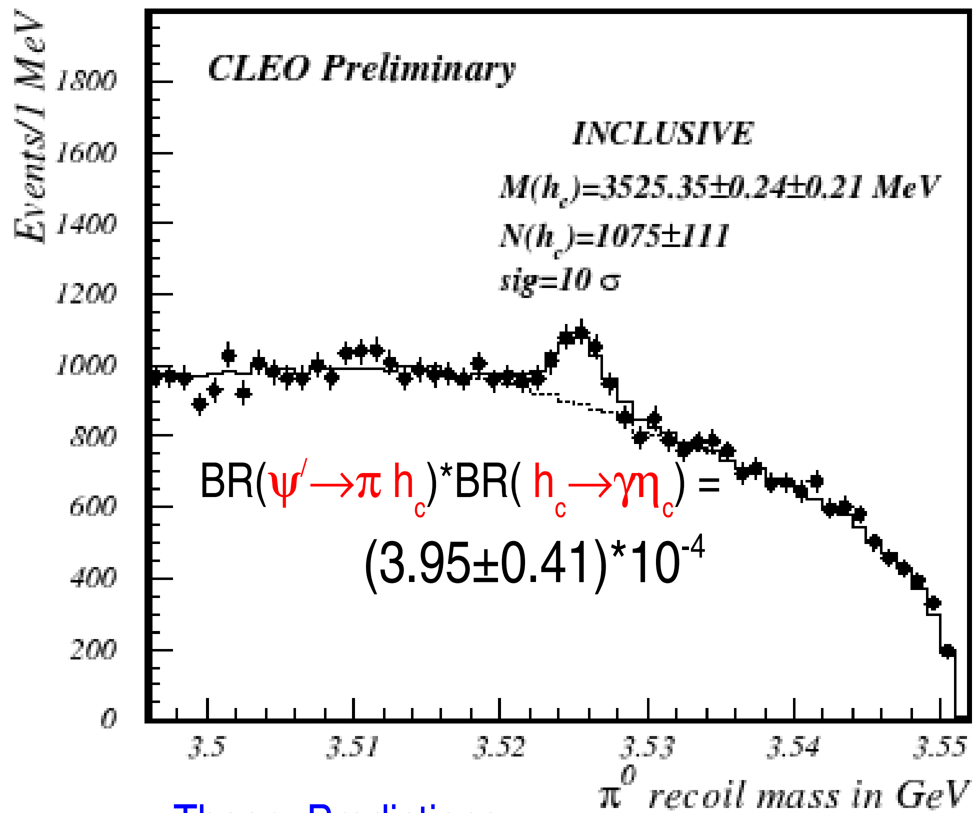



# Double hunt: $h_b$ (1P) and $\eta_b$(1 S) at CLEO (and Belle)




Search for of $h_b$(1P) in Bottomonium

Discovery of $h_c$(1P) in Charmonium :




$BR(\psi' \to \pi\, h_c) * BR(h_c \to \gamma \eta_c) =$

$(3.95 \pm 0.41) * 10^{-4}$

Theory Predictions:

Voloshin: Sov.JNP43 (1986) , 1011

Godfrey, Rosner, PRD 66 (2002) , 014012

$BR(\psi' \to \pi\, h_b) * BR(h_b \to \gamma \eta_b) = 4 * 10^{-4}$

# Inclusive searches w/ 100MY's

Expected significances with future BaBar Y(3S) sample and with comparable ones on Y(1,2S) (assuming BR=10-4 and Gamma=10MeV)

| | Emin-Emax (MeV) | FWHM (2%bins) | Bkg | Signal/ sqrt(Bkg) |
|---|---|---|---|---|
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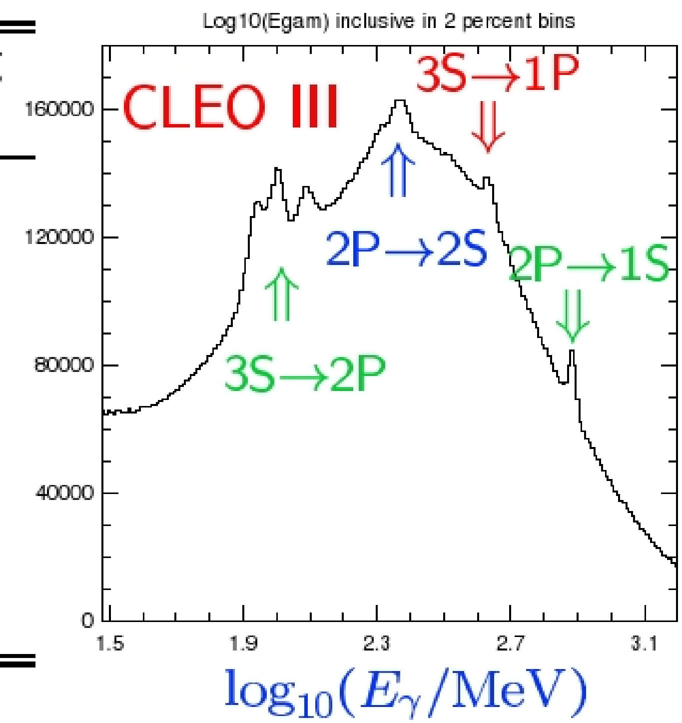
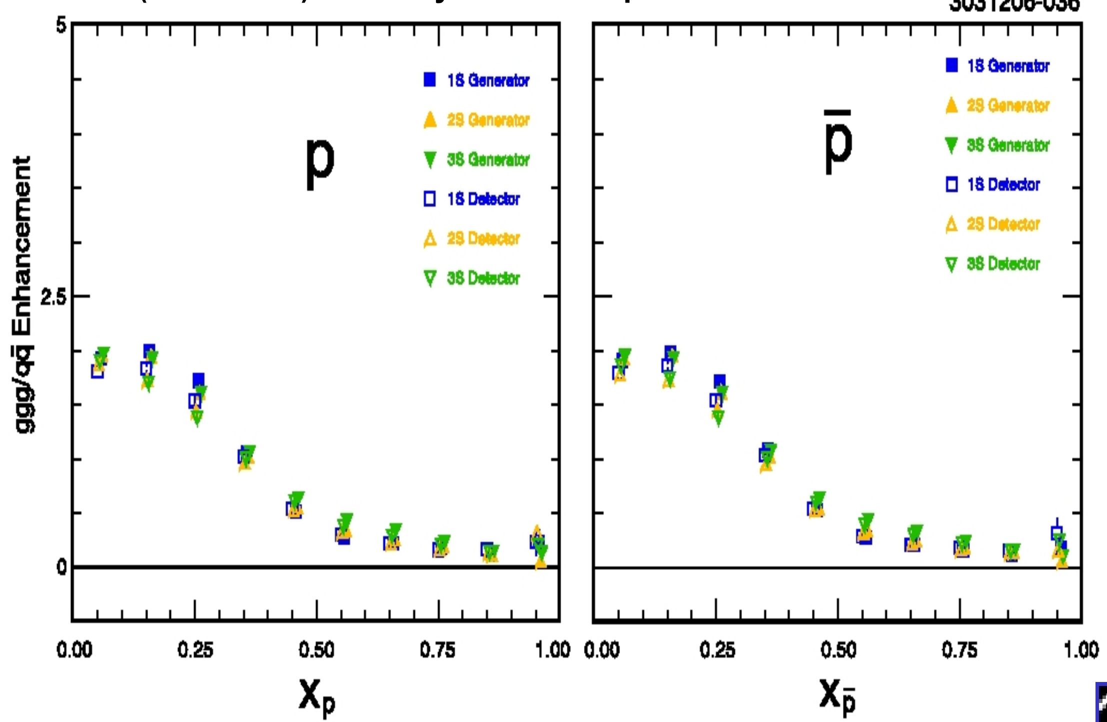
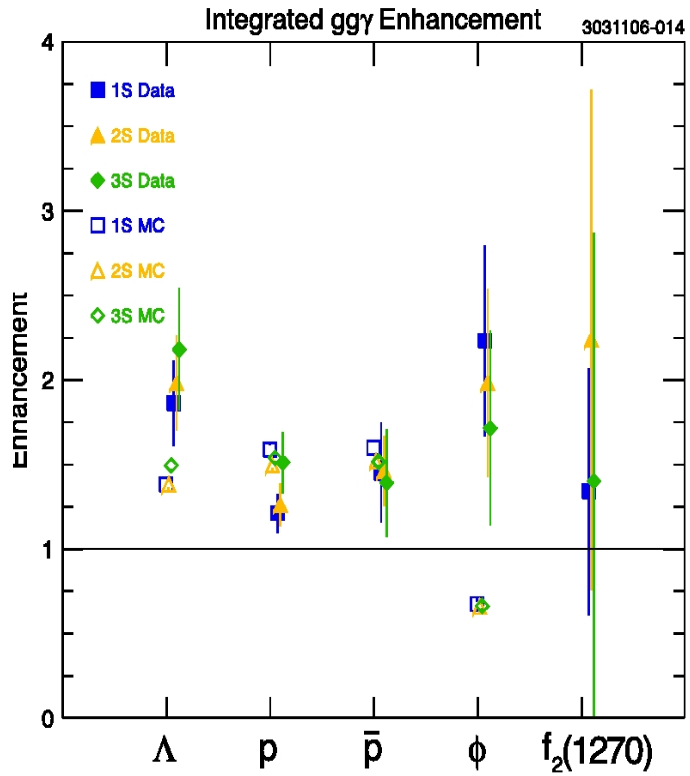


# Semi-inclusive signatures ?

ArXiv:0704.2766

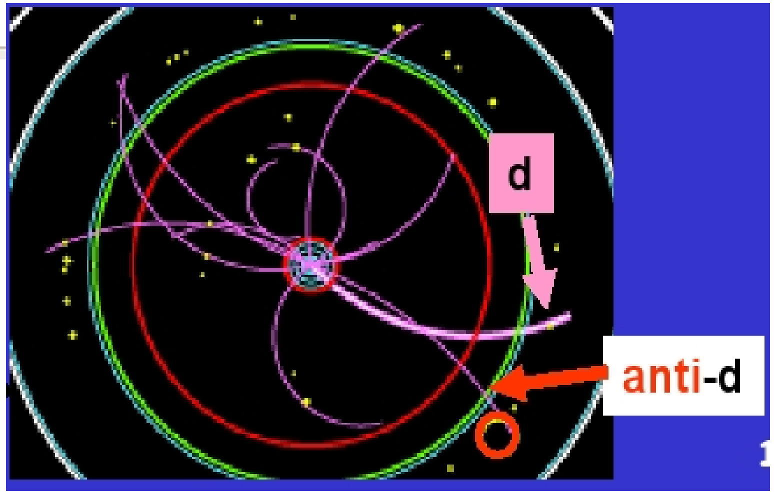
Enhanced production of low P protons, antiprotons, $\Lambda$'s in $\Upsilon(1,2,3\ S)$ decays if compared to continuum




... but BR(p+) at few percent level : too low with current samples, but may help with 100M Y's.

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



# Parabottomonia: other pathways

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

Old CLEO-II limit at 0.18% with 0.46 M Y(3S) sample

Expect limits down to 0.05 % with the current sample.

Need 20 times more statistics to get to theory predictions :

Voloshin (Sov.J.Nucl.Phys. 43,1011) $< 10^{-4}$

Kuang (hep-ph/0601044) $\sim 10^{-4}$

$\Upsilon(3S) \rightarrow \gamma\chi_{b0}(2P) \rightarrow \gamma\ \eta\eta_b(1S)$

Voloshin (Mod.Phys.Lett.:A19,2985(2004)):

Prediction for $\chi_{b0}(2P) \rightarrow \eta\eta_b(1S)$ : $\sim 10^{-3}$

*Recent observation ($5\sigma$) of $\Upsilon(2S) \rightarrow \eta\, \Upsilon(1S)$ :*

*preliminary CLEO result : $2.5*10^{-4}$*

# Summary

Study of narrow Υ decays is an extremely active field of research, both for our understanding of QCD on bound states and for searches of new physics.

The 5 states of parabottomonium expected from theory below open beauty threshold are still unfound. With less than 4 $fb^{-1}$ taken in 2003, CLEO is still leading the research on these states, and will hopefully give us first hints of their existence, But a systematic program of studies on the 'dark side of parabottomonium' will need at least 100x more statistics

Even only 1% of the 50 $ab^{-1}$ expected from super B factories, if taken at the peak of Υ(nS) states, will allow to study the holy grail of heavy quarkonium spectroscopy

# Further studies with ~100 M Υ(nS) samples

Studies on $\chi_{bJ}$ (1,2P) states : exclusive decays to light hadrons, $\gamma\gamma$ widths

Υ(3S) → $\gamma\chi_b$ (2P) : 13M,12M,6M $\chi_{bJ}$ (2P) with J=2,1,0

Υ(2S) → $\gamma\chi_b$ (1P): 7M,7M,4M $\chi_{bJ}$ (1P) with J=2,1,0

Studies on hindered radiative transitions allow to quantify the (small) relativistic effects in bottomonium

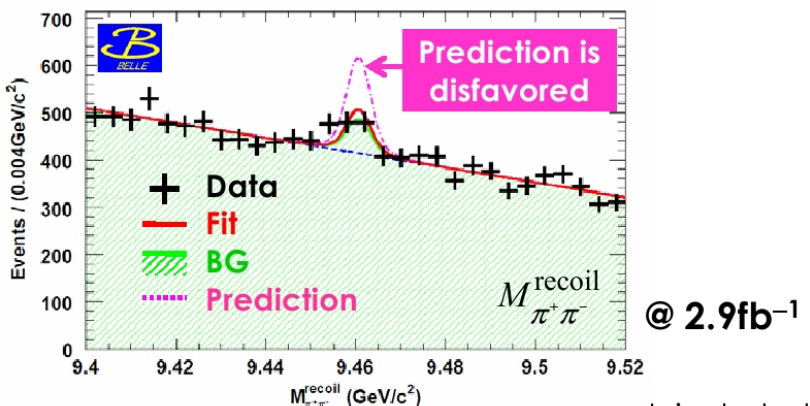
Υ(3S) → $\gamma\chi_b$ (2P)→ $\gamma\gamma$Υ(1S)→ $\gamma\gamma\mu\mu$: 25k,28k,7k via $\chi_{bJ}$ (2P) with J=2,1,0

Υ(3S) → $\gamma\chi_b$ (1P)→ $\gamma\gamma$Υ(1S)→ $\gamma\gamma\mu\mu$: 4k,6k, ~0.5k via $\chi_{bJ}$ (1P) with J=2,1,0

# Dark matter searches in Υ(1S) decays

Belle: Υ(3S) → ππ + *NOTHING*

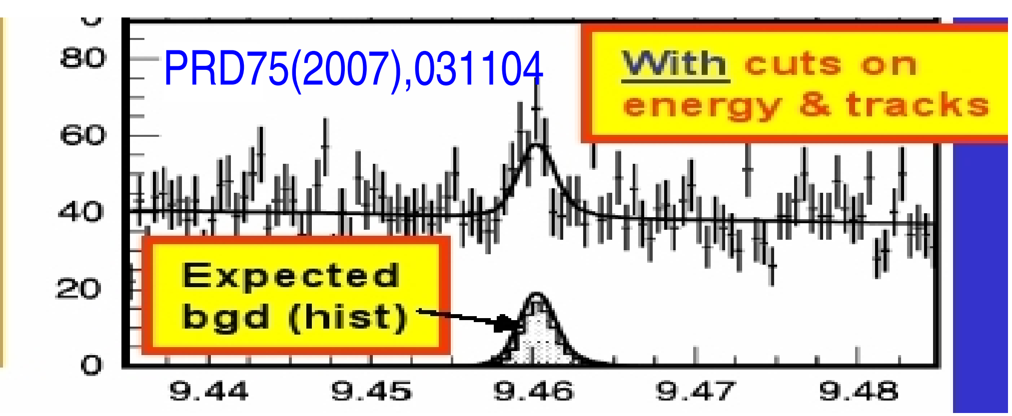
**$N_{sig}$ = 38 □ 39(stat) ⇔ 0 consistent**

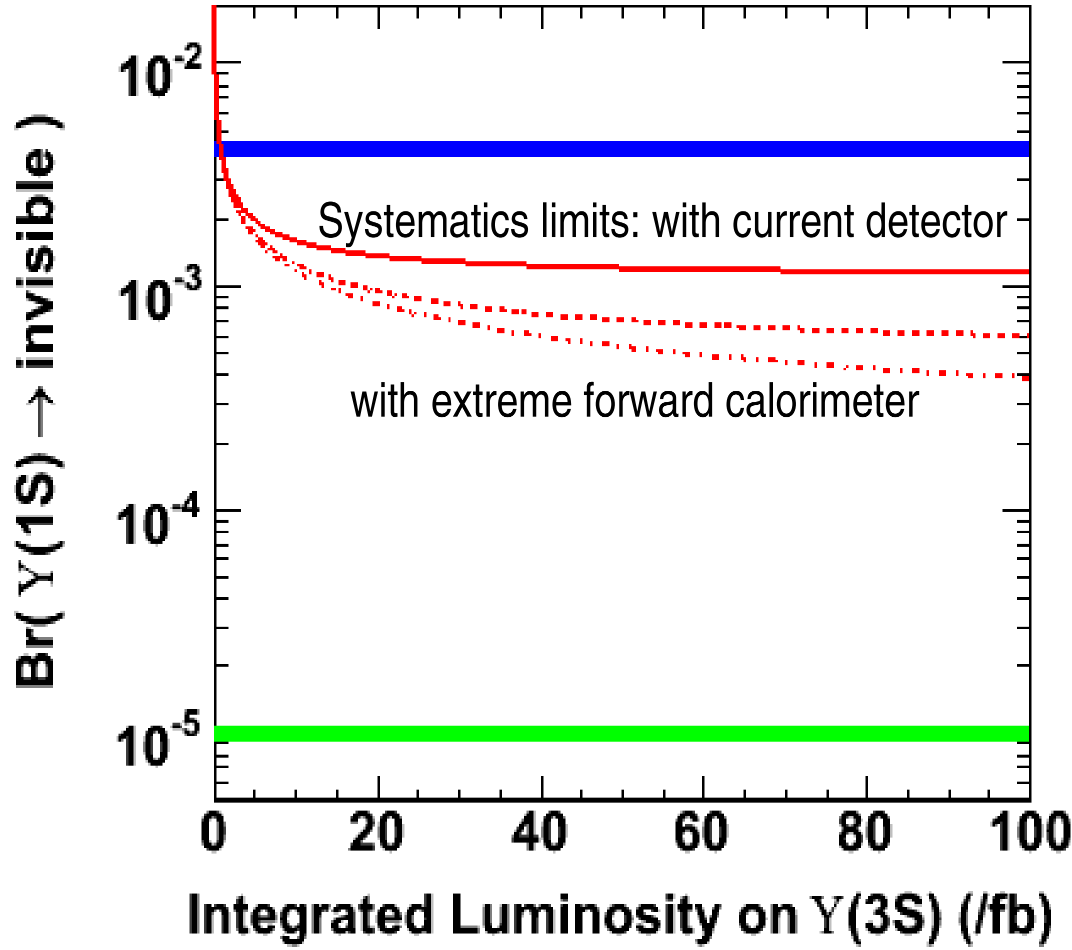



syst. included

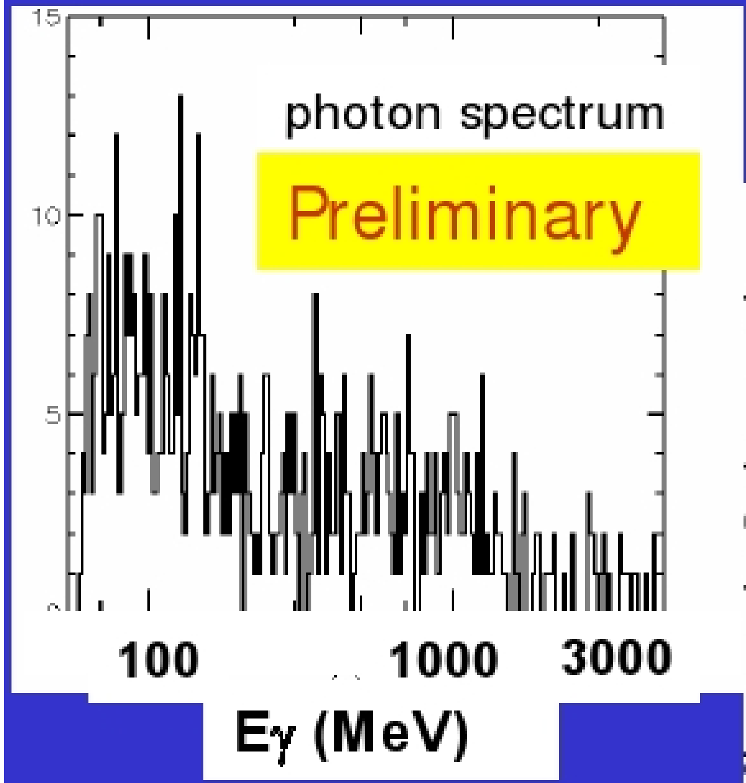
***Br*(Υ(1S) → invisible) < 2.5 x 10⁻³ (@90%C.L.)**

Cleo: Υ(2S) → ππ + *NOTHING*

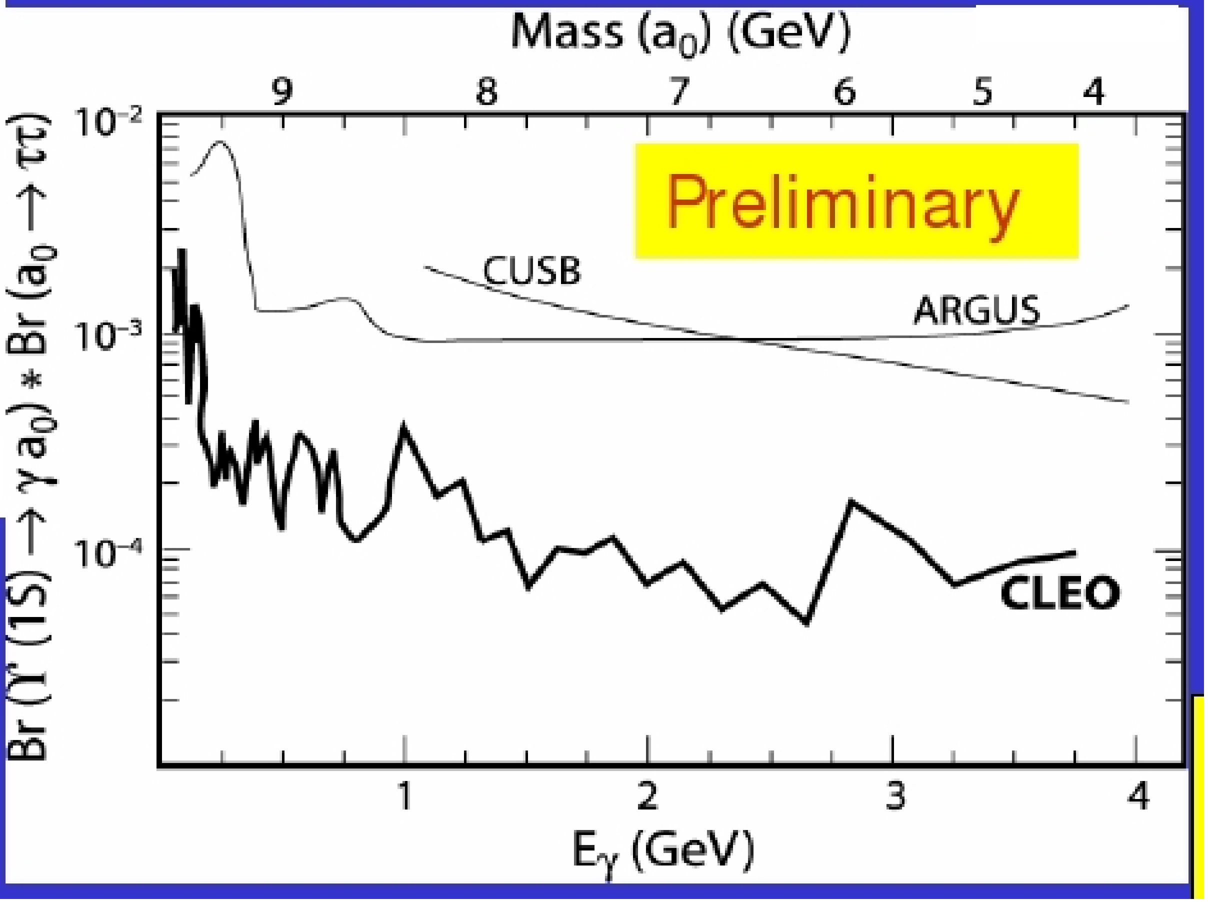


# New Physics searches from Υ(1S) peak




Search for NMSSM light Higgs




Recent limits by CLEO-III , from the Υ(1S) sample