Bottomonium Recent Results

from

BABAR, Belle & CLEO

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ON BEHALF OF THE BABAR COLLABORATION

FLAVOR PHYSICS AND CP VIOLATION 2009

Outline

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Observation of the bottomonium ground state $\eta_b(1S)$ in radiative $\Upsilon(3S)$ and $\Upsilon(2S)$ decays

II
Measurement of the $e^+e^- \rightarrow b\bar{b}$ cross section above the $\Upsilon(4S)$

III
Hadronic transitions between bottomonium states

- $\pi\pi$ & η transitions
- $\Upsilon(nS) \rightarrow \gamma\, \chi_{bJ}((n-1)P)$, n = 2 & 3
- Invisible decays of $\Upsilon(1S)$

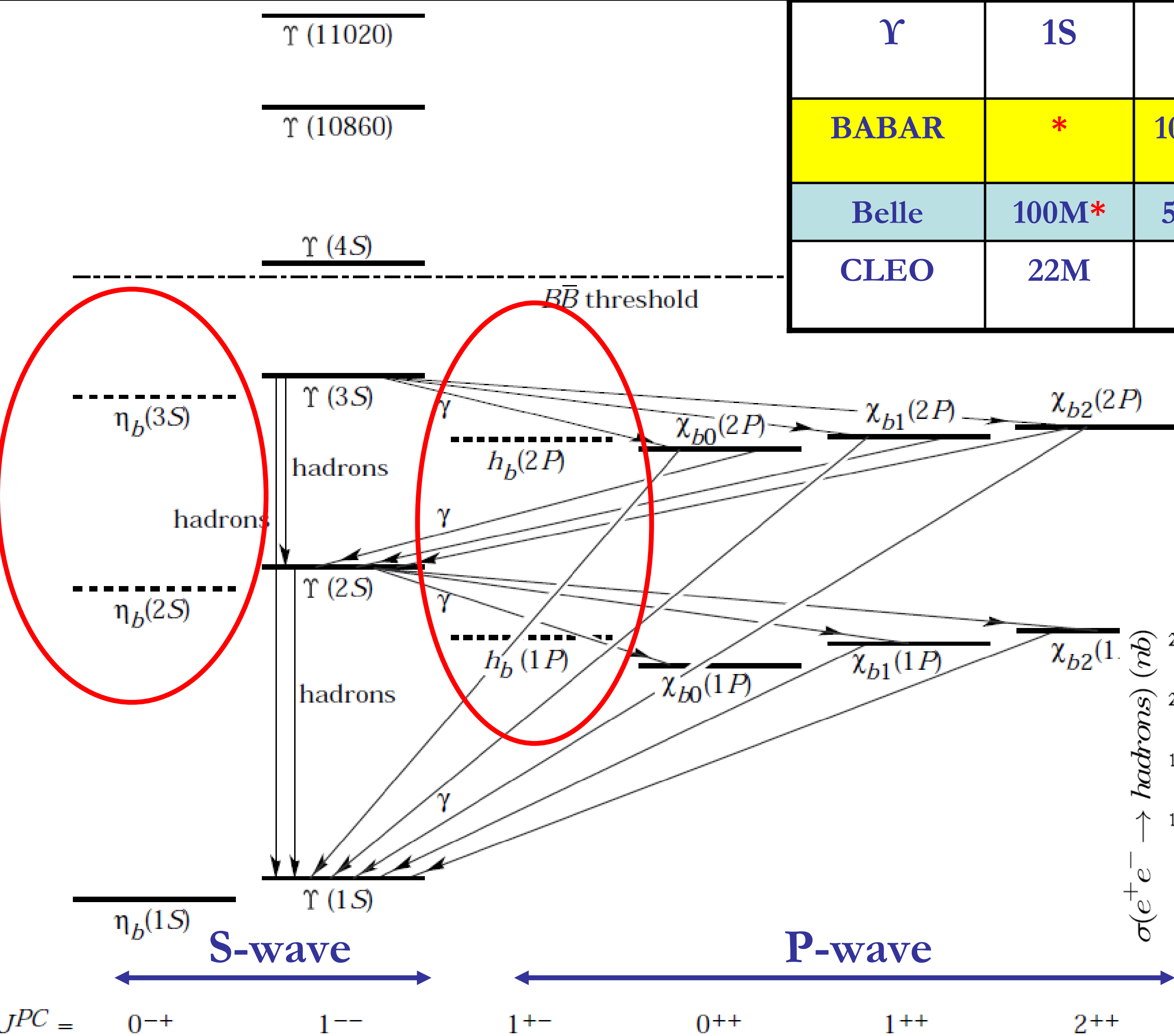
IV
Leptonic decays of Υs
Search for lepton-flavor violation and tests of lepton universality

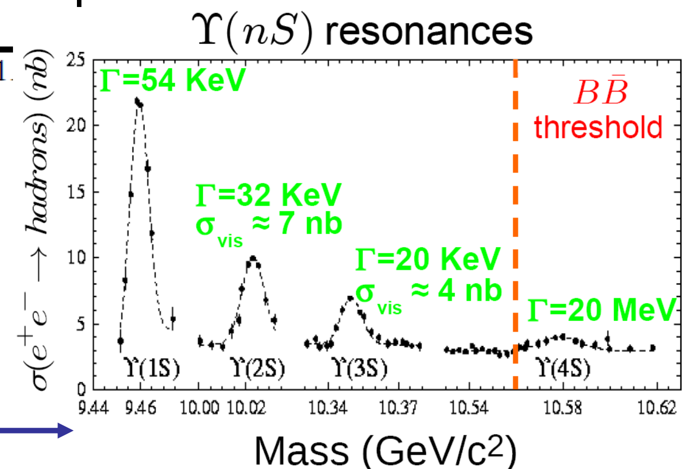
V
Searches for light Higgs-like particle in radiative decays of Υs

Bottomonium

ϒ	1S	2S	3S	4S	Beyond 4S
BABAR	*	100M*	122M*	433 fb^{-1}	~4 fb^{-1}
Belle	100M*	50M*	11M*	~900 fb^{-1}	~7.9 fb^{-1}
CLEO	22M	9M	6M		

** + ϒ(4S) ISR Contributions*





Observation of the bottomonium ground state $\eta_b(1S)$

in radiative

$\Upsilon(3S)$ and $\Upsilon(2S)$ decays

Observation of the bottomonium ground state $\eta_b(1S)$ in radiative $\Upsilon(3S)$ and $\Upsilon(2S)$ decays

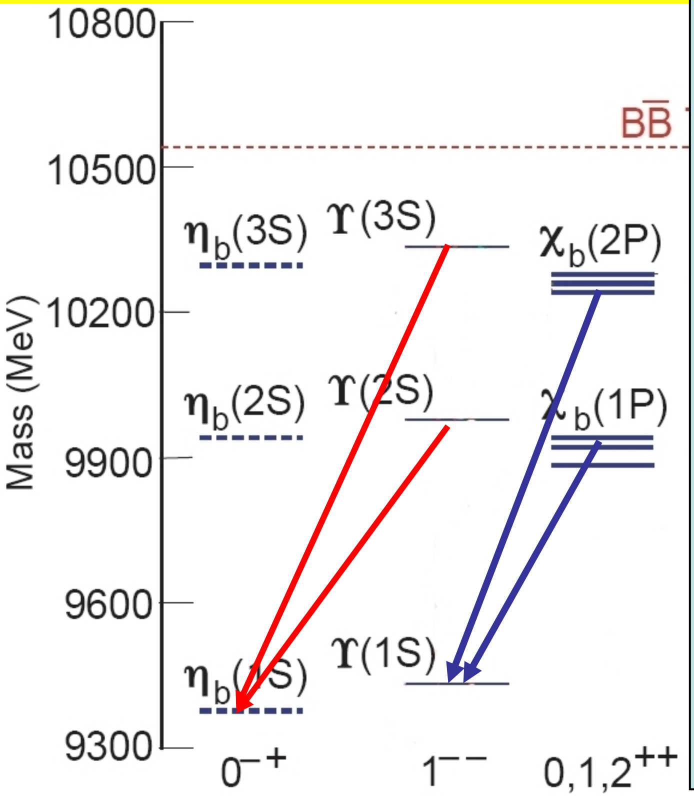
$\Upsilon(2S) \rightarrow \gamma\eta_b$ arXiv:0903.1124

$\int L \sim 14.0\ fb^{-1}$ on $\Upsilon(2S)$

Preliminary

$\Upsilon(3S) \rightarrow \gamma\eta_b$ PRL 101, 071801 (2008)

$\int L \sim 28.0\ fb^{-1}$ on $\Upsilon(3S)$

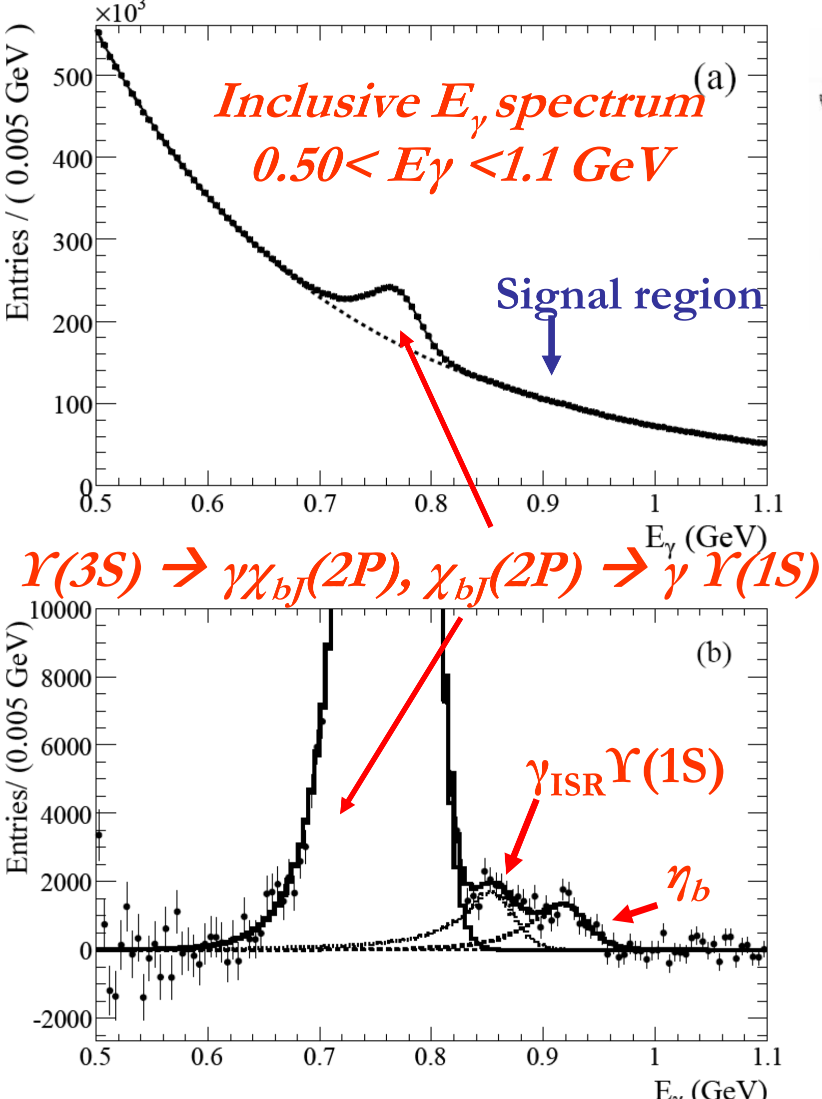


Signal: "monochromatic" photon observed as a peak in the inclusive photon energy on top of

- Smooth non-peaking background from continuum ($e^+e^- \rightarrow q\bar{q}$, q=u,d,s,c) and bottomonium decays
- Broad peak coming from double radiative decays $\Upsilon(3S, 2S) \rightarrow \gamma\chi_{bJ}(2P, 1P)$, $\chi_{bJ}(2P, 1P) \rightarrow \gamma\Upsilon(1S)$
- Initial state radiative production

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

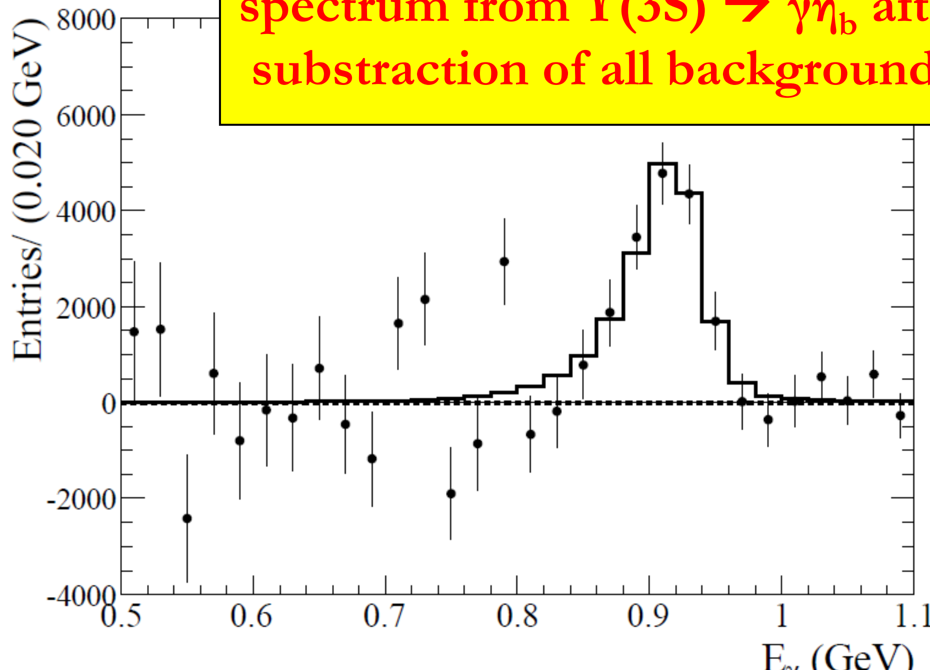
Observation of the bottomonium ground state $\eta_b(1S)$ in radiative $\Upsilon(3S)$ and $\Upsilon(2S)$ decays



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

PRL 101, 071801 (2008)

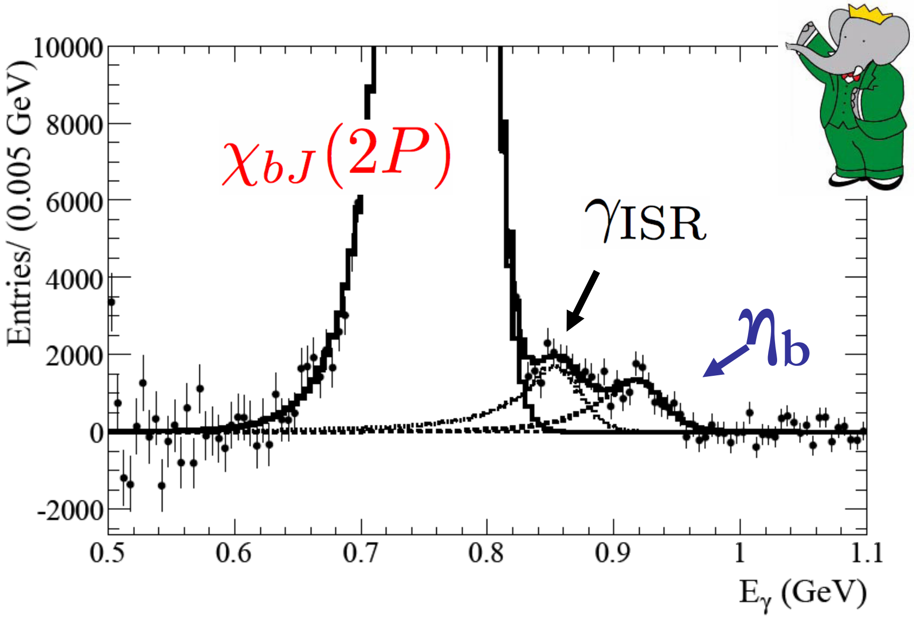
Inclusive photon energy spectrum from $\Upsilon(3S) \rightarrow \gamma\eta_b$ after substraction of all backgrounds



Observation of the bottomonium ground state η_b (1S) in radiative Υ(3S) and Υ(2S) decays

Υ(3S) → $\gamma\eta_b$

PRL 101, 071801 (2008)

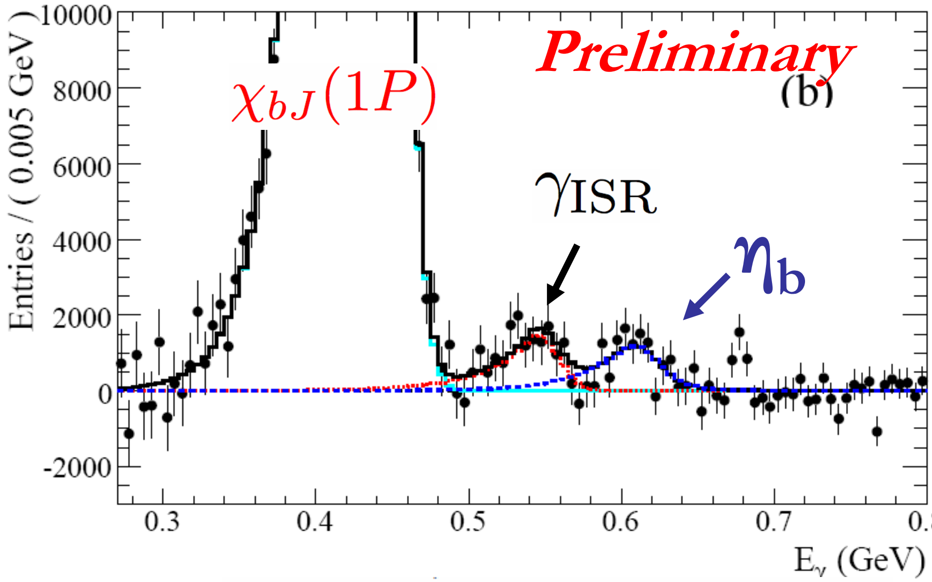


$$M(\eta_b) = 9388.9^{+3.1}_{-2.3} \pm 2.7 \ \text{MeV}/c^2$$

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

Υ(2S) → $\gamma\eta_b$

arXiv:0903.1124



$$M(\eta_b) = 9392.9^{+4.6}_{-4.8} \pm 1.9 \ \text{MeV}/c^2$$

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

$71.4^{+2.3}_{-3.1} \pm 2.7$	*(Υ(1S) – η_b) Mass Splitting (MeV/c^2)*	$67.4^{+4.8}_{-4.6} \pm 2.0$

Observation of the bottomonium ground state η_b (1S) in radiative Υ(3S) and Υ(2S) decays

	$\Upsilon(3S) \rightarrow \gamma\eta_b$ PRL 101, 071801 (2008)	$\Upsilon(2S) \rightarrow \gamma\eta_b$ arXiv:0903.1124 *Preliminary*
$\int L$	(1.09±0.01) x 10^8 Υ(3S)	(91.6±0.9) x 10^6 Υ(2S)
# η_b events	$19200 \pm 2000 \pm 2100$	$13900^{+3600+2800}_{-3500-2700}$
Significance	10σ	3.5σ
Branching Fractions	$(4.8 \pm 0.5 \pm 0.6) \times 10^{-4}$	$(4.2^{+1.1}_{-1.0} \pm 0.9) \times 10^{-4}$

$$\Delta B = \mathcal{B}(\Upsilon(2S) \rightarrow \gamma\eta_b)/\mathcal{B}(\Upsilon(3S) \rightarrow \gamma\eta_b) = 0.89^{+0.25+0.12}_{-0.23-0.16}$$

Compatible with M1 transitions

[S. Godfrey and J.L. Rosner PRD 64, 074011(2001)]

$\Delta B_{Theory} \approx 0.3 - 0.7$

Observation of the bottomonium ground state η_b (1S) in radiative Υ(3S) and Υ(2S) decays

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

PRL 101, 071801 (2008)

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

arXiv:0903.1124

Average Mass $M_{\eta b} = 9390.4 \pm 3.1$ MeV/c^2

Consistent with unquenched lattice calculation

[T. W. Chiu et al. (TWQCD Collaboration) PLB 651, 171 (2007)]

$M^{Theory}_{\eta b} = 9380 \pm 10$ MeV/c^2

But more than 2σ away from perturbative QCD predictions [e.g. B.A. Kniehl et al. PRL 92, 242001(2004)]

Preliminary

<(Υ(1S) – η_b) Mass Splitting> 69.9 ± 3.1 MeV/c^2

In agreement with lattice QCD

$\Delta M^{Theory}_{\Upsilon(1S)-\eta b} = 61 \pm 14$ MeV/c^2

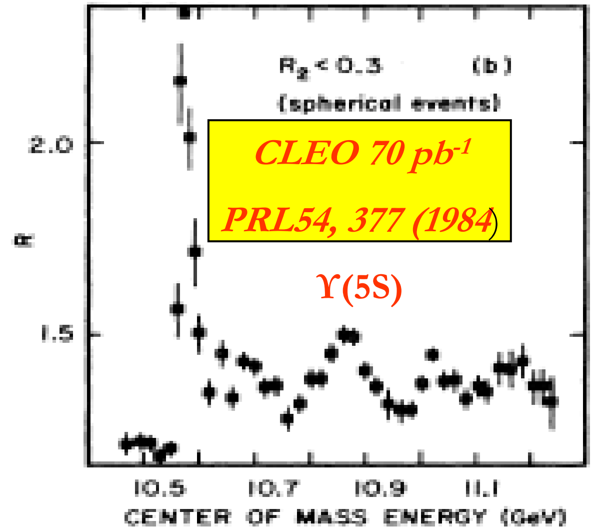
Measurement of the $e^+e^- \rightarrow b\bar{b}$ cross section

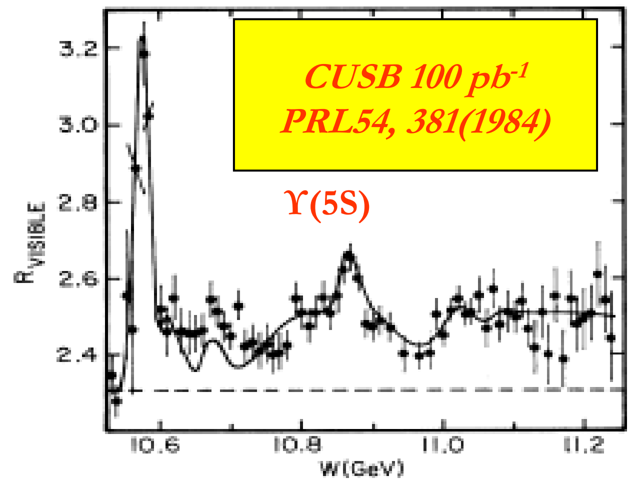
above the $\Upsilon(4S)$

Measurement of the $e^+e^- \to b\bar{b}$ cross section above the $\Upsilon(4S)$

Motivations

- Improve knowledge of above-$\Upsilon(4S)$ region:
  - ✓ *CESR-1984, 70 to 100 pb^{-1} between $\Upsilon(4S)$ and 11.3 GeV in 20 MeV steps;*
  - ✓ *Precision $\langle R_{had}=\sigma_{had}/\sigma_{\mu\mu}\rangle$ measurement from CLEO ~ 1.9% syst. error;*
- Look for structures found by CLEO and CUSB:
  - ✓ *Search for new states containing b quark pairs;*
- Search for exotic bottomonium states similar to $J^{PC} = 1^{--}$ exotic charmonium states Y(4260), Y(4350), Y(4660);
- Look for $\Upsilon(10860)$ and $\Upsilon(11020)$ candidates for $\Upsilon(5S)$ and $\Upsilon(6S)$ respectively;





Measurement of the $e^+e^- \to b\bar{b}$ cross section between $\sqrt{s}$ = 10.54 and 11.20 GeV

BABAR | **PRL102, 012001 (2009)**

Strategy : *Precision scan in E_{CM} from 10.54 GeV to 11.20 GeV with*

- 5 MeV steps with 25 pb^{-1} at each step $\to \int_{total} L \sim 3.3\ fb^{-1}$

  → 30 times more luminosity and 4 times finer steps w.r.t. previous scan (CESR)

- 8 steps non-regular energy spacing to investigate $\Upsilon(6S)$ region $\to \int_{total} L \sim 600 pb^{-1}$ for the scan in the range of $\sqrt{s}$ = 10.96 to 11.10 GeV

Inclusive approach

✓ *Search for unexpected structures in the inclusive hadronic cross section*

Measurement Strategy

- Selection of $b\bar{b}$ and $\mu\mu$ samples;
- Background estimated at reference point $\sqrt{s}$ = 10.54 GeV below $B\bar{B}$ threshold;
- Efficiencies from MC samples;

Measurement of the $e^+e^- \to b\bar{b}$ cross section between $\sqrt{s}$ = 10.54 and 11.20 GeV

BABAR PRL102, 012001 (2009)

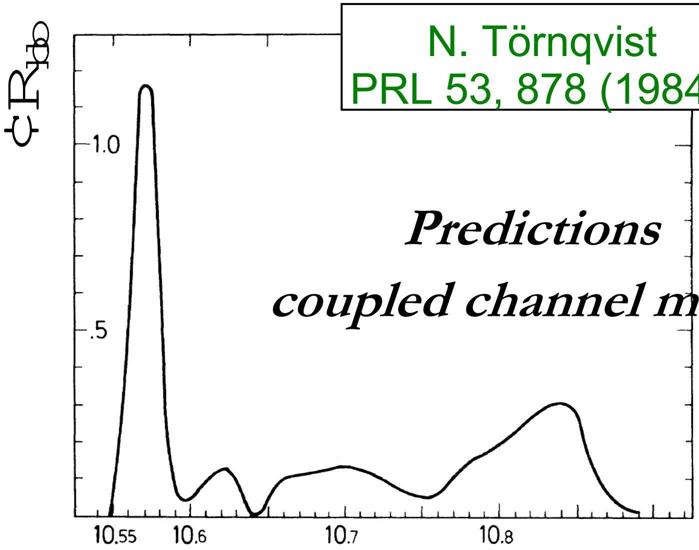
$$R_b(s) = \sigma_b(s)/\sigma^0_{\mu\mu}(s)$$

Total of more than 300 center-of-mass energy steps, separated by about 5 MeV, with a total relative error of about 5%

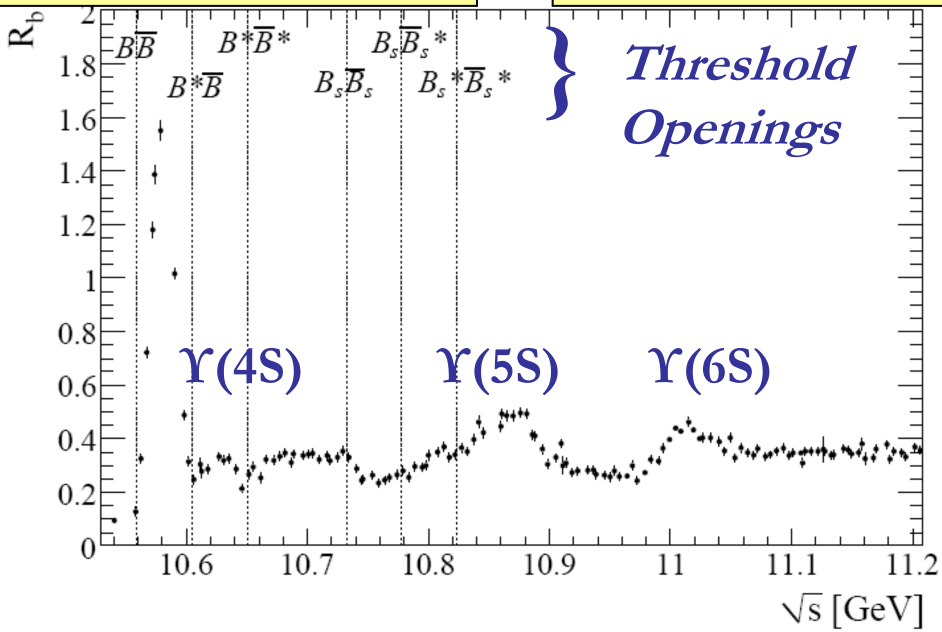
$\sigma^0_{\mu\mu} = 4\pi\alpha^2/3s$
Lowest-order cross section
$e^+e^- \to \mu^+\mu^-$

σ_b
Total cross section
$e^+e^- \to b\bar{b}(\gamma)$

N. Törnqvist
PRL 53, 878 (1984)



Predictions coupled channel model

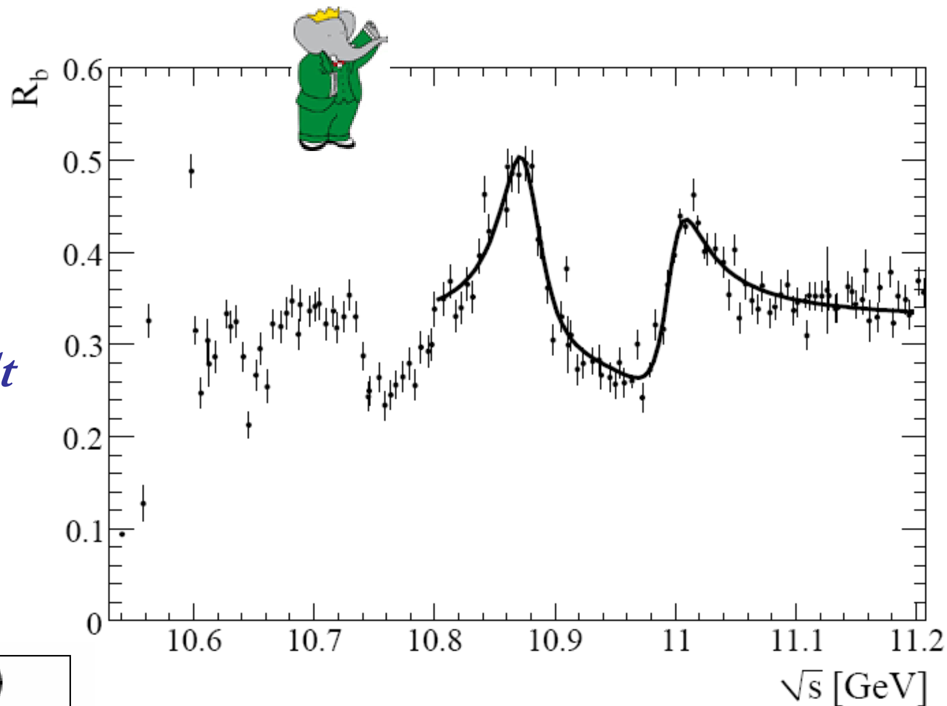


Measurement of the $e^+e^- \rightarrow b\bar{b}$ cross section between $\sqrt{s}$ = 10.54 and 11.20 GeV

BABAR **PRL102, 012001 (2009)**

Candidates $\Upsilon(5S)$ and $\Upsilon(6S)$

Simple model fit with flat component + two interfering relativistic BWs: may result with much narrower widths (than PDG values)…more proper fit might change this (complex analysis)



	$\Upsilon(10860)$	$\Upsilon(11020)$
mass (GeV)	10.876 ± 0.002	10.996 ± 0.002
width (MeV)	43 ± 4	37 ± 3
ϕ (rad)	2.11 ± 0.12	0.12 ± 0.07
PDG mass (GeV)	10.865 ± 0.008	11.019 ± 0.008
PDG width (MeV)	110 ± 13	79 ± 16

Number of states unknown → coupled channel approach with effects of various thresholds… larger width and lower mass

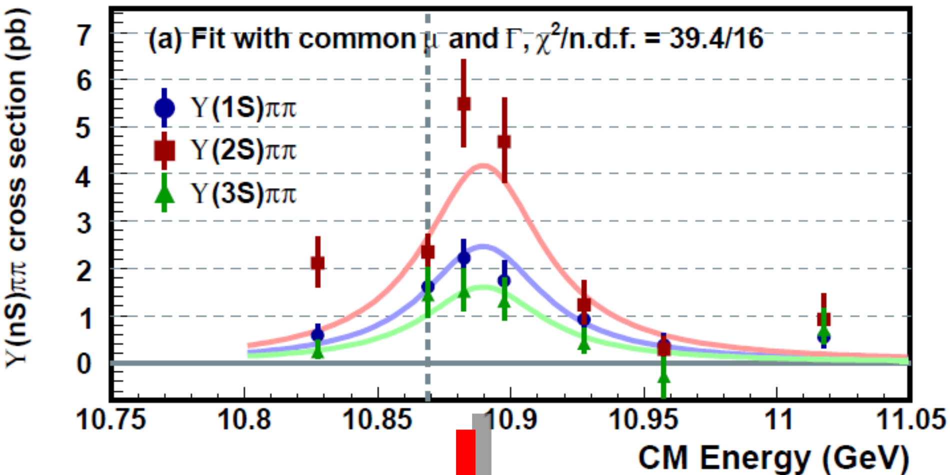
Measurement of the cross section
$e^+e^- \rightarrow \Upsilon(nS)\,\pi^+\pi^- \rightarrow \mu^+\mu^-\pi^+\pi^-$

Belle arXiv:0808.2445

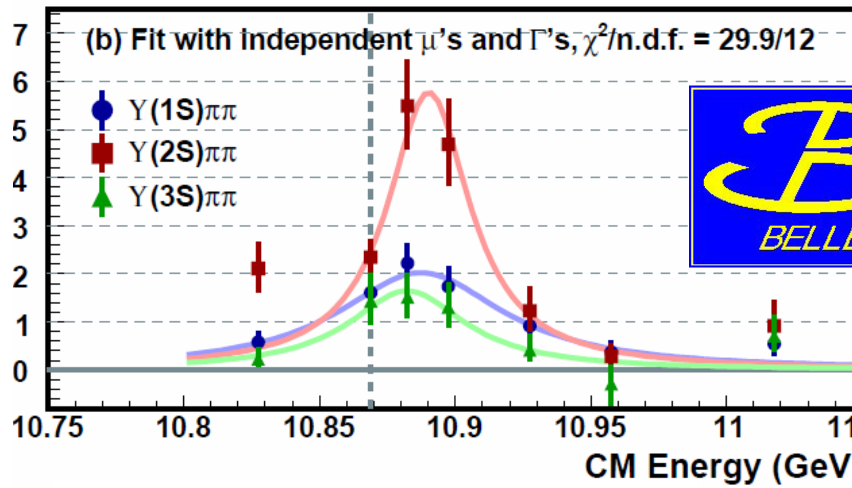
- Measure $e^+e^- \rightarrow \Upsilon(nS)\,\pi^+\pi^- \rightarrow \mu^+\mu^-\pi^+\pi^-$ in E_{CM} from 10.83 GeV to 11.02 GeV $\int L = 7.9\ fb^{-1}$

- Determine the shape of the production cross section

Fit with single Breit-Wigner resonance



Fit with different Breit –Wigner resonances



M = $10889.6 \pm 1.8 \pm 1.5\ \mathrm{MeV}/c^2$

Γ = $54.7^{+8.5}_{-7.2} \pm 2.5\ \mathrm{MeV}/c^2$

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

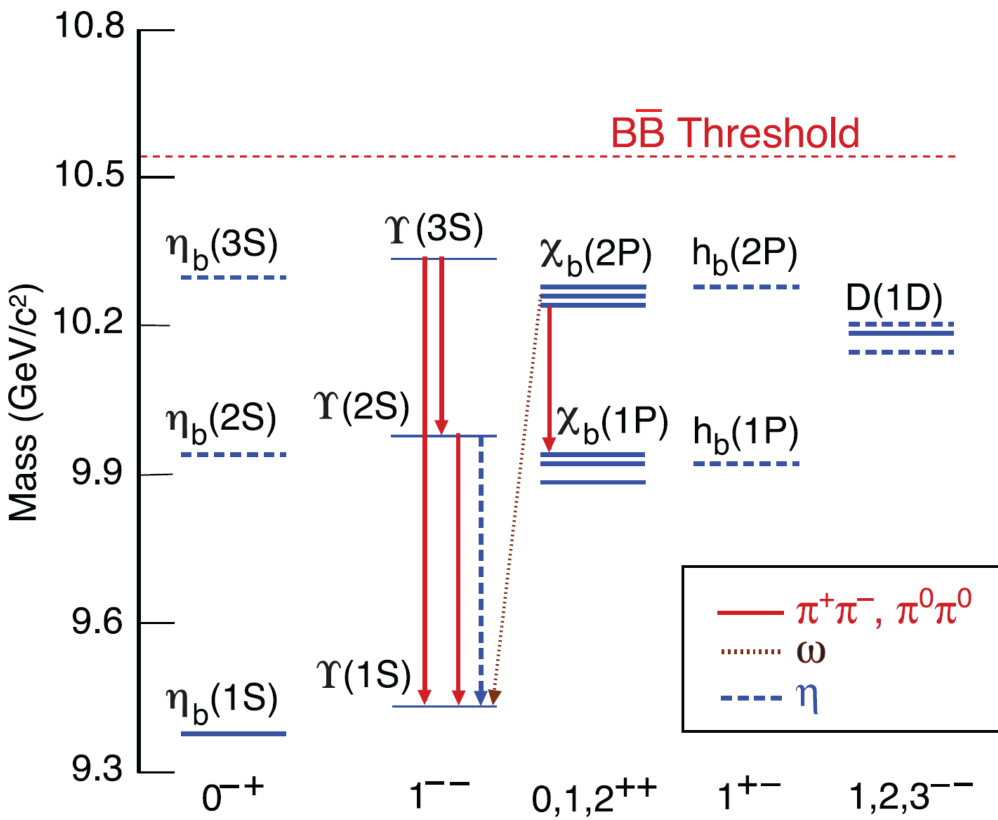
Hadronic transitions between bottomonium states

- $\pi\pi$ & η transitions
- χ_{bJ} (nP) hadronic decays
- Search for invisible decays of Υ(1S)

Hadronic transitions between bottomonium states

"…for the first 22 years after the observation of hadronic transitions among bottomonium states only 6 ππ transitions among the vector ϒ(nS) bottomonia were known…"

CLEO PRD79, 011103(R) (2009)



Recently…

CLEO observed

$\chi_{b1,2}$ (2P) → ω ϒ(1S) **PRL92,222002(2004)**

χ_b(2P) → $\pi\pi\chi_b$(1P) **PRD73, 012003(2006)**

ϒ(2S) → η ϒ(1S) **PRL101, 192001(2008)**

BABAR reported extensive measurements of hadronic transitions between ϒ states using, in particular, bottomonium states ϒ(3S) and ϒ(2S) produced via ISR from ϒ(4S) on-peak recorded data **PRD78, 112002(2008) & PRL96, 232001(2006)**

Hadronic transitions between bottomonium states

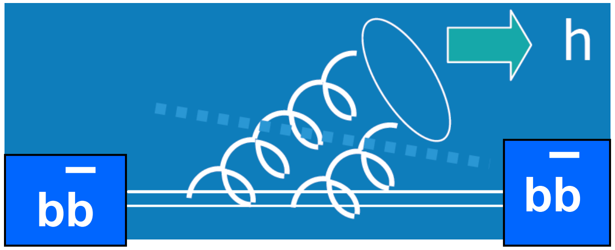
$\Upsilon(mS) \rightarrow \pi\pi + \Upsilon(nS)$, n=1, m-1

Hadronic transitions among heavy quarkonium states (low q^2 hadronization processes) → excellent testing ground for non-perturbative QCD

QCDME

gluon radiation from a heavy $q\bar{q}$ bound state calculated in terms of chromo-electric and chromo-magnetic fields in analogy to electromagnetism – transitions between colorless hadrons require emission of at least two gluons

Factorization low momentum gluon emission followed by hadronization multipole picture : 2xE1 → $h = \pi\pi$

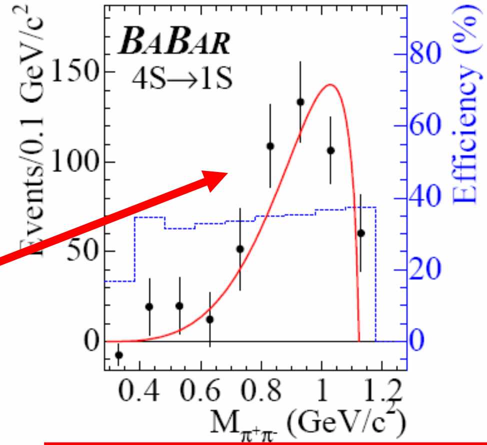


Hadronic transitions between bottomonium states
$\Upsilon(mS) \rightarrow \pi\pi + \Upsilon(nS)$, n=1, m-1

***Primary Observable* dipion system invariant mass $M(\pi\pi\text{-recoil}) = M(\Upsilon(nS))$**

QCD multipole expansion model QCDME explains

- Relative rates $\psi(2S) \rightarrow \eta\, J/\psi$ and $\psi(2S) \rightarrow \pi\pi\, J/\psi$
- $\pi\pi$ invariant mass distributions in $\psi(2S) \rightarrow \pi\pi\, J/\psi$, $\Upsilon(2S) \rightarrow \pi\pi\, \Upsilon(1S)$, $\Upsilon(3S) \rightarrow \pi\pi\, \Upsilon(2S)$, and $\Upsilon(4S) \rightarrow \pi\pi\, \Upsilon(1S)$



PRL96, 232001 (2006)

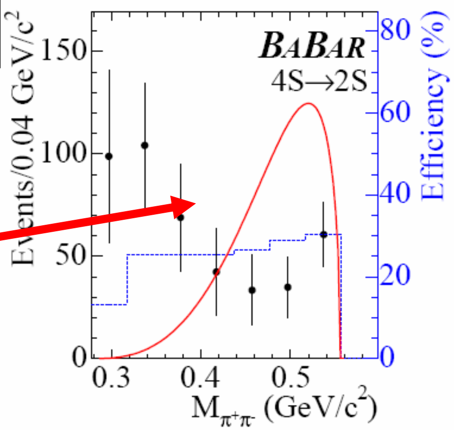
QCD multipole expansion model QCDME does not explain

- Dipion invariant mass distributions in $\Upsilon(3S) \rightarrow \pi\pi\, \Upsilon(1S)$

CLEO PRD 49, 40(1994)

and in

$\Upsilon(4S) \rightarrow \pi\pi\, \Upsilon(2S)$ *BABAR PRL96, 232001 (2006)*



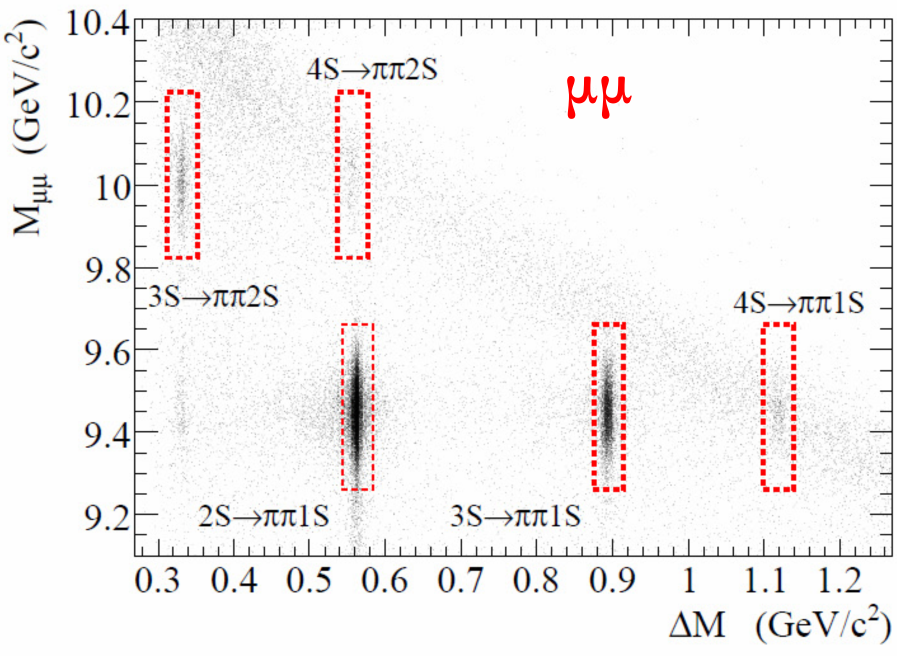
Hadronic transitions between bottomonium states

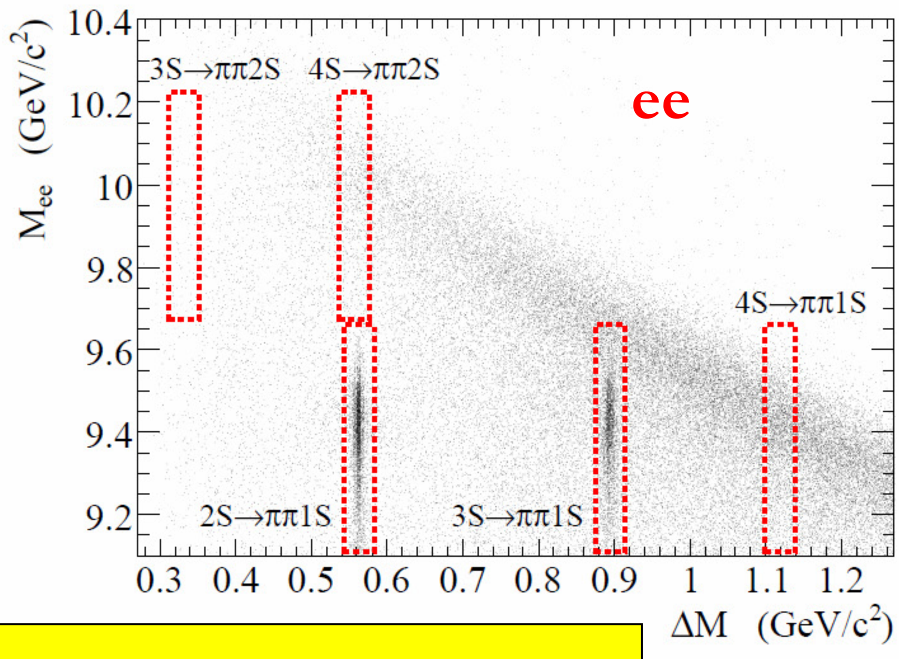
$\Upsilon(mS) \rightarrow \pi\pi + \Upsilon(2, 1S)$

BABAR **PRD 78, 112002(2008)**

$(383.2 \pm 4.2) \times 10^6$ $\Upsilon(4S)$

use $\Upsilon(4S) \rightarrow \pi^+\pi^- \Upsilon(nS)$ (n=1,2) by reconstructing $\Upsilon(nS)$ meson via leptonic decay $\mu^+\mu^-$ or e^+e^-, look at l^+l^- invariant mass M_{ll} and invariant mass difference $\Delta M = M_{\pi\pi ll} - M_{ll}$ compatible with $M(\Upsilon(4S)) - M(\Upsilon(nS))$





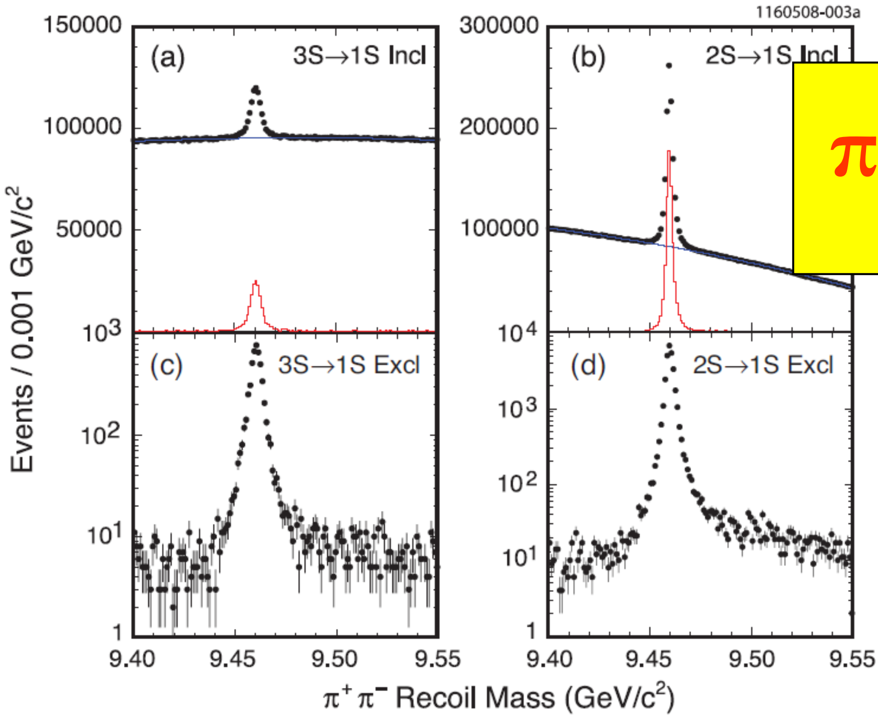
$\Delta M = M_{\pi\pi ll} - M_{ll}$, l = e, μ

Hadronic transitions between bottomonium states

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

$(5.93 \pm 0.10) \times 10^6\ \Upsilon(3S)$ and $(9.11 \pm 0.14) \times 10^6\ \Upsilon(2S)$

CLEO PRD79, 011103(R) (2009)



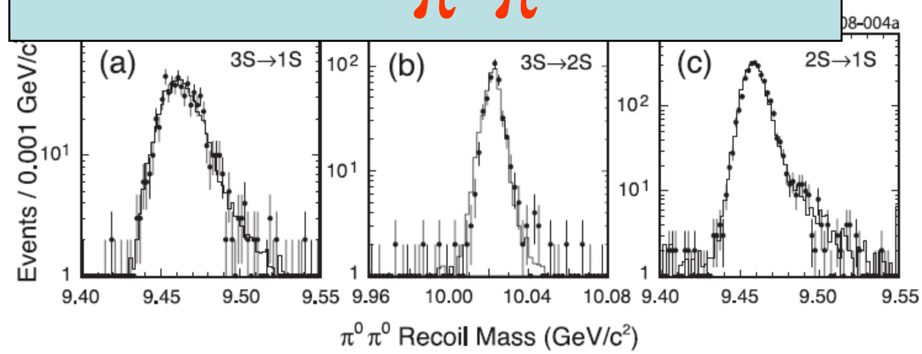
B.R. %

$\pi^+\pi^-$

3S → 1S	$4.46 \pm 0.01 \pm 0.13$
2S → 1S	$18.02 \pm 0.02 \pm 0.61$

3S → 1S	$2.24 \pm 0.09 \pm 0.11$
3S → 2S	$1.82 \pm 0.09 \pm 0.12$
2S → 1S	$8.43 \pm 0.16 \pm 0.42$

$\pi^0\pi^0$



$$\frac{B(\Upsilon(mS) \rightarrow \pi^0\pi^0\ \Upsilon(1S))}{B(\Upsilon(mS) \rightarrow \pi^+\pi^-\ \Upsilon(1S))} =$$

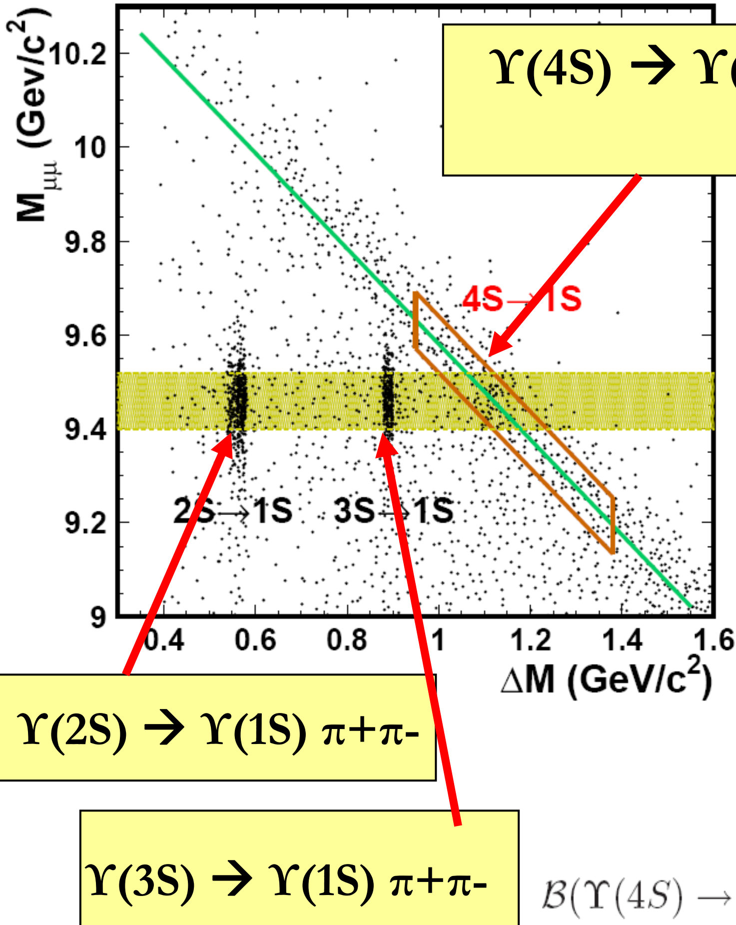
$0.501 + 0.043$ $(0.51)_{Theory}$ for m= 3

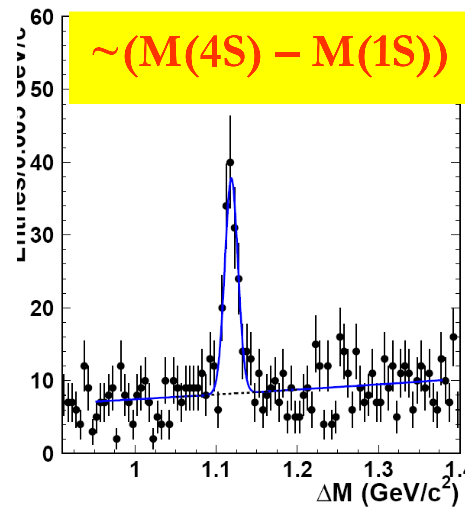
$0.462 + 0.037$ $(0.53)_{Theory}$ for m=2

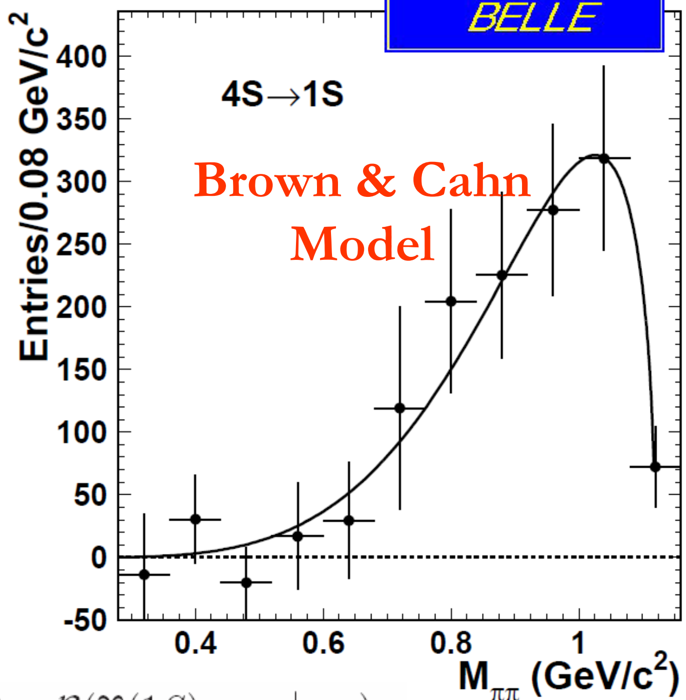
Measurement of the branching fraction for the decay $\Upsilon(4S) \rightarrow \Upsilon(1S)\,\pi^+\pi^-$

Belle PRD(RC)79, 051103 (2009)

$\int_{\Upsilon(4S)}$ 604.6 fb^{-1}







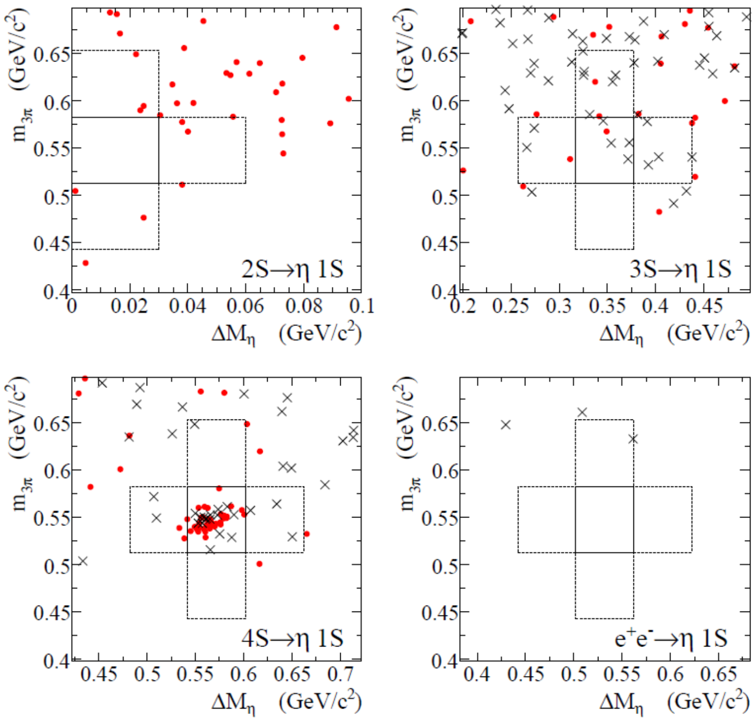
$$\mathcal{B}(\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-) \times \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-) = (2.11 \pm 0.30(\text{stat.}) \pm 0.14(\text{sys.})) \times 10^{-6}.$$

$$\mathcal{B}(\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-) = (0.85 \pm 0.12(\text{stat.}) \pm 0.06(\text{sys.})$$

$$\Gamma(\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-) = (1.75 \pm 0.25(\text{stat.}) \pm 0.24(\text{sys.}))\ \text{keV}$$

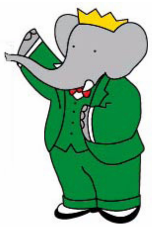
Hadronic transitions between bottomonium states

$\Upsilon(mS) \rightarrow \eta + \Upsilon(2, 1S)$



$\Upsilon(2, 3S) \rightarrow \eta\Upsilon(1S)$ searched for in ISR sample

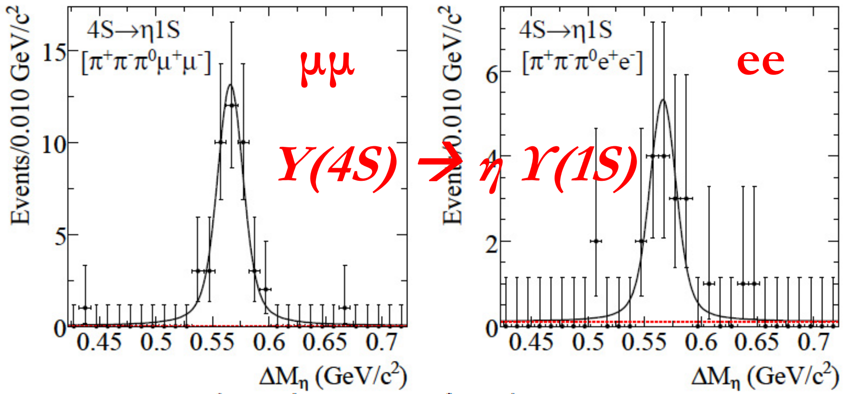
BABAR **PRD 78, 112002(2008)**



<u>90% C.L. upper limits</u>

$B(\Upsilon(2S) \rightarrow \eta\Upsilon(1S)) < 9 \times 10^{-4}$

$B(\Upsilon(3S) \rightarrow \eta\Upsilon(1S)) < 8 \times 10^{-4}$



$\Upsilon(4S) \rightarrow \eta\ \Upsilon(1S)$

$$\mathcal{B}(\Upsilon(4S) \rightarrow \eta\Upsilon(1S)) = (1.96 \pm 0.06_{stat} \pm 0.09_{syst}) \times 10^{-4}$$

$$\Gamma(\Upsilon(4S) \rightarrow \eta\Upsilon(1S))/\Gamma(\Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(1S)) = 2.41 \pm 0.40_{stat} \pm 0.12_{syst}$$

$$\Gamma(\Upsilon(2S) \rightarrow \eta\Upsilon(1S))/\Gamma(\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)) < 5.2 \times 10^{-3}$$

$$\Gamma(\Upsilon(3S) \rightarrow \eta\Upsilon(1S))/\Gamma(\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S)) < 1.9 \times 10^{-2}$$

Hadronic transitions between bottomonium states

Also ….Use of $\Upsilon(3S)$, $\Upsilon(2S)$ → $\pi\pi$ $\Upsilon(1S)$ as clean source of tagged $\Upsilon(1S)$

→ Studies of exclusive $\Upsilon(1S)$ decays, Searches for invisible decay modes, etc.

Invisible Decay

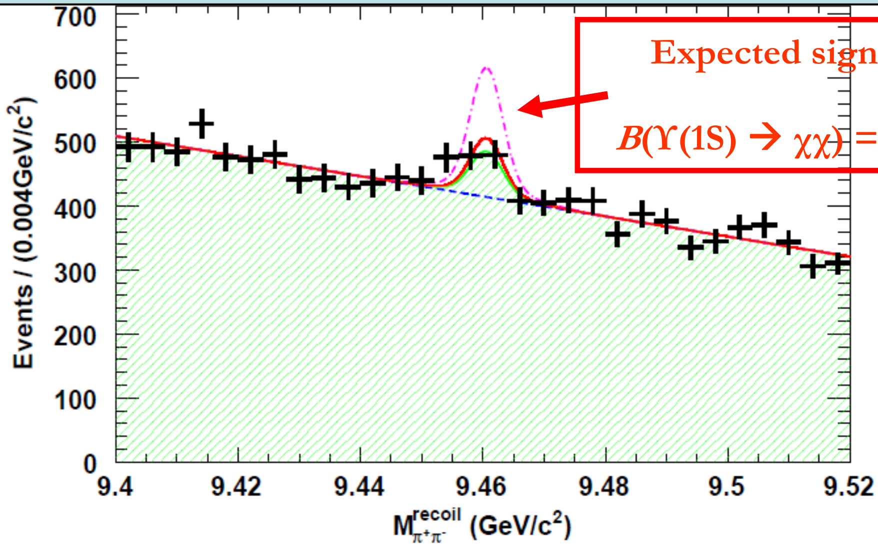
✓S.M. $B(\Upsilon(1S) \rightarrow \nu\bar{\nu}) = (9.9 \pm 0.5) \times 10^{-6}$

✓Dark matter particles χ lighter than b quark $B(\Upsilon(1S) \rightarrow \chi\chi) = 6 \times 10^{-3}$ [McElrath PRD 72, 103508(2005)]

Belle PRL 98, 132001 (2007)

2.9 fb^{-1} on $\Upsilon(3S)$ (~11 x 10^6 $\Upsilon(3S)$)

use $\Upsilon(3S) \rightarrow \pi^+\pi^- \Upsilon(1S)$ and look at recoil mass against $\pi^+\pi^-$ system $M^{recoil}_{\pi+\pi-}$ without any detected decay products from $\Upsilon(1S)$



Expected signal for $B(\Upsilon(1S) \rightarrow \chi\chi) = 6 \times 10^{-3}$

No signal found

Upper limit at 90% C.L.

$B(\Upsilon(1S) \rightarrow \text{invisible}) < 2.5 \times 10^{-3}$

Leptonic decays of Υs

Searches for lepton-flavor violation and tests of lepton universality

Di-electron widths of the Υ(1S, 2S, 3S) resonances

Γ_{ee} basic parameter of heavy-quark bound system – stringent test of lattice QCD – proportional to the square of the state's wave function at origin

CLEO **PRL 96, 092003(2006)**

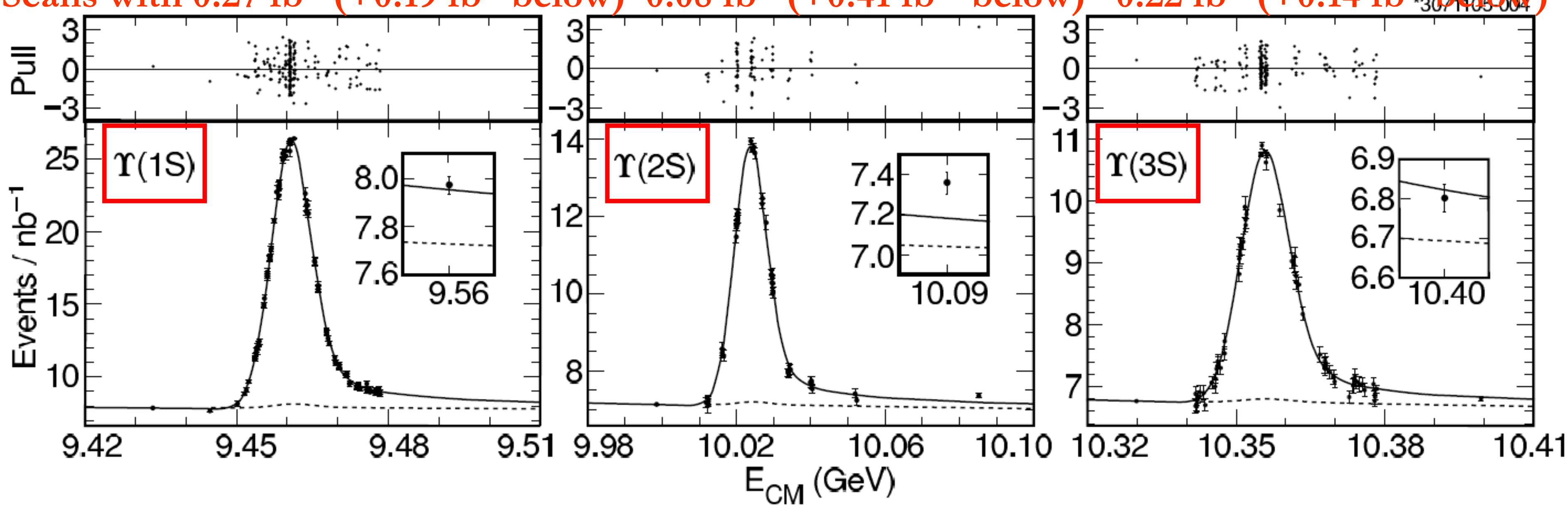
Method

measure total hadronic cross section over Υ(1S, 2S, 3S)

$\int \sigma(e^+e^- \to \Upsilon).dE$ proportional to $\Gamma_{ee}\Gamma_{had} / \Gamma_{tot}$

Hadronic yield versus E_{CM}

Scans with 0.27 fb^{-1} (+0.19 fb^{-1} below) 0.08 fb^{-1} (+0.41 fb^{-1} below) 0.22 fb^{-1} (+0.14 fb^{-1} below)



Di-electron widths of the Υ(1S, 2S, 3S) resonances

CLEO | PRL 96, 092003(2006)

Assuming lepton universality

$B_{ee}=B_{\mu\mu}=B_{\tau\tau}$

Improvement factors w.r. PDG

$\Gamma_{ee}\Gamma_{\rm had}/\Gamma_{\rm tot}(1S)$		$1.252 \pm 0.004 \pm 0.019$ keV
$\Gamma_{ee}\Gamma_{\rm had}/\Gamma_{\rm tot}(2S)$		$0.581 \pm 0.004 \pm 0.009$ keV
$\Gamma_{ee}\Gamma_{\rm had}/\Gamma_{\rm tot}(3S)$		$0.413 \pm 0.004 \pm 0.006$ keV
$\Gamma_{ee}(1S)$	X 1.5	$1.354 \pm 0.004 \pm 0.020$ keV
$\Gamma_{ee}(2S)$	X 2.5	$0.619 \pm 0.004 \pm 0.010$ keV
$\Gamma_{ee}(3S)$	X 5.2	$0.446 \pm 0.004 \pm 0.007$ keV
$\Gamma_{ee}(2S)/\Gamma_{ee}(1S)$		$0.457 \pm 0.004 \pm 0.004$
$\Gamma_{ee}(3S)/\Gamma_{ee}(1S)$		$0.329 \pm 0.003 \pm 0.003$
$\Gamma_{ee}(3S)/\Gamma_{ee}(2S)$		$0.720 \pm 0.009 \pm 0.007$

CLEO arXiv:hep-ex/0604025v2

(T. Ferguson)

$$\frac{\Gamma_{ee}(2S)\ M^2(2S)}{\Gamma_{ee}(1S)\ M^2(1S)}$$

✓Measured 0.517 ± 0.007

✓LQCD 0.48 ± 0.05
[A. Gray et al. PRD 72, 094507(2005)]

Searches for lepton flavor violation in Υ decays

Signal Channels

- $\Upsilon(3S) \to e^{\pm}\tau^{\mp}, \tau^- \to \mu^- \nu_\tau \bar{\nu_\mu}$ (leptonic $e\tau$ channel)
- $\Upsilon(3S) \to e^{\pm}\tau^{\mp}, \tau^- \to \pi^-\pi^0\nu_\tau / \pi^-\pi^0\pi^0\nu_\tau$ (hadronic $e\tau$ channel)
- $\Upsilon(3S) \to \mu^{\pm}\tau^{\mp}, \tau^- \to e^- \nu_\tau \bar{\nu_e}$ (leptonic $\mu\tau$ channel)
- $\Upsilon(3S) \to \mu^{\pm}\tau^{\mp}, \tau^- \to \pi^-\pi^0\nu_\tau / \pi^-\pi^0\pi^0\nu_\tau$ (hadronic $\mu\tau$ channel)

Background Channels $\tau\tau$ resonant and continuum, Bhabha, misidentified e or μ

Searches for lepton flavor violation in Υ decays

Effective Field Theory allows BSM physics at some large mass contributing to CLFV Υ(3S) decays to be parameterized at low energy by a four-fermion interaction with coupling constant α_N and mass scale Λ

➔ dilepton and LFV branching fractions of Υ to the scale Λ of LFV BSM physics are then related by

$$\frac{\Gamma(\Upsilon(3S) \to \ell^{\pm}\tau^{\mp})}{\Gamma(\Upsilon(3S) \to \ell^{+}\ell^{-})} = \frac{1}{2q_b^2}\left(\frac{\alpha_N^{(\ell\tau)}}{\alpha}\right)^2 \left(\frac{M_{\Upsilon(3S)}}{\Lambda^{(\ell\tau)}}\right)^4 (\ell = e, \mu)$$

Searches for lepton flavor violation in Υ decays

	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
Mass (GeV/c^2)	9.46	10.02	10.36
N decays (millions)	20.8	9.3	5.9
$\Gamma(\Upsilon \to \mu\mu)$ (keV)	1.252	0.581	0.413
$\Gamma(\Upsilon)$ (keV)	53.0	43.0	26.3
$\mathcal{B}(\mu\mu)$ ($\times 10^{-3}$)	23.6	13.5	15.7
$\mathcal{B}(\mu\tau)$ (95% CL UL, $\times 10^{-6}$)	6.0	14.4	20.3
$\mathcal{B}(\mu\tau)/\mathcal{B}(\mu\mu)$ (95% CL UL, $\times 10^{-3}$)	0.25	1.1	1.3
Λ (95% CL LL, TeV, $\alpha_N = 1.0$)	1.30	0.98	0.98

CLEO PRL101, 201601 (2008)

Data Sample

20.8 x 10^6 Υ(1S)

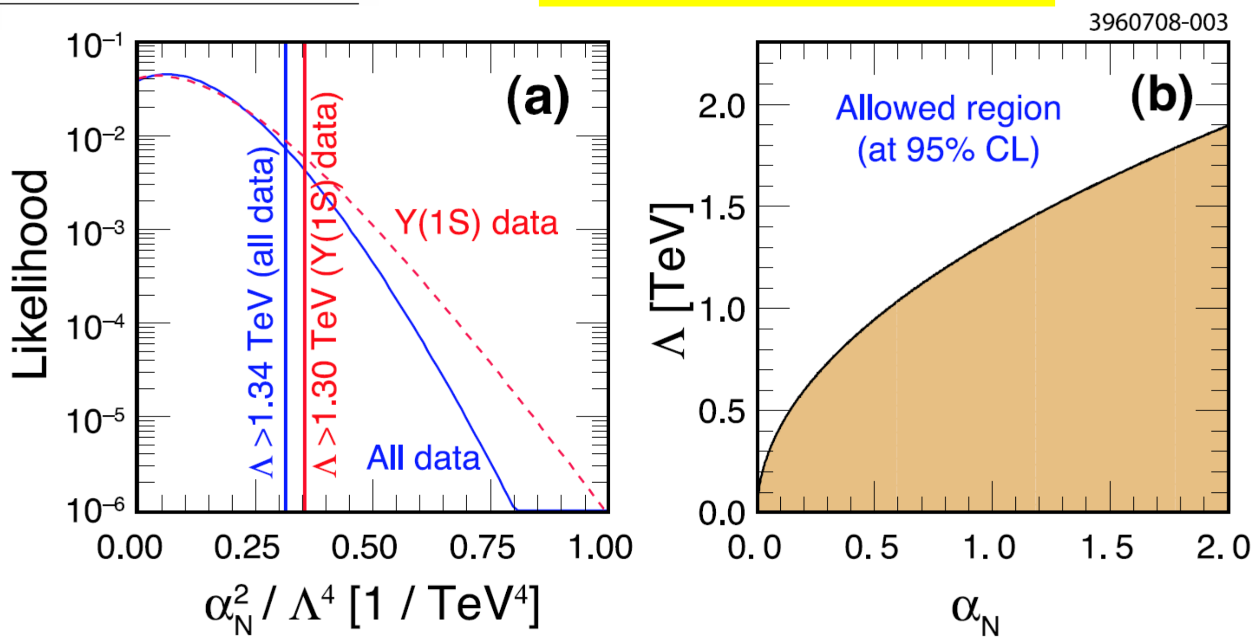
9.3 x 10^6 Υ(2S)

5.9 x 10^6 Υ(3S)

Assuming $\alpha_N^{\mu\tau} = 1$ and with all data

95% C.L. lower limits

$\Lambda_{\mu\tau} > 1.34$ TeV



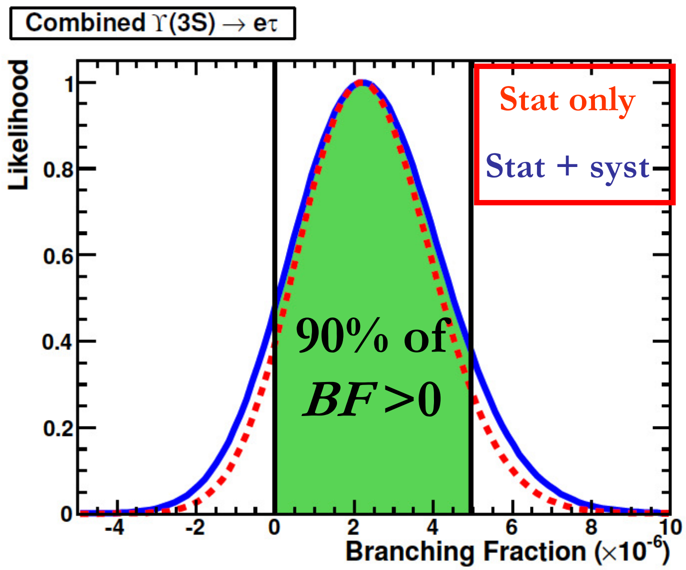
Searches for lepton flavor violation in Υ decays

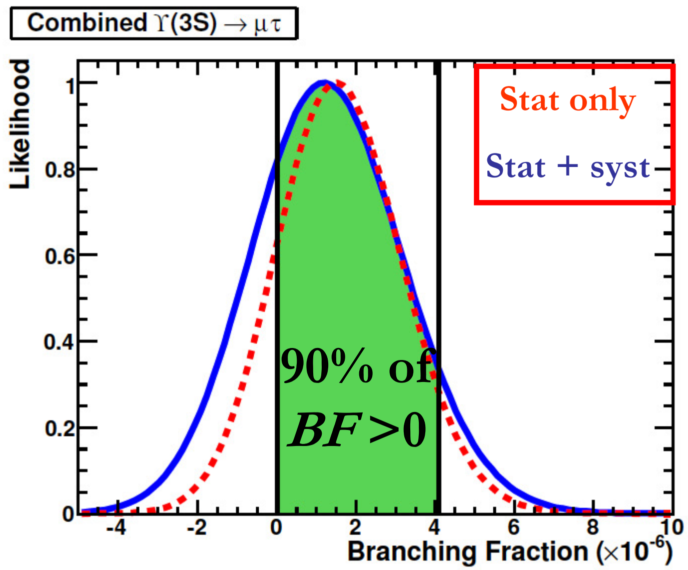
BABAR arXiv:0812.1021

$\Upsilon(3S)$ sample of $(116.7\pm1.2)\times10^6$ or 27.5 fb^{-1}

	UL	MPV
$BF(\Upsilon(3S)\to e^{\pm}\tau^{\mp})$ $(\times10^{-6})$	<5.0	$2.2^{+1.9}_{-1.8}$
$BF(\Upsilon(3S)\to \mu^{\pm}\tau^{\mp})$ $(\times10^{-6})$	<4.1	$1.2^{+1.9}_{-1.9}$

Preliminary





90% C.L. upper limits

$BF(\Upsilon(3S)\to e\tau) < 5.0\times10^{-6}$ — First upper limit

$BF(\Upsilon(3S)\to \mu\tau) < 4.1\times10^{-6}$ — Factor > 4 improvement to CLEO

BABAR arXiv:0812.1021

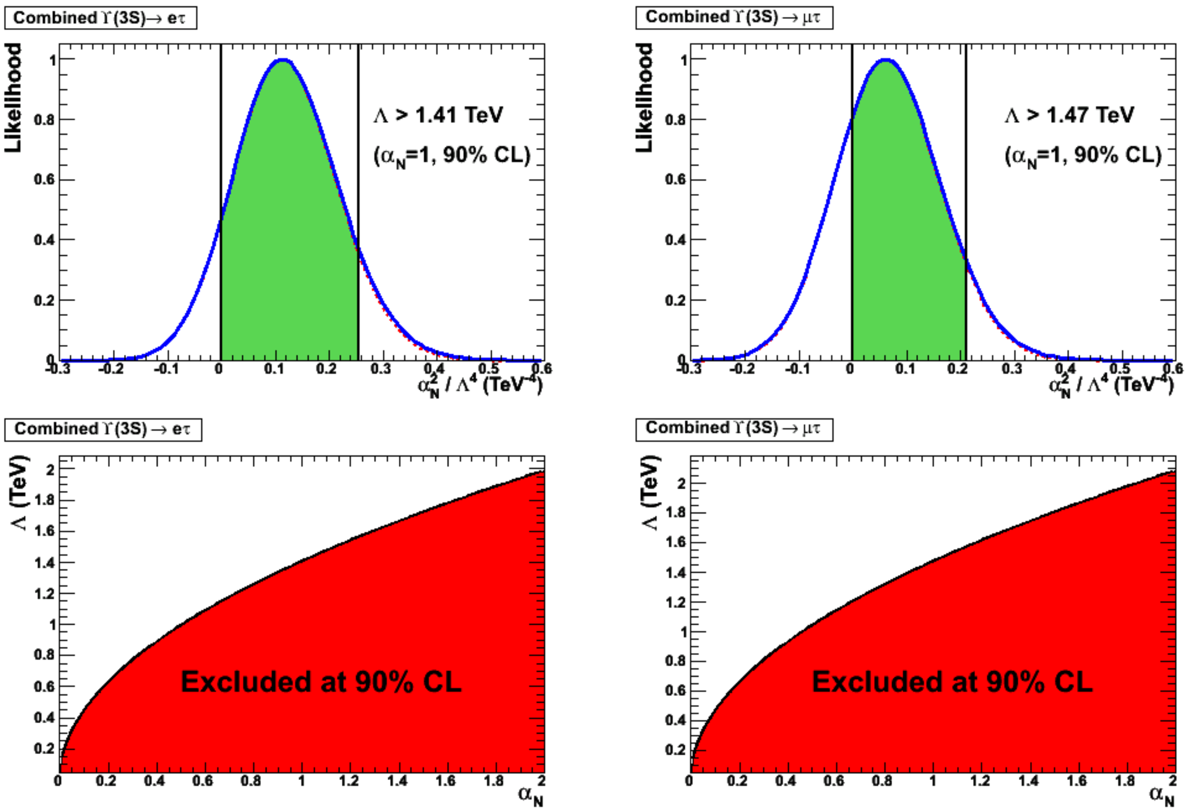
Preliminary

Assuming $\alpha_N^{e\tau} = \alpha_N^{\mu\tau} = 1$

90% C.L. lower limits

$\Lambda_{e\tau} > 1.41$ TeV

$\Lambda_{\mu\tau} > 1.47$ TeV



Test of lepton universality in Υ decays

$\Upsilon(3S) \to \Upsilon(1S)\,\pi^+\pi^-$ with $\Upsilon(1S) \to l^+l^-$ where $l = \mu, \tau$

B*AB*A*R* Preliminary

- *SM couplings between gauge bosons and leptons independent of flavor*

$$R_{\tau\mu} = \mathrm{BR}(\Upsilon(1S) \to \tau^+\tau^-)/\mathrm{BR}(\Upsilon(1S) \to \mu^+\mu^-) = 1$$

(to very small lepton-mass effects)

- *BSM – e.g. NMSSM CP-odd Higgs A^0 may mediate*

$\Upsilon \to \gamma\, A^0 \to \gamma\, l^+ l^-$ with $l = e, \mu, \tau$

$\Upsilon \to \gamma\, \eta_b$ with $\eta_b \to A^0 \to l^+ l^-$ *($\eta_b(^1S_0 b\bar{b}) \to l^+l^-$ forbidden in SM!)*

Coupling to A^0 proportional to mass $\to$ possible deviation of $R_{ll'}$ from 1

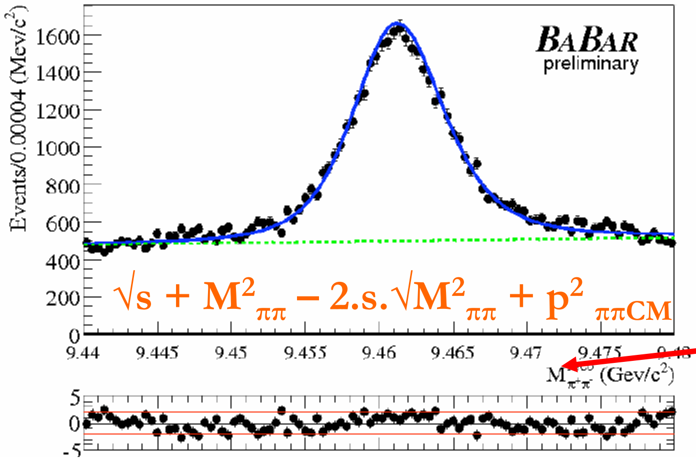
lepton universality breaking

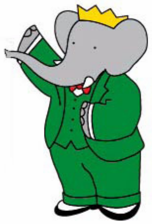
$\to$ deviation from few % for given values of tanβ and $|m_{A0} - m_{\eta b}|$ up to ~10% for $\tan\beta \sim 7:21$ and $|m_{A0} - m_{\eta b}| \sim 250\ MeV/c^2$ [Sanchiz-Lozano Int.J.Mod.Phys. A19, 2183(2004) & Fullana et al. PL B 653(2007)67]

Test of lepton universality in Υ decays

$\Upsilon(3S) \to \Upsilon(1S)\, \pi^+\pi^-$ with $\Upsilon(1S) \to l^+l^-$ where $l = \mu, \tau$

BABAR Preliminary



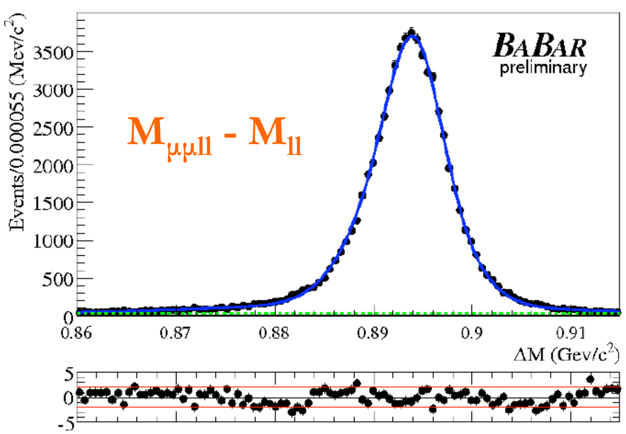


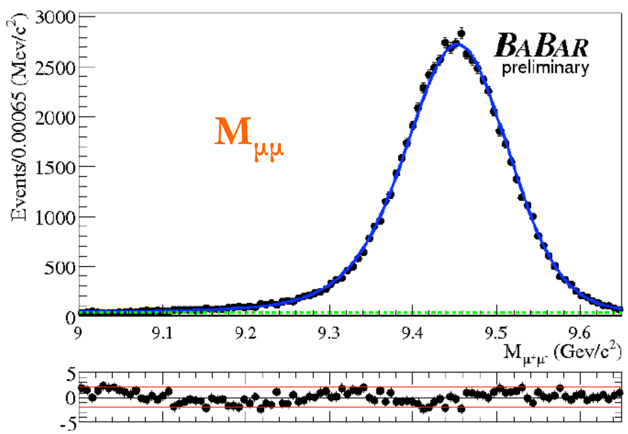
Signal datasets 122×10^6 $\Upsilon(3S)$

$\Upsilon(3S) \to \pi^+\pi^-\, \Upsilon(1S) \to \pi^+\pi^-\, \mu^+\mu^-$

$\Upsilon(3S) \to \pi^+\pi^-\, \Upsilon(1S) \to \pi^+\pi^-\, \tau^+\tau^-$

Recoil mass of the pion pair with invariant mass $M_{\pi\pi}$ and $p_{\pi\pi CM}$ momentum in the center of mass frame with s as nominal energy





BABAR Preliminary

$R_{\tau\mu} = 1.009 \pm 0.010 \pm 0.024$

CLEO with Υ(1S)

PRL 101, 151802(2008)

$R_{\tau\mu} = 1.02 \pm 0.02 \pm 0.05$

Searches for light Higgs-like particle in radiative decays of $\Upsilon(1S, 2S, 3S)$

Search for light Higgs-like particle in radiative decays of Υ(1S, 2S, 3S)

Next-to-Minimal Supersymmetric Standard Model NMSSM introduces a singlet Higgs field: linear combination with member of electroweak doublet produces a CP-odd Higgs state A^0 whose mass is not required to be large … below $b\bar{b}$ threshold

Radiative production $\Upsilon \rightarrow \gamma A^0$ ideal to search for!

[Wilczek PRL 39, 1304(1977)]

Search for monochromatic peak in E_γ distribution

- For $2\,m_\tau < M_{A0} < 2\,m_b$ $A^0 \rightarrow \tau^+\tau^-$ dominates
- For $M_{A0} < 2\,m_\tau$ $A^0 \rightarrow \mu^+\mu^-$ copious below $s\bar{s}$ threshold

Search for light Higgs-like particle in radiative decays of Υ(1S, 2S, 3S)

Branching Fractions related to effective coupling f_Υ of the bound b-quark to A^0

$$\frac{\mathcal{B}(\Upsilon(nS) \to \gamma A^0)}{\mathcal{B}(\Upsilon(nS) \to l^+ l^-)} = \frac{f_\Upsilon^2}{2\pi\alpha}\left(1 - \frac{m_{A^0}^2}{m_{\Upsilon(nS)}^2}\right)$$

Effective coupling f_Υ includes b-quark Yukawa coupling + M_{A0}- dependent QCD and relativistic corrections to $B_{\Upsilon(nS)}$ and to leptonic width of Υ(nS)

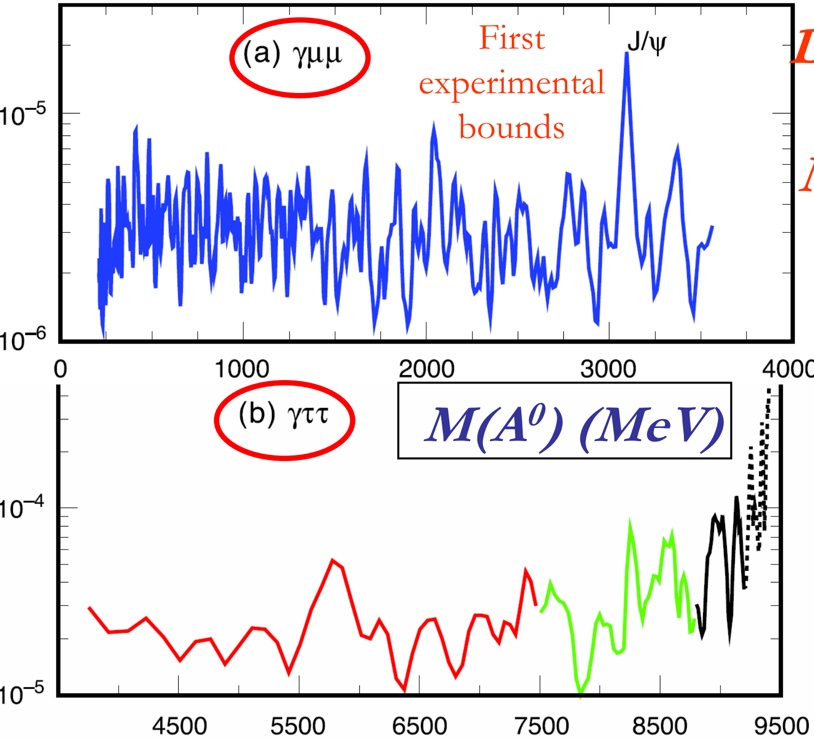
Search for light Higgs-like particle in radiative decays of Υ(1S, 2S, 3S)

$\Upsilon(1S) \rightarrow \gamma A^0$ with $A^0 \rightarrow \mu^+\mu^-$ or $\tau^+\tau^-$

CLEO PRL 101, 151802(2008)

1.1 fb^{-1} (21.5±0.4) x 10^6 $\Upsilon(1S)$

90% U.L. on $B(\Upsilon(1S) \rightarrow \gamma A^0) \times B(A^0 \rightarrow l^+l^-)$ ($l = \mu, \tau$)



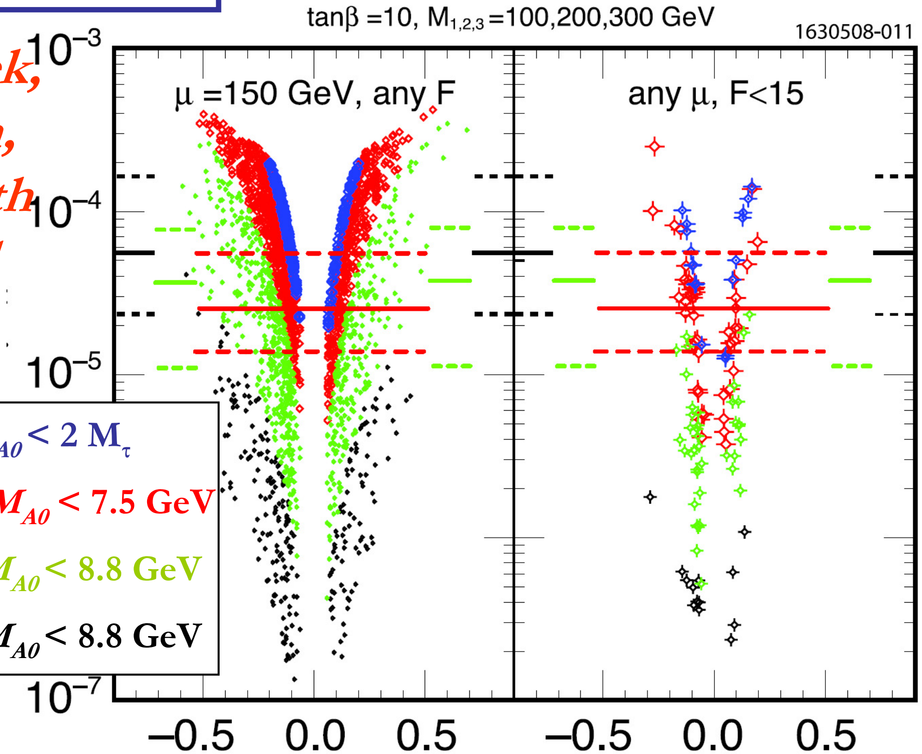
Dermisek, Gunion, McElrath Model

$M_{A0} < 2\,M_\tau$

$2\,m_\tau < M_{A0} < 7.5$ GeV

$7.5 < M_{A0} < 8.8$ GeV

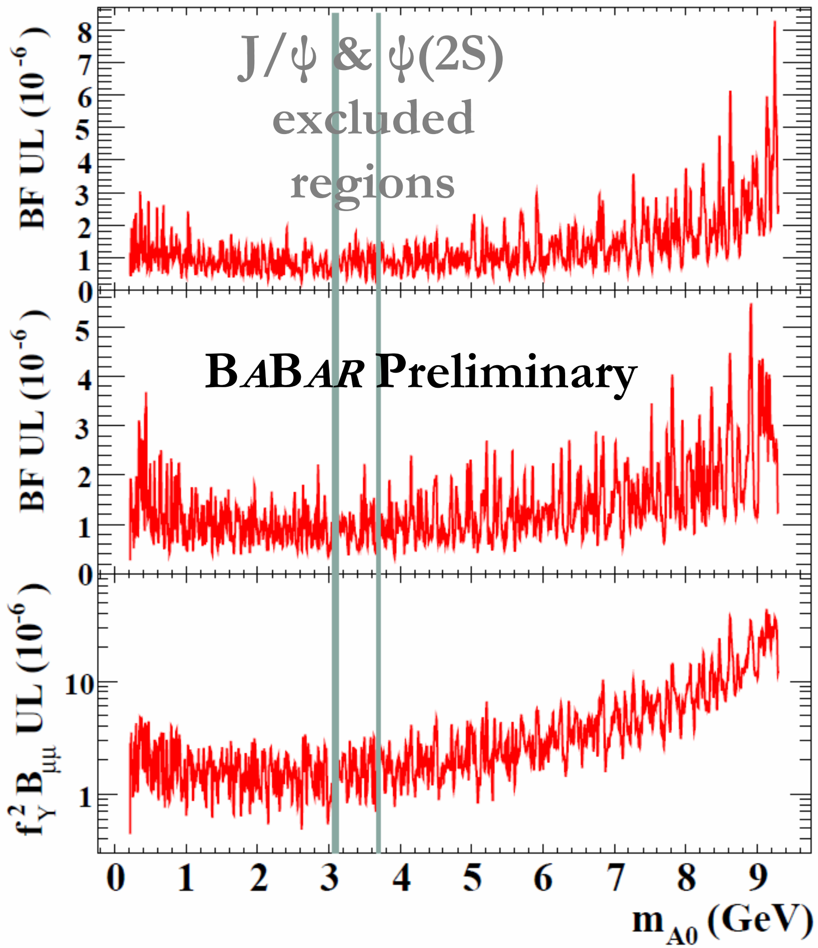
$7.5 < M_{A0} < 8.8$ GeV



Search for light Higgs-like particle in radiative decays of $\Upsilon(1S, 2S, 3S)$

$\Upsilon(2S, 3S) \rightarrow \gamma A^0$ with $A^0 \rightarrow \mu^+\mu^-$

BABAR arXiv:0905.4539



90% C.L. upper limits

$0.212 \leq M_{A0} \leq 9.3$ GeV

$B(\Upsilon(2S) \rightarrow \gamma A^0) \times B_{\mu\mu}$

$B(\Upsilon(3S) \rightarrow \gamma A^0) \times B_{\mu\mu}$

$f^2_{\Upsilon} \times B_{\mu\mu}$

Preliminary

Data Sample

99×10^6 $\Upsilon(2S)$

122×10^6 $\Upsilon(3S)$

Also

$B(\eta_b \rightarrow \mu^+\mu^-) < 0.9\%$ at 90% C.L.

Assuming $B_{\mu\mu} \approx 1$ (for $2m_\mu < M_{A0} < 1$ GeV), $f_\Upsilon <$ 12% of SM b-quark coupling to Higgs

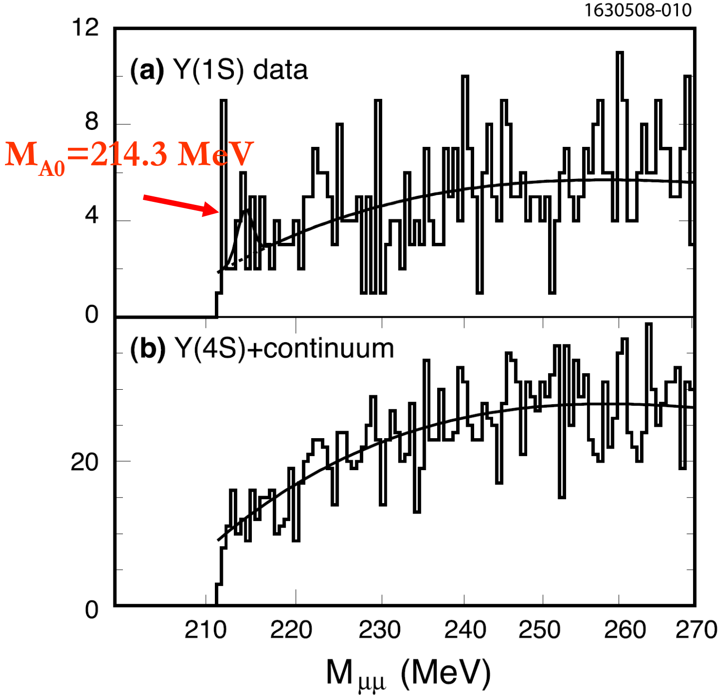
Search for light Higgs-like particle in radiative decays of Υ(1S, 2S, 3S)

The 3 HyperCP events $\Sigma^+ \rightarrow p\mu^+\mu^-$

Park et al., PRL 94, 021801(2005)

CLEO PRL 101, 151802(2008)

90% C.L. $B(\Upsilon(1S) \rightarrow \gamma A^0) < 2.3 \times 10^{-6}$



BABAR Preliminary

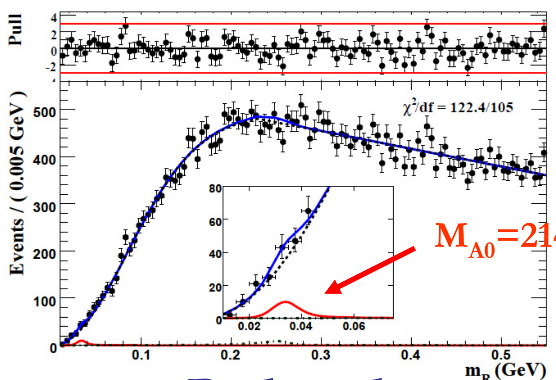
No significant signal at M_{A0} = 214.3 MeV

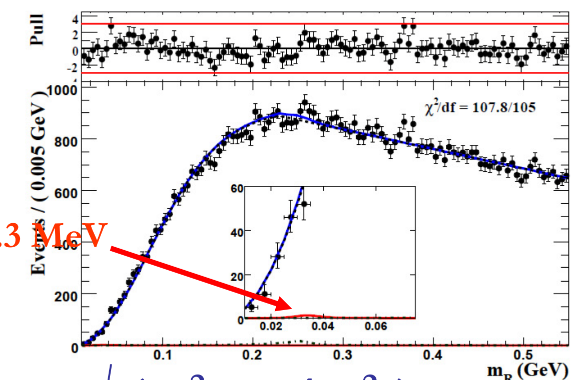
$f^2_\Upsilon(M_{A0}) < 1.6 \times 10^{-6}$ at 90% C.L.

assuming $B_{\mu\mu} = 1$

$\Upsilon(2S) \rightarrow \gamma A^0$

$\Upsilon(3S) \rightarrow \gamma A^0$



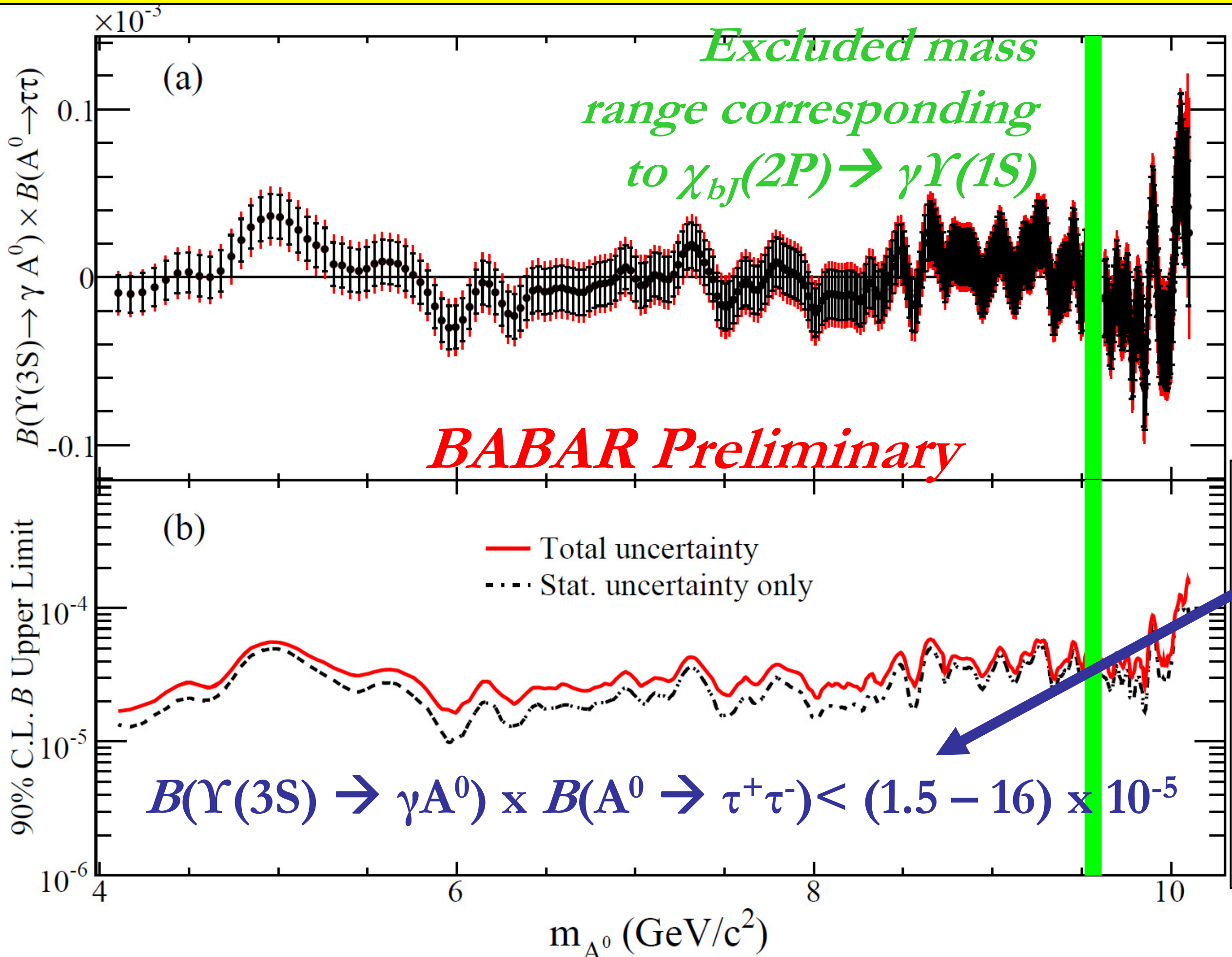


Reduced mass $m_R = \sqrt{(m^2_{\mu\mu} - 4m^2_\mu)}$

Search for light Higgs-like particle in radiative decays of $\Upsilon(1S, 2S, 3S)$

$\Upsilon(3S) \rightarrow \gamma A^0$ with $A^0 \rightarrow \tau^+\tau^-$

BABAR Preliminary



Data Sample

122×10^6 $\Upsilon(3S)$

Signal

$\tau \rightarrow e\, \nu_e\, \nu_\tau$ or $\mu\, \nu_\mu\, \nu_\tau$

90% C.L. upper limits

$4.03 < M_{A0} < 10.10$ GeV/c²

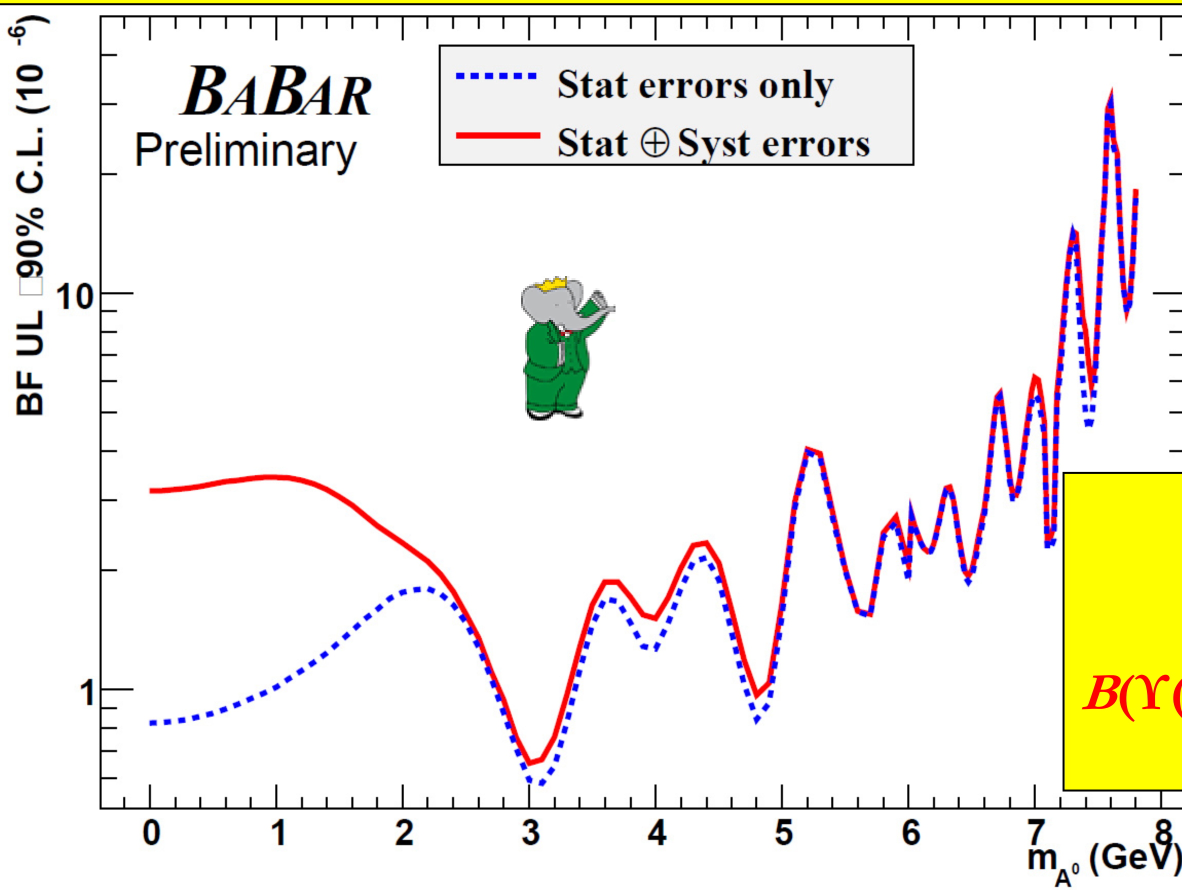
Also

$B(\eta_b \rightarrow \tau^+\tau^-) < 8\%$

Search for light Higgs-like particle in radiative decays of Υ(1S, 2S, 3S)

Υ(3S) → γ A^0 with A^0 → invisible

BABAR arXiv:0808.0017



Data Sample 122 x 10^6 Υ(3S)

Signal Single photon + missing mass consistent with 2-body Υ(3S) decay

Preliminary

For M_{A0} < 7.8 GeV

90% C.L. upper limits

B(Υ(3S) → A^0) x *B*(A^0 → invisible) < (0.7 – 31) x 10^{-6}

Summary

- Many new results!
- Bottomonium Spectroscopy : progresses but still undiscovered states (singlets) !
- Bottomonium dynamics: unique and crucial to test non-relativistic QCD but also to look for possible mixing between Higgs, or Higgs-like scalars, and bottomonium states, leading to discrepancies with SM expectations (e.g. hyperfine splittings);
- Bottomonium : ideal place to search for new physics beyond SM; e.g. a light Higgs could induce a slight but observable lepton universality breakdown in Upsilon decays;
- Bottomonium and Charmonium spectra : very similar - search for states analogue to recently discovered "charmonium" states, etc.

  - ✓ …..efforts on Bottomonium physics should be increased, and coordinated, to fully exploit the large statistics of B-Factories!
  - ✓ theoretical predictions have to be improved (from 10-20% to a few %)!

Backup Slides

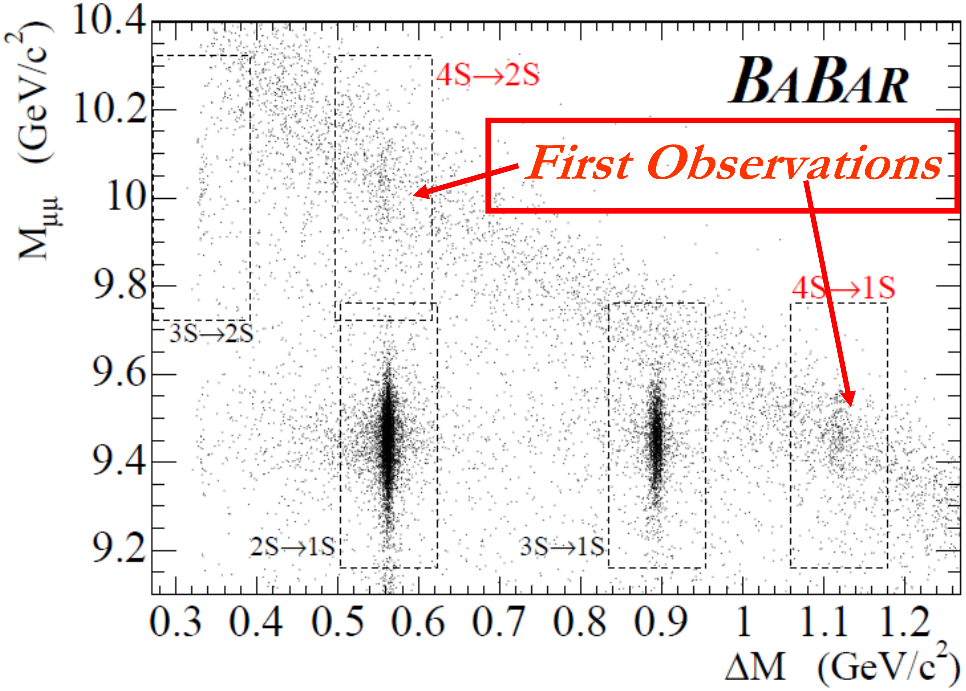
Hadronic transitions between bottomonium states

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

BABAR PRL96, 232001(2006)

230×10^6 $\Upsilon(4S)$

use $\Upsilon(4S) \rightarrow \pi^+\pi^- \Upsilon(nS)$ (n=1,2) by reconstructing $\Upsilon(nS)$ meson via its leptonic decay to $\mu^+\mu^-$ and look at $\mu^+\mu^-$ invariant mass $M_{\mu\mu}$ and invariant mass difference $\Delta M = M_{\pi\pi\mu\mu} - M_{\mu\mu}$ compatible with $M(\Upsilon(4S)) - M(\Upsilon(nS))$



$B(\Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(1S)) \times B(\Upsilon(1S) \rightarrow \mu^+\mu^-) = (2.23 \pm 0.25 \pm 0.27) \times 10^{-6}$

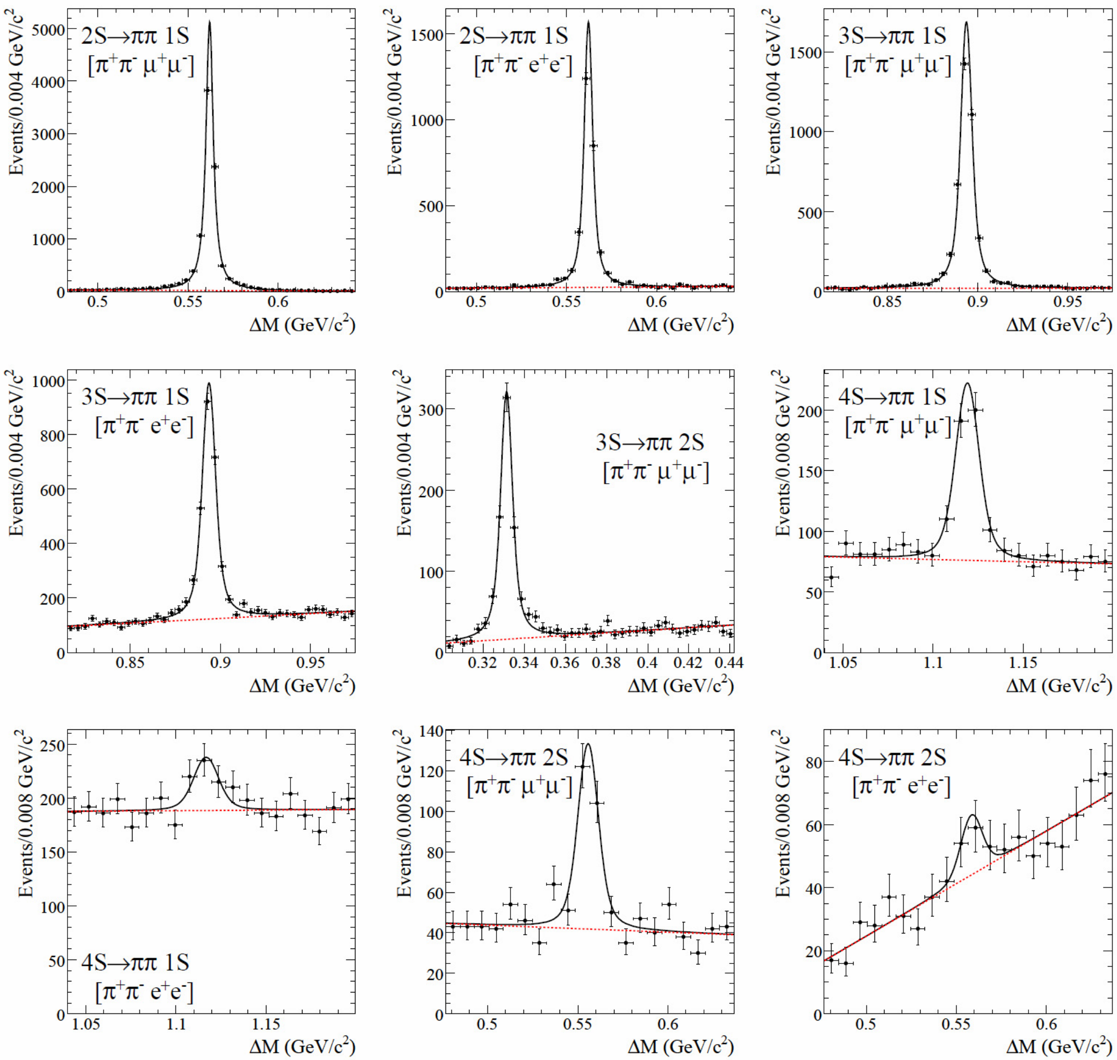
$\Gamma(\Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(1S)) = (1.8 \pm 0.4)$ keV

$B(\Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(2S)) \times B(\Upsilon(2S) \rightarrow \mu^+\mu^-) = (1.69 \pm 0.26 \pm 0.20) \times 10^{-6}$

$\Gamma(\Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(2S)) = (2.7 \pm 0.8)$ keV

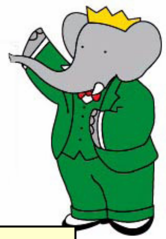
Hadronic transitions between bottomonium states

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



BABAR **PRD 78, 112002(2008)**

Transitions from 2S, 3S, 4S observed in e^+e^- and $\mu^+\mu^-$ modes



2S → 1S

(17.22±0.17±0.75)%

3S → nS

1S: (4.17±0.06±0.19)%

2S: (2.40±0.10±0.26)%

4S → nS

1S: $(0.800\pm0.064\pm0.027) \times 10^{-4}$

2S: $(0.86\pm0.11\pm0.07) \times 10^{-4}$

Hadronic transitions between bottomonium states
$\Upsilon(mS) \rightarrow \eta/\pi^0 + \Upsilon(1S)$

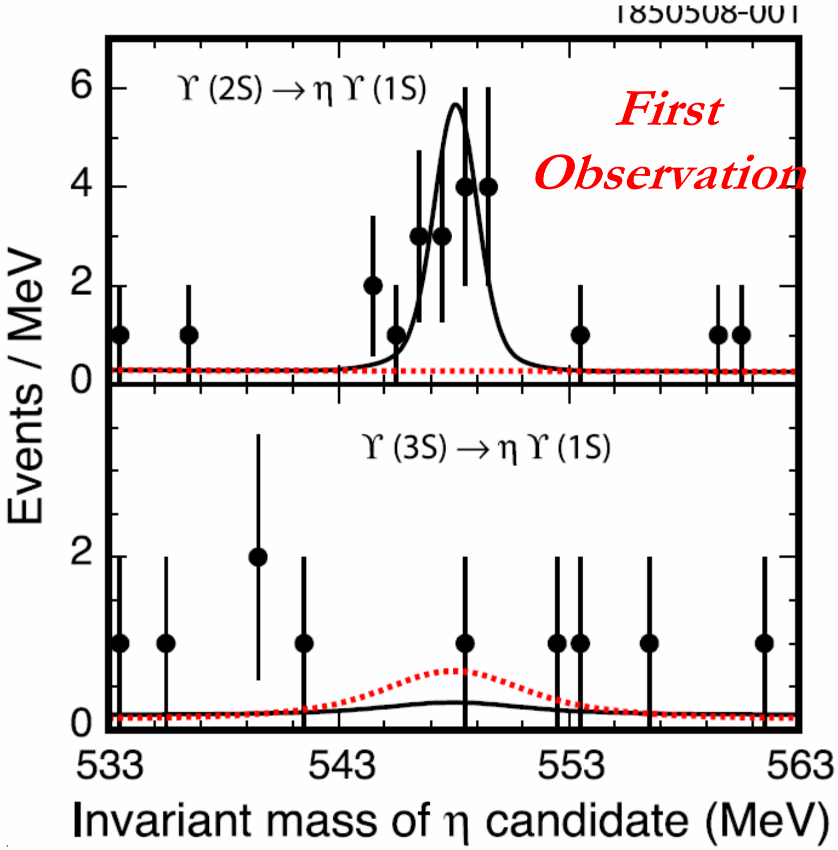
CLEO **PRL 101, 192001(2008)**

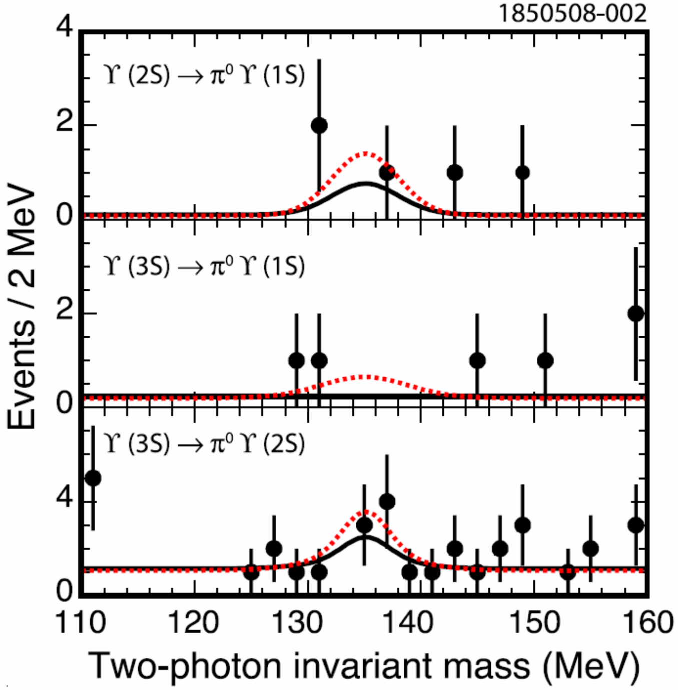
$(9.32\pm0.14) \times 10^6\ \Upsilon(2S)$
$(5.88\pm0.10) \times 10^6\ \Upsilon(3S)$

$$\mathcal{B}[\Upsilon(2S) \rightarrow \eta\Upsilon(1S)] = (2.1^{+0.7}_{-0.6} \pm 0.3) \times 10^{-4}$$

90% C.L. upper limits

$B(\Upsilon(2S) \rightarrow \pi^0\ \Upsilon(1S)) < 1.8 \times 10^{-4}$
$B(\Upsilon(3S) \rightarrow \eta\ \Upsilon(1S)) < 1.8 \times 10^{-4}$
$B(\Upsilon(3S) \rightarrow \pi^0\ \Upsilon(1S)) < 0.7 \times 10^{-4}$
$B(\Upsilon(3S) \rightarrow \pi^0\ \Upsilon(2S)) < 5.1 \times 10^{-4}$





Hadronic transitions between bottomonium states

$\Upsilon(mS) \to \pi\pi + \Upsilon(2, 1S)$

All 90% C.L. upper limits

BABAR **PRD 78, 112002(2008)**

		This work	PDG [12]	Prediction
$\Gamma_{ee}(2S) \times \mathcal{B}(\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S))$	(eV)	105.4±1.0±4.2	115±5	
$\Gamma(\Upsilon(2S) \to \eta\Upsilon(1S))/\Gamma(\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S))$	$(\times 10^{-3})$	< 5.2	< 11	2.5 [2]
$\Gamma_{ee}(3S) \times \mathcal{B}(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S))$	(eV)	18.46±0.27±0.77	19.8±1.0	
$\Gamma(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(2S))/\Gamma(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S))$		0.577±0.026±0.060	0.63±0.14	0.3 [2]
$\Gamma(\Upsilon(3S) \to \eta\Upsilon(1S))/\Gamma(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S))$	$(\times 10^{-2})$	< 1.9	< 5	1.7 [2]
$\mathcal{B}(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S))$	$(\times 10^{-4})$	0.800±0.064±0.027	$0.90\pm0.15^{(*)}$	–
$\Gamma(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S))/\Gamma(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S))$		1.16±0.16±0.14		–
$\Gamma(\Upsilon(4S) \to \eta\Upsilon(1S))/\Gamma(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S))$		2.41±0.40±0.12	–	–
$\mathcal{B}(\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S))$	(%)	17.22±0.17±0.75	18.8±0.6	27±2 [2]
$\mathcal{B}(\Upsilon(2S) \to \eta\Upsilon(1S))$	$(\times 10^{-4})$	< 9	< 20	8.1±0.8 [14]
$\mathcal{B}(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S))$	(%)	4.17±0.06±0.19	4.48±0.21	3.3±0.3 [2]
$\mathcal{B}(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(2S))$	(%)	2.40±0.10±0.26	2.8±0.6	1.0±0.1 [2]
$\mathcal{B}(\Upsilon(3S) \to \eta\Upsilon(1S))$	$(\times 10^{-4})$	< 8	< 22	6.7±0.7 [14]
$\mathcal{B}(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S))$	$(\times 10^{-4})$	0.86±0.11±0.07	$0.88\pm0.19^{(*)}$	-
$\mathcal{B}(\Upsilon(4S) \to \eta\Upsilon(1S))$	$(\times 10^{-4})$	1.96±0.06±0.09	–	–

Hadronic transitions between bottomonium states

$\Upsilon(mS) \rightarrow \pi\pi/\eta/\pi^0 + \Upsilon(nS)$

Branching Fractions %	BABAR PRD78, 112002(2008) PRL96, 232001(2006)	Belle PRD(RC)79, 051103 (2009)	CLEO PRD79, 011103(2009) PRL101, 192001(2008)
$\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$	$17.22\pm0.17\pm0.75$		$18.02\pm0.02\pm0.61$
$\Upsilon(2S) \rightarrow \pi^0\pi^0\Upsilon(1S)$			$8.43\pm0.16\pm0.42$
$\Upsilon(2S) \rightarrow \eta\ \Upsilon(1S)$	$<9 \times 10^{-2}$		$2.1^{+0.7}_{-0.6}\pm0.3$
$\Upsilon(2S) \rightarrow \pi^0\ \Upsilon(1S)$			$<1.8 \times 10^{-2}$
$\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$	$4.17\pm0.06\pm0.19$		$4.46\pm0.01\pm0.13$
$\Upsilon(3S) \rightarrow \pi^0\pi^0\Upsilon(1S)$			$2.24\pm0.09\pm0.11$
$\Upsilon(3S) \rightarrow \eta\ \Upsilon(1S)$	$<8 \times 10^{-2}$		$<1.8 \times 10^{-2}$
$\Upsilon(3S) \rightarrow \pi^0\ \Upsilon(1S)$			$<0.7 \times 10^{-2}$
$\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(2S)$	$2.40\pm0.10\pm0.26$		
$\Upsilon(3S) \rightarrow \pi^0\pi^0\Upsilon(2S)$			$1.82\pm0.09\pm0.12$
$\Upsilon(3S) \rightarrow \pi^0\ \Upsilon(2S)$			$<5.1 \times 10^{-2}$
$\Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(1S)$	$(0.90\pm0.15) \times 10^{-2}$	$(0.85\pm0.12\pm0.06) \times 10^{-2}$	
$\Upsilon(4S) \rightarrow \eta\Upsilon(1S)$	$(1.96\pm0.06\pm0.09) \times 10^{-2}$		
$\Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(2S)$	$(0.86\pm0.11\pm0.07) \times 10^{-2}$		

Searches for lepton flavor violation in Υ decays

BABAR arXiv:0812.1021

Υ(3S) sample of (116.7±1.2) x 10^6 or 27.5 fb^{-1}

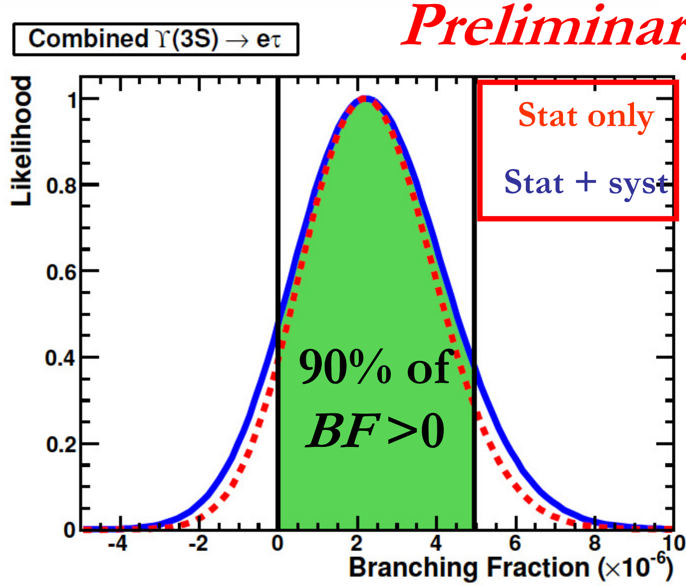
	UL	MPV
$BF(\Upsilon(3S) \to e^{\pm}\tau^{\mp})\ (\times 10^{-6})$	< 5.0	$2.2^{+1.9}_{-1.8}$
$BF(\Upsilon(3S) \to \mu^{\pm}\tau^{\mp})\ (\times 10^{-6})$	< 4.1	$1.2^{+1.9}_{-1.9}$

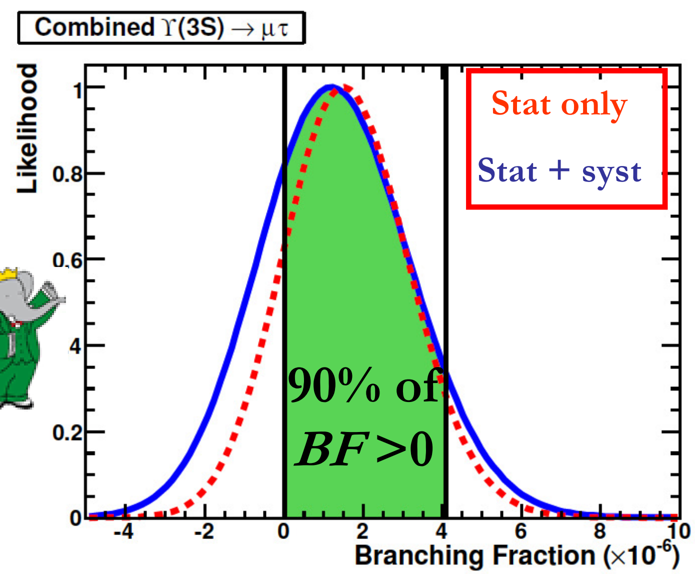
Assuming $\alpha_N^{e\tau} = \alpha_N^{\mu\tau} = 1$

90% C.L. lower limits

$\Lambda_{e\tau}$ > 1.4 TeV and $\Lambda_{\mu\tau}$ > 1.5 TeV

Preliminary





90% C.L. upper limits

BF(Υ(3S) → eτ) **< 5.0 x 10^{-6}**

First upper limit

BF(Υ(3S) → μτ) **< 4.1 x 10^{-6}**

Factor > 4 improvement to CLEO