Recent Results in Bottomonium Spectroscopy

VIII International Workshop on Heavy Quarks and Leptons

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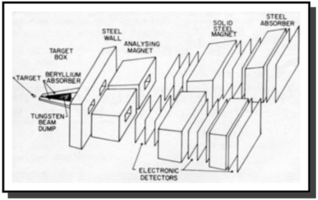
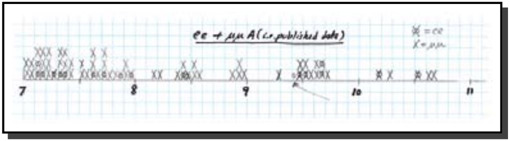
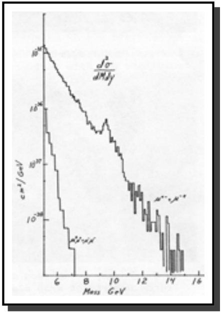
Outline

1. Introduction:
   - A wee bit of history
2. The Renaissance: CLEO III
   - New CLEO Data at $\Upsilon(nS)$
   - $\Upsilon(\mathrm{nS})$ Leptonic Widths
3. The Enlightenment: A New Host of Hadronic Transitions
   - CLEO: New Hadronic Transitions
   - B-factory Contributions in $\pi^+\pi^-$ Transitions
   - All Together Now: $\pi^+\pi^-$ Invariant Mass Distributions
4. Conclusions and Future Prospects

Roughly 30 years ago, at Fermilab (E288) a hint of something odd near 9.5 GeV was seen in online-reconstruction of $e^+e^-\&\mu^+\mu^-$ events :





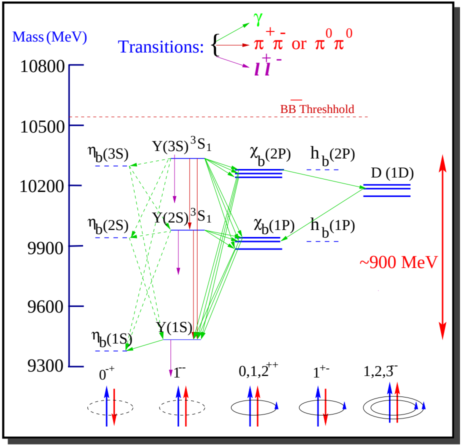


For a very interesting history of the discovery of the Υ:

http://history.fnal.gov/jyoh_docs/e288_internal_notes.html

Subsequent History

- Over the course of the next 20 years, spectroscopy of the system revealed a rich set of bound states
- Contributions from CLEO, CUSB, Crystal Ball, Doris, ARGUS and others



Motivations

Among the many things motivating our further study of bottomonium are:

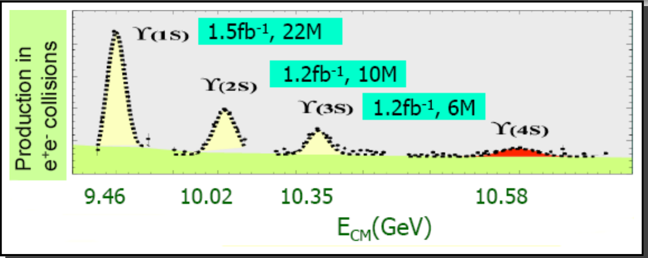
- Test Lattice QCD - masses, hyperfine splittings, $\ell\ell$ widths, other rates
- Develop QCD and potential models: spin-orbit coupling, color octet/singlet
- Develop decay models (particularly hadronic transitions)
- Compare to charmonium (particularly radiative decays and $\ell\ell$ widths)

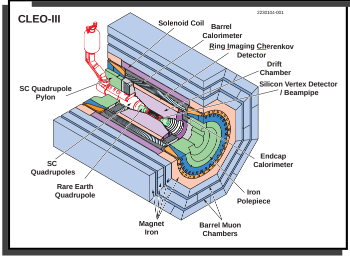
We now undertake a survey of results obtained over the past few years

The Renaissance

- During the first 20 years of bottomonium spectroscopy, much of the spectroscopic map was laid out
- Subsequently (as CLEO-III) CLEO has ushered in a new period in the study of the Υ system
- Recently, the B-factory experiments have joined the fun, reporting new hadronic transitions from $\Upsilon(4S)$ to bottomonium daughters (and BELLE has taken an engineering run at $\Upsilon(3S)$)

CLEO $\Upsilon(nS)$ Data Sets



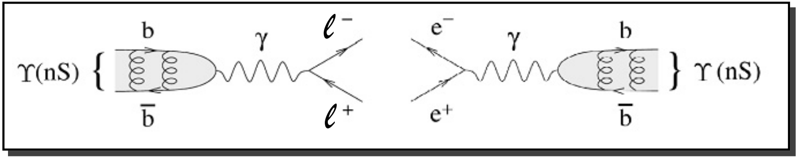


CLEO III ran on the Υ Resonances for a year between 2001 and 2002, collecting samples of Υ decays larger by factors of 10-20 compared to previous best (CLEO II)

Recent CLEO III bottomonium spectroscopy results

- E1 Transitions (including $\Upsilon(3S)\to\gamma\chi_{b0}(1P)$) PRL 94, 032001 (2004)
- 1D Discovery (first CLEOIII 'confrontation' with LQCD) PRD 70, 032001 (2004)
- Discovery of $\chi_{b1,2}(2P)\to\omega\Upsilon(1S)$ PRL 92, 222002 (2004)
- Discovery of $\chi_b(2P)\to\pi^+\pi^-\chi_b(1P)$ PRD 73, 012003 (2006)
- New Studies of $\Upsilon(\mathrm{nS})\to\ell\ell$ Widths and BRs PRL 94, 012001 (2005), PRL 96, 092003 (2006), hep-ex/0607019 (sub. to PRL)
- New Measurement of $B(\Upsilon(1S)\to\eta' X)$, hep-ex/0610032, sub. to PRD
- Studies of $\Upsilon(1S)$ Radiative Decays and Direct Photon Spectra, PRD 73, 032001 (2006), hep-ex/0512003, sub. to PRD
- B_s Studies at $\Upsilon(5S)$, PRL 95, 261801 (2005), PRL 96 022002 (2006), PRL 96 152001 (2006), PRD 74, 012003 (2006)

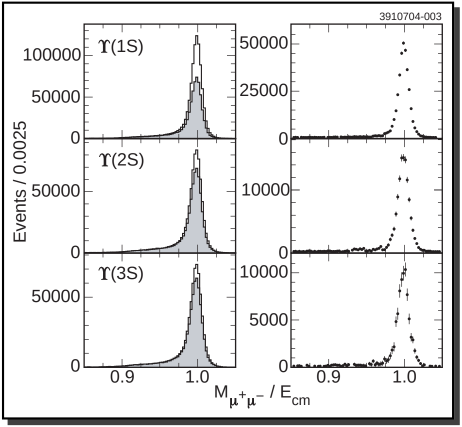
$\Upsilon(\mathrm{nS})$ Leptonic Decays



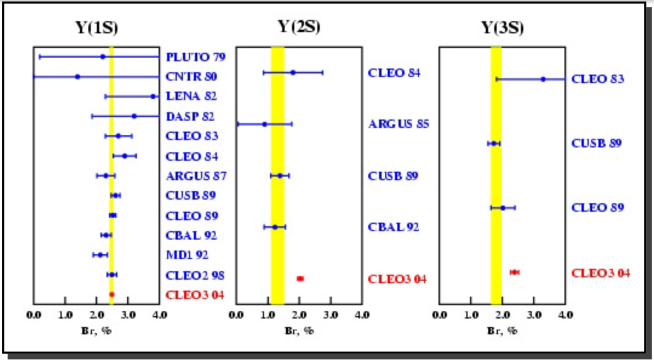
- The leptonic width of a quarkonium state is one of the basic parameters calculable in LQCD.
- At CLEO, we have recently measured leptonic widths or branching ratios for all three $\Upsilon(\mathrm{nS})$ states that lie below open-bottom threshold to all three lepton flavors (e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$).

$\mu^+\mu^-$ Branching Fractions: PRL 94 012001(2005)

- In 2005, we published new measurements of $\mathcal{B}(\Upsilon(\mathrm{nS})\rightarrow\mu^+\mu^-)$
- Based on $1.1 - 1.2 fb^{-1}$ at each $\Upsilon(\mathrm{nS})$
- Open histograms: all on-resonance data satisfying analysis cuts
- Shaded: scaled continuum data
- Points with errors: difference



$\mu^+\mu^-$ Branching Fractions: PRL 94 012001(2005)



PDG2004

$\mathcal{B}_{\mu\mu}(\Upsilon(1S)) = (2.49 \pm 0.02 \pm 0.07)\%$ *c.f.* $2.49 \pm 0.06\%$

$\mathcal{B}_{\mu\mu}(\Upsilon(2S)) = (2.03 \pm 0.03 \pm 0.08)\%$ *c.f.* $1.31 \pm 0.21\%$

$\mathcal{B}_{\mu\mu}(\Upsilon(3S)) = (2.39 \pm 0.07 \pm 0.10)\%$ *c.f.* $1.81 \pm 0.17\%$

e^+e^- Partial Widths

More recently, we have reported measurements of the Γ_{ee} for $\Upsilon(\mathrm{nS})$ with significant improvement in precision (c.f Relative Uncertainty on PDG 2004 Averages):

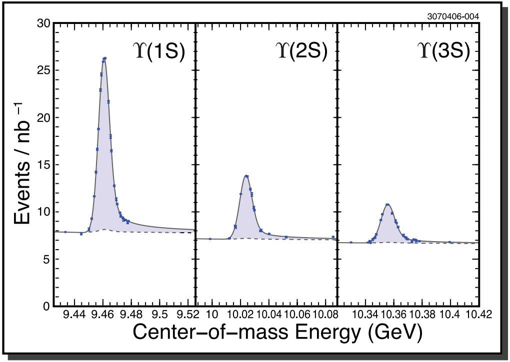
$$\Upsilon(1\mathrm{S}) : 2.2\% \quad \Upsilon(2\mathrm{S}) : 4.2\% \quad \Upsilon(3\mathrm{S}) : 9.4\%$$

Method:

- Observe Hadronic Cross Section as function of $\sqrt{s}$
- Lineshape scanned by varying E_{beam}
- Area under lineshape $\propto \Gamma_{ee}\Gamma_{had}/\Gamma_{tot}$.

Approx 1.25 fb^{-1} invested in the 3S, 2S and 1S scans

e^+e^- Partial Widths: PRL 96 092003(2006)

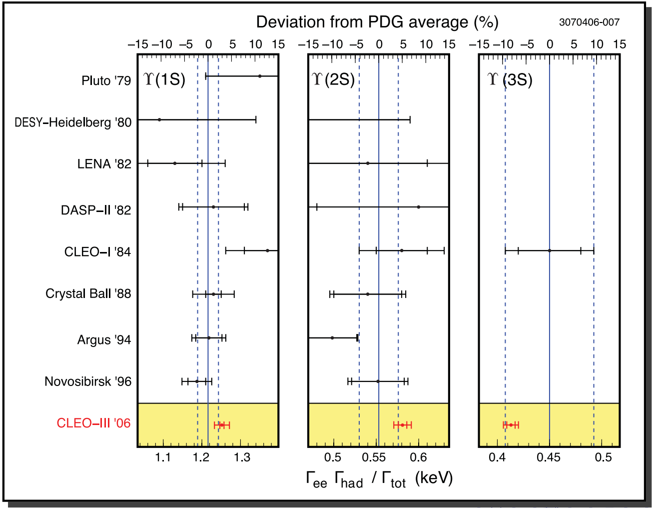


Use Lepton universality: $\Gamma_{ee} = (\Gamma_{ee}\Gamma_{had}/\Gamma_{tot})/(1-3B_{\mu\mu})$
Stat err: $\Upsilon(1S, 2S, 3S)$: $0.3\%, 0.7\%, 1.0\%$.
Chief Syst. Err: $\mathcal{L}$: 1.3%, ϵ_{had} : 0.5%.

e^+e^- Partial Widths: PRL 96 092003(2006)

		%
$\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}(1S)$	$(1.252 \pm 0.005 \pm 0.019)$ keV	
$\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}(2S)$	$(0.581 \pm 0.006 \pm 0.009)$ keV	
$\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}(3S)$	$(0.413 \pm 0.004 \pm 0.006)$ keV	
$\Gamma_{ee}(1S)$	$(1.354 \pm 0.005 \pm 0.020)$ keV	1.5
$\Gamma_{ee}(2S)$	$(0.619 \pm 0.007 \pm 0.009)$ keV	1.9
$\Gamma_{ee}(3S)$	$(0.446 \pm 0.004 \pm 0.007)$ keV	1.8
$\Gamma_{ee}(2S)/\Gamma_{ee}(1S)$	$(0.457 \pm 0.006 \pm 0.003)$	1.5
$\Gamma_{ee}(3S)/\Gamma_{ee}(1S)$	$(0.329 \pm 0.004 \pm 0.002)$	1.3
$\Gamma_{ee}(3S)/\Gamma_{ee}(2S)$	$(0.720 \pm 0.011 \pm 0.006)$	1.7

Comparison to Previous Measurements of Γ_{ee}

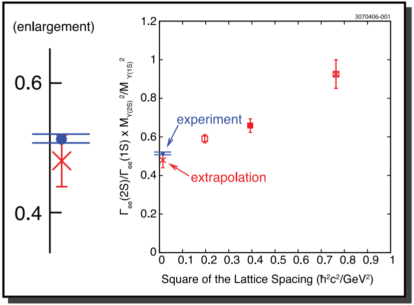


Comparison to unquenched LQCD

The best object for comparison is: $\frac{\Gamma_{ee}(\Upsilon(2S))M^2(\Upsilon(2S))}{\Gamma_{ee}(\Upsilon(1S))M^2(\Upsilon(1S))}$

CLEO-c: 0.514 ± 0.007 PRL 96, 092003 (2006).

LQCD: 0.48 ± 0.05 PRD 72, 094507 (2005).

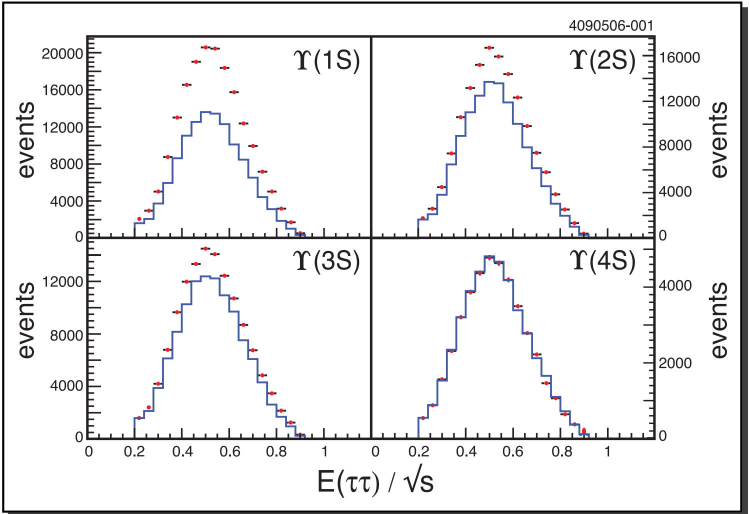


$\Upsilon(\mathrm{nS})\to\tau^+\tau^-$: hep-ex/0607019 (sub to PRL)

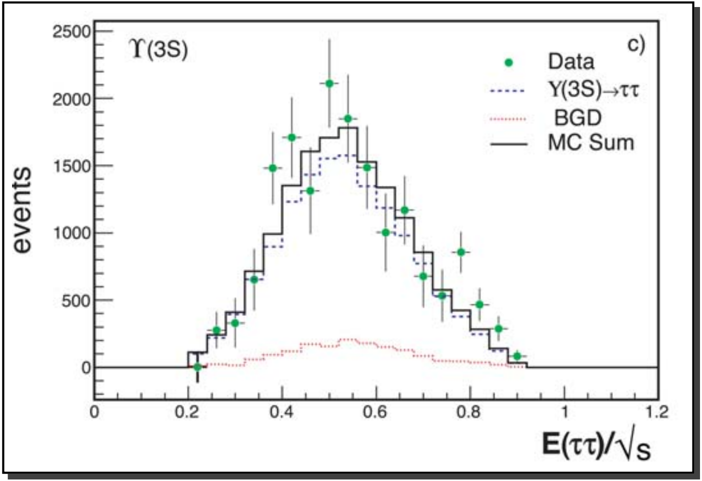
- We have recently measured $\tau^+\tau^-$ decays at all 3 lowest $\Upsilon(\mathrm{nS})$ resonances
- Previously: $\mathcal{B}(\Upsilon(1\mathrm{S})\to\tau^+\tau^-)$ known to 10%, $\Upsilon(2\mathrm{S})\to\tau^+\tau^-$ "seen", $\Upsilon(3\mathrm{S})\to\tau^+\tau^-$ unknown.
- Use 1-prong τ decays ($\tau\to h\nu$, $\tau\to\ell\nu\nu$), about 75% of the total.
- Ratio to $\mu^+\mu^-$ reported:

$$\mathcal{R} \equiv \frac{\mathcal{B}(\Upsilon(\mathrm{nS})\to\tau^+\tau^-)}{\mathcal{B}(\Upsilon(\mathrm{nS})\to\mu^+\mu^-)}$$

$\Upsilon(1S)\to\tau^+\tau^-$: hep-ex/0607019 (sub to PRL)

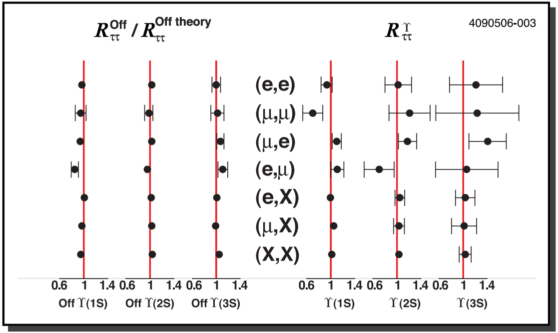


$\Upsilon(1S)\rightarrow\tau^+\tau^-$: hep-ex/0607019 (sub to PRL)

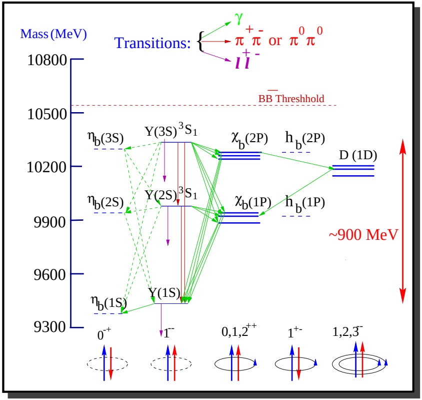


$R \equiv B(\tau\tau)/B(\mu\mu)$: hep-ex/0607019 (sub to PRL)

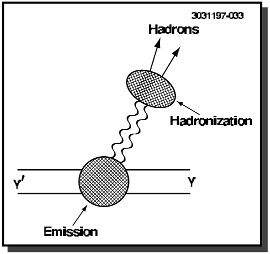
$R(\Upsilon(1S))$:	$1.02 \pm 0.02 \pm 0.05$
$R(\Upsilon(2S))$:	$1.04 \pm 0.04 \pm 0.05$
$R(\Upsilon(3S))$:	$1.07 \pm 0.08 \pm 0.05$



$\Upsilon(nS)$ Hadronic Transitions



- Low q^2 processes
- Expt. serves different role than in leptonic case



New Transitions: $\chi_b(2P)\to\omega\Upsilon(1S)$, $\pi^+\pi^-\chi_b(1P)$

With CLEO-III data, studies of previously unknown hadronic transitions made possible.

- Discovery of $(\chi_{b1,2}(2P)\to\omega\Upsilon(1S))$ PRL 92, 222002 (2004)

$$B(\chi_{b2}(2P)\to\omega\Upsilon(1S)) = 1.6 \pm 0.3 \pm 0.2\%$$

$$B(\chi_{b1}(2P)\to\omega\Upsilon(1S)) = 1.1 \pm 0.3 \pm 0.1\%$$

Ratio of these consistent with Gottfried (PRL 40, 598 (1978)) and Voloshin (Mod. Phys. Lett A18, 1067 (2003))

- Discovery of $\chi_b(2P)\to\pi^+\pi^-\chi_b(1P)$ PRD 73, 012003 (2006)

$$\Gamma(\chi_b(2P)\to\pi^+\pi^-\chi_b(1P)) = 0.83 \pm 0.22 \pm 0.08 \pm 0.19 \text{ keV}$$

Consistent with Kuang/Yan (PRD 24, 2874 (1981)), which predicted ~ 0.4 keV)

New Developments in $\Upsilon(\mathrm{nS})\ \pi^+\pi^-$ Transitions

Some new developments of late in $\pi^+\pi^-$ transitions among $\Upsilon(\mathrm{nS})$ states:

- CLEO: finalizing high-statistics studies of $\pi^+\pi^-$ transitions $\Upsilon(\mathrm{nS})\to\Upsilon(\mathrm{mS})\pi\pi$. Plots shown today are preliminary
- Belle: Observed $\Upsilon(4S)\to\Upsilon(1\mathrm{S})\pi^+\pi^-$
- BaBar: Observed $\Upsilon(4S)\to\Upsilon(1\mathrm{S})\pi^+\pi^-$ and $\Upsilon(4S)\to\Upsilon(2\mathrm{S})\pi^+\pi^-$

and an interesting picture emerges...

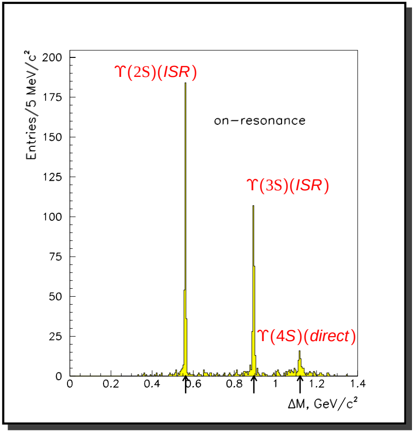
Belle: $\Upsilon(4S)\to\Upsilon(1S)\pi^+\pi^-$ (hep-ex/0512034)

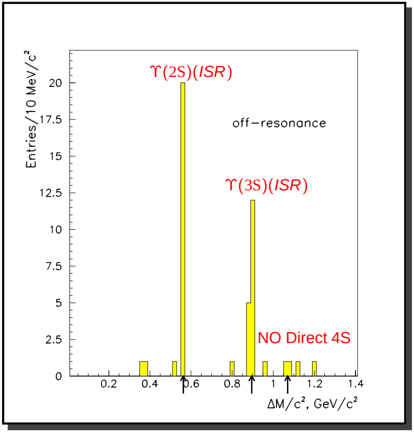
At EPS05, BELLE reported a study of $\pi^+\pi^-$ transitions at $\Upsilon(4S)$

Luminosity On 4S (fb^{-1})	398
Number of 4S ($x10^6$)	386
Luminosity Off 4S (fb^{-1})	40

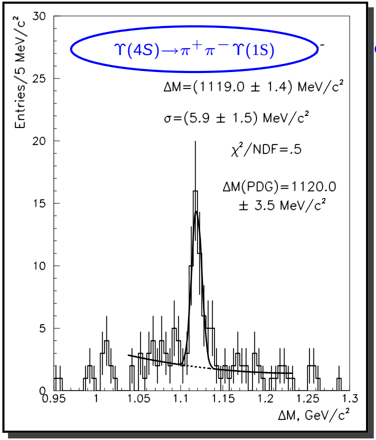
- Require $\mu^+\mu^-$ candidate, $M_{\mu^+\mu^-}$ consistent w/$M(\Upsilon(1S)) = 9.460$ GeV
- Also a $\pi^+\pi^-$ candidate, w/$\Delta M \equiv M_{\pi^+\pi^-\mu^+\mu^-} - M_{\mu^+\mu^-}$
- Remove bkg from $e^+e^-\to\gamma\mu^+\mu^-$, w/$\gamma\to e^+e^-$ in detector by cut on $\theta_{\pi^+\pi^-}$
- Fit ΔM spectrum in region near $M(\Upsilon(4S)) - M(\Upsilon(1S))$

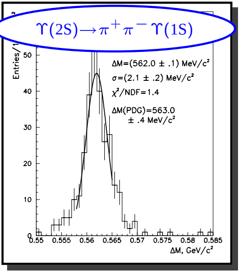
Belle: ΔM Spectra On and Off 4S (hep-ex/0512034)

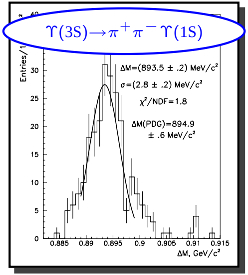




Belle: $\mathcal{B}(\Upsilon(4S)\to\Upsilon(1S)\pi^+\pi^-)$ (hep-ex/0512034)







From the fit to the 3rd peak:
Yield: 38.0 ± 6.9 events (7.3σ)
$\mathcal{B}(4S\to 1S\pi^+\pi^-) = (1.1\pm0.2\pm0.4)\times10^{-4}$
$\Gamma(4S\to 1S\pi^+\pi^-)) = 2.2\pm1.0$ keV

c.f. $\Gamma_{1S\pi^+\pi^-}(\Upsilon(2S)) = 8.1\pm1.2keV$
$\Gamma_{1S\pi^+\pi^-}(\Upsilon(3S)) = 1.2\pm0.2keV$

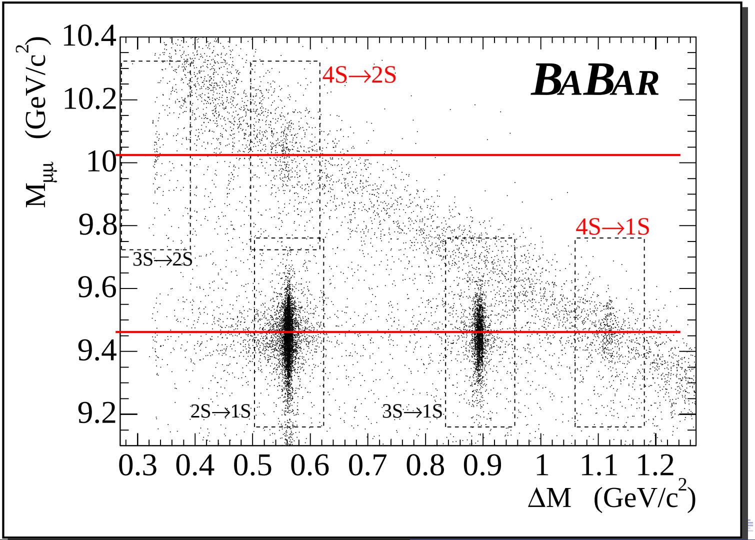
Bottomonia at BaBar: PRL 96 232001

BaBar has reported a study of $\Upsilon(4S)\to(\Upsilon(2S,1S))\pi^+\pi^-$. $\Upsilon(1S)$ and $\Upsilon(2S)$ candidates are identified via $\mu^+\mu^-$ decay. Daughter decays to e^+e^- seen, but not as clean (or as significant)

Luminosity On 4S (fb^{-1})	211
Number of 4S ($x10^6$)	230
Luminosity Off 4S (fb^{-1})	22

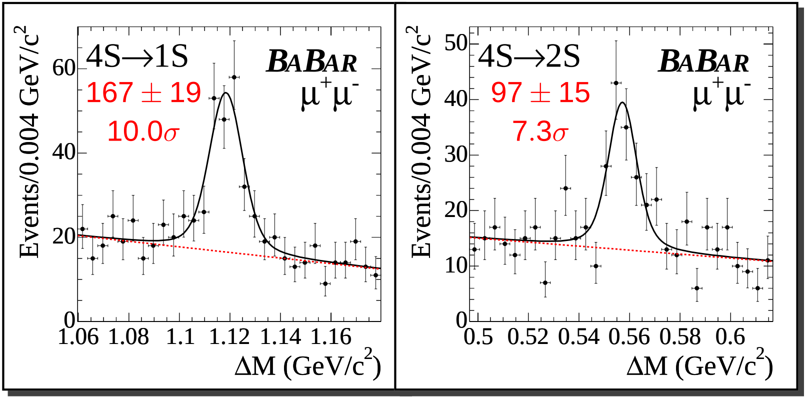
- Select events with 4 tracks w/in fiducial volume, constrained to common vertex
- Two tracks consistent with μ, two tracks NOT consistent with e^+e^-; needed to reject $\mu^+\mu^-\gamma$ events in which $\gamma\to e^+e^-$ in detector.

BaBar: ΔM vs. $M(\mu^+\mu^-)$ PRL 96 232001



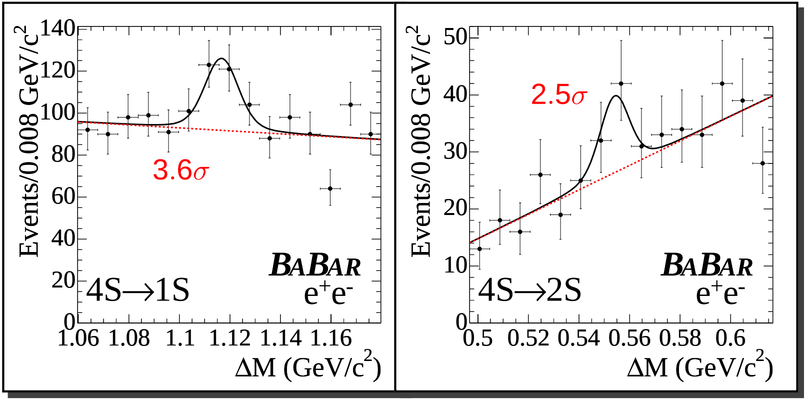
Results of fits to ΔM spectra PRL 96 232001

Highly significant signals (10.0σ and 7.3σ), for 1S and 2S respectively).



Results of fits to ΔM spectra PRL 96 232001

Clear, but less significant e^+e^- peaks



Yields from fits to ΔM spectra PRL 96 232001

Transition	N_{sig}	signif.	$\epsilon(\%)$
$4S \rightarrow 1S$	167 ± 19	10.0σ	32.5 ± 3.9
$4S \rightarrow 2S$	97 ± 15	7.3σ	24.9 ± 3.0

From the above, BaBar reports:

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

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

BaBar Results: PRL 96 232001

Using world average values for $B(\Upsilon(\mathrm{nS})\to\mu^+\mu^-)$, and a recent measurement (BaBar) of $\Gamma_{tot}(\Upsilon(4S))$ BaBar reports:

$$B(\Upsilon(4S)\to\Upsilon(1S)\pi^+\pi^-) = (0.90 \pm 0.15) \times 10^{-4}$$

$$\Gamma(\Upsilon(4S)\to\Upsilon(1S)\pi^+\pi^-) = 1.8 \pm 0.4 \text{ keV}$$

$$B(\Upsilon(4S)\to\Upsilon(2S)\pi^+\pi^-) = (1.29 \pm 0.32) \times 10^{-4}$$

$$\Gamma(\Upsilon(4S)\to\Upsilon(2S)\pi^+\pi^-) = 2.7 \pm 0.8 \text{ keV}$$

BaBar Results: PRL 96 232001

Using world average values for $B(\Upsilon(\mathrm{nS})\to\mu^+\mu^-)$, and a recent measurement (BaBar) of $\Gamma_{tot}(\Upsilon(4S))$ BaBar reports:

$$B(\Upsilon(4S)\to\Upsilon(1S)\pi^+\pi^-) = (0.90 \pm 0.15) \times 10^{-4}$$

$$\Gamma(\Upsilon(4S)\to\Upsilon(1S)\pi^+\pi^-) = 1.8 \pm 0.4 \text{ keV}$$

With the more recent CLEO result of $B_{\mu^+\mu^-}(\Upsilon(2S))$:

$$B(\Upsilon(4S)\to\Upsilon(2S)\pi^+\pi^-) = (0.83 \pm 0.16) \times 10^{-4}$$

$$\Gamma(\Upsilon(4S)\to\Upsilon(2S)\pi^+\pi^-) = 1.7 \pm 0.5 \text{ keV}$$

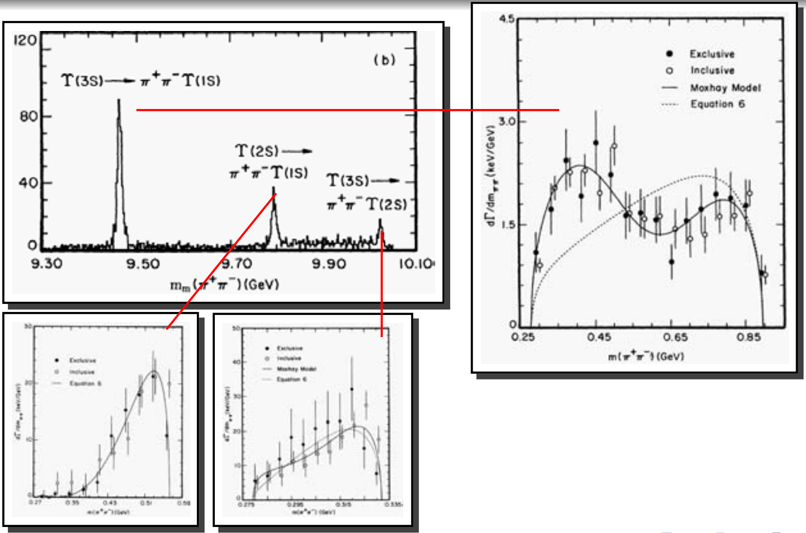
c.f. Belle's

$$\Gamma(\Upsilon(4S)\to\Upsilon(1S)\pi^+\pi^-) = 1.1 \pm 0.2 \pm 0.4 \text{ keV.}$$

The question of $\pi^+\pi^-$ Invariant Mass

- The subject of $\pi^+\pi^-$ invariant mass distributions for transitions among bottomonia has a long history of interest.
- $\Upsilon(3S)\to\Upsilon(2S)\pi^+\pi^-$, $\Upsilon(2S)\to\Upsilon(1S)\pi^+\pi^-$ well fit by an S-wave model (Kuang/Yan PRD 24, 2874 (1981)), but NOT $\Upsilon(3S)\to\Upsilon(1S)\pi^+\pi^-$.
- A better fit to $\Upsilon(3S)\to\Upsilon(1S)\pi^+\pi^-$ is found with Moxhay's model (PRD 39, 3497 (1989)) and others (coupled-channel effects, etc.)
- New information on 4S decays from BaBar and Belle: a very interesting picture indeed.

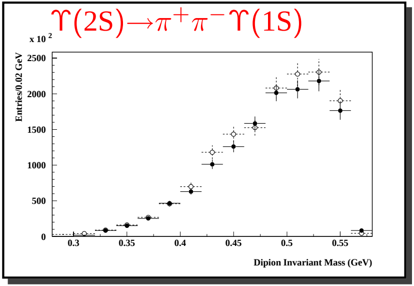
The Question of $\pi\pi$ Invariant Mass

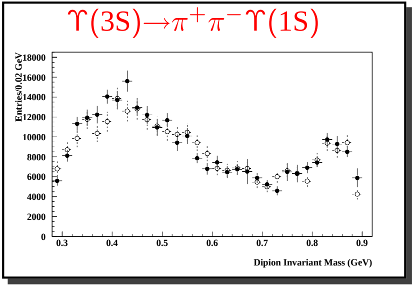


CLEO: $\pi^+\pi^-$ Invariant Mass PRELIMINARY

Data shown are from $\Upsilon(2S)$ and $\Upsilon(2S)$, wherein a $\pi^+\pi^-$ candidate recoils against $\Upsilon(1S)$.

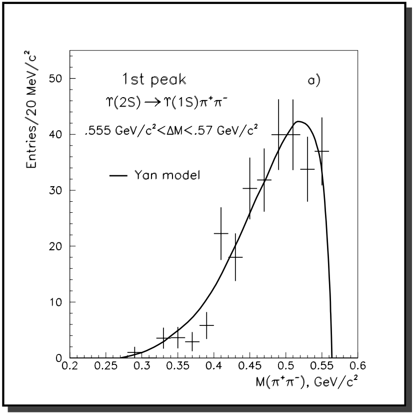
- Open circles: $\Upsilon(1S)$ is observed via $\ell\ell$.
- Closed circles: $\Upsilon(1S)$ is unobserved.

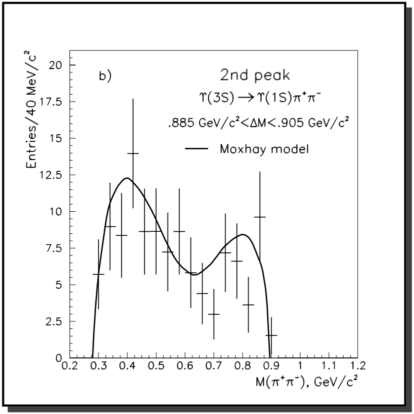




Belle: $\pi^+\pi^-$ Invariant Mass hep-ex/0512034

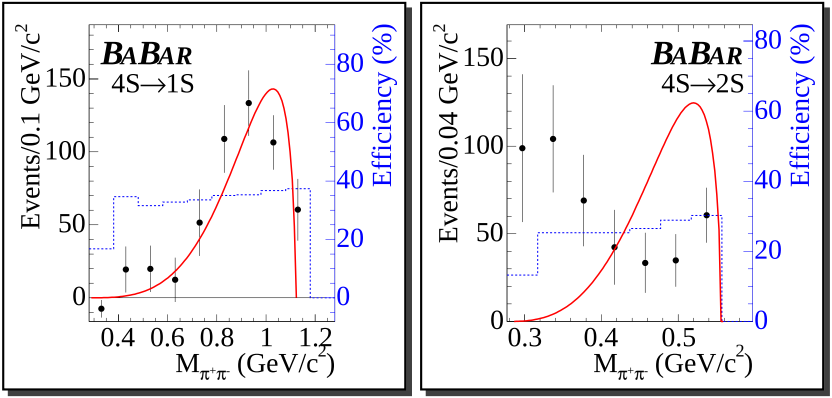
$M(\pi^+\pi^-)$ for selected ΔM regions near ISR peaks.





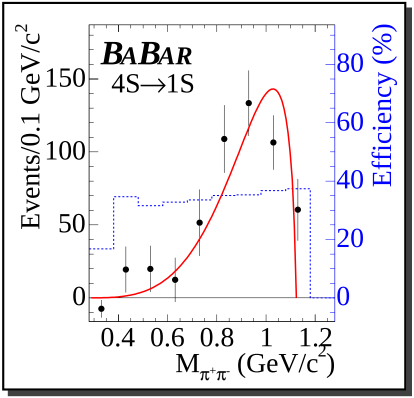
BABAR: $\pi^+\pi^-$ Invariant Mass PRL 96 232001

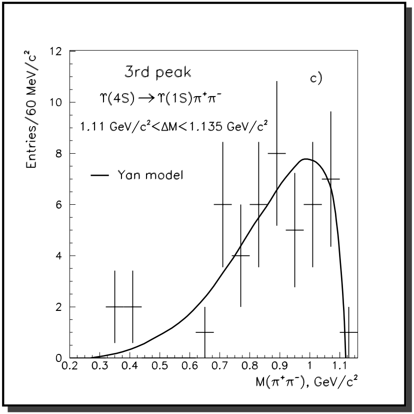
$M(\pi^+\pi^-)$ for selected ΔM regions near 4S peaks



BABAR/Belle: $\pi^+\pi^-$ Invariant Mass

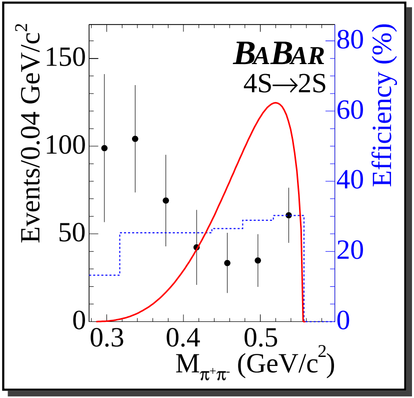
For comparison: Note the Yan-type mass distribution of $\Upsilon(4S) \to \Upsilon(1S)$

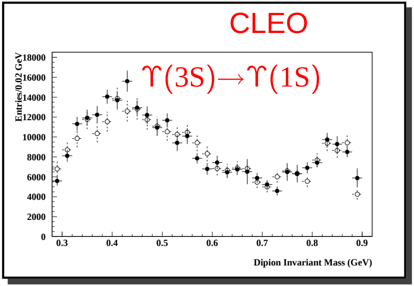




BABAR/CLEO: $\pi^+\pi^-$ Invariant Mass

For comparison: Note the Moxhay-type mass distribution of $\Upsilon(nS)\rightarrow\Upsilon([n-2]S)$





An aside: $\pi^+\pi^-$ Invariant Mass in $c\bar{c}$

compare with

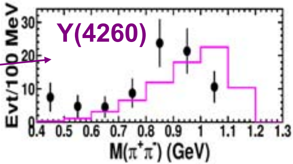
Dipion Transitions in $c\bar{c}$

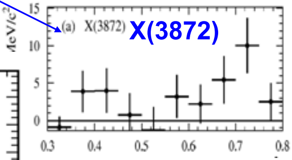
CLEO-c $Y(4260) \to \pi\pi\, J/\psi$

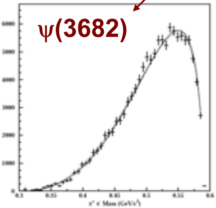
BaBar $X(3872) \to \pi\pi\, J/\psi$

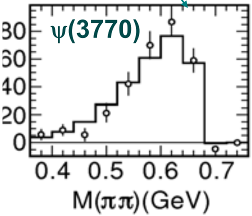
CLEO-c $\psi(3770) \to \pi\pi\, J/\psi$

BES $\psi(3682) \to \pi\pi\, J/\psi$









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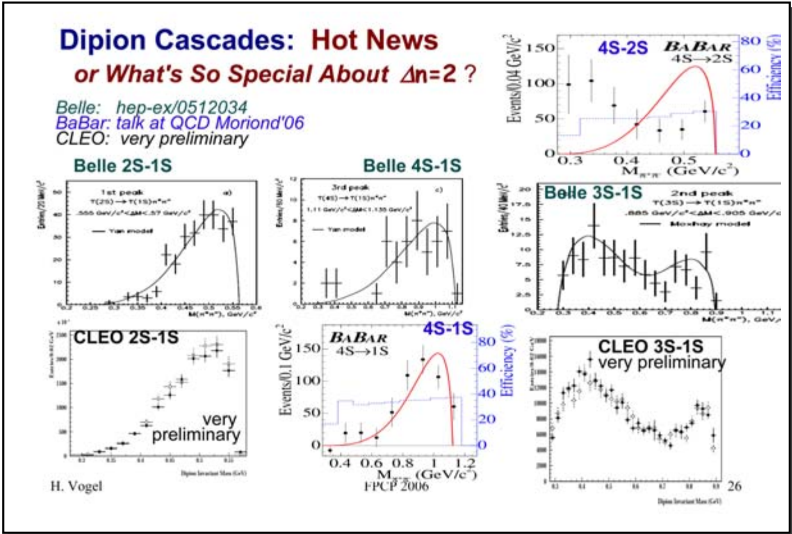
PRD 62 (2000) 032002

Conclusions and Future Prospects

- 30 years after the discovery of bottomonium, a new era in the spectroscopy of the system has been opened
- New states (1D) and new transitions ($\chi_b(2P) \to \omega\Upsilon(1S)$, $\chi_b(2P) \to \pi^+\pi^-\chi_b(1P)$) have been discovered
- New, very precise measurements of all leptonic decay modes have beem made
- BELLE and BaBar have presented some tantalizing new results involving $\pi^+\pi^-$ transitions from $\Upsilon(4S)$
- Stay tuned for several upcoming results from CLEO

RESERVE SLIDES

$\Upsilon(nS)$ Hadronic Transitions



$\Upsilon(nS)$ Hadronic Transitions