Upsilon Decays

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upsilon decay (*'up-si-”l&n di-'kA*). 1. decay of a bound *bb* state,
2. decay of an unbound *bb* state to a bound *bb* state.

Motivation for Studying Bound State $b\bar{b}$

Test Lattice QCD – Masses, Transition Rates, Γ_{ee}, HF splittings

Decay Models – $\pi\pi$ via E1E1 gluons, ω *vs.* γ transitions

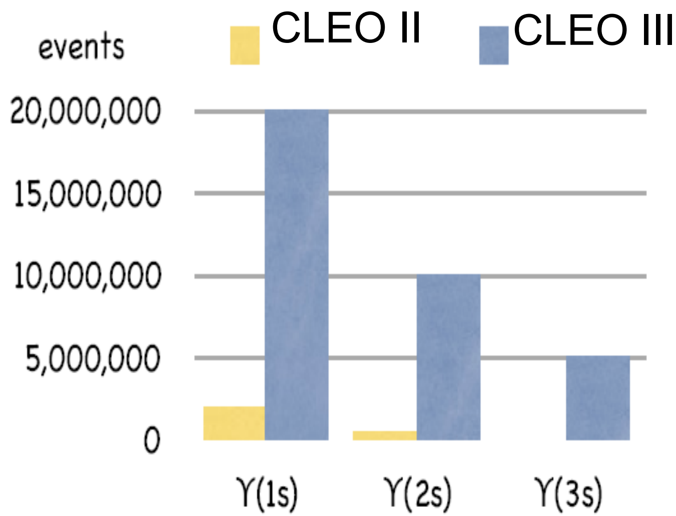
QCD & Potential Models – α_s, LS coupling, color octet/singlet

Comparison to charmonium -- radiative decays, *e.g.*, $\gamma\,\eta(')$

Correlation to B physics – inclusive η, η'

Beyond SM tests – *e.g.*, LFV via $\mu\,\tau$

The Renaissance in Υ Physics



CESR, Nov 2001 – Dec 2002:
* Dedicated Υ(1S), Υ(2S), Υ(3S) runs
* 10-20-fold increase in world supply
* State-of-the-art detector, CLEO III

B Factories, since 2000:
produce Υ(nS), n=1,2,3 via ISR
(but have only recently begun to exploit them)

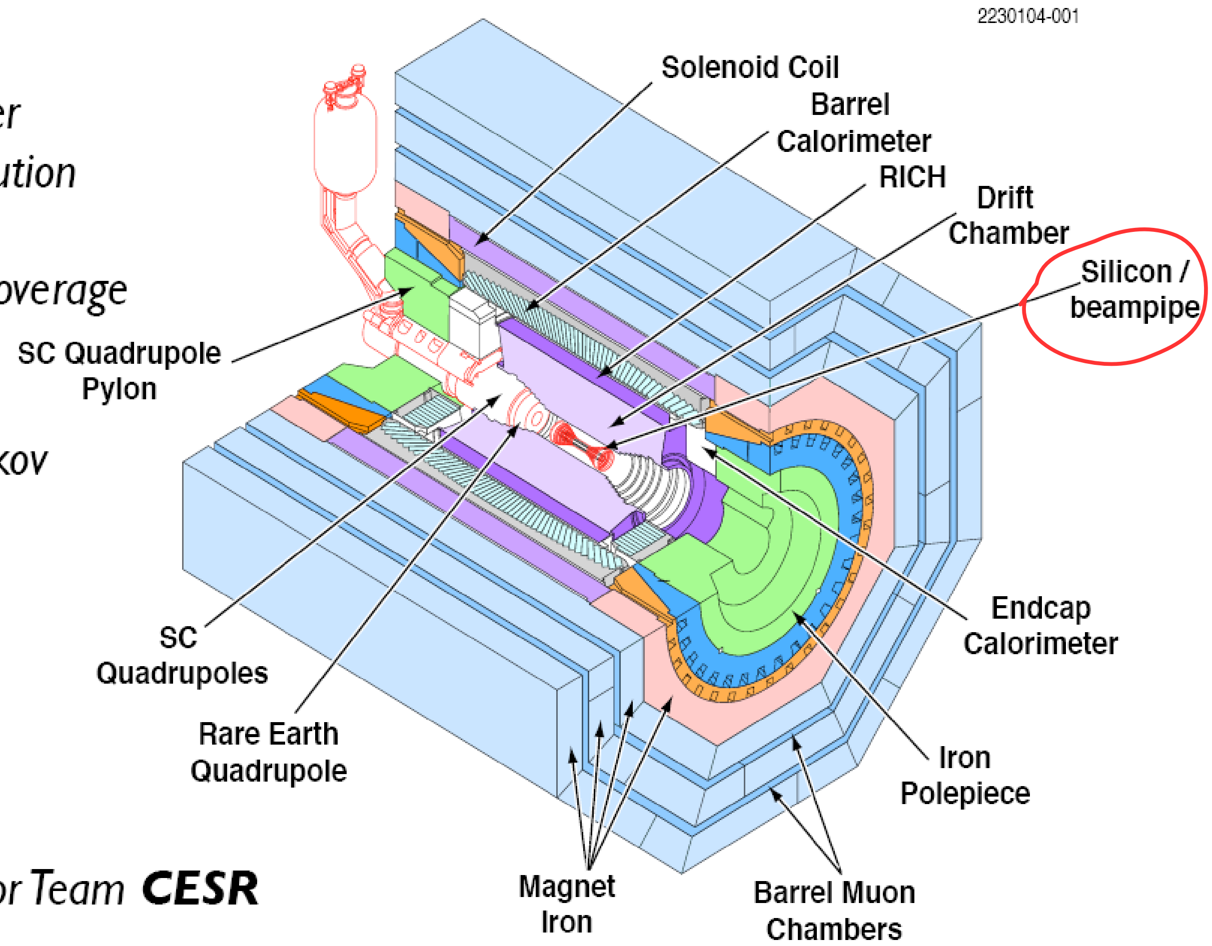
The CLEO III Detector

Excellent Calorimeter Coverage and Resolution

Excellent Tracking Coverage and Resolution

Ring Imaging Cerenkov and dE/dx for PID

Muon Chambers



+ A Great Accelerator Team ***CESR***

Recent and Hot News in Upsilon Decay

(incomplete overview)

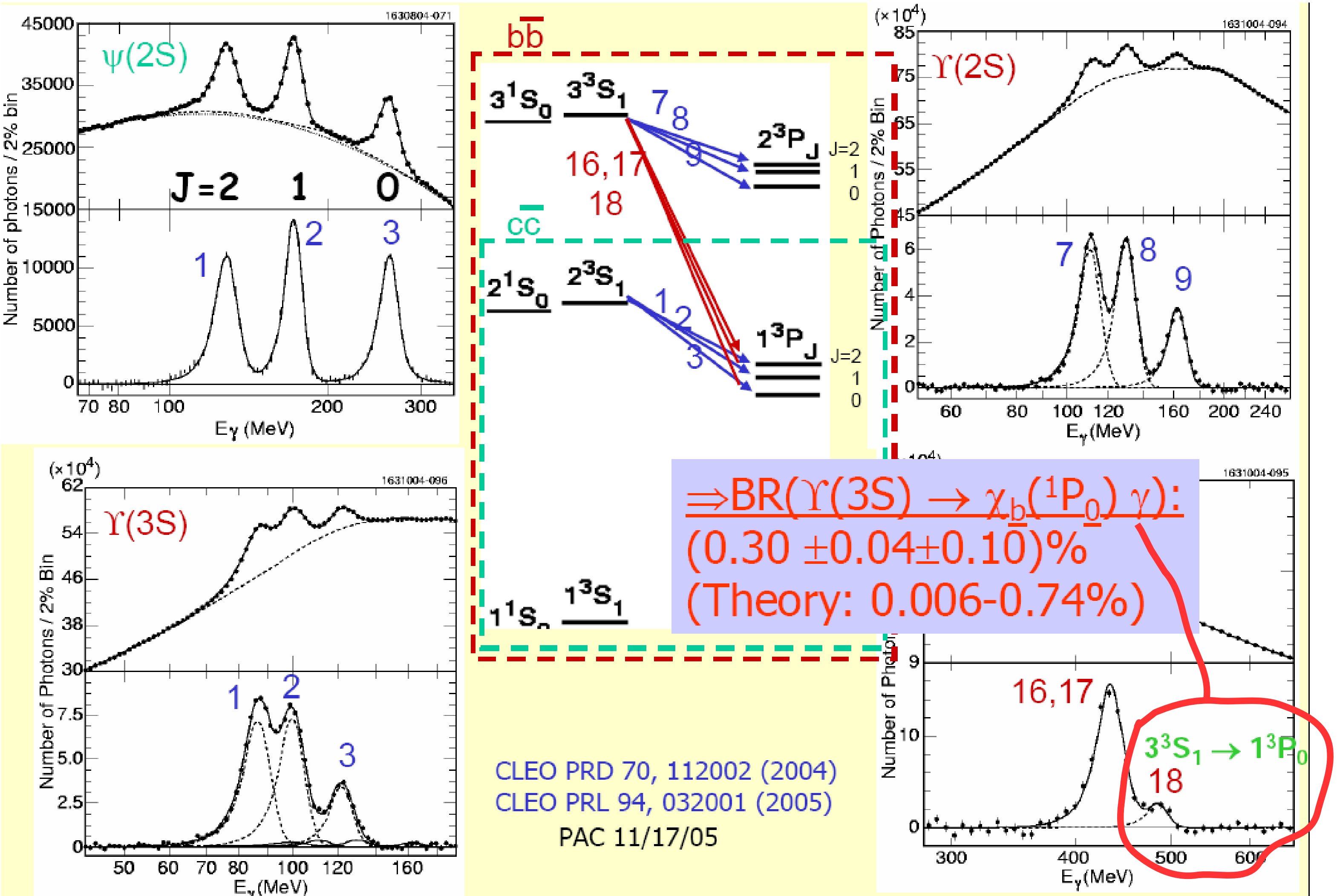
- Photon Transitions from $\Upsilon(2S)$ and $\Upsilon(3S)$
- Decay of $\Upsilon(1S)$ to Charmonium
- Radiative Decays: $\Upsilon(1S) \to \gamma\, h^+ h^-$, $\Upsilon(1S) \to \gamma\, \eta(')$
- "Unusual" Hadronic Transitions within the Upsilon System
- Precision Measurement of $B_{\mu\mu}$ and Γ_{ee} of $\Upsilon(1S,2S,3S)$

} CLEO

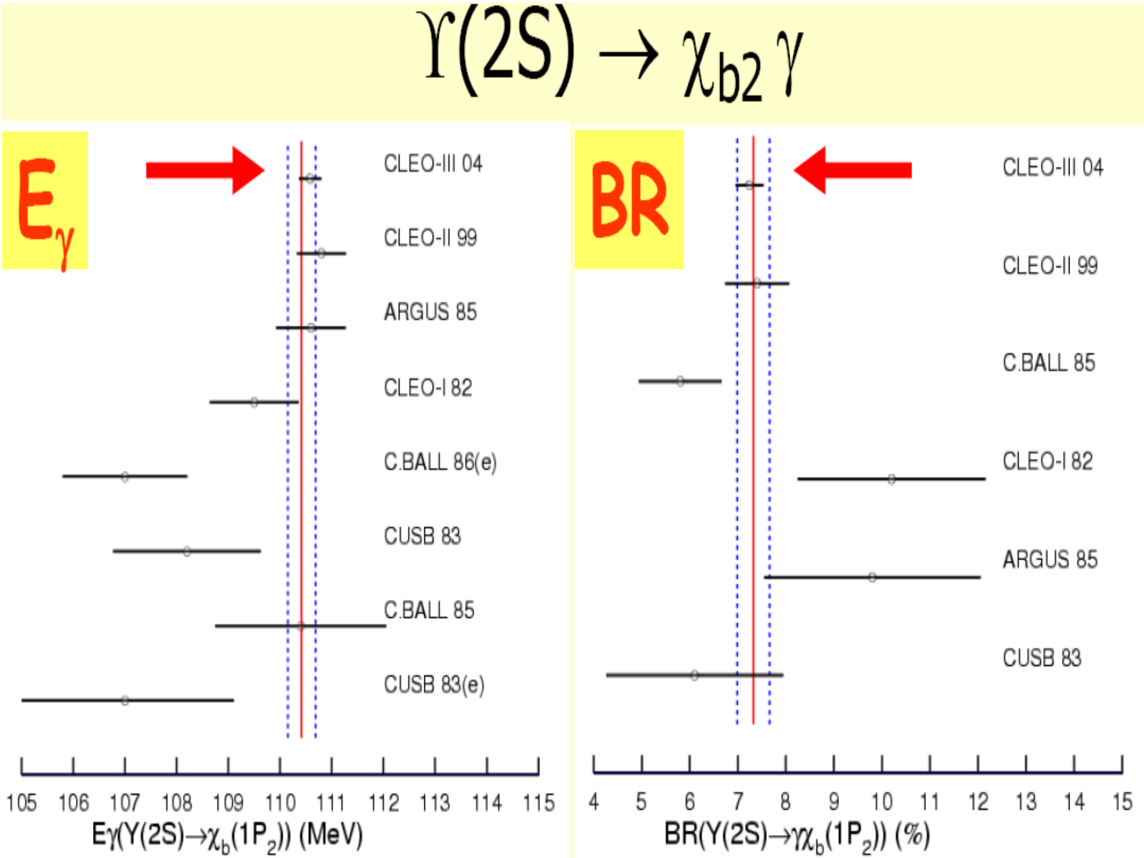
- "Usual" (but intriguing) Dipion Transitions (CLEO, Belle, BaBar)

- and more-- $B_{\tau\tau}$, study of $\Upsilon(5S)$, $\Upsilon(1S) \to \gamma X$, ... (sorry, not enough time!)

E1 Photon Transitions: Δn=1 and Δn=2



Photon Transitions: Impact of E1 Results



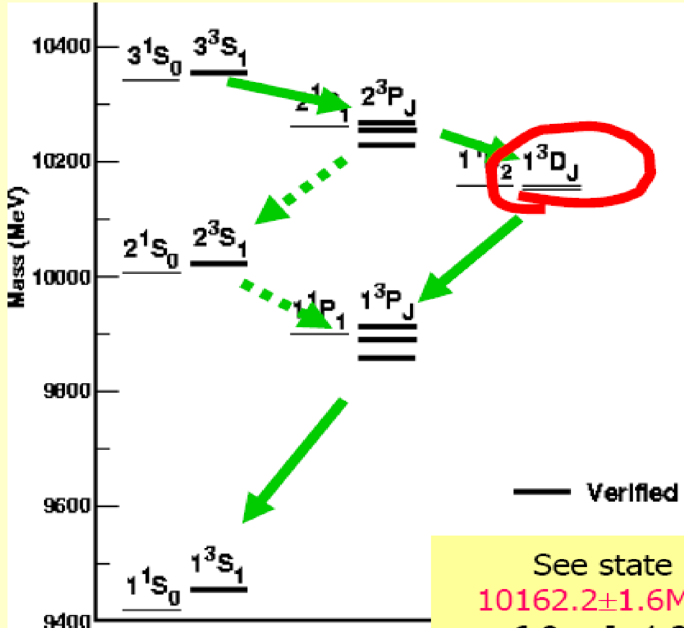
Significant improvement in **precision** (by now systematics dominated)

Test **relativistic corrections** in bb potential models (indeed smaller in bb than in cc)

Verify **spin dependence** of E1 matrix element, $(2J+1)(E_\gamma)^3$

E1 transitions have **large BRs** -- copious **production of P states** (not directly accessible in e+e- collisions)

Photon Transitions: the 1^3D_J State



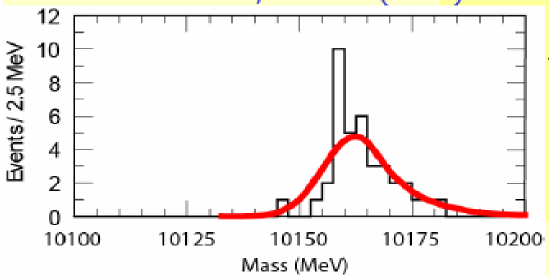
See state at 10162.2±1.6MeV at 6.8σ: J=1,2,3?

inconsistent with J=3

Theory: $\Upsilon(1^3D_2)/\Upsilon(13D1)=6$

Υ(13D2) most likely

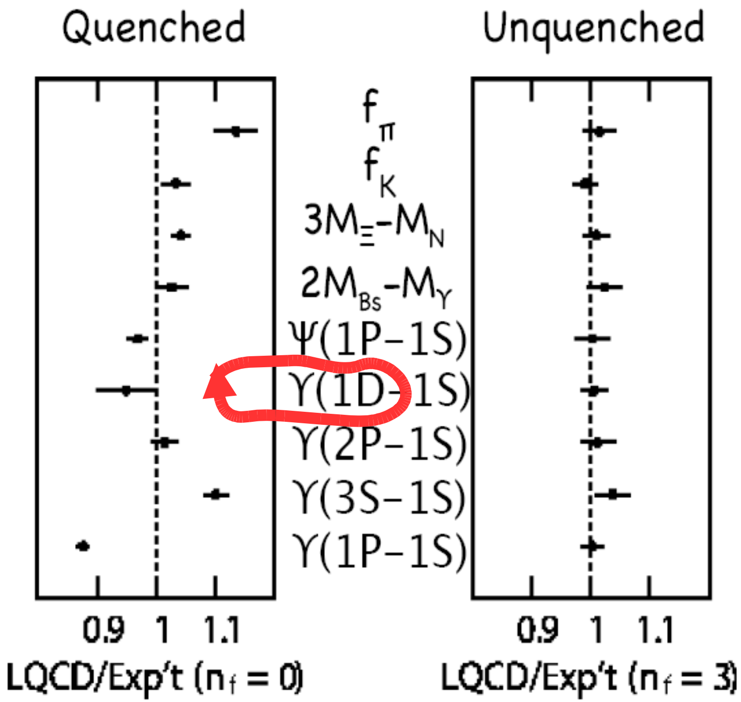
CLEO PRD 70, 032001 (2004)



Recoil mass against two lowest energy photons; cascade through Υ(2S) already suppressed

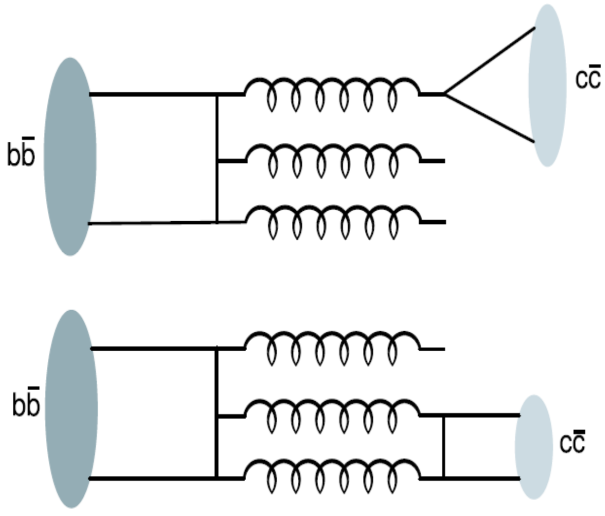
First new Upsilon state in 20 years
First long-lived L=2 meson
below open-flavor threshold

Test of LQCD

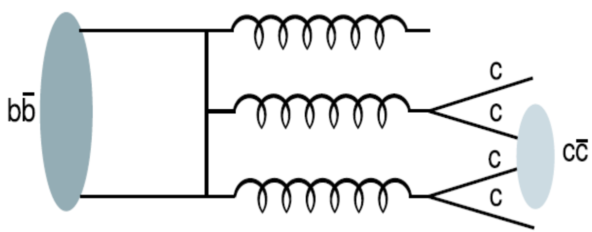


hep-lat/0304004

$\Upsilon(1S)$ Decay to Charmonium: Motivation



(a) Color - Octet Diagrams



(b) Color - Singlet Diagram

Tests models of charmonium production in gluon-rich environments

(cf. copious production of "prompt" J/ψ at the Tevatron)

Candidate Models:

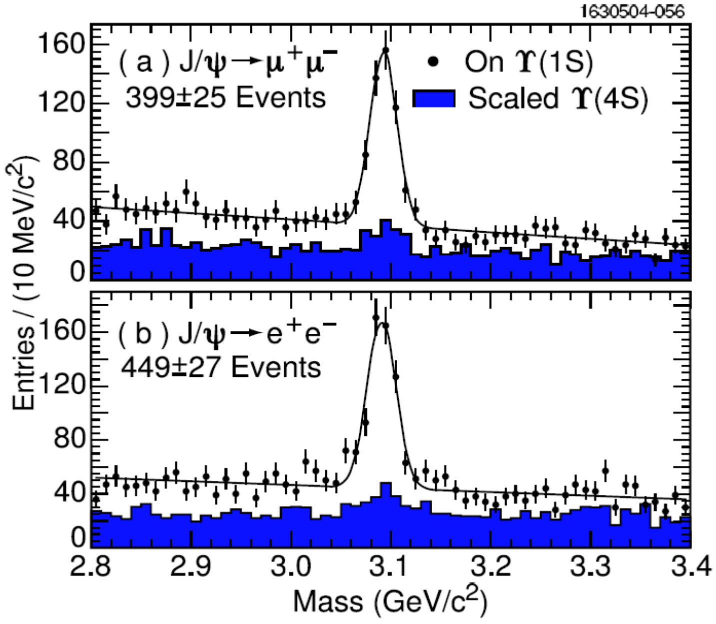
*** Color-Octet (Braaten & Fleming 1995)**

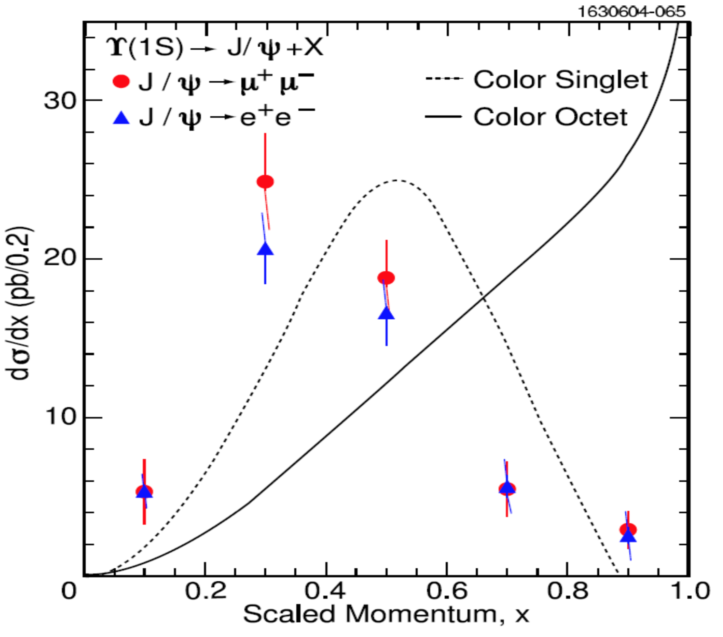
*** Color-Singlet (Li, Xie, & Wang 2000)**

predict BR and J/ψ momentum spectrum

Υ(1S) Decay to Charmonium: Results

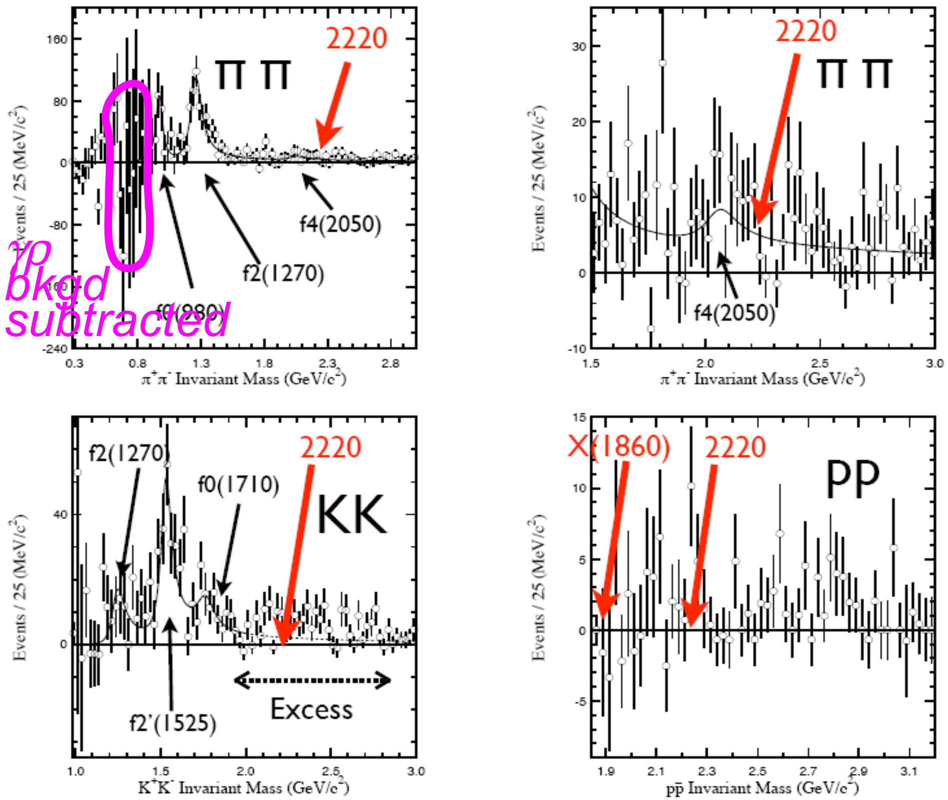
CLEO PRD 70 (2004) 072001





- $B(\Upsilon(1S) \rightarrow J/\psi + X) = (6.4 \pm 0.4 \pm 0.6) \times 10^{-4}$ favors color-octet.
- Momentum spectrum of J/ψ's is softer than predicted (FSI?)
- Transitions to $\psi(2S)$ and χ_c states are also observed.

Radiative Decays: $\Upsilon(1S) \rightarrow \gamma\, h^{+} h^{-}$ (h = π, K, p)



The hadron pair is produced in a glue-rich environment --
Ideal source of glueballs (if they exist)

Probe two-gluon structure

Expected **scaling from J/ψ** :

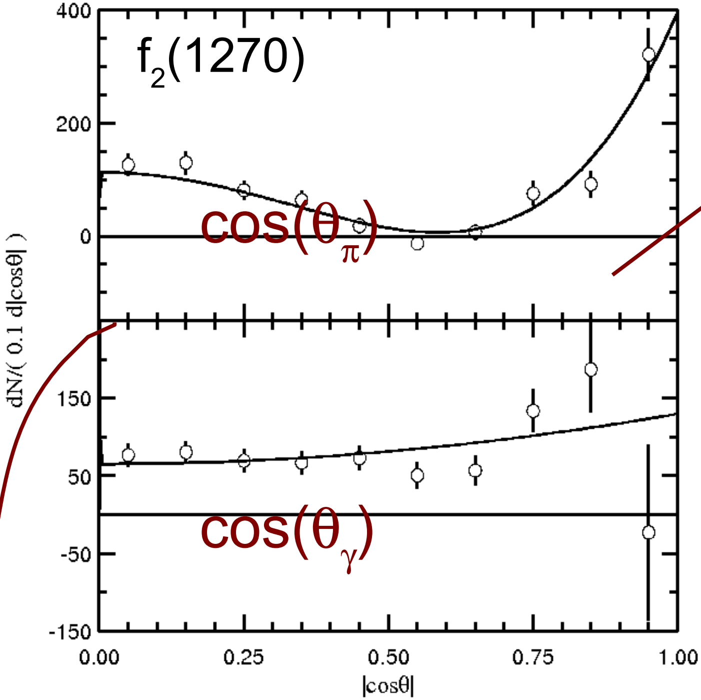
rates suppressed by $((q_b m_c)/(q_c m_b))^2 \approx 1/40$
BF's suppressed by ≈1/25

Fit observed structure with relativistic, spin dependent Breit-Wigner curves

Also studied the $\gamma\,\pi^0\pi^0$ final state
(no $\gamma\,\rho$ continuum background)

Radiative Decays, $\Upsilon(1S) \to \gamma h^+ h^-$: Results

CLEO PRD 73 (2006) 032001



fit to J=2 helicity formalism

Confirm **f_2(1270)** in ππ channel
Establish J=2 assignment

Observe **f_2'(1525)** in KK channel; also J=2

BR = (10.2 ± 0.8 ± 0.7) x 10^{-5} (f_2(1270))
BR = (3.7 ± 0.8 ± 0.8) x 10^{-5} (f_2'(1525))

Consistent with scaling from J/ψ

Tensor mesons dominate the observed structure

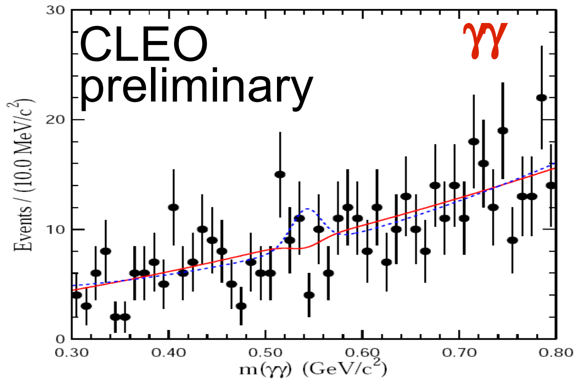
No signal for f_J(2200), set UL:

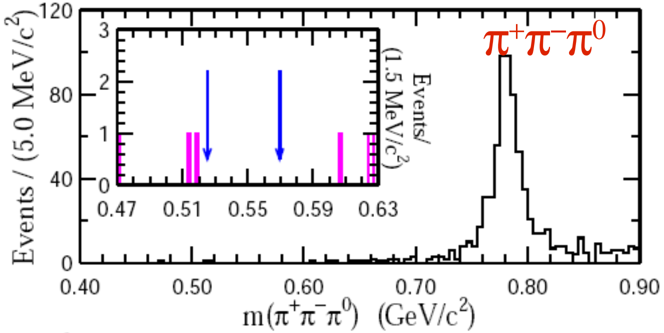
$$\mathcal{B}(\Upsilon(1S) \to \gamma f_J(2200)) \times \mathcal{B}(f_J(2200) \to \pi^+\pi^-) < 8 \times 10^{-7},$$

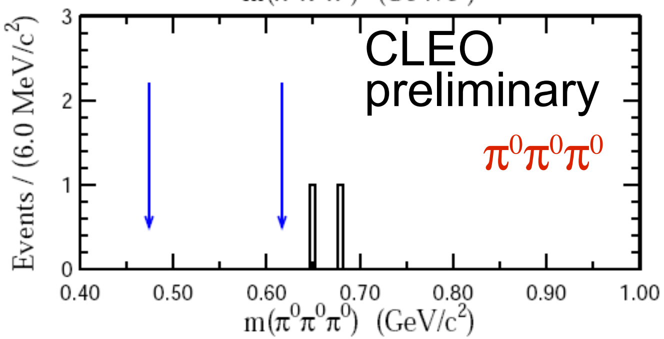
$$\mathcal{B}(\Upsilon(1S) \to \gamma f_J(2200)) \times \mathcal{B}(f_J(2200) \to K^+K^-) < 6 \times 10^{-7},$$

$$\mathcal{B}(\Upsilon(1S) \to \gamma f_J(2200)) \times \mathcal{B}(f_J(2200) \to p\bar{p}) < 11 \times 10^{-7}.$$

Radiative Decays: Search for $\Upsilon(1S) \to \gamma\,\eta(')$







Motivation:

Theoretically simple process (no hadronic FSI)

Extensively studied in J/ψ radiative decay - good agreement with theory

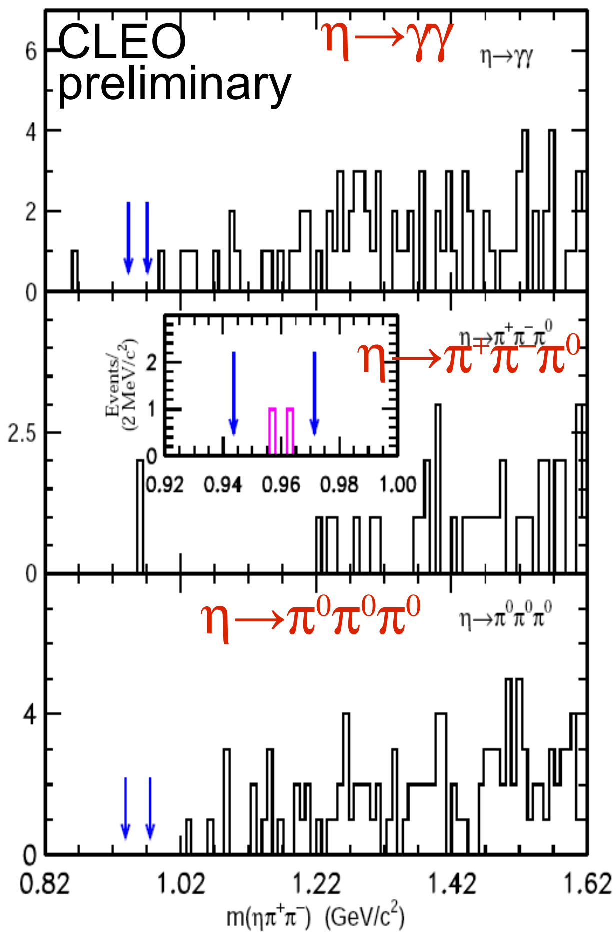
Test models of scaling:
- **VDM**
- **NRQCD**
- **mixing with η_b**

Previous UL ≈ 2×10^{-5} (CLEO II)

Choose 3 main decay modes for η and 4 for η' (3x ($\eta\,\pi^+\pi^-$) and $\gamma\,\rho$)

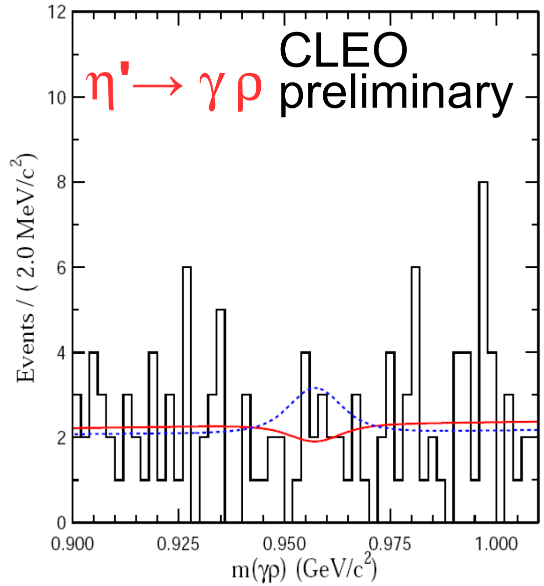
No candidates seen in any η channel

Radiative Decays: Search for $\Upsilon(1S) \to \gamma\,\eta(')$



No signal observed

in 21M Υ(1S) events



Set upper limits,

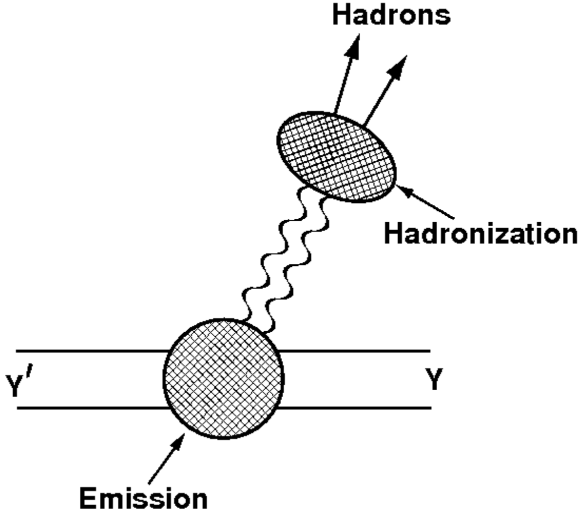
$$\mathcal{B}(\Upsilon(1S) \to \gamma\eta) < 9.3 \times 10^{-7},$$

preliminary

$$\mathcal{B}(\Upsilon(1S) \to \gamma\eta') < 1.77 \times 10^{-6}$$

Strongly disfavors mixing with η_b
Still consistent with VDM and (barely) with NRQCD

Hadronic Transitions between Upsilon States



Motivation:

Test of models of gluon (E1E1) emission

(e.g., Yan, Gottfried)

Most common process (known for decades):

Dipion transition between $^3S_1$ states,
***e.g.*, $\Upsilon(mS) \rightarrow \pi\pi\, \Upsilon(nS)$, m>n**

(BR ≈ 50% in cc, BR ≈ 5 - 20 % in bb)

"Unusual" Hadronic Transition #1

$\chi_b' \rightarrow \omega\, \Upsilon(1S)$

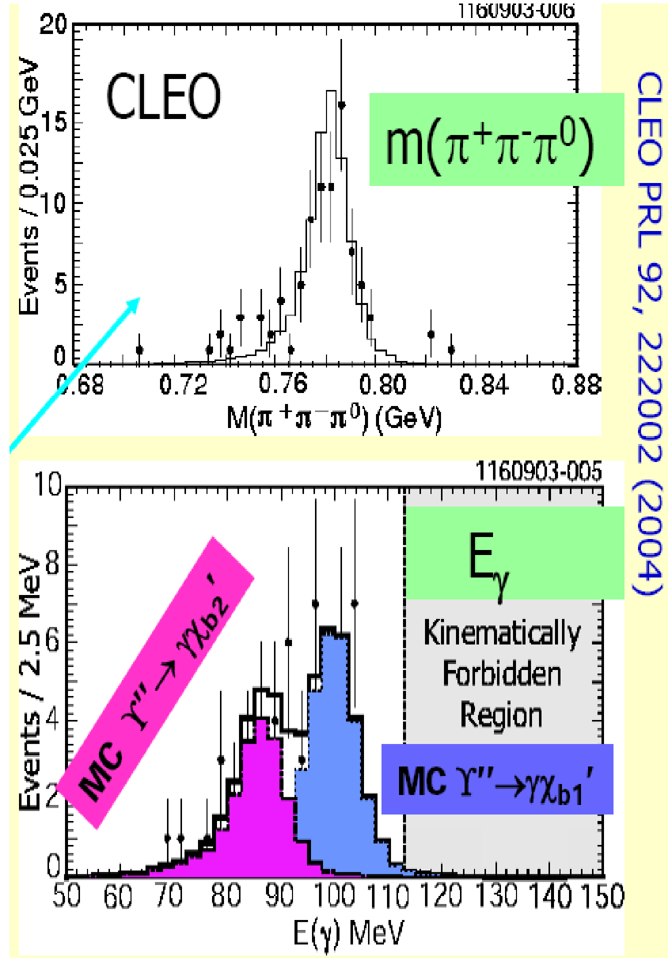
observed via

$\Upsilon(3S) \rightarrow \gamma\, \chi_b'$
Final state: $\gamma + \pi^+\pi^-\pi^0 + l^+l^-$

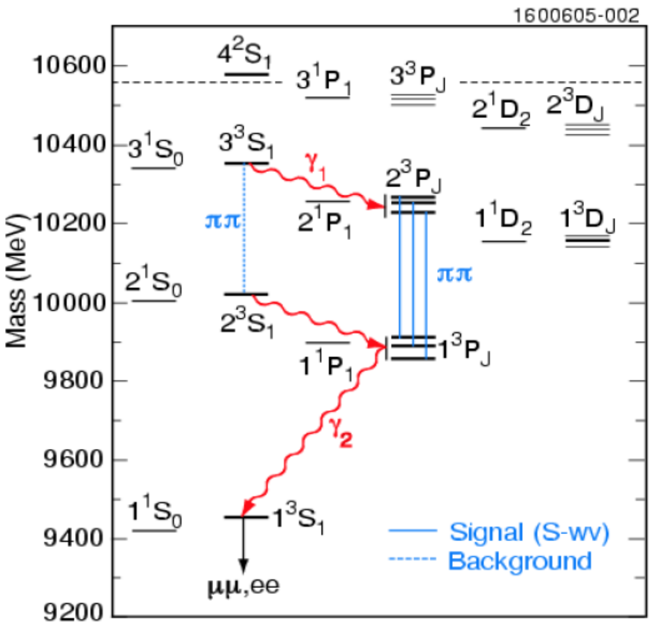
First non-pionic hadronic transition between Upsilon states

$B(\chi_{b1}' \rightarrow \omega\, \Upsilon(1S)) = 1.6\ \%$
$B(\chi_{b2}' \rightarrow \omega\, \Upsilon(1S)) = 1.1\ \%$

very large, considering phase space -- and nearly equal.
Agrees with prediction by Gottfried, *cf*. also Voloshin hep-ph/0304165



"Unusual" Hadronic Transition #2



$\chi'_b(2P) \rightarrow \pi\pi\ \chi_b(1P)$

observed via cascade,

$\Upsilon(3S) \rightarrow \gamma\ \chi'_b(2P)$

$\chi'_b(2P) \rightarrow \pi\pi\ \chi_b(1P)$

$\chi_b(1P) \rightarrow \gamma\ \Upsilon(1S)$

$\Upsilon(1S) \rightarrow l^+l^-$

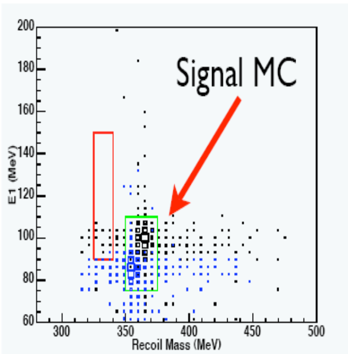
Very soft pions, plus substantial background from $\Upsilon(3S) \rightarrow \pi\pi\ \Upsilon(2S)$!

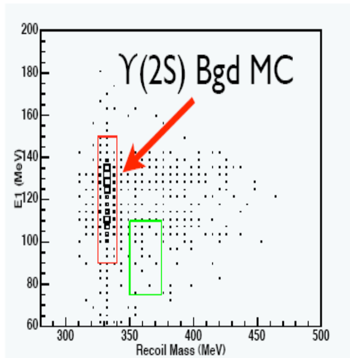
Four independent analyses

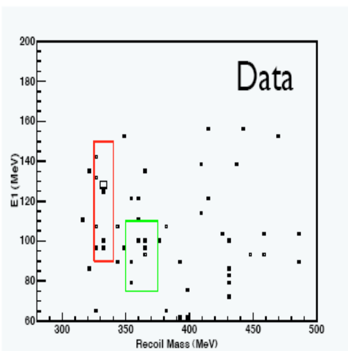
- Charged two-pion (observe both $\pi^{\pm}$)
- Charged one-pion (observe only 1 $\pi^{\pm}$)
- Neutral two-pion (observe both π^0)
- Neutral one-pion (observe only 1 π^0)

"Unusual" Hadronic Transition #2: Results

Example:
Observe both charged pions







7 Events Observed

1.2 Expected background

Size of Υ(2S) is as expected

$\epsilon \approx 4.5\%$

Combining all analyses:

Significance 6 σ

First observation of a dipion cascade between non- S states

Partial width

$$\Gamma_{\pi\pi} = (0.83 \pm 0.22 \pm 0.08 \pm 0.19)\ \mathrm{keV}$$

consistent with $\Gamma_{\pi\pi} \approx 0.4$ keV

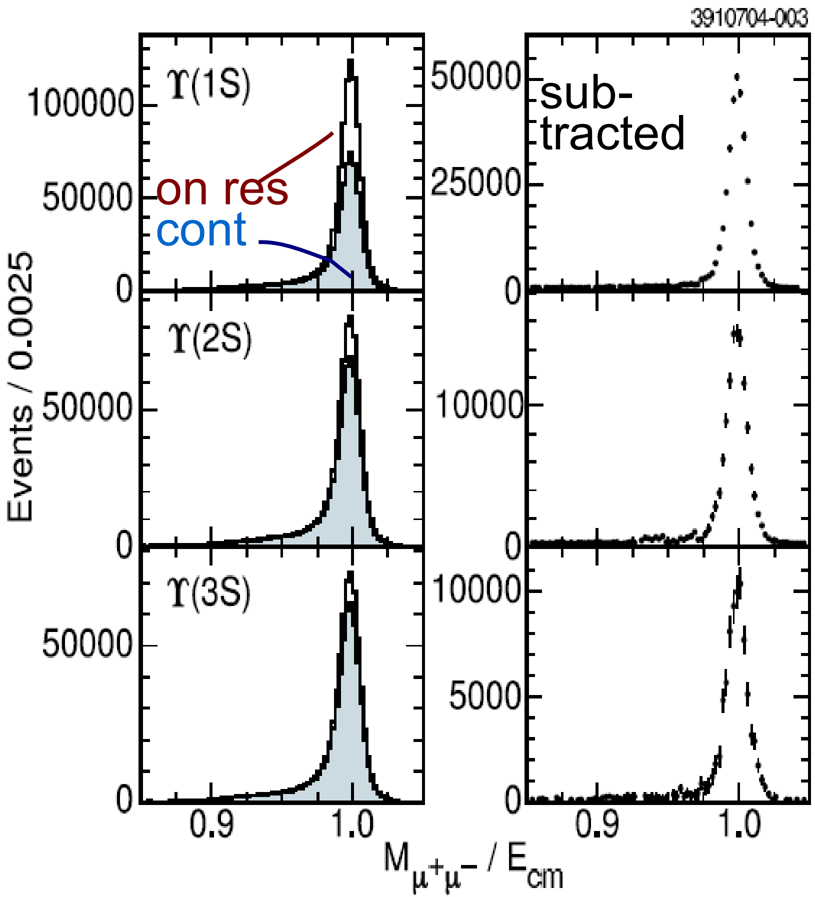
predicted by Kuang & Yan

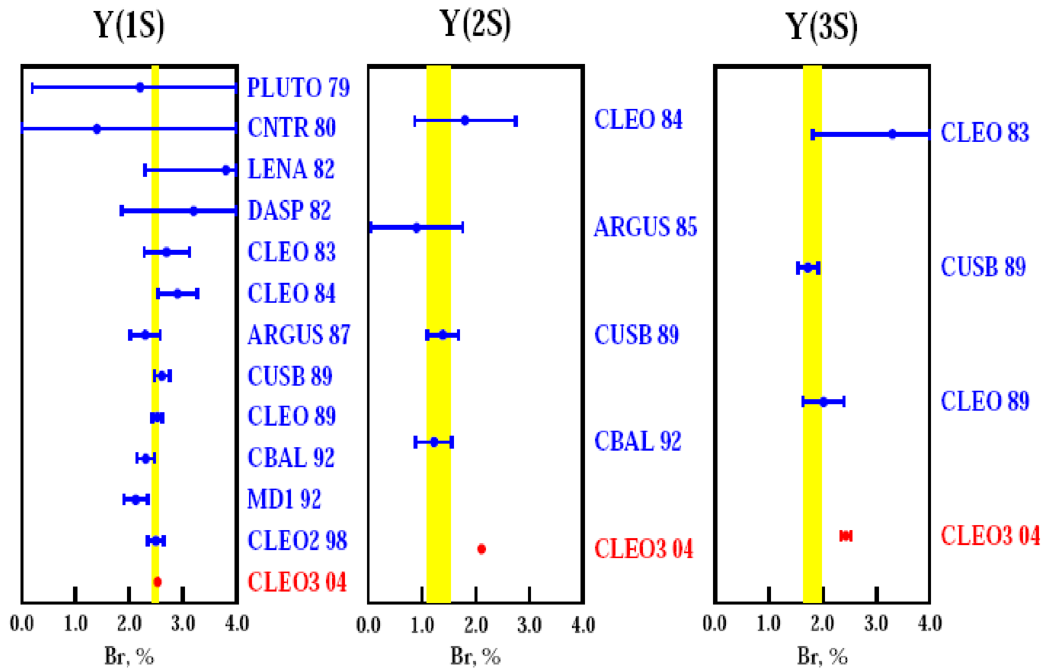
CLEO PRD 73 (2006) 012003

Precision Measurement of $B_{\mu\mu}$ of Υ(1S,2S,3S)

(a fundamental quantity in many analyses of widths and branching fractions!)

CLEO PRL 94 (2005) 012001

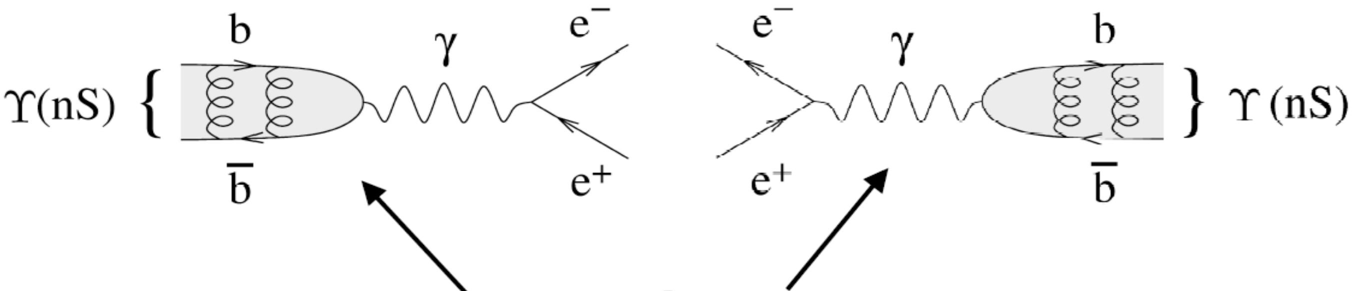




The results for Υ(2S) and Υ(3S) are significantly above previous PDG values!

Achieved relative precision of 2-3%

Precision Measurement of Γ_{ee}, of Υ(1S,2S,3S)



$$\Gamma_{ee} = \frac{M_{\Upsilon}{}^2}{6\pi^2} \int \sigma(e^+e^- \to \Upsilon)\, dE,$$

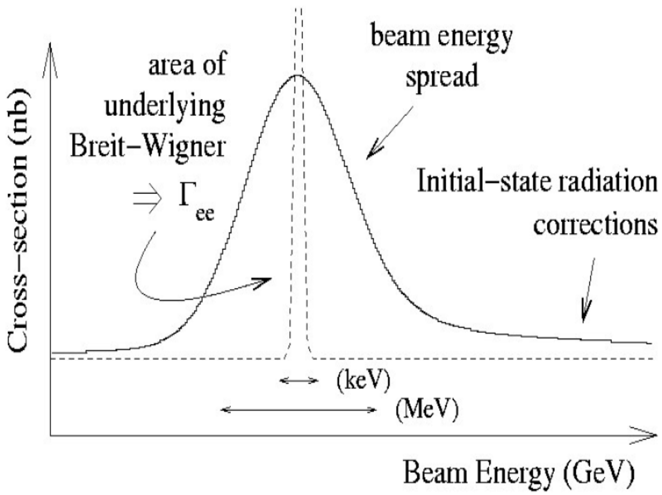
Basic plan … scan the three resonances and integrate the hadronic cross section!!

Get $\Gamma_{ee}\ \Gamma_{had} /\ \Gamma_{tot}$ without knowing $B_{\mu\mu}$

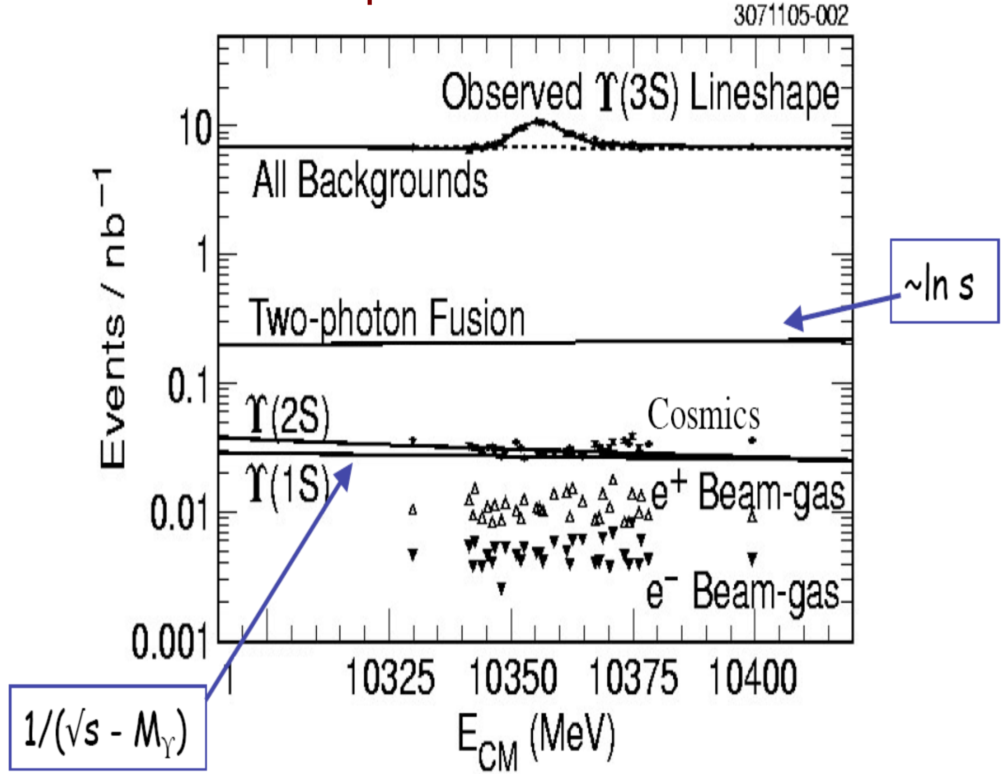
Use $B_{\mu\mu}$ to get Γ_{ee}

Use $B_{\mu\mu}$ again to get $\Gamma_{tot} = \Gamma_{ee} / B_{\mu\mu}$

Precision Measurement of Γ_{ee} of $\Upsilon(1S,2S,3S)$



Example:

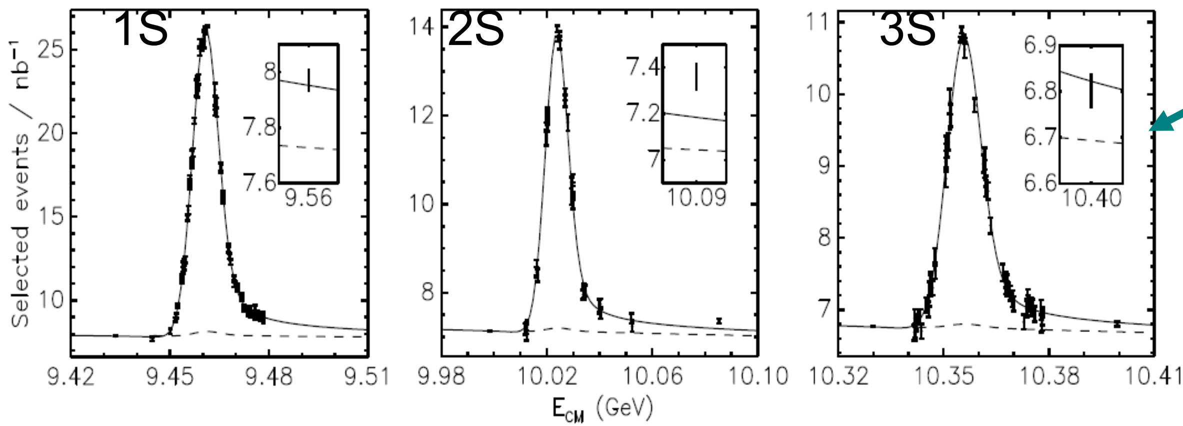


Observed lineshape is convolution of intrinsic width (O(keV)) with beam energy spread (4 MeV)
Area is preserved;
must track "height" (lumi, eff'cy, bkg) and "width" (shift in beam energy)

Performed repeated scans

Many backgrounds contribute to the observed lineshape!

Precision Measurement of Γ_{ee} of Υ(1S,2S,3S)



All the scans:
11 on Υ(1S),
6 on Υ(2S),
7 on Υ(3S) ...

...and the results:

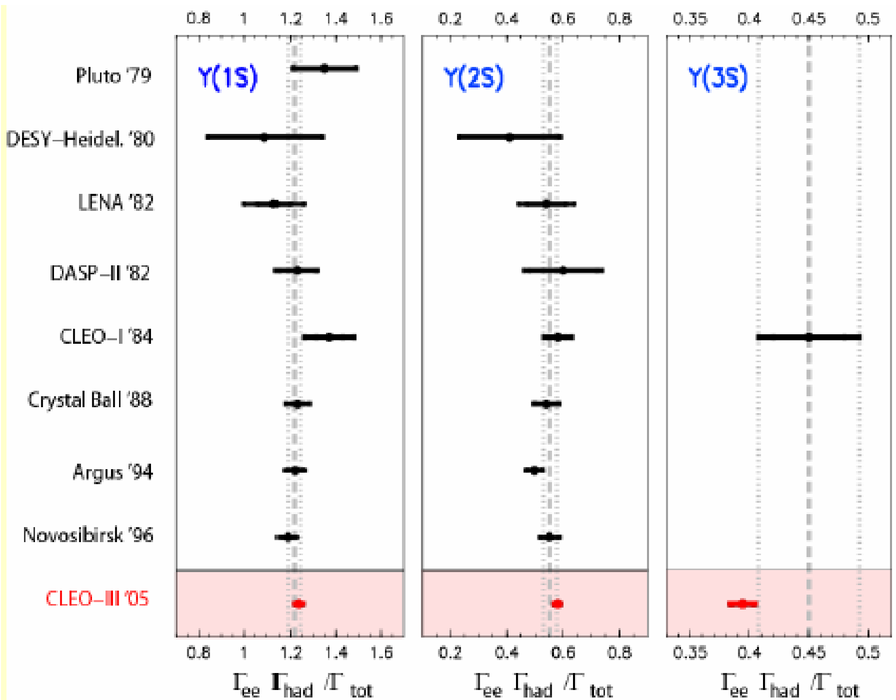
		%
$\Gamma_{ee}\Gamma_{\rm had}/\Gamma_{\rm tot}(1S)$	$(1.252 \pm 0.005 \pm 0.019)$ keV	
$\Gamma_{ee}\Gamma_{\rm had}/\Gamma_{\rm tot}(2S)$	$(0.581 \pm 0.006 \pm 0.009)$ keV	
$\Gamma_{ee}\Gamma_{\rm had}/\Gamma_{\rm tot}(3S)$	$(0.413 \pm 0.004 \pm 0.006)$ keV	
$\Gamma_{ee}(1S)$	$(1.354 \pm 0.005 \pm 0.020)$ 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

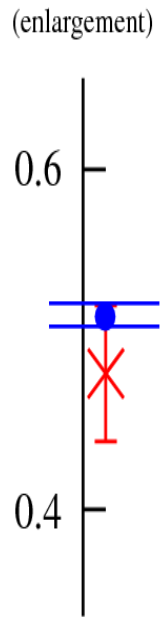
CLEO hep-ex/0512056

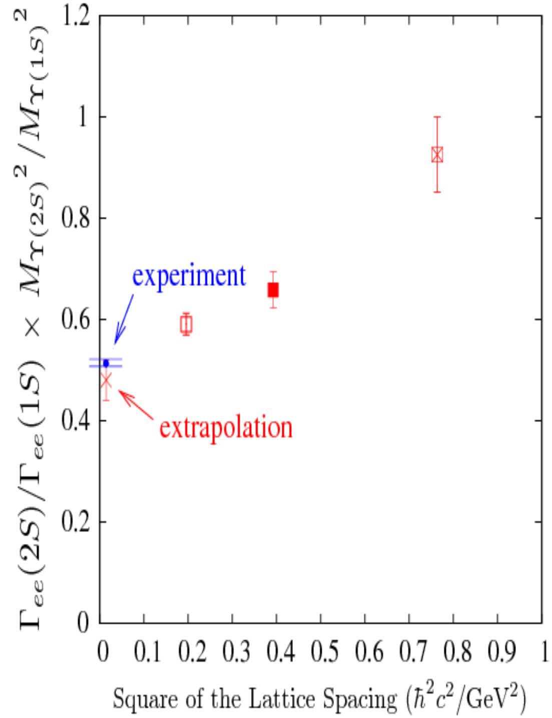
Precision Measurement of Γ_{ee} of Υ(1S,2S,3S)

Comparison of results --

with previous experiments **with LQCD calculations**







Hadronic Transitions (once more): Dipion Cascades between $\Upsilon(nS)$ States

News from CLEO: currently finalizing high statistics measurement of $\Upsilon(3S) \rightarrow \pi\pi\,\Upsilon(1S, 2S)$ and $\Upsilon(2S) \rightarrow \pi\pi\,\Upsilon(1S)$.
(Almost ready! Plots shown today are for qualitative comparison only.)

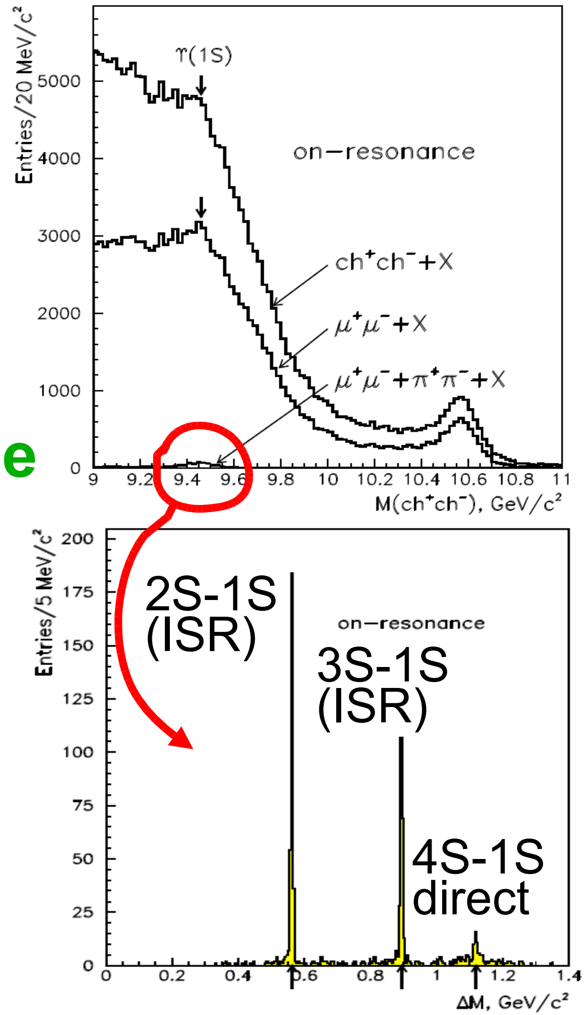
News from Belle: observed $\Upsilon(4S) \rightarrow \pi^+\pi^-\,\Upsilon(1S)$! (BR $\approx 1\text{x}10^{-4}$)

News from BaBar: observed $\Upsilon(4S) \rightarrow \pi^+\pi^-\,\Upsilon(1S)$ ($\Gamma \approx 2$ keV)
AND $\Upsilon(4S) \rightarrow \pi^+\pi^-\,\Upsilon(2S)$! ($\Gamma \approx 2$ keV)

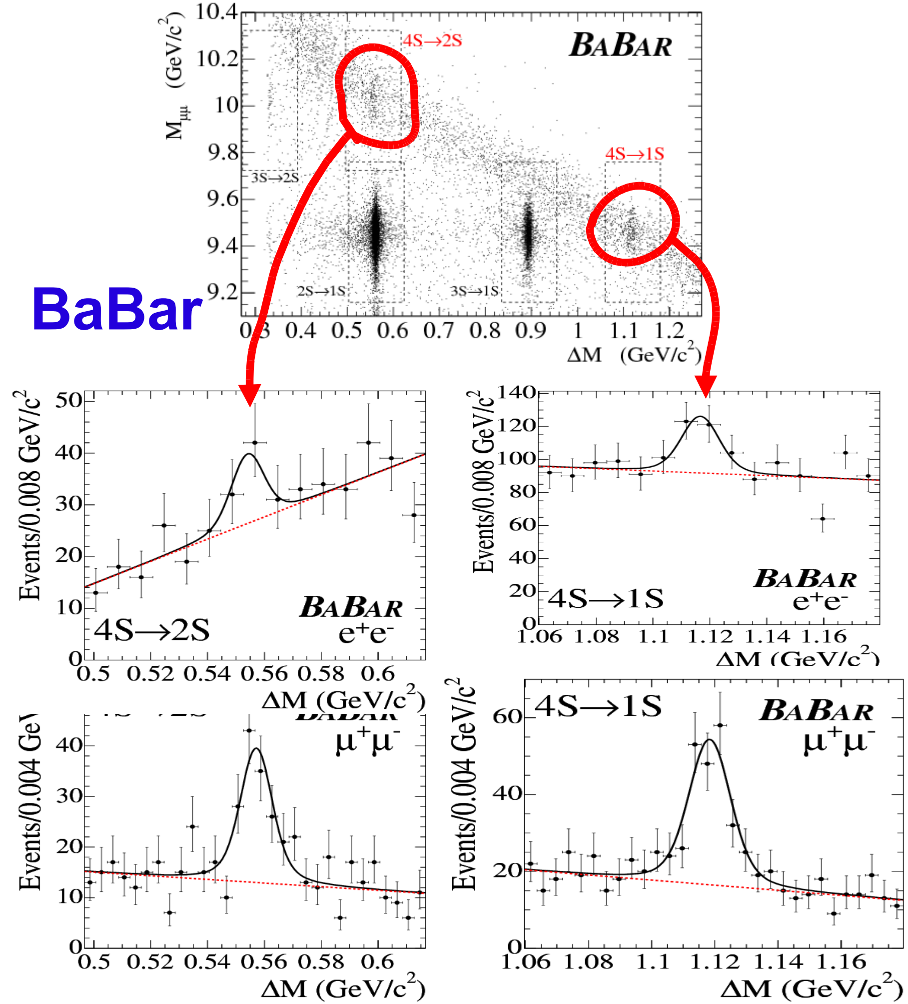
... and an intriguing picture emerges!

Dipion Cascades from the $\Upsilon(4S)$

Belle



BaBar

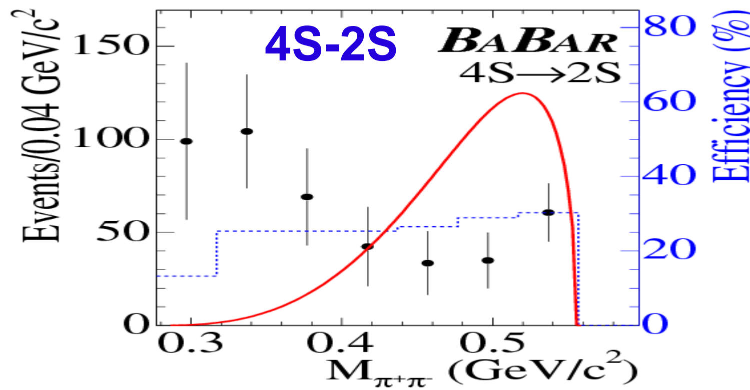


$\Delta M = M(\pi\pi\mu\mu)\text{-}M(\mu\mu)$ with $M(\mu\mu)$ near $\Upsilon(1S)$

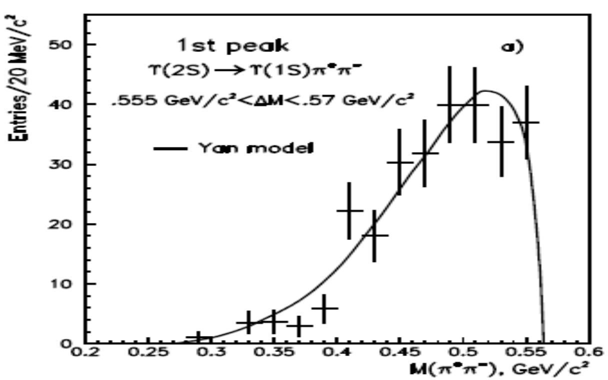
Dipion Cascades: Hot News

or What's So Special About $\Delta n=2$?

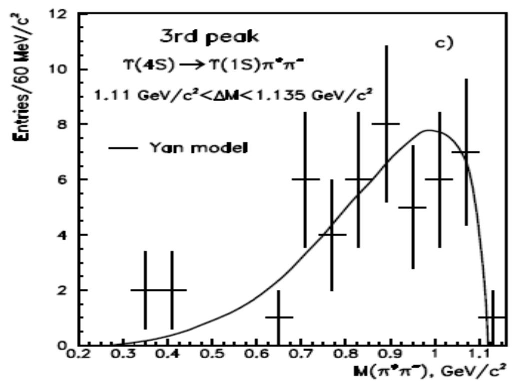
Belle: hep-ex/0512034
BaBar: talk at QCD Moriond'06
CLEO: very preliminary

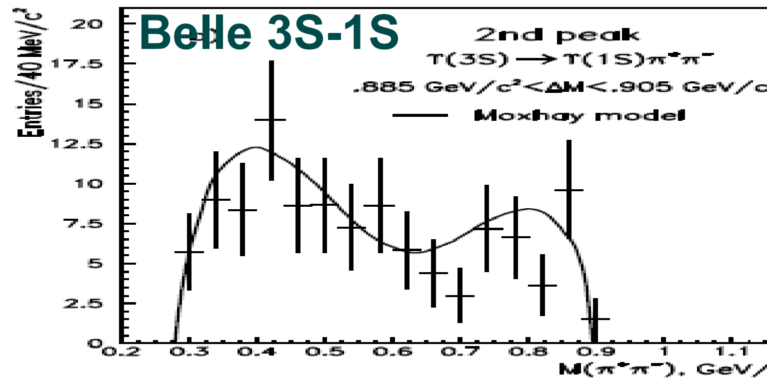


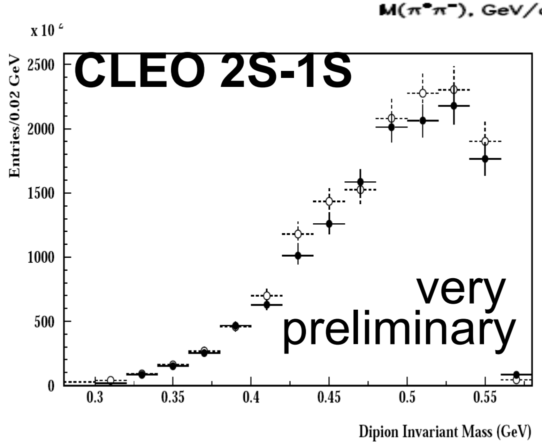
Belle 2S-1S

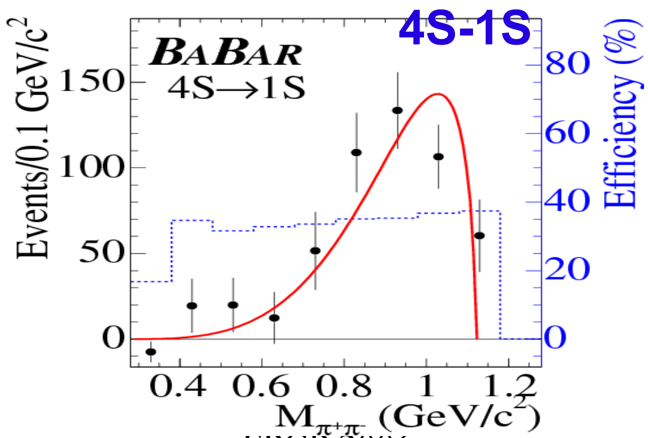


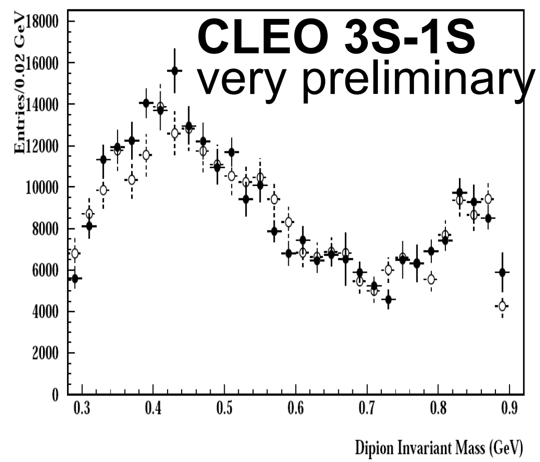
Belle 4S-1S











compare with

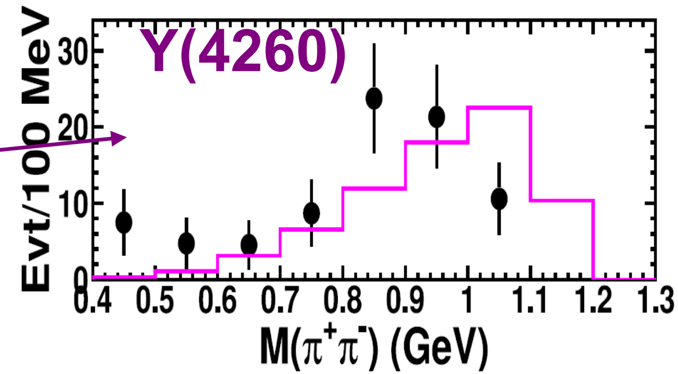
Dipion Transitions in $c\bar{c}$

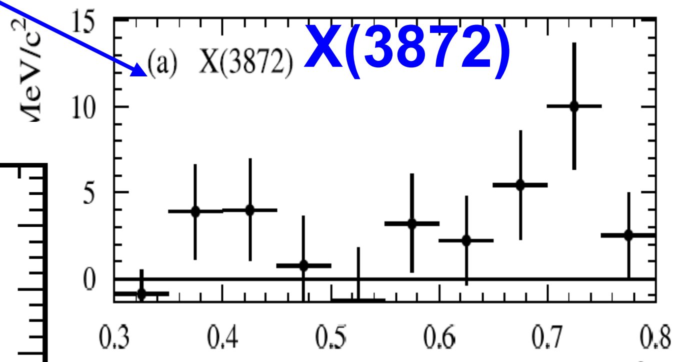
CLEO-c $Y(4260) \rightarrow \pi\pi J/\psi$

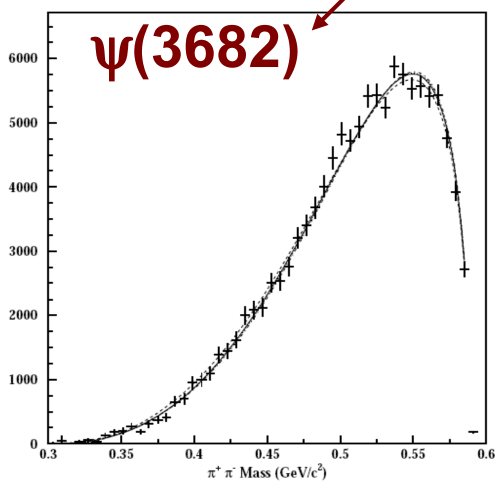
BaBar $X(3872) \rightarrow \pi\pi J/\psi$

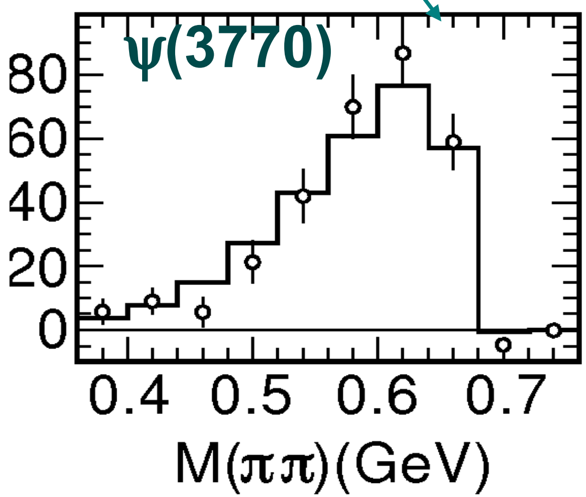
CLEO-c $\psi(3770) \rightarrow \pi\pi J/\psi$

BES $\psi(3682) \rightarrow \pi\pi J/\psi$









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Summary

- Renaissance in non-BB Upsilon Physics (CLEO since 2001)
- Test LQCD
- Test basic QCD
- Test scaling between charmonium and bottomium
- Probe qq potential and test decay models
- Explore the puzzle of dipion cascades
- CLEO III has largest dedicated Υ(1S,2S,3S) data sample (produced many papers already; many more in the pipeline)
- Good to see BaBar & Belle also getting into the act!
  (dedicated Υ(3S) run at KEK?)

Backup Slides

Dipion Cascades: Old News (1994-2000)