CLEO Bottomonium Results

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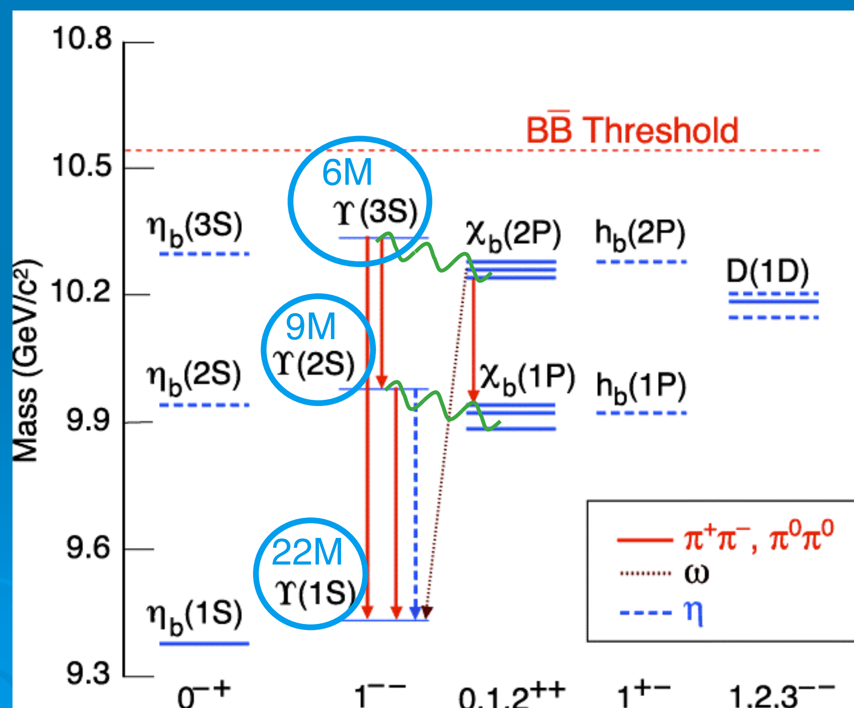
on behalf of the CLEO Collaboration

**6th International
Workshop on Heavy Quarkonia
Nara, Japan December 2008**

Outline:

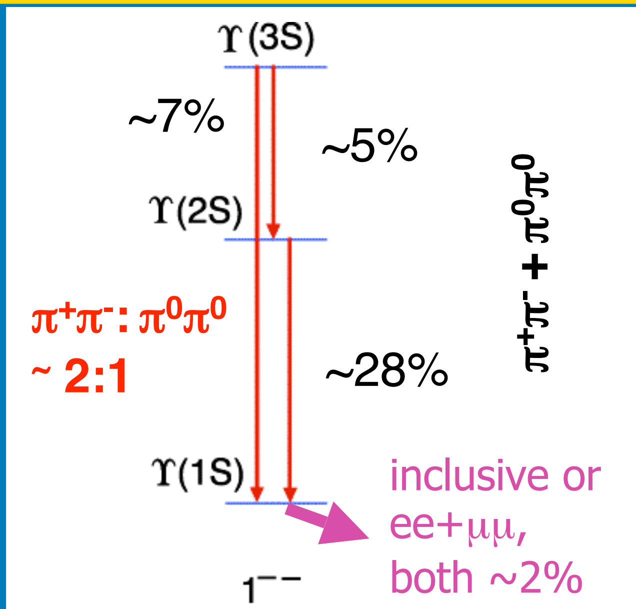
Transition:
$\pi\pi$ – precision
η / π^0 – discovery

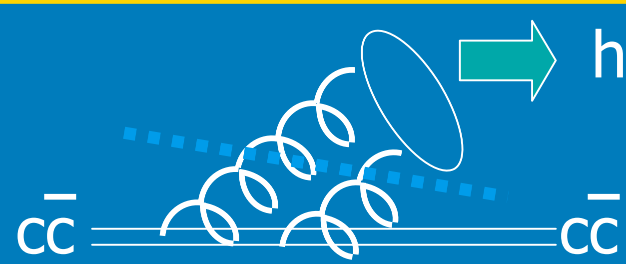
Decay:
Charm production – copious
Light quark modes – many but rare



CORNELL UNIVERSITY LEPP
LABORATORY FOR ELEMENTARY-PARTICLE PHYSICS

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





Factorization:
gluon emission
followed by
hadronization

multipole picture: $2\times E1 \Rightarrow h=\pi\pi$

Other hadronic transitions in the Υ system:
$\chi_{bJ}(2P)\rightarrow\omega\Upsilon(1S)$, $\chi_{bJ}(2P)\rightarrow\pi\pi\chi_{bJ}(1P)$,
other Υ dipion transitions,
$\Upsilon(2,3S)\rightarrow\eta/\pi^0\ \Upsilon(1S)$ (later)

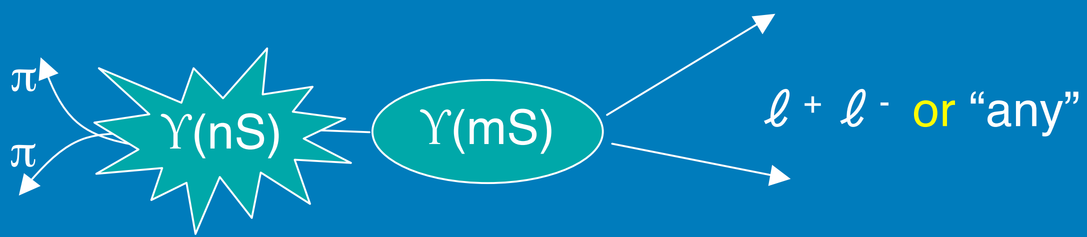
- **Substantial branching fraction, precision measurement possible and desirable**
  - **Dipion tag often used to clean up lower-n decay samples**
- **Test non-perturbative, non-relativistic calculations:**
  - **Predictions: $\Upsilon(2S)\rightarrow\pi^+\pi^- + \pi^0\pi^0\ \Upsilon(1S)$ 50% [Yan PRD 22, 1652 (1980)]**
    40.6% [Kuang hep-ph/0601044]

$\Upsilon(nS) \to \pi\pi + \Upsilon(mS)$

Goal: <u>precision</u> rate measurement.
As much statistics as possible, as little systematics as necessary.

Primary observable:
m($\pi\pi$-recoil) = m(Υ(mS))
$\pi\pi$: charged or neutral

- **two low-momentum tracks** (pion hypothesis)
- **or $4\gamma = 2\pi^0$ and allow one extra shower**



<u>Exclusive selection:</u> identify dilepton decay
(two stiff tracks, no particle ID needed).
Momentum conservation cut
<u>inclusive ($\pi^+\pi^-$):</u> don't require anything
(no momentum conservation cut)

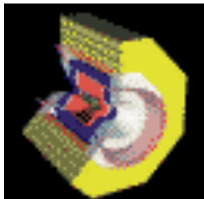
Backgrounds:

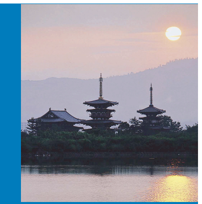
- **Inclusive:**
  - Continuum: $e^+e^- \to \pi^+\pi^- X$
  - direct decay: $\Upsilon \to \pi^+\pi^- X$
- **Exclusive:**
  - direct Υ(nS) decay
  - other hadronic transitions
  - $\pi^0\pi^0$: four-photon cascades through χ_{bJ}

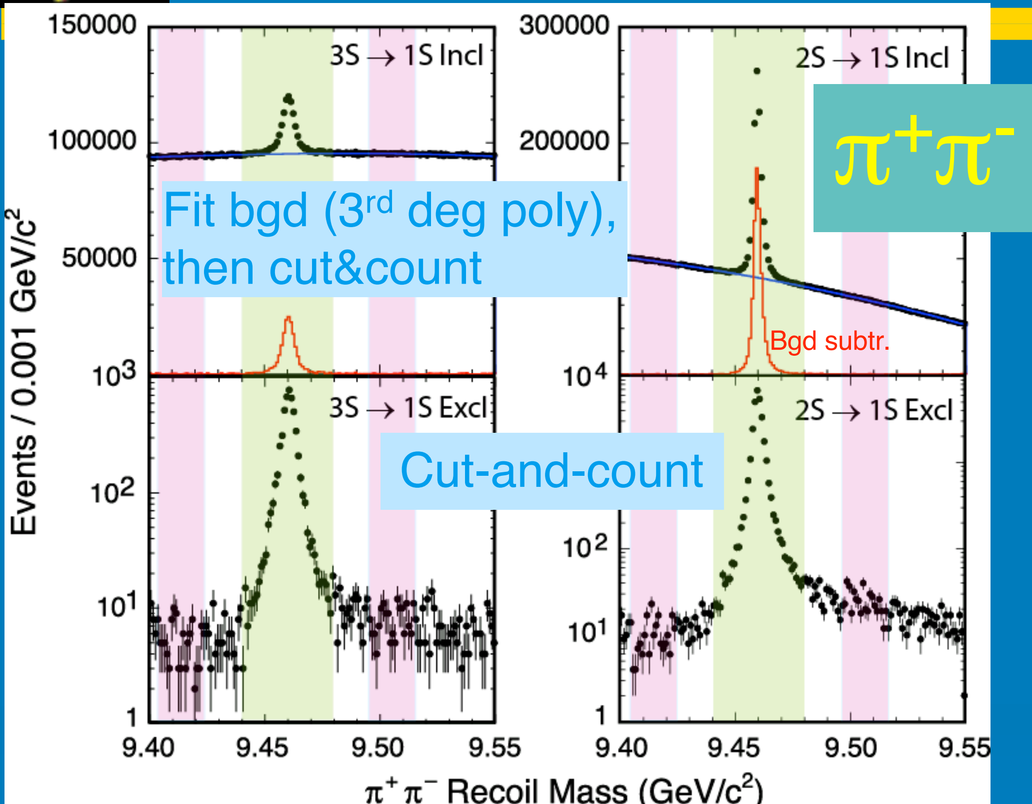
} **No m($\pi\pi$–recoil) peak, can sort out through fit** (Inclusive)

} **Tiny rate, subtract via sidebands** (Exclusive)

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





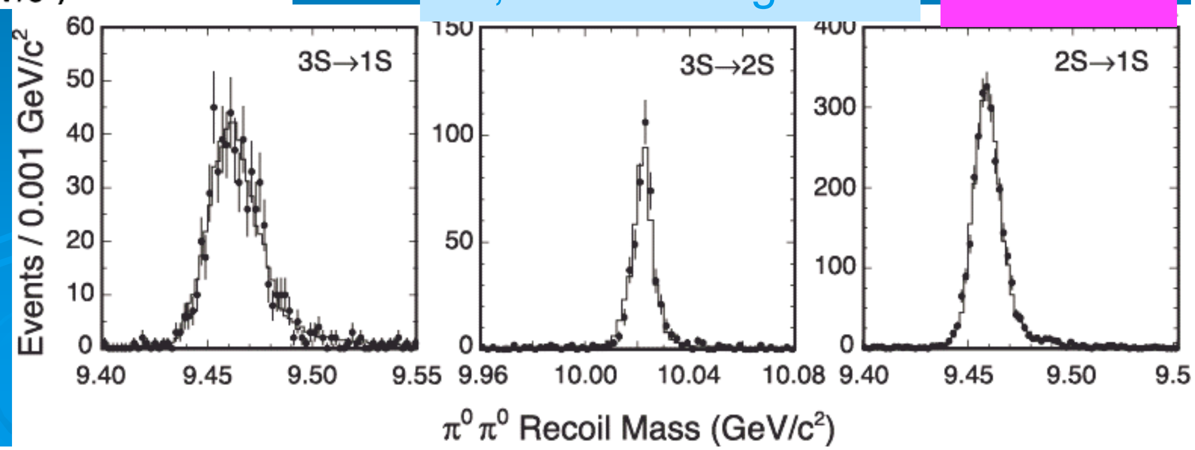


arXiv:0809.1110	BR (%)
3S→1S incl	4.47±0.06±0.18
excl	4.46±0.01±0.14
ave	4.46±0.01±0.13
2S→1S incl	18.26±0.11±0.81
excl	17.99±0.02±0.59
ave	18.02±0.02±0.61
3S → 1S	2.24±0.09±0.11
3S → 2S	1.82±0.09±0.12
2S → 1S	8.43±0.16±0.42

Systematics:3-6%

$\pi^0\pi^0$

Fit, linear background



$$\frac{\Upsilon(nS) \rightarrow \pi^0\pi^0\,\Upsilon(1S)}{\Upsilon(nS) \rightarrow \pi^+\pi^-\,\Upsilon(1S)}:$$

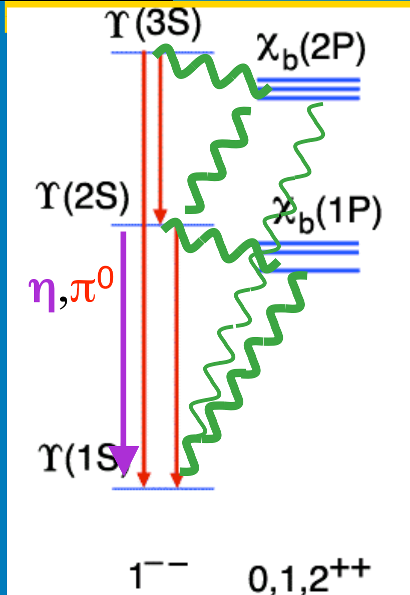
n=2:

0.462 ± 0.037, expect 0.53

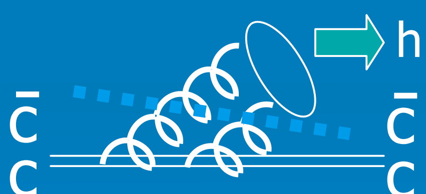
n=3:

0.501 ± 0.043, expect 0.51

$\Upsilon \to \pi^0/\eta + \Upsilon$: Strategy

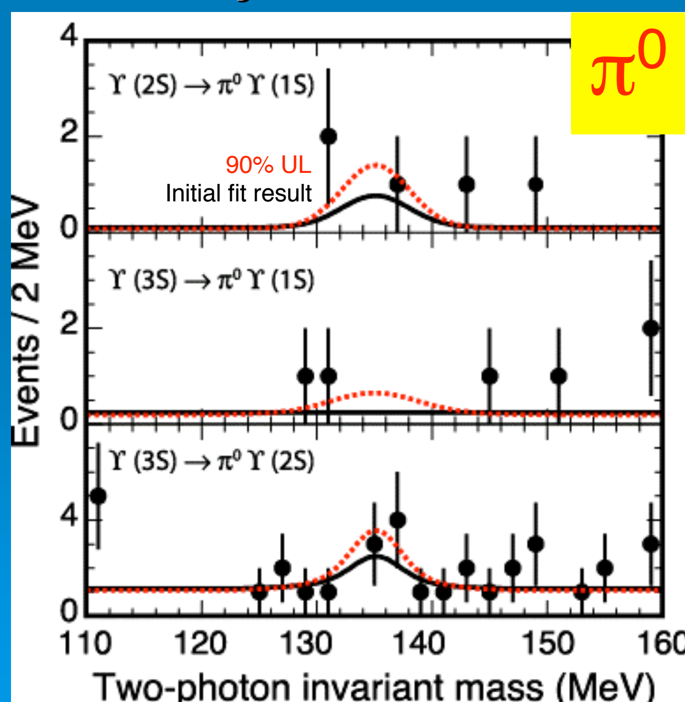


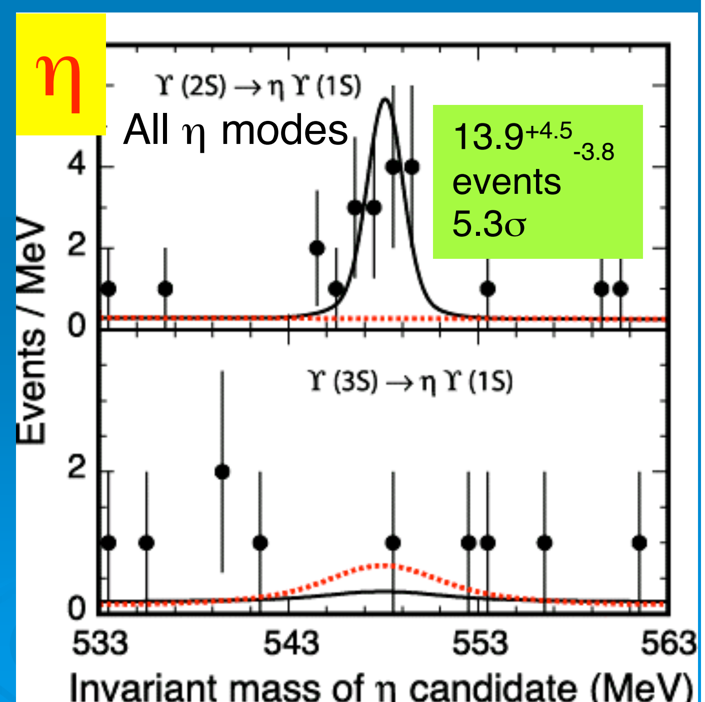
- $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$ (dominant), $\pi^+\pi^-\pi^0$, $3\pi^0$
- Lepton species identified
- Kinematic fitting applied to whole event
  - Observable: m(π^0, η decay products)
- Background suppression:
  - $\Upsilon(2,3S) \to \gamma\chi_{bJ} \to \gamma\gamma\Upsilon(1S)$ reduced through E_γ cut
  - $e^+e^- \to \gamma\gamma e^+e^-$: fit quality cut
- Systematics: ~15%



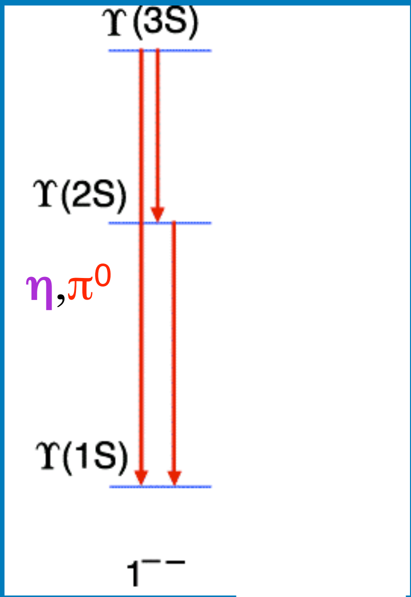
E1+M2 / M1+M1: h=η

h=π^0:
isospin suppressed
η/π^0 mixing
$\leftrightarrow m_d - m_u \neq 0$
produces rate ≠ 0.





$\Upsilon \rightarrow \pi^0/\eta + \Upsilon$: Results



PRL 101, 192001 (2008)	BR (10^{-4})	Pred. (10^{-4})
$\Upsilon(2S)\rightarrow\eta\Upsilon(1S)$	$2.1^{+0.7}_{-0.6}\pm0.3$	8.0, 6.9
$\psi(2S)\rightarrow\eta J/\psi$	343±4±9	
$\Upsilon(2S)\rightarrow\pi^0\Upsilon(1S)$	< 1.8	1.6
$\psi(2S)\rightarrow\pi^0 J/\psi$	13.3±0.8±0.3	
$\Upsilon(3S)\rightarrow\eta\Upsilon(1S)$	< 1.8	6.5, 5.4
$\Upsilon(3S)\rightarrow\pi^0\Upsilon(1S)$	< 0.7	0.03
$\Upsilon(3S)\rightarrow\pi^0\Upsilon(2S)$	< 5.1	none

Predictions:

η:

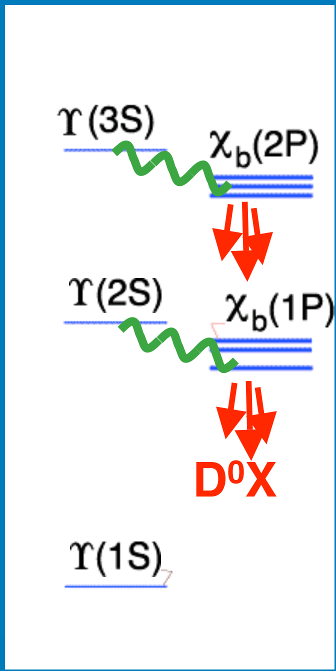
- Extrapolate from charm scaling with $p^{*}_{h}{}^{3}/m_Q{}^4$
- Direct potential model calculation

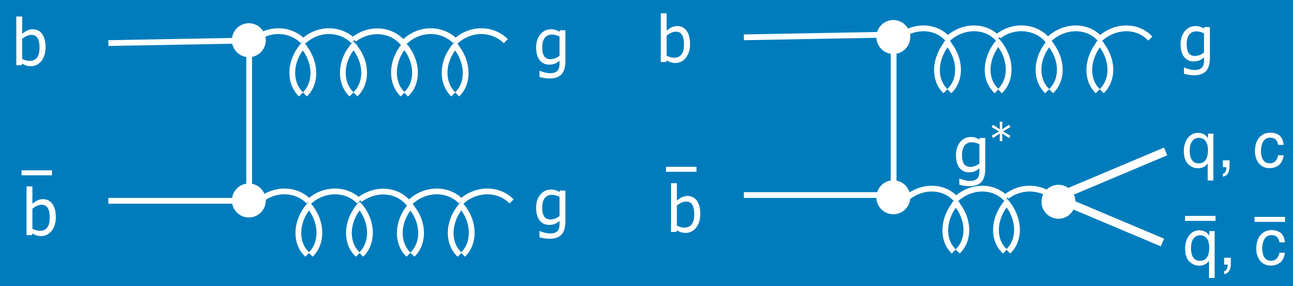
π^0:

- From $\pi^0:\eta$

- $\Upsilon(2S)\rightarrow\eta\Upsilon(1S)$ transition clearly seen, rate is about ¼ of expectation
  - Two-gluon hadronization picture too naïve?
  - Fundamental suppression of the chromomagnetic moment of the b quark?
- UL for others:
  - η UL lower than prediction
  - π^0 limits consistent

$\chi_{bJ}(1,2P)\rightarrow D^0+X$





$\chi_{b0,2}$: gg » $gq\bar{q}$ χ_{b1}: $gc\bar{c} \approx 1/4\ gq\bar{q}$, gg = 0

$\Upsilon(1S)\rightarrow ggg\rightarrow D^{*+}X$: charm is suppressed
Continuum $e^+e^-\rightarrow q\bar{q}$: charm is not suppressed

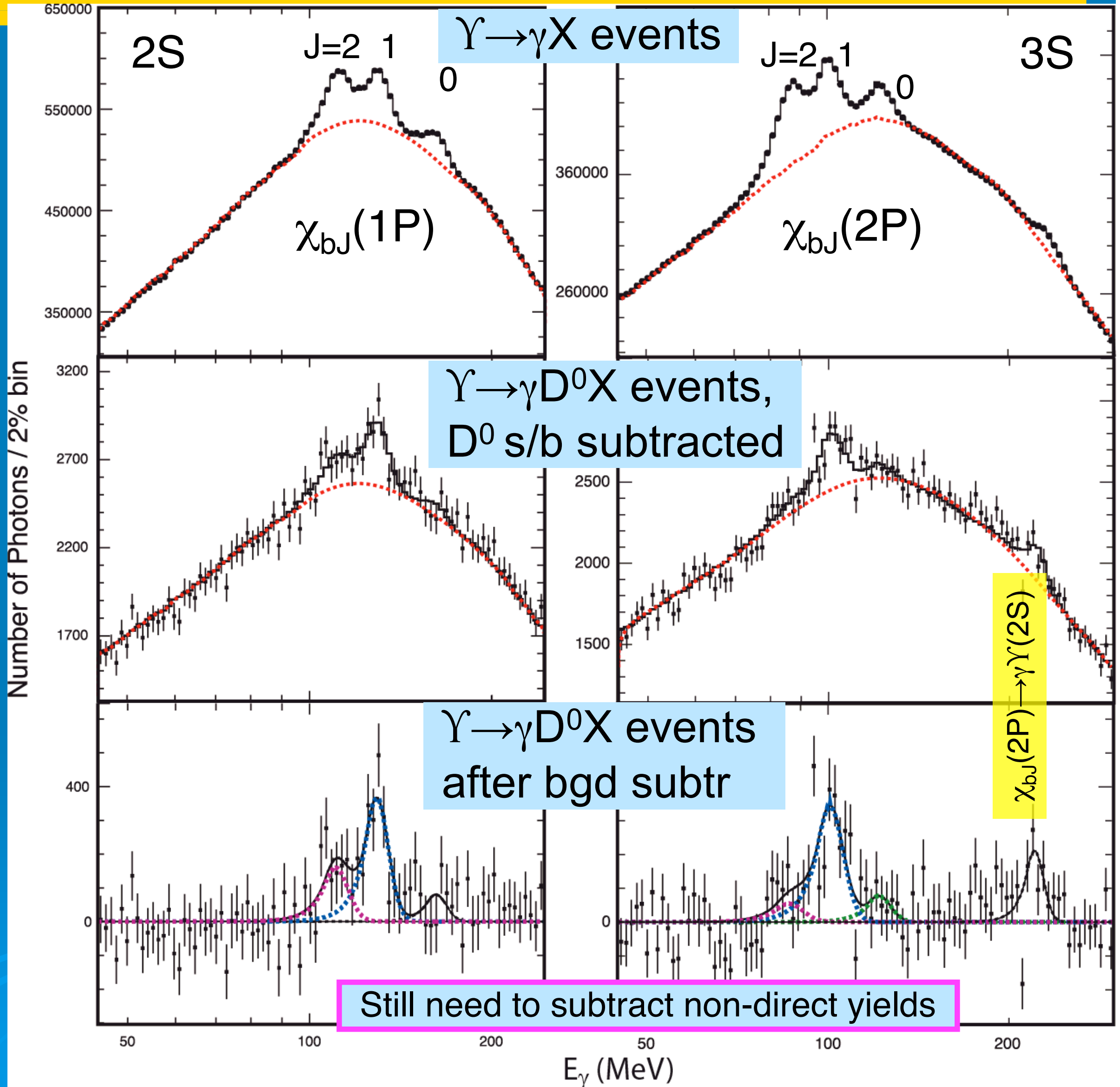
NRQCD prediction:

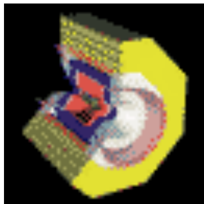
$$R_J = \frac{B(\chi_{bJ}\rightarrow gg,gq\bar{q}\rightarrow c\bar{c}\ X)}{B(\chi_{bJ}\rightarrow gg,gq\bar{q}\ )} = 5\%,\ 23\%,\ 8\%\ \text{for}\ J=0,1,2$$

25% means “flavor blindness”

$\chi_{bJ}(1,2P) \to D^0 + X$

- **Strategy:**
  - Tag χ_{bJ} with γ^{E1}
  - $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^-\pi^+\pi^+$
    - Uses particle ID
    - Subtract D^0 sidebands
- **$p(D^0) > 2.5$GeV**
- **Backgrounds:**
  - $\Upsilon \to \pi^0 D^0 X$ – veto
  - $\chi_{bJ} \to b\bar{b}$, $b\bar{b} \to D^0X$ (non-direct) – subtract using $\Upsilon(1S)$ data





χ_{bJ}(1,2P) → D^0+X: Results

… after subtracting non-direct yields:

B(χ_{bJ}(nP)→gg,gq$\bar{q}$→D^0X, p(D^0)>2.5GeV

PRD 78, 092007 (2008)

State	$\mathcal{B}(\chi_{bJ}(nP) \to gg, q\bar{q}g \to D^0X)$ (%)	90% CL UL (%)
$\chi_{b0}(1P)$	$5.6 \pm 3.6 \pm 0.5$	< 10.4
$\chi_{b1}(1P)$	$12.6 \pm 1.9 \pm 1.1$	
$\chi_{b2}(1P)$	$5.4 \pm 1.9 \pm 0.5$	< 7.9
$\chi_{b0}(2P)$	$4.1 \pm 3.0 \pm 0.4$	< 8.2
$\chi_{b1}(2P)$	$8.8 \pm 1.5 \pm 0.8$	
$\chi_{b2}(2P)$	$0.2 \pm 1.4 \pm 0.1$	< 2.4

Model independent

Unambiguous signal seen for J=1 in 1P,2P: substantial BR!

Limits in the % range for the others.

Translate measurement into R_J:

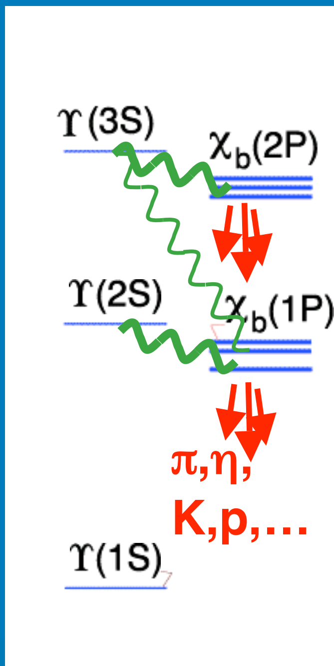
	$\frac{B(\chi_{bJ} \to gg, gq\bar{q} \to c\bar{c}X)}{B(\chi_{bJ} \to gg, gq\bar{q})}$ (%)	(90%CL UL)	NRQCD Fit (*)
χ_{b0}(1P)	9.6±6.2±0.8±0.8	(<17.9)	6.3
χ_{b1}(1P)	24.8±3.8±2.2±3.6		23.7
χ_{b2}(1P)	9.8±3.5±0.9±0.9	(<14.6)	10.8
χ_{b0}(2P)	8.7±6.4±0.9±0.7	(<17.7)	4.9
χ_{b1}(2P)	25.3±4.3±2.5±2.4		22.1
χ_{b2}(2P)	0.4±3.5±0.4±0.1	(<6.1)	7.4

Comparison with theory: Extrapolated experimental value depends, through efficiencies, on parameter "ρ_8" for NRQCD calculation: Find best value, quote NRQCD prediction for it (*).

Data support general picture within errors.

Bodwin et al., PRD 51, 1125 (1995), 55, 5853(E) (1997)
Bodwin et al., PRD 76, 054001 (2007)

$\chi_{bJ} \rightarrow$ light hadrons



- Fully reconstructed final state:
  Υ(2S, 3S)→ γ X_i , X_i = final state with light mesons or protons

  i=1…659

- Measurement:

  $B(\ \Upsilon(3S,2S)\rightarrow\gamma\chi_{bJ}(2P,1P)\ )$

  $\times\ B(\ \chi_{bJ}(2P,1P) \rightarrow X_i)$

- Same strategy <u>might</u> work for

  $\Upsilon(3S,2S,1S)\rightarrow\gamma^{M1}\eta_b(3S,2S,1S)$

  $\times\ \eta_b(3S,2S,1S) \rightarrow X_i$

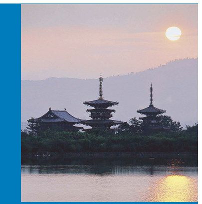
- Results:

  Those with >5σ → 14 new $B(\ \chi_{bJ}(2P,1P) \rightarrow X_j)$: all firsts

  j=1…14

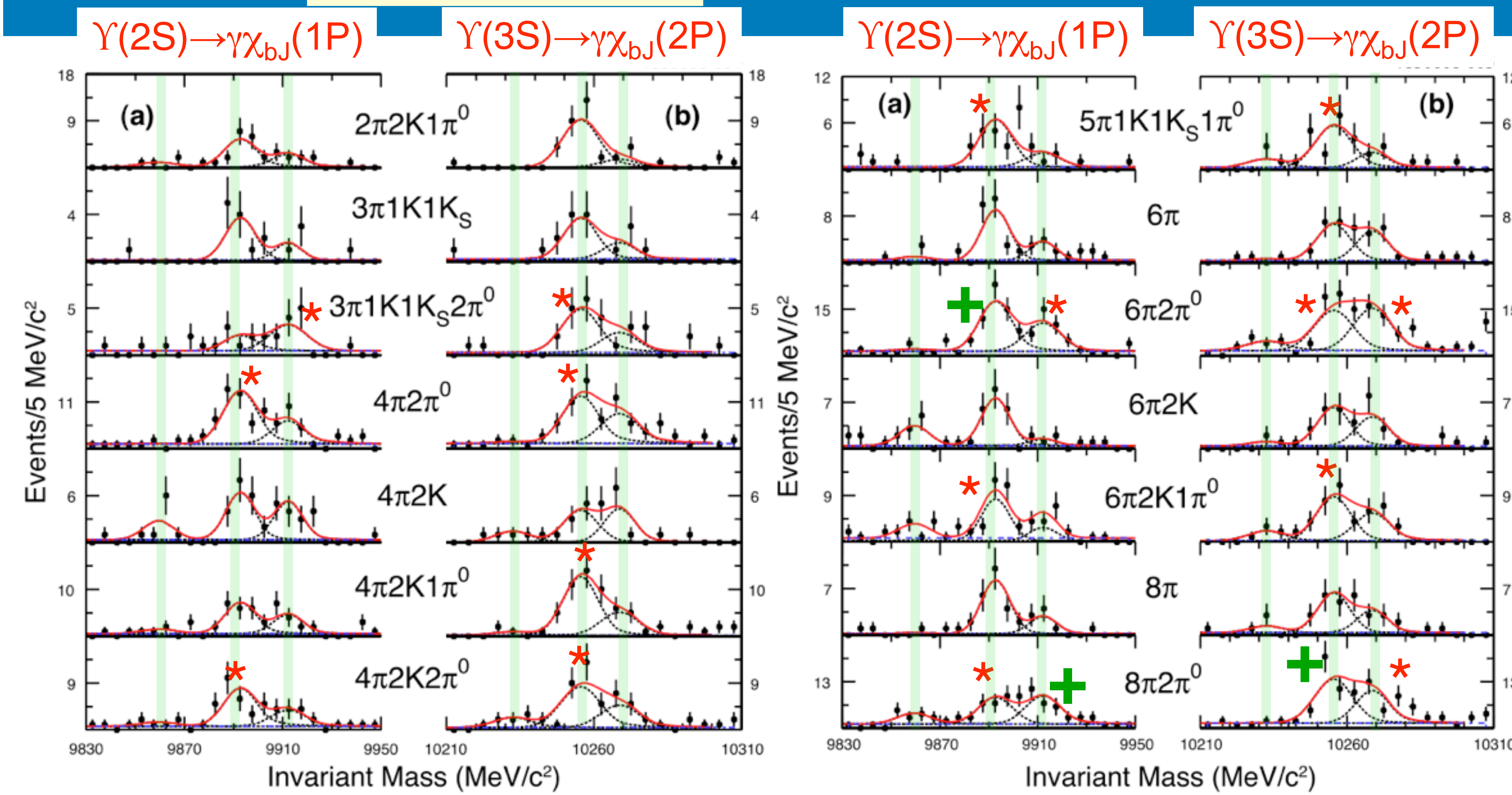
  - UL on $B(\ \Upsilon(3S)\rightarrow\gamma\chi_{bJ}(1P)\ )$: constraint for theory

$\chi_{bJ} \to$ light hadrons



*[+]: B=1 [2] ×10^{-3}

Sums to less than 1% total.

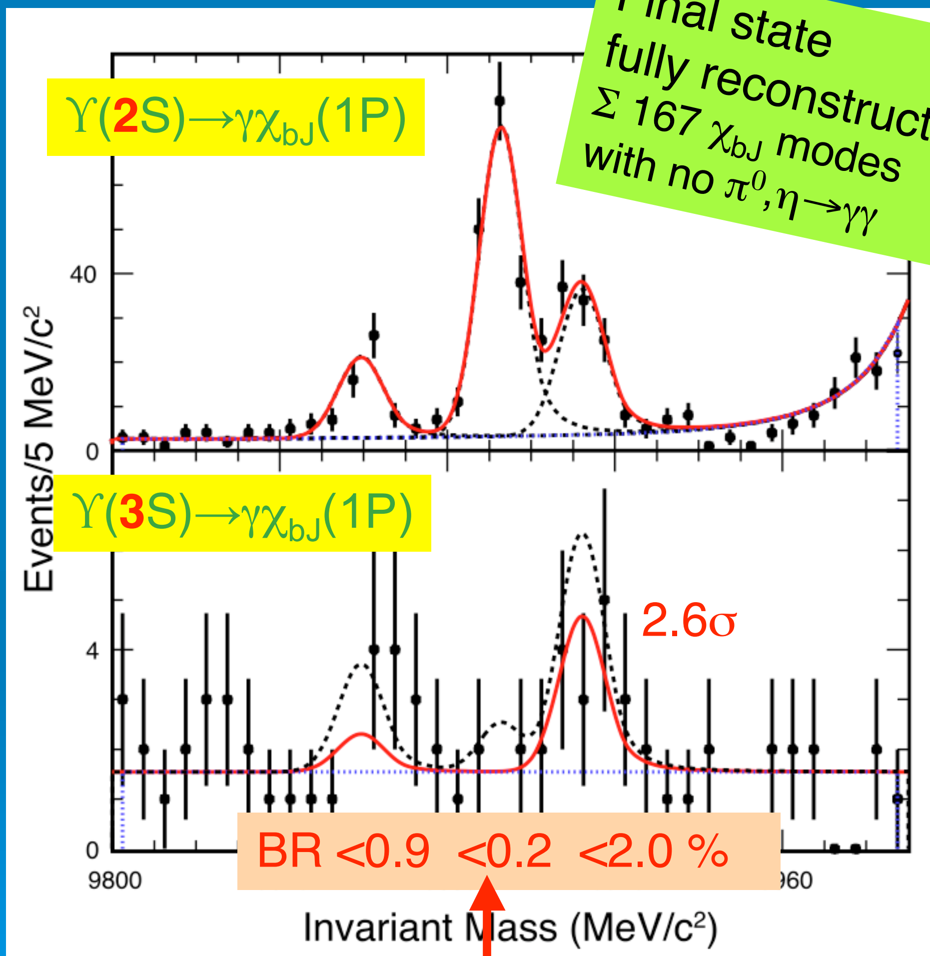


PRD 78, 091103(R) (2008)

χ_{bJ} → light hadrons spin-off: 3S-1P hindered transition

Δn=2!

PRD 78, 091103(R) (2008)



Final state fully reconstructed
Σ 167 χ_{bJ} modes with no $\pi^0,\eta\to\gamma\gamma$

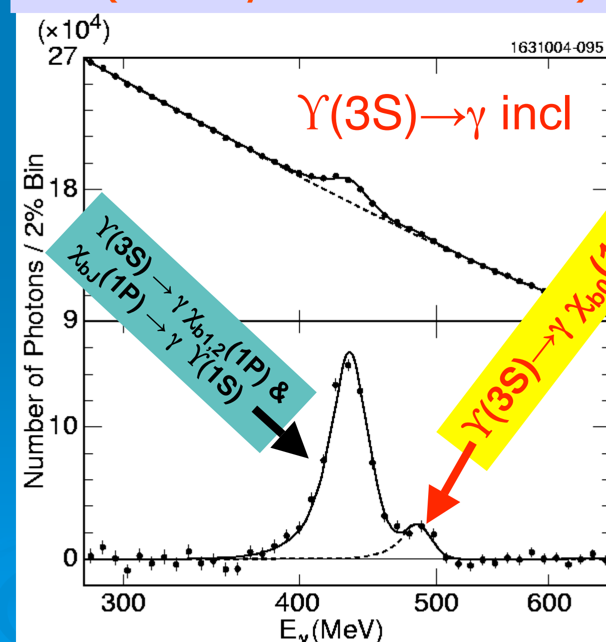
BR <0.9 <0.2 <2.0 %

Tight enough to constrain theory

2005 CLEO paper:
Measure only transition photon $\Upsilon(3S)\to\gamma\chi_{bJ}(1P)$:

BR($\Upsilon(3S)\to\gamma\chi_{b0}$):
(0.30 ±0.04±0.10)%
(Theory: 0.006-0.74%)

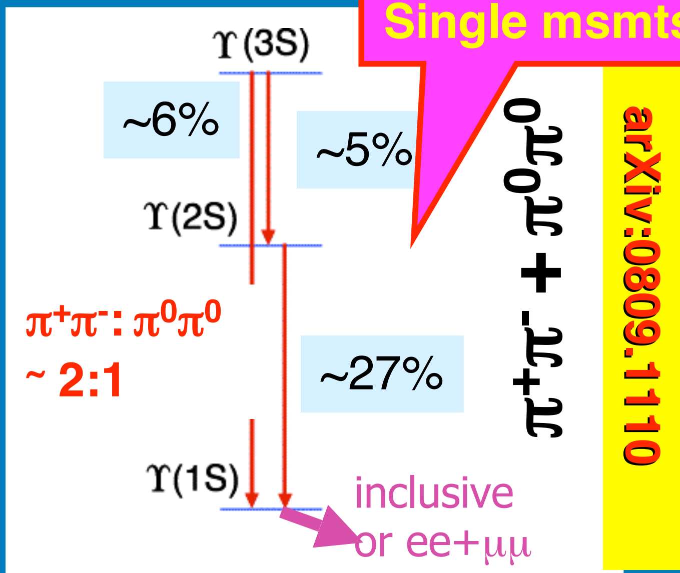
PRL 94, 032001 (2005)

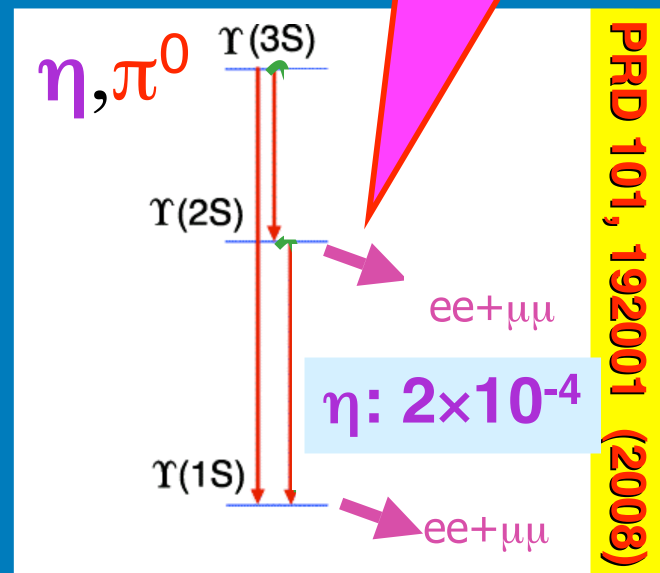


Summary

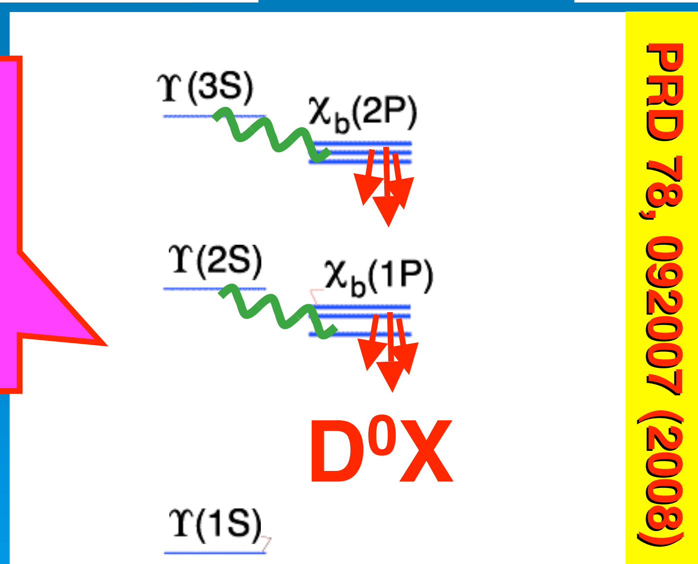
1st observation @1/4 of prediction

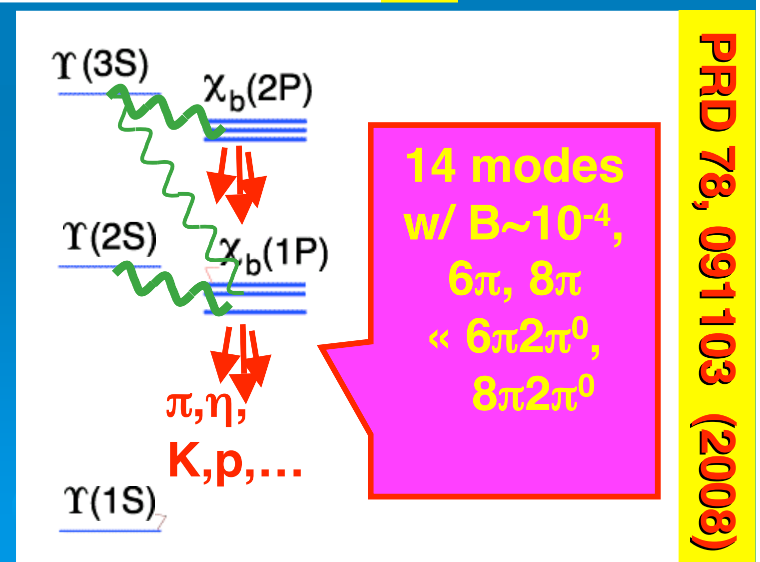
Most precise Single msmts!





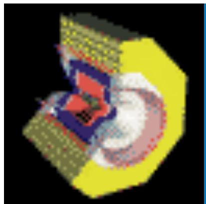
$R_1 \approx 25\%$ $gq\bar{q}$ is ~Flavor Blind





14 modes w/ B~10^{-4}, 6π, 8π « $6\pi2\pi^0$, $8\pi2\pi^0$

Backup Section



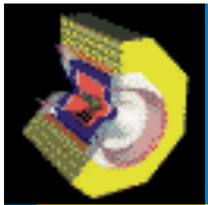
χ_{bJ}(1,2P)→D^0+X: Results

TABLE I: $\Upsilon(2S) \to \gamma\chi_{bJ}(1P)$ $(J = 0, 1, 2)$ transition yields and $\chi_b \to gg, q\bar{q}g \to D^0X$ rates, for $p_{D^0} > 2.5$ GeV/c. Errors shown are statistical only.

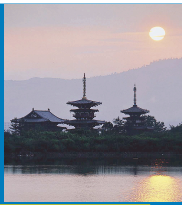
Final state	$\chi_{b0}(1P)$	$\chi_{b1}(1P)$	$\chi_{b2}(1P)$
$N^{\rm Incl}_{\chi_{bJ}}$	166860 ± 5988	363825 ± 6793	379457 ± 7243
$N^{D^0}_{\chi_{bJ}}$ (raw)	501 ± 303	2561 ± 346	1207 ± 360
D^0 sideband correction	11 ± 5	60 ± 6	57 ± 7
non-direct D^0	16 ± 9	191 ± 58	125 ± 34
$N^{D^0,dir}_{\chi_{bJ}}$ (direct)	474 ± 303	2310 ± 351	1025 ± 362
$\mathcal{B}(\chi_{bJ}(1P) \to gg, q\bar{q}g \to D^0X)$	**$5.63 \pm 3.61\%$**	**$12.59 \pm 1.94\%$**	**$5.36 \pm 1.90\%$**

TABLE II: $\Upsilon(3S) \to \gamma\chi_{bJ}(2P)$ $(J = 0, 1, 2)$ transition yields and $\chi_b \to gg, q\bar{q}g \to D^0X$ rates, for $p_{D^0} > 2.5$ GeV/c. Errors shown are statistical only.

Final state	$\chi_{b0}(2P)$	$\chi_{b1}(2P)$	$\chi_{b2}(2P)$
$N^{\rm Incl}_{\chi_{bJ}}$	219773 ± 5201	491818 ± 5197	524549 ± 5628
$N^{D^0}_{\chi_{bJ}}$ (raw)	565 ± 341	2757 ± 366	477 ± 370
D^0 sideband correction	39 ± 7	122 ± 7	122 ± 7
non-direct D^0	53 ± 24	392 ± 70	311 ± 50
$N^{D^0,dir}_{\chi_{bJ}}$ (direct)	473 ± 342	2243 ± 373	44 ± 373
$\mathcal{B}(\chi_{bJ}(2P) \to gg, q\bar{q}g \to D^0X)$	**$4.13 \pm 3.00\%$**	**$8.75 \pm 1.47\%$**	**$0.16 \pm 1.37\%$**



$\chi_{bJ}(1,2P) \rightarrow D^0+X$



With these factors in hand, we fit our data for the D^0X branching fractions with $p_{D^0} > 2.5$ GeV/c to the NRQCD predictions [9] and extract ρ_8, the ratio of color-octet to color-singlet matrix elements, in χ_{bJ} decays. Recall that both $f_{2.5}$ and $R_J^{(c)}$ depend on ρ_8 and that $f_{2.5}$ depends on fragmentation functions. For each value of ρ_8, we may convert our directly measured branching fractions into extracted values for $R_J^{(c)}$ in the context of this NRQCD calculation (which includes the assumption that e^+e^- charm fragmentation data is representative of our charm fragmentation). The best value of ρ_8 is obtained from a fit which finds the best agreement between the predicted and extracted $R_J^{(c)}$.

TABLE VI: Summary of factors used to relate our measured D^0X branching fractions to $R_J^{(c)}$, which measures the total $c\bar{c}X$ rate. The values of $f_{2.5}$ are evaluated at the independently fitted best values of ρ_8 for each triplet.

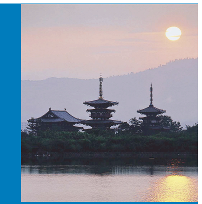
Factor	$\chi_{b0}(1P)$	$\chi_{b1}(1P)$	$\chi_{b2}(1P)$	$\chi_{b0}(2P)$	$\chi_{b1}(2P)$	$\chi_{b2}(2P)$
$\mathcal{B}(\chi \to gg, q\bar{q}g)$	0.97 ± 0.03	0.65 ± 0.08	0.78 ± 0.04	0.93 ± 0.07	0.68 ± 0.04	0.75 ± 0.03
$f_{2.5}$	0.54	0.70	0.63	0.45	0.46	0.47
f_{D^0}	1.11 ± 0.08	1.11 ± 0.08	1.11 ± 0.08	1.11 ± 0.08	1.11 ± 0.08	1.11 ± 0.08
$1/(f_{D^0} f_{2.5} \mathcal{B})$	1.70 ± 0.13	1.97 ± 0.28	1.83 ± 0.16	2.15 ± 0.23	2.89 ± 0.28	2.56 ± 0.21

PRD 78, 092007 (2008)

We fit separate ρ_8 values for each triplet by minimizing a χ^2 which has one term for each of the three states. Each term in the χ^2 is formed from the square of the deviation of the predicted and extracted $R_J^{(c)}$ values, normalized by the errors on the extracted value. Note that *both* the predicted and extracted $R_J^{(c)}$ values depend on ρ_8. Correlated systematic uncertainties on the branching fractions are incorporated into the covariance matrix used to evaluate the χ^2 in our fits. We find, however, that results are insensitive to correlations due to the dominance of statistical errors. The best-fit values are $\rho_8(1P) = 0.160^{+0.071}_{-0.047}$ and $\rho_8(2P) = 0.074^{+0.010}_{-0.008}$ with $\chi^2(1P) = 0.40$ and $\chi^2(2P) = 4.71$, respectively, for $3-1$ degrees of freedom each. The errors are larger for the $1P$ states primarily due to the non-linear dependence of the branching fractions on ρ_8: for larger ρ_8, the branching fractions are less sensitive to changes in its value.

It has been argued [21] that ρ_8 should be largely independent of radial quantum number. While we prefer not to assume such an equality, a joint fit to our branching fractions for both triplets obtains a best-fit common value of $\rho_8 = 0.086^{+0.009}_{-0.013}$, with $\chi^2 = 10.1$ for $6-1$ degrees of freedom.

$\chi_{bJ} \to X_j$ Branching Fraction



All in 10^{-4}

X_i	J=0 2S→1P	J=0 3S→2P	J=1 2S→1P	J=1 3S→2P	J=2 2S→1P	J=2 3S→2P
$2\pi 2K 1\pi^0$	< 1.6	< 0.3	$2.0 \pm 0.5 \pm 0.5$	$3.0 \pm 0.6 \pm 0.8$	$0.9 \pm 0.4 \pm 0.2$	< 1.1
$3\pi 1K 1K^0_S$	< 0.5	< 0.5	$1.3 \pm 0.4 \pm 0.3$	$1.1 \pm 0.4 \pm 0.3$	< 1.2	< 0.9
$3\pi 1K 1K^0_S 2\pi^0$	< 4.7	< 2.3	< 6.1	$7.7 \pm 2.3 \pm 2.2$	$5.3 \pm 1.9 \pm 1.5$	< 6.7
$4\pi 2\pi^0$	< 2.1	< 2.5	$7.9 \pm 1.4 \pm 2.1$	$5.9 \pm 1.2 \pm 1.6$	$3.5 \pm 1.1 \pm 0.9$	$3.9 \pm 1.2 \pm 1.1$
$4\pi 2K$	$1.2 \pm 0.5 \pm 0.3$	< 1.5	$1.5 \pm 0.4 \pm 0.4$	$0.9 \pm 0.3 \pm 0.2$	$1.2 \pm 0.3 \pm 0.3$	$0.9 \pm 0.3 \pm 0.2$
$4\pi 2K 1\pi^0$	< 2.7	< 2.2	$3.4 \pm 0.8 \pm 0.9$	$5.5 \pm 1.0 \pm 1.5$	$2.1 \pm 0.7 \pm 0.5$	$2.4 \pm 0.8 \pm 0.7$
$4\pi 2K 2\pi^0$	< 5.4	< 10.8	$8.6 \pm 2.0 \pm 2.4$	$9.6 \pm 2.3 \pm 2.8$	$3.9 \pm 1.6 \pm 1.1$	$4.7 \pm 1.8 \pm 1.4$
$5\pi 1K 1K^0_S 1\pi^0$	< 1.7	< 6.7	$9.2 \pm 2.3 \pm 2.5$	$6.7 \pm 1.9 \pm 1.9$	< 5.0	< 4.5
6π	< 0.8	< 0.7	$1.8 \pm 0.4 \pm 0.4$	$1.2 \pm 0.3 \pm 0.3$	$0.7 \pm 0.3 \pm 0.2$	$0.9 \pm 0.3 \pm 0.2$
$6\pi 2\pi^0$	< 5.9	< 12.3	$17.2 \pm 2.7 \pm 4.8$	$11.9 \pm 2.4 \pm 3.4$	$10.2 \pm 2.2 \pm 2.8$	$12.1 \pm 2.5 \pm 3.6$
$6\pi 2K$	$2.4 \pm 0.9 \pm 0.7$	< 1.5	$2.6 \pm 0.6 \pm 0.7$	$2.0 \pm 0.6 \pm 0.5$	< 0.8	$1.4 \pm 0.5 \pm 0.4$
$6\pi 2K 1\pi^0$	< 9.9	< 7.3	$7.5 \pm 1.6 \pm 2.1$	$6.1 \pm 1.4 \pm 1.8$	$3.7 \pm 1.2 \pm 1.0$	$4.2 \pm 1.2 \pm 1.2$
8π	< 0.7	< 1.7	$2.7 \pm 0.6 \pm 0.7$	$1.7 \pm 0.5 \pm 0.5$	$0.8 \pm 0.4 \pm 0.2$	$0.9 \pm 0.4 \pm 0.3$
$8\pi 2\pi^0$	< 20.5	< 6.5	$14.0 \pm 3.5 \pm 4.3$	$19.2 \pm 3.7 \pm 6.0$	$18.5 \pm 4.4 \pm 5.6$	$12.6 \pm 3.5 \pm 4.1$

Notice:

$6\pi 2\pi^0$ and $8\pi 2\pi^0$ are largest; about 10× larger than 6π and 8π.

Comparing same number of pions – $4\pi 2\pi^0 > 6\pi$, $6\pi 2\pi^0 > 8\pi$.

Less than a percent of the χ_{bJ} width is reconstructed.

Comparison of Hindered E1 UL's to Theory

	$J = 0$	$J = 1$	$J = 2$
Inclusive expt. [4]	61 ± 22	-	-
Exclusive expt. (this work)	< 186	< 38	< 413
Moxhay–Rosner (1983)	25	25	150
Grotch *et al.* (1984) (a)	114	3.4	194
Grotch *et al.* (1984) (b)	130	0.3	430
Daghighian–Silverman (1987)	16	100	650
Fulcher (1990)	10	20	30
Lähde (2003)	150	110	40
Ebert *et al.* (2003)	27	67	97

(a) Confining potential is purely scalar.
(b) Confining potential is purely vector.

Rules out several calculations

Summary - in words

- Bottomonium provides a unique QCD laboratory:
  - Transitions: non-perturbative, non-relativistic
  - Decay: charm and light quark production
- Four CLEO bottomonium results:
  - Transitions:
    - Dipion transitions: precision
    - η/π^0 transitions: discovery
  - Decay:
    - Open charm copiously produced
    - Many small light hadron modes
- Experimental and theoretical progress is encouraging, but we're not done yet!