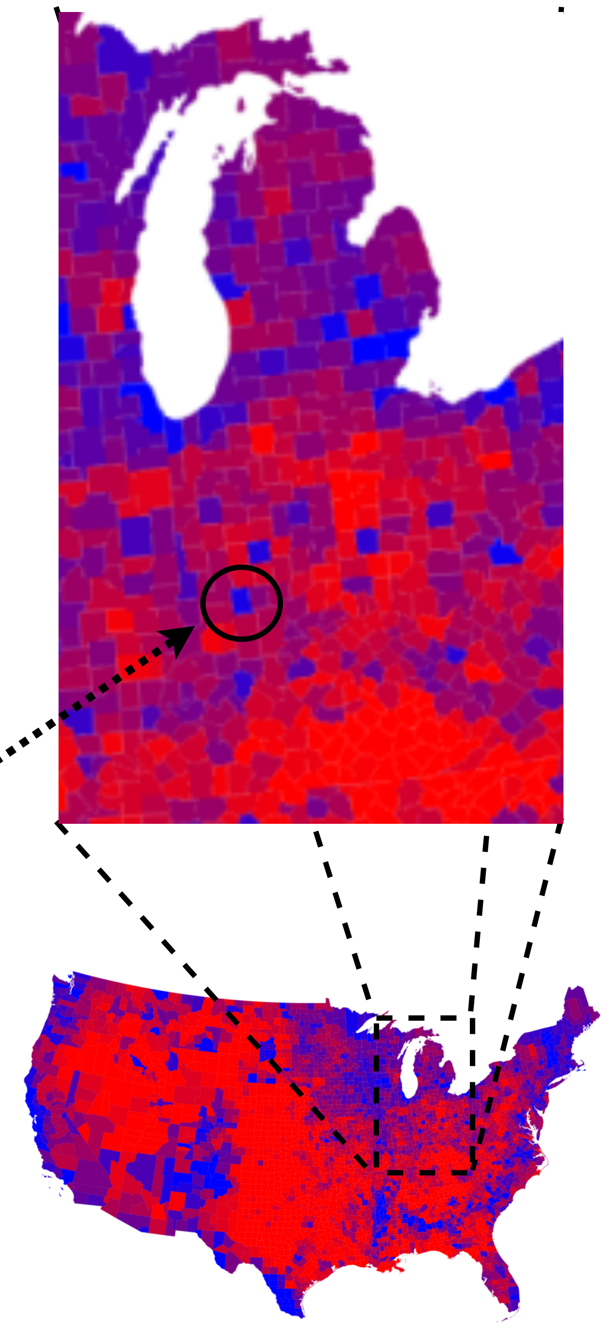
Heavy Quarkonia Results from CLEO-c

PANIC08
Particles and Nuclei
International Conference
Eilat, Israel



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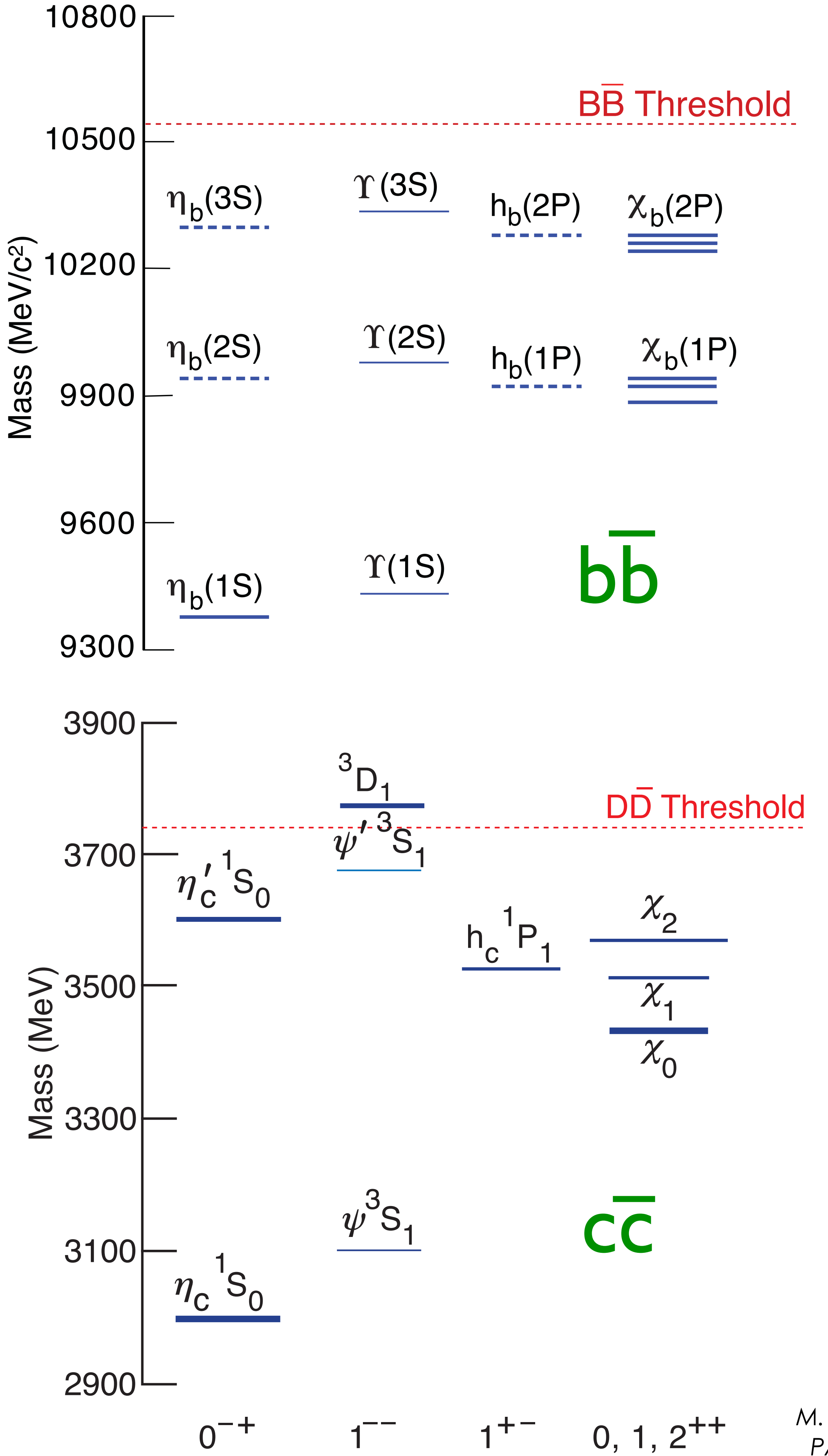
(on behalf of the CLEO Collaboration)

Overview

- Rich spectrum: physics topics are very diverse as are various experimental observables and analysis techniques
- Focus on a sample of recent highlights, primarily:
  - transitions between states
  - properties (mass, branching fractions) of states
- Notable omissions:
  - onia as a source for light meson spectroscopy (η' mass: PRL 101, 182002; rare η' decays: arXiv: 0809.2587 [hep-ex])
  - decays of onia as a probe for physics beyond the standard model (LFV: arXiv:0807.2695 [hep-ex]; light Higgs search: PRL101,151802)

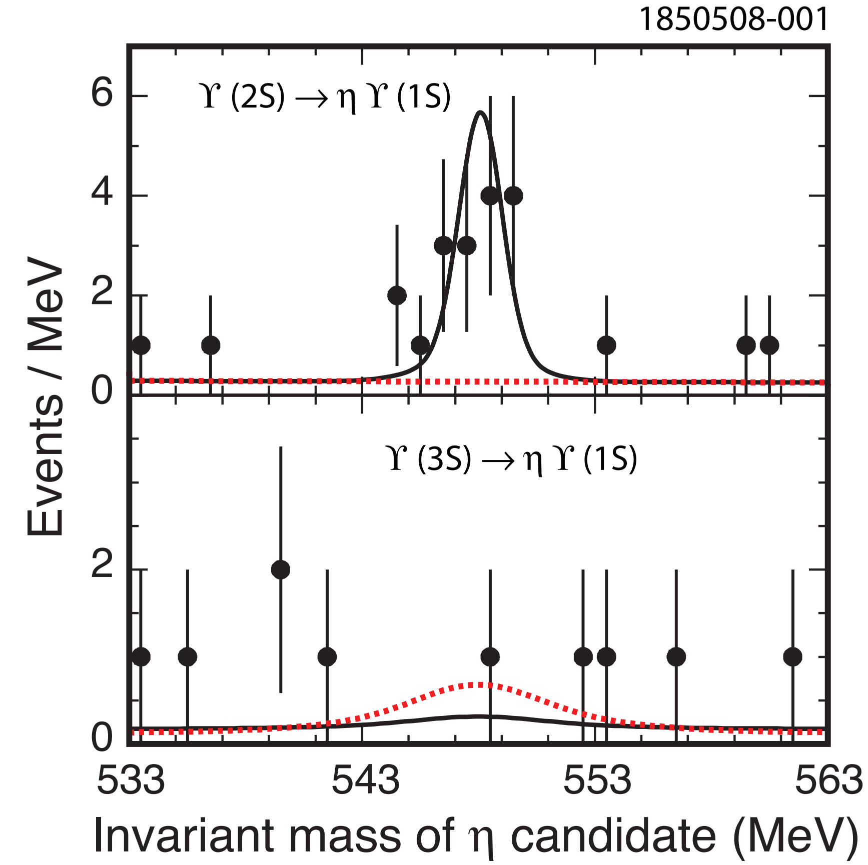


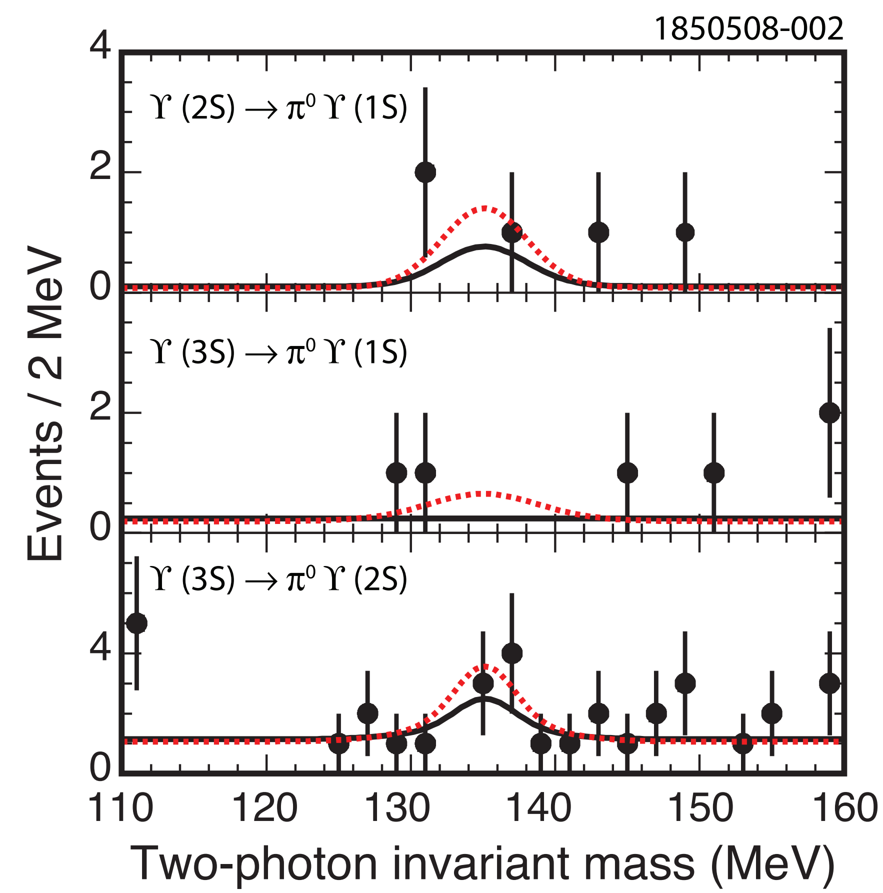
$\Upsilon(nS)\rightarrow(\pi^0,\eta)\Upsilon(mS)$

- Process sensitive to the chromomagnetic moment of the b quark, rate scales like $1/m_b^4$
- Scaling from $\psi(2S)\rightarrow\eta\, J/\Psi$ predicts a rate for $\Upsilon(nS)\rightarrow\eta\Upsilon(mS)$ of about 7×10^{-4}; isospin violating π^0 further suppressed
- Tag dilepton decay of Υ; use $\gamma\gamma$, $3\pi^0$, and $\pi^+\pi^-\pi^0$ decays of the η
- Results about 1/4 of what is expected from predictions based on the quark mass

Mode	B.F. $[10^{-4}]$
$\Upsilon(2S)\rightarrow\eta\Upsilon(1S)$	$2.1^{+0.7}_{-0.6}\pm0.3$
$\Upsilon(3S)\rightarrow\eta\Upsilon(1S)$	< 1.8
$\Upsilon(2S)\rightarrow\pi^0\Upsilon(1S)$	< 1.8
$\Upsilon(3S)\rightarrow\pi^0\Upsilon(1S)$	< 0.7
$\Upsilon(3S)\rightarrow\pi^0\Upsilon(2S)$	< 5.1

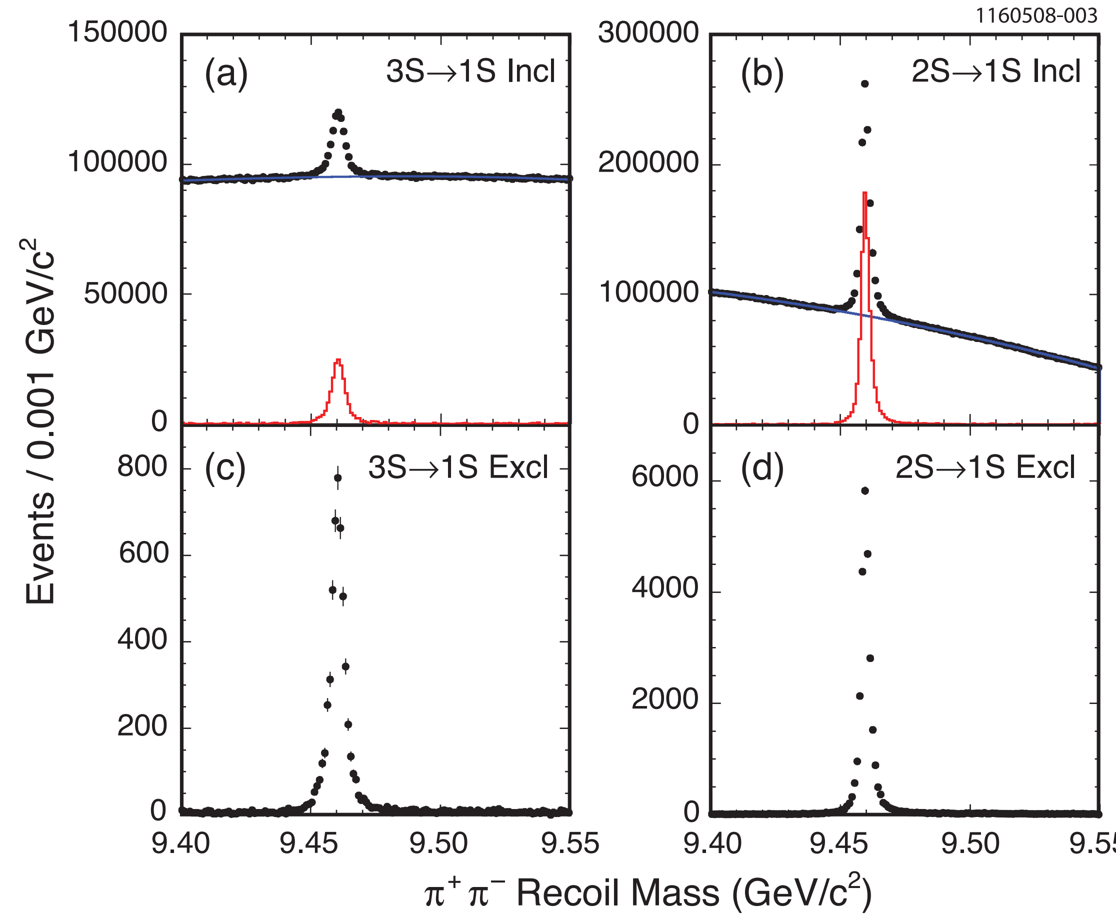
PRL 101, 192001 (2008)





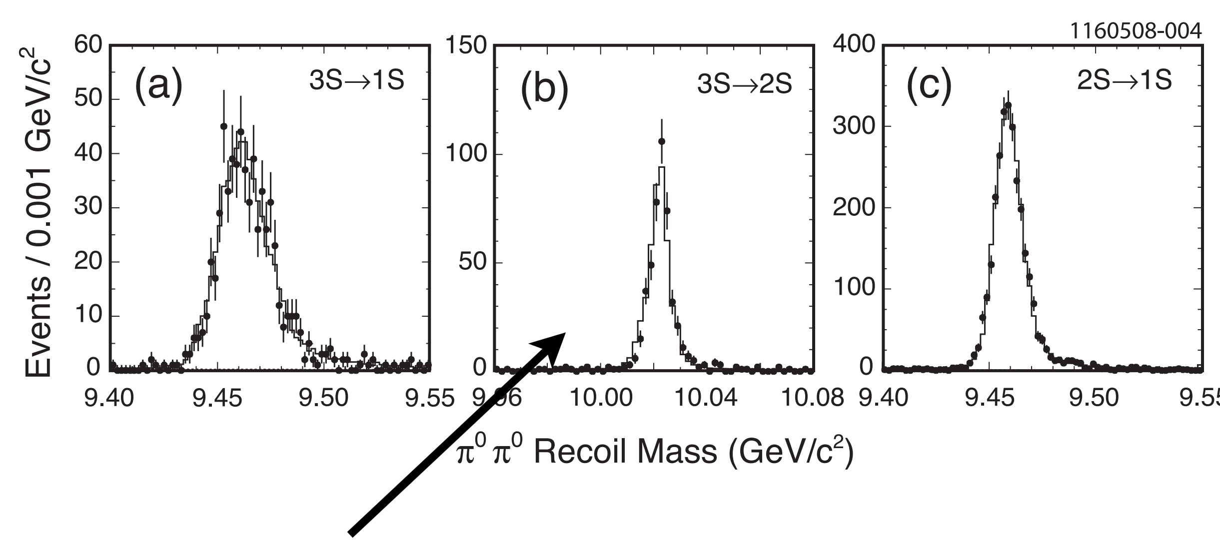
$\Upsilon(nS) \to \pi\pi\Upsilon(mS)$

- Proceeds by emission and hadronization of soft gluons
- Experimentally important since they provide rates for most likely transitions in bottomonium (access to one Υ state from another)
- $\pi^+\pi^-$: measure inclusively or reconstruct dilepton decay of Υ; $\pi^0\pi^0$: exclusive dilepton decay only



Mode	B.F. [%]	PDG B.F. [%]
$\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$	4.46±0.01±0.13	4.48±0.21
$\Upsilon(3S) \to \pi^0\pi^0\Upsilon(1S)$	2.24±0.09±0.11	2.06±0.28
$\Upsilon(3S) \to \pi^0\pi^0\Upsilon(2S)$	1.82±0.09±0.12	2.00±0.32
$\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$	18.02±0.02±0.61	18.8±0.6
$\Upsilon(2S) \to \pi^0\pi^0\Upsilon(1S)$	8.43±0.16±0.42	9.0±0.8

PRD(R) 78, 091103 (2008)



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PANIC08, Eilat
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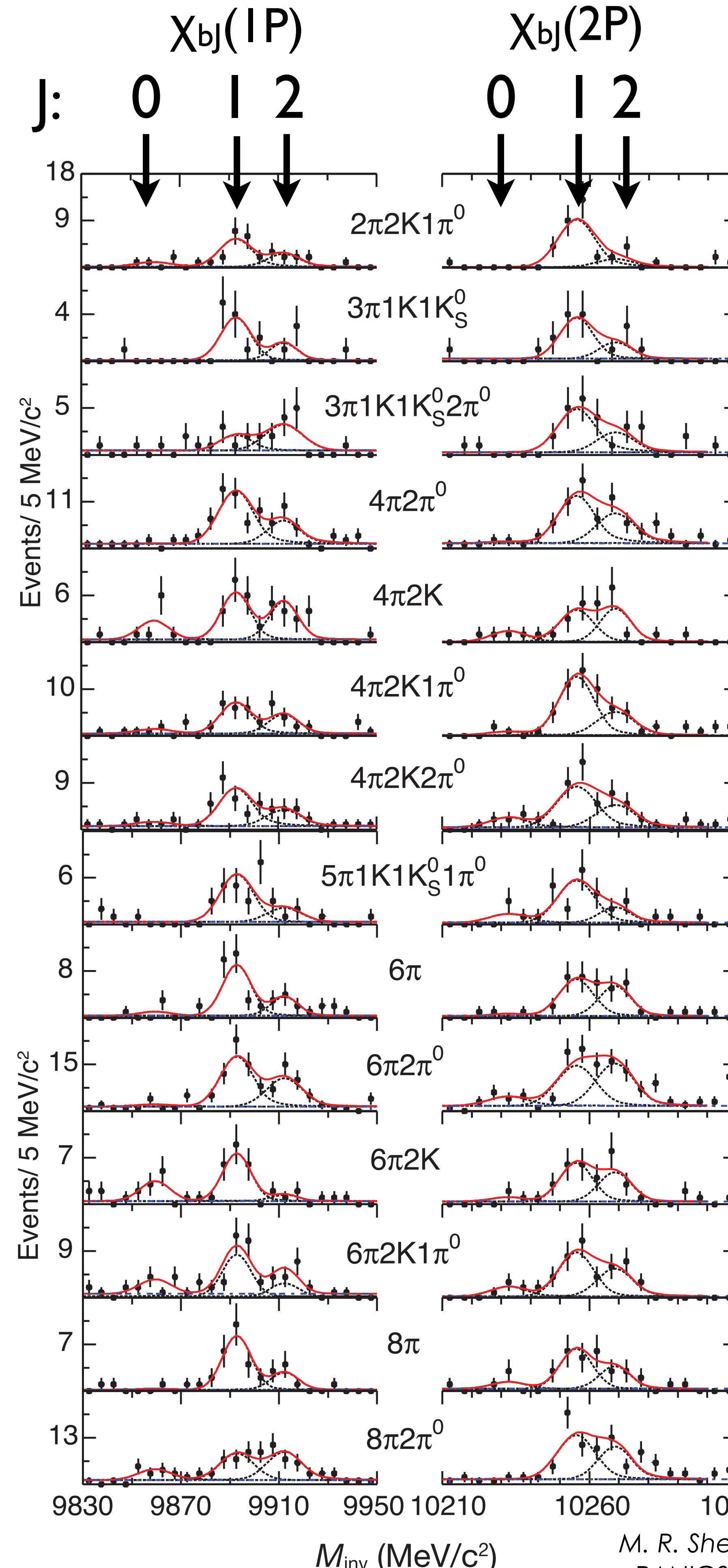
Exclusive χ_b Decays

- Very little is known about hadronic decays of the χ_b
- Theoretical interest in gluon hadronization processes
- Experimentally interesting since modes may provide hints for how to search for exclusive decays of unobserved bottomonium states
- Search 659 different exclusive modes; up to 12 particles, conserve strangeness, < 5 η or π^0, ...

Branching Fractions or 90% CL Limit [10^{-4}]

X_i	J=0		J=1		J=2	
	$n=2$	$n=3$	$n=2$	$n=3$	$n=2$	$n=3$
$2\pi 2K 1\pi^0$	<1.6	<0.3	$2.0\pm0.5\pm0.5$	$3.0\pm0.6\pm0.8$	$0.9\pm0.4\pm0.2$	<1.1
$3\pi 1K 1K_S^0$	<0.5	<0.5	$1.3\pm0.4\pm0.3$	$1.1\pm0.4\pm0.3$	<1.2	<0.9
$3\pi 1K 1K_S^0 2\pi^0$	<4.7	<2.3	<6.1	$7.7\pm2.3\pm2.2$	$5.3\pm1.9\pm1.5$	<6.7
$4\pi 2\pi^0$	<2.1	<2.5	$7.9\pm1.4\pm2.1$	$5.9\pm1.2\pm1.6$	$3.5\pm1.1\pm0.9$	$3.9\pm1.2\pm1.1$
$4\pi 2K$	$1.2\pm0.5\pm0.3$	<1.5	$1.5\pm0.4\pm0.4$	$0.9\pm0.3\pm0.2$	$1.2\pm0.3\pm0.3$	$0.9\pm0.3\pm0.2$
$4\pi 2K 1\pi^0$	<2.7	<2.2	$3.4\pm0.8\pm0.9$	$5.5\pm1.0\pm1.5$	$2.1\pm0.7\pm0.5$	$2.4\pm0.8\pm0.7$
$4\pi 2K 2\pi^0$	<5.4	<10.8	$8.6\pm2.0\pm2.4$	$9.6\pm2.3\pm2.8$	$3.9\pm1.6\pm1.1$	$4.7\pm1.8\pm1.4$
$5\pi 1K 1K_S^0 1\pi^0$	<1.7	<6.7	$9.2\pm2.3\pm2.5$	$6.7\pm1.9\pm1.9$	<5.0	<4.5
6π	<0.8	<0.7	$1.8\pm0.4\pm0.4$	$1.2\pm0.3\pm0.3$	$0.7\pm0.3\pm0.2$	$0.9\pm0.3\pm0.2$
$6\pi 2\pi^0$	<5.9	<12.3	$17.2\pm2.7\pm4.8$	$11.9\pm2.4\pm3.4$	$10.2\pm2.2\pm2.8$	$12.1\pm2.5\pm3.6$
$6\pi 2K$	$2.4\pm0.9\pm0.7$	<1.5	$2.6\pm0.6\pm0.7$	$2.0\pm0.6\pm0.5$	<0.8	$1.4\pm0.5\pm0.4$
$6\pi 2K 1\pi^0$	<9.9	<7.3	$7.5\pm1.6\pm2.1$	$6.1\pm1.4\pm1.8$	$3.7\pm1.2\pm1.0$	$4.2\pm1.2\pm1.2$
8π	<0.7	<1.7	$2.7\pm0.6\pm0.7$	$1.7\pm0.5\pm0.5$	$0.8\pm0.4\pm0.2$	$0.9\pm0.4\pm0.3$
$8\pi 2\pi^0$	<20.5	<6.5	$14.0\pm3.5\pm4.3$	$19.2\pm3.7\pm6.0$	$18.5\pm4.4\pm5.6$	$12.6\pm3.5\pm4.1$

write this down instead: arXiv:0808.0933 [hep-ex] (PRD, accepted)



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Inclusive χ_b Decays to Open Charm

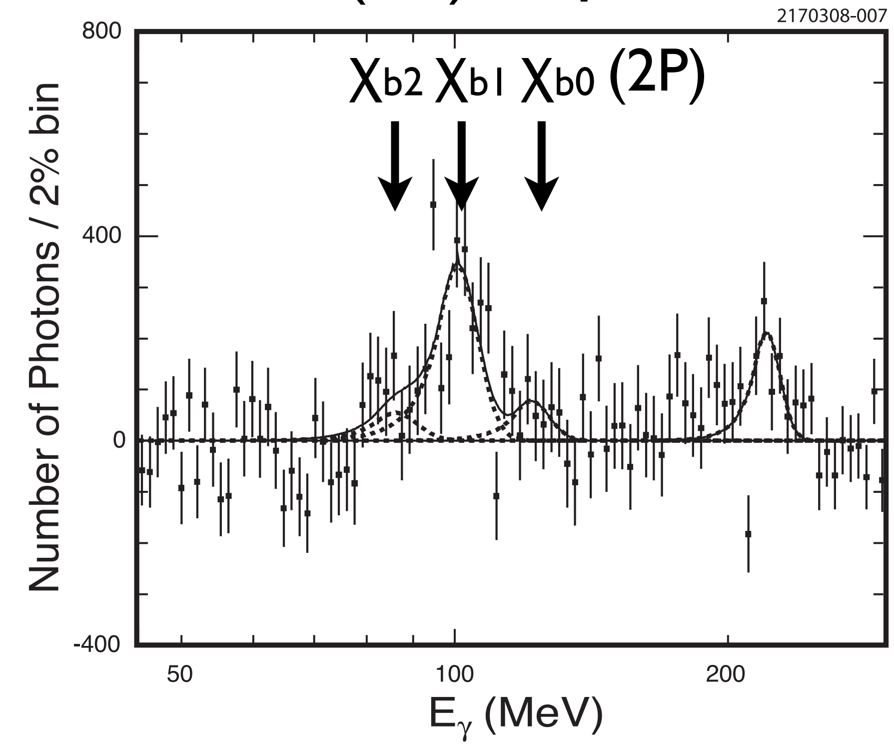
- All states except $\chi_{b1}(nP)$ decay dominantly to gg; $\chi_{b1}(nP) \to qqg$
- cc production suppressed in gg hadronization, but not in qqg hadronization
- Expect (and observed) enhanced $\chi_{b1}(nP) \to D^0X$, consistent with NRQCD predictions
- Consistent with relative charm production of 25% in qqg hadronization

fraction of charm production in hadronization

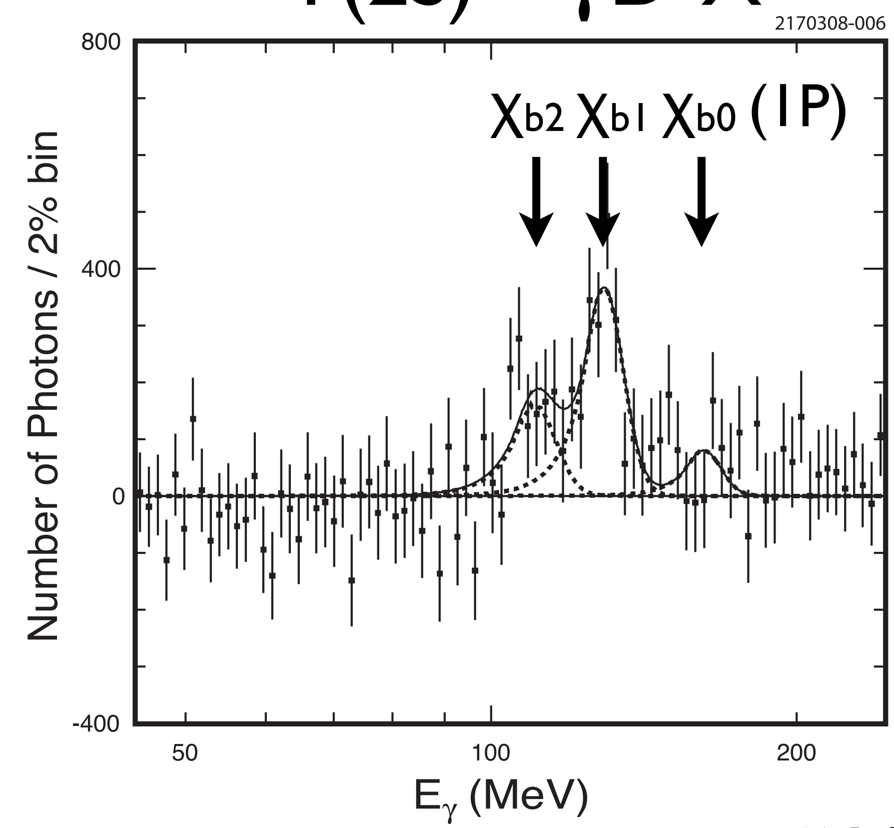
State	$R_J^{(c)}$ (%)	90% CL UL (%)
$\chi_{b0}(1P)$	$9.6 \pm 6.2 \pm 0.8 \pm 0.8$	< 17.9
$\chi_{b1}(1P)$	$24.8 \pm 3.8 \pm 2.2 \pm 3.6$	
$\chi_{b2}(1P)$	$9.8 \pm 3.5 \pm 0.9 \pm 0.9$	< 14.6
$\chi_{b0}(2P)$	$8.7 \pm 6.4 \pm 0.9 \pm 0.7$	< 17.7
$\chi_{b1}(2P)$	$25.3 \pm 4.3 \pm 2.5 \pm 2.4$	
$\chi_{b2}(2P)$	$0.4 \pm 3.5 \pm 0.4 \pm 0.1$	< 6.1

PRD 78, 092007 (2008)

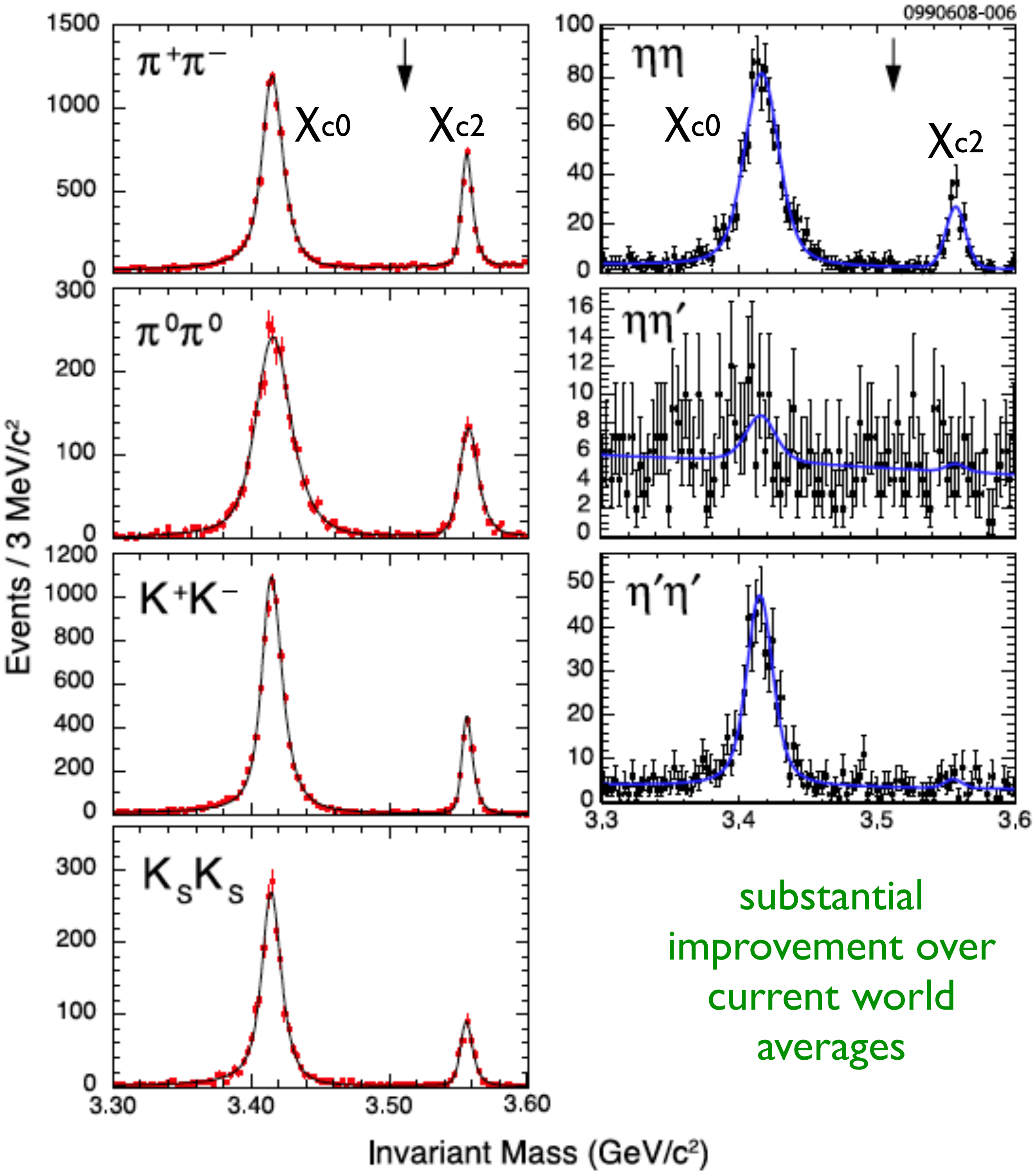
$\Upsilon(3S) \to \gamma D^0 X$



$\Upsilon(2S) \to \gamma D^0 X$



χ_{cJ}(1P) Two-body Decays



substantial improvement over current world averages

- Variety of physics applications -- two body decays are theoretically more clean
  - role of the color octect mechanism in decay
  - probe gluon content in final state mesons
- CLEO results for two-baryon final states have also recently been published: PRD 78, 031101(R) (2008)

Branching Fractions or 90% CL UL [10^{-3}]

Mode		χ_{c0}	χ_{c2}
$\pi^+\pi^-$	This Work	$6.37 \pm 0.08 \pm 0.29 \pm 0.32$	$1.59 \pm 0.04 \pm 0.07 \pm 0.10$
	PDG	4.87 ± 0.40	1.42 ± 0.16
$\pi^0\pi^0$	This Work	$2.94 \pm 0.07 \pm 0.32 \pm 0.15$	$0.68 \pm 0.03 \pm 0.07 \pm 0.04$
	PDG	$2.43 \pm .20$	0.71 ± 0.08
K^+K^-	This Work	$6.47 \pm 0.08 \pm 0.33 \pm 0.32$	$1.13 \pm 0.03 \pm 0.06 \pm 0.07$
	PDG	5.5 ± 0.6	0.78 ± 0.14
$K^0_SK^0_S$	This Work	$3.49 \pm 0.08 \pm 0.17 \pm 0.17$	$0.53 \pm 0.03 \pm 0.03 \pm 0.03$
	PDG	2.77 ± 0.34	0.68 ± 0.11
$\eta\eta$	This Work	$3.18 \pm 0.13 \pm 0.31 \pm 0.16$	$0.51 \pm 0.05 \pm 0.05 \pm 0.03$
	PDG	2.4 ± 0.4	< 0.5
$\eta\eta'$	This Work	< 0.25	< 0.06
		$(0.16 \pm 0.06 \pm 0.01 \pm 0.01)$	$(0.013 \pm 0.031 \pm 0.001 \pm 0.001)$
	PDG	< 0.5	< 0.26
$\eta'\eta'$	This Work	$2.12 \pm 0.13 \pm 0.18 \pm 0.11$	< 0.10
			$(0.056 \pm 0.032 \pm 0.005 \pm 0.003)$
	PDG	1.7 ± 0.4	< 0.4

arXiv:0811.0586 [hep-ex] (PRD, submitted)

Observation of $\chi_{cJ}(1P) \rightarrow \gamma(\rho,\omega,\varphi)$

Look for:

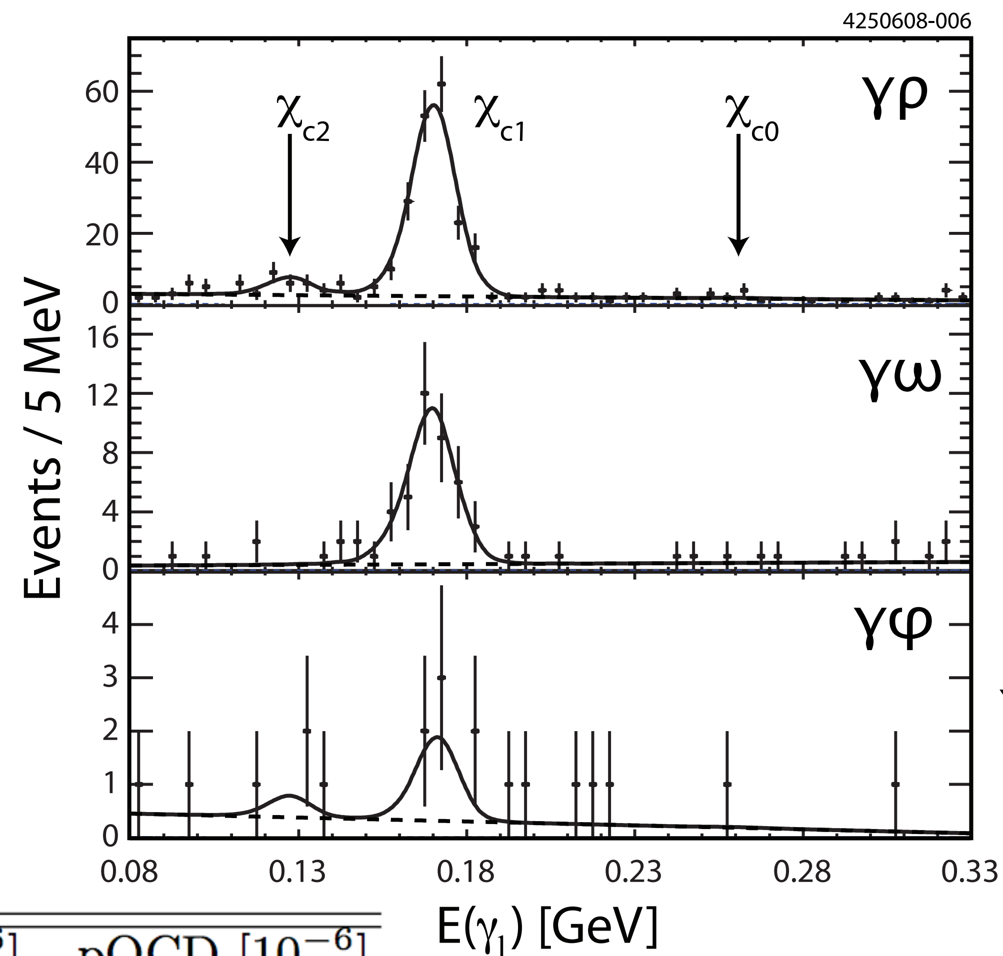
$\psi(2S) \rightarrow \gamma_{(low)} \chi_{cJ}$

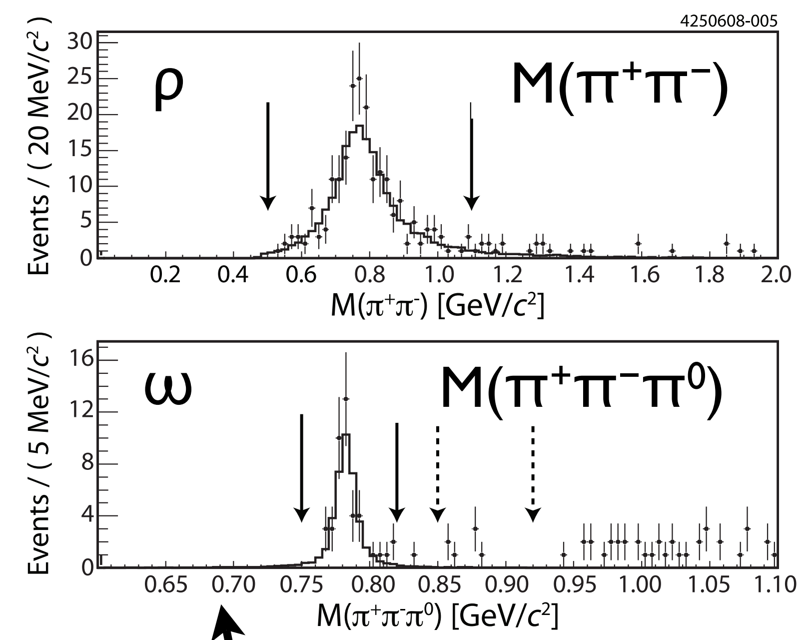
$\chi_{cJ} \rightarrow \gamma_{(high)}(\rho,\omega,\varphi)$

Significant signals seen for:

$\chi_{c1} \rightarrow \gamma\rho$

$\chi_{c1} \rightarrow \gamma\omega$





1. cut on hadronic mass

2. look at E_γ(low)

Mode	$\mathcal{B} \times 10^6$	U.L. $[10^{-6}]$	pQCD $[10^{-6}]$
$\chi_{c0} \rightarrow \gamma\rho^0$		< 9.6	1.2
$\chi_{c1} \rightarrow \gamma\rho^0$	$243 \pm 19 \pm 22$		14
$\chi_{c2} \rightarrow \gamma\rho^0$	$25 \pm 10^{+8}_{-14}$	< 50	4.4
$\chi_{c0} \rightarrow \gamma\omega$		< 8.8	0.13
$\chi_{c1} \rightarrow \gamma\omega$	$83 \pm 15 \pm 12$		1.6
$\chi_{c2} \rightarrow \gamma\omega$		< 7.0	0.50
$\chi_{c0} \rightarrow \gamma\phi$		< 6.4	0.46
$\chi_{c1} \rightarrow \gamma\phi$	$12.8 \pm 7.6 \pm 1.5$	< 26	3.6
$\chi_{c2} \rightarrow \gamma\phi$		< 13	1.1

PRL 101, 151801 (2008)

The form of the decay is similar to $J/\psi \rightarrow \gamma f$, an important reaction for glueball searches.

pQCD, however, predicts rates an order of magnitude below the observations!

(Gao,Zhang,Chao, Chin.Phys.Lett.23,2376 (2006) [arXiv:hep-ph/0607278])

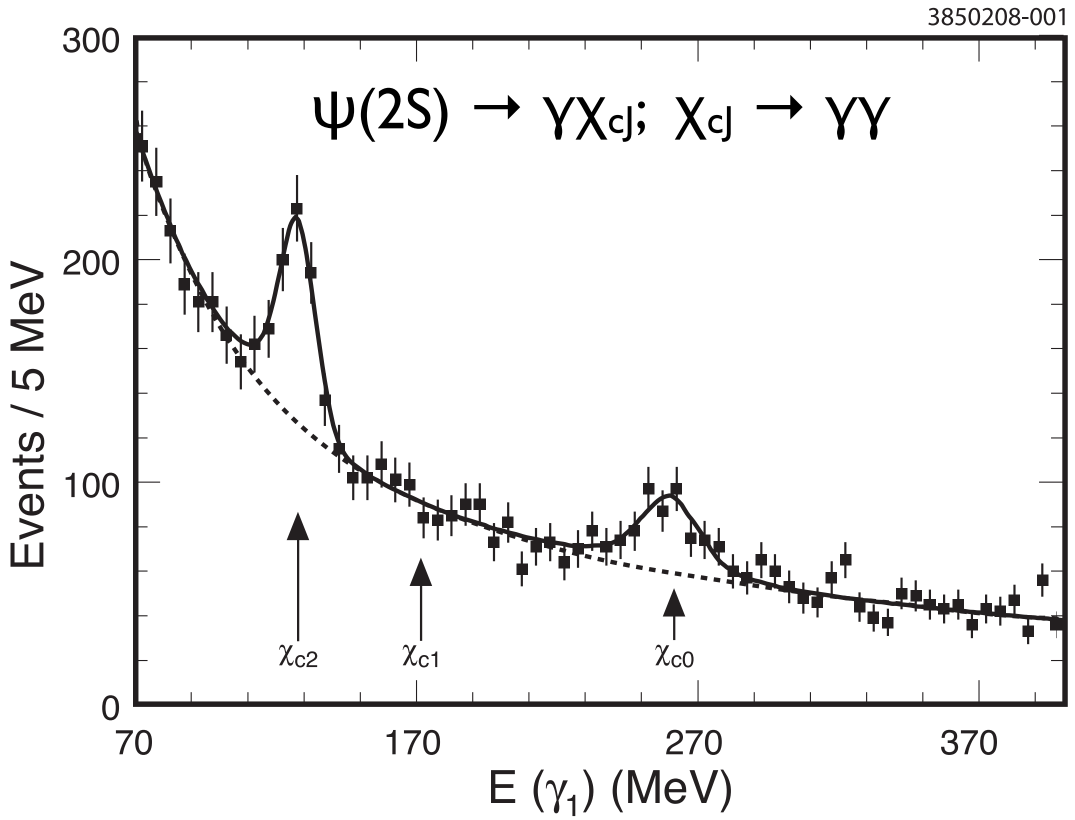
χ_{cJ}(1P) Two-Photon Widths

- Two-photon decays of χ_{cJ} probe relativistic and radiative corrections known to be significant in the charmonium system

$\Gamma_{\gamma\gamma}(\chi_{c0}) = 2.53 \pm 0.37_{stat} \pm 0.11_{syst} \pm 0.24_{PDG}$ keV

$\Gamma_{\gamma\gamma}(\chi_{c2}) = 0.60 \pm 0.06_{stat} \pm 0.03_{syst} \pm 0.05_{PDG}$ keV

Ratio $= 0.237 \pm 0.043_{stat} \pm 0.015_{syst} \pm 0.03_{PDG}$



In pQCD quark mass and wave function uncertainties cancel, making the ratio of widths *R* a key quantity -- at first order in α_s:

$$\mathcal{R}_{th} = \frac{\Gamma_{\gamma\gamma}(\chi_{c2}) \ = \ 4(|\Psi'(0)|^2\alpha_{em}^2/m_c^4) \times [1 - 1.70\alpha_s]}{\Gamma_{\gamma\gamma}(\chi_{c0}) \ = \ 15(|\Psi'(0)|^2\alpha_{em}^2/m_c^4) \times [1 + 0.06\alpha_s]} = (4/15)\,[1 - 1.76\alpha_s]$$

$\alpha_s = 0.32 \to R = 0.12$

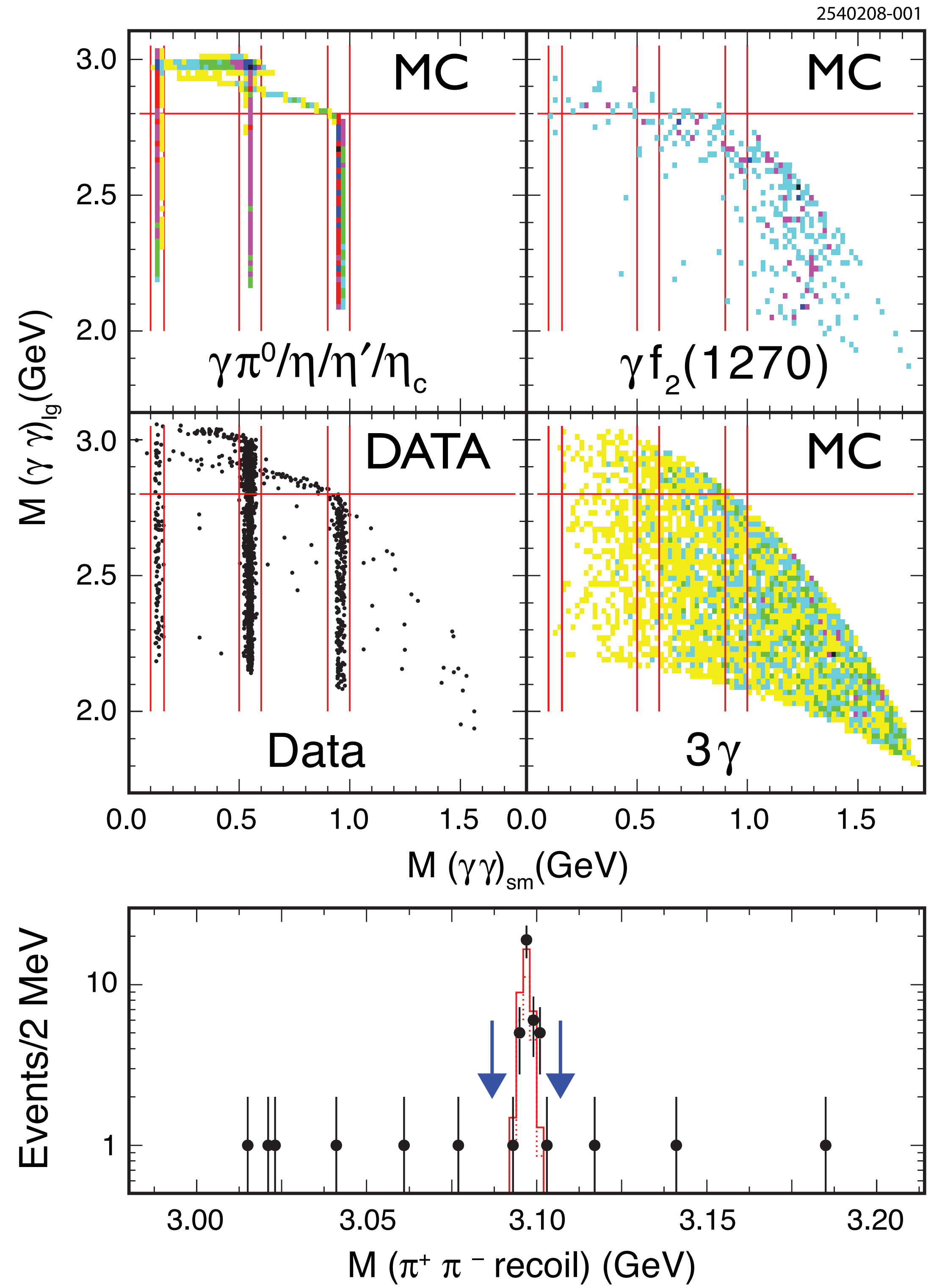
new world avg.: $R = 0.20 \pm 0.02$

higher order corrections very significant

arXiv:0803.2869 [hep-ex]
(PRD, accepted)

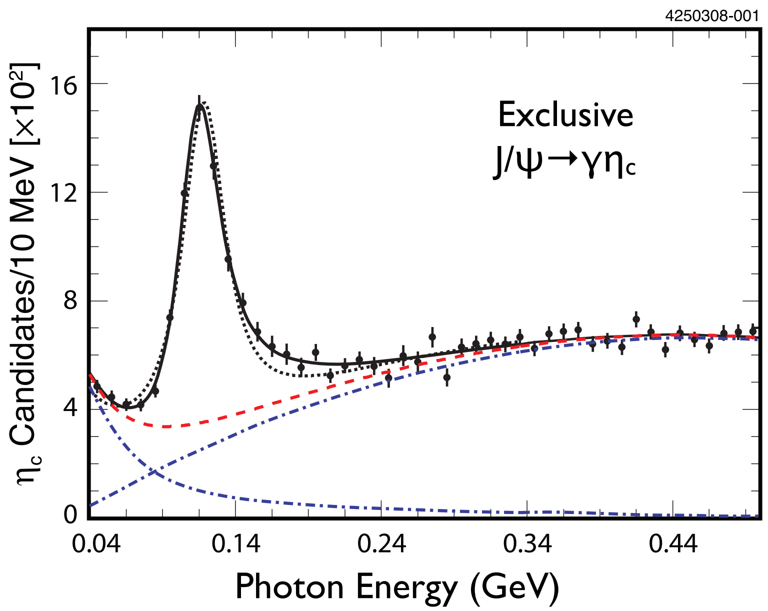
J/ψ → γγγ

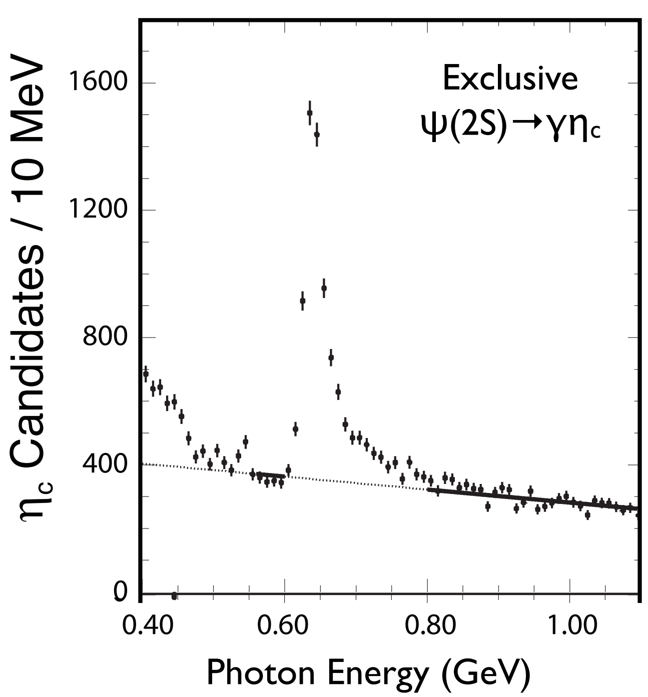
- This is the quarkonium analogue of ortho-positronium.
- Tag J/ψ with $\psi(2S) \to \pi^+\pi^- J/\psi$.
- 37 events are inconsistent with $\gamma\pi^0/\eta/\eta'/\eta_c$.
- 24.2 events remain after subtracting backgrounds (dominantly $\gamma\pi^0\pi^0$).
- $B(J/\psi \to \gamma\gamma\gamma) = (1.2 \pm 0.3 \pm 0.2) \times 10^{-5}$.
- Agrees with leading order QED prediction, but NLO correction takes rate negative! (Higher order corrections very significant.)
- A search for $J/\psi \to \gamma\eta_c$; $\eta_c \to \gamma\gamma$ leads to upper limits on $B(\eta_c \to \gamma\gamma)$:
  $B(\eta_c \to \gamma\gamma) < 3 \times 10^{-4}$ at 90% C.L.
  (PDG: $B(\eta_c \to \gamma\gamma) = (2.7 \pm 0.9) \times 10^{-4}$)



PRL 101, 101801 (2008)

$J/\psi,\psi' \to \gamma\eta_c$





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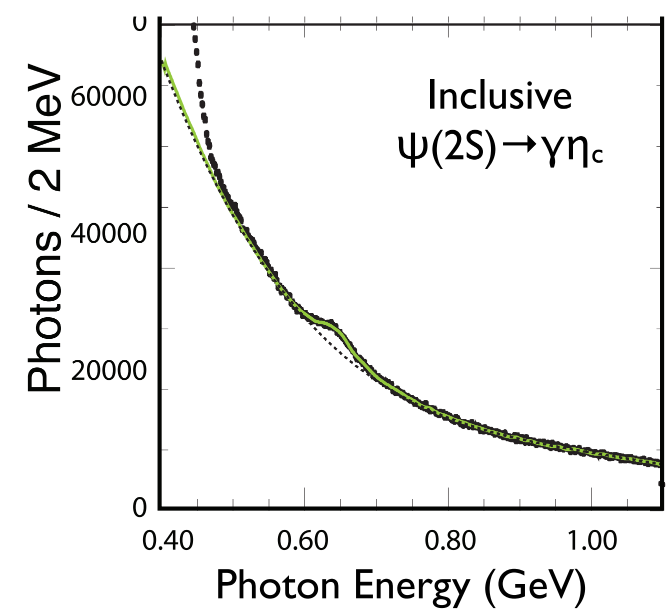


= $B(J/\psi \to \gamma\eta_c)$

<u>Three Measurements of M1 Transitions:</u>

A. $B(\psi(2S) \to \gamma\eta_c) = (4.32 \pm 0.16 \pm 0.60) \times 10^{-3}$ from inclusive η_c decays.

B. $B(J/\psi \to \gamma\eta_c) / B(\psi(2S) \to \gamma\eta_c)$ using exclusive η_c decays.

C. $B(J/\psi \to \gamma\eta_c) = (1.98 \pm 0.09 \pm 0.30)\%$ taking A×B.

One “surprise” was the non-trivial line-shape of the η_c.

Recent Lattice QCD Results (Dudek et al, PRD73,07450(2006)) predict

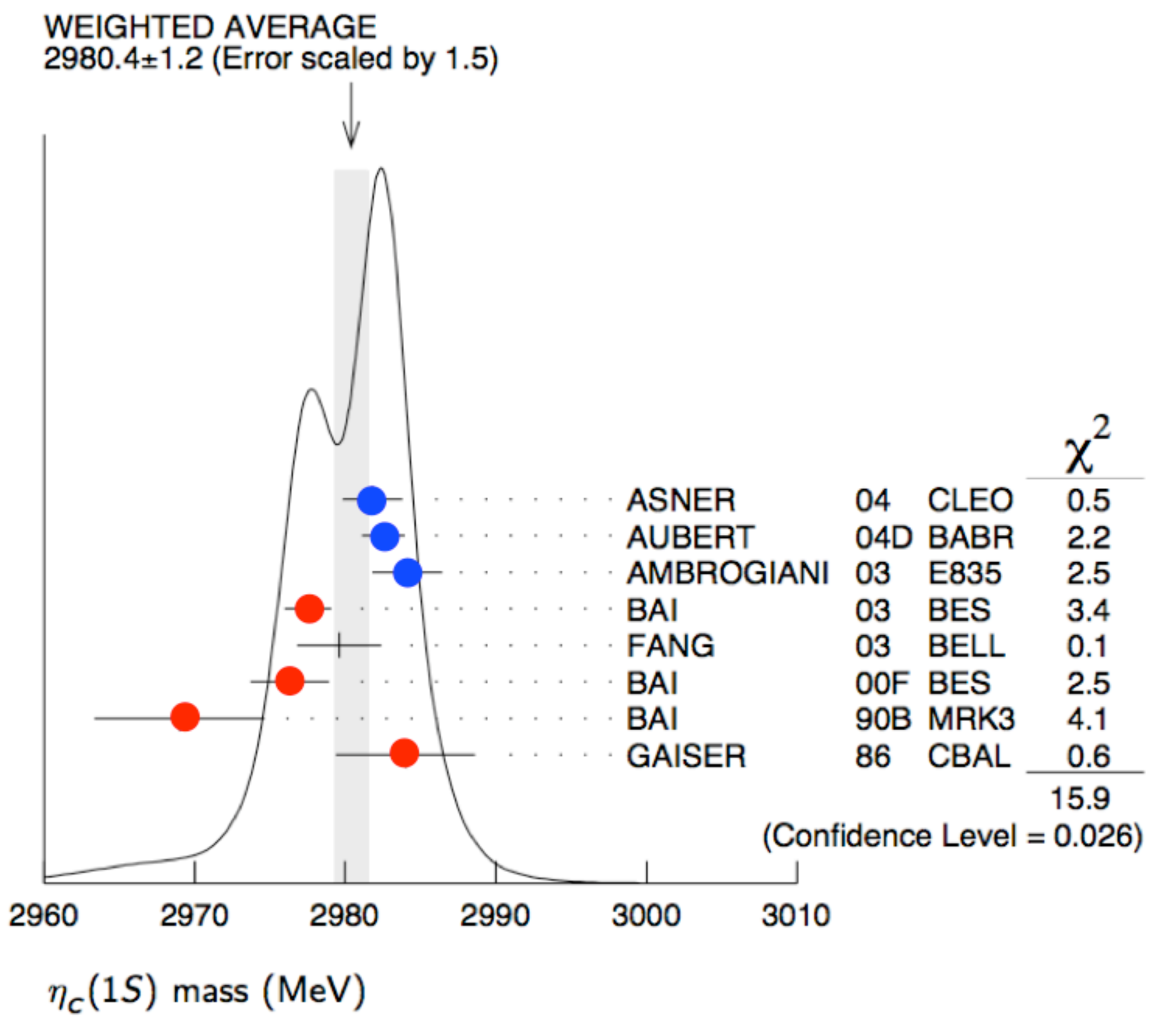
$\Gamma_{\gamma\eta c} = (2.0 \pm 0.1 \pm 0.4)$ keV

$\Rightarrow B(J/\psi \to \gamma\eta_c) = (2.1 \pm 0.1 \pm 0.4)\%$

arXiv:0805.0252 [hep-ex]
(submitted to PRL)

The $\eta_c(1S)$ Mass

PDG 2006 Mass



From $\psi(1S,2S)\to\gamma\eta_c$:
average = 2977.3 ± 1.3 MeV/c^2
From $\gamma\gamma$ or p^+p^- production:
average = 2982.6 ± 1.0 MeV/c^2
⇒ >3σ difference!

From CLEO fits to $J/\psi\to\gamma\eta_c$ (previous slide):
$M(\eta_c)$ = 2976.7 ± 0.6 MeV/c^2 (unmodified BW)
$M(\eta_c)$ = 2982.2 ± 0.6 MeV/c^2 (BW modified by energy dependence in the matrix element).
(statistical errors only!)

Recent Belle $\gamma\gamma$ measurements:
$\eta_c\to$4-body (EPJ,C53:1-14(2008)):
$M(\eta_c)$ = 2986.1 ± 1.0 ± 2.5 MeV/c^2
$\eta_c\to K_S K\pi$ (photon 2007):
$M(\eta_c)$ = 2981.4 ± 0.5 ± 0.4 MeV/c^2

Understanding the energy dependence of the $\psi(1S,2S)\to\gamma\eta_c$ matrix element is crucial for an accurate mass measurement from radiative decays.

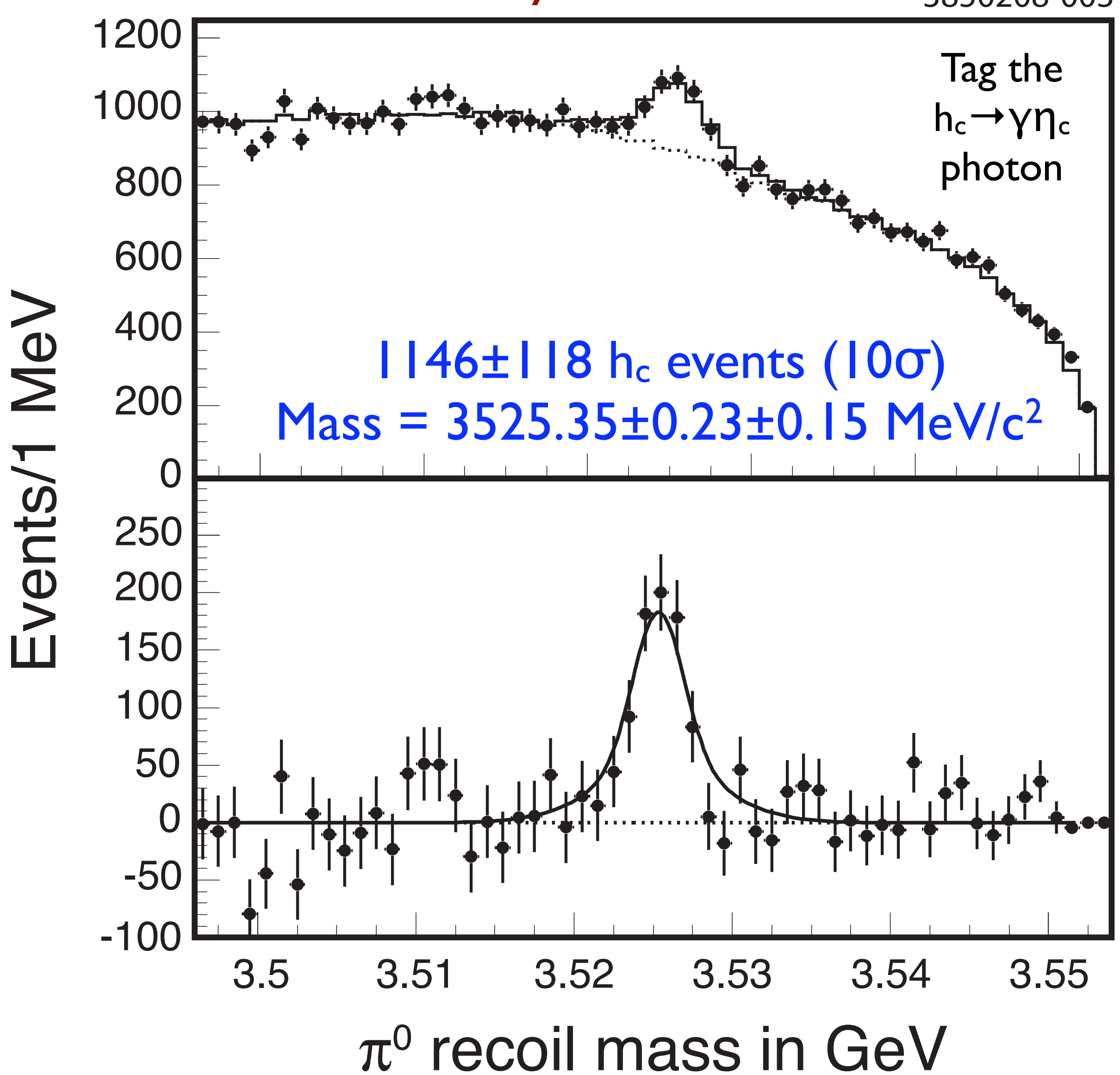
η_c mass uncertainty drives experimental error on 1S hyperfine splitting.

The $h_c(1P)$ Mass

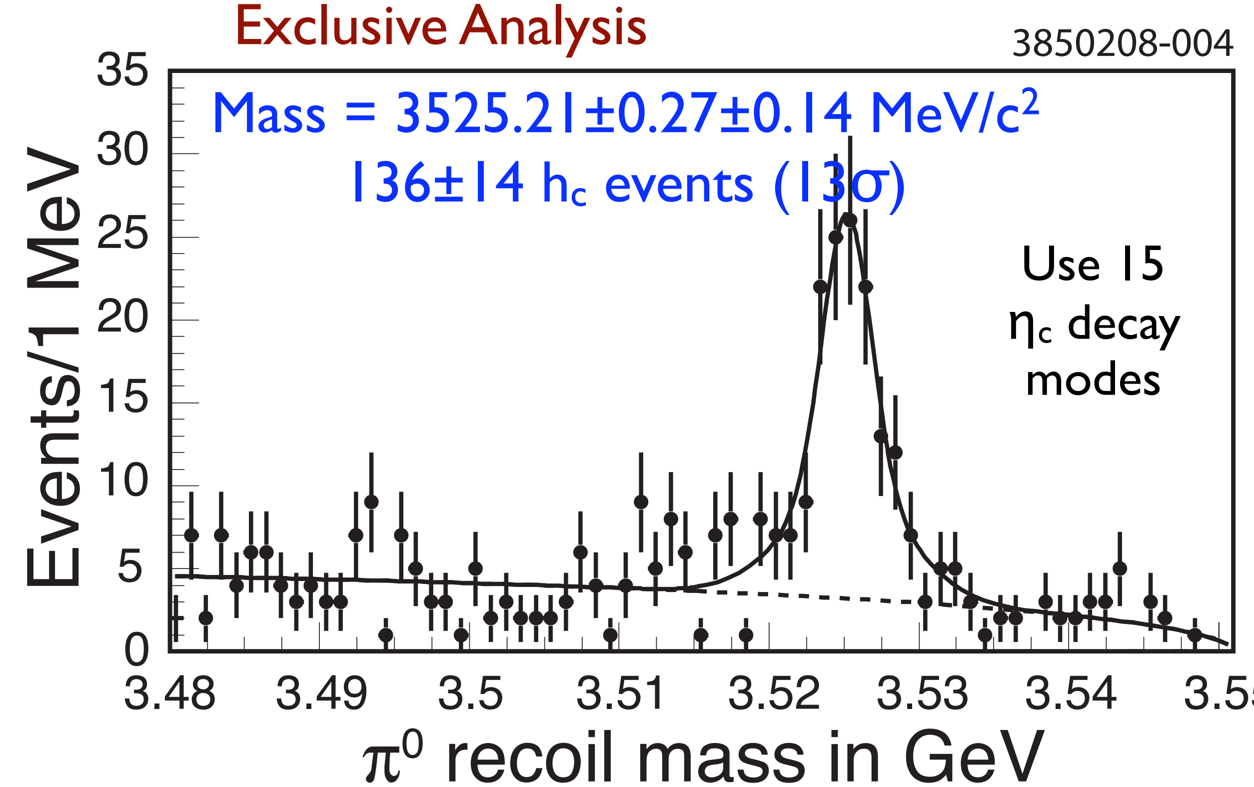
$\psi(2S) \rightarrow \pi^0 h_c(1P)$; $h_c(1P) \rightarrow \gamma\eta_c$

(factor of 9 more data than previous measurement)

Inclusive Analysis



Exclusive Analysis



Combined Mass = 3525.28±0.19±0.12 MeV/c^2

Compare to:

$\langle M(\chi_{cJ}(1P))\rangle$=(3525.30±0.11) MeV/$c^2$ (PDG)

⇒ Hyperfine splitting of 1P states is small (or 0).

PRL 101, 182003 (2008)

Summary

- Diverse range of QCD physics is accessible by studying the heavy quarkonia systems -- only a small sample presented here:
  - gluon hadronization
  - quark and wave function structure
  - qq interactions: hyperfine splitting, radiative and relativistic effects
- Experimental outlook is promising
  - CLEO-c data collection is complete, final analysis underway
  - BaBar and Belle are exploring the bottomonia states
  - BES III will acquire an enormous data sample in the charmonium region