Charmonium:
An Experimental Review

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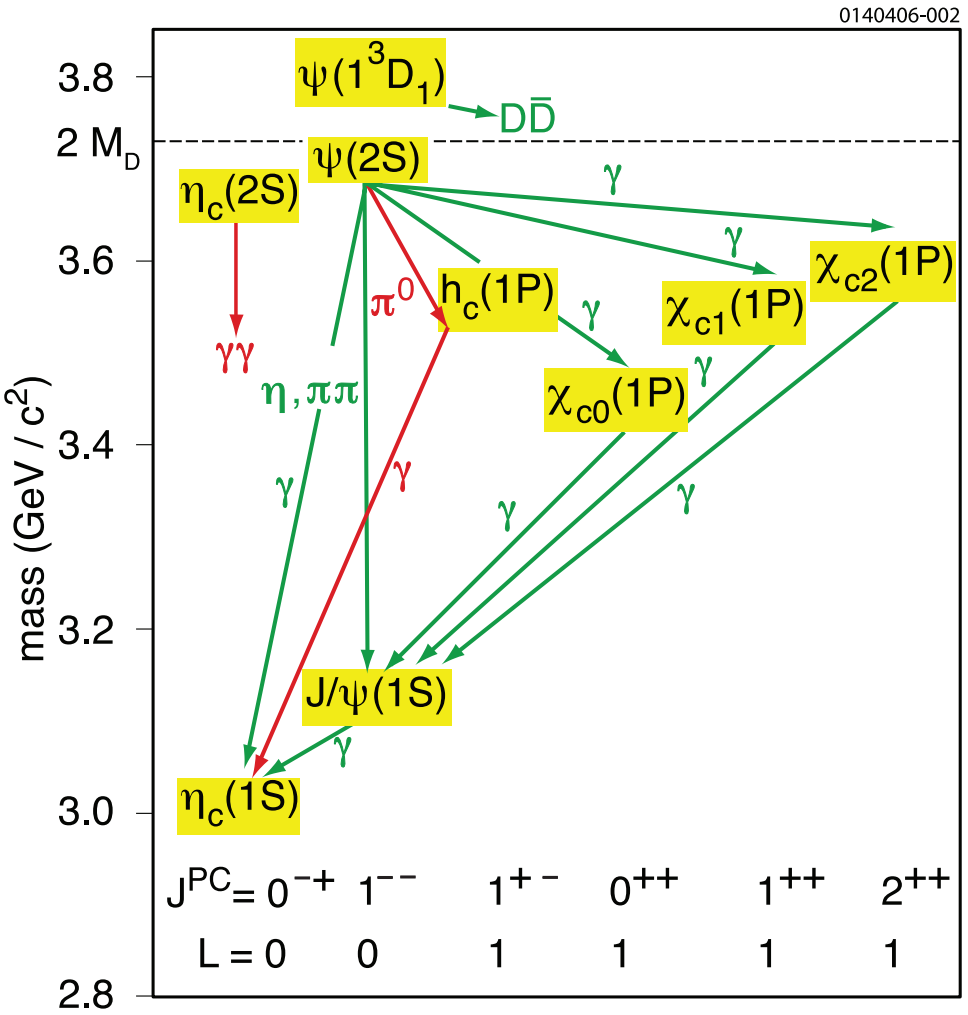
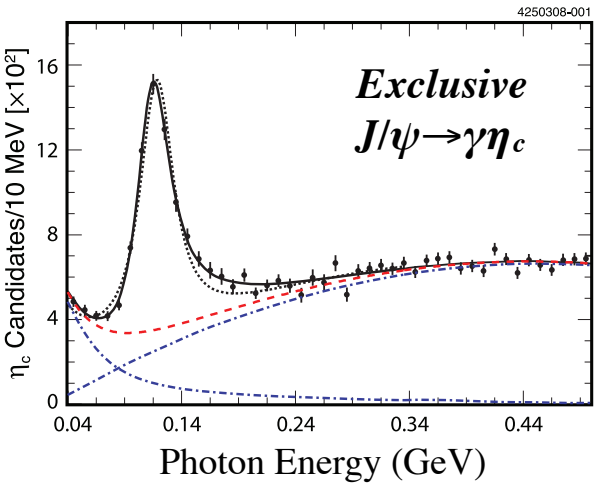
Introduction

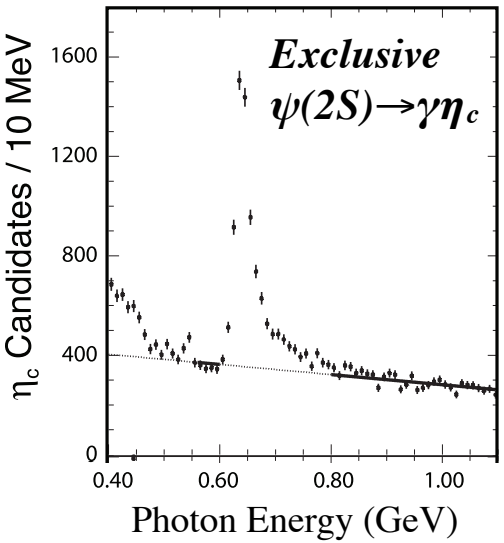
- The **charmonium system** provides a laboratory for the study of the strong force.
- Progress is piecemeal.
- This talk will cover recent results from:
  - **CLEO**'s total sample of 27M ψ(2S), mostly collected in August, 2006.
  - Recent **Belle** γγ results and **BaBar** B decays to charmonium.
- Note:
  - We are about to enter a new **BES III** era.
  - Heavy charmonia (**Belle**, **BaBar**) will be covered in separate talks.



$J/\psi, \psi(2S) \rightarrow \gamma\eta_c(1S)$

CLEO: 24.5M $\psi(2S)$ arXiv:0805.0252[hep-ex] (submitted to PRL)



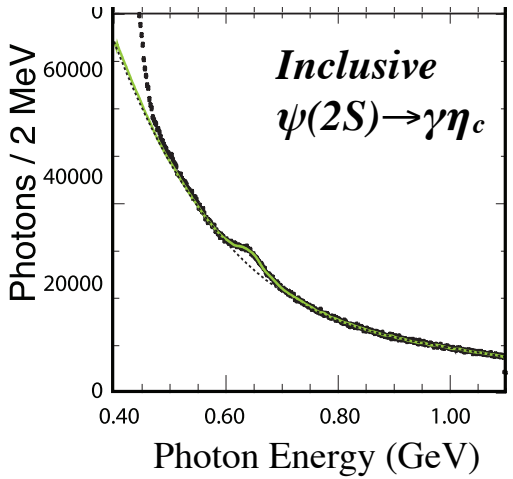


Three Measurements of M1 Transitions:

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

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

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



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

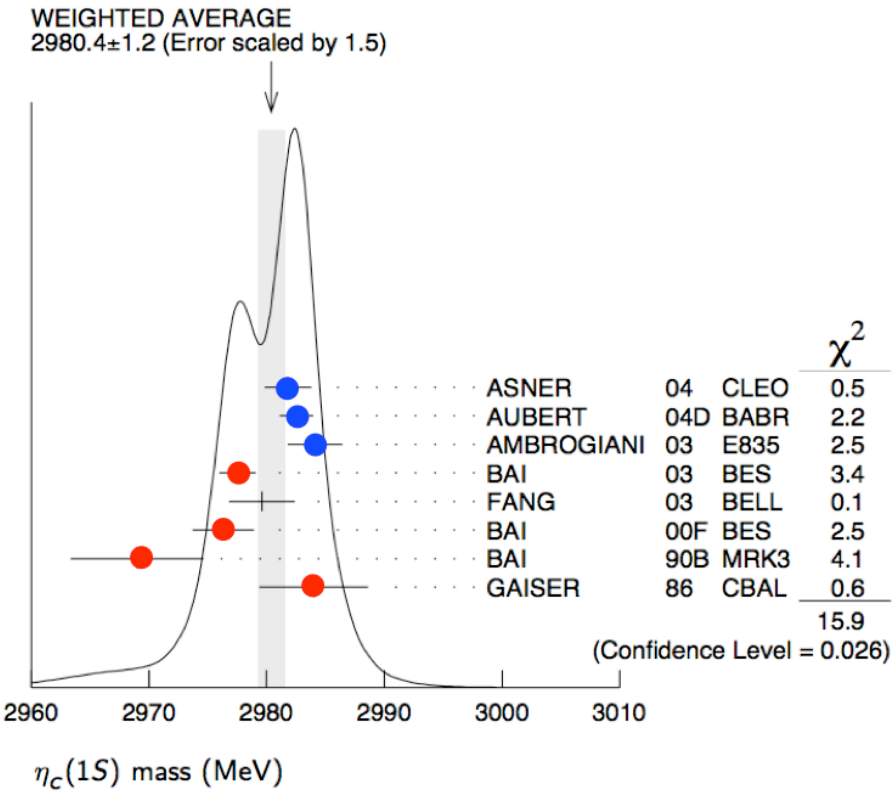
- One "surprise" was the non-trivial line-shape of the η_c.
- Recent Lattice QCD Results **(Dudek et al, PRD73,07450(2006))** predict $\Gamma_{\gamma\eta c} = (2.0 \pm 0.1 \pm 0.4)$ keV

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

The experimental value of $B(J/\psi \rightarrow \gamma\eta_c)$ is now in line with theoretical expectations.

Note on the $\eta_c(1S)$ Mass

PDG 2006 Mass



- From $\psi(1S,2S)\to\gamma\eta_c$:
  average = **2977.3 ± 1.3 MeV/c²**
- From $\gamma\gamma$ or p^+p^- production
  average = **2982.6 ± 1.0 MeV/c²**

⇒ >3σ difference!

From CLEO fits to $J/\psi\to\gamma\eta_c$ (previous slide):

$M(\eta_c) = 2976.7 \pm 0.6$ MeV/c² (unmodified BW)

$M(\eta_c) = 2982.2 \pm 0.6$ MeV/c² (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))**:

$M(\eta_c) = 2986.1 \pm 1.0 \pm 2.5$ MeV/c²

$\eta_c\to K_S K\pi$ **(photon 2007)**:

$M(\eta_c) = 2981.4 \pm 0.5 \pm 0.4$ MeV/c²

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.

Observation of $J/\psi \to \gamma\gamma\gamma$

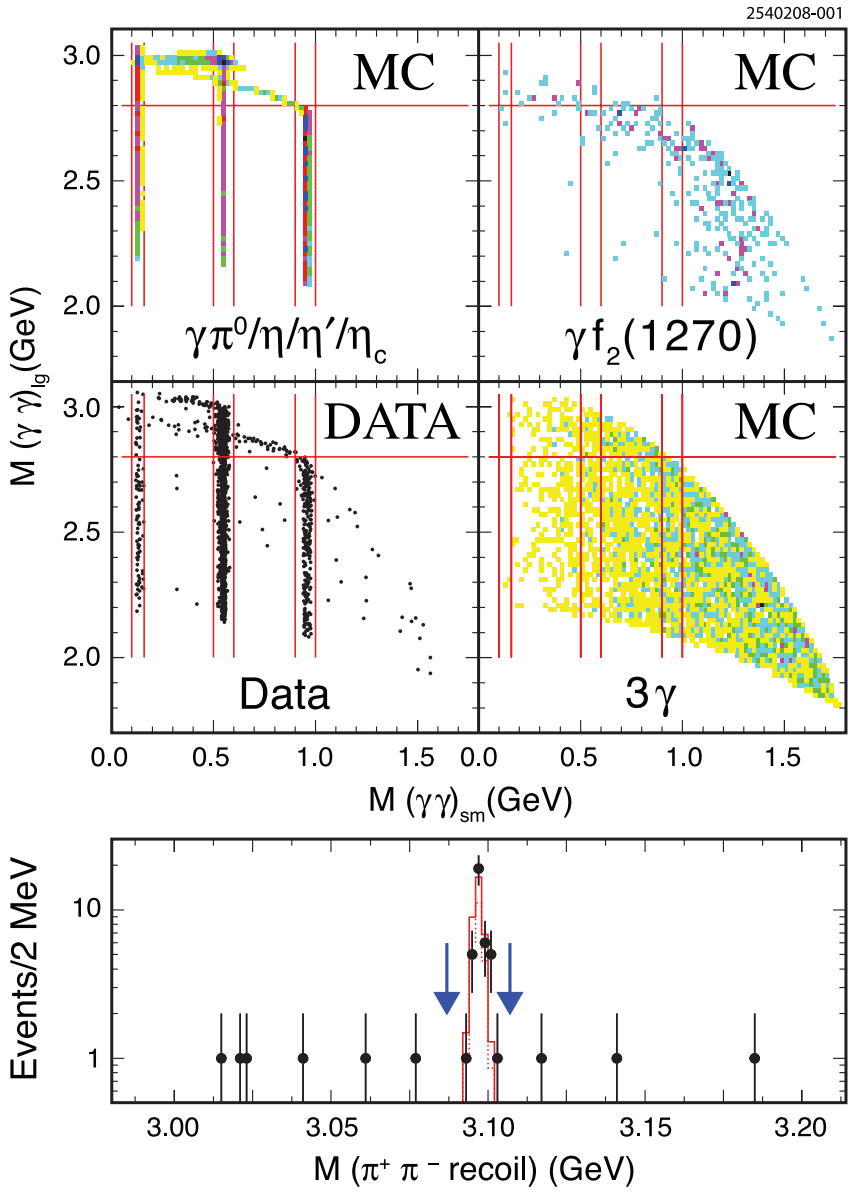
CLEO 27M $\psi(2S)$ arXiv:0806.0315 [hep-ex] (accepted by PRL)

- 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 $\gamma\pi^0\pi^0$).
- **$B(J/\psi \to \gamma\gamma\gamma) = (1.2 \pm 0.3 \pm 0.2) \times 10^{-5}$.**

•A search for $J/\psi \to \gamma\eta_c$; $\eta_c \to \gamma\gamma$ leads to upper limits on $B(\eta_c \to \gamma\gamma)$:

$B(\eta_c \to \gamma\gamma) < 3\times10^{-4}$ at 90% C.L.

(PDG: $B(\eta_c \to \gamma\gamma) = (2.7\pm0.9)\times10^{-4}$)



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

CLEO 27M $\psi(2S)$ arXiv:0807.3718 [hep-ex] (submitted to PRL)

Look for:

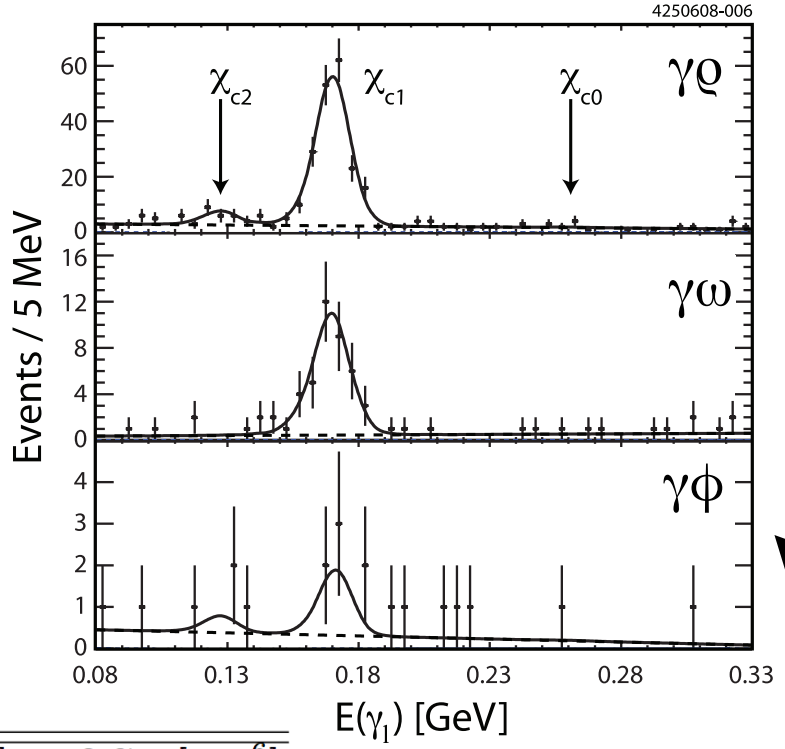
$\psi(2S) \rightarrow \gamma_{(low)}\chi_{cJ}$

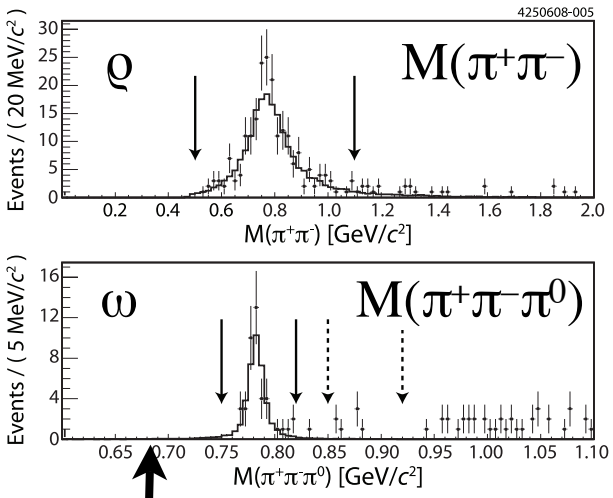
$\chi_{cJ} \rightarrow \gamma_{(high)}(\varrho,\omega,\phi)$

Significant signals seen for:

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

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





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

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

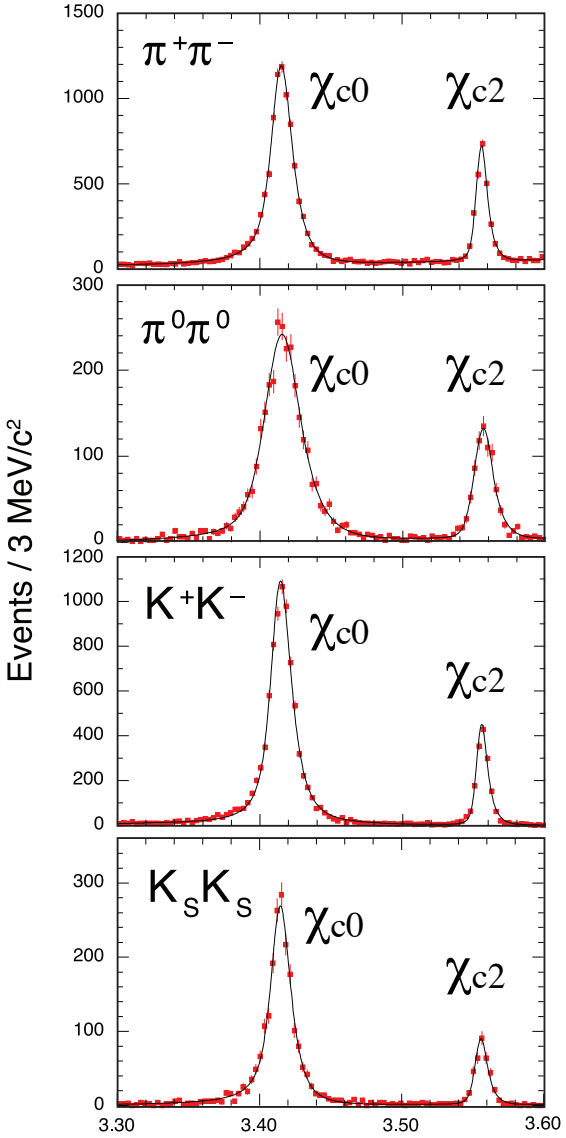
pQCD, however, predicts rates an order of magnitude below the observations!

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

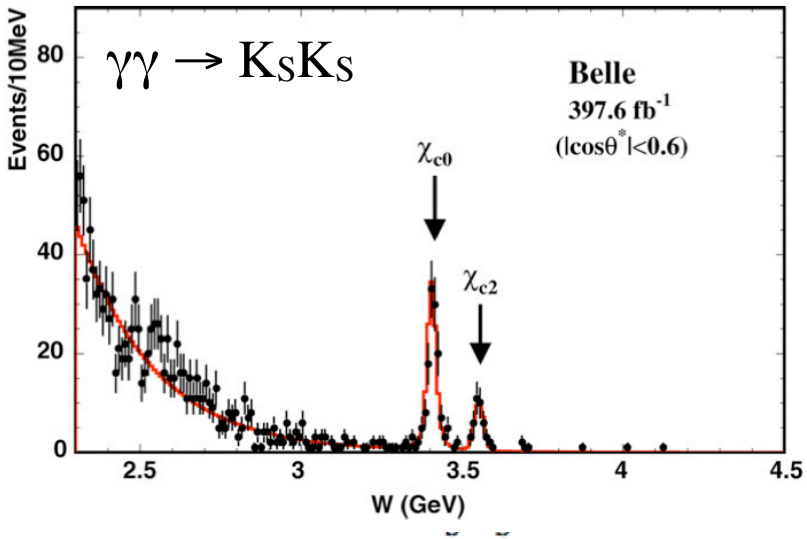
$\chi_{cJ}(1P)$ Two-body Decays

26M ψ(2S); CLEO Preliminary

(from $\psi(2S)\to\gamma\chi_{cJ}$)



Belle; PLB 651, 15 (2007)



Can be used to derive $\Gamma_{\gamma\gamma}(\chi_{c0,2})$.

Resonance	χ_{c0}	χ_{c2}
$\Gamma_{\gamma\gamma}\mathcal{B}(K^0_SK^0_S)$, eV	$7.00\pm0.65\pm0.71$	$0.31\pm0.05\pm0.03$
$\mathcal{B}(K^0_SK^0_S)/\mathcal{B}(K^+K^-)$	$0.49\pm0.07\pm0.08$	$0.70\pm0.21\pm0.12$
$\mathcal{B}(K^0_SK^0_S)/\mathcal{B}(\pi^+\pi^-)$	$0.46\pm0.08\pm0.07$	$0.40\pm0.10\pm0.06$
$\Gamma_{\gamma\gamma}$, keV	$2.50\pm0.23\pm0.23\pm0.62(br.)$	$0.46\pm0.08\pm0.04\pm0.08(br.)$

CLEO Ratios (Preliminary):

	χ_{c0}	χ_{c2}
K_SK_S/K^+K^-:	$0.54\pm0.01\pm0.03$	$0.47\pm0.03\pm0.03$
$K_SK_S/\pi^+\pi^-$:	$0.55\pm0.01\pm0.03$	$0.33\pm0.02\pm0.02$

Absolute BF's still hard to understand theoretically.

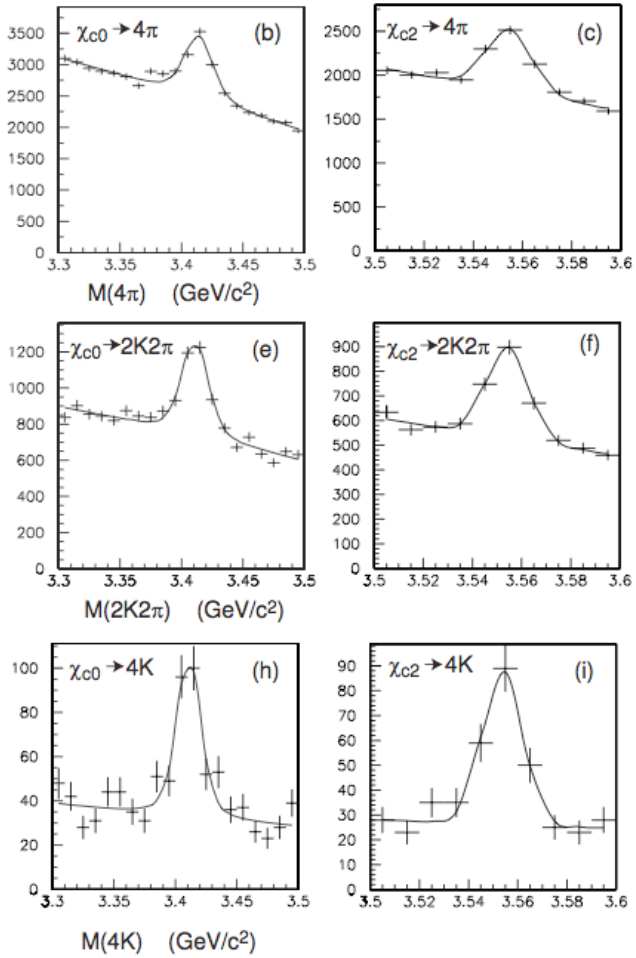
$\chi_{cJ}(1P)$ Two-Photon Widths

Belle; arXiv:0706.3955 [hep-ex]; EPJ C53,1(2008).

$\gamma\gamma \rightarrow \chi_{c0,2}$

Measure
$\Gamma_{\gamma\gamma} \times B(\chi_{c0,2} \rightarrow X)$.

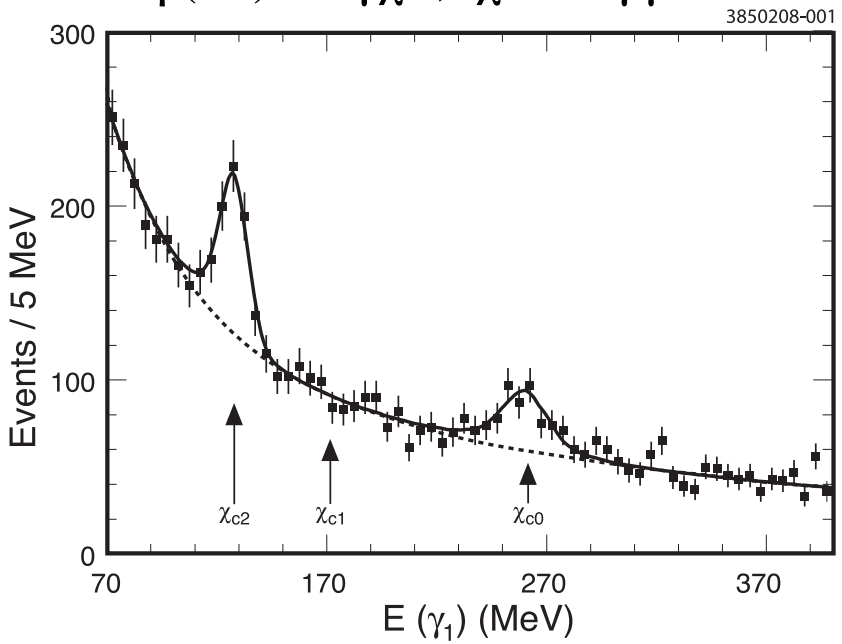
Divide by BR's obtained elsewhere.



	$\Gamma_{\gamma\gamma}(\chi_{c0})$(keV)	$\Gamma_{\gamma\gamma}(\chi_{c2})$(keV)	Ratio
K_SK_S	2.53±0.23±0.40	0.46±0.08±0.09	0.18±0.03±0.04
4π	1.84±0.15±0.27	0.40±0.04±0.07	0.22±0.03±0.05
$2K2\pi$	2.07±0.20±0.40	0.44±0.04±0.16	0.21±0.03±0.09
$4K$	2.88±0.47±0.53	0.62±0.12±0.12	0.21±0.05±0.06

CLEO 24.5M $\psi(2S)$
arXiv:0803.2869 [hep-ex] (submitted to PRL)

$\psi(2S) \rightarrow \gamma\chi_{cJ}$; $\chi_{cJ} \rightarrow \gamma\gamma$



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

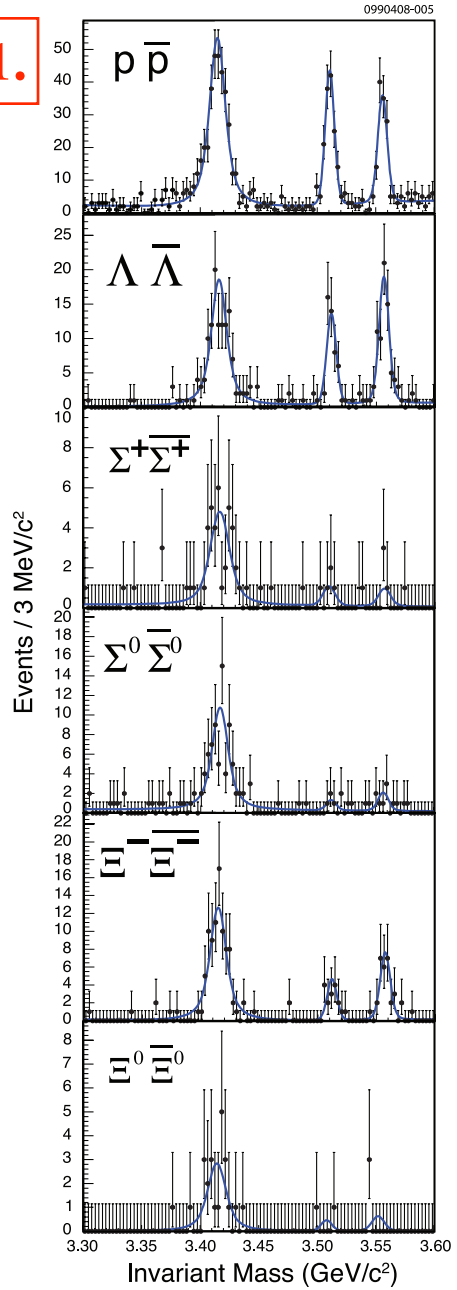
$\Gamma_{\gamma\gamma}(\chi_{c2}) = 0.60 \pm 0.06_{stat} \pm 0.03_{syst} \pm 0.05_{PDG}$ keV

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

Sensitive to relativistic and radiative corrections in the charmonium system.

A Survey of Other χ_{cJ}(1P) Decays

1.



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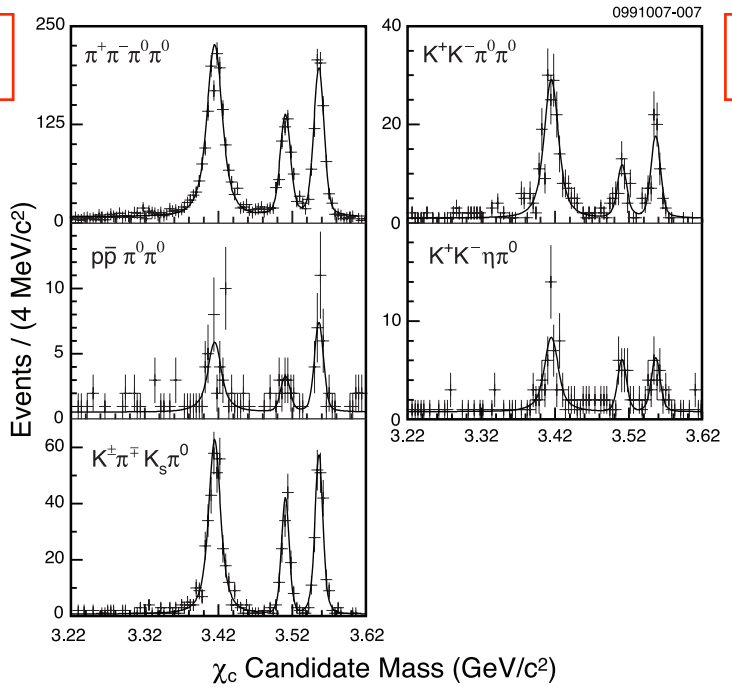

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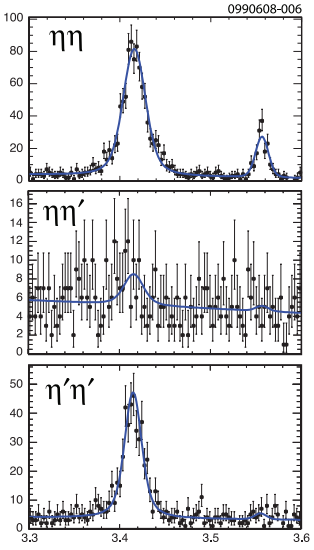

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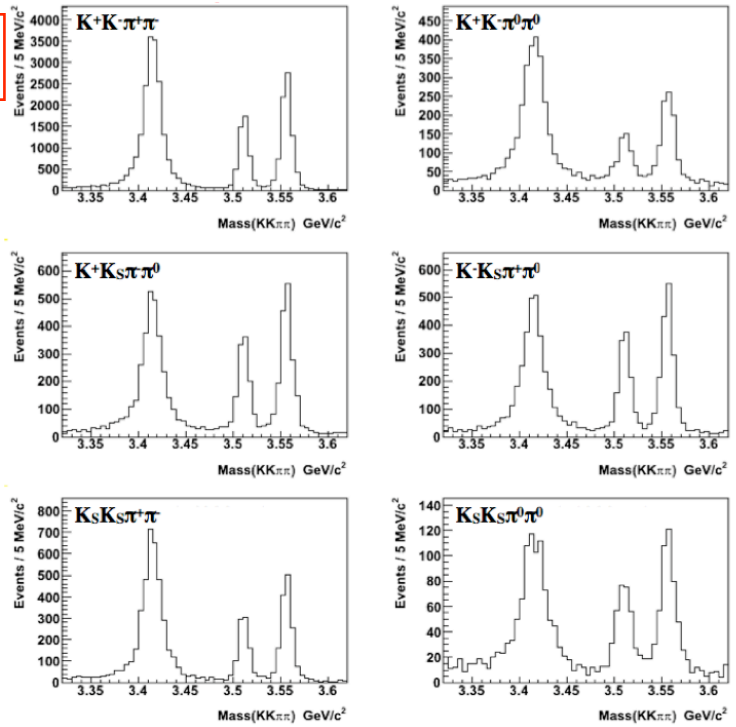


1. B(χ_{cJ} → baryon antibaryon); CLEO 26M ψ(2S); arXiv:0806.1715 [hep-ex] (accepted by PRD RC)

2. B(χ_{cJ} → $h^+h^-h^0h^0$); CLEO 3.1M ψ(2S); arXiv:0806.1227 [hep-ex] (submitted to PRD RC)

3. B(χ_{cJ} → $\eta^{(\prime)}\,\eta^{(\prime)}$); CLEO Preliminary 26M ψ(2S); (older data: hep-ex/0611013; PRD 75, 071101(R) (2007).)

4. B(χ_{cJ} → KK$\pi\pi$); CLEO "first look" 24.5M ψ(2S)

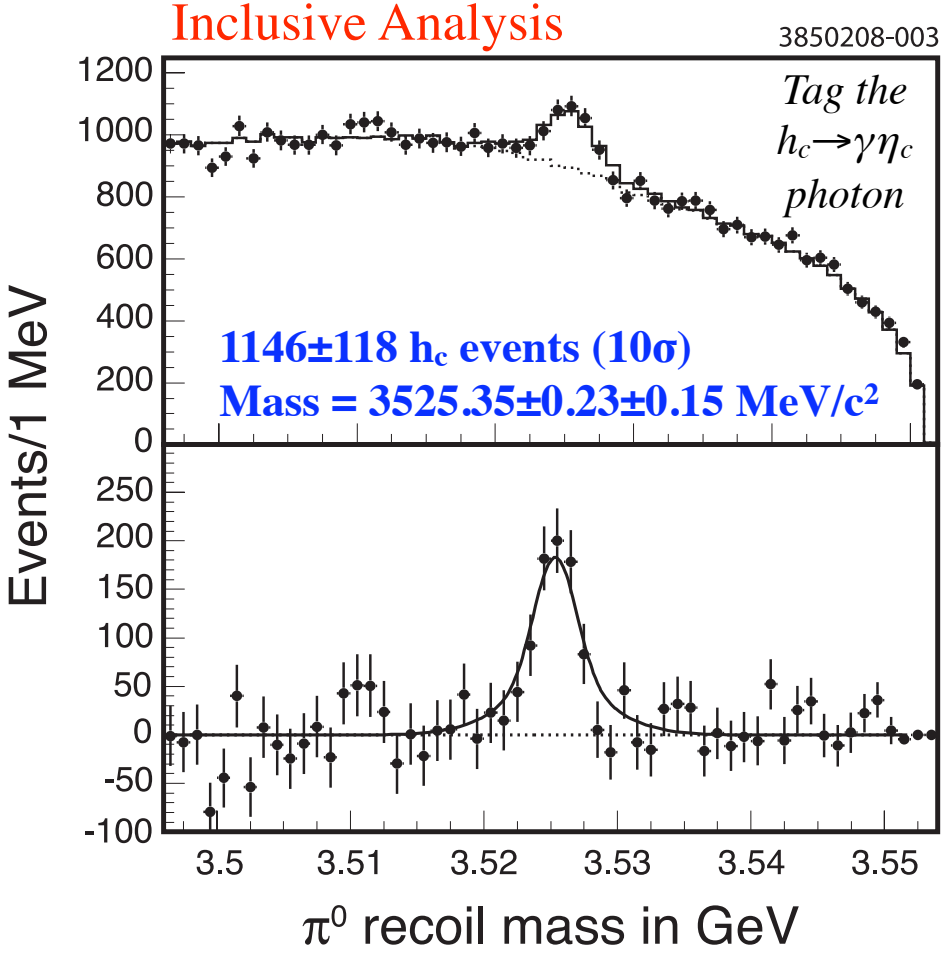
The $h_c(1P)$ Mass

CLEO 24.5M ψ(2S) arXiv:0805.4599 [hep-ex] (submitted to PRL)

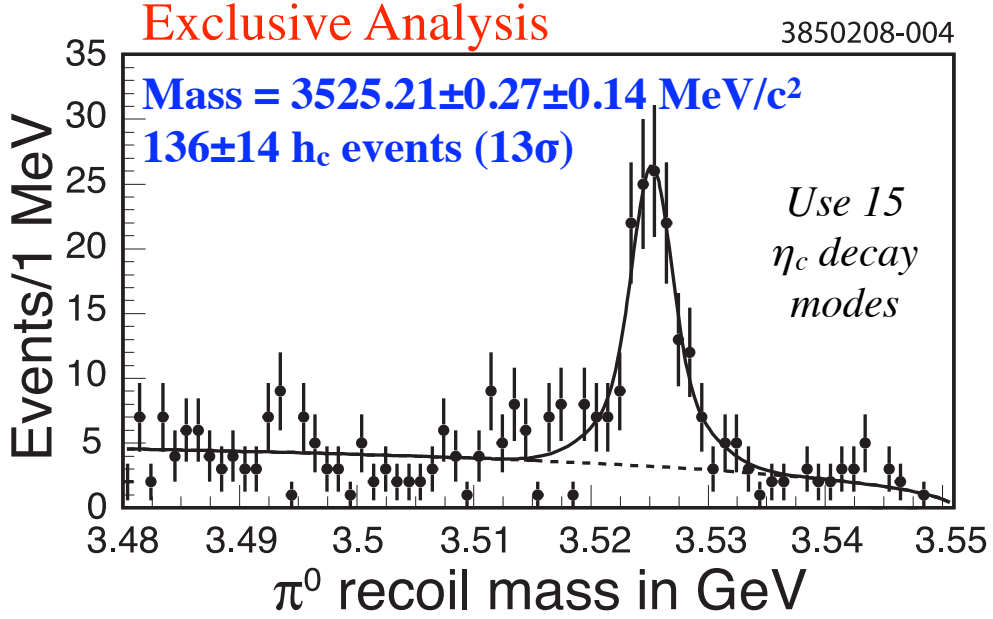
$\psi(2S) \rightarrow \pi^0 h_c(1P);\ h_c(1P) \rightarrow \gamma\eta_c$

(factor of 9 more data than previous measurement)

Inclusive Analysis



Exclusive Analysis



Combined Mass = 3525.28±0.19±0.12 MeV/c²

Compare to:

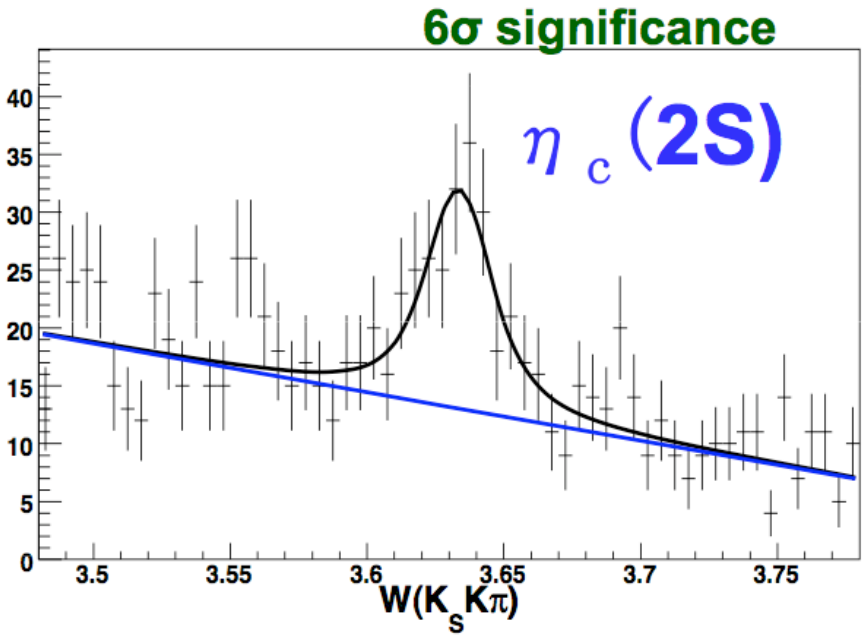
$\langle M(\chi_{cJ}(1P))\rangle = (3525.30 \pm 0.11)$ MeV/c² (PDG)

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

Properties of the $\eta_c(2S)$

Belle; Photon 2007

$\gamma\gamma \to K_S K\pi$

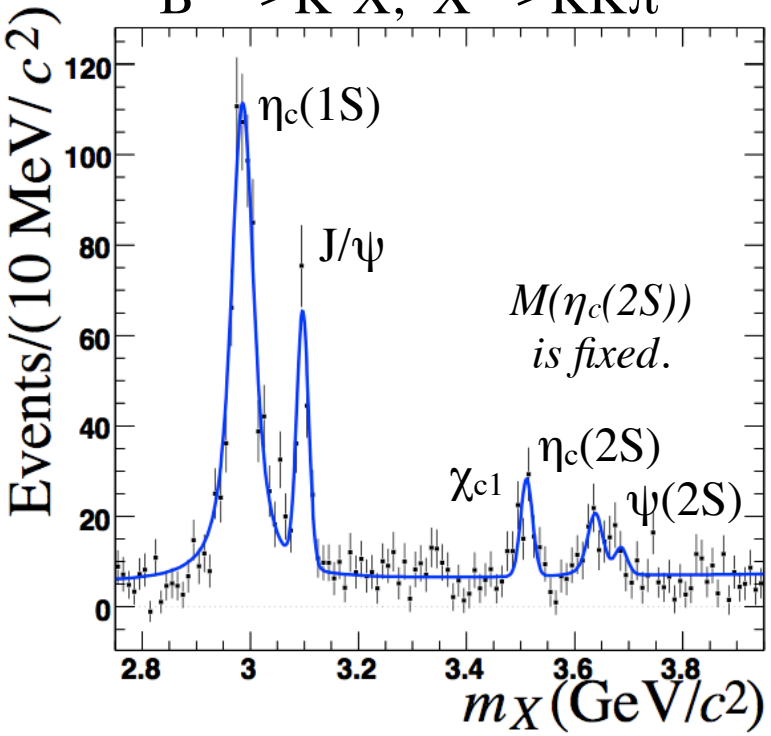


Mass = 3633.7 ± 2.3 ± 1.9 MeV/c²
Width = 19.1 ± 6.9 ± 6.0 MeV/c²

Interference with the continuum complicates the extraction of $\Gamma_{\gamma\gamma}$.

BaBar; arXiv:0804.1208 [hep-ex]; PRD 78, 012006 (2008)

$B^+ \to K^+X;\ X \to KK\pi$



Previous inclusive $B^+ \to K^+X$ measurements can be used to turn product BF's into absolute BF's:

$\Rightarrow$ **$B(\eta_c(2S) \to KK\pi) = (1.9 \pm 0.4 \pm 0.5 \pm 1.0)\%$**

c.f. $B(\eta_c(1S) \to KK\pi) = (7.0 \pm 1.2)\%$ (PDG)

$KK\pi$ is still the only observed decay mode of the $\eta_c(2S)$.

Conclusions

- After more than 30 years, the charmonium system continues to provide important insight into the strong force.

- This Talk:
  - M1 radiative transitions:
    $\psi(1S,2S) \rightarrow \gamma\eta_c(1S)$ and $\eta_c(1S)$ mass
  - $J/\psi \rightarrow \gamma\gamma\gamma$
  - χ_{cJ} decays:
    → $\gamma(\varrho,\omega,\phi)$
    → two bodies
    → $\gamma\gamma$
    → etc.
  - h_c mass
  - $\eta_c(2S)$ properties

- We are looking forward to new results from **BES-III**!