New Charmonium Results from CLEO-c

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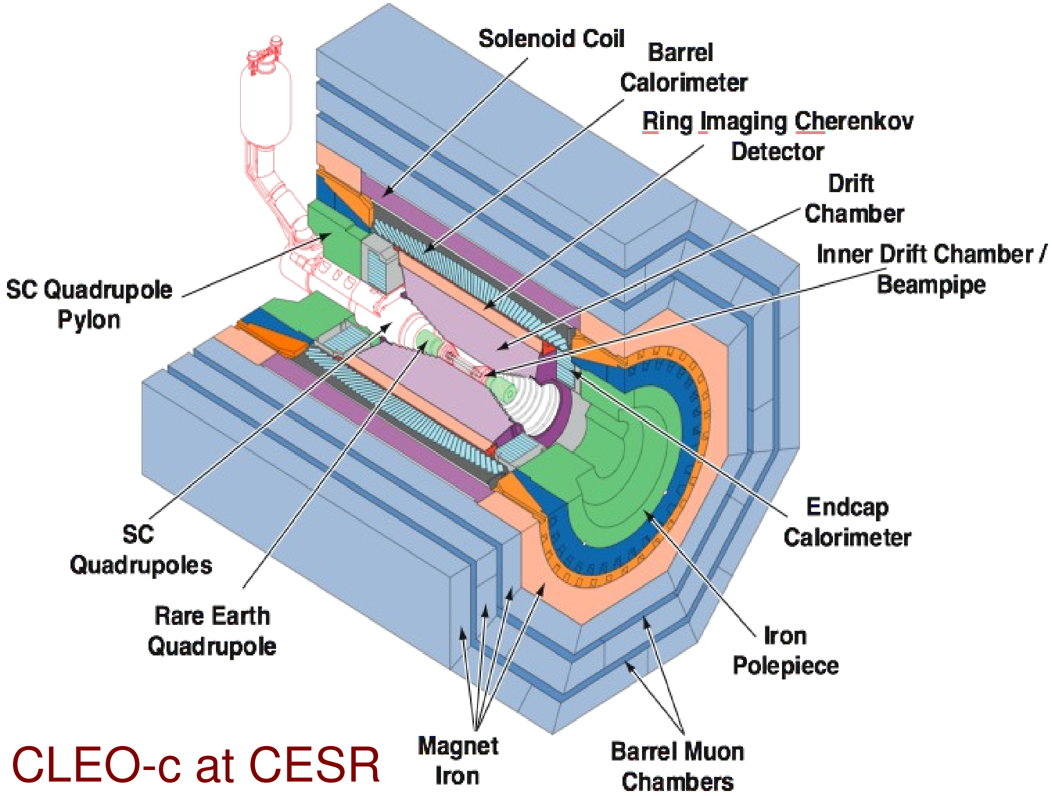
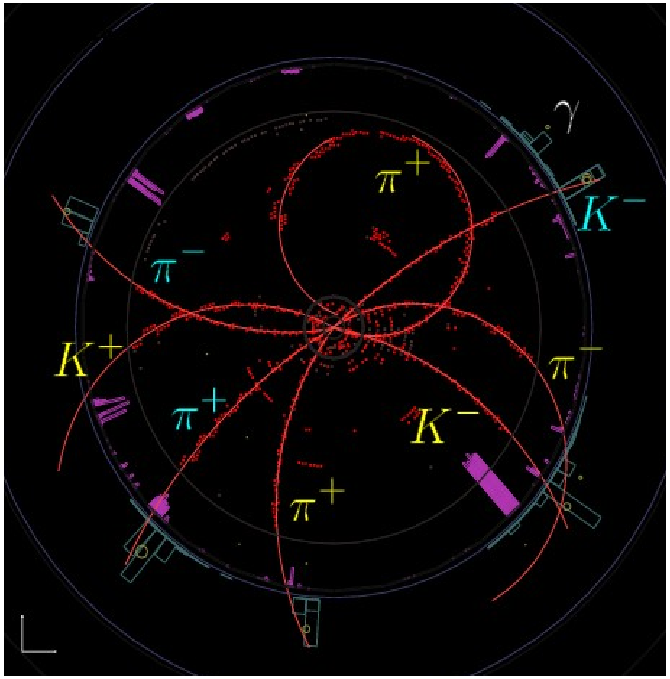


CLEO-c at CESR



One of the last CLEO-c events
(taken on 3-March-2008)
$e^+e^- \to D_s^{*+} D_s^-$

CLEO-c Data Sample for Charmonium Program

818/pb at ψ(3770)
(mostly open charm
but also charmonium)

54/pb at ψ(2S) ---> 27 M ψ(2S)

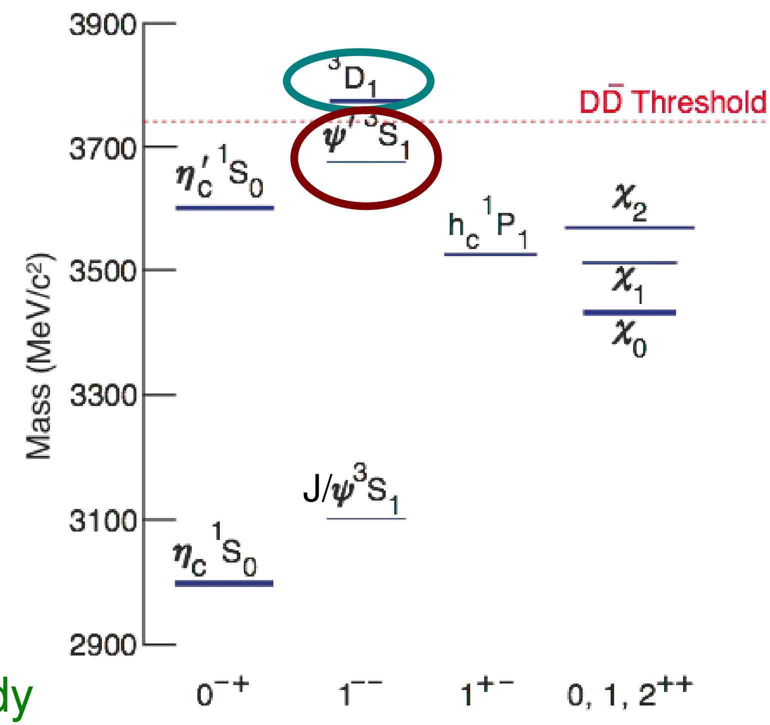
(largest pre-BESIII world supply)

In praise of ψ(2S):

$B(\psi(2S) \rightarrow \pi^+\pi^- J/\psi = 32\%$ ($\varepsilon \approx 75\%$)

$B(\psi(2S) \rightarrow \gamma\, \chi_{cJ} \approx 9\%$ for each of J=0,1,2

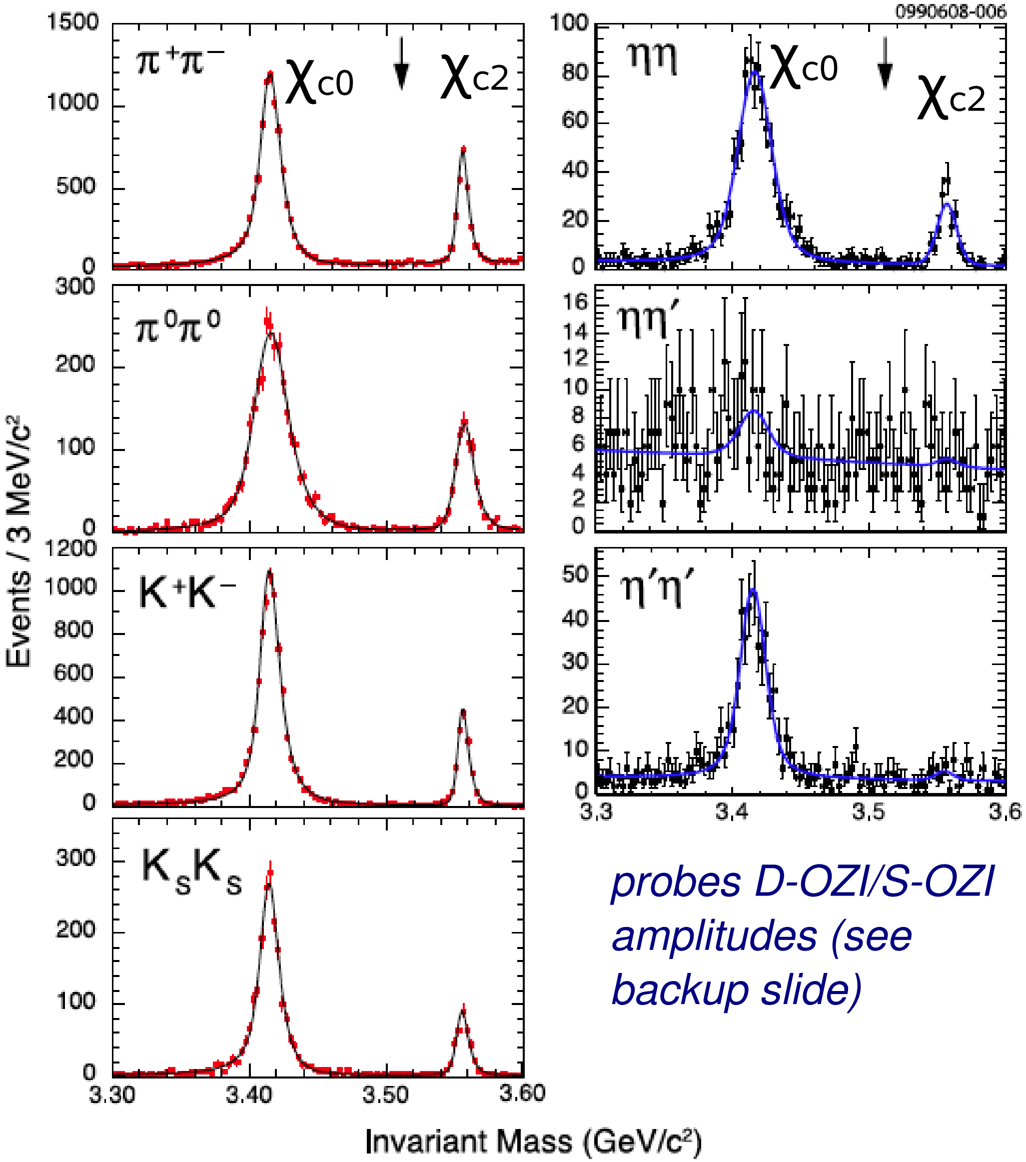
Clean, tagged, abundant J/ψ, χ_{cJ} (and h_c)!



Study
- **Decays** of states (hadronic & radiative)
- **Transitions** between states
- **Spectrum** of states

Overarching theme: Use charmonium as a laboratory to test
- quarkonium potential models
- QCD, pQCD, NRQCD, LQCD

Two-Body Mesonic Decays of χ_{cJ}



probes D-OZI/S-OZI amplitudes (see backup slide)

- Two-body decays are theoretically “clean”:
  - probe role of the color octet mechanism
  - probe gluon content of final state mesons
- Results for two-body baryonic decays have also recently been published: *CLEO PRD 78, 031101(R) (2008)*

BF 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 [5]	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
$K^0_S K^0_S$	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

CLEO PRD 79, 072007 (2009)

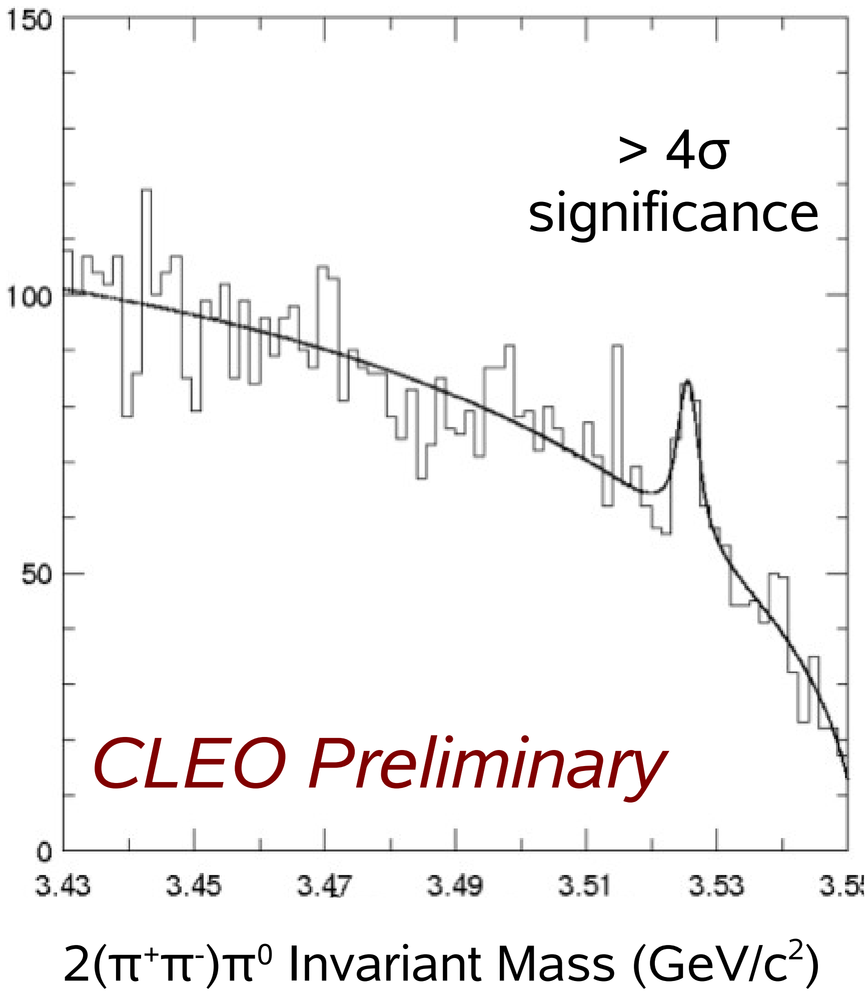
Substantial improvement over current world averages in some channels!

Evidence for Hadronic Decay of the h_c

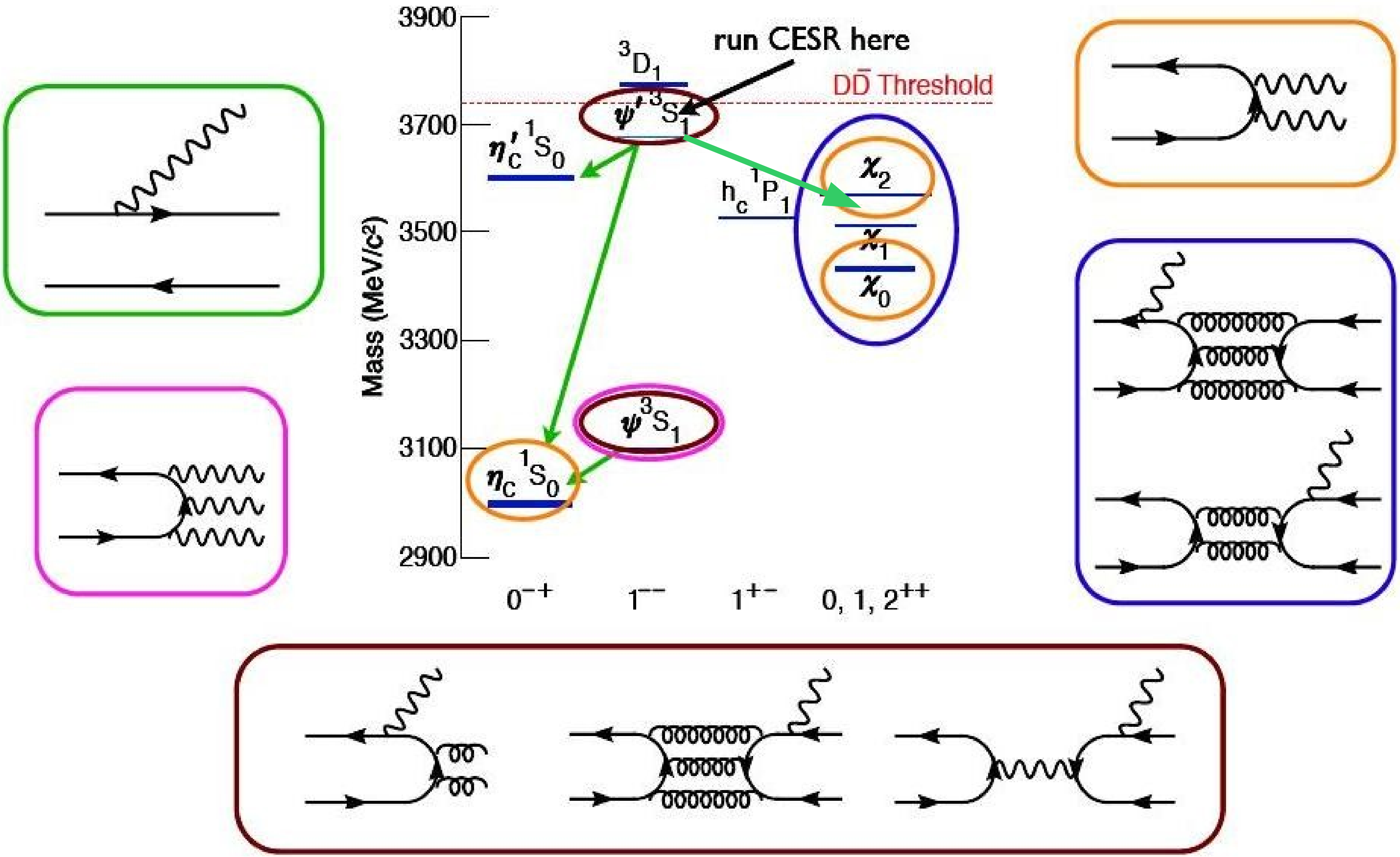
The only previously observed decay:
$\psi(2S) \rightarrow \pi^0 h_c$) x $B(h_c \rightarrow \gamma\eta_c)$;
product BF: $(4.2 \pm 0.6) \times 10^{-4}$
(CLEO *PRL* 101, 182003 (2008))
(Our recent precision mass measurement finds HF splitting <1*MeV* for 1P states)

Godfrey & Rosner predict 73% direct hadronic decay (*PRD* 66, 014012 (2002))
Expect **odd number of pions**
(negative G parity)
Measure $B(\psi(2S) \rightarrow \pi^0 h_c) \times B(h_c \rightarrow X)$
$X = n(\pi^+\pi^-)\,\pi^0 \quad (n=1,2,3)$:

Mode	*Product BF (10^{-5})*
$\pi^+\pi^-\pi^0$	< 0.2
$2(\pi^+\pi^-)\,\pi^0$	**1.9 ± 0.5 ± 0.4**
$3(\pi^+\pi^-)\,\pi^0$	< 2.4

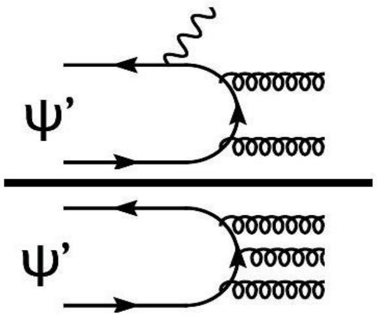


Radiative Decays and Transitions



$B(\psi(2S)\rightarrow\gamma gg)$ / $B(\psi(2S)\rightarrow ggg)$

Rough expectation for ratio of rates:



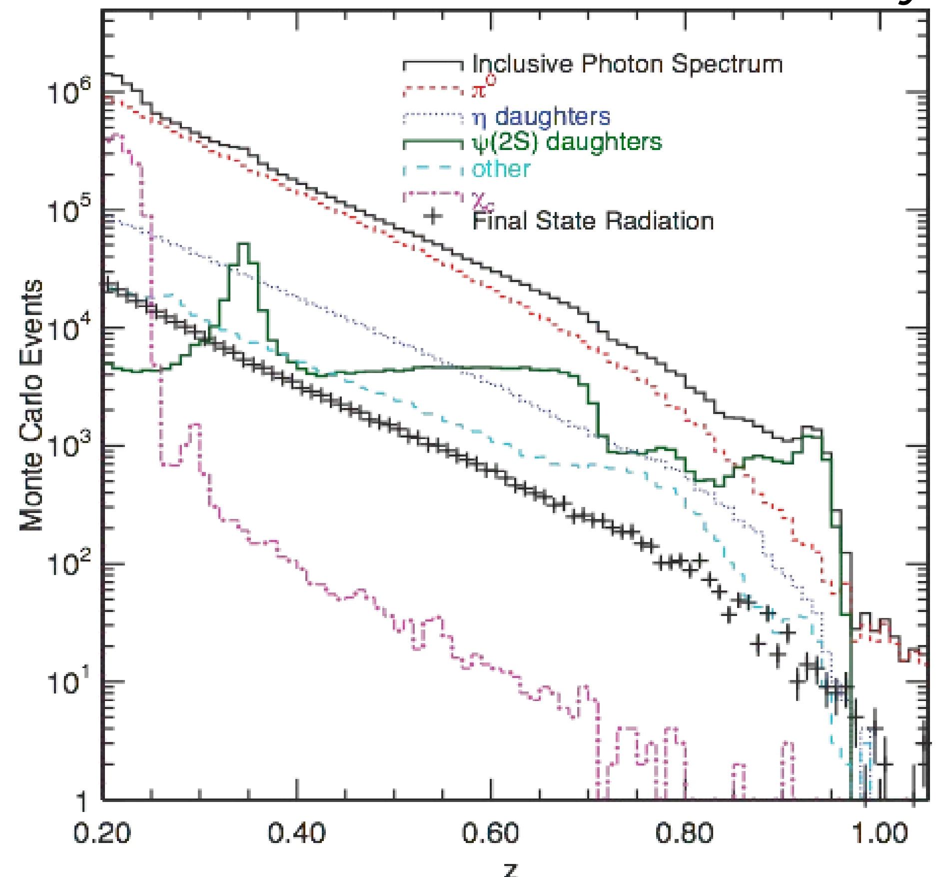
$\propto q_c^2\alpha_{EM}/\alpha_S\,[1 + \ldots]$

Experimental challenge: subtracting backgrounds

- utilize three separate techniques; dominant systematic error

Measure $\psi'\rightarrow\gamma gg$, subtract all other known decays and transitions (87%), infer $\psi'\rightarrow ggg$

CLEO Preliminary



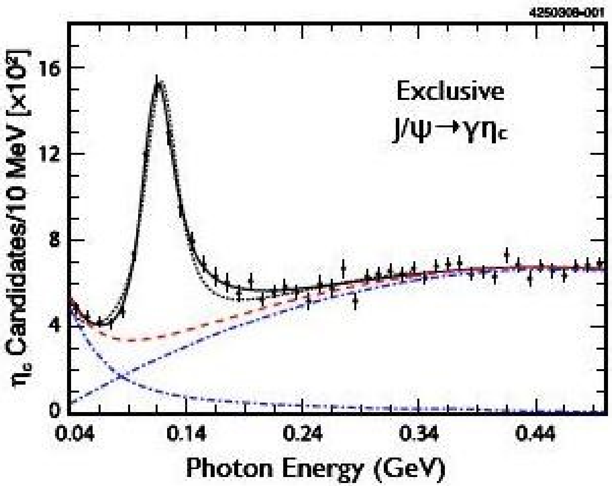
State	$B(X\rightarrow\gamma gg)$ / $B(X\rightarrow ggg)$
J/ψ	0.137 ± 0.001 ± 0.016
$\psi(2S)$	***0.091 ± 0.003 ± 0.027***
$\Upsilon(1S)$	0.027 ± 0.001 ± 0.003
$\Upsilon(2S)$	0.032 ± 0.001 ± 0.005
$\Upsilon(3S)$	0.027 ± 0.001 ± 0.005

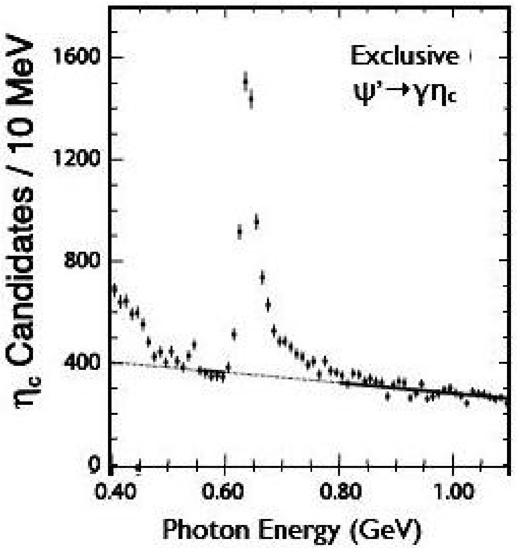
CLEO PRD 78, 032012 (2008)

CLEO Preliminary

CLEO PRD 74, 012003 (2006)

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





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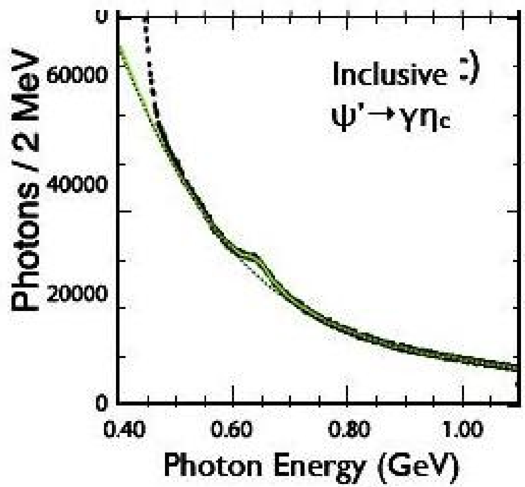


$= \quad B(J/\psi \rightarrow \gamma\eta_c)$

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

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.

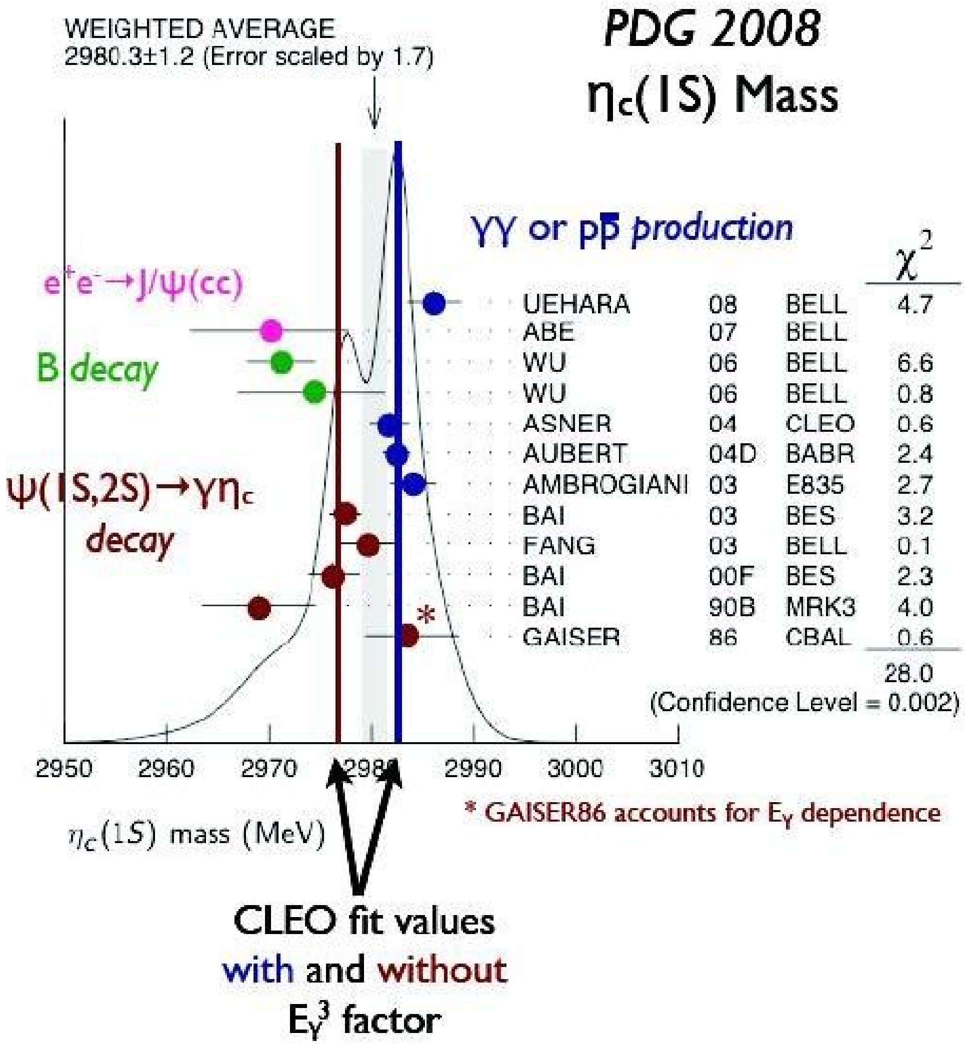
C. $B(J/\psi \rightarrow \gamma\eta_c) = (1.98 \pm 0.09 \pm 0.30)\%$ taking A×B.

Recent Lattice QCD Results (Dudek *et al.*, PRD 73, 07450(2006))
predict $\Gamma_{\gamma\eta_c} = (2.0 \pm 0.1 \pm 0.4)$ keV
$\Rightarrow B(J/\psi \rightarrow \gamma\eta_c) = (2.1 \pm 0.1 \pm 0.4)\%$

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

CLEO PRL 102, 011801 (2009)

The η_c Lineshape



Asymmetric lineshape is expected:

$$\Gamma_{n^3S_1\to n'^1S_0\gamma} = \frac{4}{3}\alpha\, e_Q^2 \frac{k_\gamma^3}{m^2}\left|\int_0^\infty dr\, r^2\, R_{n'0}(r)\, R_{n0}(r)\, j_0\left(\frac{k_\gamma r}{2}\right)\right|^2$$

$$j_0(k_\gamma r/2) = 1 - (k_\gamma r)^2/24 + \ldots$$

c.f.: Brambilla *et al.*, PRD 73, 054005 (2006)

$\Gamma(\psi' \to \gamma\eta_c)$ [n≠n'] ∝ E_γ^7

$\Gamma(J/\psi \to \gamma\eta_c)$ [n=n'] ∝ E_γ^3

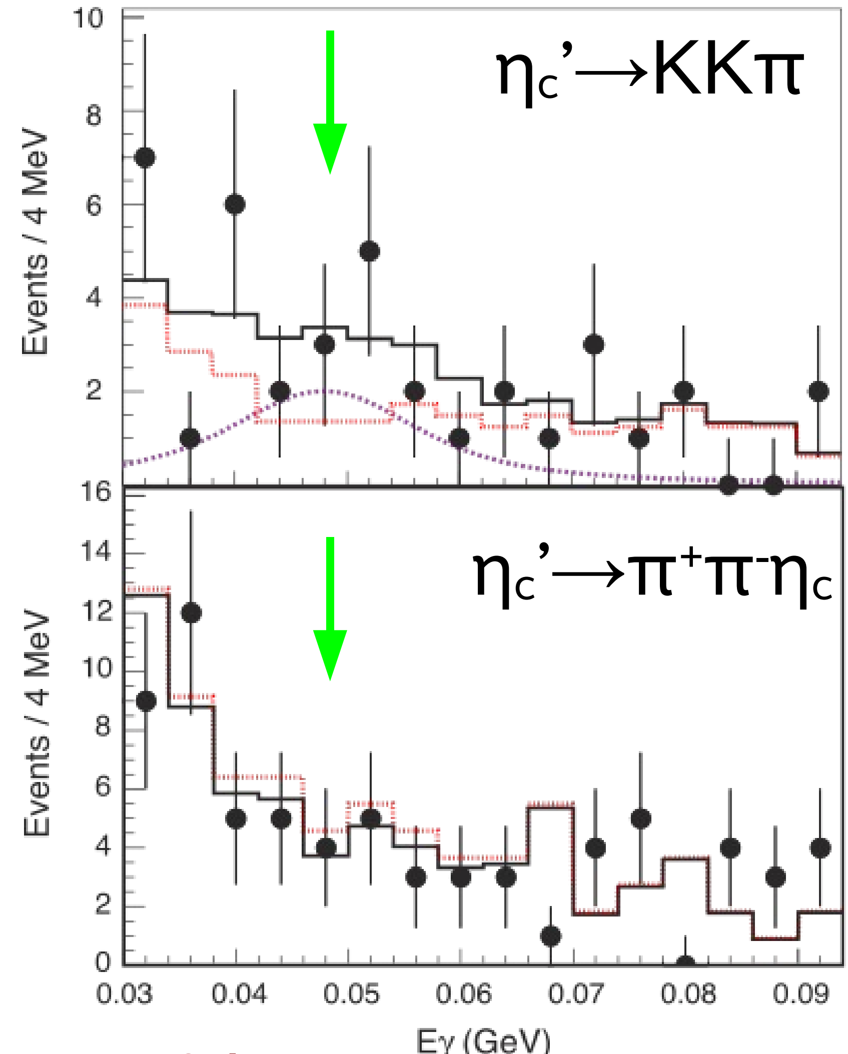
...but these factors cause total width to diverge at high E_γ

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 charmonium 1S hyperfine splitting.

$\psi(2S) \to \gamma \eta_c'$?

- E_γ = 48 MeV -- inclusive analysis too difficult; instead search for--
  - $\psi(2S) \to \gamma \eta_c'$; $\eta_c' \to X$
  - $\psi(2S) \to \gamma \eta_c'$; $\eta_c' \to \pi^+\pi^-\eta_c$; $\eta_c \to X$
- Calibrate analysis on $\psi(2S) \to \gamma \chi_{c2}$ transition
- Using known $B(\eta_c' \to KK\pi)$ and η_c branching fractions, can set 90% C.L. limits
- Scaling from $J/\psi \to \gamma \eta_c$ one expects $B(\psi(2S) \to \gamma \eta_c') = 4 \times 10^{-4}$

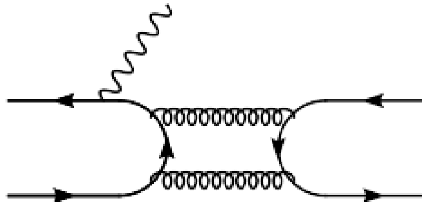


Results (*CLEO PRELIMINARY*):

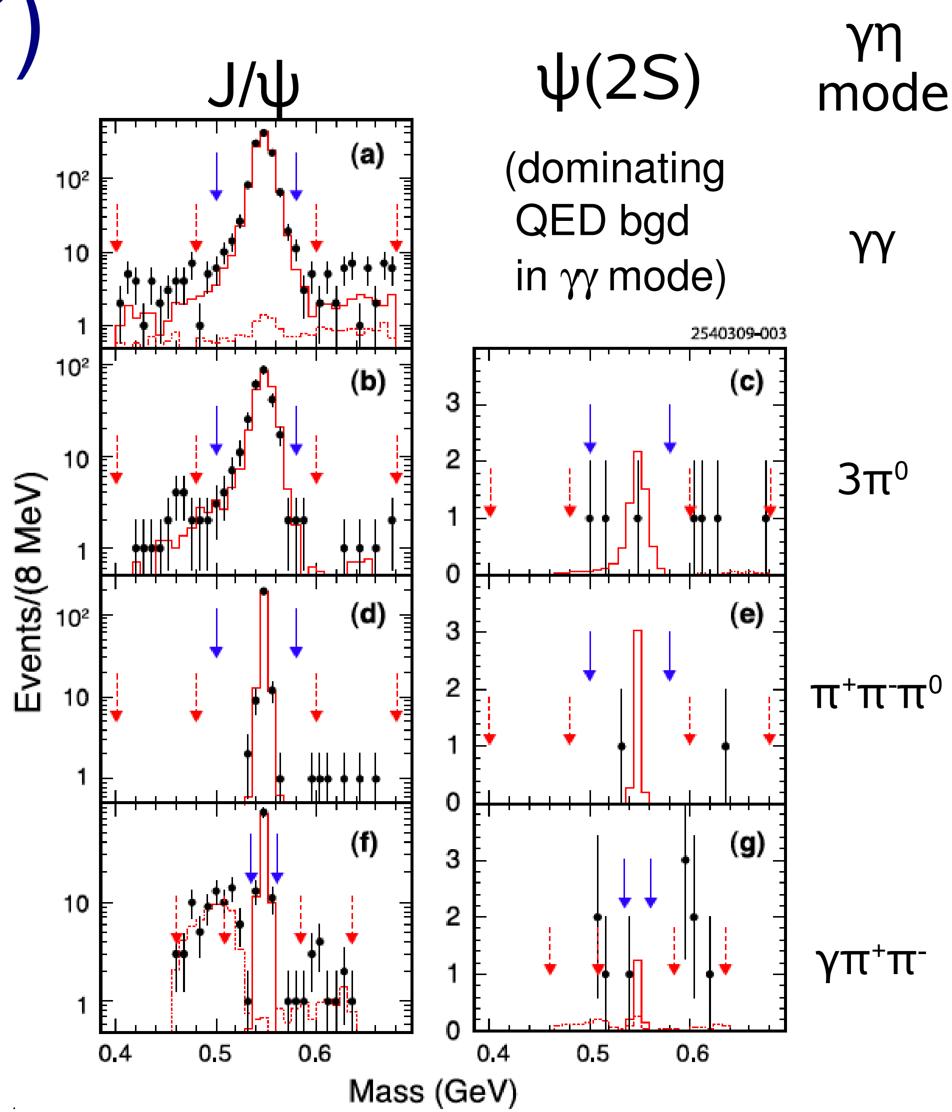
$B(\psi(2S) \to \gamma \eta_c') < 7.4 \times 10^{-4}$

$B(\psi(2S) \to \gamma \eta_c') \times B(\eta_c' \to \pi^+\pi^-\eta_c) < 1.4 \times 10^{-4}$

$J/\psi,\psi(2S)\to\gamma(\pi^0,\eta,\eta')$



Mode	This result (10^{-4})
$J/\psi\to\gamma\pi^0$	$0.363\pm0.036\pm0.013$
$\to\gamma\eta$	$11.01\pm0.29\pm0.22$
$\to\gamma\eta'$	$52.4\pm1.2\pm1.1$
$\psi(2S)\to\gamma\pi^0$	<0.07
$\to\gamma\eta$	<0.02
$\to\gamma\eta'$	$1.19\pm0.08\pm0.03$



$$R_n \equiv \frac{\mathcal{B}(\psi(nS)\to\gamma\eta)}{\mathcal{B}(\psi(nS)\to\gamma\eta')}$$

Results:

$$R_1 = (21.1\pm0.9)\%$$

consistent with known η–η' mixing

$$R_2 < 1.8\%\text{ at }90\%\text{ C.L.}$$

surprise: R1, R2 expected to be about equal!

CLEO arXiv: 0904.1394 [hep-ex], accepted by PRL

$\chi_{cJ} \rightarrow \gamma(\rho,\omega,\phi)$

Look for:

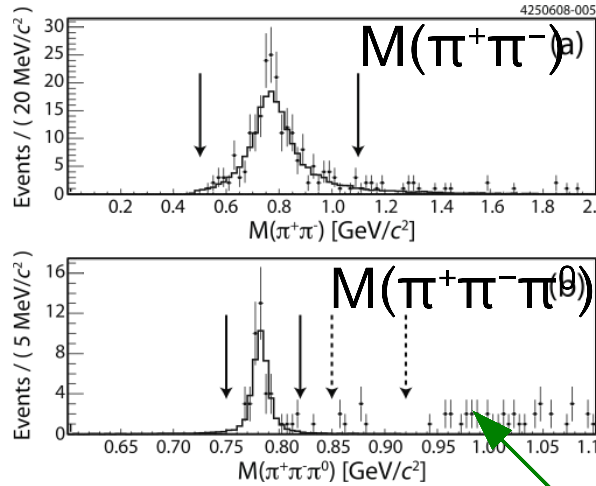
$\psi(2S) \rightarrow \gamma_{(low)}\chi_{cJ}$

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

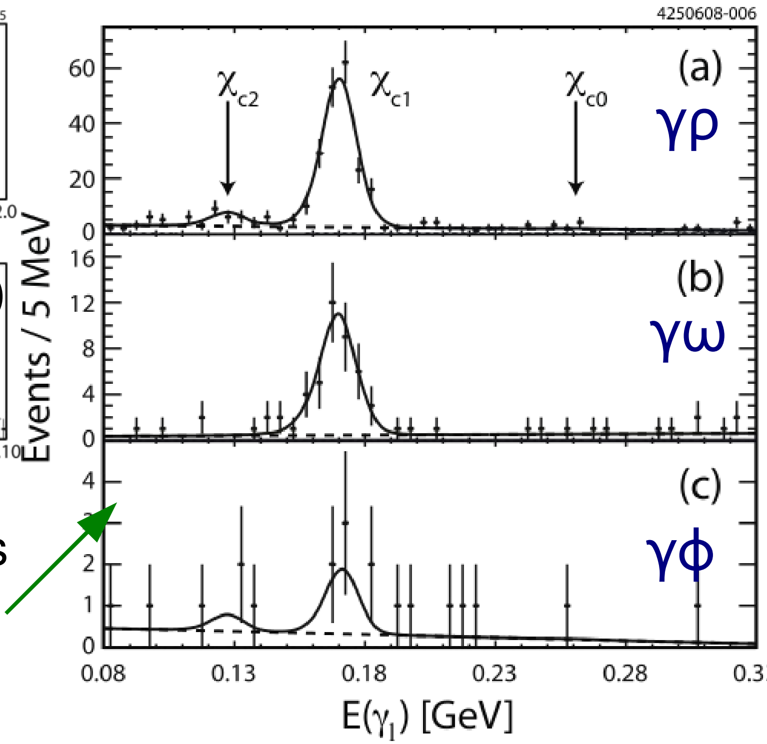
Significant signals observed in:

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

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



1. cut on hadronic mass
2. look at low-E photon



CLEO PRL 101, 151801 (2008)

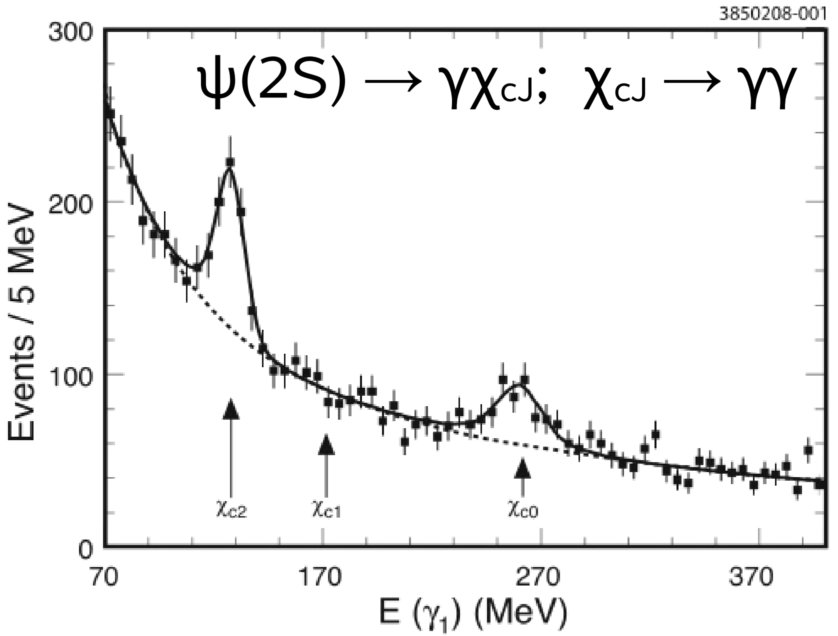
Mode	$\mathcal{B} \times 10^6$	U.L. $[10^{-6}]$	pQCD $[10^{-6}]$
$\chi_{c0} \rightarrow \gamma\rho^0$		< 9.6	1.2
$\chi_{c1} \rightarrow \gamma\rho^0$	$243 \pm 19 \pm 22$		14
$\chi_{c2} \rightarrow \gamma\rho^0$	$25 \pm 10^{+8}_{-14}$	< 50	4.4
$\chi_{c0} \rightarrow \gamma\omega$		< 8.8	0.13
$\chi_{c1} \rightarrow \gamma\omega$	$83 \pm 15 \pm 12$		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

Expect process to be analogous to that of glueball production, e.g., in $J/\psi \rightarrow \gamma f_J$

pQCD predicts rates an order of magnitude lower than observed! (Gao, Zhang, Chao, Chin.Phys.Lett. 23, 2376 (2006) [arXiv:hep-ph/0607278])

$\chi_{cJ} \rightarrow \gamma\gamma$

Two-photon widths of χ_{cJ} probe relativistic and radiative corrections known to be significant in charmonium.



Results:

$\Gamma_{\gamma\gamma}(\chi_{c2}) = 0.66 \pm 0.07_{stat} \pm 0.04_{syst} \pm 0.05_{PDG}$ keV

$\Gamma_{\gamma\gamma}(\chi_{c0}) = 2.36 \pm 0.35_{stat} \pm 0.11_{syst} \pm 0.19_{PDG}$ keV

Ratio $= 0.278 \pm 0.050_{stat} \pm 0.018_{syst} \pm 0.031_{PDG}$

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

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

prediction:
$\alpha_s = 0.32 \rightarrow R = 0.12$

New world avg.: $R = 0.22 \pm 0.03$
higher order corrections very significant

CLEO PRD 78, 091501 (2008)

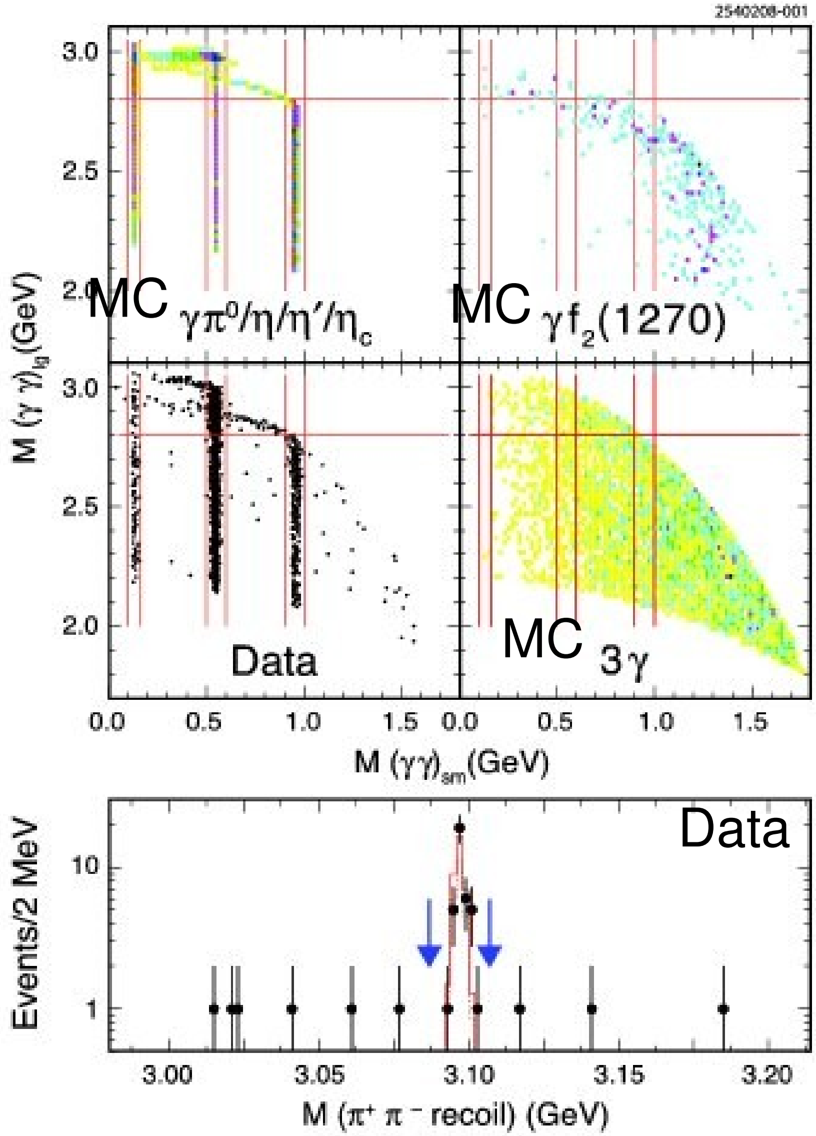
$J/\psi \to 3\gamma$

This is the quarkonium analogue of ortho-positronium decay.
No 3γ decay of a particle has been observed before.

Tag via $\psi(2S) \to \pi^+\pi^- J/\psi$
(eliminates QED background!)

Veto resonances π^0, η, η', η_c

Main remaining background:
$J/\psi \to \gamma\, \pi^0\pi^0$



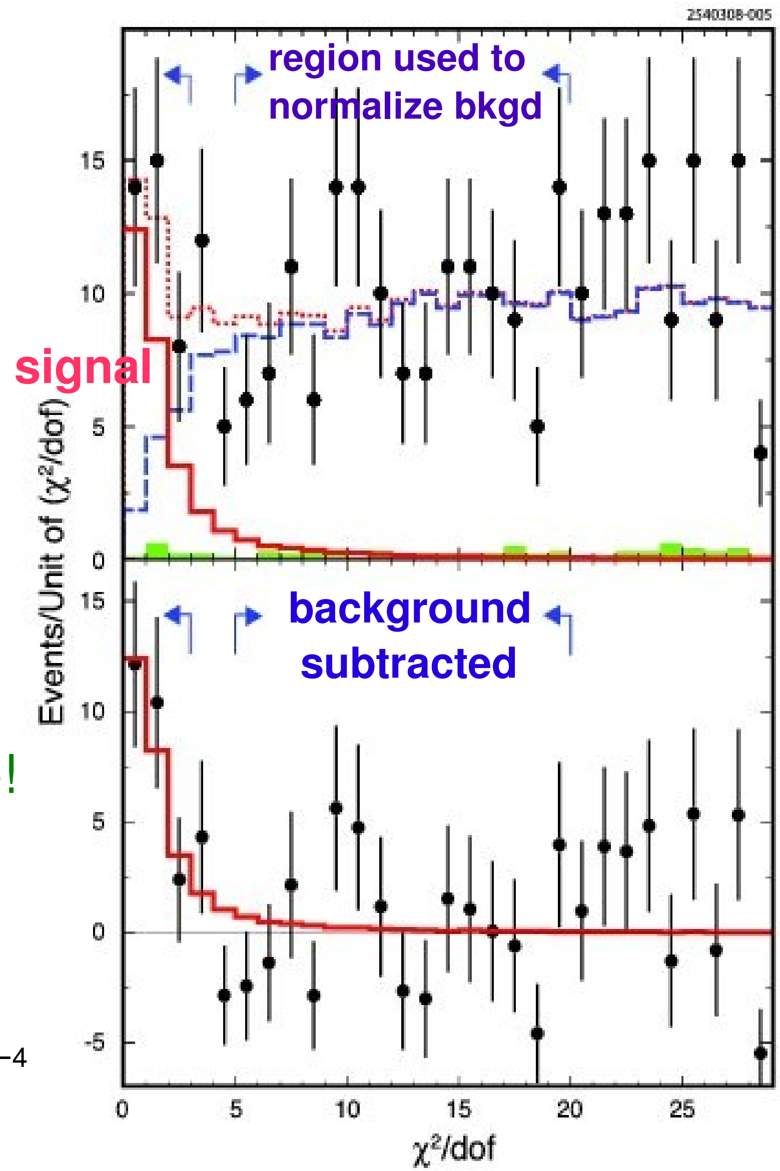
$J/\psi \rightarrow 3\gamma$

Perform kinematic fit;

Signal peaks at low χ^2/dof

Background rises away from zero

(and is independent of $\pi^0\pi^0$ substructure!)



Result (CLEO *PRL* 101, 101801 (2008)):

$B = (1.2 \pm 0.3 \pm 0.2) \times 10^{-5}$ (6σ)

First observed 3γ decay of any hadron!

Theory: in QED, $B(3\gamma)/B(3g) \approx (\alpha/\alpha_s)^3$

and $B(3\gamma) \approx (\alpha/14) B_{\mu\mu} \approx 3 \times 10^{-5}$

But NLO QCD corrections give negative rate!

(Higher order corrections very significant)

As "byproduct" we obtain upper limit on $\eta_c \rightarrow \gamma\gamma$:

$B(\eta_c \rightarrow \gamma\gamma) < 3 \times 10^{-4}$ (90% CL), PDG: $(2.7 \pm 0.9) \times 10^{-4}$

Summary of CLEO-c Charmonium Results

- Precision measurement of hadronic two-body decays of χ_{cJ}

- First evidence for hadronic h_c decay (and precision measurement of the h_c mass)

- First measurement of $B(\psi(2S)\rightarrow\gamma gg)/B(\psi(2S)\rightarrow ggg)$; completes the set for heavy vector states

- New measurements for M1 transitions $J/\psi,\psi(2S)\rightarrow\gamma\eta_c$ Understanding of lineshape crucial for η_c mass and BF measurements

- New limit on $\psi(2S)\rightarrow\gamma\eta_c'$

- Study of $J/\psi,\psi(2S)\rightarrow\gamma(\pi^0,\eta,\eta')$; surprising suppression of $\psi(2S)\rightarrow\gamma\eta$

- First observation of $\chi_{cJ} \rightarrow \gamma(\rho,\omega)$; rates much larger than predicted

- Precision measurement of two-photon widths of $\chi_{c(0,2)}$

- First observation of the 3-photon decay of a meson: $J/\psi \rightarrow 3\gamma$

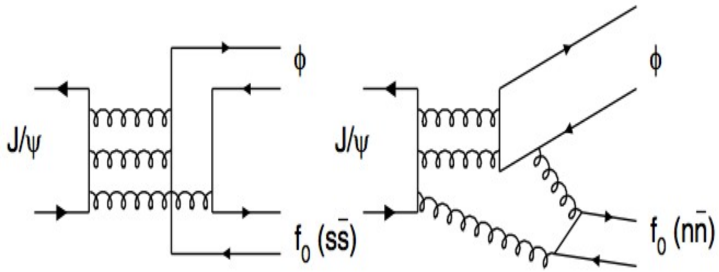
Concluding Remarks

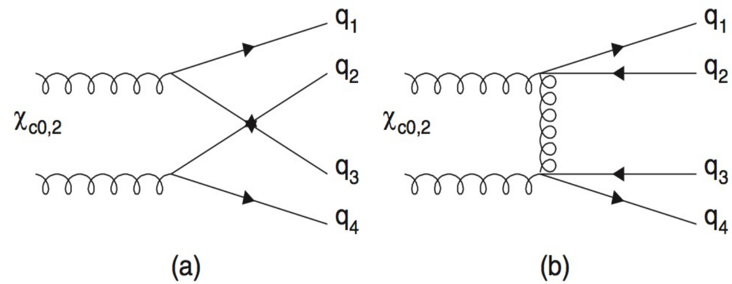
- Rich program of hadronic physics at CLEO-c (too extensive to cover it all here) --
  - precision measurements of the mass of η (*PRL 99, 122002 (2007)*), and η' (*PRL 101, 182002 (2008)*)
  - most precise single measurement of all dominant η B.F.'s (*PRL 99, 122001 (2008)*), η' B.F.'s (arXiv: 0904.1394), and rare η' decays (*PRL 102, 061801 (2008)*)
  - precision branching fractions for $\psi' \to X\ J/\psi$ (*PRD 78, 011102(R) (2008)*)
- ...and several analyses still in the pipeline --
  - M2/E1 in χ_{cJ} transitions
  - analysis of $\psi' \to \pi\pi\ J/\psi$ matrix elements
  - $(J/\psi, \psi') \to (\gamma, \pi^0)pp$; $\chi_{cJ} \to Xpp$
  - search for invisible (radiative) decays of J/ψ
  - spectroscopy in hadronic χ_{cJ} decay
- *CLEO-c has been laying a solid foundation for BESIII to build on.*

Backup Slides

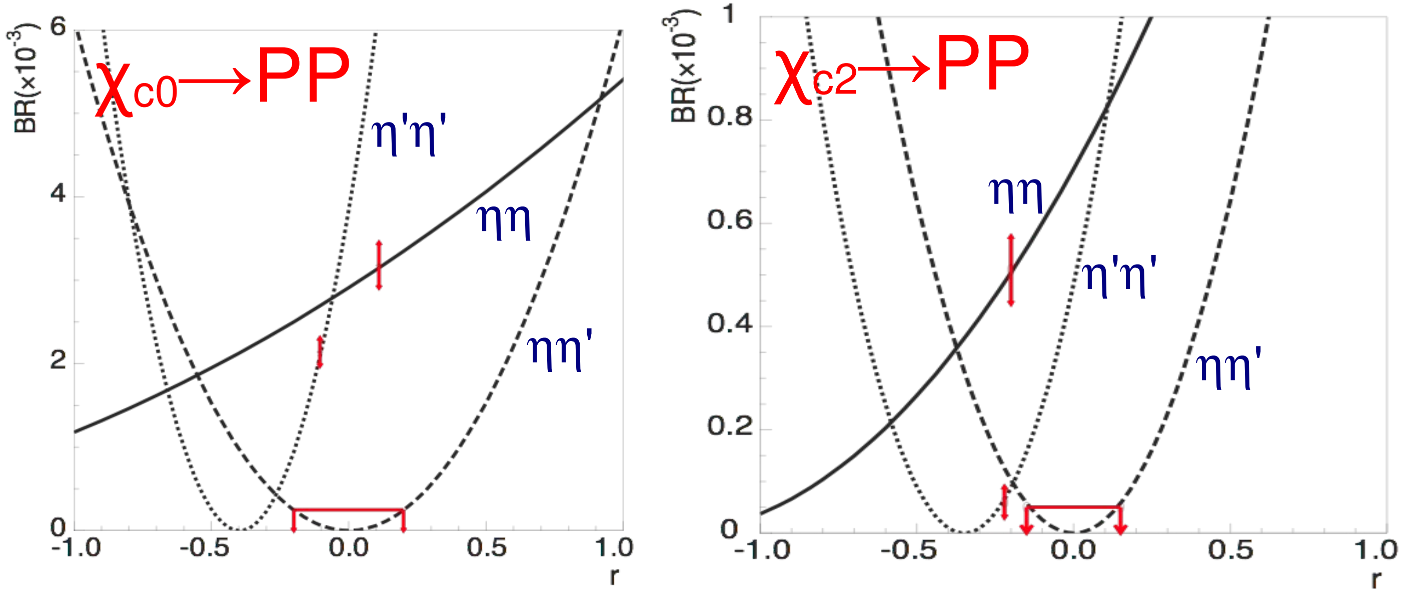
Example: $\chi_{cJ} \to \eta^{(\prime)}\eta^{(\prime)}$

Measured BRs constrain ratio of Double-OZI to Single-OZI amplitudes





Theory: Close & Zhao, *PRD* 71, 094022, factorization a la Zhao, *PRD* 72, 074001; *PLB* 659, 221

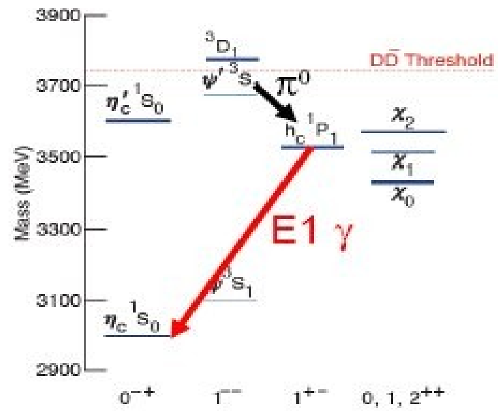


Data suggest small (if any) contribution of DOZI decays in 0^{-+} channel.

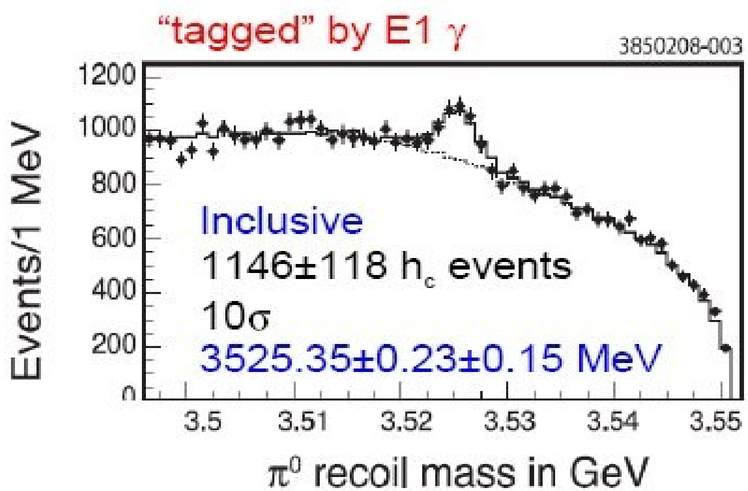
(Aside: Precision h_c Mass Measurement)

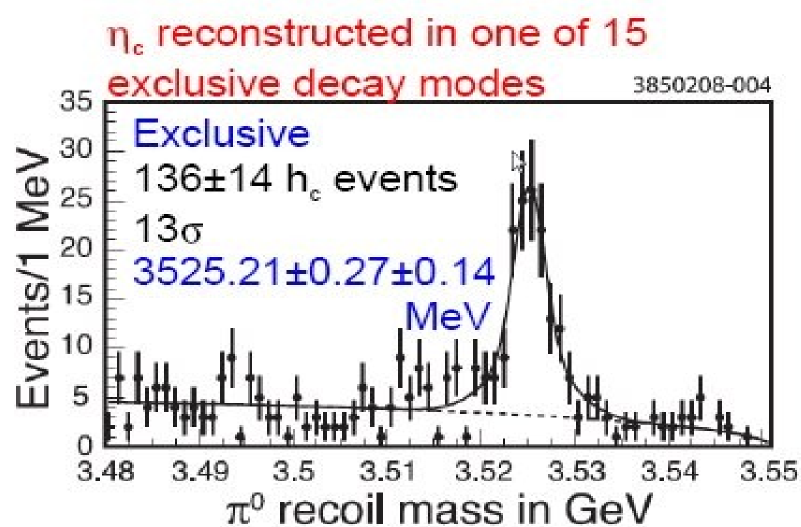
CLEO *PRL* 101, 182003 (2008)

CLEO-c arXiv:0805.4599 [hep-ex]



- A factor of ~9 larger statistics than in the initial publication



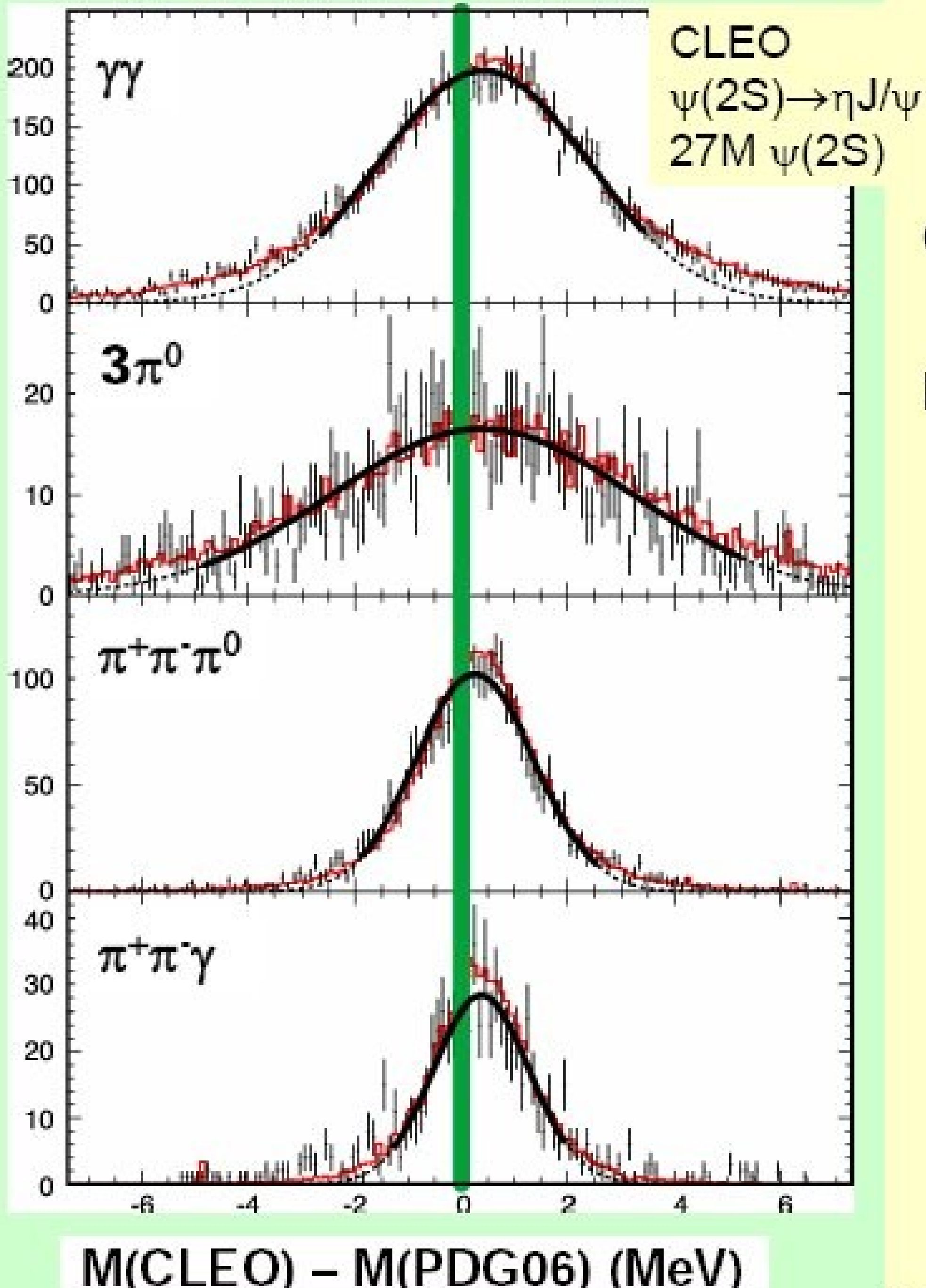


Result: **$M(h_c)$=(3525.28±0.19±0.12) MeV**

cf. $\langle M(\chi_{cJ})\rangle$ =(3525.30±0.11) MeV (PDG)

→ **HF splitting of 1P states is negligibly small!**

Invariant mass of η decay products:

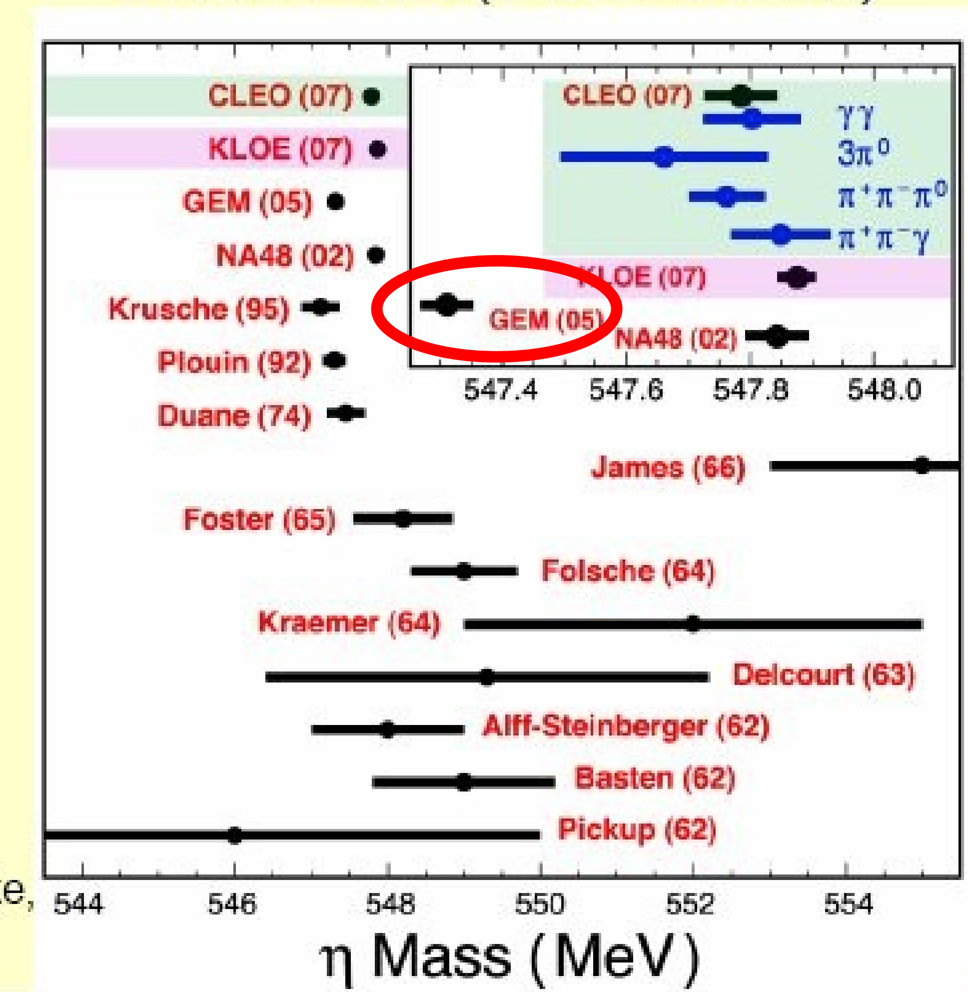


16k fully reconstructed events

η Mass

CLEO: $M(\eta) = 547.785 \pm 0.017 \pm 0.057$ MeV
PRL 99, 122002 (2007) (arXiv:0707.1810)

KLOE: $M(\eta) = 547.873 \pm 0.007 \pm 0.031$ MeV
arXiv:0707.4616 (LP07 contribution)

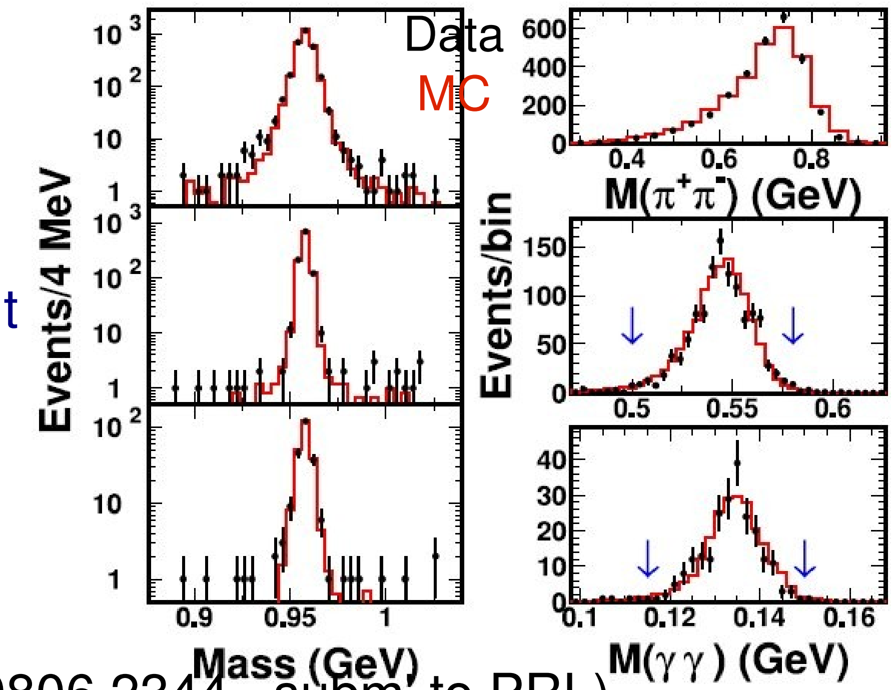


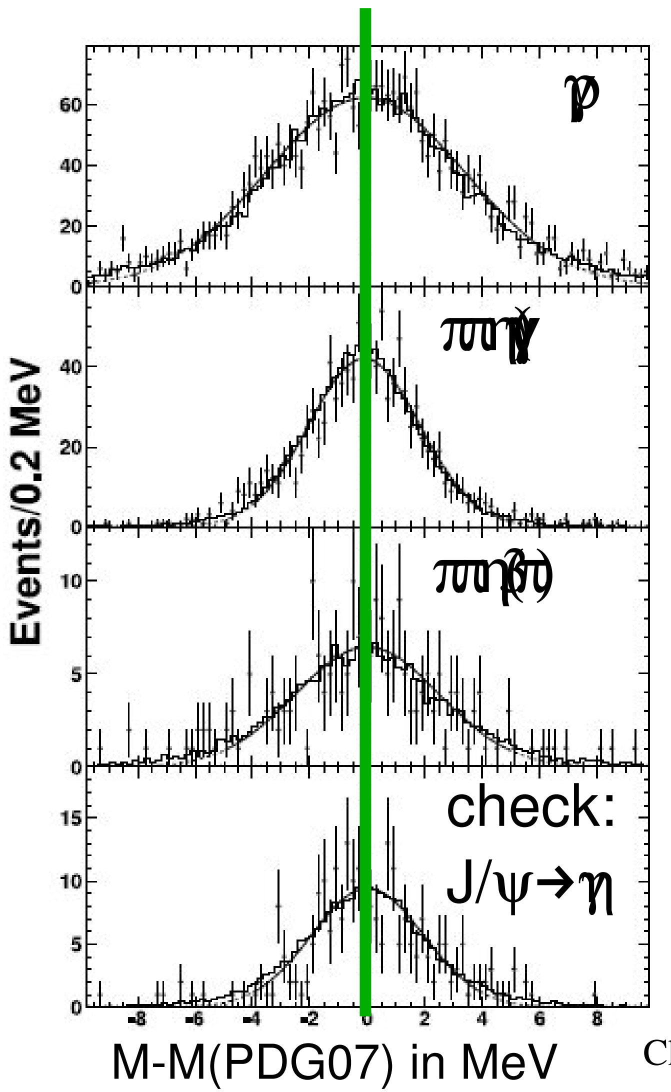
lahlke,

η' Mass

Use **ψ(2S) → π⁺π⁻ J/ψ, J/ψ → γ η'**

Similar technique as in η mass measurement





Result:

(CLEO arXiv:0806.2344, subm' to PRL)

M(η')=(957.793±0.054±0.036) MeV

consistent with and substantially more precise than previous world average

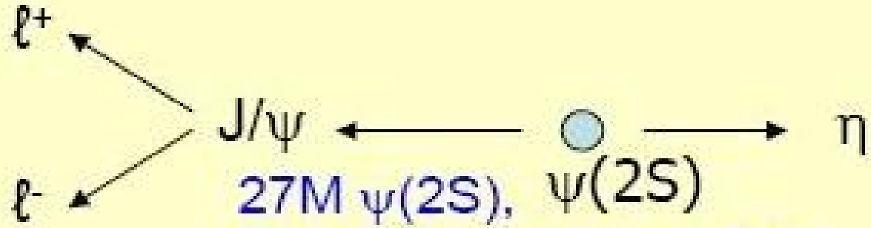
Implication for the pseudoscalar η-η' mixing angle:

$\phi_P=(41.461\pm0.008)^0$ (Jones & Scadron 1979)

Agrees with ϕ_P from BFs: flavor symm' breaking small?

$$\tan^2\phi_P = \frac{(M_{\eta'}^2 - 2M_K^2 + M_\pi^2)(M_\eta^2 - M_\pi^2)}{(2M_K^2 - M_\pi^2 - M_\eta^2)(M_{\eta'}^2 - M_\pi^2)}$$

η branching fractions



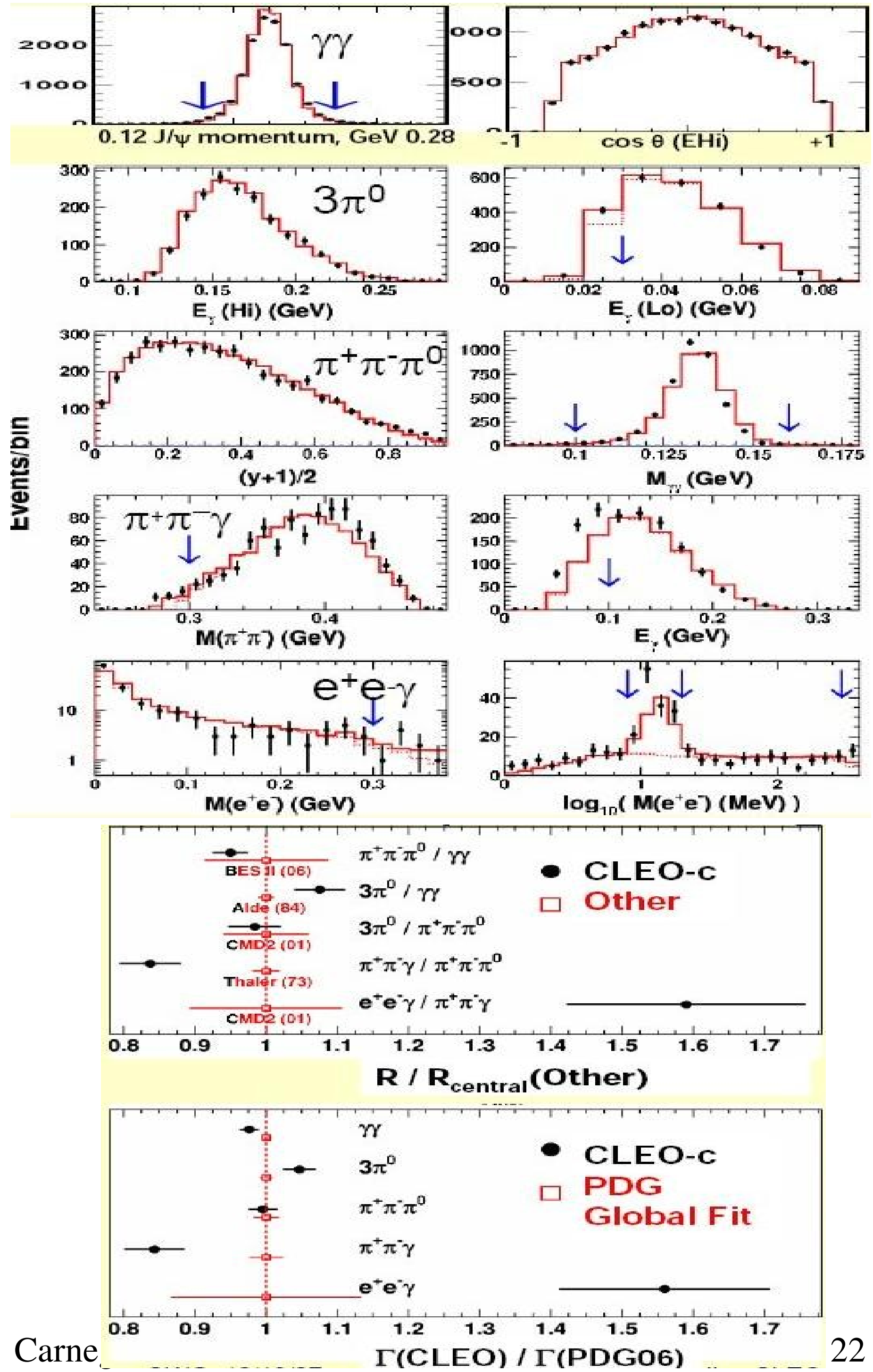
27M ψ(2S),
B(ψ(2S)→ηJ/ψ) = 3.1%,
B(J/ψ→l^+l^-) = 12%,

Fully reconstruct five final states:
$\gamma\gamma$ + $3\pi^0$ + $\pi^+\pi^-\pi^0$ + $\pi^+\pi^-\gamma$ + $e^+e^-\gamma$
38.5 34.0 22.6 4.0 0.9%

Follow PDG procedure: sum of the above five modes is ~ 100%
⇒ build absolute Br's from ratios

$\pi^+\pi^-\gamma$ and $e^+e^-\gamma$: 3σ deviation

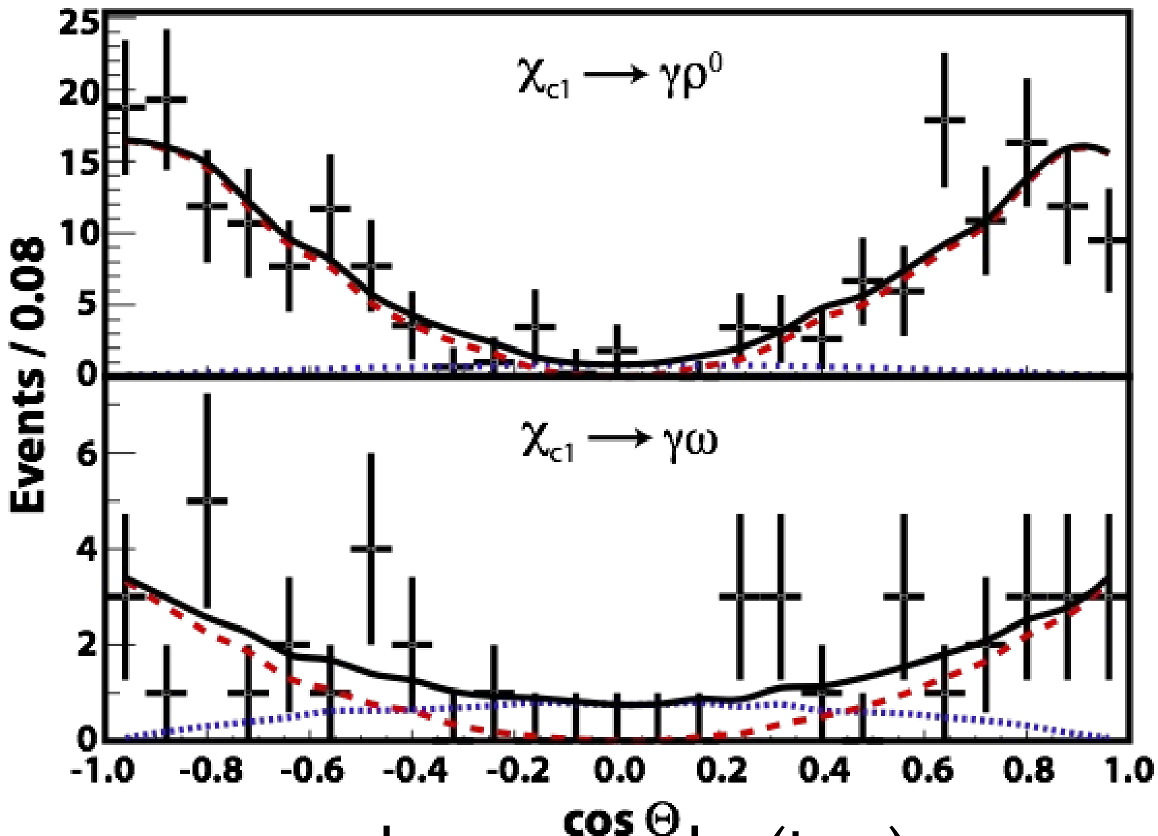
CLEO, PRL 99, 122001 (2007) or arXiv:0707.1601



$\chi_{c1}(1P) \to \gamma(\rho,\omega)$ Polarization

structure in the decay

- The ρ decay exhibits longitudinal polarization
- Statistics are less precise for ω, but it is also consistent with longitudinal polarization
- This parallels that measured for $a_1 \to \gamma\rho$ by VES (Z. Phys. C 66, 71 (1995))
- Expected from Landau-Yang



ρ decay angle (top)
orientation of ω decay plane (bottom)