New Charmonium Results from CLEO-c

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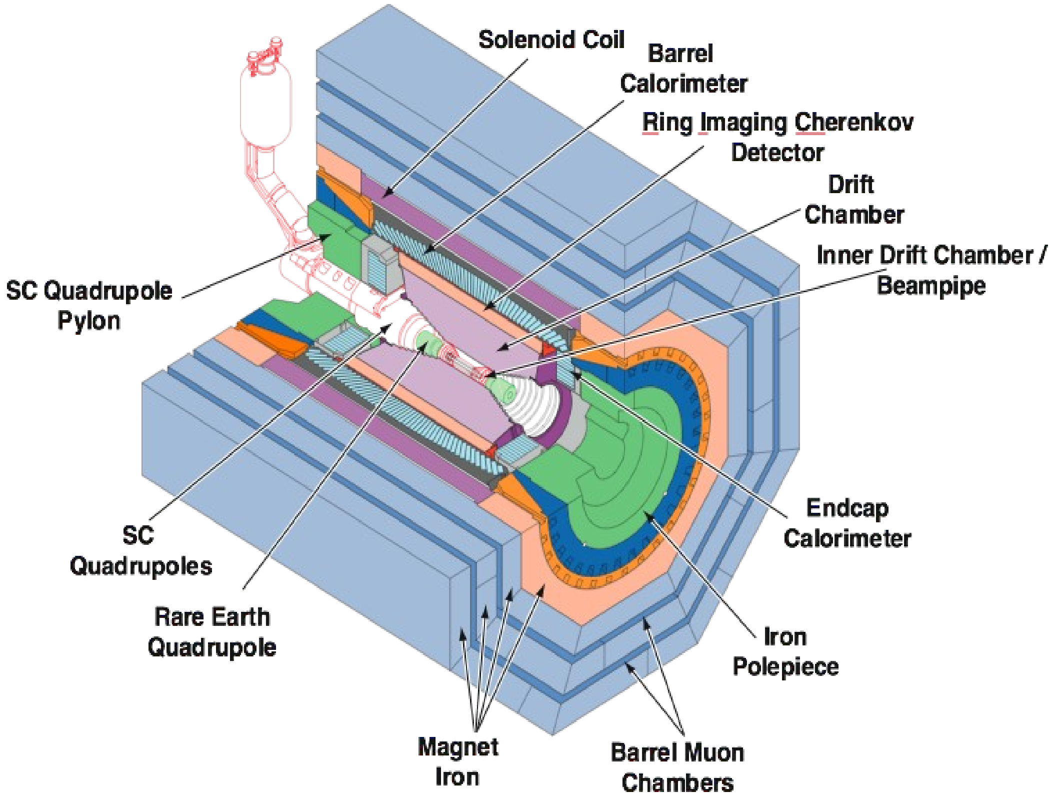
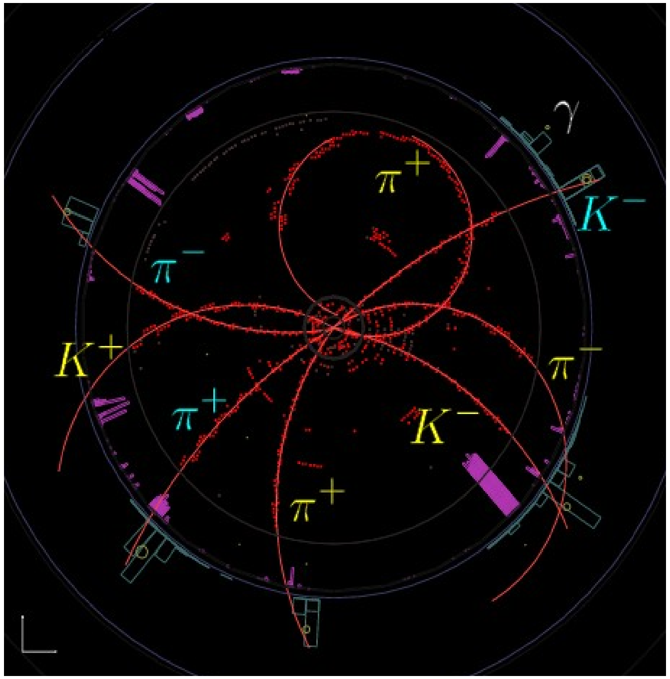
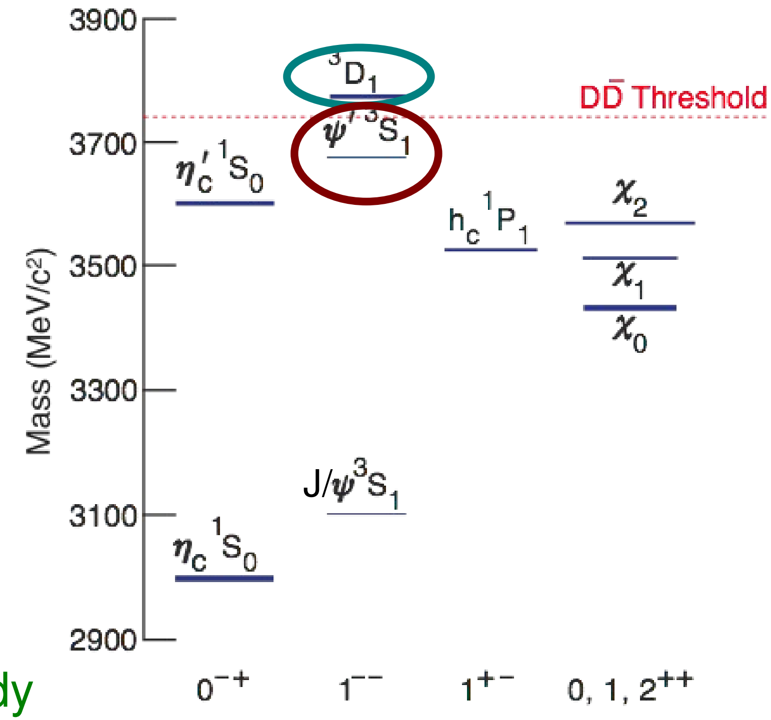




One of the last CLEO-c events
(taken on 3-March-2008)
$e^+e^- \to D_s^{*+} D_s^-$

CLEO-c Data Sample for Charmonium Program



818/pb at $\psi(3770)$
(mostly open charm
but also charmonium)

54/pb at $\psi(2S)$ ---> 27 M $\psi(2S)$

(largest pre-BESIII world supply)

In praise of $\psi(2S)$:

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

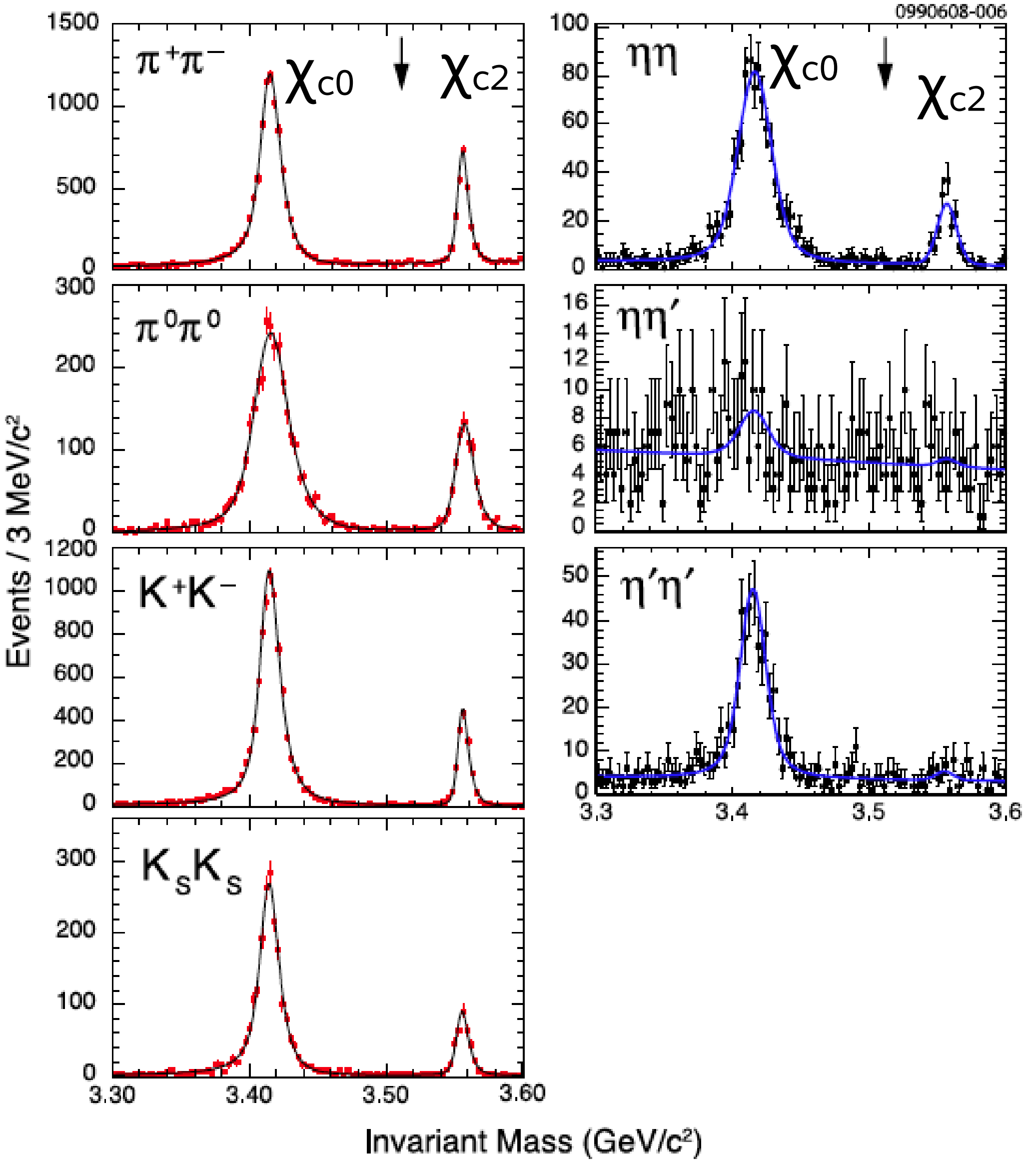
$B(\psi(2S) \to \gamma\, \chi_{cJ}$ $\approx$ 9% for each of J=0,1,2

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}



- 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})

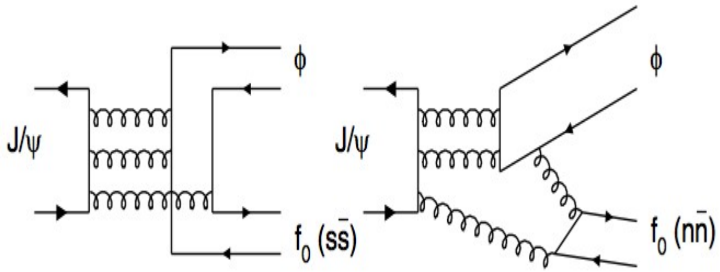
Mode		χ_{c0}	χ_{c2}
$\pi^+\pi^-$	This Work	$6.37 \pm 0.08 \pm 0.29 \pm 0.32$	$1.59 \pm 0.04 \pm 0.07 \pm 0.10$
	PDG [5]	4.87 ± 0.40	1.42 ± 0.16
$\pi^0\pi^0$	This Work	$2.94 \pm 0.07 \pm 0.32 \pm 0.15$	$0.68 \pm 0.03 \pm 0.07 \pm 0.04$
	PDG	$2.43 \pm .20$	0.71 ± 0.08
K^+K^-	This Work	$6.47 \pm 0.08 \pm 0.33 \pm 0.32$	$1.13 \pm 0.03 \pm 0.06 \pm 0.07$
	PDG	5.5 ± 0.6	0.78 ± 0.14
$K^0_SK^0_S$	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

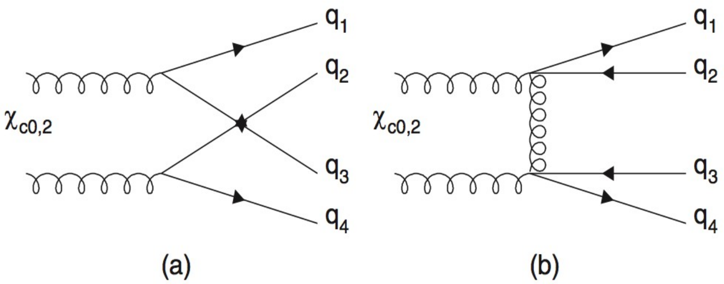
CLEO PRD 79, 072007 (2009)

Substantial improvement over current world averages in some channels!

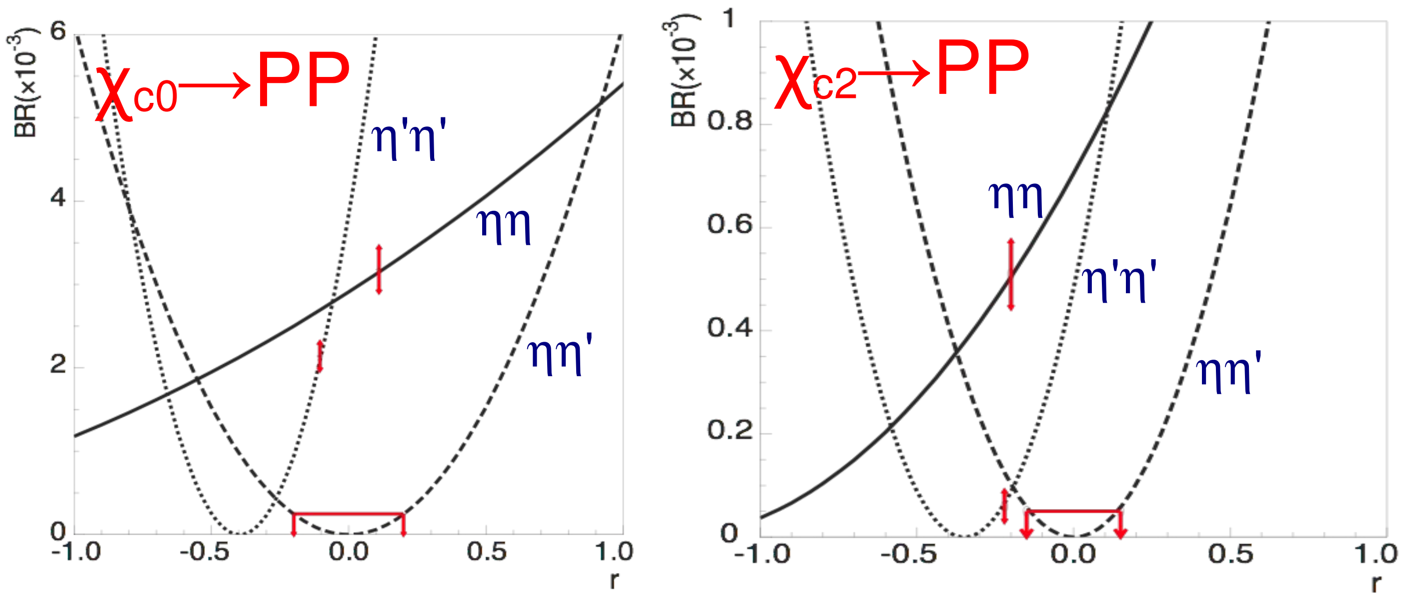
Example: $\chi_{cJ} \rightarrow \eta^{(\prime)}\eta^{(\prime)}$

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.

Evidence for Hadronic Decay of the h_c

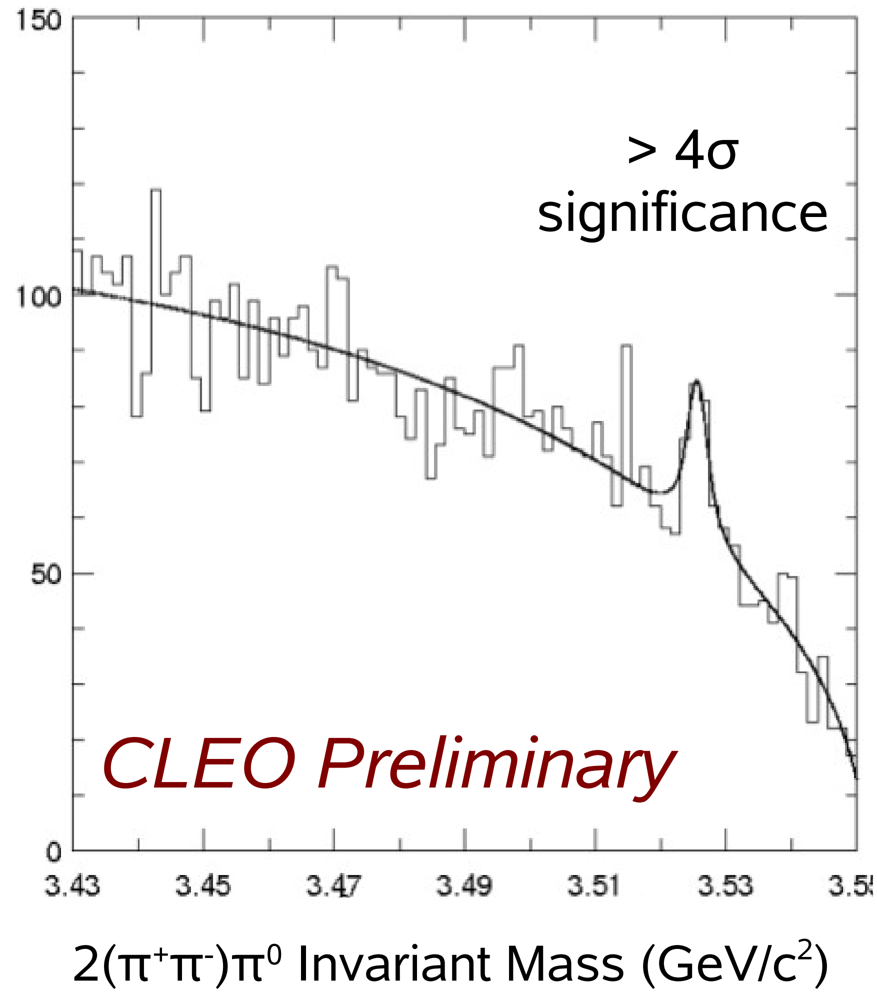
The only previously observed decay:
$\psi(2S) \to \pi^0 h_c)$ x $B(h_c \to \gamma \eta_c)$;
product BF: 4.2 ± 0.6) x 10^{-4}
(CLEO *PRL* 101, 182003 (2008))

Godfrey & Rosner predict 73% direct hadronic decay (*PRD* 66, 014012 (2002))

Expect **odd number of pions**
(negative G parity)

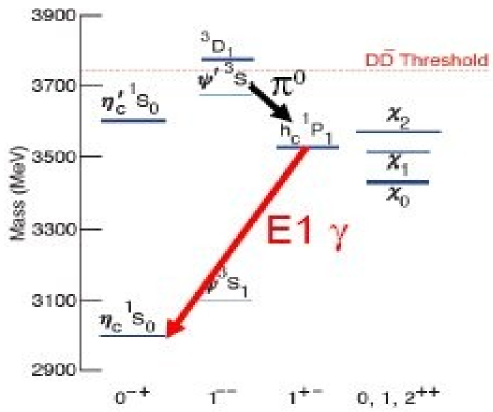
Measure $B(\psi(2S) \to \pi^0 h_c)$ x $B(h_c \to X)$
$X = n(\pi^+\pi^-)\,\pi^0$ (n=1,2,3):

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

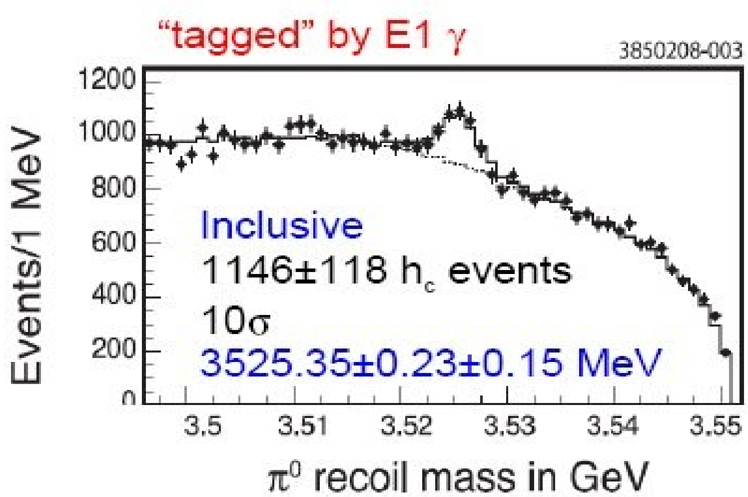


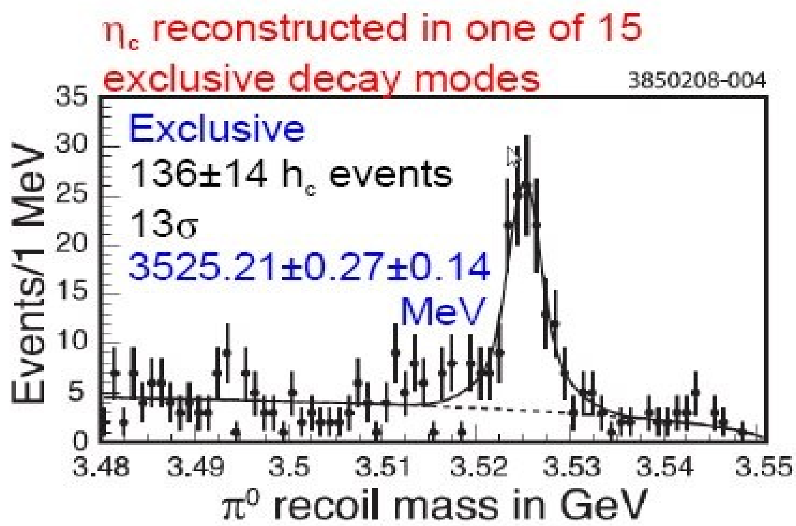
(Aside: Precision h_c Mass Measurement)

CLEO *PRL* 101, 182003 (2008)
CLEO-c arXiv:0805.4599 [hep-ex]



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



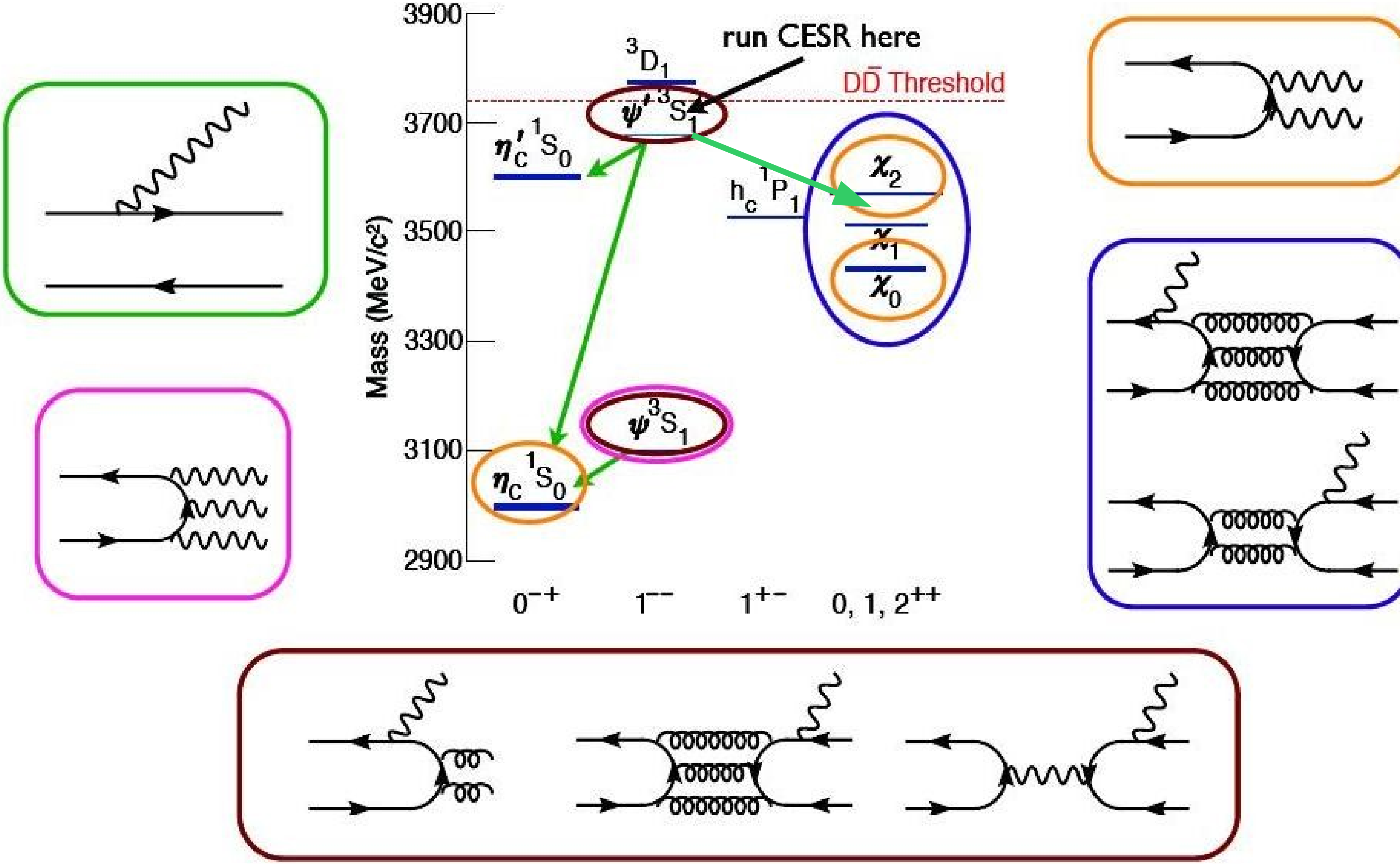


Result: **$M(h_c)$=(3525.28±0.19±0.12) MeV**

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

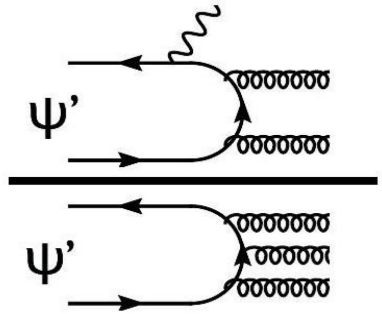
→ **HF splitting of 1P states is negligibly small!**

Radiative Decays and Transitions



B(ψ(2S)→γgg) / B(ψ(2S)→ggg)

Rough expectation for ratio of rates:



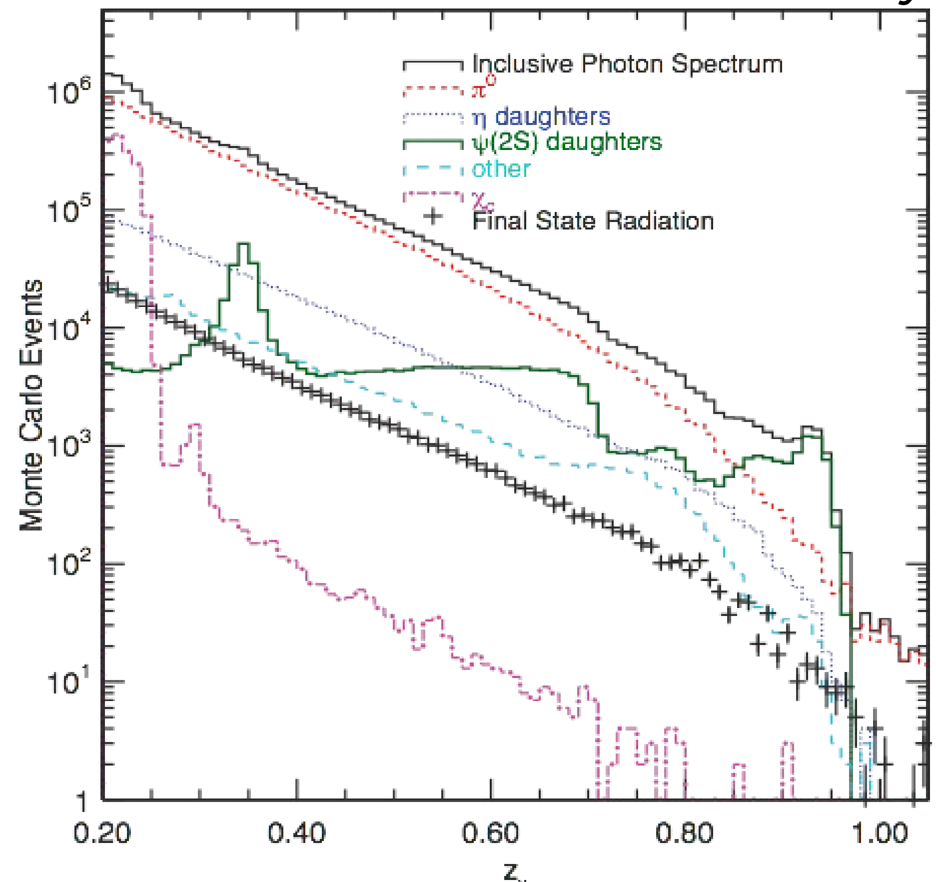
$\propto q_c^2 \alpha_{EM}/\alpha_S\,[1 + \ldots]$

Experimental challenge: subtracting backgrounds

- utilize three separate techniques; dominant systematic error

Measure ψ’→γgg, subtract all other known decays and transitions (87%), infer ψ’→ggg

CLEO Preliminary



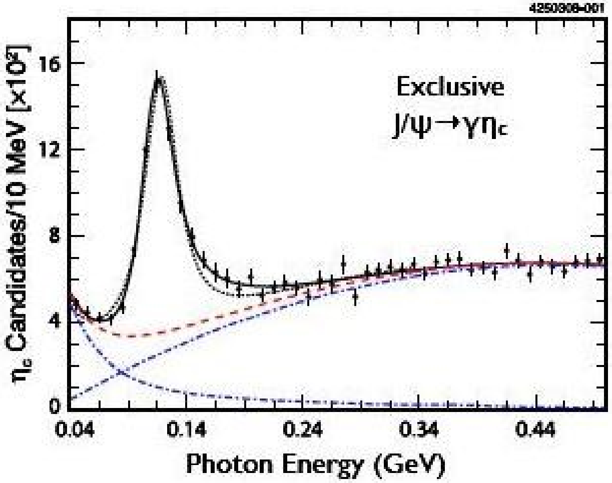
State	B(X →γgg) / B(X →ggg)
J/ψ	0.137 ± 0.001 ± 0.016
ψ(2S)	***0.091 ± 0.003 ± 0.027***
ϒ(1S)	0.027 ± 0.001 ± 0.003
ϒ(2S)	0.032 ± 0.001 ± 0.005
ϒ(3S)	0.027 ± 0.001 ± 0.005

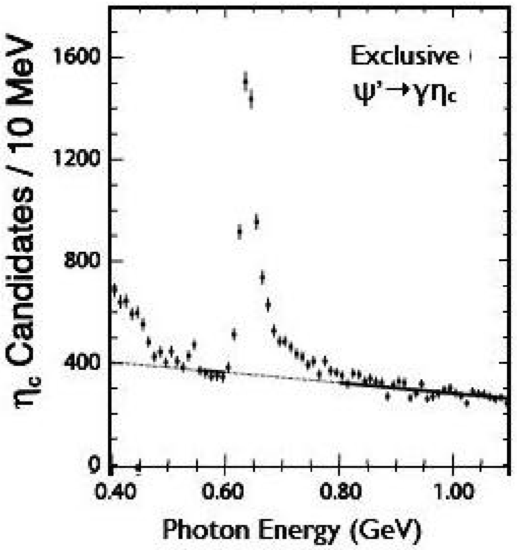
CLEO PRD 78, 032012 (2008)

← *CLEO Preliminary*

CLEO PRD 74, 012003 (2006)

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





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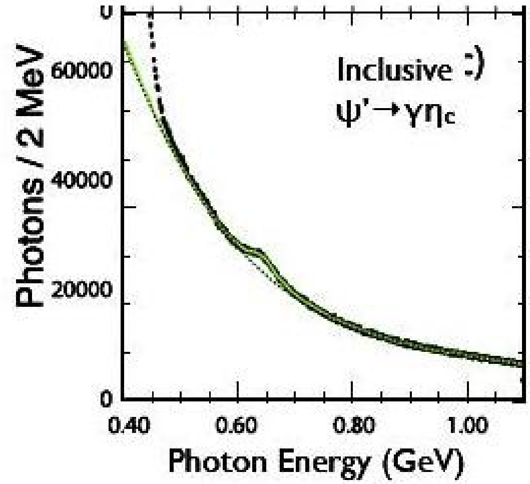


= $B(J/\psi \rightarrow \gamma\eta_c)$

<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.

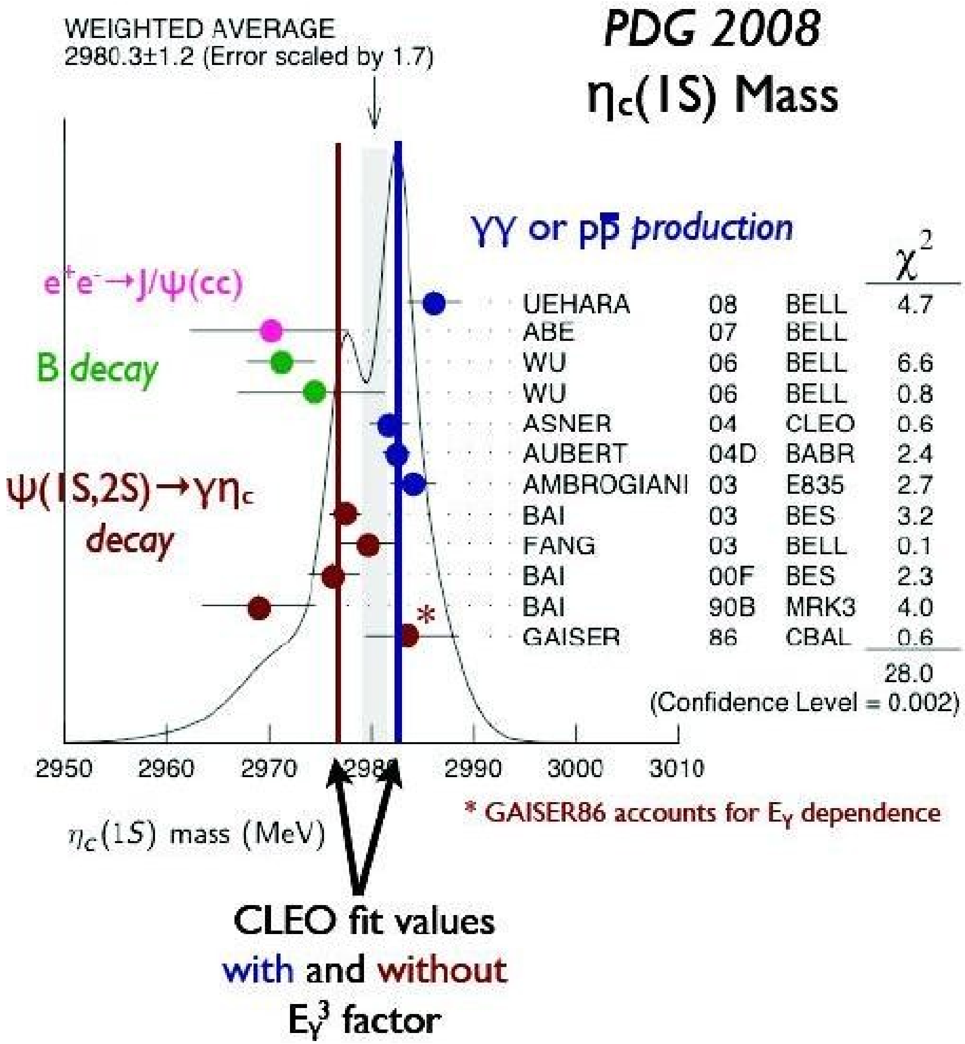
C. $B(J/\psi \rightarrow \gamma\eta_c) = (1.98 \pm 0.09 \pm 0.30)\%$ taking A×B.

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

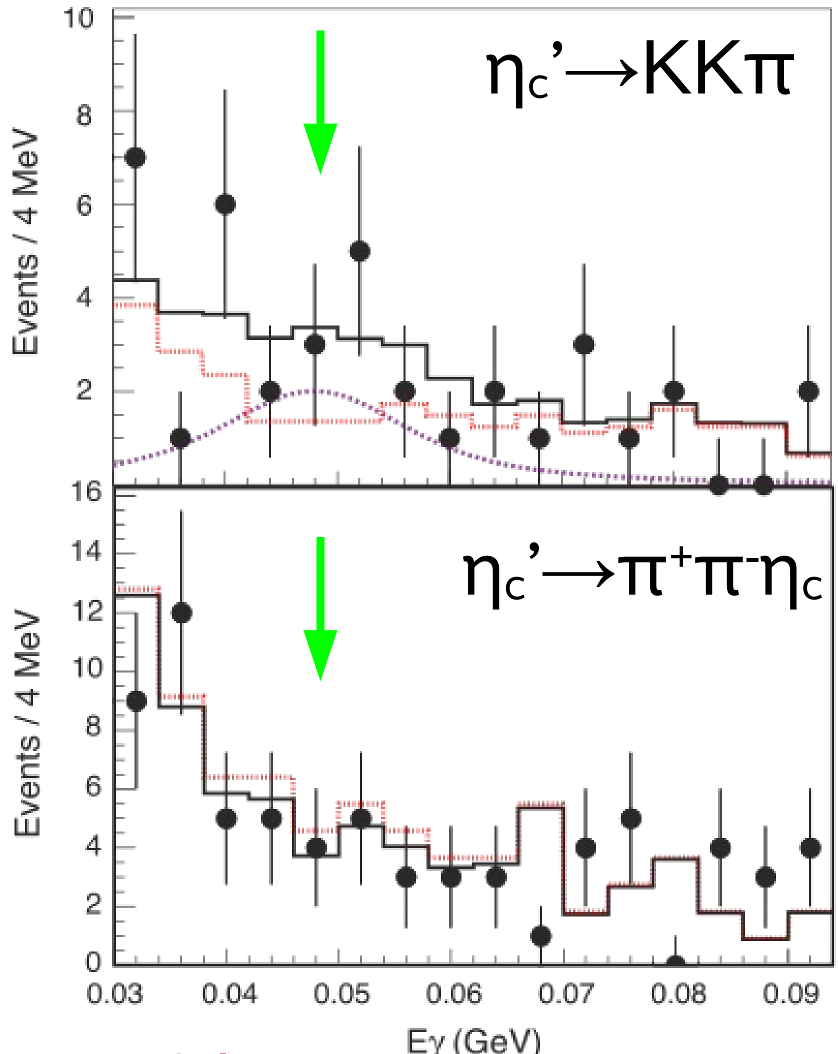
...but these factors cause total width to diverge at high E_γ

Understanding the energy dependence of the ψ(1S,2S)→γη_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.

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

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

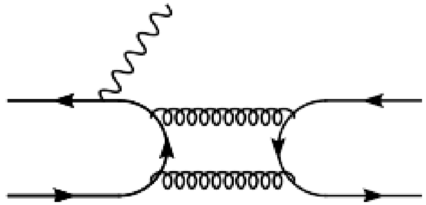


Results (*CLEO PRELIMINARY*):

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

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

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



Mode	This result (10^{-4})
$J/\psi \to \gamma\pi^0$	$0.363 \pm 0.036 \pm 0.013$
$\to \gamma\eta$	$11.01 \pm 0.29 \pm 0.22$
$\to \gamma\eta'$	$52.4 \pm 1.2 \pm 1.1$
$\psi(2S) \to \gamma\pi^0$	< 0.07
$\to \gamma\eta$	< 0.02
$\to \gamma\eta'$	$1.19 \pm 0.08 \pm 0.03$

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

Results:

$$R_1 = (21.1 \pm 0.9)\%$$

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

J/ψ | $\psi(2S)$ | $\gamma\eta$ mode

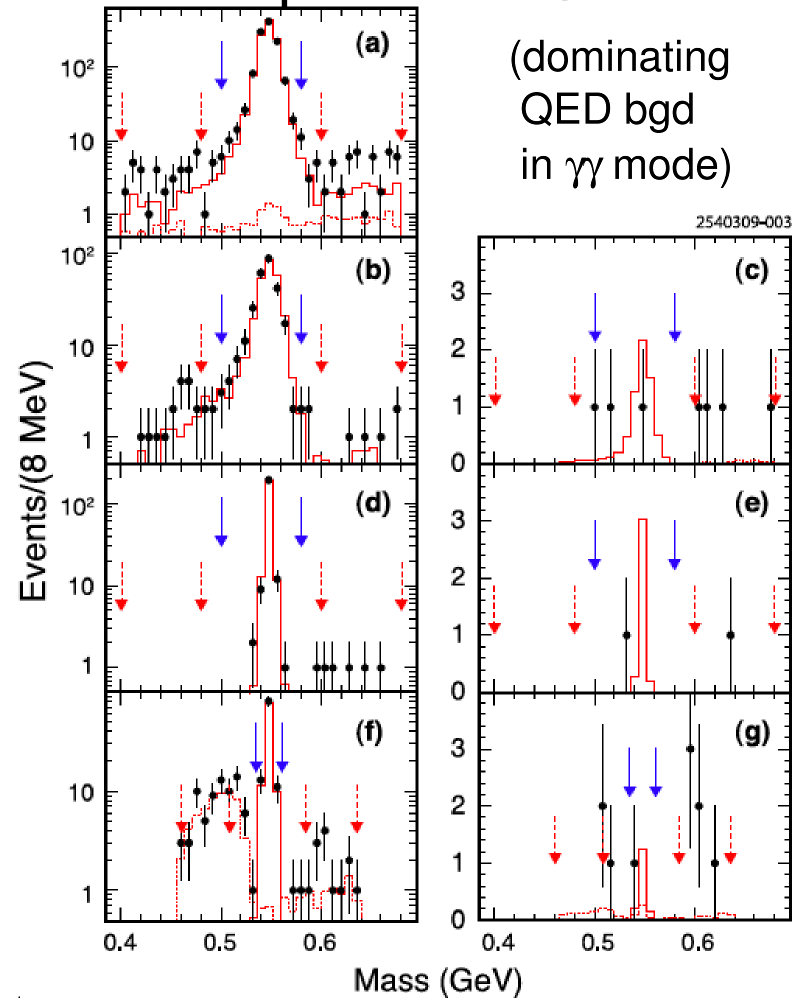
(dominating QED bgd in $\gamma\gamma$ mode)

$\gamma\gamma$

$3\pi^0$

$\pi^+\pi^-\pi^0$

$\gamma\pi^+\pi^-$



consistent with known η–η' mixing

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:

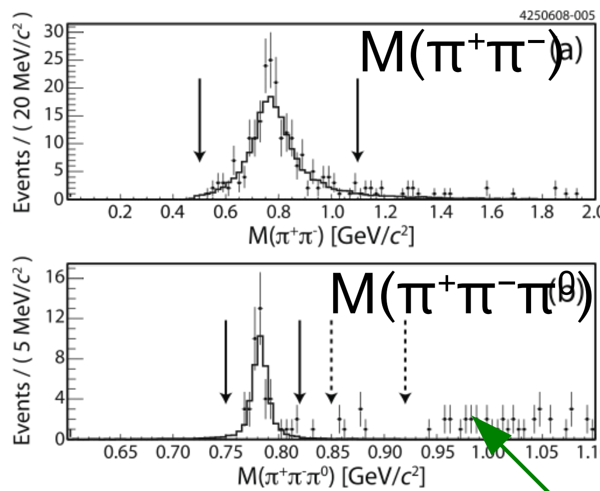
$\psi(2S) \rightarrow \gamma_{(low)} \chi_{cJ}$

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

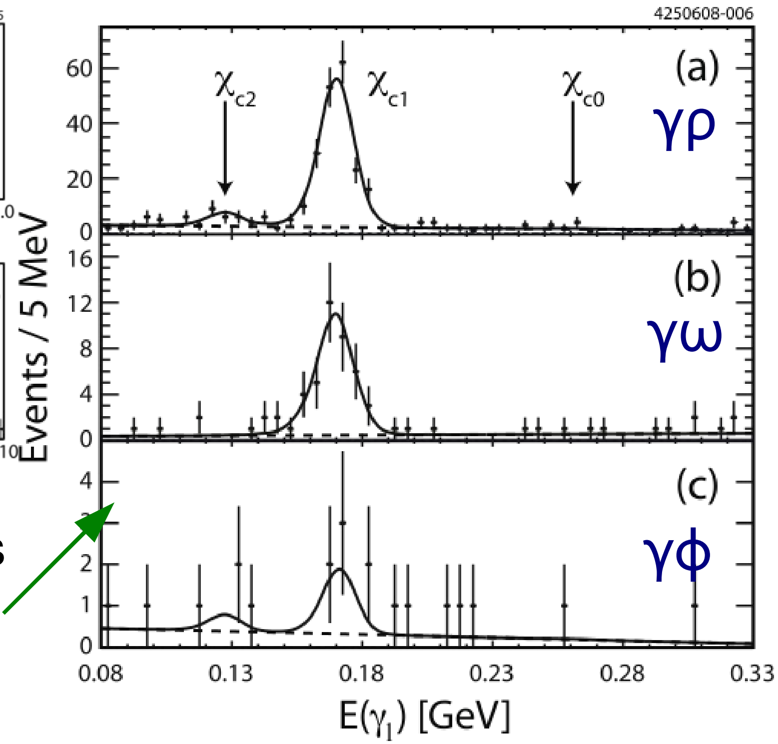
Significant signals observed in:

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

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



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])

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

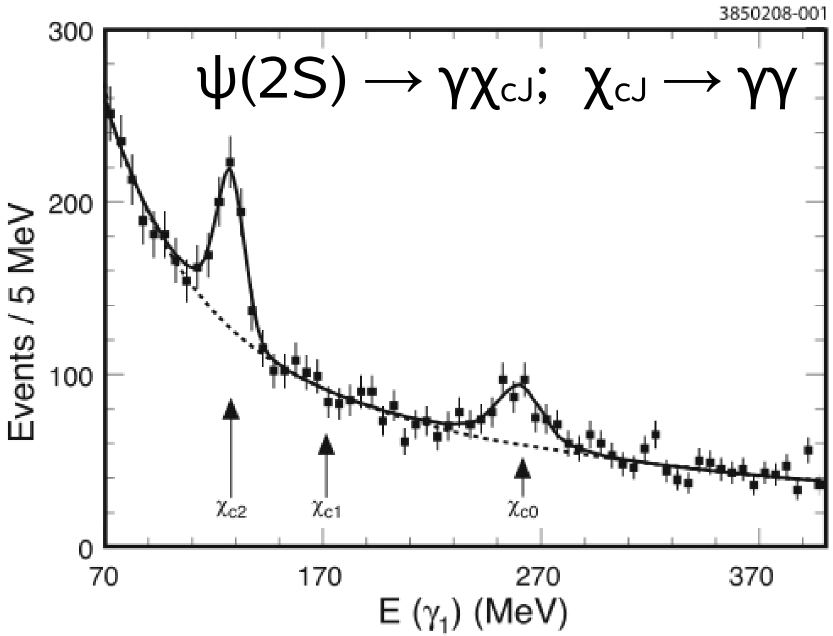
Two-photon widths of χ_{cJ} probe
relativistic and radiative corrections
known to be significant in charmonium.

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)

$J/\psi \rightarrow 3\gamma$

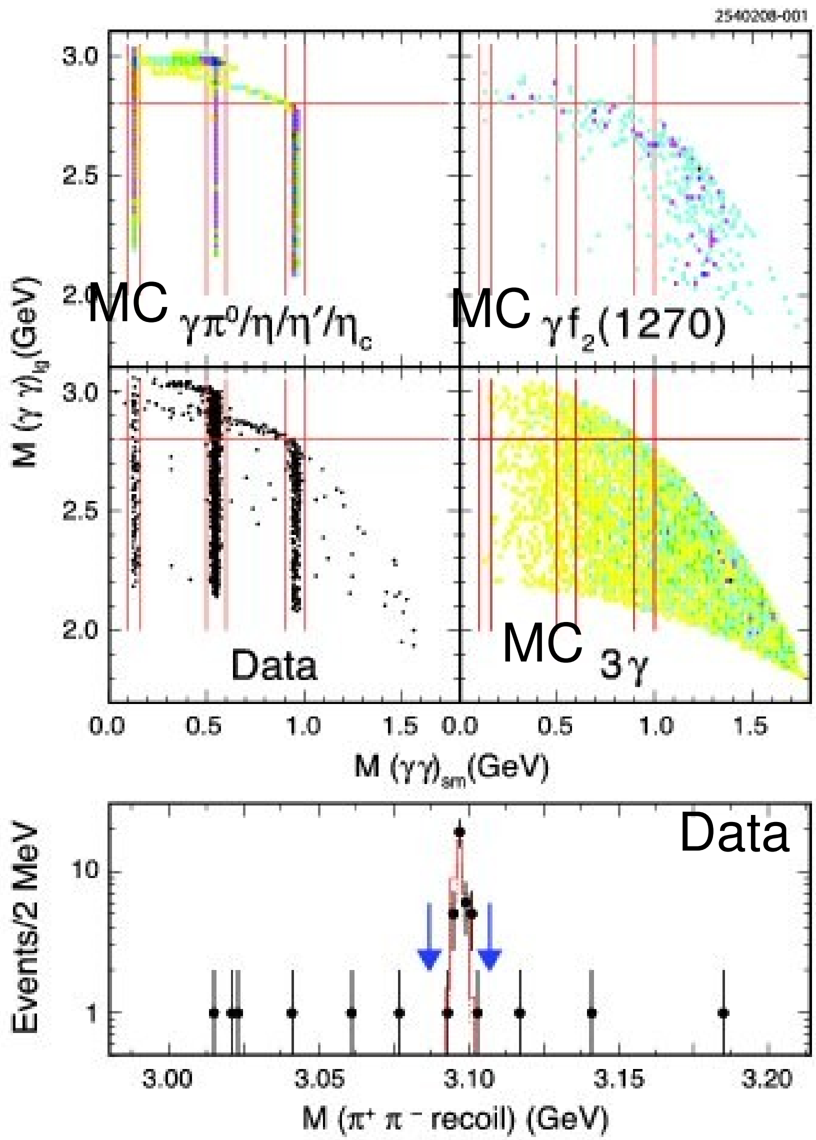
This is the quarkonium analogue of orthopositronium decay.

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

Veto resonances π^0, η, η', η_c

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

Tagging gives very clean J/ψ sample!

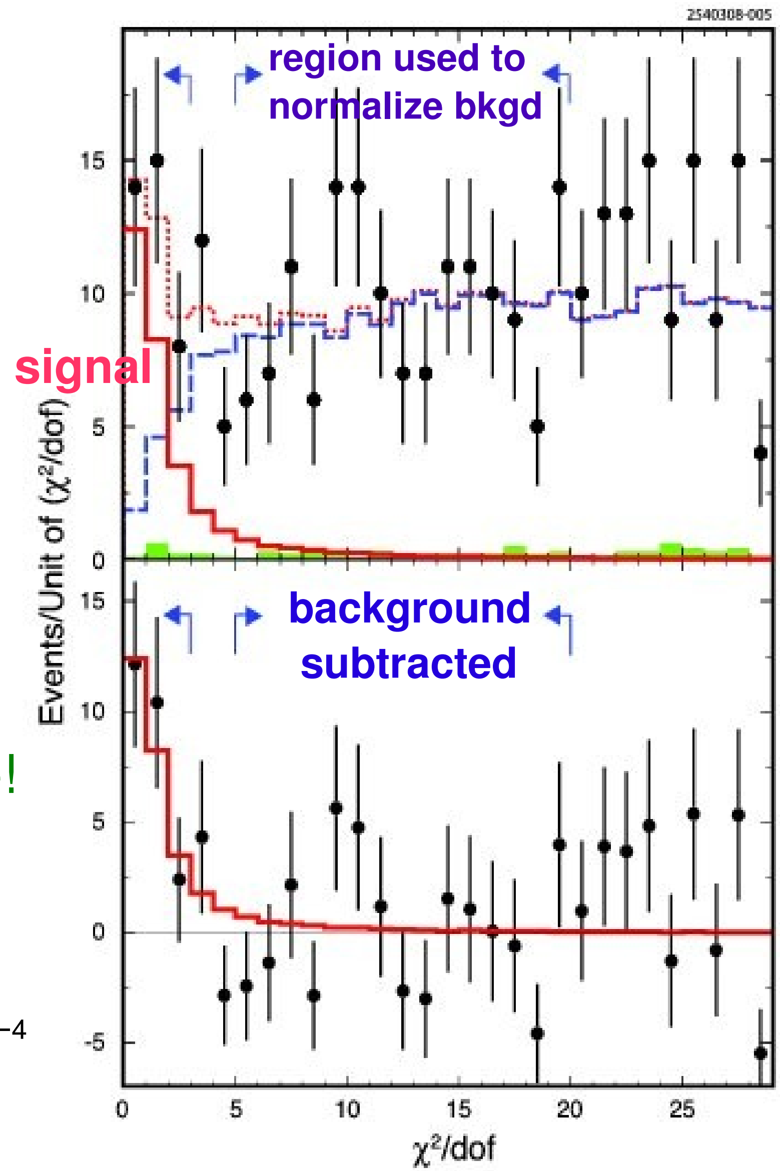


$J/\psi \rightarrow 3\gamma$

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 ± 0.3 ± 0.2) x 10^{-5} (6σ)
First observed 3γ decay of any hadron!

Theory: in QED, $B(3\gamma)/B(3g) \approx (\alpha/\alpha_s)^3$
and $B(3\gamma \approx (\alpha/14)B_{\mu\mu} \approx 3\ x10^{-5}$
But NLO QCD corrections give negative rate!
(Higher order corrections very significant)



As "byproduct" we obtain upper limit on $\eta_c \rightarrow \gamma\gamma$:
$B(\eta_c \rightarrow \gamma\gamma) < 3\times10^{-4}$ (90% CL), PDG: $(2.7+0.9)\times10^{-4}$

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 $B(\psi(2S)\to\gamma gg)$ / $B(\psi(2S)\to ggg)$; completes set for heavy vector states

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

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

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

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

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

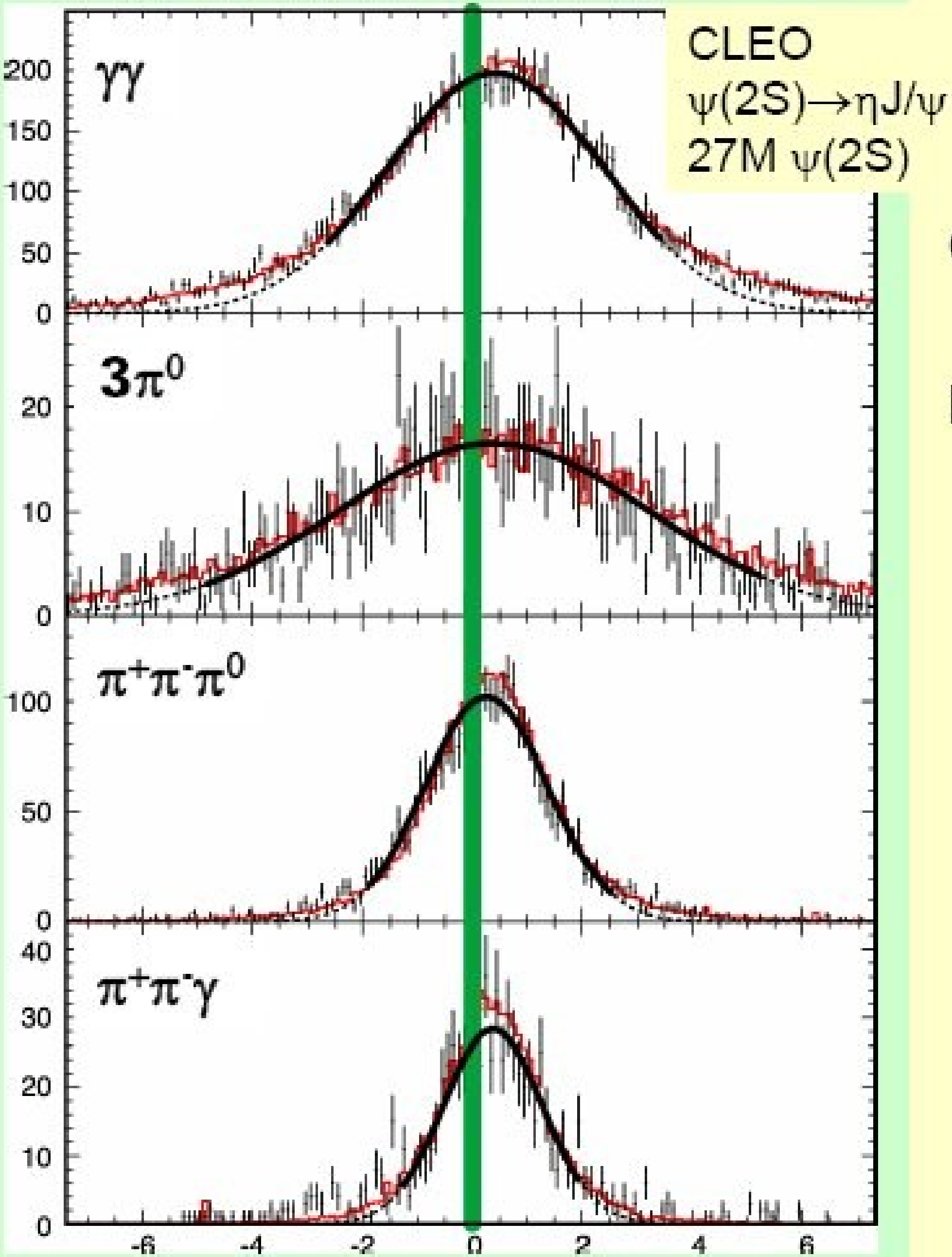
- First observation of the 3-photon decay of a meson: $J/\psi \to \gamma\gamma\gamma$

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
  - $(J/\psi, \psi') \to (\gamma, \pi^0) p\bar{p}$; $\chi_{cJ} \to X p\bar{p}$
  - 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

Invariant mass of η decay products:



M(CLEO) – M(PDG06) (MeV)

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)

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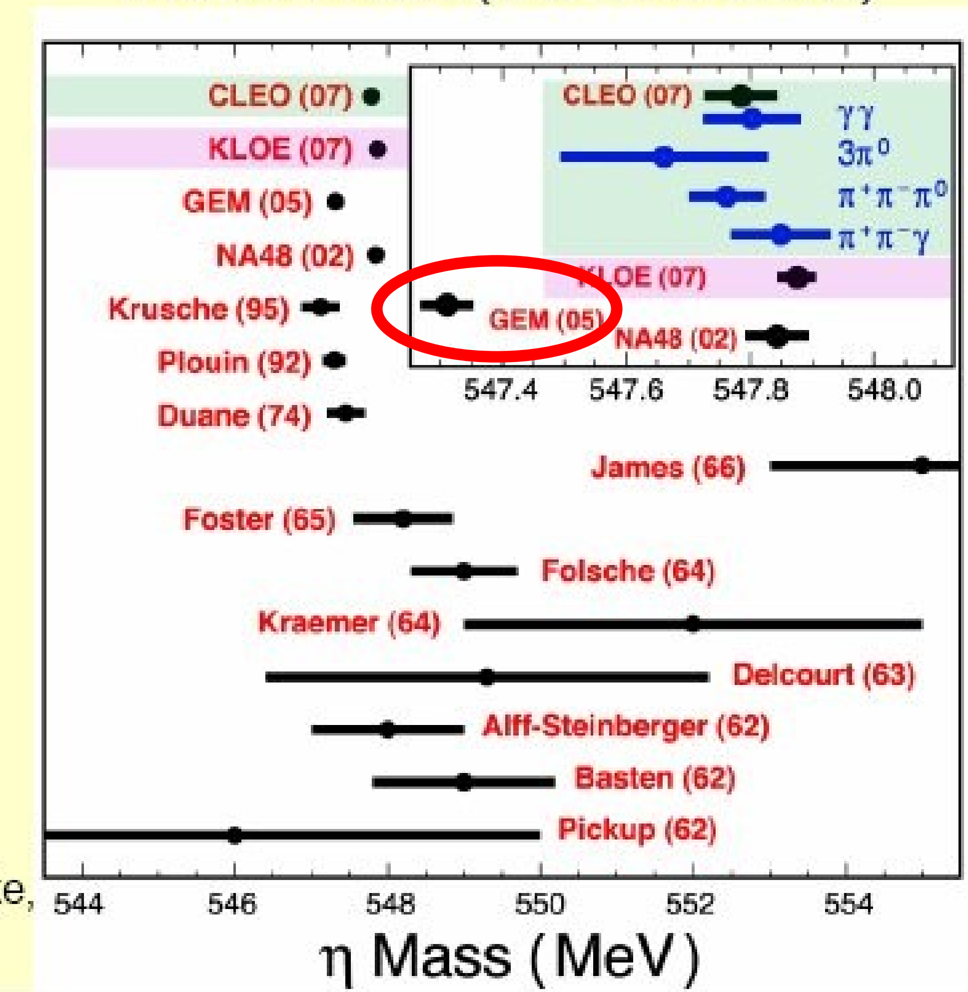
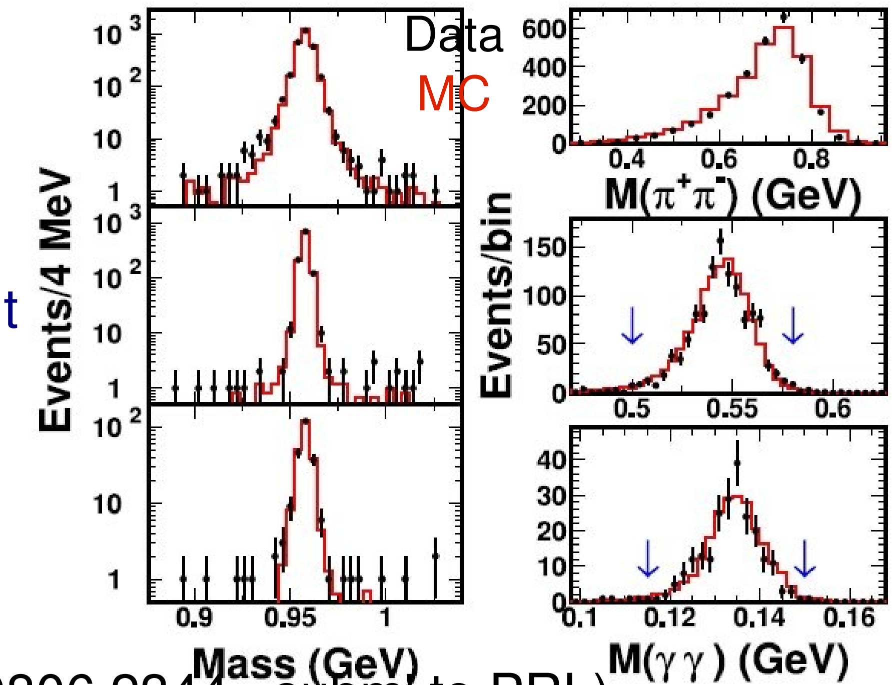
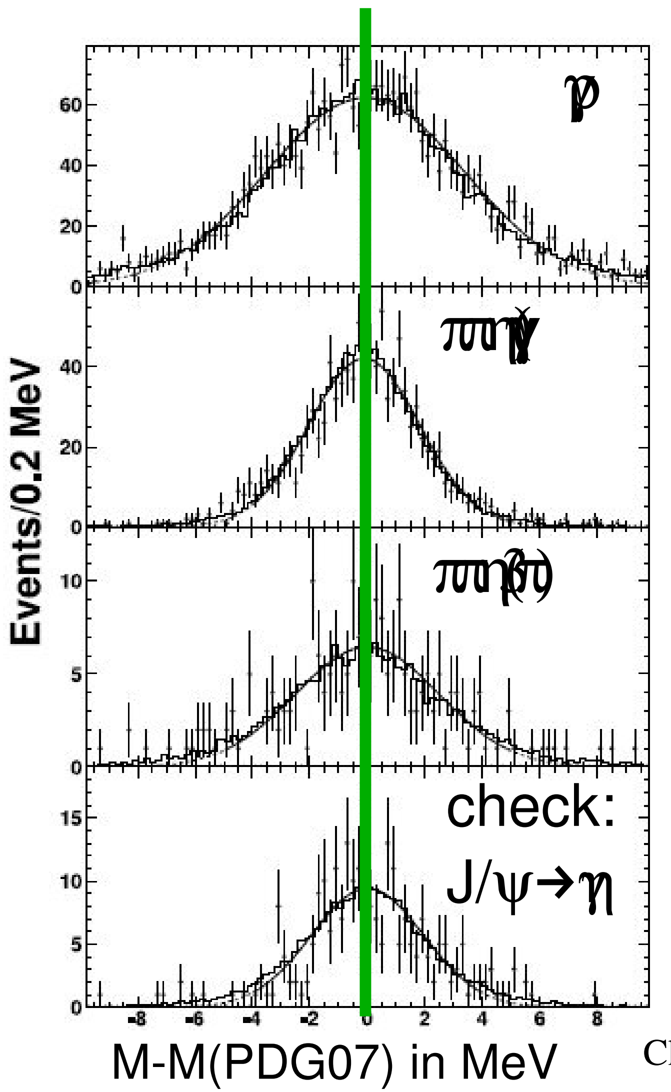


η' Mass

Use **ψ(2S) → $\pi^+\pi^-$ 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

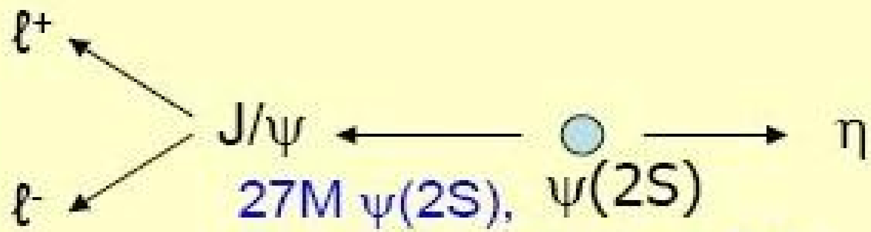
Implication for the pseudoscalar η-η' mixing angle:

ϕ_P=(41.461±0.008)^0 (Jones & Scadron 1979)

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

$$\tan^2 \phi_P = \frac{(M^2_{\eta'} - 2M^2_K + M^2_\pi)(M^2_\eta - M^2_\pi)}{(2M^2_K - M^2_\pi - M^2_\eta)(M^2_{\eta'} - M^2_\pi)}$$

η branching fractions



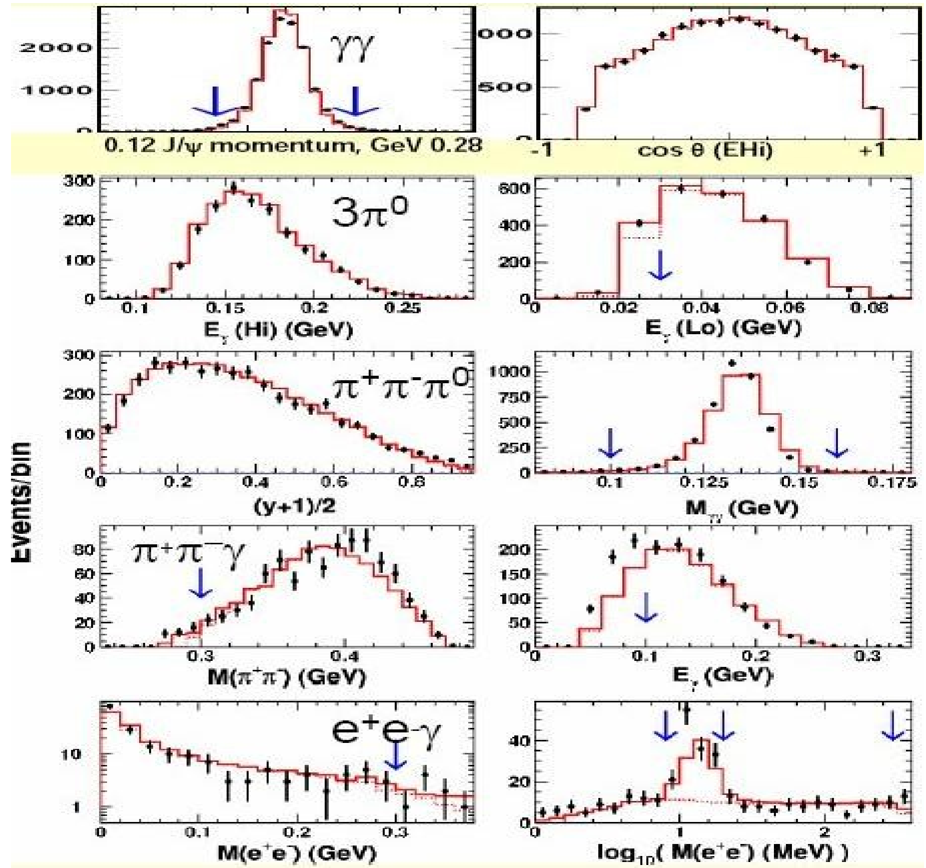
27M ψ(2S),
B(ψ(2S)→ηJ/ψ) = 3.1%,
B(J/ψ→l^+l^-) = 12%,

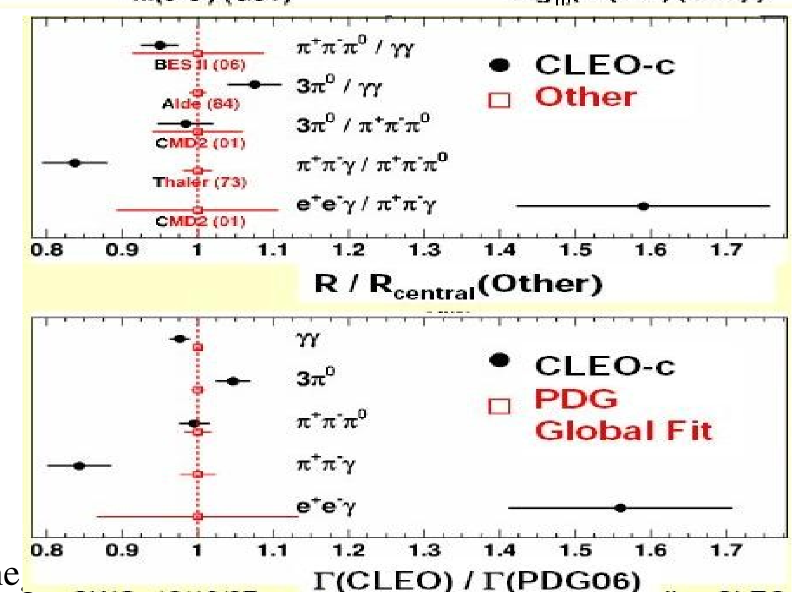
Fully reconstruct five final states:
γγ + $3\pi^0$ + $\pi^+\pi^-\pi^0$ + $\pi^+\pi^-\gamma$ + $e^+e^-\gamma$
38.5 34.0 22.6 4.0 0.9%

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





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

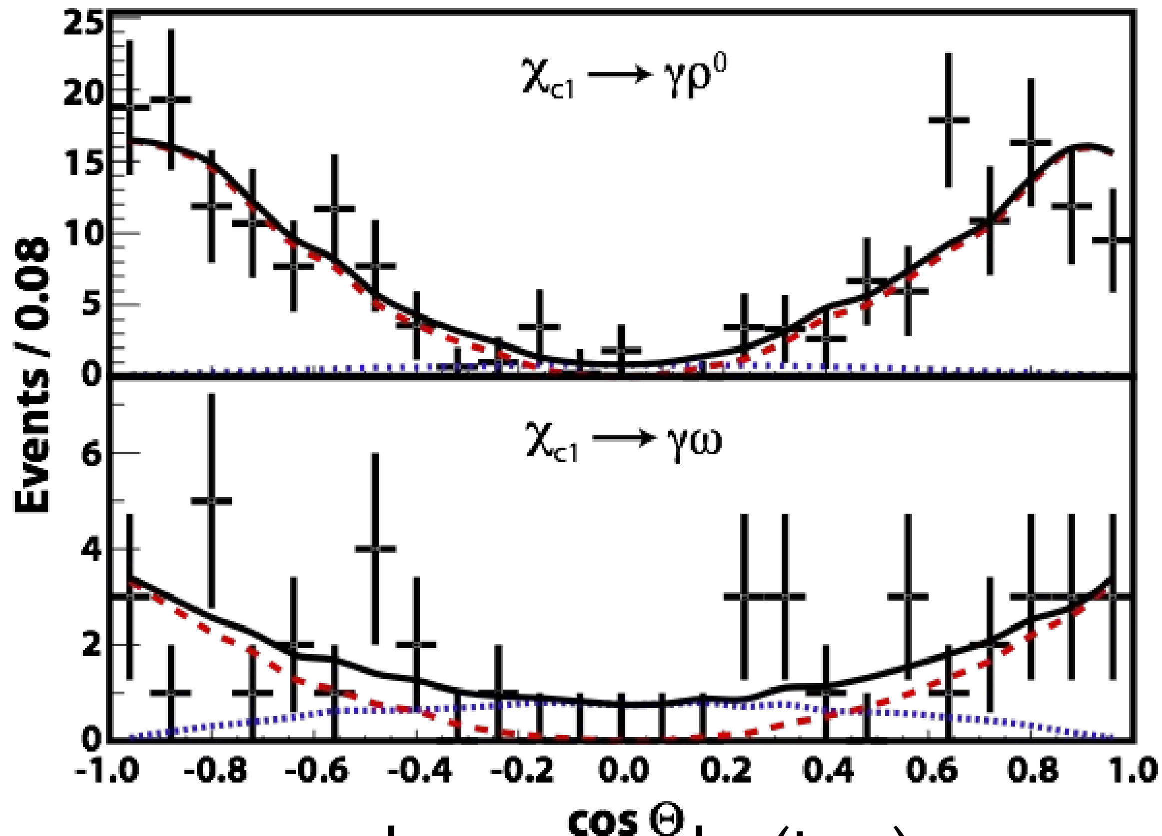
structure in the decay

- 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 $a_1 \rightarrow \gamma\rho$ by VES (Z. Phys. C 66, 71 (1995))

- Expected from Landau-Yang



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