



CLEO Charmonium Results



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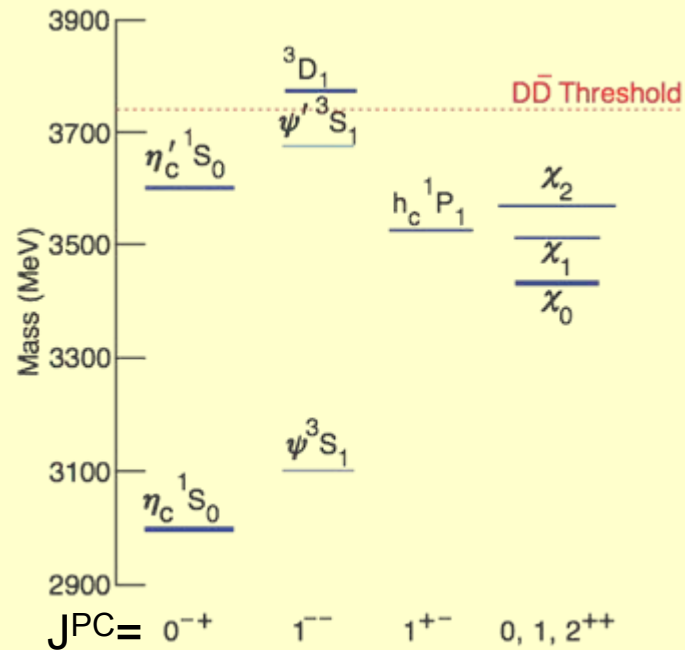
Quarkonium Working Group Meeting
10/17-20/07
DESY, Hamburg



Cornell University
Laboratory for Elementary-Particle Physics

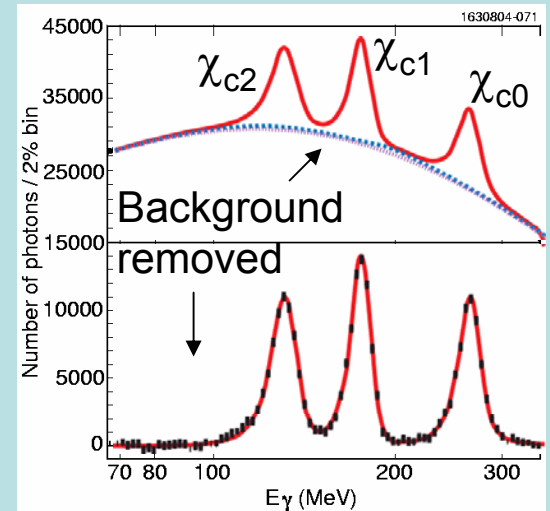
The Landscape

- All states below $D\bar{D}$ threshold observed
- 1--** states known best, large samples
 $\psi(2S)$: 14M BES,
 27M CLEO
 J/ψ :
 * on-resonance – 58M BES,
 * from $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$ decay:
 BR $\sim 32\%$, can tag the transition pions
 (CLEO: $\epsilon_{\text{tag}} = 75\% \Rightarrow 6.5\text{M}$ tagged J/ψ)
 – Era of precision studies and
 discovery of rare phenomena in
 1-- decay
- $B(\psi(2S) \rightarrow \gamma \chi_{cJ}) \sim 9\%$, $E(\gamma)$ selects
 between $J=0, 1, 2$: not far behind
 1-- in statistical power
 – Performing similar kinds of studies as
 for 1-- decays
- Singlets** less well known



$\psi(2S) \rightarrow \gamma \chi_{cJ}$
 inclusive
 photon
 spectrum:

CLEO
 1.5M $\psi(2S)$



New CLEO charmonium results discussed in other presentations:

□ $\psi(2S) \rightarrow \gamma \eta_c(1S)$:

- Exclusive and inclusive $\eta_c(1S)$ decays
- $\eta_c(1S)$ line shape
- $\text{BR}(\psi(2S) \rightarrow \gamma \eta_c(1S))$

➤ Ryan Mitchell's talk (Wednesday)

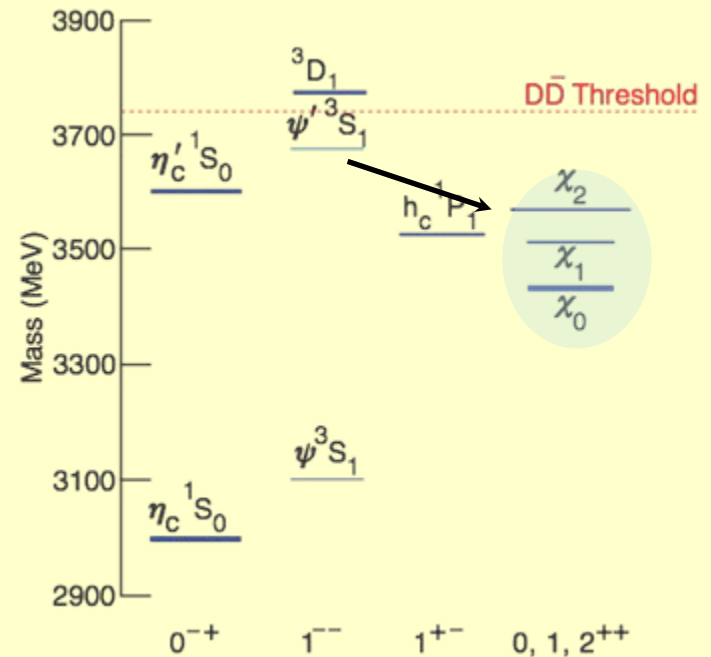
□ $\psi(2S) \rightarrow \pi^0 h_c$,
 $h_c \rightarrow \gamma \eta_c(1S)$:

- Exclusive and inclusive $\eta_c(1S)$ decays
- $M(h_c)$ and hyperfine splitting
- Product branching fraction $\text{BR}(\psi(2S) \rightarrow \pi^0 h_c) \times \text{BR}(h_c \rightarrow \gamma \eta_c(1S))$

➤ Kam Seth's talk (Friday)

χ_{cJ} Decays to...

... $\gamma\gamma$
 ... $\pi\pi, KK$
 ... $\eta(')\eta(')$
 ... baryon/anti-baryon
 ... multibody final states



Detailed comparisons between decay modes allow to assess the role of the color octet configuration

27M $\psi(2S)$ decays $\Rightarrow$ over 2M χ_{cJ} produced for $J=0,1,2$ each

Can probe exclusive decays down to BR $\sim 10^{-4}$

Exploit kinematic constraints in a fit of measured momenta/energies to $m(\psi(2S))$, don't need to constrain to $m(\chi_{cJ})$ in addition

$\chi_{cJ} \rightarrow 2 \text{ hadrons}$

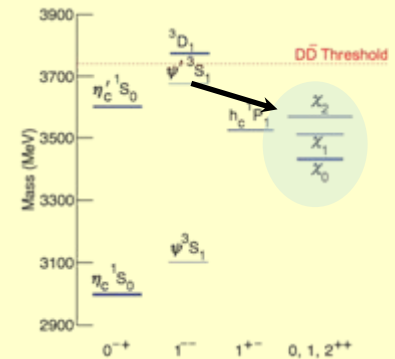
- Glue-rich environment – different from 1^- states
- “ $|\chi_{cJ}\rangle = |c\bar{c}\rangle$ ” $\Rightarrow$ many theory predictions $\ll$ experimental BR results
- Accurate prediction of 2-hadron decay rates of 3P_J states rely on understanding of the role of the color octet contribution:

$$|\chi_{cJ}\rangle = c_0 |(c\bar{c})_1\rangle + c_1 |(c\bar{c})_8 g\rangle$$

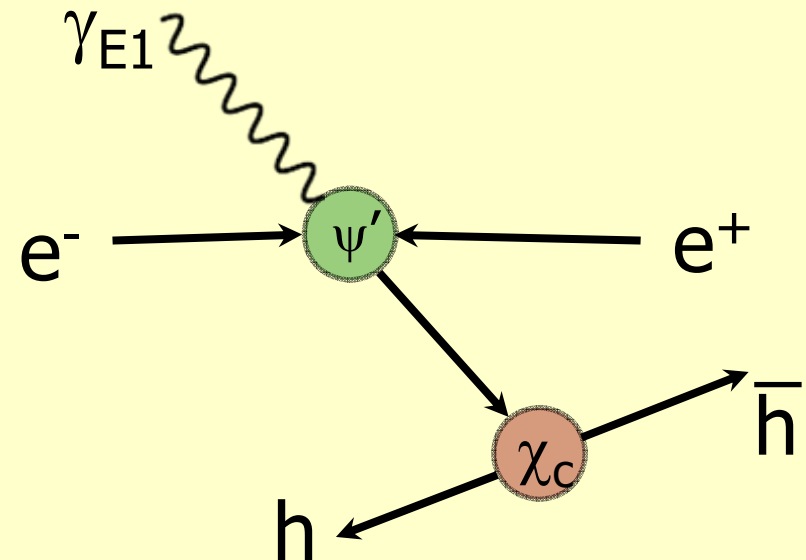
“Is that all?”

- Known 2-body modes amount to only a few percent of χ_{cJ} decays

Next: 14 two-body decay modes of χ_{cJ}
(13x hadronic + $\gamma\gamma$)

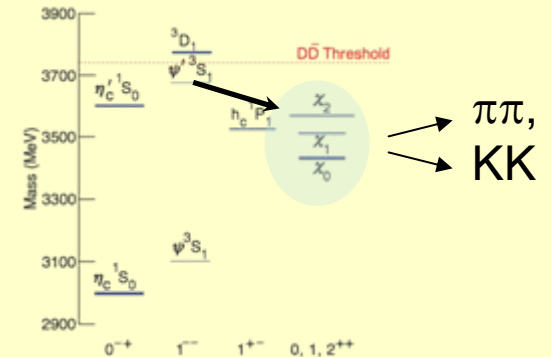
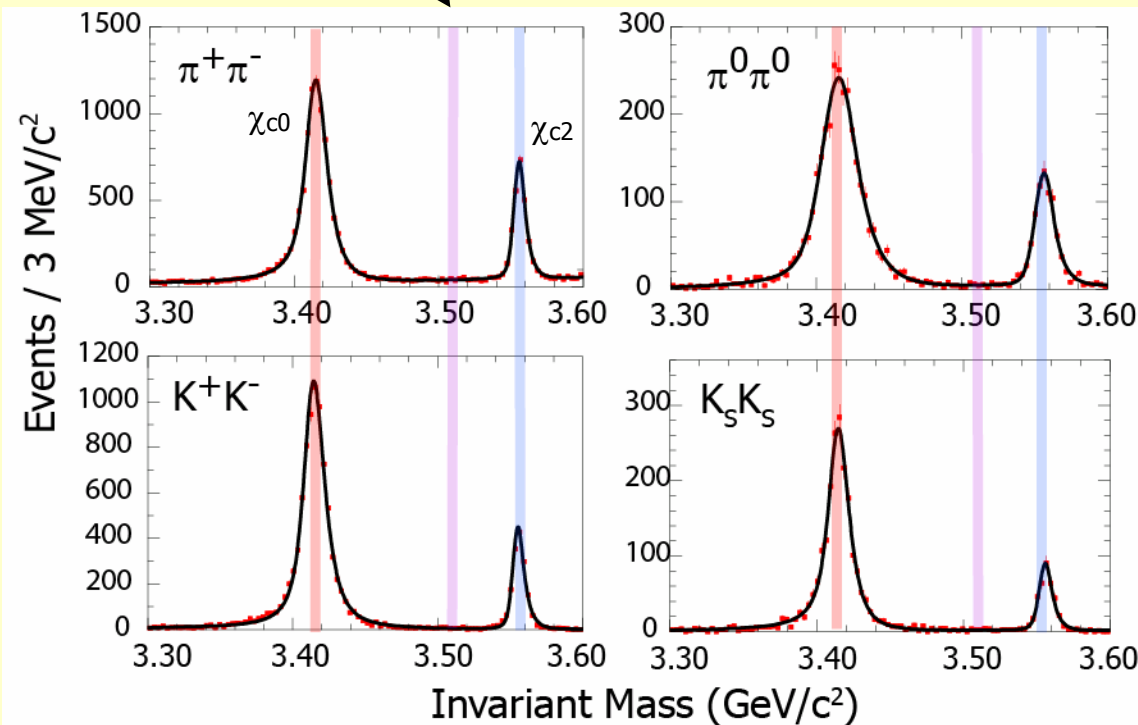


Analysis relies on identification of all decay products and kinematic fit to initial $\psi(2S)$ four-momentum.



$$\chi_{cJ} \rightarrow M\bar{M}, M=\pi, K$$

($\chi_{c1} \rightarrow PP$ is forbidden)



Previous measurements had uncertainties of 10% or larger

Clean signals seen in CLEO data

CLEO uncertainties $\leq 10\%$

$\chi_{cJ} \rightarrow M\bar{M}, M=\pi, K$

Branching Fraction Results: CLEO preliminary

BR (10^{-3})		$\pi^+\pi^-$	$\pi^0\pi^0$	K^+K^-	$K_S K_S$
χ_{c0}	PDG	4.9 ± 0.6	3.1 ± 0.6	6.0 ± 0.9	2.8 ± 0.7
	CLEO 27M (total error)	$6.37 \pm 0.11 \pm 0.20 \pm 0.32$ (6%)	$2.94 \pm 0.07 \pm 0.16 \pm 0.15$ (8%)	$6.47 \pm 0.11 \pm 0.29 \pm 0.32$ (7%)	$3.49 \pm 0.01 \pm 0.15 \pm 0.17$ (7%)
χ_{c2}	PDG	1.8 ± 0.3	1.1 ± 0.3	0.9 ± 0.2	0.7 ± 0.1
	CLEO 27M (total error)	$1.59 \pm 0.04 \pm 0.06 \pm 0.10$ (8%)	$0.68 \pm 0.03 \pm 0.05 \pm 0.04$ (10%)	$1.13 \pm 0.03 \pm 0.05 \pm 0.07$ (8%)	$0.53 \pm 0.03 \pm 0.02 \pm 0.03$ (7%)

Ratios:

	χ_{c0}	χ_{c2}
$K_S K_S / K^+ K^-$	0.54 ± 0.03 Belle: 0.49 ± 0.11	0.47 ± 0.05 Belle: 0.70 ± 0.24
$\pi^0 \pi^0 / \pi^+ \pi^-$	0.46 ± 0.05	0.43 ± 0.13
$K_S K_S / \pi^+ \pi^-$	0.55 ± 0.03 Belle: 0.46 ± 0.11	0.33 ± 0.03 Belle: 0.40 ± 0.12

Errors:
(stat.) $\pm$ (syst.) $\pm$ (BR($\psi' \rightarrow \gamma \chi_{cJ}$)) CLEO, PRD 70, 112002 (2004)

CLEO improves upon precision,
is consistent with Belle and
with isospin counting expectations
 $K_S K_S : K^+ K^- = 1:2$,
 $\pi^0 \pi^0 : \pi^+ \pi^- = 1:2$

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

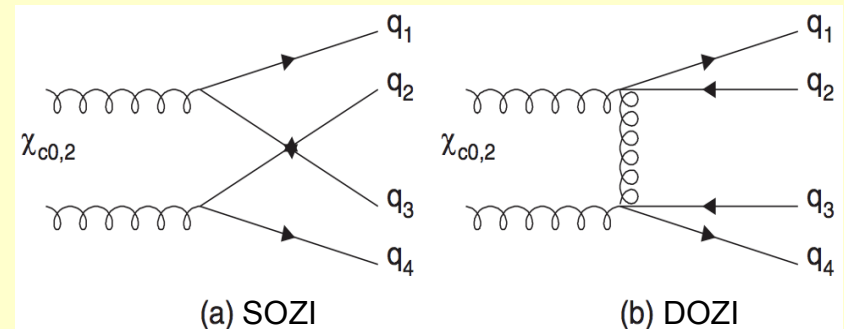
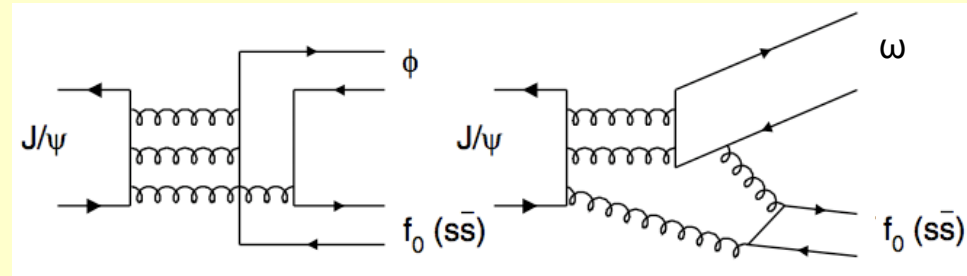
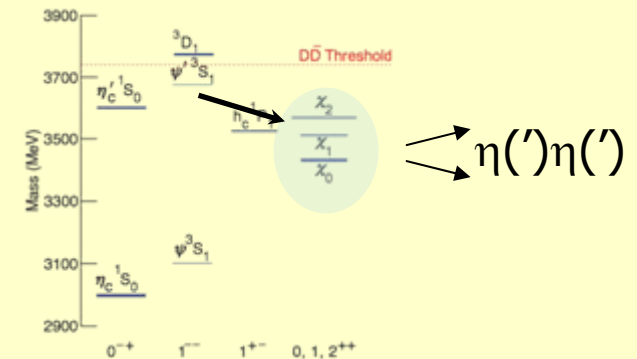
$B(J/\psi \rightarrow \omega f_0(1710)) \sim B(J/\psi \rightarrow \phi f_0(1710))$:
 $f_0(1710)$ is thought to be largely $s\bar{s}$
 $\Rightarrow$ naively expect ϕ preferred over ω

Suggestive of large OZI violating effects
in J/ψ decay?glueball mixing?
F. Close, Q. Zhao, PRD 71, 094022 (2005)

Look for similar effects in $\chi_c \rightarrow \eta^{(\prime)} \eta^{(\prime)}$

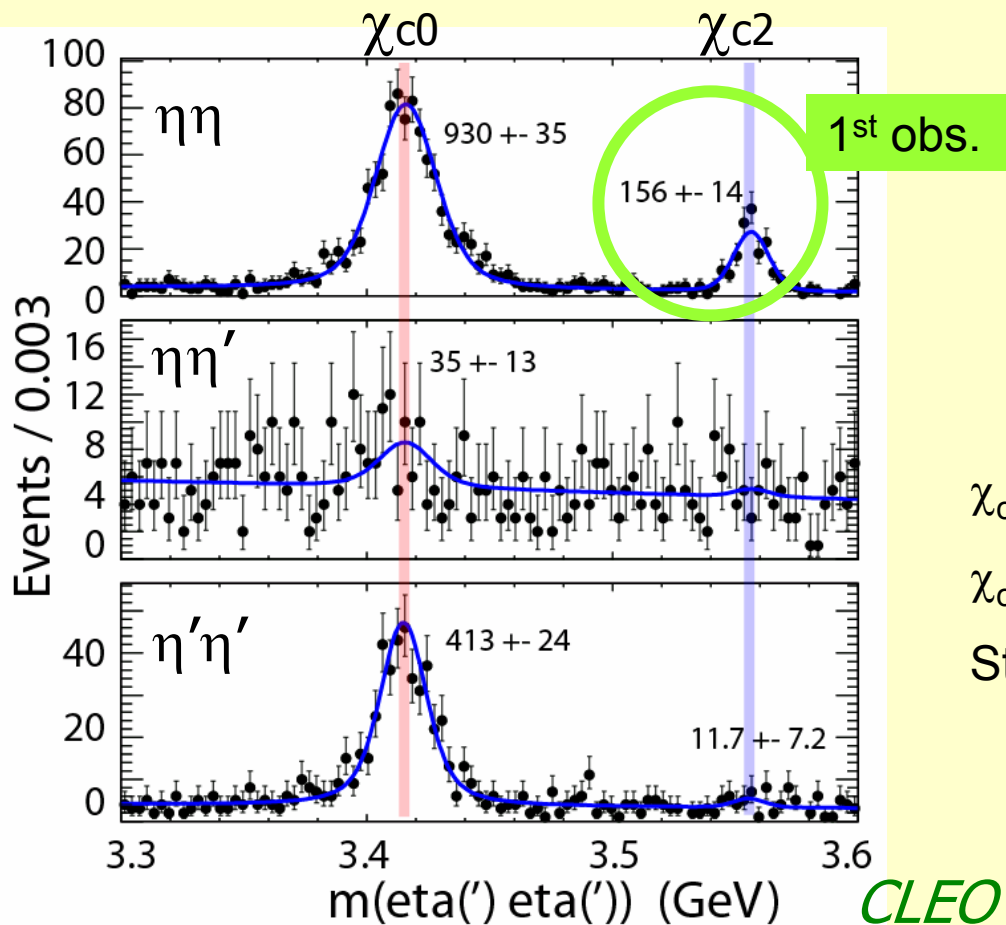
Use the factorization scheme proposed by
Q. Zhao (PRD 72, 074001 (2005))

$\eta\eta'$ can only go through DOZI,
 $\chi_{c1} \rightarrow PP$ is forbidden



r = relative strength between singly-OZI and doubly-OZI suppressed transition amplitudes

$\chi_{cJ} \rightarrow \eta^{(\prime)}\eta^{(\prime)}$ branching fractions



$\chi_{c0} \rightarrow \eta\eta$ and $\eta'\eta'$ improved
 $\chi_{c2} \rightarrow \eta\eta$ observed (1st time)
 Still no signal for $\eta\eta'$

CLEO, PRD 70, 112002

CLEO Preliminary

Errors: (stat.) $\pm$ (syst.) $\pm$ (B($\psi' \rightarrow \gamma\chi_{cJ}$))

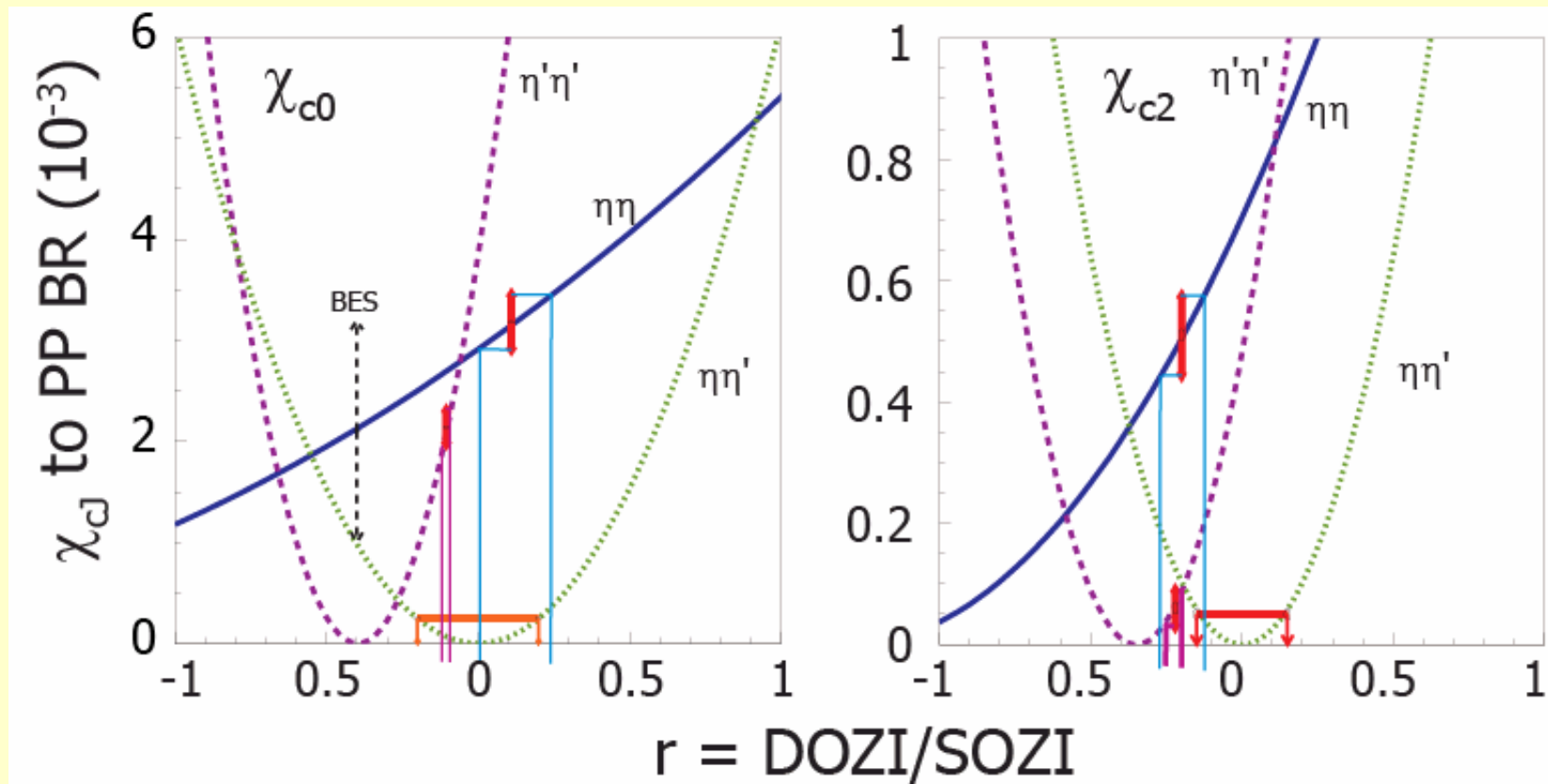
Uses similar analysis
technique as for
other two-body
modes

BR, 10 ⁻³	χ_{c0}	χ_{c2}
$\eta\eta$	3.18 $\pm$ 0.13 $\pm$ 0.18 $\pm$ 0.16	0.51 $\pm$ 0.05 $\pm$ 0.03 $\pm$ 0.03
$\eta'\eta$	<0.25 (90% CL)	<0.05 (90% CL)
$\eta'\eta'$	2.12 $\pm$ 0.13 $\pm$ 0.11 $\pm$ 0.11	< 0.10 (90%CL)

$\chi_{cJ} \rightarrow \eta^{(\prime)}\eta^{(\prime)}$, comparison with theory

Predicted dependence of BR on r (DOZI/SOZI)

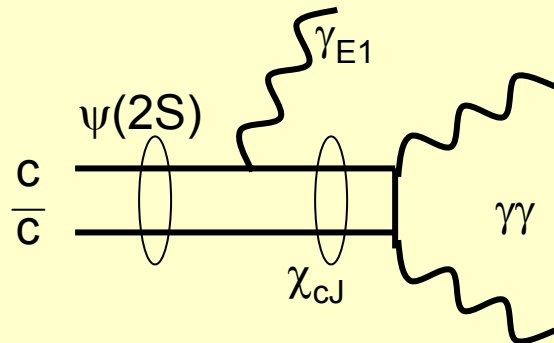
Q. Zhao (PRD 72, 074001) (2005)



CLEO Preliminary Results

Result: Data suggest small if any contribution for DOZI decays in 0^{++} channel.

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



$\chi_{cJ} \rightarrow \gamma\gamma$ is pure QED in first approximation

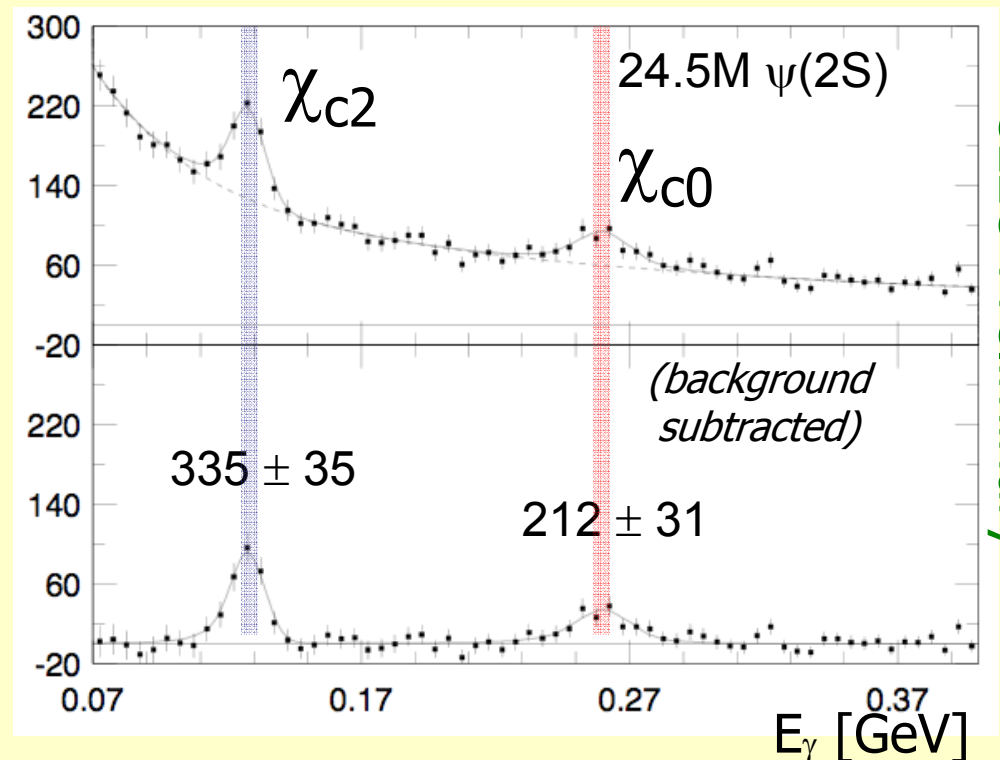
Decay rates $\Rightarrow$ relativistic and radiative corrections
(significant in the charmonium system!)

$\Gamma(\chi \rightarrow \gamma\gamma)$ measurements range from 2-4keV, with smallest error 0.6keV

Experimental technique similar to that for χ_{cJ} decays to 2 hadrons

Fit E1 photon or $m(\gamma\gamma)$ distribution after selecting $\chi_{cJ} \rightarrow \gamma\gamma$

Determine QED background shape from continuum and $\psi(3770)$ samples

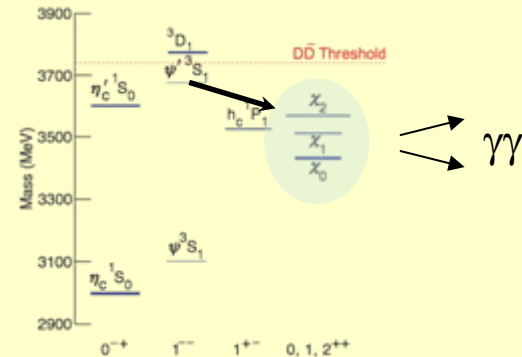


CLEO Preliminary

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

CLEO Preliminary Results

Errors: (stat.) $\pm$ (syst.) $\pm$ (PDG Input)



PDG
ave

Parameter	This measurement	PDG 2007
$B_1(\psi(2S) \rightarrow \gamma\chi_0) \times B_2(\chi_0 \rightarrow \gamma\gamma) \times 10^{-5}$	2.32$\pm$0.33$\pm$0.15	
$B_1(\psi(2S) \rightarrow \gamma\chi_2) \times B_2(\chi_2 \rightarrow \gamma\gamma) \times 10^{-5}$	2.82$\pm$0.29$\pm$0.21	
$B_2(\chi_0 \rightarrow \gamma\gamma) \times 10^{-4}$	2.52 $\pm$ 0.36 $\pm$ 0.16 $\pm$ 0.11	2.76 $\pm$ 0.33
$B_2(\chi_2 \rightarrow \gamma\gamma) \times 10^{-4}$	3.20 $\pm$ 0.33 $\pm$ 0.24 $\pm$ 0.18	2.58 $\pm$ 0.19
$\Gamma(\chi_0 \rightarrow \gamma\gamma) \text{ keV}$	2.65$\pm$0.38$\pm$0.17$\pm$0.25	2.87 $\pm$ 0.39
$\Gamma(\chi_2 \rightarrow \gamma\gamma) \text{ keV}$	0.62 $\pm$ 0.07 $\pm$ 0.05 $\pm$ 0.06	0.53 $\pm$ 0.05
$R = \Gamma(\chi_0 \rightarrow \gamma\gamma) / \Gamma(\chi_2 \rightarrow \gamma\gamma)$	0.235$\pm$0.042$\pm$0.005$\pm$0.030	0.184 $\pm$ 0.030

Also limit the forbidden process:

$$B(\chi_1 \rightarrow \gamma\gamma) < 3.6 \times 10^{-5}, \text{ 90\% CL.}$$

Most precise
measurement

In the non-
relativistic limit:
 $R = 4/15 = 0.27$

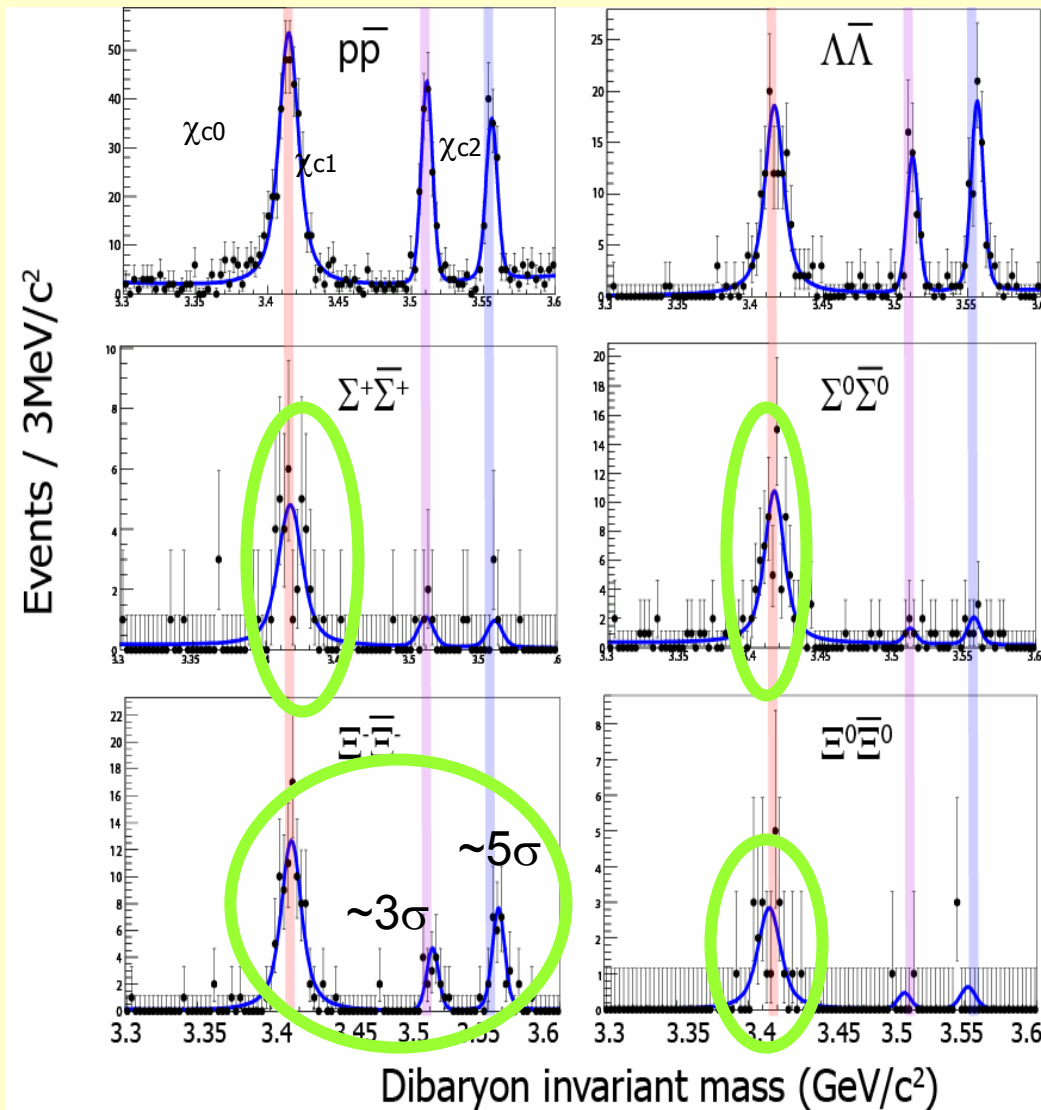
Two-photon widths – comparison with theory

* -- includes relativistic corrections

† -- includes radiative corrections

Author Year	α_s	$\Gamma(\chi_{c0} \rightarrow \gamma\gamma)$	$\Gamma(\chi_{c2} \rightarrow \gamma\gamma)$
Barbieri 1976	0.18	3.50	0.93
Bhaduri 1981	0.39	1.27	0.26
Godfrey 1985*	0.34	1.29	0.46
Barnes 1992*	0.4	1.56	0.56
Bodwin 1995	0.25	6.80 ± 1.90	0.82 ± 0.23
Resag 1995	0.365	1.62	0.60
Gupta 1996*†	0.316	6.38	0.57
Munz 1996*	0.365	1.39	0.44 ± 0.14
Huang 1996†	0.29	3.72 ± 1.11	0.49 ± 0.15
Schuler 1998		2.50	0.28
Fajfer 2000*		4.61	-
Ebert 2003*†	0.26	2.90	0.50
CLEO preliminary		2.65 ± 0.49	0.62 ± 0.10

$\chi_{cJ} \rightarrow$ baryon antibaryon



$\Lambda\bar{\Lambda}$: only direct production;
kin. fit weeds out $\Sigma^0 \rightarrow \Lambda\gamma$

$p\bar{p}$ and $\Lambda\bar{\Lambda}$ have been seen before;
puzzle over relative production rates:

Color Octet Model reproduces
 $p\bar{p}$ rates:

Extend to $\Lambda\bar{\Lambda}$ (J=1,2):
expect $\Lambda\bar{\Lambda}:p\bar{p} = 1:2$,
see $\Lambda\bar{\Lambda} \gg p\bar{p}$ for J=0,1,2
[BES PRD 67, 112001 \(2003\)](#)

$\chi_{cJ} \rightarrow$ other baryon pairs?

CLEO studied B=p, Λ , Σ , Ξ
[some new discoveries](#)

$\chi_{cJ} \rightarrow \text{baryon antibaryon}$

BR, 10^{-5} (UL at 90% CL): Errors: (stat.) $\pm$ (syst.) $\pm$ (BR($\psi' \rightarrow \gamma \chi_{cJ}$))

↓ CLEO, PRD 70,
112002 (2004)

CLEO preliminary

PDG CLEO	χ_{c0}	χ_{c1}	χ_{c2}
$\overline{p}p$	22.5 ± 2.7 $25.7 \pm 1.5 \pm 1.5 \pm 1.3$	7.2 ± 1.3 $9.0 \pm 0.8 \pm 0.4 \pm 0.5$	6.8 ± 0.7 $7.7 \pm 0.8 \pm 0.4 \pm 0.5$
$\overline{\Lambda}\Lambda$	47 ± 16 $33.8 \pm 3.6 \pm 2.3 \pm 1.7$	26 ± 12 $11.6 \pm 1.8 \pm 0.7 \pm 0.7$	34 ± 17 $17 \pm 2.2 \pm 1.1 \pm 1.1$
$\overline{\Sigma^0}\Sigma^0$	- $44.1 \pm 5.6 \pm 2.5 \pm 2.2$	- <4	- <6
$\overline{\Sigma^+}\Sigma^+$	- $32.5 \pm 5.7 \pm 4.9 \pm 1.7$	- <6	- <6
$\overline{\Xi^-}\Xi^-$	<103 $51.4 \pm 6.0 \pm 3.8 \pm 2.6$	<34 $8.6 \pm 2.2 \pm 0.6 \pm 0.5$	<37 $14.5 \pm 1.9 \pm 1.0 \pm 0.9$
$\overline{\Xi^0}\Xi^0$	- $33.4 \pm 7.0 \pm 3.2 \pm 1.7$	- <5	- <9

New and/or improved
branching fraction
measurements

Lambda production,
as seen by BES,
not found to be
suppressed relative
to protons

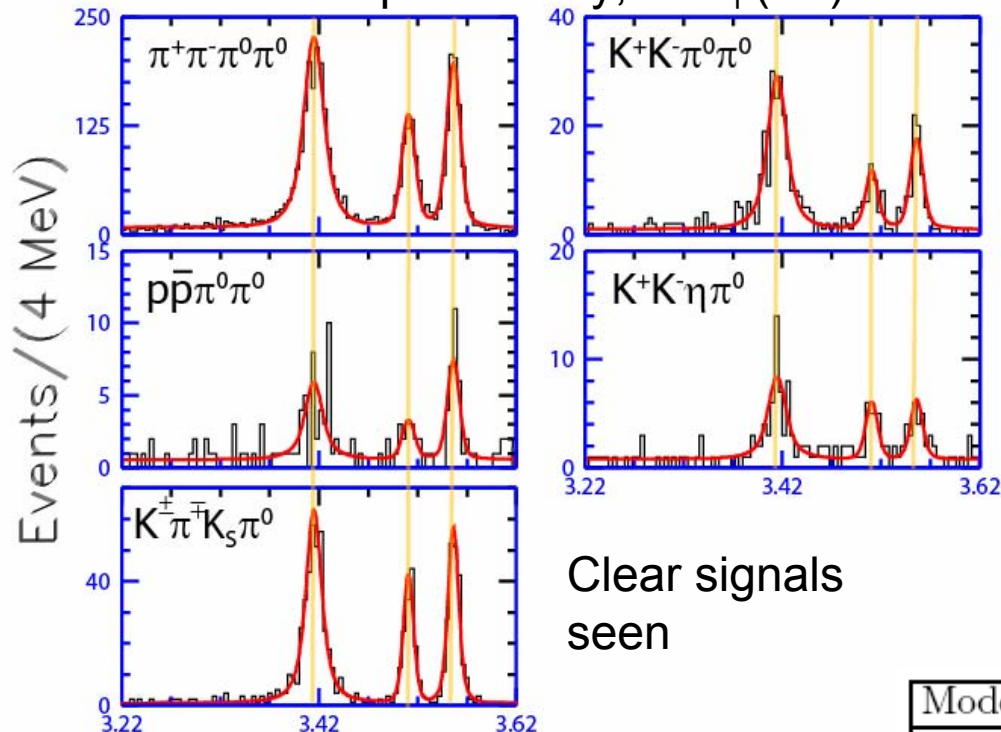
$$\mathcal{R}_B = \Gamma(\Lambda\Lambda)/\Gamma(p\overline{p})$$

(prediction only
for J=1,2)

χ_{c1}			χ_{c2}		
Theory	Exp. (BES)	CLEO-c	Theory	Exp. (BES)	CLEO-c
~0.6	4.6 ± 2.3	1.3 ± 0.3	~0.45	5.1 ± 3.1	2.2 ± 0.4

$$\chi_{cJ} \rightarrow h^+ h^- h^0 \pi^0$$

CLEO preliminary, 3M $\psi(2S)$



Clear signals
seen

$M(4\text{hadrons}) \text{ (GeV}/c^2\text{)}$

Survey of four-body decays

Resonant substructure is important for 4π and $KK\pi\pi$, ($\rho\pi\pi$ or $K^*K\pi$ or $KK\rho$ or ...)

Branching fractions and contributions from intermediate resonances determined

Isospin relations:

$$\rho^+\pi^-\pi^0 = \rho^0\pi^+\pi^- ? \quad \checkmark$$

$K^*K\pi$ modes: $\checkmark$

Expect
1:2

Mode	χ_{c0}	χ_{c1}	χ_{c2}
	B.F. (%)	B.F. (%)	B.F. (%)
$K^{*0} K^0 \pi^0$	0.56 ± 0.15	0.38 ± 0.11	0.59 ± 0.14
$K^{*0} K^\pm \pi^\mp$	-	-	0.90 ± 0.25
$K^{*\pm} K^\mp \pi^0$	0.74 ± 0.18	-	0.57 ± 0.13
$K^{*\pm} \pi^\mp K^0$	0.96 ± 0.25	-	0.90 ± 0.25

CLEO preliminary

$\chi_{cJ} \rightarrow h^+h^-\pi^0\pi^0$ branching fractions

CLEO preliminary, 3M $\psi(2S)$

TABLE IV: Branching fractions (B.F.) with statistical and systematic uncertainties are shown. The symbol “ $\times$ ” indicates product of B.F.’s. The third error in each case is due to the $\psi(2S) \rightarrow \gamma\chi_c$ branching fractions. Upper limits shown are at 90% C.L and include all the systematic errors. The measurements of the three-hadron final states are inclusive branching fractions, and do not represent the amplitudes for the three-body non-resonant decays.

Mode	χ_{c0}	χ_{c1}	χ_{c2}
	B.F.(%)	B.F.(%)	B.F.(%)
$\pi^+\pi^-\pi^0\pi^0$	$3.54 \pm 0.10 \pm 0.43 \pm 0.18$	$1.28 \pm 0.06 \pm 0.15 \pm 0.08$	$1.87 \pm 0.07 \pm 0.22 \pm 0.13$
$\rho^+\pi^-\pi^0$	$1.48 \pm 0.13 \pm 0.18 \pm 0.08$	$0.78 \pm 0.09 \pm 0.09 \pm 0.05$	$1.12 \pm 0.08 \pm 0.13 \pm 0.08$
$\rho^-\pi^+\pi^0$	$1.56 \pm 0.13 \pm 0.19 \pm 0.08$	$0.78 \pm 0.09 \pm 0.09 \pm 0.05$	$1.11 \pm 0.09 \pm 0.13 \pm 0.08$
$K^+K^-\pi^0\pi^0$	$0.59 \pm 0.05 \pm 0.08 \pm 0.03$	$0.12 \pm 0.02 \pm 0.02 \pm 0.01$	$0.21 \pm 0.03 \pm 0.03 \pm 0.01$
$p\bar{p}\pi^0\pi^0$	$0.11 \pm 0.02 \pm 0.02 \pm 0.01$	< 0.05	$0.08 \pm 0.02 \pm 0.01 \pm 0.01$
$K^+K^-\eta\pi^0$	$0.32 \pm 0.05 \pm 0.05 \pm 0.02$	$0.12 \pm 0.03 \pm 0.02 \pm 0.01$	$0.13 \pm 0.04 \pm 0.02 \pm 0.01$
$K^\pm\pi^\mp K^0\pi^0$	$2.64 \pm 0.15 \pm 0.31 \pm 0.14$	$0.92 \pm 0.09 \pm 0.11 \pm 0.06$	$1.41 \pm 0.10 \pm 0.16 \pm 0.10$
$K^{*0}K^0\pi^0 \times K^{*0} \rightarrow K^\pm\pi^\mp$	$0.37 \pm 0.09 \pm 0.04 \pm 0.02$	$0.25 \pm 0.06 \pm 0.03 \pm 0.02$	$0.39 \pm 0.07 \pm 0.05 \pm 0.03$
$K^{*0}K^\pm\pi^\mp \times K^{*0} \rightarrow K^0\pi^0$			$0.30 \pm 0.07 \pm 0.04 \pm 0.02$
$K^{*\pm}K^\mp\pi^0 \times K^{*\pm} \rightarrow \pi^\pm K^0$	$0.49 \pm 0.10 \pm 0.06 \pm 0.03$		$0.38 \pm 0.07 \pm 0.04 \pm 0.03$
$K^{*\pm}\pi^\mp K^0 \times K^{*\pm} \rightarrow K^\pm\pi^0$	$0.32 \pm 0.07 \pm 0.04 \pm 0.02$		$0.30 \pm 0.07 \pm 0.04 \pm 0.02$
$\rho^\pm K^\mp K^0$	$1.28 \pm 0.16 \pm 0.15 \pm 0.07$	$0.54 \pm 0.11 \pm 0.06 \pm 0.03$	$0.42 \pm 0.11 \pm 0.05 \pm 0.03$

Sum:

7.2%

2.4%

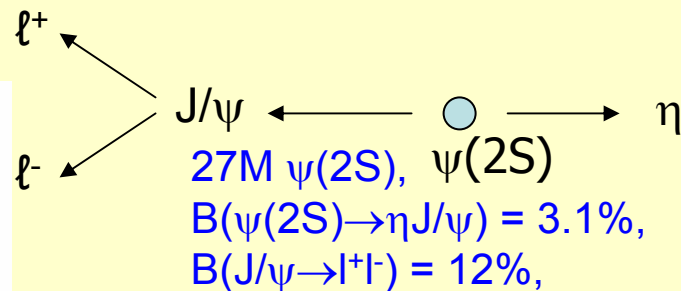
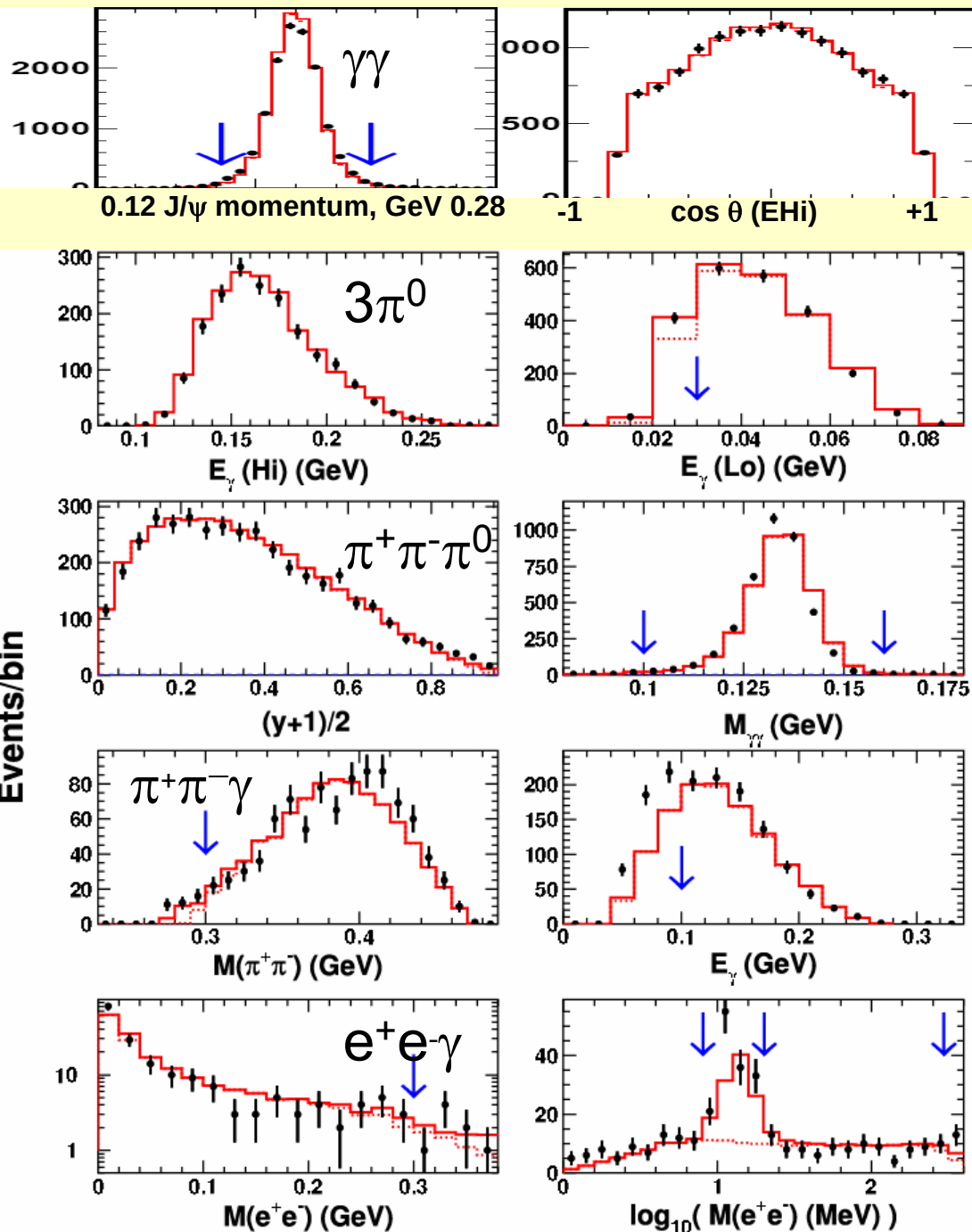
3.7%

Ties to lighter systems

η properties

Resonances observed in χ_{cJ}
multibody decays

η branching ratios



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%

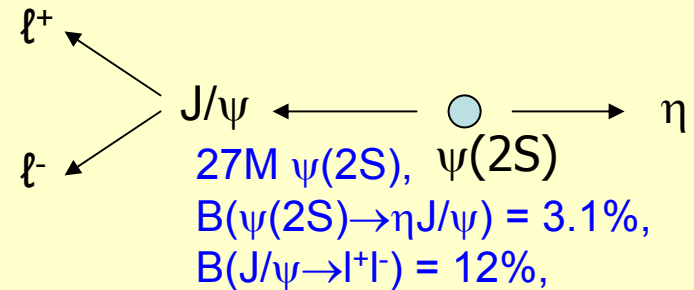
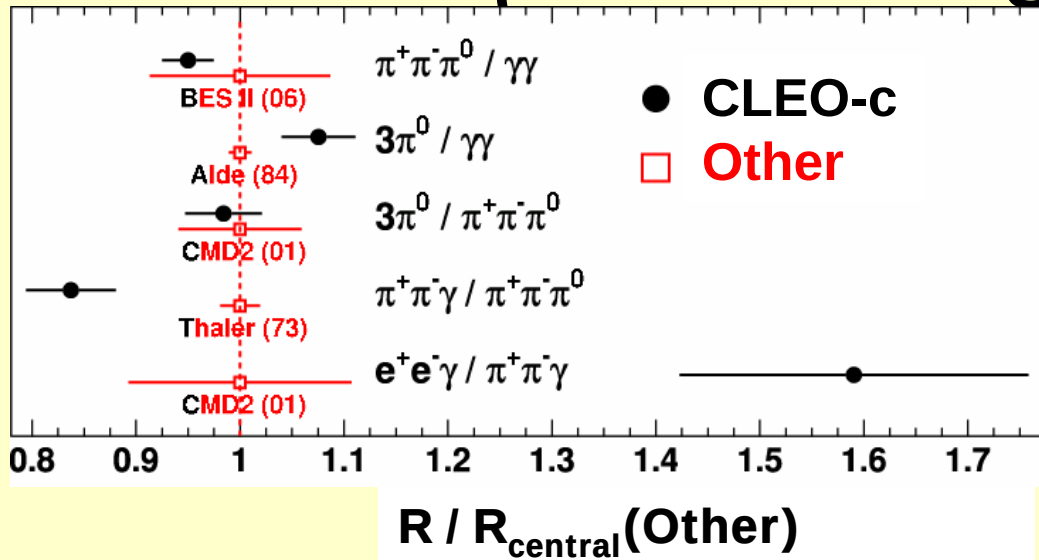
Constrain ℓ^+ , $\ell^- \Rightarrow J/\psi$,
 constrain J/ψ , η products $\Rightarrow \psi(2S)$

Excellent data/MC agreement

Measurement of ratios allow
 cancellation of systematics



η branching fractions



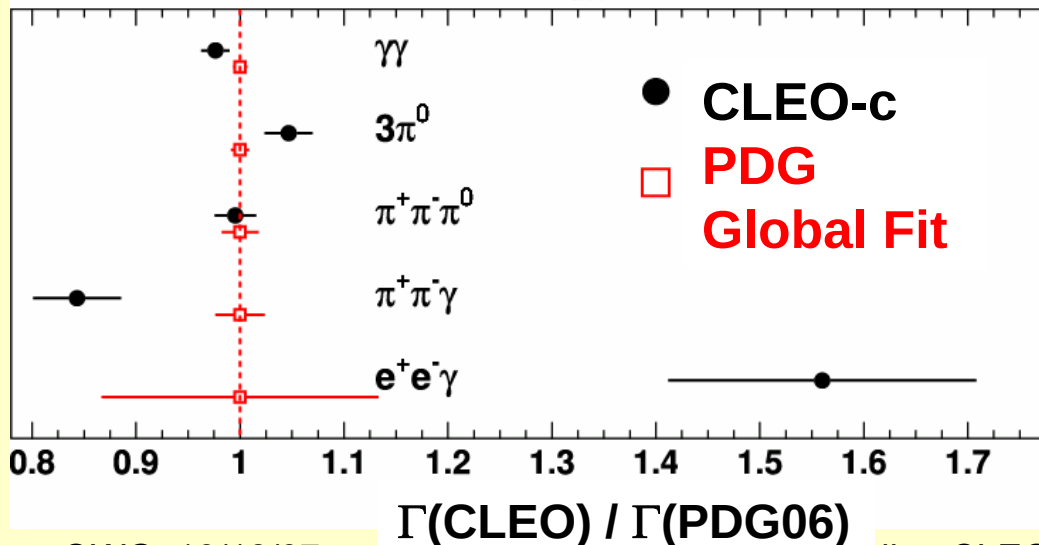
Fully reconstruct five final states:

$\gamma\gamma + 3\pi^0 + \pi^+\pi^-\pi^0 + \pi^+\pi^-\gamma + e^+e^-\gamma$
 38.5 34.0 22.6 4.0 0.9%

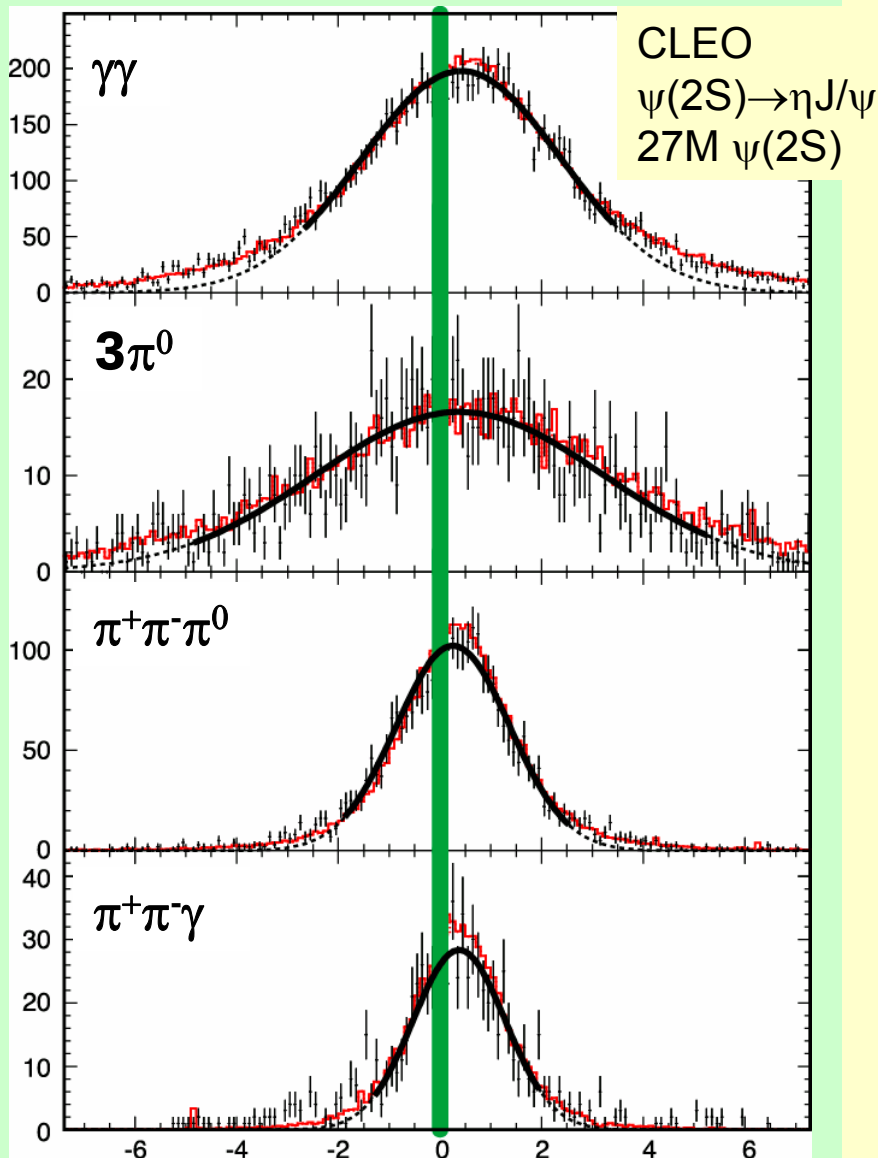
Follow PDG procedure: sum of the above five modes is $\sim 100\%$
 $\Rightarrow$ build absolute Br's from ratios

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

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



Invariant mass of η decay products:



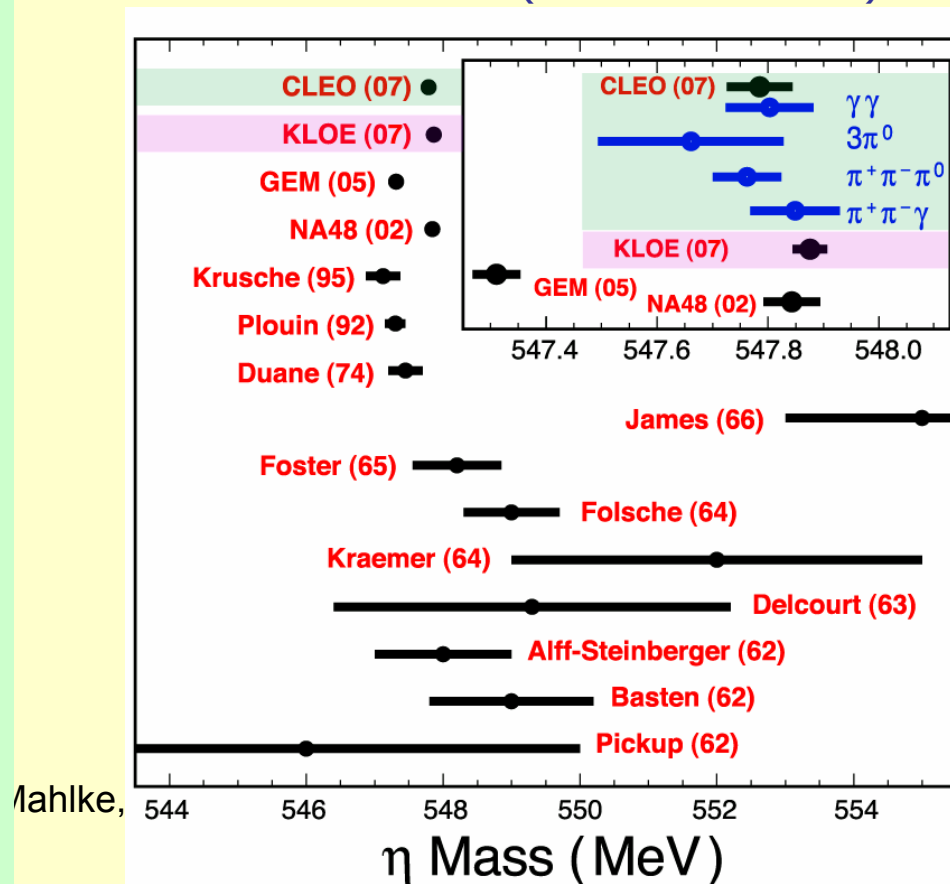
$M(\text{CLEO}) - M(\text{PDG06}) \text{ (MeV)}$

16k fully reconstructed events

η Mass

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

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

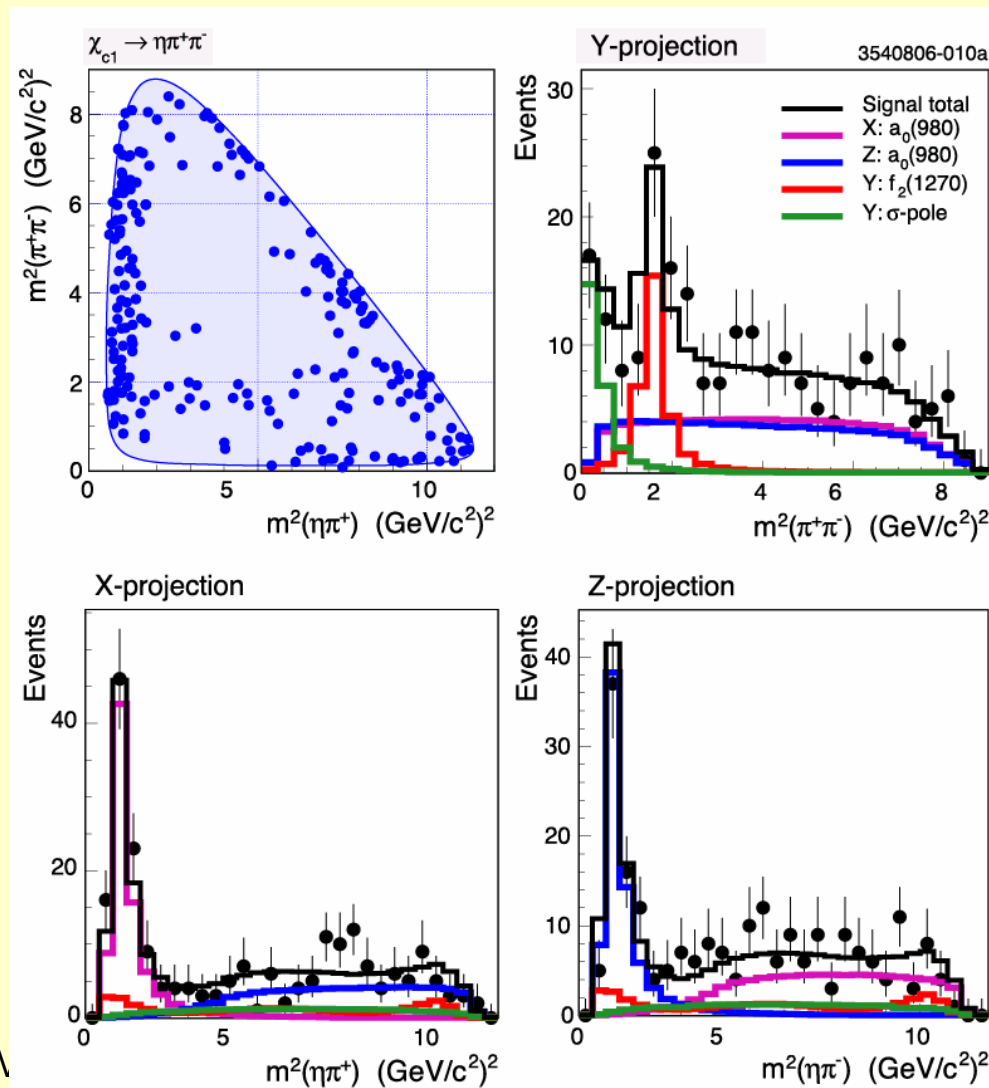


χ_{cJ} multibody decays

3M psi(2S)

Interest:

- Branching fractions
 - Likely a lot
 - Substructure analysis
 - CLEO studied $h^+h^-h^0$ in 3M decays, sufficient events for simple Dalitz analysis in $\eta\pi^+\pi^-$, $K^+K^-\pi^0$, and $K^-K_S^0\pi^+$ - model describes dominant features, but ignores interference – 20% systematic uncertainty
 - $h^+h^-h^0\pi^0$ also looked promising
- Enlarged data sample will allow to refine technique and to study other multibody modes

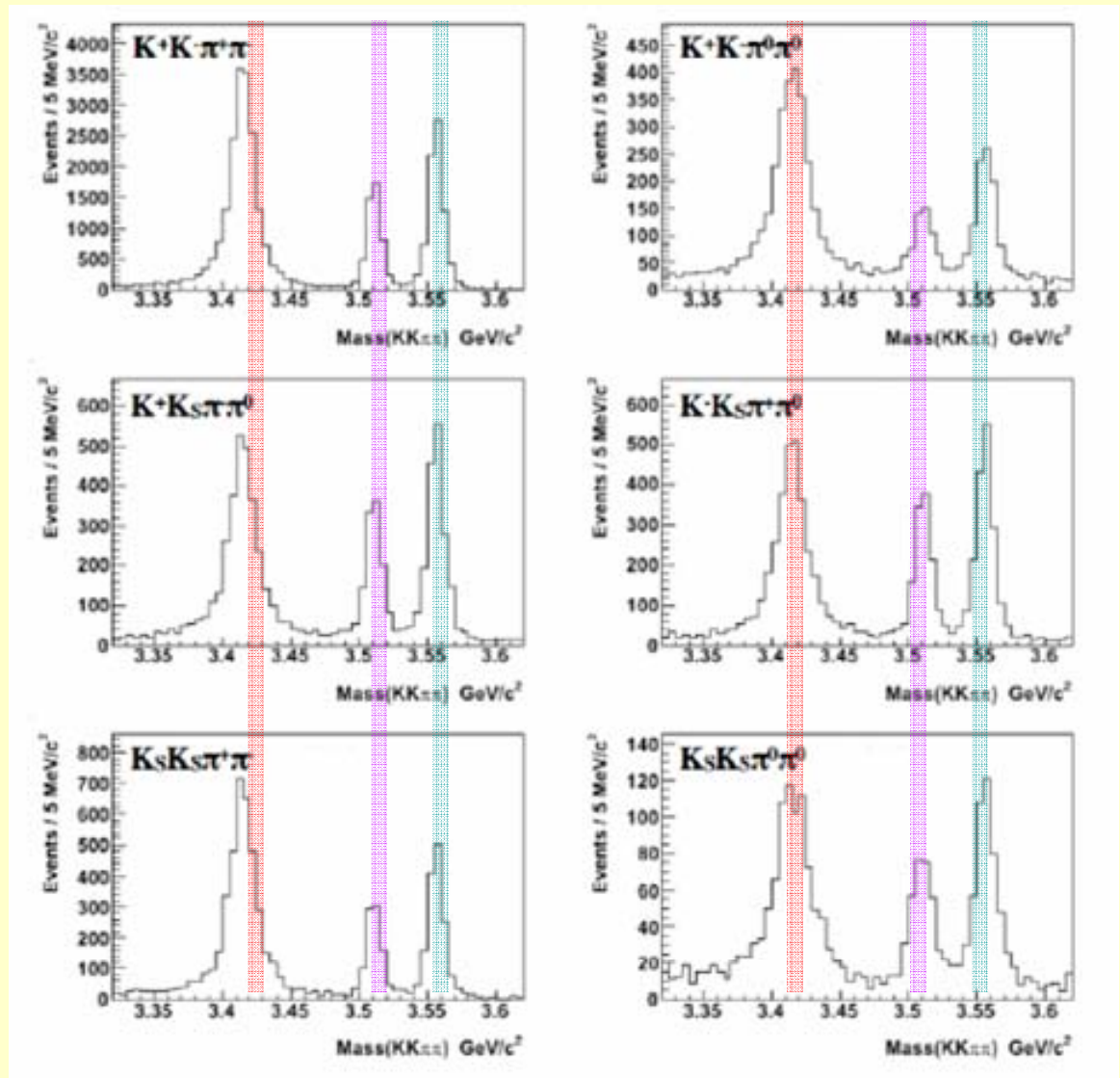


$$\chi_{cJ} \rightarrow KK\pi\pi$$

27M $\psi(2S)$ - first look...

Can study
charged and neutral
pion and kaon
combinations

χ_{cJ} decays to
all combinations from
all three J states
visible,
well separated



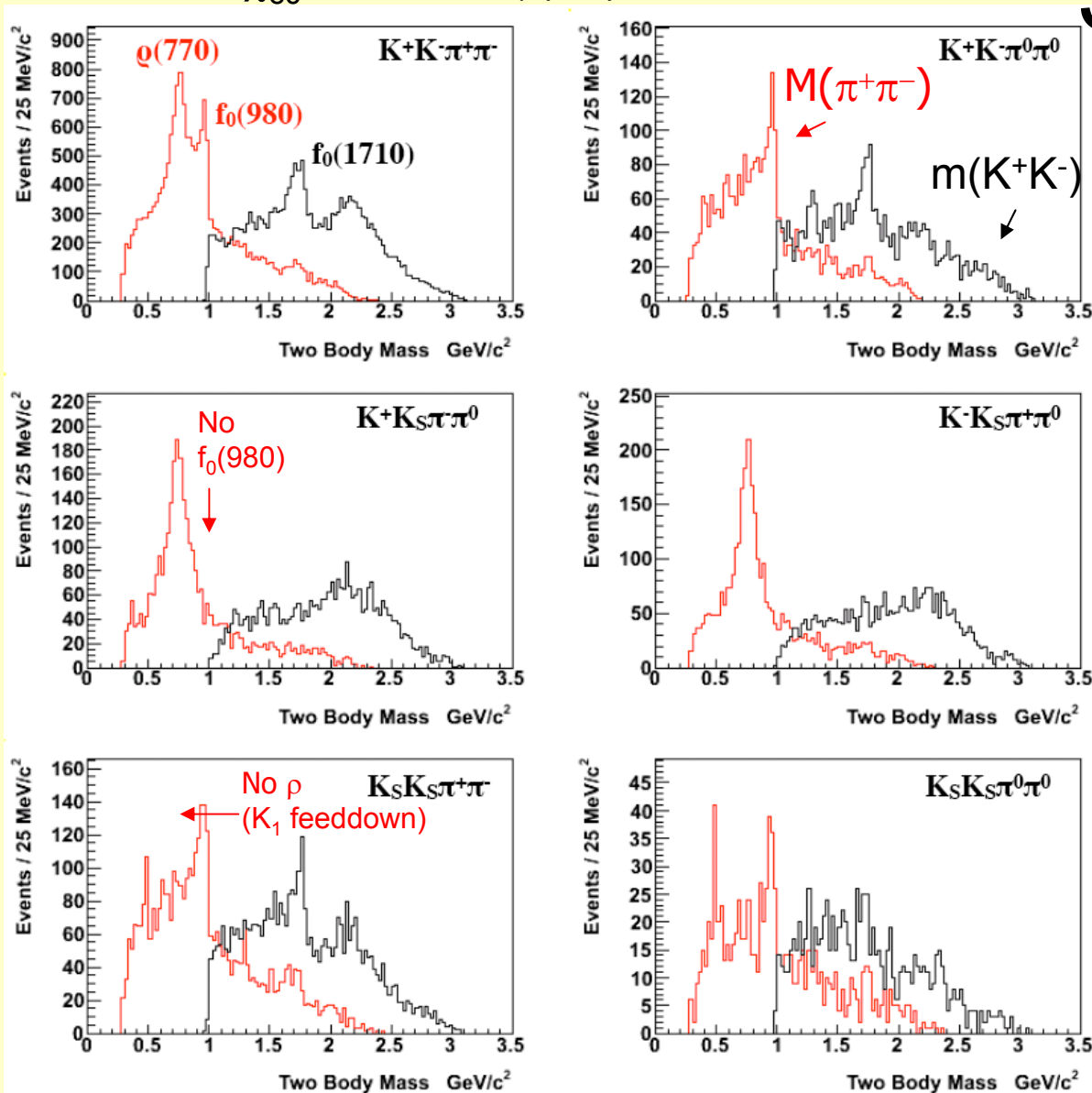
χ_{c0} from 27M $\psi(2S)$ - first look...

Substructure: KK and $\pi\pi$

χ_{c0}

Complementary
and different
structure in six
KK $\pi\pi$ submodes

Looking at
different isospin
configurations
allows to
disentangle
components



Summary

- Charmonium is a testing ground for many areas of QCD:
 - Spectroscopy of charmonium states
 - Decay of charmonium states
 - Production of lighter systems
- New results cascading down on the community
 - need to sort, digest, understand (exp + th!)
- At today's data sample sizes, sensitive to small effects $\Rightarrow$ discovery and precision studies
- CLEO's 27M $\psi(2S)$ dataset will lay the foundation for future BES studies



Backups

chicJ
information:
pion and
kaon
samples
combined

