CLEO Charmonium Results

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The Landscape

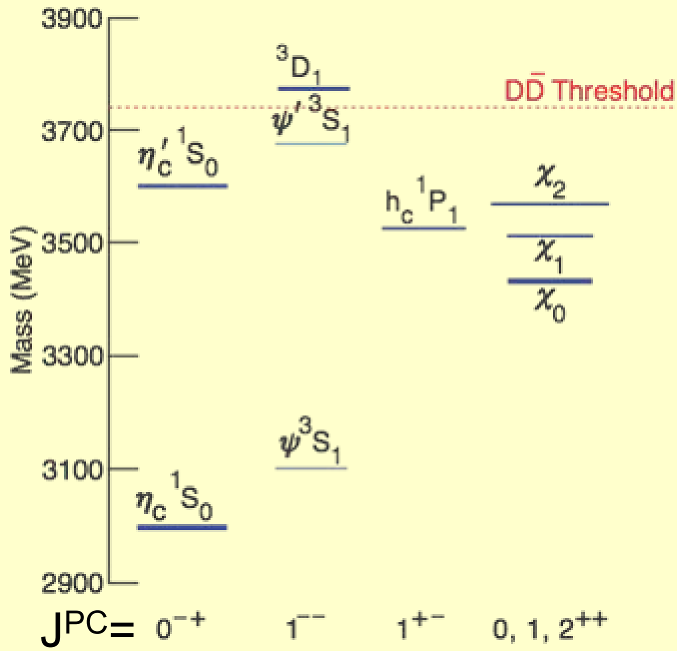
- All states below $D\bar{D}$ threshold observed
- **1--** states known best, large samples

  ψ(2S): 14M BES,
  27M CLEO

  J/ψ:

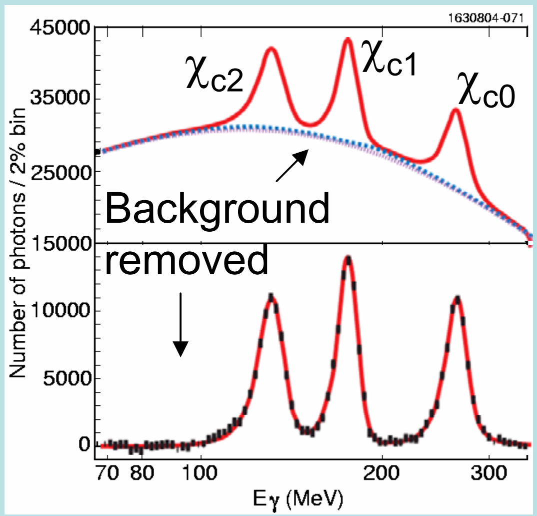
  * on-resonance – 58M BES,
  * from $\psi(2S)\to\pi^+\pi^- J/\psi$ decay:
  BR ~32%, can tag the transition pions (CLEO: ε_{tag} =75%⇒ 6.5M tagged J/ψ)

  – Era of precision studies and discovery of rare phenomena in 1-- decay
- $B(\psi(2S)\to\gamma\chi_{cJ})$~9%, E(γ) 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



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

CLEO
1.5M ψ(2S)



New CLEO charmonium results discussed in other presentations:

- $\psi(2S) \to \gamma\, \eta_c(1S)$:
  - Exclusive and inclusive $\eta_c(1S)$ decays
  - $\eta_c(1S)$ line shape
  - $BR(\psi(2S) \to \gamma\, \eta_c(1S))$

➢ Ryan Mitchell's talk (Wednesday)

- $\psi(2S) \to \pi^0 h_c$, $h_c \to \gamma\eta_c(1S)$:
  - Exclusive and inclusive $\eta_c(1S)$ decays
  - $M(h_c)$ and hyperfine splitting
  - Product branching fraction $BR(\psi(2S) \to \pi^0 h_c) \times BR(h_c \to \gamma\eta_c(1S))$

➢ Kam Seth's talk (Friday)

χ_{cJ} Decays to…

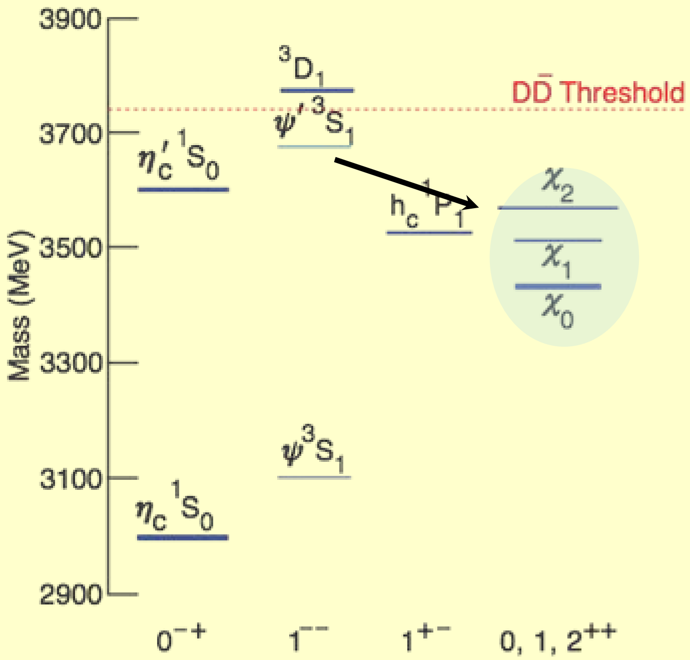
… $\gamma\gamma$

… $\pi\pi$, KK

…$\eta(')\eta(')$

…baryon/anti-baryon

… multibody final states



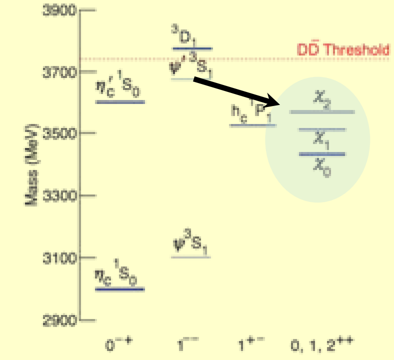
Detailed comparisons between decay modes allow to assess the role of the color octet configuration

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

Can probe exclusive decays down to BR ~10^{-4}

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

$\chi_{cJ} \rightarrow$ 2 hadrons



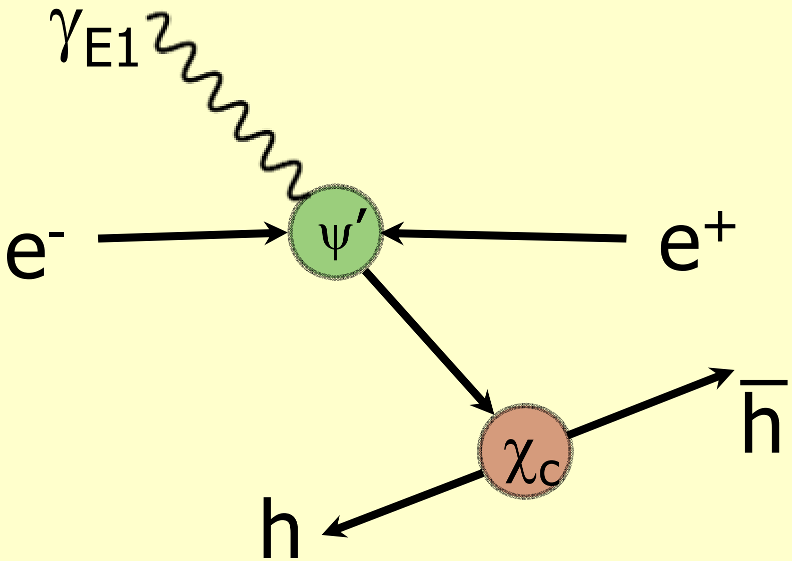
- Glue-rich environment – different from 1^- states
- "$|\chi_{cJ}\rangle = |c\bar{c}\rangle$" $\Rightarrow$ many theory predictions « experimental BR results
- Accurate prediction of 2-hadron decay rates of ^3P_J states rely on understanding of the role of the color octet contribution:

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

"Is that all?"

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

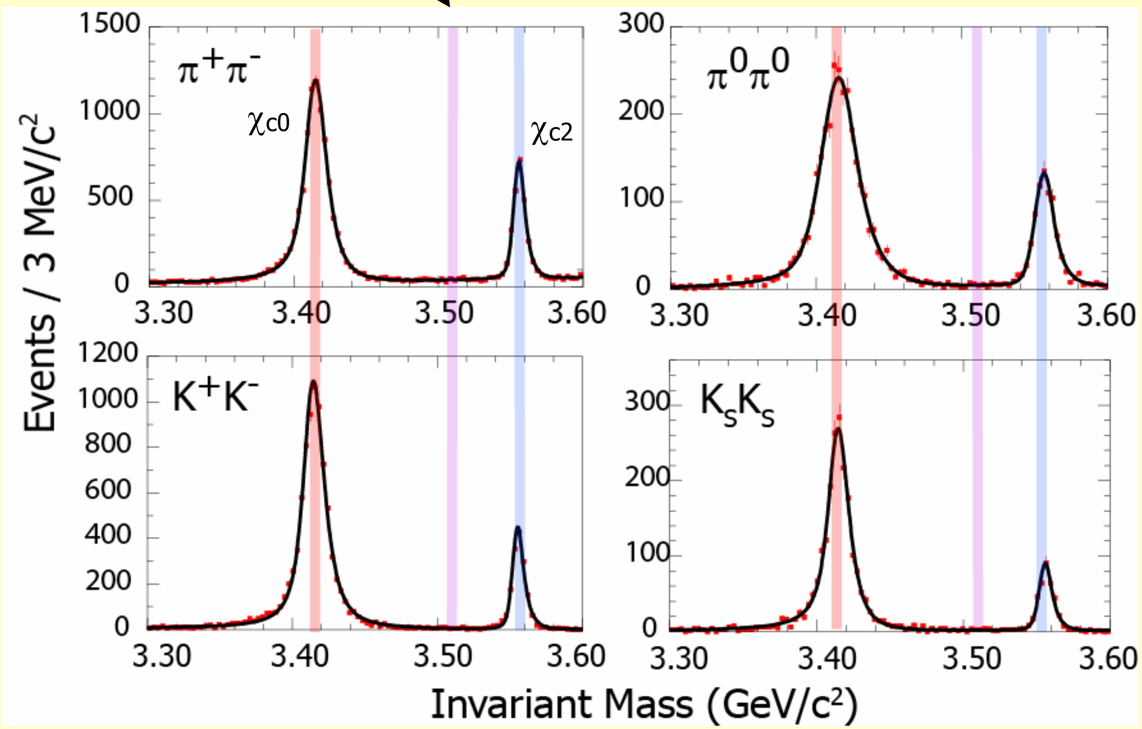
Analysis relies on identification of all decay products and kinematic fit to initial $\psi(2S)$ four-momentum.

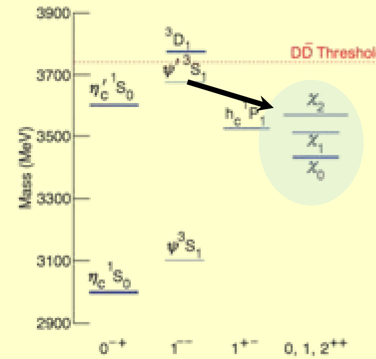


Next: 14 two-body decay modes of χ_{cJ}
(13x hadronic + $\gamma\gamma$)

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

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





Previous measurements had uncertainties of 10% or larger

Clean signals seen in CLEO data

CLEO uncertainties <=10%

$\chi_{cJ} \to M\bar{M}$, M=π,K

Branching Fraction Results: CLEO preliminary

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

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

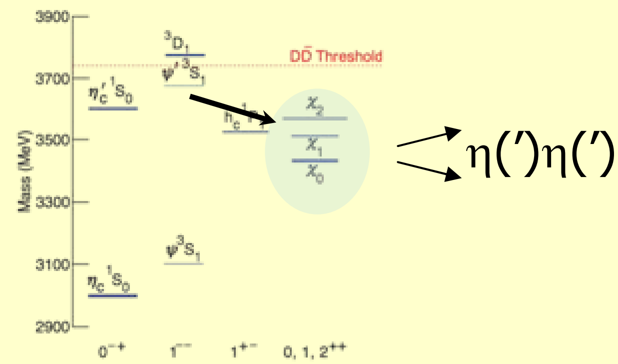
Ratios:

	χ_{c0}	χ_{c2}
K_sK_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
$K_sK_s/\pi^+\pi^-$	0.55±0.03 Belle: 0.46±0.11	0.33±0.03 Belle: 0.40±0.12

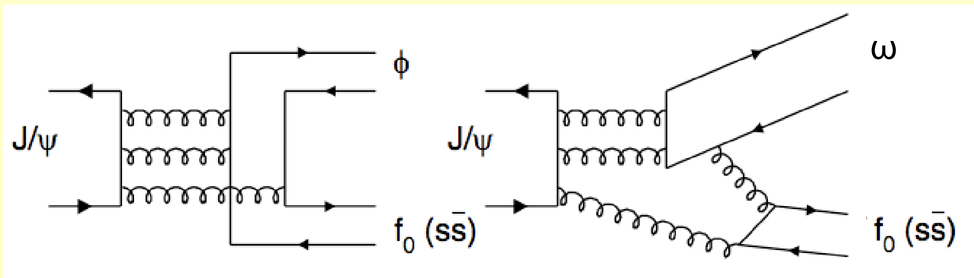
Belle PLB 651, 15 (2007)

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

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



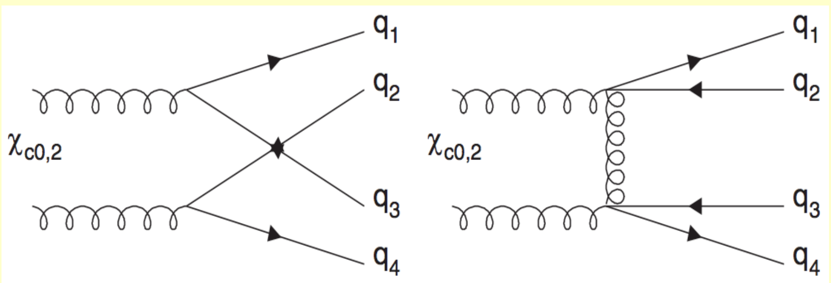
B(J/ψ→ωf₀(1710)) ~ B(J/ψ→φf₀(1710)):
f₀(1710) is thought to be largely $s\bar{s}$
⇒ naively expect φ preferred over ω



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 $\chi_c \rightarrow \eta(')\eta(')$

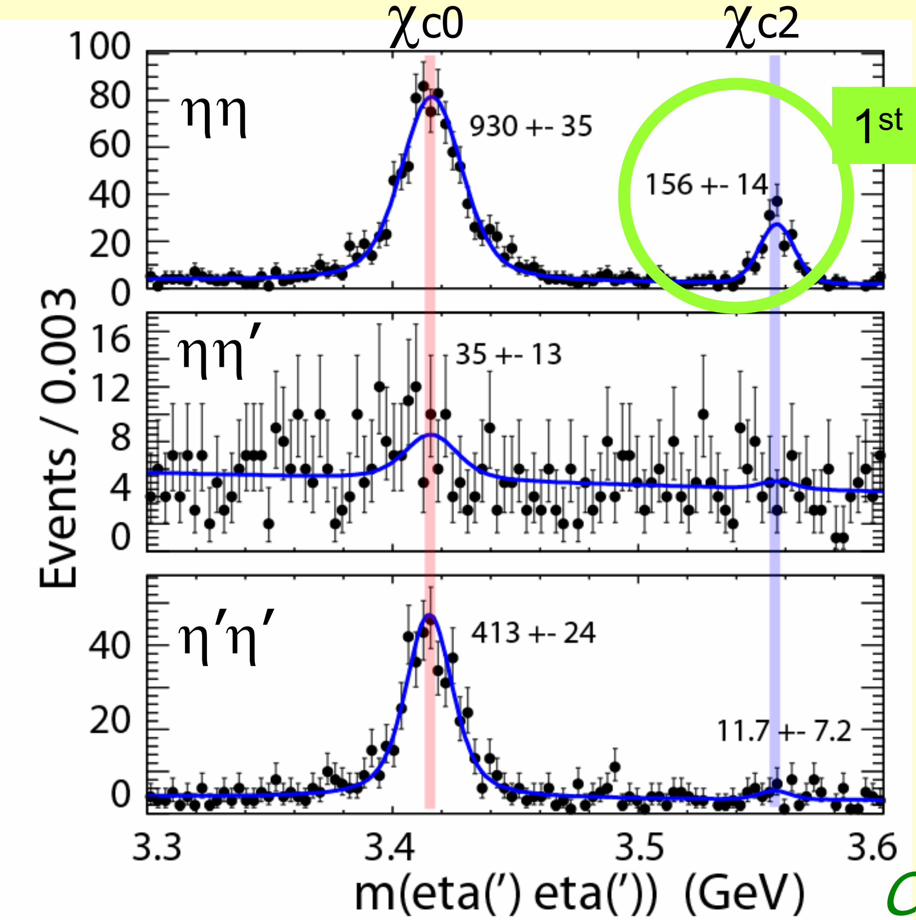
Use the factorization scheme proposed by Q. Zhao (PRD 72, 074001 (2005))



(a) SOZI (b) DOZI

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

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



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

$\chi_{c0} \to \eta\eta$ and $\eta'\eta'$ improved

$\chi_{c2} \to \eta\eta$ observed (1st time)

Still no signal for $\eta\eta'$

CLEO, PRD 70, 112002

CLEO Preliminary

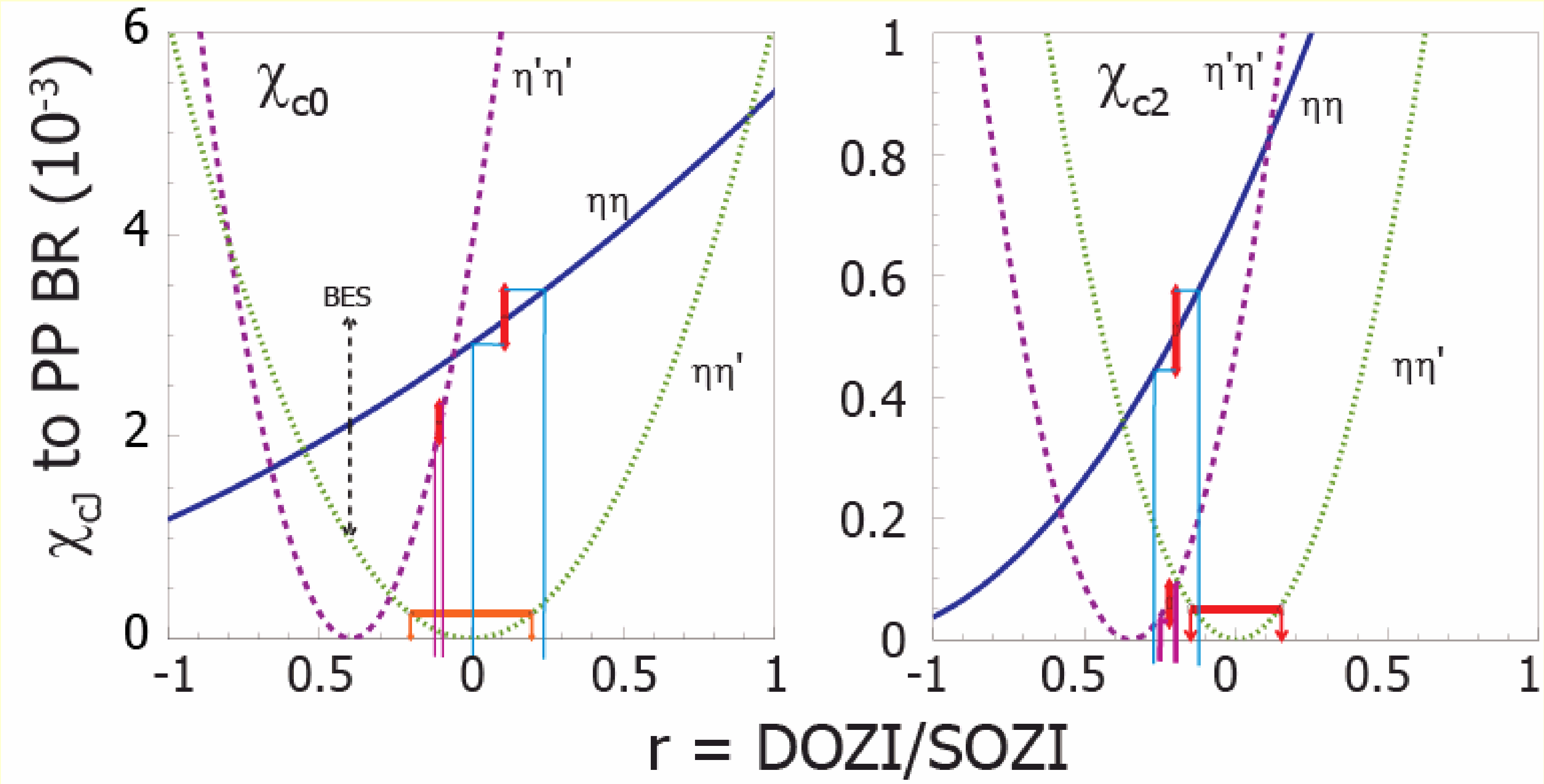
Errors: (stat.) ± (syst.) ± ($B(\psi' \to \gamma\chi_{cJ})$)

Uses similar analysis technique as for other two-body modes

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

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

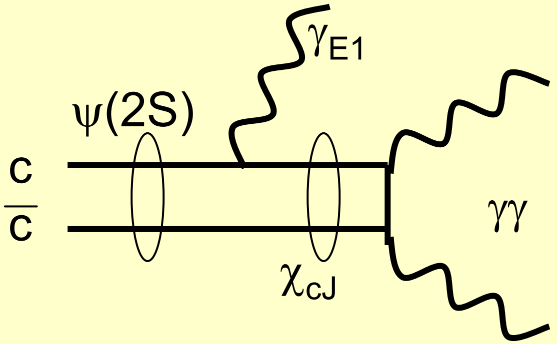
Predicted dependence of BR on r (DOZI/SOZI)
Q. Zhao (PRD 72, 074001) (2005)



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

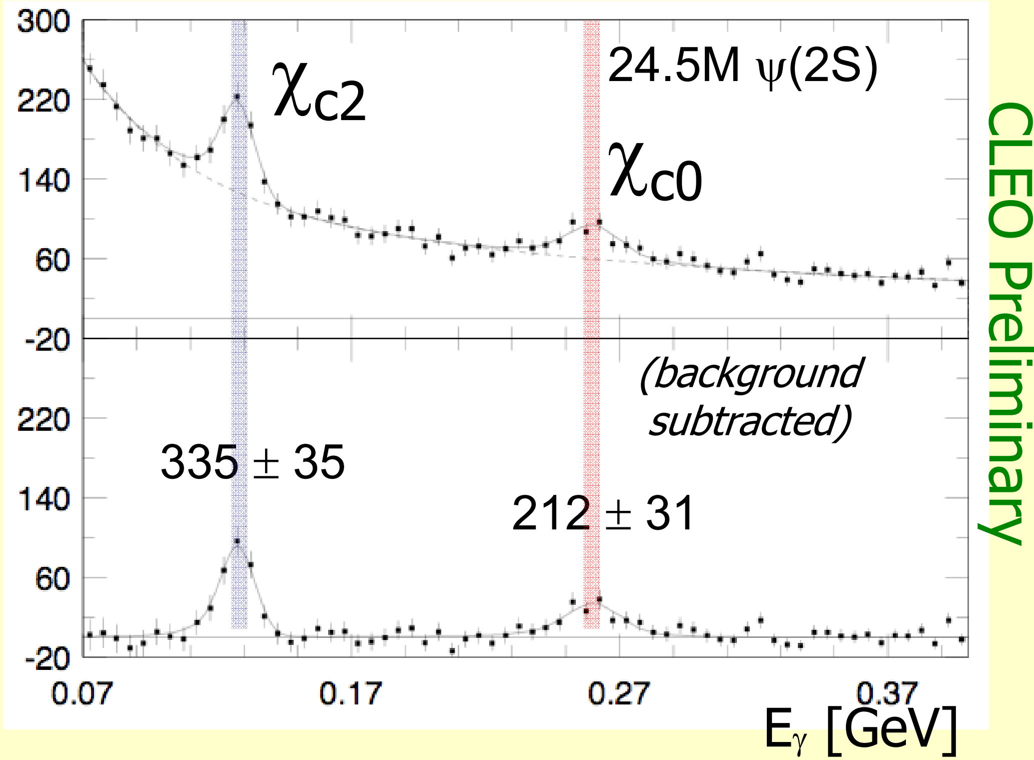
Decay rates $\Rightarrow$ relativistic and radiative corrections (significant in the charmonium system!)

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

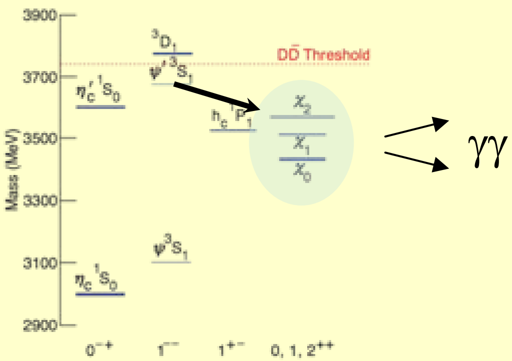
Experimental technique similar to that for χ_{cJ} decays to 2 hadrons

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



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



CLEO Preliminary Results

Errors: (stat.) ± (syst.) ± (PDG Input)

PDG ave

Parameter	This measurement	PDG 2007
$B_1(\psi(2S)\rightarrow\gamma\chi_0)\times B_2(\chi_0\rightarrow\gamma\gamma)\times10^{-5}$	**2.32±0.33±0.15**	
$B_1(\psi(2S)\rightarrow\gamma\chi_2)\times B_2(\chi_2\rightarrow\gamma\gamma)\times10^{-5}$	**2.82±0.29±0.21**	
$B_2(\chi_0\rightarrow\gamma\gamma)\times10^{-4}$	**2.52±0.36±0.16±0.11**	2.76±0.33
$B_2(\chi_2\rightarrow\gamma\gamma)\times10^{-4}$	**3.20±0.33±0.24±0.18**	2.58±0.19
$\Gamma(\chi_0\rightarrow\gamma\gamma)$ keV	**2.65±0.38±0.17±0.25**	2.87±0.39
$\Gamma(\chi_2\rightarrow\gamma\gamma)$ keV	**0.62±0.07±0.05±0.06**	0.53±0.05
$R=\Gamma(\chi_0\rightarrow\gamma\gamma)/\Gamma(\chi_2\rightarrow\gamma\gamma)$	**0.235±0.042±0.005±0.030**	0.184±0.030

Most precise measurement

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

Also limit the forbidden process:

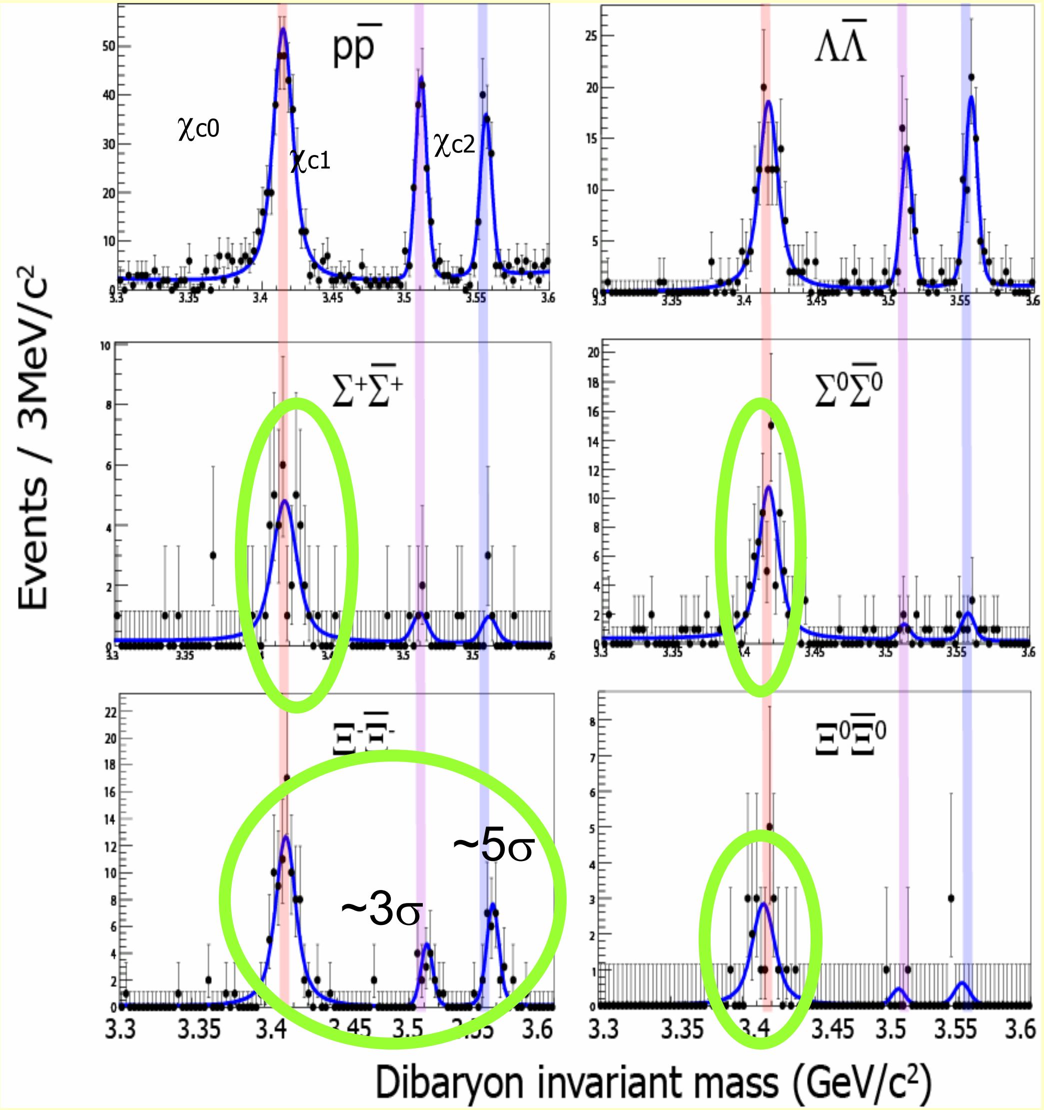
$B(\chi_1\rightarrow\gamma\gamma) < 3.6\times10^{-5}$, 90% CL.

Two-photon widths – comparison with theory

* -- includes relativistic corrections
† -- includes radiative corrections

Author Year	α_s	$\Gamma(\chi_{c0} \to \gamma\gamma)$	$\Gamma(\chi_{c2} \to \gamma\gamma)$
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 $\Lambda\bar{\Lambda}$»$p\bar{p}$ forJ=0,1,2
BES PRD 67, 112001 (2003)

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

CLEO studied B=p,Λ,Σ,Ξ
some new discoveries

$\chi_{cJ} \rightarrow$ baryon antibaryon

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

↓ CLEO, PRD 70, 112002 (2004)

CLEO preliminary

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

New and/or improved branching fraction measurements

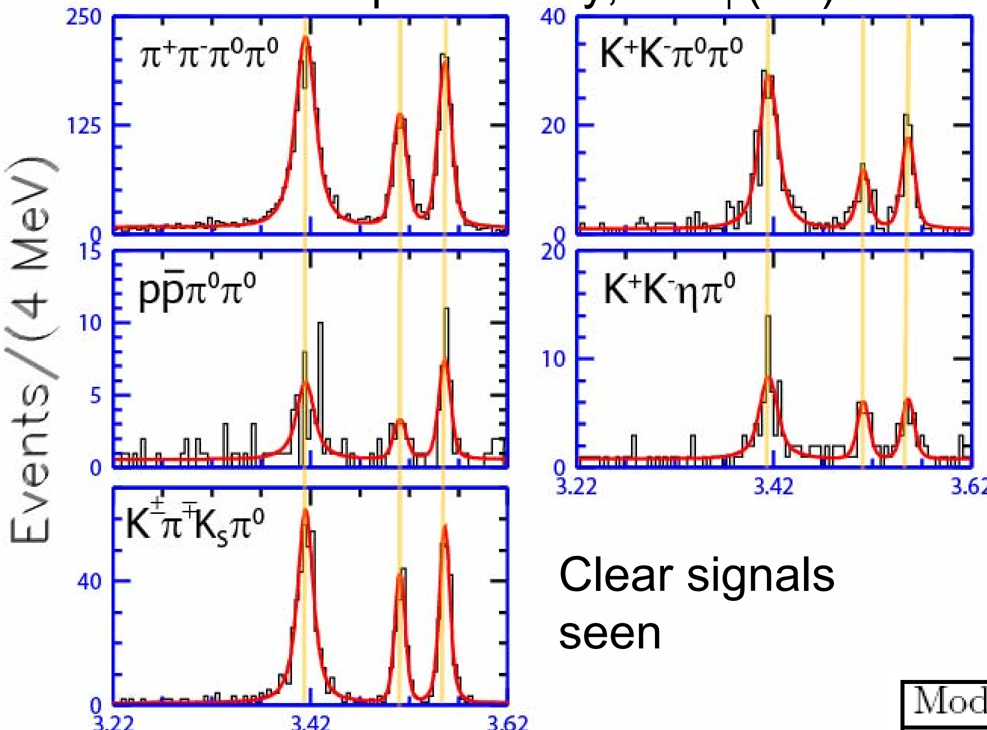
Lambda production, as seen by BES, not found to be suppressed relative to protons

(prediction only for J=1,2)

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

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

CLEO preliminary, 3M ψ(2S)



Clear signals seen

M(4hadrons) (GeV/c^2)

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:

$\rho^+\pi^-\pi^0 = \rho^0\pi^+\pi^-$? ✓

$K^*K\pi$ modes: ✓

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

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

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

TABLE IV: Branching fractions (B.F.) with statistical and systematic uncertainties are shown. The symbol "×" indicates product of B.F.'s. The third error in each case is due to the $\psi(2S) \to \gamma\chi_c$ 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.

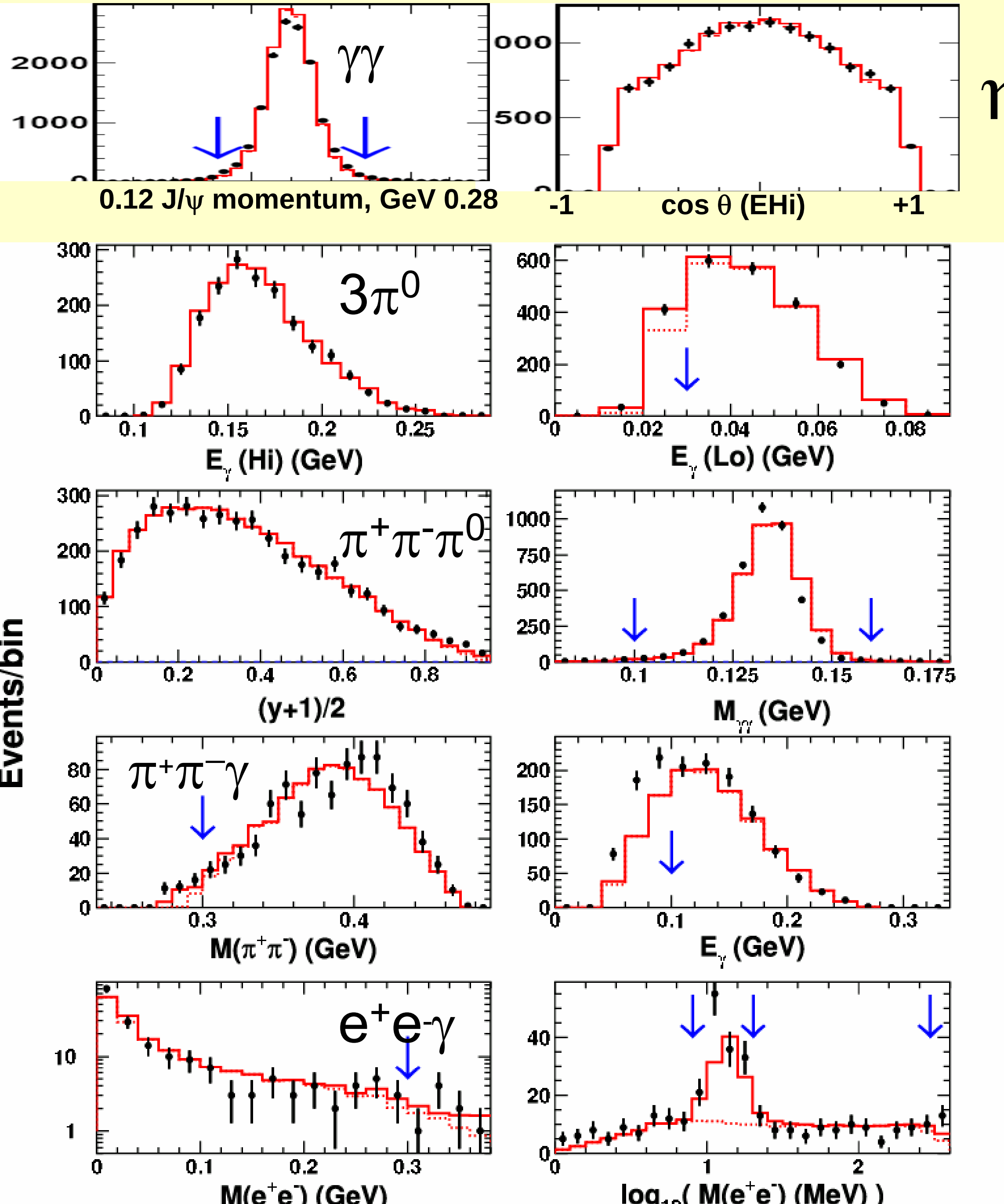
Mode	χ_{c0}	χ_{c1}	χ_{c2}
	B.F.(%)	B.F.(%)	B.F.(%)
$\pi^+\pi^-\pi^0\pi^0$	3.54±0.10±0.43±0.18	1.28±0.06±0.15±0.08	1.87±0.07±0.22±0.13
$\rho^+\pi^-\pi^0$	1.48±0.13±0.18±0.08	0.78±0.09±0.09±0.05	1.12±0.08±0.13±0.08
$\rho^-\pi^+\pi^0$	1.56±0.13±0.19±0.08	0.78±0.09±0.09±0.05	1.11±0.09±0.13±0.08
$K^+K^-\pi^0\pi^0$	0.59±0.05±0.08±0.03	0.12±0.02±0.02±0.01	0.21±0.03±0.03±0.01
$p\bar{p}\pi^0\pi^0$	0.11±0.02±0.02±0.01	< 0.05	0.08±0.02±0.01±0.01
$K^+K^-\eta\pi^0$	0.32±0.05±0.05±0.02	0.12±0.03±0.02±0.01	0.13±0.04±0.02±0.01
$K^\pm\pi^\mp K^0\pi^0$	2.64±0.15±0.31±0.14	0.92±0.09±0.11±0.06	1.41±0.10±0.16±0.10
$K^{*0}K^0\pi^0\times\ K^{*0}\to K^\pm\pi^\mp$	0.37±0.09±0.04±0.02	0.25±0.06±0.03±0.02	0.39±0.07±0.05±0.03
$K^{*0}K^\pm\pi^\mp\times\ K^{*0}\to K^0\pi^0$			0.30±0.07±0.04±0.02
$K^{*\pm}K^\mp\pi^0\times\ K^{*\pm}\to\pi^\pm K^0$	0.49±0.10±0.06±0.03		0.38±0.07±0.04±0.03
$K^{*\pm}\pi^\mp K^0\times\ K^{*\pm}\to K^\pm\pi^0$	0.32±0.07±0.04±0.02		0.30±0.07±0.04±0.02
$\rho^\pm K^\mp K^0$	1.28±0.16±0.15±0.07	0.54±0.11±0.06±0.03	0.42±0.11±0.05±0.03
Sum:	7.2%	2.4%	3.7%

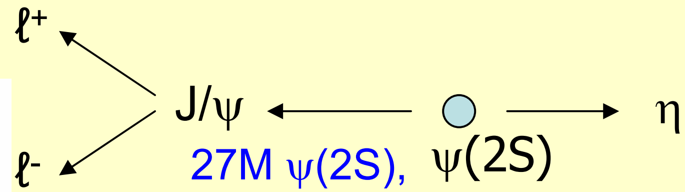
Ties to lighter systems

η properties

Resonances observed in χ_{cJ} multibody decays

η branching ratios





27M ψ(2S),
$B(\psi(2S)\to\eta J/\psi) = 3.1\%$,
$B(J/\psi\to l^+l^-) = 12\%$,

Fully reconstruct five final states:

$\gamma\gamma + 3\pi^0 + \pi^+\pi^-\pi^0 + \pi^+\pi^-\gamma + e^+e^-\gamma$

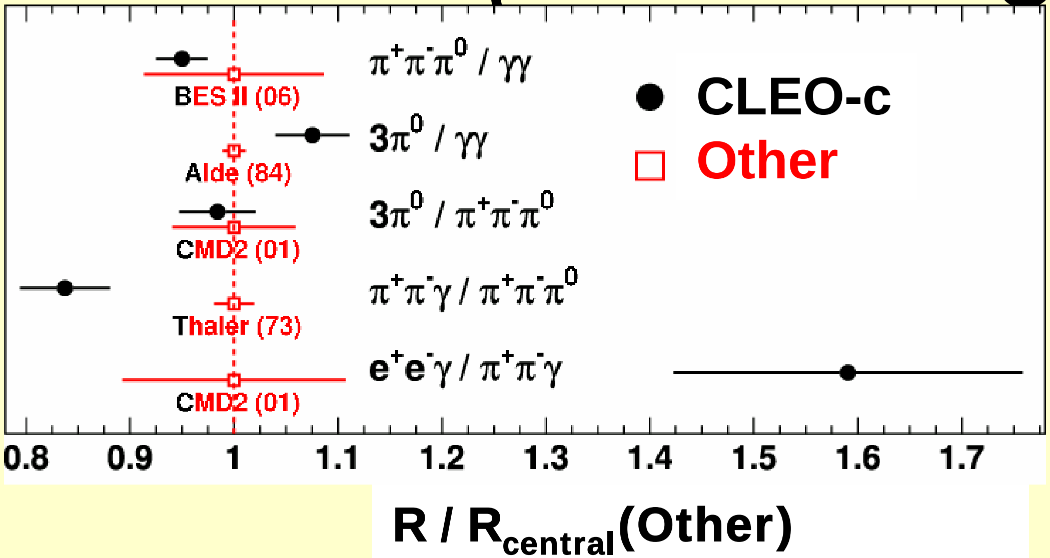
38.5 34.0 22.6 4.0 0.9%

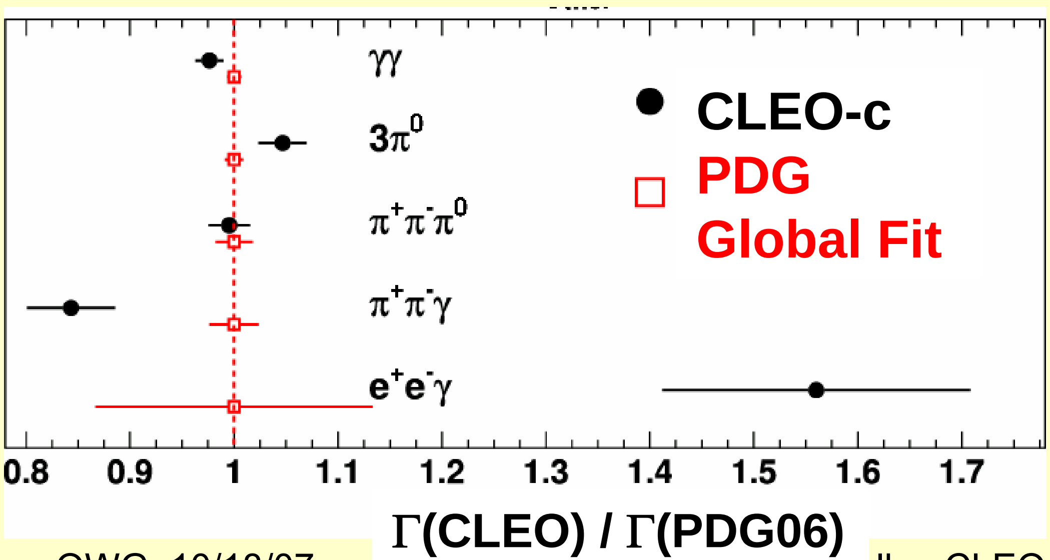
Constrain ℓ^+, ℓ^- ⇒J/ψ,
constrain J/ψ, η products ⇒ ψ(2S)

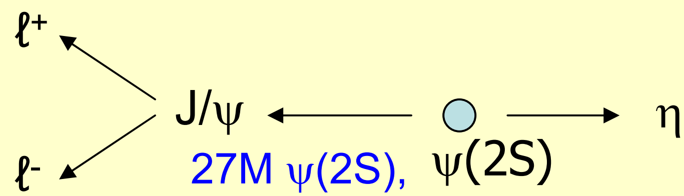
Excellent data/MC agreement

Measurement of ratios allow cancellation of systematics

η branching fractions







27M ψ(2S),
$B(\psi(2S)\to\eta J/\psi)$ = 3.1%,
$B(J/\psi\to l^+l^-)$ = 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%

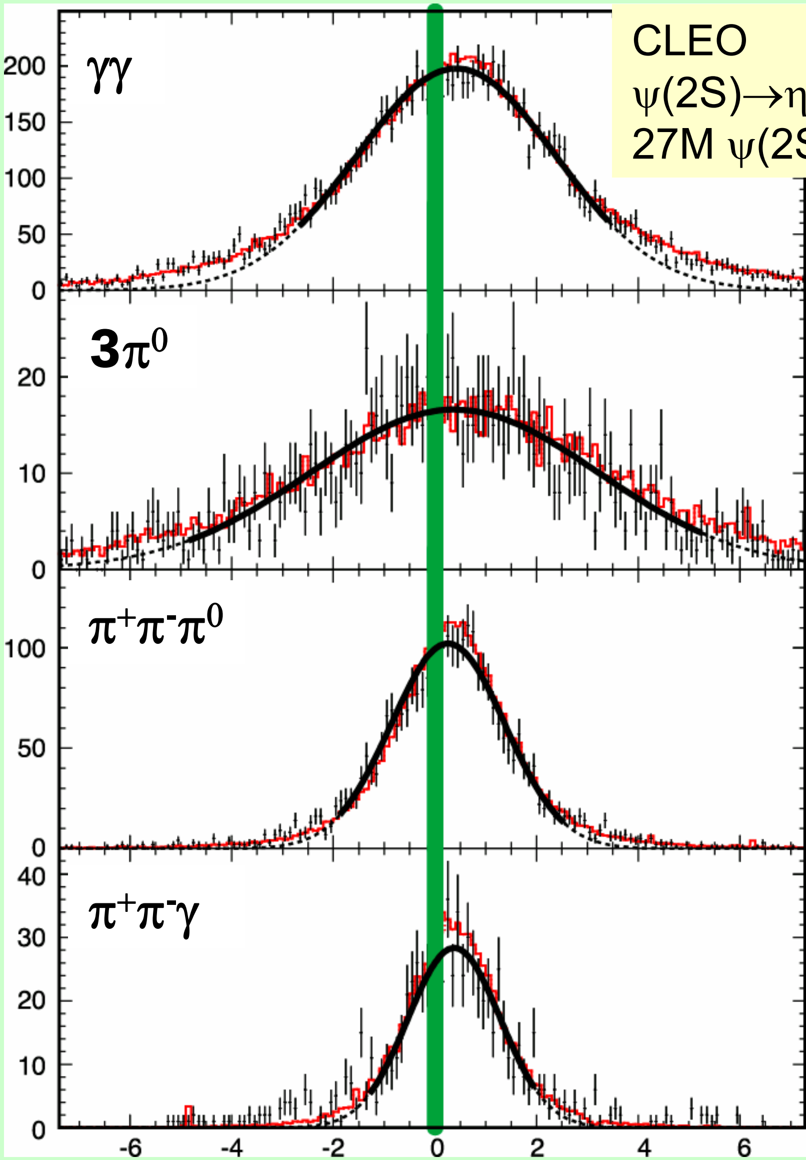
Follow PDG procedure: sum of the above five modes is ~ 100%
⇒ build absolute Br's from ratios

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

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

η Mass

Invariant mass of η decay products:



CLEO
ψ(2S)→ηJ/ψ
27M ψ(2S)

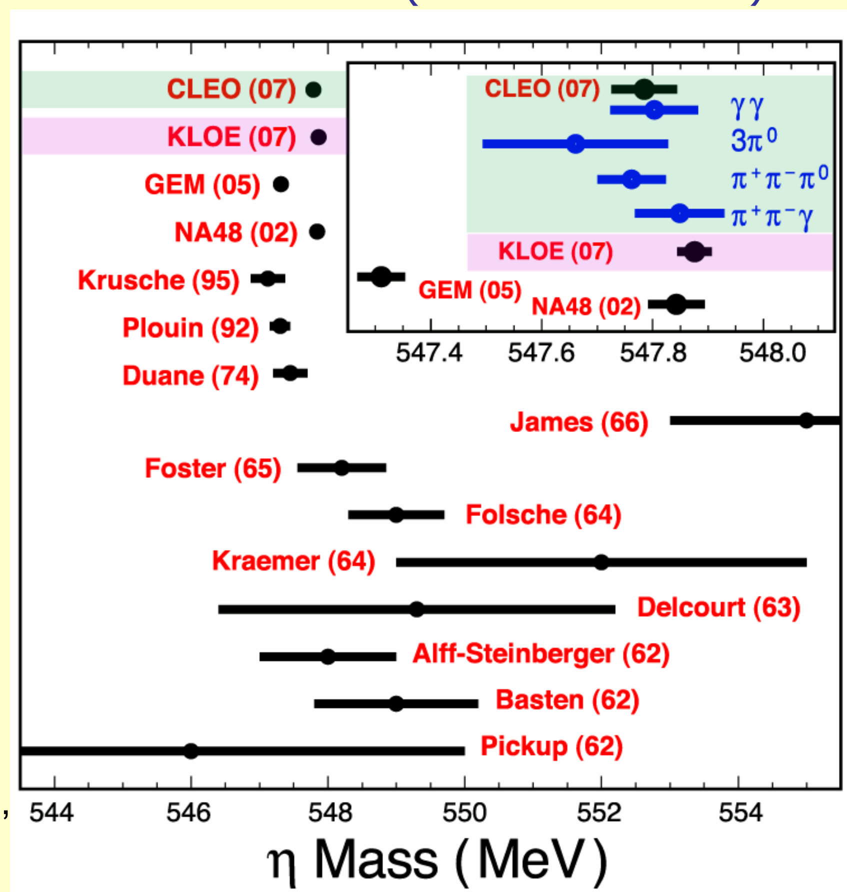
M(CLEO) – M(PDG06) (MeV)

16k fully reconstructed events

CLEO: M(η) =547.785 ± 0.017 ± 0.057 MeV
PRL 99, 122002 (2007) (arXiv:0707.1810)

KLOE: M(η) = 547.873 ± 0.007 ± 0.031 MeV
arXiv:0707.4616 (LP07 contribution)

ahlke,



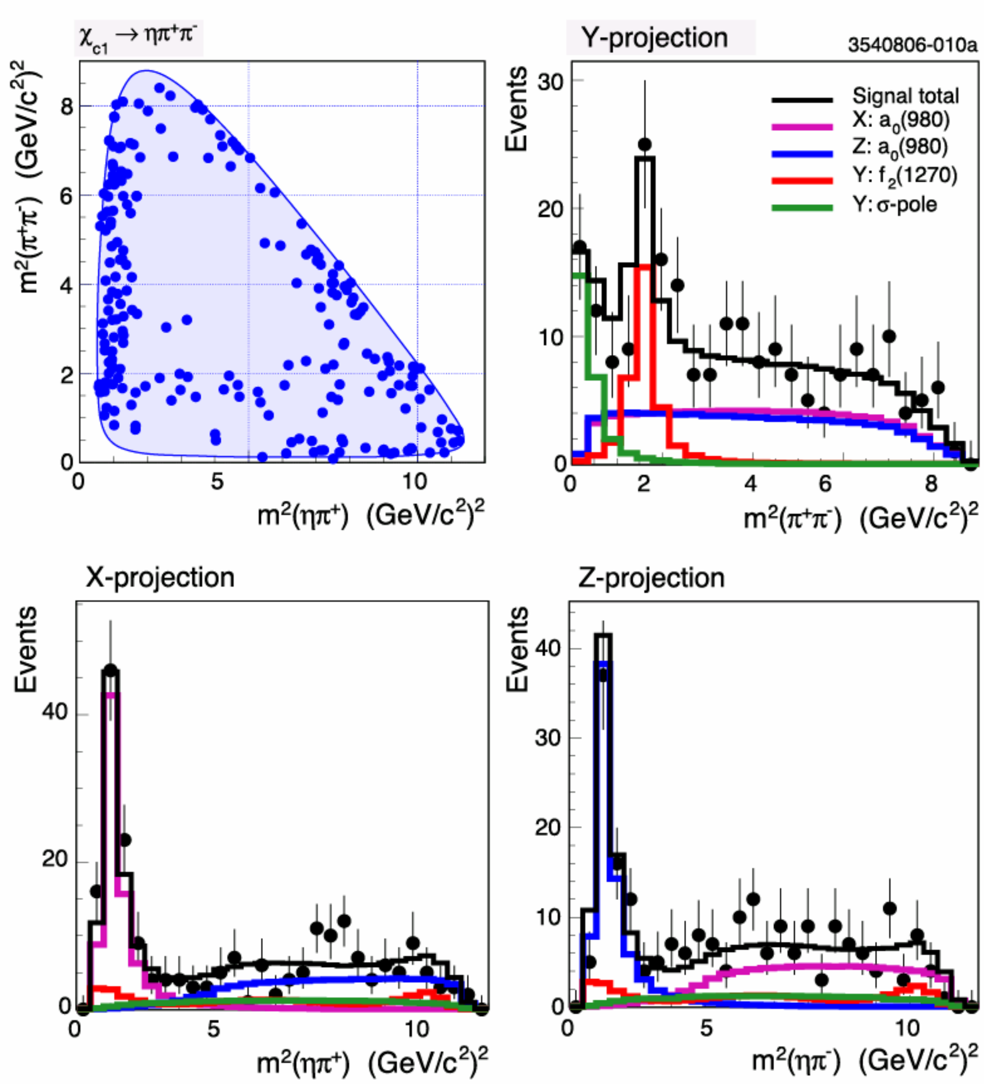
χ_{cJ} multibody decays

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 $K^-K_S\pi^+$ - 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



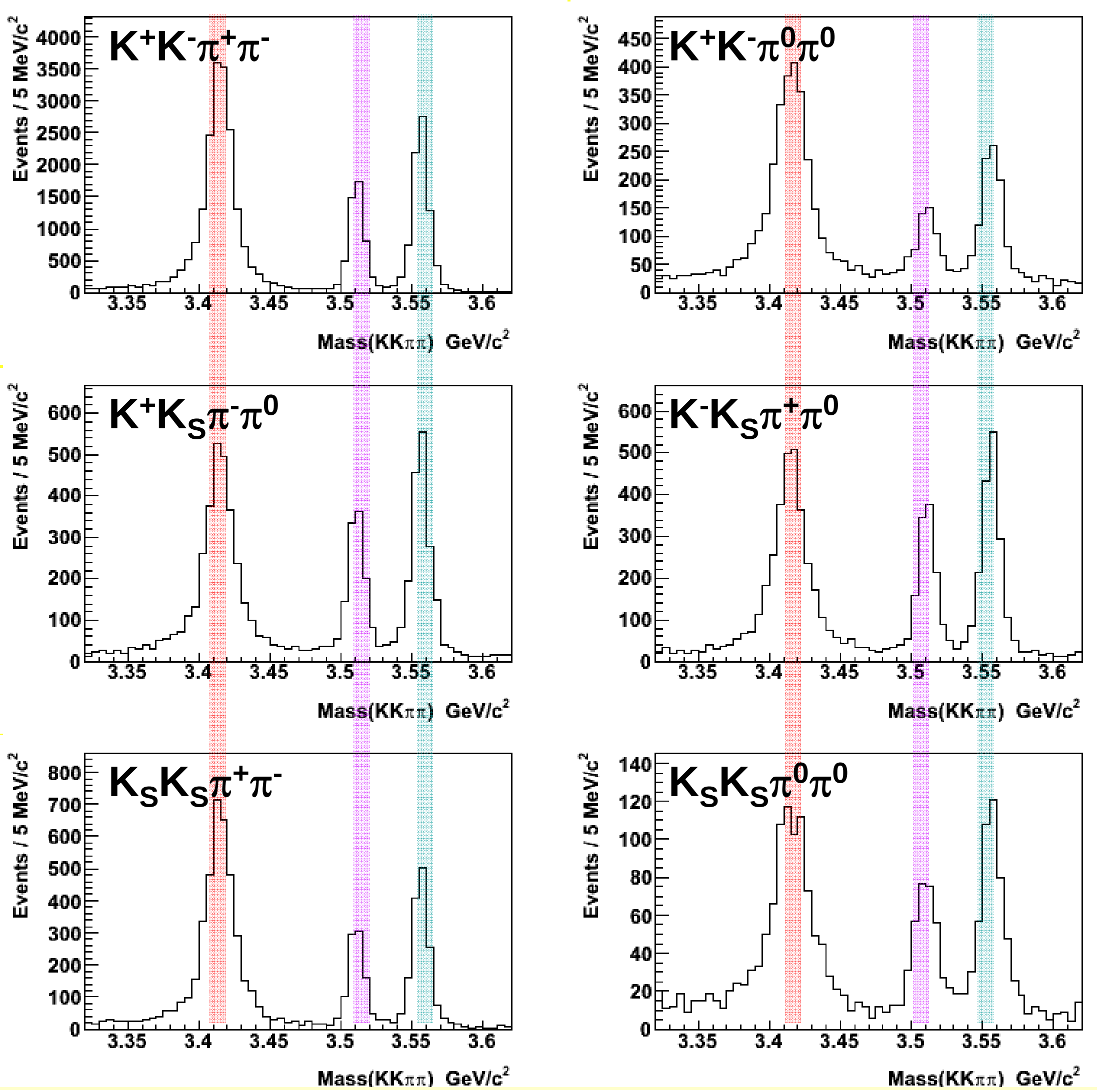
CLEO PRD 75, 032002 (2007)

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

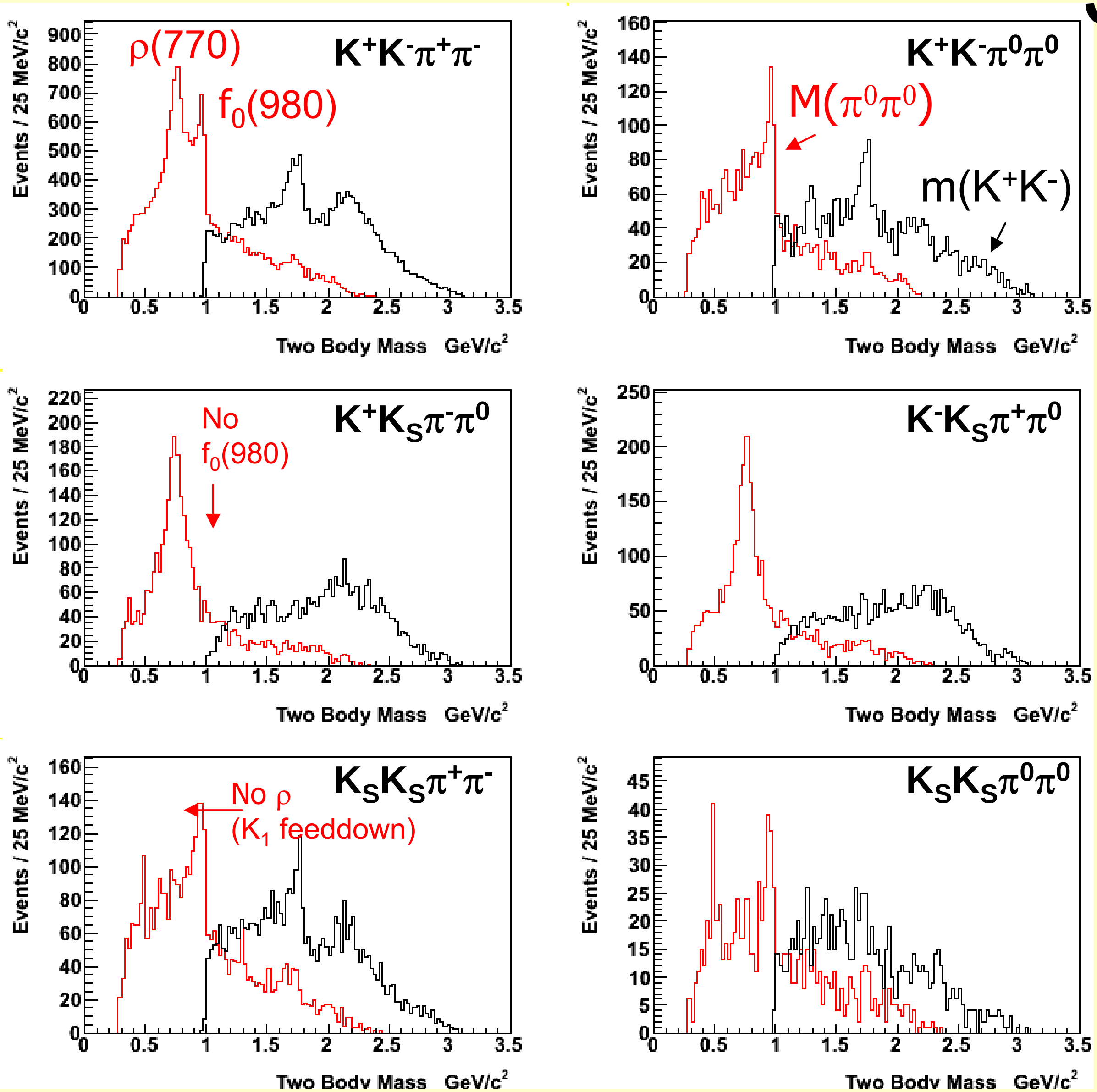
27M $\psi(2S)$ - first look…

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}

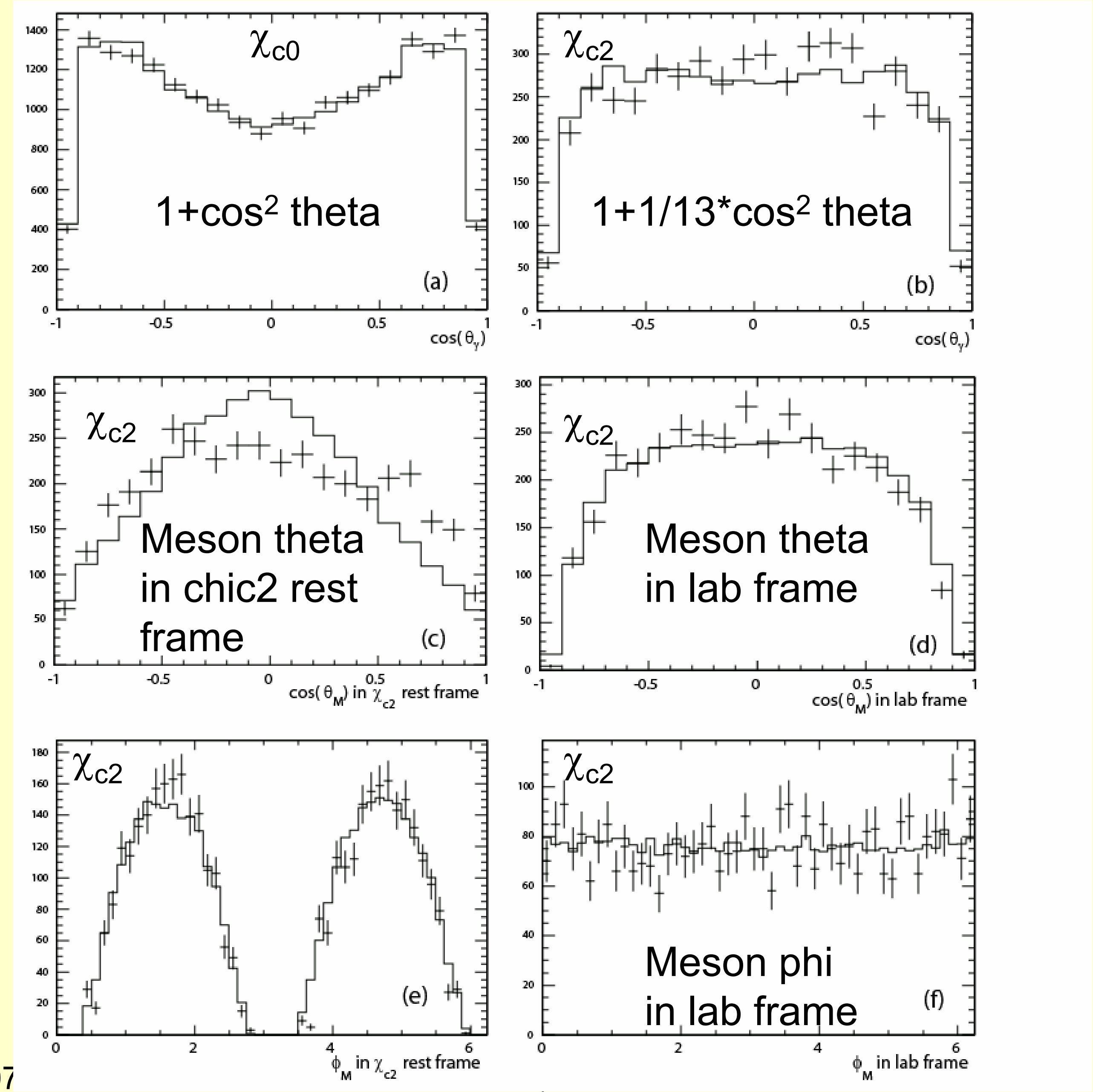
Complementary and different structure in six $KK\pi\pi$ submodes

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