Charmonium Decays in CLEO

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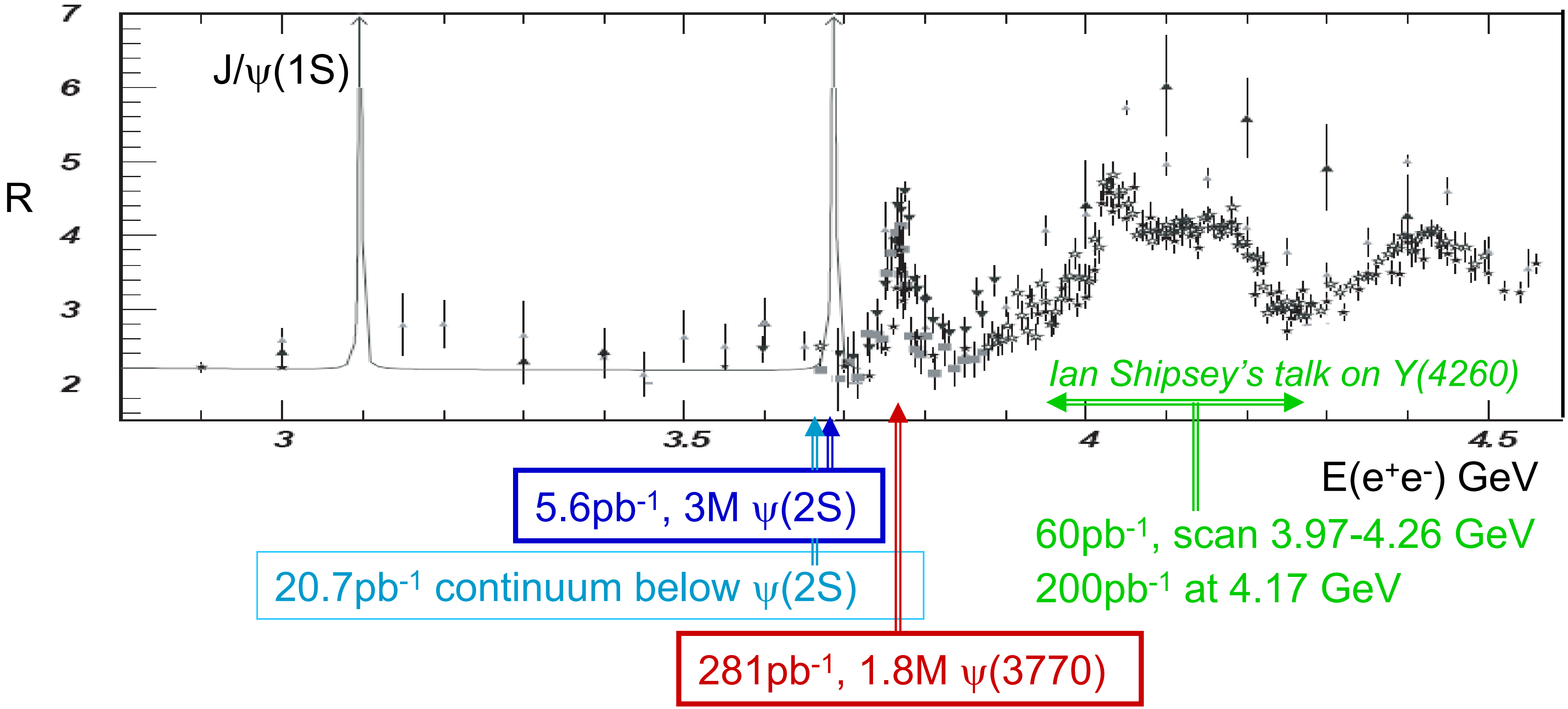
I will concentrate on the recent results.
Separate talk covering Y(4260).

CLEO-c Data Samples



Ian Shipsey's talk on Y(4260)

5.6pb^{-1}, 3M ψ(2S)

20.7pb^{-1} continuum below ψ(2S)

281pb^{-1}, 1.8M ψ(3770)

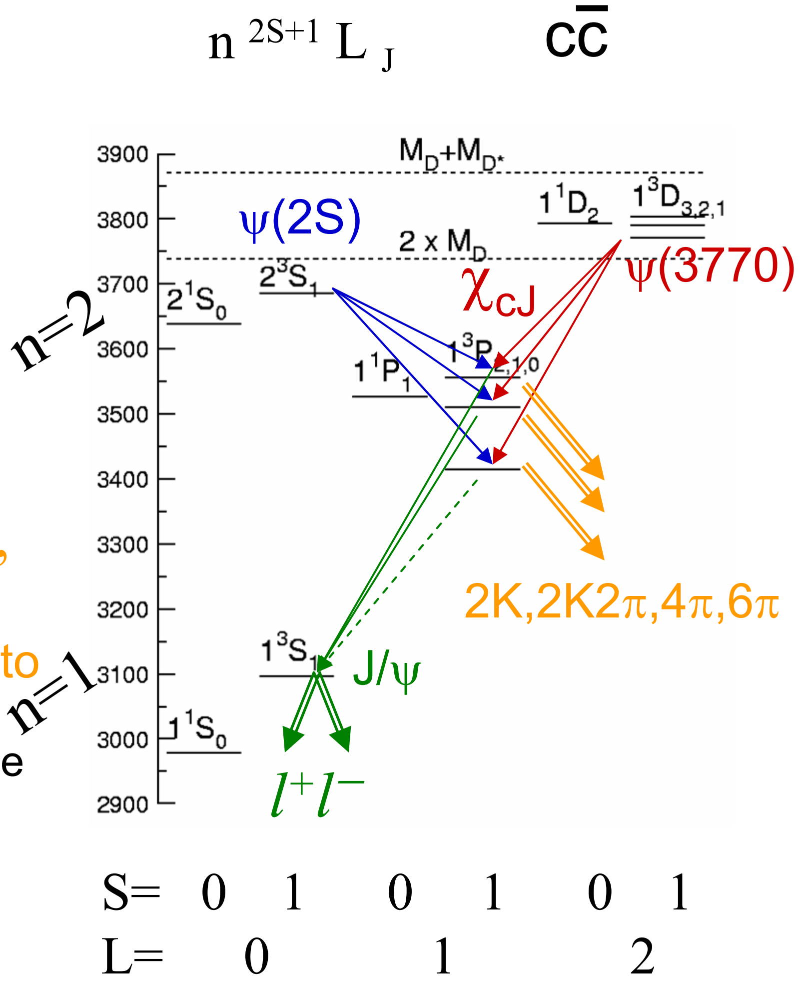
60pb^{-1}, scan 3.97-4.26 GeV

200pb^{-1} at 4.17 GeV

- By far the largest ψ(3770) sample
- The ψ(2S) sample not the largest, but still unique because of the CLEO detector capabilities (excellent tracking, EM calorimeter and PID)

Photon transitions: $\psi(3770) \to \gamma\, \chi_{cJ}$

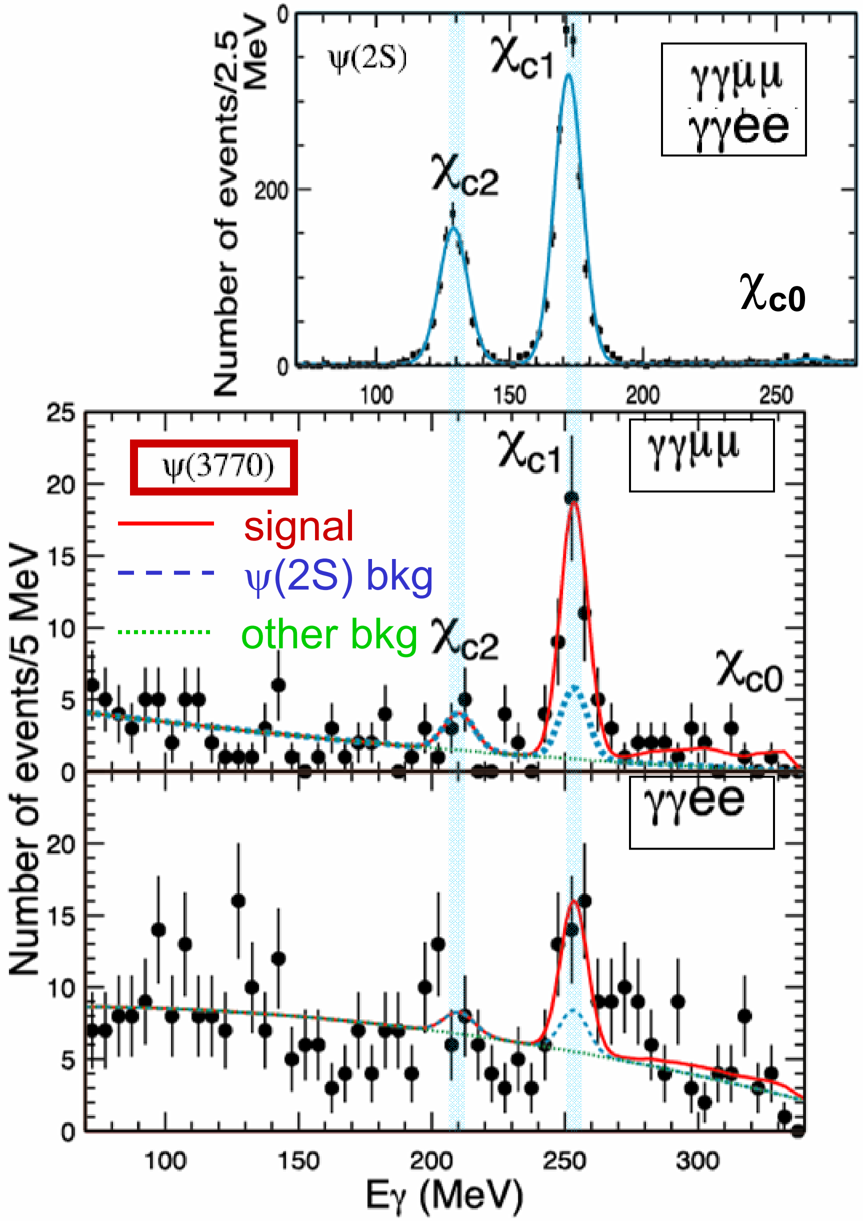
- Rare because $\Gamma_{E1} \sim 10^0$-10^2 keV while $\Gamma_{\psi(3770)\to D\bar{D}}$ =25 MeV
- Interesting because of well grounded potential model predictions for $\Gamma_{E1}[\psi(1^3D_1) \to \gamma\, \chi(1^3P_J)]$:
  - Is $\psi(3770)$ a regular $c\bar{c}$ state?
  - Effects due to 1^3D_1 - 2^3S_1 mixing?
  - Reliability of the Γ_{E1} predictions for states above the open charm threshold?
- Two complementary methods:
  - $\chi_{cJ} \to \gamma J/\psi$, $J/\psi \to e^+e^-, \mu^+\mu^-$
    - Excellent background suppression but poor sensitivity to χ_{c0}
  - $\chi_{cJ} \to K^+K^-$, $K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$
    - More backgrounds but good sensitivity to χ_{c0}
  - Total energy-momentum constraints suppress the backgrounds and improve the photon energy resolution
- $\psi(2S) \to \gamma\, \chi_{cJ}$ as control sample

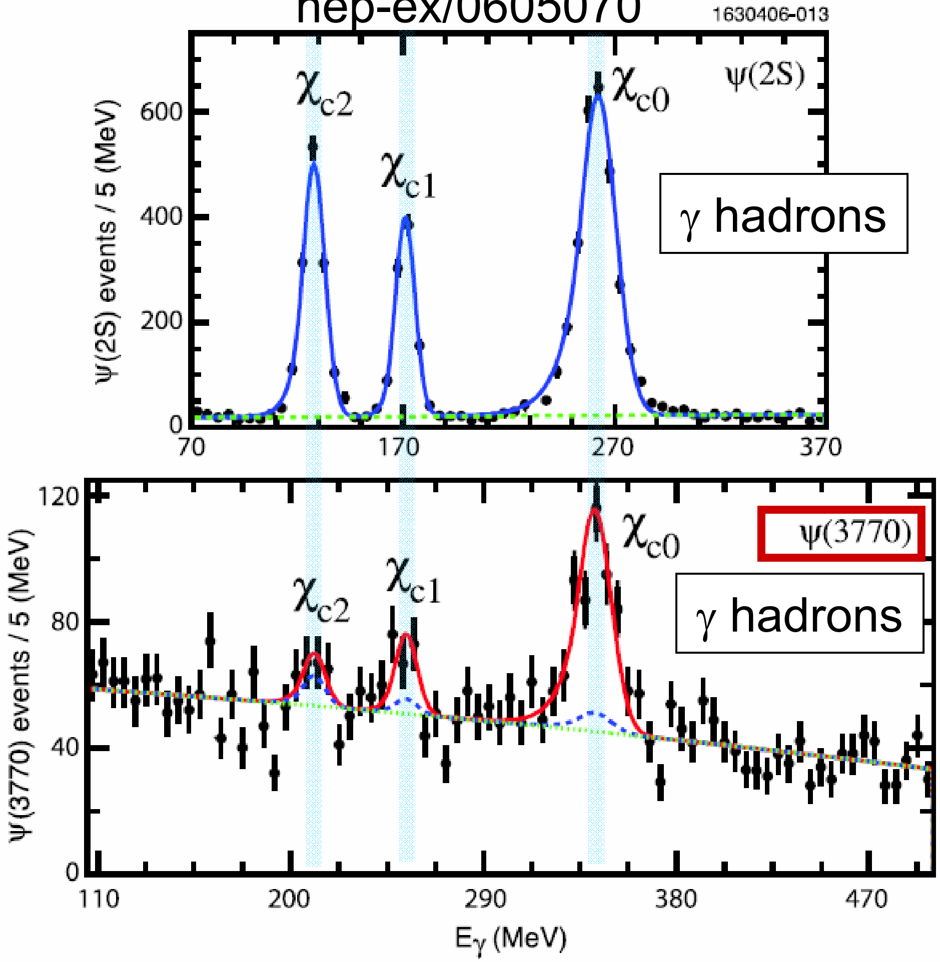


Photon transitions: $\psi(3770) \rightarrow \gamma\ \chi_{cJ}$

PRL 96 182002 (06)

CLEO-CONF-06-6
hep-ex/0605070





$$B(\psi(3770) \rightarrow \gamma\ \chi_{cJ})$$

$$J = 0 \quad (0.73 \pm 0.07 \pm 0.06)\%$$

$$J = 1 \quad (0.29 \pm 0.05 \pm 0.04)\%$$

$$J = 2 \quad < 0.09\% \quad (90\%\ \text{C.L.})$$

Photon transitions: $\psi(3770) \rightarrow \gamma\, \chi_{cJ}$

$$\Gamma_{E1} = \frac{4}{3} e_Q^{\,2} \alpha\, C_{J_f L_f J_i L_i S}\, E_\gamma^{\,3} \boxed{< n_f\, {}^{2S+1}L_{f\,J_f} \,|\, r \,|\, n_i\, {}^{2S+1}L_{i\,J_i} >^2}$$

In non-relativistic limit no *J*-dependence of the E1 matrix element

$$C_{J_f L_f J_i L_i S} = \max(L_i, L_f)(2J_f+1) \begin{Bmatrix} L_f & J_f & S \\ J_i & L_i & 1 \end{Bmatrix}^2$$

Dominant *J*-dependence

$$\text{for } 2^3S_1 \rightarrow 1^3P_J \quad C_{J1111} \equiv C_J' \quad C_0' = \frac{1}{9} \quad C_1' = \frac{3}{9} \quad C_2' = \frac{5}{9}$$

$$\text{for } 1^3D_1 \rightarrow 1^3P_J \quad C_{J1121} \equiv C_J \quad C_0 = \frac{2}{9} \quad C_1 = \frac{1}{6} \quad C_2 = \frac{1}{90}$$

signature of the 1^3D_1 state

	Γ_0 :	Γ_1 :	Γ_2
non-relativistic prediction	1	0.31	0.01
CLEO-c data	1	0.4 ± 0.1	<0.13

- $\psi(3770)$ photon transition rates fit the pattern expected for the 1^3D_1 $c\bar{c}$ state

$2^3S_1 - 1^3D_1$ Mixing ?

$$|\psi(3770)> \;=\; \cos\varphi|1^3D_1> + \sin\varphi|2^3S_1>$$

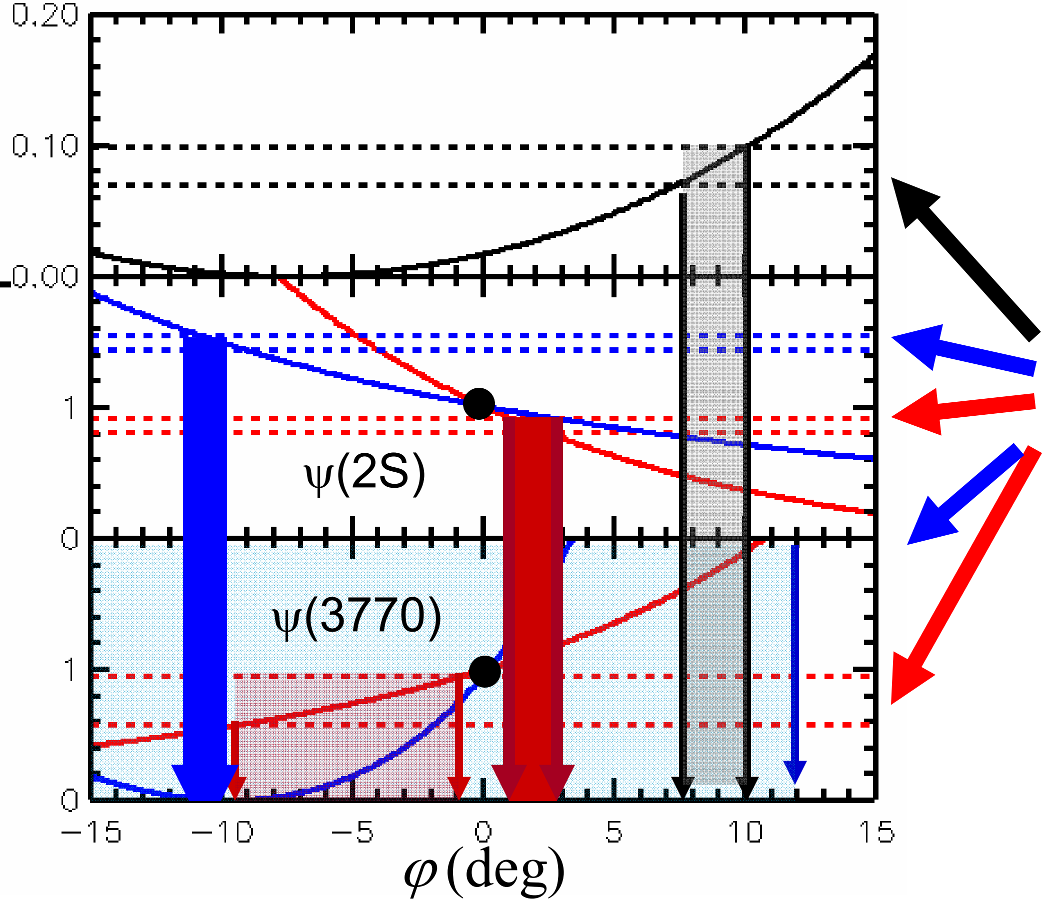
$$|\psi(2S)> \;=\; -\,\sin\varphi|1^3D_1> + \cos\varphi|2^3S_1>$$

Theoretical curves from the non-relativistic calculations by J. Rosner hep-ph/0411003

$$\frac{M_{\psi(3770)}{}^2\,\Gamma_{\psi(3770)\to ee}}{M_{\psi(2S)}{}^2\,\Gamma_{\psi(2S)\to ee}}$$

$$\frac{\tilde{\Gamma}_0}{\tilde{\Gamma}_1} \quad or \quad \frac{\tilde{\Gamma}_2}{\tilde{\Gamma}_1}$$

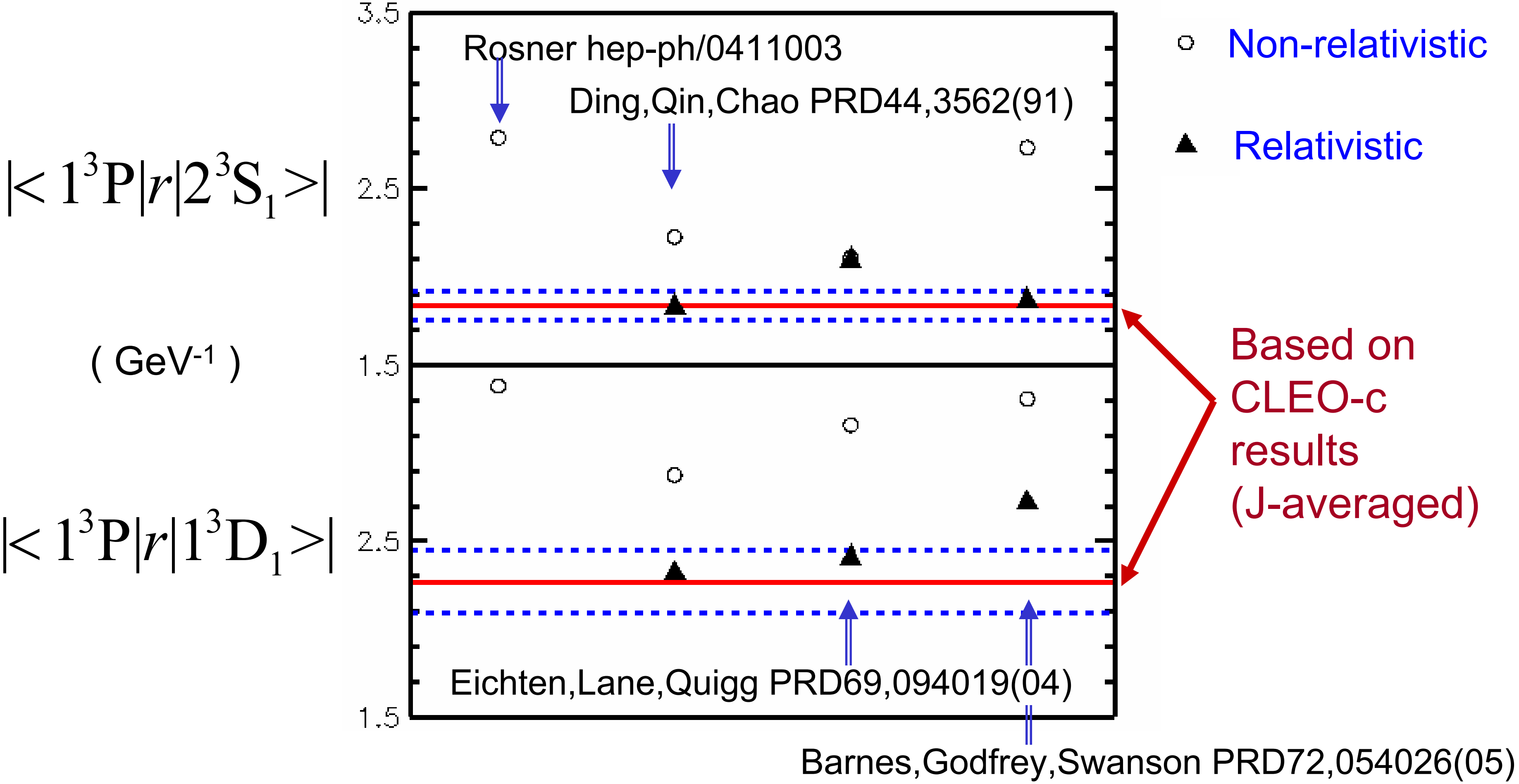
$$\tilde{\Gamma}_J \equiv \frac{\Gamma_J}{C_J E_\gamma{}^3}$$



CLEO-c results

- No consistent solution can be obtained in the non-relativistic approach
- Mixing angle is small

Importance of relativistic corrections



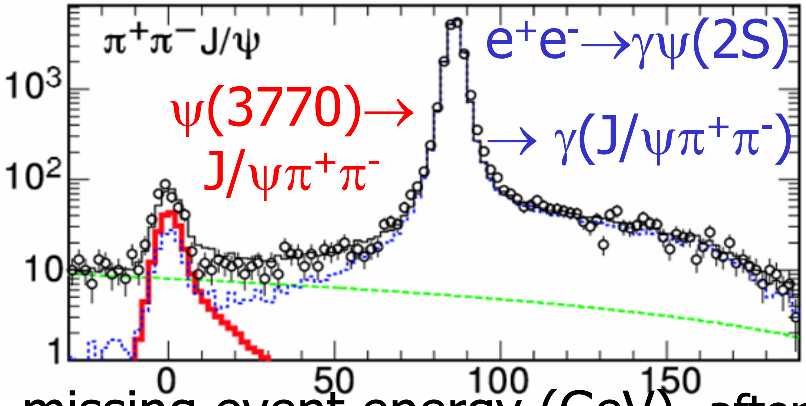
Based on CLEO-c results (J-averaged)

- Non-relativistic calculations overestimate photon transition rates for the charmonium
- Qualitatively, potential model predictions work for the 1^3D_1 state equally well as for the 2^3S_1 state

non-D$\bar{D}$ decays of ψ(3770)

CLEO	BR [%]
$\gamma\chi_{c0}$	0.73±0.07±0.06
$\gamma\chi_{c1}$	0.29±0.05±0.04
$\gamma\chi_{c2}$	<0.09
$\pi^+\pi^- J/\psi$	0.19±0.02±0.02
$\pi^0\pi^0 J/\psi$	0.08±0.02±0.02
$\eta J/\psi$	0.09±0.03±0.02
$\pi^0 J/\psi$	<0.03
$\phi\eta$	0.03±0.01
$K^0_S K^0_L$	<0.001
Detected so far	1.41±*0.10*±*0.16*

CLEO PRL,96,082004 (06)



missing event energy (GeV) after finding π^+, π^-, J/ψ(→ll)

CLEO PRD,73,012002 (06)
(many upper limits presented in this paper too)

CLEO hep/ex-0603026 CLEO-CONF-06-7

vs. $\Gamma_{tot\,\psi(2S)} / \Gamma_{tot\,\psi(3770)} \sim 1.1\%$

$$\sigma(\psi(3770) \to hadrons) = (6.38 \pm 0.08^{+0.41}_{-0.30})\,nb$$

CLEO PRL,95,121801 (05)

$$\sigma(e^+e^- \to D\bar{D}) = (6.39 \pm 0.10^{+0.17}_{-0.08})\,nb$$

CLEO PRL,96,092002 (06)

The difference $(-0.01 \pm 0.12^{+0.40}_{-0.33})\,nb$

$$\Rightarrow B(\psi(3770) \to non\text{-}D\bar{D}) < 9\%$$

vs. (9 ± 2 ± 6)% BES-II Gang Rong's talk

- No evidence for anomalously large non-D$\bar{D}$ component

Results relevant for the interpretation of X(3872)

- Combining results from the previous slides:

$$\frac{\Gamma(\psi(3770)\to\gamma\,\chi_{c1})}{\Gamma(\psi(3770)\to\pi^+\pi^-\,J/\psi)} = 1.5\pm0.3\pm0.3$$

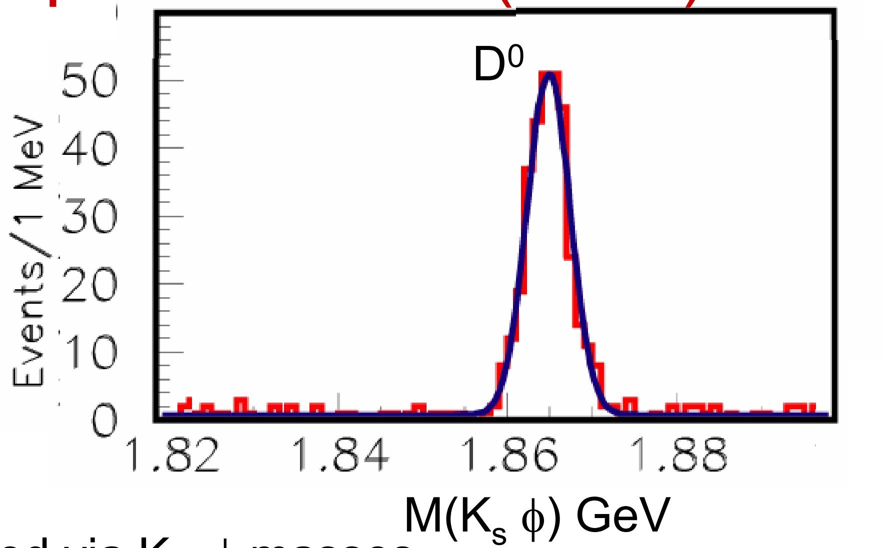
$$\Downarrow \times(2-3.5) \quad \text{for } 1^3\mathrm{D}_2 \text{ at } 3872\,\mathrm{MeV}$$

$$\frac{\Gamma(\psi(1^3D_2)\to\gamma\,\chi_{c1})}{\Gamma(\psi(1^3D_2)\to\pi^+\pi^-\,J/\psi)} > 2.0 \text{ vs. } \frac{\Gamma(X(3872)\to\gamma\,\chi_{c1})}{\Gamma(X(3872)\to\pi^+\pi^-\,J/\psi)} < 0.9\ (Belle)$$

  - X(3872) cannot be 1^3D_2 cc state!
  - A moot point by now, since Belle, CDF, BaBar have shown X(3872) is $J^{PC}=1^{++}$

Results relevant for the interpretation of X(3872)

- D0 mass:
  - $\psi(3770) \to \overline{D^0} D^0$ ($\overline{D^0}$ → tag; $D^0 \to K_s\, \phi$, $(\pi^+\pi^-)(K^+K^-)$)
    - Very small background
    - D^0, K_s, ϕ have small momenta
      - D^0 mass scale well calibrated via K_s, ϕ masses

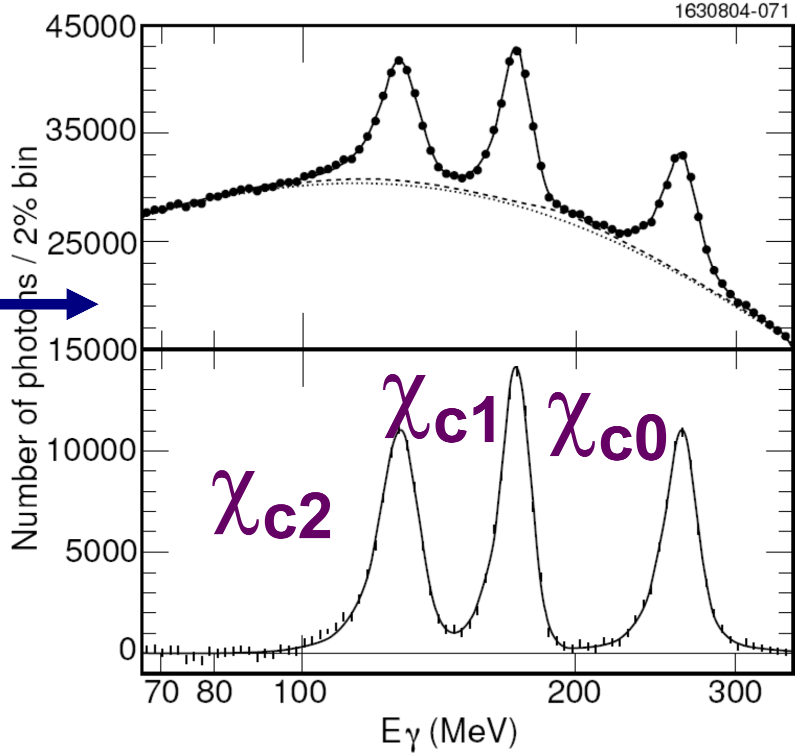


  - 1864.85±0.15±0.20 MeV CLEO PRELIMINARY
  - 1864.5±0.40 MeV PDG'06 fit
  - 1864.1±1.00 MeV PDG'06 average
- $M_{X(3872)} - M_{D^0\overline{D^0}{}^*} = M_{X(3872)} - (2M_{D^0} + \Delta M_{D^{0*}-D^0}) =$
  - +0.1±1.0 MeV PDG'06
  - –0.4±0.7 MeV PDG'06+CLEO
    - The error is now limited by the X(3872) mass measurement
- Accidental mass coincidence even less likely. $D^0\overline{D^0}{}^*$ molecule, other 4-quark state with small binding energy, or a threshold cusp?

$\psi(2S)$ as χ_{cJ} factory

- $e^+e^- \rightarrow \psi(2S)$
  - $5pb^{-1}$, CLEO III+c, 3M $\psi(2S)$
  - by the end of the year ×10
- $\psi(2S) \rightarrow \gamma\chi_{cJ}$, J=0,1,2
  - B~9% each J, "χ_{cJ} factory"
  - observed in inclusive analysis
  - B(χ_{cJ}→hadrons) are not well known

CLEO PRD,70, 112002 (2004)



- Selected analyses of χ_{cJ} hadronic decays:
  - Channels involving neutrals:
    - $\chi_{cJ} \rightarrow \eta^{(')}\eta^{(')}$
    - $\chi_{cJ} \rightarrow h^+h^-h^0$, 3-body decays, Dalitz plot analysis

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

$B(\chi_{c0} \rightarrow \eta\,\eta) = 0.31 \pm 0.05 \pm 0.04\,\%$

$B(\chi_{c0} \rightarrow \eta^{\prime}\,\eta^{\prime}) = 0.18 \pm 0.04 \pm 0.02\,\%$

$B(\chi_{c0} \rightarrow \eta\,\eta^{\prime}) < 0.05\%$ (90% CL)

$B(\chi_{c2} \rightarrow \eta\,\eta) < 0.05\%$ (90% CL)

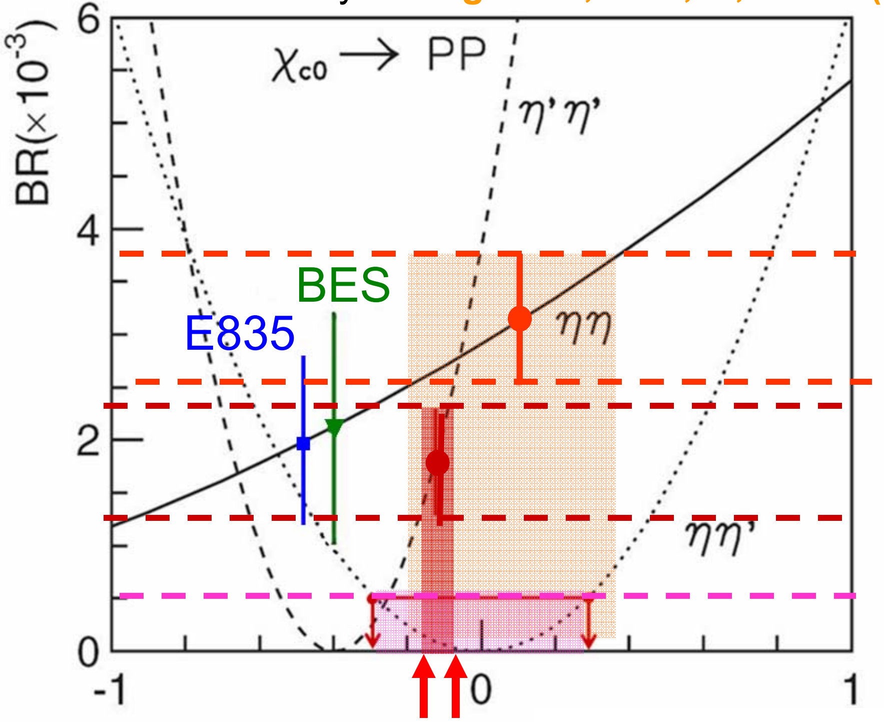
$B(\chi_{c2} \rightarrow \eta^{\prime}\,\eta^{\prime}) < 0.03\%$ (90% CL)

$B(\chi_{c2} \rightarrow \eta\,\eta^{\prime}) < 0.023\%$ (90% CL)

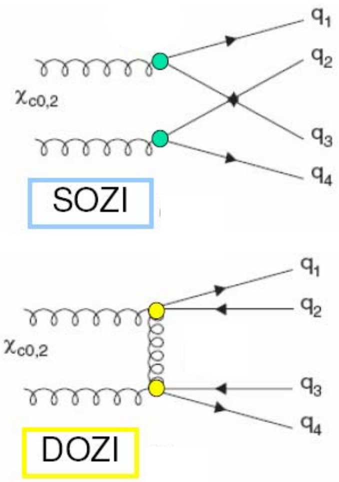
χ_{c1} spin-parity forbidden

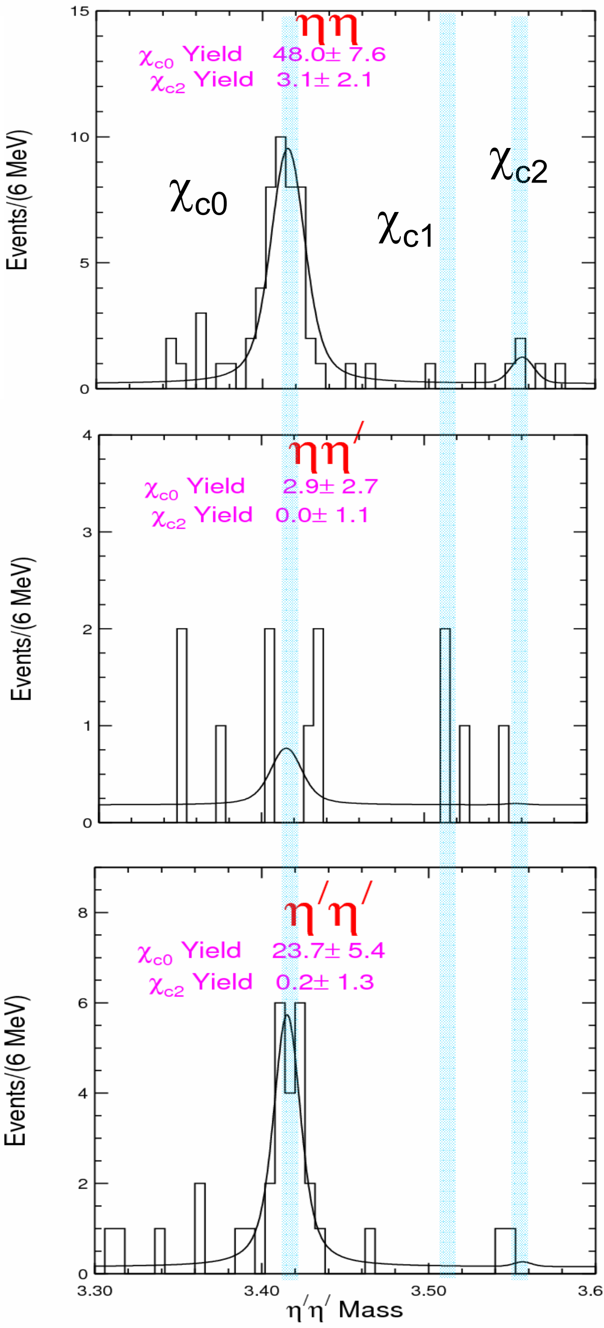
CLEO preliminary

Theoretical model by: **Qiang Zhao, PRD,72,074001(05)**

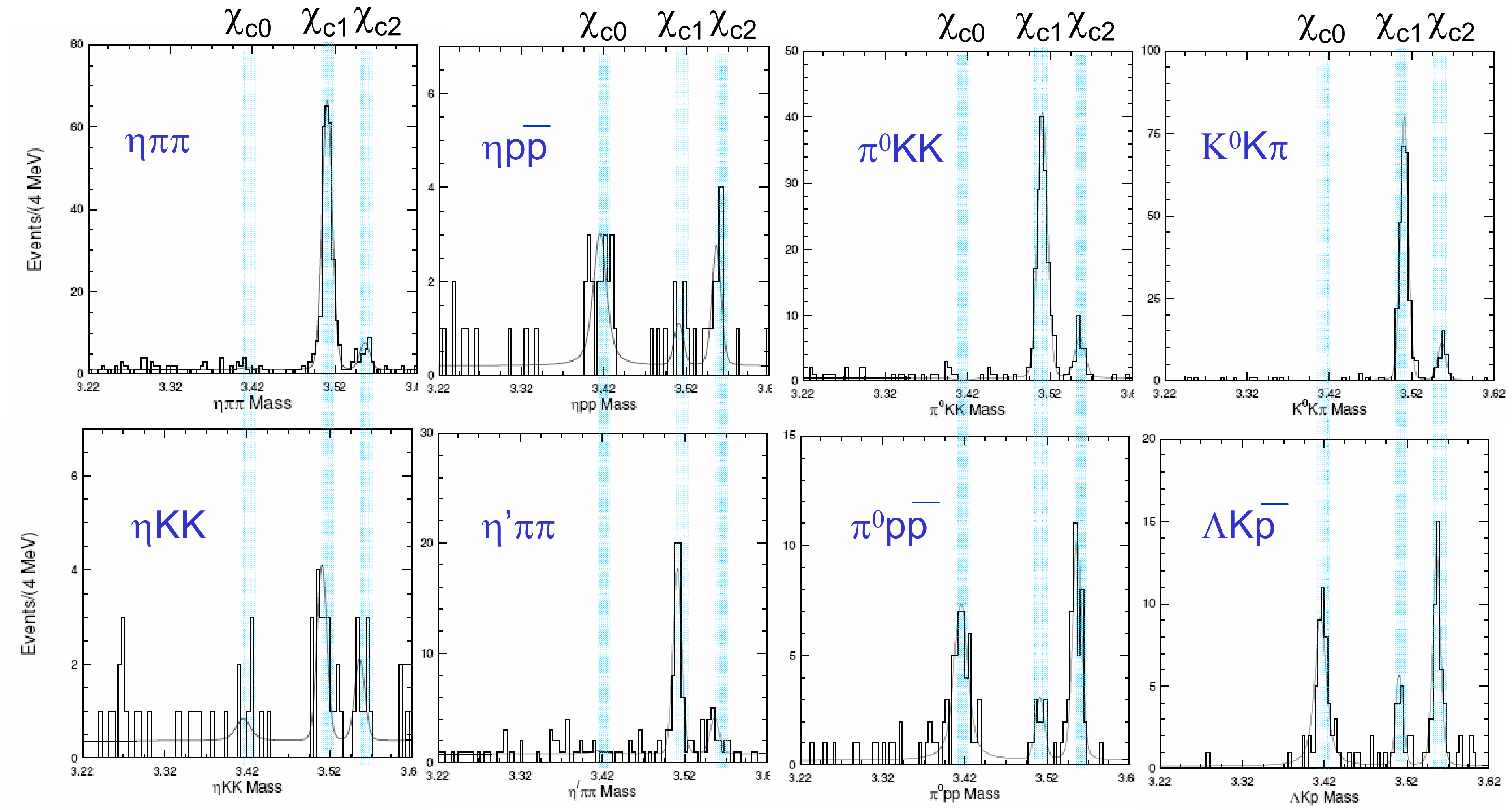


Fits all r = Double-OZI/Single-OZI





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



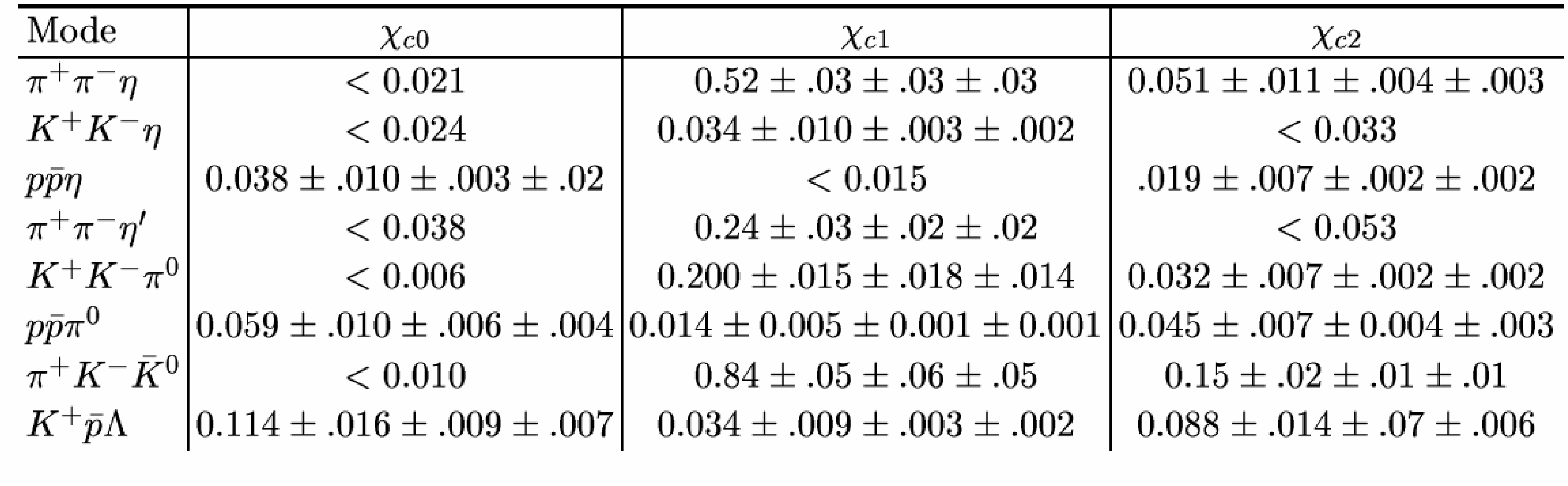
- See results on the next slide

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

CLEO-CONF-06-9

CLEO PRELIMINARY

(in %)

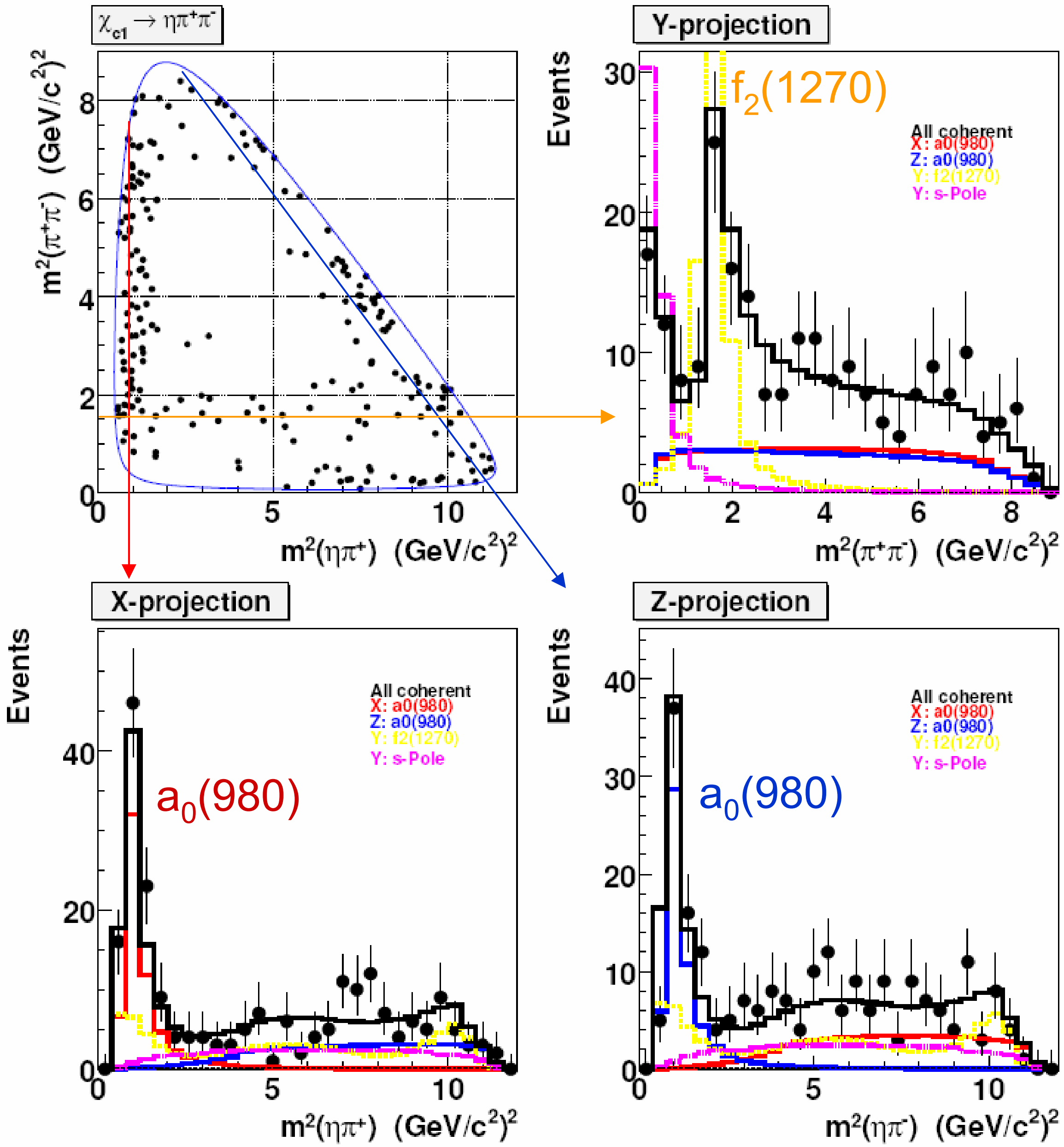


Mode	χ_{c0}	χ_{c1}	χ_{c2}
$\pi^+\pi^-\eta$	< 0.021	$0.52 \pm .03 \pm .03 \pm .03$	$0.051 \pm .011 \pm .004 \pm .003$
$K^+K^-\eta$	< 0.024	$0.034 \pm .010 \pm .003 \pm .002$	< 0.033
$p\bar{p}\eta$	$0.038 \pm .010 \pm .003 \pm .02$	< 0.015	$.019 \pm .007 \pm .002 \pm .002$
$\pi^+\pi^-\eta'$	< 0.038	$0.24 \pm .03 \pm .02 \pm .02$	< 0.053
$K^+K^-\pi^0$	< 0.006	$0.200 \pm .015 \pm .018 \pm .014$	$0.032 \pm .007 \pm .002 \pm .002$
$p\bar{p}\pi^0$	$0.059 \pm .010 \pm .006 \pm .004$	$0.014 \pm 0.005 \pm 0.001 \pm 0.001$	$0.045 \pm .007 \pm 0.004 \pm .003$
$\pi^+K^-\bar{K}^0$	< 0.010	$0.84 \pm .05 \pm .06 \pm .05$	$0.15 \pm .02 \pm .01 \pm .01$
$K^+\bar{p}\Lambda$	$0.114 \pm .016 \pm .009 \pm .007$	$0.034 \pm .009 \pm .003 \pm .002$	$0.088 \pm .014 \pm .07 \pm .006$

(upper limits at 90% C.L.)

- Most of them are the first observations!
- Statistics in $\chi_{c1}\rightarrow\eta\pi^+\pi^-$, $K^+K^-\pi^0$, $K^0_sK\pi$ sufficient for Dalitz plot analysis of resonant substructure (following slides)

Dalitz plot analysis of $\chi_{c1}\rightarrow\eta\pi^+\pi^-$



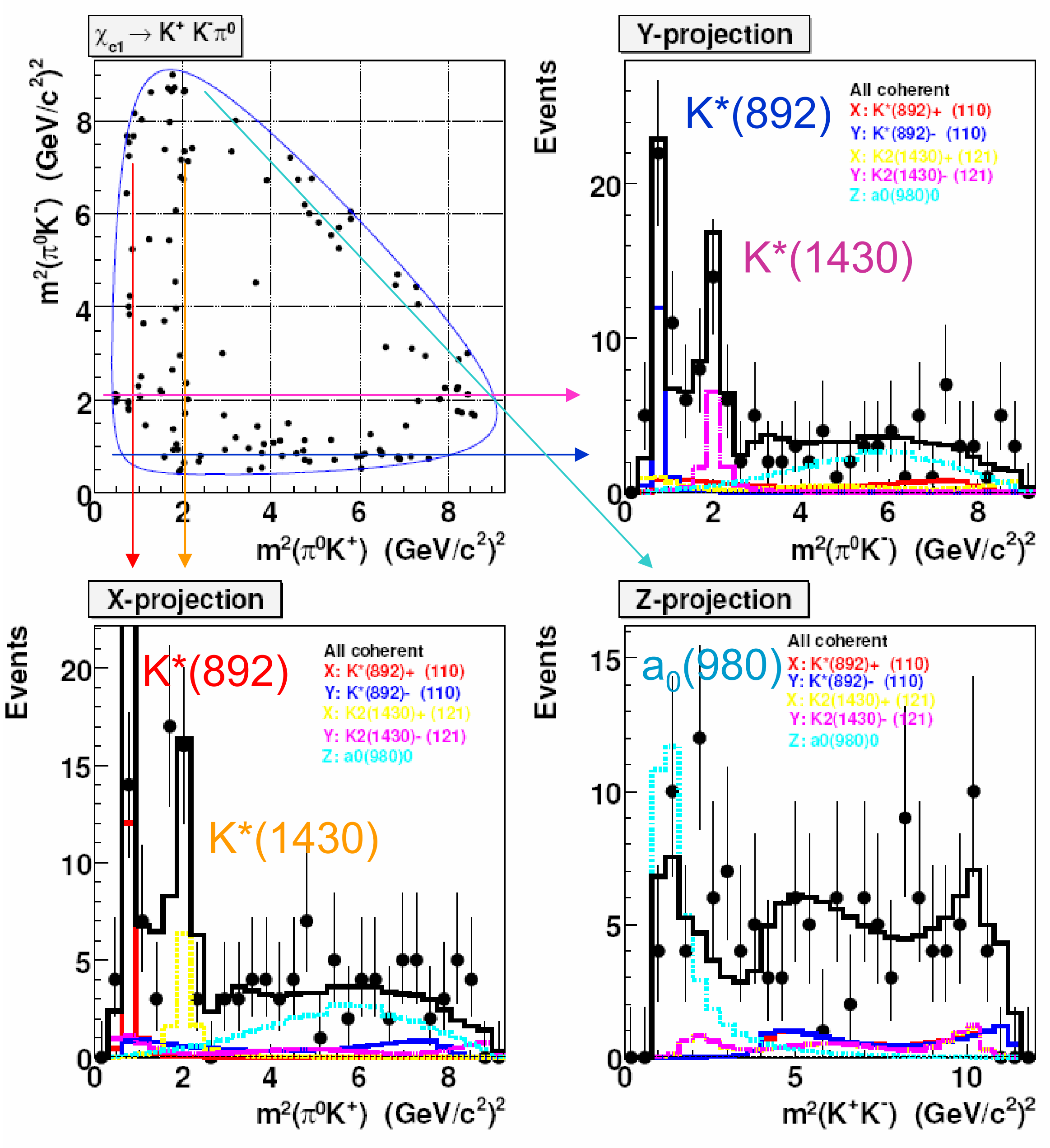
Contribution	Amplitude	Phase (°)
$a_0(980)^\pm\pi^\mp$	1	0
$f_2(1270)\eta$	$0.186\pm0.017\pm0.003$	$-118\pm10\pm4$
$\sigma\eta$	$0.68\pm0.07\pm0.05$	$-85\pm18\pm15$

Contribution	Fit Fraction (%)
$a_0(980)^\pm\pi^\mp$	$56.2\pm3.6\pm1.4$
$f_2(1270)\eta$	$35.1\pm2.9\pm1.8$
$\sigma\eta$	$21.7\pm3.3\pm0.5$

CLEO PRELIMINARY

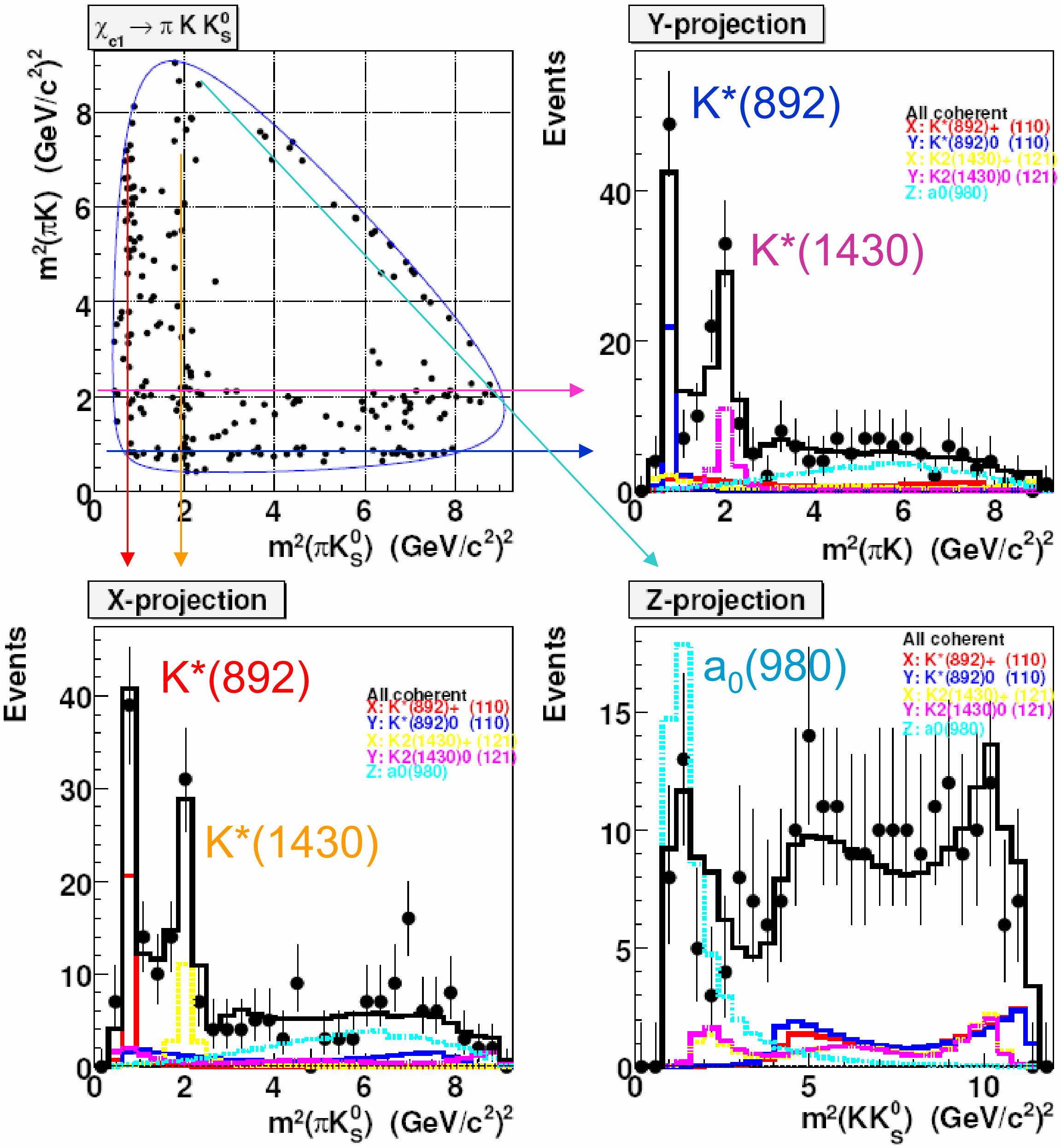
- May offer the best way to determine $a_0(980)$ parameters in the future
- 10x increase in statistics expected this year

Dalitz plot analysis of $\chi_{c1}\rightarrow K^+K^-\pi^0$



- Analyzed together with $K^0_sK\pi$
- see the next slide for the fit results

Dalitz plot analysis of $\chi_{c1} \rightarrow K^0_s K\pi$



CLEO PRELIMINARY

KKπ fit results

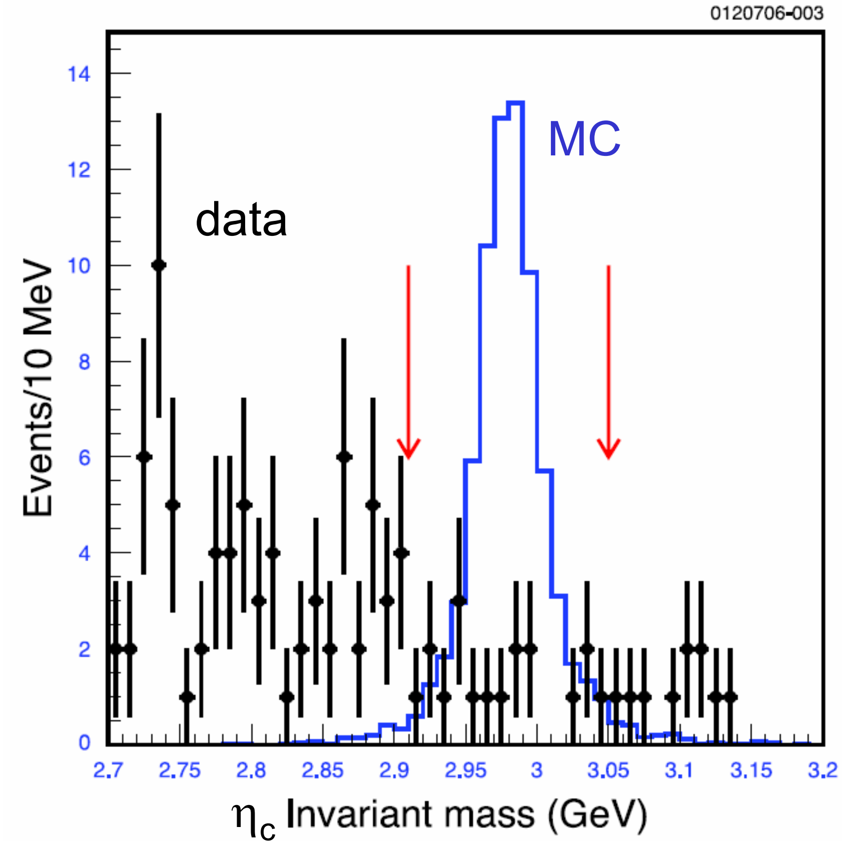
Contribution	Amplitude	Phase (°)
$K^*(892)K$	1	0
$K_2^*(1430)K$	$0.50 \pm 0.09 \pm 0.12$	$-2 \pm 13 \pm 6$
$K_0^*(1430)K$	$5.3 \pm 1.0 \pm 0.1$	$77 \pm 12 \pm 16$
$K^*(1680)K$	$2.3 \pm 0.5 \pm 0.5$	$-38 \pm 12 \pm 12$
$a_0(980)\pi$	$10.8 \pm 1.2 \pm 1.2$	$-112 \pm 12 \pm 3$

Contribution	Fit Fraction (%)
$K^*(892)K$	$19.7 \pm 4.0 \pm 2.0$
$K_2^*(1430)K$	$18.0 \pm 6.6 \pm 3.2$
$K_0^*(1430)K$	$36.0 \pm 12.8 \pm 3.0$
$K^*(1680)K$	$11.2 \pm 5.4 \pm 2.7$
$a_0(980)\pi$	$29.5 \pm 7.1 \pm 2.6$

↕ Model dependent

- $K^*(892)K, a_0(980)\pi$ clearly seen
- Need more data to sort out other contributions

Search for $\psi(2S) \to \eta_c(1S)\,\pi^+\pi^-\pi^0$



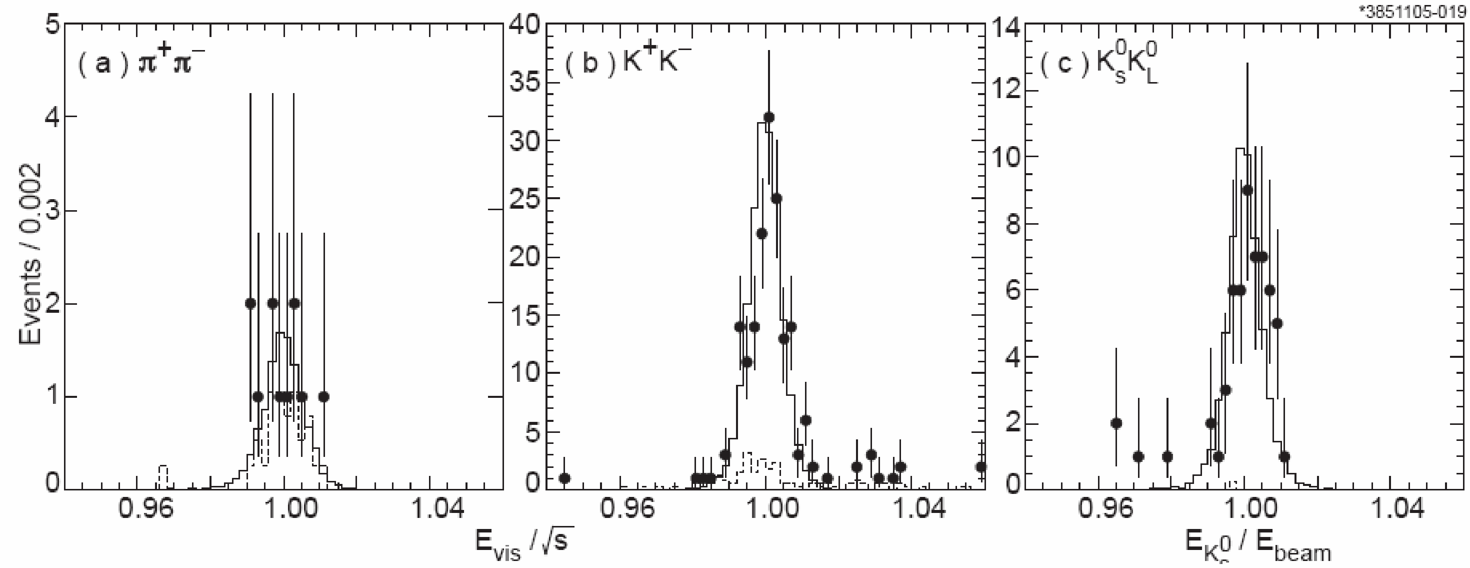
CLEO PRELIMINARY

$\eta_c \to K^+K^-\pi^0$, $\pi^+\pi^-\eta$, $K^+K^-K^+K^-$, $\pi^+\pi^-\pi^+\pi^-$, $K^0K^-\pi^+$

- $B(\psi(2S) \to \eta_c\,\pi^+\pi^-\pi^0) < 0.1\%$ (90% C.L.)
- Rules out “survival before annihilation” model by P.Artoisenet *et al.* PLB,628,211 (05) invented to explain the “$\rho\pi$ puzzle” (predicted $B > 1\%$)

Analysis of ψ(2S) → 2 pseudo-scalars

CLEO hep-ex/0603020
CLEO-CONF-06-8



	DASP [15]	BES [6, 16]	CLEO	World Avg.
$\mathcal{B}_{\pi^+\pi^-}$	8±5	0.84±0.65	0.8±0.8	0.9±0.5
$\mathcal{B}_{K^+K^-}$	10±7	6.1±2.1	6.3±0.7	6.3±0.7
$\mathcal{B}_{K^0_S K^0_L}$	—	5.24±0.67	5.8±0.9	5.4±0.6
$R(\psi(2S))$	—	2.6±1.0	2.8±1.4	2.6±0.7
$\Delta(\psi(2S))$	—	(89±35)°	(93±20)°	(89±14)°

$$R(\psi(2S)) = \frac{A(ggg)}{A(\gamma)} = \sqrt{\frac{\mathcal{B}_{K^0_S K^0_L}}{\rho \mathcal{B}_{\pi^+\pi^-}}},$$

$$\Delta(\psi(2S)) = \cos^{-1}\left(\frac{\mathcal{B}_{K^+K^-} - \mathcal{B}_{K^0_S K^0_L} - \rho \mathcal{B}_{\pi^+\pi^-}}{2\sqrt{\mathcal{B}_{K^0_S K^0_L} \cdot \rho \mathcal{B}_{\pi^+\pi^-}}}\right)$$

phase space ratio $\rho = (p_K/p_\pi)^3 = 0.902$.

- Confirm BES results
- The phase difference Δ between the EM and strong amplitudes around 90°, which is consistent with the J/ψ value, contrary to some theoretical speculations that it might be very different

Summary

- Potential models predict Γ_{E1} for $\psi(3770) \to \gamma\, \chi_{cJ}$ equally well as for $\psi(2S) \to \gamma\, \chi_{cJ}$
- No evidence for anomalously high $\psi(3770) \to$ non-$D\overline{D}$
- $\psi(3770)$ appears to be standard 1^3D_1 $c\overline{c}$ state with a small admixture of 2^3S_1
- Preliminary precision measurement of D^0 mass improves $M_{X(3872)} - M_{D^0\overline{D}^{0*}}$ determination to -0.4 ± 0.7 MeV
- Vast improvement in measurements of exclusive hadronic decay modes of the χ_{cJ} states.
- An order of magnitude increase in $\psi(2S)$ statistics (x10) expected soon. Significant improvement in $\psi(3770)$ statistics (x3) expected by 2008.