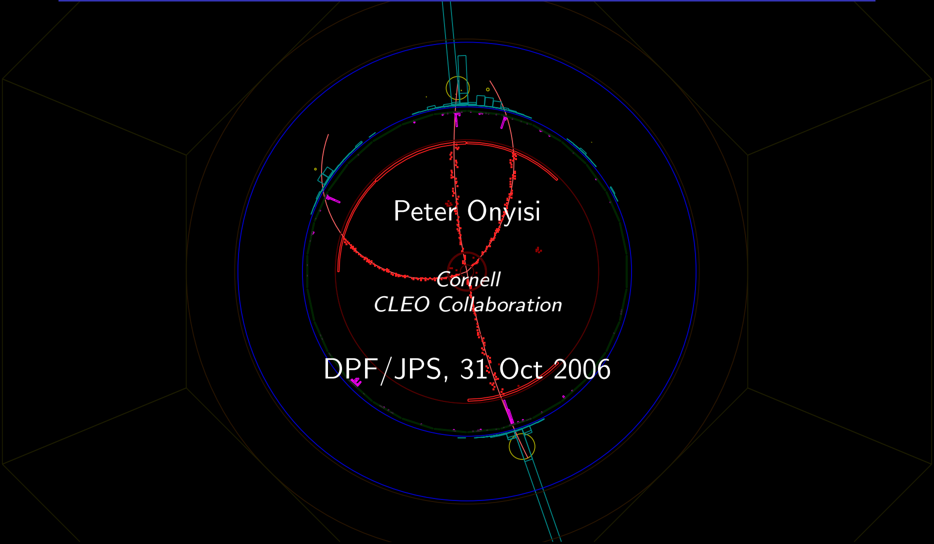
Charmonium Decays and Spectroscopy at CLEO



Peter Onyisi

Cornell
CLEO Collaboration

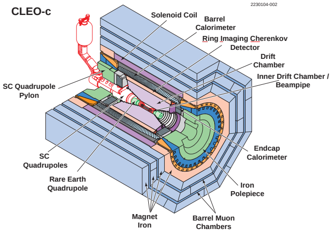
DPF/JPS, 31 Oct 2006

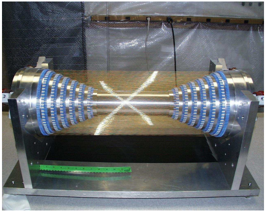
CLEO's well-understood detector and large samples in the charmonium region provide powerful probes of the $c\bar{c}$ system. In this talk I'll cover:

- **Resonance properties:** Γ_{ee}, widths of J/ψ, $\psi(2S)$
- **Decays:** $\chi_{cJ} \to h^+h^-h^0$, $\eta^{(\prime)}\eta^{(\prime)}$; search for $\psi(2S) \to \eta_c 3\pi$
- **Above threshold charmonium:** $\psi(3770) \to XJ/\psi$, $\gamma\chi_{cJ}$
- **New States:** $Y(4260)$

Not covering many topics...

The CLEO-c Detector



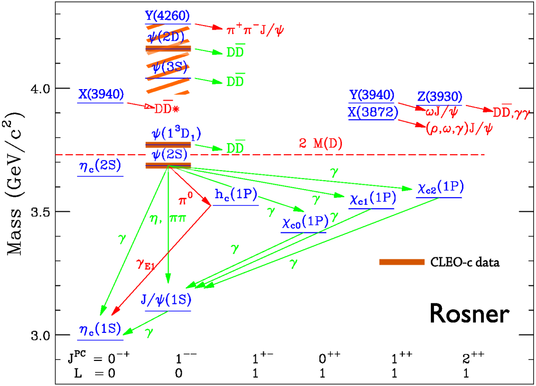


- Detector slightly modified from Υ physics configuration: silicon vertex detector replaced with (all stereo) drift chamber
- DAQ, trigger, software, etc. from CLEO-III with only minor changes
- Particle ID (from dE/dx, Čerenkov) better due to lower p tracks
- For charmonium analyses typically identify leptons with calorimeter information
- Tracking: $\delta p/p = 0.6\%$ at 1 GeV
- CsI calorimeter: $\delta E/E = 4\%$ at 100 MeV

All CLEO-c data is relevant to charmonium analyses.

Critical samples:

- 3 million $\psi(2S)$ decays (half in the CLEO III configuration)
- 281 pb^{-1} at 3.77 GeV (1.8 million $\psi(3770)$ decays)
- 13.2 pb^{-1} at 4.26 GeV



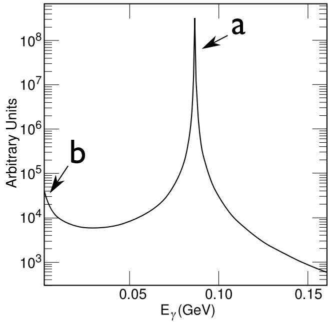
In addition we have

- 25 million more $\psi(2S)$ decays on tape
- 300 pb^{-1} at 4.17 GeV
- 47 pb^{-1} at other points between 3.97–4.2 GeV

Radiative Return

Can produce a 1^{--} resonance below the nominal collision energy with two different enhancements:

- The incoming particles can emit a photon and lower their energy to the resonance's peak (**a**);
- The resonance can be produced on the tail of its lineshape (+ soft photons) (**b**).
- The latter forms an irreducible background to searches for transitions in higher charmonia



E_γ in $e^+e^- \to \gamma_{ISR}\psi(2S)$, $E_{cm} = 3.77$ GeV

Example: $e^+e^- \to \psi(3770) \to \pi^+\pi^- J/\psi$ contaminated by $e^+e^- \to \gamma_{soft}\psi(2S)$, $\psi(2S) \to \pi^+\pi^- J/\psi$

Γ_{ee} in Radiative Return

Γ_{ee} values of various $c\bar{c}$ states measure the wavefunctions and are prime targets for lattice calculations.

- Total radiative return cross-section $\propto \Gamma_{ee}$
- For nominal CM energy far out on the tail of the resonance, the total radiative return cross-section is essentially independent of Γ_{tot}
- If we reconstruct a particular decay X, we measure $\Gamma_{ee}\mathcal{B}_X$; combine with our high-precision branching fraction measurements to get Γ_{ee} or Γ_{tot}

We use the radiative kernel of Kuraev & Fadin (Sov. J. Nucl. Phys. **41**, 466 (1985)).

Measurements (all at $E_{cm} = 3.77$ GeV):

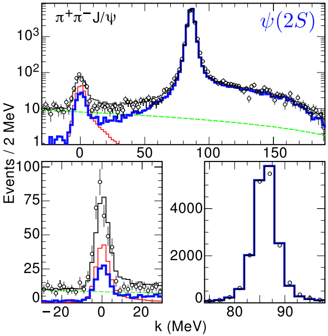
Mode	Measures
$\gamma + XJ/\psi,\ J/\psi \to \ell^+\ell^-$	$\Gamma_{ee}(\psi(2S))$
$\gamma + \mu^+\mu^-$	$\Gamma_{ee}(J/\psi)$, $\Gamma_{tot}(J/\psi)$

$\Gamma_{ee}(\psi(2S))$

- Consequence of search for hadronic transitions $\psi(3770) \to XJ/\psi$ (more later)
- Fit for the missing momentum distribution of XJ/ψ candidates
- Use precision $\psi(2S) \to XJ/\psi$ BFs (PRL **94**, 232002 (2005)) to get Γ_{ee}
- Combining $X = \pi^+\pi^-, \pi^0\pi^0, \eta$, we get

$$\boxed{\Gamma_{ee}(\psi(2S)) = 2.54 \pm 0.03 \pm 0.11 \text{ keV}}$$

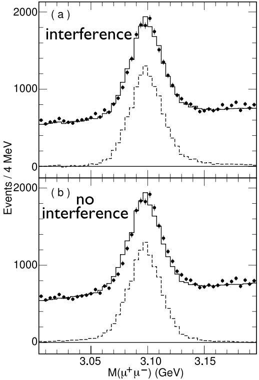
(PDG: 2.48 ± 0.06 keV)



Missing momentum of $\pi^+\pi^- J/\psi$

PRL **96**, 082004 (2006)

- Look for J/ψ peak in $\mu^+\mu^-$ mass spectrum (ignore ISR photon)
- Suppress radiative return to $\psi(2S)$
- Normalize observed yield with either luminosity and expected efficiency or the yield ratio with the observed nonresonant $\gamma\mu^+\mu^-$ using QED prediction of rate. Quoted result combines these methods.
- For $\mathcal{B}(J/\psi \to \mu\mu)$ use CLEO measurement (PRD **71**, 111103(R) (2005))



$$\Gamma_{ee}\mathcal{B}(J/\psi \to \mu\mu) = 0.3384 \pm 0.0058 \pm 0.0071 \text{ keV}$$
$$\Gamma_{ee} = 5.68 \pm 0.11 \pm 0.13 \text{ keV}$$
$$\Gamma_{tot} = 95.5 \pm 2.4 \pm 2.4 \text{ keV (PDG04: } 91.0 \pm 3.2 \text{ keV)}$$
$$\Gamma_{ee}(\psi(2S))/\Gamma_{ee}(J/\psi) = 0.45 \pm 0.01 \pm 0.02$$

PRD **73**, 051103(R) (2006)

Charmonium Above $D\overline{D}$ Threshold

Although the wide $c\bar{c}$ states above $D\overline{D}$ threshold are usually considered only as sources of open charm, they still exhibit typical onia behavior

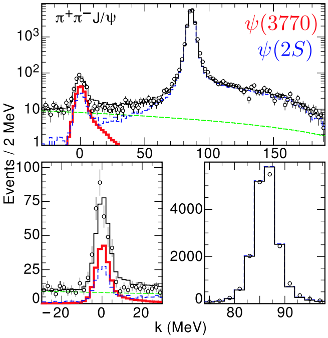
- Expect radiative and hadronic transitions to lower charmonium states
- Rates for $\psi(3770)$ will be affected by admixture of 2^3S_1 state

We have observed both hadronic and radiative transitions from $\psi(3770)$ to other charmonium states.

$\psi(3770) \to XJ/\psi$

- BES found $\mathcal{B}(\psi(3770) \to \pi^+\pi^- J/\psi) = (0.34 \pm 0.14 \pm 0.09)\%$ (PL B**605**, 63 (2005))
- Search for $\psi(3770) \to XJ/\psi$, $X = \pi^+\pi^-$, $\pi^0\pi^0$, η, π^0
- Major background is tail of $\psi(2S)$ Breit-Wigner

Mode	Sig	$\mathcal{B}$ (%)
$\pi^+\pi^-$	11.6σ	$0.189 \pm 0.020 \pm 0.020$
$\pi^0\pi^0$	3.4σ	$0.080 \pm 0.025 \pm 0.016$
η	3.5σ	$0.087 \pm 0.033 \pm 0.022$
π^0	—	< 28 (90% C.L.)

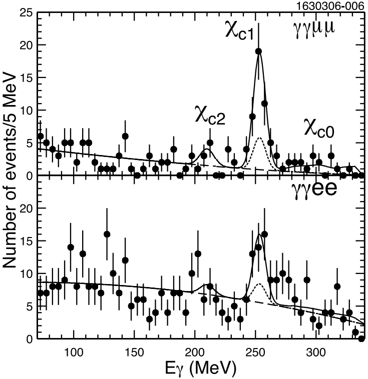


Missing momentum of $\pi^+\pi^- J/\psi$

PRL **96**, 082004 (2006)

$\psi(3770) \to \gamma\chi_{cJ} \to \gamma\gamma J/\psi$

- Reconstruct $\gamma\gamma\ell^+\ell^-$
- Veto $\gamma\gamma$ mass consistent with π^0 or η
- $\ell^+\ell^-$ has J/ψ mass, $\gamma\gamma$ has correct recoil mass
- Radiative Bhabha suppression in $\gamma\gamma e^+e^-$
- Fit the energy spectrum of the softer photon



Softer photon energy spectrum. Dotted line is contribution from $\psi(2S)$ radiative return.

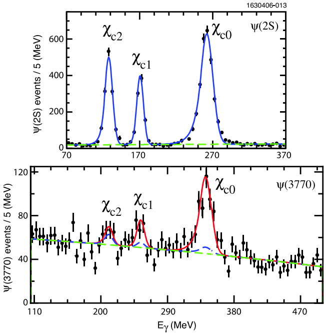
$$\mathcal{B}(\gamma\chi_{c0}) < 44 \times 10^{-3} \text{ (90\% C.L.)}$$
$$\mathcal{B}(\gamma\chi_{c1}) = (2.8 \pm 0.5 \pm 0.4) \times 10^{-3}$$
$$\mathcal{B}(\gamma\chi_{c2}) < 0.9 \times 10^{-3} \text{ (90\% C.L.)}$$

PRL **96**, 182002 (2006)

$\psi(3770) \to \gamma\chi_{cJ} \to \gamma(nK^{\pm})(m\pi^{\pm})$

- χ_{c0} suppressed in $\gamma\gamma J/\psi$ analysis due to small $\mathcal{B}(\chi_{c0} \to \gamma J/\psi)$
- Instead reconstruct χ_{cJ} decays to hadrons
- Use four modes: $2K$, $2K2\pi$, 4π, 6π
- Measure ratios to equivalent $\psi(2S)$ transitions to cancel the χ_{cJ} branching fractions

$$\mathcal{B}(\gamma\chi_{c0}) = (7.3 \pm 0.7 \pm 0.6) \times 10^{-3}$$
$$\mathcal{B}(\gamma\chi_{c1}) = (3.9 \pm 1.4 \pm 0.6) \times 10^{-3}$$
$$\mathcal{B}(\gamma\chi_{c2}) < 2.0 \times 10^{-3} \text{ (90\% C.L.)}$$



Photon energy spectrum, summed over all modes. Blue dashed line is contribution from $\psi(2S)$ radiative return.

PRD **74**, 031106 (2006)

$\psi(3770)$ Radiative Transitions Summary

- Combine two analyses' results to get $\mathcal{B}(\gamma\chi_{c1}) = (0.29 \pm 0.05 \pm 0.04)\%$

	$\psi(3770) \to \gamma\chi_{cJ}$		
	$J=0$	$J=1$	$J=2$
$\mathcal{B}$ (%)	0.73 ± 0.09	0.29 ± 0.06	< 0.09
Γ (keV)	172 ± 30	70 ± 17	< 21
Theory Γ predictions			
Rosner non-relativistic	523 ± 12	73 ± 9	24 ± 4
Ding-Qin-Chao			
non-relativistic	312	95	3.6
relativistic	199	72	3.0
Eichten-Lane-Quigg			
non-relativistic	254	183	3.2
coupled-channel	225	59	3.9
Barnes-Godfrey-Swanson			
non-relativistic	403	125	4.9
relativistic	213	77	3.3

- Relativistic corrections needed for quantitative agreement

(Rosner, PRD **64**, 094002 (2001); DQC, PRD **44**, 3562 (1991); ELQ, PRD **69**, 094019 (2004); BGS, PRD **72**, 054026 (2005))

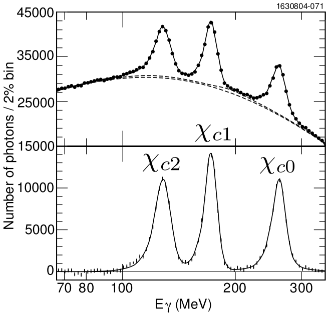
χ_{cJ} Decays

$\mathcal{B}(\psi(2S) \to \gamma\chi_{cJ}) \sim 9\%$ per state makes $\psi(2S)$ data very useful for probing χ_c properties

With 3×10^6 $\psi(2S)$ decays, can begin to perform Dalitz analysis on χ_{c1} decays!

Will discuss:

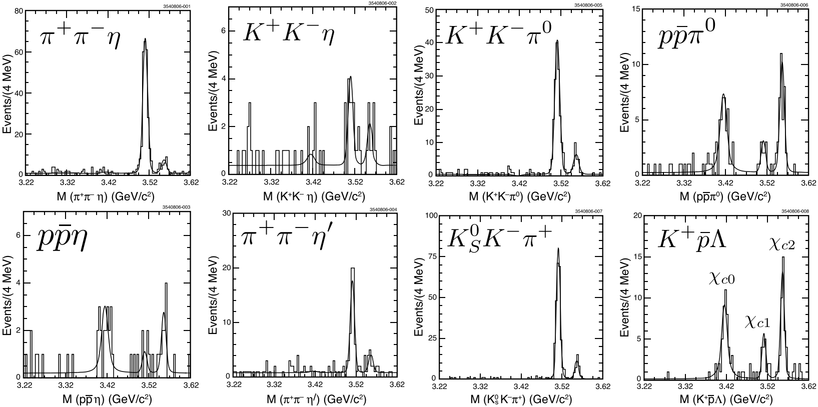
- A selection of three-body decays, Dalitz structure
- $\eta^{(\prime)}\eta^{(\prime)}$ decays



Inclusive photon spectrum from $\psi(2S)$ decays showing peaks for $\gamma\chi_{cJ}$ transitions (PRD **70**, 112002 (2004))

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

Preliminary CLEO CONF 06-9



- Not exhaustive three-body decay list
- Peaks clearly separated
  - We actually see signals in modes with charged multiplicity up to 8, and modes with multiple neutrals

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

Preliminary branching fractions (%):

Mode	χ_{c0}	χ_{c1}	χ_{c2}
$\eta\pi^+\pi^-$	< 0.021	$0.52 \pm .03 \pm .03 \pm .03$	$0.051 \pm .011 \pm .004 \pm .003$
ηK^+K^-	< 0.024	$0.034 \pm .010 \pm .003 \pm .002$	< 0.033
$\eta p\bar{p}$	$0.038 \pm .010 \pm .003 \pm .02$	< 0.015	$0.019 \pm .007 \pm .002 \pm .002$
$\eta'\pi^+\pi^-$	< 0.038	$0.24 \pm .03 \pm .02 \pm .02$	< 0.053
$\pi^0 K^+K^-$	< 0.006	$0.200 \pm .015 \pm .018 \pm .014$	$0.032 \pm .007 \pm .002 \pm .002$
$\pi^0 p\bar{p}$	$0.059 \pm .010 \pm .006 \pm .004$	$0.014 \pm .005 \pm .001 \pm .001$	$0.045 \pm .007 \pm .004 \pm .003$
$\overline{K}^0 K^+\pi^-$ *	< 0.010	$0.84 \pm .05 \pm .06 \pm .05$	$0.15 \pm .02 \pm .01 \pm .01$
$\Lambda K^+\bar{p}$*	$0.114 \pm .016 \pm .009 \pm .007$	$0.034 \pm .009 \pm .003 \pm .002$	$0.088 \pm .014 \pm .007 \pm .006$

* includes charge conjugate

- CsI resolution allows easy access to the π^0 and η modes
- Most are first measurements or vastly improved limits

$\chi_{c1} \to h^+ h^- h^0$ Dalitz

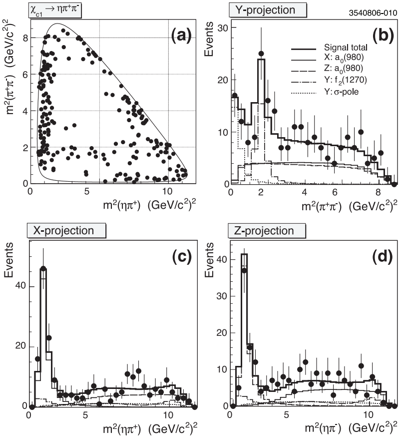
- Sufficient statistics in $\chi_{c1} \to \pi^+\pi^-\eta$ and $KK\pi$ to investigate substructure, but:
  - χ_{c1} polarization depends on polar angle, so *should* do a partial wave analysis, but not enough events
  - Instead do "incoherent" analysis where intermediate states don't interfere
  - Account for angular distributions from a spin 1 decay (assume random parent polarization)
- Use isospin to relate amplitudes contributing to $\overline{K}^0 K^+\pi^-$, $K^0 K^-\pi^+$, $K^+K^-\pi^0$ and fit simultaneously; this results in e.g.

$$a_{K^{*+}} = a_{K^{*-}} = a_{K^{*0}} = a_{\overline{K}^{*0}}$$

$\chi_{c1} \to \pi^+\pi^-\eta$ Dalitz

- Dominant features: $a_0(980)\pi$ and $f_2(1270)\eta$
- Significant contribution from low-mass $\pi^+\pi^-$, parametrized with a simple "σ-pole"

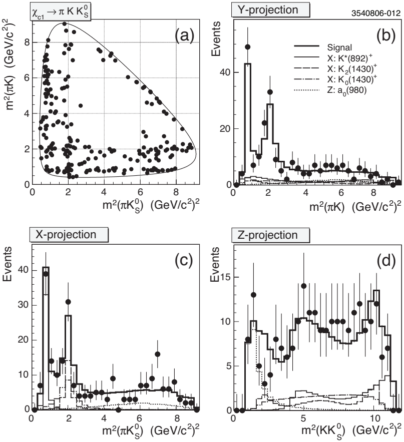
Preliminary



Prob 66%

$\chi_{c1} \to KK\pi$ Dalitz

Preliminary



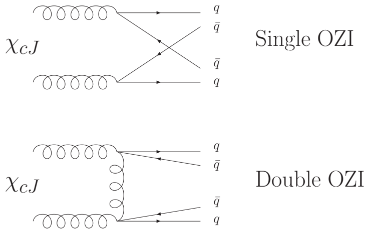
- $K^*(892)$, $K_0^*(1430)$, $K_2^*(1430)$, $a_0(980)$ seen
- Non-resonant component or κ doesn't improve fit probability

$\chi_{c1} \to K_S^0 K\pi$ only

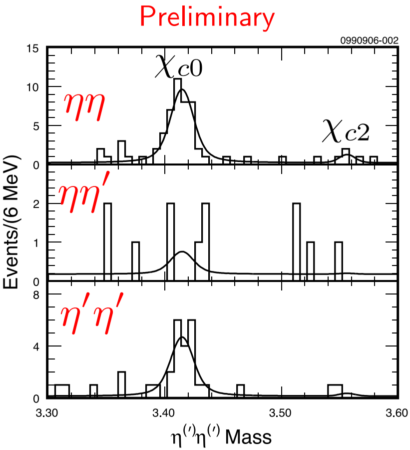
Prob 73%

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

- Probe ratios of singly and doubly OZI-suppressed diagrams (Q. Zhou, PRD **72**, 074001 (2005))
- Reconstruct:
  - $\eta \to \gamma\gamma$, $\pi^+\pi^-\pi^0$, $\pi^+\pi^-\gamma$
  - $\eta' \to \pi^+\pi^-\eta$, $\pi^+\pi^-\gamma$
- Combine two $\eta^{(\prime)}$ candidates to form a χ_{cJ}, then combine with a photon to obtain a $\psi(2S)$
  - Don't use $\chi_{cJ} \to 4\gamma$ mode due to inefficient trigger in CLEO III
- $\chi_{c1} \to PP$ forbidden



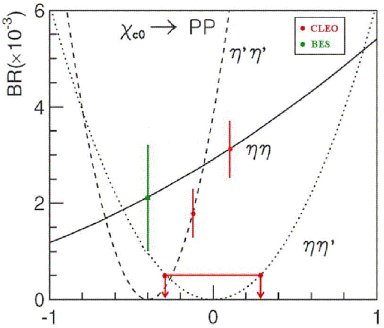
$\chi_{cJ} \to \eta^{(\prime)}\eta^{(\prime)}$



Branching fractions (%):

Mode	χ_{c0}	χ_{c2}
$\eta\eta$	$0.31 \pm .05 \pm .04 \pm .02$	< 0.047
$\eta\eta'$	< 0.050	< 0.023
$\eta'\eta'$	$0.17 \pm .04 \pm .02 \pm .01$	< 0.031

Third uncertainty from $\mathcal{B}(\psi(2S) \to \gamma\chi_{cJ})$



CLEO, BES results on plot from Zhou
x-axis is DOZI/SOZI amplitude ratio

$\psi(2S) \to \eta_c 3\pi$

Suggestion that $\psi(2S)$ does not annihilate directly to three gluons, but instead the $c\bar{c}$ pair survives soft gluon emission (Artoisenet *et al.*, PL B**628**, 211 (2005))

Estimate $\mathcal{B}(\psi(2S) \to \eta_c \pi^+\pi^-\pi^0) \sim \mathcal{O}(1\%)$
$(> \mathcal{B}(\psi(2S) \to \gamma\eta_c)!)$

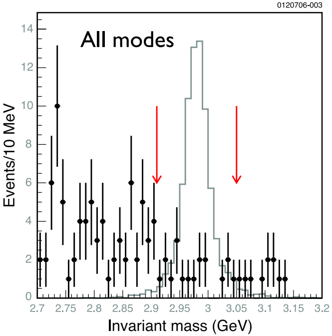
CLEO searches for this mode, reconstructing exclusive η_c decays:

η_c decay mode	Branching ratio (%)
$K^+K^-\pi^0$	0.95 ± 0.27
$\eta\pi^+\pi^-$, $\eta \to \gamma\gamma$	1.288 ± 0.473
$\eta\pi^+\pi^-$, $\eta \to \pi^+\pi^-\pi^0$	0.738 ± 0.271
$K^+K^-\pi^+\pi^-$	1.5 ± 0.6
$\pi^+\pi^-\pi^+\pi^-$	1.2 ± 0.3
$K^-K^0\pi^+$*	3.8 ± 1.1

* $K^-K^0\pi^+$ searched for both in $K_S \to \pi^+\pi^-$ and in $K^-4\pi$ recoil mass.

- $\psi(2S) \to J/\psi + X$ vetoed
- Positive particle ID for all tracks
- $0.98 < \text{Visible energy}/E_{cm} < 1.02$
- Efficiency $\sim 0.8\% - 3.1\%$ depending on mode
- 90% upper limit: 1.1×10^{-3}

Preliminary



Histogram: MC expectation from $\mathcal{B}(\psi(2S) \to \eta_c 3\pi) = 1\%$

$Y(4260)$

New state $Y(4260)$ seen by BaBar in $e^+e^- \to \gamma_{ISR}\pi^+\pi^- J/\psi$
(PRL **95**, 142001 (2005))

For ISR production must be 1^{--} state, but not at an expected mass for a charmonium vector

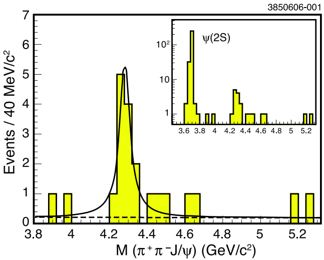
$\Gamma(Y(4260) \to \pi^+\pi^- J/\psi)$ much larger than expected for above-threshold charmonium

CLEO has two confirmations of BaBar signal:

- Same mode using CLEO III Υ data
- Direct production at $E_{cm} = 4.26$ GeV

$Y(4260)$ in ISR

- Uses 13.3 fb^{-1} taken from the $\Upsilon(1S)$ to the $\Upsilon(4S)$
- Reconstruct $\pi^+\pi^-e^+e^-$ and $\pi^+\pi^-\mu^+\mu^-$
- Leptons kinematically fit to J/ψ mass; Y mass resolution ~ 5 MeV
- 4.9σ detection; excellent signal to background



Submitted to PRD-RC

Fit to single Gaussian-smeared Breit-Wigner + ISR cross-sections gives:

$$M = 4284\,^{+17}_{-16} \pm 4 \text{ MeV}$$
$$\Gamma = 73\,^{+39}_{-25} \pm 5 \text{ MeV}$$
$$\Gamma_{ee}\mathcal{B}(Y \to \pi^+\pi^- J/\psi) = 8.9\,^{+3.9}_{-3.1} \pm 1.9 \text{ eV}$$

No suggestion of multiple resonances

$Y(4260)$ direct production

Can produce $Y(4260)$ directly in e^+e^- collisions at the appropriate energy

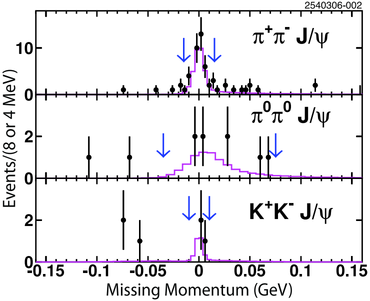
- Clean, high rate, and sensitive to rarer decays, but
- Cannot probe lineshape without a scan

Use same apparatus as for $\psi(3770) \to \pi^+\pi^- J/\psi$

Use 13.2 pb^{-1} at 4.26 GeV (+ other points at $E_{cm} = 3.97 - 4.20$ GeV)

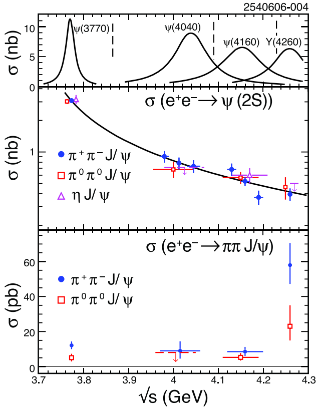
Signal is $\pi^+\pi^- J/\psi$ at zero missing momentum

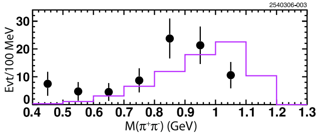
$E_{cm} = 4260$ MeV



- Radiative return to $\psi(2S)$ checks analysis; consistent with expectations
- $\pi^0\pi^0 : \pi^+\pi^-$ ratio suggests isospin zero (disfavors e.g. $\rho^0\chi_{cJ}$ molecule)
- Evidence for K^-K^+ transition
- Lower charmonium states have small $\pi^+\pi^- J/\psi$ couplings: disfavors $Y(4260)$ enhancement through $\psi(3S)$ mixing
- **No sign of $\sigma(600)$ or $f_0(980)$ in $\pi^+\pi^-$ mass distribution.**

Mode	σ (pb), $\sqrt{s} = 4260$ MeV
$\pi^+\pi^- J/\psi$	$58\,^{+12}_{-10} \pm 4$
$\pi^0\pi^0 J/\psi$	$23\,^{+12}_{-8} \pm 1$
$K^-K^+ J/\psi$	$9\,^{+9}_{-5} \pm 1$





PRL **96**, 162003 (2006)

Summary

- CLEO-c's detector and direct production of charm states enables clean and high-precision spectroscopy and measurements of $c\bar{c}$ decays
- Hadronic and radiative transitions have been seen from $\psi(3770)$
- $Y(4260)$ decays have been probed
- We will soon be able to analyze a $\psi(2S)$ dataset $\approx$ 8 times larger
- There's a lot of excitement ahead!