CLEO Charmonium Results

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For the CLEO Collaboration

Outline

- Charmonium Above the $c\bar{c}$ Threshold
- Charmonium Below the $c\bar{c}$ Threshold and $\psi(3770)$
- Using $\psi(2S)$ Decays to Study the η
- Summary and Conclusions

Principal Data Sets

Data Set	Luminosity	Events
$\psi(2S)$	54 pb^{-1}	27×10^6
$\psi(3770)$	281 pb^{-1}	1.8×10^6

$\psi(2S)$ measurements use 3M events, about half CLEO III and half CLEO-c

CLEO detectors have excellent and well-understood:

- acceptance
- efficiency
- resolution
- particle identification

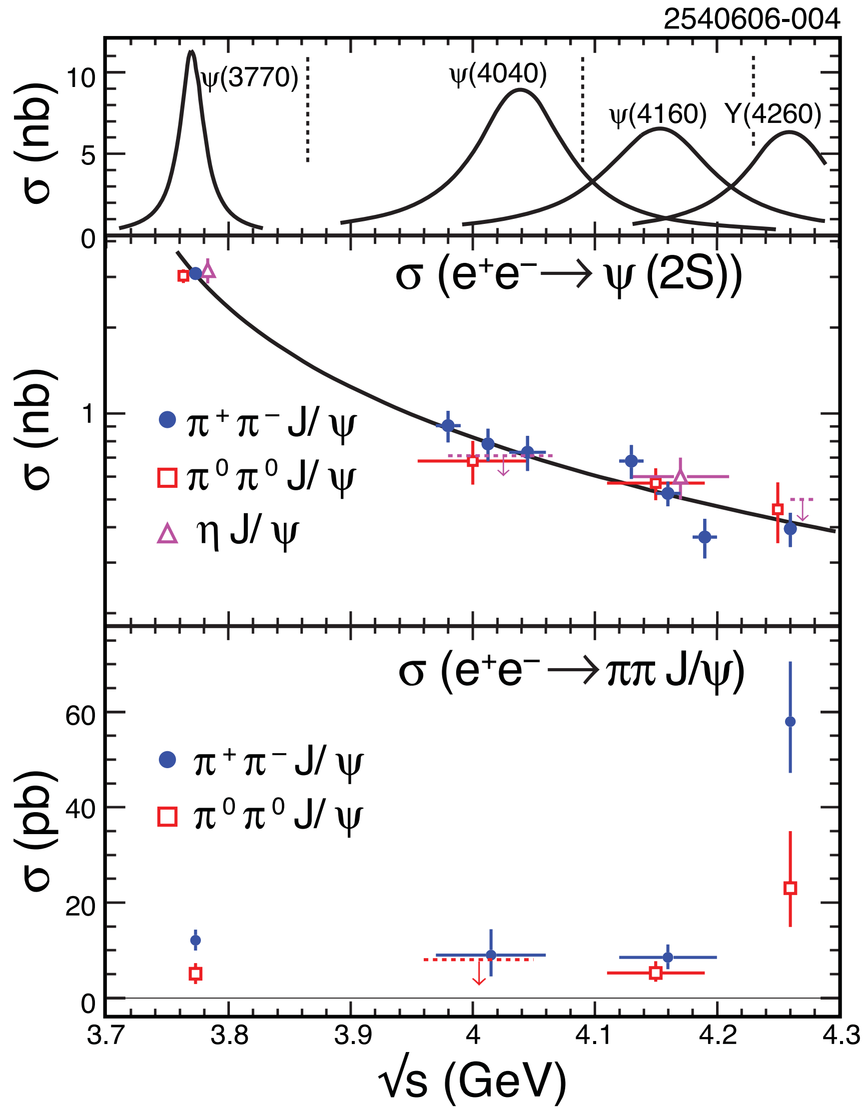
EPS HEP2007 Conference
Manchester, July 19, 2007

Charmonium Decays of $Y(4260)$, $\psi(4160)$, and $\psi(4040)$

Several states above the $D\bar{D}$ threshold:

- $\psi(4160)$ and $\psi(4040)$ known
- BaBar discovered $Y(4260)$ in ISR $e^+e^- \to \gamma\pi^+\pi^- J/\psi$
  - Confirmed by CLEO in ISR
- Little is know about these states
  - Next step is understanding decays
- CLEO searched for 16 decay modes of $Y(4260)$, $\psi(4160)$, and $\psi(4040)$ with $\psi(2S)$, χ_{cJ}, J/ψ, or ϕ in the final state
  - Significant signals found in $Y(4260) \to \pi^+\pi^- J/\psi$ and $\pi^0\pi^0 J/\psi$
    - $\pi^+\pi^- J/\psi$ confirms BaBar again with high statistics
    - $\pi^0\pi^0 J/\psi$ disagrees with $\chi_{cJ}\rho^0$ molecular model
    - $\mathcal{B}(\pi^0\pi^0 J/\psi)/\mathcal{B}(\pi^+\pi^- J/\psi)$ disagrees with baryonium model
    - Hint of $K^+K^- J/\psi$ disagrees with both models

CLEO Results



$\pi^+\pi^- J/\psi$ and $\pi^0\pi^0 J/\psi$ signals at 4160 MeV due to low-side tail of the $Y(4260)$

$X(3872)$ and the Mass of the D^0

$X(3872)$ discovered by Belle may be a loosely bound $D^0\bar{D}^{0*}$ state

- Binding energy from PDG 06
  $E_B = M(D^0) + M(\bar{D}^{0*}) - M(X(3872)) = -0.9 \pm 2.1$ MeV
- Clearly more precision required
- $M(D^0)$ error significant

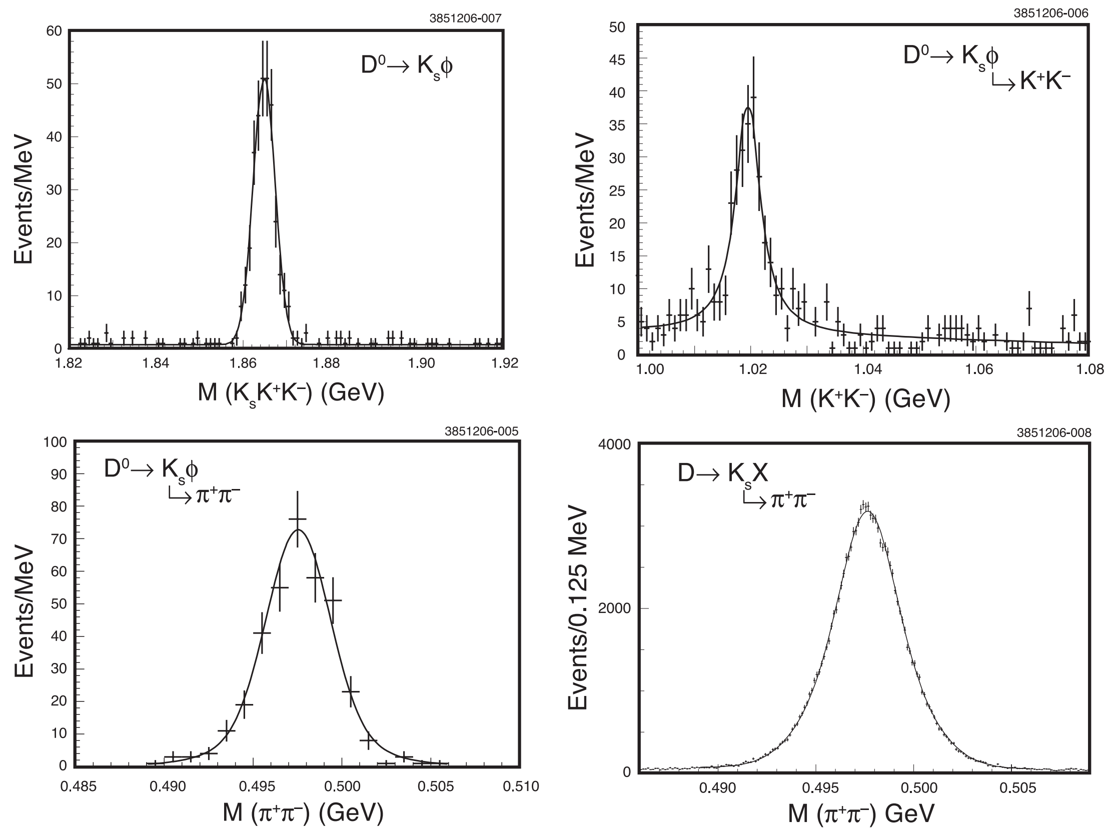
Measure $M(D^0)$ using
$D^0 \to K_S^0\phi$
Advantages:

- $M(K_S^0)$ and $M(\phi)$ well measured
- Beam energy not important
- Daughter momenta small
- Kinematic constraints
- Large $D^0\bar{D}^0$ data sample

$M(D^0) =$
$1864.847 \pm 0.150 \pm 0.095$ MeV$/c^2$

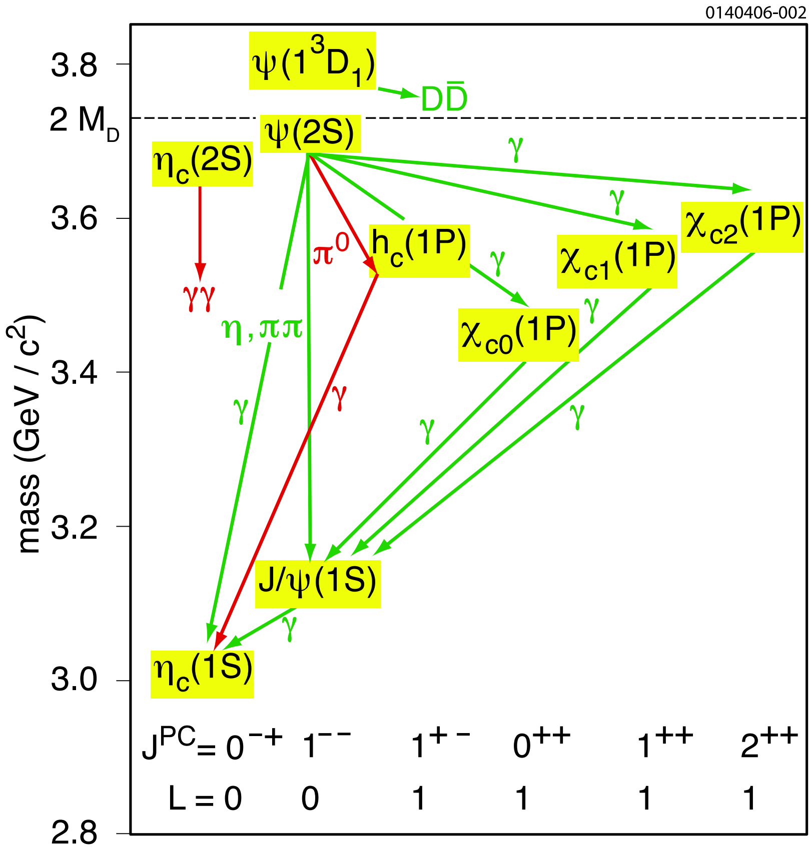
$X(3872)$: $E_B = 0.6 \pm 0.6$ MeV

$D^0 \to K_S^0\phi$ data



Charmonium Below the $D\bar{D}$ Threshold and $\psi(3770)$

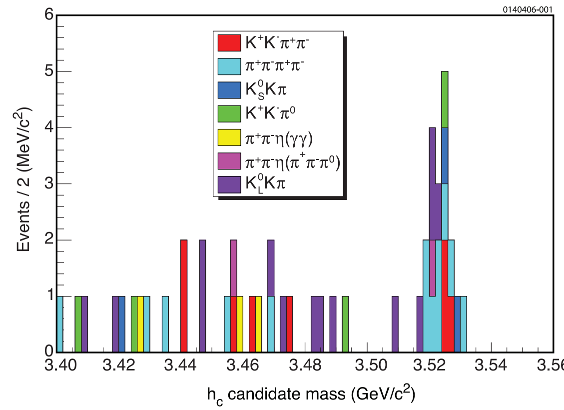
Spectroscopy



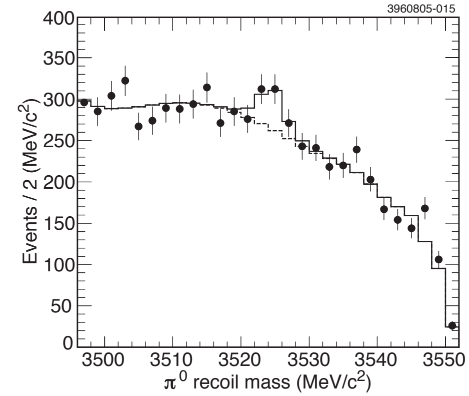
h_c discovery using $\psi(2S) \to \pi^0 h_c$ & $h_c \to \eta_c\gamma$

$M(h_c)$ from π^0 recoil

η_c reconstruction



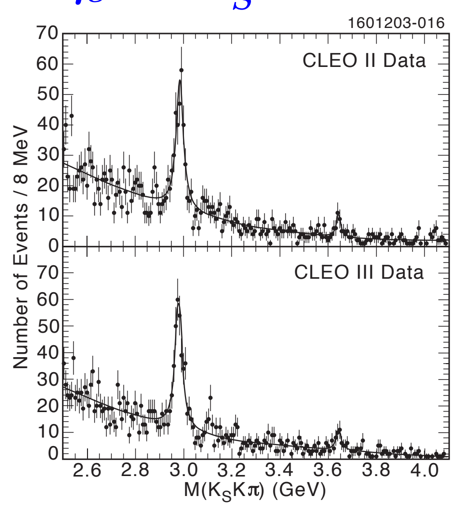
E_γ cut



$\eta_c(2S)$ Confirmation

$\psi(2S) \to \gamma\eta_c$

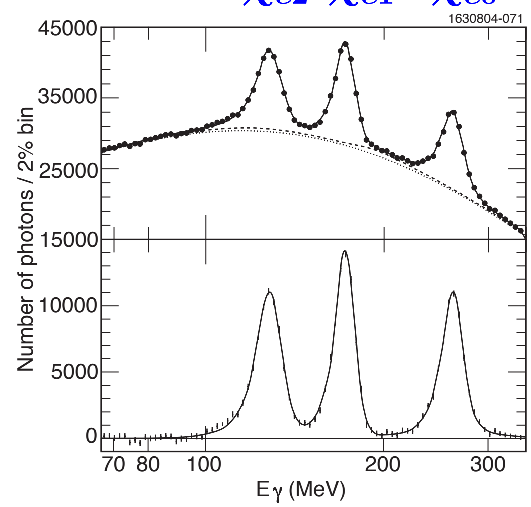
$\eta_c \to K^0_S K^\pm \pi^\mp$



χ_{cJ} Spectroscopy

$\psi(2S) \to \gamma\chi_{cJ}$

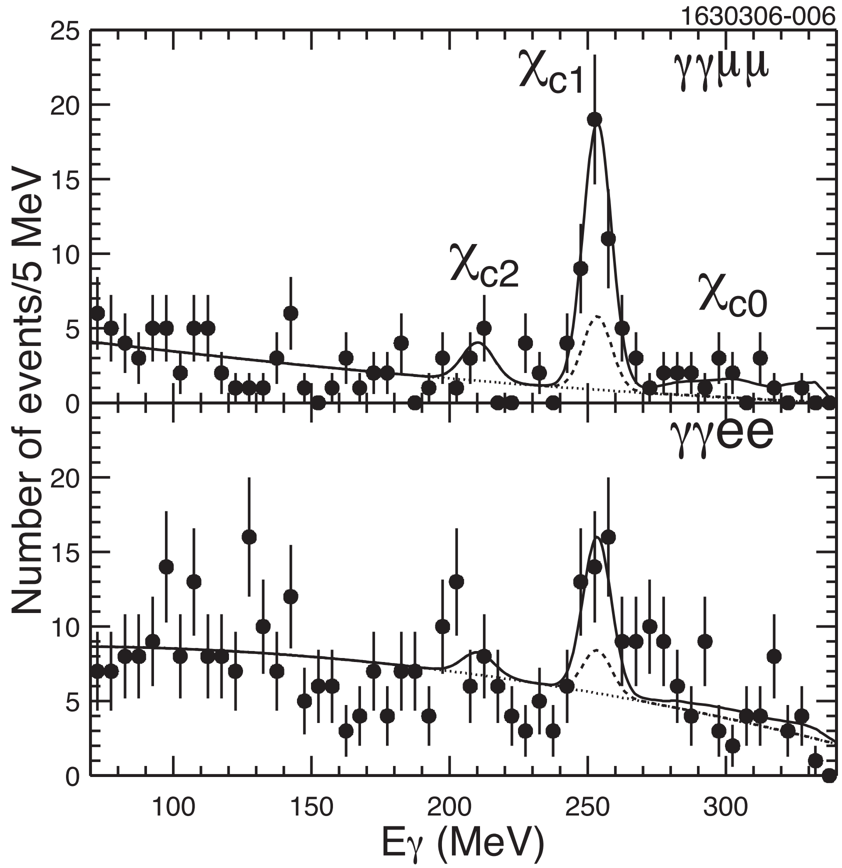
χ_{c2} χ_{c1} χ_{c0}



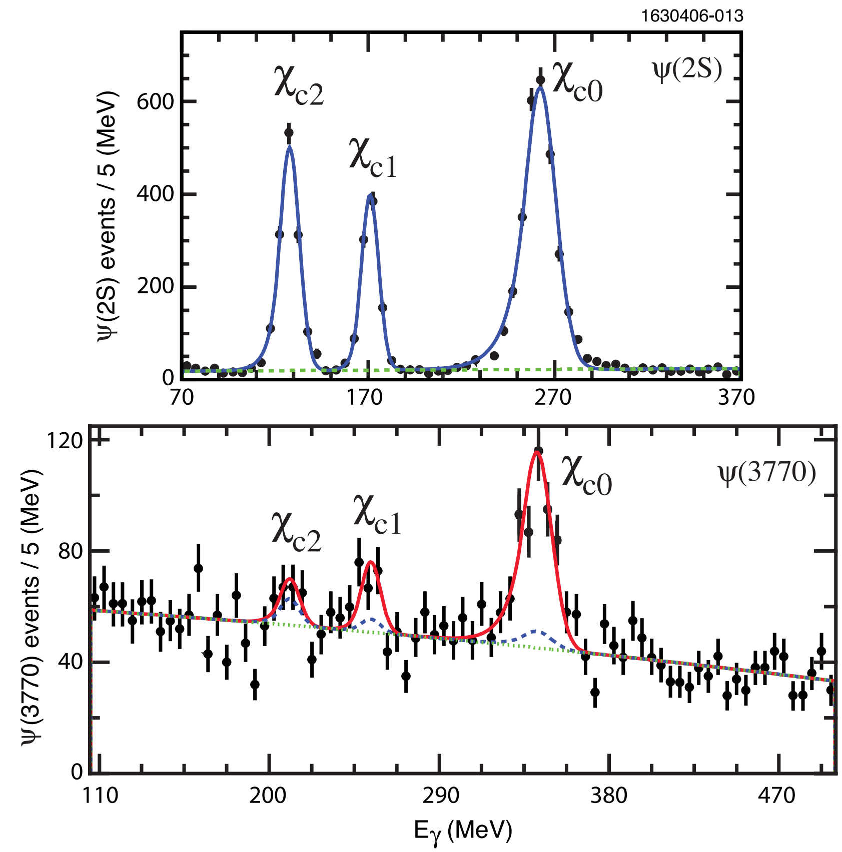
$\psi(3770) \to \gamma\chi_{cJ}$

CLEO observed $\psi(3770) \to \gamma\chi_{cJ}$ decays in two independent analyses

$\psi(3770) \to \gamma\chi_{cJ} \to \gamma\ell^+\ell^-$



$\psi(3770) \to \gamma\chi_{cJ}$ & $\chi_{cJ} \to$ hadrons



Pattern of branching fractions agrees with *relativistic* calculations

Reinforces interpretation of $\psi(3770)$ as primarily a $^3D_1$ $c\bar{c}$ state

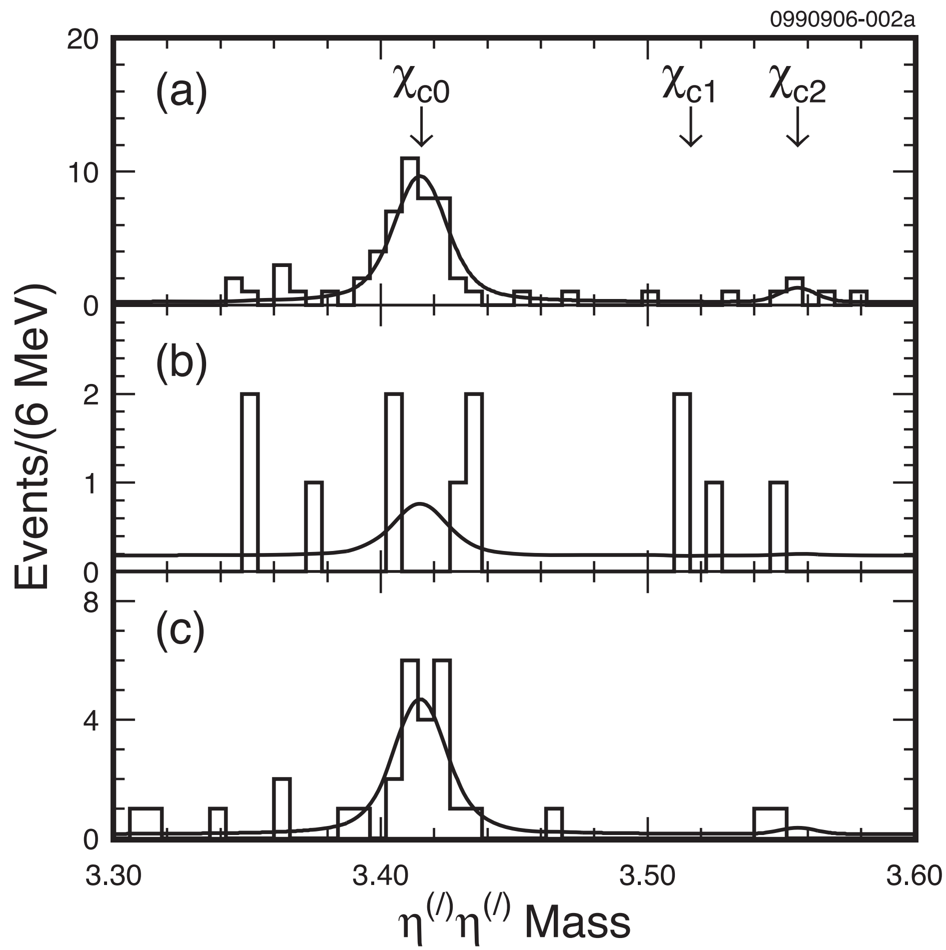
χ_{c0} and χ_{c2} Decays to $\eta\eta$, $\eta\eta'$, and $\eta'\eta'$

Search for $\psi(2S) \to \gamma\chi_{cJ}$ followed by $\chi_{cJ} \to \eta^{(\prime)}\eta^{(\prime)}$ in 3 M $\psi(2S)$ decay events

- Motivations
  - $\eta\eta$, $\eta\eta'$, and $\eta'\eta'$ are simple final states
  - Can illuminate the quark and gluon nature of the χ_{cJ} and the daughters (Q. Zhao)
- Results
  - $\mathcal{B}(\chi_{c0} \to \eta\eta) = (0.31 \pm 0.05 \pm 0.04)\%$
  - $\mathcal{B}(\chi_{c0} \to \eta'\eta') = (0.17 \pm 0.04 \pm 0.02)\%$
  - Upper limits for other modes
- In the model of Q. Zhao, these results imply that single-OZI suppression dominates double-OZI suppression in these decays

CLEO data

Mode



$\eta\eta$

$\eta'\eta$

$\eta'\eta'$

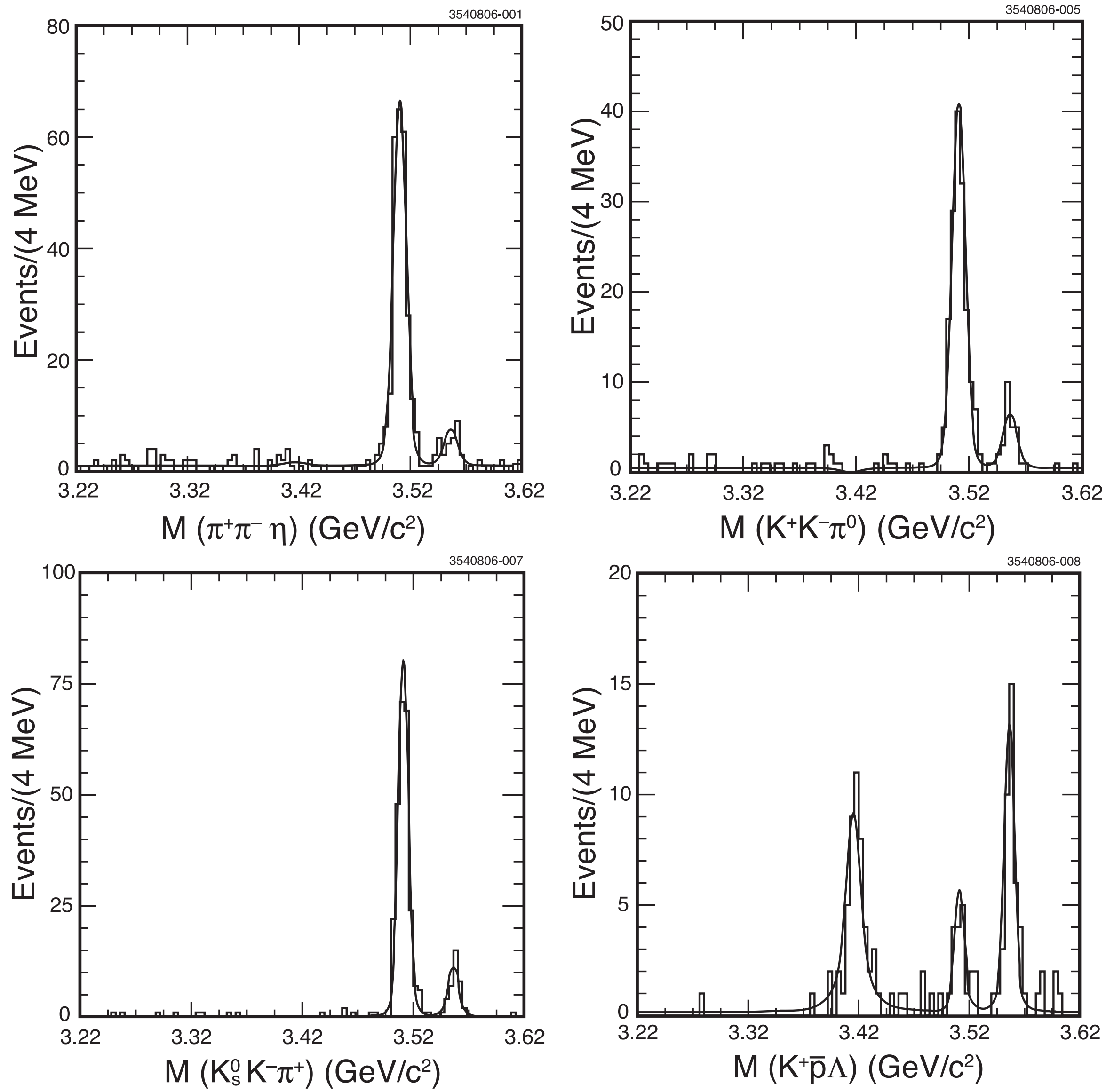
$\chi_{c1} \to \eta^{(\prime)}\eta^{(\prime)}$ forbidden by spin-parity

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

CLEO searched in 3M events for signals in 8 modes and all χ_{cJ}

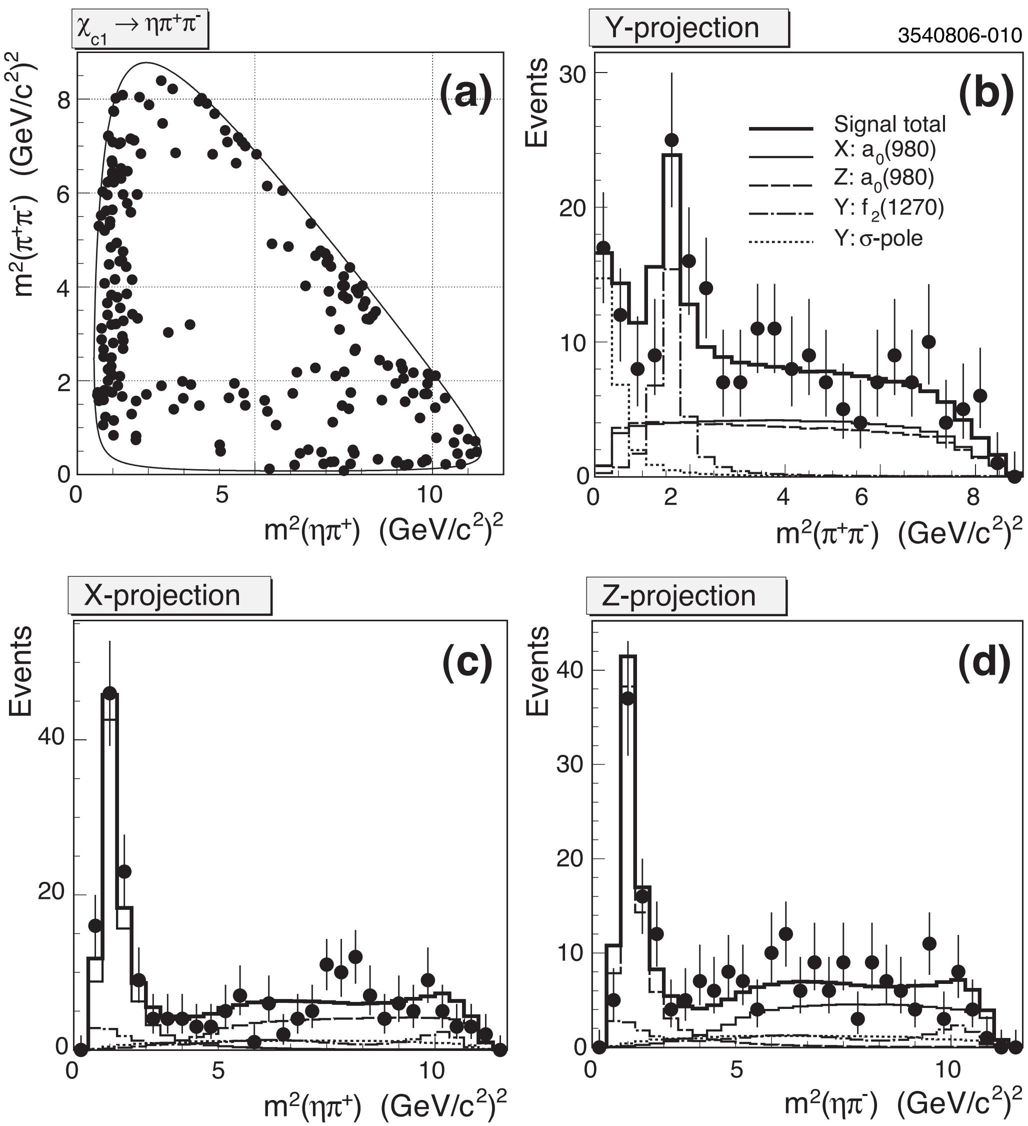
- $\pi^+\pi^-\eta$
- $K^+K^-\eta$
- $p\bar{p}\eta$
- $\pi^+\pi^-\eta'$
- $K^+K^-\pi^0$
- $p\bar{p}\pi^0$
- $K^-K^0_S\pi^+$
- $K^+\bar{p}\Lambda$
- Significant signals found for most of the 24 mother-daughter pairs
- Enough events for simple Dalitz analyses in $\pi^+\pi^-\eta$, $K^+K^-\pi^0$, and $K^-K^0_S\pi^+$
  - Ignored interference

CLEO data



$\chi_{cJ} \to \pi^+\pi^-\eta$

$\chi_{cJ} \to \pi^+\pi^-\eta$



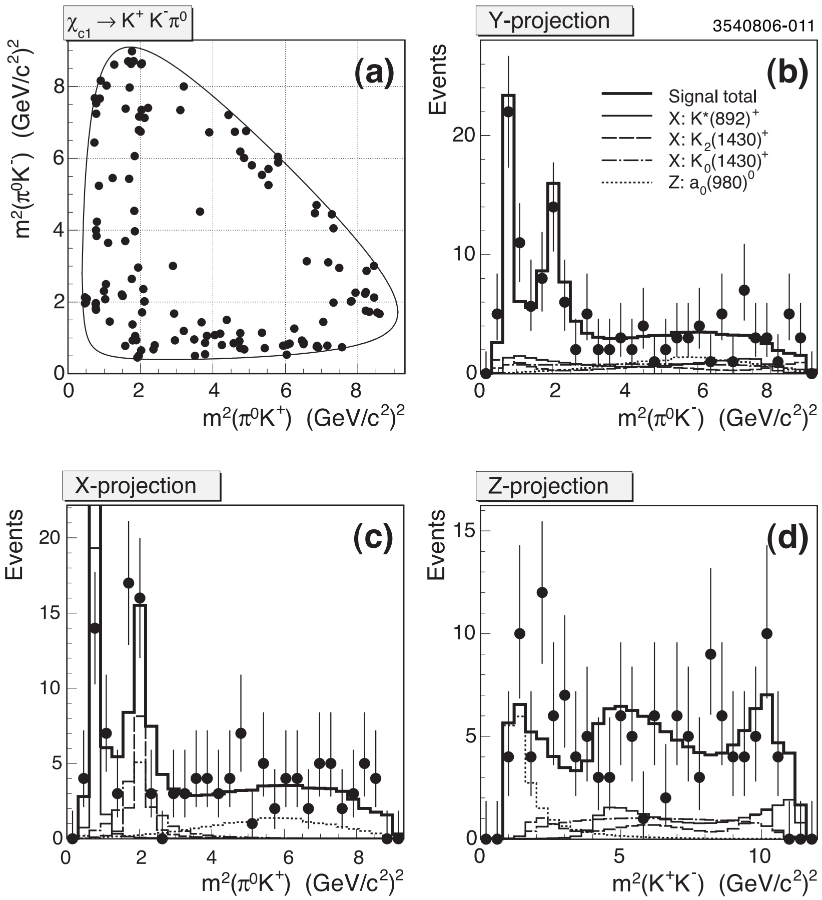
Non-interfering Dalitz analysis:

Mode	Fit Fraction (%)
$a_0(980)^\pm\pi^\mp$	$75.1 \pm 3.5 \pm 4.3$
$f_2(1270)\eta$	$14.4 \pm 3.1 \pm 1.9$
$\sigma\eta$	$10.5 \pm 2.4 \pm 1.2$

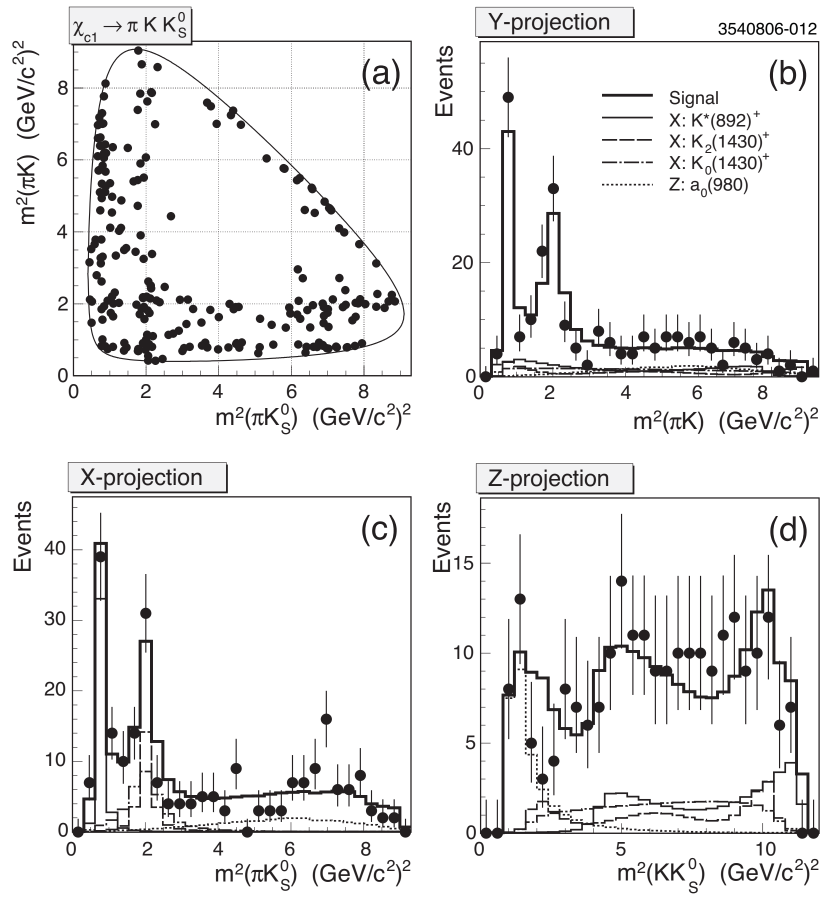
Data require low $\pi^+\pi^-$ mass contribution

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

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



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



Combined fit with isospin constraints

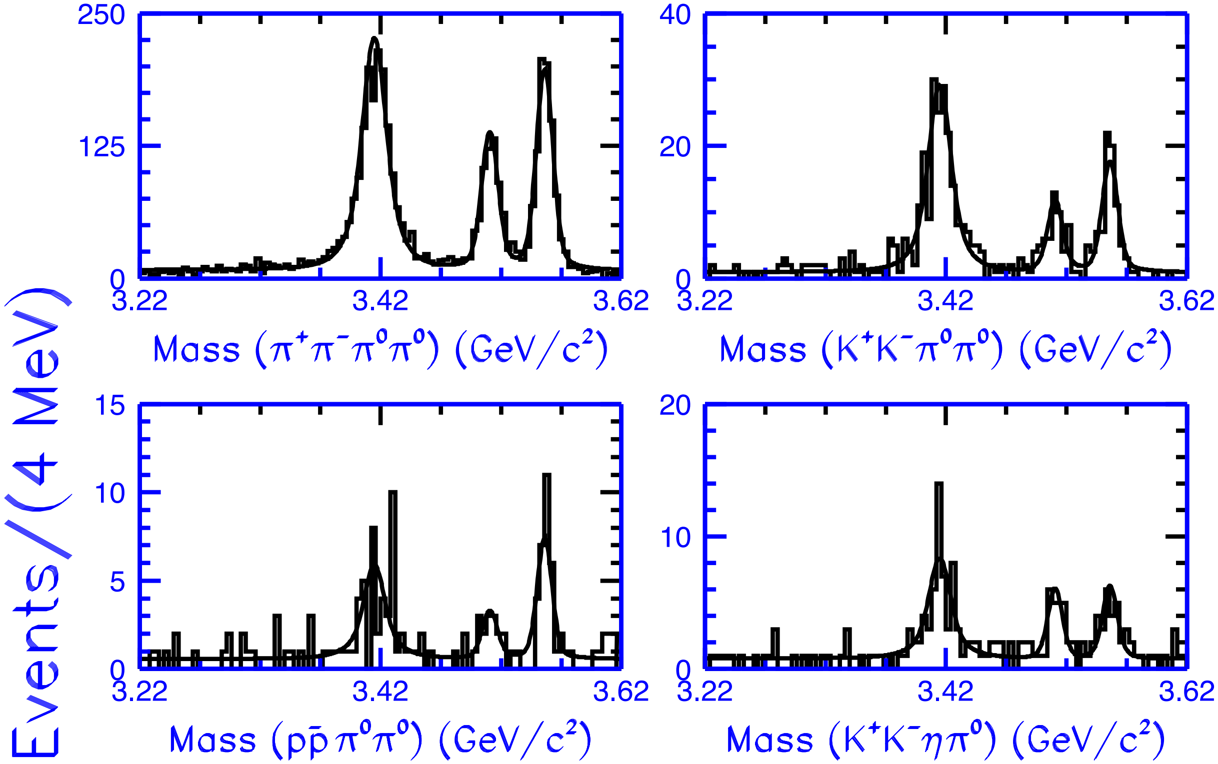
- Non-interfering Dalitz analysis
- Data do not require a κK contribution

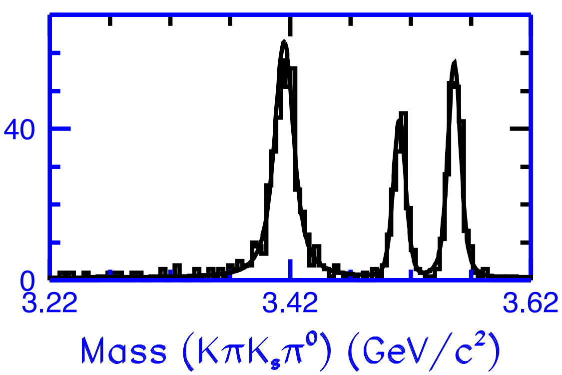
Mode	Fit Fraction (%)
$K^*(892)K$	$31.4 \pm 2.2 \pm 1.7$
$K_0^*(1430)K$	$30.4 \pm 3.5 \pm 3.7$
$K_2^*(1430)K$	$23.1 \pm 3.4 \pm 7.1$
$a_0(980)\pi$	$15.1 \pm 2.7 \pm 1.5$

χ_{cJ} Decays to Two Charged and Two Neutral Hadrons

$\psi(2S) \to \gamma\chi_{cJ}$ and $\chi_{cJ} \to h^+h^-h^0h'^0$ using 3M $\psi(2S)$ events **Preliminary**

CLEO data





Isospin related modes

Mode	χ_{c0}	χ_{c1}	χ_{c2}
	$\mathcal{B}$ (%)	$\mathcal{B}$ (%)	$\mathcal{B}$ (%)
$K^{*0}K^0\pi^0$	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

χ_{cJ} Decays to Two Charged and Two Neutral Hadrons

Fits for other decay modes **Preliminary**

Mode	χ_{c0}	χ_{c1}	χ_{c2}
	$\mathcal{B}$ (%)	$\mathcal{B}$ (%)	$\mathcal{B}$ (%)
$\pi^+\pi^-\pi^0\pi^0$	3.54±0.10±0.43±0.18	1.28±0.06±0.16±0.08	1.87±0.07±0.23±0.13
$\rho^+\pi^-\pi^0\pi^0$	1.48±0.13±0.18±0.08	0.78±0.09±0.09±0.05	1.12±0.08±0.14±0.08
$\rho^-\pi^+\pi^0\pi^0$	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

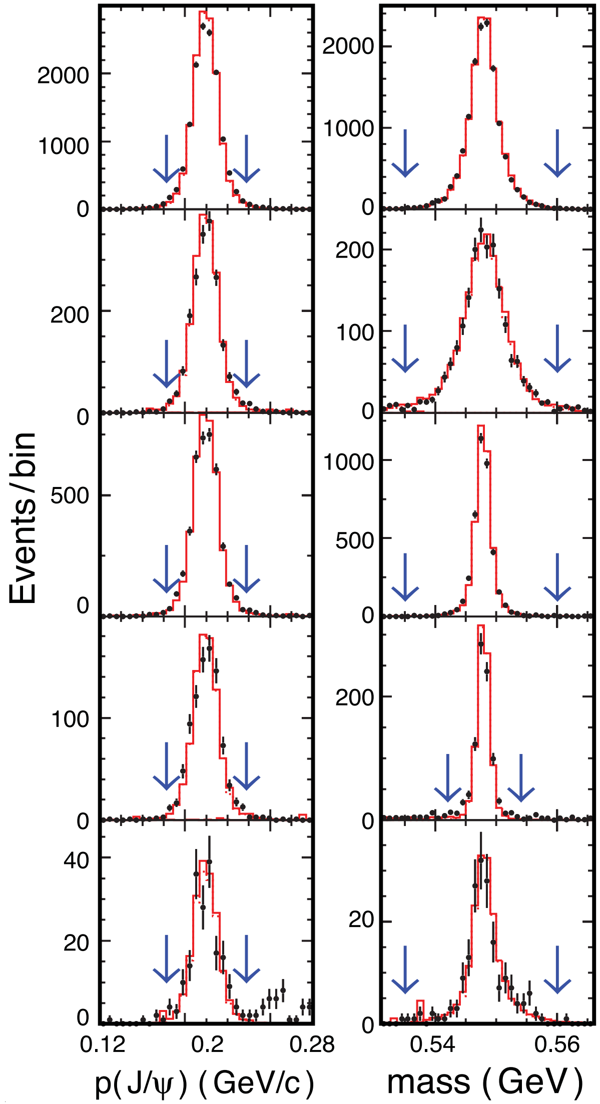
Very rich substructure of intermediate resonances

Measuring Prominent η Branching Fractions

PDG 06 gets η branching fractions from 43 measurements from many experiments

- CLEO measures the most important branching fractions using $\psi(2S) \to \eta J/\psi$
- 27 M $\psi(2S)$ events
  - CLEO fully reconstructs η decays to $\gamma\gamma$, $3\pi^0$, $\pi^+\pi^-\pi^0$, $\pi^+\pi^-\gamma$, and $e^+e^-\gamma$
  - Covers 99.88% of the PDG 07 total
  - Includes all branching fractions of $\mathcal{O}(0.1\%)$ or more
  - Consistent measurement of branching ratios in one experiment!
  - Very clean signals
  - Reconstruct $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$
  - Kinematically constrain $J/\psi \to \ell^+\ell^-$ and $\psi(2S) \to \eta J/\psi$
    - Do not constrain to the η mass

Kinematic Cuts | Mode



$\gamma\gamma$

$\pi^0\pi^0\pi^0$

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

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

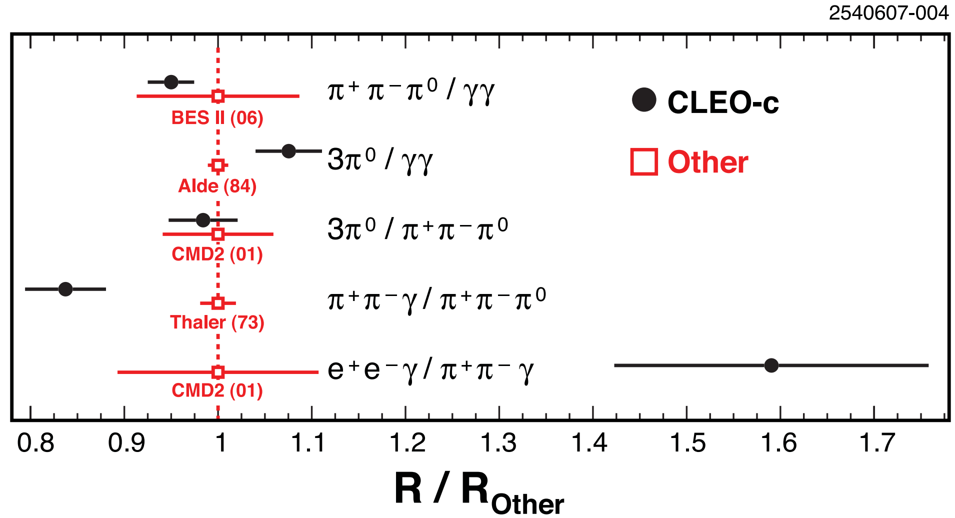
$e^+e^-\gamma$

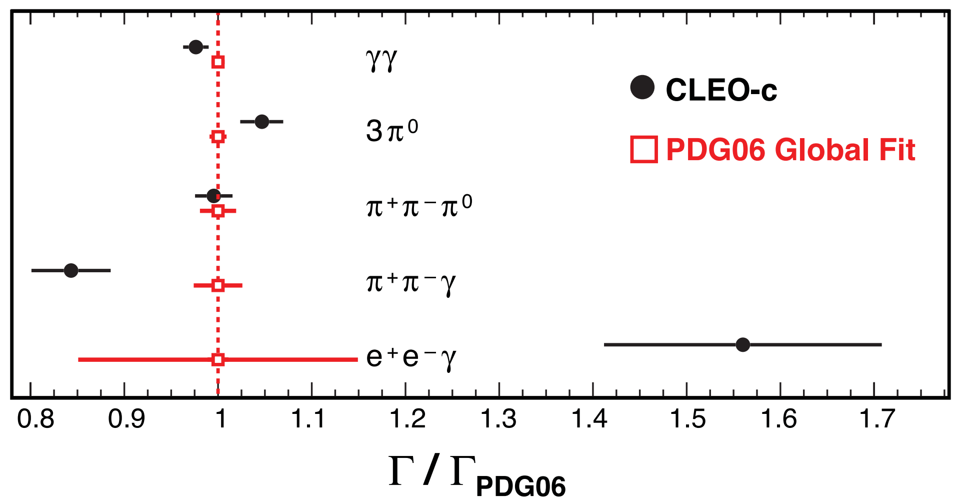
Measuring Prominent η Branching Fractions

Procedure

- Determine 8 branching ratios:
  - $\mathcal{B}(\pi^0\pi^0\pi^0)/\mathcal{B}(\gamma\gamma)$
    $\mathcal{B}(\pi^+\pi^-\pi^0)/\mathcal{B}(\gamma\gamma)$
    $\mathcal{B}(\pi^+\pi^-\gamma)/\mathcal{B}(\gamma\gamma)$
    $\mathcal{B}(e^+e^-\gamma)/\mathcal{B}(\gamma\gamma)$
    $\mathcal{B}(\pi^0\pi^0\pi^0)/\mathcal{B}(\pi^+\pi^-\pi^0)$
    $\mathcal{B}(\pi^+\pi^-\gamma)/\mathcal{B}(\pi^+\pi^-\pi^0)$
    $\mathcal{B}(e^+e^-\gamma)/\mathcal{B}(\pi^+\pi^-\pi^0)$
    $\mathcal{B}(e^+e^-\gamma)/\mathcal{B}(\pi^+\pi^-\gamma)$
  - Many systematic errors cancel
- Find individual branching fractions assuming that these 5 branching fractions add to 100%

Comparison to other measurements



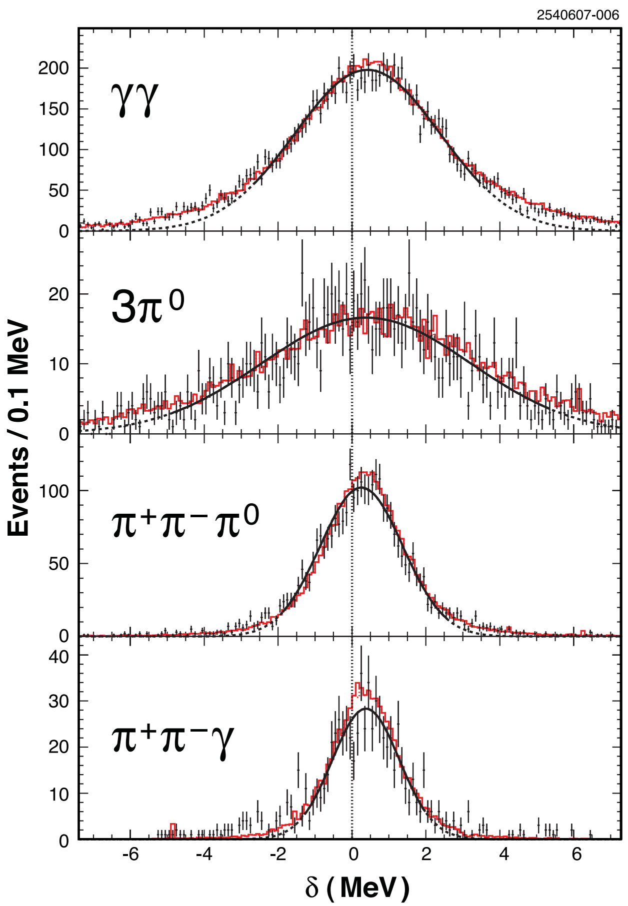


Measurement of the η Mass Using $\psi(2S) \to \eta J/\psi$

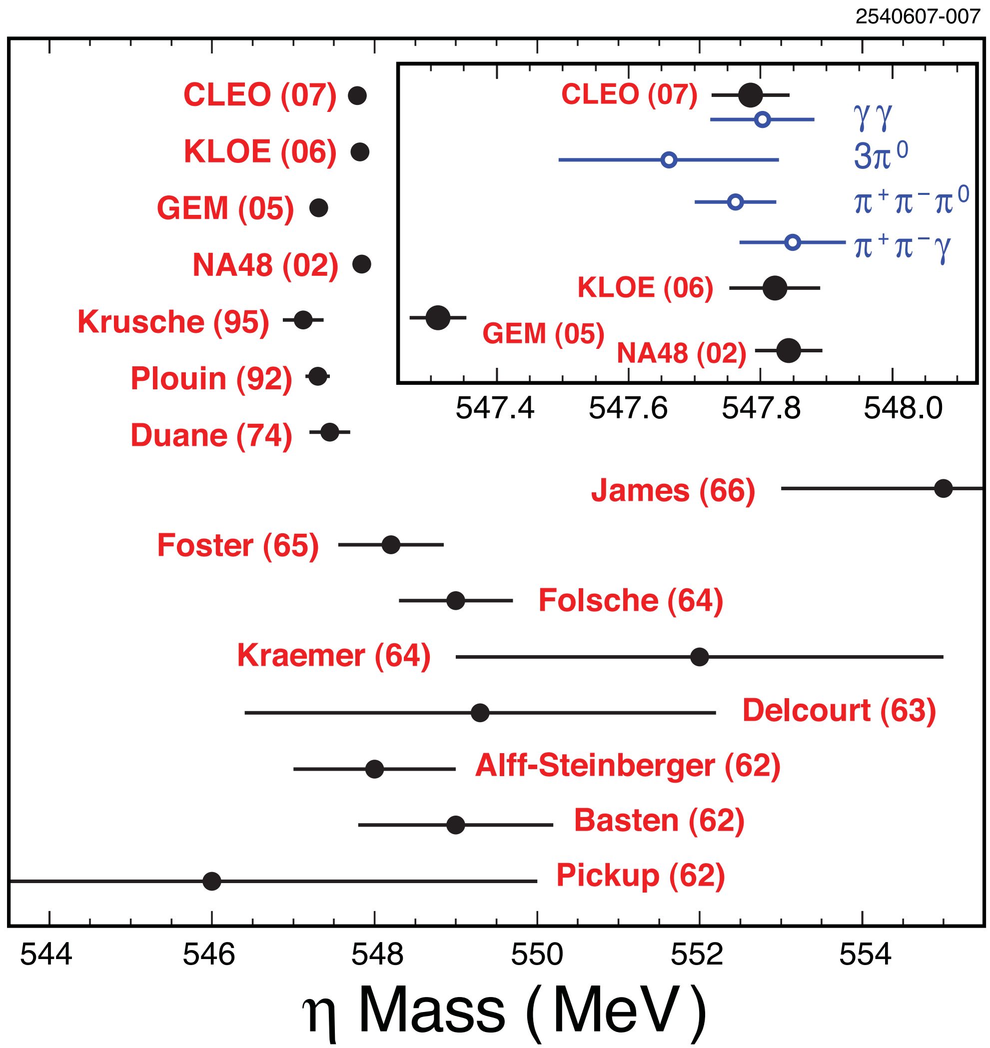
Prompted by disagreement: GEM (2005) differs from NA48 (2002) & KLOE (2006)
All three measurements have small quoted errors

- CLEO $M_\eta = 557.785 \pm 0.017 \pm 0.057$ MeV/c^2

$\delta \equiv M(CLEO) - M(PDG\ 06)$



Comparison to other measurements

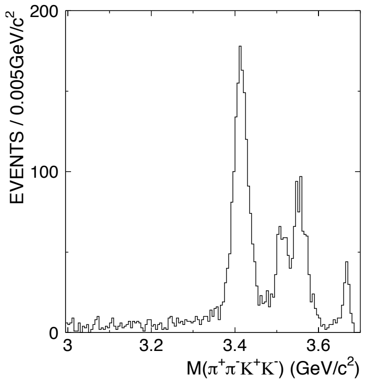


$\chi_{c0} \rightarrow K^+K^-\pi^+\pi^-$

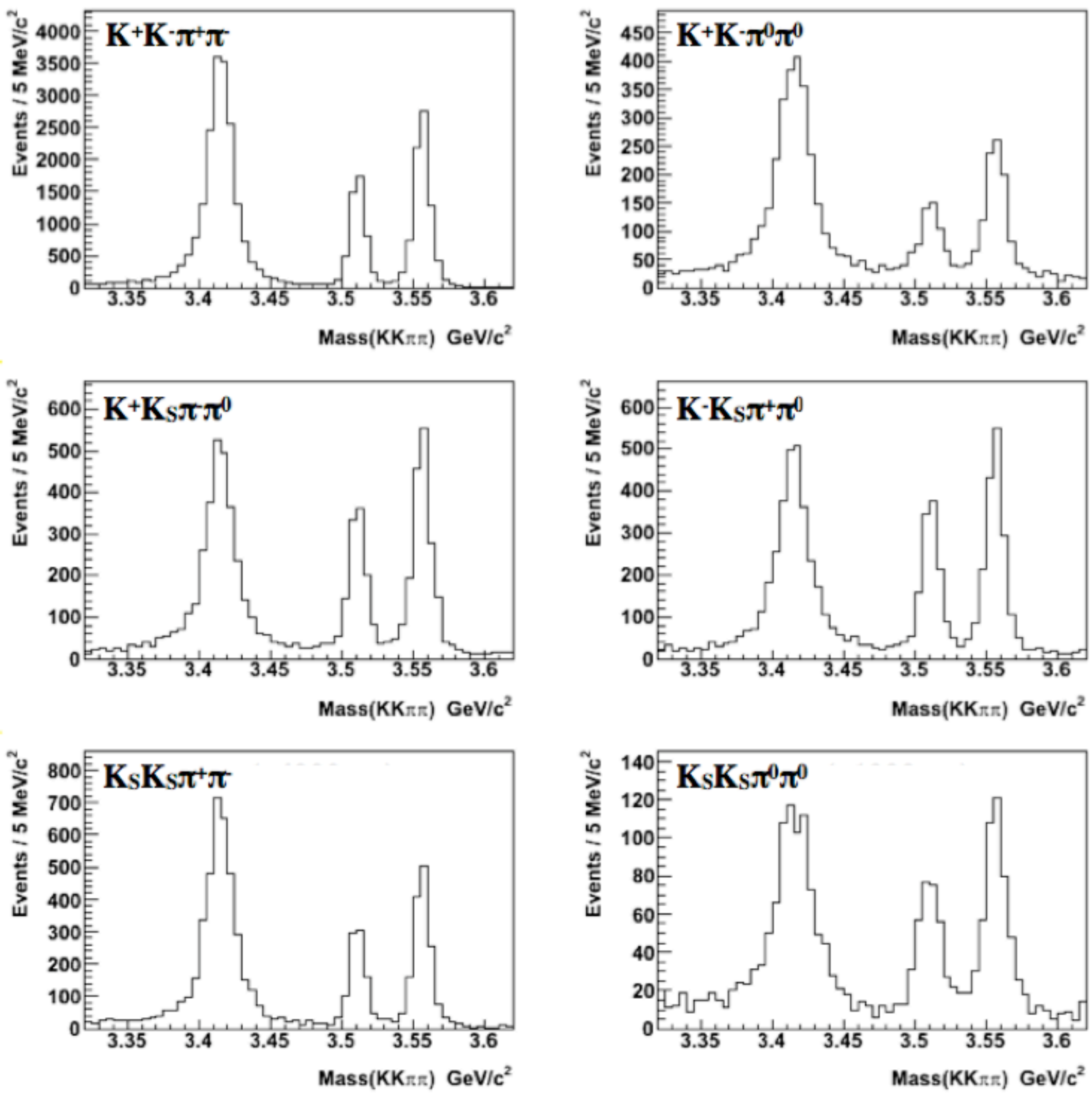
CLEO's 27M $\psi(2S)$ events show great promise for studying multibody decays

BESII 14M $\psi(2S)$

$K^+K^-\pi^+\pi^-$



CLEO 27M $\psi(2S)$



Summary and Conclusions

CLEO contributed significantly to charmonium physics using 3M $\psi(2S)$ events

- Charmonium decays of $Y(4260)$, $\psi(4160)$, and $\psi(4040)$
- Precision measurement of $M(D^0)$ impacts understanding of $X(3872)$
- Discovery of the h_c and confirmation of the $\eta_c(2S)$
- $\psi(3770) \to \gamma\chi_{cJ}$ reinforces interpretation of $\psi(3770)$ as primarily a $^3D_1$ $c\bar{c}$ state
- χ_{c0} and χ_{c2} decays to $\eta\eta$, $\eta\eta'$, and $\eta'\eta'$ suggest single-OZI suppression dominates double-OZI suppression
- Rich substructure in $\chi_{cJ} \to h^+h^-h^0$ decays from non-interfering Dalitz analysis
- Many $\chi_{cJ} \to h^+h^-h^0h'^0$ modes observed – Dalitz analyses of substructure next
- Precision measurements of η branching fractions and $M(\eta)$

All of these analyses can profit significantly from analysis of the full 27M $\psi(2S)$ data sample!