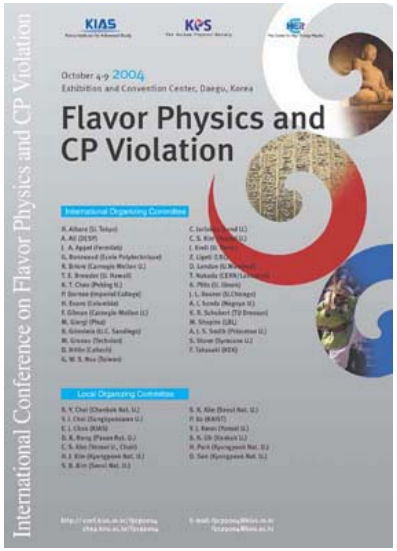
ψ' Decays and Transitions



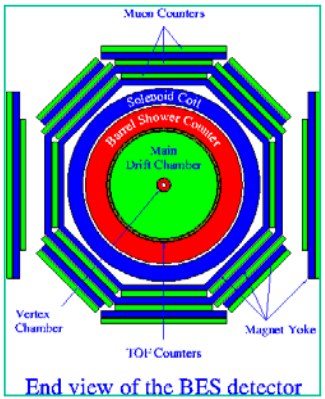
Daniel Cronin-Hennessy
University of Minnesota
CLEO Collaboration
FPCP '04
Daegu, Korea
Oct 4-9, 2004

Outline

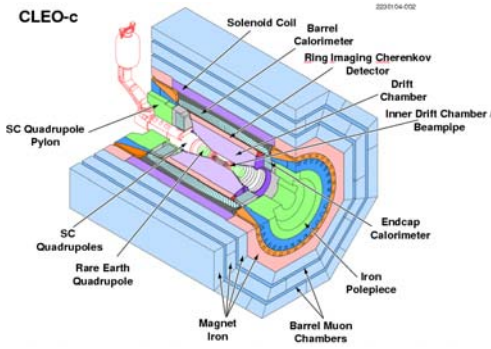
- Hadronic Decays of ψ'
- Radiative Decays of ψ'
- Search for h_c
- Future

Experiments

BESII



Variable	BESII	CLEO-c
Lum on Peak	19.7 /pb	6.1 /pb
#of ψ(3685)	14.0 E6	3.1 E6
Below Resonance Lum	6.4 /pb @3.65 GeV	20.5 /pb @3.67 GeV
Tracking acc	80%	93%
Tracking res.	2%	0.3% (.5-1 GeV/c)
Calorimeter acc.	75%	95%
Calorimeter Res	21%	2.1% (1 GeV)



CLEO-c

More ψ′ events (~4X)

History of charmonium analyses

More off-resonance data

State-of-the-art detector

Competitive and complementary experiments!

Hadronic Decays

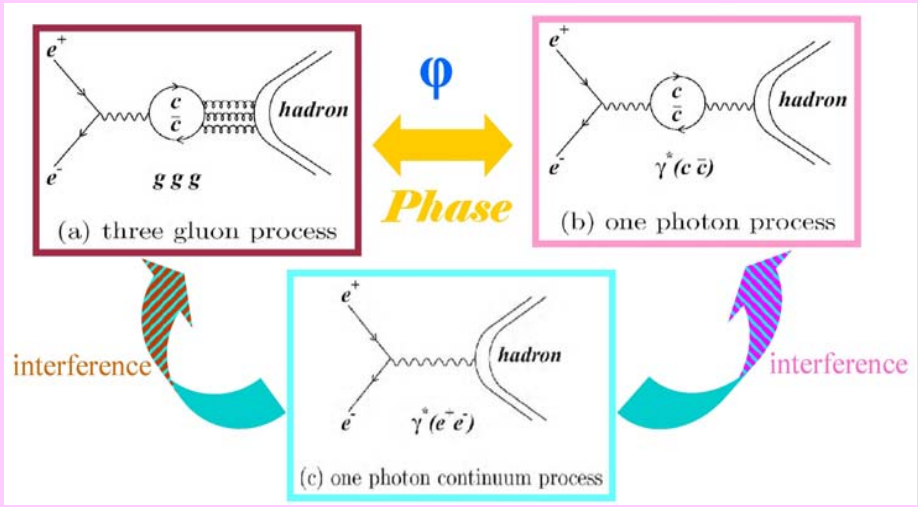
Motivation:
ψ' decay to hadrons proceeds through annihilation of c and $\bar{c}$.

Therefore expectation of relative rates in ψ' to ψ can be derived from the known μ pair rates (~12% rule)

$$\frac{\psi(2S) \to hadrons}{\psi(1S) \to hadrons} \approx \frac{\psi(2S) \to \mu^+ \mu^-}{\psi(1S) \to \mu^+ \mu^-} \approx 12\%$$

Complications include α_s evolution, interference and S-D wave mixing (for ψ' and $\psi(3770)$).

MARK II (1983) observed suppression in $\rho\pi$ mode. PDG 2004 has a limit Q<.7%.



Today: First measurements on $\psi' \to \rho\pi$ BR, improved measurements in other modes and previously unobserved decays.

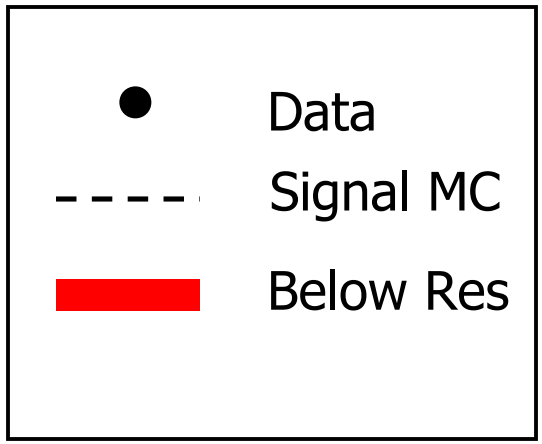
Analysis Strategy

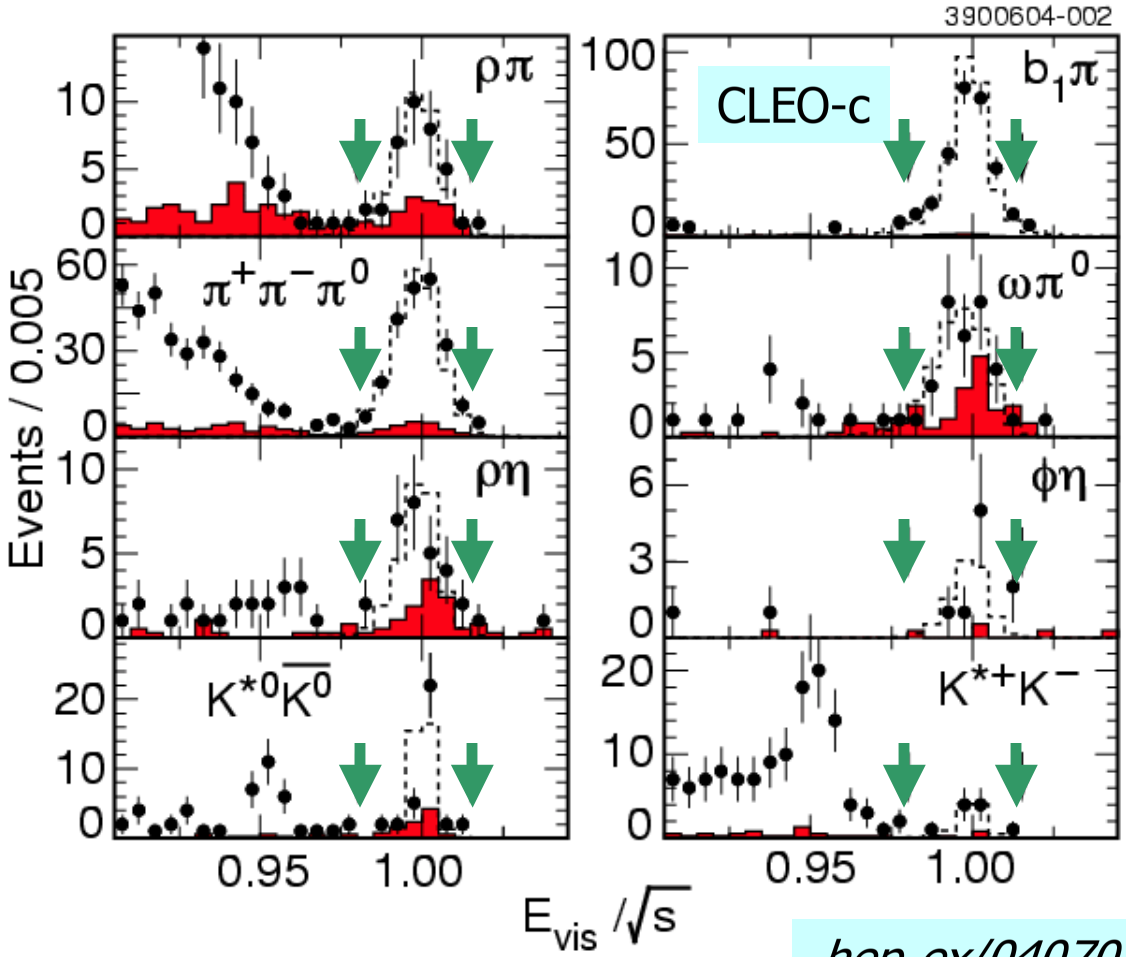
- Particle Selection
  - Standard track and shower selection
  - dEdx and RICH for particle ID
  - Reconstruction of intermediate particles
  - Energy-Momentum Conservation
- Corrected for continuum using scaled below-resonance data
- Efficiencies from MC
- Results quoted relative to $\psi' \rightarrow \pi\pi\psi$ (CLEO)

Signals

Expect:

$$\frac{E_{visible}}{\sqrt{S}} \approx 1$$





hep-ex/0407028
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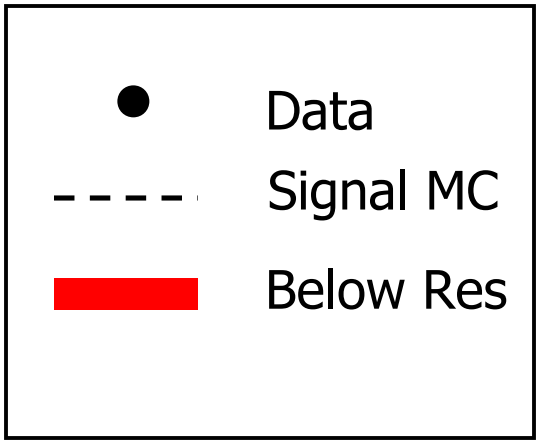
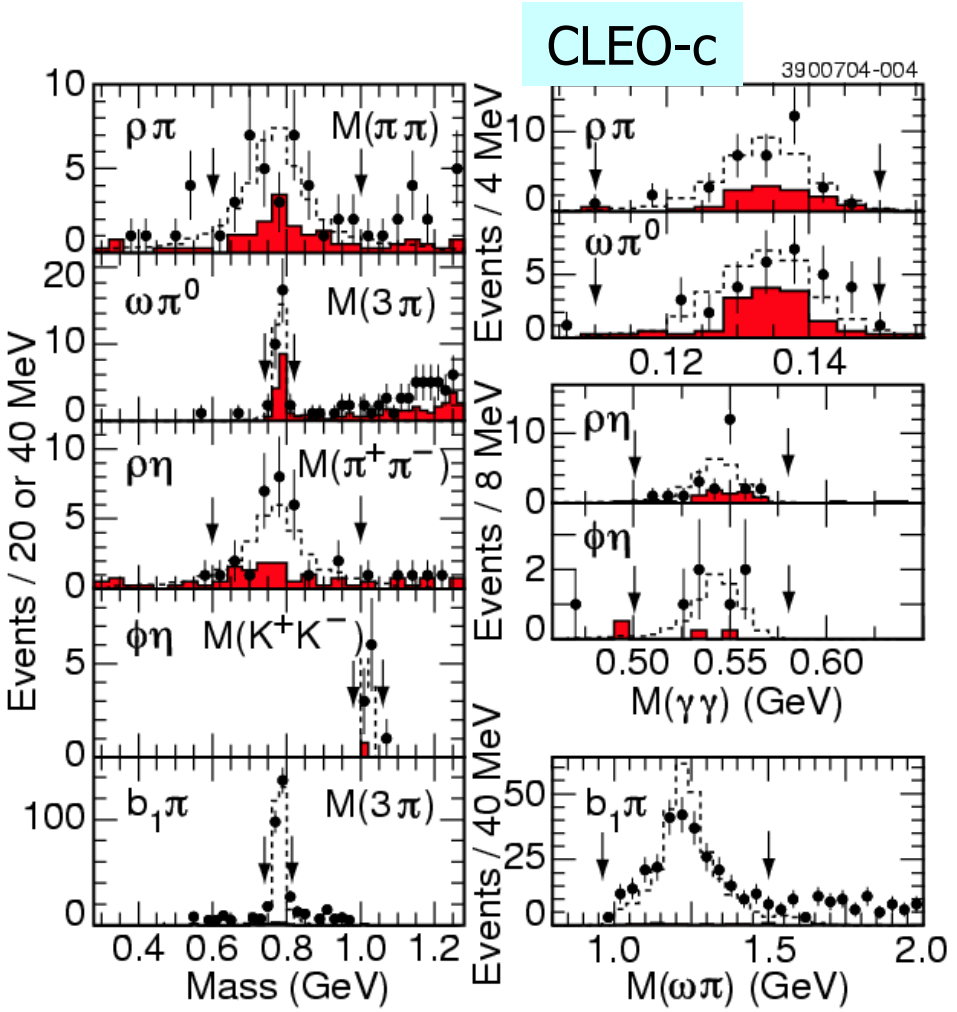
Intermediate Resonances





BR Results: ψ'→ VP

CLEO-c

Two-body Modes

σ = continuum cross section ($\sqrt{s} = 3670$ MeV)
$\mathcal{B}_{CLEO}$ assumes $\mathcal{B}(\pi^+\pi^-\psi) \times \mathcal{B}(\psi \to \mu\mu) = 0.019$
$\mathcal{B}_{PDG}$ from PDG-2004, $\mathcal{B}_{BES}$ from hep-ex/0407037

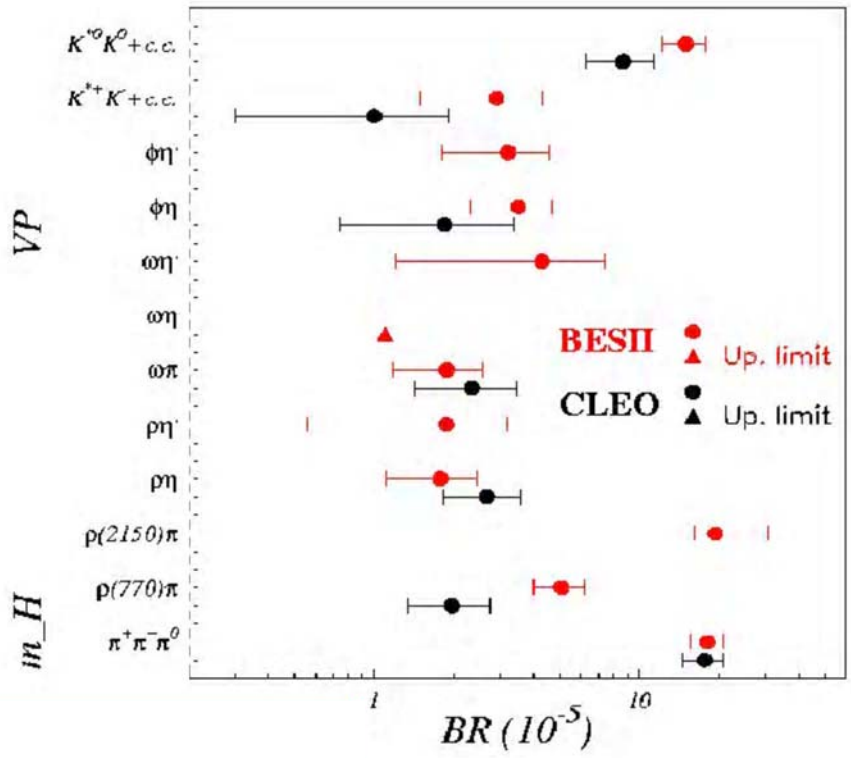
Mode	σ(pb)	$\mathcal{B}_{CLEO}(10^{-5})$	$\mathcal{B}_{PorB}(10^{-5})$
$\pi^+\pi^-\pi^0$	$13.1^{+2.0}_{-1.8} \pm 3.0$	$17.7^{+1.5}_{-1.3} \pm 2.7$	
$\rho^0\pi^0$	$3.2^{+1.1}_{-0.9} \pm 0.5$	$0.9^{+0.4}_{-0.4} \pm 0.1$	
$\rho^+\pi^-$	$5.2^{+1.7}_{-1.1} \pm 0.5$	$1.0^{+0.6}_{-0.5} \pm 0.1$	
$\rho\pi$	$8.3^{+1.7}_{-1.4} \pm 1.2$	$2.0^{+0.7}_{-0.6} \pm 0.2$	< 8.3
$\omega\pi$	$14.2^{+2.7}_{-2.4} \pm 2.0$	$2.3^{+1.1}_{-0.9} \pm 0.2$	
$\phi\pi$	$0.8^{+1.3}_{-0.6} \pm 01.1$	< 0.6	
$\rho\eta$	$10.2^{+2.2}_{-1.9} \pm 1.6$	$2.7^{+0.9}_{-0.8} \pm 0.2$	
$\omega\eta$	$1.8^{+1.7}_{-0.9} \pm 0.2$	< 1.0	
$\phi\eta$	$2.0^{+2.0}_{-1.1} \pm 0.2$	$1.8^{+1.5}_{-1.0} \pm 0.4$	
$K^{*0}\bar{K}^0$	$24.6^{+5.1}_{-4.4} \pm 3.0$	$8.7^{+2.5}_{-2.1} \pm 0.8$	$15.0 \pm 2.1 \pm 1.9$
$K^{*+}K^-$	$0.8^{+1.4}_{-0.6} \pm 0.8$	$1.0^{+0.9}_{-0.6} \pm 0.2$	$2.9 \pm 1.3 \pm 0.4$
$b_1^0\pi^0$	$1.9^{+3.9}_{-1.7} \pm 1.4$	$20.5^{+4.4}_{-3.8} \pm 2.9$	
$b_1^+\pi^-$	$6.4^{+2.5}_{-2.0} \pm 1.0$	$36.8 \pm 4.0 \pm 7.4$	32 ± 8
$b_1\pi$	$8.9^{+3.5}_{-2.9} \pm 1.9$	$56.6^{+5.5}_{-5.3} \pm 10.8$	

BESII

ψ'→	Nevt	B(ψ') (×10^{-5})	B(J/ψ) (×10^{-4}) PDG04	Q (%)
ρ (770) π		5.1 ± 0.7 ± 0.8	127 ± 9	0.40 ±0.08
ρ (2150) π		$19.4 \pm 2.5^{+11.2}_{-2.1}$		
ρ η	13.2 ± 4.8	1.78 ± 0.65 ± 0.22	1.93 ± 0.23	9.2 ± 3.7
ρ η'	2.5 ± 1.7	1.87 ± 1.27 ± 0.36	1.05 ± 0.18	17.8 ± 12.9
ω π	14.0 ±4.8	1.88 ± 0.64 ± 0.32	4.2 ± 0.6	4.5 ± 1.8
ω η	<3.3	< 1.1	15.8 ± 1.6	< 0.7
ω η'	4.1 ±2.8	4.3 ± 2.9 ± 1.0	1.67 ± 0.25	26 ± 19
φ π	< 3.0	< 0.3	< 0.068	
φ η	17.8 ± 5.3	3.5 ± 1.0 ± 0.6	6.5 ± 0.7	5.4 ± 1.9
φ η'	9.1 ± 3.6	3.2 ± 1.3 ± 0.6	3.3 ± 0.4	9.7 ± 4.5
K$^+$K^{*-}+c.c.	9.6 ± 4.2	2.9 ± 1.3 ± 0.4	50 ± 4	0.58 ± 0.27
K^{0}K^{*0}+c.c.	65.6 ± 9.0	15.0 ± 2.1 ± 1.9	42 ± 4	3.6 ± 0.8

ICHEP '04

BR Results: $\psi' \rightarrow$ VP



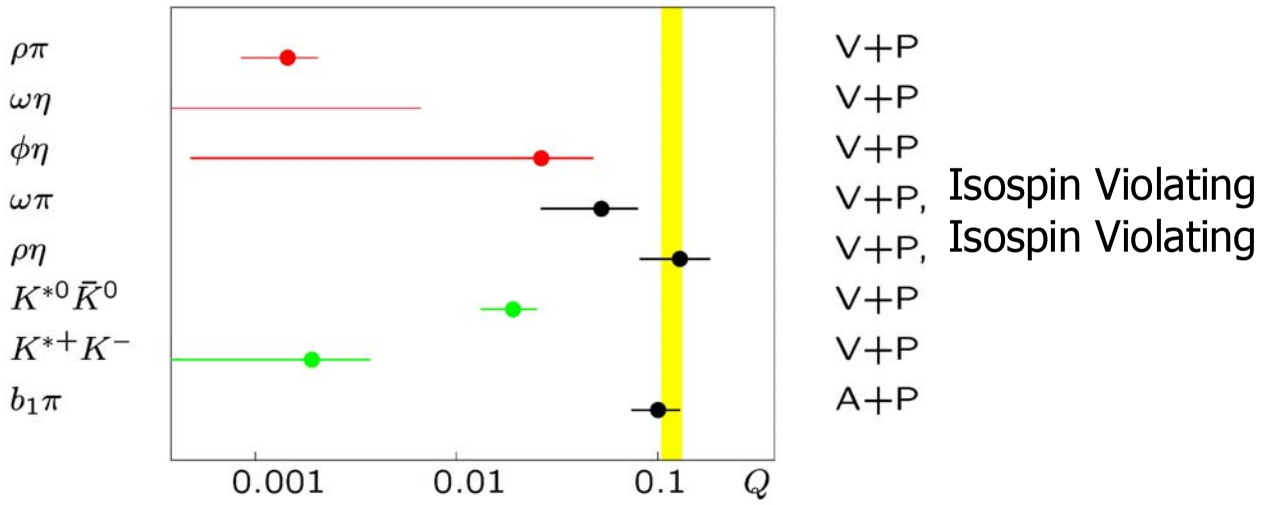
Comparison of branching ratios.
Yields from resonance and continuum agree for $\rho\pi$ and K*K.

There exists differences in treatment of continuum background & interference.

ICHEP' 04 presented by Yongsheng Zhu (BES)

Compare to 12% Rule

CLEO-c



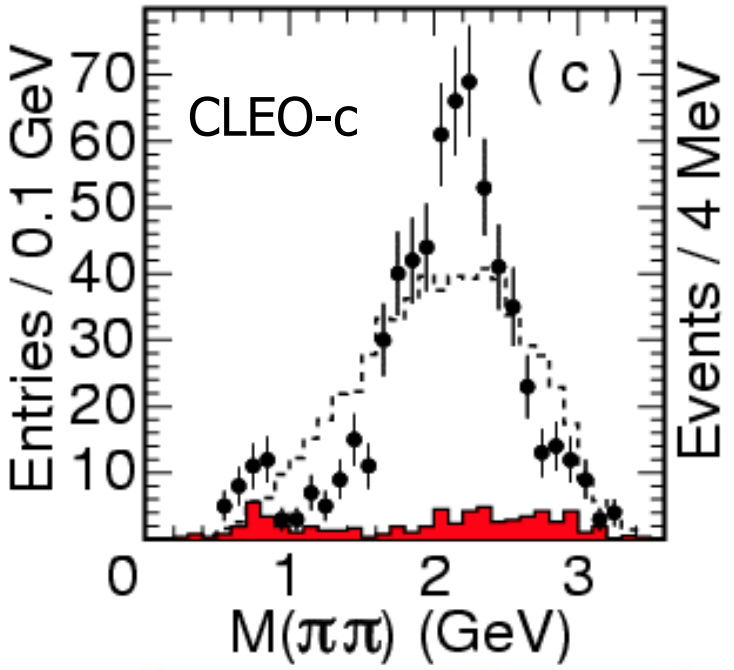
$\pi^+\pi^-\pi^0$ Mode

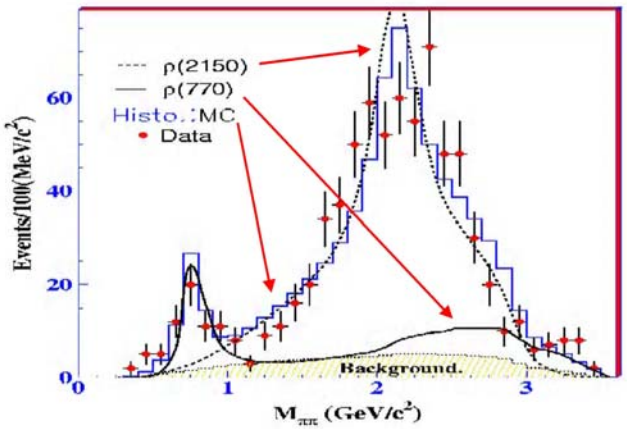
hep-ex/0407028

BR($\pi\pi\pi$) measured by both experiments are consistent. Note $\rho(770)$ is not the dominant contribution.

High $\pi\pi$ mass component is not consistent with phase space.

BES interpretation is observation of $\rho(2150)$.





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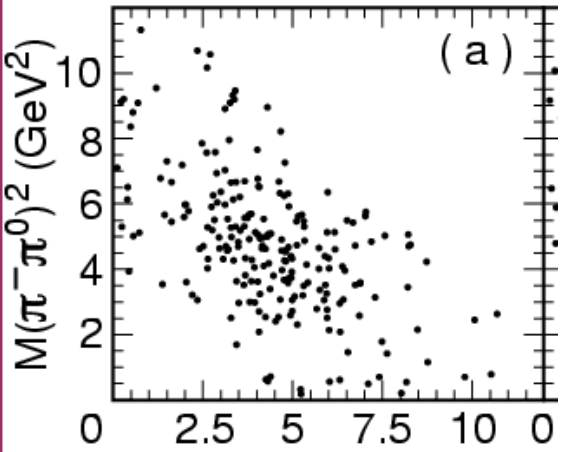
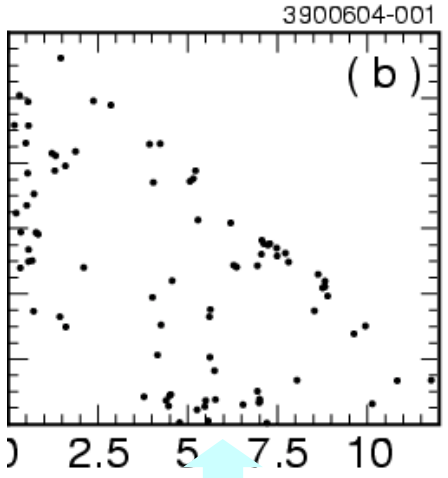
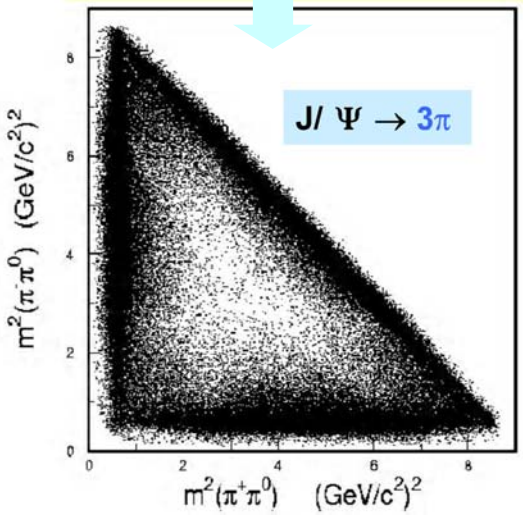
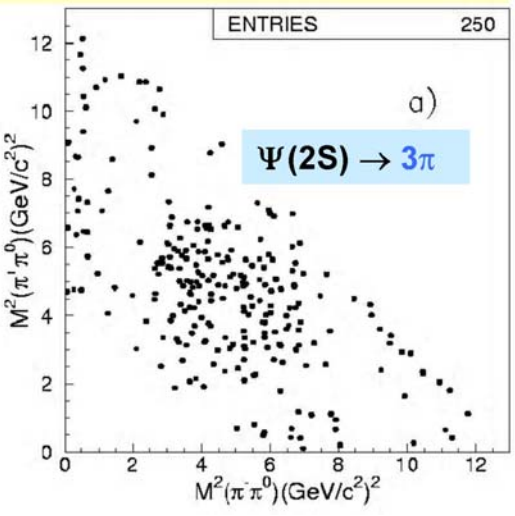
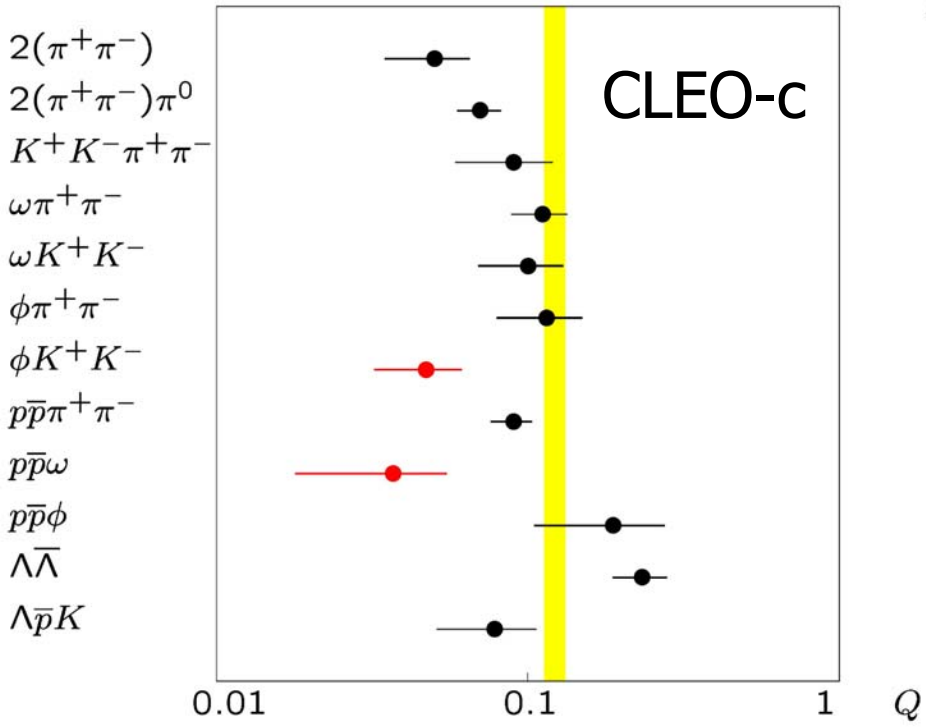
$\pi^+\pi^-\pi^0$ Mode Dalitz Structure

	J/ψ	ψ′	below res
CLEO			
BES			

BES as large J/ψ sample. ρ(770) dominant.

CLEO has large below-resonance sample ρ(770) dominant.

Multi-body Modes



Multibody Modes

$\mathcal{B}_{CLEO}$ assumes $\mathcal{B}(\pi^+\pi^-\psi) \times \mathcal{B}(\psi \to \mu\mu) = 0.019$

Mode	$\mathcal{B}_{CLEO}$ (10^{-4})	$\mathcal{B}_{PDG}$ (10^{-4})
$2(\pi^+\pi^-)$	$2.0 \pm 0.2 \pm 0.3$	4.5 ± 1.0
$2(\pi^+\pi^-)\pi^0$	$23.7 \pm 0.6 \pm 3.3$	30 ± 8
$K^+K^-\pi^+\pi^-$	$6.5 \pm 0.3 \pm 0.8$	16 ± 4
$2(K^+K^-)$	$0.6 \pm 0.1 \pm 0.1$	
$\omega\pi^+\pi^-$	$8.0 \pm 0.5 \pm 1.1$	4.8 ± 0.9
ωK^+K^-	$1.9 \pm 0.3 \pm 0.3$	1.5 ± 0.4
$\phi\pi^+\pi^-$	$0.9 \pm 0.2 \pm 0.2$	1.5 ± 0.3
ϕK^+K^-	$0.7 \pm 0.2 \pm 0.1$	0.6 ± 0.2
$\eta\pi^+\pi^-\pi^0$	8.5 ± 1.3	
$\eta'\pi^+\pi^-\pi^0$	$4.3 \pm 1.5 \pm 1.2$	
$p\bar{p}\pi^+\pi^-$	$5.4 \pm 0.2 \pm 0.7$	8.0 ± 2.0
$p\bar{p}K^+K^-$	$0.2 \pm 0.1 \pm 0.0$	
$p\bar{p}\omega$	$0.5 \pm 0.2 \pm 0.1$	0.8 ± 0.3
$p\bar{p}\phi$	$0.1 \pm 0.1 \pm 0.0$	< 0.3
$\Lambda\bar{\Lambda}$	$3.0 \pm 0.3 \pm 0.4$	1.8 ± 0.3
$\Lambda\bar{\Lambda}\pi^+\pi^-$	$2.7 \pm 0.5 \pm 0.6$	
$\Lambda\bar{p}K$	$0.7 \pm 0.2 \pm 0.1$	
$\Lambda\bar{p}K\pi^+\pi^-$	$1.2 \pm 0.3 \pm 0.3$	

CLEO CONF 04-6

Summary of ψ' Hadronic Decays

A wealth of new and improved measurements have appeared recently.
(could not show all of them!)

First $\rho\pi$ branching ratio measurements by BES and CLEO.

$\psi' \rightarrow \pi\pi\pi$ is not dominated by $\rho(770)\pi$. In contrast to J/ψ and continuum production. BESII interprets as $\rho(2150)$.

12% rule is violated in many 2-body modes. Multi-body modes as measured by CLEO are fairly consistent with rule.

Several 2-body modes used by BES (e.g. $\pi\pi$, K^+K^-, K^0K^0) to extract a preferred phase: $\phi \sim -90^o$. Note isospin violating modes tend to follow 12% rule (though not many measured).

Measurements are valuable for constraining predictions for future precision ψ'' measurements → quantitative test of S-D mixing phenomenology.

Future: More resonant/non-resonant data for improved BRs. Data at various off-resonance energies needed to improve understanding of interference effects.

Radiative Transitions

Motivation:

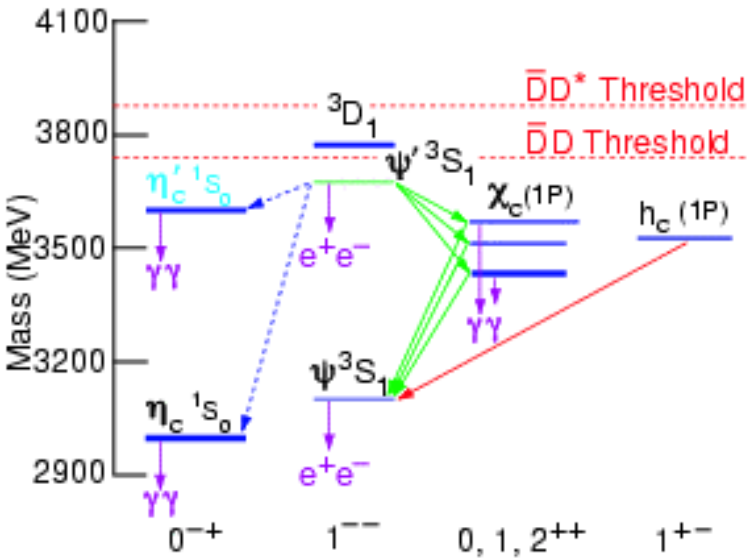
Analysis of γ transitions lines provide discovery opportunities for charmonium levels not produced directly from e^+e^- annihilation. This can be done without explicit reconstruction of the meson given a precision EM calorimeter.

Analysis of final state decay particles can probe nature of transition (E1,M1…).

Measurements of level splittings confronts our understanding of QCD (lattice predictions).

CLEO's smaller ψ' sample is compensated by excellent photon energy resolution. Inclusive measurements of χ_{cJ} transitions lines are systematics dominated.

BESII leverages their large sample via exclusive reconstruction of charmonium states.

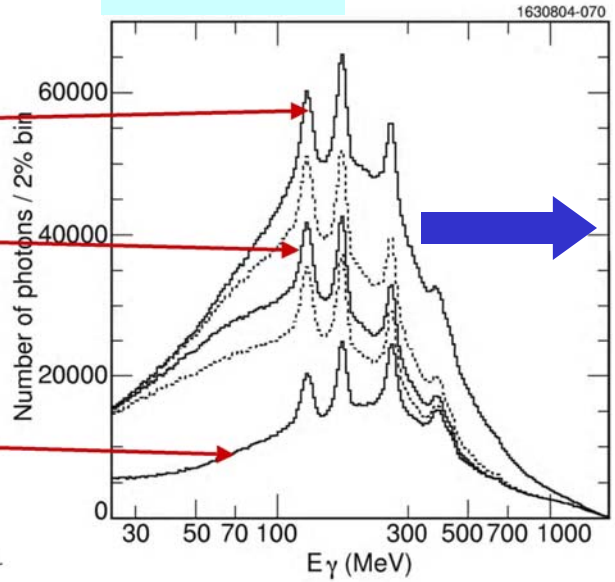


hep-ex/0408133 Submitted PRL

Radiative Transitions

CLEO-c

- No π^0 suppression
- $\cos\theta_{\gamma\gamma}>0.5$ – used in analysis
- Max π^0 suppression



18 August 2004 CL

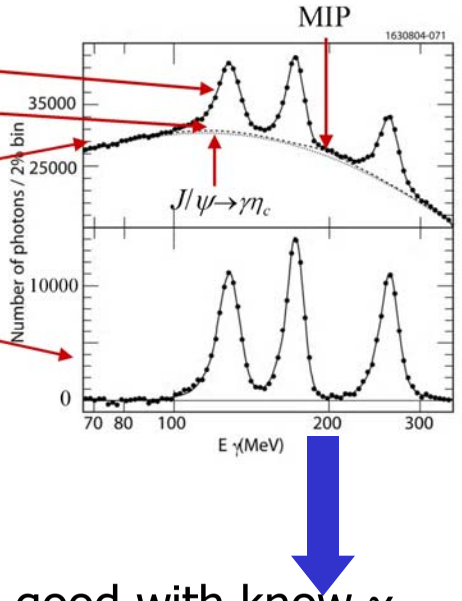
Solid: Signal+background

Dotted: generic background only

Dashed: generic + MIP background

Background subtracted

Systematic errors:
Event selection,
Fitting,
π^0 suppression



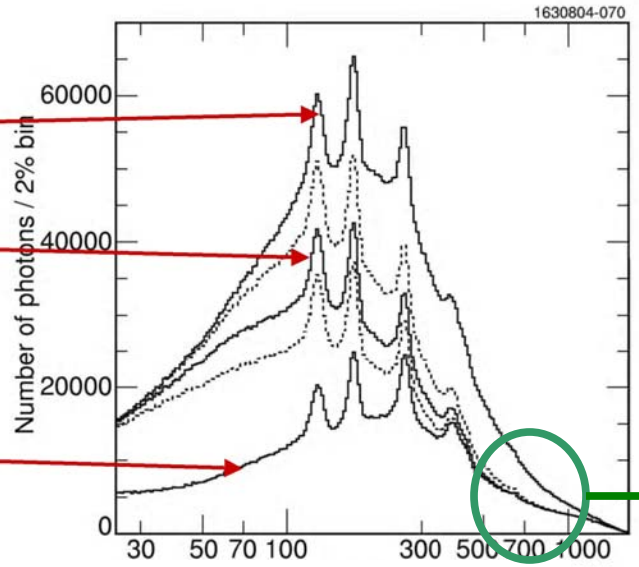
γ energies in good with know χ_c masses.

Branching fractions behavior versus J deviates from NR expectations: ~(2J+1)*Eγ³

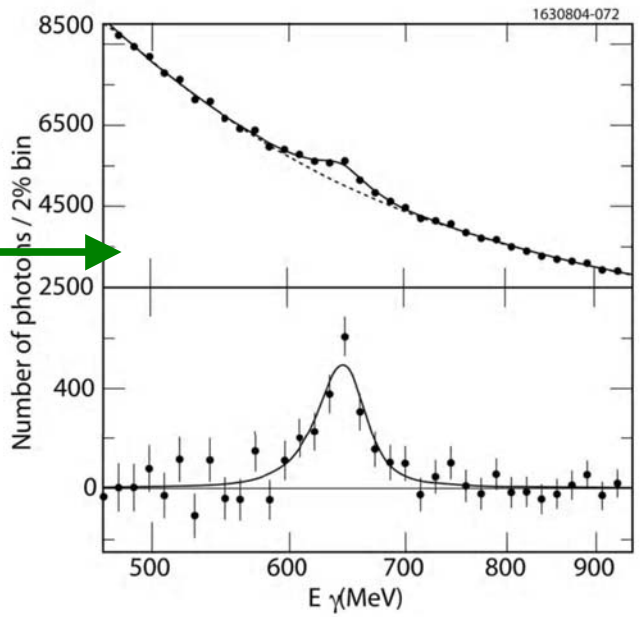
BF (%)	χ_{c2}	χ_{c1}	χ_{c0}
CLEOc	9.33±0.14±0.61	9.07±0.11±0.54	9.22±0.11±0.46
Crystal Ball	8.0±0.5±0.7	9.0±0.5±0.7	9.0±0.5±0.8

Hindered Transitions (η_c)

- No π^0 suppression
- $\cos\theta_{\gamma\gamma}$>0.5 – used in analysis
- Max π^0 suppression



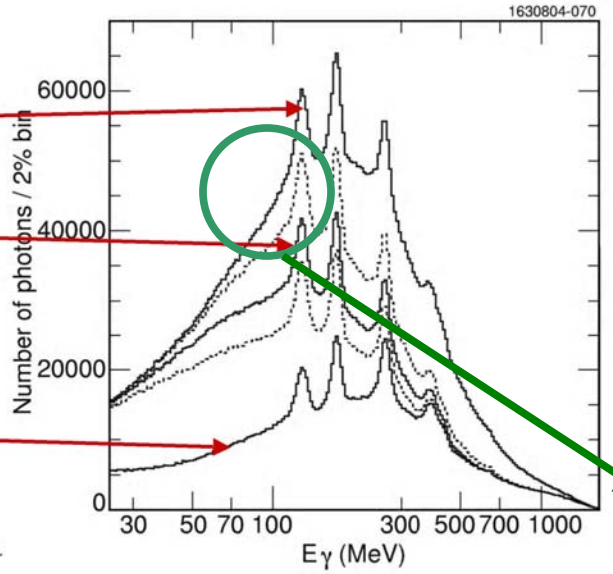
First confirmation of transition since observation by crystal ball.



- m_{η_c} = (2970±7) MeV
  - Consistent w/ world average of ~2980 MeV.
- $B(\psi(2S)\rightarrow\gamma\eta_c)$ = (0.32±0.04±0.06)%
  - Sensitive to relativistic corrections.
  - Crystal Ball obtained (0.28±0.06)% for Γ_{η_c} = (11.5±4.5)MeV.
  - CLEOc would have given (0.25±0.06)% for this Γ_{η_c} – entirely consistent.
- About expected level by theories.

Hindered Transitions (η_c')

- No π^0 suppression
- $\cos\theta_{\gamma\gamma}>0.5$ – used in analysis
- Max π^0 suppression



18 August 2004 CL

No confirmation of η_c' transition.

- No trace of this transition at $E_\gamma = 91$ MeV
- BF < 0.2% at 90% C.L.
- C-Ball presented BF ~ (0.2-1.3)% with 95% C.L.
- Given the mass & width of $\eta_c(2S)$ of 3638 and 25 MeV at recent experiments (Belle, CLEO, Babar), we expect $E_\gamma = 47$ MeV and width ~ 10 MeV
- No meaningful sensitivity exists at this energy and width.

hep-ex/0409034

"E1" Transitions -Again

BESII has ψ' sample sizes permitting precision analysis of transitions identified using γ selection and a full reconstruction of the meson, χ_{cJ}.

Reconstructing the χ_{cJ} allows the study of angular distributions which can be used to extract the helicity amplitude ratios: $x=A_1/A_0$ $y=A_2/A_0$.

The presence of higher order multipole moments may explain differences between measured transition rates and those calculated assuming pure E1.

Also, an E3 contribution is be expected in S-D wave mixing models.

Previous Crystal Ball measurements consistent with no higher moment contributions but the uncertainties are large.

Recent BESII analysis uses alternative χ_{cJ} (J=0,2) decays modes: KK & $\pi\pi$. No contamination from χ_{c1} (parity violating). J=0 and J=2 well separated in mass.

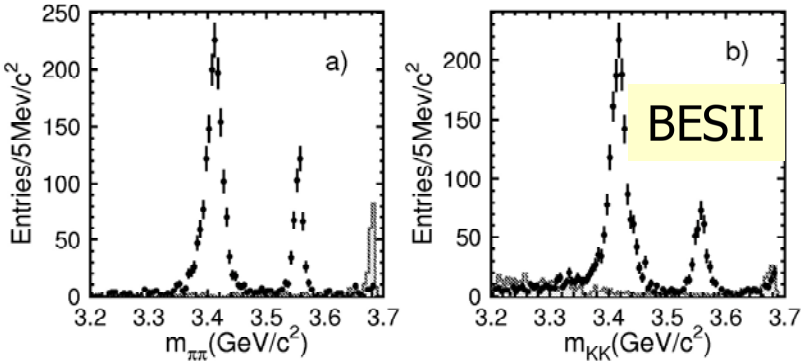


FIG. 1: Invariant mass distributions of the two charged tracks in (a) $\gamma\pi^+\pi^-$ and (b) γK^+K^-. Dots with error bars are data, and the shaded histograms are the MC simulated backgrounds.

"E1" Transitions

Angular distributions:
θ_γ polar angle of photon
θ_m and ϕ_m are meson polar and azimuthal angles of meson with respect to γ direction in rest frame of χ_{c2}.

Fits extracted:
x=2.08±0.44 → a'_2=-0.051 +0.054 -0.036 (M2)
y=3.03±0.66 → a'_3=-0.027 +0.043 -0.029 (E3)
(ρ=.92)

Contributions from quadrupole and octupole moments consistent with 0. E3 measurement not inconsistent with small contribution predicted by S-D wave mixing.

BESII

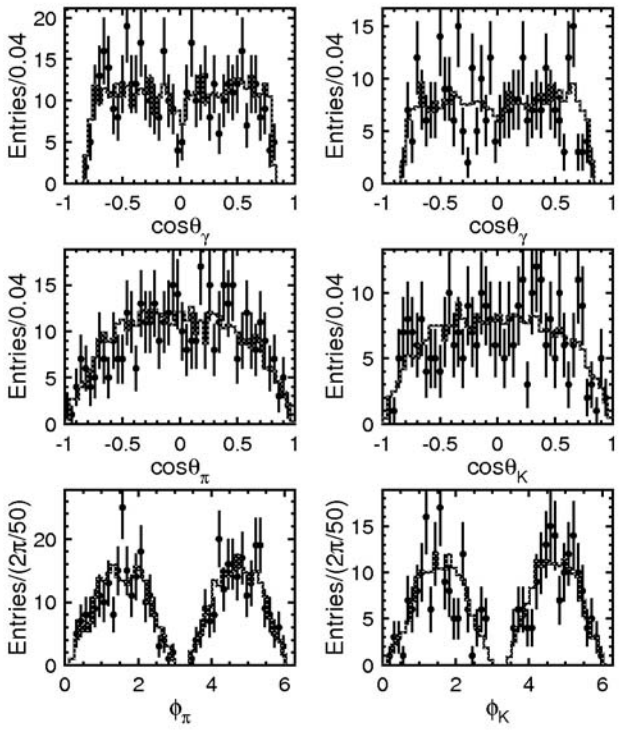


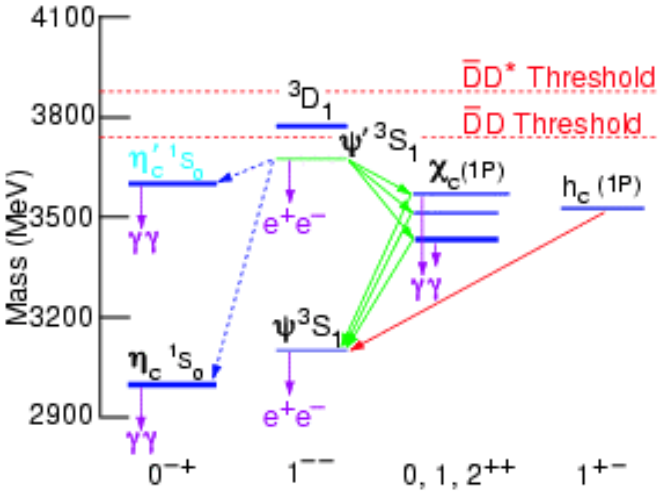
FIG. 2: Comparison between data and the final fit for $\gamma\pi^+\pi^-$(left) and γK^+K^- (right), where dots with error bars are data and the histograms are the fit.

Search for h_c

New and very preliminary!

CLEO-c has searched for the charmonium state, h_c, via the hadron transition $\psi' \rightarrow \pi^0 h_c$ followed by the radiative transition $h_c \rightarrow \gamma \eta_c$

Recent evidence for h_c announced by E835 this year (BEACH04).



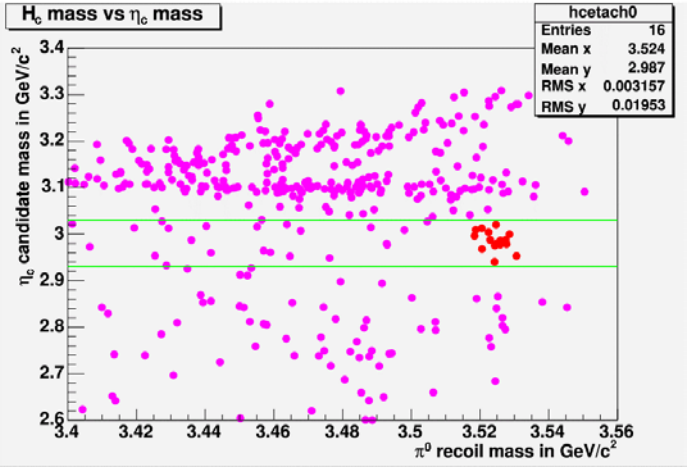
Key ingredients:

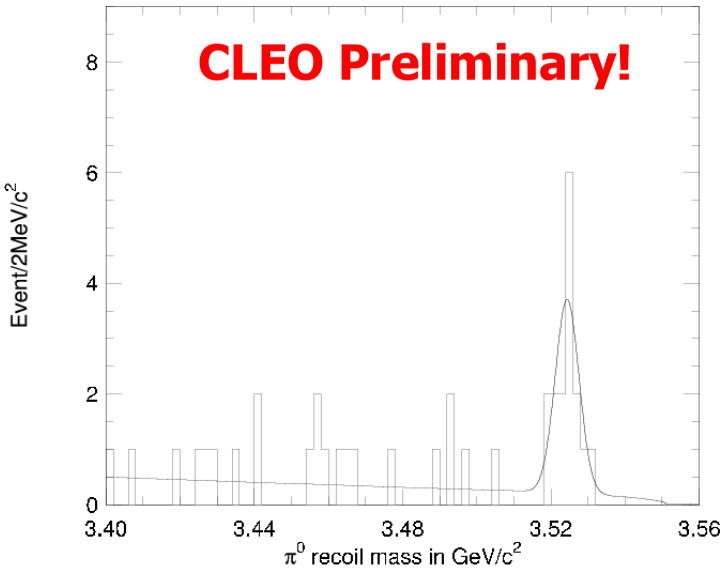
$\pi^0 \rightarrow \gamma\gamma$ reconstruction
γ reconstruction (π^0 veto)
Look for peak in recoil mass
use η_c mass window cut

Exclusive Analysis:
Explicitly reconstruct η_c through known decay modes.
($K_S K\pi$, $KK\pi^0$, $K^+K^-\pi^+\pi^-$, $2\pi^+2\pi^-$, $\pi^+\pi^-\eta$)

Inclusive Analyses:
Use photon energy window.
Doppler broadening small.
And can be corrected for.

Search for h_c





Exclusive Results:

yield = 15 +5 -4
significance ~ 5
mass = 3524.4+/-0.9 (stat) MeV
(no systematic unc yet)

Inclusive Results:

Efforts still underway to combine multiple inclusive approaches.

Mass from inclusive and exclusive analyses consistent:

mass = 3524.8 + .7(stat) +1.0(sys) MeV
significance ~3

Mass consistent with E835.

More details at QWG04!

Summary ψ' Transitions

- **CLEO-c has measured the rates for charmonium E1 transitions $\psi' \rightarrow \gamma \chi_{cJ}$. Results are improvement to previous measurements and are in agreement. The rate versus J does not agree with expectations from NR models.**
- **BESII, using full reconstruction of the χ_{c2}, has fit the photon and meson angular distributions. They found no significant higher multipole contributions that could arise from relativistic corrections or S-D wave mixing.**
- **CLEO-c provided first confirmation of the M1 transition ($\psi' \rightarrow \gamma \eta_c$).**
- **CLEO-c found no evidence of a 91 MeV line interpreted in an earlier crystal ball analysis as the η_c'.**
- **CLEO-c has reported evidence for h_c in searches that use the hadron transition $\psi' \rightarrow \pi^0 h_c$ followed by the radiative transition $h_c \rightarrow \gamma \eta_c$ (preliminary). More ψ' data are needed given previous comment!**

Future

Data sample goals for future charm factories.

Channel	W (GeV)	CLEO-c			BESIII		
		σ (nb)	$\mathcal{L}T$ (fb^{-1})	Events	σ (nb)	$\mathcal{L}T$ (fb^{-1})	Events
J/ψ	3.097	1000	1	10^9	3400	3	10×10^9
τ	3.67				2.4	5	1.2×10^7
$\psi(2S)$	3.686				640	5	3×10^9
$D\bar{D}$	3.770	5	3	1.5×10^7	5	5	2.5×10^7
$D_s\bar{D}_s$	4.03				0.32	3	1×10^6
$D_s\bar{D}_s$	4.140	0.5	3	1.5×10^6	0.67	3	2×10^6
$\Lambda_c\bar{\Lambda}_c$	4.6		1	3.7×10^7			

Note: CLEO-c results presented today were based on pilot runs (as seen above we had no ψ′ data runs planned in the official run plan). CLEO-c running (with finished configuration) started only a few weeks ago! Expect high precision results in the future.

BESIII scheduled to turn on near end of CLEO-c (need date). BESIII will improve on J/ψ samples, ψ(3770) samples and has dedicated a large fraction to ψ′ running.

Over the next year CLEO-c will greatly increase the world's ψ(3770) sample. Our knowledge of charmless hadronic decays and radiative transitions will improve significantly → Theorists, get your predictions in now!