Evidence for h_c production from ψ' at CLEO

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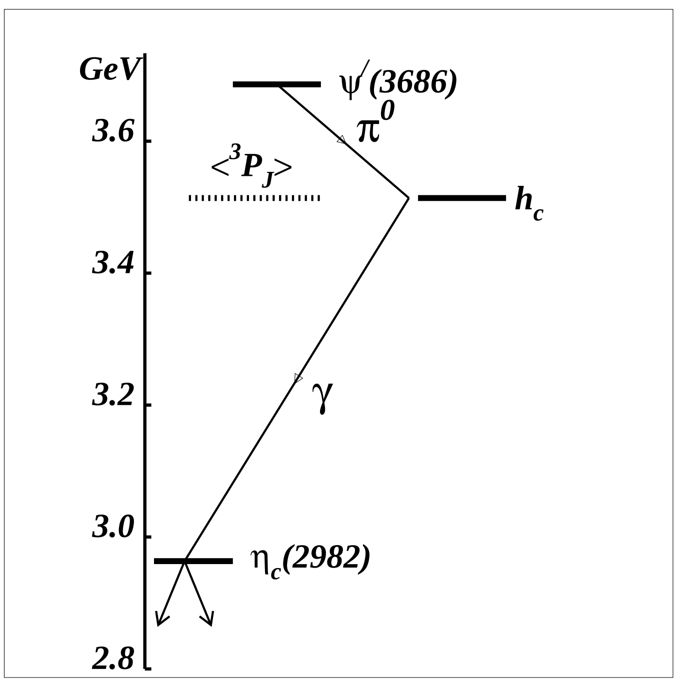
We present the results of our search for the $h_c(^1P_1)$ state of charmonium in reaction

$$e^+e^- \to \psi' \to \pi^0 h_c \to (\gamma\gamma)(\gamma\eta_c)$$

using CLEO data.



This Presentation Includes:

- Importance of Identifying h_c
- Prior Experimental Searches for h_c
- CLEO Searches and Results

THE IMPORTANCE OF $h_c(^1P_1)$

- Of the 8 bound states of charmonium, $h_c(^1P_1)$ is the only one 'undiscovered' (or unconfirmed) in the last 28 years since the discovery of J/ψ.

- There is an important physics reason to identify h_c.
  - The spin-independent part of the QCD $q\bar{q}$ interaction is well-established.
  - The spin-dependent part is not.
    In particular, the $\vec{s_1} \cdot \vec{s_2}$ spin–spin, or hyperfine interaction is not well understood, because there is little experimental data to provide the required constraints for theory.

- The primary experimental data required for understanding the $q\bar{q}$ hyperfine interaction is hyperfine, or spin-singlet/spin-triplet splitting:

$$\Delta M_{hf}(nL) \equiv \left\langle M(n^3L_J)\right\rangle - M(n^1L_{J=L})$$

- No spin-singlet states have so far been identified in bottomonium. Charmonium is our only source.

THE IMPORTANCE OF $h_c(^1P_1)$

- For nearly 20 years, the only hyperfine splitting known was that for the $1S$ states of charmonium

$$\Delta M_{hf}(1S) = M(J/\psi) - M(\eta_c) = 116 \pm 2 \text{ MeV}$$

- Very recently, Belle, CLEO and BaBar, succeeded in identifying η_c', with the rather surprising result that

$$\Delta M_{hf}(2S) = M(\psi') - M(\eta_c') = 48 \pm 4 \text{ MeV}$$

  Potential model and quenched lattice calculations predicted larger $\Delta M_{hf}(2S)$. This 'surprise' emphasizes that we have much to learn about the hyperfine interaction in QCD.

- It is of great importance to find out how the hyperfine interaction manifests itself in P states, i.e., to find $\Delta M_{hf}(1P) \equiv M(<^3 P_J>) - M(^1P_1)$
- With scalar confinement, $\Delta M_{hf}(1P) = 0$ is expected. It is necessary to determine if this is true.
- The c.o.g. of ^3P states, $M(<^3 P_J>)$, is well measured, $M(<^3 P_J>)$=3525.3±0.1 MeV,

  What we need is to identify h_c and make a precision measurement of its mass.

$h_c(^1P_1)$ - EXPERIMENTAL

- 1982: Crystal Ball (SLAC), not observed in $M = 3440 - 3543$ MeV

$$\psi' \to \pi^0 h_c \quad , \quad h_c \to \gamma\eta_c \quad , \qquad B_{in} \times B_{out} < 0.32 \times 10^{-2}$$

NO

- 1992: E760 (FNAL), $p\bar{p}$ in $M = 3523 - 3527$ MeV, $\mathcal{L} = 16$ pb^{-1}

$$p\bar{p} \to (h_c) \to \pi^0 J/\psi \qquad , \qquad B_{in} \times B_{out} \approx 2 \times 10^{-7}$$

$$M = 3526.2 \pm 0.3 \text{ MeV} \quad , \quad \Gamma \leq 1.1 \text{ MeV}$$

YES

- 2004: E835 (FNAL), $p\bar{p}$ in $M = 3523 - 3529$ MeV, $\mathcal{L} = 45$ pb^{-1}

$$p\bar{p} \to (h_c) \to \pi^0 J/\psi \qquad , \qquad B_{in} \times B_{out} \leq 1 \times 10^{-7} \text{ (90\%CL)}$$

NO

$$p\bar{p} \to (h_c) \to \eta_c\gamma \ , \ M = 3525.8 \pm 0.2(stat) \text{ MeV}$$

PRELIMINARY YES

- 2004: CLEO in $e^+e^- \to \psi' \to \pi^0 h_c$, $h_c \to \gamma\eta_c$ with 3 million ψ'

POSITIVE EVIDENCE

CLEO Searches and Results

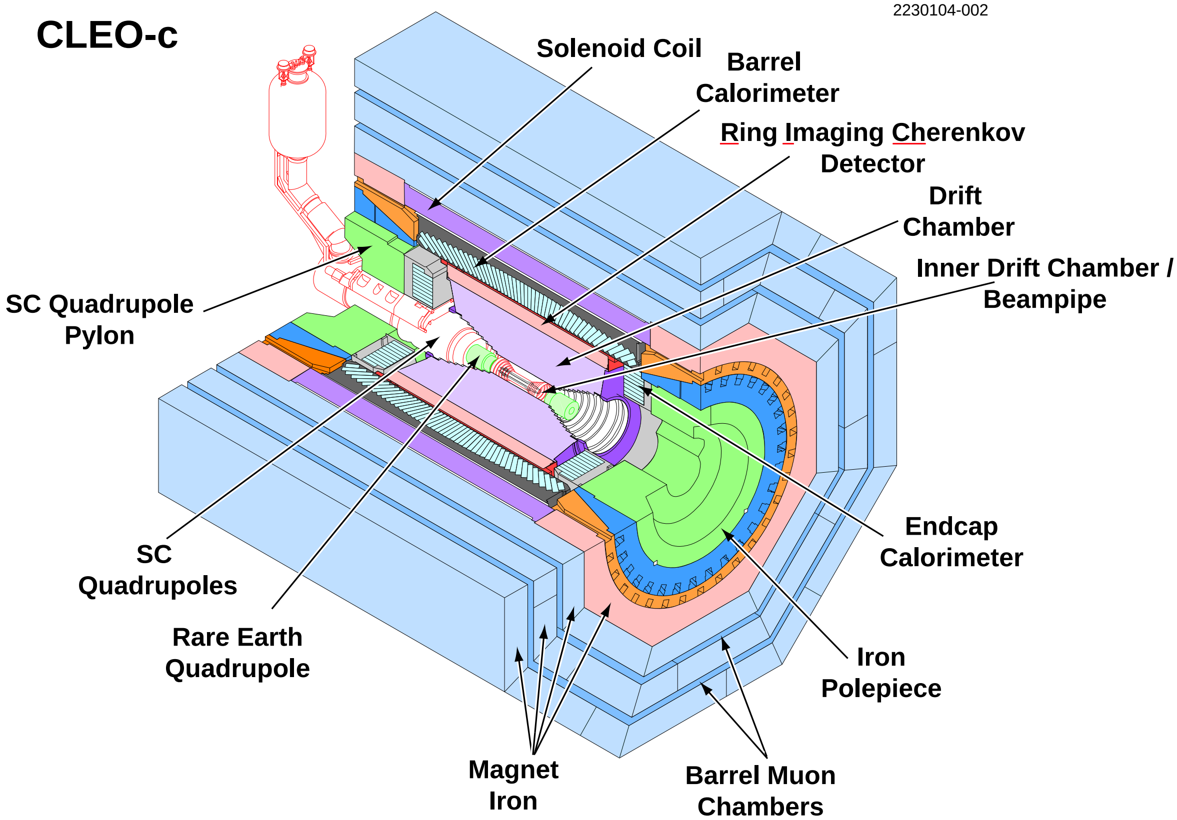
We analyze $\sim 6pb^{-1}$ of CLEO III and CLEO-c data with estimated $\sim 3.0 \times 10^6$ ψ' events, for $\psi' \to \pi^0 h_c,\ \pi^0 \to \gamma\gamma,\ h_c \to \gamma\eta_c$.

1. We search for this channel without using η_c decays (INCLUSIVE approach).
2. We search for this channel using six dominant η_c decay modes (EXCLUSIVE approach).

In both methods we search for h_c in the mass recoiling against π^0 from decay $\psi' \to \pi^0 h_c$.

This method benefits from the excellent resolution of the CLEO calorimeter.

ALL RESULTS ARE PRELIMINARY !



CLEO-c Calorimeter

- 7800 Tl(CsI) crystals
- 93% of 4π coverage
- Energy resolution: $\sigma_E/E = 1.5\%$ at 5 GeV, 4% at 100 MeV.

Inclusive Analyses, Event Selection

Two independent analyses have been done. The results from the two are consistent.
I will describe one of them in detail, and will later mention the differences between the two analyses.

We use the following selection criteria to select $\psi' \to \pi^0 h_c \to (\gamma\gamma)(\gamma\eta_c)$ events.

– $N_{shower} \geq 3$.
– $N_{track} \geq 2$.

Photon shower selection

Standard photon selections were used.
– $E_\gamma > 30$ MeV, if shower is in the barrel
– $E_\gamma > 50$ MeV, if shower is in the endcap

Track selection

The selection of charged particles which is used for rejection of $(\psi' \to \pi^+\pi^- J/\psi)$ and $(J/\psi \to charged)$ events is done using the standard quality cuts.

Event Selection

- Reconstruction of π^0's: $M_{\gamma\gamma}$=135±15 MeV.

The fitted π^0's are used and a mass pull of $\leq 3\sigma$ is required. In case of ambiguity (when same γ makes more than one π^0), only the π^0 with the best mass pull is accepted. We require that there be only one π^0 in the event with recoil mass in range of expected h_c mass of 3526±30 MeV.

- Reject $\psi' \to \pi^+\pi^- J/\psi$ events by cutting out recoils against $\pi^+\pi^-$.

- Reject $\psi' \to \pi^0\pi^0 J/\psi$ events by cutting out recoils against $\pi^0\pi^0$.

- Reject event if mass of all charged particles is around invariant mass of J/ψ .

- Reject candidate hard γ (from $h_c \to \gamma\eta_c$ decays) which makes π^0 or η with any other γ's.

- Cut on hard γ energy , E_γ=503±40 MeV, which corresponds to $M(h_c)$=3526±47 MeV in π^0 recoil.

Monte Carlo Studies

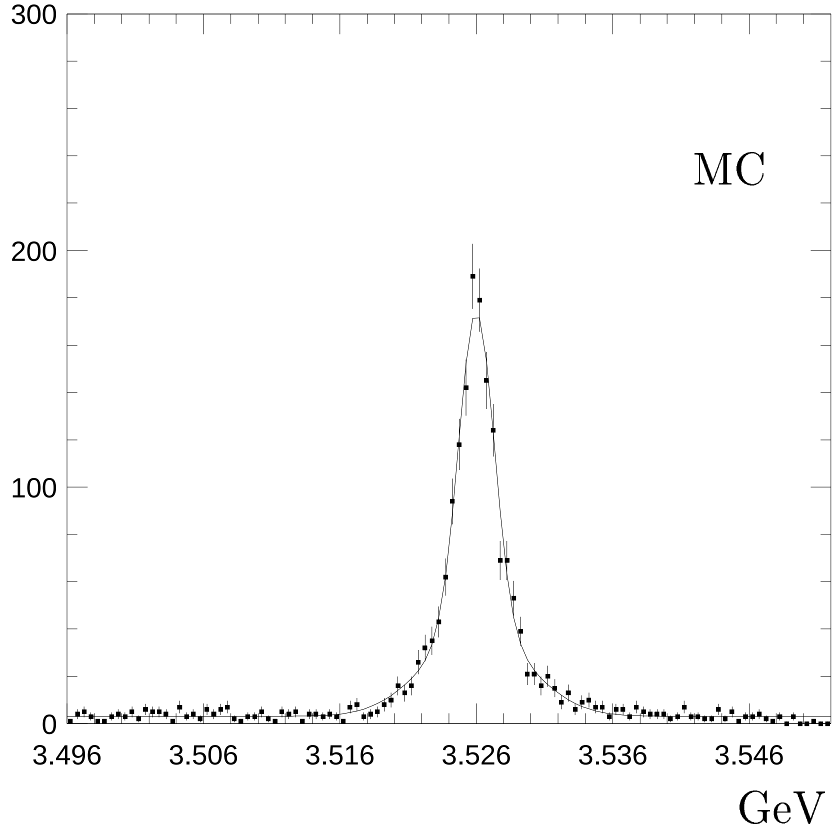
- We analyzed a sample of $\sim 12 \times 10^6$ generic ψ' Monte Carlo events (events containing all measured ψ' decays except those via h_c), and also analyzed the same events in four separate samples, each with approximately the same size ($\sim 3 \times 10^6$) as the data, in order to study statistical effects.

- The 10,000 signal MC events for the channel $\psi' \to \pi^0 h_c \to (\gamma\gamma)(\gamma\eta_c)$ were simulated, assuming:
$M(h_c) = 3526$ MeV, $\Gamma(h_c) = 0.0, 0.5, 0.9$ MeV
$M(\eta_c) = 2982$ MeV, $\Gamma(\eta_c) = 24.8$ MeV.

- The signal MC events were added in to the generic MC assuming:
$B(\psi' \to \pi^0 h_c) \times B(h_c \to \gamma\eta_c) = 5.0 \times 10^{-4}$.

- The event selection criteria applied to the Monte–Carlo samples were identical to those applied to the data.

Recoil Mass Resolution at h_c



Recoil mass distribution against π^0 in reaction $\psi' \to \pi^0 h_c \to (\gamma\gamma)(\gamma\eta_c)$ in signal Monte–Carlo, for input $M(h_c)$=3526 MeV, $\Gamma(h_c)$=0 MeV.

The full curve shows fit with a double Gaussian (σ_1=1.3 MeV, σ_2=3.7 MeV, area2/area=0.43) which gives the efficiency=16%. These parameters are used to fit the signal in the data.

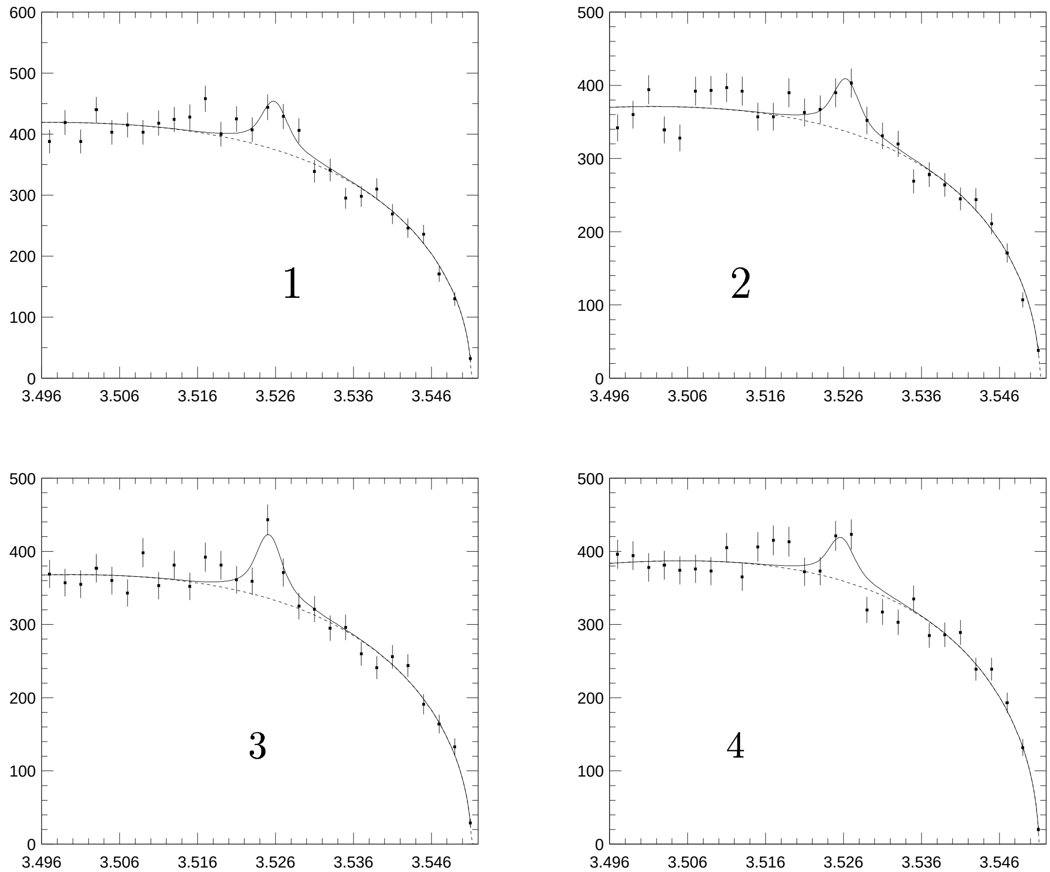
Background Shape

The background in the data has been fitted in three ways:

- ARGUS shape, $y = x \times \sqrt{1-(x/a)^2} \times exp(b \times [1-(x/a)^2])$,
- 3 parameter polynomial shape,
- Background shape from Monte–Carlo.

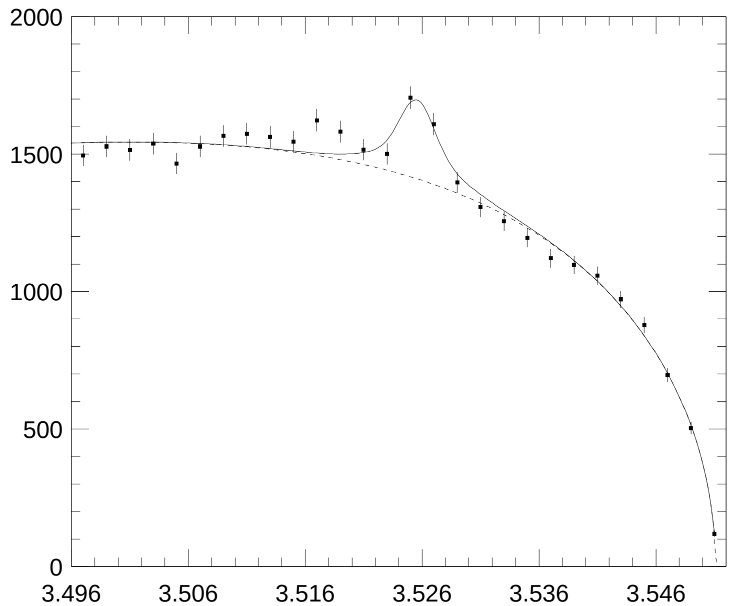
Significance levels are obtained as $\sigma \equiv \sqrt{-2\ln(L_0/L_{max})}$, where L_{max} and L_0 are the likelihoods of the fits with and without the h_c resonance.

GEANT MC, π^0 recoil mass in GeV



	$M(h_c)$ (MeV)	$B_1 \times B_2$ (10^4)	signif.
input	3526.0	5.0	–
1st sample	3525.9 ± 0.6	4.5 ± 1.0	4.5σ
2nd sample	3526.3 ± 0.6	4.6 ± 1.0	4.3σ
3rd sample	3525.2 ± 0.4	5.5 ± 1.1	5.3σ
4th sample	3525.7 ± 0.5	3.7 ± 1.1	3.4σ
χ^2/d.o.f.	1.4	1.0	–
Sum	3525.6 ± 0.3	4.4 ± 0.6	8.4σ

GEANT MC



Recoiling mass against π^0 for $\sim$12 million ψ' (the sum of the four plots shown in previous transparency).

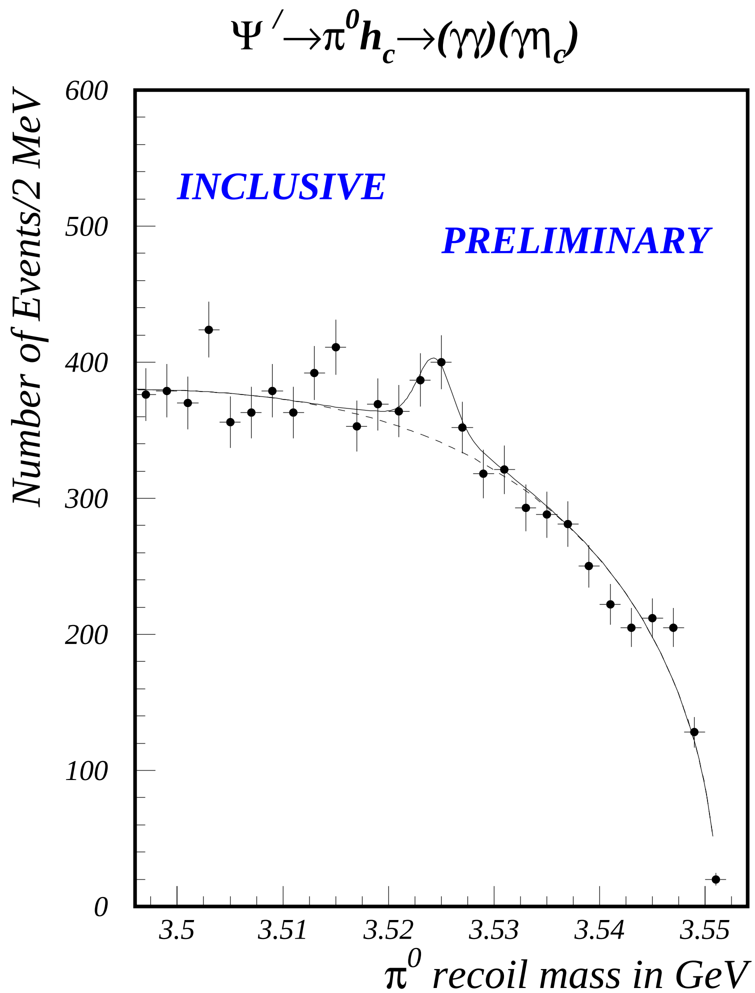
	Result	Input
$M(h_c)$	3525.6 ± 0.3 MeV	3526.0 MeV
$B(\psi' \to \pi^0 h_c) \times B(h_c \to \gamma\eta_c)$	$(4.4 \pm 0.6) \times 10^{-4}$	5.0×10^{-4}

Significance level = 8.4 σ.

The conclusions from the MC studies are:

- With large MC samples (presently $\sim$12 million ψ') the input and output for both $M(h_c)$ and $B(\psi' \to \pi^0 h_c) \times B(h_c \to \gamma\eta_c)$ are in good agreement.
- When the event sample is small, even in MC, output results for parameters and significance levels can vary substantially.

CLEO DATA



Distribution of the recoiling mass against π^0 in data. (Double Gaussian + ARGUS background)

The best fit results are

N(h_c)=156±48, significance(h_c) $= 3.3\sigma$,

$M(h_c) = 3524.4 \pm 0.7$ MeV.

Alternative Inclusive Analysis

- Independent inclusive search for h_c
- Different but overlapping event selection
- Select candidates based on recoil against $\pi^0\gamma$ (η_c mass) rather than γ energy
- Consistent results with previously described analysis

Thus our PRELIMINARY CLEO results from two inclusive analyses are:

- $M(h_c)$=3524.8±0.7(stat)± ~1(syst) MeV.
- $B(\psi' \to \pi^0 h_c) \times B(h_c \to \gamma\eta_c)$ =(2–6)×10^{-4},
- The significance of h_c detection $> 3\ \sigma$.

Systematics in $M(h_c)$

Estimates of systematic errors in $M(h_c)$ have been made by studying the following:

– π^0 energy scale

– background shapes

– Monte Carlo input/output differences

– non-resonant background

– assumed h_c width

– binning effects

– cut variations

and finally

– the difference in $M(h_c)$ in the two inclusive analyses

These studies also convinced us that the significance of the h_c signal is safely $>3\ \sigma$.

I now want to present the preliminary results of an exclusive analysis.

Exclusive Analysis

In this analysis, instead of constraining η_c mass, or hard photon energy, several exclusive decays of η_c are reconstructed.

$$\psi' \to \pi^0 h_c \to (\gamma\gamma)(\gamma\eta_c) \; , \; \eta_c \to hadrons$$

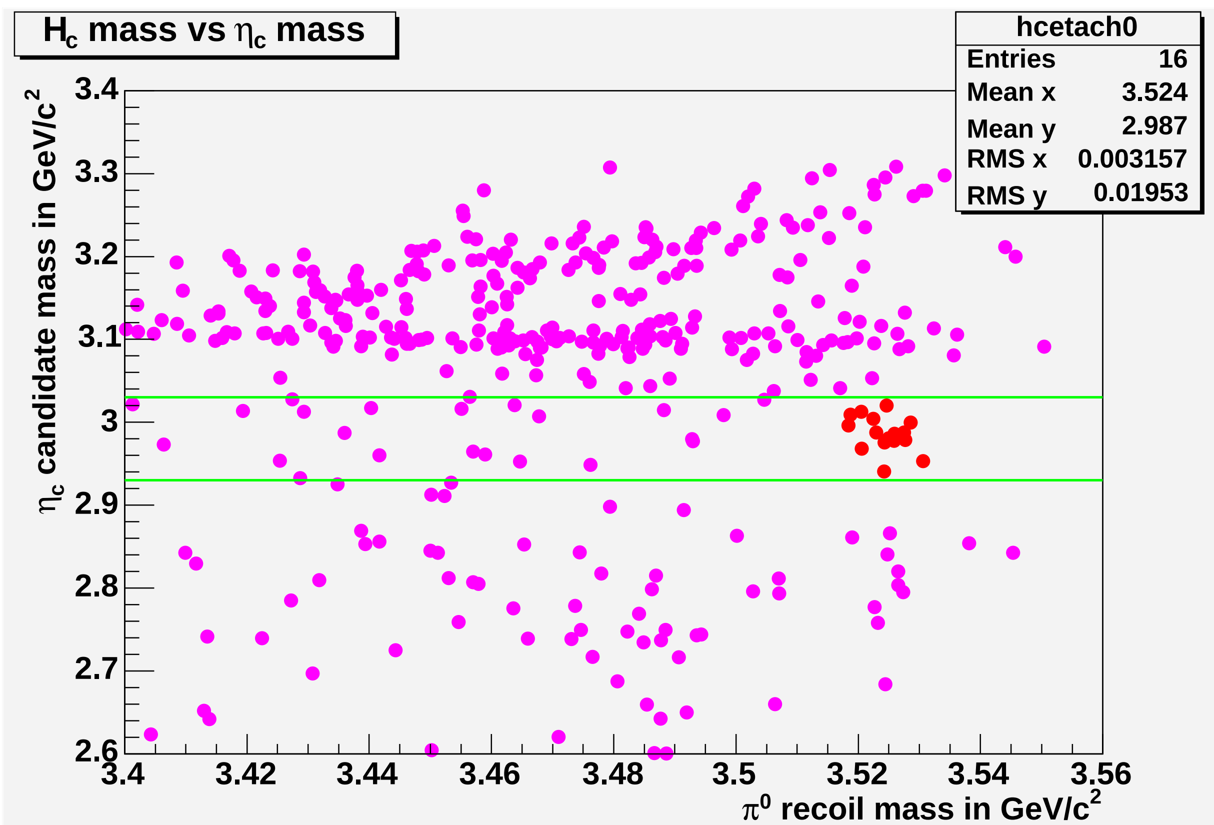
The six η_c decay modes which have reasonably high PDG04 branching ratios have been studied:

$\eta_c \to K_s K^\pm \pi^\mp$	BR=(1.8±0.6)%
$\eta_c \to K^+ K^- \pi^0$	BR=(0.9±0.3)%
$\eta_c \to K^+ K^- \pi^+ \pi^-$	BR=(2.0±0.7)%
$\eta_c \to 2\pi^+ 2\pi^-$	BR=(1.2±0.4)%
$\eta_c \to \pi^+\pi^-\eta, \quad \eta \to \gamma\gamma$	BR=(1.3±0.4)%
$\eta_c \to \pi^+\pi^-\eta, \quad \eta \to \pi^+\pi^-\pi^0$	BR=(0.7±0.2)%

Event Selection

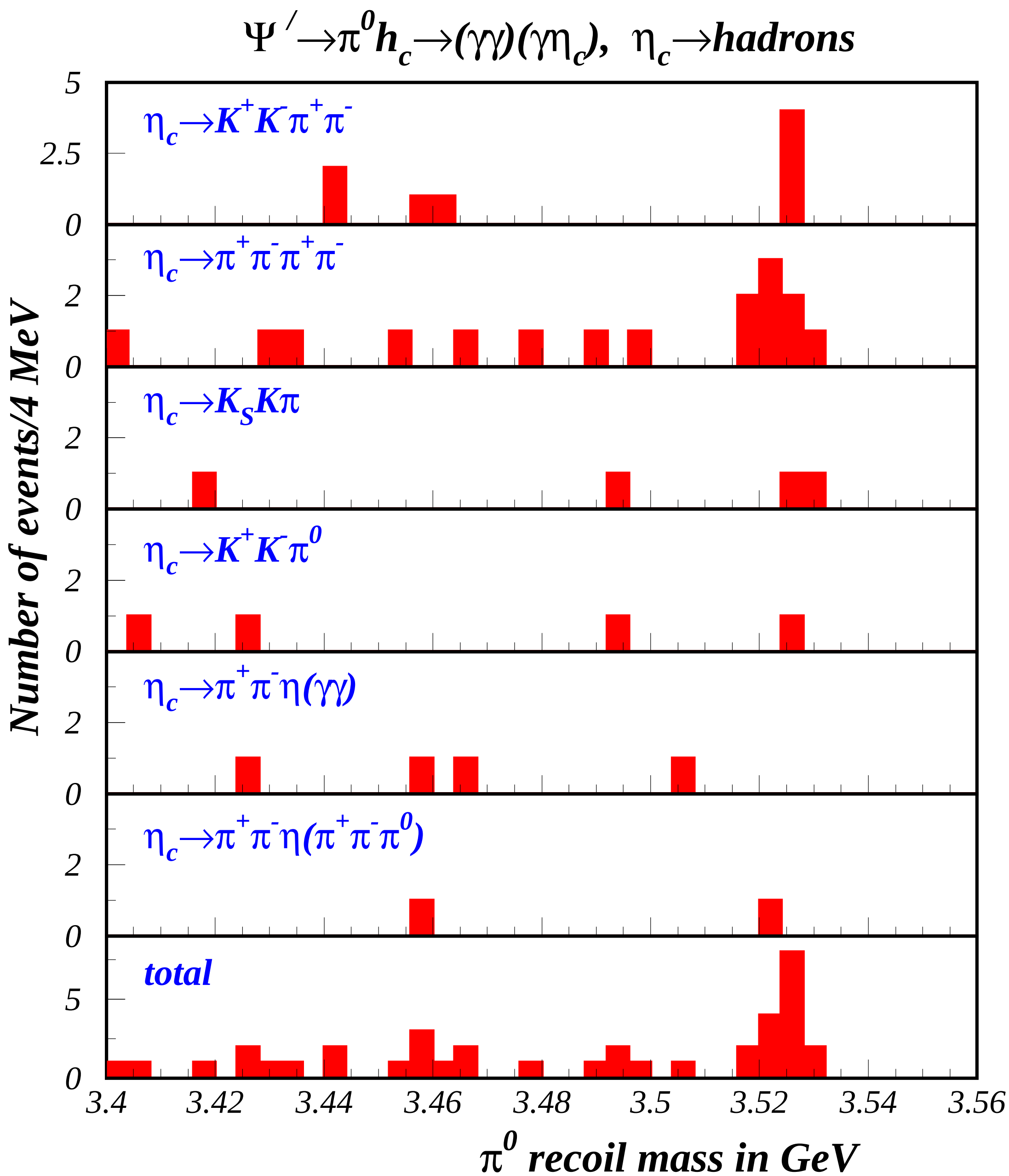
- Standard photon and track selection criteria were used.
- The charged pions and kaons have been identified by RICH and dE/dx .
- Signal γ (from $h_c \to \gamma\eta_c$): $E_\gamma > 300$ MeV, π^0 suppressed.
- π^0: fitted with mass pull $< 3\sigma$, $E_\gamma > 15$ MeV.
- K_S: flight significance $> 3\sigma$, invariant mass of $\pi^+\pi^-$ within 10 MeV of nominal.
- η's were detected in two decay modes:
  $\eta \to \gamma\gamma$: mass pull $< 3\sigma$
  $\eta \to \pi^+\pi^-\pi^0$: invariant mass within 20 MeV of nominal.
- $\psi' \to \pi^+\pi^- J/\psi$ rejected by cutting out recoils against $\pi^+\pi^-$.
- The total energy–momentum conservation of the event has been required.
- The invariant mass of the η_c candidates are required to be close to the nominal η_c mass (within 50 MeV).

CLEO DATA



H_c mass vs η_c mass
hcetach0
Entries 16
Mean x 3.524
Mean y 2.987
RMS x 0.003157
RMS y 0.01953
η_c candidate mass in GeV/c^2
3.4
3.3
3.2
3.1
3
2.9
2.8
2.7
2.6
3.4 3.42 3.44 3.46 3.48 3.5 3.52 3.54 3.56
π^0 recoil mass in GeV/c^2

CLEO DATA



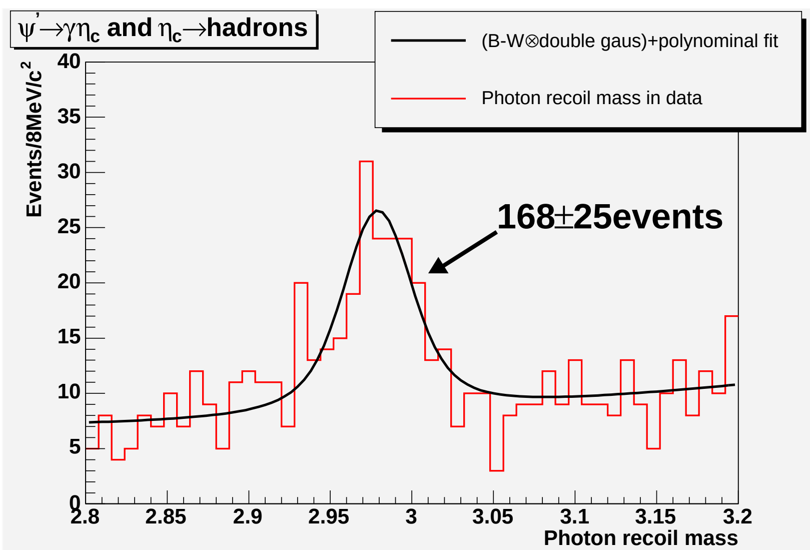
$\Psi' \to \pi^0 h_c \to (\gamma\gamma)(\gamma\eta_c)$, $\eta_c \to hadrons$
$\eta_c \to K^+K^-\pi^+\pi^-$
$\eta_c \to \pi^+\pi^-\pi^+\pi^-$
$\eta_c \to K_S K\pi$
$\eta_c \to K^+K^-\pi^0$
$\eta_c \to \pi^+\pi^-\eta(\gamma\gamma)$
$\eta_c \to \pi^+\pi^-\eta(\pi^+\pi^-\pi^0)$
total
Number of events/4 MeV
π^0 recoil mass in GeV
3.4
3.42
3.44
3.46
3.48
3.5
3.52
3.54
3.56
0
2
2.5
5

A Useful Comparison.

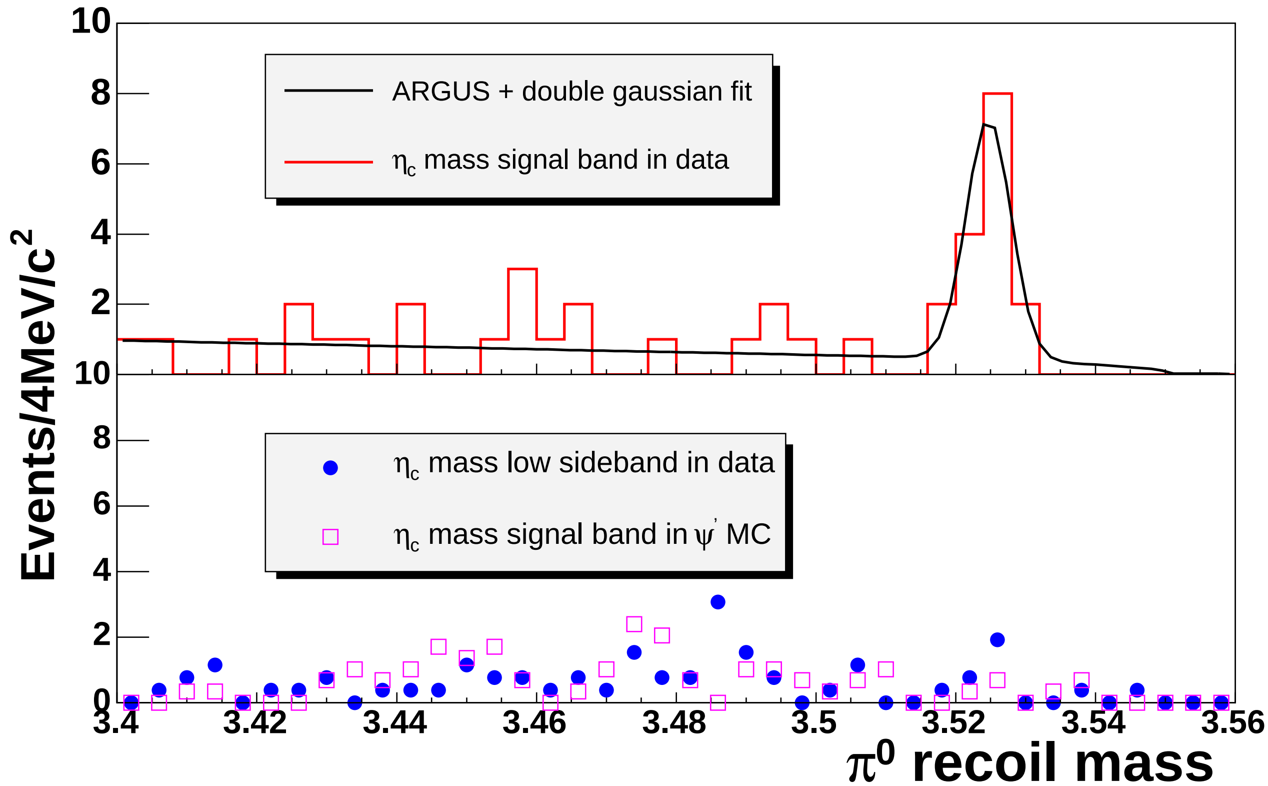
$\psi' \to \pi^0 h_c \to \pi^0\gamma\eta_c$ versus $\psi' \to \gamma\eta_c$

Decay Mode	$N(\pi^0\gamma\eta_c)$	$N(\gamma\eta_c)$, normalized to $N(\pi^0\gamma\eta_c)$
$K^+K^-\pi^+\pi^-$	4	1.6 ± 0.9
$\pi^+\pi^-\pi^+\pi^-$	8	5.5 ± 1.5
$K_S K \pi$	2	4.0 ± 0.9
$K^+K^-\pi^0$	1	2.0 ± 0.8
$\pi^+\pi^-\eta(\gamma\gamma)$	0	2.0 ± 0.4
$\pi^+\pi^-\eta(\pi^+\pi^-\pi^0)$	1	1.0 ± 0.5

The observed counts in the h_c decay to η_c are in agreement with what is expected for the direct decay of ψ' to η_c.



CLEO DATA



The results are

N(h_c)=15.0±4.2, significance(h_c)∼ 5 σ,

$M(h_c) = 3524.4 \pm 0.9(\text{stat})$ MeV.

Note that the significance is calculated using likelihood differences.

The background estimation by using η_c sidebands, or by using Monte–Carlo events, yielded consistent results.

No estimate of the systematic uncertainty in $M(h_c)$ has been made so far.

SUMMARY

- We have analyzed $\sim 3.0 \times 10^6$ ψ' from CLEO III and CLEO-c to search for $h_c(^1P_1)$ production in the reaction $\psi' \to \pi^0 h_c$, $h_c \to \gamma\eta_c$ by two methods
1. INCLUSIVE – which does not use η_c decay modes,
2. EXCLUSIVE – which uses six hadronic decay modes of η_c.

- In the recoil mass spectrum of π^0 , we see an enhancement in both analyses.

- In INCLUSIVE analysis we obtain
$M(h_c)$=3524.8±0.7(stat)± ~1(syst) MeV MeV,
$B(\psi' \to \pi^0 h_c) \times B(h_c \to \gamma\eta_c) = (2\text{–}6)\times 10^{-4}$,
significance >3 σ.

Thus,

$$\Delta M_{hf} \equiv \langle M(\chi_J)\rangle - M(^1P_1) = 0.5\pm 0.7(\text{stat})\pm \sim 1(\text{syst})\ \text{MeV}$$

- In EXCLUSIVE analysis we obtain
$M(h_c)$=3524.4±0.9(stat) MeV,
significance ~ 5 σ.

- The inclusive and exclusive results for $M(h_c)$ are in excellent agreement.