# The $h_c(1^1P_1)$ State of Charmonium

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## Introduction

- The spin–independent potential for $q\bar{q}$ onia is well-represented as

$$V(r) = \frac{4}{3}\alpha_S \frac{1}{r} + kr$$

  The Coulombic, $1/r$, part is of course a Lorentz vector. The confinement, $kr$, part is generally **assumed** to be Lorentz scalar.

- The spin–dependent potential is not so well modeled. A Breit-Fermi reduction of the Coulombic part leads to a spin-orbit $\vec{L} \cdot \vec{S}$, a tensor, $T_{12}$, and a spin-spin $\vec{s}_1 \cdot \vec{s}_2$ part, which is in the lowest order a contact or a delta function interaction, finite for $L = 0$, and zero for $L \neq 0$. No long-range spin–dependent part arises from the scalar confinement potential.

- As we know from textbooks, in the quark model, the ground state masses of hadrons depend only on quark masses and the hyperfine $\vec{s}_1 \cdot \vec{s}_2$ interaction. The hyperfine interaction is all-important. It gives rise to the splitting of spin–singlet and spin–triplet, or

$$\Delta M_{hf}(nL) \equiv M(n^3L - n^1L)$$

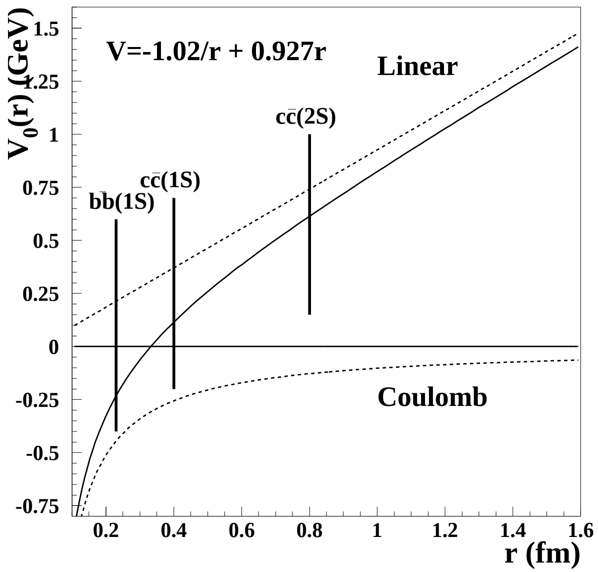
## Introduction, cont'd

- According to the potential model described above

$$\Delta M_{hf}(1S, 2S, ...) = \text{finite}, \quad \Delta M_{hf}(1P, 2P, ...) = 0$$

Of course, we do not know how the hyperfine interaction, and the consequent $\Delta M_{hf}$ changes with quark mass, or for radial excitations (different $n$), or the radius of the meson, as the potential changes from being dominated by the Coulombic or confinement parts.

- We also do not know if the simple prediction $\Delta M_{hf}(L \neq 0) = 0$, based on the rather ad-hoc assumptions, is true.
- To answer these questions, we need to measure as many different $\Delta M_{hf}$, singlet–triplet splittings, as possible. Since the triplet quarkonium states are generally well-studied, the job amounts to identifying the spin–singlet states.



## Spin Singlets—What is Known

The bound charmonium singlets are $\eta_c(1^1S_0)$, $\eta'_c(2^1S_0)$, and $h_c(1^1P_1)$.

- $\eta_c(1^1S_0)$ was firmly identified at SLAC about 30 years ago, and we know that

$$\Delta M_{hf}(1S) \equiv M(J/\psi) - M(\eta_c) = 117.1 \pm 1.2 \text{ MeV}$$

- In 2004, after many false starts $\eta'_c(2^1S_0)$ was identified by Belle, CLEO, and BaBar, and PDG07 lists its average mass as $3637 \pm 4$ MeV, so that

$$\Delta M_{hf}(2S) \equiv M(\psi') - M(\eta'_c) = 49 \pm 4 \text{ MeV}$$

  Some claims to the contrary, the factor 2.4 smaller $2S$ hyperfine splitting came as a surprise. Of course, **post**dictions abound.

  **The unavoidable lesson is that hyperfine splittings can present surprises.**

- This makes it imperative to find $h_c(^1P_1)$ and measure its mass with precision. This has now been done.

## The Search for $h_c(1^1P_1)$

- The $p\bar{p}$ measurements by the Fermilab experiments E760/E835 have determined the masses of the triplet $P$ states $\chi_{cJ}$ with great precision, so that their centroid is

$$\langle M(\chi_{cJ})\rangle = (5M(\chi_{c2}) + 3M(\chi_{c1}) + M(\chi_{c0}))/9 = 3525.4 \pm 0.1 \text{ MeV}$$

- If **we assume** that

$$M(^3P) = \langle M(\chi_{cJ})\rangle\,, \text{ as determined above,}$$

the prediction that $\Delta M_{hf}(1P) = 0$ would **imply** $M(h_c) = 3525.4$ MeV.

- Let us go and find it.
- In 1982 Crystal Ball failed in the search for $h_c$ in the reaction

$$\psi(2S) \to \pi^0 h_c,\ h_c \to \gamma\eta_c.$$

- In 1992 Fermilab E760 studied the reaction $p\bar{p} \to h_c \to \pi^0 J/\psi$ and claimed the observation of a signal for $h_c$. However, higher luminosity runs in 1996 and 2000 failed to confirm this observation.

## The Search for $h_c(1^1P_1)$, cont'd

- In 2005, Fermilab E835 searched for $h_c$ in their 1996/2000 data in the reaction $p\bar{p} \to h_c \to \gamma\eta_c$, and reported

$$\Delta M_{hf}(1P) = -0.4 \pm 0.2 \pm 0.2 \text{ MeV}$$

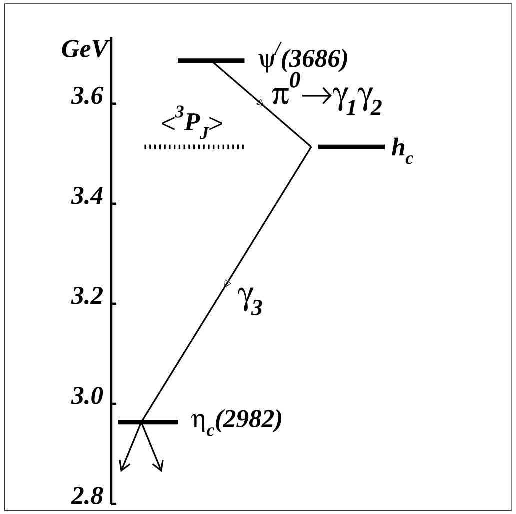
with 13 counts, and a significance of the $h_c$ signal at $\sim 3\sigma$ level.

- In 2005, CLEO reported a $6\sigma$ identification of $h_c$ with 3.08 million $\psi(2S)$ in the reaction

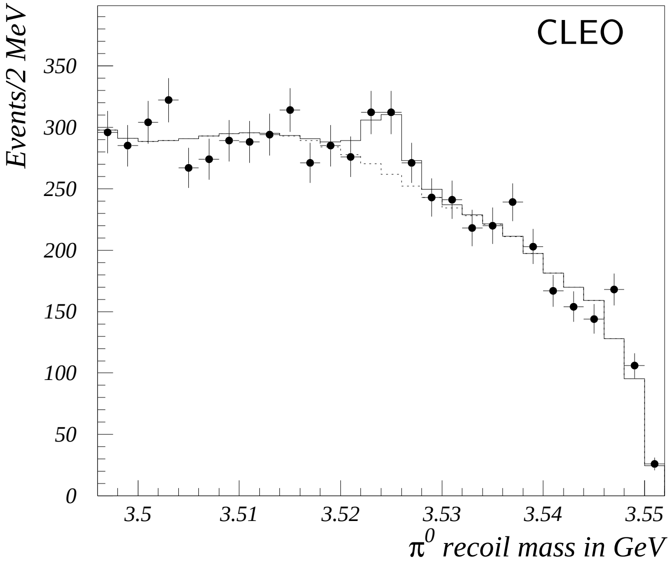
$$\psi(2S) \to \pi^0 h_c, \;\; h_c \to \gamma_3\eta_c, \;\; \pi^0 \to \gamma_1\gamma_2$$

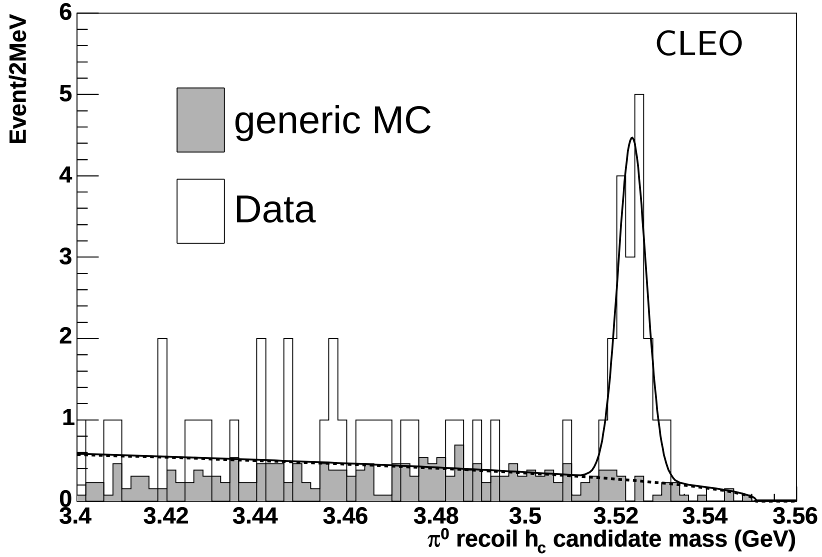
**Inclusive** analyses were made by loosely constraining either $E(\gamma_3)$ or $M(\eta_c)$. **Exclusive** analysis was made with no constraints on $E(\gamma_3)$ or $M(\eta_c)$, but by reconstructed $\eta_c$ in several hadronic decays. Consistent results were obtained.

- The present report is the result of a similar analysis of CLEO-c data with **24.5 million $\psi(2S)$**.



# The Published CLEO Results (PRL **95**, 102003 (2005))




INCLUSIVE, N(evt)=150±40, $3.8\sigma$ EXCLUSIVE, N(evt)=17.5±4.5, $5.2\sigma$

The combined results are

$$\mathcal{B}(\psi'(2S) \to \pi^0 h_c) \times \mathcal{B}(h_c \to \gamma\eta_c) = (4.0 \pm 0.8 \pm 0.7)\ 10^{-4},\ 6\sigma$$

$$M(h_c) = 3524.4 \pm 0.6 \pm 0.4\ MeV,\ \text{using}\ \langle M(\chi_{cJ})\rangle = 3525.4 \pm 0.1\ MeV$$

$$\Delta M_{hf}(1P) = \langle M(\chi_{cJ})\rangle - M(h_c) = +1.0 \pm 0.6 \pm 0.4\ MeV$$

- Conclusion: The simple pQCD expectation, $\Delta M_{hf}(1P) = 0$, is not strongly violated.
- The magnitude and sign of $\Delta M_{hf}$ are not well determined.

## The New Results For $h_c$

The CLEO-c data for 24.5 million $\psi(2S)$ has been analyzed for the reaction

$$\psi(2S) \to \pi^0 h_c, \quad h_c \to \gamma\eta_c, \quad \pi^0 \to \gamma\gamma$$

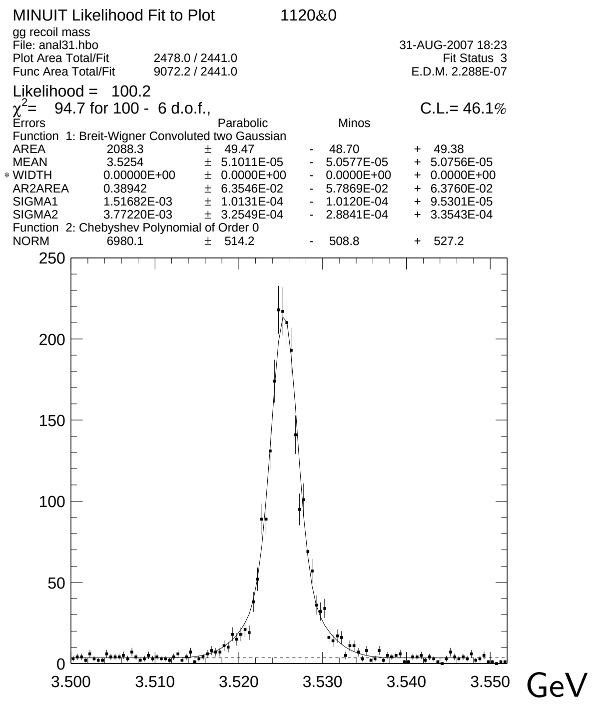
The event selection criteria were the same as in our published paper.

- N(showers)$\geq$3, N(tracks)$\geq$2
- CLEO standard criteria for good showers and tracks
- Reject $\pi^+\pi^-$ and $\pi^0\pi^0$ transitions to $J/\psi$
- For **inclusive analysis**, accept hard $\gamma$ (E1 gamma $h_c \to \eta_c$) only with $E_\gamma$(hard)$=503 \pm 35$ MeV.
- For **exclusive analysis**, put no restriction on $E_\gamma$(hard), but reconstruct $\eta_c$ decays to hadrons.
- Reconstruct $\pi^0 \to \gamma\gamma$, and analyze spectra for recoil against $\pi^0$

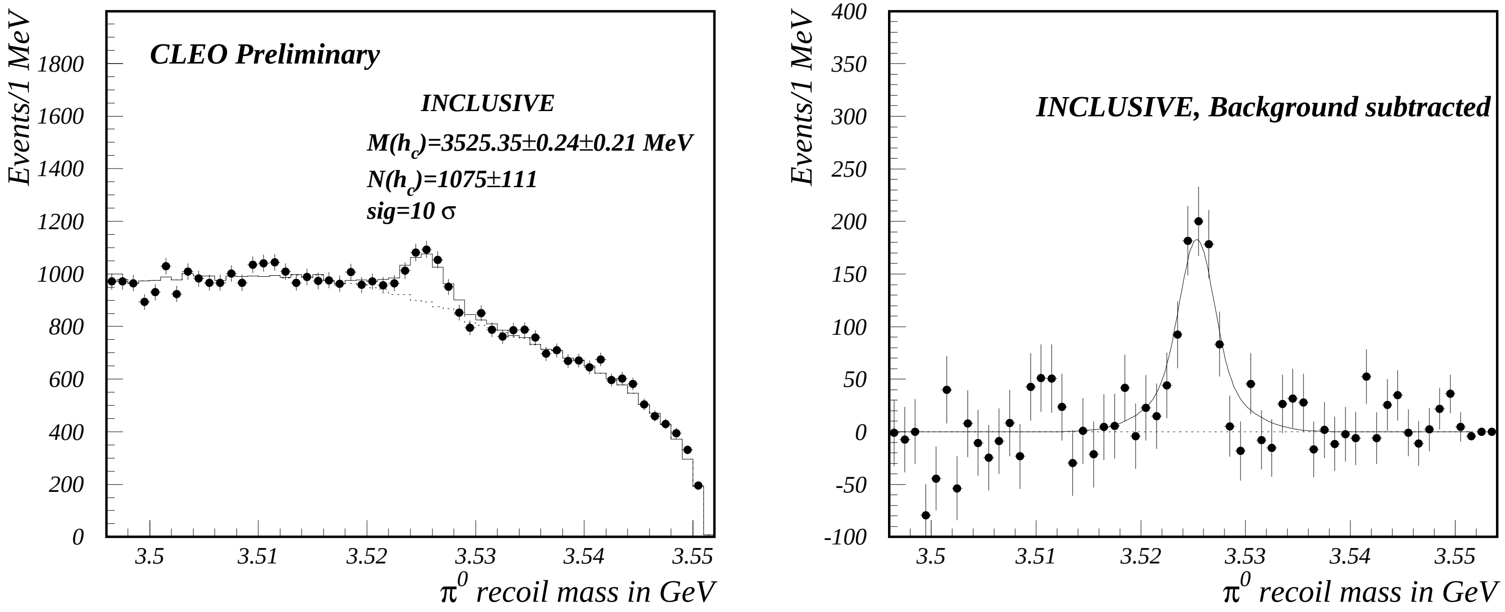
# INCLUSIVE ANALYSIS

# Inclusive Analysis

To analyze the inclusive spectrum of $\pi^0$ recoils in the $\psi(2S) \to \pi^0 h_c$, $h_c \to \gamma\eta_c$ it is required to model the background and the signal peak.




- **Background Shape:** To determine the background shape, we use the $\pi^0$ recoil spectrum from the data itself, when the requirement $E_\gamma = 503 \pm 35$ MeV for the E1 photon is not applied. This recoil spectrum is essentially all background because the product branching fraction for the $h_c$ production and decay is $\sim 10^{-4}$.
- **Peak Shape:** The experimental resolution function was determined by Monte Carlo simulation of the reaction. Its shape was fitted with a double Gaussian and convoluted with an **assumed** Breit-Wigner width of $\Gamma(h_c) = 0.9$ MeV to fit the observed signal in the data.




Inclusive Analysis: $N(h_c) = 1075 \pm 111$, significance$=10\sigma$

$M(h_c) = 3525.35 \pm 0.24$ MeV

$\mathcal{B}_1(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}_2(h_c \to \gamma\eta_c) = (3.95 \pm 0.41) \times 10^{-4}$

# Inclusive Analysis, Summary of Systematic Errors

| Systematics in | $M(h_c)$ – MeV | $B_1 \times B_2 \times 10^4$ |
|---|---|---|
| Background shape | 0.10 | 0.26 |
| $\pi^0$ energy scale | 0.08 | – |
| Event selection | 0.14 | 0.31 |
| Monte Carlo Input/Output | 0.06 | – |
| Signal shape | 0.03 | 0.14 |
| $h_c$ width | 0.03 | 0.27 |
| Binning, fitting range | 0.03 | 0.08 |
| Efficiency | – | 0.20 |
| Sum in quadrature | 0.21 | 0.55 |

## Inclusive Analysis Results

CLEO Preliminary

| | $24.5\times10^{6}\ \psi'$ |
|---|---|
| $N(h_c)$ | $1075 \pm 111$ |
| Significance | $10\sigma$ |
| $M(h_c)$, MeV | $3525.35\pm0.24 \pm 0.21$ |
| $B_1 \times B_2$ | $(3.95\pm0.41\pm0.55)\times10^{-4}$ |

## EXCLUSIVE ANALYSIS

## Exclusive Analysis

In the exclusive analysis, instead of constraining $E_\gamma$ of the photon candidate from the decay $h_c \to \gamma\eta_c$, 18 $\eta_c$ hadronic decay channels were reconstructed.

$$\psi' \to \pi^0 h_c, h_c \to \gamma\eta_c, \eta_c \to \text{hadrons}$$

2 body: one channel, $p\bar{p}$

3 body: 9 channels, $\eta\pi^+\pi^-$ ($\eta \to \gamma\gamma$), $\eta\pi^+\pi^-$ ($\eta \to \pi^+\pi^-\pi^0$), $K_S K^+\pi^-$,$K^+K^-\pi^0$, $K_S K_S \pi^0$, $\eta K^+K^-$ ($\eta \to \gamma\gamma$), $\eta K^+K^-$ ($\eta \to \pi^+\pi^-\pi^0$), $p\bar{p}\pi^0$,$p\bar{p}\eta$

4 body: 5 channels, $\pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-\pi^0\pi^0$, $K^+K^-\pi^+\pi^-$, $K^+K^-K^+K^-$, $p\bar{p}\pi^+\pi^-$

6 body: 3 channels, $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$, $K^+K^-\pi^+\pi^-\pi^+\pi^-$

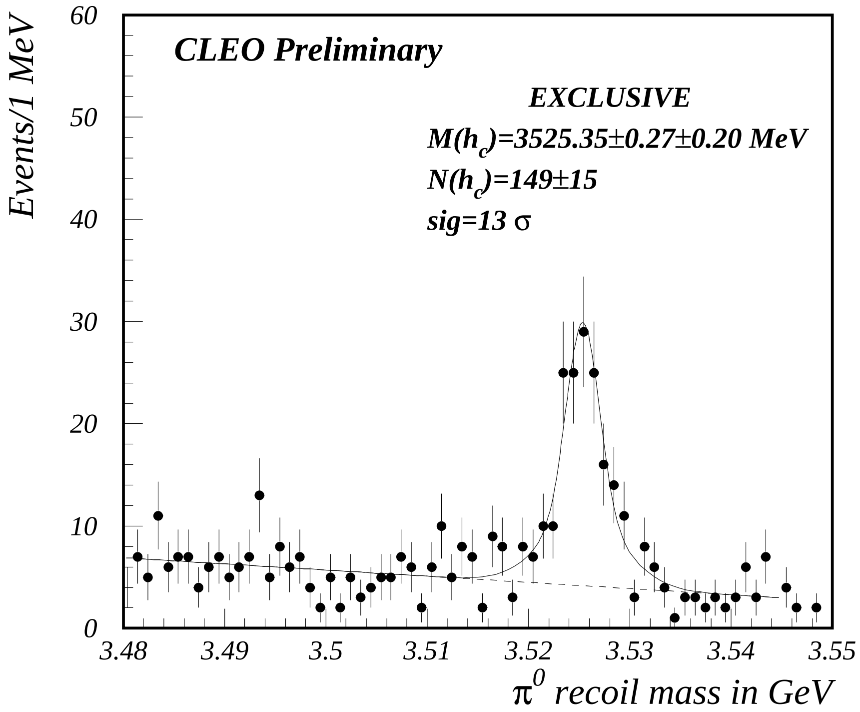
# Exclusive Analysis, selection criteria

- The charged $\pi^+/\pi^-$ were selected using $\sigma$(dE/dx,$\pi$)<4.
- The charged $K^+/K^-$ were selected using $\sigma$(dE/dx,K)< $\sigma$(dE/dx,$\pi$), and $\sigma$(dE/dx,K)< $\sigma$(dE/dx,p). We also used RICH information, if it was available.
- The protons/antiprotons were selected using $\sigma$(dE/dx,p)< $\sigma$(dE/dx,$\pi$), and $\sigma$(dE/dx,p)< $\sigma$(dE/dx,K). We also used RICH information, if it was available.

A four-constraint kinematic fit of the events was done, with $\chi^2(4C) < 15$

The invariant mass of $\eta_c$ decay candidates was required to be within $\pm$30 MeV of the nominal $\eta_c$ mass of 2980 MeV.

## Recoiling Mass Against $\pi^0$ for sum of all $\eta_c$ decay channels




Fit to the data was done using a Breit-Wigner with $\Gamma$=0.9 MeV convoluted with the experimental resolution function for signal plus a linear background.

$N(h_c)$=149±15, significance=13$\sigma$

$M(h_c)$=3525.35±0.27 MeV

# Exclusive Analysis, Systematic Errors

Systematic errors in exclusive analysis have been obtained using the same procedures which we use in inclusive analysis.

| Systematics in | $M(h_c)$ – MeV |
|---|---|
| $\pi^0$ energy scale | 0.08 |
| Event Selection | 0.13 |
| Monte Carlo Input/Output | 0.11 |
| Background shape | 0.01 |
| Signal shape | 0.01 |
| $h_c$ width | 0.01 |
| Binning, fitting range | 0.08 |
| Sum in quadrature | 0.20 |

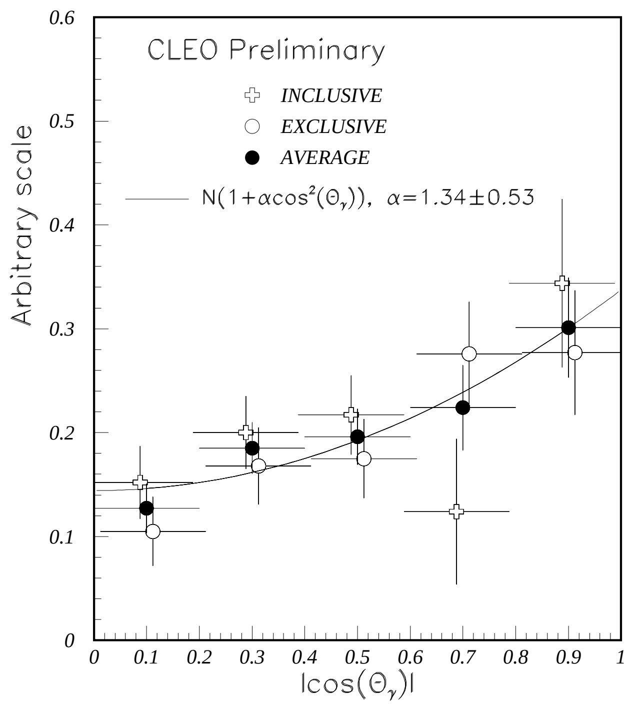
## Exclusive Analysis Results

CLEO Preliminary

| | $24.5\times10^6\ \psi'$ |
|---|---|
| $N(h_c)$ | $149 \pm 15$ |
| Significance | $13.1\sigma$ |
| $M(h_c)$, MeV | $3525.35\pm0.27 \pm 0.20$ |

## Angular Distributions from Inclusive and Exclusive Analyses

The angular distributions of the E1 photon in both inclusive and exclusive analysis were obtained by fitting separately the $h_c$ peak in the different angular ranges. The exclusive events were removed from the inclusive sample to enable averaging the two results.




Fit to $N(1 + \alpha \cos^2 \theta)$ gave:

$\alpha_{incl}$=0.87±0.65

$\alpha_{excl}$=1.89±0.94

$\alpha_{average}$=1.34±0.53

which are consistent with $\alpha$=1 expected for an E1 transition from $h_c(J^{PC} = 1^{+-})$ to $\eta_c(J^{PC} = 0^{--})$.

# SUMMARY

We have analyzed the new $\psi'$ data with estimated $\sim 24.5 \times 10^6$ $\psi'$ events, for

$$\psi' \to \pi^0 h_c \to (\gamma\gamma)(\gamma\eta_c) \ .$$

| | CLEO Preliminary, $24.5\times10^6$ $\psi'$ | Published, $3\times10^6$ $\psi'$ |
|---|---|---|
| **Inclusive**, $N(h_c)$ | $1075 \pm 111$ | $140 \pm 40$ |
| Significance | $10.0\sigma$ | $3.8\sigma$ |
| $M(h_c)$, MeV | $3525.35 \pm 0.24 \pm 0.21$ | $3524.9 \pm 0.7 \pm 0.4$ |
| $B_1 \times B_2 \times 10^4$ | $3.96 \pm 0.41 \pm 0.55$ | $3.5 \pm 1.0 \pm 0.7$ |
| **Exclusive**, $N(h_c)$ | $149 \pm 15$ | $17.5 \pm 4.5$ |
| Significance | $13.1\sigma$ | $5.2\sigma$ |
| $M(h_c)$, MeV | $3525.35 \pm 0.27 \pm 0.20$ | $3523.6 \pm 0.9 \pm 0.5$ |

**Average for $24.5\times10^6$ $\psi'$: $M(h_c)$(Incl+Excl)=3525.35±0.19±0.15 MeV.**

Exclusive sample events were removed from the inclusive events before averaging.

Common contributions to systematics errors were not averaged.

The angular distribution of the photon is determined to be $1 + \alpha\cos^2\theta, \ \alpha = 1.3 \pm 0.5$, consistent with its E1 nature.

## DISCUSSION

- In the lowest order, when the spin–orbit splitting is perturbatively small

  $M(^3P) = \langle M(^3P_J) \rangle = [5M(^3P_2) + 3M(^3P_1) + M(^3P_0)]/9 = 3525.4 \pm 0.1$ MeV (PDG)

  Our determination of

  $$M(h_c) = 3525.35 \pm 0.19 \pm 0.15 \text{ MeV}$$

  leads to

  $$\mathbf{\Delta M_{hf}(1P) = -0.05 \pm 0.19 \pm 0.16 \text{ MeV}}$$

  which is consistent with the lowest order expectation that $\Delta M_{hf}(1P) = 0$.

- It has been pointed out (mainly by A. Martin and J. M. Richard) that the $\vec{L} \cdot \vec{S}$ splitting with $M(\chi_{c2}) - M(\chi_{c0}) = 141$ MeV can hardly be considered perturbatively small.

  The triplet mass $M(^3P)$ should not be equated with the average obtained above, but should be obtained by turning off the $\vec{L} \cdot \vec{S}$ and tensor parts in the potential model calculations.

## DISCUSSION, cont'd

- At our request, T. Barnes (priv. comm.) has done so, and obtains $M(^3P) = 3516$ MeV, whereas in the same calculation, $\langle M(^3P_J) \rangle = 3525$ MeV. This corresponds to the true prediction of the calculation being

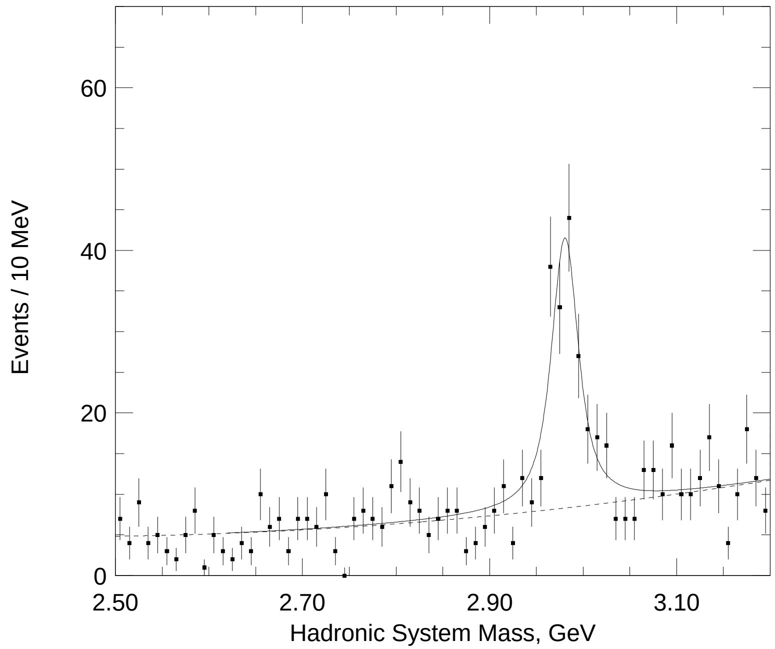
$$\Delta M_{hf}(1P) = -9 \text{ MeV}, \quad \text{not} = 0$$

- Admittedly, the result from these potential model calculations depend very much on how the hyperfine contact interaction (?) is regularized in order to use it in a Schroedinger equation. Nevertheless, caution should be exercised in interpreting our result as confirming the perturbative prediction, $\Delta M_{hf}(1P) = 0$.
- We can only hope that this problem can be resolved one day by lattice calculations of sufficient precision. The presently available lattice results have stated errors $\gtrsim \pm 20$ MeV in all masses.

# Backup Slides

# Exclusive Analysis, Hadronic system mass

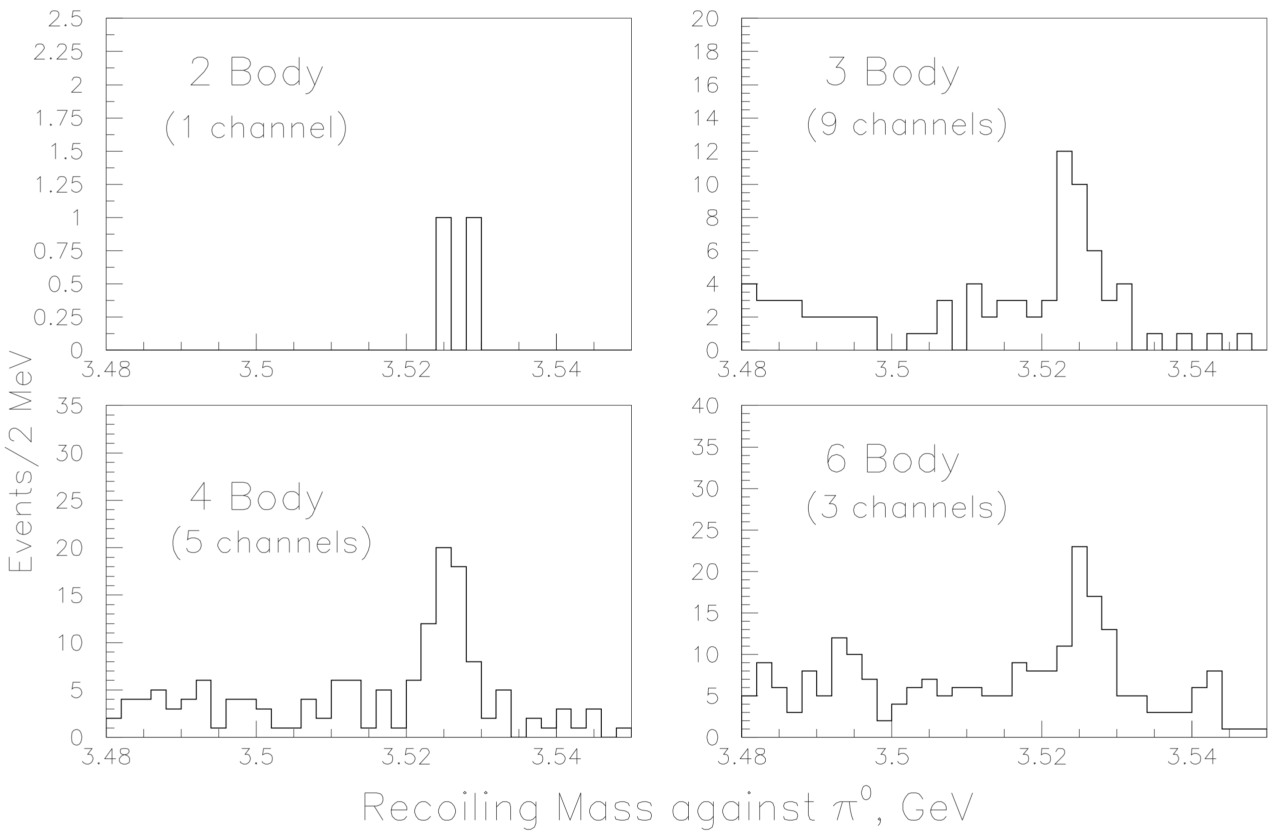
CLEO Preliminary




Mass of the hadronic system for sum of 18 exclusive channels for events with recoil mass against $\pi^0$ in range of $h_c$ mass of 3525±5 MeV.
The fit gave $\boldsymbol{M(\eta_c) = 2981 \pm 2}$**(stat) MeV.**

## $\pi^0$ Recoil Mass Spectra for Different Multiplicities

CLEO Preliminary




The sum of these spectra is used for the fit for $M(h_c)$.