Recent Heavy Flavor Results from CLEO-c

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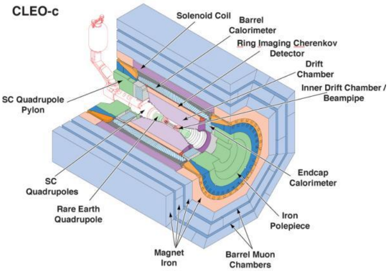
CLEO-c

CLEO-c is about to complete (3 March) its 5th and final year, ending $\sim$ 30 years of heavy flavor physics at CESR

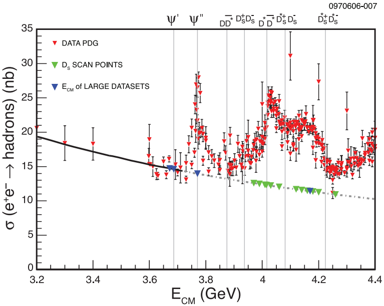
CLEO-c Data Sets for Today's talk:

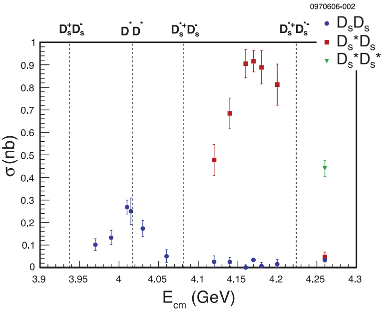
- $\sim 300 \times 10^3 (D_S D_S{}^*)$
- $\sim 24.5 \times 10^6 \psi'$



D_S Studies at $\sqrt{s} = 4170 MeV$

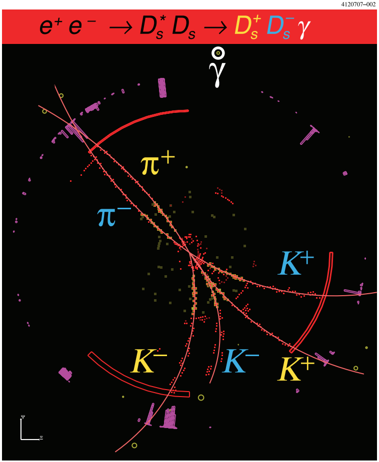
- D_S Physics is studied at CLEO by running at the energy providing maximal yield of $D_S^{*\pm} D_S^{\mp}$
- Scan found max at 4170 MeV of $\sigma(D_S D_S^*) \simeq 1$nb





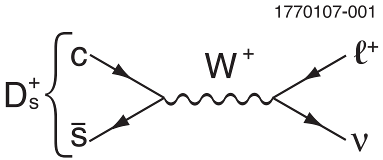
Submitted to PRD - arxiv.org/0801.1092

CLEO Charm Studies at $\sqrt{s} = 4170 MeV$



- For the two D_S analyses which follow, we employ double tagging
- Fully reconstruct one charm decay: $n_{ST} = 2N\mathcal{B}_{ST}\epsilon_{ST}$
- Observe other D_S (sig) decay
- (Possibly) observe photon from $D_S{}^*$ and combine with tag OR signal side, and kin. fit
- $n_{DT} = 2N\mathcal{B}_{ST}\mathcal{B}_{sig}\epsilon_{DT}$
- Finally obtain $\mathcal{B}_{sig} = \frac{n_{DT}}{n_{ST}}\frac{\epsilon_{ST}}{\epsilon_{DT}}$

$D_S{}^+ \to \tau^+ \bar{\nu}_\tau$ Br. Frac. and f_{D_S}



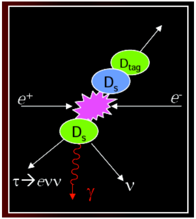
- Purely leptonic decays of pseudoscalars like D_S probe the hadronic annihilation vertex:

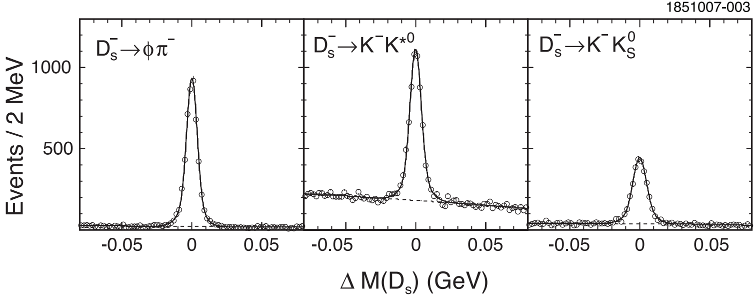
$$\Gamma(P^+ \to \ell^+ \nu) = \frac{1}{8\pi} G_F^2 f_P^2 m_\ell^2 M_P \left(1 - \frac{m_\ell^2}{M_P^2}\right) |V_{cs}|^2$$

- Measurement provides important input/test for theory in calculating f_{B_S}

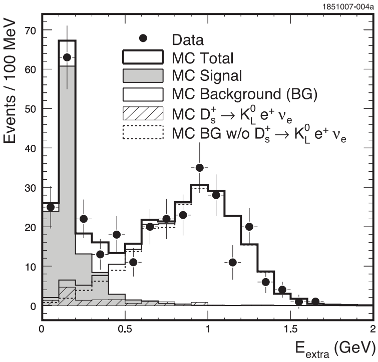
Basic Analysis Method

- Previous CLEO results measure $D_S{}^+ \to \tau^+ \bar{\nu}_\tau$ with $\tau^+ \to \pi^+ \nu_\tau$. In this present analysis we use $\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$
- First - identify $D_S{}^-$ tag in one of three modes (12947 ± 150 ST):





$D_S{}^+ \to \tau^+ \bar{\nu}_\tau$: From ST to DT to signal yield



$$n_{ST} = 12947 \pm 150$$
$$n_{DT} = 102 \pm 12$$
$$B_{sig} = \frac{n_{DT}}{n_{ST}} \frac{\epsilon(ST)}{\epsilon(DT)}$$

- Next - Allow one additional track (e^+) opposite ST
- Use $E_{extra} \equiv \Sigma(E_{\gamma,unassoc.})$. Expect peak corresponding to $D_S{}^{*+} \to D_S{}^+(\gamma, \pi^0)$
- Bkg in side-band subtracted E_{extra} dominated by $D_S{}^+ \to X e^+ \nu$
- Syst err dominated by the uncertainty in $D_S{}^+ \to X e^+ \nu$ branching fractions.

$D_S{}^+ \to \tau^+ \bar{\nu}_\tau$ and f_{D_S} Summary

Final BF result: $B(D_S{}^+ \to \tau^+ \bar{\nu}_\tau) = (6.17 \pm 0.71 \pm 0.34)\%$ and using $|V_{cs}| = 0.9738$ (and G_F, m_τ, M_{D_S}) we obtain f_{D_S}

- With this measurement:

$$f_{D_S} = 273 \pm 16 \pm 8 \ MeV$$

- Combined with the previous result (which used $\tau^- \to \pi^- \nu_\tau$ and $D_S{}^+ \to \mu^+ \bar{\nu}_\mu$) of $f_{D_S} = 274 \pm 13 \pm 7 \ MeV$, (PRD95, 251801 (2005)) we have

$$f_{D_S} = 274 \pm 10 \pm 5 \text{ MeV},$$

which is the most precise result to date.

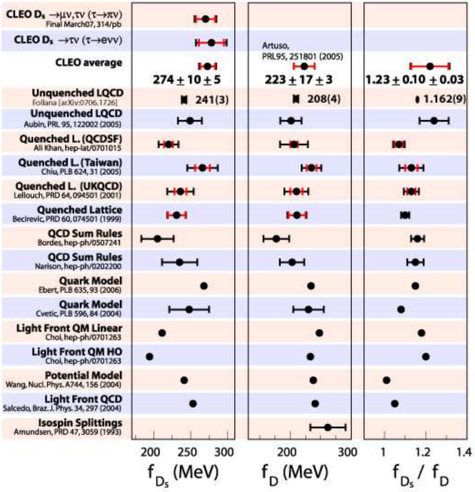
Submitted to PRL: arxiv.org/0712.1175

$D_S{}^+ \to \tau^+ \bar{\nu}_\tau$ and f_{D_S} Summary

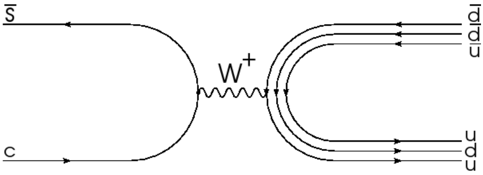
- Finally, combine w/our result $f_{D^+} = 223 \pm 17 \pm 3$ MeV to obtain

$$\frac{f_{D_S}}{f_{D^+}} = 1.23 \pm 0.10 \pm 0.03$$

- Ultimate $\sqrt{s} = 4170$ MeV sample will push rel. uncertainty on f_{D_S} to $\sim 2.5\%$
- Submitted to PRD: arxiv.org/0712.1175



Discovery of $D_S{}^+ \to p\bar{n}$



- The only kinematically-allowed baryon-antibaryon decay of any ground-state charmed meson
- The mechanism? weak annihilation. Interestingly, was predicted in 1980 by Pham (PRL45, 1663) as 'smoking gun' signal for annihilation
- Rather than searching for the $\bar{n}$ directly, instead we use a double-tag + missing mass strategy very similar to that used in the measurement of $D_S{}^+ \to \ell^+ \bar{\nu}_\ell$

Observation of $D_S{}^-$ Tags

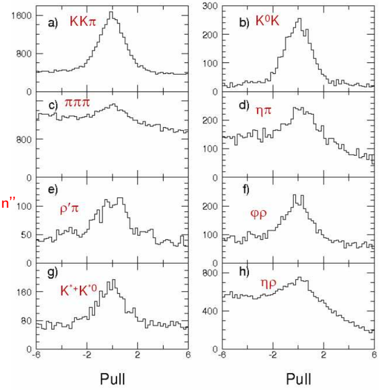
Step 1: Observe $D_S{}^-$ in one of 8 tag modes (27700 ST's)

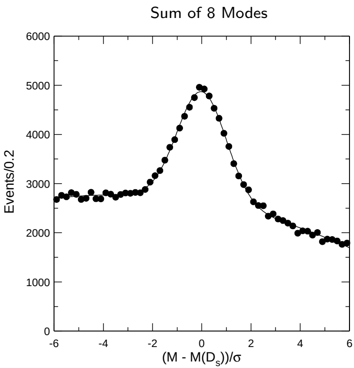
"Clean"

Modes

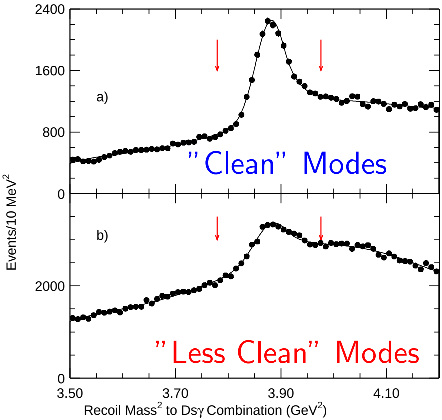
"Less Clean"

Modes





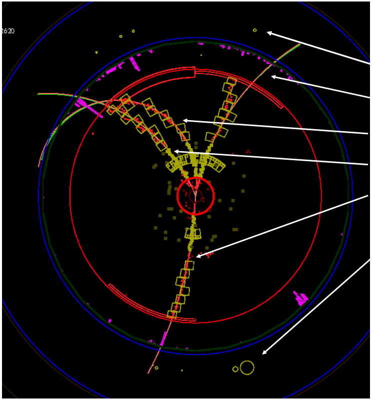
Mass Recoiling against $D_S(tag)\gamma$ Combination



- Step 2: Find γ and calculate mass recoiling against it and D_S ST's within 2σ of D_S mass*
- Selection for further analysis lies between the two arrows (16955 $D_S{}^+\gamma$ candidates)

* Note: The D_S and γ needn't actually be daughters of $D_S{}^*$ for this to work

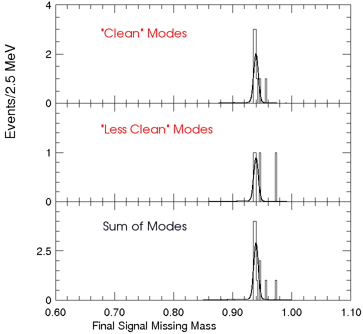
Next Step: Got Proton?



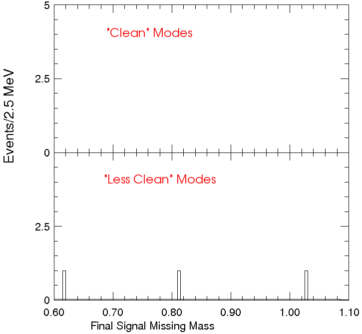
- Observe proton and calculate missing p^μ. Combine missing p^μ and proton for $D_S{}^+ \to p\bar{n}$ candidate
- Kin. fit for $D_S{}^{*+} \to \gamma D_S{}^+(sig)$ or $D_S{}^{*-}\gamma D_S{}^-(tag)$
- Select better fit and calculate missing mass

Missing Mass Distributions (Data)

D_S Signal band $\pm 2\sigma$



D_S Sidebands $\pm(3.5 - 6\sigma)$



Essentially no background! (<1.1 events in signal region)

Signal events: 13.0 ± 3.6

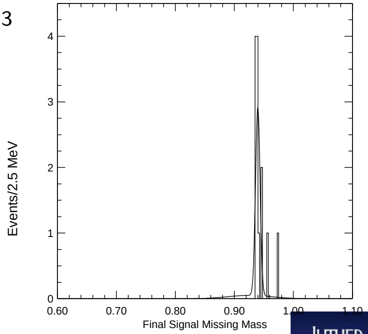
Discovery of $D_S{}^+ \to p\bar{n}$ Summary

- Final result:

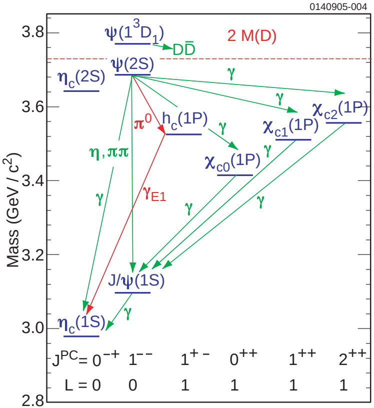
CLEO Preliminary

$$B(D_S{}^+ \to p\bar{n}) = (1.30 \pm 0.36^{+0.12}_{-0.16}) \times 10^{-3}$$

- Syst. uncertainties primarily come from $D_S{}^-$ tags, signal shape, fitting, bkg subtraction
- From this and the $D_S{}^+ \to \mu^+ \bar{\nu}_\mu$ rate, we may learn something about baryon production
- We know of no recent prediction of the rate for this process



Charmonium Physics Results



We present these new results taken from our sample of 24.5M ψ' decays

- Radiative decay BFs for $\psi(nS) \to \gamma\eta_c$
- Discovery of $J/\psi \to \gamma\gamma\gamma$
- Mass and product BF for h_c produced in $\psi' \to \pi^0 h_c$

History of η_c Observed in $\psi(nS) \to \gamma\eta_c$

$\Gamma(\gamma\eta_c(1S))/\Gamma_{total}$ — Γ_{99}/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
0.30±0.05 OUR AVERAGE					
0.32±0.04±0.06	2560	[85] ATHAR	04	CLEO	$e^+e^- \to \gamma X$
0.28±0.06		[86] GAISER	86	CBAL	$e^+e^- \to \gamma X$

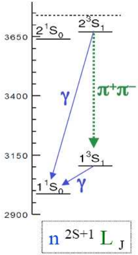
[85] ATHAR 04 used $\Gamma_{\eta_c(1S)} = 24.8 \pm 4.9$ MeV to obtain this result.
[86] GAISER 86 used $\Gamma_{\eta_c(1S)} = 11.5 \pm 4.5$ MeV to obtain this result.

$\Gamma(\gamma\eta_c(1S))/\Gamma_{total}$ — Γ_{108}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0127±0.0036		GAISER	86	CBAL	$J/\psi \to \gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.0079±0.0020	273 ± 43	[60] AUBERT	06E	BABR	$B^\pm \to K^\pm X_{c\overline{c}}$
seen	16	BALTRUSAIT...	84	MRK3	$J/\psi \to 2\phi\gamma$

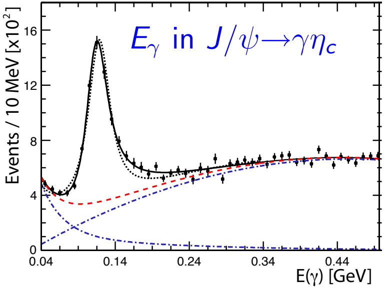
[60] Calculated by the authors using an average of $B(J/\psi \to \gamma\eta_c) \times B(\eta_c \to K\overline{K}\pi)$ from BALTRUSAITIS 86, BISELLO 91, BAI 04 and $B(\eta_c \to K\overline{K}\pi) = (8.5 \pm 1.8)\%$ from AUBERT 06E.

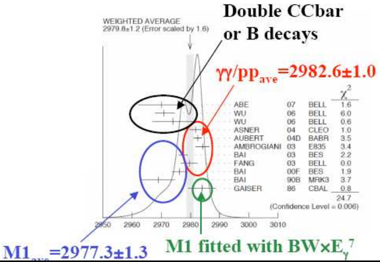
- Most η_c decay rates pegged to these BFs
- J/ψ rad decay has always been "too small"
- (Recent JLab calculation $2.0 \pm 0.1 \pm 0.4$ keV)



- In addition: some discrepancies concerning η_c mass and width among raditative decay vs direct formation methods

E_γ lineshape: $J/\psi \to \gamma\eta_c(exc.)$

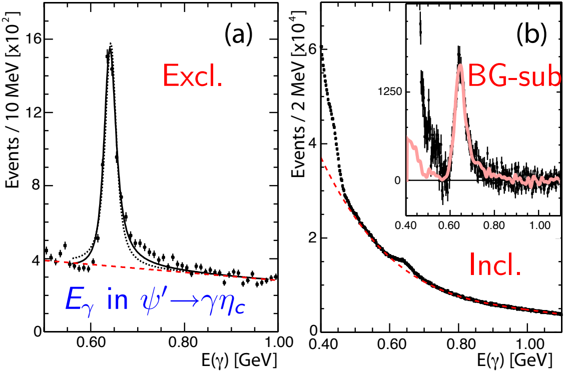




- BKG determined by MC
- Good fit requires modification of simple BW by factors $\propto E_\gamma^3$ and $exp(E_\gamma^2/\beta)$
- M using unmodified BW: 2976.7 ± 0.6 MeV (c.f. previous radiative decay measurements)
- M using modified form: 2982.2 ± 0.6 MeV (c.f. direct formation measurements)
- Note: we are not claiming a mass measurement

Measurement of $B(\psi(nS) \to \gamma\eta_c)$

- We find a similarly lineshape in $\psi(2S)$ radiative decay:
- In this hindered M1 decay, the BW is modified by a factor $\propto E_\gamma^7$



- Fit isn't good, however - so the exclusive shape will in fact be used to fit the inclusive spectrum (12 modes, summed)

Measurement of $B(\psi(nS)\to\gamma\eta_c)$:

$$B(\psi(2S)\to\gamma\eta_c(1S)) = \frac{[N_{2S,INC}]}{[\varepsilon_{2S,INC}]} \times \frac{1}{N_{\psi(2S)}}$$

$$\frac{B(J/\psi\to\gamma\eta_c(1S))}{B(\psi(2S)\to\gamma\eta_c(1S))} = \frac{[N_{1S,EXC}]}{[N_{2S,EXC}]\times\left[\frac{\varepsilon_{1S,EXC}}{\varepsilon_{2S,EXC}}\right]} \times \frac{1}{B_{\pi\pi}}$$

$$B(J/\psi\to\gamma\eta_c(1S)) = \frac{\left[\frac{N_{2S,INC}}{N_{2S,EXC}}\right]\times[N_{1S,EXC}]}{[\varepsilon_{2S,INC}]\times\left[\frac{\varepsilon_{1S,EXC}}{\varepsilon_{2S,EXC}}\right]} \times \frac{1}{N_{\psi(2S)}\times B_{\pi\pi}}$$

N_{2S} Fits: Use the exclusive histogram to fit the inclusive spectrum.

N_{1S} Fits: Use the BW×E^3×f(E) line shape.

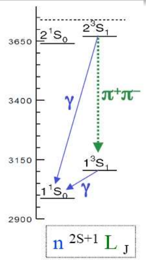
$N_{2S,INC}$: Number of inclusive $\psi(2S)\to\gamma\eta_c$

$N_{2S,EXC}$: Number of exclusive $\psi(2S)\to\gamma\eta_c$

$N_{1S,EXC}$: Number of exclusive $\psi(2S)\to\pi\pi J/\psi$; $J/\psi\to\gamma\eta_c$

$N_{\psi(2S)}$: Number of $\psi(2S)$

$B_{\pi\pi}$: $B(\psi(2S)\to\pi^+\pi^- J/\psi)$ (currently using CLEO's published number).



Branching Fraction	CLEO-c	PDG2006
$\mathcal{B}(\psi'\to\gamma\eta_c)$	$(4.02\pm0.11\pm0.52)\times10^{-3}$	$2.6\pm0.4\times10^{-3}$
$\mathcal{B}(J/\psi\to\gamma\eta_c)$	$(2.07\pm0.09\pm0.35)\%$	$1.3\pm0.4\%$

- This supercedes our previous result based on 3M ψ' decays in PRD 70, 112002 (2004)
- Note: $\mathcal{B}(J/\psi\to\gamma\eta_c)$ is substantially higher than the C.Ball result of $1.3\pm0.4\%$

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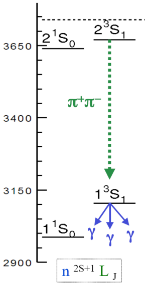
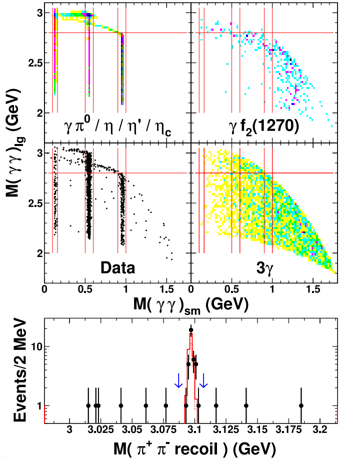
CLEO Preliminary

Discovery of $J/\psi \to \gamma\gamma\gamma$

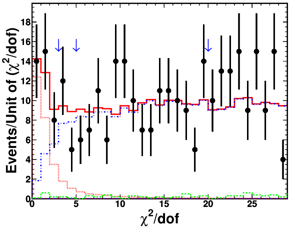
- Only one system has been observed to decay to a non-resonant combination of three γ: ortho-positronium
  - $\mathcal{B}(J/\psi \to \gamma\gamma\gamma) < 5.5 \times 10^{-5}$.
  - $\mathcal{B}(\omega \to \gamma\gamma\gamma) < 1.9 \times 10^{-4}$.
  - $\mathcal{B}(Z \to \gamma\gamma\gamma) < 1 \times 10^{-5}$.
- Kwong predicts $\mathcal{B}(J/\psi \to \gamma\gamma\gamma) \sim 10^{-5}$
- We present here the first observation, a 6σ measurement, of this decay of J/ψ
- Method in brief:
  - Tag J/ψ in $\pi^+\pi^-$ decay of ψ'
  - Require 3 γ with no $\pi^0/\eta/\eta\prime/\eta_c$ substructure
  - Kin. fit of $\pi^+\pi^-\gamma\gamma\gamma$ to p^μ of ψ' (tight χ^2 cut)



Discovery of $J/\psi \to \gamma\gamma\gamma$

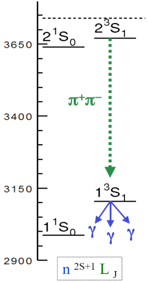


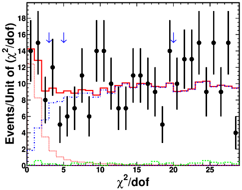
- Hard cuts in $M_{\gamma\gamma}$ to reject $Ps \to \gamma\gamma$
- Remaining bkg. removed thru kin. fit:
  - (blue:) $J/\psi \to \gamma\pi^0\pi^0$
  - (green:) NR bkg (determined from $\pi^+\pi^-$ recoil mass sb)

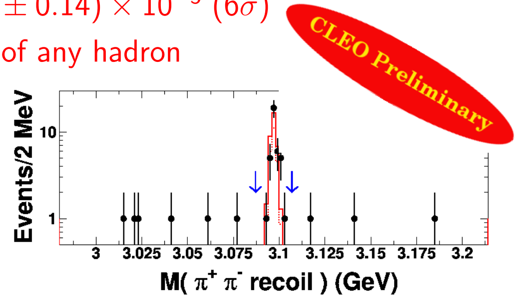


Discovery of $J/\psi \to \gamma\gamma\gamma$

- Signal/background = 37/12.8
- Number of $\pi^+\pi^- J/\psi$ tags: 9.6M ($\pm 0.7\%$)
- Efficiency: 21.5%
- $\mathcal{B} = (1.17^{+0.34}_{-0.29} \pm 0.14) \times 10^{-5}$ (6σ)
- First 3γ decay of any hadron







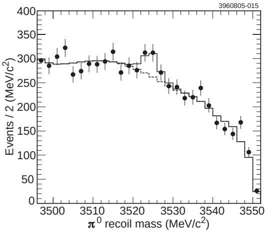
The Singlet States of Heavy Quarkonia

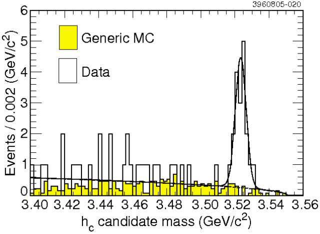
- In the past few years, new experimental work in the charmonium region has yielded observation of the previously unseen states below open charm threshold: namely, $\eta_c(2S)$ and $h_c(1P)$.
- These states are of critical importance in understanding the $q\bar{q}$ potential: only handle on the spin-spin (or hyperfine) interaction (excellent tests of LQCD and QCD Potential models)

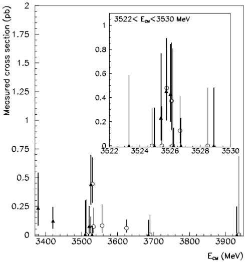
$$\Delta M_{hf} \equiv M(^3L) - M(^1L); \quad M(^3L) = \frac{\Sigma_J[J(J+1)M_J]}{\Sigma_J[J(J+1)]}$$

- Neither the 2S nor the 1P splittings are known well: we present here an updated measurement from CLEO-c of the 1P splitting.

Previous CLEO and E835 Results (2005)



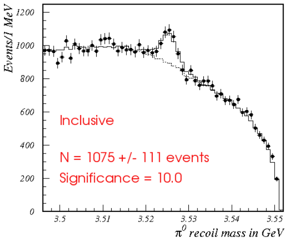


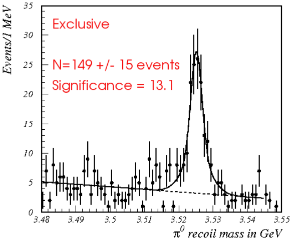


- E835 and CLEO both observe $h_c \to \gamma\eta_c$
- Their masses disagreed ... and lay on opposite sides of $(\langle M(^3P)\rangle = 3525.4$ MeV).

$$M_{h_c,CLEO} = 3524.4 \pm 0.6 \pm 0.4\ MeV\ \text{PRD72,092004 (2005)}$$
$$M_{h_c,E835} = 3525.8 \pm 0.2 \pm 0.2\ MeV\ \text{PRL}$$

Measurements of h_c Properties





Inclusive:

- Observe γ, $E_\gamma = 503 \pm 35$ MeV
- Reconstruct $\pi^0 \to \gamma\gamma$ and fit spectrum of masses recoiling against π^0
- Signal shape from MC; Bkg. obtained from data (no E_γ cut)

Exclusive:

- No constraint on E_γ
- Reconstruct 18 different hadronic final states of η_c
- Reconstruct $\pi^0 \to \gamma\gamma$ and analyze spectrum of masses that recoil against π^0

h_c Properties - Results

Inclusive:

$$\mathcal{B}(\psi' \to \pi^0 h_c) \times \mathcal{B}(h_c \to \gamma \eta_c) = (3.95 \pm 0.41 \pm 0.52) \times 10^{-4}$$
$$M(h_c) = 3525.35 \pm 0.24 \pm 0.21 \; MeV$$

CLEO Preliminary

Exclusive:

$$M(h_c) = 3525.35 \pm 0.27 \pm 0.20 \; MeV$$

Combined Mass Measurements:

$$M(h_c) = 3525.35 \pm 0.19 \pm 0.15 \; MeV$$
$$\Delta M_{hf} = -0.05 \pm 0.19 \pm 0.16 \; MeV$$

Additional Comments on the h_c Results

Comments on partial widths:

- Expect $\Gamma(h_c \to \gamma\eta_c)$ and $\Gamma_{tot}(h_c)$ to be similar to the analogous χ_1 quantities: Thus expect $\mathcal{B}(h_c \to \gamma\eta_c) = 0.36 \pm 0.02$.
- Our $\mathcal{B}_1 \times \mathcal{B}_2$ then implies $\mathcal{B}(\psi' \to \pi^0 h_c) = (1.10 \pm 0.14) \times 10^{-3}$, which is similar to the other isospin violating ψ' decay: $\mathcal{B}(\psi' \to \pi^0 J/\psi) = (1.26 \pm 0.13) \times 10^{-3}$.

CLEO Preliminary

and on mass:

- $\Delta M(1P) = -0.05 \pm 0.19 \pm 0.16$ MeV is $\simeq 0$
- Caveat: the standard spin-weighting used in calculating $\langle M(^3P)\rangle$ is good only to first order: hence it assumes the spin-orbit splitting is perturbatively small. In charmonium, the $M(^3P_2) - M(^3P_0)$ isn't *exactly* small (~ 140 MeV).

Summary

(Prelim: red; Submitted: blue)

- New measurement: $f_{D_S} = 274 \pm 10 \pm 5$
- First Observation :
  $\mathcal{B}(D_S \to p\bar{n}) = (1.30 \pm 0.36^{+0.12}_{-0.16}) \times 10^{-3}$
- New measurements
  $\mathcal{B}(\psi' \to \gamma\eta_c) = (4.32 \pm 0.16 \pm 0.65) \times 10^{-3}$
  $\mathcal{B}(J/\psi \to \gamma\eta_c) = (2.07 \pm 0.09 \pm 0.35)\%$
- First Observation:
  $\mathcal{B}(J/\psi \to \gamma\gamma\gamma) = (1.17^{+0.34}_{-0.29} \pm 0.14) \times 10^{-5}$
- New measurement of
  $M(h_c) = 3525.26 \pm 0.19 \pm 0.12$ MeV
- Keep listening... more to come.

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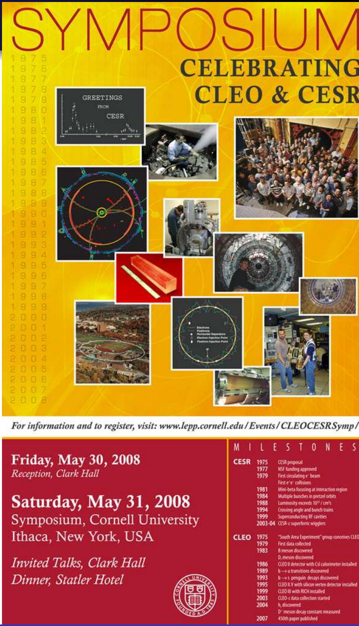


BACKUP SLIDES

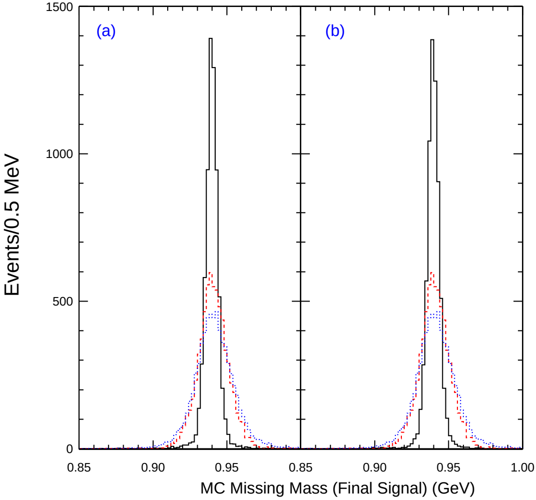
$D_S{}^+ \to \tau^+ \nu_\tau$

TABLE I: Summary of ST yield ($n_{\rm ST}$), ST mass sideband scaling factor (s), DT yield ($n_{\rm DT}$), and the number of estimated backgrounds (b), where $n(R)$ is the yield in the ST mass signal region, $n(B)$ is the yield in the ST mass sideband, and $n_{\rm DT}^{(0)}$ is the sideband subtracted DT yield before background correction.

Tag Mode	$n_{\rm ST}(R)$	$n_{\rm ST}(B)$	s	$n_{\rm ST}$	$n_{\rm DT}(R)$	$n_{\rm DT}(B)$	$n_{\rm DT}^{(0)}$	b	$n_{\rm DT}$
$D_s^- \to \phi\pi^-$	5243	391	0.997	4853.0 ± 75.1	49	0	49.0 ± 7.0	8.8 ± 0.6	40.2 ± 7.0
$D_s^- \to K^- K^{*0}$	9020	3661	1.010	5321.0 ± 112.8	55	3	52.0 ± 7.6	8.6 ± 0.7	43.4 ± 7.6
$D_s^- \to K^- K_S^0$	3499	710	1.022	2773.1 ± 65.0	24	2	22.0 ± 5.1	4.0 ± 0.4	18.0 ± 5.1

- $n_{ST} = 12947 \pm 150$; $n_{DT} = 102 \pm 12$
- $B_{SG} = \frac{n_{DT}}{n_{ST}} \frac{\epsilon(ST)}{\epsilon(DT)}$
- $\epsilon(DT)$ includes $B(\tau^+ \to e^+ + \bar{\nu}_\tau + \nu_e) = (17.84 \pm 0.05)\%$
- Syst err dominated by branching fractions of D_S decays which compose the backgrounds in the E_{energy} distribution (4.5% relative). Total syst. err is 5.5% relative.
- Final result: $B(D_S{}^+ \to \tau^+ \bar{\nu}_\tau = 6.17 \pm 0.71(stat) \pm 0.34(syst)$

$D_S \longrightarrow p\bar{n}$ Missing Mass (γ-tagged Monte Carlo)



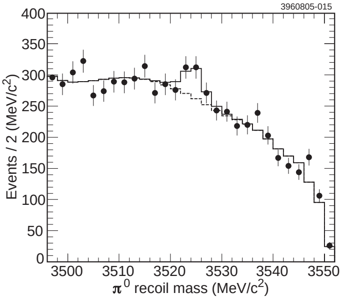
- Left (Right) Uses γ paired with $D_S(tag)$ $(D_S(signalside))$
- Blue: No Kin Fit
- Red: D_S Mass Constraint
- Black: Full Kin Fit

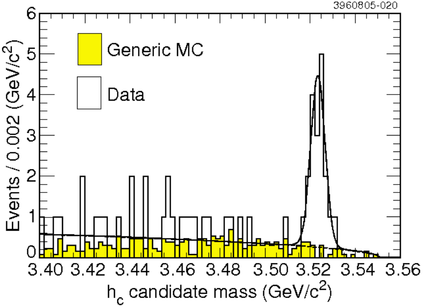
h_c Properties: η_c decays used

- No constraint on E_γ
- Reconstruct 18 different hadronic final states:

$p\bar{p}$	$\eta(\rightarrow\gamma\gamma)\pi^+\pi^-$	$\eta(\rightarrow\pi^+\pi^-\pi^0)\pi^+\pi^-$
$K_S K^+\pi^-$	$K^+K^-\pi^0$	$K_S K_S\pi^0$
$\eta(\rightarrow\gamma\gamma)K^+K^-$	$\eta(\rightarrow\pi^+\pi^-\pi^0)K^+K^-$	$p\bar{p}\pi^0$
$p\bar{p}\eta$	$2(\pi^+\pi^-)$	$\pi^+\pi^-\pi^0\pi^0$
$K^+K^-\pi^+\pi^-$	$2(K^+K^-)$	$p\bar{p}\pi^+\pi^-$
$3(\pi^+\pi^-)$	$2(\pi^+\pi^-)\pi^0\pi^0$	$K^+K^-2(\pi^+\pi^-)$

Previous CLEO Results on h_c





Incl, $N_{evt} = 150 \pm 40,\ 3.8\sigma$

Excl, $N_{evt} = 17.5 \pm 4.5,\ 5.2\sigma$

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

$$M(h_c) = 3524.4 \pm 0.6 \pm 0.4\ MeV$$

$$\Delta M_{hf} = +0.9 \pm 0.6 \pm 0.4\ MeV$$