Hadronic Decays of Charmonia at CLEO

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Plan of the Presentation

- Branching fractions for:
  - $\psi(2S) \to \gamma p\bar{p}$
  - $\pi^0 p\bar{p}$
  - $\eta\, p\bar{p}$

  Preliminary

- Search for $p\bar{p}$ threshold resonances in:
  - $\psi(2S) \to \gamma p\bar{p}$
  - $J/\psi \to \gamma p\bar{p}$

  Preliminary

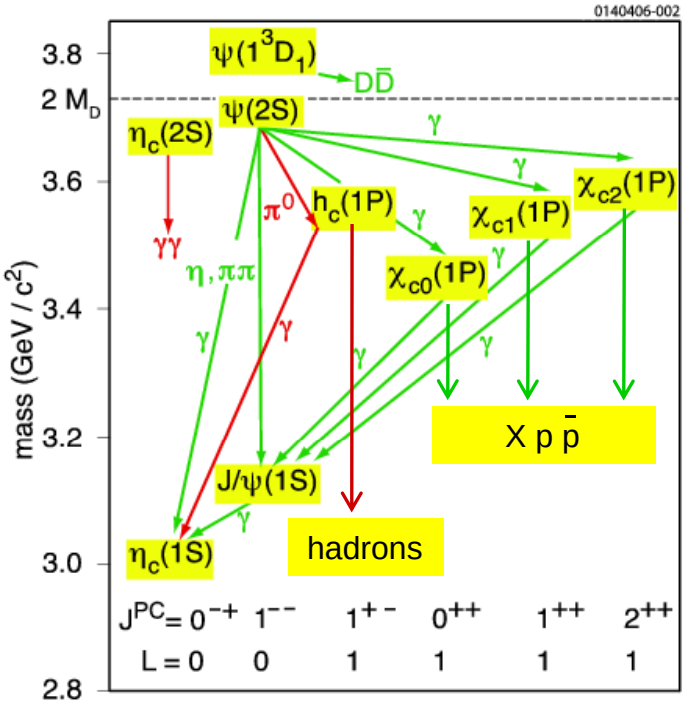
- Branching fractions for:

  $\chi_{cJ} \to \pi^0 p\bar{p}$, $\eta\, p\bar{p}$, $\omega\, p\bar{p}$

  Preliminary

- Decays of $h_c(^1P_1)$ to multi-pion final states.

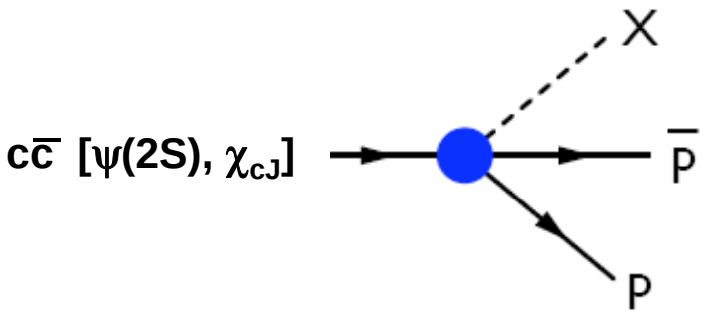
  PRD 80 (2009) 051106(R)



CLEO data used in these analyses:

25.9 million $\psi(2S)$ events (51.8 pb^{-1})

$\psi(2S) \to X p\bar{p}$, $\chi_{cJ} \to X p\bar{p}$ - Motivation



X = (γ, π^0, η, ω)

Recent theoretical calculations link

$\Gamma(c\bar{c} \to X p\bar{p})$ to $\sigma(p\bar{p} \to X c\bar{c})$

PRD 73 (2006) 096003
PRD 75 (2007) 054018
PRD 77 (2008) 056001
PRD 81 (2010) 034025
} Ted Barnes et al.

$\sigma(p\bar{p} \to X c\bar{c})$ is of particular interest to the PANDA ($p\bar{p}$ experiment at FAIR)

$\psi(2S)\to\gamma p\bar{p}$, $J/\psi\to\gamma p\bar{p}$ - Motivation

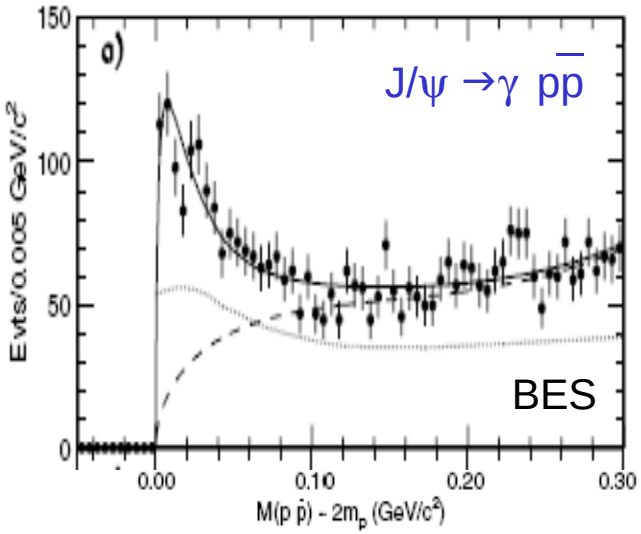
- This investigation was motivated by BES report of a baryonium ($p\bar{p}$) resonance near threshold in the reaction

$$J/\psi \to \gamma\, p\bar{p}$$

with 58 million J/ψ [PRL 91 (2003) 022001].

- $M(R) = 1859^{+3}_{-10}(stat)^{+5}_{-25}(syst)$ (MeV)

$\Gamma(R) = 0\pm21(stat)$ (MeV), $\Gamma(R) < 30$ MeV, 90% CL

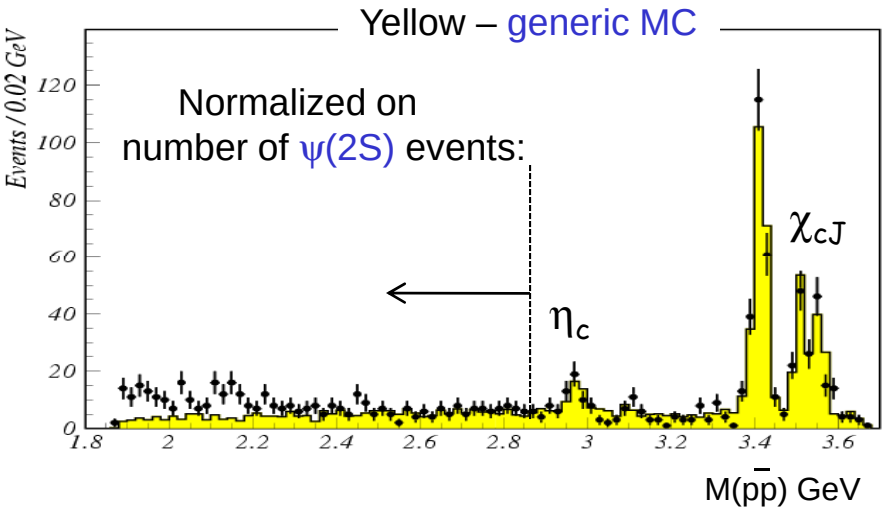


- Using $\psi(2S)$ data available at CLEO determine if there is evidence for $M(p\bar{p})$ threshold enhancement in $\psi(2S)\to\gamma\, p\bar{p}$ decays.

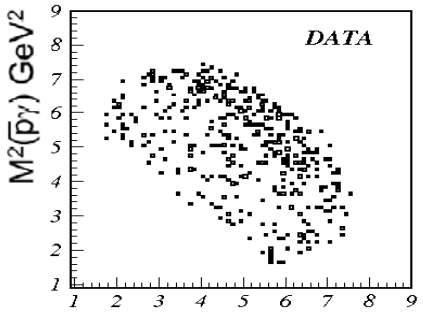
- Using a sample of ~5 million J/ψ available at CLEO from the decay $\psi(2S)\to\pi^+\pi^- J/\psi$ determine if there is evidence for $M(p\bar{p})$ threshold enhancement in $J/\psi\to\gamma\, p\bar{p}$ decays.

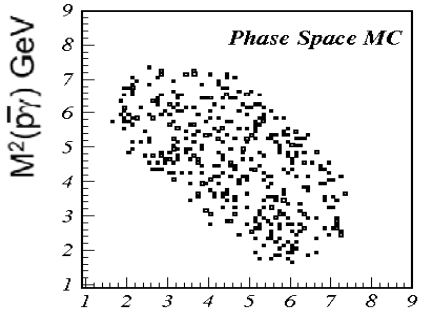
$\psi(2S)\to\gamma\, p\bar{p}$ – Branching Fraction

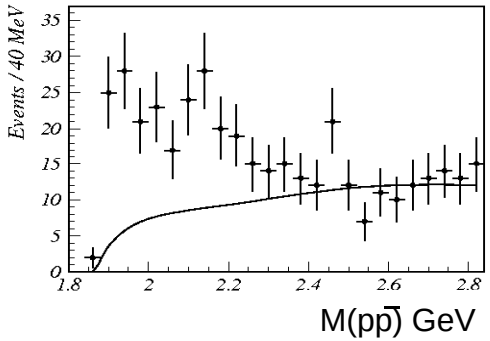
Preliminary

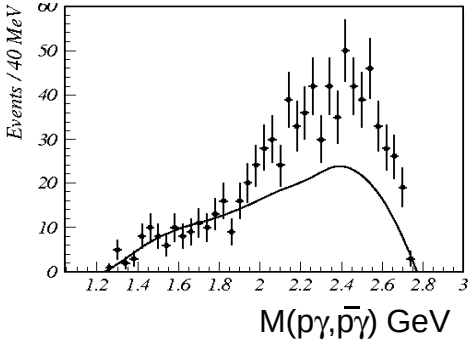


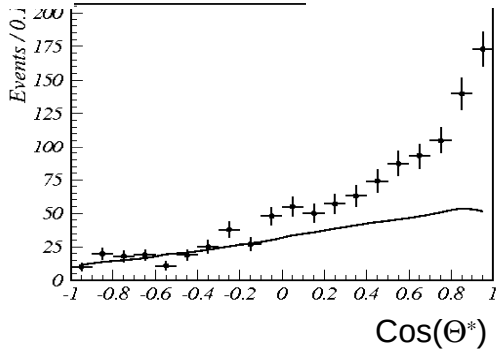
❖ $M(p\bar{p}) < 2.85$ GeV in order to reject contributions from χ_{cJ} and η_c states.











❖ Comparisons of the data and phase space distributions show that phase space alone can not explain the data, and *excitation of intermediate resonances must be considered*.

❖ The candidate resonances from PDG08 are:

$f_2(1950)$ with $J^{PC}=2^{++}$, M=1944±22 (MeV), Γ=472±18 (MeV)

$f_2(2150)$ with $J^{PC}=2^{++}$, M=2156±11 (MeV), Γ=167±30 (MeV)

$\psi(2S)\to\gamma\, p\bar{p}$ – Branching Fraction

Preliminary

- We fit M($p\bar{p}$) distribution with the sum of shapes from the following MC distributions:

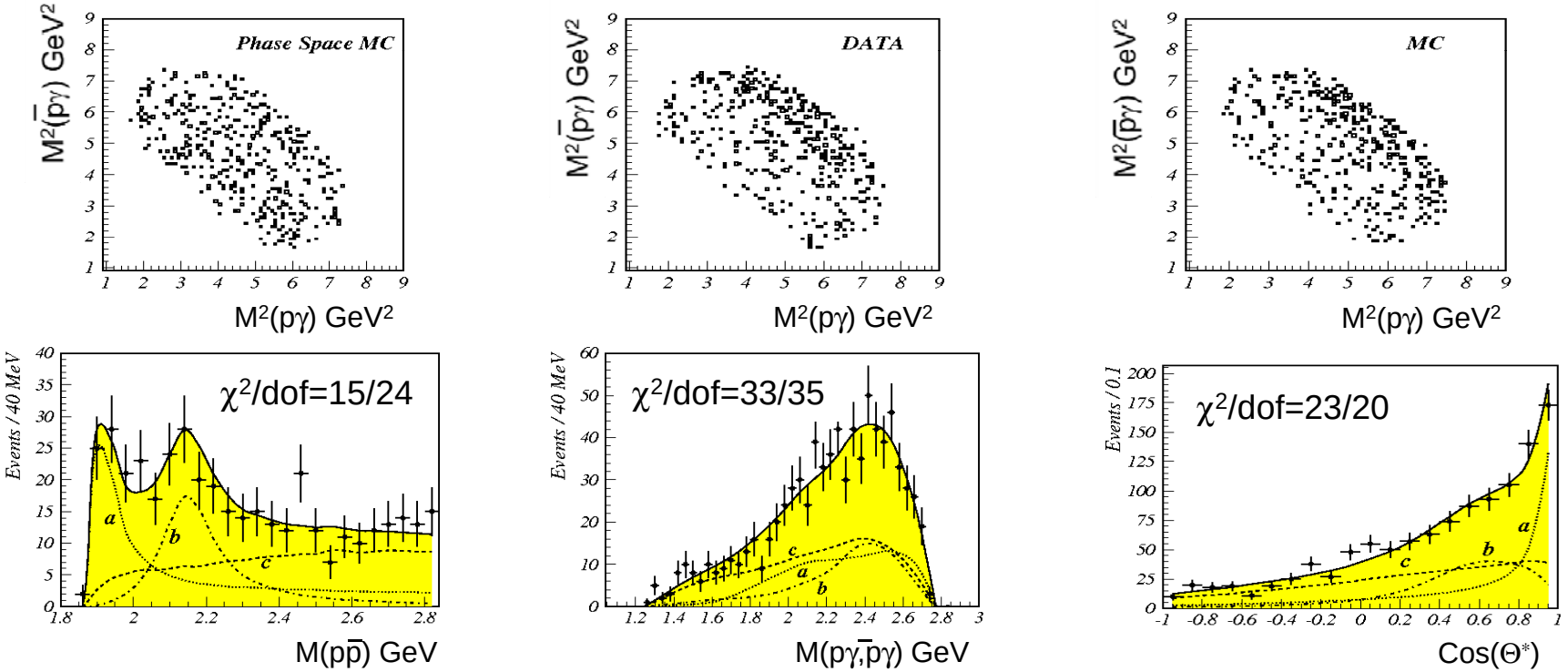
  $\psi(2S)\to\gamma f_2(1950)$, $f_2(1950)\to p\bar{p}$ $\psi(2S)\to\gamma f_2(2150)$, $f_2(1950)\to p\bar{p}$ $\psi(2S)\to\gamma p\bar{p}$ phase space

  with the optimum fractions determined by best fit to the data projections.

- Efficiencies are determined for each decay channel separately.

(a) (b) (c)

$(0.32 \pm 0.05) \times f_2(1950) + (0.21 \pm 0.05) \times f_2(2150) + (0.47 \pm 0.05) \times$ Phase Space



$\psi(2S)\to\gamma\, p\bar{p}$ – Branching Fraction

Preliminary

$B(\psi(2S)\to\gamma p\bar{p})$ in Data $(M(p\bar{p}) = 1.88 – 2.85$ GeV)

$N_{ev} = 407 \pm 20$, $N^{\pi 0 p\bar{p}}_{bkgd} = 33 \pm 4$, $N^{cont}_{bkgd} = 26 \pm 8$

$\langle\varepsilon\rangle = (0.32\pm0.05) \times 0.375 + (0.21\pm0.05) \times 0.410 + (0.47\pm0.05) \times 0.277 = 0.336 \pm 0.008$

$$B(\psi(2S)\to\gamma p\bar{p}) = (N_{ev} - N^{\pi 0 p\bar{p}}_{bkgd} - N^{cont}_{bkgd}) / (\langle\varepsilon\rangle \times N_{\psi(2S)})$$

- $B(\psi(2S)\to\gamma\, p\bar{p}) = \mathbf{(4.24 \pm 0.27 \pm 0.18) \times 10^{-5}}$ $\quad (2.9 \pm 0.6) \times 10^{-5}$ (PDG08)

  Error is smaller by factor 2. This differs by 2σ from the PDG08 value.

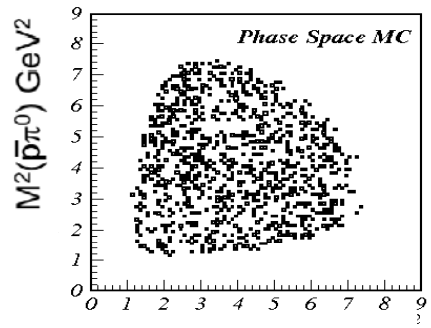
The following branching fractions are determined for the first time:

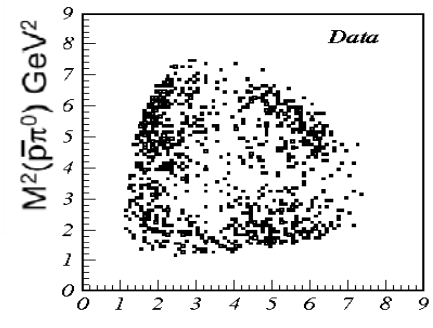
- $B_1(\psi(2S)\to\gamma f_2(1950)) \times B_2(f_2(1950)\to p\bar{p}) + c.c. = \mathbf{(1.2 \pm 0.2 \pm 0.1) \times 10^{-5}}$

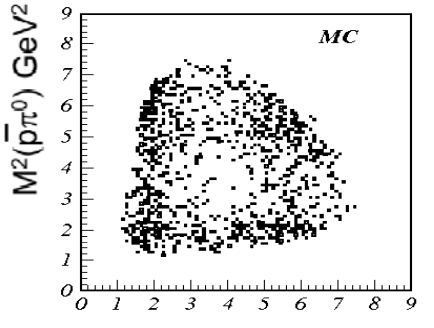
- $B_1(\psi(2S)\to\gamma f_2(2150)) \times B_2(f_2(2150)\to p\bar{p}) + c.c. = \mathbf{(0.73 \pm 0.18 \pm 0.03) \times 10^{-5}}$

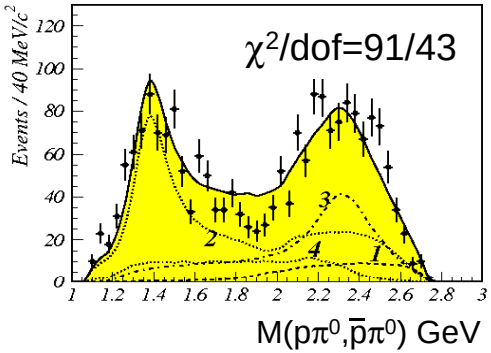
$\psi(2S)\to\pi^0 p\bar{p}$ – Branching Fraction

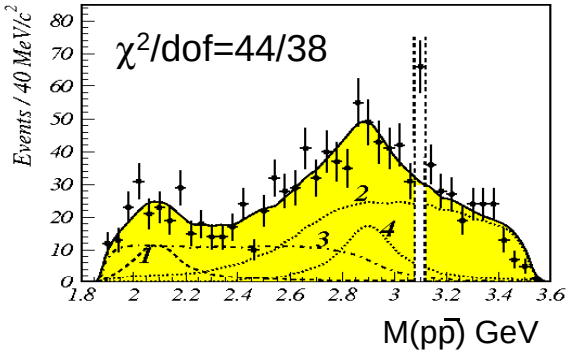
Preliminary

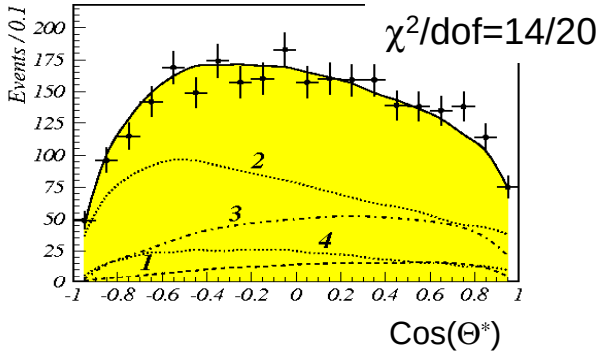












❖ The candidate resonances are:

(2) $\psi(2S)\to\bar{p}N^*_1(1440)$, $N^*_1(1440)\to\pi^0 p$, M = 1400 MeV, Γ = 220 MeV

(3) $\psi(2S)\to\bar{p}N^*_2(2300)$, $N^*_2(2300)\to\pi^0 p$, M = 2320 MeV, Γ = 300 MeV

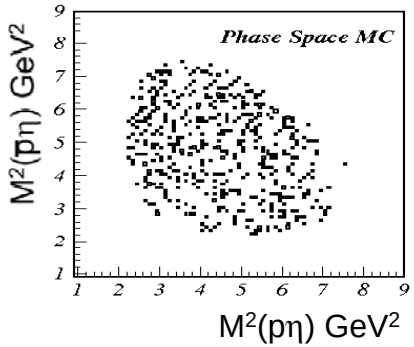
(1) $\psi(2S)\to\pi^0 R_1(2100)$, $R_1(2100)\to p\bar{p}$, M = 2100 MeV, Γ = 200 MeV

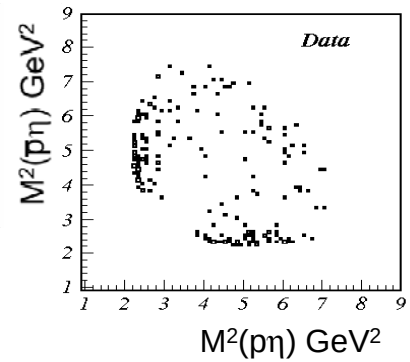
(4) $\psi(2S)\to\pi^0 R_2(2900)$, $R_2(2900)\to p\bar{p}$, M = 2900 MeV, Γ = 250 MeV

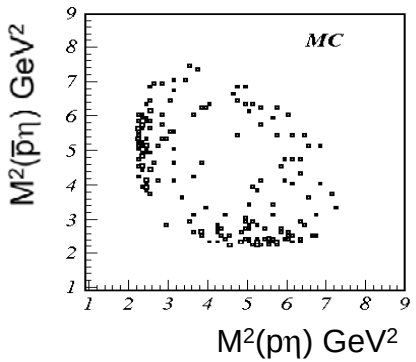
$(0.08\pm0.03)\times R_1(2100)+(0.14\pm0.04)\times R_2(2900)+(0.50\pm0.04)\times N^*_1(1440)+(0.28\pm0.04)\times N^*_2(2300)$

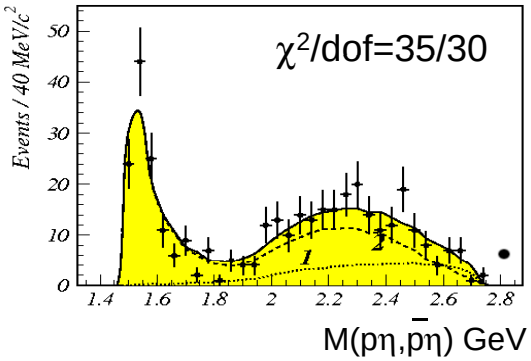
ψ(2S)→ηpp̄ – Branching Fraction

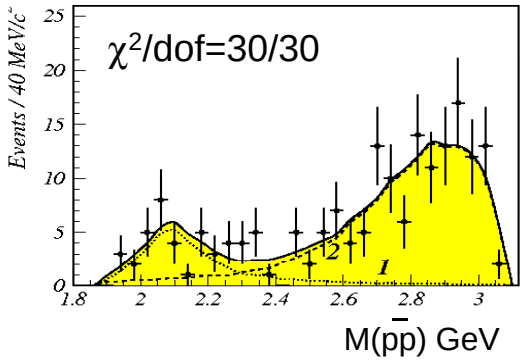
Preliminary

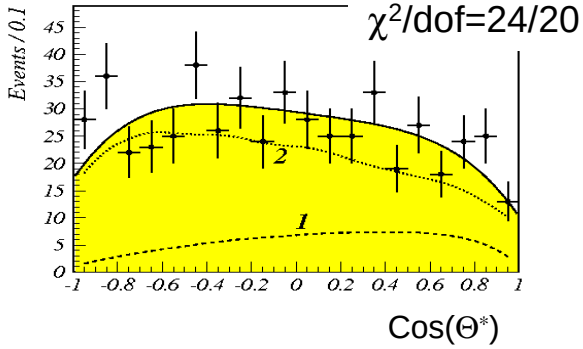












- The candidate resonances are:

(1) ψ(2S)→π⁰R(2100), R(2100)→pp̄, M = 2100 MeV, Γ = 200 MeV

(2) ψ(2S)→p̄N*(1535), N* (1535)→ηp, M = 1535 MeV, Γ = 150 MeV

$(0.20\pm0.06) \times R_1(2100) + (0.80\pm0.06) \times N^*(1535)$

$\psi(2S) \to X p\bar{p}$ - Summary of Results

Preliminary

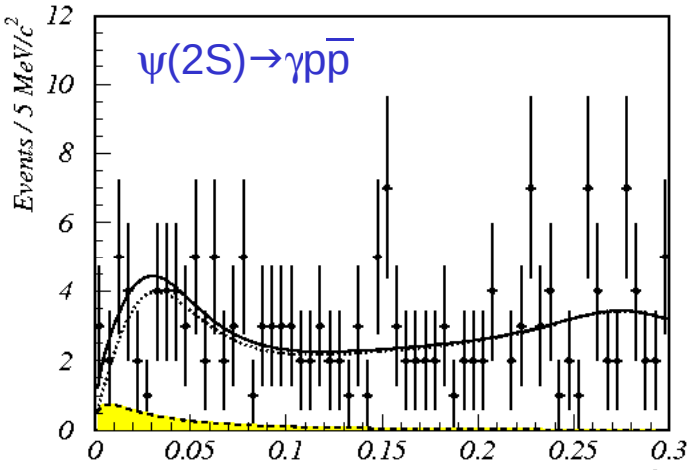
Quantity	Events	CLEO result in 10^{-5}	PDG08 in 10^{-5}	
$\mathcal{B}(\psi(2S) \to \gamma p\bar{p})$	348±22	4.24±0.27±0.18	2.9±0.6	
$\mathcal{B}(\psi(2S) \to \pi^0 p\bar{p})$	948±37	15.5±0.6±0.6	13.3±1.7	
$\mathcal{B}(\psi(2S) \to \eta p\bar{p})$	154±16	5.6±0.6±0.3	6.0±1.2	
$\mathcal{B}_1(\psi(2S) \to \gamma f_2(1950)) \times \mathcal{B}_2(f_2(1950) \to p\bar{p}) + c.c.$	111±19	1.2±0.2±0.1		First measurements
$\mathcal{B}_1(\psi(2S) \to \gamma f_2(2150)) \times \mathcal{B}_2(f_2(2150) \to p\bar{p}) + c.c.$	73±18	0.73±0.18±0.03		
$\mathcal{B}_1(\psi(2S) \to \bar{p}N_1^*(1440)) \times \mathcal{B}_2(N_1^*(1440) \to p\pi^0) + c.c.$	474±42	8.2±0.7±0.3		
$\mathcal{B}_1(\psi(2S) \to \bar{p}N_2^*(2300)) \times \mathcal{B}_2(N_2^*(2300) \to p\pi^0) + c.c.$	265±39	4.0±0.6±0.2		
$\mathcal{B}_1(\psi(2S) \to \pi^0 R(2100)) \times \mathcal{B}_2(R(2100) \to p\bar{p}) + c.c.$	76±29	1.1±0.4±0.1		
$\mathcal{B}_1(\psi(2S) \to \pi^0 R(2900)) \times \mathcal{B}_2(R(2900) \to p\bar{p}) + c.c.$	133±38	2.3±0.6±0.1		
$\mathcal{B}_1(\psi(2S) \to \bar{p}N^*(1535)) \times \mathcal{B}_2(N^*(1535) \to p\eta) + c.c.$	123±16	4.4±0.6±0.3		
$\mathcal{B}_1(\psi(2S) \to \eta R(2100)) \times \mathcal{B}_2(R(2100) \to p\bar{p}) + c.c.$	31±10	1.2±0.4±0.1		

- $B(\psi(2S) \to \gamma p\bar{p})$, $B(\psi(2S) \to \pi^0 p\bar{p})$ and $B(\psi(2S) \to \eta p\bar{p})$ have been measured with a factor 2 better precision than PDG08.
- The product branching fractions for intermediate resonances have been measured for the first time.

$\psi(2S)\to\gamma\, p\bar{p}$, Threshold Resonance

Preliminary

- We fit the $\Delta M = M(p\bar{p}) - 2m_p$ distribution in the range 0 – 300 (MeV) with the contributions of $f_2(1950)$, $f_2(2150)$ and phase space, as determined earlier by the fit in the extended range $\Delta M = 0 - 970$ MeV, plus a efficiency corrected S-wave Breit-Wigner resonance at threshold.



- Weighted average efficiency is 55.8%.
- Fit, assuming $M(p\bar{p}) = 1859$ MeV, $\Gamma(p\bar{p}) = 20$ MeV from $J/\psi\to\gamma p\bar{p}$ leads to

CLEO:

$N_{ev} = 9\ ^{+10}_{-9}$, χ^2/d.o.f. = 53/58

$B(\psi(2S)\to\gamma R)\times B(R\to p\bar{p}) = (0.66^{+0.73}_{-0.66})\times 10^{-6}$

$B(\psi(2S)\to\gamma R)\times B(R\to p\bar{p}) < \mathbf{1.6 \times 10^{-6}}$ 90% CL

BES(2007) PRL 99 (2007) 011802

$N_{ev} = 11.7 \pm 6.7$, sig.=2.0s

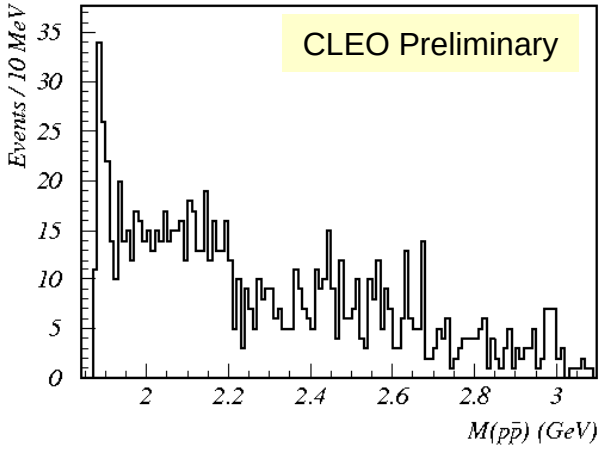
$B(\psi(2S)\to\gamma R)\times B(R\to p\bar{p}) < 5.4 \times 10^{-6}$

Three times more strict upper limit

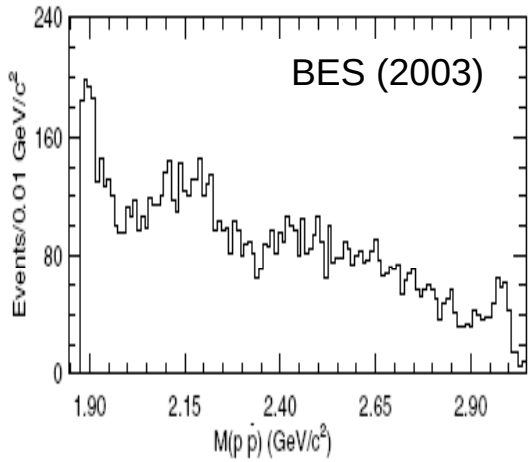
J/ψ →γ pp̄, Threshold Resonance

- An enhancement in M(pp̄) at threshold is observed in CLEO data, and in BES data.
- A broad enhancement in M(pp̄) centered at ~2100-2150 MeV is observed in all data.
- In order to analyze the threshold enhancement, we use the data in the full range, M(pp̄)<2.85 GeV. (BES do the analysis in the range M(pp̄)<2.18 GeV).

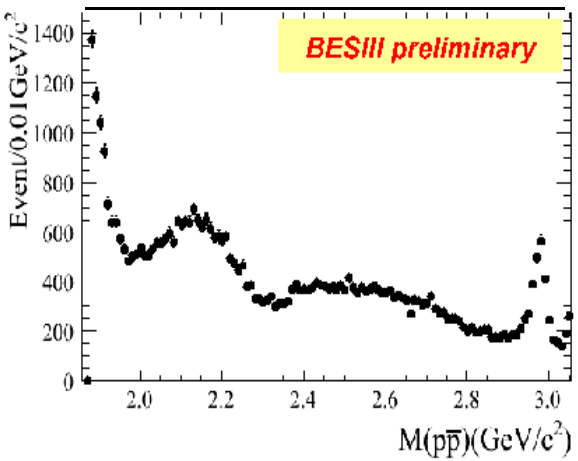
25x10^6 ψ(2S) data, corresponds to 5x10^6 ψ(1S) events



58x10^6 ψ(1S) data



220x10^6 ψ(1S) data



$J/\psi \to \gamma p\bar{p}$, Threshold Resonance

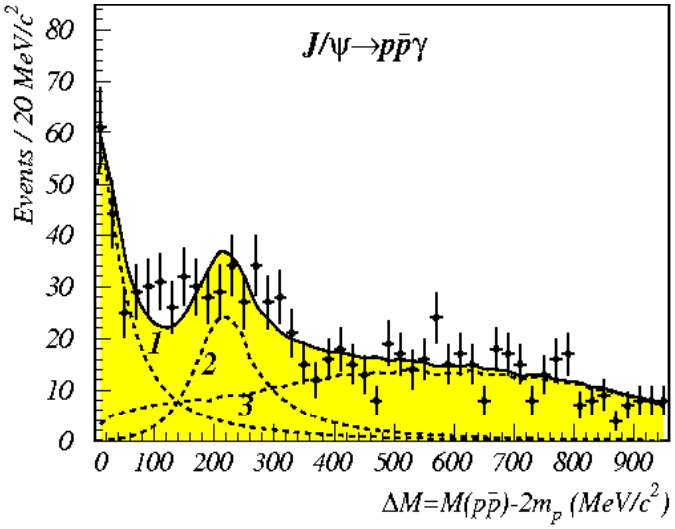
Preliminary

- We fit with the contributions: R_{thr} + $f_0(2100)$ + PS
  (1) (2) (3)

$M(R_{thr}) = 1837^{+10}_{-12}{}^{+9}_{-7}$ (MeV),

$\Gamma(R_{thr}) = 0^{+44}_{-0}$ (MeV), CL = 26.1%

$B_1(J/\psi \to \gamma R_{thr}) \times B_2(R_{thr} \to p\bar{p}) = (11.4^{+4.3}_{-3.0}{}^{+4.2}_{2.6}) \times 10^{-5}$



- The central value of the mass is close to the sub-threshold resonance mass reported by BES with M(R) = 1833.7±6.1±2.7 (MeV), observed in $J/\psi \to \gamma R$, $R \to \pi^+\pi^-\eta'$ [PRL 95 (2005) 262001].

- If we fit our spectrum only in the region ΔM = 0 – 300 MeV, and like BES do not include any higher resonances, the best fit results are:

$M(R_{thr}) = 1861^{+6}_{-16}$ (MeV), $\Gamma(R_{thr}) = 0^{+32}_{-0}$ (MeV),

$B_1(J/\psi \to \gamma R_{thr}) \times B_2(R_{thr} \to p\bar{p}) = (5.9^{+2.8}_{-3.2}) \times 10^{-5}$

BES (2003) results from ψ(1S) data:

$M(R_{thr}) = 1859^{+6}_{-27}$ MeV,

$\Gamma(R_{thr}) < 30$ MeV,

$B_1 \times B_2 = (7.0^{+1.9}_{-0.9}) \times 10^{-5}$

$\chi_{cJ} \to X\, p\bar{p}$ – Branching Fractions

Preliminary

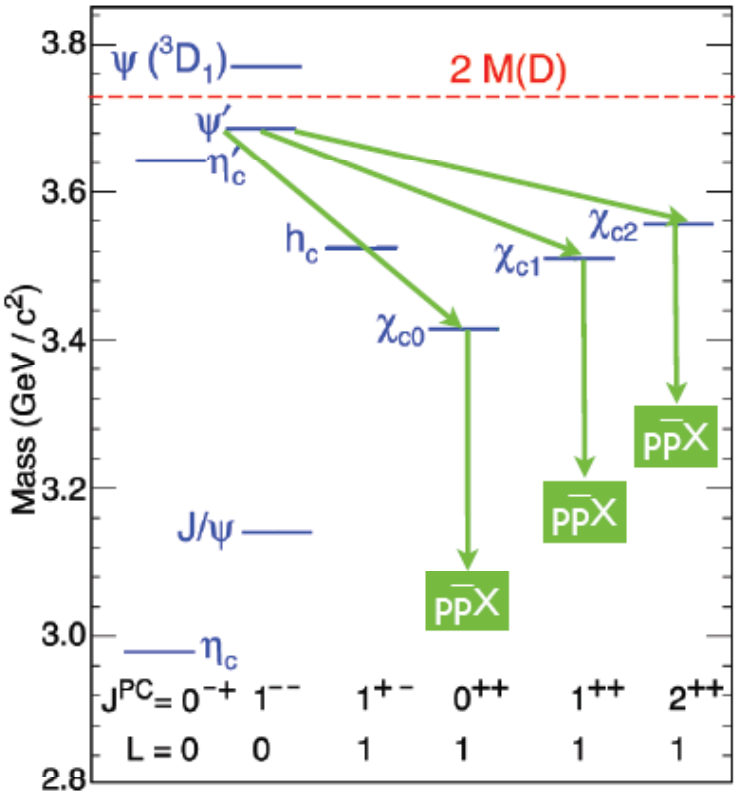
- Reactions studied:

$\psi(2S) \to \gamma\, \chi_{cJ}$, $\chi_{cJ} \to \pi^0 p\bar{p}$ $\pi^0 \to \gamma\gamma$

$\to \eta\, p\bar{p}$ $\eta \to \gamma\gamma$

$\to \omega\, p\bar{p}$ $\eta \to \pi^+\pi^-\pi^0$

$\omega \to \pi^+\pi^-\pi^0$



- Basic approach:

  - Kinematic fit of γ, p, $\bar{p}$, X to $\psi(2S)$ 4-momentum;

  - Extract $N_{pp\bar{X}}$ from the fit to χ_{cJ} candidate mass $M(pp\bar{X})$.

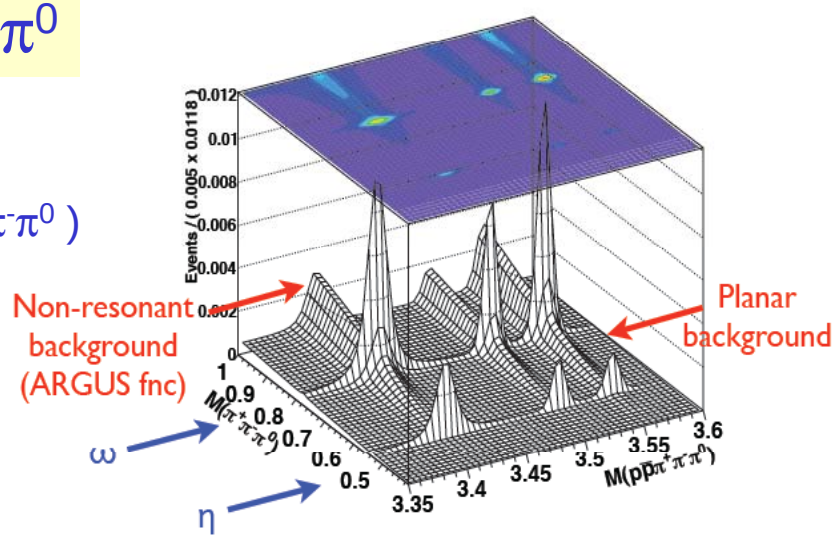
$\chi_{cJ} \to X\, p\bar{p}$ – Branching Fractions

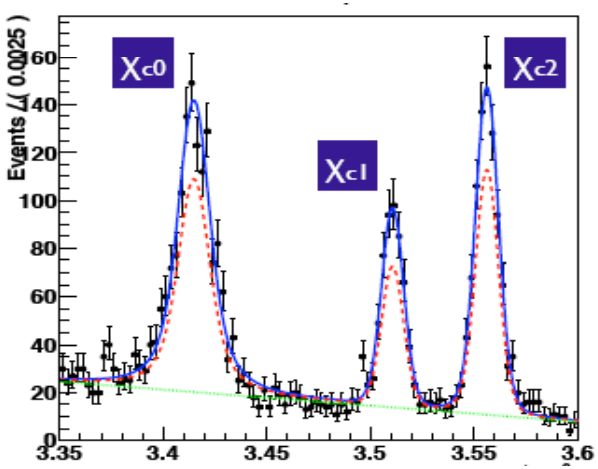
Preliminary

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

- Perform 2-dimensional unbinned extended maximum likelihood fit in $M(p\bar{p}\pi^+\pi^-\pi^0)$ and $M(\pi^+\pi^-\pi^0)$

- Extract simultaneously yields for $\chi_{cJ} \to \eta\, p\bar{p}$ and $\chi_{cJ} \to \omega\, p\bar{p}$



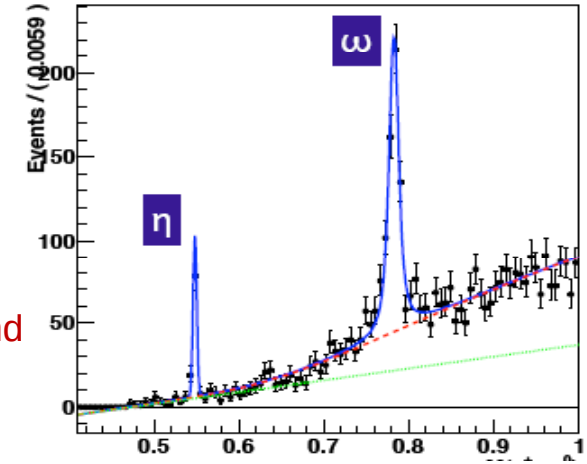


Results of 2-D fit.

Total PDF

Non-resonant background

Polynomial background



$\chi_{cJ} \to X\, p\bar{p}$ – Branching Fractions

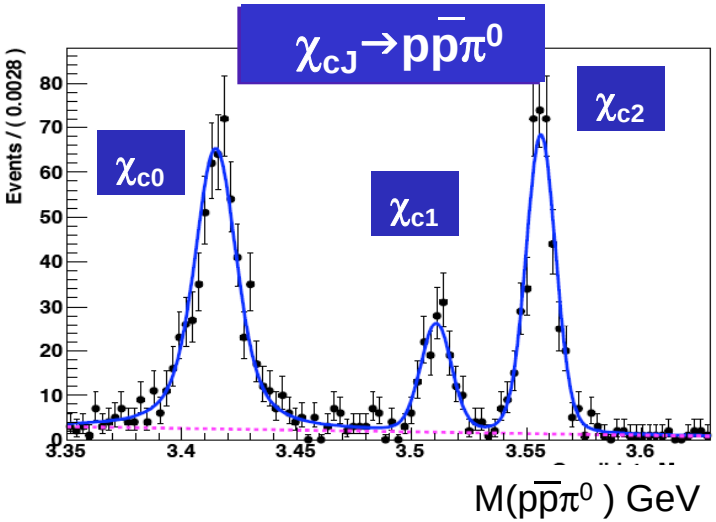
Preliminary

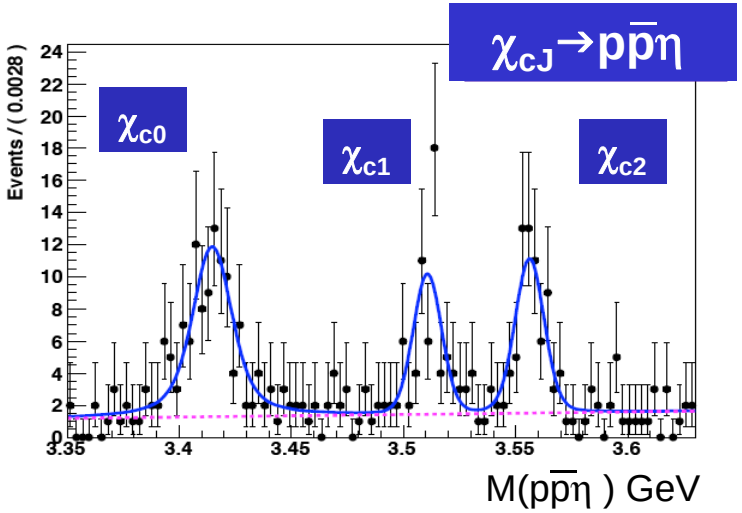
$\chi_{cJ} \to p\bar{p}\gamma\gamma$

- Perform 1-dimensional unbinned extended maximum likelihood fit in $M(p\bar{p}X)$.

Total PDF: sum of Breit-Wigner shapes convolved with resolution, plus background.

Linear background





$\chi_{cJ} \to X\, p\bar{p}$ – Summary of Results

Preliminary

Branching fractions $B(\chi_{cJ} \to X p\bar{p})$

$(\times 10^{-4})$	χ_{c0}	χ_{c1}	χ_{c2}
$p\bar{p}\pi^0$	$7.76 \pm 0.37 \pm 0.64$	$1.75 \pm 0.16 \pm 0.17$	$4.83 \pm 0.25 \pm 0.47$
$p\bar{p}\eta$[mean]	$3.73 \pm 0.38 \pm 0.33$	$1.56 \pm 0.22 \pm 0.17$	$1.76 \pm 0.23 \pm 0.18$
$p\bar{p}\omega$	$5.57 \pm 0.48 \pm 0.51$	$2.28 \pm 0.28 \pm 0.21$	$3.68 \pm 0.35 \pm 0.35$

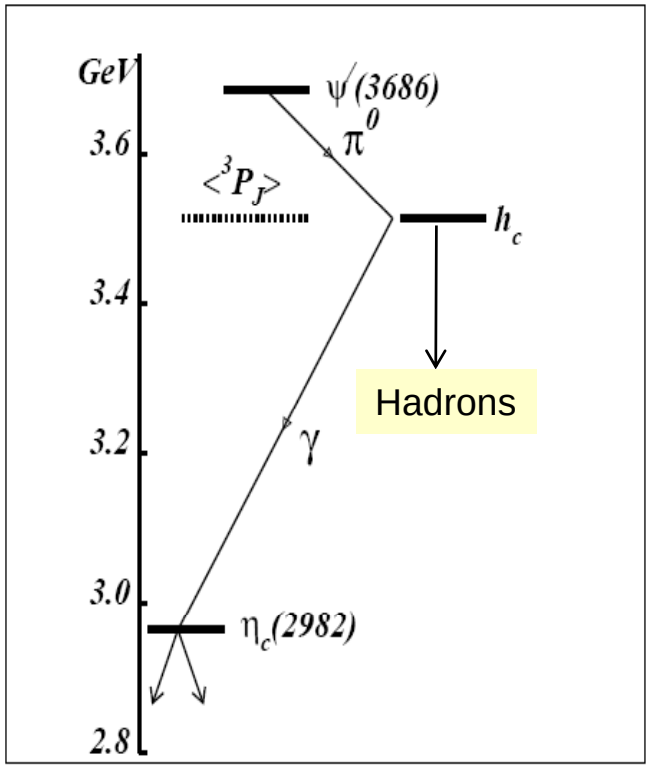
- $B(\chi_{cJ} \to \omega\, p\bar{p})$ have been measured for the first time.
- $B(\chi_{cJ} \to \pi^0\, p\bar{p})$ and $B(\chi_{cJ} \to \eta\, p\bar{p})$ have been measured with a factor 3 better precision than PDG08.
- The meson emission model predictions [T. Barnes et al., PRD 81 (2010) 034025] $B(\chi_0 \to \pi^0 p\bar{p}) = 2.5 \times 10^{-4}$ and $B(\chi_1 \to \pi^0 p\bar{p}) = 0.2 \times 10^{-4}$ are below the experimental measurements by factors 3 and 10, respectively.
- This suggests that meson emission, described in the model, is not the dominant decay mechanism.

Decays of $h_c(^1P_1)$ to Multi-Pion Final States

- The only previously observed decays:
  - $\psi(2S)\to\pi^0 h_c$, $h_c\to\gamma\eta_c$, $\eta_c\to$hadrons

    CLEO PRL 101 (2008) 182003
    BES III PRL 104 (2010) 132002
  - $p\bar{p}\to h_c$, $h_c\to\gamma\eta_c$, $\eta_c\to\gamma\gamma$

    E835 PRD 72 (2005) 032001



- Average mass and Branching Fraction:

  $M(h_c) = 3525.42 \pm 0.14$ (MeV)

  $B(\psi(2S)\to\pi^0 h_c) \times B(h_c\to\gamma\eta_c) = (4.31\pm 0.38)\times10^{-4}$

- Godfrey & Rosner predict [PRD 66 (2002) 014012]:

  57% $B(h_c\to$hadrons$)$

  38% $B(h_c\to\gamma\eta_c)$

  $B(h_c\to\gamma\eta_c) = (54.3 \pm 8.6)\%$ (BES III)

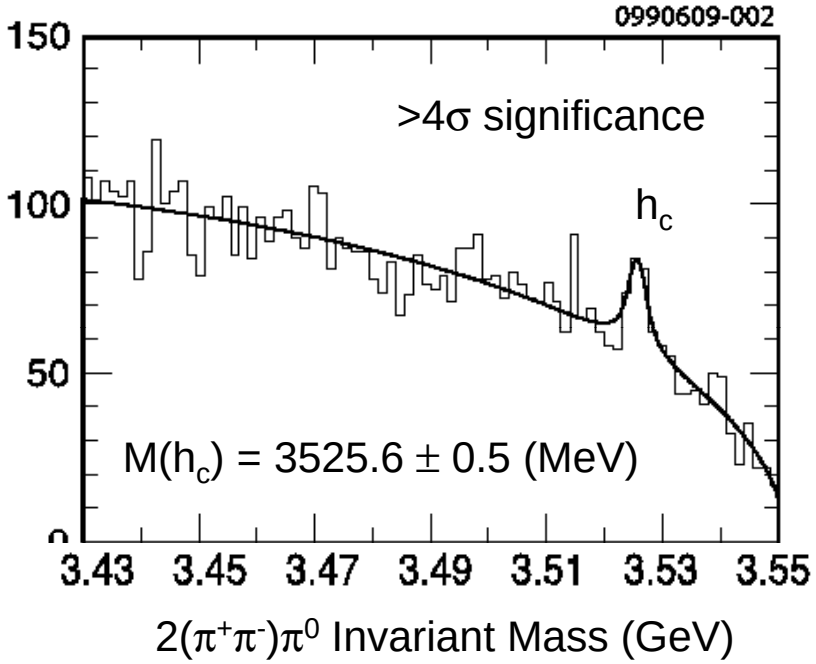
Decays of $h_c(^1P_1)$ to Multi-Pion Final States

PRD 80 (2009) 051106(R)

- Expect h_c decays in odd number of pions (negative G parity)
- Search for decays

  $\psi(2S)\to\pi^0 h_c$, $h_c\to n(\pi^+\pi^-)\,\pi^0$ with n=1,2,3

Mode	$B(\psi(2S)\to\pi^0 h_c) \times B(h_c\to\text{pions})$
$\pi^+\pi^-\pi^0$	< 0.2
$2(\pi^+\pi^-)\pi^0$	$1.9 \pm 0.5 \pm 0.4$
$3(\pi^+\pi^-)\pi^0$	< 2.5



Using $B(\psi(2S)\to\pi^0 h_c) = (8.4 \pm 1.6) \times 10^{-4}$ (BES III)

- $B(h_c\to 2(\pi^+\pi^-)\pi^0) =$ **$(2.3 \pm 0.8)\%$**

Summary

CLEO-c data at $\psi(2S)$ were analyzed (26 million) to study hadronic decays of charmonia.

- $B(\psi(2S)\to\gamma\, p\bar{p})$, $B(\psi(2S)\to\pi^0 p\bar{p})$ and $B(\psi(2S)\to\eta\, p\bar{p})$ have been measured with a factor 2 better precision than PDG08.
- The product branching fractions have been measured for the first time for intermediate resonances produced in the reactions above.
- No evidence for a $p\bar{p}$ threshold enhancement was found in either $\psi(2S)\to\gamma\, p\bar{p}$, $\psi(2S)\to\pi^0 p\bar{p}$, or $\psi(2S)\to\eta\, p\bar{p}$.
- Evidence for a $p\bar{p}$ threshold enhancement was found in $J/\psi\to\gamma p\bar{p}$ and the resonance parameters were determined.
- $B(\chi_{cJ}\to\omega\, p\bar{p})$ have been measured for the first time.
- $B(\chi_{cJ}\to\pi^0\, p\bar{p})$ and $B(\chi_{cJ}\to\eta\, p\bar{p})$ have been measured with a factor 3 better precision than PDG08.
- Decay of $h_c\to 2(\pi^+\pi^-)\pi^0$ has been measured for the first time.
  Upper limits were set for the decays $h_c\to\pi^+\pi^-\pi^0$ and $h_c\to 3(\pi^+\pi^-)\pi^0$.