

# E835 at FNAL: Charmonium Spectroscopy in $\bar{p}p$ Annihilations

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I present preliminary results on the search for  $h_c$  in its  $\eta_c\gamma$  and  $J/\psi\pi^0$  decay modes. We observe an excess of  $\eta_c\gamma$  events near 3526 MeV that has a probability  $\mathcal{P} \sim 0.001$  to arise from background fluctuations. The resonance parameters are  $M = 3525.8 \pm 0.2 \pm 0.2$  MeV,  $\Gamma \leq 1$  MeV, and  $10.6 \pm 3.7 \pm 3.4(br) < \Gamma_{\bar{p}p} B_{\eta_c\gamma} < 12.8 \pm 4.8 \pm 4.5(br)$  eV. We find no event excess within the search region in the  $J/\psi\pi^0$  mode.

## 1. INTRODUCTION

Charmonium states have been successfully studied in  $\bar{p}p$  annihilations, where all states can be formed, and detected in their decay to electromagnetic final states. E760 and E835 measured precisely masses and widths of  $\eta_c$ ,  $J/\psi$ ,  $\psi(2S)$  and  $\chi_{cJ}$  states as well as other properties for these states, e.g.,  $\Gamma_{\gamma\gamma}$  and  $\mathcal{B}_{p\bar{p}}[1]$ .

The  $h_c$  is so far the most elusive charmonium state below  $\bar{D}D$  threshold [2]. It has not been observed yet in  $\psi(2S)$  decays, where it could be produced by sequential radiative transitions through the  $\chi_{c2}$  (E1 followed by M1), or by I spin violating  $\pi^0$  transition, nor in B decays whose branching ratios to  $h_c$  could be as large as  $\mathcal{O}(10^{-4})$  [3].

Observation of the  $h_c(1^1P_1(1^{+-}))$  will allow to

determine the splitting between singlet P and the spin-weighted average mass of the triplet P states ( $\chi_{c.o.g} = 3525.30 \pm 0.07$  MeV [4]). In one-gluon potential model, this splitting is zero. Corrections are small and the mass difference between the  $h_c$  and the  $\chi_{c.o.g}$  is in general predicted to be at most a few MeV [5], thus it is important to measure the  $h_c$  mass to better than  $\approx 1$  MeV.

The  $h_c$  is expected to be narrow ( $< 1$  MeV in width), to have a dominant E1 transition to  $\eta_c\gamma$ , and large branching ratio to light hadrons [6].

Our study of  $\chi_{c0}$  has shown that E1 transitions of triplet P states are in excellent agreement [4] with the predicted scaling as the third power of photon momentum. Assuming that the  $h_c$  has the same radial wave function as the other P states, this would imply  $\Gamma(h_c \rightarrow \eta_c\gamma) \approx 600$  keV for an  $h_c$  mass close to the  $\chi_{c.o.g}$ .

In 1992, E760 (our former experiment) reported observation of a structure in the cross section  $\bar{p}p \rightarrow J/\psi\pi^0$  (an I-violating mode) close to the  $\chi_{c.o.g}$ . interpreted as the  $h_c$  [7]. Neglecting interference with continuum  $\bar{p}p \rightarrow J/\psi\pi^0$ , resonance parameters were determined as  $M = 3526.2 \pm 0.15 \pm 0.2$  MeV;  $\Gamma \leq 1.1$  MeV (90% CL); and  $(1.8 \pm 0.4) \cdot 10^{-7} < \mathcal{B}(p\bar{p})\mathcal{B}(J/\psi\pi^0) < (2.5 \pm 0.6) \cdot 10^{-7}$ . The probability for such structure to arise from background was estimated to be 1/400.

Observation of the  $h_c$  is one of the principal objectives of experiment E835 at Fermilab.

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## 2. EXPERIMENT E835

Charmonium states are studied by a scan of the  $\bar{p}p$  annihilation cross section for exclusive final states at different center of mass energies ( $E_{CM}$ ). An excess of events at any value of  $E_{CM}^*$  over the background measured on a broader  $E_{CM}$  range signals the formation of a resonance. Resonance parameters are then determined with precision up to 100 keV on masses and widths. The experiment is designed to observe charmonium states in their decays to electromagnetic final states such as  $J/\psi X \rightarrow e^+e^- X$  and  $\eta_c(\gamma) \rightarrow \gamma\gamma(\gamma)$ .

E835 is a major upgrade of E760 and is described in detail in [8]. The detector is a non-magnetic, large acceptance, cylindrical spectrometer, covering the complete azimuth ( $\phi$ ) and from  $2^\circ$  to  $70^\circ$  in polar angle ( $\theta$ ). It consists of a lead glass electromagnetic calorimeter divided into a barrel and a forward sections; the inner part of the barrel section is instrumented with a multi-cell threshold Čerenkov counter, for electron detection, three concentric scintillator hodoscopes, and a tracking system to measure charged particles. To withstand the  $\sim 5$  MHz continuous interaction rate, all channels are instrumented with multi-hit TDCs.

The required high luminosity is achieved by a  $H_2$  jet target intersecting the  $\bar{p}$  beam in the Fermilab Antiproton Accumulator. The beam is decelerated from the accumulation energy to the value appropriate for the formation of each resonance. The density of the target is continuously adjusted to compensate for beam loss keeping the instantaneous luminosity constant at  $\sim 2 \times 10^{31}$   $\text{cm}^{-2}\text{s}^{-1}$ . The stochastic cooling keeps beam momentum constant with a  $\Delta p/p \approx 2 \times 10^{-4}$ , compensating for energy losses in the target.

The integrated luminosity  $L_{int}$  for each energy setting is measured to  $< 2\%$  by counting recoil protons from  $\bar{p}p$  scattering at  $\theta \approx 90^\circ$ .

## 3. SEARCH FOR $h_c \rightarrow \eta_c\gamma$ and $J/\psi\pi^0$

E835 took data in 1996/1997 (E835-I) for an integrated luminosity  $L_{int} \approx 140 \text{ pb}^{-1}$ , and again in 2000 (E835-II) for  $L_{int} \approx 110 \text{ pb}^{-1}$ .

We search for  $h_c$  in the following reactions

$$\bar{p}p \rightarrow h_c \rightarrow J/\psi\pi^0 \rightarrow e^+e^-\gamma\gamma \quad (1)$$

$$\bar{p}p \rightarrow h_c \rightarrow \eta_c\gamma \rightarrow 3\gamma \quad (2)$$

The scan for the  $h_c$  was based on assumptions for the mass (close to  $\chi_{c.o.g.}$ ), total width ( $< 1$  MeV) and expected yields at resonance peak:  $3\text{-}8 \text{ ev/pb}^{-1}$  (above a continuum yield of  $\approx 2 \text{ ev/pb}^{-1}$ ) for reaction (1) and  $< 1 \text{ ev/pb}^{-1}$  for reaction (2) [9].

We have taken data for about  $215 \text{ pb}^{-1}$  in the range  $3300 < E_{CM} < 4400$  MeV. Approximately  $70 \text{ pb}^{-1}$  were spent in a fine scan of the  $\chi_{c.o.g.}$  region  $3525.2 < E_{CM} < 3527.2$  MeV and  $20 \text{ pb}^{-1}$  a coarser scan of  $3520 < E_{CM} < 3540$  MeV (see Fig. 2), while the remaining data are used to measure background. Data taken at  $\chi_{c1}$  and  $\chi_{c2}$ , on which we performed repeated scans which will provide new measurements of their masses and widths, provide also clean  $J/\psi\gamma$  events to monitor efficiencies and nearby background measurement for reaction (2) on either side of the  $\chi_{c.o.g.}$ .

### 3.1. Search for $\bar{p}p \rightarrow h_c \rightarrow \eta_c\gamma \rightarrow 3\gamma$

The analysis is based on the study of simulated  $h_c$  events and a background sample of  $p\bar{p} \rightarrow 3\gamma$  candidates (prior to the  $\eta_c$  mass constraint) from a fraction of data taken outside the  $\chi_{c.o.g.}$ , then counting  $\eta_c\gamma$  candidates in the whole sample.

Candidates for neutral final states are selected by the trigger if there are no charged tracks from the interaction point and there are at least 2 energy deposits in the Central Calorimeter (CCAL) with invariant mass  $\geq 2.2$  GeV, or if the energy detected in CCAL is  $> 80\%$  of the total energy.

Offline we select events with 3 “on-time” *candidate* photons in CCAL, defined as clusters with energy  $> 20$  MeV occurring within 6 ns of the trigger. We reject events with on-time clusters in the forward calorimeter. Since timing efficiency and resolution are worse for low energy photons, clusters without timing information, or with  $E < 300$  MeV and occurring within 6 and 15 ns of the trigger are considered *undetermined*. If a candidate photon paired with any other candidate or undetermined cluster forms a  $\pi^0$  ( $|m_{\gamma\gamma} - m_{\pi^0}| < 35$  MeV) the event is rejected. Events with signals

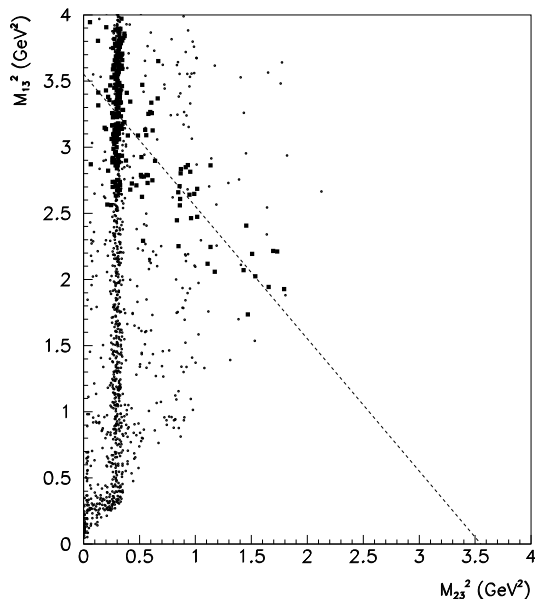


Figure 1. Dalitz plot for candidates  $\bar{p}p \rightarrow 3\gamma$  events in the  $\cos\theta^*$  acceptance described in the text (small dots) for  $3524 < E_{CM} < 3527$  MeV and  $\bar{p}p \rightarrow \eta_c \gamma$  candidates (large squares). The dotted line shows the center of the  $\eta_c \gamma$  band.  $\bar{p}p \rightarrow \eta_c \gamma$  candidates with  $M_{23} > 1$  GeV have relatively little background. (*Preliminary*)

in the two outer hodoscopes not in coincidence with the corresponding Cerenkov counter are rejected; those with coincidences are retained as events in which a  $\gamma$  converted after the innermost hodoscope. We impose a likelihood ratio test (PW) on photon showers analogous to the electron weight (EW) described in Ref. [8], but based only on CCAL cluster moments. We require  $PW_1 \times PW_2 > 1$  and  $PW_3 > 1.5$ , where the photons are ordered by their CM energies:  $E_{\gamma 1} > E_{\gamma 2} > E_{\gamma 3}$ . The efficiency of this cut on clean  $J/\psi \gamma \rightarrow e^+ e^- \gamma$  events at  $\chi_{c1}$  and  $\chi_{c2}$ , of energies comparable to those of  $h_c$  radiative decay, is constant and it is well modeled by the simulation.

A 4C kinematic fit to the hypothesis  $\bar{p}p \rightarrow 3\gamma$  is

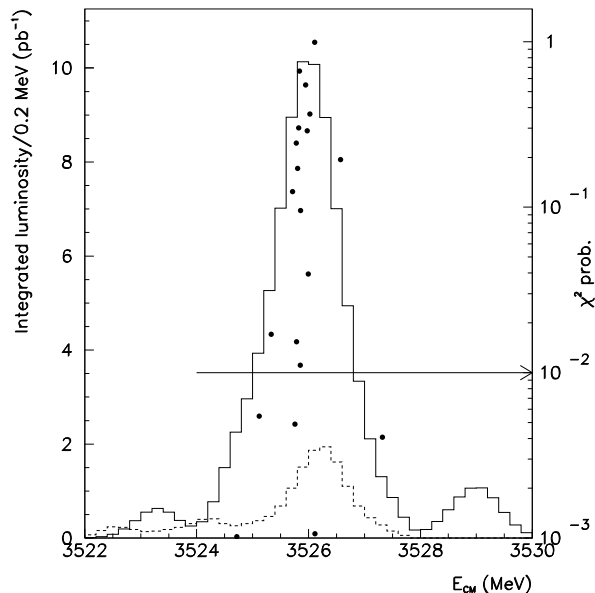


Figure 2. E835 integrated luminosity vs  $E_{CM}$  in the  $\chi_{c.o.g.}$  region. Dashed histogram is the corresponding E760 luminosity. Superimposed (dots, scale on right) we show the  $\chi^2$  probability distribution vs  $E_{CM}$  for  $\eta_c \gamma$  candidates. Events with large probabilities are observed in a narrow  $E_{CM}$  range of our high-luminosity scan. Arrow indicates the probability cut applied. (*Preliminary*)

performed and we require a nominal  $\chi^2$  probability  $P(3\gamma) > 10^{-4}$ . If there are undetermined clusters, we require that  $P(3\gamma) > P(4\gamma)$ , the latter being the probability for any fit to  $\bar{p}p \rightarrow 4\gamma$ .

$3\gamma$  candidates have background mostly from  $\bar{p}p \rightarrow \pi^0 \eta$ ,  $\pi^0 \eta'$ , and  $3\pi^0$  events, where the  $\pi^0$ s decay symmetrically or highly asymmetrical; for such  $\pi^0$ s only one cluster, in approximately the direction of the  $\pi^0$ , is detected and identified as a  $\gamma$ . We refer to such events as *feed-down* events.  $\bar{p}p$  annihilations to two and three light mesons are strongly forward/backward-peaked and high energy photons from feed-down events tend to have large  $|\cos\theta_{1,2}^*|$ .  $\bar{p}p \rightarrow \pi^0 X^0$  reactions are forward-backward symmetric, but forward  $\pi^0$  are more

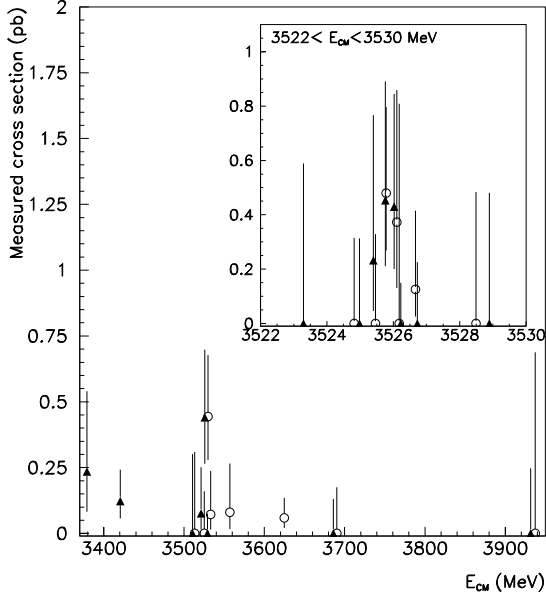


Figure 3. Cross section for  $\bar{p}p \rightarrow \eta_c \gamma \rightarrow \gamma \gamma \gamma$ . The inset is an expanded view of the  $\chi_{c.o.g}$  region. E835-I data are open circles and E835-II data closed triangles. (*Preliminary*)

likely to be misidentified as single photons, thus feed-down events have often low energy  $\gamma$ s emitted backwards, with invariant mass of the two lowest energy candidates  $M_{23} \approx M_X$ .

For reaction (2) the angular distribution is nearly uniform in  $\cos \theta_{12}^*$  for the two photons from  $\eta_c$  and  $\propto \sin^2 \theta_3^*$  for the radiative decay photon.

Based on signal and background characteristic we cut at  $M_{23} > 1 \text{ GeV}$ ,  $|\cos \theta_{1,2}^*| < 0.5$  and  $-0.4 < \cos \theta_3^* < 0.7$ .

We apply a 5C kinematical fit to  $\eta_c \gamma$  and set a  $\chi^2$  probability cut at  $> 0.01$ . The overall efficiency of this selection is 3.2%.

The final sample has 23  $\eta_c \gamma$  candidates; 15 of them are at  $\chi_{c.o.g}$  (Fig. 2). Candidates in each energy interval and the corresponding integrated luminosities are listed in Table 1. The observed cross section for  $\bar{p}p \rightarrow \eta_c \gamma$  is plotted in Fig. 3. The background is large near  $E_{CM} = 3400 \text{ MeV}$

$E_{CM}$ range (MeV)	E835-I		E835-II	
	$L_{int}$ ( $\text{pb}^{-1}$ )	$\eta_c \gamma$ cand.	$L_{int}$ ( $\text{pb}^{-1}$ )	$\eta_c \gamma$ cand.
3300 – 3400	-	-	8.51	2
3400 – 3440	-	-	21.83	3
3440 – 3500	0.50		2.51	
$\chi_{c1}, \chi_{c.o.g}$ region and $\chi_{c2}$				
3500 – 3520	5.32		5.98	
3520.0 – 3525.7	11.24		13.40	1
3525.7 – 3526.2	17.61	7	11.56	6
3526.2 – 3526.7	5.23	1	17.53	
3526.7 – 3540.0	8.12		8.22	
3540 – 3560	11.10	1	0.90	
3560 – 3675	33.99	2	0.78	
3680 – 3700	9.00		12.58	
3700 – 3850	0.98		6.32	
3850 – 4400	1.63		2.10	

Table 1

$\eta_c \gamma$  candidates in each energy interval and corresponding integrated luminosities (*Preliminary*)

but decreases rapidly with energy. We performed several checks, in particular: we have analyzed the two data sets separately and we find compatible excess at the same mass; If we impose in the fit  $M_{\eta_c} = 2850; 3150 \text{ MeV}$ , the cross section agrees very well with smooth background; For data outside the  $\chi_{c.o.g}$ . we rescale all energies by  $3526.2/E_{CM}$  and verify that events would not form an  $\eta_c$ .

We estimate the significance of the excess in the  $\eta_c \gamma$  channel with several methods:

1. Binomial significance with *a priori* hypothesis: We calculate the cumulative probability for detecting at least  $N_s$  candidates in an *a priori* signal bin, having observed  $N_{tot}$  candidates in the  $E_{CM}$  range that extends from the  $\chi_{c1}$  to  $\chi_{c2}$ , under the hypothesis of constant cross section. As signal bin we take  $3525.6 < E_{CM} < 3526.4 \text{ MeV}$  where E760 observed an excess of  $J/\psi \pi^0$ .

2. Binomial significance with *a posteriori* hypothesis with correction for multiple hypotheses: We observe the excess of events in a 0.5 MeV bin between  $3525.7 < E_{CM} < 3526.2 \text{ MeV}$

$\Gamma_R$ (MeV)	$M_R$ (MeV)	$\Gamma_{in}B_{out}$ (eV $\times 10^3$ )	$\sigma_0$ (fb)	$b$ (fb/MeV)	$-\log \mathcal{L}$	$\mathcal{P}$ (nominal)	$\mathcal{P}$ (sim)	$\mathcal{P}$ (sim)*
0.5(fixed)	$3525.83^{+0.15}_{-0.16}$	$4.6^{+1.7}_{-1.5}$	$77^{+30}_{-24}$	-0.36	34.19	$0.30\cdot 10^{-3}$	$0.98\cdot 10^{-3}$	$0.86\cdot 10^{-3}$
1.0(fixed)	$3525.81^{+0.22}_{-0.23}$	$5.5^{+2.3}_{-1.9}$	$81^{+32}_{-25}$	-0.38	35.66	$1.5\cdot 10^{-3}$	$3.16\cdot 10^{-3}$	$2.76\cdot 10^{-3}$
No resonance:			$156^{+35}_{-30}$	-0.74	40.72			

Table 2

Fits to the  $\eta_c\gamma$  cross section in the energy range  $3300 < E_{CM} < 4400$  MeV.  $\mathcal{P}$ (nominal) is calculated from  $\chi^2 \approx -2\Delta \ln \mathcal{L}$ .  $\mathcal{P}$ (sim) and  $\mathcal{P}$ (sim)\* are the probabilities that  $\Delta \ln \mathcal{L}$  or both  $\Delta \ln \mathcal{L}$  and  $\Gamma_{\bar{p}p}B_{\eta_c\gamma}$  exceed the experimental values on simulated experiments. (*Preliminary*)

or a 1.0 MeV bin between  $3525.7 < E_{CM} < 3526.7$  MeV. Since this bin is chosen *a posteriori*, the significance is estimated from the cumulative binomial probability, calculated as above, multiplied by a conservative factor 10 (or 5) for the number of possible signal bin choices.

3. Poisson significance: From a linear fit to the background cross section  $\sigma_b$  over the full energy range  $3300 < E_{CM} < 4400$  MeV, we estimate  $\sigma_b(3526.2 \text{ MeV}) = 0.079 \pm 0.016$  pb. We then estimate the significance from the probability that the expected background fluctuates to  $\geq 13$  events in  $3525.7 < E_{CM} < 3526.2$  MeV, or  $\geq 14$  events in  $3525.7 < E_{CM} < 3526.7$  MeV, multiplied by 10 (or 5).

4. Significance from likelihood ratio: We simulate the outcome of 50,000 experiments under the hypothesis of a linear background, whose parameters are Gaussian distributed with mean and variance taken from the “no resonance” fit to the data in Tab. 2. For each experiment we perform maximum likelihood fits to the null hypothesis ( $H_0$ ) (no resonance) and the alternate hypothesis ( $H_1$ ) that includes a resonance as described below. We then estimate the significance from the probability that a likelihood ratio at least as large as that observed on data can arise by chance.

The most conservative estimate of the significance is obtained by method 4 which gives  $\mathcal{P}$  between 1 and  $3 \times 10^{-3}$  depending upon the assumed resonance width. Other methods yield  $8 \cdot 10^{-5} < \mathcal{P} < 3 \cdot 10^{-3}$ . In the absence of a narrow peaking background, this is strong evidence for a resonance near 3526 MeV.

We perform a Poisson maximum likelihood fit to the measured cross section between 3300 and 4400 MeV as the sum of a linearly varying back-

ground cross section ( $\sigma_b(E) = \sigma_0 + b(E(\text{MeV}) - 3526.2)$ ) and a Breit Wigner convolved with a Gaussian describing the beam energy distribution.

The parameters determined by the fit are  $\sigma_0$ ,  $b$ ,  $M_R$ , and  $\Gamma_{in}B_{out} = \Gamma(h_c \rightarrow p\bar{p})\mathcal{B}(h_c \rightarrow \eta_c\gamma)\mathcal{B}(\eta_c \rightarrow \gamma\gamma)$ . Data are insufficient to fit for  $\Gamma_R$  and we perform fits for fixed values of  $\Gamma_R$  between 0.5 and 1 MeV. The results are given in Table 2 for two values of  $\Gamma_R$ . The background parameters are relatively independent of  $\Gamma_R$ , and  $\Gamma_{in}B_{out}$  only changes by  $\approx 20\%$  as  $\Gamma_R$  is increased from 0.5 to 1.0 MeV. The maximum of the likelihood seem to favour smaller  $\Gamma_R$ .

We also perform a fit including in the model the  $\propto \sin^2 \theta_3^*$  distribution of the E1 radiative transition. The background angular distribution, measured on a sample enriched with feed-down events at the  $\chi_{c.o.g.}$  region, is compatible with isotropy in  $-0.4 < \cos \theta_3^* < 0.7$ . The fitted parameters do not significantly change but  $\ln \mathcal{L}$  increases by 2.68 suggesting that the expected angular distribution is a better hypothesis than isotropic decay.

Dividing  $\Gamma_{in}B_{out}$  by the value of  $\mathcal{B}(\eta_c \rightarrow \gamma\gamma) = (4.3 \pm 1.5)10^{-4}$  [4], we derive  $10.6 \pm 3.7 \pm 3.4$  (br)  $< \Gamma_{\bar{p}p}B_{\eta_c\gamma} < 12.8 \pm 4.8 \pm 4.5$  (br) eV, consistent with  $\mathcal{B}(p\bar{p}) \approx 1 - 3 \times 10^{-5}$  in the expected range [10] for  $\Gamma(h_c \rightarrow \eta_c\gamma) \approx 600$  keV.

### 3.2. Search for $\bar{p}p \rightarrow h_c \rightarrow J/\psi\pi^0 \rightarrow e^+e^-\gamma\gamma$

The trigger for  $e^+e^-X$  final states requires at least two charged tracks from the interaction point associated to a signal in the threshold Čerenkov counter and at least 2 energy deposits in the CCAL with invariant mass  $\geq 2.2$  GeV.

Events must have two electrons identified by a likelihood ratio test ( $EW_1EW_2 > 1.5$  [8]) based

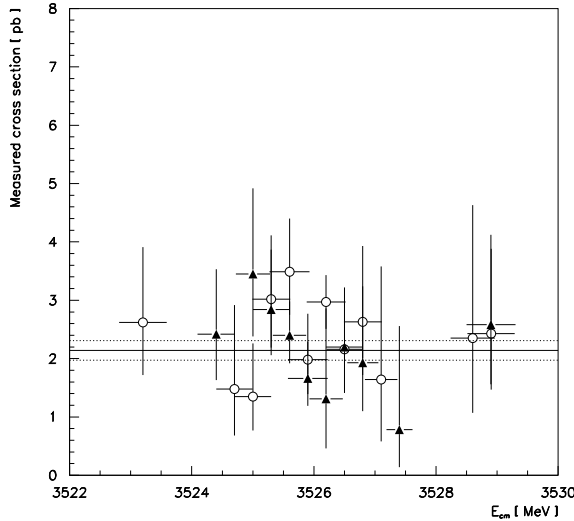


Figure 4. Cross section for  $\bar{p}p \rightarrow J/\psi\pi^0 \rightarrow e^+e^-\gamma\gamma$ . E835-I data are open circles and E835-II data closed circles (*Preliminary*)

on  $dE/dX$  in the scintillators, number of p.h.e. in Čerenkov and shower lateral shape in the CCAL. We require that the  $e^+e^-$  invariant mass is  $> 2800$  MeV and limit the  $e^+(e^-)$  acceptance to  $15^\circ < \theta < 60^\circ$ . Acceptance for photons is  $11^\circ < \theta < 70^\circ$ . We allow additional on-time CCAL clusters only if compatible with photons radiated by the  $e^\pm$  ( $E < 100$  MeV and  $\theta_{\gamma e} < 10^\circ$ ). Finally the  $\chi^2$  probability for the 6C fit to  $J/\psi\pi^0$  must exceed 0.01.

We exclude the  $\chi_{c1}$  and  $\chi_{c2}$  data, since radiative decays to  $J/\psi\gamma$  constitute a background to  $J/\psi\pi^0$ , and consider only data for  $3.52$  GeV  $< \sqrt{s} < 3.54$  GeV. The observed cross section for  $\bar{p}p \rightarrow J/\psi\pi^0$  is plotted in Fig. 4. Data are compatible with a flat cross section between 3.52 and 3.54 GeV. Within our acceptance (smaller than that of E760) we see no excess of events that would correspond to a narrow ( $< 1$  MeV) resonance.

#### 4. CONCLUSIONS

We have measured the cross section for  $\bar{p}p \rightarrow \eta_c\gamma \rightarrow 3\gamma$  near the center of gravity of the charmonium  $^3P_J$  states and observe a narrow struc-

ture ( $\Gamma \leq 1$  MeV) centered at  $3528.8 \pm 0.2 \pm 0.2$  MeV. The statistical significance is  $\mathcal{P} \sim 0.001$ . The value of  $\Gamma_{\bar{p}p}B_{\eta_c\gamma} \sim 12.0 \pm 4.5 \pm 4.3$  eV is compatible with the expected  $\mathcal{B}(\bar{p}p)$  and E1 radiative width of the  $h_c$ . The signal is seen with comparable yield and at the same  $M_R$  in both runs. Our former experiment E760 had no sensitivity to this channel: with a factor 5 less luminosity in this region, it would have observed between 2 and 3 events. This observation is evidence for the  $h_c$  at its expected location near the  $\chi_{c.o.g.}$ . We have measured the cross section for  $\bar{p}p \rightarrow J/\psi\pi^0$  and observe no significant excess in the  $\chi_{cJ}$  center-of-gravity region.

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