SLAC-PUB-10696

Charmonium Production at *BABAR*

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We present three analyses on charmonium production using 89 fb^{-1} of e^+e^- collision data collected by the *BABAR* detector at the PEP-II storage ring operating at the $\Upsilon(4S)$ at SLAC. A precise measurement of the η_c total width is obtained from a study of the invariant $K^0_S K^\pm \pi^\mp$ mass spectrum for a sample of η_c mesons produced in two-photon interactions. The total width of the J/ψ meson is measured using initial state radiation $e^+e^- \to \mu^+\mu^-\gamma$ events. Finally branching fraction measurements for the exclusive B meson decays $B^0 \to J/\psi\, p\overline{p}$ and $B^+ \to J/\psi\, p\overline{\Lambda}$ are presented.

1. Introduction

2. The *BABAR* Detector

The *BABAR* detector is described in detail elsewhere [1]. Charged particles are detected by a five layer silicon vertex tracker (SVT) and a 40 layer drift chamber (DCH) both operating in a 1.5T solenoidal magnetic field. The transverse momentum resolution for charged tracks is given by

$$\sigma(p_T)/p_T = 0.13\%(??) + 0.45\% \qquad (1)$$

where p_T is the transverse momentum in GeV/c.

The energy of photons and electrons are measured in a CsI(Tl) electromagnetic calorimeter (EMC) with energy resolution given by

$$\sigma(E)/E = \frac{2.32\%}{\sqrt[4]{E(\mathrm{GeV})}} \oplus 1.85\% \qquad (2)$$

where E is the energy in GeV.

Charged particle identification is provided by energy loss measurements in the SVT and DCH, and by an internally reflecting ring imaging Cherenkov detector (DIRC). Muons and neutral hadrons are identified in the solenoids flux return which is instrumented with resistive plate chambers interleaved with iron (IFR).

The data sample used in the analyses presented in this paper corresponds to 89 fb^{-1} of e^+ e^- collison data.

3. η_c production in $\gamma - \gamma$ collisions

The mass and in particular the width of the η_c are not well determined when compared to the J/ψ. Accurate measurement of the η_c total width and $\gamma\gamma$ width allow tests of perturbative QCD caluation realting the two [3]. The world average of the width $\Gamma^{\eta_c}_{tot} = 16^{+3.6}_{-3.2}$ MeV/c [2] is inconsistent with recent higher width measurements by CLEO [4] and BELLE [5] of $\Gamma^{\eta_c}_{tot} = 27.0 \pm 5.8\ (stat) \pm 1.4\ (syst)$ MeV/c^2 and $\Gamma^{\eta_c}_{tot} = 29 \pm 8\ (stat) \pm 6\ (syst)$ MeV/c^2 respectivly. In this analysis the η_c width is measured using a sample of η_c mesons produced in the reaction $\gamma\gamma \to X \to K^0_S\, K^\pm\, \pi^\mp$.

The final state of the η_c decay is fully reconstruted but the final state electrons are not detected. Events are selected requiring that the total observed energy in the laboratory frame is less than 9 GeV to suppress B decays, and that the total transverse momentum in the laboratory frame is less than 0.5 GeV/c. The events are required to have one charged track identified as a kaon, an oppositly charged track (assumed to be a pion) and a $K^0_S \to \pi^+\pi^-$ candidate. The $K^0_S \to \pi^+\pi^-$ candidate is formed by combining 2 oppositly charged tracks with an invarient mass

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Supported by PPARC.

Work Supported in part by the Department of Energy Contract DE-AC02-76SF00515

Presented at the Photon 2003: International Conference on the Structure and Interactions of the Photon and 15th International Workshop on Photon-Photon Collisions, 4/7/2003 - 4/11/2003, Frascati, Italy

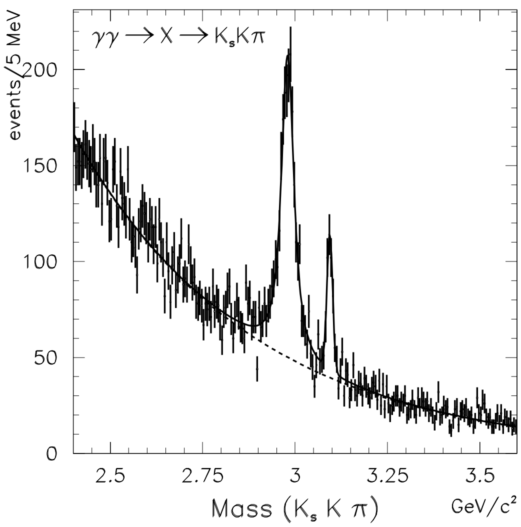

Figure 1. The (K_S^0 $K^{\pm}$ $\pi^{\mp}$) mass spectrum fitted as explained in the text.

in the range $0.491 < M_{\pi^+\pi^-} < 0.503\,\mathrm{GeV}/c^2$. The $K^{\pm}$, $\pi^{\mp}$ and K_S^0 candidates are refitted with kinematic constraints and with the K_S^0 candidate mass constrained to its world average value [2]. The χ^2 probability of the vertex fit is required to be greater than 0.01. The K_S^0 momentum vector is required to point back to the $K^{\pm}$ $\pi^{\mp}$ vertex such that $\cos\theta > 0.999$ (where θ is the angle between K_S^0 momentum vector and the vector between the K_S^0 vertex and the K_S^0 $K^{\pm}$ $\pi^{\mp}$ vertex).

The width is measured by fitting to the K_S^0 $K^{\pm}$ $\pi^{\mp}$ invarient mass spectrum. The mass spectrum for the selected events is shown in figure 1. There is a large peak at the η_c mass and a smaller peak at the J/ψ mass. The J/ψ cannot be produced in two photon collisions but it is produced in hard photon emission in initial state radiation, and the observed yield is consistent with expectations for this production mechanism. The J/ψ peak allows the experimental mass resolution to be obtained in the fit. This is nescassary to measure the η_c width accurately.

In the fit the η_c is described by a Breit-Wigner convoluted with a Gaussian to represent the detector resolution. The J/ψ peak is represented by a single Gaussian and the background is described by an exponential function. The free parameters of the fit are: the J/ψ mass, the difference between the J/ψ and η_c mass, the η_c width, the J/ψ resolution, the normalisation and shape of the background, and the number of events in the η_c and J/ψ peaks. The resolution of the η_c is fixed to a value 0.8 MeV/c^2 lower than the J/ψ resolution as suggested by Monte Carlo. The resolutions are different due to the different angular directions of the decay products, the decay products of J/ψ decay tend to travel in the backward direction whereas the η_c decay products tend to travel in the forward direction.

The result of the unbinned maximum liklihood fit is presented in table **??**. Systematic uncertainties are estimated by fixing the resolutions to the Monte Carlo values, and by varying the mass range over which the background is fitted.These lead to a systematic uncertainty of 0.8 MeV/c^2 on the width measurement. A systematic uncertainty on the mass measurement is estimated as the difference between the fitted mass of the J/ψ and the world average of the J/ψ mass [2], this leads to an uncertainty of 1.8 MeV/c^2 on the mass measurement. The final results are: $\Gamma_{tot}^{\eta_c} = 33.3 \pm 2.5 \pm 1.2$ MeV/c^2 and $M_{\eta_c} = 2983.3 \pm 1.2 \pm 1.8$ MeV/c^2, where the first uncertainty is statistical and the second systematic.

Table 1
The η_c parameters extracted from the unbinned maximum likelihood fit of the mass spectrum. The shown uncertainties are only statistical.

η_c parameter	Fitted result
N_{η_c}	1715 ± 70
$\Gamma_{tot}^{\eta_c}$ (MeV/c^2)	33.3 ± 2.5
$M_{J/\psi} - M_{\eta_c}$ (MeV/c^2)	113.6 ± 1.2
$M_{J/\psi}$ (MeV/c^2)	3094.0 ± 0.8

The same analysis method, applied to higher K_S^0 $K^{\pm}$ $\pi^{\mp}$ masses, result in the mass spectra

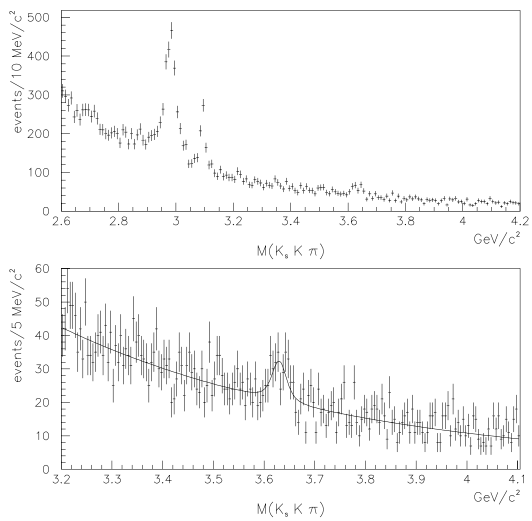

Figure 2. The (K_S^0 $K^{\pm}$ $\pi^{\mp}$) mass over a larger mass range (top). A close up of the η_c (2S) region with the fit overlaid (bottom).

shown in figure 2. A peak is seen in the mass spectrum at about 3.63 GeV/c^2. This could be the expected $\eta_c(2S)$ state, a radial excitation of the η_c, and it would be the first evidence of the $\eta_c(2S)$ coupling to two photons. A fit to this peak yields the preliminary results shown in table 2.

Table 2
Preliminary results of the η_c (2S) parameters extracted from the unbinned maximum likelihood fit. The first error is statistical and the second systematic.

η_c (2S) parameter	Fitted result
$N_{\eta_c(2S)}$	106 ± 28
$\Gamma_{tot}^{\eta_c(2S)}$ (MeV/c^2)	19.5 ± 9.9 ± 3.7
$M_{\eta_c(2S)}$ (MeV/c^2)	3633.4 ± 5.1 ± 1.8

4. J/ψ Production in Initial State Radiation (ISR) events

A study of the $e^+ e^- \to \mu^+ \mu^- \gamma$ process in the $\mu^+ \mu^-$ invarient mass range near the J/ψ mass is carried out to measure the total width of the J/ψ .

The Born cross section for J/ψ ISR production integrated over angles of the final particles is given by the following formula

$$\frac{d\sigma_{J/\psi}(s,x)}{dx} = W(s,x) \cdot \sigma_0(s(1-x)), \qquad (3)$$

where $x = \frac{2E_\gamma}{\sqrt{s}}$, E_γ is the photon energy. The functions $W(s,x)$ describes the probability of photon emission and is well known. It should be noted that ISR photons are emitted dominantly at small angles relative to the electron direction. Only about 10% of the photons have a polar angle (in CM frame) in the range $30° < \theta < 150°$ and can be detected in BaBar. The cross section of $e^+e^- \to J/\psi \to \mu^+\mu^-$ is given by the Breit-Wigner formula

$$\sigma_0(s) = \frac{12\pi B_{ee} B_{\mu\mu}}{m^2} \cdot \frac{M_{J/\psi}^2 \Gamma_{tot}^{J/\psi\, 2}}{(s - M_{J/\psi}^2)^2 + M_{J/\psi}^2 \Gamma_{tot}^{J/\psi\, 2}}, (4)$$

where $M_{J/\psi}$ and $\Gamma_{tot}^{J/\psi}$ are the J/ψ mass and width respectively. B_{ee} and $B_{\mu\mu}$ are branching fractions into e^+e^- and $\mu^+\mu^-$ pairs. For a very narrow resonance, such as J/ψ, we can replace the Breit-Wigner function with a δ distribution $\pi M_{J/\psi} \Gamma_{tot}^{J/\psi} \delta(s - M_{J/\psi}^2)$ and perform the integration over photon energy:

$$\sigma_{J/\psi}(s) = \frac{12\pi^2 \Gamma_{e^+e^-}^{J/\psi} B_{\mu\mu}}{m \cdot s} \cdot W(s, x_0), x_0 = (1 - \frac{M_{J/\psi}^2}{s}). (5)$$

Here $\Gamma_{e^+e^-}^{J/\psi} = \Gamma_{tot}^{J/\psi} \cdot B_{ee}$.

By fitting for the ratio of the number of resonant to nonresonant dimuon events the total cross section can be measured, this in turn can give the product $\frac{\Gamma_{e^+e^-}^{J/\psi} \Gamma_{\mu^+\mu^-}^{J/\psi}}{\Gamma_{tot}^{J/\psi}}$ using equation 5. By substituting in the relatively well measured value of $B_{\mu\mu}$ the total J/ψ width $\Gamma_{tot}^{J/\psi}$ and the electron width $\Gamma_{e^+e^-}^{J/\psi}$ can be extracted.

The two final state muons and the photon are fully reconstructed. The photon is required to have an energy of greater than 3 GeV and the absolute value of the angle between the momenta of the dimuon system and the photon is required to be less than 7 mrad. The total energy of the photon and the two muons is required to be within 1.5 GeV of the centre of mass energy of the beams. The muons are identifed using cuts on the calorimeter energy deposit and the track momentum. A 1C kinematic fit is carried out on the dimuon system with the constraint that the recoiling system has an invarient mass of 0. This fit improves the J/ψ mass resolution and also rejects background. After this selection the estimated ammount of background is less than 0.3%.

The dimuon mass spectrum is shown in figure 3. This spectrum is fitted using a binned likelihood fit. The fit function is of the form

$$f(m_i) = N_0 \left[R \cdot H(m_i; M_{J/\psi}, \sigma_G) + I(m_i)\right] \quad (6)$$

where H is the signal J/ψ probability density function (PDF) and I is the nonresonant PDF, m_i is the dimuon mass in bin i. The signal J/ψ PDF is derived from Monte Carlo simulation, convoluted by a Gaussian (of width σ_G) to take into account detector resolution. I is a second order polynomial, as predicted by simulation. The main fit parameter is R which describes the ratio of J/ψ production to nonresonant production, this is related to the total crosssection by

$$R = \frac{\sigma^{Born}_{J/\psi}}{\frac{d\sigma^{Born}_{ISR}}{dM} \cdot 4\ \mathrm{MeV/c^2}} \cdot \frac{1}{K} \quad (7)$$

here K is a correction due to the final state radiation (FSR) events given by

$$K = \frac{d\sigma^{vis}_{Total}/dM}{d\sigma^{vis}_{ISR}/dM}, \quad (8)$$

This is evaluated using simulation to be 1.11 ± 0.01. An advantage of this method is that uncertainties due to the selection efficiency cancel in the ratio R, reducing the overall systematc uncertainty.

Systematic uncertainties considered include uncertainties on the value of K due to modelling of FSR (1.3%), background uncertainty (0.5%), the J/ψ lineshape (1.4%) and uncertainty due to interference effects (0.3%) adding in quadrature to give a total uncertainty of 2.2%.

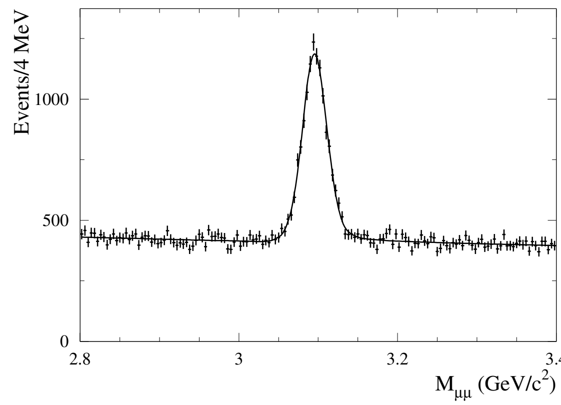

Figure 3. The dimuon mass spectrum for selected events. The fit described in the text is shown on the plot. The χ^2/NDof for the fit is 124/144.

The result of the fit is $R = 18.94 \pm 0.44$, which translates into a measurement of the total cross section of $\sigma_{J/\psi} = 2124 \pm 49 \pm 47\,\mathrm{fb}$.

Using equation 5 this leads to a measurement of $\Gamma^{J/\psi}_{e^+e^-} \cdot B_{\mu\mu} = 0.3301 \pm 0.0077 \pm 0.0073\ \mathrm{keV}/c^2$. By substituting in the world average of $B_{\mu\mu}$ and B_{ee} [2] this leads to the results $\Gamma^{J/\psi}_{e^+e^-} = 5.61 \pm 0.21\ \mathrm{keV}/c^2, \Gamma^{J/\psi}_{tot} = 94.7 \pm 4.4\ \mathrm{keV}/c^2$. These results are in agreement and more precise than the current world averages [2].

5. $B \to J/\psi$ baryon anti-baryon Branching fraction measurements

Studies of the inclusive production of charmonium mesons in B decays at the $\Upsilon(4S)$ [6] [7] [8] have shown an excess of J/ψ mesons being produced with low centre of mass momentum, when compared to the predictions of non-relativistic QCD calculations [9]. Figure 4 shows the centre-of-mass momenta (p^*) for J/ψ mesons produced directly in B decay, the excess below 0.8 GeV/c corresponds to a BF of $\approx 6 \times 10^{-4}$. Possible sources for the excess include an intrinsic charm

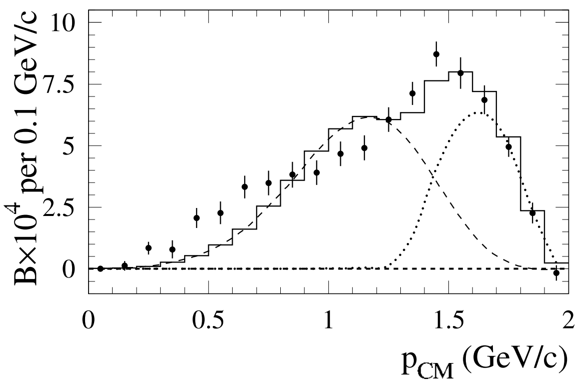

Figure 4. p^* of directly produced J/ψ mesons in B decays. The hisogram shows the non-relativistic QCD expectation and the points show the data. This figure is taken from [7].

component of the B [10], the production of an $s\bar{d}g$ hybrid in conjuction with the J/ψ [11] or decays such as $B \to J/\psi$ *baryon anti-baryon* [12].

Here we present the results of a search for the decays $B^0 \to J/\psi\, p\overline{p}$ and $B^+ \to J/\psi\, p\overline{\Lambda}$. The rate of these decays could be enhanced by the intermiediate production of an exotic state allowed by QCD but not yet observed such as nuclear-bound quarkonium, baryonium or a pentaquark. If such such resonances were narrow the other particle in the decay would be monoenergetic in the B rest frame. The $B^0 \to J/\psi\, p\overline{p}$ decay is cabbibo supressed with respect to the $B^+ \to J/\psi\, p\overline{\Lambda}$ decay.

Signal events are selected by fully reconstructing the decay chain. The J/ψ is only reconstructed in its leptonic decay modes (BF $(J/\psi \to l^+l^-) \approx 12\%$), and the $\overline{\Lambda}$ is reconstructed in the decay mode $\overline{\Lambda} \to \overline{p}\pi^+$. Electrons are identified using there energy deposit and cluster shape in the EMC, the Cherenkov angle in the DIRC and the energy loss measurements in the DCH. Muons are identifed using the EMC energy deposit and hits in the IFR. J/ψ candidates are formed by combining oppositly charged pairs of electron or muon candidates. The J/ψ is required to have a mass in the range 2.95(3.05)-3.13 GeV/c^2 for the $\mu^+\ \mu^-$ ($e^+\ e^-$) mode. Protons are identifed using the DIRC cherenkov angle as well as energy loss measurements in the DCH and SVT. At 0.3 GeV/c (a typical proton momentum) the algorithm has an efficiency greater than 98% with a kaon mis-identification of less than 1%. Λ candidates are formed by combining a proton candidate with an oppositly charged track (assumed to be a pion).

Signal and background are distinguished by two almost uncorrelated kinematic variables [1]: the difference between the reconstructed and the expected B candidate energy, $\Delta E = (q_\Upsilon \cdot q_B - s/2)/\sqrt{s}$, and the beam-energy substituted mass, $m_{\rm ES} = \sqrt{(0.5s + \vec{p}_B \cdot \vec{p}_\Upsilon)^2/E_\Upsilon^2 - p_B^2}$. Where $q_\Upsilon = (E_\Upsilon, \vec{p}_\Upsilon)$ is the four vector of the initial state (such that $s \equiv |q_\Upsilon|^2$), and $q_B = (E_B, \vec{p}_B)$ is the four vector of the reconstructed B candidate. Signal decays are clusted around $\Delta E = 0$ GeV, and $m_{\rm ES} = 5.279$ GeV/c^2. An analysis window (AW) is defined in these 2 variables as $5.2 < m_{\rm ES} < 5.3$ GeV/c^2, and $-0.10 < \Delta E < 0.25$ GeV (B^+ candidates) and $-0.25 < \Delta E < 0.25$ GeV (B^0 candidates) (the ΔE range is smaller for the charged B decay mode due to a kinematic cutoff in this mode). When more than one B candidate falls into the AW in the same event only the one with the smallest value of $|\Delta E|$ is kept for further analysis. An elliptical signal region is defined in the $m_{\rm ES}$ ΔE plane as: $[(m_{\rm ES} - M_B)/\sigma_m]^2 + [\Delta E/\sigma_E]^2 < S^2$, where the resolutions σ_m and σ_E are estimated from simulated data to be 3.1 MeV/c^2 and 6.5 MeV, respectively. The values used are $S = 2.4$ for $B^+ \to J/\psi\, p\overline{\Lambda}$ and $S = 2.2$ for $B^0 \to J/\psi\, p\overline{p}$. The selection criteria for charged and neutral B candidates, including the values for S, have been chosen to minimize the 90% CL upper limit expected in the absence of real signal, based on simulated signal and background events.

The selection efficiency is determined from Monte Carlo simulation of the signal decay modes. Particle identification efficiencies are taken from dedicated data control samples. The final efficiency for the mode $B^+ \to J/\psi\, p\overline{\Lambda}$ is 4.9±0.9% with the largest systematic uncertainty coming from the uncertainty in the Λ reconstruction. The efficiency for the $B^0 \to J/\psi\, p\overline{p}$ mode is

18.4±2.4%.

Monte Carlo simulation studies show that the background is predominatly combinatoric $B\overline{B}$, in which tracks from both B mesons are used to reconstruct the B candidate. The background does not peak in either $m_{\rm ES}$ or ΔE. The expected background in the signal region is estimated from the number of events in the elsewhere in the AW.

For the $B^+ \to J/\psi\, p\overline{\Lambda}$ decay mode 39 events are observed in the AW not including the signal region which corresponds to an expected background in the signal region of 0.21 ± 0.14 events. Four candidates are seen in the signal region (Fig 5). The probability of observing ≥ 4 events when expecting 0.21 ± 0.14 is 2.5 x 10^{14}. Using a Bayesian approach with a uniform prior the branching fraction for this decay can be calculated to be $(11.6^{+8.5}_{-5.6})$ where systematic uncertainties on the selection efficiency and the number of B mesons in the sample have been included in the errors.

For the $B^0 \to J/\psi\, p\overline{p}$ decay mode, there are 126 events outside the signal region indicating an expected background of 0.64 ± 0.17 events. One event is observed in the signal region (Fig 5). This leads to an upper limit on the branching fraction for this decay mode of 1.9 x 10^{-6} (90% CL). This limit is dominated by the statistical uncertainty.

For the events in the signal region for the $B^+ \to J/\psi\, p\overline{\Lambda}$ decay we plot the centre-of-mass momentum of the J/ψ , p, and $\overline{\Lambda}$ in figure 6. If this decay was proceeding through a narrow intermediate exotic QCD resonance we would expect the other particle to have a narrow p* distribution. We do not observe any significant clustering in this distribution, and thus no evidence for such exotic resonance production.

The measurement of these branching fractions indicate that neither of these final states makes a significant contribution to the observed excess of J/ψ mesons in inclusive B decays at low p^*.

6. Conclusions

We have presented a measurement of the η_c total width determined using a sample of 1715 ± 70 $\gamma\gamma \to \eta_c \to K^0_S K^{\pm}\pi^{\mp}$ events. The result is

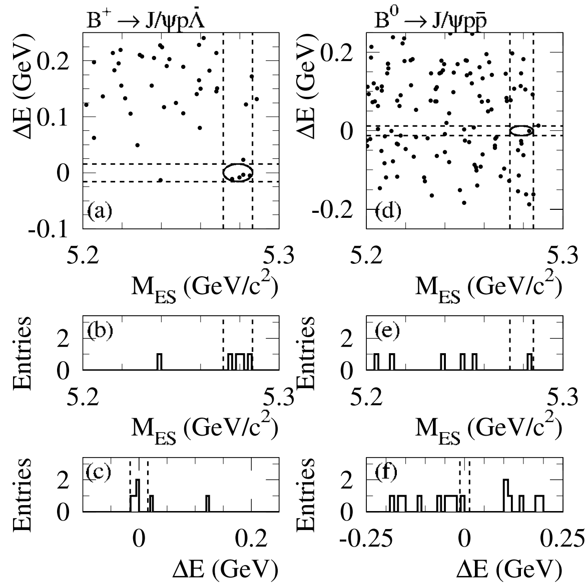

Figure 5. Left: The $m_{\rm ES}$ ΔE plane for events passing the $B^+ \to J/\psi\, p\overline{\Lambda}$ event selection. 4 events are observed in the signal region. Right: The $m_{\rm ES}$ ΔE plane for events passing the $B^0 \to J/\psi\, p\overline{p}$ event selection. 1 event is observed in the signal region.

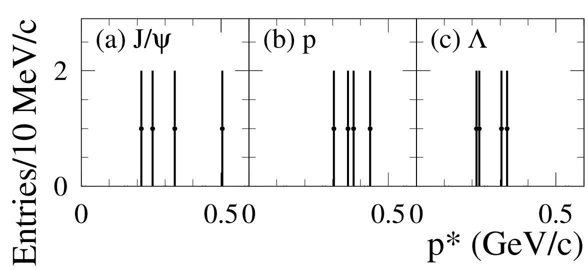

Figure 6. The p^* of the J/ψ , the p and the $\overline{\Lambda}$ candidates for the 4 $B^+ \to J/\psi\, p\overline{\Lambda}$events in the signal region.

$\Gamma^{\eta_c}_{tot} = 33.3 \pm 2.5(stat) \pm 0.8(syst)$ MeV/c^2. This measurement is considerably higher than the current world average but in agreement with higher width measurements from BELLE and CLEO. Preliminary evidence of η_c (2S) production in $\gamma\gamma$ collisions yield a mass of the η_c (2S) of $3633.4 \pm 5.1 \pm 1.8$ MeV/c^2.

The total width of the J/ψ has been measured using a sample of $e^+ e^- \rightarrow \mu^+ \mu^- \gamma$ events where the dimuon mass is in the J/ψ mass region. The total width is measured to be $\Gamma^{J/\psi}_{tot} = 94.7 \pm 0.4.4\,\mathrm{keV}/c^2$ and the electron width is $\Gamma^{J/\psi}_{e^+e^-} = 5.61 \pm 0.20\,\mathrm{keV}/c^2$. These measured values are in agreement and more precise than the current world averages [2].

An analysis of the decays $B^+ \rightarrow J/\psi\, p\overline{\Lambda}$ and $B^0 \rightarrow J/\psi\, p\overline{p}$ has also been presented. The branching fraction for the $B^+ \rightarrow J/\psi\, p\overline{\Lambda}$ decay is measured to be $(11.6^{+8.5}_{-5.6})$. Whereas for the Cabbibo supressed decay $B^0 \rightarrow J/\psi\, p\overline{p}$ we present an upper limit of 1.9 x 10^{-6} (90% CL). These branching fractions are too small to explain the discrepancy between the observed inclusive J/ψ momentum spectrum and that predicted by non-relativistic QCD (see figure 4).

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