SLAC-PUB-8526
BABAR-CONF-00/04
hep-ex/0008049
August, 2000

Measurement of inclusive production of charmonium states in $\boldsymbol{B}$ meson decays

The *BABAR* Collaboration

Abstract

We reconstruct the charmonium mesons J/ψ, $\psi(2S)$ and χ_c using a sample of 8.46×10^6 $B\overline{B}$ events collected by the *BABAR* detector operating at e^+e^- center of mass energies near the $\Upsilon(4S)$ resonance. By measuring rates relative to the branching fraction of the J/ψ, we obtain preliminary inclusive B branching fractions of $(0.25 \pm 0.02 \pm 0.02)\%$ to the $\psi(2S)$ and $(0.39 \pm 0.04 \pm 0.04)\%$ to the χ_{c1}, and set a 90% confidence level limit of 0.24% on decays through the χ_{c2}.

Submitted to the 30^{th} International Conference on High Energy Physics,
7/27/2000—8/2/2000, Osaka, Japan

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Work supported in part by Department of Energy contract DE-AC03-76SF00515.

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1 Introduction

Observation of the charmonium mesons J/ψ, $\psi(2S)$ and χ_c is a critical component of the measurement of *CP* violation in B decays at *BABAR* and other facilities. Measurements of the inclusive branching fractions of B mesons to these states are made using the decays $J/\psi \to \ell^+\ell^-$, $\psi(2S) \to \ell^+\ell^-$, $\psi(2S) \to \pi^+\pi^- J/\psi$ and $\chi_c \to \gamma J/\psi$, with $J/\psi \to \ell^+\ell^-$ in the latter two cases; the leptons ℓ may be either electrons or muons. The production rates of the $\psi(2S)$ and χ_c mesons are measured relative to the J/ψ in order to eliminate common systematic errors in tracking and particle identification.

2 The *BABAR* detector and dataset

The data used in this analysis were collected with the *BABAR* detector at the PEP-II storage ring, which collides 9.0 GeV electrons with 3.1 GeV positrons. A luminosity of 7.7 fb^{-1} was collected on the $\Upsilon(4S)$ resonance, $\sqrt{s} = 10.58\,\mathrm{GeV}$ ("on-resonance"), with an additional 1.2 fb^{-1} collected at $\sqrt{s} = 10.54\,\mathrm{GeV}$, below the threshold for $B\overline{B}$ production ("off-resonance"). The off-resonance data set is used to statistically subtract the non-$B\overline{B}$ component of signals.

The *BABAR* detector is described elsewhere [1]. The tracking system, which is used for pattern recognition and reconstruction of the momenta of charged particles, consists of two sub-detectors. The inner is a five-layer double sided silicon vertex tracker (SVT) which gives precision spatial information for all charged particles and is the primary detection device for low momentum charged particles. It is surrounded by a 40-layer drift chamber (DCH), which provides measurements of track momenta.

The primary sources of information used in lepton identification are the calorimeter and the muon system. The DCH also provides $\mathrm{d}E/\mathrm{d}x$ information which is used in the identification of electrons. The calorimeter is constructed from CsI crystals and, in addition to distinguishing electrons, hadrons and muons on the basis of their energy depositions, is used to locate and measure photons. The muon system, known as the Instrumented Flux Return (IFR) in *BABAR*, consists of resistive plate chambers interleaved with iron plates. There are 19 layers in the central region of the detector, 18 in the endcap regions.

3 Event selection

The event selection criteria are designed to select $B\overline{B}$ decays with high efficiency while suppressing lepton pairs, two-photon events, and interactions with the beam pipe or residual gas in the beam line. We require the event to have:

- at least four charged tracks in the active volume of the tracking system;
- total energy (charged tracks plus photons) greater than 5 GeV;
- a primary vertex within 5 mm of the beam interaction region; and
- a normalized second-order Fox-Wolfram moment [2] less than 0.7.

A total of $(8.46 \pm 0.14) \times 10^6$ $B\overline{B}$ events satisfy these criteria. This value is obtained by scaling the number of events selected in the off resonance sample by the ratio of muon pairs (luminosities) and subtracting it from the total number of events selected in the on-resonance sample. The uncertainty

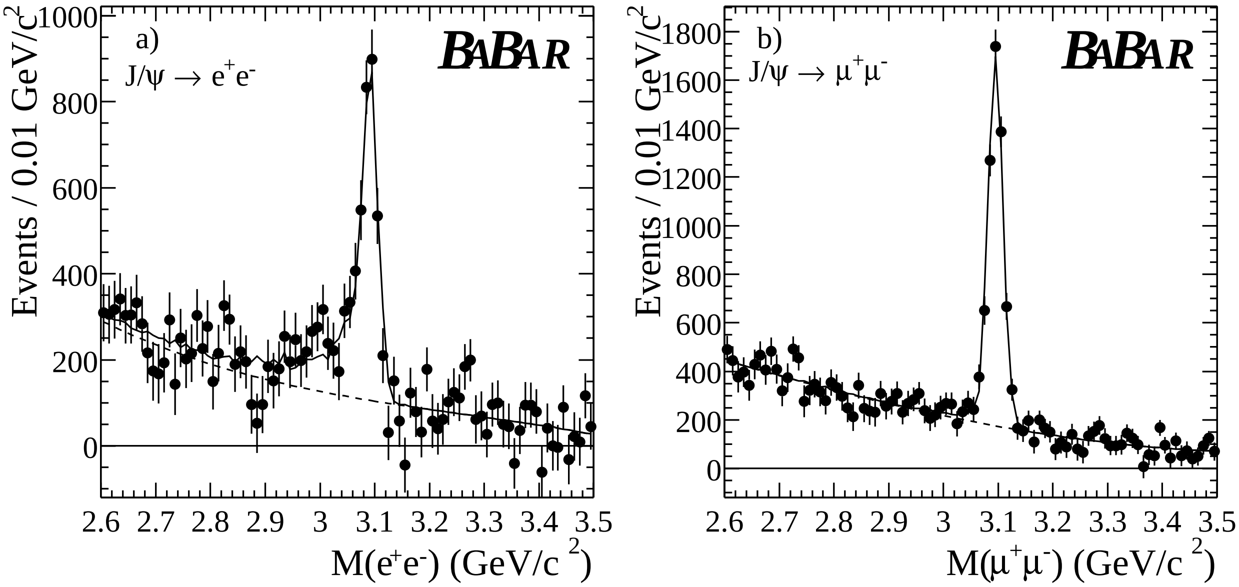

Figure 1: Mass distribution of J/ψ candidates to (a) electron pairs and (b) muon pairs after the continuum subtraction.

is dominated by variations in the ratio of selected events to muon pairs in the off-resonance running periods throughout the data collection period.

4 Reconstruction of charmonium mesons

4.1 Reconstruction of J/ψ

J/ψ candidates are formed from pairs of charged tracks in the active fiducial volume of the tracking system and calorimeter. Tracks are required to pass within 1.5 cm of the beam line and to include information from the DCH.

Both tracks are required to satify lepton-identification criteria. Electrons must have an energy deposition in the calorimeter of at least 75% of that expected from the track's momentum and a shape consistent with an electromagnetic shower. Muons must have an energy deposition in the calorimeter of less than 0.5 GeV—approximately twice the expectation for a minimum ionizing track—and traverse an amount of material that is within two interaction lengths of that expected for a muon of the measured momentum. The pattern of energy deposition in the IFR must be narrow, perpendicular to the flight path of the track, and the location of the hits must have an acceptable χ^2 when fit to the trajectory extrapolated from the DCH.

The two tracks are fit to a single vertex, if possible, before calculating the mass of the candidate J/ψ. Otherwise, the mass is derived from a simple sum of their four-vectors.

Histograms of mass distributions are accumulated for both the on- and off-resonance data sets. These are then subtracted, after weighting for the difference in luminosities, to give "continuum subtracted" distributions. Figure 1 shows the resulting mass distributions for $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$ candidates.

The number of J/ψ mesons is extracted from the mass distribution using a probability distribution function (p.d.f.) derived from a simulation that includes final state radiation and bremsstrahlung. The mass resolution of the detector simulation is increased from 11.0 to 13.3 MeV/c^2 to match the observed value.

A systematic error on the fit to the e^+e^- final state is obtained by varying by ±10% the number of J/ψ mesons in which an electron undergoes bremsstrahlung in the simulation. This variation, which reflects possible differences between the detector simulation and reality, translates to a 3.5% systematic error.

Systematic errors for both final states are obtained by modifying the selection criteria in two ways. First, the momentum of the J/ψ candidate in the $\Upsilon(4S)$ center of mass (CM) system, p^*, is required to be less than 2.0 GeV/c; all J/ψ mesons from B decays should pass. Second, the number of charged tracks required is increased to five in order to reject remaining lepton pair events. These studies produce systematic errors of 1.3% for e^+e^- and 1.6% for $\mu^+\mu^-$.

We find $4920 \pm 100 \pm 180$ $J/\psi \to e^+e^-$ and $5490 \pm 90 \pm 90$ $J/\psi \to \mu^+\mu^-$ events with mass greater than 2.6 GeV/c^2.

4.2 Reconstruction of $\psi(2S)$

The reconstruction of the $\psi(2S)$ through its decay to e^+e^- or $\mu^+\mu^-$ is similar to that of the J/ψ. In order to reduce the relatively higher background rates, additional selection criteria are applied to the $\psi(2S)$ candidate. First, its momentum in the CM system (p^*) must be less than 1.6 GeV/c, true for all $\psi(2S)$ mesons from B decays. Second, the two tracks must be consistent with coming from a common vertex with a probability greater than 1%. Finally, more stringent particle identification criteria are applied. Muon candidates must penetrate to within one interaction length of the expected amount of material and at least one electron candidate must have an energy deposition between 0.88 and 1.30 times its momentum.

The number of signal events is extracted from the mass distribution using a p.d.f. from simulation, as for the J/ψ. We do not perform a continuum subtraction in this case, as the requirement on p^* is expected to remove most backgrounds from the continuum. Variation of the amount of bremsstrahlung in the detector simulation leads to a 1.7% systematic error on the number of $\psi(2S) \to e^+e^-$ events, although this error is negligible compared to the statistical errors in this case. We find $131 \pm 29 \pm 2$ $\psi(2S) \to e^+e^-$ and 125 ± 19 $\psi(2S) \to \mu^+\mu^-$ events (Fig. 2).

Due to their lower momentum, the pion candidates used to reconstruct $\psi(2S) \to \pi^+\pi^- J/\psi$ are not required to have DCH information. Pairs of pions with mass between 0.45 and 0.59 GeV/c^2 are combined with J/ψ candidates with mass between 2.60 and 3.13 GeV/c^2 for e^+e^- and 3.06 and 3.13 GeV/c^2 (-2.8 to $+2.5$ standard deviations) for $\mu^+\mu^-$. The wider window for e^+e^- is necessitated by the larger radiative tail in this final state. The above requirements on p^* and on vertex quality are applied in this final state as well.

To reduce the impact of the radiative tail and the mass resolution of the J/ψ candidate, the number of $\psi(2S)$ events is extracted from a fit to the distribution of the mass difference between the $\psi(2S)$ and the J/ψ (Fig. 3), with a Gaussian distribution for the signal and a Chebychev polynomial for background. In candidates with $J/\psi \to e^+e^-$, we obtain 126 ± 44 $\psi(2S)$ events, while for $J/\psi \to \mu^+\mu^-$, we obtain 162 ± 23.

4.3 Reconstruction of χ_c

χ_c mesons are reconstructed through the radiative decay $\chi_c \to \gamma J/\psi$. The selected photon candidates must be reconstructed within the same fiducial region used for leptons and have an energy

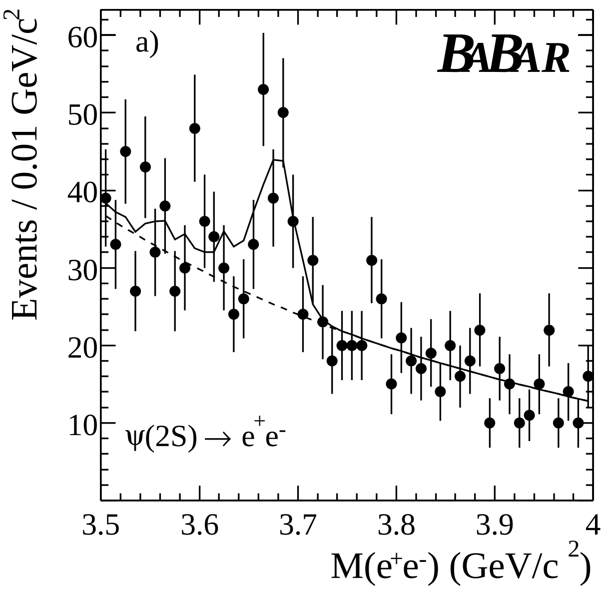

Figure 2: Mass distribution of $\psi(2S)$ candidates to (a) electron pairs and (b) muon pairs.

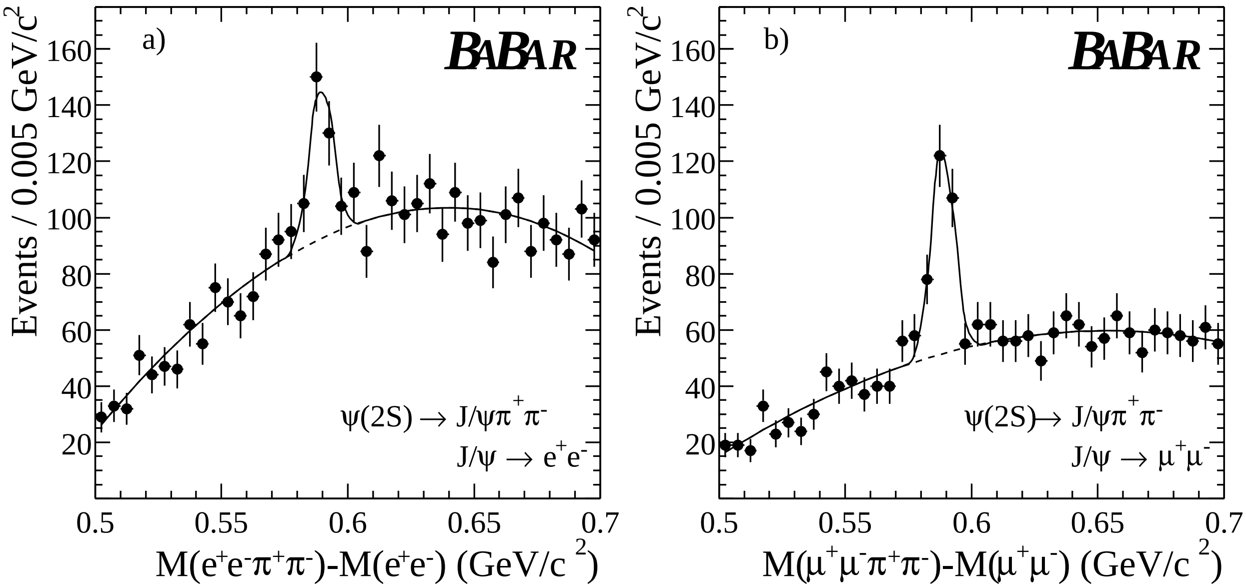

Figure 3: Mass difference between the $\psi(2S)$ and J/ψ candidates, where $\psi(2S) \to \pi^+\pi^- J/\psi$ and (a) $J/\psi \to e^+e^-$ and (b) $J/\psi \to \mu^+\mu^-$.

between 0.20 and 0.65 GeV in the CM system. The shape of the energy deposition must be consistent with an electromagnetic shower. To reject photons from nearby hadronic showers, the photon must be at least 9° from the nearest charged track in the calorimeter. The substantial combinatorial background from π^0 decays is reduced by rejecting any photon that, when combined with any other photon, forms a π^0 candidate with mass between 0.109 and 0.147 GeV/c^2 (-4.0 to $+2.0$ standard deviations about the π^0 mass).

In selecting the J/ψ, muon candidates must satisfy the more stringent requirement that they penetrate to within one interaction length of the expected amount of material. J/ψ candidates with mass between 3.05 and 3.14 GeV/c^2 are combined with photon candidates to form χ_c candidates.

As for the $\psi(2S)$, the number of events is extracted by fitting the distribution of the mass difference between the χ_c and J/ψ candidates (Fig. 4). The resolution is dominated by the angular and energy resolutions for the photon, and includes a low-side tail due to preshowering before the calorimeter. χ_c signals are extracted from a fit with a "Crystal Ball" function, which includes this feature. The parameter that describes the tail is fixed to the value determined from a complete detector simulation[3].

A 4.2% systematic error due to a possible mismatch between the fitting function and the true distribution is estimated from fits to simulated data. An additional systematic error is evaluated by requiring $p^* < 2.0\,\mathrm{GeV}/c$ for the J/ψ candidate. The resulting variation in the signal, 9.3% for e^+e^- and 2.0% for $\mu^+\mu^-$, although not inconsistent with a statistical fluctuation, is taken as a systematic error.

We simultaneously fit for a χ_{c1} and a possible χ_{c2} component. The only additional free parameter is the number of χ_{c2} candidates: the mass difference between the χ_{c2} and the χ_{c1} is fixed to the Particle Data Group value and the resolution and tail parameters are fixed to those of the χ_{c1}[4].

We find $129 \pm 26 \pm 13$ χ_{c1} and 3 ± 21 χ_{c2} events in candidates in which $J/\psi \to e^+e^-$ and $204 \pm 47 \pm 12$ χ_{c1} and 47 ± 21 χ_{c2} in candidates in which $J/\psi \to \mu^+\mu^-$.

5 Calculation of branching fractions

5.1 $B \to J/\psi X$

The number of J/ψ mesons produced in our data sample is related to the number extracted from the fit by a correction for the reconstruction efficiency and by the branching fraction for $J/\psi \to \ell^+\ell^-$. We average the published $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$ branching fractions, assuming a common systematic error, to get $(5.91 \pm 0.10)\%$[4].

A complete detector simulation is used to extract the probability that both leptons are reconstructed as tracks of sufficient quality within the fiducial volume, with a combined mass greater than 2.6 GeV/c^2 (the region used in the fit to the data).

The accuracy of the detector simulation in reproducing tracking efficiency has been studied in $D^0 \to K^-\pi^+\pi^+\pi^-$ decays and in τ pairs in which one τ decays to a single charged track and the other decays to three charged track [1]. From these studies, a uncorrelated systematic error of 2.5% per track is assigned to the overall efficiency.

The probability of the leptons being identified correctly is determined using "control samples"— sets of tracks in which the nature of the particle is known without the use of the particle identification systems. For both electrons and muons, we use lepton pairs and radiative lepton pairs produced in two-photon events. A track is included in the control sample if the kinematics of the event are consistent with expectations and if the other track in the event passes strict particle

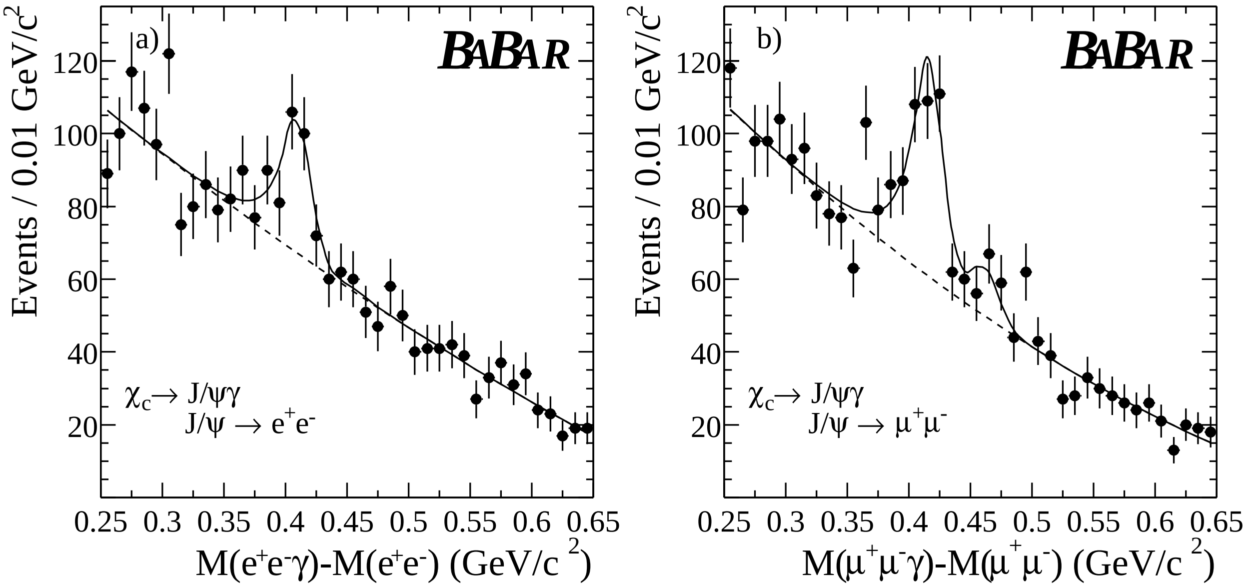

Figure 4: Mass difference between the χ_c and J/ψ candidates, where $\chi_c \to \gamma J/\psi$ and (a) $J/\psi \to e^+e^-$ and (b) $J/\psi \to \mu^+\mu^-$.

identification requirements. The control sample tracks are then used to evaluate the efficiency of the selection criteria as a function of momentum and location in the detector. A value for the branching fraction $B \to J/\psi\ X$ will be determined once this study has been completed.

5.2 $B \to \psi(2S)X$

To minimize systematic errors from tracking and lepton identification, we calculate the ratio of $\psi(2S)$ and J/ψ inclusive branching fractions using the ratio of observed $\psi(2S)$ to J/ψ mesons. For the purposes of this calculation, we refit the J/ψ signal after applying the more stringent particle identification criteria used in reconstructing the $\psi(2S)$. Simulation studies indicate that the probability for the $\psi(2S) \to \ell^+\ell^-$ leptons to be reconstructed and pass the identification criteria is equal to that for the $J/\psi \to \ell^+\ell^-$ decay.

The ratio of $\psi(2S)$ to J/ψ inclusive branching fractions is equal to the ratio of observed mesons, corrected for acceptance, the branching fractions $J/\psi \to \ell^+\ell^-$ and $\psi(2S) \to \ell^+\ell^-$ and a correction for the efficiency of the vertexing requirement. The vertexing efficiency is found by simulation to be 0.941 with a 2% systematic error, which is determined from vertexing studies of the J/ψ.

For the branching fraction of $\psi(2S) \to \ell^+\ell^-$ we average the two Particle Data Group values and obtain $(0.90 \pm 0.12)\%$. This is the dominant systematic error.

The ratio of $\psi(2S)$ to J/ψ inclusive branching fractions is calculated from the $\pi^+\pi^- J/\psi$ final state data in a similar fashion. It is equal to the number of reconstructed $\psi(2S)$ mesons divided by the number of J/ψ mesons reconstructed within the tighter mass windows used in this analysis, with corrections for the pion reconstruction probability, the vertexing efficiency and the $\psi(2S) \to \pi^+\pi^- J/\psi$ branching fraction. The probability for the two pions to be reconstructed within the fiducial requirements and the mass window is 0.524. The efficiency of the requirement for a good vertex is found by simulation to be 0.89 with a 4% systematic error. The uncertainty in the published branching fraction for $\psi(2S) \to \pi^+\pi^- J/\psi$, $(31.0 \pm 2.8)\%$, is the largest component of the systematic error.

The two decay modes give consistent values for the ratio of inclusive branching fractions $\mathcal{B}(B \to \psi(2S)X)/\mathcal{B}(B \to J/\psi X)$ and are combined to give an overall value in Table 1. The ratio is multiplied by the Particle Data Group value for $\mathcal{B}(B \to J/\psi X)$, $(1.15 \pm 0.06)\%$, to obtain the inclusive $\psi(2S)$ branching fraction.

5.3 $B \to \chi_c X$

The ratio of χ_{c1} to J/ψ inclusive branching fractions is computed from the number of reconstructed $\psi(2S)$ mesons divided by the number of J/ψ mesons reconstructed within the tighter mass windows and tighter particle identification criteria used in this analysis, the published $\chi_{c1} \to \gamma J/\psi$ branching fraction, and a correction for the photon reconstruction probability.

The efficiency for the photon reconstruction is calculated from the simulation to be 0.550. A systematic error of 1.6% is obtained by varying the calorimeter simulation resolution and energy scales over bounds determined by studies of π^0 reconstruction. The branching fraction for $\chi_{c1} \to \gamma J/\psi$, $(27.3 \pm 1.6)\%$, contributes a 5.8% systematic error. The systematic errors on the fit have been described earlier.

To obtain a limit on the production of the χ_{c2}, the fit results from Fig. 4 are recast in terms of the ratio of χ_{c2} to J/ψ inclusive branching fractions. The likelihood function for each fit is then normalized to unity for $N_{\chi_{c2}} \geq 0$ and multiplied together to give the combined likelihood. The 90% confidence level is taken to be the ratio of branching fractions that bounds 90% of the area of the likelihood function.

The statistical errors from the fit lead to a 90% confidence limit on $\mathcal{B}(B \to \chi_{c2})/\mathcal{B}(B \to J/\psi)$ of 0.186. However, there is an 8% systematic error in converting the fits into limits on χ_{c2} production due to the uncertainty in the published branching fraction for $\chi_{c2} \to \gamma J/\psi$. We include this uncertainty by increasing the limit by 1.28 times this error, giving a limit of 0.205.

The results for χ_{c1} and χ_{c2} are summarized and presented as inclusive B branching fractions in Table 1.

Table 1: Summary of inclusive B branching ratios measured with respect to $B \to J/\psi X$. The total systematic error in the e^+e^- and $\mu^+\mu^-$ final states is the sum in quadrature of the final-state-specific values and the systematic error common to both. The results are combined and multiplied by the PDG value for $\mathcal{B}(B \to J/\psi X)$ to obtain inclusive branching fractions (%).

	Branching ratio relative to J/ψ							Branching fraction (%)		
	e^+e^-			$\mu^+\mu^-$			Common Sys (%)	Combined		
		Stat	Sys		Stat	Sys			Stat	Sys
$\chi_{c1} \to \gamma J/\psi$	0.28	0.06	0.03	0.38	0.05	0.02	7.3	0.39	0.04	0.04
χ_{c2} 90% CL	0.16			0.28			8.1	0.24		
$\psi(2S) \to \ell^+\ell^-$	0.22	0.05	0.01	0.23	0.04	0.01	13.6	0.26	0.03	0.04
$\psi(2S) \to \pi^+\pi^- J/\psi$	0.18	0.06	0.01	0.22	0.03	0.00	9.9	0.24	0.03	0.03
Combined $\psi(2S)$								0.25	0.02	0.02

6 Summary

The charmonium states J/ψ, $\psi(2S)$ and χ_c have been reconstructed in B meson decays. Preliminary measurements of the ratio of branching fractions $\mathcal{B}(B \to \psi(2S)X)/\mathcal{B}(B \to J/\psi X)$ and $\mathcal{B}(B \to \chi_{c1}X)/\mathcal{B}(B \to J/\psi X)$ have been presented and a limit set on the ratio for χ_{c2}. Using the Particle Data Group value for the inclusive branching fraction for J/ψ, these values have been converted into inclusive B branching fractions.

A direct value for the J/ψ branching fraction will be available upon completion of particle identification studies. Several of these results are statistically limited; more precise values will be available based on data that are currently being recorded. The new data will also permit measurements of the p^* and helicity distributions for these charmonium mesons.

7 Acknowledgments

We are grateful for the contributions of our PEP-II colleagues in achieving the excellent luminosity and machine conditions that have made this work possible. We acknowledge support from the Natural Sciences and Engineering Research Council (Canada), Institute of High Energy Physics (China), Commissariat à l'Energie Atomique and Institut National de Physique Nucléaire et de Physique des Particules (France), Bundesministerium für Bildung und Forschung (Germany), Istituto Nazionale di Fisica Nucleare (Italy), The Research Council of Norway, Ministry of Science and Technology of the Russian Federation, Particle Physics and Astronomy Research Council (United Kingdom), the Department of Energy (US), and the National Science Foundation (US). In addition, individual support has been received from the Swiss National Foundation, the A. P. Sloan Foundation, the Research Corporation, and the Alexander von Humboldt Foundation. The visiting groups wish to thank SLAC for the support and kind hospitality extended to them.

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