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Measurements of Inclusive $B \to \psi$ Production

S. Anderson,[1] V. V. Frolov,[1] Y. Kubota,[1] S. J. Lee,[1] S. Z. Li,[1] R. Poling,[1] A. Smith,[1] C. J. Stepaniak,[1] J. Urheim,[1] Z. Metreveli,[2] K.K. Seth,[2] A. Tomaradze,[2] P. Zweber,[2] S. Ahmed,[3] M. S. Alam,[3] L. Jian,[3] M. Saleem,[3] F. Wappler,[3] E. Eckhart,[4] K. K. Gan,[4] C. Gwon,[4] T. Hart,[4] K. Honscheid,[4] D. Hufnagel,[4] H. Kagan,[4] R. Kass,[4] T. K. Pedlar,[4] J. B. Thayer,[4] E. von Toerne,[4] T. Wilksen,[4] M. M. Zoeller,[4] H. Muramatsu,[5] S. J. Richichi,[5] H. Severini,[5] P. Skubic,[5] S.A. Dytman,[6] J.A. Mueller,[6] S. Nam,[6] V. Savinov,[6] S. Chen,[7] J. W. Hinson,[7] J. Lee,[7] D. H. Miller,[7] V. Pavlunin,[7] E. I. Shibata,[7] I. P. J. Shipsey,[7] D. Cronin-Hennessy,[8] A.L. Lyon,[8] C. S. Park,[8] W. Park,[8] E. H. Thorndike,[8] T. E. Coan,[9] Y. S. Gao,[9] F. Liu,[9] Y. Maravin,[9] I. Narsky,[9] R. Stroynowski,[9] M. Artuso,[10] C. Boulahouache,[10] K. Bukin,[10] E. Dambasuren,[10] K. Khroustalev,[10] G. C. Moneti,[10] R. Mountain,[10] R. Nandakumar,[10] T. Skwarnicki,[10] S. Stone,[10] J.C. Wang,[10] A. H. Mahmood,[11] S. E. Csorna,[12] I. Danko,[12] Z. Xu,[12] G. Bonvicini,[13] D. Cinabro,[13] M. Dubrovin,[13] S. McGee,[13] A. Bornheim,[14] E. Lipeles,[14] S. P. Pappas,[14] A. Shapiro,[14] W. M. Sun,[14] A. J. Weinstein,[14] G. Masek,[15] H. P. Paar,[15] R. Mahapatra,[16] H. N. Nelson,[16] R. A. Briere,[17] G. P. Chen,[17] T. Ferguson,[17] G. Tatishvili,[17] H. Vogel,[17] N. E. Adam,[18] J. P. Alexander,[18] K. Berkelman,[18] F. Blanc,[18] V. Boisvert,[18] D. G. Cassel,[18] P. S. Drell,[18] J. E. Duboscq,[18] K. M. Ecklund,[18] R. Ehrlich,[18] L. Gibbons,[18] B. Gittelman,[18] S. W. Gray,[18] D. L. Hartill,[18] B. K. Heltsley,[18] L. Hsu,[18] C. D. Jones,[18] J. Kandaswamy,[18] D. L. Kreinick,[18] A. Magerkurth,[18] H. Mahlke-Krüger,[18] T. O. Meyer,[18] N. B. Mistry,[18] E. Nordberg,[18] J. R. Patterson,[18] D. Peterson,[18] J. Pivarski,[18] D. Riley,[18] A. J. Sadoff,[18] H. Schwarthoff,[18] M. R. Shepherd,[18] J. G. Thayer,[18] D. Urner,[18] B. Valant-Spaight,[18] G. Viehhauser,[18] A. Warburton,[18] M. Weinberger,[18] S. B. Athar,[19] P. Avery,[19] L. Breva-Newell,[19] V. Potlia,[19] H. Stoeck,[19] J. Yelton,[19] G. Brandenburg,[20] A. Ershov,[20] D. Y.-J. Kim,[20] R. Wilson,[20] K. Benslama,[21] B. I. Eisenstein,[21] J. Ernst,[21] G. D. Gollin,[21] R. M. Hans,[21] I. Karliner,[21] N. Lowrey,[21] M. A. Marsh,[21] C. Plager,[21] C. Sedlack,[21] M. Selen,[21] J. J. Thaler,[21] J. Williams,[21] K. W. Edwards,[22] R. Ammar,[23] D. Besson,[23] and X. Zhao[23]

(CLEO Collaboration)

[1]*University of Minnesota, Minneapolis, Minnesota 55455*
[2]*Northwestern University, Evanston, Illinois 60208*
[3]*State University of New York at Albany, Albany, New York 12222*
[4]*Ohio State University, Columbus, Ohio 43210*
[5]*University of Oklahoma, Norman, Oklahoma 73019*
[6]*University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[7]*Purdue University, West Lafayette, Indiana 47907*
[8]*University of Rochester, Rochester, New York 14627*
[9]*Southern Methodist University, Dallas, Texas 75275*
[10]*Syracuse University, Syracuse, New York 13244*
[11]*University of Texas - Pan American, Edinburg, Texas 78539*
[12]*Vanderbilt University, Nashville, Tennessee 37235*
[13]*Wayne State University, Detroit, Michigan 48202*
[14]*California Institute of Technology, Pasadena, California 91125*

[15]*University of California, San Diego, La Jolla, California 92093*
[16]*University of California, Santa Barbara, California 93106*
[17]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213*
[18]*Cornell University, Ithaca, New York 14853*
[19]*University of Florida, Gainesville, Florida 32611*
[20]*Harvard University, Cambridge, Massachusetts 02138*
[21]*University of Illinois, Urbana-Champaign, Illinois 61801*
[22]*Carleton University, Ottawa, Ontario, Canada K1S 5B6*
and the Institute of Particle Physics, Canada M5S 1A7
[23]*University of Kansas, Lawrence, Kansas 66045*
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Abstract

Using the combined CLEO II and CLEO II.V data sets of 9.1 fb^{-1} at the $\Upsilon(4S)$, we measure properties of ψ mesons produced directly from decays of the B meson, where "B" denotes an admixture of B^+, B^-, B^0, and $\bar{B}^0$, and "ψ" denotes either $J/\psi(1S)$ or $\psi(2S)$. We report first measurements of ψ polarization in $B \to \psi(\text{direct})X$: $\alpha_{\psi(1S)} = -0.30^{+0.07}_{-0.06} \pm 0.04$ and $\alpha_{\psi(2S)} = -0.45^{+0.22}_{-0.19} \pm 0.04$. We also report improved measurements of the momentum distributions of ψ produced directly from B decays, correcting for measurement smearing. Finally, we report measurements of the inclusive branching fraction for $B \to \psi X$ and $B \to \chi_{c1} X$.

Inclusive production of ψ is currently understood in the framework of Non-Relativistic QCD (NRQCD) effective field theory [1]. In 1995, measurements of prompt ψ production at the Tevatron [2, 3] ruled out the then-dominant Color Singlet Model (CSM); in contrast, NRQCD calculations [4] could accommodate the relatively large production rate. However, measurements of the polarization of these prompt ψ [5] deviated from NRQCD calculations at high p_T. The precision of these calculations is limited by the knowledge of the process-independent, long-distance matrix elements (LDME's), which also appear in NRQCD calculations of ψ production in B decays. The polarization of ψ produced from B decays [6, 7] is sensitive to the color-octet LDME's; however, these calculations have been done only to leading order (LO). The momentum distribution of ψ produced in B decays [8–10] is also sensitive to the dominant color octet terms, particularly at low p_ψ. Additionally, the low-momentum region would also be affected by the existence of an intrinsic charm component in B mesons [11]. Finally, the inclusive branching fraction $\mathcal{B}(B \to \psi X)$ [9, 12, 13] constrains a sum of LDME's. This Letter reports measurements of these three properties of ψ production in B decays, which could significantly improve the knowledge of the non-perturbative parameters of NRQCD.

Our analysis [14] is based on 9.7 million $B\overline{B}$ events ($9.1\,\mathrm{fb}^{-1}$) produced on the $\Upsilon(4S)$ resonance. Additionally, $4.4\,\mathrm{fb}^{-1}$ of data collected slightly below the $\Upsilon(4S)$ resonance were used to subtract the small ($\approx 2\%$) contribution of continuum ($e^+e^- \to q\overline{q}, q \in \{u, d, c, s\}$) $\psi(1S)$ production. The e^+e^- collisions were delivered by the Cornell Electron Stoarge Ring (CESR) and detected with two configurations of the CLEO detector, CLEO II [15] and CLEO II.V [16].

We select events that have spherical energy distributions and are likely to be hadronic. We reconstruct ψ candidates in the dilepton modes $\psi \to \mu^+\mu^-$ and $\psi \to e^+(\gamma)e^-(\gamma)$. The selection criteria were chosen with a goal of high detection efficiency. In the di-muon channel, at least one of the muon candidates must penetrate at least 3 interaction lengths into the iron of the solenoid return yoke; if only one candidate satisfies this, then the other candidate must leave a shower in the crystal calorimeter which is consistent with that of a minimum ionizing particle. In the di-electron channel, we use shower information from the crystal calorimeter and measurements of specific ionization from the drift chamber to identify electron candidates. We also attempt to recover up to one Bremsstrahlung photon for each electron candidate. To do this, we select the most collinear shower within a five-degree cone around the initial electron direction; furthermore, the shower must not be associated with any track, and, when combined with any other shower in the event, must not result in an invariant mass consistent with a π^0. The PDG 2001 [17] branching fractions are used to combine results from the electron and muon channels, except for $\mathcal{B}(\psi(2S) \to \mu^+\mu^-)$, which we assume by lepton universality to be equal to $\mathcal{B}(\psi(2S) \to e^+e^-)$, with an uncertainty of 20% of itself; this is consistent with recent measurements [18].

About 30% of $\psi(1S)$ from B decays have intermediate parents of $\psi(2S)$ or χ_{c1} [17]. Our measurements of directly produced $\psi(1S)$ are obtained by subtracting the contributions of these "feed-down" $\psi(1S)$ from the inclusive $\psi(1S)$ sample. For every event with a $\psi(1S)$ candidate within $^{+25}_{-50}$ MeV of the nominal mass, we search for these intermediate parents through the decay chains $\chi_{c1} \to \psi(1S)\gamma$ and $\psi(2S) \to \psi(1S)\pi^+\pi^-$. We reconstruct $(M_{\ell^+\ell^-\pi^+\pi^-} - M_{\ell^+\ell^-})$ and $(M_{\ell^+\ell^-\gamma} - M_{\ell^+\ell^-})$, which have better resolution than the reconstructed $\psi(2S)$ and χ_{c1} invariant masses themselves. In the $\psi(2S) \to \psi(1S)\pi^+\pi^-$ decay chain, we reduce low-momentum pion background by requiring $M_{\pi^+\pi^-} > 0.45$ GeV, which has a efficiency of about 85%, from Monte Carlo simulation. This decay mode is also used to improve the statistics in our measurements of the inclusive branching fraction and the $\psi(2S)$ momentum distribution in $B \to \psi(2S)X$. We do not reconstruct the related decay $\psi(2S) \to \psi(1S)\pi^0\pi^0$, and argue that the properties of $\psi(1S)$ from this decay are identical to those of $\psi(1S)$ from $\psi(2S) \to \psi(1S)\pi^+\pi^-$; the kinematic difference in the momentum distribution is small compared to the experimental resolution, and the isospin state of the $\pi\pi$ state has no bearing on the polarization of the $\psi(1S)$.

The CLEO Monte Carlo simulation, based on GEANT [19], is used to obtain the invariant mass lineshape for signal events and to estimate the detection efficiency. In these simulated signal events, one of the B mesons decays via one of the decay chains listed above. For each decay chain, we generate two samples of events; one with all ψ longitudinally polarized, the other with all ψ transversely polarized. We find that the detection efficiency varies slightly as a function of ψ momentum and polarization.

The procedure and results for the inclusive branching fraction and momentum distribution measurements are as follows. We divide the data into partitions in p_ψ, the momentum of the ψ candidate, using a binsize of 0.1 GeV/c. For each partition, the invariant mass distribution of ψ candidates is fit to a sum of a signal lineshape, obtained from the Monte Carlo simulation, and a cubic polynomial background. The average χ^2 of the fits is consistent with the number of degrees of freedom, thus justifying our choice of the above parametrization. We repeat this procedure using signal Monte Carlo events, binning in generated ψ momentum, to obtain detection efficiencies as a function of p_ψ. The data is then corrected for detection efficiency bin by bin; this minimizes the effect of any discrepancy between the true p_ψ distribution and that generated by the Monte Carlo simulation. Similarly, we fit the invariant mass distributions of $(M_{\ell^+\ell^-\pi^+\pi^-} - M_{\ell^+\ell^-})$ and $(M_{\ell^+\ell^-\gamma} - M_{\ell^+\ell^-})$, to extract efficiency-corrected yields of feed-down $\psi(1S)$. We thus obtain momentum distributions of $\psi(1S)$ and $\psi(2S)$ which have been corrected for detection efficiency, $\psi(1S)$ feed-down, and continuum background. The yields are then normalized by $n_B \times \mathcal{B}(\psi \to \ell^+\ell^-(\pi^+\pi^-))$, where n_B is the number of B and $\overline{B}$ mesons in the data; the uncertainties in these quantities are reflected in our results as an overall scale factor error. Inclusive branching fractions are obtained by summing the normalized momentum distributions over all bins. Finally, the Monte Carlo simulation is used to obtain a matrix which correlates the momentum of the ψ as generated to the momentum as measured; by inverting this matrix and applying it to the observed momentum distribution, we are able to deconvolve the effects of detector measurement smearing from the distribution.

We investigate the possible sources of systematic error; for each source, we make an appropriate modification to the measurement procedure and observe the deviation of the resulting yield relative to the nominal procedure. The deviations are then combined to obtain final systematic errors. The sources of error are grouped as follows: (1) Monte Carlo simulation of track and shower finding, electron and muon identification, ψ polarization, global event and kinematic cuts, (2) invariant mass fit procedure; (3) branching fractions of unmeasured modes; and (4) overall scale factor.

The results for the inclusive branching fractions are given in Table I and the momentum distributions are shown in Figure 1. Our branching fraction results are consistent with previous published measurements [20] as well as preliminary measurements [21], and are limited by systematic errors. The combined error for $\mathcal{B}(B \to \psi(1S)(\text{direct})X)$ is smaller than the error of the PDG 2001 average [17] by a factor of two. However, the theoretical uncertainties in the NRQCD calculations of the branching fractions are such that the improved accuracy of this measurement is unlikely to further constrain the NRQCD LDME's. The momentum distributions reported here are the first to subtract the *measured* distributions of feed-down and continuum ψ, correct for detector measurement smearing, and analyze systematic errors for each bin individually. Figure 1(b) is also the first to show the momentum distribution of multibody ($\geq$ 3-body) decays in $B \to \psi(2S)X$ production; these decays account for much of the total $B \to \psi(2S)X$ production, as is also the case with $B \to \psi(1S)X$ [9]. It should be possible to update previous phenomenological studies of the ψ momentum distribution with these improved measurements.

Decay	Branching Fraction (%)
$B \to \psi(1S)X$	$1.121 \pm 0.013 \pm 0.040 \pm 0.013$
$B \to \psi(1S)(\text{direct})X$	$0.813 \pm 0.017 \pm 0.036 \pm 0.010$
$B \to \chi_{c1}X \to \psi(1S)X$	$0.119 \pm 0.008 \pm 0.009 \pm 0.001$
$B \to \chi_{c1}X$	$0.435 \pm 0.029 \pm 0.031 \pm 0.026$
$B \to \psi(2S)X \to \psi(1S)X$	$0.189 \pm 0.010 \pm 0.018 \pm 0.002$
$B \to \psi(2S)X$	$0.316 \pm 0.014 \pm 0.023 \pm 0.016$

TABLE I: Inclusive branching fraction results. The errors shown are (in order) statistical, systematic, and due to an overall scale factor uncertainty.

The polarization parameter α is equal to ($+1$, 0, -1) for a population of (transversely, randomly, longitudinally) polarized ψ. For $\psi \to \ell^+\ell^-$ decays, it is determined experimentally by measuring the decay angle θ, which is defined as the angle between the ℓ^+ direction in the ψ rest frame and the ψ direction in the B rest frame. The $\cos\theta$ distribution for a population of ψ is proportional to $(1 + \alpha\cos^2\theta)$. The angular distribution is obtained in a similar manner as the momentum distributions: the dataset is partitioned into 5 equal bins in $\cos\theta$ between -1 and 1; for each partition, we fit the invariant mass distribution to find the signal yield. In addition to measuring the polarization of direct $\psi(1S)$ and $\psi(2S)$ for all momenta, we also extract $\alpha_{\psi(1S)}$ in 3 coarse momentum bins.

At CLEO, B mesons are produced with a small boost in the $\Upsilon(4S)$ (lab) frame, the direction of which is unknown. The boost of the B results in a smeared measurement of $\cos\theta$; directly fitting for α using the measured $\cos\theta$ distribution would yield a biased result. However, this kinematic smearing is accurately modeled by the Monte Carlo simulation. Our procedure is to generate Monte Carlo events in two sets; one with all ψ generated longitudinally, the other with all transverse. The measured $\cos\theta$ distribution from the data is then fit to a sum of the reconstructed $\cos\theta$ distributions from the polarized Monte Carlo sets. This procedure correctly accounts for both the boost smearing and detection efficiency. Since the efficiency also depends on p_ψ, we must ensure that the Monte Carlo distributions of generated p_ψ match those of Figure 1; this is accomplished through a rejection technique. Because the observed $\cos\theta$ distributions are not directly corrected for detection efficiency, the observed feed-down distributions are corrected only for the efficiency of detecting the additional particles needed to reconstruct the $\psi(2S)$ or χ_{c1}. The final feed-down and continuum-subtracted angular distributions are shown in Figure 2. The systematic error study included the previously mentioned sources of bias; additionally, we have investigated the possible systematic error arising for the methods for feed-down subtraction and fitting for α.

The final polarization results are listed in Table II; these are the first results for the polarization of $\psi(1S)$ and $\psi(2S)$ from $B \to \psi(\text{direct})X$. For comparison, we measure $\alpha = -0.35 \pm 0.03$ (statistical error only) for $\psi(1S)$ from $B \to \psi(1S)(\text{all})X$. Our result

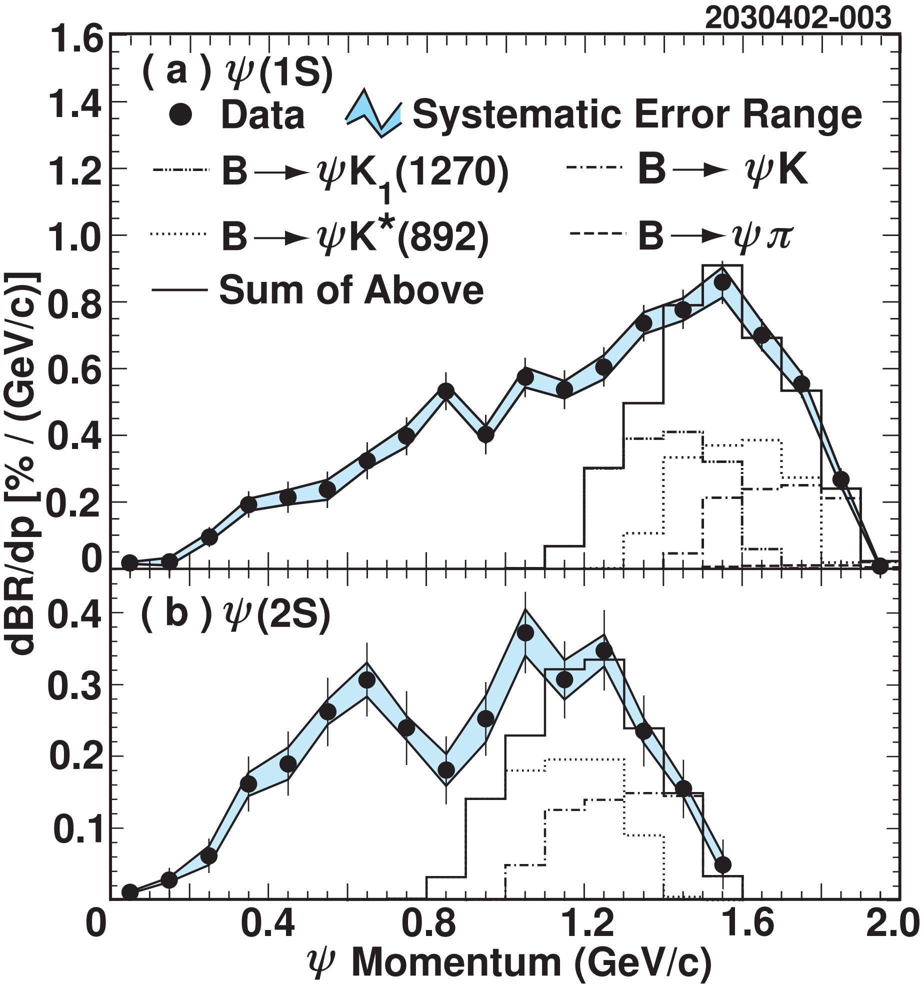

FIG. 1: Momentum distributions of (a) $\psi(1S)$ and (b) $\psi(2S)$ produced directly from B decays. There is an additional overall scale uncertainty of 1.2% for $\psi(1S)$ and 5.1% for $\psi(2S)$ which is not depicted in the plots. The histograms show the contributions of two-body $B \to \psi X$ decays, where the lineshapes are obtained from Monte Carlo simulation and the normalizations are from previous determinations of exclusive branching fractions [17, 22, 23].

for $\alpha_{\psi(1S)}$ is about 4 standard deviations from zero; this measurement therefore strongly disfavors the color evaporation model of charmonium production [24], which predicts zero net polarization, independent of the production mechanism. When next-to-leading-order calculations become available, these results also have the potential to significantly constrain the long-distance matrix elements of NRQCD.

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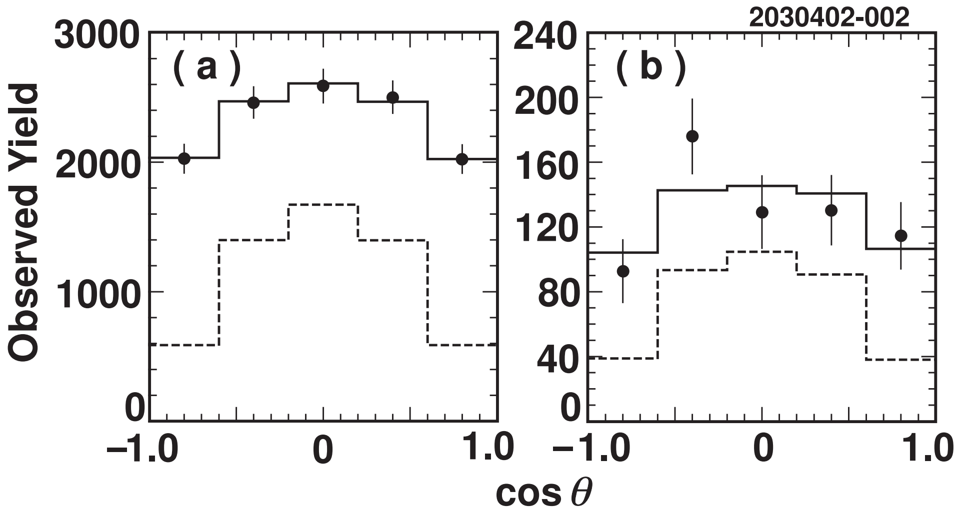

FIG. 2: Decay angle distributions of (a) $\psi(1S)$ and (b) $\psi(2S)$ from $B \to \psi(\text{direct})X$, summed over all p_ψ. The points represent the data, showing 1σ statistical errors. In both figures, the fit result (solid histogram) is the sum of a longitudinal component (dashed histogram) and a transverse component.

ψ Meson	p_ψ (GeV/c)	α
$\psi(1S)$	$0.0 - 2.0$	$-0.30^{+0.07}_{-0.06}\pm0.04$
$\psi(2S)$	$0.0 - 1.6$	$-0.45^{+0.22}_{-0.19}\pm0.04$
$\psi(1S)$	$0.0 - 0.8$	$+0.32^{+0.33}_{-0.27}\pm0.15$
$\psi(1S)$	$0.8 - 1.4$	$-0.37^{+0.09}_{-0.09}\pm0.04$
$\psi(1S)$	$1.4 - 2.0$	$-0.52^{+0.08}_{-0.07}\pm0.03$

TABLE II: Polarization of $\psi(1S)$ and $\psi(2S)$ from $B \to \psi(\text{direct})X$ over the full momentum range (top two values) and for $\psi(1S)$ in three momentum ranges. The errors are statistical and systematic.

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