Measurement of J/ψ and $\psi(2S)$ polarization in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV

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Abstract

We have measured the polarization of J/ψ and $\psi(2S)$ mesons produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, using data collected at CDF during 1992-95. The polarization of promptly produced J/ψ [$\psi(2S)$] mesons is isolated from those produced in B-hadron decay, and measured over the kinematic range $4[5.5] < P_T < 20$ GeV/c and $|y| < 0.6$. For $P_T \gtrsim 12$ GeV/c we do not observe significant polarization in the prompt component.

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The production of heavy quarkonia states, $c\bar{c}$ and $b\bar{b}$, provides a useful system for the study of Quantum Chromodynamics (QCD), as it involves both perturbative and nonperturbative energy scales. In $p\bar{p}$ collisions, charmonium production occurs through three mechanisms: direct production, the decay of heavier charmonia, and the decay of b-flavored hadrons. The first two mechanisms are collectively known as "prompt" because they are observed to occur at the $p\bar{p}$ interaction point.

The Collider Detector at Fermilab (CDF) collaboration previously reported results on the production of J/ψ and $\psi(2S)$ mesons [1,2]. The measured cross sections for direct production were on the order of 50 times larger than predicted by the Color Singlet Model (CSM) [3]. However, calculations based on the Nonrelativistic QCD (NRQCD) factorization formalism [4,5] are able to account for the observed cross sections by including color octet production mechanisms. This leads to the prediction that directly produced ψ mesons will be increasingly transversely polarized at high P_T [5–7]. (In this Letter we use ψ to denote either J/ψ or $\psi(2S)$ mesons.) This is because the production of ψ mesons with $P_T \gg M_\psi$ is dominated by gluon fragmentation. It is predicted that the gluon's transverse polarization is preserved as the $c\bar{c}$ pair evolves into a bound state ψ meson. On the other hand, the Color Evaporation Model predicts an absence of polarization [8]. In this Letter, we report on measurements of the polarization of promptly produced ψ mesons at CDF. Our analysis also yields as a byproduct the effective polarization of the ψ mesons produced in B-hadron decays.

CDF is a multi-purpose detector designed to study high energy $p\bar{p}$ collisions produced by the Tevatron [9]. The CDF coordinate system is defined with the z axis along the proton beam direction. The polar angle θ is defined relative to the z axis, r is the perpendicular radius from this axis, and ϕ is the azimuthal angle. Pseudorapidity is defined as $\eta \equiv -\ln[\tan(\theta/2)]$. Three charged-particle tracking detectors immersed in a 1.4 T solenoidal magnetic field surround the beamline. This tracking system is contained within a calorimeter, while drift chambers outside the calorimeter identify muon candidates.

The innermost tracking device is a four-layer silicon microstrip detector (SVX) located at radii between 2.9 and 7.9 cm from the beam axis. The SVX is surrounded by a set of time projection chambers (VTX) extending out to a radius of 22 cm. An 84 layer cylindrical drift chamber (CTC) measures the particle trajectories in the region between 30 and 132 cm from the beam. This tracking system has high efficiency for detecting charged particles with momentum transverse to the beam $P_T > 0.4$ GeV/c and $|\eta| \lesssim 1.1$. Together, the CTC and SVX measure charged particle transverse momenta with a precision of $\sigma_{P_T}/P_T = 0.007 \oplus 0.001 \cdot P_T$ (with P_T in GeV/c). The impact parameter resolution is $\sigma_d = (13 + 40/P_T)$ μm for tracks with SVX and CTC information.

The central muon detection system consists of four layers of planar drift chambers separated from the interaction point by five interaction lengths of material. This system detects muons with $P_T \gtrsim 1.4$ GeV/c and $|\eta| \lesssim 0.6$. Dimuon candidates used in this analysis are collected using a three-level $\mu^+\mu^-$ trigger. The first level trigger requires that two candidates be observed in the muon chambers. For each muon candidate the first level trigger efficiency rises from $\sim$40% at $P_T = 1.5$ GeV/c to $\sim$93% for muons with $P_T > 3.0$ GeV/c. The second level trigger requires one or more charged particle tracks in the CTC, reconstructed using the central fast track processor (CFT). The CFT performs a partial reconstruction of all charged tracks with P_T above $\sim$2 GeV/c. Muon candidates found by the first level trigger are required to match a CFT track within 15 degrees in azimuth. The third level trigger performs three-dimensional track reconstruction and accepts dimuon masses in a broad window around the J/ψ and $\psi(2S)$ masses.

The data used in this study correspond to an integrated luminosity of 110 pb^{-1} and were collected between 1992 and 1995. Following the online data collection, additional requirements are made offline to identify the signals and to reduce the backgrounds. To identify muon candidates and reduce the rate from sources such as π/K meson decay-in-flight, we require that each track observed in the muon chambers be associated with a matching CTC track. These matches are required to pass a maximum χ^2 cut of 9 and 12 (for 1 degree of freedom) in the ϕ and z views respectively. Also, we require P_T greater than about 2 GeV/c for each muon candidate. This requirement ensures that the muon trigger and reconstruction efficiencies are well understood, to avoid biases in the decay angular distributions of the charmonia states studied below.

The measurement of the polarization of ψ mesons is made by analyzing their decays to $\mu^+\mu^-$ in the helicity basis, in which the spin quantization axis lies along the ψ direction in the $p\bar{p}$ center-of-mass (lab) frame. We define θ^* as the angle between the μ^+ direction in the ψ rest frame and the ψ direction in the lab frame. The normalized angular distribution $I(\cos\theta^*)$ is given by

$$I(\cos\theta^*) = \frac{3}{2(\alpha+3)}(1+\alpha\ \cos^2\theta^*) \qquad (1)$$

Unpolarized ψ mesons have $\alpha = 0$ whereas $\alpha = +1$ or -1 correspond to fully transverse or longitudinal polarizations respectively. Experimentally, the acceptance is severely reduced as $|\cos\theta^*|$ approaches 1, due to the P_T cuts on the muons. Our method for determining α is to fit the observed distributions of $\cos\theta^*$ to distributions derived from simulated $\psi \to \mu^+\mu^-$ decays. The Monte Carlo simulation accounts for the geometric and kinematic acceptance of the detector as well as the reconstruction efficiency as a function of $\cos\theta^*$.

In order to extract the polarization parameter α for promptly produced ψ mesons, we separate the prompt component from the B-decay component using the proper decay length of each event. For ψ candidates with one or both muons reconstructed in the SVX (the SVX sample), we define a vector pointing from the $p\bar{p}$ collision point to the ψ decay vertex. The transverse decay length L_{xy} is then defined as the projection of this vector onto the ψ transverse momentum. The proper decay length ct is related to the transverse decay length by $ct = (M_\psi L_{xy})/(F^\psi_{corr} P^\psi_T)$, where M_ψ is the ψ mass. Here F^ψ_{corr} is a correction factor obtained from Monte Carlo studies [10], which accounts for the fact that we are using the ψ P_T instead of the B-hadron P_T. Prompt events have ct consistent with zero whereas B-decays have an exponential ct distribution; the detector resolution smears the ct distribution. We fit the ct distribution to obtain the relative fractions of prompt and B-decay production. Details of this fitting procedure are given in [10]. The measured fraction of J/ψ mesons which come from B-hadron decay increases from $(13.0 \pm 0.3)\%$ at $P_T^{J/\psi} = 4$ GeV/c

to $(40 \pm 2)\%$ at 20 GeV/c. For $\psi(2S)$ mesons, an increase from $(21 \pm 2)\%$ to $(35 \pm 4)\%$ is seen in the range from 5.5 to 20 GeV/c.

The proper decay length measurement allows us to divide the data into two samples: a short-lived sample dominated by prompt production, and a long-lived sample dominated by B-decays. The short-lived sample is defined by $-0.1 \leq ct \leq 0.013[0.01]$ cm, and the long-lived sample by $0.013[0.01] \leq ct \leq 0.3$ cm, for the J/ψ [$\psi(2S)$] analysis respectively. The boundary between the two ct regions has been optimized separately for the J/ψ and $\psi(2S)$ samples, to maximize the purity of prompt decays in the short-lived sample and B-decays in the long-lived sample. Depending on P_T^{ψ}, the prompt fraction in the short-lived sample ranges from 85%[86%] to 96%[95%], and the B-decay fraction in the long-lived sample ranges from 83%[86%] to 98%[91%], for $J/\psi[\psi(2S)]$ respectively.

The J/ψ polarization is measured in seven P_T bins, covering a range of $4 - 20$ GeV/c. Using a 3 standard deviation mass window around the J/ψ peak, our data sample consists of 180,000 signal J/ψ events, with a signal to background ratio of about 13. The J/ψ sample is divided into three subsamples: the short-lived and long-lived SVX samples described above, and a third sample (the CTC sample) in which neither muon has SVX information and no ct measurement is made. In each $P_T^{J/\psi}$ bin, we measure the prompt polarization (α_P) and the effective polarization of J/ψ mesons from B-hadron decays (α_B). (We refer to α_B as "effective" because θ^* is defined using the lab frame, not the B-hadron rest frame — in effect this dilutes any polarization from the B-decay toward zero.) We find that it is not feasible to make separate polarization measurements for direct J/ψ production and for production from χ_c and $\psi(2S)$ decays. The latter sources account for 36$\pm$6% of the prompt component, with only a small $P_T^{J/\psi}$ dependence [2].

The J/ψ polarization is measured by fitting $\cos\theta^*$ distributions in data to a set of Monte Carlo templates [11]. The templates are generated by processing simulated samples of $J/\psi \to \mu^+\mu^-$ decays with a detector and trigger simulation. The polarization is obtained using a χ^2 fit of the data to a weighted sum of transversely polarized and longitudinally polarized templates. The fitted weights yield the polarization. Two transverse/longitudinal template pairs are generated, using measured prompt and B-decay $P_T^{J/\psi}$ spectra [1]. The $\cos\theta^*$ distribution of background events is modeled in the fit using sidebands around the J/ψ mass peak. The fit is performed simultaneously on the SVX short-lived, SVX long-lived and CTC samples, with two fit parameters: α_P and α_B. To account for the mixture of prompt and B-decay components in each sample, the relative fractions of prompt and B-decay templates in each are fixed in the fit using the results of the lifetime fit. The B-decay fraction in the CTC sample is assumed to be the same as in the SVX sample, because the two samples differ primarily in the z position of the primary vertex. Within each $P_T^{J/\psi}$ bin, a small correction is applied to the $P_T^{J/\psi}$ distributions of the Monte Carlo samples so that they match with those in the data. As an example, the fit in the P_T range 12-15 GeV/c is shown in Fig. 1.

Three sources of systematic uncertainty are evaluated: the trigger efficiency, the fitted prompt and B-decay fractions, and the $P_T^{J/\psi}$ spectra used in making the Monte Carlo templates. Except in the lowest P_T bins, the systematic uncertainties are much smaller than the statistical uncertainties. Our fit results are listed in Table I, and α_P is compared with a theoretical NRQCD prediction [7] in Fig. 2.

The measurement of the $\psi(2S)$ polarization is made in three P_T bins covering $5.5-20.0$ GeV/c. Both muons are required to be reconstructed in the SVX. The resulting dimuon mass distribution is fitted with a Gaussian signal and a linear background. We find a total of 1855 ± 65 signal $\psi(2S)$ events, with a signal to background ratio of about 1 in a 3 standard deviation mass window around the $\psi(2S)$ mass.

As discussed above, the sample in each P_T bin is further divided into two subsamples based on the ct distribution. Because the statistics are lower than in the J/ψ case, we use 10 bins in $|\cos\theta^*|$. The number of signal events in each $|\cos\theta^*|$ bin is obtained by fitting its mass distribution. The resulting $|\cos\theta^*|$ distributions in the two ct subsamples are fitted simultaneously to the predicted number of events to extract the $\psi(2S)$ polarizations for prompt and B-decay production. The number of predicted events in each $|\cos\theta^*|$ bin is derived by weighting the normalized angular distribution $I(\cos\theta^*)$ with the detector acceptance [12]. We use the measured prompt and B-decay $P_T^{\psi(2S)}$ distributions [1] to calculate the acceptance. As in the J/ψ case, there is a small correlation between the measured $P_T^{\psi(2S)}$ distributions and the polarization. A correction is applied iteratively in the fits to account for this dependence. Figure 3 shows the observed angular distributions with their polarization fits for the short-lived sample in the three $P_T^{\psi(2S)}$ bins.

Three sources of systematic uncertainty are considered: the uncertainty in the event yield from the mass fits in the $|\cos\theta^*|$ bins, the uncertainty due to the error on the fitted prompt and B-decay fractions, and the uncertainty on the $|\cos\theta^*|$ acceptance from the Monte Carlo modeling of the $P_T^{\psi(2S)}$ distributions. The uncertainty due to the trigger efficiency is negligible in the $P_T^{\psi(2S)}$ range used. The systematic uncertainties are much smaller than the statistical uncertainties. The fitted values of α_P and α_B as a function of $P_T^{\psi(2S)}$ are listed in Table II, and α_P is shown in Fig. 2 with the NRQCD predictions [6,7].

In conclusion, we have measured the polarization of J/ψ and $\psi(2S)$ mesons produced in 1.8 TeV $p\bar{p}$ collisions. The polarization from B-decays is generally consistent with zero, as expected. In both the J/ψ and $\psi(2S)$ cases, we do not observe increasing prompt transverse polarization at $P_T \gtrsim 12$ GeV/c. Our measurements are limited by statistics, especially for the $\psi(2S)$, but they appear to indicate that no large transverse prompt polarization is present at high P_T, in disagreement with NRQCD factorization predictions.

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REFERENCES

[1] F. Abe *et al.* (The CDF Collaboration), Phys. Rev. Lett. **79**, 572 (1997).

[2] F. Abe *et al.* (The CDF Collaboration), Phys. Rev. Lett. **79**, 578 (1997).

[3] M. Cacciari and M. Greco, Phys. Rev. Lett. **73**, 1586 (1994); E. Braaten *et al.*, Phys. Lett. **B 333**, 548 (1994); D.P. Roy and K. Sridhar, Phys. Lett. **B 339**, 141 (1994).

[4] G. Bodwin, E. Braaten and G. Lepage, Phys. Rev. D **51**, 1125 (1995) (Erratum *ibid.* **55**, 5853 (1997)) ; E. Braaten and S. Fleming, Phys. Rev. Lett. **74**, 3327 (1995); M. Cacciari *et al.*, Phys. Lett. **B 356**, 553 (1995); E. Braaten and Y. Chen, Phys. Rev. D **54**, 3216 (1996); P. Cho and A.K. Leibovich, Phys. Rev. D **53**, 150 (1996), *ibid.* **53**, 6203 (1996).

[5] P. Cho and M. Wise, Phys. Lett. **B 346**, 129 (1995).

[6] M. Beneke and M. Krämer, Phys. Rev. D **55**, 5269 (1997).

[7] E. Braaten, B. Kniehl and J. Lee, hep-ph/9911436.

[8] J. Amundson *et al.*, Phys. Lett. **B 390**, 323 (1997).

[9] F. Abe *et al.* (The CDF Collaboration), Nucl. Instrum. Methods Phys. Res. **A 271**, 387 (1988); F. Abe *et al.* (The CDF Collaboration), Phys. Rev. D **52**, 4784 (1995); P. Azzi *et al.*, Nucl. Instrum. Methods Phys. Res. **A 360**, 137 (1995).

[10] F. Abe *et al.* (The CDF Collaboration), Phys. Rev. D **57**, 5382 (1998).

[11] R. Cropp, Ph.D. thesis, University of Toronto, 2000.

[12] C.-Y. P. Ngan, Ph.D. thesis, M.I.T., 2000.

TABLES

TABLE I. Fit results for J/ψ polarization, with statistical and systematic uncertainties.

P_T bin (GeV/c)	Mean P_T (GeV/c)	α_P	α_B
$4-5$	4.5	$0.30 \pm 0.12 \pm 0.12$	$-0.49 \pm 0.41 \pm 0.13$
$5-6$	5.5	$0.01 \pm 0.10 \pm 0.07$	$-0.18 \pm 0.33 \pm 0.07$
$6-8$	6.9	$0.178 \pm 0.072 \pm 0.036$	$0.10 \pm 0.20 \pm 0.04$
$8-10$	8.8	$0.323 \pm 0.094 \pm 0.019$	$-0.06 \pm 0.20 \pm 0.02$
$10-12$	10.8	$0.26 \pm 0.14 \pm 0.02$	$-0.19 \pm 0.23 \pm 0.02$
$12-15$	13.2	$0.11 \pm 0.17 \pm 0.01$	$0.11 \pm^{0.31}_{0.28} \pm 0.02$
$15-20$	16.7	$-0.29 \pm 0.23 \pm 0.03$	$-0.16 \pm^{0.38}_{0.33} \pm 0.05$

TABLE II. Fit results for $\psi(2S)$ polarization, with statistical and systematic uncertainties.

P_T bin (GeV/c)	Mean P_T (GeV/c)	α_P	α_B
$5.5-7.0$	6.2	$-0.08 \pm 0.63 \pm 0.02$	$-0.26 \pm 1.26 \pm 0.04$
$7.0-9.0$	7.9	$0.50 \pm 0.76 \pm 0.04$	$-1.68 \pm 0.55 \pm 0.12$
$9.0-20.0$	11.6	$-0.54 \pm 0.48 \pm 0.04$	$0.27 \pm 0.81 \pm 0.06$

FIGURES

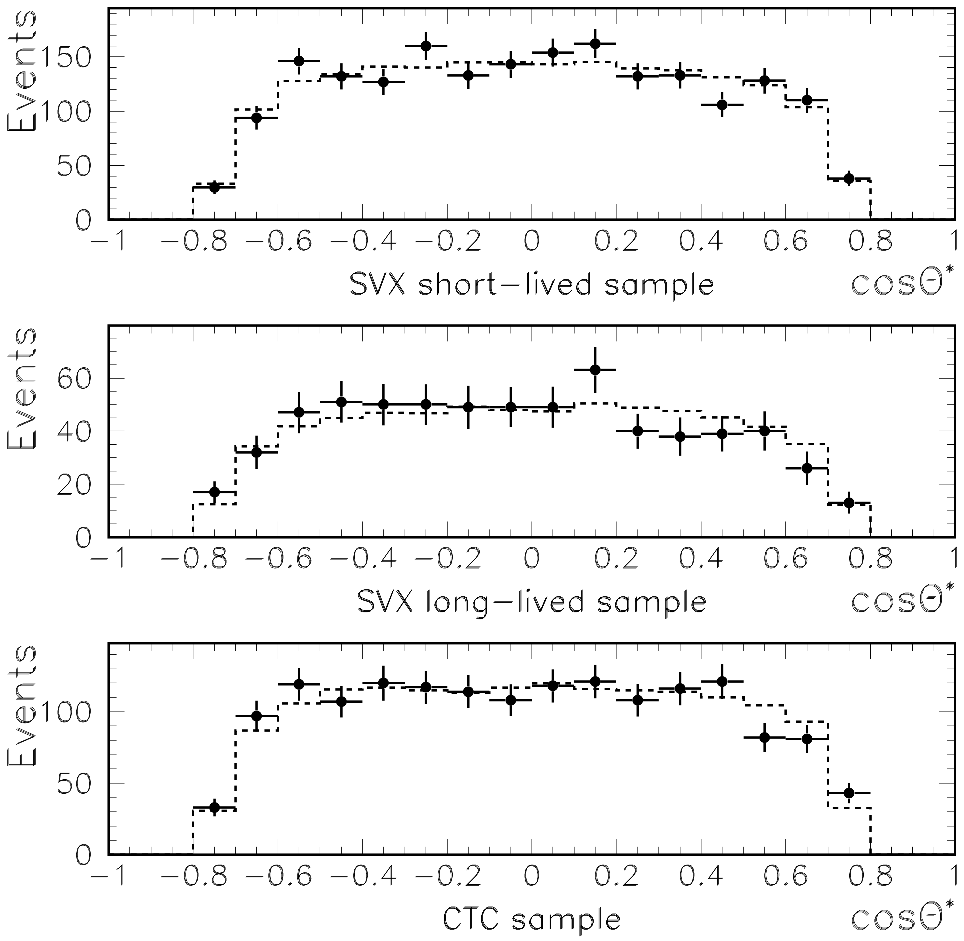

FIG. 1. The J/ψ polarization fit to $\cos\theta^*$ distributions in the 12-15 GeV/c bin. Points: sideband-subtracted data in the SVX short-lived, SVX long-lived and CTC samples. Dashed lines: fit.

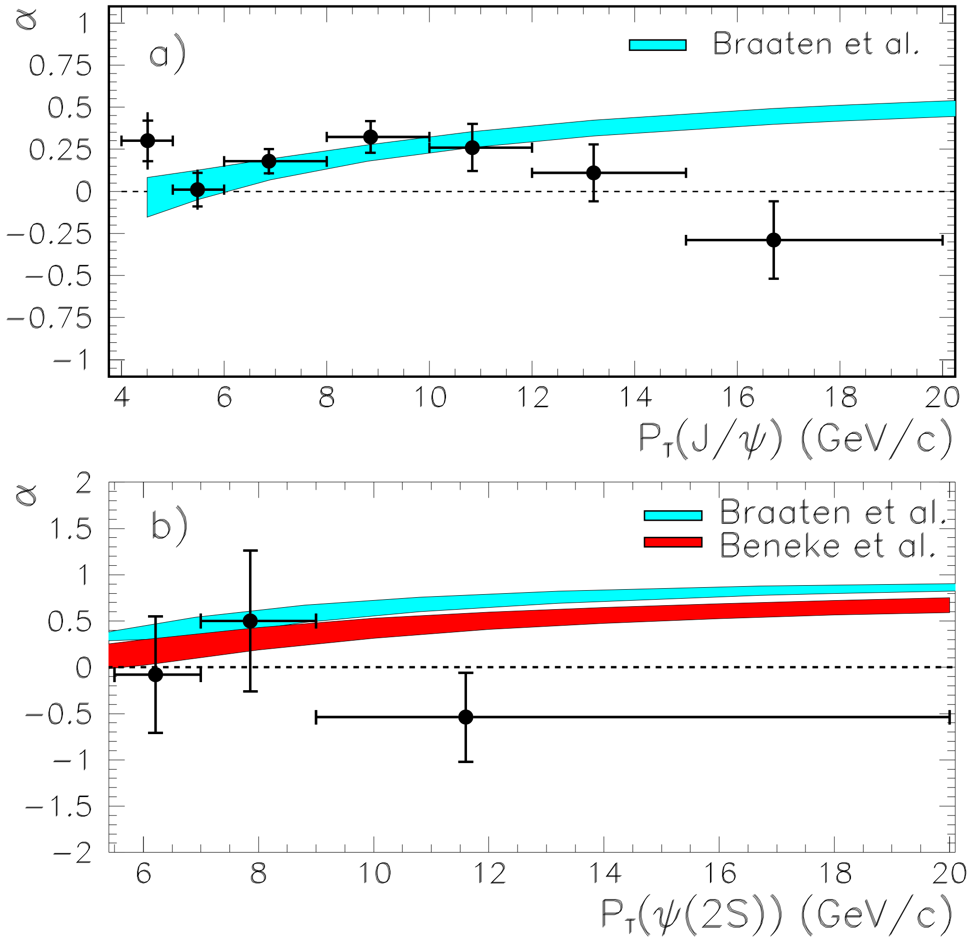

FIG. 2. (a) The fitted polarization of prompt J/ψ mesons for $|y^{J/\psi}| < 0.6$. Full error bars denote statistical and systematic uncertainties added in quadrature; ticks denote statistical errors alone. The shaded band shows an NRQCD factorization prediction [7] which includes the contribution from χ_c and $\psi(2S)$ decays. (b) The fitted polarization of prompt $\psi(2S)$ mesons for $|y^{\psi(2S)}| < 0.6$. Error bars denote statistical and systematic uncertainties added in quadrature. Shaded bands show two NRQCD factorization predictions [6,7].

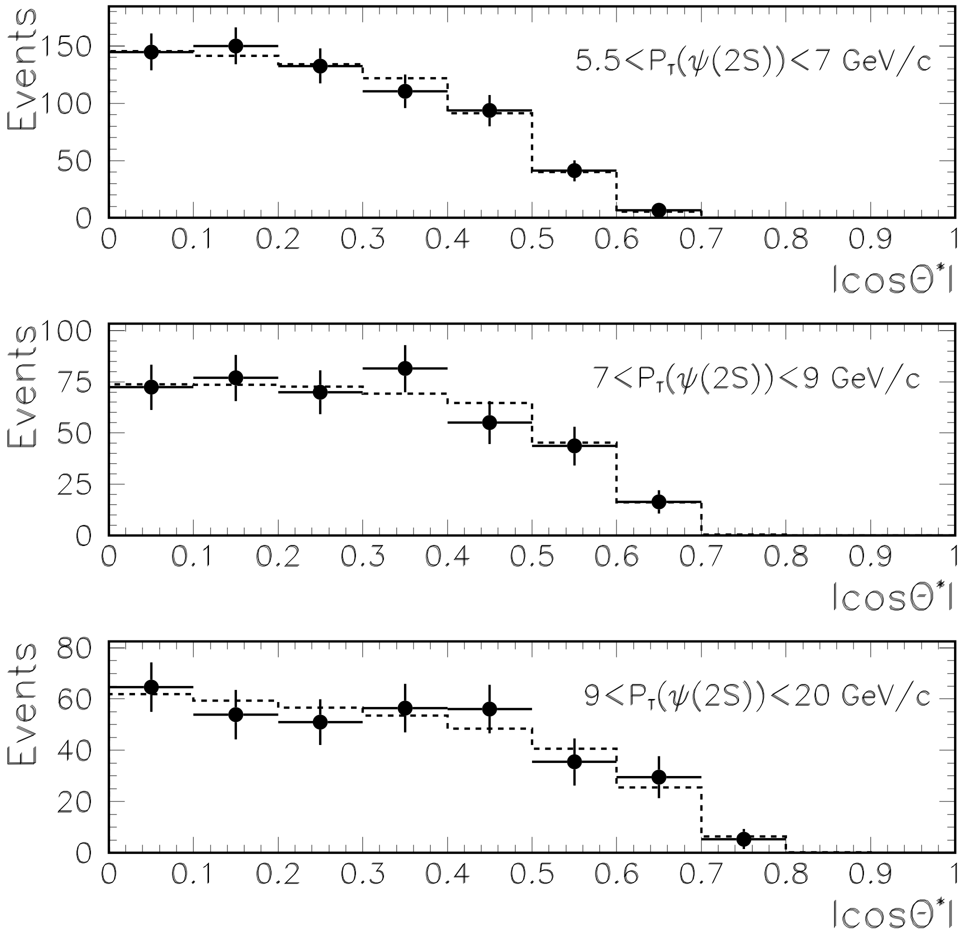

FIG. 3. Fits to $|\cos\theta^*|$ distributions in the short-lived $\psi(2S)$ data sample, in the three P_T bins. Points: data, dashed lines: fit. The acceptance extends further out in $|\cos\theta^*|$ as P_T increases.