Measurement of the Polarization of the $\Upsilon(1S)$ and $\Upsilon(2S)$ States in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We present a study of the polarization of the $\Upsilon(1S)$ and $\Upsilon(2S)$ states using a 1.3 fb^{-1} data sample collected by the D0 experiment in 2002–2006 during run II of the Fermilab Tevatron Collider. We measure the polarization parameter $\alpha = (\sigma_T - 2\sigma_L)/(\sigma_T + 2\sigma_L)$, where σ_T and σ_L are the transversely and longitudinally polarized components of the production cross section, as a function of the transverse momentum (p_T^{Υ}) for the $\Upsilon(1S)$ and $\Upsilon(2S)$. Significant p_T^{Υ}-dependent longitudinal polarization is observed for the $\Upsilon(1S)$. A comparison with theoretical models is presented.

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The production of heavy quarks and quarkonium states at high energies is under intense experimental and theoretical study [1]. The nonrelativistic QCD (NRQCD) factorization approach has been developed to describe the inclusive production and decay of quarkonia [2] including high transverse momentum (p_T) S-wave charmonium production at the Fermilab Tevatron Collider [3]. The theory introduces several nonperturbative color-octet matrix elements (MEs). These MEs are universal and are fitted to data of the Fermilab Tevatron Collider [4]. The universality of the MEs has been tested in various experimental situations [5]. A remarkable prediction of the NRQCD approach is that the S-wave quarkonium produced in the $p\bar{p}$ collision should be transversely polarized at sufficiently large p_T [6]. This prediction is based on the dominance of gluon fragmentation in quarkonium production at large p_T [6] and on the approximate heavy-quark spin symmetry of NRQCD [2]. Measurements of the polarization of prompt J/ψ by the CDF Collaboration do not confirm this prediction [7].

A convenient measure of the polarization is the variable

$$\alpha = (\sigma_T - 2\sigma_L)/(\sigma_T + 2\sigma_L), \quad (1)$$

where σ_T and σ_L are the transversely and longitudinally polarized components of the production cross section. If we consider the decays of quarkonium to a charged lepton-antilepton pair, then the angular distribution is given by

$$\frac{dN}{d(\cos\theta^*)} \propto 1 + \alpha\cos^2\theta^*, \quad (2)$$

where θ^* is the angle of the positive lepton in the quarkonium center-of-mass frame with respect to the momentum of the decaying particle in the laboratory frame.

Quantitative calculations of the polarization for inclusive $\Upsilon(nS)$ mesons are carried out [8] by using the ME for direct bottomonium production determined from an analysis of Tevatron data [9]. They predict that the transverse polarization of $\Upsilon(1S)$ should dominate and increase steadily with p_T^Υ for $p_T^\Upsilon \gtrsim 10$ GeV/c and that the $\Upsilon(2S)$ and $\Upsilon(3S)$ should be even more strongly transversely polarized. The k_t-factorization model [10], using a semihard approach, predicts a longitudinal polarization of $\Upsilon(1S)$ at $p_T^\Upsilon > 5$ GeV/c [11]. In this context, the experimental measurement of the Υ polarization is a crucial test of two theoretical approaches to parton dynamics in QCD.

The D0 detector is described in detail elsewhere [12]. The main elements relevant to this analysis are a central-tracking system, consisting of a silicon microstrip tracker (SMT), a central fiber tracker (CFT), and muon detector systems.

The data set used for this analysis includes approximately 1.3 fb^{-1} of integrated luminosity collected by the D0 detector between April 2002 and the end of 2006. We selected events where the $\Upsilon(nS)$ decayed into two muons. Muons were required to have hits in three muon layers, to have an associated track in the central tracking system with hits in both the SMT and CFT, and to have transverse momentum $p_T^\mu > 3.5$ GeV/c. In this analysis, only events that passed a dimuon trigger, which requires two opposite charge muon candidates, were included in the final sample. We observed about 260 000 $\Upsilon(nS)$ with rapidity $|y^\Upsilon| < 1.8$ when fitting the dimuon invariant mass distribution as described below.

Monte Carlo (MC) samples for unpolarized $\Upsilon(1S)$ and $\Upsilon(2S)$ inclusive production were generated using the PYTHIA [13] event generator and then passed through a GEANT-based [14] simulation of the D0 detector. The simulated events were then required to satisfy the same selection criteria as the data sample including a detailed simulation of all aspects of the trigger requirements.

We fitted the dimuon invariant mass distribution in several intervals of p_T^Υ for a set of $|\cos\theta^*|$ bins. A previous measurement of the $\Upsilon(1S)$ cross section by the D0 experiment [15] showed that a double Gaussian function is required to model the mass distribution of the $\Upsilon(1S)$ candidates. Studies performed on the $\Upsilon(1S)$ Monte Carlo sample suggest that a more sophisticated parameterization of the invariant mass distribution for some $|\cos\theta^*|$ bins, where we observe non-Gaussian tails, is required. Two different parameterizations of the mass distribution were used, referred to as "data-driven" and "MC-driven" functions. The data-driven function has the advantage that no assumptions are made about how well the MC-driven function reproduces the true resolution. It consists of a double Gaussian function with equal means. The mean, widths, and relative fraction are free parameters. In contrast, the MC-driven function allows for a test of the effect of non-Gaussian components to the resolution that are observable in MC calculations but are hidden in data by the detector resolution and the combinatoric background. Non-Gaussian tails are implemented via a third Gaussian component with a floating mean to account for an asymmetric tail in the reconstructed $\Upsilon(nS)$ mass. The width and relative fraction are taken from Monte Carlo calculations. Figure 1 shows an example of a fit to the mass distribution for a single p_T^Υ and $|\cos\theta^*|$ bin ignoring or including non-Gaussian tails. The signal consists of three mass peaks, the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ where the mass differences were fixed to the measured values [16]. The background was modeled with a convolution of an exponential and a polynomial function. The degree of the polynomial was chosen to be between one and six depending on the complexity of the shape of the background. The χ^2 values in Fig. 1 do not allow us to differentiate between the two approximations, and hence we average them.

The data were divided into bins in p_T^Υ and $|\cos\theta^*|$. For each of these bins, the numbers of $\Upsilon(1S)$ and $\Upsilon(2S)$ candidates were extracted from the mass distribution. The number of $\Upsilon(3S)$ candidates was insufficient to extract angular distributions.

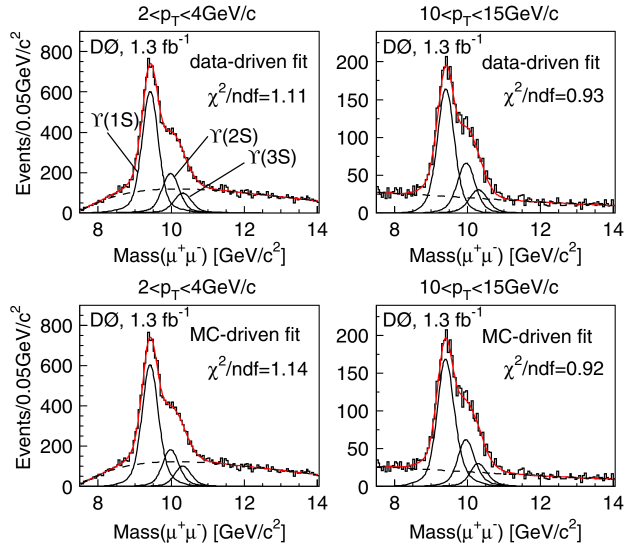

FIG. 1 (color online). Signal extraction from the dimuon invariant mass distribution for events in the $0.4 < |\cos\theta^*| < 0.5$ region. (a), (c) $2 < p_T^{\Upsilon} < 4$ GeV/c; (b), (d) $10 < p_T^{\Upsilon} < 15$ GeV/c. Dashed curves are the combinatoric background.

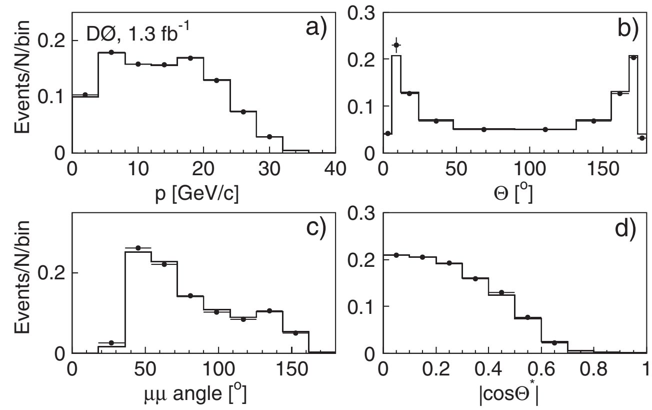

FIG. 3. Comparison of data (points) and Monte Carlo (solid histogram) for $\Upsilon(1S)$ with $2 < p_T^{\Upsilon} < 4$ GeV/c: (a) momentum of $\Upsilon(1S)$, (b) polar angle of $\Upsilon(1S)$, (c) angle between muons, (d) $|\cos\theta^*|$.

Polarization was not taken into account in the Monte Carlo generation. To compare them with data, we calculated for each event the weight w_α, which converts the initial Monte Carlo $|\cos\theta^*|$ distribution with $\alpha = 0$ to a distribution with the chosen α. Figure 2 shows the sensitivity of the D0 detector to the $\Upsilon(1S)$ polarization for the lowest and highest $p_T^{\Upsilon(nS)}$ intervals. The PYTHIA simulation does not accurately model the kinematic distributions of $\Upsilon(nS)$ production at the Tevatron (e.g., the $p_T^{\Upsilon(nS)}$ distribution). To correct the Monte Carlo distributions, we introduced additional weights to improve the agreement with data of the $\Upsilon(nS)$ momentum distribution. Instead of the weight w_α in our algorithm, we used the weight $w = w_\alpha w_{p_T^\Upsilon} w_{p^\Upsilon}$, where $w_{p_T^\Upsilon}$ and w_{p^Υ} are weights to achieve agreement between data and Monte Carlo distributions of p_T^Υ and p^Υ. After this reweighting procedure, we obtained good agreement between data and MC calculations for the $\Upsilon(nS)$ and muon kinematic distributions. An example for $\Upsilon(1S)$ with $2 < p_T^{\Upsilon} < 4$ GeV/c, using the MC-driven fit, is presented in Fig. 3. All data distributions were derived by estimating the number of $\Upsilon(1S)$ events from a fit to the dimuon mass distribution for the corresponding bin of the histogram.

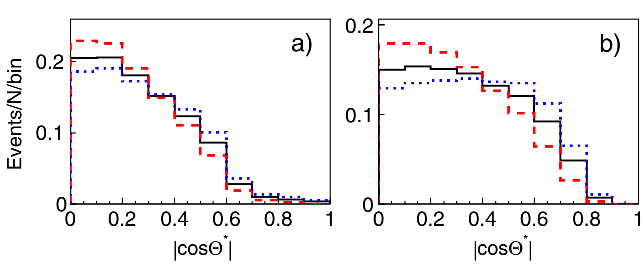

FIG. 2 (color online). Monte Carlo $|\cos\theta^*|$ distributions after all selection requirements for different α values: -1 (dashed histogram), 0 (solid histogram), and $+1$ (dotted histogram). (a) $0 < p_T^{\Upsilon} < 1$ GeV/c, (b) $p_T^{\Upsilon} > 15$ GeV/c.

The systematic uncertainties on α for $\Upsilon(1S)$ are summarized in Table I. Values of α were found for several p_T^Υ intervals, using both parameterizations (data-driven and MC-driven) of the dimuon invariant mass distribution for the signal. Both α measurements are averaged, and one half of the difference between them is assigned as systematic uncertainty due to the signal model. The uncertainty in the background was estimated by varying the mass range of the fit and the degree of the polynomial used to parameterize the background. The MC simulation does not reproduce exactly the mass of the $\Upsilon(1S)$ peak, which differs by about 40 MeV/c^2 from the PDG value. The effect on the α determination was estimated and shown in Table I under "muon momentum." Finally, the systematic uncertainty due to the trigger simulation has also been considered and shown in Table I. The $\Upsilon(1S)$ polarization was calculated assuming that it is constant within a given p_T^Υ bin. This assumption leads to a small bias in the measured α that is estimated by reweighting the simulation using the observed p_T^Υ dependence of α. The final measured α is

TABLE I. Systematic uncertainties on α for $\Upsilon(1S)$.

Source	Uncertainty on α [a]	p_T^Υ [b] [GeV/c]
Signal model	0.01–0.15	1–2
Background model	0.04–0.21	0–1
Muon momentum	0.00–0.06	0–1
Trigger simulation	0.00–0.06	>15

[a]For all p_T^Υ intervals.
[b]Interval with maximal uncertainty.

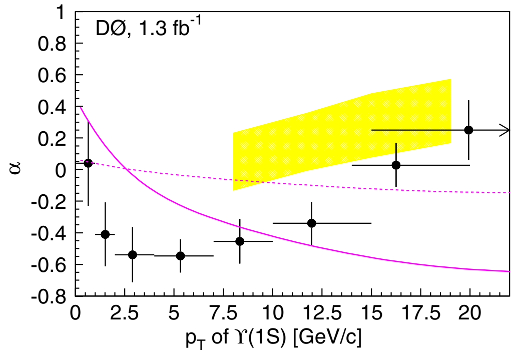

FIG. 4 (color online). Dependence of α on p_T^{Υ} for inclusive $\Upsilon(1S)$ candidates. Black circles are data. The band is the NRQCD prediction [15]. Curves are two limiting cases (see text) of the k_t-factorization model [11].

corrected by a factor ranging between -0.03 and $+0.06$, depending on p_T^{Υ}.

Figure 4 shows the measured α as a function of p_T^{Υ} for $\Upsilon(1S)$. Note that the bin for 14–20 GeV is not statistically independent from the adjacent bins. The arrow indicates that the highest p_T^{Υ} interval considered, $p_T^{\Upsilon} > 15$ GeV$/c$, does not have an upper limit. The uncertainties are the systematic and statistical uncertainties added in quadrature. Also shown are the NRQCD prediction [8] (yellow band), and the two limits of the k_t-factorization model [11] (curves). The lower line corresponds to the quark-spin conservation hypothesis, and the upper one to the full quark-spin depolarization hypothesis. The previous measurement by CDF of the polarization of $\Upsilon(1S)$ with rapidity $|y^{\Upsilon}| < 0.4$ is consistent with α equal to zero [17]. We expect the CDF and D0 results to be similar, and we have no explanation for the observed difference. We also extracted the polarization of the $\Upsilon(2S)$, which is shown in Fig. 5 along with the NRQCD predictions [8]. Values of α for statistically independent p_T^{Υ} intervals, shown in Figs. 4 and 5, are given in Table II.

In conclusion, we have presented measurements of the polarization of the $\Upsilon(1S)$ and $\Upsilon(2S)$ as functions of p_T^{Υ}

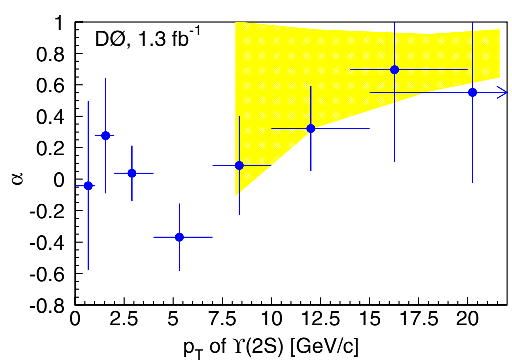

FIG. 5 (color online). Dependence of α on p_T^{Υ} for inclusive $\Upsilon(2S)$ production. Circles are our data. The band is the NRQCD prediction [8].

TABLE II. Measurements of α for $\Upsilon(1S)$ and $\Upsilon(1S)$.

p_T^{Υ} [GeV/c]	$\alpha[\Upsilon(1S)]$	$\alpha[\Upsilon(2S)]$
0–1	0.04 ± 0.27	-0.04 ± 0.54
1–2	-0.41 ± 0.20	0.28 ± 0.37
2–4	-0.54 ± 0.17	0.04 ± 0.18
4–7	-0.55 ± 0.10	-0.37 ± 0.21
7–10	-0.45 ± 0.14	0.09 ± 0.32
10–15	-0.34 ± 0.14	0.32 ± 0.27
>15	0.25 ± 0.19	0.55 ± 0.58

from 0 GeV$/c$ to 20 GeV$/c$. Significant p_T-dependent longitudinal polarization is observed for the $\Upsilon(1S)$ inconsistent with NRQCD predictions. At $p_T^{\Upsilon} > 7$ GeV$/c$, the fraction of transversely polarized $\Upsilon(2S)$ particles is higher than in $\Upsilon(1S)$ at the same value of p_T^{Υ}, in agreement with NRQCD predictions.

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