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We present measurements of Υ(1S) polarization using 2.9 fb^{-1} of data obtained by the CDF II detector at the Tevatron. The analysis is performed on Υ mesons having rapidity |y| < 0.6 and $2 < p_T \leq 40$ GeV/c via the decay channel $\Upsilon(1S) \rightarrow \mu^+\mu^-$. Employing a template method, we observe a longitudinal polarization at high pT.

I. INTRODUCTION

Vector meson production and polarization in hadronic collisions is usually discussed within the framework of non-relativistic QCD (NRQCD), following the Tevatron Run I observations of surprisingly large production cross sections for all three vector mesons J/ψ, ψ(2S), and Υ. This theoretical framework separates the heavy flavor production into a perturbative short-distance process to produce the $Q\overline{Q}$ pair times a long-distance matrix element to create the vector meson (or, more generally, any quarkonium state). The short-distance process can include color-octet $Q\overline{Q}$ contributions as well as color singlet configurations because the long-distance matrix elements can absorb soft gluon emission terms. This *factorization* hypothesis lies at the core of the NRQCD analysis [2]. The long-distance part is expanded in powers of the heavy quark velocities, using the vacuum expectation values of appropriate 4-fermion operators with parametrized coefficients. These coefficients are *universal* in that they are the same for all quarkonium states. Fixing them from data in one process leads to predictions valid in all other quarkonium production processes.

Using the degrees of freedom available in the parametrization, NRQCD modelers can fit the Tevatron production cross sections for the three vector mesons [3, 5]. However, the theory predicts that the vector meson polarization should become transverse in the perturbative regime, i.e., at large transverse momentum p_T of the vector meson. Recent CDF measurements of polarization for J/ψ and ψ(2S) do not support this prediction [6, 10]. Other measurements, e.g., the fixed-target production ratio for the p-wave states χ_1/χ_2 do not match NRQCD predictions well. Some theorists have proposed a different NRQCD expansion for c-quark states and b-quark states [7]. The NRQCD predictions for Υ polarization for Tevatron Run I from Braaten and Lee [9] are shown in Figure 3.

A. Υ Spin Alignment and Decay Angular Distributions

This analysis, like all proton collider polarization analyses to date, uses a quantization axis defined in the s-channel helicity frame. In this frame, the quantization axis is defined as the negative of the boost direction that takes the Υ from the laboratory frame to its rest frame, i.e,. the negative of the Υ direction in the lab. In the rest frame of the Υ meson, the μ^+ makes an angle θ^* with respect to the Υ direction in the lab frame. The angular distribution depends on the polarization parameter α, which lies in the interval -1 to 1:

$$\frac{d\,\Gamma}{d\cos\theta^*} \propto\ 1 + \alpha\cos^2\theta^*. \tag{1}$$

If the Υ meson is fully polarized in the transverse direction, $\alpha = 1$. If it is fully aligned longitudinally, $\alpha = -1$. In our later discussion we use a related alignment parameter η that measures the fraction of longitudinal alignment. The two parameters are simply related:

$$\eta = \frac{1-\alpha}{3+\alpha} \quad (0 \le \eta \le 1). \tag{2}$$

II. DATA SAMPLE & EVENT SELECTION

This analysis uses data taken with the CDF detector from February 2002 to April 2006, comprising 2.9 fb^{-1} of data. The CDF detector is described in detail in [1]. Only data from runs that satisfy the standard CDF requirements for good detector performance are used.

Events are taken from a dimuon trigger path which requires a pair of oppositely-charged muons with $p_T \ge 3GeV/c$. As an additional requirement, one of the muons has to have $p_T \ge 4GeV/c$. This analysis is based on dimuon events in the central region $\eta < 0.6$. Muons in more forward regions are not used. In offline reconstruction for both data and Monte Carlo we confirm the trigger selection and impose additional cuts on the dimuon vertex probability, the number of drift chamber hits, and the axial (z) position of the two muons.

For the analysis we use a signal region based upon a fit of the Monte Carlo mass peak, accepting events within 2.5σ from the center of the peak. The background in the signal region is estimated from the upper and lower mass sidebands, which are weighted by the exponential shape of the mass background distribution.

III. POLARIZATION FITTER

The apparatus acceptance and trigger conditions restrict the decay phase space of the $\Upsilon(1S)$ and so affect the determination of the polarization. We utilize a template method to correct for the apparatus effects in measuring the polarization of the Υ. Monte Carlo samples of $\Upsilon(1S) \to \mu^+\mu^-$ decays are generated with fully-transverse and fully-longitudinal polarizations, using the EvtGen software package. These events are passed through the CDF GEANT simulation package, a simulated trigger and then the reconstruction package. The resulting templates, originally generated flat in $p_T(\Upsilon)$, are weighted to match the p_T distribution of the data. After applying simulated trigger conditions and offline software cuts, using muon trigger efficiencies as determined from data, we obtain template files representing fully-polarized decay samples as they would appear in the CDF detector.

The polarization is measured in each of eight Υp_T bins ranging from $2-40 GeV/c$. To determine the Υ polarization in a given p_T bin, we make an angular distribution of the events in the Υ mass peak, working in the s-channel helicity frame. Because of the limited statistics for Υ production at high p_T, we exploit the parity-conserving nature of the decay to fold the muon decay angle distribution about $\cos\theta^* = 0$, then divide the interval (0,1) into ten equal bins. The signal region has both signal and background events from the $\Upsilon(1S)$ mass peak region. The input background angular distribution is made using events in the mass sidebands. The χ^2 fitter chooses the best value of the polarization parameter by matching the signal $\cos\theta^*$ distribution to the polarization-weighted sum of the T and L $\cos\theta^*$ distributions and simultaneously recomputes the background in each $\cos\theta^*$ bin to minimize the total χ^2. This same fitter was used for the Run I polarization analyses and the Run II J/ψ and $\psi(2S)$ polarization studies.

IV. SYSTEMATIC UNCERTAINTIES

The polarization is determined by the muon angular distribution. Anything which affects the yield as a function of angle in the Υ rest frame can generate a systematic uncertainty. We have considered several potential sources of systematic error. The muon efficiency function used on Monte Carlo has some systematic uncertainty associated with it. We check for a resulting change in acceptance as a function of $\cos\theta^*$ by varying the muon efficiency function by $\pm 1\sigma_{syst}$. In doing so, we see changes in the η as large as 0.003. We conservatively assign this as the systematic uncertainty to every bin.

A number of potential sources showed negligible effect on the polarization when evaluated. Changing the mass parametrization or signal range or changing the minimum muon p_T cut had no discernable effect within our statistical precision. Therefore, we assign no systematic uncertainty from this source.

We also varied the Υp_T re-weighting procedure, using weights calculated from fits of data as well as weighting directly to the data itself. The difference in polarization from the two methods is negligible.

The polarization could also be sensitive to $\cos\theta^*$ bin width and resolution. The standard analysis uses $\cos\theta^*$ bins of width 0.1, which simulation shows is far larger than the worst-case resolution. We also checked this experimentally by redoing the analysis in $\cos\theta^*$ bins of 0.05. The polarization did not change outside the range of statistical fluctuations. We also confirmed by Monte Carlo studies that the p_T resolution is good enough over the entire p_T range that there is no effect from p_T bin migration.

V. RESULTS

The results of the fit are listed in Table I and show nearly-unpolarized events at lower $p_T(\Upsilon)$, consistent with the CDF Run I result [11]. At higher p_T, the results tend toward longitudinal polarization. These results are compared with NRQCD predictions and with the Run I result in Figures 3 and 2, respectively. These results do not agree with a recent D0 measurement of the $\Upsilon(1S)$ polarization [12].

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Υ(1S) Polarization			
$p_T(\Upsilon)[GeV/c]$	Data Yield	Background	η
2-3	17316 ± 294	11147 ± 172	0.332 ± 0.020($stat$) ± 0.003($syst$)
3-4	16819 ± 283	9819 ± 161	0.317 ± 0.019($stat$) ± 0.003($syst$)
4-6	22012 ± 312	10636 ± 168	0.315 ± 0.019($stat$) ± 0.003($syst$)
6-8	11291 ± 217	4300 ± 107	0.326 ± 0.032($stat$) ± 0.003($syst$)
8-12	9846 ± 197	3104 ± 91	0.351 ± 0.038($stat$) ± 0.003($syst$)
12-17	3740 ± 117	1035 ± 53	0.290 ± 0.058($stat$) ± 0.003($syst$)
17-23	1182 ± 71	372 ± 32	0.586 ± 0.126($stat$) ± 0.003($syst$)
23-40	430 ± 47	208 ± 23	0.685 ± 0.229($stat$) ± 0.003($syst$)

TABLE I: Measured yields and polarization parameters for Υ(1S)

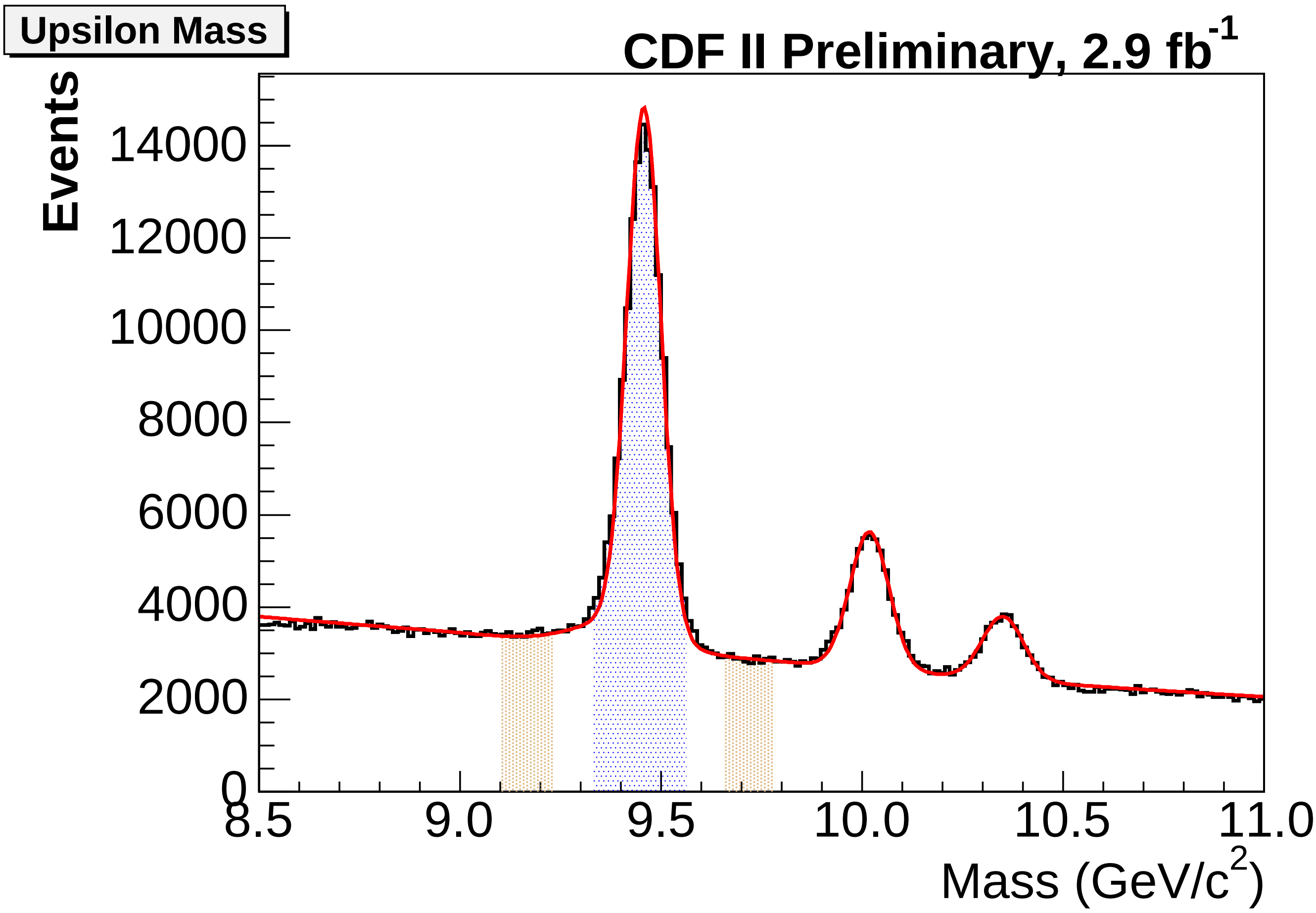

FIG. 1: Mass distribution in the Υ(nS) region. Signal and sideband regions are shaded.

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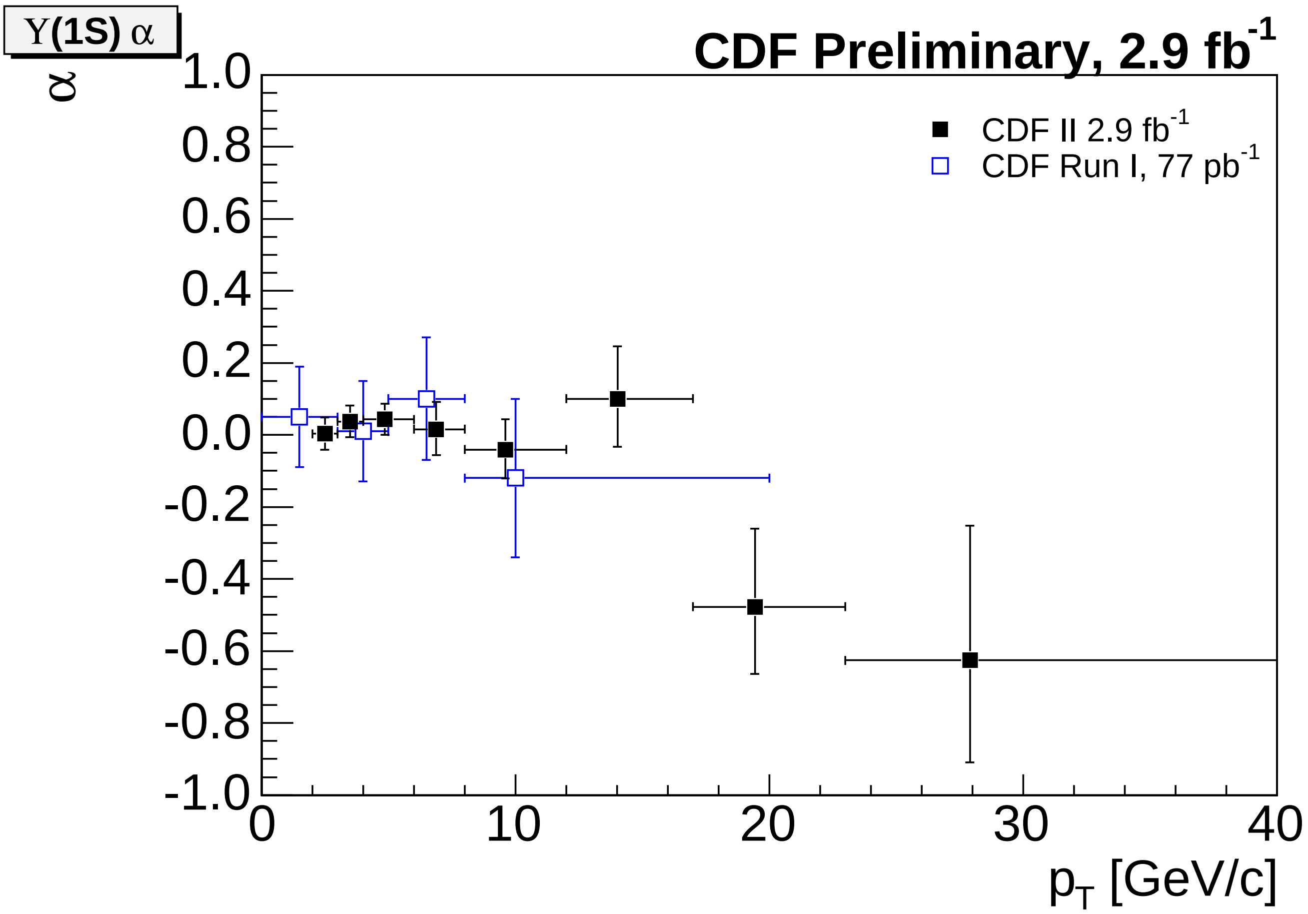

FIG. 2: Υ(1S) polarization results agree well with the CDF Run I measurement.

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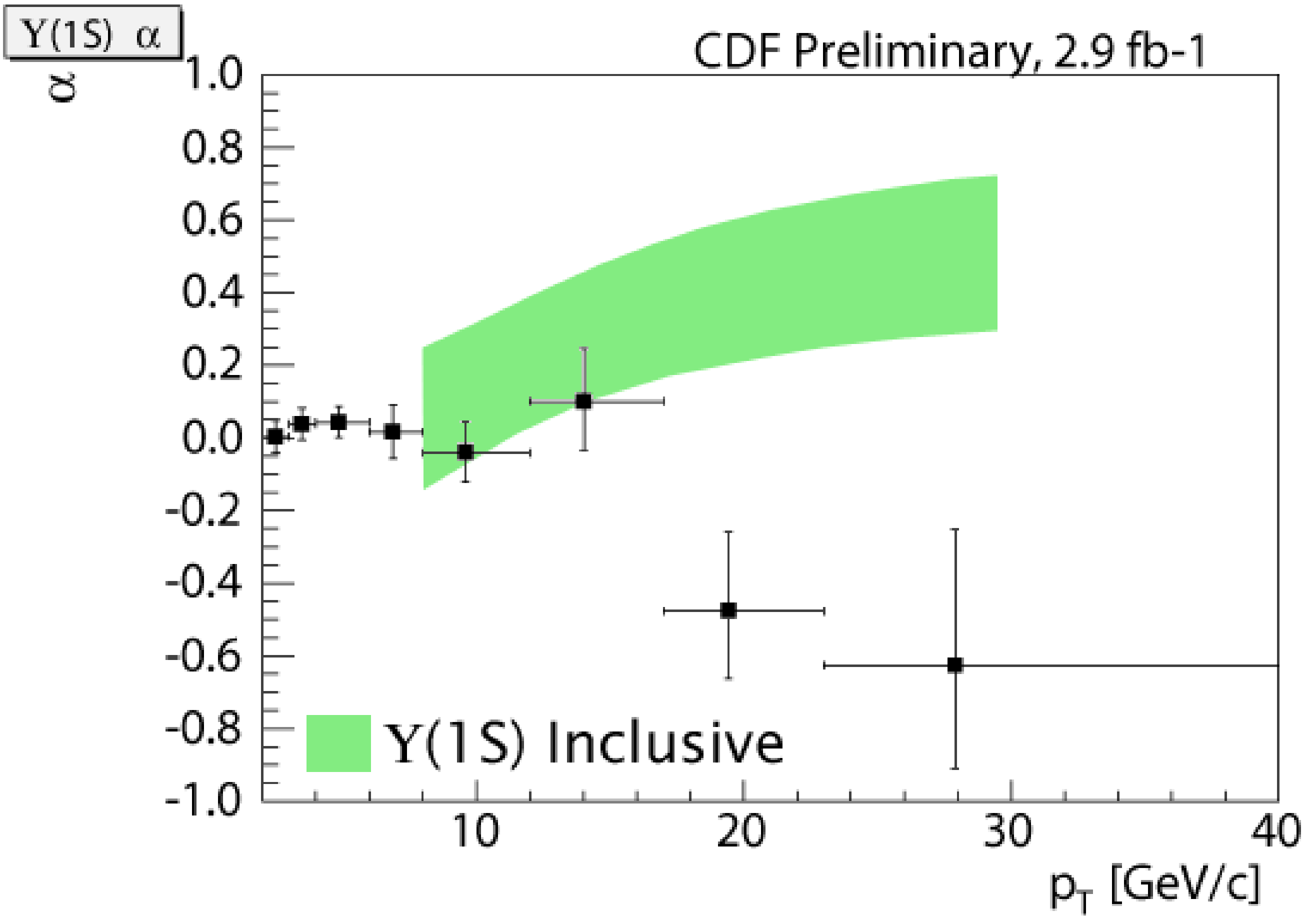

FIG. 3: Υ(1S) polarization results, overlaid with NRQCD predictions.