PROCEEDINGS OF SCIENCE

Upsilon Polarization Measurements

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Hadroproduction of heavy quarkonia remains poorly understood. Measurements of the polarization in $\Upsilon \to \mu^+\mu^-$ are essential to validating theoretical models. Results from the CDF and DØ experiments at the Tevatron are presented corresponding to $2.9\,\mathrm{fb}^{-1}$ and $1.3\,\mathrm{fb}^{-1}$, respectively, of $p\bar{p}$ collisions at $\sqrt{s} = 1.96\,\mathrm{TeV}$. The results are inconsistent both with each other and available theories.

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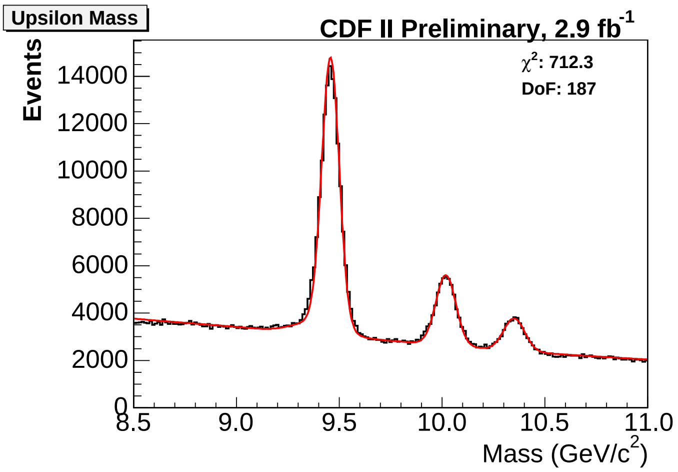

Figure 1: Fit of the mass distribution for the yields of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ decays to muon pairs in CDF.

Hadroproduction of heavy quarkonia continues to be incompletely understood. In the simplest models, production is suppressed by a mechanism much like the OZI rule in reverse where a $b\bar{b}$ ($c\bar{c}$) can yield the colorless, odd-parity final state Υ (ψ) meson only via the interaction of three gluons. Thus when early CDF measurements [1] showed large cross sections for J/ψ and ψ' production, the expectation was that these were a result of feed-down from the decay of bottom hadrons. However, with the addition of a silicon vertex detector, CDF was able to differentiate between prompt production and long-lived bottom feed down and found [2] that prompt particles overwhelmingly dominated both J/ψ and ψ' production, with the cross section for ψ' about 50 times greater than the color-singlet model prediction. CDF's measurement [3] of the $\Upsilon(1S)$ differential cross section was also much larger than theoretical expectations.

A much studied explanation of this behavior came from the Color Octet Model (COM) [4] which is an application of the Non-Relativistic QCD [5] effective theory. In the COM, the production process is factorized into a short-distance, hard process creating a $Q\bar{Q}$ pair and a long-distance hadronization process. The hard process can yield either a color-singlet state from three gluons or a color-octet state from two, with the cross section for the two-gluon fusion considerably larger than for three. In the long-distance process, additional gluons can be radiated. The model includes an expansion in terms of the quark velocity v and is governed by a set of universal four-quark operators corresponding to the final-state meson spin-parity combinations. The amplitudes of those operators are not predicted and must be determined by experiment. While it was possible to fit the COM functions to the CDF data, the model also predicts that for large momentum ($p_T^2 \gg M^2$), the J/ψ or Υ should be produced from the hadronization of a single gluon and maintain the transverse polarization of the parent. However, this prediction is inconsistent with J/ψ and ψ' polarization measurements [7] from CDF.

Next-to-next-to-leading-order (NNLO) QCD [6] also predicts momentum spectra for charmonium and bottomonium that agree with experiment, but with longitudinal polarization at high-momentum. Thus, while the prediction of a differential cross section alone is not sufficient to differentiate among models, measurements of the polarization at large momenta can do so. Fur-

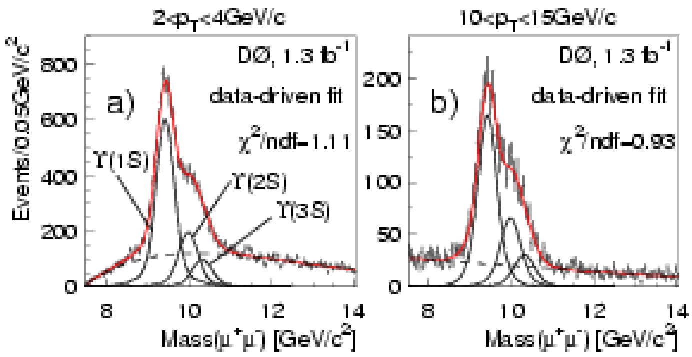

Figure 2: Fit of the mass distribution for two ranges of transverse momentum for the yields of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ decays to muon pairs in DØ.

thermore, because the theories rely on the quarks being truly heavy, the mass of the charm quark may not be sufficient for the theories to be applicable. Therefore, both the CDF and DØ [8] experiments have recently measured the polarization of Υ mesons in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV.

CDF and DØ have collected large samples of $\Upsilon \to \mu^+\mu^-$ events. Fits to the dimuon mass distribution to determine the of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ yields are shown in Figure 1 for CDF and Figure 2 for DØ. The CDF [9] and DØ [10] detectors have been described in detail elsewhere. Both are large solenoidal detectors with muon detectors outside the calorimeters. However, they bring different strengths. CDF has superior momentum, and thus mass, resolution enabling the three Υ states to be resolved, while DØ has muon coverage over a wider range of rapidity enabling reconstruction of Υ mesons for $|y| < 1.8$ compared to $|y| < 0.6$ for CDF. The samples include 260,000 $\Upsilon(nS)$ decays in 1.3 fb^{-1} for DØ and 83,000 $\Upsilon(1S)$ decays in 2.9 fb^{-1} for CDF.

The polarization is measured in the s-channel helicity frame where the quantity of interest is the angle θ^* between the momentum of μ^+ in the Υ rest frame and the Υ boost direction. Typically the polarization is expressed in terms of a quantity α where the angular distribution is

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

Thus for purely transverse (longitudinal) polarization $\alpha = 1$ (-1). Experimentally, the acceptance for $\Upsilon \to \mu^+\mu^-$ decays is a strong function of both transverse momentum p_T and $\cos\theta^*$. Rather than attempting to correct the data for the acceptance, the technique employed by both groups is to divide the data into bins of p_T and $\cos\theta^*$ and fit the dimuon mass distributions to get the Υ yield in each bin. In each p_T bin, the yield as a function of $\cos\theta^*$ can be fit to distributions derived from Monte Carlo simulation of transversely and longitudinally polarized decays. The simulations include all effects of the detectors. The fraction η of longitudinal decays is simply related to α:

$$\eta \equiv \frac{\sigma_L}{\sigma_L + \sigma_T} = \frac{1-\alpha}{3+\alpha}. \tag{2}$$

This method requires the simulations to be tuned well. The CDF and DØ groups have investigated many quantities that are sculpted by the geometric and kinematic acceptance of their experiments and verified good agreement between the simulation and the data. Some examples from DØ are shown in Figure 3.

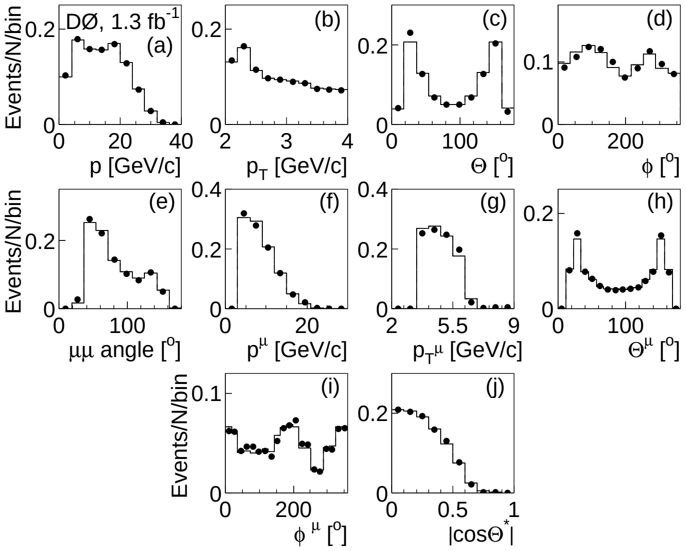

Figure 3: Comparison between data (points) and Monte Carlo simulation (histogram) distributions for a variety of quantities in $\Upsilon \to \mu^+\mu^-$ decays from DØ. Plots *a-d* related to the Υ candidates and *e-j* to the muons. Very good agreement is observed.

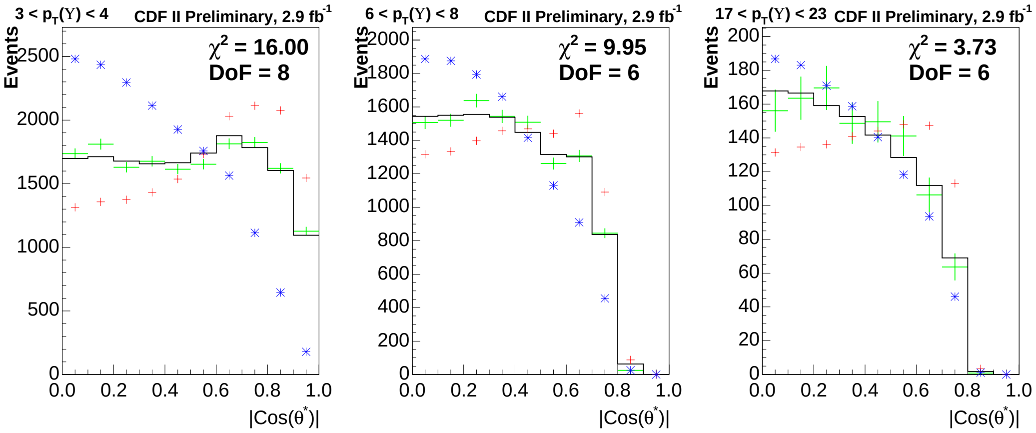

Figure 4: Polarization fits from CDF for three characteristic momentum bins: 3-4 GeV$/c$ (left), 6-8 GeV$/c$ (center), and 17-23 GeV$/c$ (right). The green crosses show the data and the histograms show the best fits. The red and blue points are the scaled transverse and longitudinal templates, respectively.

The signal line shapes in the dimuon mass are a set of Gaussian distributions. For DØ the shape is set in a fit to the dimuon mass in a p_T bin for all $\cos\theta^*$. Then that shape is fixed in fits for each (p_T,$\cos\theta^*$) bin to get the $\Upsilon(1S)$ or $\Upsilon(2S)$ yield. In CDF, the shapes are found in a similar way. They are then used to determine signal and sideband regions, and the $\Upsilon(1S)$ yield is determined from a sideband subtraction. Figure 4 shows the event yields from CDF and the fits to the templates for three characteristic momentum bins. The sensitivity is limited by the sharp decrease in efficiency at large $\cos\theta^*$ where in the absence of detector effects there would be the largest difference between yields for transverse and longitudinal polarization. Systematic uncertainties on α are small and come from the counting technique and trigger turn-on efficiency.

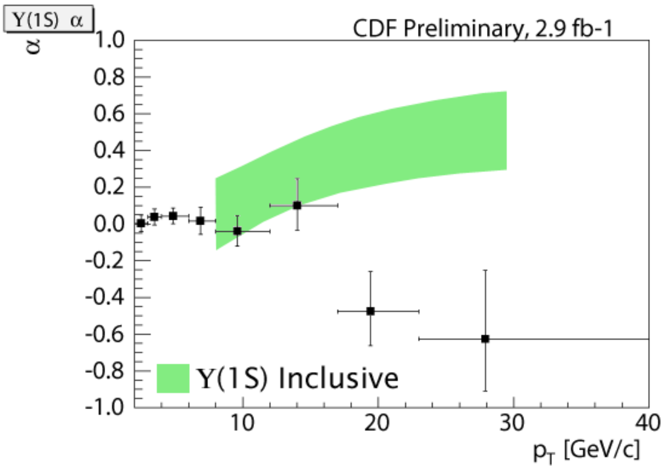

Figure 5: Longitudinal polarization parameter α for $\Upsilon(1S)$ production as a function of p_T from CDF. The green band shows the prediction of NRQCD. The width of the band results from the uncertainty in the amount of χ_b feed down.

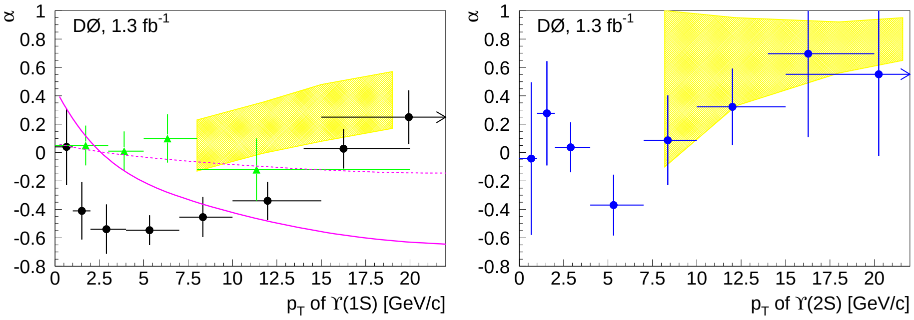

Figure 6: Longitudinal polarization parameter α for $\Upsilon(1S)$ (left) and $\Upsilon(2S)$ (right) production as a function of p_T. The black points are the result from DØ. The yellow bands show the prediction of NRQCD, while the purple line is the k_T-factorization model prediction. The green points are the earlier CDF result[3].

Figure 5 shows the results of the fits for α as a function of $p_T[\Upsilon(1S)]$ from CDF. The NRQCD prediction [11] is largely inconsistent with the data. The polarization results for the $\Upsilon(1S)$ and $\Upsilon(2S)$ from DØ are shown in Figure 6. These results show better agreement with NRQCD, but the $\Upsilon(1S)$ result is quite inconsistent with the results from CDF. The CDF results also agree with earlier measurements [3] from Run 1. In addtion, Figure 6 shows the prediction [12] of a k_T factorization model which is also inconsistent with both experiments. One possible reason for the difference between the CDF and DØ results is the difference in rapidity range. However, Faccioli *et al.* [13] suggest that such a large difference is unlikely to come from the underlying physics and rather is an artifact of differences in acceptance. In order to understand whether a model properly describes the data, it is necessary to examine more than the longitudinal polarization in a single frame. One can also fit for the azimuthal asymmetry, or one can make the longitudinal polarization measurement in the Collins-Soper frame which is more properly suited to production polarization while the helicity frame is actually most appropriate for decay polarization studies.

While much has been learned in the past 20 years about quarkonium production, the puzzles still remain. Many models can describe the p_T spectra; however, none adequately predicts the polarization. Furthermore, there is substantial disagreement between the $\Upsilon(1S)$ polarization measurements of CDF and DØ. Both collaborations have larger data sets and are expanding their analyses to include additional quantities beyond the longitudinal polarization in the helicity frame. The LHC experiments [14] will soon have results on the subject as well. We can expect great progress the study of the production of heavy quarkonia to be reported at the next FPCP meeting.

References

[1] F. Abe, *et al.*, *Phys. Rev. Lett.* **69**, 3704 (1992).

[2] F. Abe, *et al.*, *Phys. Rev. Lett.* **79**, 572 (1997).

[3] D. Acosta, *et al.*, *Phys. Rev. Lett.* **88**, 161802 (2002).

[4] P. Cho and M. Wise, *Phys. Lett.* B **346**, 129 (1995); M. Beneke and I.Z. Rothstein, *Phys. Lett.* B **372**, 157 (1996); Erratum, *ibid.* **389**, 769 (1996); E. Braaten, B.A. Kniehl, and J. Lee, *Phys. Rev.* D **62**, 094005 (2000).

[5] G.T. Bodwin, E. Braaten, and G.P. LePage, *Phys. Rev.* D **51**, 1125 (1995); Erratum, *ibid.* **55**, 5853 (1997); E. Braaten and S. Fleming, *Phys. Rev. Lett.* **74**, 3327 (1995).

[6] P. Artoisenet, *et al.*, *Phys. Rev. Lett.* **101**, 152001 (2008).

[7] A. Abulencia *et al.*, *Phys. Rev. Lett.* **99**, 132001 (2007).

[8] V.M. Abazov, *et al.*, *Phys. Rev. Lett.* **101**, 182004 (2008).

[9] D. Acosta, *et al.*, *Phys. Rev.* D **71**, 032001 (2005).

[10] V.M. Abazov, *et al.*, *Nucl. Instrum. Methods* A **565**, 463 (2006).

[11] E. Braaten and J. Lee, *Phys. Rev.* D **63**, 071501 (2001).

[12] S.P. Baranov and N.P. Zotov, Pis'ma v ZhETF **86**, 499 (2007).

[13] P. Faccioli, *et al.*, Submitted to *European Physics Journal C* [`hep-ph/1006.2738`].

[14] See articles by S. Hassani and U. Langenegger in these proceedings.