Production of Heavy Flavor and Quarkonia at CDF

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The production cross sections and polarizations of Υ mesons in hadron collisions are important observables with which to test different QCD models at low energy. This article describes the CDF measurement of the spin alignment of the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ states produced at the Tevatron using a data sample of 6.7 fb^{-1}. Compared to earlier CDF measurements, it extends the analysis technique in several ways. A new method to estimate the background angular distribution is used, a full angular analysis is performed for the first time and a consistency check is carried out by using two different reference frames. It is also the first measurement of the spin alignment of the $\Upsilon(3S)$.

1 Introduction

The decays of heavy quarkonia to $\mu^+\mu^-$ have been studied at hadron colliders for almost four decades. However, describing their production accurately based on QCD proved to be challenging and new models had to accommodate the surprisingly large measured J/ψ and Υ production cross sections [1, 2]. These models make specific predictions about the production polarization of the quarkonia, but these are generally in poor agreement with experimental measurements.
Moreover, there are discrepancies between results obtained by different experiments [3, 4]. The reason was thought to be possibly due to different detector acceptances, combined with the measurement of the distribution of only the polar angle of the positive muon in a reference frame that could not easily be transformed between different experiments [7].
In fact, the distribution of both polar and azimuthal angles of the positive muon from an Υ decay can be written as

$$\frac{dN}{d\Omega} \sim 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi \equiv w(\cos\theta, \phi; \vec{\lambda})$$

in the Υ rest frame. While previous experiments have only measured the parameter λ_θ, it is possible that Υ polarization is present and manifests itself by large values of λ_ϕ $\lambda_{\theta\phi}$, while λ_θ is close to zero.
Measuring Υ mesons instead of J/ψ has the advantage that they cannot originate for B meson decays, while limitations are imposed by χ_b feed-down.

2 Data sample

The dataset used in the analysis described here [5] corresponds to an integrated luminosity of 6.7 fb^{-1} of proton-antiproton collisions at the Tevatron at a center of mass energy of 1.96 TeV recorded by the CDF II detector [6] and contains 550 000 $\Upsilon(1S)$, 150 000 $\Upsilon(2S)$ and 76 000 $\Upsilon(3S)$ decays to $\mu^+\mu^-$ decays. It was collected with dimuon triggers, requiring a pair of oppositely charged muons in the invariant mass range $8 < m(\mu^+\mu^-) < 12$ GeV$/c^2$, among them one central muon with $p_T > 4$ GeV$/c$ and an either central ($|\eta| < 0.6$) or forward ($0.6 < |\eta| < 1$) muon with $p_T > 3$ GeV$/c$.

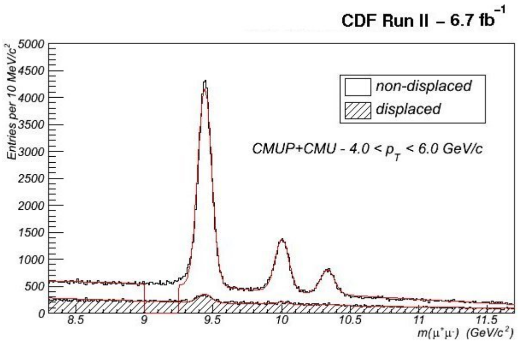

Figure 1: Dimuon mass spectra for the prompt and the displaced sample. The region from 9 to 9.25 GeV$/c^2$ is not fitted in order to reduce sensitivity to the modeling of final state radiation.

From this dataset, two samples are selected: the prompt or non-displaced sample, where both muons originate from the primary vertex, and the displaced sample, where at least one muon has an impact parameter of more than 150 μm. As can be seen from Fig. 1, the prompt sample contains most of the signal but also contains a significant level of background. The background is expected to be dominated by semileptonic decays of B hadrons which will have the same properties in the displaced sample, in which $\Upsilon(nS)$ decays are highly suppressed.
Furthermore, the shape of the background component in the dimuon mass is identical in both samples, so that the amount of background in the prompt sample can be constrained by scaling the background distribution observed in the displaced component by a linear function of mass. The displaced sample is more suitable than the mass sideband for extracting the angular distribution of the background, because there is evidence that the properties of muons in the background evolve rapidly with invariant mass and transverse momentum.

3 Analysis method

The analysis is performed separately in 8 ranges of dimuon transverse momentum. The events are analyzed in 12 separate ranges of invariant mass: the three $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ signal regions and nine more regions containing background.
The number of expected signal events in the 20×36 bins of $(\cos\theta, \phi)$ is proportional to the product of the detector acceptance $\mathcal{A}$, which depends on the geometric coverage of the detector and on the kinematic requirements of the trigger, and the underlying angular distribution w: $dN/d\Omega \sim \mathcal{A}(\cos\theta, \phi) \cdot w(\cos\theta, \phi; \vec{\lambda})$. The signal acceptance is calculated from Monte Carlo

events using the full detector simulation, where the p_T distributions of the Υ states are tuned to match those in the data. Separate acceptance distributions are calculated for the background, where p_T, rapidity and invariant mass distributions are tuned to agree with the observed distributions in the background. The angular analysis is performed both in the s-channel helicity frame and in the Collins-Soper frame.

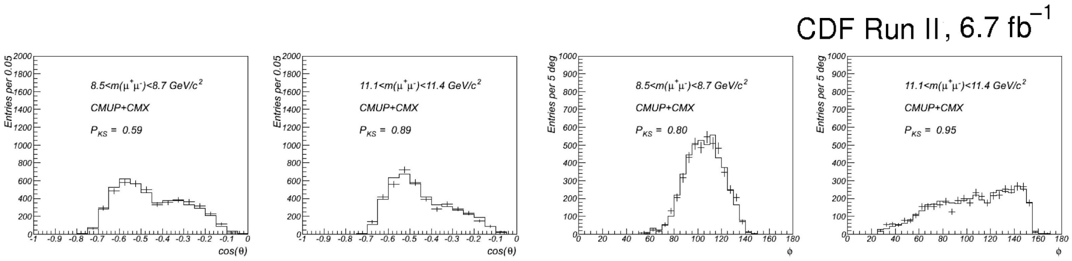

Figure 2: Projections of the angular distributions of prompt (histogram) and displaced samples (error bars) in the lower and upper mass sideband regions in the Collins-Soper frame. The agreement is quantified using the Kolmogorov-Smirnov P-value, shown with each distribution.

Figure 2 shows projections of the angular distribution of the background in the prompt and the displaced sample. They are found to be very similar in both sideband regions, so one can infer that the displaced sample provides a good background description also in the signal region.
The displaced sample is used to describe the background in the prompt sample, while it still contains some signal. Therefore, the fit to determine the polarization parameters $\vec{\lambda}$ is performed simultaneously to the two-dimensional angular distributions of the prompt and the displaced sample in the following way:

$$\frac{dN_p}{d\Omega} \sim \sigma_\Upsilon f_p \mathcal{A}_\Upsilon(\cos\theta, \phi) \cdot w(\cos\theta, \phi; \vec{\lambda}_\Upsilon) + \sigma_d s_p \mathcal{A}_{bkg}(\cos\theta, \phi) \cdot w(\cos\theta, \phi; \vec{\lambda}_{bkg})$$

$$\frac{dN_d}{d\Omega} \sim \sigma_\Upsilon (1 - f_p) \mathcal{A}_\Upsilon(\cos\theta, \phi) \cdot w(\cos\theta, \phi; \vec{\lambda}_\Upsilon) + \sigma_d \mathcal{A}_{bkg}(\cos\theta, \phi) \cdot w(\cos\theta, \phi; \vec{\lambda}_{bkg})$$

with the Υ and displaced background yields σ_Υ and σ_d, the fraction of Υ events in the prompt sample f_p and the ratio of background yields in both samples s_p. The scale factor s_p is constrained by fits to the dimuon mass spectrum. In order to facilitate the background description in some p_T and invariant mass ranges, a phenomenological $\cos^4\theta$ term is added to the angular distribution functions for the background.

4 Results

Figure 3 shows the measured parameters λ_θ and λ_ϕ in the s-channel helicity frame. It demonstrates the significant difference between the angular distributions of signal and background and the significant variation of the angular shape of the background over the considered dimuon mass region.
The analysis is performed in both the Collins-Soper and s-channel helicity frames. The rotationally invariant quantity $\tilde{\lambda} = (\lambda_\theta + 3\lambda_\phi)/(1 - \lambda_\phi)$ is calculated in each reference frame in bins of p_T for the three Υ states. Ensembles of Monte Carlo simulations indicated that the

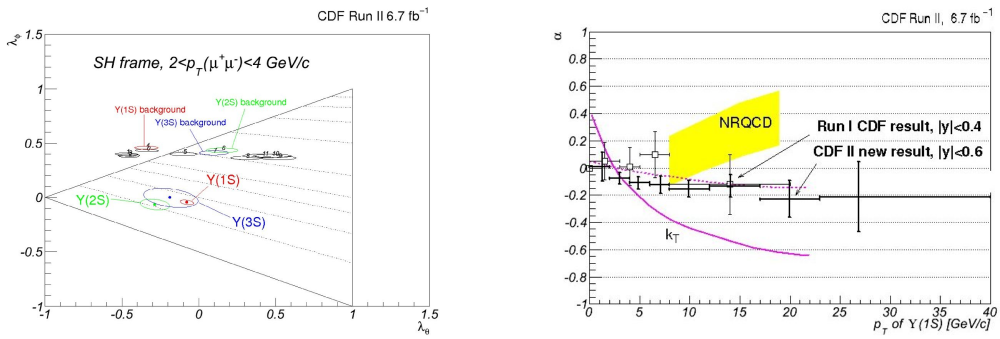

Figure 3: Left: 68% CL regions of λ_θ and λ_ϕ in the s-channel helicity frame for both signal and background in a given p_T range. The triangular region indicates the physical region. Right: Result for λ_θ for the $\Upsilon(1S)$ resonance and comparison with the CDF Run I result.

differences between measurements in both frames are consistent with statistical fluctuations. For the systematic uncertainties, a quadratic function with which to parameterize the prompt scale factor as a function of invariant mass was considered, the statistical contribution of Monte Carlo samples used to calculate the acceptance was calculated, and differences in $\tilde{\lambda}$ measured in the two coordinate frames were propagated into systematic uncertainties on λ_θ and λ_ϕ.

5 Summary

The complete angular distributions of muons from decays of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ mesons were analyzed and no evidence for strong polarization over a wide range of p_T has been found. It is the first measurement in three dimensions and the first measurement of the $\Upsilon(3S)$. The measurement for the $\Upsilon(1S)$ can be compared to previously published measurements. It is consistent with a Run I CDF analysis [3] and inconsistent at about the 4.5σ level with a Run II DØ measurement [4].

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