POLARIZATION OF PROMPT J/ψ AND $\Upsilon(nS)$*

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We review predictions, based on the nonrelativistic QCD factorization framework, for the polarizations of prompt J/ψ's and $\Upsilon(nS)$'s produced at the Fermilab Tevatron. We also discuss the effect of relativistic corrections on the theoretical prediction for the polarization of prompt J/ψ's at the Tevatron.

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1. Introduction

The nonrelativistic QCD (NRQCD) factorization approach has been developed to describe inclusive quarkonium production and decay [1]. It is the first effective field theory providing infrared-finite predictions of the hadronic decay rates of P-wave quarkonium [2]. It also explains large-$p_{\rm T}$ S-wave charmonium production at the Tevatron [3]. The theory introduces several nonperturbative color-octet Matrix Elements (ME's). It also includes color-singlet ME's. These are equivalent to the heavy-quark wave function at the origin and it's derivatives, which appear in the color-singlet model. The ME's are universal and fitted to the CDF data at the Tevatron [4]. The universality of the ME's has been tested in various experimental situations [5]. (A recent review can be found in Chap. 9 of Ref. [6].) A remarkable prediction of the NRQCD is that the S-wave quarkonium produced in the $p\bar{p}$ collision should be transversely polarized at sufficiently large $p_{\rm T}$ [7]. This prediction is based on the dominance of gluon fragmentation into quarkonium in quarkonium production at large $p_{\rm T}$ [3] and on the approximate heavy-quark spin symmetry of NRQCD [1]. Recent measurements at the Tevatron by the CDF Collaboration do not confirm this prediction [8]. However, the experimental uncertainties are large.

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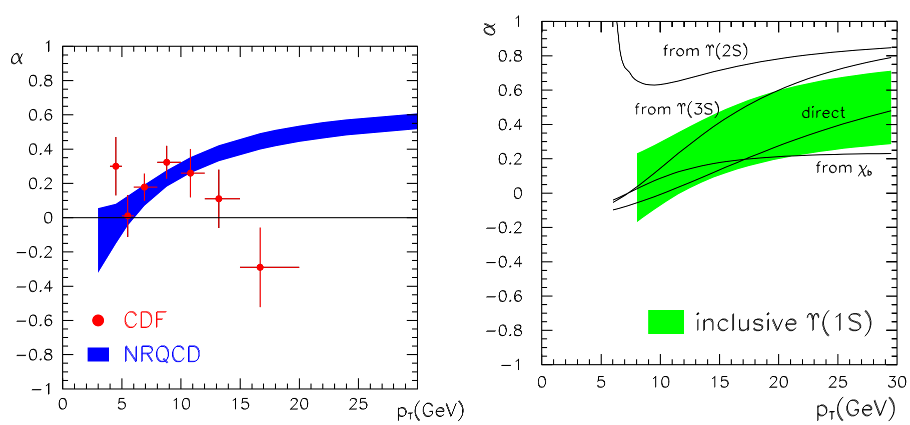
In this proceedings, we review predictions, based on the NRQCD factorization framework, for the polarizations of prompt J/ψ's [10] and $\Upsilon(nS)$'s produced at the Tevatron [11]. As a possible source of depolarizing contributions to the prompt J/ψ production at large $p_{\rm T}$, we consider the relativistic corrections to the gluon fragmentation into J/ψ. Finally, we summarize recent developments in the application of NRQCD to low-energy supersymmetry.

2. Polarization of prompt J/ψ

A convenient measure of the polarization is the variable $\alpha = (\sigma_{\rm T} - 2\sigma_{\rm L})/(\sigma_{\rm T} + 2\sigma_{\rm L})$, where $\sigma_{\rm T}$ and $\sigma_{\rm L}$ are the transverse and longitudinal components of the cross section, respectively. The variable α is fitted to the angular distribution ($\propto 1 + \alpha\cos^2\theta$) of the positive lepton with respect to the J/ψ momentum in the hadron center-of-momentum frame. The polarizations of the ψ''s and direct J/ψ's (J/ψ's that do not come from decays) produced at the Tevatron are predicted to be transverse [9,10]. The CDF measurement does not show the predicted tendency, but the error bars are too large to draw any definitive conclusions [8]. CDF also measured the polarization of prompt J/ψ's with a data that is larger than that of ψ' by about a factor 100. The prompt signal is composed of direct J/ψ's (60%) and J/ψ's that come from decays of the higher charmonium states χ_{c1} (15%), χ_{c2} (15%), and ψ' (10%). The contribution from the radiative decays of χ_{cJ}'s decreases, but does not eliminate the transverse polarization at large transverse momentum [10]. In Fig. 1(a) the theoretical prediction of the po-



(a) (b)

Fig. 1. Polarization variable α *vs.* $p_{\rm T}$ (a) for prompt J/ψ [10] and (b) $\Upsilon(1S)$ [11] compared to CDF data.

larization parameter α for prompt J/ψ's is shown as a band along with the CDF data [10]. While the prediction is in good agreement with the data in the moderate-$p_{\rm T}$ region, it disagrees with the data in the bin at the largest $p_{\rm T}$. However, the discrepancies with the theoretical predictions are significant only for the bin at the largest $p_{\rm T}$, and so a definitive conclusion must await the higher statistics measurements that will be possible in Run II of the Tevatron.

3. Polarization of $\boldsymbol{\Upsilon(nS)}$

The CDF Collaboration also measured the polarization of inclusive $\Upsilon(1S)$ in Run IB of the Tevatron [12]. The results for the $p_{\rm T}$ bins from 2 to 20 GeV and from 8 to 20 GeV are both consistent with no polarization. Since the cross section falls rapidly with $p_{\rm T}$, this indicates that there is little if any polarization for $p_{\rm T}$'s below about 10 GeV. Quantitative calculations of the polarization for inclusive $\Upsilon(nS)$ mesons are carried out [11] by using ME's for direct bottomonium production, which have been recently determined from an analysis of data from Run IB at the Tevatron [13]. There are more feed-down channels than for prompt J/ψ, but the generalization to inclusive $\Upsilon(nS)$ production is straightforward [11]. The theoretical prediction for the polarization of $\Upsilon(1S)$ ($\alpha = 0.13 \pm 0.18$ in the $p_{\rm T}$ bin from 8 to 20 GeV) is consistent with the recent measurement by the CDF Collaboration in the $p_{\rm T}$ bin from 8 to 20 GeV [11]. It is also predicted that the transverse polarization of $\Upsilon(1S)$ should increase steadily for $p_{\rm T}$ greater than about 10 GeV (see Fig. 1(b)) and that the $\Upsilon(2S)$ and $\Upsilon(3S)$ should be even more strongly transversely polarized [11].

4. Relativistic corrections to the fragmentation process

The CDF measurement of the polarization of prompt J/ψ's disagrees with the NRQCD prediction in the large-$p_{\rm T}$ region. Since the production rate is dominated by gluon fragmentation in this region, it may be worthwhile to check the size of corrections that are neglected in the available predictions for the fragmentation process. There are many effects that could change the quantitative prediction for α, such as next-to-leading order QCD corrections. The QCD correction for the color-octet spin-triplet channel has been calculated [14] but other next-to-leading order corrections are, as yet, uncalculated. The virtual gluon fragmentation that originates from light-quark fragmentation also contributes to the large transverse polarization [15].

It is known that there are large v^2 corrections to various charmonium decay rates [16]. (Recently, the v^4 correction factors for S-wave states have been calculated [16].) If there are also large v^2 corrections to the gluon fragmentation into J/ψ, then the prediction of the prompt J/ψ may change significantly. The fragmentation probability is estimated by integrating the fragmentation functions $D_n(z)$ ($n = 8$ for octet) over the longitudinal fraction z [17]:

$$\int_0^1 dz\, D_8(^3S_1)(z) \;\approx\; \left(1 - 0.54\,\frac{v^2}{0.3}\right) \int_0^1 dz\, D_8^{\rm LO}(z)\,, \tag{1}$$

where the superscript LO denotes the limit $v \to 0$. For charmonium, $v^2 \approx 0.3$. The large negative correction (≈ 0.54) to the color-octet spin-triplet fragmentation should increase the numerical value of the octet matrix element by about a factor 2. The phenomenological consequences of this correction require further study.

5. SUSY NRQCD

One of the exciting new developments in quarkonium physics is its application to low-energy supersymmetry. In Ref. [18], it was proposed that a light bottom squark $\tilde{b}$ with a mass similar to or less than the mass of the b quark may provide a solution to the puzzle that the b production rate measured at the Tevatron is two to three times greater than the theoretical prediction from quantum chromodynamics [19]. If the $\tilde{b}$ is lighter than the b, one may observe $\tilde{b}\tilde{b}^*$ pairs in Υ [20] and χ_b [21] decays. Furthermore, forthcoming high-statistics data from the CLEO Collaboration offer possibilities of discovery or significant new bounds on the existence and masses of supersymmetric particles through the search for the monochromatic photon that is emitted from the radiative decay of the Υ into S-wave sbottomonium (a $\tilde{b}\tilde{b}^*$ bound state) [22].

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