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Fragmentation contributions to hadroproduction of prompt J/ψ, χ_{cJ}, and $\psi(2S)$ states

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We compute leading-power fragmentation corrections to hadroproduction of charmonium states J/ψ, χ_{cJ}, and $\psi(2S)$ in the nonrelativistic QCD factorization formalism. We include fragmentation functions through order α_s^2 and parton production cross sections through order α_s^3. We also resum leading logarithms of the transverse momentum divided by the charm-quark mass to all orders in α_s. We find that the fragmentation corrections have a significant impact on the hadroproduction cross section of charmonia. We obtain good fits to the hadroproduction cross sections measured at the Tevatron and the LHC. Using the long-distance matrix elements obtained from the fits, we make predictions for prompt J/ψ polarization that are in good agreement with the LHC data.

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1. Introduction

In the nonrelativistic QCD (NRQCD) factorization conjecture, the inclusive production cross section of a charmonium H is written as [1]

$$d\sigma_{H+X} = \sum_n d\sigma_{c\bar{c}(n)+X} \langle \mathcal{O}^H(n) \rangle, \tag{1.1}$$

where c and $\bar{c}$ are the charm quark and charm antiquark, respectively. The $d\sigma_{c\bar{c}(n)+X}$ are perturbative short-distance cross sections (SDCSs), which are the cross sections to produce a $c\bar{c}$ pair in a color and angular-momentum state n. $\langle \mathcal{O}^H(n) \rangle$ are long-distance matrix elements (LDMEs) that describe the evolution of the state $c\bar{c}(n)$ into H. The LDMEs scale with powers of v, where v is a typical velocity of a charm quark or a charm antiquark inside the H [1]. For charmonia, $v^2 \approx 0.3$.

In current-level quarkonium phenomenology, the sum in Eq. (1.1) is truncated at relative order v^4. For $H = J/\psi$ or $\psi(2S)$, Eq. (1.1) involves four LDMEs to relative order v^4: $\langle \mathcal{O}^H({}^3S_1^{[1]}) \rangle$, $\langle \mathcal{O}^H({}^3S_1^{[8]}) \rangle$, $\langle \mathcal{O}^H({}^1S_0^{[8]}) \rangle$, and $\langle \mathcal{O}^H({}^3P_J^{[8]}) \rangle$. Here, the color and angular-momentum states of the $c\bar{c}$ pair are given in spectroscopic notation. For $H = \chi_{cJ}$, $\langle \mathcal{O}^{\chi_c}({}^3P_J^{[1]}) \rangle$ and $\langle \mathcal{O}^{\chi_c}({}^3S_1^{[8]}) \rangle$ contribute in Eq. (1.1). The color-singlet LDMEs can be measured in lattice QCD, computed in potential models, or extracted from decay widths. The color-octet LDMEs are usually obtained by comparing Eq. (1.1) with data.

The SDCSs for the hadroproduction of J/ψ have been calculated to next-to-leading order (NLO) in α_s [2, 3, 4, 5, 6, 7]. At large p_T, the SDCSs can be written as a convolution of parton production cross sections (PPCSs) and fragmentation functions (FFs) [8, 9]. In this work, we compute fragmentation contributions to hadroproduction of J/ψ, χ_{cJ} and $\psi(2S)$ at leading power (LP) in m_c^2/p_T^2, where m_c is the charm quark mass and p_T is the transverse momentum of the charmonium. Our approach is based on Refs. [10, 11]. We refer the reader to Ref. [11] for the details of the calculation. We use the PPCSs through NLO in α_s (order α_s^3), FFs through order α_s^2, and resum the leading logarithms of p_T/m_c to all orders in α_s. This goes beyond the fixed-order NLO calculations of the SDCSs. We find that the LP fragmentation contributions, combined with the NLO calculations, have a significant effect on the shapes of the SDCSs.

The remainder of this paper is organized as follows. We present our results in Section 2, followed by summary in Section 3.

2. Results

By using the LP fragmentation contributions, combined with the NLO SDCSs, we obtain good fits to cross section data [12, 13, 14, 15]. The color-singlet LDMEs for the J/ψ and $\psi(2S)$ were obtained from leptonic decay rates, and the color-singlet LDME for the χ_{cJ} and the color-octet LDMEs were extracted from fits to data. The χ^2/d.o.f. is 1.71/29, 1.19/8, and 8.20/40 for $\psi(2S)$, χ_{cJ}, and J/ψ, respectively. In the case of the J/ψ, the feeddown contribution from decays of $\psi(2S)$ and χ_{cJ} have been taken into account. In order to suppress non-factorizing contributions that may arise at small p_T, we use only the data with p_T larger than 3 times the charmonium mass in the fit. We use a correlation matrix method to compute uncertainties in the LDMEs. We refer the reader to Ref. [11] for details of the fit. In Fig. 1, we show the LP+NLO prediction for the cross section against the experimental data.

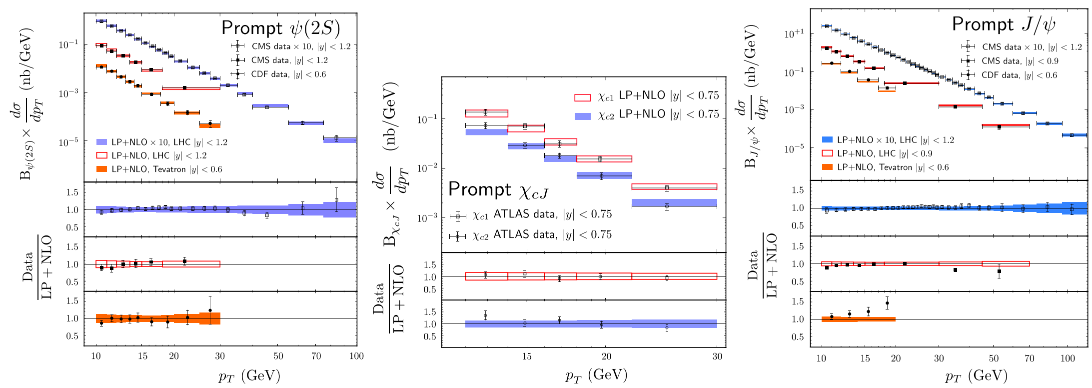

Figure 1: Prompt $\psi(2S)$ and J/ψ cross section at the Tevatron and the LHC, and prompt χ_{cJ} cross section at the LHC.

Using the LDMEs obtained from the fit, we make predictions for J/ψ polarization at the Tevatron and at the LHC. Our results are shown in Fig. 2 against CDF [16, 17] and CMS [18] data. Our results agree well with the CMS data [18], whereas the agreement is only fair with the CDF data [16, 17].

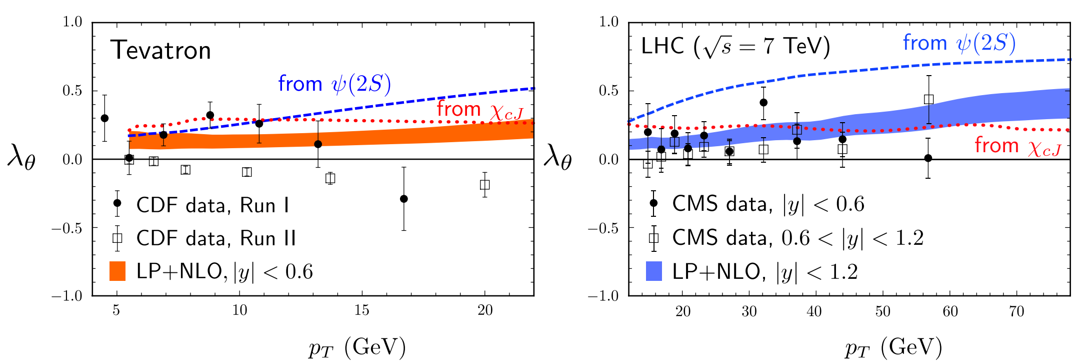

Figure 2: Polarization of prompt J/ψ at the Tevatron (left) and at the LHC (right). The polarization of J/ψ's from decays of $\psi(2S)$ and χ_{cJ} states are shown with dashed and dotted lines, respectively.

3. Summary

We computed leading-power (LP) fragmentation corrections to hadroproduction cross sections of the charmonium states J/ψ, χ_{cJ} and $\psi(2S)$. We employed parton production cross sections at next-to-leading order (order α_s^3) and fragmentation functions at order α_s^2, and resummed leading logarithms of p_T/m_c to all orders. The LP fragmentation contributions we computed goes beyond the fixed-order NLO calculations of the short-distance cross sections (SDCSs), and give part of the non-logarithmic contributions at next-to-next-to-leading order in α_s. The LP fragmentation corrections we found have a significant effect on the shapes of the SDCSs.

We obtain good fits to measured charmonium cross sections at large p_T. By using the LDMEs obtained from the fit, we make predictions for the polarization of J/ψ at the Tevatron and at the LHC. Our predictions are in good agreement with the CMS data [18], and in fair agreement with the CDF data [16, 17].

Although we have obtained good agreement with the data at large p_T, a complete calculation of order α_s^5 may be necessary in order to reduce the theoretical uncertainties. Measurements of the cross sections and polarizations of charmonium states at much larger values of p_T at the LHC can provide good tests of the theoretical predictions.

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