PROCEEDINGS OF SCIENCE

Quarkonium production to explore hadron 3D structure

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We discuss how quarkonium production, in particular η_c production in proton-proton collisions, can be used to access gluon transverse-momentum-dependent parton distribution functions (TMDPDFs). To do so, we apply the effective field theory machinery to factorize the process in terms of gluon TMDPDFs at low transverse momentum, and match this result with the collinear framework to obtain the full transverse-momentum spectrum. This matching is performed by applying the newly devised inverse-error weighting method, based on an estimation of the uncertainties coming from power corrections to construct a weighted average of both factorization theorems.

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1. Introduction

Quarkonium production is an interesting class of processes potentially useful to access gluon TMDPDFs (see e.g. Refs. [1–19]), which encode the rich three-dimensional inner structure of the hadrons in momentum space (see e.g. Ref. [20]). Below we consider one of them: η_c production in proton-proton collisions at the LHC, for which the hard scale $Q = M_{\eta_c} = 2.98$ GeV [21]. Since the hard scale is so low, there is no a clear separation between the regions in transverse momentum where either the TMD or the collinear frameworks can be applied, which makes this process very sensitive to the applied matching scheme, and which can affect the future extraction of the gluon TMDPDFs from experimental data.

2. TMD and collinear frameworks

At low transverse momentum the cross-section is factorized in terms of gluon TMDPDFs [22–24] (see also Refs. [25–27]), whereas at high transverse momentum the cross-section is factorized in terms of collinear integrated PDFs. Below we present the relevant results for both frameworks.

The formalism for the production of a pseudo-scalar quarkonioum η_c at low transverse momentum has been presented in Refs. [3, 14, 28]. Following an effective theory approach [14, 28, 29] based on a combination of soft-collinear effective theory and non-relativistic QCD (NRQCD), and considering unpolarized protons only, we derive the needed TMD factorization theorem.

The most common approach to calculate quarkonium production is the NRQCD formalism [30], where we can write the cross-section for η_c production in proton-proton collisions as:

$$d\sigma[pp \to \eta_c X] = \sum_n d\sigma[pp \to c\bar{c}(n)X] \left\langle \mathscr{O}^{\eta_c}(n) \right\rangle , \tag{2.1}$$

where $d\sigma[pp \to c\bar{c}(n)X]$ is the short-distance cross-section for producing the $c\bar{c}$ pair in a state n with definite color and angular momentum quantum numbers and $\left\langle \mathscr{O}^{\eta_c}(n) \right\rangle$ is a long distance matrix element (LDME) that describes the non-perturbative formation of the bound-state η_c from the $c\bar{c}$ pair in the state n. X denotes other possible particles in the final state which are integrated over. The quantum numbers n will be denoted by ${}^{2S+1}L^{[i]}_J$, where the notation for angular momentum is standard and $i = 1(8)$ for color-singlet (color-octet) states. The short distance cross-sections are perturbatively calculable (apart from the parton distribution functions) in a power series in α_s, while the LDMEs are nonperturbative and must be extracted from data. The LDMEs scale with definite powers of the quark-pair relative velocity v, so the NRQCD factorization formalism organizes the calculation of quarkonium production (and decay) into a systematic double expansion in α_s and v.

Given that the color singlet state ${}^1S_0$ dominates this process, we can argue that it is analogous to Higgs boson production in proton-proton collisions, in the sense that we have a glue-glue fusion into a color-singlet state, and then make use of the following TMD factorization ansatz:

$$\begin{aligned}\frac{d\sigma}{dy\,d^2q_T} = {}& \frac{2\pi^3\alpha_s^2}{9sM_{\eta_c}^3} H(\mu^2, M_{\eta_c}^2)\,\left\langle \mathcal{O}^{\eta_c}(^1S_0)\right\rangle \int \frac{d^2b_T}{(2\pi)^2}\, e^{ib_T\cdot q_T} \\ & \times \Big[\tilde{f}_{1g/A}(x_A,b_T;\mu,\zeta_A)\tilde{f}_{1g/B}(x_B,b_T;\mu,\zeta_B) - \tilde{h}^{\perp(2)}_{1g/A}(x_A,b_T;\mu,\zeta_A)\tilde{h}^{\perp(2)}_{1g/B}(x_B,b_T;\mu,\zeta_B)\Big] \\ & + \Big[\mathcal{O}(q_T/M_{\eta_c})^a\Big]\sigma\,. \end{aligned} \tag{2.2}$$

The NRQCD matrix element is [30] $\left\langle \mathcal{O}^{\eta_c}(^1S_0)\right\rangle = \frac{N_c}{2\pi}\,|R_n(0)|^2\,[1+\mathcal{O}(v^4)]$, where R_n is the radial wave-function of the $q\bar{q}$ pair with quantum number n, and v is the relative velocity of the quarks in the pair. According to Ref. [31] (see Table I) we choose $|R_n(0)|^2 = 0.921533\ \text{GeV}^{-3}$.

The gluon TMDPDFs $\tilde{f}_1^g$ and $\tilde{h}_1^{\perp g(2)}$ provide the distribution of the initial state gluons [22–24] as a function of their collinear momentum fraction x_h, at given values for the UV-renormalization and rapidity-renormalization scales (e.g. $\mu^2 = \zeta_h = M_{\eta_c}^2$). The function $\tilde{f}_1^g(x,k_T)$ is the TMDPDF for unpolarized gluons in unpolarized hadrons whereas the $\tilde{h}_1^{\perp g(2)}(x,k_T)$ TMDPDF accounts for linearly polarized gluons in unpolarized protons [23]. The Fourier transforms of the functions and their moments $\tilde{f}_1^g(x,b_T)$, $\tilde{h}_1^{\perp g(2)}(x,b_T)$ are defined in [23].

A necessary condition for the factorization theorem to hold is that the structure of the infrared poles at a specific perturbative order in α_s is the same for the cross-section in full QCD and in the factorized form (the hard part H should be free from infrared divergences) This argument can be used backwards, to establish a factorization theorem ansatz at a given perturbative order by checking if the obtained hard part (by subtraction) is actually free from divergences. For η_q production this has been verified at $\mathcal{O}(\alpha_s)$ [28, 29], where the hard part H is [1]

$$H^{(1)} = \sigma^{(1)}_{\text{virt}} - \big[\tilde{f}_1^{g/A}\tilde{f}_1^{g/B}\big]^{(1)}_{\text{virt}} = \frac{\alpha_s}{2\pi}\left[-C_A\ln^2\frac{\mu^2}{M_{\eta_c}^2} + 2C_A\left(1+\frac{\pi^2}{3}\right) + 2C_F\left(-5+\frac{\pi^2}{4}\right)\right], \tag{2.3}$$

with $H^{(0)} = 1$. This result, together with the known gluon TMDPDFs, allows us to perform the resummation of large logarithms at NNLL accuracy.

At large transverse momentum ($q_T \sim M_{\eta_c} \gg m \sim 1$ GeV) the cross-section is described by collinear factorization. For the unpolarized case, consistently with the α_s accuracy at low q_T, we describe the cross-section at fixed $\mathcal{O}(\alpha_s^3)$ order. At $q_T \geq M_{\eta_c}$ the hard scale is given by the transverse mass $m_T = \sqrt{M_{\eta_c}^2 + q_T^2}$ and the cross-section is given by [32] [2]

$$\begin{aligned}\frac{d\sigma}{dy\,d^2q_T} = {}& \sum_{a,b}\int dx_a dx_b\, f_1^{a/A}(x_a;\mu) f_1^{b/B}(x_b;\mu)\ \delta(\hat{s}+\hat{t}+\hat{u}-M_h^2)\ \frac{\hat{s}}{\pi}\,\frac{d\sigma}{d\hat{t}}(ab\to hd) \\ & + \Big[\mathcal{O}(m/q_T)^b\Big]\sigma\,, \end{aligned} \tag{2.4}$$

where a, b are partons in the initial state, h is the produced hadron and d a parton radiated in the final state. $\hat{s}$, $\hat{t}$, $\hat{u}$ are the partonic Mandelstram variables [33] and the partonic cross-section $d\sigma/d\hat{t}$ is given at $\mathcal{O}(\alpha_s^3)$ in Refs. [34–36] for different channels.

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[1] We notice that only the virtual contributions are necessary to obtain the hard part of the TMD factorization theorem, since real-gluon emission diagrams live at a lower scale and match exactly between the full and the factorized theories.

[2] Note that we generalize the result in [32] to the massive case.

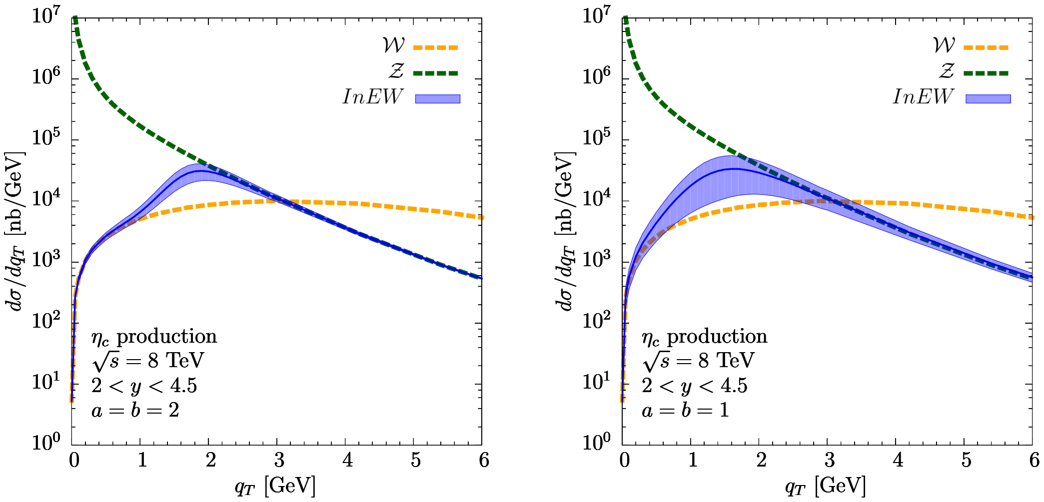

Figure 1: *The TMD resummed term $\mathscr{W}$ (yellow curve), the collinear fixed-order term $\mathscr{Z}$ (green curve), and the matched cross section with the inverse-error weighting (InEW) method (blue band) for η_c production in proton-proton collisions at $\sqrt{s} = 8$ TeV.*

3. Phenomenology: the complete transverse-momentum spectrum

In Fig. 1 we show the matched cross-section for η_c production in proton-proton collisions at the LHC at $\sqrt{s} = 8$ TeV. To do so, we apply the recently devised inverse-error weighting method (*InEW*) [37], which makes use of estimations of the power-corrections to both TMD and collinear factorization theorems to construct their weighted average. As can be seen, the matched cross-section overlaps with the TMD result ($\mathscr{W}$) at low q_T and with the collinear result ($\mathscr{Z}$) at large q_T, as expected. The values of a and b are related to the strength of the power corrections, and varied here between 1 and 2 to show their impact. Notice that the uncertainty on the matched cross section is only due to the matching scheme, i.e. including power-correction uncertainties, and no other effects are added, such as the perturbative-scale variations and the non-perturbative contributions. All these effects should be properly included in an actual comparison to experimental data.

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