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Upsilon Transverse Momentum at Hadron Colliders

Edmond L. Berger*
High Energy Physics Division, Argonne National Laboratory
Argonne, IL 60439

Jianwei Qiu† and Yili Wang‡
Department of Physics and Astronomy, Iowa State University
Ames, IA 50010

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We predict the shape of the transverse momentum p_T spectrum of Υ production. The distribution at low p_T is dominated by the region of small impact parameter b and may be computed reliably in perturbation theory. We resum to all orders in the strong coupling α_s the process-independent large logarithmic contributions that arise from initial-state gluon showers in the small $p_T(\leq M_\Upsilon)$ region. The cross section at large p_T is represented by the $\mathcal{O}(\alpha_s^3)$ lowest-order non-vanishing perturbative contribution.

Keywords: Heavy Quarkonium; QCD Resummation; Perturbative QCD.

Perturbative calculations in quantum chromodynamics (QCD) reproduce the transverse momentum distribution of Υ production at large p_T at hadron colliders but tend not to address the region of low p_T where the bulk of the data is [1]. The distribution at low p_T is strongly influenced by initial-state gluon showers. A fixed-order perturbative treatment in QCD leads to $1/p_T^2$-type singular terms enhanced by large higher-order logarithmic contributions caused by initial-state gluon radiation. These contributions have the form $\alpha_s \log^2(M_\Upsilon^2/p_T^2)$ for every power of the strong coupling α_s, and reliable predictions in the regions of small and moderate p_T require that the logarithmic contributions be summed to all orders in α_s.

This paper is a brief summary of a study reported elsewhere [2], along with a new comparison with preliminary DØ Run 2 data [3]. We use a two-step factorization procedure to represent production of the Υ. We assume that a pair of bottom quarks $b\bar{b}$ is produced in a hard-scattering short-distance process. The pair is produced at a distance scale $\sim 1/(2m_b) \sim 1/45$ fm, which is much smaller than the physical size of a Υ meson. The compact $b\bar{b}$ system is unlikely to become an Υ meson at the

*berger@anl.gov
†jwq@iastate.edu
‡yiliwa@iastate.edu, conference speaker

production point. Instead, the pair must expand, and the b and $\bar{b}$ will interact with each other coherently until they transmute into a physical Υ meson. A $b\bar{b}$ pair with invariant mass $Q > 2M_B$ is more likely to become a pair of B mesons. We can write the differential cross section in the usual way [4]:

$$\frac{d\sigma_{AB\to\Upsilon X}}{dp_T^2 dy} = \sum_{a,b} \int dx_a\, \phi_{a/A}(x_a)\, dx_b\, \phi_{b/B}(x_b)\, \frac{d\hat{\sigma}_{ab\to\Upsilon X}}{dp_T^2 dy}\,. \tag{1}$$

Since the momentum of the heavy quark in the pair's rest frame is much less than the mass of the pair, the parton-level production cross section might be factored further [4]:

$$\frac{d\hat{\sigma}_{ab\to\Upsilon X}}{dp_T^2 dy} \approx \sum_{[b\bar{b}]} \int dQ^2 \left[\frac{d\hat{\sigma}_{ab\to[b\bar{b}](Q)X'}}{dQ^2 dp_T^2 dy}\right] \mathcal{F}_{[b\bar{b}]\to\Upsilon\bar{X}}(Q^2)\,. \tag{2}$$

The function $\mathcal{F}_{[b\bar{b}]\to\Upsilon\bar{X}}(Q^2)$ represents a transition probability for a $b\bar{b}$ pair with quantum numbers $[b\bar{b}]$ to transmute into an Υ meson. Different models of quarkonium production lead to different choices for $\mathcal{F}(Q^2)$. In a color evaporation (or color-bleaching) model (CEM) [5], $\mathcal{F}_{[b\bar{b}]\to\Upsilon}(Q^2) = C_\Upsilon$ if $4m_b^2 \leq Q^2 \leq 4M_B^2$. The non-perturbative constant C_Υ sets the overall normalization of the cross section. Its value cannot be predicted. It changes with the specific state of the Υ meson.

Adopting the Collins, Soper, and Sterman (CSS) impact-parameter b-space (Fourier conjugate to p_T) approach [6], we write

$$\frac{d\sigma^{\rm resum}_{AB\to[b\bar{b}](Q)X'}}{dQ^2 dp_T^2 dy} = \int \frac{db}{2\pi}\, J_0(p_T\, b)\, b\mathcal{W}_{AB\to[b\bar{b}](Q)}(b, Q, x_A, x_B)\,. \tag{3}$$

The resummed calculation of the transverse momentum distribution at low p_T is reliable because the Fourier transform in Eq. (3) is dominated by the region of small b, and is not sensitive to the extrapolation to the large b [2]. We keep only the process-independent terms in the Sudakov exponential functions. The QCD resummed p_T distribution of Υ production can be predicted reliably in the region of small and intermediate p_T. At larger p_T, $p_T \geq M_\Upsilon$, we use the $\mathcal{O}(\alpha_s^3)$ lowest-order non-vanishing perturbative contribution that we denote as $\sigma^{\rm pert}$.

Because the $b\bar{b}$ system is not necessarily in a color neutral state, $\sigma^{\rm pert}$ includes radiation from the heavy quark system as well as from the incoming partons. This final state radiation is not included in $\sigma^{\rm resum}$. To avoid extrapolation of $\sigma^{\rm pert}$ into region of low p_T, we match the resummed and perturbative components of the p_T distribution at a value p_{T_M}. As we do not calculate the order α_s corrections to $\sigma^{\rm resum}$, we compensate by increasing $\sigma^{\rm resum}$ by a resummation enhancement factor K_r and assume that K_r is a constant.

The principal predictive power of our calculation is the shape of the p_T-distribution for the full p_T region. In Fig. 1, we present our calculation of the transverse momentum distribution for hadronic production of $\Upsilon(nS)$, $n = 1-3$. The shapes of the p_T distributions are consistent with experimental results. We find best fit values $K_r = 1.22\pm0.02$ and $p_{T_M} \sim 4.27$ GeV. The value of C_Υ: 0.044, 0.040,

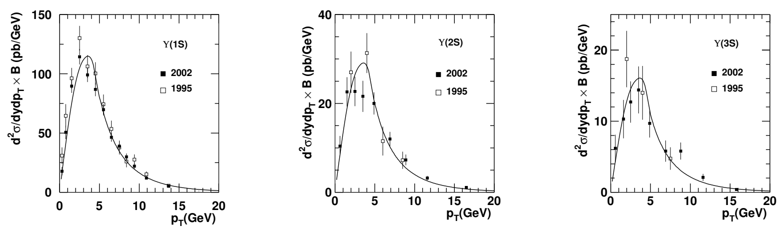

Fig. 1. Differential cross sections times leptonic branching fractions B, at rapidity $y = 0$, as functions of transverse momentum for hadronic production of (a) $\Upsilon(1S)$, (b) $\Upsilon(2S)$, and (c) $\Upsilon(3S)$ at $\sqrt{S} = 1.8$ TeV along with published Run 1 data from the CDF collaboration .

and 0.041 for $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$, respectively, is approximately independent of M_Υ. The essential similarity of the production differential cross sections for the

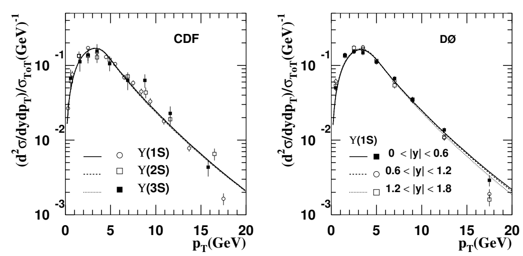

Fig. 2. Normalized transverse momentum distribution for Υ production at a) $\sqrt{S} = 1.8$ TeV along with published Run 1 data and b) $\sqrt{S} = 1.96$ TeV along with preliminary DØ Run 2 data .

three $\Upsilon(nS)$ states is illustrated in frame a) of Fig. 2. The three theory curves are practically indistinguishable. The curves in frame b) are our predictions for Run 2 at $\sqrt{S} = 1.96$ TeV for three different ranges of rapidity, along with preliminary DØ data [3]. Since the curves in Fig. 2 are normalized by the integrated cross sections, dependence on the normalization parameters C_Υ cancels in the ratio. The good agreement with data is based on the choice of only two adjustable constants, the resummation enhancement factor K_r and the matching point p_{T_M}.

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