

# The Resummed Photon Spectrum in Radiative Upsilon Decays (And More)

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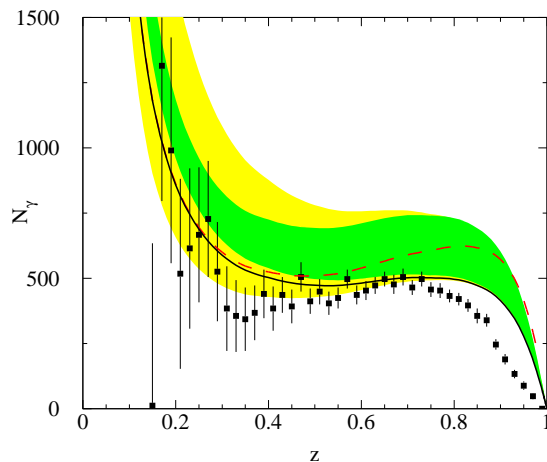
**Abstract.** In this talk I present the results of two calculations that make use of Non-Relativistic QCD and the newly developed Soft-Collinear Effective Theory. The first process considered is inclusive radiative  $\Upsilon$  decay. The second process considered is the leading color-octet contribution to  $e^+e^- \rightarrow J/\psi + X$ .

Bound states of heavy quarks and antiquarks have been of great interest since the discovery of the  $J/\psi$  [1, 2]. In particular the decay and production of quarkonium is an interesting probe of both perturbative and nonperturbative aspects of QCD dynamics. A systematic theoretical framework for handling the different scales characterizing both the decay and production of quarkonium is Non-Relativistic Quantum Chromodynamics (NRQCD) [3, 4]. NRQCD solves important conceptual as well as phenomenological problems in quarkonium theory. For instance, perturbative calculations of the inclusive decay rates for  $\chi_c$  mesons in the color-singlet model suffer from nonfactorizable infrared divergences [5, 6, 7]. NRQCD provides a generalized factorization theorem so that infrared safe calculations of inclusive decay rates are possible [8]. In addition, color-octet production mechanisms are critical for understanding the production of  $J/\psi$  at large transverse momentum,  $p_\perp$ , at the Fermilab Tevatron [9, 10, 11]. There are still many challenging problems in quarkonium physics that remain to be solved [12]. One important problem is the polarization of  $J/\psi$  at the Tevatron. NRQCD predicts the  $J/\psi$  should become transversely polarized as the  $p_\perp$  of the  $J/\psi$  becomes much larger than  $2m_c$  [13, 14, 15, 16]. The theoretical prediction is consistent with the experimental data at intermediate  $p_\perp$ , but at the largest measured values of  $p_\perp$  the discrepancies are at the  $3\sigma$  level [17]. In this talk I present two additional puzzles where progress has been made lately: radiative  $\Upsilon$  decay, and  $e^+e^- \rightarrow J/\psi + X$ .

Inclusive decays of quarkonium are understood in the framework of the operator product expansion (OPE), with power-counting rules given by NRQCD. The OPE for the direct photon spectrum of  $\Upsilon$  decay is [3]

$$\frac{d\Gamma}{dz} = \sum_n C_n(M, z) \langle \Upsilon | \mathcal{O}_n | \Upsilon \rangle, \quad (1)$$

where  $z = 2E_\gamma/M$ , with  $M = 2m_b$ . The  $C_i$  are short-distance coefficients, and the  $\mathcal{O}$  are NRQCD operators. At leading order in  $v$  only one term in the sum must be kept, the so called color-singlet contribution.



**FIGURE 1.** The inclusive radiative  $\Upsilon$  photon spectrum, compared with data from CLEO [28].

This simple picture of the photon spectrum in inclusive  $\Upsilon$  decays is only valid in the intermediate range of the photon energy spectrum ( $0.3 \lesssim z \lesssim 0.7$ ). In the lower range,  $z \lesssim 0.3$ , photon-fragmentation contributions are important [18, 19]. At large values of the photon energy,  $z \gtrsim 0.7$ , both the perturbative expansion [19] and the OPE [20] break down.

The breakdown at the endpoint is a consequence of NRQCD not containing the correct low energy degrees of freedom. The effective theory which correctly describes this kinematic regime is a combination of NRQCD for the heavy degrees of freedom, and the soft-collinear effective theory (SCET) [21, 22, 23, 24] for the light degrees of freedom. In Refs. [25, 26, 27] SCET was applied to radiative  $\Upsilon$  decay. A comparison of the calculation to CLEO [28] data is shown in Fig. 1.

The error bars on the data are statistical only. The dashed line is the direct tree-level and fragmentation result, and the solid curve is the sum of the interpolated resummed result and the fragmentation result. For these two curves we used the value of  $\alpha_s$  extracted by CLEO from these data,  $\alpha_s(M_\Upsilon) = 0.163$ , which corresponds to  $\alpha_s(M_Z) = 0.110$  [28]. We also show in this plot the interpolated resummed and fragmentation result, using the PDG value of  $\alpha_s(M_Z)$ , including theoretical uncertainties, denoted by the shaded region. The lighter band also includes the variation, within the errors, of the parameters for the quark to photon fragmentation function extracted by ALEPH [29].

New problems have arisen as a result of recent measurements of the spectra of  $J/\psi$  produced at the  $\Upsilon(4S)$  resonance in  $e^+e^-$  collisions by the BaBar and Belle experiments [30, 31]. Leading order NRQCD calculations predict that for most of the range of allowed energies prompt  $J/\psi$  production should be dominated by color-singlet production mechanisms, while color-octet contributions dominate when the  $J/\psi$  energy is within a few hundred MeV of the maximum allowed. Furthermore, as pointed out in

Ref. [32], color-octet processes predict a dramatically different angular distribution for the  $J/\psi$ .

Experimental results do not agree with these expectations: the data does not exhibit any enhancement in the bins closest to the endpoint. However, the total cross section measured by the two experiments exceeds predictions based on the color-singlet model alone. The total prompt  $J/\psi$  cross section, which includes feeddown from  $\psi'$  and  $\chi_c$  states but not from  $B$  decays, is measured to be  $\sigma_{tot} = 2.52 \pm 0.21 \pm 0.21$  pb by BaBar, while Belle measures  $\sigma_{tot} = 1.47 \pm 0.10 \pm 0.13$  pb. Estimates of the color-singlet contribution range from  $0.4 - 0.9$  pb [33, 34, 35, 36]. Furthermore, the angular distribution disagrees with color-singlet result. These aspects of the data suggest that there is a substantial color-octet contribution which is not confined to the very endpoint.

In Ref. [37] the endpoint region is treated within the framework of NRQCD and SCET. The calculation depends on a nonperturbative function, and thus is not predictive. However, moments of the shape function are NRQCD operators whose size is constrained by the velocity scaling rules of NRQCD. Choosing a simple ansatz for the shape function whose moments are consistent with velocity scaling rules, one finds that the combined perturbative and nonperturbative effects lead to substantial broadening of the color-octet spectrum in a manner that is consistent with data.

In Fig. 2 I show the sum of the color-octet and color-singlet contributions as the upper line, and the color-singlet contribution only as the lower line. The color-octet matrix elements set the normalization. In the graph on the left they are chosen to be  $\langle \mathcal{O}_8^\psi(^1S_0) \rangle = \langle \mathcal{O}_8^\psi(^3P_0) \rangle / m_c^2 = 1.3 \times 10^{-1} \text{ GeV}^3$ . This is plotted against the BaBar data [31]. In the graph on the right they are chosen to be  $\langle \mathcal{O}_8^\psi(^1S_0) \rangle = \langle \mathcal{O}_8^\psi(^3P_0) \rangle / m_c^2 = 6.6 \times 10^{-2} \text{ GeV}^3$ , and is plotted against the Belle data [30].

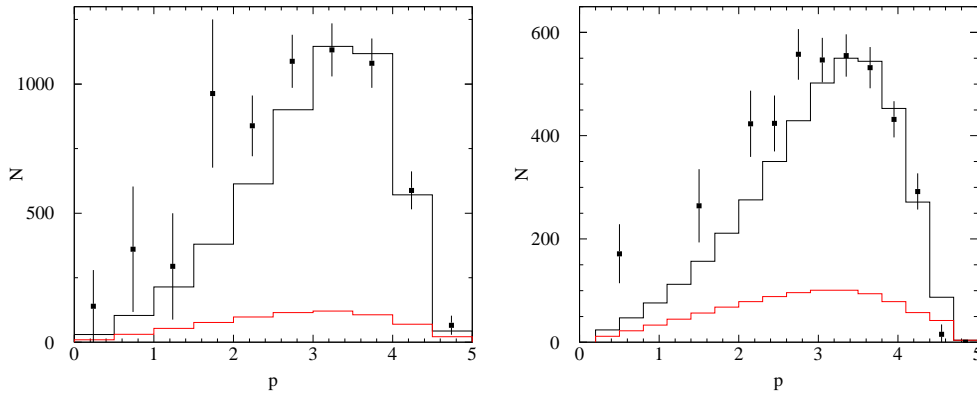
While the calculations of Ref. [37] show that the leading color-octet contribution is broad enough to be compatible with the observed  $p_\psi$  distributions, other features of the  $e^+e^-$  data remain puzzling. In particular, Belle reports a large ratio of  $J/\psi + c\bar{c}$  over inclusive  $J/\psi$  [38]. The predicted ratio from leading order color-singlet production mechanisms alone is at least a factor of three too small [33, 35] and a large color-octet contribution makes this ratio even smaller.

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**FIGURE 2.** The sum of the color-octet and color-singlet contributions are plotted as the upper line. The lower line is the color-singlet contribution only. The graph on the left shows data from the BaBar collaboration [31]. The graph on the right shows data are from the Belle collaboration [30].

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