1. MOTIVATION

One of the most interesting features of quantum chromodynamics (QCD) is the apparent discrepancy between the fundamental role of color as a conserved quantum number carried by quarks and gluons and the non-observation of color in physical hadronic states. As a non-perturbative phenomenon, the confinement mechanism responsible for the color-singlet nature of hadrons is still not fully understood. One can hope to gain more insight by studying the relatively simple bound states of heavy charm and bottom quarks, such as $J/\psi$ or $\Upsilon$ mesons.

Ever since QCD emerged as the fundamental theory of the strong interaction, models have been designed to explain the compensation of color in heavy quarkonia. Well-known examples are the Color Evaporation \cite{1,2,3} and Hard Comover Scattering Models \cite{4,5}, which assume that color is restored by soft and hard gluon exchange with the underlying event, respectively, and the Color Singlet Model (CSM) \cite{6,7}, which requires the heavy quark pair to be produced in a color singlet state. The CSM leads to strong selection rules and connects the production cross section with the quarkonium wave function. Today, a rigorous effective field theory exists in the form of non-relativistic QCD (NRQCD) \cite{8}, which utilizes a double expansion in the strong coupling constant $\alpha_s$ and the relative quark-antiquark velocity $v$ in order to factorize the hard production from the soft binding process \cite{9}. Left-over singularities in the CSM can be removed systematically into non-perturbative color-octet operator matrix elements (OMEs), and their numerical values can be fitted to describe the hadroproduction cross sections observed at the Tevatron. However, it is necessary to demonstrate the universality of these OMEs in other production processes, such as $\gamma\gamma$ collisions. Since the theoretical uncertainties from scale variations in leading order (LO) of $\alpha_s$ are quite substantial, it is furthermore important to include also contributions from next-to-leading order (NLO) virtual loop and real emission processes. In this paper, we report on recent progress along these lines.

2. REAL CORRECTIONS TO $J/\psi$ PRODUCTION IN DIRECT $\gamma\gamma$ COLLISIONS

In direct $\gamma\gamma$ collisions, $J/\psi$ mesons with mass $M = 2m_c$ and finite transverse momentum $p_T$ are produced in association with either a photon (see Fig. 1) or a jet, where the final state photon in Fig. 1 has to be replaced by a gluon. In the first case, the physical color-singlet state ($^3S_1^{[1]}$ in spectroscopic notation) is produced directly, whereas in the second case the intermediate color-octet state ($^3S_1^{[8]}$) transforms into the physical $J/\psi$ through soft gluon emission. Although the strong coupling of the hard gluon enhances the second process, it is strongly suppressed by the relevant color-octet OME, which is subleading in $v$. In NLO of $\alpha_s$, an unresolved dijet system with invariant mass $s_{jj}$, originating from two gluons...
Figure 1. Feynman diagrams pertinent to the partonic subprocess $\gamma\gamma \rightarrow J/\psi\gamma$. 

or a light quark-antiquark pair, allows for the production of intermediate $1S_0^{[8]}$, $3S_1^{[8]}$, and $3P_j^{[8]}$ states. At small $p_T$, virtual loop corrections have to be included to cancel the unphysical dependence on the cut-off $s_{jj} > M^2$, but at large $p_T$ these contributions become unimportant. As can be observed clearly in Fig. 2, the cut-off dependence on the cut-off becomes large [10]. At small $p_T$, one does, however, not expect large radiative corrections, as has also been shown in a full NLO calculation for direct color-singlet $J/\psi$ photoproduction [11].

3. COMPARISON OF $J/\psi$ PRODUCTION IN COMPLETE $\gamma\gamma$ COLLISIONS WITH CERN LEP2 DATA

$J/\psi$ production in $\gamma\gamma$ collisions proceeds not only through direct interactions of photons with charm quarks, but also through resolved processes, where one or two of the photons emit quarks and gluons which then interact with the heavy quarks. In the small-$p_T$ range recently studied by the DELPHI experiment at CERN LEP2 [12], $J/\psi$ production is dominated by the single-resolved process $\gamma g \rightarrow J/\psi g$, where one initial state photon and the final state photon in Fig. 1 have to be replaced with gluons. In addition, processes with non-abelian coupling of the gluons and processes involving light quarks have to be taken into account using the relevant color-octet OMEs. Furthermore, contributions from $\chi_{cJ}$ and $\psi'$ decays have to be included, whereas those from $B$ meson decays are suppressed by the small branching fraction.

The differential cross section of $e^+e^- \rightarrow e^+e^-H + X$, where $H$ denotes a generic charmonium state, can be written as

$$d\sigma(e^+e^- \rightarrow e^+e^-H + X) = \int dx_+ f_{\gamma/e}(x_+) \times \int dx_- f_{\gamma/e}(x_-) \sum_{a,b,d} \int dx_a f_{a/\gamma}(x_a, \mu_f) \times \int dx_b f_{b/\gamma}(x_b, \mu_f) \sum_n \langle O^H[n] \rangle \times d\sigma(ab \rightarrow \alpha[n] + d),$$

where $f_{\gamma/e}(x_\pm)$ is the equivalent number of transverse photons radiated by the initial-state positrons and electrons [13], $f_{a/\gamma}(x_a, \mu_f)$ are the PDFs of the photon, $\langle O^H[n] \rangle$ are the OMEs of the $H$ meson, $d\sigma(ab \rightarrow \alpha[n] + d)$ are the differential partonic cross sections, the integrals are over the longitudinal-momentum fractions of the emitted particles w.r.t. the emitting ones, and it is summed over $a, b = \gamma, g, q, \bar{q}$ and $d = g, q, \bar{q}$, with $q = u, d, s$. To leading order in $v$, we need to include the $c\bar{c}$ Fock states $n = 3S_1^{[1]}, 1S_0^{[8]}, 3S_1^{[8]}, 3P_j^{[8]}$ if $H = J/\psi, \psi'$ and $n = 3P_j^{[1]}, 5S_1^{[8]}$ if $H = \chi_{cJ}$, where $J = 0, 1, 2$. With the definition $f_{\gamma/\gamma}(x_\gamma, \mu_f) = \delta(1 - x_\gamma)$, Eq. (1) accommodates the direct, single-resolved, and double-resolved channels.

In our numerical analysis, we use $m_c = (1.5 \pm 0.1)$ GeV, $\alpha = 1/137.036$, and the LO formula for $\alpha_s^{(n_f)}(\mu)$ with $n_f = 3$ active quark flavors. As for the photon PDFs, we use the LO set from
ee → J/ψ + X at LEP2 (Bremsstr.)

![Graph](image)

Figure 2. Transverse-momentum distribution $d\sigma/dp_T$ of $\gamma\gamma \rightarrow J/\psi + X$ via bremsstrahlung at CERN LEP2. The sum of the LO contributions for $X = j$ and $X = \gamma$ is compared with the $2 \rightarrow 3$ part of the NLO contribution for dijet invariant mass $s_{jj} > M^2$ and $M^2/20$. For comparison, also the $3S_1^{[8]}$-channel contributions to the latter are shown.

Glück, Reya, and Schienbein (GRS) [14], which is the only available one that is implemented in the fixed-flavor-number scheme, with $n_f = 3$. We choose the renormalization and factorization scales to be $\mu = \xi_\mu m_T$ and $\mu_f = \xi_f m_T$, respectively, where $m_T = \sqrt{M^2 + p_T^2}$ is the transverse mass of the $J/\psi$ meson, and independently vary the scale parameters $\xi_\mu$ and $\xi_f$ between 1/2 and 2 about the default value 1. As for the $J/\psi$, $\chi_{cJ}$, and $\psi'$ OMEs, we adopt the set determined in Ref. [15] by fitting the Tevatron data using the LO proton PDFs from Martin, Roberts, Stirling, and Thorne (MRST98LO) [16] as our default and the one referring to the LO proton PDFs from the CTEQ Collaboration (CTEQ5L) [17] for comparison (see Table I in Ref. [15]). In the first (second) case, we employ $\Lambda_{QCD}^{(3)} = 204$ MeV (224 MeV), which corresponds to $\Lambda_{QCD}^{(4)} = 174$ MeV (192 MeV [17]), so as to conform with the fit [15]. Incidentally, the GRS photon PDFs are also implemented with $\Lambda_{QCD}^{(3)} = 204$ MeV [14]. In the cases $\psi = J/\psi, \psi'$, the fit results for $\langle O^\psi[1S_0^{[8]}] \rangle$ and $\langle O^\psi[3P_0^{[8]}] \rangle$ are strongly correlated, and one is only sensitive to the linear combination

$$M^\psi_r = \langle O^\psi[1S_0^{[8]}] \rangle + \frac{r}{m^2} \langle O^\psi[3P_0^{[8]}] \rangle, \tag{2}$$
with an appropriate value of $r$. Since Eq. (1) is sensitive to a different linear combination of $\langle O^{c}[S_0^{[8]}] \rangle$ and $\langle O^{c}[P_0^{[8]}] \rangle$ than appears in Eq. (2), we write $\langle O^{c}[S_0^{[8]}] \rangle = \kappa M_r^c$ and $\langle O^{c}[P_0^{[8]}] \rangle = (1 - \kappa) (m_c^2 / r) M_r^c$ and vary $\kappa$ between 0 and 1 about the default value 1/2. The $J$-dependent OMEs $\langle O^{c}[P_0^{[8]}] \rangle$, $\langle O^{\chi_J}[P_0^{[8]}] \rangle$, and $\langle O^{\chi_J}[S_0^{[8]}] \rangle$ satisfy multiplicity relations, which follow to leading order in $v$ from heavy-quark spin symmetry. In order to estimate the theoretical uncertainties in our predictions, we vary the unphysical parameters $\xi_u$, $\xi_f$, and $\kappa$ as indicated above, take into account the experimental errors on $m_c$, the decay branching fractions, and the default OMEs, and switch from our default OME set to the CTEQ5L one, properly adjusting $\Lambda_{QCD}^{(3)}$. We then combine the individual shifts in quadrature, allowing for the upper and lower half-errors to be different.

In Fig. 5, we confront the $p_T^2$ distribution of $e^+ e^- \rightarrow e^+ e^- J/\psi + X$ measured by DELPHI [12] with our NRQCD and CSM predictions. The solid lines and shaded bands represent the central results, evaluated with our default settings, and their uncertainties, respectively. We observe that the DELPHI data clearly favors the NRQCD prediction, while it significantly overshoots the CSM one [18].

4. CONCLUSION

In summary, the production of $J/\psi$ mesons in $\gamma\gamma$ collisions allows for a test of factorization in color-octet processes as predicted by NRQCD and observed at the Tevatron. We have calculated the contributions from direct and resolved photons to $J/\psi$ mesons produced directly or from $\chi_{cJ}$ and $\psi'$ decays. Our NRQCD predictions are nicely confirmed by recent data from the DELPHI collaboration at CERN LEP2, whereas the CSM prediction is clearly disfavored.

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\[ e^+ e^- \rightarrow e^+ e^- J/\psi X \] at LEP2

Figure 3. The cross section \( d\sigma/dp_T^2 \) of \( e^+ e^- \rightarrow e^+ e^- J/\psi + X \) measured by DELPHI [12] as a function of \( p_T^2 \) is compared with the theoretical predictions of NRQCD and the CSM. The solid and dashed lines represent the central predictions obtained with the ME sets referring to the MRST98LO [16] (default) and CTEQ5L [17] PDFs, respectively, while the shaded bands indicate the theoretical uncertainties on the default predictions. The arrows indicate the NRQCD prediction for \( p_T = 0 \) and its \( ^3P_J^{[1]} \), \( ^1S_0^{[8]} \), \( ^3S_1^{[8]} \), and \( ^3P_J^{[8]} \) components.