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ESTIMATES OF Z BOSON AND J/ψ PRODUCTION CROSS SECTIONS AT THE LARGE HADRON COLLIDER

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We calculate the leading-order cross section for the associated production of Z and J/ψ. Processes that include associated production of electroweak bosons and heavy quarkonium can give valuable insight into the production mechanism of quarkonia. We conclude that this process is accessible by the LHC statistics.

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1. INTRODUCTION

The quarkonium is a conceptually simple system that can be described by quantum chromodynamics (QCD) as a pair of quarks with the same flavor. However, the formation and kinematics of heavy quarkonia are still under investigation, with various models (perturbative and nonperturbative QCD) trying to explain it [1].

Theoretical progress has been made on the factorization between the short-distance physics of the heavy-quark creation and the long-distance physics of the bound state formation. The effective field theory, including the color-octet mechanisms based on nonrelativistic QCD (NRQCD) [2], replaced the color singlet model [3, 4]. The color-octet mechanism was used to cancel the infrared divergences in the decay widths of P-wave and D-wave heavy quarkonia [5, 6]. Another very interesting model under test is the color evaporation model [7, 8].

The color singlet model requires that the type of quarkonia produced be determined by the state of the original quarks; just that gives the name to the model. The color evaporation model does not demand the quark pair to be produced in a color singlet state. It can be produced as a color octet state, and the color and spin are then modified via soft interactions with the color field. The color octet mechanism proposes that the quark pairs produced by hard process are not produced with the quantum numbers of the physical quarkonia but evolve into the quarkonia state through radiation of soft gluons.

The framework of NRQCD postulates that color-octet processes associated with Fock state components of the quarkonia contribute to the cross section. The difference from the color-singlet model is that the quarkonium system is produced from heavy quark pairs generated at short distances in color-octet states with the emission of soft gluons (when the quark pair has the quarkonia size), while a color singlet implies that the quark pair is generated with quantum numbers of spin and angular momentum of the meson. In NRQCD, high-energy scales (of the order of m_Q) are separated from low-energy scales in quarkonium production or annihilation rates. The NRQCD Lagrangian is derived from the QCD Lagrangian by integrating out energy–momentum modes of the order of m_Q and higher [9]. It has the form,

$$\mathcal{L} = \mathcal{L}_{heavy} + \mathcal{L}_{light} + \delta\mathcal{L}, \tag{1}$$

where $\mathcal{L}_{light}$ is the standard relativistic QCD Lagrangian for gluons and light quarks,

$$\mathcal{L}_{light} = -\frac{1}{2}\,\mathrm{Tr}(G_{\mu\nu}G^{\mu\nu}) + \sum \bar{q} i \not{D} q, \tag{2}$$

and $\mathcal{L}_{heavy}$ describes the low-momentum modes associated with the heavy quarks:

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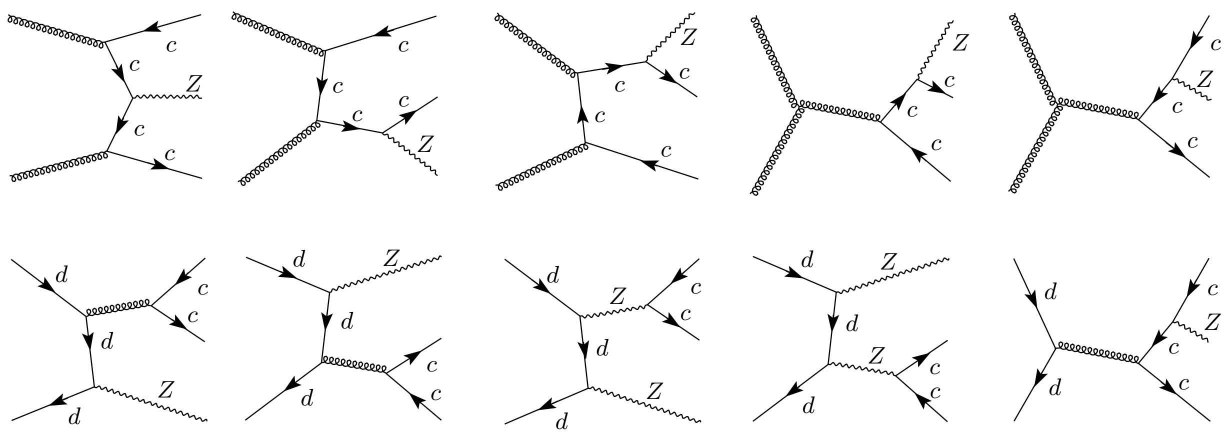

Fig. 1. Leading-order Feynman diagrams for the associated production of a Z boson and J/ψ

$$\mathcal{L}_{heavy} = \psi^\dagger \left(iD_0 + \frac{\mathbf{D}^2}{2m_Q} \right) \psi + \\ + \chi^\dagger \left(iD_0 + \frac{\mathbf{D}^2}{2m_Q} \right) \chi. \quad (3)$$

We let D^μ denote the covariant derivate, which is given by $D^\mu = \partial^\mu + ig_s A^\mu$, where the SU(3) gauge field is $A^\mu = (\phi, \mathbf{A}^\mu)$ and g_s is the QCD coupling given by $\sqrt{4\pi\alpha_s}$; ψ is the Pauli spinor field that annihilates a heavy quark and χ is the Pauli spinor field that creates the heavy antiquark. D_0 and $\mathbf{D}$ are the time and space components of D^μ. The correction term $\delta\mathcal{L}$ includes all possible operators consistent with QCD symmetries.

The measurement of the cross section of the associated production of electroweak bosons and heavy quarkonium cross section is crucial because it can shed light on the production of the quarkonium formation. Also, an excess of events might be a signal for decays of a fermiophobic Higgs boson [10].

It is our purpose to estimate the production cross section for the processes

$$q + \bar{q} \to Z + c\bar{c}\,(^{2S+1}L_J^{(n)}),$$

where $q = u, d, c, s$, and

$$g + g \to Z + c\bar{c}\,(^{2S+1}L_J^{(n)}),$$

where S is the definite spin, L is the orbital angular momentum, J is the total angular momentum, and c is the color multiplicity, considering $c = 1$ (color singlet) and $c = 8$ (color octet). We focus on color-octet states, in which the quarkonium system is produced at short distances and evolves into a color singlet state by the emission of soft gluons. Examples of tree-level Feynman diagrams can be seen in Fig. 1.

We consider these particular processes because they are experimentally favored, due to clean signals from the purely leptonic decays $Z \to l^+l^-$, $W \to l\nu$ and the quarkonia ($\Upsilon \to \mu^+\mu^-$, $J/\psi \to \mu^+\mu^-$) with a highly suppressed background. Searches have been performed in the past at CDF ($\Upsilon + W^\pm$ or Z) with no indication of a signal [11], but recently ATLAS at CERN had an observation of $W^\pm + J/\psi$ with a $5.3\,\sigma$ significance at $\sqrt{s} = 7$ TeV [12]. Unfortunately, theoretical predictions are not in good agreement with the experimental measurements. This discrepancy may be resolved by including contributions from higher-order diagrams and intrinsic charm content in the proton [13].

Our results were obtained using MADONIA (based on MadGraph [14] matrix element generator), which allows calculating the cross sections of these processes. MadGraph provides partonic helicity amplitudes for tree-level Standard Model processes. We focus on the result and the possibility that these processes are accessible by the LHC, rather than on a detailed numerical analysis. We show that the process of $Z + J/\psi$ is also accessible with the current statistics of the LHC.

2. CROSS SECTION RESULTS

There are many studies in the literature involving the associated production of electroweak bosons (W or Z) and heavy quarkonia (Υ or J/ψ) [15–17] and many studies of the specific process of $Z + J/\psi$ that we discuss here [18–20].

We consider two processes that contribute to $p + p \to J/\psi + Z$ at the leading order. We first consider $g + g \to c\bar{c}[n] + Z$ and then $q + \bar{q} \to c\bar{c}[n] + Z$, where q can be either of u, d, s, c and $n = {}^3S_1^{(8)}$, ${}^1S_0^{(8)}$, or ${}^3S_1^{(1)}$.

The cross section of the associated production of J/ψ and Z in the framework of NRQCD is given by

$$\sigma(pp \to \mathcal{Q} + Z + X) = \\ = \sum_n \hat{\sigma}(pp \to c\bar{c}(n) + Z + X)\langle \mathcal{O}^{\mathcal{Q}}(n)\rangle, \quad (4)$$

where $\hat{\sigma}(pp \to c\bar{c}(n)+Z+X)$ is the short-distance cross section and $\langle \mathcal{O}^{\mathcal{Q}}(n)\rangle$ is the long-distance matrix element (LDME). Effects of the order of $Q^2/m_Q^2 \geq 1$ (m_Q being the quark mass and Q the momentum transfer in a production process), which are encoded in short-distance coefficients, can be estimated using the perturbation theory. On the other hand, effects of the order of $Q^2/m_Q^2 < 1$ hadronization are factored into long-distance matrix elements, expressed in powers of v and measured from lattice simulations or from experimental data. LDMEs are expected to be process-independent, not to depend on the production mechanism of the perturbative heavy quarks, and cannot currently be computed from first principles.

The LDMEs are related to the nonperturbative transition probabilities from a $Q\bar{Q}$ system in a quarkonium state, and they scale with a definite power of the intrinsic heavy-quark velocity v. Thus, studies including Υ may be more suitable for the understanding of the NRQCD factorization formalism, since the mass of the bottomonium is greater than that of the charmonium by about three orders of magnitude, implying smaller v^2, and hence faster convergence[1)]. In addition, the asymptotic behavior of the Υ is reached at much higher values of the transverse momentum (p_T), because $m_b > m_c$.

Charmonium on the other hand has the advantage that its mass is closer to Λ_{QCD} than the bottomonium mass. This enables us to perform a nonrelativistic treatment of a quarkonium system for the understanding of the production and decay of bound states of heavy quarks. This strategy makes it possible to embed the present approach in the framework of NRQCD.

The parameter values used as an input for the calculations are [21]:

- CTEQ6L1 parton distribution functions set;
- $m_Z = 91.18$ GeV;
- $\alpha_S(m_Z) = 0.1184$;
- $m_c = 1.275$ GeV, $m_u = 2.3$ MeV, $m_d = 4.8$ MeV, $m_s = 95.5$ MeV;
- $\alpha = 7.297 \cdot 10^{-3}$;
- $\mu_R = \mu_F = m_Z$;

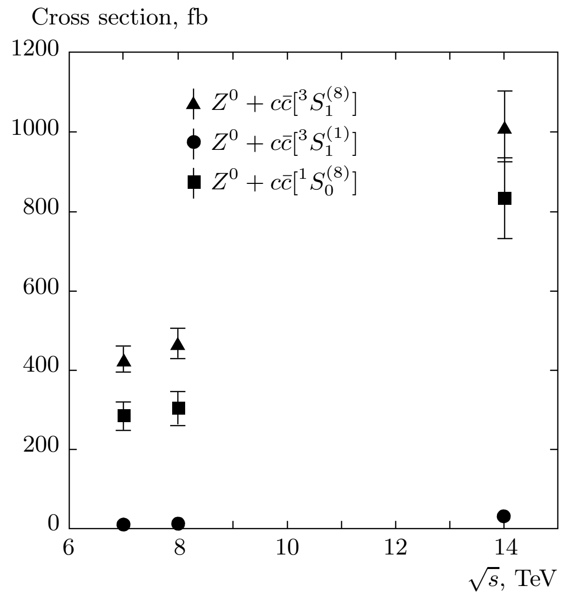

Fig. 2. Cross section as a function of $\sqrt{s}$

- NRQCD matrix elements for the charmonium production [22]

$$– \langle \mathcal{O}(J/\psi)[^3S_1^{(1)}]\rangle = 1.64\,\mathrm{GeV}^3,$$

$$– \langle \mathcal{O}(J/\psi)[^3S_1^{(8)}]\rangle = 0.3 \cdot 10^{-3}\,\mathrm{GeV}^3,$$

$$– \langle \mathcal{O}(J/\psi)[^1S_0^{(8)}]\rangle = 8.9 \cdot 10^{-2}\,\mathrm{GeV}^3.$$

Additional kinematic cuts were applied to J/ψ, following the acceptance of the experiments in LHC. The transverse momentum of J/ψ is required to be $p_T^{J/\psi} > 8$ GeV and its rapidity $|y^{J/\psi}| < 2.4$.

The results of every process is presented in Table 1, where only statistical errors are shown. Processes of the format

$$q + \bar{q} \to c\bar{c}[^3S_1^{(1)}] + Z$$

are expected to have very low cross sections. This is because the c-quark line of the charmonium is connected with the q-quark line by the gluon that transmits color to $c\bar{c}$. This was checked with our simulation and can be seen from the absence of these processes in Table 1 and the very low cross section of the process where $q = c$.

We calculated the cross section for the associated production of a Z boson with J/ψ in proton–proton collisions to the leading order. We list all the partonic contributions to the total cross section considering the $c\bar{c}[^{2S+1}L_J^{(c)}]$, with $S = 1, 2$, $L = S$, $J = 0, 1$, and $c = 1, 8$. The results obtained are visualized in Fig. 2 and summarized in Table 2.

[1)] For the charmonium ground state, $v^2 \approx 0.3$, and for the bottomonium ground state, $v^2 \approx 0.1$.

Table 1. Tree-level cross sections at $\sqrt{s} = X$ TeV

Process	Cross section, fb $\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV	$\sqrt{s} = 14$ TeV
$g + g \to Z + c\bar{c}[^3S_1^{(8)}]$	11.3 ± 3.6	14.1 ± 5.0	32.8 ± 12.1
$c + \bar{c} \to Z + c\bar{c}[^3S_1^{(8)}]$	15.7 ± 5.2	19.7 ± 6.0	47.4 ± 26.1
$u + \bar{u} \to Z + c\bar{c}[^3S_1^{(8)}]$	195.5 ± 20.4	204.4 ± 29.7	408.3 ± 50.7
$d + \bar{d} \to Z + c\bar{c}[^3S_1^{(8)}]$	148.0 ± 21.3	157.4 ± 19.8	342.5 ± 40.4
$s + \bar{s} \to Z + c\bar{c}[^3S_1^{(8)}]$	56.0 ± 10.7	70.3 ± 13.3	181.1 ± 54.4
$g + g \to Z + c\bar{c}[^1S_0^{(8)}]$	281.0 ± 36.0	300.5 ± 42.5	823.1 ± 101.3
$c + \bar{c} \to Z + c\bar{c}[^1S_0^{(8)}]$	0.4 ± 2.9	1.1 ± 1.7	8.2 ± 8.4
$g + g \to Z + c\bar{c}[^3S_1^{(1)}]$	7.0 ± 0.9	9.1 ± 1.0	20.5 ± 2.7
$c + \bar{c} \to Z + c\bar{c}[^3S_1^{(1)}]$	1.8 ± 0.4	2.1 ± 0.8	5.4 ± 1.9

Table 2. Tree-level cross sections at $\sqrt{s} = X$ TeV

Process	Cross section, fb $\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV	$\sqrt{s} = 14$ TeV
$Z + c\bar{c}[^3S_1^{(8)}]$	426.6 ± 32.0	465.8 ± 38.9	1012.1 ± 89.4
$Z + c\bar{c}[^1S_0^{(8)}]$	281.4 ± 36.2	301.6 ± 42.5	831.3 ± 101.3
$Z + c\bar{c}[^3S_1^{(1)}]$	8.8 ± 1.0	11.1 ± 1.3	25.9 ± 3.3

The production of Z in association with J/ψ has been studied before in within the next-to-leading-order (NLO) accuracy [19, 20]. Based on our selections of $p_T^{J/\psi}$ and renormalization and factorization scales, we expect small next-to-leading-order contributions.

It is clear that these processes are reachable within the statistics at the LHC, with the color-octet process dominating. The observation of the associated production will provide a better determination of the $\langle \mathcal{O}^{J/\psi}[^{2S+1}L_J^{(c)}]\rangle$ elements and a good test of the NRQCD factorization formalism.

3. CONCLUSIONS

The vast statistics of the LHC can prove useful in the understanding and testing of the quarkonium sector. Although the study of this sector begun in the late 1970s, there still does not exist a model that can describe the experimental data with high accuracy. Associated production processes of electroweak bosons and heavy quarkonia can be a powerful input for the models to produce more accurate predictions.

We studied the associated production of $Z + c\bar{c}\,(^{2S+1}L_J^{(c)})$, where $S = 0, 1$, $J = 0, 1$, and $c = 1, 8$. We find that the color-octet process is dominantly contributing at the tree level. We listed all the parton contributions to the cross section of this process. We expect that with the collected luminosity at the LHC, there will be enough events to derive a cross section.

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