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Research Article

Z Boson Production via p-p and Pb-Pb Collisions at $\sqrt{s_{pp}} = 5.02\,\text{TeV}$

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We estimate the production of Z^a bosons, with a as the component of a Z vector boson, via p-p collisions using previous work on $J/\Psi, \Psi(2S)$ production in p-p collisions, with the new aspect being the creation of Z^a bosons via quark interactions. We then estimate the production of Z^a bosons via Pb-Pb collisions using modification factors from previous publications.

1. Introduction

This is an extension of our recent work on heavy quark state production via Xe-Xe collisions at $\sqrt{s_{pp}} = 5.44\,\text{TeV}$ [1] and heavy quark state production in Pb-Pb collisions at $\sqrt{s_{pp}} = 5.02\,\text{TeV}$ [2]. More than three decades ago, W and Z bosons were observed at CERN via proton-antiproton experiments at $\sqrt{s_{pp}} = 540\,\text{GeV}$ [3]. CMS experiments on electroweak boson production via relativistic heavy ion collisions (RHIC) are related to our present research [4].

As the photon is the quantum of electromagnetic interactions, a Z boson is a quantum of weak interactions with no electric charge. The Z boson with mass $M_Z \simeq 91\,\text{GeV}$ is a vector boson with quantum spin 1 [5]. Therefore, a Z boson has three components, Z^a, with $a = -1$, 0, and 1.

Our present estimate of the production of Z^a bosons, via Pb-Pb collisions, is motivated by the fact that since Z bosons have only a weak interaction [5], they have little interaction with the nuclear medium and by ALICE experiments that measured Z boson production in Pb-Pb collisions [6] and in p-Pb collisions [7, 8] at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$. The estimate of Z boson production via Pb-Pb collisions makes use of Ref [9], which was based estimates of heavy quark state production in p-p collisions [10]. Note that when the final calculation and results are presented in Sections 3 and 4, the momentum $p^a \rightarrow p_Z$, the momentum of the Z boson produced by Pb-Pb collisions at $\sqrt{s_{pp}} = 5.02\,\text{TeV}$, and $Z^a \rightarrow Z$, a Z boson.

Our present work is also related to an estimate of $\Psi(2S)$ to J/Ψ decay to π mesons [11] except the quarks have a vertex with Z bosons rather than pions and there is no gluon-Z vertex. Also, it was shown [12] that the $\Psi(2S)$ state is approximately a 50%-50% mixture of a standard charmonium and hybrid charmonium state:

$$|\Psi(2S)> \simeq -0.7|c\bar{c}(2S)> + \sqrt{1-0.5}|c\bar{c}g(2S)>, \quad (1)$$

while J/Ψ is essentially a standard $q\bar{q}$ state $|J/\Psi(1S)> \simeq |c\bar{c}(1S)>$, which we use in our estimate of Z^a boson production via $\Psi(2S) \rightarrow J/\Psi(1S) + Z^a$. Having a hybrid component, $c\bar{c}g$, is important for Z boson production from $\Psi(2S)$ decay as the active gluon component of $\Psi(2S)$ produces a Z boson, as shown in Figure 1 (Section 2).

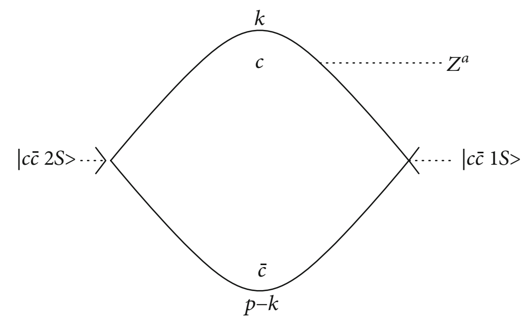


FIGURE 1: $\Psi(2S)$, a hybrid component, to J/psi(1S) + Z^a.

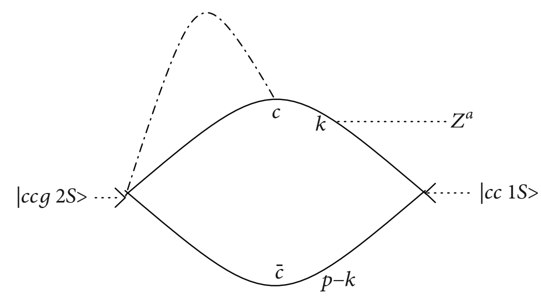


FIGURE 2: $\Psi(2S)$, a standard component, to J/psi(1S) + Z^a.

2. $J/\Psi + Z$ Production in p-p Collisions with $\sqrt{s_{pp}} = 5.02$ TeV

The cross section for $pp \to \Psi(2S) \to J/\Psi(1S) + Z^a$ in terms of f_q [10, 13], the quark distribution function, is

$$\sigma_{pp\to\Psi(2S)\to\frac{J}{\Psi(1S)}+Z^a} = f_q(\bar{x}(y), 2m) f_q\left(\frac{a}{\bar{x}(y)}, 2m\right) \sigma_{\Psi(2S)\to\frac{J}{\Psi(1S)}+Z^a}, \tag{2}$$

where y is the rapidity, $a = 4\,\mathrm{m}^2/\mathrm{s} = 3.6 \times 10^{-7}$, and $\bar{x}(y) = 1.058x(y)$. We take $y = 0$ in the present work, so $\bar{x}(0) \simeq 6.4 \times 10^{-4}$.

For $\sqrt{s} = 5.02$ TeV, the quark distribution functions f_q [10, 13] are

$$\begin{aligned} f_q(\bar{x}(0), 2m) &\simeq 82.37 - 63582.36x(0) \simeq 41.6, \\ f_q\left(\frac{a}{\bar{x}(0)}, 2m\right) &\simeq 82.37 - \frac{a}{\bar{x}(0)} \simeq 82.4. \end{aligned} \tag{3}$$

Therefore, from equations (30), (2), and (3),

$$\sigma_{\mathrm{PbPb}\to\Psi(2S)\to\frac{J}{\Psi(1S)}+Z^a} \simeq 4.46 \times 10^5 \sigma_{pp\to\Psi(2S)\to\frac{J}{\Psi(1S)}+Z^a}. \tag{4}$$

We use the following notation:

$$\sigma_{pp\to\Psi(2S)\to\frac{J}{\Psi(1S)}+Z^a} \equiv \sigma_{HHZ}(p) = g^{\mu\nu}\left(\prod_{HZ^a}^{\mu\nu}(p) + \prod_{HHZ^a}^{\mu\nu}(p)\right), \tag{5}$$

with $\Pi^{\mu\nu}_{HZ^a}(p)$ and $\Pi^{\mu\nu}_{HHZ^a}(p)$ defined below.

The normal $|c\bar{c}(2S)>$ component of $\Psi(2S)$ decaying to $|c\bar{c}(1S)>$ with Z^a production via quark-Z coupling is shown in Figure 2.

In Figure 1, Z^a production with the hybrid $|c\bar{c}g(2S)>$ component of $\Psi(2S)$ is shown.

Figure 3 shows the coupling processes needed for Figures 1 and 2.

In Figure 3(a), the operator giving the gluon sigma coupling is

$$\begin{aligned} \text{gluon-quark coupling} &= \frac{1}{4} S^G_{\kappa\delta}(k) G^{\kappa\delta}(0), \\ S^G_{\kappa\delta}(k) &= \left[\sigma_{\kappa\delta}, S(k)\right]_+ = \sigma_{\kappa\delta} S(k) + S(k)\sigma_{\kappa\delta}, \end{aligned} \tag{6}$$

where $\sigma_{\kappa\delta} = i(\gamma_\kappa\gamma_\delta - g^{\kappa\delta})$ and $G^{\kappa\delta}$ is the gluon field.

In Figure 3(b), with Z^a with a as the component of the vector Z boson and defining $g_c \equiv g_c^V \simeq 0.25$ [5], the ccZ^α coupling is [14]

$$S_{Z^a} = \gamma^a\left(g_c - g_c^A \gamma^5\right). \tag{7}$$

As shown in Section 3.2, the $\gamma^a\gamma^5$ term does not contribute to $\sigma_{HHZ}(p)$, so we define $g_c^A = g_c$.

3. $\Psi(2S)$ Decay to $J/\Psi + Z^a$

In this section, we estimate the decay of $|\Psi(2S)>$ to $|J/\Psi(1S)> + Z^a$ for both the standard and hybrid components of $|\Psi(2S)>$ as shown in Figures 1 and 2.

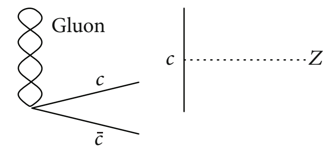
3.1. $\Psi(2S)$ Decay to $J/\Psi + Z^a$ via the Standard Component of $\Psi(2S)$. As in Ref [11], the correlator corresponding to Figure 2 is

$$\prod_{HZ^a}^{\mu\nu}(p) = \sum_{ab} g^2 \int \frac{d^4k}{(2\pi)^4} Tr\left[S(k)\gamma^\mu S_{Z^a} S(p-k)\gamma^\nu\right], \tag{8}$$

where the quark propagator $S(k) = (k + M)/(k^2 - M^2)$, M is the mass of a charm quark (M_c), $k = \sum_\mu k^\mu\gamma^\mu$, and $g^2 = 4\pi\alpha_s \simeq 1.49$ [5]. Since $Tr[S(k)\gamma^\mu S_{Z^a}(k)S(p-k)\gamma^\nu]$ is independent of color, $\sum_{ab} = 3$.

Thus, the correlator for $\Psi(2S)_{\mathrm{normal}}$ decay to $J/\Psi(1S) + Z$ is

$$\prod_{HZ^a}^{\mu\nu}(p) = 3g^2 g_c \int \frac{d^4k}{(2\pi)^4} Tr\left[S(k)\gamma^\mu\gamma^a\left(1-\gamma^5\right)S(p-k)\gamma^\nu\right]. \tag{9}$$



(a) (b)

FIGURE 3: (a) Gluon-quark coupling and (b) c-Z coupling.

The trace in equation (9) is

$$Tr\left[S(k)\gamma^{\mu}\gamma^{a}\left(1-\gamma^{5}\right)S(p-k)\gamma^{\nu}\right] = \frac{Tr\left[(k+M)\gamma^{\mu}\gamma^{a}\left(1-\gamma^{5}\right)\left[(\not p-k)+M\right)\gamma^{\nu}\right]}{\left(k^{2}-M^{2}\right)\left[(k-p)^{2}-M^{2}\right]}. \quad (10)$$

Using the fact that the trace of an odd number of γs vanishes and $Tr[\gamma^5\gamma^\alpha\gamma^\beta\gamma^\delta\gamma^\lambda] = -4i\varepsilon^{\alpha\beta\delta\lambda}$,

$$\begin{aligned} &Tr\left[(k+M)\gamma^{\mu}\gamma^{a}\left(1-\gamma^{5}\right)\left[(\not p-k)+M\right)\gamma^{\nu}\right] \\ &= 4M\left[p_{\nu}g^{a\mu}+p_{a}g^{\mu\nu}-p_{\mu}g^{a\nu}+i\varepsilon^{\mu a\alpha\nu}+2k_{\mu}g^{a\nu}\right. \\ &\quad \left.-2k_{a}g^{\mu\nu}-2ik_{\alpha}\varepsilon^{\alpha\mu a\nu}\right]. \end{aligned} \quad (11)$$

Therefore,

$$\begin{aligned} \prod_{HZ^{a}}^{\mu\nu}(p) &= 12g^{2}g_{c}M\int\frac{d^{4}k}{(4\pi)^{4}} \\ &\cdot\frac{p_{\nu}g^{a\mu}+p_{a}g^{\mu\nu}-p_{\mu}g^{a\nu}+ip_{\alpha}\varepsilon^{\mu a\alpha\nu}+2k_{\mu}g^{a\nu}-2k_{a}g^{\mu\nu}-2ik_{\alpha}\varepsilon^{\alpha\mu a\nu}}{\left(k^{2}-M^{2}\right)\left[(k-p)^{2}-M^{2}\right]}. \end{aligned} \quad (12)$$

Using

$$\begin{aligned} \int\frac{d^{4}k}{(4\pi)^{4}}\frac{1}{\left(k^{2}-M^{2}\right)\left[(k-p)^{2}-M^{2}\right]} &= \frac{\left(2M^{2}-p^{2}/2\right)}{(4\pi)^{2}}I_{0}(p), \\ \int\frac{d^{4}k}{(4\pi)^{4}}\frac{k^{\mu}}{\left(k^{2}-M^{2}\right)\left[(k-p)^{2}-M^{2}\right]} &= \frac{p^{\mu}\left(\left(2M^{2}-p^{2}\right)/2\right)}{(4\pi)^{2}}I_{1}(p), \end{aligned} \quad (13)$$

one finds

$$\begin{aligned} \prod_{HZ^{a}}^{\mu\nu}(p) &= AM\frac{\left(2M^{2}-p^{2}\right)/2}{(4\pi)^{2}}\left[\left(p_{\nu}g^{a\mu}-p_{\mu}g^{a\nu}+ip_{\alpha}\varepsilon^{\mu a\alpha\nu}\right)I_{0}(p)\right. \\ &\quad \left.+\left(2p_{\mu}g^{a\nu}-2p_{a}g^{\mu\nu}-2ip_{\alpha}\varepsilon^{\mu a\alpha\nu}\right)I_{1}(p)\right]A = 12g^{2}g_{c}, \end{aligned} \quad (14)$$

with

$$\begin{aligned} I_{0}(p) &= \int_{0}^{1}d\alpha\frac{1}{p^{2}\left(\alpha-\alpha^{2}\right)-M^{2}}, \\ I_{1}(p) &= \int_{0}^{1}d\alpha\frac{\alpha}{p^{2}\left(\alpha-\alpha^{2}\right)-M^{2}}. \end{aligned} \quad (15)$$

3.2. $\Psi(2S)$ Decay to $J/\Psi + Z^a$ via the Hybrid Component of $\Psi(2S)$. The two-point correlator for the hybrid $\Psi(2S)$-J/Ψ, corresponding to Figure 1, without the gluon-Z or quark-Z coupling is [12] (see equation (18))

$$\begin{aligned} \prod_{HH}^{\mu\nu}(p) &= \frac{3g^{2}}{4}\int\frac{d^{4}k}{(2\pi)^{4}}Tr\left[\left[\sigma_{\kappa\delta}S(k)\right]_{+}\gamma_{\lambda}S(p-k)\gamma_{\mu}\right] \\ &\quad\cdot Tr\left[G^{\nu\lambda}(0)G^{\kappa\delta}(0)\right]. \end{aligned} \quad (16)$$

The correlator $\Pi^{\mu\nu}_{HHq\bar{q}Z^a}$, obtained from Figure 1, is

$$\begin{aligned} \prod_{HHZ^{a}}^{\mu\nu}(p) &= \frac{3g^{2}}{4}\int\frac{d^{4}k}{(2\pi)^{4}}Tr\left[\left[\sigma_{\kappa\delta}S(k)\right]_{+}\gamma_{\lambda}S_{Z^{a}}S(p-k)\gamma_{\mu}\right] \\ &\quad\cdot Tr\left[G^{\nu\lambda}(0)G^{\kappa\delta}(0)\right]. \end{aligned} \quad (17)$$

Note that [15] (with $\langle G^2\rangle = 0.476\,\mathrm{GeV}^2$)

$$Tr\left[G^{\nu\lambda}(0)G^{\kappa\delta}(0)\right] = (2\pi)^{4}\frac{12}{96}\left\langle G^{2}\right\rangle\left(g^{\nu\kappa}g^{\lambda\delta}-g^{\nu\delta}g^{\kappa\lambda}\right), \quad (18)$$

$$\left[\sigma_{\kappa\delta}S(k)\right]_{+} = \frac{i\left[-2g^{\kappa\delta}(k+M)+2M\gamma^{\kappa}\gamma^{\delta}+k_{\alpha}\left(\gamma^{\kappa}\gamma^{\delta}\gamma^{\alpha}+\gamma^{\alpha}\gamma^{\kappa}\gamma^{\delta}\right)\right]}{k^{2}-M^{2}}. \quad (19)$$

Therefore,

$$\begin{aligned} \prod_{HHZ^{a}}^{\mu\nu}(p) &= B\int\frac{d^{4}k}{(2\pi)^{4}}\frac{i}{\left(k^{2}-M^{2}\right)\left[(p-k)^{2}-M^{2}\right]} \\ &\quad\cdot\left(g^{\nu\kappa}g^{\lambda\delta}-g^{\nu\delta}g^{\lambda\kappa}\right)Tr^{A1}, \\ M^{2}B &= \frac{3g^{2}g_{c}}{4}(2\pi)^{4}\frac{12}{96}\left\langle G^{2}\right\rangle \simeq 25.87\,\mathrm{GeV}^{2}, \end{aligned} \quad (20)$$

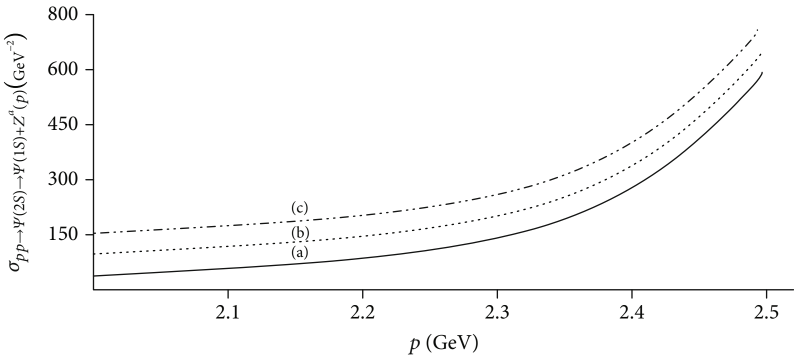


FIGURE 4: $\sigma_{pp\to\Psi(2S)\to J/\Psi(1S)+Z^a}$ with p_Z = (a) 1, (b) 2, and (c) 3 MeV.

with

$$Tr^{A1} \equiv Tr\Big[(k_\alpha\left(\gamma^\kappa\gamma^\delta\gamma^\alpha + \gamma^\alpha\gamma^\kappa\gamma^\delta\right)\gamma^a(1-\gamma_5)\gamma^\lambda((\not p - k) + M)\gamma^\mu \cdot \left[-2g^{\kappa\delta}(k+M) + 2M\gamma^\kappa\gamma^\delta\right]\gamma^\lambda\gamma^a(1-\gamma_5)((\not p - k) + M)\gamma^\mu\Big]. \tag{21}$$

Note that $(g^{\nu\kappa}g^{\lambda\delta} - g^{\nu\delta}g^{\lambda\kappa})g^{\kappa\delta} = 0.0$, so the $g^{\kappa\delta}$ term in equation (21) vanishes. Therefore, from equation (21),

$$\left(g^{\nu\kappa}g^{\lambda\delta} - g^{\nu\delta}g^{\lambda\kappa}\right)Tr^{A1} = 2Tr\Big[\Big[(k_\alpha\left(\gamma^\nu\gamma^\lambda\gamma^\alpha + \gamma^\alpha\gamma^\nu\gamma^\lambda - 2g^{\lambda\nu}\gamma^\alpha\right) \cdot \gamma^a(1-\gamma_5)\gamma^\lambda + 4M\left(\gamma^\nu - \gamma^\lambda\right)\gamma^a(1-\gamma_5)\Big] \cdot ((\not p - k) + M)\gamma^\mu\Big]. \tag{22}$$

Since $Tr[\text{odd number of } \gamma\, s] = 0$,

$$\left(g^{\nu\kappa}g^{\lambda\delta} - g^{\nu\delta}g^{\lambda\kappa}\right)Tr^{A1} = 2MTr\Big[(k_\alpha\left(\gamma^\nu\gamma^\lambda\gamma^\alpha + \gamma^\alpha\gamma^\nu\gamma^\lambda - 2g^{\lambda\nu}\gamma^\alpha\right)\gamma^a(1-\gamma_5)\gamma^\lambda\gamma^\mu + 4\left(p_\beta - k_\beta\right)\left(\gamma^\nu - \gamma^\lambda\right)\gamma^a(1-\gamma_5)\gamma^\beta\gamma^\mu\Big]. \tag{23}$$

As in equation (11), using $\varepsilon^{\alpha\beta\lambda\lambda} = 0$, one obtains for the $4-\gamma$ terms

$$\begin{aligned} &2MTr\Big[-2k_\alpha g^{\lambda\nu}\gamma^\alpha\gamma^a(1-\gamma_5)\gamma^\lambda\gamma^\mu + 4\left(p_\beta - k_\beta\right)\left(\gamma^\nu - \gamma^\lambda\right)\gamma^a(1-\gamma_5)\gamma^\beta\gamma^\mu\Big] \\ &= 16M\big[-\left(k_a g^{\mu\nu} + k_\mu g^{a\nu} - k_\nu g^{a\mu}\right) + ik_\alpha\varepsilon^{\alpha a\nu\mu}) \\ &\quad + 2\Big[\left(p_\mu - k_\mu\right)g^{\nu a} + (p_a - k_a)g^{\nu\mu} - (p_\nu - k_\nu)g^{\mu a} \\ &\quad - \left(p_\mu - k_\mu\right)g^{\nu a} - (p_a - k_a)g^{\nu\mu} + (p_\nu - k_\nu)g^{\mu a} \\ &\quad + 2i\left(p_\beta - k_\beta\right)\left(\varepsilon^{\nu a\beta\mu} - \varepsilon^{\nu a\beta\mu}\right)\Big]\Big]. \end{aligned} \tag{24}$$

For the $6-\gamma$ terms in equation (22),

$$\begin{aligned} Tr\left[\gamma^\alpha\gamma^\beta\gamma^\delta\gamma^\lambda\gamma^\mu\gamma^\nu\right] = 4\Big(&g^{\alpha\beta}Tr\left[\gamma^\delta\gamma^\lambda\gamma^\mu\gamma^\nu\right] + g^{\alpha\delta}Tr\left[\gamma^\beta\gamma^\lambda\gamma^\mu\gamma^\nu\right] \\ &+ g^{\alpha\lambda}Tr\left[\gamma^\beta\gamma^\delta\gamma^\mu\gamma^\nu\right] + g^{\alpha\mu}Tr\left[\gamma^\beta\gamma^\delta\gamma^\lambda\gamma^\nu\right] \\ &+ g^{\alpha\nu}Tr\left[\gamma^\beta\gamma^\delta\gamma^\lambda\gamma^\mu\right]\Big), \end{aligned} \tag{25}$$

$$Tr\left[\gamma^\alpha\gamma^\beta\gamma^\delta\gamma^\lambda\gamma^\mu\gamma^\nu\gamma_5\right] = -16i\left(g^{\alpha\beta}\varepsilon^{\delta\lambda\mu\nu} + g^{\alpha\delta}\varepsilon^{\beta\lambda\mu\nu} + g^{\alpha\lambda}\varepsilon^{\beta\delta\mu\nu} + \cdots\right). \tag{26}$$

From equations (22), (25), and (26) and using $\varepsilon^{\beta\beta\mu\nu} = 0$, the $6-\gamma$ terms in equation (22) are

$$\begin{aligned} &2MTr\Big[(k_\alpha\left(\gamma^\nu\gamma^\lambda\gamma^\alpha + \gamma^\alpha\gamma^\nu\gamma^\lambda\right)\gamma^a(1-\gamma_5)\gamma^\beta\gamma^\mu\Big] \\ &= 4M\left(3k_a g^{\nu\mu} + k_\mu g^{a\nu} + k_\nu g^{a\mu}\right). \end{aligned} \tag{27}$$

Defining $\Pi_Z^{\mu\nu}(p) = \Pi_{HZ^a}^{\mu\nu}(p) + \Pi_{HHZ^a}^{\mu\nu}(p)$, with p_Z as the Z boson momentum, from equations (14), (22), (23), (24), (27), and (13),

$$\begin{aligned} \prod_Z^{\mu\nu}(p) = M\frac{(2M^2 - p^2)/2}{(4\pi)^2}\Big[\Big(&A\left(p_\nu g^{a\mu} - p_\mu g^{a\nu} + ip_\alpha\varepsilon^{\mu a\alpha\nu}\right) \\ &+ B\Big(3\left(p_\mu g^{\nu a} + p_Z g^{\nu\mu} - p_\nu g^{\mu a} - p_\mu g^{\nu a} - p_Z g^{\nu\mu}\right. \\ &+ p_\lambda g^{\mu a} + p_\lambda g^{\mu a})))I_0(p) + \Big(A\left(2p_\mu g^{a\nu} - 2p_Z g^{\mu\nu} - 2ip_\alpha\varepsilon^{\mu a\alpha\nu}\right) \\ &- 32B\left(p_Z g^{\nu\mu} + p_\mu g^{a\nu} - p_\nu g^{a\mu} - p_Z g^{\mu\nu} - p_\mu g^{a\nu} + p_\mu g^{a\nu}\right) \\ &+ ip_\alpha\varepsilon^{\alpha a\nu\mu}) - 2\left(p_\mu g^{\nu a} + p_Z g^{\nu\mu} - p_\nu g^{\mu a} + p_\mu\right)g^{\nu a} - p_Z)g^{\nu\mu} \\ &+ p_\nu)g^{\mu a})I_1(p). \end{aligned} \tag{28}$$

From equations (5) and (20), taking the μ sum with $g^{\mu\nu}$,

$$\begin{aligned}\sigma_{HHZ}(p) &= 4.46\times 10^5 M\frac{(2M^2-p^2)/2}{(4\pi)^2}Bp_Z(I_0(p)+I_1(p)) \\ &= 7.4\times 10^4\,\mathrm{GeV}^{-2}\times p_Z\frac{(2M^2-p^2)/2}{M}(I_0(p)+I_1(p)),\end{aligned} \tag{29}$$

with the Z boson momentum $p_Z \simeq 1-3\,\mathrm{MeV}$, so $p_z \ll p$ as $p \simeq 2-3\,\mathrm{GeV}$ in our calculation.

4. Calculation of $\sigma_{pp\to\Psi(2S)} \to \Psi(1S) + Z^a$ via Calculation of $\sigma_{HHZ}(p)$ for $p \simeq M_c \simeq 1.27\,\mathrm{GeV}$

Carrying out the integrals for $I_0(p), I_1(p)$ shown in equation (15), one obtains from equation (29) the values of $\sigma_{HHZ}(p)$, with $p_Z = 1, 2, 3\,\mathrm{MeV} = 0.001, 0.002, 0.003\,\mathrm{GeV}$, which from equation (5) is the cross section $\sigma_{pp\to\Psi(2S)\to J/\Psi(1S)+Z^a}$ with the proton-proton energy = 5.02 TeV, shown in Figure 4.

Note that [5] the units for a cross section are $nb \propto h\,c$ GeV^{-2}. As it is customary, we take $h = c = 1$.

5. $J/\Psi + Z$ Production in Pb-Pb Collisions with $\sqrt{s_{pp}} = 5.02\,\mathrm{TeV}$

The cross section for the production of a heavy quark state Φ with helicity $\lambda = 0$ (for unpolarized collisions [10]) in the color octet model in Pb-Pb collisions is given by [9]

$$\sigma_{\mathrm{PbPb}\to\Phi} = R^E_{\mathrm{PbPb}}N^{\mathrm{PbPb}}_{\mathrm{bin}}\sigma_{pp\to\Phi}, \tag{30}$$

where $N^{\mathrm{PbPb}}_{\mathrm{bin}}$ is the number of binary collisions, R^E_{PbPb} is the nuclear modification factor, and E is the total energy in Pb-Pb collisions.

From [2], $R^E_{\mathrm{PbPb}}N^{\mathrm{PbPb}}_{\mathrm{bin}} \simeq 130$. Therefore,

$$\sigma_{\mathrm{Pb\text{-}Pb}\to\Psi(2S)\to\frac{J}{\Psi(1S)}+Z^a} \simeq 130\times\sigma_{pp\to\Psi(2S)\to\frac{J}{\Psi(1S)}+Z^a}, \tag{31}$$

or $\sigma_{\mathrm{Pb\text{-}Pb}\to\Psi(2S)\to J/\Psi(1S)+Z^a}$ is approximately 130 times the results shown in Figure 4.

6. Conclusions

Using the relationship between the cross sections $\sigma_{\mathrm{PbPb}\to\Psi(2S)\to J/\Psi(1S)+Z}$ and $\sigma_{pp\to\Psi(2S)\to J/\Psi(1S)+Z}$ shown in equation (30) and $\Psi(2S)$ decay to J/Ψ + Z for both the standard and hybrid components of $\Psi(2S)$, the cross section $\sigma_{HHZ}(p) \equiv \sigma_{\mathrm{PbPb}\to\Psi(2S)\to J/\Psi(1S)+Z}$ was estimated for $\sqrt{s_{pp}} = 5.02$ TeV and the Z boson momentum $p_Z = 1, 2,$ and 3 MeV, as shown in the figure. This should be useful for the experimental measurement of Z boson production via Pb-Pb collisions at $\sqrt{s_{pp}} = 5.02\,\mathrm{TeV}$. For simplicity, we assumed that the rapidity $= y = 0$, where $y \equiv \ln((E+p_L)/(E-p_L))$ with p_L as the longitudinal momentum. Current experiments [6] measure Z boson production via Pb-Pb collisions at $\sqrt{s_{pp}} = 5.02\,\mathrm{TeV}$ at large rapidities.

Data Availability

All data for our article can be found in the references, especially Refs [4–6, 12, 15], as is stated in our article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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