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$\bar{f}f \to \phi Z$ Collision in the Randall-Sundrum Model

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Abstract: The Randall-Sundrum (RS) model is one of the most attractive candidates to solve the gauge hierarchy problem in the Standard Model (SM). This is a model in five-dimensional space time with a warped extra spatial dimension compactified on the orbifold S^1/Z_2. This paper studies the production of the radion and Z boson in the $\bar{f}f \to Z\phi$ collision process with the polarization of the $\bar{f}, f$ beams. The study results show that the value of the differential cross-section is the greatest when the angle between the direction of the beam radion and beam f approximately 90 degrees for $e_L^+ e_L^-$ and 180 degrees for $\mu_L^+ \mu_R^-$. Based on the results, it is expected that the reaction can give observable cross-sections in Larger Hadron Collider (LHC) at a high degree of polarization.

Keywords: Higgs boson, radion, RS, cross-section, $\bar{f}f$.

1. Introduction

The Randall-Sundrum model with compact extra dimensions explain hierarchy in terms of geometry and at the same time, the hierarchical structures observed in the fermionic masses and mixing angles via so-called geometrical sequestering [1]. This can be achieved naturally within the framework of a warped extra dimension, first proposed by Randall and Sundrum [2]. The SM on a background consisting of Minkowski space, embedded in a slice of five-dimensional anti de-Sitter geometry (AdS_5) with curvature *k*. The fifth dimension is an orbifold S^1/Z_2 of size *r*, and has two branes located at orbifold fixed points, the UV and the IR brane.

In the original RS model, there are two new particles beyond the Standard Model. One is a spin-2 graviton (and its Kaluza-Klein excitations) and the other is a spin -0 scalar-field radion ϕ (radion is a electrically neutral particle) which is a metric fluctuation along the extra dimension. The radion acquires the mass of the order of the electroweak scale due to the Goldberger-Wise mechanism and it could be a lightest extra particle in the RS model [3, 4]. The radion, therefore, is expected to be the first signature of warped extra dimension models in direct search experiments such as the LHC. Phenomenology of the radion can be characterized by two parameters, a radion mass m_ϕ and a scale parameter Λ_ϕ. The search experiments of the Higgs boson at the LHC give stringent constraints on the parameters of the radion [5]. Furthermore, there could be a mixing between the radion and the SM Higgs boson through the scalar-curvature mixing term

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in the four dimensional effective action [6, 7]. The characteristic features of the radion have been studied, including the phenomenological aspects of the radion in various colliders [8, 9, 10, 11, 12, 13, 14]. In the papers ago [15, 16, 17, 18], we studies the $e^+e^- \to \gamma\phi$, $\bar{f}f \to \phi\phi, \phi h$ $\gamma f \to f\phi$ collisions. Next, in this paper, we have studied the production of the radion at $\bar{f} f \to Z\phi$ collider.

This paper is organized as follows: In Sec.2, we briefly review the RS model. Production of the radion and Z boson in the $\bar{f} f$ collider is calculated in Sec.3. We show our numerical results with discussion in Sec.4 and our conclusions in Sec.5.

2. A review of RS model

The experiments at the LHC have already used the dijet invariant mass to constrain the mass of these new resonances [19, 20]. The RS model is one of a number of new physics models which can solve the large hierarchy problem of the weak and the Plank scale.

The RS model is based on a 5D space-time with the fifth dimension is compactified on an S^1/Z_2 orbifold which has two fixed points, $\phi = 0$ and $\phi = \pi$. They correspond to the high energy brane and the brane we live on, respectively. Graviton is the only particle that can propagate through the bulk between these two branes. The 5-dimensional warped matric is given by [21]:

$$ds^2 = e^{-2kr|\phi|}(\eta_{\mu\nu} + \frac{2}{M_{PL}^{\frac{3}{2}}} h_{\mu\nu})dx^\mu dx^\nu - r^2 d\phi^2, \quad 0 \le |\phi| \le \pi, \quad (1)$$

with $\eta_{\mu\nu} = diag(1,-1,-1,-1)$ and where ϕ is the five dimensional coordinate, k is a scale of order of the Plank scale, r is compactification radius of the extra dimensional circle and $h_{\mu\nu}$ is the graviton metric.

The 4-dimensional efective Lagrangian is then:

$$L = -\frac{\phi_0}{\Lambda_\phi} T^\mu_\mu - \frac{1}{\hat{\Lambda}_W} T^{\mu\nu}(x) \sum_{n=1}^{\infty} h^n_{\mu\nu}, \quad (2)$$

where $\Lambda_\phi \equiv \sqrt{6} M_{PL}\Omega_0$ is the VEV of the radion field and $\hat{\Lambda}_W \equiv \sqrt{2} M_{PL}\Omega_0$. $T^{\mu\nu}(x)$ is the energy-momentum tensor of TeV brane localized SM fiels. The T^μ_μ is the trace of the energy-momentum tensor which is given at the tree level as

$$T^\mu_\mu = \sum_f m_f \bar{f}f - 2m_W^2 W^+_\mu W^{-\mu} - m_Z^2 Z_\mu Z^\mu + (2m_{h_0}^2 h_0^2 - \partial_\mu h_0 \partial^\mu h_0) + ... \quad (3)$$

For the interaction of the h, ϕ and $h^n_{\mu\nu}$, we begin with the ZZ couplings of the h and ϕ. The h_0 has standard ZZ coupling while the ϕ_0 has ZZ coupling deriving from the interaction $-\frac{\phi_0}{\Lambda_\phi} T^\mu_\mu$ using the covariant derivative portions of $T^\mu_\mu(h_0)$. After rewriting these interactions in terms of the mass eigenstates, the top interaction of the h, ϕ with ZZ couplings is given by the Feynman rules [8]:

$$V(Z,Z,h) = i\frac{gm_Z}{c_W}(d+\gamma b)\eta^{\mu\nu}, \; V(Z,Z,\phi) = \frac{gm_Z}{c_W}(c+\gamma a)\eta^{\mu\nu}. \quad (4)$$

The h_0 has standard fermionic couplings and the fermionic couplings of the ϕ_0 derive from $-\frac{\phi_0}{\Lambda_\phi}T^\mu_\mu$ using the Yukawa interaction contributions to T^μ_μ. The results Feynman rules for interactions of the h, ϕ with fermionic couplings [8]:

$$V(\bar{f},f,h) = -i\frac{gm_Z}{2m_W}(d+\gamma b),\ V(\bar{f},f,\phi) = -i\frac{gm_Z}{2m_W}(c+\gamma a). \quad (5)$$

Here: $a = -\frac{\cos\theta}{Z}; b = \frac{\sin\theta}{Z}; c = \sin\theta + \frac{6\xi\gamma}{Z}\cos\theta;\ d = \cos\theta - \frac{6\xi\gamma}{Z}\sin\theta;$

where: $\tan 2\theta \equiv 12\xi\gamma Z\frac{m^2_{h_0}}{m^2_{\phi_0} - m^2_{h_0}(Z^2 - 36\xi^2\gamma^2)};\ Z^2 \equiv 1 + 6\xi\gamma^2(1-6\xi); \gamma \equiv \frac{v_0}{\Lambda_\phi}.$

3. The matrix element of $\bar{f}f \to Z\phi$ collisions

In this paper, we are interested in the production of radion and Z boson in the high energy $\bar{f}f$ colliders when the $\bar{f}, f$ beams are polarized,

$$f(p_1) + \bar{f}(p_2) \to \phi(k_1) + Z(k_2). \quad (6)$$

Here p_i, k_i stand for the momentum of the particle, respectively. There are three Feynman diagrams contributing to reaction (6), representing the s, u, t – channel exchange depicted in Figure 1.

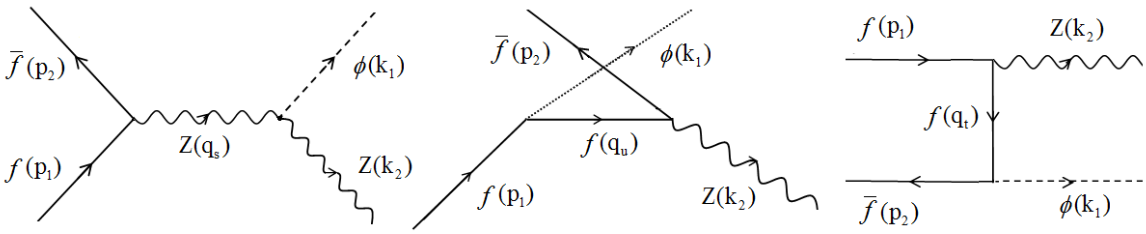

Figure 1. Feynman diagrams for $\bar{f}f \to \phi Z$.

Use Feynman rules, the matrix element for this process can be written as the following cases:

+ For s – channel:

$$M_s = \frac{-ig^2 m_Z}{4C_w^2(q_s^2 - m_Z^2)}\left(g_{\nu\mu} - \frac{q_\mu q_\nu}{m_Z^2}\right)(c+\gamma a)\eta^{\nu\alpha}\bar{v}(p_2)\gamma^\mu(v_f - a_f\gamma^5)u(p_1)\varepsilon^*_\alpha(k_2), \quad (7)$$

$$M_{sLL} = \frac{-ig^2 m_Z(v_f + a_f)}{8C_w^2(q_s^2 - m_Z^2)}\left(g_{\nu\mu} - \frac{q_\mu q_\nu}{m_Z^2}\right)(c+\gamma a)\eta^{\nu\alpha}\bar{v}(p_2)\gamma^\mu(1-\gamma^5)u(p_1)\varepsilon^*_\alpha(k_2), \quad (8)$$

$$M_{sRR} = \frac{-ig^2 m_Z(v_f - a_f)}{8C_w^2(q_s^2 - m_Z^2)}\left(g_{\nu\mu} - \frac{q_\mu q_\nu}{m_Z^2}\right)(c+\gamma a)\eta^{\nu\alpha}\bar{v}(p_2)\gamma^\mu(1+\gamma^5)u(p_1)\varepsilon^*_\alpha(k_2), \quad (9)$$

+ For u – channel:

$$M_u = \frac{ig^2 m_f}{8C_W^2(q_u^2 - m_f^2)}(c+\gamma a)\bar{v}(p_2)\gamma^\mu(v_f - a_f\gamma^5)(\hat{q}_u + m_f)u(p_1)\varepsilon_\mu^*(k_2), \quad (10)$$

$$M_{uLR} = \frac{ig^2 m_f(v_f + a_f)}{16C_W^2(q_u^2 - m_f^2)}(c+\gamma a)\bar{v}(p_2)\gamma^\mu\hat{q}_u(1+\gamma^5)u(p_1)\varepsilon_\mu^*(k_2), \quad (11)$$

$$M_{uRL} = \frac{ig^2 m_f(v_f - a_f)}{16C_W^2(q_u^2 - m_f^2)}(c+\gamma a)\bar{v}(p_2)\gamma^\mu\hat{q}_u(1-\gamma^5)u(p_1)\varepsilon_\mu^*(k_2), \quad (12)$$

$$M_{uLL} = \frac{ig^2 m_f^2(v_f + a_f)}{16C_W^2(q_u^2 - m_f^2)}(c+\gamma a)\bar{v}(p_2)\gamma^\mu(1-\gamma^5)u(p_1)\varepsilon_\mu^*(k_2), \quad (13)$$

$$M_{uRR} = \frac{ig^2 m_f^2(v_f - a_f)}{16C_W^2(q_u^2 - m_f^2)}(c+\gamma a)\bar{v}(p_2)\gamma^\mu(1+\gamma^5)u(p_1)\varepsilon_\mu^*(k_2). \quad (14)$$

+ For t – channel:

$$M_t = \frac{ig^2 m_f}{8C_W^2(q_u^2 - m_f^2)}(c+\gamma a)\bar{v}(p_2)(\hat{q}_t + m_f)\gamma^\mu(v_f - a_f\gamma^5)u(p_1)\varepsilon_\mu^*(k_2), \quad (15)$$

$$M_{tLR} = \frac{ig^2 m_f(v_f - a_f)}{16C_W^2(q_u^2 - m_f^2)}(c+\gamma a)\bar{v}(p_2)(1+\gamma^5)\hat{q}_t\gamma^\mu u(p_1)\varepsilon_\mu^*(k_2), \quad (16)$$

$$M_{tRL} = \frac{ig^2 m_f(v_f + a_f)}{16C_W^2(q_u^2 - m_f^2)}(c+\gamma a)\bar{v}(p_2)(1-\gamma^5)\hat{q}_t\gamma^\mu u(p_1)\varepsilon_\mu^*(k_2), \quad (17)$$

$$M_{tLL} = \frac{ig^2 m_f^2(v_f + a_f)}{16C_W^2(q_u^2 - m_f^2)}(c+\gamma a)\bar{v}(p_2)(1+\gamma^5)\gamma^\mu u(p_1)\varepsilon_\mu^*(k_2), \quad (18)$$

$$M_{tRR} = \frac{ig^2 m_f^2(v_f - a_f)}{16C_W^2(q_u^2 - m_f^2)}(c+\gamma a)\bar{v}(p_2)(1-\gamma^5)\gamma^\mu u(p_1)\varepsilon_\mu^*(k_2). \quad (19)$$

Using these matrix elements, we evaluated the differential and total cross-section for radion and Z boson production in the $\bar{f}f$ collider in the next section.

4. Numerical results

In this section, we present the numerical results for differential and total cross-section for radion and Z boson production in the $\bar{f}f$ collider when the $\bar{f}, f$ beams are polarized. From the expression of the cross-section:

$$\frac{d\sigma}{d(\cos\theta)} = \frac{1}{64\pi s}\frac{|\vec{k}|}{|\vec{p}|}|M|^2, \quad (20)$$

where M is the matrix element, we assess the number, make the identification and evaluation of the results obtained from the dependence of the differential cross-section by $\cos\theta$, the total cross-section fully follows $\sqrt{s}$ while the $\bar{f}, f$ beams are polarization. We obtain some estimates for the cross-section as follows:

i) We show in Fig.2, Fig.3 the behavior of $d\sigma / d\cos\theta$ at fixed collision energy $\sqrt{s} = 3000GeV$ (this energy can be done in LHC, in future can up to 14TeV [22]). We have chosen mass Higgs boson is $125GeV$ and mass radion is $10GeV$. The $\bar{f}, f$ beams are polarized the polarization left (L) or right (R), respectively. For $e^+e^- \to \phi Z$ collision (Fig.2), we see that the differential cross-section obtained is the biggest when e^+, e^- beams are polarized left-left and the largest when $\cos\theta = 0$. For the mixing between the case polarization of e^+, e^-, we obtain the differential cross-section is less than $e_L^+ e_L^-$, $e_R^+ e_R^-$, $e_L^+ e_R^-$, $e_R^+ e_L^-$.

For $\mu^+\mu^- \to \phi Z$ collision (Fig.3), we see that the differential cross-section obtained is the biggest when μ^+ beams are polarized left, μ^- beams are polarized right and the largest when $\cos\theta \approx -1$. The maximum differential cross-section obtained in $\mu^+\mu^-$ collision bigger than e^+e^- collision about 10^3 time.

ii) In Fig.4, Fig.5, we plot total cross-section as function of the collision energy $\sqrt{s}$ with the collision energy is in region $1000GeV \le \sqrt{s} \le 5000GeV$.

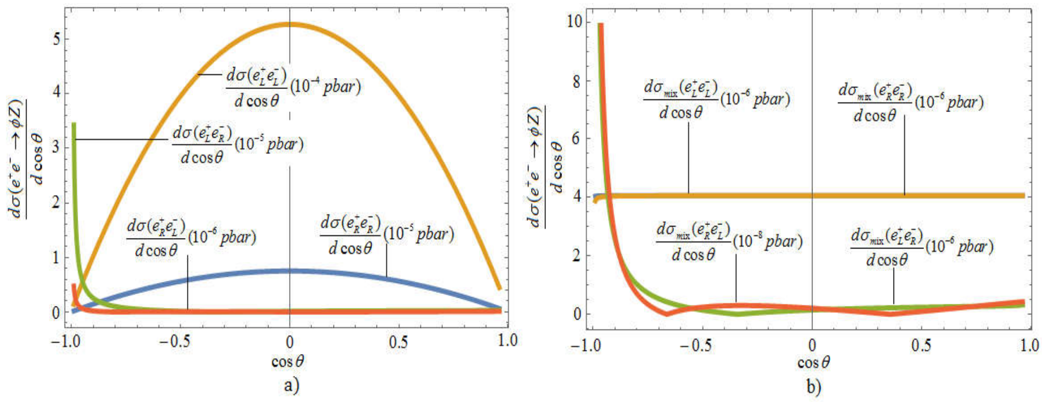

Figure 2. Differential cross-section of the process $e^+e^- \to \phi Z$ as a function of $\cos\theta$.

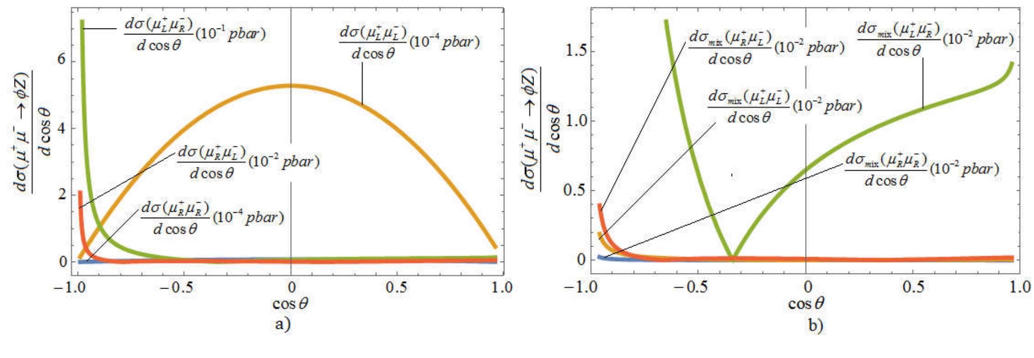

Figure 3. Differential cross-section of the process $\mu^+\mu^- \to \phi Z$ as a function of cosθ.

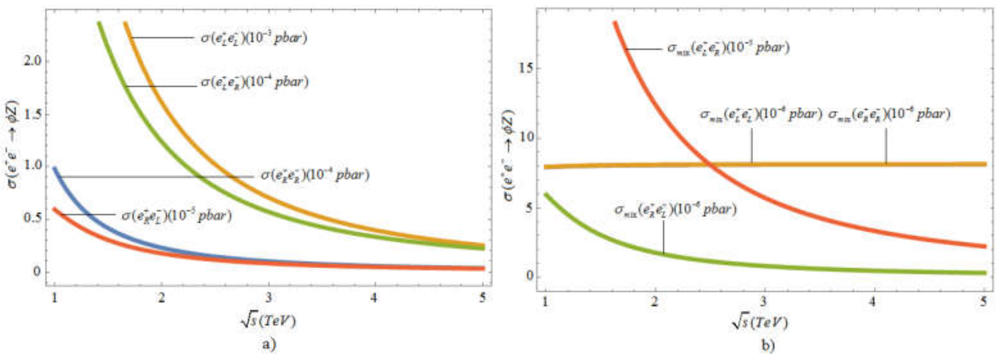

Figure 4. Total cross-section of the process $e^+e^- \to \phi Z$ as a function of the collision energy $\sqrt{s}$.

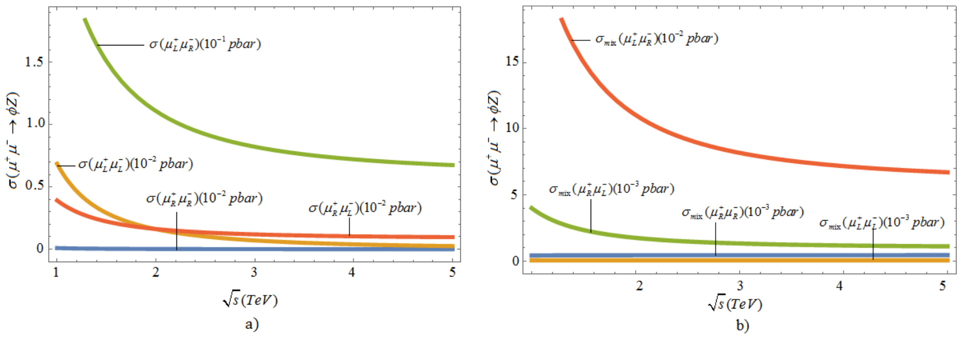

Figure 5. Total cross-section of the process $\mu^+\mu^- \to \phi Z$ as a function of the collision energy $\sqrt{s}$.

5. Conclusion

In this paper, we have calculated production of radion and Z boson in the $\bar{f}f$ collider when the $\bar{f}, f$ beams are polarized, the results have shown that, contributions is biggest when the e^+e^- beams are completely polarized same the left at $\cos\theta \approx 0$ and the μ^+ beams are polarized left, μ^- beams are polarized right and the largest at $\cos\theta \approx -1$. The value of differential cross-section is biggest when the angle between the direction of the beam radion and beam e^- approximately 0 degrees for e^+e^- collision. For $\mu^+\mu^-$ collision, the value of differential cross-section is greatest when the angle between the direction of the beam radion and beam μ^- approximately 180 degrees. For the total cross-section is bigger in energy region from 1000GeV to 2000GeV, so the ability to capture radion in this energy region is better than in energy region from 2000GeV to 5000GeV. For this reason, we are expectation that the reaction can give observable cross-section in LHC at the high degree of polarization of $\bar{f}, f$ beams.

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