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Z boson pair production at LHC in a stabilized Randall-Sundrum scenario

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Abstract

We study the Z boson pair production at LHC in the Randall-Sundrum scenario with the Goldberger-Wise stabilization mechanism. It is shown that comprehensive account of the Kaluza-Klein graviton and radion effects is crucial to probe the model: The KK graviton effects enhance the cross section of $gg \to ZZ$ on the whole so that the resonance peak of the radion becomes easy to detect, whereas the RS effects on the $q\bar{q} \to ZZ$ process are rather insignificant. The p_T and invariant-mass distributions are presented to study the dependence of the RS model parameters. The production of longitudinally polarized Z bosons, to which the SM contributions are suppressed, is mainly due to KK gravitons and the radion, providing one of the most robust methods to signal the RS effects. The 3σ sensitivity bounds on (Λ_π, m_ϕ) with $k/M_{\rm Pl} = 0.1$ are also obtained such that the effective weak scale Λ_π of about 10 TeV can be experimentally probed.

I. INTRODUCTION

Recent advances in string theories have inspired particle physicists to approach the gauge hierarchy problem of the standard model (SM) in a very novel way, i.e., by introducing extra dimensions. First Arkani-Hamed, Dimopoulos and Dvali (ADD) proposed that there exist n large extra dimensions with factorizable geometry, whereas the SM fields are confined to our four-dimensional world [1]. The observed largeness of Planck scale $M_{\rm Pl}$ is attributed to the large volume of the extra dimensions V_n, as can be seen from the relation $M_{\rm Pl}^2 = M_S^{n+2} V_n$ with M_S being the fundamental scale. Since the M_S can be maintained around TeV scale, the hierarchy problem is answered. Unfortunately criticism arose such that the ordinary gauge hierarchy is replaced by a new hierarchy between the M_S and the compactification scale $\mu_c = V_n^{-1/n}$. Based on two branes and a single extra dimension with non-factorizable geometry, Randall and Sundrum (RS) have proposed another higher dimensional scenario where, without *large* volume of the extra dimension, the hierarchy problem is solved by a geometrical exponential factor [2]. Here the stabilization of the compactification radius is very crucial: Otherwise a fine-tuning between the matter densities on the two branes is required, which induces non-conventional cosmologies [3]. Goldberger and Wise (GW) have shown that a bulk scalar field with interactions localized on the two branes generates for the modulus field a potential which allows a minimum appropriate to the hierarchy problem [4].

Of great interest and significance is that the ADD and RS models could have chances to be detected at future collider experiments. Even more interestingly, they provide possible accounts for the recently reported deviation of the muon anomalous magnetic moment from its SM prediction [5]. In the ADD case, even though the coupling of each Kaluza-Klein (KK) graviton state with the SM fields is suppressed by Planck scale, the summation over almost continuous KK spectrum compensates the suppression and leaves the effective coupling of $\sim 1/M_S$ [6,7]. In the RS scenario, the zero mode of the KK graviton states couples with the usual Planck strength, whereas the mass and couplings of all the excited KK states are characterized by some electroweak scale Λ_π [8,9]. This discrete spectrum is to yield the clean signal of graviton resonance production. Another key ingredient of the RS model from the stabilization mechanism is the radion. Since the radion can be much lighter than Λ_π [10,11], it is likely that the first signal of the RS effects may come from the radion.

Various phenomenological aspects of the radion have been extensively studied in the literature: The decay modes of the radion are different from those of the Higgs boson (e.g., the radion with mass smaller $2m_Z$ dominantly decays into two gluons) [10,11]; without a curvature-scalar Higgs mixing, the radion effects on the oblique parameters of the electroweak precision observations are small [12]; the radion effects on the phenomenology at low energy colliders [13] and at high energy colliders [14–16] have been also discussed.

On the other hand we notice that the presence of the radion in the RS model should be concomitant with that of the KK gravitons. Moreover, in spite of its lighter mass than the KK gravitons, the radion interacts with the SM particles more weakly than the KK gravitons due to the following reasons: The characteristic scale of the radion coupling, inversely proportional to the vacuum expectation value (VEV) of the radion (Λ_ϕ), is smaller than the coupling of the KK gravitons, since $\Lambda_\phi = \sqrt{6}\Lambda_\pi$ [10]; the degrees of freedom of the spin-0 radion are less than those of the spin-2 massive KK gravitons. And the Λ_ϕ, usually treated as a free parameter, is also constrained through the relation with the Λ_π which receives various constraints from the LEP II and Tevatron experiments [8]. Thus comprehensive study of both indirect effects, especially at high energy colliders, is worthwhile and inevitable. It is to be shown that the comprehensive accommodation leads to different phenomenologies at high energy colliders from that with only the radion effects.

Note that the radion interacts with the SM fields through the trace of the energy-momentum tensor: The coupling becomes stronger as the interacting SM particles are more massive; QCD trace anomaly enhances the coupling of the radion to a pair of gluons. The process $gg \to ZZ$, therefore, can be a good complementary channel to examine the radion effects. This process has been extensively studied with special attention to the Higgs search at the LHC [17]. The double leptonic decay of the Z-boson, $gg \to ZZ \to l^+l^-l'^+l'^-$, generates a clean signal. Unfortunately the main background of the continuum production of Z-boson pairs via $q\bar{q}$ annihilation is known to be order of magnitude dominant except for a limited range of the Higgs resonance. For example, full one-loop calculations for the $gg \to ZZ$ in the minimal supersymmetric standard model (MSSM) with the squark loop contributions have shown that the irreducible background of $q\bar{q} \to ZZ$ surpasses even resonant peaks of the supersymmetric Higgs bosons [19].

As shall be shown, comprehensive accommodation of both the KK graviton and radion effects is very crucial to prove the RS model, as well as reasonable. The contributions of the KK gravitons enhance the Z-boson pair production via gluon fusion more than that via $q\bar{q}$ annihilation, which shall be apparently shown in the p_T and invariant-mass distributions. As a result, the radion effects on the $gg \to ZZ$ as resonant signal have much more chance to be detected. Moreover the measurement of the Z polarization shall provide another efficient method for probing the effects of the RS model which accommodates spin-2 KK gravitons and spin-0 radions.

This paper is organized as follows. In Sec. II, we briefly review the RS model with the GW mechanism, and summarize the effective Lagrangian between the KK graviton, radion and SM particles. Model parameters are carefully notified. In Sec. III, the parton level helicity amplitudes for $gg \to ZZ$ and $q\bar{q} \to ZZ$ to leading order are given. In Sec. IV, we present numerical results of the p_T and invariant-mass distributions. After presenting the RS model dependence on the distributions, we shall show the RS effects on various configurations of Z-boson polarization. The sensitivity bounds for parameter space of Λ_π and the radion mass are to be given. Finally, Sec. V deals with summary and conclusions.

II. STABILIZED RANDALL-SUNDRUM SCENARIO

For the hierarchy problem, Randall and Sundrum have proposed a five-dimensional non-factorizable geometry with the extra dimension compactified on a S_1/Z_2 orbifold of radius r_c. Reconciled with four-dimensional Poincaré invariance, the RS configuration has the following solution to Einstein's equations:

$$ds^2 = e^{-2kr_c|\varphi|}\eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\varphi^2, \tag{1}$$

where $0 \leq |\varphi| \leq \pi$, and k is AdS_5 curvature. Two orbifold fixed points accommodate two three-branes, the hidden brane at $\varphi = 0$ and our visible brane at $|\varphi| = \pi$. The arrangement of our brane at $|\varphi| = \pi$ renders a fundamental scale m_0 to appear as the four-dimensional physical mass $m = e^{-kr_c\pi}m_0$. The hierarchy problem can be answered if $kr_c \approx 12$. ¿From the four-dimensional effective action, the relation between the four-dimensional Planck scale $M_{\rm Pl}$ and the fundamental string scale M_S is obtained by

$$M_{\rm Pl}^2 = \frac{M_S^3}{k}(1 - e^{-2kr_c\pi}). \tag{2}$$

The compactification of the fifth dimension leads to the following four-dimensional effective Lagrangian [8],

$$\mathcal{L} = -\frac{1}{M_{\rm Pl}}T^{\mu\nu}h_{\mu\nu}^{(0)} - \frac{1}{\Lambda_\pi}T^{\mu\nu}\sum_{n=1}^{\infty}h_{\mu\nu}^{(n)}\,, \tag{3}$$

where $\Lambda_\pi \equiv e^{-kr_c\pi}M_{\rm Pl}$ is at the electroweak scale. The coupling of the zero mode of the KK-gravitons is suppressed by usual Planck scale, while those of the massive KK-gravitons by the electroweak scale Λ_π. The masses of the KK-gravitons are also at the electroweak scale, given by [8,9],

$$m_n = kx_n e^{-kr_c\pi} = \frac{k}{M_{\rm Pl}}\Lambda_\pi x_n\,, \tag{4}$$

where the x_n's are the n-th roots of the first order Bessel function. The condition $k < M_{\rm Pl}$ is to be imposed to maintain the reliability of the RS solution in Eq. (1) [18]. We take the value in the conservative range of $0.1 < k/M_{\rm Pl} < 0.7$. Then, the first excited KK graviton has mass slightly larger than 1 TeV for $\Lambda_\pi \sim 3$ TeV and so there might be a chance to see the effects of KK gravitons at future colliders.

In the original RS scenario, the compactification radius r_c is assumed to be constant. According to the studies of cosmological evolution, however, two branes wants to blow apart, i.e., $r_c \to \infty$, unless we impose a fine-tuning between the densities on two branes, which will lead to non-conventional cosmologies [3]. A stabilization mechanism is required. Goldberger and Wise have introduced a bulk scale field with the bulk mass somewhat smaller than the k. The assumption of localizing the bulk scalar interactions on two branes determines the four-dimensional effective potential for the radion, which can allow the minimum for $kr_c \approx 12$ without an extreme fine-tuning. Furthermore, the radion mass is roughly an order of magnitude below Λ_π [12].

It was shown that the radion couples to ordinary matter through the trace of the symmetric and conserved energy-momentum tensor with TeV scale suppressed coupling;

$$\mathcal{L} = \frac{1}{\Lambda_\phi}\,\phi\, T^\mu_\mu, \tag{5}$$

where Λ_ϕ, the VEV of the radion field, is related such that $\Lambda_\phi = \sqrt{6}\,\Lambda_\pi$ [10]. The coupling of the radion with a fermion or massive gauge boson pair is the same as that of the Higgs, except for a factor of (v/Λ_ϕ), with v being the VEV of the SM Higgs boson. The massless gluons and photons also contribute to the T^μ_μ, due to the trace anomaly which appears since the scale invariance of massless fields is broken by the running of gauge couplings [20]. Thus the interaction Lagrangian between two gluons and the radion or Higgs boson is

$$\mathcal{L}_{h(\phi)-g-g} = \left[\left(\frac{v}{\Lambda_\phi}\right)\left\{b_3 + I_{1/2}(z_t^\phi)\right\}\phi + I_{1/2}(z_t^h)h\right]\frac{\alpha_s}{8\pi v}\,\mathrm{Tr}(G^C_{\mu\nu}G^{C\mu\nu})\,, \tag{6}$$

where $z_t^{\phi(h)} = 4m_t^2/m^2_{\phi(h)}$, m_t is the top quark mass, and the QCD beta function coefficient is $b_3 = 11 - 2n_f/3$ with the number of dynamical quarks n_f. The loop function $I_{1/2}(z)$ is defined by

$$I_{1/2}(z) = z[1 + (1-z)f(z)]\,, \tag{7}$$

where the $f(z)$ is

$$f(z) = \begin{cases} \arcsin^2(1/\sqrt{z})\,, & z \geq 1\,, \\ -\frac{1}{4}\left[\ln\left(\frac{1+\sqrt{1-z}}{1-\sqrt{1-z}}\right) - i\pi\right]^2\,, & z < 1\,. \end{cases} \tag{8}$$

It is to be noted that the phenomenology of radions and KK gravitons in the RS model can be determined by three parameters, m_ϕ, Λ_π, and $k/M_{\rm Pl}$.

III. Z BOSON PAIR PRODUCTION AT LHC

A. The $gg \to ZZ$ helicity amplitudes

Generally for the process $g(\lambda_1)g(\lambda_2) \to Z(\lambda_3)Z(\lambda_4)$, there are 36 helicity amplitudes according to two and three polarization states of initial gluons and final Z-bosons, respectively. Various symmetry arguments reduce these 36 amplitudes into eight independent ones [17]. First parity invariance implies

$$\mathcal{M}_{\lambda_1\lambda_2\lambda_3\lambda_4} = \mathcal{M}^*_{-\lambda_1-\lambda_2-\lambda_3-\lambda_4}. \tag{9}$$

Bose statistics and the standard form of the Z-boson polarization vectors demand

$$\mathcal{M}_{++--}(\beta) = \mathcal{M}_{++++}(-\beta), \tag{10}$$

$$\mathcal{M}_{+++-}(\beta) = \mathcal{M}_{++-+}(\beta), \tag{11}$$

$$\mathcal{M}_{+---}(\beta) = \mathcal{M}_{+-++}(\beta), \tag{12}$$

$$\mathcal{M}_{+--+}(\beta) = \mathcal{M}_{+-+-}(-\beta), \tag{13}$$

$$\mathcal{M}_{+++0}(\beta) = \mathcal{M}_{++0+}(\beta) = \mathcal{M}_{++-0}(-\beta) = \mathcal{M}_{++0-}(-\beta), \tag{14}$$

$$\mathcal{M}_{+-+0}(\beta) = -\mathcal{M}_{+-0+}(-\beta) = \mathcal{M}_{+--0}(-\beta) = -\mathcal{M}_{+-0-}(\beta). \tag{15}$$

For the explicit calculations, we consider the following four momenta for the initial gluons and final Z bosons in the gluon-gluon center-of-momentum (c.m.) frame;

$$\begin{aligned} p_1 &= \frac{\sqrt{\hat{s}}}{2}(1,0,0,1), \quad p_2 = \frac{\sqrt{\hat{s}}}{2}(1,0,0,-1), \\ p_3 &= \frac{\sqrt{\hat{s}}}{2}(1,\beta\sin\theta,0,\beta\cos\theta), \quad p_4 = \frac{\sqrt{\hat{s}}}{2}(1,-\beta\sin\theta,0,-\beta\cos\theta), \end{aligned} \tag{16}$$

where $\beta = \sqrt{1-4m_Z^2/\hat{s}}$ and $\hat{t} = (p_1-p_3)^2$. The polarization vectors for the spin-1 particles with momentum $p^\mu = (p^0, \vec{p})$ are

$$\epsilon^\mu(p,\lambda) = \frac{e^{i\lambda\phi}}{\sqrt{2}}(0, -\lambda\cos\theta\cos\phi + i\sin\phi, -i\cos\phi - \lambda\cos\theta\sin\phi, \lambda\sin\theta), \tag{17}$$

$$\epsilon^\mu(p,0) = (|\vec{p}|/m,\ p^0\hat{p}/m), \tag{18}$$

where the angles θ and ϕ specify the direction of $\vec{p}$.

In the SM, there are two types of Feynman diagrams for the $gg \to ZZ$ process, through the box and triangle quark loops shown in Fig. 1. In spite of the loop suppression by a factor of α_s^2, high luminosity of the gluon in a proton at the LHC yields substantial cross section for the process. The SM helicity amplitudes have been studied in detail. We refer the reader to Ref. [17].

In the RS model, the KK gravitons mediate the s-channel Feynman diagram at tree level (see Fig. 2). The helicity amplitudes are cast into

$$\mathcal{M}^G_{\lambda_1\lambda_2\lambda_3\lambda_4}(gg \to ZZ) = -\frac{1}{8\Lambda_\pi^2}\sum_n \frac{\delta^{ab}}{\hat{s}-m_n^2}\mathcal{A}_{\lambda_1\lambda_2\lambda_3\lambda_4} , \tag{19}$$

where δ^{ab} denotes the color factor. There are six non-vanishing independent helicity amplitudes:

$$\mathcal{A}_{++++} = -\frac{1}{2}(\beta^4-1)(\hat{t}-\hat{u})^2 + \frac{1}{2}(\beta^2+1)\hat{s}^2 + (\hat{t}+\hat{u})\hat{s}, \tag{20}$$

$$\mathcal{A}_{+-+-} = \frac{1}{2}\{\beta(\hat{t}-\hat{u})+\hat{s}\}^2, \tag{21}$$

$$\mathcal{A}_{+-++} = \frac{1}{2}(\beta^2-1)\{\beta^2(\hat{t}-\hat{u})^2-\hat{s}^2\}, \tag{22}$$

$$\mathcal{A}_{+-+0} = -\frac{\sqrt{\hat{s}}}{2\sqrt{2}m_Z}(1-1/\beta^2)(\hat{t}-\hat{u}+\beta\hat{s})\sqrt{(\beta\hat{s})^2-(\hat{t}-\hat{u})^2}, \tag{23}$$

$$\mathcal{A}_{++00} = \frac{(1+\beta^2)\{(1+\beta^2)\hat{s}+2(\hat{t}+\hat{u})\}\hat{s}^2}{8m_Z^2},$$

$$\mathcal{A}_{+-00} = \frac{(1-1/\beta^2)(\beta^2-2)\{(\hat{t}-\hat{u})^2-\beta^2\hat{s}^2\}\hat{s}}{8m_Z^2}. \tag{24}$$

The second ingredient of the RS model, the radion, couples to two gluons through its Yukawa coupling to a quark inside a triangle loop diagram, as well as through QCD trace anomaly. Since the radion interaction with quarks is proportional to the mass, only top quark loop is to be considered. Two of the eight independent helicity amplitudes receive non-vanishing contributions from the radion:

$$\mathcal{M}^\phi_{++++} = -\frac{\alpha_s\delta^{ab}}{\pi}[b_{QCD}+I(z_t)]\left(\frac{m_Z}{\Lambda_\phi}\right)^2\frac{1}{\hat{s}-m_\phi^2+i\Gamma_\phi m_\phi}\frac{\hat{s}}{2}, \tag{25}$$

$$\mathcal{M}^\phi_{++00} = -\frac{\alpha_s\delta^{ab}}{\pi}[b_{QCD}+I(z_t)]\left(\frac{m_Z}{\Lambda_\phi}\right)^2\frac{1}{\hat{s}-m_\phi^2+i\Gamma_\phi m_\phi}\frac{\hat{s}^2(\beta^2+1)}{8m_Z^2}.$$

B. The $q\bar{q} \to ZZ$ helicity amplitudes

In the SM the process $q\bar{q} \to ZZ$ surpass the gluon fusion process due to the presence of tree level Feynman diagrams: At the LHC, $\sigma(gg \to ZZ)$ is only about $33 - 43\%$ of $\sigma(q\bar{q} \to ZZ)$. Accurate structure functions at low values of x, and higher order corrections are necessary for the precise ratio of the $q\bar{q}$ annihilation and gluon fusion processes. Even though higher order corrections of the $q\bar{q} \to ZZ$ is known with the K-factor of $\mathcal{O}(30\%)$ [21], the absence of the corresponding calculation for the gluon fusion process leads us not to include any higher order corrections. We also assume that the uncertainties with leading contributions from soft gluon emission in both processes cancel to some extent in the ratio of cross sections, hardly affecting our main interest, the distribution shapes.

To leading order, the SM contributions are from t- and u-channel Feynman diagrams. Since the radion coupling to fermions is proportional to the fermion mass, we can safely neglect the radion effects here. The s-channel diagram mediated by the KK gravitons, which is similar to the diagram (a) in Fig. 2, still influence the production. For the process $q(\lambda_1)\bar{q}(\lambda_2) \to Z(\lambda_3)Z(\lambda_4)$, the helicity amplitudes due to the KK gravitons are written by

$$\mathcal{M}^G_{\lambda_1\lambda_2\lambda_3\lambda_4}(q\bar{q} \to ZZ) = -\frac{1}{4\Lambda_\pi^2}\sum_n \frac{\delta^{\alpha\beta}}{\hat{s} - m_n^2}\mathcal{B}_{\lambda_1\lambda_2\lambda_3\lambda_4}, \tag{26}$$

where non-zero and independent $\mathcal{B}$'s are, in the parton c.m. frame,

$$\begin{aligned}
\mathcal{B}_{+-++} &= \frac{\hat{s}(\hat{t} - \hat{u})(\beta^2 - 1)\sin\theta}{\beta}, \\
\mathcal{B}_{+-+-} &= \frac{\hat{s}(\hat{t} - \hat{u} + \beta\hat{s})\sin\theta}{\beta}, \\
\mathcal{B}_{+-+0} &= -\frac{(\beta^2 - 1)\hat{s}^{3/2}(1 + \cos\theta)\{\beta\hat{s} - 2(\hat{t} - \hat{u})\}}{2^{3/2}m_Z\beta}, \\
\mathcal{B}_{+--+} &= \hat{s}^2\sin\theta(\cos\theta - 1), \\
\mathcal{B}_{+--0} &= -\frac{(\beta^2 - 1)\hat{s}^{3/2}(1 - \cos\theta)(\beta\hat{s} + 2(\hat{t} - \hat{u}))}{2^{3/2}m_Z\beta}, \\
\mathcal{B}_{+-00} &= \frac{\hat{s}^2(\beta^2 - 1)(\beta^2 - 2)(\hat{t} - \hat{u})\sin\theta}{4m_Z^2\beta},
\end{aligned} \tag{27}$$

where $\cos\theta = (\hat{t} - \hat{u})/\beta\hat{s}$.

IV. CONTINUUM Z BOSON PAIR PRODUCTION AT THE LHC

The physical production rate of Z boson pair at pp colliders is obtained by convoluting over the parton structure functions [22]:

$$\sigma(pp \to ij \to ZZ) = \int dx_1 dx_2 \sum_{i,j} f_i(x_1, Q^2) f_j(x_2, Q^2) \hat{\sigma}_{ij}(x_1 x_2 s)\,, \tag{28}$$

where i and j denote the parton such as the gluon or quark, x_1 and x_2 denote the momentum fraction of the parton from the parent proton beam. For the numerical analysis, we use the leading order MRST parton distribution functions (PDF) for a gluon in a proton [23]. The QCD factorization and renormalization scales Q are set to be the m_Z. The Q^2-dependence is expected to be small on our main interest, the distribution shapes. The c.m. energy at pp collisions is $\sqrt{s} = 14$ TeV. And we have employed the kinematic cuts of $p_T \geq 25$ GeV and $|\eta| \leq 2.5$ throughout the paper. As discussed before, the RS effects are determined by three parameters, $(\Lambda_\pi, k/M_{\rm Pl}, m_\phi)$. ¿From the above arguments, we consider $\Lambda_\pi = 2,\ 3,\ 5$ TeV, $k/M_{\rm Pl} = 0.1,\ 0.3,\ 0.7$, and $m_\phi = 300,\ 500,\ 700$ GeV.

The SM Higgs boson mass has not been experimentally confirmed yet. Recently, the ALEPH group has reported the observation of an excess of 3σ in the search of the SM Higgs boson, which corresponds to the Higgs mass about 114 GeV [24]. As the operation of LEP II has been completed, the decision whether the observations are only the results of statistical fluctuations or the first signal of the Higgs boson production is suspended until the Tevatron II and/or LHC running [25]. In the following, the Higgs boson mass is set to be 114 GeV except in Fig. 3 for the comparison of the contributions from the Higgs boson and radion with the same mass.

First we present the p_T and invariant-mass distributions for unpolarized Z-bosons. Figure 3 shows the radion and KK graviton effects for the process $gg \to ZZ$ on the distributions. For comparison, both the Higgs boson and radion masses are set to be 300 GeV with $\Lambda_\pi = 2$ TeV and $k/M_{\rm Pl} = 0.1$. The long dashed line denotes the SM results with the Higgs mass of 300 GeV. The short dashed line includes only the radion effects, whereas the dotted line incorporates both the KK graviton and radion effects. The SM contribution to $q\bar{q} \to ZZ$ denoted by the dash-dotted line is also plotted for comparison. The p_T distributions apparently show that the KK graviton effects enhance the cross section on the whole, which also increase the chance to probe the presence of radions. Any other new physics beyond the SM, including supersymmetric models, hardly generate such elevated resonance behavior. Moreover, even in the large Λ_π cases where the KK graviton effects are negligible, the distinction between the Higgs boson and radion is possible: The resonance peak of the radion becomes narrower as the radion total decay width (Γ_ϕ) decreases, which is inversely proportional to $\Lambda_\phi^2 = (\sqrt{6}\Lambda_\pi)^2$.

In Fig. 4, we present the RS effects on the process $q\bar{q} \to ZZ$, which are determined solely by the Λ_π due to the ignorance of the radion influence. The KK gravitons can be recognized by broad peaks. The RS effects are less important than those on the $gg \to ZZ$ process: The effects appear beyond 300 GeV of p_T and 700 GeV of M_{ZZ}, generating at most 10^{-3} pb/GeV of the differential cross section with respect to p_T or M_{ZZ}; the effects on the gluon fusion shall be shown to appear in the low p_T and M_{ZZ} region where the cross sections are substantial.

Now we illustrate each parameter dependence of the RS model to the gluon fusion process. In Fig. 5, we plot the distributions for the $m_\phi = 300$, 500, 700 GeV, whereas we set $\Lambda_\pi = 2$ TeV and $k/M_{\rm Pl} = 0.1$. It can be seen that the resonance peak of light radions is sharper. We can understand this behavior since the decay width decreases with the radion mass. If the radion is quite heavy (around 500 GeV in this parameter space), the contribution of the KK gravitons to the p_T distributions overwhelms the radion resonance; the invariant-mass distribution is more appropriate to probe. If the radion is too heavy (more than 700 GeV in this case), large contributions of the KK gravitons obscure the radion effects. Figure 6 presents the Λ_π-dependence on the $gg \to ZZ$ process for $\Lambda_\pi = 2$, 3, and 5 TeV with $m_\phi = 300$ GeV and $k/M_{\rm Pl} = 0.1$. The M_{ZZ} distributions show a sharp resonance peak from the radion and the successive broad peaks from the KK gravitons. In the p_T-distributions, the KK graviton effects yield a plateau region. The case of $\Lambda_\pi \gtrsim 5$ TeV would be difficult to probe. The $k/M_{\rm Pl}$ dependence is presented in Fig. 7, for $k/M_{\rm Pl} = 0.1$, 0.3, and 0.7 with $m_\phi = 300$ GeV and $\Lambda_\pi = 2$ TeV. Since the $k/M_{\rm Pl}$ is proportional to the masses of the KK gravitons (see Eq. (4)), the KK graviton effects in the large $k/M_{\rm Pl}$ cases are hardly detected. Note that in the RS model the magnitude of the five-dimensional curvature ($R_5 = -20\,k^2$) is required to be smaller than M_S^2 ($\simeq M_{\rm Pl}^2$) for the reliability of the classical RS solution derived from the leading order term in the curvature. The value of $k/M_{\rm Pl}$ less than about 0.1 is theoretically favored [18].

We present the influence of the Z polarization measurement on the distributions. The polarizations of the Z-boson pair have been known to be determined by studying the polar angle of the decaying leptons with respect to each Z-boson. Figures 8 and 9 are for the polarization states $Z_T Z_T$ and $Z_L Z_L$, respectively. We set $\Lambda_\pi = 2$ TeV, $k/M_{\rm Pl} = 0.1$ and $m_\phi = 300$ GeV for illustration. As expected from the scalar nature of the radion and the spin-2 nature of massive KK gravitons, the longitudinally polarized Z bosons are produced more in the RS model, while the SM production of $Z_L Z_L$ through both gluon fusion and $q\bar{q}$ annihilation is suppressed. Thus the measurement of the longitudinally polarized Z bosons would provide one of the most robust methods to single out the effects of the RS model.

Some discussions about the unitarity violation in the RS model are in order here. According to the analysis of $e^+e^- \to \mu^+\mu^-$ with the KK graviton effects, the large $k/M_{\rm Pl}$ cases appear to violate the partial wave unitary bound since the resonant peaks of the KK gravitons become very wide and the cross section is too largely enhanced [8]. In the range of small $k/M_{\rm Pl}$ such as 0.1, the unitarity seems to be preserved below several TeV scale. In order to eliminate the concern for the unitarity violation, it is reasonable that we only consider the region where our perturbative calculations are trustworthy, which can be achieved by excluding the data with high invariant-mass. In Ref. [26], the partial wave amplitudes of the elastic process $\gamma\gamma \to \gamma\gamma$ in the ADD model have been examined, yielding the bound on the ratio $M_S/\sqrt{\hat{s}}$: Conservative one is shown to be $\sqrt{\hat{s}} \leq 0.9 M_S$. In the following analysis of the sensitivity bounds in (Λ_π, m_ϕ), therefore, we impose an additional kinematic cut such as

$$M_{ZZ} < 900\,\mathrm{GeV}. \tag{29}$$

Finally, we obtain the 3σ limits for the effective quantum gravity scale Λ_π and the radion mass, requiring that

$$\frac{\sigma_{tot}^{<} - \sigma_{sm}^{<}}{\sqrt{\sigma_{sm}^{<}}} \sqrt{\mathcal{L}}\,\epsilon \geq 3, \tag{30}$$

where the $\sigma_{tot}^{<}$ denotes the total cross section including the RS effects with the constraint in Eq. (29), ϵ is the reconstruction efficiency for the Z-boson pair which is set to be 0.6×0.6. The LHC luminosity $\mathcal{L}$ is 100 pb^{-1}. In Fig. 10, we show the 3σ attainable bounds on Λ_π and m_ϕ with $k/M_{\rm Pl}$ =0.1. Even with restrictive efficiency, the Λ_π of about 10 TeV can be experimentally examined. Since the radion has relatively small influence upon the total cross section, the p_T or invariant-mass distribution would be more appropriate to signal the radion effects.

V. SUMMARY AND CONCLUSION

We have studied the $gg \to ZZ$ process at LHC as a probe of the Randall-Sundrum scenario with the Goldberger-Wise stabilization mechanism. Even though the process has been regarded significant in various aspects (e.g., in examining the Higgs sector), the main background of the continuum production of $q\bar{q} \to ZZ$ is known to be order of magnitude dominant in the SM and MSSM. It has been shown that the comprehensive effects of Kaluza-Klein gravitons and the radion enhance the chance to probe the model: The RS effects on the $q\bar{q} \to ZZ$ process, which occur only through the KK gravitons, are much smaller than those on the $gg \to ZZ$ one; the KK graviton effects increase the cross section of $gg \to ZZ$ throughout the p_T and invariant-mass distributions; the resonance peak of the radion becomes easier to be detected. Numerical results of the p_T and invariant-mass distributions have been obtained to show the dependence of the RS model parameters, $(\Lambda_\pi, k/M_{\rm Pl}, m_\phi)$.

The distinction between the Higgs boson and radion even with the same mass is feasible since the resonance peak of the radion is narrower than that of the Higgs boson in most of the parameter space. The p_T and invariant-mass distributions for the polarized Z boson pair have been also presented. We have shown that especially the production of longitudinally polarized Z bosons, to which the SM contributions are suppressed, receives substantial corrections due to KK gravitons and the radion. Polarization measurements would provide one of the most robust methods to signal the RS effects. The 3σ sensitivity bounds on (Λ_π, m_ϕ) with $k/M_{\rm Pl} = 0.1$ have been also obtained. The Λ_π of about 10 TeV can be experimentally searched even with restrictive experimental efficiency. In conclusion, the channel of Z-boson pair production at LHC with the measurements of the Z-polarizations and the p_T and invariant-mass distributions can provide an efficient chance to probe the effects of the RS scenario with the modules fields being stabilized by the Goldberger-Wise mechanism.

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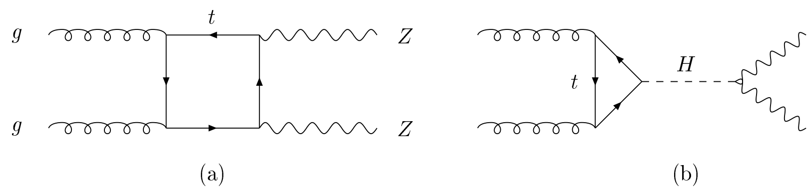

FIG. 1. Feynman diagrams for the process $gg \to ZZ$ in the SM.

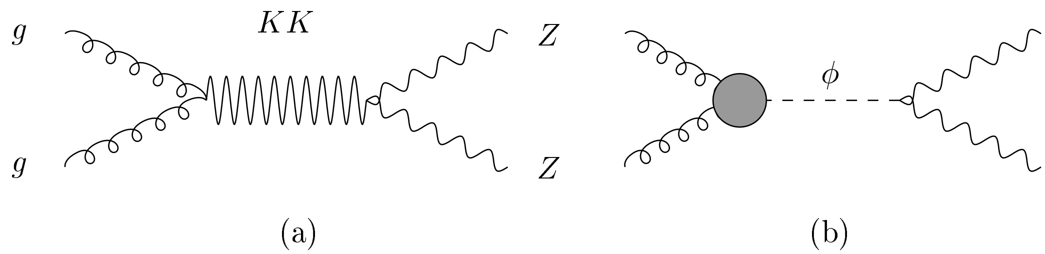

FIG. 2. Feynman diagrams for the process $gg \to ZZ$ mediated (a) KK gravitons and (b) the radion in the RS model.

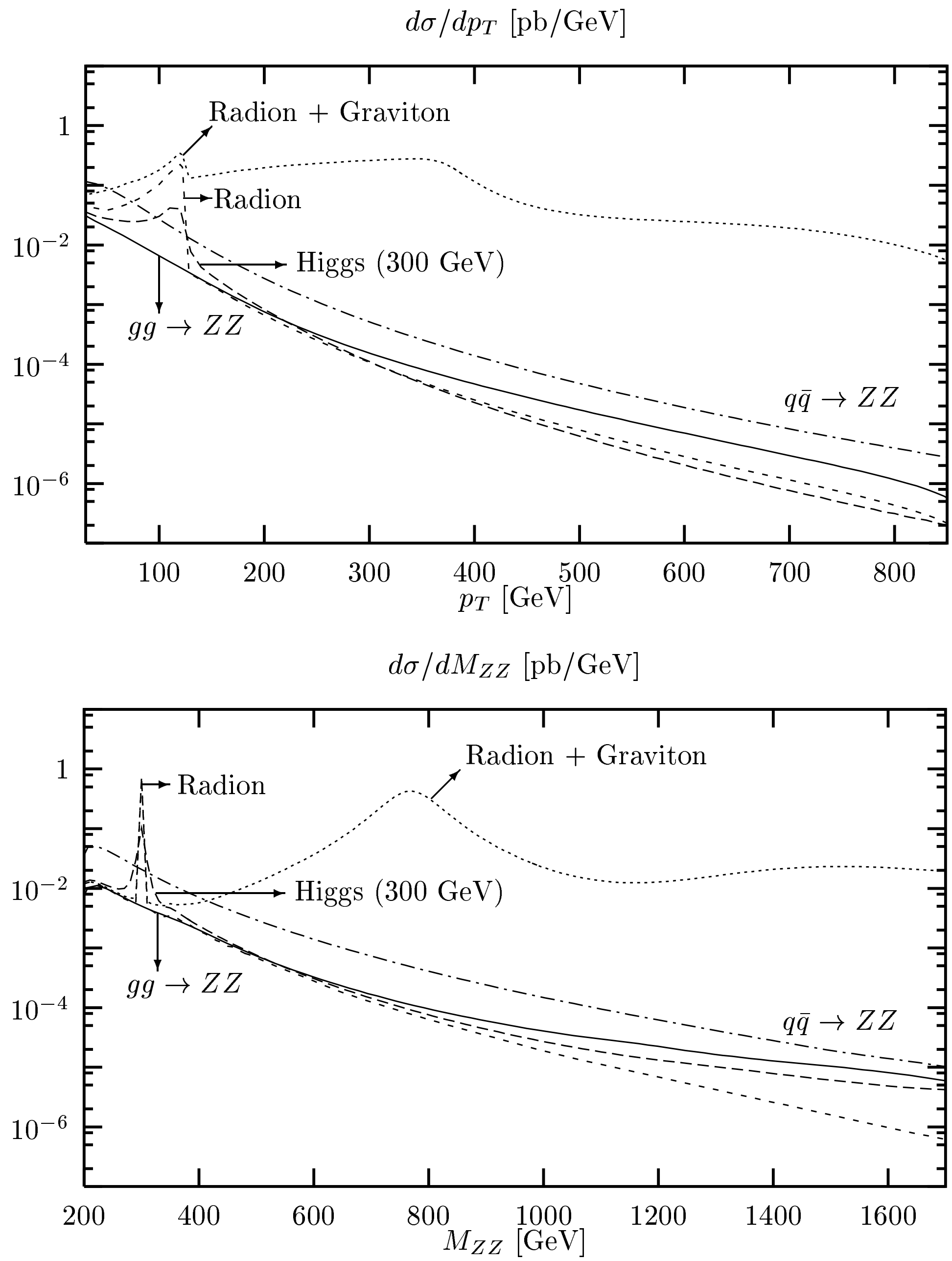

FIG. 3. The p_T and invariant-mass distributions of the $gg \to ZZ$ process when both the SM Higgs boson and radion masses are 300 GeV with $\Lambda_\pi = 2$ TeV and $k/M_{\rm Pl} = 0.1$. The SM results for $q\bar{q} \to ZZ$ are plotted for comparison.

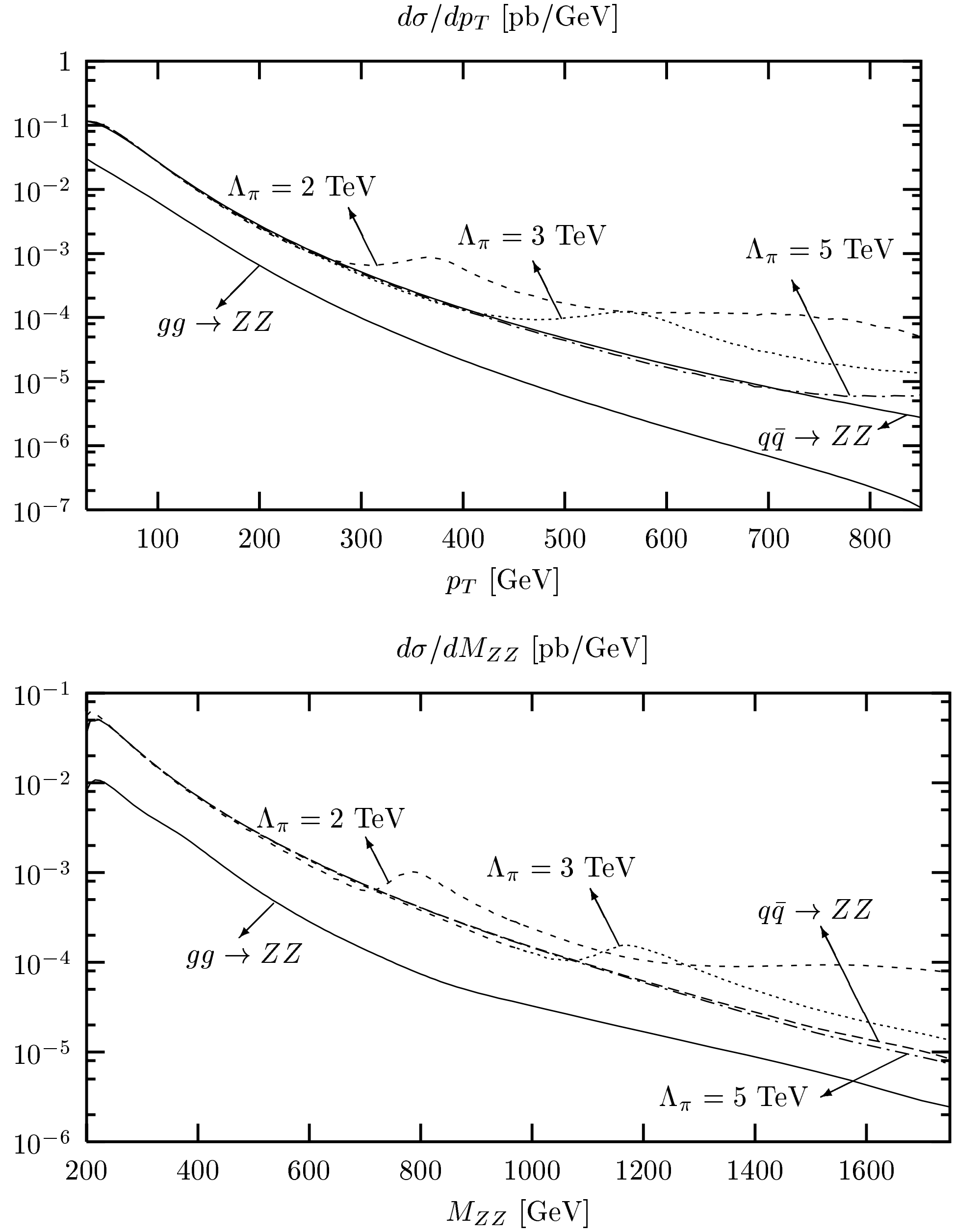

FIG. 4. The p_T and invariant-mass distributions of the $q\bar{q} \to ZZ$ process for $\Lambda_\pi = 2$, 3, and 5 TeV. The SM results for $gg \to ZZ$ are plotted for comparison.

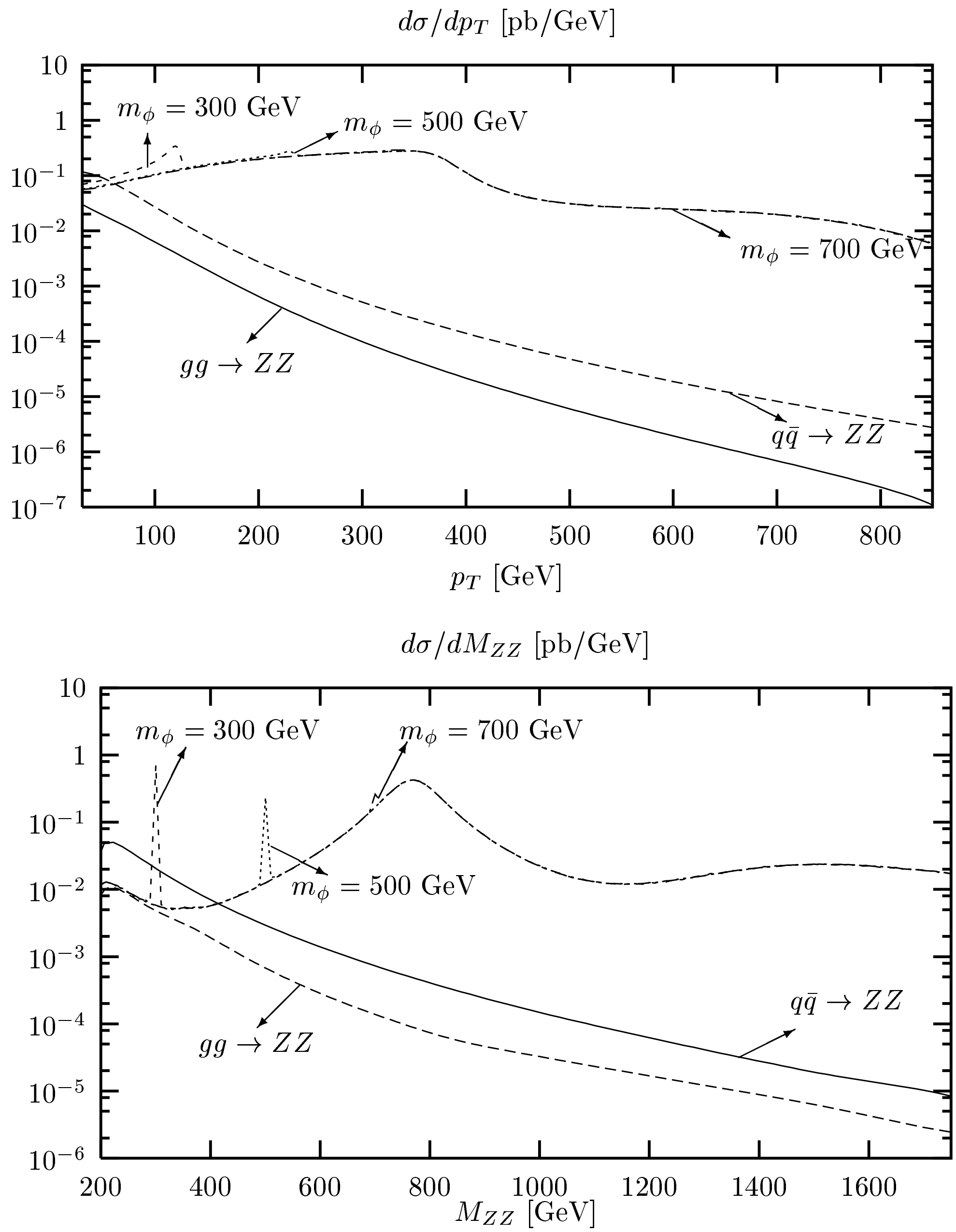

FIG. 5. The p_T and invariant-mass distributions of the $gg \to ZZ$ process for $m_\phi = 300$, 500, and 700 GeV with $\Lambda_\pi = 2$ TeV and $k/M_{\rm Pl} = 0.1$. The SM results for $q\bar{q} \to ZZ$ are plotted for comparison.

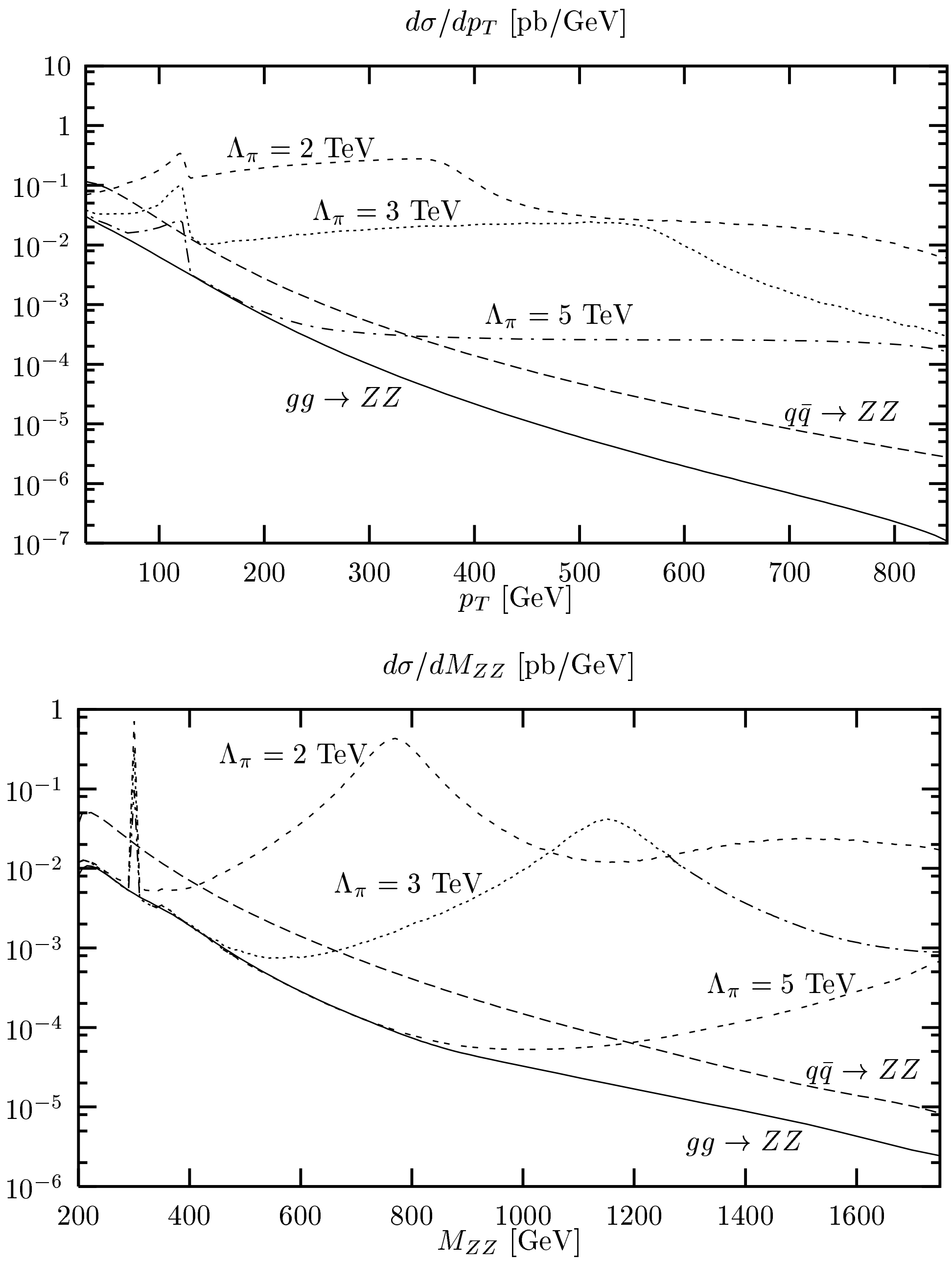

FIG. 6. The Λ_π-dependence on the p_T and invariant-mass distributions of the $gg \to ZZ$ process for $\Lambda_\pi = 2$, 3, and 5 TeV with $m_\phi = 300$ GeV and $k/M_{\rm Pl} = 0.1$.

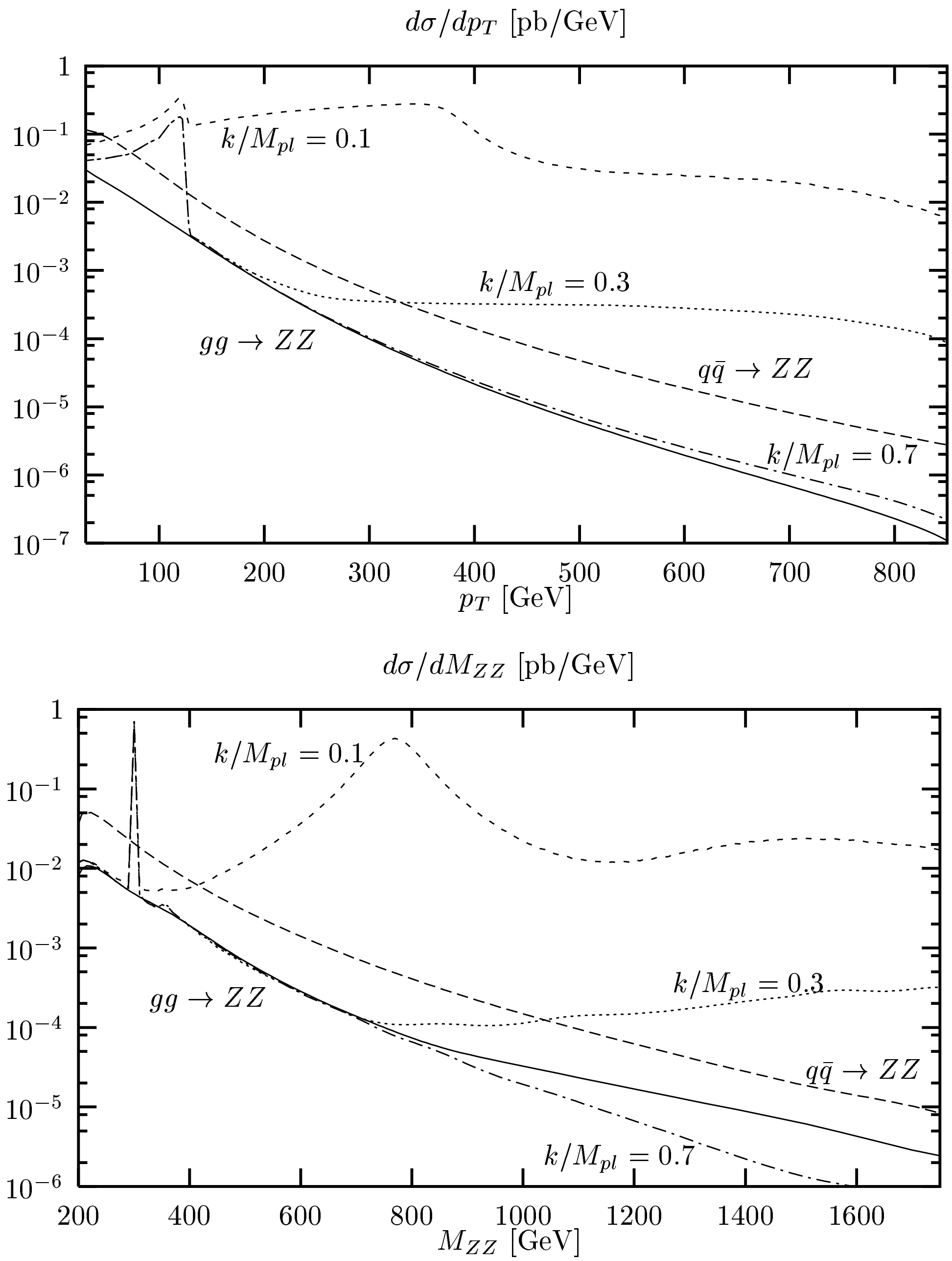

FIG. 7. The $k/M_{\rm Pl}$-dependence on the p_T and invariant-mass distributions of the $gg \to ZZ$ process for $k/M_{\rm Pl} = 0.1$, 0.3, and 0.7 with $m_\phi = 300$ GeV and $\Lambda_\pi = 2$ TeV.

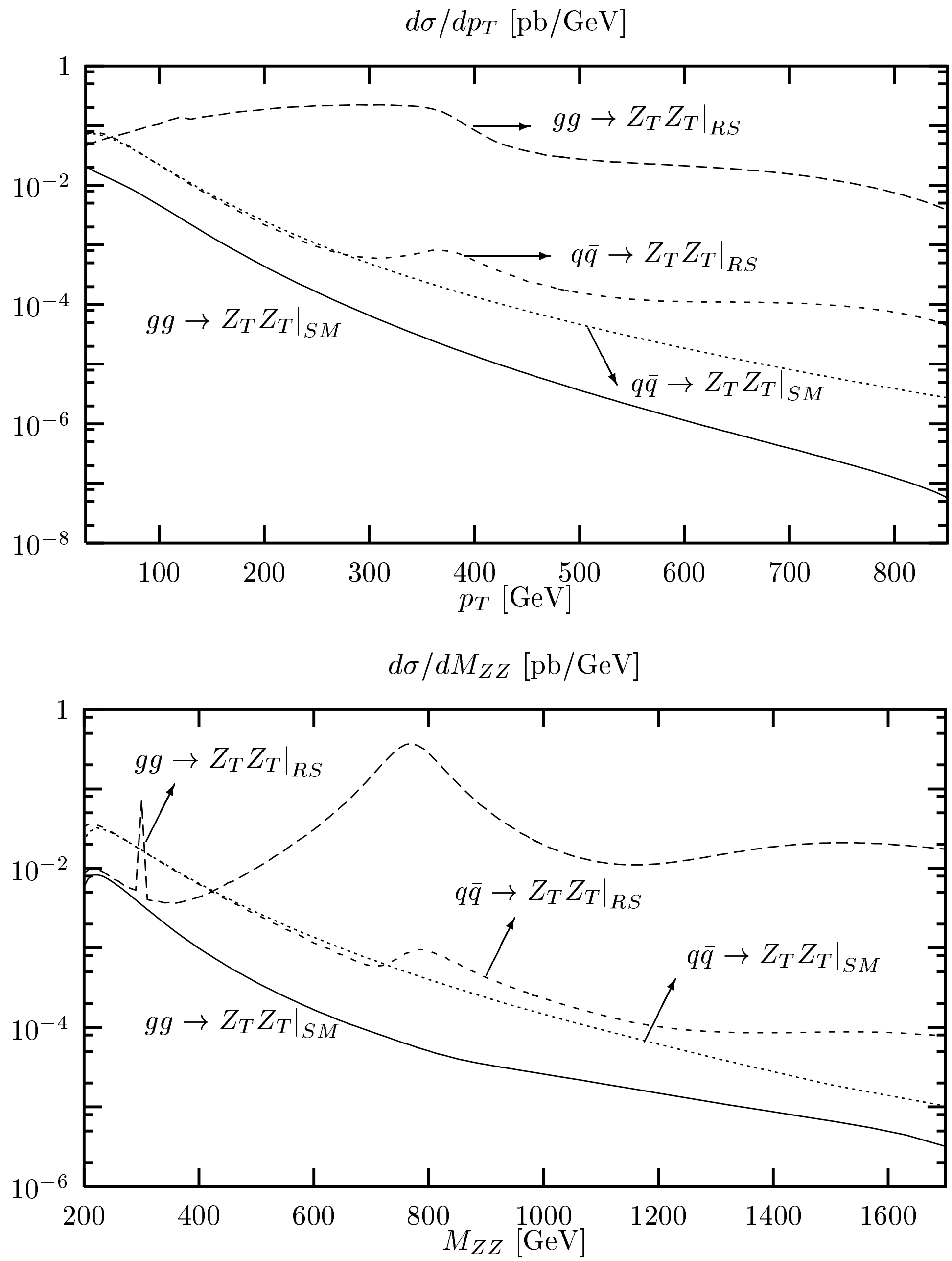

FIG. 8. The p_T and invariant-mass distributions of the $gg \to Z_T Z_T$ process. We set $k/M_{\rm Pl} = 0.1$, $m_\phi = 300$ GeV and $\Lambda_\pi = 2$ TeV.

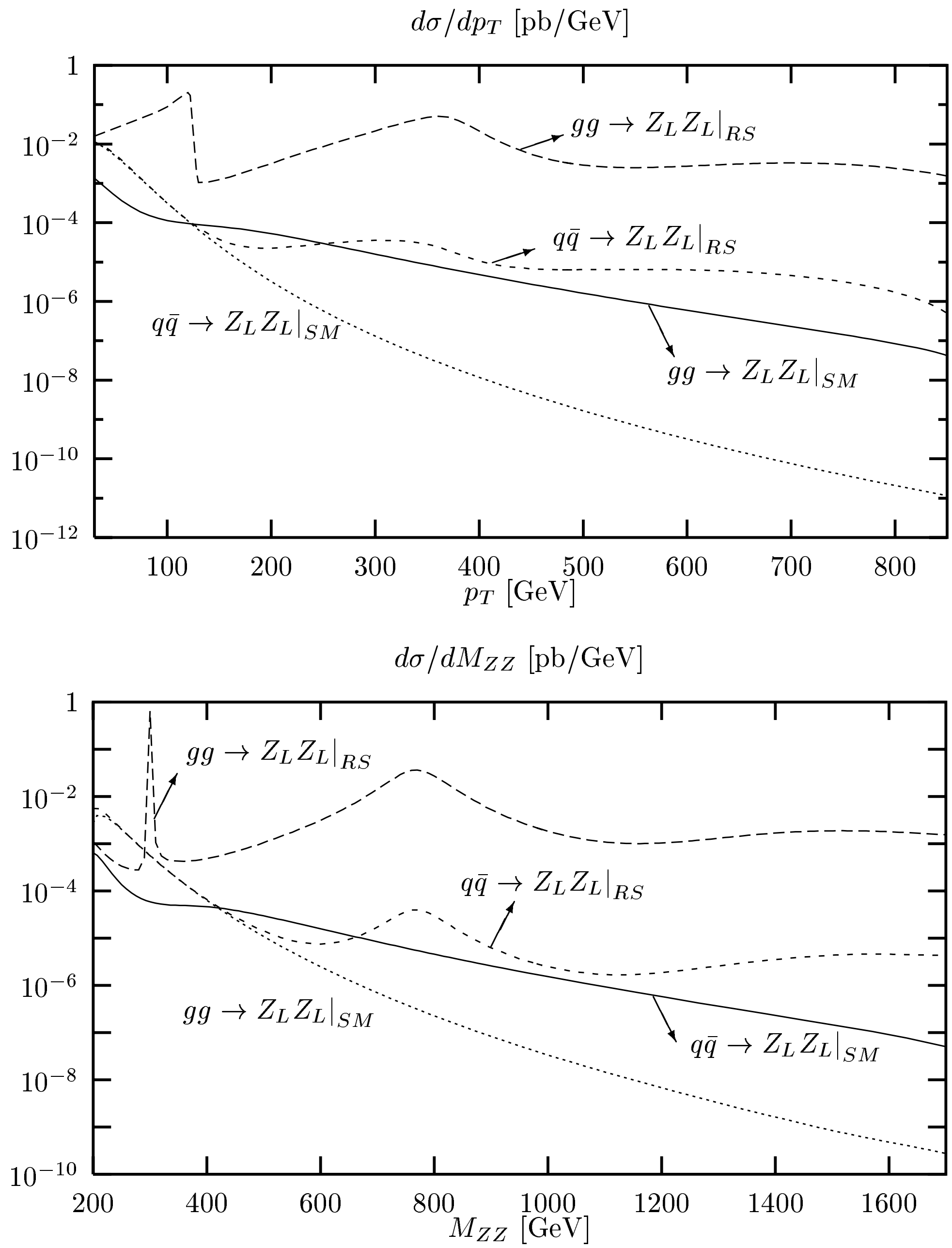

FIG. 9. The p_T and invariant-mass distributions of the $gg \to Z_L Z_L$ process. We set $k/M_{\rm Pl} = 0.1$, $m_\phi = 300$ GeV and $\Lambda_\pi = 2$ TeV.

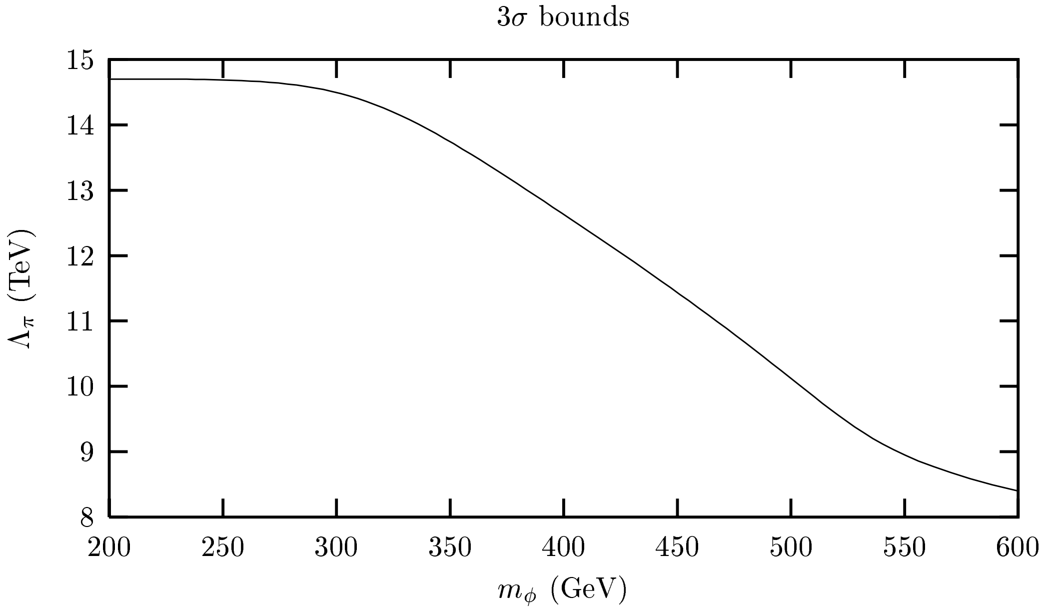

FIG. 10. The 3σ sensitivity bounds on (Λ_π, m_ϕ) with $k/M_{\rm Pl} = 0.1$.