Abstract

The radion is expected to be the first signal of the Randall-Sundrum (RS) model. We explore the possibility of finding it in the ongoing Higgs searches at the LHC. The little RS model (LRS), which has a fundamental scale at $\sim 10^3$ TeV, is excluded over wide ranges of the radion mass from the latest $WW$ and $\gamma\gamma$ data by ATLAS and CMS.

Key words: radion, RS model, LHC
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1 Introduction

The Standard Model (SM) successfully explains almost all present experimental data; however, it is an unsatisfactory model to be the ultimate theory of particle physics. One of its defects is a large hierarchy between the two fundamental scales, the Planck scale $M_{Pl} = M_{Pl}/\sqrt{8\pi} \approx 2 \times 10^{18}$ GeV and the weak scale $\sim 100$ GeV, which requires an unnatural fine-tuning of model-parameters when the model is applied to weak-scale phenomenology. The Randall-Sundrum model[1] was originally proposed to solve this hierarchy problem. RS introduced the five-dimensional anti-de Sitter spacetime,

$$ds^2 = e^{-2ky} g_{\mu\nu} dx^\mu dx^\nu - dy^2,$$

with a $S^1/Z_2$ compactified 5-th dimension, denoted as $y \in [0, L]$; there are two three-branes at $y = 0$ and $y = L$, called UV and IR branes, respectively. All the SM fields are confined to the IR brane in the original setup of Randall-Sundrum model, denoted as the RS1 model, and the 5-dimensional fundamental scale $M_5$ at UV brane is scaled down to $M_5 e^{-kL}$ at the IR brane by the warp factor $e^{-kL}$ appearing in the metric of Eq. (1). By taking $kL \approx 35$, 

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the fundamental scale $M_5 = M_{Pl}$ is scaled down to the TeV scale. In order to suppress unwanted higher dimensional operators, which are not sufficiently suppressed by the TeV-scale cutoff on the IR brane in the RS1 model, SM gauge fields$^{2,3,4,5}$ and fermions$^{6,7}$ are considered to propagate in the bulk space. In this new setup$^{2,3,4,5,6,7,8,9,10,11,12,13,14,15,16}$, denoted as the \textit{RS model}, RS can address both the hierarchy problem and fermion mass hierarchies. From the electroweak precision measurements and various flavor physics, the new Kaluza-Klein (KK) modes of the bulk SM fields are constrained to be heavier than a few TeV$^{2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23}$. The radion $\phi$ was introduced as a quantum fluctuation of the modulus $L$ of the 5-th dimension. It is necessary to stabilize $L$ to the above value. Goldberger and Wise showed that a bulk scalar field propagating in the background geometry, Eq. (1), can generate a potential that can stabilize $L$.$^{24}$ In order to reproduce the value $kL \simeq 35$, the radion should have a lighter mass than that of the Kaluza-Klein modes of all bulk fields$^{25}$. Thus, the detection of the radion may well be expected as the first signal to indicate that the RS model is truly realized in nature.

From a purely phenomenological perspective, the fundamental scale $M_5$ is scaled down far below the 4-dimensional $M_{Pl}$, by increasing the size $kL$ of the 5-th dimension. This is known as little Randall-Sundrum (LRS) model$^{26}$. The hierarchy problem is yet unsolved in this model. The neutral kaon mixing parameter $\varepsilon_K$ gives a strong constraint$^{27}$ on $M_5$, namely $M_5 > \text{several thousand TeV}$, in the LRS model, and this corresponds to $kL \approx 7$. The present precision measurements of SM flavors are consistent with $kL = 7$. The diphoton signal at the LHC is predicted to be largely enhanced$^{28}$ in comparison to the RS model with $kL = 35$.

In this Letter we evaluate the production and decays of the radion. Similar analyses were done in ref.$^{5,28,29,30,31,32,33,34}$. We refine the calculations appropriate to the LHC experiments at 7 TeV (LHC7), and consider the possibility of finding $\phi$ in the ongoing LHC Higgs searches. We demonstrate that $\phi$ could be found in the SM Higgs search in the $\gamma\gamma$ and $W^*W$ channels at LHC7, and consider the possibility of RS and LRS models being thereby tested. We find that the LRS model with $kL = 7$ is excluded by the latest ATLAS and CMS data over a wide range of the radion mass.

2 Coupling to the SM particles

We define the fluctuation $F$ of the metric and the canonically normalized radion field $\phi$ as
\[ ds^2 = e^{-2(ky + F)} \eta_{\mu\nu} dx^\mu dx^\nu - (1 + 2F)^2 dy^2, \]
\[ F = \frac{\phi(x)}{\Lambda_\phi} e^{2k(y-L)}, \]  
where \( \Lambda_\phi \) is the VEV of the radion field \( \phi(x) \).

The couplings of the radion to the SM particles in the original RS model are composed of two parts,

\[ L = L_{\text{trace}} + L_{\text{bulk}}, \]
where \( L_{\text{trace}} \) is determined from general covariance\textsuperscript{24,29,30} to be

\[ L_{\text{trace}} = \frac{\phi}{\Lambda_\phi} T^\mu_\mu(SM). \]

\[ T^\mu_\mu(SM) = T^\mu_\mu(SM)^{\text{tree}} + T^\mu_\mu(SM)^{\text{anom}} \]
\[ T^\mu_\mu(SM)^{\text{tree}} = \sum_f m_f \bar{f} f - 2m_W^2 W^+ W^- - m_Z^2 Z^\mu Z^\mu + 2m_h^2 h^2 - \partial_\mu h \partial^\mu h \]
\[ T^\mu_\mu(SM)^{\text{anom}} = -\frac{\alpha_s}{8\pi} b_{\text{QCD}} \sum_a F^a_{\mu\nu} F^{a\mu\nu} - \frac{\alpha}{8\pi} b_{\text{EM}} F_{\mu\nu} F^{\mu\nu}. \]  

Here \( T^\mu_\mu(SM) \), the trace of the SM energy-momentum tensor, which is defined by \( \sqrt{-g} T^\mu_\mu(SM) = 2g^{\mu\nu} L_{\text{SM}} \), is represented as a sum of the tree-level term \( T^\mu_\mu(SM)^{\text{tree}} \) and the trace anomaly term \( T^\mu_\mu(SM)^{\text{anom}} \) for gluons and photons. \( F^a_{\mu\nu} \) are their field strengths. The \( b \) values are \( b_{\text{QCD}} = 11 - (2/3)6 + F_t \), including the top loop, and \( b_{\text{EM}} = 19/6 - 41/6 + (8/3)F_t - F_W \), including the top and W loops\textsuperscript{4}.

The \( T^\mu_\mu(SM)^{\text{tree}} \) is proportional to particle masses. The new RS model with the SM fields propagating in the bulk has an additional radion interaction, \( L_{\text{bulk}} \), which is inversely proportional to the size of the 5-th dimension\textsuperscript{4,5}. There is a correction to the interactions of fermions, massless gluons and photons that have couplings to a radion at tree level.

These interactions are very similar to the interactions of SM Higgs except for an overall proportional constant\textsuperscript{2} the inverse of the radion interaction scale \( \Lambda_\phi \), which is the VEV of \( \phi \). It is given by

\[ 1 \quad F_t = \tau_t (1 + (1 - \tau_t) f(\tau_t)) \quad \text{and} \quad F_W = 2 + 3\tau_W + 3\tau_W(2 - \tau_W) f(\tau_W). \]

\[ f(\tau) = \left\{ \begin{array}{ll} \text{Arcsin} \left( \frac{1}{\sqrt{\tau}} \right)^2 & \text{for} \ \tau \geq 1 \quad \text{and} \quad -\frac{1}{4} \left[ \ln \left( \frac{2w}{\eta_+} - i\pi \right) \right]^2 & \text{for} \ \tau < 1 \quad \text{with} \ \eta_\pm = 1 \pm \sqrt{1 - \tau}. \end{array} \right. \]

\[ \tau_i \equiv \left( \frac{2m}{m_\phi} \right)^2 \quad \text{for} \ i = t, W. \]

\[ 2 \quad \text{The overall sign of the radion couplings is opposite to that of the Higgs couplings in the most frequently used definition of} \ \phi(x), \text{Eq. (2).} \]
\( \Lambda_\phi = e^{-kL} \sqrt{\frac{6M_5^3}{k}}. \) \( (5) \)

The five dimensional fundamental scale \( M_5 \) is related with \( \bar{M}_{pl} \) by

\[ \bar{M}_{pl}^2 = \frac{M_5^3}{k} (1 - e^{-2kL}) \sim \frac{M_5^3}{k}. \] \( (6) \)

Thus, Eq. \( (5) \) is rewritten by

\[ \Lambda_\phi = \sqrt{6} \frac{k}{k} \bar{M}_{pl}, \quad \bar{k} \equiv ke^{-kL}, \] \( (7) \)

where \( \bar{k} \) sets the mass scale of \( KK \)-excitations.

We adopt the radion effective interaction Lagrangian given in Ref.[5] The radion couplings to gluons and photons are

\[ L_A = -\frac{\phi}{4\Lambda_\phi} \left[ \left( \frac{1}{kL} + \frac{\alpha_s}{2\pi} b_{QCD} \right) \sum_a F_{\mu\nu}^a F^{a\mu\nu} + \left( \frac{1}{kL} + \frac{\alpha}{2\pi} b_{EM} \right) F_{\mu\nu} F^{\mu\nu} \right]. \] \( (8) \)

We note that \( L_A \) has both contributions from \( L_{\text{bulk}} \) proportional to \( (kL)^{-1} \) and \( L_{\text{trace}} \) from the trace anomaly term, while only the latter term contributes for the SM Higgs case.

The radion couplings to \( W, Z \) bosons are

\[ L_V = -\frac{2\phi}{\Lambda_\phi} \left[ \left( \mu_W^2 W_\mu^- W_\mu^- + \frac{1}{4kL} W_{\mu\nu}^+ W_{\mu\nu}^- \right) + \left( \frac{\mu_Z^2}{2} Z_\mu^+ Z_\mu^- + \frac{1}{8kL} Z_{\mu\nu} Z_{\mu\nu} \right) \right]. \] \( (9) \)

where \( V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu \) for \( V_\mu = W_\mu^\pm, Z_\mu \) and \( \mu_i^2 \) \( (i = W, Z) \), which include the contributions from the bulk wave functions of \( W, Z \), are represented by using \( W(Z) \) mass \( m_{W,Z} \) as \( \mu_i^2 = m_i^2 \left[ 1 - \frac{kL}{2} \left( \frac{m_i}{\bar{k}} \right)^2 \right] \).

The radion couplings to the fermions are proportional to their masses.

\[ L_f = -\frac{\phi}{\Lambda_\phi} m_f [I(c_L) + I(c_R)] (\bar{f}_L f_R + \bar{f}_R f_L). \] \( (10) \)

\footnote{The physical masses of \( W, Z \) bosons are identified with \( \mu_i \), not \( m_i \) \( (i = W, Z) \); however, we neglect small difference between \( \mu_i \) and \( m_i \), and the \( m_i \)'s are fixed with the physical masses.}
The coupling is proportional to a factor \( I(c_L) + I(c_R) \) that is dependent upon the bulk profile parameters \( c_L \) and \( c_R \). The \( I(c_L) + I(c_R) \) are given in ref. [5] as \( 1 \sim 1.19 \) and \( 1 \) for \( b\bar{b}, t\bar{t}, \tau\tau \) channels, respectively, while the value for \( c\bar{c} \) is model-dependent. We simply take \( I(c_L) + I(c_R) = 1 \) for all the relevant channels: \( b\bar{b}, t\bar{t}, \tau\tau, c\bar{c} \).

The coupling of the radion to the IR brane-localized Higgs scalar \( h \) is given by

\[
L_h = \frac{\phi}{\Lambda_\phi} (-\partial_\mu h \partial^\mu h + 2m_h^2 h^2). \tag{11}
\]

The model parameters are \( kL, \Lambda_\phi, m_\phi \) and \( m_h \). In the following we consider two values of \( kL \): \( kL = 7 \) corresponding to the LRS model and \( kL = 35 \) to the original RS model. The value \( \Lambda_\phi = 3 \) TeV is used [28]. \( k \) is taken as \( k < M_5 \) in the original RS model [1]. Here we simply take \( k = M_5 \). From Eq. (5) this corresponds to \( \bar{k} = \Lambda_\phi/\sqrt{6} \). The value of \( m_h \) is taken as \( 130 \) GeV unless otherwise specified, while \( m_\phi \) is treated as a free parameter. By using the effective couplings Eqs. (8) - (11) and these values of parameters, we calculate the partial decay widths and their branching ratios in §4.

3 Radion Production at the LHC

The production cross section of the radion \( \phi \) at hadron colliders is expected to be mainly via \( gg \) fusion, similarly to the production of a Higgs boson \( h^0 \). These cross sections are proportional to the respective partial decay widths to \( gg \). The production cross section of \( h^0 \) has been calculated in NNLO [36], and by using this result [5] we can directly estimate the production cross section of \( \phi \) as

\[
\sigma(pp \to \phi X) = \sigma(pp \to h^0 X) \times \frac{\Gamma(\phi \to gg)}{\Gamma(h^0 \to gg)}. \tag{12}
\]

By using the \( \Gamma(\phi \to gg) \) partial width given later and \( \Gamma(h^0 \to gg) \) of the SM we can predict \( \sigma(pp \to \phi X) \) in the two cases \( kL = 7, 35 \). The result is compared with the SM Higgs production in Fig. 1.

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\(^4\) \( c\bar{c} \) has only a tiny \( BF \). For \( b\bar{b}, I(c_L) + I(c_R) \) is given as \( 1.66 \) in another example [26]. In that case \( BF(\phi \to b\bar{b}) \) becomes about 2.5 times larger than our present result.

\(^5\) The QCD radiative corrections to the tree level \( gg \to h^0 \) and \( gg \to \phi \) should be equal in the point-like approximation of the \( gg \to h^0/\phi \) interactions, so we use the tree level result for \( \Gamma(\phi \to gg)/\Gamma(h^0 \to gg) \).
Fig. 1. The production cross sections at LHC7 of the radion $\phi$ via $gg$ fusion (solid blue $kL = 35$ corresponding to the original RS model and solid thick black $kL = 7$ to LRS model), compared with that of the SM Higgs with the same mass $m_{h^0} = m_\phi$ (solid thin red). The $\phi$ production cross sections are proportional to inverse-squared of $\Lambda_\phi$, which is taken to be $\Lambda_\phi = 3$ TeV here. The overall theoretical uncertainties\cite{36} are denoted by dotted lines.

The production of $\phi$ scales with an overall factor $(1/\Lambda_\phi)^2$. In the $\Lambda_\phi = 3$ TeV case, the production of $\phi$ in the original RS model ($kL = 35$) is almost the same as that of the SM Higgs boson of the same mass, while in the LRS case ($kL = 7$) the radion cross section exceeds that of the SM Higgs. This is because $\phi$ production from $gg$ fusion has an amplitude that includes a term proportional to $1/kL$ at tree level, while there is no such term in $h^0$ production. Our prediction of $\sigma(\phi)$ in Fig.\ref{fig1} includes the $\pm 25\%$ uncertainty associated with the theoretical uncertainty on $\sigma(h^0)$\cite{36}.

4 Radion Decay

For the radion decay channels $\phi \rightarrow AB$, we consider $AB = gg, \gamma\gamma, W^+W^-, ZZ, b\bar{b}, c\bar{c}, \tau^+\tau^-, t\bar{t}$, and $h^0h^0$. Their partial widths are given by the formula

$$\Gamma(\phi \rightarrow AB) = \frac{N_c}{8\pi(1+\delta_{AB})m_\phi^2}p(m_\phi^2; m_A^2, m_B^2) \times |M|^2$$

(13)

where $p$ is the momentum of particle $A$ (or $B$) in the CM system and $|M|^2$ represents the decay amplitude squared which are given in Table 1\cite{6}.

\footnote{For the $gg$ decay of $\phi$ we include the radiative corrections at NNLO by using the K-factor from Higgs production. We use central values of the K-factor given in Fig. 8 of Ref.\cite{37}; For $m_{h^0} = 100 \sim 600$ GeV, $K = 2.0 \sim 2.6$. This value is about 10\%}
Table 1
Decay amplitudes squared $|M|^2$ of $\phi$ decays. $|M|^2$ for $ZZ$ is obtained by replacement $W \rightarrow Z$ from $M_{T,L}^{WW}$. $gg$ includes a K-factor $K(m_\phi)$ \[36\]. $b_{QCD}$, $b_{EM}$ are given below Eq. (4) in the text. $b\bar{b}$ includes radiative corrections\[39\] of running mass $m_b(m_\phi)$ and an overall factor $C(m_\phi)$, but we adopt a fixed mass $m_b = 4.5$ GeV for the kinematical factor $(m_\phi^2/4 - m_b^2)^3/2$. Similar expressions are also applied to $t\bar{t}, c\bar{c}$ channels. The off-shell $WW^*(ZZ^*)$ channels in the low-mass $\phi$ case are treated in the same method as in ref.\[38\].

| decay channel | $|M|^2$ |
|---------------|---------|
| $W^+W^-$      | $2|M_T^{WW}|^2 + |M_L^{WW}|^2$ |
| $gg$          | $2|M_T^{gg}|^2 \cdot K(m_\phi)$ |
| $\gamma\gamma$ | $2|M_T^{\gamma\gamma}|^2$ |
| $b\bar{b}$    | $\frac{8}{\Lambda^2} C(m_\phi) m_b(m_\phi)^2 \left(\frac{m_b^2}{4} - m_b^2\right)$ |
| $\tau^+\tau^-$ | $\frac{8}{\Lambda^2} m_\tau^2 (m_\phi^2/4 - m_\tau^2)$ |
| $h^0h^0$      | $\left| - \frac{1}{\Lambda^2} (m_h^2 + 2m_b^2) \right|^2$ |

\[ M_T^{WW} = - \frac{2}{\Lambda^2} \left( \mu_W^2 - \frac{1}{2} \frac{m_\phi^2 - 2m_b^2}{2} \right) \]
\[ M_L^{WW} = -(1 - \frac{m_b^2}{2m_\phi^2}) M_T^{WW} - \frac{1}{\Lambda^2} m_b^2(m_\phi^2/4 - m_b^2) \]
\[ M_T^{gg,\gamma\gamma} = \frac{m_\phi^2}{2\Lambda^2 kL} (1 + \frac{\alpha_s b_{QCD}}{2\pi} kL), \quad \frac{m_\phi^2}{2\Lambda^2 kL} (1 + \frac{\alpha b_{EM}}{2\pi} kL) \]

The results of the decay branching fractions are given for the two cases $kL = 7, 35$ in Fig. 2.

In the $kL = 7$(LRS model) case, there is a strong enhancement of $BF(\phi \rightarrow \gamma\gamma)$, in comparison to the RS model with $kL = 35$, as was pointed out in ref.\[28\]. The $BF(\gamma\gamma)$ reaches almost $10^{-2}$ in LRS model, while it is $\sim 10^{-4}$ almost independent of $m_\phi$ in RS model. $BF(\gamma\gamma)$ is proportional to $(1/kL)^2$ in the $m_\phi \gtrsim 200$ GeV region in the LRS model. This huge enhancement is from the bulk field coupling of $\phi$ proportional to $1/kL$. We do not find sharp dips in $BF(\phi \rightarrow WW, ZZ)$ around $m_\phi \simeq 450$ GeV of Fig. 1 in ref.\[28\].

The total width of $\phi$ in Fig. 3 is one or two orders of magnitude smaller than that of the SM Higgs of the same mass. This is because the choice of $\Lambda_\phi = 3$ TeV is about one order of magnitude larger than the Higgs VEV $v = 246$ GeV. A $\phi$ resonance would be observed with the width of the exper-

larger than the K-factor of Higgs decaying into $gg$ in NNLO given in ref.\[44\] but within the uncertainty of the choice of the renormalization scale. So we assume the $\phi$ and $h$ $K$-factors are equal and adopt the value in ref.\[37\].

It should be noted that in the original RS model setup where the SM fields are confined in the IR brane, $BF(\gamma\gamma)$ steeply decreases with $m_\phi > 200$ GeV similarly to the SM Higgs. This modified behavior comes from $L_{bulk}$ in the new bulk field scenario of SM field.
Fig. 2. Decay Branching Fractions of $\phi$ versus $m_{\phi}(\text{GeV})$ for $kL = 7$ (LRS model) and 35 (RS model). $m_{h^0}$ is taken to be 130 GeV.

The experimental resolution. The $\Gamma(\phi \to WW)$ partial width is negligibly small compared with $\Gamma(h^0 \to WW)$, and thus $\phi$ production via vector boson ($WW, ZZ$) fusion is unimportant at the LHC, providing another way to distinguish $\phi$ and $h^0$. We note that double Higgs production via $\phi$ decays would uniquely distinguish $\phi$ and $h$.

5 Radion Detection compared to SM Higgs

Next we consider the detection of $\phi$ via the $W^+W^-$, $ZZ$ and $\gamma\gamma$ decay channels. The $\phi$ search can be made in conjunction with the Higgs search. The properties of $h^0$ at the LHC are well known, so we use them as benchmarks of the search for $\phi$. 

8
Fig. 3. Total widths (GeV) and $W^+W^-$ partial widths of $\phi$ compared with the SM higgs $h^0$ with the same mass $m = m_\phi = m_h$(GeV). The $\Lambda_\phi = 3$ TeV and $kL = 7, 35$ cases are shown. For $\Gamma(\phi \to \text{all})$ the $m_h$ is fixed with 130 GeV. The widths of $\phi$ are proportional to the inverse squared of $\Lambda_\phi$.

Fig. 4. $\phi$ Detection Ratio ($DR$) to the SM higgs $h^0$ of Eq. (14) for the $\bar{XX} = W^+W^-(\text{solid blue}), ZZ(\text{dashed orange}), \text{and } \gamma\gamma(\text{solid black})$ final states for $kL = 7, 35$ versus $m_\phi$(GeV).

The $\phi$ detection ratio ($DR$) to $h^0$ in the $\bar{XX}$ channel is defined by

$$DR \equiv \frac{\Gamma_{\phi \to gg} \Gamma_{\phi \to \bar{XX}} / \Gamma_{\phi \to gg}^{\text{tot}}}{\Gamma_{h^0 \to gg} \Gamma_{h^0 \to \bar{XX}} / \Gamma_{h^0 \to gg}^{\text{tot}}} ,$$

(14)
where $XX = W^+W^-, ZZ,$ and $\gamma\gamma$. The $DR$ are plotted versus $m_\phi = m_{h^0}$ in Fig. 4 for the two cases $kL = 7$ and 35.

In mass range between the $WW$ threshold and the $h^0h^0$ threshold (300 GeV in the present illustration) the $\phi$ to $h^0$ detection ratio is relatively large in both $WW$ and $ZZ$ channels. The $DR$ is almost 2 in the $kL = 7$ case. The $DR$ in $\gamma\gamma$ channel increases rapidly in the large $m_\phi = m_{h^0}$ region since $\Gamma_{h^0 \rightarrow \gamma\gamma}$ steeply decreases with increasing $m_h$ due to the cancellation between top and $W$ loops. So the $\gamma\gamma$ channel used in the search for the SH Higgs in the mass range 115-150 GeV by the LHC experiments is more sensitive for the $\phi$ search. Surprisingly large enhancements of $DR$ in the $\gamma\gamma$ channel are predicted in this mass region in the $kL = 7$ case. This is because the $BF(\phi \rightarrow \gamma\gamma)$ is hugely enhanced in LRS model, as explained in the previous section. The $\phi$ should be detected in $\gamma\gamma$ in the current LHC data in the LRS scenario. This possibility is checked in Fig. 5.

The cross-section of a putative Higgs-boson signal, relative to the Standard Model cross section, as a function of the assumed Higgs boson mass, is widely used by the experimental groups to determine the allowed and excluded regions of $m_{h^0}$. By use of the $DR$ in Fig. 4 we can determine the allowed region of $m_\phi$ from the present LHC data. Figure 6 shows the 95% confidence level upper limits on Higgs-like $\phi$ signals decaying into $XX$ versus $m_\phi$ for $XX = WW$ (ATLAS[41], CMS[42]) and $\gamma\gamma$ (ATLAS[43]).

For the LRS model with $kL = 7$, $m_\phi$ is excluded by ATLAS data at 95% CL over the $m_\phi$ range, 160 < $m_\phi$ < 220 GeV, while for RS model $kL = 35$ almost no regions of $m_\phi$ are yet excluded. Similar results are found from CMS data[42].

The $\phi$ search is also applicable to the Tevatron data. The CDF and D0 experiments excluded a SM Higgs with mass 158 GeV < $m_{h^0}$ < 175 GeV from data on $WW, ZZ$ channels. The same data exclude $\phi$ in the $kL = 7$ case in $m_\phi$ range, 163 GeV < $m_\phi$ < 180 GeV, while for $kL = 35$, only 165 GeV < $m_\phi$ < 171 GeV is excluded.

The $\gamma\gamma$ final state is very promising for $\phi$ detection, because the $\phi$ to $h^0$ detection ratio is generally very large in all the mass range of $m_\phi$, as shown in Fig. 4. The $\gamma\gamma$ data of ATLAS do not show any resonance enhancements in 110 < $m$ < 150 GeV (cf. Fig. 5) so $\phi$ is excluded in this mass region in the LRS model ($kL = 7$) case, while no $m_\phi$ regions are excluded in the RS model with $kL = 35$. The radion upper limits in the diphoton channel have similar shapes of the curve for the Higgs because the detection ratios are relatively constant in this narrow mass range $m = 110 \sim 150$ GeV: See Fig. 4.

For $m_\phi > 150$ GeV, the $\gamma\gamma$ signal of $h^0$ is too small to be detected at present, but future data in this region can determine the existence of $\phi$. 
Fig. 5. The 95% confidence level upper limits on $(1/DR) \times (\sigma_{\text{exp}}/\sigma(h^0 \rightarrow \bar{X}X))$. This is the signal of a scalar boson decaying into $\bar{X}X$ relative to the radion cross section $[\sigma(\phi \rightarrow \bar{X}X) = \sigma(h^0 \rightarrow \bar{X}X) \times DR]$ for $\bar{X}X = WW \rightarrow l\nu l\nu$ (ATLAS [41], CMS [42]) and $\gamma\gamma$ (ATLAS [43]) data. The cases $kL = 35$ (solid blue) and 7 (solid black) are shown. Similar results for the SM Higgs boson are also given (red thin-solid curve).

We take $\Lambda_\phi = 3$ TeV in our analyses. By taking larger values of $\Lambda_\phi$, the detection ratios of $\phi$ decrease since the $\phi$ production cross section is proportional to $(1/\Lambda_\phi)^2$. By taking $\Lambda_\phi > 5$ TeV, all values of $m_\phi$ become allowed by the latest ATLAS and CMS $WW^*$ data. By taking $\Lambda_\phi > 10$ TeV, all values of $m_\phi$ become allowed by the latest ATLAS $\gamma\gamma$ data.

A comment should be added here. There is a possible mixing effect [29] between the radion and SM Higgs boson through the action.
\[ S_\xi = -\xi \int d^4x \sqrt{-g} R \ H^\dagger H \] (15)

where \( H \) is Higgs doublet and \( H = ((v + h^0)/\sqrt{2}, 0) \). Because of the Higgs-like nature of the radion coupling, its effect can be very large even if the mixing angle is very small. We have excluded wide \( m_\phi \)-regions in LRS model with \( \Lambda_\phi = 3 \text{ TeV} \) in the no-mixing case. The effect of Eq. (15) is studied in detail in ref. [35] including a large \( \xi \) case of the RS1 model[32]. Generally speaking, when \( \text{BF}(\phi \rightarrow WW/ZZ) \) becomes larger(smaller) owing to the mixing effect, \( \text{BF}(\phi \rightarrow \gamma\gamma) \) becomes smaller(larger) than in the no-mixing case. So the \( WW/ZZ \) and \( \gamma\gamma \) channels are complementary for the detection of the radion.

6 Concluding Remarks

We have investigated the possibility of finding the radion \( \phi \) at the Tevatron and LHC7. The radion can be discovered in the \( WW, ZZ \), and \( \gamma\gamma \) channels in the search for the SM Higgs \( h^0 \). The \( WW \) signal rate can be comparable to that of the SM \( h^0 \), in the mass region \( m_\phi \sim 160 \text{ GeV} \) up to \( 2m_{h^0} \) as shown in Fig. 4. The \( \gamma\gamma \) search channel is especially promising, since \( \text{BF}(\phi \rightarrow \gamma\gamma) \) is almost constant at \( \sim 10^{-4} \) for \( m_\phi \) below 600 GeV, and the corresponding \( \phi \) detection ratio compared to \( h^0 \) is very large above \( m_\phi = 180 \text{ GeV} \). Combining the \( WW, \gamma\gamma \) data of ATLAS and CMS, the LRS model with \( kL = 7 \) is already excluded over wide ranges of \( m_\phi \) for \( \Lambda_\phi = 3 \text{ TeV} \).

Note added A constraint on the mass of the first KK-graviton, \( m_{G1} \), was reported[43] by the ATLAS collaboration from the 2-photon channel: \( m_{G1} > 0.80(1.95) \text{ TeV} \) for \( k/M_{Pl} = 0.01(0.1) \). \( m_{G1} \) is given by \( x_1 \bar{k} \), where \( x_1 = 3.83 \) is the first root of \( J_1 \) bessel function, and thus, a very strong constraint is obtained for the \( \Lambda_\phi \) in Eq. (7): \( \Lambda_\phi = \sqrt{6m_\phi x_1} \left( \frac{k}{M_{Pl}} \right)^{-1} \) which gives \( \Lambda_\phi > 50(12) \text{ TeV} \) for \( \frac{k}{M_{Pl}} = 0.01(0.1) \). However, the lower limit of \( \Lambda_\phi \) is strongly dependent upon the value of \( m_\phi \), and if this ratio is taken to be unity[46], the lower limit on \( \Lambda_\phi \) will be relaxed to a few TeV; The curvature \( k \) should be less than the Planck mass \( M_{Pl} \) in the RS model[1].

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