Could the Excess Seen at 124 – 126 GeV be due to the Randall-Sundrum Radion?

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Current Higgs boson searches in various channels at the LHC point to an excess at around 124–126 GeV due to a possibly standard-model-like Higgs boson. If one examines more closely the channels ($\gamma\gamma$, $WW^*$, and $ZZ^*$) that have excess, this “Higgs boson” may be the Randall-Sundrum radion $\phi$. Because of the trace anomaly the radion has stronger couplings to the photon and gluon pairs. Thus, it will enhance the production rates into $gg$ and $\gamma\gamma$ while those for $WW^*$, $ZZ^*$ and $bb$ are reduced relative to their standard-model values. We show that it can match well with the data from CMS for $m_\phi = 124$ GeV and the required scale $\Lambda_\phi \sim \langle \phi \rangle$ is about 0.68 TeV.

This is the main result of this work.

A large number of works appeared to interpret the 124 – 126 GeV Higgs boson in the MSSM framework \cite{ref1}, in the NMSSM framework \cite{ref2}, in 2HDM \cite{ref3}, in other SUSY framework \cite{ref4}, and others \cite{ref5}.

The Radion.— The RS model \cite{ref6} that uses a warped space-time in a slice of extra dimension explains the gauge hierarchy problem well. The RS model has a four-dimensional massless scalar, the modulus or radion $\phi$ \cite{ref7,ref8,ref9}, about the background geometry:

$$ds^2 = e^{-2k_\phi |T(x)|} g_{\mu\nu}(x) dx^\mu dx^\nu - T^2(x) d\phi^2,$$

where $g_{\mu\nu}(x)$ is the four-dimensional graviton and $T(x)$ is the modulus field. The most important ingredients of the above brane configuration for phenomenological studies are the required size of the modulus field such that it generates the desired weak scale from the high scale $M$ and the stabilization of the modulus field at this value. A stabilization mechanism was proposed by Goldberger and Wise \cite{ref10} that a bulk scalar field propagating in the background solution of the metric can generate a potential that can stabilize the modulus field. The minimum of the potential can be arranged to give the desired value of $k_{\phi}$ without fine-tuning of parameters. It has been shown \cite{ref11,ref12} that if a large value of $k_{\phi}$ ~ 12, needed to solve the hierarchy problem, arises from a small bulk scalar mass, then the modulus potential near its minimum is nearly flat for values of the modulus vacuum expectation value that solves the hierarchy problem. As a consequence, besides getting a mass, the modulus field is likely to be lighter than any Kaluza-Klein modes of any bulk field.

The lightest mode is the radion, which has a mass of the order of 100 GeV to a TeV, and the strength of its coupling to the SM fields is of the order of $O(1/\text{TeV})$. There is no theoretical preferred mass region for the radion, and it was shown in Ref. \cite{ref13} that the un mixed radion is consistent with electroweak precision data. Therefore, the detection of this radion may be the first signature of the RS model.
The interactions of the radion $\phi$ with the SM particles on the brane are model-independent and are governed by four-dimensional general covariance given by the following Lagrangian:

$$\mathcal{L}_{\text{int}} = \frac{\phi}{\Lambda_{\phi}} T_{\mu}^{\mu}(\text{SM}),$$

where $\Lambda_{\phi} = \langle \phi \rangle$ is of the order of TeV and $T_{\mu}^{\mu}$ is the trace of the SM energy-momentum tensor, which is given by

$$T_{\mu}^{\mu}(\text{SM}) = \sum f f - 2 m_{W}^{2} W_{\mu}^{+} W^{-\mu} - m_{Z}^{2} Z_{\mu} Z^{\mu} + (2 m_{H}^{2} H^{2} - \partial_{\mu} H \partial_{\mu} H) + \cdots,$$  

where $\cdots$ denotes higher order terms. The couplings of the radion with fermions $f$, gauge bosons $W$ and $Z$, and Higgs boson $H$ are completely fixed by Eq. (2).

For the coupling of the radion to a pair of gluons (photons), there are contributions from 1-loop diagrams with the top quark (top quark and $W$) in the loop as well as from the trace anomaly. The contribution from the trace anomaly for gauge fields is given by

$$T_{\mu}^{\mu}(\text{SM})^{\text{anom}} = \sum a \frac{\beta_{a}(g_{a})}{2 g_{a}} F_{\mu}^{a} F^{a \mu \nu},$$

For QCD, $\beta_{\text{QCD}} / 2 g_{s} = -(\alpha_{s} / 8 \pi) b_{\text{QCD}} g_{s}$, where $b_{\text{QCD}} = 11 - 2 n_{f} / 3$ with $n_{f} = 6$. Thus, the effective coupling of $\phi g(p_{1}) g(p_{2})$, including the 1-loop diagrams of the top quark and the trace anomaly contributions, is given by

$$i \frac{\alpha_{s} \Lambda_{\phi}}{2 \pi} \left[ b_{\text{QCD}} + y_{t} (1 + (1 - y_{t}) f(y_{t})) \right] (p_{1} \cdot p_{2} g_{\mu \nu} - p_{2} g_{\mu \nu} - p_{1} g_{\mu \nu}),$$

where $y_{t} = 4 m_{t}^{2} / p_{1} \cdot p_{2}$ with the gluon incoming momenta $p_{1}$ and $p_{2}$. Similarly, the effective coupling of $\phi \gamma(p_{1}) \gamma(p_{2})$, including the 1-loop diagrams of the top quark and $W$ boson and the trace anomaly contributions, is given by

$$i \frac{\alpha_{\text{em}}}{2 \pi} \left[ b_{\text{em}} + y_{t} (1 + (1 - y_{t}) f(y_{t})) \right] (p_{1} \cdot p_{2} g_{\mu \nu} - p_{2} g_{\mu \nu} - p_{1} g_{\mu \nu}),$$

where $b_{\text{em}} = 19 / 6, b_{t} = -41 / 6$ and $y_{t} = 4 m_{t}^{2} / p_{1} \cdot p_{2}$ with $i = W, t$. In the above Eqs. (2) and (3), the function $f(z)$ is given by

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

There have been many phenomenological studies of the radion or dilaton at colliders in the literature. More recent works related to the LHC can be found in Ref. [13].

Decays and Production of the Radion. With the above interactions, we can calculate the partial widths of the radion into $gg, \gamma \gamma, f \bar{f}, W^{+}W^{-}, ZZ$, and $HH$. The partial widths are given by

$$\Gamma(\phi \rightarrow gg) = \frac{\alpha_{s}^{2} m_{\phi}^{3}}{32 \pi \Lambda_{\phi}^{2}} \left| b_{\text{QCD}} + x_{t} (1 + (1 - x_{t}) f(x_{t})) \right|^{2},$$

$$\Gamma(\phi \rightarrow \gamma \gamma) = \frac{\alpha_{\text{em}}^{2} m_{\phi}^{3}}{256 \pi^{3} \Lambda_{\phi}^{2}} b_{2} + b_{\gamma} - (2 + 3 x_{W} + 3 x_{W})$$

$$\times (2 - x_{W}) f(x_{W}) + \frac{8}{3} x_{t} (1 + (1 - x_{t}) f(x_{t}))^{2},$$

$$\Gamma(\phi \rightarrow f \bar{f}) = \frac{N_{c} m_{f}^{2} m_{\phi}}{8 \pi \Lambda_{\phi}^{2}} (1 - x_{f})^{3 / 2},$$

$$\Gamma(\phi \rightarrow ZZ) = \frac{m_{f}^{3}}{16 \pi \Lambda_{\phi}^{2}} \sqrt{1 - x_{Z} (1 - x_{Z} + \frac{3}{4} x_{Z}^{2})},$$

$$\Gamma(\phi \rightarrow HH) = \frac{m_{f}^{3}}{32 \pi \Lambda_{\phi}^{2}} \sqrt{1 - x_{H} (1 + \frac{x_{H}}{2})^{2}},$$

where $x_{i} = 4 m_{i}^{2} / m_{\phi}^{2}$ ($i = f, W, Z, H$) and $N_{c} = 3 (1)$ for quarks (leptons). Note that the branching ratios are independent of $\Lambda_{\phi}$.

In calculating the partial widths into fermions, we have used the 3-loop running masses with scale $Q^{2} = m_{\phi}^{2}$. We have also allowed the off-shell decays of the $W$ and $Z$ bosons and that of the top quark. The features of radion decay branching ratios are similar to the decay of the Higgs boson, except the following. At $m_{\phi} \lesssim 140$ GeV, the decay width is dominated by $\phi \rightarrow gg$, while the decay width of the SM Higgs boson is dominated by the $bb$ mode. At larger $m_{\phi}$, $\phi$ also decays into a pair of Higgs bosons ($\phi \rightarrow HH$) if kinematically allowed, while the SM Higgs boson cannot. Similar to the SM Higgs boson, as $m_{\phi}$ goes beyond the $WW$ and $ZZ$ thresholds, the $WW$ and $ZZ$ modes dominate with the $WW$ partial width about a factor of 2 of the $ZZ$ partial width. We list the relevant branching ratios of the radion in Table II for $m_{\phi} = 123 - 126$ GeV. Just for comparison with the SM Higgs boson, we also list the branching ratios and production cross sections of the SM Higgs boson in Table III (from Ref. [14]).

The production channels of the radion at hadronic colliders include

$$gg \rightarrow \phi$$
versus Λ

The production channel for the radion is gg fusion

We show the production cross sections for gg fusion in the following. We shall consider only the gluon fusion in the following. We show the production cross sections for mφ = 120 – 130 GeV versus Λφ in Fig. 1.

Comparison to the LHC data. - Using the appropriate entries from Tables I and II for mφ/H = 124 GeV, we can compute the following ratio:

\[
\frac{\sigma(\phi) \times B(\phi \rightarrow \gamma\gamma)}{\sigma(H) \times B(H \rightarrow \gamma\gamma)} = \frac{\sigma(\phi) \times 0.918 \times 10^{-3}}{15.6 \text{ pb} \times 2.29 \times 10^{-3}} = 2.1
\]

where 2.1 is the central value of the CMS data for this ratio. Therefore, the value of \( \sigma(\phi) \) obtained in the above equation is 82 pb, which corresponds to \( \Lambda_\phi = 0.68 \) TeV from Fig. 1. If we use the diphoton data with error bars (2.1 \( ^{+0.7}_{-0.5} \)), the corresponding \( \Lambda = 0.68 ^{+0.15}_{-0.08} \) TeV. Once the ratio for \( \gamma\gamma \) is fixed, the other ratios can be easily obtained by using Tables I and II.

\[
\frac{\sigma(\phi) \times B(\phi \rightarrow b\bar{b})}{\sigma(H) \times B(H \rightarrow b\bar{b})} = \frac{82 \text{ pb} \times 0.0598}{15.6 \text{ pb} \times 0.592} = 0.53, \quad (14)
\]

\[
\frac{\sigma(\phi) \times B(\phi \rightarrow \tau\tau)}{\sigma(H) \times B(H \rightarrow \tau\tau)} = \frac{82 \text{ pb} \times 9.34 \times 10^{-3}}{15.6 \text{ pb} \times 0.065} = 0.75, \quad (15)
\]

\[
\frac{\sigma(\phi) \times B(\phi \rightarrow WW^*)}{\sigma(H) \times B(H \rightarrow WW^*)} = \frac{82 \text{ pb} \times 0.0267}{15.6 \text{ pb} \times 0.200} = 0.70, \quad (16)
\]

\[
\frac{\sigma(\phi) \times B(\phi \rightarrow ZZ^*)}{\sigma(H) \times B(H \rightarrow ZZ^*)} = \frac{82 \text{ pb} \times 3.25 \times 10^{-3}}{15.6 \text{ pb} \times 0.0242} = 0.70. \quad (17)
\]

Therefore, we obtain a set of ratios which match well with the central values of the CMS data, provided that we first match the \( \gamma\gamma \) mode to the experimental data. We repeat the exercise for other \( m_\phi = 123 – 126 \) GeV with the results shown in Table III. The ratios vary very little in this radion mass range.

Implications. – The radion has a large branching ratio into gg, which will give rise to a dijet signal at the Tevatron and the LHC. The cross section \( \sigma(gg \rightarrow \phi) \times B(\phi \rightarrow gg) \approx 73 \) pb at the LHC and only 3.4 pb at the Tevatron. The huge QCD background will overwhelm the dijet signal. The only possibility is to consider the associated production with a W or a Z boson. In Table IV, we calculate the production cross section of Wφ and Zφ at the Tevatron and at the LHC, multiplied by the gluonic branching ratio. With this level of cross sections it is still difficult to beat the Wjj and Zjj background. If the systematics can be reduced to a few percent level, it may have some chance to see this dijet signal.

In conclusion, the CMS and ATLAS Collaborations have seen excess in a number of channels; in particular, the \( \gamma\gamma \) channel has a cross section about twice the SM value, while the other channels are slightly suppressed (by about 0.5 – 0.7) relative to their SM values. We have proposed the RS radion as a possible candidate for the particle observed. While it is not easy to accommodate a 125 GeV Higgs boson with an enhanced diphoton rate in the MSSM [16, 17], NMSSM [18], and a number of other popular models [19, 20], the RS radion provides the most economical way to interpret the data. In order to give a 124 – 126 GeV Higgs boson within MSSM, the stop sector must consist of a large mixing that gives rise to one very heavy stop \( \tilde{t}_2 \) and one relatively light stop \( \tilde{t}_1 \). Within the MSSM and NMSSM, it is rather difficult to enhance the \( \gamma\gamma \) production rate [16, 17]; only in some less restrictive NMSSM can the rate be enhanced by a factor up to 2 [18]. The littlest Higgs model [16] always gives a slight reduction in the diphoton rate. The inert Higgs doublet model [17] gives a diphoton rate in the range of 0.8 – 1.3 relative to the SM rate, but it can hardly go over 1.5. In a type-II seesaw model [18], the diphoton production rate can be enhanced significantly because of the contribution from the double-charged Higgs boson but at relatively large values of self-couplings. The radion, due to the trace anomaly, has enhanced couplings to a pair of photons and gluons. Thus, the production rate of \( \sigma(\phi) \times B(\phi \rightarrow \gamma\gamma) \) can be enhanced relative to the SM cross section. The data requires \( \Lambda_\phi \approx 0.68 \) TeV. At the same time, the other channels bb, ττ, WW, and ZZ are all suppressed by a factor of 0.5 – 0.7 (shown in Table III) relative to the SM. Therefore, the RS radion provides a reasonably good interpretation to the data. Such a radion will give rise to a large dijet resonance signal, though it is still very difficult to identify it in the presence of huge QCD background, unless the systematic uncertainty can be reduced to a few percent level.
### TABLE I: The branching ratios of the RS radion for $m_{\phi} = 123 - 126$ GeV.

| $m_{\phi}$ (GeV) | gg | $b\bar{b}$ | $\tau\tau$ | $WW^*$ | $ZZ^*$ | $\gamma\gamma$ |
|------------------|-----|------------|-------------|--------|-------|-------------|
| 123              | 0.899 | 0.0608 | $9.49 \times 10^{-3}$ | 0.0246 | 2.93 $\times 10^{-3}$ | 0.912 $\times 10^{-3}$ |
| 124              | 0.897 | 0.0598 | $9.34 \times 10^{-3}$ | 0.0267 | 3.25 $\times 10^{-3}$ | 0.918 $\times 10^{-3}$ |
| 125              | 0.896 | 0.0588 | $9.2 \times 10^{-3}$ | 0.0291 | 3.6 $\times 10^{-3}$ | 0.925 $\times 10^{-3}$ |
| 126              | 0.894 | 0.0578 | $9.05 \times 10^{-3}$ | 0.0317 | 3.98 $\times 10^{-3}$ | 0.931 $\times 10^{-3}$ |

### TABLE II: A few production cross sections and branching ratios of the SM Higgs boson for $m_H = 123 - 126$ GeV. We borrow the values from Ref. [12].

| $m_H$ (GeV) | Cross sections (pb) | Branching ratios |
|-------------|---------------------|-----------------|
|             | gg → H | WH | ZH | $b\bar{b}$ | $\tau\tau$ | $WW^*$ | $ZZ^*$ | $\gamma\gamma$ |
| 123         | 15.8   | 0.61 | 0.33 | 0.607 | 0.067 | 0.185 | 0.022 | 2.28 $\times 10^{-3}$ |
| 124         | 15.6   | 0.59 | 0.32 | 0.592 | 0.065 | 0.200 | 0.0242 | 2.29 $\times 10^{-3}$ |
| 125         | 15.3   | 0.57 | 0.32 | 0.577 | 0.064 | 0.216 | 0.0266 | 2.29 $\times 10^{-3}$ |
| 126         | 15.1   | 0.56 | 0.31 | 0.561 | 0.062 | 0.233 | 0.0291 | 2.29 $\times 10^{-3}$ |

### TABLE III: The ratio $\frac{\sigma(\phi) \times B(\phi \to X)}{\sigma(H) \times B(H \to X)}$ for $m_{\phi/H} = 123 - 126$ GeV.

| $m_{\phi/H}$ (GeV) | $\gamma\gamma$ | $b\bar{b}$ | $\tau\tau$ | $WW^*$ | $ZZ^*$ |
|---------------------|-------------|--------|---------|--------|------|
| 123                 | 2.1         | 0.53   | 0.74    | 0.70   | 0.70 |
| 124                 | 2.1         | 0.53   | 0.75    | 0.70   | 0.70 |
| 125                 | 2.1         | 0.53   | 0.75    | 0.70   | 0.70 |
| 126                 | 2.1         | 0.53   | 0.75    | 0.70   | 0.71 |

### TABLE IV: Production cross sections in femtobarns for $\sigma(W\phi \to Wgg)$ and $\sigma(Z\phi \to Zgg)$ at the Tevatron and at the LHC-7. The $\Lambda_0$ is set at 0.68 TeV.

| $m_{\phi}$ (GeV) | $\sigma(W\phi \to Wgg)$ Tevatron | $\sigma(W\phi \to Wgg)$ LHC-7 | $\sigma(Z\phi \to Zgg)$ Tevatron | $\sigma(Z\phi \to Zgg)$ LHC-7 |
|------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 123              | 19.1                            | 73.4                            | 11.5                            | 39.1                            |
| 124              | 18.5                            | 71.2                            | 11.1                            | 38.0                            |
| 125              | 17.9                            | 69.2                            | 10.8                            | 36.9                            |
| 126              | 17.4                            | 67.1                            | 10.5                            | 35.8                            |

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