Radion Higgs mixing at the LHC

[arxiv:1512.06674 with D. B, D. B, A. C, S. R and T.S ,
work in progress with A. C, S. R and T.S,
work in progress with M.F, K. H and M. P]

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Outline

Introduction to RS model

- RS model offers a mechanism to generate hierarchy between the weak scale and the Planck scale.
- The idea is that we live in a five dimensional space-time, where the 5th dimension is a compactified S^1/Z_2 orbifold - hep-th/9905221
- The two branes with opposite tensions are placed at the orbifold fixed points $\phi = 0$(Hidden Brane) and $\phi = \pi$(Visible Brane).
- The action for the above configuration is given by

$$
\begin{aligned}
S &= S_{gravity} + S_{vis} + S_{hid} \\
S_{gravity} &= \int d^4x \int_{-\pi}^{\pi} d\phi \sqrt{-G}(-\Lambda + \frac{M^3}{2} R) \\
S_{vis} &= \int d^4x \sqrt{-g_{vis}}(L_{vis} - V_{vis}) \\
S_{hid} &= \int d^4x \sqrt{-g_{hid}}(L_{hid} - V_{hid})
\end{aligned}
$$

RS model

- In the minimal version, SM particles are on the visible brane and gravity propagates in the bulk
- On solving the Einstein's equation, 5D metric solution is given by

$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

where $y = r_c\phi$, $k = \sqrt{\frac{-\Lambda}{6M_5^3}}$, $V_{hid} = -V_{vis} = M_5^3 k$ and Λ is the bulk cosmological constant.

- The 4D Planck mass is related to 5D Planck mass by $M_{Pl}^2 = \frac{M_5^3}{k}(1 - e^{-2kr_c\pi})$.

Metric Fluctuations

- The gravitational fluctuations of the metric about its classical solution are
- Tensor fluctuation about the Minkowski space
  - generates bulk graviton where $\eta_{\mu\nu} \quad \rightarrow \quad \eta_{\mu\nu} + K^* h_{\mu\nu(x,y)}$
- The relative distance between two branes can be parametrized by a scalar field
  - where $r_c \quad \rightarrow \quad T(x)$ such that $< T(x) > \; = \; r_c$ which generates radion.
- Thus, the metric becomes

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

4-D Effective action

- On integrating out the extra dimension, we get

$$\begin{aligned} S = & \int d^4x(\sqrt{-g_4}\frac{M^3}{k}(1-e^{-2kr_c\pi})R_4(g_{4\ \mu\nu}(x)) \\ + & \frac{1}{2}\sqrt{-g_4}\partial_\mu\varphi(x)\partial^\mu\varphi(x)) \end{aligned}$$

  where $\varphi(x) = \Lambda_\varphi e^{-k(T(x)-r_c)\phi}$ and $\Lambda_\varphi = M_{Pl}e^{-kr_c\pi}$.

- $\varphi(x)$ is known as the radion field and is massless.

- Let us consider the Higgs field at the visible brane i.e $\phi = \pi$,

$$S^h_{vis} = \int d^4x\sqrt{g_{vis}}(g^{\mu\nu}_{vis}D_\mu H^\dagger D_\nu H - \lambda(H^2 - \frac{v_0^2}{2})^2)$$

  replacing $g^{\mu\nu}_{vis} \ = e^{-2kT(x)\phi}g^{\mu\nu}_4$ and $H \ \rightarrow \ e^{-kr_c\pi}H$, we get

$$S^h_{vis} = \int d^4x\sqrt{g_4}((\frac{\varphi(x)}{\Lambda_\varphi})^2 g^{\mu\nu}_4 D_\mu H^\dagger D_\nu H - (\frac{\varphi}{\Lambda_\varphi})^4\lambda(H^2 - e^{-2kr_c\pi}v_0^2)^2)$$

Solving hierarchy problem

- Any mass parameter m_0 on the visible 3-brane will correspond to a physical mass: $m_{phys} = e^{-kr_c\pi}m_0$. If $kr_c = 12$, TeV scale can be generated from Planck scale.

- On expanding $\varphi \to \Lambda_\varphi + \varphi(x)$, we get

$$S^h_{vis} = \int d^4x\sqrt{-g}\frac{1}{2}(\partial_\mu h\partial^\mu h - \lambda(H^2 - \frac{v^2}{2})^2) + \frac{\varphi(x)}{\Lambda_\varphi}T^\mu_\mu(h)$$

  where $T^\mu_\mu = \partial_\mu h\partial^\mu h - 4V(h)$ is the trace of energy momentum tensor for the Higgs field($v = v_0 e^{-kr_c\pi}$).

- The radion field is coupled to matter field on the visible brane with TeV strength.

- We need a mechanism for stabilizing the radius of the compactified dimension. - Goldberger-Wise mechanism

Goldberger Wise stabilization

- A massive bulk scalar is considered with interactions on the visible and hidden brane.

$$\begin{aligned} S = & \int d^5x(\partial_\mu\Phi\partial^\mu\Phi - m^2\Phi^2) + \int d^5x\delta(x_5 - \pi r_c)\lambda_1(\Phi^2 - v_1^2)^2 \\ + & \int d^5x\delta(x_5)\lambda_2(\Phi^2 - v_2^2)^2 \end{aligned}$$

- The bulk scalar develops an effective potential on the visible brane for the field $\varphi(x)$,

$$V_\varphi = \frac{k^3}{144M^6}\varphi^4(v_1 - v_2(e^{-k\pi r_c}\frac{\varphi}{\Lambda_\varphi})^\epsilon)$$

where $\epsilon = m^2/4k^2$.

- The potential has a minimum when $kr_c = \frac{1}{\pi\epsilon}ln(\frac{v_2}{v_1})$ Thus, for $ln(v_2/v_1) \sim 1$, we need $\frac{m^2}{k^2} \sim 1/10$, to get $kr_c \sim 12$.

Radion

- Mass of the radion is given by

$$\begin{aligned} m_\varphi^2 &= \frac{\partial^2 V(\varphi)}{\partial \varphi^2}|_{<\varphi>} \\ &= \frac{1}{48}(\frac{v_1}{M_{Pl}})^2 k (\frac{m}{k})^4 e^{-2kr_c\pi} \end{aligned}$$

As, $\frac{m}{k} << 1$, $m_\varphi < TeV$.

- Coupling of radion with the SM particle is given by

$$S_{int} = -\int d^4 x T^\mu_\mu \frac{\varphi}{\Lambda_\varphi}$$

- Radion can be probed at the LHC - lightest signature of the RS model

Outline

Interaction of Radion

- Trace of energy momentum tensor for the SM particles is given by

$$
\begin{aligned}
L_{int} = & -\tfrac{\varphi}{\Lambda_\varphi}(\partial^\mu h \partial_\mu h - 2m_h^2 h^2 + \Sigma_f m_f \bar{f} f \\
- & \quad 2M_W^2 W_\mu^+ W^{-\mu} - M_Z^2 Z_\mu Z^\mu)
\end{aligned}
$$

- The decay width of φ to fermions
  - $\Gamma(\varphi \to f\bar{f}) \;=\; \frac{N_c m_f^2 m_\varphi}{8\pi\Lambda_\varphi^2}(1 - x_f)^{3/2}$

- The decay width of φ to weak bosons
  - $\Gamma(\varphi \to W^+W^-) \;=\; \frac{m_\varphi^3}{16\pi\Lambda_\varphi^2}\sqrt{1 - x_W}(1 - x_W + \frac{3}{4}x_W^2)$
  - $\Gamma(\varphi \to ZZ) \;=\; \frac{m_\varphi^3}{32\pi\Lambda_\varphi^2}\sqrt{1 - x_Z}(1 - x_Z + \frac{3}{4}x_Z^2)$

- If $m_\varphi > 2m_h$ then
  - $\Gamma(\varphi \to hh) \;=\; \frac{m_\varphi^3}{32\pi\Lambda_\varphi^2}\sqrt{1 - x_h}(1 + x_h)^2 \;\; x_i \;=\; 4m_i^2/m_\varphi^2$

- Suppressed by Λ_φ

Interaction of radion

- The running of QCD(QED) gauge coupling generates a trace anomaly term

$$T^{\mu}_{\mu\ QCD(QED))} = \frac{\alpha_{s(e)}}{8\pi} b_3 G^{\mu\nu a} G^{\mu\nu a} (b_{2Y} (F^{\mu\nu} F_{\mu\nu}))$$

where $b_3 = 7,\ b_{2Y} \ = \ -11/3$.

- Radion can decay to gluon(photon) pair where top(top and W) runs in the triangle loop.

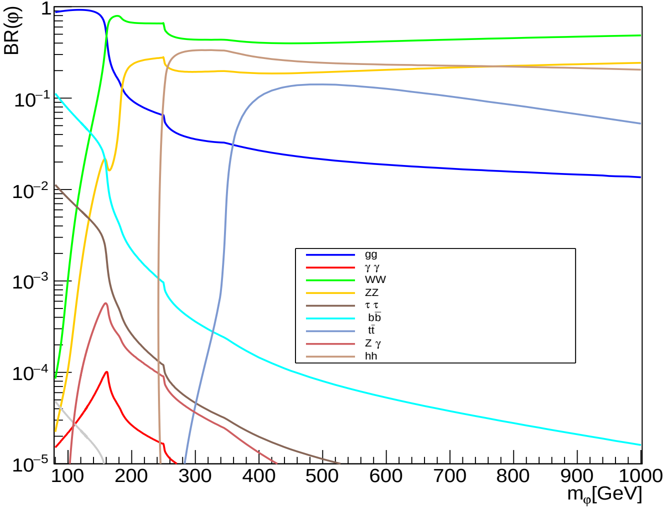
- The decay width of φ to the massless gauge bosons

$$\Gamma(\varphi \to gg) = \frac{\alpha_s^2 m_\varphi^3}{32\pi^3 \Lambda_\varphi^2} |b_3 + x_t 1 + (1 - x_t) f(x_t)|^2$$

$$\Gamma(\varphi \to \gamma\gamma) = \frac{\alpha_{em}^2 m_\varphi^3}{256\pi^3 \Lambda_\varphi^2} |b_{2Y} - (2 + 3x_W$$

$$+3x_W (2 - x_W) f(x_W) + \frac{8}{3} x_t 1 + (1 - x_t) f(x_t)|^2$$

Branching ratio of radion



Outline

Radion Higgs mixing

- The mixing between Higgs and radion is described by

$$S_\xi = -\xi \int d^4x \sqrt{-g_{vis}} R(g_{vis}) H^\dagger H$$

- Substituting $H = \frac{v+h}{\sqrt{2}}$ and $\varphi = \Lambda_\varphi + \varphi$ we get

$$S_\xi = -6\xi \int d^4x \left[\frac{v}{\Lambda_\varphi} h \Box \varphi + \frac{\gamma^2}{2} \varphi \Box \varphi + h^2 \frac{\Box \varphi}{\Lambda_\varphi} \right]$$

where $\gamma = \frac{v}{\Lambda_\varphi}$.

- On collecting terms with bilinear fields,

$$L_{mix} = -\frac{1}{2}(1 + 6\gamma^2\xi)\varphi \Box \varphi - \frac{1}{2}\varphi m_\varphi^2 \varphi - \frac{1}{2} h(\Box + m_h^2) h - 6\xi\gamma h \Box \varphi$$

Physical scalars

- Because of S_ξ, we get a kinetic mixing between radion and Higgs.

- Using the transformation,

$$\begin{aligned} h = & \quad (\cos\theta - \tfrac{6\xi\gamma}{Z}\sin\theta)[b]\varphi_2 + (\sin\theta + \tfrac{6\xi\gamma}{Z}\cos\theta)[a]\varphi_1 \\ r = & \qquad\qquad -\cos\theta\tfrac{\varphi_1}{Z}[c] + \sin\theta\tfrac{\varphi_2}{Z}[d] \end{aligned}$$

we get

$$L_{mix} = -\frac{1}{2}\varphi_1\Box\varphi_1 - \frac{1}{2}\varphi_2\Box\varphi_2 - \frac{m_{\varphi_1}^2}{2}\varphi_1^2 - \frac{m_{\varphi_2}^2}{2}\varphi_2^2$$

where $\tan 2\theta = \frac{12\xi\gamma Z m_h^2}{m_\varphi^2 - m_h^2(Z^2 - 36\xi^2\gamma^2)}$ and $Z^2 = 1 + 6\xi\gamma^2 - 36\gamma^2\xi^2$.

Masses of physical scalars

- φ_1 and φ_2 are our physical states with masses

$$m^2_{\varphi_{1(2)}} = \frac{1}{2Z^2}\left(m^2_\varphi + \beta m^2_h \pm \sqrt{[(m^2_\varphi + \beta m^2_h)^2 - 4Z^2 m^2_\varphi m^2_h]}\right)$$

  where $\beta = 1 + 6\xi\gamma^2$
- On inverting the masses, we get

$$[\beta m^2_{h0}, m^2_{\varphi 0}] = \frac{Z^2}{2}\left[m^2_{\varphi_1} + m^2_{\varphi_2} \pm \sqrt{D}\right]$$

  where $D = (m^2_{\varphi_1} + m^2_{\varphi_2})^2 - \frac{4\beta m^2_{\varphi_1} m^2_{\varphi_2}}{Z^2}$.

- Since, we started with positive $m_h(m_\varphi)$, we need $D > 0$ and $Z^2 > 0$, which gives a bound on ξ and $m_{\varphi_{1(2)}}$.

Interactions of physical scalars

- Interaction of the fermions with the two scalars are given by

$$\begin{aligned} L_{int}^{fermion} &= -\frac{m_f}{v}(h+\gamma\varphi)f\bar{f} \\ &= -\frac{m_f}{v}(A_{\varphi_1}\varphi_1 + A_{\varphi_2}\varphi_2) \end{aligned}$$

  where $A_{\varphi_1} = a + \gamma c$ and $A_{\varphi_2} = b + \gamma d$.

- Similarly, for the massive gauge bosons, we have

$$L_{int}^{VV^*} = -\frac{2M_W^2}{v}(A_{\varphi_1}\varphi_1 + A_{\varphi_2}\varphi_2)W^{+\mu}W_\mu^-$$

- For the massless gauge bosons

$$\begin{aligned} L_{int}^{\gamma\gamma(gg)} &= -\frac{\alpha_e}{8\pi v}\Big(\Big(\big(\tfrac{4}{3}F_{1/2}(\tau_t) + F_1(\tau_w)\big)A_{\varphi_1} + \tfrac{11}{3}\gamma c\Big)\,\varphi_1 \\ &+ \Big(\big(\tfrac{4}{3}F_{1/2}(\tau_t) + F_1(\tau_w)\big)A_{\varphi_2} + \tfrac{11}{3}\gamma d\Big)\,\varphi_2\Big)F^{\mu\nu}F_{\mu\nu} \end{aligned}$$

Trilinear scalar coupling

- Decay of $\varphi_1 \to \varphi_2\varphi_2$ originates from
  - mixing

$$S_\xi \ni 6\xi h^2 \Box \frac{\varphi}{\Lambda_\varphi}$$

  - scalar potential of SM Higgs

$$L_{hhh} \ni \frac{-m_h^2}{2v} h^3$$

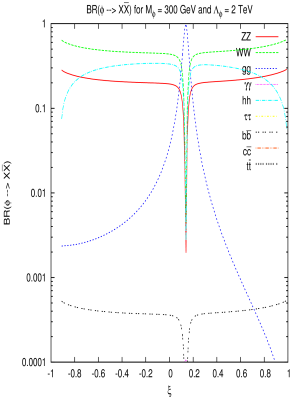
  - radion interaction with the SM Higgs

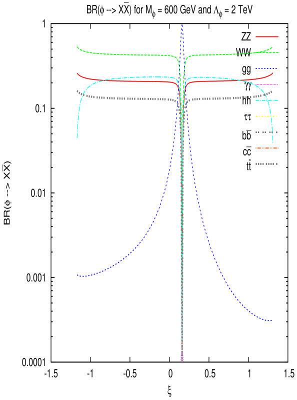
$$L_{int} \ni T_\mu^\mu(h) \frac{\varphi}{\Lambda_\varphi}$$

- Thus, we get

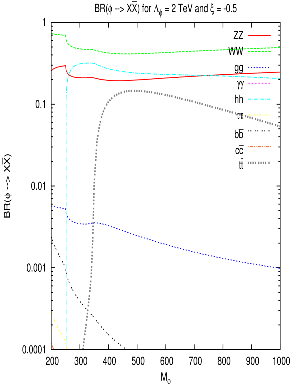
$$g_{122} = \frac{6b\xi(\gamma(ad+bc)+cd)+ad^2)2m_{\varphi_2^2}+m_{\varphi_1}^2 d(12ab\xi+2bc+ad(6\xi-1))}{\Lambda_\varphi} - \frac{4d(ad+2bc)m_h^2 - \frac{3}{\gamma}cd^2 m_h^2}{\Lambda_\varphi}$$

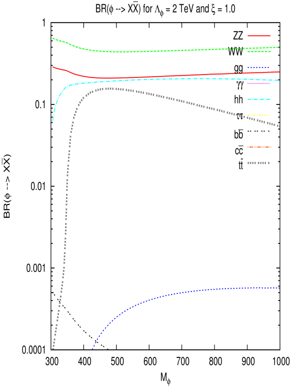
Dependence on ξ for fixed M_{φ_1}





Dependence on M_{φ_1} for fixed ξ





Scalars at LHC

- We would like to see where are these scalars at the LHC.
- We call the scalars
  - Mixed Higgs-like (H_m) when $\varphi_i(\xi = 0) \to h$.
  - Mixed Radion-like (R_m) when $\varphi_i(\xi = 0) \to \varphi$.
- Let us consider the scenario where the discovered scalar at 125 GeV is H_m,
  - How much mixing of radion is allowed by the recent data?
  - Where is R_m?

Outline

Higgs signal strength

Parameter	ATLAS+CMS Measured	ATLAS+CMS Expected uncertainty	ATLAS Measured	CMS Measured
10-parameter fit of μ_F^f and μ_V^f				
$\mu_V^{\gamma\gamma}$	$1.05^{+0.44}_{-0.41}$	$^{+0.42}_{-0.38}$	$0.69^{+0.64}_{-0.58}$	$1.37^{+0.62}_{-0.56}$
μ_V^{ZZ}	$0.48^{+1.37}_{-0.91}$	$^{+1.16}_{-0.84}$	$0.26^{+1.60}_{-0.91}$	$1.44^{+2.32}_{-2.30}$
μ_V^{WW}	$1.38^{+0.41}_{-0.37}$	$^{+0.38}_{-0.35}$	$1.56^{+0.52}_{-0.46}$	$1.08^{+0.65}_{-0.58}$
$\mu_V^{\tau\tau}$	$1.12^{+0.37}_{-0.35}$	$^{+0.38}_{-0.36}$	$1.29^{+0.58}_{-0.53}$	$0.87^{+0.49}_{-0.45}$
μ_V^{bb}	$0.65^{+0.30}_{-0.29}$	$^{+0.32}_{-0.30}$	$0.50^{+0.39}_{-0.37}$	$0.85^{+0.47}_{-0.44}$
$\mu_F^{\gamma\gamma}$	$1.19^{+0.28}_{-0.25}$	$^{+0.25}_{-0.23}$	$1.31^{+0.37}_{-0.34}$	$1.01^{+0.34}_{-0.31}$
μ_F^{ZZ}	$1.44^{+0.38}_{-0.34}$	$^{+0.29}_{-0.25}$	$1.73^{+0.51}_{-0.45}$	$0.97^{+0.54}_{-0.42}$
μ_F^{WW}	$1.00^{+0.23}_{-0.20}$	$^{+0.21}_{-0.19}$	$1.10^{+0.29}_{-0.26}$	$0.85^{+0.28}_{-0.25}$
$\mu_F^{\tau\tau}$	$1.10^{+0.61}_{-0.58}$	$^{+0.56}_{-0.53}$	$1.72^{+1.24}_{-1.13}$	$0.91^{+0.69}_{-0.64}$
μ_F^{bb}	$1.09^{+0.93}_{-0.89}$	$^{+0.91}_{-0.86}$	$1.51^{+1.15}_{-1.08}$	$0.10^{+1.83}_{-1.86}$
6-parameter fit of global μ_V/μ_F and to μ_F^f				
μ_V/μ_F	$1.06^{+0.35}_{-0.27}$	$^{+0.34}_{-0.26}$	$0.91^{+0.41}_{-0.30}$	$1.29^{+0.67}_{-0.46}$
$\mu_F^{\gamma\gamma}$	$1.13^{+0.24}_{-0.21}$	$^{+0.21}_{-0.19}$	$1.18^{+0.33}_{-0.29}$	$1.03^{+0.30}_{-0.26}$
μ_F^{ZZ}	$1.29^{+0.29}_{-0.25}$	$^{+0.24}_{-0.20}$	$1.54^{+0.44}_{-0.36}$	$1.00^{+0.33}_{-0.27}$
μ_F^{WW}	$1.08^{+0.22}_{-0.19}$	$^{+0.19}_{-0.17}$	$1.26^{+0.29}_{-0.25}$	$0.85^{+0.25}_{-0.22}$
$\mu_F^{\tau\tau}$	$1.07^{+0.35}_{-0.28}$	$^{+0.32}_{-0.27}$	$1.50^{+0.66}_{-0.49}$	$0.75^{+0.39}_{-0.29}$
μ_F^{bb}	$0.65^{+0.37}_{-0.28}$	$^{+0.45}_{-0.34}$	$0.67^{+0.58}_{-0.42}$	$0.64^{+0.54}_{-0.36}$

- We consider φ_2 as our H_m.
- Signal strength for H_m is defined as

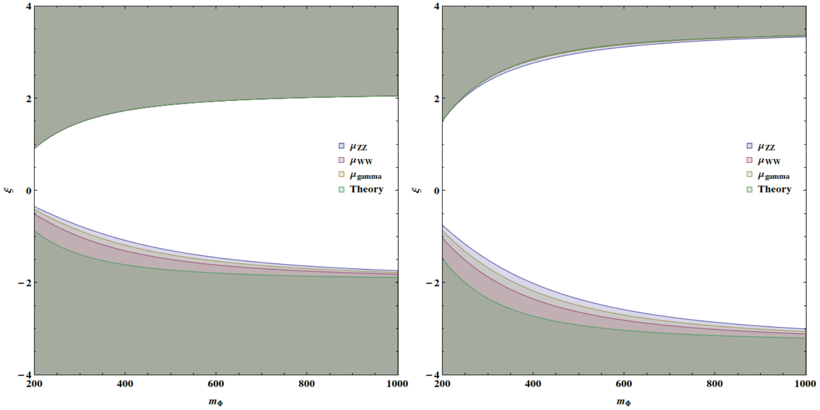
$$\mu_{abcd}^{H_m} = \frac{\sigma(pp \to H_m \to ab)}{\sigma(pp \to H_{SM}(125) \to ab)} = \frac{\Gamma(cd \to H_m) BR(H_m \to ab)}{\Gamma(cd \to H_{SM}(125)) BR(H_{SM} \to ab)} = F(\xi, m_{\varphi_1}, \Lambda_\varphi)$$

where cd is the production channel and ab is the decay channel.

- If $\mu_{abcd}^{H_m}$ lies within the 2 σ error bar of $\mu_{abcd}^{observed}$, then $\xi, \Lambda_\varphi, m_{\varphi_1}$ is allowed

Allowed parameter space

- For $\Lambda_\varphi = 3\text{TeV}, 5\text{TeV}$ [Shaded regions are excluded].



Heavy Higgs search

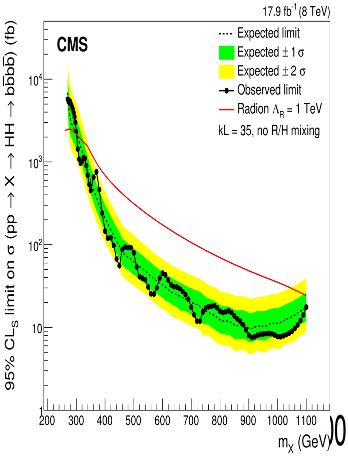
- What can we say about R_m?
- LHC heavy Higgs searches give bound on maximum cross section for each channel.
- We estimated $\sigma(pp \to R_m \to ab)$,

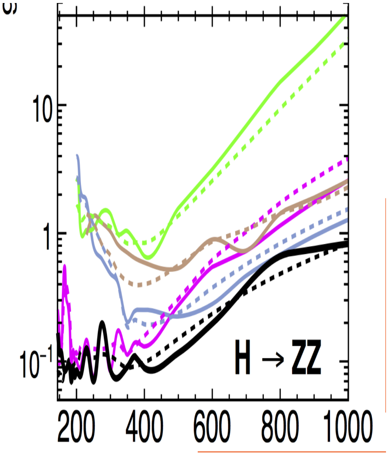
$$\begin{aligned}\sigma(pp \to R_m \to ab) = & \quad \sigma(pp \to H^{SM}(m_{\varphi_1})ab) \times \\ & \frac{\Gamma(cd \to R_m)BR(R_m \to ab)}{\Gamma(cd \to H_{SM}(m_{\varphi_1})BR(H_{SM}(m_{\varphi_1}) \to ab)} \\ = & \quad G(\xi, m_{\varphi_1}, \Lambda_\varphi)\end{aligned}$$

- If $G(\xi, m_{\varphi_1}, \Lambda_\varphi) < \sigma^{max}_{observed}(m_{\varphi_1})$, then that $m_{\varphi_1}, \Lambda_\varphi, \xi$ is allowed.

Heavy Higgs search

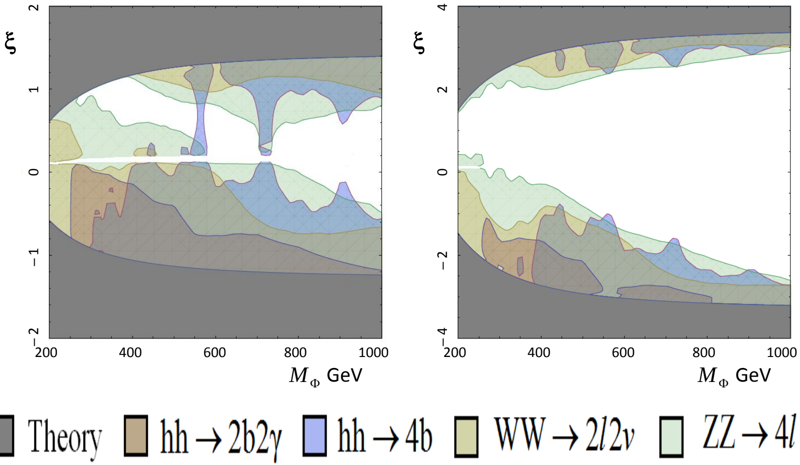
- We have used null results for heavy higgs searches in $\gamma\gamma, ZZ^*,\ WW^*,\ hh \to 2b2\gamma,\ hh\ \to 4b$ channels.



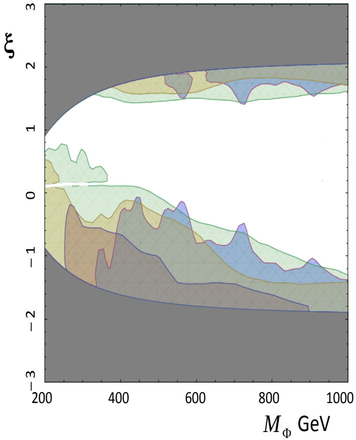


Allowed parameter space

- For $\Lambda_\varphi = 2$ and 5 TeV(clockwise) [Shaded regions are excluded by CMS data]



Features



- Narrow funnel-like white region corresponds to the limit where $A_{\varphi_1} \to 0[\Gamma(\varphi_1 \to f\bar{f}, VV^*, hh)$ vanishes].

- A_{gg} increases and then decreases while moving from $-\xi_{max}$ to $\xi_{\max}$. However, $A_{gg}(-\xi) > A_{gg}(\xi)$.Hence, lower part suffers stronger exclusion.

- The most stringent bound comes from ZZ^* channel.

- As Λ_φ increases, $\sigma(pp \to \varphi_1)$ falls and therefore, exclusion becomes weaker.

Outline

Bulk fermion

- A warped extra dimensional model with SM particles in the bulk solves fermion mass hierarchy.
- The idea is to separate light fermions from the Higgs which is placed on the visible brane.
- Yukawa interaction is given by

$$\begin{aligned} S &= \int \sqrt{-g} d^5 x \lambda^5_{ij} (\bar{\Psi}^L \Psi^R + h.c) H \delta(x_5 - \pi) \\ &= \int \sqrt{-g_{vis}} d^4 x \lambda_{ij} \Psi^0_L(x^\mu) \Psi^0_R(x^\mu) H \end{aligned}$$

- Massless zero mode of $\Psi^L(\Psi^R)$ is identified with the left(right) handed spinors in 4D.

Mass hierarchy

- On solving equation of motion for the fermion, one gets the profile for $\Psi_0^L(\Psi_0^R)$ as

$$\Psi^0_{R(L)}(r_c\phi) = \frac{(1 \pm 2c_{R(L)})k}{e^{(1\pm 2c_{R(L)})\pi k r_c} - 1} e^{(2\pm c_R(L))kr_c\phi}\Psi^0_{R(L)}(x)$$

- The Yukawa coupling becomes

$$\lambda^4_{ij} = \lambda^5_{ij} k(c - \frac{1}{2})e^{(1-2c)kr_c\phi}$$

  where $c_L = -c_R = c$.
- For $c > 1/2 (c < 1/2)$, one can localize fermions in UV(IR) brane.
- The hierarchy in Yukawa coupling is generated by choosing c to lie between [-0.5,0.6].

Radion coupling to bulk matter

- The coupling of radion to the bulk fermion is given by

$$L_{f\bar{f}} = m_f(c_L - c_R)\frac{\varphi}{\Lambda_\varphi} \tag{1}$$

  For IR localized top quarks($c_r = -1/2$ and $c_l = 1/2$), we get $m_t\frac{\varphi}{\Lambda_\varphi}$.

- The coupling of massless gauge boson comes from
  - Trace anomaly $L^{trace}_{massless} = -\frac{\varphi(x)}{\Lambda_\varphi}\frac{\alpha_e}{8\pi}b_{2y}F^{\mu\nu}F^{\mu\nu}$
  - Triangle loop $L^{triangle}_{massless} = \frac{\alpha_e}{16\pi}\frac{\varphi}{\Lambda_\varphi}(4/3F_{1/2}(\tau_t) + F_1(\tau_W))$
  - In addition there is a tree level coupling given by

$$L^{tree}_{massless} = -\frac{\varphi}{\Lambda_\varphi k r_c 4\pi}F^{\mu\nu}F_{\mu\nu}$$

Radion coupling to bulk matter

- Interaction of massless gauge boson is

$$L_{gg} = G_{\mu\nu}G^{\mu\nu}\left[\varphi\frac{\alpha_s}{8\pi\Lambda_\varphi}\left[\frac{1}{2}F_{1/2}(\tau_t)-7\right]+\varphi\frac{1}{4\pi\Lambda_\varphi kr_c}\right]$$

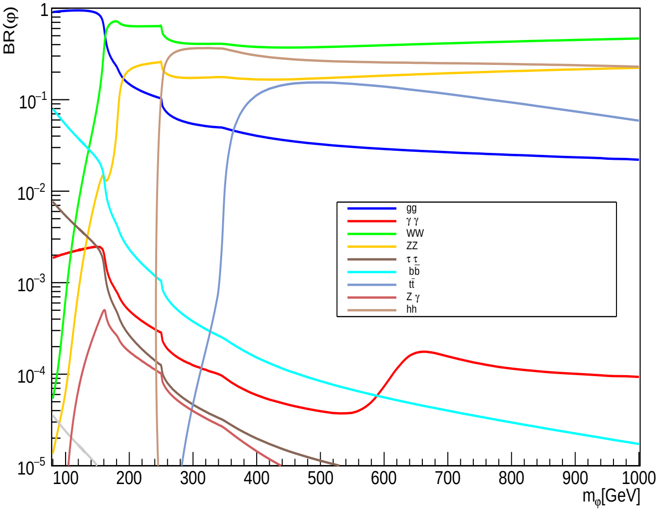
$$L_{\gamma\gamma} = F_{\mu\nu}F^{\mu\nu}\left[\varphi\frac{\alpha_e}{8\pi\Lambda_\varphi}\left[(\frac{4}{3}F_{1/2}(\tau_t)+F_1(\tau_w))+11/3\right]-\varphi\frac{1}{\Lambda_\varphi kr_c 4\pi}\right]$$

- Interaction of massive gauge boson with radion is given by

$$L_{VV^*} = \frac{\varphi}{\Lambda_\varphi}2M_V^2(1-\frac{3kr_c\pi M_V^2}{\Lambda_\varphi^2})V^\mu V_\mu$$

- The radion can decay to two SM Higgs(if allowed kinematically)
  Same as brane SM model

Branching ratio of radion



Higgs radion mixing

- One can again consider mixing between SM Higgs and the radion

$$S_\xi = \xi \int d^4x \sqrt{g_{vis}} R(g_{vis}) H^\dagger H$$

- We get two scalars φ_1 and φ_2,

$$\begin{aligned} h = & \quad (\cos\theta + \tfrac{6\xi\gamma}{Z}\sin\theta)\varphi_1 + \varphi_2(\sin\theta - \tfrac{6\xi\gamma}{Z}\cos\theta) \\ r = & \quad -\tfrac{\sin\theta}{Z}\varphi_1 + \tfrac{\cos\theta}{Z}\varphi_2 \end{aligned}$$

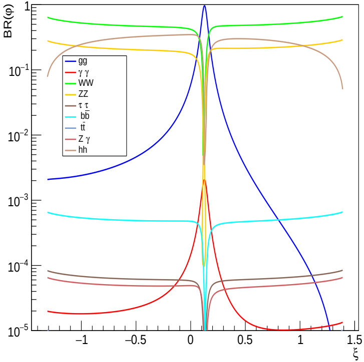
with masses,

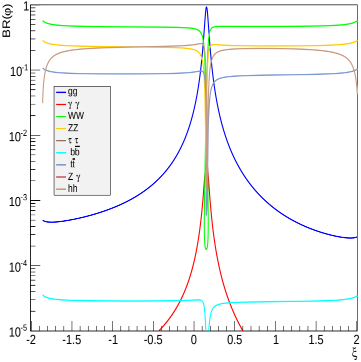
$$m^2_{\varphi_{1(2)}} = \frac{1}{2Z^2}((1+6\xi\gamma^2)m_h^2 \pm m_r^2\sqrt{D})$$

where $\tan 2\theta = \frac{12\xi\gamma Z m_h^2}{m_h^2(Z^2-36\xi^2\gamma^2)-m_r^2}$

ξ dependence

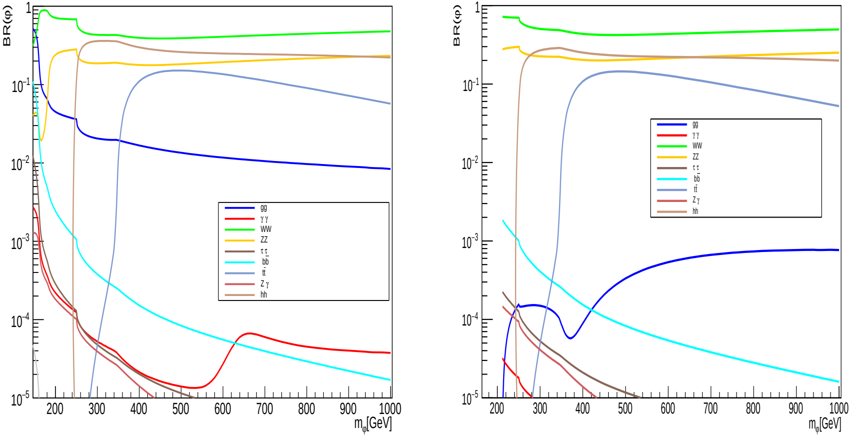
- Variation with ξ for $M_{\varphi_1} = 280,\ 800$ GeV.





ξ dependence

- Variation with M_{φ_1} for $\xi\ = -0.1,\ 1.$

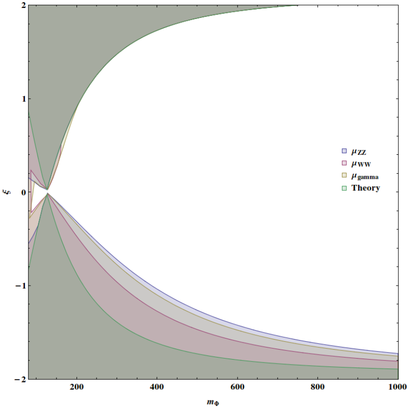


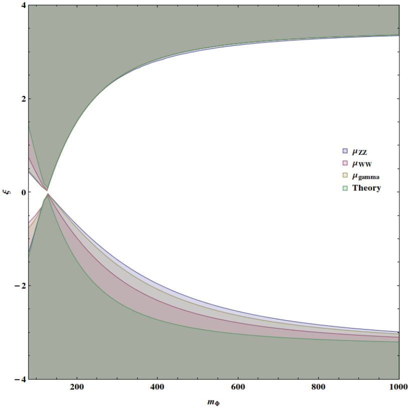
Mixed Higgs and Mixed radion

- We define Mixed Higgs(H_m) as $\varphi_{1(2)}$ such that $\varphi_{1(2)}(\xi = 0) \to h$.
- Similarly, Mixed radion (R_m) as $\varphi_{1(2)}$ such that $\varphi_{1(2)}(\xi = 0) \to \varphi$.
- We played the same game i.e
  - What if the discovered scalar is H_m?
  - What can we say about R_m?

Bound from μ

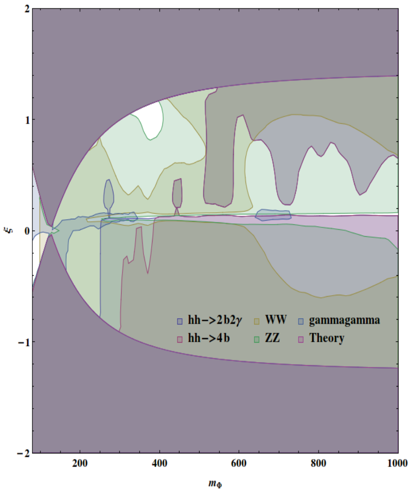
- For $\Lambda_\varphi = 3\text{TeV}, 5\text{TeV}$ [Shaded regions are excluded].

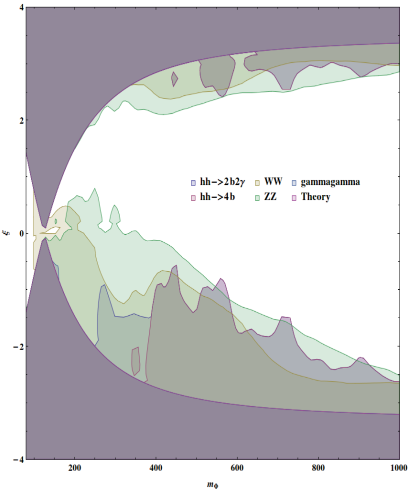




Bound from heavy Higgs searches

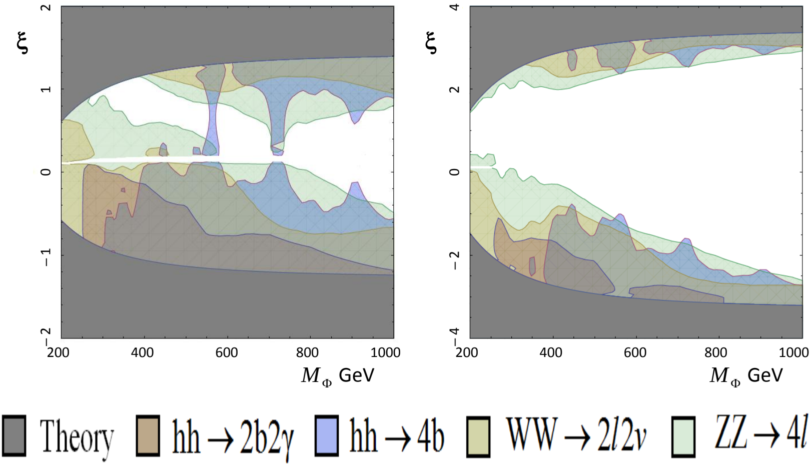
- For $\Lambda_\varphi = 2$ and 5 TeV(clockwise) [Shaded regions are excluded by CMS data]



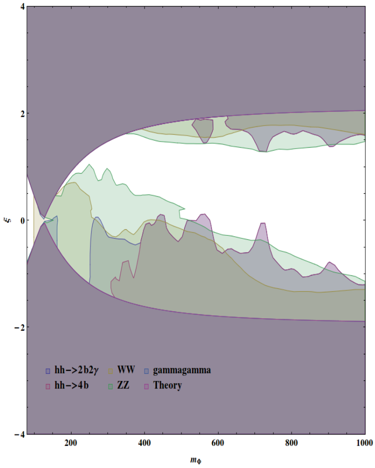


Recapitulate:SM on brane model

- For $\Lambda_\varphi = 2$ and 5 TeV(clockwise) [Shaded regions are excluded by CMS data]



Features



- Bounds are stronger as compared to the scenario with SM particles on the brane because of the additional tree level coupling for massless gauge bosons.
- Lighter mixed radion state is mostly ruled out by diphoton and WW^* searches.
- Other features are similar to the brane model.
- In both the scenarios, there exist a particular value of ξ where all the massive modes couplings vanish.

Outline

Observation?

- ATLAS and CMS found excess in invariant mass spectrum around 750 GeV.
- ATLAS found 14 diphoton events (with 3.2 fb^{-1} integrated luminosity) spreading over two bins i.e $\Gamma_{tot} = 45\ GeV$.
- CMS found 10 diphoton events (with 2.6 fb^{-1} integrated luminosity) and has a narrow width.
- No other resonance are seen at this mass for ZZ, jj, l^+l^-.
- If we consider it as a manifestation of new physics, then what is it?

Scalar resonance

- Let us assume that it is a CP-even scalar, **S**.
- Since, **S** is produced at the LHC, it should interact with pair of partons.
- As observed, it should couple to pair of photons.
- Thus, we have

$$L_{int} = y_q \mathbf{S}\bar{q}q + \frac{c_g}{M_S}\mathbf{S}G_{\mu\nu}G^{\mu\nu} + \frac{c_\gamma}{M_S}\mathbf{S}F_{\mu\nu}F^{\mu\nu}$$

- The partial decay width of **S** to pair of quark, gluon and photon is given by

$$\Gamma(\mathbf{S} \to q\bar{q}) = \frac{3}{8\pi}y_q^2 M_S, \quad \Gamma(\mathbf{S} \to gg) = \frac{2}{\pi}c_g^2 M_S, \quad \Gamma(\mathbf{S} \to \gamma\gamma) = \frac{1}{4\pi}c_\gamma^2 M_S$$

Constraints

- If **S** is the observed scalar, then
  - The total decay width of **S** should not exceed 50 GeV i.e

$$\Gamma_\varphi = \frac{2M_\varphi}{\pi}(c_g^2 + \frac{3}{16}y_q^2 + \frac{1}{8}c_\gamma^2) \; < \; 50\text{GeV}$$

  - Diphoton cross-section should lie in the range 5-15 fb, i.e

$$\sigma(pp \to \mathbf{S} \to \gamma\gamma) = (33.36c_g^2 + 1.66y_u^2) \times \frac{2c_\gamma^2}{16c_g^2 + 3y_q^2 + 2c_\gamma^2} \quad \sim \; 5 - 15\text{fb}$$

  - Dijet cross-section should be less than 1 pb.

$$\sigma(pp \to \mathbf{S} \to jj) = (33.36c_g^2 + 1.66y_u^2) \times \frac{16c_g^2 + 3y_q^2}{16c_g^2 + 3y_q^2 + 2c_\gamma^2} < 1\text{pb}$$

Mixed radion as the suitable candidate?

- There exist a value of ξ where A_{φ_1} vanishes i.e $\Gamma(\varphi_1 \to q\bar{q}, VV^*, hh) \sim 0$.
- R_m interacts with the pair of photons and gluons via trace anomaly term which is proportional to $\frac{c}{\Lambda_\varphi}$.
- We have

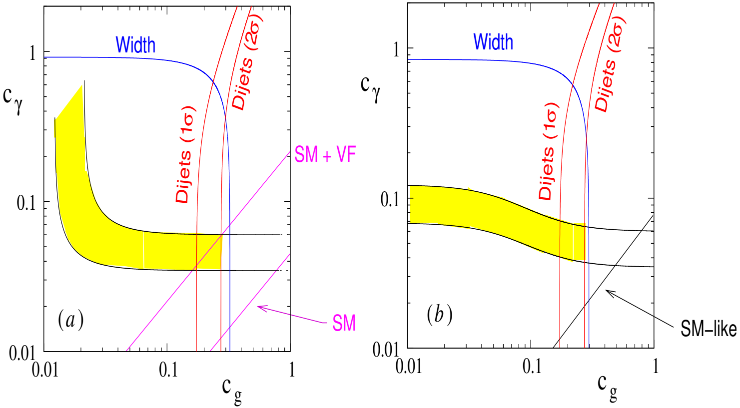
$$y_u = 0,\ c_{gg} = \frac{\alpha_s}{16\pi}\frac{M_S}{\Lambda_\varphi} b_3 c,\ c_{\gamma\gamma} = \frac{\alpha_e}{16\pi}\frac{M_S}{\Lambda_\varphi} b_{2Y} c$$

  where $b_3 = 11 - \frac{4}{3}N_f$ and $\mathrm{b_{2Y}} = \frac{22}{3} - \frac{32}{9}\mathrm{N_f} - \frac{1}{3}\mathrm{N_s}$.

- In the SM, we have $N_s = 1$ and $\mathrm{N_f} = 3$. Thus, we get $b_{2Y} = \frac{11}{3}\mathrm{and b_3} = 7$.

R_m as 750 GeV resonance

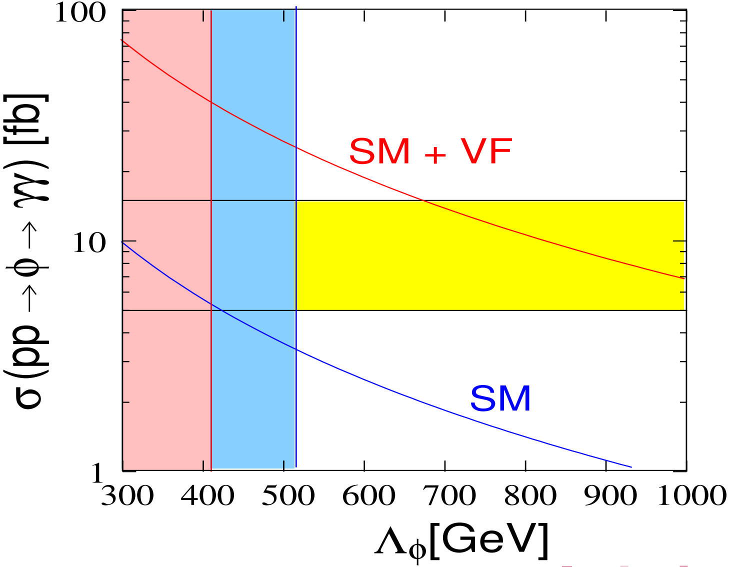
- The line denoted by SM corresponds to the Mixed radion(R_m) scenario[Yellow shaded region is allowed]



Minimal extension

- R_m with SM particles on the brane is unable to explain 750 GeV resonance.
- Let us add a single family of vector-like quarks i.e doublet under $SU(2)_L$ with masses below the resonance.
- We are still in the limit of $\xi = \xi_0$ where couplings of R_m to massive particle vanish.
- Our N_f increases from 3 to 5 which in turn reduces b_3 and increases b_{2y}.

- Variation of Diphoton cross-section with Λ_{φ},



Conclusion

- Randall Sundrum model contains a scalar called radion that acquires its mass from the Goldberger Wise stabilization.
- The radion can mix with the SM Higgs.
- The mixings scenarios are constrained from absence of new physics signal at 8 TeV.
- If the SM fermions and gauge bosons are moved to the 5D bulk, then we get stronger bound on the Higgs-radion mixing scenario.
- An unmixed radion(with mass $\leq$ 400 GeV) is ruled out by the LHC data.
- There exist a particular mixing where the coupling of the mixed radion with SM fermions and massive gauge boosns vanishes.
- With the inclusion of vector like fermions in the model, one can consider the mixed radion as a 750 GeV resonance .

Outline

Graviton and its KK mode

- KK decomposition of the bulk graviton on the visible brane generates tower of massive Kaluza-Klein(KK) graviton, where $m_n = kx_n e^{-kr_c\pi} \sim \text{TeV}$.

- The interaction of the KK mode of graviton($h^n_{\alpha\beta}$) with SM particle is given by

$$L_{int} = \frac{-1}{\bar{M}_{Pl}} T^{\alpha\beta}(x) h^0_{\alpha\beta}(x) - \frac{1}{\Lambda_\pi} T^{\alpha\beta}(x) \sum_{n=1}^{\text{inf}} h^n_{\alpha\beta}(x)$$

  where $\Lambda_\pi = \bar{M}_{Pl} e^{-kr_c\pi} \sim TeV$.

- Universal coupling($\sim TeV^{-1}$) to all SM particles.

- LHC has looked for the first KK mode of graviton.

Status of RS graviton

Till now no sign of 1st KK mode of Graviton up to 2.7 TeV