2nd year PhD student seminar

Collider phenomenology of BSM Higgs physics

Phenomenologie aupres des collisionneurs de la physique du Higgs dans des modeles au-dela du MS

Kseniia Svirina

Supervisor **Ingo Schienbein**
LPSC, Grenoble, France

April 3, 2018, Grenoble, France

Plan of the presentation

- BSM physics – motivation for study
- Higgs pair production
- X-dim models: Randall-Sundrum scenario
- R-S model phenomenology
- Progress achieved, tools and prospects (ToDo)
- Scalar potential
- RGE’s study; “dummy method”, prospects (ToDo)
- Summary

Motivation to search for a new physics (BSM)

The **Standard Model** of particle physics

classifies ✓ all known elementary particles

and describes ✓ electromagnetic interaction

✓ weak interaction

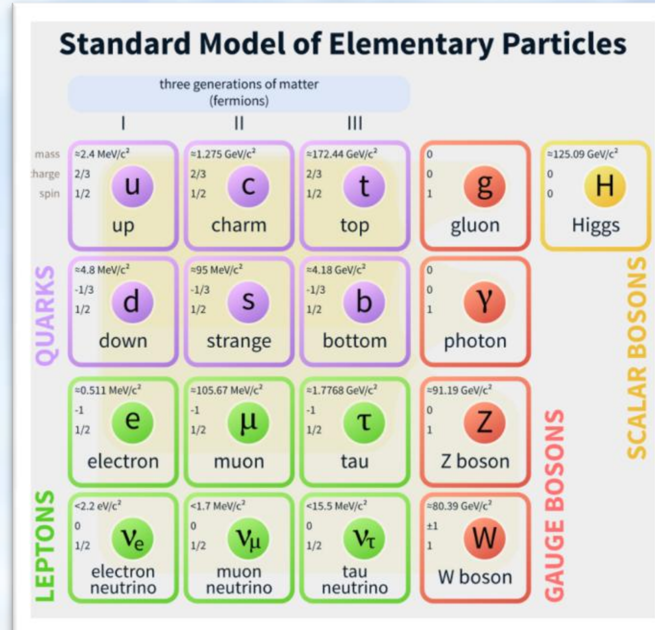
✓ strong interaction

but not ✗ gravity (including the **hierarchy problem**)

✗ dark matter and dark energy

✗ neutrino oscillations

etc.



➡ ***the SM is only the low-energy limit of some more fundamental high-scale theory***

i.e. the modern task – is the search for the Extensions of the SM (BSM physics / New physics)

Higgs pair production – a process of a particular interest

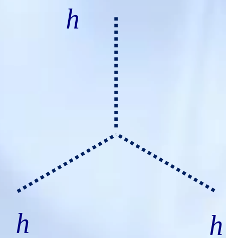
In the SM, the scalar sector takes a minimal form:

- a single Higgs doublet field,
- the tri-linear Higgs coupling λ_{3h} is related to the Higgs mass and vacuum expectation value in a specific way.

Any deviation in λ_{3h} would signal new physics beyond the SM.

$$V_H = \mu^2 H^\dagger H + \eta\left(H^\dagger H\right)^2 \rightarrow \frac{1}{2}m_h^2 h^2 + \sqrt{\frac{\eta}{2}}m_h h^3 + \frac{\eta}{4}h^4$$

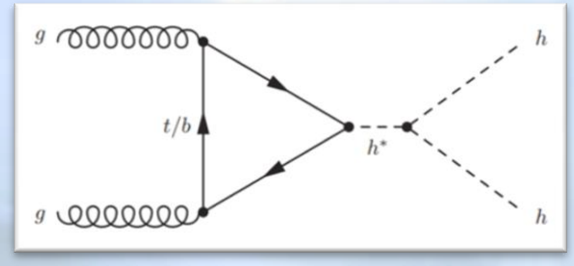
$$(m_h^2 = 2\eta v_0^2, \quad v_0^2 = -\mu^2/\eta, \quad v_0 = 246 GeV)$$



$$\lambda_{3h}^{SM} = \sqrt{\frac{\eta}{2}}m_h$$ -?

Experimental verification of this relation is needed!

The key process for testing λ_{3h} – is the **Higgs pair production**



In extended scalar sector: presence of another scalar particle can cause a deviation in λ_{3h}

Stabilized Randall-Sundrum Model

- Brane world model (2 branes: TeV and Planck)
- 1 extra dimension (5D)
- SM is localized on the TeV brane
- Gravitation and a real scalar (stabilizing) field propagate in the "bulk"
- Solution of the hierarchy problem
- Additional light scalar particle (radion)

5d space-time

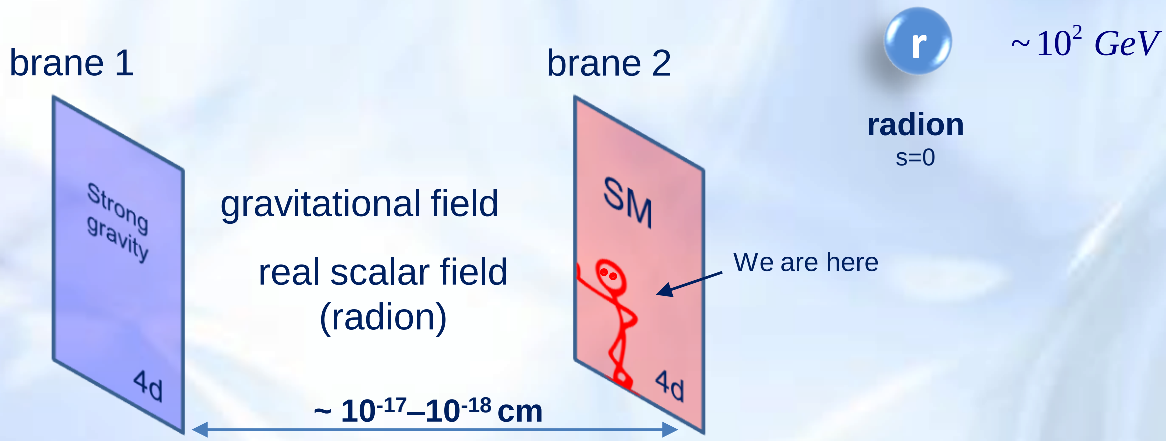
$$\{x^M\} = \{x^\mu, y\}$$

$$M = 0, 1, 2, 3, 4$$

$$\mu = 0, 1, 2, 3$$

$$x^4 \equiv y$$

$$-L \le y \le L$$



5th coordinate: $y = 0$ $y = L$

Solution of the hierarchy problem:

$$ds^2 = e^{-2A(y)}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$

Radion phenomenongy

The radion interaction with the SM fields:

$$L = -\frac{r(x)}{\Lambda_r} T^{\mu}_{\mu}$$

$r(x)$ - the radion field,

Λ_r - dimensional scale parameter,

T^{μ}_{μ} - the trace of the energy-momentum tensor of the SM

$$T^{\mu}_{\mu} = \frac{\beta(g_s)}{2g_s} G_{\rho\sigma} G^{\rho\sigma} + \frac{\beta(e)}{2e} F_{\rho\sigma} F^{\rho\sigma} + \sum_f \left[\frac{3i}{2} \left((D_\mu \bar{f}) \gamma^\mu f - \bar{f} \gamma^\mu (D_\mu f) \right) + 4 m_f \bar{f} f \left(1 + \frac{h}{v_0} \right) \right]$$

$$- \left(\partial_\mu h \right) \left(\partial^\mu h \right) + 2 m_h^2 h^2 \left(1 + \frac{h}{2 v_0} \right)^2 - \left(2 m_W^2 W_\mu^+ W^{-\mu} + m_Z^2 Z^\mu Z_\mu \right) \left(1 + \frac{h}{v_0} \right)^2$$

<u>Radion-Higgs similarity:</u>

(Phys. Rev. D 90, 095026 (2014), Phys.Rev. D94 no.2, 024047 (2016))

Single production $\quad f\bar{f} \to r V_1 \ldots V_N \quad \Leftrightarrow \quad f\bar{f} \to h V_1 \ldots V_N$ **up to** $m_r \to m_h$ **and** $\Lambda_r \to v_0$

Associated production $\quad gg \to rh \quad \Leftrightarrow \quad gg \to hh$ **up to** $m_r \to m_h, \ \Lambda_r \to v_0$

$f\bar{f} \to r h_1 \ldots h_N V_1 \ldots V_M \quad \Leftrightarrow \quad f\bar{f} \to h h_1 \ldots h_N V_1 \ldots V_M$ **and** $\lambda_{3h}^{SM} \to \left(1 + \frac{m_r^2 - m_h^2}{3 m_h^2} \right) \lambda_{3h}^{SM}$

The radion contribution can <u>mimic</u> the deviation in the trilinear Higgs coulping

Higgs-radion mixing

$$\begin{pmatrix} r_0 \\ h_0 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} r \\ h \end{pmatrix}$$

radion-dominated state

Higgs-dominated state

unphysical scalars

physical scalars (mass eigenstate basis)

where the coefficients are given by

$$A = \frac{1}{Z}\cos\theta, \quad B = -\frac{1}{Z}\sin\theta, \quad C = \sin\theta + \frac{6\gamma\xi}{Z}\cos\theta, \quad D = \cos\theta - \frac{6\gamma\xi}{Z}\sin\theta$$

with $$Z^2 = 1 + 6\xi\gamma^2(1-6\xi), \quad \gamma = \frac{v_0}{\Lambda_\phi}$$

and the mixing angle θ defined by

$$\tan 2\theta = \frac{12\xi\gamma Z m_{h_0}^2}{m_{r_0}^2 - m_{h_0}^2\left(Z^2 - 36\xi^2\gamma^2\right)}$$

RS model with FeynRules package

FeynRules is a Mathematica-based package: Implementation of particle physics models into high-energy physics tools.

```
 - FeynRules -
Version: 2.3.29 (06 July 2017).
Authors: A. Alloul, N. Christensen, C. Degrande, C. Duhr, B. Fuks

Please cite:
    - Comput.Phys.Commun.185:2250-2300,2014 (arXiv:1310.1921);
    - Comput.Phys.Commun.180:1614-1641,2009 (arXiv:0806.4194).
```

It calculates the underlying Feynman rules and outputs them to a form appropriate for various programs (CalcHep, FeynArts, MadGraph, Sherpa and Whizard)

<u>The model file:</u> description of fields, symmetries, parameters and Lagrangians

```
In[3]:= SetDirectory[$FeynRulesPath <> "/Models/RS"];
задать рабочую директорию
LoadModel["SM.fr", "Radion_Higgs_Model_v1.3.4.fr"]

Merging model-files...
This model implementation was created by
K. Svirina
I. Schienbein
B. Fuks
Model Version: 1.3.4
```

```
(* *****     Fields     ***** *)
(* ************************** *)
M$ClassesDescription = {

(* Higgs and radion: unphysical scalars  *)

  S[11] == {
    ClassName       -> Phi,
    Unphysical      -> True,
    Indices         -> {Index[SU2D]},
    FlavorIndex     -> SU2D,
    SelfConjugate   -> False,
    QuantumNumbers  -> {Y -> 1/2},
    Definitions     -> { Phi[1]->0, Phi[2]->(vev + (Sin[th] + 6
gam xi/ZZ Cos[th]) R + (Cos[th] - 6 gam xi/ZZ Sin[th])
H)/Sqrt[2] }
  },

  S[12] == {
    ClassName       -> R0,
    Unphysical      -> True,
    SelfConjugate   -> False,
    Definitions     -> { R0 -> ( 1/ZZ Cos[th]) R - (1/ZZ Sin[th])
H }
  },
```

$$H_0 = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v_0 + h_0) \end{pmatrix} \rightarrow \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v_0 + (C\,r + D\,h)) \end{pmatrix}$$

$$r_0 = A\,r + B\,h$$

The RS model is implemented in the FeynRules, automated calculation of the Feynman rules is achieved

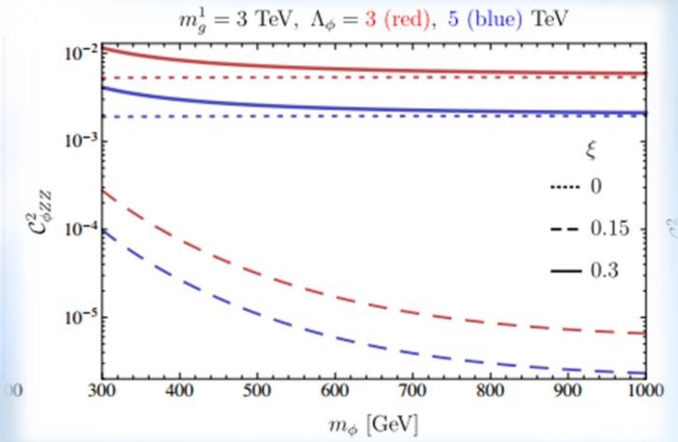
RS model with FeynRules package

Outlook

1. Implementation of the model (creation of a new model file) ✓
2. Verification of the results (examples from the literature) ✓
3. Collider phenomenology study: to interface the model file with MadGraph and to get the observables

to study the *hh, rh, rr* production *(loop level)*

to study the Higgs coupling modifications

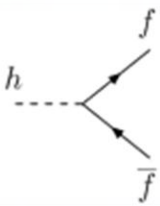


Examples

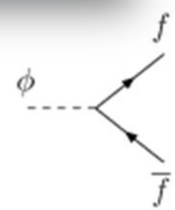
RS model with FeynRules package

Interaction with fermions

$$L_{rff} = \frac{r_0}{\Lambda_r} \sum_f m_f \bar{f} f + L_{Yukawa}$$



$$-i\frac{g}{2}\frac{m_f}{m_W}(d+\gamma b)$$



$$-i\frac{g}{2}\frac{m_f}{m_W}(c+\gamma a)$$

```
(* Vertices calculation*)

FRul = FeynmanRules[L, SelectParticles → {{H, tbar, t}, {R, tbar, t}}]

Starting Feynman rule calculation.

Expanding the Lagrangian...

2 vertices obtained.
```

$$\left\{\left\{\left\{\{\bar{t},1\},\{t,2\},\{R,3\}\right\}, \frac{i\,MT\,Cos[\theta]\,\delta_{m1,m2}\,\delta_{s1,s2}}{\Lambda_R\,ZZ} - \frac{3\,i\sqrt{2}\,\gamma\,\xi\,(y^u)^*_{3,3}\,Cos[\theta]\,\delta_{m1,m2}\,P_{-s1,s2}}{ZZ} - \frac{i\,(y^u)^*_{3,3}\,\delta_{m1,m2}\,P_{-s1,s2}\,Sin[\theta]}{\sqrt{2}} - \frac{3\,i\sqrt{2}\,\gamma\,\xi\,Cos[\theta]\,\delta_{m1,m2}\,P_{-s1,s2}\,y^u{}_{3,3}}{ZZ} - \frac{i\,\delta_{m1,m2}\,P_{-s1,s2}\,Sin[\theta]\,y^u{}_{3,3}}{\sqrt{2}}\right\},\right.$$

$$\left.\left\{\left\{\{\bar{t},1\},\{t,2\},\{H,3\}\right\}, -\frac{i\,(y^u)^*_{3,3}\,Cos[\theta]\,\delta_{m1,m2}\,P_{-s1,s2}}{\sqrt{2}} - \frac{i\,MT\,\delta_{m1,m2}\,\delta_{s1,s2}\,Sin[\theta]}{\Lambda_R\,ZZ} + \frac{3\,i\sqrt{2}\,\gamma\,\xi\,(y^u)^*_{3,3}\,\delta_{m1,m2}\,P_{-s1,s2}\,Sin[\theta]}{ZZ} - \frac{i\,Cos[\theta]\,\delta_{m1,m2}\,P_{-s1,s2}\,y^u{}_{3,3}}{\sqrt{2}} + \frac{3\,i\sqrt{2}\,\gamma\,\xi\,\delta_{m1,m2}\,P_{-s1,s2}\,Sin[\theta]\,y^u{}_{3,3}}{ZZ}\right\}\right\}$$

```
(* Htt vertex *)

DomiHtt = -I / 2 g MT / MW (d + gam b)
```
мнимая единица

$$-\frac{i\,g\,(d+b\,\gamma)\,MT}{2\,M_W}$$

```
DomiHtt =
  DomiHtt //. rep1 //. rep2 //. rep3 //.
    rep4 //. rep5 //. rep1 // Simplify
```
упростить

$$-\frac{i\,MT\,Cos[\theta]}{vev} + \frac{i\,MT\,(-1+6\,\xi)\,Sin[\theta]}{\Lambda_R\sqrt{1+\frac{6\,vev^2\,(1-6\,\xi)\,\xi}{\Lambda_R^2}}}$$

```
ResHtt - DomiHtt // Simplify
```
упростить

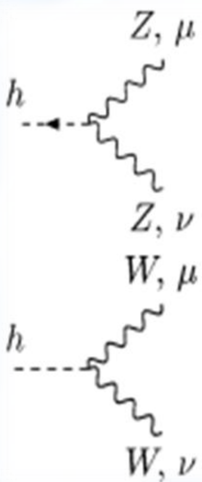
```
0
```

Comparison with D.Dominici et al. / Nuclear Physics B 671 (2003) 243–292

RS model with FeynRules package

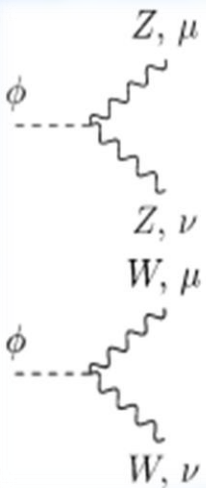
Interaction with massive gauge bosons

$$L_{rVV} = \frac{r_0}{\Lambda_r}\left[-2m_W^2 W_\mu^+ W^{\mu-} - m_Z^2 Z_\mu Z^\mu\right] + |D_\mu \Phi|^2$$



$$i\frac{g m_Z}{c_W}(d+\gamma b)\eta^{\mu\nu}$$

$$i g m_W (d+\gamma b)\eta^{\mu\nu}$$



$$i\frac{g m_Z}{c_W}(c+\gamma a)\eta^{\mu\nu}$$

$$i g m_W (c+\gamma a)\eta^{\mu\nu}$$

```
FRul = FeynmanRules[L, SelectParticles → {{H, Z, Z}, {R, Z, Z}, {H, W, Wbar}, {R, W, Wbar}}]
```

Examples

RS model with FeynRules package

Anomalous interaction

$$L_{rgg} = \left[-\frac{r_0}{\Lambda_r} b_3 - \frac{1}{2}\left(-\frac{r_0}{\Lambda_r} + \frac{h_0}{v}\right) F_{1/2}(\tau_f) \right] \frac{\alpha_s}{8\pi} G_{\mu\nu} G^{\mu\nu}$$

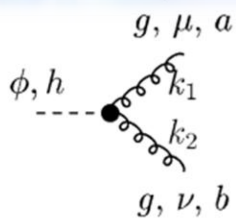
the QCD trace anomaly $(b_3 = 7)$

the effective contribution of 1-loop diagrams with virtual fermions $F_{1/2}(\tau_f) = -2\tau_f\left[1 + (1-\tau_f) f(\tau_f)\right],\ \tau_f = 4m_f^2/q^2$

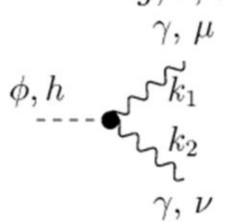
$$L_{r\gamma\gamma} = \left[-\frac{r_0}{\Lambda_r}(b_2 + b_Y) - \left(-\frac{r_0}{\Lambda_r} + \frac{h_0}{v}\right)\left(F_1(\tau_W) + \sum_i e_i^2 N_c^i F_{1/2}(\tau_i)\right) \right] \frac{\alpha_{EM}}{8\pi} F_{\mu\nu} F^{\mu\nu}$$

the QED trace anomaly $(b_2 = 19/6,\ b_Y = -41/6)$

the effective contribution of 1-loop diagrams with virtual fermions and virtual W-bosons in the loop $F_1(\tau_W) = 2 + 3\tau_W + 3\tau_W(2-\tau_W) f(\tau_W)$



$$ic_g \delta^{ab}[k_1 \cdot k_2 \eta^{\mu\nu} - k_1^\nu k_2^\mu] : c_g = -\frac{\alpha_s}{4\pi v}\left[g_{fV} \sum_i F_{1/2}(\tau_i) - 2b_3 g_r\right]$$



$$ic_\gamma [k_1 \cdot k_2 \eta^{\mu\nu} - k_1^\nu k_2^\mu] : c_\gamma = -\frac{\alpha}{2\pi v}\left[g_{fV} \sum_i e_i^2 N_c^i F_i(\tau_i) - (b_2 + b_Y) g_r\right]$$

```
FRul = FeynmanRules[ExLanomG, SelectParticles → {{H, G, G}, {R, G, G}}]

FRul1 = FeynmanRules[ExLanomA, SelectParticles → {{H, A, A}, {R, A, A}}]
```

Examples RS model with FeynRules package

Scalar interaction

$$\mathcal{L} \ni -V(H_0) = -\lambda\left(H_0^\dagger H_0 - \frac{1}{2}v_0^2\right)^2 = -\lambda\left(v_0^2 h_0^2 + v_0 h_0^3 + \frac{1}{4}h_0^4\right),$$

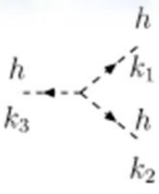
Higgs potential

$$\mathcal{L} \ni -\frac{\phi_0}{\Lambda_\phi}T_\mu^\mu(h_0) = -\frac{\phi_0}{\Lambda_\phi}\left(-\partial^\rho h_0 \partial_\rho h_0 + 4\lambda v_0^2 h_0^2\right).$$

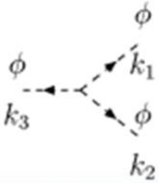
Interaction with the trace of the SM stress tensor

$$V(\phi_0) = \frac{1}{2}m_{\phi_0}^2\phi_0^2 + X_3\frac{m_{\phi_0}^2}{2\Lambda_\phi}\phi_0^3 + \cdots,$$

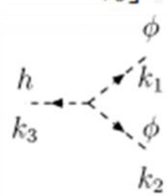
Radion potential (model-dependent)



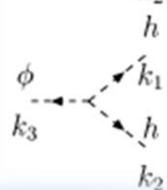
$$i\bar{g}_{hhh} \equiv \frac{i}{\Lambda_\phi}\Big[bd\{[12b\gamma\xi + d(6\xi+1)](k_1^2+k_2^2+k_3^2) - 12dm_{h_0}^2\} - 3\gamma^{-1}d^3m_{h_0}^2 - 3X_3b^3m_{\phi_0}^2\Big]$$



$$i\bar{g}_{\phi\phi\phi} \equiv \frac{i}{\Lambda_\phi}\Big[ac\{[12a\gamma\xi + c(6\xi+1)](k_1^2+k_2^2+k_3^2) - 12cm_{h_0}^2\} - 3\gamma^{-1}c^3m_{h_0}^2 - 3X_3a^3m_{\phi_0}^2\Big]$$



$$i\bar{g}_{\phi\phi h} \equiv \frac{i}{\Lambda_\phi}\Big[\{6a\xi(\gamma(ad+bc)+cd) + bc^2\}(k_1^2+k_2^2) + c\{12ab\gamma\xi + 2ad + bc(6\xi-1)\}k_3^2 - 4c(2ad+bc)m_{h_0}^2 - 3\gamma^{-1}c^2dm_{h_0}^2 - 3X_3a^2bm_{\phi_0}^2\Big]$$



$$i\bar{g}_{\phi hh} \equiv \frac{i}{\Lambda_\phi}\Big[\{6b\xi(\gamma(ad+bc)+cd) + ad^2\}(k_1^2+k_2^2) + d\{12ab\gamma\xi + 2bc + ad(6\xi-1)\}k_3^2 - 4d(ad+2bc)m_{h_0}^2 - 3\gamma^{-1}cd^2m_{h_0}^2 - 3X_3ab^2m_{\phi_0}^2\Big]$$

```
FRul = FeynmanRules[LHR,
  SelectParticles → {{R, R, R}, {H, H, H}, {R, H, H}, {R, R, H}}]
```

Scalar potential

The considered scalar potential:

$$V(r_0,h_0)=\frac{1}{2}m_{r_0}^2 r_0^2+X_3\frac{m_{r_0}^2}{2\Lambda_r}r_0^3+\ldots+\Omega^4 V_H(H_0),\quad \Omega=1-\frac{r_0}{\Lambda_r}$$

$$V_H(H_0)=V_0-\mu^2 H_0^\dagger H_0+\lambda\left(H_0^\dagger H_0\right)^2$$

<u>Possible generalizations:</u>

- **Replace V_H by the potential for a 2HDM.**
- **Consider the most general renormalizable potential for**

-- an *SU(2)* Higgs doublet and a real scalar SM singlet

SM+real scalar singlet:

$$V(\Phi,S)=\frac{m^2}{2}\Phi^\dagger\Phi+\frac{\lambda}{4}(\Phi^\dagger\Phi)^2+\frac{1}{2}\delta_1\Phi^\dagger\Phi S+\frac{1}{2}\delta_2\Phi^\dagger\Phi S^2+\kappa_1 S+\frac{1}{2}\kappa_2 S^2+\frac{1}{3}\kappa_3 S^3+\frac{1}{4}\kappa_4 S^4,$$

-- an *SU(2)* Higgs doublet and a complex scalar SM singlet

SM+complex scalar singlet:

$$V(\Phi,S_c)=\frac{m^2}{2}\Phi^\dagger\Phi+\frac{\lambda}{4}(\Phi^\dagger\Phi)^2+\left(\frac{1}{4}\delta_1\Phi^\dagger\Phi S_c+\frac{1}{4}\delta_3\Phi^\dagger\Phi S_c^2+a_1 S_c+\frac{1}{4}b_1 S_c^2+\frac{1}{6}c_1 S_c^4+\frac{1}{6}c_2 S_c|S_c|^2+\frac{1}{8}d_1 S_c^4+\frac{1}{8}d_3 S_c^2|S_c|^2+h.c.\right)+\frac{1}{4}d_2(|S_c^2|)^2+\frac{1}{2}\delta_2\Phi^\dagger\Phi|S_c|^2+\frac{1}{2}b_2|S_c|^2,$$

- **Consider higher-dimensional operators (impacting vacuum stability considerations).**

Renormalization Group Equations (RGE's)

in a General Quantum Field Theory

M.E. Machacek and M.T. Vaughn, Nucl. Phys. B222, 83 (1983)
M.E. Machacek and M.T. Vaughn, Nucl. Phys. B236, 221 (1984)
M.E. Machacek and M.T. Vaughn, Nucl. Phys. B249, 709 (1985)

(Dimensional regularization and the modified minimal subtraction algorithm)
$d=4-2\epsilon$

$$x_k^0 \mu^{-\rho_k \epsilon} = x_k + \sum_{n=1}^{\infty} a_k^{(n)} \frac{1}{\epsilon^n}$$

the bare coupling constant — the renormalized coupling constant

The **β-function** of x_k:

$$\beta_{x_k} = \mu \frac{dx_k}{d\mu}\bigg|_{\epsilon=0}$$

$$\beta_{x_k} = \sum_l \rho_l x_l \frac{\partial a_k^{(1)}}{\partial x_l} - \rho_k a_k^{(1)}$$

μ - is an arbitrary mass scale parameter

The wave function **renormalization constant** of the i-th field

$$Z_i = 1 + \sum_{n=1}^{\infty} C_i^{(n)} \frac{1}{\epsilon^n}$$

The **anomalous dimension** of the i-th field

$$\gamma_i = \frac{1}{2}\mu \frac{d}{d\mu} \log Z_i = -\frac{1}{2} \sum_l \rho_l x_l \frac{\partial C_i^{(1)}}{\partial x_l}.$$

Perturbatively:

$$\beta_{x_k} = \frac{1}{(4\pi)^2} \beta_{x_k}^{I} + \frac{1}{(4\pi)^4} \beta_{x_k}^{II} + \cdots$$

1-loop contribution — 2-loop contribution

$$\gamma_i = \frac{1}{(4\pi)^2} \gamma_i^{I} + \frac{1}{(4\pi)^4} \gamma_i^{II} + \cdots$$

1-loop — 2-loop

Renormalization Group Equations (RGE's)

Scalar wave function renormalization

The contribution of a diagram to the singular part of the scalar wave function renormalization matrix can be expressed in the form

$$\left(Z_{\tilde{s}}^{-1}\right)_{ab} = \frac{1}{(4\pi)^4} S_{ab} \left(\frac{A}{\eta^2} + \frac{B}{\eta} \right),$$

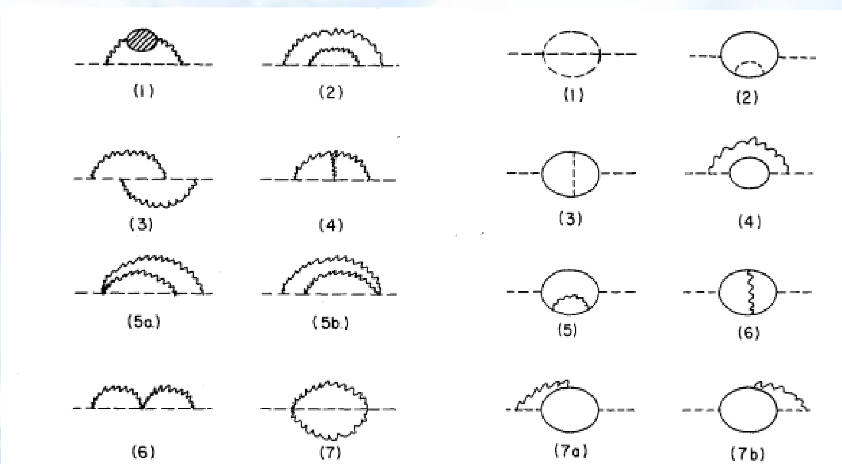


Diagram	S	A	B
1.1		eq. (3.3)	eq. (3.4)
1.2	$g^4[C_2(S)]^2$	$\frac{1}{2}(2+\alpha)^2$	$-\frac{1}{4}(2+\alpha)^2$
1.3	$g^4C_2(S)[C_2(S)-\frac{1}{2}C_2(G)]$	$(2+\alpha)(1-\alpha)$	$\frac{1}{2}-3\alpha+\frac{7}{4}\alpha^2$
1.4	$\frac{1}{2}g^4C_2(S)C_2(G)$	$\frac{3}{2}(2+\alpha)(1-\alpha)$	$-\frac{17}{8}-\frac{31}{4}\alpha+2\alpha^2$
1.5a + 1.5b + 1.6	$g^4C_2(S)[2C_2(S)-\frac{1}{2}C_2(G)]$	$-\frac{3}{2}(2+\alpha)$	$-\frac{3}{8}+\frac{5}{2}\alpha-\alpha^2$
1.7	$g^4C_2(S)[2C_2(S)-\frac{1}{2}C_2(G)]$	0	$1-\frac{1}{2}\alpha+\frac{1}{4}\alpha^2$

Diagram	S_{ab}	A	B
2.1	$\frac{1}{6}\lambda_{acde}\lambda_{bcde}$	0	$\frac{1}{4}$
2.2	$\kappa \operatorname{Tr} \underset{\sim}{Y}^b \underset{\sim}{Y}^{\dagger a} \underset{\sim}{Y}^c \underset{\sim}{Y}^{\dagger c}$	1	$-\frac{3}{2}$
2.3	$\kappa \operatorname{Tr} \underset{\sim}{Y}^b \underset{\sim}{Y}^{\dagger c} \underset{\sim}{Y}^a \underset{\sim}{Y}^{\dagger c}$	2	-1
2.4	$\kappa g^2 C_2(S) \operatorname{Tr} \underset{\sim}{Y}^a \underset{\sim}{Y}^{\dagger b}$	$-(2+\alpha)$	$1+\frac{5}{2}\alpha$
2.5	$\kappa g^2 \operatorname{Tr} \underset{\sim}{C}_2(F) \underset{\sim}{Y}^a \underset{\sim}{Y}^{\dagger b}$	$2(1-\alpha)$	$-1+\alpha$
2.6	$\kappa g^2 [\operatorname{Tr} \underset{\sim}{C}_2(F) \underset{\sim}{Y}^a \underset{\sim}{Y}^{\dagger b} - \frac{1}{2}C_2(S) \operatorname{Tr} \underset{\sim}{Y}^a \underset{\sim}{Y}^{\dagger b}]$	$-2(4-\alpha)$	$2(3-\frac{1}{2}\alpha)$
2.7a + 2.7b	$\kappa g^2 C_2(S) \operatorname{Tr} \underset{\sim}{Y}^a \underset{\sim}{Y}^{\dagger b}$	$2(1+2\alpha)$	$2(1-\frac{3}{2}\alpha)$

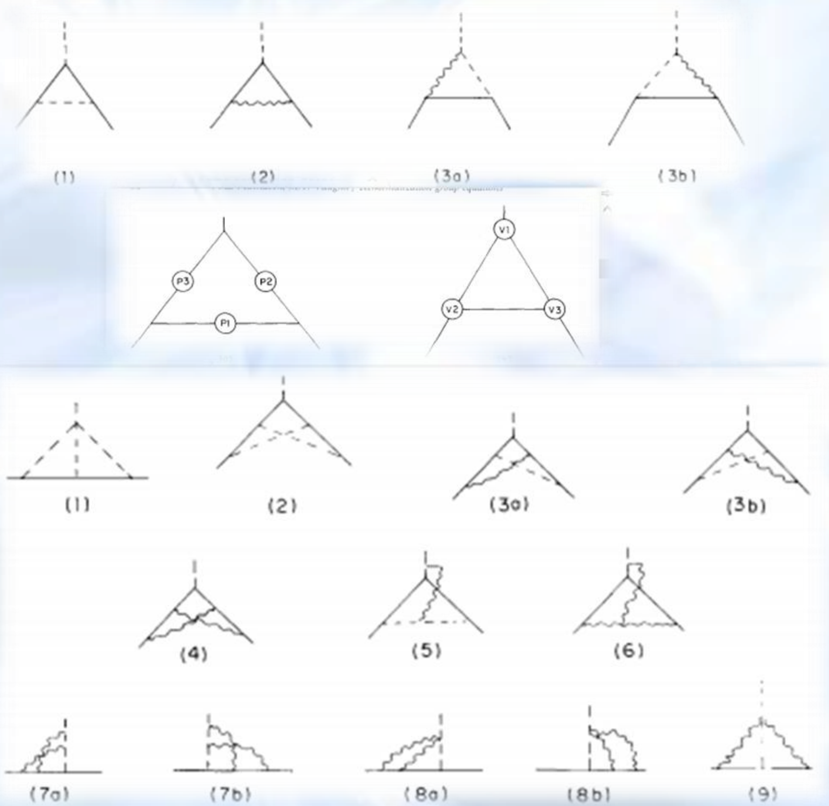
$$\gamma^s_{ab}\big|_{\text{2-loop}} = \frac{2}{(4\pi)^4} \sum_{\text{diagrams}} B S_{ab},$$

Renormalization Group Equations (RGE's)

Yukawa couplings renormalization

$$\boldsymbol{\beta}^a = \frac{\mathrm{d}\boldsymbol{Y}^a}{\mathrm{d}t} = {}^{Y}\boldsymbol{\gamma}^a + \boldsymbol{\gamma}^{\dagger\mathrm{F}}\boldsymbol{Y}^a + \boldsymbol{Y}^a\boldsymbol{\gamma}^{\mathrm{F}} + \gamma^{\mathrm{S}}_{ab}\boldsymbol{Y}^b ,$$

$${}^{Y}\boldsymbol{\gamma}^a\big|_{2\text{-loop}} = -\frac{4}{(4\pi)^4}\sum_{\text{diagrams}} \boldsymbol{BS}^a ,$$



1-loop and 2-loop results:

$$(4\pi)^2\boldsymbol{\beta}^a\big|_{1\text{-loop}} = \tfrac{1}{2}[\boldsymbol{Y}_2^\dagger(\mathrm{F})\boldsymbol{Y}^a + \boldsymbol{Y}^a\boldsymbol{Y}_2(\mathrm{F})] + 2\boldsymbol{Y}^b\boldsymbol{Y}^{\dagger a}\boldsymbol{Y}^b + 2\kappa\boldsymbol{Y}^b\,\mathrm{Tr}\,\boldsymbol{Y}^{\dagger b}\boldsymbol{Y}^a - 3g^2\{\boldsymbol{C}_2(\mathrm{F}),\boldsymbol{Y}^a\} .$$

$$\begin{aligned}
(4\pi)^4\boldsymbol{\beta}^a\big|_{2\text{-loop}} = {} & 2\boldsymbol{Y}^c\boldsymbol{Y}^{\dagger b}\boldsymbol{Y}^a(\boldsymbol{Y}^{\dagger c}\boldsymbol{Y}^b - \boldsymbol{Y}^{\dagger b}\boldsymbol{Y}^c) - \boldsymbol{Y}^b[\boldsymbol{Y}_2(\mathrm{F})\boldsymbol{Y}^{\dagger a} + \boldsymbol{Y}^{\dagger a}\boldsymbol{Y}_2^\dagger(\mathrm{F})]\boldsymbol{Y}^b \\
& - \tfrac{1}{8}[\boldsymbol{Y}^b\boldsymbol{Y}_2(\mathrm{F})\boldsymbol{Y}^{\dagger b}\boldsymbol{Y}^a + \boldsymbol{Y}^a\boldsymbol{Y}^{\dagger b}\boldsymbol{Y}_2^\dagger(\mathrm{F})\boldsymbol{Y}^b] \\
& - 4\kappa Y_2^{ac}(\mathrm{S})\boldsymbol{Y}^b\boldsymbol{Y}^{\dagger c}\boldsymbol{Y}^b - \tfrac{3}{2}\kappa Y_2^{bc}(\mathrm{S})[\boldsymbol{Y}^b\boldsymbol{Y}^{\dagger c}\boldsymbol{Y}^a + \boldsymbol{Y}^a\boldsymbol{Y}^{\dagger c}\boldsymbol{Y}^b] \\
& - \kappa\boldsymbol{Y}^b\,\mathrm{Tr}\,\{\tfrac{3}{2}[\boldsymbol{Y}_2(\mathrm{F})\boldsymbol{Y}^{\dagger b} + \boldsymbol{Y}^{\dagger b}\boldsymbol{Y}_2^\dagger(\mathrm{F})]\boldsymbol{Y}^a + 2\boldsymbol{Y}^{\dagger b}\boldsymbol{Y}^c\boldsymbol{Y}^{\dagger a}\boldsymbol{Y}^c\} \\
& - 2\lambda_{abcd}\boldsymbol{Y}^b\boldsymbol{Y}^{\dagger c}\boldsymbol{Y}^d + \tfrac{1}{12}\lambda_{acde}\lambda_{bcde}\boldsymbol{Y}^b + 3g^2\{\boldsymbol{C}_2(\mathrm{F}),\boldsymbol{Y}^b\boldsymbol{Y}^{\dagger a}\boldsymbol{Y}^b\} \\
& + 5g^2\boldsymbol{Y}^b\{\boldsymbol{C}_2(\mathrm{F}),\boldsymbol{Y}^{\dagger a}\}\boldsymbol{Y}^b - \tfrac{7}{4}g^2[\boldsymbol{C}_2(\mathrm{F})\boldsymbol{Y}_2^\dagger(\mathrm{F})\boldsymbol{Y}^a + \boldsymbol{Y}^a\boldsymbol{Y}_2(\mathrm{F})\boldsymbol{C}_2(\mathrm{F})] \\
& - \tfrac{1}{4}g^2[\mathbf{Y}^b\mathbf{C}_2(\mathrm{F})\boldsymbol{Y}^{\dagger b}\boldsymbol{Y}^a + \boldsymbol{Y}^a\boldsymbol{Y}^{\dagger b}\boldsymbol{C}_2(\mathrm{F})\boldsymbol{Y}^b] \\
& + 6g^2[\boldsymbol{t}^A\boldsymbol{Y}^a\boldsymbol{Y}^{\dagger b}\boldsymbol{t}^A\boldsymbol{Y}^b + \boldsymbol{Y}^b\boldsymbol{t}^A\boldsymbol{Y}^{\dagger b}\boldsymbol{Y}^a\boldsymbol{t}^A] \\
& + 5\kappa g^2\boldsymbol{Y}^b\,\mathrm{Tr}\,\{\boldsymbol{C}_2(\mathrm{F}),\boldsymbol{Y}^a\}\boldsymbol{Y}^{\dagger b} \\
& + 6g^2[C_2^{bc}(\mathrm{S})\boldsymbol{Y}^b\boldsymbol{Y}^{\dagger a}\boldsymbol{Y}^c - 2C_2^{ac}(\mathrm{S})\boldsymbol{Y}^b\boldsymbol{Y}^{\dagger c}\boldsymbol{Y}^b] \\
& + \tfrac{9}{2}g^2[\boldsymbol{Y}^b\boldsymbol{Y}^{\dagger c}\boldsymbol{Y}^a + \boldsymbol{Y}^a\boldsymbol{Y}^{\dagger c}\boldsymbol{Y}^b] - \tfrac{3}{2}g^4\{[C_2(\mathrm{F})]^2,\boldsymbol{Y}^a\} \\
& + g^4[6C_2(\mathrm{S}) - \tfrac{97}{6}C_2(\mathrm{G}) + \tfrac{10}{3}\kappa S_2(\mathrm{F}) + \tfrac{11}{12}S_2(\mathrm{S})]\{\boldsymbol{C}_2(\mathrm{F}),\boldsymbol{Y}^a\} \\
& - g^4C_2(\mathrm{S})[\tfrac{21}{2}C_2(\mathrm{S}) - \tfrac{49}{4}C_2(\mathrm{G}) + 2\kappa S_2(\mathrm{F}) + \tfrac{1}{4}S_2(\mathrm{S})]\boldsymbol{Y}^a , \qquad (3.3)
\end{aligned}$$

Renormalization Group Equations (RGE's)

Dimensional parameters. "Dummy"-field method

$$\mathcal{L}_0 = -\frac{1}{4}F_A^{\mu\nu}F_{\mu\nu}^A + \frac{1}{2}D^\mu\phi_a D_\mu\phi_a + i\psi_j^+\sigma^\mu D_\mu\psi_j - \frac{1}{2}\left(Y_{jk}^a\psi_j\zeta\psi_k\phi_a + h.c.\right) - \frac{1}{4!}\lambda_{abcd}\phi_a\phi_b\phi_c\phi_d,$$

contains only dimensionless parameters

$$\mathcal{L}_1 = -\frac{1}{2}\left[(m_f)_{jk}\psi_j\zeta\psi_k + h.c.\right] - \frac{m_{ab}^2}{2!}\phi_a\phi_b - \frac{h_{abc}}{3!}\phi_a\phi_b\phi_c$$

dimensional parameters

$$\mathcal{L}_1 = -\frac{1}{2}\left(Y_{jk}^{\hat{d}}\psi_j\zeta\psi_k\phi_{\hat{d}} + h.c\right) - \frac{\lambda_{ab\hat{d}\hat{d}}}{4!}\phi_a\phi_b\phi_{\hat{d}}\phi_{\hat{d}} - \frac{\lambda_{abc\hat{d}}}{4!}\phi_a\phi_b\phi_c\phi_{\hat{d}} \qquad (21)$$

dimensionless

The β-functions of m_f, m_{ab}^2, h_{abc} **are equal to those of the new Yukawa coupling** $Y^{\hat{d}}$, **quartic scalar coupling** $\lambda_{ab\hat{d}\hat{d}}$ **and** $\lambda_{abc\hat{d}}$

with $\phi_{\hat{d}}$ - a non-propagating dummy real scalar field with no gauge interactions

and the substitution: $Y_{ij}^{\hat{d}} = (m_f)_{ij},\ \lambda_{ab\hat{d}\hat{d}} = 2m_{ab}^2,\ \lambda_{abc\hat{d}} = h_{abc}$

Mingxing Luo, Huawen Wang, Yong Xiao
Phys.Rev. D67 (2003) 065019

Renormalization Group Equations (RGE's)

Dimensional parameters. "Dummy"-field method

The β-functions of fermion mass can be inferred from those of the Yukawa couplings by taking the *a*-indices to be dummy:

$$\beta_I^a = \frac{1}{2}\left[Y_2^+(F)Y^a + Y^a Y_2(F)\right] + 2Y^b Y^{+a} Y^b$$
$$+2\kappa Y^b Y_2^{ab}(S) - 3g^2\{C_2(F), Y^a\}$$

$$\beta^I_{m_f} = \frac{1}{2}\left[Y_2^+(F)m_f + m_f Y_2(F)\right] + 2Y^b m_f^+ Y^b$$
$$+\kappa Y^b \mathrm{Tr}(m_f^+ Y^b + m_f Y^{+b})$$
$$-3g^2\{C_2(F), m_f\} \qquad (62)$$

Checked and corrected both for 1- and 2-loop cases

The β-functions of trilinear scalar couplings can be inferred from those of the quartic couplings by taking one of the four indices to be dummy.

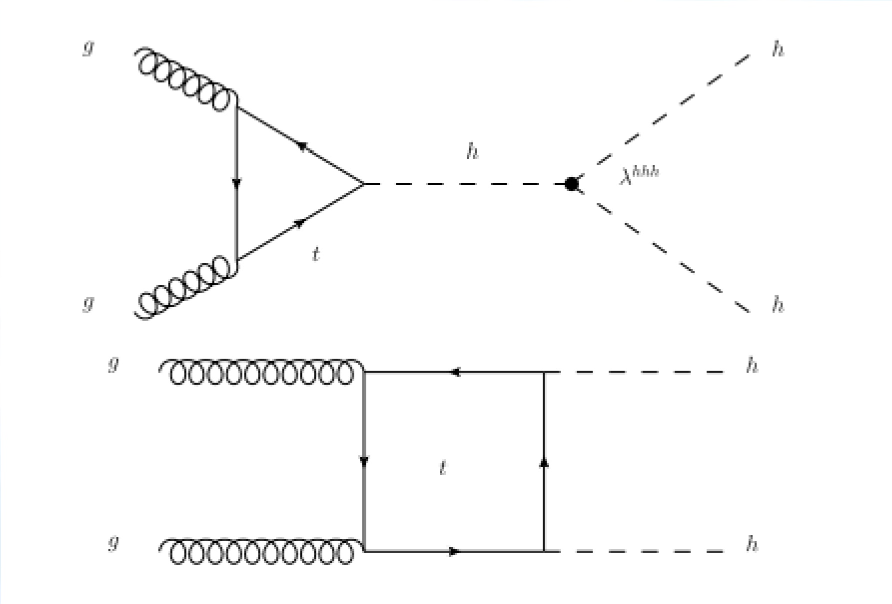
Verification in progress

Summary

- The Higgs pair production is the key process to search deviations from the SM in the trilinear Higgs coupling
- Extended scalar sector (RS model)
- The RS model has been implemented in FeynRules, automated calculation of the Feynman rules is achieved
- Prospective to interface the RS model file with MadGraph for study of collider phenomenology of the model
- Scalar potential reconstruction and study of its stability
- Study of the RGE’s is in progress (“dummy”-field method verification and correction)

Thank you for your attention!

BACK UP



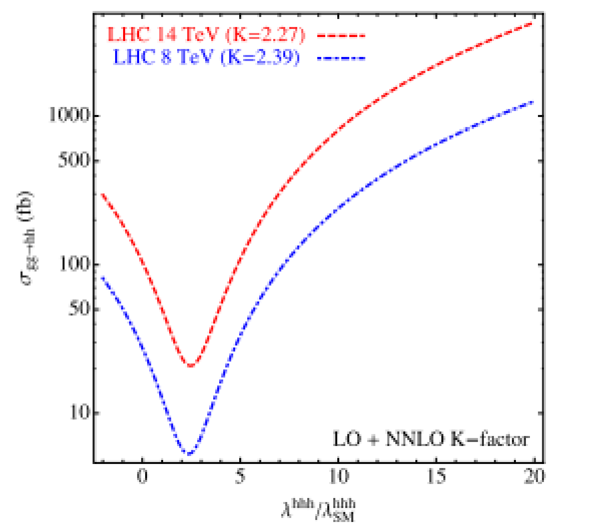


Fig. 2. Production cross section for $gg \to hh$ at the LHC with $\sqrt{s} = 8$ TeV and 14 TeV.

Radion **branching ratios**

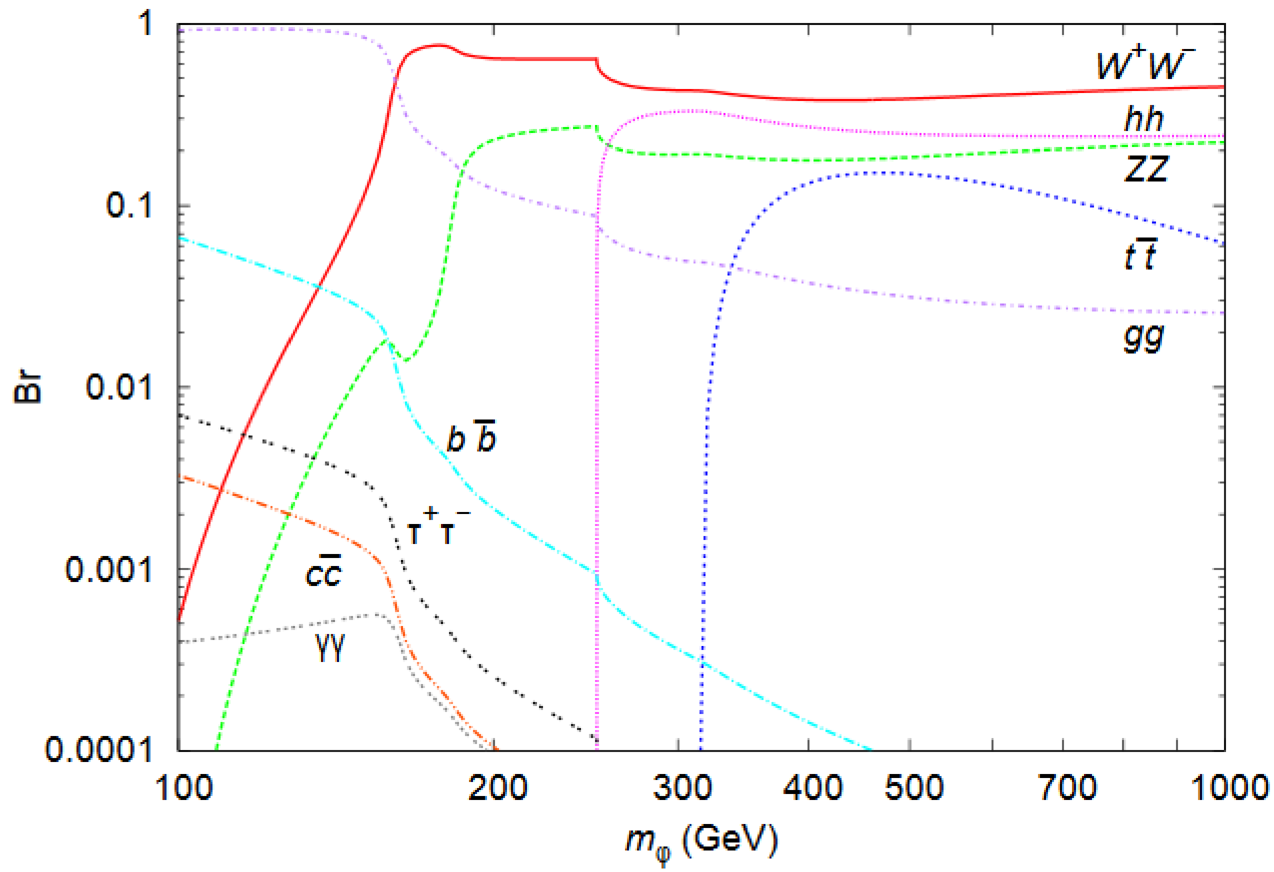
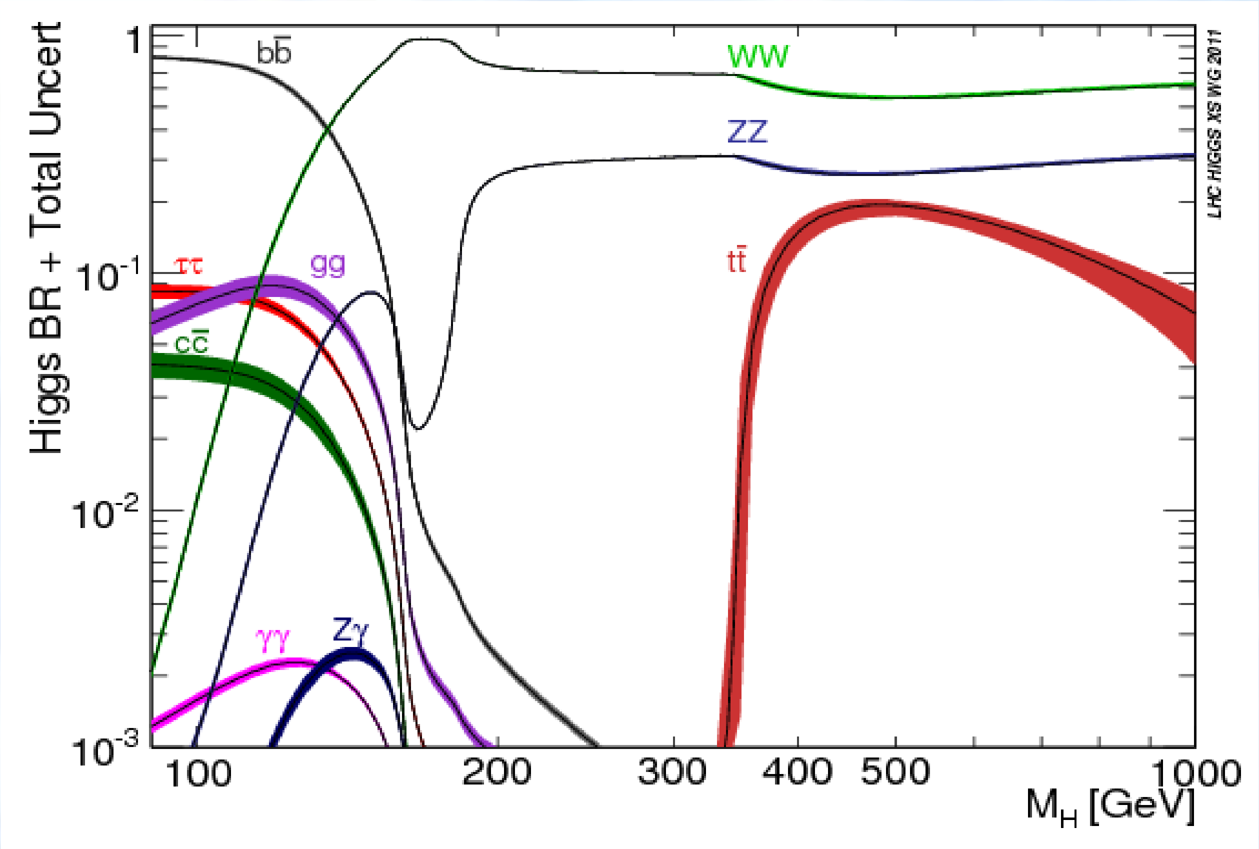


Figure 2: The decay branching ratios of the radion. The SM Higgs boson mass is taken to be 125.5 GeV.

Higgs **branching ratios**



Higgs branching ratios and their uncertainties

Constraints on radion at LHC

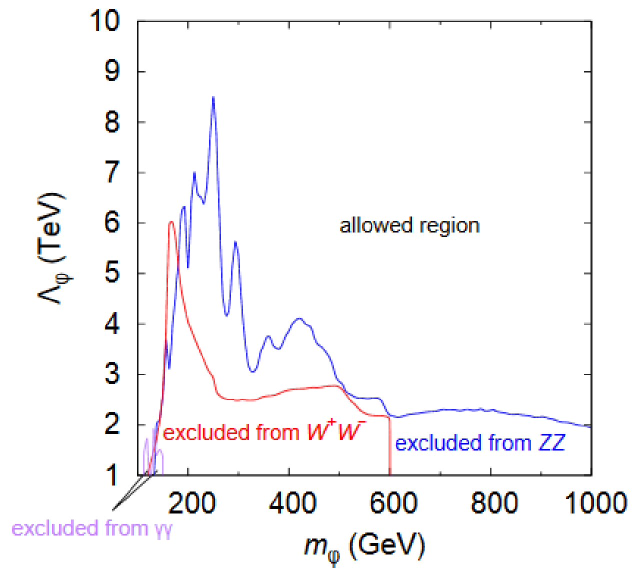
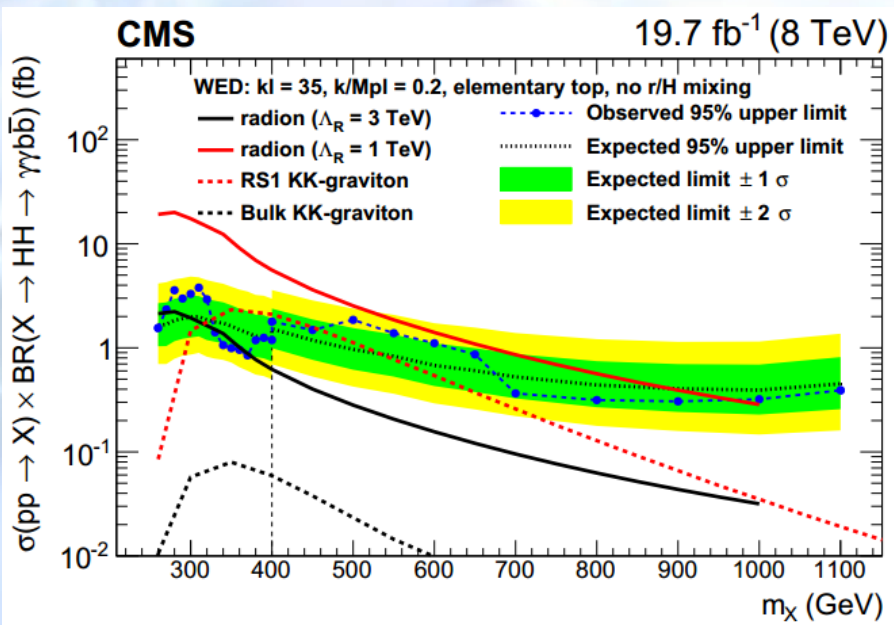


Figure 3: Excluded regions in the (m_ϕ, Λ_ϕ) plane from the SM Higgs boson searches in the ZZ, W^+W^- and $\gamma\gamma$ channels at the LHC.



The radion with **Λ_r= 1 TeV**, is observed (expected) to be excluded for masses **below 975 GeV** (850 GeV). The RS1 KK-graviton is excluded with masses between 320 and 400 GeV.

Radion-dominated state **branching ratios**

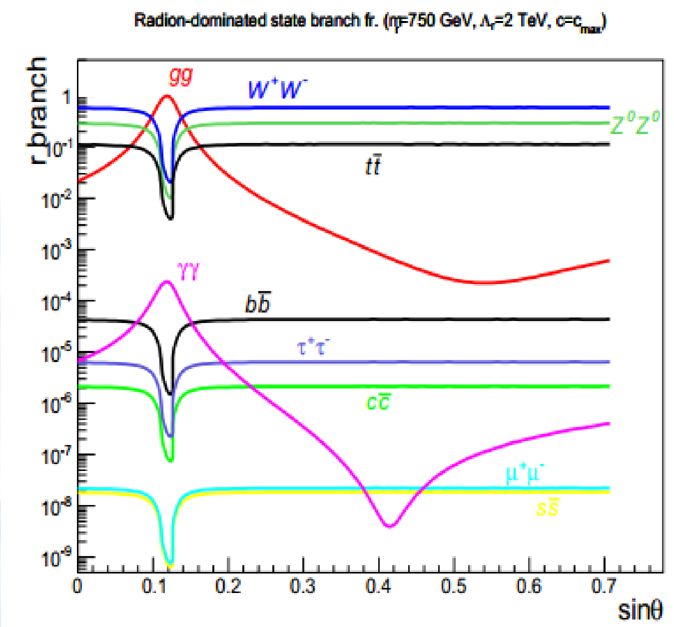


Figure 1: The decay branching ratios for the radion-dominated state with mass 750 GeV as functions of the mixing angle parameter $\sin\theta$.

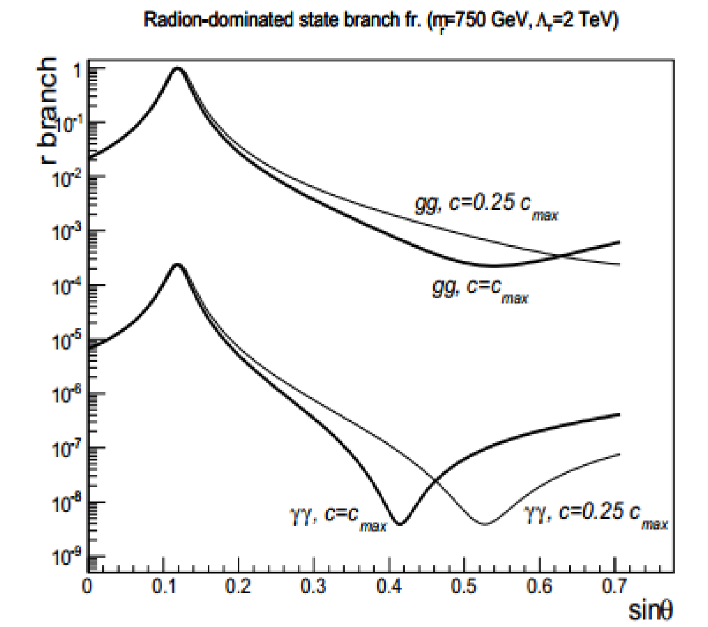


Figure 2: The gluon-gluon and photon-photon branchings as functions of $\sin\theta$ for $c = c_{max}$ and $c = 0.25c_{max}$.

for sinθ close to ~v/Λ_r all the branching ratios are significantly decreased,
the mode to 2 gluons and 2 photons are increased.
(Structure of the interaction vertices of the radion-dominated state → all the vertices for the fermions and massive gauge bosons contain the factor $\frac{\cos\theta - c\cdot\sin\theta}{\Lambda_r} - \frac{\sin\theta}{v}$ which becomes small for sin θ close to v/Λ_r)

The position of the maximum and the form of the curves close to the maximum practically do not depend on the value of the parameter c, which accumulates the contributions of the higher KK scalar modes.

Radion-dominated state **width**

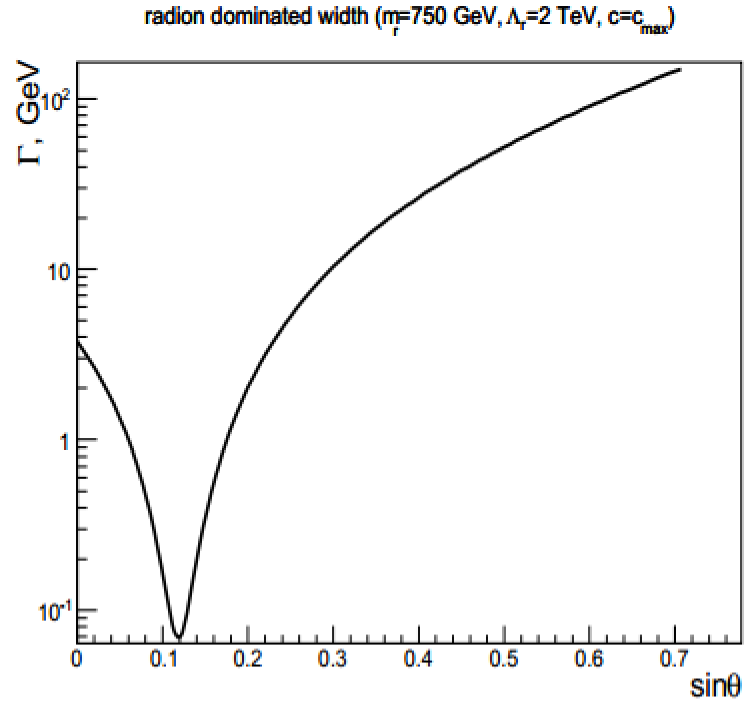


Figure 3: The total width of the radion-dominated state with mass 750 GeV as a function of the mixing angle parameter $\sin\theta$.

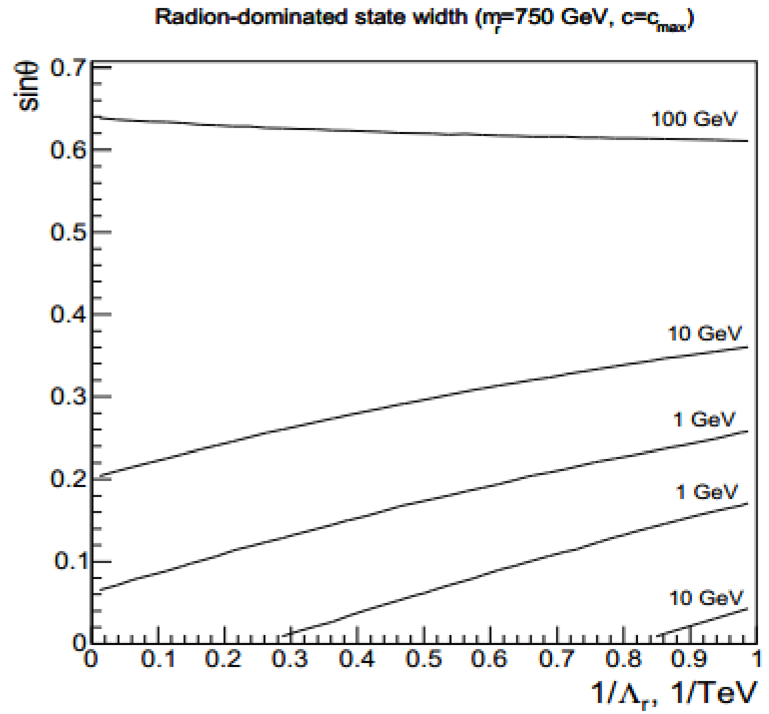


Figure 4: Equal width contours for the radion-dominated state with mass 750 GeV as functions of the parameters $\sin\theta$ and $1/\Lambda_r$.

The radion-dominated state <u>can be rather wide</u>.
The width of the 750 GeV excess observed at the LHC has a rather large value of the order of 45 GeV

Radion-dominated state **cross section**

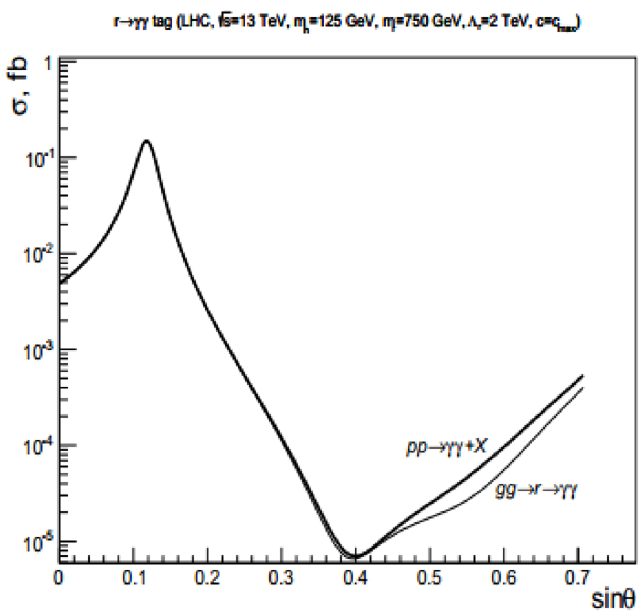


Figure 5: The production cross section of the radion-dominated state with mass 750 GeV as a function of the mixing angle parameter $\sin\theta$ including the contributions of all the production modes (thick curve) and only the leading contribution of the gluon-gluon fusion mode (thin curve)

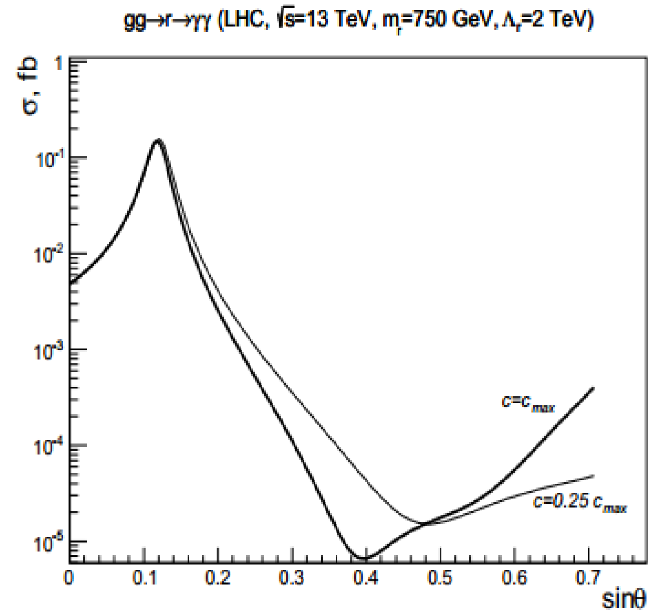


Figure 6: The production cross section of the radion-dominated state in the main gluon-gluon fusion mode with mass 750 GeV as a function of the mixing angle parameter $\sin\theta$ for the parameter $c = c_{max}$ (thick curve) and $c = 0.25c_{max}$ (thin curve).

"The interpretation of the observed excess as the radion-dominated state is very problematic or even impossible in the simplest variant of the discussed brane-world models, where only the gravitational degrees of freedom are allowed to propagate in the bulk. Indeed, as one can see in Fig. 6, the cross section has a maximum of about 0.14 fb, which is by a factor of 50 ÷ 100 smaller than what is needed to achieve the observed level of the cross section for the 750 GeV excess"

Edward E. Boos, Viacheslav E. Bunichev, Igor P. Volobuev
arXiv:1603.04495v3 [hep-ph]

$$
\begin{aligned}
T^{\mu}_{\mu} &= -(\partial_\mu h)(\partial^\mu h) + 2m_h^2 h^2\left(1+\frac{h}{2v}\right)^2 - 2m_W^2 W^+_\mu W^{\mu -}\left(1+\frac{h}{v}\right)^2 - m_Z^2 Z_\mu Z^\mu\left(1+\frac{h}{v}\right)^2 \\
&+ \sum_f \left\{-\frac{i3}{2}\left[\bar{f}\gamma^\mu(\partial_\mu f) - (\partial_\mu \bar{f})\gamma^\mu f\right] + 4m_f\bar{f}f\right\} + \frac{4h}{v}\sum_f m_f \bar{f}f - 3eA_\mu \sum_f q_f \bar{f}\gamma^\mu f \\
&- \frac{3}{2}\frac{m_Z}{v}Z_\mu \sum_f \bar{f}\gamma^\mu\left[a_f + b_f\gamma_5\right]f - \frac{3}{\sqrt{2}}\frac{m_W}{v}\left(W^-_\mu \bar{\nu}_j U^{PMNS}_{jk}\gamma^\mu\left[1-\gamma_5\right]e_k + h.c.\right) \\
&- \frac{3}{\sqrt{2}}\frac{m_W}{v}\left(W^-_\mu \bar{u}_j \gamma^\mu\left[1-\gamma_5\right]V^{CKM}_{jk} d_k + h.c.\right) - 3g_c\left(\bar{u}_j\gamma^\mu \hat{G}_\mu u_j + \bar{d}_j\gamma^\mu \hat{G}_\mu d_j\right) \\
&+ \frac{\beta(e)}{2e}F_{\mu\nu}F^{\mu\nu} + \frac{\beta(g_s)}{2g_s}G^{ab}_{\mu\nu}G^{\mu\nu}_{ab},
\end{aligned}
$$

$$
D_\mu \psi = \left[\partial_\mu - ieA_\mu + i\frac{e}{2\cos\theta_w \sin\theta_w}\left(2\sin^2\theta_w - \frac{1-\gamma^5}{2}\right)Z_\mu\right]\psi,
$$

$$
D_\mu \bar{\psi} = \left[\partial_\mu + ieA_\mu - i\frac{e}{2\cos\theta_w \sin\theta_w}\left(2\sin^2\theta_w - \frac{1+\gamma^5}{2}\right)Z_\mu\right]\bar{\psi}.
$$

1.3 Renormalization

In order to absorb the divergences of our theory we redefine fields and bare parameters in terms of renormalized quantities as follows:

$$\phi = \sqrt{Z_\phi}\phi_R, \;\; \psi = \sqrt{Z_\psi}\psi_R, \;\; m_S = \frac{Z_S}{Z_\phi} m_{S,R}, \;\; m_F = \frac{Z_F}{Z_\psi} m_{F,R}, \;\; g = \frac{Z_g}{Z_\psi\sqrt{Z_\phi}} g_R. \tag{19}$$

Note that the precise arrangement of scale factors in these definitions is arbitrary, as long as there is one for every quantity.[2] The one we chose gives

$$\mathcal{L} = \frac{1}{2} Z_\phi \partial_\mu \phi_R \partial^\mu \phi_R - \frac{1}{2} Z_S m_{S,R}^2 \phi_R^2 + \bar{\psi}_R (i Z_\psi \not{\partial} - Z_F m_{F,R}) \psi_R - i Z_g g_R \bar{\psi}_R \gamma_5 \psi_R \phi_R. \tag{20}$$

We now proceed to determine the modified Feynman rules which contain counterterms expanding the renormalization constants in powers of g,

$$Z_i = 1 + \delta Z_i + \mathcal{O}(g^2)\,. \tag{21}$$