Higgs Sector of the Left-Right Symmetric Theory

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General Motivations

- Open problem in SM: the origin of neutrino masses.

- A key is a nonstandard gauge symmetry spontaneously broken. (new Higgs boson $\longrightarrow$ a larger scalar sector).

  LR extension of the SM.

- Impact on Higgs physics.

- Test: Lepton number violation (LNV). (Majorana neutrino, neutrinoless 2-beta decay, Keung-Senjanovic process…)

Higgs boson in the Standard Model

The Higgs boson (**h**) discovery is the last triumph of the SM:

- it provides the masses of all charged fermions

- the essence of the Higgs mechanism is that the decay rate of h to two (charged)fermions f's is $\propto m_f^{\,2}$

No coupling with neutrino

$$m_\nu = 0 \quad \Longleftrightarrow \quad \Gamma_{h\to\nu\nu} = 0$$

Neutrino mass in the Standard Model

In the SM the neutrino mass can be built by the non-renormalizable operator (dimension 5):

$$L = y_{\nu_L} \frac{(\Psi_L^t i\sigma_2 \Phi) C (\Phi^t i\sigma_2 \Psi_L)}{M}$$

[Weinberg '79]

Any **NP scale**

Standard Higgs

$$\langle \Phi \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$M_{\nu_L} = y_{\nu_L} \frac{v^2}{M}$$

A UV completion of the SM is required

A Left-Right symmetry?

SM features

Mass-less neutrino
(in contrast with neutrino oscillations)
[T.Kajita, A. McDonald recent Nobel prize winners]

Possible cures

- **-Type I seesaw** ⟶ fermion singlet [Minkoswki '77, Yanagida79]
- **-Type II seesaw** ⟶ boson triplet [Lazarides et al '80, Mohapatra-Senjanovic '81]
- **-Type III seesaw** ⟶ fermion triplet [Foot et al. '86]
- **-Radiative generation** [Zee '80]
- - ....
- -Etc.

Total asymmetry between L&R, reflecting the chiral structure of weak interactions.
[Wu,'57], [Garwin, Lederman, Weinrich,'57]

A first suggestion:
mirror universe
[Lee and Yang '56]

Bringing both issues together

LR Symmetric Model

[Pati-Salam '74, Mohapatra-Senjanovic '75]

From SM to a theory of the neutrino mass: highlights of the model

$$SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \Rightarrow SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

→ new Higgs boson

[Pati-Salam '74, Mohapatra-Senjanovic '75]

Plus a generalized Parity relating left and right: $g_L = g_R \equiv g$

$$Q_{el} = T_{3L} + T_{3R} + \frac{B-L}{2}$$

$$Q_L \in (3,2,1,1/3)$$
$$Q_R \in (3,1,2,1/3)$$
$$\Psi_L \in (1,2,1,-1)$$
$$\Psi_R \in (1,1,2,-1)$$

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \qquad Q_R = \begin{pmatrix} u \\ d \end{pmatrix}_R$$

$$\Psi_L = \begin{pmatrix} \nu_l \\ l \end{pmatrix}_L \qquad \Psi_R = \begin{pmatrix} \nu_l \\ l \end{pmatrix}_R$$

→ **A RH gauge interacting neutrino**

Highlights of the model: gauge sector

- γ — Photon
- $Z_L, W_L^{\pm}$ — Standard weak bosons
- $Z_R, W_R^{\pm}$ — "Right-handed twins" bosons

RH current ⟶ NP contributions to $0\nu 2\beta$ decay

[Mohapatra,Senjanovic '81]
[Tello,Nemevsek,Nesti,Senjanovic, Vissani 2011]

Gauge Interactions

$$L_{c.c.} = \frac{g}{2\sqrt{2}}[\bar{\nu}\gamma^{\mu}(1-\gamma^5)e]W^{+}_{\mu L} + \frac{g}{2\sqrt{2}}[\bar{\nu}\gamma^{\mu}(1+\gamma^5)e]W^{+}_{\mu R} + h.c.$$

$$L^{SM}_{n.c.} = \frac{g}{c_W} Z_L (J_{3L} - \frac{s_W^2}{e} J^0) \qquad L^{N.P.}_{n.c.} = \frac{g\sqrt{c_W^2 - s_W^2}}{c_W} Z_R (J_{3R} - J_Y \frac{s_W^2}{c_W^2 - s_W^2})$$

$J^0, J_{3L}, J_{3R}, J_Y =$ Electric, left, right and Hyper-charge currents with normalization:

$$\frac{1}{e} J^0 = J_{3L} + J_{3R} + J_Y$$

Coming to Higgs Sector

SSB

at e.w. scale — at high scale

A **bi-doublet**

$\Phi \in (2_L, 2_R, 0)$

Vevs

$$\begin{pmatrix} v & 0 \\ 0 & v' e^{ia} \end{pmatrix}$$

$$e.w. = \sqrt{v^2 + v'^2}$$

Two triplets

$\Delta_L \in (3_L, 1_R 2)$

$\Delta_R \in (1_L, 3_R, 2)$

[Senjanovic '79]

Vevs

$$\begin{pmatrix} 0 & 0 \\ v_{L,R} & 0 \end{pmatrix}$$

Vevs hierarchy

$$v_L << v, v' << v_R \qquad v_L \propto e.w.^2 / v_R$$

$$\tan\beta = v'/v < 1$$

The **potential** has to contain all the possible quadratic and quartic terms in Φ and Δ allowed by symmetry

The scalar potential

$$
\begin{aligned}
\mathcal{V} = & -\mu_1^2 \mathrm{Tr}[\phi^\dagger \phi] - \mu_2^2 \left(\mathrm{Tr}\left[\tilde{\phi}\phi^\dagger\right] + \mathrm{Tr}\left[\tilde{\phi}^\dagger \phi\right] \right) - \mu_3^2 \left(\mathrm{Tr}\left[\Delta_L \Delta_L^\dagger\right] + \mathrm{Tr}\left[\Delta_R . \Delta_R^\dagger\right] \right) \\
& + \lambda_1 (\mathrm{Tr}[\phi^\dagger \phi])^2 + \lambda_2 \left(\left(\mathrm{Tr}\left[\tilde{\phi}\phi^\dagger\right] \right)^2 + \left(\mathrm{Tr}\left[\tilde{\phi}^\dagger \phi\right] \right)^2 \right) + \lambda_3 \mathrm{Tr}\left[\tilde{\phi}\phi^\dagger\right] \mathrm{Tr}\left[\tilde{\phi}^\dagger \phi\right] \\
& + \lambda_4 \mathrm{Tr}[\phi^\dagger \phi] \left(\mathrm{Tr}\left[\tilde{\phi}\phi^\dagger\right] + \mathrm{Tr}\left[\tilde{\phi}^\dagger \phi\right] \right) + \rho_1 \left(\left(\mathrm{Tr}\left[\Delta_L . \Delta_L^\dagger\right] \right)^2 + \left(\mathrm{Tr}\left[\Delta_R . \Delta_R^\dagger\right] \right)^2 \right) \\
& + \rho_2 \left(\mathrm{Tr}\left[\Delta_L \Delta_L\right] \mathrm{Tr}\left[\Delta_L^\dagger \Delta_L^\dagger\right] + \mathrm{Tr}\left[\Delta_R \Delta_R\right] \mathrm{Tr}\left[\Delta_R^\dagger \Delta_R^\dagger\right] \right) \\
& + \rho_3 \mathrm{Tr}\left[\Delta_L \Delta_L^\dagger\right] \mathrm{Tr}\left[\Delta_R \Delta_R^\dagger\right] + \rho_4 \left(\mathrm{Tr}\left[\Delta_L \Delta_L\right] \mathrm{Tr}\left[\Delta_R^\dagger \Delta_R^\dagger\right] \right. \\
& \left. + \mathrm{Tr}\left[\Delta_L^\dagger \Delta_L^\dagger\right] \mathrm{Tr}\left[\Delta_R \Delta_R\right] \right) + \alpha_1 \mathrm{Tr}[\phi^\dagger \phi] \left(\mathrm{Tr}\left[\Delta_L \Delta_L^\dagger\right] + \mathrm{Tr}\left[\Delta_R \Delta_R^\dagger\right] \right) \\
& + \alpha_2 e^{i\delta_2} \left(\mathrm{Tr}\left[\tilde{\phi}\phi^\dagger\right] \mathrm{Tr}\left[\Delta_L \Delta_L^\dagger\right] + \mathrm{Tr}\left[\tilde{\phi}^\dagger \phi\right] \mathrm{Tr}\left[\Delta_R \Delta_R^\dagger\right] \right) \\
& + \alpha_2 e^{-i\delta_2} \left(\mathrm{Tr}\left[\phi \tilde{\phi}^\dagger\right] \mathrm{Tr}\left[\Delta_L \Delta_L^\dagger\right] + \mathrm{Tr}\left[\phi^\dagger \tilde{\phi}\right] \mathrm{Tr}\left[\Delta_R \Delta_R^\dagger\right] \right) \\
& + \alpha_3 \left(\mathrm{Tr}\left[\phi \phi^\dagger \Delta_L . \Delta_L^\dagger\right] + \mathrm{Tr}\left[\phi^\dagger \phi \Delta_R \Delta_R^\dagger\right] \right) \\
& + \beta_1 \left(\mathrm{Tr}\left[\phi \Delta_R \phi^\dagger \Delta_L^\dagger\right] + \mathrm{Tr}\left[\phi^\dagger \Delta_L \phi \Delta_R^\dagger\right] \right) \\
& + \beta_2 \left(\mathrm{Tr}\left[\tilde{\phi} \Delta_R \phi^\dagger \Delta_L^\dagger\right] + \mathrm{Tr}\left[\tilde{\phi}^\dagger \Delta_L \phi \Delta_R^\dagger\right] \right) \\
& + \beta_3 \left(\mathrm{Tr}\left[\phi \Delta_R \tilde{\phi}^\dagger \Delta_L^\dagger\right] + \mathrm{Tr}\left[\phi^\dagger \Delta_L \tilde{\phi} \Delta_R^\dagger\right] \right)
\end{aligned}
$$

With $\tilde{\Phi} = i\sigma_2 \Phi^* i\sigma_2$

The β's $\cong 0$ in the **seesaw picture**:

$V_L \cong 0$

The choice of Left-Right symmetry is not univocal

$$\mathcal{P}: \begin{cases} Q_L \leftrightarrow Q_R \\ \Phi \rightarrow \Phi^\dagger \end{cases} \qquad \mathcal{C}: \begin{cases} Q_L \leftrightarrow (Q_R)^c \\ \Phi \rightarrow \Phi^T \end{cases}$$

Which leads respectively to

$$\mathcal{P}: \; Y = Y^\dagger , \qquad \mathcal{C}: \; Y = Y^T$$

[A.M., Nemevsek,Nesti,Senjanovic, 2010]

- The case of "**P**" is the original one, hence it is the most known in literature.
  Features: offers **an insight on "strong CP problem"**.

- The case of "**C**" should be considered equally.
  Features: interesting in SO(10) GUT scenario, where charge conjugation enters automatically in the algebra.
  Some quartics in the **potential** become complex (**phase**): λ**2 (d2),** λ**4 (d4),** ρ**4 (r4)**, and β's (irrelevant).

Scalar mass spectrum

Diagonalization of the mass matrix from the potential. The spectrum contains:

Higgs Bosons →

Physical scalars	Mass^2 (case $\mathcal{C}$)
$h \simeq c_\theta h_{SM} - s_\theta \Re e(\delta_R^0)$	$4(\lambda_\Phi - \frac{\alpha^2}{4\rho_1})v^2$
$\delta_R \simeq c_\theta \Re e(\delta_R^0) + s_\theta h_{SM}$	$4\rho_1 v_R^2 + \frac{\alpha^2}{\rho_1} v^2$
ϕ_{FV} (FV heavy doublet)	$\frac{\alpha_3}{c_{2\beta}} v_R^2$
$\delta_L = \Re e(\delta_L^0) \sim \Im m(\delta_L^0)$	$(\rho_3 - 2\rho_1)v_R^2 + 4\tilde{\alpha}v^2$
δ_L^-	$(\rho_3 - 2\rho_1)v_R^2 + (\frac{1}{2}\alpha_3 c_{2\beta} + 4\tilde{\alpha})v^2$
δ_L^{--}	$(\rho_3 - 2\rho_1)v_R^2 + (\alpha_3 c_{2\beta} + 4\tilde{\alpha})v^2$
δ_R^{--}	$4\rho_2 v_R^2 + \alpha_3 c_{2\beta} v^2$

$$\lambda_\Phi \equiv \lambda_1 + s_{2\beta}^2(2\lambda_2 c_{d_2+2a} + \lambda_3) + 2 s_{2\beta}\lambda_4 c_{d_4+a}$$

$$\alpha \equiv \alpha_1 + 2\alpha_2 s_{2\beta} c_{a+c} + \alpha_3 s_\beta^2 \, ,$$

$$\tilde{\alpha} \equiv \alpha_2 s_{2\beta} s_a s_c \simeq -4\alpha_3 c_{2\beta}(t_{2\beta} s_a)^2 \, ,$$

[Senjanovic '79]
[Gunion,Kayser, Olness' 89]
[Duka, Gluza, Zralek 2000]
[Kiers,Assis,Petrov 2005]
[Zhang,An,Ji,Mohapatra 2007]
[A.M.,Nemevsek,Nesti]
And recently
[A.M.,Senjanovic,Vasquez]

Mixing the two Higgs bosons

$$\theta \cong \frac{\alpha\ k}{2\rho_1 v_R} < \quad 40\%$$

2-sigma C.L.

[Falkowski,Gross,Lebedev 2015]

Possible impact of mixing on probing neutrino masses

The new Higgs boson δ_R

Majorana terms

$$L_{yuk} = (y_\delta \overline{\psi}_R \psi_R{}^c \Delta_R + R \leftrightarrow L) + h.c.$$

$$m_N = 2 y_\delta v_R \qquad M_{W_R} = g v_R \qquad m_\nu = -m_D{}^T m_N^{-1} m_D$$

See-saw

$$\Gamma_{\delta \to NN} \propto y_\delta{}^2$$

[Minkowski '77, Mohapatra Senjanovic '79, Glashow '79; Yanagida '79]

Via the mixing even h can decay to NN

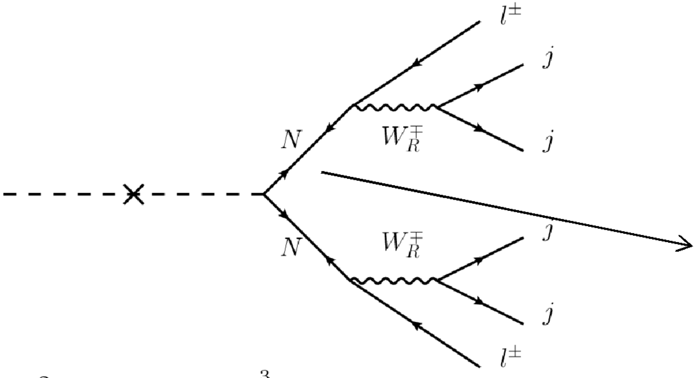
$$\frac{\Gamma_{NN}}{\Gamma_{b\bar{b}}} \simeq \frac{\tan\theta^2}{3} \left(\frac{m_N}{m_b}\right)^2 \left(\frac{M_W}{M_{W_R}}\right)^2 \left(1 - \frac{4m_N^2}{m_h^2}\right)^{\frac{3}{2}}$$

[A.M.,Nemevsek,Nesti, 2015]

$$(c\,\tau_N^0)^{-1} \simeq \frac{G_F^2 m_N^5}{16\pi^3} \left(\frac{M_W}{M_{W_R}}\right)^4$$

[Nemevsek,Nesti,Senjanovic,Zhang 2011]

Possible Impact of mixing on probing neutrino masses



The **SM-like** Higgs boson

Same sign dilepton h decay

Majorana nature of RH neutrino

Indirect information

$$\frac{\Gamma_{NN}}{\Gamma_{b\bar{b}}} \simeq \frac{\tan\theta^2}{3}\left(\frac{m_N}{m_b}\right)^2\left(\frac{M_W}{M_{W_R}}\right)^2\left(1-\frac{4m_N^2}{m_h^2}\right)^{\frac{3}{2}} \longrightarrow \theta \times y_\delta$$

≈coupling of **h** with N

$$(c\,\tau_N^0)^{-1} \simeq \frac{G_F^2 m_N^5}{16\pi^3}\left(\frac{M_W}{M_{W_R}}\right)^4 \longrightarrow M_{W_R}$$

(displacement of N decay products)

[A.M.,Nemevsek, Nesti 2015]

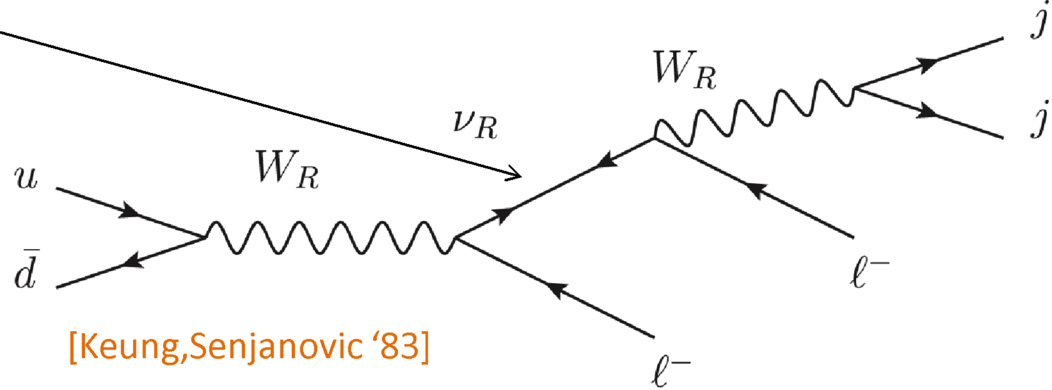
Invariant mass $\longrightarrow$ m_N

Higgs data $\longrightarrow$ θ

LNV

Majorana nature of RH neutrino

The **KS** channel to signal LNV: a collider equivalent of $\mathbf{0\nu2\beta}$



[Keung,Senjanovic ‘83]

Ideally KS⟶ $\mathbf{M_{W_R}}$,$\mathbf{M_N}$⟶ predict $\mathbf{Y_D}$, then N decay: it is possible to determine the Yukawa coupling from the neutrino masses and mixing.

⟶ [Nemevsek, Senjanovic, Tello PRL 2012]

And see the recent (P case): [Senjanovic, Tello]

The complete understanding of neutrino mass origin, requires to observe even δ_R.

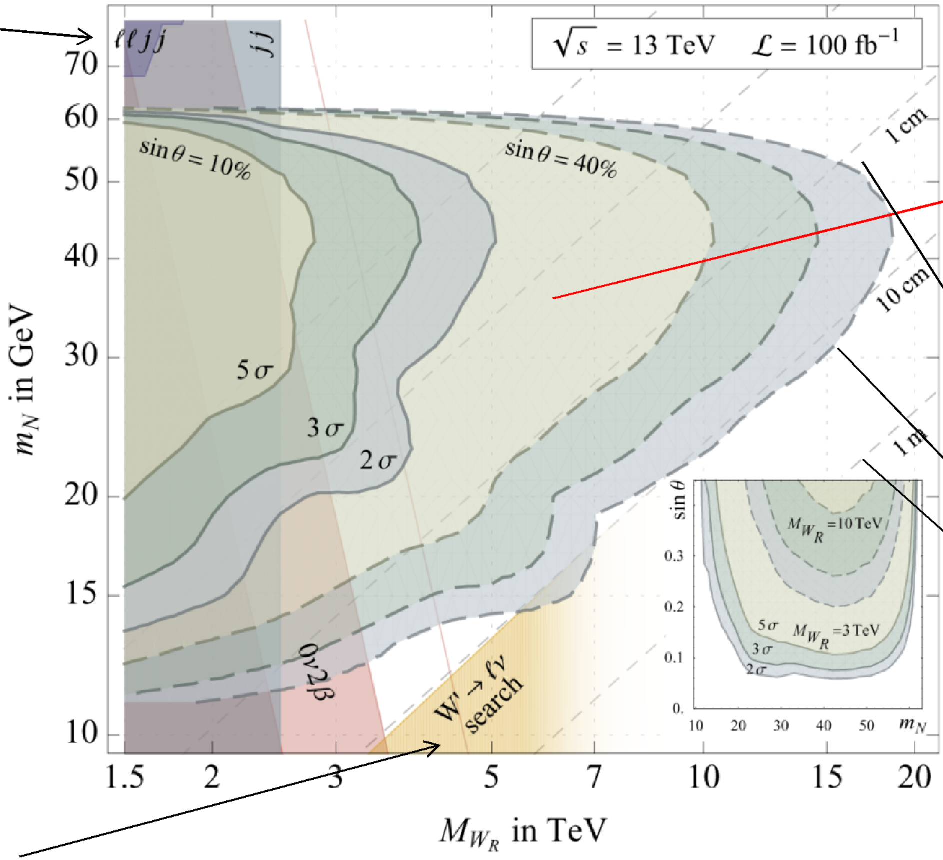
⟶ **See the recent**:

[Nemevsek, Nesti, Vasquez]

LNV Higgs decay could be a complementary process

h⟶$\mu\mu$ + jets LHC sensitivity

Keung-Senjanovic process lljj



LNV Higgs decay

N lifetime

[A.M.,Nemevsek,Nesti 2015]

W' dijet search

Other impact of mixing: deviation form SM-like h self-interaction

Physical couplings	Quartic couplings
λ_{hhhh}	$\lambda_\Phi/4$
$\lambda_{\delta_R\delta_R\delta_R\delta_R}$	$\rho_1/4$
$\lambda_{\delta_R^{++}\delta_R^{++}\delta_R^{--}\delta_R^{--}}$	ρ_1
$\lambda_{\delta_L^{+}\delta_L^{-}\delta_L^{+}\delta_L^{-}} - \lambda_{\delta_R^{++}\delta_R^{--}\delta_R^{++}\delta_R^{--}}$	ρ_2
$\lambda_{\delta_R^{++}\delta_R^{++}\delta_L^{--}\delta_L^{--}}$	ρ_3
$4\lambda_{\phi_{FV}^\dagger\phi_{FV}\delta_L^*\delta_L} - \lambda_{\phi_{FV}^\dagger\phi_{FV}\delta_R^{++}\delta_R^{--}}$	$c_{2\beta}\alpha_3$

Also, more sensitive at LHC
[Baglio, Djouadi, Grober, Muhlleitner, Quevillon, Spira,2013]

But let us focus on **tri-linear**

[A.M.,Senjanovic,Vasquez]

Effectively as
SM+singlet
[see Gupta, Rzehak , Wells]

Tri-linear couplings	Expression
λ_{hhh}	$\frac{m_h^2}{2\sqrt{2}}\frac{c_\theta^3}{v}$
$\lambda_{\delta_R\delta_R\delta_R}$	$\frac{m_{\delta_R}^2}{2\sqrt{2}}\left(\frac{s_\theta^3}{v}+\frac{c_\theta^3}{v_R}\right)$
$\lambda_{hh\delta_R}$	$\frac{s_{2\theta}c_\theta(m_{\delta_R}^2+2m_h^2)}{4\sqrt{2}v}$
$\lambda_{h\delta_R\delta_R}$	$\frac{s_{2\theta}(2m_{\delta_R}^2+m_h^2)}{4\sqrt{2}}\left(\frac{s_\theta}{v}-\frac{c_\theta}{v_R}\right)$

SM deviation

$$\Delta\lambda_{hhh} \equiv \frac{\lambda_{hhh}^{SM}-\lambda_{hhh}}{\lambda_{hhh}^{SM}} \simeq 3/2\theta^2$$

But what about the quantum corrections?

- Any vertex is affected by the corrections, for instance from a rich scalar sectors.

- There may be dominant quantum corrections.

LR-scale dependent and strictly related to the **bounds** (predictivity) on the model.

Theoretical constrains: quark mixing

$$L_Y^{had.} = [\overline{Q}_{Li}(Y_{ij}\Phi + \widetilde{Y}_{ij}\widetilde{\Phi})Q_{Rj}] + h.c.$$

$$\begin{aligned} M_u &= Y v_1 + \widetilde{Y} v_2 e^{-i\alpha} \\ M_d &= Y v_2 e^{i\alpha} + \widetilde{Y} v_1 . \end{aligned}$$

Bi-diagonalization

$$L_{cc} = \frac{g}{2\sqrt{2}}\{[\bar{u} V_L \gamma^\mu (1-\gamma_5) d] W_{L\mu} + [\bar{u} V_R \gamma^\mu (1+\gamma_5) d] W_{R\mu}\} + h.c.$$

Left and Right CKM mixing matrices

$$\begin{cases} V_L = U_{uL}^\dagger U_{dL} \\ V_R = U_{uR}^\dagger U_{dR} \end{cases}$$

Predictivity of the model

Analytic solution for V_R

[Senjanovic, Tello PRL 2014]

Previous numerical analysis

[A.M.,Nemevsek,Nesti,Senjanovic 2010]

Theoretical constrains: flavor changing

Again the spectrum

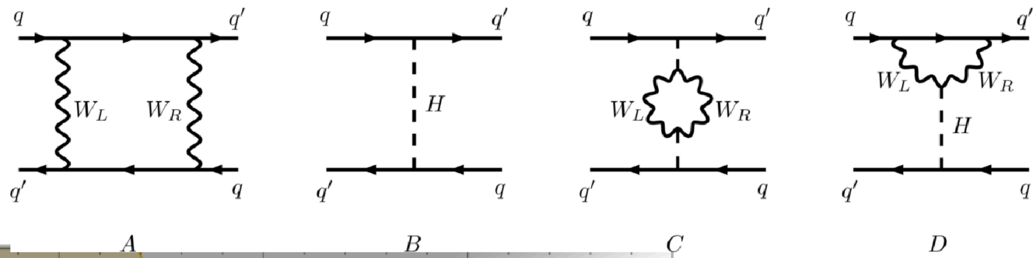
	Physical scalars	Mass^2 (case $\mathcal{C}$)
	$h \simeq c_\theta h_{SM} - s_\theta \Re e(\delta_R^0)$	$4(\lambda_\Phi - \frac{\alpha^2}{4\rho_1})v^2$
	$\delta_R \simeq c_\theta \Re e(\delta_R^0) + s_\theta h_{SM}$	$4\rho_1 v_R^2 + \frac{\alpha^2}{\rho_1} v^2$
Flavor Violating	ϕ_{FV} (FV heavy doublet)	$\frac{\alpha_3}{c_{2\beta}} v_R^2$
	$\delta_L = \Re e(\delta_L^0) \sim \Im m(\delta_L^0)$	$(\rho_3 - 2\rho_1)v_R^2 + 4\tilde{\alpha} v^2$
	δ_L^-	$(\rho_3 - 2\rho_1)v_R^2 + (\frac{1}{2}\alpha_3 c_{2\beta} + 4\tilde{\alpha})v^2$
	δ_L^{--}	$(\rho_3 - 2\rho_1)v_R^2 + (\alpha_3 c_{2\beta} + 4\tilde{\alpha})v^2$
	δ_R^{--}	$4\rho_2 v_R^2 + \alpha_3 c_{2\beta} v^2$

Possible mixing of δ_R with FV only if quasi-degenerate $\Longrightarrow$ very heavy δ_R

α_3 has to be large enough.
And how can it be large to leave a **perturbative** theory?
Notice: a large **tan(β)** worsens the issue (increasing the coupling of FV with quarks)

Theoretical constrains: meson oscillations

Meson oscillations: Bq=d,s mixing [Bertolini, A.M.,Nesti ,2014]



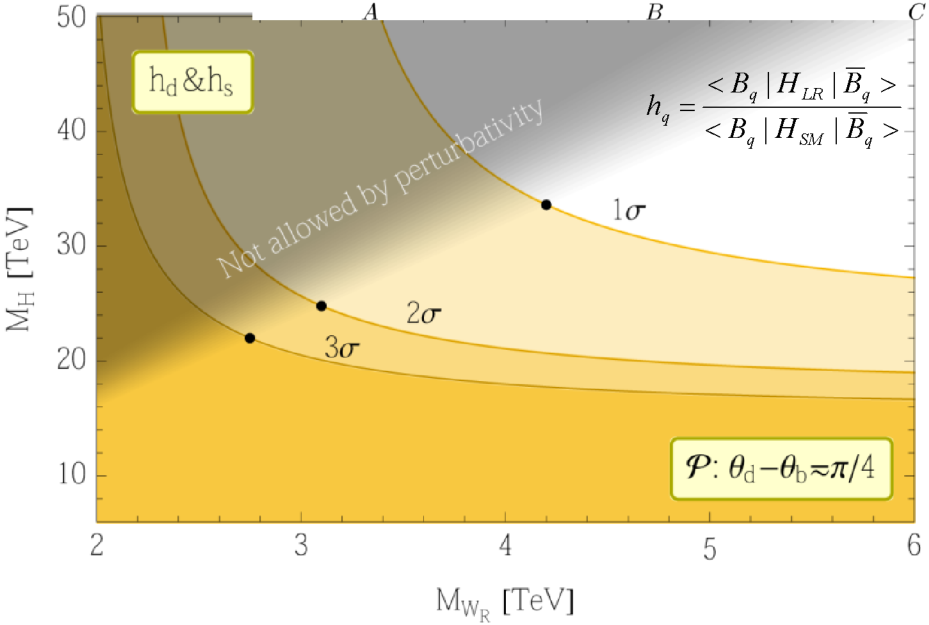


FIG. 10. Combined constraints on M_R and M_{W_R} from ε, ε' B_d and B_s mixings obtained in the $\mathcal{P}$ parity case from the numerical fit of the Yukawa sector of the model.

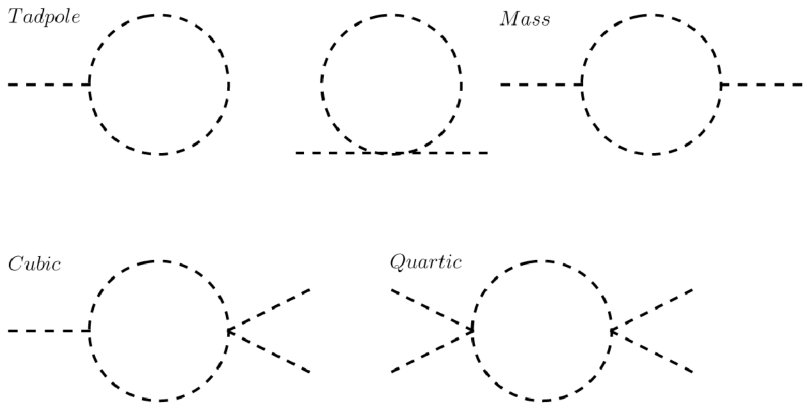
All diagrams have the same CKM structure.
V_R plays an important role in determining the LR contribution to flavor violations. If right CKM matrix were free no bound emerges.
[Langacker,Sankar '89]

But is **α_3** perturbative within the whole theory?
And what is its impact on the (effective) potential?

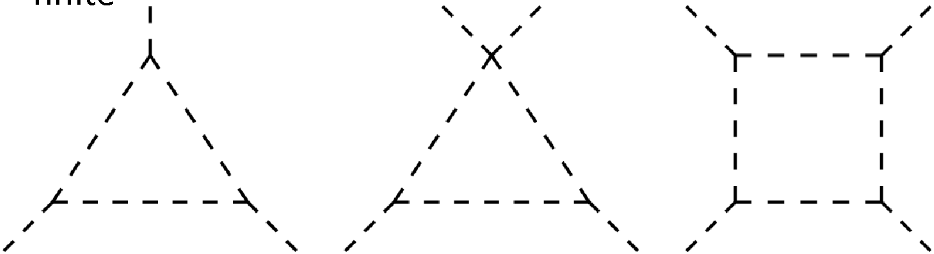
Theoretical constrains: perturbativity

At this purpose consider the loop

- divergent



- finite



Renormalization scheme: reabsorbing in counter-terms the **tadpole** and the **one-loop mass terms** (so the mass is just the tree-level one), then keeping the correction to cubic, quartic…

Matching the one-loop self-generated vertex of a given quartic, with **tree-level** equivalent.

[A.M.,Nemevsek ,Nesti 2016]

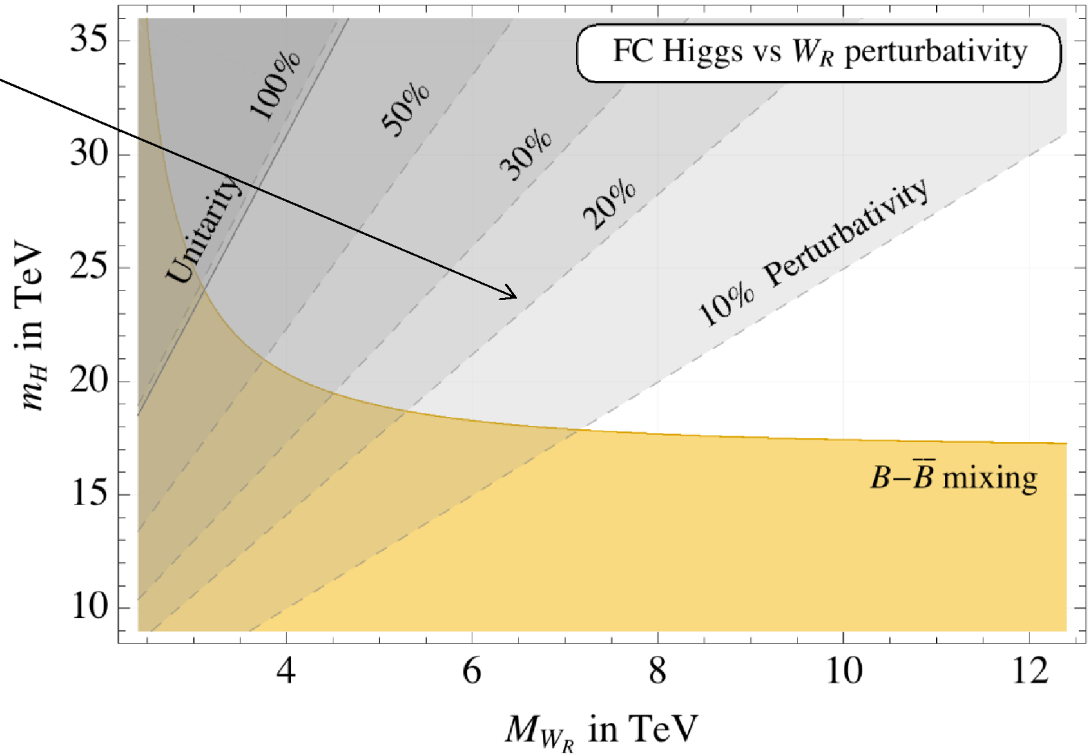
Theoretical constrains: perturbativity (unitarity)

$$\frac{\alpha_3^{(1)}}{\alpha_3} = \frac{3\alpha_3}{8\pi^2},$$

$$\frac{\rho_1^{(1)}}{\rho_1} = \frac{27\rho_1}{16\pi^2},$$

$$\frac{\rho_2^{(1)}}{\rho_2} = \frac{7\rho_2}{4\pi^2},$$

$$\frac{\rho_3^{(1)}}{\rho_3} = \frac{3\rho_3}{16\pi^2},$$



Important quartics for the leading mass spectrum

[A.M.,Nemevsek ,Nesti 2016]

Divergent loop $\longrightarrow$ RGE's

(sharpening the perturbativity issue)

We choose M_{W_R} =6 TeV corresponding to ~ an α_3 **within 10% of perturbativity**;
Vary randomly the "free" quartics within [0,0.1]

[A.M.,Senjanovic,Vasquez]

→ **Edge of LHC for W_R** [Ferrari et al.]

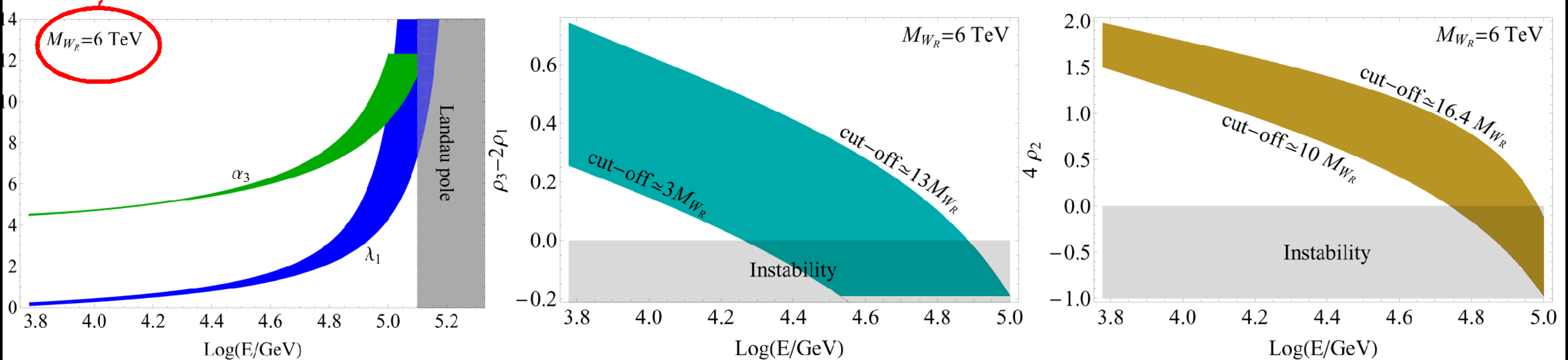


FIG. 1. Left. Running of λ_1, α_3 (the other λ and α couplings exhibit a similar behavior), they become non-perturbative around 10^5 GeV. Center. Running of $\rho_3 - 2\rho_1$ which provides the leading masses for the Δ_L multiplets. The values for the cut-off are read off from the point where $\rho_3 - 2\rho_1$ goes to zero. Right. The same for $4\rho_2$ which provides the leading mass term for δ_R^{++}. In all plots the bands denote the dependence on the random initial choices consistent with the mass spectrum.

Stronger than the limit from S,T e.w. parameters and h$\longrightarrow\gamma\gamma$
[A.M.,Nemevsek ,Nesti 2016]

$$\text{cutoff} \gtrsim 10\, M_{W_R} \;\Rightarrow\; m_{\delta_L,\delta_L^+,\delta_L^{++}} \gtrsim 9\,\text{TeV}$$

$$m_{\delta_R^{++}} \gtrsim 12\,\text{TeV}$$

A cutoff ~10 M_{W_R} is the smallest to require for holding the consistency of the theory.

RGE's

(for LR at next hadron collider)

Same logic as before – but now
-we choose M_{W_R} =20 TeV (α_3 is now ≈0.35, "rather small");
-again vary randomly the "free" quartics within [0,0.1]

$$\lambda_{Higgs} = \lambda_{\Phi} - \frac{\alpha^2}{4\rho_1}$$

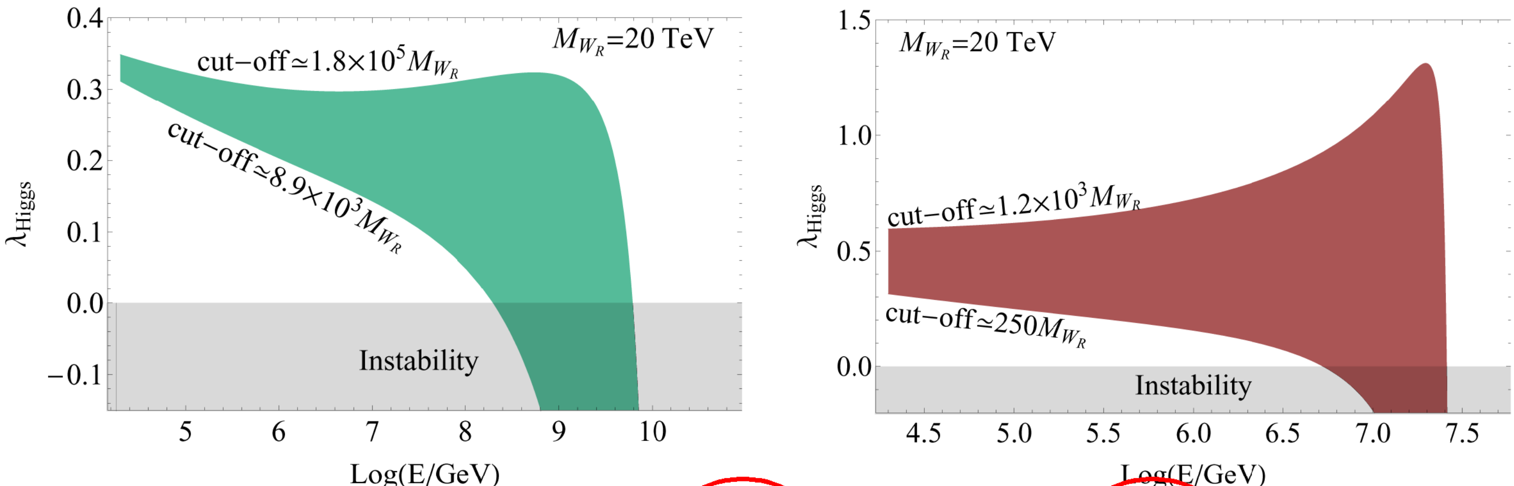


FIG. 2. Left. Running of $\lambda_{Higgs} \equiv 4\lambda_h$ defined in (19) for t_β=0. Right. The same for t_β=0.3 giving a lower cut-off. The cut-offs are defined in the same manner as in the Fig. 1

Now the cut-off (due both to Landau pole or perturbativity of quartics) is far away form the right-hand scale. The theory becomes more relaxed.

Comment: because of the heaviness of the FV, the proper machine to test the whole model is at least a next generation collider, anyway.

[A.M.,Senjanovic,Vasquez]

RGE's

(for LR at very high energy)

Running the model all together: while unifying gauge couplings, the potential has to remain perturbative and stable.

$\Longrightarrow$ **quartics rather small $\approx$ order percent**

$$\lambda_{Higgs} = \lambda_\Phi - \frac{\alpha^2}{4\rho_1}$$

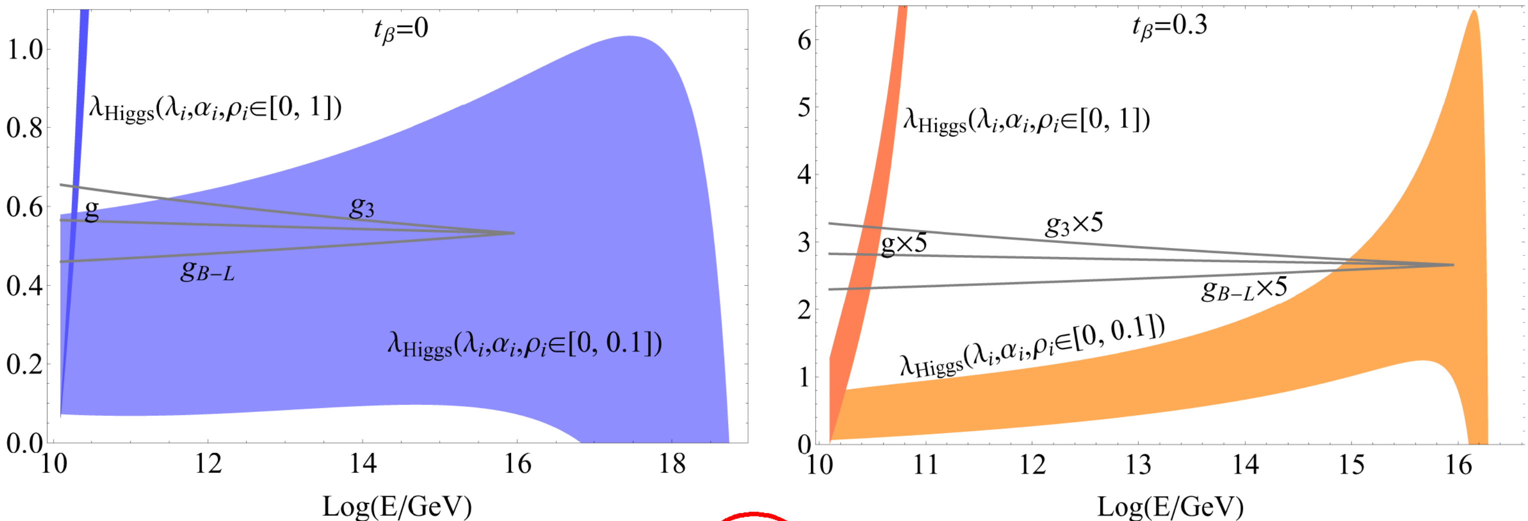


FIG. 3. Left. Running of $\lambda_{Higgs} \equiv 4\lambda_h$ defined in (19) for $t_\beta = 0$. Right. The same for $t_\beta = 0.3$ which shows a lower cut-off and λ_{Higgs} can become slightly large at GUT scale. The cut-offs are defined as in the previous figures.

[A.M.,Senjanovic,Vasquez]

All fine with the usual **GUT picture**: just the scalars tend to live slightly below **vR**

Higher order effects?

Notice that the largest coefficients come from the pure scalar sector⟶
compute the **two-loop β-function within the quartics only**

(here same (4π)^2 for direct matching of the coefficient size - λ_1 sample)

$$(4\pi)^2\beta^{\lambda_1}_{(1-loop)} = 6\alpha_1^2 + 6\alpha_3\alpha_1 + 2.5\alpha_3^2 + 32\lambda_1^2 + 64\lambda_2^2 + 16\lambda_3^2 + 48\lambda_4^2 + 16\lambda_1\lambda_3\,;$$

$$\begin{aligned}(4\pi)^2\beta^{\lambda_1}_{(2-loop)} = \frac{1}{384\pi^2}\big\{&-36\alpha_1^2\left(\alpha_3 - 30\lambda_1\right) - 2\alpha_1\left[\alpha_3\left(19\alpha_3 - 540\lambda_1\right) + 48\alpha_2\left(\alpha_2 + 3\lambda_4\right)\right] + 826\alpha_3^2\lambda_1\\ &- 48\alpha_2^2\left(\alpha_3 - 94\lambda_1 + 8\lambda_2 + 4\lambda_3\right) - 144\alpha_2\alpha_3\lambda_4 - 24\alpha_1^3 - 13\alpha_3^3 + 2304\lambda_1\rho_1^2 + 3456\lambda_1\rho_2^2\\ &+ 432\lambda_1\rho_3^2 + 2304\lambda_1\lambda_4^2 + 3456\lambda_1\rho_4^2 + 2304\lambda_1\rho_1\rho_2 + 1424\lambda_1^3 - 384\lambda_3^3 + 14592\lambda_1\lambda_2^2\\ &+ 2304\lambda_1\lambda_3^2 - 3328\lambda_2\lambda_4^2 - 1792\lambda_3\lambda_4^2 + 1152\lambda_1^2\lambda_3 - 5632\lambda_2^2\lambda_3\big\}\,.\end{aligned}$$

-Our results for next collider and very high energy **remain quite stable** (with that choice of small initial quartics);
-the delicate case is the one of **low LR-scale at (the edge of) LHC** – here some larger quartics appear. However, the running range is already short and surprisingly the corrections do not modify drastically the plot.

[A.M.,Senjanovic,Vasquez]

Vertex modification

Going back to the SM deviation of the Self-interactions of the Higgs.

$$\Delta\lambda_{hhh} \equiv \frac{\lambda_{hhh}^{SM} - \lambda_{hhh}}{\lambda_{hhh}^{SM}} \simeq 3/2\theta^2$$

It is expected to be Measured with $\pm^{30\%}_{20\%}$ **accuracy at LHC,**
[Goertz, Papaefstathiou, Yang , Zurita,2013]

and 14% at **100TeV collider**
[He, Yao , 2016]

[A.M.,Senjanovic,Vasquez]

Tri-linear couplings	Expression
λ_{hhh}	$\frac{m_h^2}{2\sqrt{2}}\frac{c_\theta^3}{v}$
$\lambda_{\delta_R\delta_R\delta_R}$	$\frac{m_{\delta_R}^2}{2\sqrt{2}}\left(\frac{s_\theta^3}{v}+\frac{c_\theta^3}{v_R}\right)$
$\lambda_{hh\delta_R}$	$\frac{s_{2\theta}c_\theta(m_{\delta_R}^2+2m_h^2)}{4\sqrt{2}v}$
$\lambda_{h\delta_R\delta_R}$	$\frac{s_{2\theta}(2m_{\delta_R}^2+m_h^2)}{4\sqrt{2}}\left(\frac{s_\theta}{v}-\frac{c_\theta}{v_R}\right)$

$$\lambda_{hhh}^{approx} = \lambda_{hhh} + \frac{1}{\pi^2}\left[\frac{v^3}{v_R^2}\left(\frac{\sqrt{2}\lambda_\Phi^3}{3\alpha_3}+\frac{\alpha_3^3}{96\sqrt{2}\rho_2}+\frac{3\alpha_3^3}{64\sqrt{2}\rho_3}\right)+\frac{9\lambda_\Phi^2 v}{8\sqrt{2}}\right]$$

$$\lambda_{hh\delta_R}^{approx} = \lambda_{hh\delta_R} + \frac{v^2\left(9\alpha_3^2+32{\lambda_\Phi}^2\right)}{32\sqrt{2}\pi^2 v_R},$$

$$\lambda_{h\delta_R\delta_R}^{approx} = \lambda_{h\delta_R\delta_R} + \frac{\alpha_3 v\left(8\left(\lambda_\Phi+\rho_2\right)+3\rho_3\right)}{16\sqrt{2}\pi^2},$$

$$\lambda_{\delta_R\delta_R\delta_R}^{approx} = \lambda_{\delta_R\delta_R\delta_R} + \frac{\left(2\alpha_3^2+16\rho_2^2+3\rho_3^2\right)v_R}{24\sqrt{2}\pi^2}.$$

Vertex modification

Plotting the full expressions

$$\left|(\lambda^{\text{total}}_{i,j,k}) - \lambda^{\text{approx}}_{i,j,k})/\lambda^{\text{approx}}_{i,j,k}\right|$$

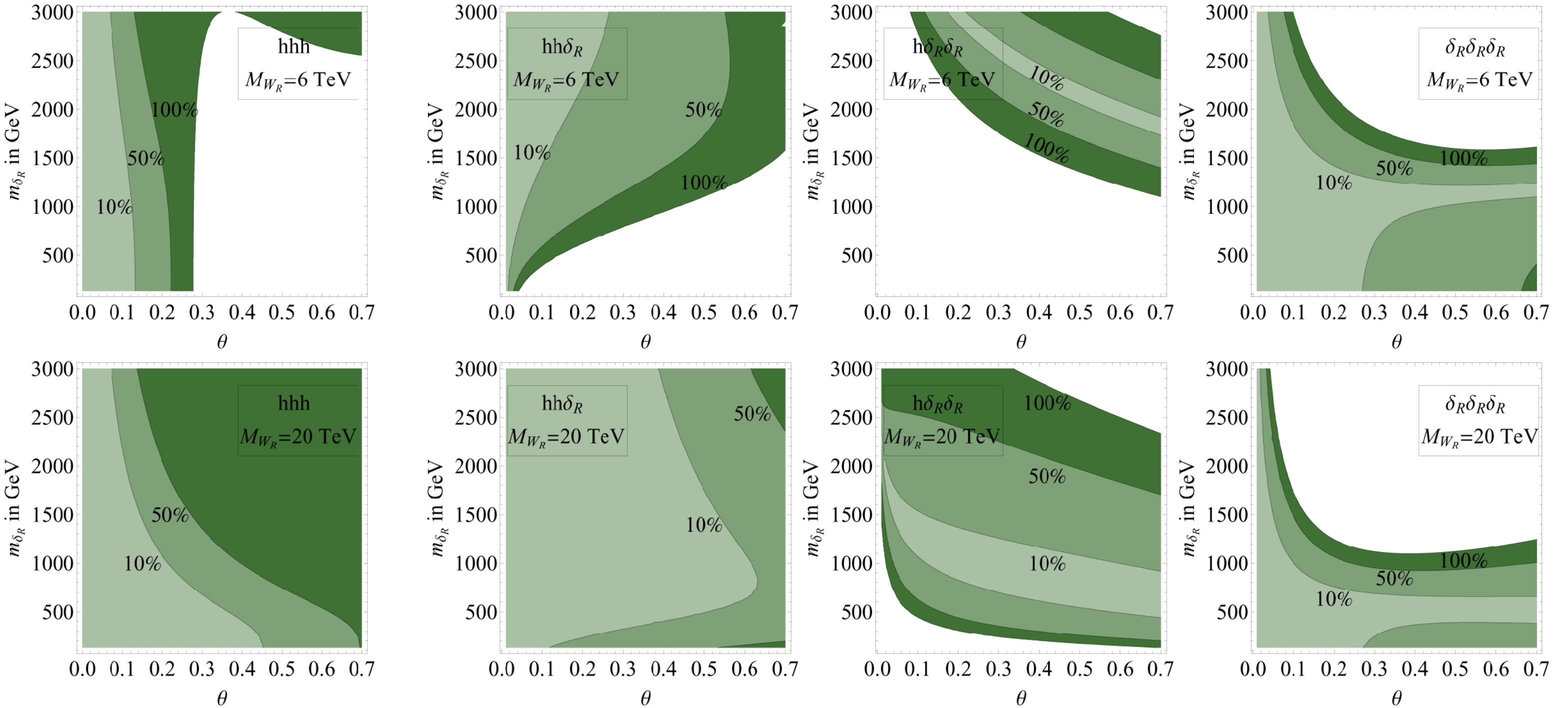


FIG. 4. Plots for the quantities shown in (26) (in %) for $M_{W_R} = 6$ TeV (Top) and $M_{W_R} = 20$ TeV (Bottom). For the sake of clearness the plots run up to $\theta \simeq 0.7$, although some regions are ruled out phenomenologically [40].

Outlook

- An in-depth analysis of the **Higgs sector of the Left-Right model**, in all the relevant parameter space.

- Discussion of the **quantum corrections** within the **constraints** on the model at low energy, and at high scale in the light of a natural **UV completion** of the model.

- The LR-scale is not strictly ruled out from LHC, but the **model lives at the edge** there $\Longrightarrow$ conversely without tensions at (expected) reach of **next collider**.

- Discussion on the implications of **Higgs physics** and Higgs **self-interaction**.

- Implications on probing the **origin of neutrino mass**.

Thanks

Back up slides

nEDM: strong source θ

For this issue the choice of **discrete symmetry** is more fundamental and the difference goes beyond the parameterization of the right-handed CKM matrix.

A restored "**P**" at high scale can be an alternative to PQ symmetry to solve the strong CP problem: it rules out automatically the strong CP-odd term $G\widetilde{G}$

[Mohapatra,Senjanovic, '79]

$$\bar{\theta} = \arg\det\, M_u M_d$$

It becomes computable and depends by the same parameters of the weak contributions (i.e. α and VEVs ratio.)

[AM, Nemevsek 2014]

This contribution in chiral loop is dominant over the weak induced one.
Imposing the stringent constraint from nEDM, while fitting together the quark mass spectrum:

$$(\tan(\beta)\ \alpha) \sim 0$$

Theoretical constrains: nEDM & ϵ with strong CP problem

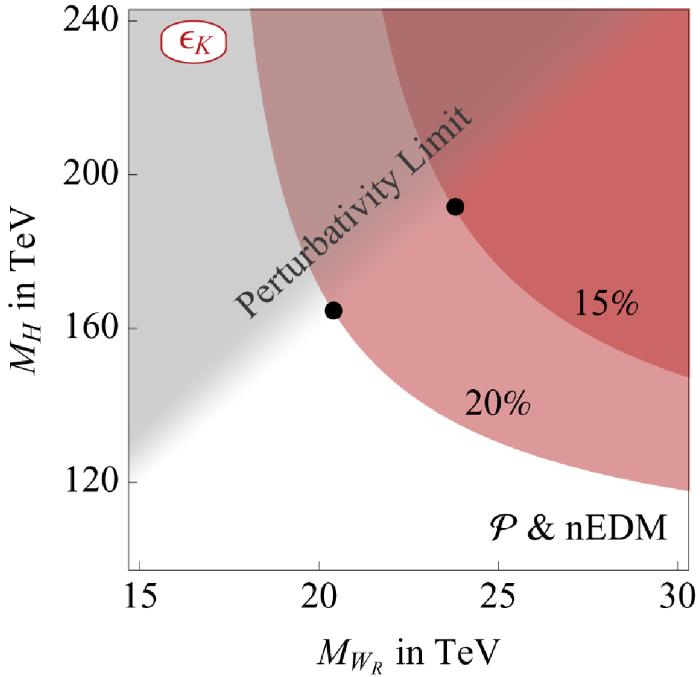


FIG. 2. The bound on the LR scale in the minimal LRSM-$\mathcal{P}$ from ε_K in the limit of vanishing spontaneous CPV. The shaded area delineates the perturbative limit, since M_H and M_{W_R} cannot be decoupled.

This depends by the UV completion of the theory, thus it is not a pure phenomenological bound.

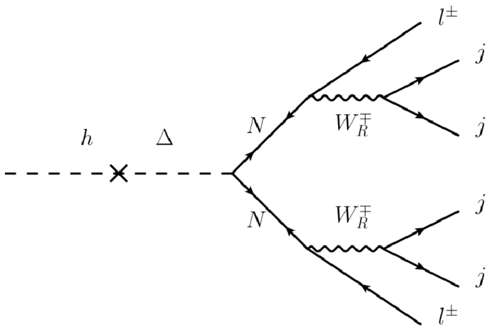
[A.M.,Nemevsek 2014]

Explicit seesaw II relation

$$v_L = \frac{k^2\left(\beta_2 \cos(\theta_L) + \beta_3 x^2 \cos(2\alpha - \theta_L)\right.}{v_R(2\rho_1 - \rho_3)} + \frac{\left.\beta_1 x \cos(\alpha - \theta_L)\right)}{v_R(2\rho_1 - \rho_3)}$$

LNV Higgs decay at LHC

Same sign muons: **h⟶$\mu\mu$ + jets**



- **Signal vs SM background**: same sign muons vs *WZ+ZZ+WW2j+ttbar (simulated), QCD (estimated as x2.5)*
- **Collider simulation**: Madgraph5 (event generator) + Pythia6(hadronization) + Delphes3(detector)

[A.M.,Nemevsek,Nesti 2015]

Process	No cuts	Imposed cuts				
		$\mu^\pm\mu^\pm + n_j$	$\not{E}_T$	p_T	m_T	$m_{\rm inv}$
WZ	2 M	544	143	78	40	20
ZZ	1 M	55	29	16	12	8
$W^\pm W^\pm 2j$	389	115	16	5	3	1
$t\bar{t}$	10 M	509	97	40	22	14
Signal (40)	543	44	43	41	38	37

TABLE I. Number of expected events at the 13 TeV LHC run with $\mathcal{L} = 100\,\text{fb}^{-1}$ after cuts described in the text. The signal is generated with 40 GeV, $\sin\theta = 10\,\%$, $M_{W_R} = 3\,\text{TeV}$ and $n_j = 1, 2, 3$.

Model-file available to:
https://sites.google.com/site/leftrighthep/

Modified from the version in:
[Roitgrund,Eilam,Bar-Shalom 2014]

LNV Higgs decay at LHC

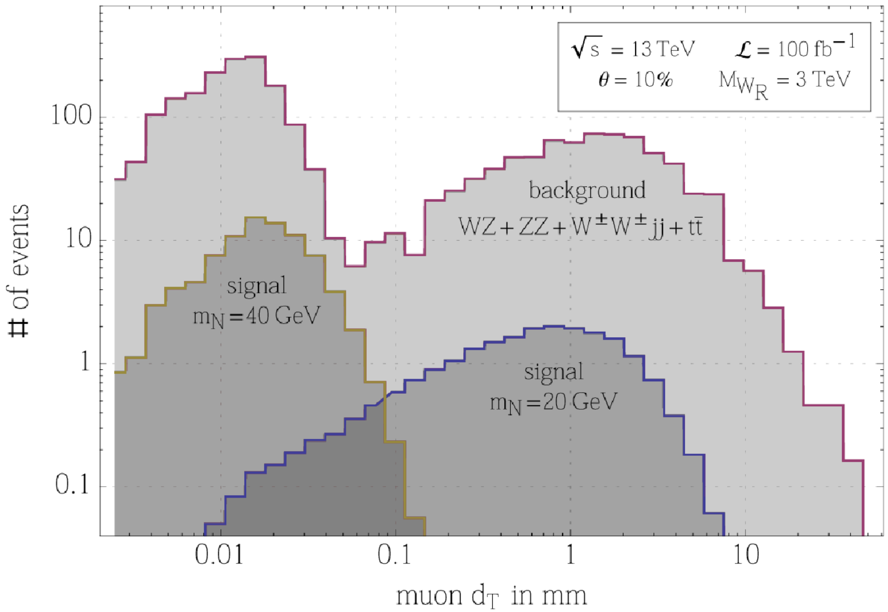
Taking advantage of displaced vertex.

- Muons are both displaced: *N lifetime depending on* m_N *and* M_{W_R}

$$(c\,\tau_N^0)^{-1} \simeq \frac{G_F^2 m_N^5}{16\pi^3}\left(\frac{M_W}{M_{W_R}}\right)^4$$

- We require two displacements and employ a sliding window cut:

$$L/10 < d_T < 5\text{x}L$$



[A.M.,Nemevsek,Nesti 2015]