Higgs boson(s) in the constrained mLRSM

Alessio Maiezza

IFIC, Universitat de València-CSIC, Apt. Correus 22085, E-46071 València, Spain

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Outline

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

- The key: A new proper gauge symmetry spontaneously broken. (new Higgs boson)
  LR extension of the SM.

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

- Predictivity and constraints on the model.

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 is $\propto m_f^{\ 2}$

No coupling with neutrino, no decay rate

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

Neutrino mass in the Standard Model

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

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

This term violates lepton number

$$M_{\nu_L} \nu_L^t C \nu_L$$

"M" is any NP scale

[Weinberg '79]

Standard Higgs

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

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

From SM to a theory of the neutrino mass

Taking care of the main esthetic defect of SM, a complete asymmetry between L & R, a natural theory for neutrino mass emerges:

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

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

via a new Higgs boson

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

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

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

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

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

A RH neutrino, gauge interacting

LR 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

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

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

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

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

LR Higgs Sector

A **bi-doublet**

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

Vevs

$$\begin{pmatrix} k & 0 \\ 0 & k' e^{i\alpha} \end{pmatrix}$$

Two triplets

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

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

[Senjanovic '79]

Vevs

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

Hierarchy

$$v_L << k << v_R \qquad v_L \propto k^2 / v_R$$

$$\tan\beta = k'/k \equiv x < 1$$

The **potential** contains all the possible quadratic and quartic terms in Φ and Δ

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}
$$

LR Higgs Sector

Mixing the two Higgs bosons

A superposition of these field gives the physical (dynamical) ones. The spectrum contains:

Higgs Bosons

FC (pseudo)-scalar

	mass^2	states
h	$\frac{k^2(4\lambda_1\rho_1-\alpha_1^2)}{\rho_1}$	$\frac{1}{\sqrt{2}}(Re\phi_1 + xRe\phi_2 - \frac{k\alpha_1}{2\rho_1 v_R} Re\delta_R)$
H	$v_R^2\left(\frac{4(4\alpha_2^2+(2\lambda_2+\lambda_3)(\alpha_3-4\rho_1))k^2}{v_R^2(\alpha_3-4\rho_1)}+\alpha_3\right)$	$\frac{1}{\sqrt{2}}(Re\phi_2 - xRe\phi_1 + \frac{4k\alpha_2}{v_R(\alpha_3-4\rho_1)} Re\delta_R)$
H’	$9(\lambda_3-2\lambda_2)k^2 + v_R^2\alpha_3$	$\frac{1}{\sqrt{2}}(Im\phi_2 + xIm\phi_1)$
Δ_R	$\frac{(\alpha_1^2(\alpha_3-4\rho_1)-16\alpha_2^2\rho_1)k^2}{(\alpha_3-4\rho_1)\rho_1} + 4v_R^2\rho_1$	$\frac{1}{\sqrt{2}}(Re\delta_R + \frac{k\alpha_1}{2\rho_1 v_R} Re\phi_1 - \frac{4k\alpha_2}{v_R(\alpha_3-4\rho_1)} Re\phi_2)$
Δ_L	$v_R^2(\rho_3-2\rho_1)$	$\frac{1}{\sqrt{2}} Re\delta_L$
Δ_L'	$v_R^2(\rho_3-2\rho_1)$	$\frac{1}{\sqrt{2}} Im\delta_L$
H^-	$\frac{1}{2}\left(k^2+2v_R^2\right)\alpha_3$	$\frac{1}{\sqrt{2}}(\phi_2^- + x\phi_1^- + \frac{k}{\sqrt{2}v_R}\delta_R^-)$
Δ_R^{--}	$\alpha_3 k^2 + 4v_R^2\rho_2$	$\frac{1}{\sqrt{2}}\delta_R^{--}$
Δ_L^-	$\frac{\alpha_3 k^2}{2} + v_R^2(\rho_3-2\rho_1)$	$\frac{1}{\sqrt{2}}\delta_L^-$
Δ_L^{--}	$\alpha_3 k^2 + v_R^2(\rho_3-2\rho_1)$	$\frac{1}{\sqrt{2}}\delta_L^{--}$

[Senjanovic ’79]
[Gunion,Kayser, Olness’ 89]
[Duka, Gluza, Zralek 2000]
[Kiers,Assis,Petrov 2005]
[Zhang,An,Ji,Mohapatra 2007]
[A.M.,Nemevsek,Nesti in prep.]

Mixing the two Higgs bosons

$$\theta \equiv \frac{\alpha_1 k}{2\rho_1 v_R} < 40\%$$ 2-sigma C.L.

[Falkowski,Gross,Lebedev 2015]

Probing neutrino masses

The new Higgs boson $m_{\Delta_R}{}^2 \approx 4\rho_1 v_R{}^2$

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

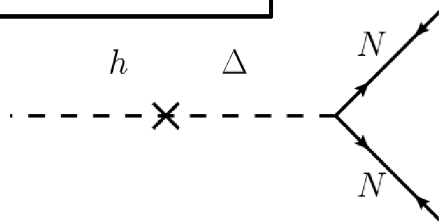
$m_N = 2 y_\Delta v_R$ $M_{W_R} = g v_R$ $m_\nu = -m_D{}^T m_N^{-1} m_D$

See-saw

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

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

Via the mixing



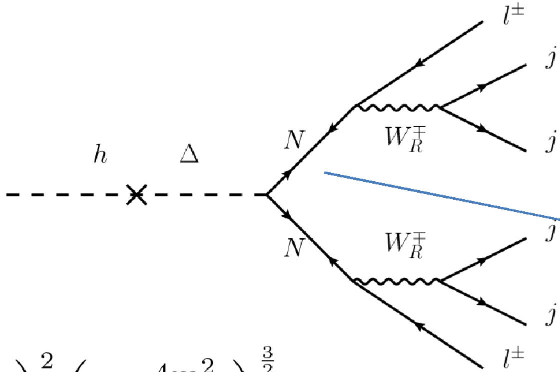
$$\frac{\Gamma_{NN}}{\Gamma_{b\bar{b}}} \simeq \frac{\tan\theta^2}{3} \left(\frac{m_N}{m_b}\right)^2 \left(\frac{M_W}{M_{W_R}}\right)^2 \left(1 - \frac{4m_N^2}{m_h^2}\right)^{\frac{3}{2}}$$

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

[A.M.,Nemevsek,Nesti PRL 2015] [Nemevsek,Nesti,Senjanovic,Zhang 2011]

Probing neutrino masses

The **SM-like** Higgs boson



Same sign dilepton h decay

Majorana nature of RH neutrino

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

[A.M.,Nemevsek, Nesti 2015]

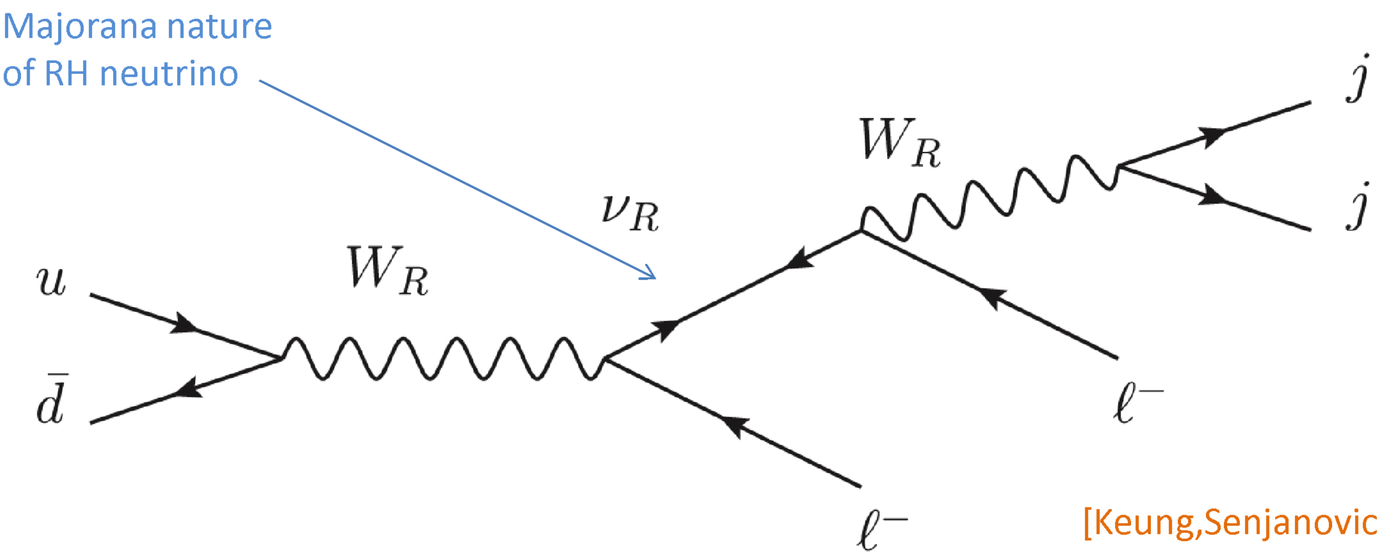
$$(c\,\tau_N^0)^{-1} \simeq \frac{G_F^2 m_N^5}{16\pi^3} \left(\frac{M_W}{M_{W_R}}\right)^4 \longrightarrow M_{W_R}$$

(displacement of N decay products)

Invariant mass $\longrightarrow$ m_N

Global fit on Higgs data $\longrightarrow$ θ

Probing neutrino masses



[Keung,Senjanovic 83]

To complete the understanding of neutrino mass origin, one would clearly like to observe Δ_R and the associated gauge boson that provides the gauge symmetry protection.

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

[Nemevsek,Senjanovic, Tello PRL 2012]

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Theoretical limits on the model

Theoretical Constraints

- meson oscillations: K (ΔM_k , ϵ_k) and B_d, B_s.

- direct CP-violating parameter epsilon-prime

- Neutron Electric Dipole Moment (nEDM)

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

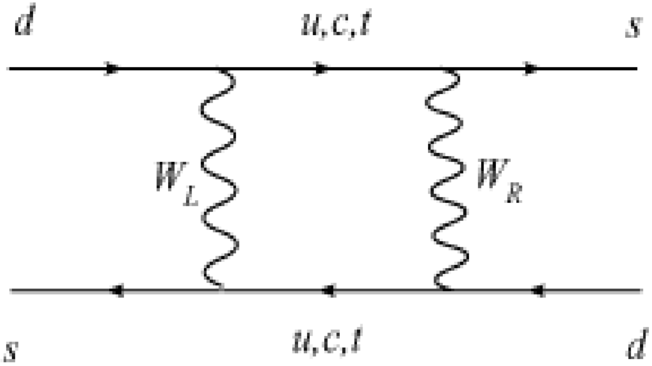
Analytic solution for V_R

[Senjanovic, Tello PRL 2014]

Previous numerical analysis

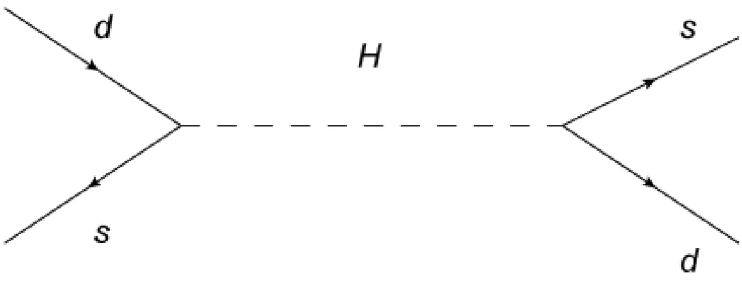
[A.M.,Nemevsek,Nesti,Senjanovic 2010]

Theoretical constrains: meson oscillations



New box diagram from charged gauge interactions. V_L and V_R entering.

[Beall, Bander ,Soni '82, Ecker,Grimus '85]



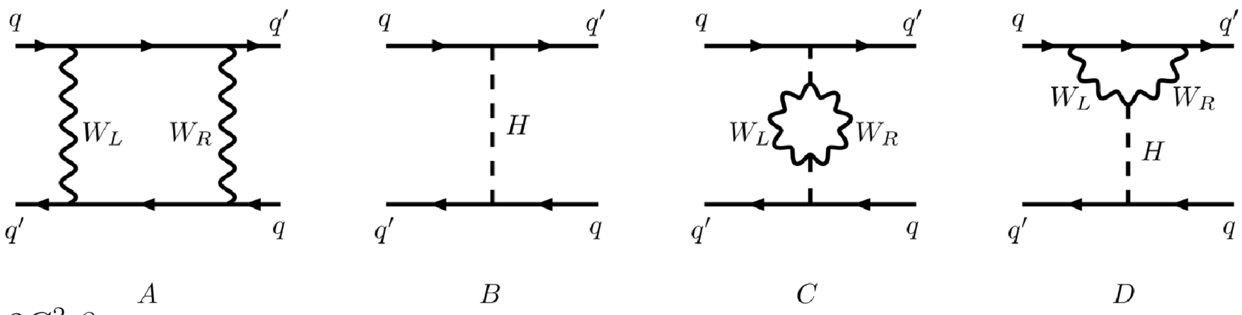
$$L \propto \bar{d}_L V_L^+ m_u V_R d_R H$$

Neutral Heavy Higgs flavor Changing at tree level.
Same V_L and V_R structure.

[G. Senjanovic, P. Senjanovic '80]

Theoretical constrains: meson oscillations

More diagrams are necessary for a **gauge independent result**: the self-energy and vertex renormalization of tree-level FC [Basecq,Li,Pal '85]



[AM, Bertolini,Nesti ,2014]

$$\mathcal{H}_A = \frac{2G_F^2\beta}{\pi^2}\sum_{i,j} m_i m_j \lambda_i^{LR}\lambda_j^{RL}\eta_{ij}^A\ F_A(x_i,x_j,\beta)\ O_S$$

$$\mathcal{H}_B = -\frac{2\sqrt{2}G_F}{M_H^2}\sum_{i,j} m_i m_j \lambda_i^{LR}\lambda_j^{RL}\eta_{ij}^B\ O_S$$

$$\mathcal{H}_C = -\frac{G_F^2\beta}{2\pi^2 M_H^2}\sum_{i,j} m_i m_j \lambda_i^{LR}\lambda_j^{RL}\eta_{ij}^C\ F_C(M_{W_L},M_{W_R},M_H)\ O_S$$

$\leftarrow$ $\left\{ \begin{array}{l} \bar{s}Ld\,\bar{s}Rd \\ \bar{b}Ld\,\bar{b}Rd \\ \bar{b}Ls\,\bar{b}Rs \end{array} \right.$

$$\mathcal{H}_D = -\frac{4G_F^2\beta}{\pi^2 M_H^2}\sum_{i,j} m_i m_j \lambda_i^{LR}\lambda_j^{RL}\eta_{ij}^D\ F_D(m_i,m_j,M_{W_L},M_{W_R},M_H)\ O_S$$

All diagrams have the same CKM structure.
V_R plays an important role in determining the LR contribution to flavor violations.

Theoretical constrains: meson oscillations

Meson oscillations: kaon mixing

[A.M.,Nemevsek,Nesti,Senjanovic 2010]
[Bertolini, A.M.,Nesti ,2014]

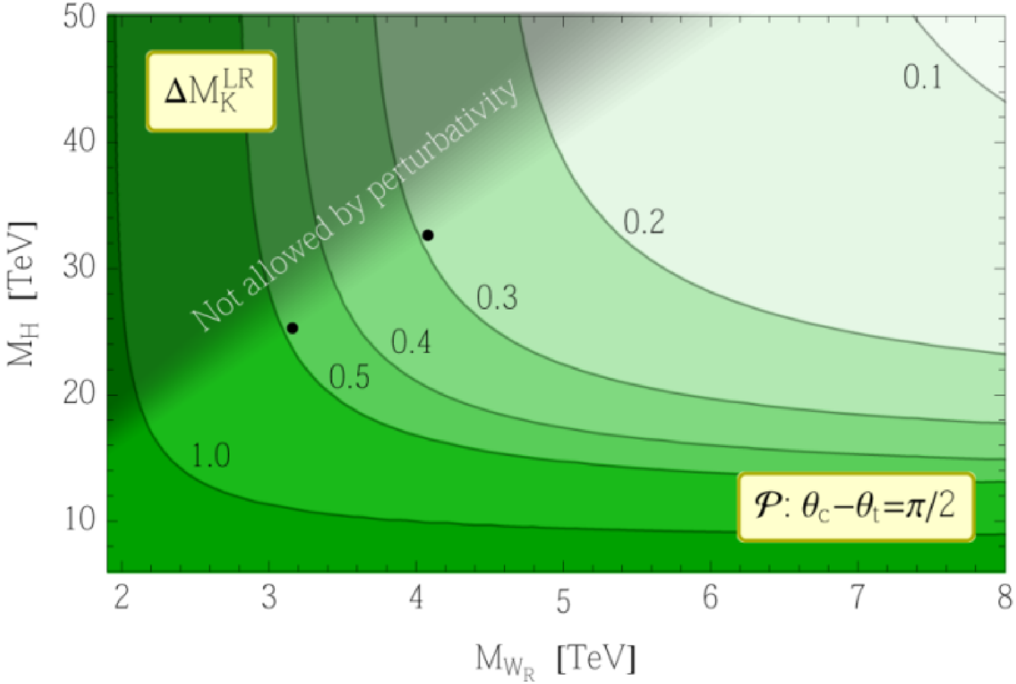


FIG. 9. Correlated bounds on M_R and M_{W_R} (region above the curves) for $\left|\Delta M_K^{LR}\right| / \Delta M_K^{exp} < 1.0, ..., 0.1$ and for $\theta_c - \theta_t = \pi/2$ in the case of $\mathcal{P}$ parity.

Theoretical constrains: meson oscillations

Meson oscillations: $B_{d,s}$ mixing

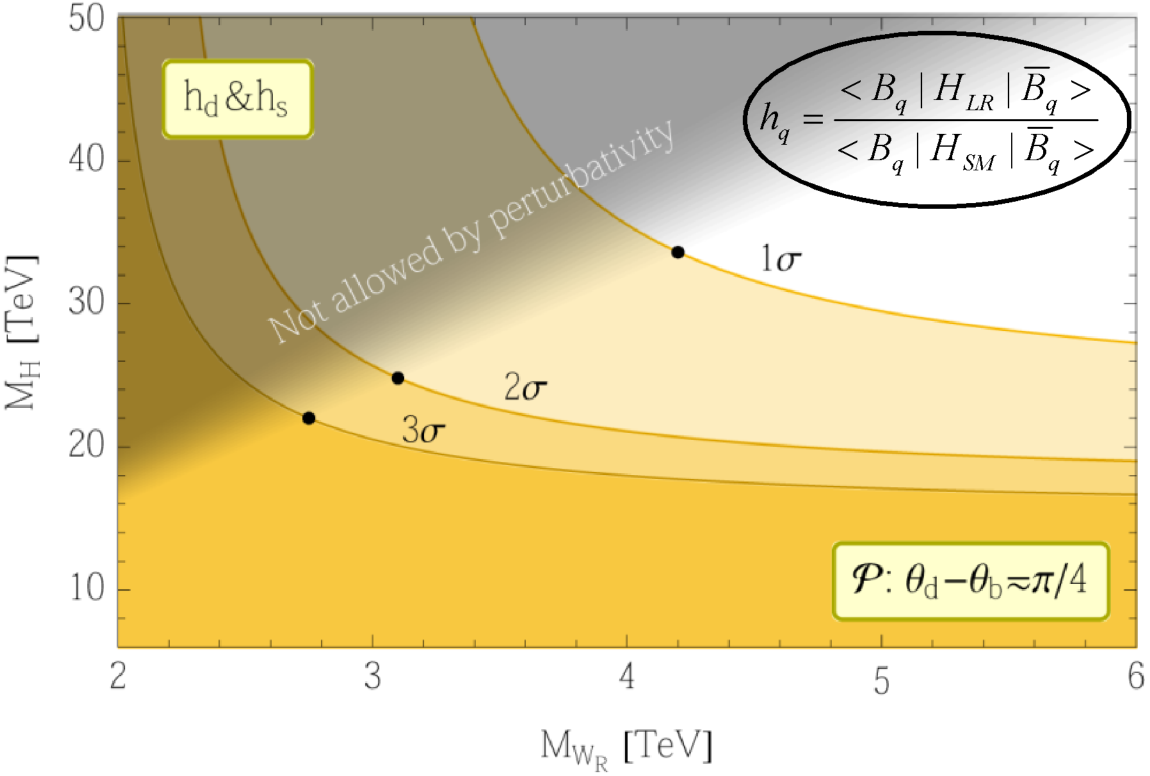


FIG. 10. Combined constraints on M_R and M_{W_R} from ε, ε' B_d and B_s mixings obtained in the $\mathcal{P}$ parity case from the numerical fit of the Yukawa sector of the model.

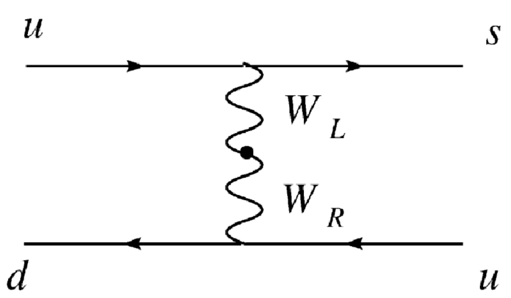
[Bertolini, A.M.,Nesti ,2014]

Theoretical constrains: ϵ' and relevant operators

Current-Current

$$Q_1^{RL} = (\bar{s}_\alpha u_\beta)_R(\bar{u}_\beta d_\alpha)_L \qquad Q_1^{LR} = (\bar{s}_\alpha u_\beta)_L(\bar{u}_\beta d_\alpha)_R$$

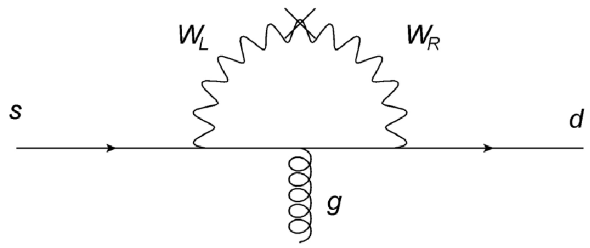
$$Q_2^{RL} = (\bar{s}u)_R(\bar{u}d)_L \qquad Q_2^{LR} = (\bar{s}u)_L(\bar{u}d)_R$$



[AM, Nesti,Bertolini,Eeg, 2013]

Dipole operators

$$Q_g^L = \frac{g_s m_s}{8\pi^2}\bar{s}\sigma_{\mu\nu}t^a G_a^{\mu\nu} Ld \qquad Q_g^R = \frac{g_s m_s}{8\pi^2}\bar{s}\sigma_{\mu\nu}t^a G_a^{\mu\nu} Rd$$



Enhanced by internal quark mass.
However It is not sufficient to compensate the gap with the current-current ones.

Theoretical constrains: ϵ' in the chiral quark model approach

Following the approach adopted in in the past for SM

[Antonelli, Bertolini, Eeg, Fabbrichesi, Lashin, '96-2001]

-By means of a **quark-meson interaction**

[Manohar, Georgi, '84, Gasser,Leutwyler,'84, Weinberg,2010]

$$L = -m(\bar{q}_R \Sigma q_L + \bar{q}_L \Sigma^\dagger q_R)$$

any kaon to pion amplitude is evaluated through quark loops.

-By matching the loop result with the transition resulting from chiral Lagrangian expansion, one determines the unknown parameters

-Finally, with the completely determined chiral Lagrangian, one can compute the chiral loop corrections to the transitions.

Theoretical constrains: M.E. for ϵ'

We give the results in the standard form, i.e. parameterizing the amplitude as

$$B_i^{(0,2)} \equiv \frac{\mathrm{Re}\langle Q_i \rangle_{0,2}^{\mathrm{model}}}{\langle Q_i \rangle_{0,2}^{\mathrm{VSA}}} \qquad \langle Q_i \rangle_{0,2} \equiv \langle (\pi\pi)_{(I=0,2)} | Q_i | K^0 \rangle$$

where VSA is the Vacuum Saturation Approximation.

B parameters (HV scheme)

$$B_0(Q_1^{LR}) = 2.26^{+0.79}_{-0.46}$$
$$B_2(Q_1^{LR}) = 1.01^{+0.25}_{-0.29}$$
$$B_0(Q_2^{LR}) = 2.20^{+0.75}_{-0.44}$$
$$B_2(Q_2^{LR}) = 1.01^{+0.30}_{-0.32}$$

[AM, Nesti, Bertolini, 2013]

-Very small dependence on the scheme.

-The errors are evaluated varying all input parameters. We use the fitted values, see: [Bertolini, Eeg, Fabbrichesi, Lashin, '98]

Note that the RL B are equal to the LR ones.

Theoretical constrains: nEDM (weak source)

In addition to $\bar{\theta}$ there are other sources of CP violation, the four-quark operators

$$Q_1^{LR} = (\overline{u}_\alpha d_\beta)_{V-A} (\overline{d}^\beta u^\alpha)_{V+A}$$
$$Q_2^{LR} = (\overline{u} d)_{V-A} (\overline{d} u)_{V+A}$$

+ RL ones

$$\mathcal{L}_{B\chi pt}^{\not{C}\not{P}} = \overline{g}_+ \left(\overline{n}\pi^- p + \overline{p}\pi^+ n\right) + \left(\overline{g}_n \overline{n} n + \overline{g}_p \overline{p} p\right) \pi^0$$

$$\overline{g}_+ << \overline{g}_n$$

For instance in VSA.
The Wilson coefficients are included.

Usual CP-conserving strong lagrangian

[A.M.,Nemevsek 2014]

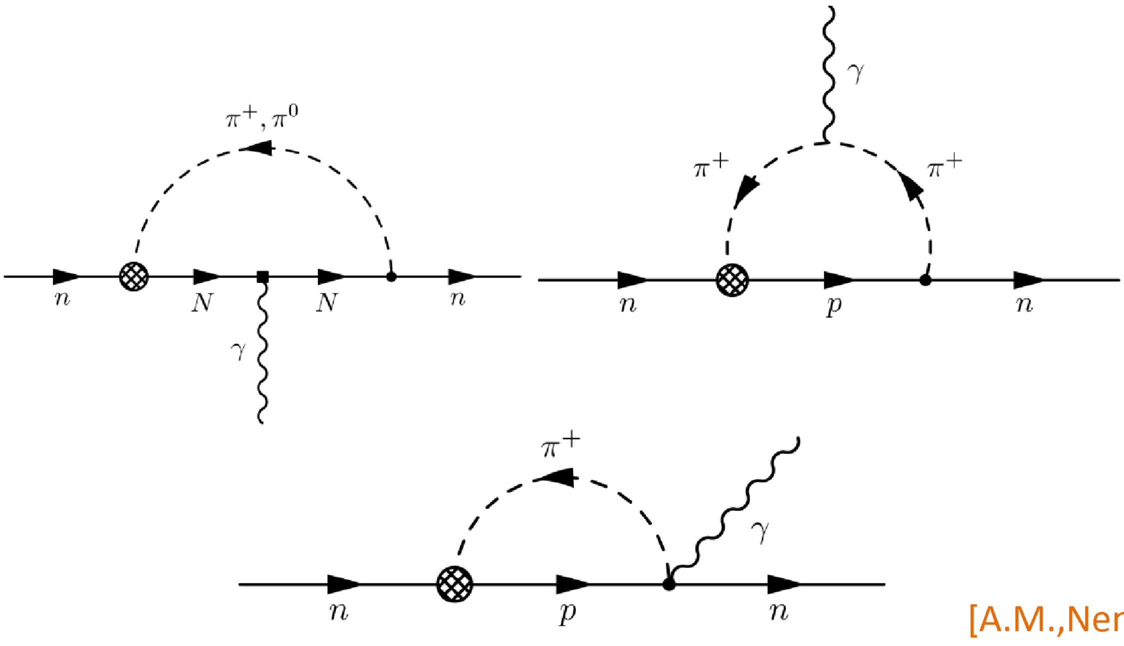
$$\mathcal{L}_{B\chi pt}^{(1)} = \overline{N} \left(i\not{D} - m_N + \frac{g_A}{2} \not{u} \gamma_5 \right) N,$$

$$\mathcal{L}_{B\chi pt}^{(2)} = -\frac{e}{4m_N} \left[\kappa_p \overline{p} \sigma^{\mu\nu} p + \kappa_n \overline{n} \sigma^{\mu\nu} n \right] F_{\mu\nu}$$

Theoretical constrains: nEDM and chiral loops

Power-counting $$D = d - N_N - 2N_\pi + 2kV_\pi^{(k)} + kV_{\pi N}^{(k)}$$

D=2(3)
for LO(NLO)



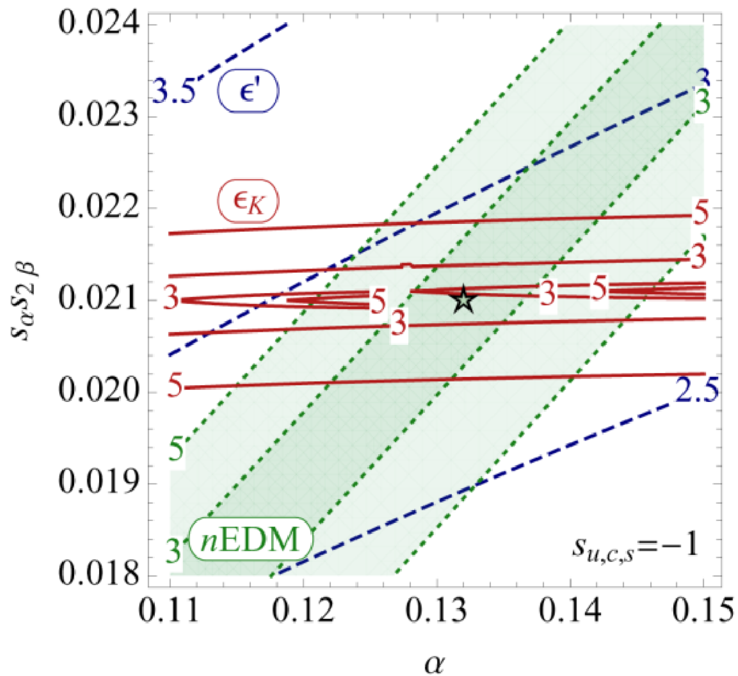
[Weinberg, '91]

[A.M.,Nemevsek 2014]

We can get automatically the right power counting in relativistic approach, via **EOMS** (extended-on-mass-shell) renormalization scheme.
Of course this confirms the well known result on theta-bar from nEDM, where there is no problem of power-counting.

[Pich, de Rafael, '91]

Theoretical constrains: nEDM together ϵ and ϵ'



[A.M.,Nemevsek 2014]

nEDM (without strong CP)

and

epsilon, epsilon-prime

[Bertolini,Eeg, A.M.,Nesti 2013

[Bertolini, A.M.,Nesti 2014]

FIG. 3. Combined CPV constraints in the LRSM-$\mathcal{P}$ extended with an "invisible" axion. The solution for V_R obtained from (16) with $s_{u,c,s} = -1$ and all others +1. Contours in dashed red, solid blue and dotted green show a bound on M_{W_R} in TeV units coming from $\varepsilon', \varepsilon_K$ and nEDM via $\bar{\theta}_{\text{ind}}$, respectively. The star denotes a point where all constraints are satisfied and $M_{W_R} \gtrsim 3$ TeV.

Theoretical constrains: Perturbativity

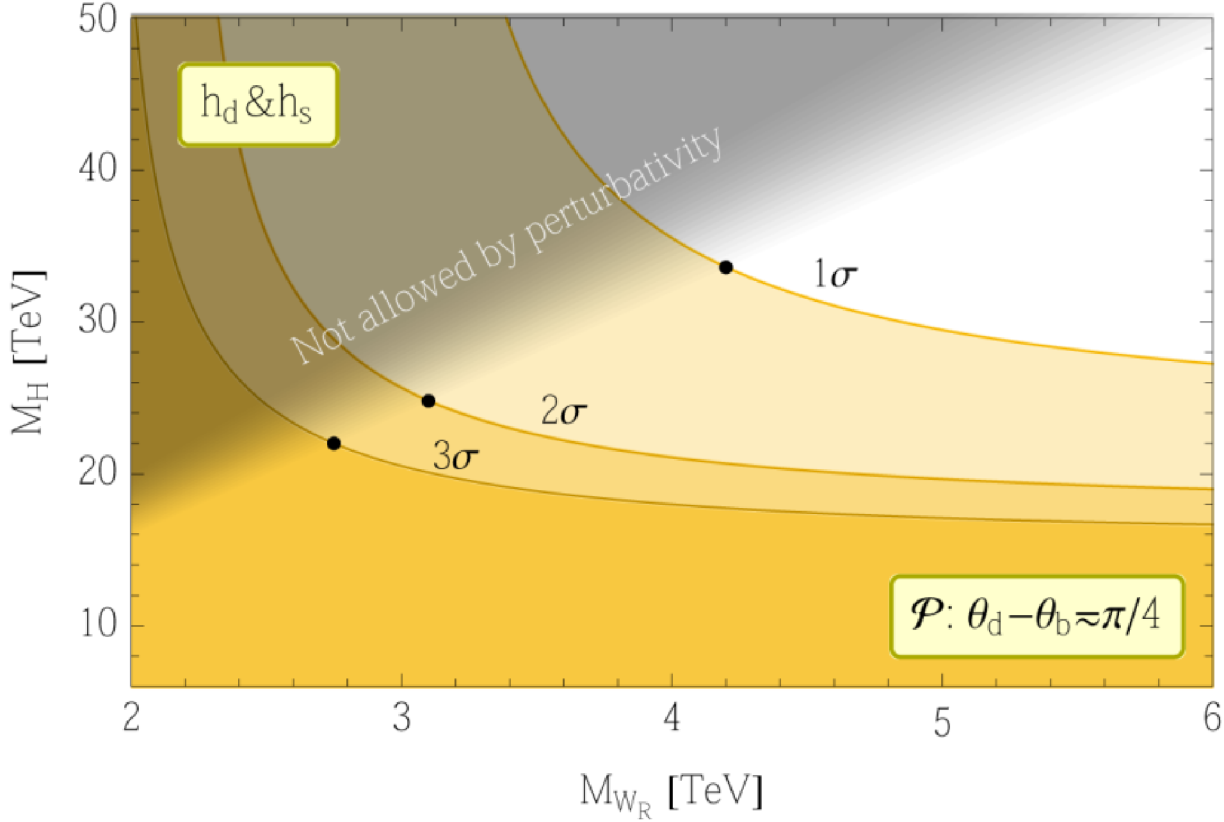


FIG. 10. Combined constraints on M_R and M_{W_R} from ε, ε' B_d and B_s mixings obtained in the $\mathcal{P}$ parity case from the numerical fit of the Yukawa sector of the model.

Theoretical constrains: Perturbativity

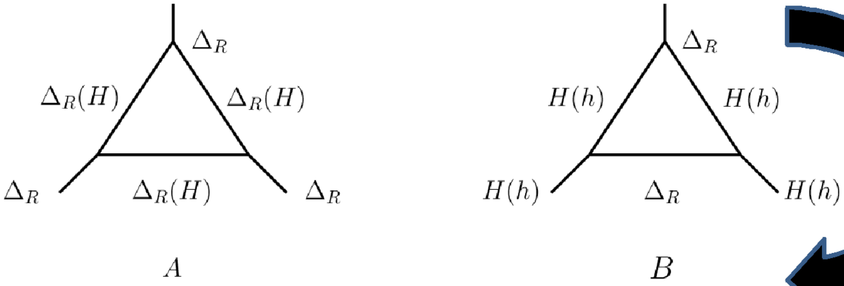
	mass^2	states
h	$\frac{k^2(4\lambda_1\rho_1-\alpha_1^2)}{\rho_1}$	$\frac{1}{\sqrt{2}}(Re\phi_1 + xRe\phi_2 - \frac{k\alpha_1}{2\rho_1 v_R}Re\delta_R)$
H	$v_R^2\left(\frac{4\left(4\alpha_2^2+(2\lambda_2+\lambda_3)(\alpha_3-4\rho_1)\right)k^2}{v_R^2(\alpha_3-4\rho_1)}+\alpha_3\right)$	$\frac{1}{\sqrt{2}}(Re\phi_2 - xRe\phi_1 + \frac{4k\alpha_2}{v_R(\alpha_3-4\rho_1)}Re\delta_R)$
H'	$9(\lambda_3-2\lambda_2)k^2 + v_R^2\alpha_3$	$\frac{1}{\sqrt{2}}(Im\phi_2 + xIm\phi_1)$
Δ_R	$\frac{\left(\alpha_1^2(\alpha_3-4\rho_1)-16\alpha_2^2\rho_1\right)k^2}{(\alpha_3-4\rho_1)\rho_1} + 4v_R^2\rho_1$	$\frac{1}{\sqrt{2}}(Re\delta_R + \frac{k\alpha_1}{2\rho_1 v_R}Re\phi_1 - \frac{4k\alpha_2}{v_R(\alpha_3-4\rho_1)}Re\phi_2)$
Δ_L	$v_R^2(\rho_3-2\rho_1)$	$\frac{1}{\sqrt{2}}Re\delta_L$
Δ'_L	$v_R^2(\rho_3-2\rho_1)$	$\frac{1}{\sqrt{2}}Im\delta_L$
H^-	$\frac{1}{2}\left(k^2+2v_R^2\right)\alpha_3$	$\frac{1}{\sqrt{2}}(\phi_2^- + x\phi_1^- + \frac{k}{\sqrt{2}v_R}\delta_R^-)$
Δ_R^{--}	$\alpha_3 k^2 + 4v_R^2\rho_2$	$\frac{1}{\sqrt{2}}\delta_R^{--}$
Δ_L^-	$\frac{\alpha_3 k^2}{2} + v_R^2(\rho_3-2\rho_1)$	$\frac{1}{\sqrt{2}}\delta_L^-$
Δ_L^{--}	$\alpha_3 k^2 + v_R^2(\rho_3-2\rho_1)$	$\frac{1}{\sqrt{2}}\delta_L^{--}$

α_3 has to be large for a low scale theory

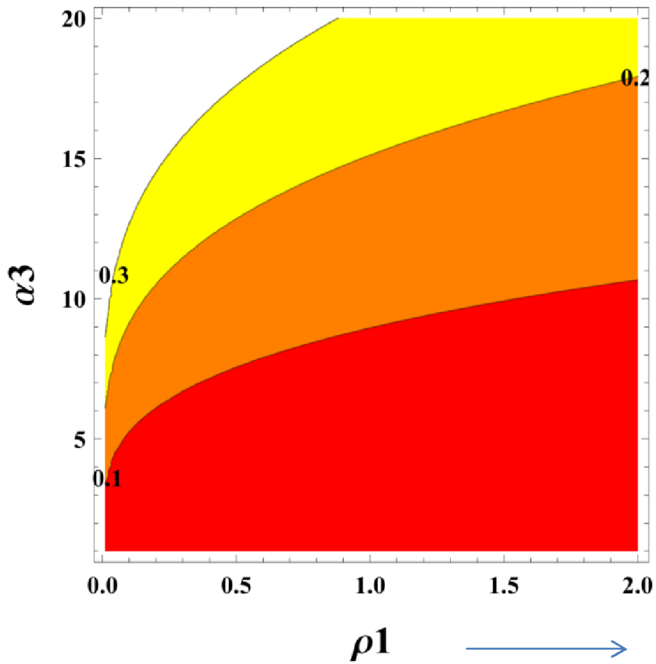
How large can α_3 be to keep the theory in a good perturbative regime in the scalar sector processes?

Theoretical constrains: perturbativity

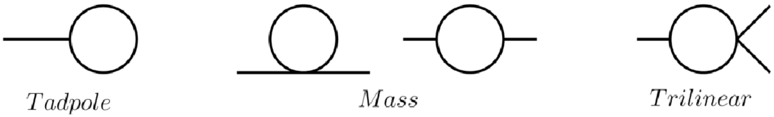
Perturbativity



Matched with tree-level equivalent



After renormalization of the divergent contributions:



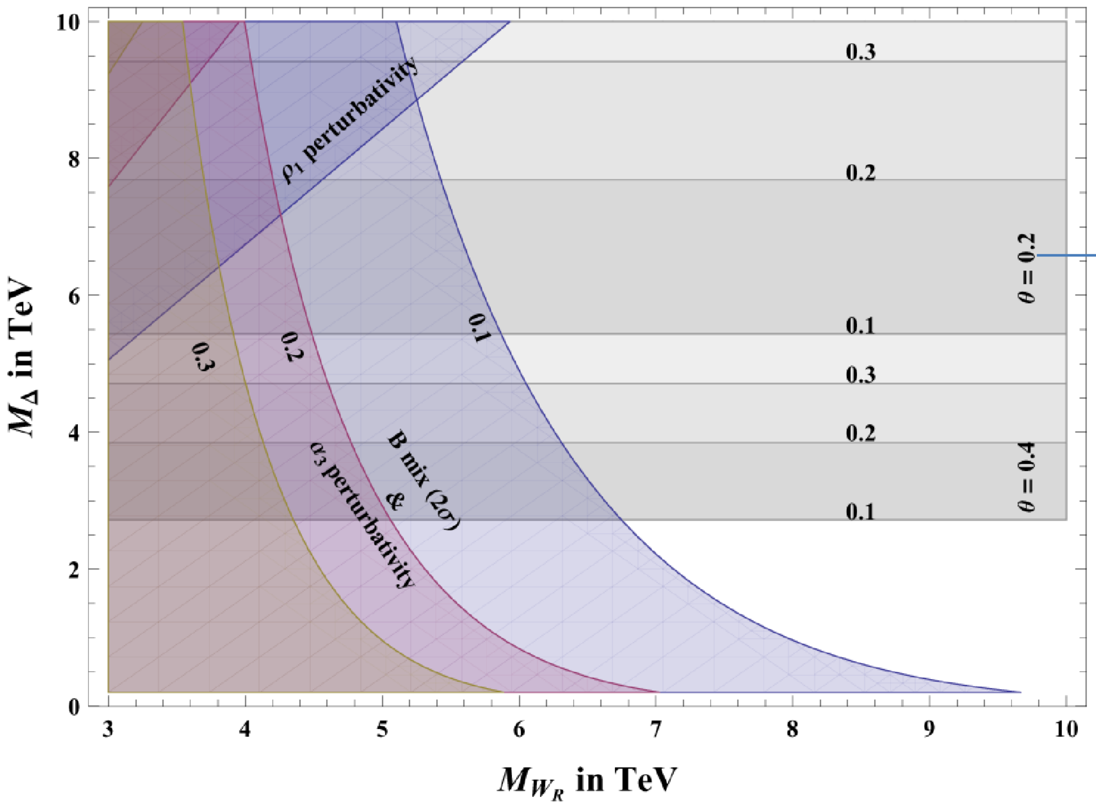
[A.M.,Nemevsek ,Nesti in preparation]

$\rho 1$ → Related to the new Higgs mass

Theoretical constrains: perturbativity

All together

[A.M.,Nemevsek ,Nesti in preparation]



Large mixing Between the two Higgs, even with a slightly heavy Delta

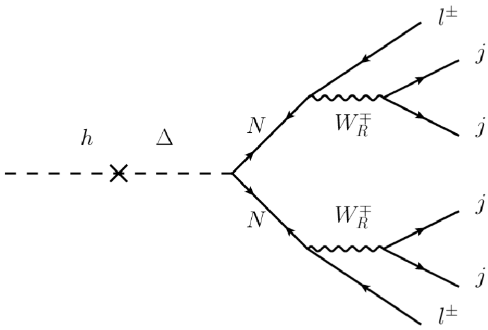
$$\theta \equiv \frac{\alpha_1 k}{2\rho_1 v_R}$$

In a pessimistic scenario the mixing could be the only way to probe neutrino masses at LHC.

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 $40\,\text{GeV}, \sin\theta = 10\,\%$, $M_{W_R} = 3\,\text{TeV}$ 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

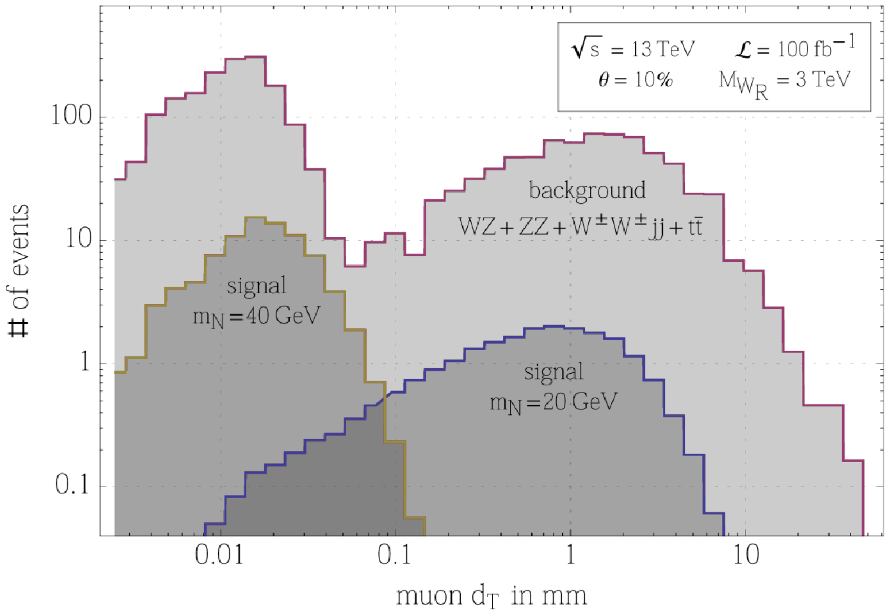
Taking advantage of displaced vertex.

- 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:

$$L/10 < d_T < 5xL$$

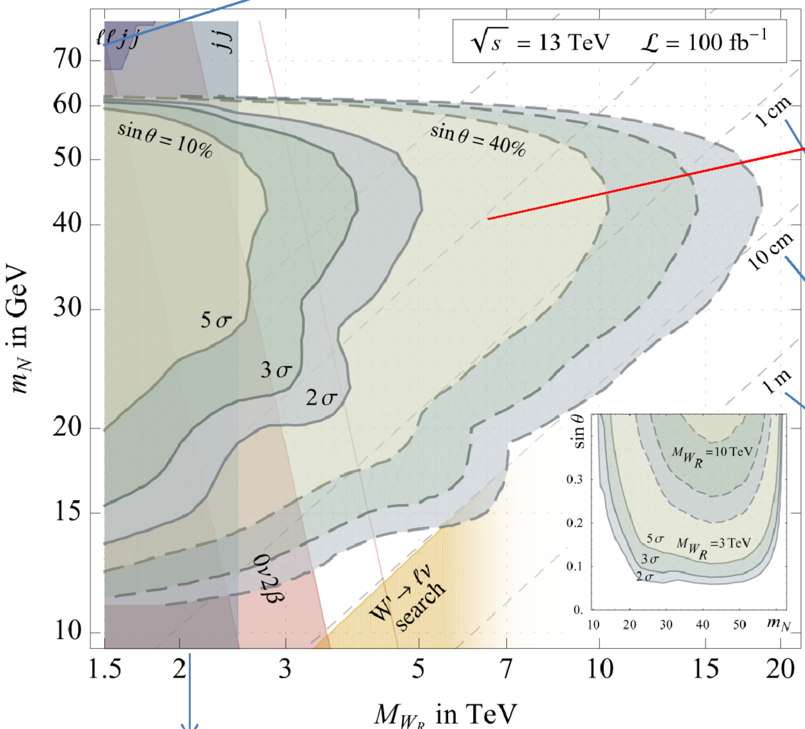


[A.M.,Nemevsek,Nesti 2015]

LNV Higgs decay at LHC

LHC sensitivity

Keung-Senjanovic process lljj



LNV Higgs decay: $h \longrightarrow \mu\mu$ + jets

N lifetime

W' dijet search

[A.M.,Nemevsek,Nesti 2015]

Outlook

- Left-Right model as a complete theory of the neutrino masses.
- Implications of a low scale left-right symmetry: low energy process and perturbativity.
- Despite several constraints on the theory(=high predictivity), the SM-like Higgs boson within the model could serve as gateway on NP via LNV.
- possibility to probe parity restoration up to 20 TeV through LNV Higgs decay.

Hvala za pažnja

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 lead 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. It can be interesting for nEDM.

- The case of "**C**" should be considered equally. It is also interesting in SO(10) GUT scenario, where charge conjugation enters automatically in the algebra. (For instance the fermions and their charge conjugated in the same important representation **16**F).

The potential with P symmetry

$$
\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}
$$

The potential with C symmetry

$$
\begin{aligned}
\mathcal{V} = & -\mu_1^2 \mathrm{Tr}[\phi^\dagger \phi] - \mu_2^2 \left(e^{i\delta_{\mu_2}} \mathrm{Tr}\left[\tilde{\phi}\phi^\dagger\right] + h.c.\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(e^{i\delta_{\lambda_2}} \left(\mathrm{Tr}\left[\tilde{\phi}\phi^\dagger\right]\right)^2 + h.c.\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(e^{i\delta_{\lambda_4}} \mathrm{Tr}\left[\tilde{\phi}\phi^\dagger\right] + h.c.\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(e^{i\delta_{\rho_4}} \mathrm{Tr}\left[\Delta_L \Delta_L\right] \mathrm{Tr}\left[\Delta_R^\dagger \Delta_R^\dagger\right] + h.c.\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(e^{i\delta_{\beta_1}} \mathrm{Tr}\left[\phi \Delta_R \phi^\dagger \Delta_L^\dagger\right] + h.c.\right) \\
& + \beta_2 \left(e^{i\delta_{\beta_2}} \mathrm{Tr}\left[\tilde{\phi} \Delta_R \phi^\dagger \Delta_L^\dagger\right] + h.c.\right) \\
& + \beta_3 \left(e^{i\delta_{\beta_3}} \mathrm{Tr}\left[\phi \Delta_R \tilde{\phi}^\dagger \Delta_L^\dagger\right] + h.c.\right)
\end{aligned}
$$

See-saw between the VEVs

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

$$+ \frac{\left.\beta_1 x\cos(\alpha - \theta_L)\right)}{v_R(2\rho_1 - \rho_3)}$$

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:

$$(\text{x } \alpha) \sim 0$$