Low scale Left-Right @ LHC through LNV

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w/ Alessio Maiezza, Miha Nemevšek, Goran Senjanović

Are we satisfied with the SM?

- SM needs extension — in addition to DM, maybe hierarchy:

  Neutrino masses → high or low scale?

  Dirac or Majorana?

  SM begging for more symmetry. . .

- Addressed within the simplest extension, the LR model.

- Can LHC help?

  Yes if parity (LR symmetry) restored at low scale,

  via Lepton Violation, with pretty low statistics

$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

Fields: fermions f_L, f_R, bidoublet $\phi \sim (h_{light}, H_{heavy})$, triplets Δ_L, Δ_R:

$$\langle\phi\rangle = \begin{pmatrix} v' & \\ & v \end{pmatrix}, \qquad \langle\Delta_R\rangle = \begin{pmatrix} & \\ v_R & \end{pmatrix}, \qquad \langle\Delta_L\rangle = \begin{pmatrix} & \\ v_L & \end{pmatrix}$$

spontaneously with $v_L \ll v' < v \ll v_R$. [Mohapatra Senjanovic '75]

- Quark masses from two yukawa matrices, $\bar\psi_L(Y\phi + \tilde{Y}\tilde{\phi})\psi_R$:

$$M_u = |v|\, Y + |v'| e^{i\alpha}\, \tilde{Y}$$
$$M_d = |v'|\, Y + |v| e^{i\alpha}\, \tilde{Y}$$

- Majorana neutrino masses, in addition to Dirac:

$$m_{LL} = Y_\Delta \langle\Delta_L\rangle \quad \ll \quad m_{RR} = Y_\Delta \langle\Delta_R\rangle$$

- Spectrum: W_R, ν_R, $\Delta_{L,R}$ may be near TeV

- H should be very heavy (tree-level FC)

[Senjanoviċ Senjanoviċ '80, ..., Zhang et al '07]

M_R scales

Can we test this model?

- High M_{W_R} up to $\sim 10^{14}$ GeV: ok with GUT.
  Still M_{ν_R} can be low – but hard to see [Kersten Smirnov '07, etc]

- Low $M_{W_R} \gtrsim$ TeV possible and testable:

  leading to striking signals

  (. . . direct probe of new interactions)
  (. . . of parity restoration)
  (. . . of majorana charachter)
  (. . . of additional flavour structure)

- Collider signals of W_R and ν_R. [Keung Senjanovic '83]

- Also, lepton number violation enters in rare processes: e.g. new contributions to $0\nu\beta\beta$

  (disentangled from neutrino masses and their (cosmological) bound)

A selection of processes. . .

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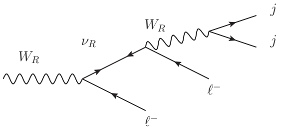
A selection of processes...

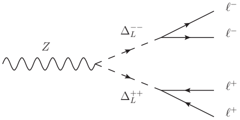
Interesting processes

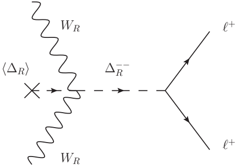
- Premium: W_R-ν_R production

  Same-sign dileptons.



- $\Delta_L^{\pm\pm}$ production (pairwise)





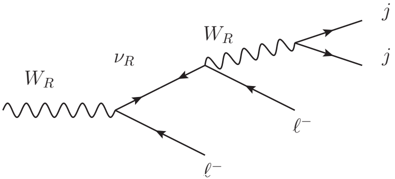
- $\Delta_R^{\pm\pm}$ production (W fusion)
- W_R-Δ_R pair production
- $0\nu 2\beta$ (LR vs RR)
- $\mu \to e\gamma$, ...

...depends of course on which particles lie at low scale.

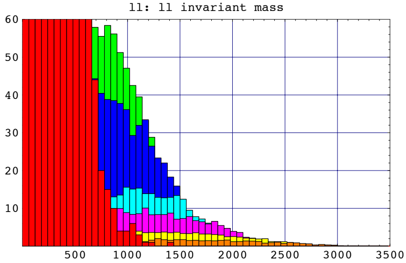
W_R-ν_R

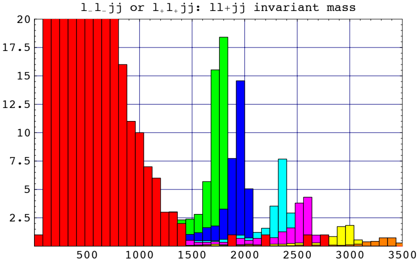
[Keung Senjanovic '83]

Yukawa-free production of W_R, ν_R possibly on-shell.



allows reconstruction of W_R and neutrino invariant mass, probing neutrino flavour structure.





$8fb^{-1}$ @ 14 TeV, PT cuts 20GeV, $t\bar{t}$ background

W_R-ν_R cont'd

- LHC reach?

$M_{W_R}[TeV]$	m_{ν_R} [TeV]	$\int L$	energy	
4 (2)	2 (1)	30 /fb	14(7) TeV	Ferrari et al '00, Gninenko et al '07
2.1 (1.5)	2.1	100/pb	14(10) TeV	Kirsanov '09

- But early signal through $\ell^\pm\ell^\pm$ large energy (wrt to $t\bar{t}$ ones)?

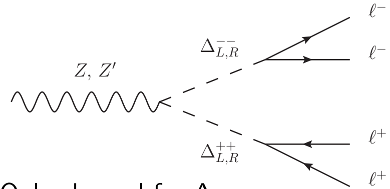
- Neutrino masses and flavour:
yukawa-free, but probing RH neutrino matrix.
For flavour need updated montecarlo (CalcHEP? Update Pythia?)

- Displaced Vertex?

$$\tau_{\nu_R} \gtrsim 1\,\text{cm} \text{ for } m_{\nu_R} \lesssim 10\,\text{GeV} \quad (M_{W_R} = 2.5\,\text{TeV})$$

Tuning, from the model point of view to have light ν_R.
On the other hand this signal would be quite unmistakable.

$\Delta_{L,R}$

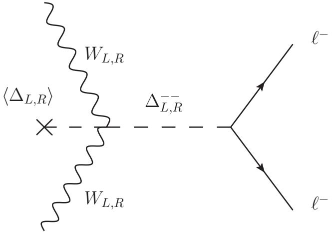


$\propto (Y_\Delta)_{ij}(Y^*_\Delta)_{kl}$

Only channel for Δ_L (except for $y_\Delta \ll 1$!)

Can probe neutrino masses, only assuming type-II seesaw...

[Kadastik Raidal Rebane '07, del Aguila et al '07, Han et al]



$\propto (Y_\Delta)_{ij}$

large VEV for Δ_R but suppressed for heavy W_R

[Azuelos '05]

VEV suppressed for Δ_L

Reach $< 1\,\text{TeV}$

$0\nu\beta\beta$

New contributions, that can compete with the standard LL $0\nu\beta\beta$ amplitude $\propto m_{ee}/p^2$ with $m_{ee} \sim 0.1\,\mathrm{eV}$:

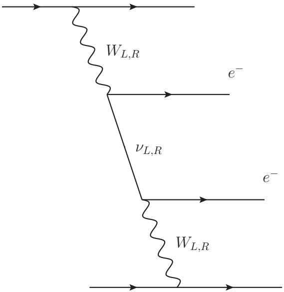
- RR important unless:

$$\left(\frac{M_{W_R}}{\mathrm{TeV}}\right)^4 \left(\frac{m_{\nu_R}}{\mathrm{TeV}}\right) > 2\,.$$

- LR important unless:

$$\left(\frac{M_{W_R}}{\mathrm{TeV}}\right)^4 \left(\frac{m_{\nu_R}}{\mathrm{TeV}}\right) > 0.2\,(U_L\, O\, U_R^t)^2_{ee}$$

where O are orthogonal complex, maybe large! (seesaw example)



- LR can (over)dominate for large Yukawa.
- RR survives even for vanishing Yukawa.

Important e.g. for $M_{W_R} \simeq 3\,\mathrm{TeV}$, $m_{\nu_R} \simeq 25\,\mathrm{GeV}$!

Limits

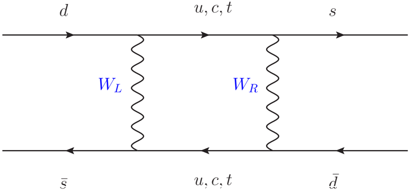
- Direct limits $M_{W_R} \geq 800\,\text{GeV}$ (from dijets @ $D0$ [PRL '96, '04, '08])
- Strongest limit comes from K mass difference:
  - If disentangled $V_{CKM\,R} \neq V_{CKM\,L}$ then no limit on M_{W_R}.
  - In models where $V_{CKM\,R} \simeq V_{CKM\,L}$, we need $M_{W_R} > 2.5 \pm \ldots$

    [Beall Bander Soni '81, ..., Zhang An Ji Mohapatra '07]
- In general ϵ, ϵ' harmless, due to phases. (also in minimal models!)

Thus it is Δm_K that matters

$K\bar{K}$

$W_R \to$ new boxes for $\Delta S = 2$ — largest is W_L-W_R:



- Dominant is c-c loop – Correlated bound V_R-M_{W_R}:

$$M_{W_R}^2 > (2.5\,\text{TeV})^2 \left(\frac{V^*_{cd\,R}}{\lambda_c}\right)\left(\frac{V_{cs\,R}}{1}\right)$$

(With hadronic matrix elements uncertainty 25–50%.)

[Baremboim, Barnabeu, Prades, Raidal, '96, Babich et al '06]

So it is V_R^{CKM} that matters...

Good mixing matrices

Good V_R have thus one of the following forms:

$$V_R = \begin{pmatrix} e^{i\psi} & 0 & 0 \\ 0 & ce^{i\sigma} & -se^{i\gamma} \\ 0 & se^{i\theta} & ce^{i\epsilon} \end{pmatrix}, \qquad \begin{pmatrix} 0 & e^{i\psi} & 0 \\ ce^{i\sigma} & 0 & -se^{i\gamma} \\ se^{i\theta} & 0 & ce^{i\epsilon} \end{pmatrix}$$

[Langacker Sankar '98, ..., Frank et al, '10]

By inspection, one checks that this is enough to relax limits from Δm_K as well from B_s, B_d.

Then also CP violation bounds can be satisfied, by exploiting the phases.

$$\theta_{12\,R} = 0 \quad \text{or} \quad \pi/2$$

Can we reach this form?

Generically, if α, Y, $\tilde{Y}$ unconstrained, $\rightarrow$ V_R free $\rightarrow$ no limits on M_{W_R}.

L-R models: two symmetries

- Generalized Parity:

$$\mathcal{P}: \; f_L \leftrightarrow f_R\,, \;\; \phi \leftrightarrow \phi^\dagger$$

Y, $\tilde{Y}$ hermitian, but $\quad \Rightarrow \quad V_R \neq V_L$

because of the 'spontaneous' phase $e^{i\alpha}$...
But how much actually different?
see Nemevšek talk

- Generalized Charge conj.:

$$\mathcal{C}: \; f_L \leftrightarrow (f_R)^c\,, \;\; \phi \leftrightarrow \phi^T$$

Y, $\tilde{Y}$ symmetric and $\quad \Rightarrow \quad V_R = K_1\, V_L^*\, K_2\,,$

with K_1, K_2 diagonal phases. So equal mixings, and from Δm_K,

$$M_{W_R} \geq 2.5\,\text{TeV}$$

Note this is gaugeable symmetry – e.g. embedded in GUT SO(10)!

Case of $\mathcal{C}$: Charge Conjugation

Mass matrices symmetric: same angles, only extra phases (5)

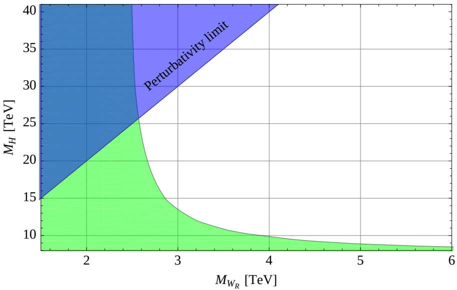
$$V_R = K_u \, V_L^* \, K_d$$

$$(K_u = \mathrm{diag}\{e^{i\theta_u}, e^{i\theta_c}, e^{i\theta_t}\},\ K_d = \mathrm{diag}\{e^{i\theta_d}, e^{i\theta_s}, e^{i\theta_b}\})$$

- Again, from Δm_K:

  $$M_{W_R} > 2.5\,\mathrm{TeV}.$$

  correlated with heavy FC higgs:



- No constraint from Δm_{B_d}, Δm_{B_d}, but

  situation with CP violation in $B_{d,s}$ is now curious...

$\mathcal{C}$, cont'd: ϵ

Possible new physics in ϵ is at most 20–30%:

$$\frac{\epsilon_{LR}}{\epsilon_{SM}} \simeq \mathrm{Im}\left[\mathrm{e}^{i(\theta_d-\theta_s)} A_{cc}\right] < 0.3$$

where $\beta = -\arg(V_{Ltd})$ and the c-c term is:

$$A_{cc} \simeq \left[150 + 8.2 \ln\left(\frac{M_{W_R}}{2.5\,\mathrm{TeV}}\right)\right]\left(\frac{2.5\,\mathrm{TeV}}{M_{W_R}}\right)^2 + 84\left(\frac{15\,\mathrm{TeV}}{M_H}\right)^2$$

Quite large contribution from LR, however:

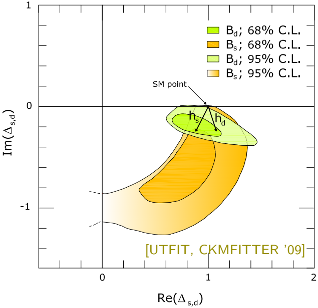
- For zero phases $\theta_{d,s}$, no CP violation (from LR graphs)
- So, no bounds, we only conclude:

$$\theta_d - \theta_s \simeq 0\,.$$

$\mathcal{C}$, cont'd, $B_{d,s}$

[W/ Maiezza, Nemevshek, Senjanovic]

New Physics in B^0-$\overline{B}^0$:



$$h_q = \frac{\langle B_q | \mathcal{H}_{LR} | \overline{B}_q \rangle}{\langle B^0_q | \mathcal{H}_{SM} | \overline{B}^0_q \rangle}, \qquad (q = d, s)$$

Need a nonzero phase.

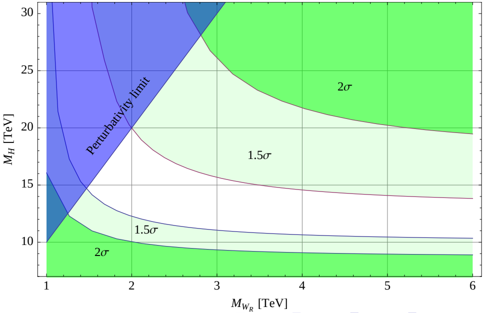
$$\theta_b - \theta_d \simeq \theta_b - \theta_s$$

(because $\theta_d - \theta_s \simeq 0$ for ϵ)

$\rightarrow h_{d,s}$ point toward same region.

Correlated bound:

In the interesting zone for LHC



Outlook

The interesting case of TeV-scale L-R symmetry with $\mathcal{C}$:

- A symmetric extension of the SM (embeddable in GUT)
- LR Parity restored, at low scale!
- Premium channel still on-shell W_R-ν_R @ LHC.
- Lepton Number Violation.
- Possibly very rich phenomenology (W_R, ν_R, Δ_L, Δ_R)
- Lower bound $M_{W_R} \gtrsim 2.5\ TeV$ (from K^0-$\overline{K}^0$)
- No bounds from CP violation...
  ...on the contrary solution of $B_{d,s}$ CP tension
- Todo WIP: update montecarlo for flavour? LD part? Polarizations? Disentangling different signals...
- Thanks!

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L-R Lagrangian

$$L = R$$

W_L-W_R mixing

In the minimal models, tree level W_L-W_R mixing angle ζ is bound by weak decays, $\zeta < 10^{-2}$ $(3\,10^{-3})$.

This translates into a limit on the W_R mass:

$$M_{W_R} > 1.5\,\text{TeV}\sqrt{\frac{2x}{1+x^2}}\,,$$

...quite harmless.

Higgs spectrum

Higgs state	m^2
$h^0 = \sqrt{2}\,\mathrm{Re}\,\left(\phi_1^{0*} + xe^{-i\alpha}\phi_2^0\right)$	$\left(4\lambda_1 - \frac{\alpha_1^2}{\rho_1}\right) v^2 + \alpha_3 v_R^2 x^2$
$H_1^0 = \sqrt{2}\,\mathrm{Re}\,\left(-xe^{i\alpha}\phi_1^{0*} + \phi_2^0\right)$	$\alpha_3 v_R^2$
$A_1^0 = \sqrt{2}\,\mathrm{Im}\,\left(-xe^{i\alpha}\phi_1^{0*} + \phi_2^0\right)$	$\alpha_3 v_R^2$
$H_2^0 = \sqrt{2}\,\mathrm{Re}\,\delta_R^0$	$4\rho_1 v_R^2$
$H_2^+ = \phi_2^+ + xe^{i\alpha}\phi_1^+ + \frac{1}{\sqrt{2}}\epsilon\delta_R^+$	$\alpha_3\left(v_R^2 + \frac{1}{2}v^2\right)$
δ_R^{++}	$4\rho_2 v_R^2 + \alpha_3 v^2$
$H_3^0 = \sqrt{2}\,\mathrm{Re}\,\delta_L^0$	$(\rho_3 - 2\rho_1)v_R^2$
$A_2^0 = \sqrt{2}\,\mathrm{Im}\,\delta_L^0$	$(\rho_3 - 2\rho_1)v_R^2$
$H_1^+ = \delta_L^+$	$(\rho_3 - 2\rho_1)v_R^2 + \frac{1}{2}\alpha_3 v^2$
δ_L^{++}	$(\rho_3 - 2\rho_1)v_R^2 + \alpha_3 v^2$

Leading order in $\epsilon = v/v_R$ and $x = v'/v$, and assuming $v_L = 0$.
The SM Higgs is identified with h^0. [Zhang et al '07]

Ugly

	Lorentz	Q $(Y+T_{3L})$	Y	SU(2)$_L$ T_{3L}			$SU(3)$
u_L	**2**	$2/3$	$1/6$	$1/2$			**3**
d_L	**2**	$-1/3$	$1/6$	$-1/2$			**3**
ν_L	**2**	0	$-1/2$	$1/2$			**1**
e_L	**2**	-1	$-1/2$	$-1/2$			**1**
u_R	$\bar{\mathbf{2}}$	$2/3$	$2/3$	0			**3**
d_R	$\bar{\mathbf{2}}$	$-1/3$	$-1/3$	0			**3**
ν_R	$\bar{\mathbf{2}}$	0	0	0			**1**
e_R	$\bar{\mathbf{2}}$	-1	-1	0			**1**

Plenty of symmetries to restore 'beauty', starting from the simplest, Left-Right symmetry, restoring a "Parity" at some scale:

$$\text{SU}(3)_c \times \text{SU}(2)_L \times \text{SU}(2)_R \times \text{U}(1)_{B-L}$$

[Pati Salam '74, Mohapatra Pati '75, Senjanović Mohapatra '75]

(Then Pati-Salam $\text{SU}(2)_L \times \text{SU}(2)_R \times \text{SU}(4)_c$, SO(10), etc, even with Lorentz)

[Pati Salam '74; Georgi '75] [FN '07, FN Percacci '09]

Nice

	Lorentz	Q $(Y+T_{3L})$	Y $(T_{3R}+\frac{(B-L)}{2})$	$SU(2)_L$ T_{3L}	$SU(2)_R$ T_{3R}	$B-L$	$SU(3)$
u_L	**2**	2/3	1/6	1/2	0	1/3	**3**
d_L	**2**	−1/3	1/6	−1/2	0	1/3	**3**
ν_L	**2**	0	−1/2	1/2	0	−1	**1**
e_L	**2**	−1	−1/2	−1/2	0	−1	**1**
u_R	$\bar{\mathbf{2}}$	2/3	2/3	0	1/2	1/3	**3**
d_R	$\bar{\mathbf{2}}$	−1/3	−1/3	0	−1/2	1/3	**3**
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$\Delta F = 2$ Hamiltonians

Effective **Hamiltonians** from the box diagrams:

$$\mathcal{H}_{LL}^{\Delta F=2} = \frac{G_F^2 M_{W_L}^2}{4\pi^2} \sum_{d,d'=d,s,b} \bar{d}'\gamma_\mu P_L d\, \bar{d}'\gamma_\mu P_L d \sum_{i,j=c,t} \lambda_i^{LL}\lambda_j^{LL} S_{LL}(x_i,x_j)\,\eta_{LL,ij}$$

$$\mathcal{H}_{LR}^{\Delta F=2} = \frac{G_F^2 M_{W_L}^2}{4\pi^2}\, 8\,\beta \sum_{d,d'=d,s,b} \bar{d}' P_L d\, \bar{d}' P_R d \sum_{i,j=u,c,t} \lambda_i^{LR}\lambda_j^{RL} S_{LR}(x_i,x_j,\beta)\,\eta_{LR,ij}$$

$$\mathcal{H}_{RR}^{\Delta F=2} = \frac{G_F^2 M_{W_L}^2}{4\pi^2}\, \beta \sum_{d,d'=d,s,b} \bar{d}'\gamma_\mu P_R d\, \bar{d}'\gamma_\mu P_R d \sum_{i,j=c,t} \lambda_i^{RR}\lambda_j^{RR} S_{RR}(x_i,x_j,\beta)\,\eta_{RR,ij}$$

where

$$\lambda_i^{AB} = V_{id'}^{A*} V_{id}^{B}\,, \quad x_i = (m_i/M_{W_L})^2\,, \quad \beta = M_{W_L}^2/M_{W_R}^2$$

and **Matrix elements** for meson M^0-$\overline{M}^0$ are:

$$\left\langle M^0 \left| \bar{d}'\gamma_\mu P_L d\, \bar{d}'\gamma_\mu P_L d \right| \overline{M}^0 \right\rangle = \frac{2}{3} f_M^2 m_M \mathcal{B}_M^{LL}$$

$$\left\langle M^0 \left| \bar{d} P_L d'\, \bar{d} P_R d' \right| \overline{M}^0 \right\rangle = \frac{1}{2} f_M^2 m_M \mathcal{B}_M^{LR} \left[\left(\frac{m_M}{m_{d'} + m_d} \right)^2 + \frac{1}{6} \right].$$

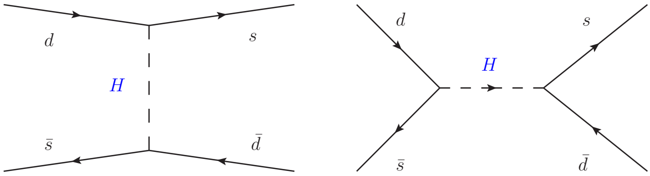
$\Delta F = 2$ FC Higgs

Effective **Hamiltonians** from the tree level Higgs:

$$\mathcal{H}_H^{\Delta F=2} = -\frac{4G_F}{\sqrt{2}M_H^2} \sum_{d,d'=d,s,b} \bar{d}' P_L d \, \bar{d}' P_R d \sum_{i,j=u,c,t} \lambda_i^{LR} \lambda_j^{RL} m_i m_j \,,$$

where again

$$\lambda_i^{AB} = V_{id'}^{A*} V_{id}^{B} \,, \quad x_i = (m_i/M_{W_L})^2$$



$\mathcal{C}$: B CP violation

The last free phase is constrained: