Left-Right @ LHC through LNV

Fabrizio Nesti

University of L'Aquila, INFN - LNGS & ICTP, Italy
ICTP, Trieste, Italy

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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 aestetically *ugly*

- 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!

Neutrino masses

- Generically by an effective operator: [Weinberg '79]

$$\frac{\lambda}{M}(\ell H)(H\ell)$$

- Seesaw by RH neutrinos: [Minkowski '77, Mohapatra Senjanovic '79] [GRS '79, Glashow '79; Yanagida '79]

$$y\,\bar{\ell}H\nu_R + M\nu_R^t\nu_R$$

. . . y and M quite free: $M \sim 10^{-6}$–10^{14}GeV.

- But. . . maybe M hints to something? New interactions?
  . . . e.g.: M breaks lepton number, $B - L$, ...

- And can we test a low M at LHC? Yes, because of LNV:

  Via standard interactions hard. (need large y and cancelations)
  Via new forces, much better! (on shell production)

Hints from quantum numbers. . .

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Hints from quantum numbers…

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:

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

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

(Then Pati-Salam $SU(2)_L \times SU(2)_R \times SU(4)_c$, 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**
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Left + Right models

Model content: bidoublet $\phi \sim (h_{light}, H_{heavy})$, triplets Δ_L, Δ_R,

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

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

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

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

- We have 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)

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

M_R scales

So long for beauty, now we want to know if testable:

- High M_{W_R} up to $\sim 10^{14}$ GeV ok with GUT.
  Still M_{ν_R} can be low – but hard to see [talk by del Aguila]

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

  leading to striking signals

  (…direct probe of new interactions)

  (…of P 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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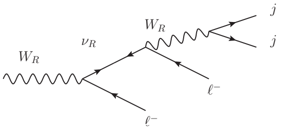
A selection of processes...

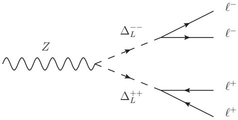
Interesting processes

- Premium: W_R-ν_R production

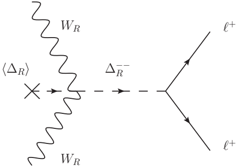
  Same-sign dileptons.



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



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

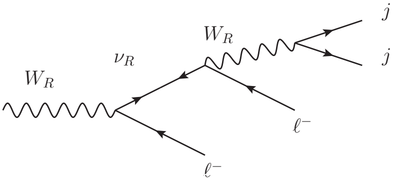


...depends of course on which particles lie at low scale.

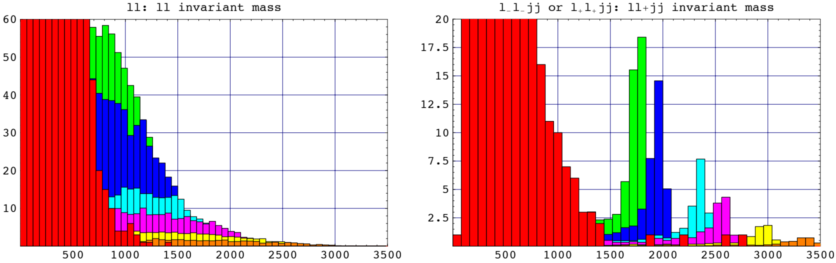
W_R-ν_R

[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	CMS talk by Kirsanov 03/09

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

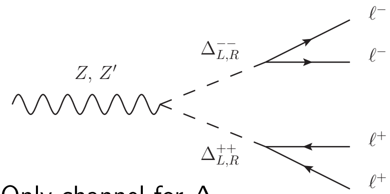
- Neutrino masses and flavour:
  yukawa-free, but probing RH neutrino matrix.
  For flavour need updated montecarlo (CalcHEP? Update Pythia?)

- Displaced Vertex?

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

  Difficult (tuning) from the model point of view to have light ν_R.
  On the other hand this signal would be quite unmistakable.

$\Delta_{L,R}$

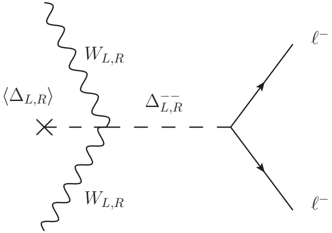


$\propto (Y_\Delta)_{ij}(Y_\Delta)_{kl}$

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 $< 1\,$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 $m_{ee} \sim 0.1\,\text{eV}$:

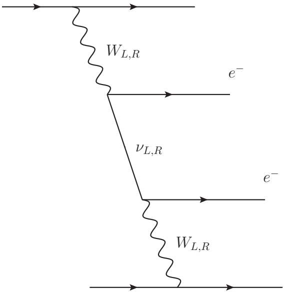
- LR important if:

$$\left(\frac{m_{W_R}}{\text{TeV}}\right)^4 \left(\frac{m_{\nu_R}}{\text{TeV}}\right) < 0.02\,(U_L\,O\,U_R^t)^2_{ee}$$

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

- RR important if:

$$\left(\frac{m_{W_R}}{\text{TeV}}\right)^4 \left(\frac{m_{\nu_R}}{\text{TeV}}\right) < 0.2\,.$$



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

Important e.g. for $m_{W_R} \simeq 1\,\text{TeV}$, $m_{\nu_R} \simeq 200\,\text{GeV}$!

Limits

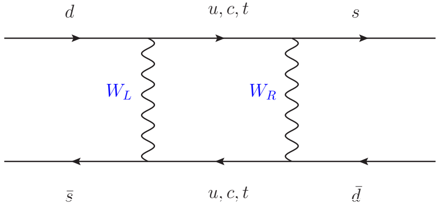
- Direct limits $M_{W_R} \geq 800\,\mathrm{GeV}$ (from dijets @ $D0$ [PRL '96, '04, '08])
- Strongest limit comes from K mass difference:
  - If disentangled $V_{CKM\,R} \neq V_{CKM\,L}$ then no limit on M_{W_R}.
  - In models where $V_{CKM\,R} \simeq V_{CKM\,L}$, we need $m_{W_R} > 2.5 \pm \ldots$

    [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 $\Delta S = 2$ — larger is W_L-W_R, e.g.:



- Dominant is c-c loop – Correlated bounds 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 50%.

[Baremboim, Barnabeu, Prades, Raidal, '96]

So it is V_R that matters. . .

Good mixing matrices

Good V_R have thus one of the following forms:

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

[Langacker Sarkar '98]

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?

L-R symmetric models

Generically, if α, h, $\tilde{h}$ unconstrained, V_R free, hence yes, no limits on m_{W_R}.

- $\mathcal{C}$-type (generalized Charge conj.): $f_L \leftrightarrow (f_R)^c$, $\phi \leftrightarrow \phi^T$:
  Here h, $\tilde{h}$ symmetric and

  $$V_R = K_1\, V_L^*\, K_2\,,$$

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

  $$m_{W_R} \geq (2.5 \pm 25\%_{had})\,\text{TeV}$$

- $\mathcal{P}$-type (generalized Parity): $f_L \leftrightarrow f_R$, $\phi \leftrightarrow \phi^\dagger$:
  Here h, $\tilde{h}$ hermitean.

  here $V_R \neq V_L$ because of the spontaneous phase $\mathrm{e}^{i\alpha}$...

$\mathcal{P}$-type: RH mixings and W_R

- Can disentangle V_R and V_L if masses are not hermitean:

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

Key parameters are α and $x = v'/v$. $(0 < x < 1)$

- For small $x \lesssim m_b/m_t$: one obtains analytically $V_R \simeq V_L$

[Zhang An Ji Mohapatra '07]

- For $x > m_b/m_t$ there may be cancellations and large angles. . .

. . . However α is limited by the
need to adjust $m_b \ll m_t$.
(plot of an analytical bound).

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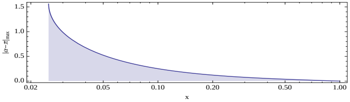

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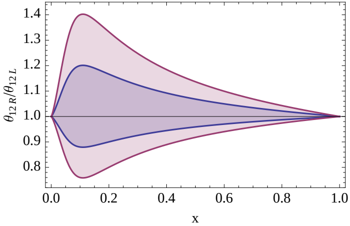
Completing the landscape

Need numerical fit (14 parameters). [W/ Maiezza, Nemevshek, Senjanovic]
Preliminary result of complete analysis:



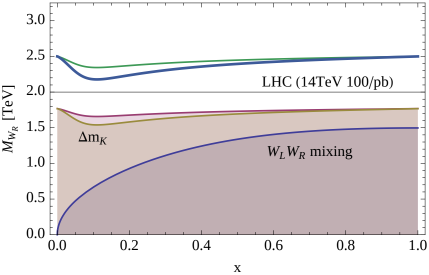
Angles are quite aligned again.

Here $\theta_{12\,R}/\theta_{12\,L}$.

Other angles similarly related.

Bound is maybe bound to stay.

(Still 25%(?) from matrix element)



Outlook

The interesting case of TeV-scale L-R symmetry:

- A symmetric extension of the SM.
- 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)
- Todo WIP: update montecarlo for flavour? Matrix element? Polarizations? Disentangling different signals. . .
- For minimal models. . .

  . . . the Right chances Left.
- 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.