Left-Right Symmetry
and the Charged Higgs Bosons at LHC

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paper on the way.
This year SM has been crowned and, finally, SSB mechanism appreciated

Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism
"Reflections on the Higgs system", M. Veltman, CERN 97-05: video

Schwinger, $\sigma$ model,
"... will produce effective mass terms for each field through the action of the vacuum fluctuations of the other fields", 1957

Gell-Mann, Levy (1960), $\sigma$ model linked to PCAC

Anderson, 1958 - massive electromagnetic fields as perceived in superconductivity

Englert, Brout (1964), Higgs (1964): scalar field shifted to the vector field, Kibble (1967) - non-abelian extension

Weinberg (1967), Glashow (1961) - $SU(2) + U(1)$ with $Z - A$ mixing
Is Particle Physics scalar landscape so simple? Mount Mayon

(Renowned as the "perfect cone" because of its almost symmetric conical shape)

\[
\Phi \equiv \Phi_{SM} = \begin{pmatrix}
\phi^+ \\
\phi^0
\end{pmatrix}
\]

\[
V = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2
\]

\[
V_{\text{min}} = v/\sqrt{2}, v = \sqrt{\mu^2/\lambda} \simeq 250 \text{ GeV}
\]
What if not?

e.g.

\[ V = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \frac{\lambda_5}{2} \left[ (\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2 \right], \]

\[ \Phi_a = \left( \frac{\phi_a^+}{(v_a + \rho_a + i\eta_a)/\sqrt{2}} \right), \quad a = 1, 2. \]
One fact and two important questions

- There is a scalar, fundamental particle!
- Do we need more of them?
- What kind of?

I focus on non-supersymmetric theories (see Fred Jegerlehner: The hierarchy problem of the electroweak Standard Model revisited, e-Print: arXiv:1305.6652 [hep-ph]) ... the existence of quadratic cutoff effects in the SM cannot motivate the need for a super symmetric extensions of the SM...
MOTIVATIONS FOR MORE FUNDAMENTAL SCALARS
Low energy constraints: $\rho$

Plenty of them, but of special importance is the $\rho$ parameter $= \frac{M_W^2}{M_Z^2 \cos^2 \Theta_W}$, for which

$$\rho = \frac{\sum [t_i(t_i + 1) - t_{3i}^2]v_i^2}{2 \sum_i t_{3i}^2 v_i^2}.$$ 

$\rho_{\text{exp}}$ is one, with a very good accuracy, it is automatically one for doublet Higgs fields, $(t, t_3) = (1/2, \pm 1/2)$, but: for what values, of $(t, t_3)$ can we obtain $\rho = 1$ independent of value of $v_i$?
T. Rizzo showed in 1980 (PRD) that it happens for values which satisfies the equation \( 3t_3^2 = t(t + 1) \), so, e.g. \((1/2, \pm 1/2)\), next is \((3, \pm 2)\) - 7-plet (note, usual triplet models \((\Phi^0, \Phi^-, \Phi^{--})\) gives \(\rho \neq 1\)):

\[
(\Phi^+, \Phi^0, \Phi^-, \Phi^{--}, ..., \Phi^{----})
\]

| \(t^H\) | \(|t^H_3|\) |
|---|---|
| \(1/2\) | \(1/2\) |
| \(3\) | \(2\) |
| \(25/2\) | \(15/2\) |
| \(48\) | \(28\) |
Low energy constraints: Neutrinos

- Gauge singlet right-handed neutrino: minuscule Yukawa Dirac couplings - no other effects than explaining neutrino oscillations

- Additional heavy particles - see-saw mechanism, Majorana terms - lepton number violation, $0\nu\beta\beta$
Heavy neutrinos: see-saw type-I

Seesaw I: right handed singlets

\[ \mathcal{L}_Y = -Y_{ij} \overline{L}_i L \overline{N}_j R \tilde{\phi} + \text{H.c.} \]

\[ \mathcal{L}_M = -\frac{1}{2} M_{ij} \overline{N}_i L \overline{N}_j R + \text{H.c.} \]

\[ \mathcal{L}_{\text{mass}} = -\frac{1}{2} (\overline{\nu}_L N_L) \begin{pmatrix} 0 & \frac{v \sqrt{2} Y}{M} \\ \frac{v}{\sqrt{2}} Y^T & M \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \overline{N}_R \end{pmatrix} + \text{H.c.} \]

The neutrino mass matrix

\[ M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R(v_R) \end{pmatrix} \]

with \( M_D \ll M_R \).

\[
m_N \sim M_R \\
m_{\text{light}} \sim M_D^2 / M_R
\]

\[ M_D \sim \mathcal{O}(1) \text{ GeV} \rightarrow M_R \sim 10^{15} \text{ GeV} \], if light neutrino masses of the order of 0.1 eV.
Effective operators - Weinberg,...

This is a typical situation for effective dimension-5 operators generated by $\kappa L L H H$ terms, for $M_R \sim 1 \text{ TeV} \ M_D \sim 10^{-6}$. Consequently, Yukawa couplings $Y$ are small, no effects in colliders

To lower see-saw scale to TeV, higher dimension operators can be used, e.g. dimension-7

Examples (1305.2795) - 7-dimensional and 5-dimensional induced loop operators

$\Sigma$s here are triplet fermions
Seesaw II (scalar triplets)

\[ \mathcal{L}_Y = \frac{1}{\sqrt{2}} Y_{ij} \bar{L}_i \bar{\Delta} \cdot \bar{L}_j + \text{H.c.}, \]

\[ \Delta^{++} = \frac{1}{\sqrt{2}} (\Delta^1 - i \Delta^2), \quad \Delta^+ = \Delta^3, \quad \Delta^0 = \frac{1}{\sqrt{2}} (\Delta^1 + i \Delta^2) \]

can be left and right handed triplets

possible messengers at LHC

\[ q \bar{q} \rightarrow Z^* / \gamma^* \rightarrow \Delta^{++} \Delta^{--}, \]
\[ q \bar{q}' \rightarrow W^* \rightarrow \Delta^{\pm \pm} \Delta^{\mp \mp}, \]
\[ q \bar{q} \rightarrow Z^* / \gamma^* \rightarrow \Delta^+ \Delta^- \].
Seesaw III (3 leptonic triplets)

\( \mathcal{L}_Y = -Y_{ij} \bar{L}_{iL} (\sum_j \cdot \bar{\tau}) \tilde{\phi} + \text{H.c.}, \)

\( \mathcal{L}_M = -\frac{1}{2} M_{ij} \bar{\Sigma}_i \cdot \sum_j + \text{H.c.}, \)

\( \Sigma_j^+ = \frac{1}{\sqrt{2}} (\Sigma_j^1 - i \Sigma_j^2), \quad \Sigma_j^0 = \Sigma_j^3, \quad \Sigma_j^- = \frac{1}{\sqrt{2}} (\Sigma_j^1 + i \Sigma_j^2) \)

\( \mathcal{L}_{\nu,\text{mass}} = -\frac{1}{2} (\bar{\nu}'_L \bar{\Sigma}'_L) \begin{pmatrix} 0 & \frac{v}{\sqrt{2}} Y^T \\ \frac{v}{\sqrt{2}} Y & M \end{pmatrix} \begin{pmatrix} \nu'_R \\ \bar{N}'_R \end{pmatrix} + \text{H.c.} \)

possible messengers at LHC

\[ q\bar{q} \rightarrow Z^* / \gamma^* \rightarrow E^+ E^-, \]

\[ q\bar{q}' \rightarrow W^* \rightarrow E^\pm N. \]  

(1)
## Example

|                | Seesaw I  
<table>
<thead>
<tr>
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<tr>
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<td>$m_N = 100$ GeV</td>
</tr>
<tr>
<td>Six leptons</td>
<td>$-$</td>
</tr>
<tr>
<td>Five leptons</td>
<td>$-$</td>
</tr>
<tr>
<td>$\ell^\pm \ell^\pm \ell^\pm \ell^\mp$</td>
<td>$-$</td>
</tr>
<tr>
<td>$\ell^+ \ell^+ \ell^- \ell^-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$\ell^\pm \ell^\pm \ell^\pm$</td>
<td>$-$</td>
</tr>
<tr>
<td>$\ell^\pm \ell^\pm \ell^\mp$</td>
<td>$&lt; 180$ fb$^{-1}$</td>
</tr>
<tr>
<td>$\ell^\pm \ell^\mp$</td>
<td>$&lt; 180$ fb$^{-1}$</td>
</tr>
<tr>
<td>$\ell^+ \ell^-$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$\ell^\pm$</td>
<td>$\times$</td>
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<td>$m_\Delta = 300$ GeV</td>
</tr>
<tr>
<td>Six leptons</td>
<td>$-$</td>
</tr>
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<td>Five leptons</td>
<td>$-$</td>
</tr>
<tr>
<td>$\ell^\pm \ell^\pm \ell^\pm \ell^\mp$</td>
<td>$-$</td>
</tr>
<tr>
<td>$\ell^+ \ell^+ \ell^- \ell^-$</td>
<td>$19 / 2.8$ fb$^{-1}$</td>
</tr>
<tr>
<td>$\ell^\pm \ell^\pm \ell^\pm$</td>
<td>$-$</td>
</tr>
<tr>
<td>$\ell^\pm \ell^\mp$</td>
<td>$3.6 / 0.9$ fb$^{-1}$</td>
</tr>
<tr>
<td>$\ell^+ \ell^-$</td>
<td>$15 / 27$ fb$^{-1}$</td>
</tr>
<tr>
<td>$\ell^\pm$</td>
<td>$\times$</td>
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</table>

<table>
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<th>Seesaw III</th>
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</thead>
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<td>$m_\Sigma = 300$ GeV</td>
</tr>
<tr>
<td>Six leptons</td>
<td>$\times$</td>
</tr>
<tr>
<td>Five leptons</td>
<td>$28$ fb$^{-1}$</td>
</tr>
<tr>
<td>$\ell^\pm \ell^\pm \ell^\pm \ell^\mp$</td>
<td>$15$ fb$^{-1}$</td>
</tr>
<tr>
<td>$\ell^+ \ell^+ \ell^- \ell^-$</td>
<td>$7$ fb$^{-1}$</td>
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<td>$\ell^\pm \ell^\pm \ell^\pm$</td>
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<td>$\ell^+ \ell^-$</td>
<td>$80$ fb$^{-1}$</td>
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<tr>
<td>$\ell^\pm$</td>
<td>$\times$</td>
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</table>
Another way out, observable TeV scale see-saw I and II models

\[ M_D = \begin{pmatrix} m_1 & \delta_1 & \epsilon_1 \\ m_2 & \delta_2 & \epsilon_2 \\ m_3 & \delta_3 & \epsilon_3 \end{pmatrix} \quad \text{and} \quad M_N = \begin{pmatrix} 0 & M_1 & 0 \\ M_1 & \delta M & 0 \\ 0 & 0 & M_2 \end{pmatrix} \]

with \( \epsilon_i, \delta_i \ll m_i \) and \( \delta M \ll M_i \).

- In the limit of \( \epsilon_i, \delta_i, \delta M \to 0 \), the neutrino masses vanish, although the heavy-light mixing parameters given by \( \xi_{ij} \sim m_i/M_j \) can be quite large.
- The neutrino masses given by the seesaw formula are dependent upon small parameters \( \epsilon_i \) and \( \delta_i \).
- If by some symmetry one can guarantee the smallness of \( \delta_i \) and \( \epsilon_i \), then we have a TeV-scale seesaw model with enhanced heavy-light mixing.
- Model can be embedded into LR models (plus global \( D \equiv Z_4 \times Z_4 \times Z_4 \) symmetry)

The sensitivities for various nuclei are expected to be improved by several orders of magnitude, as compared to the present sensitivities:

\[
\begin{align*}
R_{\mu \rightarrow e}^{Ti} & \lesssim 10^{-18}, \\
R_{\mu \rightarrow e}^{Al} & \lesssim 10^{-16}, \\
R_{\mu \rightarrow e}^{Au} & < 4.3 \times 10^{-12}, \\
R_{\mu \rightarrow e}^{Pb} & < 7 \times 10^{-13}, \\
R_{\mu \rightarrow e}^{Pb} & < 4.6 \times 10^{-11}.
\end{align*}
\]
arXiv:1209.2679, Muon conversion to electron in nuclei in type-I seesaw models, Rodrigo Alonso, Mikael Dhen, Belen Gavela, Thomas Hambye

\[
\text{BR}(\mu \rightarrow 3e) \simeq \frac{1}{2} \left( \frac{M_{WL}}{M_{WR}} \right)^4 \left( \frac{M_{N,12} M_{N,11}}{M_{\Delta R}^2} \right)^2, \quad M_{WR} = 3 \text{ TeV}
\]
\[ M_{\Delta^+} \text{(GeV)} \]

\[ m_{N,\text{lightest}} \text{(GeV)} \]

arXiv:1309.0774
\( \mu \rightarrow e\gamma \)

\[
\text{BR}(\mu \rightarrow e\gamma)_{\Delta^{++}_R} \simeq \frac{2\alpha_W M_{WL}^4}{3\pi g^4} \left[ \frac{(f \tilde{f})_{12}}{M_{\Delta^{++}_R}^2} \right]^2
\]

e.g. \( M_{\Delta^{++}_R} \geq 1.7 \text{ TeV} \) for RH charged current mixing \( \sim 0.01 \)
$0\nu\beta\beta$
\[
\frac{\Gamma_{0\nu\beta\beta}}{\ln 2} = G \cdot \left| \frac{M_\nu}{m_e} \right|^2 \left( |m_{ee}^\nu|^2 + \left| p^2 \frac{M_W^4}{M_{WR}^4} \frac{V_{Rej}}{m_{Nj}} \right|^2 \right)
\]

Left-Right Symmetry: from LHC to Neutrinoless Double Beta Decay, arXiv:1011.3522, Tello et al
\[ |m_{\Delta}^{ee}| = \left| p^2 \frac{M_{WL}^4}{M_{WR}^4} \frac{2 M_N}{M_{\Delta R}^2} \right| \]
PRESENT EXPERIMENTAL STATUS
Impressive LHC results, e.g. CMS report HIG-12-005

Figure 1: Feynman diagrams of both pair and associated production.
Table 6: Summary of the results

<table>
<thead>
<tr>
<th>Benchmark point</th>
<th>Published limit</th>
<th>CMS combined result</th>
<th>CMS result for pair production only</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR(Φ⁺⁺ → e⁺e⁺) = 100%</td>
<td>225 GeV [34]</td>
<td>445 GeV</td>
<td>387 GeV</td>
</tr>
<tr>
<td>BR(Φ⁺⁺ → e⁺μ⁺) = 100%</td>
<td>210 GeV [34]</td>
<td>455 GeV</td>
<td>389 GeV</td>
</tr>
<tr>
<td>BR(Φ⁺⁺ → e⁺τ⁺) = 100%</td>
<td>112 GeV [34]</td>
<td>352 GeV</td>
<td>300 GeV</td>
</tr>
<tr>
<td>BR(Φ⁺⁺ → μ⁺μ⁺) = 100%</td>
<td>355 GeV [35] (245 GeV [34])</td>
<td>457 GeV</td>
<td>391 GeV</td>
</tr>
<tr>
<td>BR(Φ⁺⁺ → μ⁺τ⁺) = 100%</td>
<td>144 GeV [36]</td>
<td>369 GeV</td>
<td>313 GeV</td>
</tr>
<tr>
<td>BR(Φ⁺⁺ → τ⁺τ⁺) = 100%</td>
<td>128 GeV [36]</td>
<td>198 GeV</td>
<td>165 GeV</td>
</tr>
<tr>
<td>BP1</td>
<td>N/A</td>
<td>380 GeV</td>
<td>326 GeV</td>
</tr>
<tr>
<td>BP2</td>
<td>N/A</td>
<td>410 GeV</td>
<td>361 GeV</td>
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<tr>
<td>BP3</td>
<td>N/A</td>
<td>406 GeV</td>
<td>350 GeV</td>
</tr>
<tr>
<td>BP4</td>
<td>N/A</td>
<td>399 GeV</td>
<td>353 GeV</td>
</tr>
</tbody>
</table>

Figure 5: Observed Φ⁺⁺ mass limits at 95% C.L. in different lepton final states. The branching ratios assumed in the limit calculation are indicated.
CMS, $\sqrt{s} = 7$ TeV, 5.0 fb$^{-1}$

$M_{N_{\mu}} > M_{W_R}$

Excluded by Tevatron

Expected Limit

CMS, arXiv:1210.2402
MASS LIMITS for $W'$ (Heavy Charged Vector Boson Other Than $W$) in Hadron Collider Experiments

Couplings of $W'$ to quarks and leptons are taken to be identical with those of $W$. The following limits are obtained from $p\bar{p} \rightarrow W'X$ with $W'$ decaying to the indicated in the comments. New decay channels (e.g., $W' \rightarrow WZ$) are assumed to be suppressed. The most recent preliminary results can be found in the "$W'$-searches" review above.

<table>
<thead>
<tr>
<th>VALUE (GeV)</th>
<th>CL%</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
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</thead>
<tbody>
<tr>
<td>&gt;2150</td>
<td>95</td>
<td>AAD</td>
<td>1</td>
<td>$W' \rightarrow e\nu, \mu\nu$</td>
</tr>
<tr>
<td>none 180–690</td>
<td>95</td>
<td>ABAZOV</td>
<td>11H</td>
<td>$W' \rightarrow WZ$</td>
</tr>
<tr>
<td>&gt; 863</td>
<td>95</td>
<td>ABAZOV</td>
<td>11L</td>
<td>$W' \rightarrow t\bar{b}$</td>
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<tr>
<td>&gt;1510</td>
<td>95</td>
<td>CHATRCHYAN</td>
<td>11Y</td>
<td>$W' \rightarrow q\bar{q}$</td>
</tr>
</tbody>
</table>

HTTP://PDG.LBL.GOV Page 1 Created: 6/18/2012
Note, difference with low energy

**$W_R$ (Right-Handed $W$ Boson) MASS LIMITS**

Assuming a light right-handed neutrino, except for BEALL 82, LANGACKER 89, and COLANGELO 91. $g_R = g_L$ assumed. [Limits in the section MASS LIMITS $W'$ below are also valid for $W_R$ if $m_{\nu_R} \ll m_{W_R}$.] Some limits assume manifest left-right symmetry, *i.e.*, the equality of left- and right Cabibbo-Kobayashi-Maskawa matrices. For a comprehensive review, see LANGACKER 89b. Limits on the $W_L$-$W_R$ mixing angle $\zeta$ are found in the next section. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

<table>
<thead>
<tr>
<th>VALUE (GeV)</th>
<th>CL%</th>
<th>DOCUMENT ID</th>
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<td>&gt; 245</td>
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<td>WAUTERS 19</td>
<td>CNTR</td>
<td>$^{60}$Co $\beta$ decay</td>
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<tr>
<td>&gt; 180</td>
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<td>MELCONIAN 20</td>
<td>CNTR</td>
<td>$^{37}$K $\beta^+$ decay</td>
</tr>
<tr>
<td>&gt; 290.7</td>
<td>90</td>
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<td>CNTR</td>
<td>Polarized neutron decay</td>
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<tr>
<td>[&gt; 3300]</td>
<td>95</td>
<td>CYBURT 22</td>
<td>COSM</td>
<td>Nucleosynthesis; light $\nu_F$</td>
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<td>&gt; 310</td>
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<td>THOMAS 23</td>
<td>CNTR</td>
<td>$\beta^+$ decay</td>
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<td>&gt; 137</td>
<td>95</td>
<td>ACKERSTAFF 24</td>
<td>OPAL</td>
<td>$\tau$ decay</td>
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Looking for more (gauge) symmetries
Simple picture again?

- Maxwell (1873), Hertz (1888)
- Glashow, Weinberg, Salam (1967), Gargamelle (1973)
- Georgi, Salam, ..., 70 – ties
- SU(5), SO(10), ..., supersymmetric models
- Witten, ...
- Superstrings...

- $\vec{E}$
- $\vec{B}$
- $W^\pm, Z^0, \nu$
- $U(1)$
- $SU(2) \otimes U(1)$
- quarks and gluons
- gravitation
Simple picture again?

Start: 1973-1974,
Pati, Salam, Senjanovic, Mohapatra

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

(i) restores left-right symmetry to e-w interactions

\[
\begin{pmatrix}
\nu_L \\ e_L
\end{pmatrix}, \quad
\begin{pmatrix}
\nu_R \\ e_R
\end{pmatrix}, \quad
\begin{pmatrix}
u_L \\ d_L
\end{pmatrix}, \quad
\begin{pmatrix}
u_R \\ d_R
\end{pmatrix}
\]

(ii) hypercharge interpreted as a difference of baryon and lepton numbers

\[
Q = T_{3L} + T_{3R} + \frac{B - L}{2}
\]

$W^\pm_L, W^0_L \quad W^\pm_R, W^0_R \rightarrow [SSB?] \quad W^\pm_1, W^\pm_2 \quad B^0 \rightarrow Z_1, Z_2 \quad \gamma$
however, when going into details...

breaking chains \( G \rightarrow G^{(1)} \rightarrow G^{(2)} \ldots \rightarrow G^{(n)} \rightarrow G_{SM} \)

<table>
<thead>
<tr>
<th>ARE GRAND UNIFIED THEORIES RULED OUT BY THE LEP DATA?</th>
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</table>

**Table I.** \( E_6 \) and its subgroups which contain \( G_{SM} \). Here we use the inclusion relation \( SO(7) \supset SU(4) \supset SU(3) \times U(1) \).

<table>
<thead>
<tr>
<th>( E_6 )</th>
<th>( F_4 )</th>
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<tbody>
<tr>
<td>( SO(10) \times U(1) )</td>
<td>( SO(9) )</td>
</tr>
<tr>
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<td>( SU(3) \times SU(3) )</td>
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<tr>
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<th>( SO(9) )</th>
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<th>( SU(5) \times U(1) )</th>
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<td>( SU(3) \times SU(3) \times U(1) )</td>
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</tbody>
</table>

| \( SU(5) \) | \( SU(3) \times SU(2) \times U(1) \) |
**Extra gauge bosons**

Table II. - Group hierarchies which allow unification. Here the dots indicate that the hierarchy chains break directly into $G_{\text{SM}}$ and $G_{\text{LR}} = SU(3) \times SU(2)_L \times SU(2)_R \times U(1)$ indicates the left-right-symmetric gauge group.

<table>
<thead>
<tr>
<th>$E_6$</th>
<th>$G_{\text{LR}}$</th>
<th>$\rightarrow \ldots$</th>
<th>$\rightarrow \ldots$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$SU(2) \times SU(2) \times SU(4)$</td>
<td>$G_{\text{LR}}$</td>
<td>$\rightarrow \ldots$</td>
<td>$\rightarrow \ldots$</td>
</tr>
<tr>
<td>$SO(10) \times U(1)$</td>
<td>$G_{\text{LR}}$</td>
<td>$\rightarrow \ldots$</td>
<td>$G_{\text{SM}}$</td>
</tr>
<tr>
<td>$SU(2) \times SU(3) \times SU(3)$</td>
<td>$G_{\text{LR}}$</td>
<td>$\rightarrow \ldots$</td>
<td></td>
</tr>
<tr>
<td>$SO(10)$</td>
<td>$G_{\text{LR}}$</td>
<td>$\rightarrow \ldots$</td>
<td>$\rightarrow \ldots$</td>
</tr>
</tbody>
</table>
Diagrammatic sketch of 18 symmetry-breaking chains in SO(10).

Chang et al, PRD31, 1718 (1985)
\[ \mathcal{L}_{\text{Higgs}} = \]
\[-\mu_1^2 Tr[\Phi^\dagger \Phi] - \mu_2^2 (Tr[\Phi \Phi^\dagger] + Tr[\Phi^\dagger \Phi]) - \mu_3^2 (Tr[\Delta_L \Delta^\dagger_L] + Tr[\Delta_R \Delta^\dagger_R])
+ \lambda_1 Tr[\Phi \Phi^\dagger]^2 + \lambda_2 (Tr[\Phi \Phi^\dagger]^2 + Tr[\Phi^\dagger \Phi]^2) + \lambda_3 (Tr[\Phi \Phi^\dagger] Tr[\Phi^\dagger \Phi])
+ \lambda_4 (Tr[\Phi \Phi^\dagger] (Tr[\Phi \Phi^\dagger] + Tr[\Phi^\dagger \Phi])) + \rho_1 (Tr[\Delta_L \Delta^\dagger_L]^2 + Tr[\Delta_R \Delta^\dagger_R]^2)
+ \rho_2 (Tr[\Delta_L \Delta_R] Tr[\Delta^\dagger_L \Delta^\dagger_R] + Tr[\Delta_R \Delta_R] Tr[\Delta^\dagger_L \Delta^\dagger_R]) + \rho_3 (Tr[\Delta_L \Delta^\dagger_L] Tr[\Delta_R \Delta^\dagger_R])
+ \rho_4 (Tr[\Delta_L \Delta_R] Tr[\Delta^\dagger_R \Delta^\dagger_R] + Tr[\Delta_R \Delta_R] Tr[\Delta^\dagger_L \Delta^\dagger_R]) + \alpha_1 (Tr[\Phi \Phi^\dagger] (Tr[\Delta_L \Delta^\dagger_L] + Tr[\Delta_R \Delta^\dagger_R]))
+ \alpha_2 (Tr[\Phi \Phi^\dagger] Tr[\Delta_R \Delta^\dagger_R] + Tr[\Phi^\dagger \Phi] Tr[\Delta_L \Delta^\dagger_L]) + \alpha_2^* (Tr[\Phi^\dagger \Phi] Tr[\Delta_R \Delta^\dagger_R] + Tr[\Phi \Phi^\dagger] Tr[\Delta_L \Delta^\dagger_L])
+ \alpha_3 (Tr[\Phi \Phi^\dagger \Delta_L \Delta^\dagger_L] + Tr[\Phi^\dagger \Phi \Delta_R \Delta^\dagger_R]) + \beta_1 (Tr[\Phi \Delta_R \Phi^\dagger \Delta^\dagger_L] + Tr[\Phi^\dagger \Phi \Delta_L \Phi^\dagger R])
+ \beta_2 (Tr[\Phi \Delta_R \Phi^\dagger \Delta^\dagger_L] + Tr[\Phi^\dagger \Phi \Delta_R \Phi^\dagger L]) + \beta_3 (Tr[\Phi \Delta_R \Phi^\dagger \Delta^\dagger_L] + Tr[\Phi^\dagger \Phi \Delta_R \Phi^\dagger R]), \]

invariant under the symmetry \( \Delta_L \leftrightarrow \Delta_R, \quad \Phi \leftrightarrow \Phi^\dagger, \quad \beta_i = 0. \)
The minimal Higgs sector consists of two triplets and one bidoublet

\[ \Delta_{L,R} = \begin{pmatrix} \delta_{L,R}^+/\sqrt{2} & \delta_{L,R}^{++} \\ \delta_{L,R}^0 & -\delta_{L,R}^+/\sqrt{2} \end{pmatrix}, \]

\[ \Phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix}. \]

with vacuum expectation values allowed for the neutral particles

\[ \frac{v_L}{\sqrt{2}} = \langle \delta_L^0 \rangle, \]
new HE scale : \[ \frac{v_R}{\sqrt{2}} = \langle \delta_R^0 \rangle, \]
SM VEV scale : \[ \sqrt{\kappa_1^2 + \kappa_2^2} \]

\[ \frac{\kappa_1}{\sqrt{2}} = \langle \phi_1^0 \rangle, \]
\[ \frac{\kappa_2}{\sqrt{2}} = \langle \phi_2^0 \rangle. \]
The result is 20 real scalar fields, of which 14 are physical (the rest are Goldstone bosons):

- 4 neutral scalars: $H_0^0, H_1^0, H_2^0, H_4^0$,
  (the first can be considered to be the light Higgs of the SM at tree level),
- 2 neutral pseudo-scalars: $A_1^0, A_2^0$,
- 2 charged scalars: $H_1^\pm, H_2^\pm$,
- 2 doubly-charged scalars: $H_1^{\pm\pm}, H_2^{\pm\pm}$.

See-saw mechanism for the generation of light neutrino masses, with specific SB sectors. The neutrino mass matrix

$$M_\nu = \begin{pmatrix} M_L(v_L) & M_D(\kappa_{1,2}) \\ M_D^T & M_R(v_R) \end{pmatrix}$$

with $M_L \ll M_D \ll M_R$. 

Results

Strategy: already now $M_{W^2} > 2.5$ TeV, it means $v_R \geq 5$ TeV, for such a high scale most of effects connected with heavy gauge bosons decouples.

We choose conservatively:

- $v_R = 8$ TeV ($M_{W^2} \geq 3.5$ TeV, expected limit in the next LHC run);
- masses of neutral Higgs particles $\simeq 10$ TeV (demanded also by problems with FCNC);
- charged Higgs particles with masses testable by LHC

In such a scenario there is a chance to pin down charged Higgs boson signals
<table>
<thead>
<tr>
<th>Primary production</th>
<th>Secondary production</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. $H_1^+ H_1^-$</td>
<td>$\ell^+ \ell^- \nu_L \nu_L$</td>
<td>$\ell^+ \ell^- \oplus \text{MET}$</td>
</tr>
<tr>
<td>-</td>
<td>$\ell^+ \ell^- \nu_R \nu_R$</td>
<td>depends on $\nu_R$ decay modes</td>
</tr>
<tr>
<td>-</td>
<td>$\ell^+ \ell^- \nu_L \nu_R$</td>
<td>depends on $\nu_R$ decay modes</td>
</tr>
<tr>
<td>II. $H_2^+ H_2^-$</td>
<td>$\ell^+ \ell^- \nu_L \nu_L$</td>
<td>$\ell^+ \ell^- \oplus \text{MET}$</td>
</tr>
<tr>
<td>-</td>
<td>$\ell^+ \ell^- \nu_R \nu_R$</td>
<td>depends on $\nu_R$ decay modes</td>
</tr>
<tr>
<td>-</td>
<td>$\ell^+ \ell^- \nu_L \nu_R$</td>
<td>depends on $\nu_R$ decay modes</td>
</tr>
<tr>
<td>III. $H_1^{++} H_1^{--}$</td>
<td>-</td>
<td>$\ell^+ \ell^- \ell^+ \ell^-$</td>
</tr>
<tr>
<td>-</td>
<td>$H_1^+ H_1^- H_1^+ H_1^-$</td>
<td>See I</td>
</tr>
<tr>
<td>-</td>
<td>$H_1^+ H_1^- H_2^+ H_2^-$</td>
<td>See I &amp; II</td>
</tr>
<tr>
<td>-</td>
<td>$H_2^+ H_2^- H_2^+ H_2^-$</td>
<td>See II</td>
</tr>
<tr>
<td>-</td>
<td>$W_i^+ W_i^+ W_j^- W_j^-$</td>
<td>depends on $W$’s decay modes</td>
</tr>
<tr>
<td>IV. $H_2^{++} H_2^{--}$</td>
<td>-</td>
<td>$\ell^+ \ell^- \ell^+ \ell^-$</td>
</tr>
<tr>
<td>-</td>
<td>$H_2^+ H_2^- H_2^+ H_2^-$</td>
<td>See II</td>
</tr>
<tr>
<td>-</td>
<td>$H_2^+ H_2^- H_1^+ H_1^-$</td>
<td>See I &amp; II</td>
</tr>
<tr>
<td>-</td>
<td>$H_2^+ H_2^- H_1^+ H_1^-$</td>
<td>See I</td>
</tr>
<tr>
<td>-</td>
<td>$W_i^+ W_i^+ W_j^- W_j^-$</td>
<td>depends on $W$’s decay modes</td>
</tr>
<tr>
<td>V. $H_1^{\pm\pm} H_1^{\mp\mp}$</td>
<td>-</td>
<td>$l^\pm l^\mp l^\mp l^\pm \nu_L$</td>
</tr>
<tr>
<td>VI. $H_2^{\pm\pm} H_2^{\mp\mp}$</td>
<td>-</td>
<td>$l^\pm l^\mp l^\mp l^\pm \nu_L$</td>
</tr>
<tr>
<td>VII. $H_1^{\pm} Z_i, H_1^{\pm} W_i$</td>
<td>-</td>
<td>See I &amp; $Z_i, W_i$ decay modes</td>
</tr>
<tr>
<td>VIII. $H_2^{\pm} Z_i, H_1^{\pm} W_i$</td>
<td>-</td>
<td>See II &amp; $Z_i, W_i$ decay modes</td>
</tr>
<tr>
<td>IX. $H_1^{\pm} A$</td>
<td>-</td>
<td>See I</td>
</tr>
<tr>
<td>X. $H_2^{\pm} A$</td>
<td>-</td>
<td>See II</td>
</tr>
</tbody>
</table>
Branching ratios

(i) \( H_{1}^{\pm \pm} \rightarrow l^{\pm} l^{\pm} \), where \( l = e, \mu, \tau \);
(ii) \( H_{1}^{\pm \pm} \rightarrow H_{1}^{\pm} W_{1}^{\mp} \);
(iii) \( H_{2}^{\pm \pm} \rightarrow l^{\pm} l^{\pm} \), where \( l = e, \mu, \tau \);
(iv) \( H_{2}^{\pm \pm} \rightarrow H_{2}^{\pm} W_{2}^{\mp} \);
(v) \( H_{2}^{\pm \pm} \rightarrow W_{2}^{\pm} W_{2}^{\mp} \);
(vi) \( H_{2}^{\pm \pm} \rightarrow H_{2}^{\pm} W_{1}^{\mp} \);

In principle we can have both LNV and LFV,

\[
BR(H_{1/2}^{\pm \pm} \rightarrow e^{\pm} e^{\pm}) = 37.9% \\
BR(H_{1/2}^{\pm \pm} \rightarrow \mu^{\pm} \mu^{\pm}) = 37.9% \\
BR(H_{1/2}^{\pm \pm} \rightarrow \tau^{\pm} \tau^{\pm}) = 24.2%.
\]
\[ \Delta M = M_{R_{N_1}} - M_{R_{N_3}} = M_{R_{N_2}} - M_{R_{N_3}} \]

\[ M_{R_{N_3}} = 800 \text{ GeV} \]

\[ H_{1}^{++} \rightarrow (e^+ e^+ + \mu^+ \mu^+) \]

\[ H_{1}^{++} \rightarrow \tau^+ \tau^+ \]
$W_2$ decays

$Z_2$ decays

$M_{W_2}$ vs. BR

$M_{Z_2}$ vs. BR

$M_{W_2}$ = $M_{H_1^{+/-}} = M_{H_2^{+/-}} = 600$ GeV

$M_{Z_2}$ = $M_{H_1^{+/-}} = M_{H_2^{+/-}} = 600$ GeV
substantial Higgs boson decay mode
\[ m_{H_{1,2}^{\pm \pm}} = 400 \text{GeV} : \]
\[ \sigma(pp \to H_{1,2}^{++} H_{1,2}^{--} \to l_i^+ l_i^+ l_j^- l_j^-) = 1.441(6.059) \text{ fb for } \sqrt{s} = 8(14) \text{ TeV}, \]
\[ m_{H_{1,2}^{\pm \pm}} = 600 \text{GeV} : \]
\[ \sigma(pp \to H_{1,2}^{++} H_{1,2}^{--} \to l_i^+ l_i^+ l_j^- l_j^-) = 0.144(0.9498) \text{ fb for } \sqrt{s} = 8(14) \text{ TeV}. \]
Non degenerate scenarios

\[ \sigma(pp \rightarrow H_1^{++} H_1^{--} + H_2^{++} H_2^{--}) \text{ (fb)} \]

\[ M_{H_1^{++}} \text{ (GeV)} \]

\[ M_{H_2^{++}} \text{ (GeV)} \]

\[ 0.001 \quad 0.01 \quad 0.1 \quad 1 \quad 10 \]

\[ 200 \quad 400 \quad 600 \quad 800 \quad 1000 \quad 1200 \quad 1400 \quad 1600 \]
summary for productions, without cuts

$$\sqrt{s} = 14 \text{ TeV}$$

$$\sigma (\text{fb})$$

$$M_{H_{\text{charged}}} = M_{H_1^{++}} = M_{H_2^{++}} = M_{H_1^+} = M_{H_2^+}$$

$$\begin{align*}
\text{(pp} & \rightarrow H_1^{++} H_1^- + H_2^{++} H_2^- + cc) \\
\text{(pp} & \rightarrow H_1^{++} H_1^{--} + H_2^{++} H_2^{--}) \\
\text{(pp} & \rightarrow H_1^+ H_1^- + H_2^+ H_2^-)
\end{align*}$$

$$M_{H_{\text{charged}}} (\text{GeV})$$
Kinematic cuts

- The Parton Distribution Function (PDF) CTEQ6L1
- Initially to select a lepton, CALCHEP, PYTHIA, $|\eta| < 2.5$ and $p_T > 10$ GeV
- Detector efficiency cut for leptons is as follows:
  - For electron (either $e^-$ or $e^+$) detector efficiency is 0.7 (70%);
  - For muon (either $\mu^-$ or $\mu^+$) detector efficiency is 0.9 (90%).
- Smearing of electron energy and muon $p_T$ are done
- Lepton-lepton separation. $\Delta R_{ll} \geq 0.2$
- Lepton-photon separation cut is also applied: $\Delta R_{l\gamma} \geq 0.2$ with all the photons having $p_T \gamma > 10$ GeV;
- Lepton-jet separation: The separation of a lepton with all the jets should be $R_{lj} \geq 0.4$, otherwise that lepton is not counted as lepton. Jets are constructed from hadrons using PYCELL within the PYTHIA.
- Hadronic activity cut. This cut is applied to take only pure kind of leptons that have very less hadronic activity around them. Each lepton should have hadronic activity, $\sum \frac{p_T_{hadron}}{p_T_{l}} \leq 0.2$ within the cone of radius 0.2 around the lepton.
- Hard $p_T$ cuts: $p_{Tl1} > 30$ GeV, $p_{Tl2} > 30$ GeV, $p_{Tl3} > 20$ GeV, $p_{Tl4} > 20$ GeV.
- Missing $p_T$ cut. Since 4-lepton final state is without missing $p_T$, missing $p_T$ cut is not applied while for 3-lepton final state there is a missing neutrino, so missing $p_T$ cut ($p_T > 30$ GeV) is applied.
- Z-veto is also applied to suppress the SM background. This has larger impact while reducing the background for four-lepton without missing energy.
Signal events for doubly charged Higgs particles in MLRSM: 4l signals

All analysis for: $\sqrt{s} = 14$ TeV and $L = 300$ $fb^{-1}$

- no missing energy or jet involved
- reconstructed invariant masses for same sign dileptons (SSDL) and opposite sign dileptons (OSDL). As the doubly charged scalars are the parents of the dilepton pair, invariant mass of the SSDL is expected to give a clean peak around the mass of the doubly charged scalar: a smoking gun feature indicating the presence of doubly charged scalars

![Dilepton invariant mass (m_{ll}) plot]

$m_{H_1^{++}} = m_{H_2^{++}} = 400$ GeV
Another interesting variable which can be used for determination of signals

\[ \Delta R_{\ell_1 \ell_2} = \sqrt{(\eta_1 - \eta_2)^2 + (\phi_1 - \phi_2)^2} \geq 0.2, \]

we choose only events for which leptons are well separated.

The distribution peaks at smaller \( \Delta R_{\ell \ell} \) for same sign lepton pair (SSDL) while that for the oppositely charged lepton pair (OSDL) peaks at larger value of \( \Delta R_{\ell \ell} \), as expected.
\( pp \rightarrow H_1^{\pm\pm} H_1^{\mp} \text{ and } pp \rightarrow H_2^{\pm\pm} H_2^{\mp} \): tri-lepton events with missing \( p_T \)

e.g. "Trilepton signals: the golden channel for seesaw searches at LHC", F. del Aguila et al, APPB40 (2009) 2901.

\[ M_{H_1^+} = 392.2 \text{ GeV}, \quad M_{H_2^+} = 4490 \text{ GeV} \\
M_{H_1^{++}} = 404.56 \text{ GeV}, \quad M_{H_2^{++}} = 525 \text{ GeV} \]

in the opposite sign lepton pairs two leptons have different origin thus their invariant mass distribution is continuous while the same sign dilepton invariant mass distributions always peak around mass of the doubly charged scalars
$W_1^+$ and $W_1^-$ are involved, thus we can estimate the charge asymmetry, define as the ratio of the number of events of $\ell^+\ell^+\ell^-$ type to the number of events of $\ell^-\ell^-\ell^+$ type at the LHC, it depends on Parton Distribution Functions (PDF) and thus is a special feature of LHC.

We estimate for $\sqrt{s} = 14$ TeV and integrated luminosity $300 \, fb^{-1}$ 671 tri-lepton signal events after all the cuts

$$R_+ = \frac{\text{# of events for } \ell^+\ell^+\ell^-}{\text{# of events for } \ell^-\ell^-\ell^+} = \frac{464}{207} \simeq 2.24. \quad (2)$$
Background estimation

The cuts are optimised in a way such that we can reduce the SM background and enhance the signal events.

Standard Model background cross-sections for tri- and four-lepton signals are as follow:

<table>
<thead>
<tr>
<th>processes</th>
<th>$3\ell$ (fb)</th>
<th>$4\ell$ (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$tt\bar{t}$</td>
<td>18.245</td>
<td>–</td>
</tr>
<tr>
<td>$tt(Z/\gamma^*)$</td>
<td>1.121</td>
<td>0.069</td>
</tr>
<tr>
<td>$ttW^{\pm}$</td>
<td>0.656</td>
<td>–</td>
</tr>
<tr>
<td>$W^{\pm}(Z/\gamma^*)$</td>
<td>10.590</td>
<td>–</td>
</tr>
<tr>
<td>$(Z/\gamma^<em>)(Z/\gamma^</em>)$</td>
<td>1.287</td>
<td>0.047</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>31.899</strong></td>
<td><strong>0.116</strong></td>
</tr>
<tr>
<td>Luminosity</td>
<td>Background $3\ell$ events</td>
<td>Signal $3\ell$ events</td>
</tr>
<tr>
<td>-----------</td>
<td>---------------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>25 $fb^{-1}$</td>
<td>797.5</td>
<td>55.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300 $fb^{-1}$</td>
<td>9569.7</td>
<td>671</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- 4-lepton signals are well beyond the SM background (about ten times) so new limits on the parameters can be obtained in the future.
- 3-lepton positive signals from processes with doubly charged scalars in MLRSM is hopeless as the SM background is much higher (this time SM background is about ten times larger).
Charged scalar contribution to the $H_0^0 \rightarrow \gamma\gamma$ channel at the LHC. In the loop there are four contributions coming from the charged scalars ($H_1^{\pm\pm}$, $H_2^{\pm\pm}$, $H_1^\pm$, $H_2^\pm$).

Present values

$$R_{\gamma\gamma} = 1.65 \pm 0.24 (stat)^{+0.25}_{-0.18} (syst) \ (ATLAS) ,$$

$$R_{\gamma\gamma} = 0.78^{+0.28}_{-0.26} \ (CMS) .$$
\[ R_{\gamma\gamma} = \left| 1 + \sum_{s=H_{1,2}^{\pm\pm},H_{1,2}^{\pm}} Q_s^2 c_s \frac{k_+^2}{2 M_s^2 A_1(\tau_{WL})} A_0(\tau_s) + N_c Q_t^2 A_{1/2}(\tau_t) \right|^2. \]
Remark, models consistency

"Left-Right Symmetry at LHC and Precise 1-Loop Low Energy Data", J. Chakrabortty et al, JHEP 1207 (2012) 038
Summary

- we are in an exciting moment, there is still place at LHC on many potential discoveries, including GUT models,
- or we will stay with much shifted limits,
- and what then?