GUT models and relatively light charged Higgs bosons at LHC

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Left-Right Symmetry and the Charged Higgs Bosons at LHC

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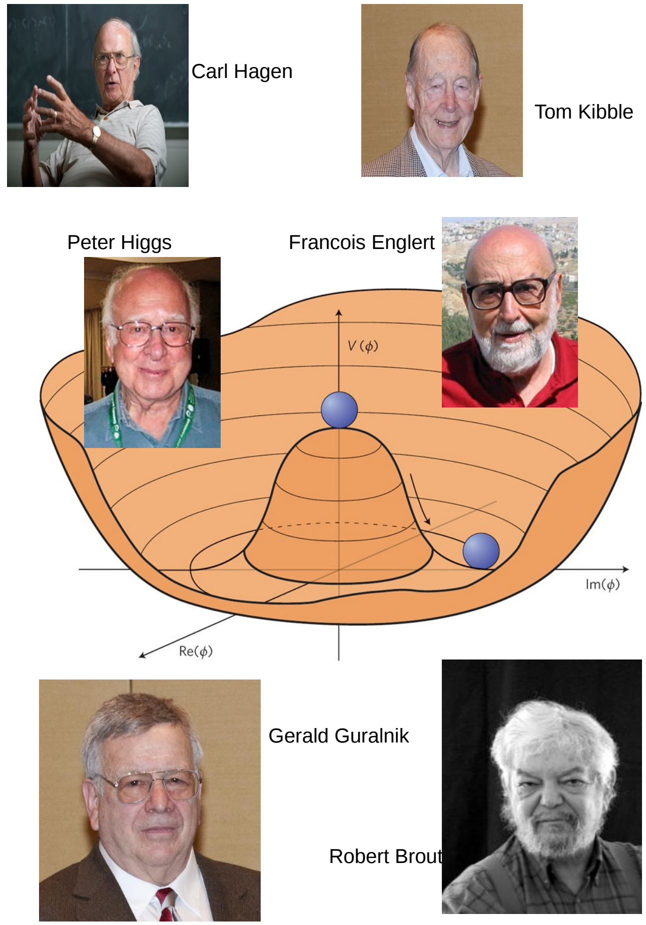
paper on the way.

This year SM has been crowned
and, finally, SSB mechanism appreciated

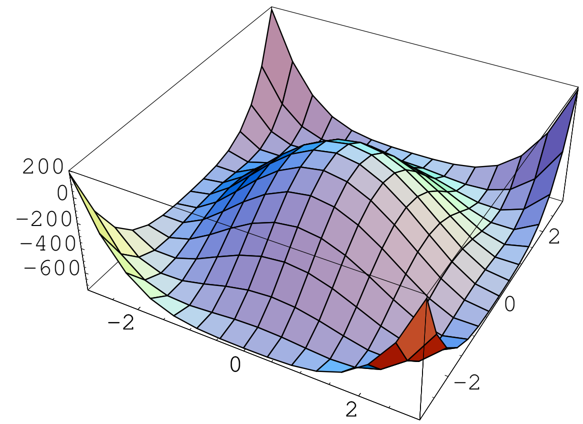


Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism

- "Reflections on the Higgs system", M. Veltman, CERN 97-05: video
- **Schwinger**, σ 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), σ 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)



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

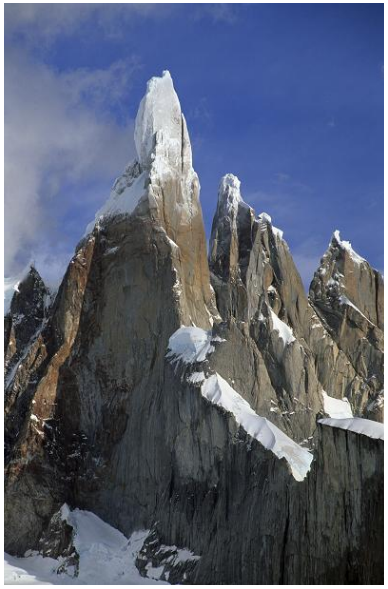
$$V = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

$$V_{min} = v/\sqrt{2}, v = \sqrt{\mu^2/\lambda} \simeq 250 \text{ GeV}$$

What if not?

e.g.

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



$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ (v_a + \rho_a + i\eta_a)\big/\sqrt{2} \end{pmatrix}, \quad a = 1, 2.$$

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: ρ

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

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

ρ_{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 $\rho \neq 1$):

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

TABLE III. Values of t^H and t_3^H which yield $\kappa^2 = 1$ for $t_3^H \leqslant 28$ $(t = \frac{1}{2})$.

t^H	$\lvert t_3^H \rvert$
$\frac{1}{2}$	$\frac{1}{2}$
3	2
$\frac{25}{2}$	$\frac{15}{2}$
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

$$\mathcal{L}_{\mathsf{Y}} = -Y_{ij}\,\overline{L'_{iL}}N'_{jR}\,\tilde{\phi} + \mathsf{H.c.}$$

$$\mathcal{L}_{\mathsf{M}} = -\frac{1}{2}M_{ij}\overline{N'_{iL}}N'_{jR} + \mathrm{H.c.}\,,$$

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

The neutrino mass matrix

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

with $M_D \ll M_R$.

$$m_N \sim M_R$$

$$m_{\mathrm{light}} \sim M_D^2/M_R$$

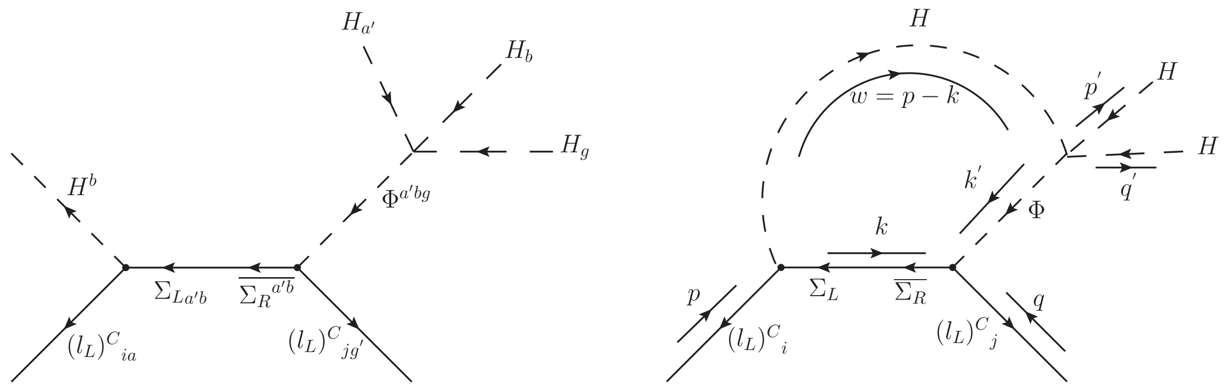
$M_D \sim \mathcal{O}(1)\ \mathrm{GeV} \rightarrow \mathrm{M_R} \sim 10^{15}\ \mathrm{GeV}$, if light neutrino masses of the order of 0.1 eV.

Effective operators - Weinberg,...

This is a typical situation for effective dimension-5 operators generated by $\kappa LLHH$ terms, for $M_R \sim 1$ 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



Σs here are triplet fermions

Seesaw II (scalar triplets)

$$\mathcal{L}_{\mathsf{Y}} = \frac{1}{\sqrt{2}} Y_{ij}\, \overline{\tilde{L}_{iL}}\, (\vec{\tau}\cdot\vec{\Delta})\, L_{jL} + \text{H.c.}\,,$$

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

can be left and right handed triplets

possible messengers at LHC

$$q\bar{q} \to Z^* \,/\, \gamma^* \to \Delta^{++}\Delta^{--}\,,$$

$$q\bar{q}' \to W^* \to \Delta^{\pm\pm}\Delta^{\mp}\,,$$

$$q\bar{q} \to Z^* \,/\, \gamma^* \to \Delta^{+}\Delta^{-}\,.$$

Seesaw III (3 leptonic triplets)

$$\begin{aligned}
\mathcal{L}_{\mathsf{Y}} &= -Y_{ij}\,\bar{L}'_{iL}(\vec{\Sigma}_j\cdot\vec{\tau})\,\tilde{\phi} + \text{H.c.}\,,\\
\mathcal{L}_{\mathsf{M}} &= -\frac{1}{2}\,M_{ij}\,\overline{\vec{\Sigma}^c_i}\cdot\vec{\Sigma}_j + \text{H.c.}\,,\\
\Sigma^+_j &= \frac{1}{\sqrt{2}}(\Sigma^1_j - i\Sigma^2_j)\,,\quad \Sigma^0_j = \Sigma^3_j\,,\quad \Sigma^-_j = \frac{1}{\sqrt{2}}(\Sigma^1_j + i\Sigma^2_j)\\
\mathcal{L}_{\nu,\text{mass}} &= -\frac{1}{2}\,(\bar{\nu}'_L\ \bar{N}'_L)\begin{pmatrix} 0 & \frac{v}{\sqrt{2}}Y \\ \frac{v}{\sqrt{2}}Y^T & M \end{pmatrix}\begin{pmatrix} \nu'_R \\ N'_R \end{pmatrix} + \text{H.c.}
\end{aligned}$$

possible messengers at LHC

$$\begin{aligned}
q\bar{q} &\to Z^*\,/\,\gamma^* \to E^+E^-\,,\\
q\bar{q}' &\to W^* \to E^\pm N\,. \qquad (1)
\end{aligned}$$

Example

	Seesaw I $m_N = 100$ GeV	Seesaw II $m_\Delta = 300$ GeV	Seesaw III $m_\Sigma = 300$ GeV
Six leptons	–	–	$\times$
Five leptons	–	–	28 fb^{-1}
$\ell^\pm\ell^\pm\ell^\pm\ell^\mp$	–	–	15 fb^{-1} m_E rec
$\ell^+\ell^+\ell^-\ell^-$	–	19 / 2.8 fb^{-1} $m_{\Delta^{++}}$ rec	7 fb^{-1} m_E rec
$\ell^\pm\ell^\pm\ell^\pm$	–	–	30 fb^{-1}
$\ell^\pm\ell^\pm\ell^\mp$	< 180 fb^{-1}	3.6 / 0.9 fb^{-1} $m_{\Delta^{++}}$ rec	2.5 fb^{-1} m_N rec
$\ell^\pm\ell^\pm$	< 180 fb^{-1} m_N rec	17.4 / 4.4 fb^{-1} $m_{\Delta^{++}}$ rec	1.7 fb^{-1} m_Σ rec
$\ell^+\ell^-$	$\times$	15 / 27 fb^{-1} m_Δ rec	80 fb^{-1} m_Σ rec
$\ell^\pm$	$\times$	$\times$	$\times$

Aguilar-Saavedra et al, NPB

Another way out, observable TeV scale see-saw I and II models

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

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 ϵ_i and δ_i.
- If by some symmetry one can guarantee the smallness of δ_i and ϵ_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)

Natural TeV-Scale Left-Right Seesaw for Neutrinos and Experimental Tests P. S. Bhupal Dev, Chang-Hun Lee, R.N. Mohapatra, arXiv:1309.0774

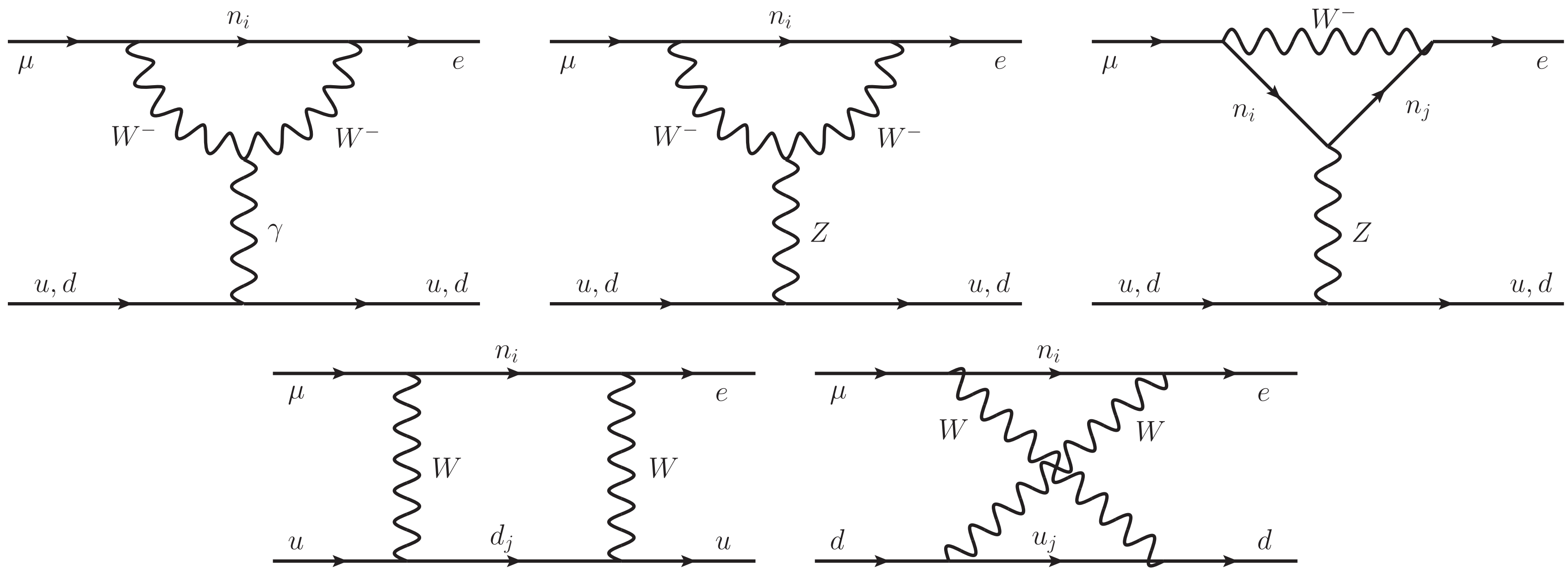
$\mu \to 3e$ conversion

The sensitivities for various nuclei are expected to be improved by several orders of magnitude,

$$R^{Ti}_{\mu\to e} \lesssim 10^{-18} \quad ,$$
$$R^{Al}_{\mu\to e} \lesssim 10^{-16} \quad ,$$

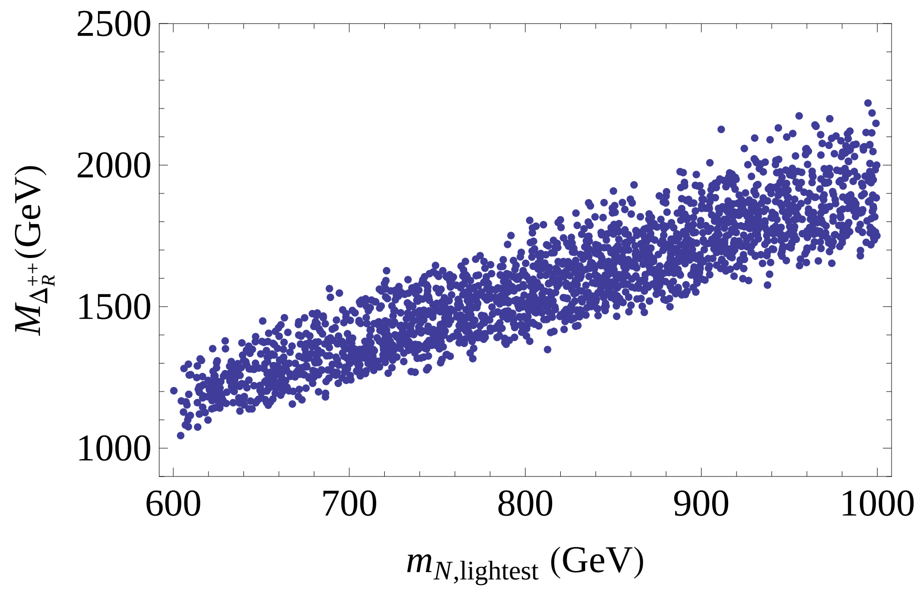
as compared to the present sensitivities

$$R^{Ti}_{\mu\to e} < 4.3 \times 10^{-12} ,$$
$$R^{Au}_{\mu\to e} < 7 \times 10^{-13},$$
$$R^{Pb}_{\mu\to e} < 4.6 \times 10^{-11} .$$



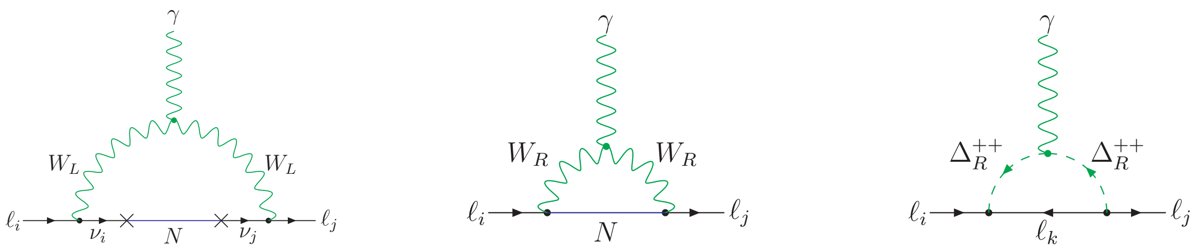
arXiv:1209.2679, Muon conversion to electron in nuclei in type-I seesaw models, Rodrigo Alonso, Mikael Dhen, Belen Gavela, Thomas Hambye

$$\mathrm{BR}(\mu \to 3e) \simeq \frac{1}{2}\left(\frac{M_{W_L}}{M_{W_R}}\right)^4 \left(\frac{M_{N,12}M_{N,11}}{M^2_{\Delta_R^{++}}}\right)^2 , \quad M_{W_R} = 3\ TeV$$



arXiv:1309.0774

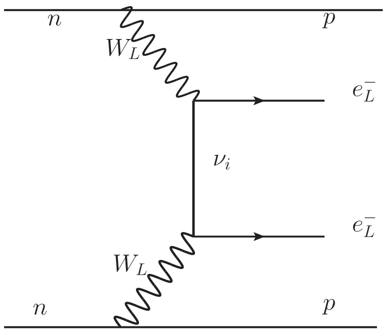
$\mu \to e\gamma$



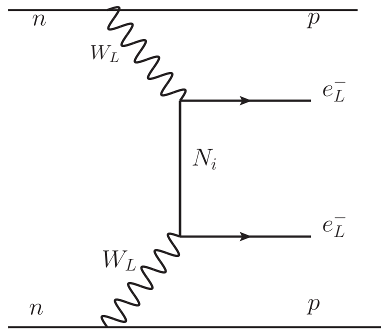
$$\mathrm{BR}(\mu \to e\gamma)_{\Delta_R^{++}} \simeq \frac{2\alpha_W M_{W_L}^4}{3\pi g^4} \left[\frac{(f f^\dagger)_{12}}{M^2_{\Delta_R^{++}}} \right]^2$$

e.g. $M_{\Delta_R^{++}} \geq 1.7$ TeV for RH charged current mixing ~ 0.01

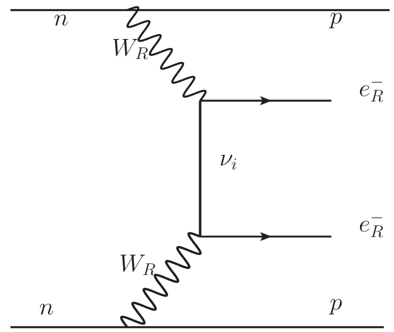
$0\nu\beta\beta$



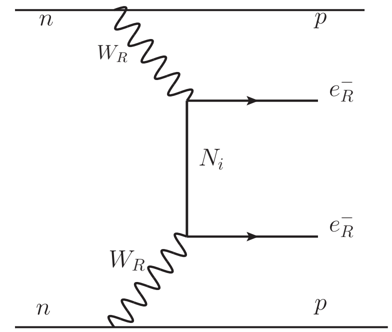
(a)



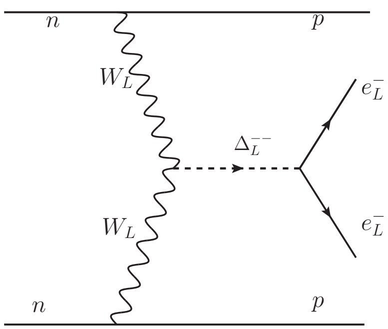
(b)

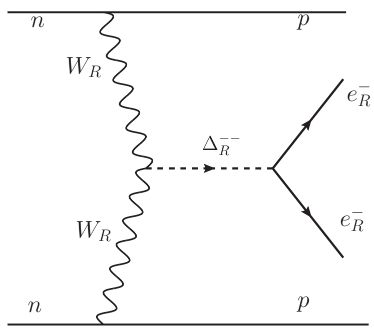


(a)

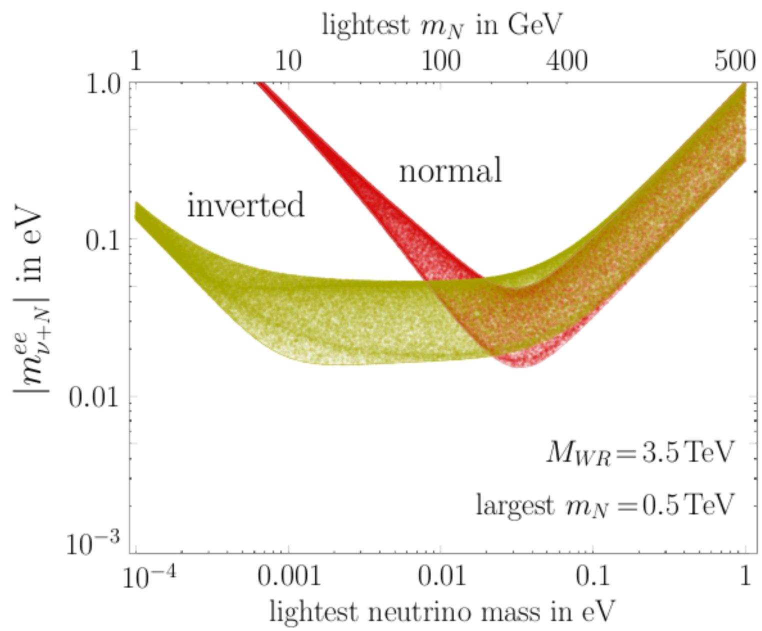


(b)



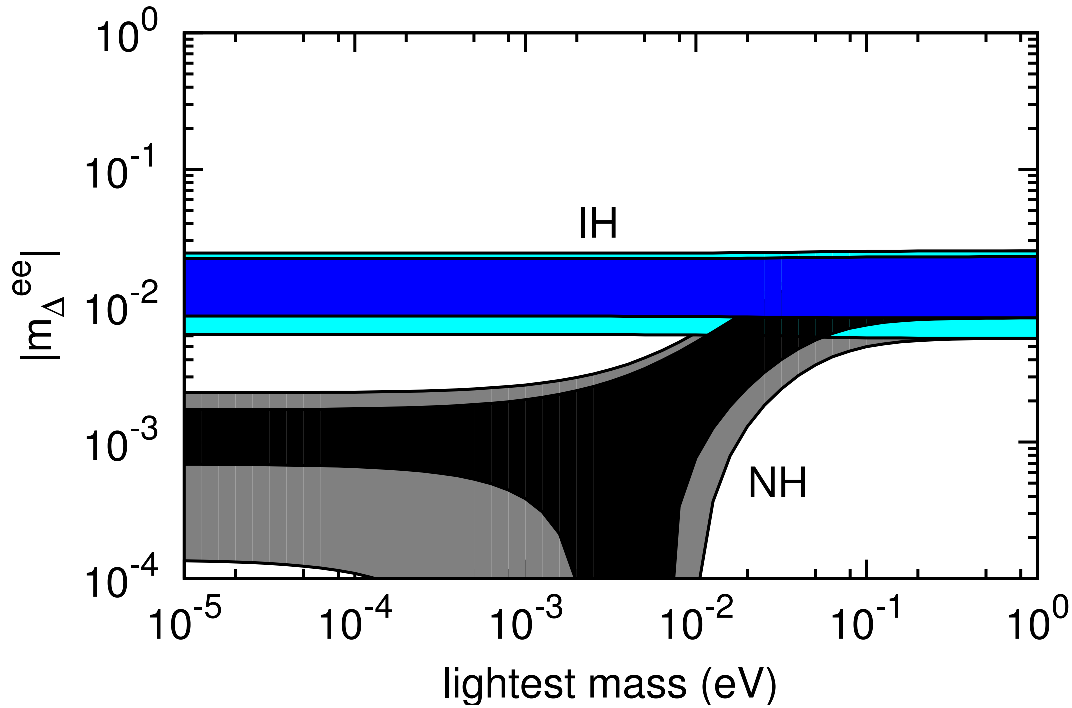


$$\frac{\Gamma_{0\nu\beta\beta}}{\ln 2} = G \cdot \left|\frac{\mathcal{M}_\nu}{m_e}\right|^2 \left(|m_\nu^{ee}|^2 + \left| p^2 \frac{M_W^4}{M_{W_R}^4} \frac{V_{Rej}^2}{m_{N_j}} \right|^2 \right)$$



Left-Right Symmetry: from LHC to Neutrinoless Double Beta Decay, arXiv:1011.3522, Tello et al

$$|m_\Delta^{ee}| = \left| p^2 \, \frac{M_{W_L}^4}{M_{W_R}^4} \, \frac{2\,M_N}{M_{\Delta_R}^2} \right|$$



PRESENT EXPERIMENTAL STATUS

Impressive LHC results, e.g. CMS report HIG-12-005

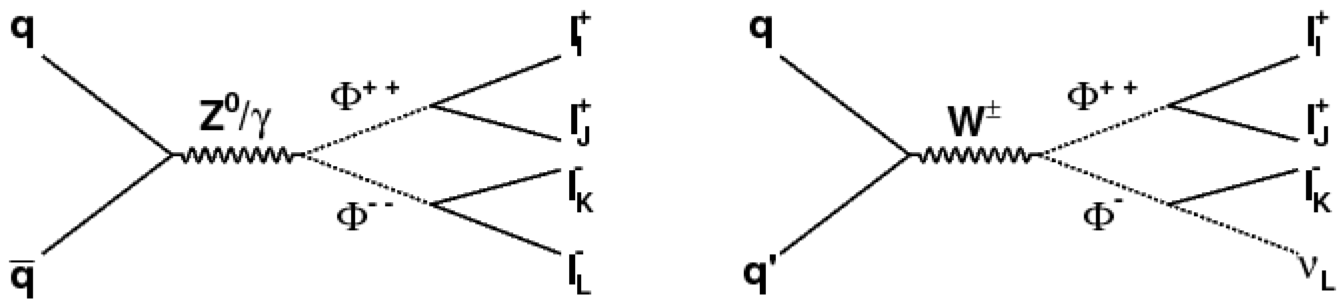


Figure 1: Feynman diagrams of both pair and associated production.

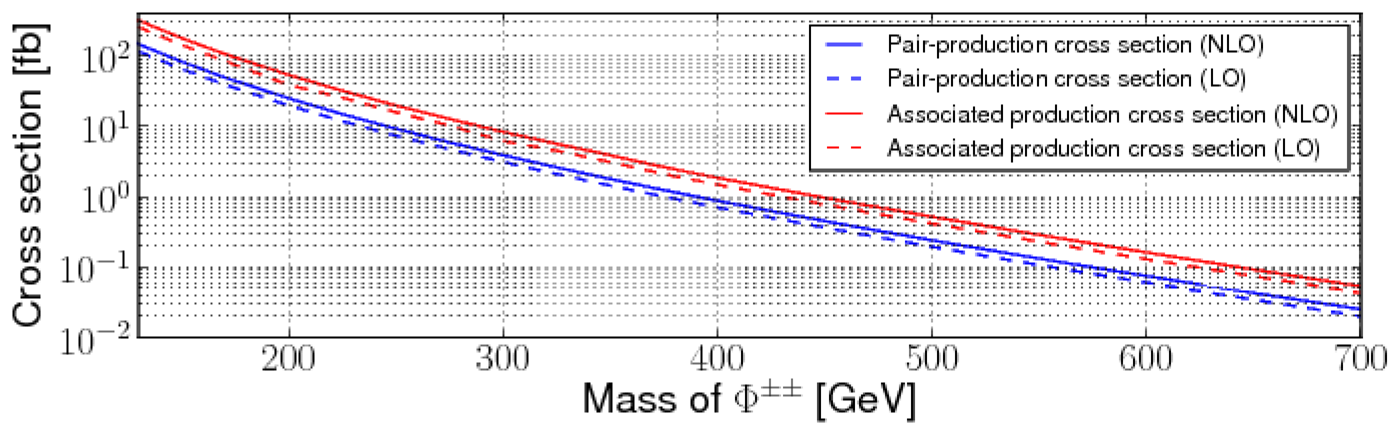


Table 6: Summary of the results

Benchmark point	Published limit	CMS combined result	CMS result for pair production only
$BR(\Phi^{++} \to e^+e^+) = 100\%$	225 GeV [34]	445 GeV	387 GeV
$BR(\Phi^{++} \to e^+\mu^+) = 100\%$	210 GeV [34]	455 GeV	389 GeV
$BR(\Phi^{++} \to e^+\tau^+) = 100\%$	112 GeV [34]	352 GeV	300 GeV
$BR(\Phi^{++} \to \mu^+\mu^+) = 100\%$	355 GeV [35] (245 GeV [34])	457 GeV	391 GeV
$BR(\Phi^{++} \to \mu^+\tau^+) = 100\%$	144 GeV [36]	369 GeV	313 GeV
$BR(\Phi^{++} \to \tau^+\tau^+) = 100\%$	128 GeV [36]	198 GeV	165 GeV
BP1	N/A	380 GeV	326 GeV
BP2	N/A	410 GeV	361 GeV
BP3	N/A	406 GeV	350 GeV
BP4	N/A	399 GeV	353 GeV

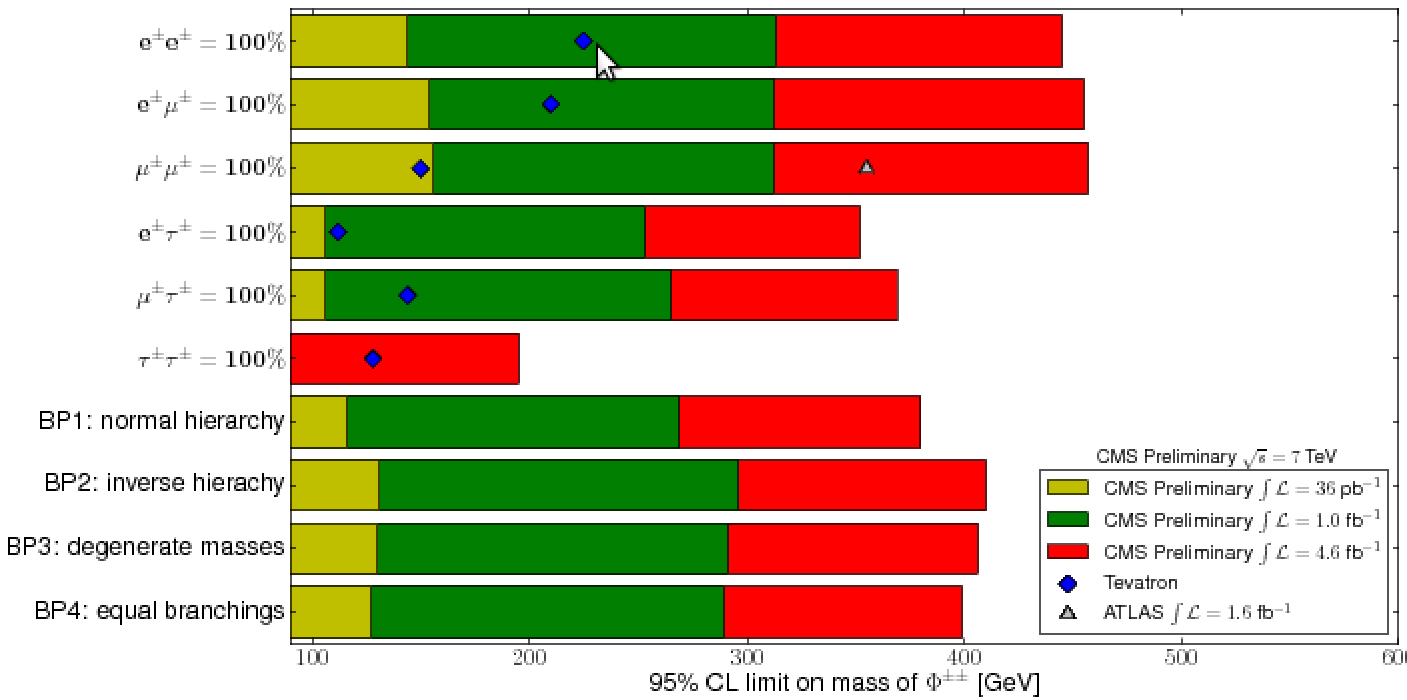
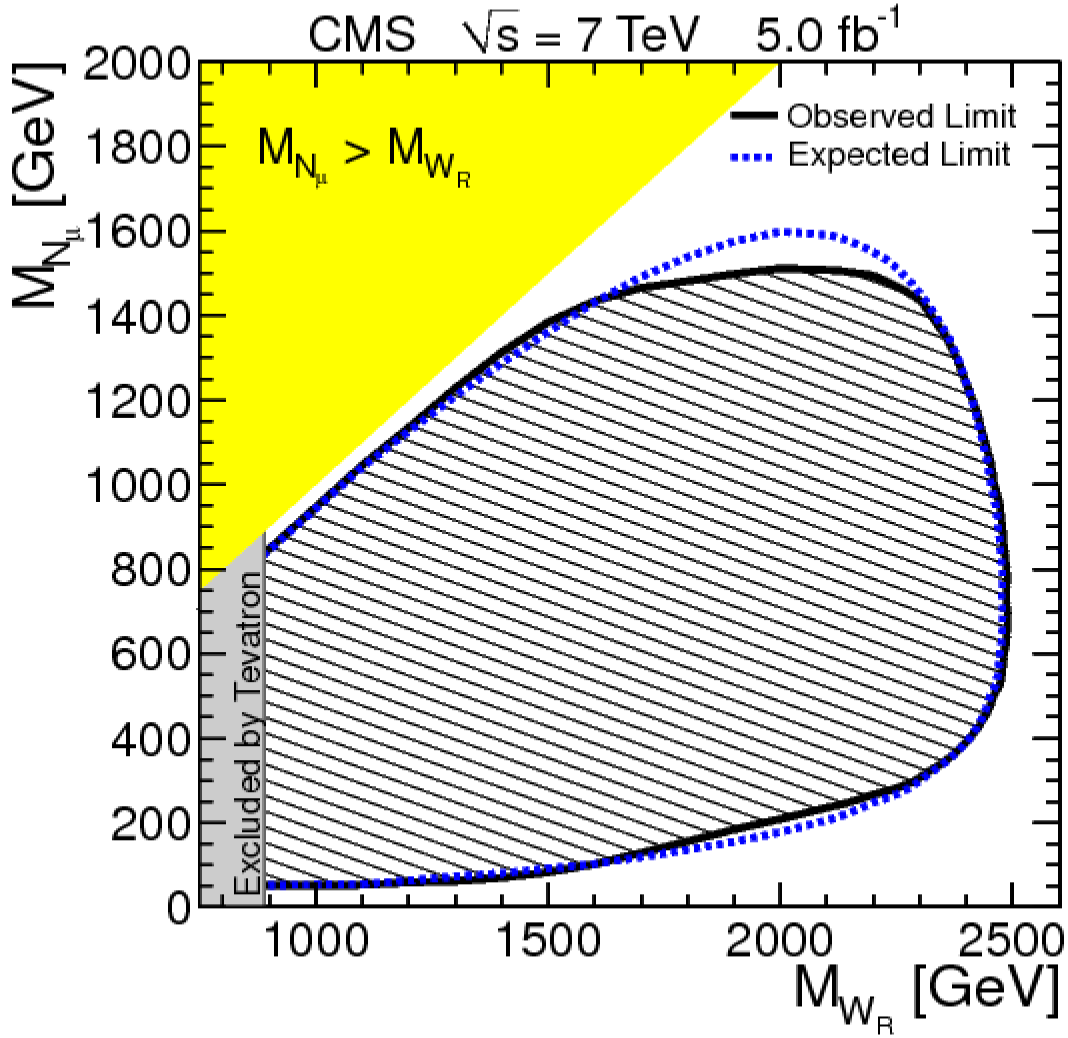


Figure 5: Observed Φ^{++} mass limits at 95% C.L. in different lepton final states. The branching ratios assumed in the limit calculation are indicated.



CMS, arXiv:1210.2402

PDG 2012

A REVIEW GOES HERE – Check our WWW List of Reviews

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
The following limits are obtained from $p\overline{p} \rightarrow W'X$ with W' decaying to the
indicated in the comments. New decay channels (*e.g.*, $W' \rightarrow WZ$) are assun
be suppressed. The most recent preliminary results can be found in the "W'-
searches" review above.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>2150	95	AAD	11Q	ATLS	$W' \rightarrow e\nu,\ \mu\nu$
none 180–690	95	[1] ABAZOV	11H	D0	$W' \rightarrow WZ$
> 863	95	[2] ABAZOV	11L	D0	$W' \rightarrow tb$
>1510	95	CHATRCHYAN	11Y	CMS	$W' \rightarrow q\overline{q}$

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Note, differcence with low energy

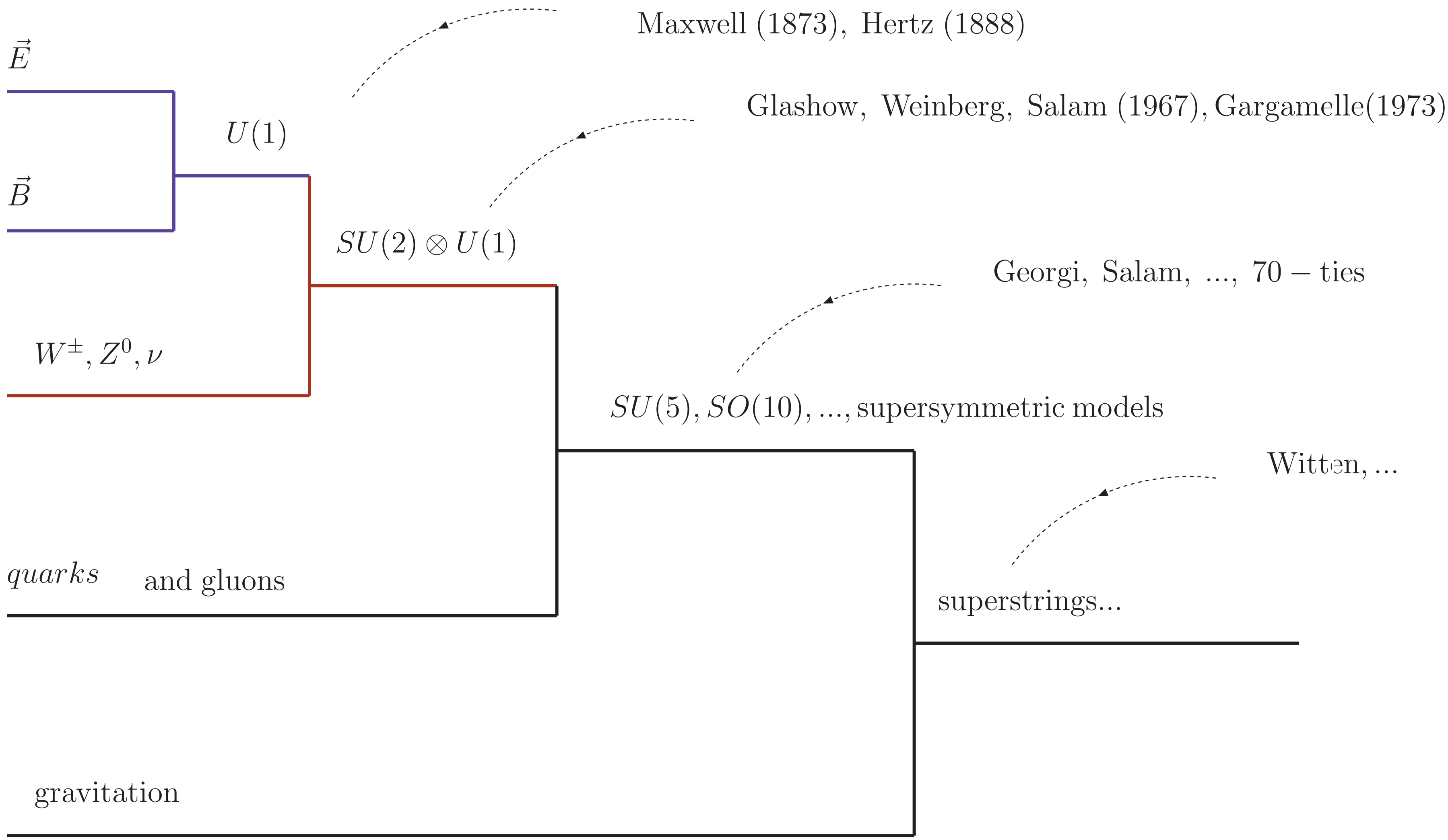
W_R (Right-Handed W Boson) MASS LIMITS

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 manif
left-right symmetry, *i.e.*, the equality of left- and right Cabibbo-Kobayashi-Maska
matrices. For a comprehensive review, see LANGACKER 89B. Limits on the W_L-W
mixing angle ζ are found in the next section. Values in brackets are from cosmologi
and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
> 715	90	[18] CZAKON	99	RVUE	Electroweak
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 245	90	[19] WAUTERS	10	CNTR	^{60}Co β decay
> 180	90	[20] MELCONIAN	07	CNTR	^{37}K β^+ decay
> 290.7	90	[21] SCHUMANN	07	CNTR	Polarized neutron decay
[> 3300]	95	[22] CYBURT	05	COSM	Nucleosynthesis; light ν_R
> 310	90	[23] THOMAS	01	CNTR	β^+ decay
> 137	95	[24] ACKERSTAFF	99D	OPAL	τ decay

Looking for more (gauge) symmetries

Simple picture again?



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

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

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

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

$$\begin{matrix} W_L^{\pm}, W_L^0 & & W_1^{\pm}, W_2^{\pm} \\ W_R^{\pm}, W_R^0 & \rightarrow [SSB?] & Z_1, Z_2 \\ B^0 & & \gamma \end{matrix}$$

however, when going into details...

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

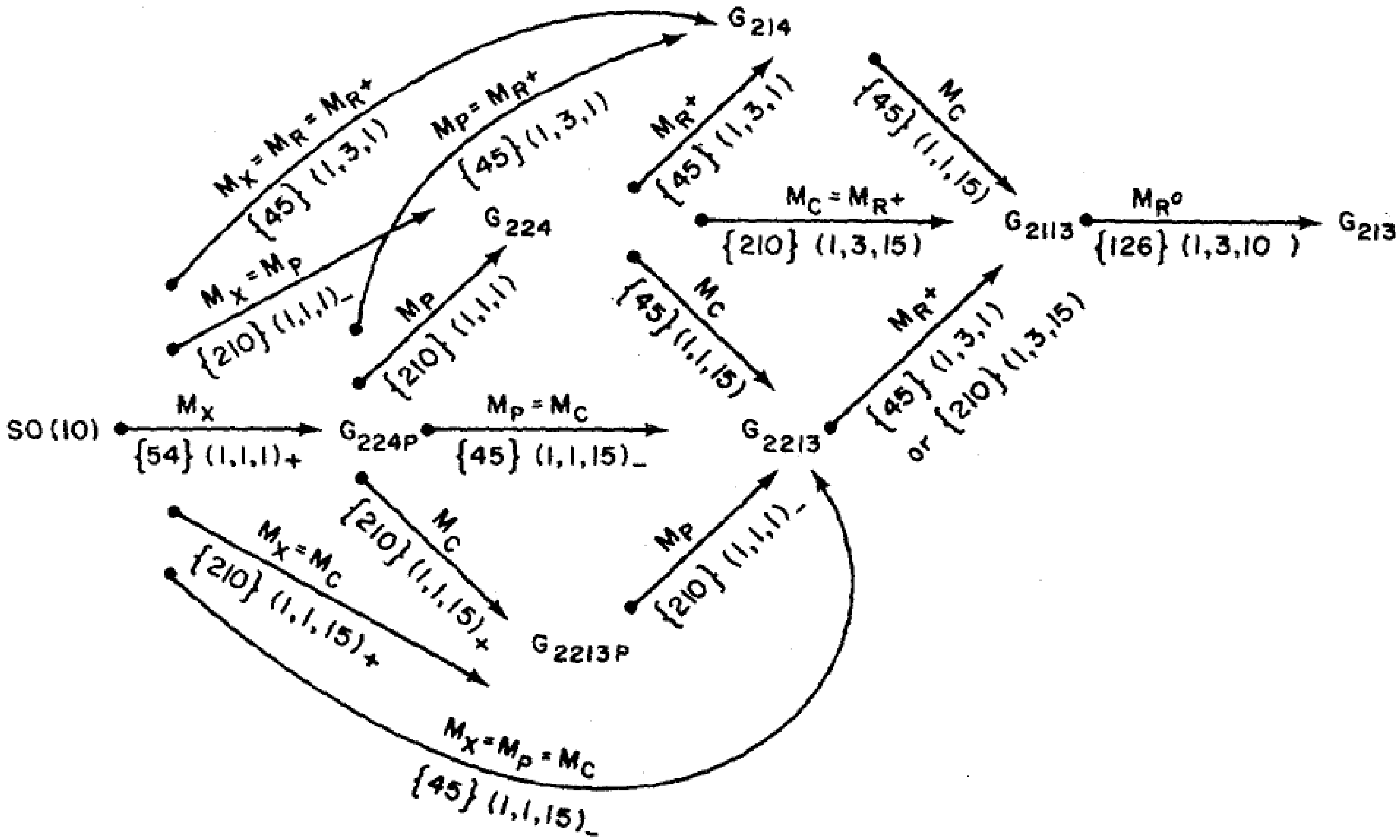
TABLE I. – E_6 *and its subgroups which contain* G_{SM}. *Here we use the inclusion relation* $SO(7) \supset SU(4) \supset SU(3) \times U(1)$.

E_6	F_4 $SO(10) \times U(1)$ $SU(2) \times SU(6)$ $SU(3) \times SU(3) \times SU(3)$
F_4	$SO(9)$ $SU(3) \times SU(3)$
$SO(9)$	$SU(2) \times SU(4)$
$SO(10)$	$SU(5) \times U(1)$ $SU(2) \times SU(2) \times SU(4)$ $SU(2) \times SO(7)$
$SU(6)$	$SU(5) \times U(1)$ $SU(2) \times U(1) \times SU(4)$ $SU(3) \times SU(3) \times U(1)$
$SU(5)$	$SU(3) \times SU(2) \times U(1)$

Extra gauge bosons

TABLE II. – *Group hierarchies which allow unification. Here the dots indicate that the hierarchy chains break directly into* G_{SM} *and* $G_{\mathrm{LR}} = SU(3) \times SU(2)_{\mathrm{L}} \times SU(2)_{\mathrm{R}} \times U(1)$ *indicates the left-right–symmetric gauge group.*

E_6	G_{LR}	$\rightarrow \ldots$	$\rightarrow \ldots$	
	$SU(2) \times SU(2) \times SU(4)$	$\rightarrow \ldots$	$\rightarrow \ldots$	
		G_{LR}	$\rightarrow \ldots$	
	$SO(10) \times U(1)$	$SU(2) \times SU(2) \times SU(4) \times U(1)$	$\rightarrow \ldots$	G_{SM}
			G_{LR}	
		G_{LR}	$\rightarrow \ldots$	
	$SU(2) \times SU(6)$	$SU(2) \times SU(3) \times SU(3) \times U(1)$	G_{LR}	
		$SU(2) \times SU(2) \times SU(4) \times U(1)$	$\rightarrow \ldots$	
			G_{LR}	
		G_{LR}	$\rightarrow \ldots$	
	$SU(3) \times SU(3) \times SU(3)$	G_{LR}	$\rightarrow \ldots$	
$SO(10)$	$SU(2) \times SU(2) \times SU(4)$	$\rightarrow \ldots$	$\rightarrow \ldots$	
		G_{LR}	$\rightarrow \ldots$	
	G_{LR}	$\rightarrow \ldots$	$\rightarrow \ldots$	



Diagrammatic sketch of 18 symmetry-breaking chains in SO(10).

Chang et al, PRD31, 1718 (1985)

Deshpande, Gunion, Kayser, Olness, 1991

$$
\begin{aligned}
&\mathcal{L}_{Higgs} = \\
&-\mu_1^2 Tr[\Phi^\dagger\Phi] - \mu_2^2(Tr[\tilde{\Phi}\Phi^\dagger] + Tr[\tilde{\Phi}^\dagger\Phi]) - \mu_3^2(Tr[\Delta_L\Delta_L^\dagger] + Tr[\Delta_R\Delta_R^\dagger]) \\
&+\lambda_1 Tr[\Phi\Phi^\dagger]^2 + \lambda_2(Tr[\tilde{\Phi}\Phi^\dagger]^2 + Tr[\tilde{\Phi}^\dagger\Phi]^2) + \lambda_3(Tr[\tilde{\Phi}\Phi^\dagger]Tr[\tilde{\Phi}^\dagger\Phi]) \\
&+\lambda_4(Tr[\Phi\Phi^\dagger](Tr[\tilde{\Phi}\Phi^\dagger] + Tr[\tilde{\Phi}^\dagger\Phi])) + \rho_1(Tr[\Delta_L\Delta_L^\dagger]^2 + Tr[\Delta_R\Delta_R^\dagger]^2) \\
&+\rho_2(Tr[\Delta_L\Delta_L]Tr[\Delta_L^\dagger\Delta_L^\dagger] + Tr[\Delta_R\Delta_R]Tr[\Delta_R^\dagger\Delta_R^\dagger]) + \rho_3(Tr[\Delta_L\Delta_L^\dagger]Tr[\Delta_R\Delta_R^\dagger]) \\
&+\rho_4(Tr[\Delta_L\Delta_L]Tr[\Delta_R^\dagger\Delta_R^\dagger] + Tr[\Delta_R\Delta_R]Tr[\Delta_L^\dagger\Delta_L^\dagger]) + \alpha_1(Tr[\Phi\Phi^\dagger](Tr[\Delta_L\Delta_L^\dagger] + Tr[\Delta_R\Delta_R^\dagger])) \\
&+\alpha_2(Tr[\Phi\tilde{\Phi}^\dagger]Tr[\Delta_R\Delta_R^\dagger] + Tr[\tilde{\Phi}\Phi^\dagger]Tr[\Delta_L\Delta_L^\dagger])) + \alpha_2^*(Tr[\Phi^\dagger\tilde{\Phi}]Tr[\Delta_R\Delta_R^\dagger] + Tr[\tilde{\Phi}^\dagger\Phi]Tr[\Delta_L\Delta_L^\dagger])) \\
&+\alpha_3(Tr[\Phi\Phi^\dagger\Delta_L\Delta_L^\dagger] + Tr[\Phi^\dagger\Phi\Delta_R\Delta_R^\dagger]) + \beta_1(Tr[\Phi\Delta_R\Phi^\dagger\Delta_L^\dagger] + Tr[\Phi^\dagger\Delta_L\Phi\Delta_R^\dagger]) \\
&+\beta_2(Tr[\tilde{\Phi}\Delta_R\Phi^\dagger\Delta_L^\dagger] + Tr[\tilde{\Phi}^\dagger\Delta_L\Phi\Delta_R^\dagger]) + \beta_3(Tr[\Phi\Delta_R\tilde{\Phi}^\dagger\Delta_L^\dagger] + Tr[\Phi^\dagger\Delta_L\tilde{\Phi}\Delta_R^\dagger]),
\end{aligned}
$$

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

$$\Delta_{L,R} = \begin{pmatrix} \delta^+_{L,R}/\sqrt{2} & \delta^{++}_{L,R} \\ \delta^0_{L,R} & -\delta^+_{L,R}/\sqrt{2} \end{pmatrix},$$

$$\Phi = \begin{pmatrix} \phi^0_1 & \phi^+_1 \\ \phi^-_2 & \phi^0_2 \end{pmatrix}.$$

with vacuum expectation values allowed for the neutral particles

$$\frac{v_L}{\sqrt{2}} = \langle \delta^0_L \rangle,$$

$$\text{new HE scale}: \frac{v_R}{\sqrt{2}} = \langle \delta^0_R \rangle,$$

$$\text{SM VEV scale}: \sqrt{\kappa_1^2 + \kappa_2^2}$$

$$\frac{\kappa_1}{\sqrt{2}} = \langle \phi^0_1 \rangle,$$

$$\frac{\kappa_2}{\sqrt{2}} = \langle \phi^0_2 \rangle.$$

- 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

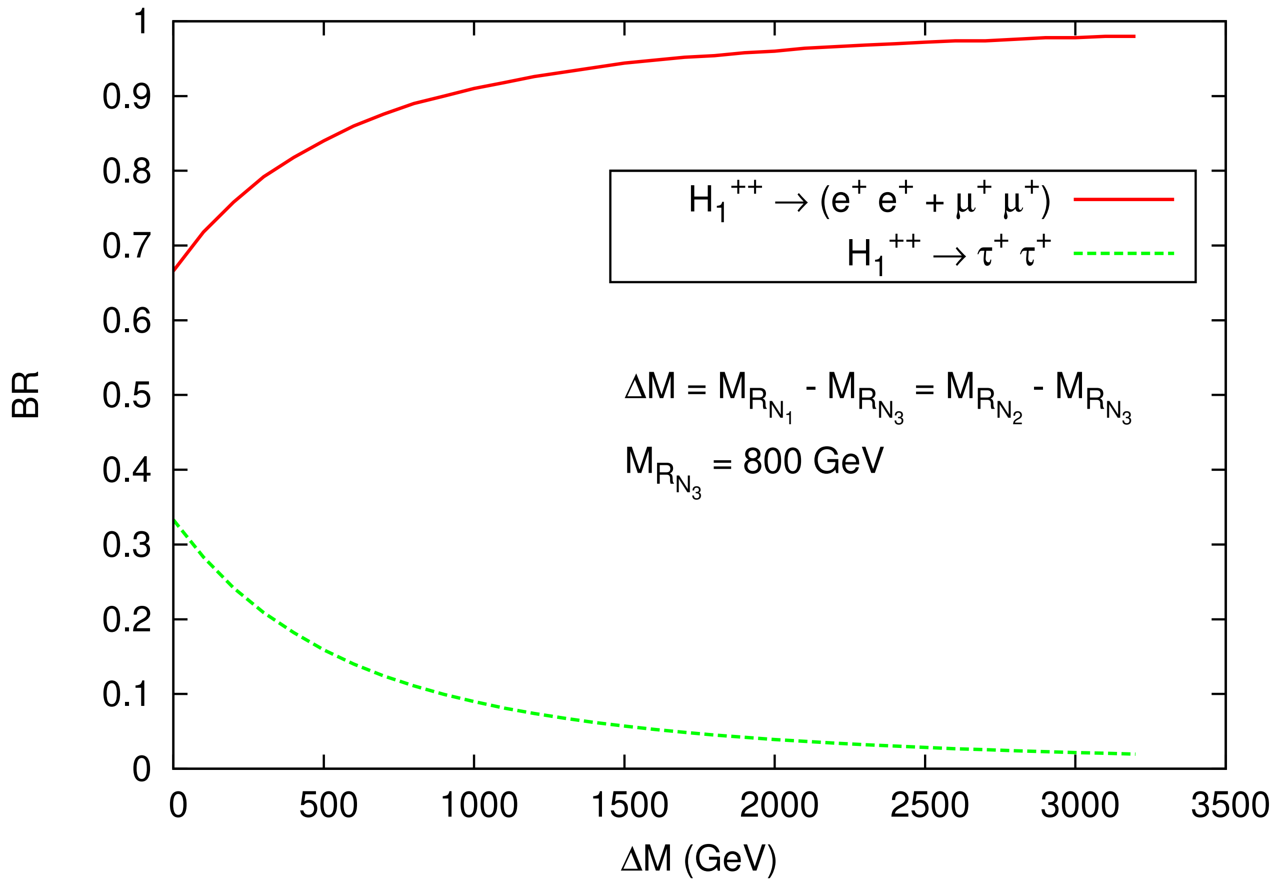
Primary production	Secondary production	Signal
I. $H_1^+ H_1^-$	$\ell^+ \ell^- \nu_L \nu_L$	$\ell^+ \ell^- \oplus MET$
–	$\ell^+ \ell^- \nu_R \nu_R$	depends on ν_R decay modes
–	$\ell^+ \ell^- \nu_L \nu_R$	depends on ν_R decay modes
II. $H_2^+ H_2^-$	$\ell^+ \ell^- \nu_L \nu_L$	$\ell^+ \ell^- \oplus MET$
–	$\ell^+ \ell^- \nu_R \nu_R$	depends on ν_R decay modes
–	$\ell^+ \ell^- \nu_L \nu_R$	depends on ν_R decay modes
III. $H_1^{++} H_1^{--}$	–	$\ell^+ \ell^+ \ell^- \ell^-$
–	$H_1^+ H_1^+ H_1^- H_1^-$	See I
–	$H_1^\pm H_1^\pm H_2^\mp H_2^\mp$	See I & II
–	$H_2^+ H_2^+ H_2^- H_2^-$	See II
–	$W_i^+ W_i^+ W_j^- W_j^-$	depends on W's decay modes
IV. $H_2^{++} H_2^{--}$	–	$\ell^+ \ell^+ \ell^- \ell^-$
–	$H_2^+ H_2^+ H_2^- H_2^-$	See II
–	$H_1^\pm H_1^\pm H_2^\mp H_2^\mp$	See I & II
–	$H_1^+ H_1^+ H_1^- H_1^-$	See I
–	$W_i^+ W_i^+ W_j^- W_j^-$	depends on W's decay modes
V. $H_1^{\pm\pm} H_1^\mp$	–	$l^\pm l^\pm l^\mp \nu_L$
VI. $H_2^{\pm\pm} H_2^\mp$	–	$l^\pm l^\pm l^\mp \nu_L$
VII. $H_1^\pm Z_i, H_1^\pm W_i$	–	See I & Z_i, W_i decay modes
VIII. $H_2^\pm Z_i, H_1^\pm W_i$	–	See II & Z_i, W_i decay modes
IX. $H_1^\pm A$	–	See I
X. $H_2^\pm A$	–	See II

Branching ratios

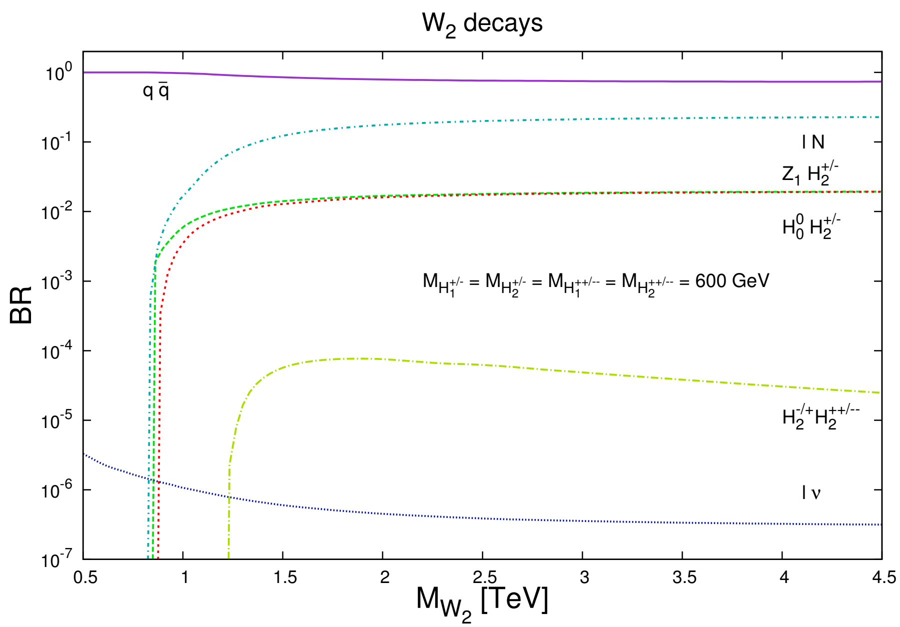
$$
\begin{array}{ll}
\text{(i)} & H_1^{\pm\pm} \to l^\pm l^\pm, \text{ where } l = e, \mu, \tau; \\
\text{(ii)} & H_1^{\pm\pm} \to H_1^\pm W_1^\pm; \\
\text{(iii)} & H_2^{\pm\pm} \to l^\pm l^\pm, \text{ where } l = e, \mu, \tau; \\
\text{(iv)} & H_2^{\pm\pm} \to H_2^\pm W_2^\pm; \\
\text{(v)} & H_2^{\pm\pm} \to W_2^\pm W_2^\pm; \\
\text{(vi)} & H_2^{\pm\pm} \to H_2^\pm W_1^\pm;
\end{array}
$$

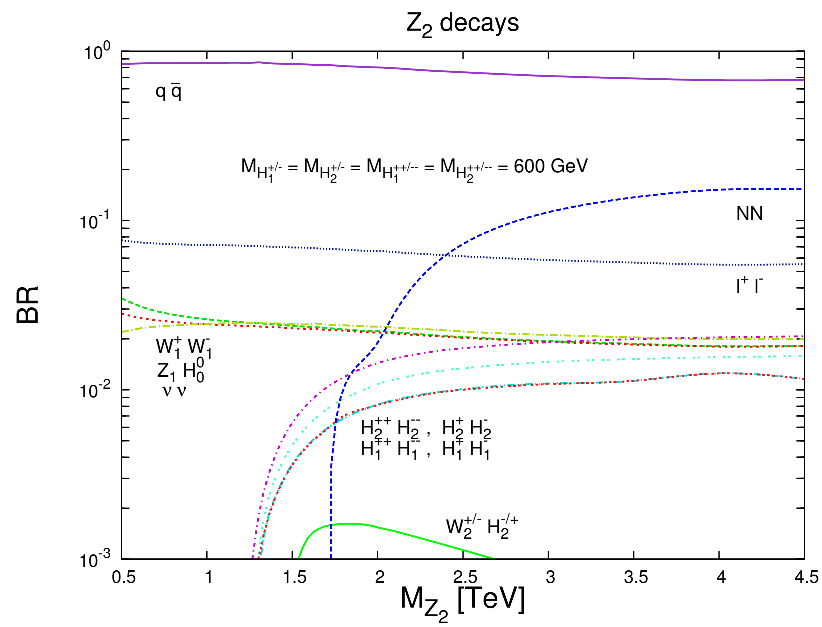
In principle we can have both LNV and LFV,

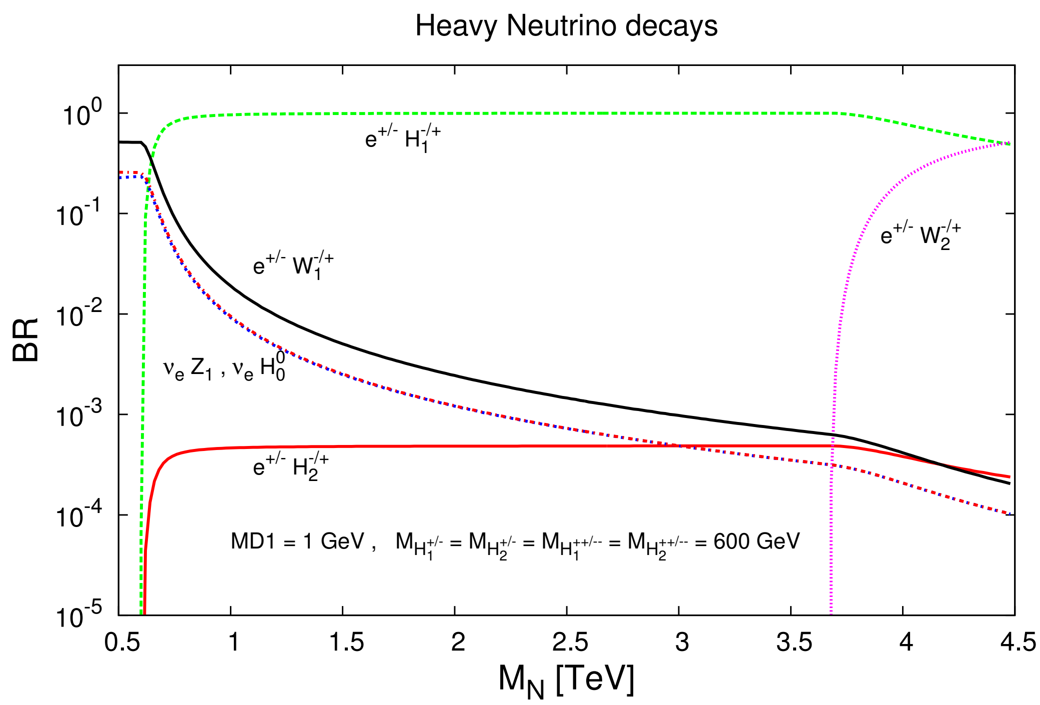
$$
\begin{aligned}
BR(H_{1/2}^{\pm\pm} \to e^\pm e^\pm) &= 37.9\% \\
BR(H_{1/2}^{\pm\pm} \to \mu^\pm \mu^\pm) &= 37.9\% \\
BR(H_{1/2}^{\pm\pm} \to \tau^\pm \tau^\pm) &= 24.2\%.
\end{aligned}
$$



1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
BR
0
500
1000
1500
2000
2500
3000
3500
ΔM (GeV)
H1++ → (e+ e+ + μ+ μ+)
H1++ → τ+ τ+
ΔM = MRN1 - MRN3 = MRN2 - MRN3
MRN3 = 800 GeV


W2 decays
BR
MW2 [TeV]
q q̄
l N
Z1 H2+/-
H0 H2+/-
MH1+/- = MH2+/- = MH1++/-- = MH2++/-- = 600 GeV
H2-/+H2++/--
l ν


Z2 decays
BR
MZ2 [TeV]
q q̄
MH1+/- = MH2+/- = MH1++/-- = MH2++/-- = 600 GeV
NN
l+ l-
W1+ W1-
Z1 H0
ν ν
H2++ H2--, H2+ H2-
H1++ H1--, H1+ H1-
W2+/- H2-/+



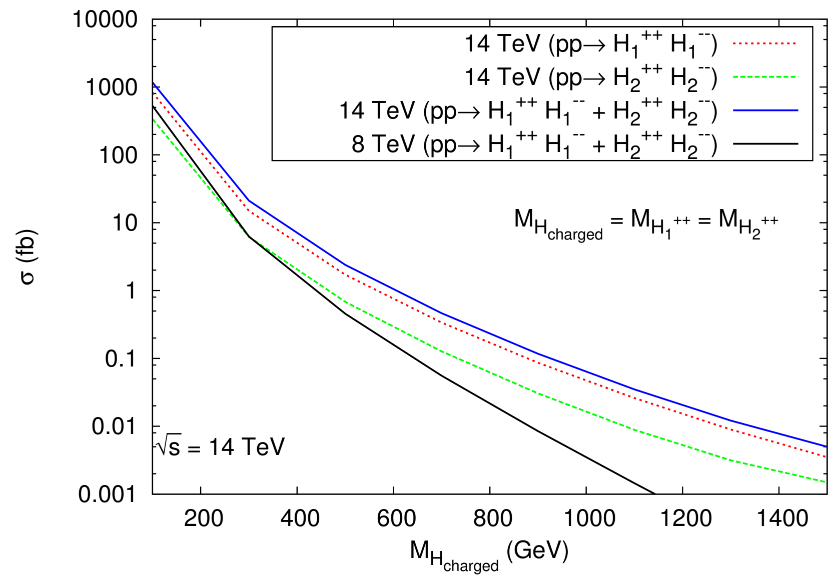
substantial Higgs boson decay mode

$$m_{H^{\pm\pm}_{1,2}} = 400\text{GeV}:$$

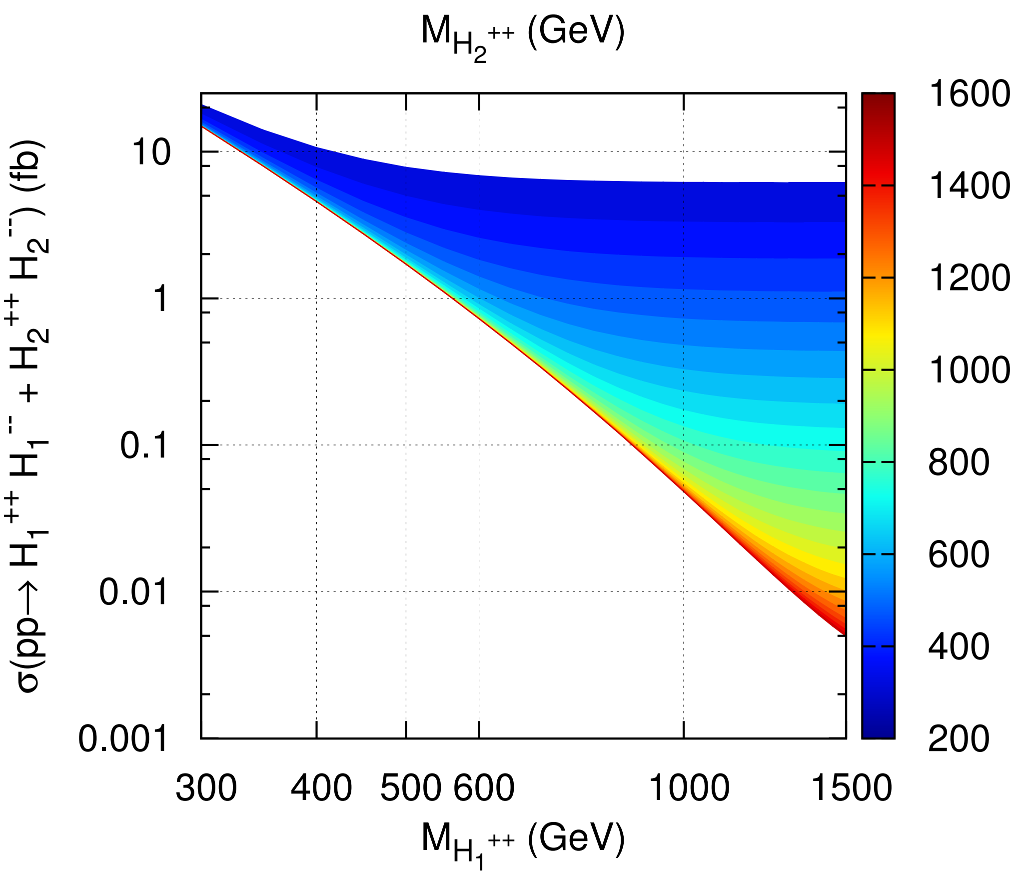
$$\sigma(pp \to H^{++}_{1,2} H^{--}_{1,2} \to l_i{}^+ l_i{}^+ l_j{}^- l_j{}^-) = 1.441(6.059)\ fb \text{ for } \sqrt{s} = 8(14)\ \text{TeV},$$

$$m_{H^{\pm\pm}_{1,2}} = 600\text{GeV}:$$

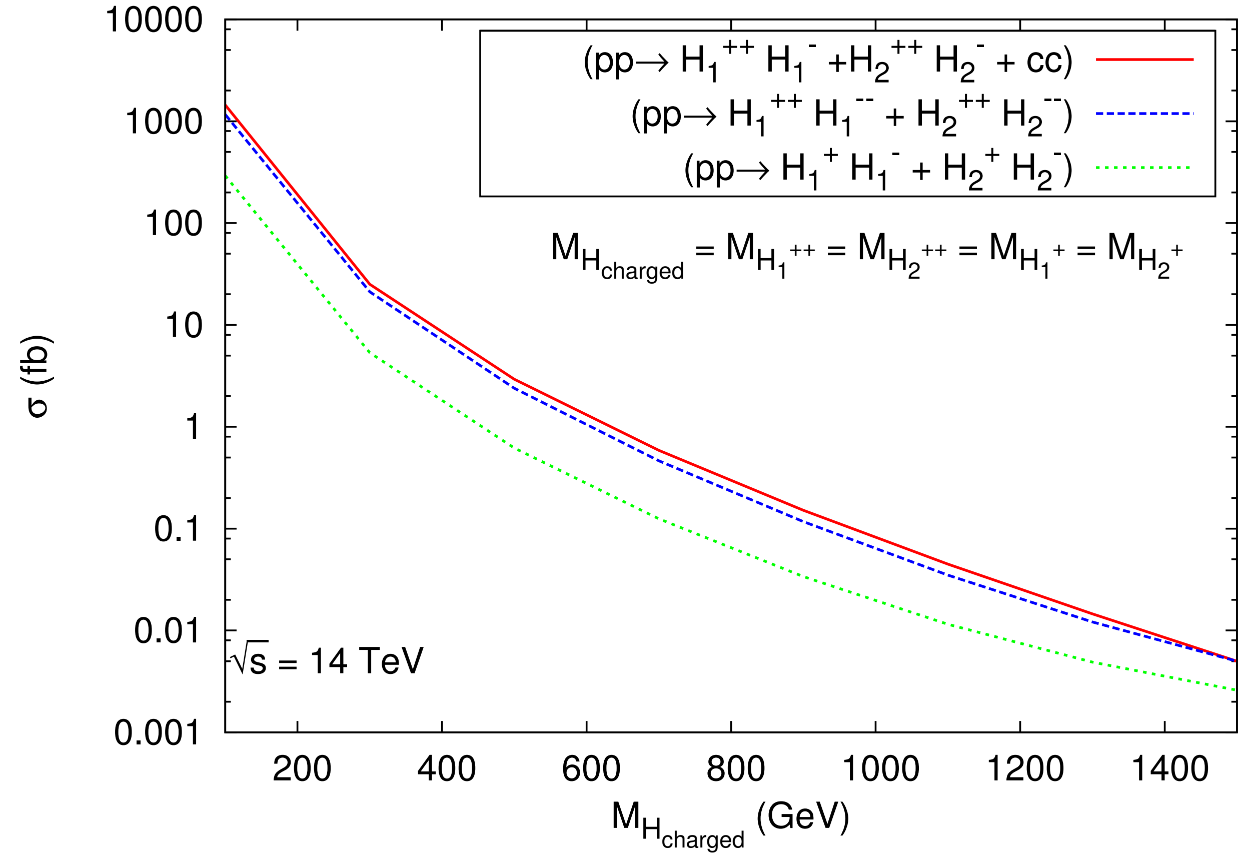
$$\sigma(pp \to H^{++}_{1,2} H^{--}_{1,2} \to l_i{}^+ l_i{}^+ l_j{}^- l_j{}^-) = 0.144(0.9498)\ fb \text{ for } \sqrt{s} = 8(14)\ \text{TeV}.$$



Non degenerate scenarios



summary for productions, without cuts



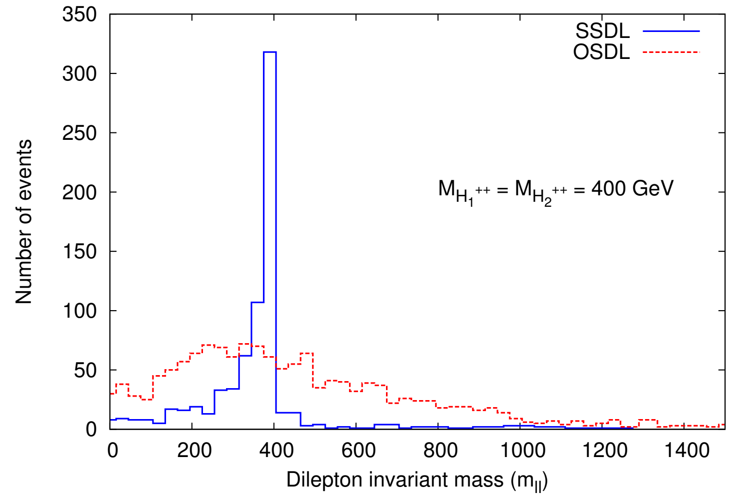
Kinematic cuts

- 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 μ^- or μ^+) 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, $\frac{\sum p_{T_{hadron}}}{p_{T_l}} \leq 0.2$ within the cone of radius 0.2 around the lepton.
- Hard p_T cuts: $p_{Tl_1} > 30$ GeV, $p_{Tl_2} > 30$ GeV, $p_{Tl_3} > 20$ GeV, $p_{Tl_4} > 20$ 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 $L = 300\ fb^{-1}$

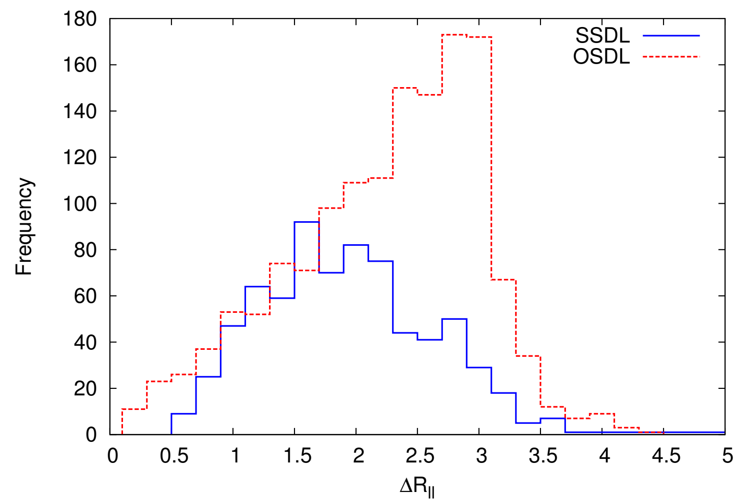
- no missing energy or jet involved
- reconstructed invariant masses for same sign dileptons (SSDL) and opposite sign dileptons (OSDL). As the doubly charged scalars are the parents of the dilepton pair, invariant mass of the SSDL is expected to give a clean peak around the mass of the doubly charged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



Another interesting variable which can be used for determination of signals

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

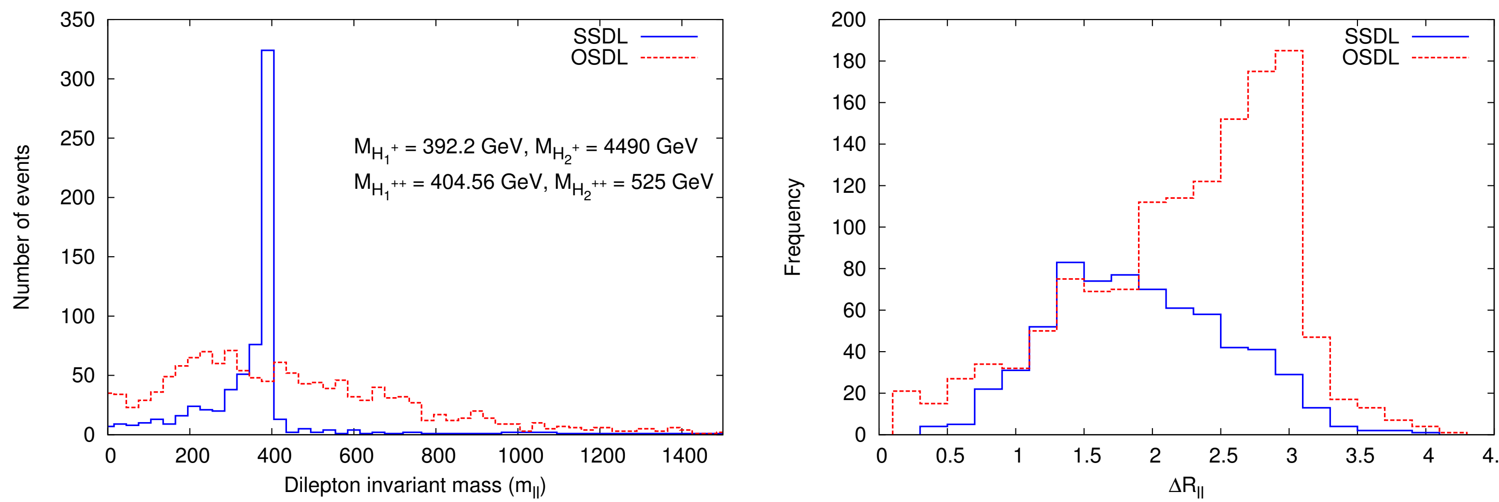
we choose only events for which leptons are well separated.



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

$pp \to H_1^{\pm\pm} H_1^{\mp}$ and $pp \to H_2^{\pm\pm} H_2^{\mp}$: 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.



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

$$R_-^+ = \frac{\#\text{ of events for } \ell^+\ell^+\ell^-}{\#\text{ of events for } \ell^-\ell^-\ell^+} = \frac{464}{207} \simeq 2.24. \tag{2}$$

Background estimation

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

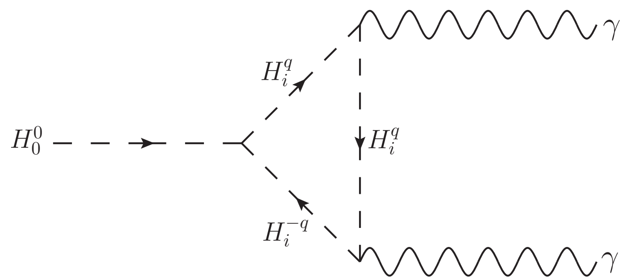
Standard Model background cross-sections for tri- and four-lepton signals are as follow:

processes	3ℓ (fb)	4ℓ (fb)
$t\bar{t}$	18.245	–
$t\bar{t}(Z/\gamma^\star)$	1.121	0.069
$t\bar{t}W^\pm$	0.656	–
$W^\pm(Z/\gamma^\star)$	10.590	–
$(Z/\gamma^\star)(Z/\gamma^\star)$	1.287	0.047
TOTAL	**31.899**	**0.116**

Luminosity	Background 3ℓ events	Signal 3ℓ events	Background 4ℓ events	Signal 4ℓ events scenario I	scenario II
25 fb^{-1}	797.5	55.9	2.9	(i) 30 (ii) 4.4	24.8
300 fb^{-1}	9569.7	671	34.8	(i) 360 (ii) 53	298

- 4-lepton signals are well beyound 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)

$H_0^0 \to \gamma\gamma$



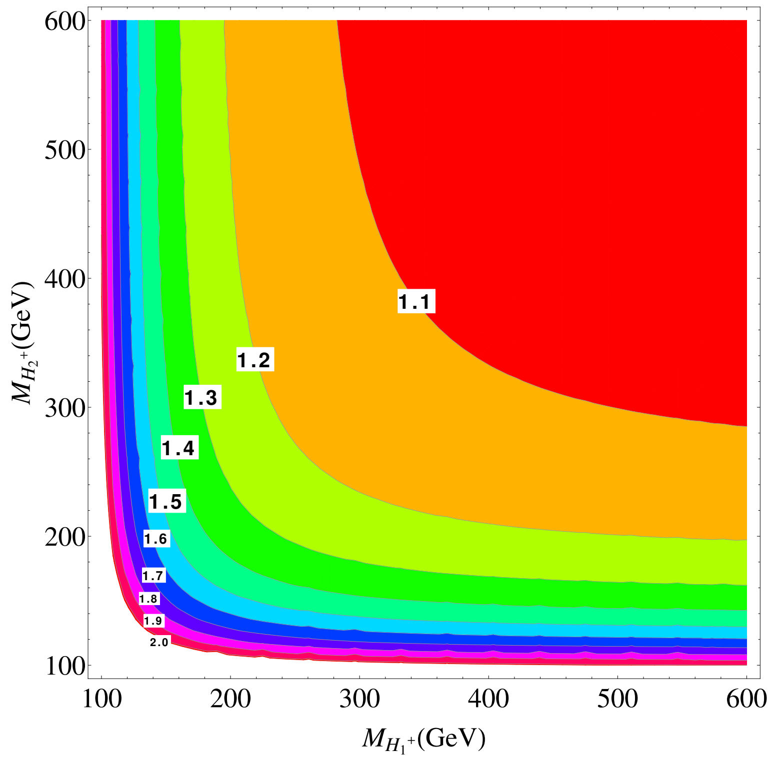
Charged scalar contribution to the $H_0^0 \to \gamma\gamma$ channel at the LHC. In the loop there are four contributions coming from the charged scalars ($H_1^{\pm\pm}$, $H_2^{\pm\pm}$, $H_1^{\pm}$, $H_2^{\pm}$).

Present values

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

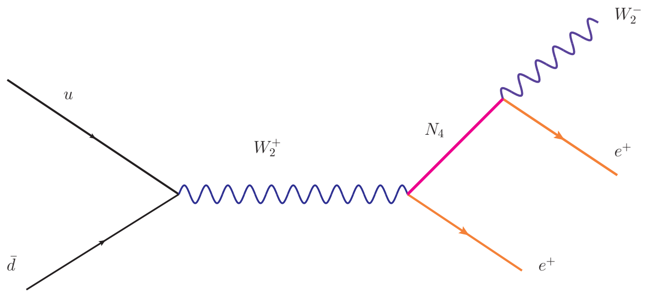
$$R_{\gamma\gamma} = 0.78^{+0.28}_{-0.26} \text{ (CMS)} .$$

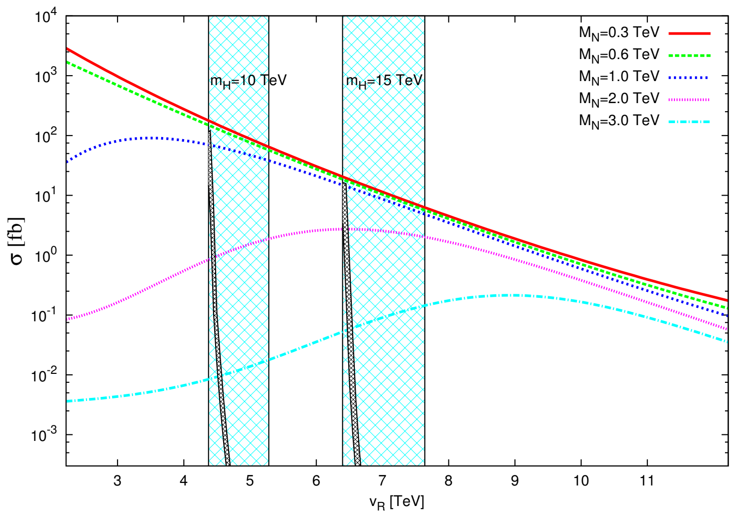
$$R_{\gamma\gamma} = \left| 1 + \sum_{s=H_{1,2}^{\pm\pm}, H_{1,2}^{\pm}} Q_s^2 \frac{c_s}{2} \frac{k_+^2}{M_s^2} \frac{A_0(\tau_s)}{A_1(\tau_{W_L}) + N_c Q_t^2 A_{1/2}(\tau_t)} \right|^2 .$$



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?