BSM-GUT particles at LHC

Janusz Gluza
Katowice, Poland

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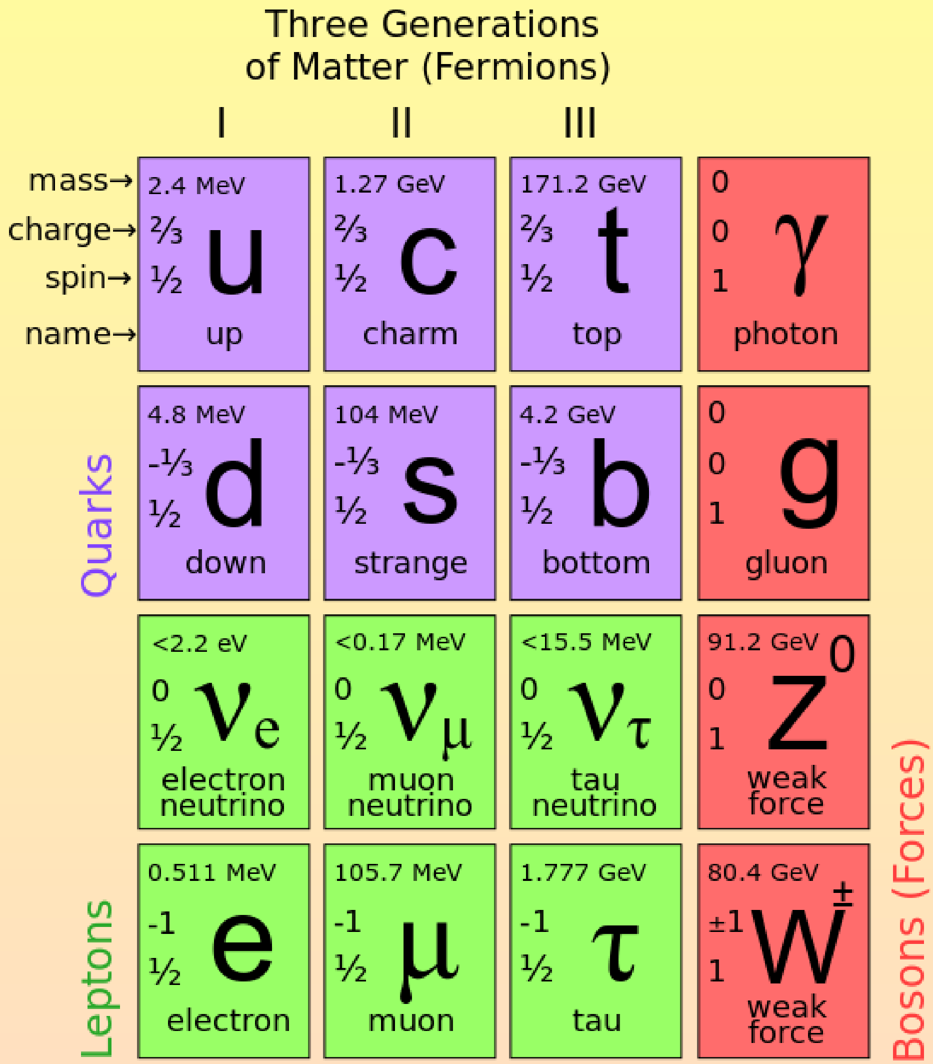
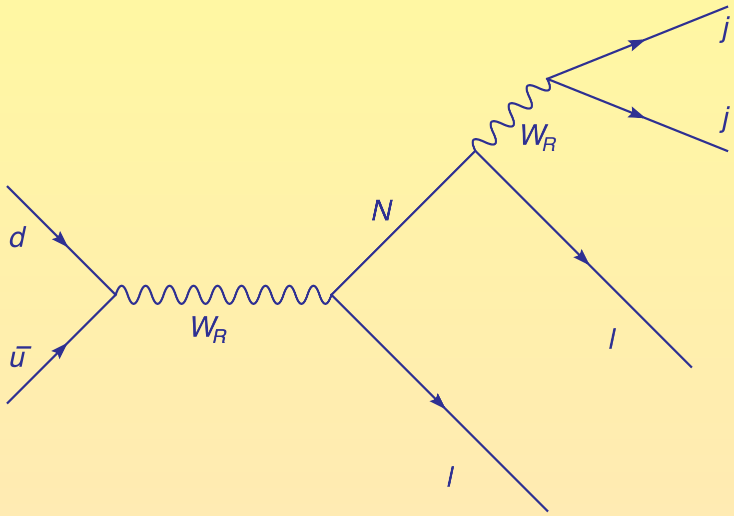
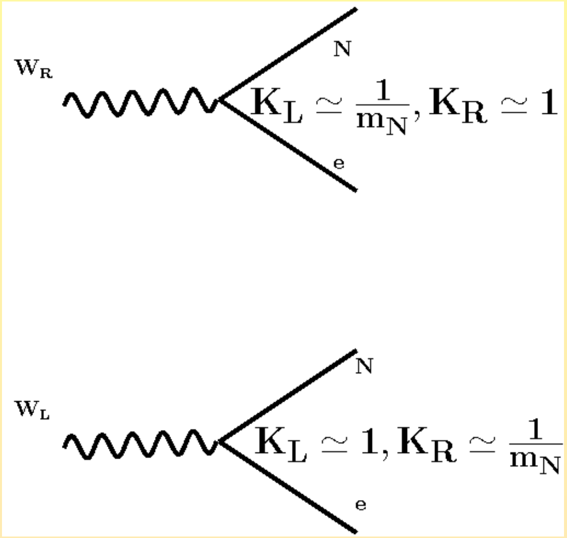
- we should be ready to distinct them (and exclude unapropriate, finally)

”Mendeleev” table of particle physics



Extra gauge bosons, heavy neutrinos: Golden Event

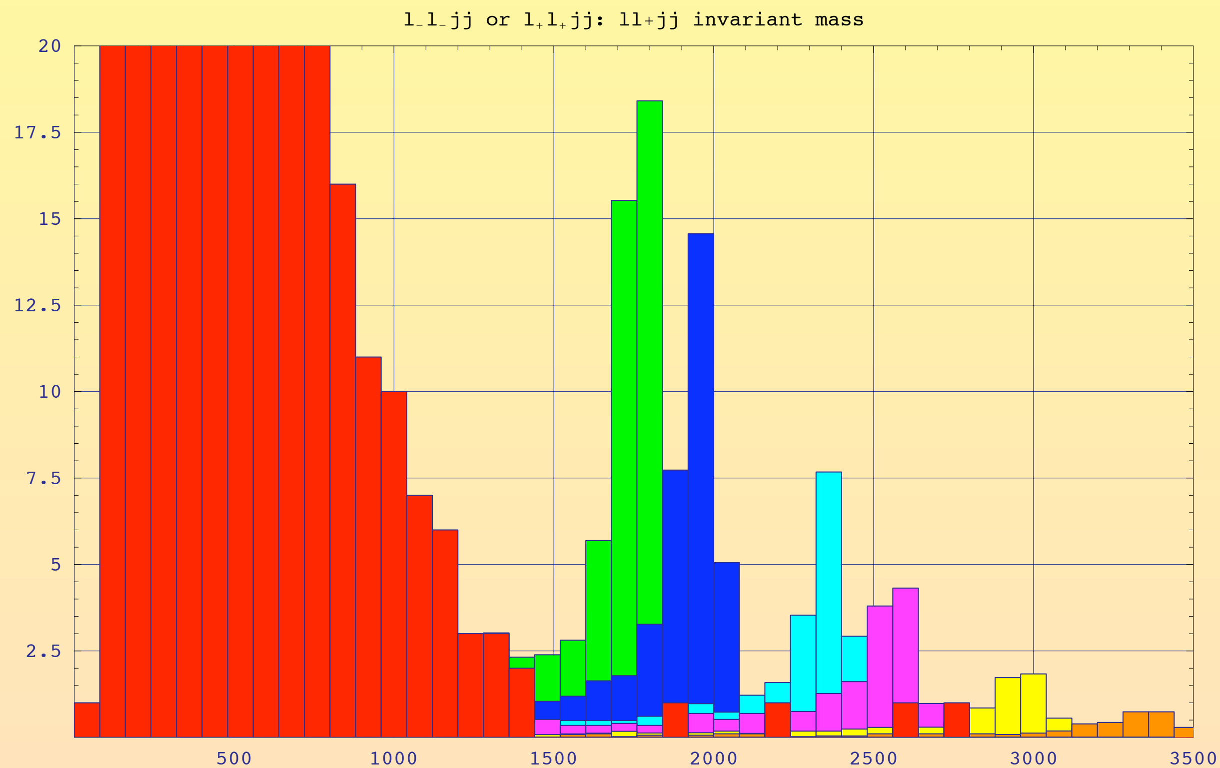




For right-handed charged currents there is no damping factors like $\sin(\xi)$
$[W_L - W_R$ mixing]
and/or [light state]-[heavy neutrino] mixing, K_R right- (~ 1)

for more discussion on couplings, see e.g. JG, Zralek, PRD48, 1993, JG, APPB33, 2002

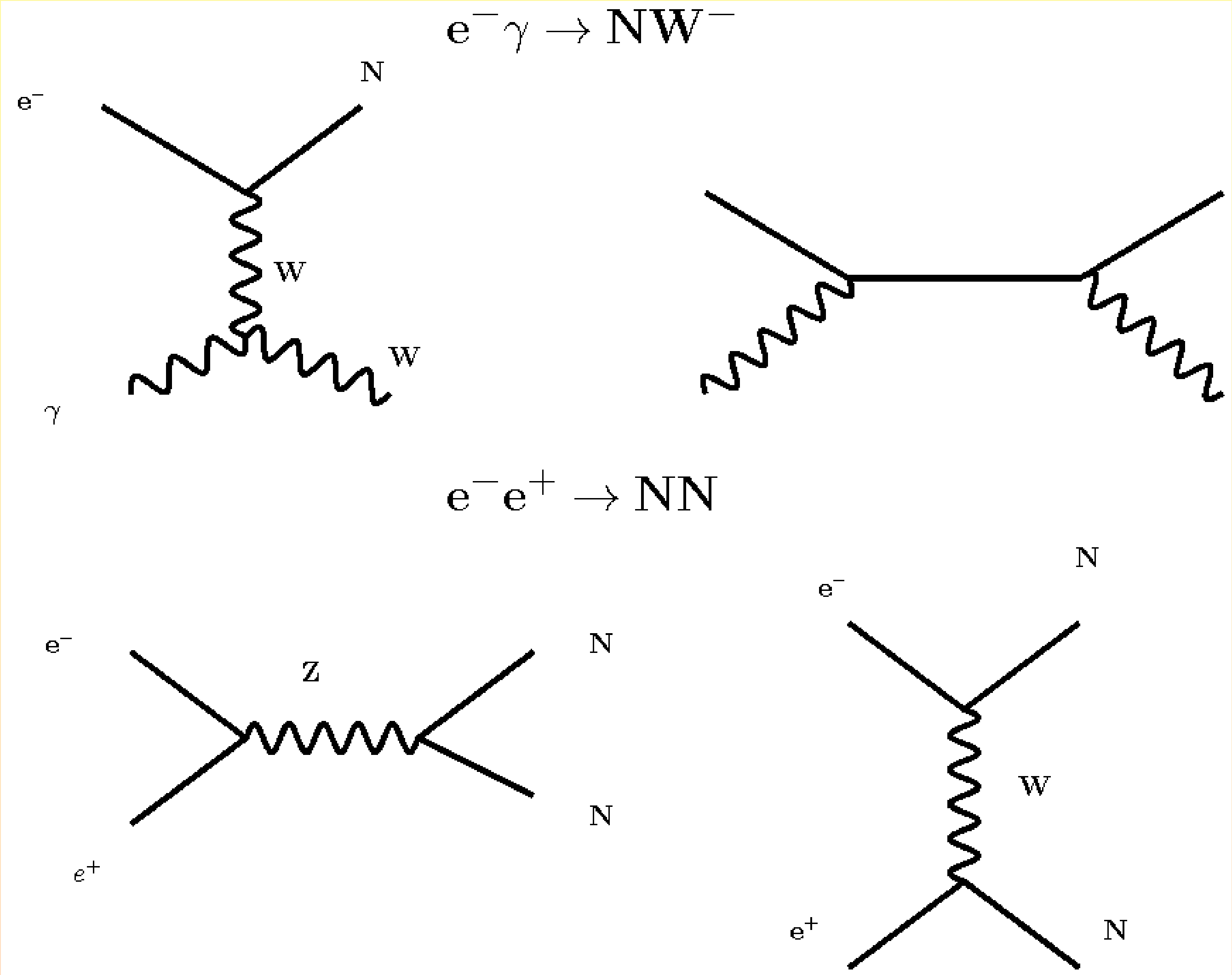
Reconstruction of M_N and M_{W_R} at LHC



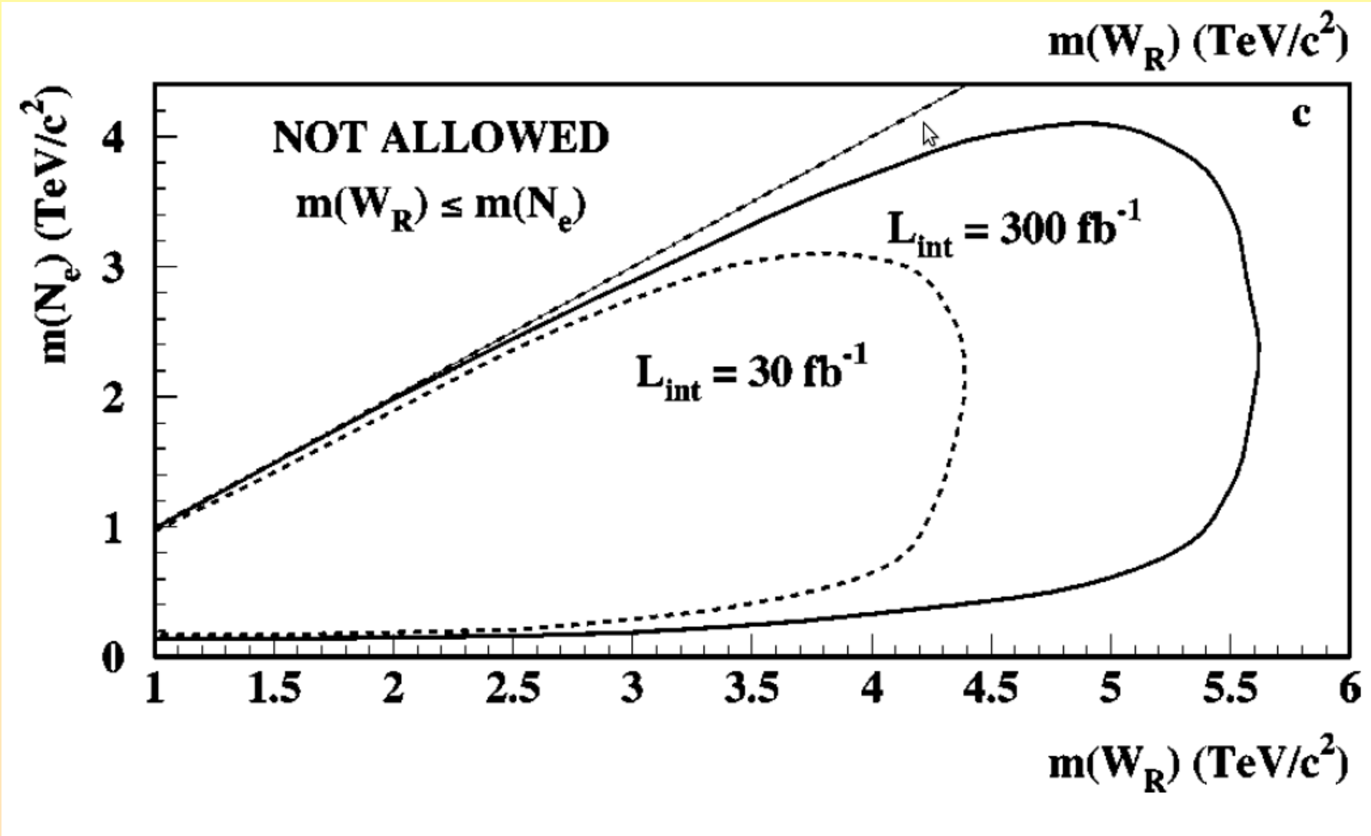
Senjanovic et al, arXiv:1012.4104

$M_{W_2} \simeq 1.8 \div 3.4$ TeV, detectable signal after a few months running with 200-300 pb^{-1}

ILC option: suppresed (depends on $\sin(\xi)$ and K_L, K_R mixing matrices)



W_R and N in Atlas



Discovery potential of $pp \to W_R \to eN_e \to eejj$

Ferrari et al, PRD62, 013001

Heavy neutrinos: see-saw type-I, type-II, type-III

Seesaw I: right handed singlets

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

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

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

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The neutrino mass matrix

$$M_\nu = \begin{pmatrix} 0 & M_D(\kappa_{1,2}) \\ M_D^T & M_R(v_R) \end{pmatrix}$$

with $M_D \ll M_R$.

$$\begin{aligned} m_N &\sim M_R \\ m_{\mathrm{light}} &\sim M_D^2/M_R \end{aligned}$$

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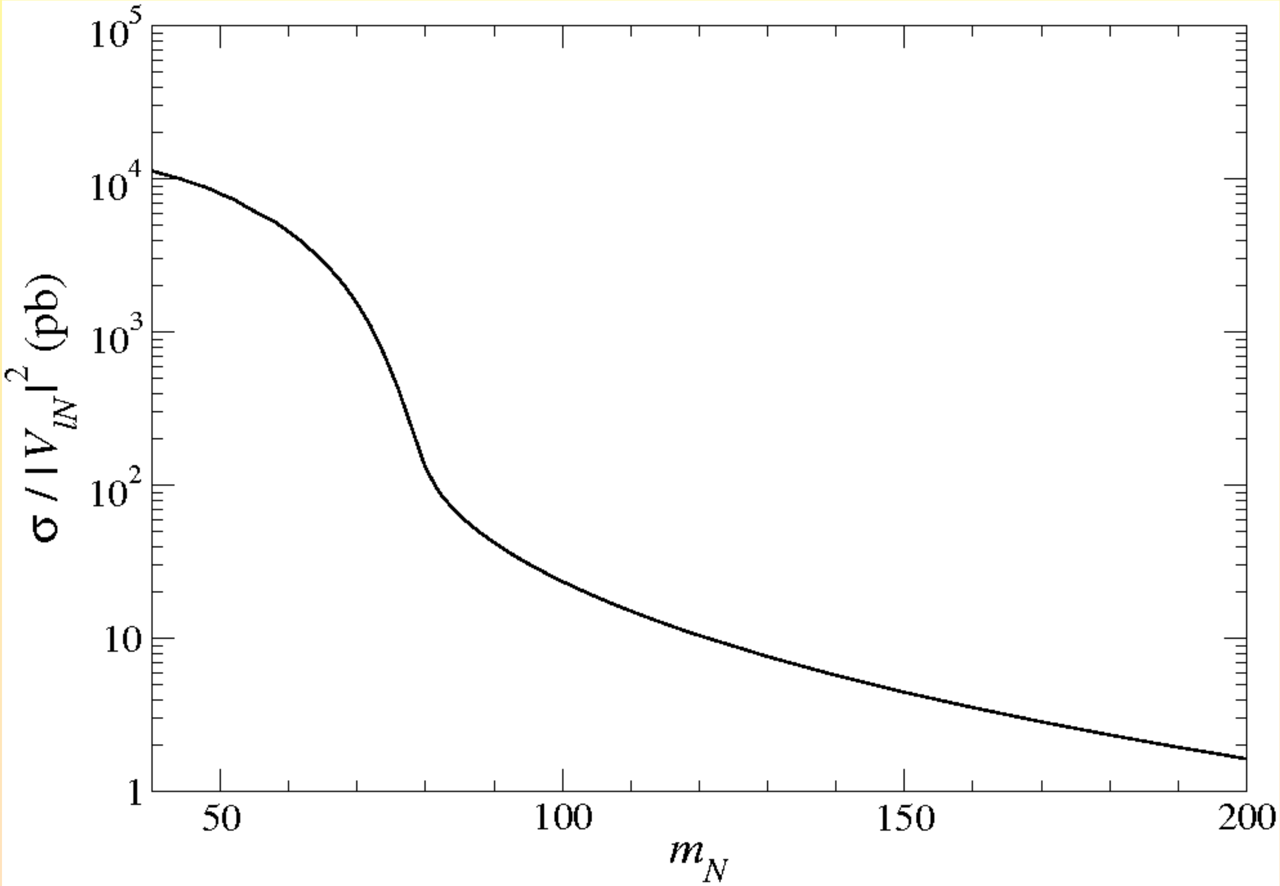
$M_D \sim \mathcal{O}(1)\ \mathrm{GeV} \rightarrow \mathrm{M_R} \sim 10^{15}\ \mathrm{GeV}$, if light neutrino masses of the order of 0.1 eV.

$$q\bar{q}' \to W^* \to l^{\pm}N$$



e.g. Aguilar-Saavedra et al, NPB

Seesaw II (scalar triplets)

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

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

can be left and right handed triplets

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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} + \mathsf{H.c.}\,, \\
\mathcal{L}_{\mathsf{M}} &= -\frac{1}{2}\,M_{ij}\,\overline{\vec{\Sigma}^c_i}\cdot\vec{\Sigma}_j + \mathsf{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,\mathrm{mass}} &= -\frac{1}{2}\begin{pmatrix}\bar{\nu}'_L & \bar{N}'_L\end{pmatrix}\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} + \mathrm{H.c.}
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possible messengers at LHC

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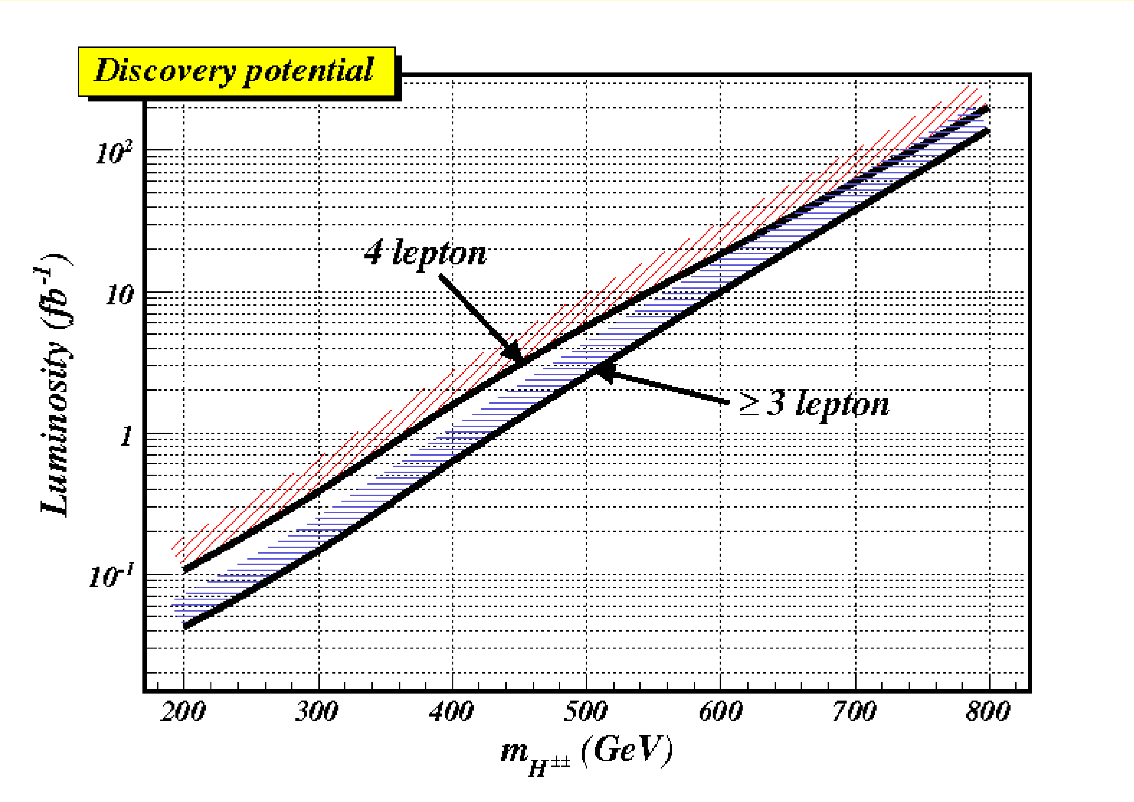
\begin{aligned}
q\bar{q} &\to Z^*\,/\,\gamma^* \to E^+E^-\,,\\
q\bar{q}' &\to W^* \to E^\pm N\,.
\end{aligned}
\tag{1}
$$

	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

Double charged Higgs particles 5σ at LHC

$q\bar{q} \to H^{++}H^{--}$ and $\overline{qq'} \to H^{\pm\pm}H^{\mp}$ and decays: $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ and $H^{\pm} \to \ell^{\pm}\nu$



Akeroyd et al, JHEP 1011:005,2010

Conclusions (I)

all looks promising, many non-standard particles can be probed at LHC

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there are some grains of pain ...

Breaking chains

$$G \rightarrow G^{(1)} \rightarrow G^{(2)} ... \rightarrow G^{(n)} \rightarrow G_{SM}$$

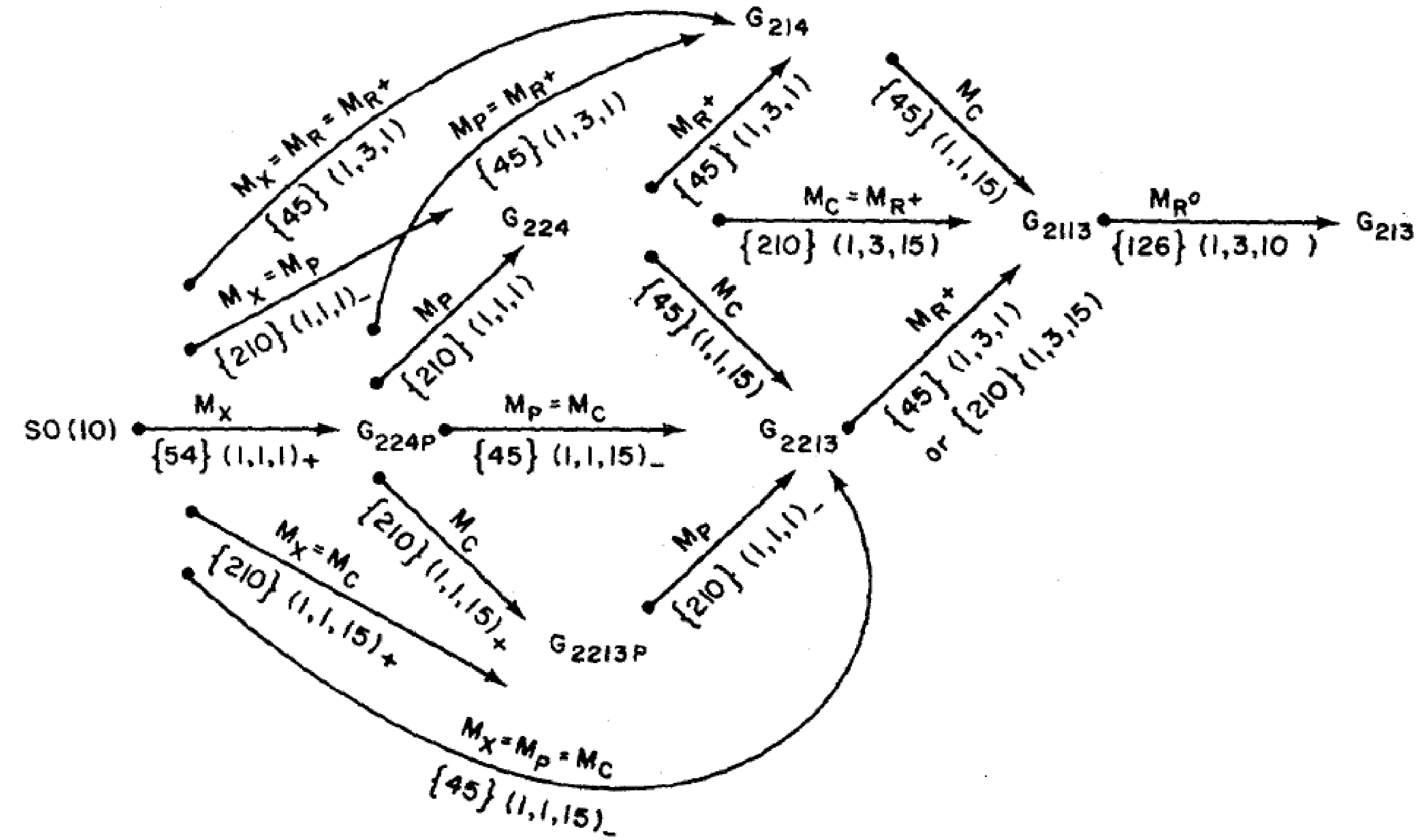
TABLE I. – *E_6 and its subgroups which contain G_{SM}. Here we use the inclusion relation $SO(7) \supset SU(4) \supset SU(3) \times U(1)$.*

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* $G_{LR} = SU(3) \times SU(2)_L \times SU(2)_R \times U(1)$ *indicates the left-right–symmetric gauge group.*

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



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

Chang et al, PRD31, 1718 (1985)

Investigation of unification (at 10^{15} GeV) through G_{LR} groups and running of couplings (RGE) plus consistency with LEP data require

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$$\begin{aligned} 10^9\, GeV < \quad & M_{W_R} \quad < 5 \cdot 10^{10}\, GeV, \quad \mathrm{LR\ model} \\ & M_{W_R} \quad \simeq 10^{15}\, GeV, \quad \mathrm{Pati-Salam\ model} \end{aligned}$$

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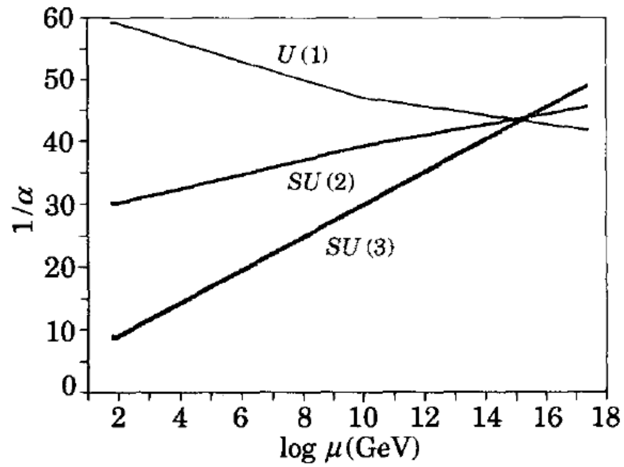
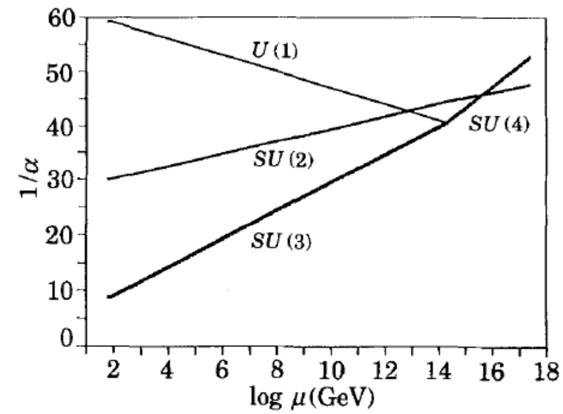


Evolution of the inverse couplings in the LR model.

ARE GRAND UNIFIED THEORIES RULED OUT BY THE LEP DATA?



Evolution of the inverse couplings in the $SU(2)_L \times SU(2)_R \times SU(4)$ Pati-Salam model.

Galli, Il Nuovo Cimento, 106A, 1309 (1993)

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Cocolicchio, Fogli, PRD30, 2391

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* - FCNC put limits $M_H > 50$ TeV, Pospelov, PRD56, 1997

Seesaw I and II

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

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$b \simeq 1\, GeV, \quad c \simeq 10^{15}\, GeV$

$$\begin{aligned} m_{1,2} &= \frac{1}{2}\left(a + c \mp \sqrt{(a-c)^2 + 4b^2}\right), \\ \sin 2\xi &= \frac{2b}{\sqrt{(a-c)^2 + 4b^2}}. \end{aligned}$$

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If $c >> b, a$ then we get

$$\begin{aligned} |m_1| &\simeq b^2/c, \\ m_2 &\simeq c \gg |m_1| \end{aligned}$$

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Neutrino oscillation parameters, LFV processes ($\mu \to e\gamma$) make the issue of large LH mixings even harder, JG, APPB, 2002

Consistency at the loop level: muon decay

Gauge Sector Renormalization

❖ The SSB leads to the following gauge-boson mass matrices

$$\frac{g^2}{4}\begin{pmatrix} \kappa_+^2 & -2\kappa_1\kappa_2 \\ -2\kappa_1\kappa_2 & \kappa_+^2+2v_R^2 \end{pmatrix},$$

$$\frac{1}{2}\begin{pmatrix} \frac{1}{2}g^2\kappa_+^2 & -\frac{1}{2}g^2\kappa_+^2 & 0 \\ -\frac{1}{2}g^2\kappa_+^2 & \frac{1}{2}g^2(\kappa_+^2+4v_R^2) & -2gg'v_R^2 \\ 0 & -2gg'v_R^2 & 2{g'}^2v_R^2 \end{pmatrix}$$

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- The diagonalization introduces various mixing angles. It is possible to write the respective matrices as

$$\begin{pmatrix} W_L^\pm \\ W_R^\pm \end{pmatrix} = \begin{pmatrix} \cos\xi & \sin\xi \\ -\sin\xi & \cos\xi \end{pmatrix}\begin{pmatrix} W_1^\pm \\ W_2^\pm \end{pmatrix},$$

$$\begin{pmatrix} W_L^3 \\ W_R^3 \\ B \end{pmatrix} = \begin{pmatrix} c_W c & c_W s & s_W \\ -s_W s_M c - c_M s & -s_W s_M s + c_M c & c_W s_M \\ -s_W c_M c + s_M s & -s_W c_M s - s_M c & c_W c_M \end{pmatrix} \begin{pmatrix} Z_1 \\ Z_2 \\ A \end{pmatrix},$$

$$M^2_{W_{1,2}} = \frac{g^2}{4}\left(\kappa_+^2 + v_R^2 \mp \sqrt{v_R^4 + 4\kappa_1^2\kappa_2^2}\right),$$

$$M^2_{Z_{1,2}} = \frac{1}{4}\left(\left((g^2\kappa_+^2 + 2v_R^2(g^2 + g'^2)\right)\right.$$

$$\left.\mp \sqrt{(g^2\kappa_+^2 + 2v_R^2(g^2 + g'^2))^2 - 4g^2(g^2 + 2g'^2)\kappa_+^2 v_R^2}\right)$$

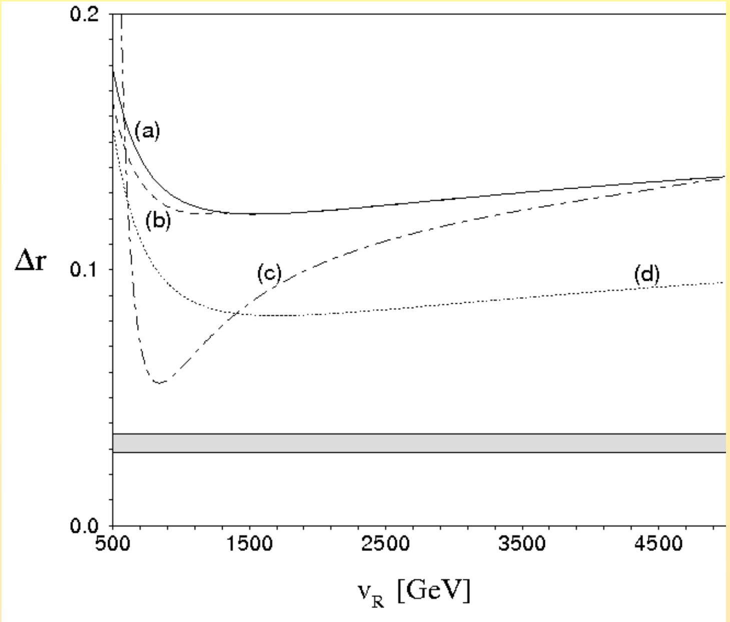
and

The one-to-one correspondence of the parameters exploited and adopt an on-shell scheme in which the self-energies of the gauge-bosons are renormalized by requiring that they vanish at the physical mass squared.

$$\begin{array}{ccc} g & & e, \\ g' & & M_{W_1}, \\ \kappa_1 & \rightarrow & M_{W_2}, \\ \kappa_2 & & M_{Z_1}, \\ v_R & & M_{Z_2}. \end{array}$$

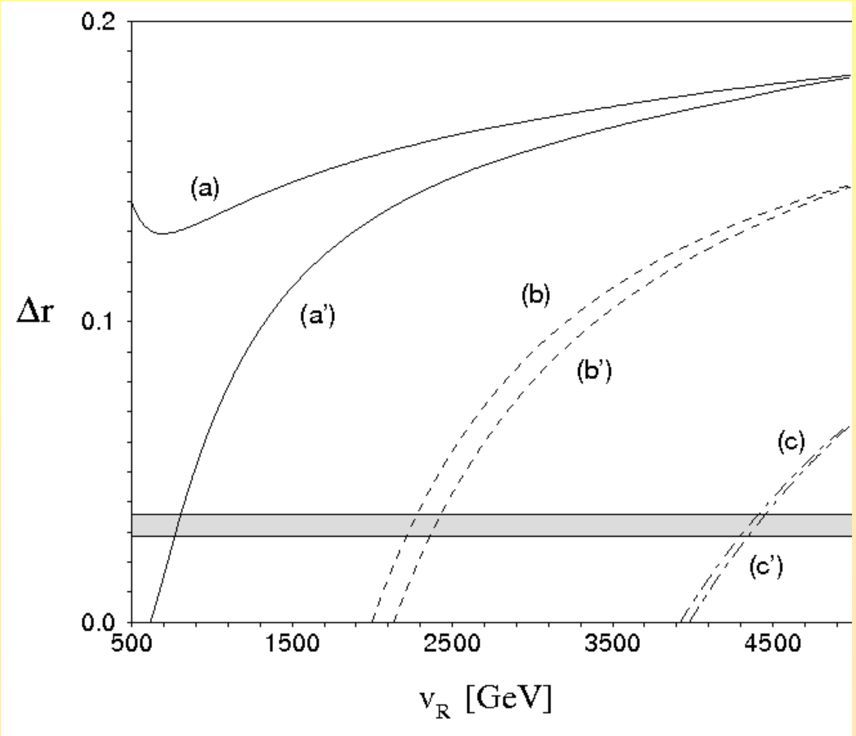
“Natural” scalar potential, Czakon, JG, Hejczyk NPB,2002

(a) line (three heavy neutrinos) $m_N = 100$ GeV;
(b) $m_N = 500$ GeV;
(c) $m_N = 2$ TeV.



$$
\begin{aligned}
M_{H_a} &\equiv M_{H_1^0} = M_{H_3^0} = M_{A_1^0} = M_{A_2^0} \\
&= M_{H_1^+} = M_{H_2^+} = M_{\delta_L^{++}} = v_R/\sqrt{2}, \\
M_{H_b} &\equiv M_{H_2^0} = M_{\delta_R^{++}} = \sqrt{2} v_R, \\
M_{H_0^0} &= \sqrt{2}\kappa_1.
\end{aligned}
$$

All Higgs particle masses equal (apart from H_0^0):



Sets with and without primes show results for three heavy neutrino masses with $m_N = 100$ GeV and $m_N = 2$ TeV respectively. For $M_H \simeq 2v_R$ (and large v_R), Δr can be accomodated,

remark: fine tuned masses

Muon decay in LR models

Leading terms:

$$(\Delta\rho)_{SM} \simeq \frac{m_t^2}{M_W^2}$$

$$(\Delta\rho)_{LRM} \simeq \frac{m_t^2}{M_{W_2}^2 - M_{W_1}^2}$$

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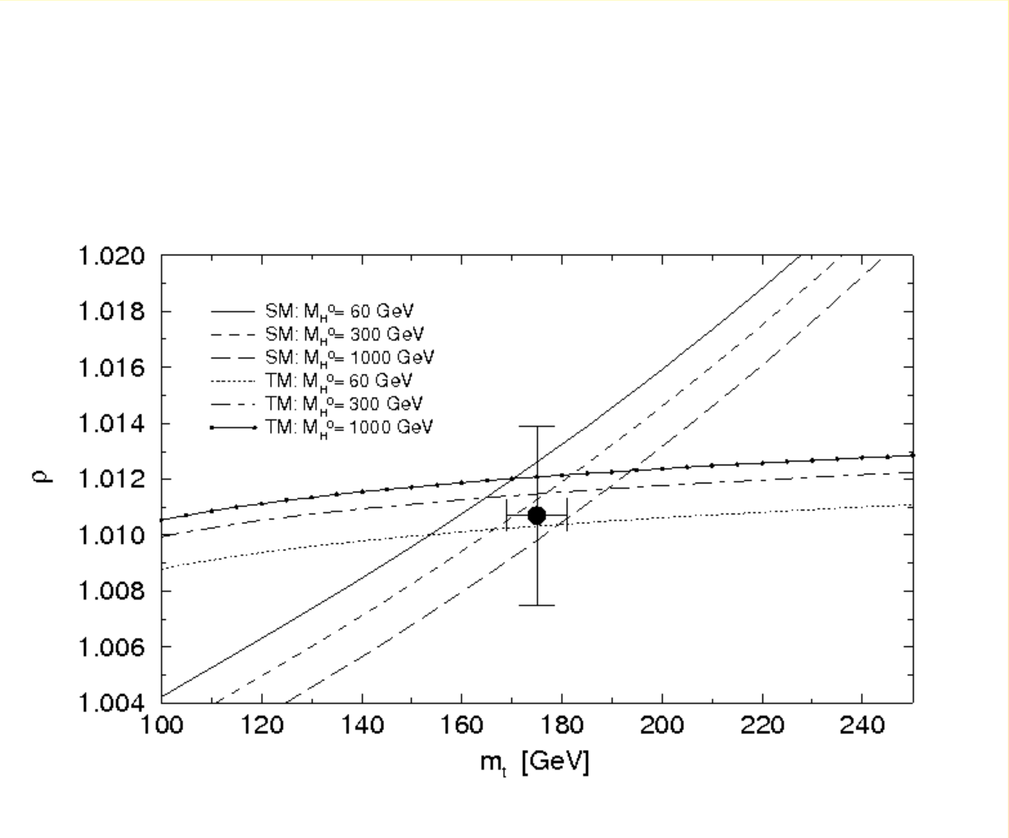
Corrections coming from SM particles within LR model do not constitute a structure equivalent to their SM structure, e.g. top quark and $\Delta\rho$, the lightest Higgs

Czakon, JG, Hejczyk NPB,2002
Czakon, JG, Jegerlehner, Zrałek, EPJ, 2000

Triplets



Hollik, Blank, NPB, 1994, Dawson et al.

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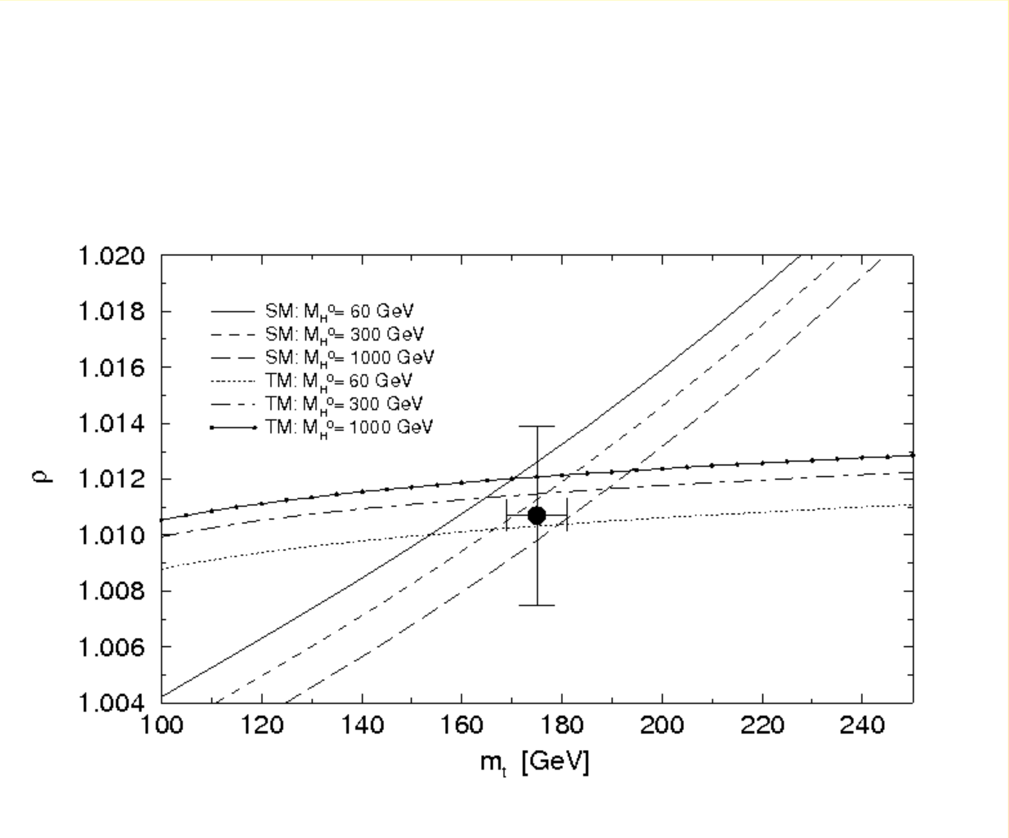
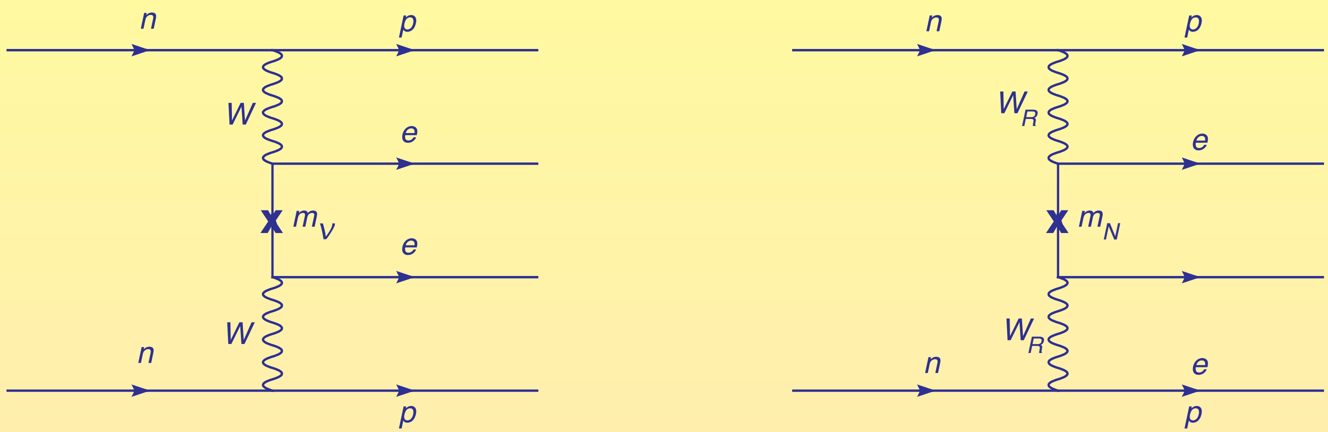


Hollik, Blank, NPB, 1994, Dawson et al.
Chankowski, Wagner

Link between TeV energies and low energies



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

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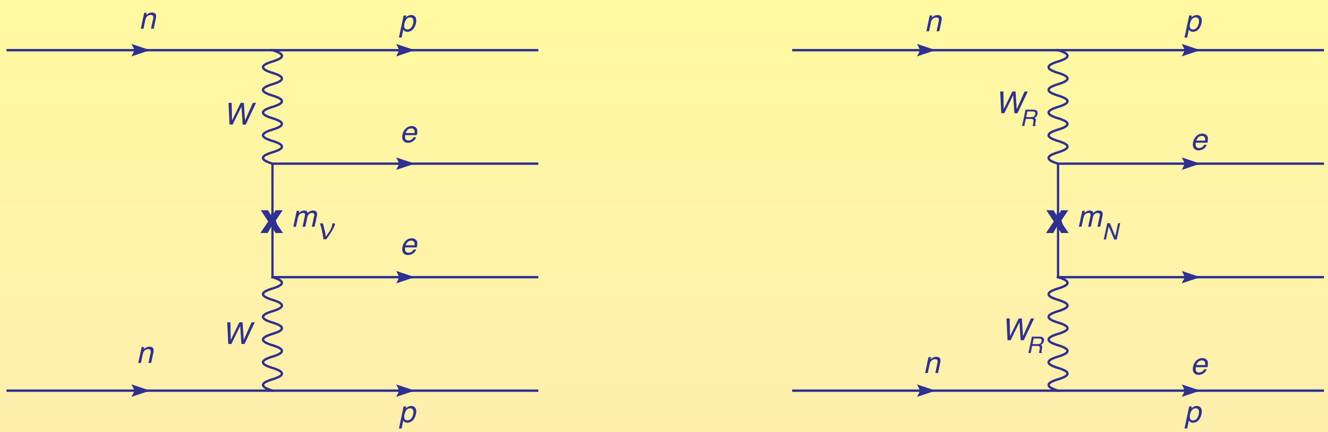

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plus $\mu \to e\gamma$, $\mu \to 3e$,...

LHeC

$$\begin{aligned} e^-p &\rightarrow N_i j + X \rightarrow e^+ W^- j + X, \\ e^-p &\rightarrow N_i j + X \rightarrow \tau^\pm W^\mp j + X, \\ e^-p &\rightarrow E_i j + X \rightarrow \tau^- Z j + X \end{aligned}$$

$N_{1,2,3}$ and $E_{1,2,3}$ are heavy Majorana neutrinos and heavy charged leptons. Han et al, JHEP

Conclusions (II)

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- just today:
  arXiv:1101.5778, “Lepton Number Violation in TeV Scale See-Saw Extensions of the Standard Model”, A. Ibarra, E. Molinaro, S.T. Petcov