New neutrino interactions at large colliders

- Introduction
- Non-standard neutrino interactions
- TeV signatures of see-saw messengers: Multilepton signals
- Tau custodians

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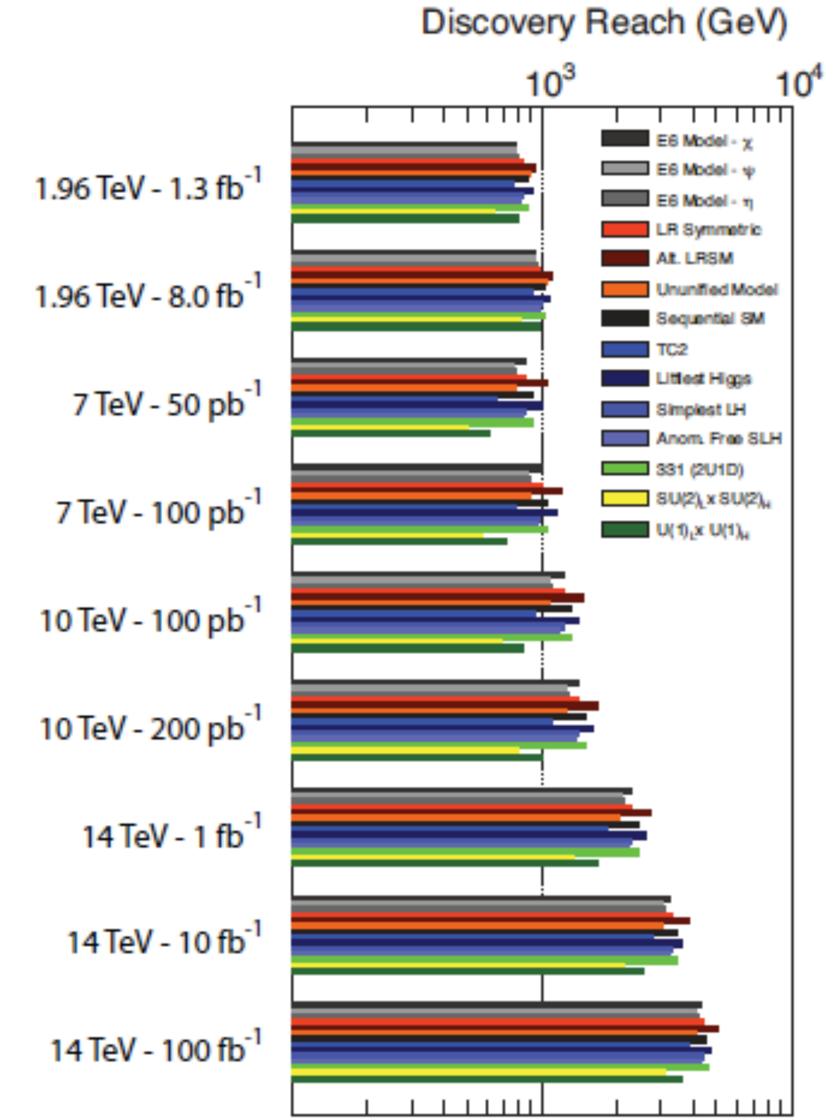
Neutrino masses have no observable effects at large colliders because they are suppressed by large factors, a power of

$$\frac{m_\nu}{\mathrm{TeV}} \sim 10^{-12}.$$

However, neutrinos are produced and detected as missing energy for they have electroweak interactions. Then the question, for instance, at LHC is if neutrinos have further interactions which can be observed. The answer is obviously positive (for example, almost any new gauge boson couples to them).

Diener, Godfrey, Martin 09

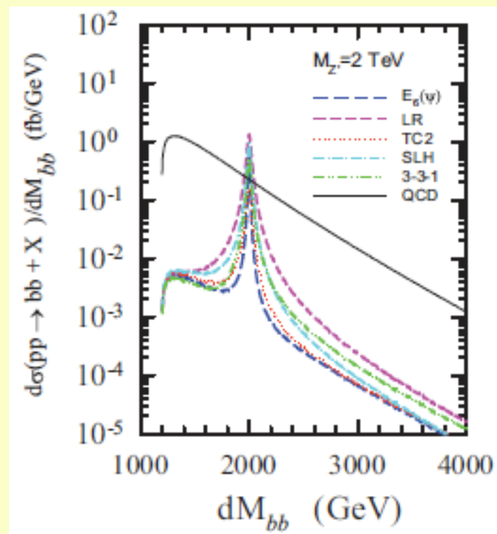


F.A., de Blas, Perez-Victoria 10

95% C.L. Electroweak Limits on

Model	$\sin\theta_{ZZ'}$ [$\times 10^{-4}$] EWPD (no LEP 2)	LEP 2	All Data	$M_{Z'}$ [TeV] EWPD (no LEP 2)	LEP 2	All Data
Z'_χ	[−10, 7]	[−80, 118]	[−11, 7]	1.123	0.772	1.022
Z'_ψ	[−19, 7]	[−196, 262]	[−19, 7]	0.151	0.455	0.476
Z'_η	[−22, 25]	[−150, 164]	[−23, 27]	0.422	0.460	0.488
Z'_I	[− 5, 9]	[−144, 96]	[− 5, 10]	1.207	0.652	1.105
Z'_N	[−14, 6]	[−165, 223]	[−14, 6]	0.635	0.421	0.699
Z'_S	[− 9, 5]	[−85, 129]	[−10, 5]	1.249	0.728	1.130
Z'_R	[−17, 7]	[−166, 177]	[−15, 5]	0.439	0.724	1.130
Z'_{LR}	[−13, 5]	[−147, 189]	[−12, 4]	0.999	0.667	1.162

Salvioni, Villadoro, Zwirner 09, Langacker 09



@ 14 TeV

Non-standard neutrino interactions

$$\mathcal{L}^{M}_{\rm NSI} = -2\sqrt{2} G_F \varepsilon^{fP}_{\alpha\beta} [\bar{f}\gamma^\mu P f][\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta]$$

LH neutrinos

One extra operator at a time

Antusch, Biggio, Fernández-Martínez, Gavela, Lopez-Pavon 06, Abada, Biggio, Bonnet, Gavela, Hambye 07, Gavela, Hernandez, Ota, Winter 08, Biggio, Blennow,Fernandez-Martinez 09

$\varepsilon^{\mu e}_{\alpha\beta}$	**Kin. G_F (L,R)**	**CKM unit. (V)**	**Lept. univ. (A)**	**Oscillation (L,R)**
$\varepsilon^{\mu e}_{ee}$	< 0.030	< 0.030	< 0.080	< 0.025
$\varepsilon^{\mu e}_{e\mu}$	$(-1.4 \pm 1.4)\cdot 10^{-3} (\mathbb{R},L)$ < 0.030	$< 4 \cdot 10^{-4} (\mathbb{R})$ < 0.030	$(-0.4 \pm 3.5)\cdot 10^{-3} (\mathbb{R})$ < 0.080	-
$\varepsilon^{\mu e}_{e\tau}$	< 0.030	< 0.030	< 0.080	< 0.087
$\varepsilon^{\mu e}_{\mu e}$	< 0.030	< 0.030	< 0.080	< 0.025
$\varepsilon^{\mu e}_{\mu\mu}$	< 0.030	< 0.030	< 0.080	-
$\varepsilon^{\mu e}_{\mu\tau}$	< 0.030	< 0.030	< 0.080	< 0.087
$\varepsilon^{\mu e}_{\tau e}$	< 0.030	< 0.030	< 0.080	< 0.025
$\varepsilon^{\mu e}_{\tau\mu}$	< 0.030	< 0.030	< 0.080	-
$\varepsilon^{\mu e}_{\tau\tau}$	< 0.030	< 0.030	< 0.080	< 0.087

In general the (gauge invariant) dimension six operators must have coefficients not much larger than 1 %

F.A., de Blas, Szafron, Wudka, Zralek 09

Gauge invariance

$$\mathcal{L}^{M}_{\rm NSI} = -2\sqrt{2}G_F\varepsilon^{fP}_{\alpha\beta}[\bar{f}\gamma^\mu P f][\bar{\nu}_\alpha\gamma_\mu P_L\nu_\beta]$$

Light RH neutrinos P_R

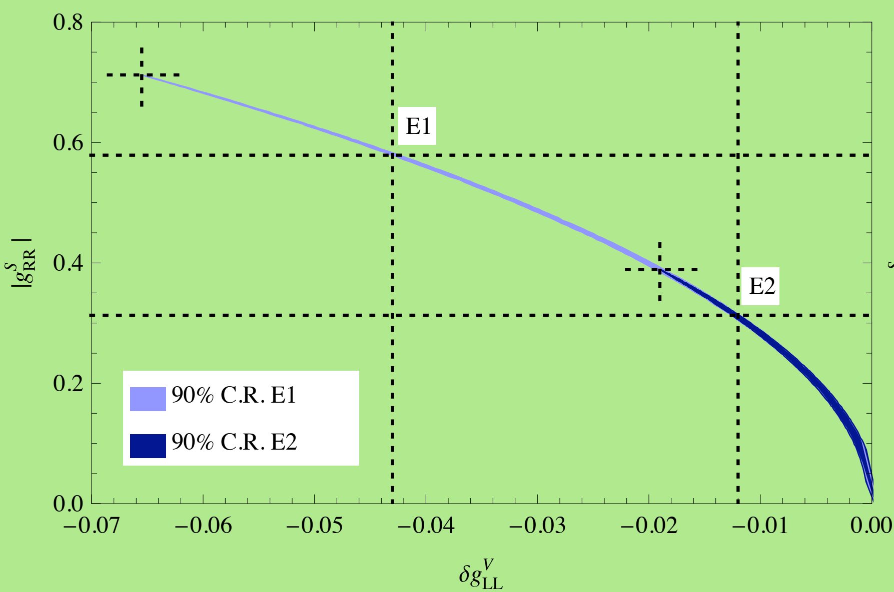
More than one extra operator

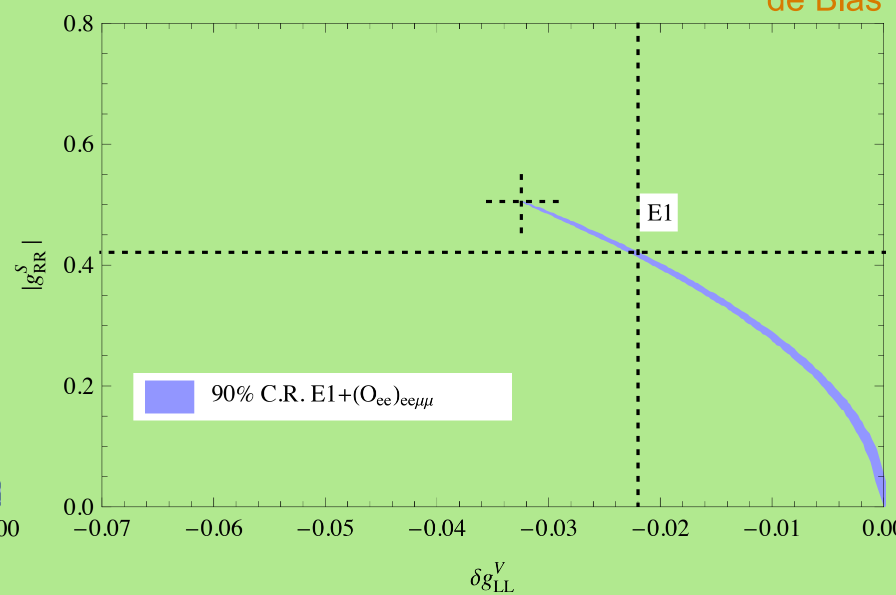
$$\begin{aligned}
&\frac{4G_F}{\sqrt{2}}\Big[g^S_{LL}\,(\overline{e_R}l^e_L)\left(\overline{l^\mu_L}\mu_R\right) + g^S_{RR}\,(\overline{l^e_L}\nu^e_R)\left(\overline{\nu^\mu_R}l^\mu_L\right)\\
&+\ g^S_{LR}\,(\overline{e_R}l^e_L)\,i\sigma_2\left(\overline{\nu^\mu_R}l^\mu_L\right) - g^S_{RL}\,(\overline{l^e_L}\nu^e_R)\,i\sigma_2\left(\overline{l^\mu_L}\mu_R\right)\\
&+\ \frac{\delta g^V_{LL}}{2}\,(\overline{l^e_L}\gamma^\mu l^\mu_L)\left(\overline{l^\mu_L}\gamma_\mu l^e_L\right) + g^V_{RR}\,(\overline{e_R}\gamma^\mu\nu^e_R)\left(\overline{\nu^\mu_R}\gamma_\mu\mu_R\right)\\
&-\ \frac{g^V_{LR}}{v^2}\,(\overline{l^e_L}\sigma_a\gamma^\mu l^e_L)\,(\phi^T i\sigma_2\sigma_a\phi)\left(\overline{\nu^\mu_R}\gamma_\mu\mu_R\right)\\
&+\ \frac{g^V_{RL}}{v^2}\,(\overline{e_R}\gamma_\mu\nu^e_R)\,(\phi^\dagger\sigma_a i\sigma_2\phi^*)\left(\overline{l^\mu_L}\sigma_a\gamma^\mu l^\mu_L\right)\\
&+\ g^T_{LR}\,(\overline{e_R}\sigma^{\mu\nu}l^e_L)\,i\sigma_2\left(\overline{\nu^\mu_R}\sigma^{\mu\nu}l^\mu_L\right) - g^T_{RL}\,(\overline{l^e_L}\sigma^{\mu\nu}\nu^e_R)\,i\sigma_2\left(\overline{l^\mu_L}\sigma^{\mu\nu}\mu_R\right)\Big] + \text{h.c.}
\end{aligned}$$

LEP1 and low energy data

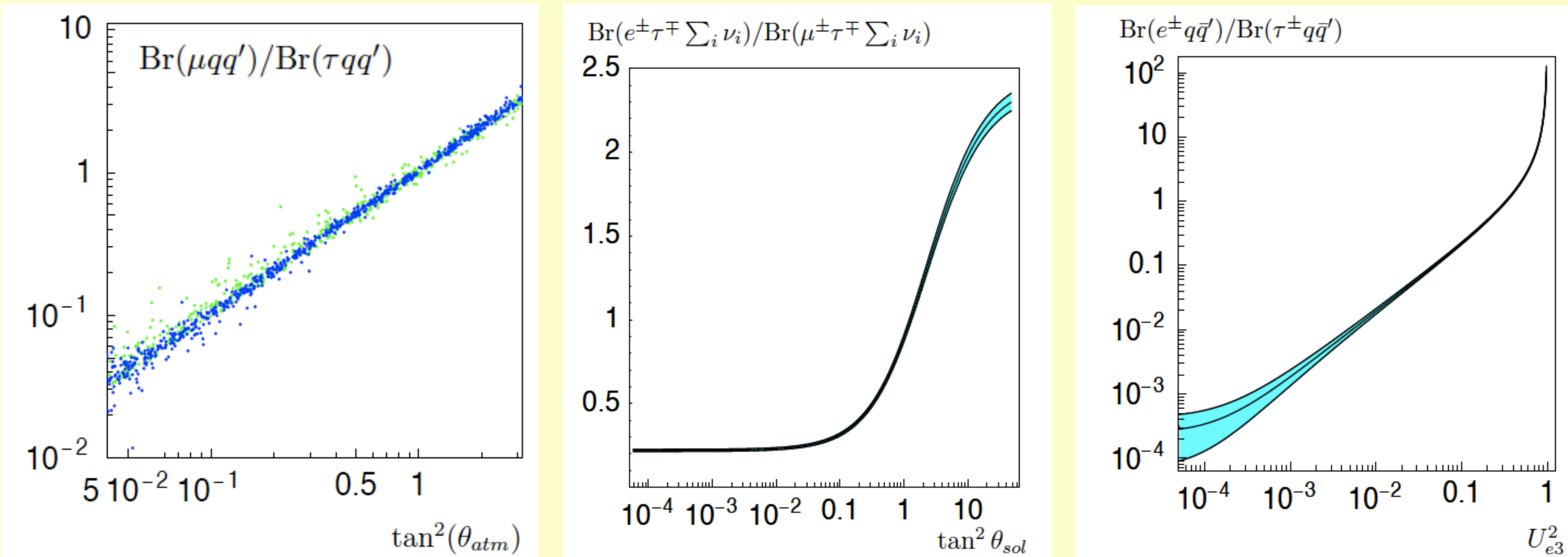
plus LEP2 data $\delta g^V_{LL} > -9\cdot 10^{-4}, \quad |g^S_{RR}| < 0.09$

de Blas



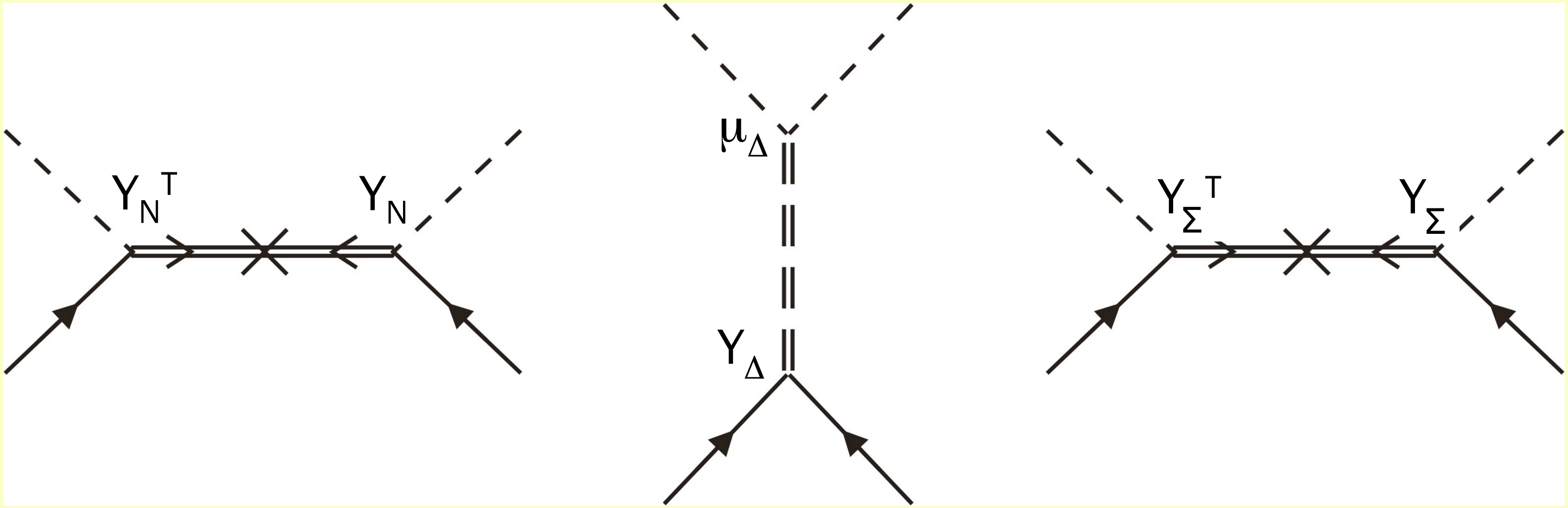


A more pertinent question is if we can be learned something about neutrino masses and mixings. In general they must be inferred from definite model dependent relations. Thus, within a given neutrino mass model these parameters can be related to other ones entering in observable processes (as in some supersymmetric models).



Ratio of neutralino branching ratios as a function of the mixing angles. The model mixes neutrinos and the lightest neutralino. Only the atmospheric scale comes out at tree level through bilinear breaking of R-parity. Porod, Hirsch, Romao, Valle, 00

We can even observe at the LHC neutrino mass mediators if they have a mass below the TeV. They can be tree-level (see-saw) messengers (as we shall review) or higher order ones, Ma 00; Nandi's and Babu's talks today or new particles with particular properties but with no information on the neutrino spectrum (relics). Feruglio's talk today, Santiago's talk on Monday



$^1/_2 Y_N{}^T M_N{}^{-1} Y_N$ | $-2\, Y_\Delta \mu_\Delta M_\Delta{}^{-2}$ | $^1/_2 Y_\Sigma{}^T M_\Sigma{}^{-1} Y_\Sigma$

Phase cancellation or small couplings

Minkowski 77, ...

small coupling(s)

Magg, Wetterich 80, ...

Phase cancellation or small couplings

Foot, Lew, He, Joshi 89, ...

The three mechanisms must violate Lepton Number for they are assumed to generate Majorana masses, $\mathcal{O}_5 = \overline{l^c_L}\tilde{\phi}^*\tilde{\phi}^\dagger l_L$. I and III involve fermions: singlets N (I) or triplets Σ (III), and II scalar triplets: Δ.

Type I

Dimension	Operator	Coefficient
5	$\mathcal{O}_5 = \overline{l^c_L}\tilde{\phi}^*\tilde{\phi}^\dagger l_L$	$\frac{1}{2}Y_N^T M_N^{-1} Y_N$
6	$\mathcal{O}_{\phi l}^{(1)} = \left(\phi^\dagger i D_\mu \phi\right)\left(\overline{l_L}\gamma^\mu l_L\right)$ $\mathcal{O}_{\phi l}^{(3)} = \left(\phi^\dagger i \sigma_a D_\mu \phi\right)\left(\overline{l_L}\sigma_a\gamma^\mu l_L\right)$	$\frac{1}{4}Y_N^\dagger (M_N^\dagger)^{-1} M_N^{-1} Y_N$ $-\frac{1}{4}Y_N^\dagger (M_N^\dagger)^{-1} M_N^{-1} Y_N$

Weinberg 79, Buchmuller, Wyler 86, ...

Type II

Dimension	Operator	Coefficient
4	$\mathcal{O}_4 = \left(\phi^\dagger \phi\right)^2$	$2\left\|\mu_\Delta\right\|^2/M_\Delta^2$
5	$\mathcal{O}_5 = \overline{l^c_L}\tilde{\phi}^*\tilde{\phi}^\dagger l_L$	$-2\,Y_\Delta \mu_\Delta / M_\Delta^2$
6	$\mathcal{O}_{ll}^{(1)} = \frac{1}{2}\left(\overline{l^i_L}\gamma^\mu l^j_L\right)\left(\overline{l^k_L}\gamma_\mu l^l_L\right)$ $\mathcal{O}_{\phi} = \frac{1}{3}\left(\phi^\dagger \phi\right)^3$ $\mathcal{O}_{\phi}^{(1)} = \left(\phi^\dagger \phi\right)\left(D_\mu \phi\right)^\dagger D^\mu \phi$ $\mathcal{O}_{\phi}^{(3)} = \left(\phi^\dagger D_\mu \phi\right)\left(D^\mu \phi^\dagger \phi\right)$	$2(Y_\Delta)_{jl}(Y_\Delta^\dagger)_{ki}/M_\Delta^2$ $-6\left(\lambda_3+\lambda_5\right)\left\|\mu_\Delta\right\|^2/M_\Delta^4$ $4\left\|\mu_\Delta\right\|^2/M_\Delta^4$ $4\left\|\mu_\Delta\right\|^2/M_\Delta^4$

Type III

Dimension	Operator	Coefficient
5	$\mathcal{O}_5 = \overline{l^c_L}\tilde{\phi}^*\tilde{\phi}^\dagger l_L$	$\frac{1}{2}Y_\Sigma^T M_\Sigma^{-1} Y_\Sigma$
6	$\mathcal{O}_{\phi l}^{(1)} = \left(\phi^\dagger i D_\mu \phi\right)\left(\overline{l_L}\gamma^\mu l_L\right)$	$\frac{3}{4}Y_\Sigma^\dagger (M_\Sigma^\dagger)^{-1} M_\Sigma^{-1} Y_\Sigma$
	$\mathcal{O}_{\phi l}^{(3)} = \left(\phi^\dagger i \sigma_a D_\mu \phi\right)\left(\overline{l_L}\sigma_a\gamma^\mu l_L\right)$	$\frac{1}{4}Y_\Sigma^\dagger (M_\Sigma^\dagger)^{-1} M_\Sigma^{-1} Y_\Sigma$
	$\mathcal{O}_{e\phi} = \left(\phi^\dagger \phi\right)\overline{l_L}\phi e_R$	$Y_\Sigma^\dagger (M_\Sigma^\dagger)^{-1} M_\Sigma^{-1} Y_\Sigma Y_e$

There is a question about the relative size of the coefficients of the operators of dimension 5 and 6:

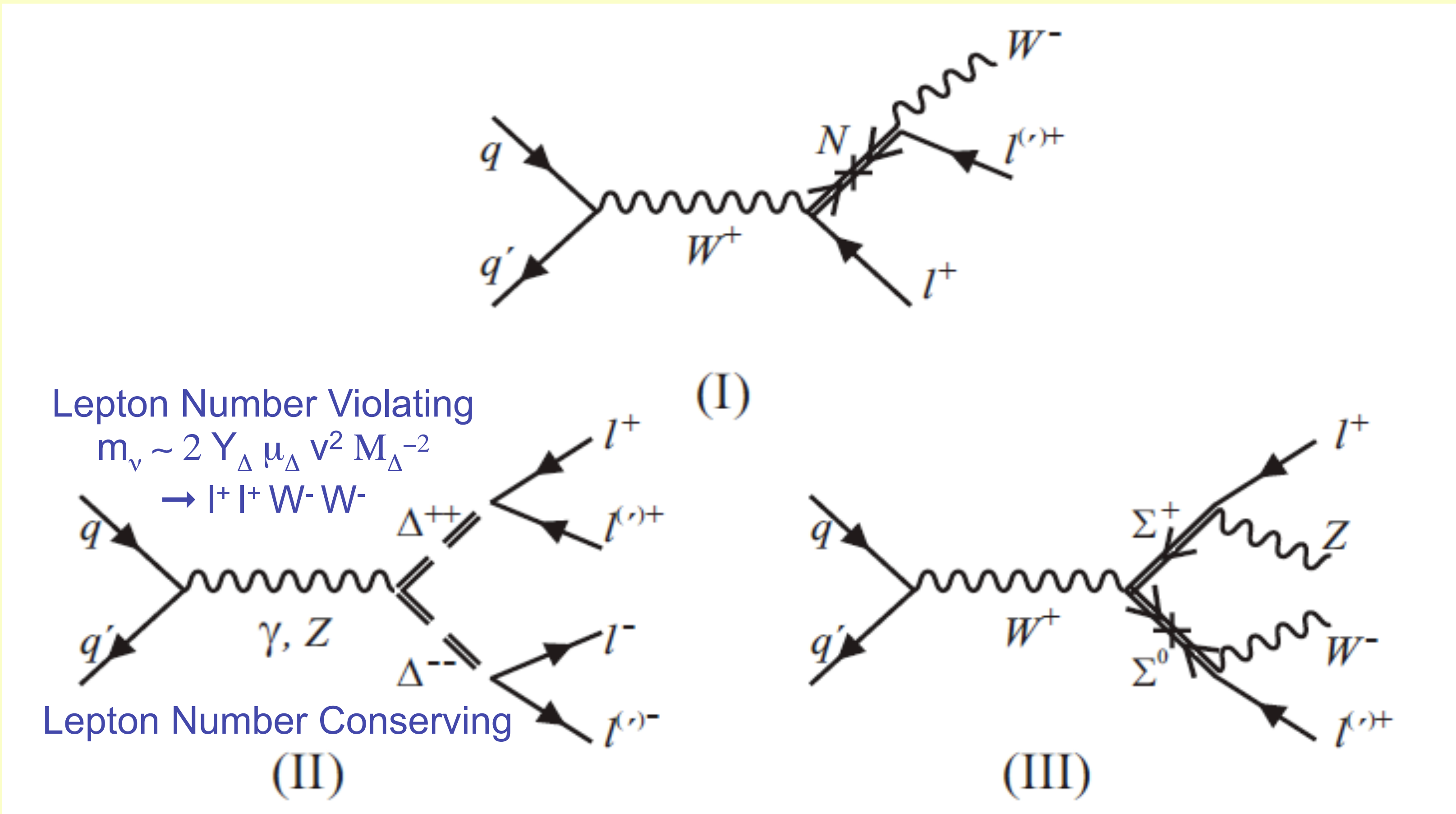
Can the dimension 5 operator coefficient be negligible but dimension 6 operator coefficients sizeable ?

The answer is positive, for instance, if Lepton Number is (quasi-)conserved.

$$\begin{array}{c} \\ \nu_L \\ N \end{array}\begin{array}{c} \begin{array}{cc} \nu_L & N \end{array} \\ \begin{pmatrix} 0 & Y_N^T \frac{v}{\sqrt{2}} \\ Y_N \frac{v}{\sqrt{2}} & M_N \end{pmatrix} \end{array} \longrightarrow \begin{array}{c} \\ \nu_L \\ N_L \\ N_R^c \end{array}\begin{array}{c} \begin{array}{ccc} \nu_L & N_L & N_R^c \end{array} \\ \begin{pmatrix} 0 & 0 & \frac{y_N v}{\sqrt{2}} \\ 0 & 0 & m_N \\ \frac{y_N v}{\sqrt{2}} & m_N & 0 \end{pmatrix} \end{array}$$

Type I and III: Light neutrinos are massless.

TeV signatures of see-saw messengers: Multilepton signals

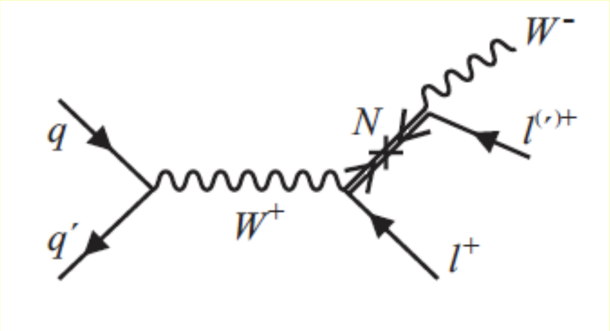


LNV signals have smaller backgrounds than LNC ones (Keung, Senjanovic 83) BUT for a fixed number of final particles. As a matter of fact the significance of trilepton LNC signals is similar to the significance of LNV dilepton signals. F.A., Aguilar-Saavedra 08

At any rate, multilepton signals are complementary in order to discriminate between models. Scalar and fermion triplets mediating the see-saw mechanism have final states with many leptons (up to 6), as many other new particles at the TeV scale (as, for example, heavy leptons or quarks, or new neutral gauge bosons decaying into them). F.A., Aguilar-Saavedra 08, Aguilar-Saavedra 09, F.A., Aguilar-Saavedra, de Blas 09

Fermion singlet N

$$V_{lN} \simeq \frac{Y_{lN} v}{\sqrt{2} m_N}$$



(I)

$$m_\nu \simeq - V_{lN_i}^{*2} \, m_{N_i}$$

The production mechanism is proportional to the mixing between the light leptons and the new heavy neutrino N, as there are the light neutrino masses (if they have a see-saw origin as in the usual MAJORANA case). BUT in the first case enters the specific mixing matrix element and in the second one the combination of all of them and cancellations are possible. Although this can be considered arbitrary in the absence of a symmetry, and unstable because corrections may be large.

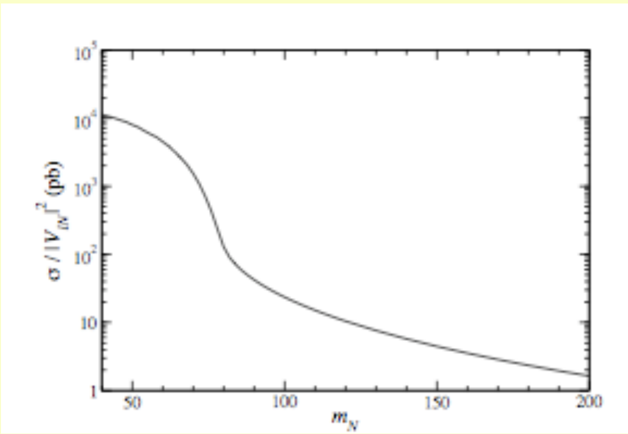
$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \left(V_{lN}\, \bar{l} \gamma^\mu P_L N\, W_\mu^- + V_{lN}^*\, \bar{N} \gamma^\mu P_L l\, W_\mu^+ \right) ,$$
$$\mathcal{L}_Z = -\frac{g}{2c_W} \left(V_{lN}\, \bar{\nu}_l \gamma^\mu P_L N + V_{lN}^*\, \bar{N} \gamma^\mu P_L \nu_l \right) Z_\mu ,$$
$$\mathcal{L}_H = -\frac{g\, m_N}{2M_W} \left(V_{lN}\, \bar{\nu}_l P_R N + V_{lN}^*\, \bar{N} P_L \nu_l \right) H ,$$

90 % C.L.

$|V_{eN}|^2 < 0.003$

$|V_{\mu N}|^2 < 0.0032$

$|V_{\tau N}|^2 < 0.0062$ unobservable



Total cross sections are the same, although the total width for a Majorana neutrino is twice than for a Dirac one

$$q\bar{q}' \to W^* \to l^\pm N ,$$
$$q\bar{q} \to Z^* \to \nu N ,$$
$$gg \to H^* \to \nu N$$

F.A., Aguilar-Saavedra 08

Overwhelming background

$$N \to \ell W \quad \begin{cases} \ell^+ N \to \ell^+ \ell^- W^+ \\ \ell^+ N \to \ell^+ \ell^+ W^- \end{cases} \quad \begin{pmatrix} \to \ell^+ \ell^- \ell^+ \bar{\nu} \\ \to \ell^+ \ell^+ \ell^- \nu \end{pmatrix}$$

Han, Zhang 06 $\ell^\pm \ell^\pm$ $\ell^\pm \ell^\pm \ell^\mp$

$$q\bar{q} \to Z^* \to NN$$

Too small cross section

Majorana particles give LNV as well as LNC signals, whereas Dirac particles only give LNC ones. In any case there are SM backgrounds.

LNC signals may be more significant than LNV ones

m_N = 100 GeV
$|V|^2$ = 0.003

	$\ell^\pm\ell^\pm\ell^\mp$ (2e)	$\ell^\pm\ell^\pm\ell^\mp$ (2μ)	$\ell^\pm\ell^\pm$ (2e)	$\ell^\pm\ell^\pm$ (2μ)
N (S1,M)	28.6	0	(11.3)	0
N (S1,D)	44.8	0	0.4	0
N (S2,M)	0	29.6	0	(13.4)
N (S2,D)	0	45.8	0	0.5
SM Bkg	116.4	45.6	36.1	20.2

Difference due to kinematics

Table 1: Number of events with 30 fb^{-1} for the Majorana (M) and Dirac (D) neutrino singlet signals in scenarios S1 and S2, and SM background in different final states.

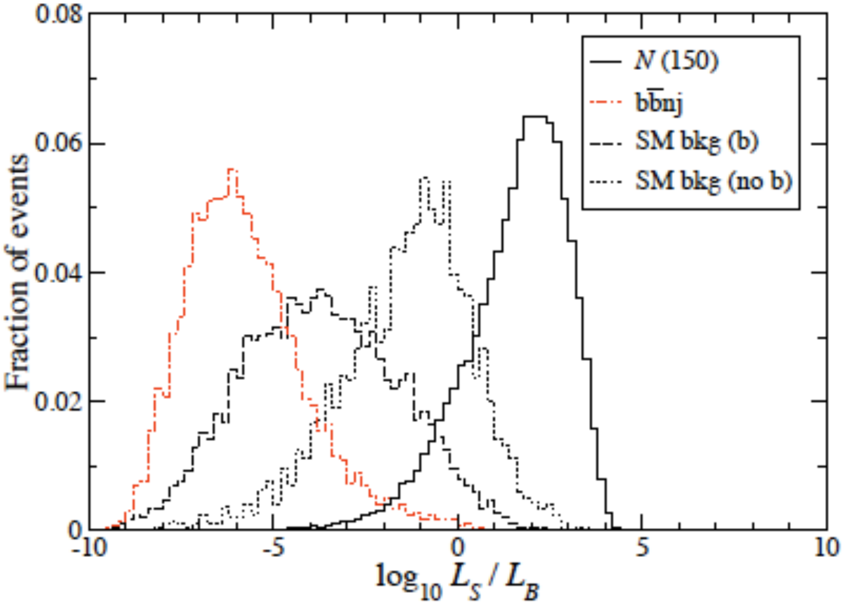
Coupling to e and μ, respectively

Broad dilepton invariant mass distributions

A case for MULTILEPTON searches

	Pre-selection			Selection		
	$\mu^\pm\mu^\pm$	$e^\pm e^\pm$	$\mu^\pm e^\pm$	$\mu^\pm\mu^\pm$	$e^\pm e^\pm$	$\mu^\pm e^\pm$
N (a)	113.6	0	0	(59.1)	0	0
N (b)	0	72.0	0	0	(17.6)	0
N (c)	78.4	25.5	82.6	41.6	4.7	22.4
$b\bar{b}nj$	14800	52000	82000	0	0	0
$c\bar{c}nj$	(11)	300	200	(0)	0	0
$t\bar{t}nj$	1162.1	8133.0	15625.3	2.4	8.3	7.7
tj	60.8	176.5	461.5	0.0	0.0	0.1
$Wb\bar{b}nj$	124.9	346.7	927.3	0.4	0.6	0.3
$Wt\bar{t}nj$	75.7	87.2	166.9	0.3	0.0	0.0
$Zb\bar{b}nj$	12.2	68.9	117.0	0.0	0.2	0.0
$WWnj$	82.8	89.0	174.8	0.5	0.1	0.7
$WZnj$	162.4	252.0	409.2	4.8	1.8	2.3
$ZZnj$	3.8	13.3	12.9	0.0	0.6	0.1
$WWWnj$	31.9	30.1	64.8	0.9	0.1	0.0

Table 1: Number of $\ell^\pm\ell^\pm jj$ events at LHC for 30 fb^{-1}, at the pre-selection and selection levels. The heavy neutrino signal is evaluated assuming $m_N = 150$ GeV and coupling (a) to the muon, $V_{\mu N} = 0.098$; (b) to the electron, $V_{eN} = 0.073$; (c) to both, $V_{eN} = 0.073$ and $V_{\mu N} = 0.098$.



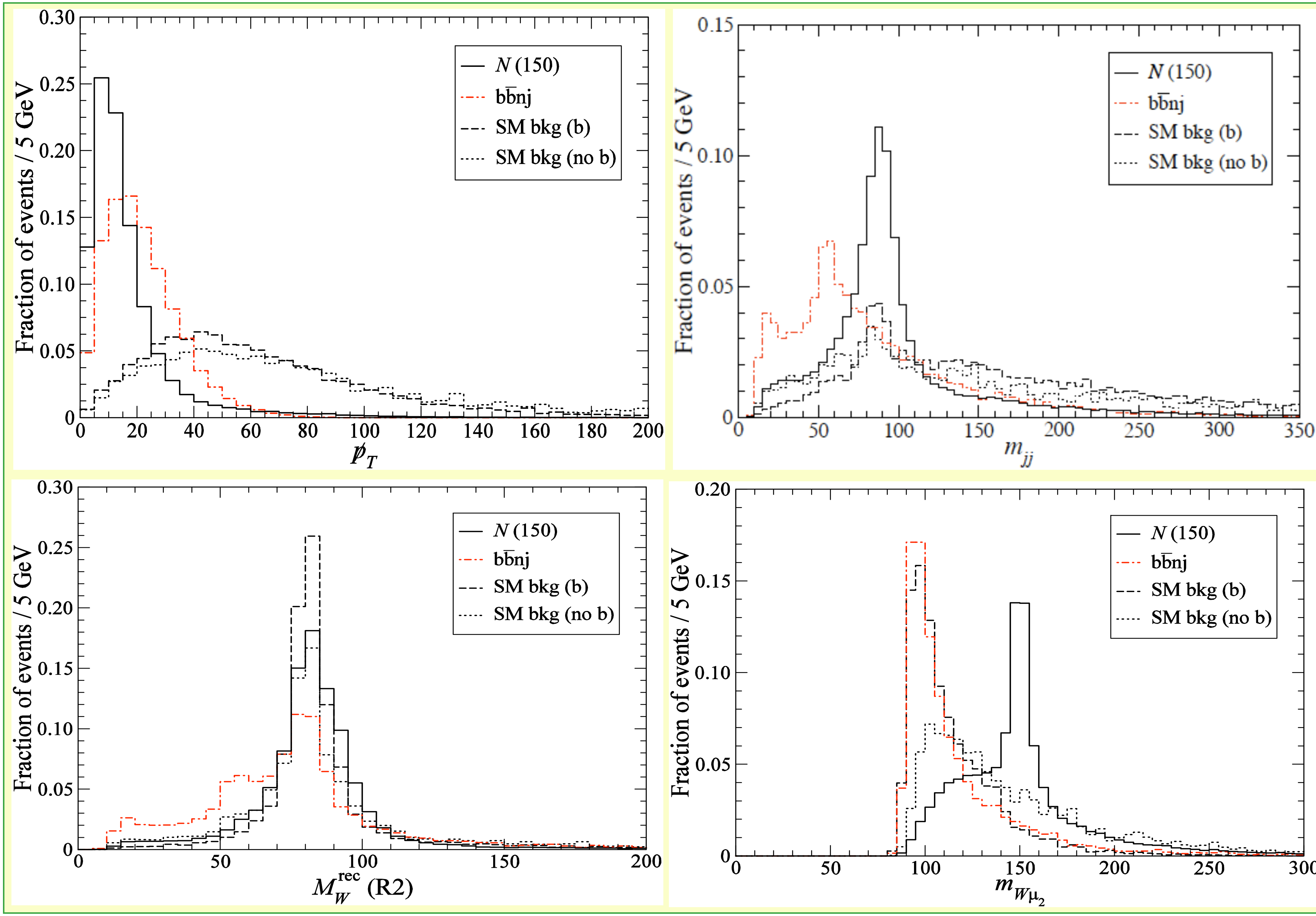
Large backgrounds

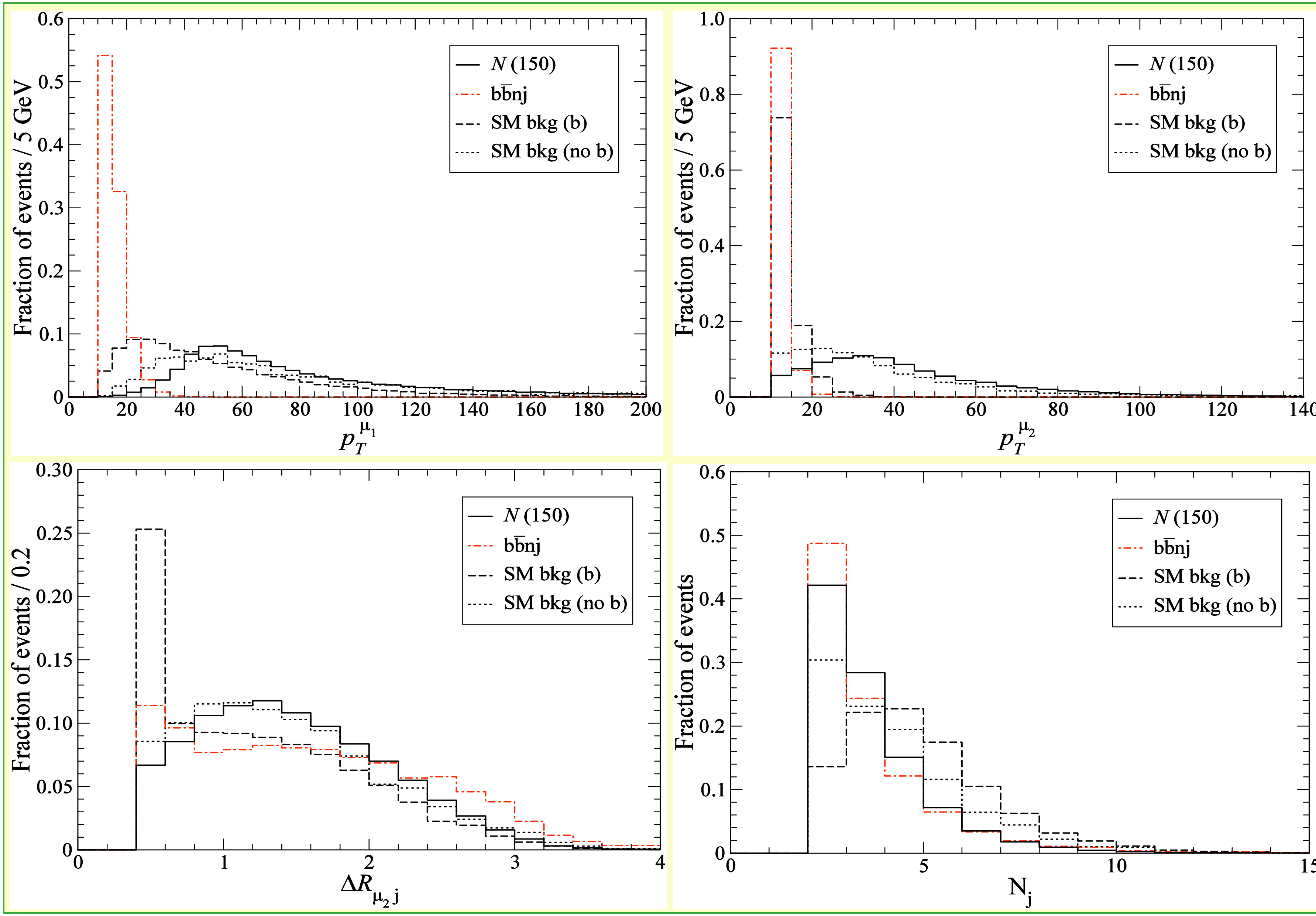
Likelihood analysis
with many distributions

Limit on their mass
~ 120 (150) GeV for D (M)

CLIC does better
F.A., Aguilar-Saavedra 07

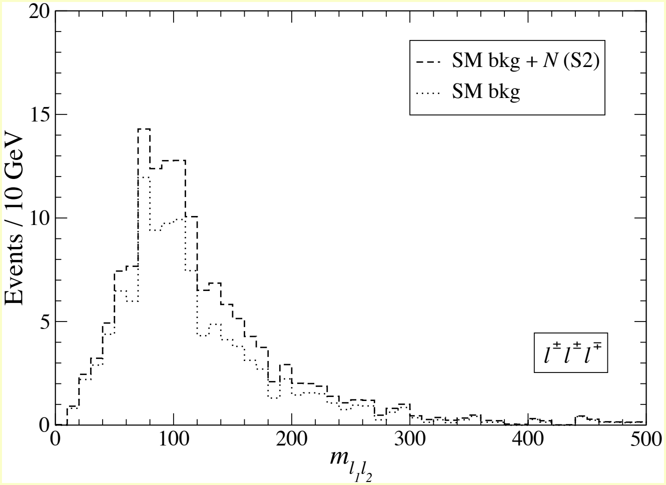
60 GeV neutrino coupling to the muon up to $|V_{\mu N}|^2 = 4.9 \times 10^{-5}$


Fraction of events / 5 GeV
N (150)
bb̄nj
SM bkg (b)
SM bkg (no b)
$\not{p}_T$
Fraction of events / 5 GeV
N (150)
bb̄nj
SM bkg (b)
SM bkg (no b)
m_{jj}
Fraction of events / 5 GeV
N (150)
bb̄nj
SM bkg (b)
SM bkg (no b)
M_W^{rec} (R2)
Fraction of events / 5 GeV
N (150)
bb̄nj
SM bkg (b)
SM bkg (no b)
$m_{W\mu_2}$


Fraction of events / 5 GeV
N (150)
bb̄nj
SM bkg (b)
SM bkg (no b)
$p_T^{\mu_1}$
$p_T^{\mu_2}$
Fraction of events / 0.2
$\Delta R_{\mu_2 j}$
Fraction of events
N_j

	Pre-selection		Selection		Impr. selection	
	$2e$	2μ	$2e$	2μ	$2e$	2μ
N (S1)	37.1	0	32.4	0	28.6	0
N (S2)	0	37.8	0	33.1	0	29.6
$t\bar{t}nj$	244.8	78.0	159.8	52.4	58.4	16.3
tW	14.8	3.0	10.5	1.7	6.5	0.6
$Wt\bar{t}nj$	25.6	19.9	20.6	14.5	3.8	2.6
$Zb\bar{b}nj$	17.1	16.2	1.1	0.9	0.5	0.1
$Zt\bar{t}nj$	82.5	69.9	10.3	6.5	2.6	1.1
$WZnj$	2166.4	1947.3	49.2	24.3	36.8	17.8
$ZZnj$	141.0	135.0	2.8	1.4	1.6	1.2
$WWWnj$	10.8	12.0	7.9	8.9	4.7	5.3
$WWZnj$	23.9	18.8	1.1	0.7	0.8	0.4

Preselection



Preselection:

- Three charged leptons (e or μ)
- Same sign leptons with $p_T > 30$ GeV (to reduce b's)

Selection:

- Invariant mass of opposite sign pairs differing from the Z boson mass by at least 10 GeV

Improved selection:

- No b jets
- Like sign leptons back-to-back ($> \pi/2$)

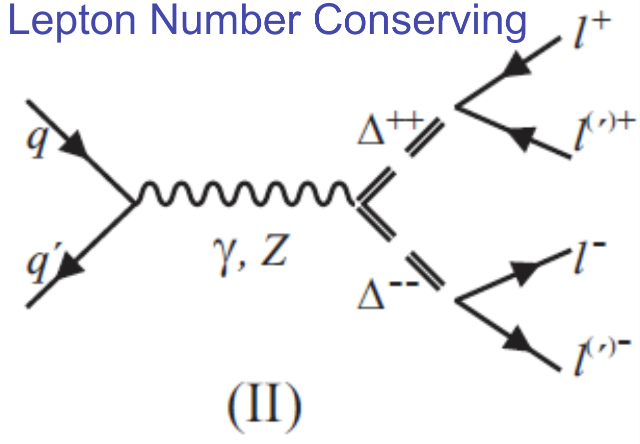
Process	Decay
$t\bar{t}nj$, $n=0,\dots,6$	semileptonic
$t\bar{t}nj$, $n=0,\dots,6$	dileptonic
$b\bar{b}nj$, $n=0,\dots,3$	all
$c\bar{c}nj$, $n=0,\dots,3$	all
tj	$W\to l\nu$
$t\bar{b}$	$W\to l\nu$
tW	all
$t\bar{t}t\bar{t}$	all
$t\bar{t}b\bar{b}$	all
Wnj, $n=0,1,2$	$W\to l\nu$
Wnj, $n=3,\dots,6$	$W\to l\nu$
$Wb\bar{b}nj$, $n=0,\dots,4$	$W\to l\nu$
$Wc\bar{c}nj$, $n=0,\dots,4$	$W\to l\nu$
$Wt\bar{t}nj$, $n=0,\dots,4$	$W\to l\nu$
$Z/\gamma\,nj$, $n=0,1,2$, $m_{ll}<120$ GeV	$Z\to l^+l^-$
$Z/\gamma\,nj$, $n=3,\dots,6$, $m_{ll}<120$ GeV	$Z\to l^+l^-$
$Z/\gamma\,nj$, $n=0,\dots,6$, $m_{ll}>120$ GeV	$Z\to l^+l^-$
$Zb\bar{b}nj$, $n=0,\dots,4$	$Z\to l^+l^-$
$Zc\bar{c}nj$, $n=0,\dots,4$	$Z\to l^+l^-$
$Zt\bar{t}nj$, $n=0,\dots,4$	$Z\to l^+l^-$
$WWnj$, $n=0,\dots,3$	$W\to l\nu$
$WZnj$, $n=0,\dots,3$	$W\to l\nu$, $Z\to l^+l^-$
$ZZnj$, $n=0,\dots,3$	$Z\to l^+l^-$
$WWWnj$, $n=0,\dots,3$	$2W\to l\nu$
$WWZnj$, $n=0,\dots,3$	all
$WZZnj$, $n=0,\dots,3$	all
$ZZZnj$, $n=0,\dots,3$	$2Z\to l^+l^-$

ALPGEN for the backgrounds (interfaced to PYTHIA using the MLM prescription)

Signals calculated with a Monte Carlo generator (TRIADA -for triplets-, ALPGEN -for singlets-) using HELAS (width and spin), VEGAS (phase space integration), interface to PYTHIA (ISR and FSR, pile-up, and hadronisation), and AcerDET (fast LHC detector simulation)

Scalar triplet Δ

Lepton Number Conserving



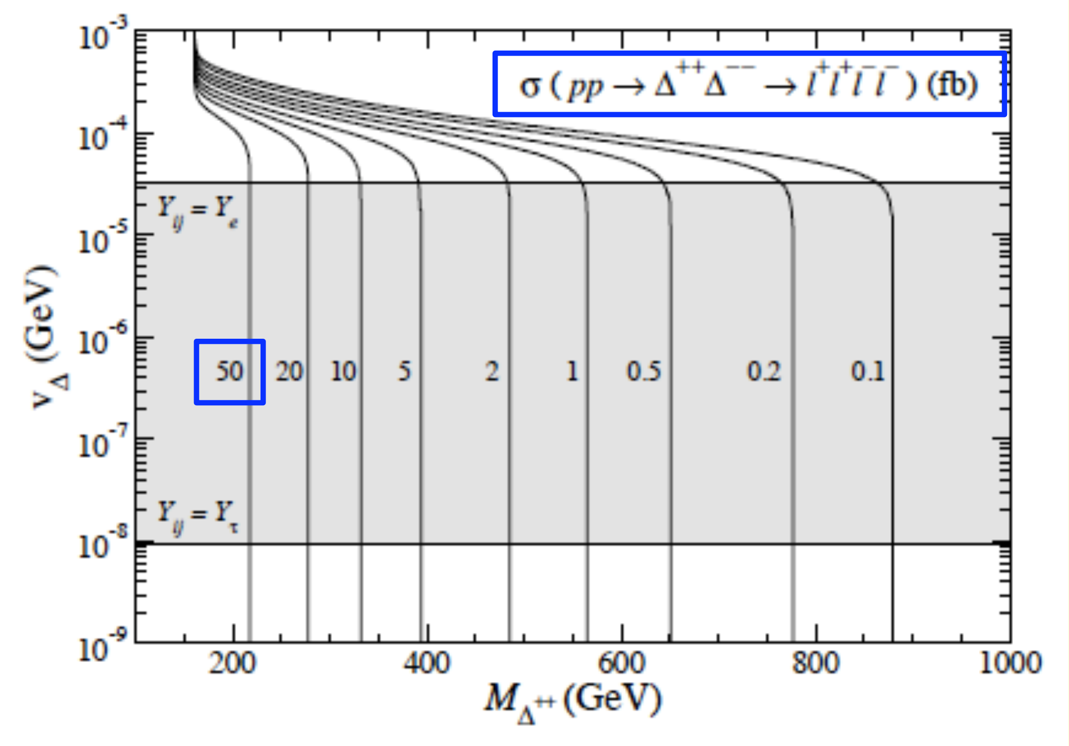
$$v_\Delta = \frac{v^2|\mu_\Delta|}{\sqrt{2}M_\Delta^2} < 2 \text{ GeV}$$

EWPD

Lepton Number Violating

$m_\nu \sim 2\, Y_\Delta\, \mu_\Delta\, v^2\, M_\Delta^{-2}$

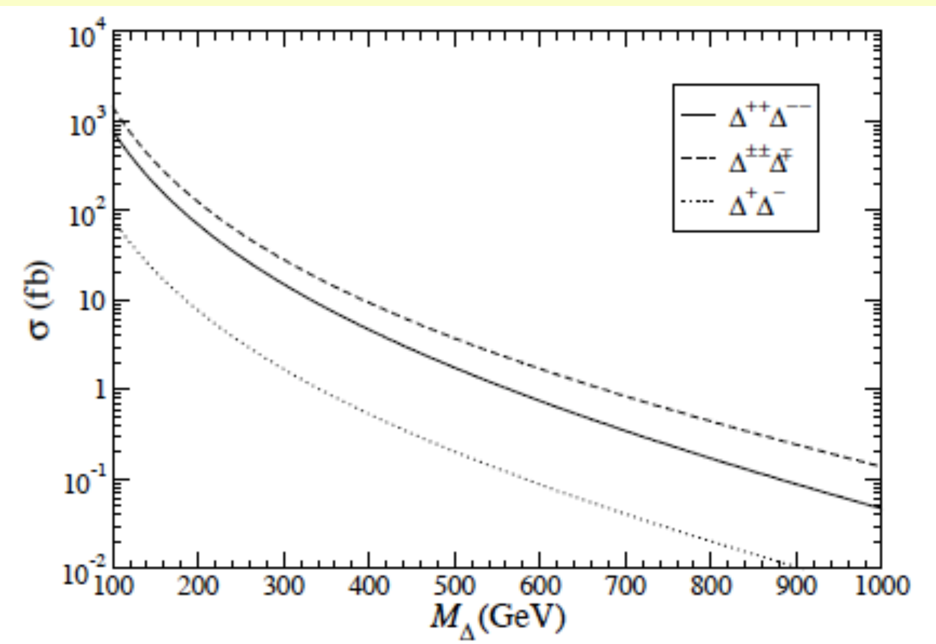
$\rightarrow l^+ l^+ W^- W^-$



F. del Águila
Universidad de Granada

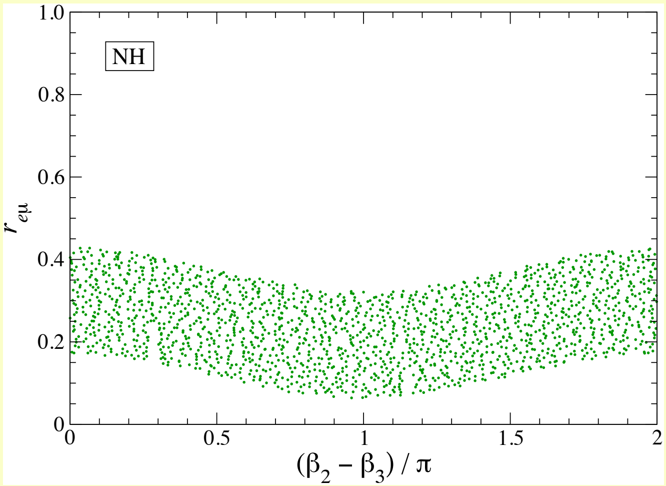
$$\mathcal{L}_{K.T.} = (D^\mu \vec{\Delta})^\dagger \cdot (D_\mu \vec{\Delta}) \;\rightarrow$$

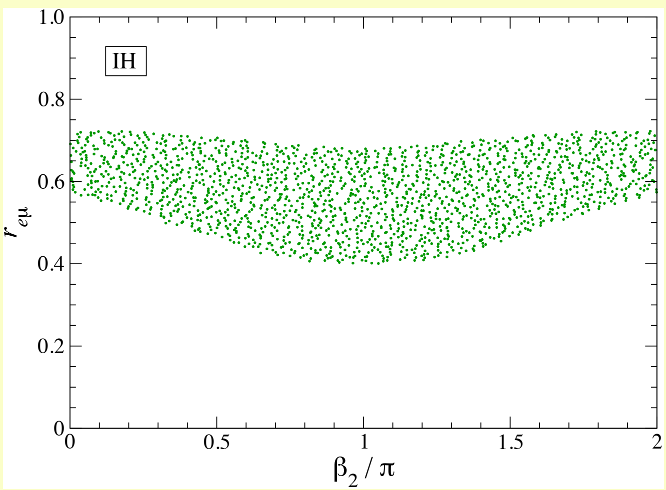
$$\begin{aligned}
\mathcal{L}_W &= -ig\left[(\partial^\mu \Delta^{--})\Delta^{+} - \Delta^{--}(\partial^\mu \Delta^{+})\right] W^{+}_{\mu}\,, \\
&\quad -ig\left[(\partial^\mu \Delta^{-})\Delta^{++} - \Delta^{-}(\partial^\mu \Delta^{++})\right] W^{-}_{\mu}\,, \\
\mathcal{L}_Z &= \frac{ig}{c_W}(1-2s_W^2)\left[(\partial^\mu \Delta^{--})\Delta^{++} - \Delta^{--}(\partial^\mu \Delta^{++})\right] Z_\mu \\
&\quad -\frac{ig}{c_W} s_W^2 \left[(\partial^\mu \Delta^{-})\Delta^{+} - \Delta^{-}(\partial^\mu \Delta^{+})\right] Z_\mu\,, \\
\mathcal{L}_\gamma &= i2e\left[(\partial^\mu \Delta^{--})\Delta^{++} - \Delta^{--}(\partial^\mu \Delta^{++})\right] A_\mu \\
&\quad +ie\left[(\partial^\mu \Delta^{-})\Delta^{+} - \Delta^{-}(\partial^\mu \Delta^{+})\right] A_\mu\,.
\end{aligned}$$



Δ BR's into leptons are a high energy window to neutrino masses and mixings, and may even allow for reconstructing the MNS matrix.

$$r_{e\mu} \equiv \mathrm{Br}(\Delta^{\pm\pm} \to e^\pm e^\pm / \mu^\pm \mu^\pm / e^\pm \mu^\pm)$$





They depend on the neutrino masses and mixings, being the main dependance on α_2 (in the plots $\beta_2 - \beta_3$ and β_2, respectively). We assume in our simulations:

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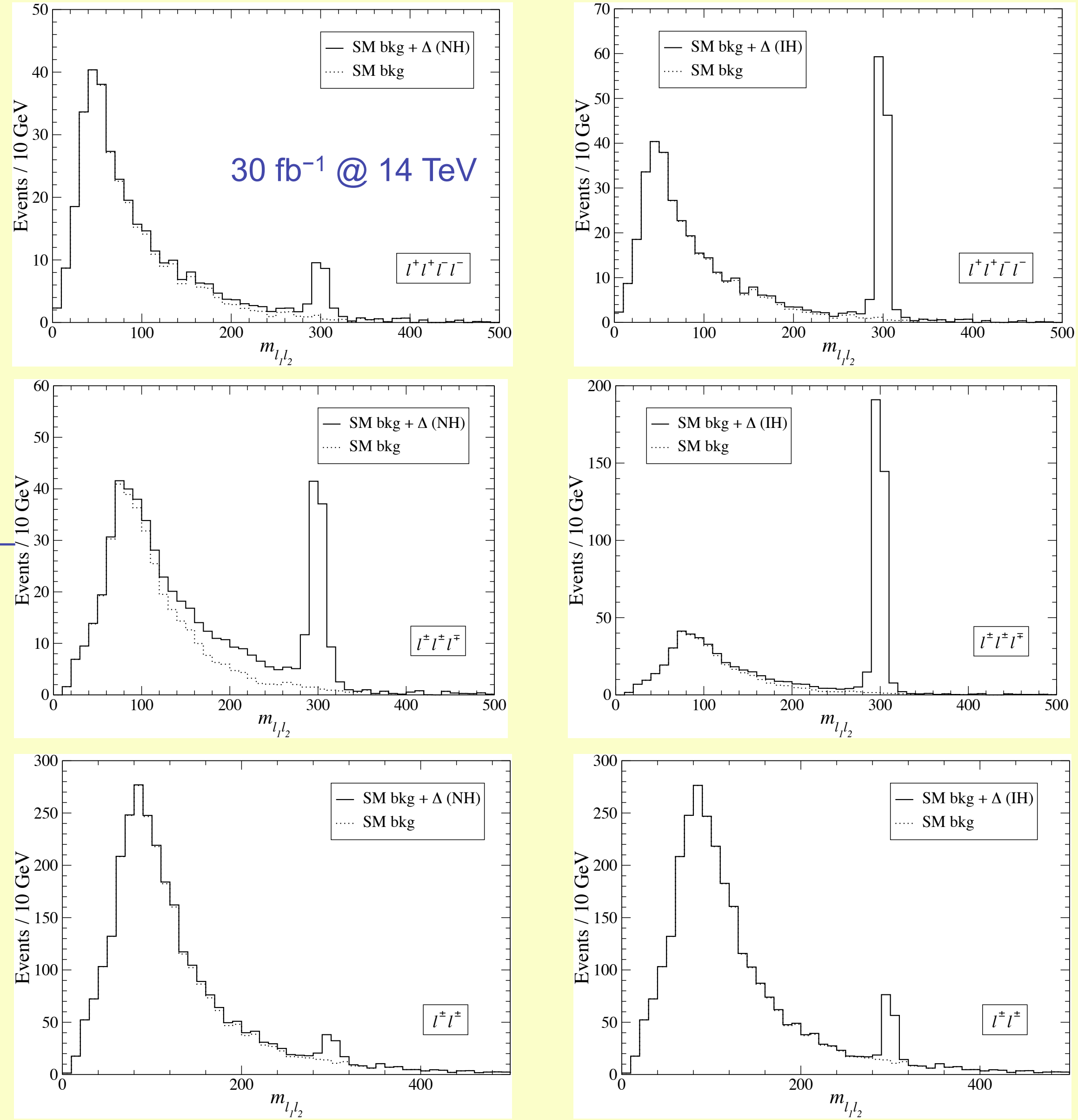
	$e^\pm e^\pm$	$\mu^\pm \mu^\pm$	$\mu^\pm \tau^\pm$	$\tau^\pm \tau^\pm$
NH	0.00	0.20	0.49	0.29
IH	0.50	0.15	0.25	0.10

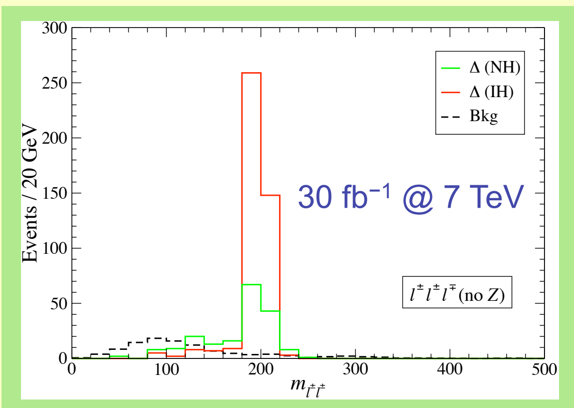
Hektor, Kadastik, Muntel, Raidal, Rebane 07

Garayoa, Schwetz 08

Fileviez Perez, Han, Huang, Li, Wang 08

$\ell_1\ell_2$ invariant mass distribution for the SM and the SM plus the triplet signal in the cases of NH (left) and IH (right).





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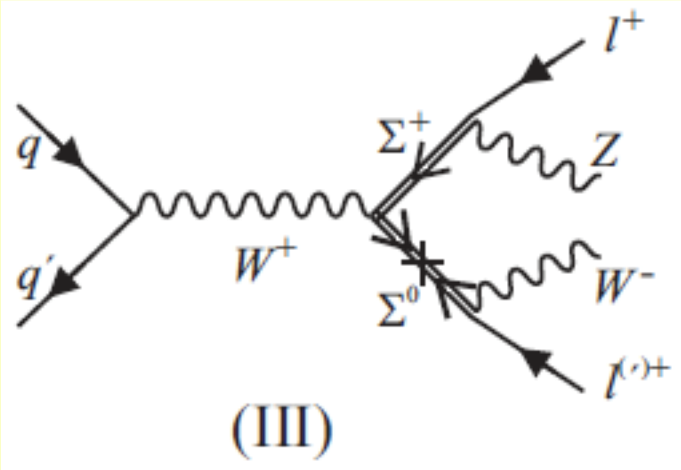
LHC reach at 14 TeV for 30 fb^{-1}

Δ: 600 (800) GeV for NH (IH)

Fermion triplet Σ



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Franceschini, Hambye, Strumia 08

Arhrib, Bajc, Ghosh, Han, Huang, Puljak, Senjanovic 09

FCNC Ibañez, Morisi, Valle 09

m_Σ = 300 GeV

$\sigma_D = 2\ \sigma_M$

	6ℓ	5ℓ	$\ell^\pm\ell^\pm\ell^\pm\ell^\mp$	$\ell^+\ell^+\ell^-\ell^-$	$\ell^\pm\ell^\pm\ell^\pm$	$\ell^\pm\ell^\pm\ell^\mp$	$\ell^\pm\ell^\pm$	$\ell^+\ell^-$	$\ell^\pm$
Σ (M)	0.6	10.6	17.4	55.7	10.2	110.3	177.8	178.7	232.4
Σ (D)	1.9	21.4	9.1	173.4	2.9	194.4	4.4	607.0	314.9
SM Bkg	0.0	0.9	2.5	14.3	1.9	15.9	19.5	548.3	1328

Table 2: Number of events with 30 fb^{-1} for the fermion triplet signals with Majorana (M) and Dirac (D) neutrinos, and SM background in different final states.

LHC reach (30 fb^{-1} and 14 TeV)

Σ: 750 (700) GeV for Majorana (Dirac) coupling to e or μ

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

$N_{M/D}$ $\Delta_{NH/IH}$ Σ_M

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Aguilar-Saavedra 09 up to a factor 2 and other multiplets

with or without Z (factor 10 reduction)

missing momentum < 30 GeV

no Z

missing momentum < 30 GeV

Aguilar-Saavedra

$\sqrt{s} = 7$ TeV, $m_{\Delta,\Sigma} = 200$ GeV	$\Delta_{NH/IH}$	$\Sigma_{M/D}$
$l^+l^+l^-l^-$	11.5 / 2.0 fb^{-1}	3.6 / 1.0 fb^{-1}
$l^\pm l^\pm l^\mp$	2.7 / 0.74 fb^{-1}	2.0 / 0.97 fb^{-1}
$l^\pm l^\pm$	5.9 / 2.1 fb^{-1}	1.4 / - fb^{-1}

Tau custodians (WED models)

Santiago's talk on Monday

Csaki, Delaunay, Grojean, Grossman 08, Chen, Mahanthappa, Yu 09, F.A., Carmona, Santiago 10, Kadosh, Pallante 10

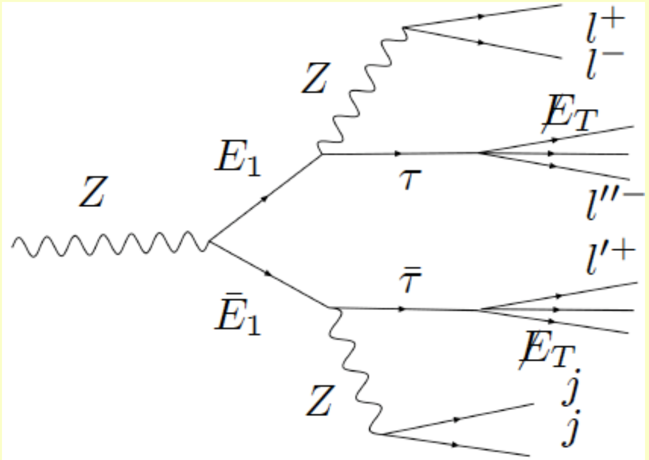
$\mathbf{5} = (\mathbf{2},\mathbf{2}) \oplus (\mathbf{1},\mathbf{1})$

$$\zeta_1 = \begin{pmatrix} \widetilde{X}_1[-+] & \nu_1[++] \\ \tilde{\nu}_1[-+] & e_1[++] \end{pmatrix} \oplus \nu_1'[-+], \quad \zeta_2 = \begin{pmatrix} \widetilde{X}_2[+-] & \nu_2[+-] \\ \tilde{\nu}_2[+-] & e_2[+-] \end{pmatrix} \oplus \nu_2'[--],$$

$$\zeta_3 = \begin{pmatrix} \nu_3[-+] & \tilde{e}_3[-+] \\ e_3[-+] & \widetilde{Y}_3[-+] \end{pmatrix} \oplus e_3'[-+], \quad \zeta_\alpha = \begin{pmatrix} \nu_\alpha[+-] & \tilde{e}_\alpha[+-] \\ e_\alpha[+-] & \widetilde{Y}_\alpha[+-] \end{pmatrix} \oplus e_\alpha'[--],$$

e, μ, τ

	A_4	Z_8		A_4	Z_8
ζ_1	$\mathbf{3}$	1	$\phi(\mathrm{UV})$	$\mathbf{3}$	4
ζ_2	$\mathbf{3}$	2	$\eta(\mathrm{UV})$	$\mathbf{1}$	4
ζ_3	$\mathbf{3}$	1	$\phi'(\mathrm{IR})$	$\mathbf{3}$	5
ζ_α	$\mathbf{1}, \mathbf{1}', \mathbf{1}''$	4	$\eta'(\mathrm{IR})$	$\mathbf{1}$	7



$$N \to \tau W^+, \quad E_1 \to \tau Z, \quad Y \to \tau W^-, \quad E_2 \to \tau H,$$

$$pp \to \bar{E}_1 E_1 \to ZZ\bar{\tau}\tau, \qquad pp \to \bar{E}_1 Y \to ZW^-\bar{\tau}\tau,$$

$$pp \to \bar{E}_1 E_2 \to ZH\bar{\tau}\tau, \qquad pp \to \bar{E}_1 N \to ZW^+\bar{\tau}\tau,$$

$$pp \to l^+ l^- l'^+ l''^- jj \not{E}_T, \quad \text{with } l, l', l'' = e, \mu.$$

F.A., Carmona, Santiago, to appear

The LHC reach for these new lepton doublets decaying into τ's is up to 240, 480, 720 GeV at √s = 14 TeV and an integrated luminosity of 30, 300 and 3000 fb^{-1}, respectively.

To be compared with 1.1 (0.75) fb^{-1} (5σ discovery luminosity @ 14 (7) TeV for a lepton doublet of mass 300 (200) GeV decaying into *e*,μ).

Aguilar-Saavedra

Summary

• Many experiments give a consistent picture of non-zero neutrino masses and charged Lepton Flavour transitions. In contrast with the quark sector the mixing angles are large, and the neutrino masses tiny. A bottom-up approach leave many questions open, giving further motivation to new experiments

• Indirect limits constrain new physics relevant for neutrino oscillation experiments typically below 1 % (at the amplitude level), making their effects hardly visible without large cancellations (which would point to new physics).

• There are many models which do accommodate the observed pattern, with no apparently favoured scenario given the preferred hipotheses. LHC may observed see-saw messengers below ~ 700 GeV (@ 14 TeV with $\mathcal{L}$ = 30 fb^{-1}) studying multilepton channels, which are the main signatures for many other new particles. [~ 400 (200) GeV @ 7 TeV with $\mathcal{L}$ = 30 (1) fb^{-1}.]

Thanks for your attention