Testing neutrino mass generation at LHC

- Introduction: Anything LHC has to say about ν oscillations is model dependent.
- Neutrino masses and lepton number violation
- Signatures of see-saw messengers at LHC
- Multilepton signals at LHC

Neutrino masses and lepton number violation

The signals of new physics at large colliders depend on the new masses and couplings.

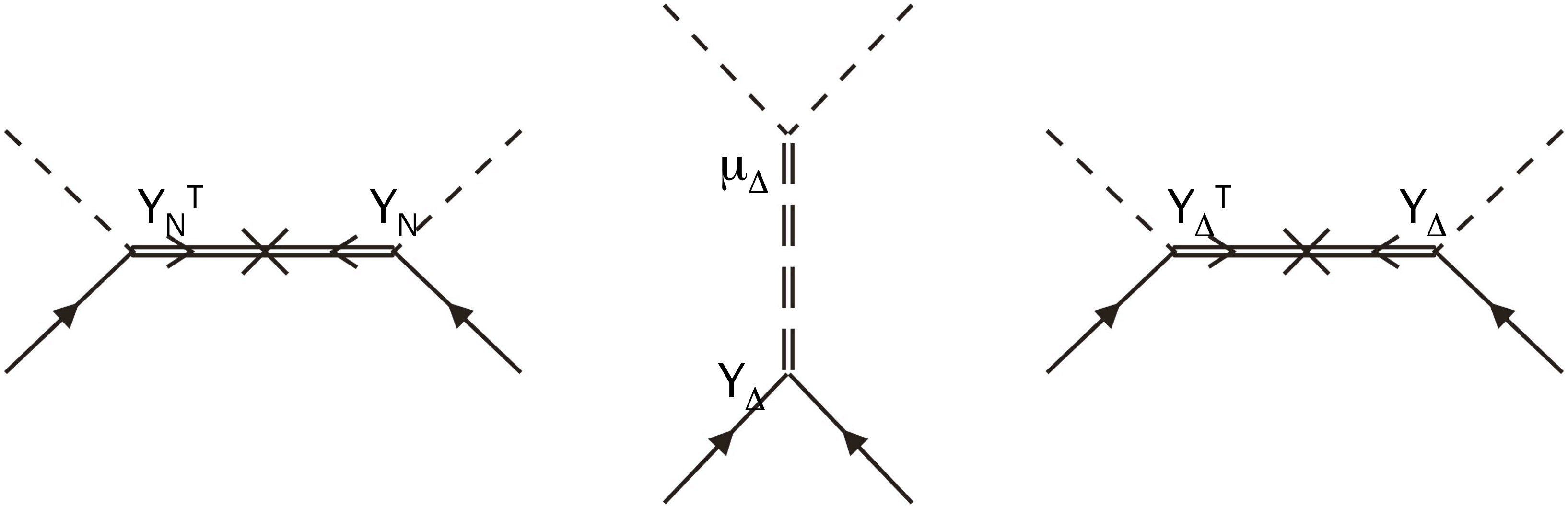
Here, we are mainly interested in new particles which may contribute to light neutrino masses, in particular which result upon integration in the only dimension 5 operator involving Standard Model fields and generating Majorana masses for the 3 known ν's.

$$\mathcal{O}_5 = \overline{l^c_L}\tilde{\phi}^* \tilde{\phi}^\dagger l_L$$

S. Weinberg, Phys. Rev. Lett. 43 (1979) 1566

There are 3 such tree level messengers: N, Δ, Σ. (There are other ways to give neutrino masses if they are, for instance, Dirac particles. E. Ma, arXiv: 0905.0221 [hep-ph])

See-saw messengers of type I,II and III



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

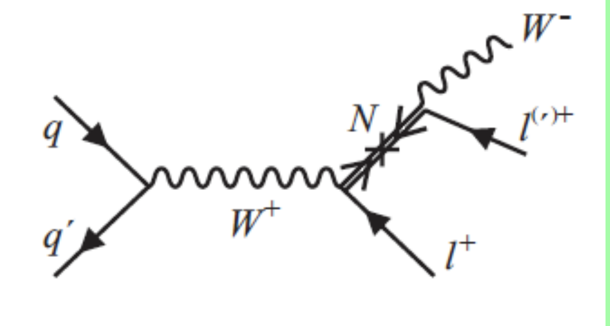
Phase cancellation or small couplings — small coupling(s) — Phase cancellation or small couplings

A. Abada, C. Biggio, F. Bonnet, M.B. Gavela and T. Hambye, JHEP 0712 (2007) 061

Some debate on N production and detection

X.-G. He, S. Oh, J. Tandean and C.-C. Wen, arXiv: 0907.1607

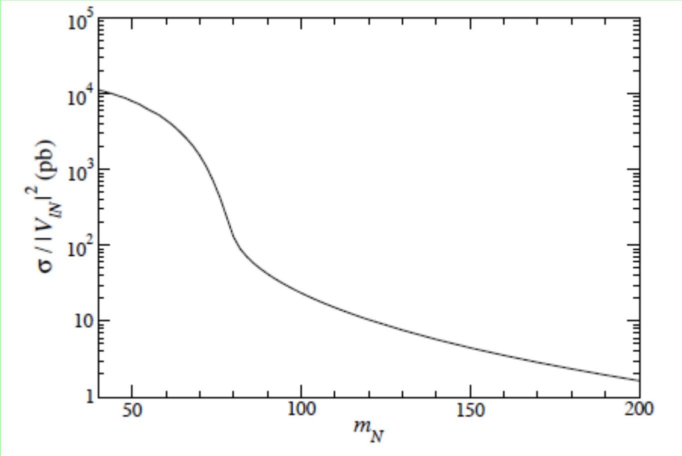
The production mechanism is proportional to the mixing between the light leptons and the new heavy neutrino N,



(I)

as there are the light neutrino masses, 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.

Some debate on N production and detection



Otherwise,
V_{eN} = 0.045
V_{mN} = 0.006

Without CKM data

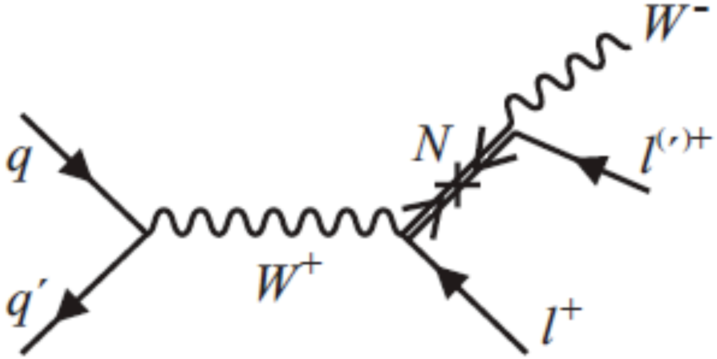
Coupling		N	E	Δ_1	Δ_3	Σ_0	Σ_1
Only with e	$\|V\| <$	0.055	0.018	0.018	0.025	0.019	0.013
	$\|V_{\rm min}\| =$	0.035	0	0	0.018	0.014	0
Only with μ	$\|V\| <$	0.057	0.034	0.045	0.024	0.017	0.022
	$\|V_{\rm min}\| =$	0.036	0.020	0.035	0	0	0
Only with τ	$\|V\| <$	0.079	0.030	0.030	0.042	0.027	0.026
	$\|V_{\rm min}\| =$	0.057	0	0	0.028	0.015	0
Universal	$\|V\| <$	0.038	0.018	0.019	0.022	0.016	0.011
	$\|V_{\rm min}\| =$	0.025	0	0	0.014	0.012	0

F.A., J. de Blas and M. Pérez.-Victoria, Phs. Rev. D78 (2008) 013010

The observation of this signal requires, as always, relatively small backgrounds, which are different for heavy Majorana and Dirac neutrinos. T. Han and B. Zhang, Phys. Rev. Lett. 97 (2006) 171804

Although for heavy Majorana neutrinos the signal is lepton number violating, the backgrounds are not completely negligible for the energies and cross sections involved.

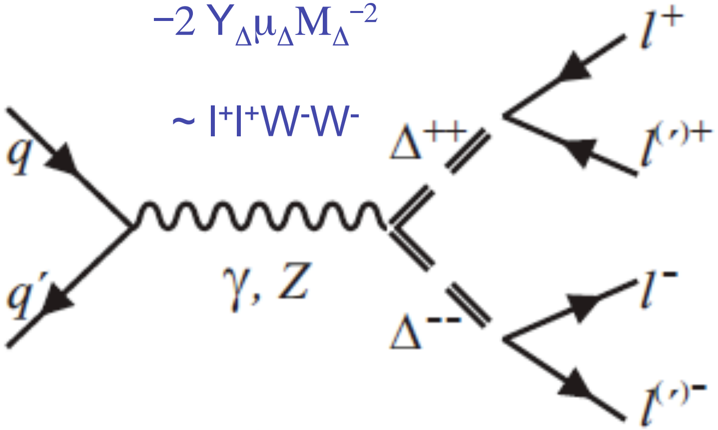
Signatures of see-saw messengers at LHC



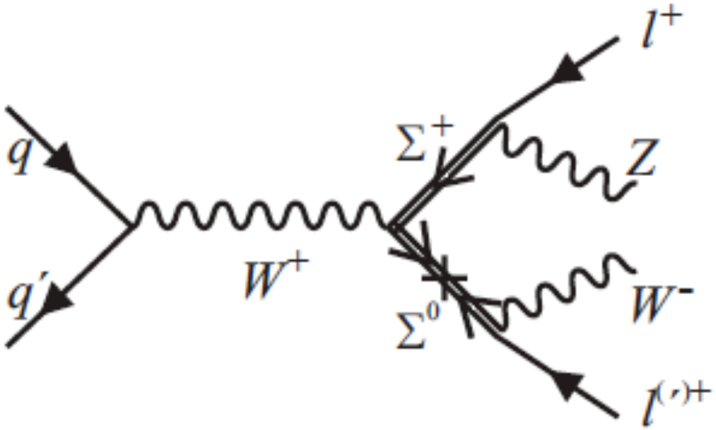
(I)

$-2\, Y_\Delta \mu_\Delta M_\Delta^{-2}$

$\sim l^+ l^+ W^- W^-$



(II)



(III)

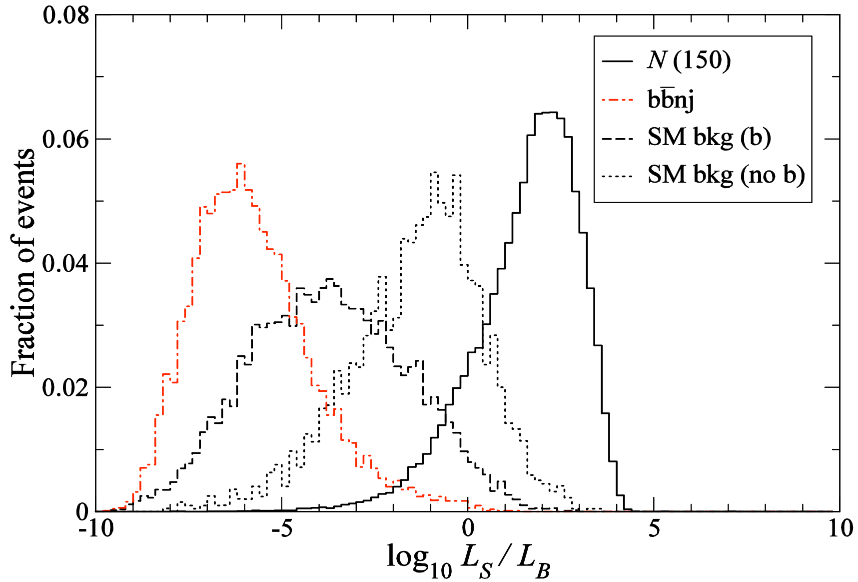
Fermion singlet N

F.A., J.A. Aguilar-Saavedra and R. Pittau,
JHEP 0710 (2007) 047

	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

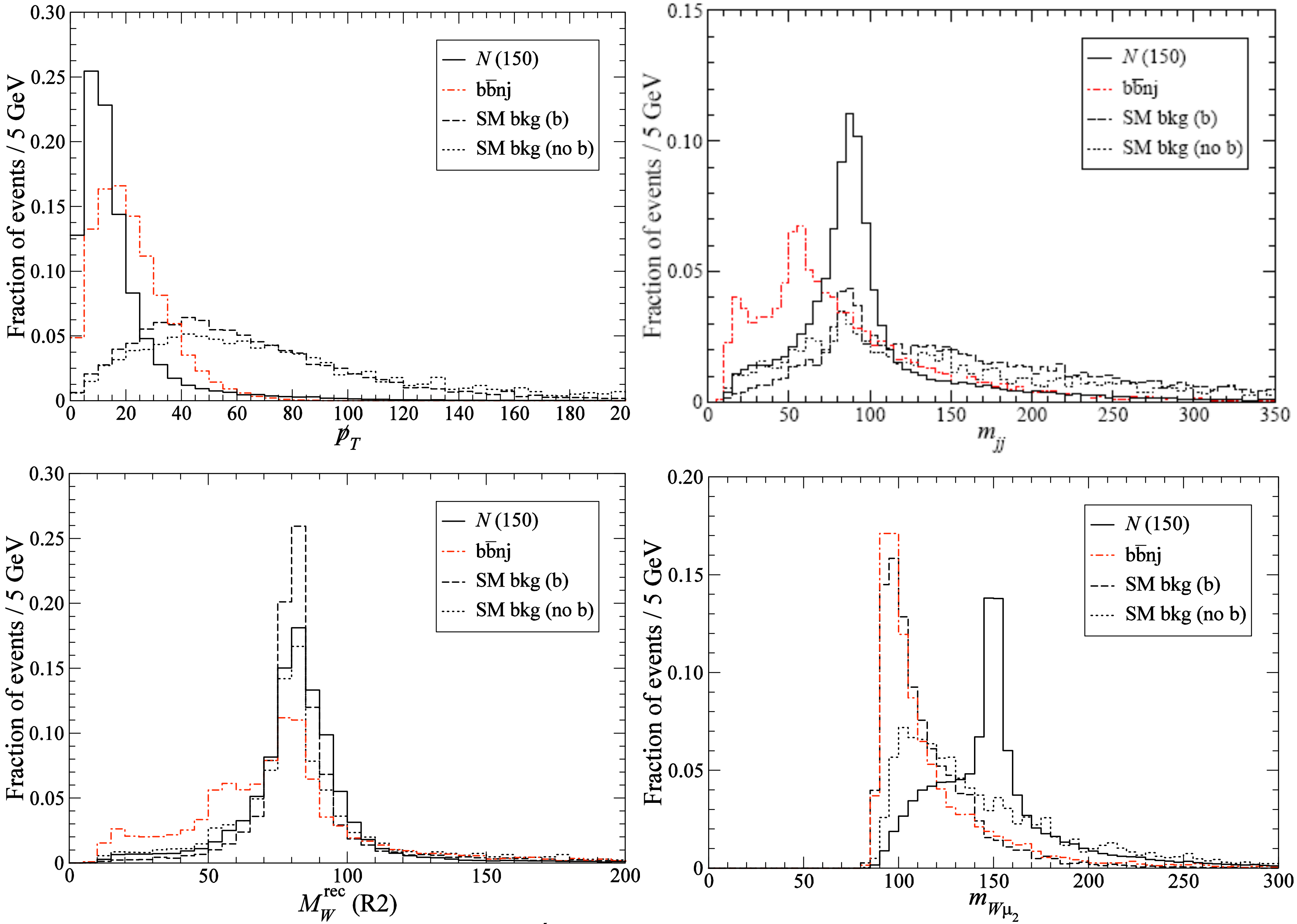
Table 1: Number of $\ell^\pm\ell^\pm jj$ events at LHC for 30 fb^{-1}, at the pre-selection and selection levels. The heavy neutrino signal is evaluated assuming $m_N = 150$ GeV and coupling (a) to the muon, $V_{\mu N} = 0.098$; (b) to the electron, $V_{eN} = 0.073$; (c) to both, $V_{eN} = 0.073$ and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

Large backgrounds

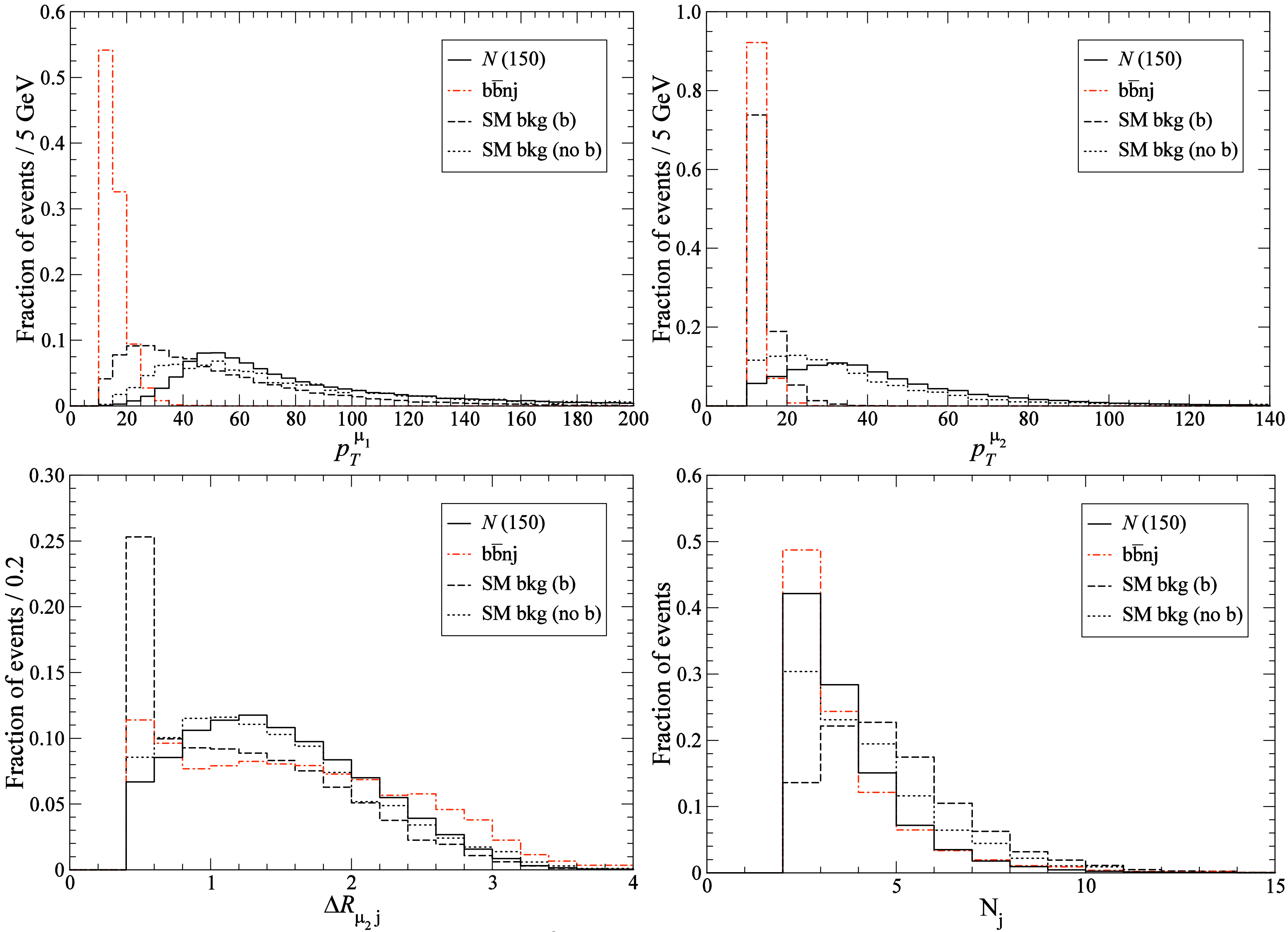


Limit on their mass
~ 120 (150) GeV for D (M)

Likelihood analysis



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


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

LNC signals may be more significant than LNV ones

$$q\bar{q}' \to \ell^+ N \to \ell^+\ell^- W^+ \to \ell^+\ell^-\ell^+\nu \quad \text{(LNC)}$$
$$q\bar{q}' \to \ell^+ N \to \ell^+\ell^+ W^- \to \ell^+\ell^+\ell^-\bar{\nu} \quad \text{(LNV)}$$

F.A. and J.A. Aguilar-Saavedra, Phys. Lett. B672 (2009) 158

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

Some debate on LNV versus LNC signals

LNV signals have smaller backgrounds than LNC ones 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.

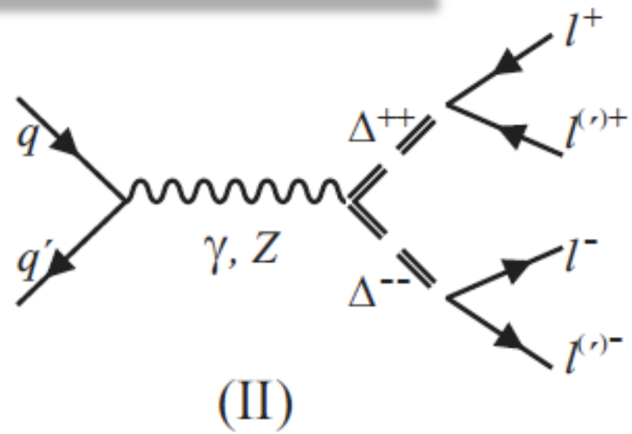
At any rate, multilepton signals are complementary in order to discriminate between models. Scalar and fermion triplets mediating the see-saw mechanism have final states with many leptons (up to 6), as many other new particles at the TeV scale (as, for example, heavy leptons or quarks, or Z's decaying into them).

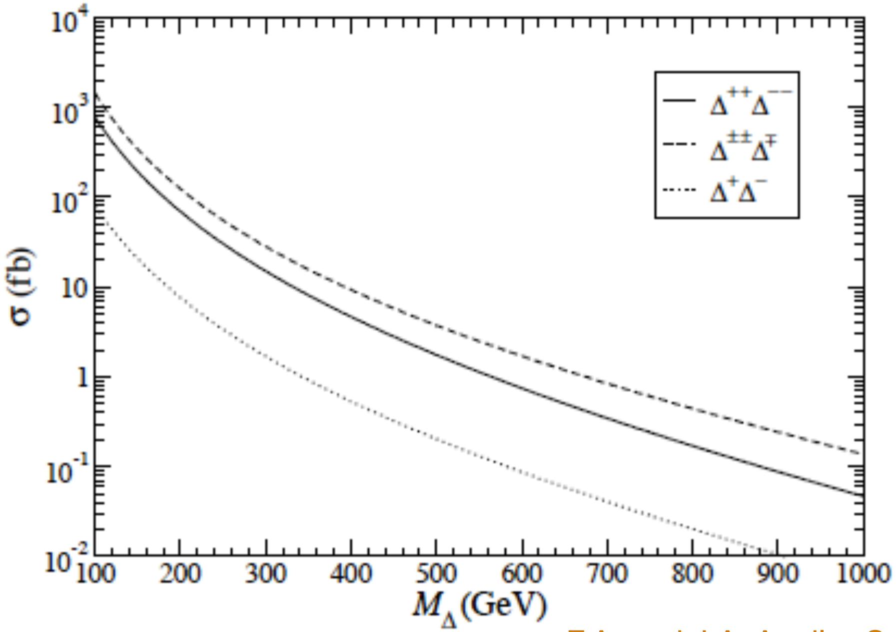
Multilepton signals at LHC

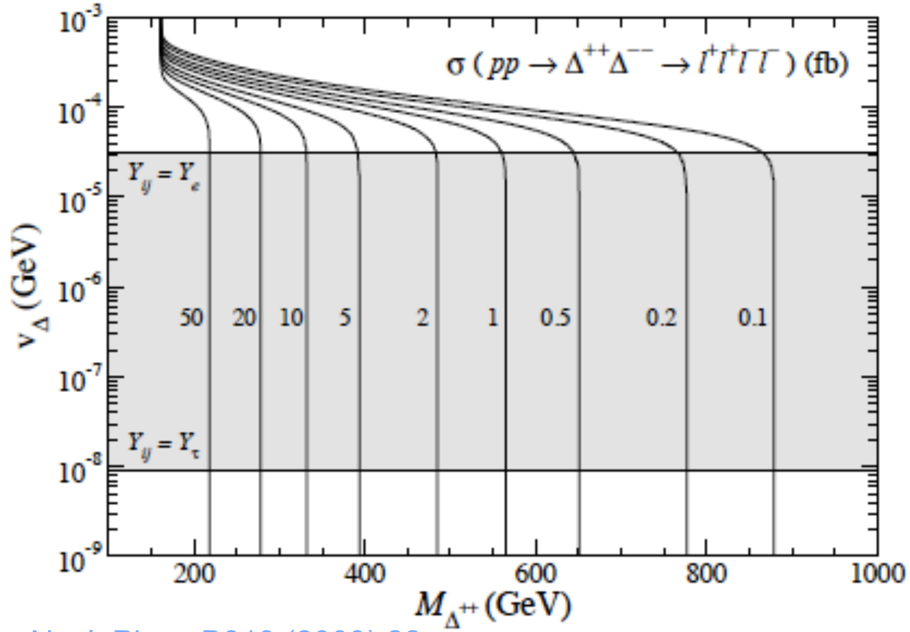
Scalar triplet Δ

$-2\, Y_\Delta \mu_\Delta M_\Delta^{-2}$

$\sim l^+ l^+ W^- W^-$







F.A. and J.A. Aguilar-Saavedra, Nucl. Phys. B813 (2009) 22

Scalar triplet decay

A. Hektor, M. Kadastik, M. Muntel, M. Raidal and L. Rebane, Nucl. Phys. B787 (2007) 198

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

J. Garayoa and T. Schwetz, JHEP 0803 (2008) 009

P. Fileviez Perez, T. Han, G.-Y. Huang, T. Li and K. Wang, Phys. Rev. D78 (2008) 015018

F.A. and J.A. Aguilar-Saavedra, Nucl. Phys. B813 (2009) 22

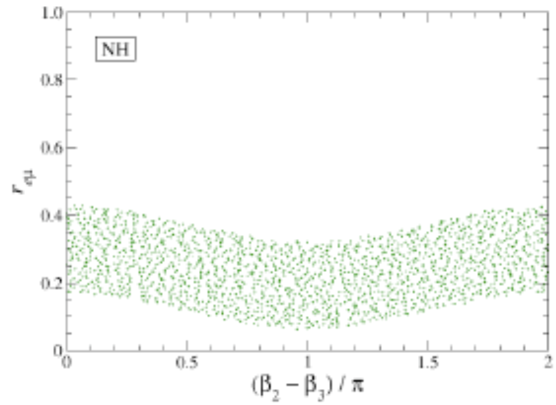
Approximate branching ratios

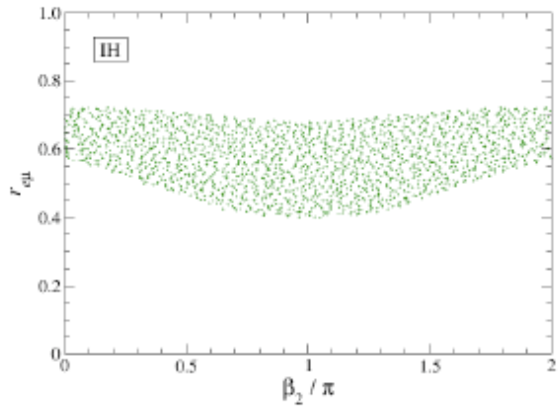
	e^+e^+	$\mu^+\mu^+$	$\mu^+\tau^+$	$\tau^+\tau^+$
NH	0.00	0.20	0.49	0.29
IH	0.50	0.15	0.25	0.10

Relevant quantity

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

depends on m_ν, θ, δ, β





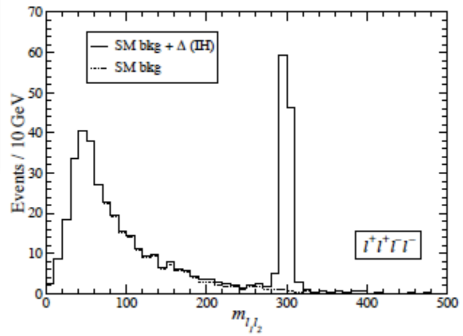
Results

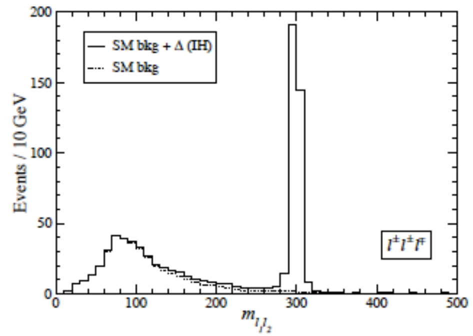
$M_\Delta = 300$ GeV

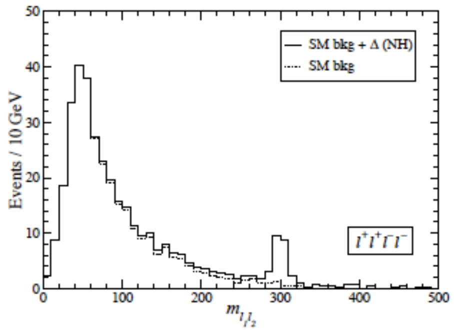
Approximate branching ratios

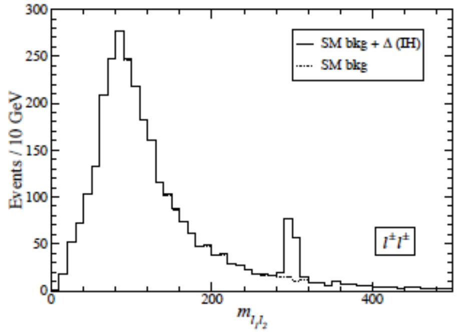
	e^+e^+	$\mu^+\mu^+$	$\mu^+\tau^+$	$\tau^+\tau^+$
NH	0.00	0.20	0.49	0.29
IH	0.50	0.15	0.25	0.10

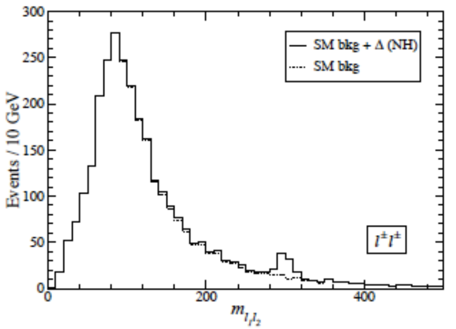
Results











Luminosity for discovery (IH)

$\ell^+\ell^+\ell^-\ell^-$	→	2.8 fb^{-1}
$\ell^\pm\ell^\pm\ell^\mp$	→	0.87 fb^{-1}
$\ell^\pm\ell^\pm$	→	4.4 fb^{-1}

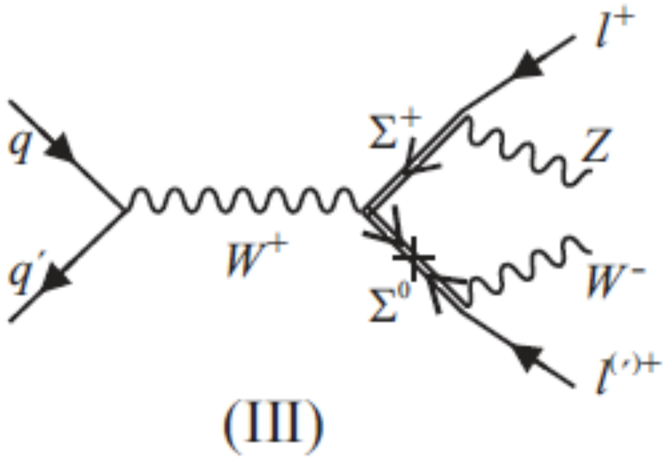
Luminosity for discovery (NH)

$\ell^+\ell^+\ell^-\ell^-$	→	18.6 fb^{-1}
$\ell^\pm\ell^\pm\ell^\mp$	→	3.6 fb^{-1}
$\ell^\pm\ell^\pm$	→	17.4 fb^{-1}

$$\frac{1}{\sqrt{2}} Y_{ij} \overline{\widetilde{L}_{iL}} \left(\vec{\tau} \cdot \vec{\Delta}\right) L_{jL}$$

LHC reach Δ: 600 (800) GeV for NH (IH)

Fermion triplet Σ



R. Franceschini, T. Hambye and A. Strumia, Phys. Rev. D78 (2008) 033002

A. Arhrib, B. Bajc, D.K. Ghosh, T. Han, G.Y. Huang, I. Puljak and G. Senjanovic, arXiv:0904.2390 [hep-ph]

F.A. and J.A. Aguilar-Saavedra, Phys. Lett. B672 (2009) 158

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.

FCNC D. Ibañez, S. Morisi and J.W.F. Valle, arXiv:0907.3109 [hep-ph]

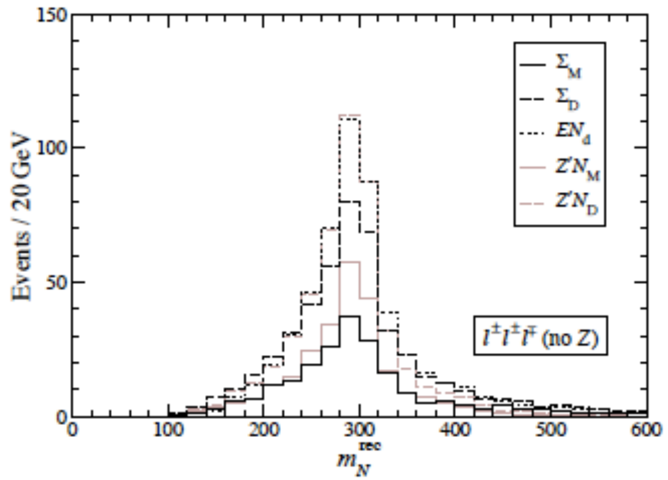
$m_{\Sigma,...}$ = 300 GeV

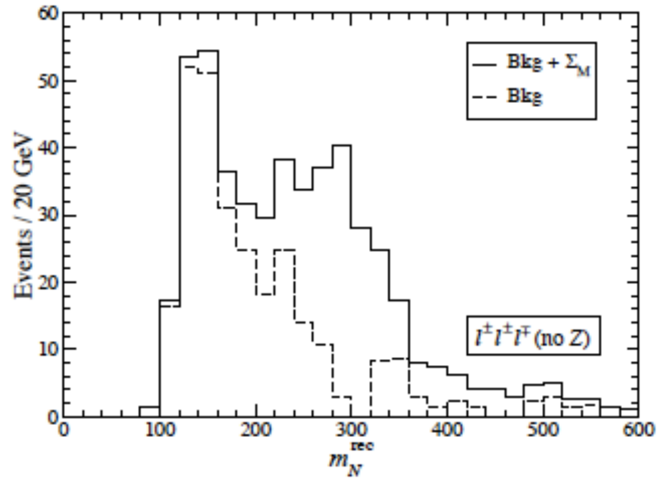
$240 < m_N^{\rm rec} < 360$ GeV

	Pre.	Sel.	Peak		Pre.	Sel.	Peak
E^+E^- ($\Sigma_{\rm M}$)	58.1	26.3	5.7	E^+E^- ($EN_{\rm d}$)	38.3	23.7	5.4
$E^\pm N$ ($\Sigma_{\rm M}$)	269.2	192.2	86.3	$E^\pm N$ ($EN_{\rm d}$)	393.2	355.1	183.8
$E_1^+E_1^-$ ($\Sigma_{\rm D}$)	127.2	80.9	20.0	NN ($EN_{\rm d}$)	164.4	155.7	87.8
$E_2^+E_2^-$ ($\Sigma_{\rm D}$)	0.0	0.0	0.0	E^+E^- ($E_{\rm s}$)	8.2	3.1	0.7
$E_1^\pm N$ ($\Sigma_{\rm D}$)	502.1	370.2	181.9	NN ($Z'N_{\rm M}$)	311.0	252.6	143.2
$E_2^\pm N$ ($\Sigma_{\rm D}$)	36.1	28.1	3.3	NN ($Z'N_{\rm D}$)	576.2	481.9	285.5
$t\bar{t}nj$	236	156	0	$WZnj$	1540	38	2
$Wt\bar{t}nj$	54	47	6	$ZZnj$	86	5	0
$Zt\bar{t}nj$	151	20	3	$WWWnj$	17	12	3

Table 4: Number of events in the $\ell^\pm\ell^\pm\ell^\mp$ (no Z) sample for the signals and main backgrounds with a luminosity of 30 fb^{-1}.

J.A. Aguilar-Saavedra, arXiv:0905.2221 [hep-ph]





$m_{\Sigma,...}$ = 300 GeV

	Pre.	Sel.	Peak		Pre.	Sel.	Peak
E^+E^- (Σ_M)	21.7	1.6	0.3	E^+E^- (EN_d)	10.5	1.2	0.3
$E^\pm N$ (Σ_M)	658.0	240.0	144.8	$E^\pm N$ (EN_d)	111.8	6.2	1.9
$E_1^+E_1^-$ (Σ_D)	25.6	4.2	0.7	NN (EN_d)	47.7	1.9	0.8
$E_2^+E_2^-$ (Σ_D)	0.0	0.0	0.0	E^+E^- (E_s)	2.5	0.0	0.0
$E_1^\pm N$ (Σ_D)	174.4	9.4	2.7	NN $(Z'N_M)$	433.5	202.1	132.0
$E_2^\pm N$ (Σ_D)	472.0	2.9	0.9	NN $(Z'N_D)$	206.0	8.1	3.1
$t\bar{t}nj$	1412	194	7	$WWnj$	245	15	3
tW	96	6	0	$WZnj$	1056	24	1
$Wt\bar{t}nj$	184	12	1	$ZZnj$	110	7	1

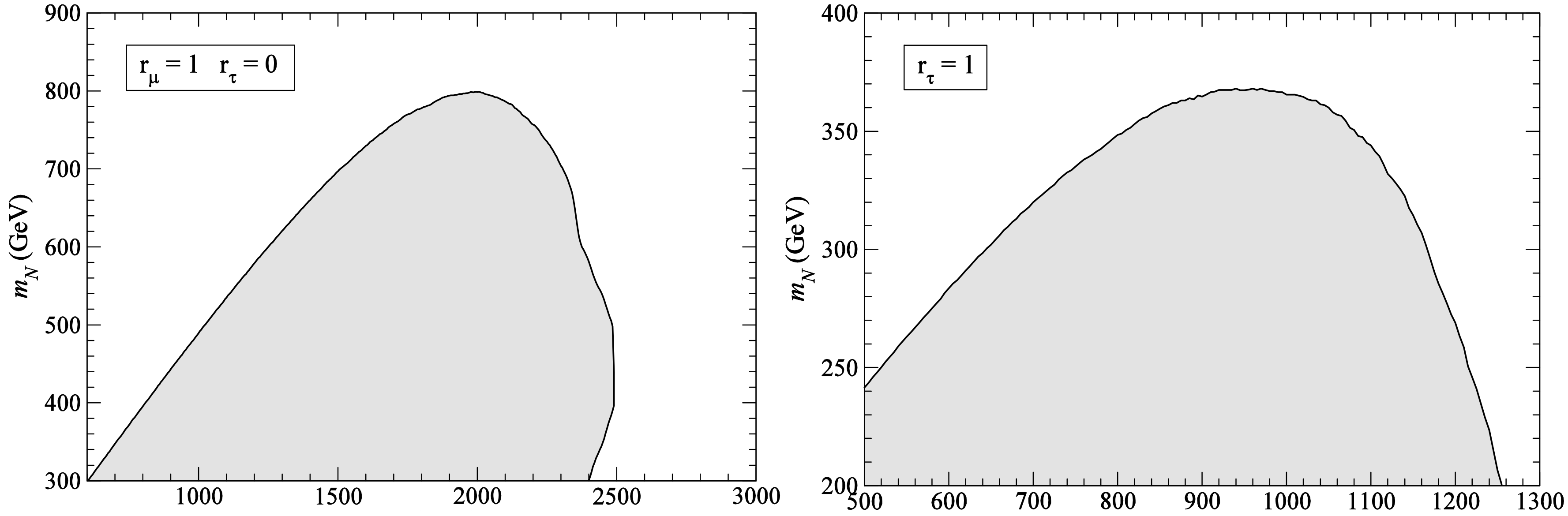
Table 8: Number of events in the $\ell^\pm\ell^\pm$ (no $p\!\!\!/_T$) sample for the signals and main backgrounds with a luminosity of 30 fb^{-1}.< 30 GeV

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

Many other Standard Model additions give multilepton signals, and the comparison of different channels in general allows for discriminating between them. F. A., Ll. Ametller, G.L. Kane and J. Vidal, Nucl. Phys. B 334 (1990) 1

$qq \xrightarrow{Z'} NN \longrightarrow WWll$

F.A. and J.A. Aguilar-Saavedra, JHEP 0711 (2007) 072



	$\ell^\pm\ell^\pm\ell^\mp$ (no Z)	$\ell^\pm\ell^\pm\ell^\mp$ (Z)	$\ell^\pm\ell^\pm$ (no $\not{p}_T$)	$\ell^\pm\ell^\pm$ ($\not{p}_T$)	$\ell^+\ell^+\ell^-\ell^-$
Σ_M	3.3	25	2.1	3.5	6.6
Σ_D	1.5	17	–	1.8	1.8
EN_d	1.1	–	–	–	3.0
E_s	–	–	–	–	–
$Z'N_M$	2.1 P	–	2.3 P	13	–
$Z'N_D$	1.1 P	–	–	22	–

Table 14: Luminosities (in fb^{-1}) required for 5σ discovery for the models in the left column in the final states indicated. The presence of a peak in the heavy lepton pair invariant mass is indicated with a "P". A dash indicates an unobservable signal, or a discovery luminosity larger than 30 fb^{-1}.

	T_s	B_s	TB_d	XT_d	BY_d
$\ell^+\ell^+\ell^-\ell^-$ (ZZ)	–	24 fb^{-1}	18 fb^{-1}	23 fb^{-1}	10 fb^{-1}
$\ell^+\ell^+\ell^-\ell^-$ (Z)	11 fb^{-1}	14 fb^{-1}	5.7 fb^{-1}	3.3 fb^{-1}	50 fb^{-1}
$\ell^+\ell^+\ell^-\ell^-$ (no Z)	35 fb^{-1}	25 fb^{-1}	11 fb^{-1}	3.5 fb^{-1}	–
$\ell^\pm\ell^\pm\ell^\mp$ (Z)	3.4 fb^{-1}	3.4 fb^{-1}	1.1 fb^{-1}	0.72 fb^{-1}	26 fb^{-1}
$\ell^\pm\ell^\pm\ell^\mp$ (no Z)	11 fb^{-1}	3.5 fb^{-1}	1.1 fb^{-1}	0.25 fb^{-1}	–
$\ell^\pm\ell^\pm$	17 fb^{-1}	4.1 fb^{-1}	1.5 fb^{-1}	0.23 fb^{-1}	–
$\ell^+\ell^-$ (Z)	22 fb^{-1}	4.5 fb^{-1}	2.4 fb^{-1}	4.4 fb^{-1}	1.8 fb^{-1}
$\ell^+\ell^-$ $(Z, 4b)$	–	–	30 fb^{-1}	–	9.2 fb^{-1}
$\ell^+\ell^-$ (no Z)	2.7 fb^{-1}	9.3 fb^{-1}	0.83 fb^{-1}	1.1 fb^{-1}	0.87 fb^{-1}
$\ell^\pm$ $(2b)$	1.1 fb^{-1}	–	0.60 fb^{-1}	–	0.18 fb^{-1}
$\ell^\pm$ $(4b)$	0.70 fb^{-1}	1.9 fb^{-1}	0.25 fb^{-1}	0.16 fb^{-1}	6.2 fb^{-1}
$\ell^\pm$ $(6b)$	11 fb^{-1}	–	9.4 fb^{-1}	2.7 fb^{-1}	–

Table 34: Luminosity required to have a 5σ discovery in all final states studied.

J.A. Aguilar-Saavedra, arXiv:0907.3155 [hep-ph]

Summary

LHC reach

N: 120 (150) GeV for D / M coupling to e (μ)

Δ: 600 (800) GeV for NH (IH)

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

Multilepton 5σ discovery luminosity

M = 300 GeV

	$\ell^\pm\ell^\pm\ell^\mp$ (no Z)	$\ell^\pm\ell^\pm\ell^\mp$ (Z)	$\ell^\pm\ell^\pm$ (no $\not{p}_T$)	$\ell^\pm\ell^\pm$ ($\not{p}_T$)	$\ell^+\ell^+\ell^-\ell^-$
Σ_{M}	3.3	25	2.1	3.5	6.6
Σ_{D}	1.5	17	–	1.8	1.8
EN_{d}	1.1	–	–	–	3.0
E_{s}	–	–	–	–	–
$Z'N_{\mathrm{M}}$	2.1 P	–	2.3 P	13	–
$Z'N_{\mathrm{D}}$	1.1 P	–	–	22	–

Thanks for your attention

F.A. et al., NPB 813 (2009) 22,
Distinguishing see-saw models at LHC with multi-lepton signals

$$\frac{S}{\sqrt{B}}$$

Significance with 1 fb^{-1}

	$M_1 + M_2$	0ℓ	$\ell^\pm$	$\ell^+\ell^-$	$\ell^\pm\ell^\pm$	$\ell^\pm\ell^\pm\ell^\mp$
Δ (NH)	$300+300$	–	–	1.9	2.2	4.2
Δ (IH)	$300+300$	–	–	1.1	3.1	8.3
Σ (M)	$300+300$	–	–	1.4	(5.0)	3.9
Σ (D)	$300+300$	–	–	4.7	–	6.2
mSUGRA (SU1)	$264+262$	6.3	18.0	6.9	7.2	1.3
mSUGRA (SU2)	$160+149$	0.9	6.0	1.07	1.9	2.7
mSUGRA (SU3)	$219+218$	13	17.7	11.5	7.7	11.5
mSUGRA (SU4)	$113+113$	25	33.7	24.7	19.9	24.4

☞ with same M, multi-lepton signals larger in seesaw II, III

Note: seesaw signals not optimised (scaled from 30 fb^{-1} analysis)

J.A. Aguilar-Saavedra

Results $m_N = m_E = 300$ GeV $M_{Z'_\lambda} = 650$ GeV

Signals in many final states with 1 to 6 leptons

Only one triplet Σ / one doublet $(N\ E)$ / one singlet N assumed for these numbers

Number of events after cuts — 30 fb^{-1}

	$\ell^\pm\ell^\pm\ell^\pm\ell^\mp$	$\ell^+\ell^+\ell^-\ell^-$	$\ell^\pm\ell^\pm\ell^\mp$	$\ell^\pm\ell^\pm$
Σ (M)	23.5	55.7	110.3	177.8
Σ (D)	19.8	173.4	194.4	4.4
$(N\ E)$	14.8	52.9	253.7	1.7
$Z'_\lambda + N$ (M)	0.5*	22.0*	165.9*	156.1*
$Z'_\lambda + N$ (D)	0.7*	35.4*	325.0*	3.8*
SM bkg	12.1	14.3	15.9	19.5

Heavy leptons

B. Bajc, M. Nemevsek and G. Senjanovic, hep-ph/0703080

F. del Aguila, Ll. Ametller, G.L. Kane and J. Vidal, Nucl. Phys. B 334 (1990) 1

		Tevatron ($M_L = 100$ GeV) $\|\eta\| < 4$ $p_t > 10$ GeV No $M_{\ell\bar{\ell},\ell\nu}$ cut	UNK ($M_L = 200$ GeV) $\|\eta\| < 4$ $p_t > 10$ GeV $M_{\ell\bar{\ell},\ell\nu} > 100$ GeV	LHC ($M_L = 500$ GeV) $\|\eta\| < 4$ $p_t > 50$ GeV $M_{\ell\bar{\ell},\ell\nu} > 200$ GeV	SSC ($M_L = 500$ GeV) $\|\eta\| < 4$ $p_t > 50$ GeV $M_{\ell\bar{\ell},\ell\nu} > 200$ GeV
$\ell\bar{\ell}$jjjj	E	0.01	0.5	1	5
	$\left(\frac{N}{E}\right)$	0.9	18	54	239
$\ell\nu$jjjj	E	0.02	0.9	2	9
	$\left(\frac{N}{E}\right)$	—	—	—	—
$\ell\bar{\ell}\ell\nu$jj	E	7×10^{-4}	0.03	0.08	0.3
	$\left(\frac{N}{E}\right)$	0.4	5	17	72

Summary. II

- Independently of the heavy neutrino character EWPD require

Fermion singlet $m_N > M_W$

$\lvert V_{lN} V_{l'N}\rvert <$	0.012	0.0001	0.01	S. Bergmann et al., hep-ph/9803305
	0.003	0.0096	0.01	D. Tommasini et al., hep-ph/9503228
		0.0032	0.016	F. del Aguila et al., 0803.4008[hep-ph]
			0.0062	

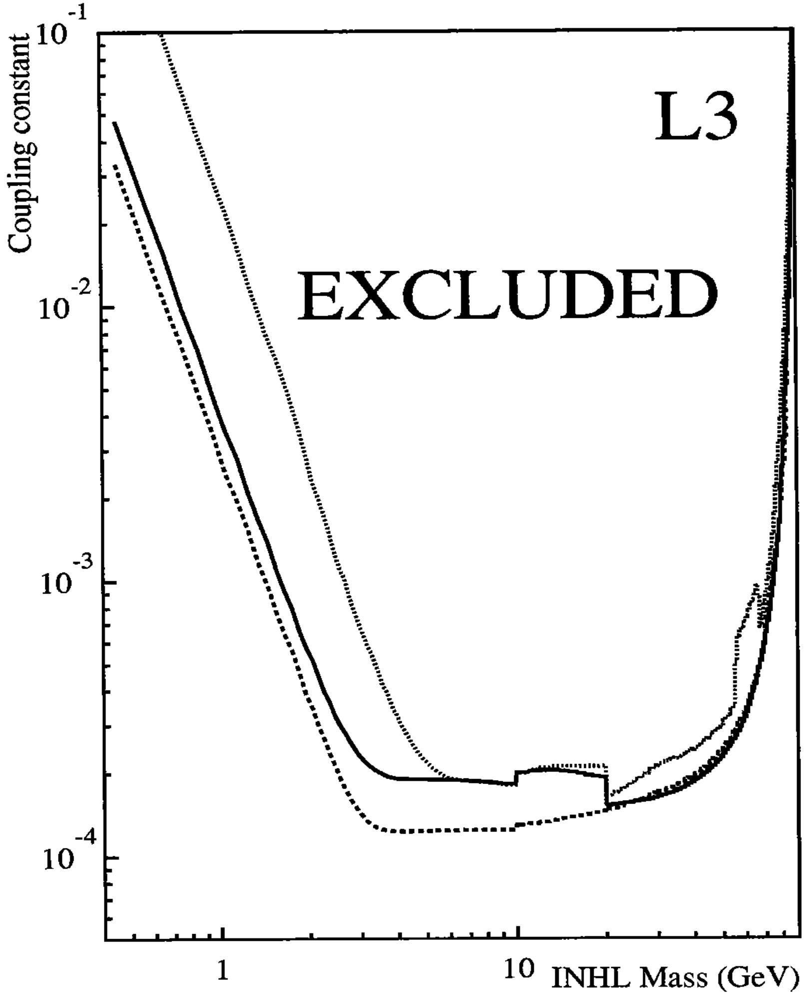
$m_N < M_W$

$|V_{lN}|^2 < 0.0002$ L3, Phys. Lett. B 295 (1992) 371

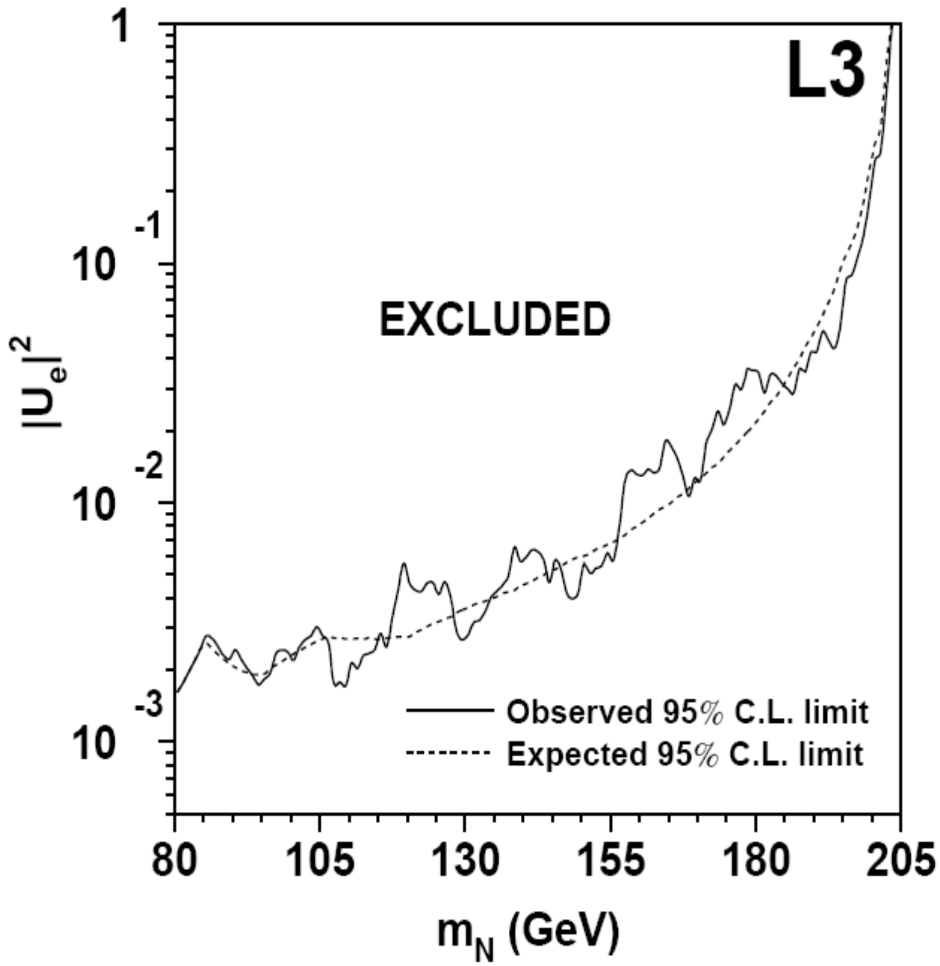
Fermion triplet $m_N > M_W$

$\lvert V_{lN} V_{l'N}\rvert <$	0.0004	$1.1\mathrm{X}10^{-6}$	0.0005	A. Abada et al., 0803.0481[hep-ph]
		0.0003	0.0005	M. Raidal et al., 0801.1826 [hep-ph]
			0.0007	

L3, Phys. Lett. B 295 (1992) 371

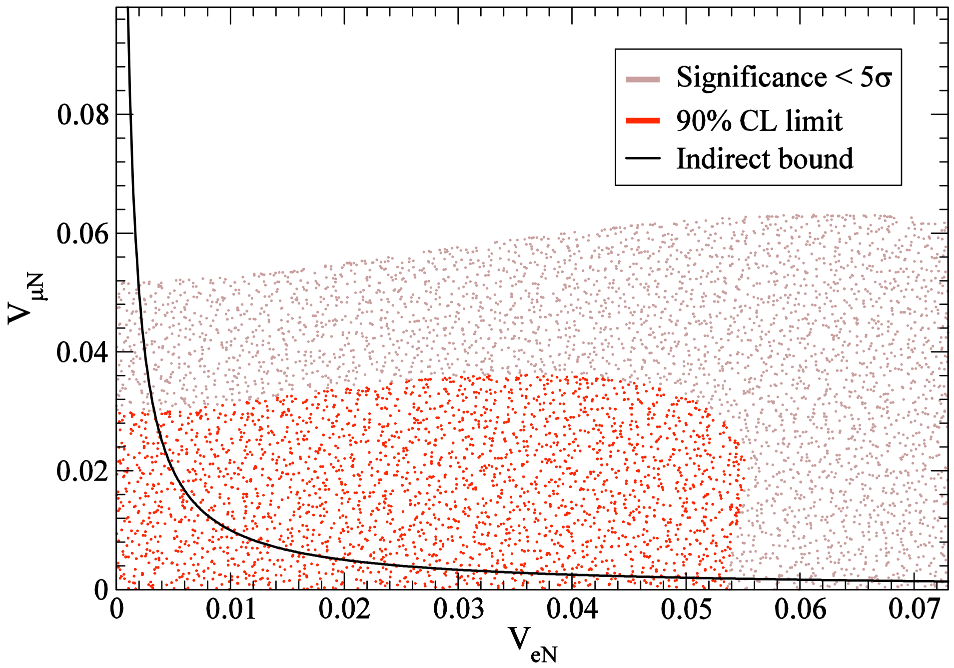


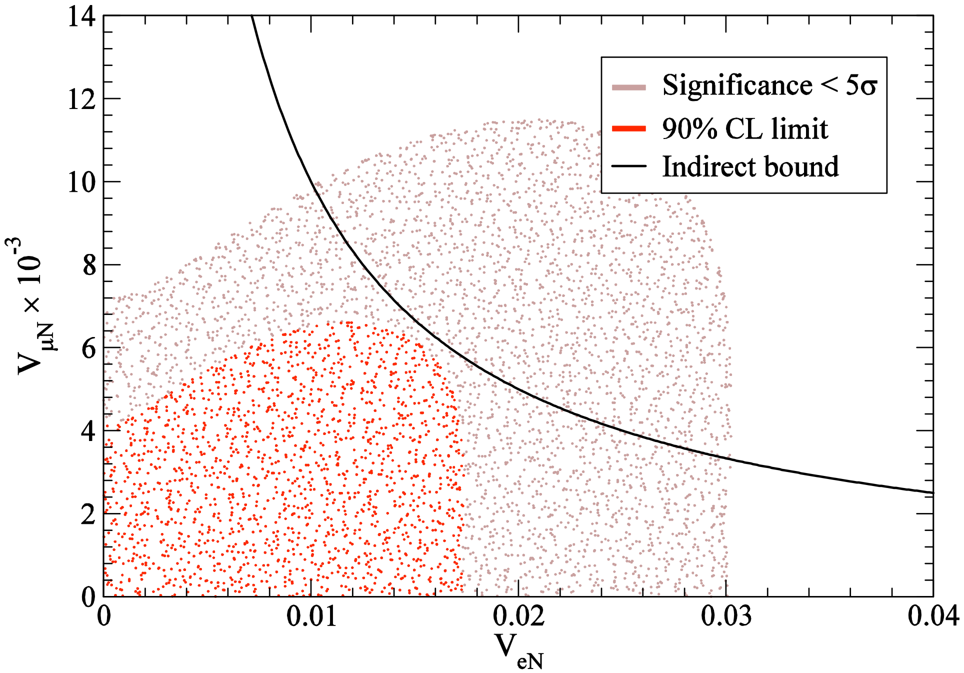
L3, hep-ex/0107014



Heavy Majorana neutrino

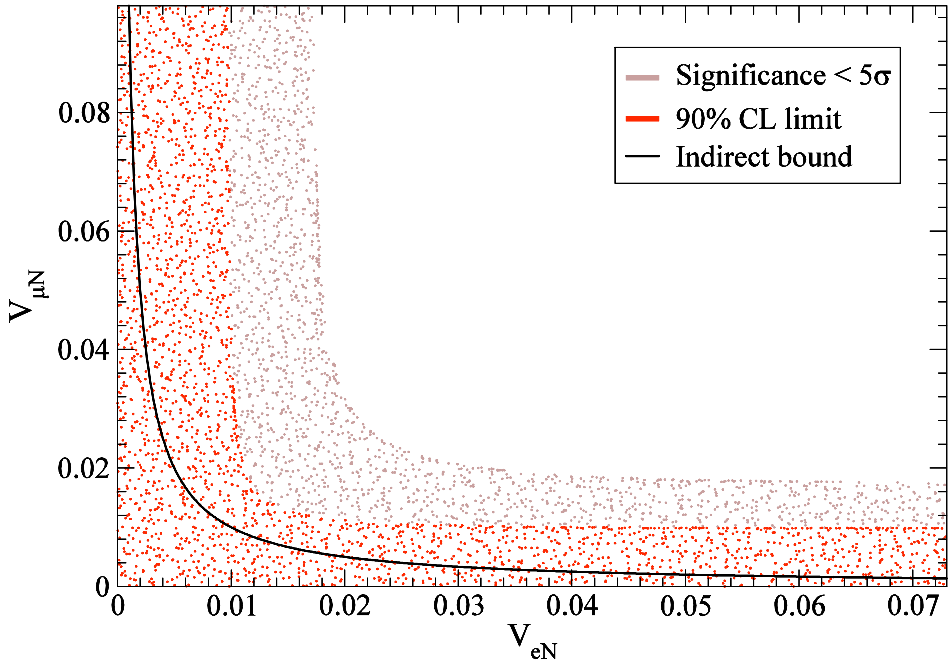
$m_N > M_W$ $m_N < M_W$





Heavy Dirac neutrino

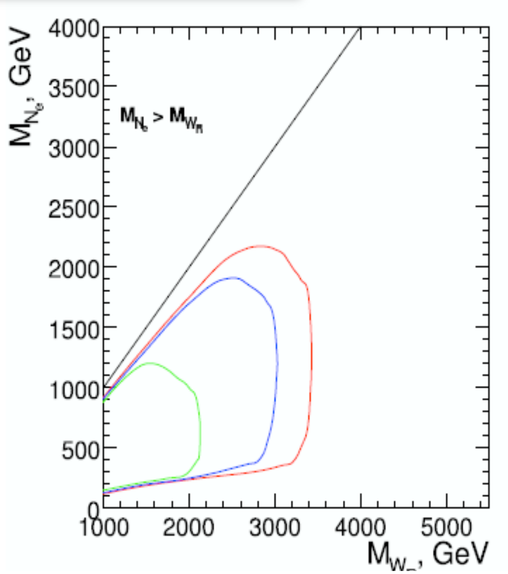
$m_N < M_W$

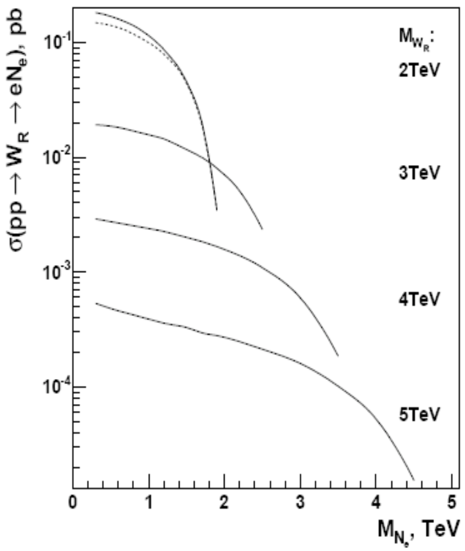


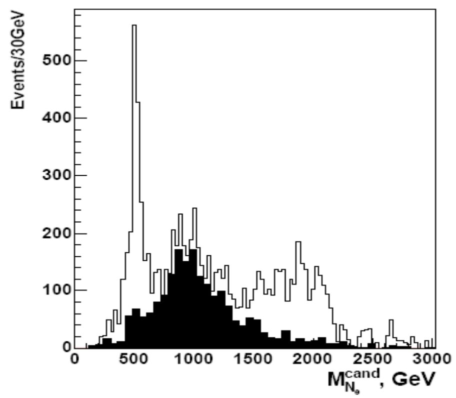
N production with extra interactions

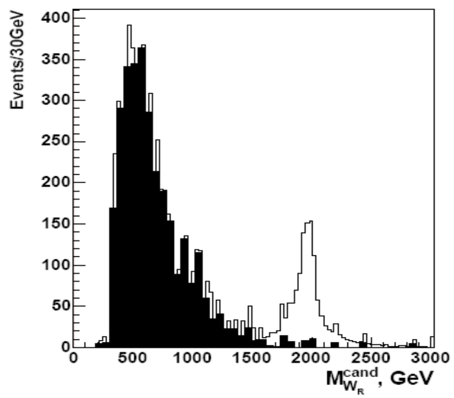
$pp \to W_R \to eN \to eejj$

Observable for M_{W_R} and M_N up to 3.5 TeV and 2.3 TeV for L = 30 fb^{-1}





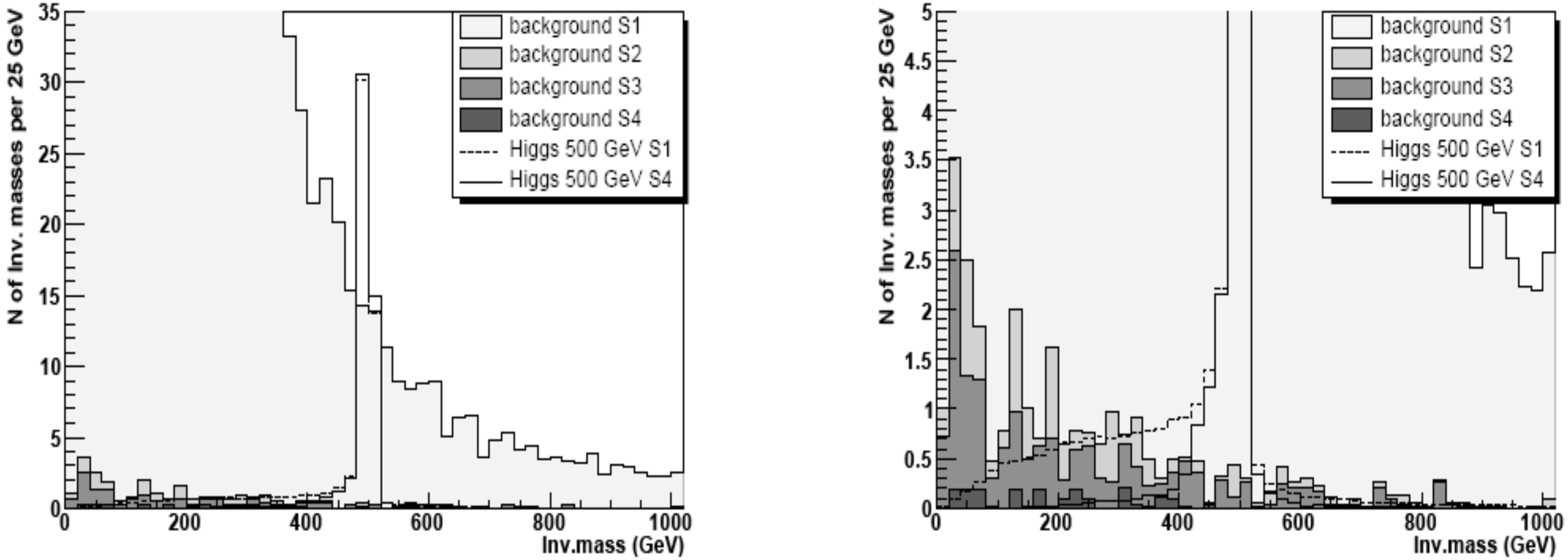




S.N. Gninenko, M.M. Kirsanov, N.V. Krasnikov and V.A.Matveev, Phys. Atom. Nucl. 70 (2007) 441

Scalar triplets

Scalar masses up to 800 GeV can be discovered at LHC for a $\mathcal{L}$ = 30 fb^{-1}



A.Hektor, M. Kadastic, M. Muntel, M. Raidal and L. Rebane,

0705.1495 [hep-ph]

Fermion triplets

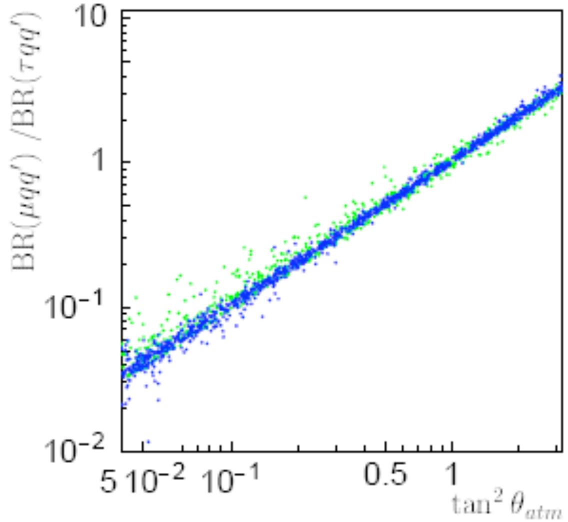
B. Bajc, M. Nemevsek and G. Senjanovic, hep-ph/0703080

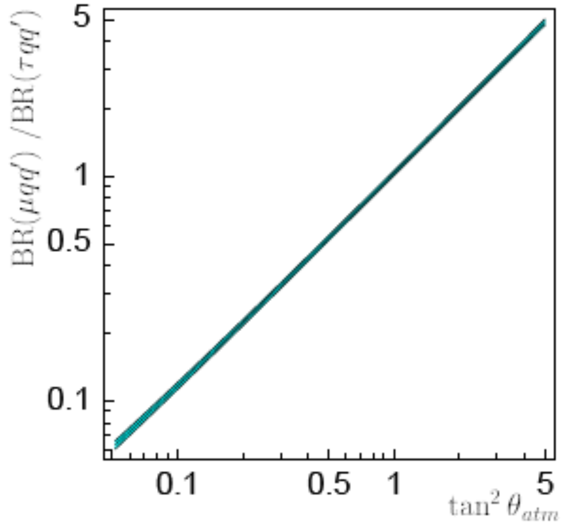
F. del Aguila, Ll. Ametller, G.L. Kane and J. Vidal, Nucl. Phys. B 334 (1990) 1

		Tevatron (M_L = 100 GeV) $\|\eta\| < 4$ $p_t > 10$ GeV No $M_{\ell\bar{\ell},\ell\nu}$ cut	UNK (M_L = 200 GeV) $\|\eta\| < 4$ $p_t > 10$ GeV $M_{\ell\bar{\ell},\ell\nu} > 100$ GeV	LHC (M_L = 500 GeV) $\|\eta\| < 4$ $p_t > 50$ GeV $M_{\ell\bar{\ell},\ell\nu} > 200$ GeV	SSC (M_L = 500 GeV) $\|\eta\| < 4$ $p_t > 50$ GeV $M_{\ell\bar{\ell},\ell\nu} > 200$ GeV
$\ell\bar{\ell}$jjjj	E	0.01	0.5	1	5
	(N E)	0.9	18	54	239
$\ell\nu$jjjj	E	0.02	0.9	2	9
	(N E)	—	—	—	—
$\ell\bar{\ell}\ell\nu$jj	E	7×10^{-4}	0.03	0.08	0.3
	(N E)	0.4	5	17	72

Other model dependent neutrino signals at large colliders

W. Porod, M.Hirsch, J.C. Romao and J.W.F. Valle, hep-ph/0011248





Ratio of neutralino branching ratios as a function of the atmospheric mixing angle

S. Bar-Shalom, A. Rajamaran, D. Whiteson and F. Yu, 0803.3795[hep-ph]

$$\mathcal{L}_{FV} = \xi_{ij} \bar{Q}_{iL} \tilde{\Phi}_{FV} u_{jR} + h.c. \,,$$

$$ug \to t\eta^0 \to tt\bar{u} + h.c. \,,$$
$$u\bar{u} \to \eta^0\eta^0 \to tt\bar{u}\bar{u} + h.c. \,,$$
$$uu \to tt + h.c. \,,$$

	M_{η^0} [GeV/c^2]	180	190	200	225	250	300
	σ [pb]	0.50	0.45	0.41	0.33	0.27	0.19
tt	ϵ [%]	0.5	0.5	0.5	0.5	0.5	0.5
	N	4.8	4.4	4.1	3.3	2.6	1.8
	σ [pb]	0.54	0.50	0.42	0.28	0.22	0.10
$tt\bar{u}$	ϵ [%]	0.5	0.5	0.5	0.5	0.5	0.5
	N	5.3	4.9	4.3	3.0	2.4	1.1
	σ [pb]	0.68	0.45	0.38	0.17	0.06	0.02
$tt\bar{u}\bar{u}$	ϵ [%]	0.5	0.5	0.5	0.5	0.5	0.5
	N	6.4	4.7	4.1	1.8	0.7	0.2
Total	$N(l^\pm l^\pm b \not{E}_T)$	16.5	14.0	12.5	8.1	5.7	3.1

S. Bar-Shalom, G. Eilam, T. Han and A. Soni, 0803.2835[hep-ph]

$$\sigma(pp \to \mu^+\mu^+W^\mp) \sim \sigma(pp \to \mu^+N) \times BR(N \to \mu^+W^-) \ ,$$
$$\sigma(pp \to \mu^+\mu^+H^\mp) \sim \sigma(pp \to \mu^+N) \times BR(N \to \mu^+H^-) \ ,$$

m_N [GeV]	m_{H^+} [GeV]	$pp \to \mu^+N$ σ [fb]	$pp \to \mu^-N$ σ [fb]	$N \to \mu^\pm W^\mp$ BR	$N \to \mu^\pm H^\mp$ BR	$pp \to \mu\mu W$ σ [fb]	$pp \to \mu\mu H$ σ [fb]
100	80	155.6	106.9	0.008	0.49	2.1	128.6
150	120	29.4	18.9	0.022	0.46	1.1	22.2
200	150	10.4	6.3	0.02	0.47	0.33	7.9
220	200	7.4	4.4	0.07	0.25	0.83	2.95

Summary. III

- Heavy Majorana neutrino coupled to muons: V_{eN} a factor 2 better at LHC, but
- new EWPD analysis reduces V_{eN} by a similar factor. Moreover, a complicated cancellation is needed not to disturb light neutrino masses.
- Heavy Dirac neutrino can not improve indirect limits but they do not contribute to light Majorana masses. However, they have not LNV signals either.
- In both cases $|V_{eN}| < 0.007$ for m_N around 300 GeV at ILC, and a factor ~ 3 better for a several TeV heavy neutrino at CLIC.

Summary. IV

- In the presence of extra interactions these limits increase up to several TeV (no mixing suppression and resonance enhancement) for both heavy fermions and gauge bosons.
- Heavy scalar triplets can be observed at LHC for masses up to 800 GeV.
- Fermion triplets have similar discovery limits.

90 % C.L.

Fermion singlet $|V_{lN}| < 0.039$

Best value $|V_{lN}| = 0.026$, $m_h = 121.5$ GeV

Scalar triplet $2\,(Y_\Delta)_{e\mu}\,(Y_\Delta^+)_{\mu e}\,M_\Delta^{-2}$ $\{$ $|(Y_\Delta)_{e\mu}\,M_\Delta^{-1}| < 0.47\ \text{TeV}^{-1}$

$$\mathcal{O}_\phi^{(3)} = \left(\phi^\dagger D_\mu \phi\right)\left(\left(D^\mu \phi\right)^\dagger \phi\right)$$

$\{$ $4\,|\mu_\Delta|^2\,M_\Delta^{-2}$; $|\mu_\Delta M_\Delta^{-2}| < 0.043\ \text{TeV}^{-1}$

Fermion triplet $|V_{l\Sigma}| < 0.018$

Best value $|V_{l\Sigma}| = 0.015$, $m_h = 116.2$ GeV

Light neutrino masses and mixings

$$m_\beta = \sqrt{\sum_i m_i^2 |U_{ei}|^2} < 2.2 \text{ eV} \qquad 95\% \text{ confidence level (CL)}$$

$$\Delta m^2_{21} = 7.67\,^{+0.22}_{-0.21}\,\left(^{+0.67}_{-0.61}\right) \times 10^{-5} \text{ eV}^2 ,$$

$$\Delta m^2_{31} = \begin{cases} -2.37 \pm 0.15\,\left(^{+0.43}_{-0.46}\right) \times 10^{-3} \text{ eV}^2 & \text{(inverted hierarchy)} , \\ +2.46 \pm 0.15\,\left(^{+0.47}_{-0.42}\right) \times 10^{-3} \text{ eV}^2 & \text{(normal hierarchy)} \end{cases}$$

$$|U|_{3\sigma} = \begin{pmatrix} 0.77 \to 0.86 & 0.50 \to 0.63 & 0.00 \to 0.22 \\ 0.22 \to 0.56 & 0.44 \to 0.73 & 0.57 \to 0.80 \\ 0.21 \to 0.55 & 0.40 \to 0.71 & 0.59 \to 0.82 \end{pmatrix}$$

M.C. Gonzalez-Garcia and M. Maltoni, 0704.1800 [hep-ph]