TeV LFV in non-SUSY BSM models

- Neutrino masses and lepton number violation
- Leptonic sector in Extra Dimensional models
- Lepton masses in Little Higgs models
- Multilepton signals BSM at LHC

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M. Maltoni et al. '06

		lower limit (2σ)	best value	'08	upper limit (2σ)
$(\Delta m^2_{sun})_{\rm LA}$ $(10^{-5}$ eV$^2)$		7.2	7.9		8.6
Δm^2_{atm} $(10^{-3}$ eV$^2)$		1.8	2.4		2.9
$\sin^2\theta_{12}$	$\boxed{0.33}$	0.27	0.31	$0.304^{+0.022}_{-0.016}$	0.37
$\sin^2\theta_{23}$	$\boxed{0.50}$	0.34	0.44	$0.50^{+0.07}_{-0.06}$	0.62
$\sin^2\theta_{13}$	$\boxed{0.00}$	0	0.009	$0.010^{+0.016}_{-0.011}$	0.032

$$U_{HPS} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

P.F. Harrison et al. '02

Neutrino masses and lepton number violation

Although there are alternative models reproducing the observed neutrino masses and mixing, they can often accommodate other values.

On the contrary, models based on A_4 predict, at least to LO, the HPS mixing matrix, which approximately describes the observed mixing.

E. Ma et al. ‘01

In general these models also make use of the see-saw mechanism.

The new scalars realising A_4 also need an appropriate pattern of vevs.

(Although there are other constructions which also give the HPS mixing matrix from symmetry only, A_4 seems to be the most economical one.)

W. Grimus et al. ’09, G. Altarelli et al. ‘09 G.Ross talk

$\underline{(ll)_{symmetric}}$:

$(3X3)_{symm}$ =

1+1'+1''+

$$a=\begin{pmatrix}1&&\\&&1\\&1&\end{pmatrix},\ b=\begin{pmatrix}&&1\\&1&\\1&&\end{pmatrix},\ c=\begin{pmatrix}&1&\\1&&\\&&1\end{pmatrix},$$

3_{symm}

$$d=\begin{pmatrix}2&&\\&&-1\\&-1&\end{pmatrix},\ e=\begin{pmatrix}&&-1\\&2&\\-1&&\end{pmatrix},\ f=\begin{pmatrix}&-1&\\-1&&\\&&2\end{pmatrix}$$

In the basis where the charged lepton masses are diagonal

$$a,\ b+c,\ d+e+f$$

$$3\boxed{\begin{pmatrix}x&y&y\\y&x+v&y-v\\y&y-v&x+v\end{pmatrix}}=(x+2y-2v)\begin{pmatrix}1&&\\&&1\\&1&\end{pmatrix}+(x+2y+v)\begin{pmatrix}&1&1\\1&1&\\1&&1\end{pmatrix}+(x-y+v)\begin{pmatrix}2&-1&-1\\-1&2&-1\\-1&-1&2\end{pmatrix}$$

They form a group

<1>

It is not in A_4:
<1'>=<1''>

<3>~(1,1,1)

Leptonic sector in Extra Dimensional models

Almost all the former models assume a very heavy cut-off scale, near M_{GUT}. Hence, all other effects (including LFV transitions) are strongly suppressed.

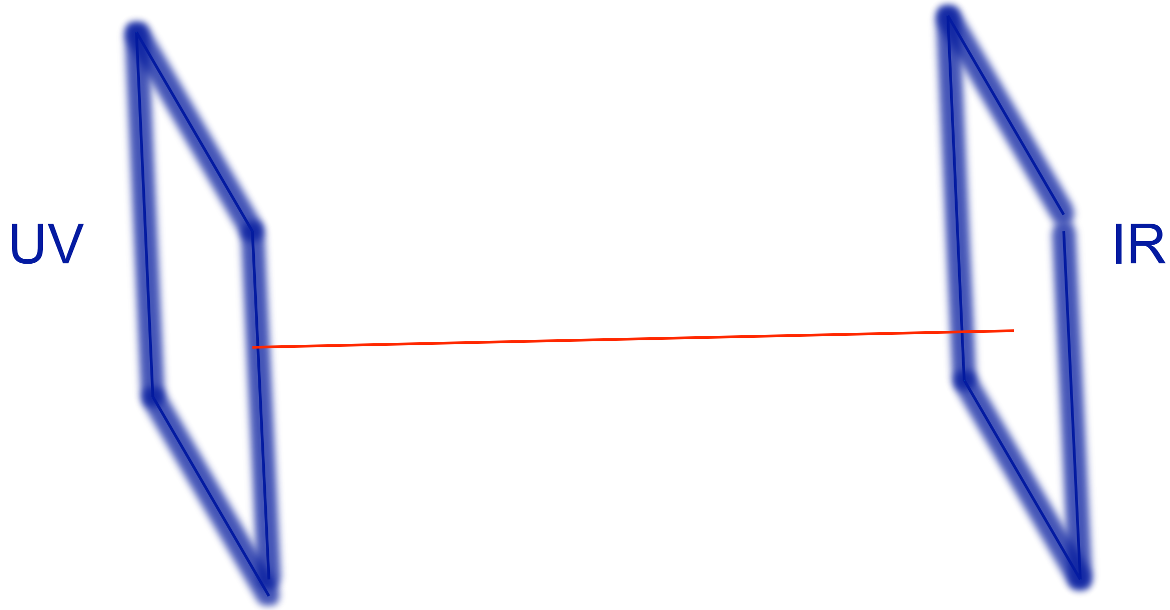
The situation is very different in Little Higgs, as well as in Extra Dimensional models, and in general in models where the new physics scale is ~ TeV.

In the later case although it seems that there are no obstacles to implement any preferred texture of lepton masses, the corresponding models can take profit of the new mechanisms at hand: geometrical hierarchies can explain the mass splittings and the symmetry breaking through boundary conditions allow for a rather natural vacuum alignment.

C. Csáki et al. '08

C. Csáki et al., JHEP10 (2008) 055,

A model of lepton masses from a warped extra dimension



and custodial symmetry

	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$	$A4$	Z_2
Ψ_L	$\square$	1	-1	3	$-$
$\Psi_{e,\mu,\tau}$	1	$\square$	-1	$1, 1', 1''$	$+$
Ψ_ν	1	$\square$	-1	3	$-$
$H\ (IR)$	$\square$	$\square$	0	1	$+$
$\phi'\ (IR)$	1	1	0	3	$-$
$\phi\ (UV)$	1	1	0	3	$+$

$$\Psi_L = \begin{pmatrix} L\ [+,+] \end{pmatrix}\ \Psi_{e,\mu,\tau} = \begin{pmatrix} \tilde{\nu}_{e,\mu,\tau} & [+,-] \\ e,\mu,\tau & [-,-] \end{pmatrix}\ \Psi_\nu = \begin{pmatrix} \nu & [-,-] \\ \tilde{l} & [+,-] \end{pmatrix}$$

Zero modes correspond to [UV=+,IR=+]
Opposite chiralities have opposite signs

$$\mathcal{L}_{\rm UV} = -\frac{M}{2\Lambda}\psi_\nu\psi_\nu - x_\nu\frac{\phi}{2\Lambda}\psi_\nu\psi_\nu + {\rm h.c.} + \cdots\,,$$
$$\mathcal{L}_{\rm IR} = -\frac{y_\nu}{\Lambda'}\overline{\Psi}_L H\Psi_\nu - \frac{y_e}{\Lambda'^2}\left(\overline{\Psi}_L\phi'\right)H\Psi_e - \frac{y_\mu}{\Lambda'^2}\left(\overline{\Psi}_L\phi'\right)''H\Psi_\mu - \frac{y_\tau}{\Lambda'^2}\left(\overline{\Psi}_L\phi'\right)'H\Psi_\tau + {\rm h.c.} + \cdots\,,$$

$$\langle\phi'\rangle = (v',v',v'),\qquad \langle\phi\rangle = (v,0,0)$$

With this vacuum alignment which is easy to arrange for the scalar fields are at different branes we obtain a combination of the first and third matrices in page 4, and all the good features of A_4.

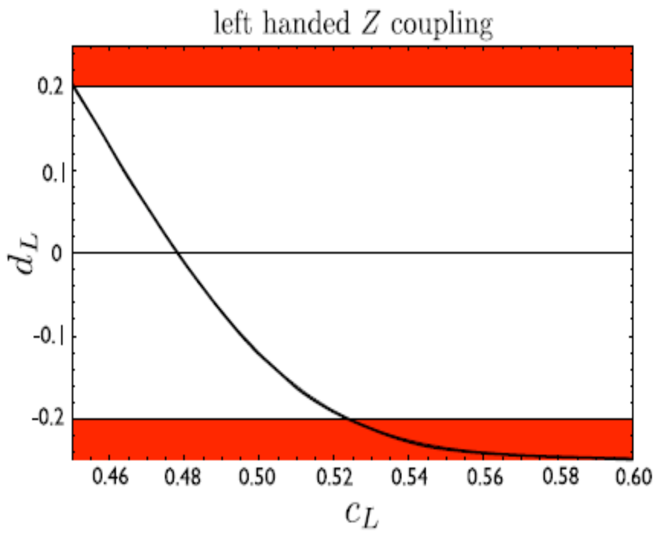
Higher order corrections only generate two new structures:

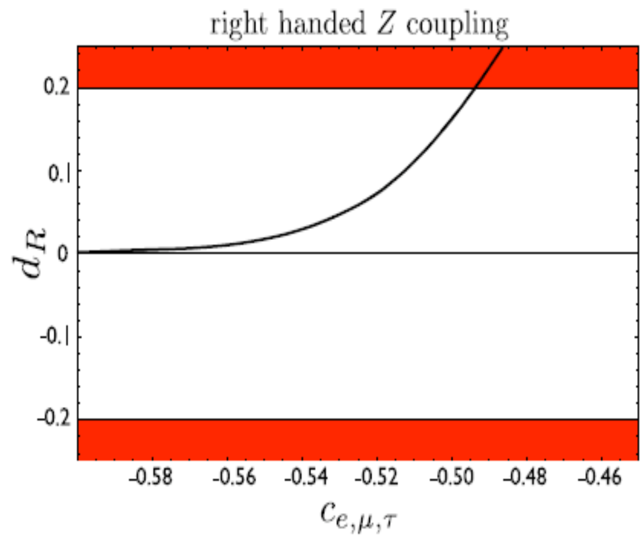
$$-\delta\mathcal{L}_{\rm UV} = \lambda_2\frac{\phi^2}{\Lambda^2}\psi_\nu\psi_\nu + {\rm h.c.}$$
$$-\delta\mathcal{L}_{\rm IR} = \frac{\kappa_2}{2\Lambda'^3}\bar{\Psi}_L H\phi'^2\Psi_\nu + {\rm h.c.}$$

Moreover, there are no tree level LFV, and to one loop we are safe for M_{KK} ~ 3 TeV. Otherwise $M_{KK} \geq 25$ TeV   R. Kitano '00

Deviation from the SM prediction

%





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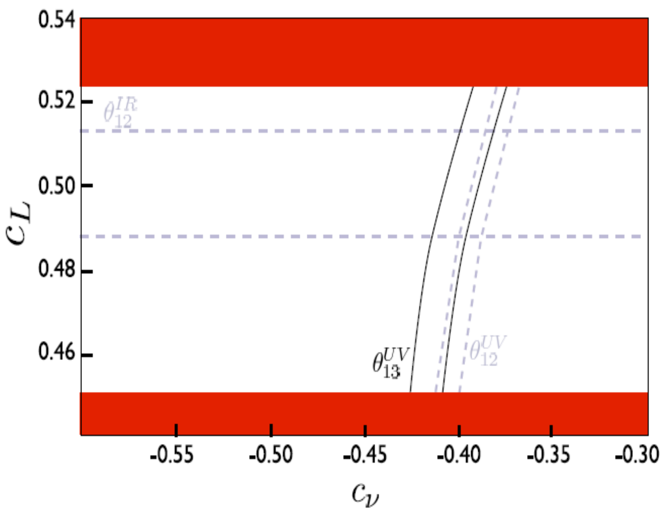


$\sin^2(2\theta_{12}) = 0.90\text{-}0.95$

$\sin^2(2\theta_{13}) = 0.01\text{-}0.19$

Higher order corrections

In summary, although quarks and leptons are treated differently, the A_4 extension of Extra Dimensional models is rather economical: one has to add a multiplet for each type of SM fermion (L_L, e_R, ν_R) as in any see-saw model, transforming under the desired gauge group ($SU(2)_L X SU(2)_R$ if custodial symmetry is enforced to control EWPD constraints [SO(5) if one requires gauge-Higgs unification]).

M. Carena et al., '09

[F.A. et al., in preparation]

The observed hierarchy of lepton masses is due to the different zero mode localization, the charged current mixing to the A_4 symmetry and the vev structure to the UV-IR boundary conditions interplay.

Imposing flavour conservation at the required level is also less demanding than in models not realising A_4.

Lepton masses in Little Higgs models

These models are described by an effective lagrangian with the Higgs being a pseudo Goldstone boson of a global symmetry spontaneously broken. This in general implies enlarging the matter content, in particular if we require a matter parity for dealing with the tension between EWPD and a relatively low cut-off. They tend to become at the end complicated, especially when one insists in a detailed description of fermion masses.

F.A. et al., JHEP01 (2009) 080,

Precise limits from LFV processes on the littlest Higgs model with T-parity

Littlest Higgs model

D. Kaplan et al.. '03

SU(5) ➔ SO(5) global symmetry
but only gauged $[SU(2)XU(1)]^2$

4 WBGB: $(\eta, \omega^0, \omega^+, \omega^-)$ eaten by A_H, Z_H, W_H^+, W_H^-

10 GB: complex $H = \frac{1}{\sqrt{2}}(h^+ \; h^0)^T$ and $\Phi = (\Phi^{++} \; \Phi^+ \; \Phi^0)^T$

Littlest Higgs with T-parity

H.C. Cheng et al., '03

Having added new particles at the TeV scale that couple to the SM particles one finds tension with EW precision tests

⇒ Introduce a discrete symmetry called T-parity under which (most of) the SM particles are even and the new particles are odd

J.I. Illana

T-even: SM H doublet

T-odd: all the others

– Gauge sector: $G_1 \stackrel{T}{\longleftrightarrow} G_2$ with $G_j = (W_j^a, B_j)$ gauge bosons of $[SU(2) \times U(1)]_{j=1,2}$ and $g \equiv g_1 = g_2, g' \equiv g'_1 = g'_2$

$$\Rightarrow \quad \text{T-even:} \quad B, W^3(\gamma, Z), W^+, W^- \quad \leftarrow \frac{1}{\sqrt{2}}(G_1 + G_2)$$

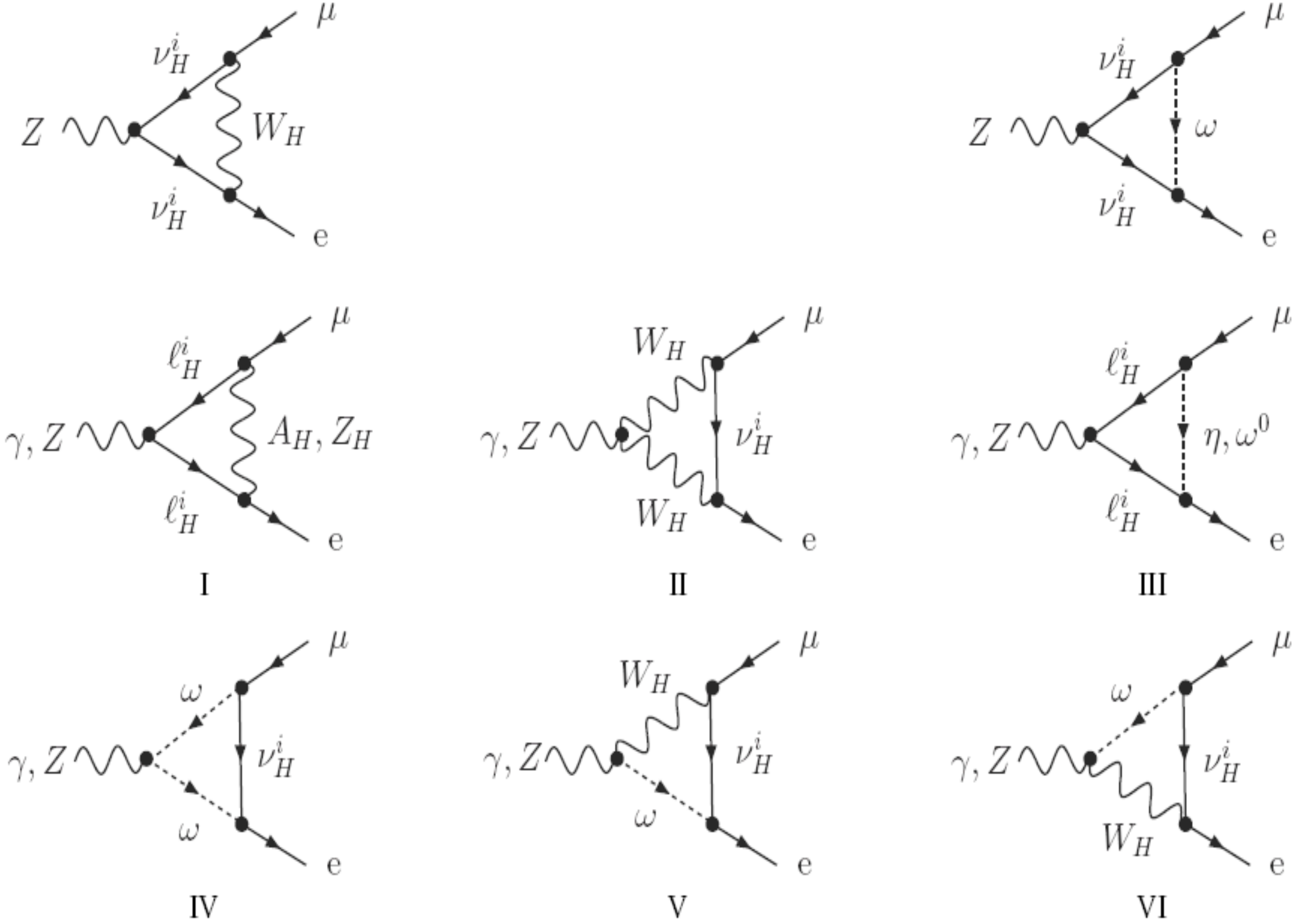
$$\text{T-odd:} \quad A_H, Z_H, W_H^+, W_H^- \quad \leftarrow \frac{1}{\sqrt{2}}(G_1 - G_2)$$

$$\mathcal{L}_G = \sum_{j=1}^{2} \left[-\frac{1}{2} \mathrm{Tr} \left(\widetilde{W}_{j\mu\nu} \widetilde{W}_j^{\mu\nu} \right) - \frac{1}{4} B_{j\mu\nu} B_j^{\mu\nu} \right]$$

- For each LH fermion we add a new vetor-like doublet

One-loop contributions to Lepton FV processes

- Triangle diagrams $\Rightarrow$ vertex and penguins



Results and experimental constraints

Necessary Feynman rules obtained to $\mathcal{O}(v^2/f^2)$

All form factors in terms of standard loop integrals computed analytically

Reduced to exact simple expressions

Ultraviolet finite

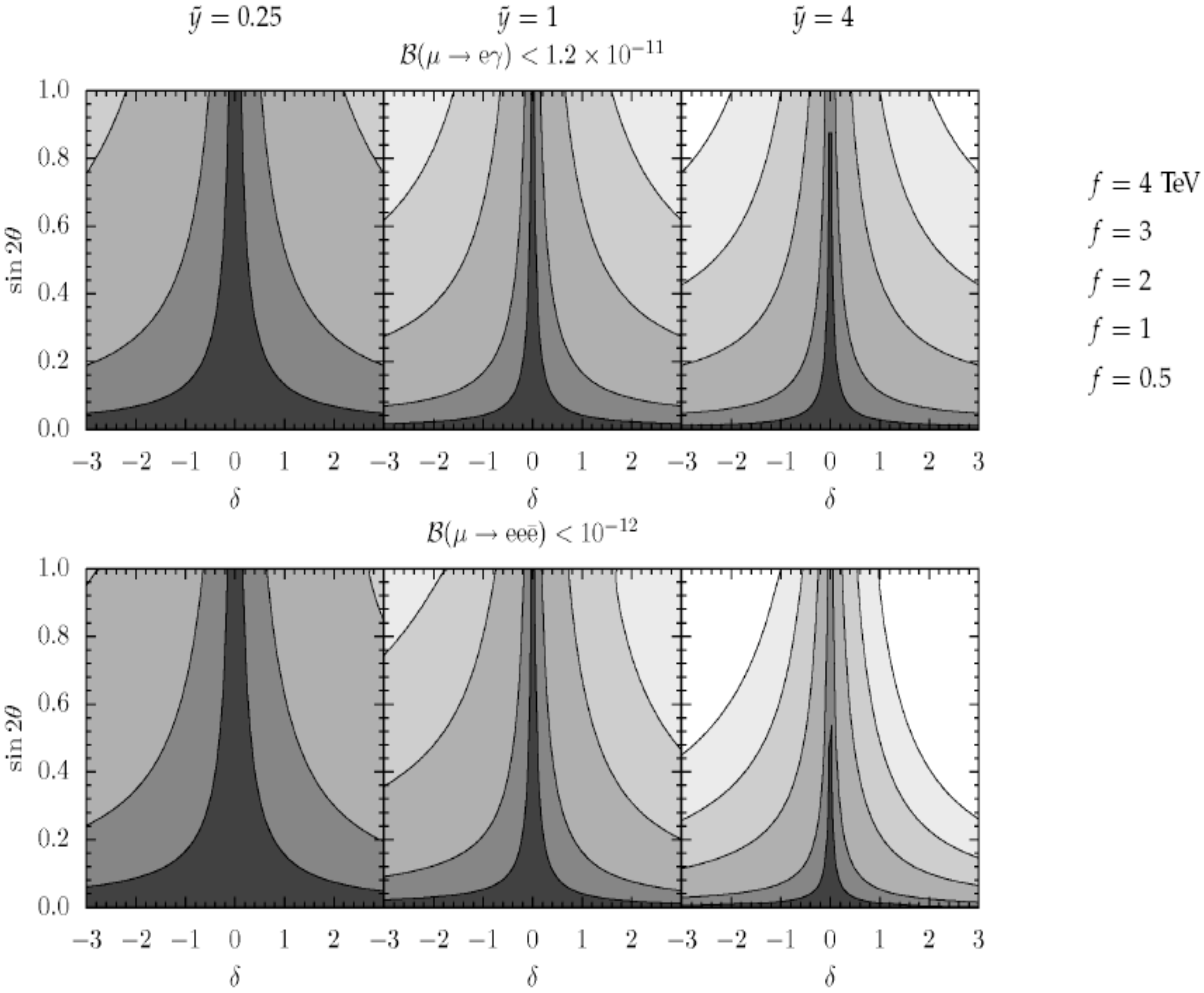
– Simplified analysis: two-generation mixing with heavy masses $m_{Hi}^2 \equiv y_i M_{W_H}^2$

$$V_{H\ell} = \begin{pmatrix} V_{H\ell}^{1e} & V_{H\ell}^{1\mu} \\ V_{H\ell}^{2e} & V_{H\ell}^{2\mu} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}, \quad \delta = \frac{m_{H2}^2 - m_{H1}^2}{m_{H1} m_{H2}}, \quad \tilde{y} = \sqrt{y_1 y_2}$$

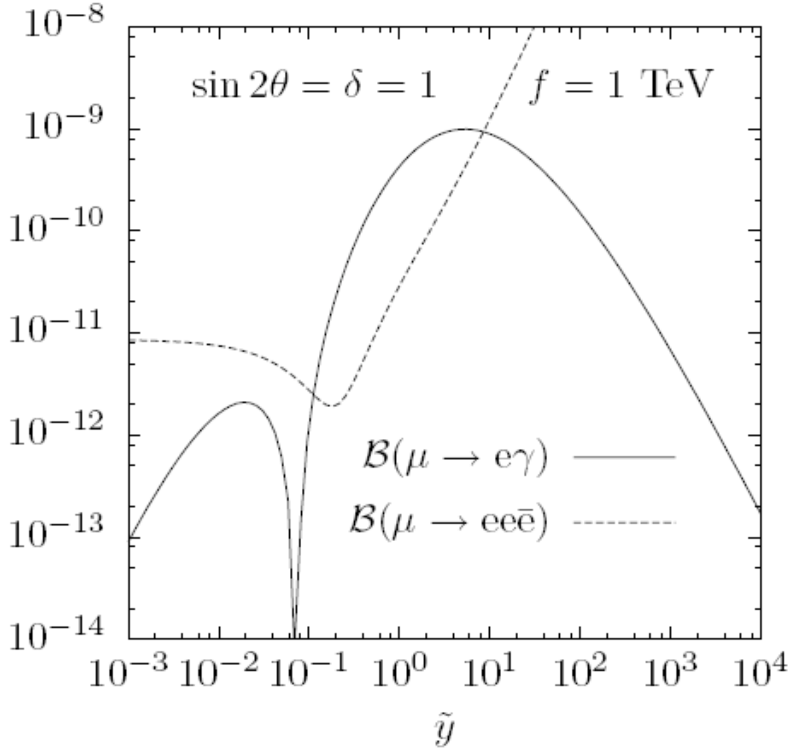
Amplitudes approximately scale like $\boxed{\frac{v^2}{f^2}\sin 2\theta\,\delta}$ and grow with $\boxed{\tilde{y}}$

– Expectations *vs* current limits: $\mathcal{B}(\mu \to e\gamma) < 1.2 \times 10^{-11}$ $\mathcal{B}(\mu \to ee\bar{e}) < 10^{-12}$

Consider as *natural* the input values: $f \sim 1$ TeV, $\sin 2\theta \sim 1$, $\delta \sim 1$, $\tilde{y} \sim 1$


$\tilde{y} = 0.25$
$\tilde{y} = 1$
$\tilde{y} = 4$
$\mathcal{B}(\mu \to e\gamma) < 1.2 \times 10^{-11}$
$\sin 2\theta$
δ
$\mathcal{B}(\mu \to ee\bar{e}) < 10^{-12}$
$f = 4$ TeV
$f = 3$
$f = 2$
$f = 1$
$f = 0.5$

	$\mathcal{B}(\mu \to e\gamma) < 1.2 \times 10^{-11}$ (10^{-13})	$\mathcal{B}(\mu \to ee\bar{e}) < 10^{-12}$ (10^{-14})
$f/\mathrm{TeV} >$	2.5 (8.1)	2.3 (7.4)
$\sin 2\theta <$	0.16 (0.015)	0.16 (0.016)
$\lvert\delta\rvert <$	0.16 (0.015)	0.18 (0.018)
$\tilde{y} <$	0.16 (*)	* (*)



Simplest Little Higgs model

M. Schmaltz (et al.), '04

$$\mathcal{L}_\nu = \lambda_\nu \phi_1^\dagger \Psi_L n^c + \text{h.c.}$$
$$\supset \lambda_\nu \left(-h^\dagger L n^c + f N n^c - \frac{1}{2f} h^\dagger h N n^c \right) + \text{h.c.}$$

$$\begin{array}{cccc} \nu & N & n^c & \\ \left(\begin{array}{ccc} 0 & 0 & -\lambda_\nu v \\ 0 & 0 & \lambda_\nu f \\ -\lambda_\nu v & \lambda_\nu f & 0 \end{array}\right) & & & \begin{array}{c} \nu \\ N \\ n^c \end{array} \end{array}$$

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

F.A. et al. '05, in preparation

E. Ma talk

$$\mathcal{L}_1 = \frac{1}{2\Lambda_\nu} (\phi_2^\dagger \Psi_L)(\phi_2^\dagger \Psi_L) + \text{h.c.}$$
$$\supset \frac{1}{2\Lambda_\nu} (h^{0\dagger} \nu + f N)(h^{0\dagger} \nu + f N) + \text{h.c.}$$

A4 can be implemented
as in the see-saw case,
with LF conserved at LO

Multilepton signals BSM at LHC

- Experimentally: smaller backgrounds, better calibration
- Allow for model discrimination: produced in many new physics scenarios, especially if they involve the lepton sector
- In general SUSY, TeV see-saw mechanisms, and eventually Little Higgs and Extra Dimensional models

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)

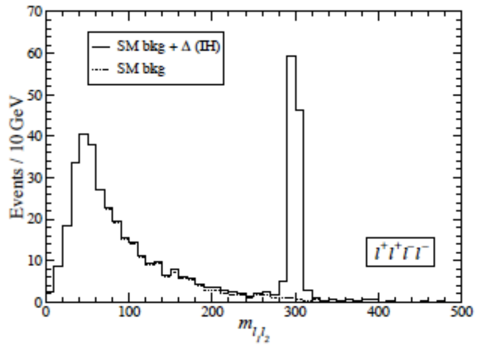
J.A. Aguilar-Saavedra

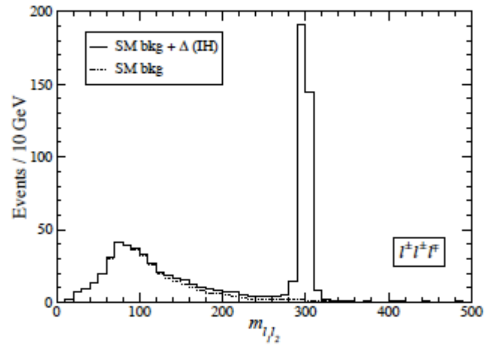
Results $M_\Delta = 300$ GeV

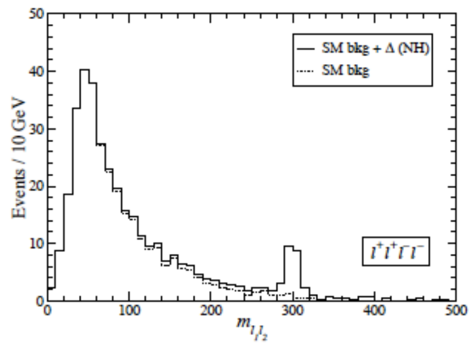
Approximate branching ratios

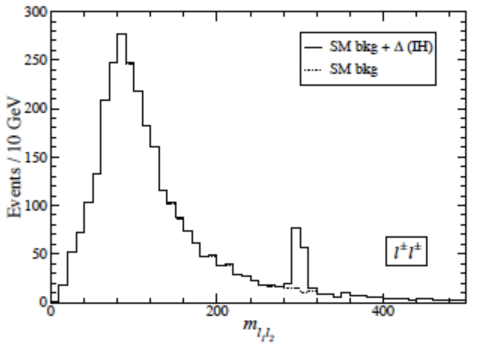
	e^+e^+	$\mu^+\mu^+$	$\mu^+\tau^+$	$\tau^+\tau^+$
NH	0.00	0.20	0.49	0.29
IH	0.50	0.15	0.25	0.10

Results







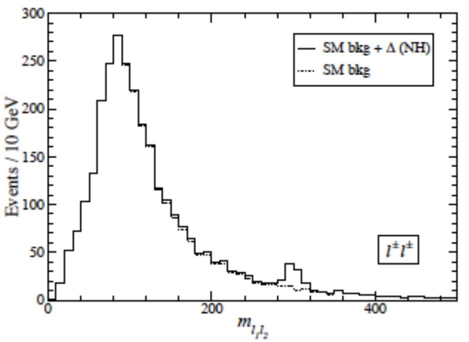


Luminosity for discovery (IH)

$\ell^+\ell^+\ell^-\ell^- \rightarrow 2.8\ \mathrm{fb}^{-1}$

$\ell^\pm\ell^\pm\ell^\mp \rightarrow 0.87\ \mathrm{fb}^{-1}$

$\ell^\pm\ell^\pm \rightarrow 4.4\ \mathrm{fb}^{-1}$



Luminosity for discovery (NH)

$\ell^+\ell^+\ell^-\ell^- \rightarrow 18.6\ \mathrm{fb}^{-1}$

$\ell^\pm\ell^\pm\ell^\mp \rightarrow 3.6\ \mathrm{fb}^{-1}$

$\ell^\pm\ell^\pm \rightarrow 17.4\ \mathrm{fb}^{-1}$

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

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

Approximate mass reach

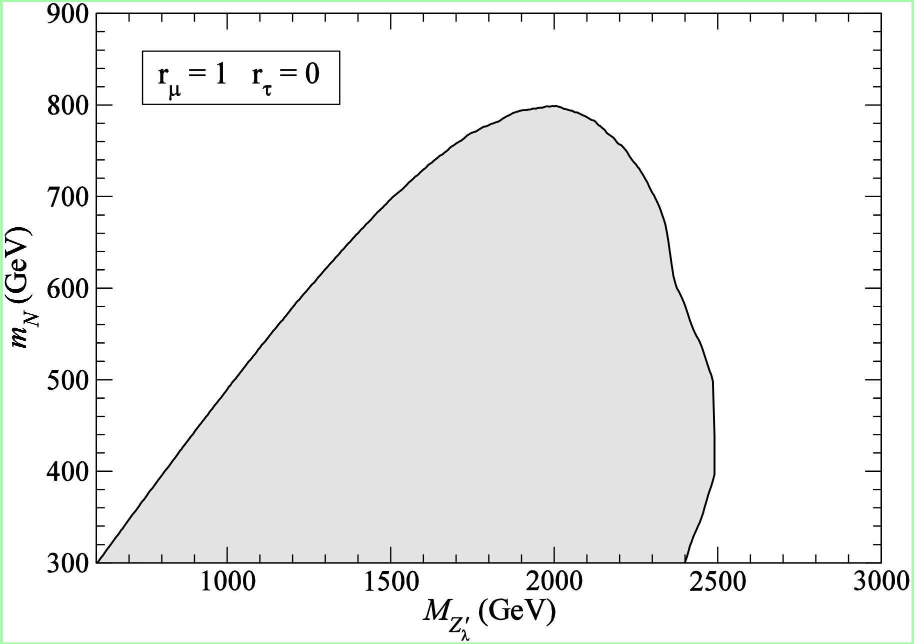
- N: 120 (150) GeV for D / M coupling to e (μ)
- Δ: 600 (800) GeV for NH (IH)
- Σ: 750 (700) GeV for Majorana (Dirac) coupling to e or μ

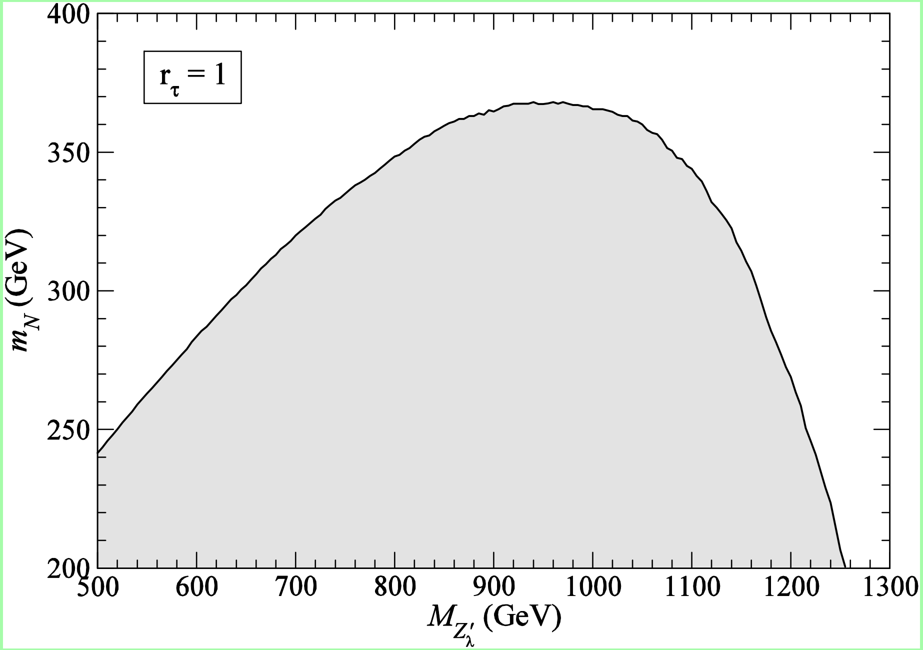
Conclusions. I

Although Extra Dimensional models can accommodate the observed pattern of neutrino masses and mixings, and they predict infinite towers of KK states (including leptons), the extended lepton sector is in general out of the LHC reach: R'^{-1} ~ few TeV whereas the LHC reach is below the TeV for SM electroweak production of new leptons. [This may be evaded by lighter (multilocalised) states if present in definite models, and by processes mediated by KK vector bosons,]

Conclusions. II

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





F. A. et al. '07

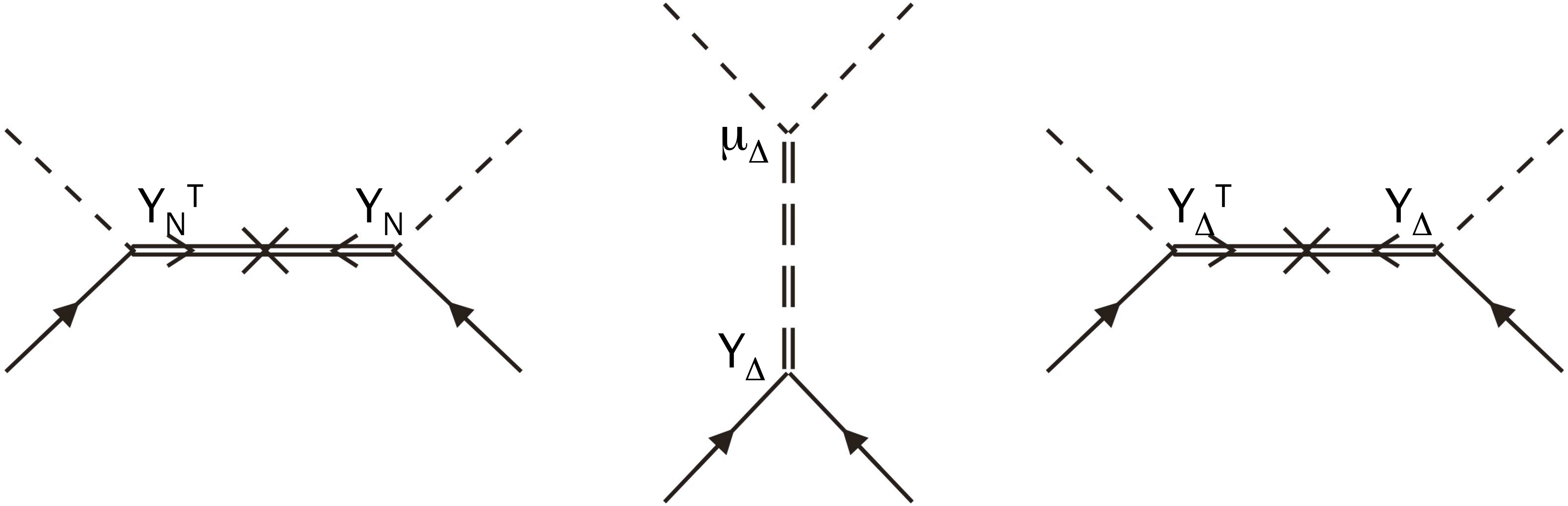
Conclusions. III

LFV rare processes are in general more sensitive to the compactification scale but in specific models like those based on A_4 can be made less restrictive than universal electroweak precision observables.

Little Higgs models should be also able to accommodate the symmetries of the observed lepton masses and mixings, fpr Instance A_4, but it is not obvious how it works in the littlest model with T parity. LFV is within experimental limits choosing appropriately the parameters.

Thanks for your attention

See-saw messengers of type I,II and III



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

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, 0707.4058 [hep-ph]

The three mechanisms must violate Lepton Number for they are assumed to generate Majorana masses. I and III involve fermions: singlets N (I) or triplets Σ (III), and II scalar triplets: Δ.

$$\mathcal{L} = \mathcal{L}_\ell + \mathcal{L}_h + \mathcal{L}_{\ell h}$$

In the fermionic case

$$\mathcal{L}_\ell \supset \overline{l_L^i} i \not{D}\, l_L^i + \overline{e_R^i} i \not{D}\, e_R^i - \left((Y_e)_i \overline{l_L^i}\, \phi\, e_R^i + \text{h.c.} \right)$$

$$\mathcal{L}_h = \eta_L \overline{L^I} i \not{D}\, L^I - \eta_L M_I \overline{L^I} L^I$$

$$\mathcal{L}_{\ell h} = - (Y_{Ll})_{Ij} \overline{L_R^I} \tilde{\phi}^\dagger l_L^j + \text{h.c.}$$

F. del Aguila, J. de Blas and M. Pérez-Victoria, 0803.4008 [hep-ph]

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	$\mathcal{O}_{\phi l}^{(1)} = \left(\phi^\dagger i D_\mu \phi\right)\left(\overline{l_L}\gamma^\mu l_L\right)$ $\mathcal{O}_{\phi l}^{(3)} = \left(\phi^\dagger i \sigma_a D_\mu \phi\right)\left(\overline{l_L}\sigma_a \gamma^\mu l_L\right)$	$\frac{1}{4} Y_N^\dagger (M_N^\dagger)^{-1} M_N^{-1} Y_N$ $-\frac{1}{4} Y_N^\dagger (M_N^\dagger)^{-1} M_N^{-1} Y_N$

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

Type III

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

W. Buchmuller and D. Wyler, Nucl. Phys. B268 (1986) 621

Then, the question arises concerning the relative size of the coefficients of dimension 5 and 6.

- If the smallness of the neutrino masses is due to the cut-off scale $M \sim 10^{14}$ GeV, no effect of the dimension 6 operators will be seen at the electroweak scale (LHC).

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_4 + \frac{1}{M}\mathcal{L}_5 + \frac{1}{M^2}\mathcal{L}_6 + \ldots$$

- On the contrary if the effective scale is the TeV, one has to explain why the dimension 5 coupling is so small $\sim 10^{-14}$, and not ~ 1.

  This second possibility is more interesting experimentally, for it may allow to observe new particles at LHC.

We will use the case of heavy neutrino singlets as example

The dimension 5 operator can be negligible but dimension 6 operators sizeable, for instance, if Lepton Number is (quasi) conserved.

J. Kersten and A.Y. Smirnov, 0705.3221 [hep-ph]

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

F. del Aguila, J.A. Agular-Saavedra, J. de Blas and M. Zralek, 0710.2923 [hep-ph]

$$-Y_N^T M_N^{-1} Y_N \frac{v^2}{2} \simeq -\frac{y_N^2}{2}\left[\frac{(1-\frac{\mu}{4m_N})^2}{m_N+\frac{\mu}{2}} - \frac{(1+\frac{\mu}{4m_N})^2}{m_N-\frac{\mu}{2}}\right]\frac{v^2}{2} \simeq \frac{\mu y_N^2}{m_N^2}\frac{v^2}{2}$$

$$\begin{array}{cc} & \begin{array}{ccc} \nu_L & N_L & N_R^c \end{array} \\ \begin{array}{c} \nu_L \\ N_L \\ N_R^c \end{array} & \begin{pmatrix} 0 & 0 & \frac{y_N v}{\sqrt{2}} \\ 0 & \mu & m_N \\ \frac{y_N v}{\sqrt{2}} & m_N & 0 \end{pmatrix} \end{array}$$

Limits on the new lepton mixing (as a function of the Higgs mass)

$$\delta g_L^\nu = \frac{1}{4}\left(-\alpha_{\phi l}^{(1)} + \alpha_{\phi l}^{(3)} + \text{h.c.}\right)\frac{v^2}{M^2}$$

$$\delta g_L^e = -\frac{1}{4}\left(\alpha_{\phi l}^{(1)} + \alpha_{\phi l}^{(3)} + \text{h.c.}\right)\frac{v^2}{M^2}$$

$$\delta g_R^e = -\frac{1}{4}\left(\alpha_{\phi e}^{(1)} + \text{h.c.}\right)\frac{v^2}{M^2}$$

$$\delta V_L^{e\nu} = \left(\alpha_{\phi l}^{(3)}\right)^\dagger \frac{v^2}{M^2}$$

$$\mathcal{O}_{\phi l}^{(1)} = \left(\phi^\dagger i D_\mu \phi\right)\left(\overline{l_L}\gamma^\mu l_L\right)$$
$$\mathcal{O}_{\phi l}^{(3)} = \left(\phi^\dagger i \sigma_a D_\mu \phi\right)\left(\overline{l_L}\sigma_a\gamma^\mu l_L\right)$$

$$\alpha_{\phi l}^{(1)} = \frac{1}{4} Y_N^\dagger (M_N^\dagger)^{-1} M_N^{-1} Y_N$$
$$\alpha_{\phi l}^{(3)} = -\frac{1}{4} Y_N^\dagger (M_N^\dagger)^{-1} M_N^{-1} Y_N$$

$$V^{\ell N} = \frac{Y_{N\ell}^* v}{\sqrt{2} M_N}$$

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

Summary. I

- We are interested in see-saw messenger production. In particular, for heavy neutrinos

$$
\begin{aligned}
\mathcal{L}_W &= -\frac{g}{\sqrt{2}}\left(\bar{\ell}\gamma^\mu V_{\ell N} P_L N\, W_\mu + \bar{N}\gamma^\mu V_{\ell N}^* P_L \ell\, W_\mu^\dagger\right) \\
\mathcal{L}_Z &= -\frac{g}{2c_W}\left(\bar{\nu}_\ell\gamma^\mu V_{\ell N} P_L N + \bar{N}\gamma^\mu V_{\ell N}^* P_L \nu_\ell\right) Z_\mu \\
\mathcal{L}_H &= -\frac{g\, m_N}{2M_W}\left(\bar{\nu}_\ell\, V_{\ell N} P_R N + \bar{N}\, V_{\ell N}^* P_L \nu_\ell\right) H
\end{aligned}
$$

- m_ν ~ eV imply they are (quasi)Dirac: Lepton Number is very tiny broken, or there is a very precise cancellation. So, to produce same sign dileptons through fermion mixing, we must allow for some fine tuning in the model.

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	

$m_N < M_W$

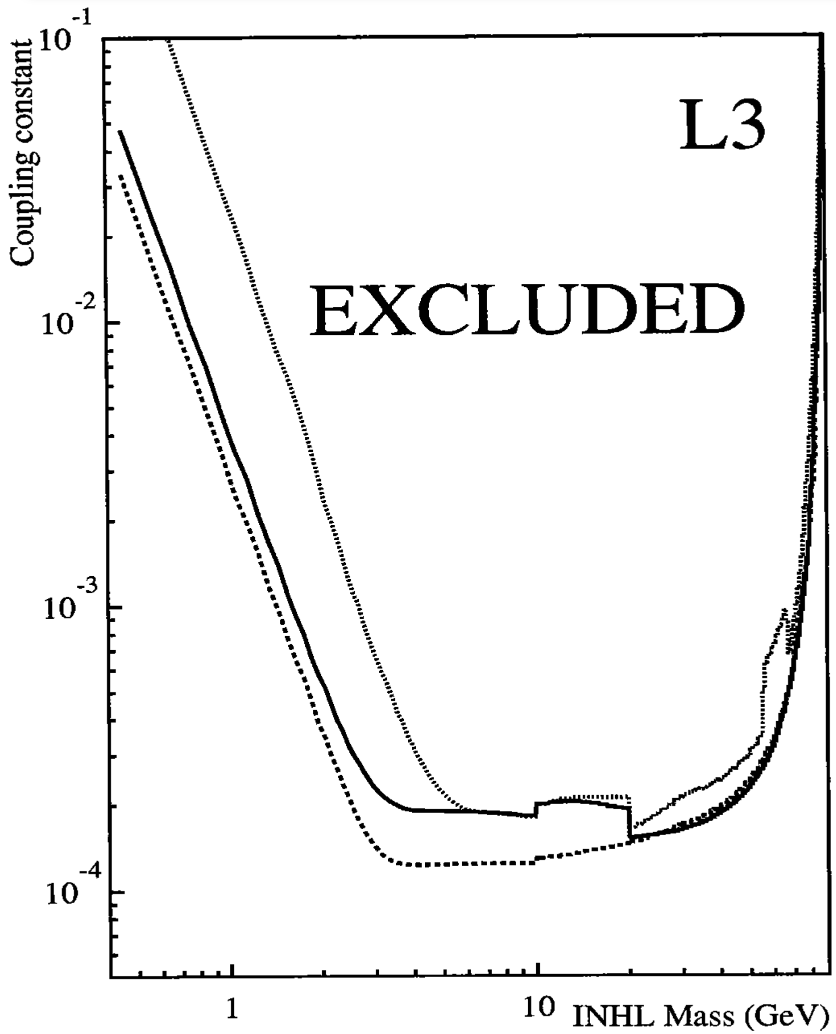
$|V_{lN}|^2 < 0.0002$ L3, Phys. Lett. B 295 (1992) 371

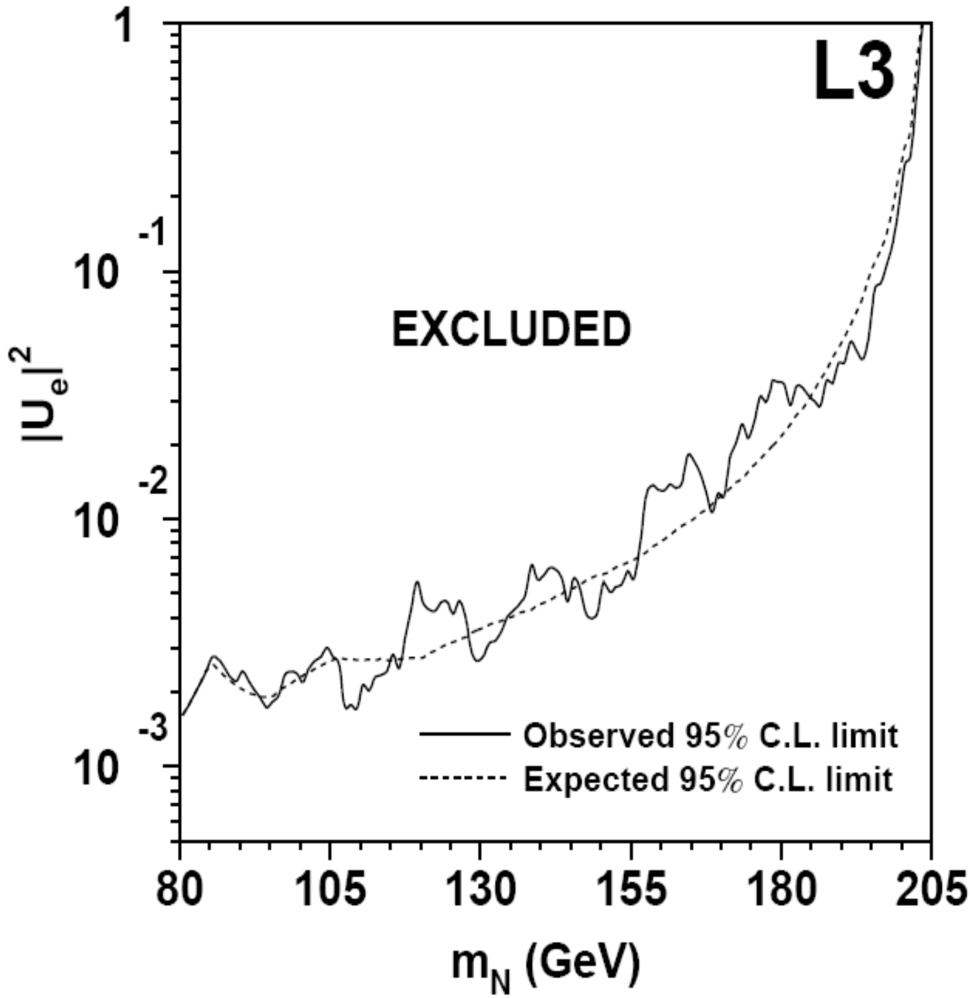
Fermion triplet $m_N > M_W$

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

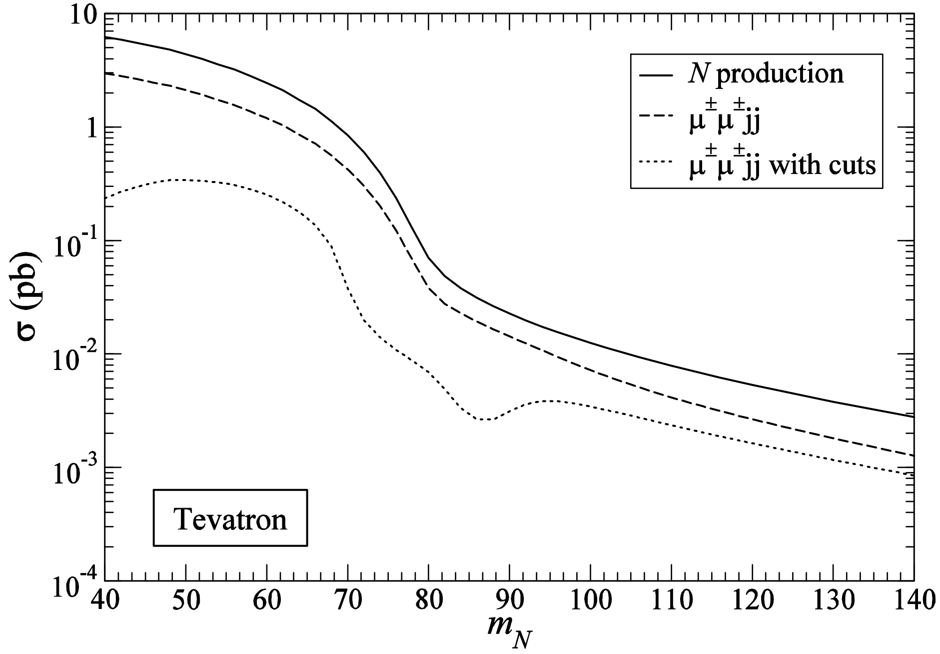
L3, Phys. Lett. B 295 (1992) 371

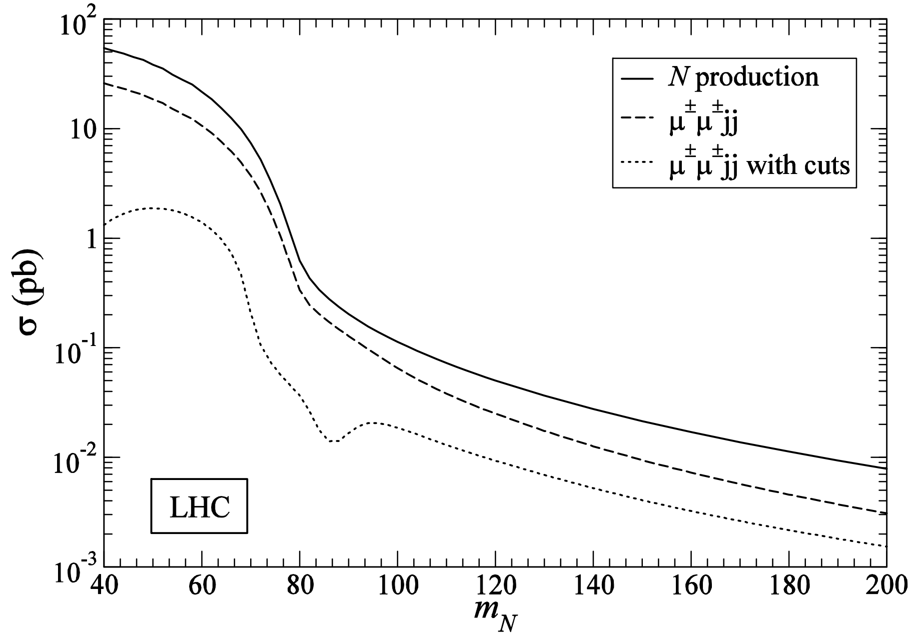
L3, hep-ex/0107014





Small cross sections



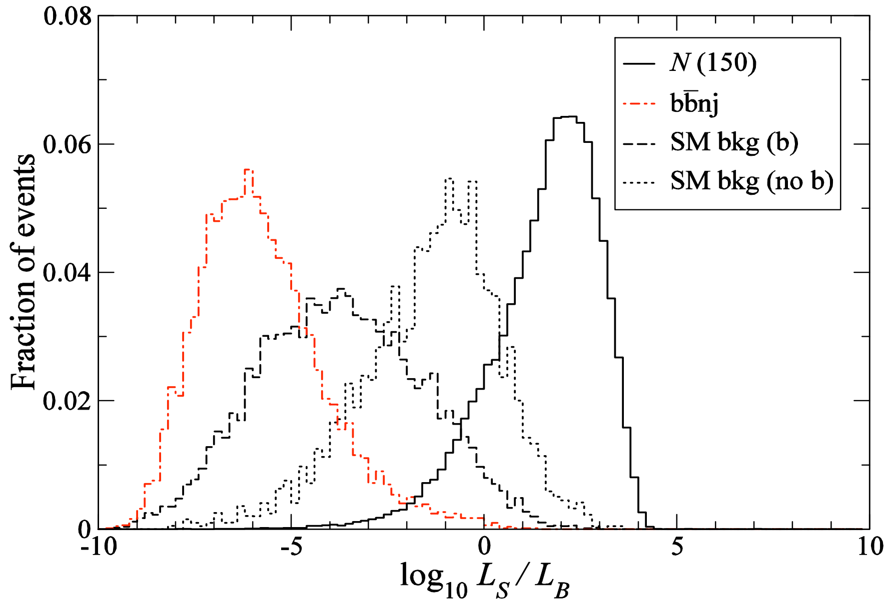


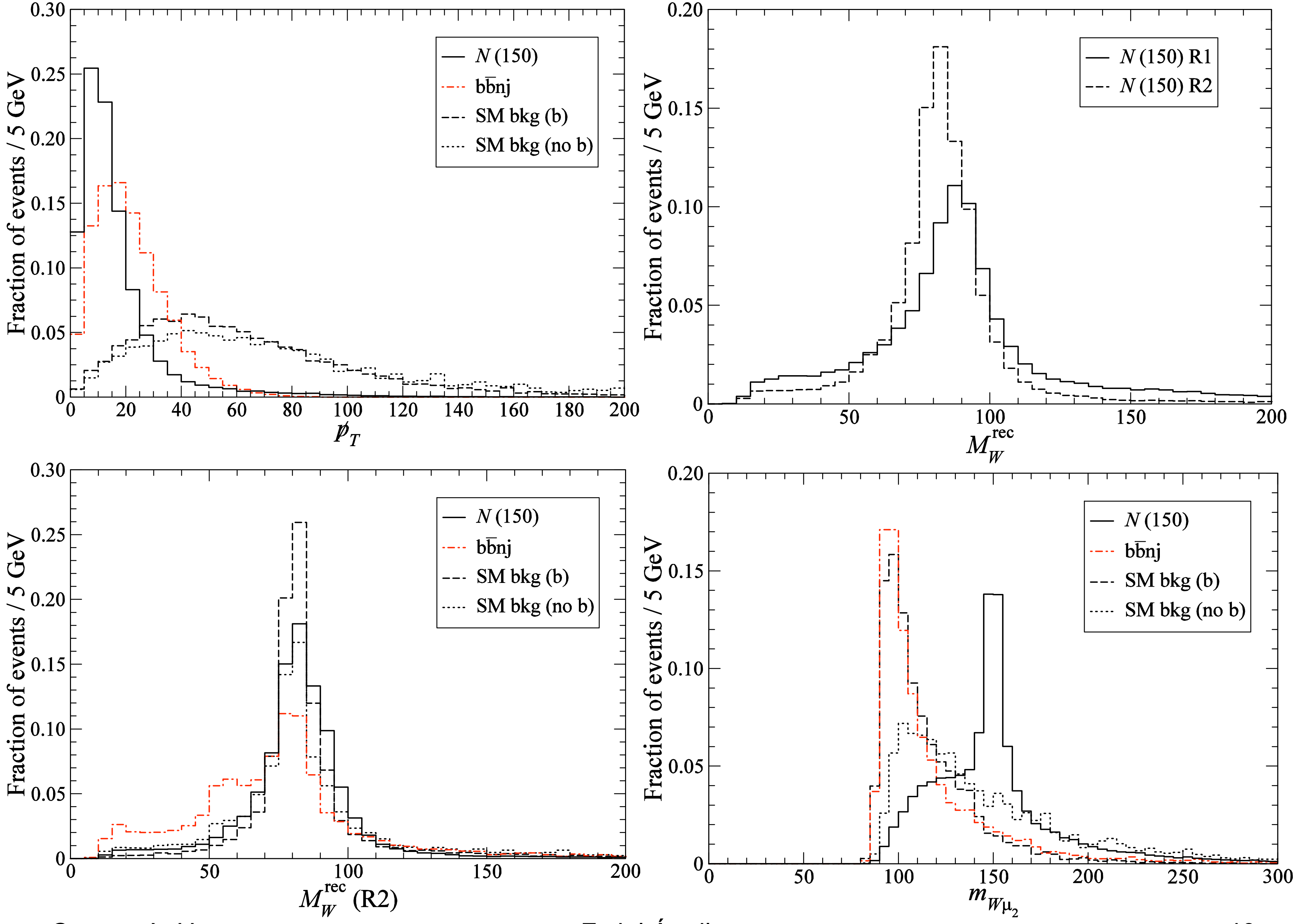
Large backgrounds

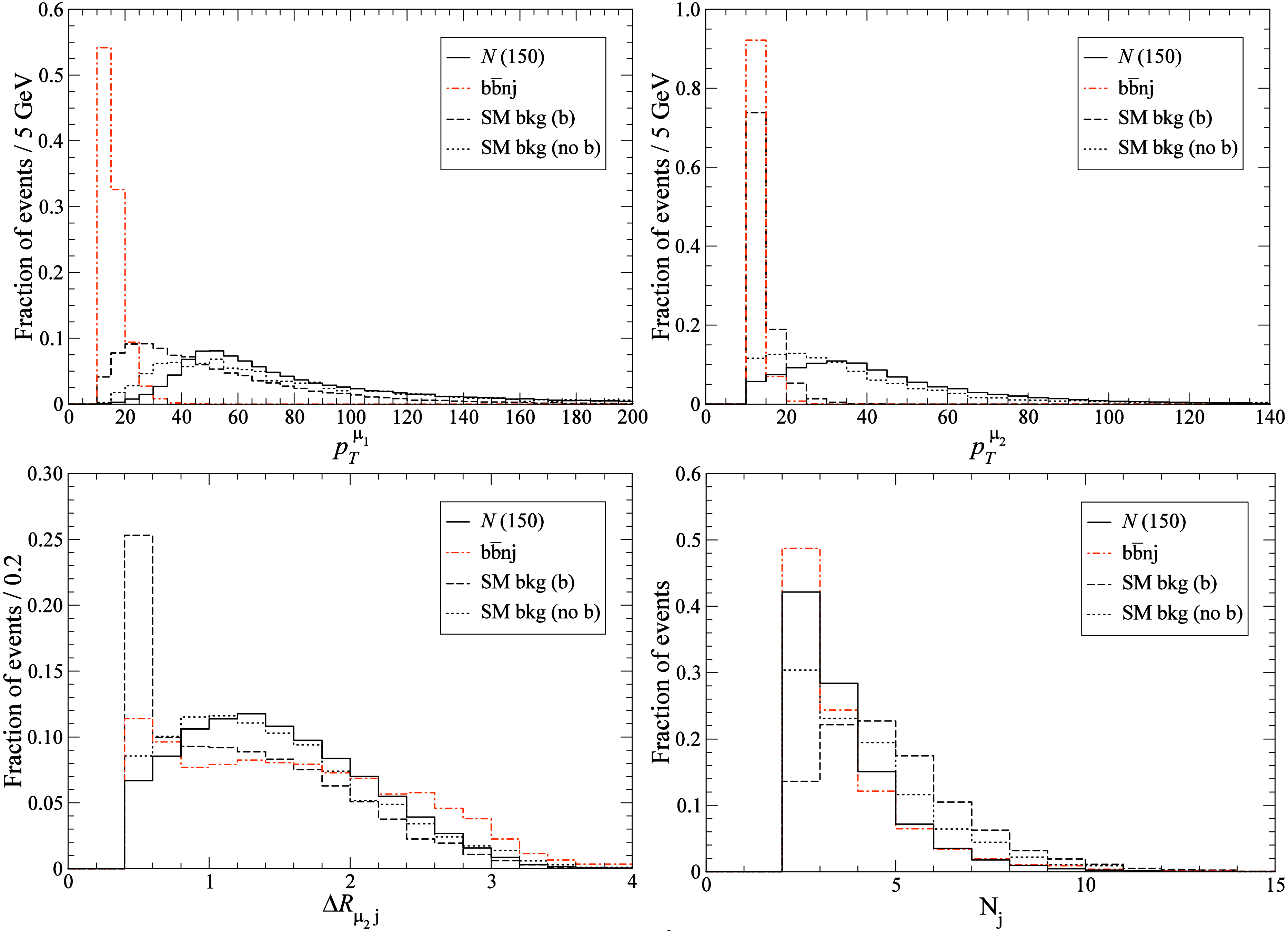
	Pre-selection			Selection		
	$\mu^\pm\mu^\pm$	$e^\pm e^\pm$	$\mu^\pm e^\pm$	$\mu^\pm\mu^\pm$	$e^\pm e^\pm$	$\mu^\pm e^\pm$
N (a)	113.6	0	0	59.1	0	0
N (b)	0	72.0	0	0	17.6	0
N (c)	78.4	25.5	82.6	41.6	4.7	22.4
$b\bar{b}nj$	14800	52000	82000	0	0	0
$c\bar{c}nj$	(11)	300	200	(0)	0	0
$t\bar{t}nj$	1162.1	8133.0	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 $V_{\mu N} = 0.098$.

Likelihood analysis

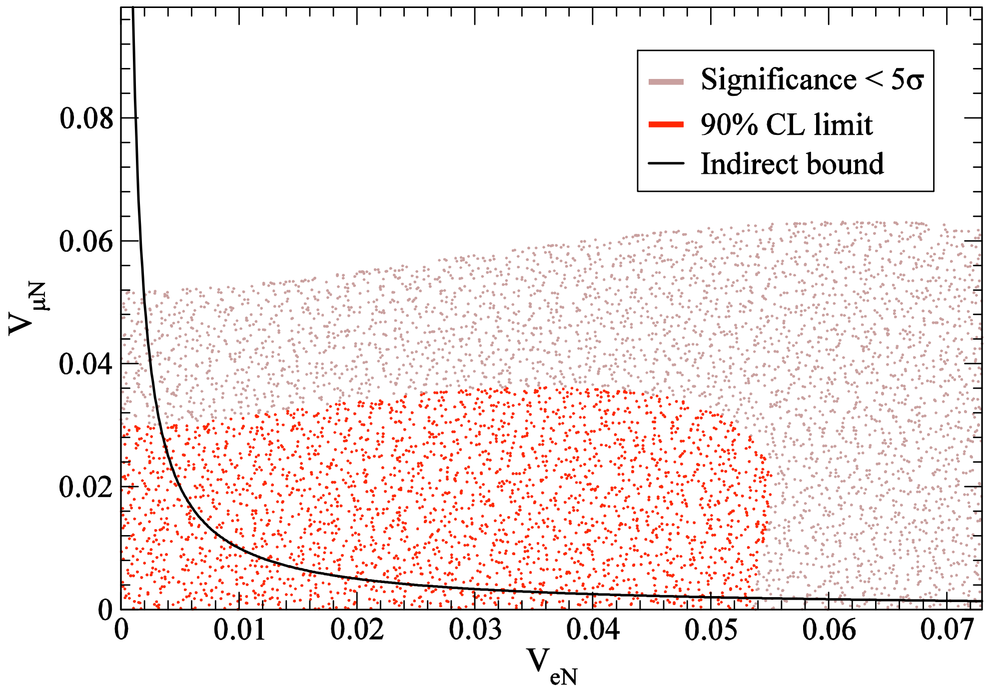



Fraction of events / 5 GeV
N (150)
$b\bar{b}nj$
SM bkg (b)
SM bkg (no b)
$\not{p}_T$
N (150) R1
N (150) R2
M_W^{rec}
M_W^{rec} (R2)
$m_{W\mu_2}$

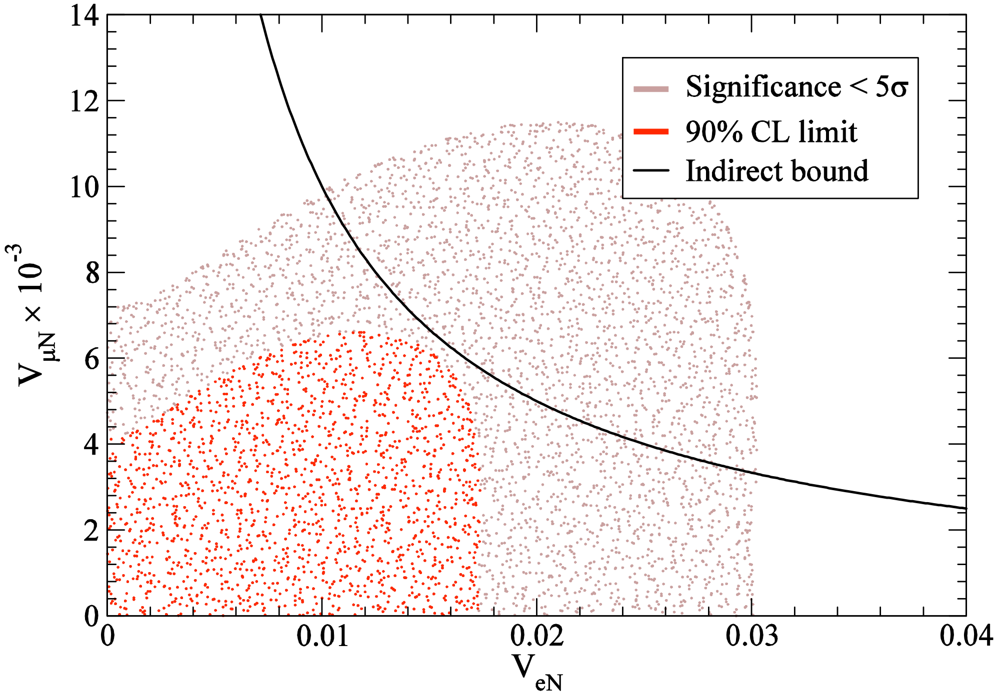

Fraction of events / 5 GeV
$N\,(150)$
$b\bar{b}nj$
SM bkg (b)
SM bkg (no b)
$p_T^{\mu_1}$
$p_T^{\mu_2}$
Fraction of events / 0.2
$\Delta R_{\mu_2 j}$
Fraction of events
N_j

Heavy Majorana neutrino

$m_N > M_W$

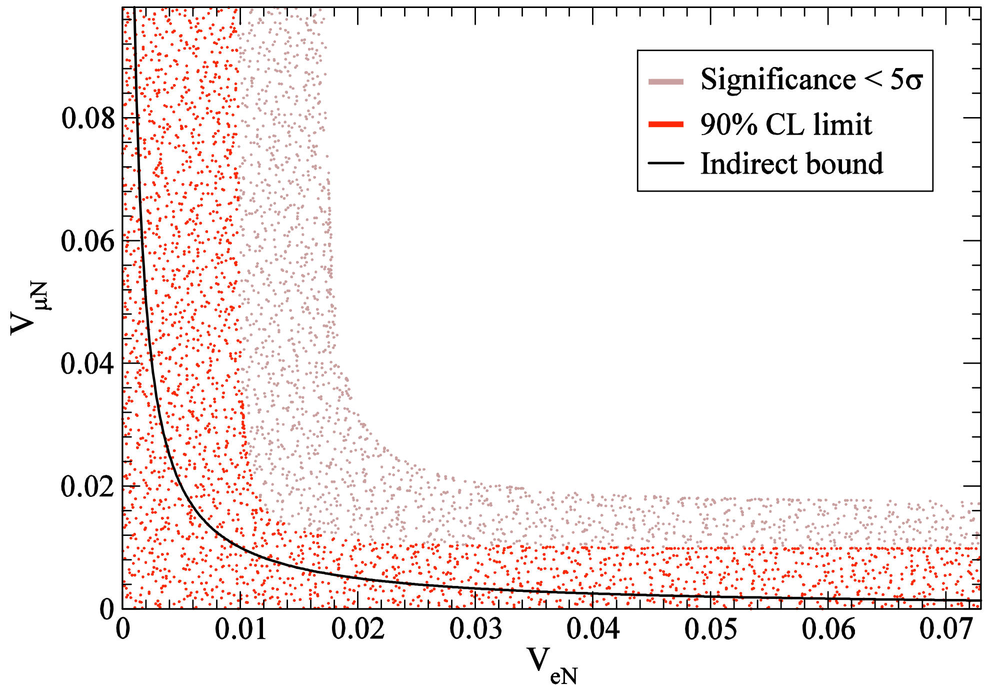


$m_N < M_W$

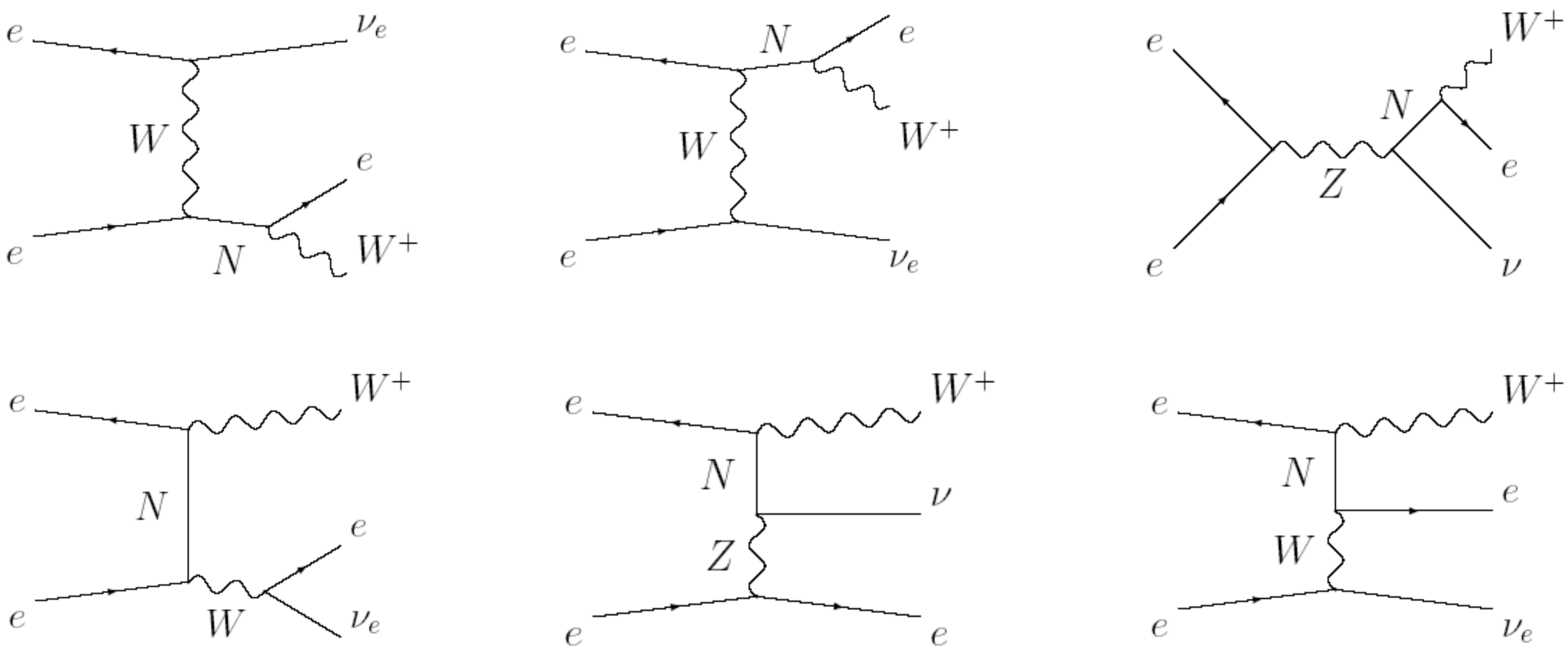


Heavy Dirac neutrino

$m_N < M_W$



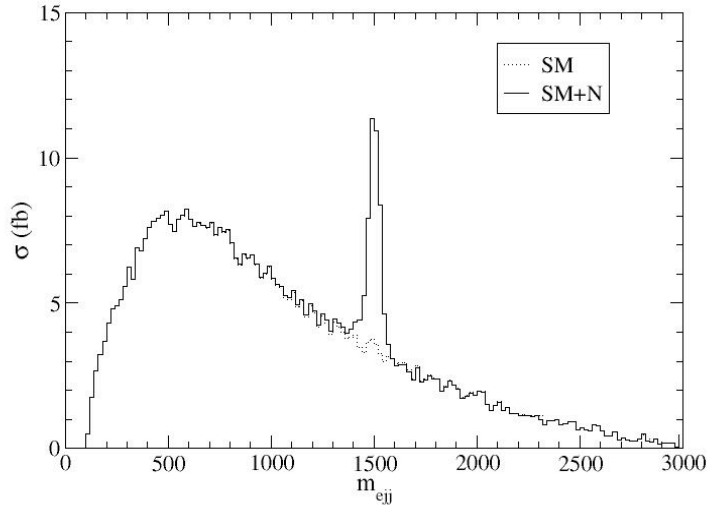
Dilepton signals beyond the Standard Model: lepton colliders

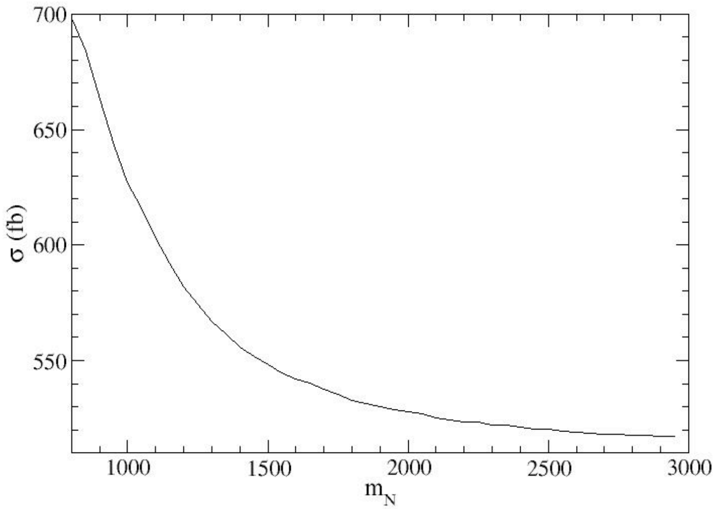


F. del Aguila and J.A. Aguilar-Saavedra, hep-ph/0503026

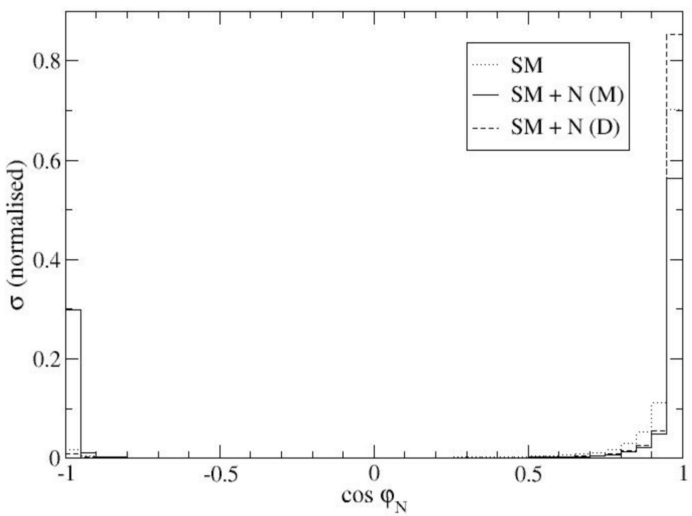
CLIC

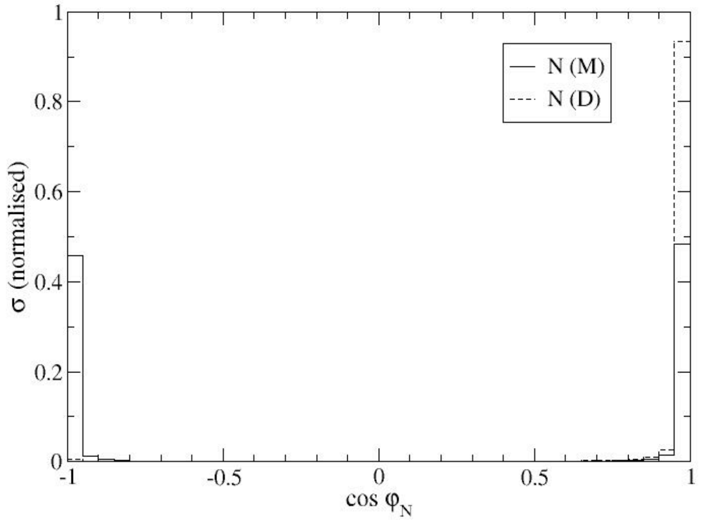
$e^+e^- \rightarrow e^- W(\rightarrow qq')\nu$





m_N=1.5 TeV
V_{eN}=0.05



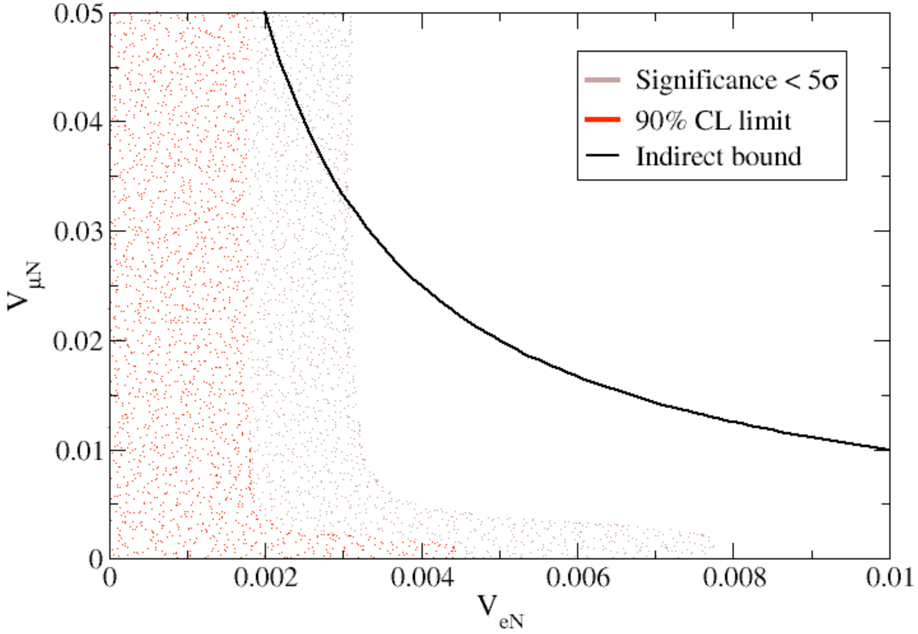


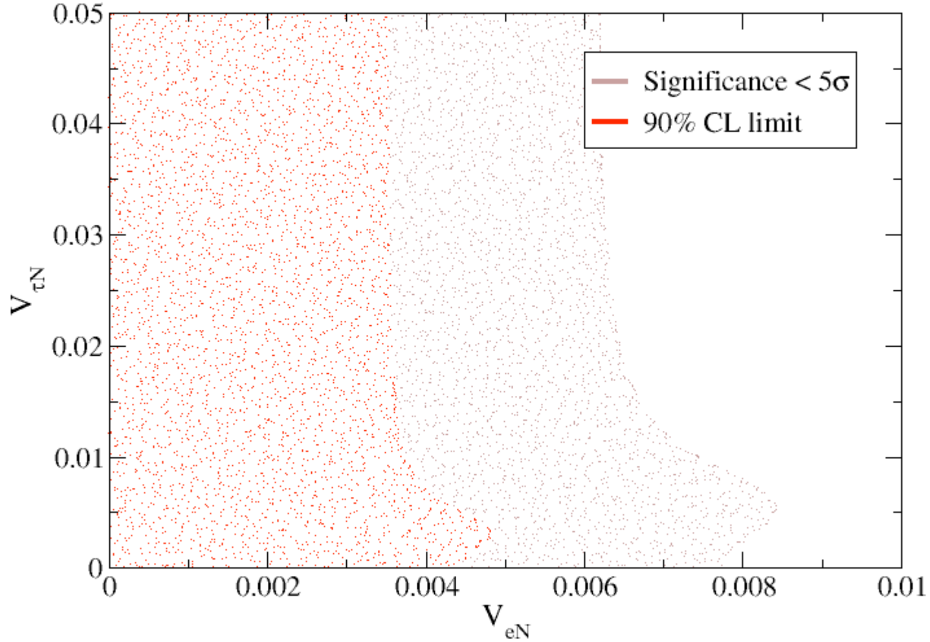
W exchange

$e^+_R\, e^-_L : e^-_L\, e^+_R$
44,000 : 1

CLIC

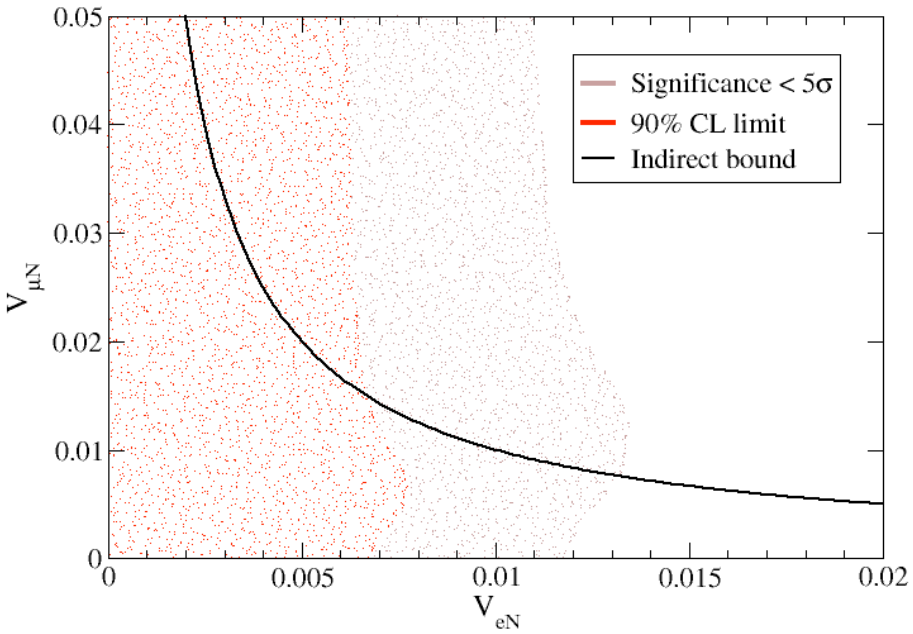
This processes will allow to detect a N with m_N = 1-2 TeV and V_{eN} > 0.004-0.01, reducing present bounds up to V_{eN} < 0.002-0.006

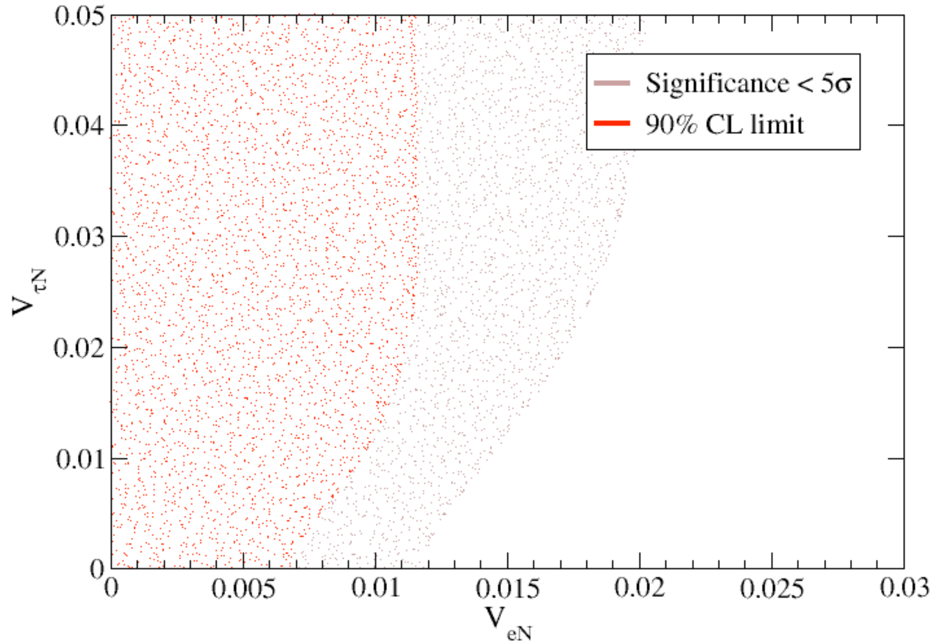




ILC

This processes will allow to detect a N with m_N = 0.2-0.4 TeV and V_{eN} > 0.01, reducing present bounds up to V_{eN} < 0.007

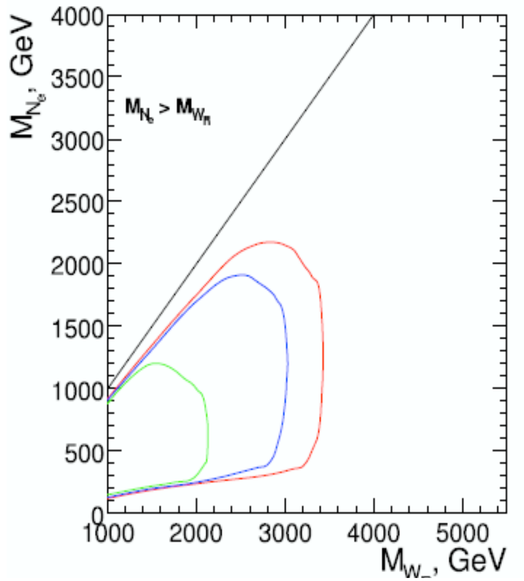


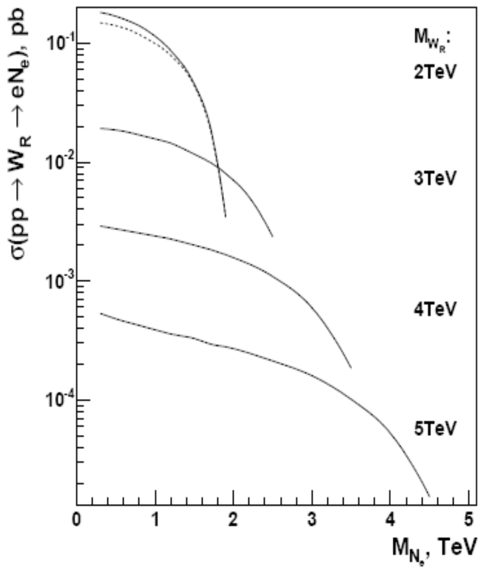


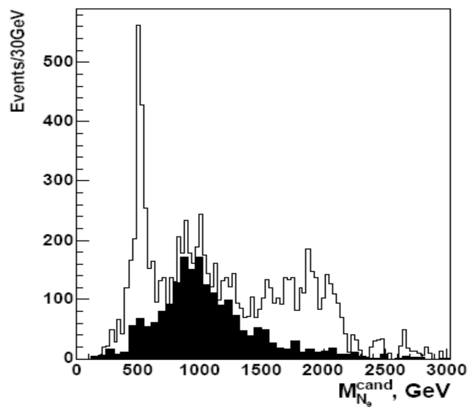
N production with extra interactions

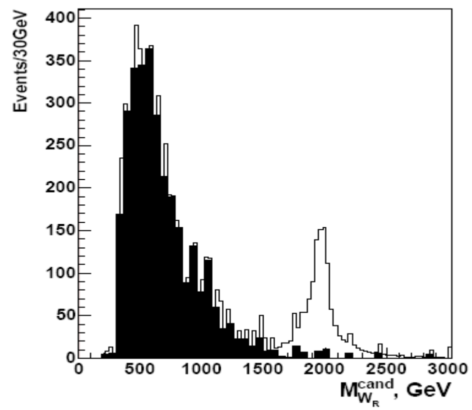
$pp \longrightarrow W_R \longrightarrow eN \longrightarrow eejj$

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





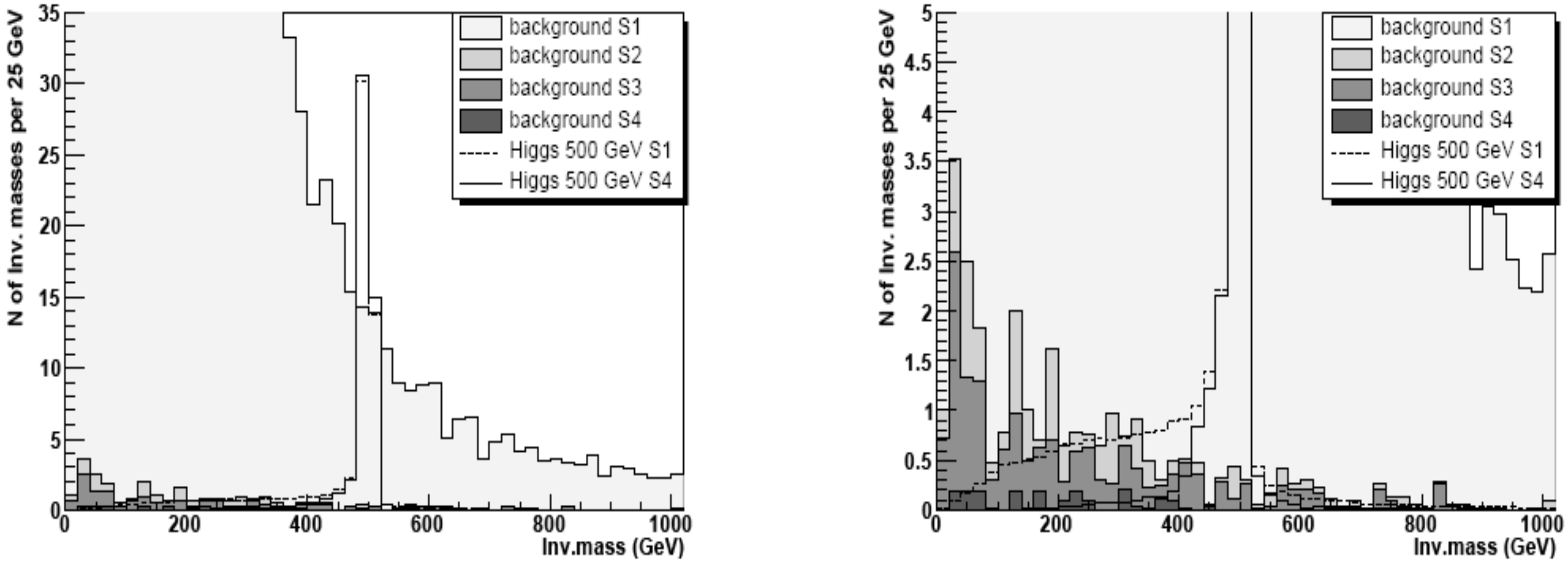




S.N. Gninenko, M.M. Kirsanov, N.V. Krasnikov and V.A.Matveev,
Phys. Atom. Nucl. 70 (2007) 441

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

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

$$\mathcal{O}_{LL}^{(1)} = \frac{1}{2}\left(\bar{L}\gamma_\mu L\right)\left(\bar{L}\gamma^\mu L\right) \quad \left\{ \begin{array}{l} 2\,(Y_\Delta)_{e\mu}\,(Y_\Delta^{+})_{\mu e}\,M_\Delta^{-2} \\ |(Y_\Delta)_{e\mu}\,M_\Delta^{-1}| < 0.47\ \mathrm{TeV}^{-1} \end{array} \right.$$

$$\mathcal{O}_{\phi}^{(3)} = \left(\phi^\dagger D_\mu \phi\right)\left(\left(D^\mu \phi\right)^\dagger \phi\right) \quad \left\{ \begin{array}{l} 4\,|\mu_\Delta|^2\,M_\Delta^{-2} \\ |\mu_\Delta M_\Delta^{-2}| < 0.043\ \mathrm{TeV}^{-1} \end{array} \right.$$

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

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