Right-Handed Neutrinos: DM and LFV vs Collider

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- In this work, we consider a class of radiative neutrino mass models that contain the following term in the Lagrangian [1, 2, 3, 4]

$$\mathcal{L}_{\mathcal{N}} \supset -\frac{1}{2} m_{N_i} \overline{N_i^c} P_R N_i + g_{i\alpha} S^+ \overline{N_i} \ell_{\alpha R} + \text{h.c.},$$

- These interactions can give rise to the LFV processes $\ell_\alpha \to \ell_\beta \gamma$ *and* $\ell_\alpha \to 3\ell_\beta$.

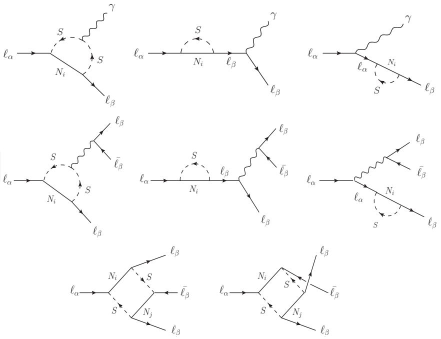
- We use the processes $\ell_\alpha \to \ell_\beta\, \gamma$ to calibrate the space parameters, their branching ratios is

$$\mathcal{B}(\ell_\alpha \to \ell_\beta \gamma) = \frac{3(4\pi)^3 \alpha}{4 G_F^2} |A_D|^2 \times \mathcal{B}(\ell_\alpha \to \ell_\beta \nu_\alpha \bar{\nu}_\beta)$$

where

$$A_D = \sum_{i=1}^{3} \frac{g_{i\beta}^* g_{i\alpha}}{2(4\pi)^2} \frac{1}{m_S^2} F\left(m_{N_i}^2 / m_S^2\right),$$

$$F(x) = \frac{1 - 6x + 3x^2 + 2x^3 - 6x^2 \log x}{6(1-x)^4}$$



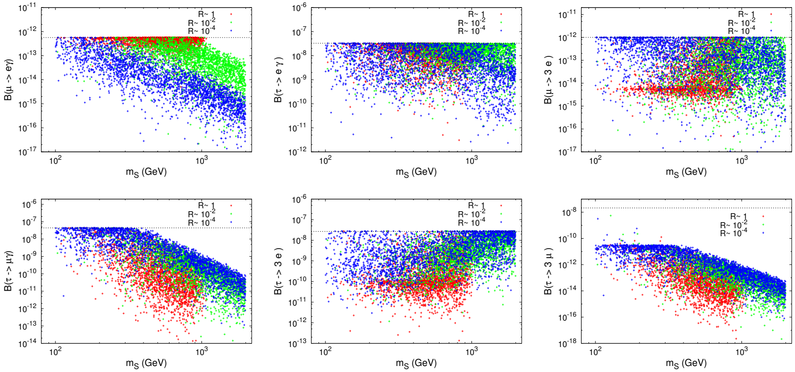
LFV process	Current bound
$\mu \to e\gamma$	5.7×10^{-13}
$\tau \to e\gamma$	3.3×10^{-8}
$\tau \to \mu\gamma$	4.4×10^{-8}
$\tau \to 3e$	1.0×10^{-12}
$\tau \to 3\tau$	2.7×10^{-8}
$\tau \to 3\tau$	2.1×10^{-8}

Class of Models & LFV Constraints

- Using process $\mu \to e\gamma$, we define the ratio R which makes possible to have larger yukawa coupling,

$$\mathrm{R} = \frac{|\sum_{i=1}^{3} g_{ie}^{*} g_{i\mu} F(x_i)|^2}{Max[|g_{ie}^{*} g_{i\mu} F(x_i)|^2]}$$

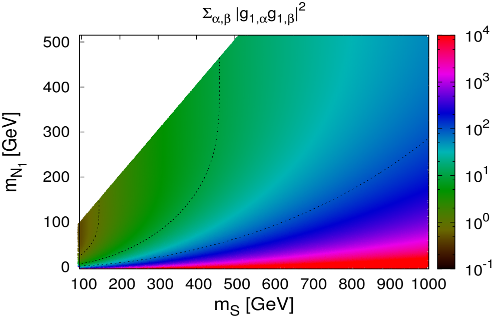
- 3 cases are considered, $R_1 \approx 1$ for a random generation without constraint, $R_2 \approx 10^{-2}$ for a moderate constraint and $R_3 \approx 10^{-4}$ for a strong constraint.



Relic Density constraint

- The lightest RH neutrino N_1 is stable and could be a good dark matter candidate.
- The relic density at the freeze-out is given by [5]

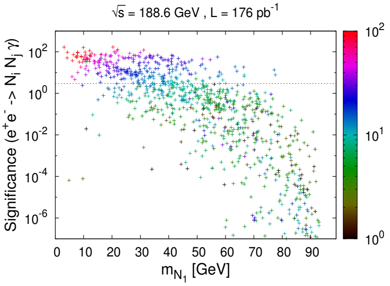
$$\Omega_{N_1} h^2 \simeq \frac{2x_f \times 1.1 \times 10^9 \text{ GeV}^{-1}}{\sqrt{g^*} M_{pl} \langle \sigma_{N_1 N_1} v_r \rangle} \simeq \frac{17.56}{\sum_{\alpha,\beta} |g_{1,\alpha} g^*_{1,\beta}|^2} \left(\frac{m_{N_1}}{50 \text{ GeV}} \right)^2 \frac{\left(1+m_S^2/m_{N_1}^2\right)^4}{1+m_S^4/m_{N_1}^4}$$



- To satisfy both DM relic density and the current bounds on LFV processes, we must impose : $m_{N_1} < 200$ GeV and $m_S < 300$ GeV while keeping $m_{N_1} < m_S$

Constraint From LEP II

- $e^- e^+ \to \gamma + E_{miss}$ search by the L3 detector at LEP-II is considered, there are no events observed for significance higher than 3.
- We apply the same kinematical cuts used by L3 collaboration on mono-photonic channel $\{|cos\,\theta_\gamma| < 0.97,\ p_T^\gamma > 0.02\sqrt{s}$ and $E_\gamma > 1\,\mathrm{GeV}\}$, use CalcHEP to generate the event of the signal and the background,



- A numerical constraint is extracted on space parameters of model,

$$Max(|g_{i,e}|) < 0.66\ \left[\frac{m_S}{100\ \mathrm{GeV}}\right]\left[\frac{m_{N_i}}{50\ \mathrm{GeV}}\right]$$

Possible Signatures At Lepton Colliders

- The main processes where the DM particles are in the final states are considered,

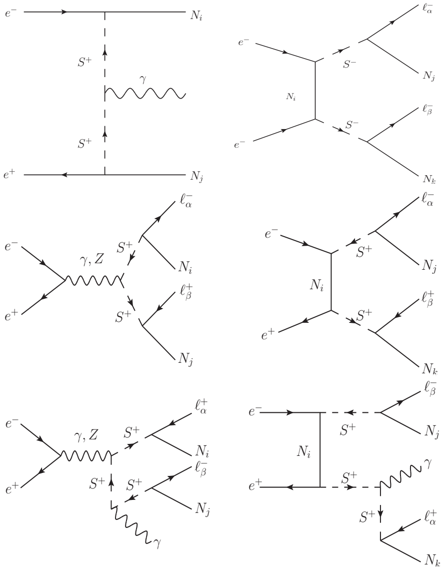
$e^- e^+ \to \gamma + E_{miss}$

$e^- e^+ \to S^+ S^- \to \ell_\alpha^+ \ell_\beta^- + E_{miss}$

$e^- e^- \to S^- S^- \to \ell_\alpha^- \ell_\beta^- + E_{miss}$

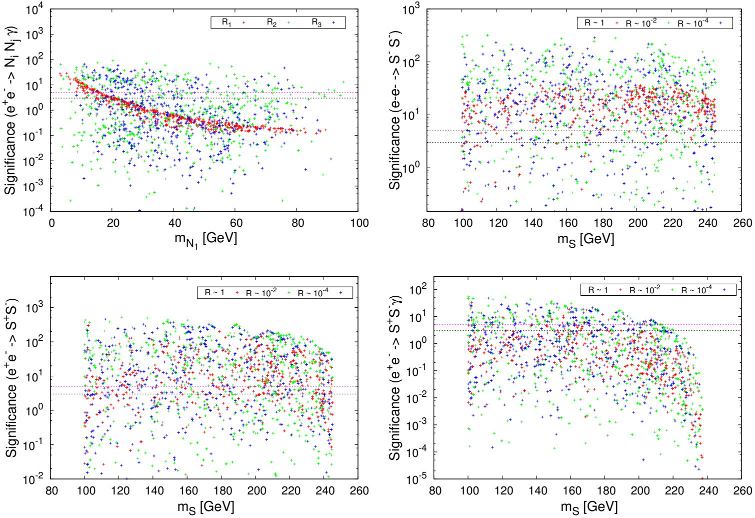
$e^- e^+ \to \gamma + S^+ S^- \to \gamma + \ell_\alpha^+ \ell_\beta^- + E_{miss}$

- All these processes are considered at $\sqrt{s} = 500\ GeV$ for a luminosity of $100\ pb^{-1}$.



Possible Signatures At Lepton Colliders

- The pre-cuts: $E_\gamma > 8$ GeV and $|cos\ \theta_\gamma| < 0.998$ for the monophoton and $S^- S^+ + \gamma$ channels are imposed.



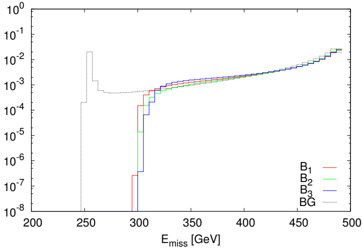
Benchmark Analysis

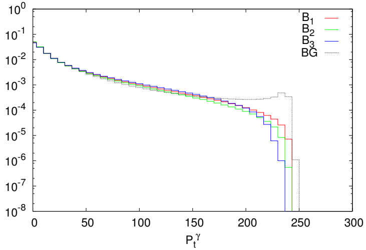
⇒ Three benchmark points selected from each R_i according to the fine-tuning degree

Point	$B_1\ (R_1)$	$B_2\ (R_2)$	$B_3\ (R_3)$
g_{1e}	$(7.506 + i0.014) \times 10^{-1}$	$(1.8284 + i0.103)$	$(-0.103 + i0.201)$
g_{2e}	$(-0.26819 - i1.5758) \times 10^{-4}$	$(1.543 + i3.004) \times 10^{-4}$	$(0.654 - i2.616) \times 10^{-2}$
g_{3e}	$(-1.360 - i0.707)$	$(0.313 - i0.549)$	$(-0.869 - i0.878)$
m_S(GeV)	196.75	242.81	104.47
m_{N_1} (GeV)	25.788	43.764	38.306
m_{N_2} (GeV)	28.885	58.182	56.481
m_{N_3} (GeV)	36.274	67.511	72.440

Using CalcHEP, we generate the distributions for different kinematic variables for both signal and background of the electron-positron

- The monophoton final state $\gamma + E_{miss}$



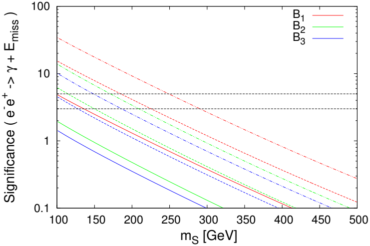


Benchmark Analysis

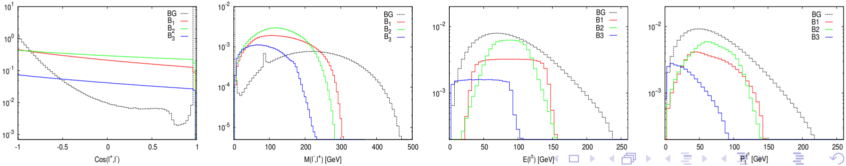
The monophotonic process cuts can be achieved as follows :

$$8 \text{ GeV} < E_\gamma < 300 \text{ GeV}, \ |cos\ \theta_\gamma| < 0.998, \ E_{miss} > 300 \text{ GeV}$$

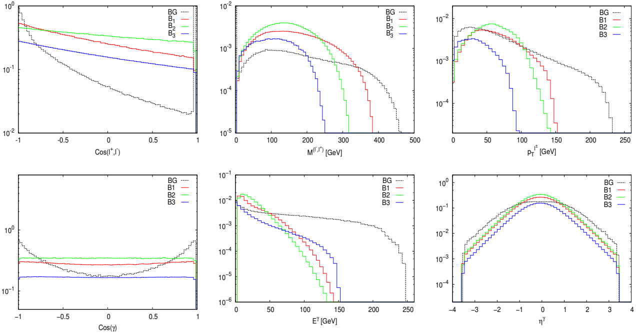
The significance is done at integrated luminosity of 10 (solid), 100 (dashed) and 500 (dash-dotted) fb^{-1}



- Final state $S^+S^-(\gamma)$



Benchmark Analysis



A similar generation to the monophoton is applied and the more relevant cuts are extracted as follows :

$$\text{Final state } S^+S^- : \left\{ \begin{array}{l} M_{\ell^+,\ell^-} < 300 \text{ GeV}, 150 \text{ GeV} < E_{miss} < 420 \text{ GeV}, \\ 30 \text{ GeV} < E^{\ell} < 180 \text{ GeV}, P_t^{\ell} < 170 \text{ GeV} \end{array} \right. \quad (1)$$

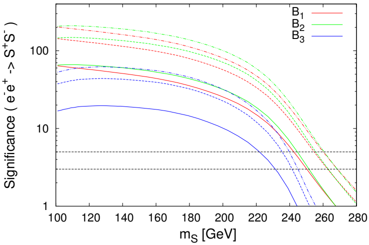
and

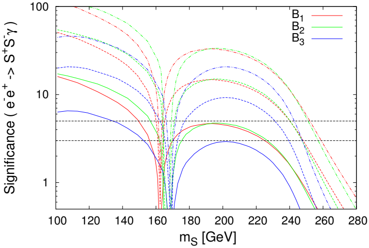
$$\text{Final state } S^+S^-\gamma : \left\{ \begin{array}{l} M_{\ell^+,\ell^-} < 300 \text{ GeV}, 150 \text{ GeV} < E_{miss} < 400 \text{ GeV}, \\ 30 \text{ GeV} < E^{\ell} < 170 \text{ GeV}, P_t^{\ell} < 170 \text{ GeV}, \\ |cos\,(\theta_\gamma)\,| < 0.5, 8 \text{ GeV} < E^{\gamma} < 120 \text{ GeV}, P_t^{\gamma} < 110 \text{ GeV} \end{array} \right. \quad (2)$$

Benchmark Analysis

- The signal significance at integrated luminosity of 0.1 (solid), 0.5 (dashed) and 1 (dash-dotted) fb^{-1} for S^-S^+ and integrated luminosity of 1 (solid), 10 (dashed) and 50 (dash-dotted) fb^{-1} for $S^-S^+ + \gamma$.

- In these figures, a charged scalars is off-shell for $m_S > 250$ GeV and $m_S > 246$ GeV.





- We re-analyze the processes discussed earlier by considering polarized beams as $P\left(e^{-},e^{+}\right) = [+0.8, -0.3]$ while applying the same cuts used previously.

Process	$P(e^-,e^+)$	N_{BG}	BP	N_S	S_{10}	S_{100}	S_{500}
$e^-e^+ \to \gamma + E_{miss}$	[0,0]	46652	B_1	270.8	0.95	3.95	8.84
			B_2	250.32	1.16	3.65	8.17
			B_3	267.35	1.23	3.90	8.73
	[+0.8,-0.3]	6541	B_1	633.62	7.48	23.65	52.89
			B_2	585.74	6.94	21.94	49.06
			B_3	626.45	7.40	23.40	52.32

Process	$P(e^-,e^+)$	N_{BG}	BP	N_S	S_1	S_{10}	S_{50}
$e^-e^+ \to S^-S^+ + \gamma$	[0,0]	876.39	B_1	248.9	2.35	7.42	16.59
			B_2	91.22	0.93	2.93	6.56
			B_3	790.16	6.12	19.36	43.28
	[+0.8,-0.3]	123.20	B_1	555.53	6.74	21.32	47.68
			B_2	213.45	3.68	11.63	26.01
			B_3	1904	13.4	42.30	94.58

Conclusion

- *The production via electron-electron collision is huge compared to the background, this process is a clean and direct probe for RH neutrinos at the ILC*
- Monophotonic process is detectable at lepton colliders for a luminosity of a few hundred fb^{-1} and for charge scalars lighter than 200 GeV
- The production of a pair charged scalars without a photon in the final state the signal-to-background ratio can be very large for $m_S < 220$ GeV even at low integrated luminosity
- Final state $S^+S^-\gamma$ is detectable at lepton colliders for a luminosity of a few tens fb^{-1} and for charge scalars lighter than 220 GeV
- *Using polarized beams we can improve the detectability of monophoton process to few tens fb^{-1} and to few fb^{-1} for The production of a pair charged scalars with a photon.*

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