Three-Loop Neutrino Mass Models and Phenomenology

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Outlines

- The Models: Neutrino Mass vs Exp. Constraints
- Dark Matter, EW Phase Transition & $h \to \gamma\gamma(\gamma Z)$ decay channels
- Collider Signatures
- Conclusion

based on A.A. & S. Nasri, JCAP 07 (2013) 035
A.A., S. Nasri & R. Soualah, Phys. Rev. D 89, 095010 (2014)
A.A., C.-S. Chen, K.L. McDonald & S. Nasri, Phys.Rev. D90, 015024 (2014)
A.A., K.L. McDonald & S. Nasri, JHEP 10, 167 (2014)
A.A., et al in preparation

The Models: Neutrino Mass vs Exp.

The SM is very succesful, but ... ν 'masses, gauge unification, hierarchy pb, BAU, DM, DE ..

Many extensions: gauge symmetry, particle content, space-time or introducing exotic ideas (SUSY, LH, UnParticle..)

A small ν 'masses: **Seesaw mechanism** ... or **Radiatively** ... Zee, Babu-Zee ... etc

Our class of models is a simple (& economical) SM extension: SM + a charged singlet scalar + a scalar N-plet + 3 generations of fermion N-plets with a global Z_2 symmetry. This leads to:

1. neutrino mass and mixing values given by the Exp;
2. DM candidate: relic density & direct detection Exp;
3. Higgs mass at 125 GeV & possible enhancement in $h \to \gamma\gamma$;
4. Strong first order phase transition;
5. Interesting signals at the colliders.

Lagrangian & Neutrino mass

$$\mathcal{L} \supset \mathcal{L}_{\rm SM} + \{f_{\alpha\beta}\,\overline{L_\alpha^c}\,L_\beta\,S^+ + g_{i\alpha}\,\overline{E_i}\,T\,e_{\alpha R} + \text{H.c}\} - \frac{1}{2}\,\overline{E_i^c}\,\mathcal{M}_{ij}\,E_j - V$$

Charged singlet scalar

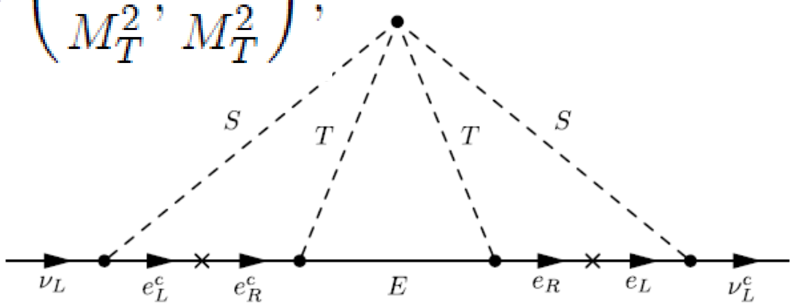
N-plet fermions

N-plet scalar

$$S^+ \sim (1,1,2) \qquad T \sim (1,2n+1,2) \qquad E_i \sim (1,2n+1,0)$$

$$Z_2: \quad \{T, E_i\} \to \{-T, -E_i\}$$

$$(\mathcal{M}_\nu)_{\alpha\beta} = \frac{(2n+1)\lambda_s}{(4\pi^2)^3}\frac{m_\gamma m_\delta}{M_T}\,f_{\alpha\gamma}\,f_{\beta\delta}\,g^*_{\gamma i}\,g^*_{\delta i} \times F\left(\frac{M_i^2}{M_T^2}, \frac{M_S^2}{M_T^2}\right),$$



$$F(\alpha,\beta) = \frac{\sqrt{\alpha}}{8\beta^2}\int_0^\infty dy\,\frac{y}{y+\alpha}\left(\int_0^1 dx \ln\frac{x(1-x)y+(1-x)\beta+x}{x(1-x)y+x}\right)^2.$$

These estimated neutrino mass matrix elements have to be matched observed values

$$(M_\nu)_{\alpha\beta} = [U \cdot diag(m_1, m_2, m_3) \cdot U^T]_{\alpha\beta},$$

$$s_{ij} \equiv \sin(\theta_{ij}) \text{ and } c_{ij} \equiv \cos(\theta_{ij}) \; s_{12}^2 = 0.320^{+0.016}_{-0.017}, \; s_{23}^2 = 0.43^{+0.03}_{-0.03}, \; s_{13}^2 = 0.025^{+0.003}_{-0.003},$$

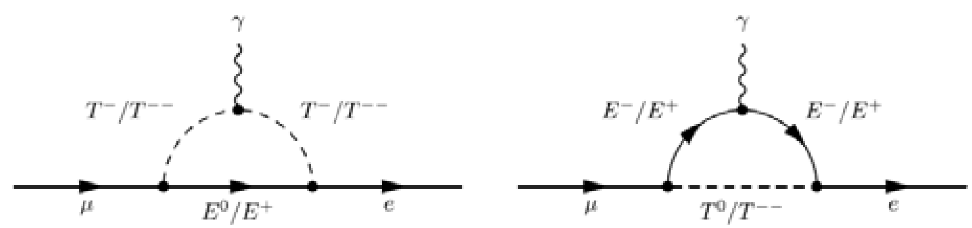
$$|\Delta m_{31}^2| = 2.55^{+0.06}_{-0.09} \times 10^{-3} \text{ eV}^2 \quad \Delta m_{21}^2 = 7.62^{+0.19}_{-0.19} \times 10^{-5} \text{eV}^2$$

We do not know the neutrinomass hierarchy: normal or inverted? and the absolute neutrino mass (m_1 ot m_3) ?

Experimental constraints

LFV

eg. triplet



$$\mathcal{B}(l_\alpha \to l_\beta e) = \frac{3\alpha v^4}{32\pi} \times \left\{ \frac{|f^*_{\alpha\kappa} f_{\kappa\beta}|^2}{36 M_s^4} + \frac{(2n+1)^2}{M_T^4} \left| \sum_i g_{i\mu} g^*_{ie} F_2(M_i^2/M_T^2) \right|^2 \right\}$$

$$F_2(x) = (1 - 6x + 3x^2 + 2x^3 - 6x^2 \ln x)/6(1-x)^4$$

Exp. Bounds: $B(\mu \to e\gamma) < 5.7 \times 10^{-13}$ $\quad B(\tau \to \mu\gamma) < 4.5 \times 10^{-8}$

Muon anomalous magnetic moment

$$\delta a_\mu = \frac{m_\mu^2}{16\pi^2} \left\{ \sum_{\alpha \neq \mu} \frac{|f_{\mu\alpha}|^2}{6 M_s^2} + \frac{n}{M_T^2} \sum_i |g_{i\mu}|^2 F_2(M_i^2/M_T^2) \right\}$$

Dark Matter

The observed relic density (Planck) $\Omega_{DM}h^2 = 0.1187 \pm 0.0017$

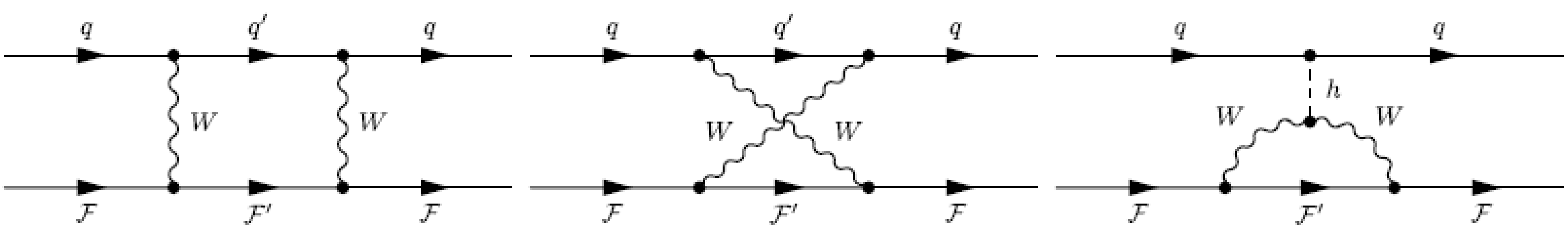
In our setup, the lightest $\mathcal{F}_1^0$ is the DM candidate, which has the self-annihilation (T and/or W-mediated) t-chennel processes; as

$$\mathcal{F}_1^0\mathcal{F}_1^0 \rightarrow \ell_\alpha^-\ell_\beta^+$$
$$\mathcal{F}_1^0\mathcal{F}_1^0 \rightarrow W^-W^+ \quad (n \neq 0)$$

However, one to consider the co-annihilation processes (for n>0):

$$\mathcal{F}_1^0\mathcal{F}_1^+\left(\mathcal{F}_1^-\mathcal{F}_1^{-+}\right) \rightarrow W_3^0W^+,\ \mathcal{F}_1^-\mathcal{F}_1^+\left(\mathcal{F}_1^{--}\mathcal{F}_1^{++}\right) \rightarrow W^-W^+$$

We have also direct detection constraints, where the detection cross section for n>0 can be estimated from :



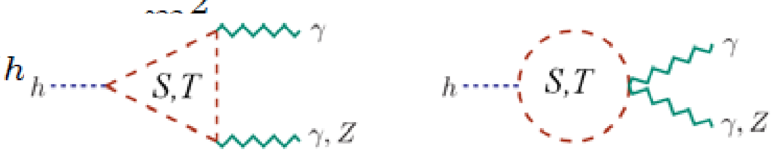
When considering LUX (together with previous constraints), this implies M_{DM}>> TeV for n>0 , while M_{DM}<225 GeV for n=0.

EW Phase Transition & decay channels $h\to\gamma\gamma$ and $h\to\gamma Z$

In our models, the Higgs mass at one-loop can be approximated as

Due to extra scalars that couple to the Higgs doublet, the rates $h\to\gamma\gamma,\gamma Z$ may be modified via

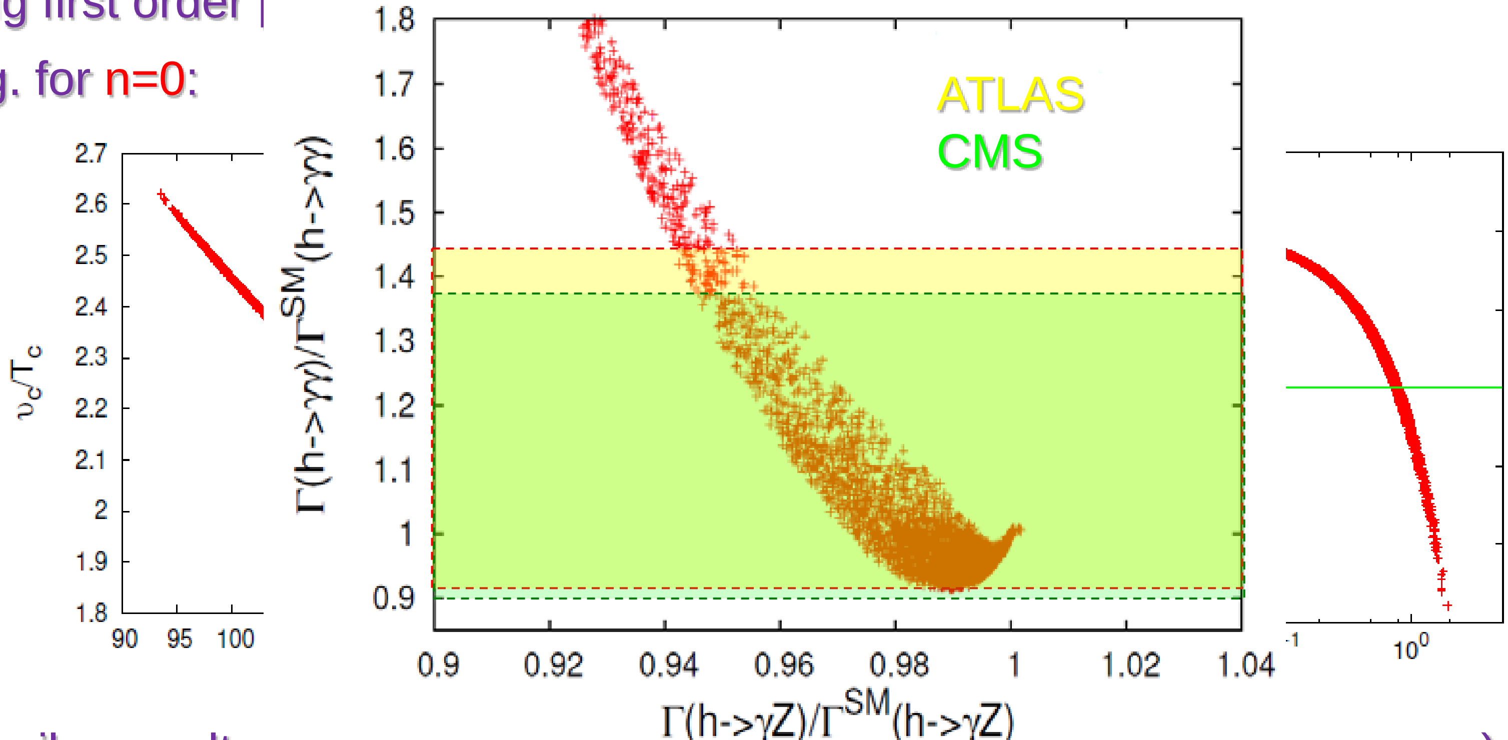
$$m_h^2 \simeq 2\lambda v^2 + \frac{v^2}{16\pi^2}\sum_{X=S,T} n_X \lambda_{Xh}^2$$



Then the Higgs mass can be fully radiative for small λ … this means that a strong first order

eg. n=0

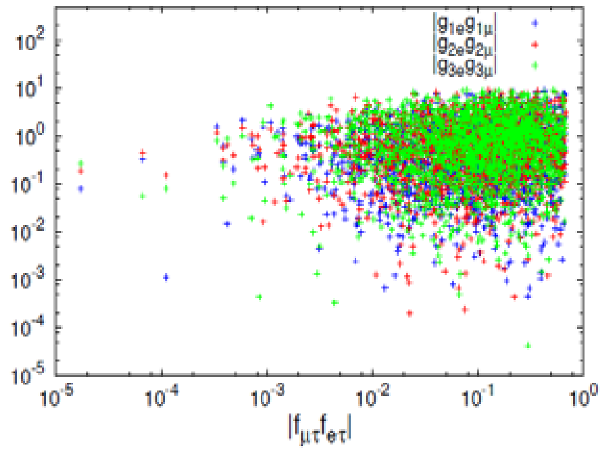
eg. for n=0:

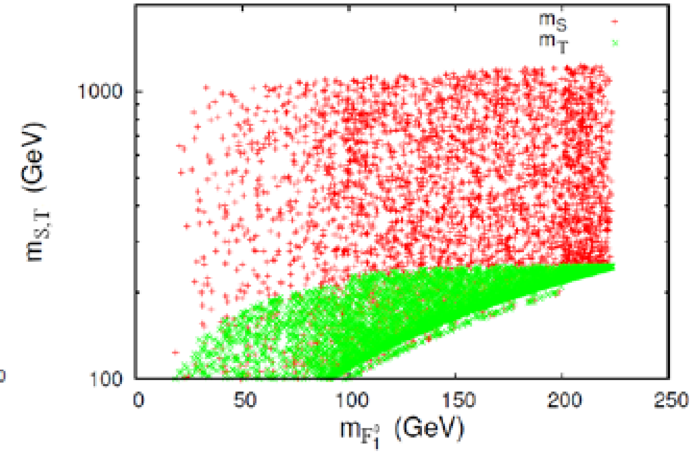


Similar results … progress)

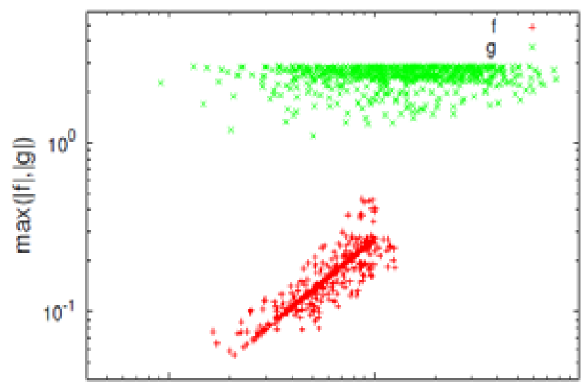
Numerical scan:

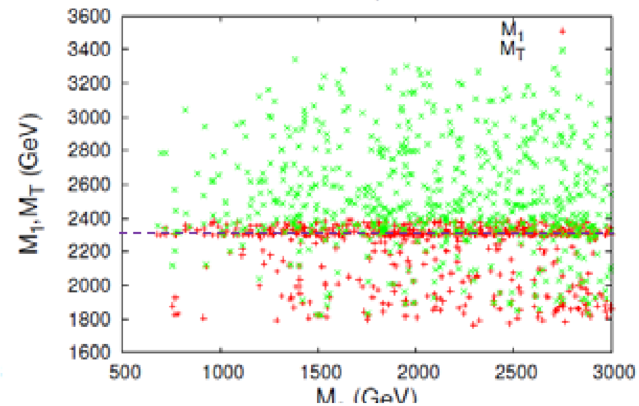
n=0



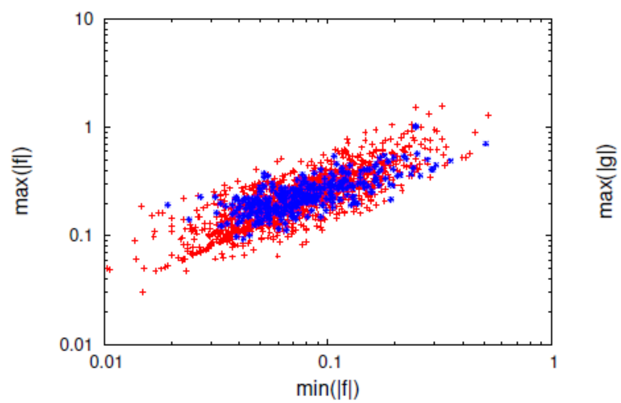


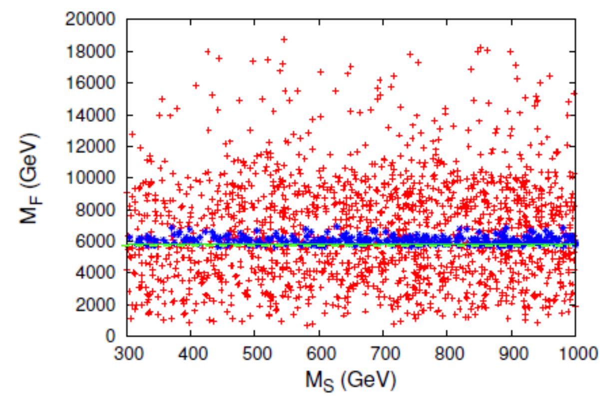
n=1





n=2





Collider Signatures

For the n=0 (KNT), we consider the process at the ILC:

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

KNT: 40 diagrams

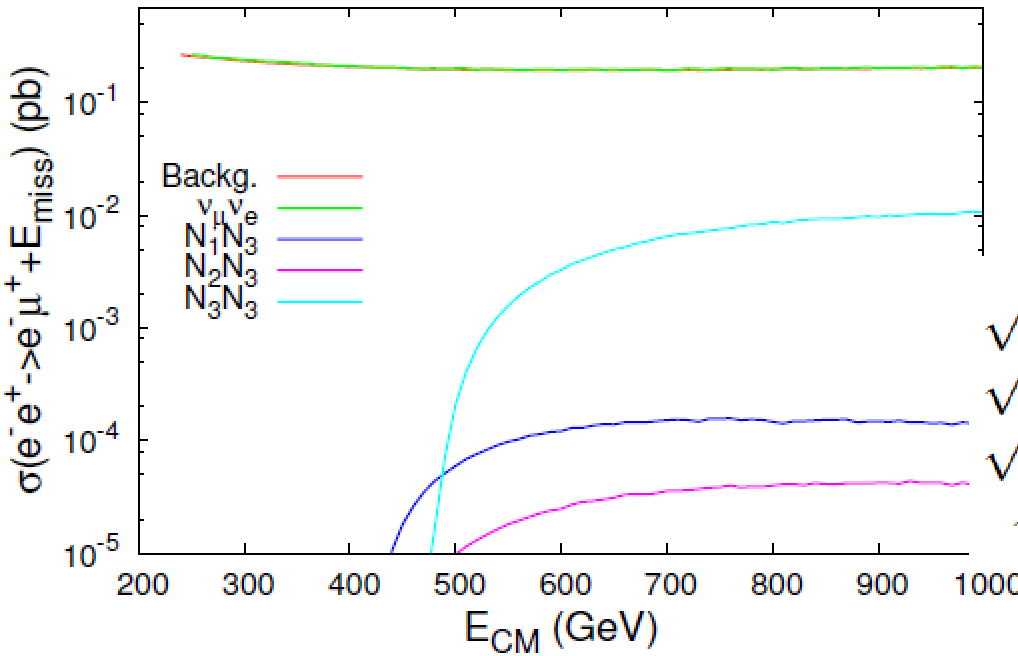
$$\nu_\mu \bar{\nu}_e, \ \nu_e \bar{\nu}_\tau, \ \nu_\tau \bar{\nu}_e, \ \nu_\mu \bar{\nu}_\mu, \ \nu_\tau \bar{\nu}_\mu, \ \nu_\tau \bar{\nu}_\tau, \ \mathcal{F}_i^0, \ \mathcal{F}_k^0$$

RH neutrinos

with the background: $e^- e^+ \to e^- \mu^+ + \nu_\mu \bar{\nu}_e$

they are not similar!!

SM: 18 diagrams



At the ILC:

$$\sqrt{s} = 250 \ GeV \qquad \mathcal{L} \sim 250 \ fb^{-1}$$
$$\sqrt{s} = 350 \ GeV \qquad \mathcal{L} \sim 350 \ fb^{-1}$$
$$\sqrt{s} = 500 \ GeV \qquad \mathcal{L} \sim 500 \ fb^{-1}$$
$$\sqrt{s} = 1 \ TeV \qquad \mathcal{L} \sim 1 \ ab^{-1}$$

In order to identify the signal, the significance $\mathcal{S} = N_S/\sqrt{N_S + N_B}$, should e be larger than 5, with $N_S = N_{EX} - N_B = L \times (\sigma^{EX} - \sigma^{BG})$,

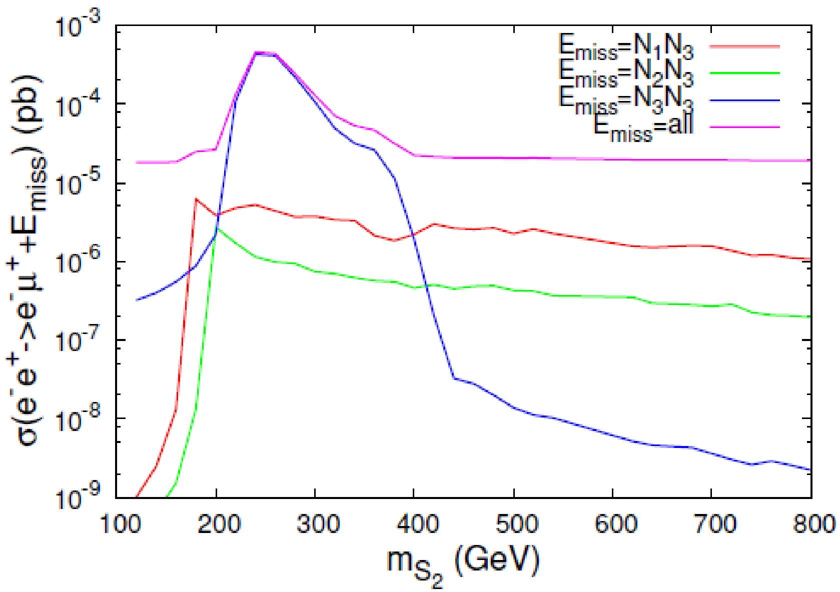
After implementing the model in LanHEP/CalcHEP, we generate different distributions and consider the selection cuts:

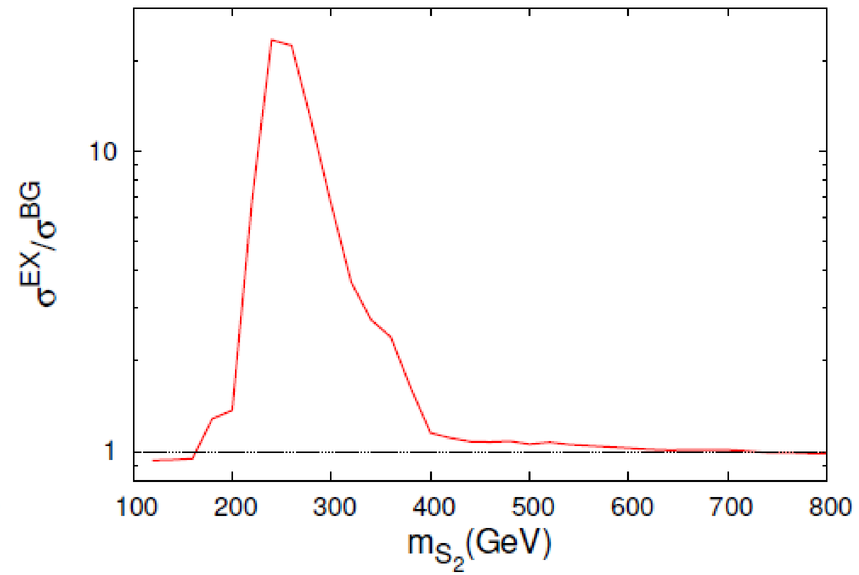
E_{CM}	Selection cuts
250	$70 < E_\ell < 110$, $70 < M_{e,\mu} < 220$, $M_{miss} < 120$, $0.4621 < \cos\theta_e < 0.9640$, $-0.9640 < \cos\theta_\mu < -0.4621$,
350	$90 < E_\ell < 165$, $100 < M_{e,\mu} < 280$, $M_{miss} < 200$, $0.4621 < \cos\theta_e < 0.9951$, $-0.9866 < \cos\theta_\mu < 0$,
500	$120 < E_\ell < 240$, $300 < M_{e,\mu} < 480$, $M_{miss} < 300$, $0.4621 < \cos\theta_e < 0.9951$, $-0.9951 < \cos\theta_\mu < 0$,
1000	$E_\ell < 70$, $M_{e,\mu} < 140$, $M_{miss} > 750$, $0.0997 < \cos\theta_e < 0.6640$, $-0.6640 < \cos\theta_\mu < -0.0997$.

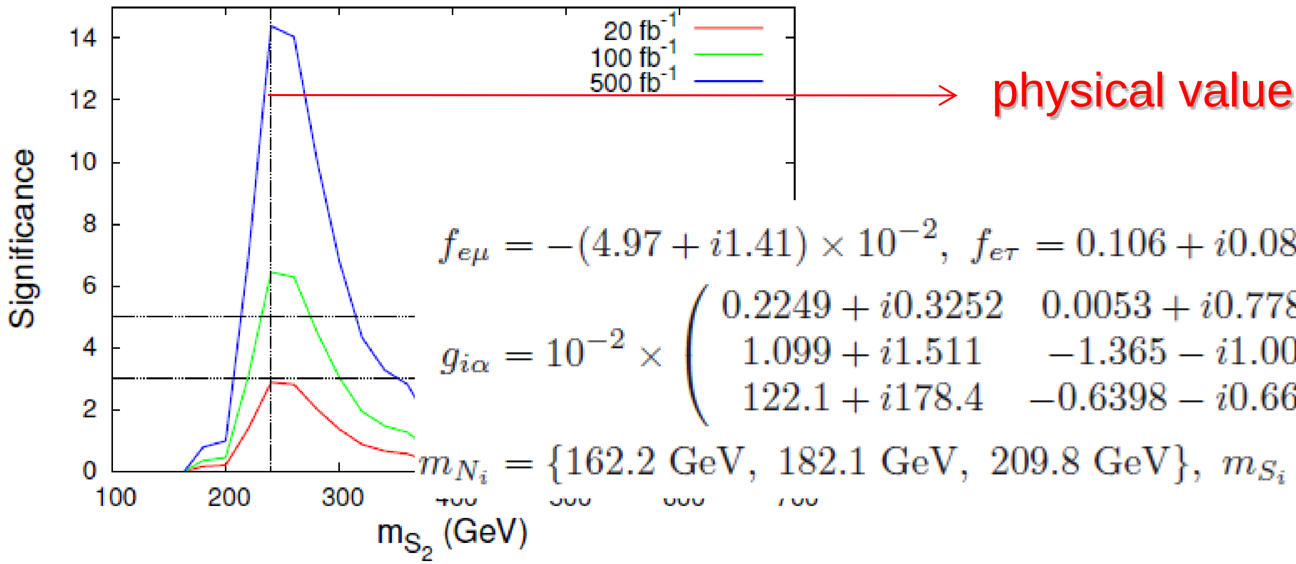
We obtain the cross section and significance values:

E_{CM}	σ^{BG}	σ^{EX}	$(\sigma^{EX} - \sigma^{BG})/\sigma^{BG}$	$\mathcal{S}_{100}$	$\mathcal{S}_{500}$
250	6.5919×10^{-2}	6.7402×10^{-2}	2.2497×10^{-2}	1.8064	4.0391
350	5.8882×10^{-2}	6.0158×10^{-2}	2.2723×10^{-2}	1.6451	3.6787
500	5.6560×10^{-2}	5.7630×10^{-2}	1.8918×10^{-2}	1.4095	3.1517
1000	1.9217×10^{-5}	4.6976×10^{-4}	23.445	6.5735	14.699

In order to identify the source of missing energy source at 1 TeV, we vary the charged scalar T^+ mass (the scalar that couples to $F_i^0 = N_i$). We find







$$f_{e\mu} = -(4.97 + i1.41)\times 10^{-2},\ f_{e\tau} = 0.106 + i0.0859,\ f_{\mu\tau} = (3.04 - i4.72)\times 10^{-6},$$

$$g_{i\alpha} = 10^{-2}\times\begin{pmatrix} 0.2249 + i0.3252 & 0.0053 + i0.7789 & 0.4709 + i1.47 \\ 1.099 + i1.511 & -1.365 - i1.003 & 0.6532 - i0.1845 \\ 122.1 + i178.4 & -0.6398 - i0.6656 & -10.56 + i68.56 \end{pmatrix},$$

$$m_{N_i} = \{162.2\ \text{GeV},\ 182.1\ \text{GeV},\ 209.8\ \text{GeV}\},\ m_{S_i} = \{914.2\ \text{GeV},\ 239.7\ \text{GeV}\},$$

Therefore, the missing energy at CM energies 250, 350 and 500 GeV is mainly LH neutrinos, while at 1 TeV, it RH Majoarana neutrinos.

Another option to enhance the significane in leptnic colliders is using polarized beams. The polarization is characterized by:

$$P(f) = (N_{f_R} - N_{f_L})/(N_{f_R} + N_{f_L})$$

At the ILC, we have:

$$\left|P(e^-)\right| \leq 0.8; \quad \left|P(e^+)\right| \leq 0.3,$$

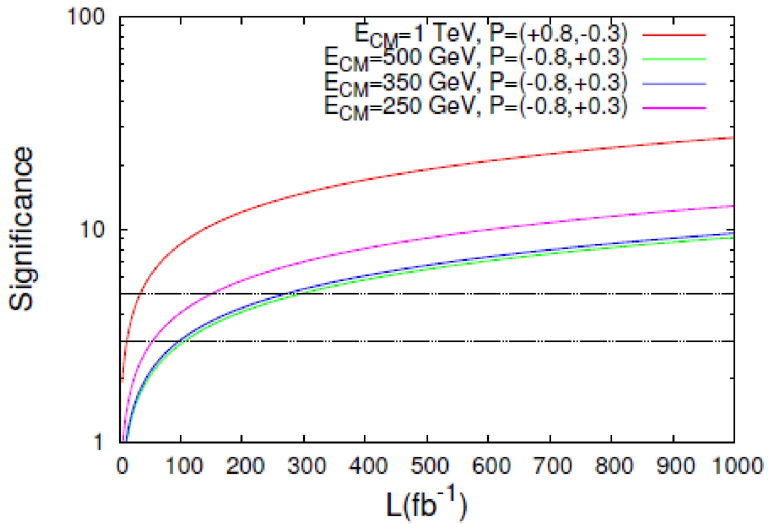
We get the cross section and significance values:

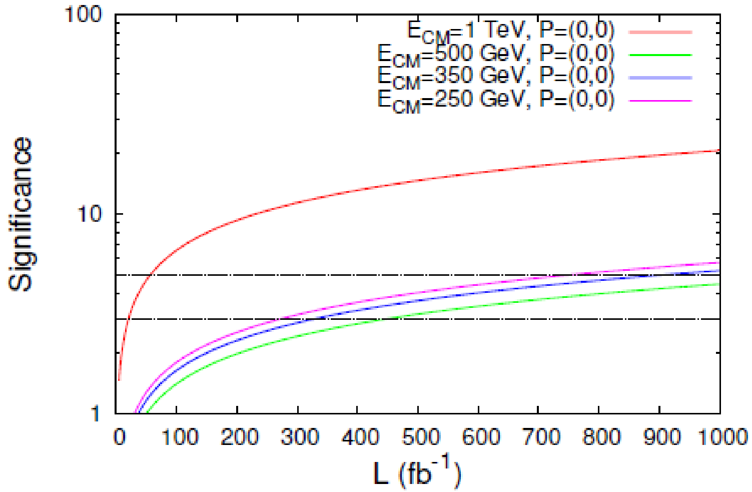
E_{CM}	$P(e^-, e^+)$	σ^{BG}	σ^{EX}	$\left(\sigma^{EX} - \sigma^{BG}\right)/\sigma^{BG}$	$\mathcal{S}_{100}$	$\mathcal{S}_{500}$
250	-0.8, +0.3	0.15399	0.15910	3.3184×10^{-2}	4.0512	9.0588
350	-0.8, +0.3	0.13640	0.13997	2.6173×10^{-2}	3.0175	6.7474
500	-0.8, +0.3	0.13100	0.13450	2.6718×10^{-2}	3.0179	6.7483
1000	+0.8, -0.3	2.0708×10^{-6}	7.2710×10^{-4}	350.12	8.5027	19.013

To summarize the results, we give the expected events numbers:

E_{CM} (GeV)	L (fb^{-1})	$P(e^-, e^+)$	N_B	N_{EX}	N_S
250	250	0, 0	16480	16851	371
		−0.8, +03	38498	39775	1277
350	350	0, 0	20609	21055	446
		−0.8, +03	47740	48990	1250
500	500	0, 0	28280	28815	535
		−0.8, +03	65500	67250	1750
1000	1000	0, 0	19.217	469.76	450.54
		+0.8, −03	2.07	727.10	725.03

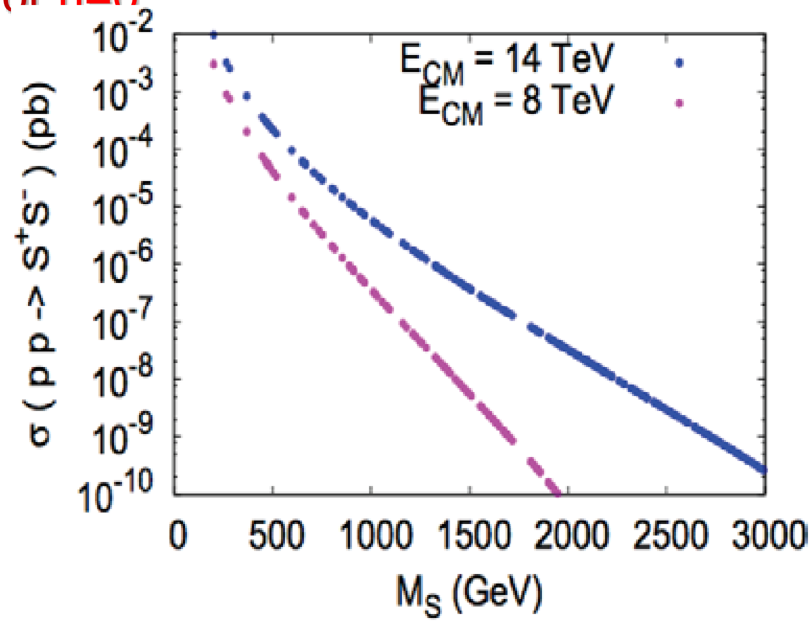
And when varying the luminosity, we get:

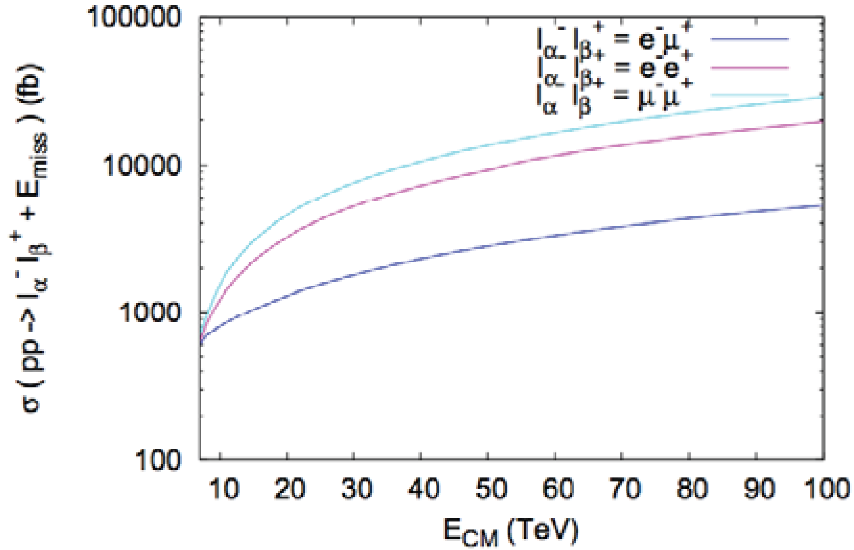




At the LHC, we consider the S-mediated process: $pp \to \ell_\alpha^- \ell_\beta^+ + E_{miss}$

For n=0:





Within the cut $M_{T2}>M_W$ and

@ 14 TeV

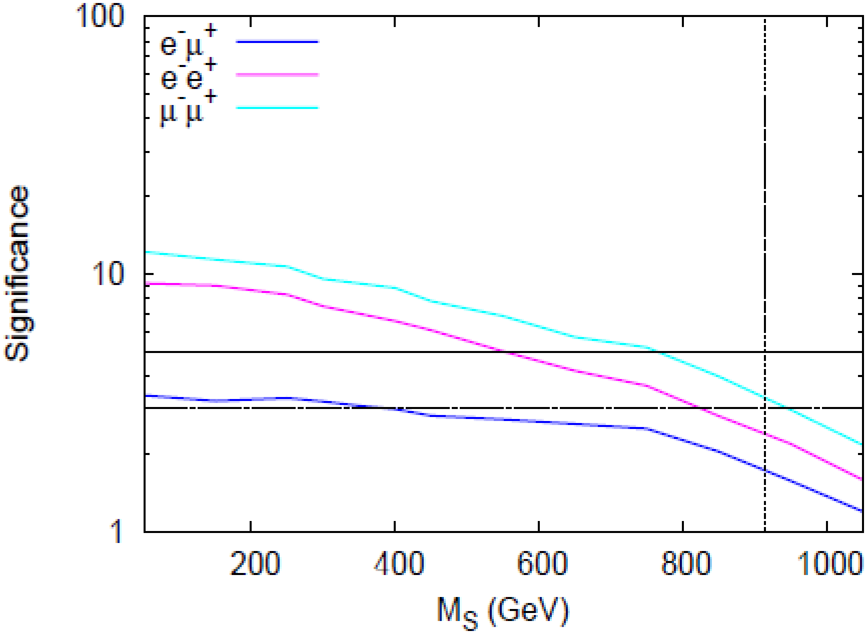
Process	Cuts
$pp \to e^-\mu^+ + E_{miss}$	$p_T^{e^-} > 180$ $\quad p_T^{\mu^+} > 170$ $1.1 < \eta_{e^-} < 2.89$ $\quad 1.2 < \eta_{\mu^+} < 3.02$
$pp \to e^-e^+ + E_{miss}$	$30 < p_T^l < 80$ $-2.8 < \eta_l < 2.95$
$pp \to \mu^-\mu^+ + E_{miss}$	$25 < p_T^l < 40$ $-0.13 < \eta_l < 3$

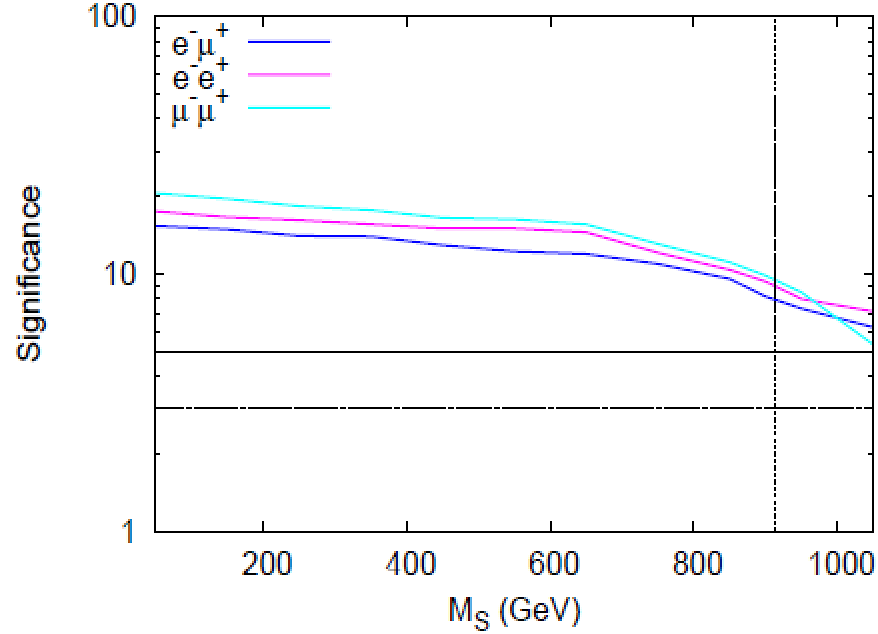
@ 8 TeV & L=20.3 fb^{-1}

Process	σ^{EX} (fb)	σ^{B} (fb)	(σ^{EX} - σ^{B})/ σ^{B}	S_{20}
$pp \to e^-\mu^+ + E_{miss}$	13.03	11.98	0.0876	1.301
$pp \to e^-e^+ + E_{miss}$	62.74	59.72	0.0506	1.7051
$pp \to \mu^-\mu^+ + E_{miss}$	81.691	77.49	0.0542	2.0786

@ 14 TeV & L=100 fb^{-1}

Process	σ^{EX} (fb)	σ^{B} (fb)	(σ^{EX} - σ^{B})/ σ^{B}	S_{100}
$pp \to e^-\mu^+ + E_{miss}$	1.253	0.459	1.7	7.093
$pp \to e^-e^+ + E_{miss}$	44.45	38.65	0.150	8.699
$pp \to \mu^-\mu^+ + E_{miss}$	65.27	56.86	0.148	10.409





From 8 TeV run, one puts the lower bound M_S > 780 GeV.

Conclusion

This calss of models gives

- *The neutrino mass and mixing data for normal and inverted hierarhy without beeing in conflict with Exp. constraints such as LFV procesess.*
- *Right amount of the relic density without being in conflcit with detection experiemetns.*
- *The Higgs mass at 125 GeV while a strong first order phase transition is easily obtained.*
- *a possible enhancement on the Higgs decay channel $h \to \gamma\gamma$ while $h \to \gamma Z$ remains almost unchanged.*
- *Possibly tested signals at both the* **ILC** *&* **LHC***.*

Thank you for your attention