

Radiative Neutrino Masses Models with Majorana Dark Matter

Amine Ahriche

Department of Physics, University of Jijel, PB 98 Ouled Aissa,
DZ-18000 Jijel, Algeria

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In collaboration with: S. Nasri, K. McDonald, M.S. Boucenna, R. Soualah, T. Toma, D. Cherigui, C. Guella & A. Jeuid.
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Outline

- 1 Some Models: Motivation & Description
- 2 Neutrino Mass versus Experimental Constraints
- 3 Dark Matter
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Some Models: Motivation & Description

- ▶ After the Higgs discovery $m_h = 125.09 \text{ GeV}$, there are still unanswered questions: EW scale origin, Dark Matter, Neutrino mass, Strong CP problem, Dark energy, Baryogenesis, Inflation .. etc.
- ▶ Neutrino oscillation data & Dark Matter and other problems must be explained Beyond SM: larger gauge symmetry (LR, SU(5), SO(10) ..etc), adding new fields to SM .. etc.

Here, we propose some models:

- ▶ KNT and KNT-like models (based on PRD67(2003)085002): SM + $S \sim (1, 1, 2) + T \sim (1, 2n + 1, 0) + 3 E_i \sim (1, 2n + 1, 0)$ with the global symmetry $Z_2: \{E_i, T\} \rightarrow \{-E_i, -T\}$ for $n = 0, 1, 2$. For $n = 3$ the global symmetry Z_2 is accidental.
- ▶ Dark Radiative Inverse Seesaw: SM + $N_L + N_R + \chi$ (DM).
- ▶ Scotogenic model with Majorana DM: SM + inert doublet + 3 N_i .

Some Models: Motivation & Description

KNT & KNT-like models: (with Nasri, McDonald ..)

- For $n = 0$:

$$\mathcal{L} \supset \{f_{\alpha\beta} L_{\alpha}^T C i_{T2} L_{\beta} S^+ + g_{i\alpha} N_i T^+ \ell_{\alpha R} + \frac{1}{2} m_{N_i} N_i^C N_i + h.c\} - V, \quad (1)$$

- For $n = 1, 2, 3$:

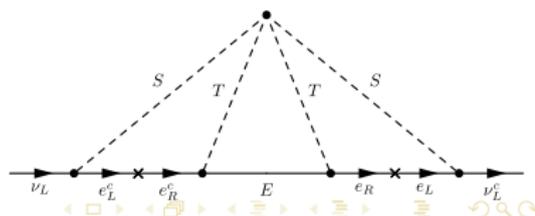
$$\mathcal{L} \supset \{f_{\alpha\beta} \bar{L}_{\alpha}^c L_{\beta} S^+ + g_{i\alpha} \bar{E}_i T \ell_{\alpha R} + H.c\} - \frac{1}{2} \bar{E}_i^c M_{ij} E_j - V, \quad (2)$$

- The scalar potential contains the terms

$$V(H, S, T) \supset \frac{\lambda_S}{4} (S^-)^2 T_{ab} T_{cd} \epsilon^{ac} \epsilon^{bd} + h.c., \quad (3)$$

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

$$F_{loop}(\alpha, \beta) = \frac{\sqrt{\alpha}}{8\beta^2} \int_0^{\infty} dr \frac{r}{r+\alpha} \left(\int_0^1 dx \ln \frac{x(1-x)r+(1-x)\beta+x}{x(1-x)r+x} \right)^2.$$



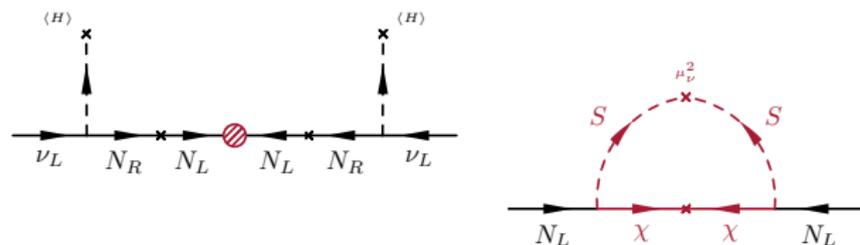
Some Models: Motivation & Description

Dark Radiative Inverse Seesaw: (with Nasri & Boucenna)

$$-\mathcal{L} \supset y_\nu \bar{L} \tilde{H} N_R + M \bar{N}_L N_R + y_N S \bar{\chi} N_L + \frac{m_\chi}{2} \chi^T C^{-1} \chi + \text{h.c.},$$

Here, the model is assigned with a global Z_4 that is softly broken to Z_2 ,

$$V = -\mu_H^2 H^\dagger H + \frac{1}{2} \lambda_H (H^\dagger H)^2 + \mu_S^2 S^* S + \frac{\mu_\nu^2}{2} (S^2 + \text{h.c.}) + \frac{\lambda_S}{2} (S^* S)^2 + \lambda_{HS} H^\dagger H S^* S.$$



This leads to the 4 matrix given in the basis $(\nu_L, N_R^c, N_L, \chi^c)$ as

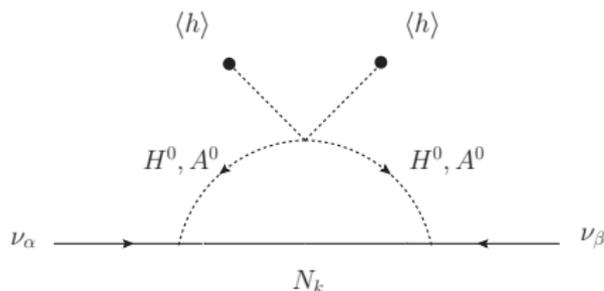
$$M = \begin{pmatrix} 0 & m_D^T & 0 & 0 \\ m_D & \epsilon_R & M & 0 \\ 0 & M^T & \epsilon_L & 0 \\ 0 & 0 & 0 & m_\chi \end{pmatrix},$$

Some Models: Motivation & Description

Schotogenic Model with Majorana DM: (with Nasri & Jeuid)

Here the SM is extended by an inert scalar doublet Φ and three singlet Majorana fermions $N_i \sim (1, 1, 0)$, $i = 1, 2, 3$.

$$\mathcal{L} \supset h_{ij} \bar{L}_i \epsilon \Phi N_j + \frac{1}{2} M_i \bar{N}_i^C N_i + h.c.,$$



$$(\mathcal{M}_\nu)_{\alpha\beta} = \sum_k \frac{h_{\alpha k} h_{\beta k} M_k}{16\pi^2} \left[\frac{m_{H^0}^2}{m_{H^0}^2 - M_k^2} \ln \frac{m_{H^0}^2}{M_k^2} - \frac{m_{A^0}^2}{m_{A^0}^2 - M_k^2} \ln \frac{m_{A^0}^2}{M_k^2} \right],$$

Neutrino Mass versus Experimental Constraints

The estimated elements of the neutrino mass matrix in each model should be matched by

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

where U is the Pontecorvo-Maki-Nakawaga-Sakata (PMNS) mixing matrix. However, we have so many constraints to confront such as:

- ▶ LFV processes $l_\alpha \rightarrow l_\beta + \gamma$ with branching ratio (KNT)

$$B(l_\alpha \rightarrow l_\beta + \gamma) \simeq \frac{\alpha v^4}{384\pi} \times \left\{ \frac{|f_{\alpha\tau} f_{\tau\beta}^*|^2}{M_S^4} + \frac{36(2n+1)^2}{M_T^4} \left| \sum_i g_{i\alpha}^* g_{i\beta} F_2(M_i^2/M_T^2) \right|^2 \right\}.$$

For the Scotogenic model: $f = 0$ and $n = 0$.

- ▶ Neutrino-less double-beta decay searches imply $(\mathcal{M}_\nu)_{ee} \lesssim 0.35$ eV.
- ▶ The Higgs decay $h \rightarrow \gamma\gamma$ due to new charged scalar in the KNT and Scotogenic, and the Higgs invisible decay in DRIS model.

Dark Matter

- ▶ In the KNT and Scotogenic models, the DM here is the lightest neutral member of the fermionic multiplets N_1 (or E_1^0 for $n=1,2,3$). While in DRIS, it is χ .
- ▶ There are many annihilation channels such as: $E_1^0 E_1^0 \rightarrow l_{\alpha} l_{\beta}$ and $E_1^0 E_1^0 \rightarrow WW$ for $n = 1..3$.
- ▶ The annihilation cross section for $E_1^0 E_1^0 \rightarrow l_{\alpha} l_{\beta}$ is given by

$$\sigma_{E_1^0 E_1^0 \rightarrow l_{\alpha} l_{\beta}} v_r \simeq \sum_{\alpha, \beta} |g_{1\alpha} g_{1\beta}^*|^2 \frac{M_{DM}^2 (M_S^4 + M_{DM}^4)}{48\pi (M_S^2 + M_{DM}^2)^4} v_r^2,$$

- ▶ and

$$\sigma_{E_1^0 E_1^0 \rightarrow WW} v_r = \frac{\pi \alpha_2^2}{M_{DM}^2} (a + b v_r^2),$$

with $(a, b) = (0, 0)$, $(\frac{37}{12}, \frac{17}{48})$, $(\frac{207}{20}, \frac{243}{28})$, $(\frac{174}{7}, \frac{263}{28})$ for $n = 0, 1, 2, 3$, respectively.

EW Phase Transition

In 1967, Sakharov criteria:

- B violation
- C CP violation
- Out-of-equilibrium

In the SM (KRS):

- B+L anomaly
- CKM matrix
- Strong first order Phase transition

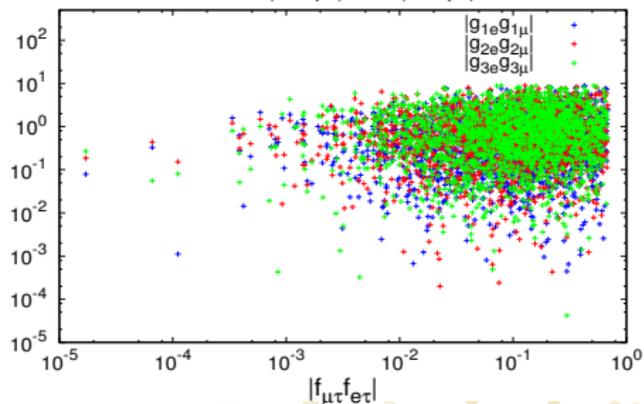
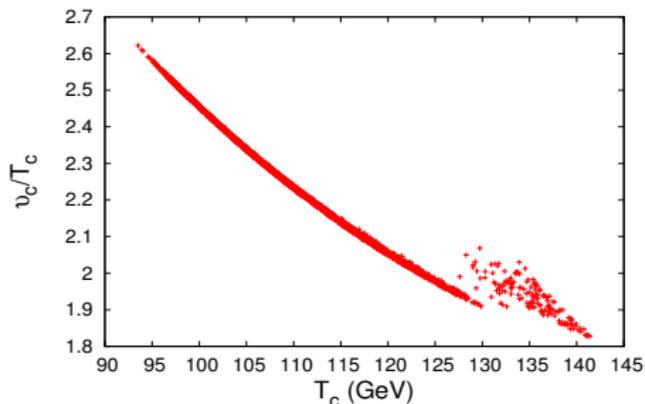
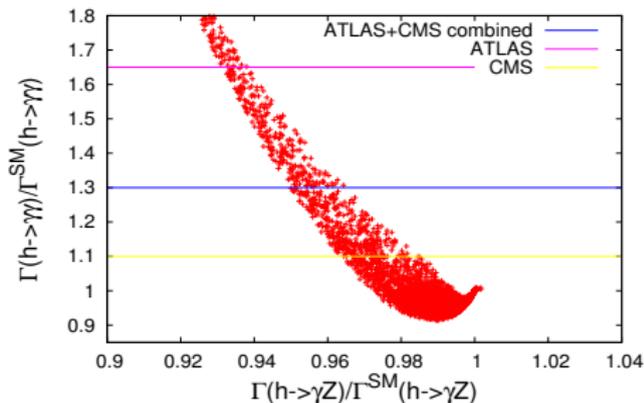
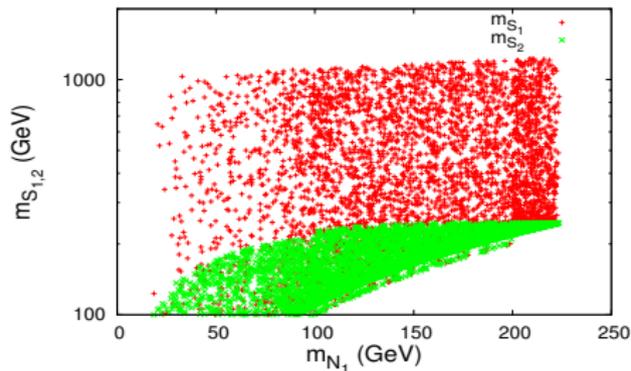
- ▶ In the SM, $v_c/T_c > 1$ implies m_h less than 45 GeV!!.
- ▶ Knowing that $v_c/T_c \sim 1/\lambda$, the quartic coupling can be relaxed to smaller value due to extra radiative contributions to the Higgs mass

$$\lambda = \frac{3m_h^2}{v^2} - \frac{3}{32\pi^2} \sum_{i=all} n_i \alpha_i^2 \log \frac{\mu_i^2 + \frac{1}{2}\alpha_i v^2}{m_h^2},$$

Then large masses of the scalar multiplet members $\mu_i^2 + \frac{1}{2}\alpha_i v^2$ can put λ to smaller values, which makes the EWPT strongly first order.

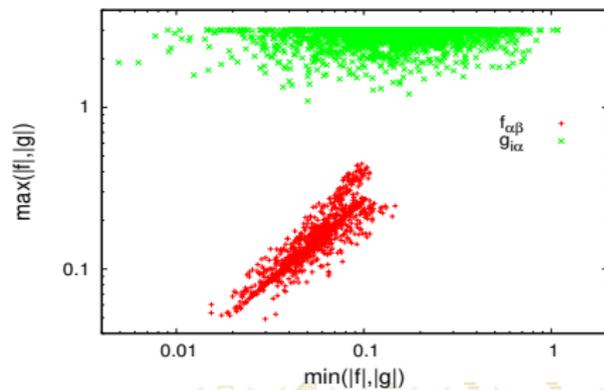
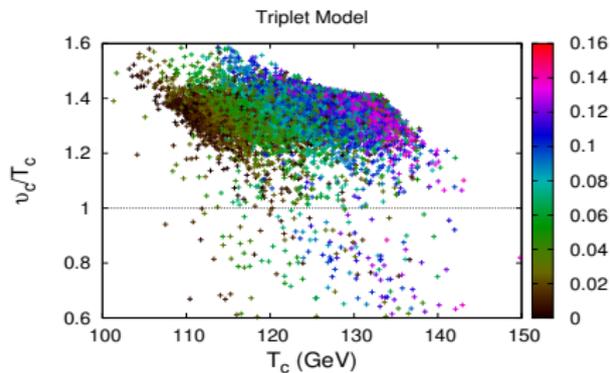
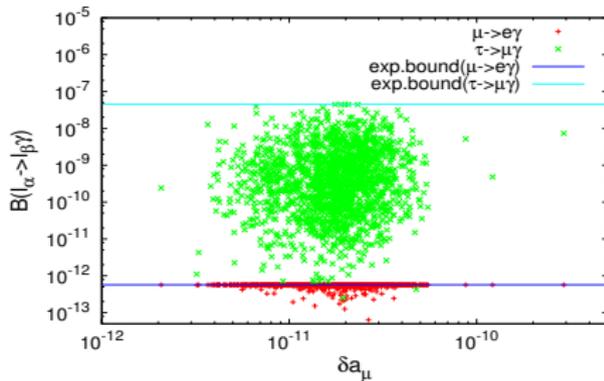
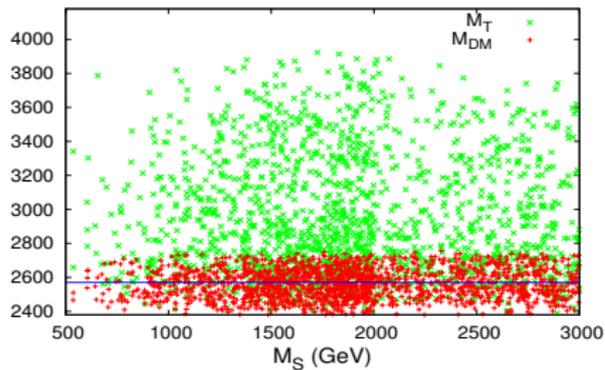
Numerical Results

KNT $n = 0$



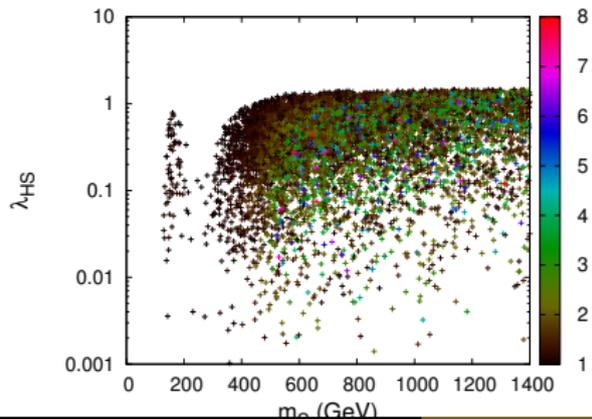
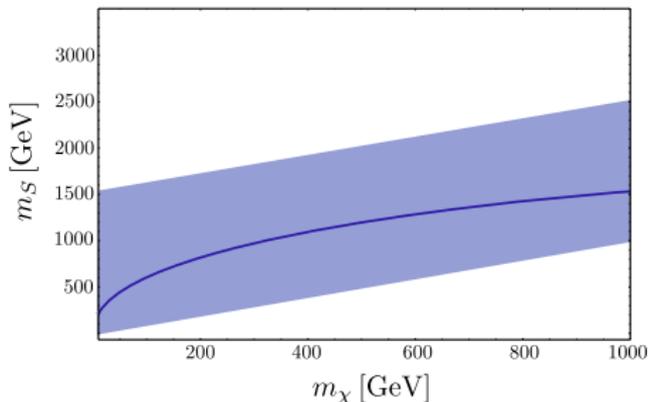
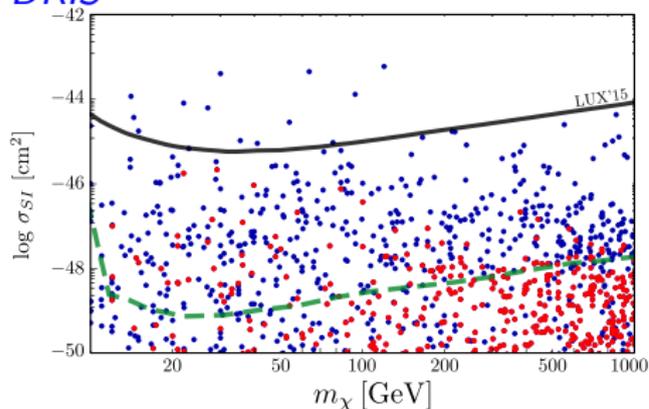
Numerical Results

KNT $n = 1$



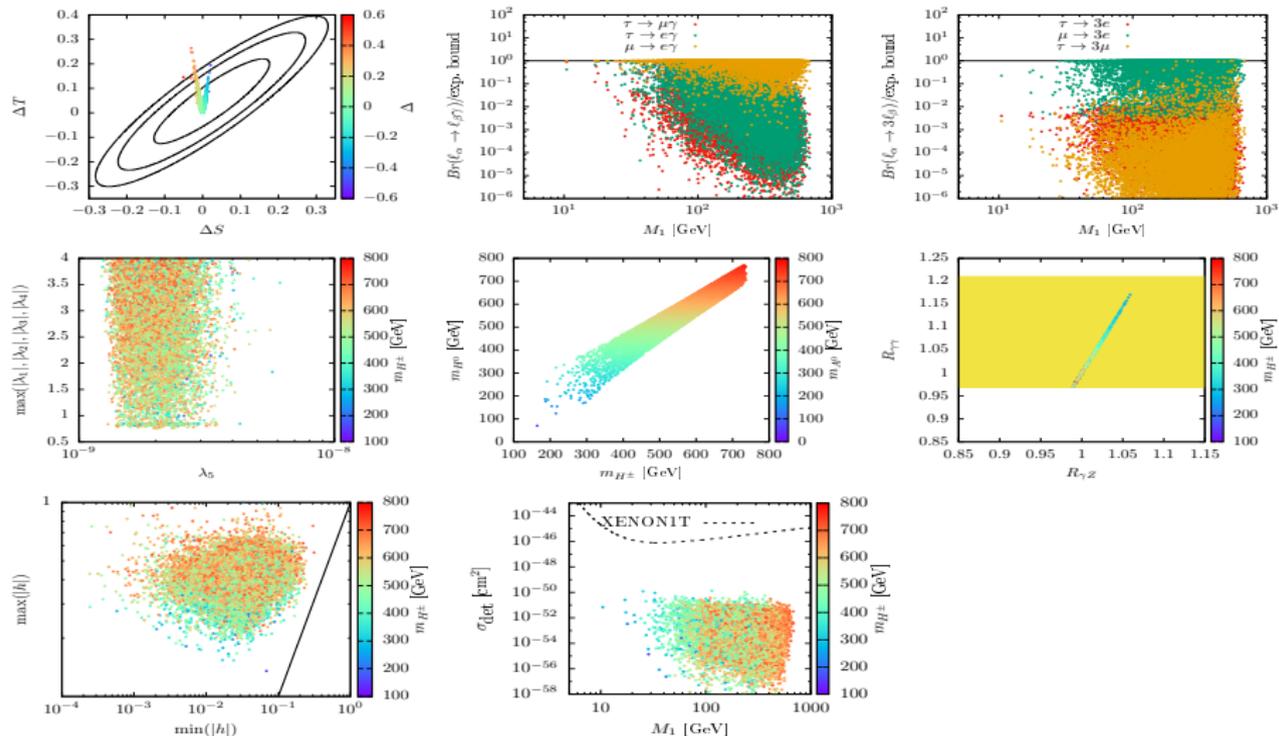
Numerical Results

DRIS



Numerical Results

Scotogenic



Collider Signatures

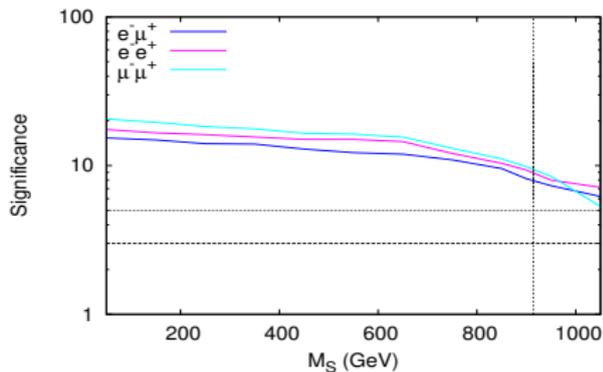
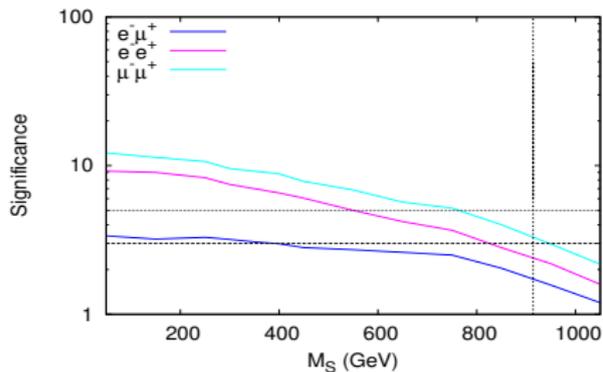
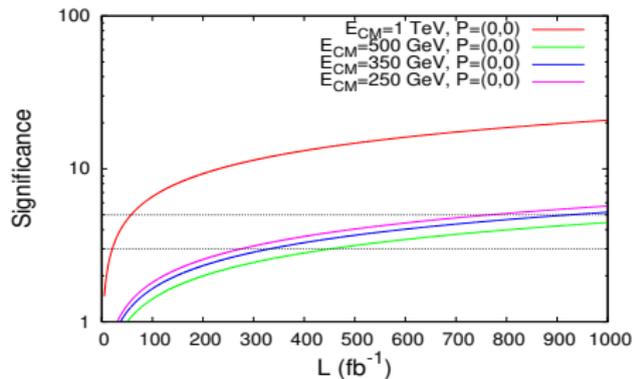
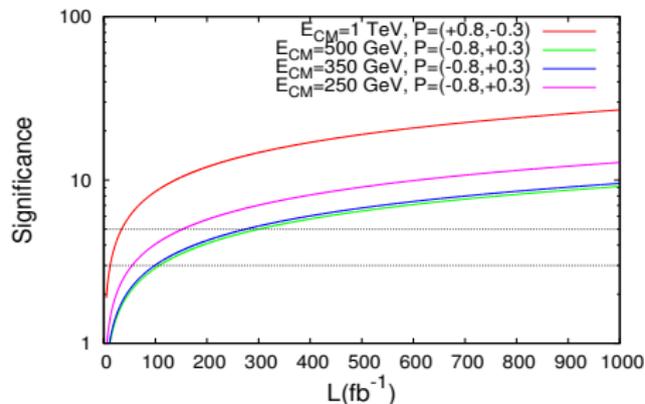
$$\text{KNT: } e^+e^- \rightarrow e^+\mu^- + E_{\text{miss}}$$

Here, there two sources of missing energy: $E_{\text{miss}} = N_i N_k$ and $E_{\text{miss}} = \nu\bar{\nu}$ where the SM final state $e^+\mu^- + \nu_e\bar{\nu}_\mu$ gets modified.

Using LanHEP/CalcHEP and after defining the cuts we get

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

Collider Signatures



- ▶ Our signal consists of requiring di-leptons plus missing energy which it is defined as

$$pp \rightarrow l_{\alpha}^{\pm} l_{\beta}^{\pm} + E_{miss} \quad (4)$$

where $l_{\alpha}^{\pm} l_{\beta}^{\pm} = \{e^{+} e^{-}, \mu^{+} \mu^{-}, e^{-} \mu^{+}\}$

- ▶ The SM background is defined as

$$pp \rightarrow W^{+} W^{-} \rightarrow l_{\alpha}^{\pm} l_{\beta}^{\pm} \nu_{\alpha} \nu_{\beta} \quad (5)$$

$$pp \rightarrow ZZ(\gamma Z) \rightarrow l_{\alpha}^{\pm} l_{\beta}^{\pm} \nu_{\alpha} \nu_{\beta} \quad (6)$$

- ▶ set a Benchmark parameter which satisfies LFV constraints.

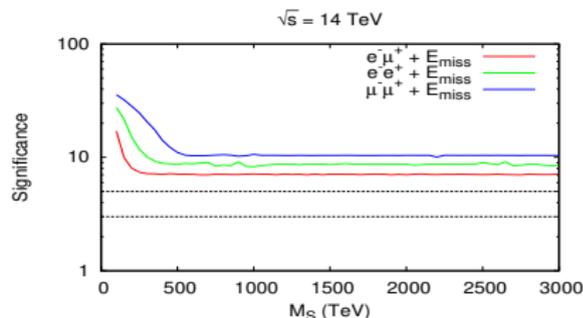
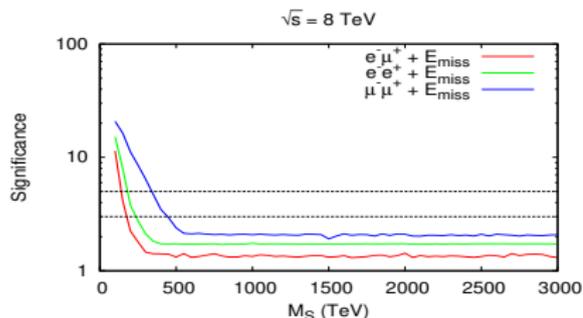
$$f_{e\mu} = -(4.97 + i1.91) \times 10^{-2}, \quad f_{e\tau} = 0.106 + i0.0859$$

$$f_{\mu\tau} = -(3.04 + i4.72) \times 10^{-6}, \quad M_S = 914.2 \text{ GeV}$$

Collider Signatures

- ▶ In order to optimize the signal significance, the event selection is performed in two steps:
 - ▶ The pre-selection : we use an accurate cut on M_{T2} ($M_{T2} > M_W$)
 - ▶ The final selection : deduce kinematic cuts

Process	cuts@8 TeV		cuts@14 TeV	
$e^- \mu^+ + E_{miss}$	$80 < p_T^{e^-} < 250$ $-1.56 < \eta_{e^-} < 2.99$	$80 < p_T^{\mu^+} < 270$ $-1.92 < \eta_{\mu^+} < 3$	$p_T^{e^-} > 180$ $1.1 < \eta_{e^-} < 2.89$	$p_T^{\mu^+} > 170$ $1.2 < \eta_{\mu^+} < 3.02$
$e^- e^+ + E_{miss}$	$25 < p_T^l < 120$ $-2.09 < \eta_l < 2.89$		$30 < p_T^{e^-} < 80$ $-2.8 < \eta_{e^-} < 2.95$	
$\mu^- \mu^+ + E_{miss}$	$30 < p_T^l < 155$ $-2.38 < \eta_l < 2.1$		$25 < p_T^{e^-} < 40$ $-0.13 < \eta_{e^-} < 3$	



Collider Signatures

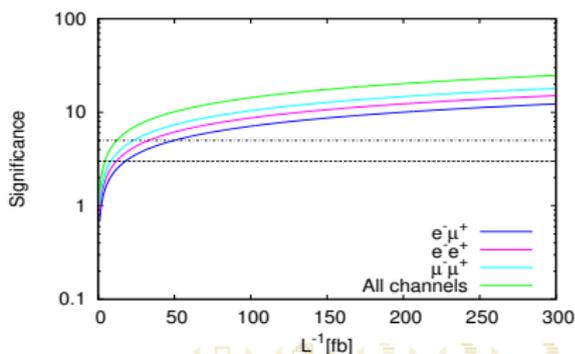
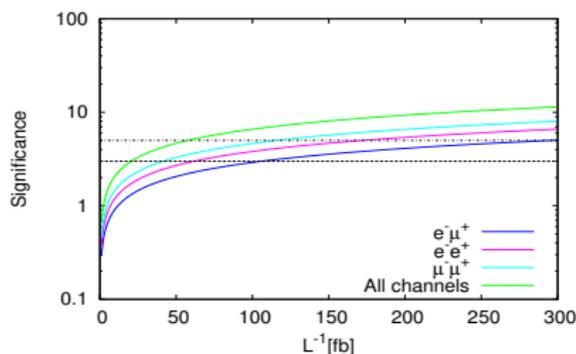
- In order to estimate the signal, the significance is given as (should be larger than 5σ)

$$S = \frac{N_{EX}}{\sqrt{N_{EX} + N_B}} \quad N_{EX} = N_M - N_B = L \times (\sigma_M - \sigma_B) \quad (7)$$

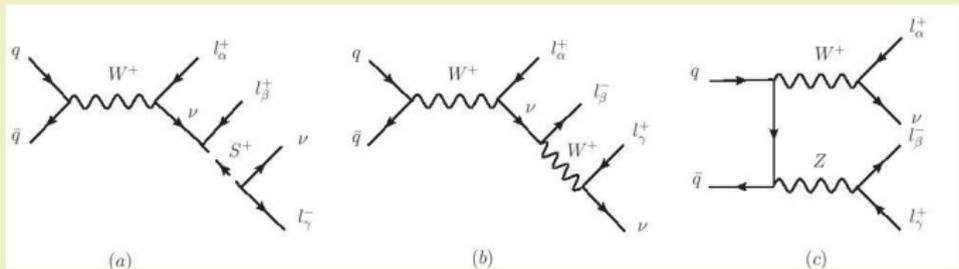
$$S \propto [2\text{Re}(\mathcal{M}_{SM}^\dagger \mathcal{M}_{non-SM}) + |\mathcal{M}_{non-SM}|^2] \propto |f_{\alpha\rho} f_{\beta\rho}|^2 \quad (8)$$

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

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



At the LHC, there is an interesting possibility to produce a singly charged scalar at the parton level process, accompanied by the irreducible SM background processes



Signal

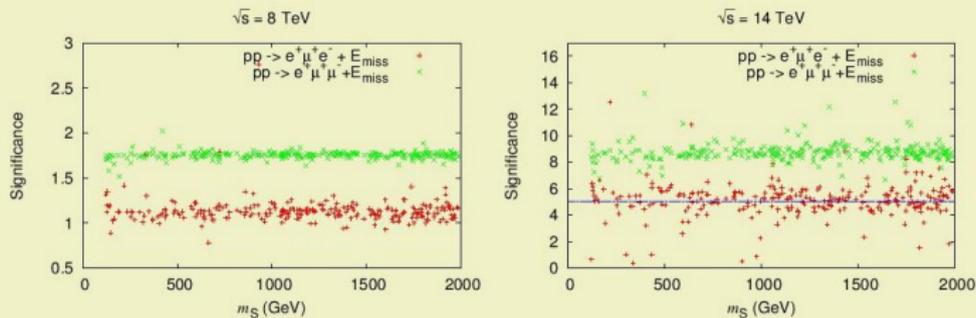
Vs

SM Background

- We have 9 contributions to this trilepton signal, three of them are background free
- CalcHEP is used to generate both the SM background events as well the events from processes due to the **FLV** interactions for $\sqrt{s} = 8, \text{ and } 14 \text{ TeV}$.
- The excess of events looked for after the selection cut is $N_{ex} = \mathcal{L}_{int} (\sigma_M - \sigma_B)$, Therefore the signal significance is given by

$$S = \frac{N_{ex}}{\sqrt{N_{ex} + N_B}} = \frac{N_{ex}}{\sqrt{N_M}}$$

The CMS collaboration presented a model-independent search for anomalous production of events with at least three isolated charged leptons using their data with $\mathcal{L}_{int} = 19.5 \text{ fb}^{-1}$ at $\sqrt{s} = 8 \text{ TeV}$.



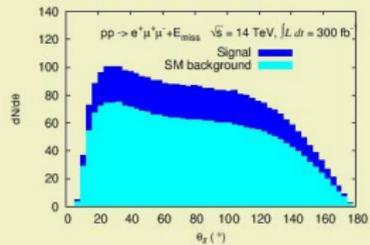
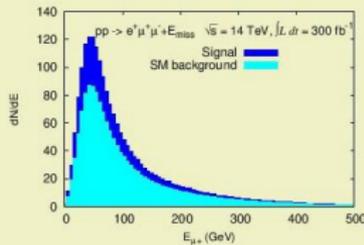
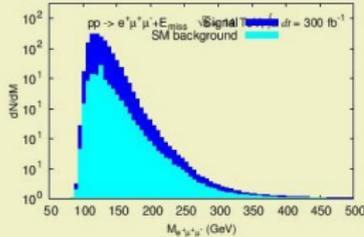
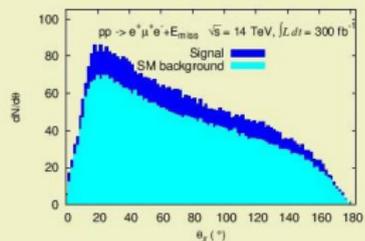
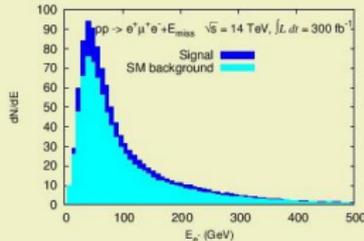
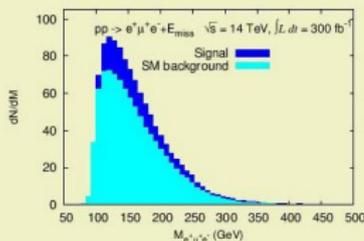
⇒ Any significant deviation from SM expectations at 8 TeV .

⇒ Two benchmark points selected from the allowed parameter space of the model

Point	$m_S(\text{GeV})$	$f_{e\mu}$	$f_{e\tau}$	$f_{\mu\tau}$
B_1	471.8	$-(9.863 + i8.774) \times 10^{-2}$	$-(6.354 + i2.162) \times 10^{-2}$	$(0.78 + i1.375) \times 10^{-2}$
B_2	1428.5	$(5.646 + i549.32) \times 10^{-3}$	$-(2.265 + i1.237) \times 10^{-1}$	$-(0.41 - i3.58) \times 10^{-2}$

- Due to the difficulty in identifying the tau lepton at the LHC, only the final state leptons $\ell = e, \mu$, is considered here, with \cancel{E}_T can be $\bar{\nu}_e, \bar{\nu}_\mu$ or $\bar{\nu}_\tau$.

$e^+\mu^+e^- + \cancel{E}_T @ 8 \text{ TeV}$	$e^+\mu^+e^- + \cancel{E}_T @ 14 \text{ TeV}$	$e^+\mu^+\mu^- + \cancel{E}_T @ 8 \text{ TeV}$	$e^+\mu^+\mu^- + \cancel{E}_T @ 14 \text{ TeV}$
$70 < M_{e^-e^+} < 110$	$70 < M_{e^-e^+} < 110$	$80 < M_{\mu^-\mu^+} < 100$	$80 < M_{\mu^-\mu^+} < 110$
$M_{e^+\mu^+} < 200$	$M_{e^+\mu^+} < 230$	$M_{e^+\mu^+} < 200$	$M_{e^+\mu^+} < 230$
$M_{e^-\nu} < 206$	$M_{e^-\nu} < 220$	$M_{\mu^-\nu} < 185$	$M_{\mu^-\nu} < 245$
$10 < p_T^\ell < 100$	$10 < p_T^\ell < 90$	$10 < p_T^\ell < 100$	$10 < p_T^\ell < 130$
$ \eta^\ell < 3$	$ \eta^\ell < 3$	$ \eta^\ell < 3$	$ \eta^\ell < 3$
$\cancel{E}_T < 100$	$\cancel{E}_T < 90$	$\cancel{E}_T < 90$	$\cancel{E}_T < 120$

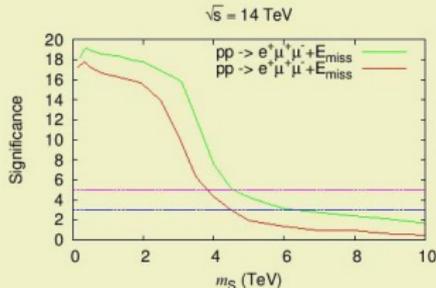
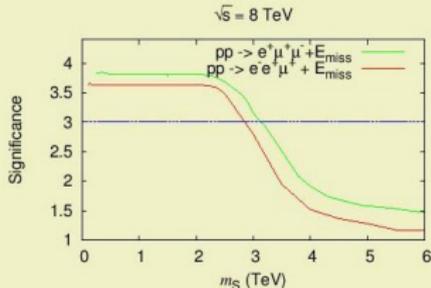


Process	Benchmark	$N_{20.3}$	$S_{20.3}$	N_{300}	S_{300}
$p, p \rightarrow e^+ \mu^+ e^- + \cancel{E}_T$	B_1	70.42	3.651	1689.6	17.363
	B_2	69.69	3.618	1470	15.289
$p, p \rightarrow e^+ \mu^+ \mu^- + \cancel{E}_T$	B_1	71.21	3.831	2066.7	19.210
	B_2	70.44	3.793	1974.9	18.983

Feynman diagrams that mediate the processes $pp \rightarrow l^+ l^+ l^- + \cancel{E}_T$ can be classified as SM and non-SM diagrams with amplitudes \mathcal{M}_{SM} and \mathcal{M}_S .

$$[N_{ex} = N_M - N_B] \propto [2 \operatorname{Re} (\mathcal{M}_{SM}^\dagger \mathcal{M}_S) + |\mathcal{M}_S|^2], \text{ where } |\mathcal{M}_S| \ll \ll.$$

The significance is directly proportional to $|f_{\alpha\rho} f_{\beta\rho}|^2$.

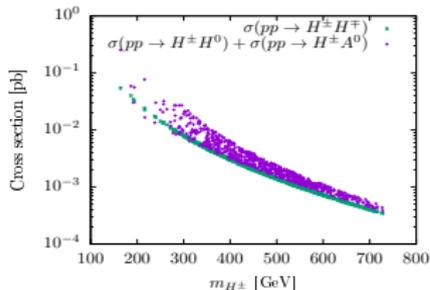
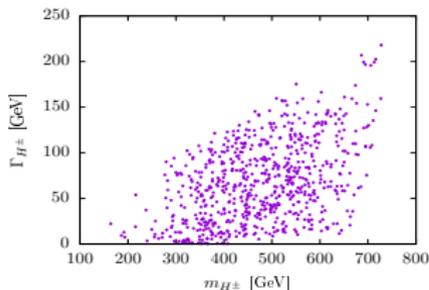


Collider Signatures

DIRS: is still dark at collider ... we do not expect too interesting signature at colliders.

Scotogenic: we have interesting signatures such as (in progress):

Process	Decay mode	signature
$pp, e^+e^- \rightarrow H^\pm H^\mp$	$H^\pm \rightarrow W^\pm H^0/A^0 \rightarrow q_1 \bar{q}_2 N_1 \nu_\ell, H^\mp \rightarrow W^\mp H^0/A^0 \rightarrow q_3 \bar{q}_4 N_1 \bar{\nu}_\ell$	4 jets + \vec{E}_T
	$H^\pm \rightarrow W^\pm H^0/A^0 \rightarrow \ell^\pm \nu_\ell N_1 \nu_\ell, H^\mp \rightarrow W^\mp H^0/A^0 \rightarrow q_3 \bar{q}_4 N_1 \bar{\nu}_\ell$	$1\ell + 2 \text{ jets} + \vec{E}_T$
	$H^\pm \rightarrow W^\pm H^0/A^0 \rightarrow \ell^\pm \nu_\ell N_1 \nu_\ell, H^\mp \rightarrow W^\mp H^0/A^0 \rightarrow \ell_2^\mp \bar{\nu}_\ell N_1 \nu_\ell$	$2\ell + \vec{E}_T$
	$H^\pm \rightarrow W^\pm H^0/A^0 \rightarrow \ell_1^\pm \nu_\ell N_1 \nu_\ell, H^\mp \rightarrow \ell_2^\mp N_1$	$2\ell + \vec{E}_T$
	$H^\pm \rightarrow W^\pm H^0/A^0 \rightarrow q_1 \bar{q}_2 N_1 \nu_\ell, H^\mp \rightarrow \ell^\mp N_1$	$1\ell + 2 \text{ jets} + \vec{E}_T$
$pp, e^+e^- \rightarrow H^\pm H^0/A^0$	$H^\pm \rightarrow W^\pm H^0/A^0 \rightarrow q_1 \bar{q}_2 N_1 \nu_\ell, H^0 \rightarrow N_1 \nu_\ell$	$1\ell + 2 \text{ jets} + \vec{E}_T$
	$H^\pm \rightarrow W^\pm H^0/A^0 \rightarrow \ell^\pm \nu_\ell N_1 \nu_\ell, H^0 \rightarrow N_1 \nu_\ell$	$1\ell + \vec{E}_T$
$pp, e^+e^- \rightarrow H^0 H^0$	$H^0 \rightarrow N_1 \nu_\ell$	$\vec{E}_T + \text{ISR (mono-jet, mono-}\gamma\text{)}$
$e^+e^- \rightarrow N_1 N_1 \gamma$	stable final state	$\vec{E}_T + \gamma$



Conclusion

These models

- ▶ explain small neutrino mass and mixing.
- ▶ provide a Majorana DM candidate at different mass ranges.
- ▶ are not in conflict with different experimental constraints such as LFV.
- ▶ could lead to a strong first order phase transition.
- ▶ provide interesting signatures at both leptonic and hadronic colliders.

Thank you for your attention.