Effective Majorana neutrino phenomenology

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Outline

The SM picture: massless neutrinos

- Leptons: $SU(2)_L$ doublet
  $L_i = \begin{pmatrix} \nu_i \\ \ell_i \end{pmatrix}_L$
- ℓ acquires a mass interacting with the Higgs v.e.v. after EWSB:
  $\langle\Phi\rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$
- Dirac mass: ℓ_R

$$-\mathcal{L}_{Yukawa} \supset Y_\ell^{ij}\overline{L^i}\Phi\ell_R^j \to \frac{Y_l^{ij}v}{\sqrt{2}}\ell_L^i\ell_R^j$$

- But...
- Neutinos change flavor as they propagate: they have masses $\sim 0.01eV$
- One has to go beyond the SM to get massive neutrinos.

One step beyond the SM : Weinberg operator

- SM as effective theory: non renormalizable operator (dim$=5$): $\mathcal{L}_{\nu SM} \supset -\frac{\lambda_{ij}}{2\Lambda} L^i L^j \Phi\Phi$
- Leads to neutrinos mass (after EWSB): $\mathcal{L}_{\nu SM} \supset -\frac{m_{ij}}{2}\nu_i\nu_j$ with $\frac{m_{ij}}{2} = \lambda_{ij}\frac{v^2}{\Lambda} \to$ If $\Lambda \gg v \to m_\nu \ll m_{fermions}$
- Lepton number violation (LNV)
- Only 3 renormalizable tree-level realizations: the most popular is sesaw mechanism Type I (Φ and L^i combine into $SU(2)_L$ scalar)
- Needs new "sterile" $SU(2)_L$ singlet neutrinos N_R:

$$\mathcal{L}_\nu = \mathcal{L}_{SM} - Y_{\alpha i}\overline{L^\alpha}\tilde{\Phi}N_{Ri} - \sum_{i,j=1}^{3}\frac{M_{N_{ij}}}{2}\overline{N_{iL}^c}N_{jR} + h.c.$$

Type I seesaw: neutrino mixing

$$\mathcal{L}_\nu = \mathcal{L}_{SM} - Y_{\alpha i}\overline{L^\alpha}\tilde{\Phi}N_{Ri} - \sum_{i,j=1}^{3}\frac{M_{N_{ij}}}{2}\overline{N^c_{iL}}N_{jR} + h.c.$$

- $\nu_{\ell L} = U_{\ell m}\nu_m + U_{\ell N}N$
- $\nu_L - \nu_m$ mixing $\rightarrow$ oscillation phenomena
- The $\nu_L - N$ mixings take values $U_{\ell N} \simeq \frac{m_D}{M_N} = \sqrt{\frac{m_\nu}{M_N}}$

- Light ν with $m_\nu = m_D M_N^{-1} m_D^T$.
- The Dirac mass (Yukawa) $m_D = Y\frac{v}{\sqrt{2}}$
- $m_\nu \simeq 0.01 eV \simeq Y^2 \frac{v^2}{2M_N} \rightarrow$ $Y \simeq 10^{-6}$ for $M_N \simeq 100 GeV$!!
- $U_{\ell N} \simeq \frac{m_D}{M_N} \lessapprox 10^{-5}\sqrt{\frac{100GeV}{M_N}}$

Type I seesaw: *N* decoupling

- The $\nu_L - N$ mixing $U_{\ell N}$ weighs the coupling between Majorana neutrinos and the standard bosons:

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} U_{\ell N} \overline{N}^c \gamma^\mu P_L l W_\mu^+ + h.c.$$

$$\mathcal{L}_Z = -\frac{g}{2c\theta_W} \overline{\nu_l} \gamma^\mu U_{\ell N} P_L N Z_\mu + h.c.$$

- The observation of LNV in these models depends only on the tiny $\nu_L - N$ mixing...

Outline

Effective approach [1]

- $SM+$ one heavy Majorana N, $m_N < \Lambda$ (not integrated out...)
- NP parameterized with a lagrangian constructed with effective operators inolving the N and the standard fields, preserving the $SU(2)_L \times U(1)_Y$ symmetry
- Low-energy limit of some unknown ultraviolet theory: suppressed by inverse powers of the new physics scale Λ:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{n=6}^{\infty} \frac{1}{\Lambda^{n-4}} \sum_{\mathcal{J}} \alpha_{\mathcal{J}} \mathcal{O}_{\mathcal{J}}^{(n)}$$

[1] F. del Aguila, S. Bar Shalom, A. Soni y J. Wudka. Phys. Lett. B 670, 399 (2009), 0806.0876

Effective approach [1]

- Neglect the $\nu_L - N$ mixing
- Dim 5 operator $\overline{N} N^c \Phi^\dagger \Phi$ reabsorbed into N mass m_N
- N pheno studied to constrain effective couplings $\alpha_{\mathcal{J}}$

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{n=6}^{\infty} \frac{1}{\Lambda^{n-4}} \sum_{\mathcal{J}} \alpha_{\mathcal{J}} \mathcal{O}_{\mathcal{J}}^{(n)}$$

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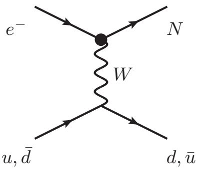
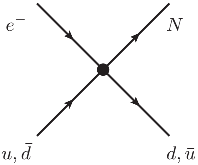
Effective operators

$\mathcal{O}_{Ne\phi}$



$\mathcal{O}_{duNe}$, $\mathcal{O}_{QuNL}$, $\mathcal{O}_{LNQd}$, $\mathcal{O}_{QNLd}$



The (dim = 6) operators are [1] (tree-level-generated):

$$\mathcal{O}^i_{LN\Phi} = (\Phi^\dagger \Phi)(\bar{L}_i N \tilde{\Phi})$$

$$\mathcal{O}^i_{NN\Phi} = i(\Phi^\dagger D_\mu \Phi)(\overline{N}\gamma^\mu N)$$

$$\mathcal{O}^i_{Ne\Phi} = i(\Phi^T \epsilon D_\mu \Phi)(\overline{N}\gamma^\mu e_i)$$

$$\mathcal{O}^i_{duNe} = (\bar{d}_i \gamma^\mu u_i)(\overline{N}\gamma_\mu e_i)$$

$$\mathcal{O}^i_{LNQd} = (\bar{L}_i N)\epsilon(\overline{Q}_i d_i)$$

$$\mathcal{O}^i_{QuNL} = (\overline{Q}_i u_i)(\overline{N} L_i)$$

$$\mathcal{O}^i_{QNLd} = (\overline{Q}_i N)\epsilon(\bar{L}_i d_i)$$

$$\mathcal{O}^i_{fNN} = (\bar{f}_i \gamma^\mu f_i)(\overline{N}\gamma_\mu N)$$

$$\mathcal{O}^i_{LNLe} = (\bar{L}_i N)\epsilon(\bar{L}_i e_i)$$

$$\mathcal{O}^i_{LN} = |\bar{L}_i N|^2$$

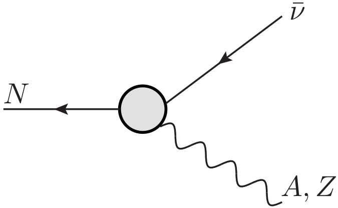
$$\mathcal{O}^i_{QN} = |\overline{Q}_i N|^2$$

[1] F. del Aguila, S. Bar Shalom, A. Soni y J. Wudka. Phys. Lett. B 670, 399 (2009), 0806.0876

Effective operators

- One loop generated: suppressed by loop factor $\frac{\alpha}{16\pi^2}$ [1]

$$\mathcal{O}^{(5)}_{NNB} = \overline{N}\sigma^{\mu\nu}N^c B_{\mu\nu}$$
$$\mathcal{O}_{NB} = (\overline{L}\sigma^{\mu\nu}N)\tilde{\Phi}B_{\mu\nu}$$
$$\mathcal{O}_{NW} = (\overline{L}\sigma^{\mu\nu}\tau^I N)\tilde{\Phi}W^I_{\mu\nu}$$
$$\mathcal{O}_{DN} = (\overline{L}D_\mu N)D^\mu\tilde{\Phi}$$
$$\mathcal{O}_{\overline{D}N} = (D_\mu\overline{L}N)D^\mu\tilde{\Phi}$$



[1] F. del Aguila, S. Bar Shalom, A. Soni y J. Wudka. Phys. Lett. B 670, 399 (2009), 0806.0876

Outline

Bounds on the couplings $\alpha_{\mathcal{J}}^{(i)}$

We exploit the existing bounds for the $U_{\ell N}$ mixings taking $U_{\ell N} \simeq \frac{\alpha v^2}{2\Lambda^2}$ for $\Lambda = 1\,TeV$

- Electroweak precision data (low energy LFV: $\mu \to e\gamma,\ m_N > m_W$)

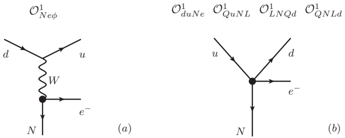
  $\alpha_{EWPD}^{bound} \lesssim 0.32$

- Belle and LHCb: $2\ GeV \lesssim m_N \lesssim 5\ GeV$

  $\alpha_{Belle}^{bound} \lesssim 0.3$

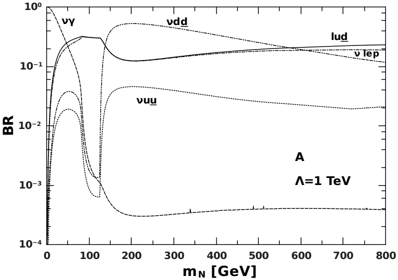
- Neutrinoless double beta decay (KamLAND-Zen)

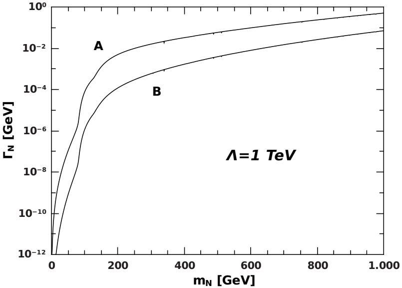
  $$\alpha_{0\nu\beta\beta}^{bound} \lesssim 3.2\times10^{-2}\left(\frac{m_N}{100\,GeV}\right)^{1/2}$$



N decay

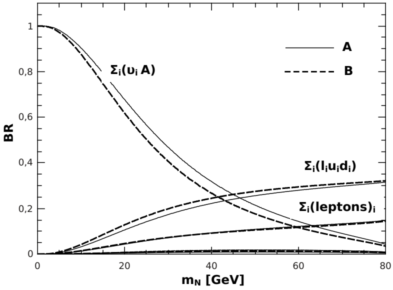
- We have studied the *N* decay channels for sub-EW masses $m_N < m_W$ [2] and generally for $m_N < 1\,TeV$ [3]





[2] L.Duarte, I. Romero, J. Peressutti and O.A.Sampayo, Phys. Rev. D 92, 091301 (2015) 1508.01588
[3] L.Duarte, J. Peressutti and O.A.Sampayo, Eur. Phys. J. C 76, 453 (2016) 1603.08052

N decay: $N \to \nu\gamma$ dominant channel [2] [3]



$$\frac{\Gamma^{(N\to\nu(\bar{\nu})\gamma)}}{\Gamma^{(N\to l^+\bar{u}d)}} \to \frac{2}{15\pi}\left(\frac{v}{m_N}\right)^2 (c_W + s_W)^2$$

- *N* could be discovered in the LHC with displaced vertices and non-pointing photon techniques: long-lived-neutral particle with measurable decay length

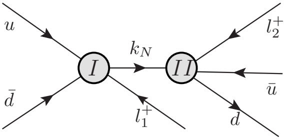
$$\vec{l}_N = \frac{\vec{k}_N}{|\vec{k}_N|}\tau_N\beta_N = \frac{\vec{k}_N}{|\vec{k}_N|}\frac{\left((E_N/m_N)^2 - 1\right)^{1/2}}{\Gamma_N}$$

[2] L.Duarte, I. Romero, J. Peressutti and O.A.Sampayo, Phys. Rev. D 92, 091301 (2015) 1508.01588
[3] L.Duarte, J. Peressutti and O.A.Sampayo, Eur. Phys. J. C 76, 453 (2016) 1603.08052

Not-that-heavy Majorana neutrino signals at the LHC [4]

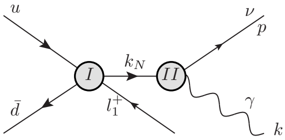
We study the ss-dilepton and neutrino plus photon processes:

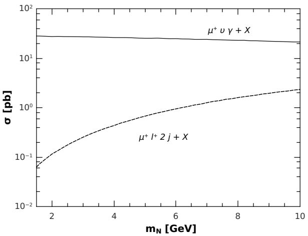
- $pp \to l_i^+ l_j^+ + 2\ jets$ (LNV $\Delta L = 2$)



- Tested at LHC for $m_N >> 100 GeV$ [5]
  Complementary study: few-GeV m_N region

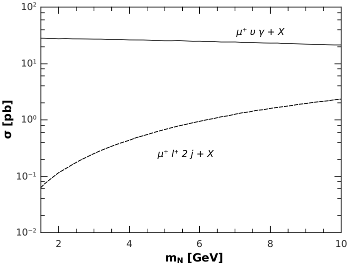
- $pp \to l_i^+ \nu \gamma$





[4] L.Duarte, J.Peresutti and O.A. Sampayo (2016), 1610.XXXXX
[5] ATLAS 1108.0366, 1203.5420

Not-that-heavy Majorana neutrino signals at the LHC [4]



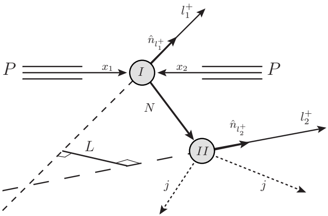
- For the few-GeV m_N region the $pp \to l_i^+ \nu\gamma$ channel dominates
- To see LNV we take $\alpha_{1-loop} = 0$, and focus on vectorial and scalar operator effects

[4] L.Duarte, J.Peresutti and O.A. Sampayo (2016), 1610.XXXXX

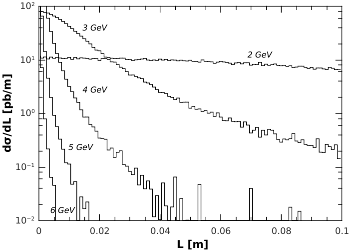
$pp \to l_i^+ l_j^+ + 2$ *jets* channel [4]

Exploit the vertex displacement...

- For $m_N \sim$ few-GeV: background from b leptonic decays $\to$ cuts in p_T affect signal



- Cut in $L^{l^+l^+}$: distance between both lepton tracks

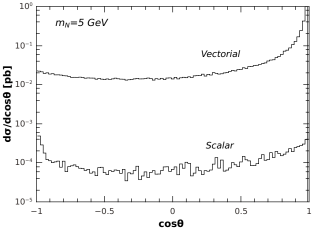


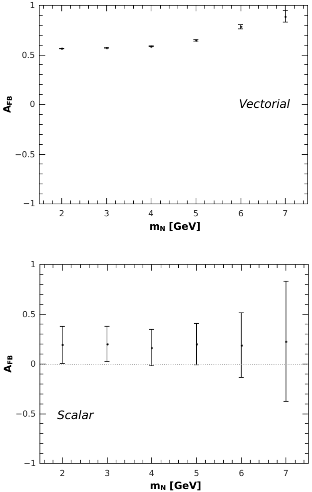
Set $L_{min}^{l^+l^+} > 1mm$

[4] L.Duarte, J.Peresutti and O.A. Sampayo (2016), 1610.XXXXX

$pp \to l_i^+ l_j^+ + 2$ *jets* channel [4]

- Disentangle vectorial (α_W, α_{V_0}) and scalar ($\alpha_{S_{1,2,3}}$) operator's contributions:





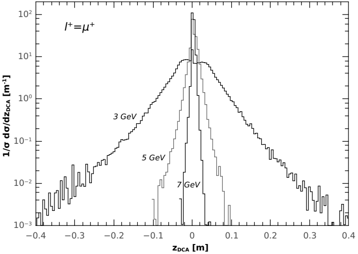
- $$A_{FB}^{l^+l^+} = \frac{N_+ - N_-}{N_+ + N_-}, \quad \Delta A_{FB}^{l^+l^+} = \sqrt{\frac{1-(A_{FB}^{l^+l^+})^2}{N_+ + N_-}}$$

[4] L.Duarte, J.Peresutti and O.A. Sampayo (2016), 1610.XXXXX

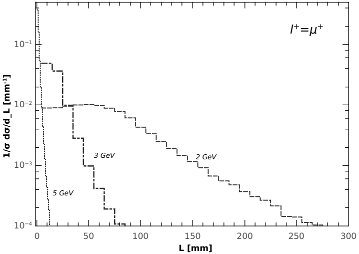
$pp \to l_i^+ \nu\gamma$ channel [4]

Exploit the vertex displacement...

- Non-pointing photon distance of closest approach to the beamline: z_{DCA} [6]



- Cut in $L^{l^+\gamma}$: distance between the prompt lepton and displaced photon tracks



[4] L.Duarte, J.Peresutti and O.A. Sampayo (2016), 1610.XXXXX
[6] ATLAS: 1409.5542, 1304.6310

Outline

Summary

- Take alternative to Seesaw Type I approach: effective theory with heavy sterile *N*, neglecting $\nu_L - N$ mixings:
- Effective lagrangian with $SU(2)_L xU(1)_Y$ symmetry
- Studied the *N* decay width and branching ratios
- Found interesting channel $N \to \nu\gamma$
- Currently studying possible *N* phenomenology in the *LHC*: exploit vertex dispacement for low m_N

Thank you,

and the

FLASY 2016 organizers.