Reconstructing the mixing angles of a Pseudo-Goldstone sterile neutrino

Stéphane Lavignac (IPhT Saclay)

- a non-standard production mechanism for heavy sterile neutrinos at colliders
- an explicit model: sterile neutrino as the supersymmetric partner of a pseudo-Goldstone boson
- sterile neutrino production and (displaced) decay
- reconstruction of the active-sterile mixing angles

based on JHEP 01 (2021) 151 [arXiv:2010.00608] with Anibal Medina
(+ work in progress with A. Medina, N. Mileo and S. Tanco)

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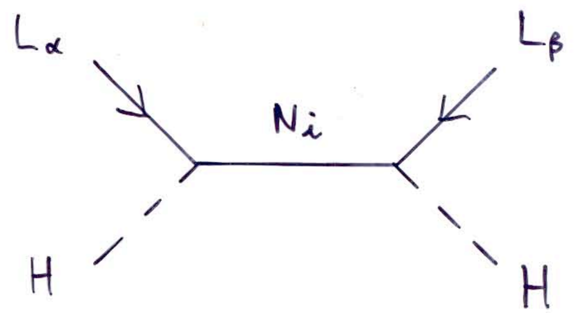
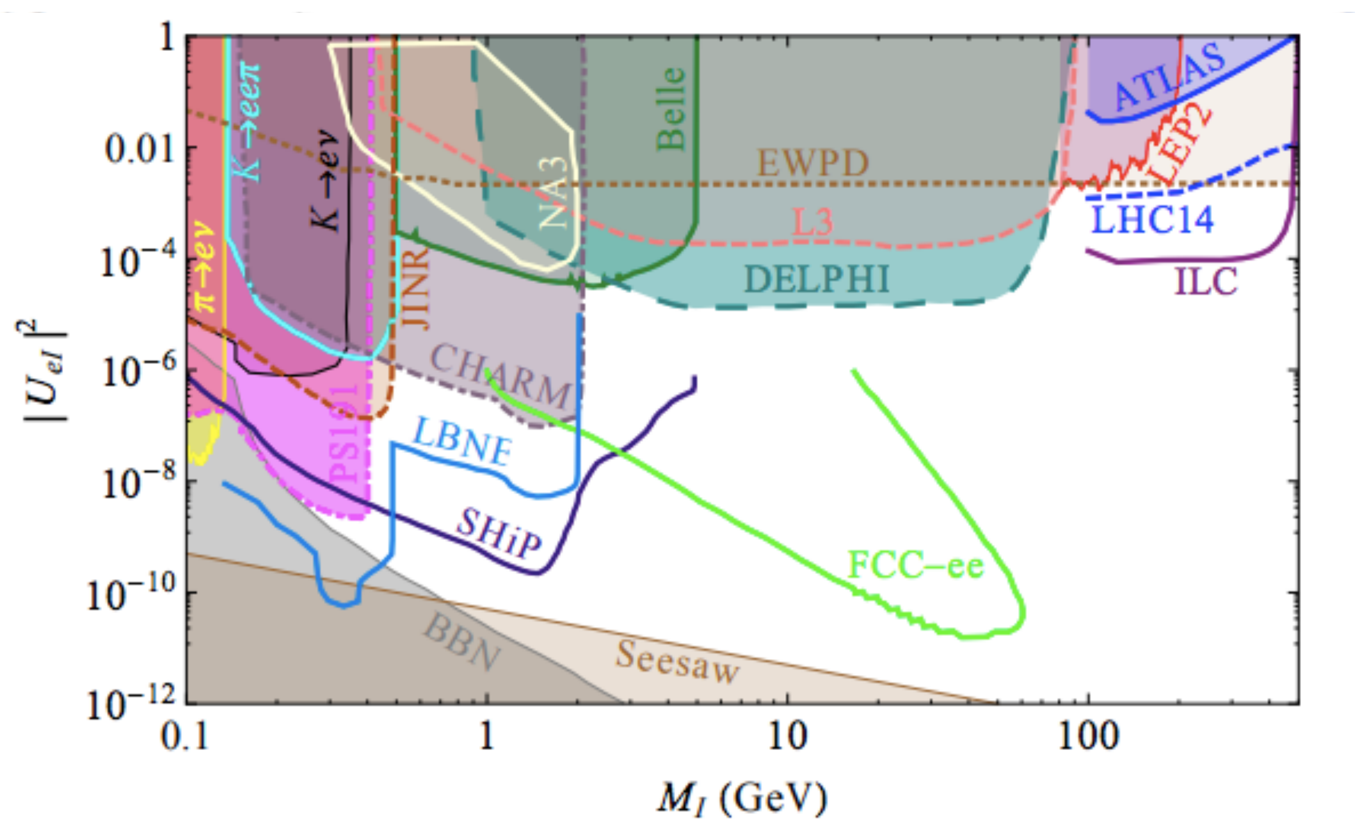
Introduction

Heavy (Majorana) sterile neutrinos are a generic prediction of the seesaw mechanism – super-heavy in the standard (GUT-inspired) picture



$$\Longrightarrow \qquad m_\nu \sim \frac{y^2 v^2}{M_R}$$

However, no model-independent prediction for their masses. Some sterile neutrinos could be much lighter, in the GeV-TeV range, and accessible at the LHC (can be natural in scenarios like the inverse seesaw)

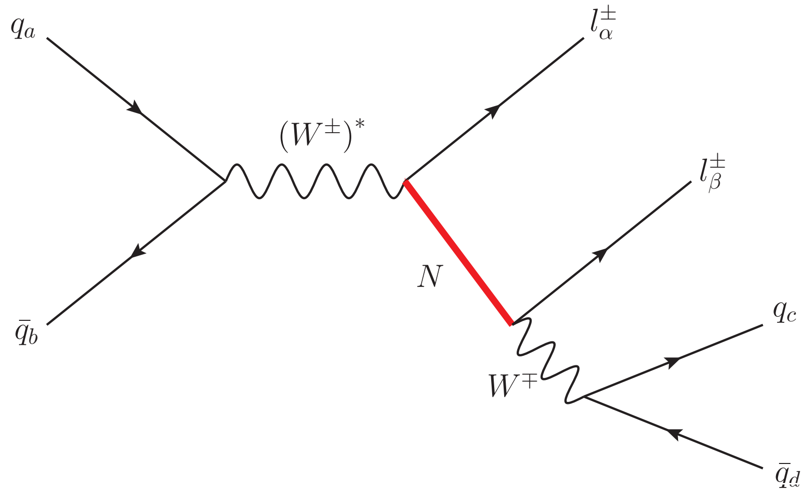


already constrained by
a number of experiments

U_{eI} = mixing of N_I with ν_e

[SHiP physics case, 1504.04855]

Collider searches rely on the production of the sterile neutrino through its mixing with the active SM neutrinos



the active-sterile mixing can be measured directly, but the production cross section is suppressed by its square

(searches for SS dileptons at the LHC)

Best current limit from DELPHI (from $e^+e^- \to Z \to N\bar{\nu}_i \,/\, \bar{N}\nu_i$)

in the range $5\,\mathrm{GeV} \lesssim m_N \lesssim 60\,\mathrm{GeV}$: $|V_{N\alpha}|^2 \lesssim 2\times 10^{-5} \quad (\alpha = e, \mu, \tau)$

Consider an alternative scenario in which N is produced in the decay of an EW-produced heavier particle:

$$X \to N + \mathrm{SM} \qquad\qquad N \to \nu + f\bar{f} \quad \mathrm{or} \quad \ell + f\bar{f'}$$

→ production of N unsuppressed by mixing with SM neutrinos
→ mixing angle enters N decays (⇒ possibility of measuring the active-sterile mixing angles if displaced decays)

Explicit realization of this mechanism: sterile neutrino as the supersymmetric partner of a pseudo-Goldstone boson (originally proposed for light sterile neutrinos by Chun, Joshipura, Smirnov '95 - Chun '99)

Sterile neutrino as a « pseudo-Goldstone fermion »

The model: supersymmetric extension of the SM with a global U(1) symmetry spontaneously broken at a scale $f \gg M_W$

Also small explicit breaking ⇒ pseudo-Goldstone boson

Only Higgs and leptons (with generation-independent and vector-like couplings to avoid FCNCs and astrophysical constraints) charged under the U(1)

$$l_i = -e_i \equiv l\,, \quad h_d\,, \quad h_u \qquad\qquad l, h_d > 0\,, \;\; h_u = 0$$

$l, h_d > 0$ ⇒ down-type Yukawa couplings and mu-term not allowed by U(1) ⇒ must be generated by higher-dimensional operators (à la Froggatt-Nielsen, but no explanation of the mass hierarchies)

$$W = \kappa_0\, H_u H_d \Phi \left(\frac{\Phi}{M}\right)^{h_d-1} + \kappa_i\, H_u L_i \Phi \left(\frac{\Phi}{M}\right)^{l-1} - y^e_{ij}\, L_i \bar{e}_j H_d \left(\frac{\Phi}{M}\right)^{h_d} - y^d_{ij}\, Q_i \bar{d}_j H_d \left(\frac{\Phi}{M}\right)^{h_d}$$
$$+ \lambda^u_{ij}\, Q_i \bar{u}_j H_u + \frac{1}{2} y_{ijk}\, L_i L_j \bar{e}_k \left(\frac{\Phi}{M}\right)^{l} + y'_{ijk}\, L_i Q_j \bar{d}_k \left(\frac{\Phi}{M}\right)^{l}$$

U(1) charge of Φ = -1 $\qquad \langle\Phi\rangle = f \qquad \dfrac{\langle\Phi\rangle}{M} = \dfrac{f}{M} \equiv \epsilon$

R-parity not imposed, but baryon parity assumed

In the EFT below f, we are left with $(\Phi' = \Phi - f)$

$$W = \mu_0\, H_u H_d + \mu_i\, H_u L_i + \lambda_0\, H_u H_d \Phi' + \lambda_i\, H_u L_i \Phi' + \ldots$$

$$\mu_0 \simeq \kappa_0 M \epsilon^{h_d}\,, \quad \mu_i \sim \frac{\kappa_i}{\kappa_0}\, \epsilon^{l-h_d}\, \mu_0\,, \quad \lambda_0 \simeq h_d\, \frac{\mu_0}{f}\,, \quad \lambda_i \sim \frac{\kappa_i}{\kappa_0}\, \epsilon^{l-h_d}\, \lambda_0$$

$\mu_i \ll \mu_0$ and $\lambda_i \ll \lambda_0$ ensured by U(1) symmetry [suppression factor ϵ^{l-h_d}], which also suppresses trilinear R-parity violating couplings

$\Phi' = \frac{s + ia}{\sqrt{2}} + \sqrt{2}\,\theta\chi + \theta^2 F$ contains the pseudo-Goldstone boson a and its partners s (assumed to get a large mass from Supersymmetry breaking) and χ (the pseudo-Goldstone fermion, whose mass also predominantly comes from Susy breaking) $\Rightarrow m_a \ll m_\chi \ll m_s$ with $10\,\mathrm{GeV} \lesssim m_\chi \lesssim 100\,\mathrm{GeV}$

The Lagrangian contains the following fermion bilinear terms:

$$-\,\mu_0\, \tilde{h}^0_u \tilde{h}^0_d - \mu_i\, \tilde{h}^0_u \nu_i - \lambda_0 v_u\, \tilde{h}^0_d \chi - \lambda_0 v_d\, \tilde{h}^0_u \chi - \lambda_i v_u\, \nu_i \chi + \text{h.c.}$$

$\Rightarrow\ \nu_i \,/\, \chi \,/\, \tilde{h}^0_{u,d}$ mixing, suppressed by $\frac{\mu_i}{\mu_0}\ (\nu_i/\tilde{h}^0)$, $\lambda_0 \sim \frac{\mu_0}{f}\ (\chi/\tilde{h}^0)$ and $\lambda_i\ (\nu_i/\chi)$

[also chargino / charged lepton mixing, but too small to be relevant]

Effect of the $\nu_i \,/\, \chi \,/\, \tilde{h}^0_{u,d}$ mixing

→ two SM neutrinos massive at tree level (also 1-loop contributions from the trilinear R-parity violating couplings)

→ interactions between the EW gauge bosons, neutralinos/charginos and the sterile neutrino (N from now on)

$$Z \tilde{\chi}^0_{1,2} N\,, \quad W^{\pm} \tilde{\chi}^{\mp}_1 N\,, \quad Z N \nu_i\,, \quad W^{\pm} N l^{\mp}_i$$

(we assume $\mu \ll M_1, M_2$ ⇒ bino and wino decoupled ⇒ the lightest chargino and neutralinos are mostly higgsinos: $\tilde{\chi}^0_{1,2} \approx (\tilde{h}^0_u, \tilde{h}^0_d)$ and $\tilde{\chi}^{\pm}_1 \approx \tilde{h}^{\pm}$)

⇒ N produced in decays of neutralinos and charginos

$$\tilde{\chi}^0_{1,2} \to Z + N\,, \qquad \tilde{\chi}^{\pm}_1 \to W^{\pm} + N$$

then decays through its mixing with active neutrinos, via an EW gauge boson

$$N \simeq \chi + \sum_\alpha V_{N\alpha}\, \nu_\alpha \quad \Longrightarrow \quad \begin{cases} N \to \ell^{\pm}_\alpha W^{\mp(*)} \to \ell_\alpha f \overline{f'} \\ N \to \nu_\alpha Z^{(*)} \to \nu_\alpha f \overline{f} \end{cases}$$

Sterile neutrino production and decay

Neglecting contributions to neutrino masses beyond $\nu_i \,/\, \chi \,/\, \tilde{h}^0_{u,d}$ mixing, the measured neutrino oscillation parameters fix most model parameters
$\Rightarrow$ left with $\mu, M_1, M_2, \tan\beta, m_N, f$ and a 2x2 complex orthogonal matrix R (= 1 complex parameter) [reminiscent of the Casas-Ibarra parametrization]

➞ active-sterile mixing angles (normal mass ordering)

$$V_{N\alpha} \simeq R_{11}\sqrt{\frac{m_3}{m_N}}\,U^*_{\alpha 3} + R_{12}\sqrt{\frac{m_2}{m_N}}\,U^*_{\alpha 2} \qquad (R_{11})^2 + (R_{12})^2 = 1$$

➞ other relevant mixing angles

$$V_{\tilde{\chi}^0_1 N},\, V_{\tilde{\chi}^0_2 N} \sim \frac{v}{f}$$

$$V_{\tilde{\chi}^0_1 \alpha},\, iV_{\tilde{\chi}^0_2 \alpha} \simeq R_{21}\sqrt{\frac{m_3}{M_{\rm eff}}}\,U^*_{\alpha 3} + R_{22}\sqrt{\frac{m_2}{M_{\rm eff}}}\,U^*_{\alpha 2} \qquad (R_{21})^2 + (R_{22})^2 = 1$$

all suppressed by small parameters

$$M_{\rm eff} \equiv \frac{2(M_1 c_W^2 + M_2 s_W^2) m_Z^2 \cos^2\beta}{M_1 M_2}$$

Benchmark point: $\mu = 500\,\text{GeV},\ M_1 = 1\,\text{TeV},\ M_2 = 2\,\text{TeV},\ \tan\beta = 10$

$m_N = 110\,\text{GeV},\ f = 15.1\,\text{TeV},\ R = \mathbf{1}$ ("maximal mixing")

$$m_{\nu_i} \ll m_N = 110\,\text{GeV} \ll m_{\tilde{\chi}_1^\pm} \simeq m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\chi}_2^0} \simeq 500\,\text{GeV}$$

V_{Ne}	$V_{N\mu}$	$V_{N\tau}$	$\lvert V_{\tilde{\chi}_1^0 N}\rvert$	$\lvert V_{\tilde{\chi}_2^0 N}\rvert$	$\lvert V_{\tilde{\chi}_{1,2}^0 \alpha}\rvert$
1.0×10^{-7}	5.0×10^{-7}	4.4×10^{-7}	0.0072	0.0095	$(4.5 - 6.2) \times 10^{-6}$

[the values of $\mu_\alpha/\mu,\ \lambda_\alpha/\lambda_0,\ \lambda_0$ needed to reproduce neutrino data correspond to the choice $\epsilon = 0.1,\ \ell = 6,\ h_d = 1$]

Dominant decay modes of the higgsino-like fermions (prompt decays)

$$\tilde{\chi}_{1,2}^0 \to Z + N\,, \qquad \tilde{\chi}_1^\pm \to W^\pm + N$$

The other decay modes are suppressed by small mixing angles (e.g. $\tilde{\chi}_{1,2}^0 \to Z + \nu_i$), phase space (e.g. $\tilde{\chi}_2^0 \to \bar{f} f \tilde{\chi}_1^0$) or 1/f (e.g. $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + a$)

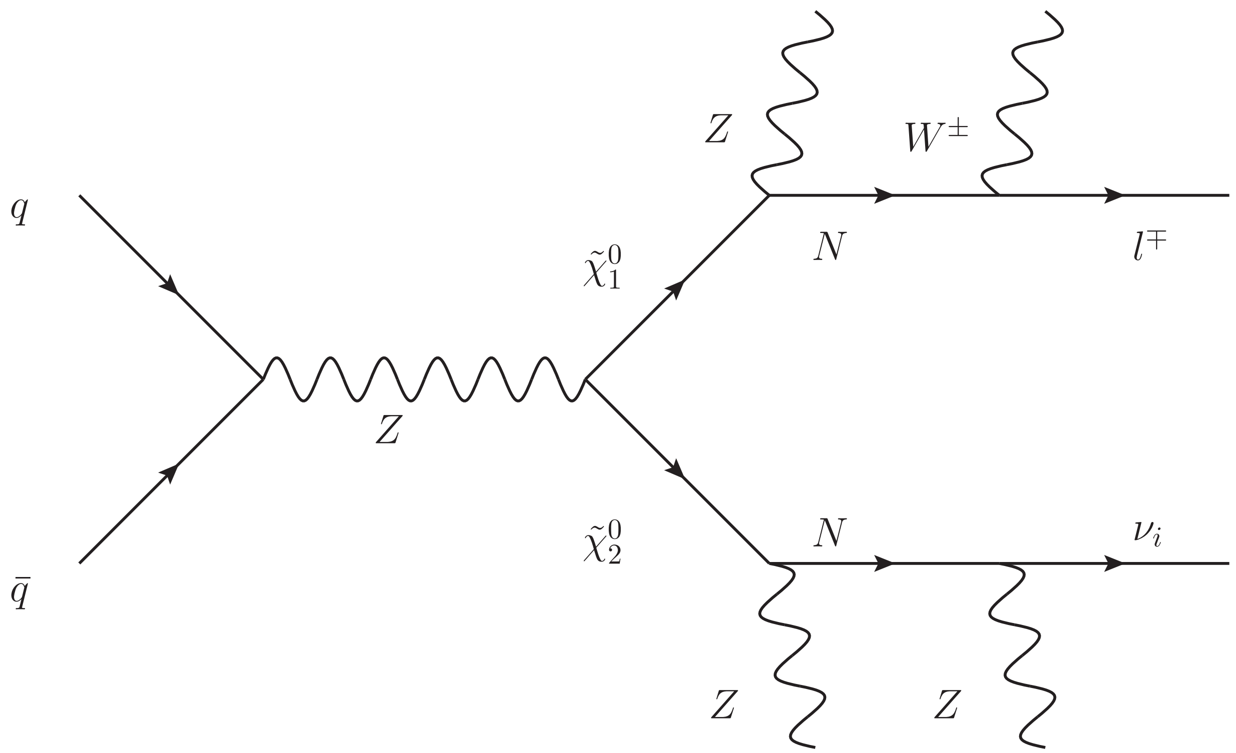
$\Rightarrow$ pair-produced $\tilde{\chi}_1^0\tilde{\chi}_2^0,\ \tilde{\chi}_{1,2}^0\tilde{\chi}_1^\pm,\ \tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ (with cross sections of order 10 fb at $\sqrt{s} = 14\,\text{TeV}$ for $\mu = 500\,\text{GeV}$) will decay with a BR close to 100% to $ZZN\bar{N},\ ZW^\pm N\bar{N},\ W^\pm W^\mp N\bar{N}$ (possibility to trigger on the Z and W decay products)

The sterile neutrinos will subsequently decay, via a W or Z boson, through their mixing with the SM neutrinos:

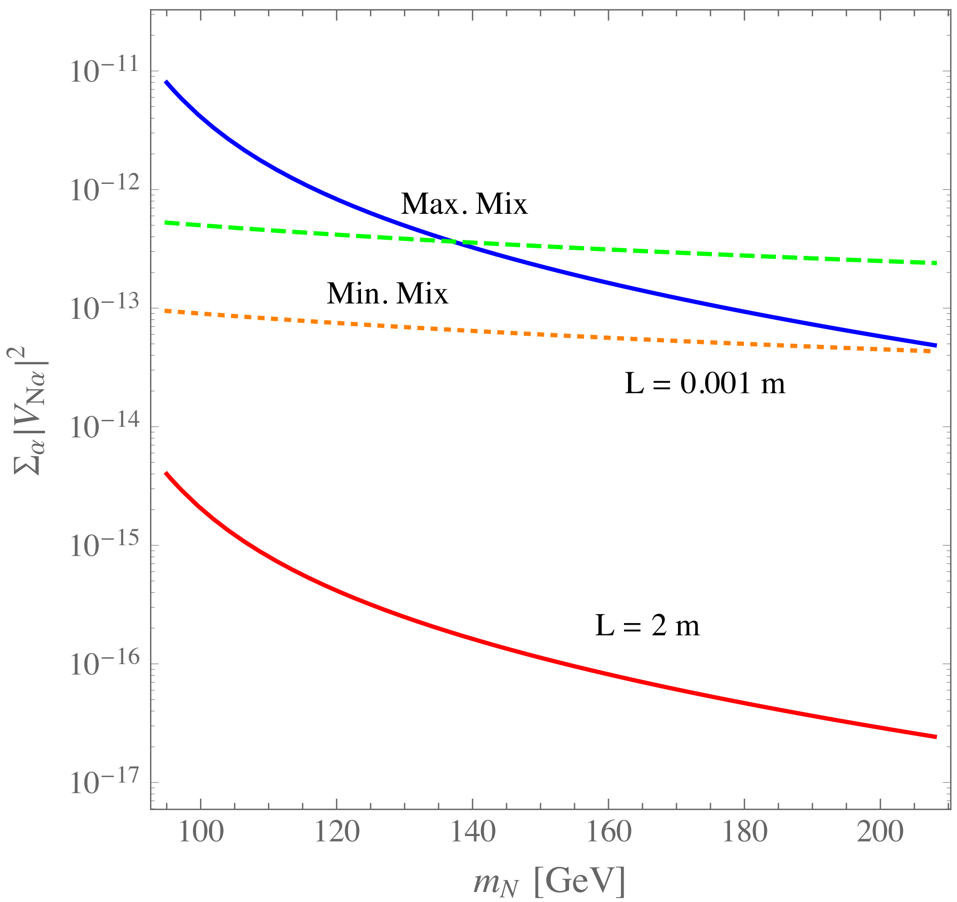
$$N \to l^{\pm} W^{\mp} \to l^{\pm} jj \quad \text{or} \quad l^{\pm} l'^{\mp} \nu_{l'}$$

$$N \to \nu Z \to \nu jj \quad \text{or} \quad l^{\pm} l^{\mp} \nu_{l'} \quad \text{or} \quad \nu \bar{\nu} \nu$$

Since the mixing is small, $V_{N\alpha} = \mathcal{O}(10^{-6})$, N decays will give rise to displaced vertices



SL & A. Medina, arXiv:2010.00608



For the benchmark point, 75% of the N's decay between 1 mm and 2 m

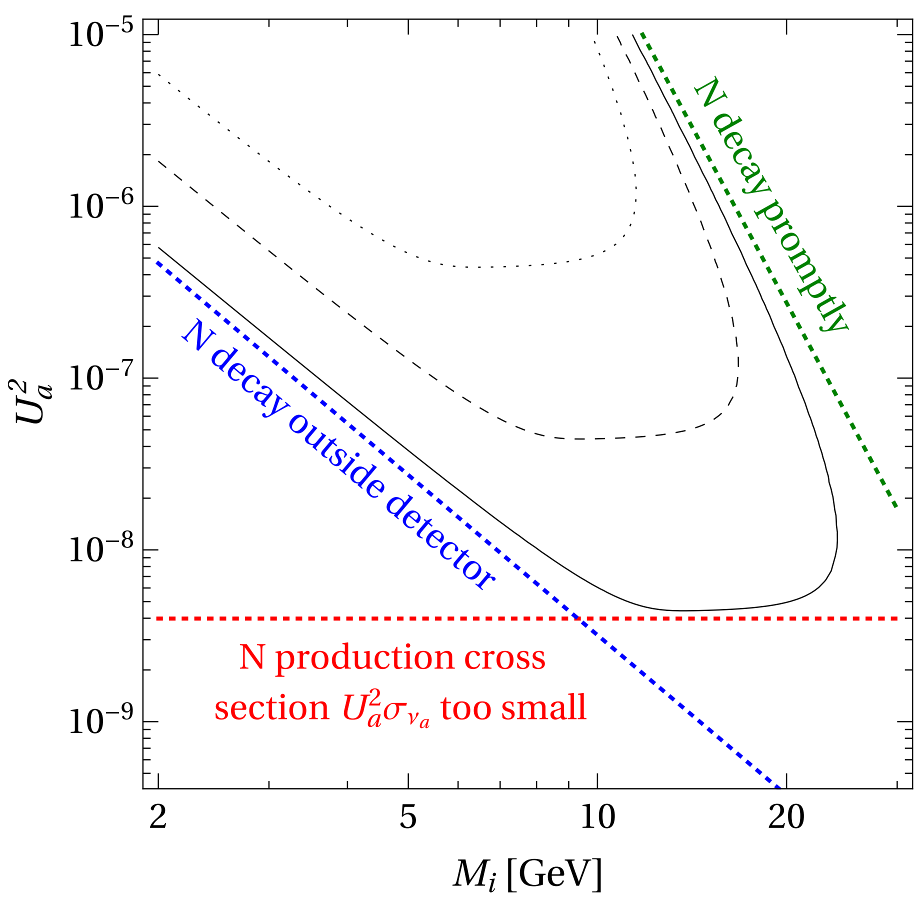
contours of constant decay length (1 mm and 2 m) in the $(m_N, \sum_\alpha |V_{N\alpha}|^2)$ plane

Displaced vertices can also be used to improve the sensitivity of the LHC in the standard scenario (SM augmented by a heavy sterile neutrino)

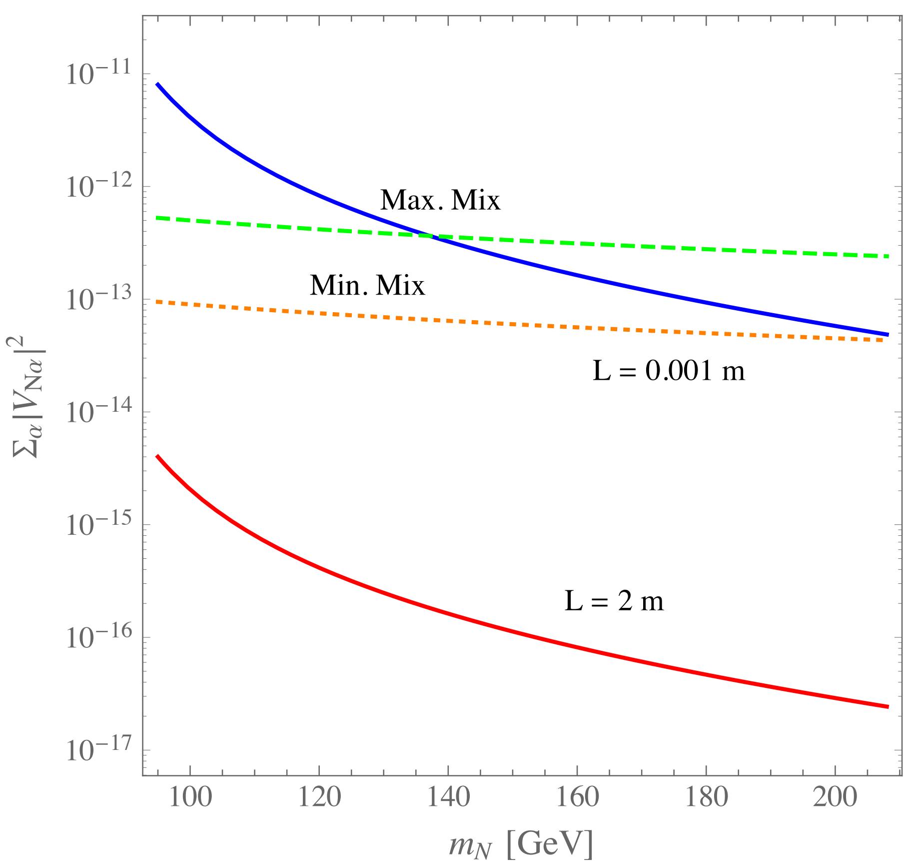
Helo, Hirsch, Kovalenko '12 - Izaguirre, Shuve '15 - Gago, Hernandez et al. '15 - Antusch, Cazzato, Fischer '17 Cottin, Helo, Hirsch '18 - Abada et al. '18 - Boiarska et al. '19 - Dib, Kim, Tapia Araya '19 - Drewes, Hajer '19 Liu, Liu, Wang, Wang '19 - Jones-Perez et al. '19 …

Difference with the pseudo-Goldstone fermion scenario: sensitivity to the mixing limited by the production cross section (suppressed by $|V_{N\nu}|^2$)

Drewes & Hajer, arXiv:1903.06100



pseudo-Goldstone fermion case



Other difference: the pseudo-Goldstone fermions are produced in pairs

In the standard scenario, can probe $m_N \leq 40\,\mathrm{GeV}\,, \quad \sum_\alpha |V_{N\alpha}|^2 \geq$ few 10^{-9}
($|V_{Ne}|^2$, $|V_{N\mu}|^2 \approx 5 \times 10^{-10}$ for $m_N \approx 35\,\mathrm{GeV}$ at the HL-LHC [Drewes & Hajer '19])
while the naive seesaw formula predicts

$$|V_{N\alpha}|^2 \sim \frac{m_\nu}{m_N} \sim 5 \times 10^{-12} \quad \text{for} \quad m_N \approx 10\,\mathrm{GeV}$$

$\Rightarrow$ bulk of the seesaw parameter space out of reach at the LH

In the pseudo-Goldstone fermion scenario, can probe the active-sterile mixing consistent with the measured neutrino oscillation parameters for $m_N \approx (\text{few}\,10 - 200)\,\mathrm{GeV}$ (namely, $\sum_\alpha |V_{N\alpha}|^2 \approx (\text{few}\,10^{-14} - 10^{-12})$)

Reconstruction of the active-sterile mixing angles

The probability density for a N to decay to a particular final state f at a distance r is

$$P_f(r) = \frac{\Gamma_f}{\beta\gamma}\, e^{-\frac{\Gamma r}{\beta\gamma}} \qquad \Gamma = \sum_f \Gamma_f \qquad \beta\gamma = \frac{|\vec{p}_N|}{m_N}$$

To compute the number of decays between r_1 and r_2, need to integrate over the momentum distribution of the produced N's

However, to a good approximation [Covi and Dradi, 1403.4923]

$$N_f(r_1, r_2) \;=\; N_0\, \frac{\Gamma_f}{\Gamma} \left(e^{-\frac{\Gamma r_1}{\beta\gamma_{eff}}} - e^{-\frac{\Gamma r_2}{\beta\gamma_{eff}}} \right)$$

N_0 = number of N's produced

$(\beta\gamma)_{\rm eff}$ = peak value of the $\beta\gamma$ distribution

For 2 intervals such that $r_1 \ll r_2$ and $r_3 \ll r_4$, one has

$$\frac{N_f(r_1, r_2)}{N_f(r_3, r_4)} \;\simeq\; e^{-\Gamma(r_1 - r_3)/(\beta\gamma)_{\rm eff}}$$

$\Rightarrow$ more generally, can extract the total decay width from the shape of the distribution of decay lengths corresponding to a particular final state [requires reconstruction of the momentum distribution of the N's]

To reconstruct the mixing angles (assuming Γ has been determined), need to distinguish different final states:

$$N \to \ell^\pm W^\mp \to \ell^\pm + 2\ \text{jets} \qquad N_{\ell\ell'} \propto N_0\,|V_{N\ell}|^2\,|V_{N\ell'}|^2$$

$$N \to \nu Z^* \to \nu + 2\ \text{jets} \qquad N_{\ell\nu} \propto N_0\,|V_{N\ell}|^2 \sum_\alpha |V_{N\alpha}|^2$$

Since the proportionality factors are known (depend on $\Gamma, \beta\gamma, m_N$ and on the relevant phase space of each channel), can solve for each $N_0\,|V_{N\nu_\alpha}|^2$ $(\alpha = e, \mu, \tau)$ (can use e.g. $N_{\mu\mu}, N_{e\mu}$ and $N_{\mu\nu}$)

Then can reconstruct $N_0\,\Gamma$, and since Γ is known from the distribution of the decay lengths, can solve for N_0 and $\sigma_0 = N_0/\mathcal{L}$

Rates for different final states ($N\bar{N}$ production cross section times branching ratios of the decay channels times decay fraction within 2m) at $\sqrt{s} = 14\,\text{TeV}$

process	rate
$e\,e + \text{jets}$	0.003 fb
$e\,\mu + \text{jets}$	0.16 fb
$\mu\,\mu + \text{jets}$	1.98 fb

process	rate
$e\,\nu + \text{jets}$	0.079 fb
$\mu\,\nu + \text{jets}$	1.94 fb

$\mu = 500\,\text{GeV}$

$m_N = 110\,\text{GeV}, \ \ R = \mathbf{1}$

Conclusions

Non-standard neutrino mass generation mechanisms may lead to sterile neutrino production at colliders with EW-size cross sections

An example is provided by a model in which the sterile neutrino is the supersymmetric partner of a pseudo-Goldstone boson. The pseudo-Goldstone fermion gets its mass from Susy breaking and mixes with the SM neutrinos and the neutralinos as a consequence of the global symmetry

Sterile neutrinos are produced in pairs and their decays lead to observable displaced vertices for $m_N \sim (\mathrm{few}\,10 - 200)\,\mathrm{GeV}$

The active-sterile mixing angles can be determined if some categories of decays of the sterile neutrino are fully reconstructed