Pseudo-Goldstone sterile neutrino at the LHC

Stéphane Lavignac (IPhT Saclay)

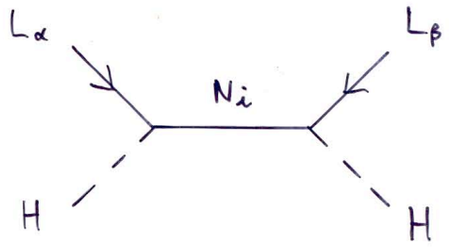
- introduction: a non-standard production mechanism for heavy sterile neutrinos at colliders
- an explicit model: sterile neutrino as the supersymmetric partner of a pseudo-Goldstone boson
- collider signature
- reconstruction of the active-sterile mixing angles

work in progress with Anibal Medina (La Plata)

Planck 2019
Granada, Spain, 4 June 2019

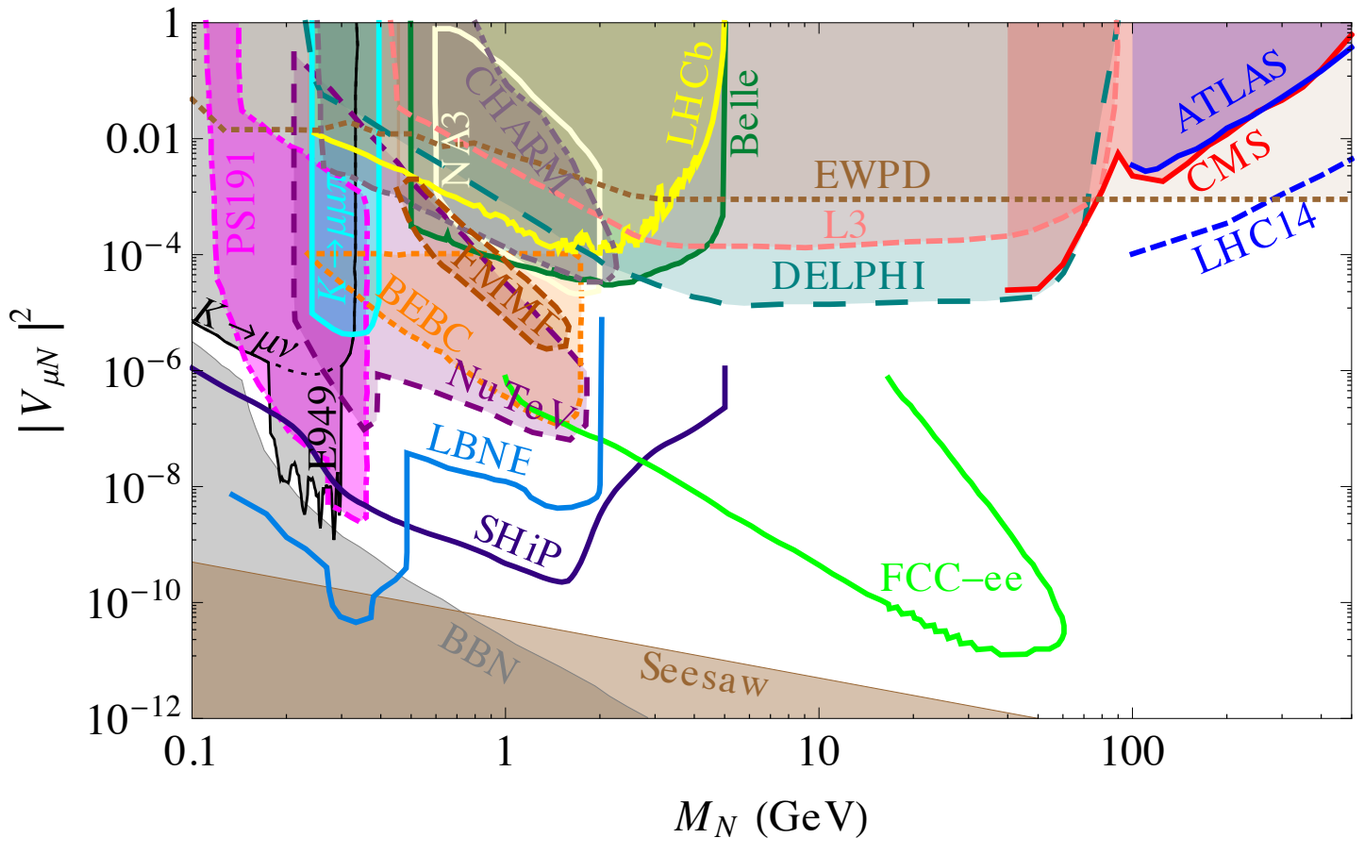
Introduction

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



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

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

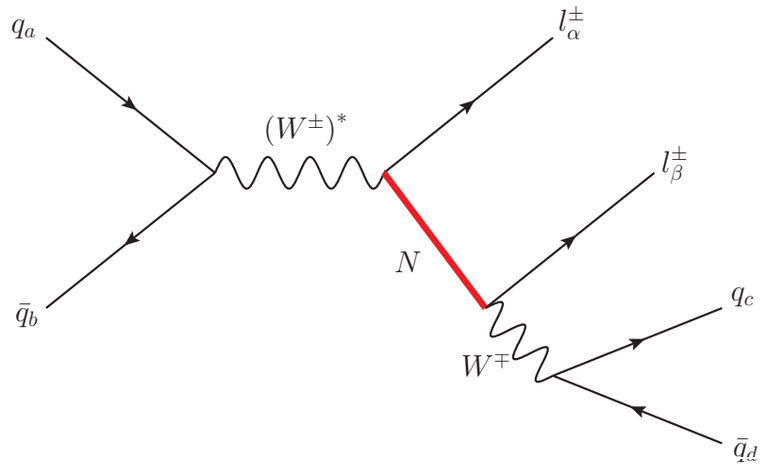


already constrained by a number of experiments

$V_{\mu N} =$ mixing of N with ν_μ

[Deppisch, Dev, Pilaftsis, 1502.06541]

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



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

Consider an alternative mechanism of neutrino mass generation in which N is produced with an order one branching ratio from an EW-produced heavier particle:

$$X \to N + \mathrm{SM} \qquad\qquad N \to \nu_i + \mathrm{SM} \,/\, \ell + \mathrm{SM}$$

→ production of N unsuppressed by mixing with SM neutrino

→ mixing angle enters N decays (⇒ possibility of displaced vertex)

Explicit realization of this mechanism: sterile neutrino as the supersymmetric partner of a pseudo-Goldstone boson

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

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

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

$\mu_i \ll \mu_0$ and $\lambda_i \ll \lambda_0$ ensured by U(1) symmetry [suppression factor ϵ^{l-h_d}] and by approximate R-parity [$\kappa_i \ll \kappa_0$]

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

The Lagrangian contains the following fermion bilinear terms:

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

$\Rightarrow$ ν_i / χ / $\tilde{h}_{u,d}^0$ mixing, whose size is suppressed by μ_i/μ_0 and $\lambda_0 \sim \mu_0/f$

[also chargino / charged lepton mixing, but not relevant in practice]

Two main effects of the ν_i / χ / $\tilde{h}^0_{u,d}$ mixing:

- tree-level neutrino masses (+ 1-loop corrections from the trilinear R-parity violating couplings)

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

In the following, assume that the lightest chargino and neutralinos are mostly higgsinos ($\mu \ll M_1, M_2 \Rightarrow$ bino and wino decoupled)

$\Rightarrow$ the relevant interactions are

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

with $\tilde{\chi}^0_{1,2} \approx (\tilde{h}^0_u, \tilde{h}^0_d)$ **and** $\tilde{\chi}^{\pm}_1 \approx \tilde{h}^{\pm}$

Benchmark point with $f = 4 \times 10^6\,\mathrm{GeV},\ \mu = 200\,\mathrm{GeV},\ m_N = 10\,\mathrm{GeV}$

μ [GeV]	M_1 [TeV]	M_2 [TeV]	ϵ	h_d	l	$\tan\beta$
200	2	10	10^{-1}	1	3	2
λ_0	λ_1	λ_2	λ_3	μ_1 [GeV]	μ_2 [GeV]	μ_3 [GeV]
5×10^{-5}	6.42×10^{-11}	2.89×10^{-8}	1.93×10^{-10}	2×10^{-4}	1.6×10^{-3}	2×10^{-3}

$$m_{\nu_i} \ll m_N = 10\,\mathrm{GeV} \ll m_{\tilde{\chi}_1^\pm} \simeq m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\chi}_2^0} \simeq 200\,\mathrm{GeV}$$

[neutrino masses consistent with the atmospheric and solar mass scales]

The dominant decay modes of the higgsino-like fermions are

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

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

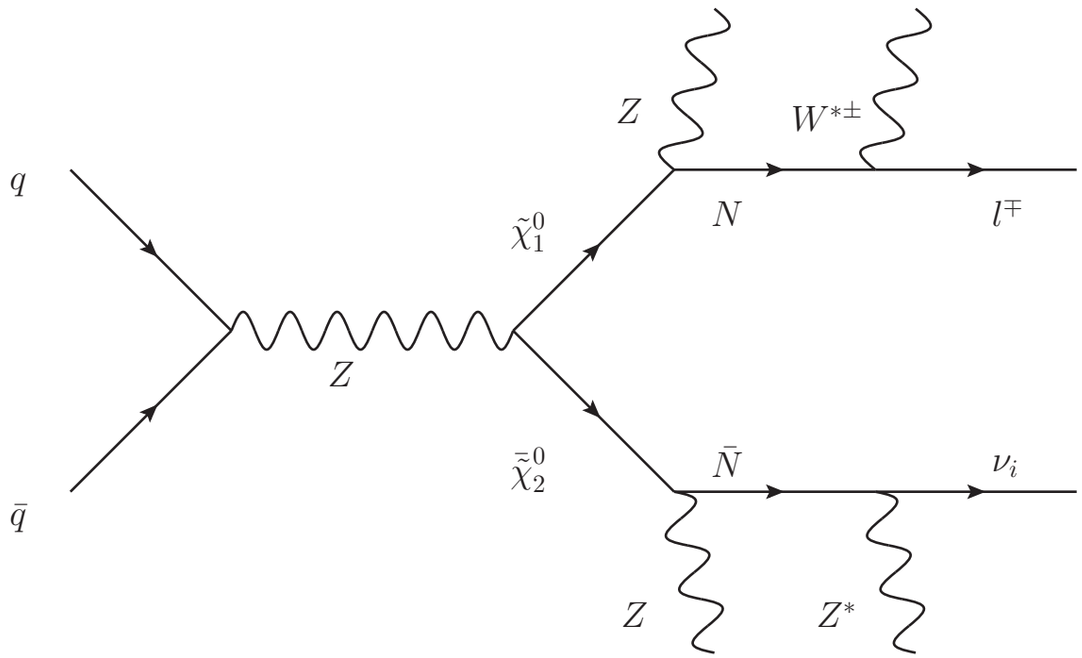
$\Rightarrow$ pair-produced $\tilde{\chi}_1^0\tilde{\chi}_2^0,\ \tilde{\chi}_{1,2}^0\tilde{\chi}_1^\pm,\ \tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ (with cross sections of order 100 fb at $\sqrt{s} = 13\,\mathrm{TeV}$ for $\mu = 250\,\mathrm{GeV}$) will decay with a BR close to 100% to $ZZN\bar{N},\ ZW^\pm N\bar{N},\ W^\pm W^\mp N\bar{N}$ (possibility to trigger on the leptons from Z and W decays)

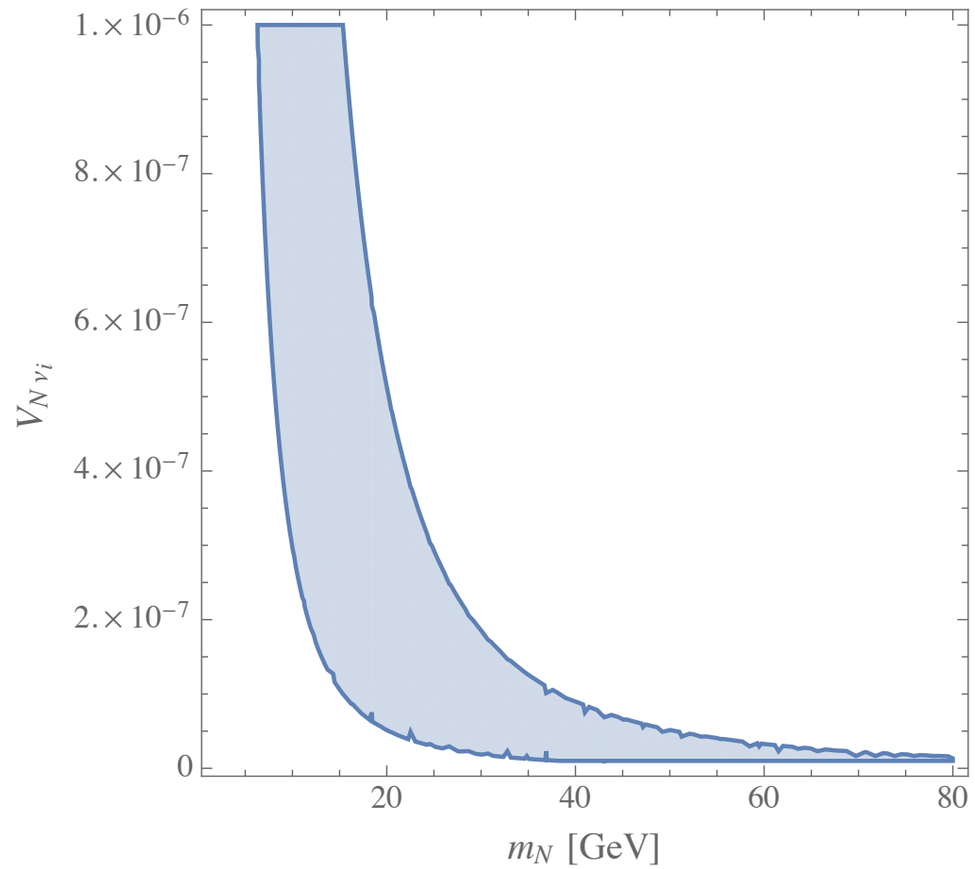
The sterile neutrinos will subsequently decay, via an off-shell Z or W boson, through their mixing with the SM neutrinos:

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

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

Since the mixing is small, $V_{N\nu_i} = \mathcal{O}(10^{-8} - 10^{-6})$, the N decays will give rise to displaced vertices





blue area = decay length between 1 cm and 1 m

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 r1 and r2, need to integrate over the momentum distribution of the produced N's

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

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

N0 = 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

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

$\Rightarrow$ 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 determine the mixing angles (assuming Γ is known), need to distinguish the different final states:

$$N \to e^{\pm} W^{*\mp} \to e^{\pm} + 2 \text{ jets} \qquad N_e \propto N_0 \, |V_{N\nu_e}|^2$$

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

$$N \to \nu Z^* \to \nu + 2 \text{ jets} \qquad N_\nu \propto N_0 \sum_i |V_{N\nu_i}|^2$$

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 $N_0 \, |V_{N\nu_i}|^2 \quad (i = e, \mu, \tau)$

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

Rates for each final state ($N\bar{N}$ production cross sections times branching ratios for each decay channel)

Process	$\mu = 250$ GeV	$\mu = 500$ GeV
$\sigma_{e,\mu}$	0.44 fb	2.5×10^{-2} fb
$\sigma_{\Sigma_{\nu_i}}$	0.98 fb	5.6×10^{-2} fb

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

Leads to displaced vertices due to the smallness of the mixing with the SM neutrinos

The active-sterile mixing angles can be reconstructed from the decays of the sterile neutrino