New ideas on sterile neutrino searches at the LHC (and beyond!)

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Acknowledgments, Apologies, and Disclaimers

finite time constraints $\implies$ many omissions

- Main focus is on heavy, sterile neutrinos ($N$) w/o new gauge bosons.
- See references below for Seesaws Types II and III

source material:

1. Review on Nu Mass Models at Colliders
   w/ Y. Cai, T. Han, T. Li [1711.02180]

2. European Strategy Update 2019 Chapter on Nu Mass Models
   w/ T. Han, T. Li, X. Marcano, S. Pascoli, C. Weiland [1812.07831]

3. Other community documents and some newer results

humble reminder: RH neutrinos are not the only explanation for tiny $\nu$ masses nor are they necessary (e.g., Type II Seesaw)

- Lack of guidance from data $\implies$ broad approach needed
- E.g., models without $N$, UV completions of NSI, ....
Motivation for new physics from $\nu$ physics.
In neutrino fixed-target expts, $\nu_\mu$ beams from collimated $\pi^\pm$, then studied at near and far detectors (reminiscent of early SLAC DIS expts)

Deficit/disappearance of expected $\nu_\mu$ (+appearance of $\nu_e/\nu_\tau$) interpreted as

$\nu_{\ell_1} \rightarrow \nu_{\text{mass}} \rightarrow \nu_{\ell_2}$ transitions/oscillations

[E.g. NO$\nu$A $\nu_\mu$ disapp., 1701.05891]

$\Longrightarrow \nu$ have mass!
Collider Connection to Neutrino Mass Models

Neutrino mass models (aka Seesaw models) hypothesize new particles of all masses, spins, charges, and color:

\( N \) (Type I), \( T^{0,\pm} \) (Type III), \( Z_{B-L} \), \( H_{R}^{\pm,\pm\pm} \) (Type I+II), ... 

Produced in \( ee/ep/pp \) collisions through gauge couplings and mixing:

\[
\begin{align*}
\text{DY} & : q\bar{q} \rightarrow \gamma^*/Z^* \rightarrow T^+ T^- \quad \text{and} \quad q\bar{q}' \rightarrow W_R^\pm \rightarrow N\ell^\pm \\
\text{VBF} & : W^\pm W^\pm \rightarrow H^{\pm\pm} \\
\text{GF} & : gg \rightarrow h^*/Z^* \rightarrow N\nu_\ell
\end{align*}
\]

Identification of Seesaw particles through decays to SM particles

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some new ideas
New Ideas

1. new channels I: $W\gamma$ fusion
   w/ Alva, Han [1411.7305]

2. new channels II: $gg$ fusion
   w/ Spannowsky, Waite [1706.02298]

3. new analysis techniques I: event-based jet vetoes
   w/ Pascoli, Weiland [1805.09335, 1812.08750]

4. new analysis techniques II: new colliders
   w/ Costantini, De Lillo, Maltoni, Mantani, Mattelaer, Zhao [2005.10289]

5. new analysis techniques III: new, off-shell gauge bosons
   RR [1703.04669]

6. new channels III: something new in progress!
   w/ Fuks, Neundorf, Peters, Saimpert [In Prep.]
(heavy) sterile neutrino production in $pp$ collisions
... can occur through a variety of mechanisms:

Since 2014, active research program to systematically compare channels

For overview, see review: [*1711.02180]

- Clarity needed on (i) $m_N$, $\sqrt{s}$ dependence and (ii) conflicting claims
- Explore how new techniques can improve analyses from 90’s-00’s
  \[ \implies \] better sensitivity, more robust analyses, new public tools
  e.g., HeavyN UFOs [feynrules.irmp.ucl.ac.be/wiki/HeavyN]

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\nu ideas at the LHC and beyond - LHCP20@Paris
New channels I:

$W\gamma$ fusion (the fun channel).
$W\gamma \rightarrow N\ell^\pm$ fusion is interesting for large $m_N$ but subtle due to QED singularities and $\gamma$ PDF matching

Dev, et al [1308.2209], w/ Alva, Han [1411.7305], w/ Degrande, Mattelaer, Turner [1602.06957]

Careful when choosing $\gamma$ PDF. Some (NN2.3QED) are just poor statistical fits

for up-to-date comparison see study w/ Fuks, Nemevšek [1912.08975]
How important is $W\gamma$ fusion?
Plotted: LHC 14 sensitivity to active-sterile neutrino mixing (coupling) vs heavy neutrino mass ($m_N$) in search for $pp \rightarrow \mu^\pm e^\mp \ell_X \ (\ell_X = e, \mu, \tau_h)$

Dash = trilepton analysis without $W\gamma$ fusion
Solid = $+ W\gamma$ fusion $\implies W\gamma$ drives high-mass sensitivity!
New channels II:

$gg$ fusion (the neglected channel).
Heavy neutrinos from GF is pretty cool

Willenbrock, Dicus ('85); Dicus, Roy ('91); Hessler, et al [1408.0983]

- manifestation of Goldstone Equiv. Theorem
- loop induced \(\rightarrow\) subleading at LHC
- \(gg\)-initiated \(\rightarrow\) interesting at higher \(\sqrt{s}\)

![Graphs showing cross sections vs. neutrino mass](image)

\[\sigma_{pp \rightarrow NN}/|V_{NN}|^2\] for 14 TeV LHC and 100 TeV VLHC

w/ Degrande, Mattelaer, Turner [1602.06957]

**a subtle point:** GF@LO is a poor estimation for true cross section

(see higgs literature)
Maturity of modern QCD formalism \( \Rightarrow \) readily applied to BSM

E.g. \( gg \rightarrow h^*/Z^* \rightarrow \nu N \) at N^{3}LL \((\approx N^{2}LO \text{ normalization})\)

- \(\mathcal{O}(+200\%)\) corrections consistent with \( gg \rightarrow H/A \) in 2HDM
- **Need**: a dedicated study on sensitivity of leading \( gg \) channel
new analysis techniques I:

reenvisioning jet vetoes in searches

with event-based\textsuperscript{1} jet vetoes\textsuperscript{2}

\textsuperscript{1}aka: “dynamic jet veto,” “phase space-dependent jet veto”, or “safe jet veto”

\textsuperscript{2}Early literature: Bjorken (dynamic rapidity gap) [PRD ('93)]; Denner, et al (regulator trick) [0906.1656]; Companario, et al ($x = E_T / \Sigma_k E_T^k$ fraction) [1410.4840]; more recent work by DESY+NIKEF+Mainz (rapidity-dependent vetoes)
In EW boson scattering, there is an absence of central color flow

\[ \implies \text{absence of central, high-}\vec{p}_T \text{ jets} \]

[“Rapidity gaps” Dokshitzer, Khoze, Troyan (’86)]

Basis for **Central Jet Veto:**

- Reject events with any jet satisfying \( p_T^j > 25 - 30 \text{ GeV}, |\eta^j| < 2 - 3 \)
  - After applying meaningful jet PID, equivalent to keeping only 0-jet bin
- Crucial to Higgs and EW physics but not perfect...

[Barger, et al, PRD (’91) + PLB (’95); Bjorken, PRD (’94)]
Leptons in Vector Boson Scattering

For production of leptons in VBS: $p_T^{\ell_k}, S_T \sim M_{VV} \gg p_T^{VBS} \sim M_V/2$

\begin{align*}
\text{Still no color flow!}
\end{align*}

an idea: on an event-by-event basis, set $p_T^{\text{Veto}} = p_T^{\ell_1}$

Inspired by CMS using the ratio $r_j^\ell = (p_T^{\ell}/p_T^j)$ for lepton isolation [1701.06940]

- VBS events pass by construction; backgrounds interestingly fail

\[3\] Pascoli, RR, Weiland [PLB ('18), 1805.09335]
The impact?
Plotted: LHC 14 sensitivity to active-sterile neutrino mixing (coupling) vs heavy neutrino mass ($m_N$) in search for $pp \rightarrow \mu^\pm e^{\mp} \ell_X$ ($\ell_X = e, \mu, \tau_h$)

- Dash = standard analysis with $b$-jet veto (mirrors 13 TeV CMS, based on [0808.2468])
- Solid = new analysis with $10 - 11 \times$ improved sensitivity!
A peak at the future.\textsuperscript{4}

\textsuperscript{4} Only a few results now. See “big” paper for various flavor, Dirac vs Majorana, and $\sqrt{s}$ permutations [1812.08750].
Heavy Neutrino Mass [GeV]

$|V_{\tau 4}|^2 = |V_{\tau 4}|^2$

$|V_{\mu 4}|^2 = 0$

$|V_{e 4}|^2$

$10^{-5}$

$10^{-4}$

$10^{-3}$

$10^{-2}$

$10^{-1}$

$10^0$

CMS upper limit on $|V_{e 4}|^2$

13 TeV, 35.9 fb$^{-1}$ [1802.02965]

LHC 14, 300 fb$^{-1}$

LHC 14, 3 ab$^{-1}$

LHC 27, 15 ab$^{-1}$

LHC 27, 3 ab$^{-1}$

LHC 100, 15 ab$^{-1}$

LHC 100, 30 ab$^{-1}$

Indirect upper limit on $|V_{e 4} V_{\tau 4}|$ [1605.08774]

$\Gamma_N/m_N > 5\%$

$\Delta \tau/\tau > 5\%$

$95\%$ Sensitivity - $pp \rightarrow \tau_h e l_X / 3e / 2e\mu$

$|V_{\tau 4}|^2$

$|V_{\mu 4}|^2 = 0$

$10^{-5}$

$10^{-4}$

$10^{-3}$

$10^{-2}$

$10^{-1}$

$10^0$

$10^1$

$10^2$

$10^3$

$10^4$

Heavy Neutrino Mass [GeV]

$|V_{\tau 4}|^2$ vs. Heavy Neutrino Mass [GeV]

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$10^4$
new analysis techniques II: new colliders
Due to energy (precision) limitations of proposed $e^+ e^-$ ($pp$) machines and novel technological advances, discussions on $\mu^+ \mu^-$ have restarted


NEW: Multi-TeV $\mu^+ \mu^-$ colliders are essentially “high-luminosity weak boson colliders” and opens many frontiers

Need: a dedicated study on sensitivity of $\mu^+ \mu^-$ collisions

w/ Costantini, De Lillo, Maltoni, Mantani, Mattelaer, Zhao [2005.10289]
new analysis techniques III:

neutrino nonstandard interactions ($\nu$NSI)

and heavy neutrino effective field theories (NEFT)
Interesting observation: vast literature on collider searches for $N$ coupling to new gauge bosons, e.g., $W_R$ in LRSM, *most always* assume that both $N$ and $W_R$ are resonantly produced.

If new gauge mediators are too heavy, light $N$ are still accessible.

Example: When $M_{W_R} \gg \sqrt{s}$ but $m_N \lesssim \mathcal{O}(1)$ TeV, $pp \to N \ell + X$ in the LRSM and phenomenological Type I Seesaw are not discernible.

- Same signature: $pp \to \ell^\pm \ell^\pm + nj + X + p_T^\ell \gtrsim \mathcal{O}(m_N) + \text{no MET}$

How about reinterpreting search for phenomenological Type I Seesaw?
At 14 (100) TeV with $\mathcal{L} = 1 (10) \text{ ab}^{-1}$, $M_{W_R} \lesssim 9 (40) \text{ TeV}$ probed

**DO NOT STOP SEARCHING FOR TYPE I LNV**
New channels III: something new?
How heavy is too heavy for the LHC?

**Question:** is a multi-TeV $N$ too heavy for the LHC?

... maybe, maybe not

- $e^+ + e^- + W^+ + W^- + \nu + \bar{\nu} + d + \bar{d}$
- $u + \bar{u}$

---

$S_{\mu\mu}$ vs. $m_N$ [GeV]

- $2\sigma, 300$ fb$^{-1}$
- $2\sigma, 1$ ab$^{-1}$
- $2\sigma, 5$ ab$^{-1}$

$\mu^+\mu^+jj$ 13 TeV LHC IN PROGRESS

w/ Fuks, Neundorf, Peters, Saimpert [In Prep.]
Heavy neutrinos remain one of the best (but not the only!) explanations for tiny neutrino masses

see review for details! [1711.02180]

Over the past few years new ideas on:

- **Production mechanisms**
- **Analysis techniques (possible with new tools)**
- **New collider scenarios**

have pushed sensitivity to neutrino mass models at colliders to new levels!

- lots of work still to do and help is always welcomed!
Thank you.
Backup I: heavy neutrino mixing for non-experts
After EWSB, $\nu_\ell$ and $N_R$ have same quantum numbers $\implies$ mixing!

**Example:** In a two-state system, mixing between chiral eigenstates and mass eigenstates is given by unitary transformation/rotation

$$
\begin{pmatrix}
\nu_L \\
N_R^c
\end{pmatrix}_{\text{chiral basis}} =
\begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix}_{\text{mixing}}
\begin{pmatrix}
\nu_1 \\
N_2
\end{pmatrix}_{\text{mass basis}}
$$

Decompose **chiral/interaction states** into **mass states** using:

$$
|\nu_L\rangle = \cos \theta |\nu_1\rangle + \sin \theta |N_2\rangle
$$

Generically, one can parameterize many heavy $N$ couplings to the SM with

$$
\nu_{\ell L} \approx \sum_{m=1}^{3} U_{\ell m} \nu_m + V_{\ell m'=4} N_{m'=4}
$$

Atre, Han, Pascoli, Zhang [0901.3589]
Backup II: heavy neutrino couplings to SM Currents
Heavy Neutrinos Couplings to EW Bosons

Consider left-handed (LH) $SU(2)\_L$ doublets (**gauge basis**):

$$L_{aL} = \begin{pmatrix} \nu_a \\ l_a \end{pmatrix}_L, \quad a = 1, 2, 3.$$ 

The SM $W$ chiral coupling to **leptons** in **flavor basis** is given by

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W^\mu_\mu \sum_\ell=e^\tau \left[ \nu_\ell \gamma^\mu P_L \ell^- \right] + H.c.$$ 

The SM $W$ chiral coupling to **leptons** in the **mass basis**

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W^\mu_\mu \sum_\ell=e^\tau \left[ \sum_{m=1}^3 \nu_m U^*_{m\ell} + \overline{N^c} V^*_N \ell^- \right] \gamma^\mu P_L \ell^- + H.c.$$ 

$\implies N$ is accessible through $W/Z/h$ currents
Backup III: heavy neutrino decoupling
In pure Type I scenarios, tiny $m_\nu$ obtained in two ways:

1. **High-scale seesaw**: $\mu_M \gg \langle \phi_{SM} \rangle \implies m_\nu \sim m_D \left( \frac{m_D}{\mu_M} \right)$, $m_N \sim \mu_M$

   Leads to generic decoupling of $N$ and LNV from colliders.

2. **Low-scale seesaw**: $\mu_M \ll \langle \phi_{SM} \rangle \implies m_\nu \sim \mu_M \left( \frac{m_D}{m_R} \right)^2$, $m_N \sim m_R$

   Known also in literature as Inverse Seesaw, Linear Seesaw, Protective Symmetries, etc.

Apriori, no preference for either without additional theory prejudice:

- **LNC Option**: Low-scale Type I + if $\nu$ approx. massless on expt scale, i.e., $\tilde{m}_\nu^2/Q^2 \approx 0 \implies$ approximate $L$ conservation
  w/ Pascoli, et al, [1812.08750]

  See also, Pilaftsis [hep-ph/9901206], Kersten and Smirnov [0705.3221], Pascoli, et al, [1712.07611]

- **LNV Options**: Collider LNV via $N_i \implies$ more new particles!

  RR [1703.04669]