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

**LHCP 2020 - Paris**

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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

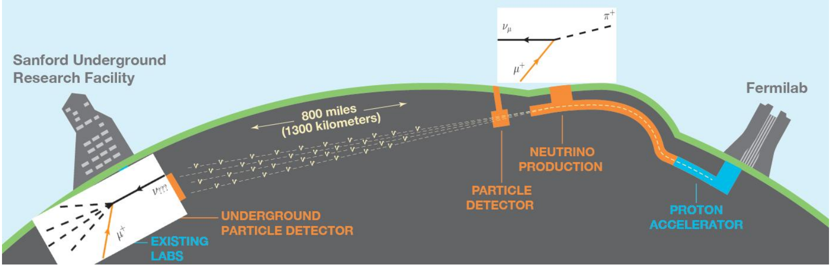
**source material**:

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

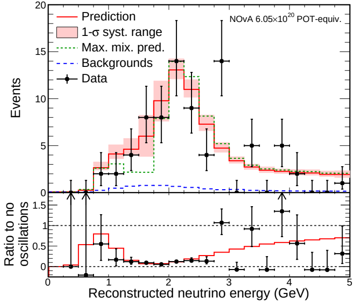
**humble reminder**: RH neutrinos are **not** the only explanation for tiny $\nu$ masses nor are they necessary (e.g., Type II Seesaw)

- 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 $\nu_\mu$ (+apperance of $\nu_e/\nu_\tau$) interpreted as $\nu_{\ell_1} \to \nu_{\rm mass} \to \nu_{\ell_2}$ transitions/oscillations [E.g. NO$\nu$A $\nu_\mu$ disapp., 1701.05891]

$\implies$ $\nu$ have mass!

# Collider Connection to Neutrino Mass Models

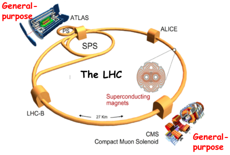
Neutrino mass models (aka Seesaw models) hypothesize new particles of all **masses**, **spins**, **charges**, and **color**:

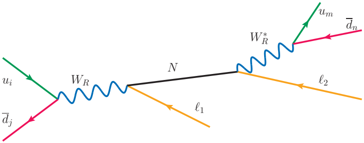
$N$ (Type I), $T^{0,\pm}$ (Type III), $Z_{B-L}$, $H_R^{\pm,\pm\pm}$ (Type I+II), ...

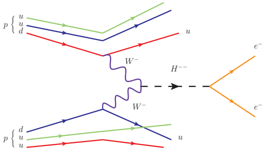
**Produced** in $ee/ep/pp$ collisions through gauge couplings and mixing:

**DY** : $q\overline{q} \rightarrow \gamma^*/Z^* \rightarrow T^+T^-$ and $q\overline{q'} \rightarrow W_R^\pm \rightarrow N\ell^\pm$

**VBF** : $W^\pm W^\pm \rightarrow H^{\pm\pm}$ **GF** : $gg \rightarrow h^*/Z^* \rightarrow N\nu_\ell$




**Identification** of Seesaw particles through **decays to SM particles**

**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

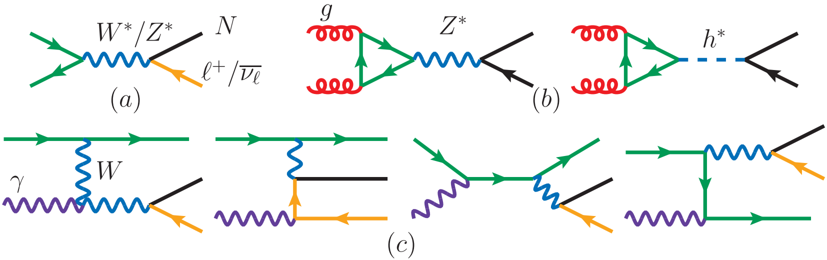
   RR [1703.04669]

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]

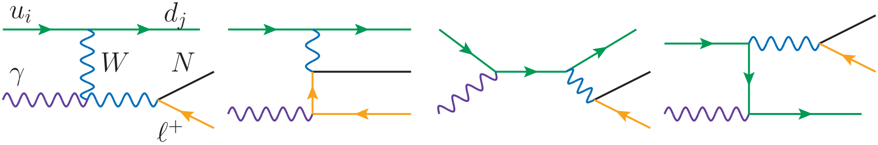
- Clarity needed on **(i)** $m_N, \sqrt{s}$ **dependence** and **(ii) conflicting claims**
- Explore **how new techniques can improve** analyses from 90's-00's

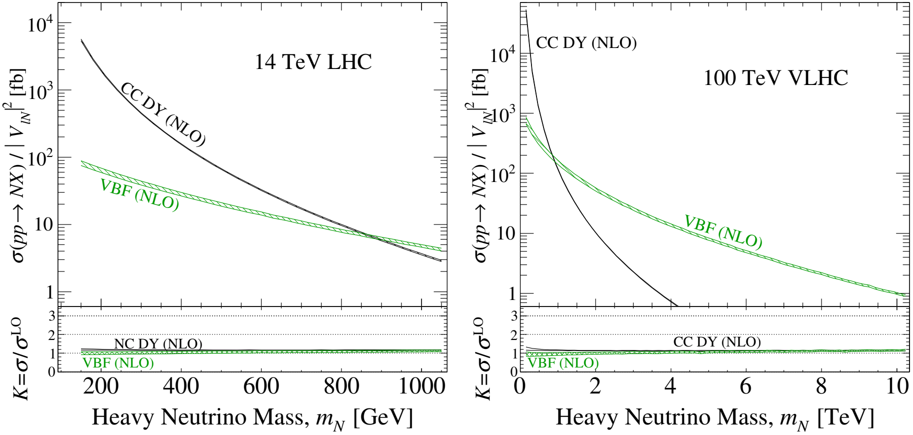
$\Longrightarrow$ better sensitivity, more robust analyses, new public tools

e.g., HeavyN UFOs [feynrules.irmp.ucl.ac.be/wiki/HeavyN]

**New channels I:**

**$W\gamma$ fusion (the fun channel).**






$W\gamma \to N\ell^{\pm}$ fusion is interesting for large $m_N$ but subtle due to QED singularities and $\gamma$ PDF matching

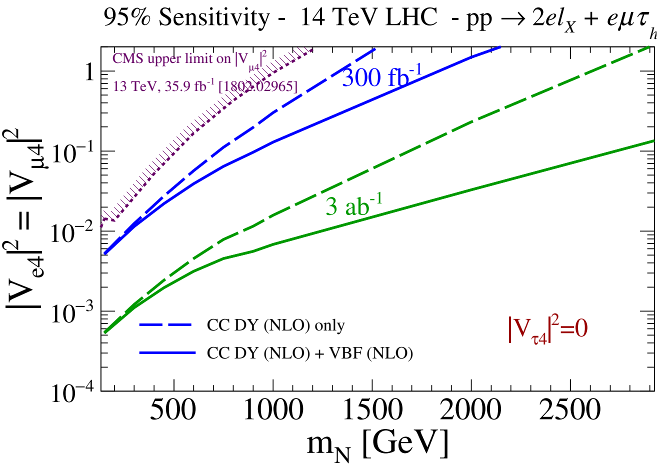
Dev, et al [1308.2209], w/ Alva, Han [1411.7305], w/ Degrande, Mattelaer, Turner [1602.06957]

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 $pp \to \mu^\pm e^\mp \ell_X \quad (\ell_X = e, \mu, \tau_h)$

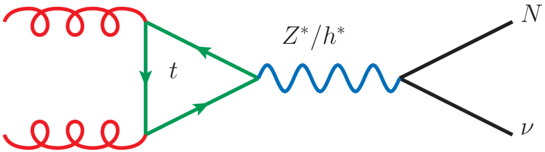



[1411.7305,1812.08750]

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

**New channels II:**

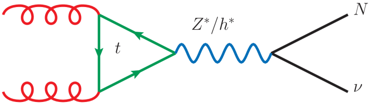
**$gg$ fusion (the neglected channel).**

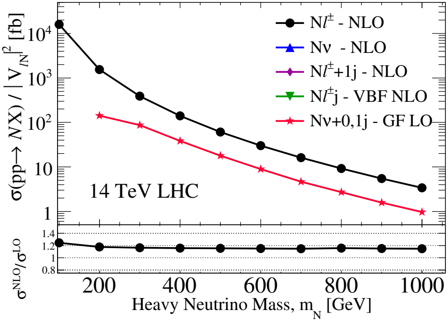


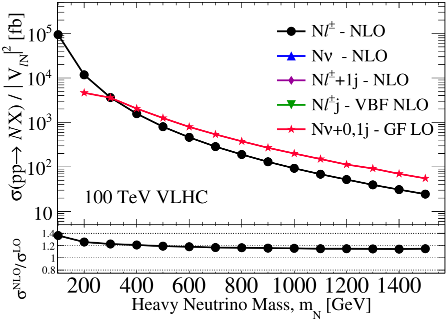
# Heavy neutrinos from GF is pretty cool

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

- manifestation of Goldstone Equiv. Theorem
- loop induced $\Longrightarrow$ **subleading** at LHC
- *gg*-initiated $\Longrightarrow$ **intesting** at higher $\sqrt{s}$



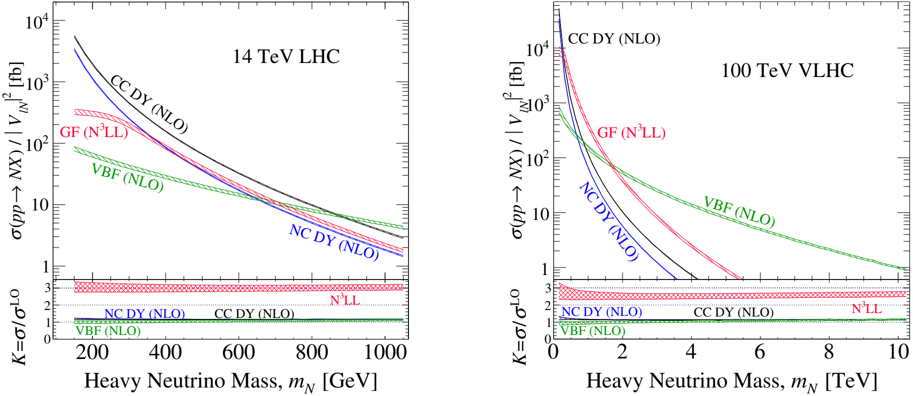

w/ Degrande, Mattelaer, Turner [1602.06957]

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

(see higgs literature!)

Maturity of modern QCD formalism $\Longrightarrow$ readily applied to BSM

E.g. $gg \to h^*/Z^* \to \nu N$ at $N^3LL$ ($\approx N^2LO$ normalization)




w/ Spannowsky, Waite [1509.05416]

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

## new analysis techniques I:

## reenvisioning jet vetoes in searches

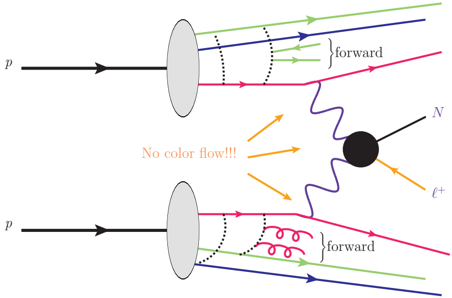
## with event-based[1] jet vetoes[2]

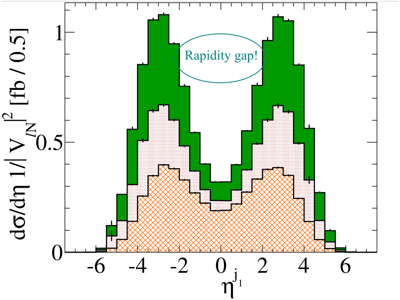
[1] aka: “dynamic jet veto," “phase space-dependent jet veto", or “safe jet veto”

[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 abscence of central color flow

$\Longrightarrow$ absence of central, high-$p_T$ jets ["Rapidity gaps" Dokshitzer, Khoze, Troyan ('86)]



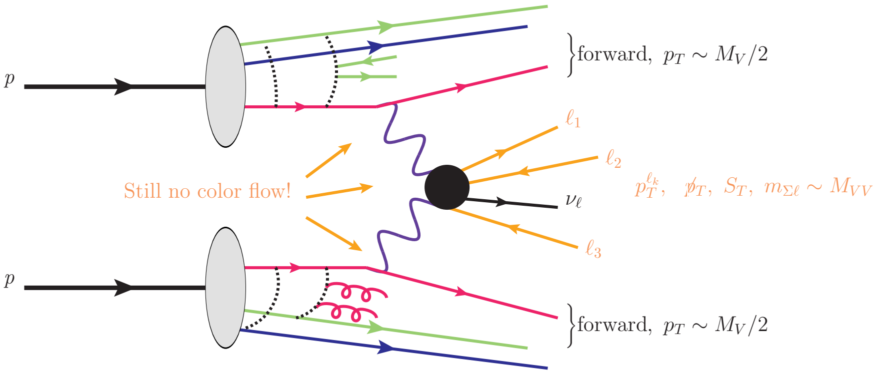




Basis for **Central Jet Veto:** [Barger, et al, PRD ('91) + PLB ('95); Bjorken, PRD ('94)]

- Reject events with any jet satisfying $p_T^j > 25 - 30$ 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...

# Leptons in Vector Boson Scattering

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




**an idea:**[3]: **on an event-by-event basis,** set $p_T^{\rm Veto} = p_T^{\ell_1}$

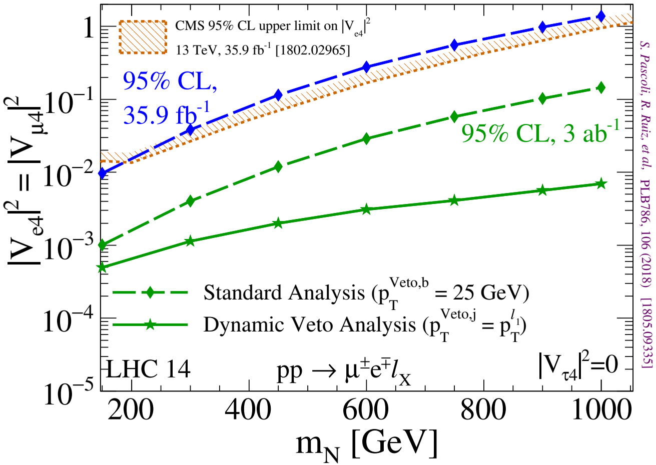
Inspired by CMS using the ratio $r_j^\ell = (p_T^\ell / p_T^j)$ for lepton isolation [1701.06940]

- 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 $pp \to \mu^\pm e^\mp \ell_X$ $\quad (\ell_X = e, \mu, \tau_h)$

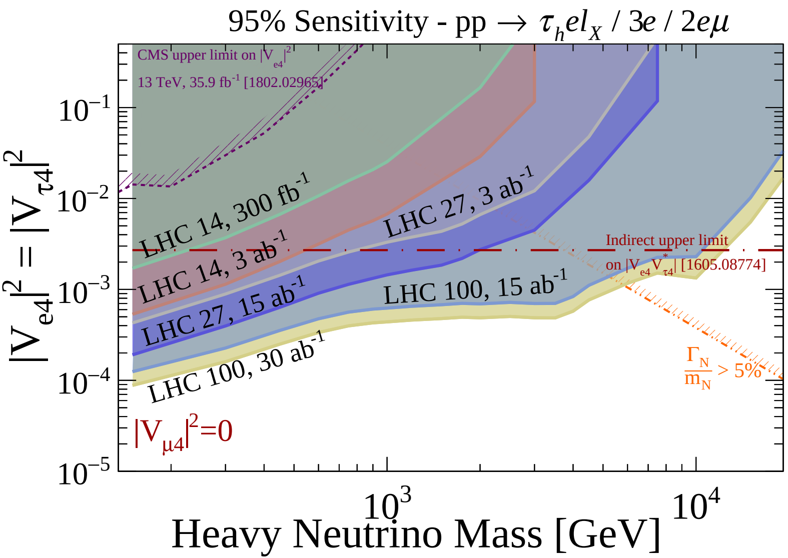



[1805.09335]

- 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.**[4]

[4] Only a few results now. See "big" paper for various flavor, Dirac vs Majorana, and $\sqrt{s}$ permutations [1812.08750]




$>10\times$ improvement $\Longrightarrow$ competitive sensitivity to cLFV at LHC

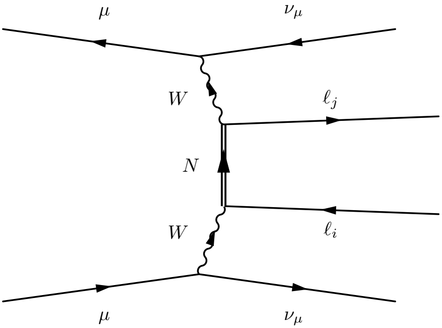
- **Relative** improvement largely flavor-hypothesis independent

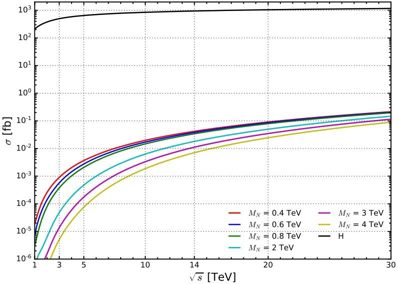
**new analysis techniques II: new colliders**

# $\mu^+\mu^-$ Colliders

Due to energy (precision) limitations of proposed $e^+e^-$ ($pp$) machines and novel technological advances, discussions on $\mu^+\mu^-$ have restarted

Antonelli, et al [1509.04454], Delahaye, et al [1901.06150], Nazar Bartosik, et al [1905.03725]




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

w/ Costantini, De Lillo, Maltoni, Mantani, Mattelaer, Zhao [2005.10289]

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

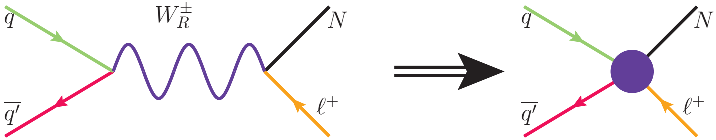
**new analysis techniques III:**

**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 produed

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

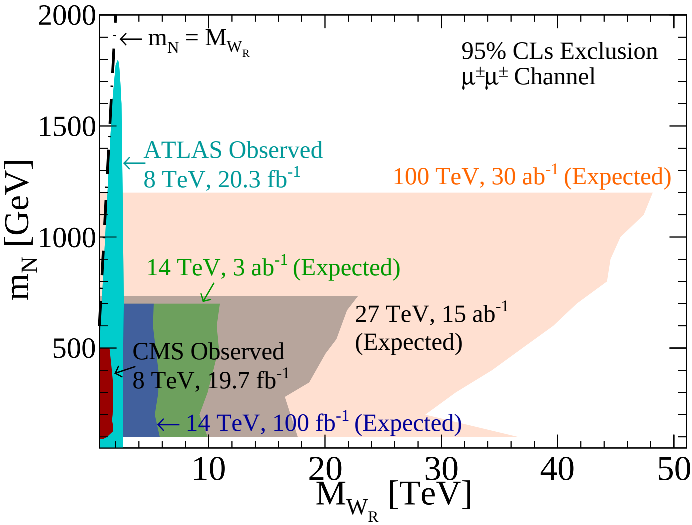



**Exmaple:** When $M_{W_R} \gg \sqrt{\hat{s}}$ but $m_N \lesssim \mathcal{O}(1)$ TeV, $pp \to N\ell + X$ in the LRSM and phenomenological Type I Seesaw are not discernible

w/ Han, Lewis, Si, [1211.6447]; RR, [1703.04669]

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

How about reinterpreting search for phenomenological Type I Seesaw?




RR [1703.04669]

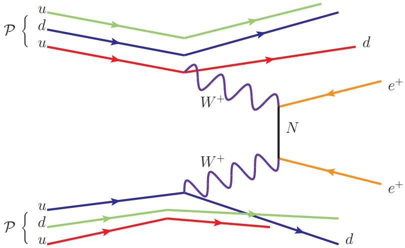
At 14 (100) TeV with $\mathcal{L} = 1$ (10) ab$^{-1}$, $M_{W_R} \lesssim 9$ (40) TeV probed

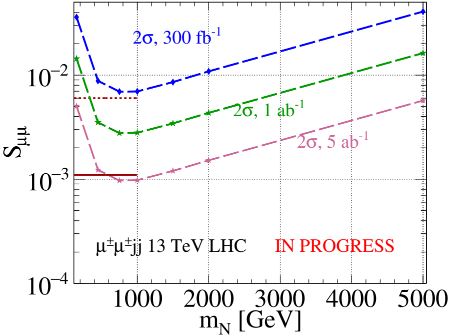
**DO NOT STOP SEARCHING FOR TYPE I LNV**

**New channels III: something new?**

How heavy is too heavy for the LHC?

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




w/ Fuks, Neundorf, Peters, Saimpert [In Prep.]

**... maybe, maybe not**

# Summary

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

# (Heavy) Neutrino Mixing for Non-experts (1/1)

After EWSB, $\nu_\ell$ and $N_R$ have same quantum numbers $\Longrightarrow$ mixing!

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

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

Decompose chiral/interaction states into mass states using:

$$\underbrace{|\nu_L\rangle}_{\text{interaction basis}} = \cos\theta \underbrace{|\nu_1\rangle}_{\textit{light}} + \sin\theta \underbrace{|N_2\rangle}_{\textit{heavy}} \overset{\theta\lll 1}{\approx} (1 - \tfrac{1}{2}\theta^2)|\nu_1\rangle + \theta|N_2\rangle$$

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

$$\nu_{\ell L} \approx \sum_{m=1}^{3} \underbrace{U_{\ell m}}_{\mathcal{O}(1)} \nu_m + \underbrace{V_{\ell m'=4}}_{\mathcal{O}(???)} N_{m'=4}$$

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

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

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

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

$\implies$ $N$ is **accessible through** $W/Z/h$ currents

## Backup III: heavy neutrino decoupling

# Agnostic Approach to Heavy $N$ Mixing

In pure Type I scenarios, tiny $m_\nu$ obtained in two ways:

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

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

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

   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]