Neutrino mass models at colliders in the post-ESU 2020 era

Energy Frontier Biweekly Meeting

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Acknowledgments, Apologies, and Disclaimers

finite time constraints $\implies$ many omissions

- **Purpose:** a snapshot of activities since European Strategy Update
- Main focus is on Type I (N) and Type II ($\Delta^{\pm\pm}$) Seesaws
- See references below for details + other Seesaws

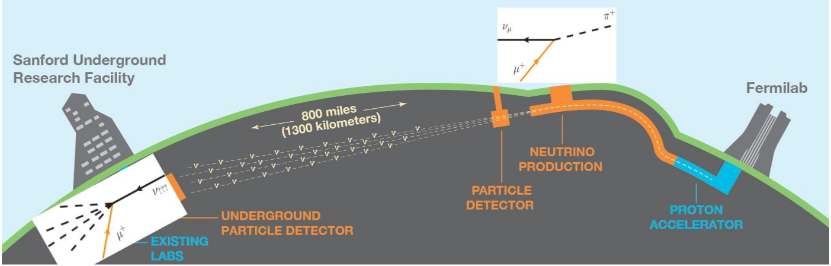
source material:

1. Review on ν mass models at colliders — w/ Y. Cai, T. Han, T. Li [1711.02180]
2. European Strategy Update Chapter on ν mass models — w/ T. Han, T. Li, X. Marcano, S. Pascoli, C. Weiland [1812.07831]
3. Other community documents and some newer results

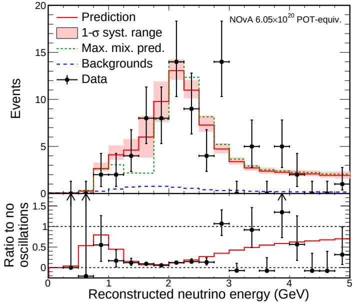
humble reminder: RH neutrinos (ν_R) are **not** the only explanation for tiny m_ν nor are they necessary (e.g., Type II Seesaw)

- Lack of guidance from data $\implies$ broad approach needed
- E.g., models without ν_R, UV completions of NSI, ...

the big physics picture



In neutrino fixed-target expts, ν_μ beams from collimated $\pi^\pm$, then studied at near and far detectors



Deficit/disappearance of expected ν_μ (+apperance of ν_e/ν_τ) interpreted as $\nu_{\ell_1} \to \nu_{\rm mass} \to \nu_{\ell_2}$ transitions/oscillations [E.g. NOνA ν_μ disapp., 1701.05891]

$\implies$ ν have mass!

So, neutrinos have masses $\lesssim \mathcal{O}(0.1)$ eV 

Is this a problem?

Yes.

Neutrinos Masses and New Particles?

Nonzero neutrino masses implies new degrees of freedom exist [Ma'98]

$$m_\nu \neq 0 + \text{left} - \text{handed (LH) Weak currents}$$

$(renormalizability)$

LH Majorana Mass : $m_\nu^L \overline{\nu_L} \nu_L^c$ | Dirac Mass : $m_\nu^D \overline{\nu_L} \nu_R$

$(gauge\ invariance)$

$m_\nu^L = y\langle\Delta\rangle$ or new dynamics | $m_\nu^D = y\langle\Phi_{\text{SM}}\rangle$

$m_\nu \neq 0$ **+ renormalizability + gauge inv.** $\Longrightarrow$ **new particles!**

- New particles might be charged under new or old gauge symm., E.g., ν_R may have $U(1)_{B-L}$ charge and Δ_L is an $SU(2)_L$ triplet
- Particles must couple to h or L, often inducing LNV/cLFV!

the slightly-less-big picture

models that explain tiny neutrino masses (Seesaw models)

are testable

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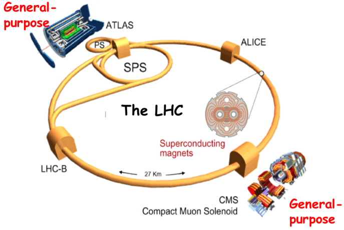
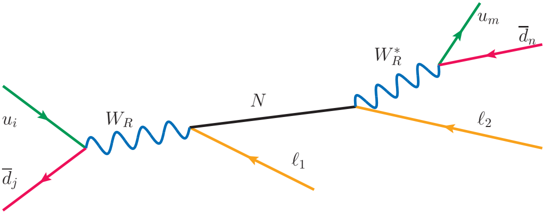
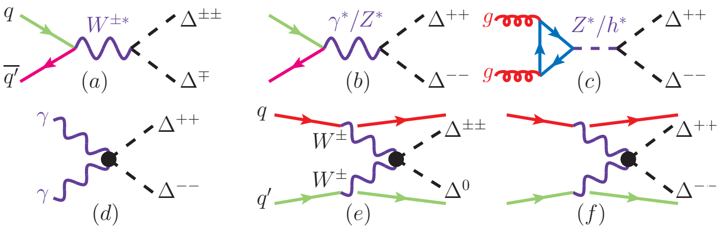
are testable, especially at colliders

for a review, see w/ Y. Cai, T. Li, and T. Han [1711.02180] as well as w/ Pascoli, et al [1812.08750]







the little picture

(our part!)

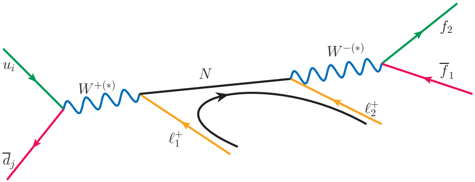
Snowmass 2013 inspired an effort to systematically modernize

the collider phenomenology for Seesaw models

for example

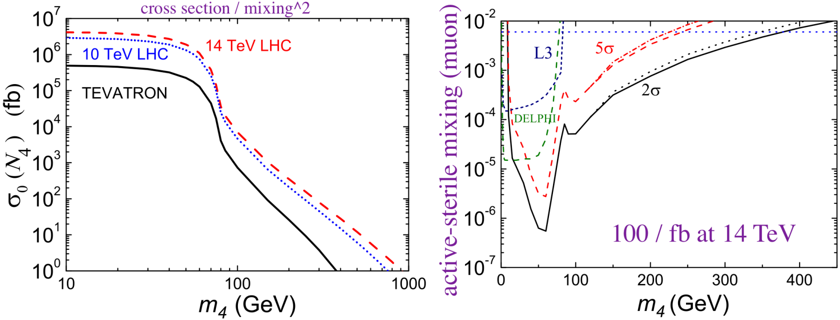
Historically, searches for N with $m_N > M_W$ relied on $(q\overline{q})$ annihilation

Keung & Senjanovic (PRL'83)



At the LHC, a canonical signature for N: $pp \rightarrow \ell_i^\pm \ell_j^\pm + nj +$ no MET

based on seminal works by K&S, del Aguila & Aguilar-Saavedra [0808.2468], and Atre, et al [0901.3589]

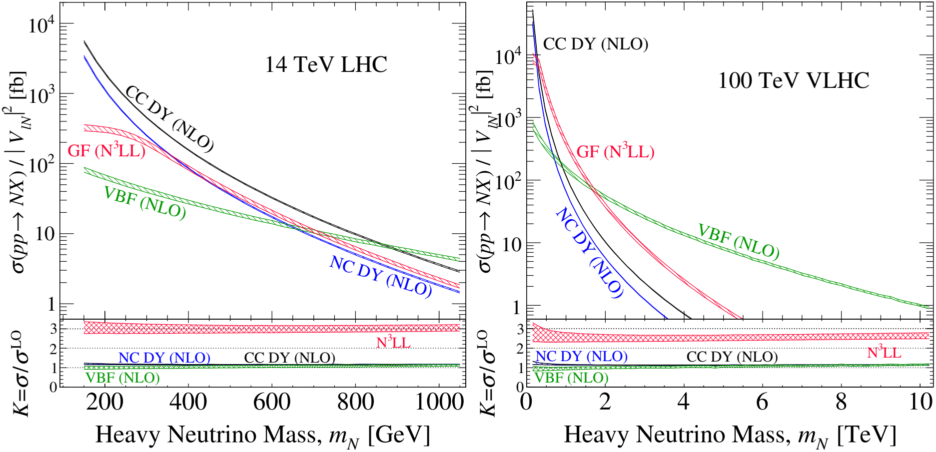


a lot has happened since 2013

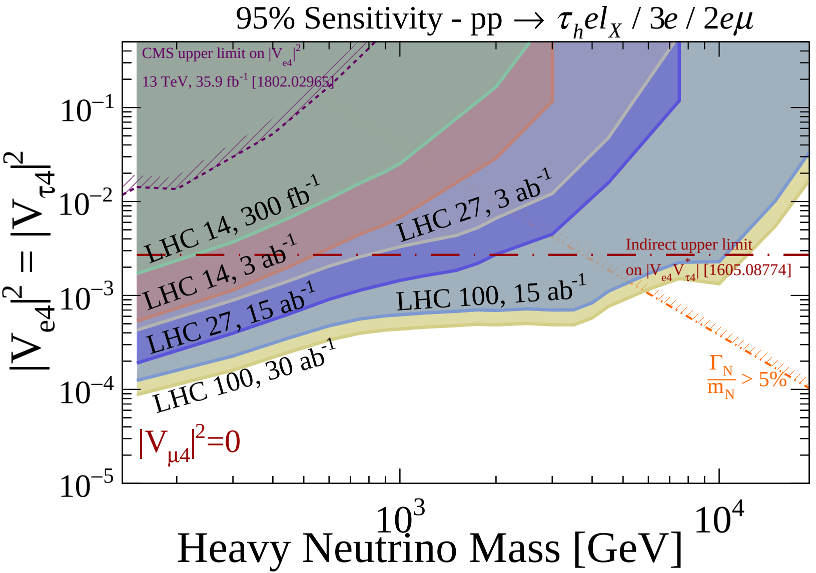
After lots of coffee and CPU hours

for details, see [1711.02180] and [1812.08750]

Plotted: Normalized production rate ($\sigma/|V|^2$) vs heavy N mass (m_N)



For $m_N = 10$ TeV and $|V_{\ell N}|^2 \sim 10^{-3}$, then at 100 TeV, one has $\mathcal{O}(30)$ VBF events after 30 ab^{-1}! If BR$\times\varepsilon\times\mathcal{A}\sim\frac{1}{3}$, then $\sqrt{N_{Obs.}} > 3\sigma$

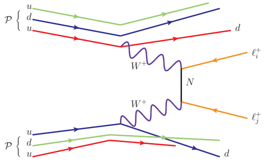


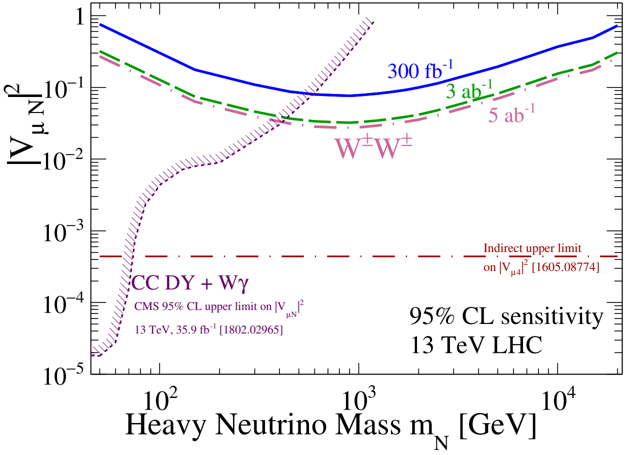
Major improvements $\implies > 10\times$ better sensitivity to LNV + cLFV

Only one example. See the big paper [1812.08750] for various flavor, Dirac vs Majorana, and $\sqrt{s}$ permutations

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

what if there are new forces?[1]

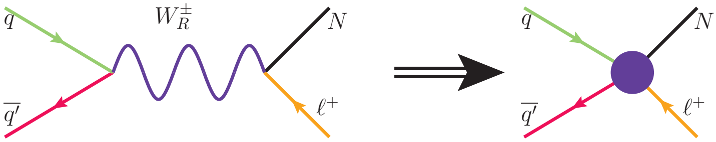
how heavy can we go?

[1] See also talk by N. Okada!

Interesting observation: vast literature on collider searches for N coupling to new gauge bosons, e.g., W_R in Left-Right Symmetric Model, *nearly everyone* assumes that both N and W_R are resonantly produed

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

(this is a UV realization of ν_REFT!)

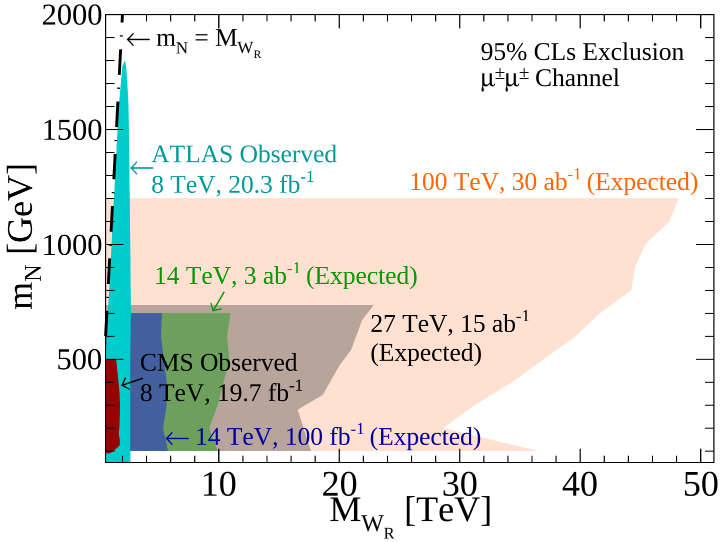


Exmaple: When $M_{W_R} \gg \sqrt{\hat{s}}$ but $m_N \lesssim \mathcal{O}(1)$ TeV, $pp \to N\ell + X$ in the LRSM and phenomenological Type I Seesaw are not discernible

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

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

How about reinterpreting search for phenomenological Type I Seesaw?



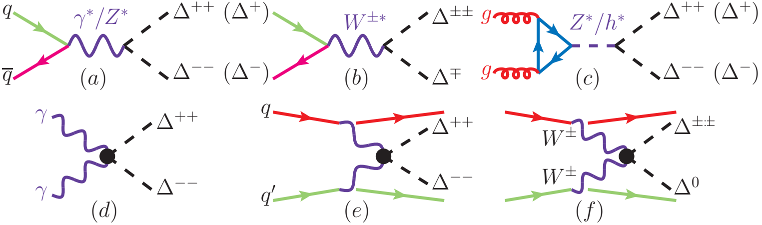
RR [1703.04669]

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

what if ν_R do not exist?

Type II Seesaw[2]



[2] Konetschny and Kummer ('77); Schechter and Valle ('80); Cheng and Li ('80); Lazarides, et al ('81); Mohapatra and Senjanovic ('81)

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Hypothesize a **scalar** $SU(2)_L$ triplet with **lepton number** $L = -2$

$$\hat{\Delta} = \frac{1}{\sqrt{2}} \begin{pmatrix} \Delta^+ & \sqrt{2}\Delta^{++} \\ \sqrt{2}\Delta^0 & -\Delta^+ \end{pmatrix}, \quad \text{with} \quad \mathcal{L}_{\Delta\Phi} \ni \mu_{h\Delta}\left(\Phi^\dagger \hat{\Delta} \cdot \Phi^\dagger + \text{H.c.}\right)$$

The mass scale $\mu_{h\Delta}$ breaks lepton number, and induces $\langle \Delta \rangle \neq 0$:

$$\sqrt{2}\langle \hat{\Delta} \rangle = v_\Delta \approx \frac{\mu_{h\Delta} v_{\rm EW}^2}{\sqrt{2} m_\Delta^2}$$

which leads to **left-handed Majorana masses** for neutrinos

$$\Delta\mathcal{L} = -\frac{y_\Delta^{ij}}{\sqrt{2}} \overline{L^c} \hat{\Delta} L = -\frac{y_\Delta^{ij}}{\sqrt{2}} \begin{pmatrix} \overline{\nu^{jc}} & \overline{\ell^{jc}} \end{pmatrix} \begin{pmatrix} 0 & 0 \\ v_\Delta & 0 \end{pmatrix} \begin{pmatrix} \nu^i \\ \ell^i \end{pmatrix}$$

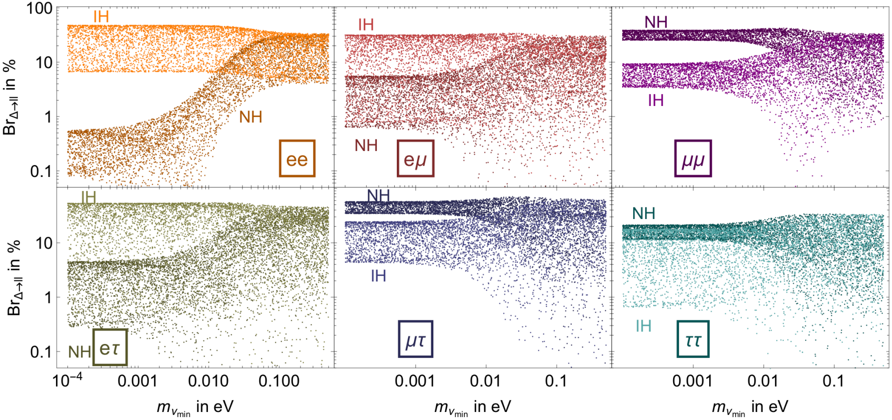
$$\ni -\frac{1}{2} \underbrace{\left(\sqrt{2} y_\Delta^{ij} v_\Delta\right)}_{= m_\nu^{ij}} \overline{\nu^{jc}} \nu^i$$

Fewer free parameters $\Longrightarrow$ richer experimental predictions

Fileviez Perez, Han, Li, et al, [0805.3536], Crivellin, et al [1807.10224], Fuks, Nemevšek, RR [1912.08975] + others

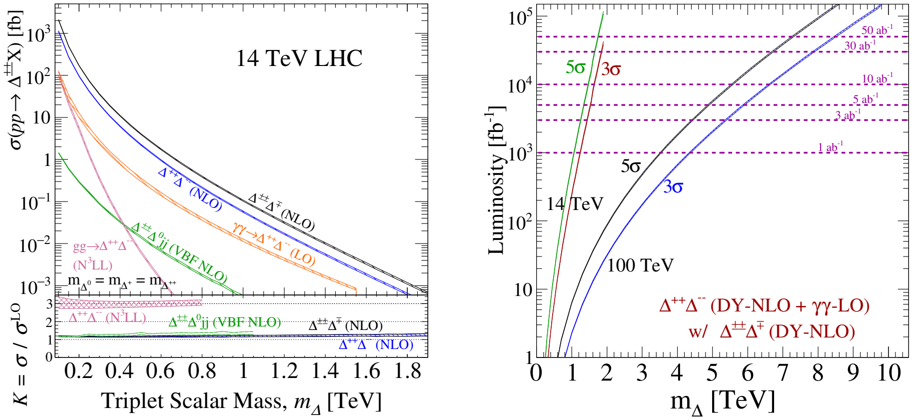
- E.g., Δ branching rates encode inverse (IH) vs normal (NH) ordering of light neutrino masses

$$\text{BR}(\Delta^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}) \sim y_\Delta^{ij} \sim (U^*_{\text{PMNS}}\tilde{m}_\nu^{\text{diag}}U^\dagger_{\text{PMNS}})_{ij}$$



NEW: a revised outlook for both $\sqrt{s} = 14$ TeV and 100 TeV!

w / Fuks and Nemevšek [1912.08975]



- At LHC with $\mathcal{L} = 5$ ab^{-1}, 3σ sensitivity up to $m_\Delta \sim 1.5$ TeV
- At $\sqrt{s} = 100$ TeV with $\mathcal{L} = 30 - 50$ ab^{-1} $\implies$ $m_\Delta \approx 8 - 9$ TeV
- **Warning**: can be improve for specialized final state / parameter space

Lots of improvement since last Snowmass. What has changed?

Improved outlook for collider tests of LNV and cLFV stems from:

- New channels, e.g., VBF, GF, $W/Z/h/\gamma$ associated production
- New kinematic limits, e.g., off-shell portals, boosted topologies
- Predictions for **both** Dirac and Majorana particles w/ LNV and cLFV
- Quantitatively reliable descriptions of jets, kinematics, and rates

[3] UFOs encode Feynman rules for mainstream event generators, e.g. `MadGraph`, to simulate BSM (not just colliders)

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Part of this stems from improved MC support!

- Ongoing efforts within `FeynRules` and `MadGraph` MC collaborations
- Mainstream tools with widespread use and technical support

Available UFOs[3]

- Type I Seesaw - feynrules.irmp.ucl.ac.be/wiki/HeavyN (Requested/used by ATLAS+CMS)
- Type II Seesaw - feynrules.irmp.ucl.ac.be/wiki/TypeIISeesaw (Requested/used ATLAS)
- Left-Right Symmetry - feynrules.irmp.ucl.ac.be/wiki/EffLRSM (Requested/used ATLAS)
- Generic W'/Z' feynrules.irmp.ucl.ac.be/wiki/WZPrimeAtNLO
- ... with more in development (collaborators and friends are welcome!)

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Summary

Lack of clear guidance from data and theory means we must take a broad, open approach to uncovering the origin of tiny ν masses.

- Colliders are *incredibly complementary* to oscillation and $0\nu\beta\beta$ expts
  - Direct production of Seesaw particles
  - Test UV realizations of low-scale neutrino EFTs / NSIs
- The **European Strategy Update** has officially concluded
  - Lots of encouraging projections on collider sensitivity to LNV and cLFV
  - New analysis techniques $\implies$ new territory for cLFV and LNV
  - N, $H^{\pm\pm}$, W_R, Z_{B-L}, $T^{0,\pm}$ masses up to 10-50 TeV at $\sqrt{s} = 100$ TeV
  - Studies aided by publication of user friendly simulation tools
- The **Snowmass Process** is underway!
  - Community studies are iterative and we plan to keep up the work!
  - Lots not covered todays, so go check out the review! [1711.02180]

Thank you.