A theory perspective on sterile neutrinos at colliders

Lomonosov Conference – Moscow State University, Zoom Campus

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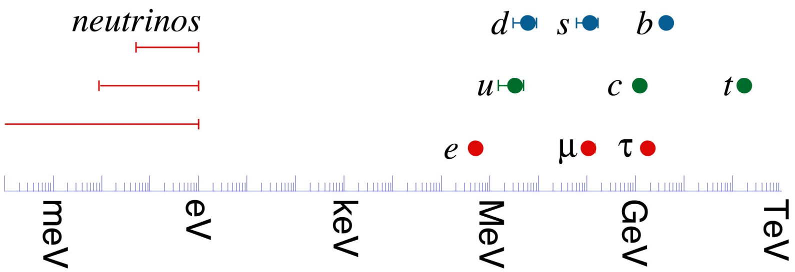
the ν case for new physics

Problem: according to the SM, $m_\nu = 0$. (The data disagree, obviously.)

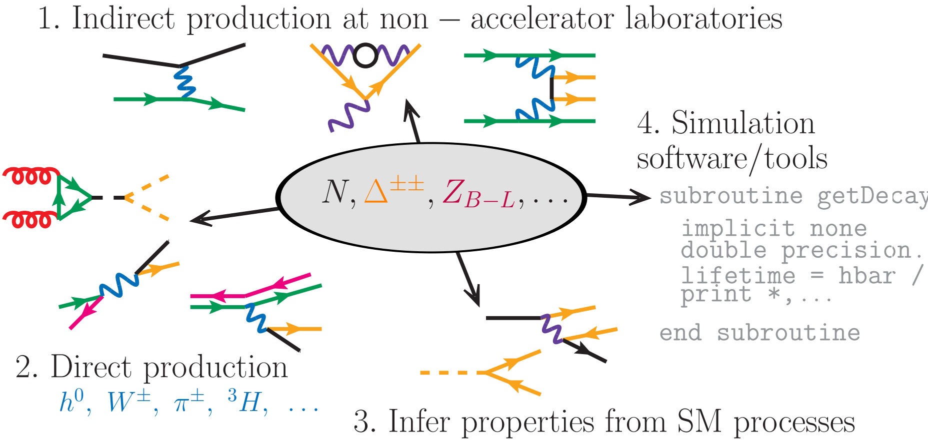


Neutrino masses ('15) $\Longrightarrow$ **many open questions:**

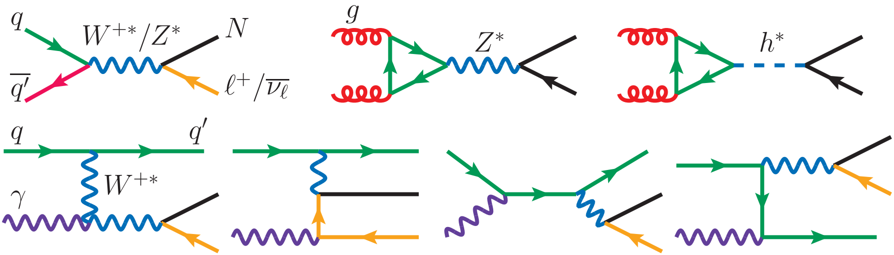
- ν have mass. What is generating m_ν?
- ν masses are *tiny*. What sets the scale of m_ν?
- m_ν are nearly degenerate. What sets the pattern of m_ν?
- ν carry no QCD/QED charge. Are $\nu, \overline{\nu}$ the same (Majorana)?

Neutrino mass (Seesaw) models give answers to these questions!

Many ways to explore neutrino mass models



Sterile neutrinos and the Type I Seesaw Mechanism(s)[1]



[1] See backup for Weinberg Operator!

To generate Dirac masses for ν like other SM fermions, we need ν_R

$$\mathcal{L}_{\nu \text{ Yuk.}} = -y_\nu \overline{L}\tilde{\Phi}\nu_R + \cdots = \underbrace{-y_\nu \langle \Phi \rangle}_{\equiv m_\nu} \overline{\nu_L}\nu_R + \ldots$$

ν_R do not exist in the SM, so pretend that they do!

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Type I Seesaw mechanisms: hypothesize SM + ν_R with right-handed Majorana mass $m_R = \Lambda_{LNV}$

- **Depending** on assumptions, $m_\nu \sim \Lambda_{LNV}$ or $\langle \Phi \rangle^2 / \Lambda_{LNV}$
- **Important:** EW-scale N do **not** decouple in pure Type I, only LNV

  Pascoli, et al [1712.07611]
- **Corollary:** EW-scale N + LNV $\implies$ more new particles RR [1703.04669]

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At low energies, ν_ℓ and ν_R have same quantum numbers $\implies$ mixing!

- Express chiral/interaction eigenstates in terms of mass states:

$$\underbrace{|\nu_L\rangle}_{\text{interaction basis}} = \cos\theta \underbrace{|\nu\rangle}_{light} + \sin\theta \underbrace{|N\rangle}_{heavy}$$

In practice (1 slide)

Generically paramerize active-sterile neutrino mixing via

Atre, Han, Pascoli, Zhang [0901.3589]

$$\underbrace{\nu_{\ell L}}_{\text{flavor basis}} \approx \underbrace{\sum_{m=1}^{3} U_{\ell m}\nu_m + V_{\ell m'=4} N_{m'=4}}_{\text{mass basis}}$$

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

$$\mathcal{L}_{\text{Int.}} = -\frac{g_W}{\sqrt{2}} W^-_\mu \sum_{\ell=e}^{\tau} \left[\bar{\ell}\gamma^\mu P_L \nu_\ell\right] + \text{H.c.}, \qquad \text{where } P_L = \frac{1}{2}(1-\gamma^5)$$

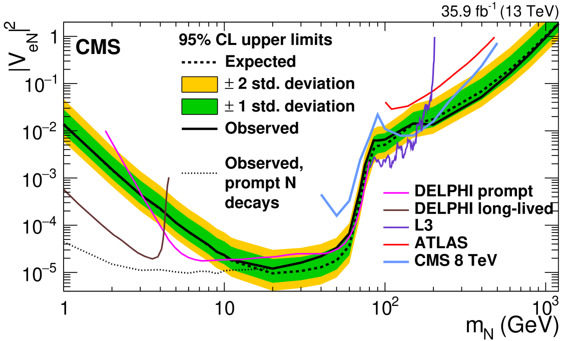
$\implies$ SM W coupling to N and charged **leptons** in the **mass basis is**

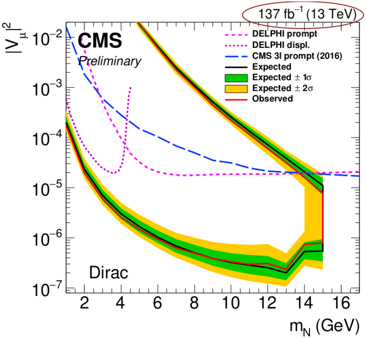
$$\mathcal{L}_{\text{Int.}} = -\frac{g_W}{\sqrt{2}} W^-_\mu \sum_{\ell=e}^{\tau} \left[\bar{\ell}\gamma^\mu P_L \left(\sum_{m=1}^{3} U_{\ell m}\nu_m + V_{\ell N} N\right)\right] + \text{H.c.}$$

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

what do the experiments say?

Plotted: LHC 13 limits in search for $pp \to 3\ell + MET \quad (\ell_X = e, \mu)$





No discovery ☹ but there is hope with 20× more data! ☺

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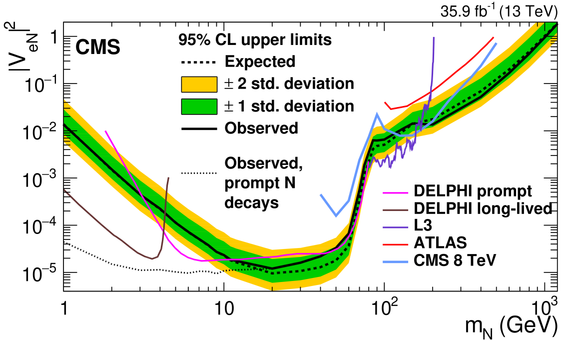

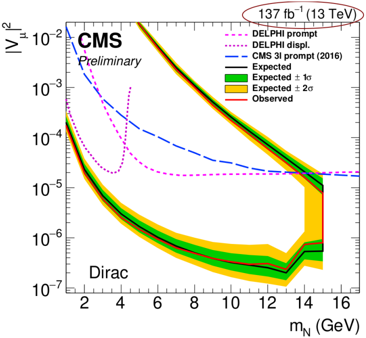

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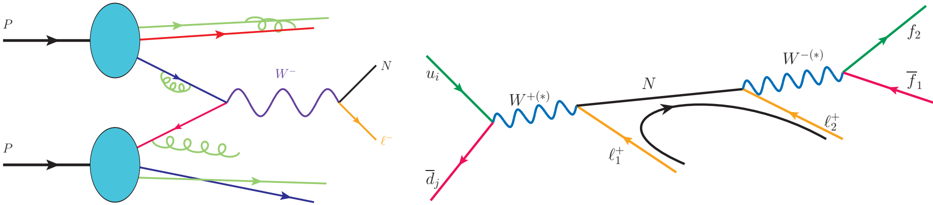
- (L) CMS experiments's trilepton search for short-lived N [1802.02965]
- (R) **NEW:** search for long-lived N [CMS-PAS-EXO-20-009]
- same-sign dilepton searches [1806.10905]
- ATLAS search for long-lived N [1905.09787]

Take away: major improvement in sensitivity! (not just energy and lumi.)

Three sources of improvement

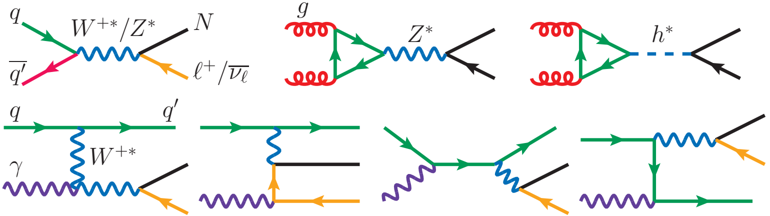
1. New production channels

Historically, searches for *N* relied on $(q\overline{q})$ annihilation   Keung & Senjanovic (PRL'83)



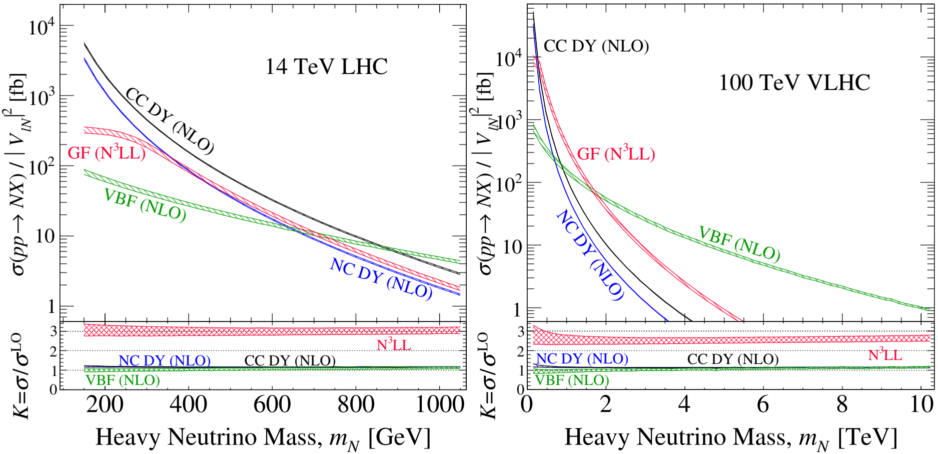
At the LHC, a **canonical** signature for *N*: $pp \to \ell_i^{\pm}\ell_j^{\pm} + nj +$ no MET

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



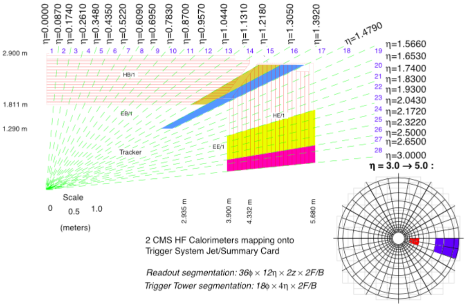
After lots of CPU hours (and coffee!) for details, see RR, et al, [1711.02180] and [1812.08750]

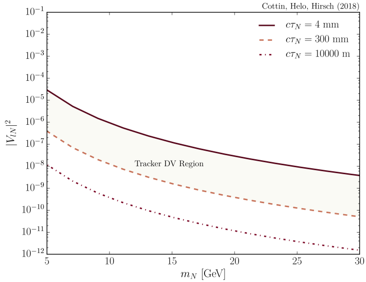
Plotted: Normalized production rate ($\sigma/|V|^2$) vs heavy N mass (m_N)



Wild interplay between proton structure and matrix elements!

2. New search strategies (e.g., displaced vertex searches)





Decays of light N through SM weak currents can be very long-lived:

$$\Gamma_{\rm Tot.} \sim G_F^2 m_N^5 \sum |V|^2 \text{ (small } |V| \implies \text{ long lifetime!)}$$

$$\implies d_0 = \beta c \tau = \frac{\beta c \hbar}{\Gamma_{\rm Tot.}} \sim \frac{1.45 \ m}{\sum |V|^2} \left(\frac{1 \ \text{GeV}}{m_N}\right)$$

(Near) detectors have *finite* detector volume, with radius $< \mathcal{O}(10)$ m

Many good works, e.g., Cottin, Helo, Hirsch, et al [1801.02734 ,1806.05191,2105.13851]

3. New tools

Searching for heavy Majorana and (pseudo)Dirac neutrinos N at LHC follows any other analysis chain

- BIG PROBLEM/SOLUTION (sterile neutrinos!)✓
- Signal/bkg simulation with favorite generator ← **updates here!**
  e.g., `MadGraph5`, `Whizard`, `SHERPA`
- Collect data, control regions, unblind, do some statistics ✓

Major effort to support neutrino mass models in your favorite generator

- Universal FeynRules Object (UFO) libs. encode Feynman rules (.py) that work with popular event generators, e.g., `MadGraph5`, `Whizard`

Alloul, Christensen, Duhr, Degrande, and Fuks feynrules.irmp.ucl.ac.be

HeavyN: feynrules.irmp.ucl.ac.be/wiki/HeavyN

HeavyN_vSMEFTdim6, TypeIISeesaw, EffLRSM, WZPrime, SMWeinberg also available feynrules.irmp.ucl.ac.be/wiki/NLOModels!

HeavyN : The Standard Model + Heavy Neutrinos at NLO in QCD

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In collaboration with:

D. Alva and T. Han [1]; C. Degrande, O. Mattelear, and J. Turner [2]; S. Pascoli and C. Weiland [3, 4]; and V. Cirigliano, W. Dekens, J. de Vries, K. Fuyuto, E. Mere

Usage resources

- For detailed instructions and examples on using the HeavyN UFO libraries, see C. Degrande, et al, arXiv:1602.06957 and S. Pascoli, et al, arXiv:1812.08750 .
- ***New*** For heavy neutrinos in vSMEFT, see V. Cirigliano, et al, arXiv:2105.11462.
- See **Validation** section below for additional information

Citation requests

- For studies of heavy Majorana neutrinos, please consider citing [6] for the Lagrangian and [1, 2] for the Majorana FR/UFO files.
- For studies of heavy Dirac neutrinos, please also consider citing [4].
- ***New*** For studies of heavy neutrinos in vSMEFT, please consider citing [5].

Model Description

Majorana N

This effective/simplified model extends the Standard Model (SM) field content by introducing three right-handed (RH) neutrinos, which are singlets under the SM gauge s
Majorana mass. After electroweak symmetry breaking, the Lagrangian with three heavy Majorana neutrinos *Ni* (for i=1,2,3) is given by [6]

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_N + \mathcal{L}_{N\ \rm Int.} \qquad (1$$

The first term is the Standard Model Lagrangian. In the mass basis, i.e., after mixing with active neutrinos, the heavy Majorana neutrinos' kinetic and mass terms are

$$\mathcal{L}_N = \frac{1}{2}\overline{N_k} i \not{\partial} N_k - \frac{1}{2} m_{N_k} \overline{N_k} N_k, \quad k = 1, \ldots, 3, \qquad (1$$

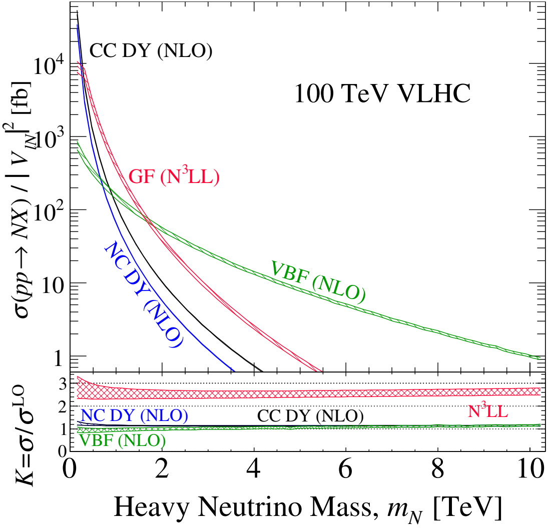
FeynRules to MadGraph5aMC@NLO

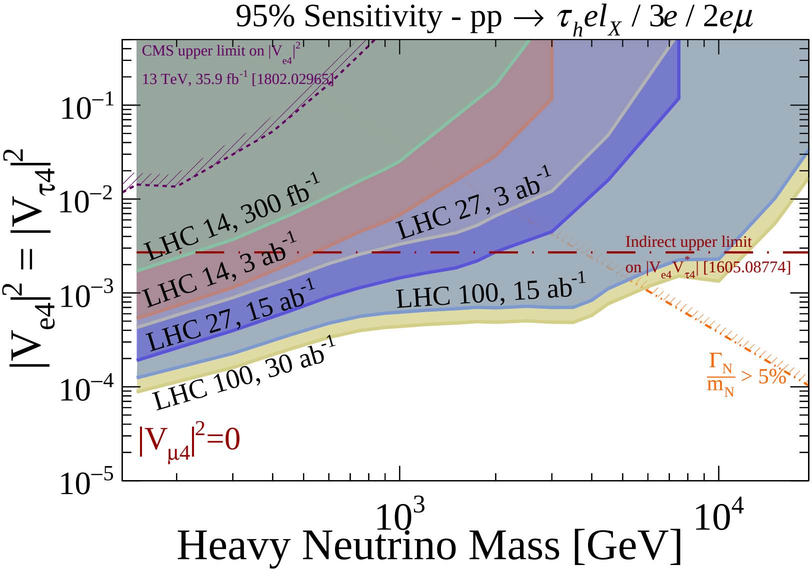
Given a *Universal FeynRules Object* (UFO) file, run `mg5amc` out of the box

```
 $ ./bin/mg5_aMC
> import model SM_HeavyN_NLO
> define p = g u c d s b u~ c~
d~ s~ b~ a
> define ell = mu+ mu-
> generate p p > n2 ell [QCD]
> output PP_Nmu_NLO
> launch PP_Nmu_NLO
> order=NLO
> fixed_order=ON
> set LHC 100
> set vmun2 1.0
> set mn2 scan:range(5,1001,25)
> set wn2 auto
```

$\mathcal{O}(10)$ lines to get each curve →

Pascoli, RR, Weiland [1812.08750]





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

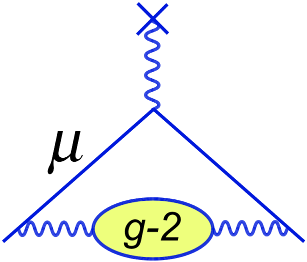
Only a few results. See the big paper for various flavor, Dirac vs Majorana, and $\sqrt{s}$ permutations [1812.08750]

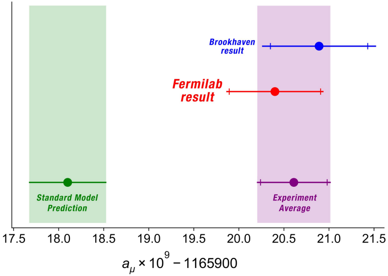
New ideas

NEW[2] sterile neutrinos and Δa_{μ}

[2] V. Cirigliano, W. Dekens, J. de Vries, K. Fuyuto, E. Mereghetti [2105.11462]

Anomalous magnetic moment of the μ





Fermilab's Muon g-2 has *confirmed* that $a_\mu = (g_\mu - 2)/2$ is *a bit* large

[2104.03281]

$$a_\mu^{\text{average}} = (116\,592\,061 \pm 41) \cdot 10^{-11}$$

$$a_\mu^{\text{SM}} = (116\,591\,810 \pm 43) \cdot 10^{-11}$$

The difference? Large enough to start taking BSM solutions seriously.

$$\Delta a_\mu = (251 \pm 59) \cdot 10^{-11} \text{ or about } 4.2\sigma!$$

Can new N interactions account for this?

Yes, in a surprisingly succinct manner.

ν**SMEFT** is the Standard Model Effective Field Theory extended by ν_R

$\psi^2 H^3$		$\psi^2 H^2 D$		$\psi^2 HX(+\text{H.c.})$	
$\mathcal{O}_{L\nu H}(+\text{H.c.})$	$(\bar{L}\nu_R)\tilde{H}(H^\dagger H)$	$\mathcal{O}_{H\nu}$	$(\bar{\nu}_R\gamma^\mu\nu_R)(H^\dagger i\overleftrightarrow{D}_\mu H)$	$\mathcal{O}_{\nu B}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\tilde{H}B^{\mu\nu}$
		$\mathcal{O}_{H\nu e}(+\text{H.c.})$	$(\bar{\nu}_R\gamma^\mu e)(\tilde{H}^\dagger iD_\mu H)$	$\mathcal{O}_{\nu W}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\tau^I\tilde{H}W^{I\mu\nu}$
$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$		$(\bar{L}R)(\bar{L}R)(+\text{H.c.})$	
$\mathcal{O}_{\nu\nu}$	$(\bar{\nu}_R\gamma^\mu\nu_R)(\bar{\nu}_R\gamma_\mu\nu_R)$	$\mathcal{O}_{L\nu}$	$(\bar{L}\gamma^\mu L)(\bar{\nu}_R\gamma_\mu\nu_R)$	$\mathcal{O}_{L\nu Le}$	$(\bar{L}\nu_R)\epsilon(\bar{L}e)$
$\mathcal{O}_{e\nu}$	$(\bar{e}\gamma^\mu e)(\bar{\nu}_R\gamma_\mu\nu_R)$	$\mathcal{O}_{Q\nu}$	$(\bar{Q}\gamma^\mu Q)(\bar{\nu}_R\gamma_\mu\nu_R)$	$\mathcal{O}_{L\nu Qd}$	$(\bar{L}\nu_R)\epsilon(\bar{Q}d)$
$\mathcal{O}_{u\nu}$	$(\bar{u}\gamma^\mu u)(\bar{\nu}_R\gamma_\mu\nu_R)$			$\mathcal{O}_{LdQ\nu}$	$(\bar{L}d)\epsilon(\bar{Q}\nu_R)$
$\mathcal{O}_{d\nu}$	$(\bar{d}\gamma^\mu d)(\bar{\nu}_R\gamma_\mu\nu_R)$				
$\mathcal{O}_{du\nu e}(+\text{H.c.})$	$(\bar{d}\gamma^\mu u)(\bar{\nu}_R\gamma_\mu e)$				
$(\bar{L}R)(\bar{R}L)$		$(\not{L}\cap B)(+\text{H.c.})$		$(\not{L}\cap\not{B})(+\text{H.c.})$	
$\mathcal{O}_{Qu\nu L}(+\text{H.c.})$	$(\bar{Q}u)(\bar{\nu}_R L)$	$\mathcal{O}_{\nu\nu\nu\nu}$	$(\bar{\nu}_R^c\nu_R)(\bar{\nu}_R^c\nu_R)$	$\mathcal{O}_{QQd\nu}$	$\epsilon_{ij}\epsilon_{\alpha\beta\sigma}(Q^i_\alpha CQ^j_\beta)(d_\sigma C\nu_R)$
				$\mathcal{O}_{udd\nu}$	$\epsilon_{\alpha\beta\sigma}(u_\alpha Cd_\beta)(d_\sigma C\nu_R)$

Table 1: The complete basis of dimension-six operators involving ν_R taken from Ref. [24]. The operators are expressed in terms of a column vector of n gauge singlet fields, ν_R, and of SM fields, the lepton and Higgs doublets, L and H, the quark left-handed doublet $Q = (u_L, d_L)^T$, and the right-handed fields e, u, and d.

Unexpectedly, only one νSMEFT can generate the right Δa_μ

$$\mathcal{L}_{H\nu e} \approx \frac{gv^2}{2\sqrt{2}\Lambda^2}\sum_{k=1}^{3}\left[\bar{C}_{H\nu e}\right]_{k\ell}\left(\overline{N_k}\gamma^\mu P_R\,\ell_R\right)W^+_\mu\left(1+\frac{h}{v}\right)^2 + \text{H.c.}$$

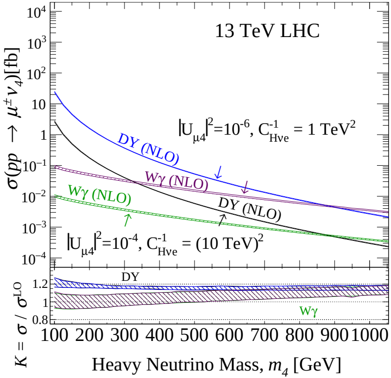
This generates Δa_μ of the form

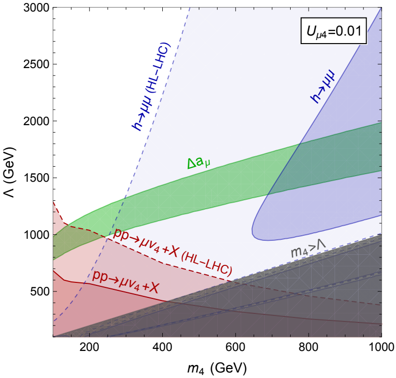
$$\Delta a_\mu \sim -\frac{2m_\mu m_N}{(4\pi)^2\Lambda^2}\text{Re}\left(V_{\mu N}\left[\bar{C}_{H\nu e}\right]_{N\mu}\right)$$

(see [2105.11462] for exact formula!)

We created a new UFO HeavyN_vSMEFTdim6 containing $\mathcal{O}_{H\nu e}$

Already available from the FeynRules UFO database: feynrules.irmp.ucl.ac.be/wiki/HeavyN





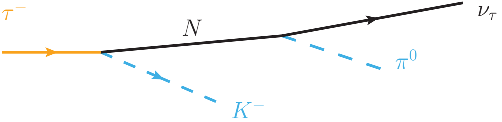
Conclusion: If N are involved in Δa_μ, then expect something in

$$pp \to N\mu^\pm + X \text{ and } H \to \mu^+\mu^-$$

in Run III data and at the HL-LHC (see the paper for more details! [2105.11462])

In development[3] ultra light sterile neutrinos

[3] Fernandez Martinez, Hernandez, Jeon, Kulkarni, Lopez, RR [In Progress]



Question: How light N can accelerator experiments see?

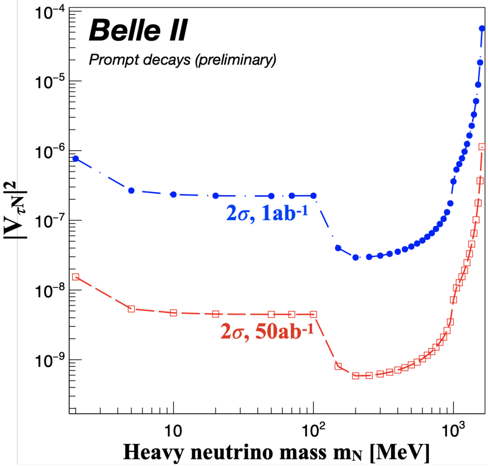
Answer: Pretty small!

- Low-$\sqrt{s}$ colliders are meson and τ factories!

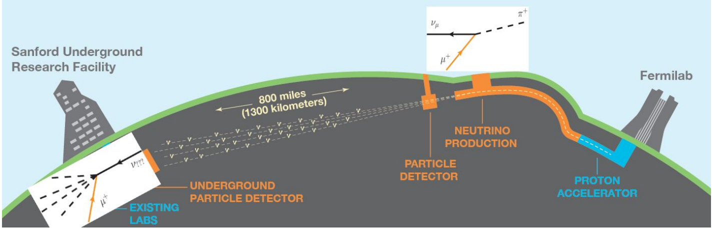
- Ultra-high lumi. for ultra-tiny masses and mixing

- Competitive with beam dumps and meson factories

e.g., Bondarenko, et al [1805.08567]; de Vries, et al [2010.07305]



Summary



Big picture: ν unambiguously point the existence of new physics!!

Active research community using accelerators to investigate how and why some matter (ν) is *much* lighter than others

Outlook: is incredibly encouraging!

- The LHC has collected only $< 5\%$ of full dataset
- New accelerator-based experiments are coming online
- New ideas are creating new windows into the nature of ν

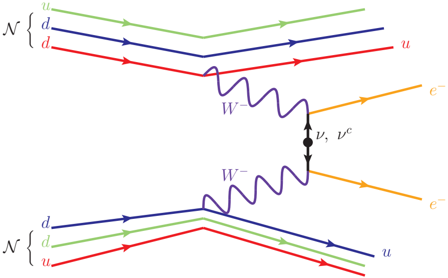

neutrino
collider
model
production
TeV
LHC
boson
hadron
heavy
decay
mass
jet
processes
searches
order
GeV
process
seesaw
standard
veto
channel
leading
data
range
test
discovery
context
Type
VBS
quark
Carlo
Monte
current
top
tool
large
well
due
probe
result
available
using
QCD
pair
one
NLO
cross
system
review
impact
mechanism
LRSM
high
rate
NNLO
via
100
iii
transverse

Thank you.

Backup: Weinberg Opterator

A fun idea: **is it possible to see the neutrinoless $\beta\beta$ process $(0\nu\beta\beta)$**

at accelerators? Fuks, Neundorf, Peters, RR, Saimpert [2011.02547, 2012.09882]



Why? **Colliders, beam dumps, etc., can access μ and τ sectors!**

Many ways to explain $m_\nu \neq 0$, so take an effective field theory approach:

The **Weinberg operator** is the only SMEFT operator at $d = 5$: Weinberg ('97)

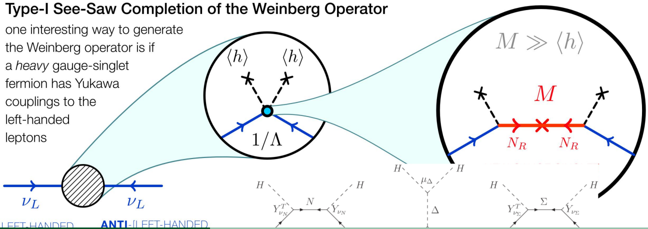
$$\mathcal{L} = \frac{C_5^{\ell\ell'}}{\Lambda}[\Phi \cdot \overline{L}_\ell^c][L_{\ell'} \cdot \Phi] \quad \overset{\text{low energies (EWBS)}}{\longrightarrow} \quad \frac{1}{2}\underbrace{\frac{C_5^{\ell\ell'}}{\Lambda}\langle\Phi\rangle^2}_{=m_{\ell\ell'}} \times \overline{\nu_{L\ell}^c}\nu_{L\ell'}$$

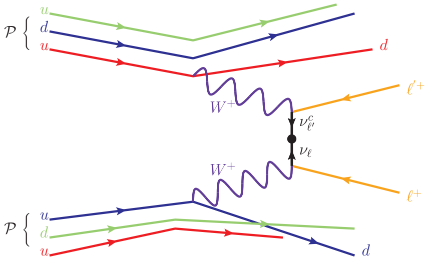
Can be generated in **many** ways at tree- and loop-level

Eg. Ma ('98), Bonnet, et al [1204.5862]

Importantly, after EWSB, generates a Majorana mass matrix for ν

$$m_{\ell\ell'} = C_5^{\ell\ell'}\langle\Phi\rangle^2/2\Lambda \quad \leftarrow \text{(flavor basis!)}$$



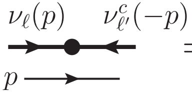


The helicity amplitude for the $0\nu\beta\beta$ process $q\overline{q'} \to \ell_1^+\ell_2^+\overline{f}f'$ is

$$\mathcal{M}_{LNV} = J^{\mu}_{f_1 f_1'} J^{\nu}_{f_2 f_2'} \Delta^W_{\mu\alpha}\Delta^W_{\nu\beta} \underbrace{T^{\alpha\beta}_{LNV}\mathcal{D}(p_\nu)}_{\text{lepton current}}$$

Difficult to simulate events since Weinberg op. modifies propagator of ν_ℓ

modern Monte Carlo tools work in mass basis and do not like the idea of modifying $\langle 0|\overline{\nu_{\ell'}}\nu_\ell|0\rangle$



$$= \frac{i\not{p}}{p^2}\ \frac{-iC_5^{\ell\ell'}v^2}{\Lambda}\ \frac{i\not{p}}{p^2} = \frac{im_{\ell\ell'}}{p^2}$$

Solution: Treat vertex as a particle! Invent unphysical Majorana fermion with (small) mass $m_{\ell\ell}$ that couples to all lepton flavors

recovers right behavior!

$$T^{\alpha\beta}_{LNV}\mathcal{D}(p_\nu) \propto \gamma^\alpha P_L \frac{i(\not{p}+m_{\ell\ell'})}{p^2-m^2_{\ell\ell'}}\gamma^\beta P_R = \gamma^\alpha P_L \frac{im_{\ell\ell'}}{p^2} P_L \gamma^\beta \times \left[1 + \mathcal{O}\left(\left|\frac{m^2_{\ell\ell'}}{p^2}\right|\right)\right]$$

Plotted: Normalized production rate ($C_5 = 1$) vs scale (Λ)

w/ Fuks, Neundorf, Peters, Saimpert [2012.09882]

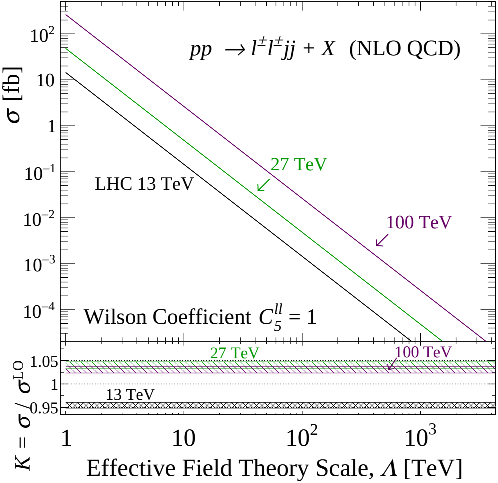
Full $2 \to 4$ calculation at NLO(+PS) in QCD is more involved

Used mg5amc + NEW SMWeinberg UFO libraries

Driven by $W_0^+ W_0^+$ scattering
$\hat{\sigma}(W^+ W^+ \to \ell^+ \ell^+) \sim \frac{|C_5^{\ell\ell}|^2}{18\pi\Lambda^2}$

Once σ is obtained for a "high" scale, i.e., $C_5^{\ell\ell'} = 1, \Lambda = 200$ TeV, rescale for other Λ / C_5.

C_5^{ee}/Λ is heavily constrained. **What can the LHC say about $C_5^{\ell\ell'}$?**

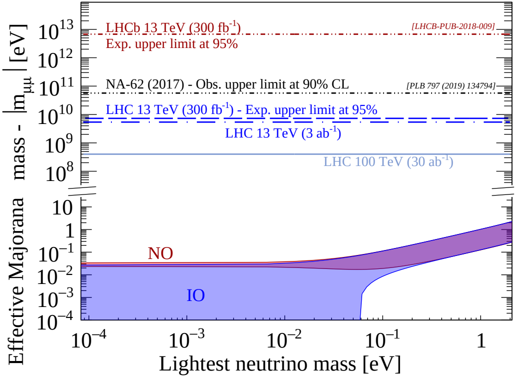


With a VBS-style analysis $\mathcal{L} = 300$ (3000) fb^{-1}

$$\Lambda/|C_5^{\mu\mu}| \lesssim 8.3\ (11)\ \text{TeV} \implies |m_{\mu\mu}| \gtrsim 7.3\ (5.4)\ \text{GeV}$$

Plotted: Allowed and projected reach of $|m_{\mu\mu}|$ vs lights ν mass

$$|m_{\ell\ell'}| = |C_5^{\ell\ell'}|\langle\Phi\rangle^2/2\Lambda = |\sum_{k=1}^{3} U_{\ell k} m_{\nu_k} U_{\ell' k}|$$



Competitive race between accelerator-based experiments; all analyses can be improved!