Theory landscape of Heavy Neutral Leptons

LHCP2022, University of Zoom

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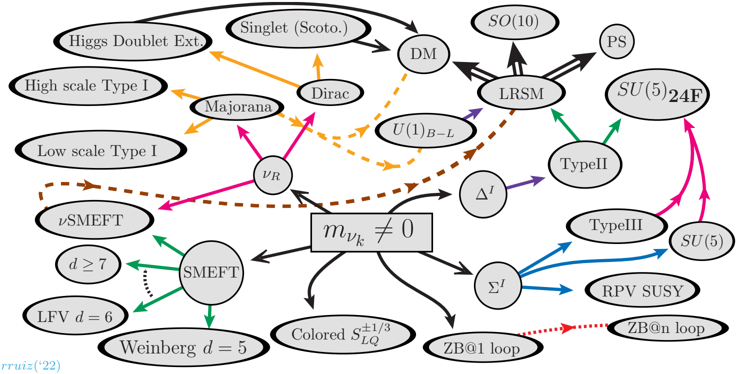
16 May 2022

good morning / afternoon / evening

and thank you for the invitation!

18'+3' ☹ to survey the "theory landscape" of heavy neutrinos[1] N



[1] My choice of languge: not "right-handed" since N are mass eigenstate (ν_R / ν_L are RH/LH chiral states); not "sterile" since could carry new gauge charges; not "HNL" because I am a proud to work on "neutrinos" ☺

stay tuned for impressive update of “experimental landscape” ☺

the big elephant: the problem of nonzero m_ν

SM's guidance on m_ν

Problem: according to the SM, $m_\nu = 0$ (not enough ingredients given SM symm.!)

SM's guidance on m_ν

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

$(renormalizability)$

LH Majorana mass : $\frac{1}{2} m_\nu^L \overline{\nu_L} \nu_L^c$ — Dirac mass : $m_\nu^D \overline{\nu_L} \nu_R$

$(gauge\ invariance)$

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

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

Ma('98) + others

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

[Ma ('98)]

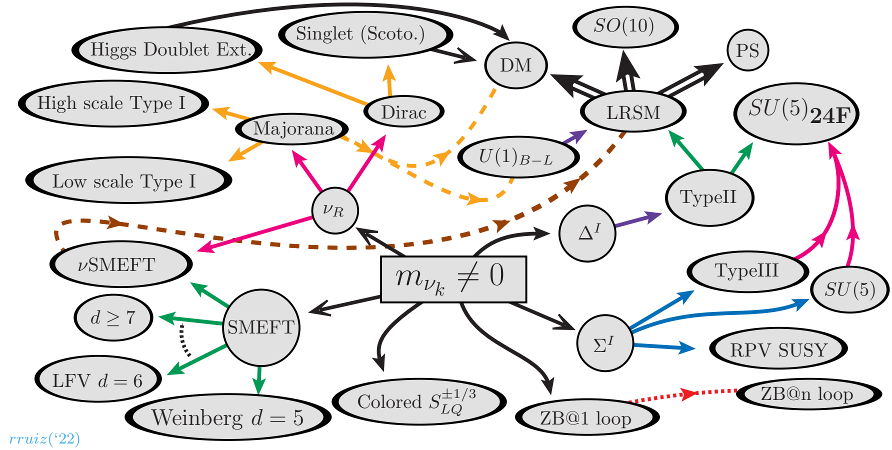
Incredibly powerful but also incredibly vague since new particles:

- ... can be light ☺ or heavy ☹
- ... can be short-lived ☺ or long-lived ☺
- ... can have SM gauge interactions, e.g., $H^{\pm\pm}$ in Type II, Zee-Babu

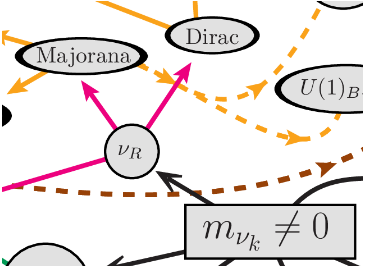
  (ν_R not always needed!)
- ... can have new gauge interactions, e.g. ν_R and Z_{B-L} in $U(1)_{\rm B-L}$
- ... must couple to Φ_{SM} and L, often inducing collider processes that do not conserve **lepton number (LNV)** and/or **lepton flavor (LFV)**

These core ideas can be realized in ***many*** ways! (including without ν_R)

Minkowski ('77); Yanagida ('79); Glashow & Levy ('80); Gell-Mann et al., ('80); Mohapatra & Senjanović ('82); + *many* others



the heavy neutrino landscape [2]



[2] For reviews at colliders, see Cai, Han, Li, RR [1711.02180] and Pascoli, RR, Weiland [1812.08750]

adding ν_R to the SM (for experts and non-experts)

For everyone

In pure Type I scenarios (SM+ν_R), tiny m_ν obtained in two ways:

greatly clarified by Pascoli, et al, [1712.07611]

1. **High-scale seesaw**:

$$\Lambda_{LNV} \gg \langle \Phi_{SM} \rangle \implies m_\nu \sim m_D \left(\frac{m_D}{\Lambda_{LNV}} \right), \quad m_N \sim \Lambda_{LNV}$$

Generically leads to decoupling of N and LNV from colliders

2. **Low-scale seesaw**:

$$\Lambda_{LNV} \ll \langle \Phi_{SM} \rangle \implies m_\nu \sim \Lambda_{LNV} \left(\frac{m_D}{m_R} \right)^2, \quad m_N \sim m_R$$

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

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

A priori, no obvious preference without additional theory prejudice:

- **Corollary 1:** Low-scale Type I + if ν approx. massless on expt scale, i.e., $\tilde{m}_\nu^2/Q^2 \approx 0 \implies$ approx. L conservation w/ Pascoli, et al, [1812.08750]

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

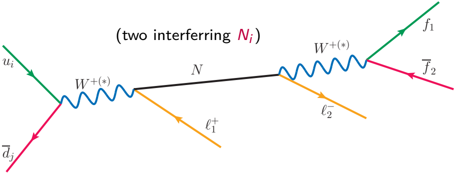
  warning: limits from **LNV** searches not applicable to Dirac N

- **Corollary 2:** Collider LNV via $N_i \implies$ *more new particles!* RR [1703.04669]

What about quasi-degenerate Majorana neutrinos?

Low-scale Seesaws (Inverse, Linear, etc.) hypothesize SM+ν_R+S and get three mass eigenstates per generation: (for a review, see C. Weiland's thesis [1311.5860])

$$m_\nu \sim \underbrace{\Lambda_{LNV}}_{\text{this is small!!}} \left(\frac{m_D}{m_R}\right)^2 \qquad m_{N_{1,2}} \sim \pm\left(\sqrt{m_R^2 + m_D^2} \mp \mathcal{O}(\Lambda_{LNV})\right)$$



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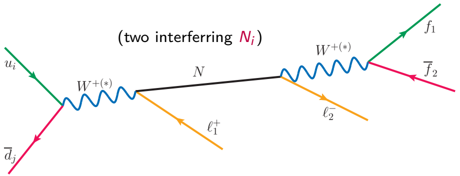
Minus sign is a CP phase but leads to cancelations in matrix elements:

$$-i\mathcal{M}_{\rm LNV}(W \to \ell^\pm\ell^\pm X) \sim m_{N_1} + e^{i\Delta\phi} m_{N_2} \sim \mathcal{O}(\Lambda_{LNV}) \sim m_\nu$$

(this is small!!)

(two interferring N_i)



Bray,Lee, Pilaftsis [hep-ph/0702294]

In $m_\nu \to 0$ limit (typical for LHC), $m_{N_2} \to m_{N_1}$ and $\Delta\phi \to \pi$:

2 quasi-degenerate, Majorana N_i with opposite CP phase ≈ 1 Dirac N_i

For everyone

For ***discovery purposes*** (not properties measurements), simplify life.
Generically paramerize active-sterile neutrino mixing via Atre, et al [0901.3589]

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

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

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

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$\implies$ W coupling to N in the **mass basis** is

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

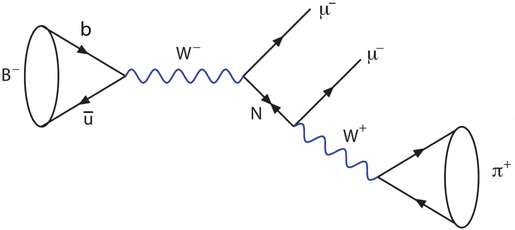
$\implies$ N is **accessible through** $W/Z/h$ bosons

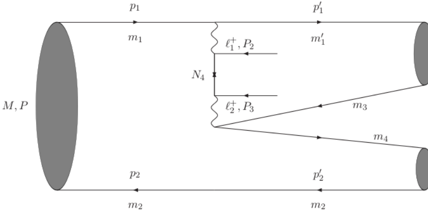
prospects and projections[3]

[3] A very bias sub-set of state-of-the-art numbers:
European Strategy updates:
- Cai, Han, Li, RR [1711.02180]
- Pascoli, RR, Weiland [1812.08750]
Snowmass updates:
- Han, Liao, Liu, Marfatia, RR [2203.06131]
- Abdullahi, et al [2203.08039]

For $m_N \ll M_W$, N can appear in decays of baryons, mesons, and τs!

Atre, Han, Pascoli, & Zhang [0901.3589]; Castro & Quintero [1302.1504]; Yuan, Wang ×2 , Ju, & Zhang [1304.3810]; + others





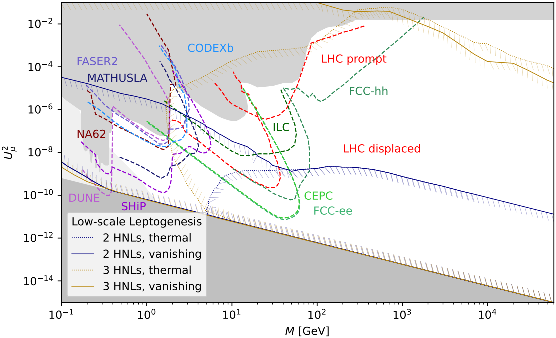
Production rate of mesons ($\pi^{\pm}, \mathcal{D}, \mathcal{B}$) at colliders is ***big*** ($\sigma_{bX}^{\rm LHC} \sim 0.1\ mb$)

- Sufficient[4] to overcome ***tiny*** mixing for MeV-scale, Majorana N
- Sufficient to probe L-conserving, charged lepton flavor violation
- Manifests as long-lived states since $\tau^{-1} \sim G_F^2 |V_{N\ell}|^2 m_N^5$

[4] Specifically, Kersten-Smirnov [0705.3221] and Pascoli, et al [1712.07611]

Light/Intermediate N at Current and Future Machines

Community Message: Current + next-gen. facilities can directly test *simplest* resonant leptogenesis scenarios with high-scale Type I Seesaw



Abdullahi, et al [2203.08039]

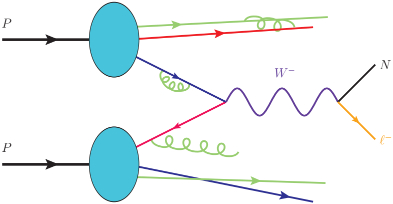
Note: LHC picture evolving with better strategies and add'l channels

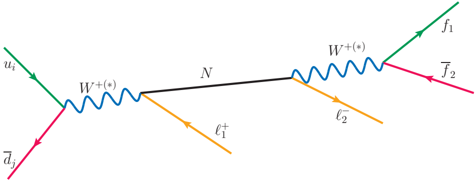
Cottin, Helo, Hirsch [1806.05191]; Abada, Bernal, Losada, Marcano [1812.01720]; K. Cheung, H. Ishida, et al [2004.11537]

how heavy can we go?

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

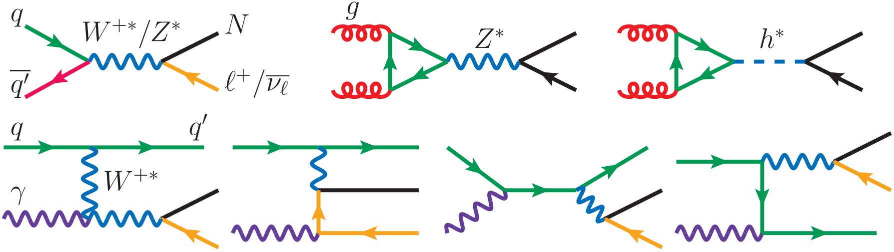
Keung & Senjanovic (PRL'83)





At the LHC, the canonical signatures: $pp \to \ell_i \ell_j$+jets or $\ell_i \ell_j \ell_k$ + nothing

many signatures proposed by K&S ('83); Willenbrock, et al ('85); Dicus, et al ('91); Datta, et al ('94)

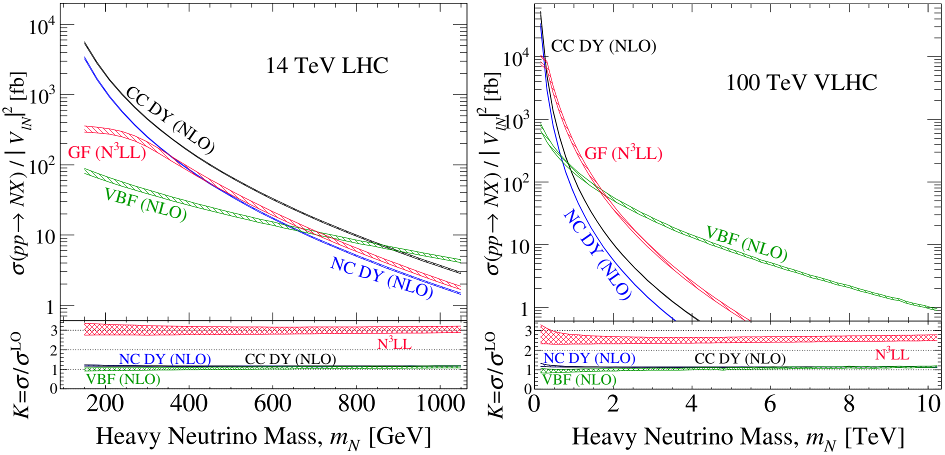


After lots of coffee and CPU hours

fully differential predictions up to NLO+LL(PS) available

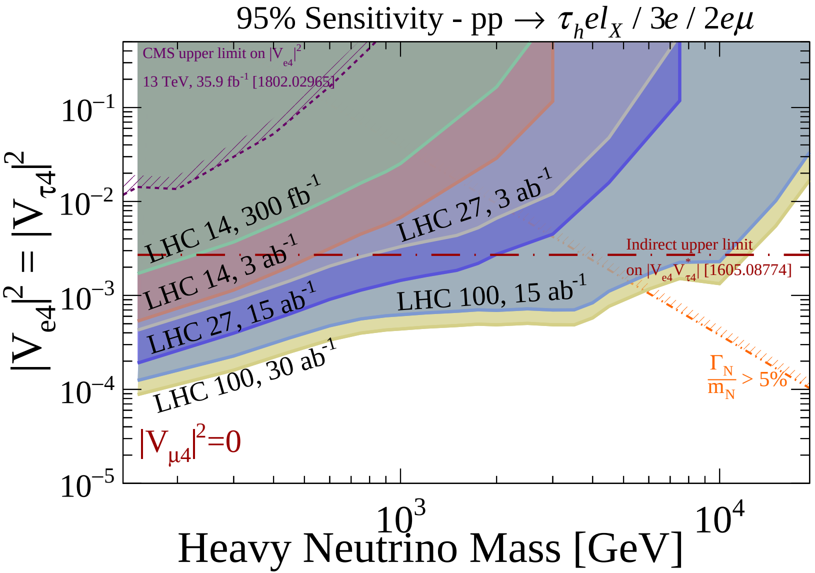
for summary, see RR, et al [JHEP('19)]

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



Precision driven by desire to capture/describe underlying hadronic activity! [1602.06957]

Discover wild interplay between proton structure and matrix elements at higher collider energies!



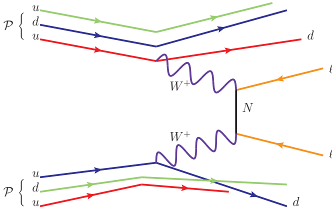
Major improvements $\Longrightarrow$ $> 10\times$ better sensitivity to LNV + cLFV

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

surely we cannot reach higher masses at the LHC! ☺

Exploiting the uniqueness of the LHC: vector boson scattering!

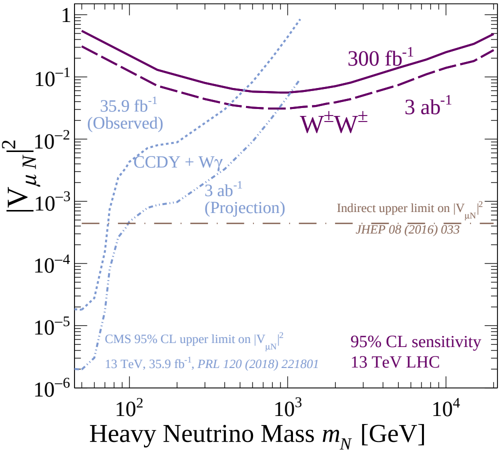
for a broad outlook on VBF@HL-LHC, see Buarque (ed.), Gallinaro (ed.), RR (ed.), et al [2106.01393]



Same-sign $W^{\pm}W^{\pm} \to \ell_i^{\pm}\ell_i^{\pm}$ scattering channel lost in the literature   Dicus, Karatas, & Roy (PRD'91)

– stronger $|V_{\ell N}|$ suppression but weaker m_N dependence

Take away: same-sign WW scattering extends LHC's reach!



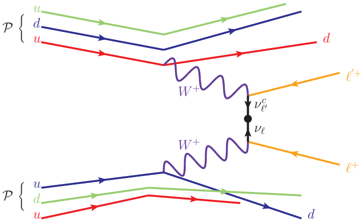
Fuks, Neundorf, Peters, RR, Saimpert [2011.02547]

Exploiting the uniqueness of the LHC: vector boson scattering!

Logical extension is identifying same-sign $W^{\pm}W^{\pm} \rightarrow \ell_i^{\pm}\ell_i^{\pm}$ as high-energy $0\nu\beta\beta$ decay

Testing the Weinberg operator:

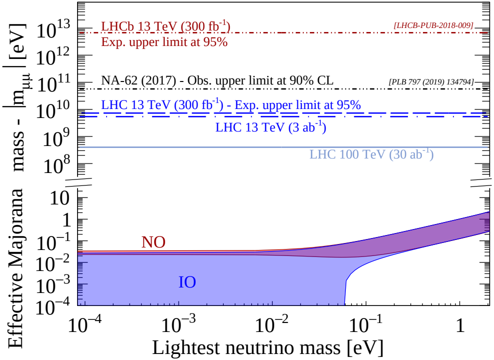
$$\mathcal{L} = \frac{C_5^{\ell\ell'}}{\Lambda}[\Phi \cdot \overline{L}_\ell^c][L_{\ell'} \cdot \Phi]$$



Sensitive to μ, τ and fine-tuning

Effective μ-μ Majorana mass:

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



Non-trivial insights needed to build user-friendly FeynRules UFO

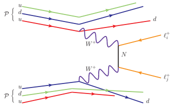
Fuks, Neundorf, Peters, RR, Saimpert [2012.09882]

Motivation for non-minimal scenarios (1 slide)

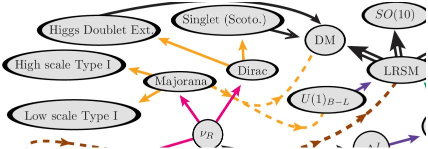
Little-known fact: $W^{\pm}W^{\pm} \to \ell_i^{\pm}\ell_i^{\pm}$ in Type I violates s-wave unitarity

Dicus & He ('04, '05); Fuks, RR, et al [2011.02547]

$$(\text{scattering energy})^3 = \frac{32\pi M_W^2}{(2-\delta_{\ell_i\ell_j})g_W^2}\frac{1}{|\sum_k \frac{V_{ik}V_{jk}}{m_{N_k}}|}$$



Life with ν_R is probably complicated:



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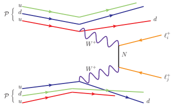
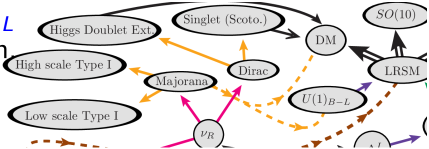


Life with ν_R is probably complicated:

- **Type III Seesaw:** ν_R is part of weak multiplet $(T^+, T^0(=\nu_R), T^-)$
- $U(1)_{B-L}$**:** ν_R couples to H_{B-L}, Z'_{B-L} since $B-L$ is a broken gauge symm.

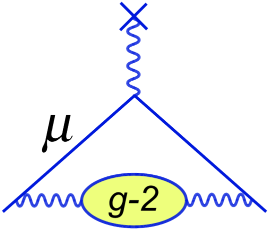


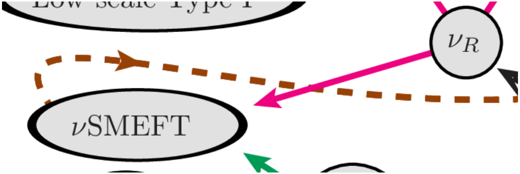
- **Left-Right Symmetric model:** ν_R is member of right-handed doublet (ν_R, e_R^-) couples to $H, H^{\pm}, H^{\pm\pm}, Z'_R, W_R$
- These models map into ν_RSMEFT $(=\text{SMEFT} + \nu_R)$ ← see backup!

No time left, but these are covered in the next talk by A. Lister!

Thank you.

can we connect LHC searches to other experiments?





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

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

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 operator at $d = 6$ can generate "right" Δa_μ

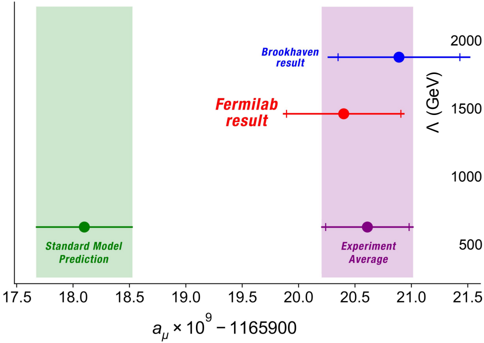
$$\mathcal{L}_{H\nu e} \approx \frac{gv^2}{2\sqrt{2}\Lambda^2}\sum_{k=1}^{3}\left[\bar{C}_{H\nu e}\right]_{k\ell}\left(\overline{N_k}\gamma^\mu P_R\,\ell_R\right)W^+_\mu\left(1+\frac{h}{v}\right)^2 + \text{H.c.}$$

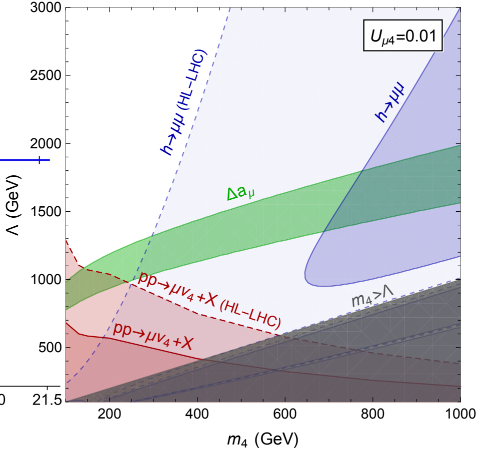
This generates Δa_μ of the form

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

(see [2105.11462] for exact formula!)

Fermilab's Muon g-2 expt. has *confirmed* that $a_\mu = (g_\mu - 2)/2$ is *a bit* large [2104.03281]





Punchline: If N are involved in generating Δa_μ, then expect something in

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

during Run III data and at the HL-LHC Cirigliano, RR, de Vries, et al (JHEP'21)

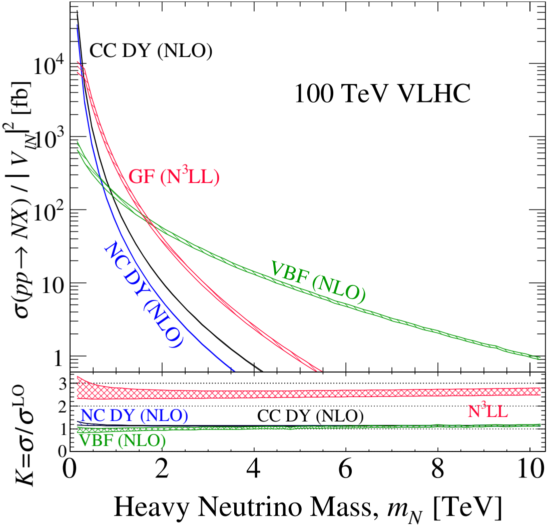
Monte Carlo tools for simulating heavy neutrinos at the LHC

Given a UFO library, HeavyN+mg5amc runs out of the box

(low barrier for new/junior researchers)

```
 $ ./bin/mg5_aMC
> import model SM_HeavyN_NLO
> define p = g u c d s u~ c~ d~
s~ 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 →



UFO	NLO	Spin	D or M	#	V'	LNV	LFV	arXiv
HeavyN	✓	✓	M	3		✓	✓	[1602.06957]
HeavyN_Dirac	✓	✓	D	3			✓	[1812.08750]
HeavyN_vSMEFTdim6	✓	✓	M	3		✓	✓	[2105.11462]
HeavyN_Meson	✓	✓	D (M)	3		(✓)	✓	[April '22]
EffLRSM	✓	✓	M	3	✓	✓	✓	[1610.08985]
WZPrime	✓	✓			✓		✓	[1701.05263]
TypeIISeesaw	✓	✓			✓	✓	✓	[1912.08975]
SMWeinberg	✓	✓				✓	✓	[2012.09882]

Legend:

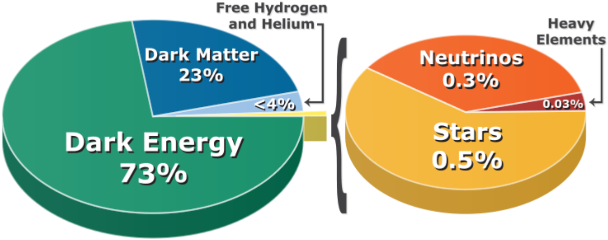
- "NLO" = simulations at LO and NLO in QCD possible
- "Spin" = spin correlation fully described — for details, see RR [2008.01092]
- "D or M" = Dirac or Majorana N
- "#" = number of N in the model file
- "V'" = new vector, scalar, or pseudoscalar (new particles can be LLP/DM candidates!)

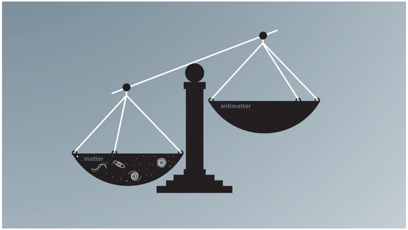
broad implications for the universe ☺

Neutrino mass models **hypothesize new particles**
with various charges, interaction strengths, masses, and spins

1. Weakly coupled states are natural candidates for **particle dark matter**
e.g., PB Pal ('87); Asaka & Shaposhnikov ('05x2); MRM, et al ('21); Cai & Chao ('14)

$\Longrightarrow$ impact on large-scale structure of universe





2. Trigger **matter-antimatter asymm.** in the early universe through **baryogenesis** and **leptogenesis**
e.g., Pilaftsis and Underwood ('04, '05); Hambye, et al ('04); MRM, et al ('21)

Bonus: 3. m_ν may be connected to breaking of fundamental symmetries, e.g., CP,P, lepton number, lepton flavor

e.g., PB Pal, et al ('88); MRM ($\times$many); ATLAS; Møller; (n)EXO