Probing Right-handed neutrinos via the Semileptonic Higgs Channel

Yu Gao

Wayne State University

1704.00881
1611.00773

Collider Dark Matter Workshop, 17', TAMU

Outline

- Searches for right-handed neutrinos
- Brief overview on collider bounds
- A search channel from $g\, g \rightarrow h\, j$ and semileptonic h decays

Why RH neutrinos & where to look

- Understanding neutrino masses: heavy Majarona fermion(s) for see-saw mechanism
- Cosmology: Relativistic species (N_{eff}), reheat, dark matter, etc.
- EW theories: Extended symmetry requirements
- Indirect search cosmic ray signals
- Correction to W, Z properties (EWPD)
- Weakly(and strongly?) produced at collider
- Associated production with (model dependent) other BSM partners

`Common' see-saw features in RH Neutrinos

- See-saw: A finite Majorana RH neutrino mass
- RH neutrino talks to SM via Yukawa (Dirac mass) terms
- Leads to a (small) mixing into SM neutrinos, hence W, Z, couplings, etc.
- Identify with "economical" SM extensions with fermion(s)

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \bar{N}_i i \partial\!\!\!/ N_i + (\lambda_N^{ij}\; N^i L^j H + \frac{M_N^{ij}}{2} N_i N_j + {\rm h.c.})$$

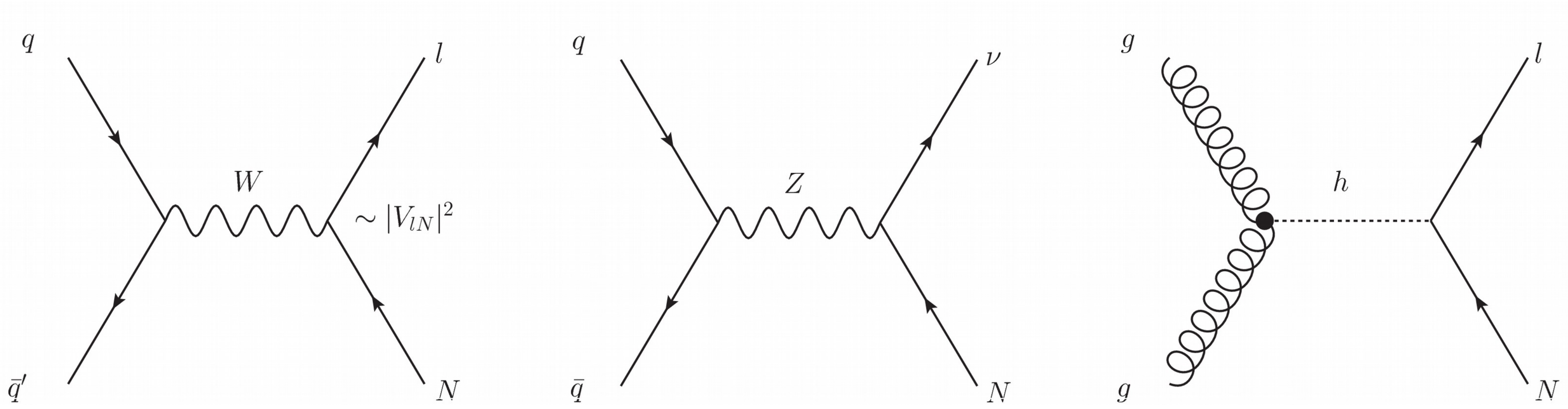
(Type-I) see-saw

$$\begin{array}{cc} & \begin{array}{cc} \nu_L & \nu_R \end{array} \\ \begin{array}{c} \nu_L \\ \nu_R \end{array} & \begin{pmatrix} 0 & \boldsymbol{\lambda}_N^T v \\ \boldsymbol{\lambda}_N v & \boldsymbol{M}_N \end{pmatrix} \end{array} \qquad \theta \approx \left(\frac{m_\nu}{M_N}\right)^{1/2}$$

Minkowski (1977) Yanagida(1979)
Gell-Mann, Ramond, & Slansky (1979)
Glashow (1980)

How to produce a RH neutrino?

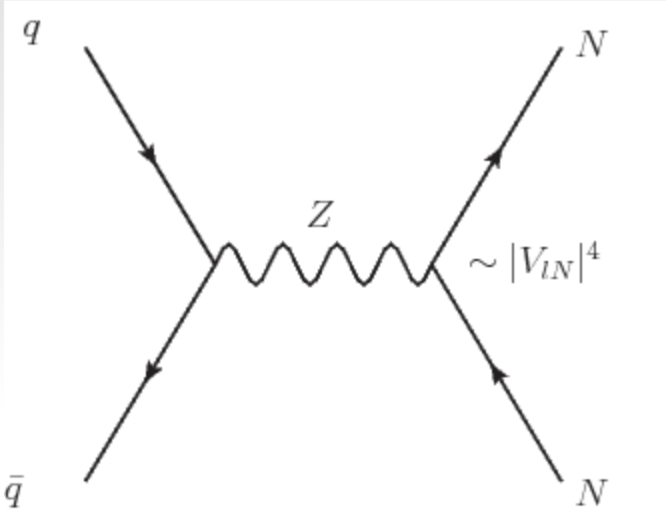
- Via mixing with the SM neutrino.
- Leading channel : Drell-Yan
- Resonant W, Z, h production (for $M_N < M_{W/Z/h}$)
- Need significant mixing $\nu \simeq \nu_m + V_{\ell N} N_m$



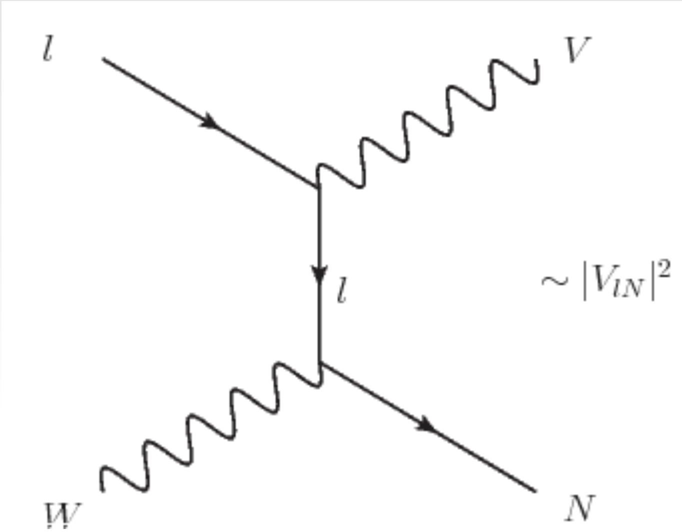
Drell - Yan

Gluon fusion

and a few other ways ...

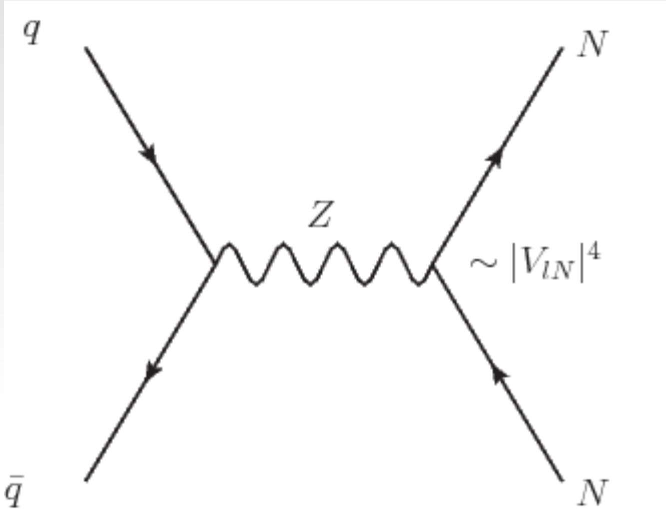


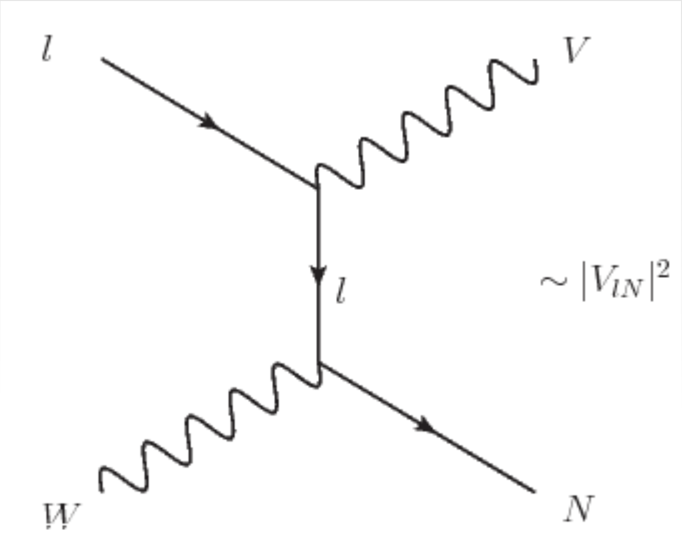
N pair production suppressed
by mixing^4



Vector-boson and/or lepton fusion:
need lepton and/or VB luminosity

and a few other less blessed ways ...





N pair production suppressed
by mixing^4
Note: Z' are not mixing-suppressed
but ($m_{Z'}/g_{z'}$) must be large

Vector-boson and/or lepton fusion:
need lepton and/or VB luminosity

Or maybe go after associated *N* partners instead

e.g. SU(2) charged triplets [Type III]

RN decays: Missing energy, or prompt decays?

- RH *N* decays weakly via its mixing into SM neutrino, yet its lifetime varies greatly...

Type I mixing is very tiny

$$\begin{array}{c c} & \begin{array}{cc} \nu_L & \nu_R \end{array} \\ \begin{array}{c} \nu_L \\ \nu_R \end{array} & \begin{pmatrix} 0 & \boldsymbol{\lambda}_N^T v \\ \boldsymbol{\lambda}_N v & \boldsymbol{M}_N \end{pmatrix} \end{array} \qquad \theta \approx \left(\frac{m_\nu}{M_N}\right)^{1/2}$$

M_D

Suppress production rate / decay branching fraction
N may become completely invisible at LHC

May search for other `associated' particles, like charged scalars in Type II, heavy Z' in extra U(1), etc.

When RH *N*'s lifetime is very long and *N* becomes MET at collider, leadings to mono-lepton signals, but measuring its mass and identifying the N can be difficult.

NOTE: A long RH N lifetime can be useful in indirect searches

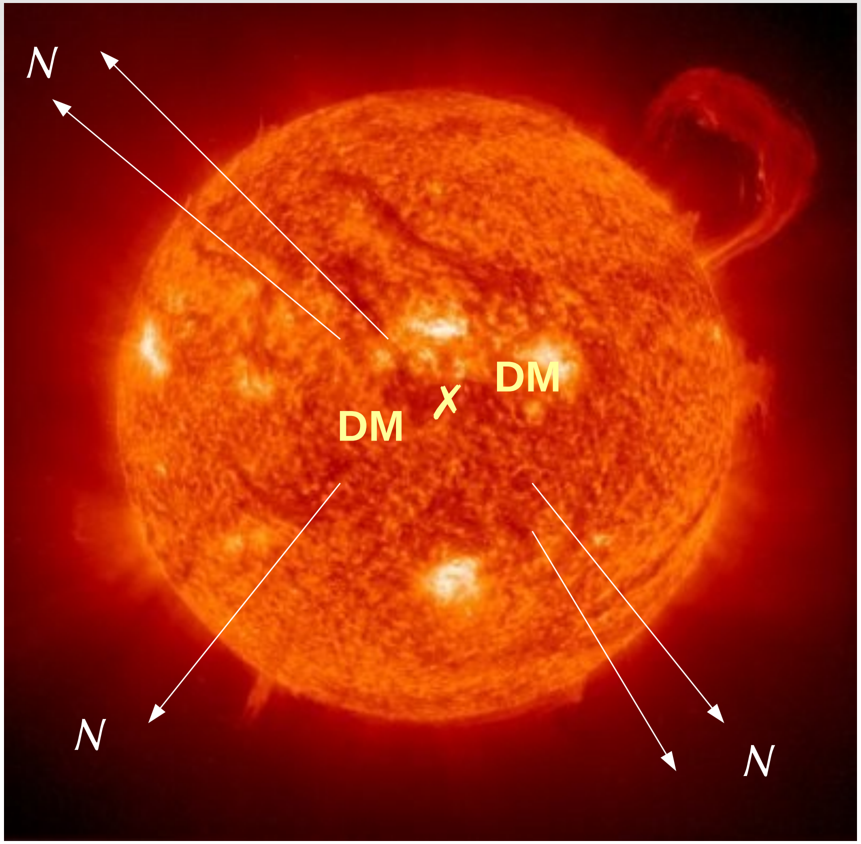
- In a 1 – 5 GeV mass range, (Type-I) RH neutrinos can escapes the Sun before decaying [with a Lorentz boost from TeV -scale dark matter annihilations]
- Signal in both high-energy *γ*-ray & neutrinos in the Sun's direction

$$\Delta\mathcal{L} \supset y_{\mathrm{D}}(L^{\dagger} \cdot i\tau_2 H)N + \mathbf{h.c.},$$

$$\Gamma_N \propto \theta^2 G_{\mathrm{F}}^2 M_N^5 \frac{M_N}{M_{\mathrm{DM}}}$$

boosted $\tau_N \propto \frac{M_{\mathrm{DM}} m_\nu}{M_N^5}$

- Leads to strong bounds from both Fermi-LAT and IceCube



R. Allahverdi, YG , B. Knockel, S. Shalgar, 1612.03110, PRD 95 no. 7, 075001 (2017)
For neutrino sector's DM, aslo see
R. Allahverdi, S.Campbell, B.Dutta, YG
PRD 90, no. 7, 073002 (2014)

Collider friendly scenario: Inverse seesaw

R. N. Mohapatra, 1986

- Outsource Maj. mass to an additional singlet fermion
- Larger mixing angle into RH *N*, but no LNV in *N* decay
- Can be flavor-diagonal in ν-*N* mixing (m_D terms)

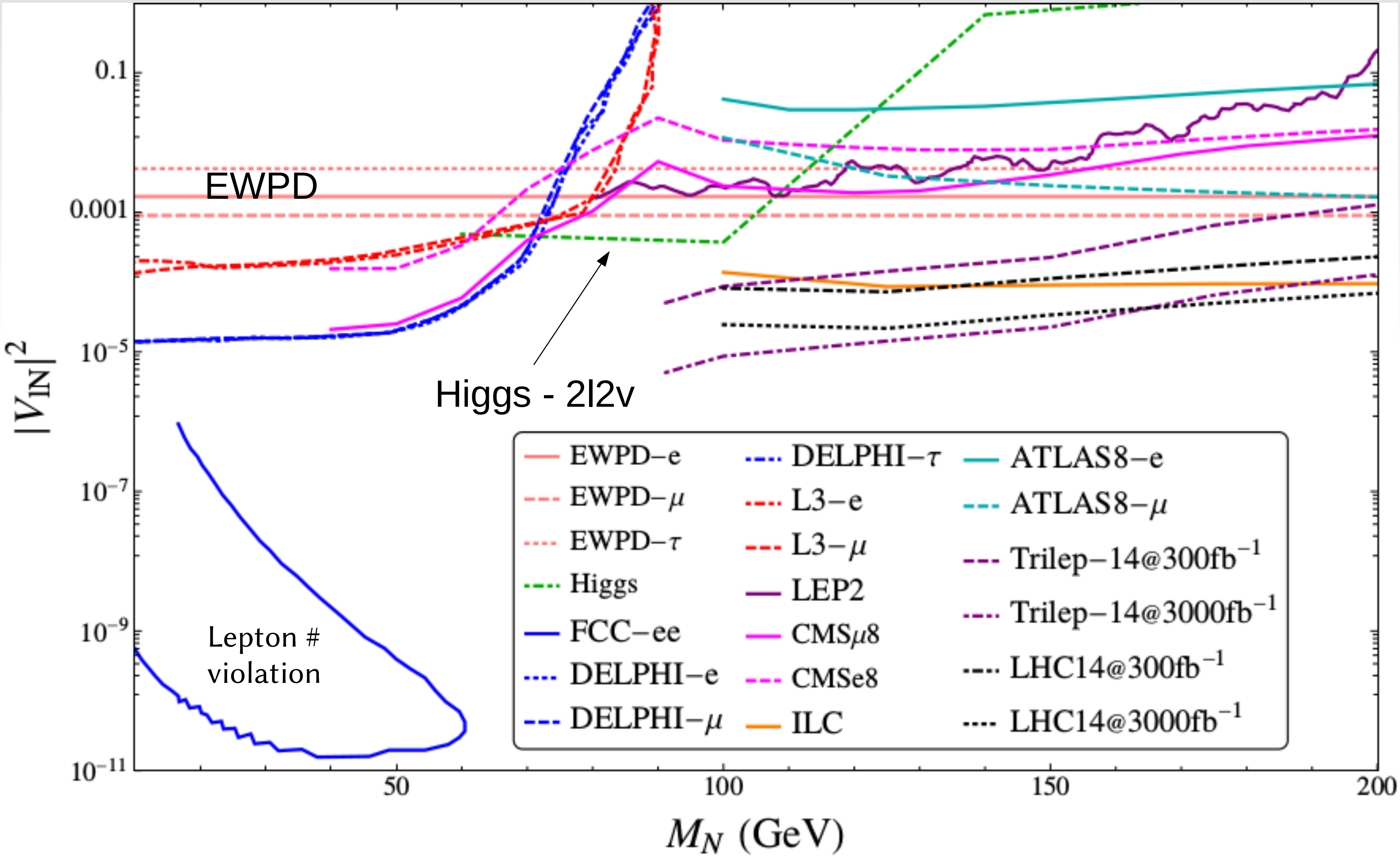
$$\mathcal{L} \supset -Y_D^{\alpha\beta}\overline{\ell_L^{\alpha}}\tilde{H}N_R^{\beta} - M_N^{\alpha\beta}\overline{S_L^{\alpha}}N_R^{\beta} - \frac{1}{2}\mu_{\alpha\beta}\overline{S_L^{\alpha}}S_L^{\beta C} + H.c.$$

	SU(2)	U(1)$_Y$
ℓ	**2**	$-1/2$
H	**2**	$+1/2$
N_R	**1**	0
S_L	**1**	0

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_N^T \\ 0 & M_N & \mu \end{pmatrix} \begin{matrix} \nu \\ N \\ S \end{matrix}$$

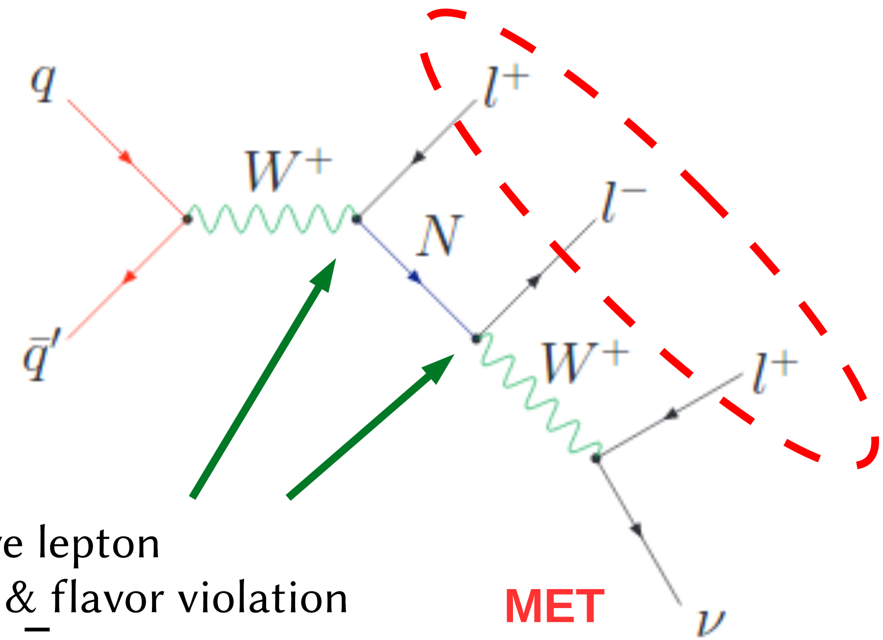
$$m_\nu \simeq (m_D M_N^{-1})\mu(M_N^{-1^T} m_D^T)$$

A quick look at the present and future...



Drell-Yan channels

- pp → $l\,N$, $N \to l\,l\,\nu$, final state: `Trilepton' $lll\nu$
- pp → $\nu\,N$, $N \to l\,l\,\nu$, final state: two lepton $ll\nu\nu$
- Semileptonic N decays $N \to j\,j\,\nu$, mass reconstruct-able
- Mediator can be on shell (resonance) for light N



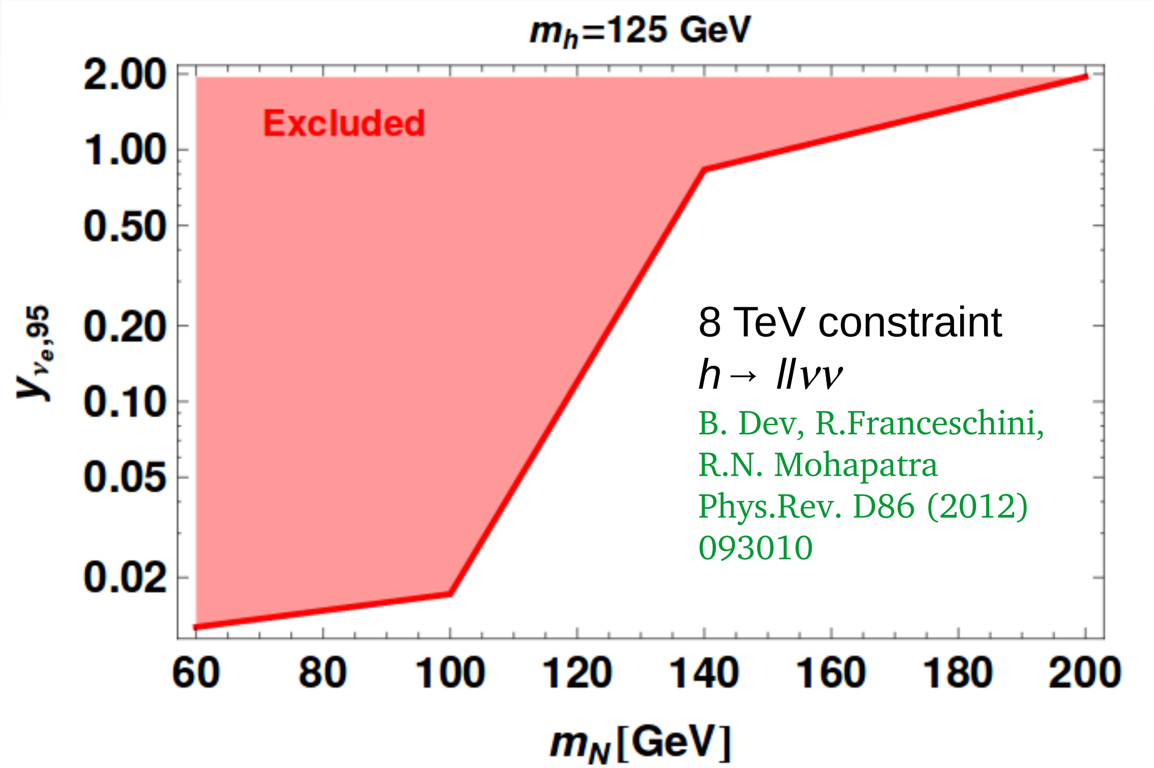
Can have lepton
number & flavor violation
e.g. $e^+e^+\mu^-\bar{\nu}$

Higgs channel ($h \to \nu N \to ll\nu\nu$)

Higgs mediation:

SM Higgs width is small, sensitive to smaller mixing

Higher resonance mass than W, Z.



$$\Gamma(h \to N\nu) = \frac{Y_N^2}{8\pi m_h^3}(m_h^2 - M_N^2)^2$$

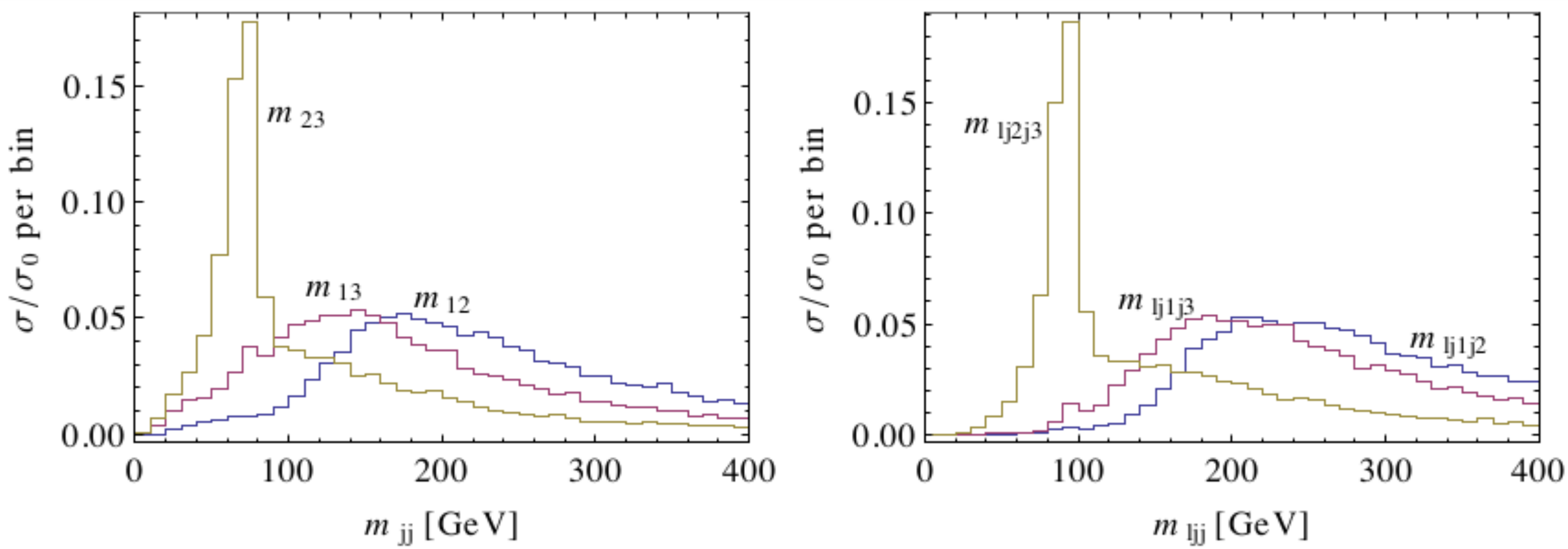
$$\mathcal{BR}_{h\to N\nu} = \frac{\Gamma(h \to N\nu)}{\Gamma_h^{SM} + \Gamma(h \to N\nu)}$$

~3MeV

Semileptonic Higgs channel ($h \to \nu N \to ljj\nu$)

- The virtual W* in $N \to lW^*$ *decays hadronically.*
- *N* mass fully reconstructible
- No leptons (Higgs channel), need ISR jet for triggering
- High P_T ISR transversely boosts *h* system – higher l, $j_2 j_3$ P_T

A. Das, YG, T.Kamon,
1704.xxxxx



Efficient reconstruction of W and N masses. M_N=100 GeV.

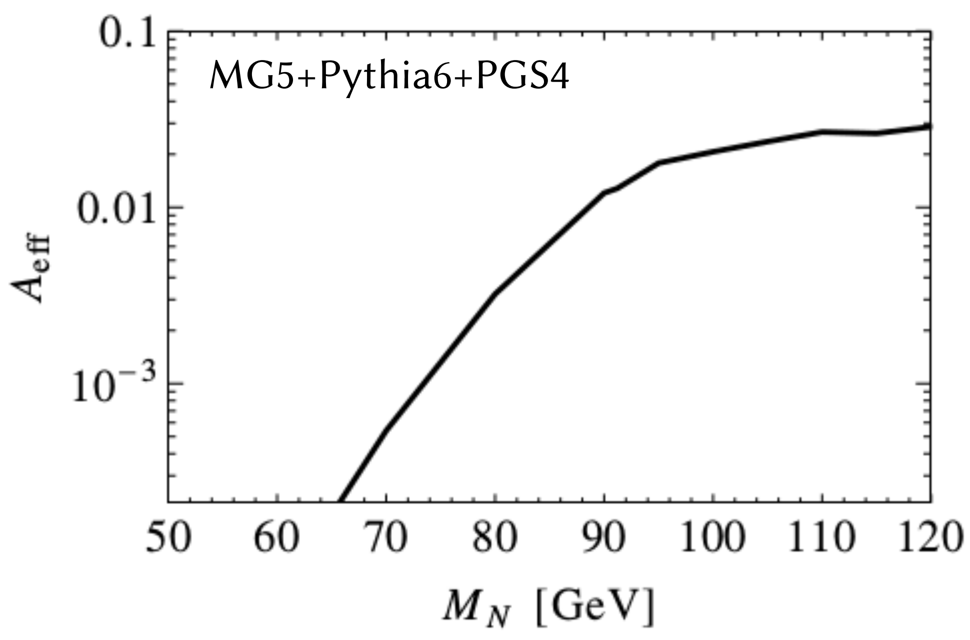
Cuts, efficiency & signal strength

(1) leading jet p_T^j >200 GeV; ← Trigger & ISR-$j_2 j_3$ separation

(2) at least three jets and exactly one lepton; ← Remove Z bkgs

(3) $|M(j_2 j_3) - M_W| < 20$ GeV; ← A physical W mass

(4) $|M(l_1 j_2 j_3) - M_N| < 20$ GeV. ← M_N mass window



$$\sigma = \sigma(hj)\mathcal{BR}_{h\to N\nu}\mathcal{BR}_{N\to\ell jj}A_{\rm eff}$$

$$\sigma(h+j)_{\rm LO} = 1.5 \text{ pb}$$

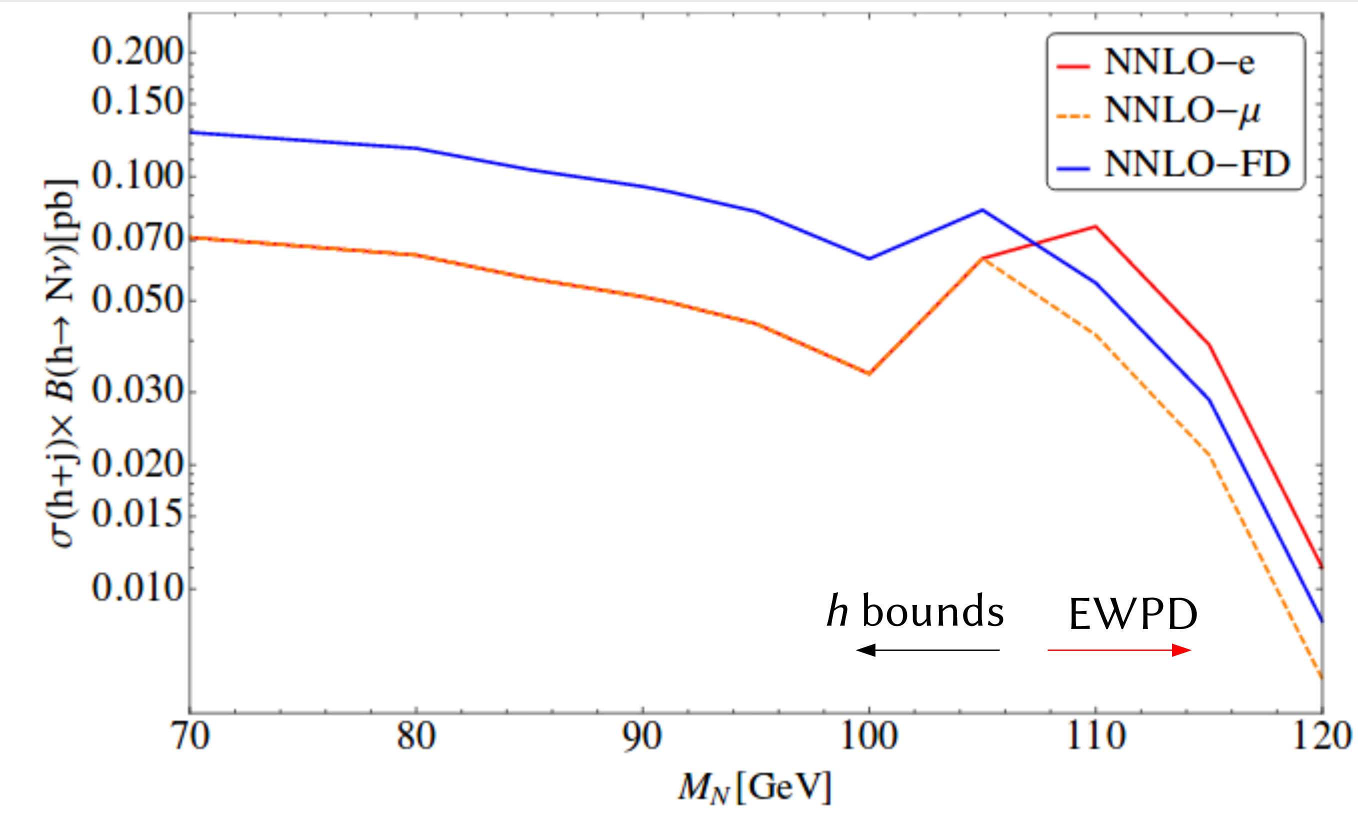
$$\sigma(h+j)_{\rm NLO} = 2.2 \text{ pb}$$

$$\sigma(h+j)_{\rm NNLO} = 2.6 \text{ pb}$$

pp⟶*hj* cross-section taken from R. Boughezal, et.al. PRL 115, no. 8, 082003 (2015), and PLB 748, 5 (2015)

Max. allowed pre-cut cross-section

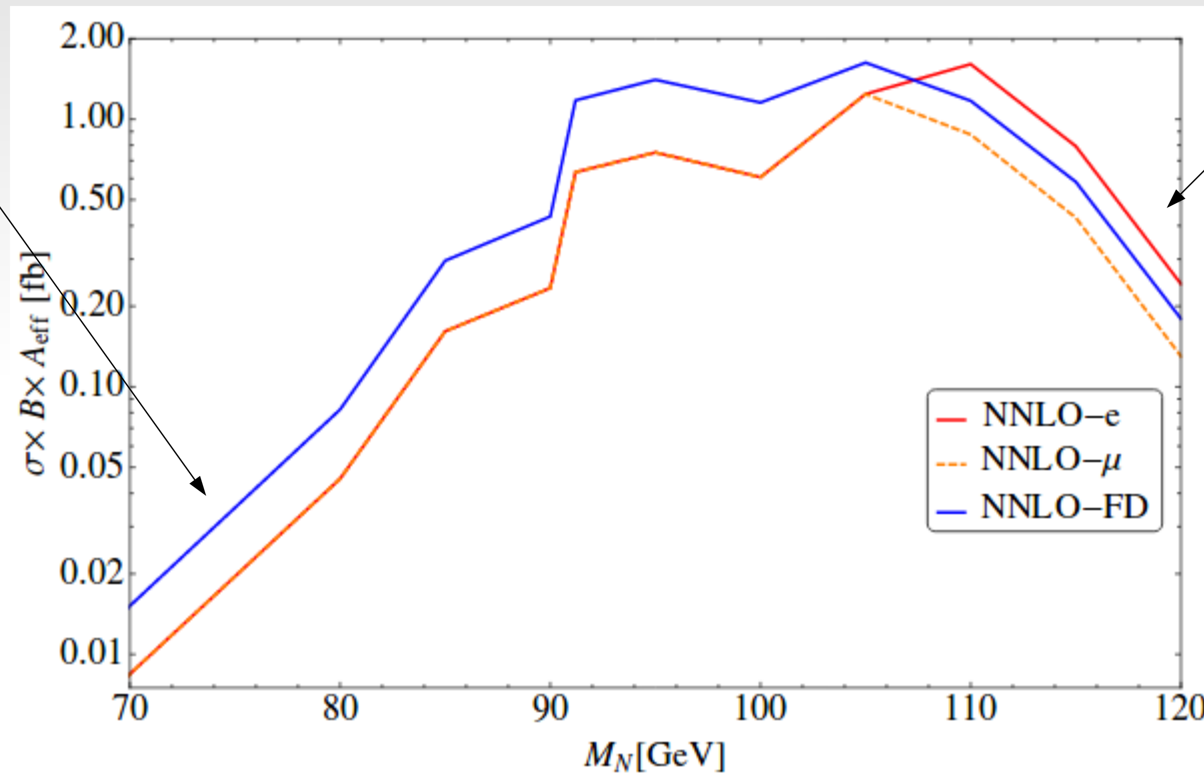
Quoting current bounds on mixings: LHC h⟶2l2v, and EWPD limits



Max. signal cross-section with efficiencies

M_W window suppressed

BR($h \longrightarrow \nu N$) drops



Optimally ~ fb signal around m_N 105-110 GeV

Backgrounds & significance...

Cross-sections in pb, pre-cut requires $P_T(j_1)$>100 GeV

Channel	tj	tW	$t\bar{t}$ ②	W+jets ①	Z+jets	WWj	WZj	ZZj	M_N=100	M_N=105	M_N=110
Pre-cut σ [pb]	40	52	4.7×10^2	2.5×10^3	9.5×10^2	7.1	5.4	0.69	0.017	0.030	0.035
Eff. $p_T(j_1)$>200	0.12	0.034	0.052	0.12	0.13	0.25	0.29	0.23	0.17	0.16	0.17
Eff. $N_j \geq 3, N_l = 1$	0.073	0.14	0.21	0.046	0.014	0.14	0.10	0.039	0.39	0.38	0.48
Eff. $M(j_2j_3)$ on M_W	0.12	0.16	0.12	0.17	0.14	0.29	0.33	0.27	0.40	0.42	0.40
σ[pb]	0.040	0.038	0.59	2.3	0.24	0.074	0.054	2.0×10^{-3}	3.8×10^{-4}	7.9×10^{-4}	1.0×10^{-3}

TABLE II: Cut efficiencies of Cuts (1)-(3) on SM background and heavy neutrino signals.

W+jets turns out to be the largest bkg, s/b ⟶ % level

Mass Window		$\sigma(tj)$	$\sigma(tW)$	$\sigma(t\bar{t})$	$\sigma(W+\text{jets})$	$\sigma(Z+\text{jets})$	$\sigma(WWj)$	$\sigma(WZj)$	$\lvert V_{\ell N}\rvert^2_{\text{max}}$	LO σ_{sig}	NNLO σ_{sig}
M_N	100	0.011	3×10^{-3}	0.028	0.20	0.022	6.0×10^{-3}	5.0×10^{-3}	3.4×10^{-4}	3.5×10^{-4}	6.1×10^{-4}
	105	0.011	4×10^{-3}	0.028	0.23	0.026	8×10^{-3}	6×10^{-3}	9.0×10^{-4}	7.2×10^{-4}	1.2×10^{-3}
	110	0.010	6×10^{-3}	0.037	0.23	0.030	9.0×10^{-3}	7.0×10^{-3}	1.7×10^{-3}	9.3×10^{-4}	1.6×10^{-3}

~ fb signal, 0.3 pb total background

(Conversative) S/Sqrt[S+B] = 2.6(3.8) at 3000 fb^{-1} (for single-flavor *N*) M_N=100(110) GeV

Summary

- RH neutrino mass fully reconstructible in semileptonic pp → *hj* channel
- Best sensitivity at *N* mass 100-110 GeV range
- Given current EWPD & Higgs bounds, discovery potential in high luminosity LHC runs
- Analysis only requires νN mixing (caveats apply)
- Multiple roles of high j_1 P_T : for both triggering & *N* mass reconstruction

Thanks!