Probing the Seesaw Singlet Scalar in the Higgs boson’s Rare Decays

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Outline

- The Higgs boson's role in the collider hunt of massive right-handed neutrinos
- A *remarkably* clean channel: $pp \longrightarrow NN \longrightarrow e^+e^+\mu^-\mu^- 2\nu$
- Promising sensitivity to a small mixing between:
  the 'Higgs' boson & a seesaw scalar boson

Search for massive RHNs because...

- RHN explains the small active neutrino mass
- RHN is motivated in TeV new physics:

helps restore Left-Right symmetry.

comes handy in extra-U(1) theories.

$$\nu_\ell = \sum_{m=1}^{3} U_{\ell m}\nu_m + \sum_{m'=1}^{n} V_{\ell m'} N_{m'}^c$$

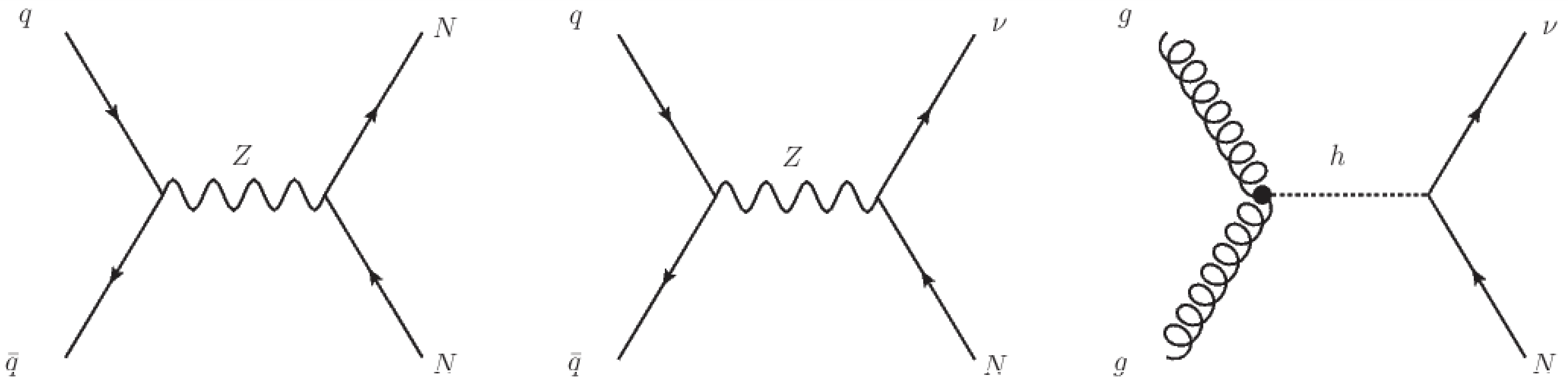
$$\begin{aligned}\mathcal{L}_{\text{Int.}} = &- \frac{g}{\sqrt{2}} W_\mu^+ \sum_{\ell=e}^{\tau} \left(\sum_{m=1}^{3} \overline{\nu_m}\, U_{\ell m}^* + \sum_{m'=1}^{n} \overline{N_{m'}^c}\, V_{\ell N_{m'}}^* \right) \gamma^\mu P_L \ell^- \\ &- \frac{g}{2\cos\theta_W} Z_\mu \sum_{\ell=e}^{\tau} \left(\sum_{m=1}^{3} \overline{\nu_m}\, U_{\ell m}^* + \sum_{m'=1}^{n} \overline{N_{m'}^c}\, V_{\ell N_{m'}}^* \right) \gamma^\mu P_L \nu_\ell \\ &- \frac{g}{2M_W} h \sum_{\ell=e}^{\tau} \sum_{m'=1}^{n} m_{N_{m'}} \overline{N_{m'}^c}\, V_{\ell N_{m'}}^* P_L \nu_\ell + \text{H.c.}\end{aligned}$$

RHN mixes with active ν_L and the heavy mass eigenstate N acquires couplings to the SM gauge bosons through its active component

A. Atre, T. Han, S. Pascoli and B. Zhang, JHEP 05 (2009) 030

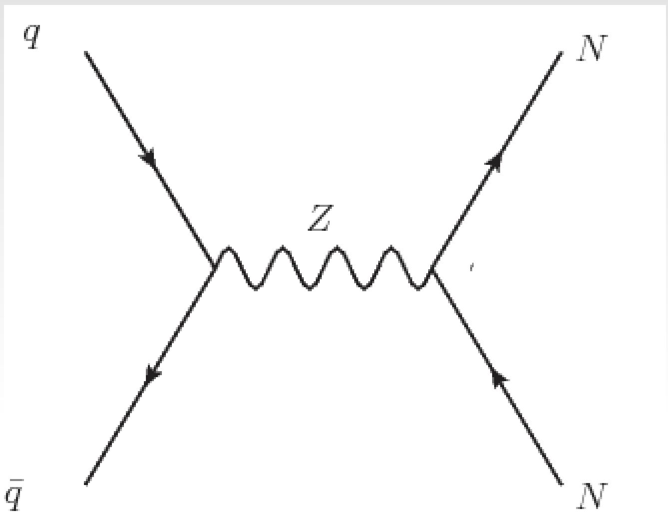
Collider search strategies

- N has a small ~$|V_{lN}|$^2 LH neutrino mixing – may produce weakly
- May carry BSM couplings – BSM mediators
- Leading production: Drell-Yan processes

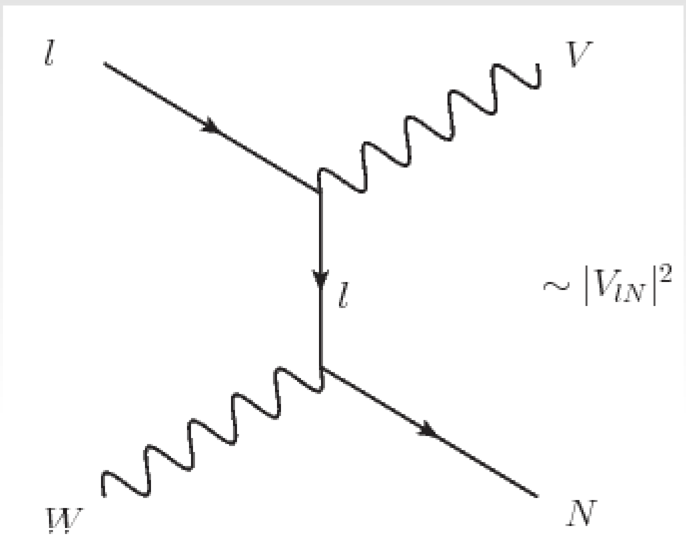


SM mediators: weak interaction via N-ν mixing

and a few other ways ...

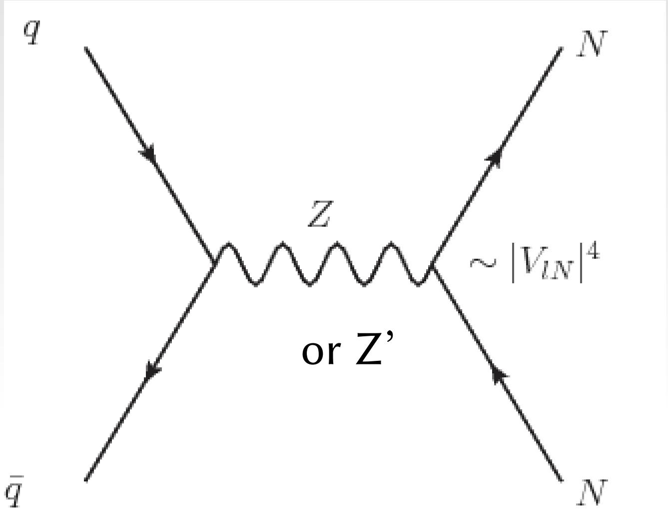


N pair production suppressed by mixing^4



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

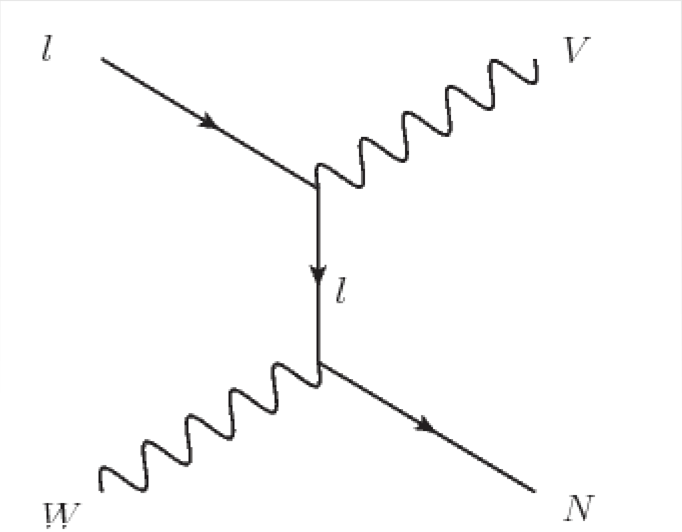
and a few challenged ways ...



N pair production suppressed
by mixing^4

Note : Z' are not mixing-suppressed;
but: $(m_{Z'}/g_{Z'})$ must be large

Or look *elsewhere*:
go for seesaw partners instead,
like H^+,H^{++}



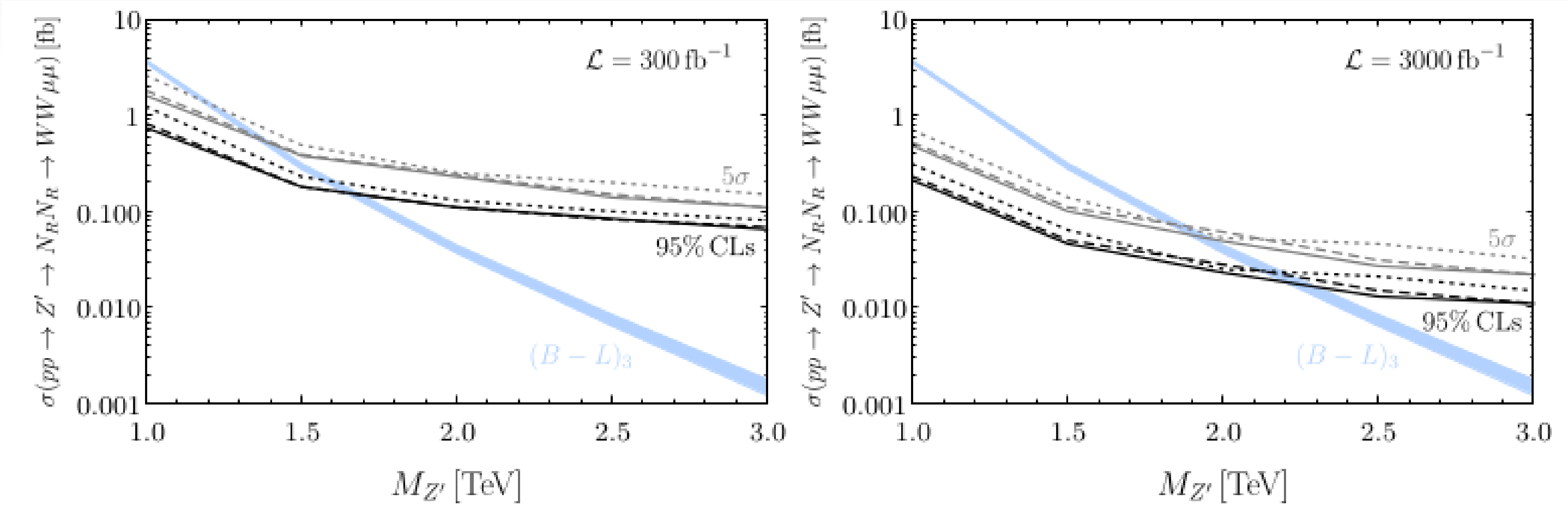
Vector-boson and/or lepton fusion:
need lepton and/or VB luminosity

VBF has cleaner bkg, yet
suffers from a small signal rate

VB-*l* fusion at e+e- collider
or even at cosmic ray experiments:
Limitation on E_{COM}

Heavy neutrinos, m_N > Weak scale

- BSM Drell-Yan is likely very effective, has reconstructible W/Z/h bosons in N decay
- Lower masses testable with the SM Z, W, h (& mesons)



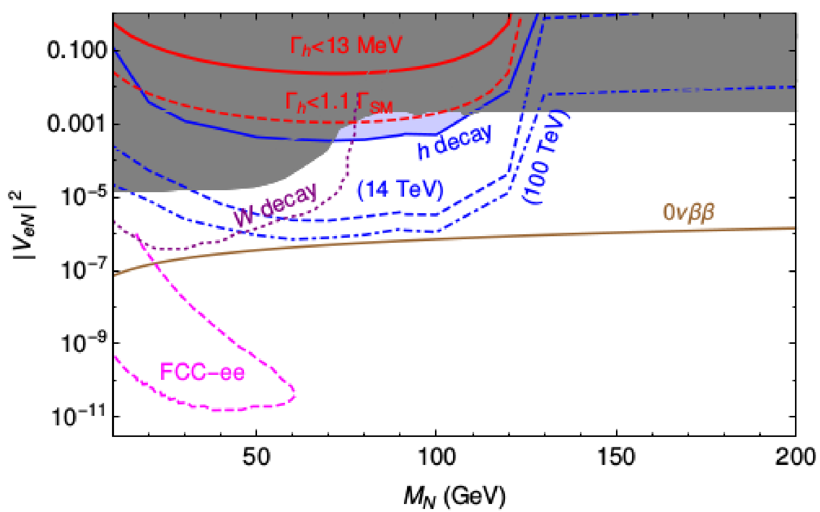
Y.Cai, T.Han, T.Li, R.Ruiz, 1711.02180

The Higgs boson as a mediator

- Like $Z \to N\nu$ *and* $W \to Nl$, $h \to N\nu$ is also $|V_{IN}|^2$ dependent
- Gluon/weak fusion has good production rate in pp collision

L-R mixing: correction to Higgs decays

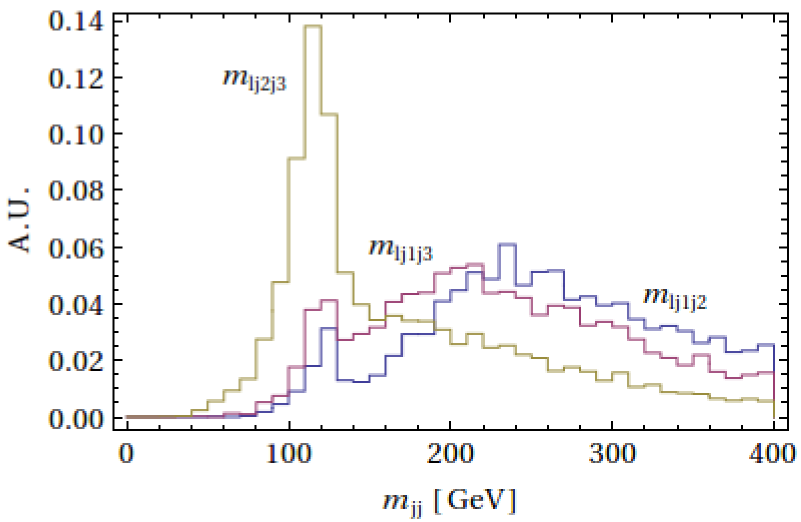
LHC has sensitivity on the $h \to N\nu \to ll\nu\nu$



A.Das, B.Dev, C.S.Kim, 1704.00880

A reconstructible mass peak

$h \to N\nu \to (ljj)\,\nu$



A.Das, Y.Gao, T.Kamon, 1704.00881

New Physics in Higgs → RHNs

- *h* can mix with BSM scalar *S*
- *h*⟶ *NN* via its *S* component if *S* gives the RHN mass

Particularly helpful if we are yet waiting for another mediator to emerge...

A left-right model example: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

EWSB via a L-R bi-doublet Φ & a R triplet Δ

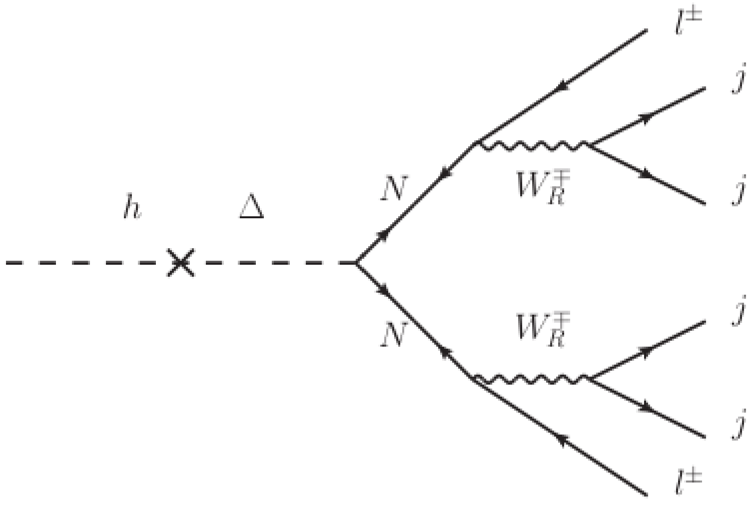
$$\mathcal{V} = -\mu_1^2(\Phi^\dagger\Phi) - \mu_2^2(\widetilde{\Phi}\Phi^\dagger + \widetilde{\Phi}^\dagger\Phi) - \mu_3^2(\Delta_R^\dagger\Delta_R) + \lambda(\Phi^\dagger\Phi)^2 + \rho(\Delta_R^\dagger\Delta_R)^2 + \alpha(\Phi^\dagger\Phi)(\Delta_R^\dagger\Delta_R)$$

Δ couples to N_R and generates its mass

$$\mathcal{L}_\Delta = Y_N L_R^T \Delta_R L_R$$

h – Δ mixing leads to h ⟶ NN decays

$$M^2 = 2\begin{pmatrix} 2\lambda v^2 & \alpha v v_R \\ \alpha v v_R & 2\rho v_R^2 \end{pmatrix}$$



Maiezza, Nemevšek, Nesti 15’

Signal via the 125 GeV boson

- Experimentally confirmed: so far it looks quite SM-like.
- Insensitive to the scale of neutrino L-R mixing $|V_{lN}|^2$.

Can be type-I

- Sensitive to `*Higgs*'-like mixing to other scalar(s)
- The SM's blessing: Higgs width is predicted small

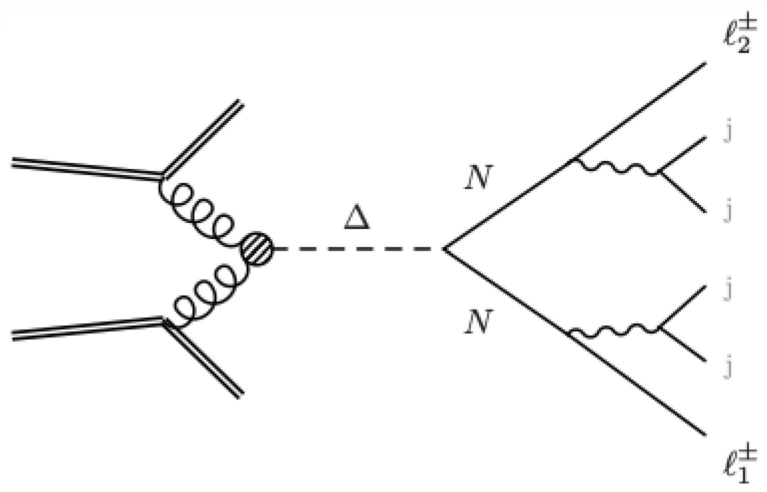
$$\Gamma(h_1 \to NN) = \frac{1}{2} \sin^2 \alpha \cdot \frac{y_N^2 m_{h_1}}{8\pi} \left(1 - \frac{4m_N^2}{m_{h_1}^2}\right)^{3/2}$$

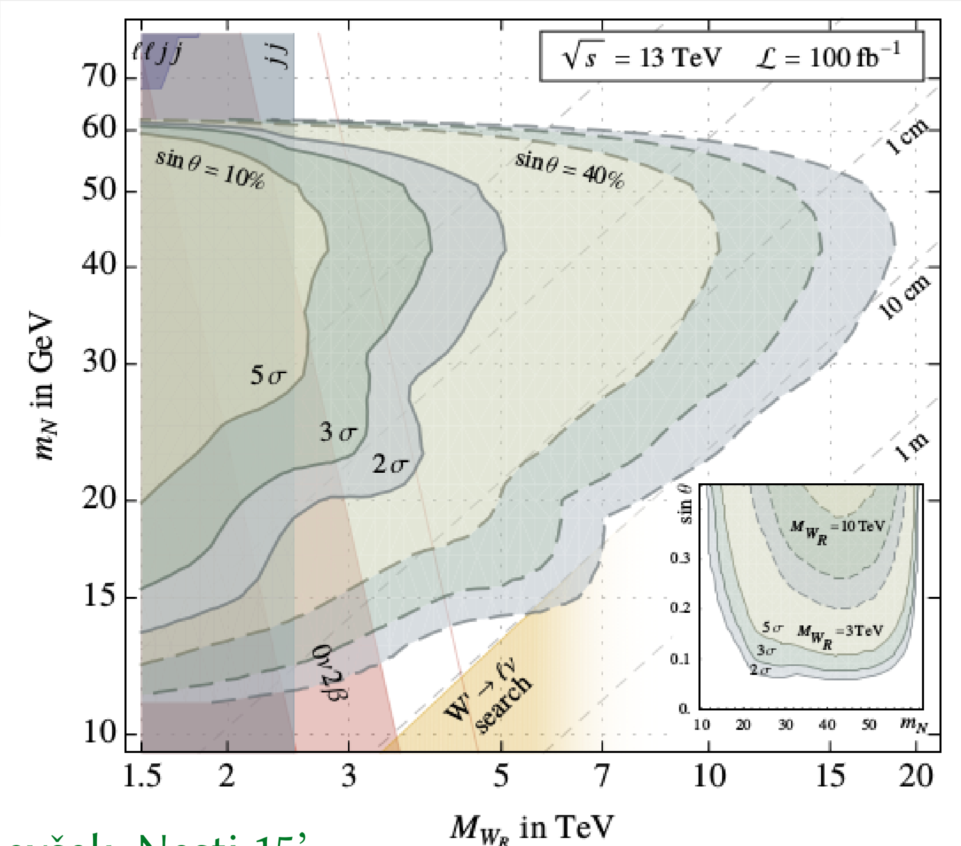
$$\mathrm{BF}_{NN} = \frac{\Gamma_{h\to NN}}{\Gamma_h + \Gamma_{h\to NN}}$$

~4MeV: sensitive to BSM corrections.
Higgs precision data much appreciated.

Definitely new physics: LNV decays

- NN ⟶ l^+l^+jjjj is a smoking gun for Majorana N
- Same-sign lepton pair
- Mass peak at ljj (x2)

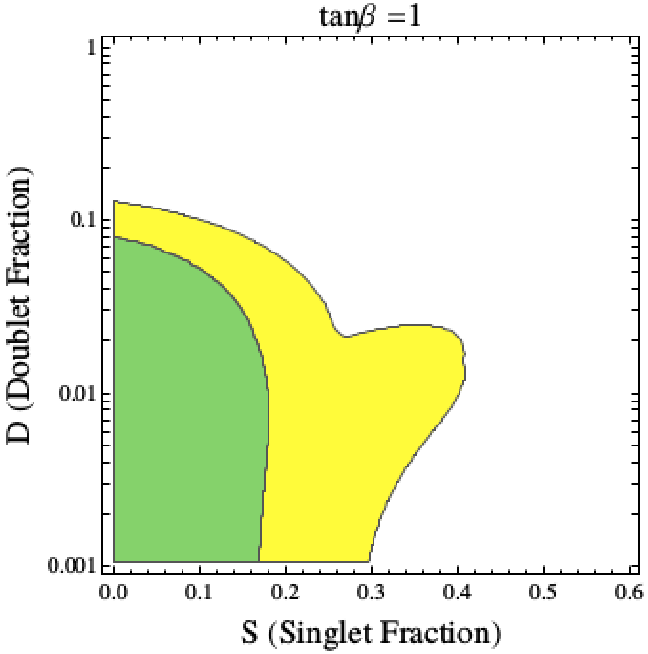




Maiezza, Nemevšek, Nesti 15'
The LRSM analysis, pp⟶h(Δ)⟶ NN⟶ ll4j
0νββ bound from GERDA II

A probe for seesaw singlet scalar?

- Non-singlet scalars have (constrained) associates.
- Gives N a dynamically generated mass.
- Motivated from non-seesaw points of view
- Current data lenient on Higgs-singlet mixing



Singlet mixing:

Leaves *h*'s SM relative decay branching ratios unchanged

M.Farina, M.Perelstein, B.Shakya, 1310.0459: an NMSSM study

$$V_{\rm soft} = m_u^2|H_u|^2 + m_d^2|H_d|^2 + m_S^2|S|^2 + \left(\lambda A_\lambda S H_u \cdot H_d + \frac{1}{3}\kappa A_\kappa S^3 + \text{ h.c.}\right)$$

For simplicity: a minimal case

- Can h⟶ NN probe the *h-s* mixing to tiny levels?
- 'small coupling' assumption:

A small coupling between the `Higgs'-like Φ and a singlet S.
Mostly decoupled Φ, S sectors if the mixing terms are small.

$$\mathcal{L} \supset V(\Phi) + V(S) + \lambda|\Phi|^2 S^2 + y_N S \bar{N}_R^c N_R + y_D \bar{L}\Phi N_R + c.c.$$

SM Higgs-like $\Phi = v_\Phi + \phi$

S vev gives the N mass $S = v_S + s$

$$m_{N_R} = 2 y_N v_S$$

	ϕ	s
ϕ	m_ϕ^2	$\lambda v_\phi v_s$
s	$\lambda v_\phi v_s$	m_s^2

Small coupling: $\lambda v_\Phi v_S \ll m_h^2, m_s^2$

& neglecting $|H|^2 S$ terms

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi \\ s \end{pmatrix}$$

- s can be light and both h_1, h_2 contribute to the signal.
- h_2's non-NN decay channels are $|\sin\alpha|^2$ suppressed.

$$\sigma_{\rm sig.} = (\sigma_{h_1} \cdot {\rm BF}_{h_1 \to NN} + \sigma_{h_2}) \cdot {\rm BF}_{\rm sig.} A_{\rm eff}$$

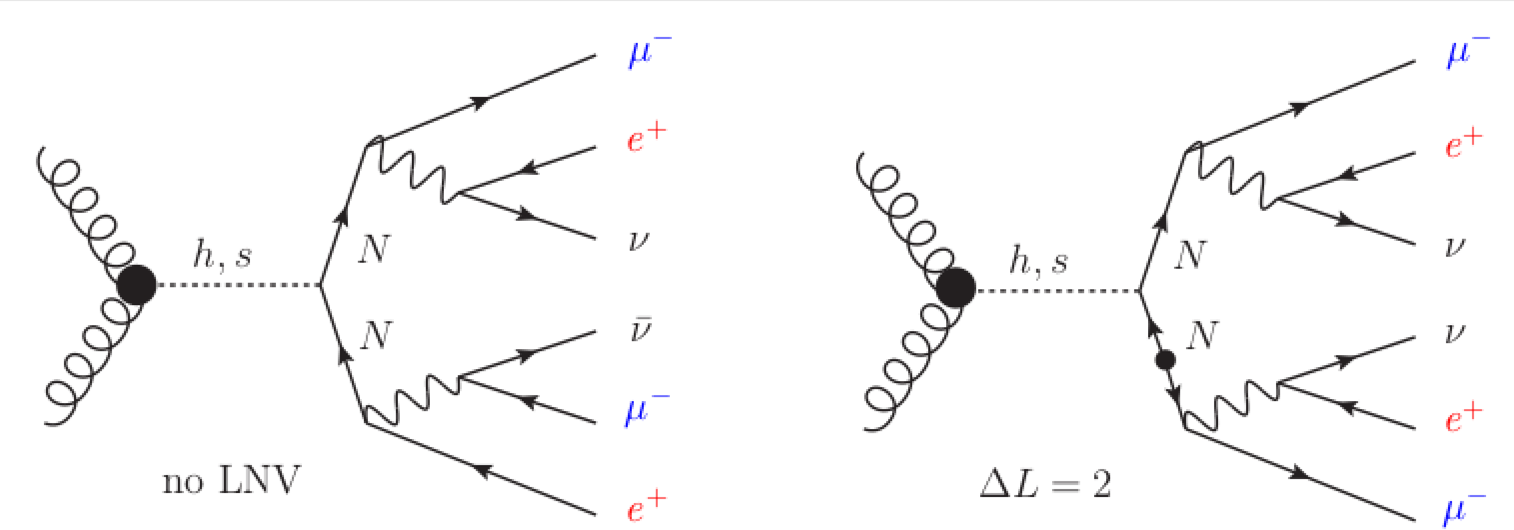
$$\Gamma(h_1 \to NN) = \frac{1}{2} \sin^2 \alpha \cdot \frac{y_N^2 m_{h_1}}{8\pi} \left(1 - \frac{4m_N^2}{m_{h_1}^2}\right)^{3/2}$$

$$\sigma(pp \to h_2) = \sin^2 \alpha \cdot \sigma(pp \to h)\Big|_{m_h^{\rm kin.} = m_{h_2}}$$

Both $h_1 \to NN$ branching and the $\sigma(h_2)$ scales ~ $|\sin\alpha|^2$

$h_2 \to NN$ branching ~ 100%

A signal of two same-sign, same-flavor lepton pairs



Y.Gao, M.Jin, K.Wang in prep.

Available w/wo LNV

* ΔL=0 requires N coupling to at least two flavors

** or taus.

NOTE: W_R & Z' do not contribute to this channel; Neutrino L-R mixing is needed!

$$\mathrm{BF_{sig.}} = \frac{1}{2}\sum_{i\neq j}\left(\frac{y_{D,i}^2}{\Sigma^2}\mathrm{BF}_j^l\right)^2 \quad \text{with LNV}$$

$$+\frac{1}{2}\sum_{i\neq j}\left(\frac{y_{D,i}^2}{\Sigma^2}\mathrm{BF}_j^l\right)\left(\frac{y_{D,j}^2}{\Sigma^2}\mathrm{BF}_i^l\right) \quad \text{w/o LNV}$$

$$\Sigma^2 \equiv y_{D,e}^2 + y_{D,\mu}^2 + y_{D,\tau}^2, \quad i,j = \{e,\mu\}$$

The pp → NN → $e^+e^+\mu^-\mu^-2\nu$ channel

- Does not guarantee LNV, but it is very clean
- Bkg contamination needs 4 $W/W^* \to l\,\nu$ systems in the final state, mostly from

  pp → 4τ, WWZ(one wrong sign *l*), etc.
- & Jets' fake leptons see ATLAS H^{++} search: CERN-EP-2017-198

Our selection criteria:

1. Exactly 4 leptons with $p_T(l_{1,2})$ >10 GeV and $p_T(l_{3,4})$ >5 GeV;
2. 2 same-sign electrons and 2 same-sign muons and the electrons and muons are opposite charged, i.e., the charges and flavors of the leptons are required to be $(\mu^\pm, \mu^\pm, e^\mp, e^\mp)$;
3. No taus or b-jets;
4. post-selection BDT

Boosted Decision Tree (BDT) analysis

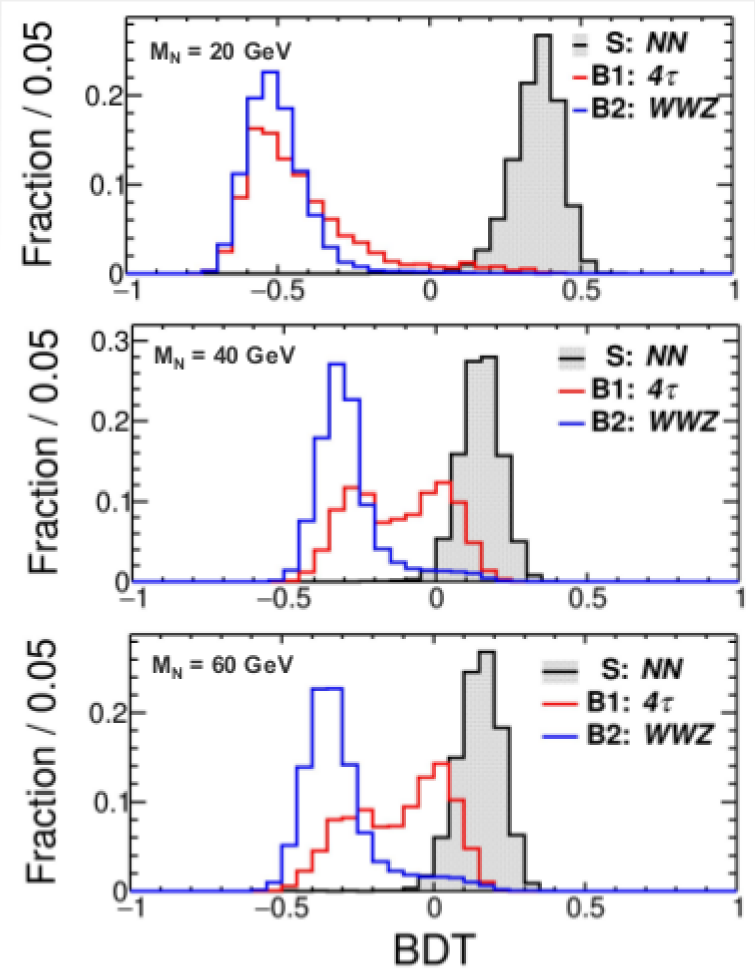
- Further separates signal from background
- Optimized for each m_N.
- TMVA: training 53 global and lepton/MET constructed variables

BDT demonstrates better kinematic differentiation at lower m_N.

No signal observation dominates the BDT at all N masses

Preliminary: only h1 contribution included
signal sample assume LNV topology.
Combined LNV & non-LNV BDT in progress

w LNV



A glance at future sensitivity

Very clean from bkgs

`signal’ rate & significance refers to m_N=20 GeV, plus a combined h_1 and NN decay branching at 10^-7.

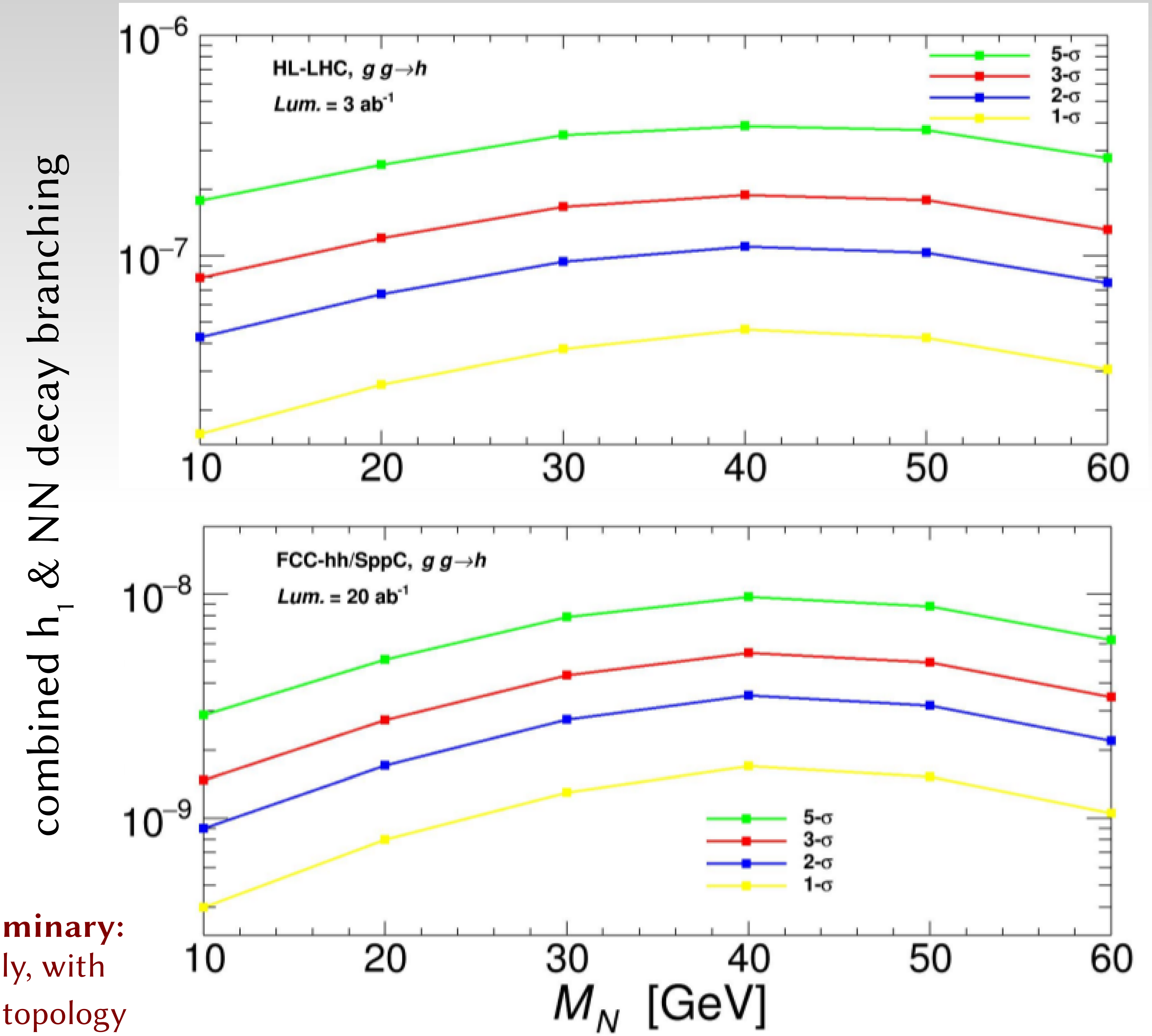
Max. NN branching ~ 0.4%, $h \longrightarrow NN$ branching ~$3x10^{-5}$

only h_1 contribution included

HL-LHC, 3 ab^{-1}	signal	4τ	WWZ
initial	16.4	2.90×10^5	1.06×10^3
pre-selection	1.81	7.00	1.40
BDT > 0.428	1.72	2.00×10^{-2}	2.11×10^{-4}
σ_{stat}	2.65		

FCC-hh/SppC, 20 ab^{-1}	signal	4τ	WWZ
initial	1481	1.18×10^7	1.06×10^5
pre-selection	343	1176	344
BDT > 0.246	252	3.35	6.40×10^{-2}
σ_{stat}	41.2		

$$\sigma_{stat} = \sqrt{2[(N_s + N_b)\ln(1 + \frac{N_s}{N_b}) - N_s]}$$



Preliminary:
h_1 only, with
LNV topology

HL-LHC 14 TeV $3ab^{-1}$	Combined decay branching	$\|\sin\alpha\|^2$	λ	Decoupled?
m_s =150 GeV v_S = 300 GeV	10^{-7}	10^{-5}	10^{-3}	√
m_s =1 TeV v_S = 2 TeV		10^{-3}	0.1	×

FCC/SppC 100 TeV 20 ab^{-1}	Combined decay branching	$\|\sin\alpha\|^2$	λ	Decoupled?
m_s =150 GeV v_S = 300 GeV	10^{-9}	10^{-6}	10^{-4}	√
m_s =1 TeV v_S = 2 TeV		10^{-4}	0.01	?

h_1+h_2 contributions: very good sensitivity for weak-scale m_S

Summary

- The Higgs boson is a viable mediator in RHN search
- pp$\longrightarrow$ h$\longrightarrow$ NN has a very clean & promising same-flavor, same-sign double lepton-pair channel, w & wo LNV.
- Can interpret h$\longrightarrow$ NN sensitivity as a probe for the Higgs mixing/coupling to the N mass generating scalar.
- High sensitivity derived for a minimal toy-model's `decoupled' Higgs, singlet sectors, in particular if the singlet mass ~ $O(m_h)$
- Applicable to realistic, 'non-decoupled' models