Multilepton Searches for Heavy Neutrino at the Higgs Factory

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CEPC study for SNOWMASS
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Outline

Remarks on seesaw
Heavy *N* opportunities @ ee
Same-Sign multiple leptons – a probe for Higgs mixing

Y.Gao, K.Wang,
2102.12826

Y.Gao. M.Jin. K.Wang.
1904.12325
A.Das. Y.Gao. T.Kamon
1704.00881

Seesaw and mixings

mixing

Type -I

$$\mathcal{L}_N = -\overline{L}\, Y_\nu^D\, \tilde{H}\, N_R - \frac{1}{2}\overline{(N^c)}_L\, M_R\, N_R$$

$$\frac{y_D\, v_0}{\sqrt{2}\, M_R}$$

Type -II

$$\Delta\mathcal{L}_{II}^m = -\overline{L^c}\, Y_\nu\, i\sigma_2\, \Delta_L\, L$$

$$\Delta\mathcal{L}_{H\Delta_L} \ni \mu H^T\, i\sigma_2\, \Delta_L^\dagger H$$

✗

Type -III

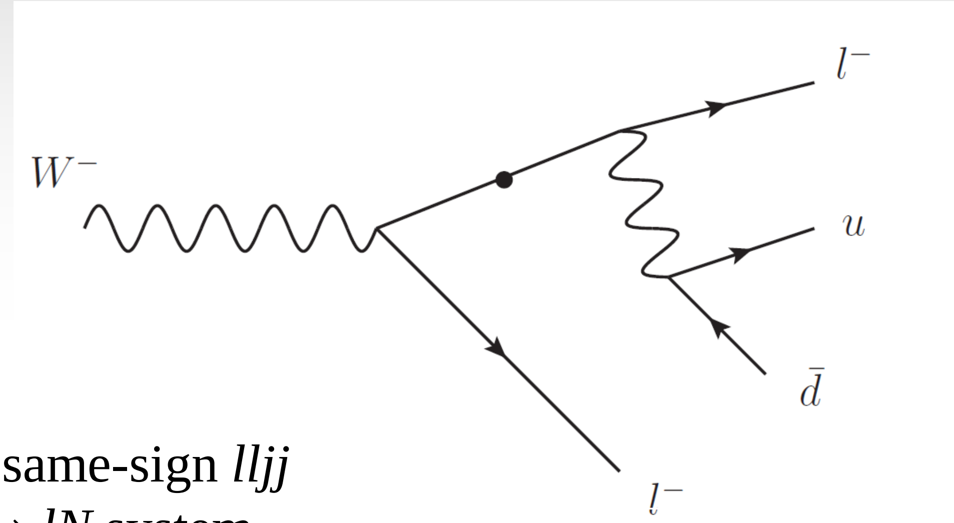
$$\mathcal{L}_Y = -Y_\Sigma \overline{L}\, \Sigma_R^c\, i\sigma^2 H^*$$

$$\mathcal{L}_T = \frac{1}{2}\mathrm{Tr}\left[\overline{\Sigma_L} i \not{D} \Sigma_L\right] - \left(\frac{M_\Sigma}{2}\overline{\Sigma_L^0}\Sigma_R^{0c} + M_\Sigma \overline{\Sigma_L^-}\Sigma_R^{+c} + \mathrm{H.c.}\right)$$

$$\frac{Y_\Sigma v_0}{\sqrt{2} M_\Sigma}$$

+ hybrids, inverse seesaw, radiative, etc.

Spotting a Majorana heavy N



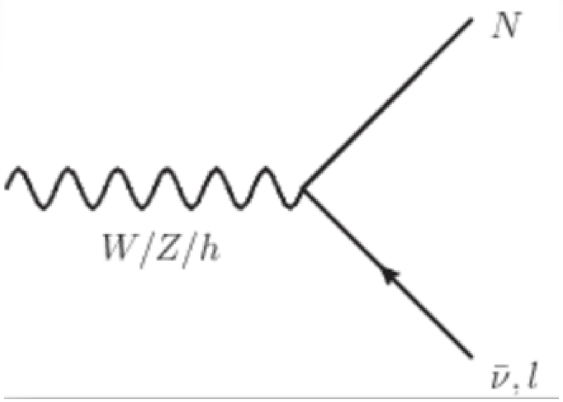
`smoking' gun same-sign *lljj*
from a W(*) → *lN* system,
$m_{ljj} \sim m_N$

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

Heavy neutrino production

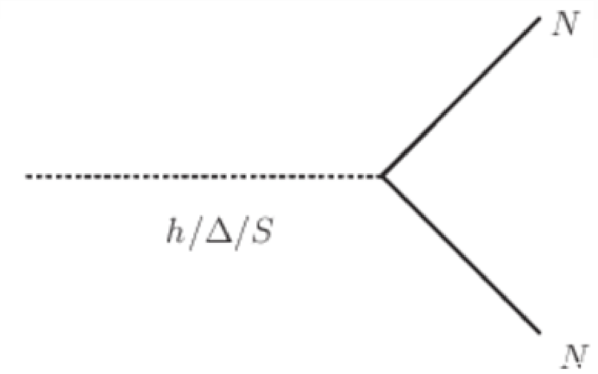
Single N production
via ν-N mixing.

effective couplings ∝ $|V_{lN}|^2$



NN pair production
via N_R couplings

∝ scalar mixing $|\sin\alpha|^2$



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

y_D is suppressed by active ν mass
y_N is **not**.

Heavy N @ ee: W,Z,h rare decays (via V_{lN})

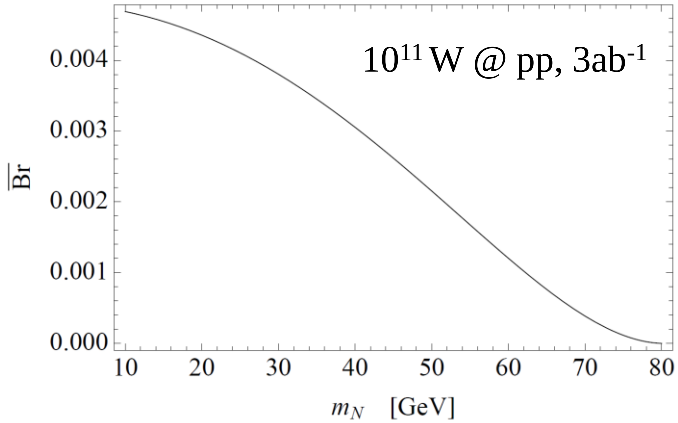
Z decay @ ee

Optimized at Z pole.
$|V_{eN}|^2$ down to ~ 10^{-8}.

W decay @ pp (LNV)

$$W^{\pm} \to e^{\pm} e^{\pm} \mu^{\mp} \nu$$

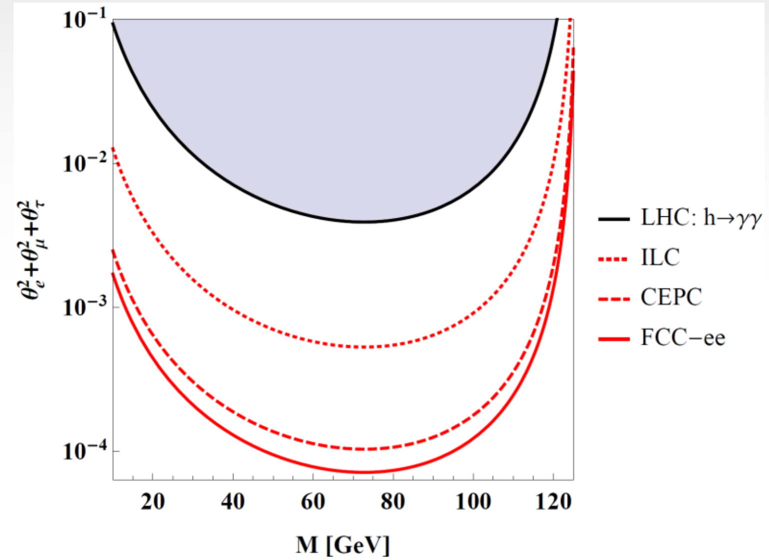
$$Br = \overline{Br} \times |U_{Ne}|^4 / (\sum_{\ell} |U_{N\ell}|^2)$$



C.O.Diba, C.S.Kim, 1509.05981

h ⟶ *ν N @ee*

S.Antusch, O.Fischer, 1502.05915



@pp, top, VV bkgs are significant.
gg ⟶ *h* ⟶ *ν N* search needs an **ISR kick**
A.Das, Y.Gao, T.Kamon, 1704.00881

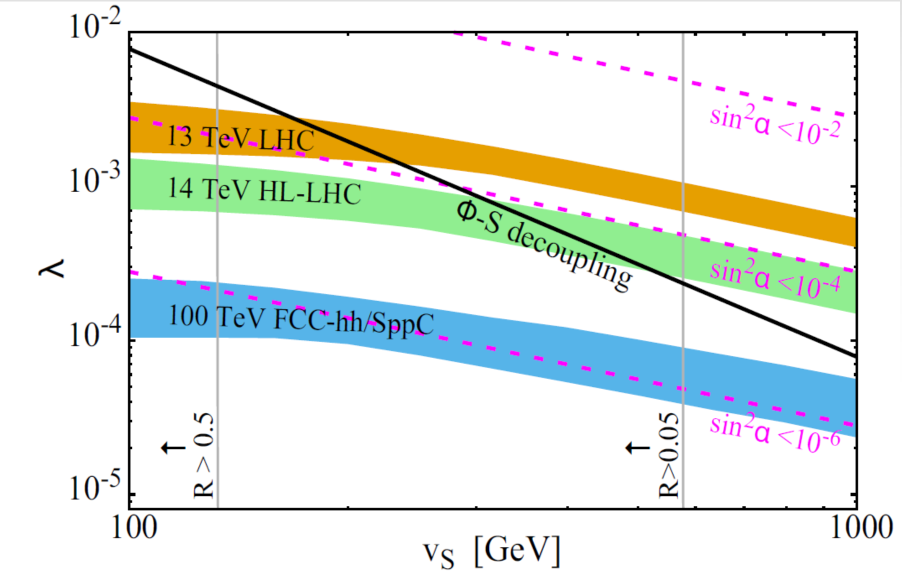
h ⟶ *$l^- l'^+$ flavor violating decays @ee*
see Q.Qin, Q.Li, C.-D.Lu, F-S.Yu, S.-H.Zhou, 1711.07243

Heavy N @ pp: Higgs mixing (with scalar)

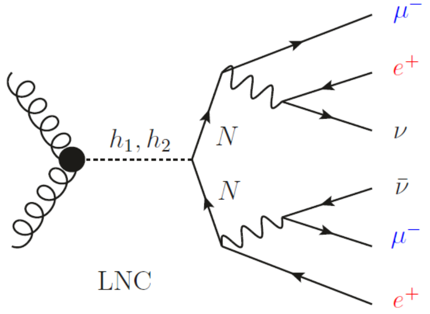
- Assuming the Higgs is the only visible scalar.
- Can h⟶ *NN* probe the *h*-*s* mixing to tiny levels? -- 'small coupling'

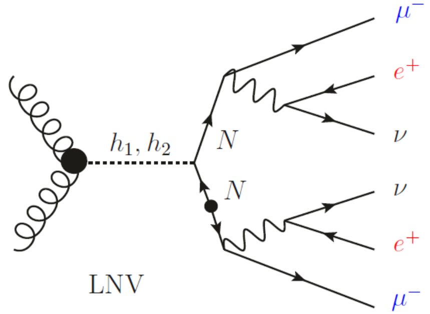
$$\sin^2\alpha \ll 1,$$
$$\lambda \cdot \max(v_S^2, v_\Phi^2) \ll \min(m_s^2, m_\phi^2).$$

- Mostly decoupled Φ, S sectors if the mixing terms are small.



pp limit, Y.Gao, M.Jin, K.Wang, 1904.12325





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

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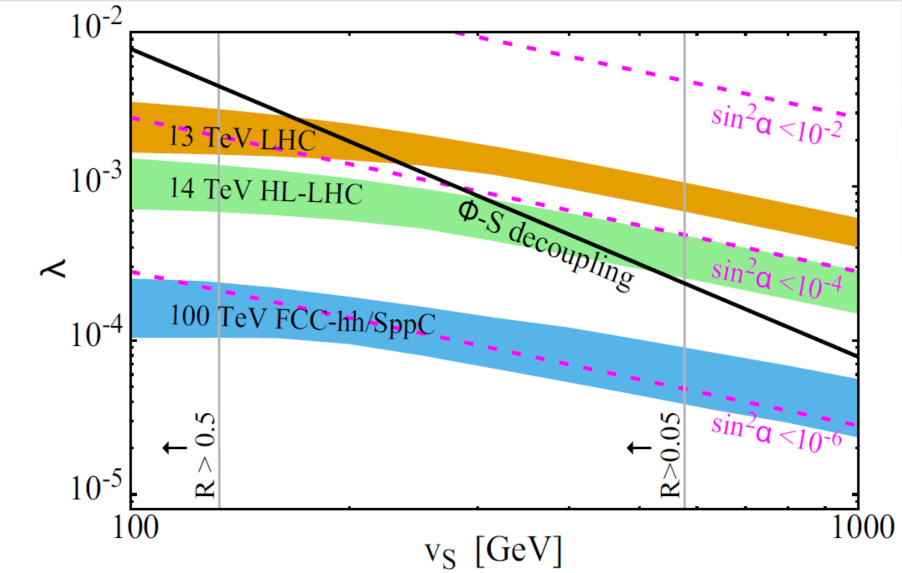
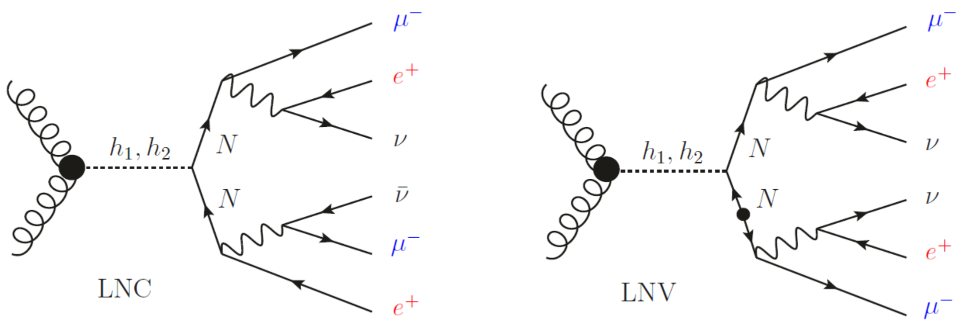


pp limit, Y.Gao, M.Jin, K.Wang, 1904.12325



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

How about using ee⟶Zh at Higgs Factory?

NN via Higgs Decay @ ee

1.How small an *h*-*s* mixing can CEPC probe?
(sensitivity on $|\sin\alpha|^2$, complementary to $|V_{lN}|^4$)

2. Are LNV (& alikes) events ***truly background free***?

10^6 Higgs events @ cleaner ee vs HL but dustier *pp*

ee: no fake leptons from soft jets, yet lower Higgs count, & extra Z boson

A minimal setup

$$\Delta\mathcal{L} \supset -y_D \bar{L}\tilde{\Phi} N_R - y_S S \overline{N_R^c} N_R + c.c. + \lambda |\Phi|^2 S^2 + V_S .$$

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

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

& neglecting $|\Phi|^2 S$ terms

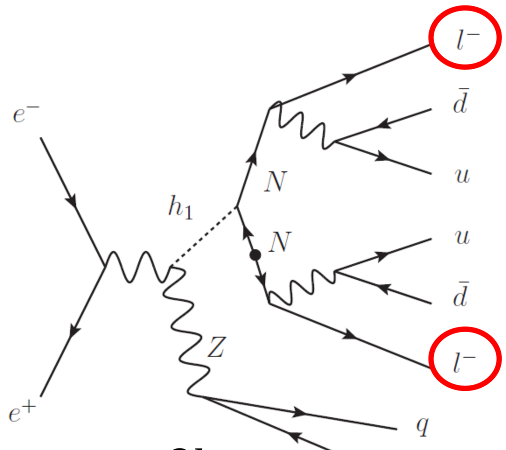
$$\sigma_{\text{sig.}} = (\sigma_{h_1} \cdot \text{BF}_{h_1 \to NN} + \sigma_{h_2}) \cdot \text{BF}_{\text{sig.}} A_{\text{eff}}$$

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

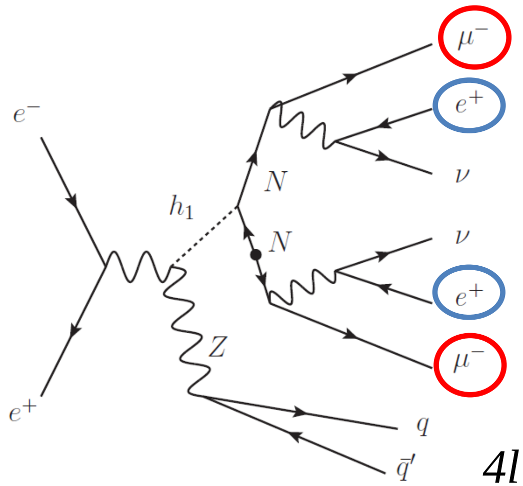
Both $h_1 \to NN$ branching and $\sigma(h_2)$ scale ~ $|\sin\alpha|^2$
$h_2 \to NN$ branching ~ 100% if $|V_{lN}|^2$ is small

ee@240 GeV: ignore $ee \to Zh_2$ as COM energy is limited

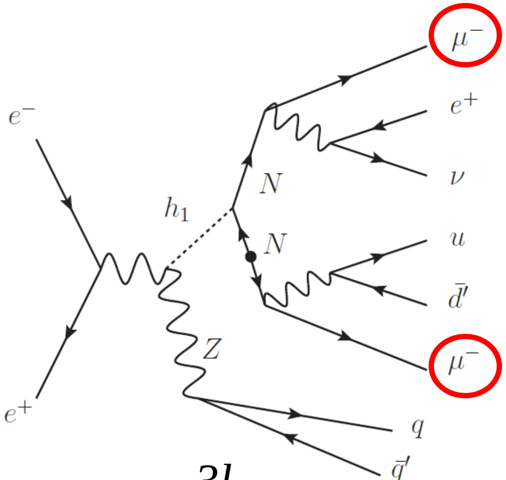
NN : Semileptonic, fully leptonic & mixed decays



2l



4l



3l

Should we included a reconstruct-able Z?

NN@ee : SM backgrounds

1. Intrinsic backgrounds

Randomly flavored leptons emerges from W/W*. i.e W & tau decays.

$\tau^+\tau^-\tau^+\tau^-$, $\tau^+\tau^-\tau^+\tau^-Z$, $\tau^+\tau^-W^+W^-$.

2. Missed leptons (& wrong signs)

$\tau^+\tau^-Z$, l^+l^-Z, $\tau^+\tau^-l^+l^-Z$, $l^+l^-l^+l^-Z$, $l^+l^-W^+W^-$

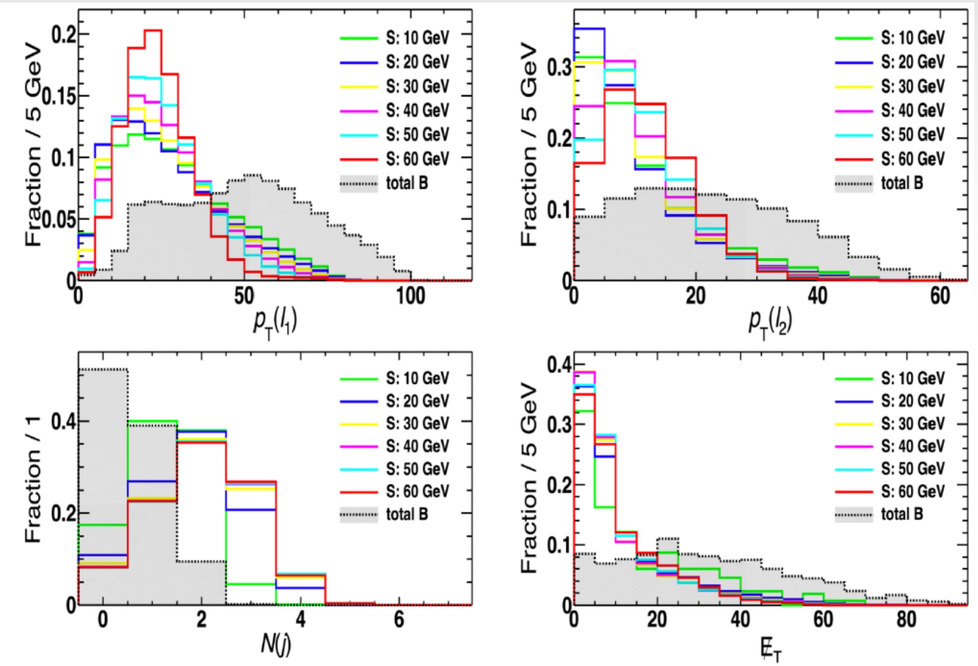
up to 2 weak bosons for 240 GeV.
τ decay may yield jets. N decay jets are soft.
Leptonic Z decay may contribute to N_l and SS
6τ, $6l$ channels are not independent.

Signal strategy:

Assume $Z\rightarrow jj$ (more jets)
Require SS leptons
Strict lepton charge & count cuts
Categorize on N_l:
- 2-4 visible leptons with flavor-distinguishable SS pairs

2l channel: SS dilepton +(≥3) jets

Y.Gao, K.Wang, 2102.12826



		initial	cuts(i-ii)	cuts(iii-iv)	cuts(v)
Sig.	10 GeV	10^3	6.3	0.29	0.18
	20 GeV	10^3	35.9	8.8	6.4
	30 GeV	10^3	72.3	22.6	17.5
	40 GeV	10^3	97.2	32.5	25.3
	50 GeV	10^3	112	37.4	28.8
	60 GeV	10^3	121	40.5	30.2
Bkg.	4τ	1.69×10^4	870	4.6×10^{-2}	7.7×10^{-3}
	$^\dagger 2\tau Z$	6.80×10^5	2.91×10^3	4.6	0.93
	$^\dagger 2\ell Z$	1.74×10^6	3.98×10^3	-	-
	$4\tau Z$	93.0	2.0	0.19	5.9×10^{-2}
	$2\tau 2W$	4.42×10^3	63.6	0.92	8.2×10^{-2}
	$^\dagger 2\ell 2\tau Z$	584	13.8	2.0	0.75
	$^\dagger 4\ell Z$	862	16.5	2.2	2.1
	$^\dagger 2\ell 2W$	2.74×10^4	639	11.7	1.2

lepton cuts — jet cuts

(i) exactly two leptons, $N(\ell) = 2$ with $p_T(\ell) > 5$ GeV;
(ii) two leptons have the same sign;
(iii) veto τ leptons, $N(\tau) = 0$;
(iv) at least three jets, $N(j) \geq 3$;
(v) small missing energy, $\not{E}_T < 15$ GeV.

MG5+Pythia8+Delphes CEPC card

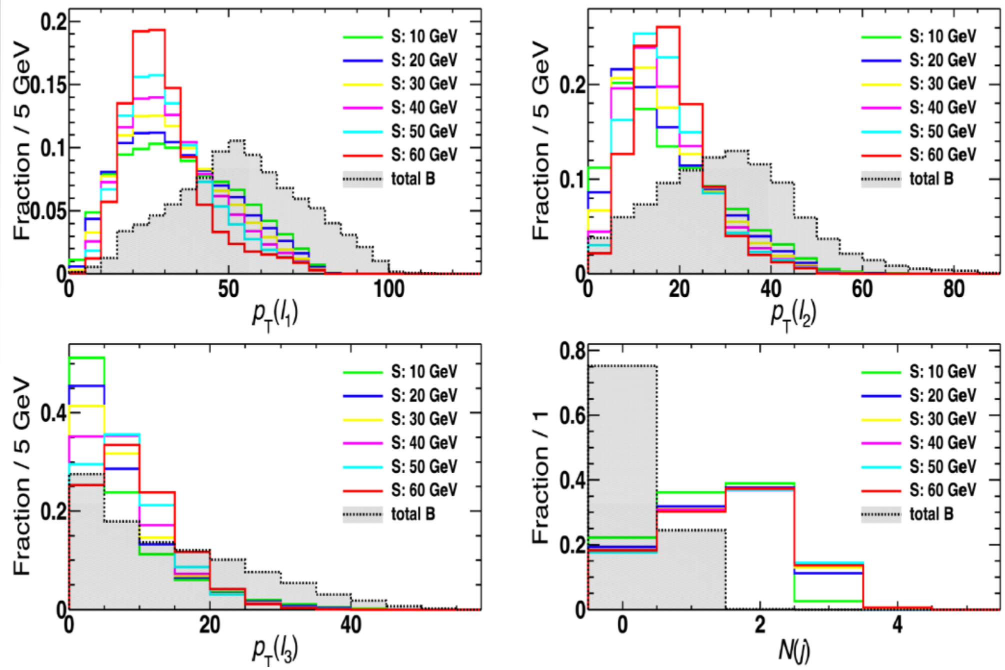
C.Chen, et.al. 1712.09517

Bkg @ 5.6 ab^{-1}

Signal ~10% eff. w lepton cuts
~2% sig. eff. at N_{bkg}~1 level

3l channel: SS dilepton +l'+(≥2) jets

Y.Gao, K.Wang, 2102.12826



		initial	cuts(i)	cuts(ii)	cuts(iii-iv)
Sig.	10 GeV	10^3	27.9	5.6	2.3
	20 GeV	10^3	62.7	13.6	6.6
	30 GeV	10^3	85.8	19.9	10.0
	40 GeV	10^3	102	24.9	12.7
	50 GeV	10^3	112	27.3	14.1
	60 GeV	10^3	115	28.2	14.4
Bkg.	4τ	1.69×10^4	614	155	3.8×10^{-2}
	$^\dagger 2\tau Z$	6.80×10^5	1.30×10^4	350	-
	$^\dagger 2\ell Z$	1.74×10^6	5.03×10^4	121	-
	$4\tau Z$	93.0	2.1	0.25	7.3×10^{-2}
	$2\tau 2W$	4.42×10^3	27.8	6.9	0.72
	$^\dagger 2\ell 2\tau Z$	584	46.5	1.1	0.44
	$^\dagger 4\ell Z$	862	132	0.27	1.4×10^{-2}
	$^\dagger 2\ell 2W$	2.74×10^4	1.30×10^3	37.8	5.0×10^{-2}

lepton cuts   jet cuts

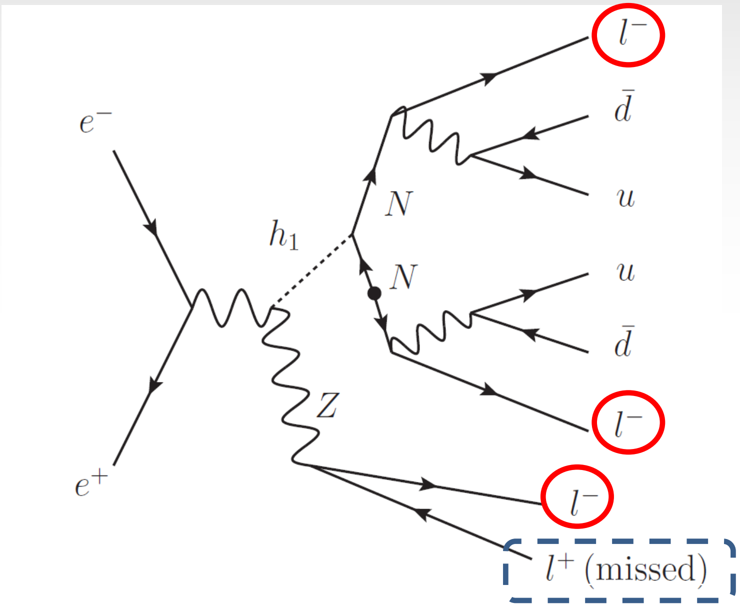
(i) exactly three leptons $N(\ell) = 3$ with $p_T \geq 5$ GeV;
(ii) veto OSSF lepton pairs;
(iii) veto τ leptons, $N(\tau) = 0$;
(iv) at least two jets, $N(j) \geq 2$.

Bkg @ 5.6 ab^{-1}

O(1%) sig. eff. at N_{bkg}~1 level

3l channel's Bonus: SS trilepton

Z decay yield `correct'-sign lepton if its `incorrect'-sign company goes missing



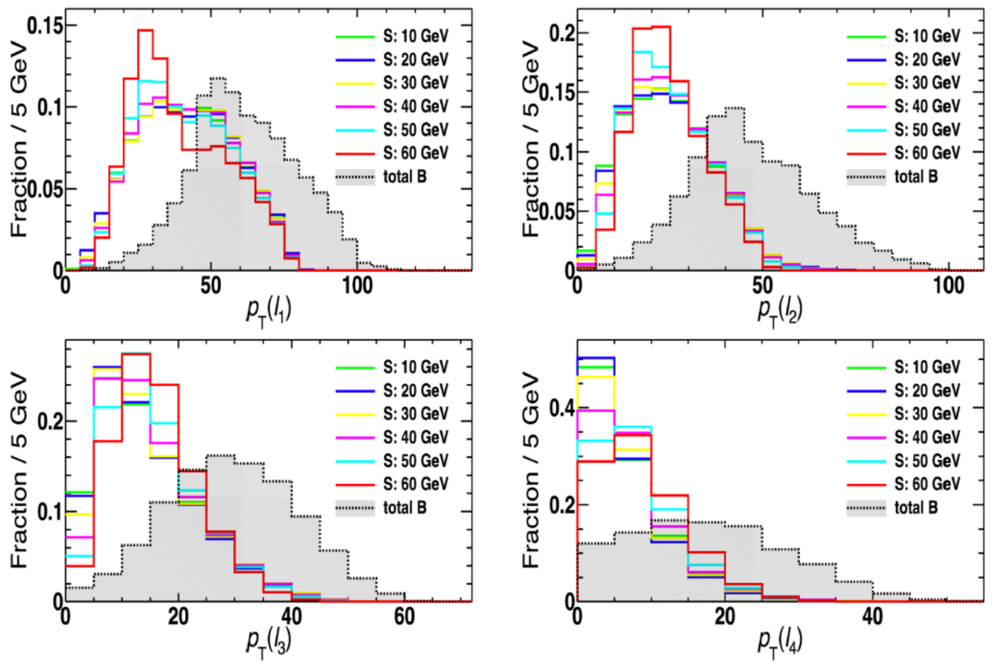
SS-trilepton post- lepton cuts (w/o jet cuts):

SM bkg ~ 0.1% of 3*l* channel after cut (ii)

Clean channel, yet signal yield is also smaller.

4l channel: two SS dileptons +(≥1) jets

Y.Gao, K.Wang, 2102.12826



(i) exactly four leptons, $N(\ell) = 4$ with $p_T(\ell) \geq 5$ GeV;
(ii) exactly two electrons with the same charges; exactly two muons with the same charges; electrons and muons have opposite charges; i.e. exactly $e^\pm e^\pm \mu^\mp \mu^\mp$ lepton pairs;
(iii) veto τ leptons, $N(\tau) = 0$;
(iv) at least one jet, $N(j) \geq 1$.

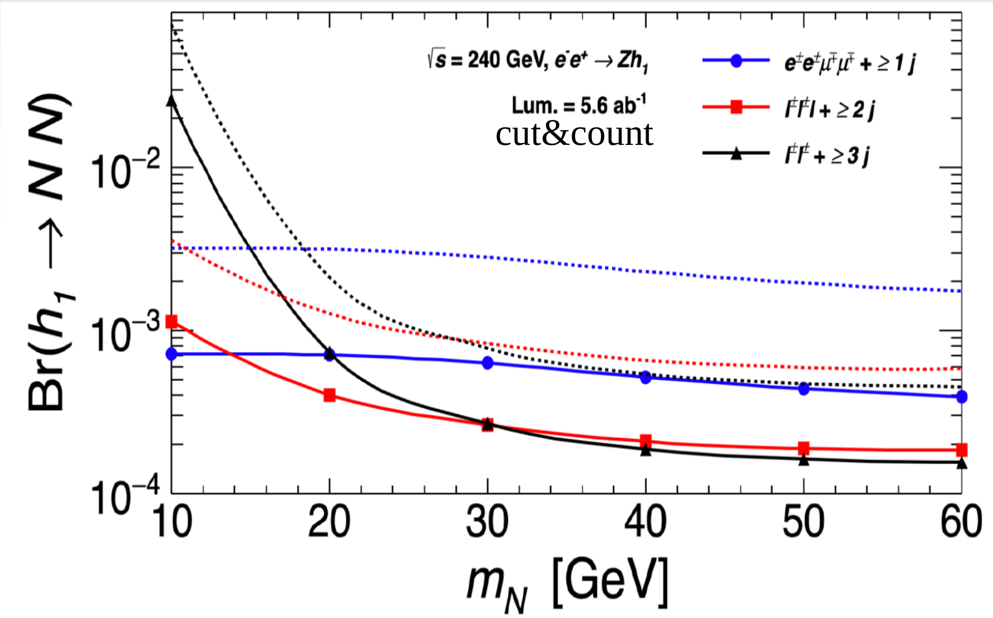
		initial	cuts(i)	cuts(ii)	cuts(iii-iv)
Sig.	10 GeV	10^3	15.9	1.1	0.71
	20 GeV	10^3	17.5	1.1	0.72
	30 GeV	10^3	22.1	1.3	0.80
	40 GeV	10^3	26.8	1.5	0.98
	50 GeV	10^3	30.1	1.8	1.2
	60 GeV	10^3	32.1	2.1	1.3
Bkg.	4τ	1.69×10^4	58.4	6.8	-
	$^\dagger 2\tau Z$	6.80×10^5	2.26×10^3	9.6	-
	$^\dagger 2\ell Z$	1.74×10^6	7.28×10^4	-	-
	$4\tau Z$	93.0	0.45	6.4×10^{-3}	2.8×10^{-3}
	$2\tau 2W$	4.42×10^3	1.3	0.17	-
	$^\dagger 2\ell 2\tau Z$	584	13.8	1.0×10^{-2}	3.2×10^{-3}
	$^\dagger 4\ell Z$	862	116	7.8×10^{-4}	-
	$^\dagger 2\ell 2W$	2.74×10^4	217	-	-

N_l=4 | Two SS dileptons | jet cuts (for sensitivity)

~10 bkg events
w two SS dileptons
@5.6 ab^{-1}

lofty cost: sig. eff ~ 0.1%

Mixing angle reach @ ee (CEPC)



2*l*, 3*l* wins over 4*l*

$$|\sin\alpha \cdot y_S|^2 = \mathrm{BR}(h_1 \to NN) \cdot 16\pi \frac{\Gamma_{h_1}}{m_{h_1}} \left(1 - \frac{4m_N^2}{m_{h_1}^2}\right)^{-3/2}$$

ee @ 240 GeV, 5.6ab^{-1}:

$|\sin\alpha|^2 < 10^{-4}$ sensitivity
for $y_S \sim O(1)$
comparable to HL-LHC

Summary

1. Heavy *N* as a good probe for Higgs - seesaw scalar mixing $|\sin\alpha|^2$ @ee
2. $|\sin\alpha|^2 \sim 10^{-4}$ for CEPC @ 240 GeV, 5.6 ab^{-1}, comparable to HL-LHC

Type equation here.

3. SS dilepton bkg not neglectable. Lofty loss on signal if assuming $N_{bkg} < 1$.
4. $Z \to ll$ yield a bonus SS trilepton signal @ ee