Heavy Neutrino Searches at the CEPC

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Based on [Yu Gao's slides; Yu Gao & K. Wang, hep-ph/2102.12826; Zeren Simon Wang & K. Wang, PRD 101 (2020) no.7, 075046]

OUTLINE

Motivations & Constraints on N Searches

Pheno. Studies on N Searches @ ee

Our Studies

→ Prompt case

→ Long-lived case

Summary

Theory Motivations

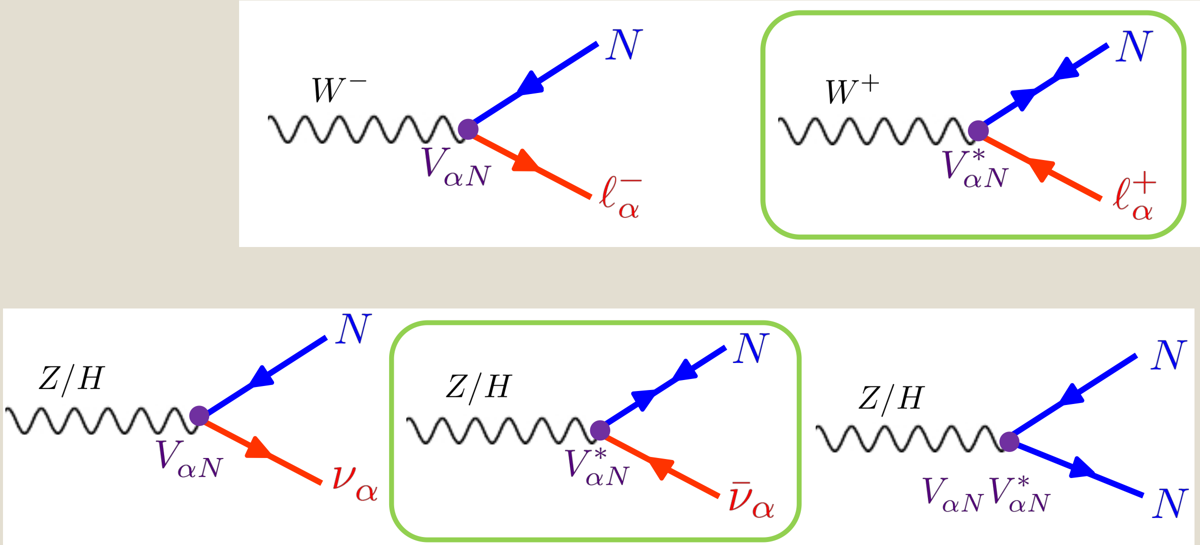
Discovery of neutrino oscillations => neutrinos have mass
→ In SM, neutrinos are massless
→ A window to BSM physics

Type-I see-saw: Singlet (Sterile) Fermions

$$-\mathcal{L} = h_{\ell\alpha}\bar{L}_\ell\widetilde{\Phi}N_\alpha + \frac{1}{2}M_{N_{\alpha\beta}}\bar{N}^C_\alpha N_\beta + \text{H.c.}$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_D \\ M_D^\mathsf{T} & M_N \end{pmatrix}$$

Interactions: [0901.3589]

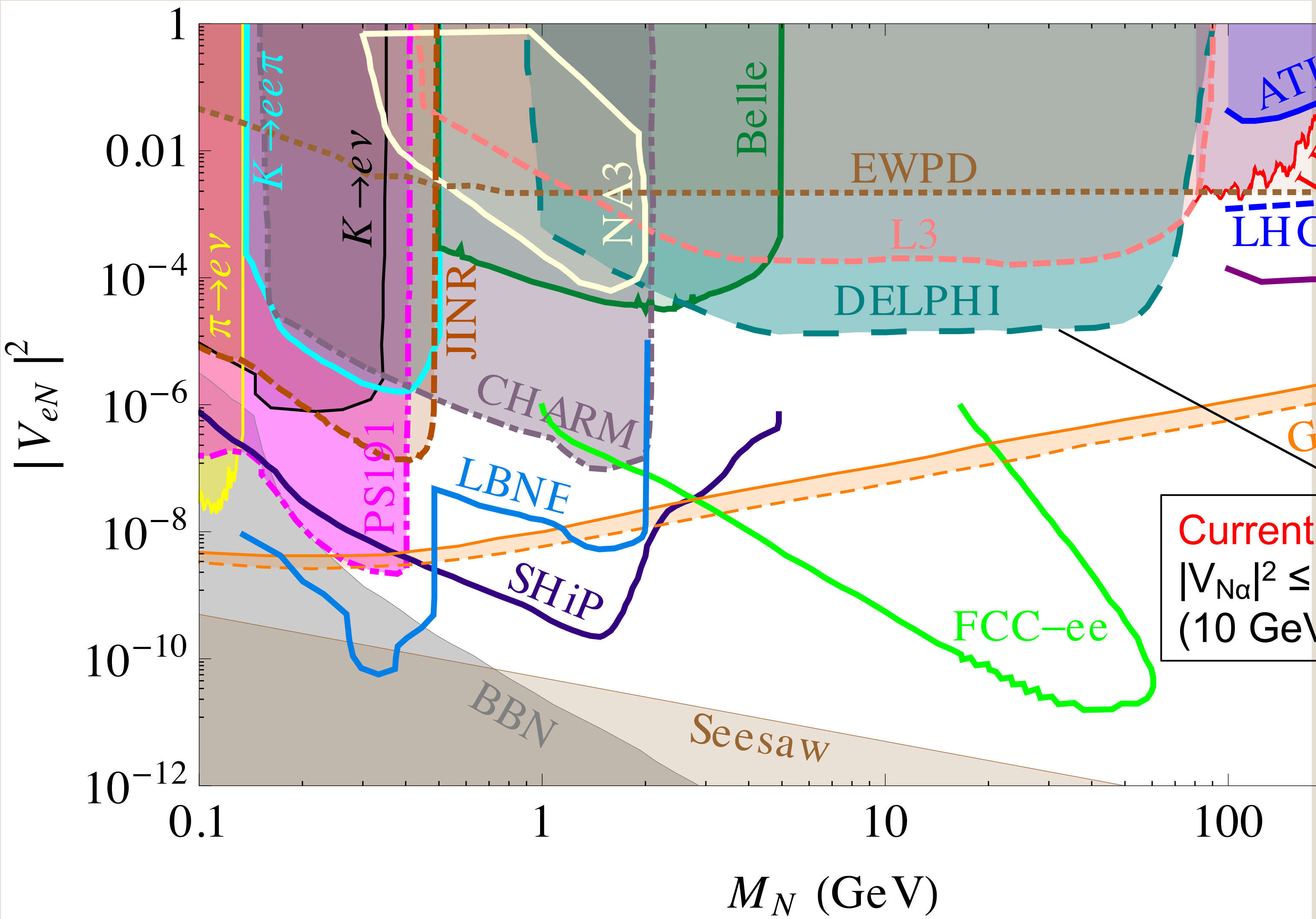


Simplified model with assumption for collider searches:
Only 1 generation of sterile neutrinos is light & within experimental reach;
$V_{N\tau} = 0$;
3 free parameters: m_N, V_{Ne}, $V_{N\mu}$, Dirac/Majorana.

Global Constraints

from [Deppisch, Dev and Pilaftsis, New J. Phys. 17 (2015) 085019]

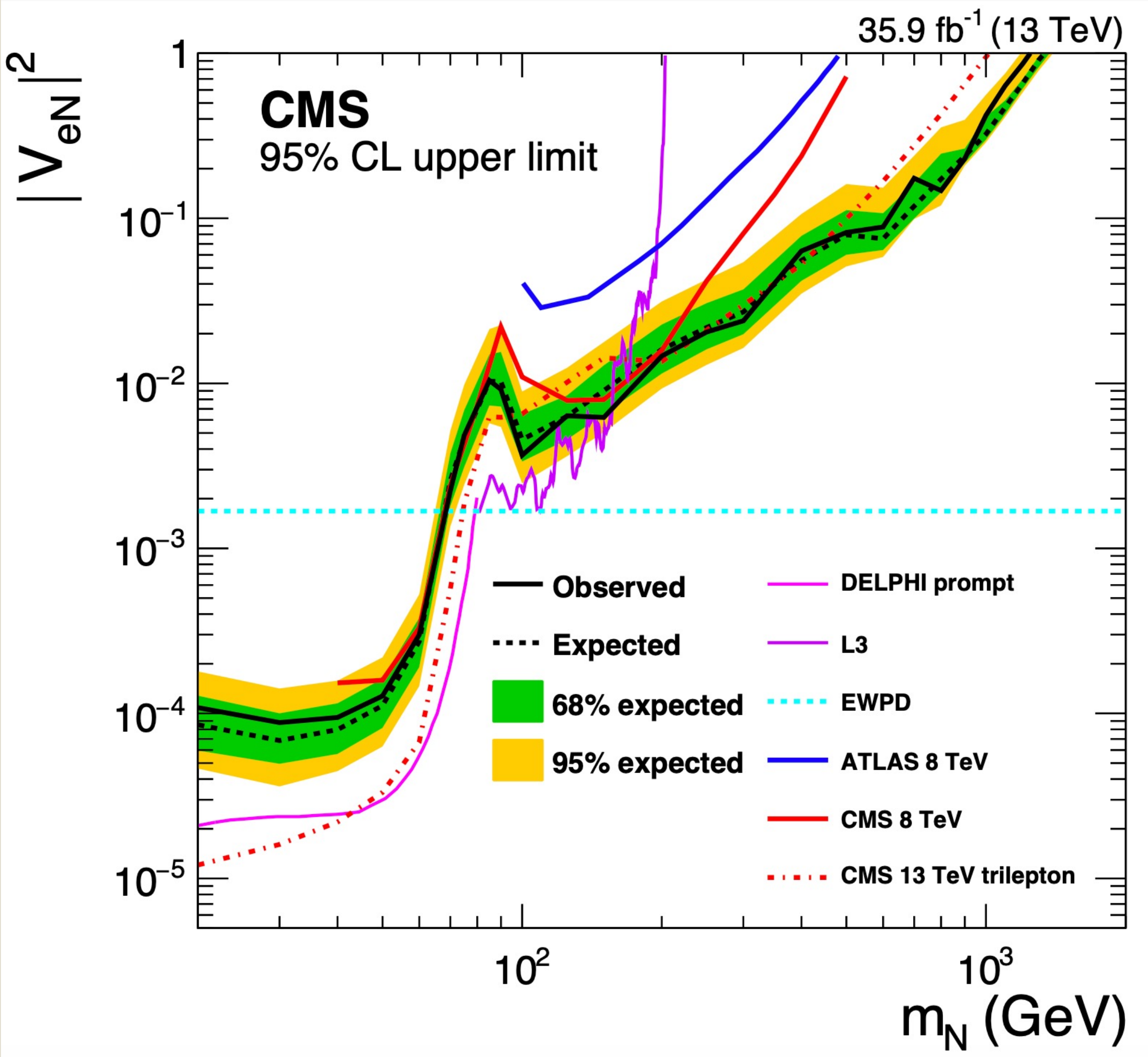
m_N: 0.1 ~ 500 GeV



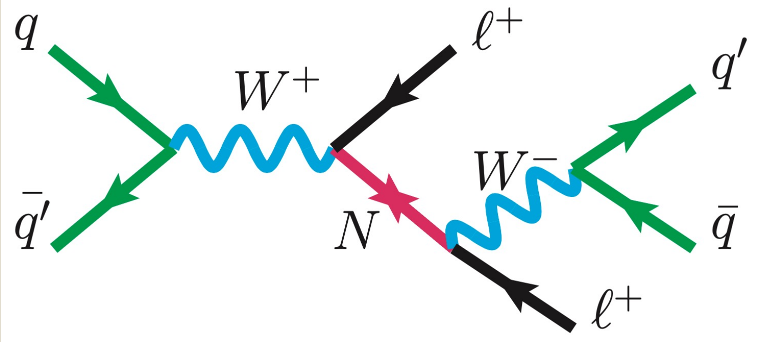
Current Limit:
$|V_{N\alpha}|^2 \le 10^{-5}$
(10 GeV < m_N < m_W)

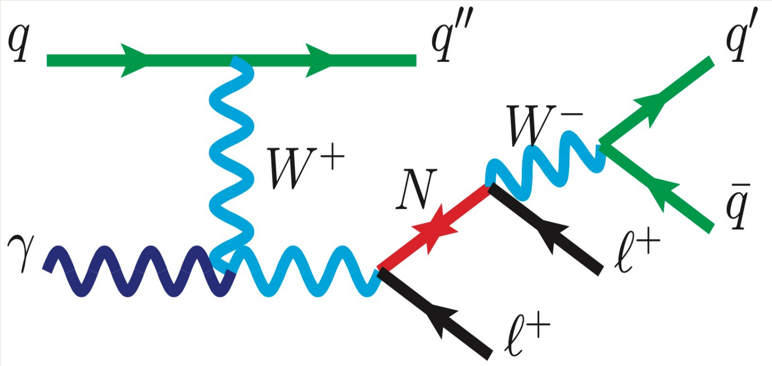
LHC Limits

[**LHC, CMS experiment:** hep-ex/1806.10905, CMS-EXO-17-028, CMS, JHEP 01 (2019) 122
"Search for heavy Majorana neutrinos in same-sign dilepton channels in proton-proton collisions at 13 TeV"]



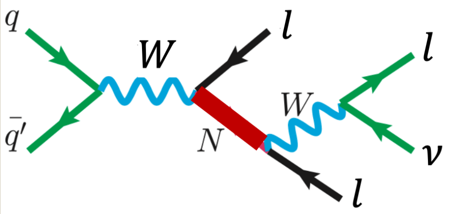
$2l$ (SS) + ≥ 1 j



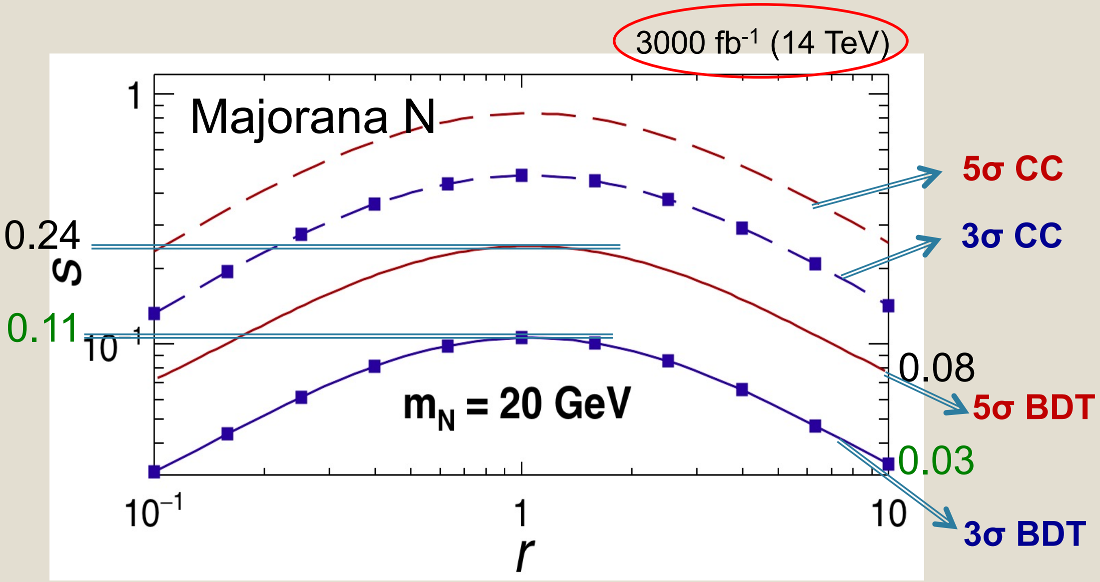


LHC Limits

3l + MET



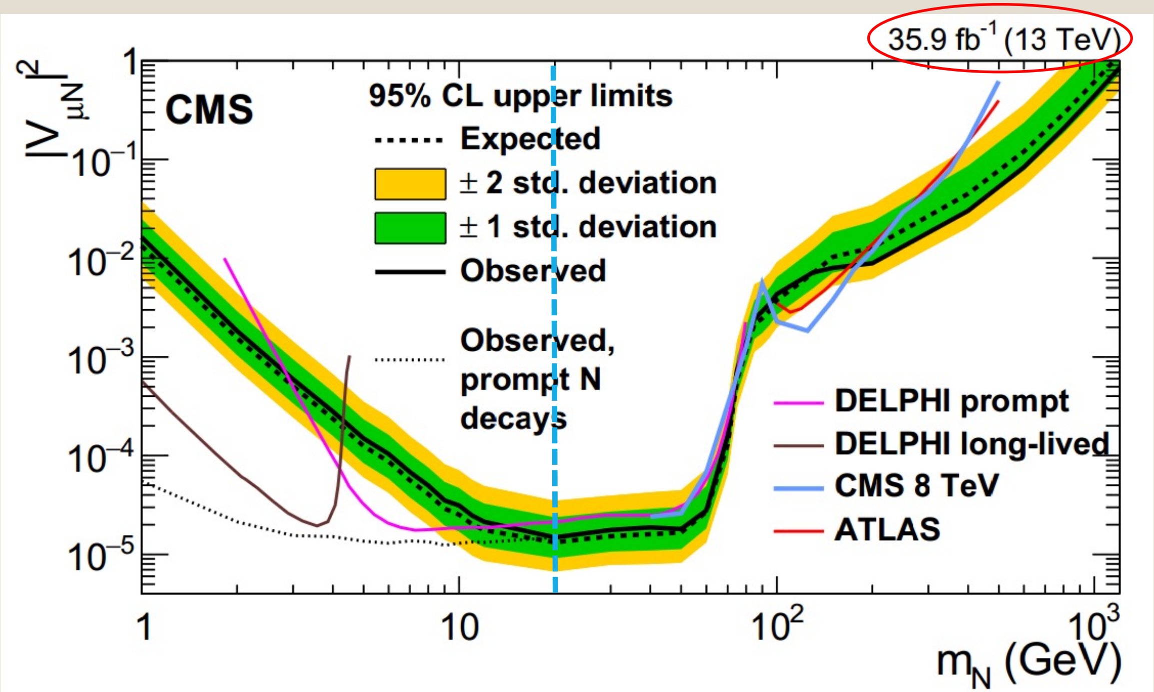
[Claudio O. Dib, C.S. Kim, **Kechen Wang**, Phys.Rev. D95 (2017) no.11, 115020, cited by CMS collaboration]



$$s \equiv 2\times 10^6 \times \frac{|U_{Ne}U_{N\mu}|^2}{|U_{Ne}|^2+|U_{N\mu}|^2} \qquad r \equiv \frac{|U_{Ne}|^2}{|U_{N\mu}|^2}$$

when $r = 1$, $|U_{Ne}|^2 = |U_{N\mu}|^2 = s \times 10^{-6}$

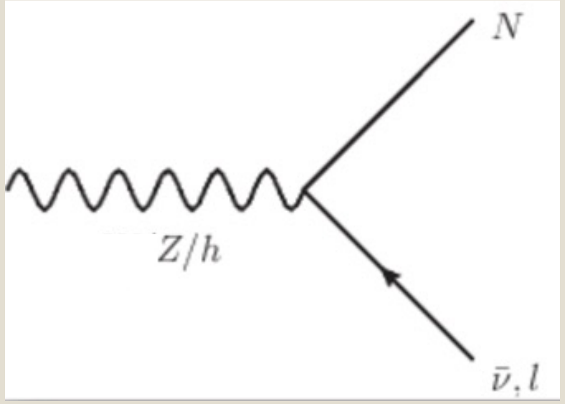
[**LHC, CMS experiment:** Phys.Rev.Lett. 120 (2018) no.22, 221801, *"Search for heavy neutral leptons in events with three charged leptons in proton-proton collisions at 13 TeV"*]



Leading Order N Productions @ ee

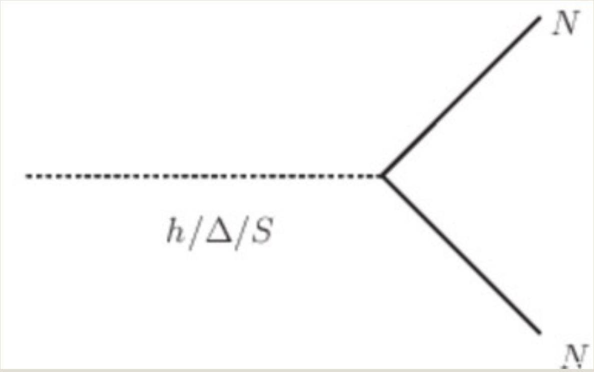
Single N production
via ν-N mixing.

effective couplings ∝ $|V_{lN}|^2$



NN pair production
via N_R couplings

∝ scalar mixing $|\sin\alpha|^2$

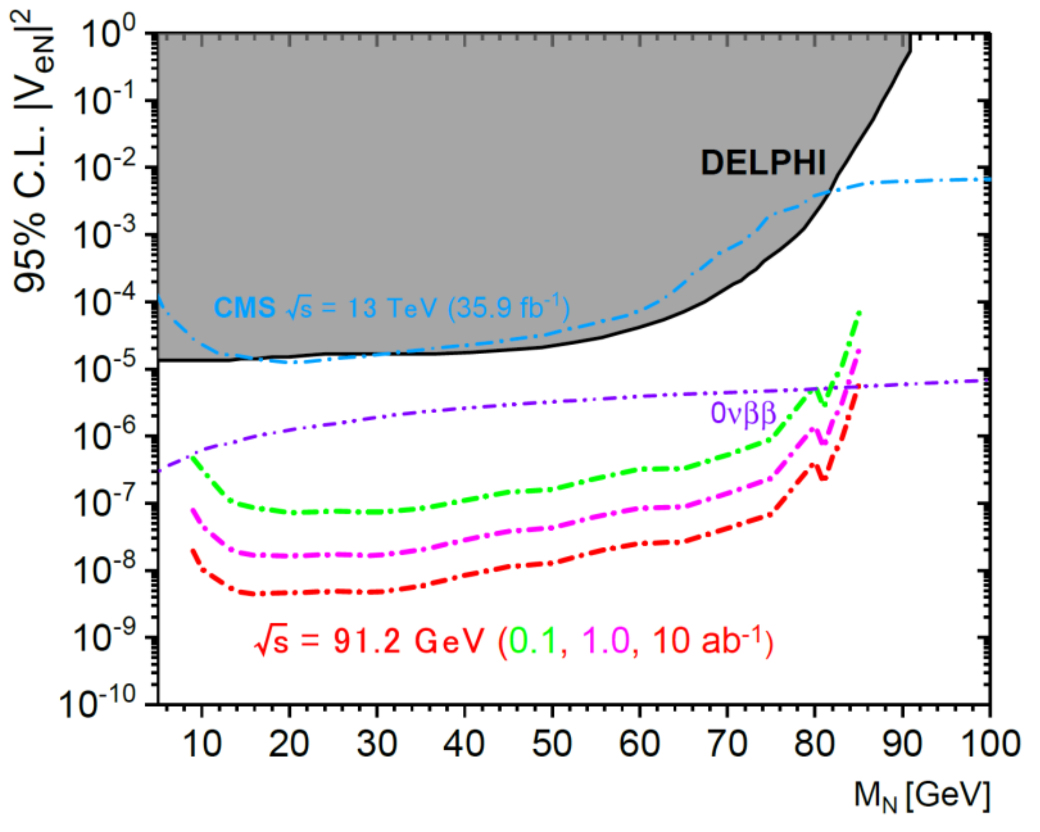


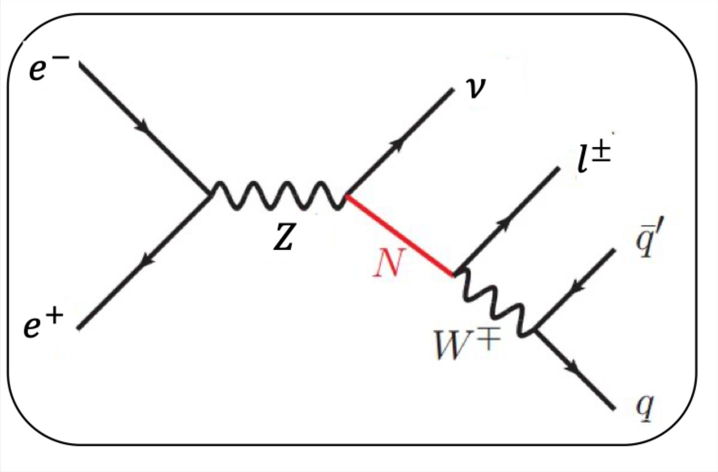
$$\mathcal{L} \supset V(\Phi) + V(S) + \lambda|\Phi|^2 S^2 + y_N S \bar{N}_R^c N_R + y_D \bar{L}\Phi N_R + c.c.$$

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

Heavy N @ ee: Single N at Z-pole

$e^- e^+ \to Z \to \nu N \to \nu lW \to \nu ljj$ @ Z pole



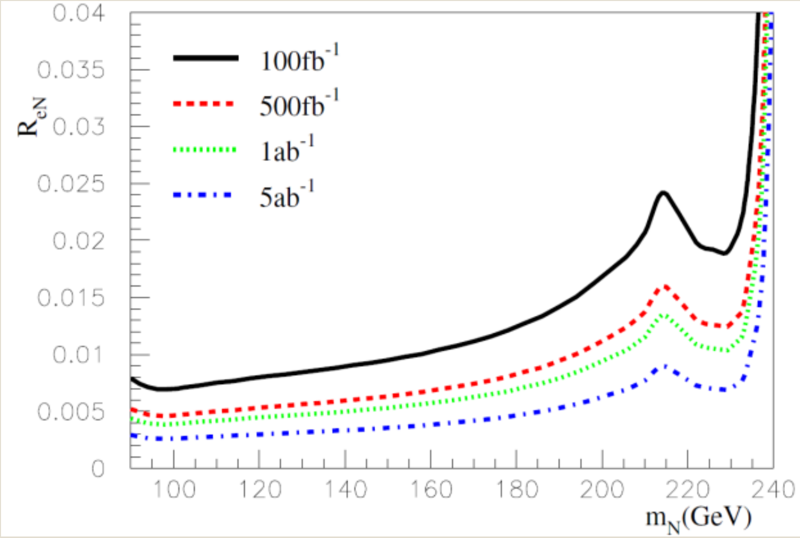


similar sensitivity reach for $V_{\mu N}$

[J.-N. Ding, Q.Qin, F.-S.Yu, 1903.02570]

Heavy N @ ee: Single N at 240 GeV

$N \to lW$

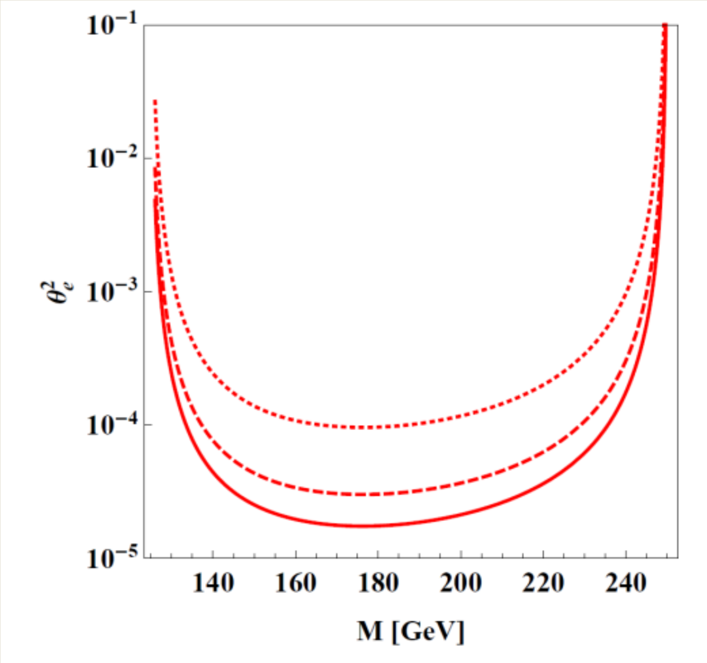


$$e^+e^- \to N\nu, N\bar{\nu} \to ljj\not{E}$$

$$\nu_l = \sum_i U_{li}\nu_i + \sum_j R_{lN_j}N_j$$

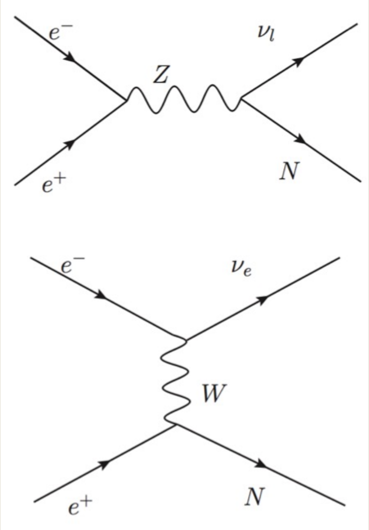
[W.Liao, X.-H.Wu, 1710.09266]

$N \to vh$



$e^+e^- \to v\,N \to h$ + MET

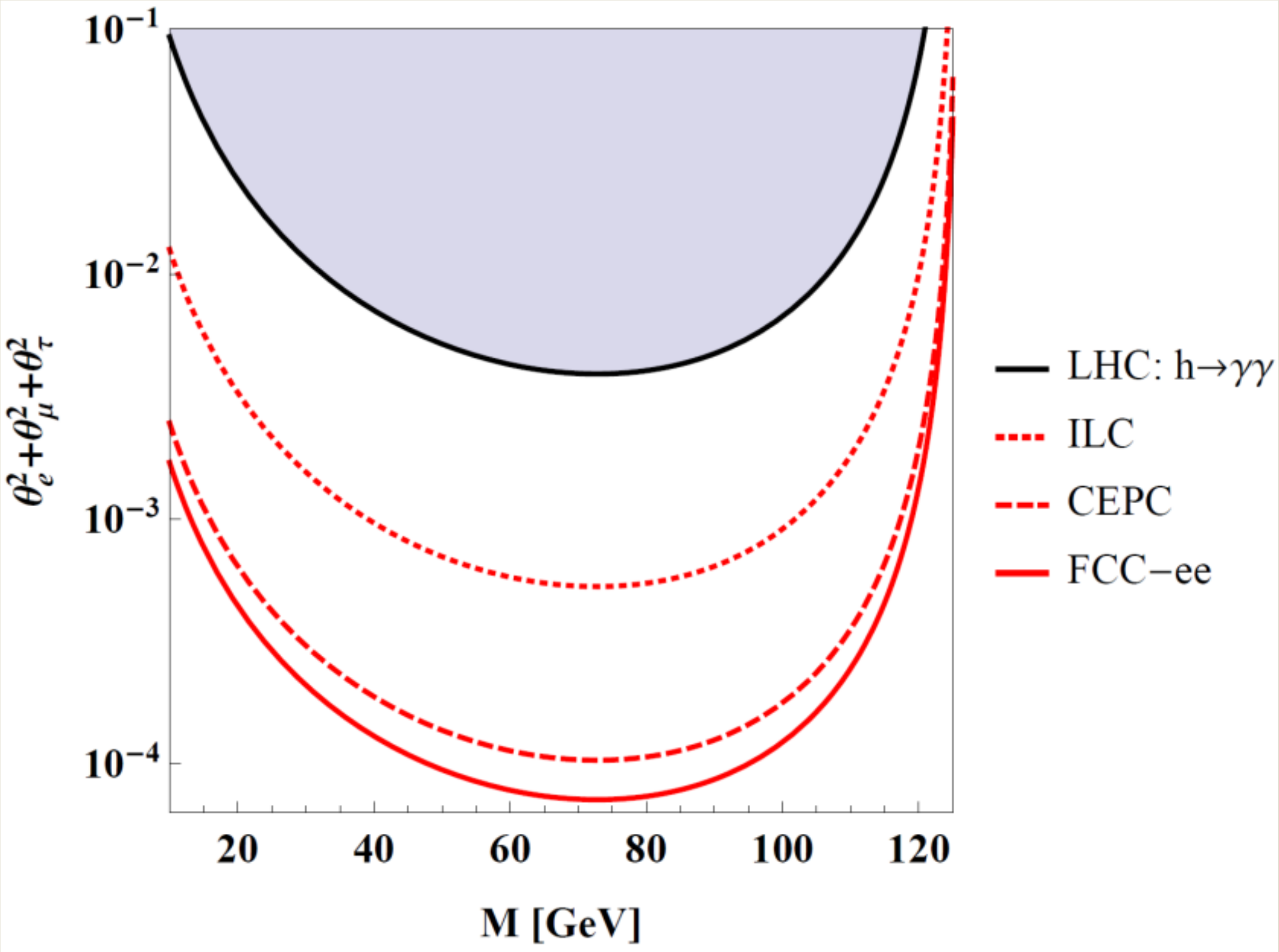
[S.Antusch, O.Fischer, 1502.05915]



Heavy N @ ee: Single N at 240 GeV

h → ν N @ ee

[S.Antusch, O.Fischer, 1502.05915]



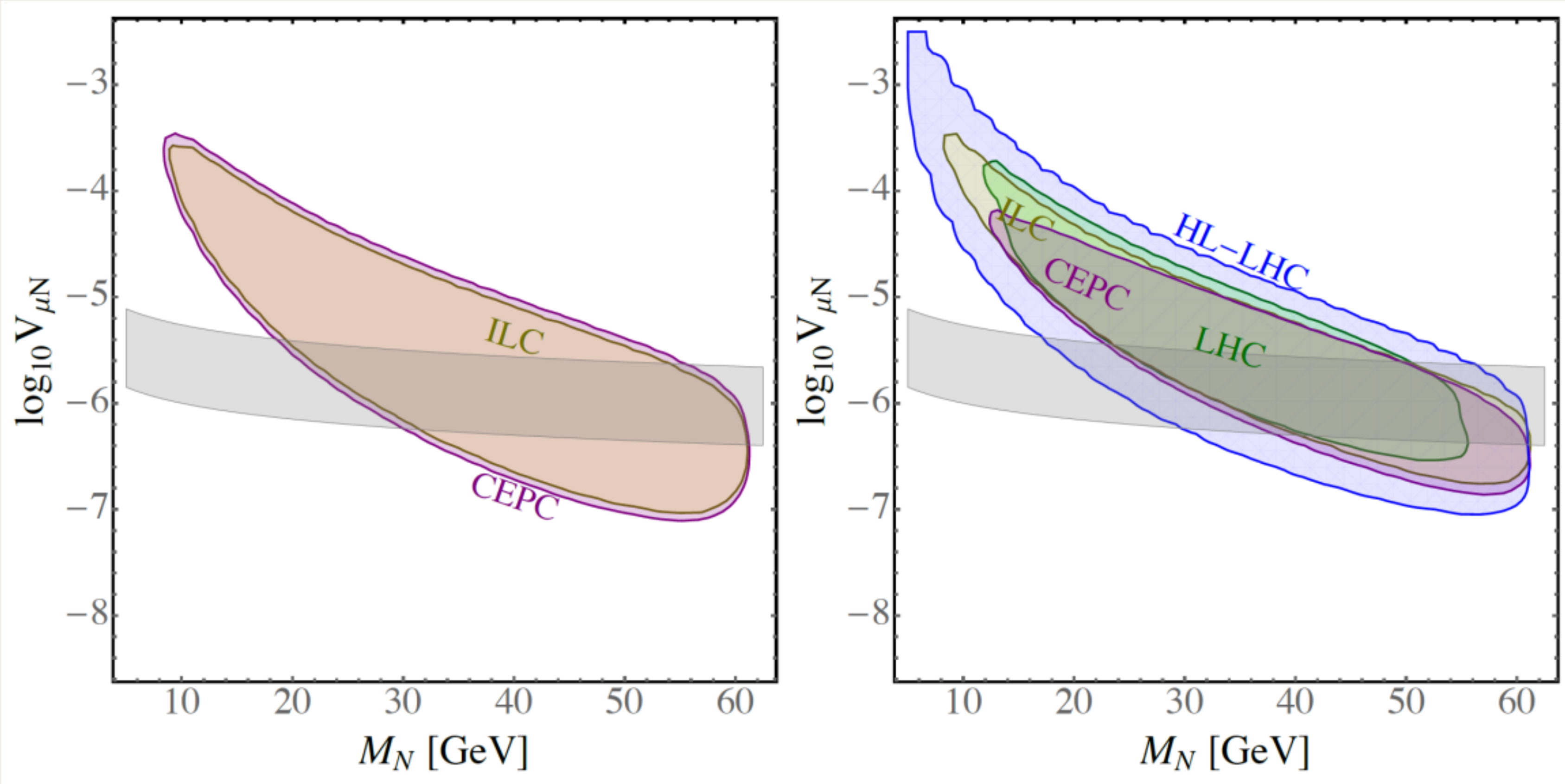
@pp, top, VV bkgs are significant.
gg → *h* → ν *N* search needs an **ISR kick**
[A.Das, Y.Gao, T.Kamon, 1704.00881]

h → l⁻l'⁺ flavor violating decays @ee

see [Q.Qin, Q.Li, C.-D.Lu, F-S.Yu, S.-H.Zhou, 1711.07243]

NN @ ee: Displaced vertex (long-lived N)

95% non-observation of a single DV, 5ab^{-1} | 95% non-observation of two DVs, 5ab^{-1}



At fixed prod. rate

$M_{h_2} = 450$ GeV, $\sin\alpha = 0.3$

$e^+e^- \to Z \to Zh_1 \to Z + NN$

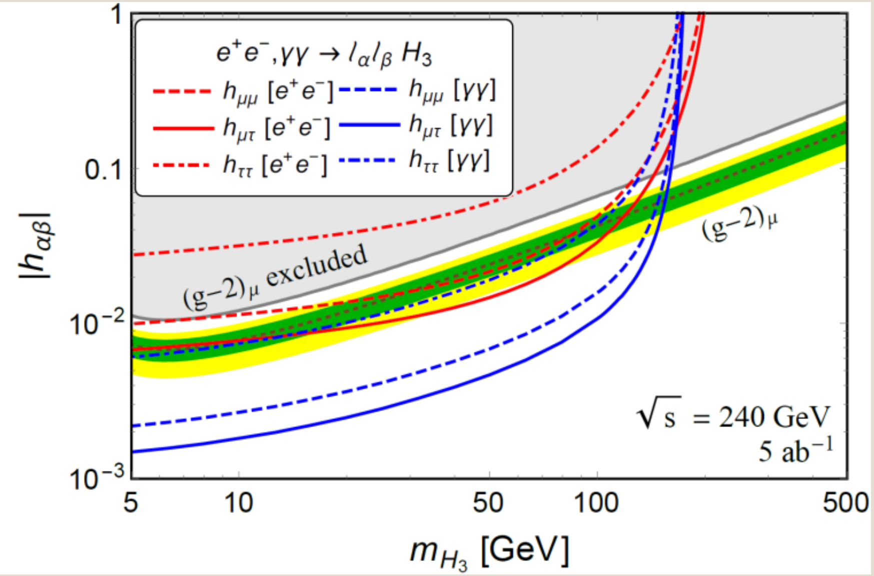
Gray: $0.01 \text{ eV} < m_\nu = V_{\mu N}^2 m_N < 0.3 \text{ eV}$

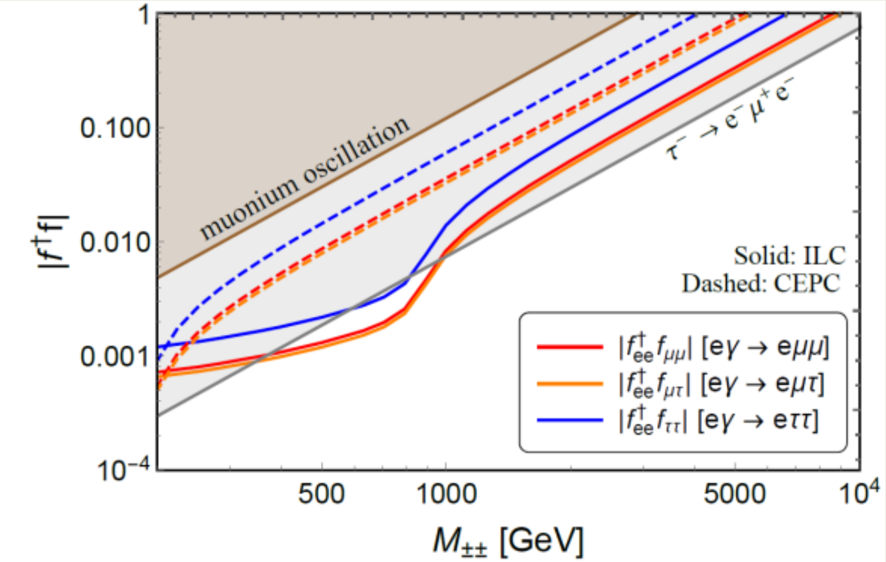
[F.F.Deppisch, W.Liu, M.Mitra, 1804.04075]

Type II @ ee: Exotic/seesaw scalar search

via coupling to leptons and SM gauge/Higgs bosons.

`Assume no LNV background'





neutral scalar production

$$\mathcal{L}_{H_3} \supset h_{\alpha\beta} H_3 \bar{\ell}_\alpha \ell_\beta, \ + \text{H.c.}$$

doubly charged scalar production

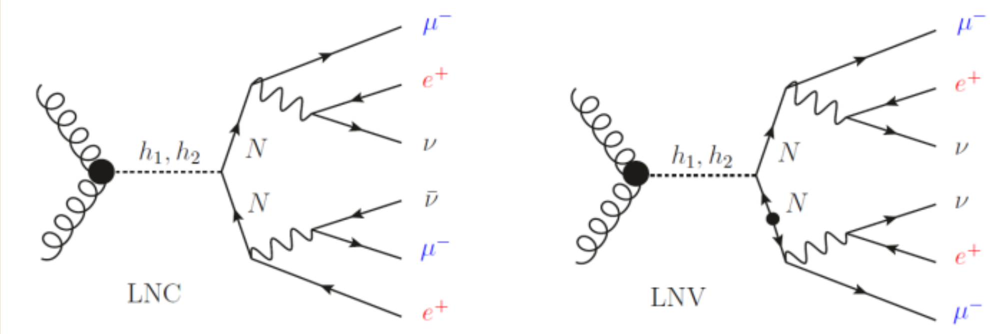
[B.Dev, R.N.Mohapatra, Y.Zhang, 1803.11167]

NN @ pp: Higgs mixing (with scalar)

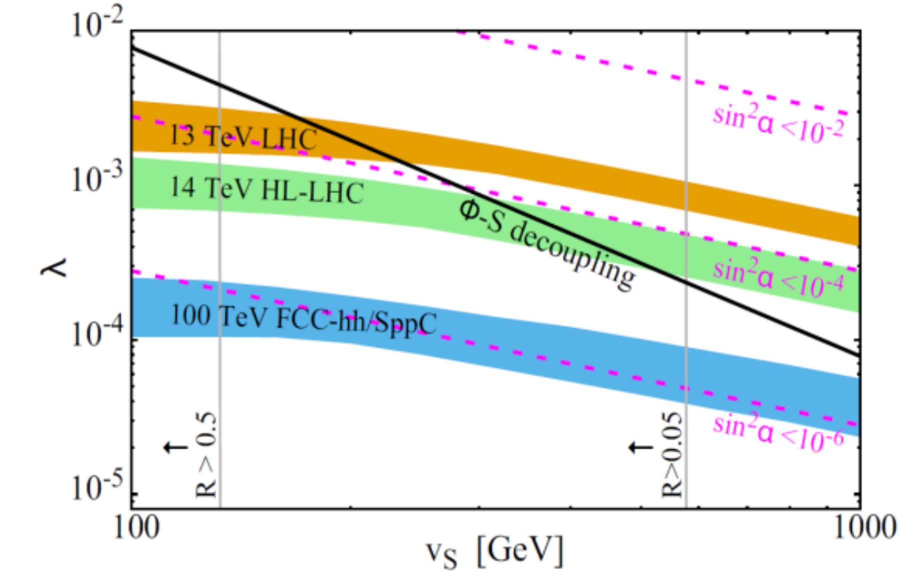
- Assuming the Higgs is the only visible scalar.
- Can h→ *NN* probe the *h*-*s* mixing to tiny levels? -- 'small coupling'

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

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



How about using ee→Zh at Higgs Factory?



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

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

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 $S = v_S + s$

$m_{N_R} = 2 y_N v_S$

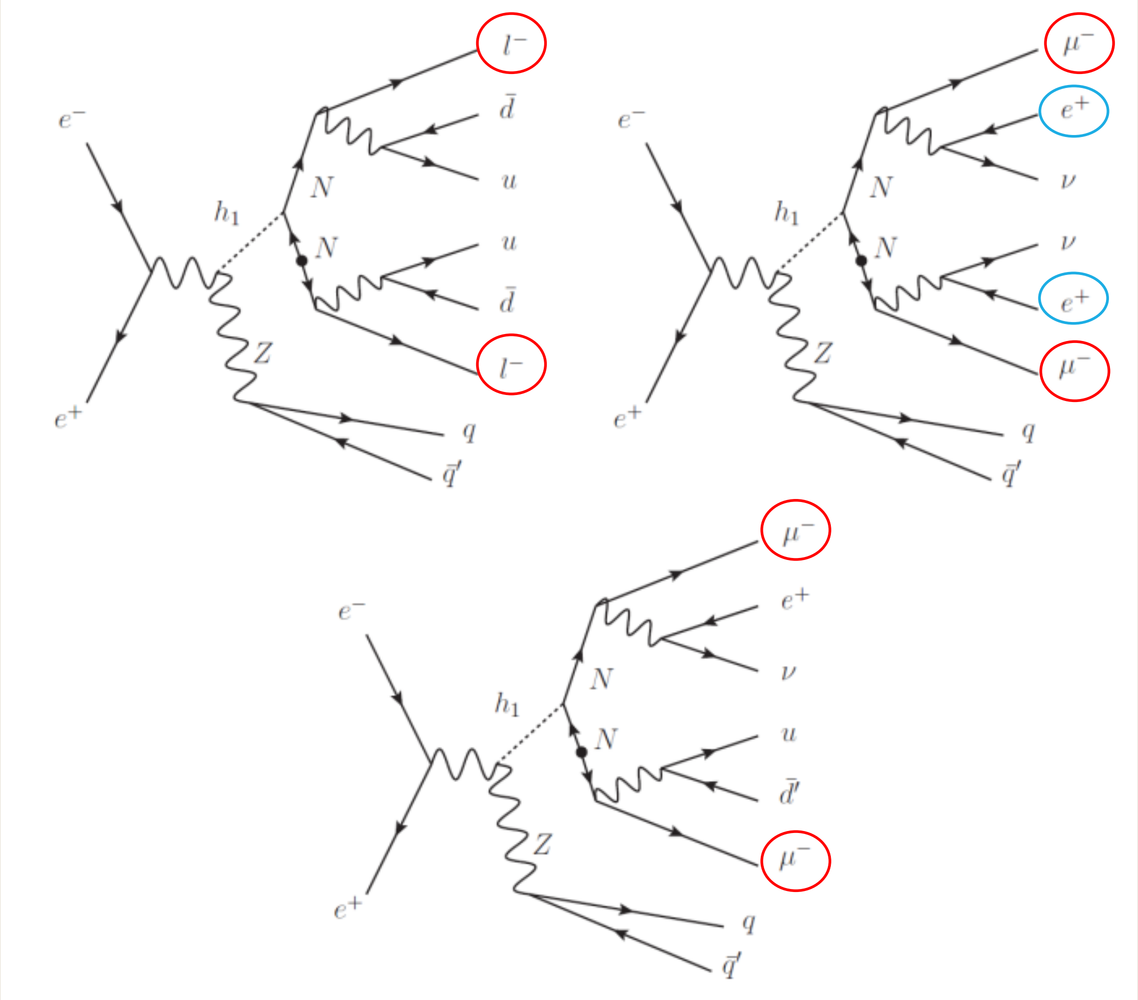
	ϕ	s
ϕ	m_ϕ^2	$\lambda v_\phi v_s$
s	$\lambda v_\phi v_s$	m_s^2

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

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

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

NN : Semileptonic, fully leptonic & mixed decays



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

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

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:
assume h_2 is much heavier & ignore $ee \to Zh_2$

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 $Z\to jj$ (more jets)

Require SS leptons

Strict lepton charge & count cuts

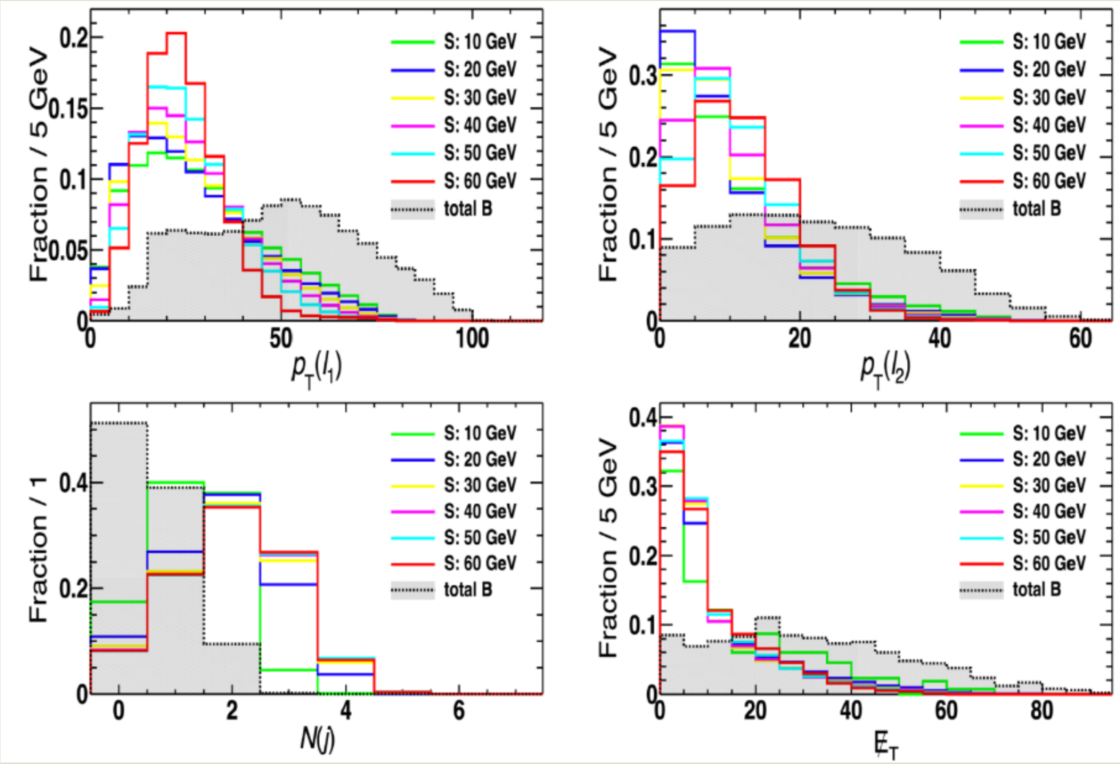
Categorize on N_l:

2-4 visible leptons with

flavor-distinguishable SS pairs

2l channel: SS dilepton +(≥3) jets

$$h_1 \rightarrow NN \rightarrow \ell^{\pm}\ell^{\pm} + 4j,\ \ell = e, \mu$$



(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.

[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

MG5+Pythia8+Delphes CEPC card

[C.Chen, et.al. 1712.09517]

Bkg @ 5.6 ab^{-1}

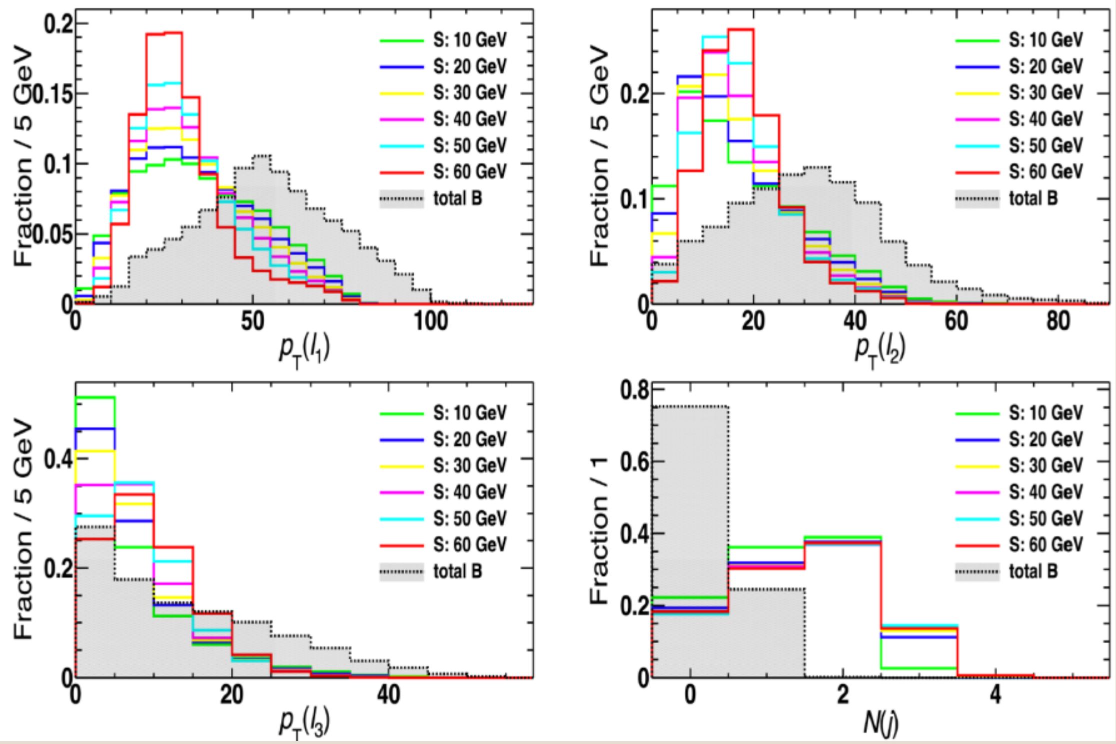
Signal ~10% eff. w lepton cuts

~2% sig. eff. at N_{bkg}~1 level

3l channel: SS dilepton + l +(≥2) jets

$Zh_1 \to \ell^{\pm}\ell^{\pm}\ell + 4j + \not{E}_T$

[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

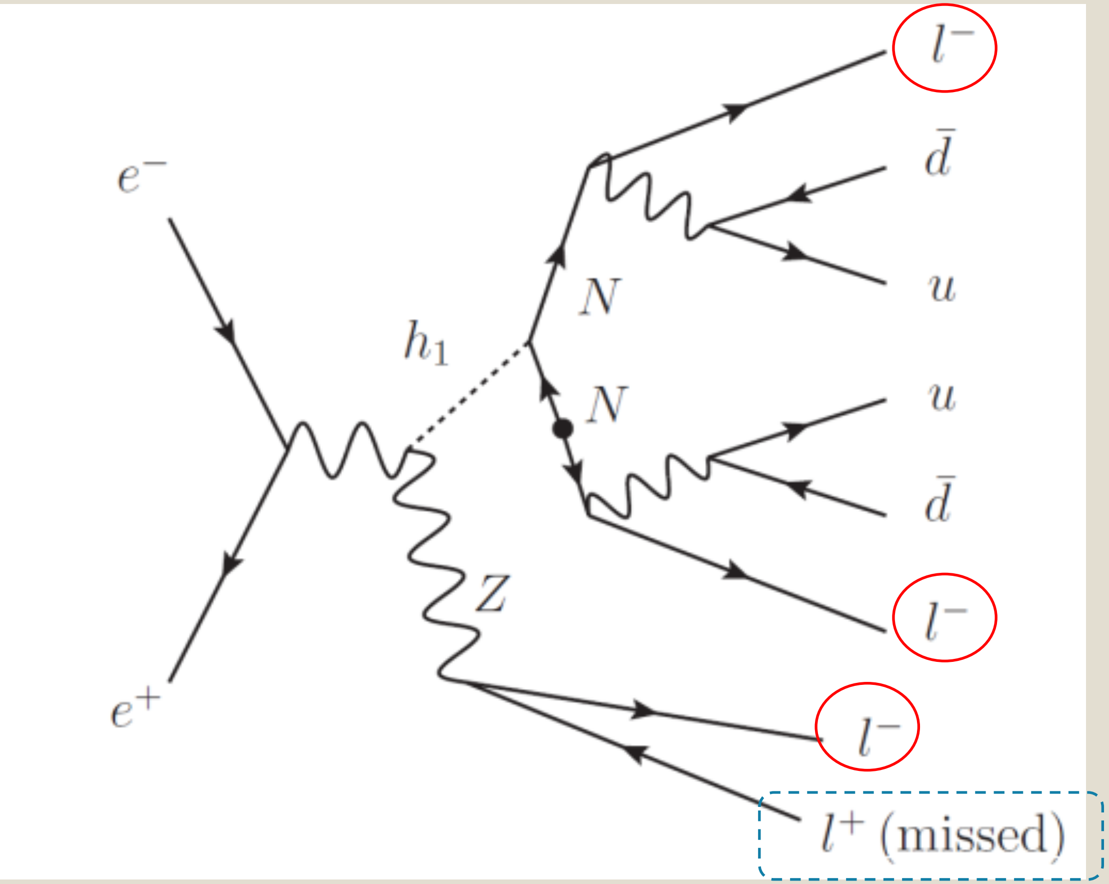
(i) exactly three leptons $N(\ell) = 3$ with $p_T \geq 5$ GeV;
(ii) veto OSSF lepton pairs;
(iii) veto τ leptons, $N(\tau) = 0$;
(iv) at least two jets, $N(j) \geq 2$.

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

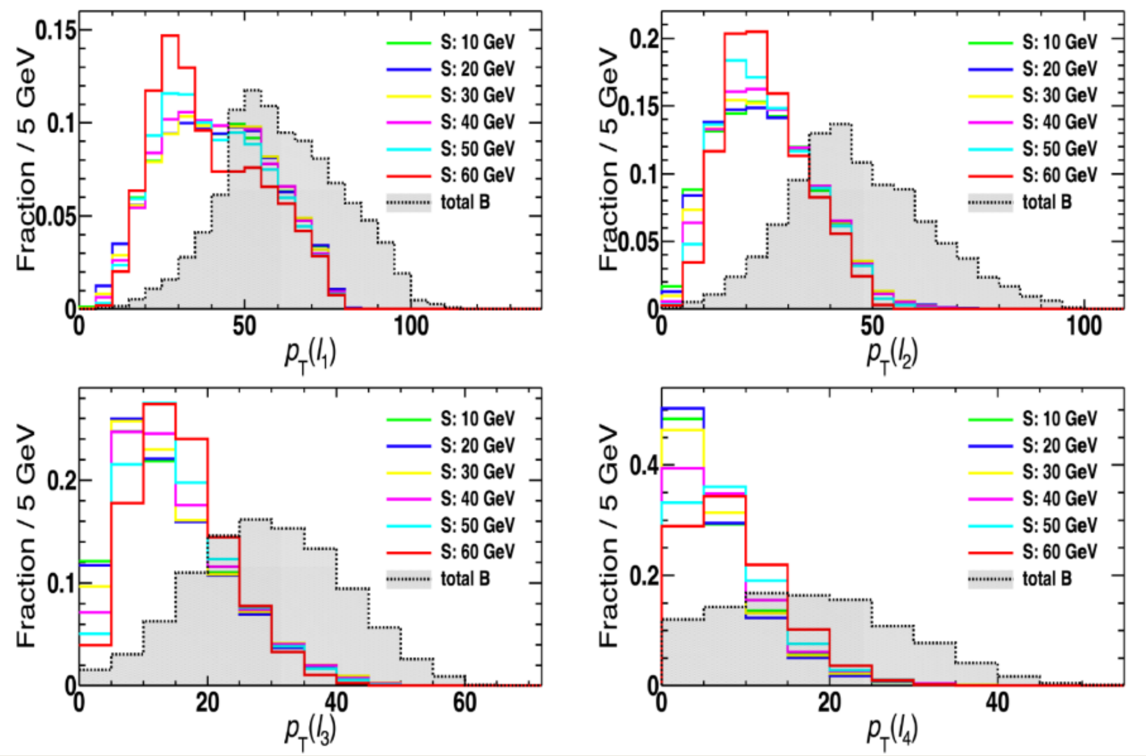


SS-trilepton arises:

after cut (i-ii), signal ~ 7.6%, while SM bkg ~ 0.2%

Clean channel, yet signal yield is also smaller.

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



(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, $N(j) \geq 1$.

[Y.Gao, K.Wang, 2102.12826]

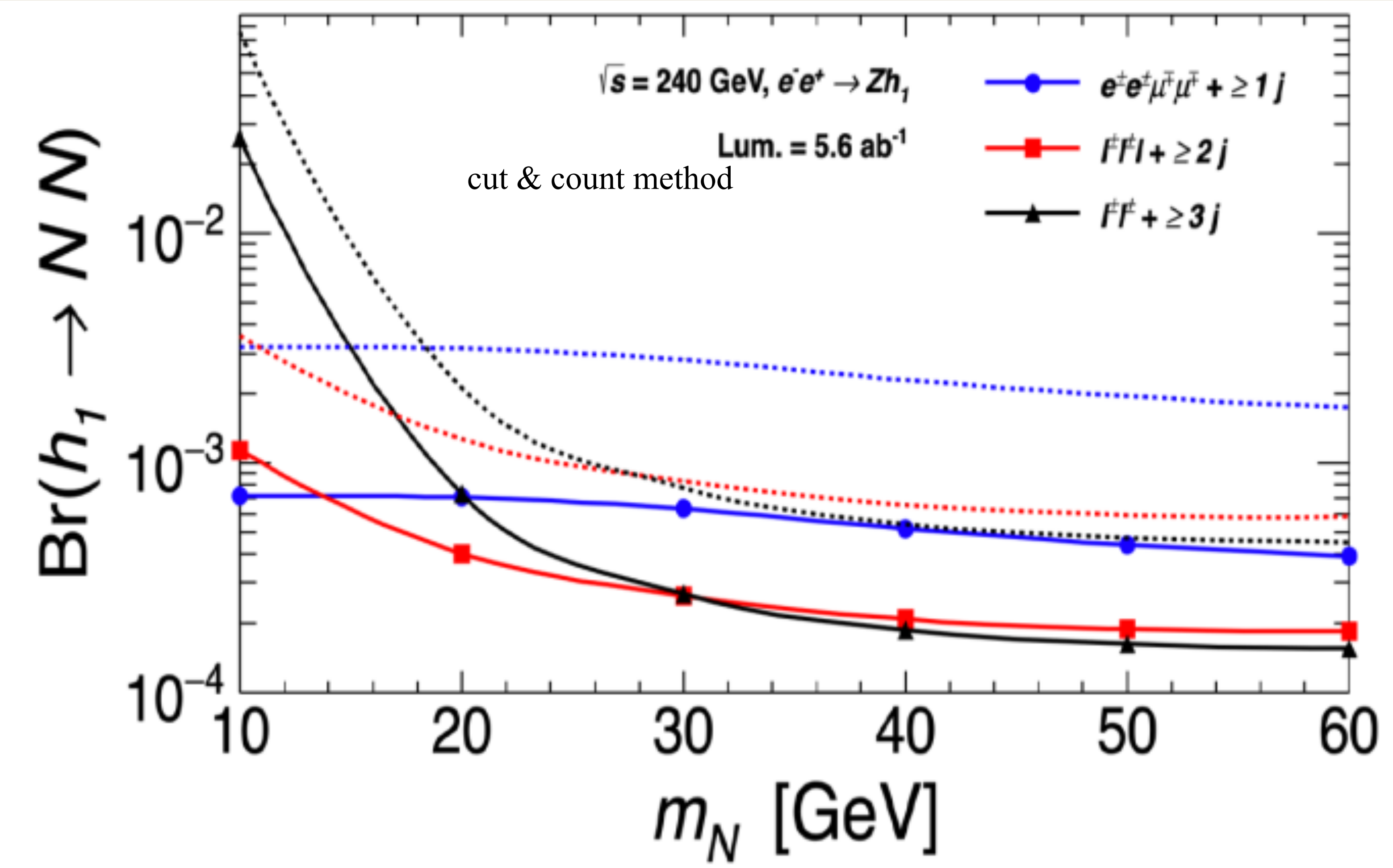
		initial	cuts(i)	cuts(ii)	cuts(iii-iv)
Sig.	10 GeV	10^3	15.9	1.1	0.71
	20 GeV	10^3	17.5	1.1	0.72
	30 GeV	10^3	22.1	1.3	0.80
	40 GeV	10^3	26.8	1.5	0.98
	50 GeV	10^3	30.1	1.8	1.2
	60 GeV	10^3	32.1	2.1	1.3
Bkg.	4τ	1.69×10^4	58.4	6.8	-
	$^\dagger 2\tau Z$	6.80×10^5	2.26×10^3	9.6	-
	$^\dagger 2\ell Z$	1.74×10^6	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 @ CEPC



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

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

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

Long-lived Heavy Neutrinos

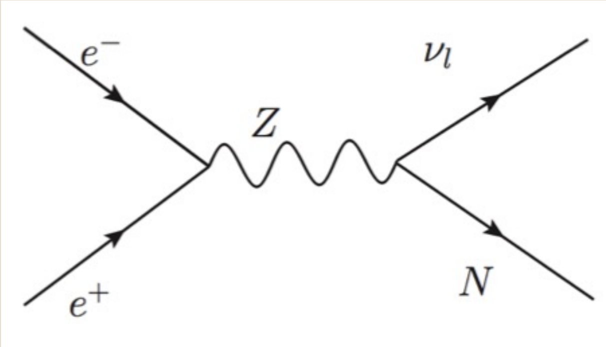
[Zeren Simon Wang & K. Wang, PRD 101 (2020) no.7, 075046]

scenario		$Z \to N\nu$
LLP		N
production $e^-e^+ \to$		Z
$\sqrt{s}$ [GeV]		91.2
N_h	CEPC	-
	FCC-ee	
N_Z	CEPC	7.0×10^{11} [16]
	FCC-ee	5.0×10^{12} [20]

$16\ ab^{-1}$, 2 years, 2 IPs

$150\ ab^{-1}$, 4 years, 2 IPs

has been updated to 1.5×10^{12}



Signal Calculation

$$N_{\rm LLP}^{\rm obs} = N_{\rm LLP}^{\rm prod} \cdot \langle P[\text{LLP in f.v.}]\rangle \cdot \text{Br}(\text{LLP} \to \text{visible})$$

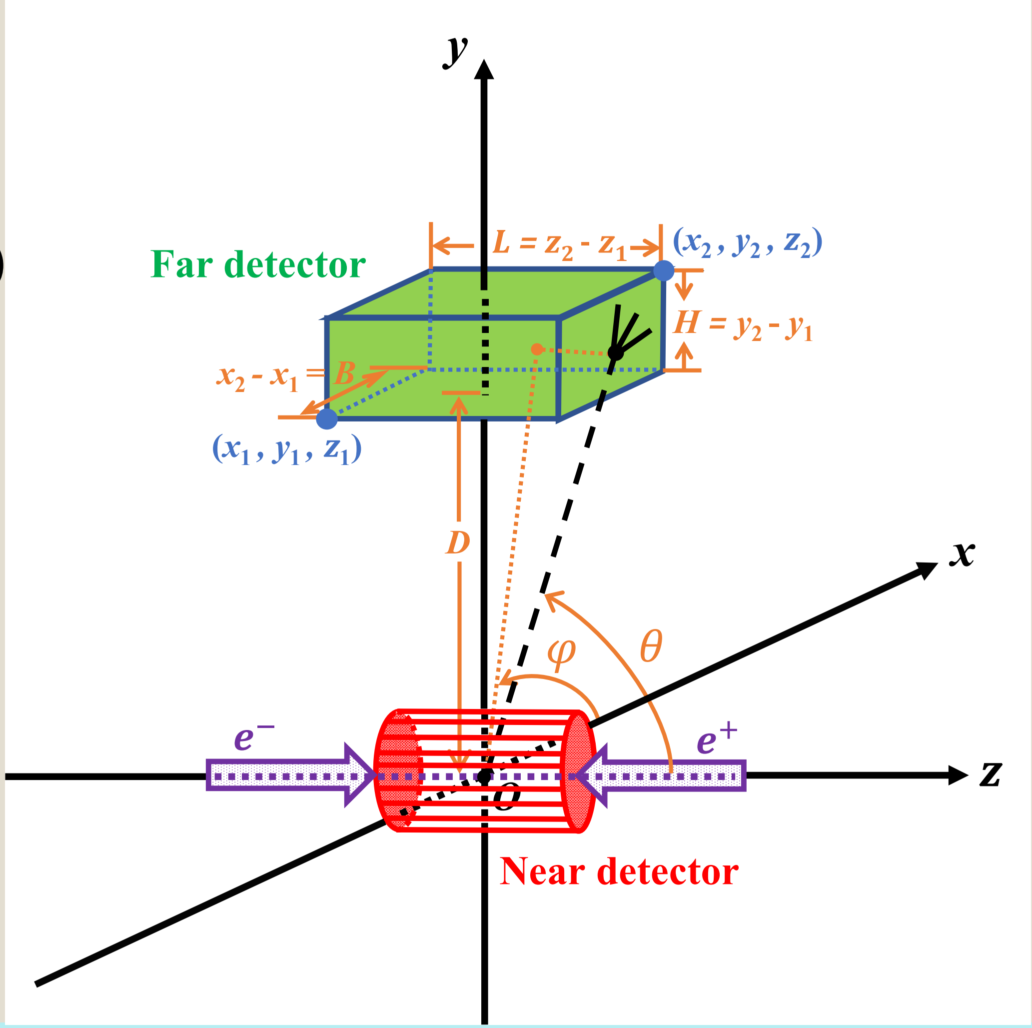
Average Decay Probabilities in FD

$P(\Delta L) = e^{-L_1/\lambda} - e^{-L_2/\lambda}$,
probability of decaying between L_1 and L_2 ($L_1 < L_2$)

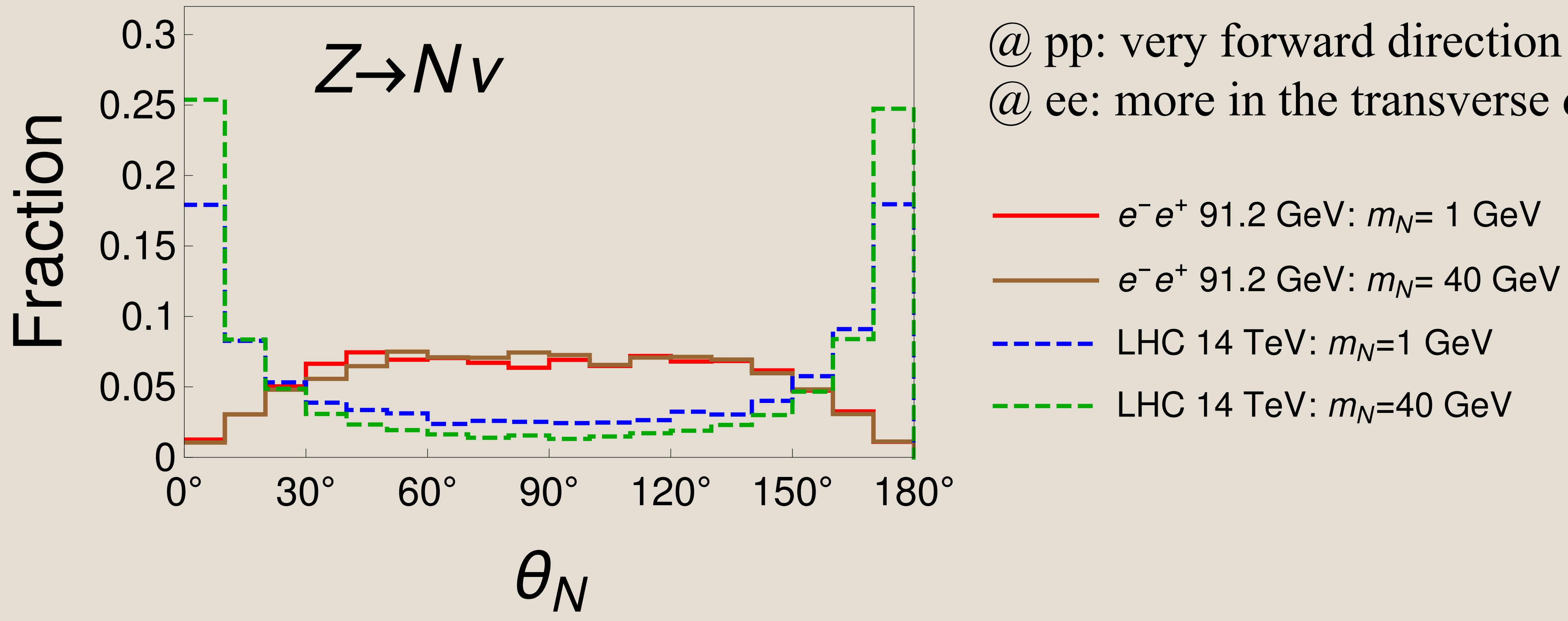
in the lab. frame:

$$\lambda = \beta c\, \gamma\tau = \frac{p}{E}\frac{E}{m} c\tau = \frac{p}{m} c\tau$$

Depends on theory model parameters (kinematics, mass, lifetime) & geometry of FD



Kinematical Distributions

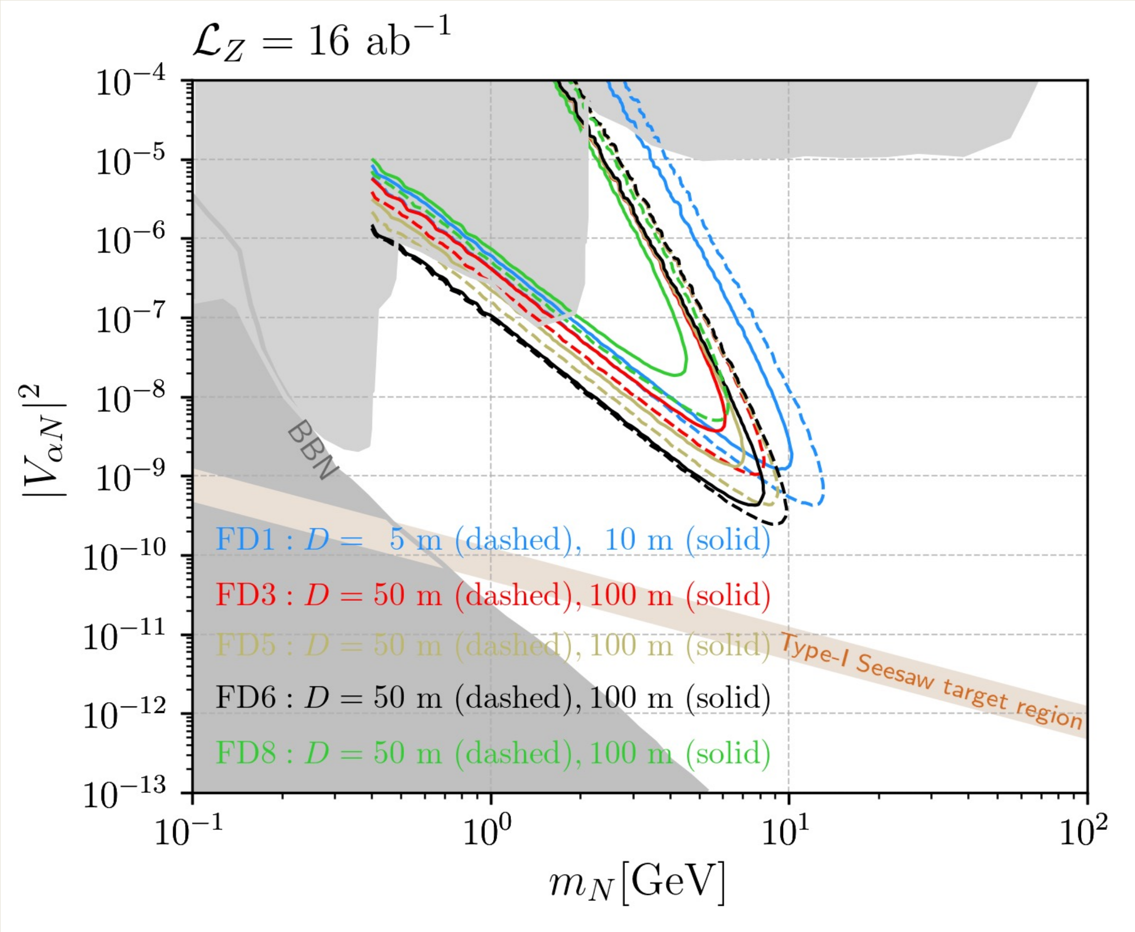


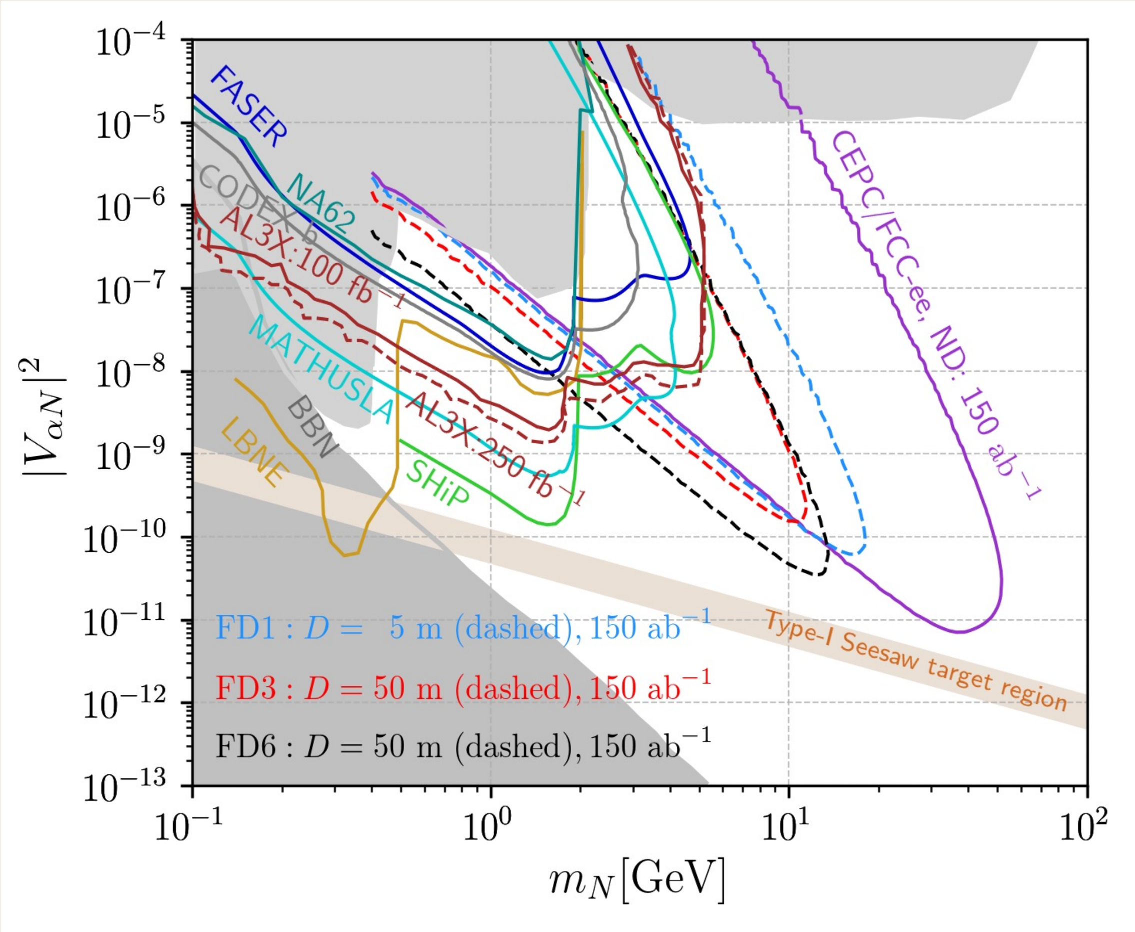
@ pp: very forward direction
@ ee: more in the transverse direction

FDs in the very forward direction like FASER may not work at ee colliders.
Better to be installed in the central region.

Limits @ Z-pole

$Z \to N\nu \ @ \sqrt{s} = 91.2$ GeV





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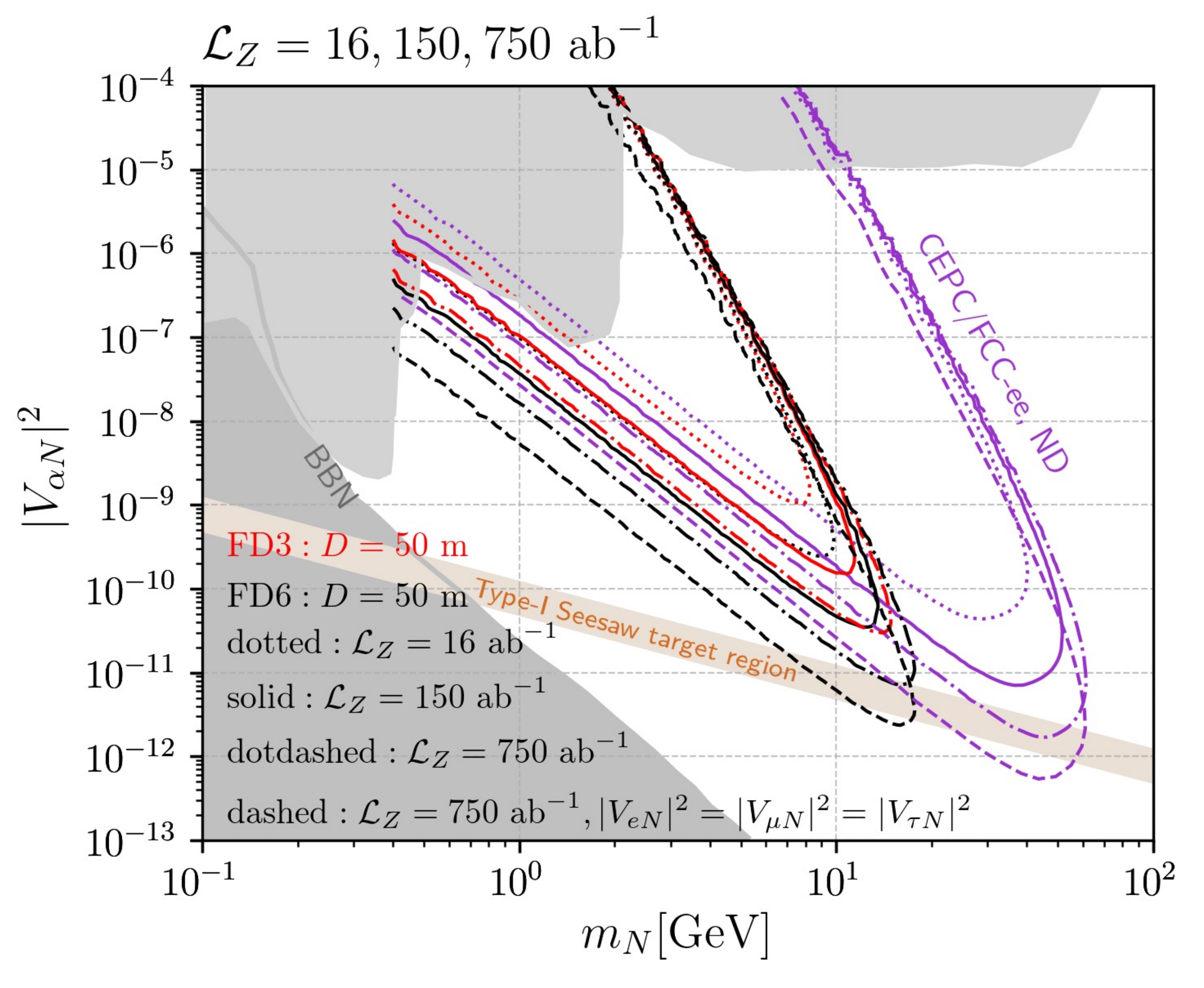

750 ab^{-1}, 10 years, 4 IPs;
or to increase the instantaneous luminosity;
or to relax the theoretical assumptions

Can test the Type-I seesaw directly!

Summary

Heavy Neutrinos are important physics targets @ future lepton colliders.

Already a few CEPC pheno. studies focusing mainly on the single N production from Z/h rare decays.

prompt N: $e^-e^+ \to Zh \to (jj)(NN)$ @ 240 GeV, 5.6 ab^{-1}
$Br(h \to NN)$, $|\sin\alpha|^2 \sim 10^{-4}$, comparable to HL-LHC

Long-lived N with ND &with FDs: $e^-e^+ \to Z \to N\nu$ @ Z-pole, 150 ab^{-1}
$|V|^2 \sim 10^{-10}$; Could test the Type-I seesaw directly with more luminosities.

More signal signatures, especially those limits can be competed with LHC, need to be investigated.