Heavy Sterile Neutrinos at CEPC

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Outline

- low energy seesaw model
  with order of $100\mathrm{GeV}$ heavy sterile neutrinos
  and large active-sterile mixing R_{lN}, relevant for colliders
- experimental searches
  LHC, LEP
- ILC perspectives
- CEPC sensitivity
  with only a single R_{lN}, $l = e$ and $l = \mu$
  the low energy seesaw model with correlated R_{lN}

The low energy seesaw model

- light neutrinos, seesaw mechanism,
  introducing heavy Majorana right-handed neutrinos
- Active neutrinos $\nu_l (l = e, \mu, \tau)$ as a mixture of light neutrinos $\nu_i (i = 1, 2, 3)$ and heavy sterile neutrinos N_j

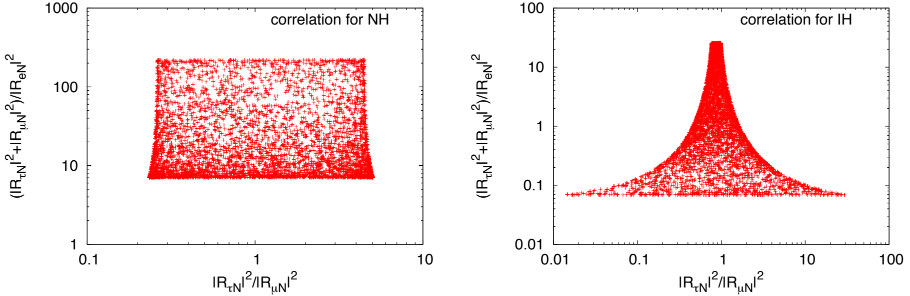
$$\nu_l = \sum_i U_{li} \nu_i + \sum_j R_{lN_j} N_j$$

- Constraint from $0\nu\beta\beta$ decay for a single heavy neutrino
  the amplitude $\propto R_{eN}^2 / m_N$,
  leading to $|R_{eN}|^2 \lessapprox 10^{-5}$ for GeV scale N.

The low energy seesaw model

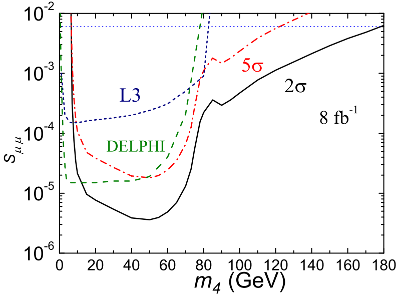
- The mass matrix of active neutrinos for neutrino ascillation phenomena is,
$$(m_\nu)_{ll'} = -v^2 \sum_i Y^*_{li} Y^*_{l'i} M_i^{-1} = -\sum_i M_i R^*_{lN_i} R^*_{l'N_i}.$$
for m_ν at $10^{-3} - 10^{-2}$ eV scale, if M_i is $100\mathrm{GeV}$ scale and there is only one N, $|R_{lN_i}|$ will be very small ($\sim 10^{-6}$).
- For 2 heavy sterile neutrinos N_1 and N_2, the amplitude of $0\nu\beta\beta$ decay is,
$$\mathcal{A} = \frac{F}{M_1^2}(R^2_{eN_1} M_1 + R^2_{eN_2} M_2) + F M_2 R^2_{eN_2}(\frac{1}{M_2^2} - \frac{1}{M_1^2})$$
the 1st term is small because of the neutrino mass matrix,
the 2nd term can be small, if N_1 and N_2 are quasi-degenerate or degenerate.
- if $R^2_{eN_1} = -R^2_{eN_2},\ \mathrm{or}\ R_{eN_1} = \pm i R_{eN_2}$, neutrino mass matrix can be at $10^{-3} - 10^{-2}$ eV scale, the 2 degenerate heavy neutrinos can have mass of GeV to hundred GeV, with large value of $|R_{eN_i}|^2$.
- heavy neutrinos interact with SM particles only through mixing

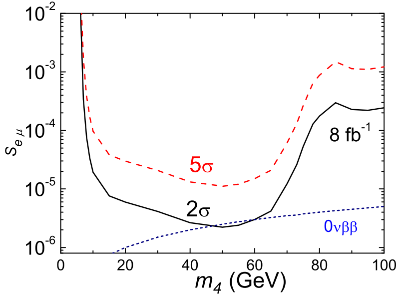
Active-sterile mixing R_{lN}



- for NH, $R_{lN_2} = \pm i R_{lN_1}$ and $M_1 = M_2$ (neutrino mass)
  $R_{lN_1} = \frac{1}{2} e^{\mp ix+|y|}(U_{l2} m_2^{1/2} e^{-i\phi_2/2} \mp i U_{l3} m_3^{1/2} e^{-i\phi_3/2})(M_1^*)^{-1/2}$
  $R_{\mu N}$ and $R_{\tau N}$ larger than R_{eN}
- for IH, $R_{lN_2} = \pm i R_{lN_1}$ and $M_1 = M_2$
  $R_{lN_1} = \frac{1}{2} e^{\mp ix+|y|}(U_{l1} m_1^{1/2} e^{-i\phi_1/2} \mp i U_{l2} m_2^{1/2} e^{-i\phi_2/2})(M_1^*)^{-1/2}$

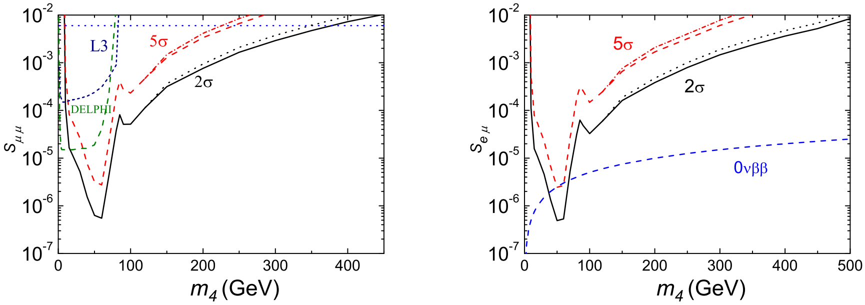
Tevatron sensitivity





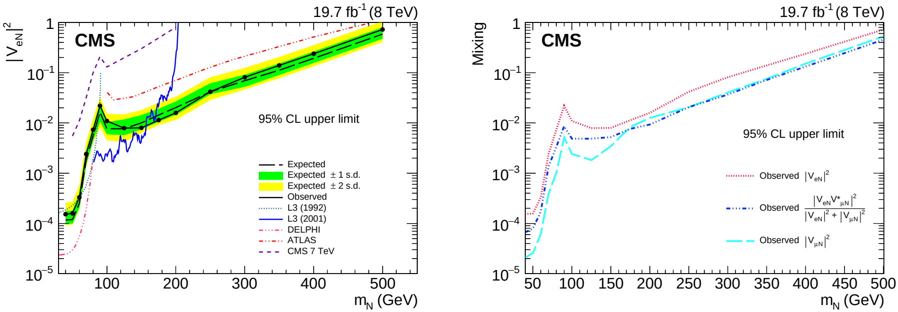
- A. Atre, T. Han, S. Pascoli, B. Zhang, 0901.3589.
- $p\bar{p} \to l_1^{\pm} l_2^{\pm} W^{\mp} \to l_1^{\pm} l_2^{\pm} jj'$
- 5σ sensitivity with $8\mathrm{fb}^{-1}$
  $|R_{\mu N}|^2$, $|R_{eN}|^2 \sim 10^{-4}$ $(50\mathrm{GeV})$, $\sim 10^{-2}$ $(100\mathrm{GeV})$

LHC sensitivity



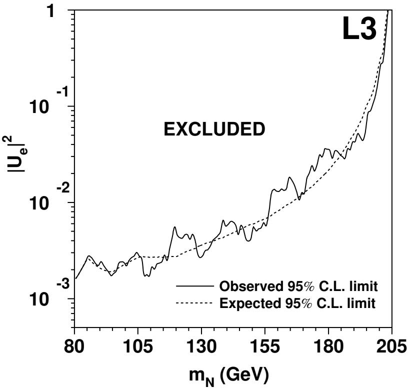
- A. Atre, T. Han, S. Pascoli, B. Zhang, 0901.3589.
- $pp \to l_1^{\pm} l_2^{\pm} W^{\mp} \to l_1^{\pm} l_2^{\pm} jj'$
- 5σ sensitivity with $100\mathrm{fb}^{-1}$
  $|R_{\mu N}|^2$, $|R_{eN}|^2 \sim 10^{-5}$ $(50\mathrm{GeV})$, $\sim 10^{-3}$ $(100\mathrm{GeV})$

CMS



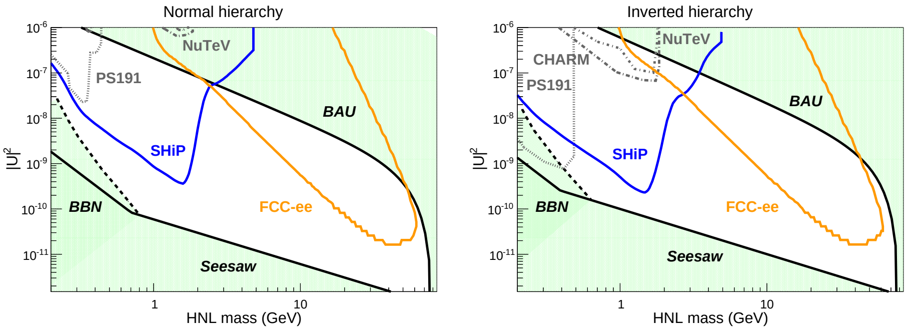
- CMS, 1503.05491 and 1603.02248
- $pp \to l^{\pm}N \to l_1^{\pm}l_2^{\pm}W^{\mp} \to l_1^{\pm}l_2^{\pm}jj'$
- 95% C.L. sensitivity with $19.7\mathrm{fb}^{-1}$
  $|R_{\mu N}|^2$, $|R_{eN}|^2 \sim 10^{-2}$ $(100\mathrm{GeV})$

L3



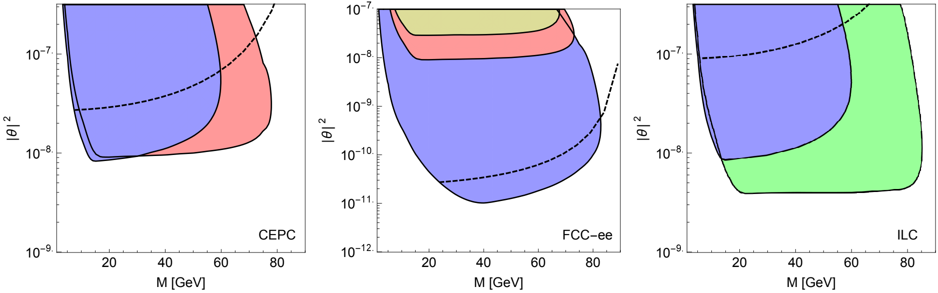
- L3, hep-ex/9909006 and hep-ex/0107014
- $e^+e^- \to N\nu \to eW\nu \to e\nu jj$
- 95% C. L., with $450\mathrm{pb}^{-1}$
  $|R_{eN}|^2 \sim 10^{-1} - 10^{-2}$ $(80 - 205\mathrm{GeV})$

FCC-ee at Z resonance



- A. Blondel, E. Graverini, N. Serra, M. Shaposhnikov, 1411.5230.
- $Z \to N\nu \to lW\nu \to l\nu jj$
- with 10^{12} Z
  $|R_{lN}|^2 \sim 10^{-11}$ $(50\mathrm{GeV})$

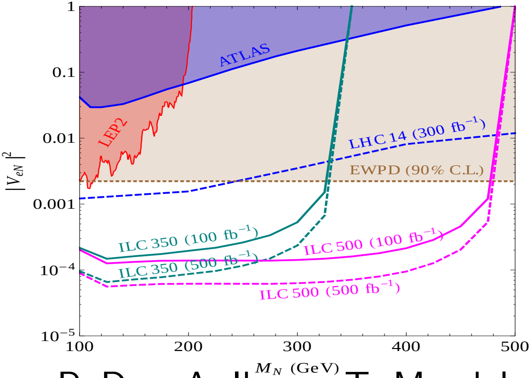
Displaced vertex searches at FLC



$E_{cm} = m_Z$; E_{cm} = 250 GeV; E_{cm} = 350 GeV; E_{cm} = 500 GeV; Conventional search (95% C.L.)

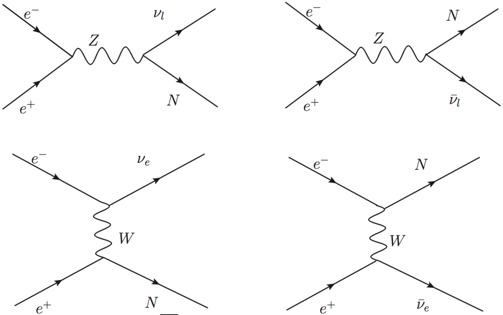
- S. Antusch, E. Cazzato, O. Fischer, 1604.02420.
- $|R_{lN}|^2 \sim 10^{-8} - 10^{-11}$ $(20 - 80\mathrm{GeV})$

ILC expected



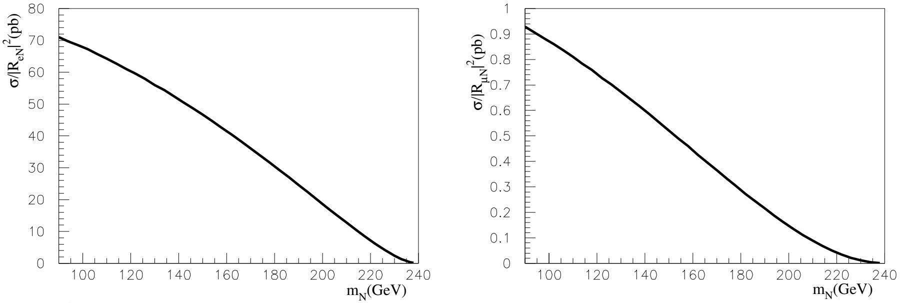
- S. Banerjee, P. Dev, A. Ibarra, T. Mandal, M.Mitra, 1503.05491.
- $e^+e^- \to N\nu \to eW\nu \to e\nu jj$
- 95% C.L. ILC with $100\mathrm{fb}^{-1}$ or $500\mathrm{fb}^{-1}$ $|R_{eN}|^2 \sim 10^{-5} - 10^{-4}$ $(100 - 400\mathrm{GeV})$

$e^+e^- \to N\nu(+\bar{\nu})$ production



- CEPC operates at $\sqrt{s} = 240\mathrm{GeV}$ with $5\mathrm{ab}^{-1}$ with 2 IPs and 10 years of operation.
- The cross section of t-channel (relevant for mixing with ν_e, R_{eN}) is 2 order of magnitude larger than that of s-channel.
- R_{eN} has better sensitivity than $R_{\mu N}$.

Production and decay



- $e^+e^- \to N\nu$, summing over neutrinos of all flavor and anti-neutrinos.
- For a heavy neutrino of about $100\mathrm{GeV}$, $\sigma/|R_{eN}|^2 \sim 60\mathrm{pb}$ and $\sigma/|R_{\mu N}|^2 \sim 0.8\mathrm{pb}$
- above Z (or H) mass, two-body decay modes dominant, $N \to lW, \nu Z, \nu H$, with $\mathrm{Br}(N \to lW) \sim 1/3$.

Cuts

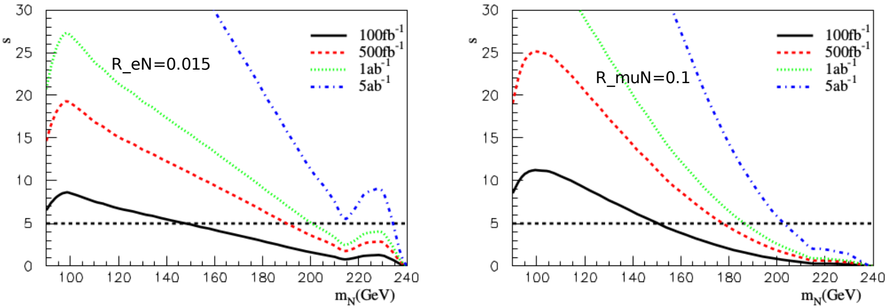
- signal $e^+e^- \to N\nu, N\bar{\nu} \to ljj\not{E}$
  main background $e^+e^- \to W^+W^-$ with one W decaying leptonically, and one W decaying hadronically
- basic cuts for lepton and jets to select the events

$$p_T^l > 10\mathrm{GeV}, |\eta^l| < 2.5, \Delta R_{ll} > 0.4,$$
$$p_T^j > 10\mathrm{GeV}, |\eta^j| < 2.5, \Delta R_{jj} > 0.4, \Delta R_{lj} > 0.4.$$

- selection cuts to suppress background events from on-shell W decay

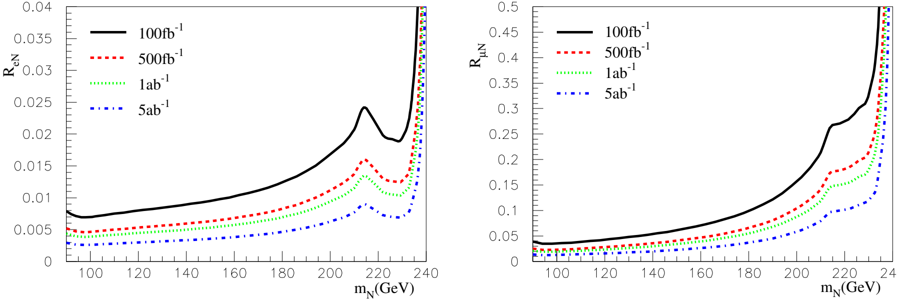
$$|M(l, \not{E}) - m_W| > 20\ \mathrm{GeV},$$
$$|M(l, j_1, j_2) - m_N| < 10\ \mathrm{GeV}.$$

A single R_{lN}



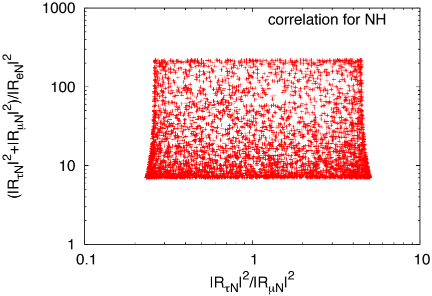
- significance, $s \equiv \mathcal{N}_s/\sqrt{\mathcal{N}_s + \mathcal{N}_b}$, $\mathcal{N}$ as event number
- for the integrated luminosity of $100\mathrm{fb}^{-1}$
  $m_N \leq 146\mathrm{GeV}(150\mathrm{GeV})$ for $l = e$ ($l = \mu$) channel
- for the integrated luminosity of $5\mathrm{ab}^{-1}$
  $m_N \leq 235\mathrm{GeV}(205\mathrm{GeV})$ for $l = e$ ($l = \mu$) channel

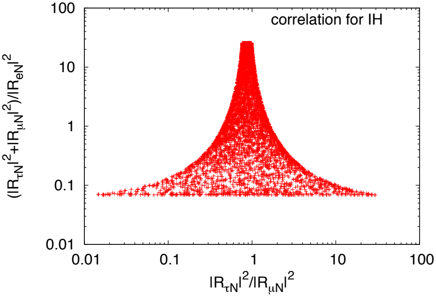
Sensitivity on a single R_{lN}



- significance $s = 5$
- a heavy neutrino mass of $120\mathrm{GeV}$ for an example
  for $l = e$ channel, $R_{eN} = 0.0080(R_{eN} = 0.0030)$ can be probed with $100\mathrm{fb}^{-1}(5\mathrm{ab}^{-1})$
  for $l = \mu$ channel, $R_{\mu N} = 0.043(R_{\mu N} = 0.016)$ can be probed with $100\mathrm{fb}^{-1}(5\mathrm{ab}^{-1})$

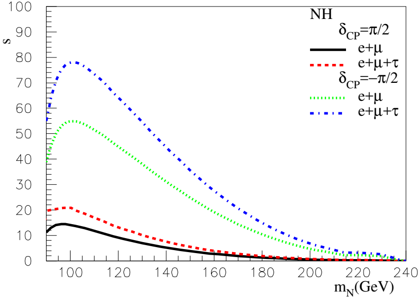
The seesaw model with correlated R_{lN}

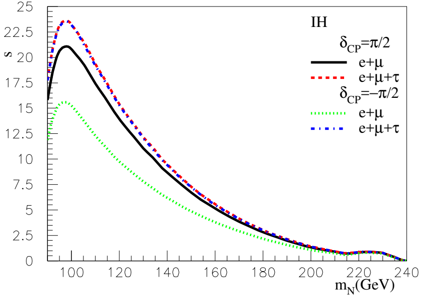




- for NH, $R_{lN_2} = \pm i R_{lN_1}$
  $R_{lN_1} = \frac{1}{2} e^{\mp ix+|y|}(U_{l2} m_2^{1/2} e^{-i\phi_2/2} \mp i U_{l3} m_3^{1/2} e^{-i\phi_3/2})(M_1^*)^{-1/2}$
  $R_{\mu N}$ and $R_{\tau N}$ larger than R_{eN}
- for IH, $R_{lN_2} = \pm i R_{lN_1}$
  $R_{lN_1} = \frac{1}{2} e^{\mp ix+|y|}(U_{l1} m_1^{1/2} e^{-i\phi_1/2} \mp i U_{l2} m_2^{1/2} e^{-i\phi_2/2})(M_1^*)^{-1/2}$

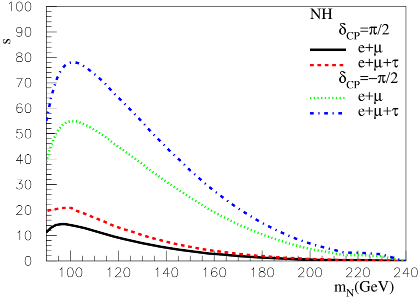
The seesaw model with correlated R_{lN}

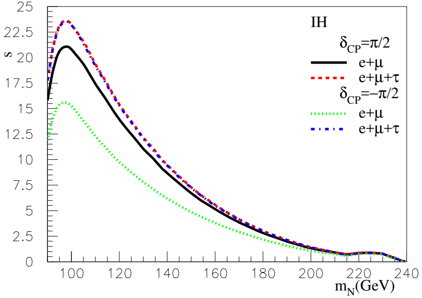




- significance $s \equiv \sqrt{\sum s_l^2}$, $l = e, \mu, \tau$ channel, $500\mathrm{fb}^{-1}$
- NH parameters, $\phi_1 = \phi_2 = \phi_3 = 0$, $e^y = 5000$ for NH
- NH, $\delta_{\mathrm{CP}} = \pi/2$, $|R_{\mu N}| \sim |R_{\tau N}| \sim 10|R_{eN}|$, μ, τ dominant $m_N \leq 152\mathrm{GeV}$ ($|R_{eN}| \sim 0.0032$, $|R_{\mu N}| \sim |R_{\tau N}| \sim 0.034$)
- $\delta_{\mathrm{CP}} = -\pi/2$, $|R_{\mu N}| \sim |R_{\tau N}| \sim 2|R_{eN}|$, μ, τ dominant $m_N \leq 206\mathrm{GeV}$ ($|R_{eN}| \sim 0.015$, $|R_{\mu N}| \sim |R_{\tau N}| \sim 0.028$)
- with a larger $|R_{eN}|$ for $\delta_{\mathrm{CP}} = -\pi/2$, t-channel production enhanced, μ, τ signal enhanced, compared with $\delta_{\mathrm{CP}} = \pi/2$

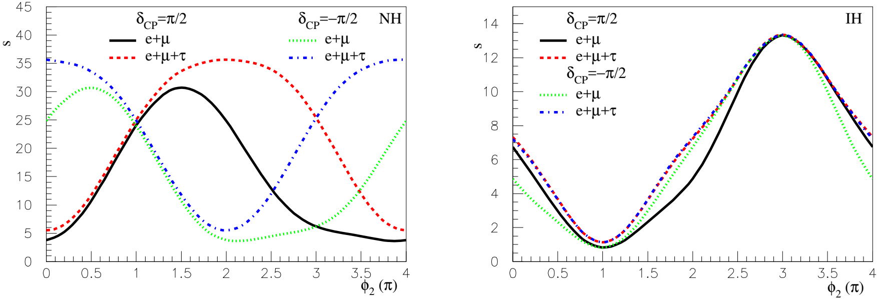
The seesaw model with correlated R_{lN}





- IH parameters, $\phi_1 = \phi_2 = \phi_3 = 0$, $e^y = 1000$
- IH, $m_N \leq 162\mathrm{GeV}$,
  $|R_{eN}| \sim 0.0086$, $|R_{\mu N}| \sim 0.0072$, $|R_{\tau N}| \sim 0.0051$ for $\delta_{\rm CP} = \pi/2$
  $|R_{eN}| \sim 0.0086$, $|R_{\mu N}| \sim 0.0053$, $|R_{\tau N}| \sim 0.0071$ for $\delta_{\rm CP} = -\pi/2$
- for both cases of $\delta_{\rm CP} = \pi/2$ and $\delta_{\rm CP} = -\pi/2$
  $|R_{eN}|$ the same, $|R_{eN}|^2 + |R_{\mu N}|^2 + |R_{\tau N}|^2$ also the same size, leading to the same production rate and ljj decay rate, then total $e + \mu + \tau$ significances the same, but different for $e + \mu$ significances

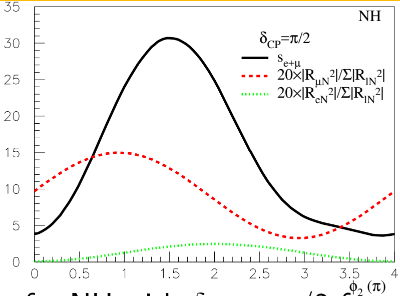
Effect of phases: $\delta_{\rm CP}$ and ϕ_2



- $m_N = 150\mathrm{GeV}$ and integrated luminosity $500\mathrm{fb}^{-1}$
- The $e + \mu$ and $e + \mu + \tau$ significance depends on both Dirac phase $\delta_{\rm CP}$ and Majorana phase ϕ_2.
- The bumps as the varied ϕ_2.

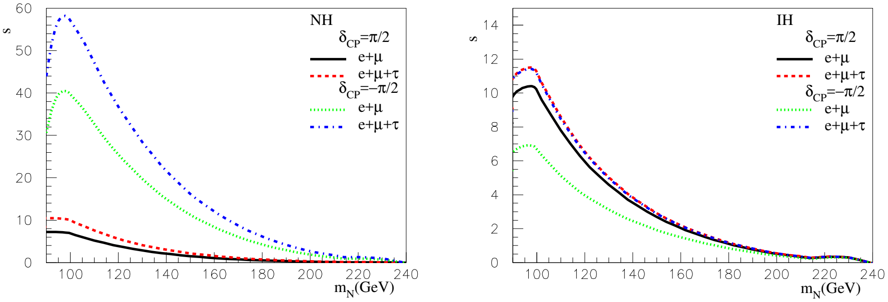
  Take the case of $e + \mu$ significance for NH with $\delta_{\rm CP} = \pi/2$ for an example. A bump at $\phi_2 \sim 1.5\pi$

Effect of phases: the bump



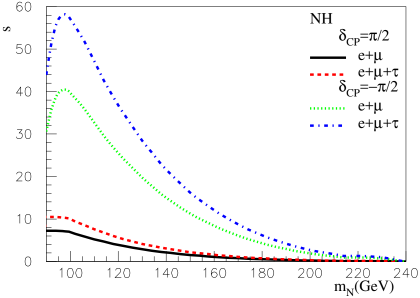
- $e + \mu$ significance for NH with $\delta_{\text{CP}} = \pi/2$ for an example
- A bump in $e + \mu$ significance (dominated by the μjj) at $\phi_2 \sim 1.5\pi$.
  1. ϕ_2 (from 0 to 2π) $\uparrow$, $|R_{eN}|^2/\sum|R_{lN}|^2 \uparrow$ and peaks at $\phi_2 = 2\pi$, then t-channel production (dominate production) $\uparrow$,
  2. ϕ_2 (from 0 to π) $\uparrow$, $|R_{\mu N}|^2/\sum|R_{lN}|^2 \uparrow$ and peaks at $\phi_2 \sim \pi$. For $\phi_2 > \pi$, $|R_{\mu N}|^2/\sum|R_{lN}|^2 \downarrow$ and $\text{Br}(N \to \mu jj) \downarrow$, but compensated by $\uparrow$ production of $e^+e^- \to N\nu$.
  3. μjj events and $e + \mu$ significance $\uparrow$ first, then $\downarrow$ and peaks at 1.5π, as $\phi_2 \uparrow$ from 0 to 2π.

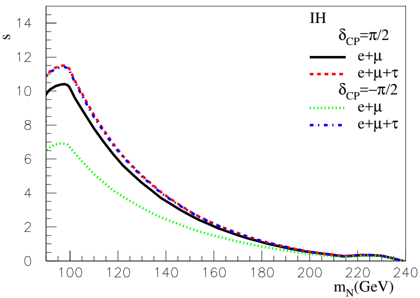
The seesaw model with $5\mathrm{ab}^{-1}$



- After 10 years of operation, CEPC may accumulate $5\mathrm{ab}^{-1}$ data.
- NH parameters, $\phi_1 = \phi_2 = \phi_3 = 0$, $e^y = 1750$
- NH, for $\delta_{\mathrm{CP}} = \pi/2$,
  $m_N \leq 124\mathrm{GeV}$, $(|R_{eN}| \sim 0.0012, |R_{\mu N}| \sim |R_{\tau N}| \sim 0.013)$
- for $\delta_{\mathrm{CP}} = -\pi/2$,
  $m_N \leq 184\mathrm{GeV}$ $(|R_{eN}| \sim 0.0055, |R_{\mu N}| \sim |R_{\tau N}| \sim 0.010)$

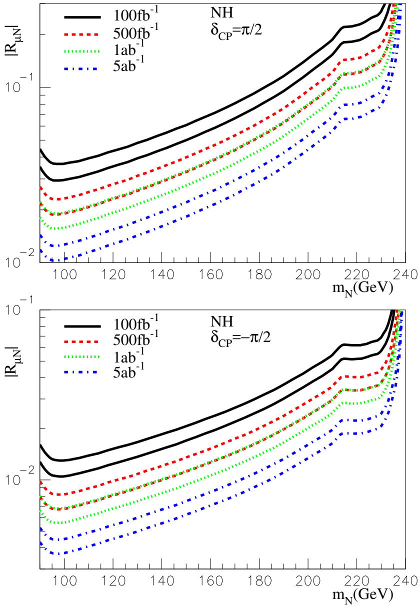
The seesaw model with $5\mathrm{ab}^{-1}$





- IH parameters, $\phi_1 = \phi_2 = \phi_3 = 0$, $e^y = 350$
- IH, $m_N \leq 130\mathrm{GeV}$,
  $|R_{eN}| \sim 0.0034$, $|R_{\mu N}| \sim 0.0028$, $|R_{\tau N}| \sim 0.0020$ for $\delta_{\mathrm{CP}} = \pi/2$
  $|R_{eN}| \sim 0.0034$, $|R_{\mu N}| \sim 0.0021$, $|R_{\tau N}| \sim 0.0028$ for $\delta_{\mathrm{CP}} = -\pi/2$

Sensitivity on R_{lN}



The seesaw model with correlated R_{lN}

- With $5\mathrm{ab}^{-1}$, CEPC can reach a 5σ sensitivity of $|R_{eN}| \sim 10^{-3}$ and $|R_{\mu N}| \sim 10^{-2}$ for a single mixing.
- With sizable R_{eN}, the significance of μ and τ channel will be enhanced, and further constrain $R_{\mu N}$ and $R_{\tau N}$.
- The significance depends on both Dirac phase δ_{CP} and Majorana phases.
- With correlated R_{lN}, a search for all 3 lepton channels are helpful to constrain the model.

Summary

- We studied the sensitivity of CEPC in a low energy seesaw model with heavy neutrino mass of order of $100\mathrm{GeV}$ and large mixing with active neutrinos.
- After 10 years of operation, with $5\mathrm{ab}^{-1}$, the sensitivity can reach $|R_{eN}| \sim 10^{-3}$ and $|R_{\mu N}| \sim 10^{-2}$ for a single mixing, and the low energy seesaw model as well.
- A search for all 3 lepton channels are helpful to constrain the model.

Thank You!

Backup slides

τ tagging

- leptonic $\tau \to \mu$ and hadronic $\tau \to jj$
- efficiency

Efficiency of different cuts

Table: The cross sections (unit fb) of signal (upper line) after imposing various cuts (a, b, c, d, e) sequentially, the background (lower line) and the significance after cuts with integrated luminosity of $500\mathrm{fb}^{-1}$. Cuts (a) $p_T^{j,l} > 1$GeV, (b) $p_T^{j,l} > 10$GeV, (c) $|M(l,\not{E}) - m_W| > 20$GeV, (d) $|M(l,j_1,j_2) - m_N| < 20$GeV, (e) $|M(l,j_1,j_2) - m_N| < 10$GeV.

	parameters	+cuts (a)	+cuts (b)	+cuts (c)	+cuts (d)	+cuts (e)	significance
A	$m_N = 150$GeV,	2.14	2.04	1.56	1.56	1.55	11.2
	$R_{\mu N} = 0.1$	2.31×10^3	2.20×10^3	52.4	16.3	8.05	
B	$m_N = 150$GeV,	7.63	7.30	5.61	5.60	5.60	18.8
	$R_{eN} = 0.02$	2.52×10^3	2.37×10^3	0.195×10^3	76.6	38.8	
C	$m_N = 90$GeV,	10.8	4.98	1.56	1.55	1.55	13.4
	$R_{eN} = 0.015$	2.52×10^3	2.37×10^3	0.195×10^3	16.8	5.14	
D	$m_N = 214$GeV,	0.852	0.827	0.243	0.242	0.241	1.75
	$R_{eN} = 0.015$	2.52×10^3	2.37×10^3	0.195×10^3	24.9	9.26	

Lepton Number Violation processes

- $e^+e^- \to Nl^\pm W^\mp \to l_1^\pm l_2^\pm + jjjj$
- $e^-e^- \to W^-W^- \to jjjj$

Indirect constraints

- $|R_{lN}|^2 \sim 10^{-3}$
  lepton flavor conserved decays of charged leptons, mesons, W and Z
- $|R^*_{\mu N} R_{eN}| \sim 10^{-5}$
  $\mu \to e\gamma$ and $\mu - e$ conversion
- complementary to direct searches