

Heavy Sterile Neutrinos at CEPC

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collaborated with Wei Liao, arXiv:1710.09266
[hep-ph].

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Outline

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

The low energy seesaw model

- 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 $|R_{eN}|^2 \lesssim 10^{-5}$ for GeV scale N .

The low energy seesaw model

- The mass matrix of active neutrinos for neutrino oscillation 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 100GeV scale, $|R_{lN_i}|$ will be very small ($\sim 10^{-6}$).

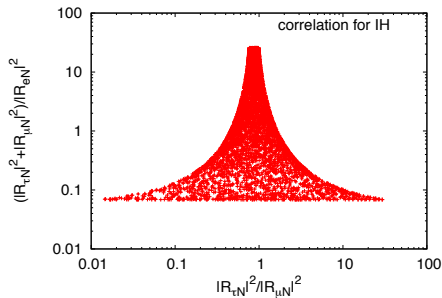
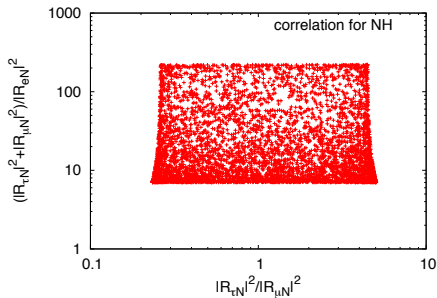
- For 2 heavy sterile neutrinos N_1 and N_2 , the amplitude of $0\nu\beta\beta$ decay is,

$$\mathcal{A} = \frac{F}{M_1^2} (R_{eN_1}^2 M_1 + R_{eN_2}^2 M_2) + FM_2 R_{eN_2}^2 \left(\frac{1}{M_2^2} - \frac{1}{M_1^2} \right)$$

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 $R_{eN_1}^2 = -R_{eN_2}^2$, 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_{IN}



- for NH, $R_{IN_2} = \pm i R_{IN_1}$ and $M_1 = M_2$ (neutrino mass)

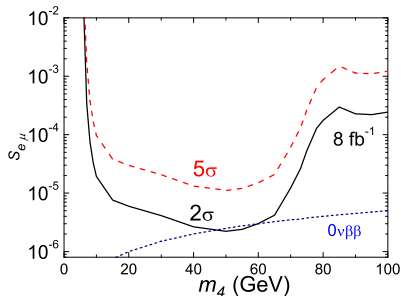
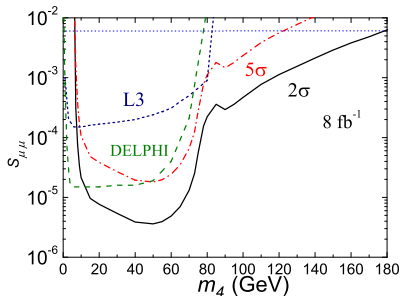
$$R_{IN_1} = \frac{1}{2} e^{\mp i x + |y|} (U_{I2} m_2^{1/2} e^{-i\phi_2/2} \mp i U_{I3} m_3^{1/2} e^{-i\phi_3/2}) (M_1^*)^{-1/2}$$

$R_{\mu N}$ and $R_{\tau N}$ larger than $R_{e N}$

- for IH, $R_{IN_2} = \pm i R_{IN_1}$ and $M_1 = M_2$

$$R_{IN_1} = \frac{1}{2} e^{\mp i x + |y|} (U_{I1} m_1^{1/2} e^{-i\phi_1/2} \mp i U_{I2} m_2^{1/2} e^{-i\phi_2/2}) (M_1^*)^{-1/2}$$

Tevatron sensitivity



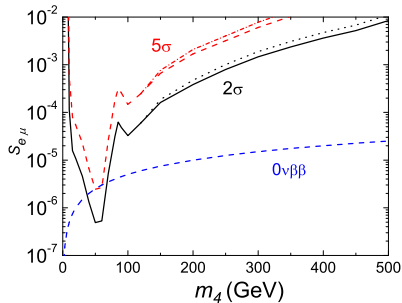
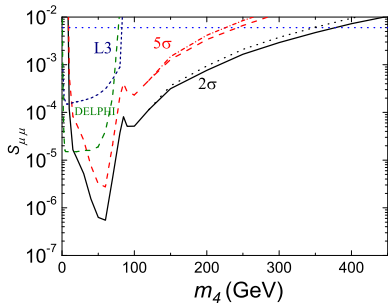
- A. Atre, T. Han, S. Pascoli, B. Zhang, 0901.3589.

- $p\bar{p} \rightarrow l_1^\pm l_2^\pm W^\mp \rightarrow l_1^\pm l_2^\pm jj'$

- 5σ sensitivity with 8fb^{-1}

$$|R_{\mu N}|^2, |R_{eN}|^2 \sim 10^{-4} (50\text{GeV}), \sim 10^{-2} (100\text{GeV})$$

LHC sensitivity

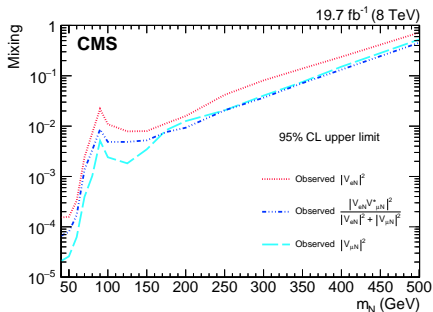
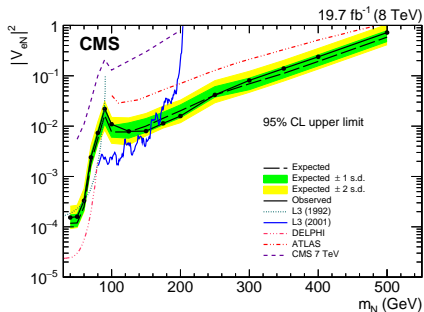


- A. Atre, T. Han, S. Pascoli, B. Zhang, 0901.3589.

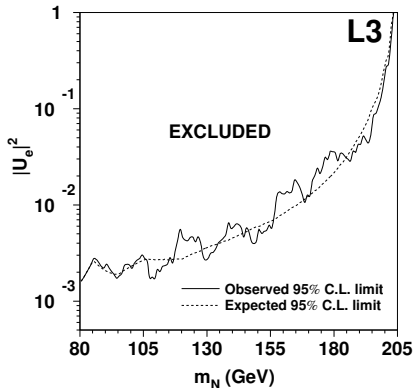
- $pp \rightarrow l_1^\pm l_2^\pm W^\mp \rightarrow l_1^\pm l_2^\pm jj'$

- 5σ sensitivity with 100fb^{-1}

$$|R_{\mu N}|^2, |R_{eN}|^2 \sim 10^{-5} (50\text{GeV}), \sim 10^{-3} (100\text{GeV})$$

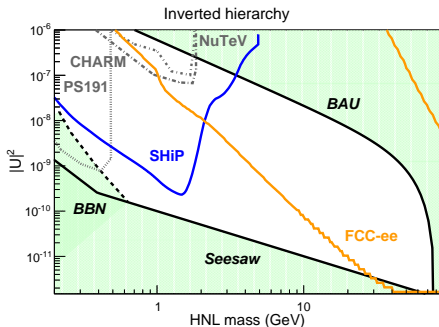
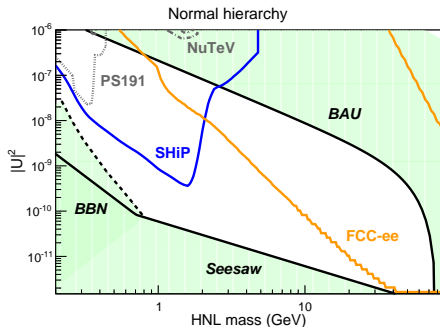


- CMS, 1503.05491 and 1603.02248
- $pp \rightarrow l^\pm N \rightarrow l_1^\pm l_2^\pm W^\mp \rightarrow l_1^\pm l_2^\pm jj'$
- 95% C.L. sensitivity with 19.7fb^{-1}
 $|R_{\mu N}|^2, |R_{eN}|^2 \sim 10^{-2}$ (100GeV)



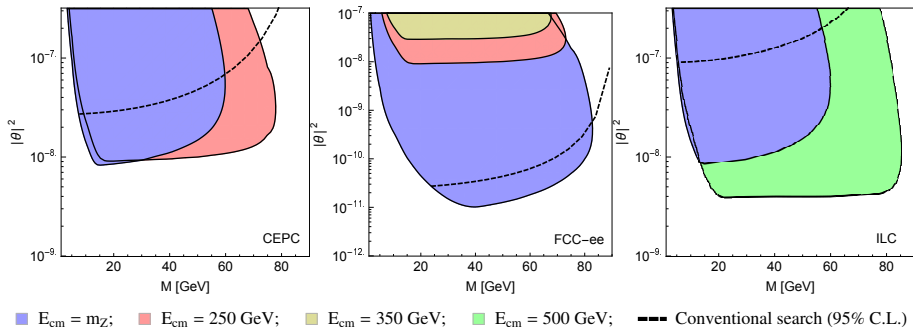
- L3, hep-ex/9909006 and hep-ex/0107014
- $e^+e^- \rightarrow N\nu \rightarrow eW\nu \rightarrow e\nu jj$
- 95% C. L., with 450pb^{-1}
 $|R_{eN}|^2 \sim 10^{-1} - 10^{-2}$ (80 – 205GeV)

FCC-ee at Z resonance



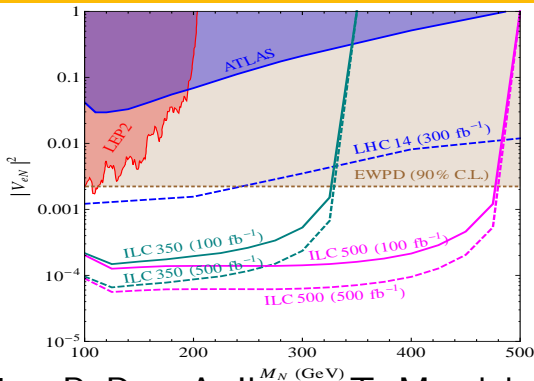
- A. Blondel, E. Graverini, N. Serra, M. Shaposhnikov, 1411.5230.
- $Z \rightarrow N\nu \rightarrow lW\nu \rightarrow l\nu jj$
- with 10^{13} Z
 $|R_{lN}|^2 \sim 10^{-12}$ (50GeV)

Displaced vertex searches at FLC



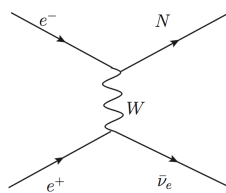
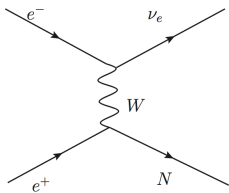
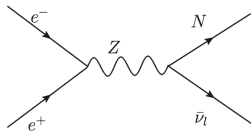
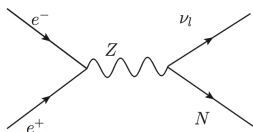
- S. Antusch, E. Cazzato, O. Fischer, 1604.02420.
- $|R_{IN}|^2 \sim 10^{-8} - 10^{-11}$ (20 – 80 GeV)

ILC expected



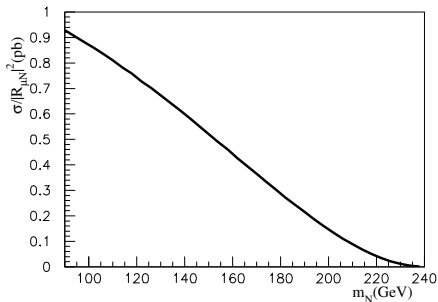
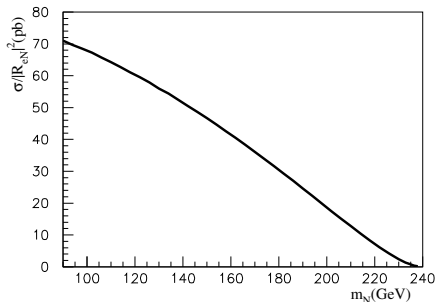
- S. Banerjee, P. Dev, A. Ibarra, T. Mandal, M. Mitra, 1503.05491.
- $e^+e^- \rightarrow N\nu \rightarrow eW\nu \rightarrow e\nu jj$
- 95% C.L. ILC with 100fb^{-1} or 500fb^{-1}
 $|R_{eN}|^2 \sim 10^{-5} - 10^{-4}$ (100 – 400 GeV)

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



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

Production and decay



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

Cuts

- signal $e^+e^- \rightarrow N\nu, N\bar{\nu} \rightarrow ljj\cancel{E}$
main background $e^+e^- \rightarrow W^+W^-$ with one W decaying leptonically, and one W decaying hadronically

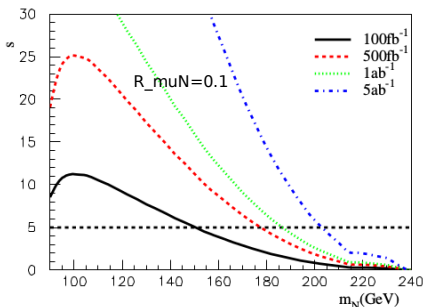
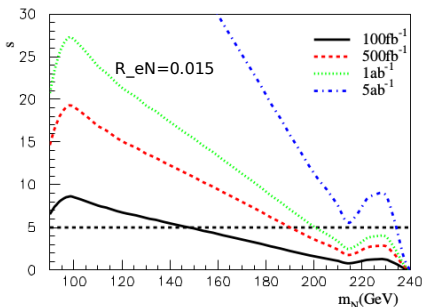
- basic cuts for lepton and jets to trigger the events

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

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

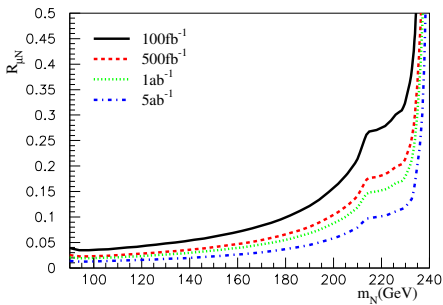
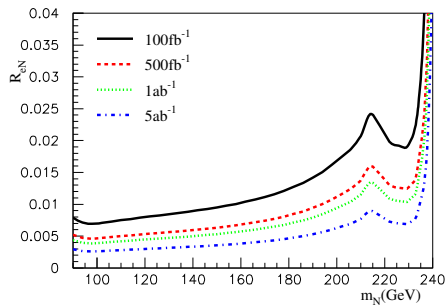
$$|M(l, \cancel{E}) - m_W| > 20 \text{ GeV}, \quad |M(j_1, j_2) - m_W| > 20 \text{ GeV},$$
$$|M(l, j_1, j_2) - m_N| < 10 \text{ GeV}.$$

A single R_{IN}



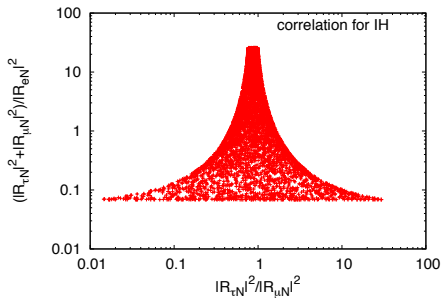
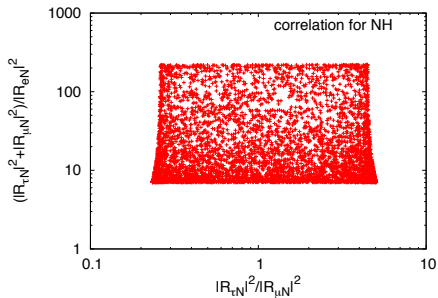
- significance, $s \equiv \mathcal{N}_s / \sqrt{\mathcal{N}_s + \mathcal{N}_b}$, \mathcal{N} as event number
- for the integrated luminosity of 100fb⁻¹
 $m_N \leq 146\text{GeV}$ (150GeV) for $l = e$ ($l = \mu$) channel
- for the integrated luminosity of 5ab⁻¹
 $m_N \leq 235\text{GeV}$ (205GeV) for $l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

Sensitivity on a single R_{lN}



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

The seesaw model with correlated R_{iN}

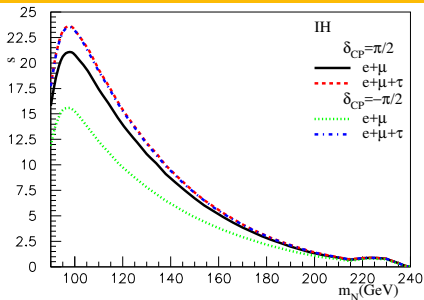
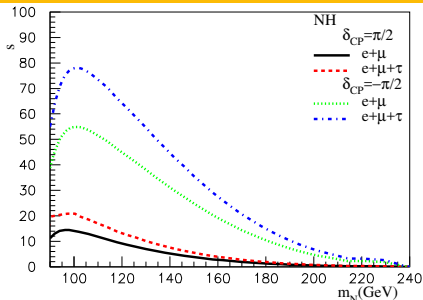


- for NH, $R_{iN_2} = \pm i R_{iN_1}$

$$R_{iN_1} = \frac{1}{2} e^{\mp i x + |y|} (U_{i2} m_2^{1/2} e^{-i\phi_2/2} \mp i U_{i3} m_3^{1/2} e^{-i\phi_3/2}) (M_1^*)^{-1/2}$$
 $R_{\mu N}$ and $R_{\tau N}$ larger than R_{eN}
- for IH, $R_{iN_2} = \pm i R_{iN_1}$

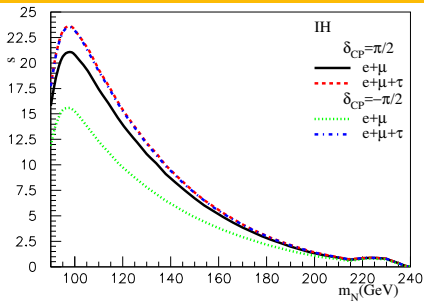
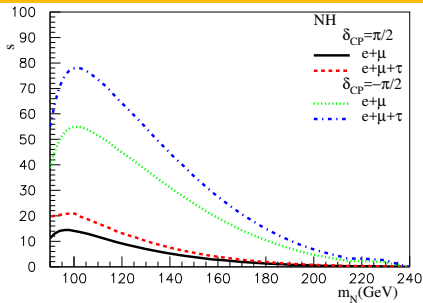
$$R_{iN_1} = \frac{1}{2} e^{\mp i x + |y|} (U_{i1} m_1^{1/2} e^{-i\phi_1/2} \mp i U_{i2} m_2^{1/2} e^{-i\phi_2/2}) (M_1^*)^{-1/2}$$

The seesaw model with correlated R_{iN}



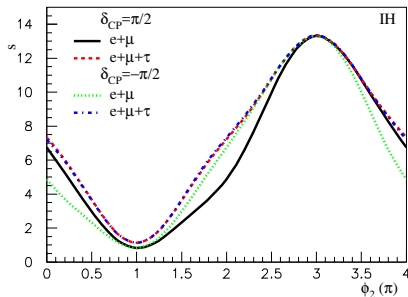
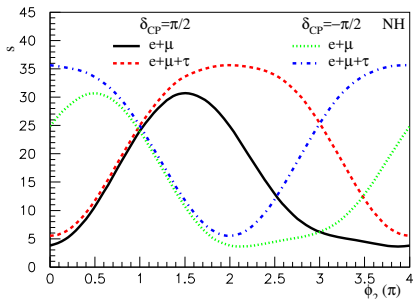
- significance $s \equiv \sqrt{\sum s_l^2}$, $l = e, \mu, \tau$ channel, 500fb^{-1}
- NH parameters, $\phi_1 = \phi_2 = \phi_3 = 0$, $e^y = 5000$ for NH
- NH, $\delta_{\text{CP}} = \pi/2$, $|R_{\mu N}| \sim |R_{\tau N}| \sim 10|R_{eN}|$, μ, τ dominant
 $m_N \leq 152\text{GeV}$ ($|R_{eN}| \sim 0.0032$,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

The seesaw model with correlated R_{iN}



- IH parameters, $\phi_1 = \phi_2 = \phi_3 = 0$, $e^Y = 1000$
- IH, $m_N \leq 162\text{GeV}$,
 $|R_{eN}| \sim 0.0086$, $|R_{\mu N}| \sim 0.0072$, $|R_{\tau N}| \sim 0.0051$ for $\delta_{\text{CP}} = \pi/2$
 $|R_{eN}| \sim 0.0086$, $|R_{\mu N}| \sim 0.0053$, $|R_{\tau N}| \sim 0.0071$ for $\delta_{\text{CP}} = -\pi/2$
- for both cases of $\delta_{\text{CP}} = \pi/2$ and $\delta_{\text{CP}} = -\pi/2$
 $|R_{eN}|$ 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

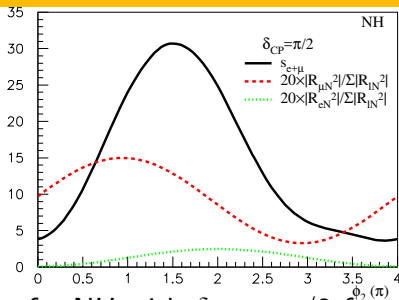
Effect of phases: δ_{CP} and ϕ_2



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

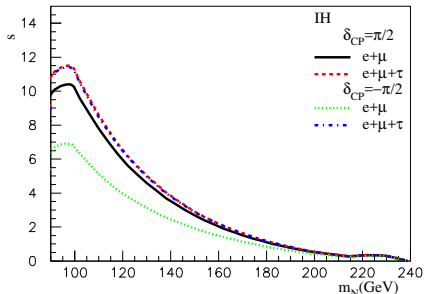
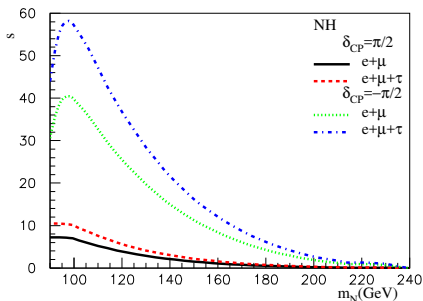
Take the case of $e + \mu$ significance for NH with $\delta_{\text{CP}} = \pi/2$ for an example. A bump at $\phi_2 \sim 1.5\pi$

Effect of phases: the bump



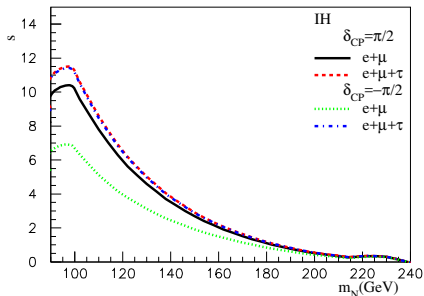
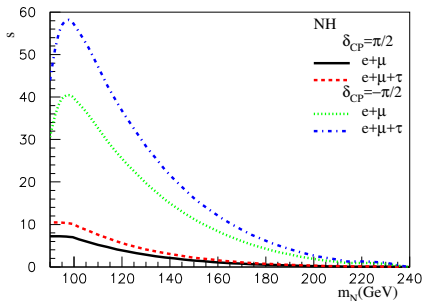
- $e + \mu$ significance for NH with $\delta_{CP} = \pi/2$ for an example
- A bump in $e + \mu$ significance (dominated by the μjj) at $\phi_2 \sim 1.5\pi$.
 1. ϕ_2 (from 0 to 2π) \uparrow , $|R_{eN}|^2 / \sum |R_{IN}|^2 \uparrow$ and peaks at $\phi_2 = 2\pi$, then t-channel production (dominate production) \uparrow ,
 2. ϕ_2 (from 0 to π) \uparrow , $|R_{\mu N}|^2 / \sum |R_{IN}|^2 \uparrow$ and peaks at $\phi_2 \sim \pi$. For $\phi_2 > \pi$, $|R_{\mu N}|^2 / \sum |R_{IN}|^2 \downarrow$ and $\text{Br}(N \rightarrow \mu jj) \downarrow$, but compensated by \uparrow production of $e^+ e^- \rightarrow N\nu$.
 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 5ab^{-1}



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

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



- IH parameters, $\phi_1 = \phi_2 = \phi_3 = 0$, $e^y = 350$

- IH, $m_N \leq 130\text{GeV}$,

$$|R_{eN}| \sim 0.0034, |R_{\mu N}| \sim 0.0028, |R_{\tau N}| \sim 0.0020 \text{ for } \delta_{CP} = \pi/2$$

$$|R_{eN}| \sim 0.0034, |R_{\mu N}| \sim 0.0021, |R_{\tau N}| \sim 0.0028 \text{ for } \delta_{CP} = -\pi/2$$

The seesaw model with correlated R_{IN}

- With 5ab^{-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_{IN} , a search for all 3 lepton channels are helpful to constrain the model.

Lepton Number Violation processes

- $e^+e^- \rightarrow NI^\pm W^\mp \rightarrow I_1^\pm I_2^\pm + jjj$
- $e^-e^- \rightarrow W^-W^- \rightarrow jjj$

Summary

- We studied the sensitivity of CEPC in a low energy seesaw model with heavy neutrino mass of order of 100GeV and large mixing with active neutrinos.
- After 10 years of operation, with 5ab^{-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 $\tau \rightarrow \mu$ and hadronic $\tau \rightarrow jj$
- 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 500fb^{-1} . Cuts (a) $p_T^{j,l} > 1\text{GeV}$, (b) $p_T^{j,l} > 10\text{GeV}$, (c) $|M(l, \cancel{E}) - m_W| > 20\text{GeV}$ and $|M(j_1, j_2) - m_W| > 20\text{GeV}$, (d) $|M(l, j_1, j_2) - m_N| < 20\text{GeV}$, (e) $|M(l, j_1, j_2) - m_N| < 10\text{GeV}$.

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