

# Heavy Sterile Neutrinos at CEPC

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arXiv:1710.09266 [hep-ph], in collaboration with  
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# Outline

- low energy seesaw model  
with order of  $100\text{GeV}$  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

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

# The low energy seesaw model

- The mass matrix of active neutrinos for neutrino oscillation phenomena is,

$$(m_\nu)_{ll'} = -v^2 \sum_i Y_{li}^* Y_{l'i}^* M_i^{-1} = - \sum_i M_i R_{iN_i}^* R_{l'N_i}^*$$

for  $m_\nu$  at  $10^{-3} - 10^{-2}$  eV scale, if  $M_i$  is 100GeV scale and there is only one  $N$ ,  $|R_{iN_i}|$  will be very small ( $\sim 10^{-6}$ ).

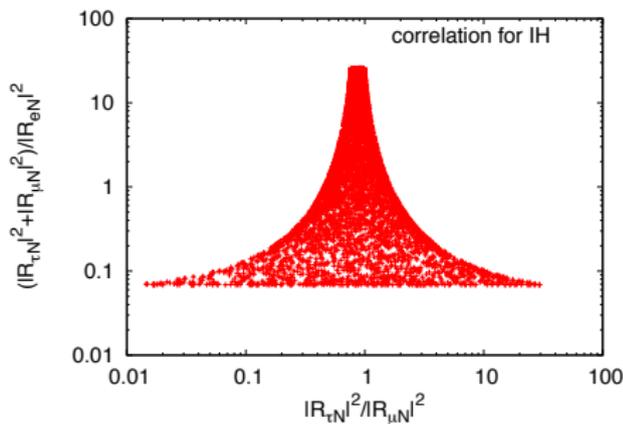
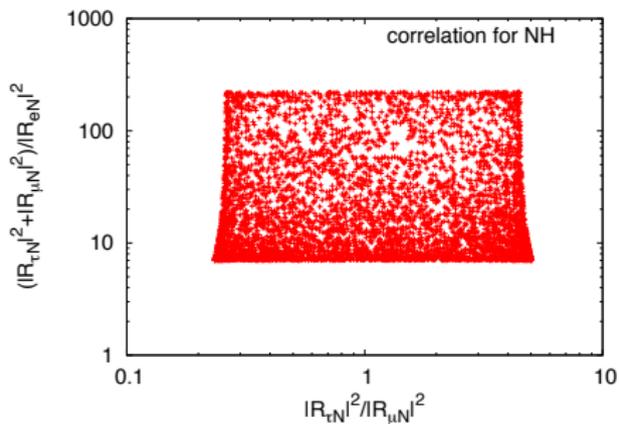
- For 2 heavy sterile neutrinos  $N_1$  and  $N_2$ , the amplitude of  $0\nu\beta\beta$  decay is,

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

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)

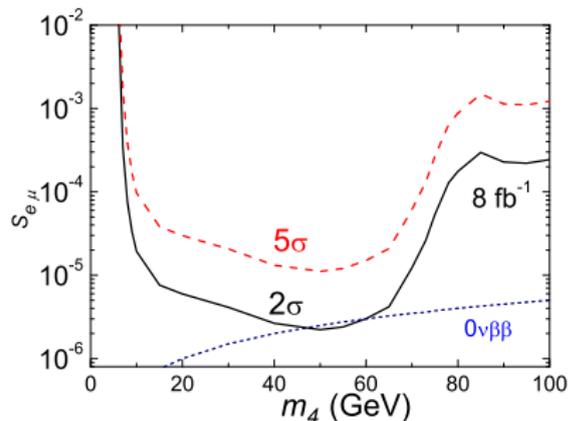
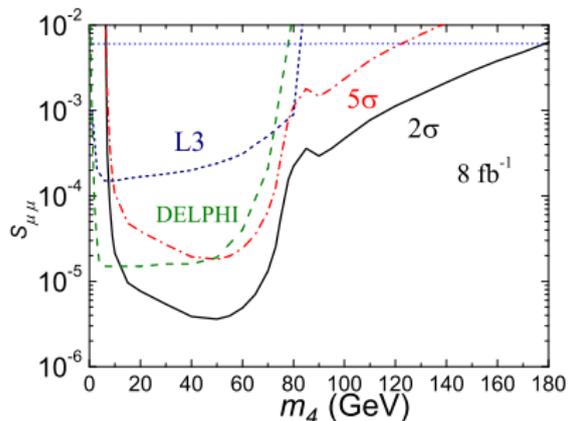
$$R_{IN_1} = \frac{1}{2} e^{\mp i x + |y|} (U_{I2} m_2^{1/2} e^{-i\phi_2/2} \mp i U_{I3} m_3^{1/2} e^{-i\phi_3/2}) (M_1^*)^{-1/2}$$

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

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

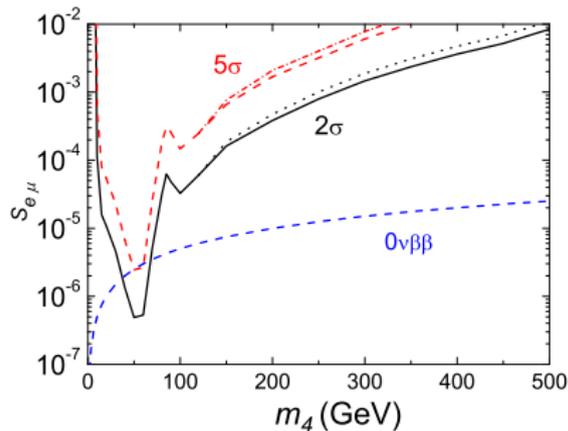
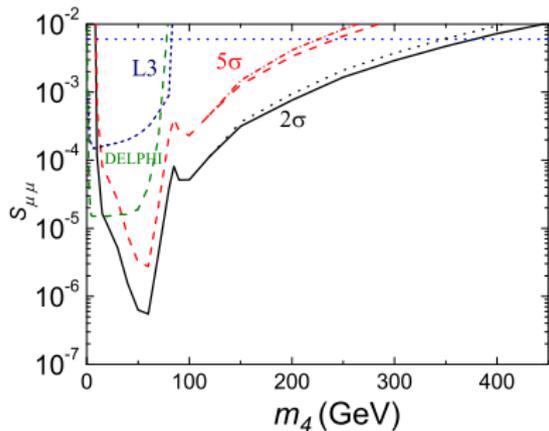
$$R_{IN_1} = \frac{1}{2} e^{\mp i x + |y|} (U_{I1} m_1^{1/2} e^{-i\phi_1/2} \mp i U_{I2} m_2^{1/2} e^{-i\phi_2/2}) (M_1^*)^{-1/2}$$

# Tevatron sensitivity



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

# LHC sensitivity

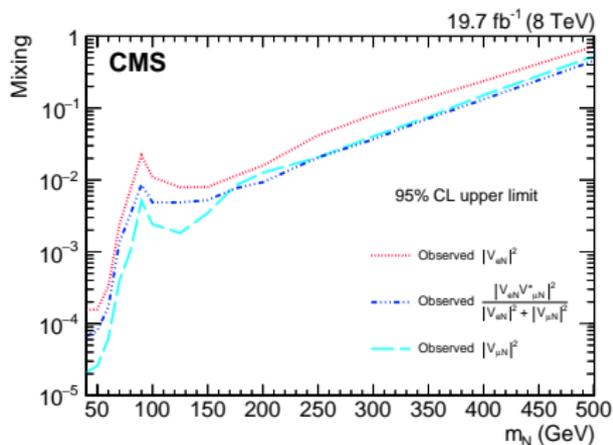
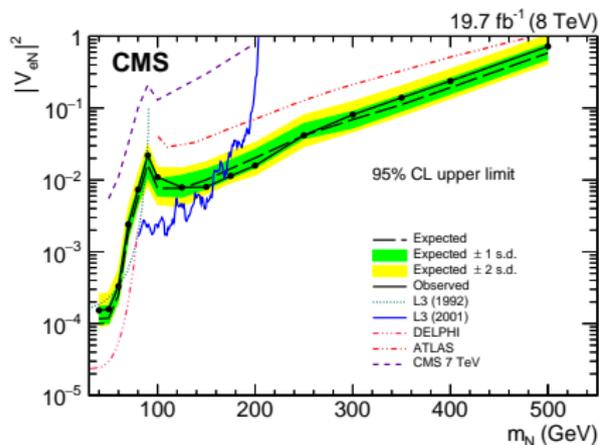


- A. Atre, T. Han, S. Pascoli, B. Zhang, 0901.3589.

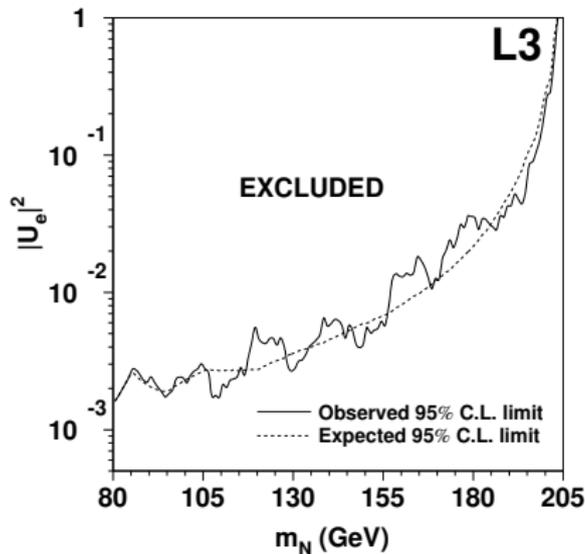
- $pp \rightarrow l_1^\pm l_2^\pm W^\mp \rightarrow l_1^\pm l_2^\pm jj'$

- $5\sigma$  sensitivity with  $100\text{fb}^{-1}$

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

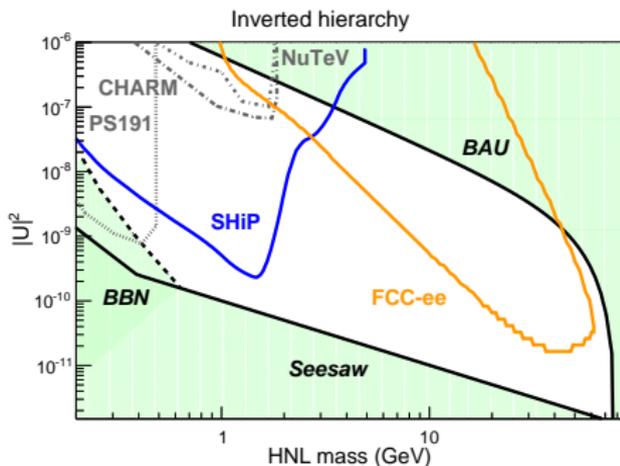
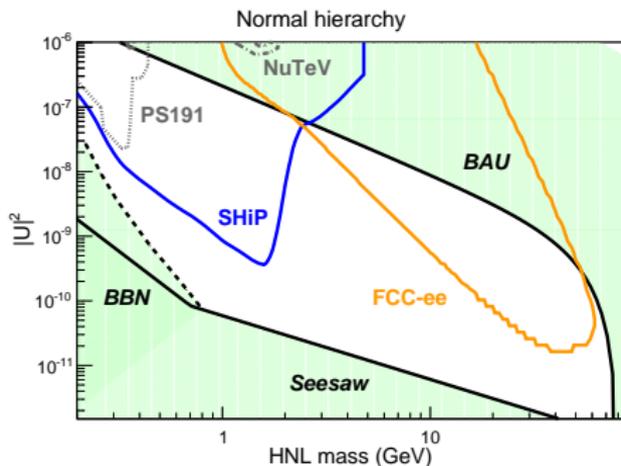


- CMS, 1503.05491 and 1603.02248
- $pp \rightarrow l^\pm N \rightarrow l_1^\pm l_2^\pm W^\mp \rightarrow l_1^\pm l_2^\pm jj'$
- 95% C.L. sensitivity with  $19.7\text{fb}^{-1}$   
 $|R_{\mu N}|^2, |R_{eN}|^2 \sim 10^{-2}$  (100GeV)



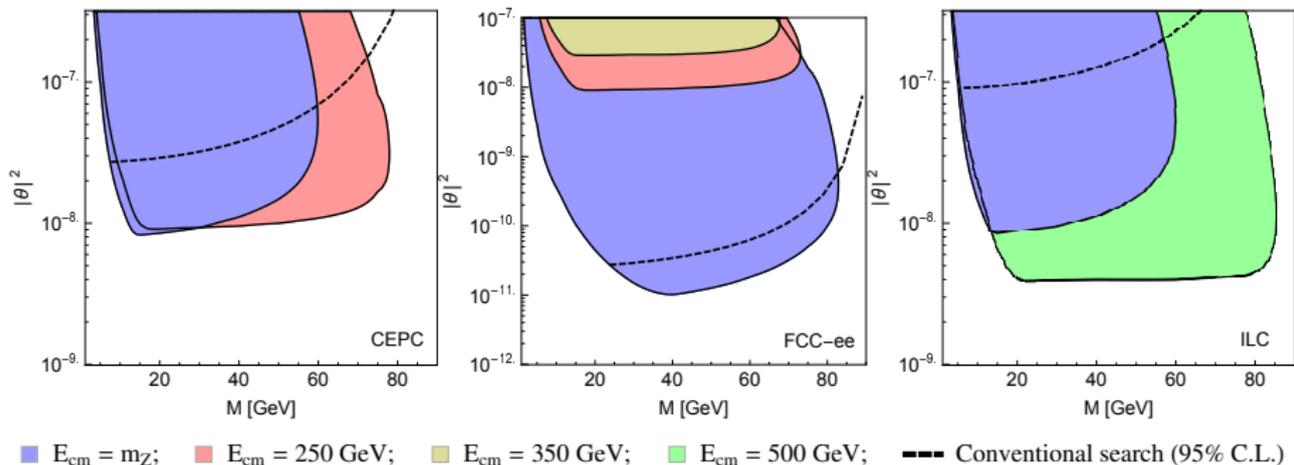
- L3, hep-ex/9909006 and hep-ex/0107014
- $e^+e^- \rightarrow N\nu \rightarrow eW\nu \rightarrow e\nu jj$
- 95% C. L., with  $450\text{pb}^{-1}$   
 $|R_{eN}|^2 \sim 10^{-1} - 10^{-2} \text{ (80 - 205 GeV)}$

# FCC-ee at $Z$ resonance



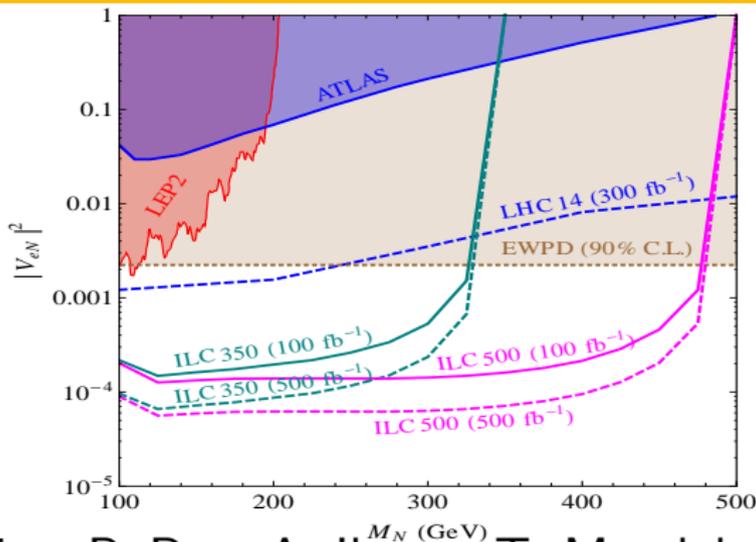
- A. Blondel, E. Graverini, N. Serra, M. Shaposhnikov, 1411.5230.
- $Z \rightarrow N\nu \rightarrow lW\nu \rightarrow l\nu jj$
- with  $10^{12}$   $Z$   
 $|R_{lN}|^2 \sim 10^{-11}$  (50GeV)

# Displaced vertex searches at FLC



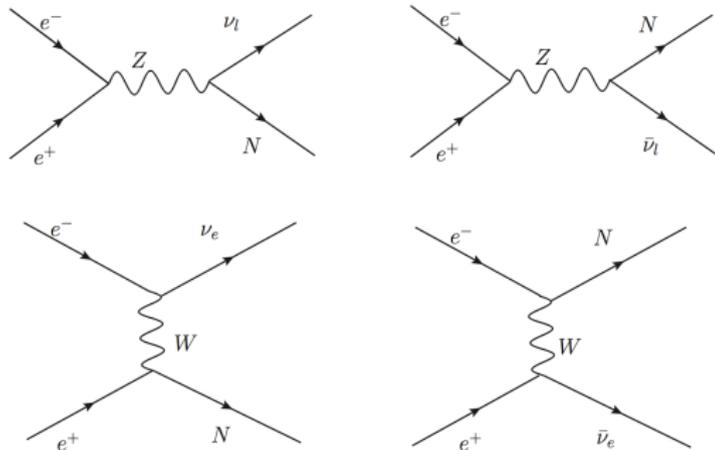
- S. Antusch, E. Cazzato, O. Fischer, 1604.02420.
- $|R_{IN}|^2 \sim 10^{-8} - 10^{-11}$  (20 – 80 GeV)

# ILC expected



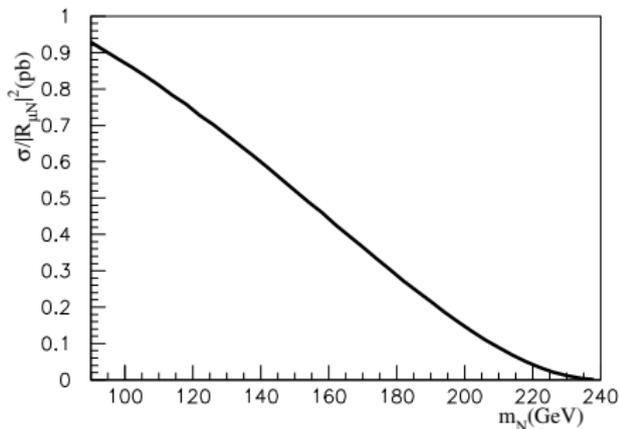
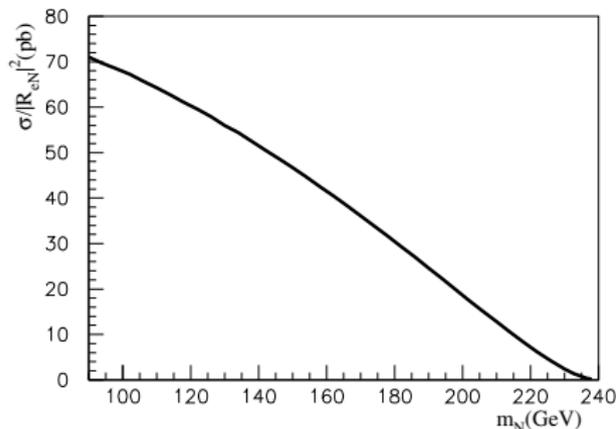
- S. Banerjee, P. Dev, A. Ibarra, T. Mandal, M. Mitra, 1503.05491.
- $e^+e^- \rightarrow N\nu \rightarrow eW\nu \rightarrow e\nu jj$
- 95% C.L. ILC with  $100\text{fb}^{-1}$  or  $500\text{fb}^{-1}$   
 $|R_{eN}|^2 \sim 10^{-5} - 10^{-4}$  (100 – 400 GeV)

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



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

# Production and decay

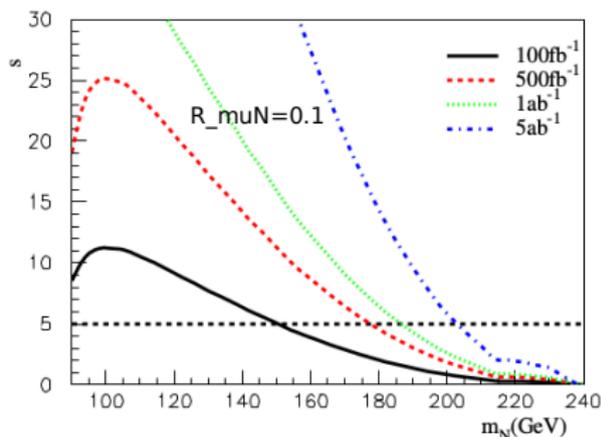
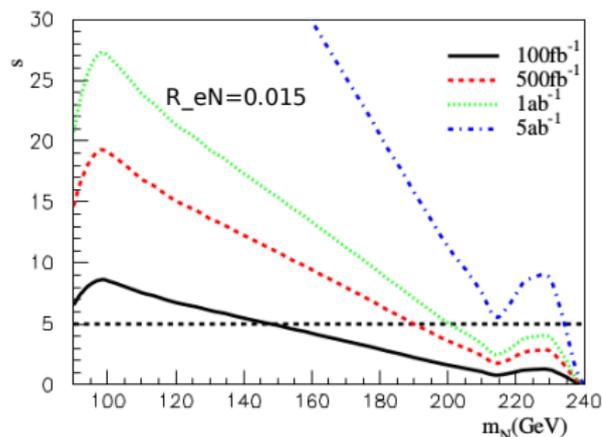


- $e^+e^- \rightarrow N\nu$ , summing over neutrinos of all flavor and anti-neutrinos.
- For a heavy neutrino of about 100GeV,  $\sigma/|R_{eN}|^2 \sim 60\text{pb}$  and  $\sigma/|R_{\mu N}|^2 \sim 0.8\text{pb}$
- above Z (or H) mass, two-body decay modes dominant,  $N \rightarrow IW, \nu Z, \nu H$ ,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

# Cuts

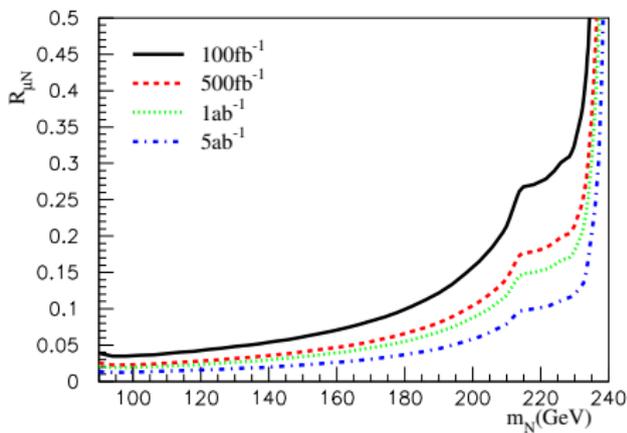
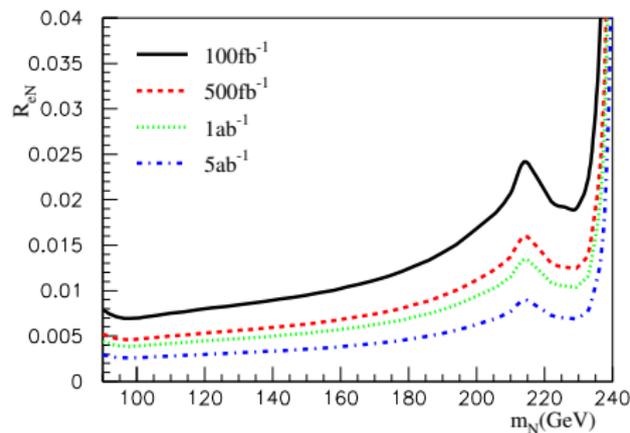
- signal  $e^+e^- \rightarrow N\nu, N\bar{\nu} \rightarrow ljj \cancel{E}$   
main background  $e^+e^- \rightarrow W^+W^-$  with one  $W$  decaying leptonically, and one  $W$  decaying hadronically
- basic cuts for lepton and jets to select the events
$$p_T^l > 10\text{GeV}, |\eta^l| < 2.5, \Delta R_{ll} > 0.4,$$
$$p_T^j > 10\text{GeV}, |\eta^j| < 2.5, \Delta R_{jj} > 0.4, \Delta R_{lj} > 0.4.$$
- selection cuts to suppress background events from on-shell  $W$  decay
$$|M(l, \cancel{E}) - m_W| > 20 \text{ GeV},$$
$$|M(l, j_1, j_2) - m_N| < 10 \text{ GeV}.$$

# A single $R_{IN}$



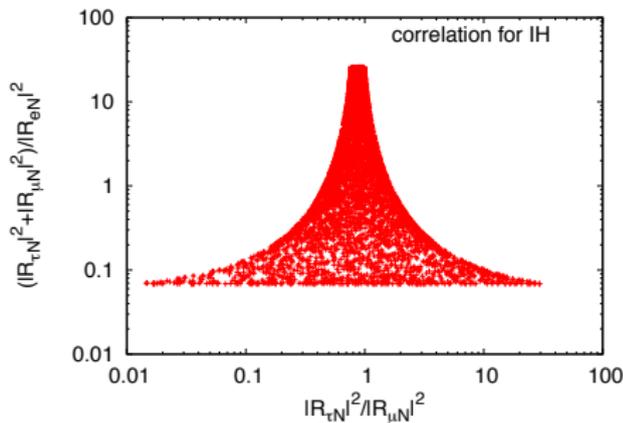
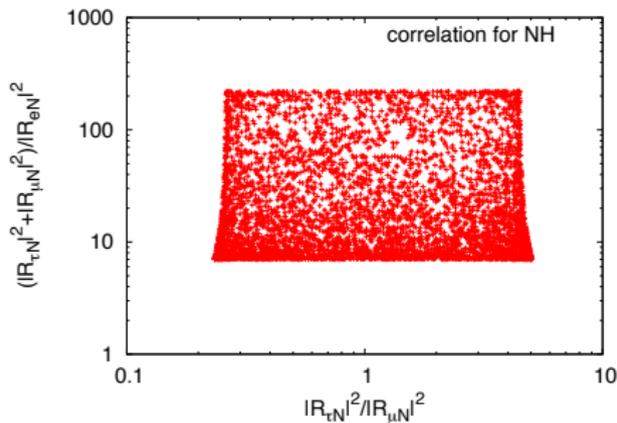
- significance,  $s \equiv \mathcal{N}_s / \sqrt{\mathcal{N}_s + \mathcal{N}_b}$ ,  $\mathcal{N}$  as event number
- for the integrated luminosity of 100 fb<sup>-1</sup>  
 $m_N \leq 146 \text{ GeV} (150 \text{ GeV})$  for  $l = e$  ( $l = \mu$ ) channel
- for the integrated luminosity of 5 ab<sup>-1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

# Sensitivity on a single $R_{lN}$



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

# The seesaw model with correlated $R_{IN}$

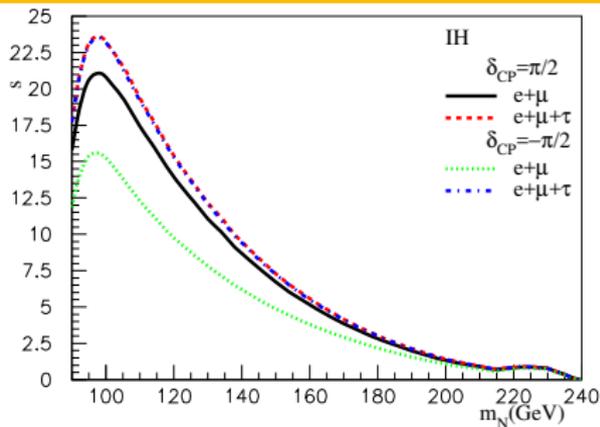
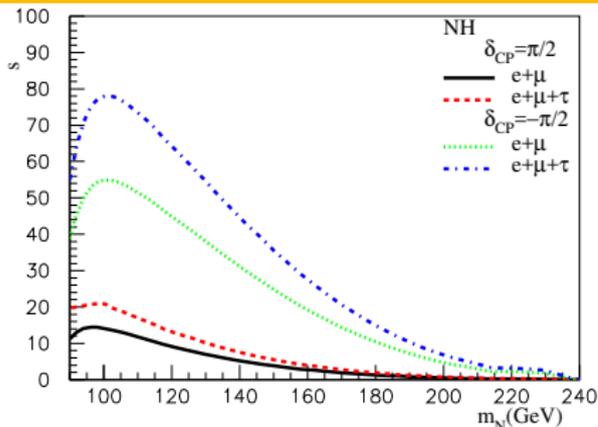


- for NH,  $R_{IN_2} = \pm i R_{IN_1}$   

$$R_{IN_1} = \frac{1}{2} e^{\mp i x + |y|} (U_{I2} m_2^{1/2} e^{-i\phi_2/2} \mp i U_{I3} m_3^{1/2} e^{-i\phi_3/2}) (M_1^*)^{-1/2}$$
 $R_{\mu N}$  and  $R_{\tau N}$  larger than  $R_{eN}$
- for IH,  $R_{IN_2} = \pm i R_{IN_1}$   

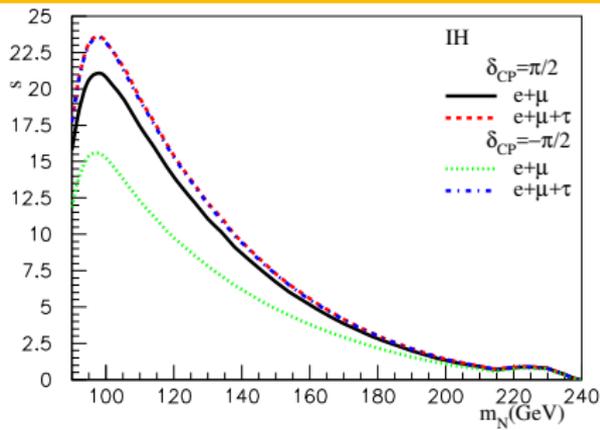
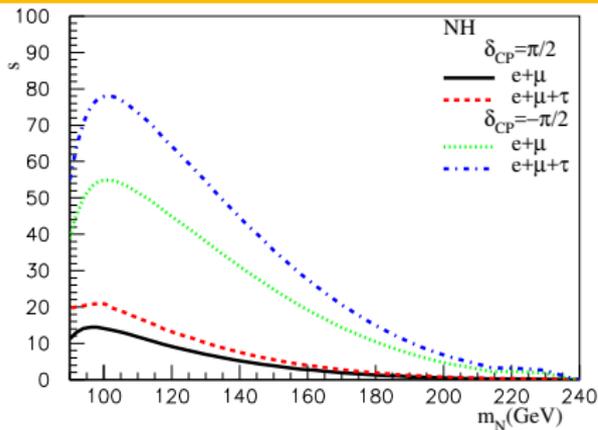
$$R_{IN_1} = \frac{1}{2} e^{\mp i x + |y|} (U_{I1} m_1^{1/2} e^{-i\phi_1/2} \mp i U_{I2} m_2^{1/2} e^{-i\phi_2/2}) (M_1^*)^{-1/2}$$

# The seesaw model with correlated $R_{iN}$



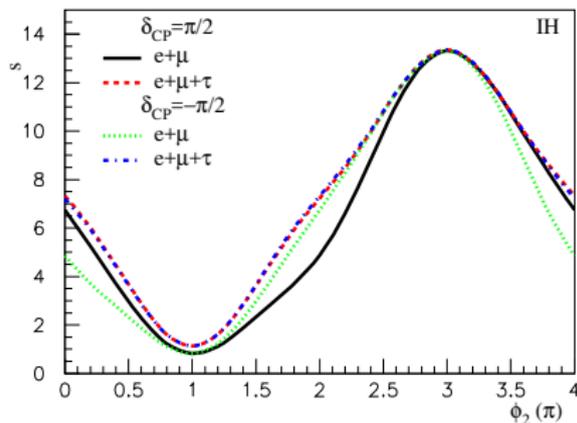
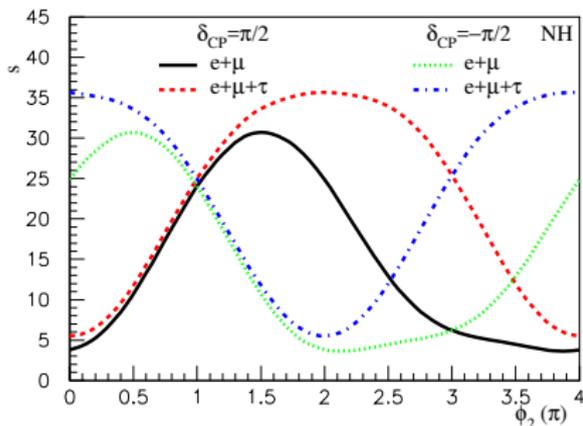
- significance  $s \equiv \sqrt{\sum s_l^2}$ ,  $l = e, \mu, \tau$  channel,  $500\text{fb}^{-1}$
- NH parameters,  $\phi_1 = \phi_2 = \phi_3 = 0$ ,  $e^y = 5000$  for NH
- NH,  $\delta_{\text{CP}} = \pi/2$ ,  $|R_{\mu N}| \sim |R_{\tau N}| \sim 10|R_{eN}|$ ,  $\mu, \tau$  dominant  
 $m_N \leq 152\text{GeV}$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

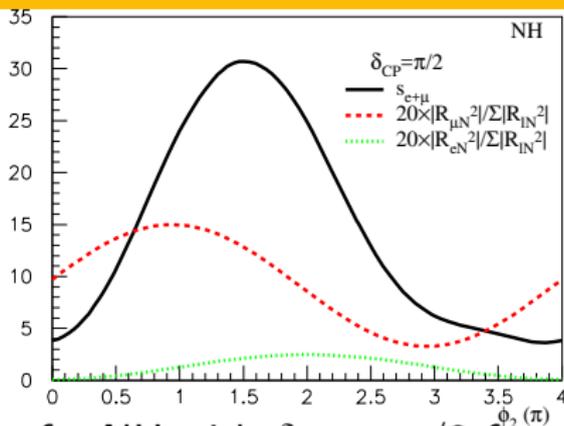
# Effect of phases: $\delta_{\text{CP}}$ and $\phi_2$



- $m_N = 150\text{GeV}$  and integrated luminosity  $500\text{fb}^{-1}$
- The  $e + \mu$  and  $e + \mu + \tau$  significance depends on both Dirac phase  $\delta_{\text{CP}}$  and Majorana phase  $\phi_2$ .
- The bumps as the varied  $\phi_2$ .

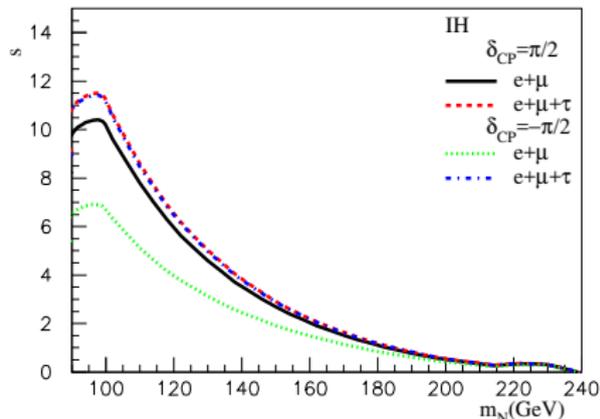
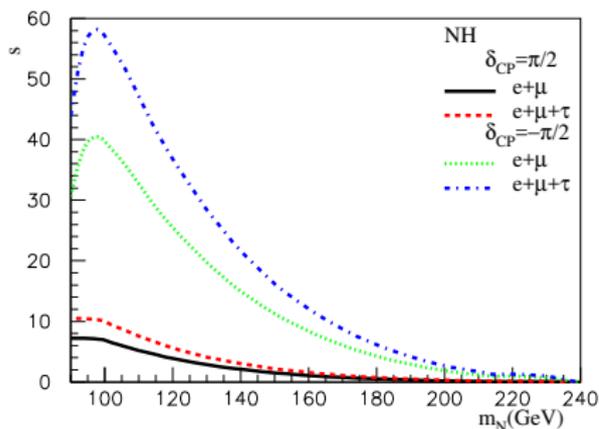
Take the case of  $e + \mu$  significance for NH with  $\delta_{\text{CP}} = \pi/2$  for an example. A bump at  $\phi_2 \sim 1.5\pi$

# Effect of phases: the bump



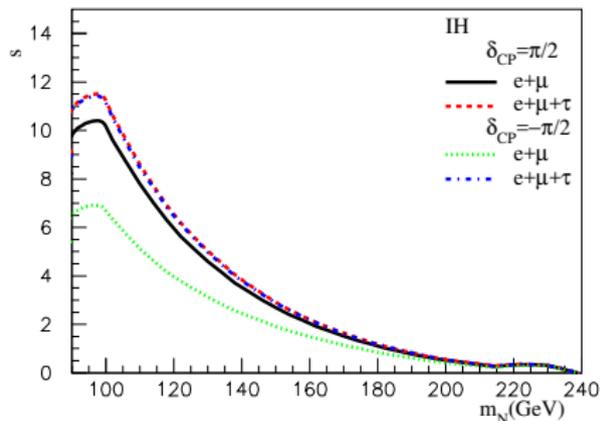
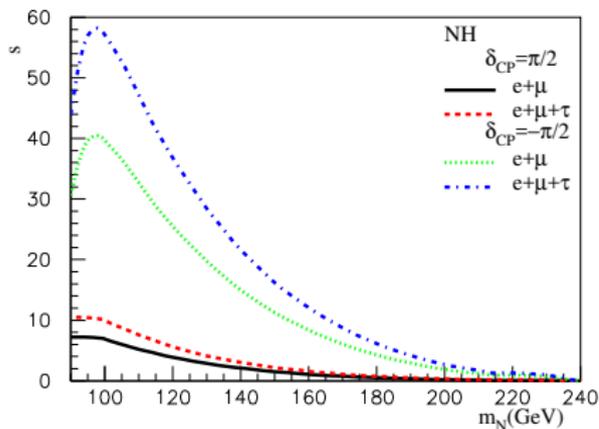
- $e + \mu$  significance for NH with  $\delta_{CP} = \pi/2$  for an example
- A bump in  $e + \mu$  significance (dominated by the  $\mu jj$ ) at  $\phi_2 \sim 1.5\pi$ .
  1.  $\phi_2$  (from 0 to  $2\pi$ )  $\uparrow$ ,  $|R_{eN}|^2 / \sum |R_{iN}|^2 \uparrow$  and peaks at  $\phi_2 = 2\pi$ , then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

# 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  $\delta_{CP} = \pi/2$ ,  
 $m_N \leq 124\text{GeV}$ , ( $|R_{eN}| \sim 0.0012$ ,  $|R_{\mu N}| \sim |R_{\tau N}| \sim 0.013$ )
- for  $\delta_{CP} = -\pi/2$ ,  
 $m_N \leq 184\text{GeV}$  ( $|R_{eN}| \sim 0.0055$ ,  $|R_{\mu N}| \sim |R_{\tau N}| \sim 0.010$ )

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



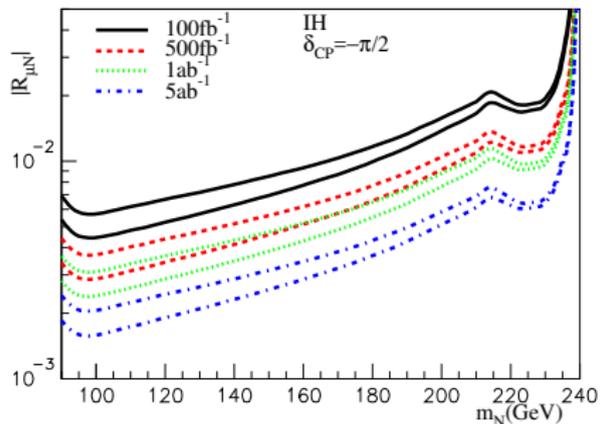
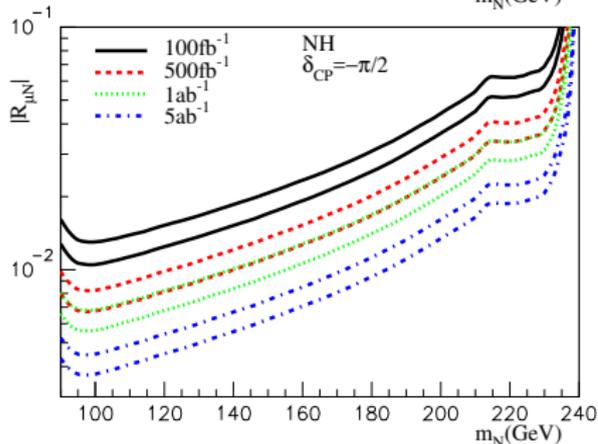
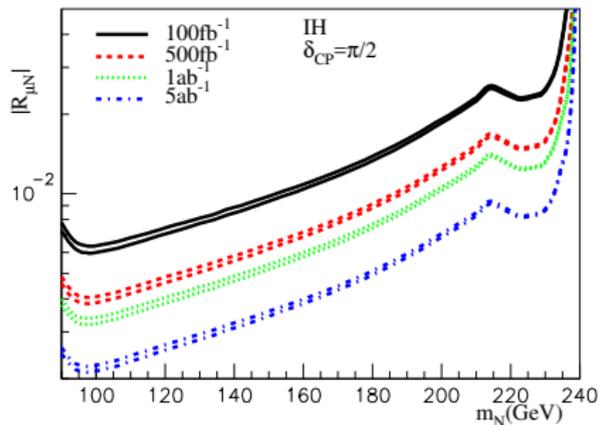
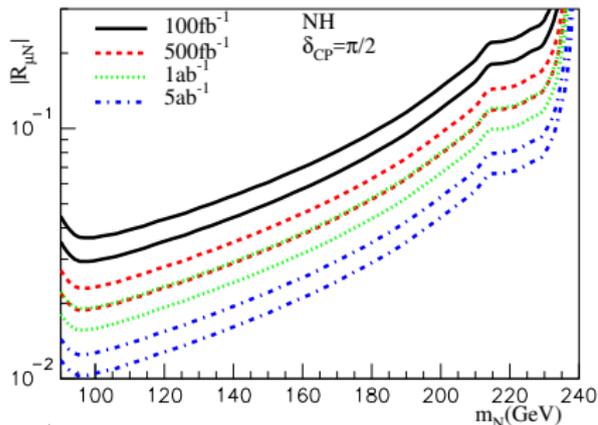
- IH parameters,  $\phi_1 = \phi_2 = \phi_3 = 0$ ,  $e^y = 350$

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

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

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

# Sensitivity on $R_{IN}$



# The seesaw model with correlated $R_{IN}$

- With  $5\text{ab}^{-1}$ , CEPC can reach a  $5\sigma$  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  $\mu$  and  $\tau$  channel will be enhanced, and further constrain  $R_{\mu N}$  and  $R_{\tau N}$ .
- The significance depends on both Dirac phase  $\delta_{\text{CP}}$  and Majorana phases.
- With correlated  $R_{IN}$ , 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 100GeV and large mixing with active neutrinos.
- After 10 years of operation, with  $5\text{ab}^{-1}$ , 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

# $\tau$ 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  $500\text{fb}^{-1}$ . Cuts (a)  $p_T^{j_1, j_2} > 1\text{GeV}$ , (b)  $p_T^{j_1, j_2} > 10\text{GeV}$ , (c)  $|M(l, \cancel{E}) - m_W| > 20\text{GeV}$ , (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 $2.31 \times 10^3$	2.04 $2.20 \times 10^3$	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 $2.52 \times 10^3$	7.30 $2.37 \times 10^3$	5.61 $0.195 \times 10^3$	5.60 76.6	5.60 38.8	18.8
C	$m_N = 90\text{GeV}$ , $R_{eN} = 0.015$	10.8 $2.52 \times 10^3$	4.98 $2.37 \times 10^3$	1.56 $0.195 \times 10^3$	1.55 16.8	1.55 5.14	13.4
D	$m_N = 214\text{GeV}$ , $R_{eN} = 0.015$	0.852 $2.52 \times 10^3$	0.827 $2.37 \times 10^3$	0.243 $0.195 \times 10^3$	0.242 24.9	0.241 9.26	1.75

# Lepton Number Violation processes

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