Heavy Neutrinos Search at future Z factory

Jian-Nan Ding

Peking University

Aug. 17, 2023

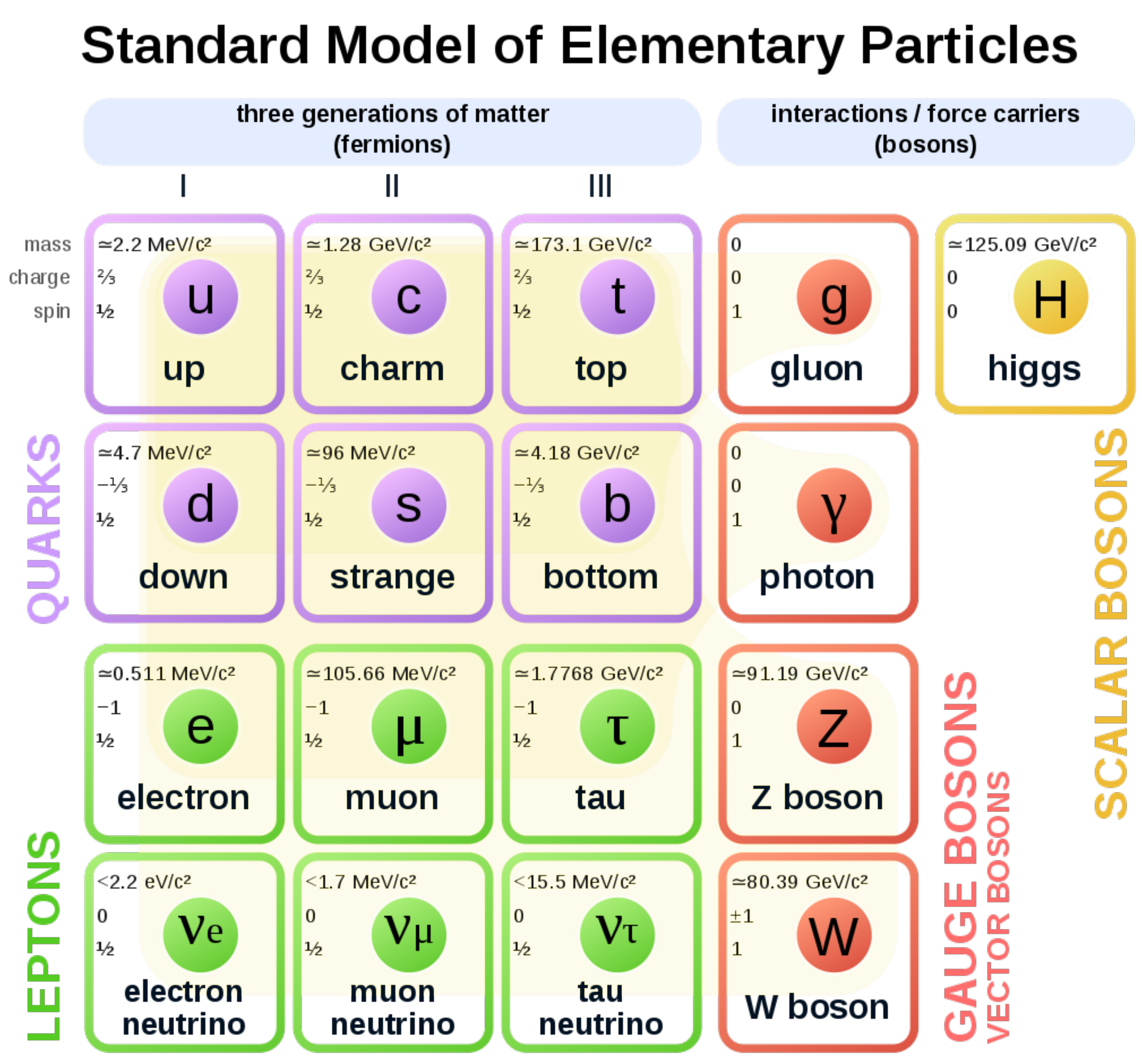
CEPC Workshop @ Fudan University

Jian-Nan Ding, Qin Qin, Fu-Sheng Yu, 1903.02570

Yin-Fa Shen, Jian-Nan Ding, Qin Qin, 2201.05831

Standard Model and Beyond

- Standard Model :



- Beyond the Standard Model:
  - Neutrino mass

    $$|m_{31}^2|^{\frac{1}{2}} \simeq 0.0506 \text{ eV} \quad |m_{21}^2|^{\frac{1}{2}} \simeq 0.0086 \text{ eV}$$

  - Higgs hierarchy problem

    $$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{\rm UV}^2 - 2m_S^2 \ln(\Lambda_{\rm UV}/m_S) + \ldots\right].$$

  - Dark energy and dark matter
  - Matter anti-matter asymmetry

Neutrino Oscillation

- Gauge symmetry forbidden the mass of neutrino

$$\mathcal{L}_{\rm SM} \not\supset m_\nu \, \bar{\nu}_L \nu_R$$

- Neutrino oscillation suggests a non-zero mass of neutrino

$$\sum m_\nu < 0.170 \text{ eV}, \quad |\mathrm{m}^2_{31}|^{\frac{1}{2}} \simeq 0.0506 \text{ eV}, \quad |\mathrm{m}^2_{21}|^{\frac{1}{2}} \simeq 0.0086 \text{ eV}.$$

Y. Fukuda et al., 1998, Q. R. Ahmad et al., 2002, Particle Data Group, 2022

- The origin of neutrino mass

  - Dirac neutrino ?

    $$m_D = y_\nu v/\sqrt{2}$$

  - Majorana neutrino ?

    $$m_\nu \simeq m_D \, M_N^{-1} \, m_D^T$$

The Origin of Neutrino Mass

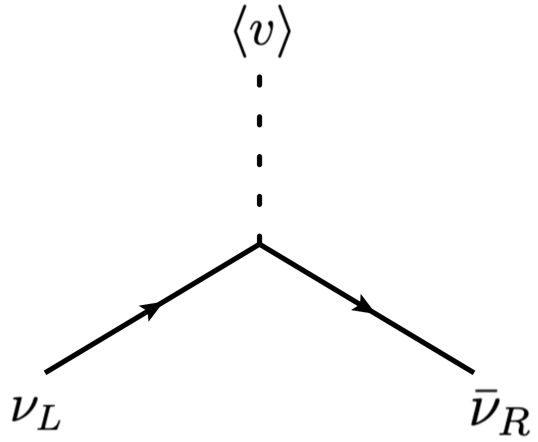
- The origin of Dirac neutrino mass

$$\mathcal{L}^{\nu}_{\text{Yukawa}} = -y_{ij}\bar{\nu}^i_R \widetilde{H} \ell^j_L.$$

$$\Big\downarrow \text{ SSB}$$

$$\mathcal{L}^{\nu}_{\text{Yukawa}} = m_D \bar{\nu}^i_R \nu^i_L + \frac{m_D}{v}\bar{\nu}^i_R \nu^i_L h$$

$$\text{Dirac mass}: \quad m_D \equiv y_\nu v/\sqrt{2}$$



- Flavor hierarchy/naturalness problem: $y_\nu / y_t = 10^{-12}$

- The origin of Majorana neutrino mass

$$\mathcal{L} \supset \frac{1}{2}\bar{N}_R i\partial\!\!\!/ N_R - y_\nu \bar{\ell}_L \tilde{H} N_R - \frac{1}{2}\boxed{M_{N_R}\bar{N}^c_R N_R} + h.c.,$$

$$\begin{aligned}\mathcal{L}^{\nu}_{\text{mass}} &= -\bar{\nu}_L m_D N_R - \frac{1}{2}\bar{N}^c_R M_{N_R} N_R \\ &= -\frac{1}{2}\left(\bar{\nu}_L \quad \bar{N}^c_R\right)\begin{pmatrix} 0 & m_D \\ m_D^T & M_{N_R}\end{pmatrix}\begin{pmatrix}\nu^c_L \\ N_R\end{pmatrix}.\end{aligned}$$

$$\longrightarrow$$

Type-I Seesaw

$$\boxed{m_\nu = m_D \frac{m_D^T}{M_{N_R}},}$$

$$M_N \simeq M_{N_R}.$$

P. Minkowski, 1977
R.N. Mohapatra et al., 1980…

The Origin of Neutrino Mass

- Flavor hierarchy/naturalness

$$m_\nu = m_D \frac{m_D^T}{M_{N_R}},$$

$$y_\nu \simeq 1 \quad \Rightarrow \quad m_D \simeq 100 \text{ GeV}.$$

$$M_N \sim \mathcal{O}(10^{14}) \text{ GeV} \quad \Rightarrow \quad m_\nu \sim \mathcal{O}(0.1) \text{ eV}.$$

→ $M_N \gg v$

$$\frac{c_\nu}{\Lambda}(\tilde{H}^\dagger \ell_p)^T C (\tilde{H}^\dagger \ell_r)$$

Weinberg operator

- Low energy seesaw model

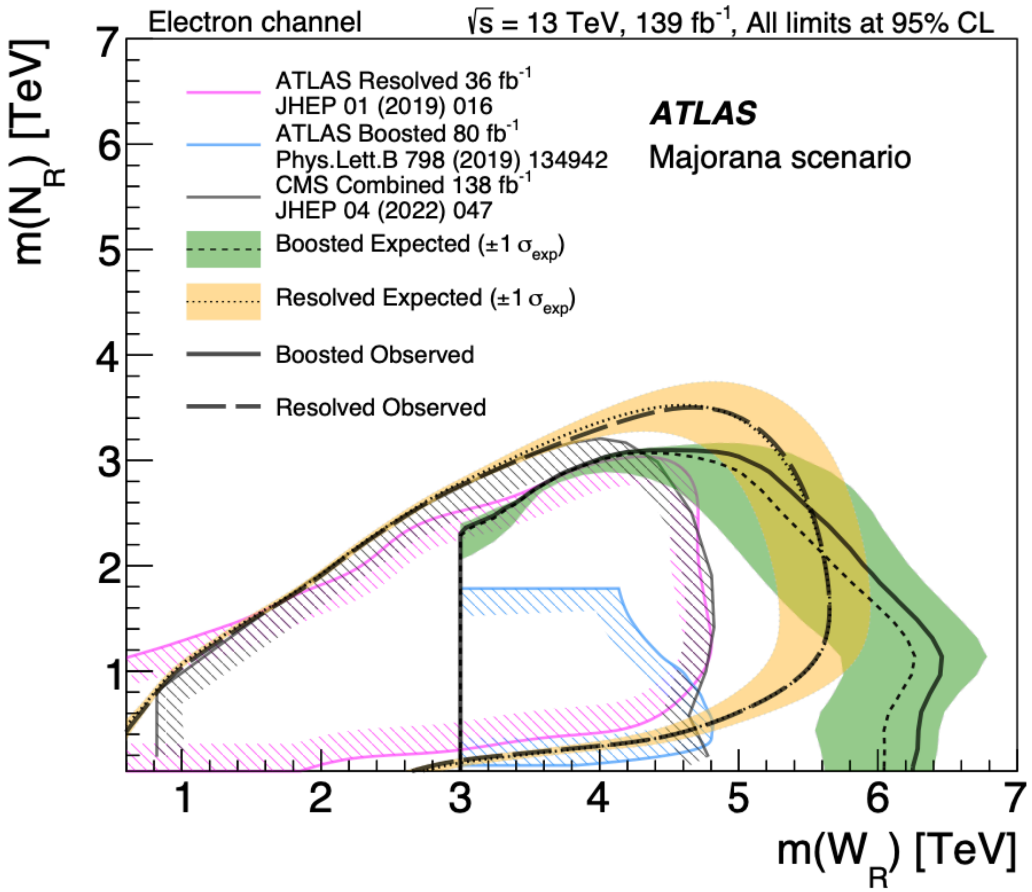
T. Asaka, et al. 2005, T. Asaka, et al. 2005

$$\mathcal{L} \supset \frac{1}{2}\sum_j \bar{N}_R^j i\partial\!\!\!/ N_R^j - \sum_{i,j} y_{ij} \bar{\ell}_L^i \widetilde{H} N_R^j - \frac{1}{2}\sum_j \bar{N}_R^{jc} M_N N_R^j + h.c. \ .$$

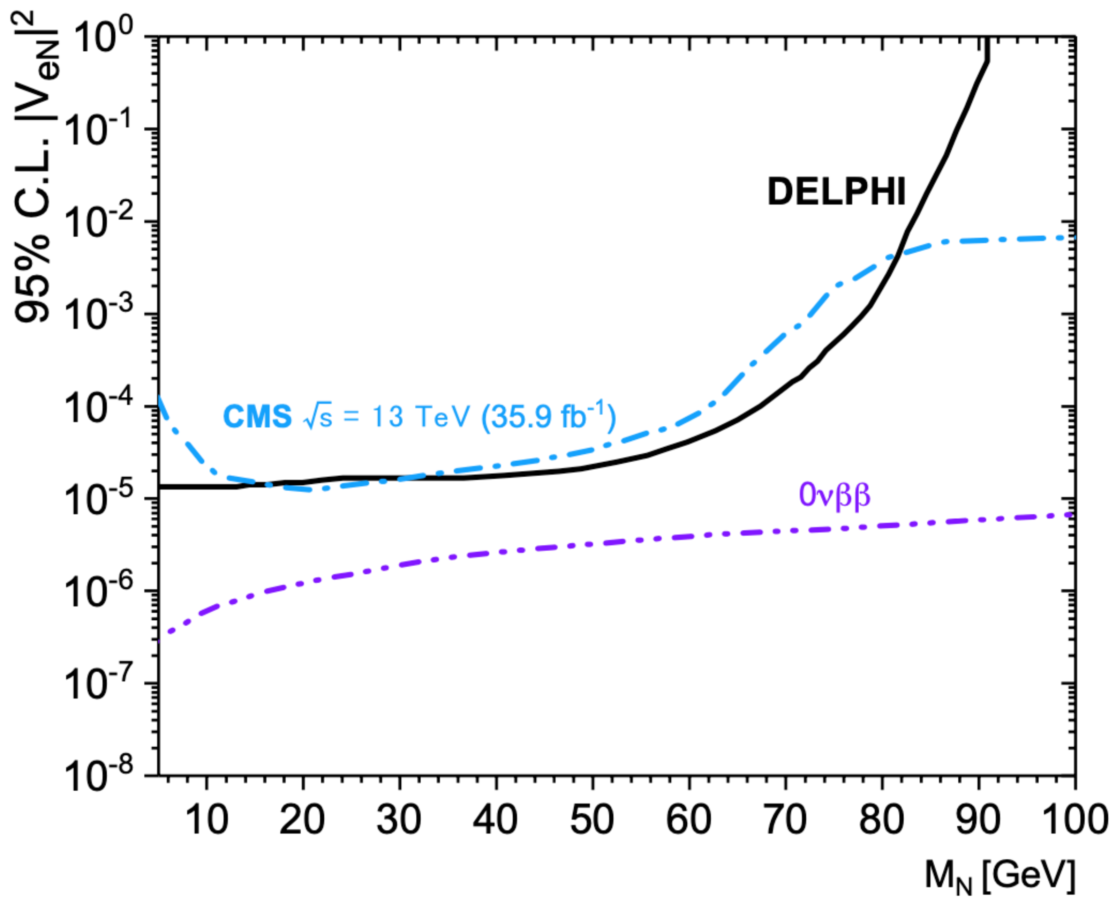
  - Yukawa couplings: $y_\nu \simeq y_e$ $\quad N_R: \ M_N \sim v$
  - Dark matter candidate: $2 \text{ keV} \lesssim M_I \lesssim 5 \text{ keV}$,
  - Matter anti-matter asymmetry in the universe

Examination on Heavy Neutrino

- Experimental examination on heavy neutrinos



ATLAS Collaboration, 2023



DEIPHI Collaboration, 1977,
CMS Collaboration, 2018,
S.R. Elliott et al., 2004…

- Future lepton colliders

  - Clean background
  - High statistic

→ **Searching for heavy neutrino**

Theoretical Scenario

- Weak interaction Lagrangian under the mass eigenstates :

$$\mathcal{L} \supset -\frac{g}{2\cos\theta_W} Z_\mu \sum_\ell \left(\sum_{i=1}^{3} \underline{U^*_{\ell i}} \bar{\nu}_i + \sum_{j=4}^{3+n} \underline{V^*_{\ell j}} \bar{N}_j \right) \gamma^\mu P_L \left(\sum_{i'=1}^{3} U_{\ell i'} \nu_{i'} + \sum_{j'=4}^{3+n} V_{\ell j'} N_{j'} \right)$$
$$- \left[\frac{g}{\sqrt{2}} W^+_\mu \sum_\ell \left(\sum_{i=1}^{3} U^*_{\ell i} \bar{\nu}_i \gamma^\mu P_L \ell + \sum_{j=4}^{3+n} V^*_{\ell j} \bar{N}_j \gamma^\mu P_L \ell \right) + h.c. \right].$$

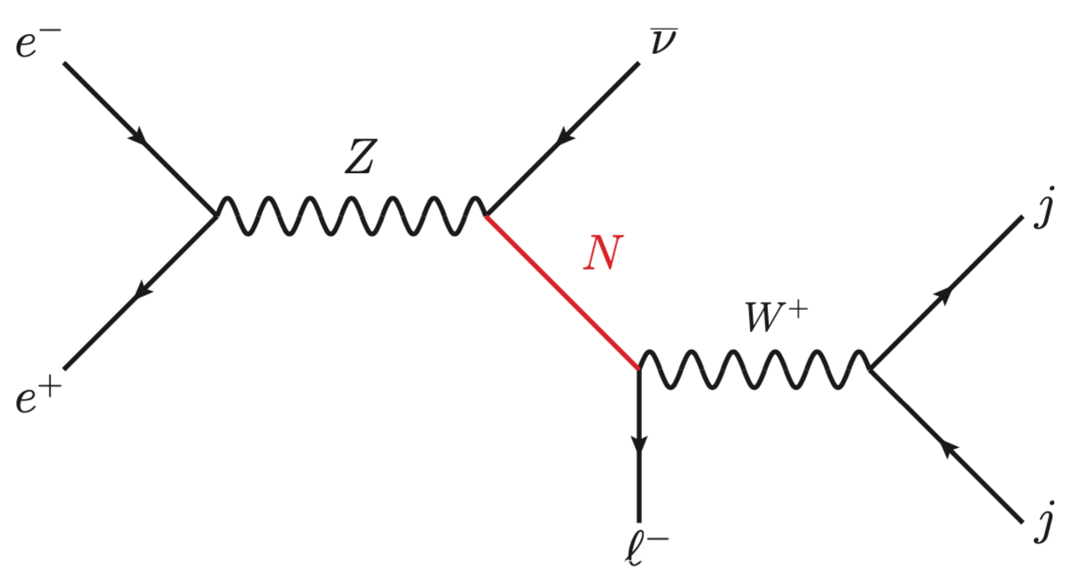
$U_{\ell i}$: PMNS matrix elements

$V_{\ell j}$: Mixing parameters

T. Asaka, et al. 2005, T. Asaka, et al. 2005

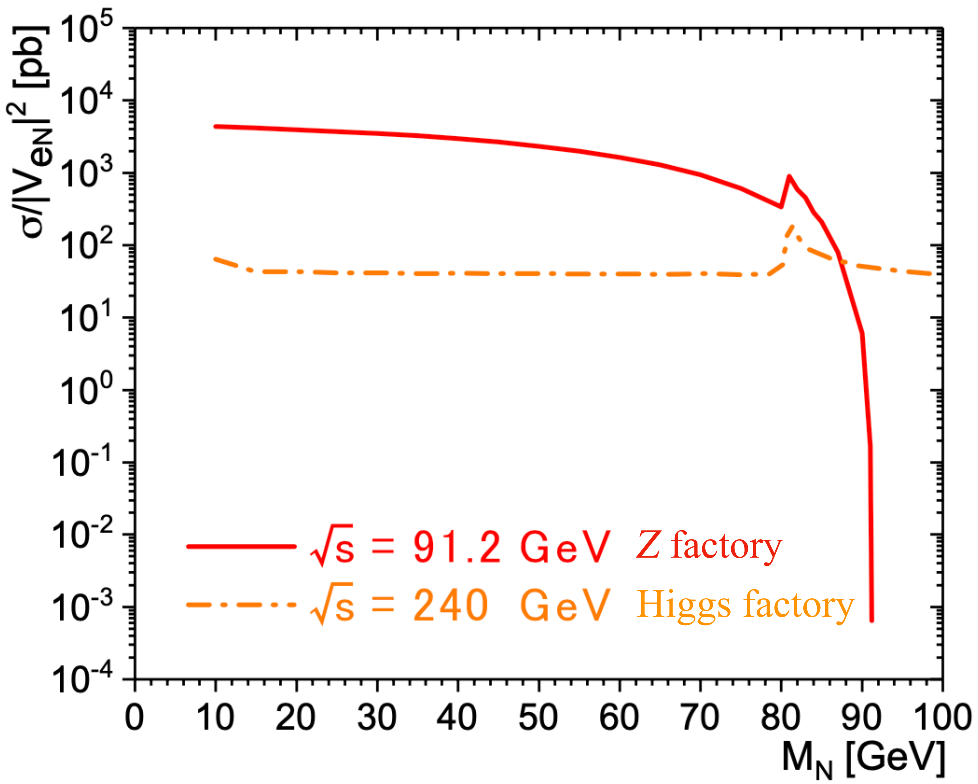
- $M_N < m_Z$: rare Z boson decay

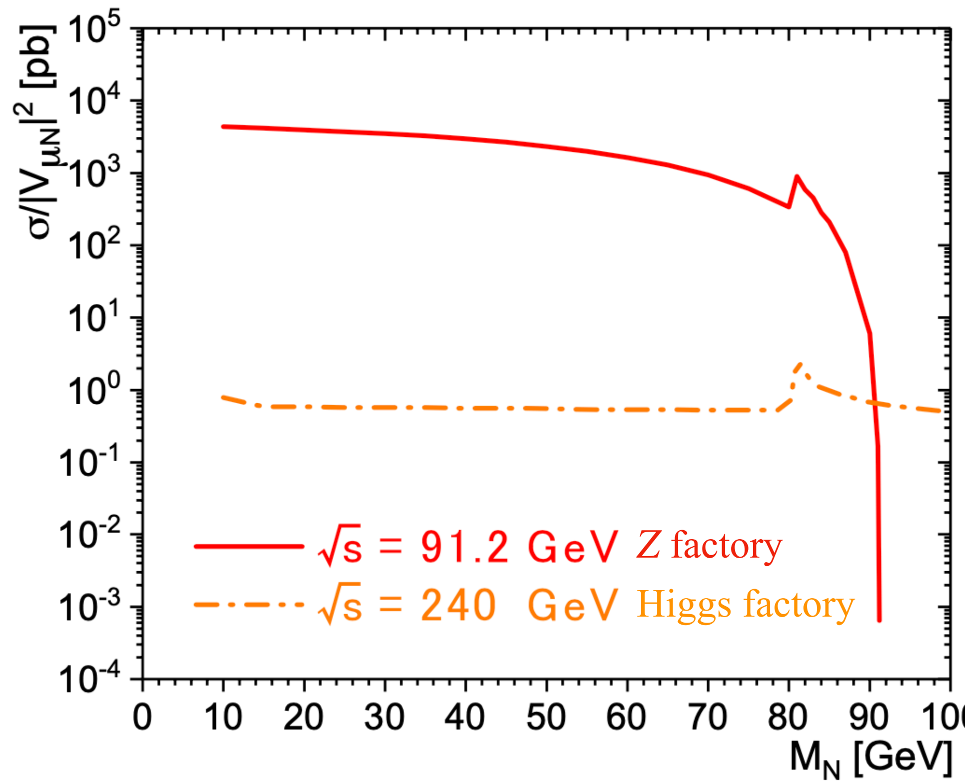
- Production channel of heavy neutrino at future lepton colliders:

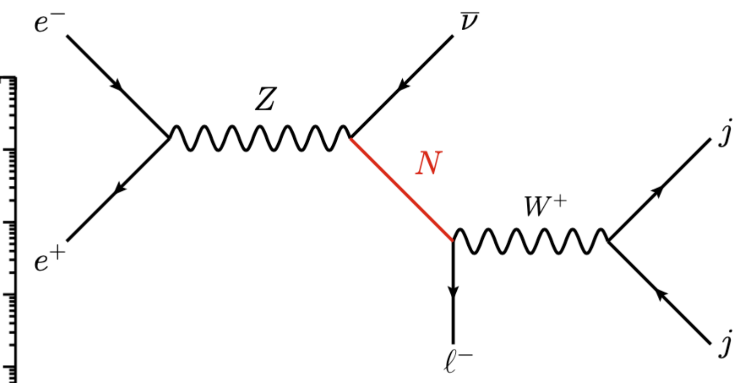


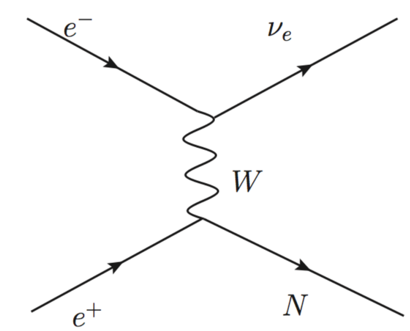
Production at Future Lepton Colliders

- Differential production cross section



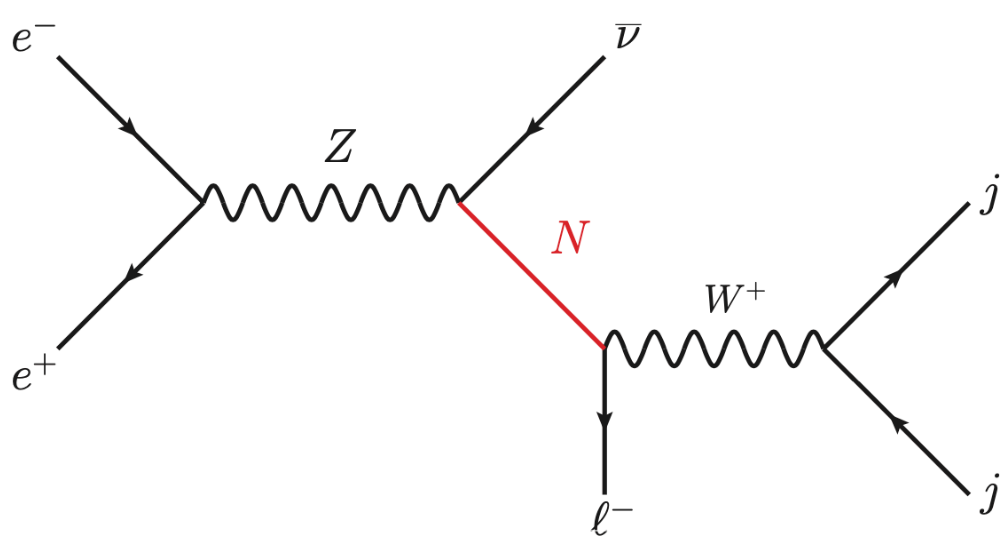






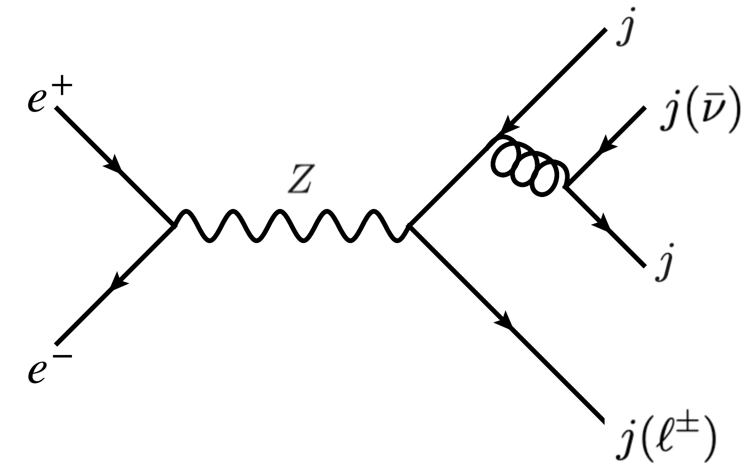
- The production of heavy neutrino on Z factory are much larger rather than that on Higgs factory;
- The small peaks appearing when N decay into on-shell W boson;
- For electron final state, t-channel production is dominant at Higgs factory.

- Signal channel

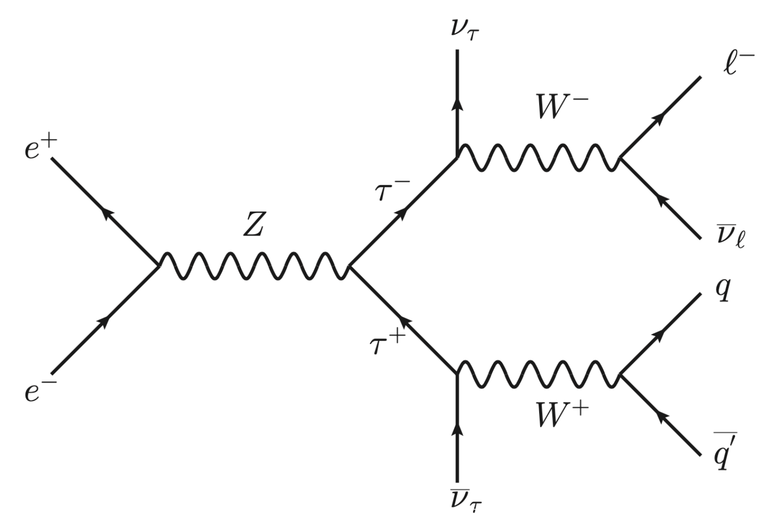


- SM background

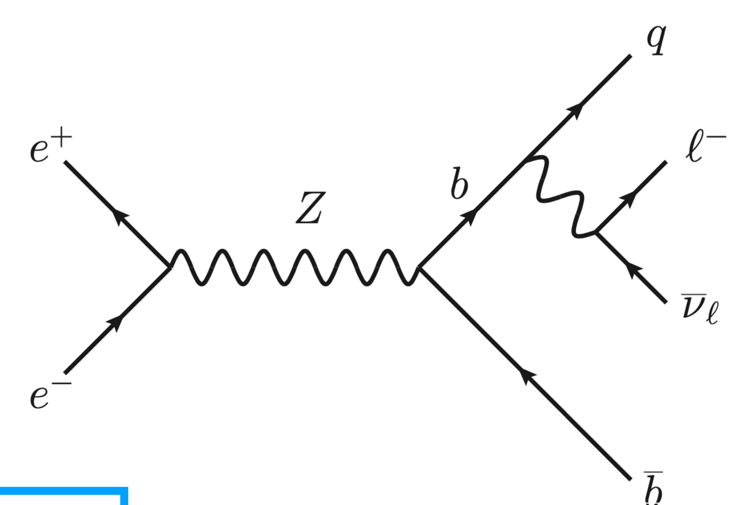
$4j$ channel



$\tau^+\tau^-$channel

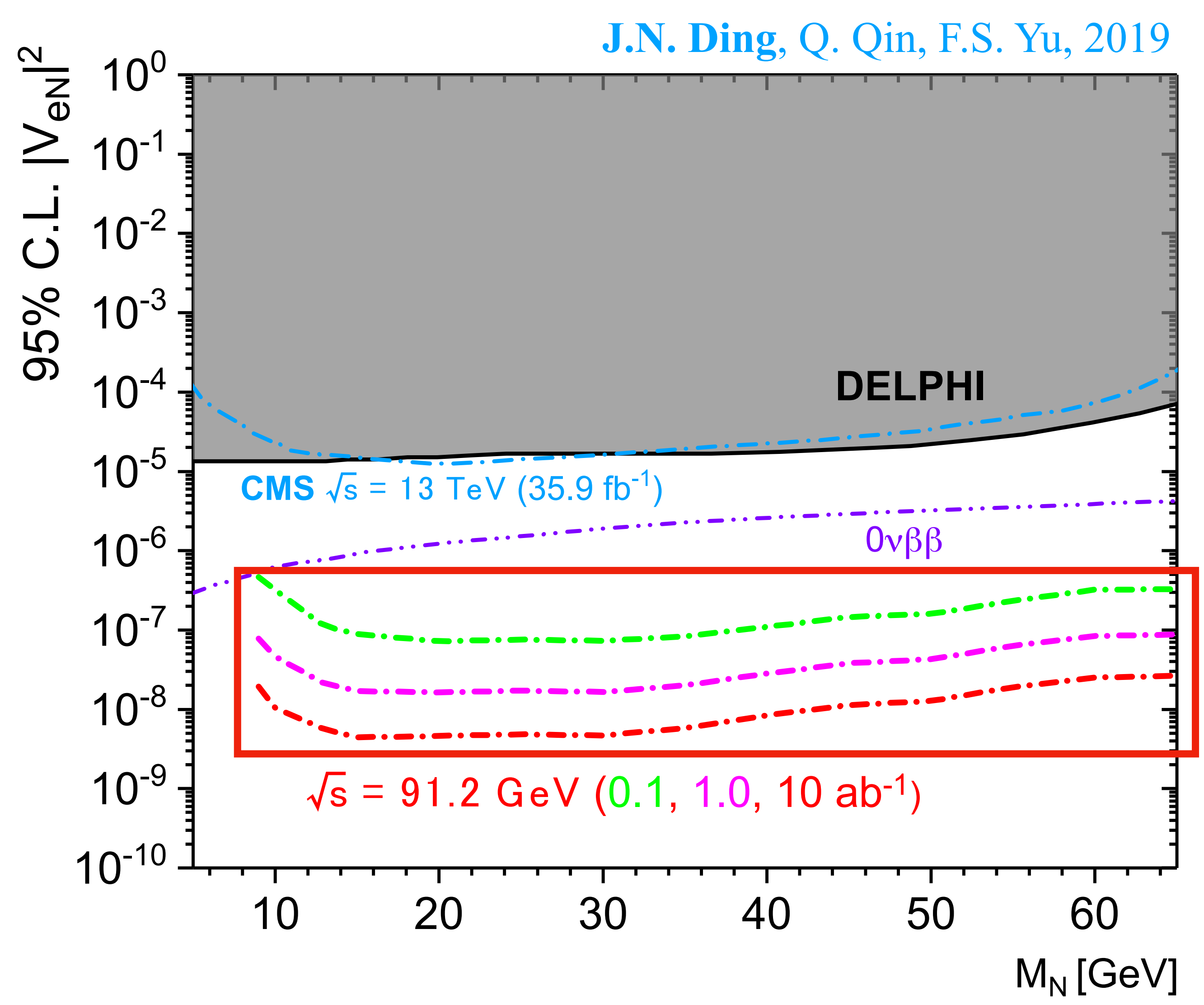


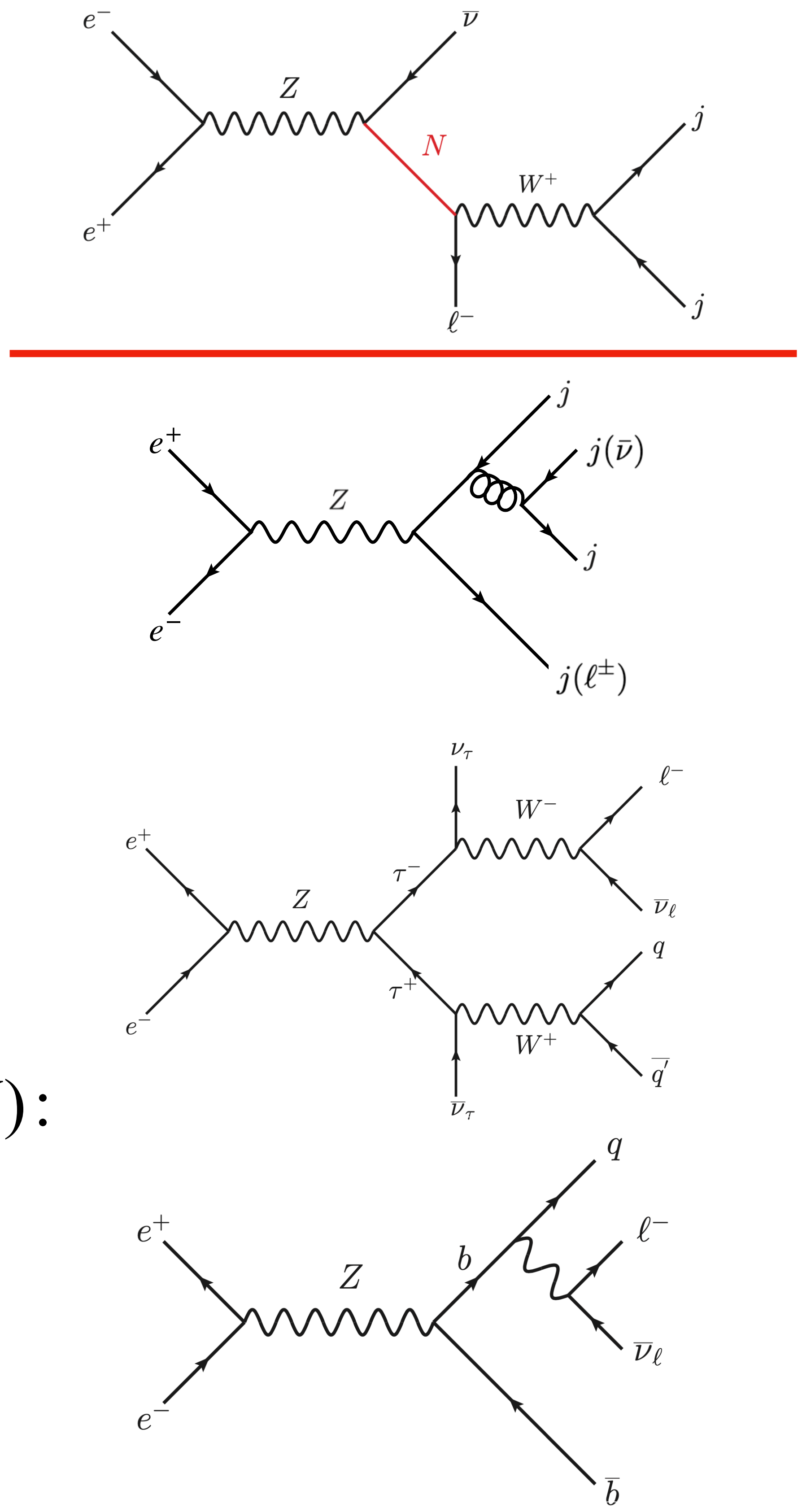
$b\bar{b}$ channel



$c\bar{c}$, $jj\ell\ell$ and $\ell\ell\ell\ell$ can be neglected

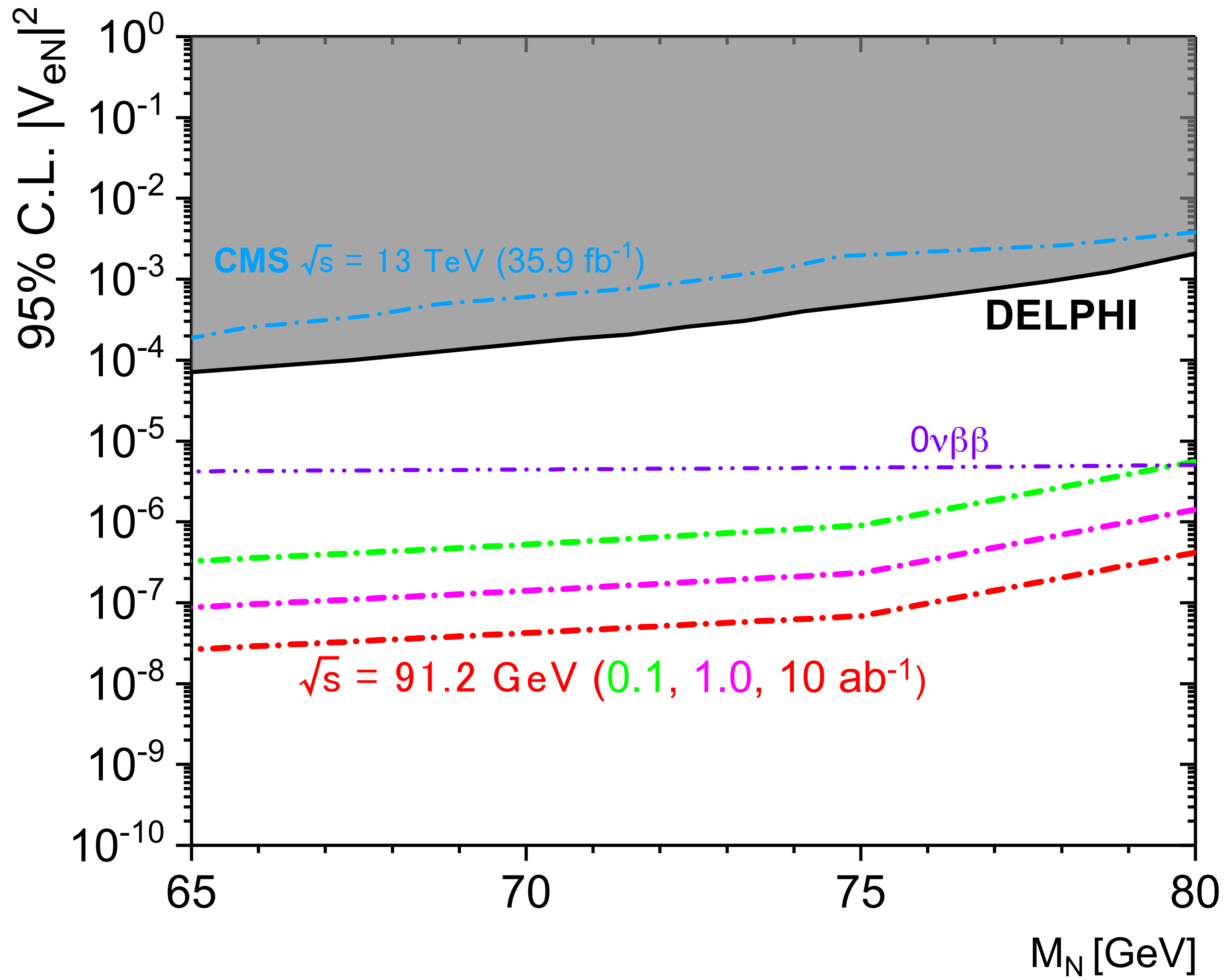
Search for Heavy Neutrino at Future Z Factory

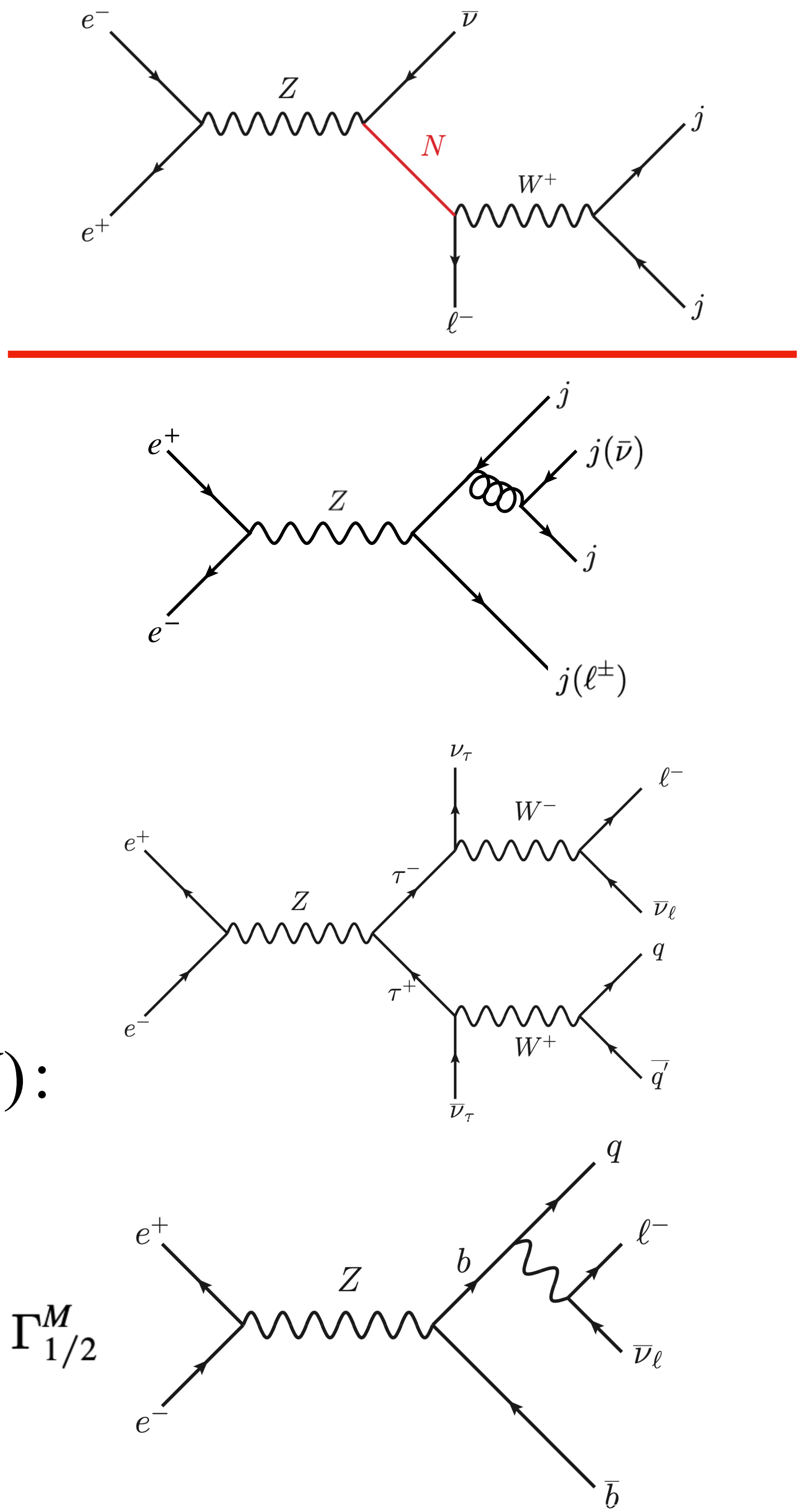




- Selection cut in small mass region ($10 < M_N < 65$ GeV):
  - $P_T^j > 5$ GeV, $|\eta_j| < 2$, $\Delta R_{jj} > 0.1$, btag < 0.8, TauTag, BTag
  - $P_T^\ell > 3$ GeV, $|\eta_\ell| < 1$
  - $\not{E}_T > 20$ GeV, $|E_{rec} - M_Z| < 10$ GeV, $|M_{\ell jj} - M_N| < \Gamma^M_{1/2}$
  - $1.0 < \Delta R_{\not{E}j} < 5.5$, $1.5 < \Delta R_{\not{E}\ell} < 5.0$

Search for Heavy Neutrino at Future Z Factory

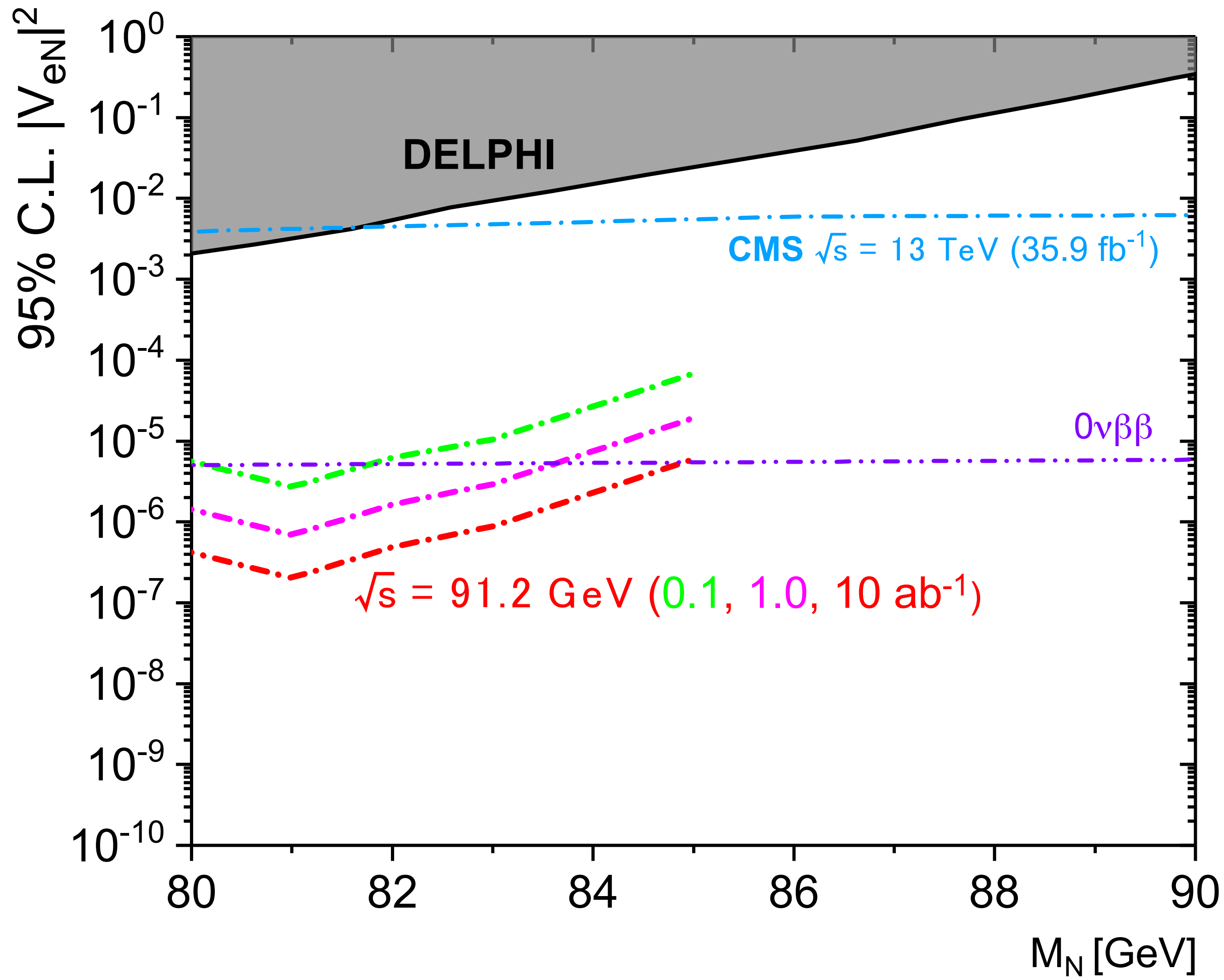


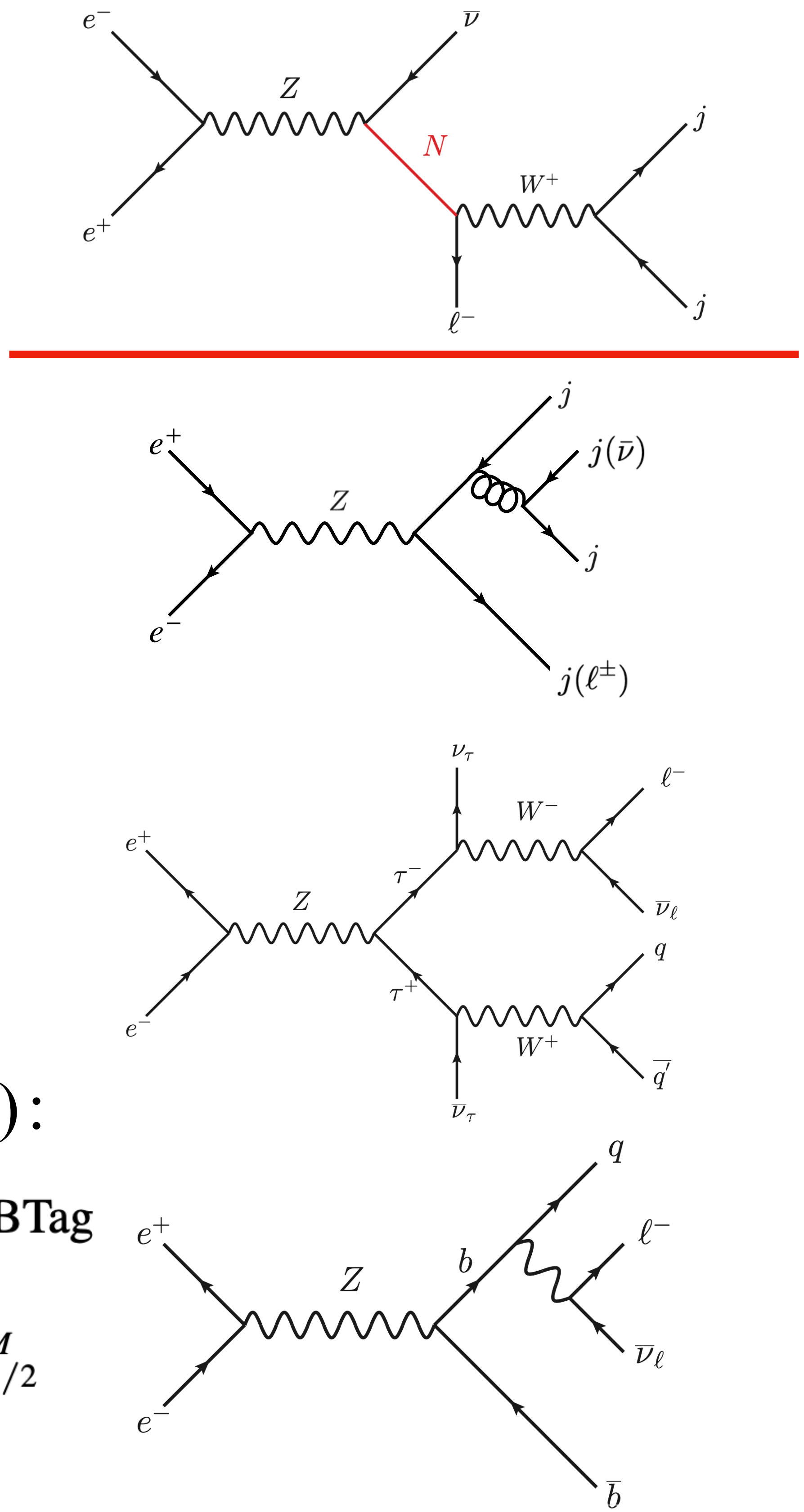


- Selection cut in middle mass region ($65 < M_N < 80$ GeV):
  - $P_T^j > 5$ GeV, $|\eta_j| < 2$, $\Delta R_{jj} > 0.4$, btag < 0.8, TauTag, BTag
  - $P_T^\ell > 3$ GeV, $|\eta_\ell| < 1$
  - $\not{E}_T > 10$ GeV, $|E_{rec} - M_Z| < 10$ GeV, $|\not{E} - \not{E}_0| < \Gamma_{1/2}^{\not{E}}$, $|M_{\ell jj} - M_N| < \Gamma_{1/2}^{M}$
  - $1.0 < \Delta R_{\not{E}j} < 5.5$, $1.5 < \Delta R_{\not{E}\ell} < 5.0$

$$\not{E} = E_\nu = \frac{m_Z^2 - M_N^2}{2m_Z}$$

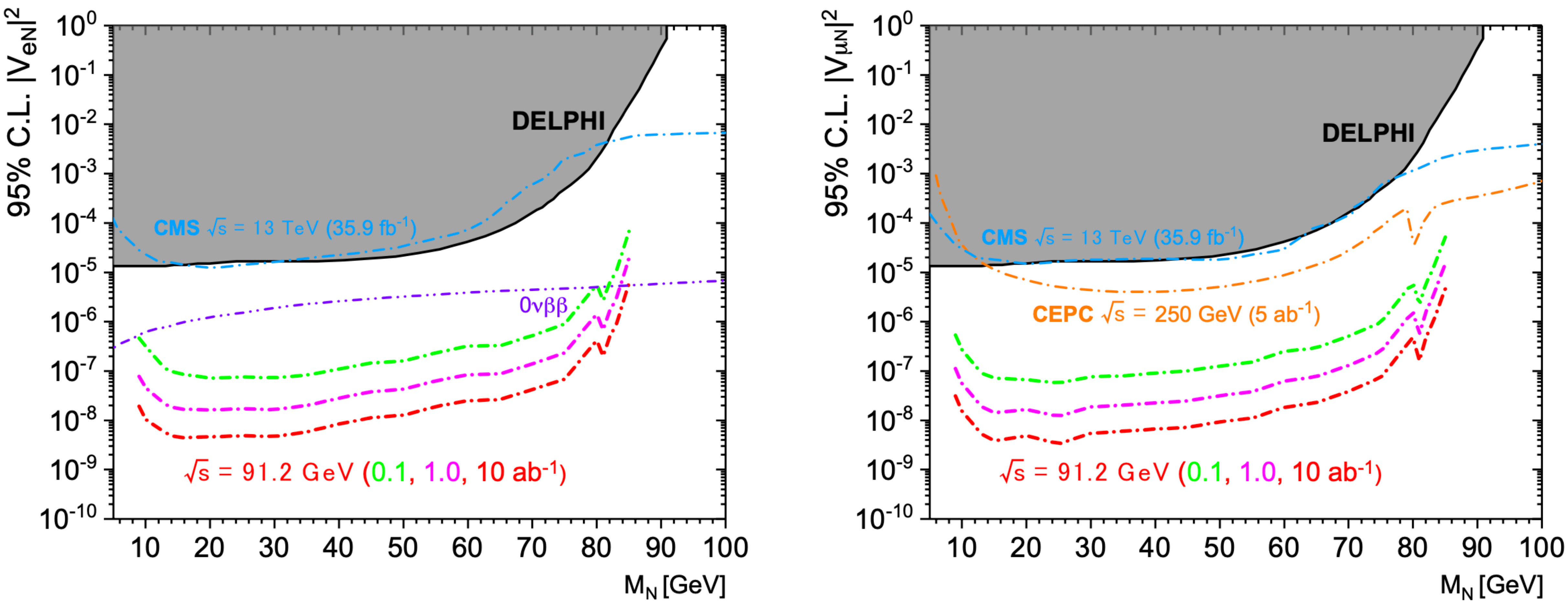
Search for Heavy Neutrino at Future Z Factory





- Selection cut in large mass region ($80 < M_N < 85$ GeV):
  - $P_T^j > 10$ GeV, $|\eta_j| < 2$, $\Delta R_{jj} > 0.4$, $M_{jj} > 55$ GeV, btag < 0.8, TauTag, BTag
  - $P_T^\ell > 3$ GeV, $|\eta_\ell| < 1$
  - $\not{E}_T > 5$ GeV, $|E_{rec} - M_Z| < 10$ GeV, $|\not{E} - \not{E}_0| < \Gamma^{\not{E}}_{1/2}$, $|M_{\ell jj} - M_N| < \Gamma^M_{1/2}$
  - $1.5 < \Delta R_{\not{E}j} < 5.5$, $1.5 < \Delta R_{\not{E}\ell} < 5.0$

Search for Heavy Neutrino at Future Z Factory

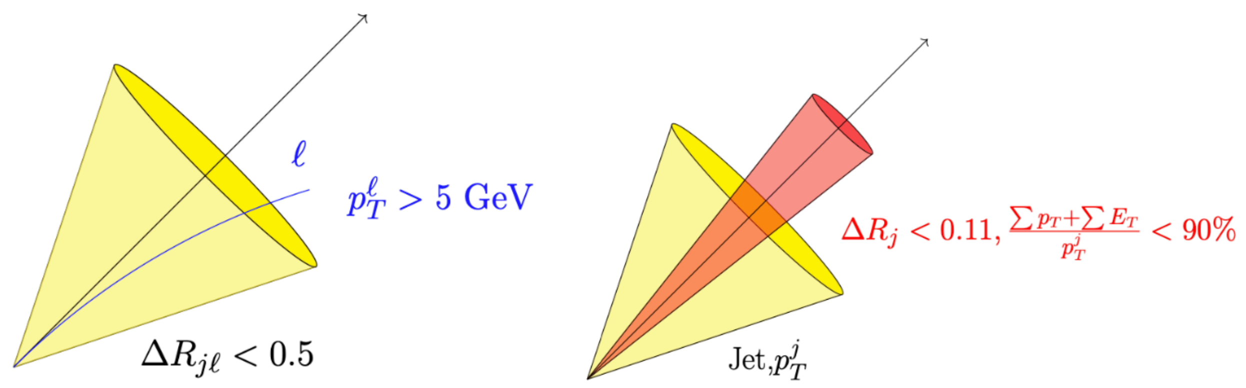


J.N. Ding, Q. Qin, F.S. Yu, 2019

- $|V_{\ell N}|^2$ can reach $\mathcal{O}(10^{-7})$ with 0.1 ab^{-1} at future Z factory;
- $|V_{eN}|^2$ is 1 order of magnitude lower than that in $0\nu2\beta$ decay at least;
- $|V_{\mu N}|^2$ is 2 orders of magnitude lower than that in Higgs factor ; W. Liao et al., 2017

Monojet with Substructure

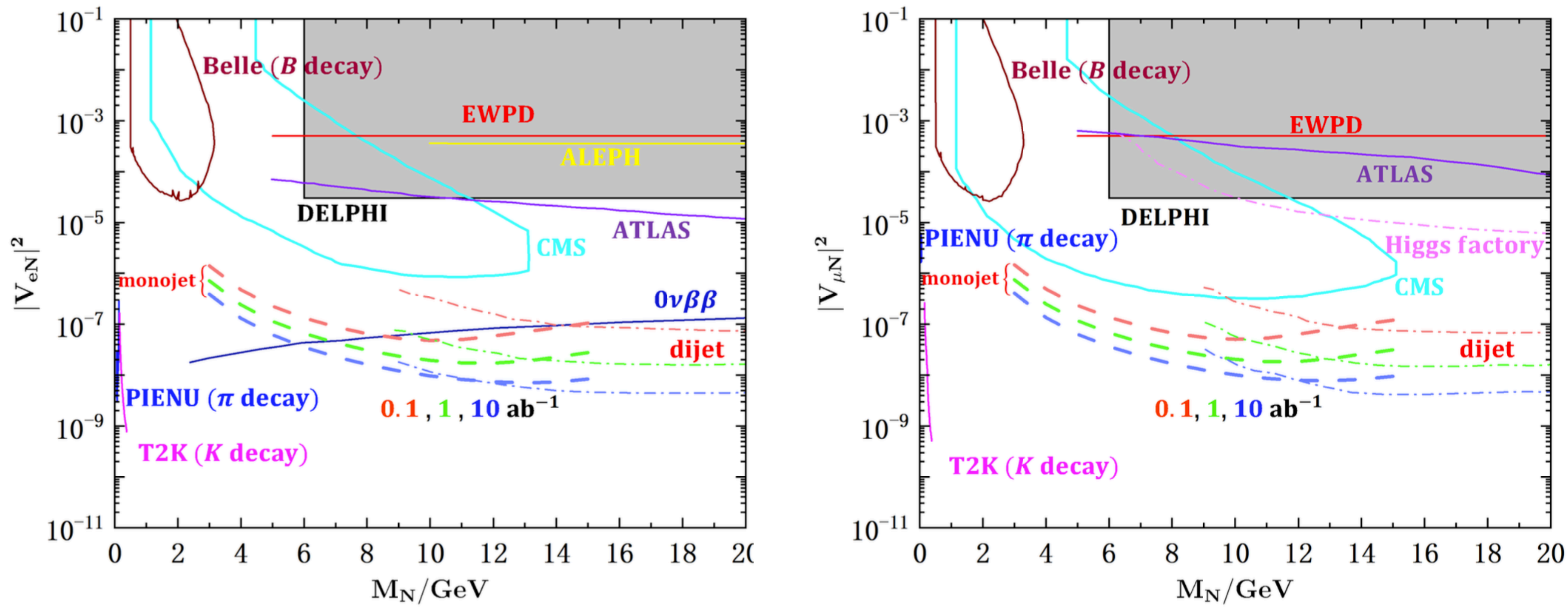
- Monojet signature of heavy neutrino：



Y.F. Shen, **J.N. Ding**, Q. Qin, 2022

	Selection condition	Bkg efficiency (cumulative) (%)	Signal efficiency (cumulative) (%)
Event type	Monojet	15.44695	78.45346
Missing energy	$\not{E}_T > 23\,\mathrm{GeV}$	0.62255	75.30132
	$40\text{ GeV} < \not{E} < 50\,\mathrm{GeV}$	0.03372	68.40370
Jet	$p_T^j > 23\,\mathrm{GeV}$	0.03337	67.81746
	$30\,\mathrm{GeV} < E_j < 50\,\mathrm{GeV}$	0.02902	67.10762
	TauTagging = 0	0.02423	67.02997
	$3 < \Delta R_{\not{E}j} < 4.1$	0.02194	66.82435
Substructure	$\ell = e\ and \Delta R_{j\ell} < 0.5\ and\ p_T^\ell > 5\,\mathrm{GeV}$	0.00053	52.20332
	$\Delta R_j < 0.11 : \frac{\sum p_T + \sum E_T}{p_T^j} < 90$	0.00050	48.54479
	$\Delta R_{\not{E}} < 2 : \sum p_T + \sum E_T < 0.3\,\mathrm{GeV}$	0.00046	48.50213
others	$\lvert E_{\text{cm-rec}} - E_{\text{cm}} \rvert < 20\,\mathrm{GeV}$	0.00046	48.50213

Monojet with Substructure



Y.F. Shen, **J.N. Ding**, Q. Qin, 2022

- Monojet with substructure can effectively cover the GeV heavy neutrino ;
- $|V_{\ell N}|^2$ can also reach $\mathcal{O}(10^{-7})$ when the heavy neutrino mass goes lighter;
- Future Z-factory measurement will improve the constraints from CMS measurement.

Summary

- CEPC might be an ideal platform to search for electroweak scale heavy neutrinos.
- For $\mathcal{O}(10)$ GeV heavy neutrinos, constraints on mixing parameters can reach $\mathcal{O}(10^{-7})$, which is 2 order of magnitude lower than that in current measurement.
- Jet with substructure is important to search for sterile neutrino.

Thanks for your attention !