# Heavy neutrino searches at future $Z$-factories

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# Outline

1. **Motivation**
2. **General setup of the scenario**
3. **Phenomenological analysis**
4. **Results and summary**

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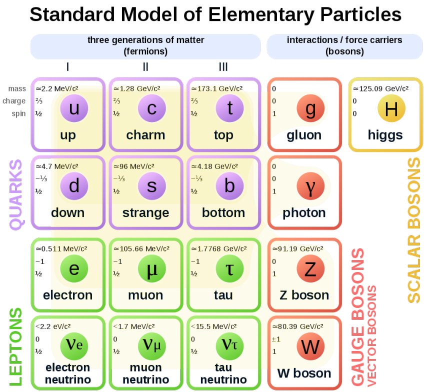
Complete yet incomplete:

## Complete

- No unknown particles in SM;
- Include 3 elementary interactions;
- Explain almost all experiment;

## Incomplete

- Hirerachy;
- Neutrino mass;
- Dark matter, dark energy;
- Matter anti-matter asymmetry;...



# Motivation

- Observables of neutrino oscillation:

  *☼ http://pdg.lbl.gov*

$$\sum m_\nu < 0.170 \, eV$$

$$|\Delta m_{31}^2|^{\frac{1}{2}} \cong 0.0506 \, eV$$

$$|\Delta m_{21}^2|^{\frac{1}{2}} \cong 0.0086 \, eV$$

- Introduce $SU(2)$ singlet right-handed neutrino $N_R$:

  *☼ Minkowski, 77; Mohapatra and Senjanovic, 80...*

  - Dirac ?

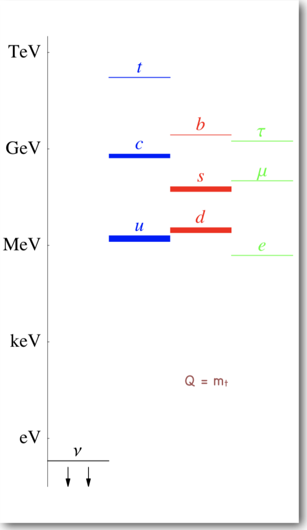
$$M_D = Y_\nu \frac{v}{\sqrt{2}} \tag{1}$$

  - Majorana ?

$$m_\nu \simeq M_D M_N^{-1} M_D^T \tag{2}$$

- It will give us hints about leptonic CP violation.

  *☼ Caputo et al., 17*

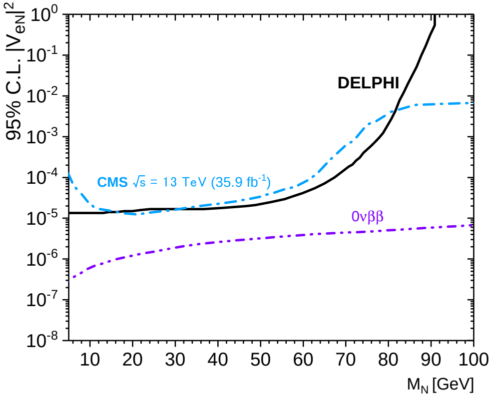



*☼ Andrea Romanino, Beyond the Standard Model, including Neutrinos.*

# Current constraints

Experiment constraints:

- CMS Collaboration: for $\mathcal{O}(10)$ GeV scale heavy neutrinos, $|V_{\ell N}|^2 \sim 10^{-5}$.
  ☼ *CMS, Sirunyan et al., 18*
- DELPHI Collaboration: for $\mathcal{O}(10)$ GeV scale heavy neutrinos, $|V_{\ell N}|^2 \sim 10^{-5}$.
  ☼ *DELPHI, Abreu et al., 97*
- Neutrinoless double $\beta$ decay: for $\mathcal{O}(10)$ GeV scale heavy neutrinos,$|V_{eN}|^2 \sim 10^{-6}$.
  ☼ *Elliott et al., 04; Benes et al., 05; Rodejohann, 11*



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# Scenario

- Originally, the mass of Majorana neutrinos in Type-I Seesaw mechanism can reach the scale of grand unified theories.

- Later, low-scale seesaw is also possible to explain the neutrino mass:
  ☼ *Asaka and Shaposhnikov, 05; Asaka, Blanchet and Shaposhnikov, 05*
  - one neutrino with mass at keV scale as a dark matter candidate;
  - other two at GeV to hundred GeV scale, which will be interesting in experiment;

- Generally, we can introduce $n$ right-handed $SU(2)_L \times U(1)_Y$ singlet neutrinos $R_j$ (j=1, ...$n$), and write down the Lagrangian:

$$\mathcal{L} \ni \frac{1}{2}\sum_j \overline{R}_j i\partial\!\!\!/ R_j - \sum_{i,j} y_{ij}\overline{L}_i \widetilde{H} R_j - \frac{1}{2}\sum_j \overline{R}^c_j M_R R_j + h.c. \,, \tag{3}$$

where $\widetilde{H} = i\tau_2 H^*$, the lepton $SU(2)_L$ doublet $L = (\nu_{\ell L}, \ell_L)^T$ with $\ell = e, \mu, \tau$ and $y_{ij}$ is Yukawa coupling of neutrinos.

# Scenario

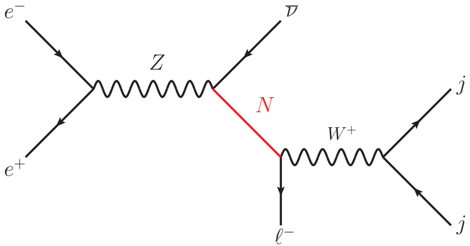
- After spontaneous symmetry breaking, we obtain $3+n$ mass eigenstates of neutrinos:
  - 3 light neutrinos $\nu_i$
  - $n$ heavy neutrinos $N_j$
- Now, a flavor eigenstate is a superposition of the mass eigenstates:

$$\nu_\ell = \sum_{i=1}^{3} U_{\ell i}\nu_i + \sum_{j=4}^{3+n} V_{\ell j}N_j \tag{4}$$

and thus the neutrino-relevant weak interaction terms are given by:

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

Future $Z$ factories will operate at $\sqrt{s} = M_Z$ with large integral luminosity.




Consider the narrow width approximation:

$$\sigma(e^+e^- \to \nu N \to \ell\nu jj) = \sigma(e^+e^- \to N\nu) \times Br(N \to \ell jj) \tag{5}$$

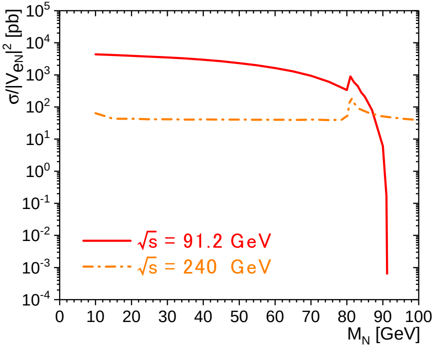
where:

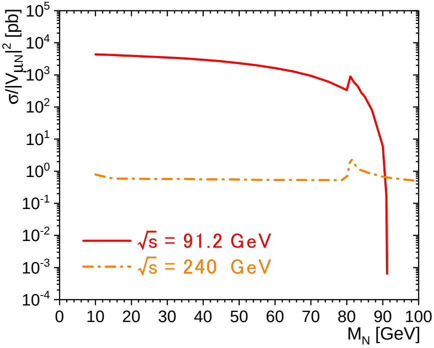
- $\sigma(e^+e^- \to N\nu) \propto \sum_{i=1}^{3} |(U^\dagger V)_{ij}|^2 \approx \sum_{\ell'} |V_{\ell' N}|^2$
- $Br(N \to \ell jj) \propto |V_{\ell N}|^2 / \sum_{\ell'} |V_{\ell' N}|^2$

we obtain the relation between cross section and mixing parameters:

$$\sigma(e^+e^- \to \nu N \to \ell\nu jj) \propto |V_{\ell N}|^2 \tag{6}$$

# $e^+e^- \to \nu N \to \nu \ell jj$




- $e^+e^- \to \nu N \to \nu \ell jj$, sum over all possible leptons and their antiparticles.
- For $M_N < M_Z$ , $\sigma/|V_{\ell N}|^2$ is about $10^3$ pb at $Z$-pole *vs* $10^2$ (1) pb at 240 GeV.
- The small peaks appearing when $N$ can decay into on-shell $W$ boson.
- For $\mathcal{O}(10)$ GeV scale, searching for heavy neutrinos at a $Z$-factory is obviously better than that at a Higgs factory.

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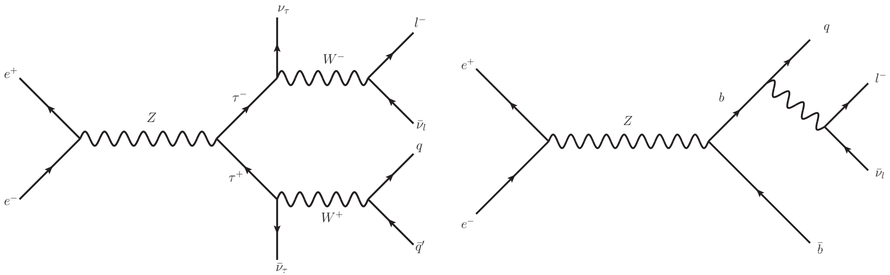
# Background analysis at future $Z$ factories

Main background comes from $e^+e^- \to jjjj$, $\tau^+\tau^-$ and $q\bar{q}$ production:

- For $jjjj$: with one jet is too soft or collinear to the beam and another jet is misidentified as an electron or muon.
- For $\tau\tau$: with one $\tau$ decaying to charged lepton while the other decaying to hadrons.
- For $q\bar{q}$: $e^+e^- \to b\bar{b} \to \ell jj\not{E}$ will be dominant. The lepton decayed from c-quark will be hidden in jets due to the large boost of c-quark.



# Background analysis at future $Z$ factories

- Simulation:
  - FeynRules: generate MG simulation model;
  - MadGraph: generator for signal and background;
  - Pythia8: parton shower and hadronization;
  - Delphes: fast jet simulation, using *eekt-exclusive* jet algorithm;
- Also, we divide the mass range into 3 areas:
  - small-mass: $10 < M_N < 65$ GeV;
  - middle-mass: $65 < M_N < 80$ GeV;
  - large-mass: $80 < M_N < 85$ GeV;
- Observables:

$$E_\nu = \frac{M_Z^2 - M_N^2}{2M_Z}$$

$$E_{rec} = \not{E} + \Sigma_i E_i, \quad \not{E} = |\Sigma_i \mathbf{p}_i|$$

# Selection cuts

For small-mass range ($10 < M_N < 65$ 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, $|M_{\ell jj} - M_N| < \Gamma^M_{1/2}$
- $1.0 < \Delta R_{\not{E}j} < 5.5$, $1.5 < \Delta R_{\not{E}\ell} < 5.0$

For middle-mass range ($65 < M_N < 80$ 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, $|\not{E} - \not{E}_0| < \Gamma^{\not{E}}_{1/2}$, $|M_{\ell jj} - M_N| < \Gamma^M_{1/2}$
- $1.0 < \Delta R_{\not{E}j} < 5.5$, $1.5 < \Delta R_{\not{E}\ell} < 5.0$

For large-mass range ($80 < M_N < 85$ 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, $|\not{E} - \not{E}_0| < \Gamma^{\not{E}}_{1/2}$, $|M_{\ell jj} - M_N| < \Gamma^M_{1/2}$
- $1.5 < \Delta R_{\not{E}j} < 5.5$, $1.5 < \Delta R_{\not{E}\ell} < 5.0$

# Significance

- After the event selection:
  - the $jjjj$ events dominate the background for all the three $M_N$ ranges;
  - $b\bar{b}$ and $\tau\tau$ contributions to the background are considerable;
  - the other contributions like $c\bar{c}$, $jj\ell\ell$ and $\ell\ell\ell\ell$ are negligible;

- Define significance $s$ as:

$$s = \frac{N_S}{\sqrt{N_B + N_S}} = \frac{N_{s0} \times (\sigma/\sigma_0)}{\sqrt{N_{B0} + N_{s0} \times (\sigma/\sigma_0)}} \sqrt{\frac{\mathcal{L}}{\mathcal{L}_0}} \tag{7}$$

  where $\sigma_0$ and $\mathcal{L}_0$ mean the reference setup of a specific cross section and luminosity.

- We estimate the expected upper bounds on the signal cross sections $\sigma(e^+e^- \to \nu N \to \nu\ell jj)$ at 95% confidence level (CL) with $s \approx 1.7$.

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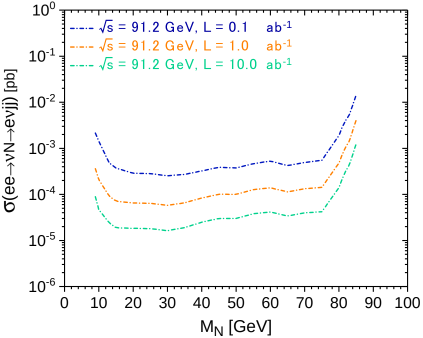
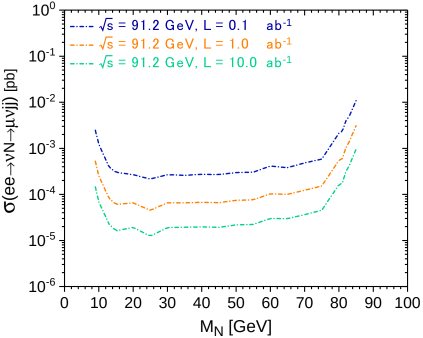
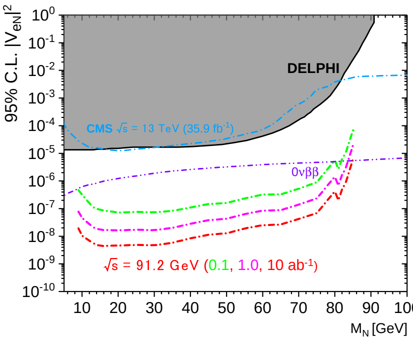
# Sensitivity of cross section at future Z factories

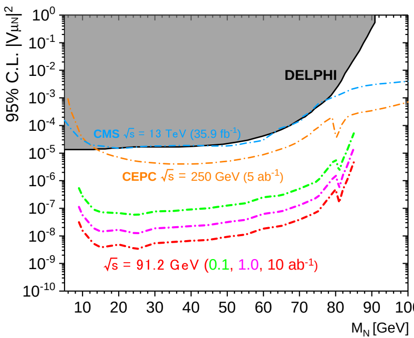



- The upper bounds on $\sigma(e^+e^- \to \nu N \to \nu e jj)$ and $\sigma(e^+e^- \to \nu N \to \nu \mu jj)$ at 95% CL given by future $Z$-factories have been shown;
- For the most of mass range, the upper bounds on the production cross section are around a few $10^{-4}$ pb to $10^{-5}$ pb in both the electron and muon cases;

# Mixing parameters at future Z factories




- $|V_{\ell N}|^2$ can reach $\mathcal{O}(10^{-7})$ with 0.1 ab$^{-1}$ at future Z factories;
- $|V_{eN}|^2$ is at least 1 order of magnitude lower than that of $0\nu 2\beta$ decay at least;
- $|V_{\mu N}|^2$ is at least 2 orders of magnitude lower than that given by Higgs factory;

## Summary

**1. We study the sensitivity of future Z factories in a low scale seesaw scenario with heavy neutrino mass among $\mathcal{O}(10)$ GeV.**

**2. Sensitivity of production cross section $\sigma(e^+e^- \to \nu N \to \nu \ell jj)$ is $\mathcal{O}(10^{-4})$ pb.**

**3. Mixing parameters $|V_{\ell N}|^2$ can reach $\mathcal{O}(10^{-8})$ at future Z factory with 10 ab$^{-1}$, which is $3$ orders of magnitude lower than that of DELPHI or CMS, and $2$ orders of magnitude lower than that of $0\nu 2\beta$ decay.**

**4. $M_N$ below Z mass: Z pole run is more sensitive!**
**$M_N$ above Z mass: high energy run win!**

*Thanks for your attention!*