Potential Heavy Neutral Lepton Searches at Lepton-Lepton Colliders

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* - one of authors of CompHEP generator, which is used in this analysis

Theoretical model

Seesaw Type I model

Generator CompHEP, Seesaw type I model with unitarity is included as proposed in arXiv: 1101.1382 (Takehiko Asaka, Shintaro Eijima, Hiroyuki Ishida, JHEP 1104:011,2011).

Model: 3 Heavy Neutral Leptons (Majorana), N1, N2, N3.
For simplicity we assume in calculations only one HNL, N with mass ≥ 100 GeV.

It can be realized in models with very large masses of N2 and N3.
Or it can be due to very small mixing for "smallest" mass HNL, that could be resulted from specific *CP*-violating phases in the PMNS matrix (arXiv:1508.04937) .

To compare our results with recent analysis based on the $e^+e^- \to N\nu$ process (arXiv:2202.06703), we also assume:

$$|V_{eN}|^2 = |V_{\mu N}|^2 = |V_{\tau N}|^2 = |V_{\ell N}|^2 = 0.0003$$

Final limits on $|V_{\ell N}|^2$ will not depend on these assumed mixing parameters.

Kinematic effect of NHL width can be neglected in these calculations.

Studied process

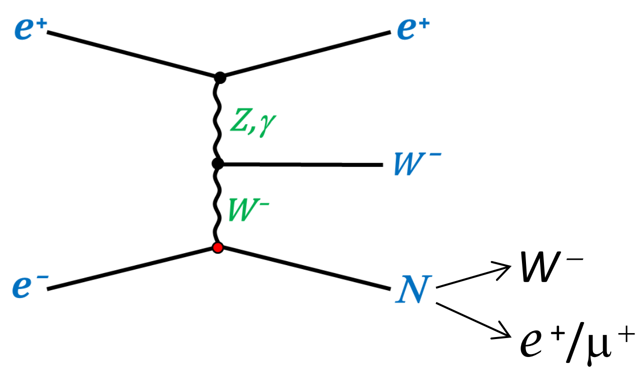
We investigate the processes with lepton number violation by 2 units (Majorana N):

$$e^+e^- \to N W^- e^+ \to W^- W^- e^+ e^+ (/\mu^+)$$

$$\mu^+\mu^- \to N W^- \mu^+ \to W^- W^- \mu^+ \mu^+ (/e^+)$$

$$e^- e^- \to N W^- e^- \to W^- W^- e^+ e^- (/\mu^-)$$

$$\mu^+\mu^+ \to N W^+ \mu^+ \to W^+ W^+ \mu^+ \mu^- (/e^-)$$



Cross sections of these processes are enhanced by infrared effect.

There are 30 diagrams which are included in CompHEP calculations (backup slides).

Diagrams with virtual NHL exchange are strongly suppressed. Cross sections are proportional to $|V_{\ell N}|^2$ in a very good approximation. NHL width can be neglected.

$$\sigma\,(\mu^+\mu^+ \to N W^+ \mu^+) = 2 \times \sigma\,(\mu^+\mu^- \to N W^- \mu^+)$$

It is possible to make the same analysis with the same-sign beams.

Known information about this process

arXiv: 1503.05491

FeynRules2.0 and MadGraph5

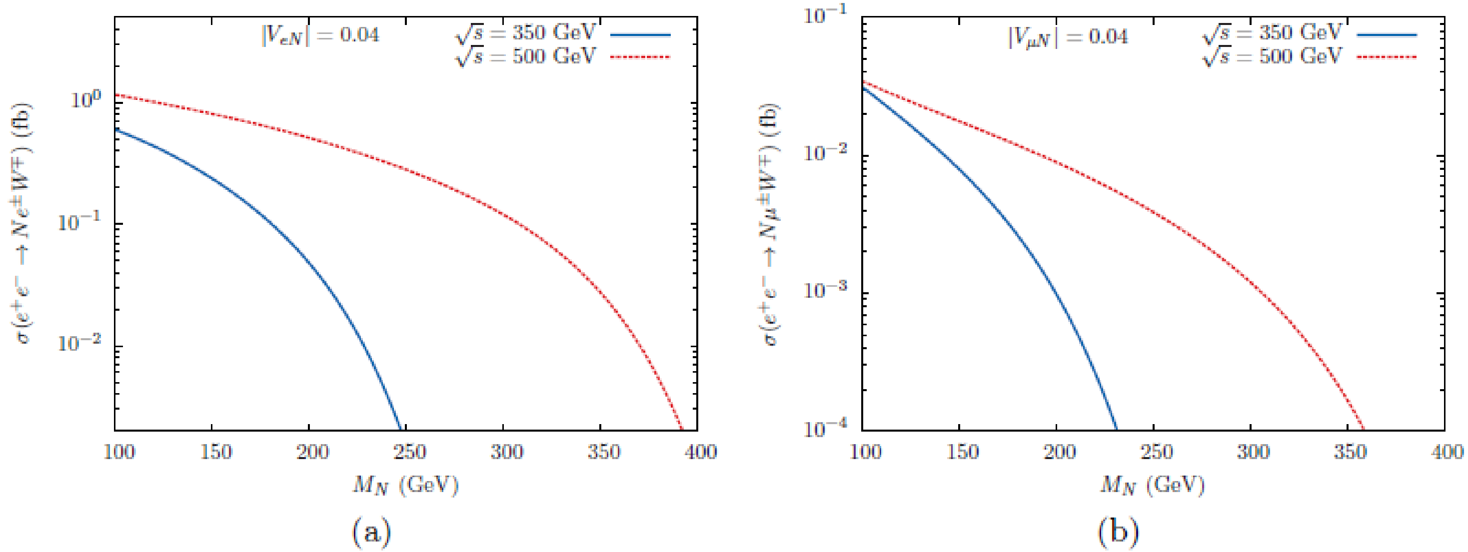
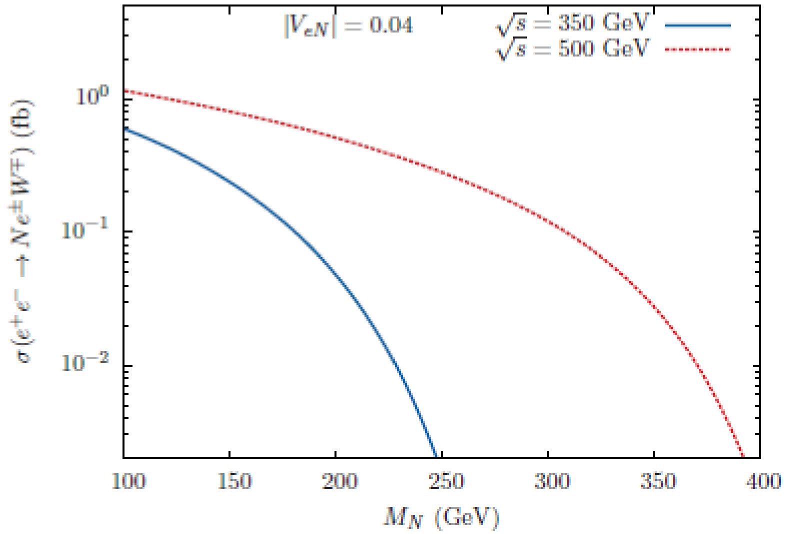


FIG. 5. Heavy neutrino production cross section for the channel $e^+e^- \to N\ell^\pm W^\mp$ for $\sqrt{s} = 350$ and 500 GeV, and with $|V_{\ell N}| = 0.04$. The left panel is for mixing with electrons, whereas the right panel is for mixing with muon and tau sectors.

For the electron sector, there is a dominant contribution from the t-channel photon diagrams [cf. Figure 4 (b)], thus leading to an infrared enhancement effect.[5] This enhancement effect is absent in muon and tau sectors for an e^+e^- collider. The total production cross section for this process is given in Figure 5.

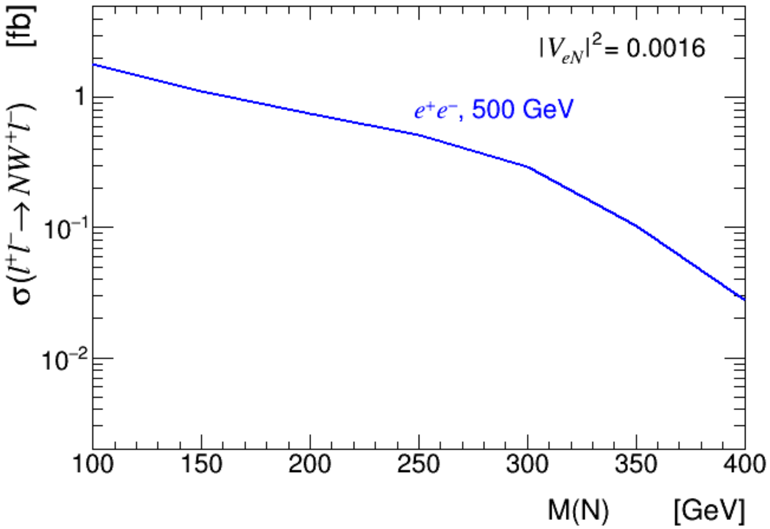
Known information about this process

arXiv: 1503.05491



FeynRules2.0 and MadGraph5

This study



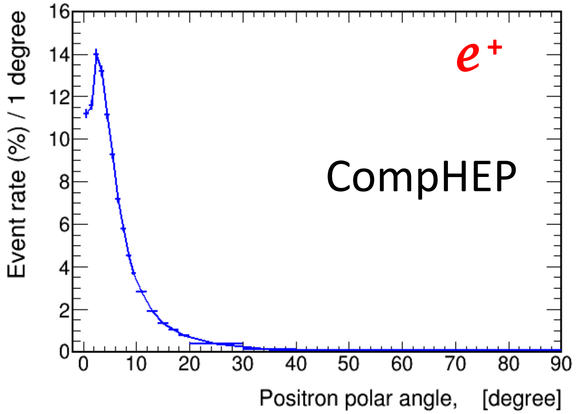
CompHEP with unitarity

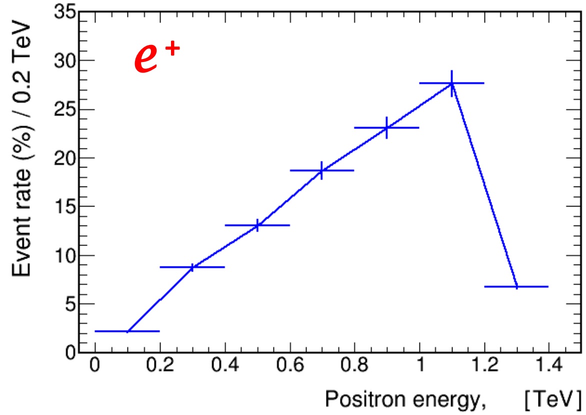
We get somewhat larger values, specially in the large M(N) region.
Possibly we have slightly different parameters in generators.

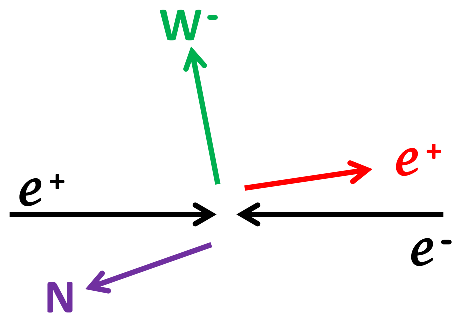
CompHEP contains unitarity cancellations, six Majorana neutrinos.
MadGraph sets up (as we understood), that active neutrinos are Dirac.

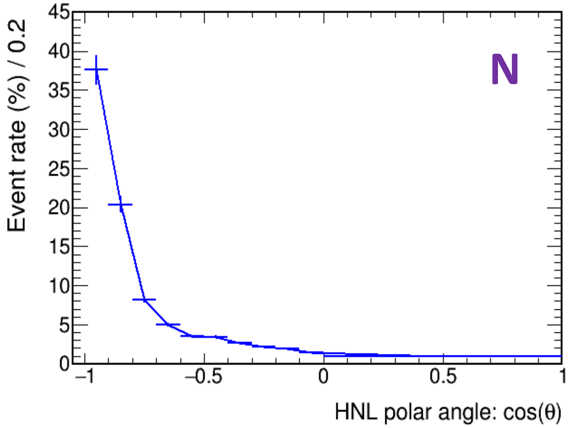
In arXiv:1503.05491 all 4 final state $W^-W^-e^+e^+$ particles were required to be detected, resulting in a very low efficiency of a few % (It is not a good idea).

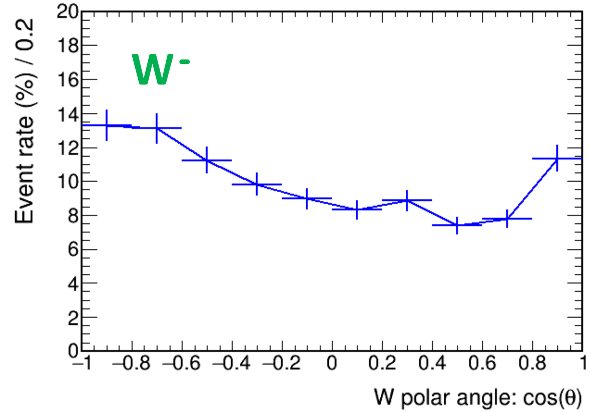
Event kinematics ($\sqrt{s}$ = 3 TeV, M(N) = 1 TeV)

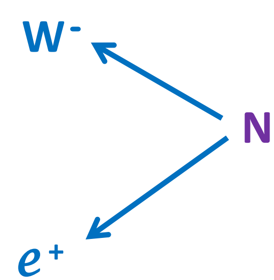










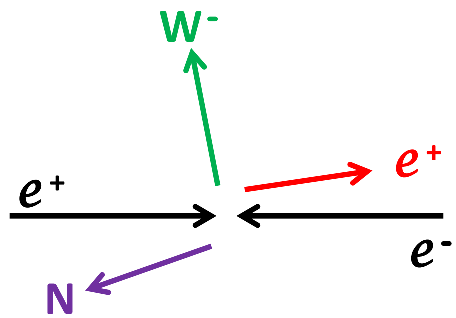


Positron is going in beam pipe in most part of events, we cannot detect this positron.

Other particles (W^-,W^-,e^+) can be reconstructed with a high acceptance (~50%).

Selections

Process $e^+e^- \to N W^- e^+ \to W^- W^- e^+ e^+$



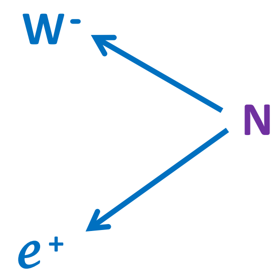
Initial positron goes to beampipe.

Reconstruction of $W^- W^- e^+$ system :

M_{miss} $(W^- W^- e^+) < 80 \times \frac{\sqrt{s}}{1000}$ GeV

P_{miss} $(W^- W^- e^+) > 400$ GeV

$\cos(\vec{P}_{miss} \wedge \vec{e^+}_{beam}) < 15°$



q_{miss} – define charge of missed lepton using $\vec{P}_{miss}$

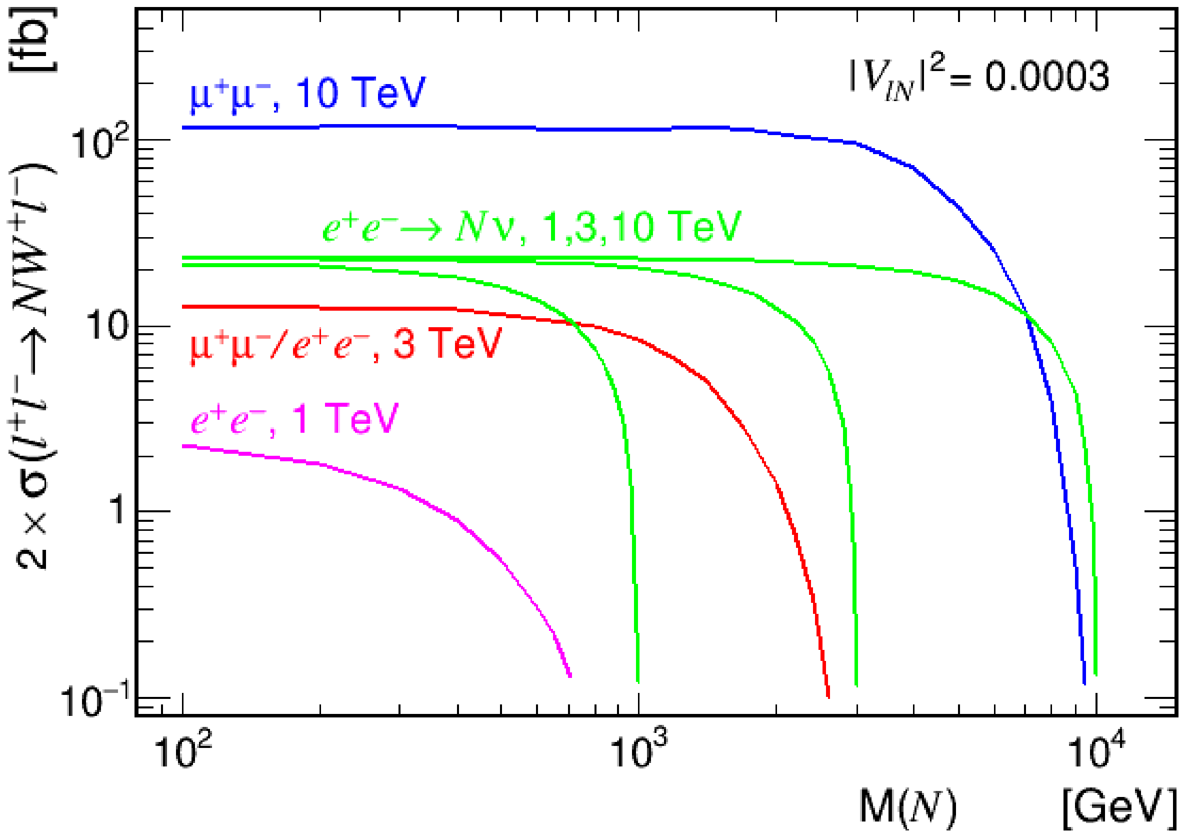
Tag isolated lepton (e^+, μ^+) with same lepton charge as q_{miss}

$\cos(e^+_{rec} \wedge e^+_{beam}) > 90°$ - to remove signal imitations from $W(\ell\nu)$ or $Z(\ell\ell)$

After all cuts we can test $M(W^- e^+)$ to search for resonance structure.

To be done: obtain reconstruction efficiencies using **Delphes** detector simulation.

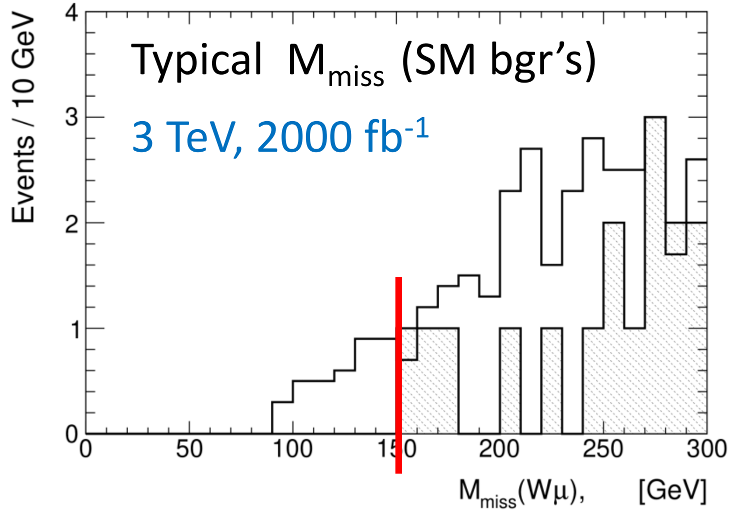
Cross sections (CompHEP)



Cross sections for processes $e^+e^- \to NW^-e^+$ and $\mu^+\mu^- \to NW^-\mu^+$ are shown as a function of M(N) for $|V_{\ell N}|^2 = 0.0003$. For comparison reason cross sections for processes $e^+e^- \to N\nu$ are given in green. Large cross sections at 3 TeV and 10 TeV. Backgrounds to $\mu^+\mu^- \to NW^-\mu^+$ process are expected to be small (?).

Backgrounds

Cut on M_{miss} will remove most of backgrounds with 2 or more lost particles.



Potential background sources:

$e^+e^- \to W^- Z \nu_e e^+, \; e^+e^- \to W^- \nu_e e^+$

Cuts on lepton charge and lepton angle will remove most of boson fusion backgrounds.

One of possibly dangerous backgrounds $e^+e^- \to W^+W^-Z$ - cut by lepton angle.

Generally, we do not expect large potential backgrounds for this event configuration.

We assumed Majorana neutrino, in case of Dirac neutrino backgrounds will be larger.

In case of same sign beams: backgrounds will be very small.

Evgeny works now to test dangerous backgrounds.

Conclusions

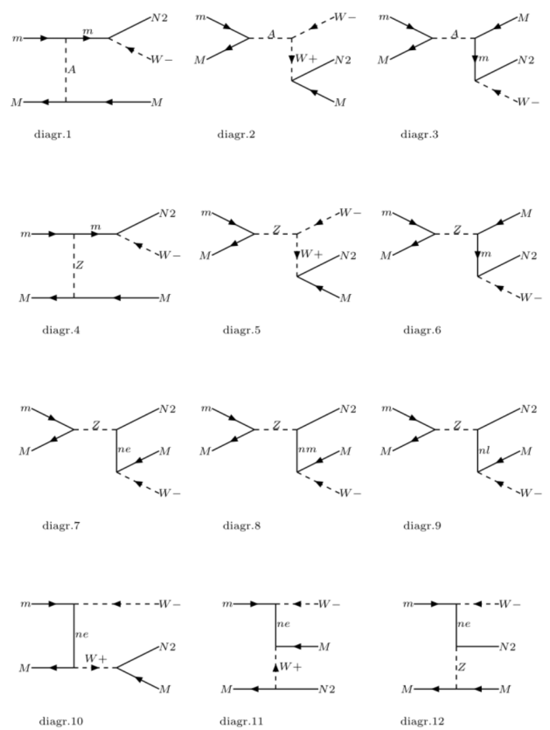
- Process $e^+e^- \to NW^-e^+$ $(N \to W^-e^+)$ and similar ones have very clean signature, when initial lepton goes to beam pipe and not detected. This process can be selected and separated from backgrounds with high efficiency.

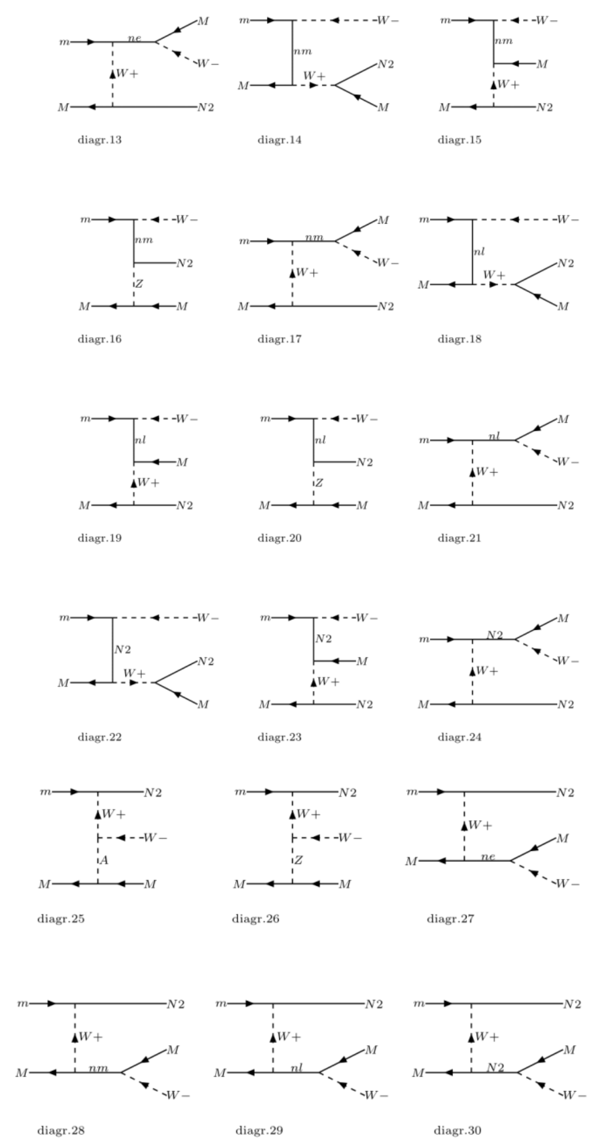
- Process $e^+e^- \to NW^-e^+$ $(N \to W^-e^+)$ has large cross section within Seesaw Type I model with Majorana neutrino. Due to low background this process can provide similar sensitivity to HNL mixing parameter $|V_{\ell N}|^2$ comparing with process $e^+e^- \to N\nu$ for CM energies $\sqrt{s}$ > (1-2) TeV.

- Almost similar analysis can be done with same sign beams for processes $e^-e^- \to NW^-e^-$ $(N \to W^-e^+)$ and $\mu^+\mu^+ \to NW^+\mu^+$ $(N \to W^+\mu^-)$ to search for heavy Majorana neutrino.

- We are working to get accurate estimates of signal reconstruction efficiency and background contributions to obtain limits on $|V_{\ell N}|^2$ as function of M(N).

Diagrams for $\mu^+\mu^- \rightarrow N W^- \mu^+$ process





$\gamma \longrightarrow$ A

N$\longrightarrow$ N2

$\mu^- \longrightarrow$ m

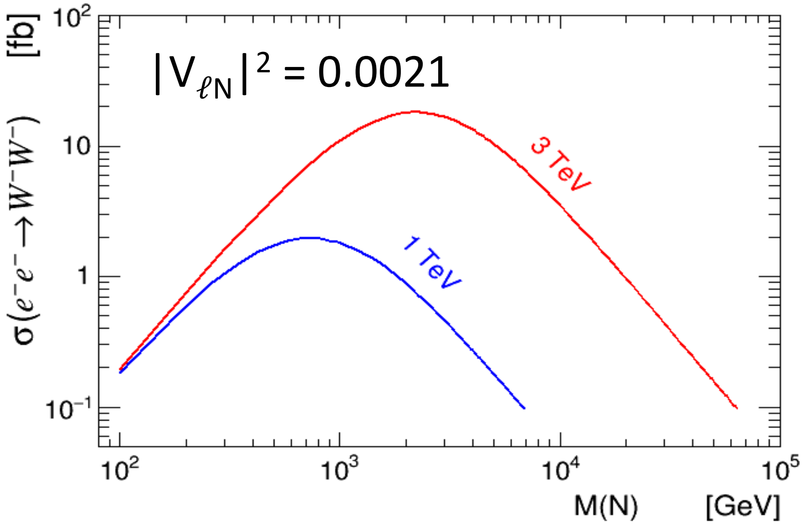
1

$\mu^+ \longrightarrow$ M

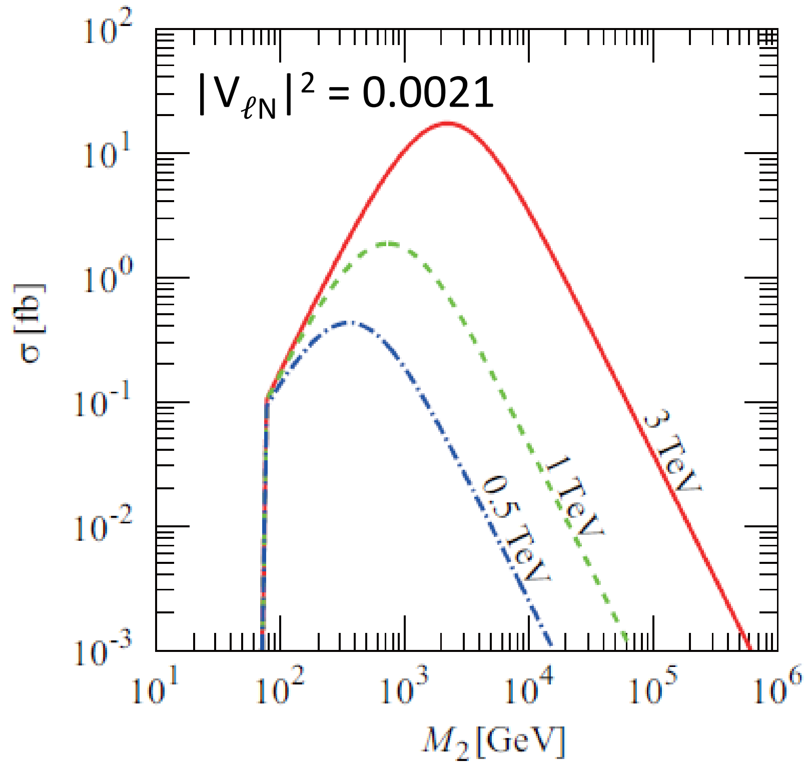
$\nu_e, \nu_\mu, \nu_\tau \longrightarrow$ ne, nm, nl

Process $e^-e^- \to W^-W^-$

CompHEP



arXiv:1508.04937



Perfect agreement between arXiv:1508.04937 and CompHEP calculations for $\sigma(e^-e^- \to W^-W^-)$.

FIG. 5: Cross section of $e^-e^- \to W^-W^-$ in the model with three right-handed neutrinos ($\mathcal{N} = 3$) with $M_1 \ll M_2 \ll M_3$ for $\sqrt{s} = 3$ TeV (the red solid line), 1 TeV (the green dashed line), and 0.5 TeV (the blue dotted-dashed line).