A possible search for Heavy Majorana neutrinos at future lepton colliders

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

Theoretical model

Seesaw Type I model

Seesaw type-I model with unitarity is installed in generator CompHEP 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 include in calculations only one HNL with M(N) ≥ 100 GeV.

It can be realized in two scenarios: 1) huge masses of N2 and N3,
2) very small mixing parameter $|V_{\ell N1}|^2$ for “small” mass N1, that could be resulted from specific *CP*-violating phases in PMNS matrix (arXiv:1508.04937) .

To compare our results with recent results obtained in studies of $e^+e^- \to N\nu$ 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 this assumption of mixing parameters.

HNL width is included in calculations (same as in arXiv:2202.06703) ➔ negligible effect.

Studied process

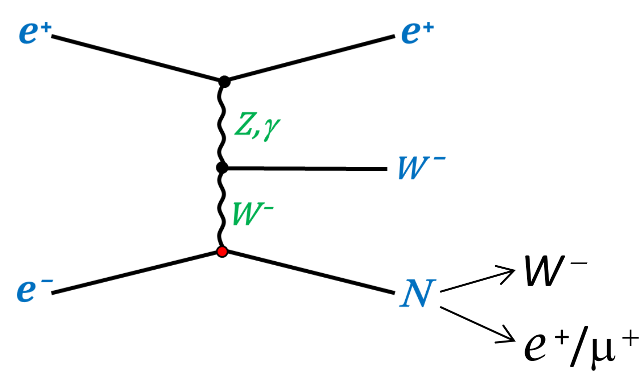
We investigate the processes with lepton number violation by 2 units (Majorana N):

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

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

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

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



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.

$$\sigma(\mu^+\mu^+ \to NW^+\mu^+) = 2 \times \sigma(\mu^+\mu^- \to NW^-\mu^+)$$

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

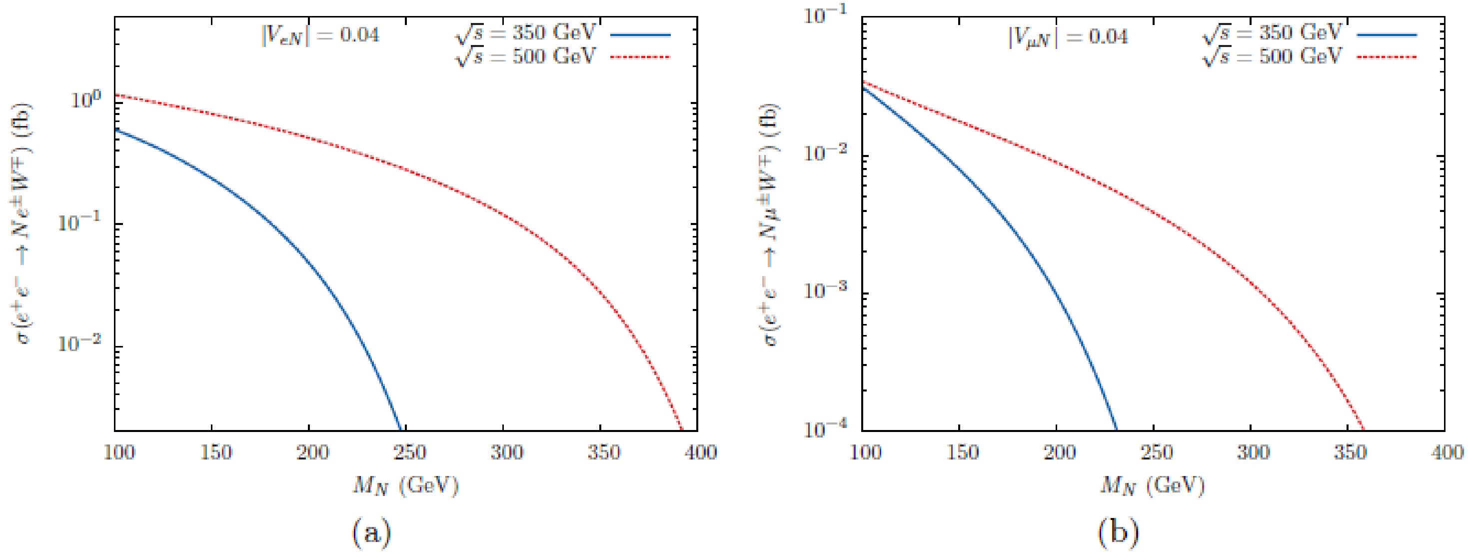
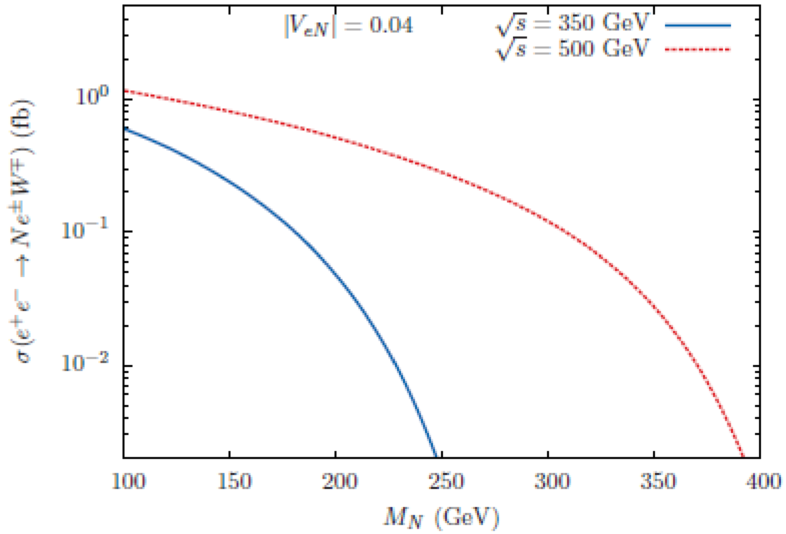
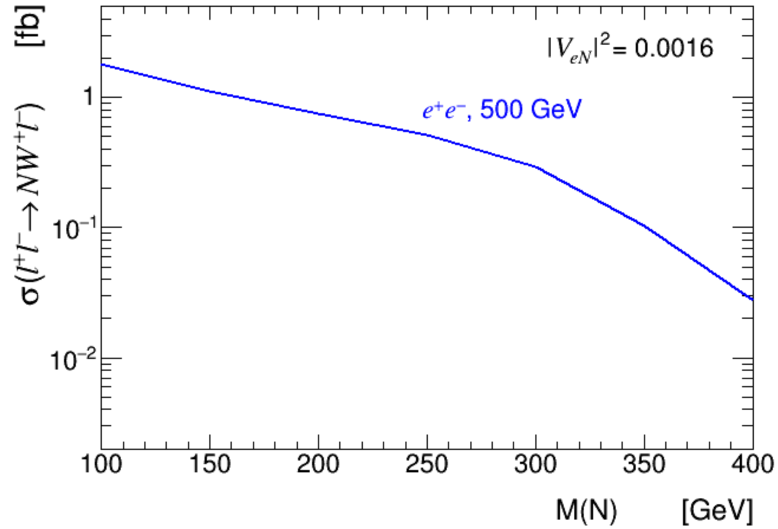


FIG. 5. Heavy neutrino production cross section for the channel $e^+e^- \to N\ell^\pm W^\mp$ for $\sqrt{s} = 350$ and 500 GeV, and with $|V_{\ell N}| = 0.04$. The left panel is for mixing with electrons, whereas the right panel is for mixing with muon and tau sectors.

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

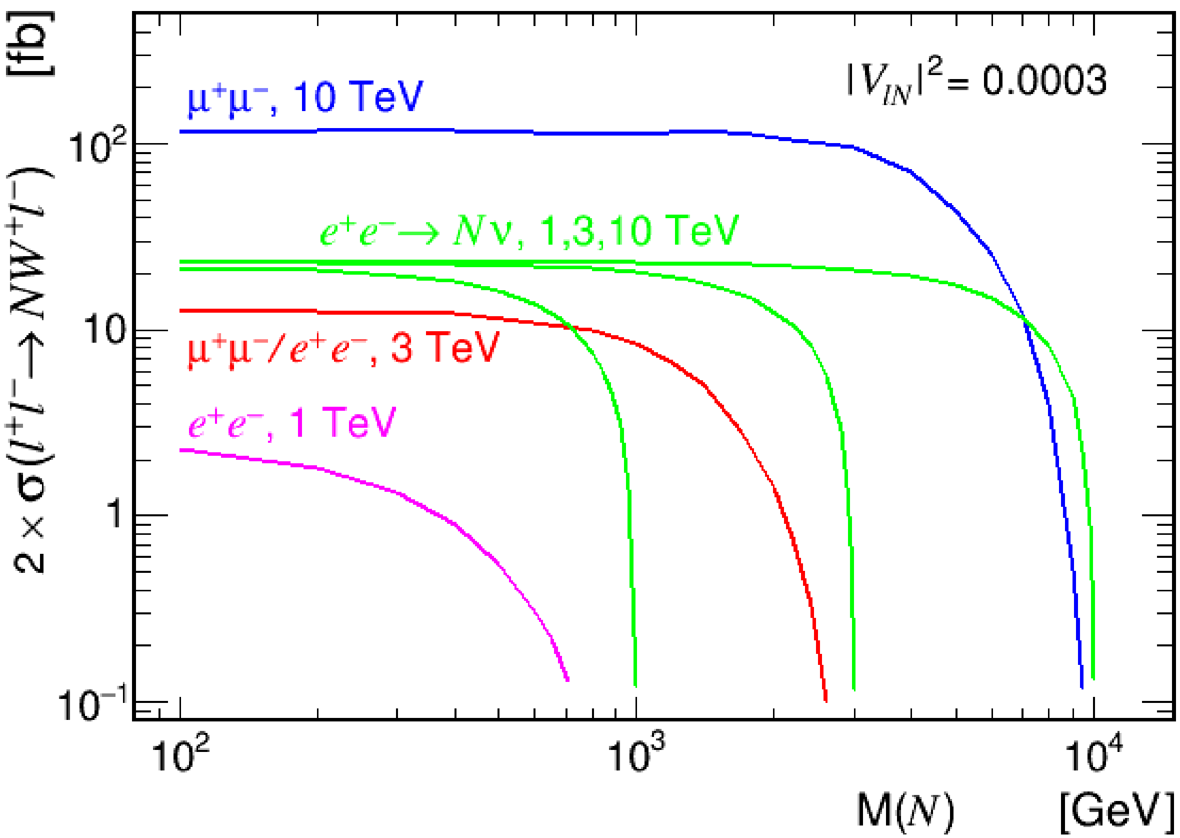
arXiv: 1503.05491	This study
	
FeynRules2.0 and MadGraph5	CompHEP with unitarity

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.

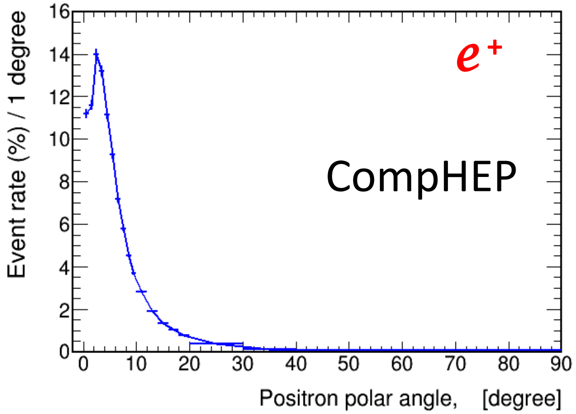
In arXiv:1503.05491 all 4 final state $W^-W^-e^+e^+$ particles were required to be detected, resulting in a very low efficiency of a few % (It is not a good idea).

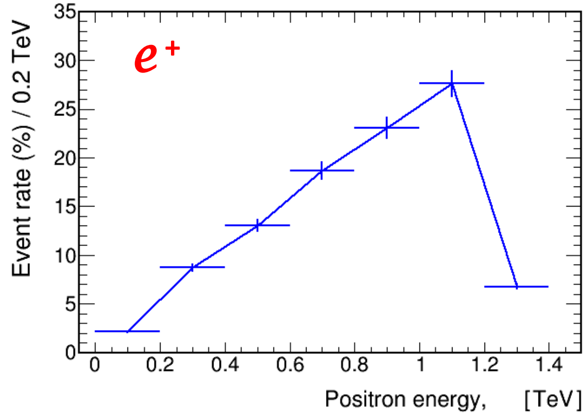
Cross sections (CompHEP)

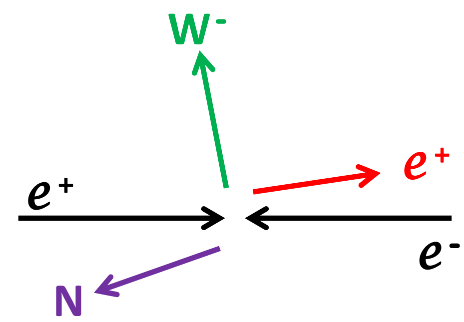


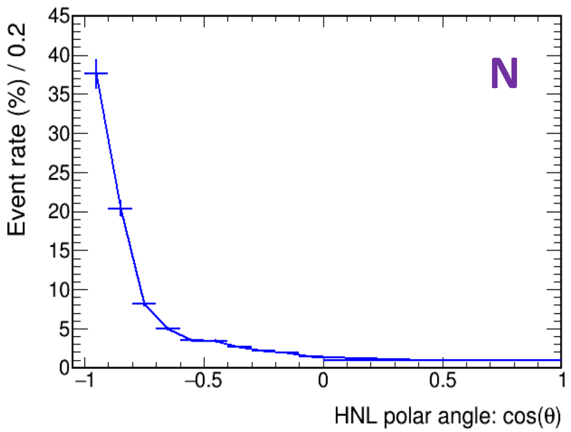
Cross sections for processes $e^+e^- \to NW^-e^+$ and $\mu^+\mu^- \to NW^-\mu^+$ are shown as a function of M(N) for $|V_{\ell N}|^2 = 0.0003$. For comparison reason cross sections for processes $e^+e^- \to N\nu$ are given in green. Large cross sections at 3 TeV and 10 TeV. Backgrounds to $\mu^+\mu^-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

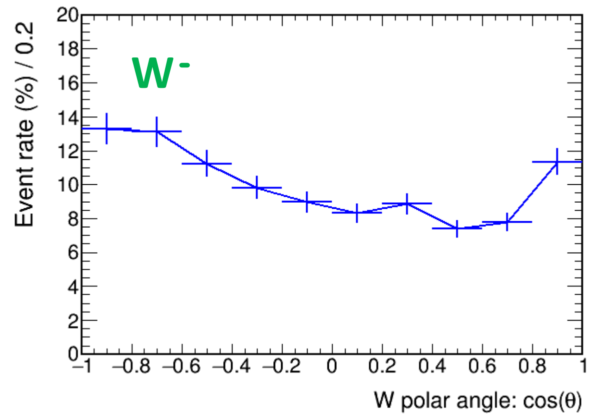
Event kinematics ($\sqrt{s}$ = 3 TeV, M(N) = 1 TeV)

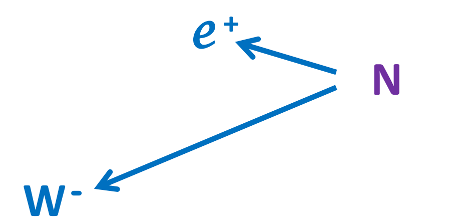










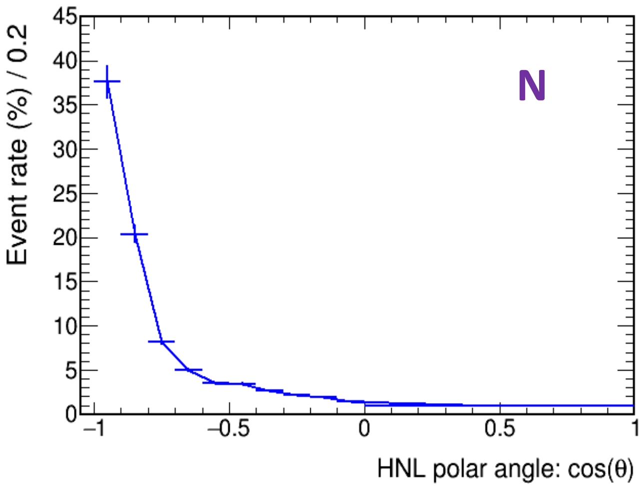


Final state: 4j + lepton

Positron is mostly going close to beam positron direction and cannot be detected.

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

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



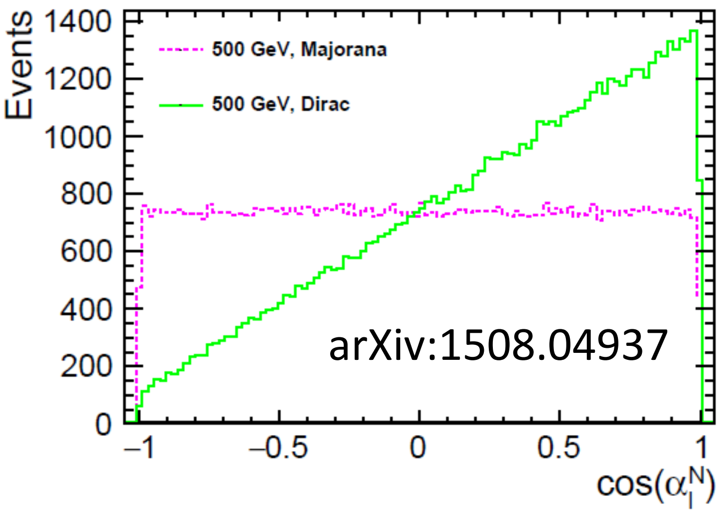


Figure 10: Distribution of the cosine of the lepton emission angle in the N rest-frame for the Majorana (pink dashed line) and the Dirac (green solid line) neutrinos with a mass of 500 GeV at CLIC3000 (generator level)

Majorana function (pink line) includes term f = N(1+cos(theta)) with lepton number conservation and term f = N(1-cos(theta)) with nonconservation.

In our case only term f = N(1-cos(theta)) with nonconservation works.

Angular distributions for jets and lepton depend on CM energy and HNL mass.

MC event simulation

Signal events : CompHEP generator ➔ Pythia 6 ➔ Delphes (detector modelling)

Background events : Whizard 2 generator (Pythia 6) ➔ Delphes

Generators: no beam polarization, ISR included

Delphes: ILD card at 1 TeV e^+e^- collisions, MuC card at 3 TeV and 10 TeV $\mu^+\mu^-$ collisions

Jet reconstruction: Valencia algorithm, reasonable shapes comparing with full simulation. Algorithm is forced to reconstruct 4 jets. At high W and Z energies we observe jet overlapping ➔ we have to treat two jets as one object (W or Z boson).

Preselections:

$|\cos\theta\ (\text{jet})| < 0.9$

$|\cos\theta\ (\text{lepton})| < 0.9$

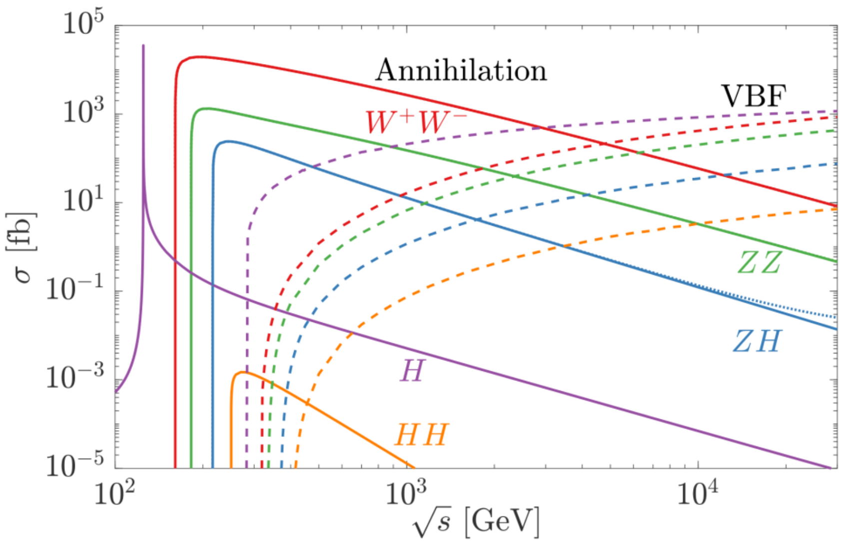
E(jet) > 30 GeV

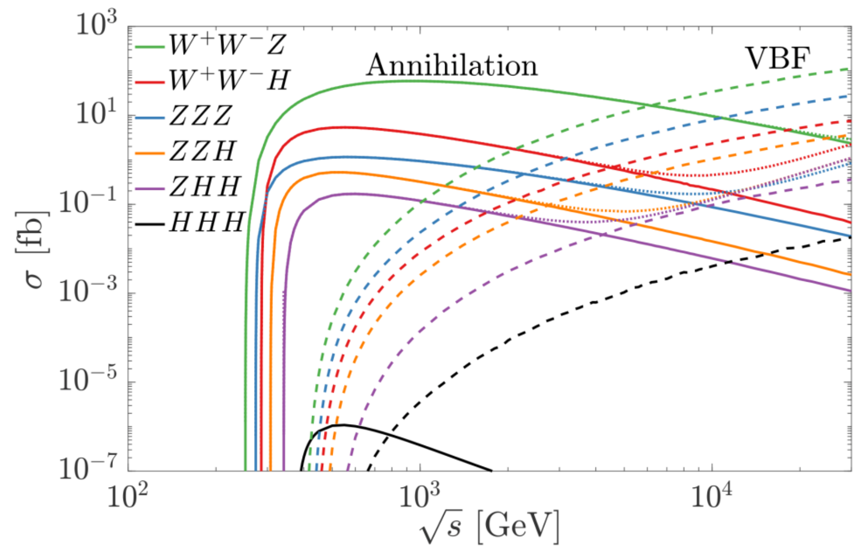
Some backgrounds are significantly suppressed by preselections, however signal acceptance is expected to be relatively large ~(20-40) %.

Work is in progress, final results will be soon.

Backgrounds

Cross sections as function of CM energy at $\mu^+\mu^-$ collisions (arXiv:2108.05362).





Background dominates by events with leptonic decay of W boson or direct lepton in VBF.

1) $e^+e^- \to W^+(\ell\nu)\, W^-(jj)\, Z(jj)$, $\sigma \sim$ 45. , 40., 13.5 fb at 1, 3, 10 TeV , Bf = 10.2%

2) $e^+e^- \to W^-(jj)\, Z(jj)\, \nu_e\, \ell^+$ with $\sigma \sim$ (50-1000) fb, Bf = 47.2%

3) $e^+e^- \to W^+(\ell\nu)\, W^-(jj)$ $\sigma \sim$ (30-5000) fb, Bf = 14.5% , can be suppressed.

4) $e^+e^- \to W^-(jj)\, \nu_e\, \ell^+$ with $\sigma \sim$ (1000-10000) fb, Bf = 67.4%, can be suppressed.

Advantage : $jjjj\ell$ background cross sections are about 50 times smaller than $jj\ell$ ones

Variables to suppress background

Sensitive variables

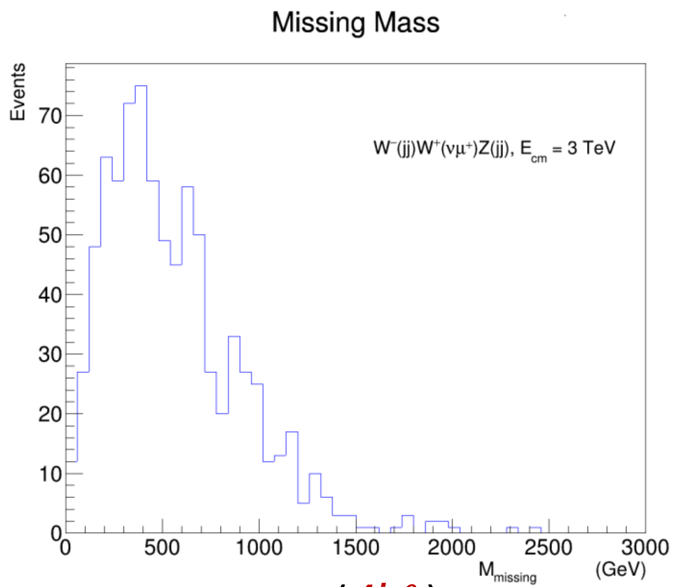
Background / Variable	Cut	$W^+(\ell\nu)\,W^-(jj)\,Z(jj)$	$W^-(jj)\,Z(jj)\,\nu_e\,\ell^+$	$W^+(\ell\nu)\,W^-(jj)$	$W^-(jj)\,\nu_e\,\ell^+$
$M_{miss}(4j\ell)$	$< 200 \times \frac{\sqrt{s}}{1000}$ GeV	← To remove backgrounds with 2 or more unmeasured			
$P_{miss}(4j\ell)$	> 500 GeV				
$\cos(P_{miss} \wedge e^+_{beam})$	> 0.8		✓		✓
$\cos(\ell^+_{rec} \wedge e^+_{beam})$	< 0.5			✓	✓
$M_{miss}(4j)$	> 500 GeV	✓	✓		
$M(P_{miss}\,\ell^+_{rec})$	> 500 GeV	✓	✓		
$M(4j)$	> 500 GeV			✓	✓
$M(W\ell)$	signal	✓	✓	✓	✓

q_{miss} – define charge of missed lepton using P_{miss}

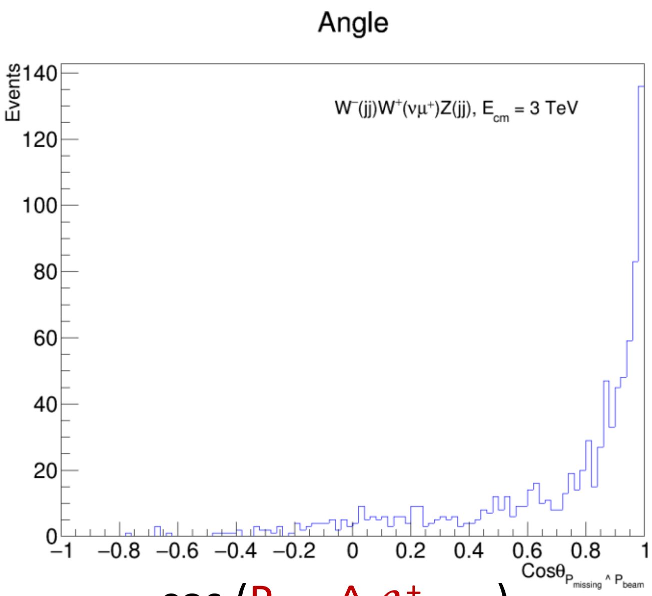
Cuts are very very preliminary. We are working to optimize cuts, planning NN.

Backgrounds

Most dangerous background $e^+e^- \to W^+W^-Z$.



M_{miss} $(4j\ell)$



$\cos\,(P_{miss} \wedge e^+_{beam})$

Distributions are very similar to ones expected for signal. We have to use small mass of νe^+ system (variables M_{miss} $(4j)$ and $M(P_{miss}\,\ell^+_{rec})$ to suppress this background.

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

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

Conclusions

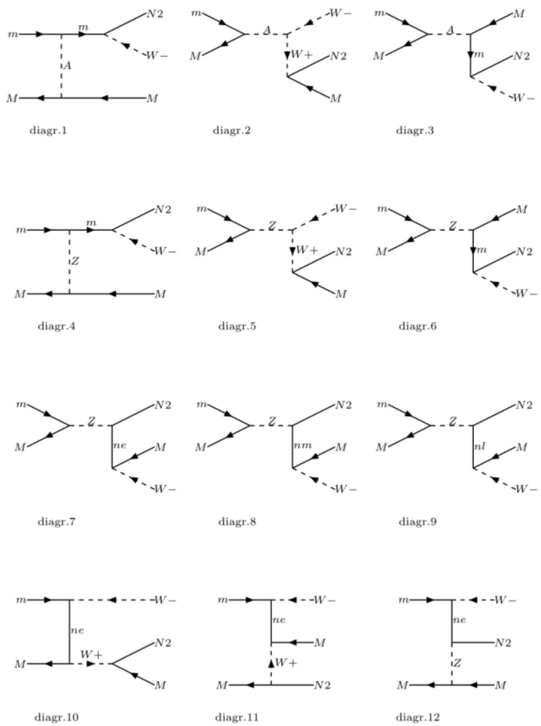
- Process $e^+e^- \to NW^-e^+$ $(N \to W^-e^+)$ and similar ones have very clean signature, when initial lepton goes to beam pipe and not detected. This process can be selected and separated from backgrounds with high efficiency.

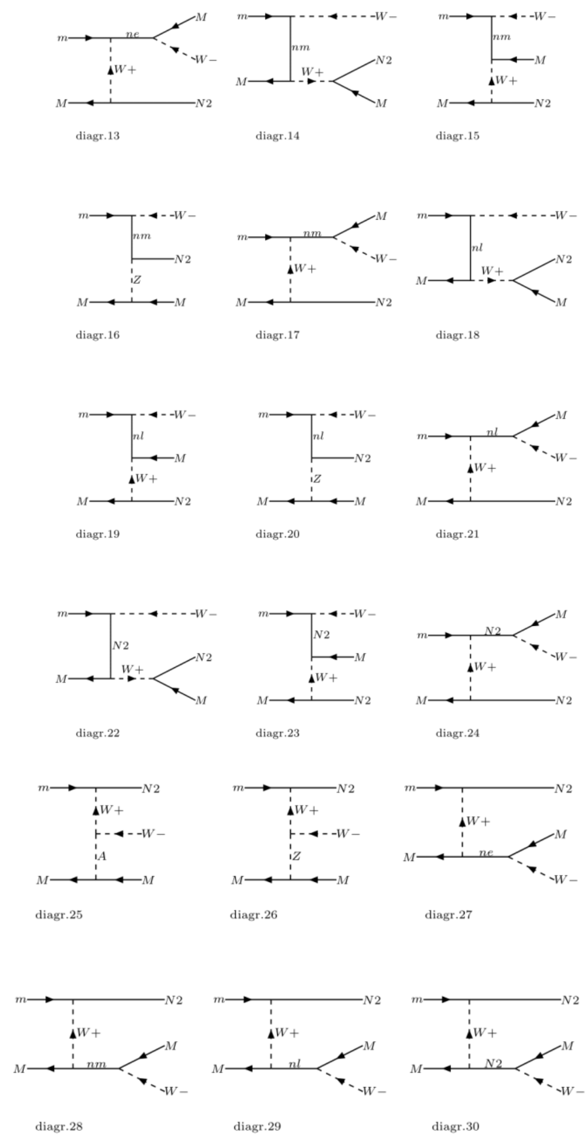
- Process $e^+e^- \to NW^-e^+$ $(N \to W^-e^+)$ has large cross section within Seesaw Type I model with Majorana neutrino. Due to low background this process can provide similar sensitivity to HNL mixing parameter $|V_{\ell N}|^2$ comparing with process $e^+e^- \to N\nu$ for CM energies $\sqrt{s}$ >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





$\gamma \rightarrow$ A

N$\rightarrow$ N2

$\mu^- \rightarrow$ m

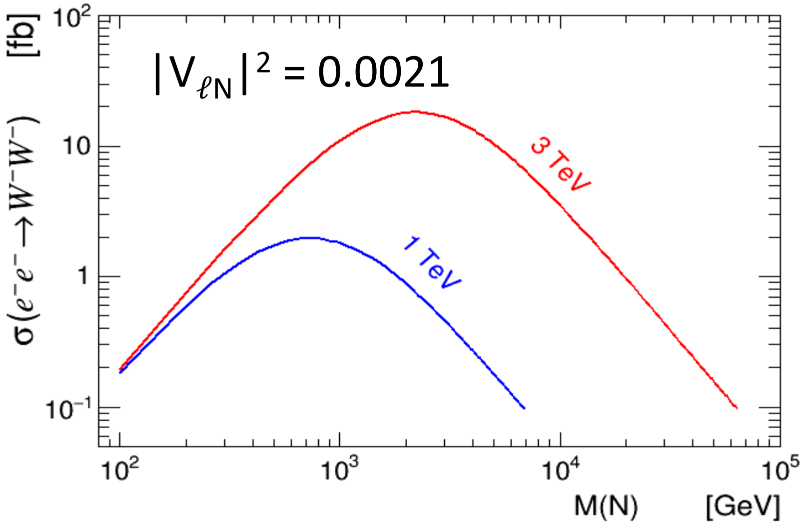
1

$\mu^+ \rightarrow$ M

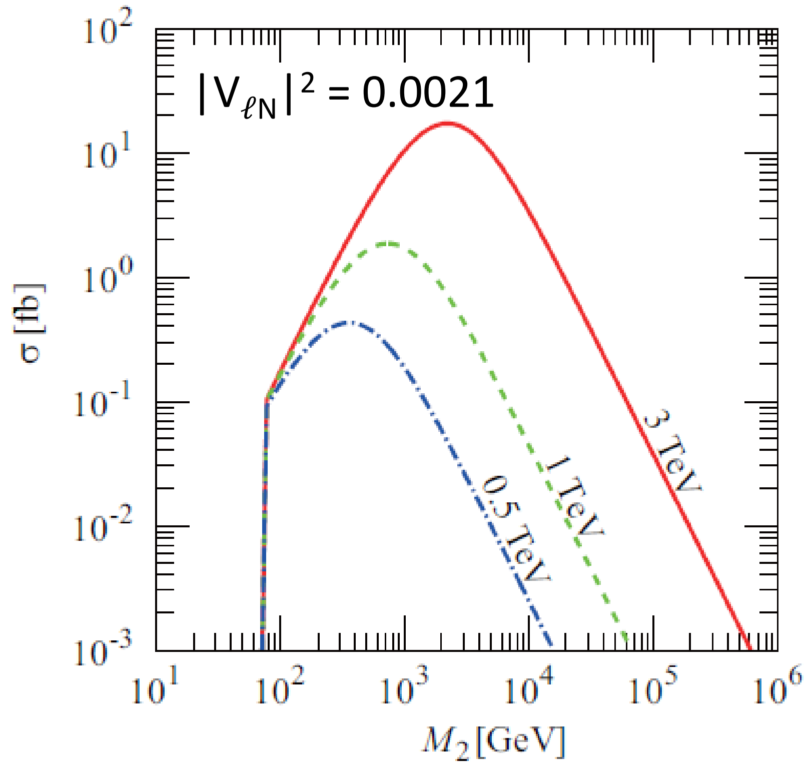
$\nu_e, \nu_\mu, \nu_\tau \rightarrow$ ne, nm, nl

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).