Monte-Carlo simulation of processes with heavy neutrino exchange on lepton colliders

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Seesaw Type I model

Model includes right-handed Heavy Neutral Leptons (Majorana), 3HNL : $N_1,\ N_2,\ N_3$

$L = L_{SM} + L_N + L_{WNl} + L_{ZN\nu} + L_{HN\nu}$

Neutrino mass matrix with Majorana and Dirac terms, y_D – Yukawa coupling matrix:

$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix},\ M_D = y_D v/\sqrt{2},\ m_\nu \approx -M_D M_N^{-1} M_D^T$$

Small masses of active neutrinos can be obtained with large M_N (HNL mass) parameters of Majorana term, e.g.

if $M_N = 100$ GeV and $y_D = 10^{-6}$ $m_\nu = 0.1$ eV – Seesaw mechanism

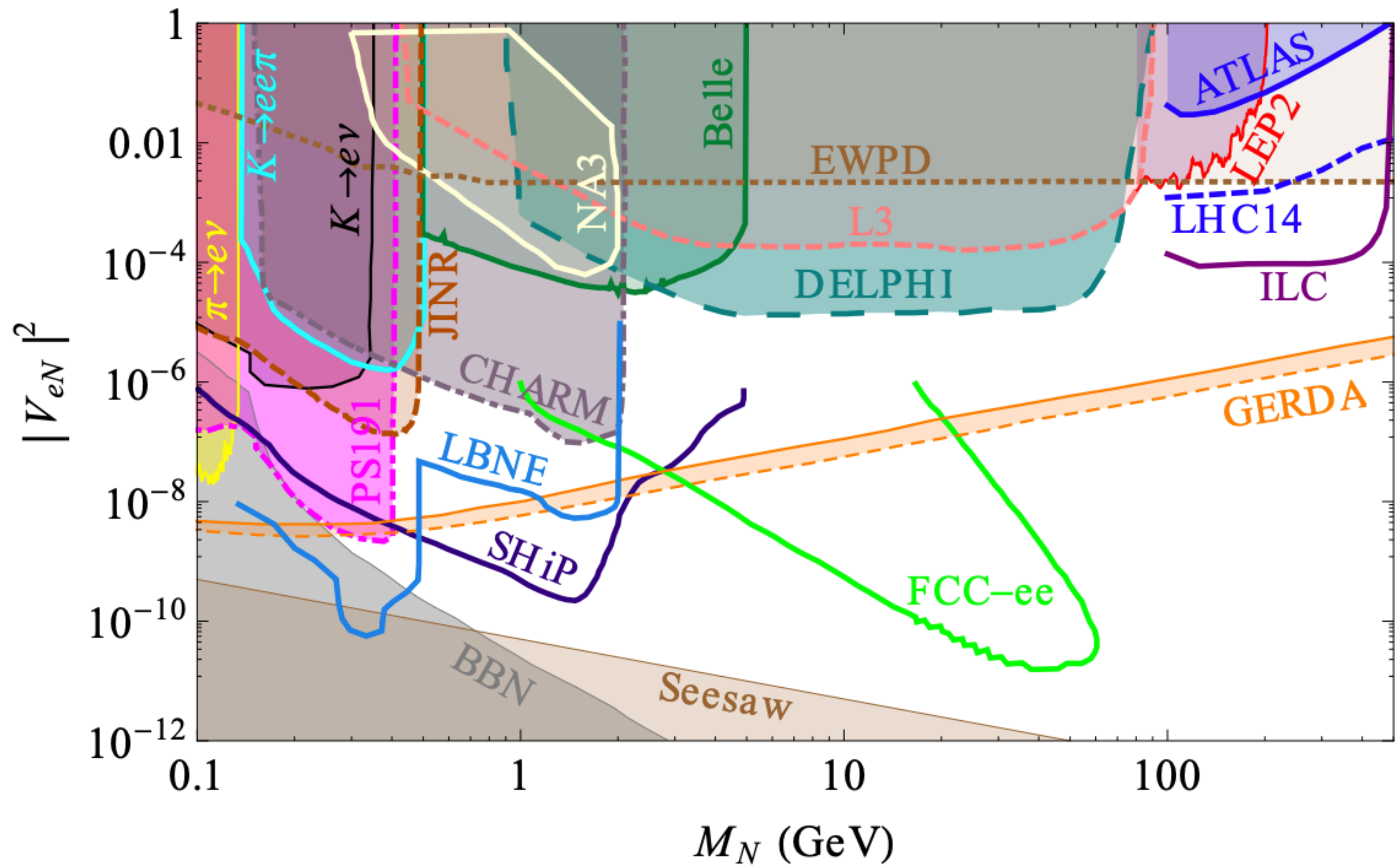
V_{lN} (neutrino mixing parameter) and M_N are parameters of model.

Experimental limits on mixing parameters.

Area of small masses is limited by decays of K-mesons, B-mesons and Z-bosons

LHC current limits and future estimates have weak upper limits larger than 90 GeV

Neutrinoless double beta decay limit (GERDA) can be circumvented in some models for large M_N



arXiv:1502.06541

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

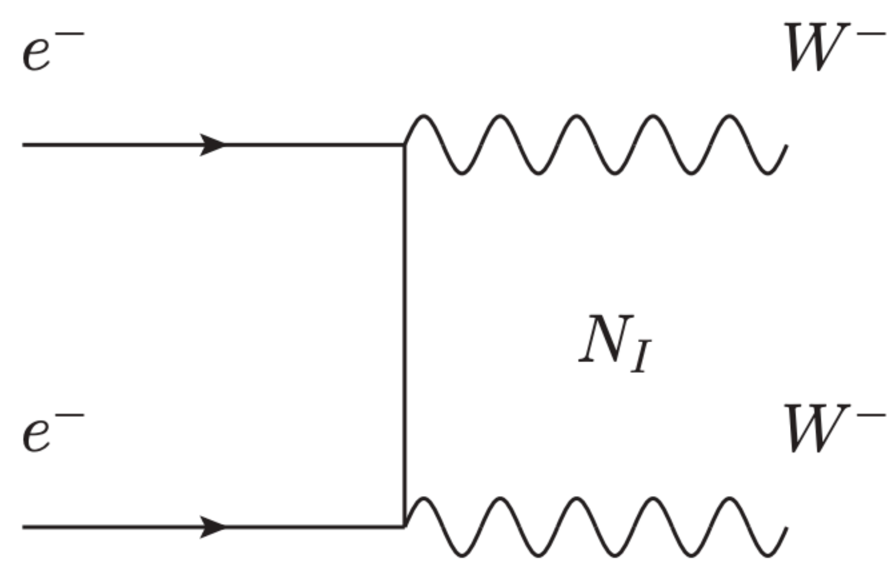
$\Delta L = 2$

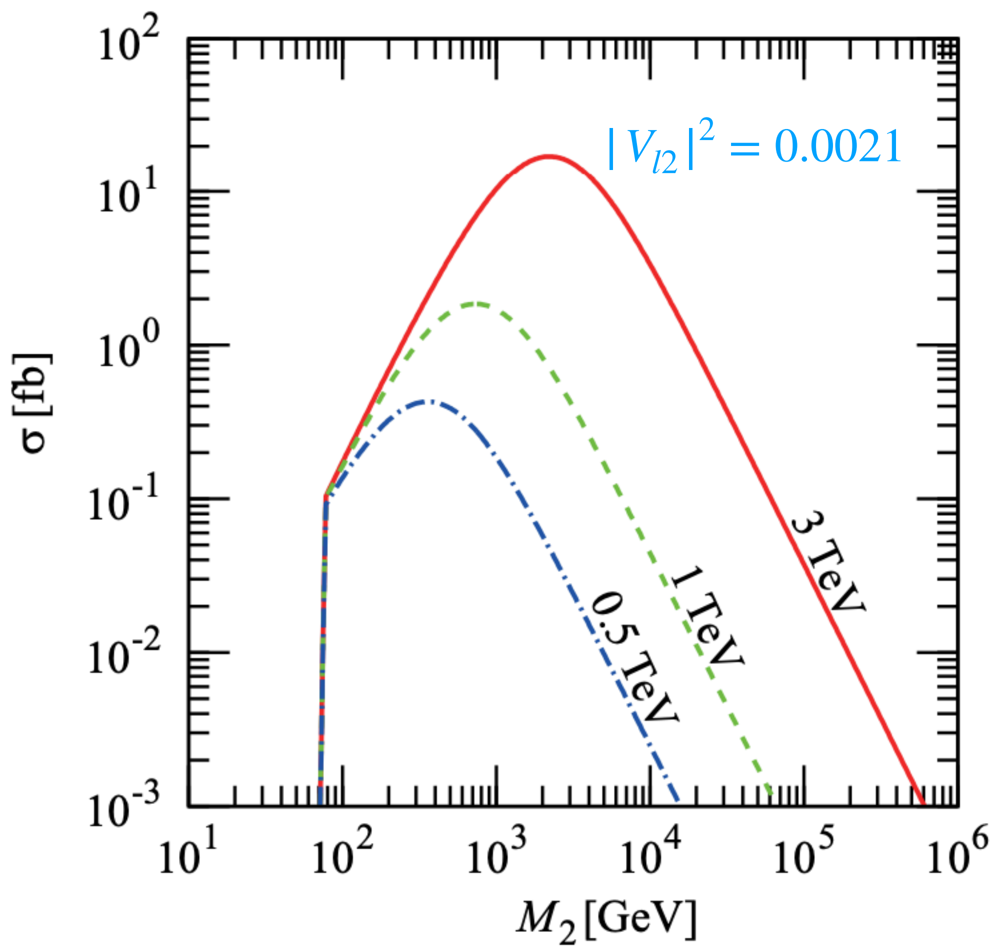
Clean hadronic final state $W(2j)$ with 4 jets

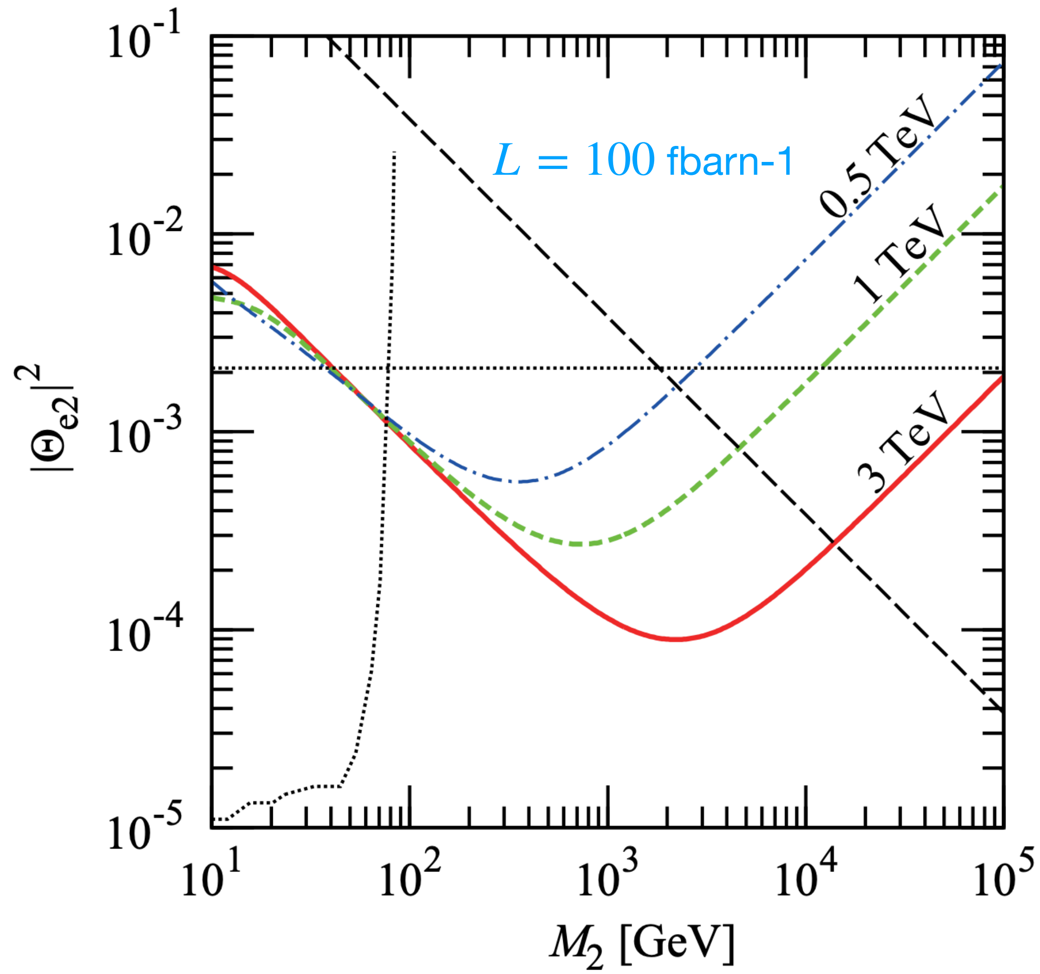
No backgrounds from Standard Model

Sensitivity to large M_N

This process is widely studied by many articles







arXiv:1508.04937

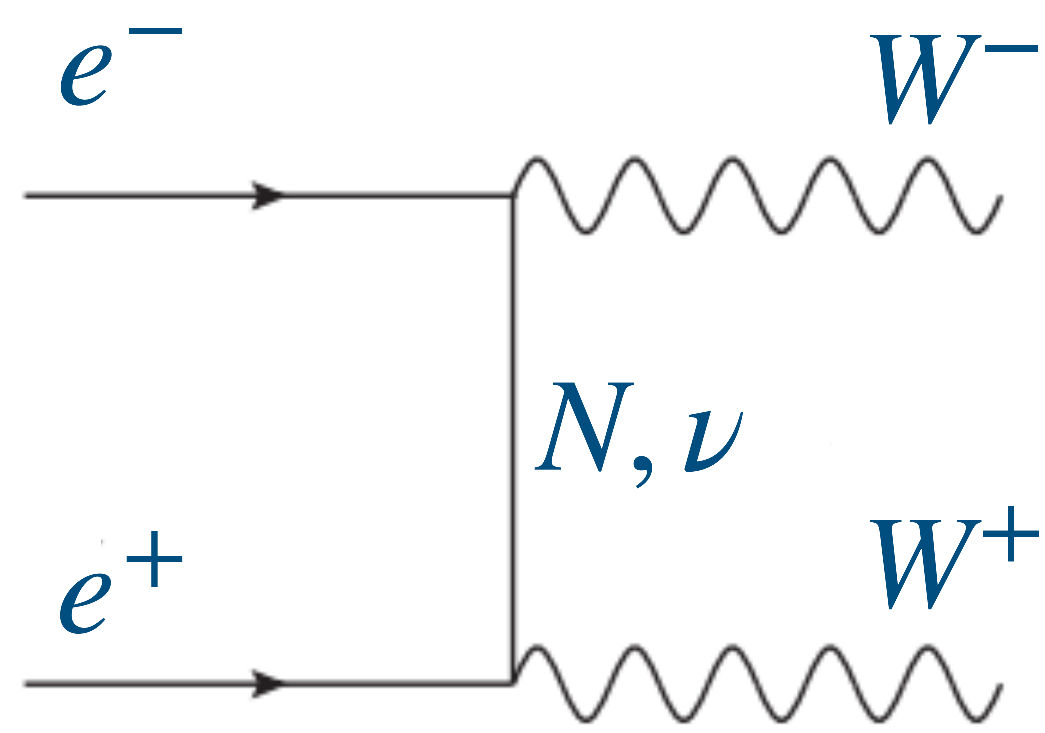
$e^-e^+ \to W^-W^+, W^\pm \to 2j$

Future colliders are planned for opposite-sign lepton beams

We study 4 jets final state

We assume that only one neutrino contribute in process

This process was not studied before

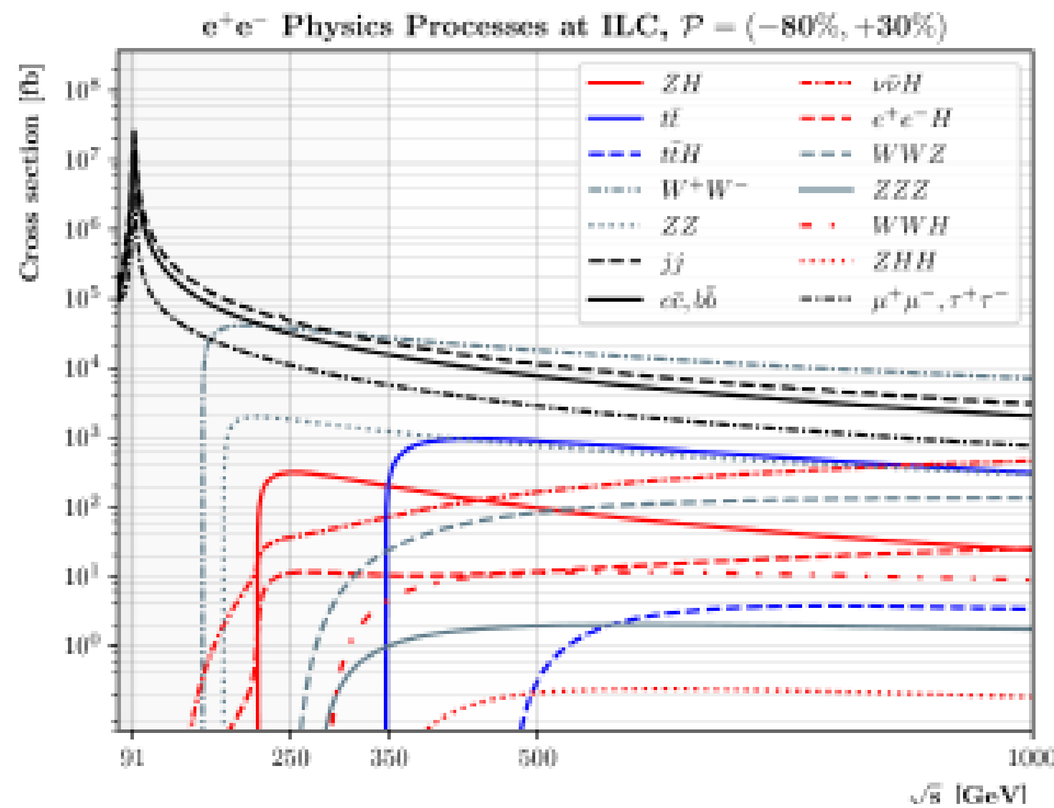


Event generation: Whizard 3
Hadronisation: Pythia6
Detector simulation and event reconstruction: Delphes/ILC card

Backgrounds and cuts

Standard Model processes with 4 jets in final state:

$$e^+e^- \rightarrow W^+W^-$$
$$e^+e^- \rightarrow W^+W^-\nu_e\bar{\nu}_e$$
$$e^+e^- \rightarrow q\bar{q}$$
$$e^+e^- \rightarrow ZZ$$

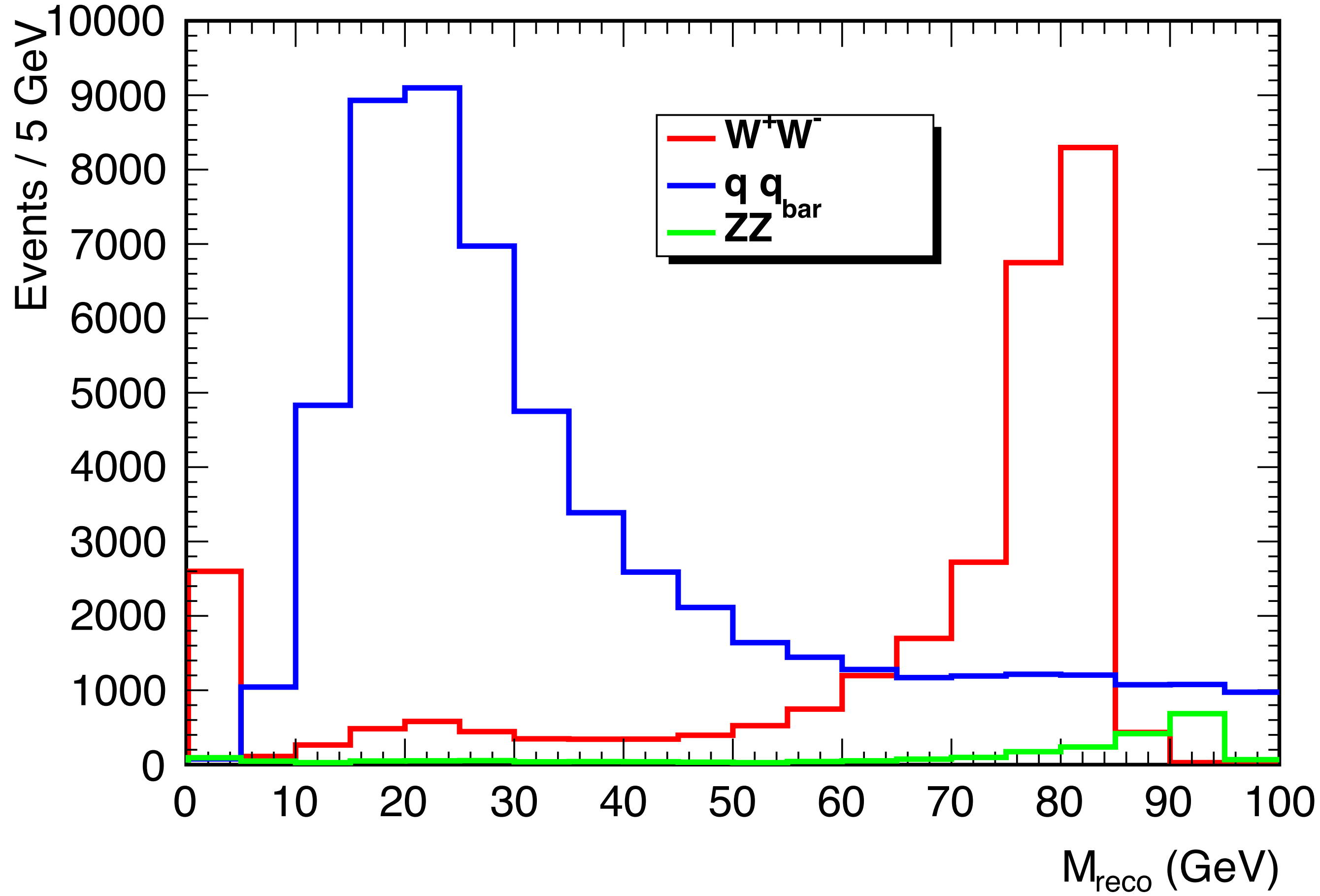


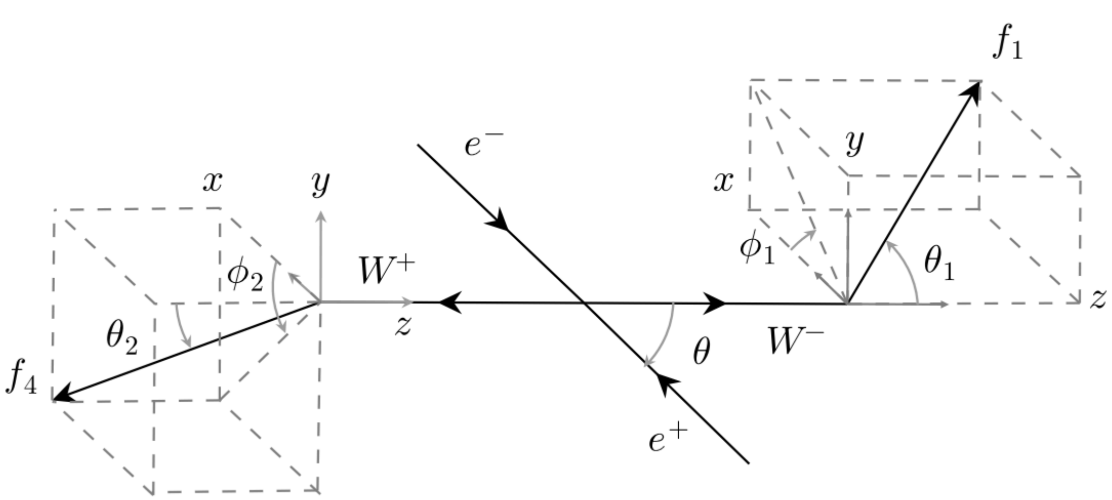
$70 \text{ GeV} < M_{\text{reco}} < 90 \text{ GeV}$

$\cos\Theta < 0.7$

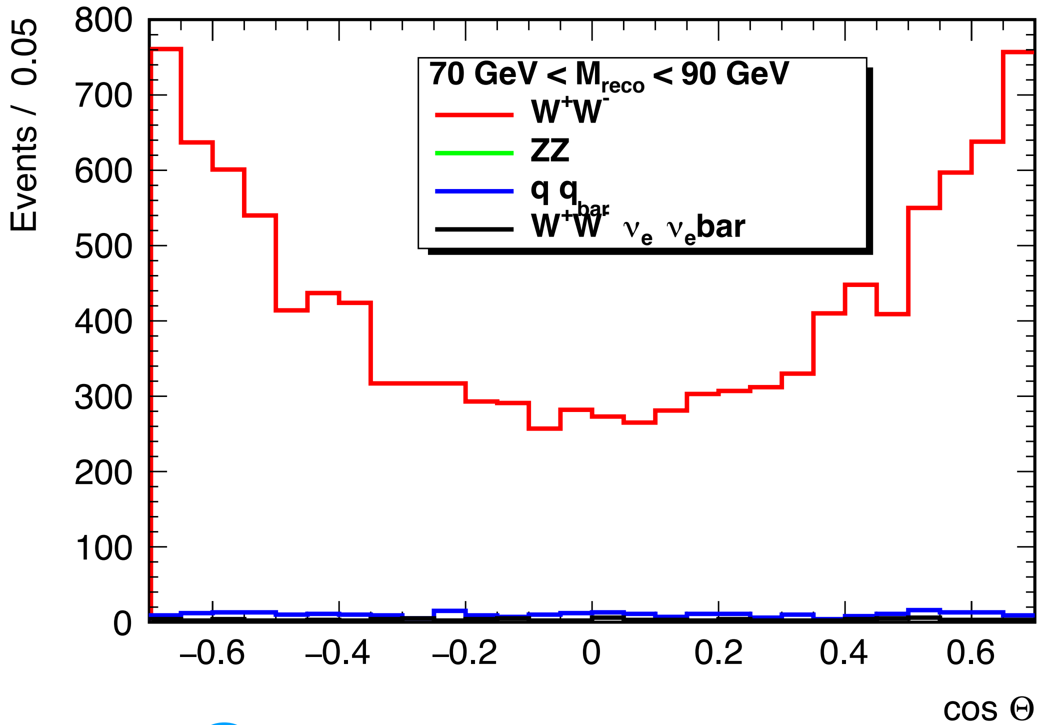
p_x, p_y balance < 20 GeV

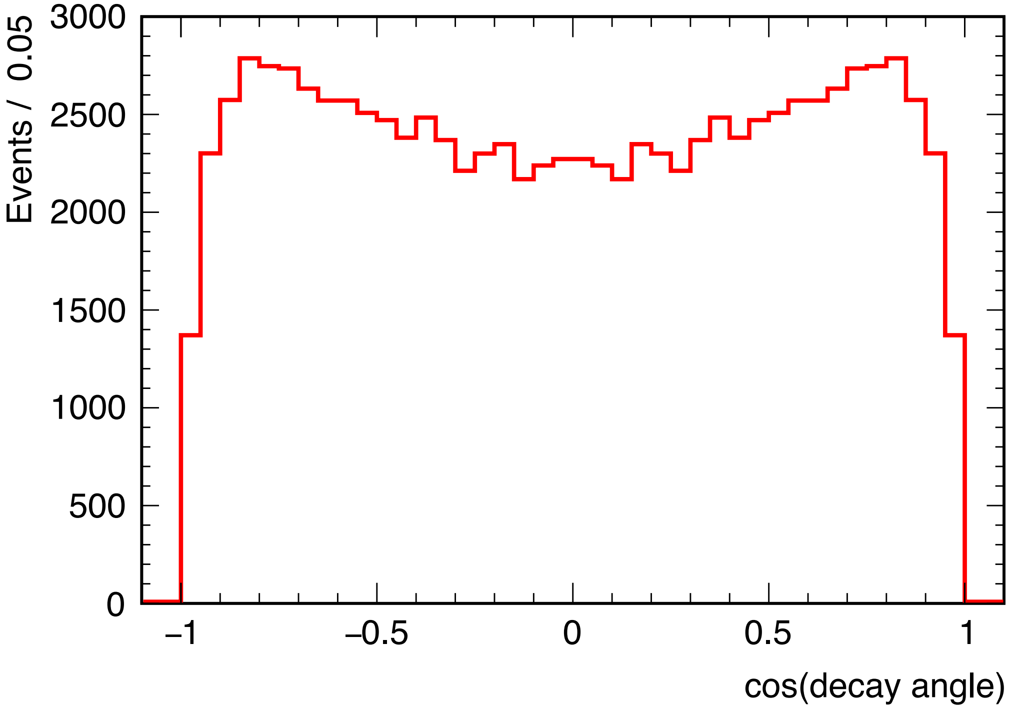
$\cos\Theta_{\text{decay}} < 0.85$





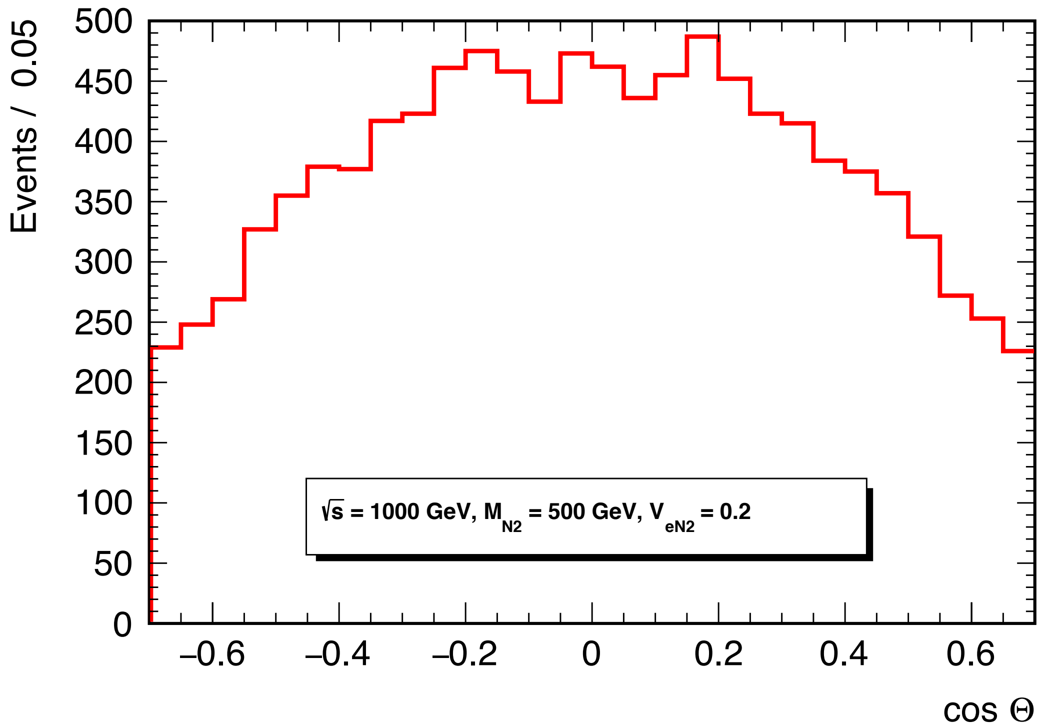
Angular distributions

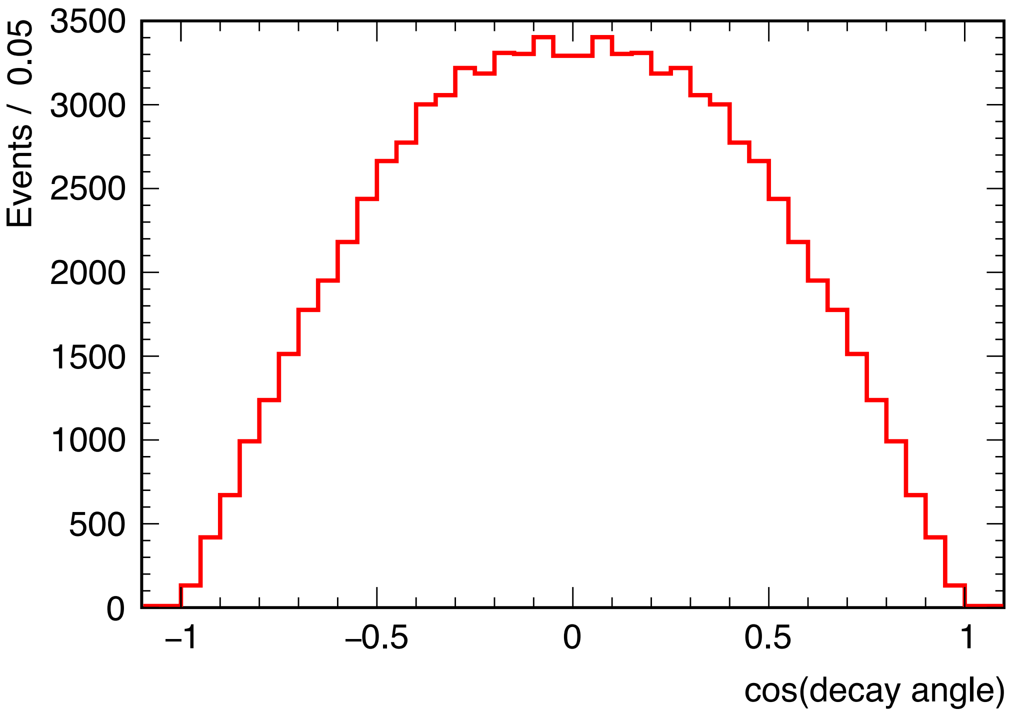




cos Θ for pure SM (up) and pure HNL signal (down)

cos decay for pure SM (up) and pure HNL signal (down)





Jets reconstruction

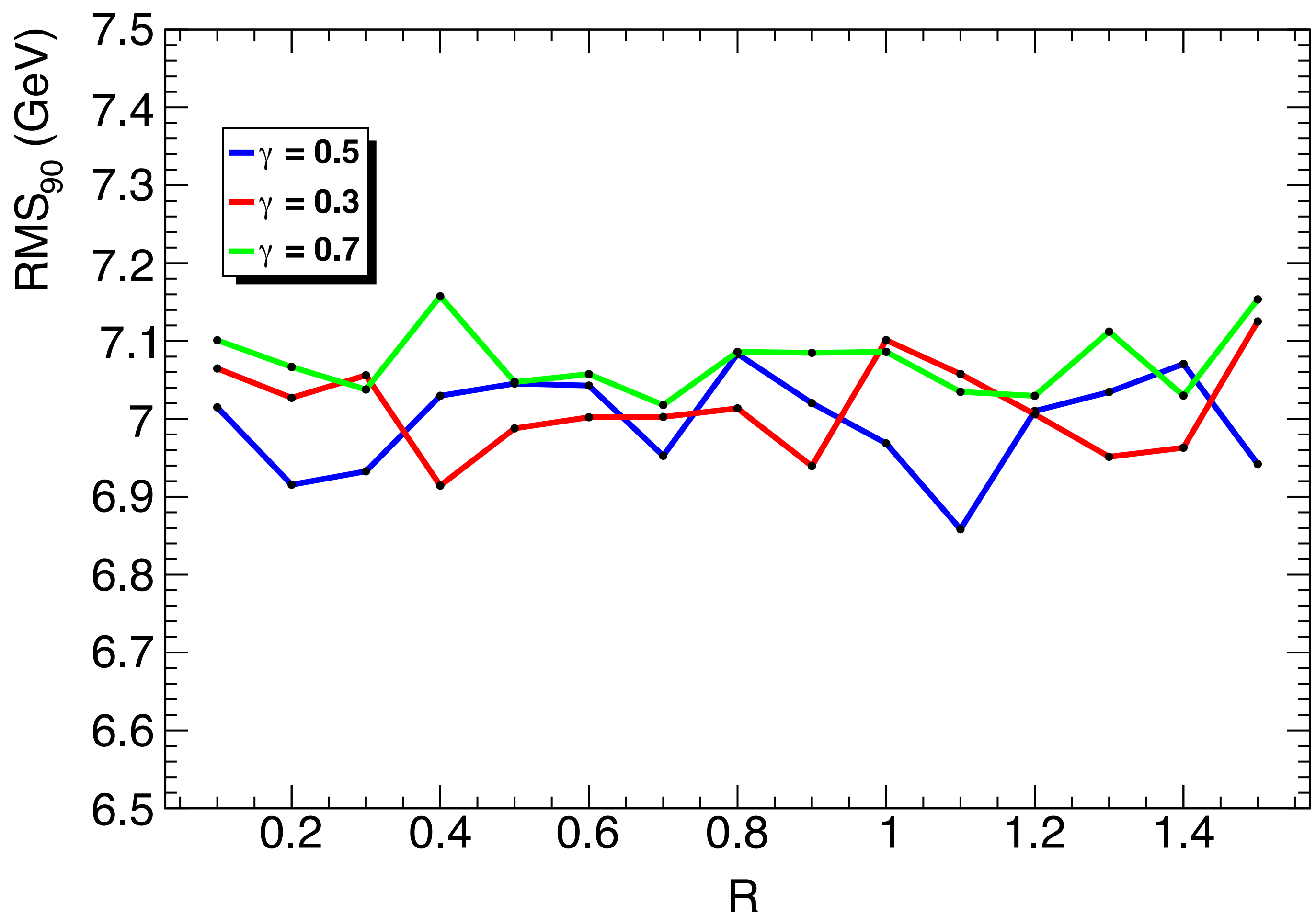
Valencia algorithm
(arXiv:1404.4294,
arXiv:1607.05039):

$$d_{ij} = 2\min(E_i^{2\beta}, E_j^{2\beta})(1-\cos\Theta_{ij})/R^2$$

$$d_{iB} = E_i^{2\beta}\sin^{2\gamma}\Theta_{iB}$$

Dependence on parameters is negligible in our reconstruction

$$\text{RMS}_{90} = \sqrt{|M^2_{\text{mean}} - (M_{\text{mean}})^2|}$$



We take $R = 1.0$, $\beta = 1.0$, $\gamma = 0.5$

Results

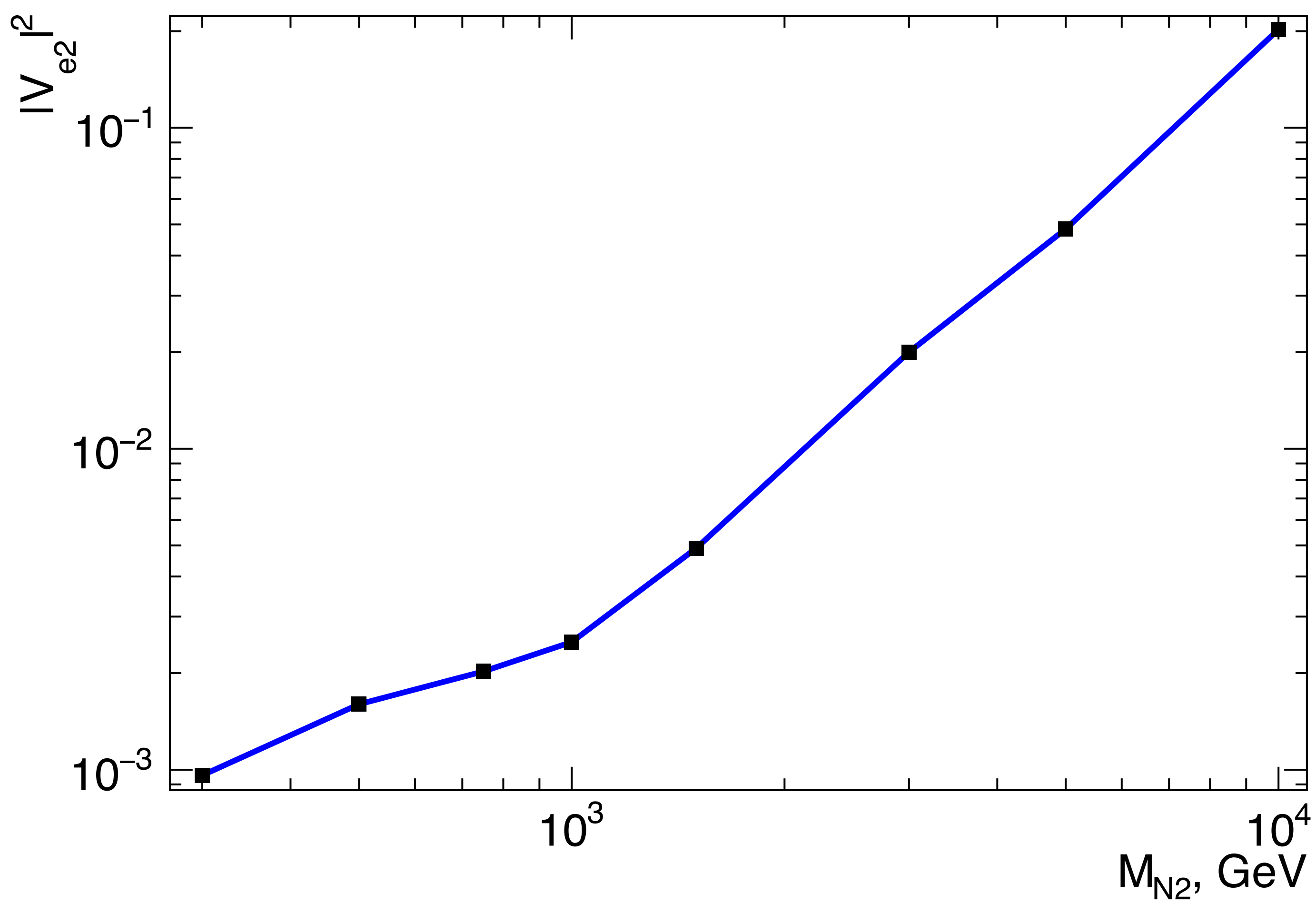
$e^+e^- \to W^+W^-$ (unpolarised beams) at $\sqrt{s} = 1$ TeV and $L = 1$ attobarn^{-1}

SM and SM+HNL fit datasets and SM+HNL analysis dataset generated for different mixing parameters and masses

PDFs of 3 angles fitted for SM and SM+HNL histograms on fit datasets

Significance = $-2 \ln \frac{L_{\text{SM}}}{L_{\text{HNL}}}$

Evidence — significance = 3σ



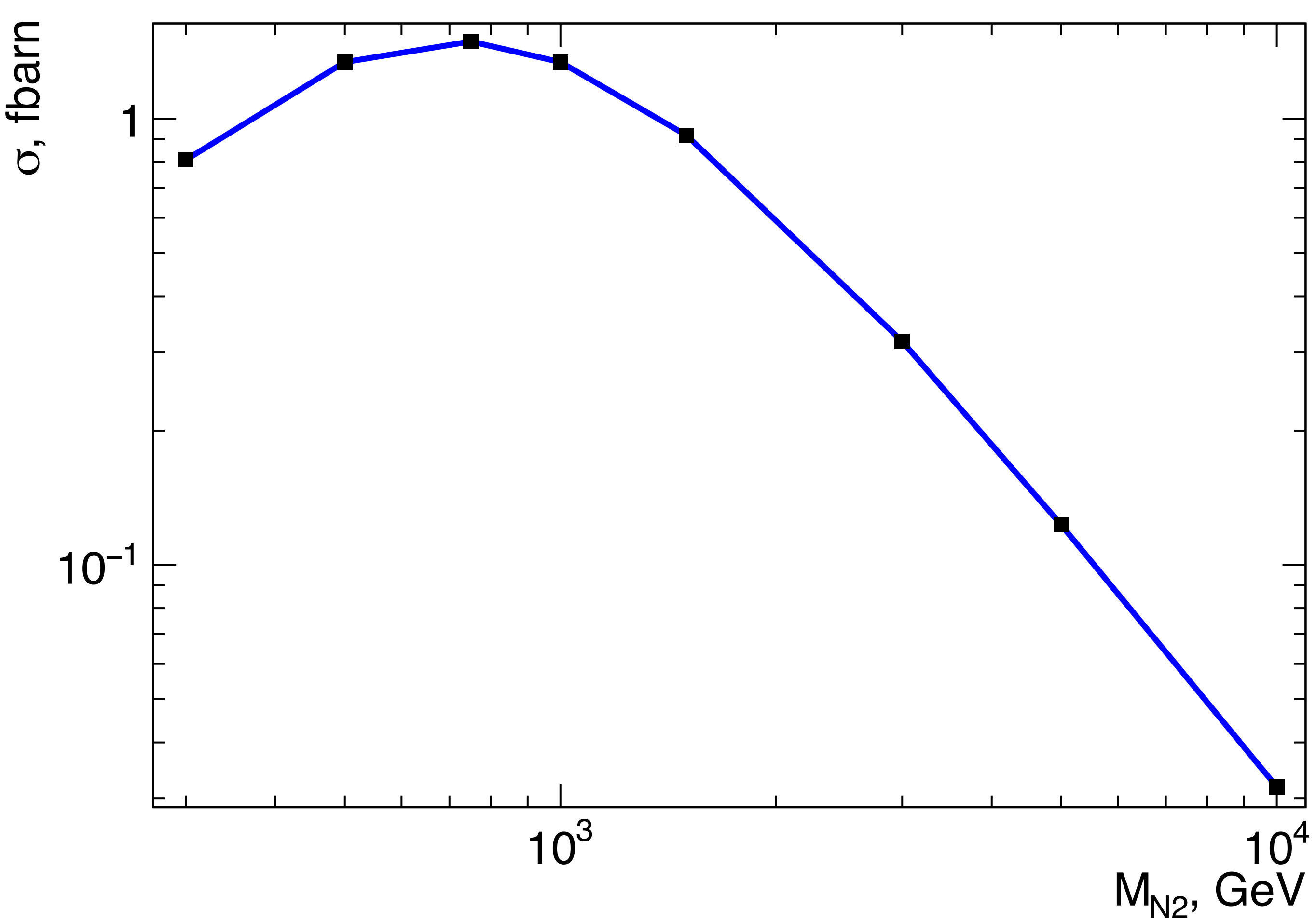
$$L_{\text{HNL}} = \text{Poiss}(N_{\text{analysis}} \,|\, N_{\text{HNL expected}}) \cdot \Pi_i \ \text{pdf}_{\text{HNL}}(x_i)$$
$$L_{\text{SM}} = \text{Poiss}(N_{\text{analysis}} \,|\, N_{\text{SM expected}}) \cdot \Pi_i \ \text{pdf}_{\text{SM}}(x_i)$$

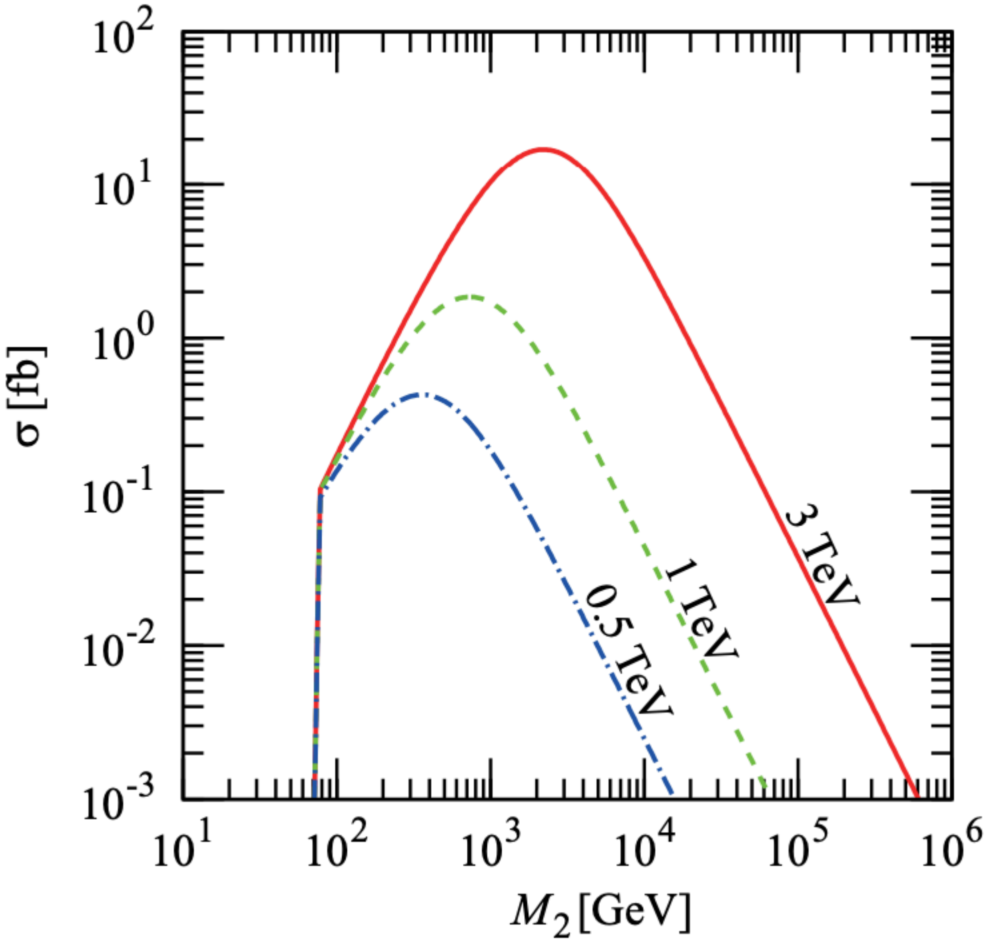
Conclusions

- Future lepton colliders can provide stronger upper limits on mixing parameters for large $M_N > 100$ GeV than existing experiments (LHC and $0\nu\beta\beta$)
- Obtained upper limits can provide strict tests of specific Seesaw Type-I models with not constrained mixing parameter.
- We plan to study process at $\sqrt{s} = 3,\ 10$ TeV
- First study on that process

Thank you for your attention

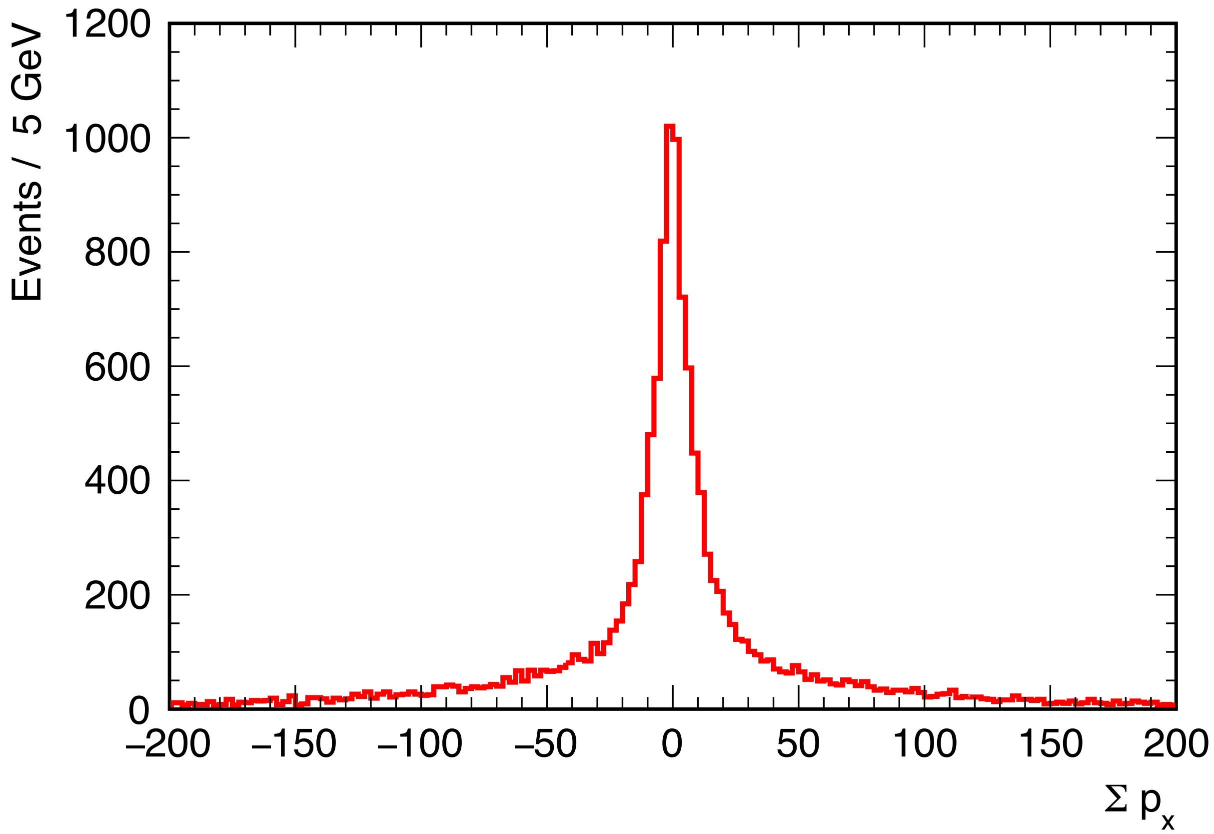
$e^- e^- \to W^- W^-$



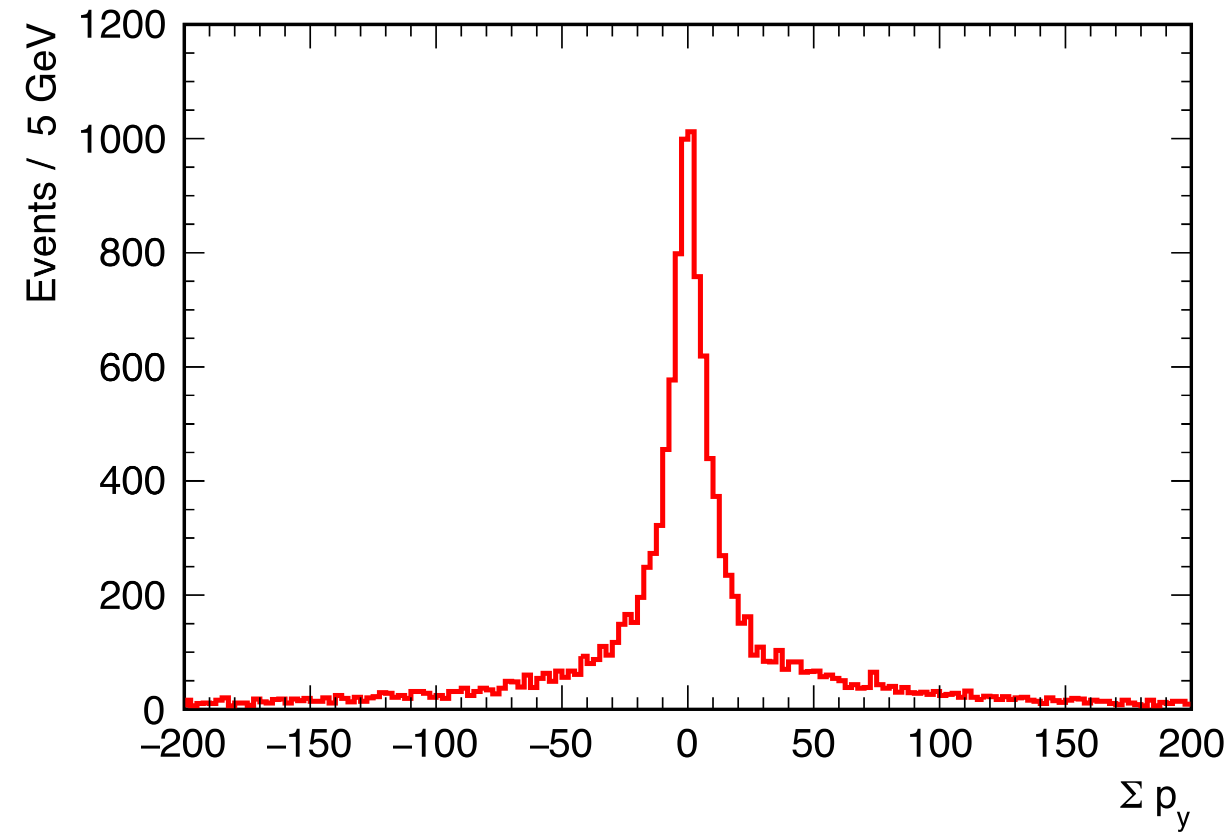


$$|V_{e2}|^2 = 0.0021$$

p_x, p_y balance



px balance



py balance

Angle between planes