Monte-Carlo simulation of processes with heavy right-handed neutrino exchange at 1 TeV e+e- collider

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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

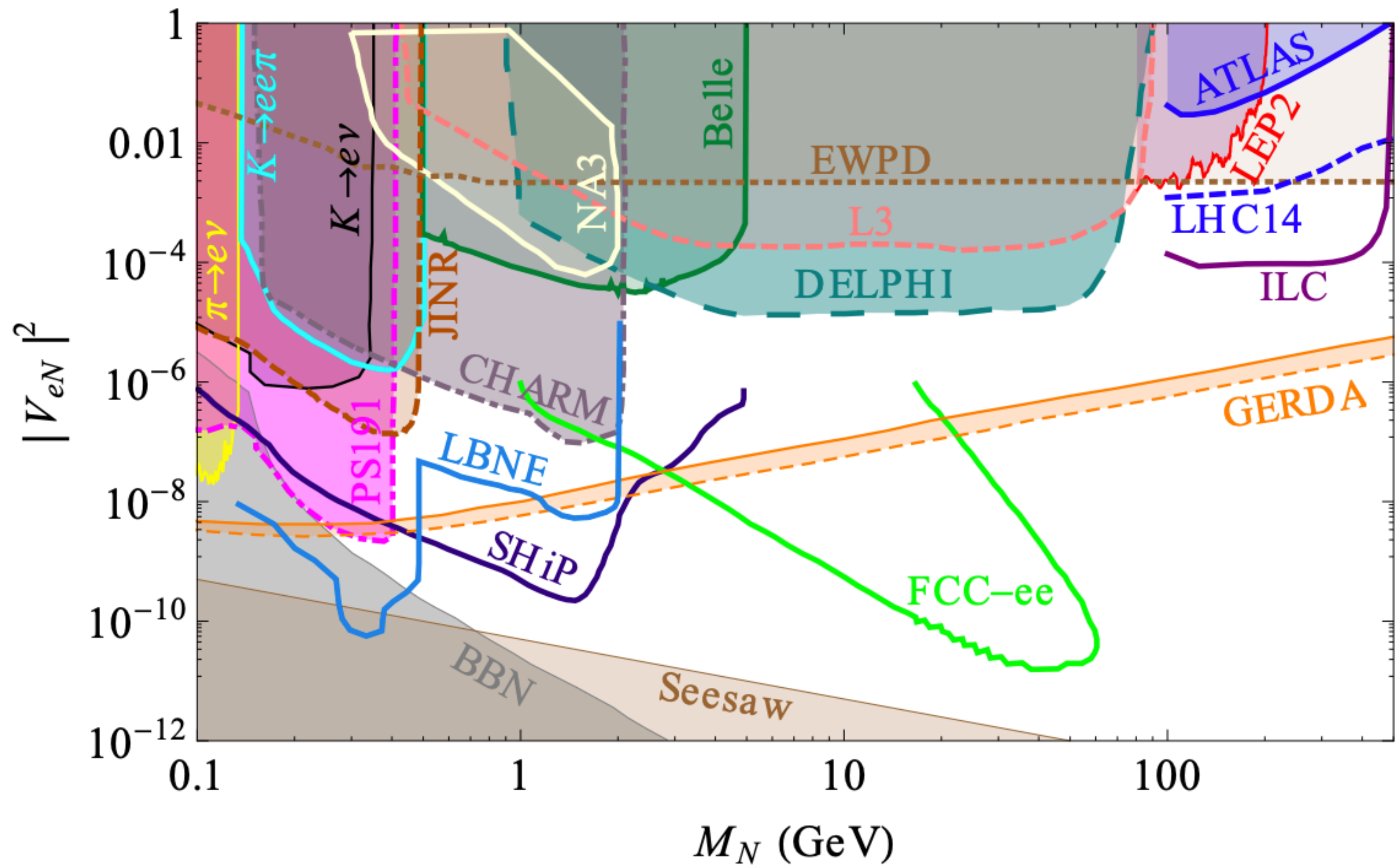
V_{lN} (neutrino mixing parameter) and M_N are parameters of model.

Experimental limits on mixing parameters.

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

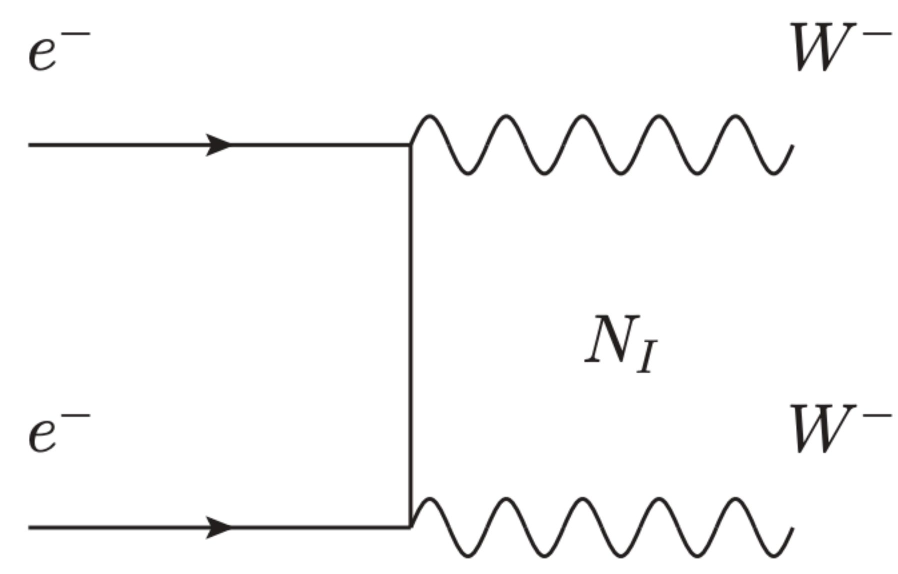
LHC current limits and future estimates have weak upper limits in the region larger than 90 GeV

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



arXiv:1502.06541

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



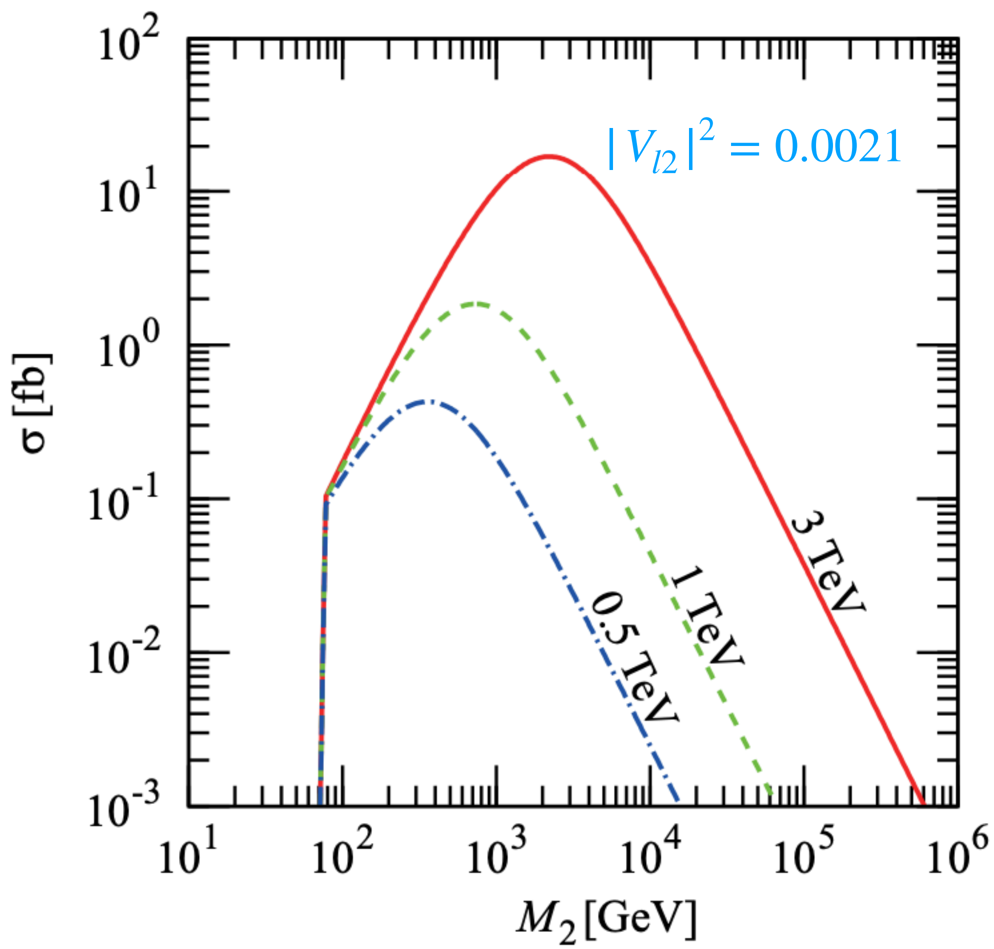
$\Delta L = 2$

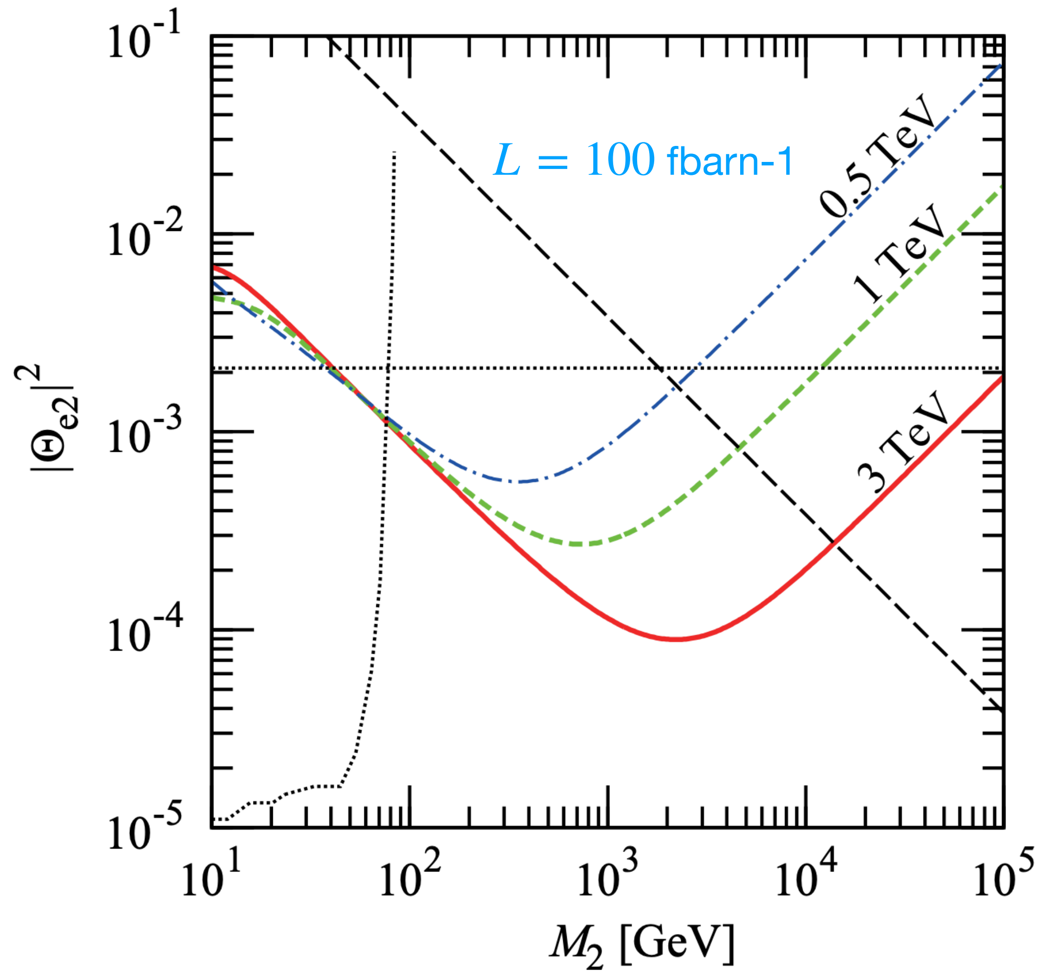
Clean hadronic final state $W(2j)$ with 4 jets

No backgrounds from Standard Model

Sensitivity to M_N larger than $\sqrt{s}$

This process is widely studied in many papers

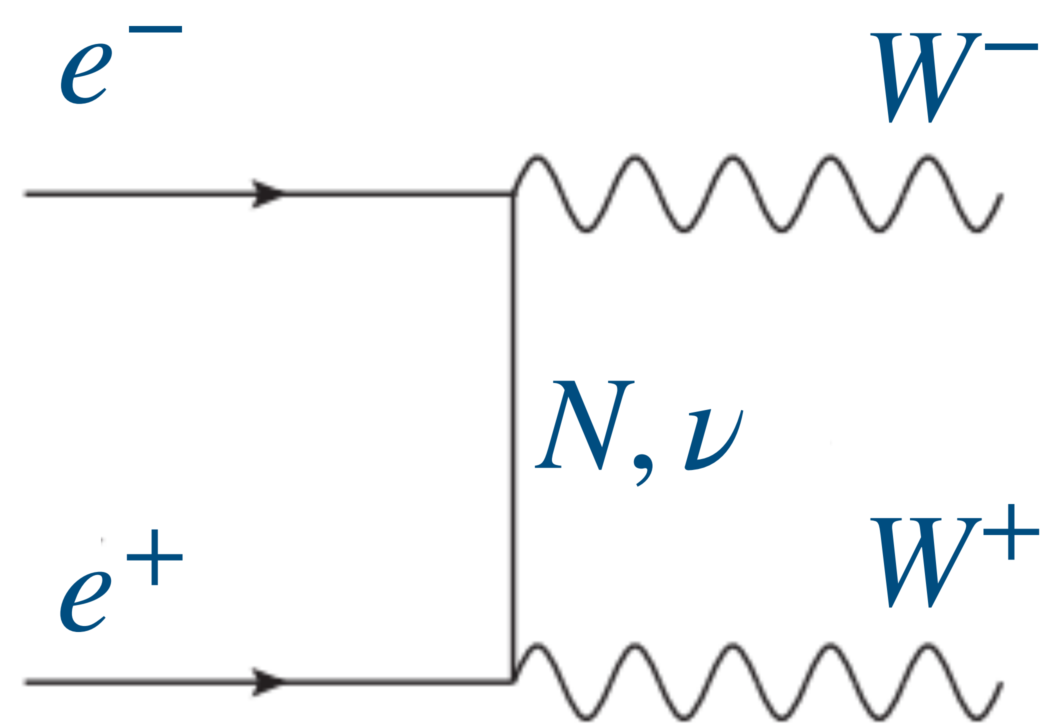




arXiv:1508.04937

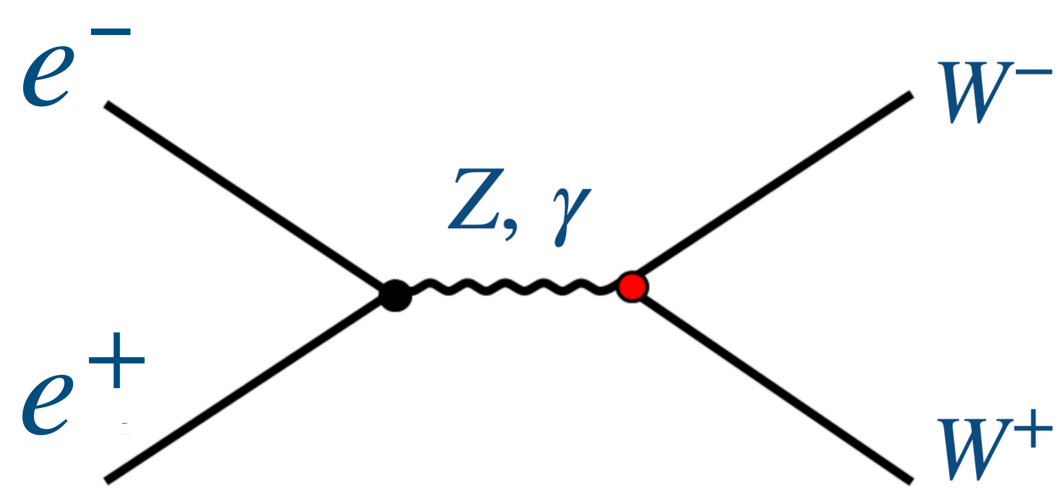
$e^-e^+ \to W^-W^+, W^\pm \to 2j$

Future colliders are planned for opposite-sign lepton beams



Study final states with 4 jets

We assume that only one right-handed neutrino N_1 contributes in process



This process was not studied before

Event generation: Whizard 3
Hadronisation: Pythia6
Detector simulation and event reconstruction: Delphes/ILC card
$W^\pm$ reconstruction is forced into 2 jets

Backgrounds and cuts

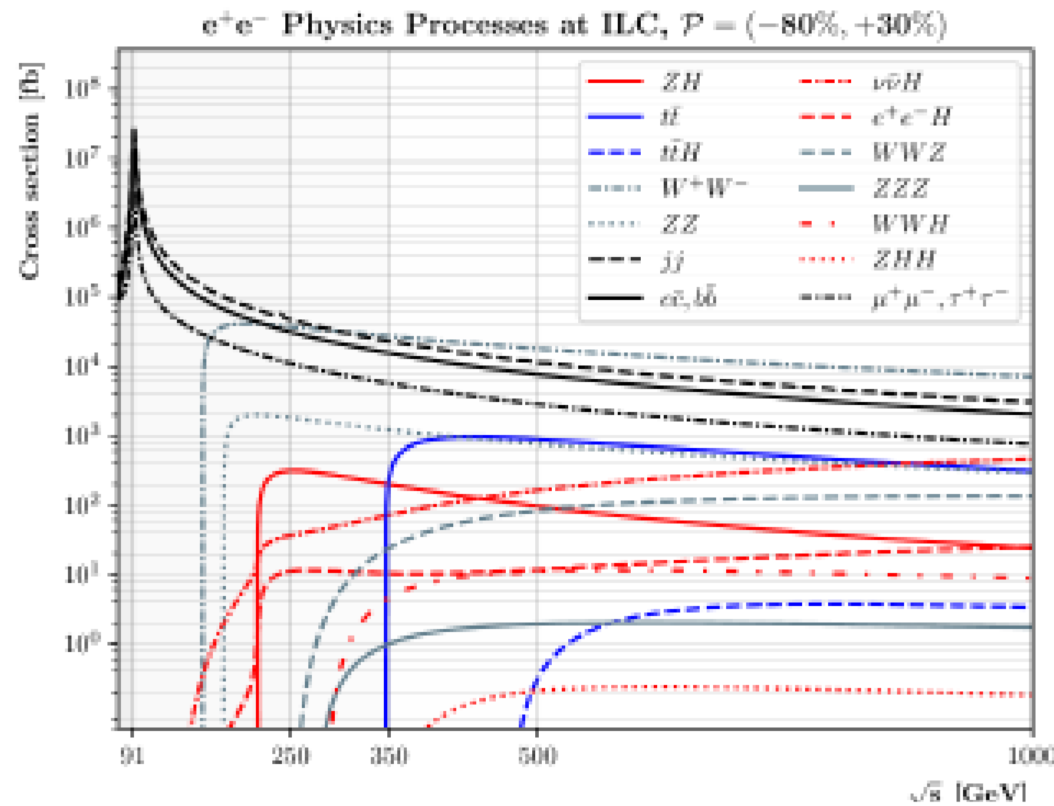
Standard Model processes with 4 jets in final state:

$e^+e^- \rightarrow W^+W^-$

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

$e^+e^- \rightarrow q\bar{q}$

$e^+e^- \rightarrow ZZ$



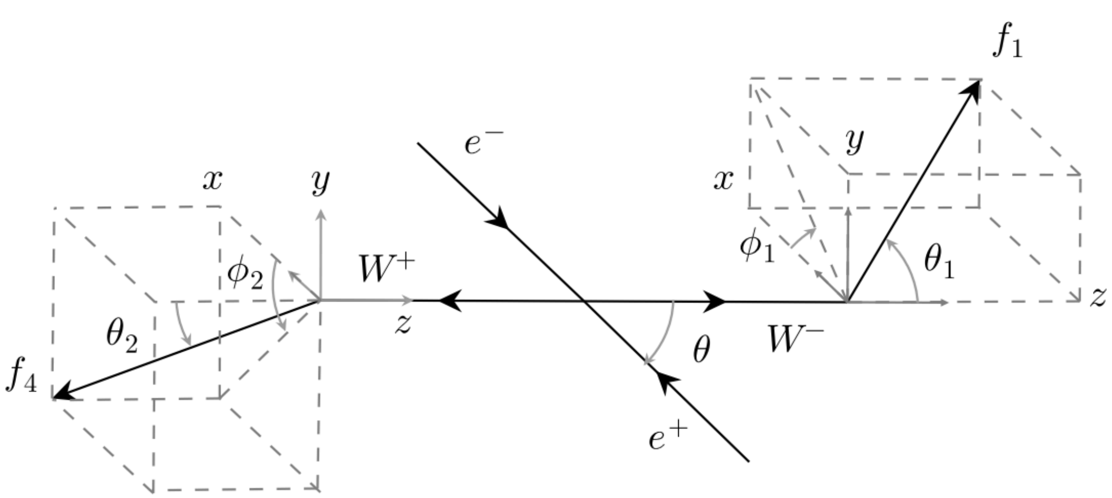
70 GeV $< M_{\text{reco}} < 90$ GeV (for each W)

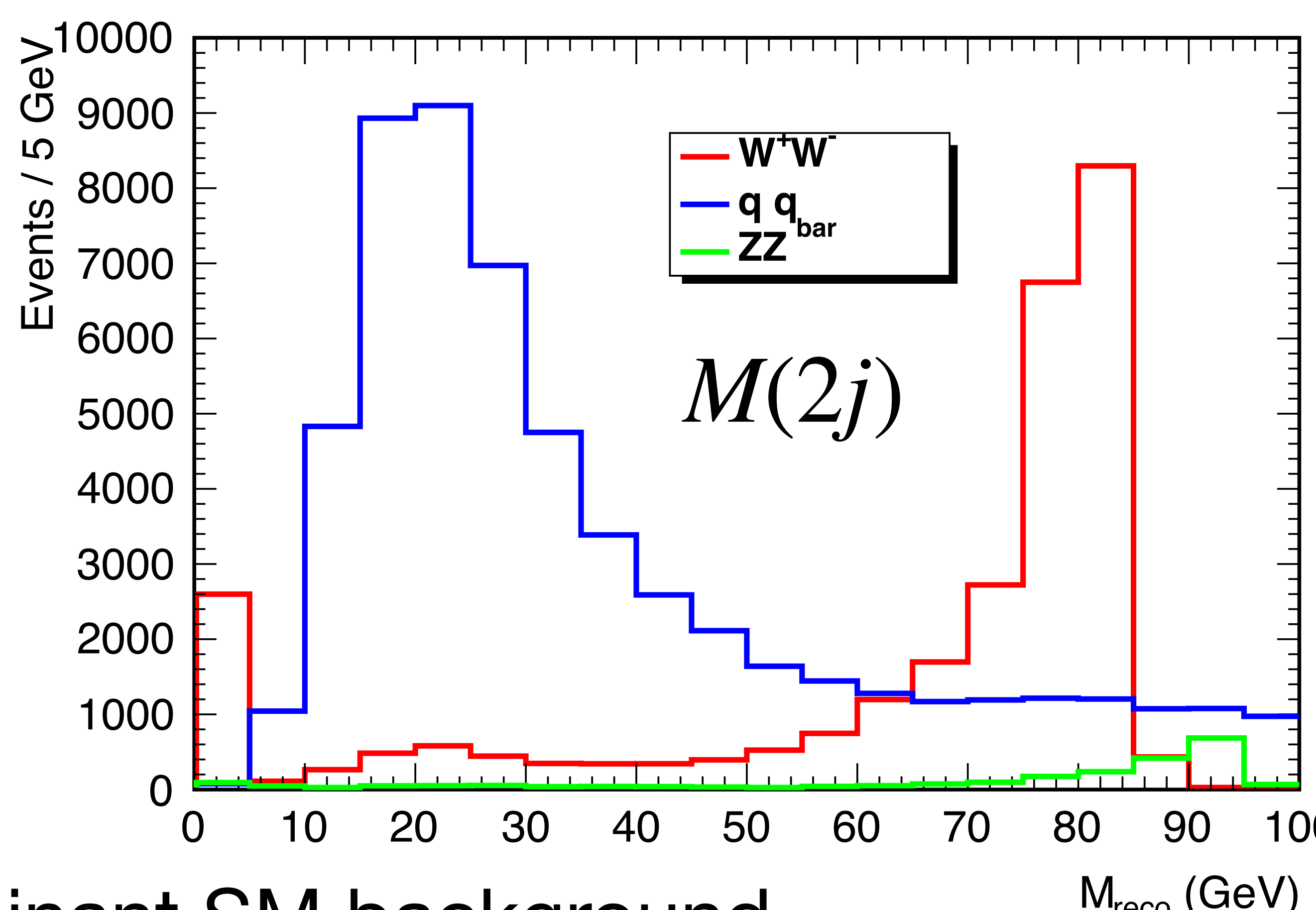
$\cos\Theta < 0.6$

p_x, p_y balance < 20 GeV

$\cos\Theta_{\text{decay}} < 0.8$

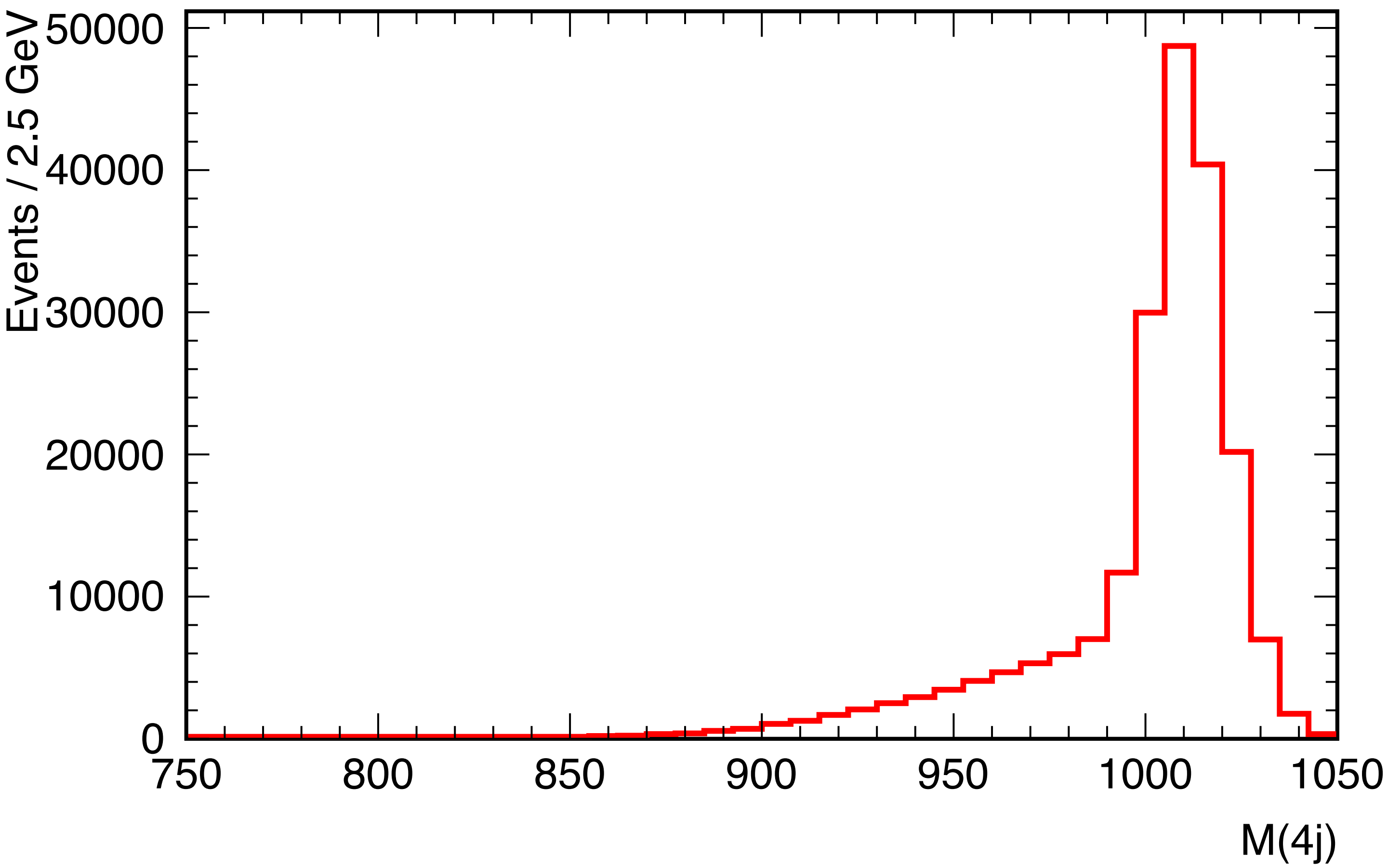
$M(4j) > 900$ GeV



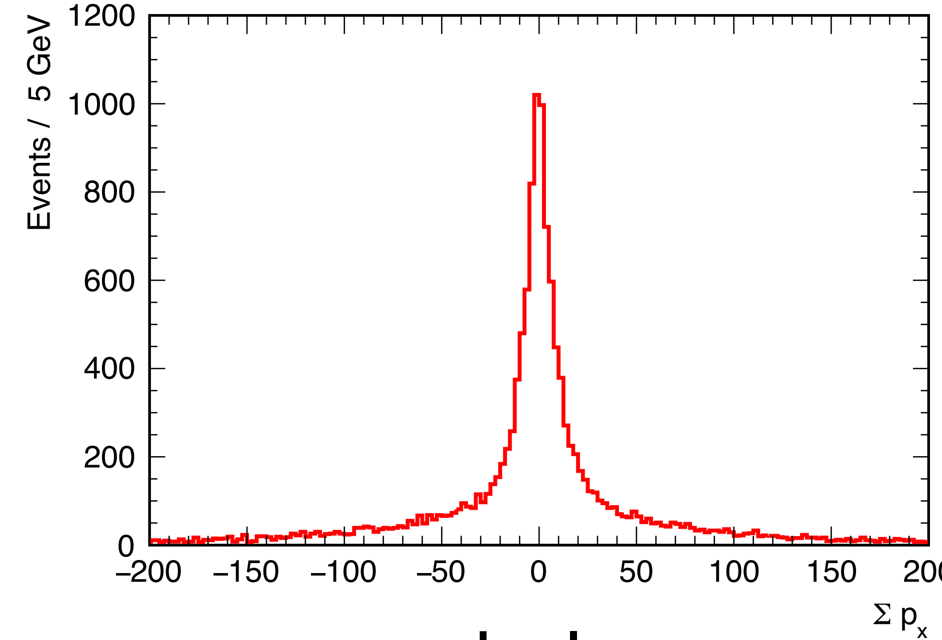


W^+W^- is dominant SM background

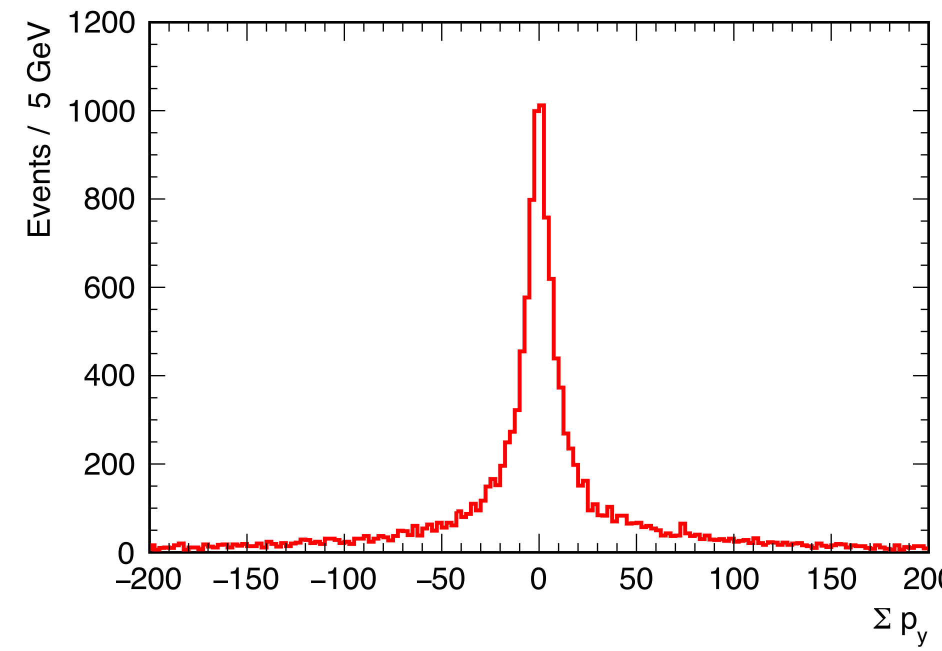
E and p distributions



M(4j)



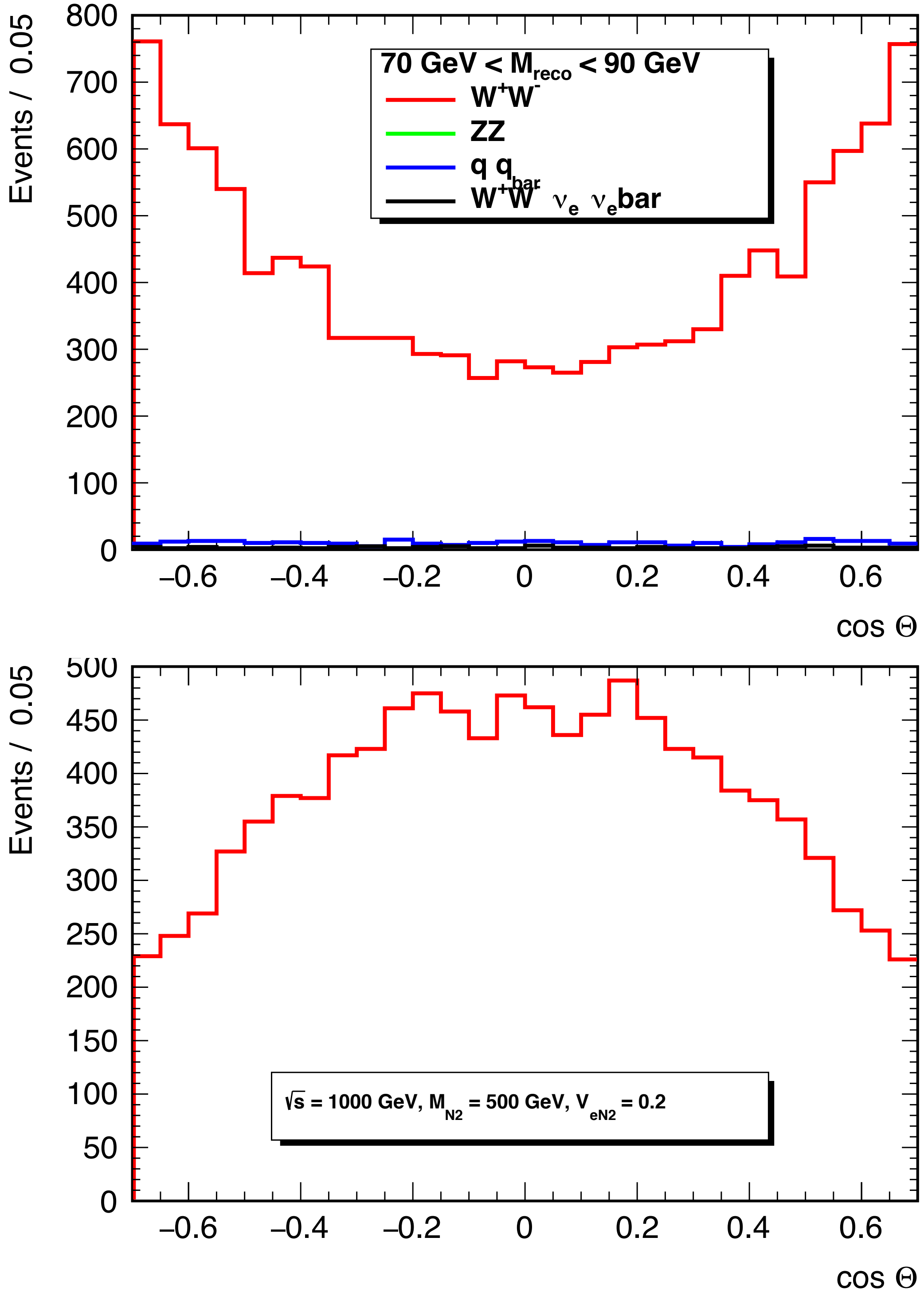
px balance



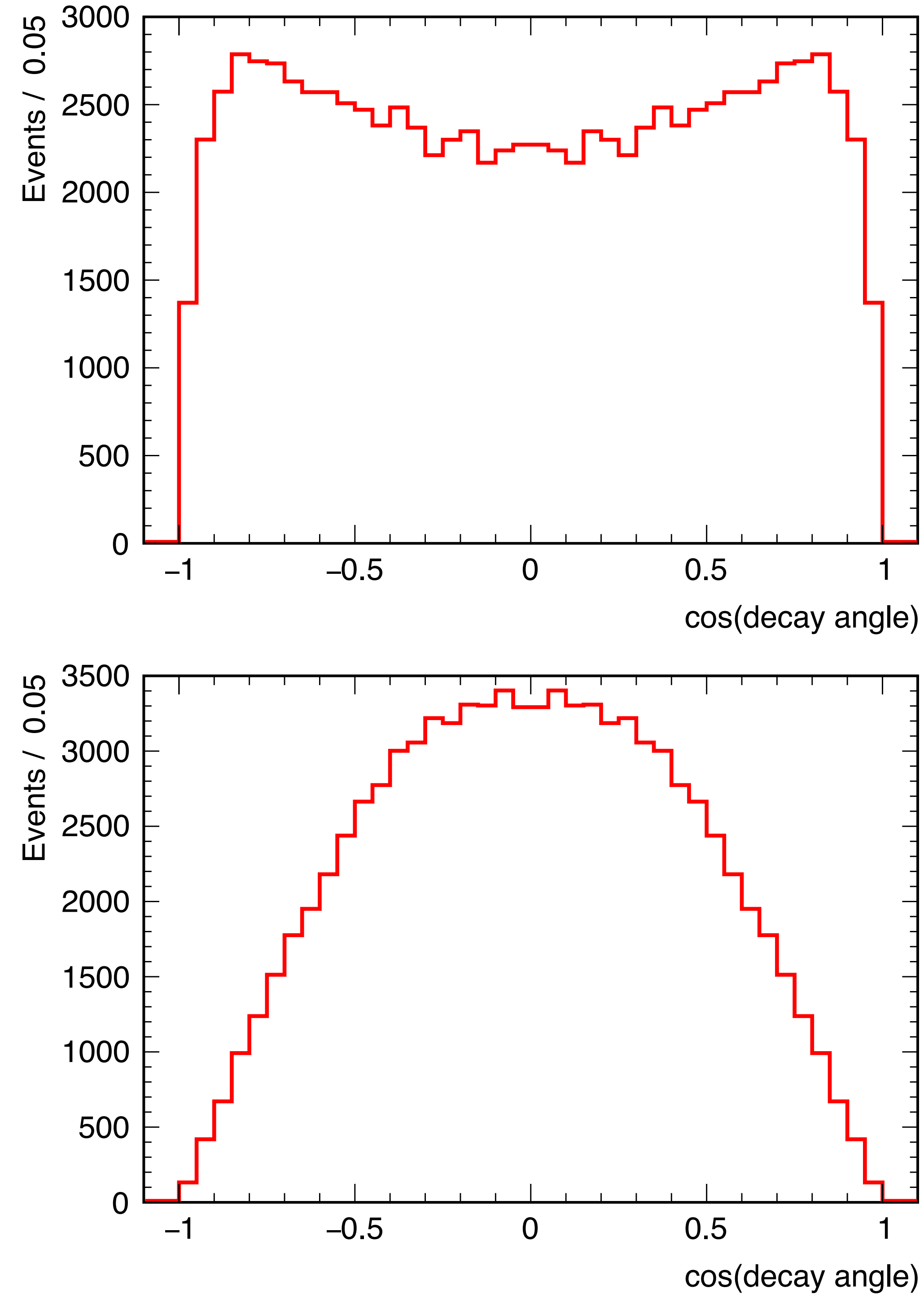
py balance

Backgrounds with unregistered particles are effectively suppressed by cuts

Angular distributions



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

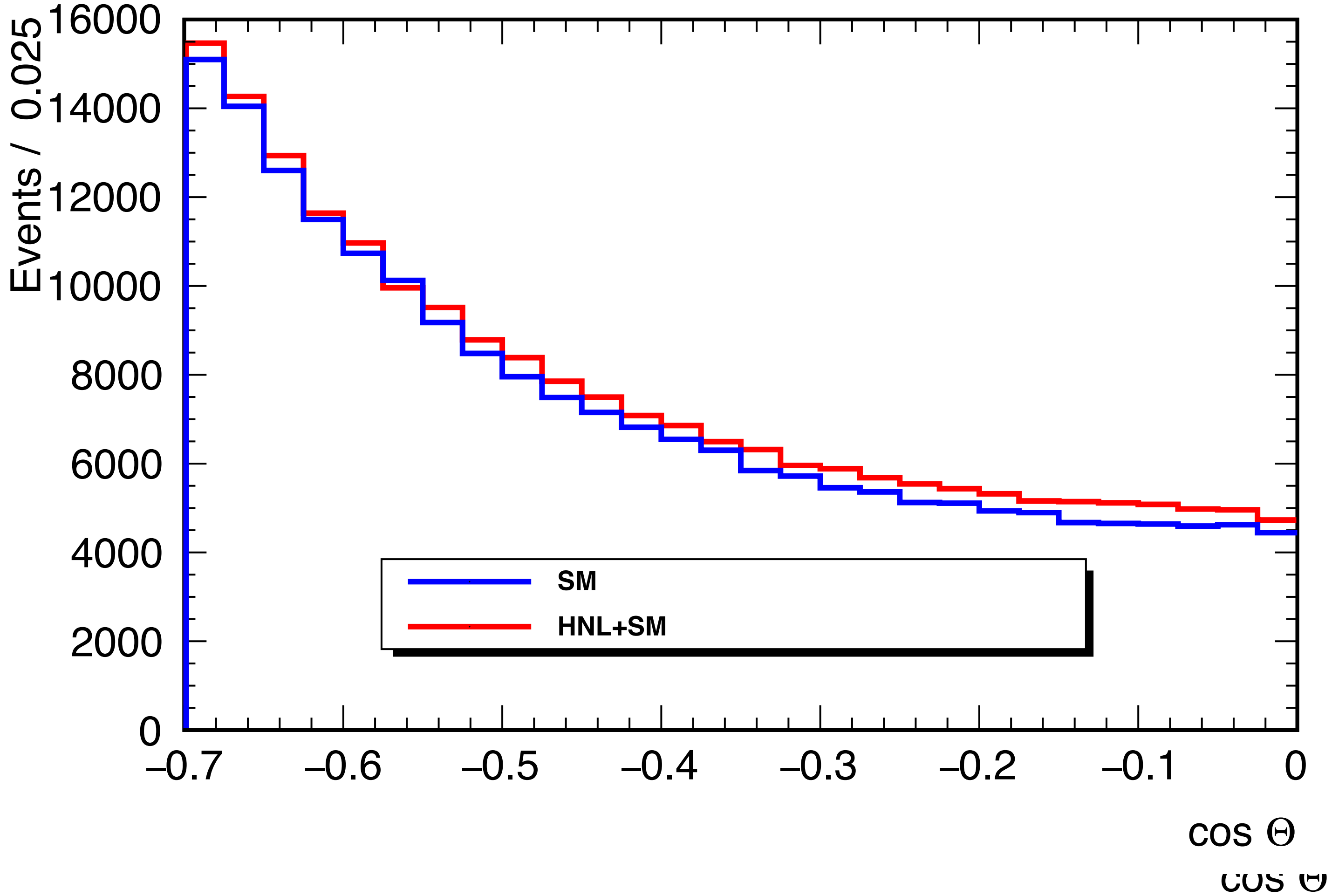


cos decay for pure SM (up) and pure HNL signal (down)

Interference

$\cos\Theta$ distribution:
blue line — pure SM

red line — interfered signal of HNL ($|V_{e1}|^2 = 0.0025$) and SM



Jets reconstruction

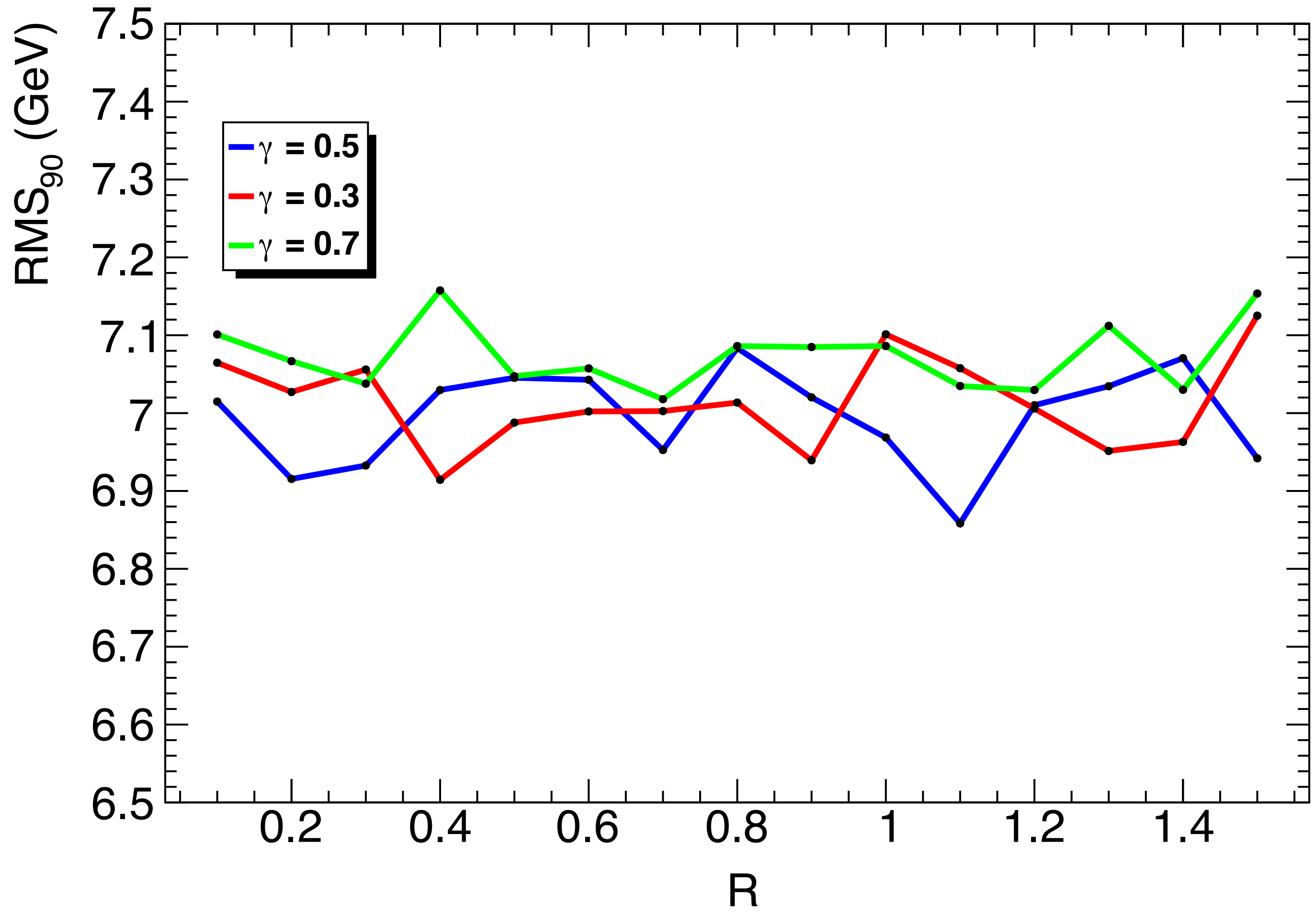
Valencia algorithm (arXiv:1404.4294, arXiv:1607.05039):

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

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

Dependence on parameters is negligible in our reconstruction

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

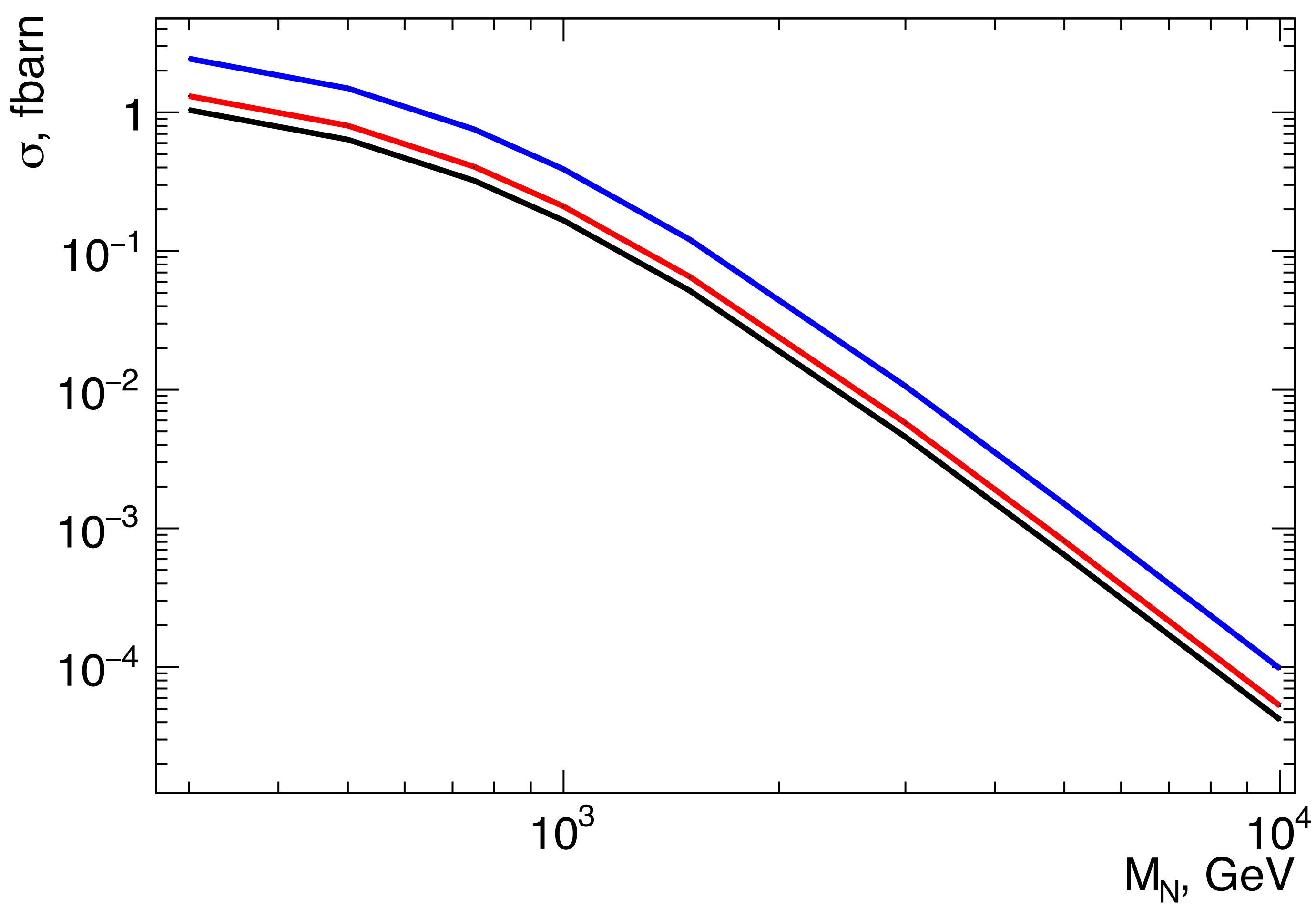


We take $R = 1.0$, $\beta = 1.0$, $\gamma = 0.5$

Cross sections

Cross sections for pure HNL with $|V_{e1}|^2 = 0.0021$

Different polarisations:
blue line — (-0.8, 0.3)
red line — (-0.8, -0.3)
black line — no polarisation



Cross sections for pure SM:
(-0.8,0.3) — $5.84 \cdot 10^2$ fb
(-0.8,-0.3) — $3.15 \cdot 10^2$ fb
no polarisation — $2.55 \cdot 10^2$ fb

σ(SM+HNL)/σ(SM),
$|V_{e1}|^2 = 0.02, M_N = 1$ TeV:
(-0.8,0.3) — 1.066
(-0.8,-0.3) — 1.067
no polarisation — 1.065

Analysis

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

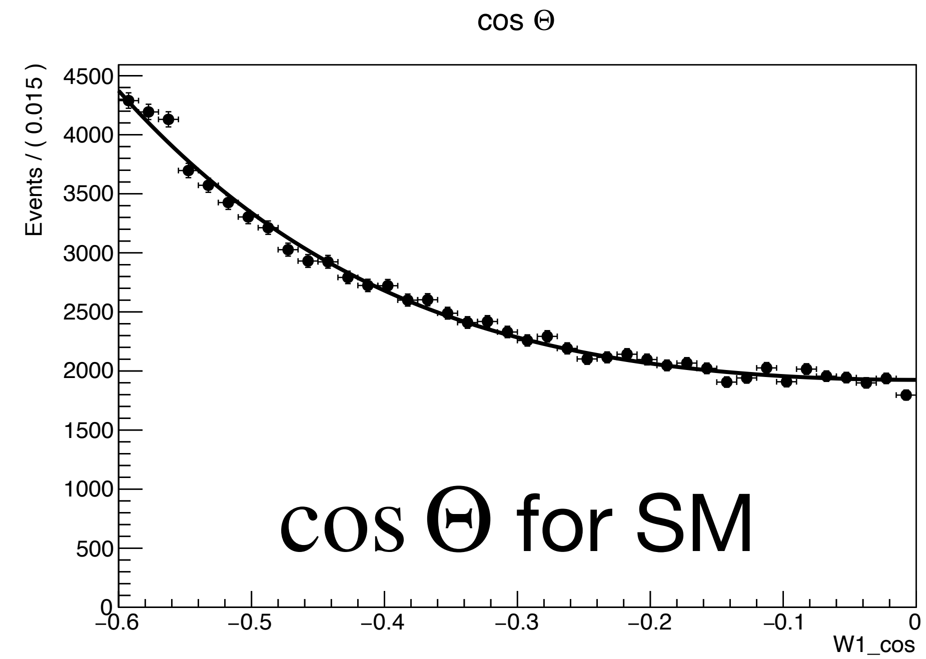
SM and SM+HNL train datasets and SM+HNL test dataset generated for different mixing parameters and masses

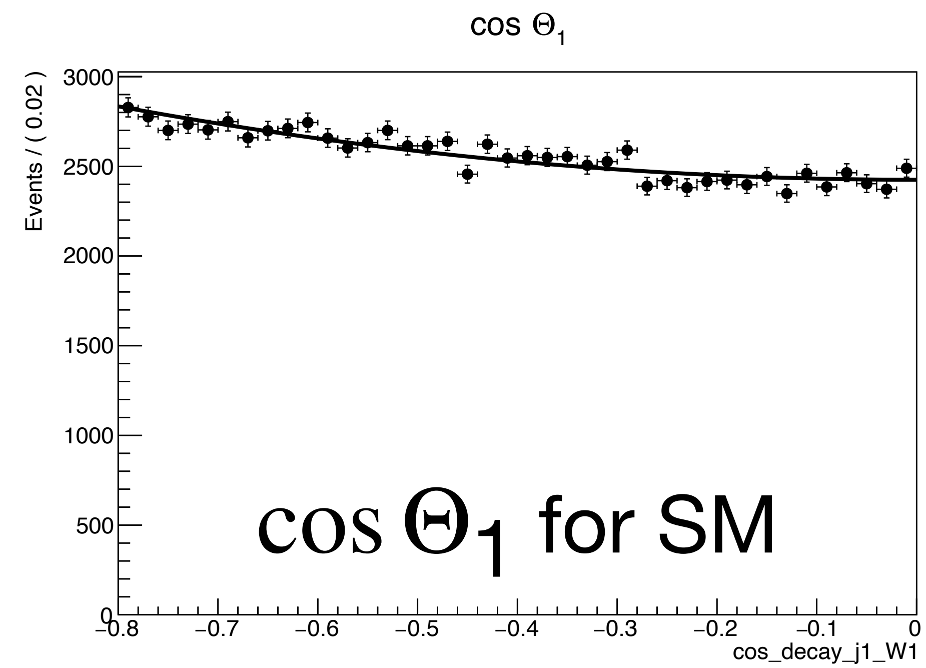
Shapes of PDF are obtained from train datasets and then test datasets are checked

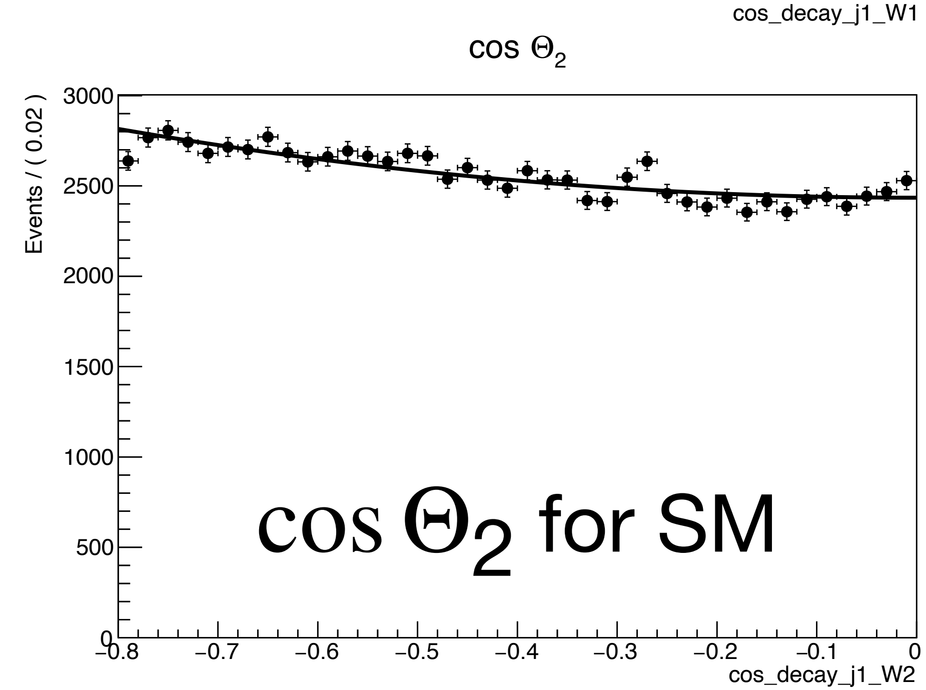
$$\text{pdf}(x_i) = \text{pdf}_{\Theta}(x_i) \cdot \text{pdf}_{\Theta_1}(x_i) \cdot \text{pdf}_{\Theta_2}(x_i)$$

$$\text{pdf}_{\Theta}(x_i) = ax^4 + bx^2 + c$$

$$\text{pdf}_{\Theta_{1,2}}(x_i) = ax^2 + b$$

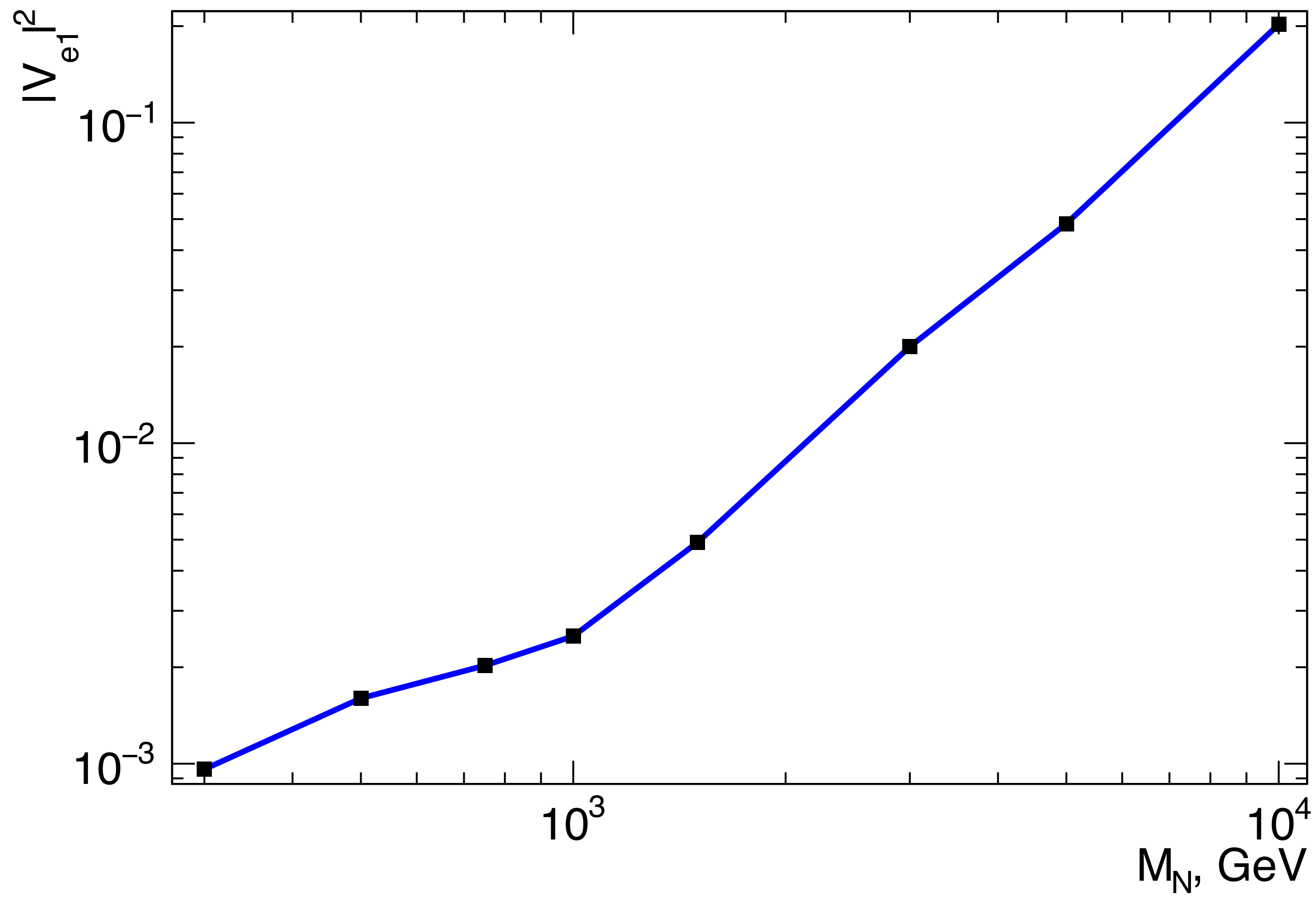






Results

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



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

Evidence — significance = 3σ

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

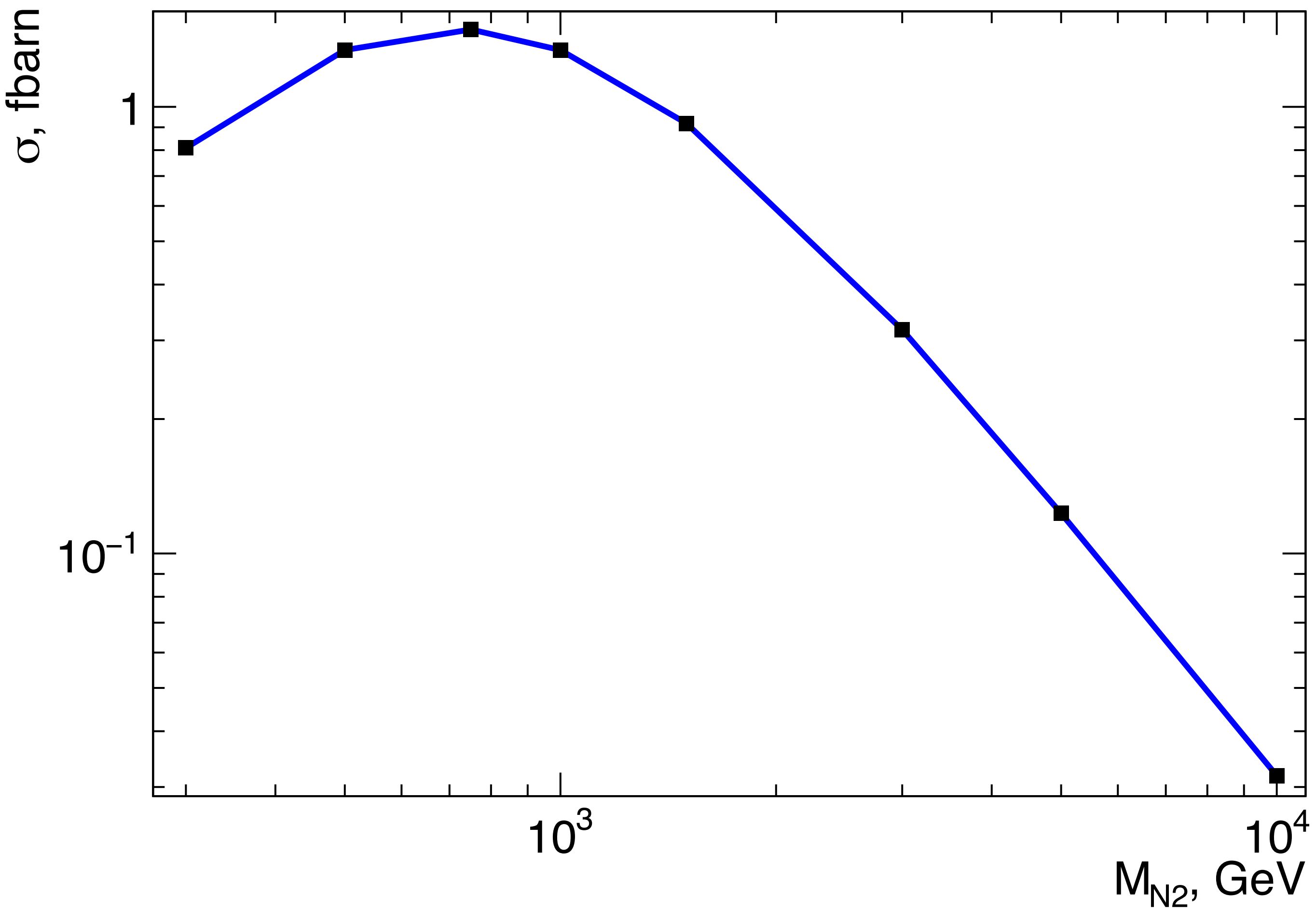
$$L_{\text{SM}} = \text{Poiss}(N_{\text{analysis}}\,|\,N_{\text{SM expected}}) \cdot \Pi_i\ \text{pdf}_{\text{SM}}(x_i)$$

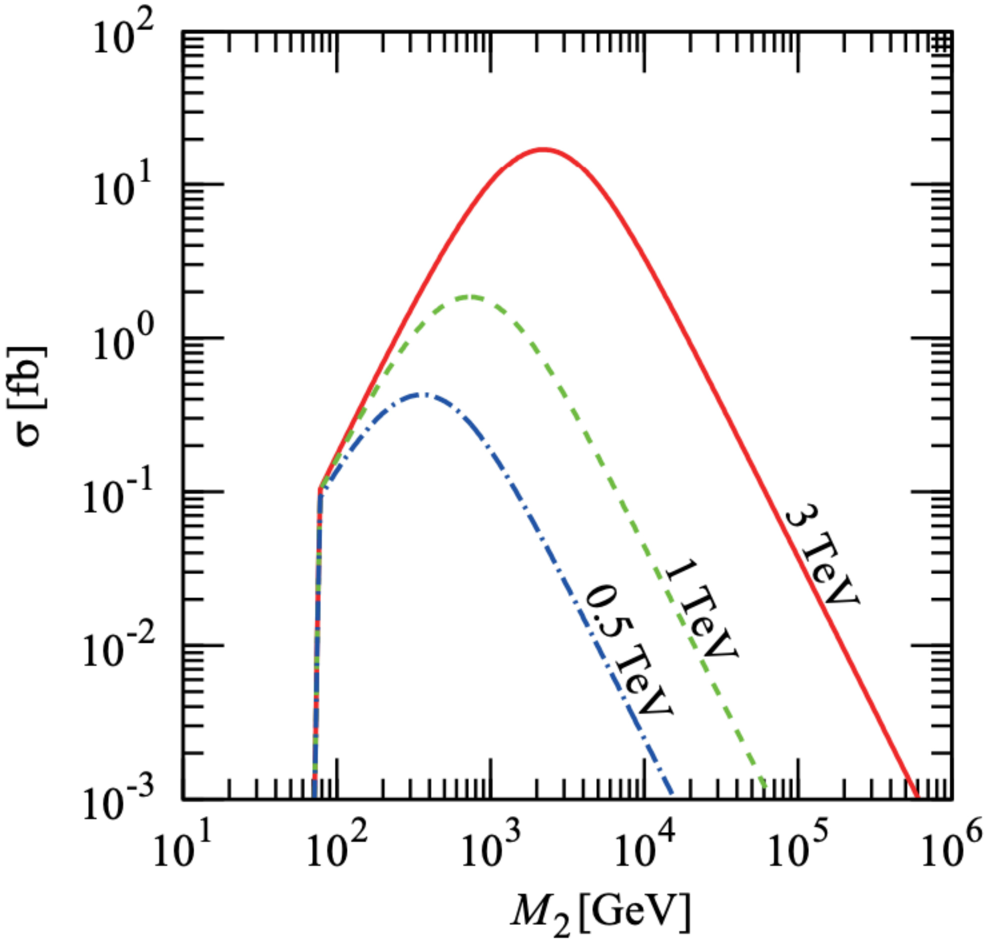
Conclusions

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

Thank you for your attention

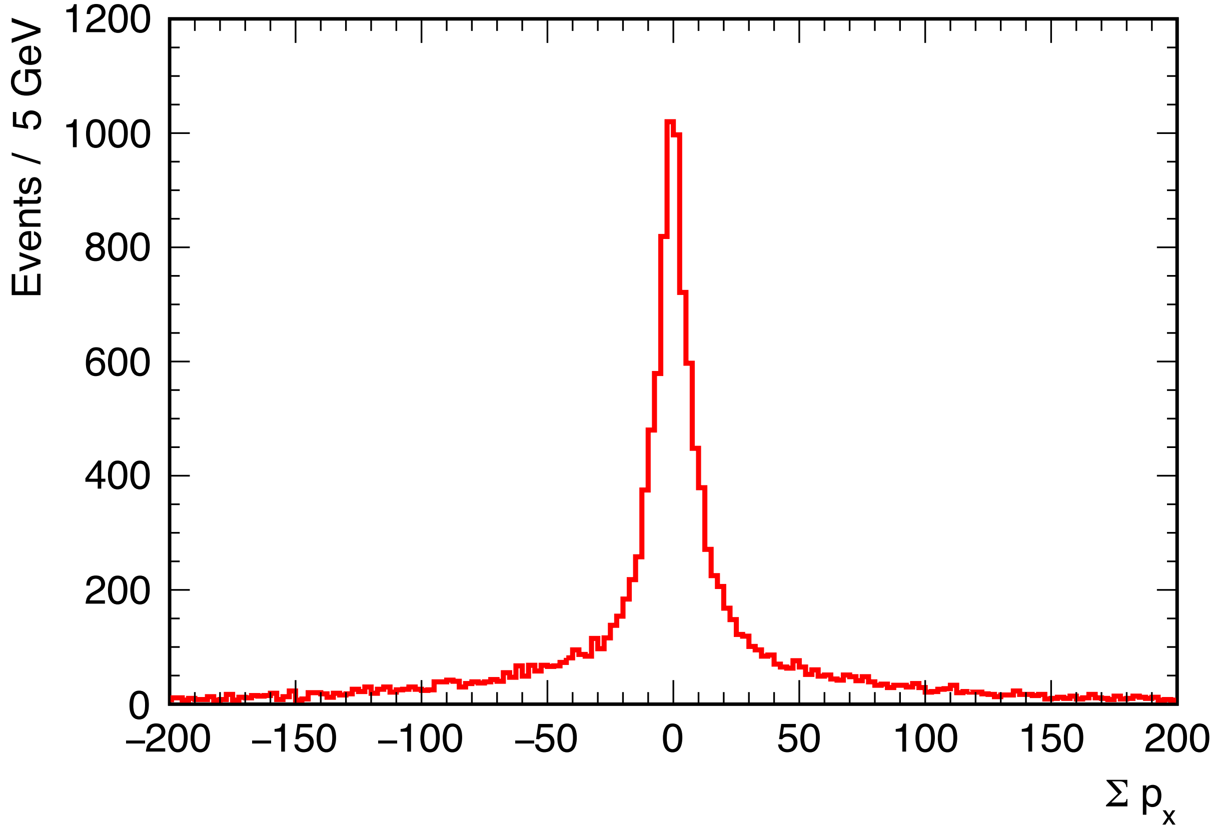
$e^- e^- \to W^- W^-$



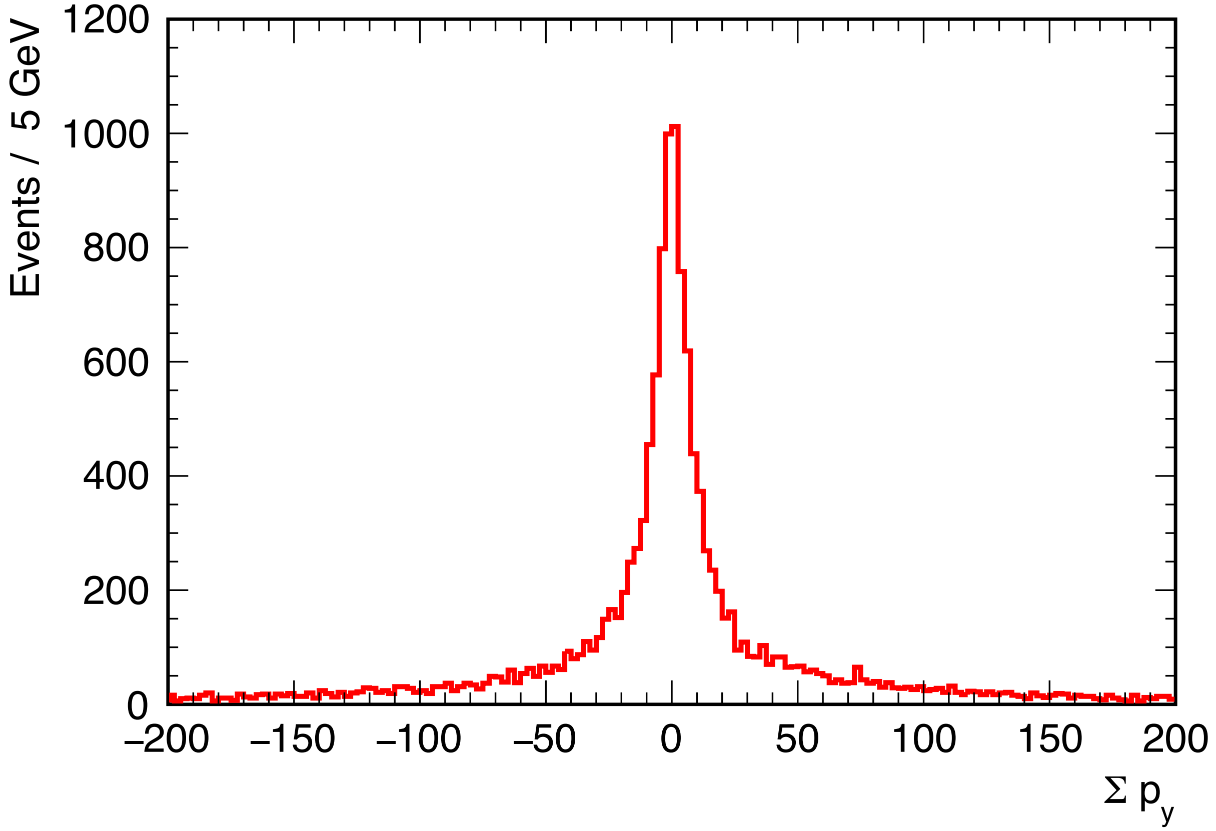


$$|V_{e2}|^2 = 0.0021$$

p_x, p_y balance



px balance



py balance

Angle between planes