Improving Heavy Dirac Neutrino Prospects at Future Hadron Colliders Using Machine Learning

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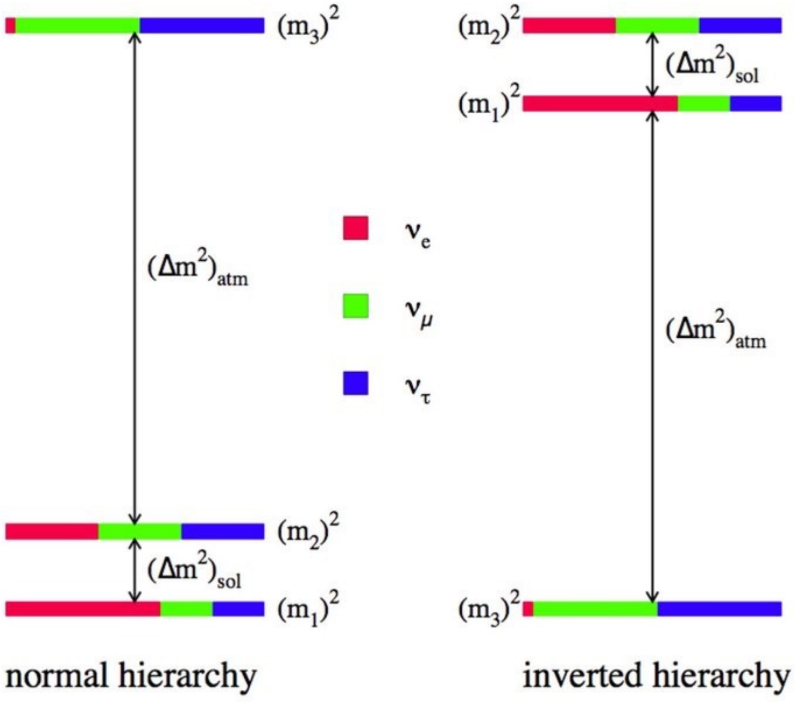
Introduction

- **Neutrino mass**
  - Confirmed by Neutrino Oscillation experiments (Super-Kamiokande, Sudbury, Daya Bay, …)
    3 neutrino mass states.
- **In particle physics**
  - Beyond the Standard Model (SM) description
    - *New physics!*

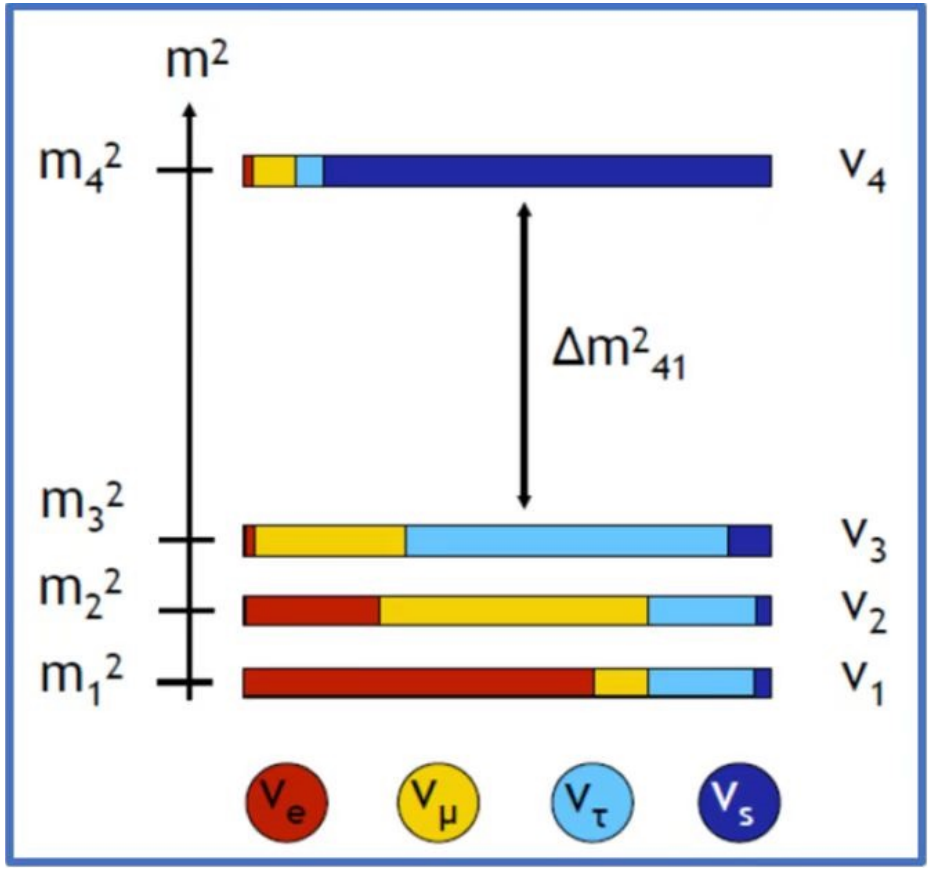


Nobel Prize for Physics in 2015.

Introduction

- **Seesaw mechanisms provide natural explanations of the tiny neutrino masses.**

- Type-I
- Type-II
- Type-III



Inverse seesaw

- **The Yukawa Lagrangian is given by** [1,2]

$$-\mathcal{L}_Y = Y_{\alpha\beta}\bar{L}_\alpha \Phi N_{R,\beta} + M_{N,\alpha\beta}\bar{S}_{L,\alpha}N_{R,\beta} + \frac{1}{2}\mu_{S,\alpha\beta}\bar{S}_{L,\alpha}S^C_{L,\beta} + \mathrm{H.c.}$$

$L_\alpha = (\nu_\alpha, \ell_\alpha)^{\mathrm{T}}$ - Standard Model lepton doublet

Φ - Standard Model Higgs doublet

$S_L^C \equiv S_L^{\mathrm{T}} C^{-1}$ - charge conjugate of S_L

M_N - Dirac mass term

μ_S - Majorana mass term

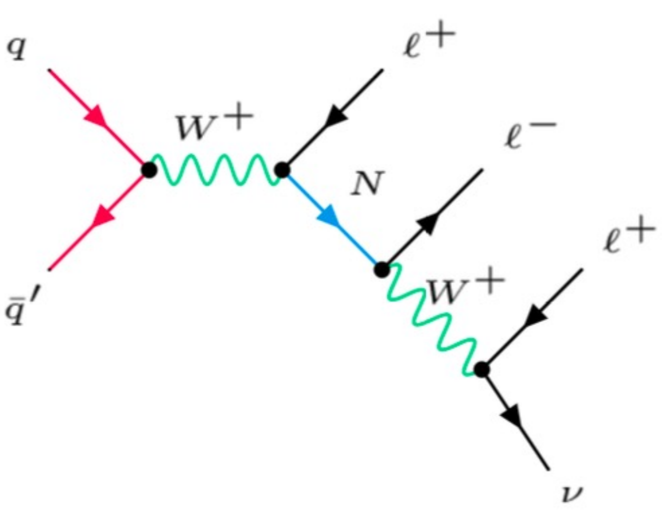
[1] R.N. Mohapatra, PRL 56 (1986) 561

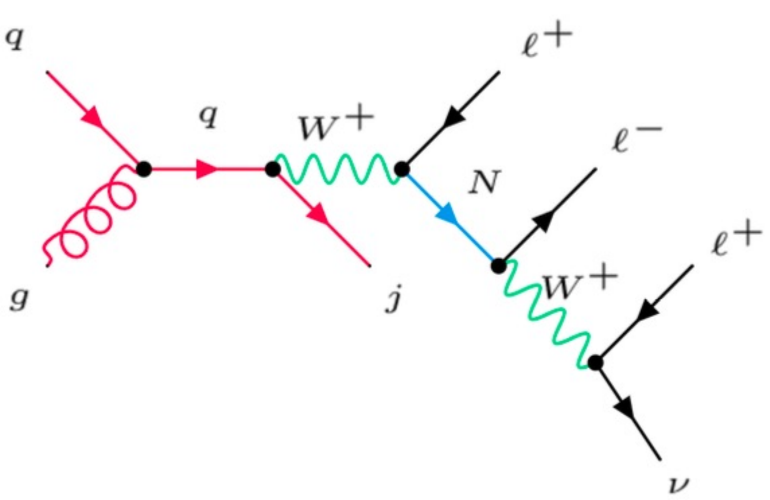
[2] R.N. Mohapatra and J.W.F. Valle, PRD 34 (1986) 1642

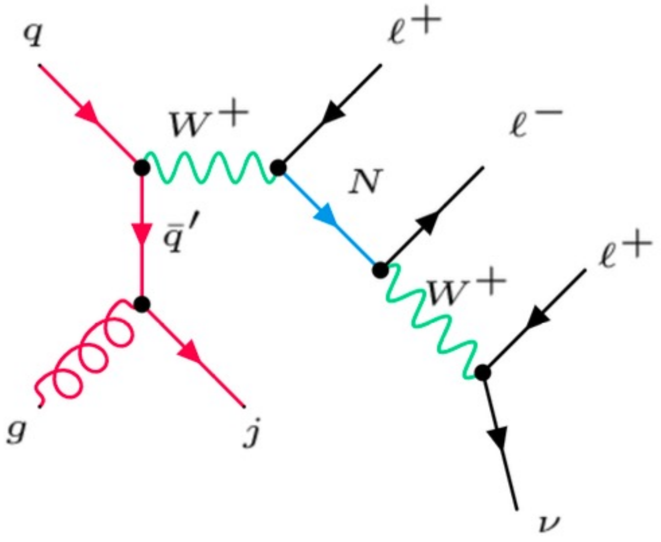
Inverse seesaw

- **In the limit of $\|\boldsymbol{\mu_S}\| \ll \|\boldsymbol{M_N}\|$ (with $\|\boldsymbol{\mu_S}\| \equiv \sqrt{\boldsymbol{tr(x^\dagger x)}}$), the primary signature of heavy neutrinos at the hadron colliders are [3,4]:**

$$pp \to \ell^\pm_\alpha N \to \ell^\pm_\alpha \ell^\mp_\beta W^\pm \to \ell^\pm_\alpha \ell^\mp_\beta \ell^\pm_\gamma \nu$$







[3] C. Degrande *et al.*, PRD 94 (2016) 053002 (arXiv:1602.06957)

[4] arXiv:1408.0983, 1706.02298

Inverse seesaw

- **The heavy neutrino *N* will decay [5,6]:**

$$\Gamma(N \to \ell^- W^+) = \frac{\alpha_W |V_{\ell N}|^2}{16} \frac{m_N^3}{m_W^2} \left(1 - \frac{m_W^2}{m_N^2}\right)^2 \left(1 + \frac{m_W^2}{m_N^2}\right)$$

$$\Gamma\left(N \to \nu_\ell \; Z\right) = \frac{\alpha_W |V_{\ell N}|^2}{32 \cos^2 \theta_W} \frac{m_N^3}{m_Z^2} \left(1 - \frac{m_Z^2}{m_N^2}\right)^2 \left(1 + \frac{m_Z^2}{m_N^2}\right)$$

$$\Gamma\left(N \to \nu_\ell \; h\right) = \frac{\alpha_W |V_{\ell N}|^2}{32} \frac{m_N^3}{m_W^2} \left(1 - \frac{m_h^2}{m_N^2}\right)^2$$

[5] A. Pilaftsis, Z. Phys. C 55 (1992) 275
[6] W. Buchmuller and C. Greub, Nucl. Phys. B 363 (1991) 345

Inverse seesaw

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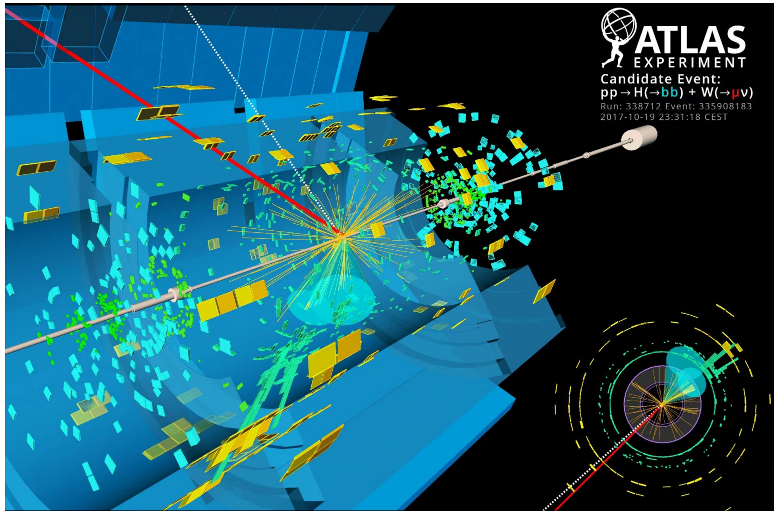
Collider analysis – Signal generation

- The final states of the signature in the detector:

  electrons, muons, jets, ⋯

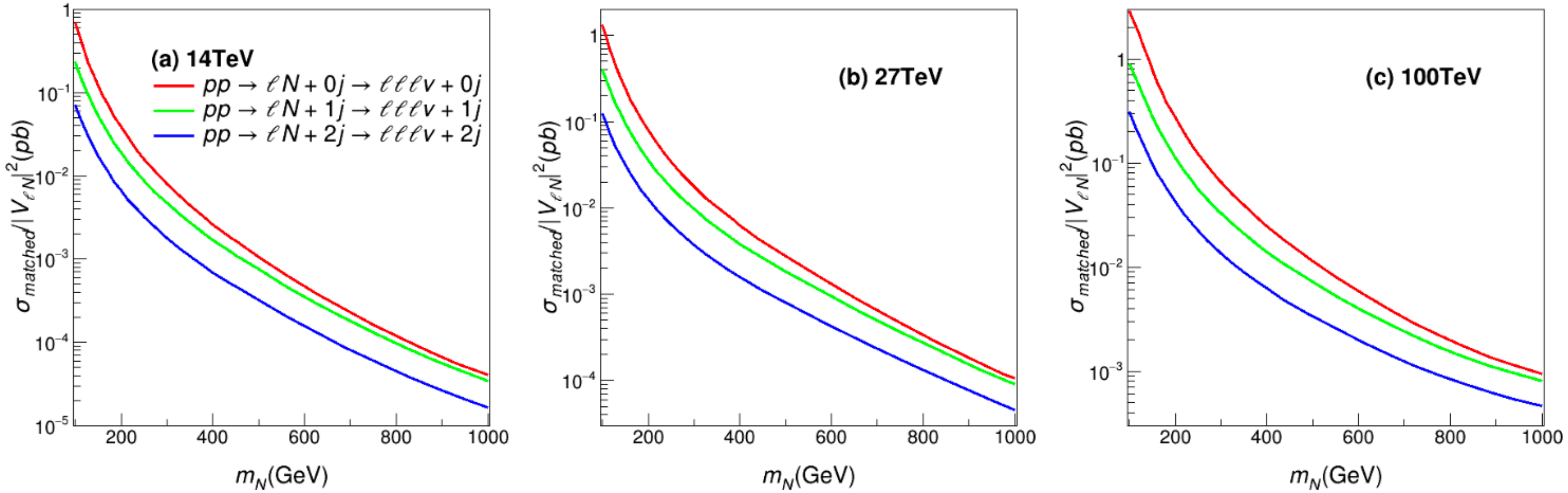


- Measurements of each particle in the detector:
  - p_T - transverse momentum
  - η - pseudorapidity
  - ϕ - azimuthal angle
- Geometrical acceptance cuts from ATLAS: $p_T^{\ell,leading} > 20\ \mathrm{GeV}$

$\sqrt{s}$ (TeV)	electron		muon		jet	
	p_T (GeV)	$\lvert\eta\rvert$	p_T (GeV)	$\lvert\eta\rvert$	p_T (GeV)	$\lvert\eta\rvert$
14	>10	< 2.47	>10	< 2.7	> 20	< 4.5
27	>10	< 2.47	>10	< 2.7	> 30	< 4.5
100	>15	< 2.47	>15	< 2.7	> 45	< 4.5

Collider analysis – Signal generation

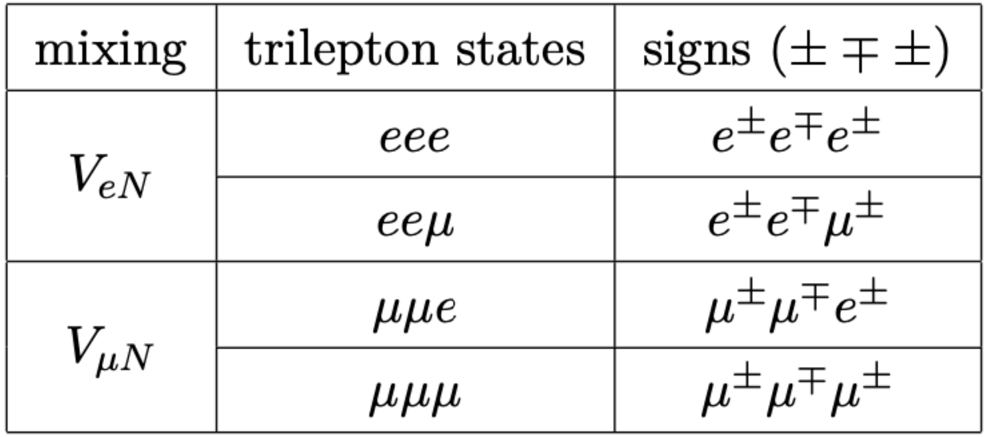
- Cross sections of trilepton signal process



- Cross sections increase with higher center of mass energies.
- Cross sections with 2jets are much smaller than those with 1jet. It is safe to neglect events with higher jet multiplicity $n_j \geq 3$.

Collider analysis – Signal generation

- Assuming either $|V_{eN}| \neq 0$ or $|V_{\mu N}| \neq 0$, in the charge space, the three leptons of an event can be either $+ - +$ or $- + -$. All the resultant trilepton states are



mixing	trilepton states	signs $(\pm \mp \pm)$
V_{eN}	eee	$e^{\pm}e^{\mp}e^{\pm}$
	$ee\mu$	$e^{\pm}e^{\mp}\mu^{\pm}$
$V_{\mu N}$	$\mu\mu e$	$\mu^{\pm}\mu^{\mp}e^{\pm}$
	$\mu\mu\mu$	$\mu^{\pm}\mu^{\mp}\mu^{\pm}$

Collider analysis – background generation

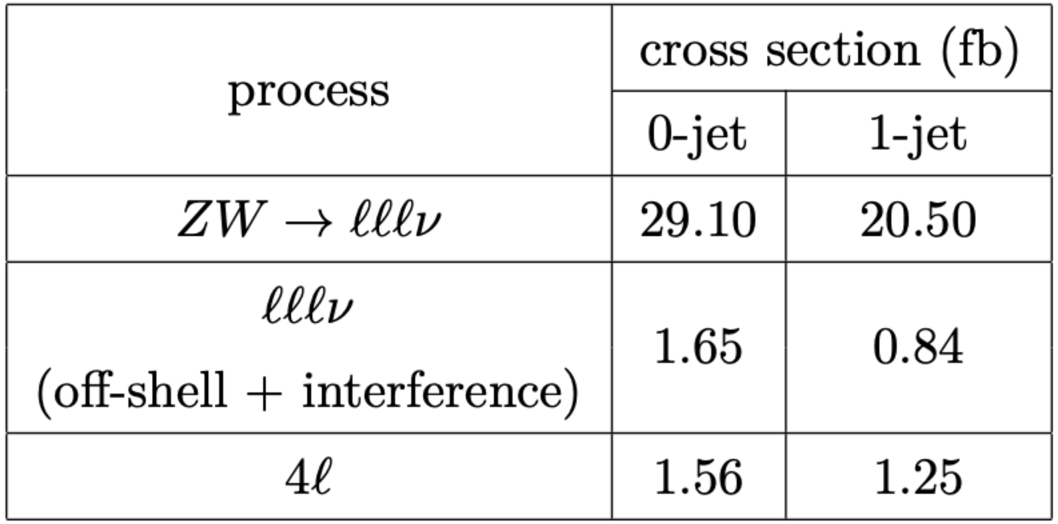
- The main background:

$$pp \to ZW^{\pm} \to \ell_1^{\pm}\ell_2^{\mp}\ell_3^{\pm}\nu$$

- Pre-selection:
  - The total number of energetic charged leptons is exactly 3, i.e. $n_e + n_\mu = 3$.
  - The invariant mass of the two leading leptons should be larger than 12 GeV, i.e. $m_{\ell_1 \ell_2}$ >12GeV.
  - The number of jets is not larger than 2, i.e. $n_j \leqslant 2$.
  - The missing transverse momentum $E_T^{miss} = | - \sum_{v_i} \overrightarrow{p_T}(v_i) |$ is larger than 20 GeV, i.e. E_T^{miss} >20GeV.

Collider analysis – background generation

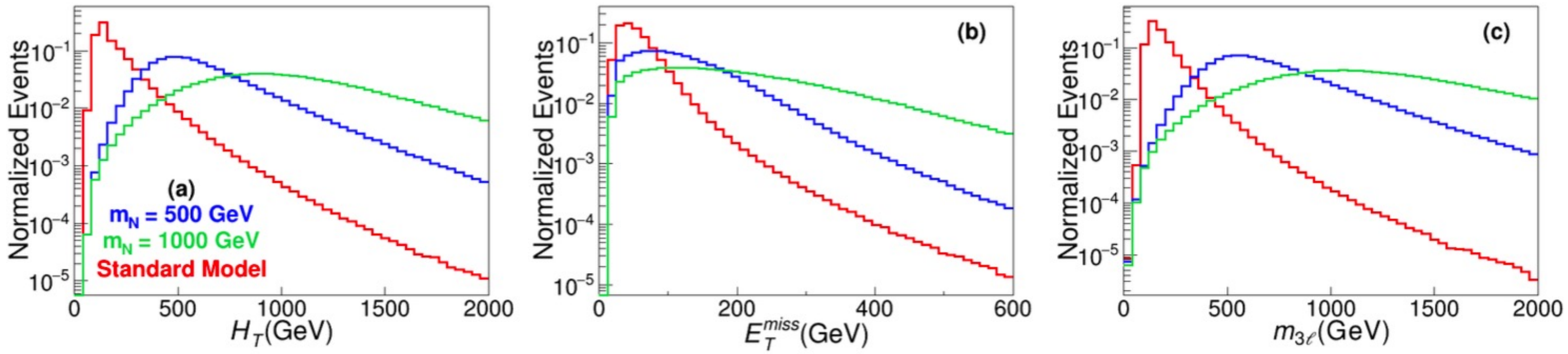
- Cross sections of all possible trilepton final state processes after pre-selections:

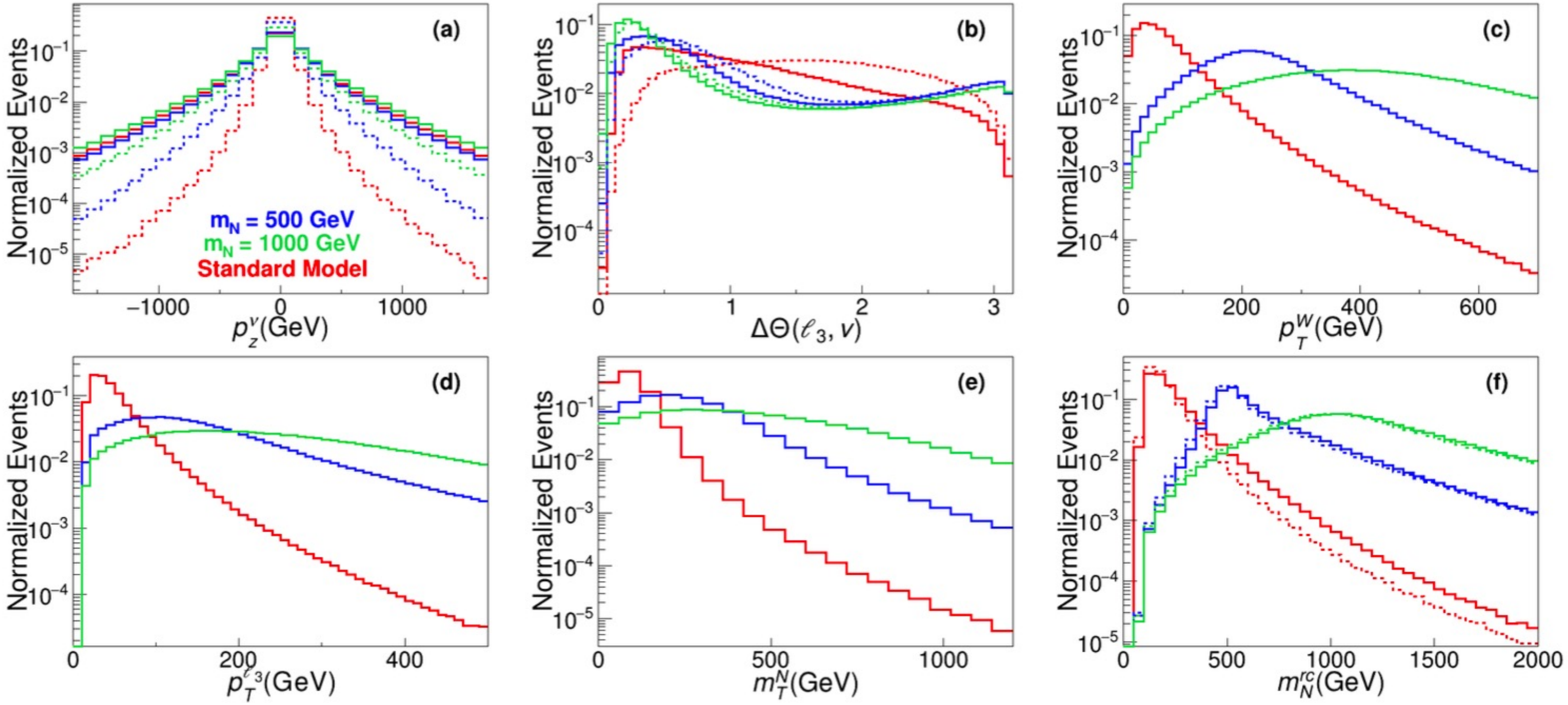


process	cross section (fb)	
	0-jet	1-jet
$ZW \to \ell\ell\ell\nu$	29.10	20.50
$\ell\ell\ell\nu$ (off-shell + interference)	1.65	0.84
4ℓ	1.56	1.25

- The contributions of the off-shell and four-lepton processes to the standard model backgrounds are small. We can just scale the *ZW* background by 1.1 to take the other two into account.

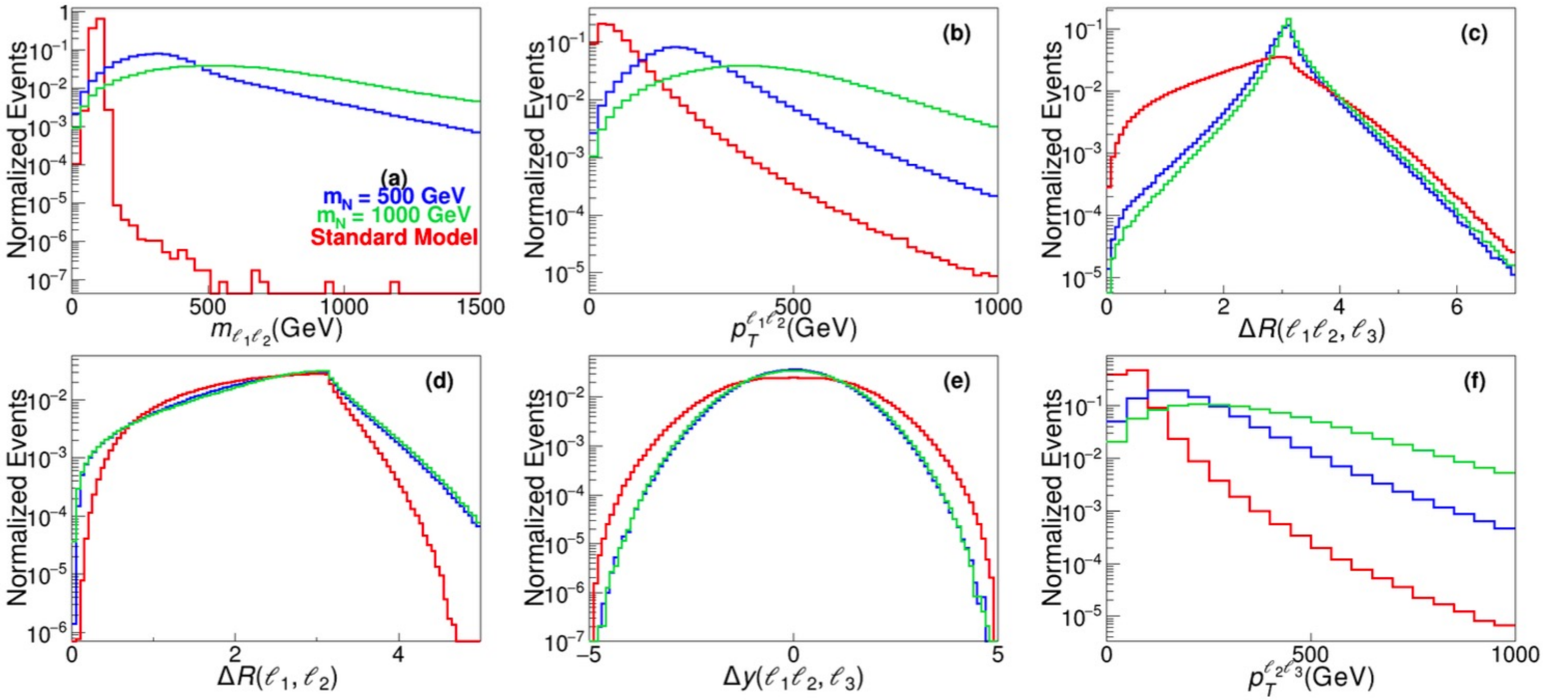
Collider analysis – Feature observables

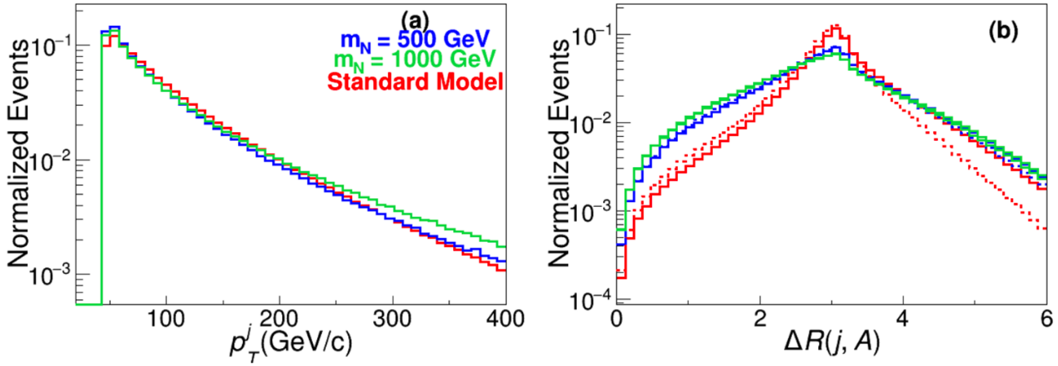




Variables reconstructed from the 3-lepton measurements.

Collider analysis – Feature observables

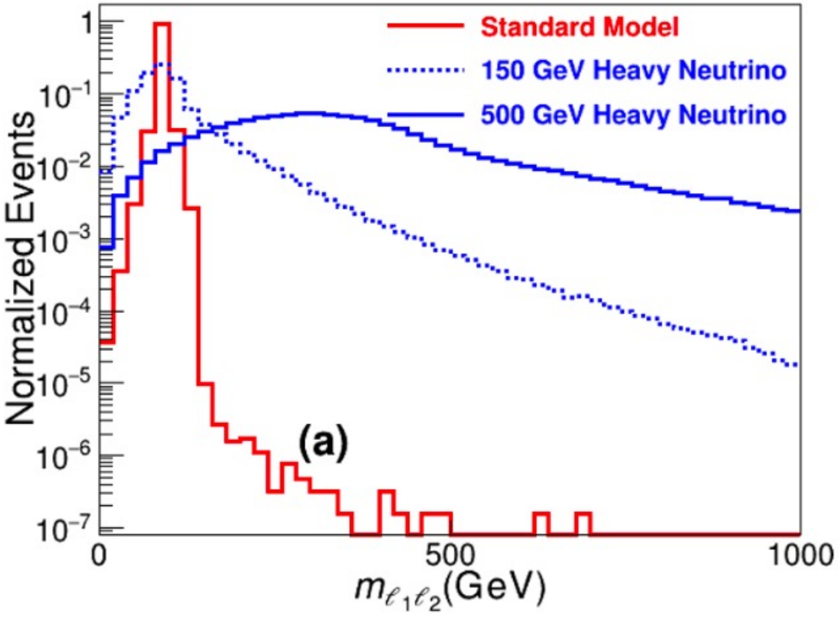




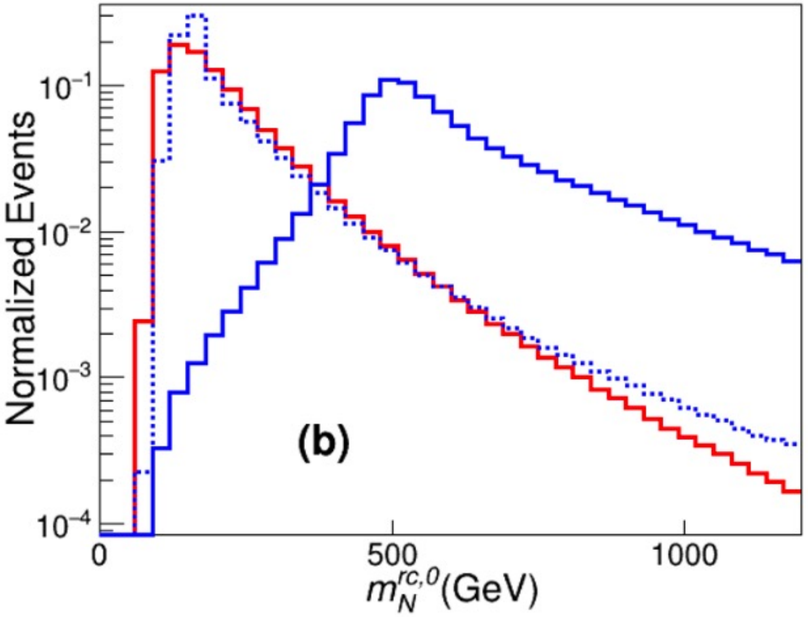
Variables reconstructed from the 3-lepton measurements.

Collider analysis – Feature observables

- Variables with the largest seperation power:



Z mass



Heavy neutrino mass (calculated from W mass assumption) $W^{\pm} \to \ell_3^{\pm}\nu$

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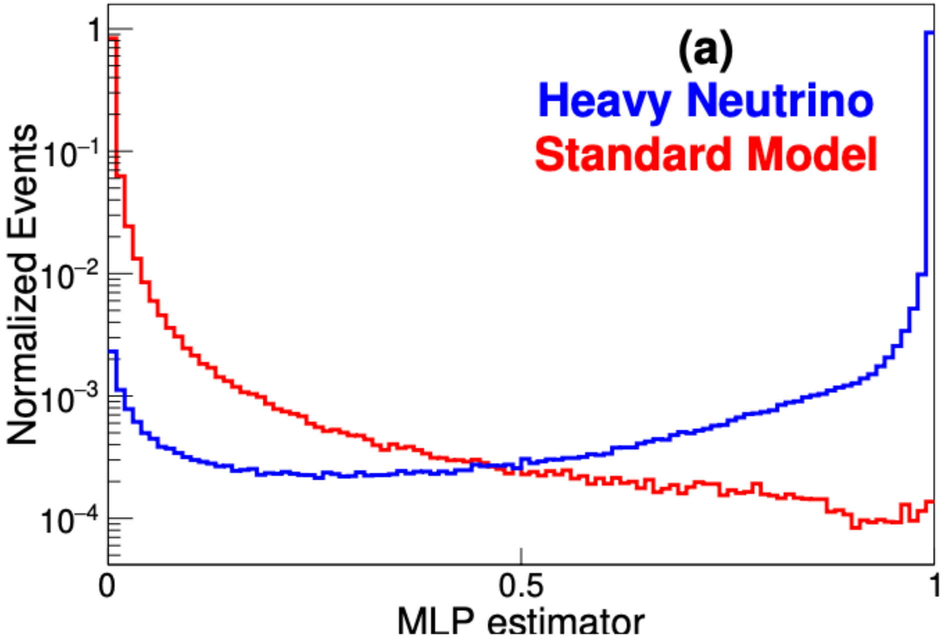
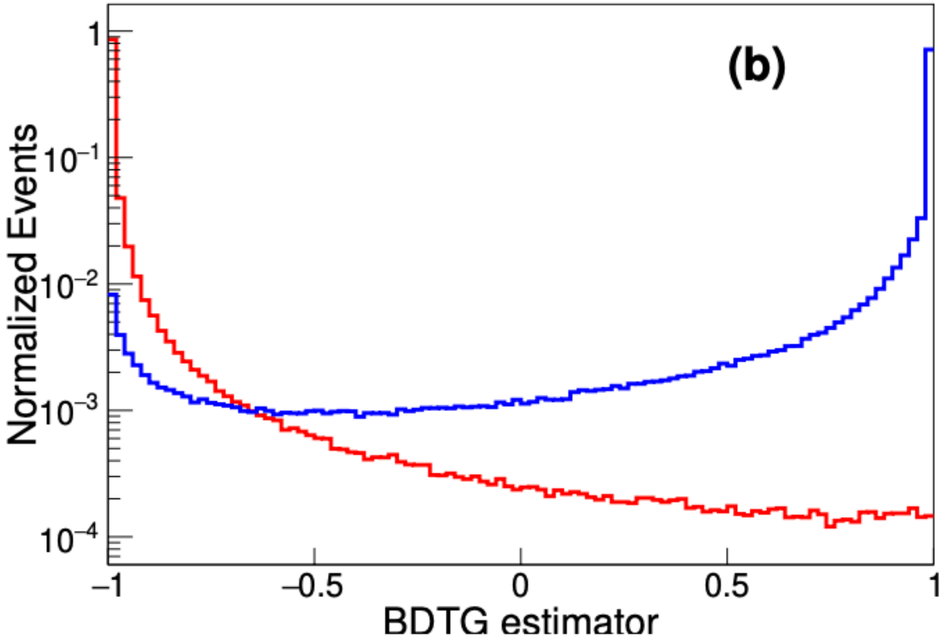
Collider analysis – Machine Learning (ML)

- The ML estimator distributions for $m_N = 500$ GeV:



Multi-Layer Perceptron (MLP)



Boosted Decision Tree with Gradient boosting (BDTG)

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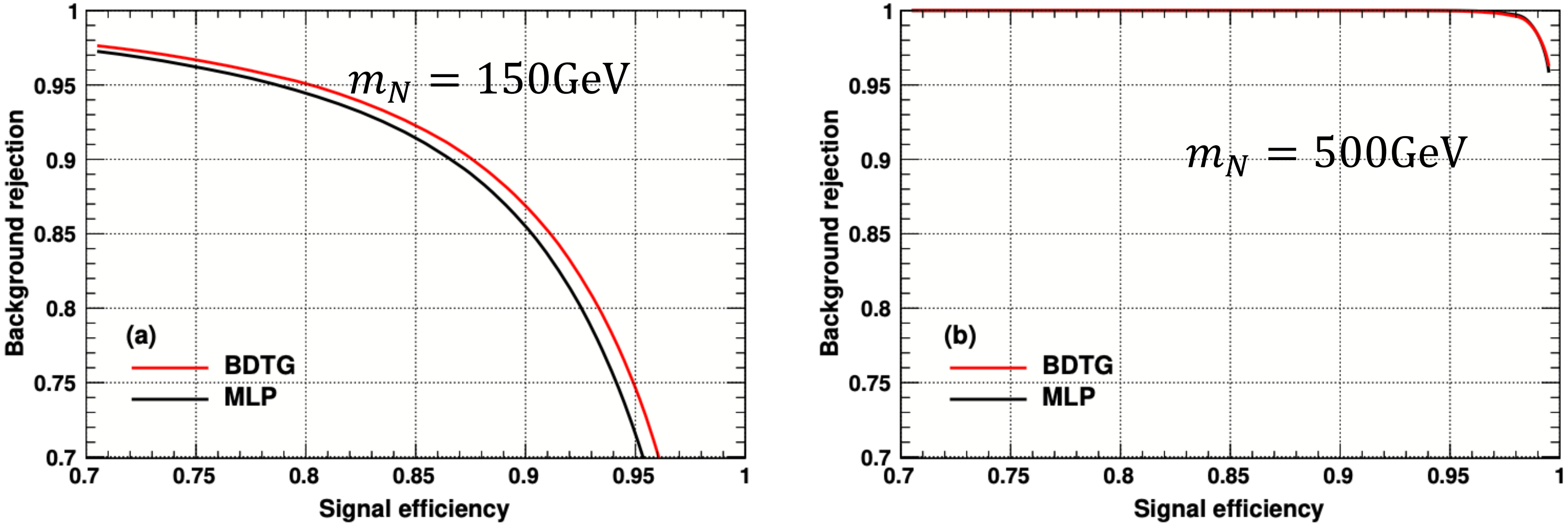
Collider analysis – Machine Learning

- The signal efficiency and background rejection power:



- BDTG and MLP methods show compatible results.
- When the heavy neutrino mass goes to a higher value, the separation becomes better.

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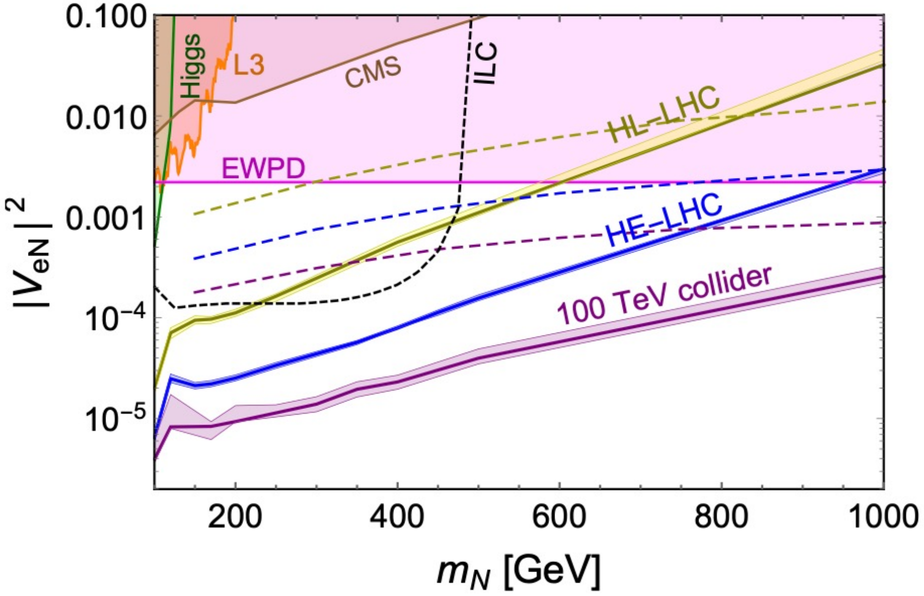
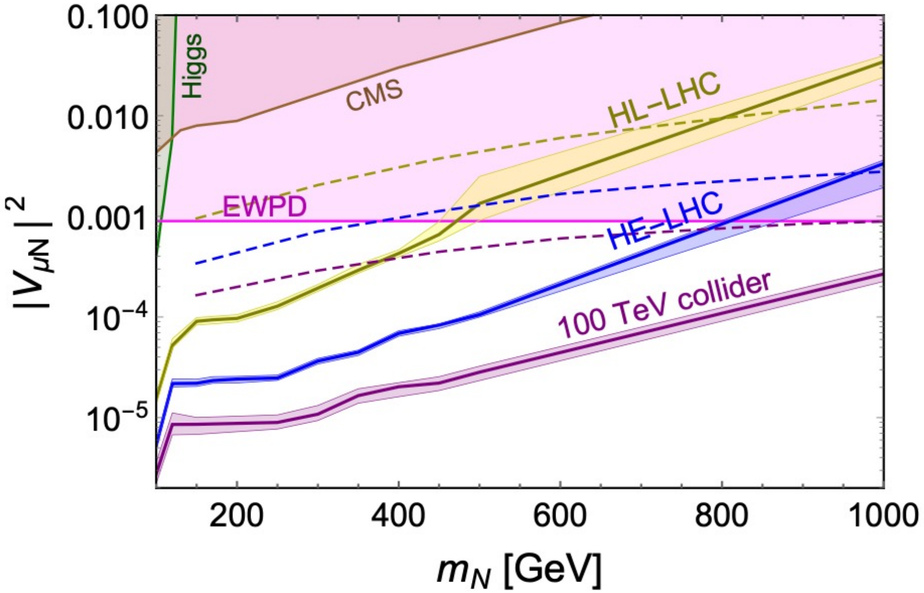
Results





- Sensitivities of the heavy-light neutrino mixing $|V_{eN}|^2$ (upper) and $|V_{\mu N}|^2$ (lower) at 95% C.L. .
- With machine learning methods, $|V_{lN}|^2$ can be improved up to O(10^{-6}) for heavy neutrino mass m_N = 100 GeV and O(10^{-4}) for m_N =1TeV.

$\sqrt{s}$= 14 TeV(3ab^{-1}), 27 TeV(15ab^{-1}), and 100 TeV(30ab^{-1})

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Summary

- By using the machine learning methods, we study the sensitivities of heavy pseudo-Dirac neutrino N in the inverse seesaw at the high-energy hadron colliders.
- We use either the Multi-Layer Perceptron or the Boosted Decision Tree with Gradient Boosting to analyze the kinematic observables and optimize the discrimination of background and signal events.
- It is found that the reconstructed Z boson mass and heavy neutrino mass play crucial roles in separating the signal from backgrounds.
- The prospects of heavy-light neutrino mixing $|V_{lN}|^2$ (with $l = e, \mu$) are estimated by using machine learning at the hadron colliders with $\sqrt{s}$= 14 TeV, 27 TeV, and 100 TeV, and it is found that $|V_{lN}|^2$ can be improved up to O(10^{-6}) for heavy neutrino mass m_N = 100 GeV and O(10^{-4}) for m_N =1TeV.

Thank you !