

# Heavy Neutral Lepton at Future Muon Collider

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# Outline

- Motivation of introducing Heavy Neutral Leptons (HNL)
- Searching muon-flavored HNL at Future Muon Collider ( $\sqrt{s} = 10 \text{ TeV}$ )
  - Muon collider
  - Signal
  - Background
  - Cutflow analysis
- Result

# Motivation

- Mass of neutrino  $0 < m_\nu < O(1)eV$

- Yukawa term:  $\lambda_\nu \bar{L} \tilde{H} \nu_R$ ,  $m_\nu = \frac{\lambda_\nu v}{\sqrt{2}}$

Yukawa coupling:  $\lambda_q \sim (10^{-5}, 1)$   
 $\lambda_l \sim (10^{-6}, 10^{-2})$   
 $\lambda_\nu < 10^{-12}$

- Seesaw mechanism (type I):  $\mathcal{L}_\nu \supset -\lambda_\nu \bar{L} \tilde{H} N - \frac{m_N}{2} \bar{N}^c N + \text{h.c.}$

- Mass of the heavy neutrino:  $m_N$

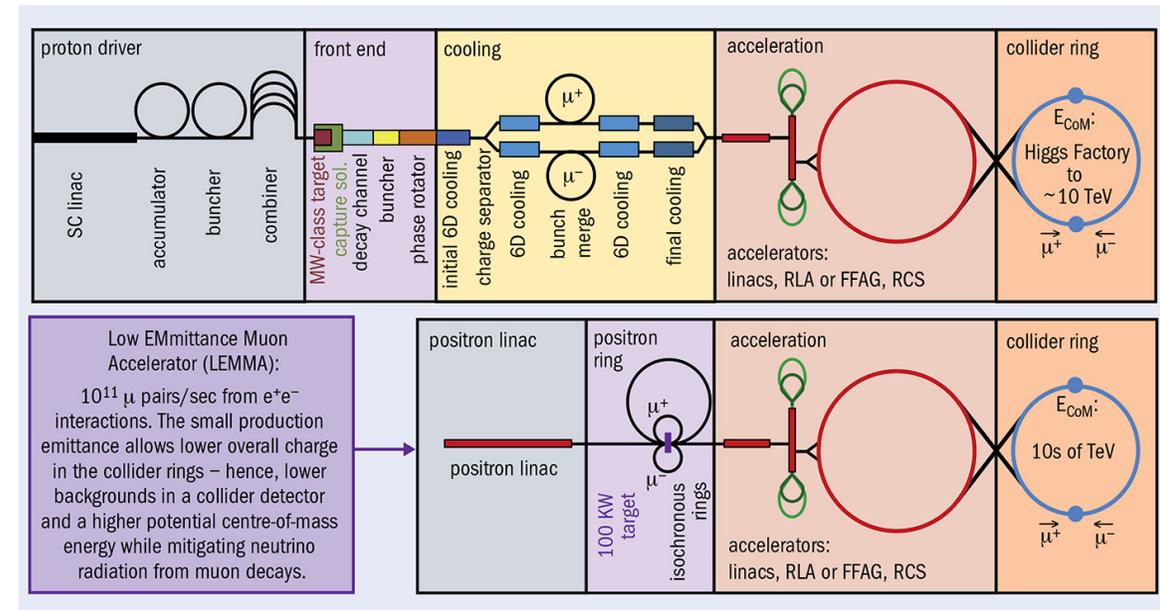
- Mixing angle between SM neutrino  $\nu$  and heavy neutrino  $N$ :  $|U_l|^2 = \sin^2 \theta_l$

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D & m_N \end{pmatrix}$$

$$m_\nu \equiv m_1 \simeq \frac{m_D^2}{m_N} = m_D \sin \theta, \quad m_2 \simeq m_N + \frac{m_D^2}{m_N} \simeq m_N \quad |U_l|^2 = \sin^2 \theta = \frac{m_\nu}{m_N}$$

# Why considering muon collider?

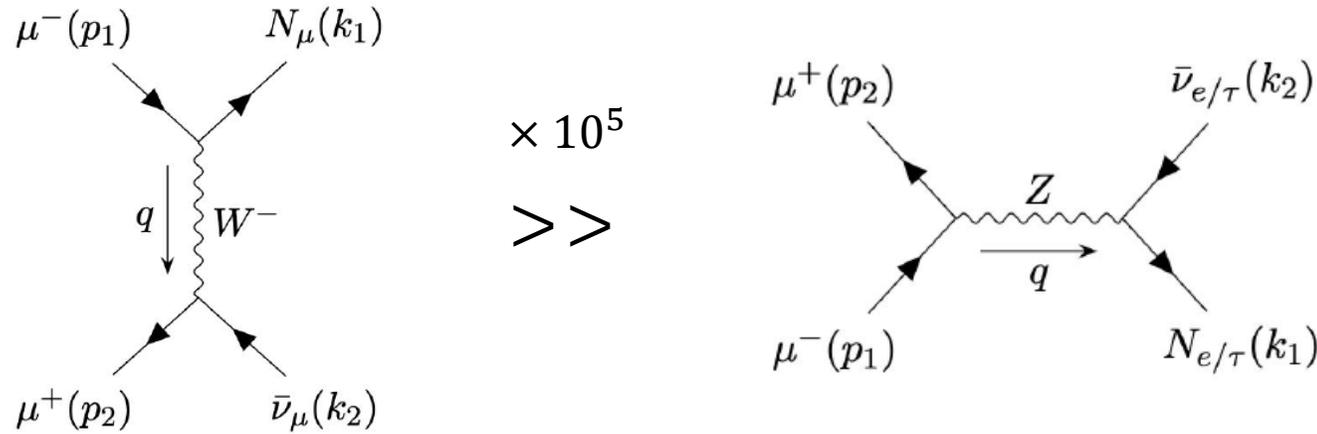
- High energy:
  - High mass (low synchrotron radiation)
  - Fundamental particle: full energy collision
- Clean environment:
  - Known initial state
  - Clean background



arxiv:1901.06150

# 10TeV Signal production of $N_\mu$

- Muon-flavored signal production is dominated by a t-channel.



Type	Signal process	$\sigma/ U_\mu ^2$ (w. conj. channel) $m_N = 1$ TeV	Pre-selection cut (PSC)	Included
$t$ -channel	$\mu^+\mu^- \rightarrow N_\mu\bar{\nu}_\mu$	20.28 pb	PSC	Yes
VBF	$\mu^+\mu^- \rightarrow \mu^+\mu^-N_\mu\bar{\nu}_\mu$	$\sim 1$ pb	–	No
VBF	$\mu^+\mu^- \rightarrow \bar{\nu}_\mu\nu_\mu N_\mu\bar{\nu}_\mu$	$\sim 0.1$ pb	–	No

**Table 3.** The signal rate for  $N_\mu$  at 10 TeV. The cross section includes the charge conjugate process.

# 10TeV Signal production of $N_\mu$

$$m_N > O(100) \text{ GeV}$$

- $N_\mu \rightarrow W^+ + \mu^-$
- $N_\mu \rightarrow Z + \nu_\mu$
- $N_\mu \rightarrow H + \nu_\mu$

Including the charge conjugation process

$$N_\mu \rightarrow W^+ + \mu^-, \quad W \rightarrow jj$$

$$\mu^+ + \mu^- \rightarrow N_\mu + \bar{\nu}_\mu \rightarrow jj + \mu^- + \bar{\nu}_\mu$$

The dijets almost come from onshell W/Z boson.

We focus on the final states of  $W$  and  $\mu$  and reconstruct its invariant mass distribution.

# 10TeV Background

Type	Background process	$\sigma$ (w. conj. channel)	Pre-selection cut (PSC)	Included
<i>t</i> -channel	$\mu^+\mu^- \rightarrow W^+\mu^-\bar{\nu}_\mu$	0.214 pb	PSC	Yes
<i>t</i> -channel	$\mu^+\mu^- \rightarrow Z\mu^+\mu^-$	0.464 pb	PSC & missing $\mu^+$	Yes
VBF	$\mu^+\mu^- \rightarrow \mu^+\mu^-W^+\mu^-\bar{\nu}_\mu$	0.401 pb	PSC & missing $\mu^+\mu^-$	Yes
VBF	$\mu^+\mu^- \rightarrow \bar{\nu}_\mu\nu_\mu W^+\mu^-\bar{\nu}_\mu$	0.0686 pb	PSC	No

**Table 4.**  $N_\mu$  background at 10 TeV. The cross section includes the charge conjugate process.

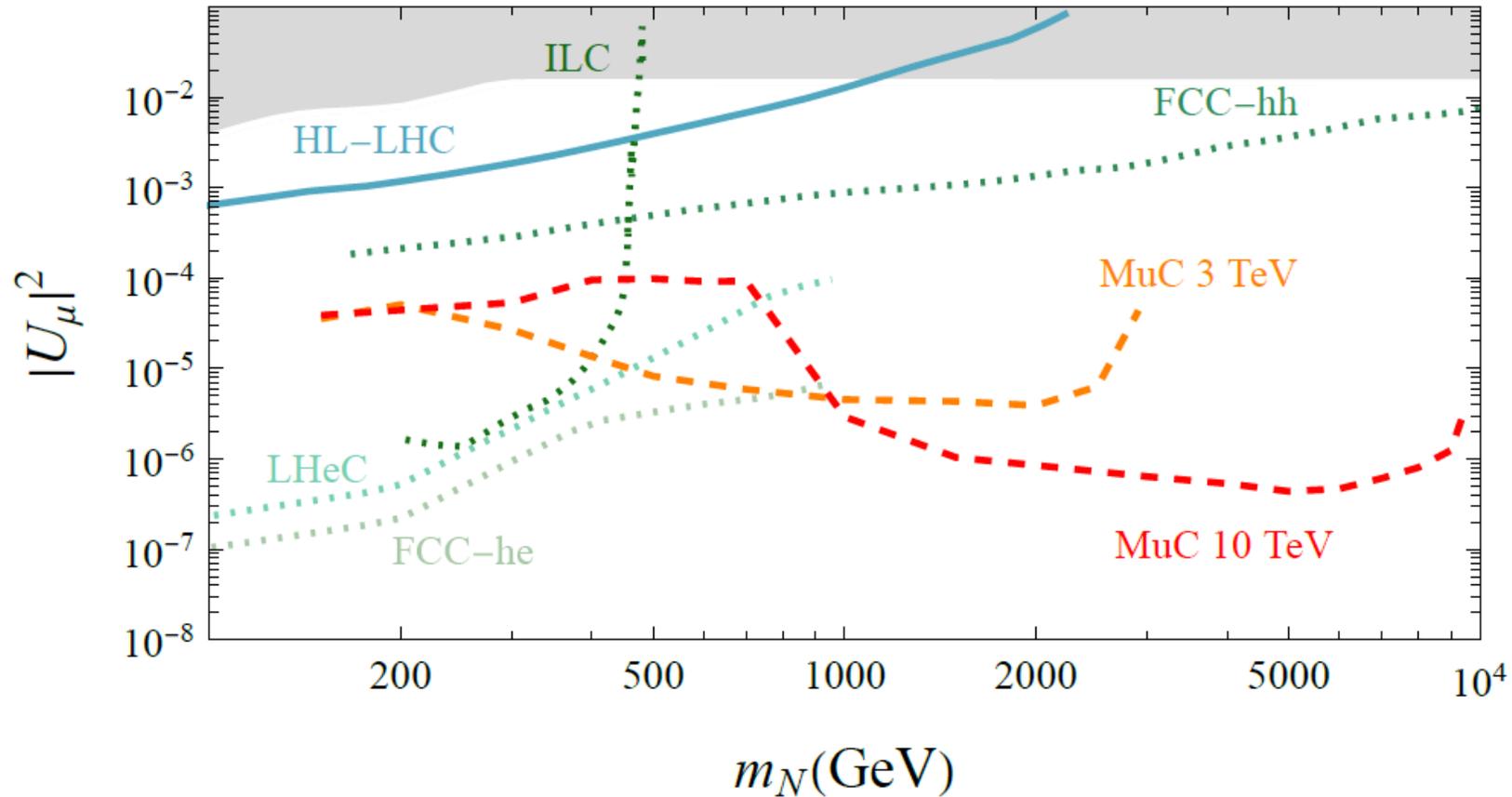
- Using EVA in MadGraph, especially photon PDF (EVA: Effective Vector-Boson Approximation)
- Including Z boson: Dijets can come from either W or Z boson.

# Cutflow Analysis

$$\mu^+ + \mu^- \rightarrow N_\mu + \bar{\nu}_\mu \rightarrow jj + \mu^- + \bar{\nu}_\mu$$

- Pre-selection: require single visible charged lepton
  - $|\eta(\mu)| < 2.5$  and  $p_T(\mu) > 20$  GeV
- Central hadronic W selection: require visible on-shell W boson
  - $|\eta(W)| < 2.5$  and  $p_T(W) > 20$  GeV
- Mass window: reconstructed mass  $m_{W\mu}$  within  $m_N \pm 5\%m_N$
- Optimization cuts:
  - Customized cut on missing  $p_T$ ,  $E(W)$ ,  $p_T(W)$  for each  $m_N$  benchmark

# Result

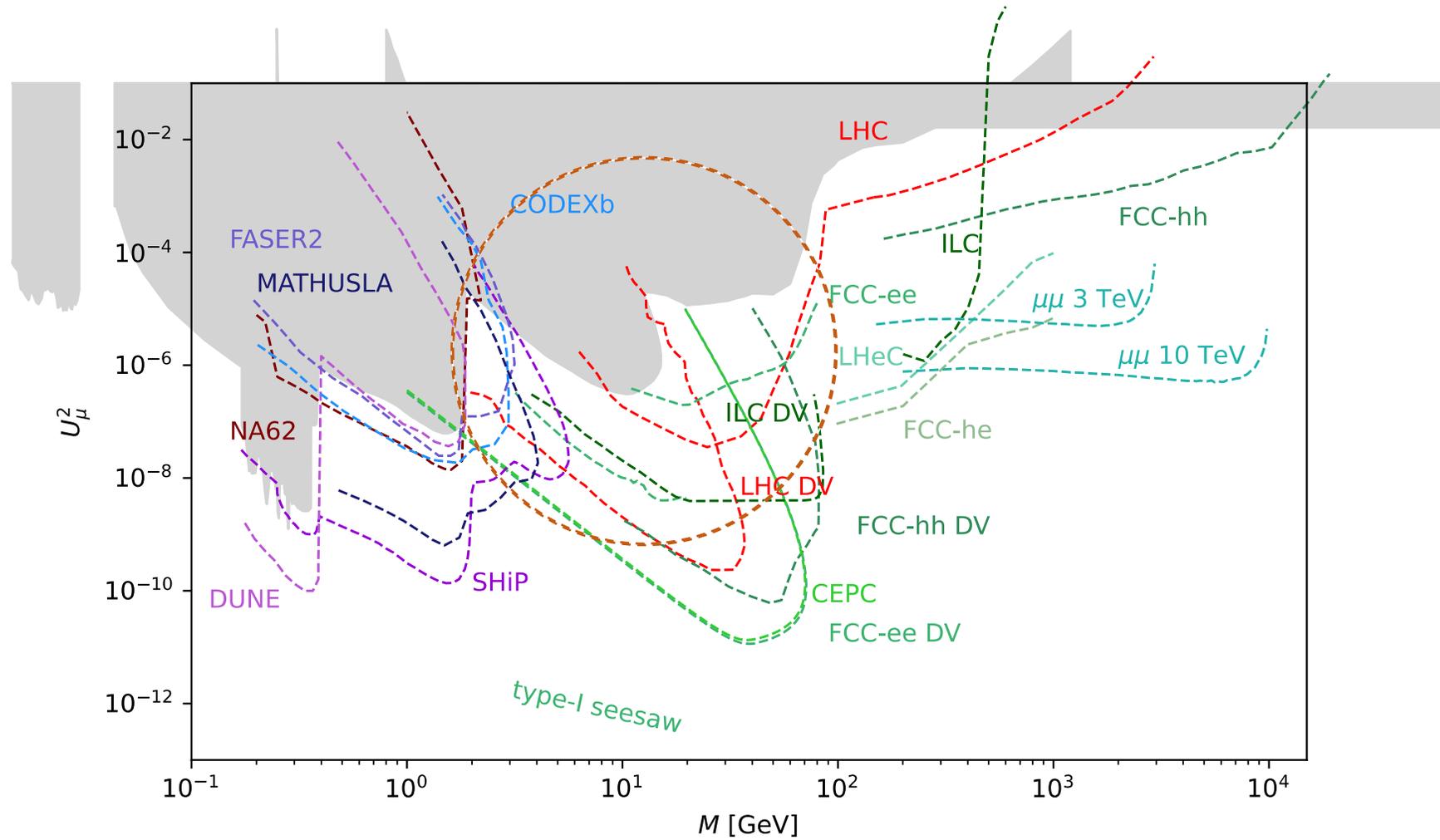


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T.H. Kwok, L. Li, T. Liu and A. Rock,  
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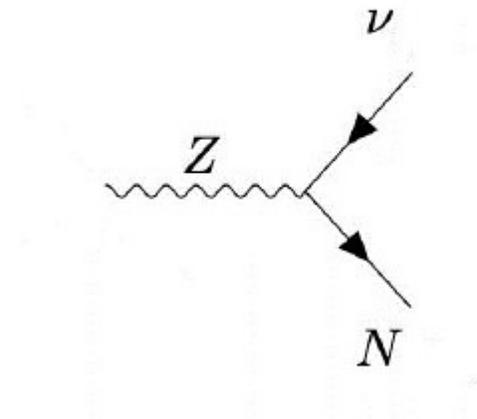
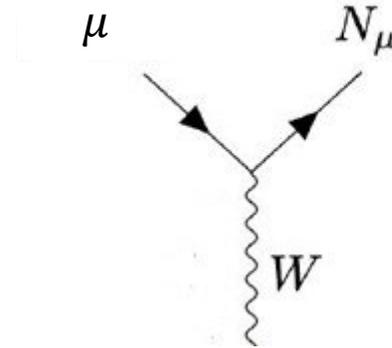
# Next step



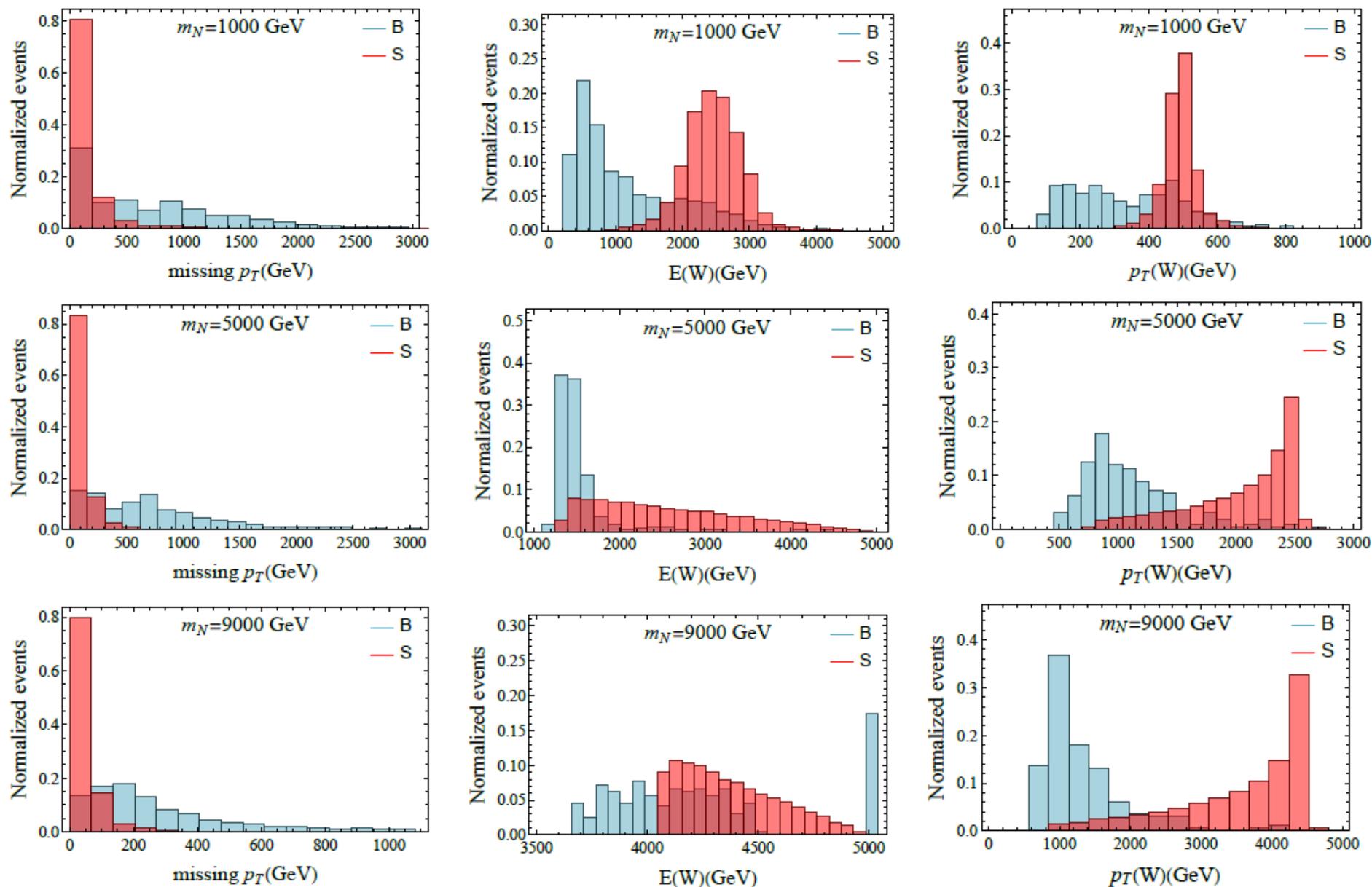
# Back up

$$\mathcal{L}_W = \frac{gU_l}{\sqrt{2}} (W_\mu \bar{l}_L \gamma^\mu N + h.c.)$$

$$\mathcal{L}_Z = -\frac{gU_l}{2 \cos \theta_w} Z_\mu (\bar{\nu}_L \gamma^\mu N + \bar{N} \gamma^\mu \nu_L)$$



# Optimization cuts



# Back up

