Novel Signatures of Heavy Neutral Lepton at Muon Collider

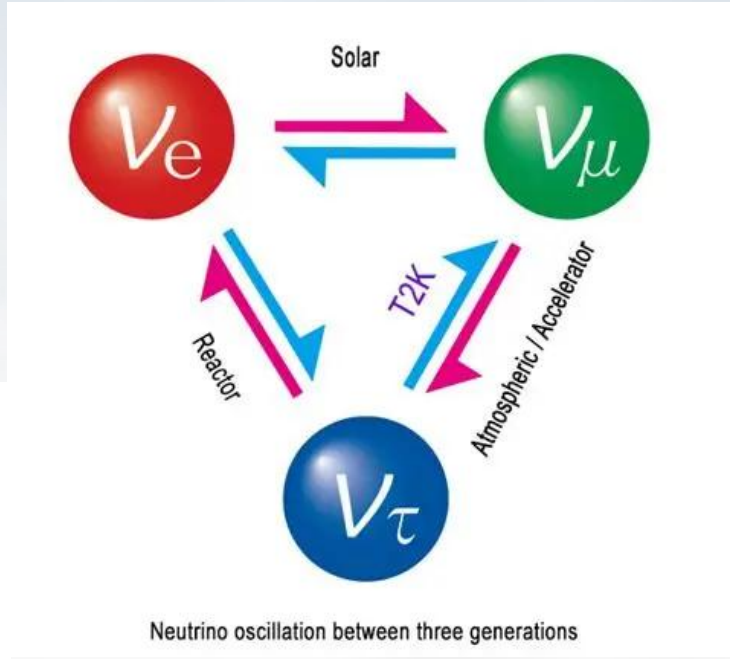
Zhi-Long Han

University of Jinan

arXiv:2606.19906，2604.24383，2602.05158，2505.07331，2401.14687

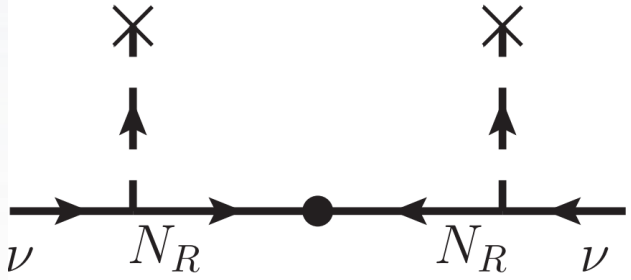
Motivation of Heavy Neutral Lepton

- Neutrino Oscillation -> $m_\nu < 1$ eV
  - SK, Phys. Rev. Lett. 81, 1562-1567 (1998)
  - SNO, Phys. Rev. Lett. 89, 011301 (2002)
  - Daya Bay, Phys. Rev. Lett. 108, 171803 (2012)



Neutrino oscillation between three generations

- Seesaw Mechanism



$$-\mathcal{L}_Y \supset y\overline{L}\widetilde{\Phi}N + \frac{1}{2}\overline{N^c}m_N N + \text{h.c.},$$

$$\Rightarrow \quad m_\nu = -\frac{v^2}{2} y\, m_N^{-1} y^T$$



- P. Minkowski, Phys. Lett. B 67, 421-428 (1977)
- R. N. Mohapatra ,G. Senjanovic, Phys. Rev. Lett. 44, 912 (1980)
- J. Schechter and J. W. F. Valle, Phys. Rev. D 22, 2227 (1980)

HNL Features

- Flavor Basis Mass Matrix

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

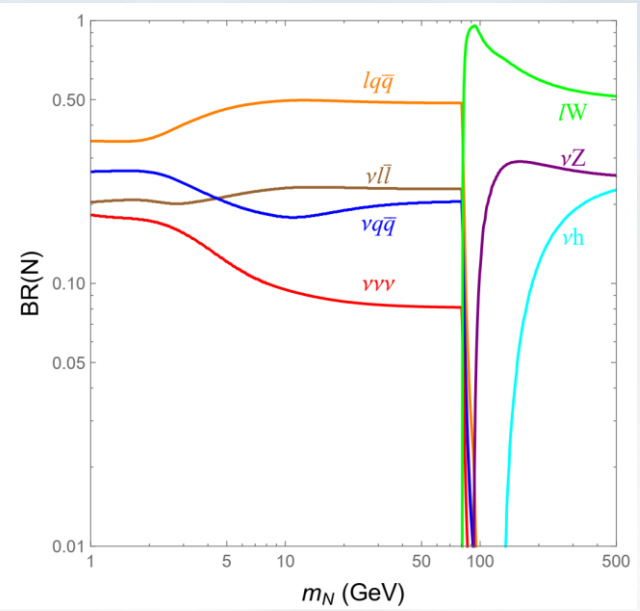
- Mixing with SM ν

$$\nu_{\ell L} = \sum_{m=1}^{3} U_{\ell m} \nu_{mL} + \sum_{m'=1}^{3} V_{\ell m'} N^c_{m' L}$$

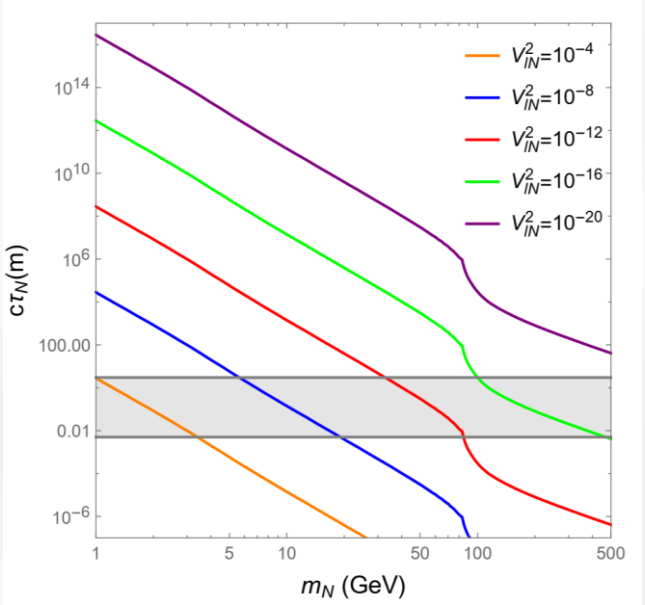
- The Effective Lagrangian

$$\begin{aligned}\mathcal{L}_{\text{Int.}} = &-\frac{g}{\sqrt{2}} W^+_\mu \sum_{\ell=e}^{\tau} \left(\sum_{m=1}^{3} \overline{\nu_m}\, U^*_{\ell m} + \sum_{m'=1}^{n} \overline{N^c_{m'}}\, V^*_{\ell N_{m'}} \right) \gamma^\mu P_L \ell^- \\ &- \frac{g}{2\cos\theta_W} Z_\mu \sum_{\ell=e}^{\tau} \left(\sum_{m=1}^{3} \overline{\nu_m}\, U^*_{\ell m} + \sum_{m'=1}^{n} \overline{N^c_{m'}}\, V^*_{\ell N_{m'}} \right) \gamma^\mu P_L \nu_\ell \\ &- \frac{g}{2M_W} h \sum_{\ell=e}^{\tau} \sum_{m'=1}^{n} m_{N_{m'}} \overline{N^c_{m'}}\, V^*_{\ell N_{m'}} P_L \nu_\ell + \text{H.c.}\end{aligned}$$

- Branching Ratio



- Decay Length



HNL at Hadron Collider

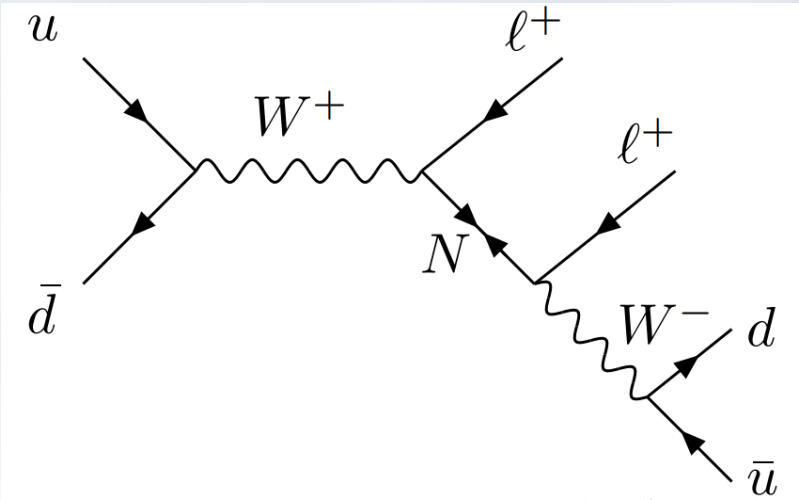
- Lepton Number Violation Signal

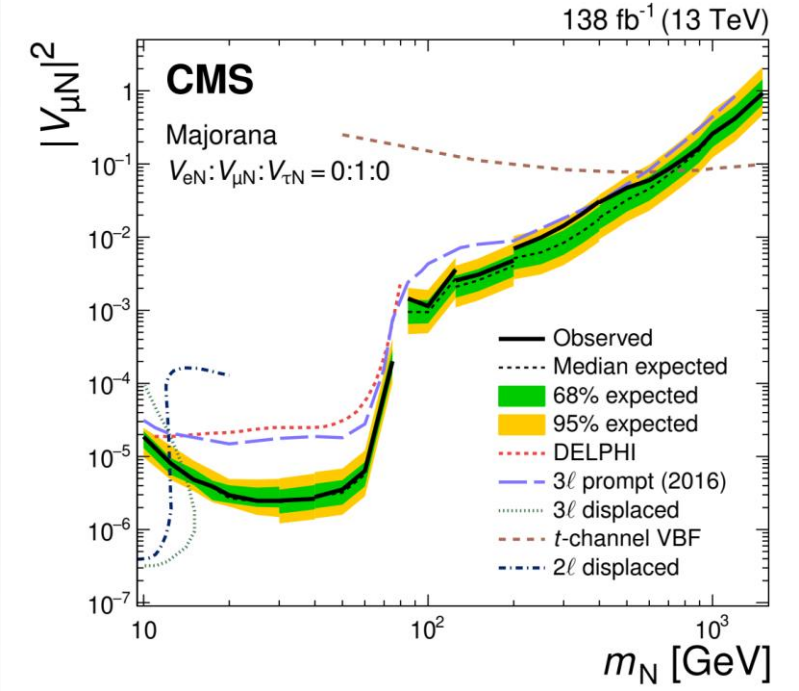
$$pp \to l^{\pm}N \to l^{\pm}l^{\pm}jj$$

- Cross Section vs Mixing Parameter

$$\sigma\left(pp \to l^{\pm}N\right) = V_{lN}^2\sigma_0$$

  - Clean background
  - $m_{jj} = m_W, m_{jjl} = m_N$



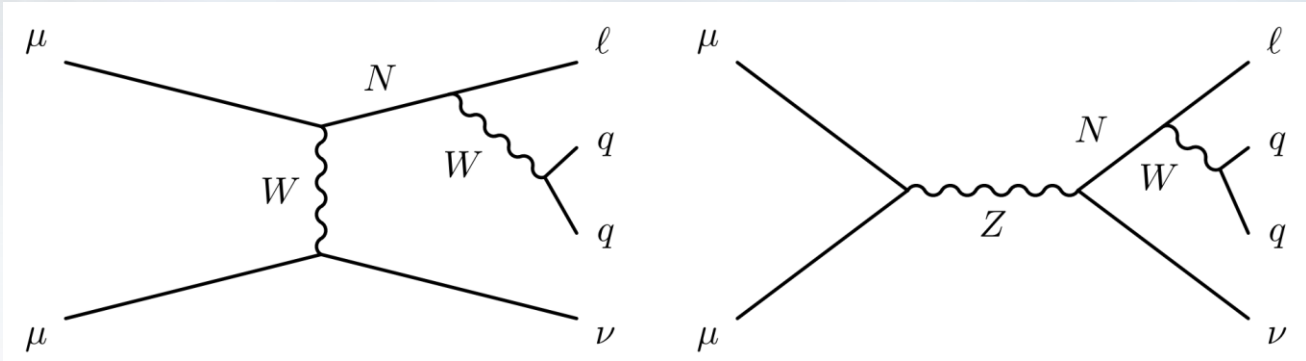


- T.Han and B.Zhang, Phys. Rev. Lett. 97,171804 (2006)
- Y.Cai, T.Han, T.Li and R.Ruiz, Front. in Phys. 6, 40 (2018)
- [CMS], JHEP 06, 123 (2024)

HNL at Muon Collider: Mixing

- Production via Mixing

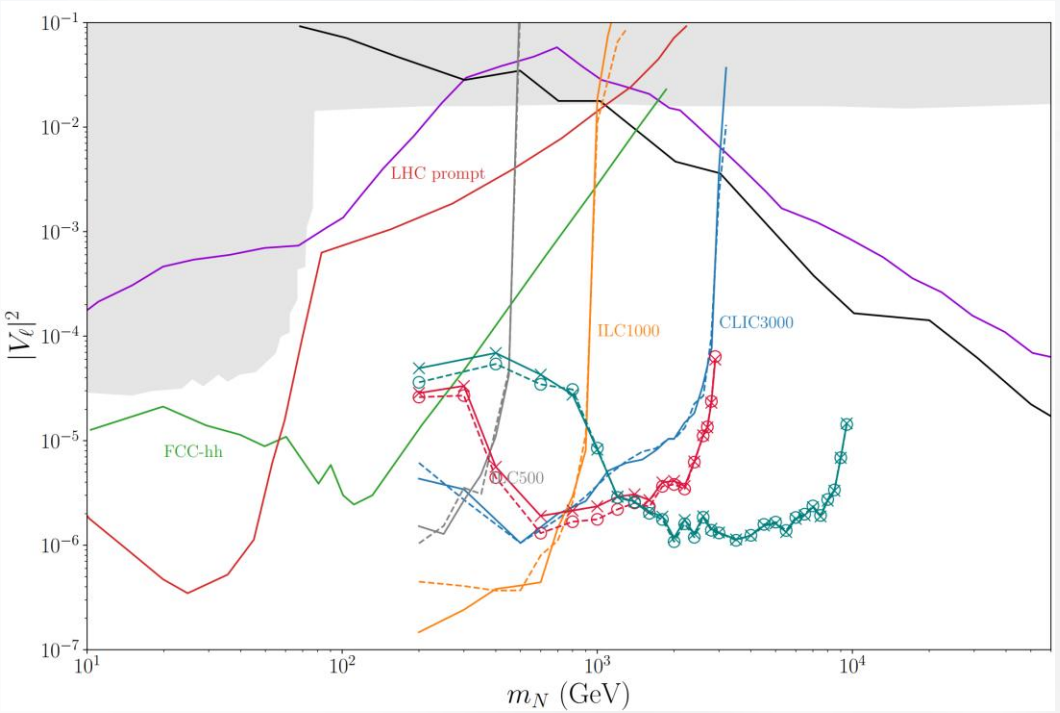
$$\mu^+\mu^- \to N\nu \to ljj\nu$$



- Background

$$\mu^+\mu^- \to qql\nu, qqll, qqll\nu\nu$$

$$\gamma\gamma \to qql\nu, \gamma\mu \to qql$$



- K. Mekala, J. Reuter and A. F.Zarnecki, Phys.Lett.B 841 (2023) 137945
- T. H. Kwok, L. Li, T. Liu and A. Rock, Phys. Rev. D 110, 075009 (2024)
- P. Li, Z. Liu and K.F.Lyu, JHEP 03, 231 (2023)
- Q. H.Cao, K.Cheng and Y.Liu, Phys. Rev. Lett. 134, 021801 (2025)

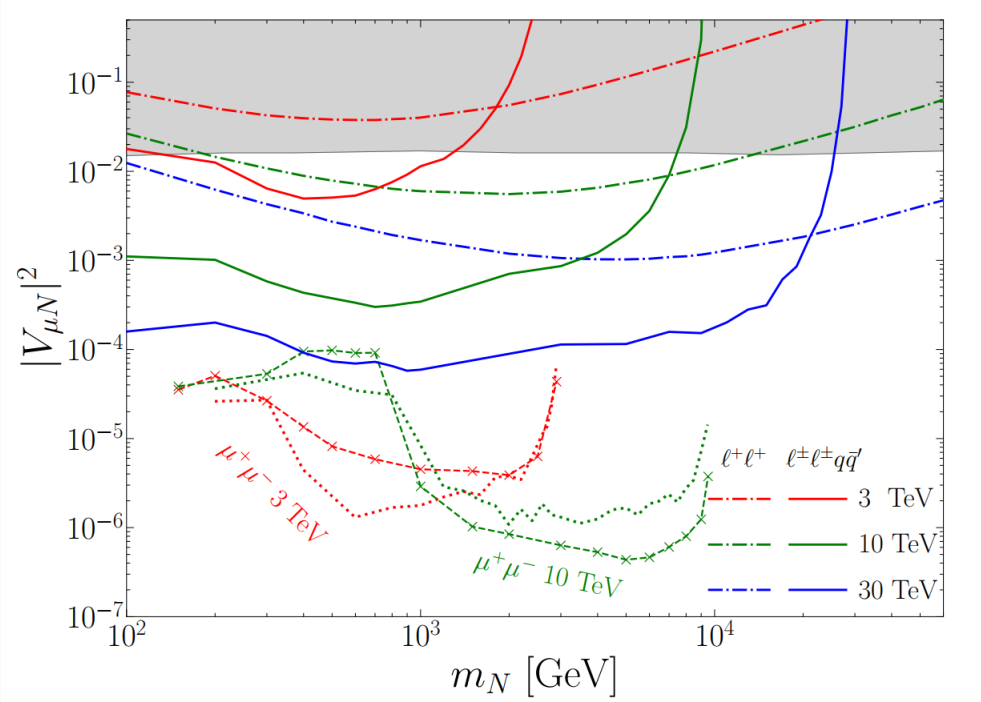
HNL at Muon Collider: VBS

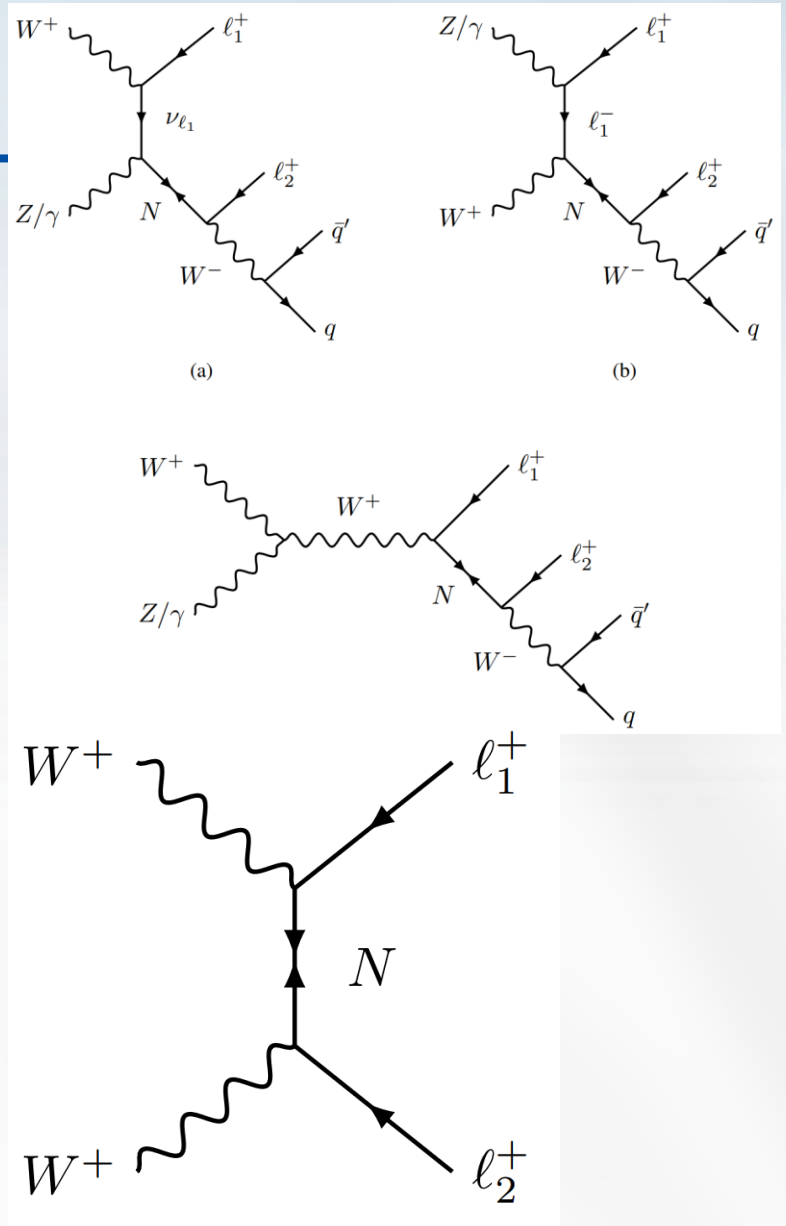
- Vector Boson Scattering

$$W^{\pm}Z/\gamma \to l^{\pm}N \to l^{\pm}l^{\pm}\,jj$$

- Same-sign Muon Collider

$$W^{+}W^{+} \to l^{+}l^{+}$$





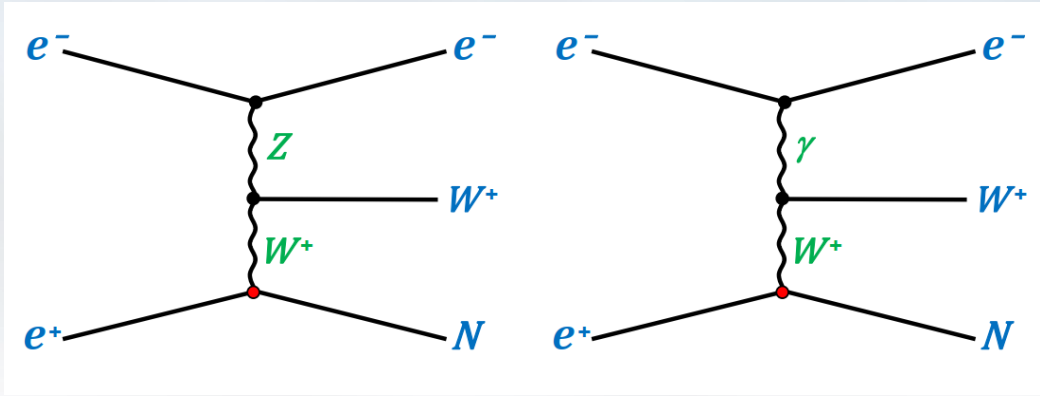
- T.Li, C.Y.Yao and M.Yuan, JHEP09, 131 (2023)
- P. Dehghani, M.Frank and B.Fuks, Phys. Rev. D 112, 035020 (2025)

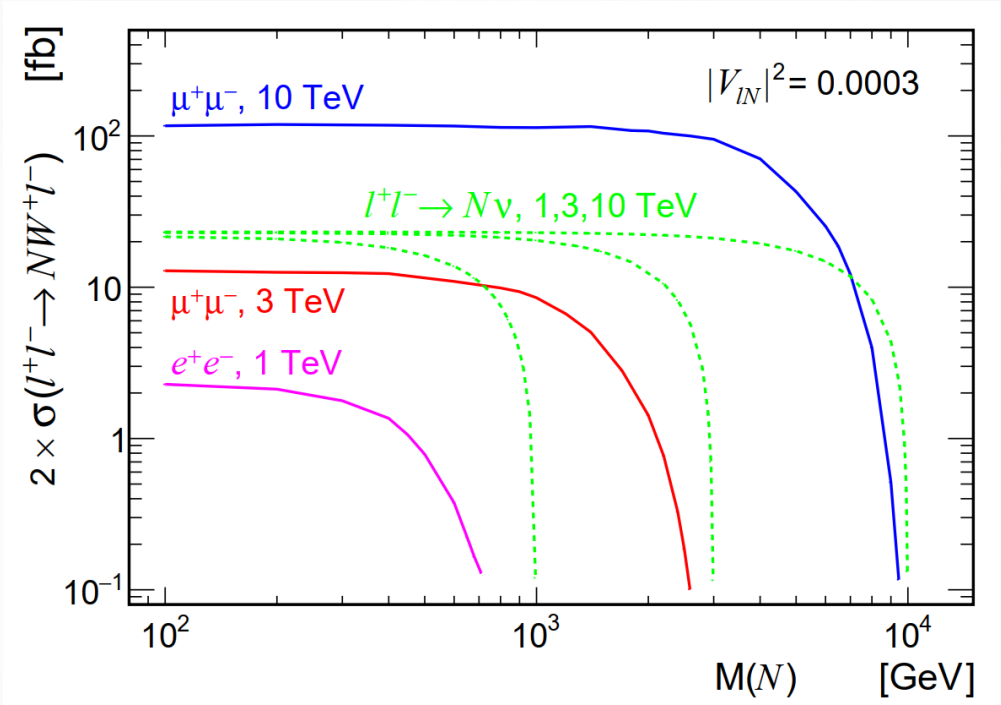
HNL at Muon Collider: Associated Production

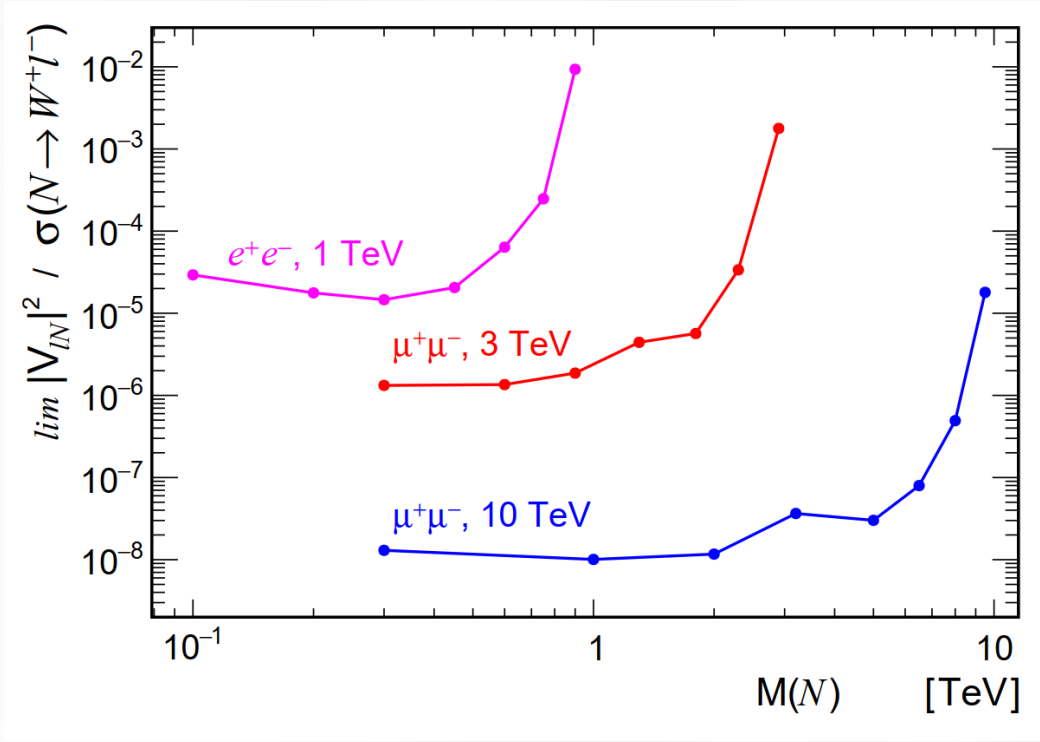
Associated Production Process

$$l^+l^- \rightarrow NW^+l^-$$

- E.Antonov, A.Drutskoy and M.Dubinin, JETP Lett. 118, no.7, 461-469 (2023)







$U(1)L_\mu - L_\tau$ Type-I Seesaw

- Kinetic Terms

$$-\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + |D_\mu S|^2$$

- Gauge Interaction

$$\mathcal{L} \supset g'(\bar{\mu}\gamma^\mu\mu - \bar{\tau}\gamma^\mu\tau + \bar{\nu}_\mu\gamma^\mu P_L\nu_\mu - \bar{\nu}_\tau\gamma^\mu P_L\nu_\tau + \bar{N}_\mu\gamma^\mu P_R N_\mu - \bar{N}_\tau\gamma^\mu P_R N_\tau)Z'_\mu$$

- Yukawa Interaction

$$\mathcal{L} \supset -y_e\bar{L}_e\tilde{\Phi}N_e - y_\mu\bar{L}_\mu\tilde{\Phi}N_\mu - y_\tau\bar{L}_\tau\tilde{\Phi}N_\tau - \frac{1}{2}M_{ee}\overline{N_e^c}N_e$$
$$-y_{e\mu}S^*\overline{N_e^c}N_\mu - y_{e\tau}S\overline{N_e^c}N_\tau - M_{\mu\tau}\overline{N_\mu^c}N_\tau + \text{h.c.},$$

- Scalar Potential

$$V = -\mu_\Phi^2\Phi^\dagger\Phi - \mu_S^2 S^*S + \lambda_\Phi(\Phi^\dagger\Phi)^2 + \lambda_S(S^*S)^2 + \lambda_{\Phi S}(\Phi^\dagger\Phi)(S^*S).$$

- Gauge Boson Mass

$$m_{Z'} = g'v_s$$

- X. G.He, G.C.Joshi, H.Lew and R.R.Volkas, Phys. Rev. D 43, 22-24 (1991)
- K.Asai, K.Hamaguchi and N.Nagata, Eur. Phys. J. C 77, no.11, 763 (2017)
- [ATLAS], Phys. Rev. D 110, 072008 (2024)

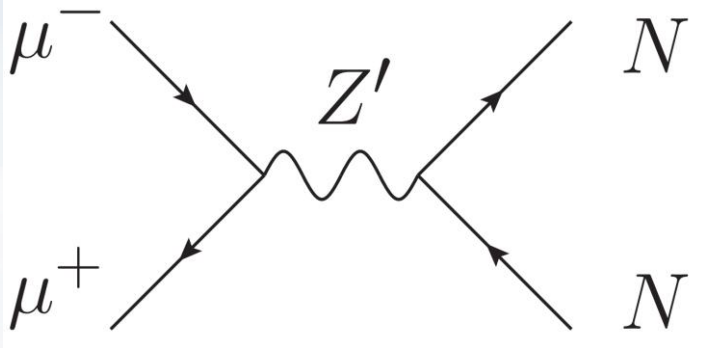
- Physical Higgs

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi^0 \\ s^0 \end{pmatrix}$$

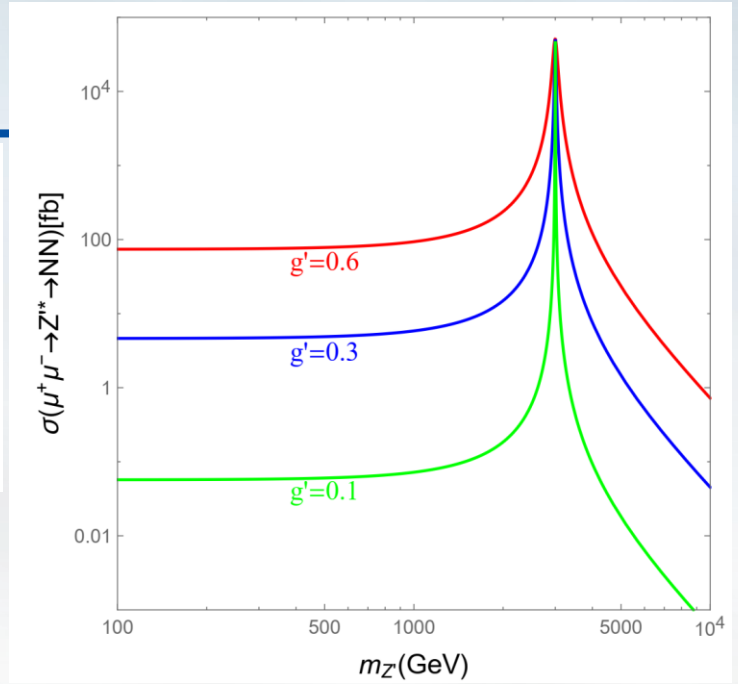
HNL at Muon Collider: Z' Portal

- Pair Production

$$\sigma(\mu^+\mu^- \to Z'^* \to NN)$$



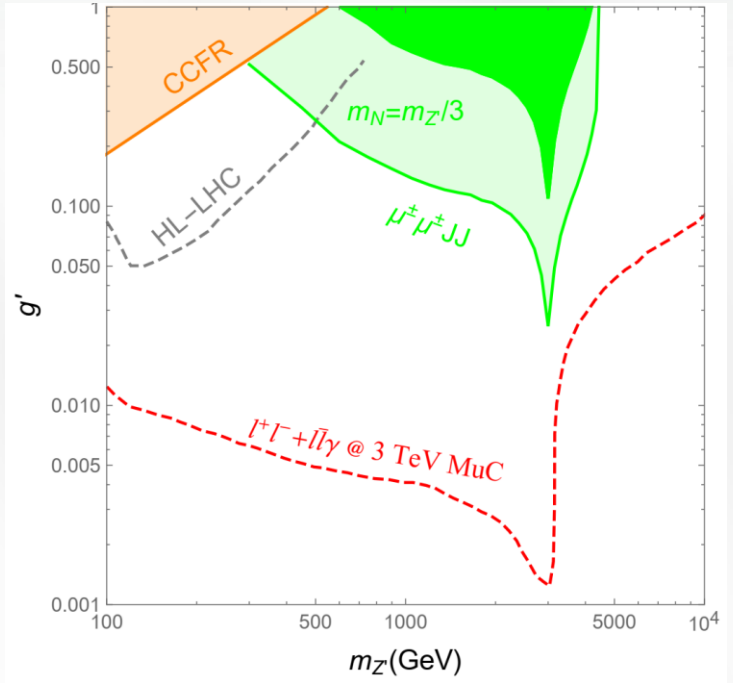
$$= \frac{g'^4}{24\pi} \frac{s}{(s - m_{Z'}^2)^2 + m_{Z'}^2 \Gamma_{Z'}^2} \left(1 - 4\frac{m_N^2}{s}\right)^{3/2}$$



- Lepton Number Violation Signal

$$\mu^+\mu^- \to Z'^* \to NN \to \mu^\pm W^\mp + \mu^\pm W^\mp$$

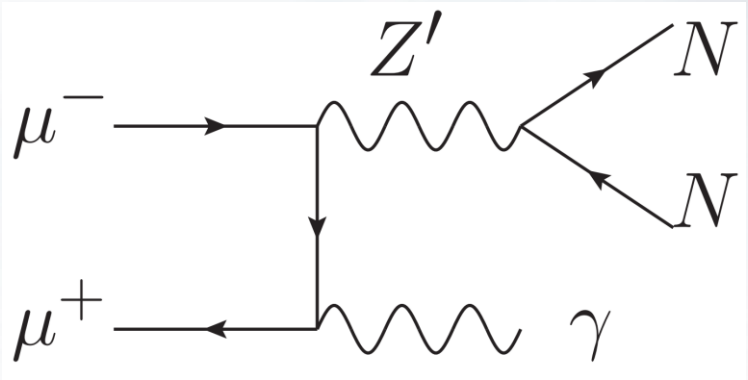
  - $W \to jj \to J$ Fat-jet
  - Valencia Algorithm



- W.Liu, K.P.Xie and Z.Yi, Phys. Rev. D 105,095034 (2022)
- R.Y.He, J.Q.Huang, J.Y.Xu, F.X.Yang, **ZLH** and F.L.Shao, Chin. Phys. C 48, 093102 (2024)
- Q.Bi, J.Guo, J.Liu, Y.Luo and X.P.Wang, Phys. Rev. D 111, 075001 (2025)

HNL at Muon Collider: Z' Portal

- With Associated Photon

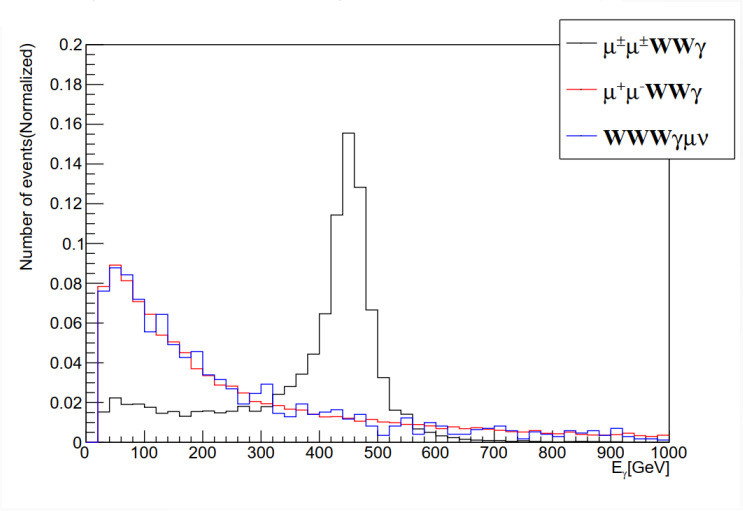


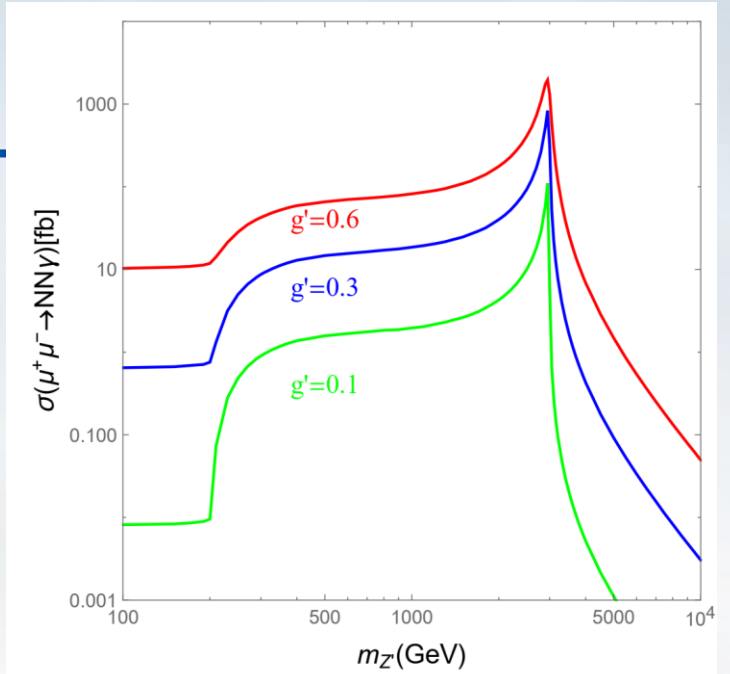
- Lepton Number Violation Signal

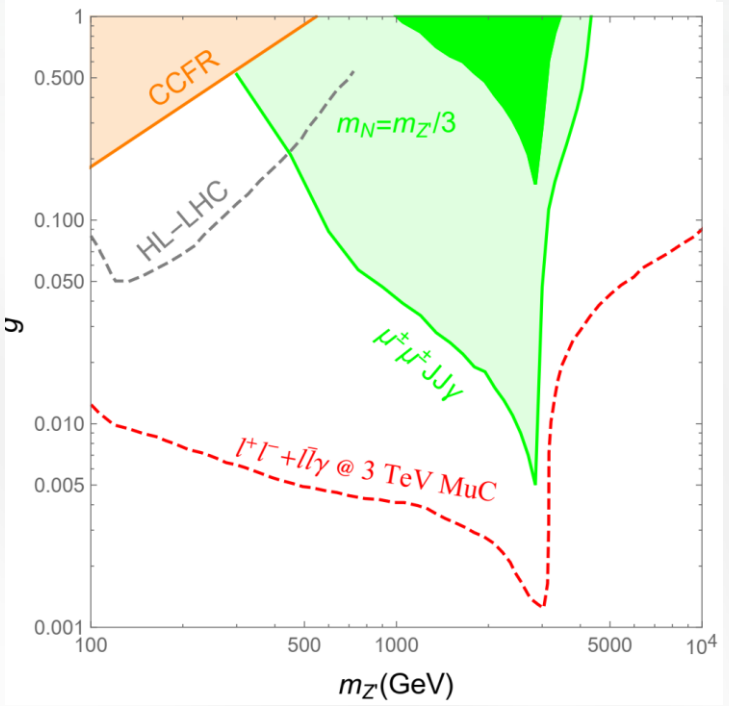
$$\mu^+\mu^- \to Z'^{(*)}\gamma \to NN\gamma \to \mu^\pm W^\mp + \mu^\pm W^\mp + \gamma$$

- Photon Energy

$$E_\gamma = \frac{s - m_{Z'}^2}{2\sqrt{s}}$$



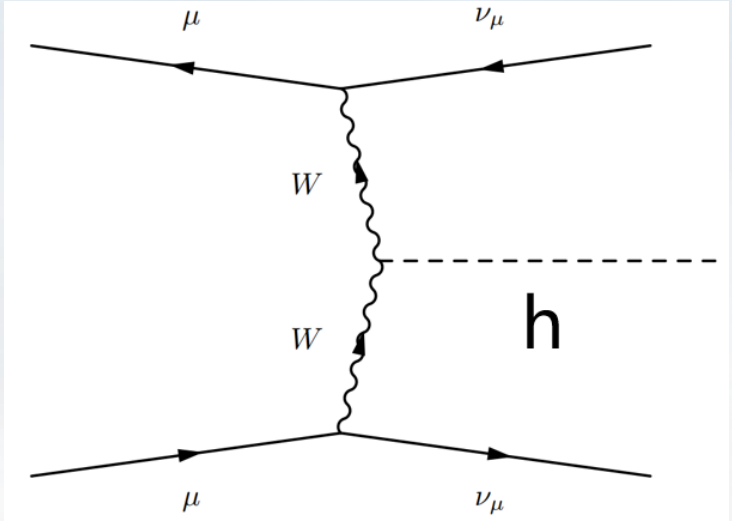




HNL at Muon Collider: h Portal

- Vector Boson Fusion

$$\sigma(\mu^+\mu^- \to \nu_\mu \bar{\nu}_\mu h) \approx \frac{g^4}{256\pi^3}\frac{1}{v_0^2}\left(\log\frac{s}{m_h^2} - 2\right)$$

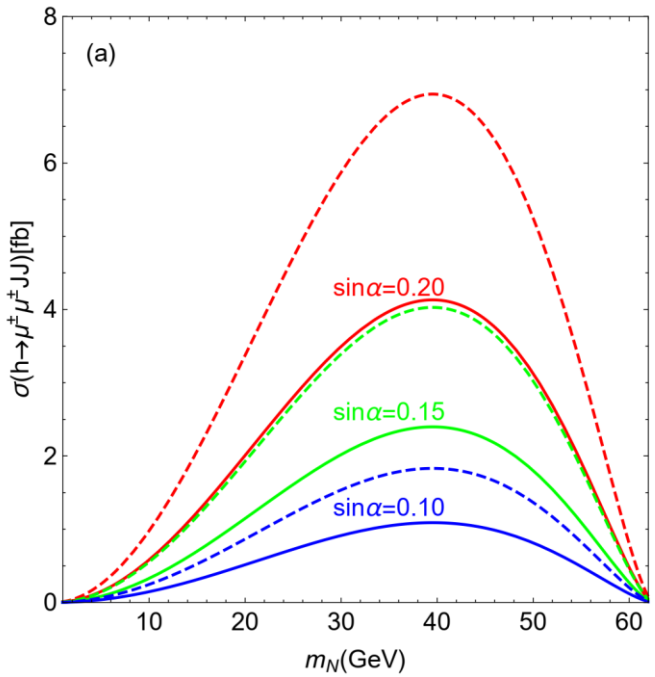


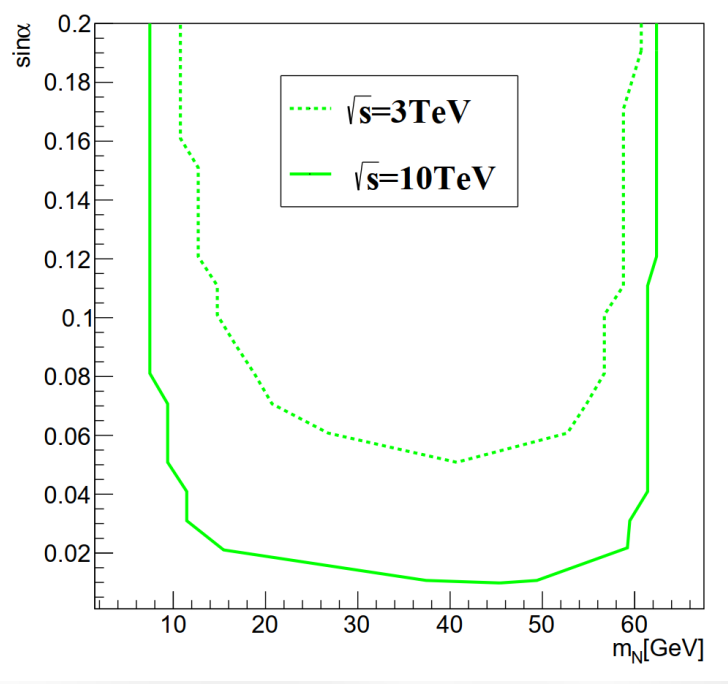
- Lepton Number Violation Signal

$$\mu^+\mu^- \to \nu_\mu \bar{\nu}_\mu h \to NN\nu_\mu\bar{\nu}_\mu \to \mu^\pm jj + \mu^\pm jj + \nu_\mu\bar{\nu}_\mu$$

- Branching Ratio

$$\Gamma(h \to NN) = \frac{m_N^2 m_h}{4\pi v_s^2}\sin^2\alpha\left(1 - \frac{4m_N^2}{m_h^2}\right)^{3/2}$$



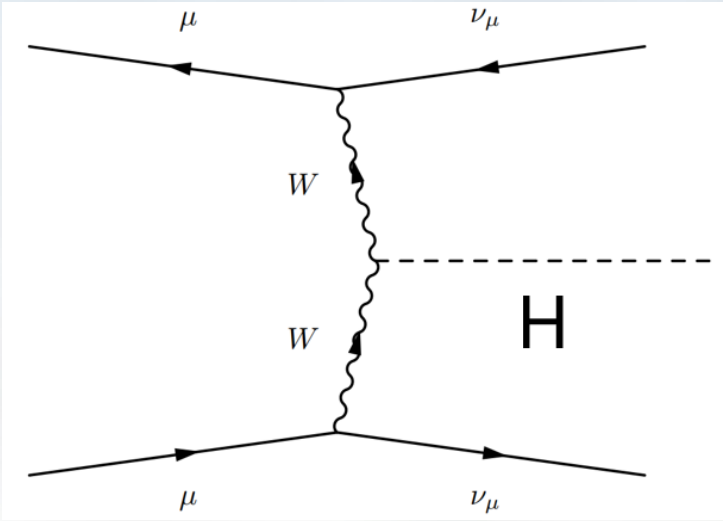


➢ F.X.Yang, F.L.Shao, **ZLH**, F.Huang, Y.Jin and H.Li, JHEP 09,200 (2025)

HNL at Muon Collider: H Portal

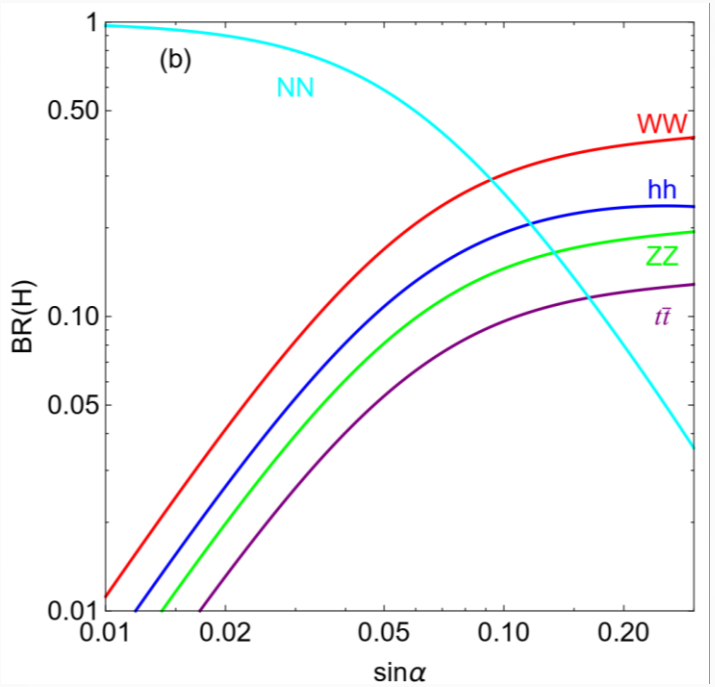
- Vector Boson Fusion

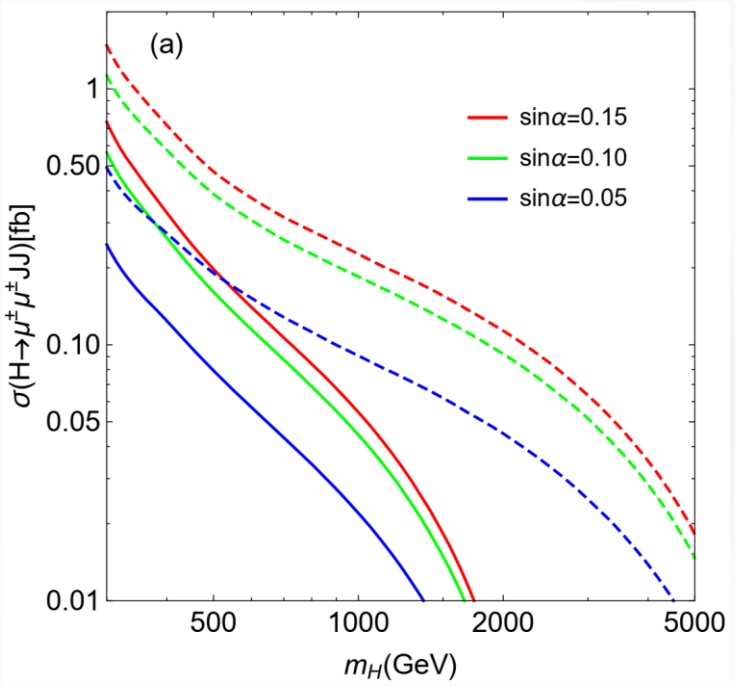
$$\sigma(\mu^+\mu^- \to \nu_\mu \bar{\nu}_\mu H) \approx \frac{g^4 \sin^2\alpha}{256\pi^3} \frac{1}{v_0^2} \left(\log \frac{s}{m_H^2} - 2 \right)$$

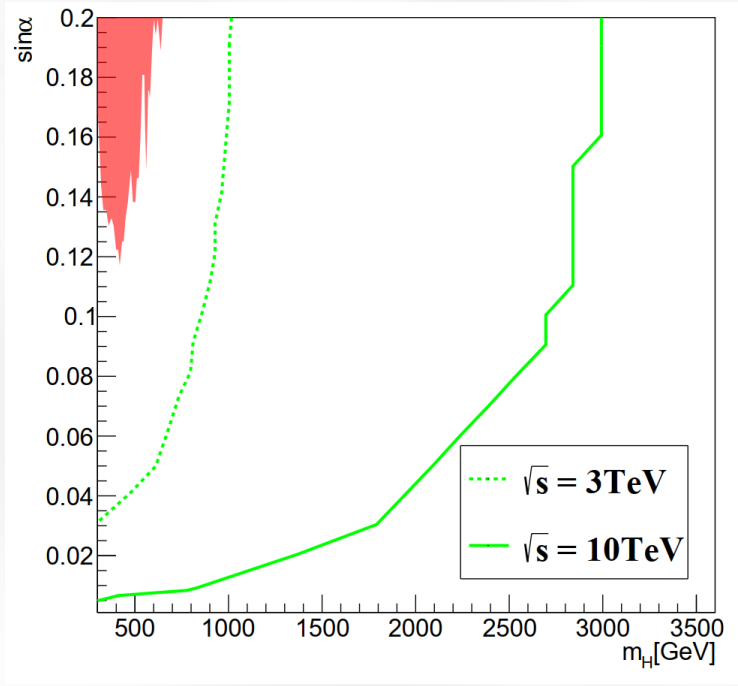


- Lepton Number Violation Signal

$$\mu^+\mu^- \to \nu_\mu \bar{\nu}_\mu H \to NN\nu_\mu \bar{\nu}_\mu \to \mu^\pm jj + \mu^\pm jj + \nu_\mu \bar{\nu}_\mu$$



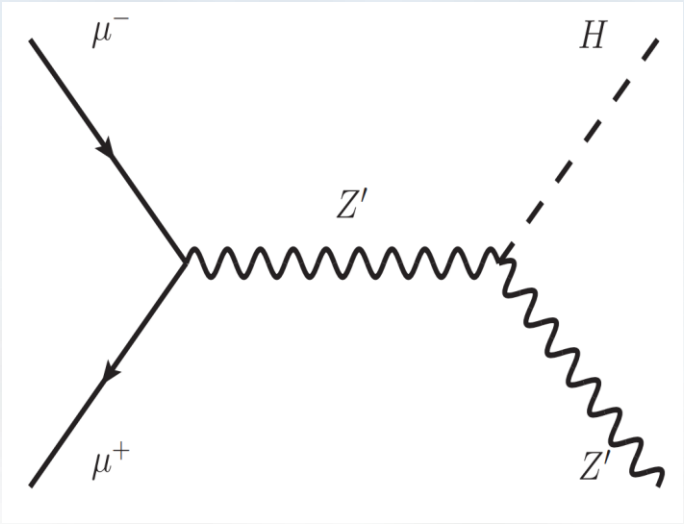




HNL at Muon Collider: Z'H Portal

- Interactions Between Z′ and H

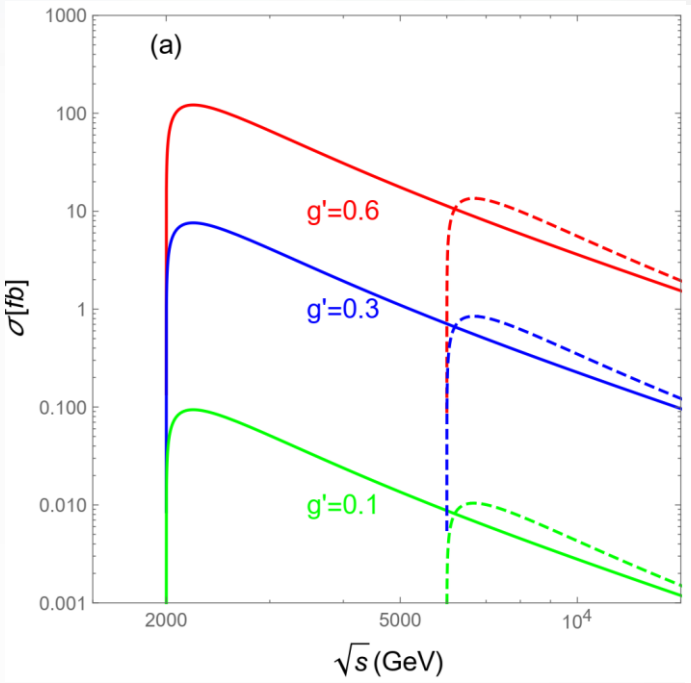
$$\mathcal{L} = \frac{m_{Z'}^2}{v_s} Z'^{\mu} Z'_{\mu} H + \frac{m_{Z'}^2}{2v_s^2} Z'^{\mu} Z'_{\mu} H^2$$

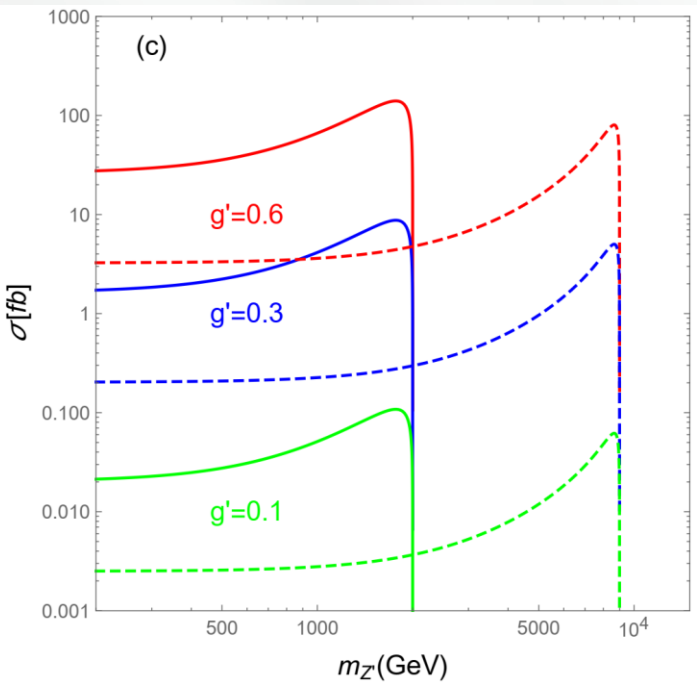


- Heavy Higgs-Strahlung

$$\sigma(\mu^+\mu^- \to Z'H) =$$

$$\frac{g'^4}{48\pi s^2} \frac{\lambda(s, m_{Z'}^2, m_H^2) + 12 s m_{Z'}^2}{(s - m_{Z'}^2)^2 + m_{Z'}^2 \Gamma_{Z'}^2} \sqrt{\lambda(s, m_{Z'}^2, m_H^2)}$$





- X.X.Zhang, **ZLH**, F.Huang and H.Li, JHEP 08, 073 (2026)

HNL at Muon Collider: Z'H Portal

- Same-sign Tetralepton

$$\mu^+\mu^- \to Z'H \to NN + NN \to 4\mu^\pm + 4W^\mp$$

  - Reconstruction HNL

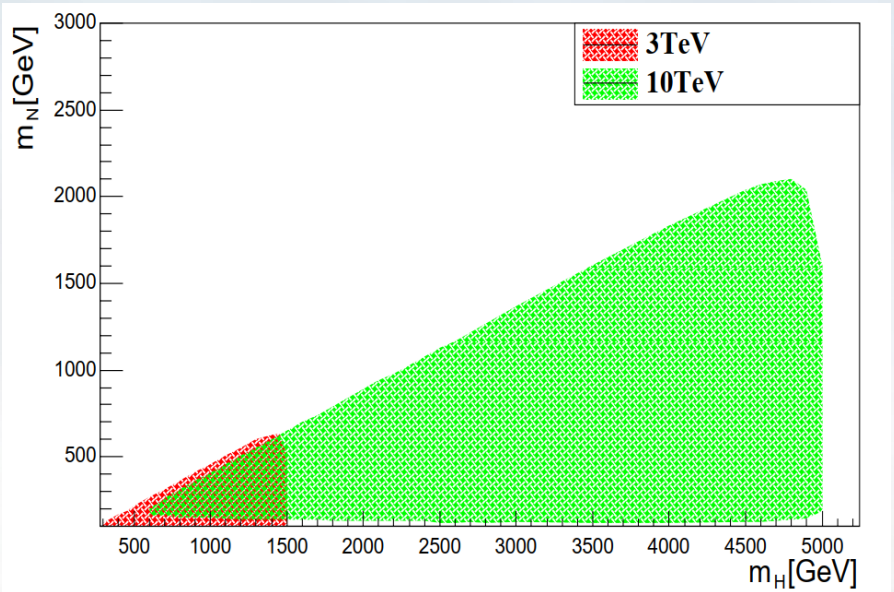
$$\chi^2_N = \sum_{i,j} (m_{\mu_i^\pm J_j} - m_N)^2$$

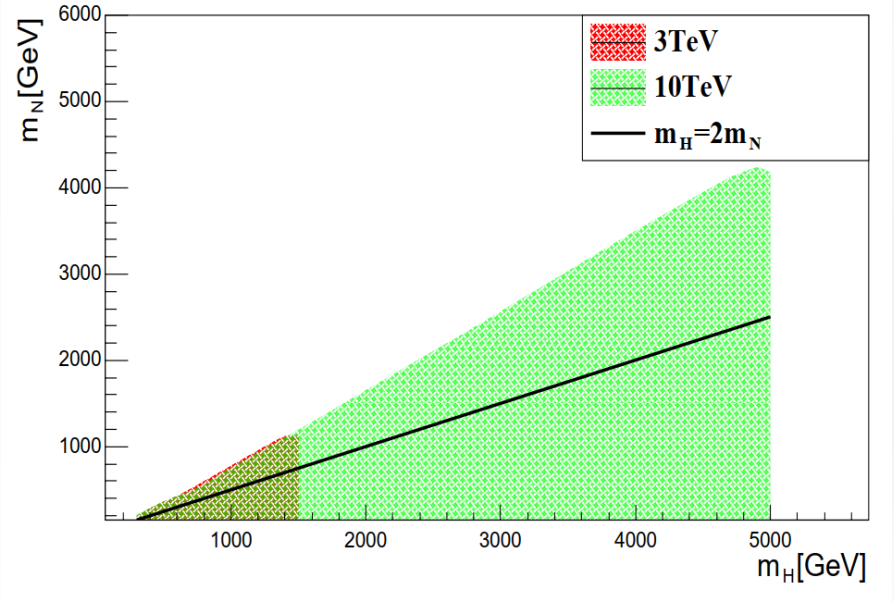
- Same-sign Trilepton

$$\mu^+\mu^- \to Z'H \to \mu^+\mu^- + NN \to \mu^+\mu^- + 2\mu^\pm + 2W^\mp$$

  - Recoil Mass

$$m^2_{\text{rec}} = (\sqrt{s} - E_{\mu^+\mu^-})^2 - p^2_{\mu^+\mu^-}$$



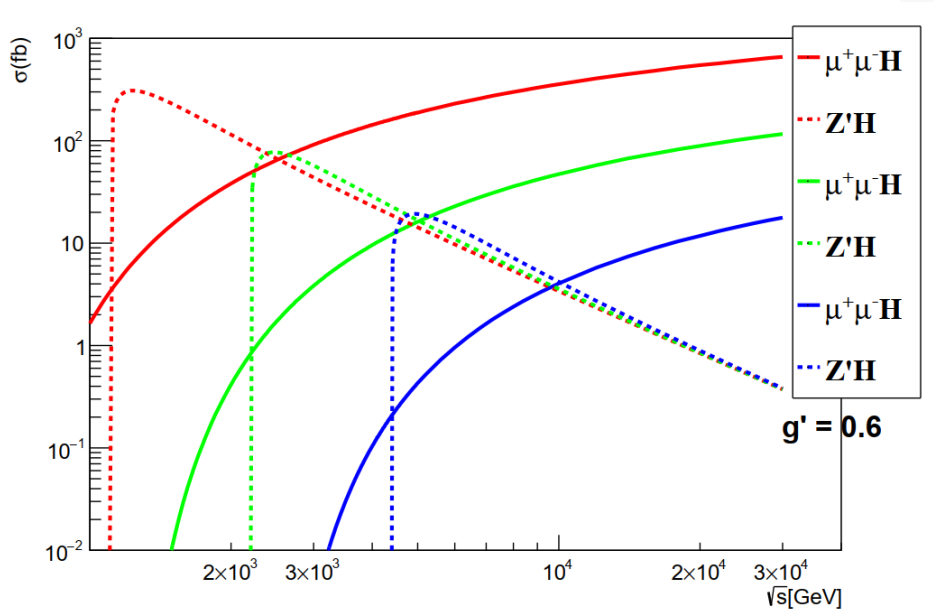


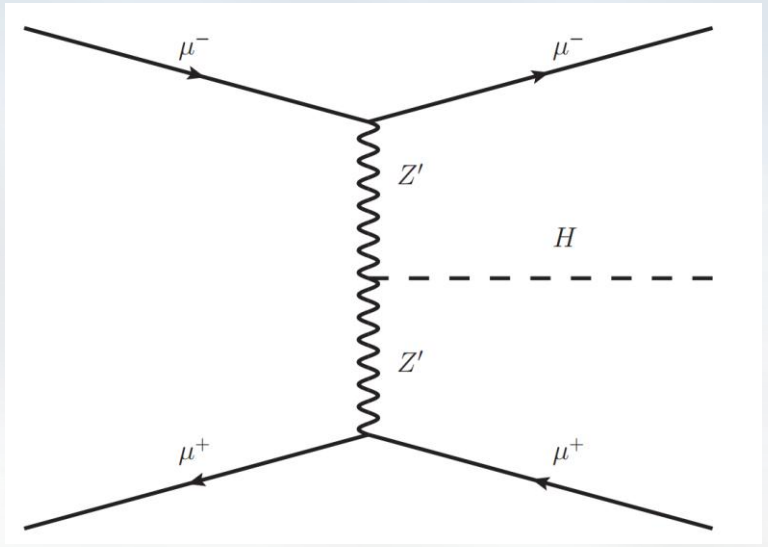
HNL at Muon Collider: Z'Z' Fusion

- New Gauge Boson Fusion

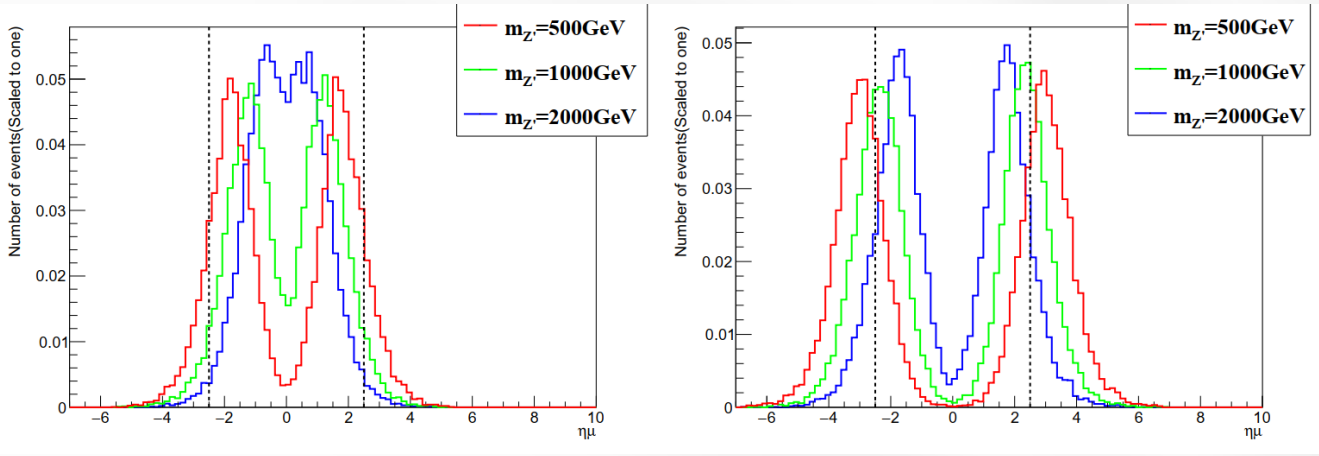
$$\sigma(\mu^+\mu^- \to \mu^+\mu^- H) \simeq$$

$$\frac{g'^6}{32\pi^3 m_{Z'}^2}\left[\left(1+\frac{m_H^2}{s}\right)\ln\frac{s}{m_H^2} - 2\left(1-\frac{m_H^2}{s}\right)\right]$$





- Pseudorapidity of Final State Muons



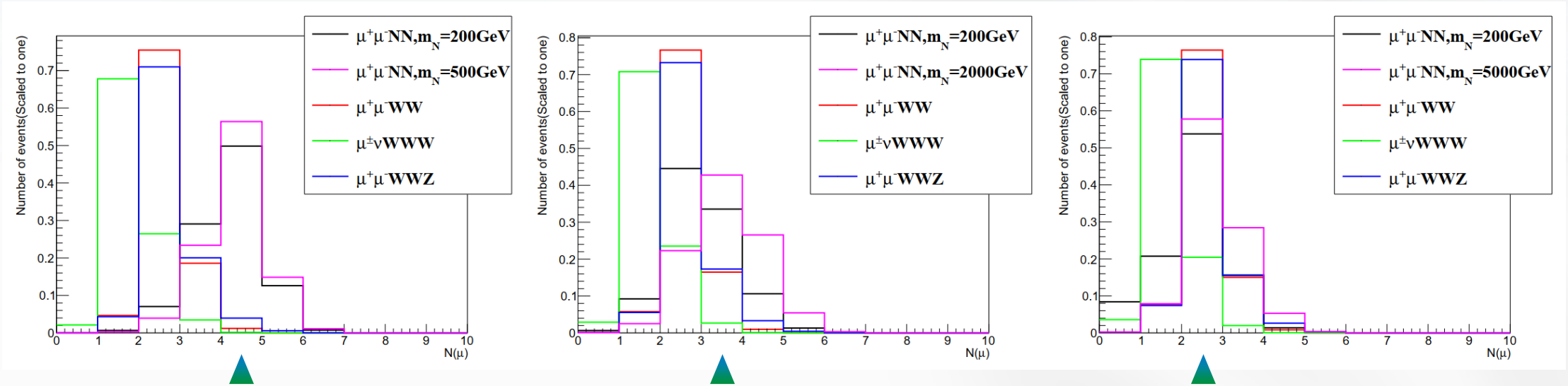
- F.X.Yang, F.L.Shao, **ZLH** and H.Li, [arXiv:2606.19906 [hep-ph]]

HNL at Muon Collider: Z'Z' Fusion

- Lepton Number Violation Signal

$$\mu^+\mu^- \to \mu^+\mu^- H \to \mu^+\mu^- NN \to \mu^+\mu^- + \mu^\pm jj + \mu^\pm jj$$

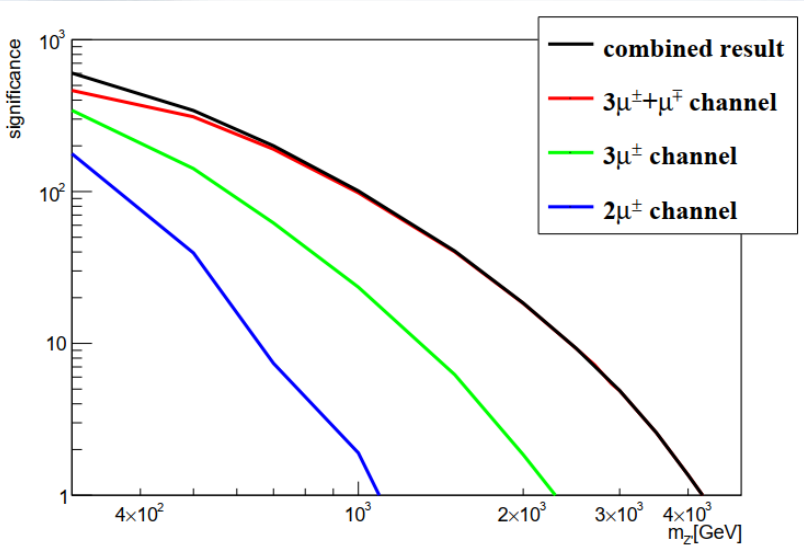
$$\begin{cases} 3\mu^\pm + \mu^\mp \\ 3\mu^\pm \\ 2\mu^\pm \end{cases}$$

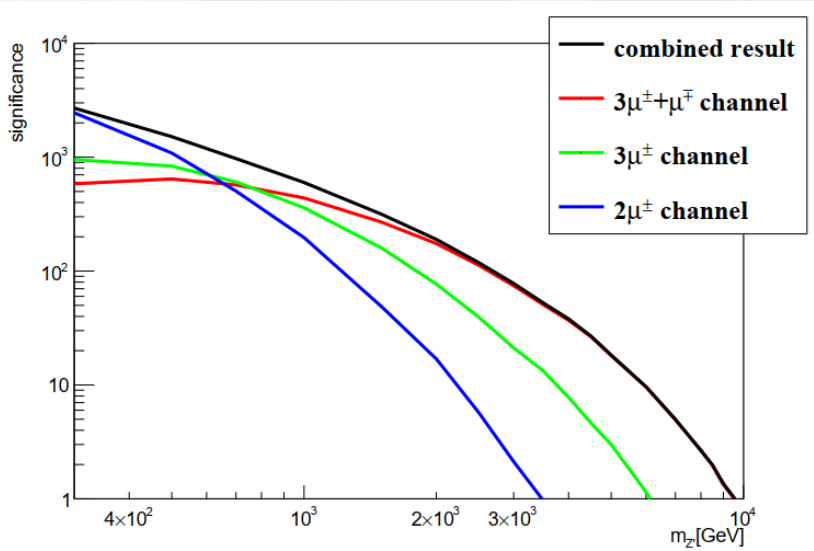


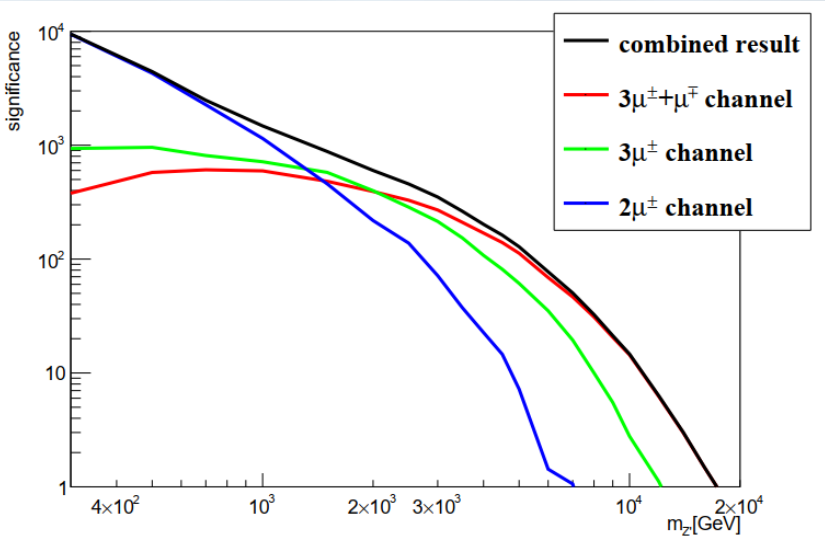
- Combined Significance

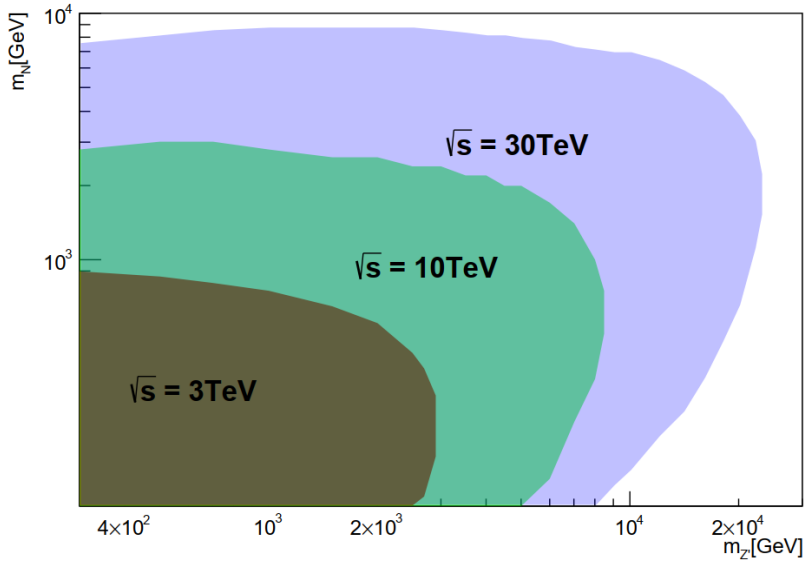
$$S_{\text{comb}} = \sqrt{S^2_{3\mu^\pm+\mu^\mp} + S^2_{3\mu^\pm} + S^2_{2\mu^\pm}}.$$

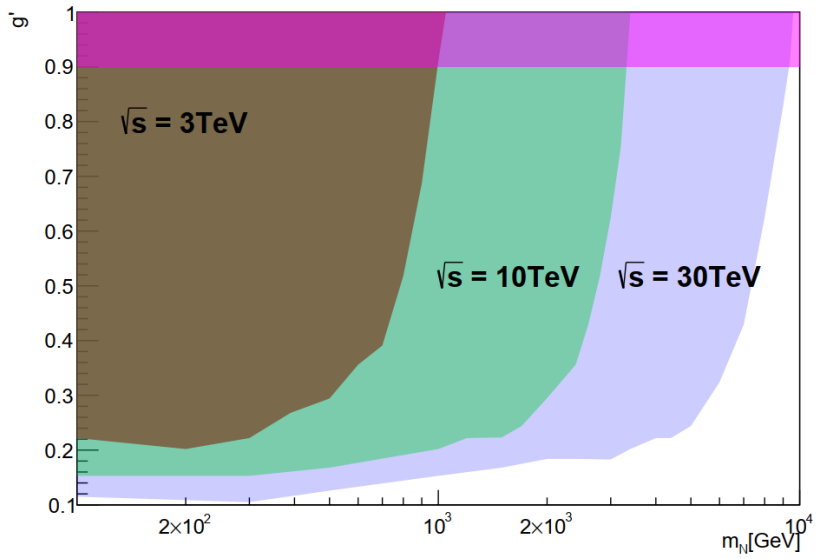
HNL at Muon Collider: Z'Z' Fusion







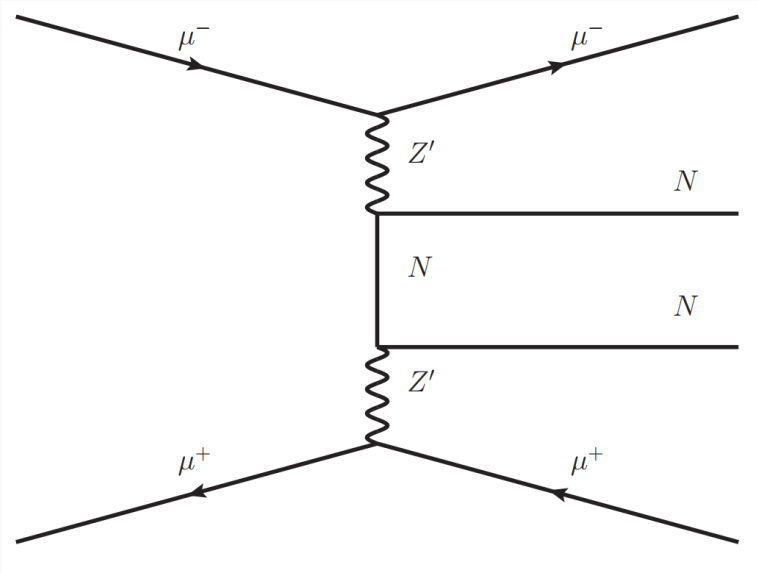


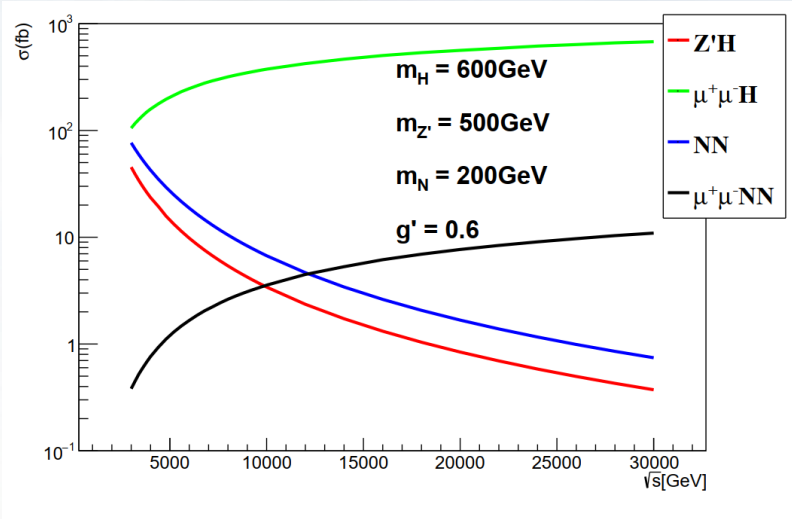


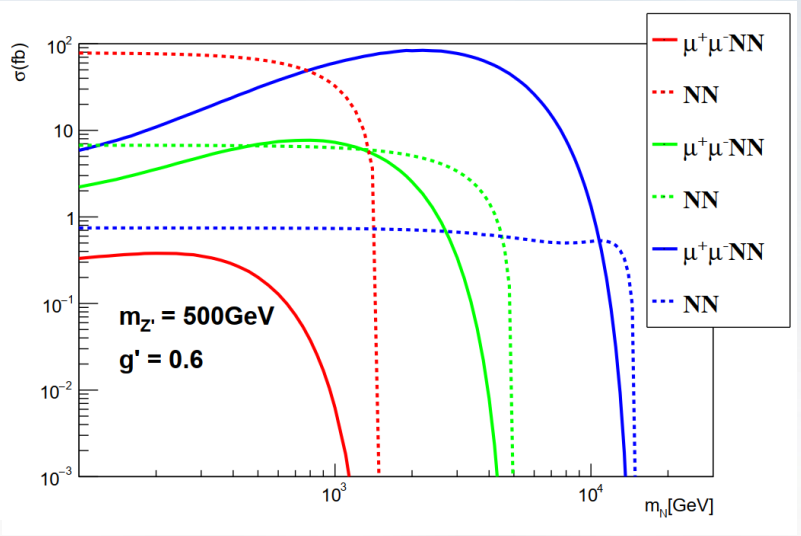
HNL at Muon Collider: Z'Z' Fusion

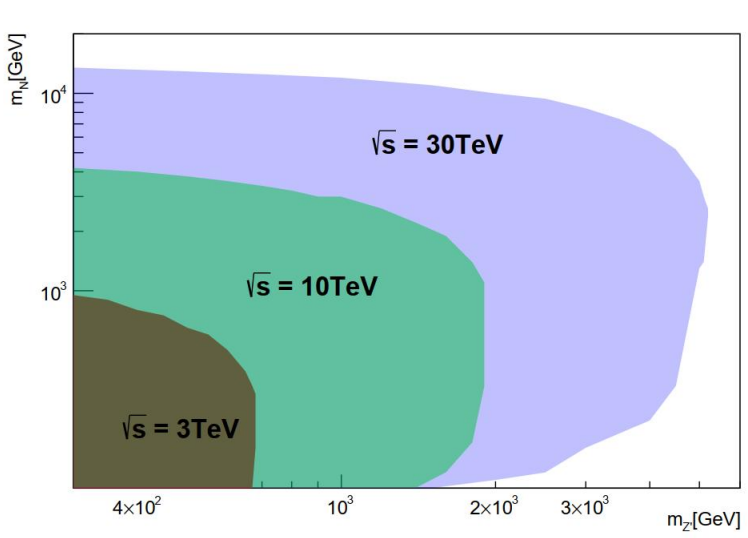
- Direct Fusion without H

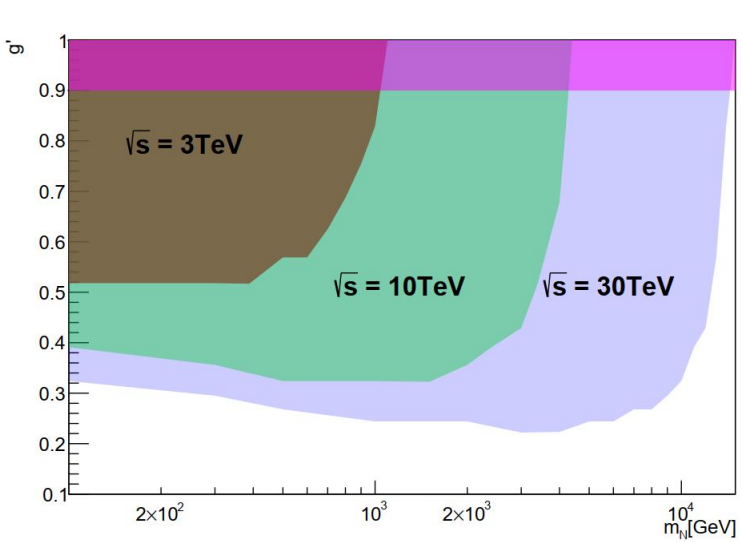
$$\mu^+\mu^- \to \mu^+\mu^- NN$$











Neutrinophilic Two Higgs Doublet Model

- Two Higgs Doublet $L(\Phi_\nu) = -1$

$$\Phi = \begin{pmatrix} \phi^+ \\ (v + \phi^{0,r} + i\phi^{0,i})/\sqrt{2} \end{pmatrix}, \quad \Phi_\nu = \begin{pmatrix} \phi_\nu^+ \\ (v_\nu + \phi_\nu^{0,r} + i\phi_\nu^{0,i})/\sqrt{2} \end{pmatrix}$$

$$\begin{aligned} H^\pm &= \phi^\pm \sin\beta - \phi_\nu^\pm \cos\beta, \\ A &= \phi^{0,i} \sin\beta - \phi_\nu^{0,i} \cos\beta, \\ H &= \phi^{0,r} \sin\alpha - \phi_\nu^{0,r} \cos\alpha, \\ h &= -\phi^{0,r} \cos\alpha - \phi_\nu^{0,r} \sin\alpha, \end{aligned}$$

- The scalar potential

$$\begin{aligned} V = &-m_\Phi^2 \Phi^\dagger\Phi + m_{\Phi_\nu}^2 \Phi_\nu^\dagger\Phi_\nu + \frac{1}{2}\lambda_1(\Phi^\dagger\Phi)^2 + \frac{1}{2}\lambda_2(\Phi_\nu^\dagger\Phi_\nu)^2 \\ &+\lambda_3(\Phi^\dagger\Phi)(\Phi_\nu^\dagger\Phi_\nu) + \lambda_4(\Phi^\dagger\Phi_\nu)(\Phi_\nu^\dagger\Phi) - \left(\mu^2\Phi^\dagger\Phi_\nu + \text{H.c.}\right) \end{aligned}$$

✓ Small VEV

$$v_\nu \simeq \frac{\mu^2 v}{m_{\Phi_\nu}^2 + (\lambda_3 + \lambda_4)v^2/2}$$

- New Yukawa interaction

$$-\mathcal{L}_N = y\overline{L}\widetilde{\Phi}_\nu N$$

✓ Tiny Neutrino Mass

$$m_\nu = -\frac{1}{2}v_\nu^2 y m_N^{-1} y^T$$

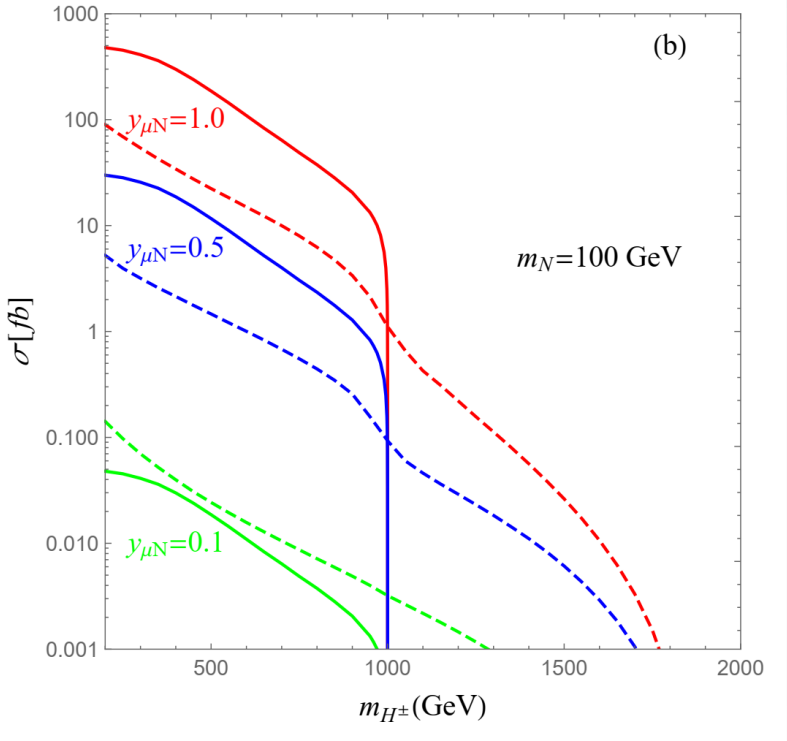
➢ E.Ma, Phys. Rev. Lett. 86, 2502-2504 (2001)

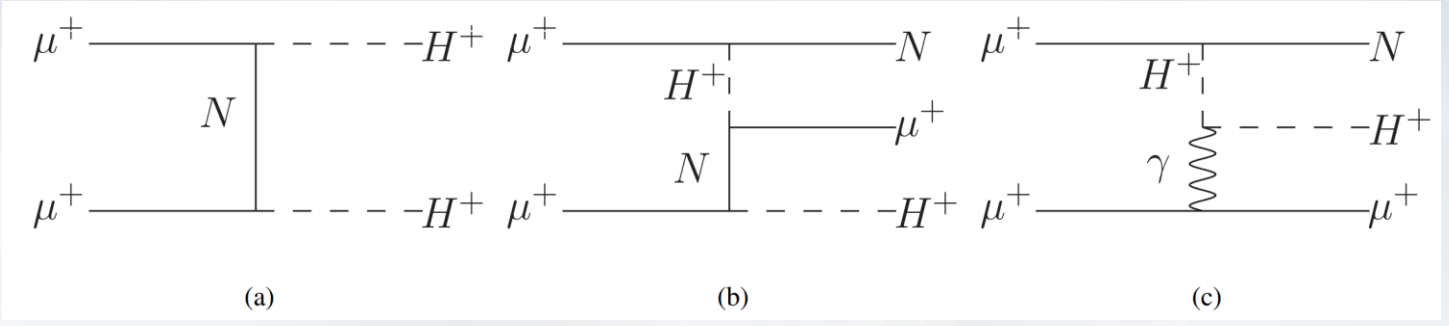
HNL at Muon Collider: Charged Higgs

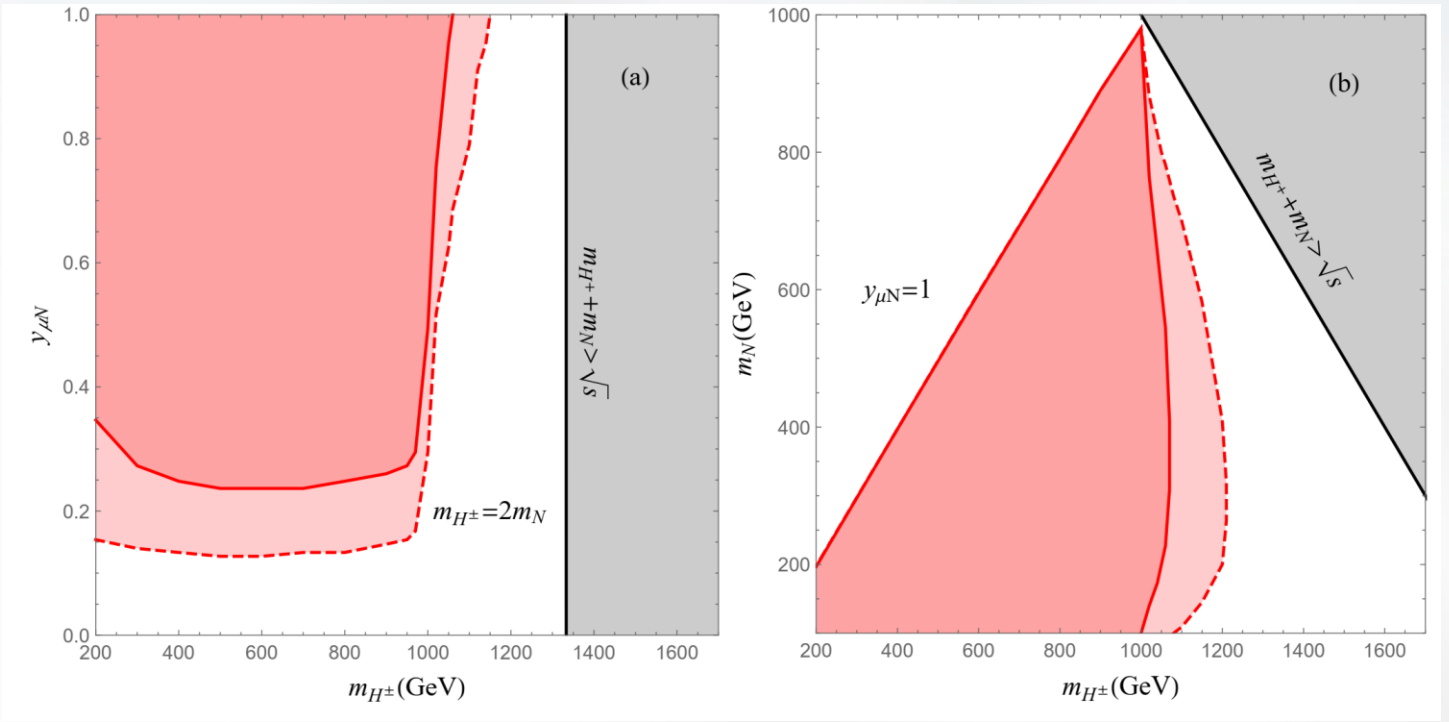
- Same-Sign Muon Collider

$$\mu^+\mu^+ \to H^+H^+ \to \mu^+N + \mu^+N,$$

$$\mu^+\mu^+ \to \mu^+H^+N \to \mu^+ + \mu^+N + N$$



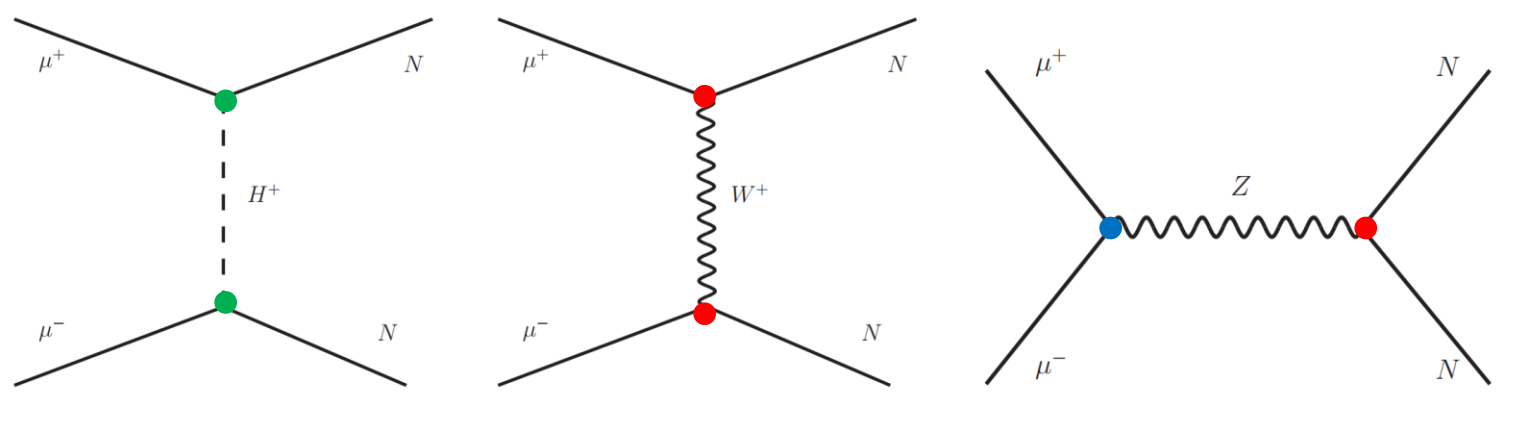


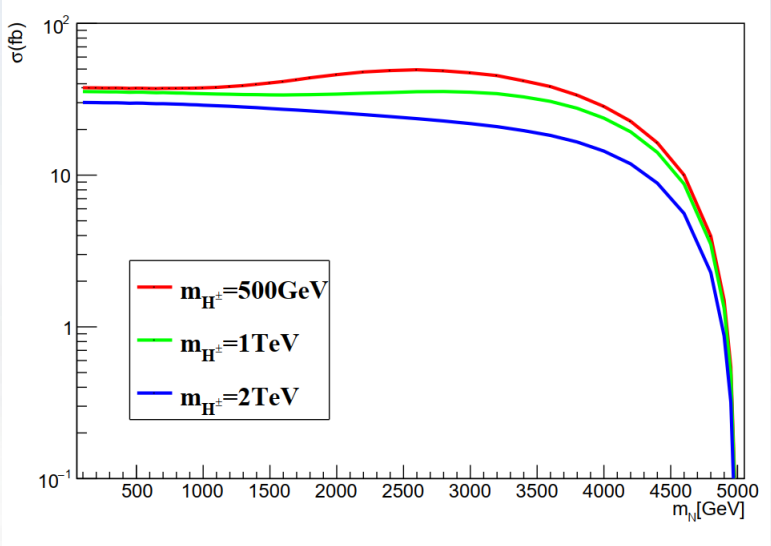


➢ L.K.Yan, **ZLH**, F.L.Shao and F.X.Yang, [arXiv:2604.24383 [hep-ph]]

HNL at Muon Collider: Charged Higgs

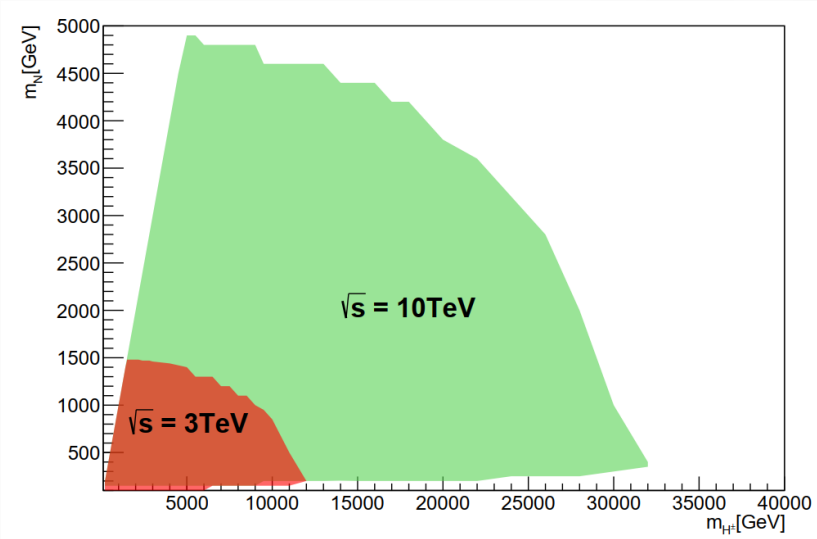
- Pair Production of HNL $\mu^+\mu^- \to NN$

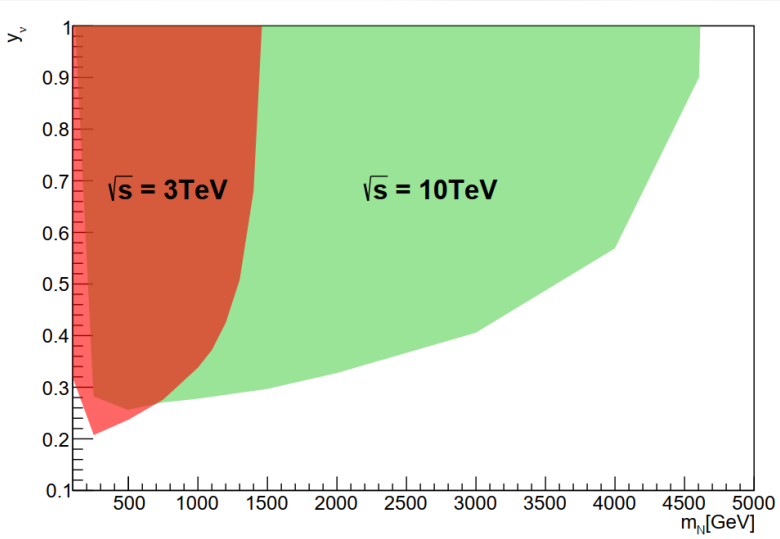




- Lepton Number Violation Signal

$$\mu^+\mu^- \to NN$$
$$\to \mu^\pm jj\mu^\pm jj$$





Conclusion

- Muon Collider is Promising to Probe HNL via
  - Mixing with ν
  - Vector Boson Scattering
  - Associated Production
  - Gauge Boson Z'
  - Higgs h, H
  - Charged Higgs $H^{\pm}$
  - …