# Searching for heavy neutral lepton and LNV through VBS at muon colliders

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## 1. Muon collider

Recently, due to the technological breakthrough of the ionization cooling by the MICE, the establishment of the muon collider has rekindled hope and again received much attention in the community. The muon collider represents an ideal machine with the advantages of high c.m. energy, high integrated luminosity, high utilization efficiency of energy, clean background environment and so on. Thus, it has a great potential for the search of new high energy physics. As shown in Fig. 1, there are two mainly proton and positron driver schemes.

At the high-energy muon colliders, the initial muon beams substantially emit the electroweak gauge bosons under an approximately unbroken SM gauge symmetry. The gauge bosons are associated with muons or muon-neutrinos in the forward region with respect to the beam. The behave of EW gauge bosons like initial state partons and lead to vector boson scattering (VBS) processes. The VBS becomes an increasingly important mode as colliding energies go higher. As an instance, the $t\bar{t}$ pair prodcution at muon collider, the contribution of total cross section from VBS process is more important than $\mu\mu$ annihilation process, as shown in Fig. 2.

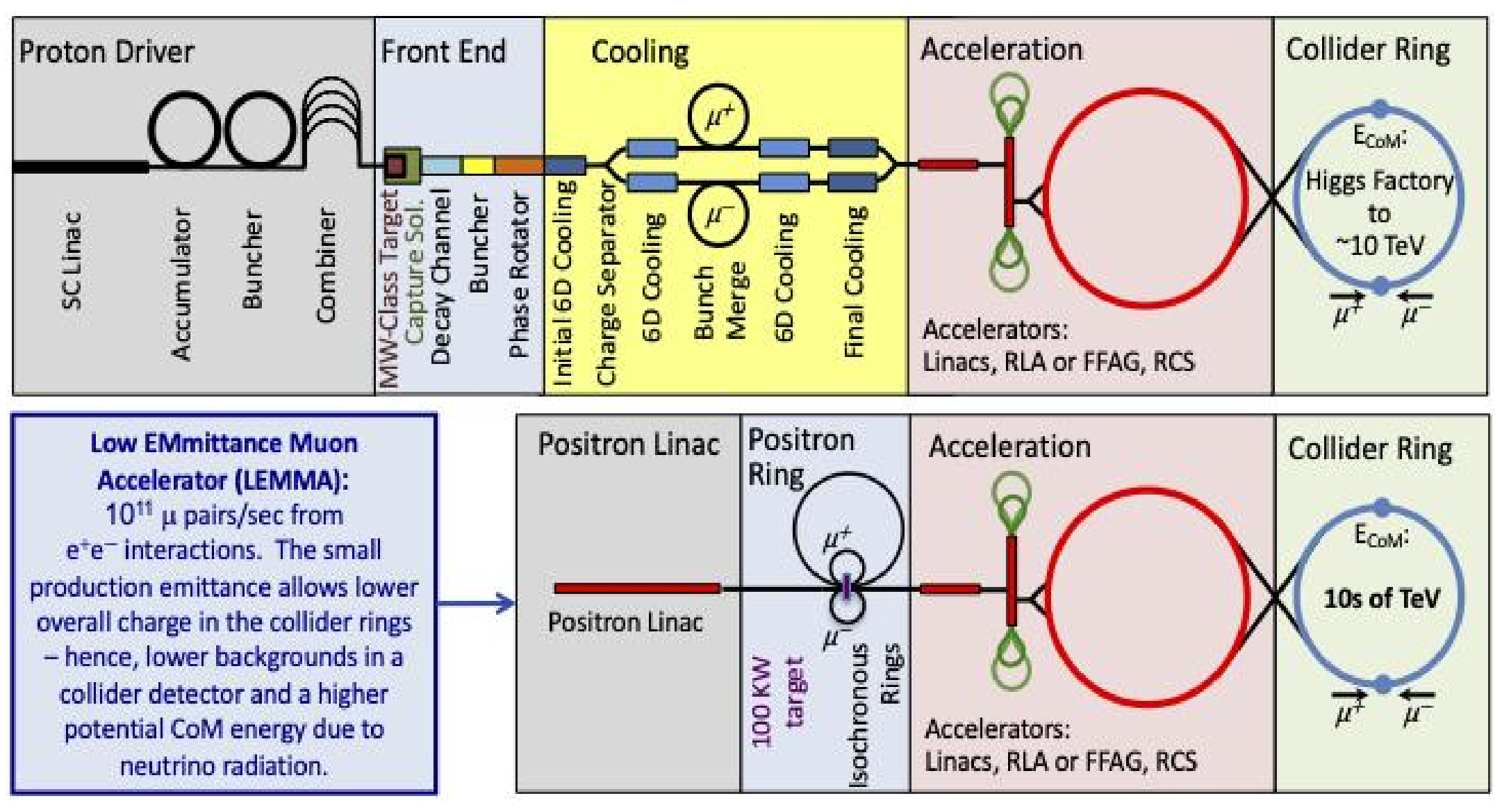

**Fig. 1 The schematic layout of the muon collider based on two kinds of source scheme. [arXiv:1808.01858]**

## 2. HNLs

It is well-know that, the neutrino masses can be realized at leading order through a dimension-5 operator $LLHH$. The minimal UV realization of this operator is the Type I Seesaw mechanism. The right-handed neutrinos can possess a Majorana mass term ($M_R$) and they are usually referred as the heavy neutral leptons (HNLs) which will be denoted as the $N$ below. The HNLs can be realized in canonical Type I and Type III Seesaw mechanisms. The neutrino Yukawa interactions in Type I Seesaw are

$$-\mathcal{L}_Y^I = Y_\nu^D \bar{\ell}_L \tilde{H} N_R + \frac{1}{2}\overline{(N^c)_L} M_R N_R + \text{h.c.}$$

After the mass mixing, one can obtain an important mixing matrix $V_{\ell N}$ transiting heavy neutrinos to charged leptons in the mixed mass-flavor basis.

$$\mathcal{L}_{\text{Type-I}} \supset -\frac{g}{\sqrt{2}} W_\mu^- \sum_{\ell=e}^{\tau} \Big( \sum_{m=1}^{3} \bar{\ell} (U_{\text{ PMNS}})_{\ell m} \gamma^\mu P_L \nu_m + \sum_{m'=1} \bar{\ell} (V_{\ell N})_{\ell m'} \gamma^\mu P_L N_{m'}^c \Big) + \text{h.c.}$$

$$-\frac{g}{2\cos\theta_W} Z_\mu \sum_{\ell=e}^{\tau} \Big( \sum_{m=1}^{3} \bar{\nu}_\ell (U_{\text{PMNS}})_{\ell m} \gamma^\mu P_L \nu_m + \sum_{m'=1} \bar{\nu}_\ell (V_{\ell N})_{\ell m'} \gamma^\mu P_L N_{m'}^c \Big) + \text{h.c.}$$

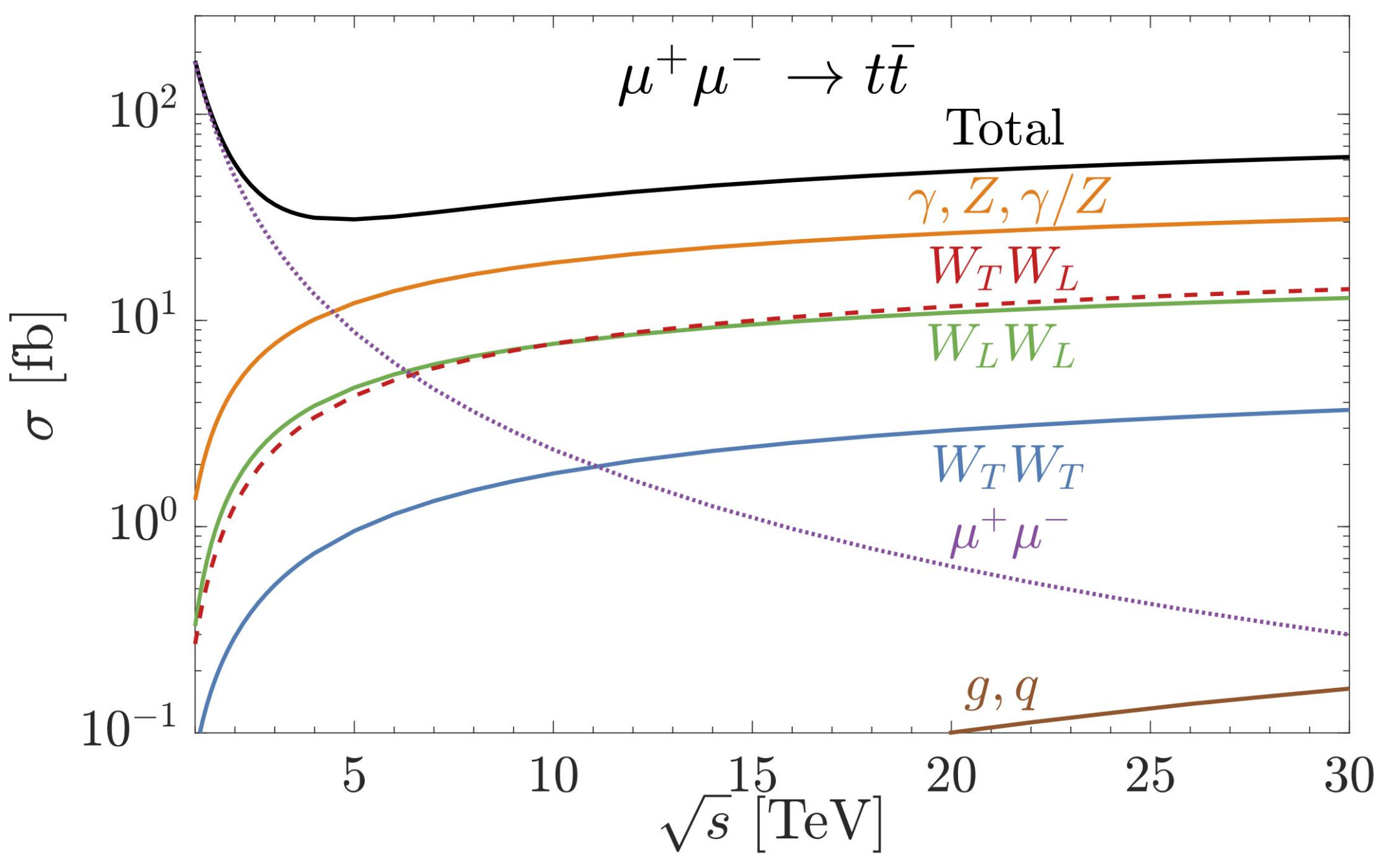

**Fig. 2 The cross section for $t\bar{t}$ pair production at muon collider versus the c.m. energy. [arXiv:2007.14300]**

Recently, there arose quite a few studies of searching for HNL at muon colliders. They proposed that an HNL can be produced together with a light neutrino $\nu_\ell$, $\mu^+\mu^- \to N_\ell\, \bar{\upsilon}_\ell$, which cannot tell whether the HNL is Majorana or Dirac fermion because of the missing neutrino in final states. An alternative approach to search for Majorana neutrino is to consider the inverse $0\nu\beta\beta$-like channel $\mu^+\mu^+ \to W^+W^+$ which however relies on a same-sign muon collider.

## 3. Results

In this work, we propose a clear way to search for the HNLs and obtain the exclusion limit on mixing matrix $V_{\ell N}$ at muon colliders. The LNV signatures can be produced through VBS processes

$$\mu^+\mu^- \text{ collider}: \ W^\pm Z/\gamma \to \ell^\pm N \to \ell^\pm \ell^\pm W^\mp \to \ell^\pm \ell^\pm q\bar{q}'$$

$$\mu^+\mu^+ \text{ collider}: \ W^+W^+ \to \ell^+\ell^+$$

For muon collider with c.m. energy $\sqrt{s}$ = 3 TeV, 10 TeV and 30 TeV, the corresponding integrated luminosities are 1 ab$^{-1}$, 10 ab$^{-1}$ and 90 ab$^{-1}$, respectively.

- $V_{\mu N}$

The $2\sigma$ exclusion limits to the mixing parameter $|V_{\mu N}|^2$ through VBS processes at the $\mu^+\mu^-$ and $\mu^+\mu^+$ muon colliders are shown in Fig. 3. Compared to the results, which from muon annihilation processes ($\mu^+\mu^- \to N_\ell\, \bar{\upsilon}_\ell$) in the previous studies, our probing potential of mixing parameter is worse, but we provide a clear LNV signature as a complement by the VBS processes at future high-energy muon colliders.

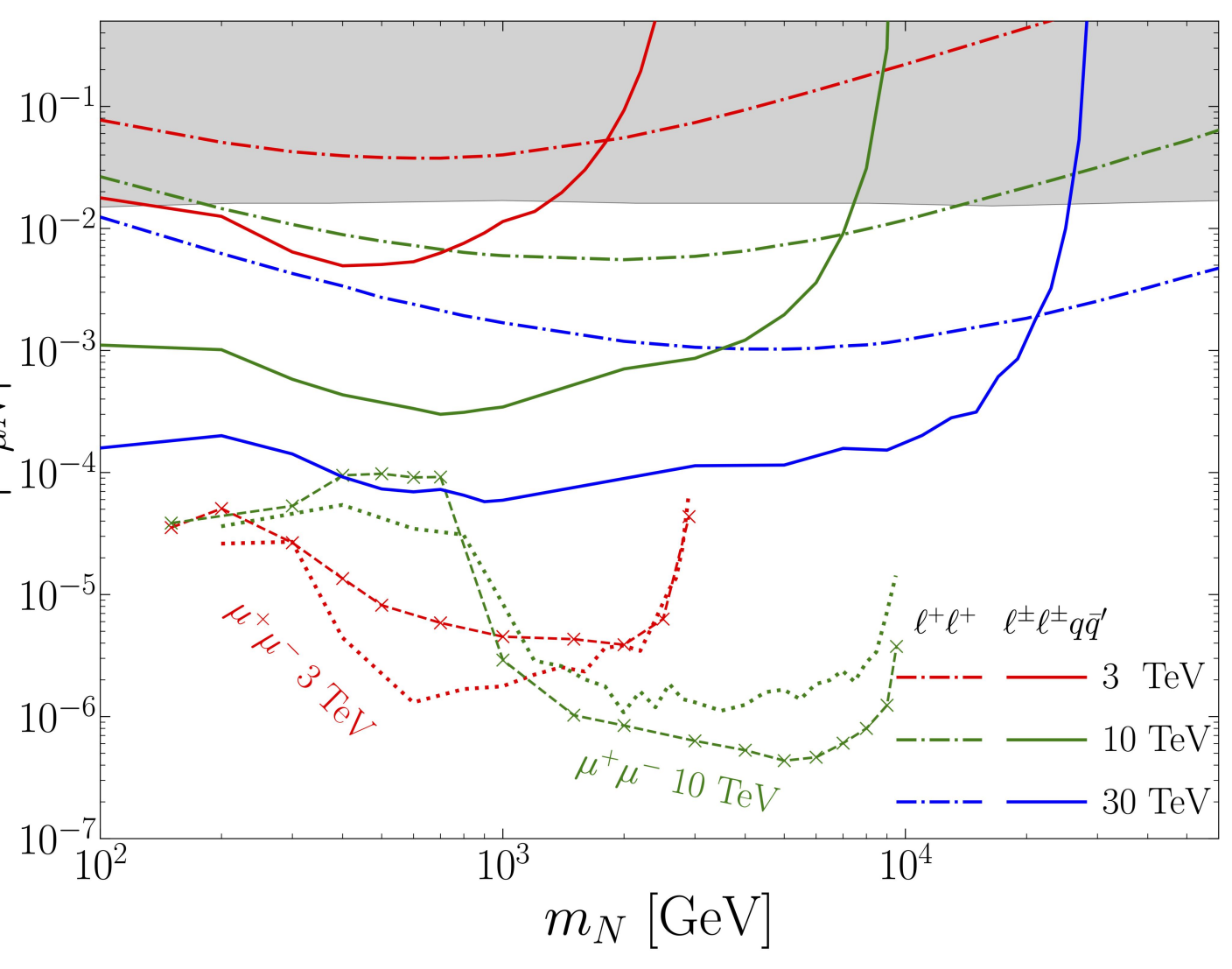

**Fig. 3 The $2\sigma$ exclusion limits to $|V_{\mu N}|^2$ at $\mu^+\mu^-$ and $\mu^+\mu^+$ collider.**

- $V_{eN}$

However, for mixing parameters related to the electron $|V_{eN}|^2$, the exclusion limits are stronger than that through annihilation channel for $\sqrt{s}$= 10 TeV and above. The reason is that the electronic HNL is only produced by annihilation via s-channel and its production cross section is exceeded by VBS production at high energies.

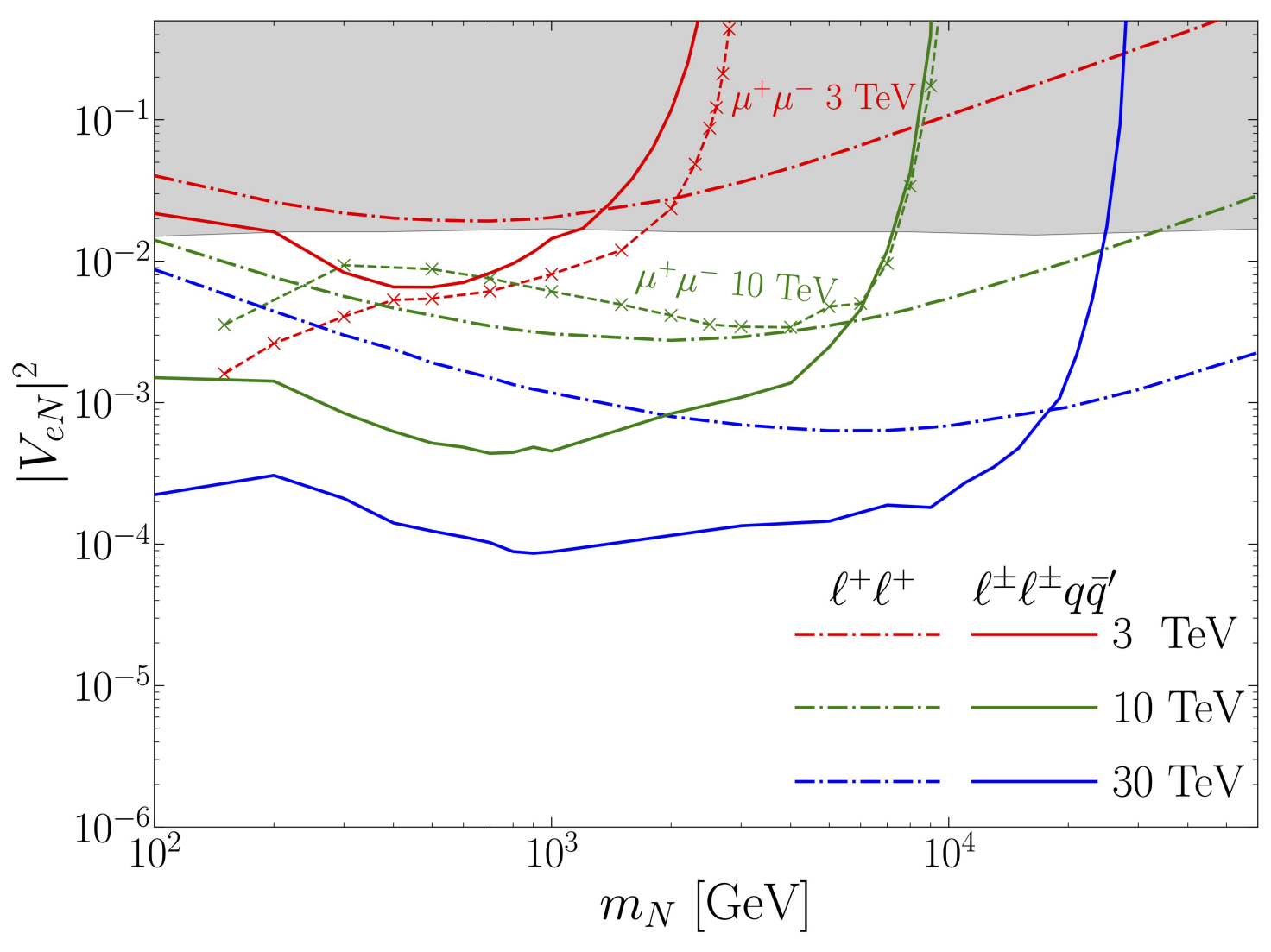

**Fig. 4 The $2\sigma$ exclusion limits to $|V_{eN}|^2$ at $\mu^+\mu^-$ and $\mu^+\mu^+$ collider.**

- $V_{eN}V_{\mu N}$

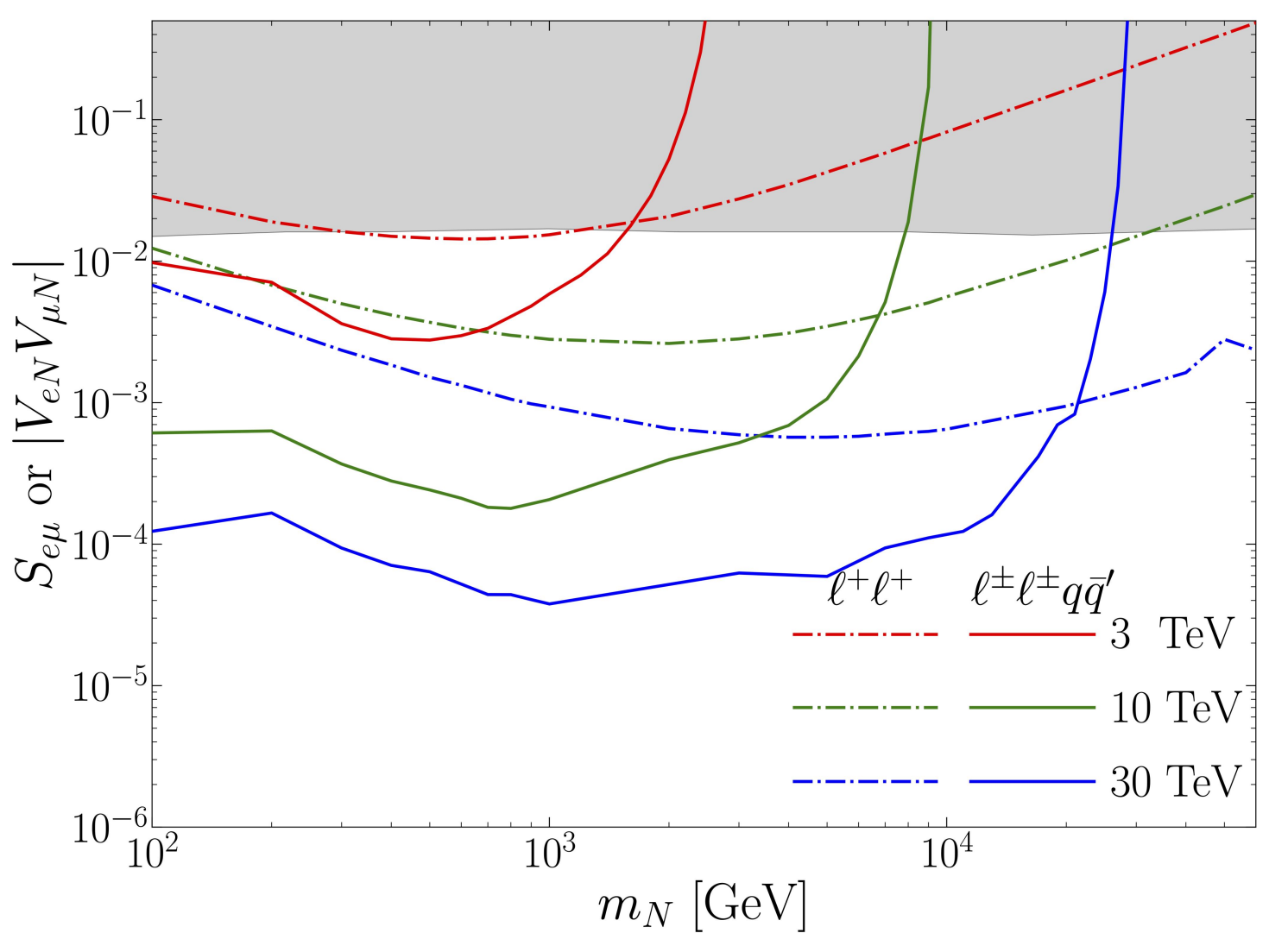

**Fig. 5 The $2\sigma$ exclusion limits to $|V_{eN}V_{\mu N}|^2$ at muon collider.**

Moreover, for different charged lepton flavors, we can also provide a clean LNV signature through the VBS process at the muon colliders. The $2\sigma$ exclusion limits for the combination of two parameters $|V_{eN}V_{\mu N}|$ are shown in Fig. 5.

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